ALMA studies of young eruptive stars

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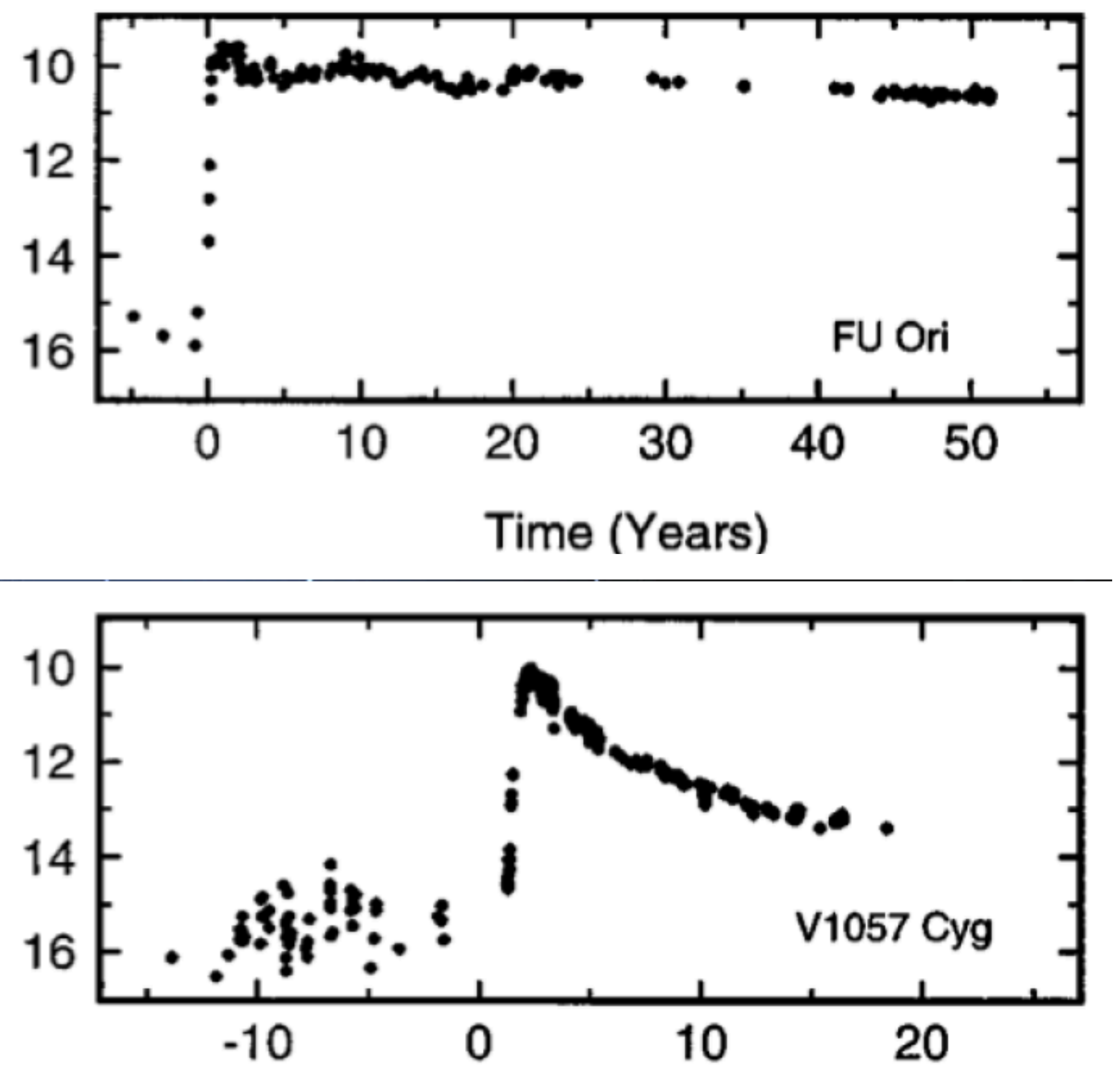
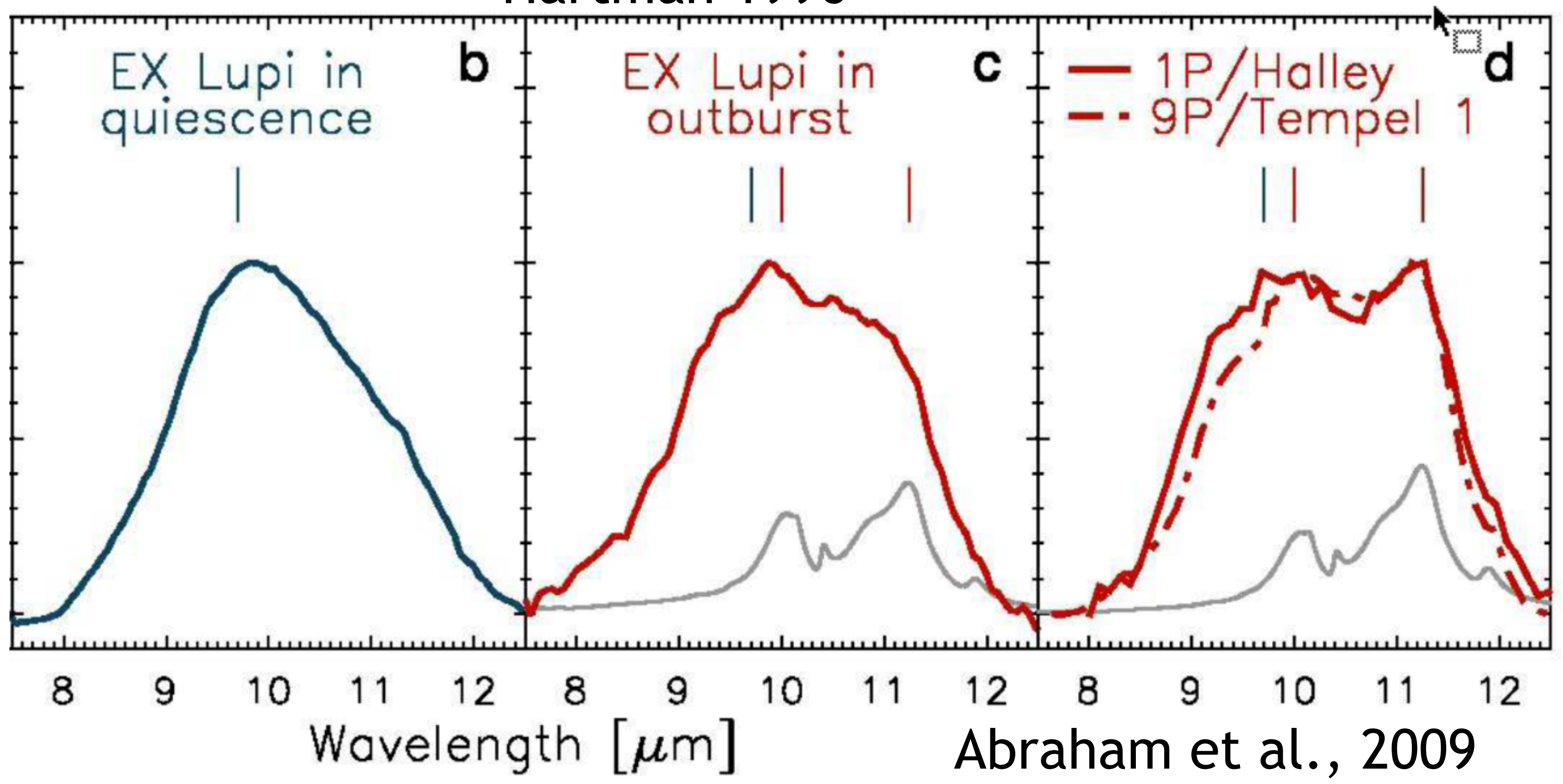
NRAO/ALMA

Accretion Bursts in Low-Mass stars



Hartman 1996



Abraham et al., 2009

Episodic Accretion is Key

$\dot{M}_{acc}$: 10^{-8} $M_\odot$ yr^{-1} → 10^{-4} $M_\odot$ yr^{-1}

Accrete fraction of total stellar mass

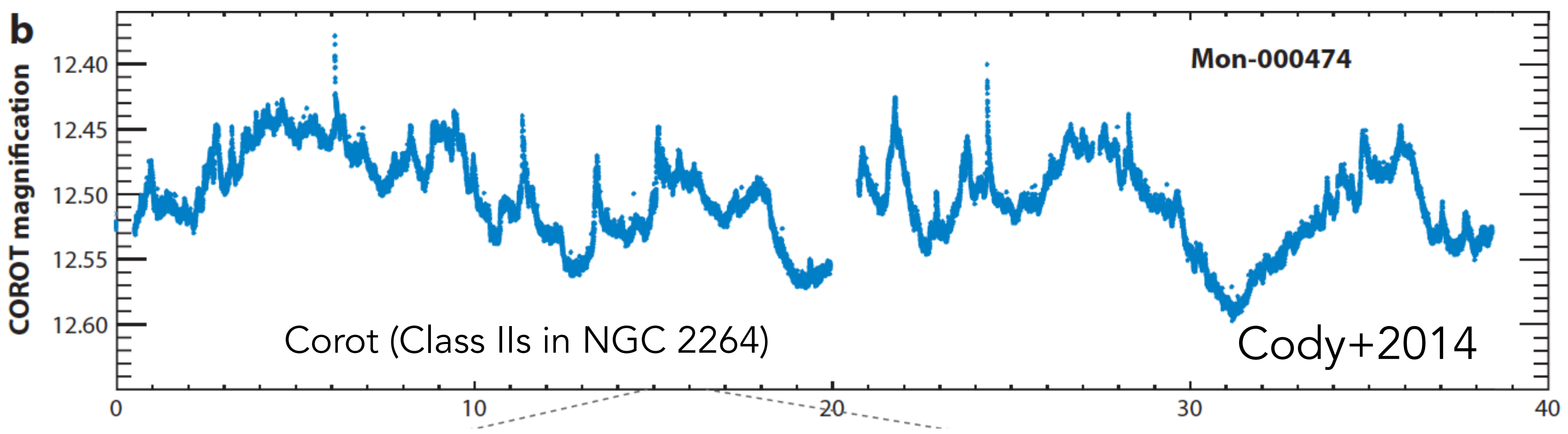
Solve the 'Luminosity Problem'

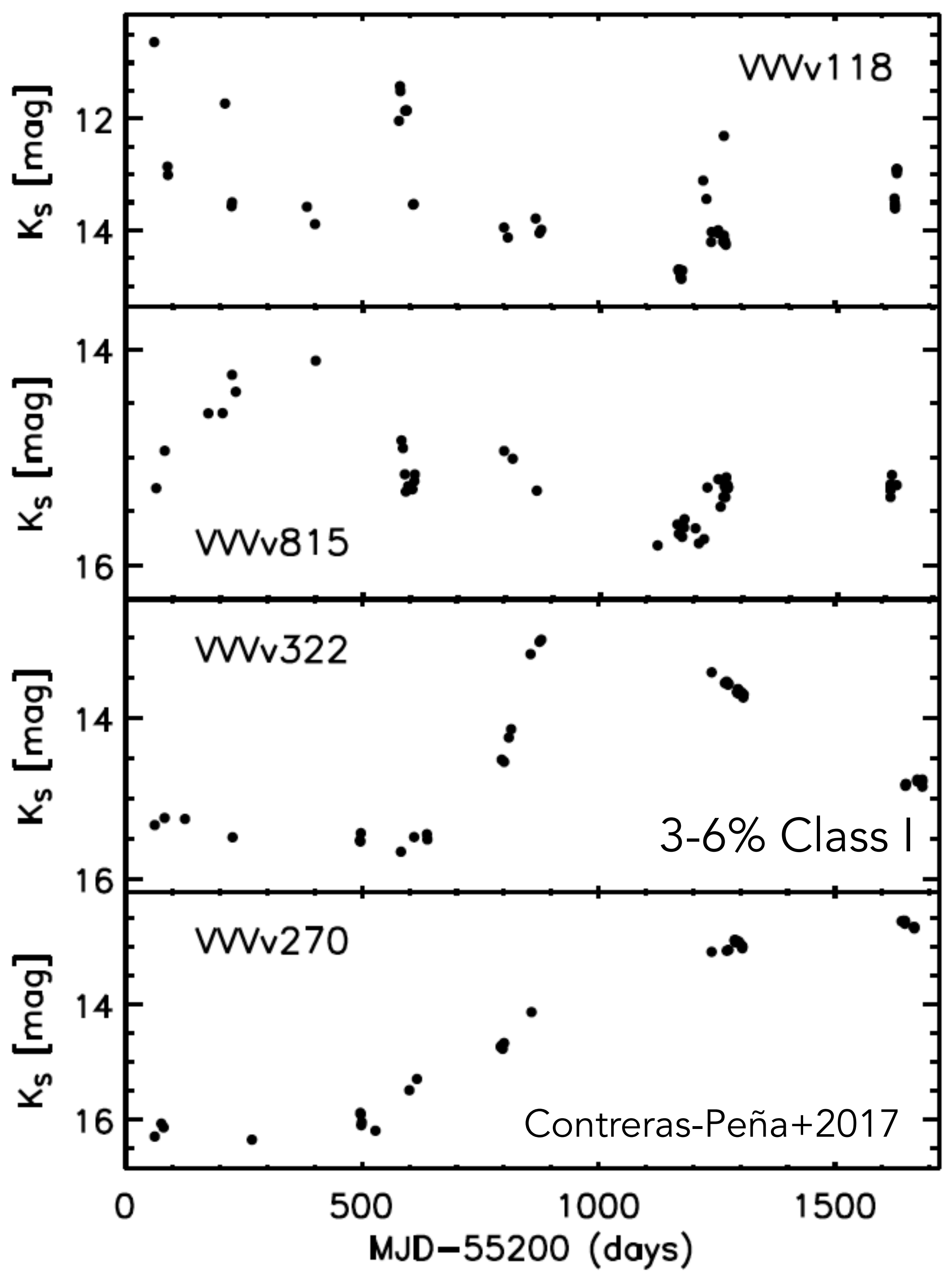
Drive Evolution of Disk Material

change properties of dust grains
disk chemistry
re-condensation of Ices, planet formation
self-regulation through outflows

Hartmann& Kenyon 1996, Hartmann 2008, 2016, Evans+2009, Kenyon 1990, Dunham & Vorobyov 2012, Juhasz+2012, **Abraham+2009**, Visser & Bergin 2012, Hubbard 2017

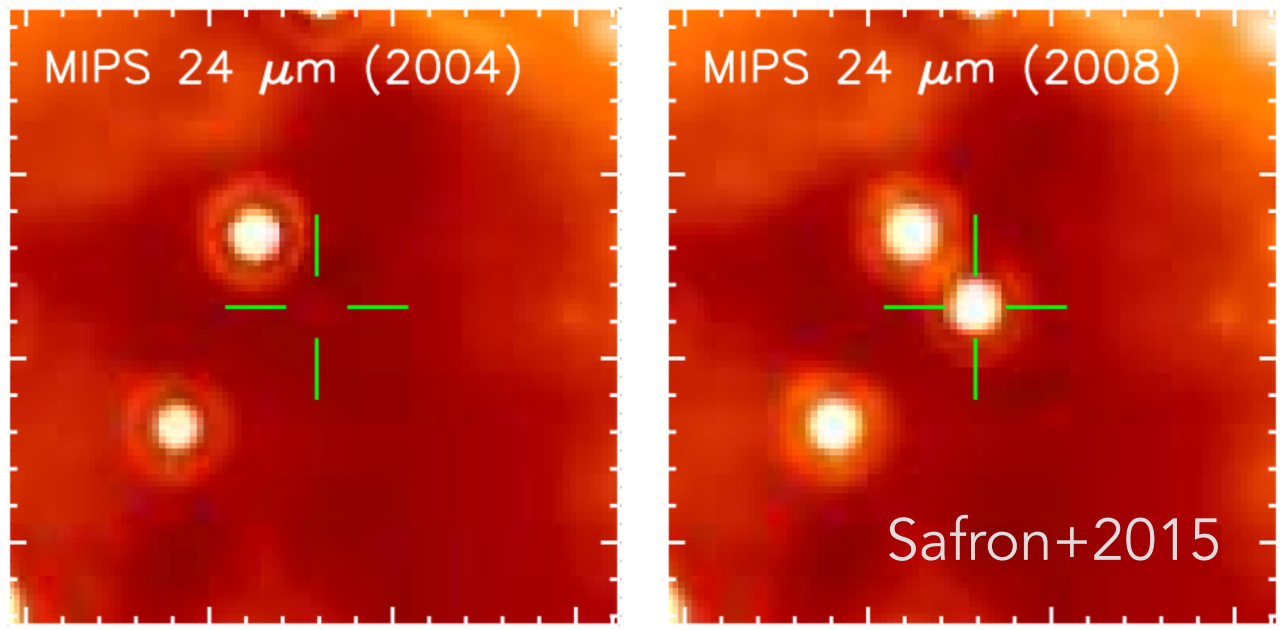
Outburst are common:

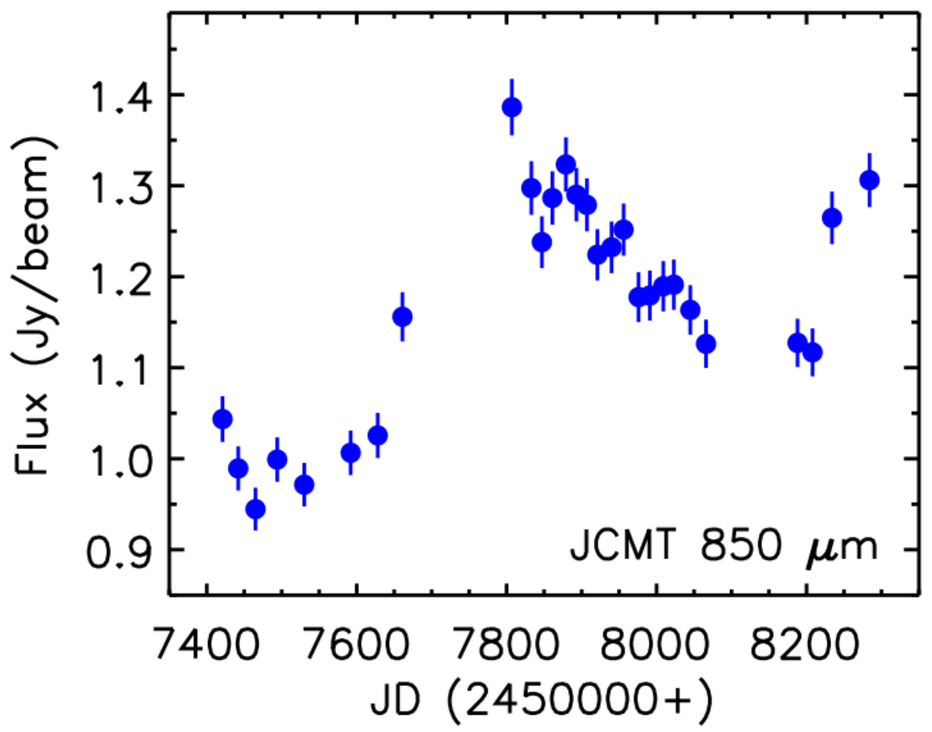


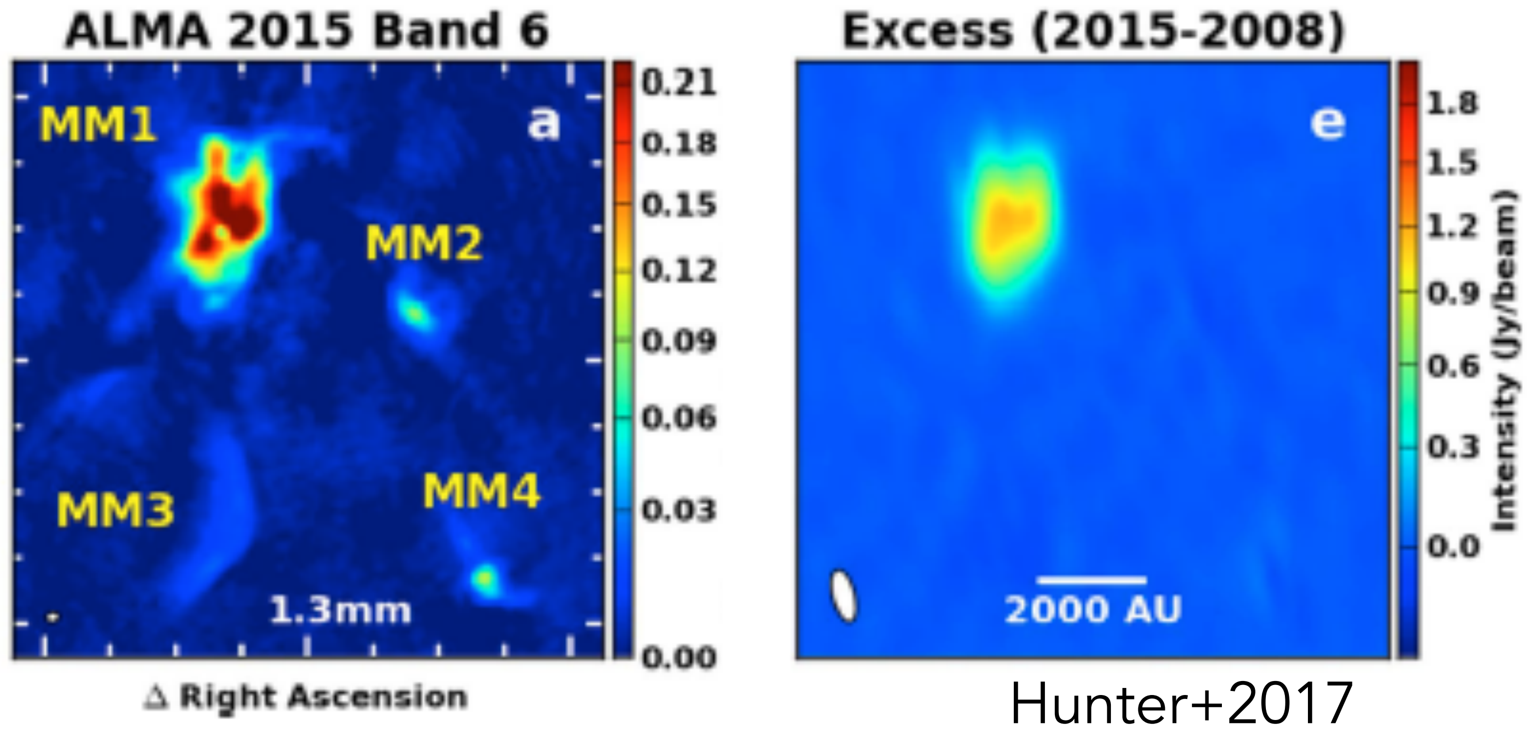


- Systematic wide field surveys (supplanting amateur astronomers) find 1 star/yr (1 outburst every 10^{-4} per accreting star per year).
- Optical Bias, not many Class 0s.
- Now variability detected in IR, submm, Class 0s and even massive protostars.
- LSST will discover thousands of eruptive variables;

JCMT finds 10% increase flux bv >5% (20% acc)







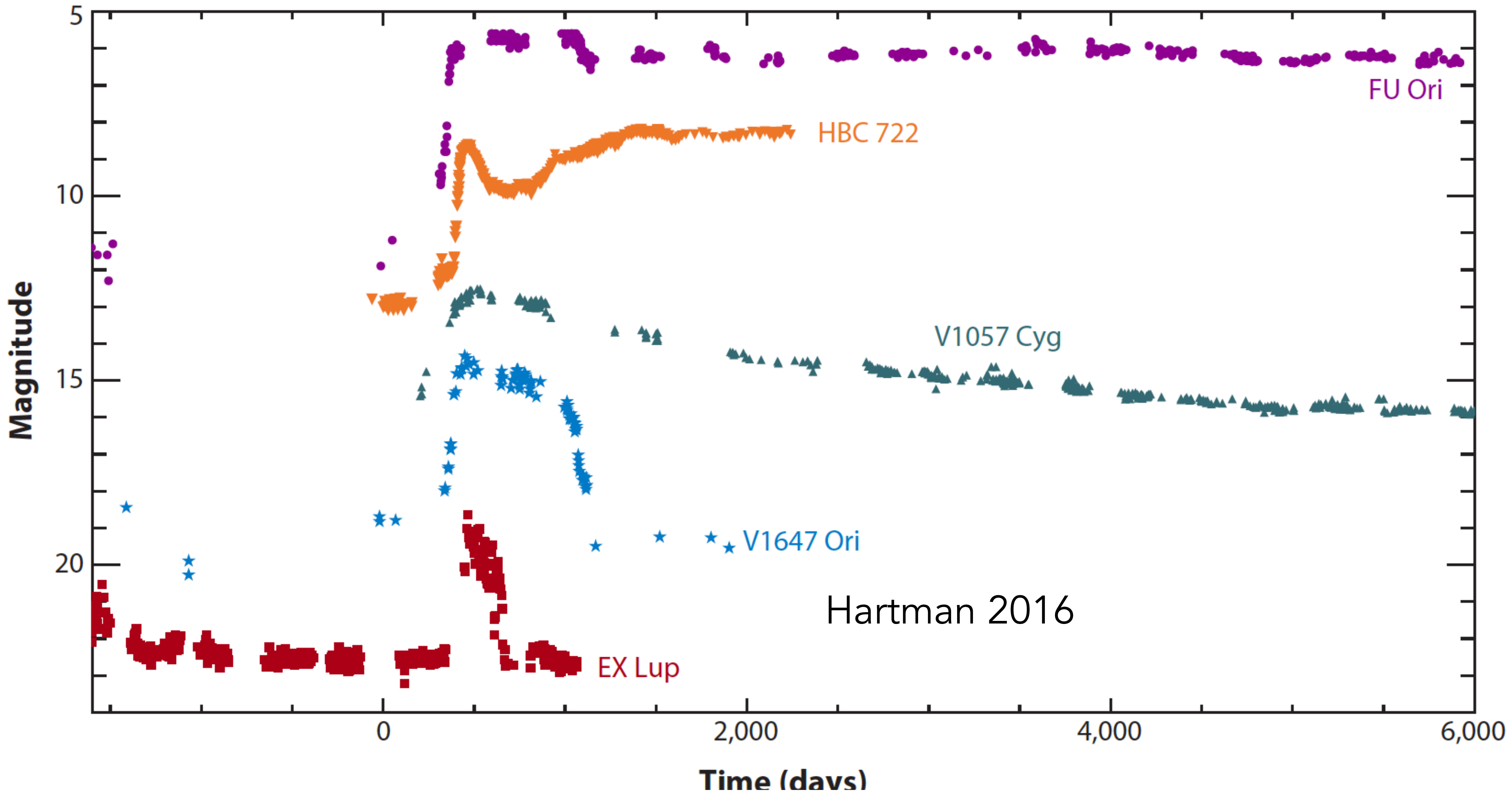
Billot+2012,Safron+2015, Hillenbrand+2015, Hartmann 2016, Hunter+2017, Yoo+2017, Contreras-Peña+2017, Johnstone+2018, Fischer+2019

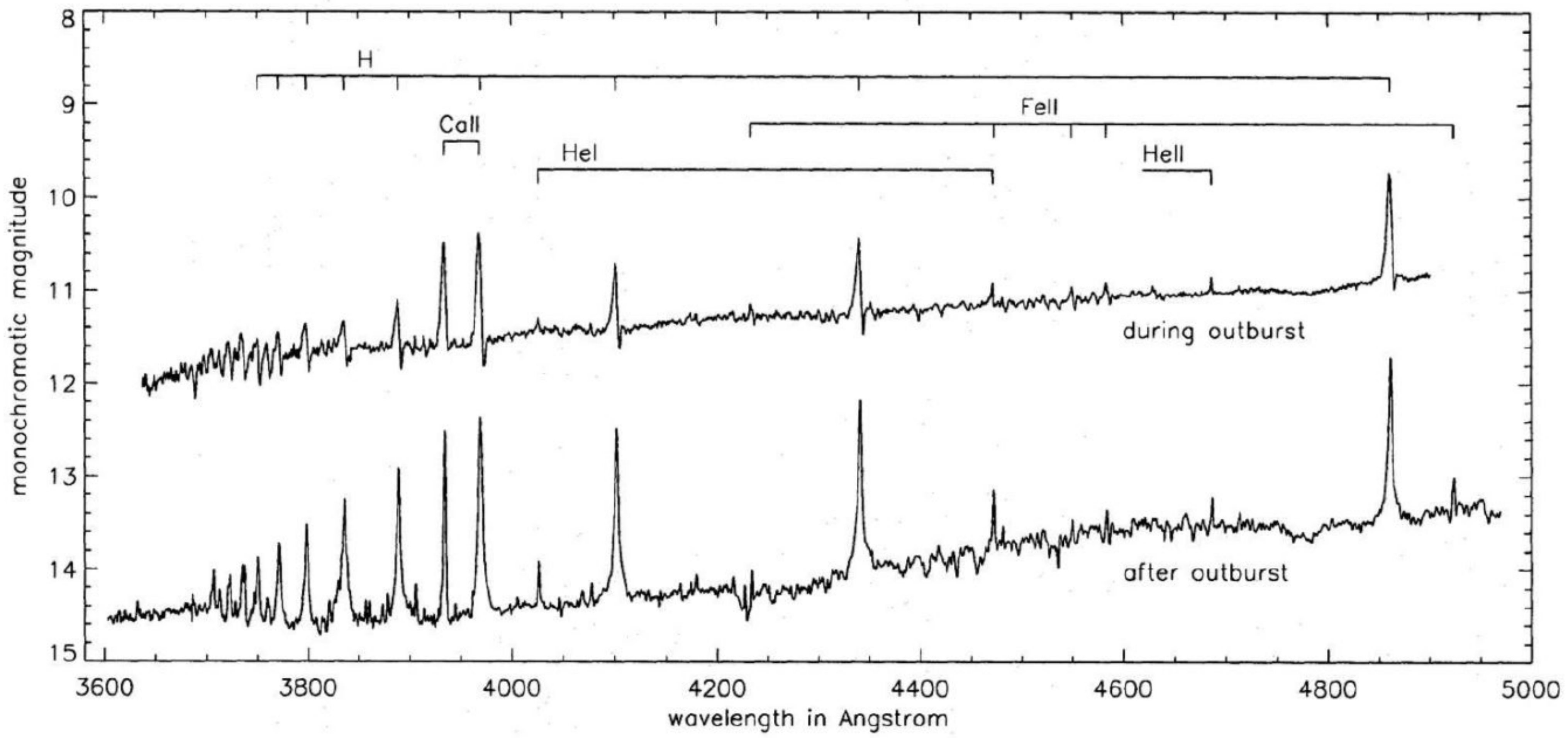
EXors (mis-named after EX Lupi)

Smaller and Shorter outbursts than FUors: 2-4 > mags, 10-100 fold accretion rate
Duration days/months

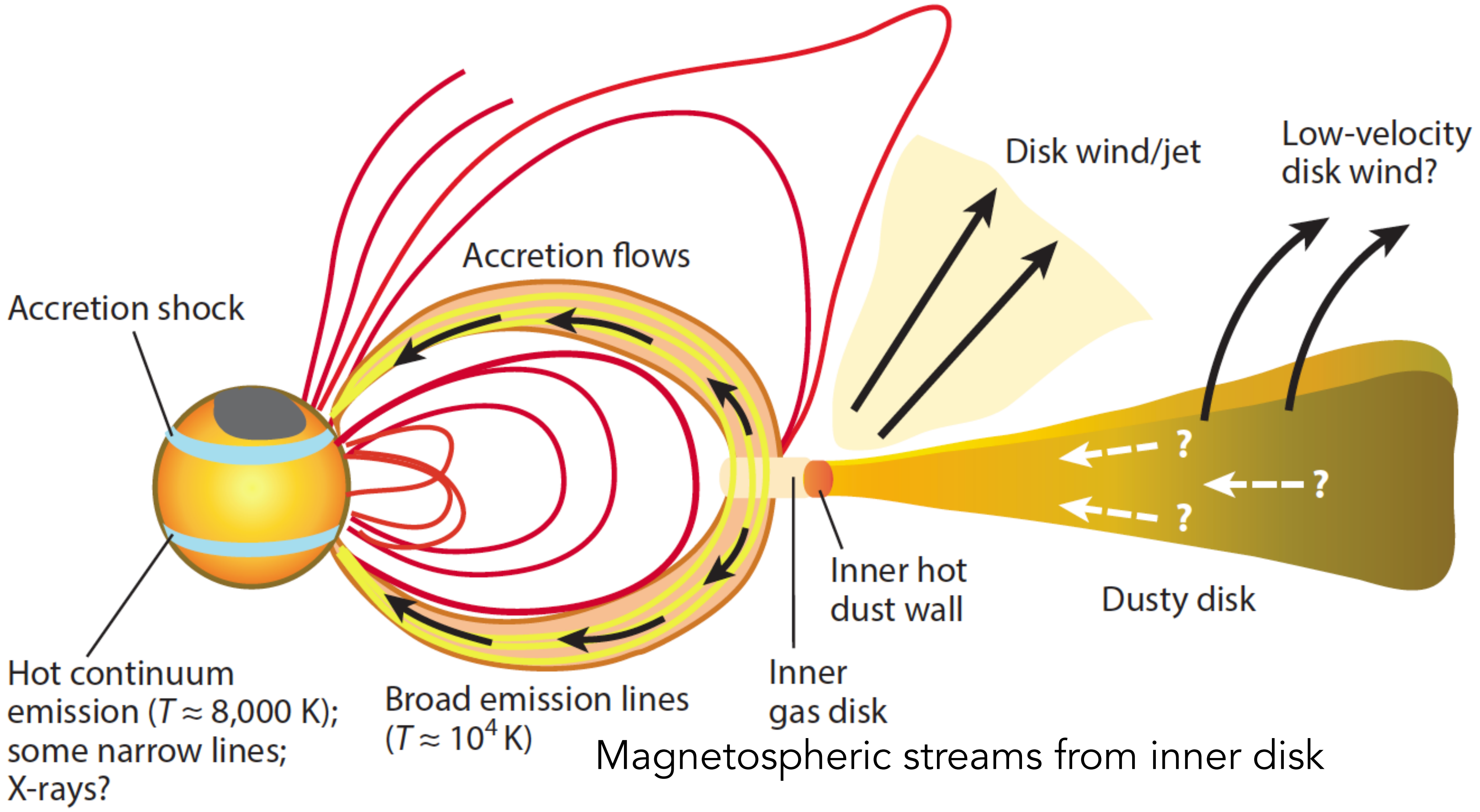
Class II SEDs. Quiescence similar to CTTS.

Outburst emission lines brighten, Photosphere veiled by accretion flow
Timescales -> inner disk instability (pile-up)





During Outburst (EX Lupi): Inverse P Cygni, emission lines



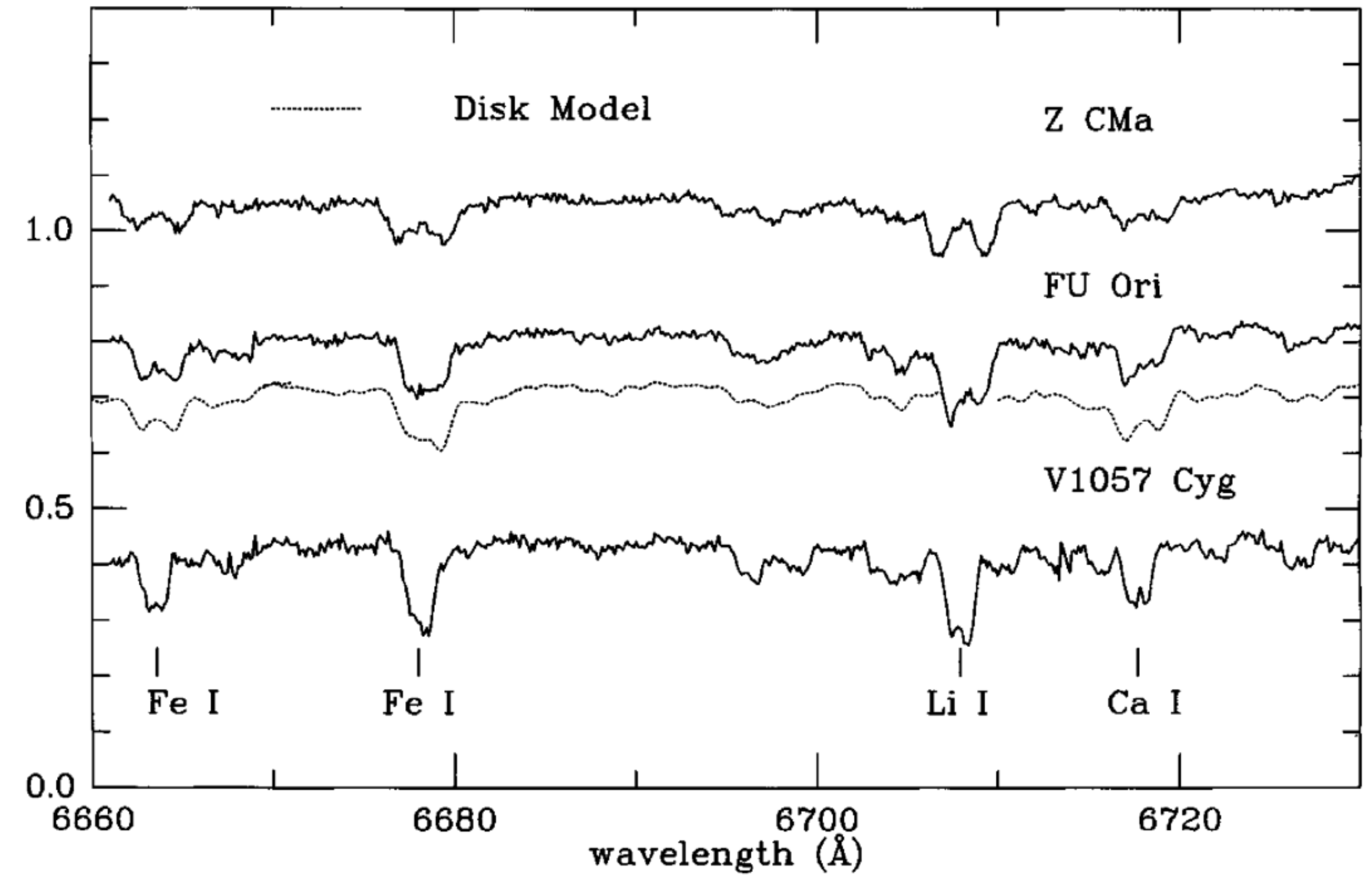
Magnetospheric streams from inner disk

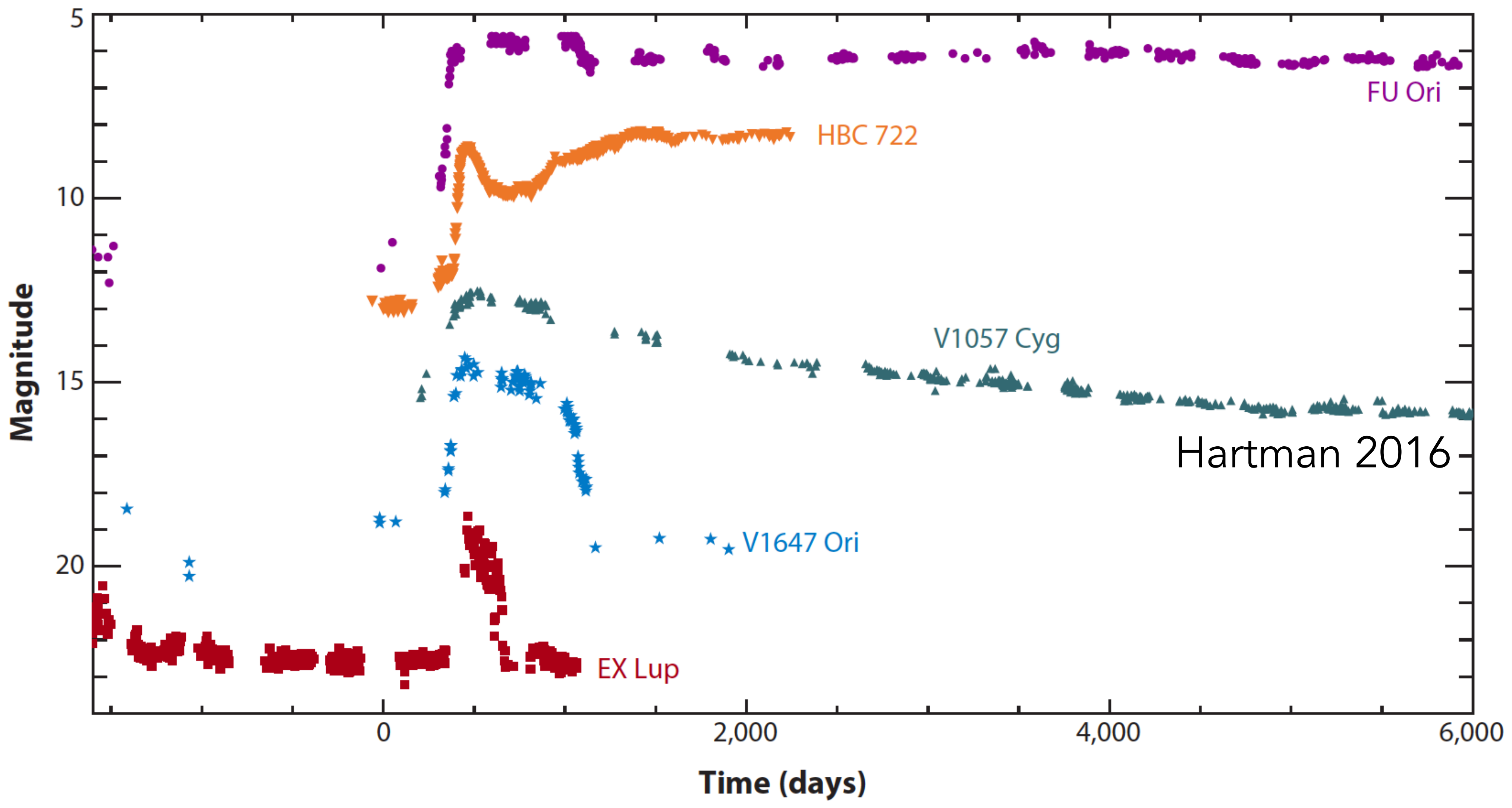
Koenigl+1991, Lehmann+1995, Audard+2014, Hartman 2016, Conneley & Reipurth 2018

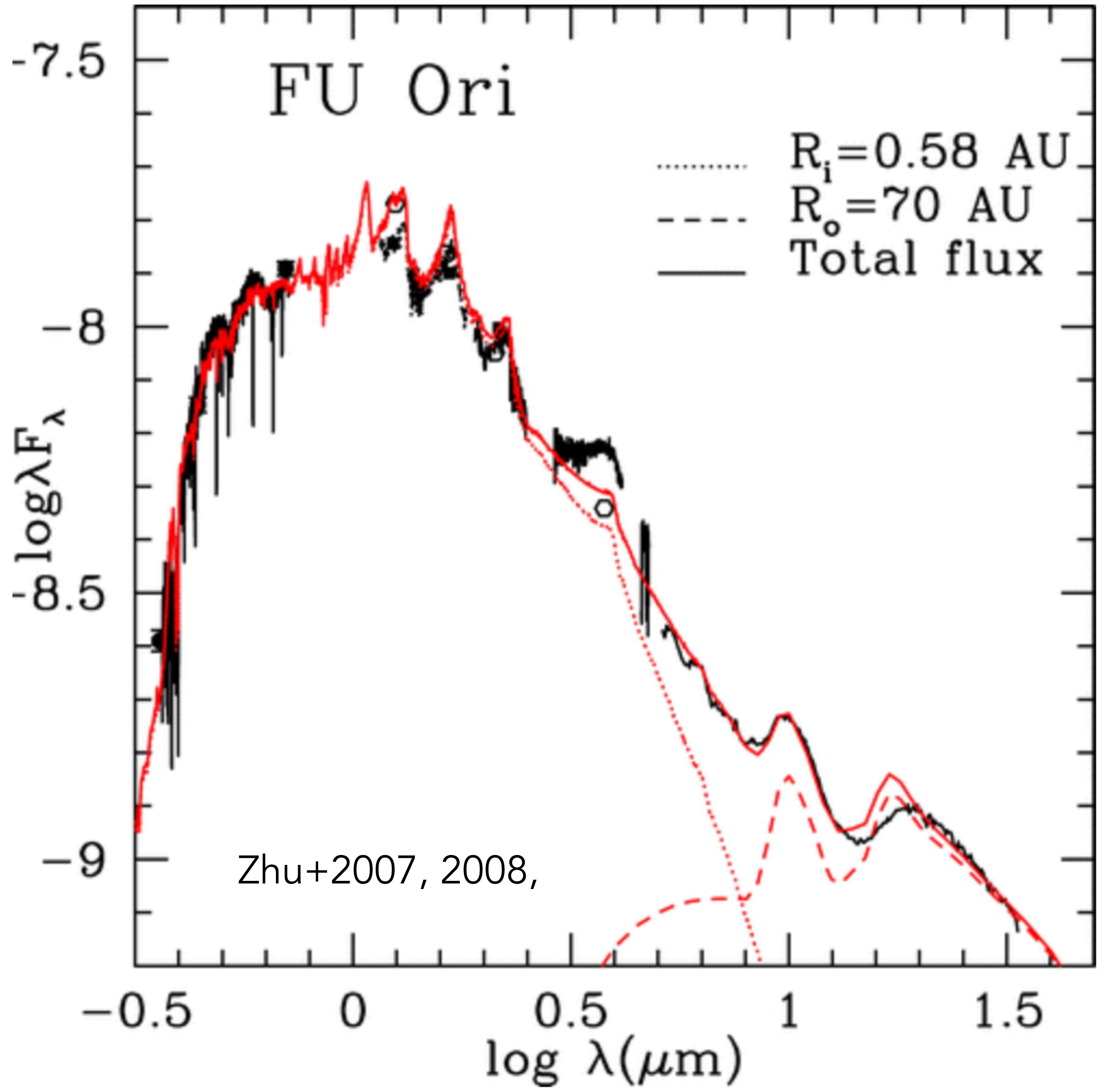
FUors (named after FU Ori)

Longer, Bigger: 5>mag, 1000 x accretion
duration year to decades

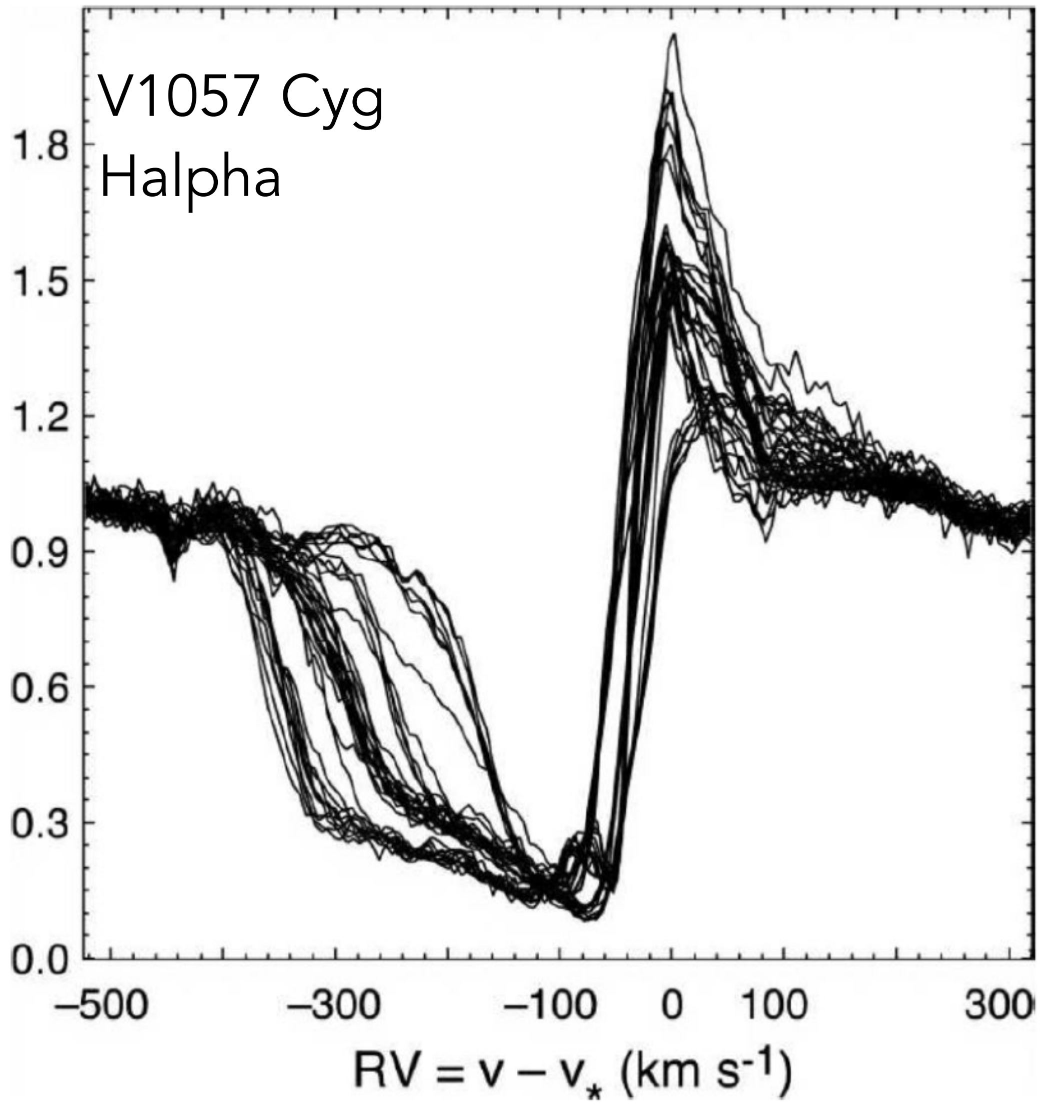
- Heterogenous photometric behaviour
- Gradually cooler spectra at longer wavelength (V1057 had TT pre-burst spectrum)
- Double peaked absorption in some lines

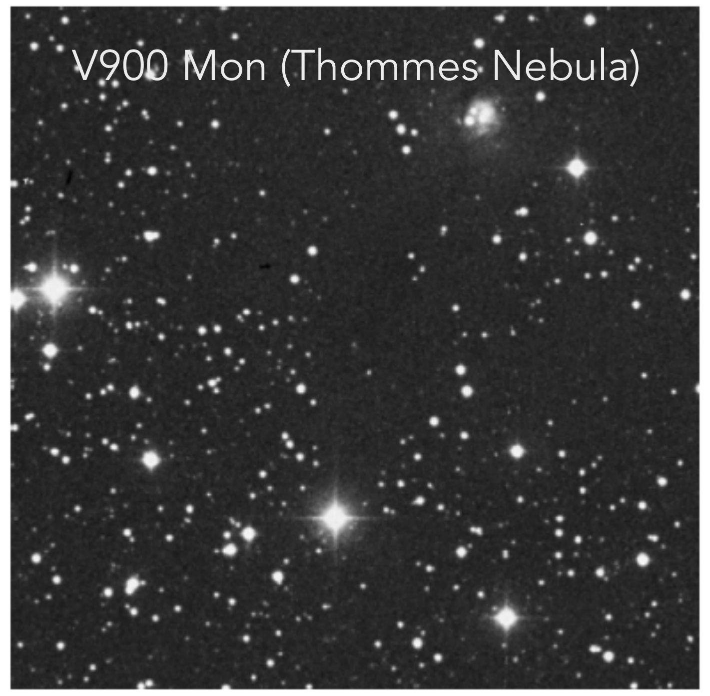






Audard+2014, Hartman 2016, Conneley & Reipurth 2018





FUors

- Longer, Bigger: 5>mag, 1000 x accretion
- Duration year to decades
- Heterogenous Photometric behaviour
- Gradually cooler spectra at longer wavelength

  (V1057 had TT spectrum prior)
- **P Cygni at specific lines (winds)**
- **Reflection nebula (that brighten up), envelopes**

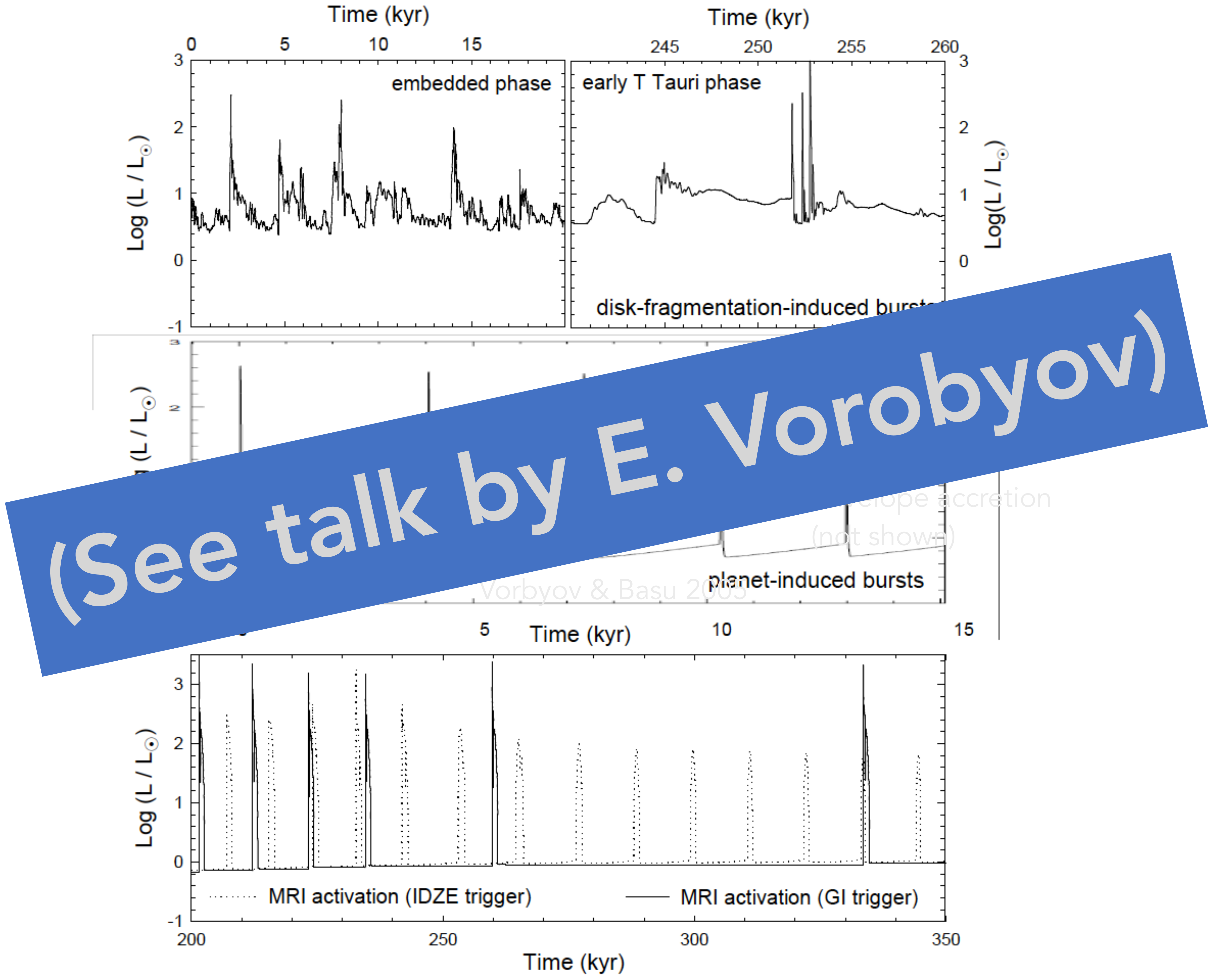
  -> Late Class I (some have Class II SED)

Outburst Mechanisms uncertain
-> disk-scale instability

Herbig+2003, Reipurth & Aspin 2010, Audard+2014, Hartman 2016, Conneley & Reipurth 2018

Outburst Mechanisms:

internal vs external

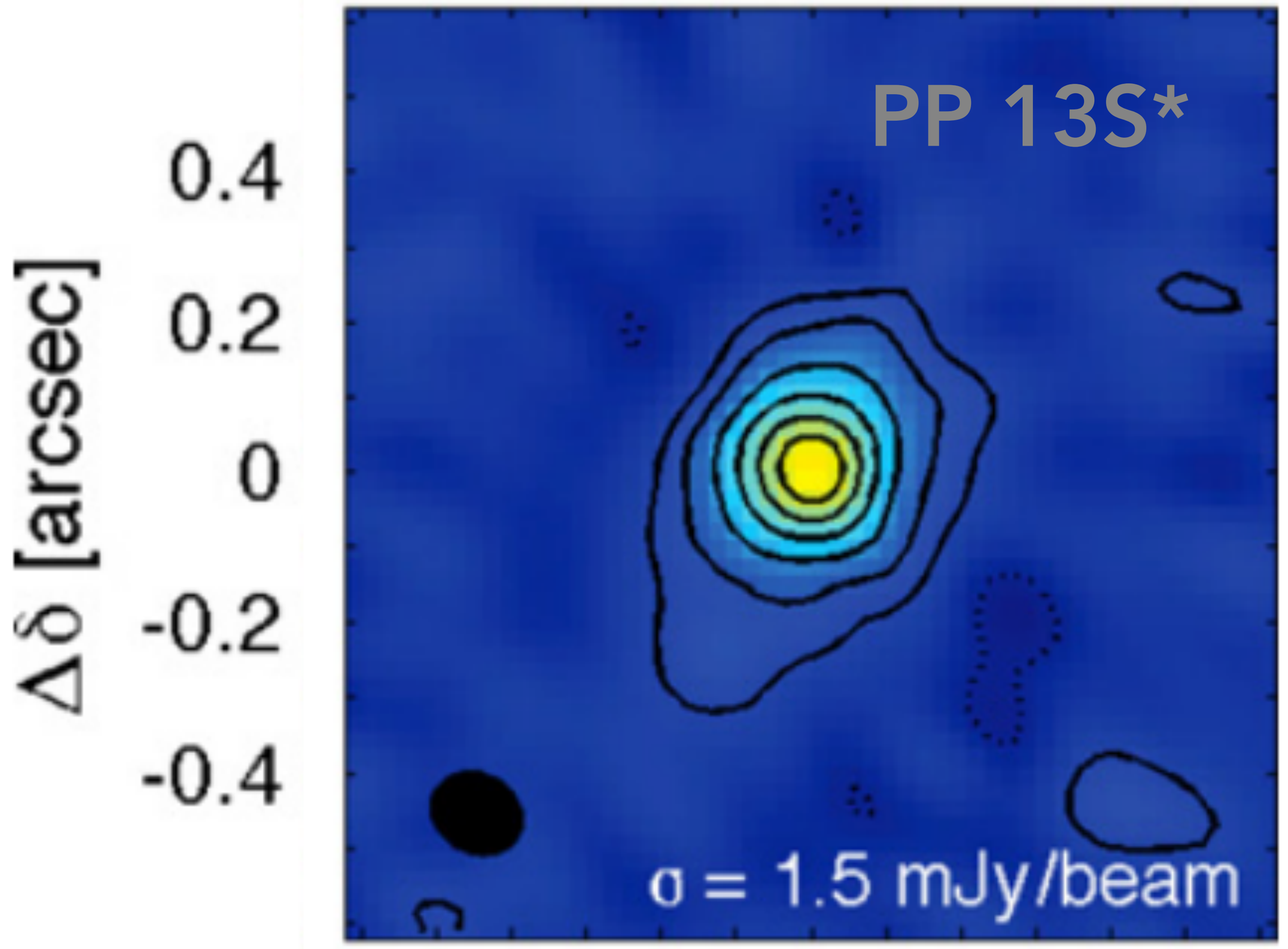


- **Thermal instabilities**
- **Disk fragmentation/Spirals**
- GI + MRI
- Magnetospheric star-disk interaction
- External perturbation **planet/stellar**
- Envelope/Disk accretion rates

Need probe disk properties

Clarke+1990, Bell&Lin1994, Armitage+2001, Zhu+2009, Vorobyov & Basu 2015 Lodato & Clarke 2004. Bonnell & Bastien 1992, D'Angelo & Spruit 2012

Pre-ALMA Era

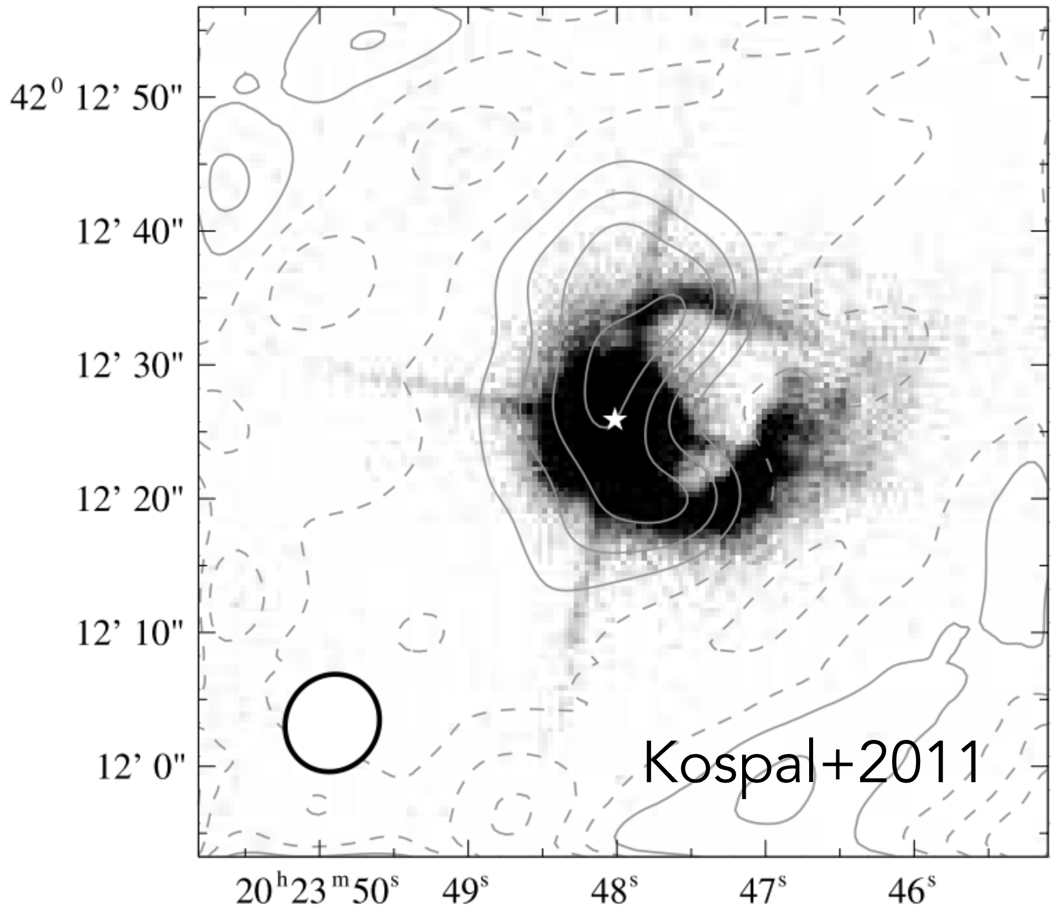


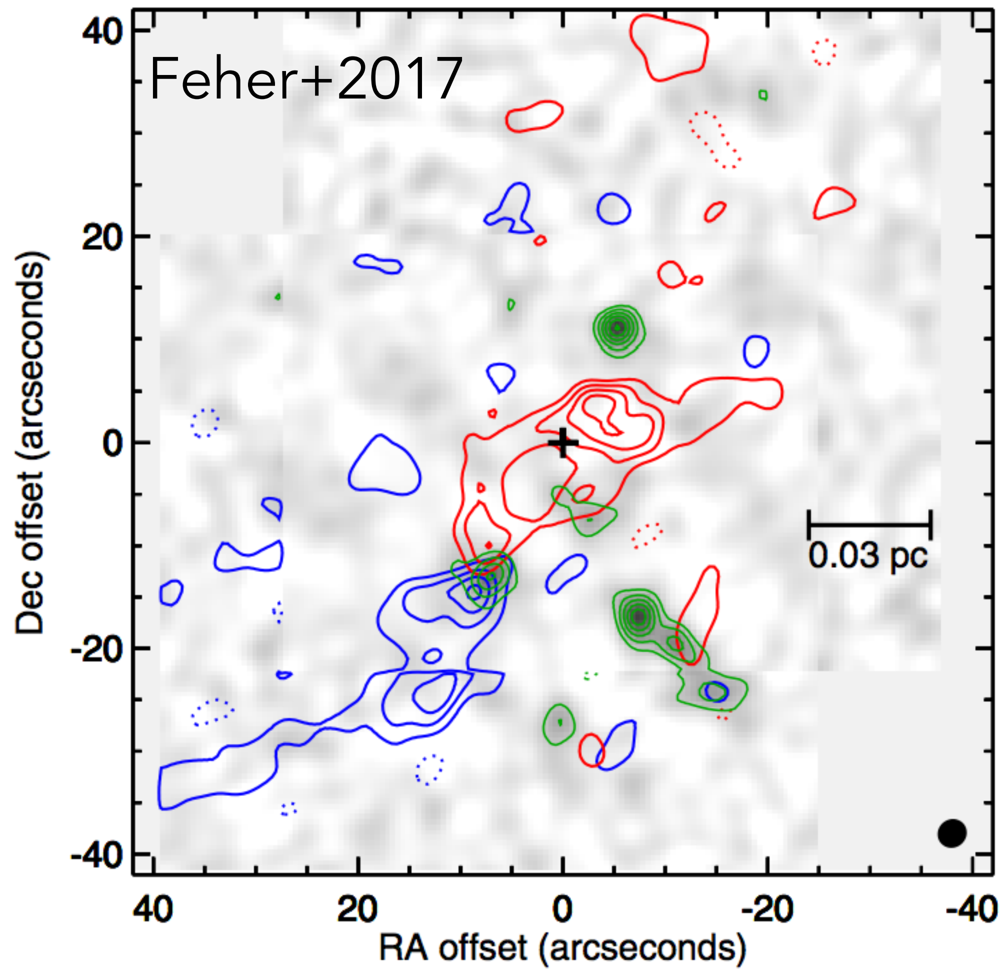
Perez+2010

Few FUor disks resolved

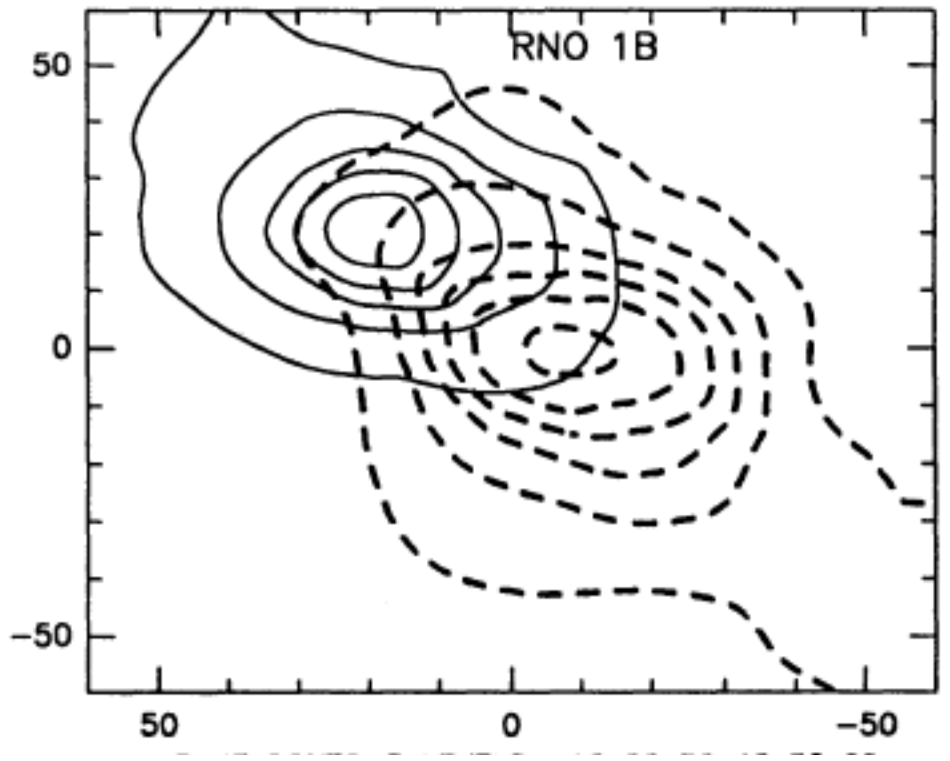
Low disk Mass

EXors mostly undetected.

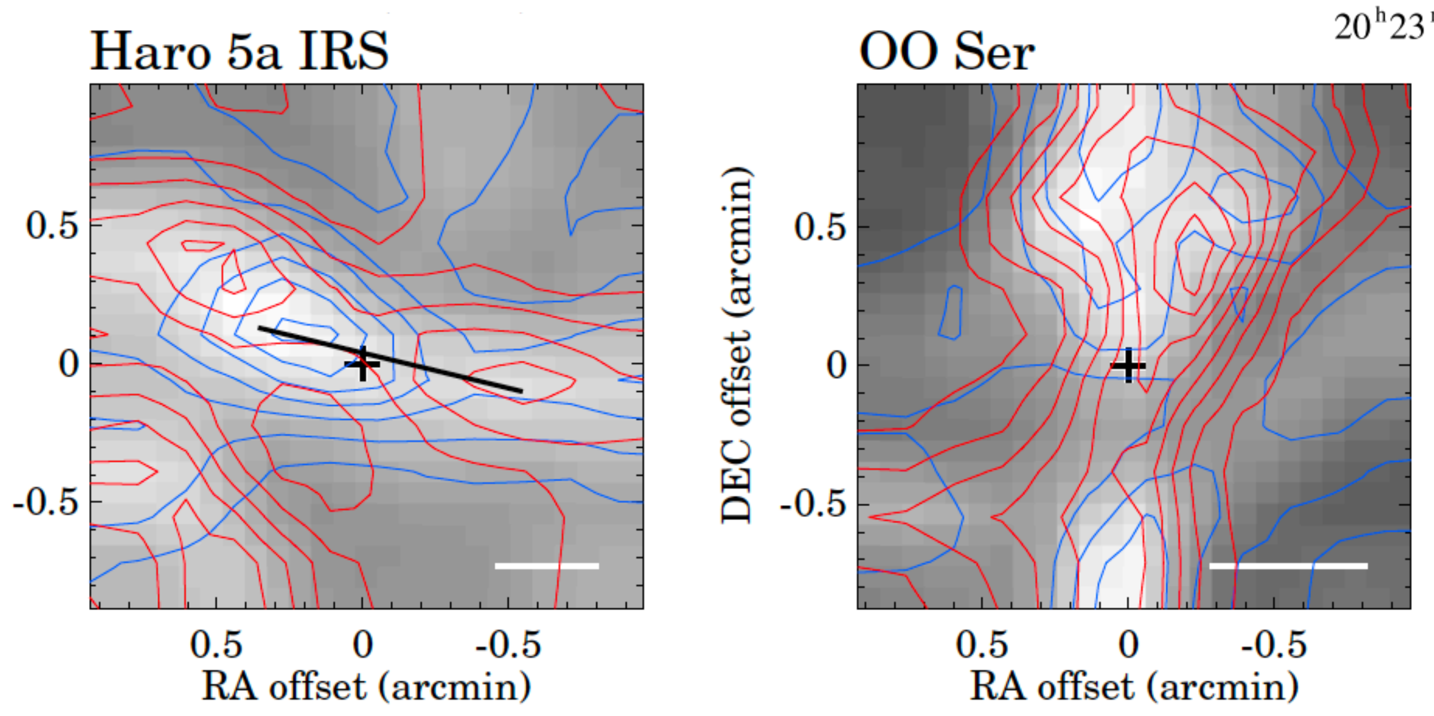




Outflows and envelopes around FUors, not EXors



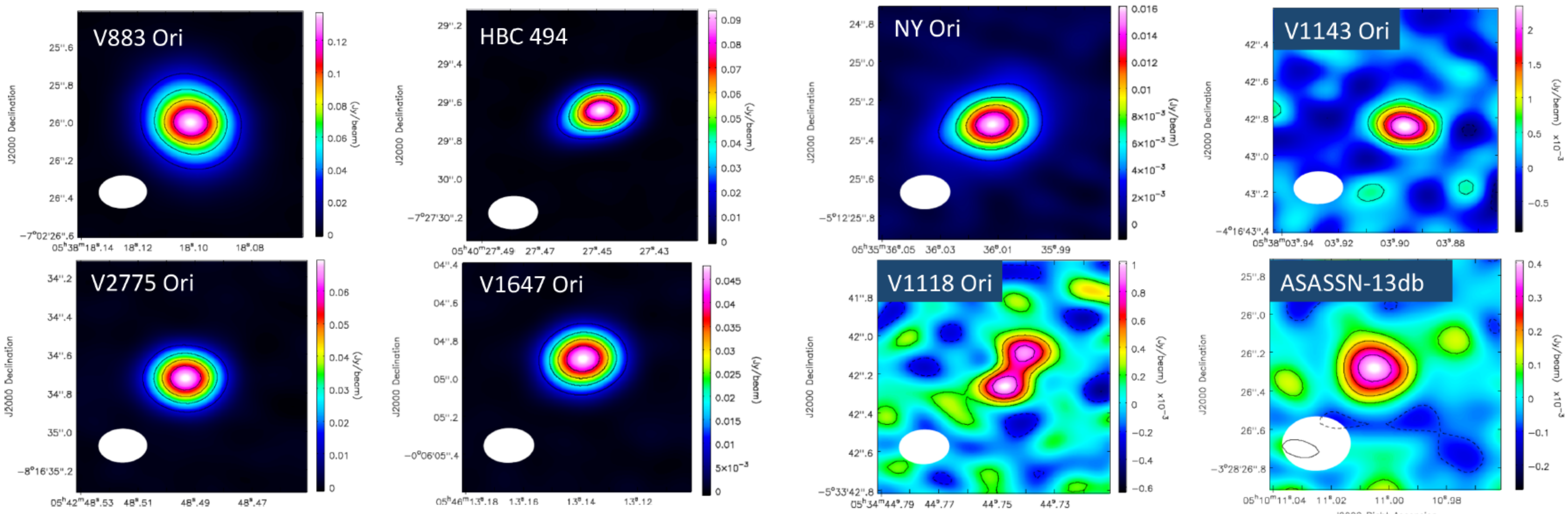
Evans+1994



Kospal+2017

Evans+1994, Polomski +2005; Perez+2010; Kospal+2011/2017,Dunham+2012; Fischer+2012, Liu+2016,2018; Feher+2017

ALMA 230 GHz : 3 FUor and 5 EXor in Orion



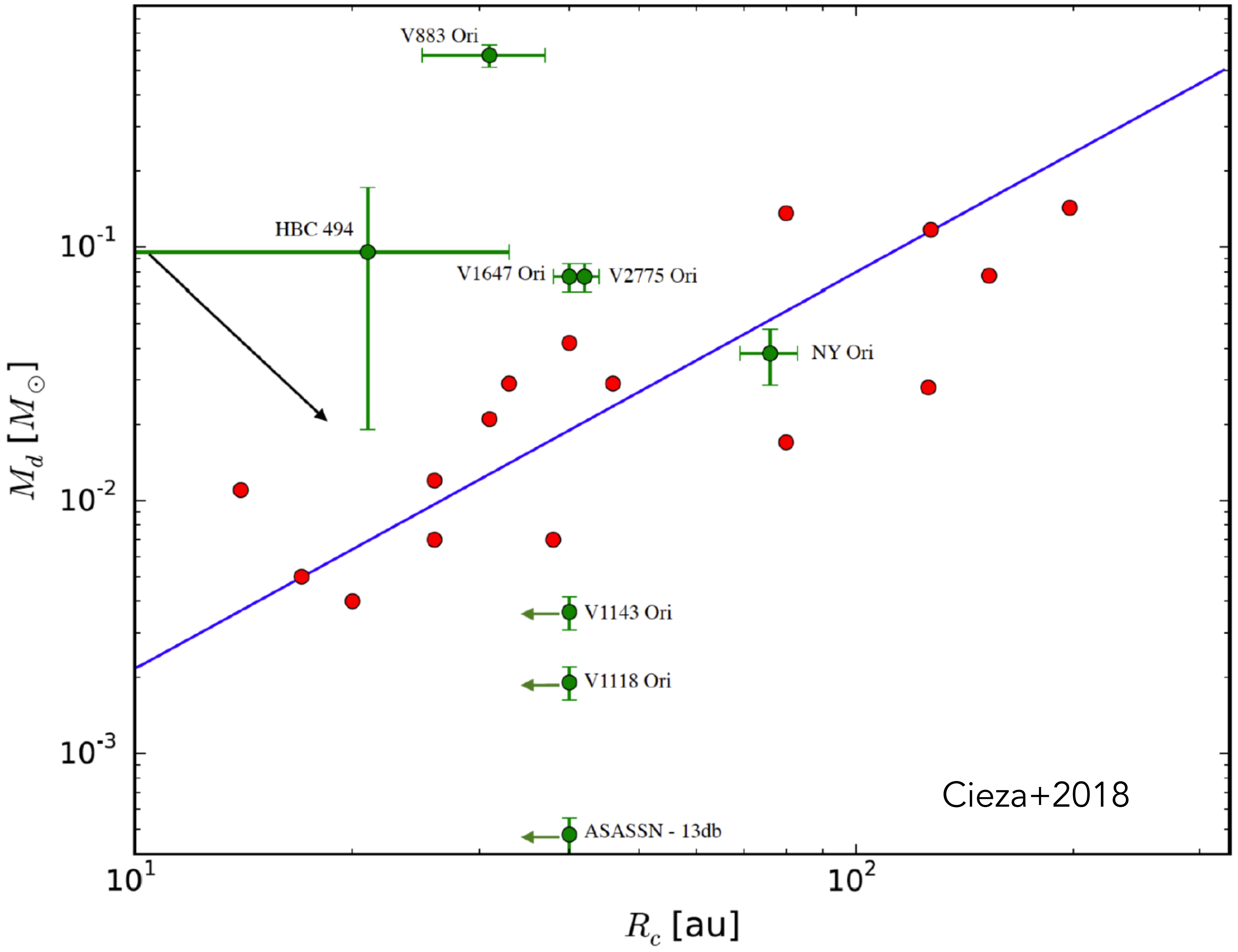
Cieza et al. 2018

No sub-structures at this resolution

No Gravitational Instability, not even in brightest disks

Some new binaries (HBC494, Zurlo et al. *in prep*)

ALMA Band 6 Obs. of EXor/FUors



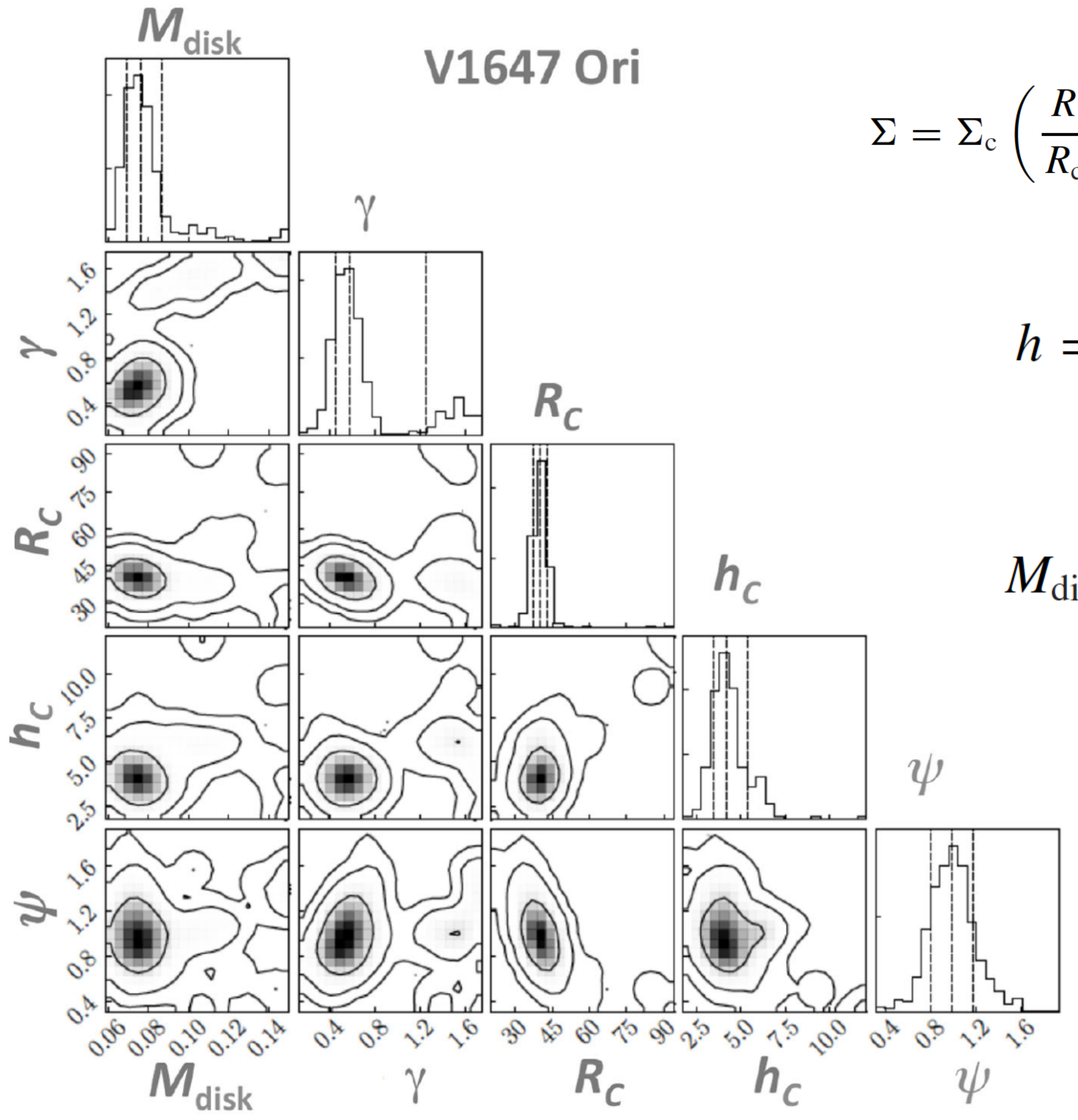
FUors brighter than EXors and Class II

Possibly more massive

- **R~30-40 au, similar to Class I disks**

(Tobin+2018, in prep. Sheehan+2017, 2019)

<u>Inner 5-10 au optically thick at mm.</u>



$$\Sigma = \Sigma_c \left(\frac{R}{R_c}\right)^{-\gamma} \exp\left[-\left(\frac{R}{R_c}\right)^{2-\gamma}\right]$$

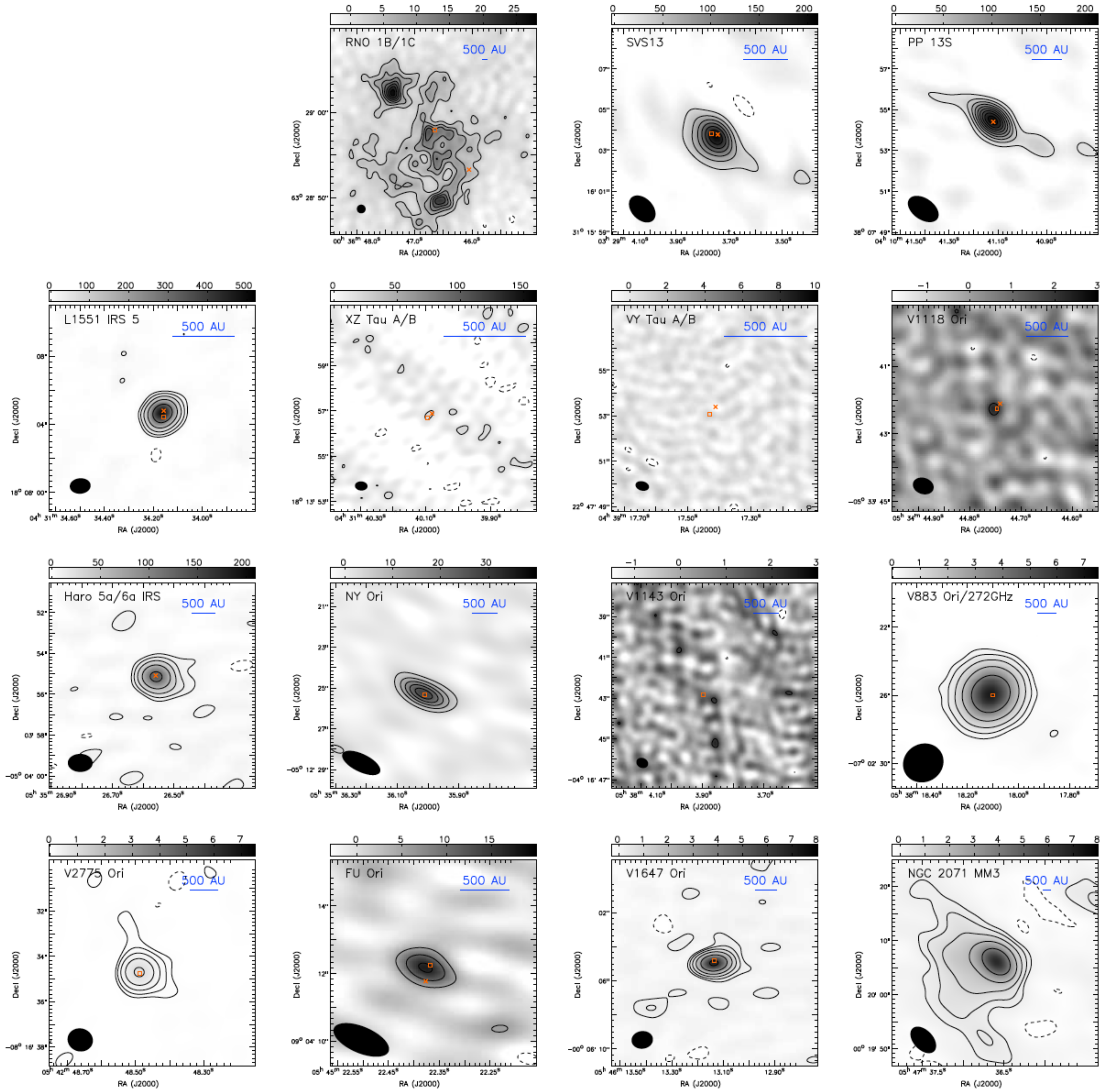
$$h = h_c \left(\frac{R}{R_c}\right)^{\Psi}$$

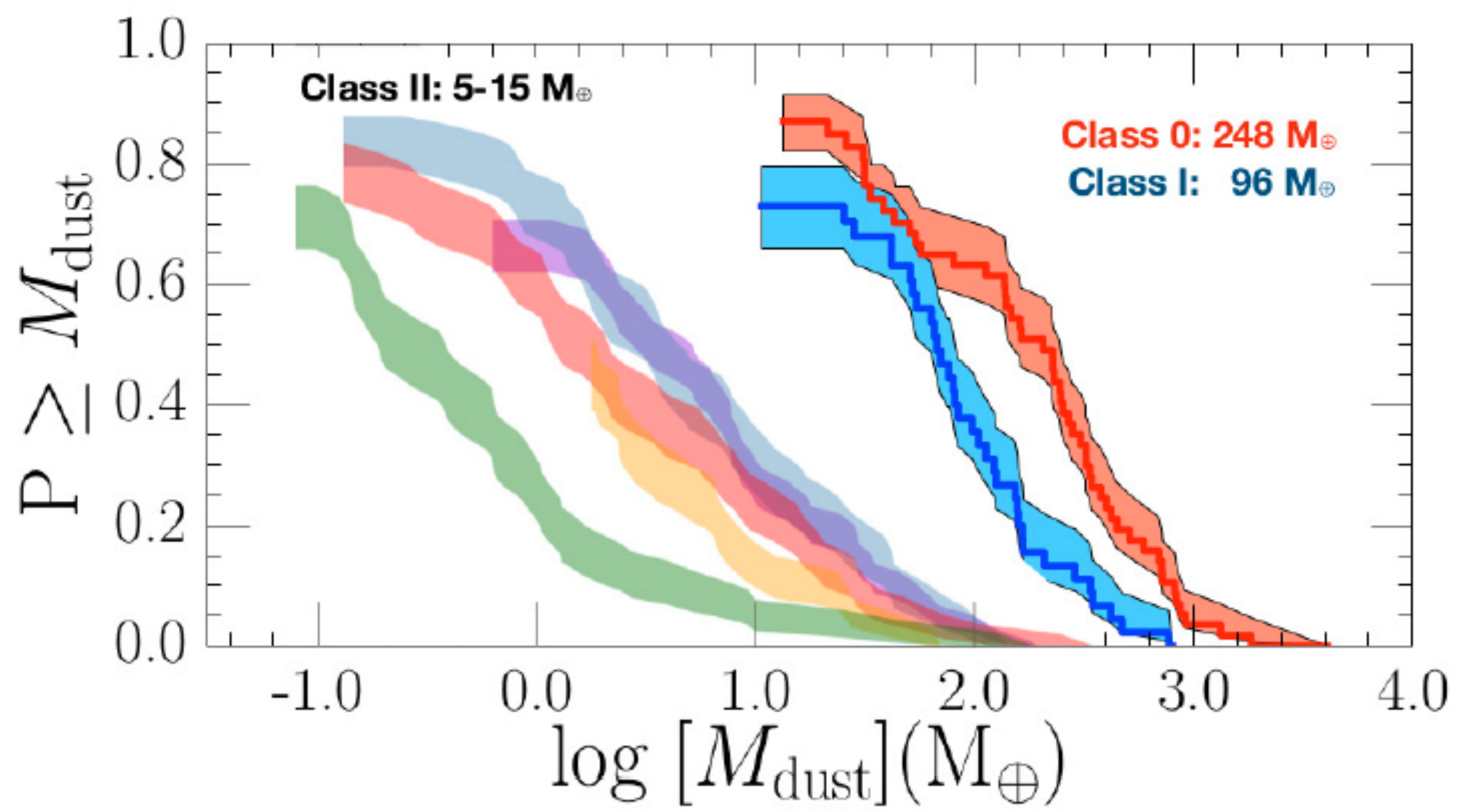
$$M_{disc} = \frac{2\pi R_c^2 \Sigma_c}{2-\gamma}$$

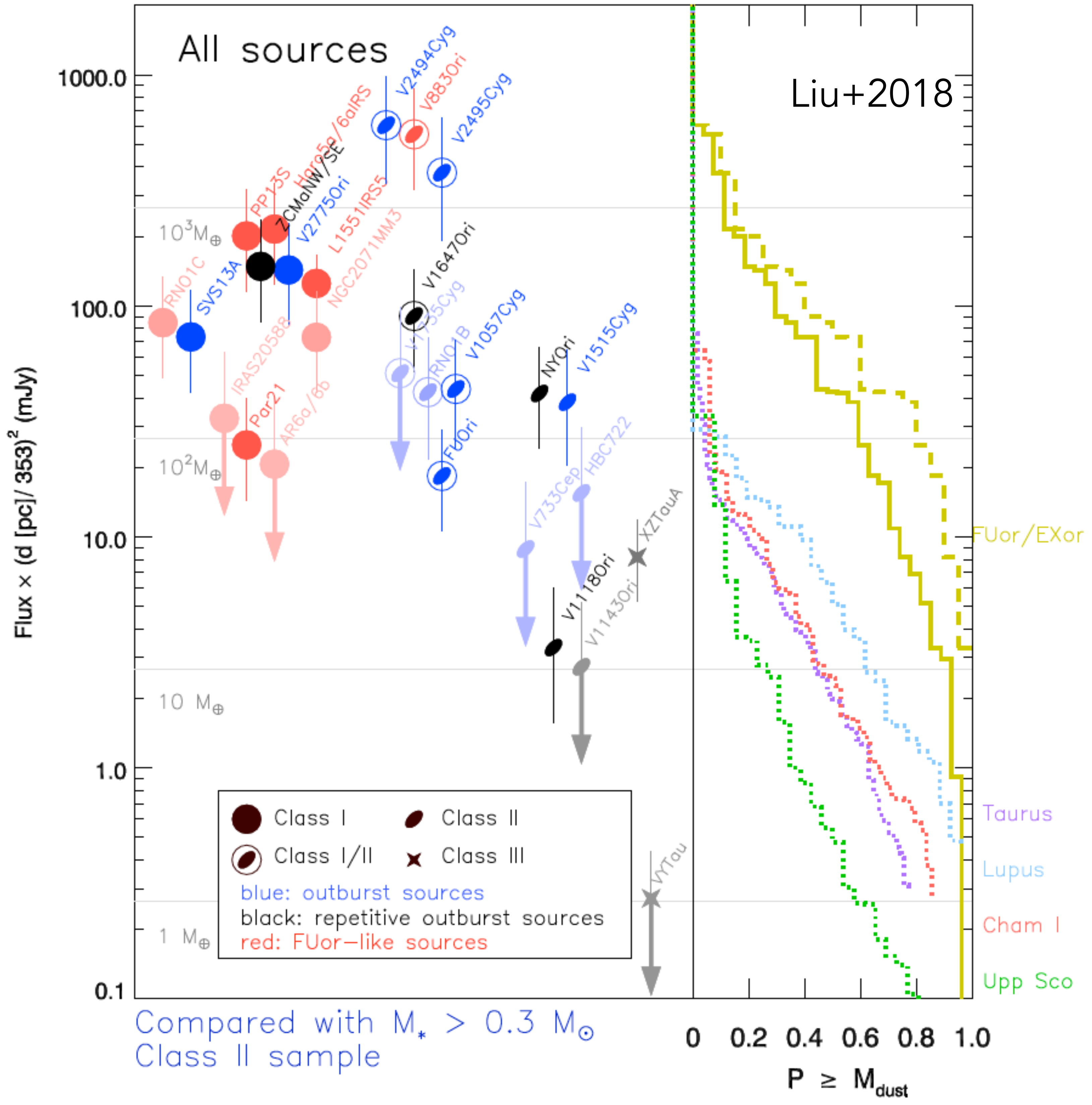
Hales+2015,Cieza+2016,17,Zurlo+2017,Ruiz-Rodriguez+2017,Principe+2018,Liu+2016,17,18, Yen+2017, Li+2017, Tychoniec+18

Trend confirmed with SMA survey

Tychoniec+2018



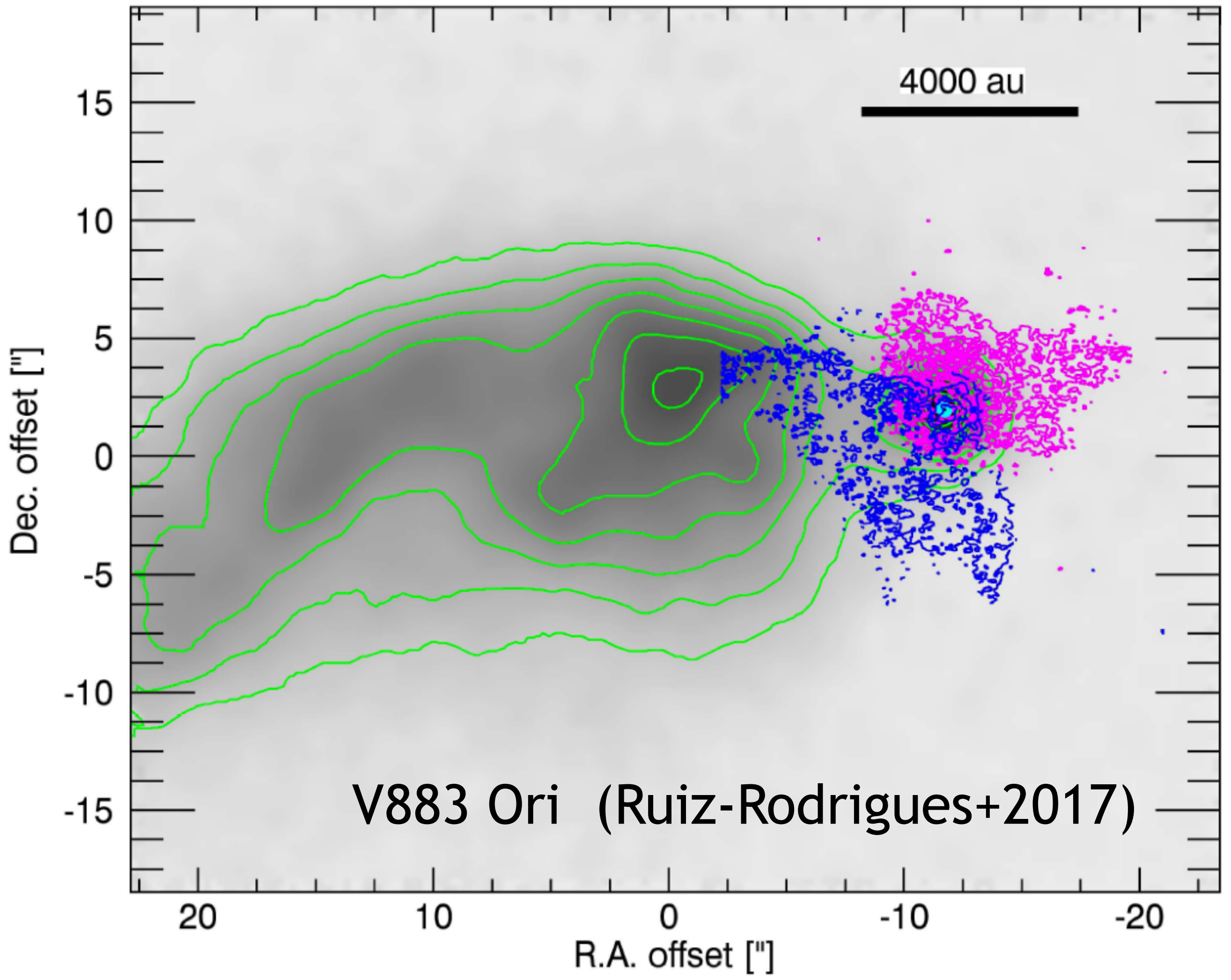


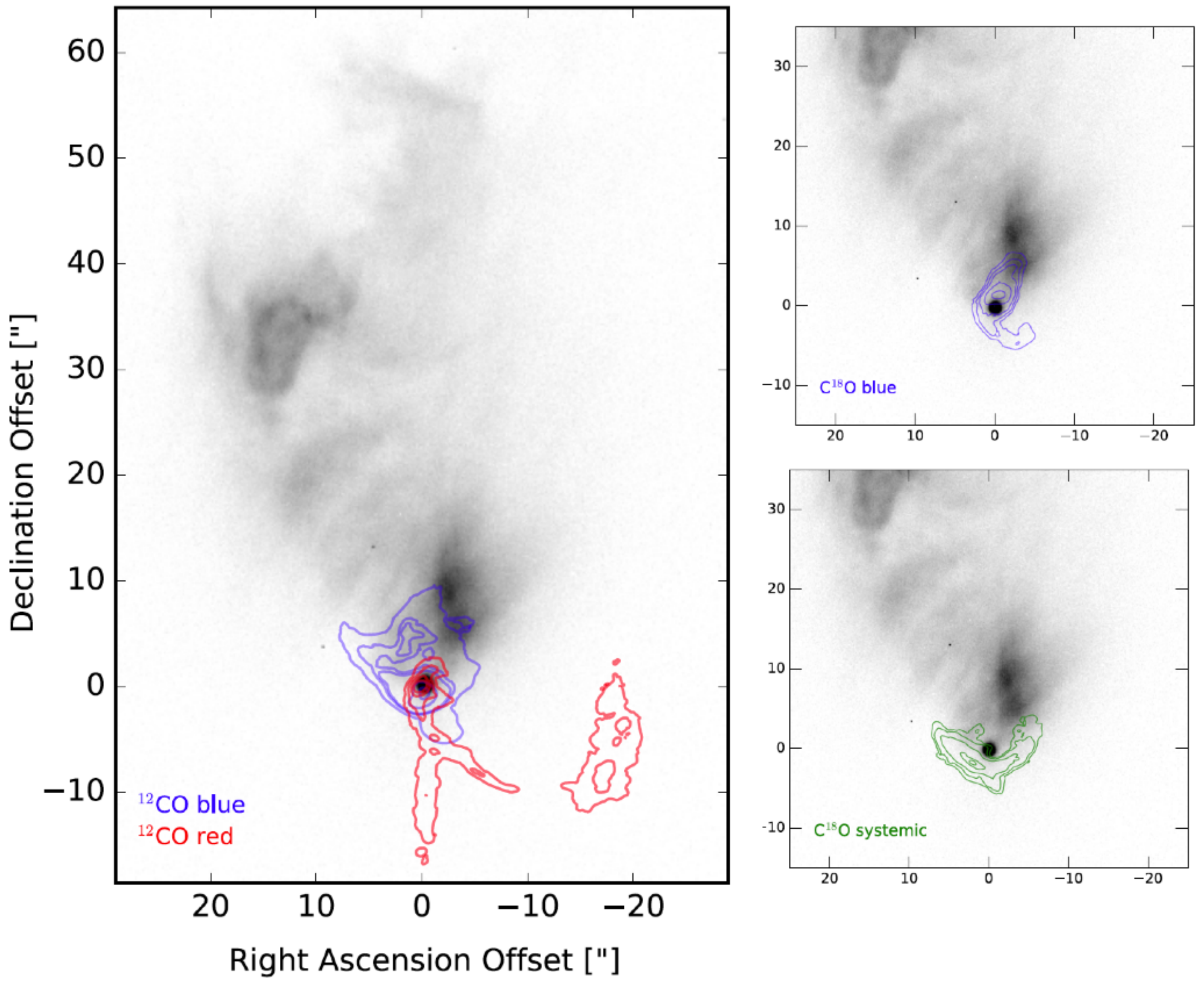


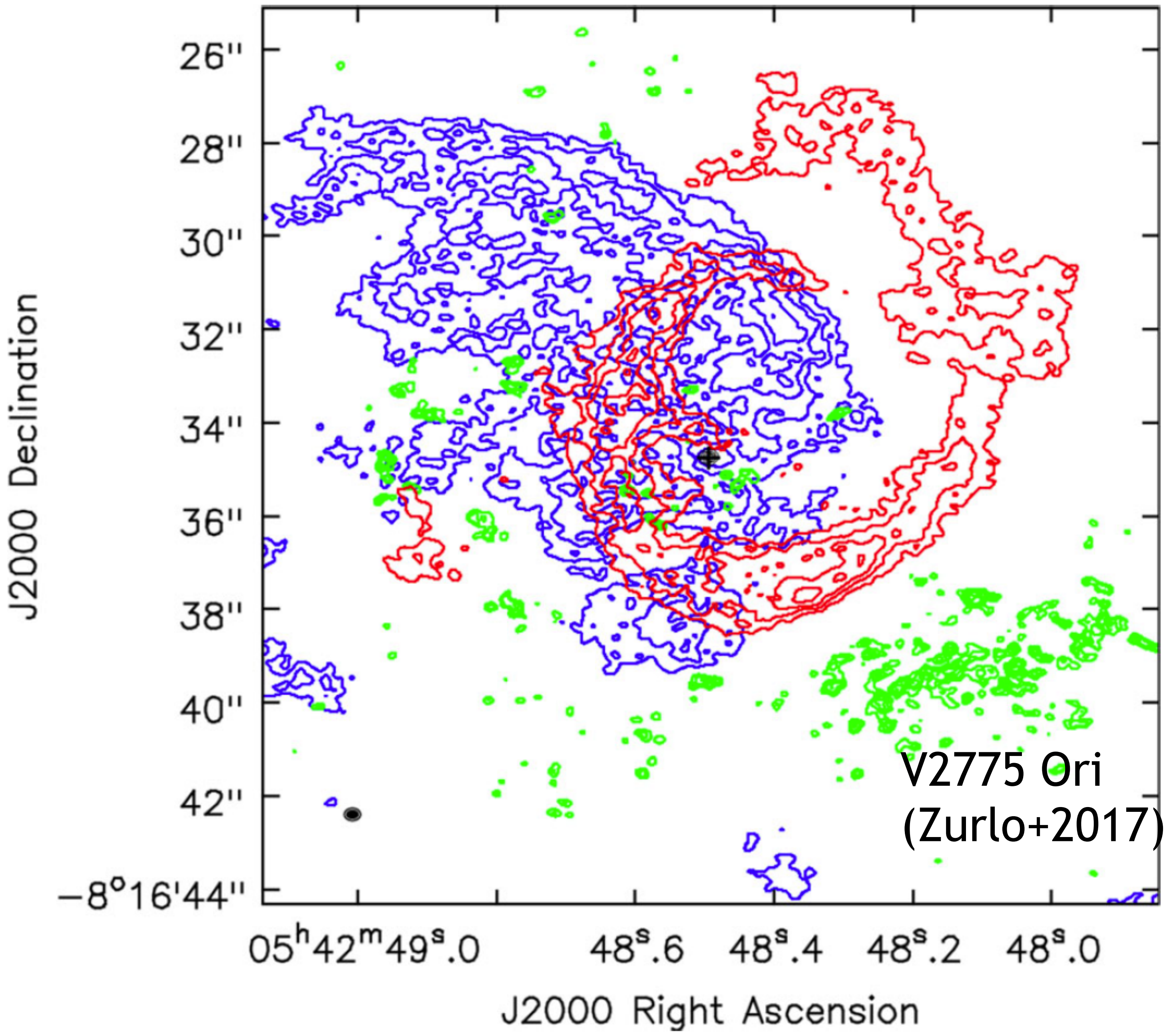
Compared with $M_* > 0.3$ $M_\odot$ Class II sample

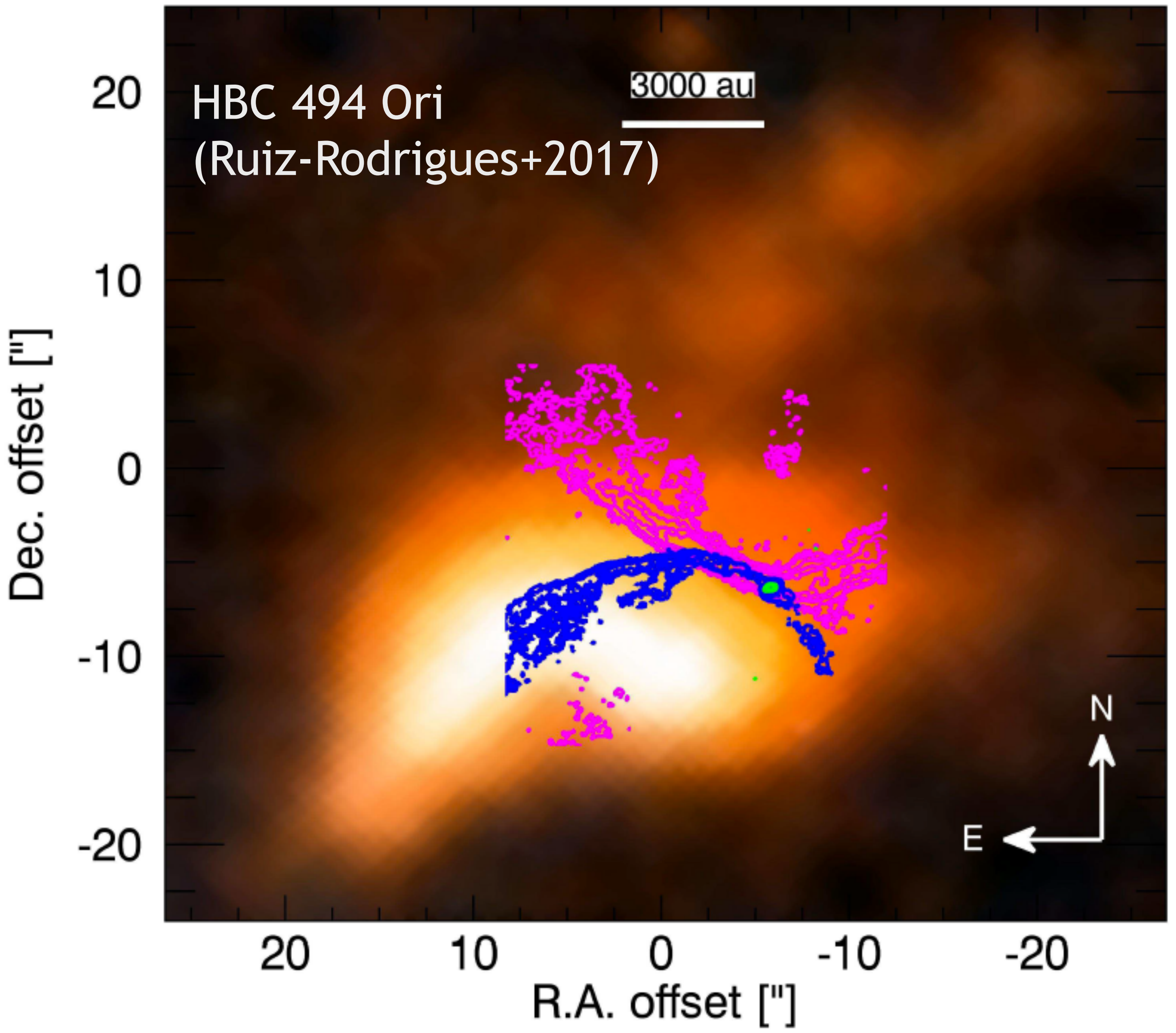
Mass distribution between Class I and II

FUors have slow, wide-angle outflows: evolved Class I ?
No outflows in EXors

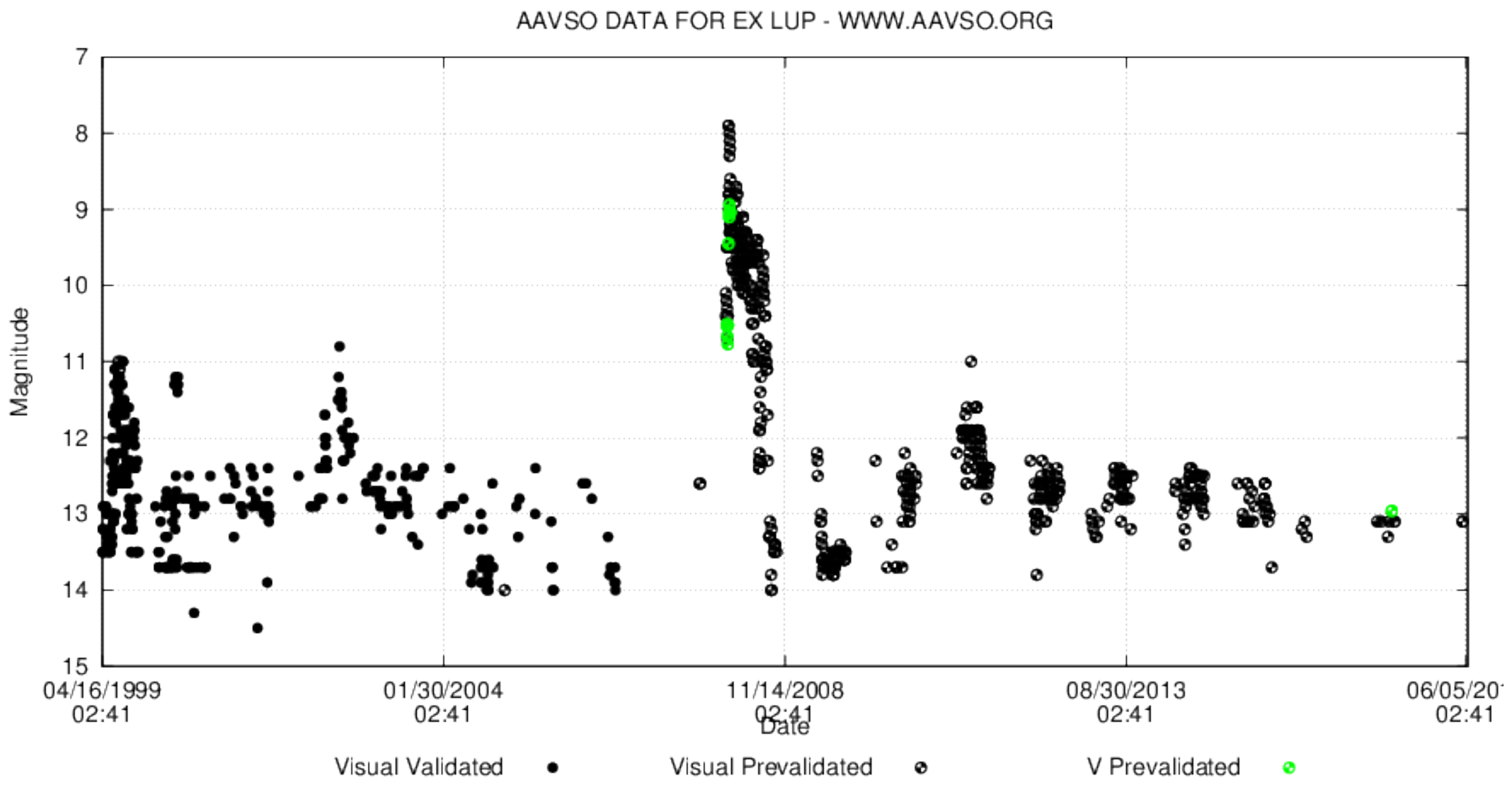


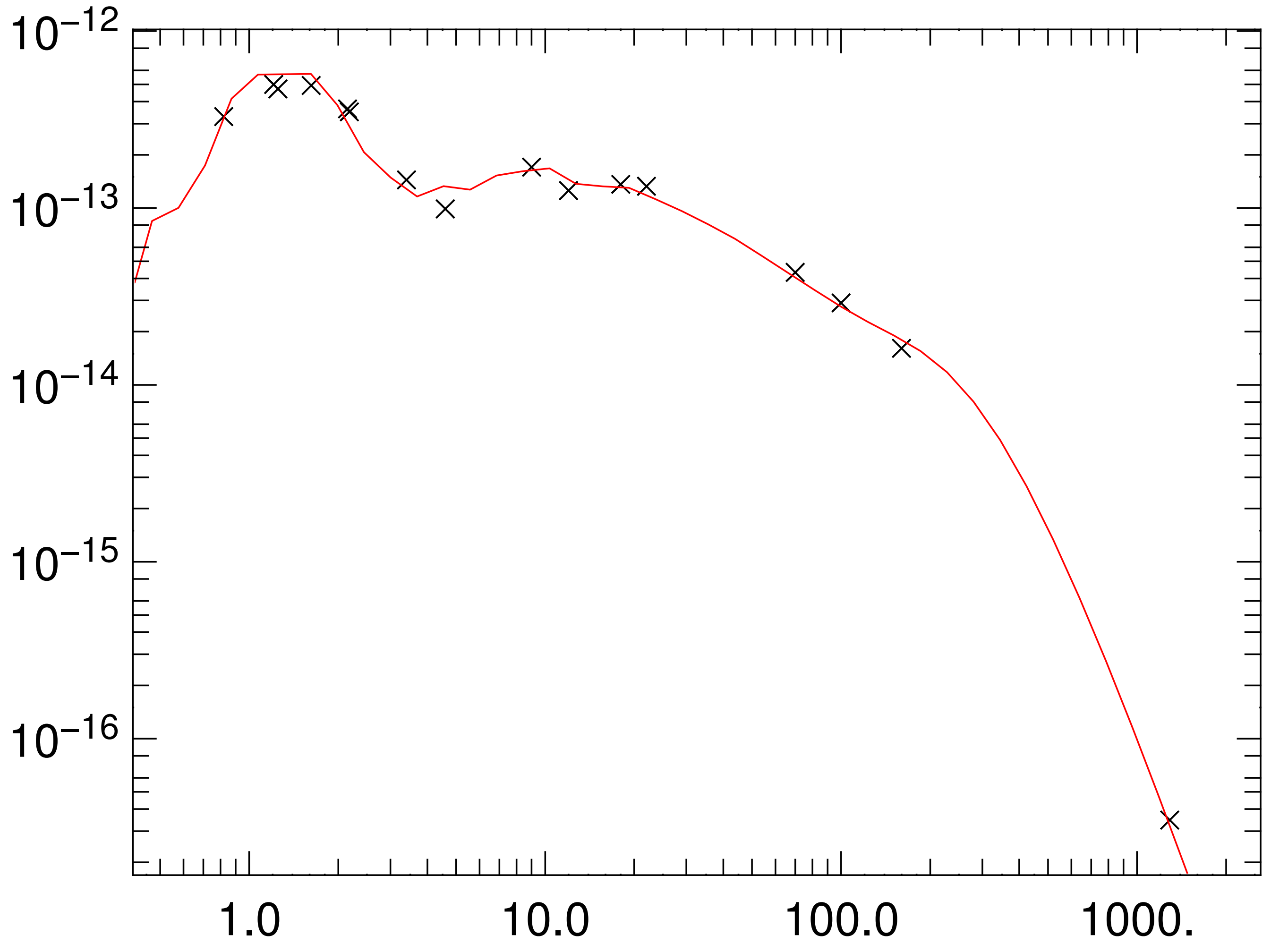


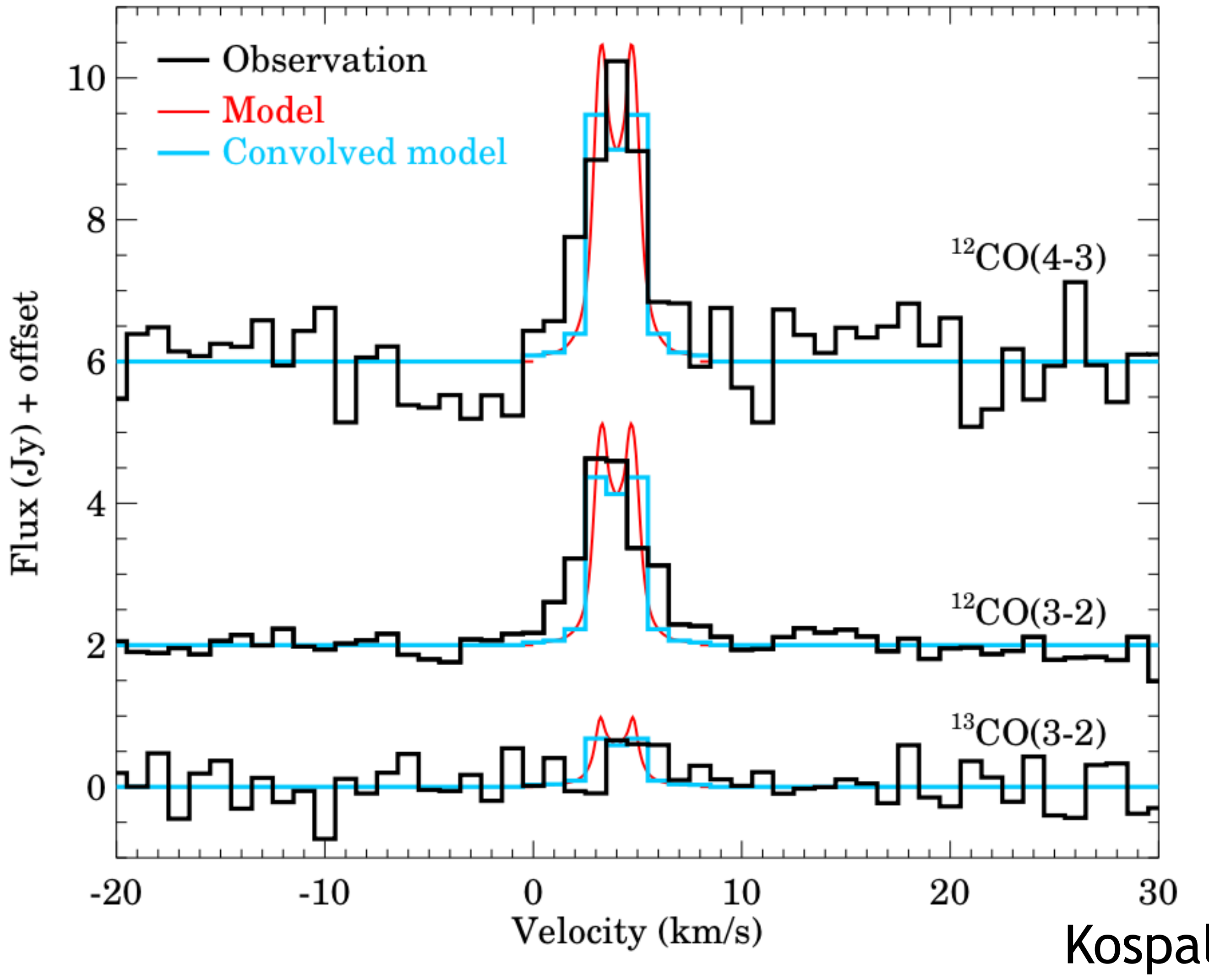




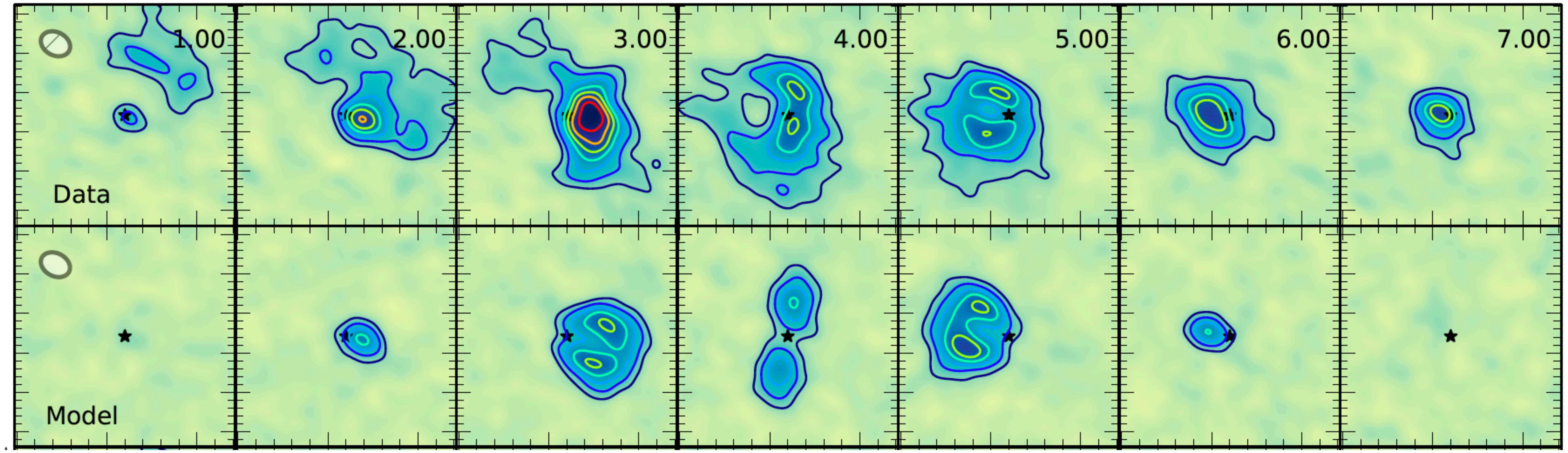
EX Lup



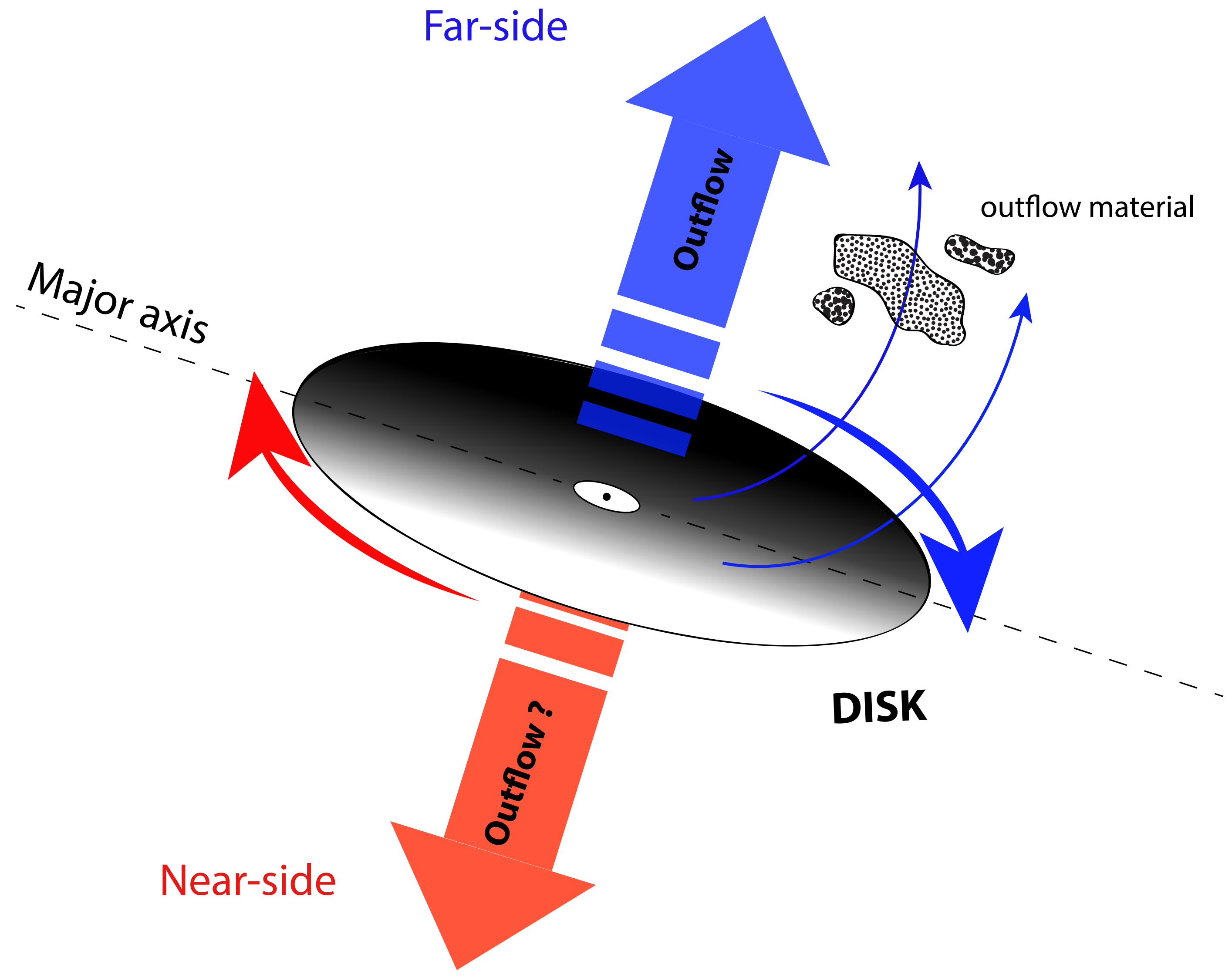


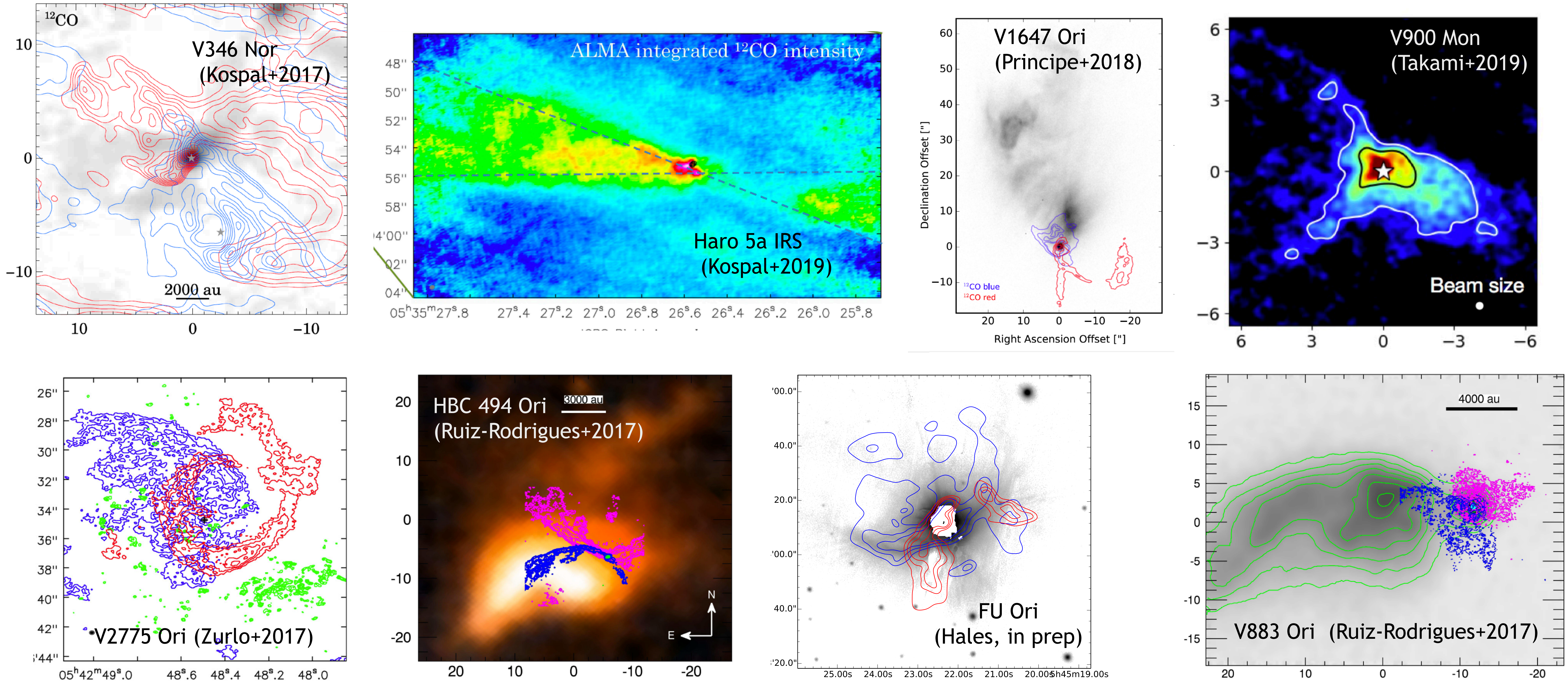


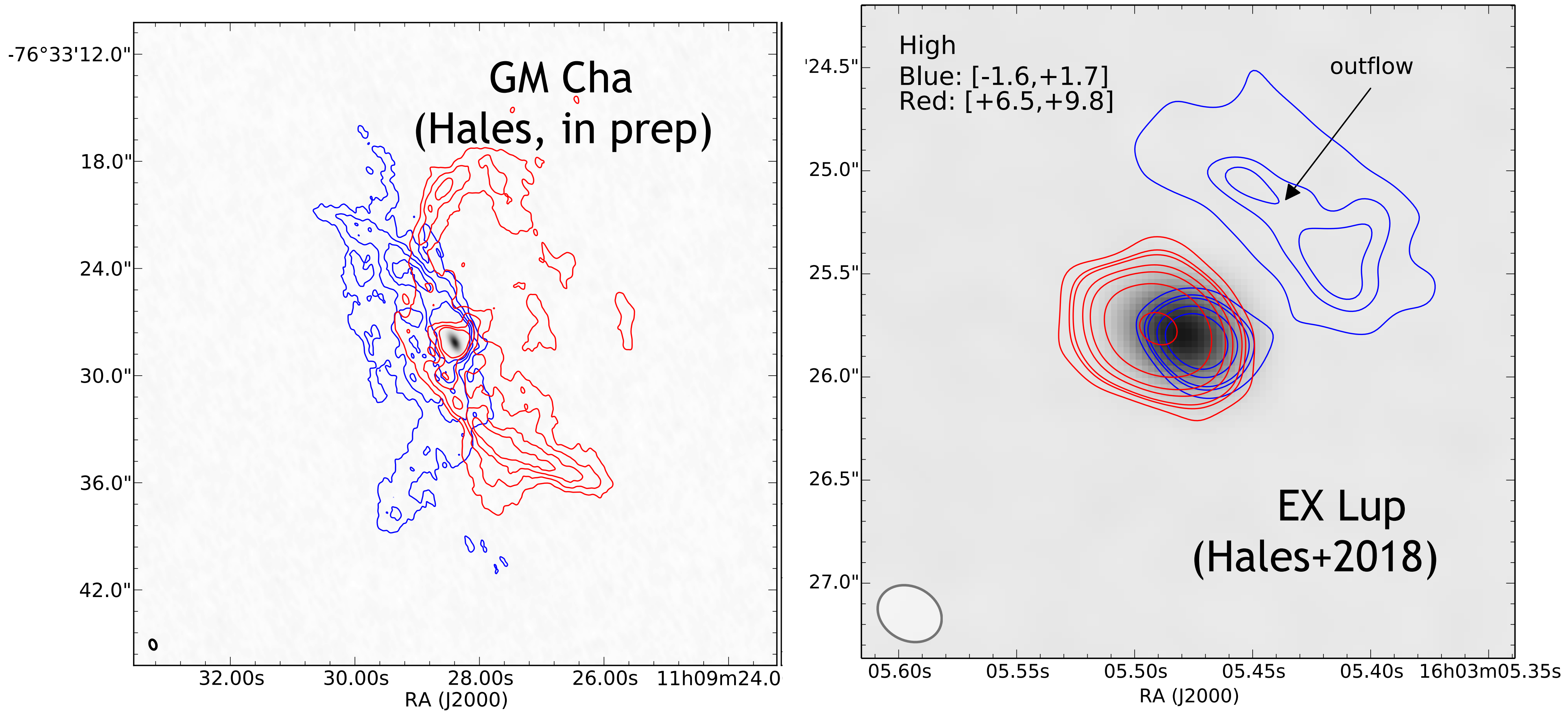
Kospal+2016

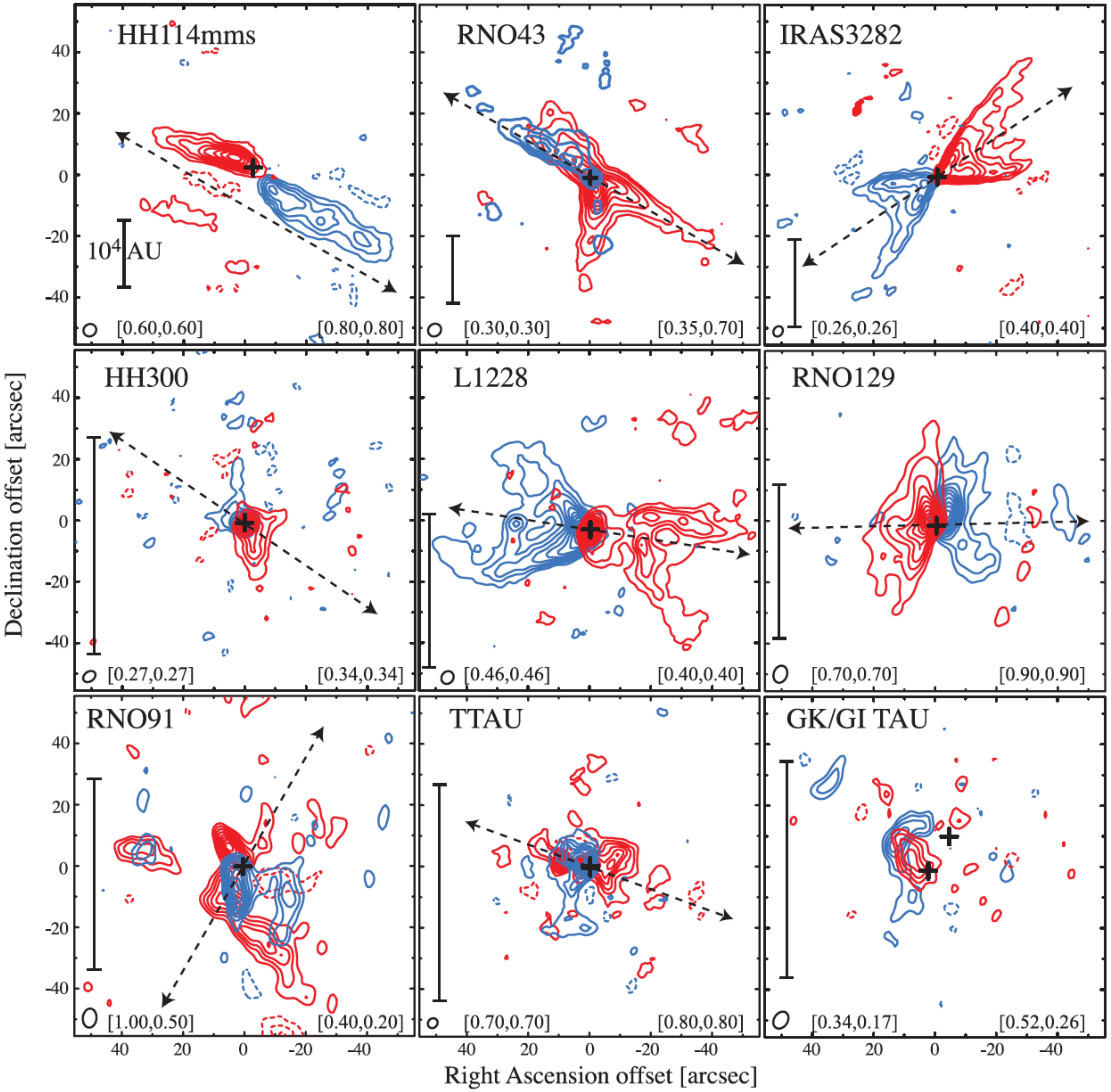


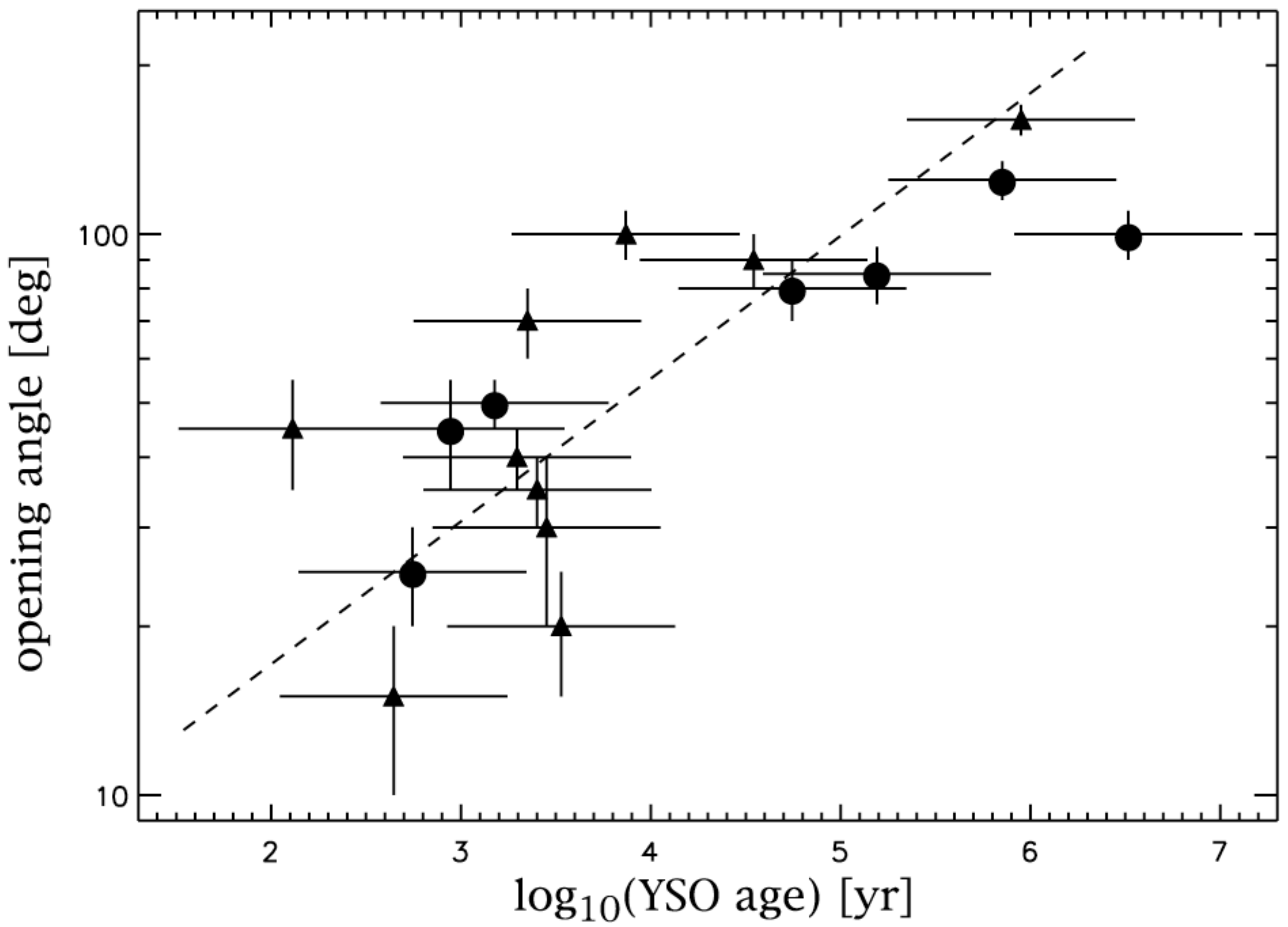
Hales+2018

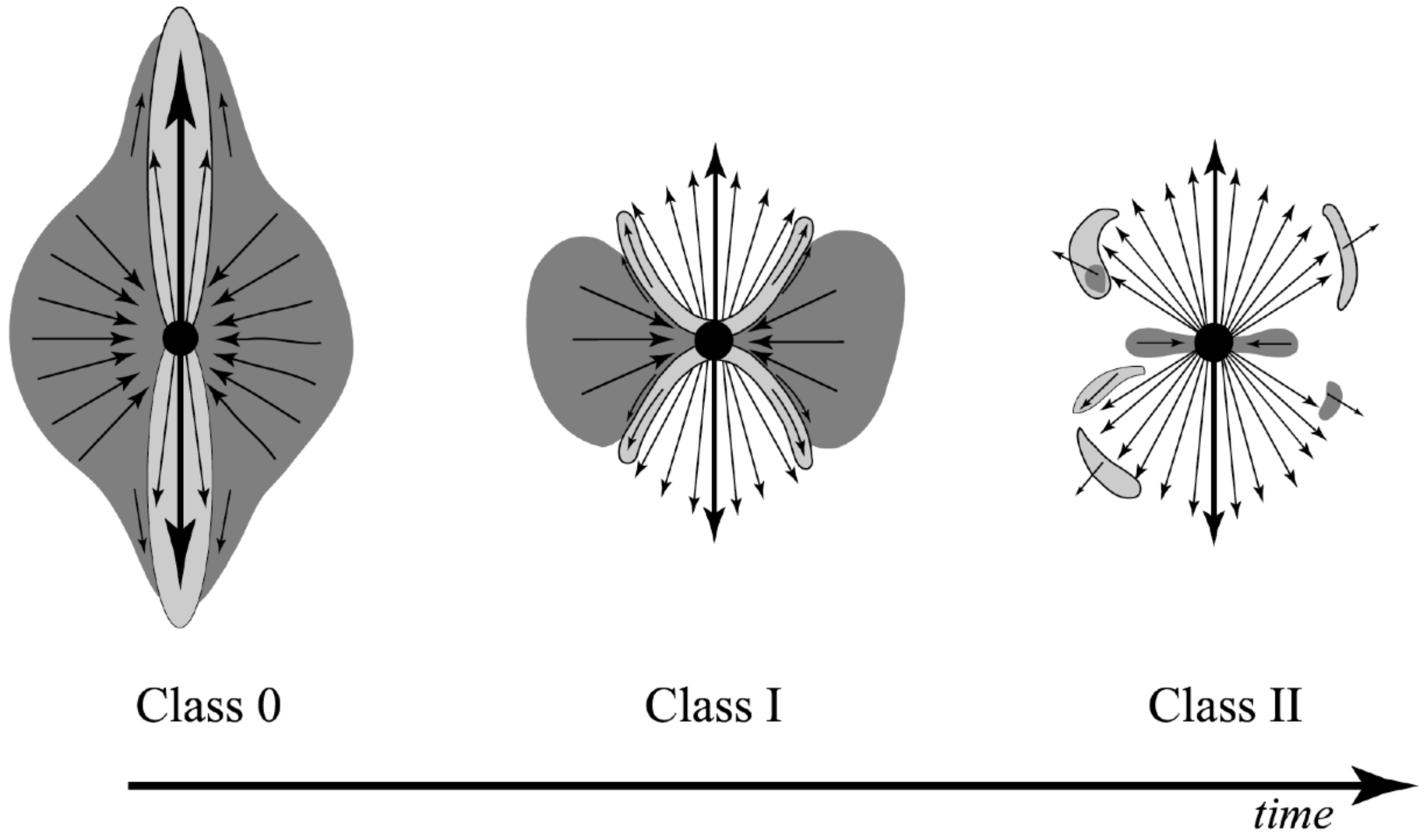



V346 Nor
(Kospal+2017)
2000 au
ALMA integrated ¹²CO intensity
Haro 5a IRS
(Kospal+2019)
V1647 Ori
(Principe+2018)
Declination Offset ["]
Right Ascension Offset ["]
V900 Mon
(Takami+2019)
Beam size
V2775 Ori (Zurlo+2017)
HBC 494 Ori
(Ruiz-Rodrigues+2017)
3000 au
FU Ori
(Hales, in prep)
4000 au
V883 Ori (Ruiz-Rodrigues+2017)


GM Cha
(Hales, in prep)
RA (J2000)
High
Blue: [-1.6,+1.7]
Red: [+6.5,+9.8]
outflow
EX Lup
(Hales+2018)
RA (J2000)







Arce and Sargent 2006
(Takami+2018)

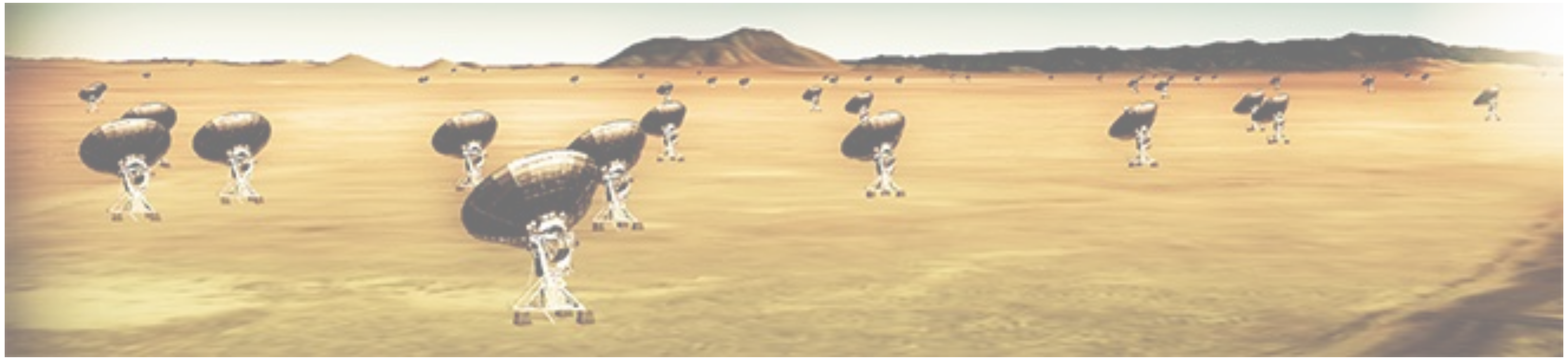
Summary

Episodic Accretion is a **common, key process in star formation**

Structure of FUors disks (compact, hot, optically thick inner disks)

FUors power large scale **outflows**. EXors resemble Class II disks.

High resolution Observations at lower frequencies needed for **piercing** through their **optically thick cores**, estimate mass, resolve inner-disk structure (**ngVLA**)

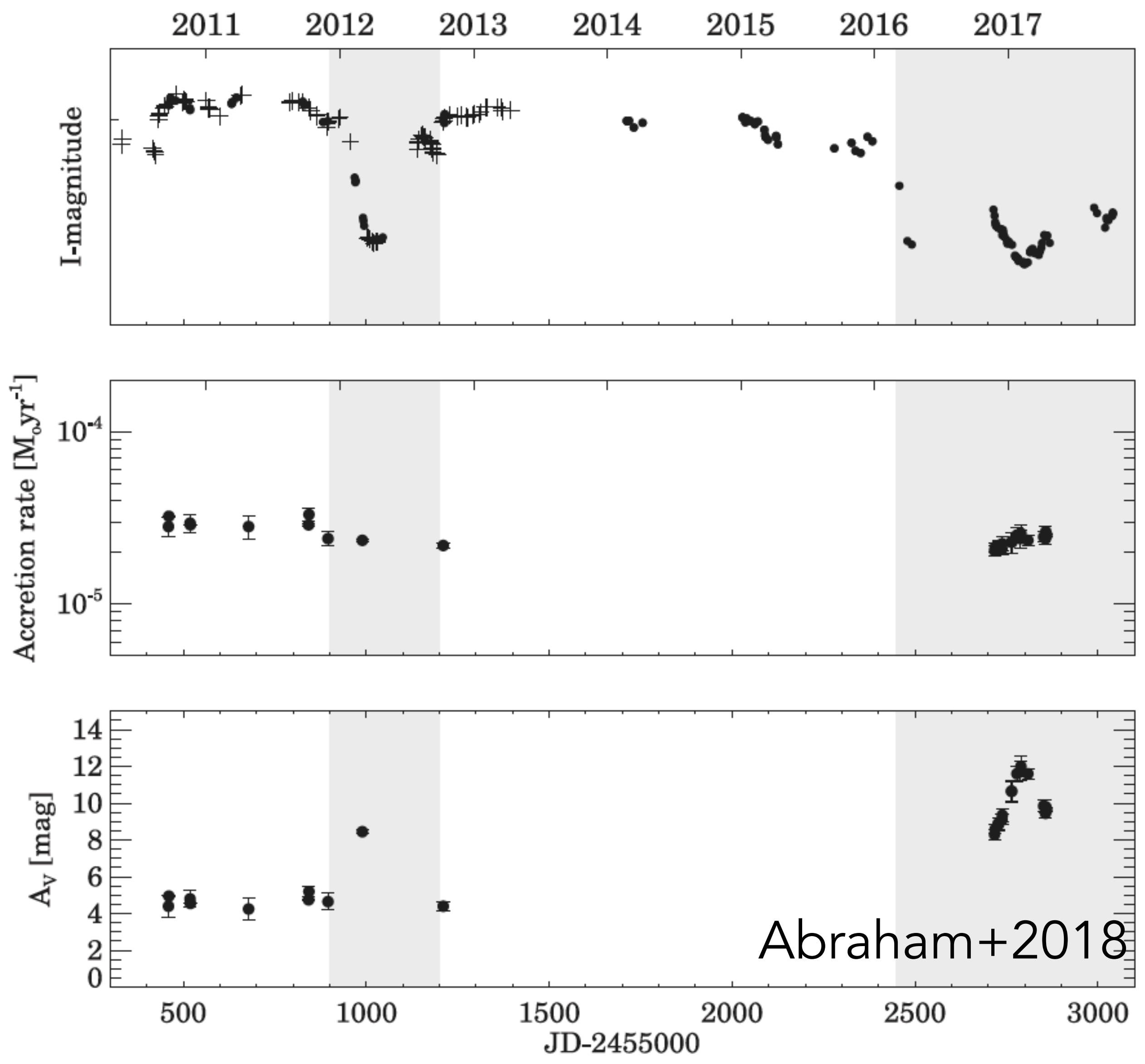


Open questions and future work

How many eruptive sources show UXor behaviour: V582 Aur, FUOr

Relation of extinction events to winds and molecular outflows

Further monitoring of eruptive sources to distinguish extinction events from accretion outbursts (e.g. V582 Aur Abraham+2018)



MOST light curve, Siwak et al. (2013)