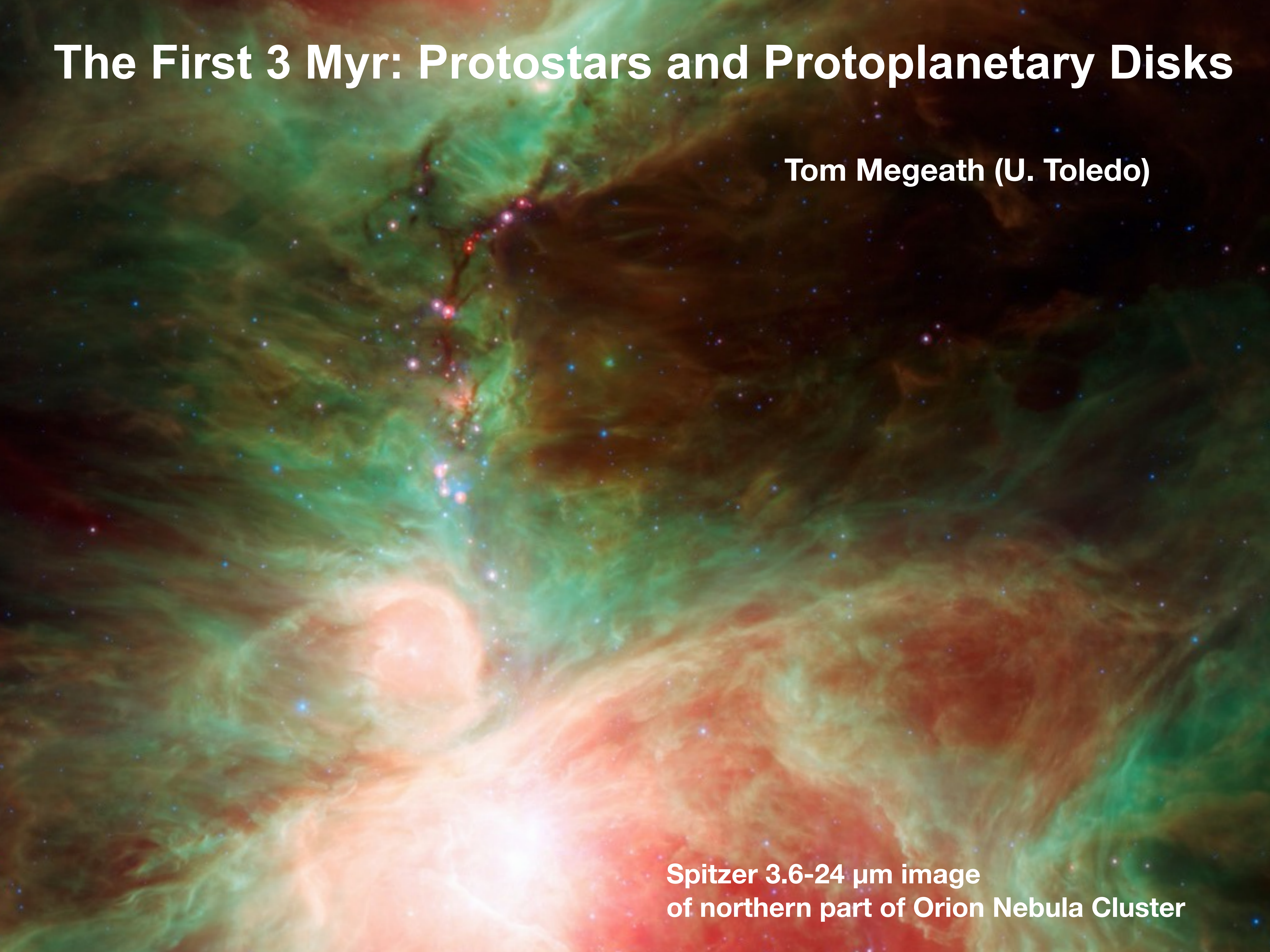
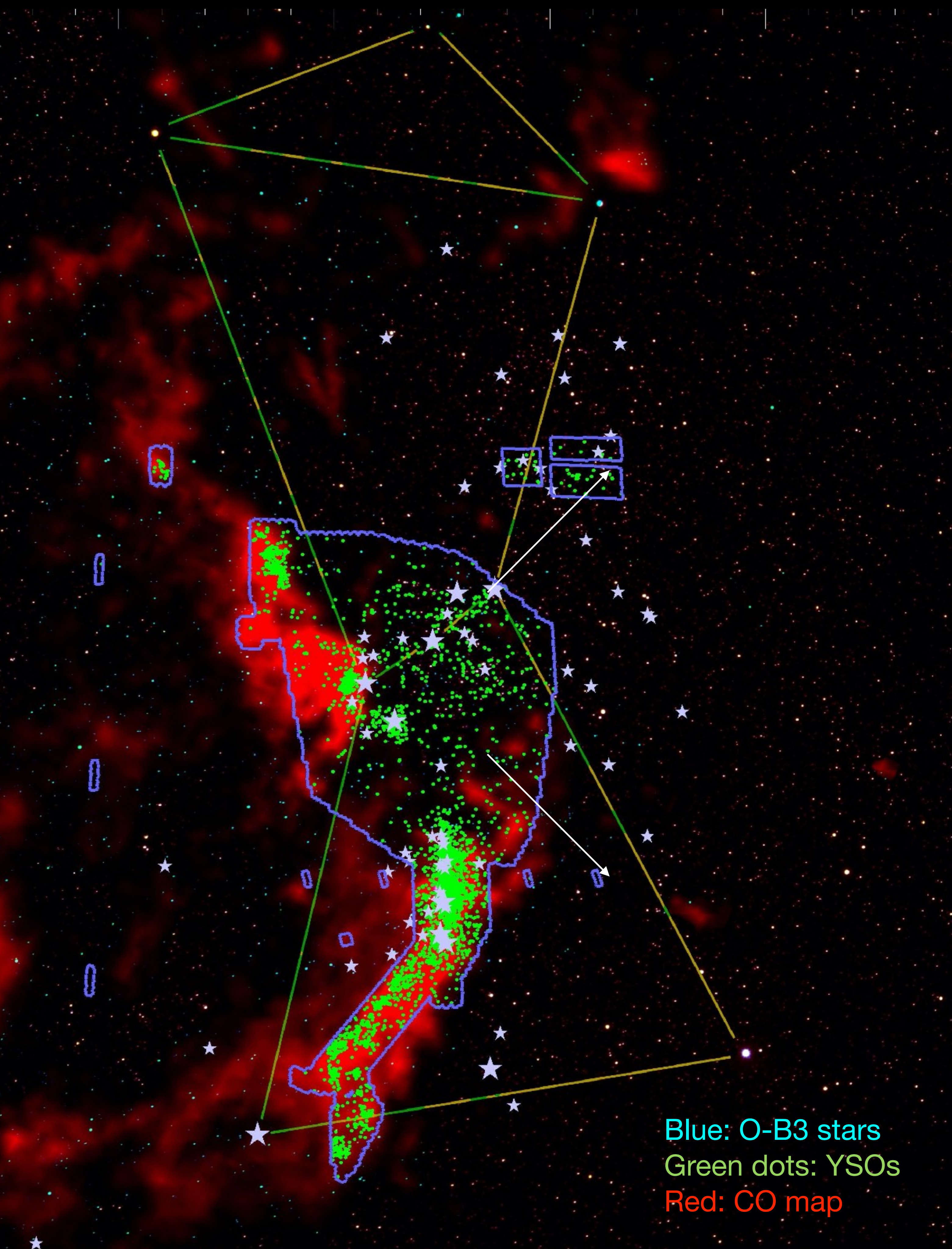
The First 3 Myr: Protostars and Protoplanetary Disks

Tom Megeath (U. Toledo)



Spitzer 3.6-24 µm image
of northern part of Orion Nebula Cluster



Blue: O-B3 stars
Green dots: YSOs
Red: CO map

Summary

1. Surveys for YSOs
2. The importance of the first 3 Myr
3. Ages of protostars
4. Evolution of disks from protostars to pre-ms stars
5. Environment
6. Variability

Glossary

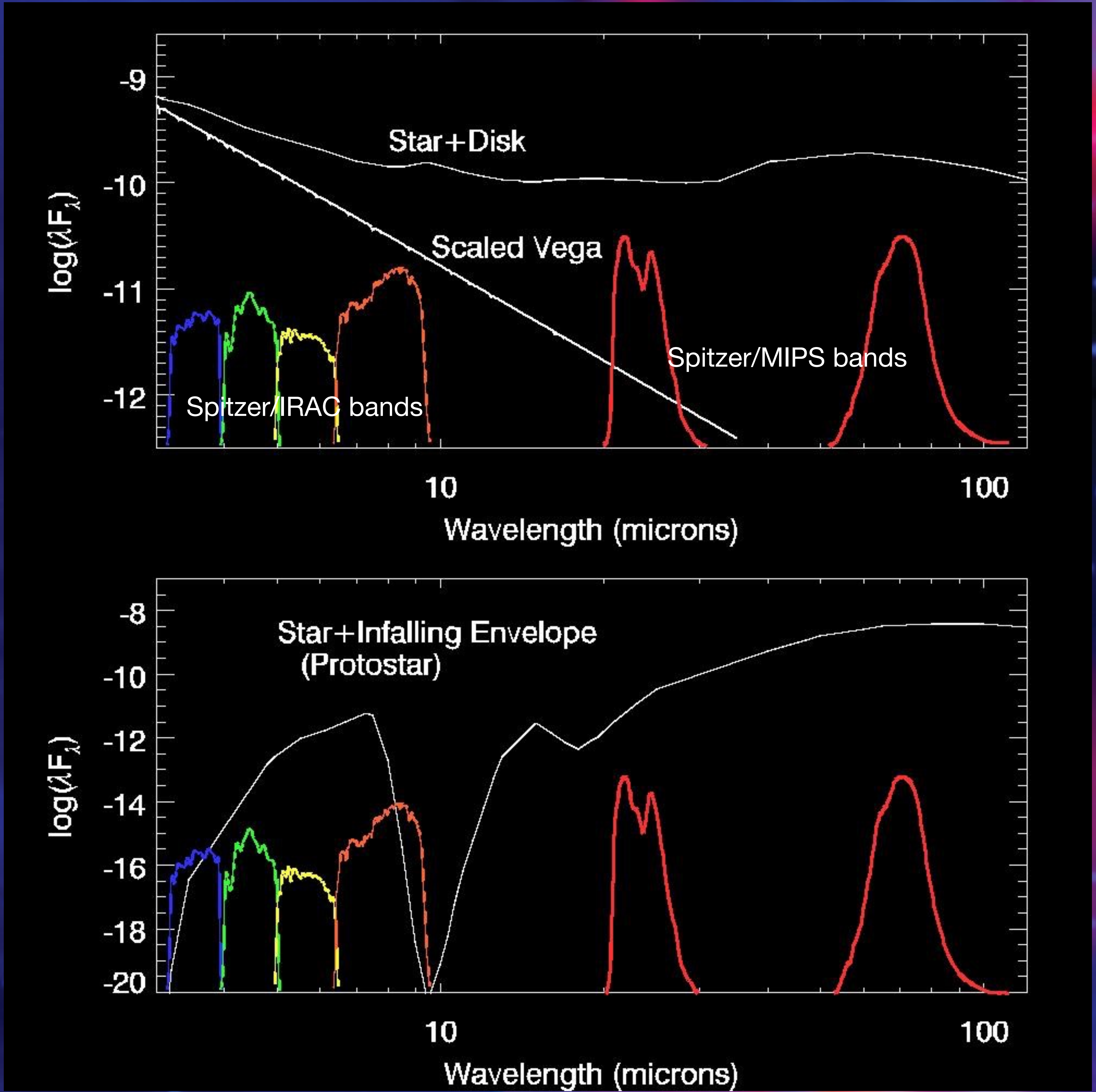
YSO = Young Stellar Object, a young (< 3 Myr) star or protostar

dusty YSO = a YSO with dusty disk or envelope

protostar = a YSO with an infalling envelope

pre-ms star = a young star contracting toward main sequence

Surveys: we now have rich catalogs of dusty YSOs due to combined near-IR+Spitzer+Herschel data

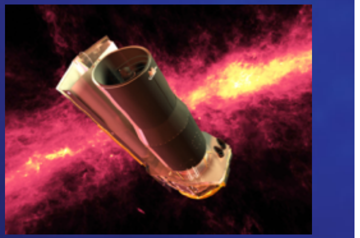


Examples of
Spitzer YSO surveys:

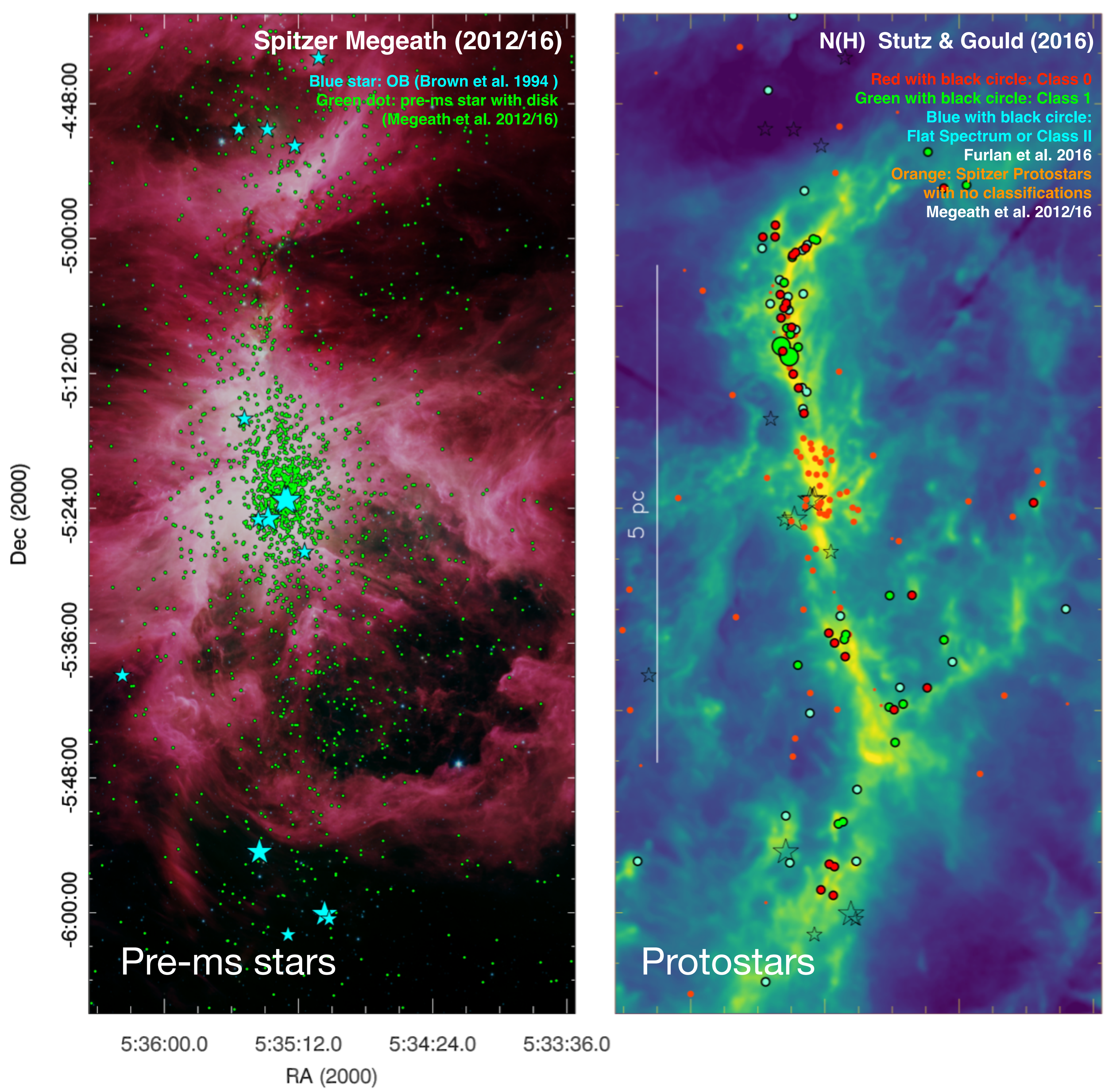
Evans+2009
Gutermuth+2009
Megeath+2012
Kryukova+2013
Dunham+2015
Furlan+2016
Winston+2019
Kuhn+2021

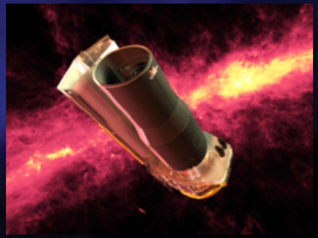
Note: young stars also be identified by elevated X-ray flux (e.g. Preibisch+2005), in visible light spectroscopy (e.g. Fang+2009). NIR spectroscopy (e.g. DaRio+2016), Gaia+NIR Spectroscopy (e.g. Kounkel+2018).

Surveys: we now have rich catalogs of dusty YSOs



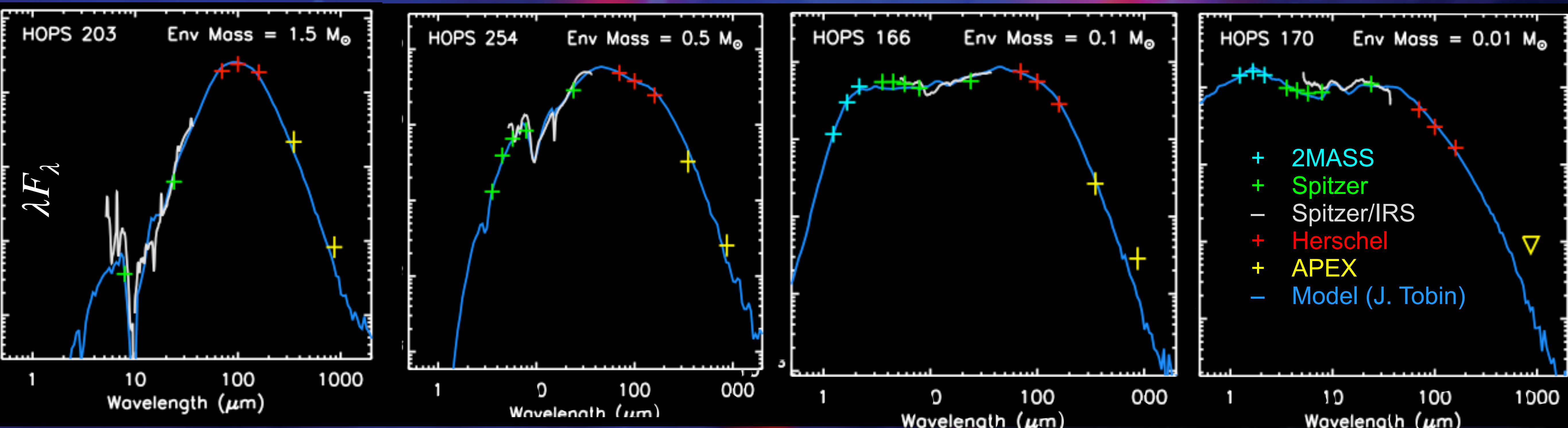
Spitzer mid-IR (with assists from Chandra X-ray)





Herschel far-IR to sub-mm (with assist from APEX)

In 0.5 Myr, protostars evolve into disk bearing pre-ms stars

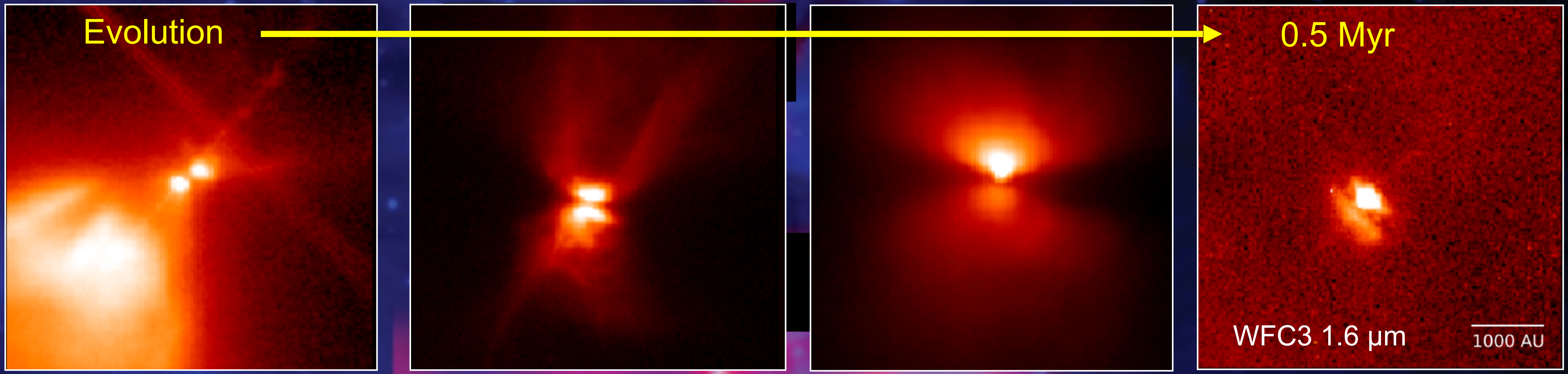


Class 0 Protostar

Class I Protostar

Flat Spectrum Protostar

Pre-ms star with disk



HERSCHEL ORION PROTOSTAR SURVEY

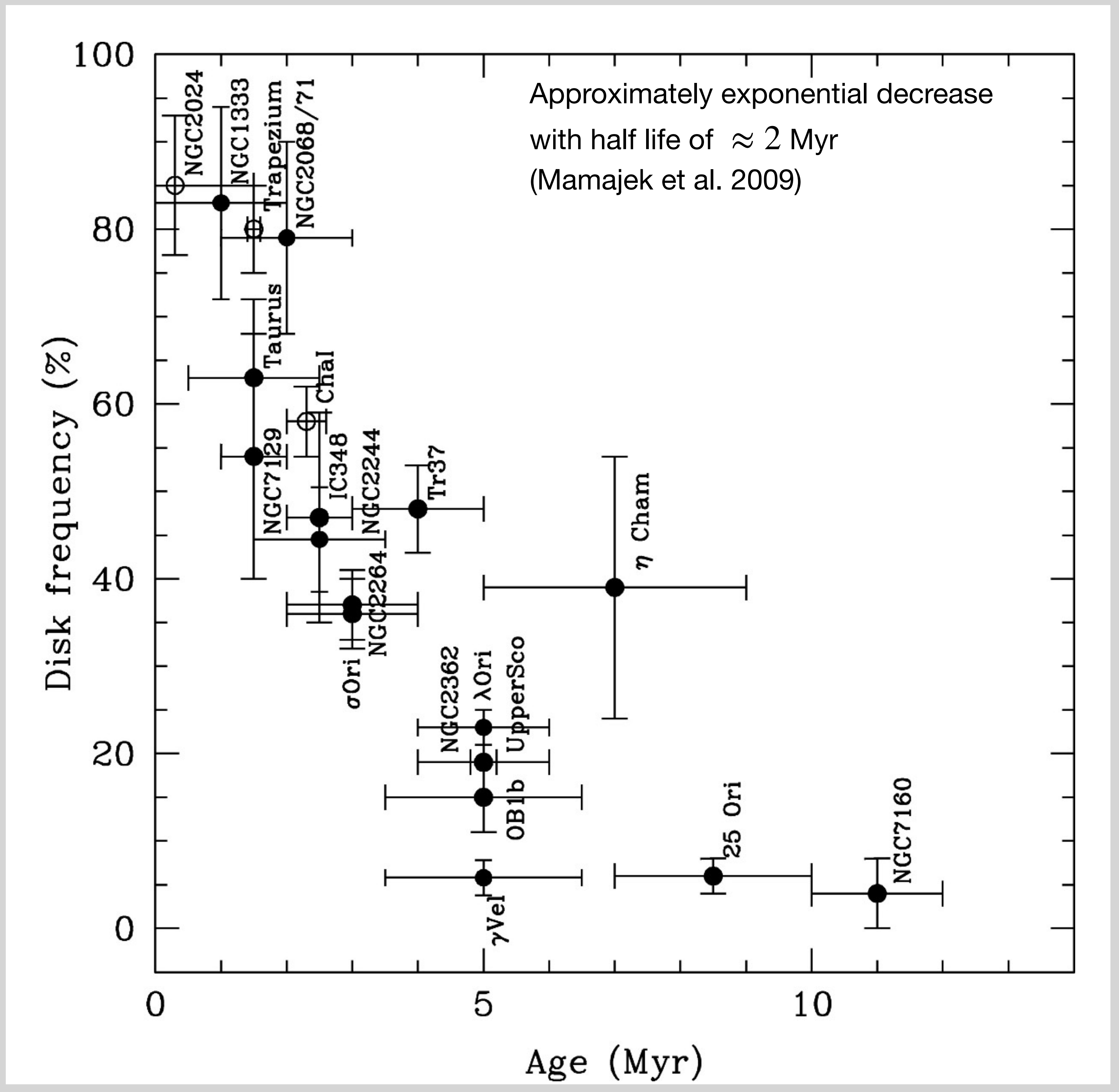
Manoj et al. 2013
Stutz et al. 2013

Fischer et al. 2017
Furlan et al 2016

Kounkel et al. 2016
Habel et al. 2021.

http://irsa.ipac.caltech.edu/data/Herschel/HOPS/overview.html

About half of optically thick, gas rich disks around pre-ms stars disappear in 3 Myr



Approximately exponential decrease
with half life of ≈ 2 Myr
(Mamajek et al. 2009)

Fraction of pre-ms
stars with
disks in clusters

vs

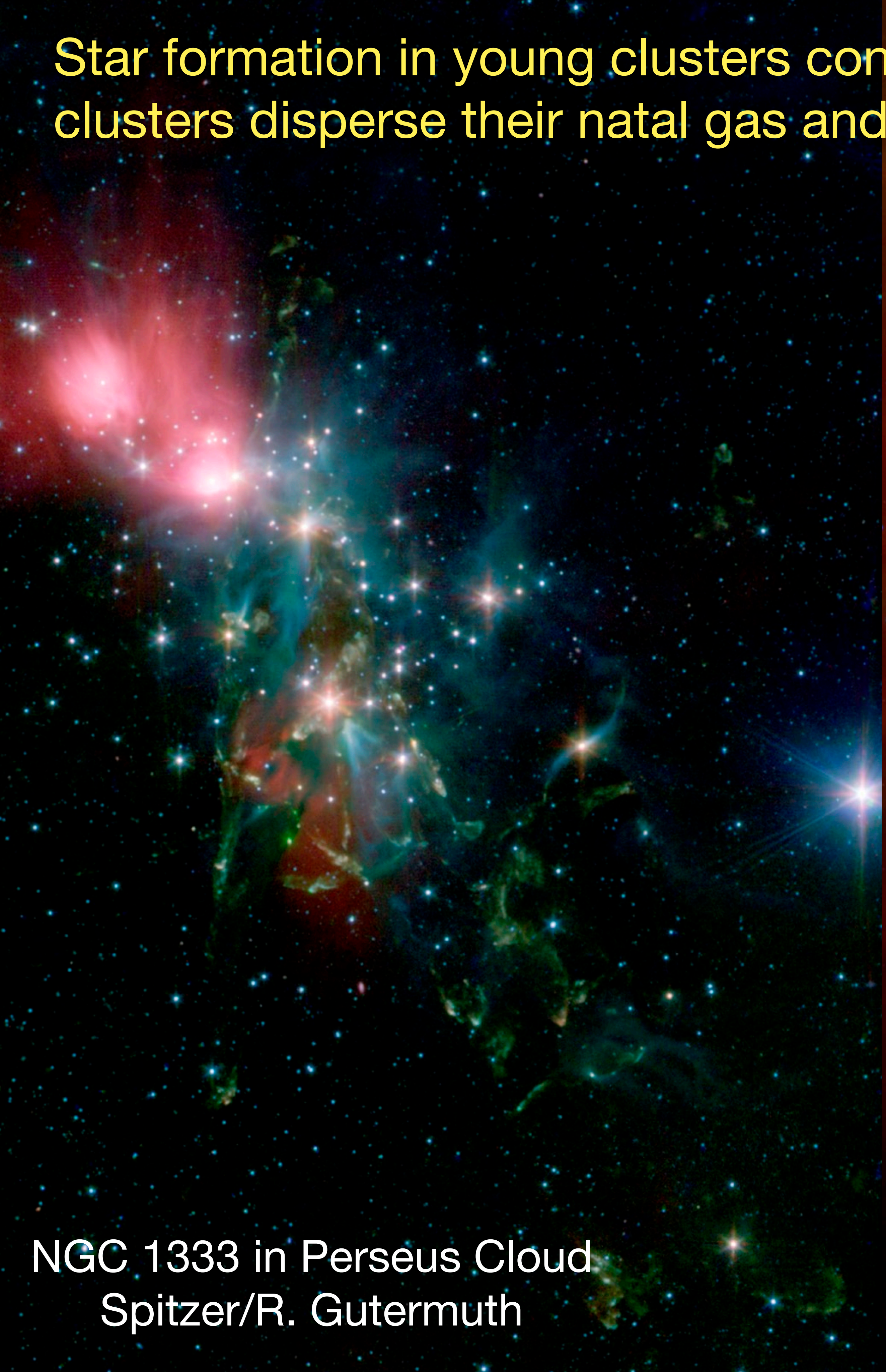
age of clusters.

Disks detected by IR
excesses with Spitzer

Hernandez+2008

Star formation in young clusters continues for 3 Myr, after this time, the clusters disperse their natal gas and expand.

Megeath+submitted



NGC 1333 in Perseus Cloud
Spitzer/R. Gutermuth

IC 348 in Perseus Cloud
Spitzer/L. Cieza

“Ages” of protostars

See talks by Hillenbrand and Baraffe for discussion of pre-ms ages.

No direct ages to protostars, we bootstrap ages from pre-ms stars (e.g. Dunham+2014)

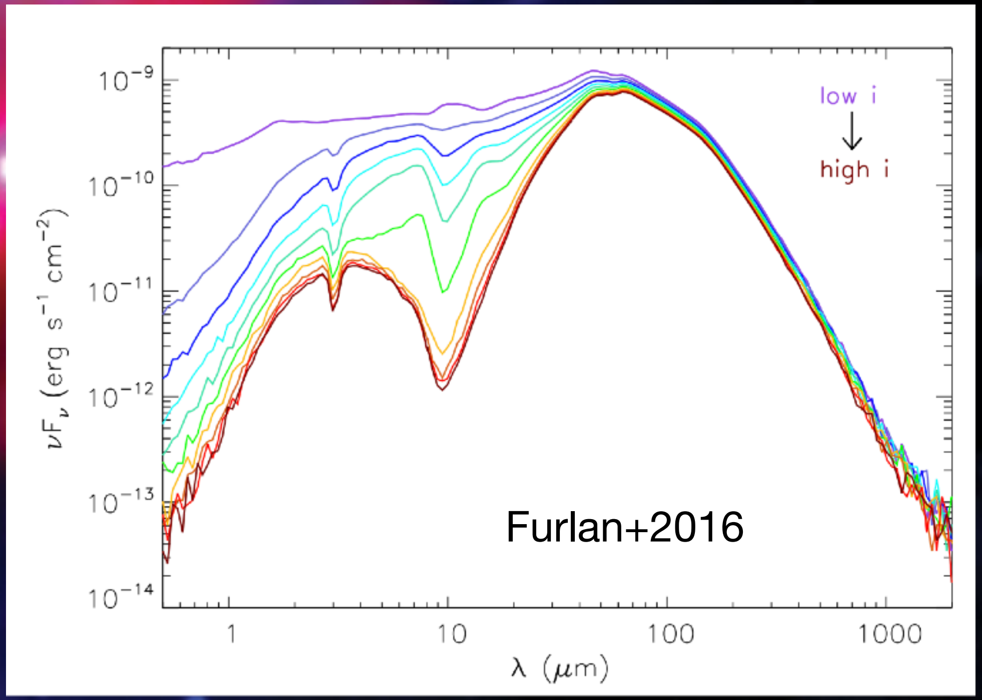
$$\tau_{protostar} \approx \frac{N_{protostars}}{N_{pre-ms}} \times \tau_{disk}$$

where τ_{disk} is pre-ms star with disk, or Class II, lifetime

$$\tau_{disk} \approx 2Myr \Rightarrow \tau_{proto} \approx 0.5Myr$$

$$\tau_{\mathrm{Class\ 0}} \approx \frac{N_{\mathrm{Class\ 0}}}{N_{protostars}} \tau_{protostar} \approx 0.13\ \mathrm{Myr}$$

Assumes constant star formation rate and protostar lifetimes, for alternative “half life” formalism, see Kristensen & Dunham (2018)



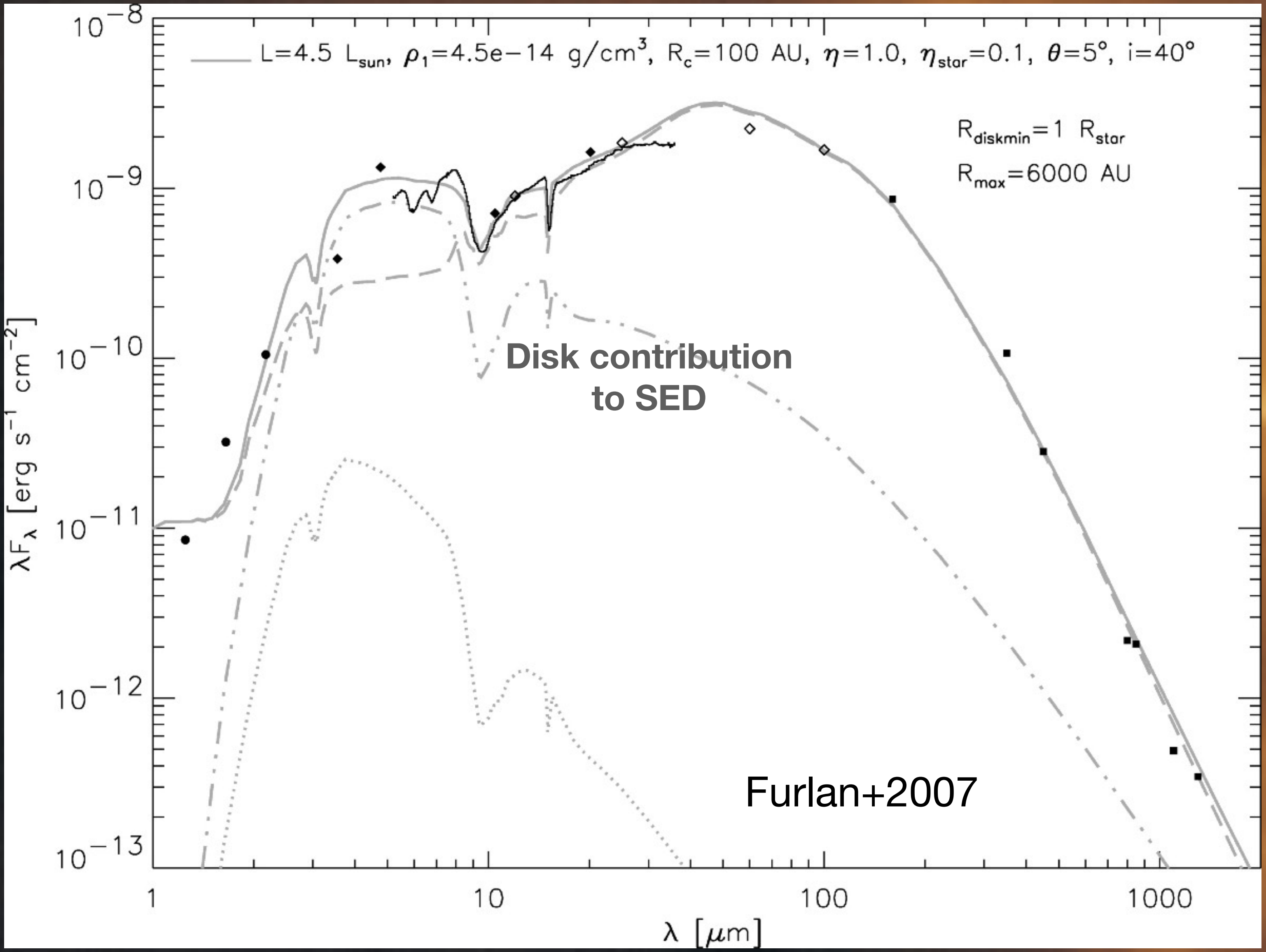
Furlan+2016

SEDs are also affected by inclination

Classification of protostars is affected by inclination *and* envelope evolution.

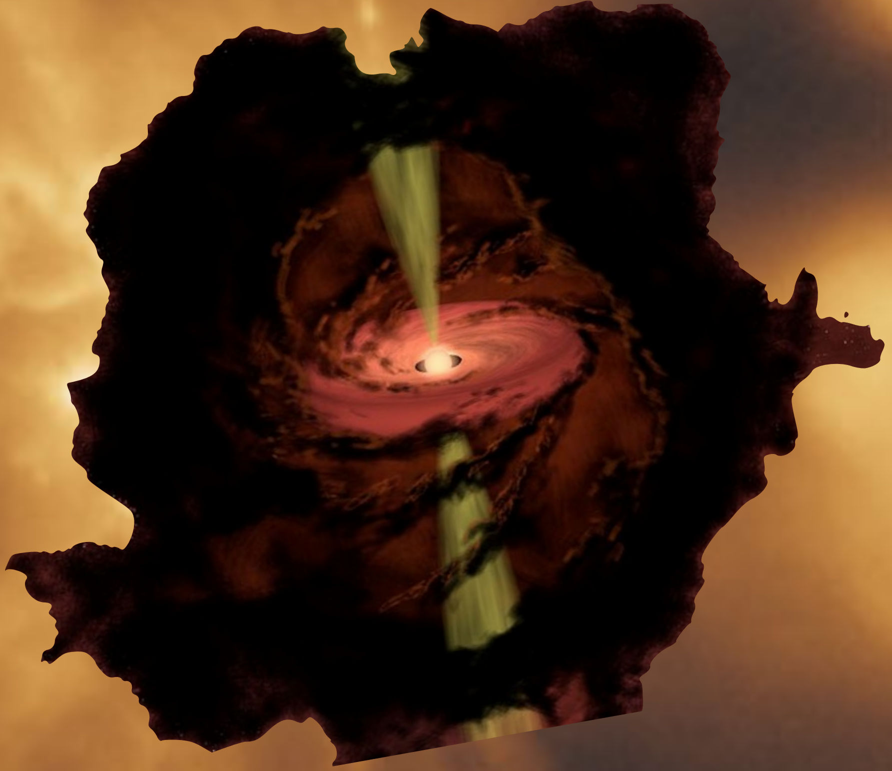
Evolutionary classes are a guide.

The evolution of disks from protostars to pre-ms stars



Disk contribution to SED

Furlan+2007



Artist conception by Robert Hurt

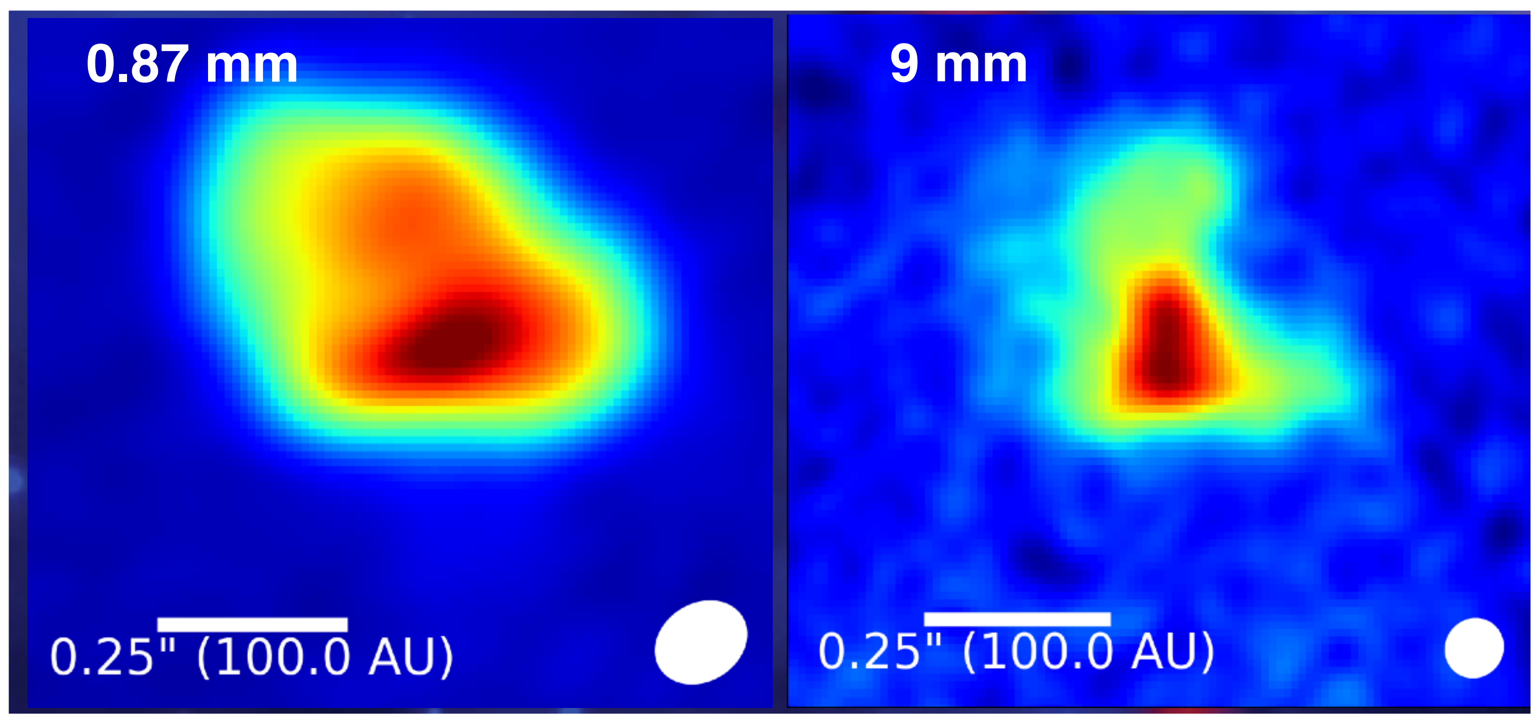
1.6 μm image from WFC3 processed Judy Schmidt

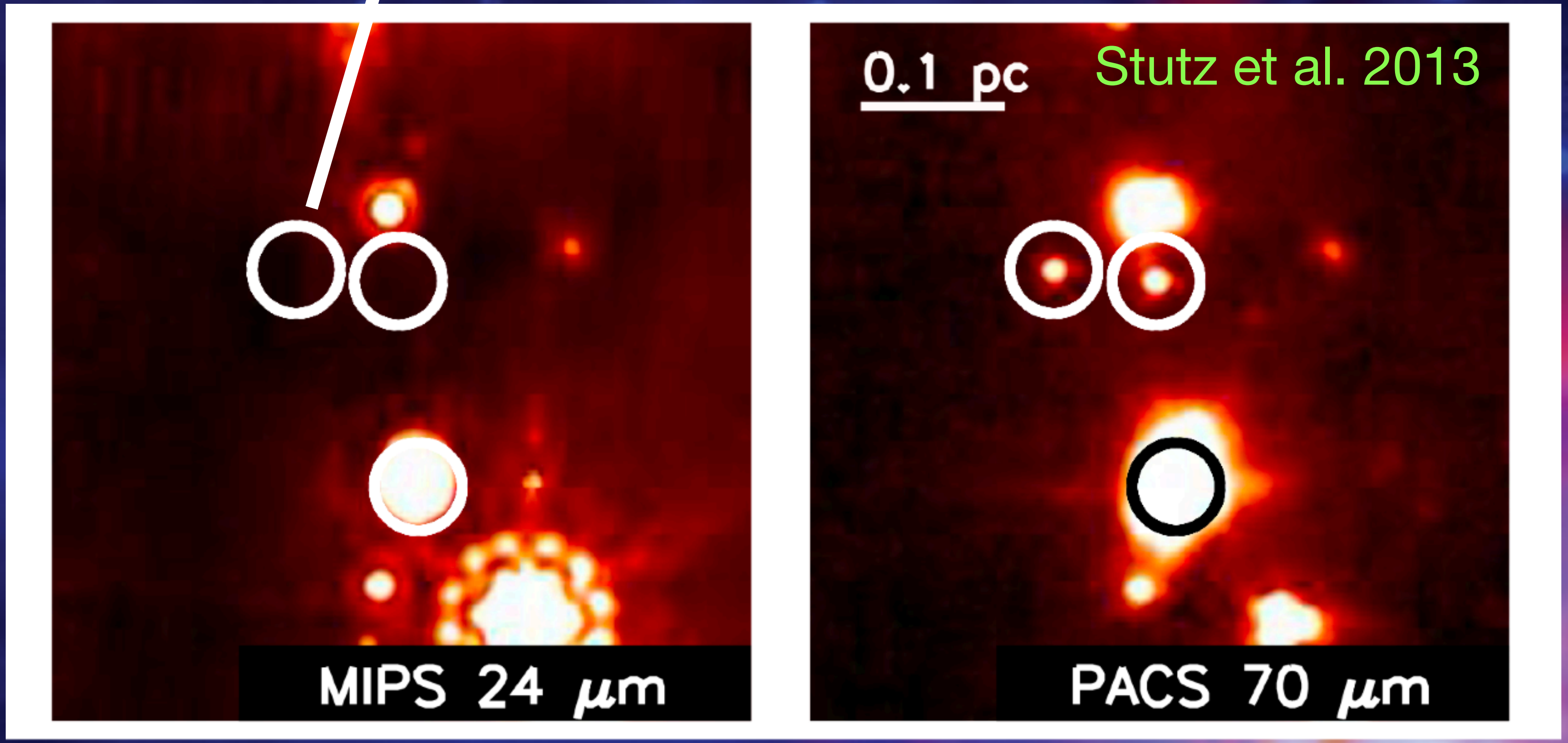
Unlike pre-ms stars, we cannot establish if a protostar has a disk from its SED.

ALMA and VLA (sub)-mm data are needed to detect disks around protostars.

The youngest protostars in Orion (< 6000 years old)?

Herschel Orion Protostar Survey (HOPS) 402





Stutz et al. 2013

Orion VANDAM

Karnath et al. 2020

$0.83\ M_\odot$ in 160 AU

$0.55\ L_\odot$

Optically thick at <870 μm

$\rho > 10^{-13}$ gm cm^{-3}

Luminosity generated by compression of gas

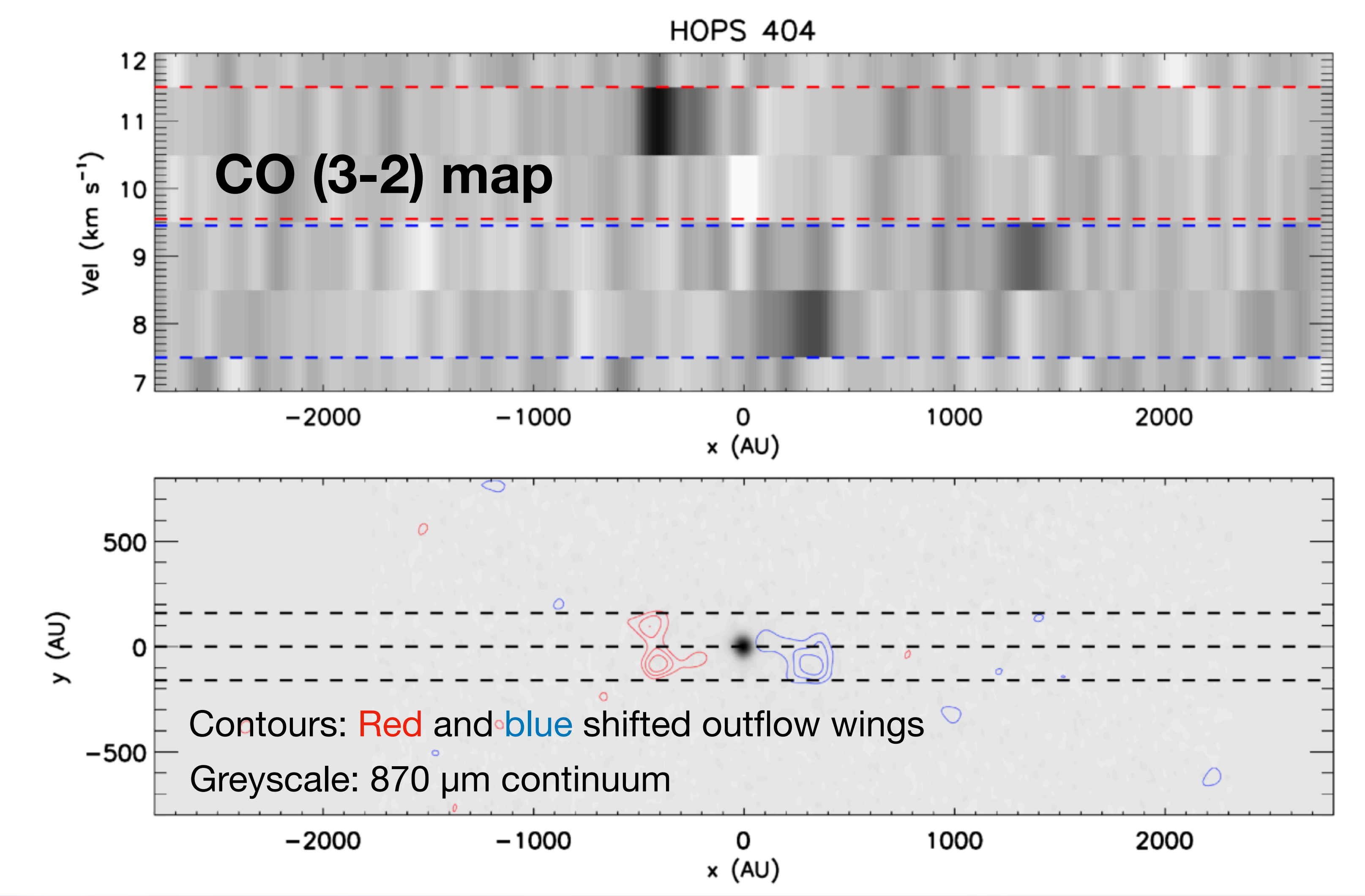
No detected outflow

The youngest protostars in Orion (< 6000 years old)?

Orion VANDAM Karnath et al. 2020

Low velocity of outflow

Contains hydrostatic core of H_2 and $T < 2000$ K (Larson et al. 1969)

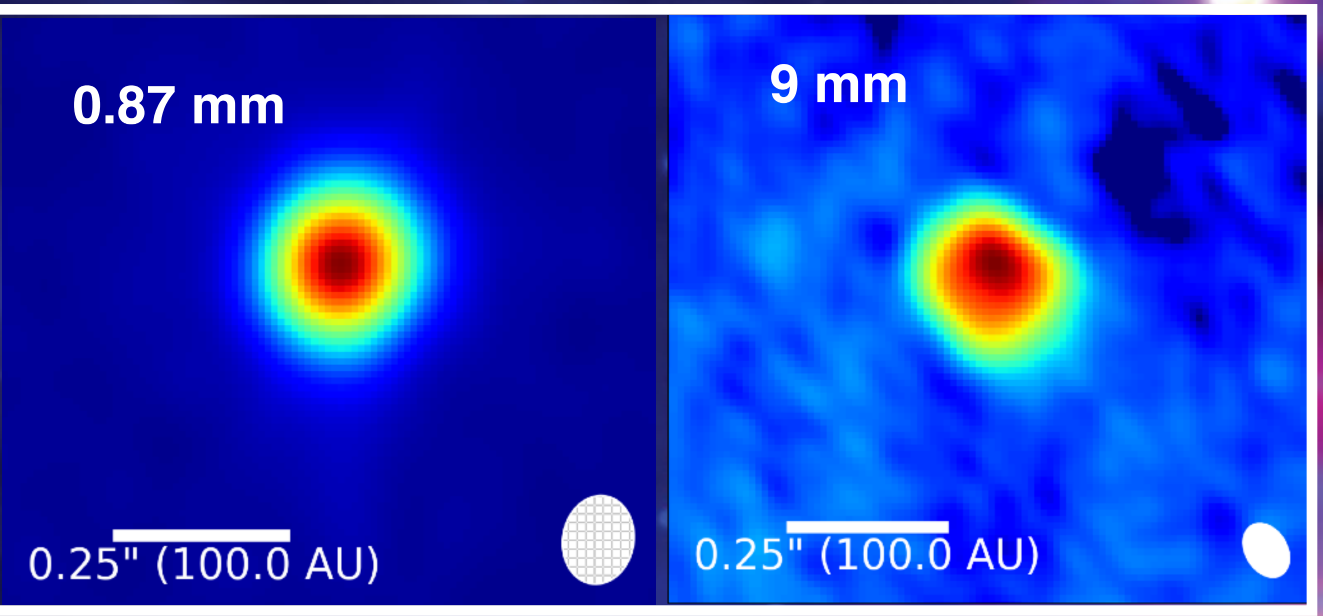


CO (3-2) map

Contours: Red and blue shifted outflow wings

Greyscale: 870 µm continuum

HOPS 404



Outflow suggests presence of disk

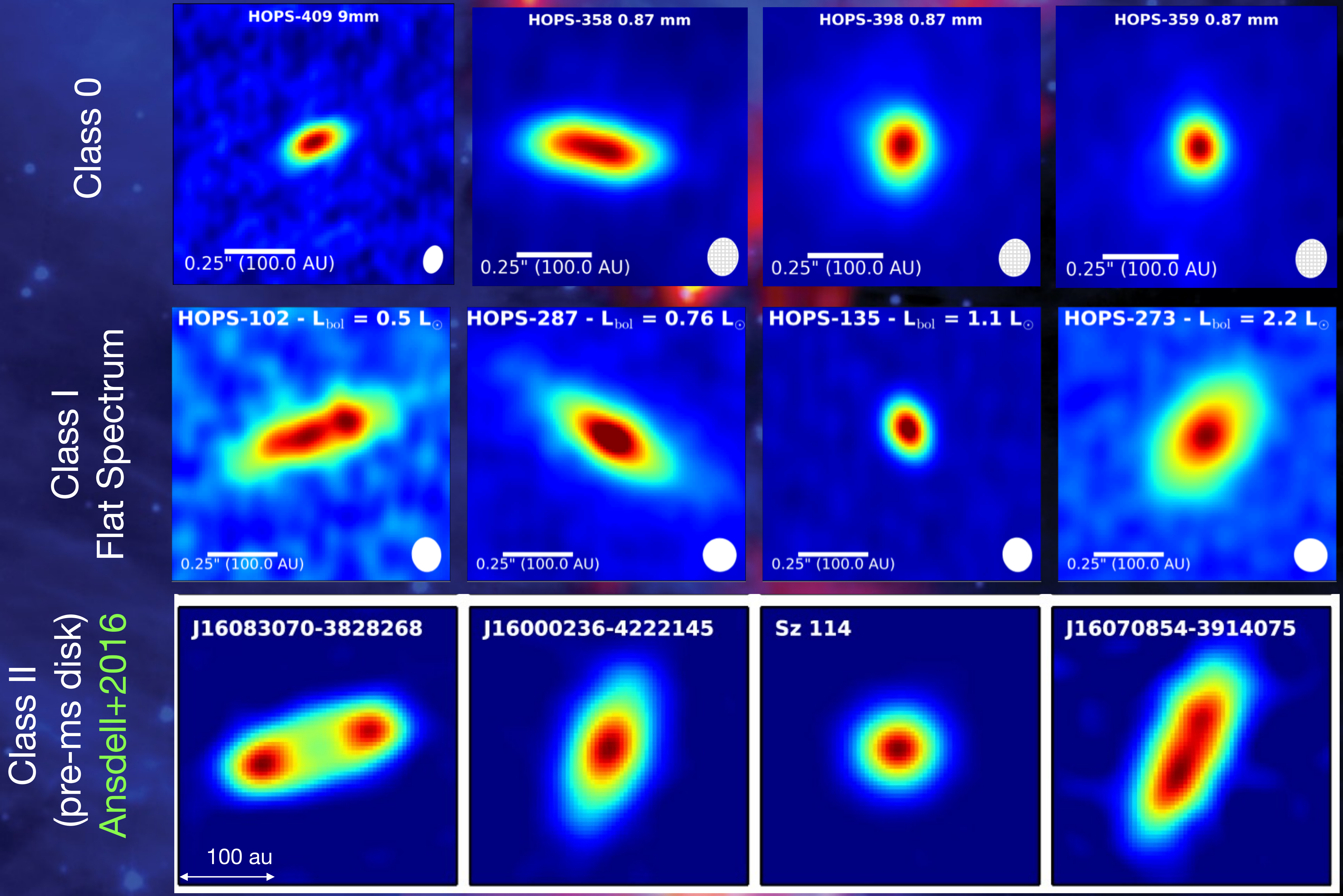
Optically thick at <870 µm

0.45 $M_\odot$ (mostly envelope)

0.95 $L_\odot$ (generated primarily by compression of envelope gas?)

ALMA + VLA Survey of HOPS prototars: many disks

(Orion VANDAM: Tobin+2020)

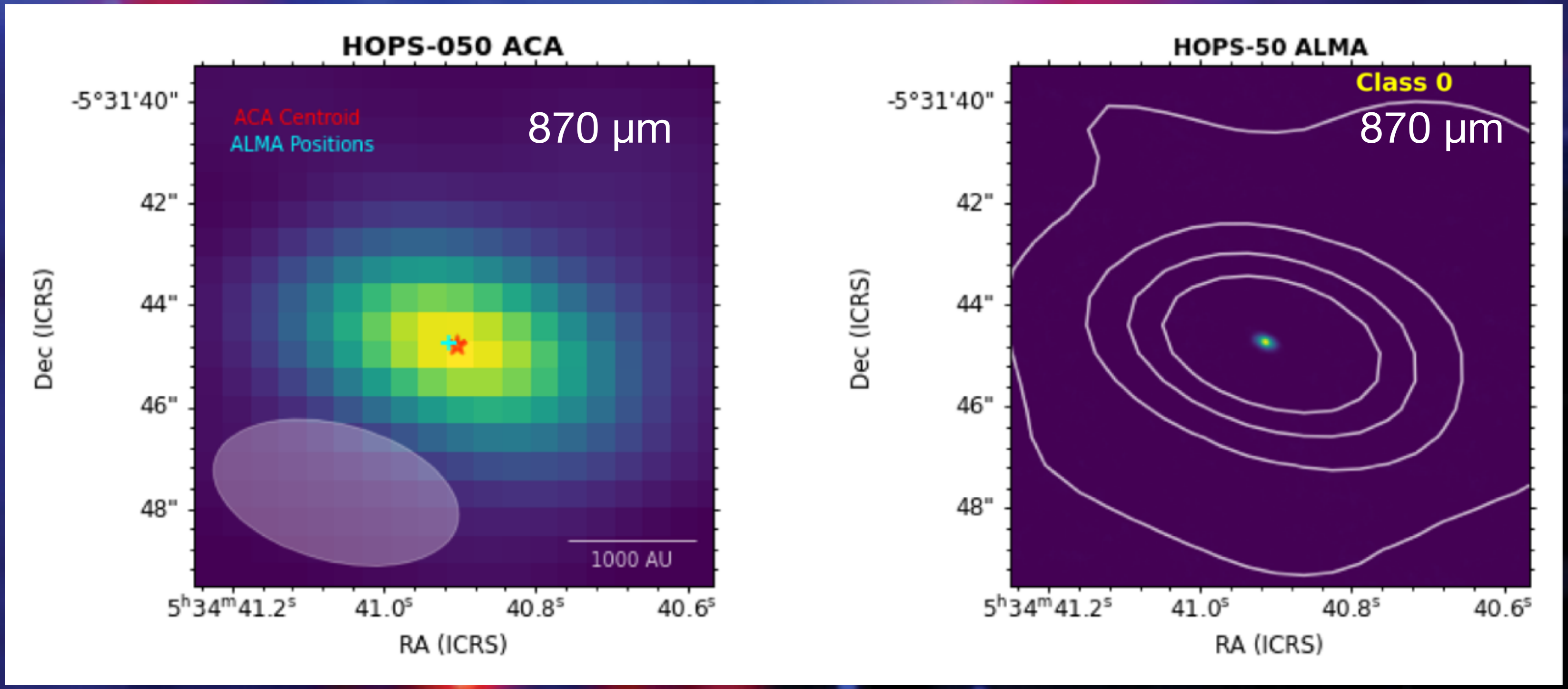


Infalling envelopes are gradually accreted/dispersed

Envelope/(Disk+Envelope) 870 μm flux ratios increase from Class0 -> Class I -> Flat spectrum

Flat spectrum likely have residual infall (Furlan et al. 2016)

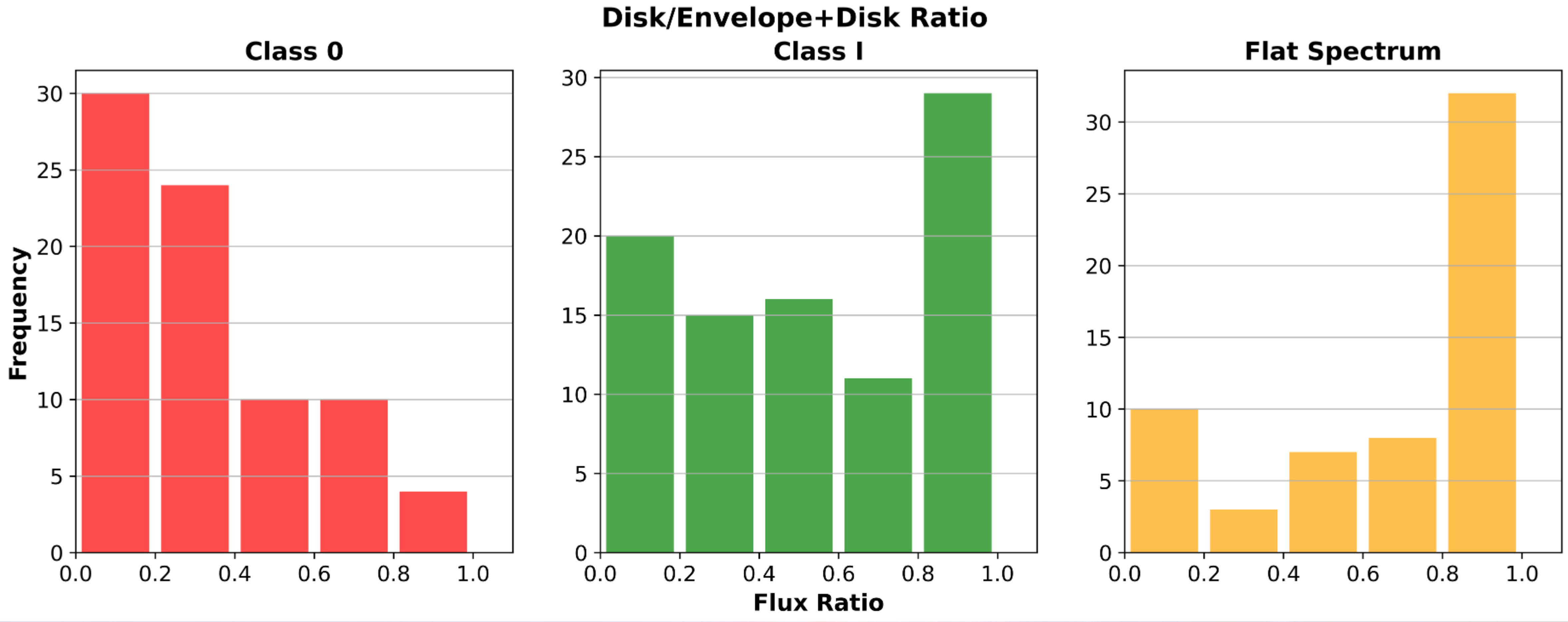
$$\tau_{disk} \approx \frac{M_{disk}}{\dot{M}_{acc}} \approx \tau_{FS}.$$



Federman+in prep

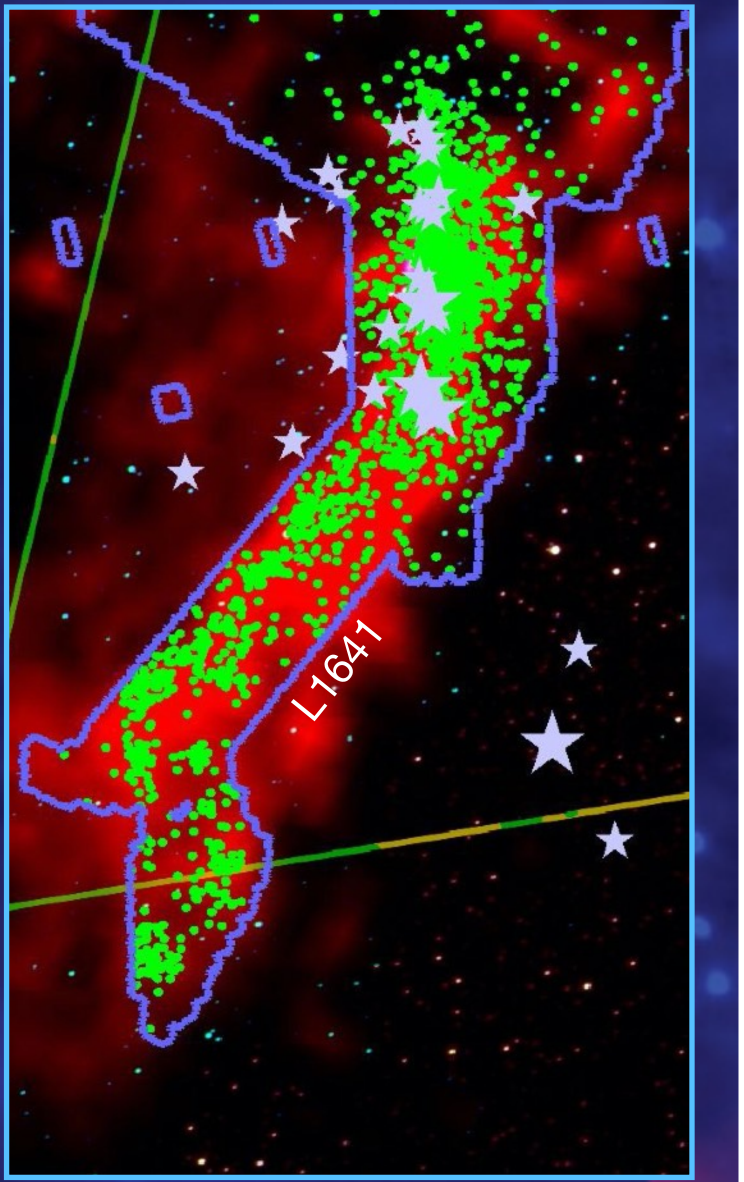
Envelope + Disk

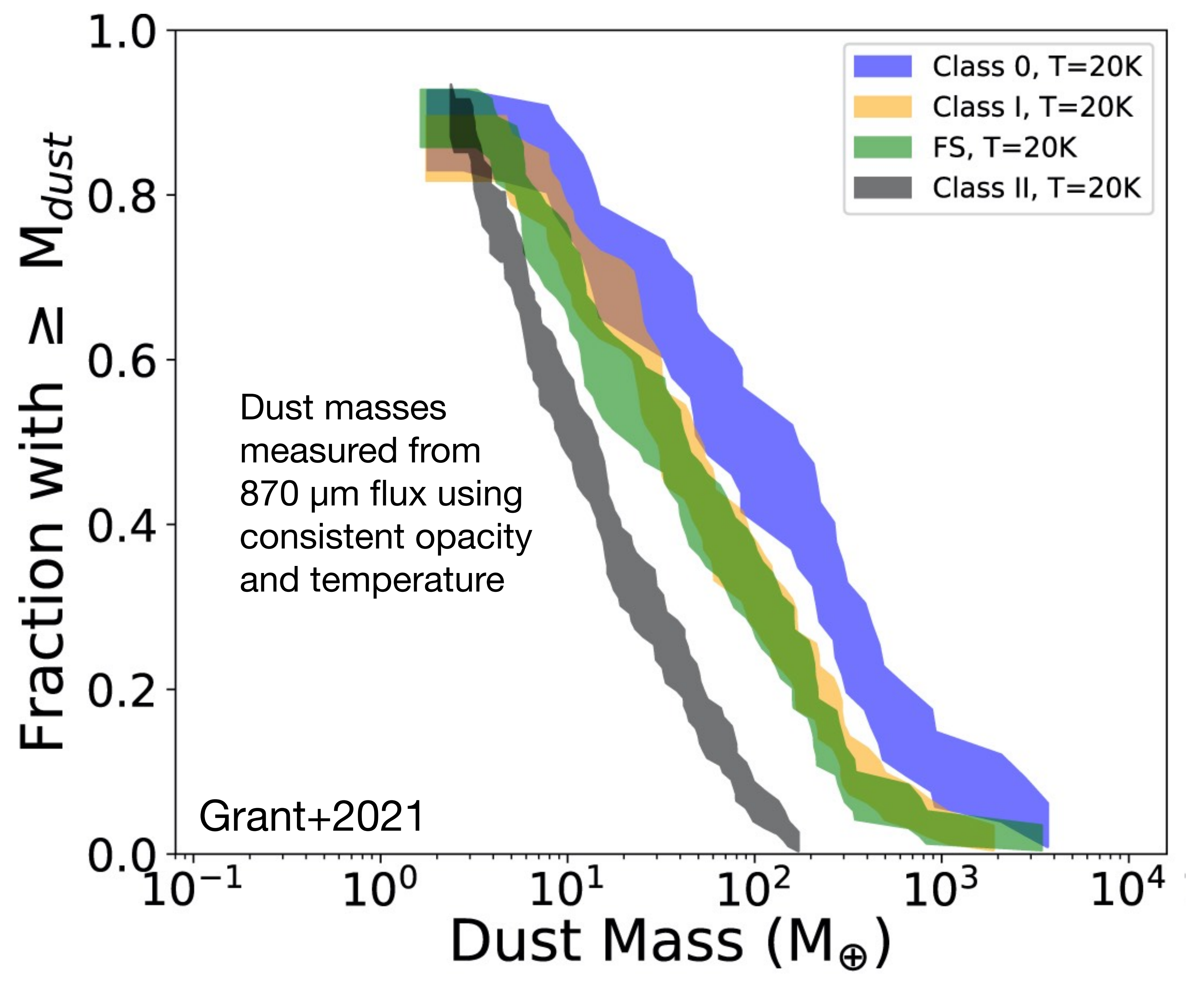
Disk



Evolution of disk masses in L1641 Cloud

(Orion VANDAM: Tobin+2020 vs Grant+2021)





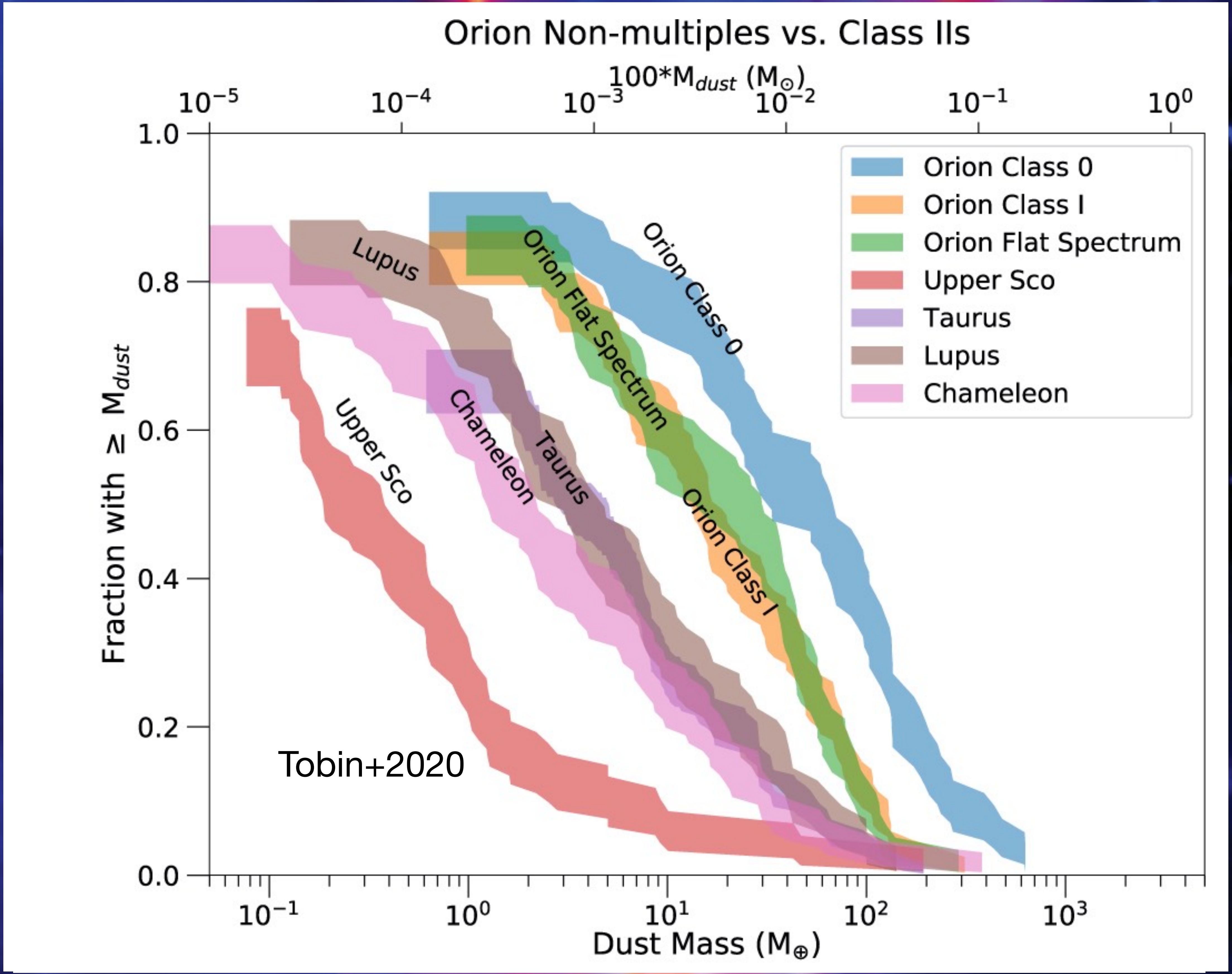
Dust masses measured from 870 μm flux using consistent opacity and temperature

Grant+2021

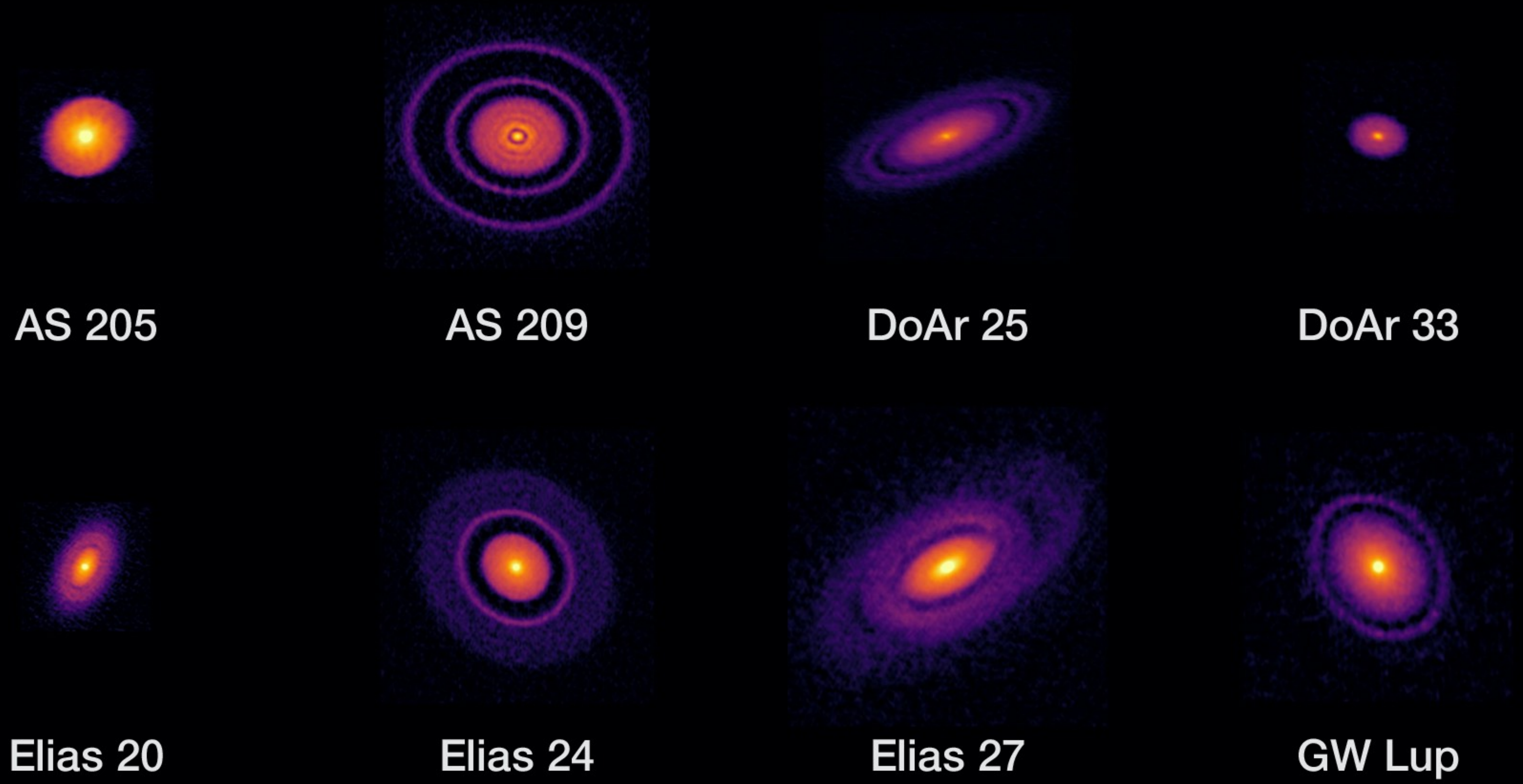
The dust masses in disk in L1641 region of Orion decrease from protostars to pre-ms stars (ClassII)

Evolution of disk masses in the Orion A an B Clouds

(Orion VANDAM: Tobin+2020)



Disk structure around pre-ms stars



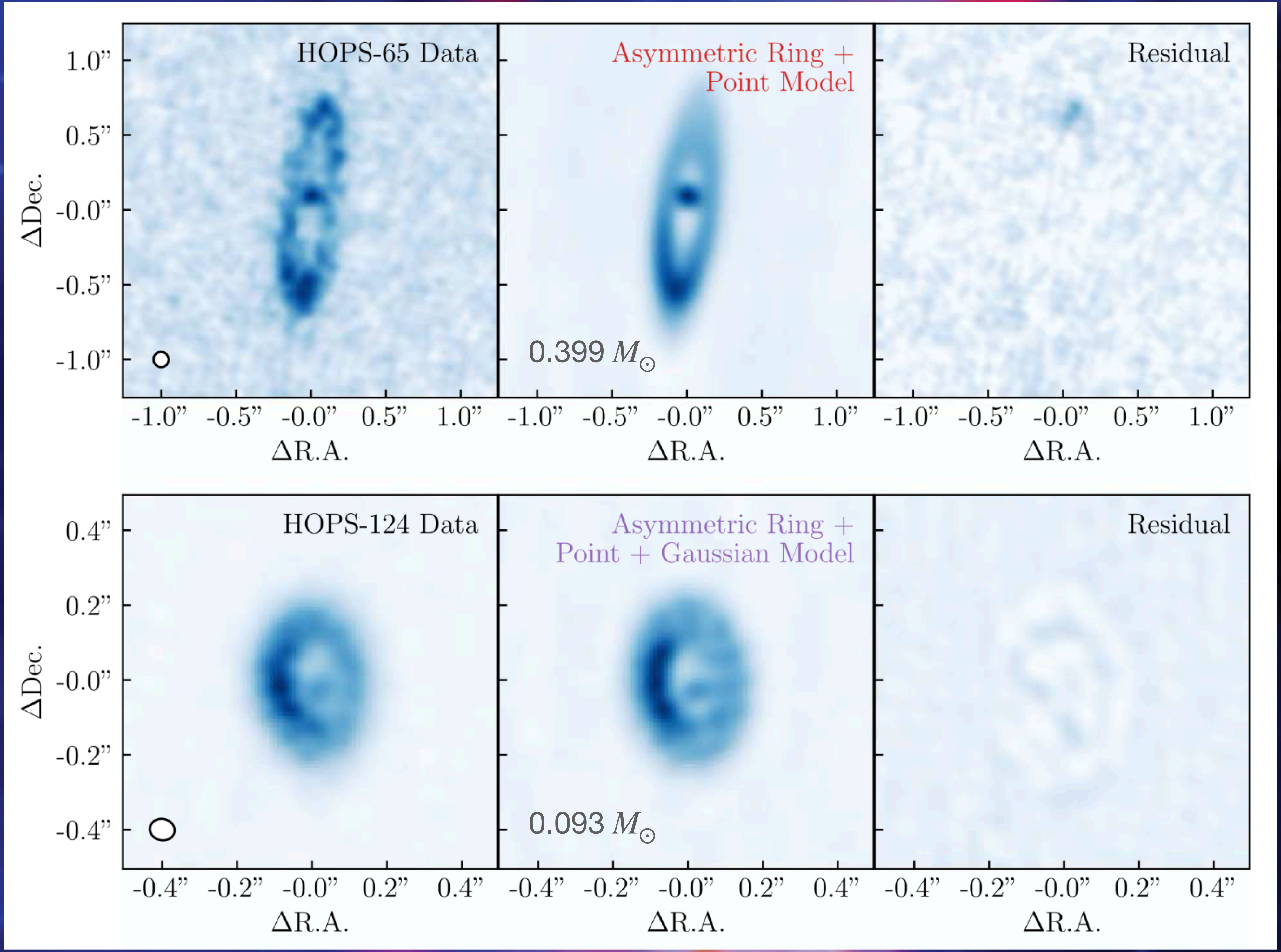
Disk Substructures at High Angular Resolution Project (DSHARP). Credit:
ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; N. Lira

Disk structure: protostars

May result from clearing by planet or close binary.

Class I

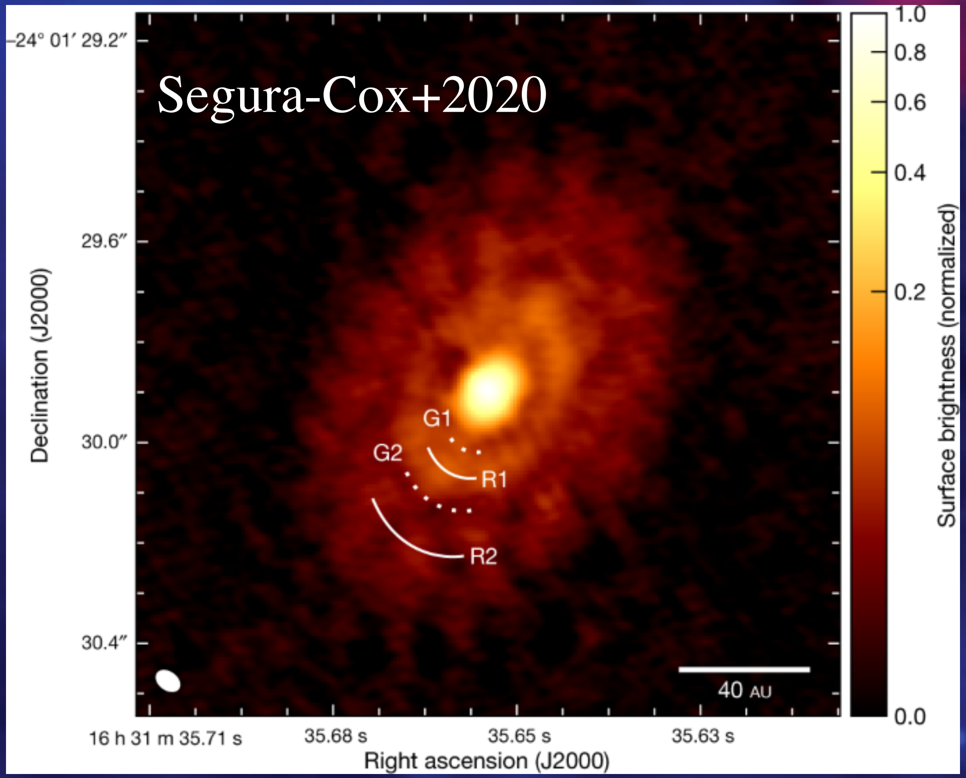
Class 0 (undergoing outburst)

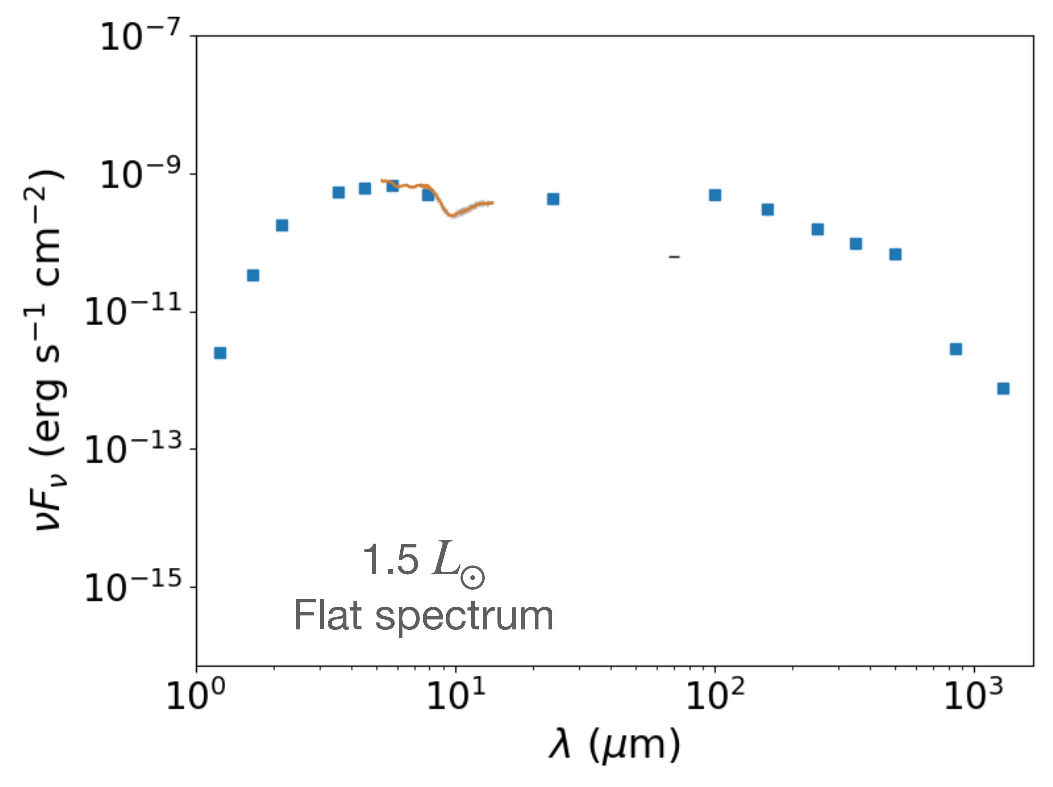


Structure found in seven Orion protostar disks

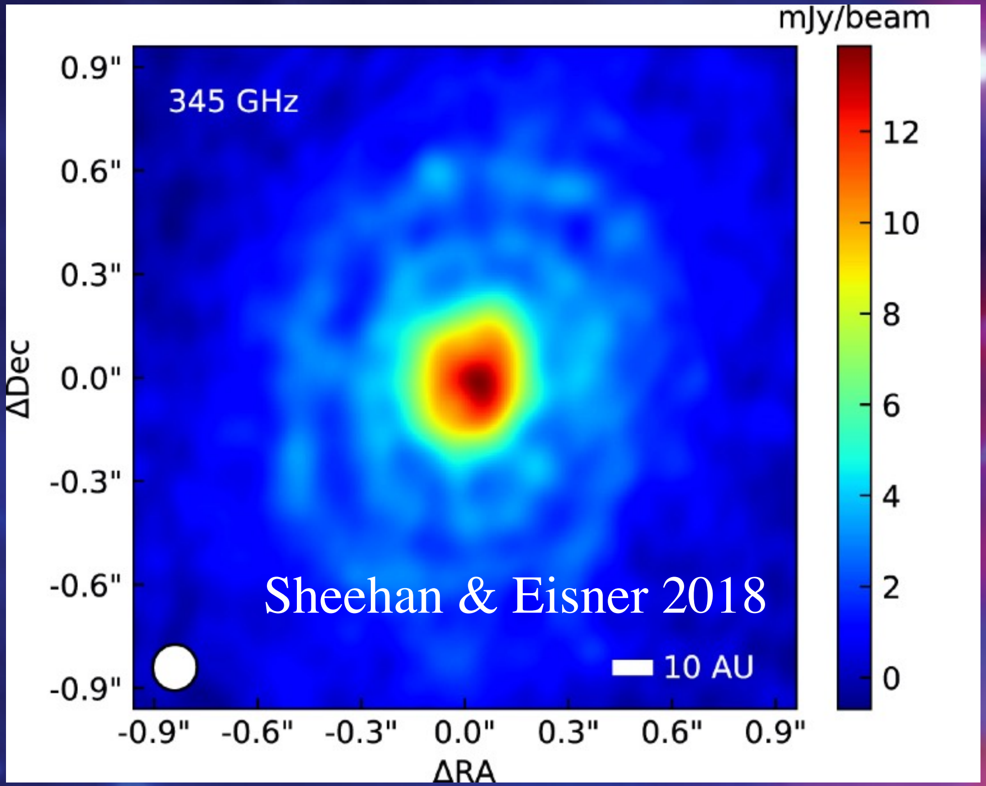
Sheehan+2020

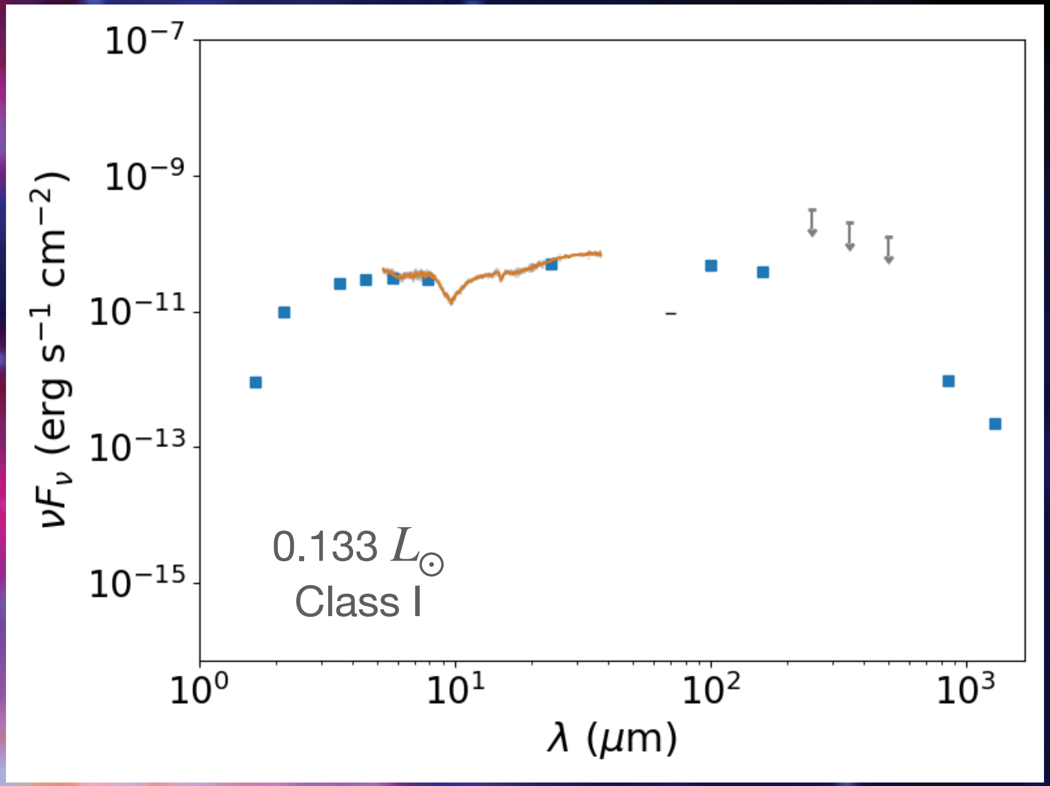
Gaps in protostellar disks


Segura-Cox+2020

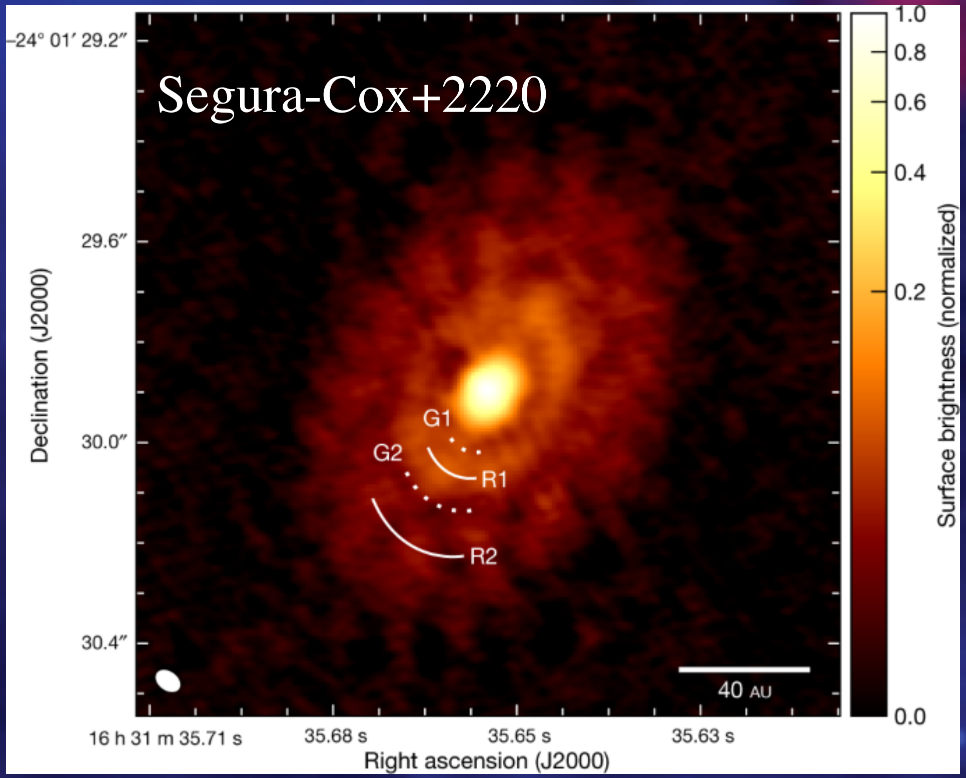


Pokhrel+in prep (eHOPS)

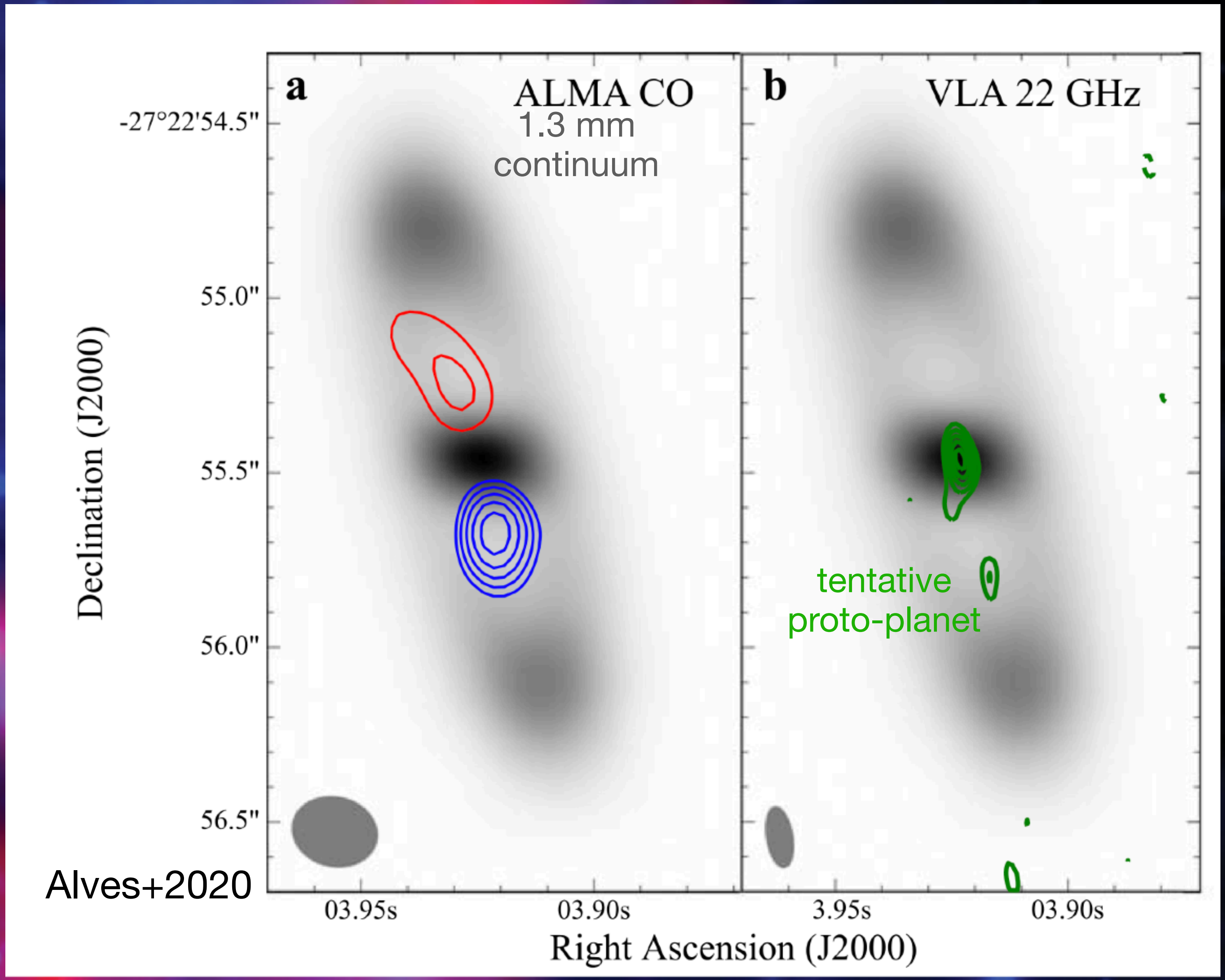

Sheehan & Eisner 2018



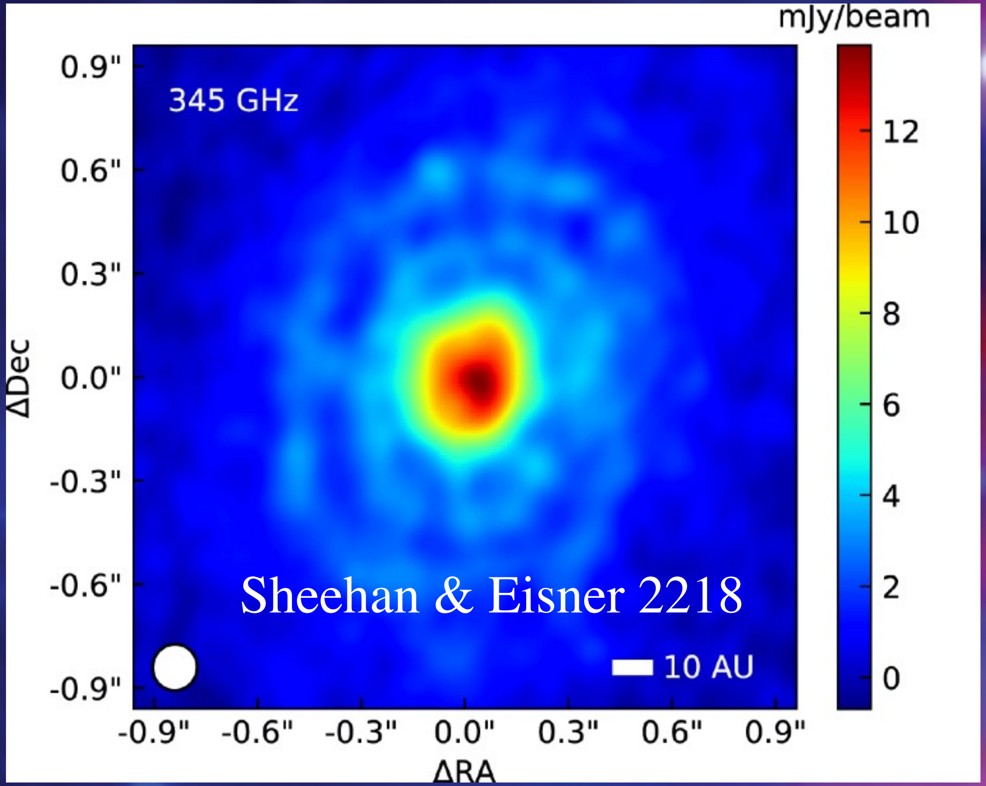
Gaps in protostellar disks


Segura-Cox+2220

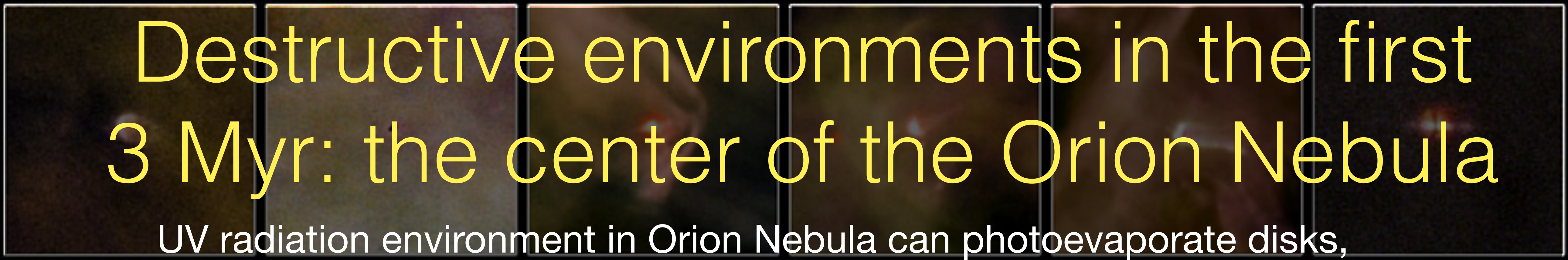
Flat Spectrum protostar BHB1 shows gap filled with gas and tentative cm detection of porto-planet in gap


Alves+2020

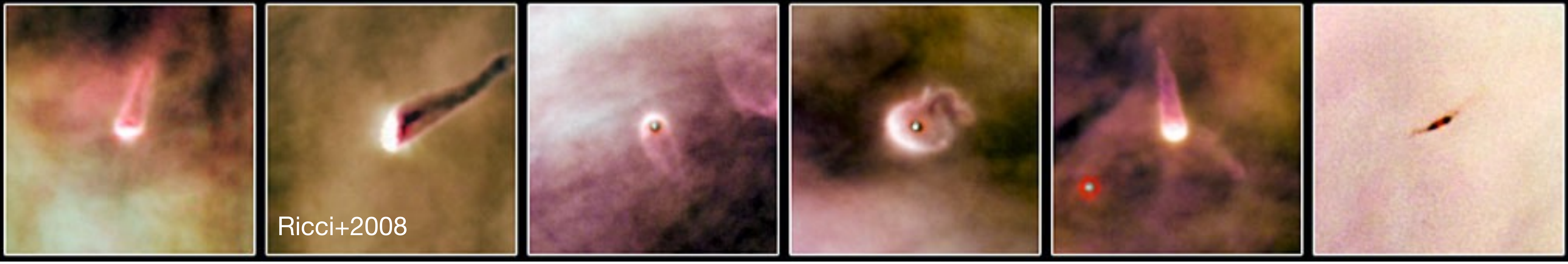
tentative proto-planet


Sheehan & Eisner 2218

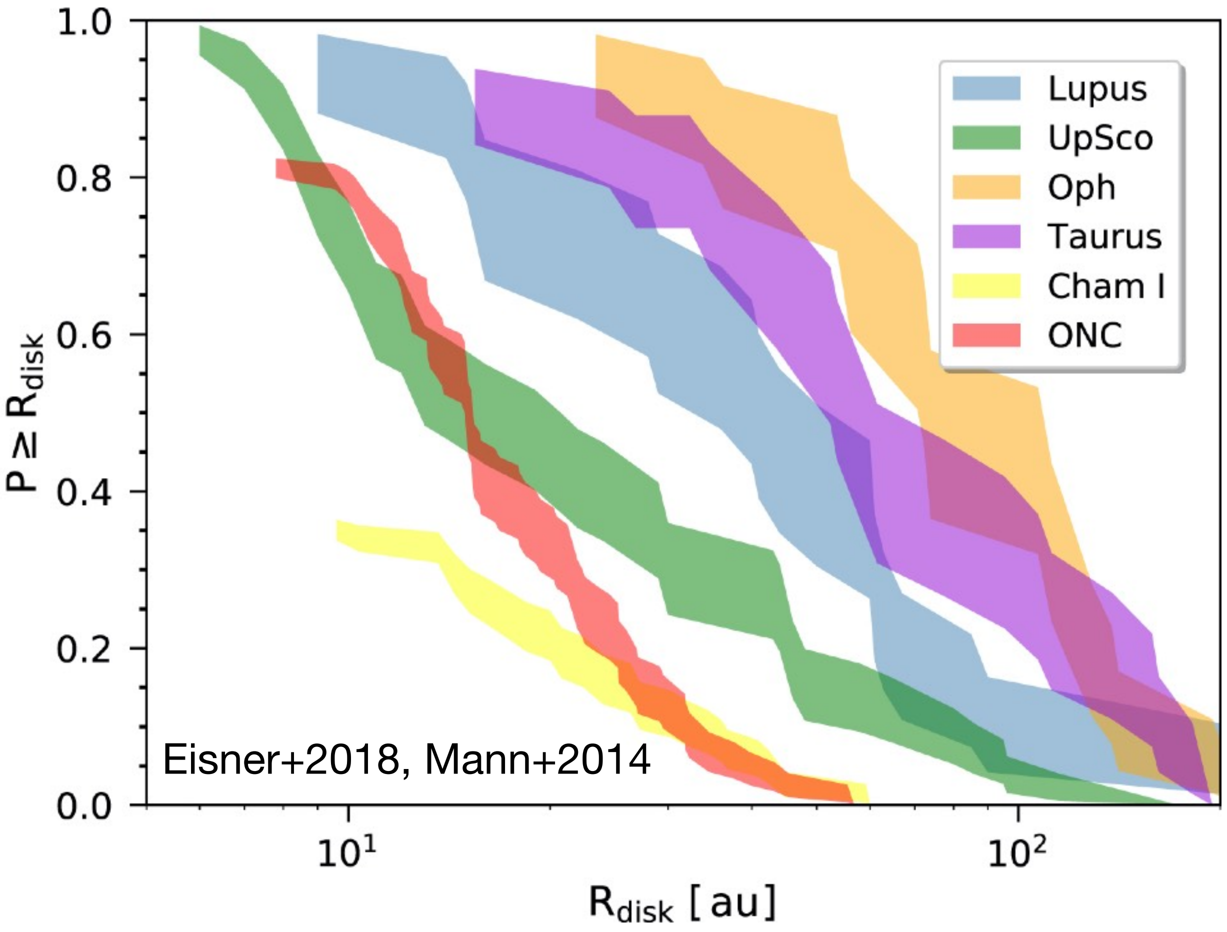
Destructive environments in the first 3 Myr: the center of the Orion Nebula



UV radiation environment in Orion Nebula can photoevaporate disks,

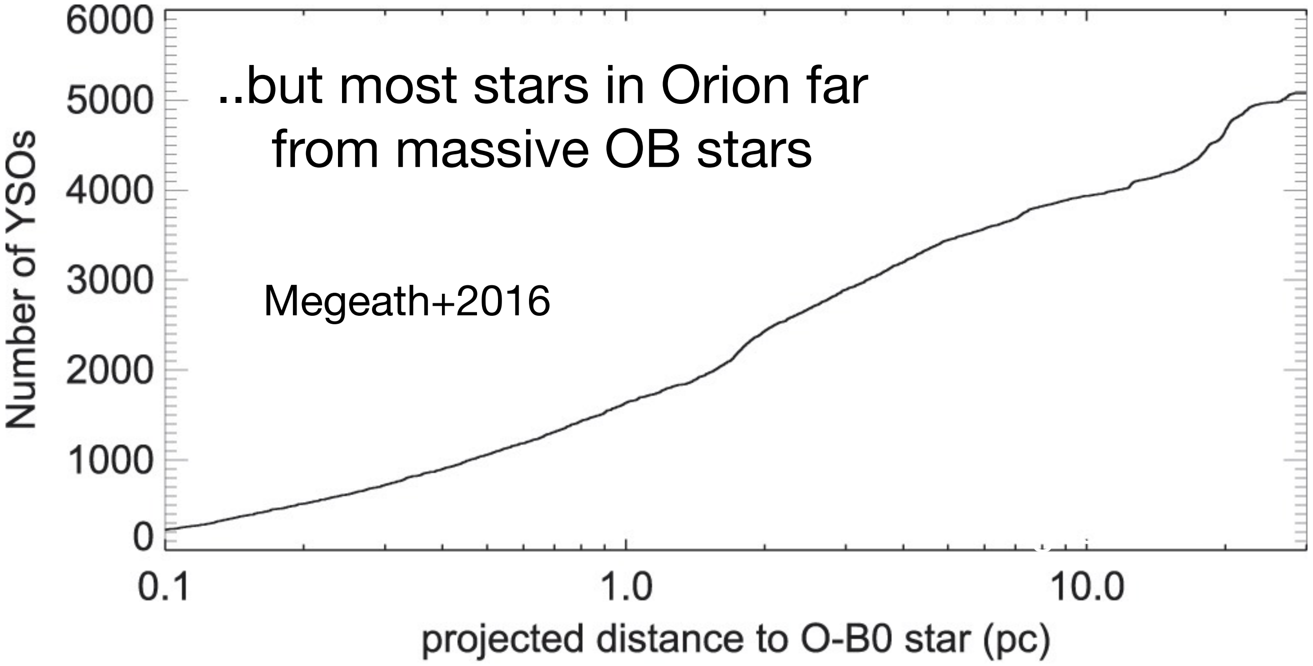


Ricci+2008



Eisner+2018, Mann+2014

and pre-ms star disks in center of Orion Nebula show systematically smaller disks,



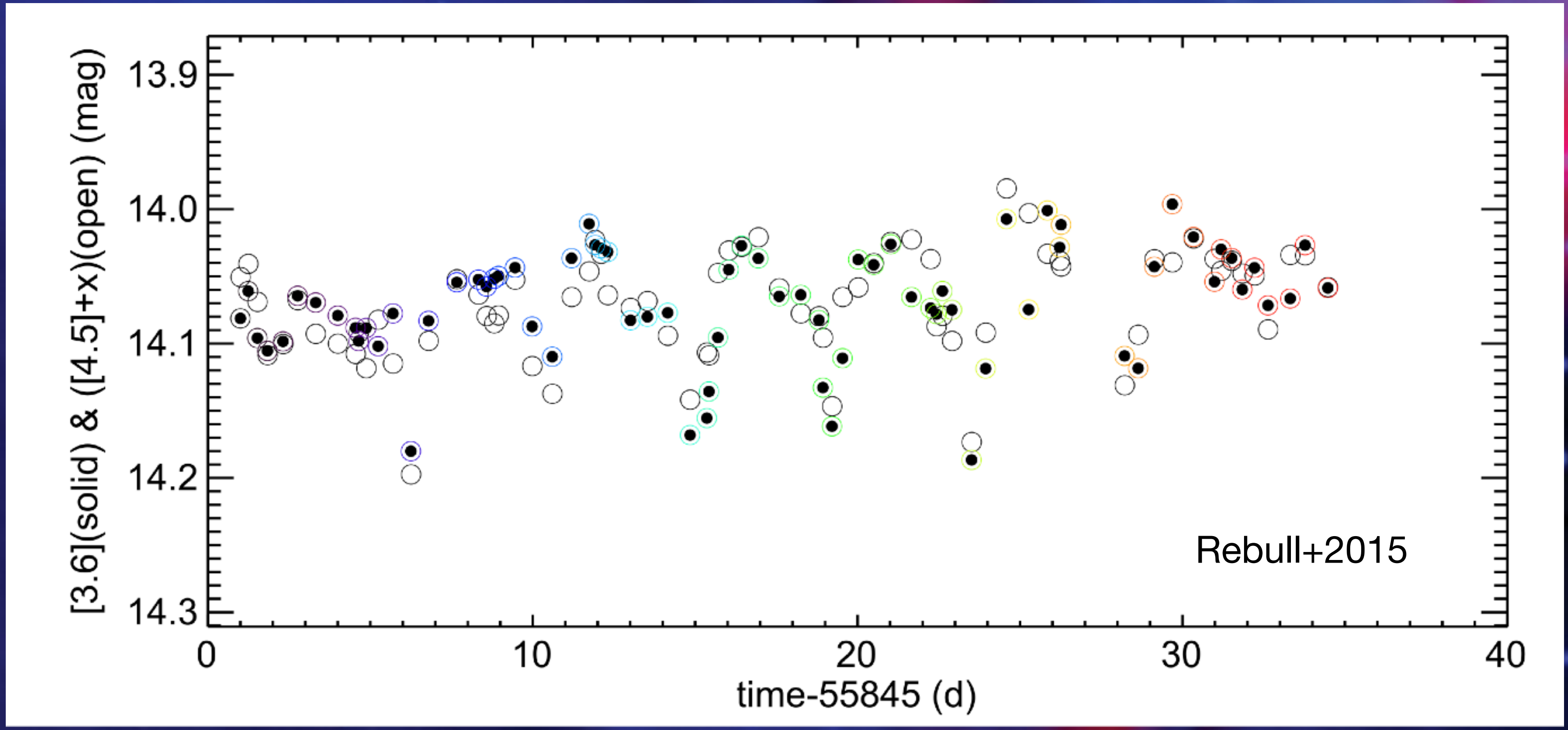
..but most stars in Orion far from massive OB stars

Megeath+2016

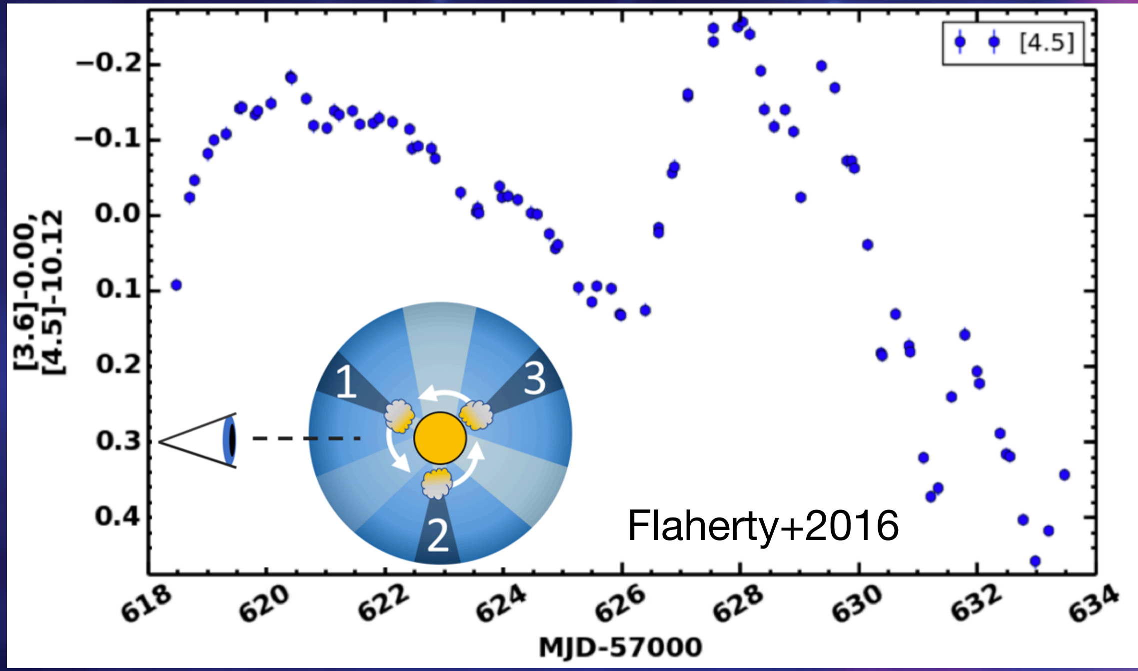
(but perhaps UV fields affect more distant YSOs, Yep+2020)

YSO variability due to disks and disk modulated accretion

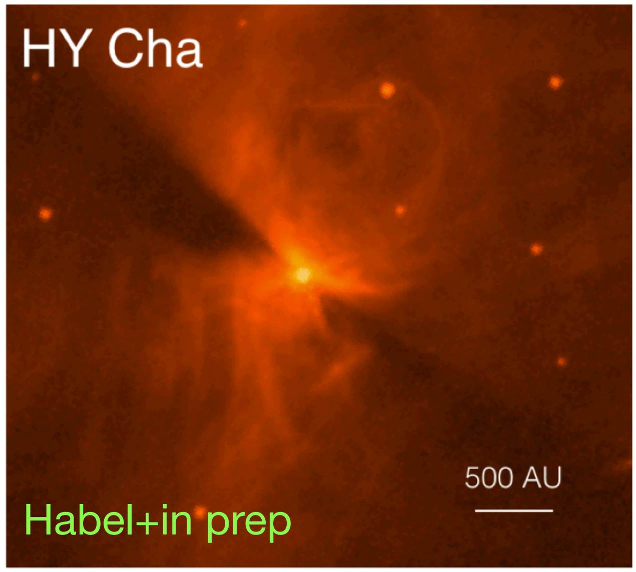
Mid-IR Variability from Spitzer



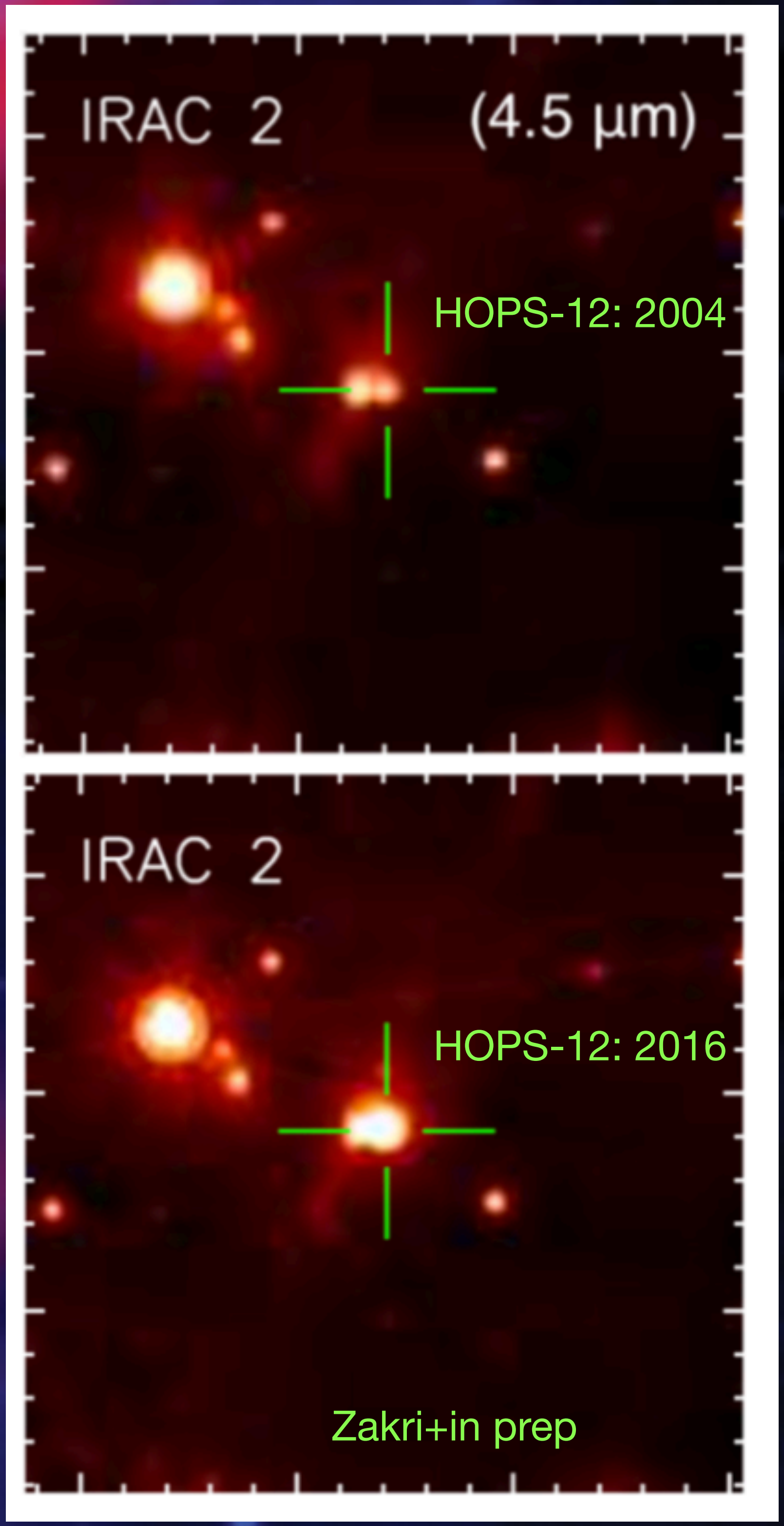
Rebull+2015



Flaherty+2016



Habel+in prep



Zakri+in prep

Protostars undergo frequent bursts

Accretion driven outbursts (>5x increase in flux) are found by comparing Spitzer surveys of Orion made 13 years apart.

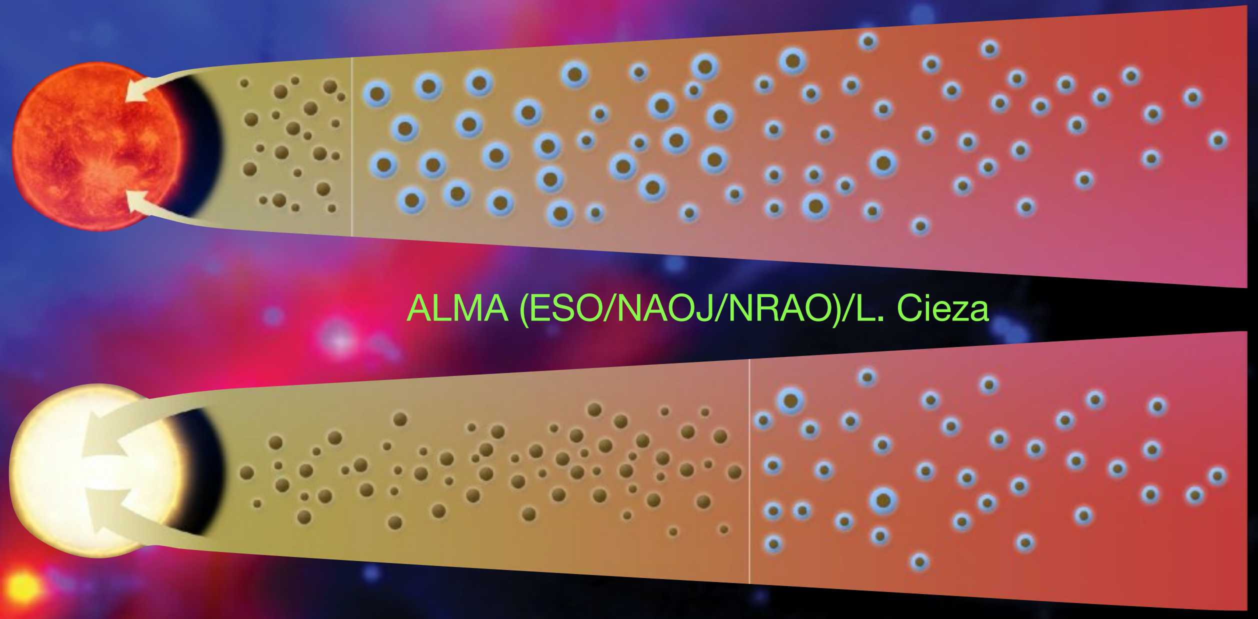
Three Class 0 burst and 1 FS/Class I burst

Burst rate highest in Class 0 phase: 1 per 350 yr

Burst rate for Class I/FS: 1 per 2900 yr

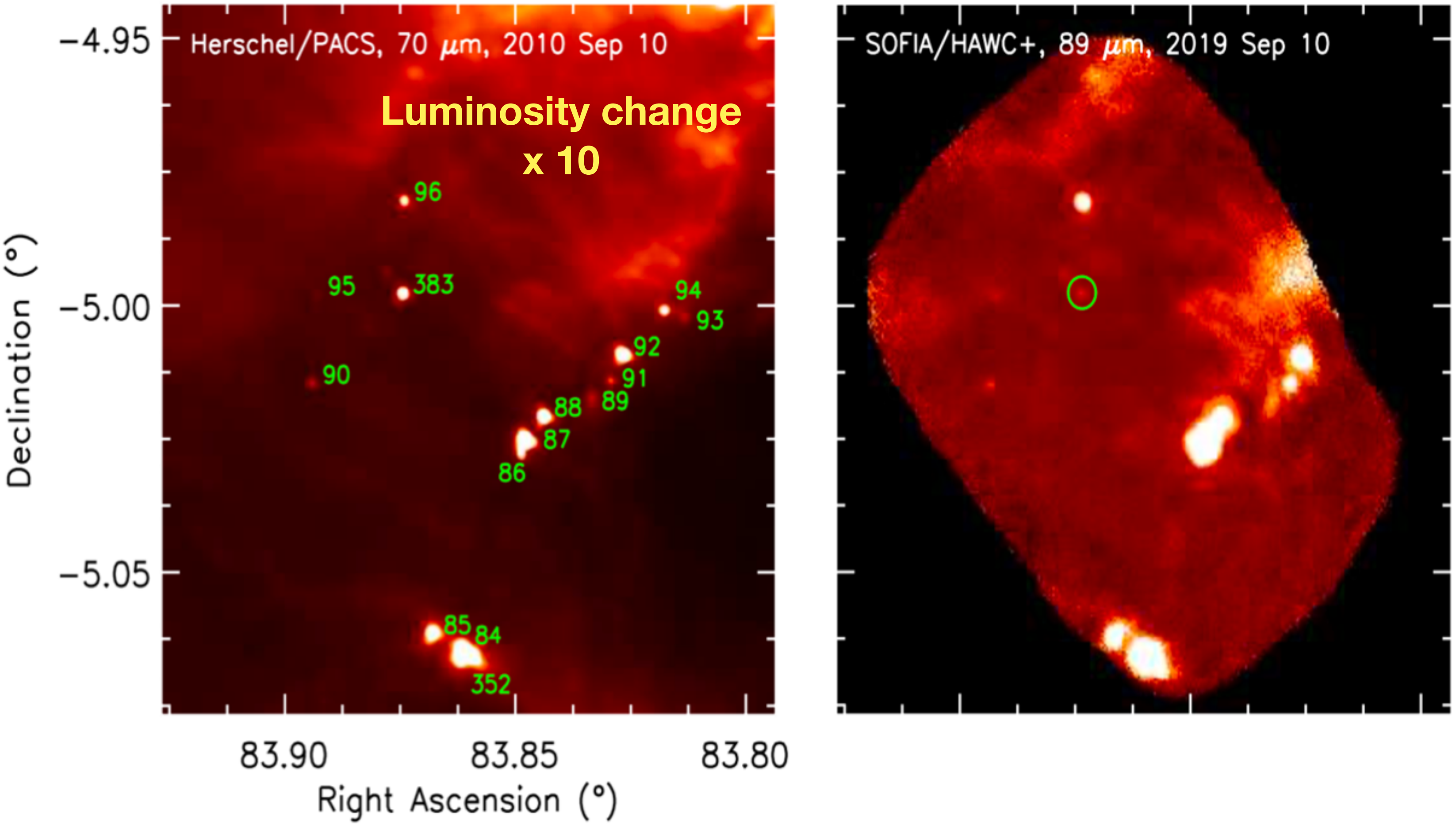
Average rate for protostars: 1 per 1000 yr

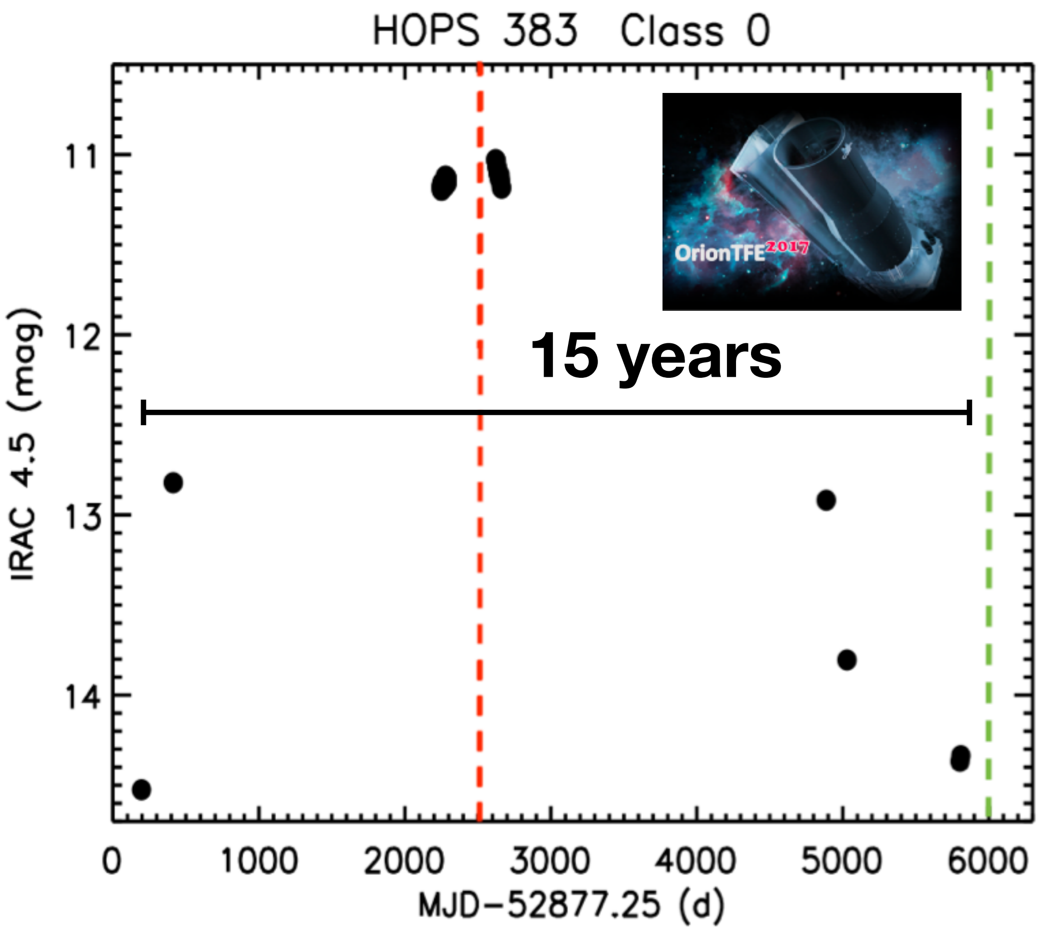
(Zakri+in prep, Fischer+2012, 2019, Caratti o Garatti+2011)



ALMA (ESO/NAOJ/NRAO)/L. Cieza

Ciesa+2016, also van t' Hoff+2018, Lee+2019





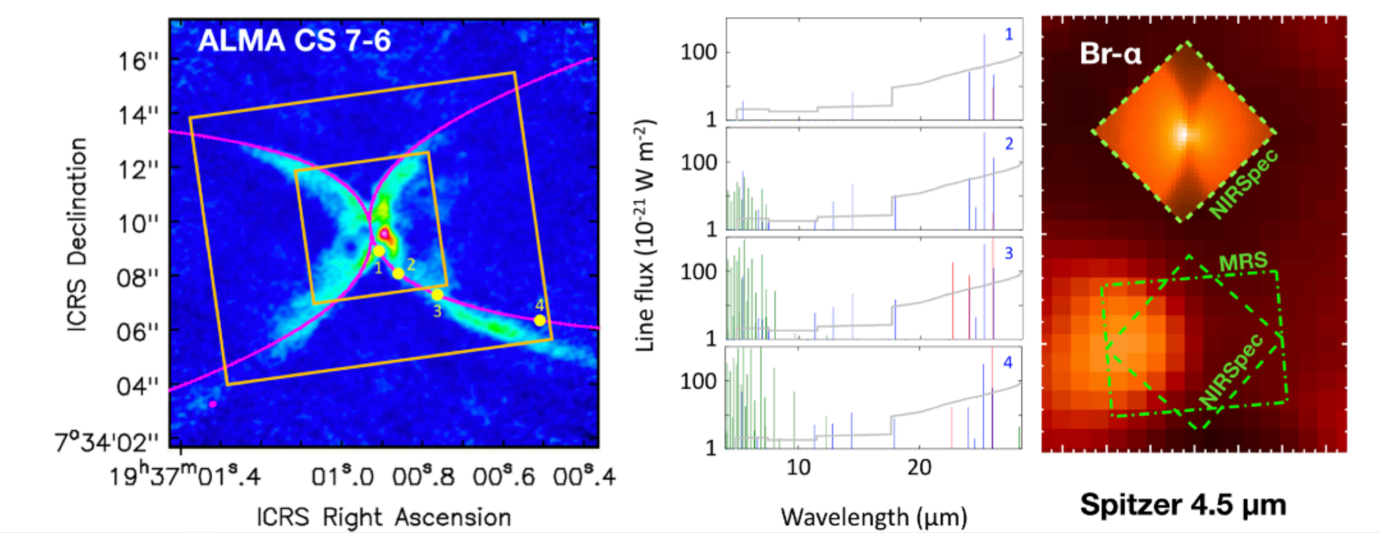
HOPS 383 outburst: Zakri+in prep., Sharma+2020, Saffron+2015

Summary

1. We now have large sample of < 3 Myr dusty YSOs from surveys Spitzer and Herschel
2. The 3 Myr timespan contains all of protostellar evolution, is the period over which 1/2 disks disappear, and is the duration of star formation in young clusters
3. Envelopes gradually disappear over protostellar lifetime.
4. ALMA and VLA show decrease in disk masses from Class 0 protostars to pre-ms stars
5. Protostellar disks show structures, some potentially due to planets
6. In first 3 Myr, UV from OB stars may turncate nearby disks
7. Mid-IR variability is a common property of YSOs
8. Frequent outbursts during protostellar phase may affect disks.

Future with JWST and Roman

JWST Investigating Protostellar Accretion Program



HST/WFC3 (Morphological variability)

Periodic outbursting protostar (Muzerolle+2013)