From protostars to adolescence: A tour of young stellar systems

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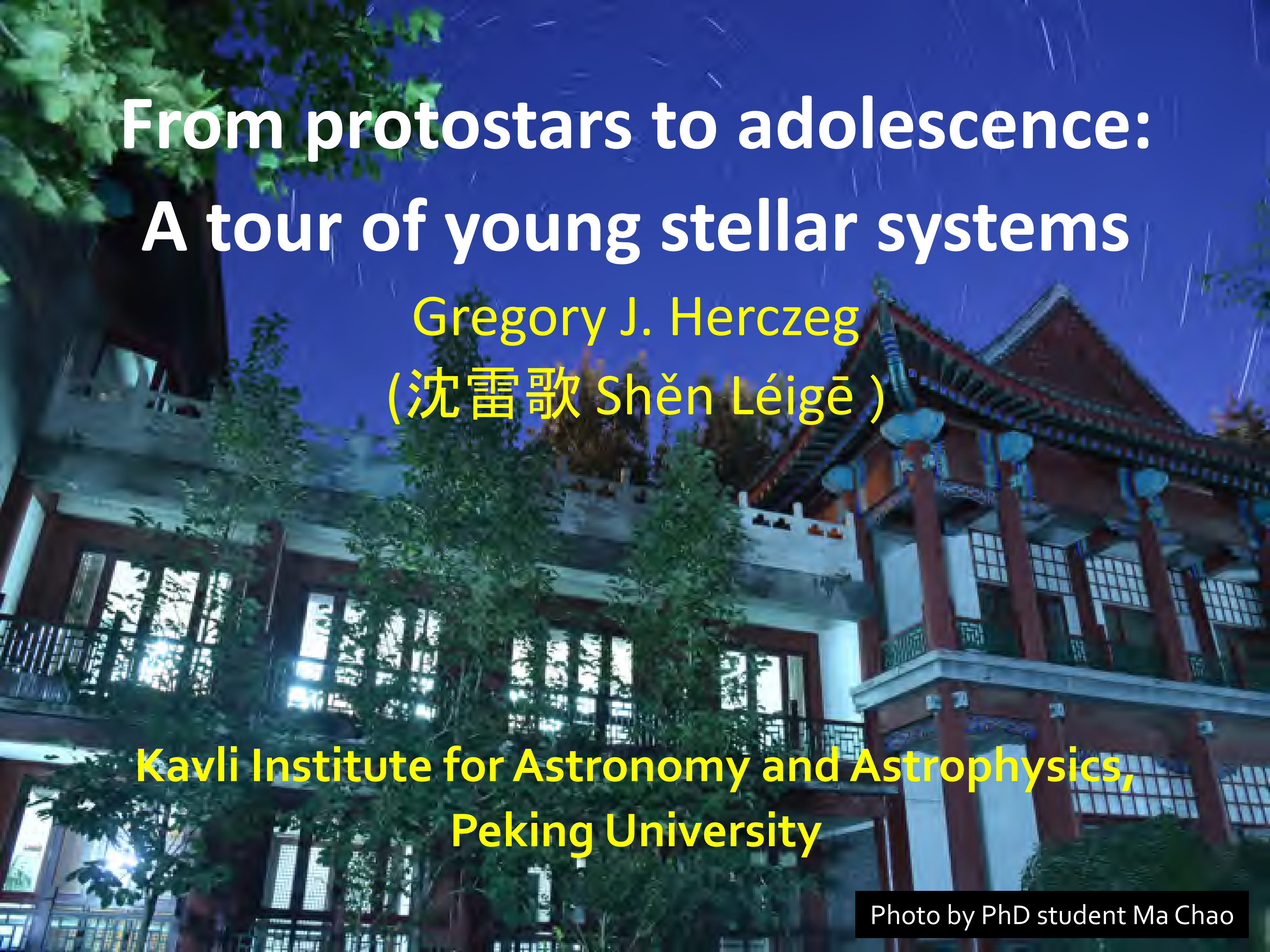


Photo by PhD student Ma Chao

The last astrophysical step of our origins

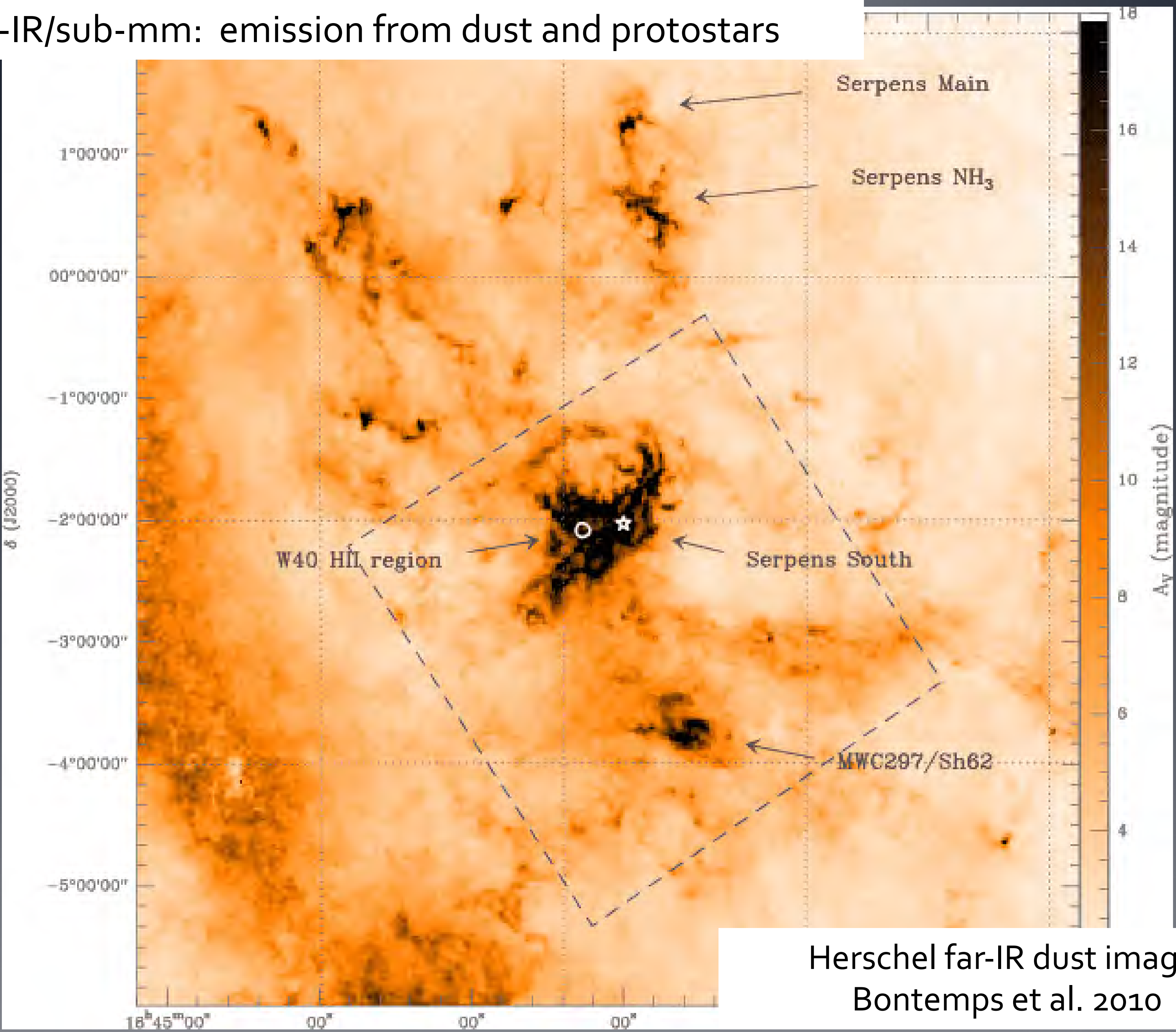
Serpens star-forming region
Courtesy Adam Block via APOD

Creating a picture of star-forming regions

- Cold ISM: dust/gas (diffuse to dense)
- Protostars
- Adolescent stars

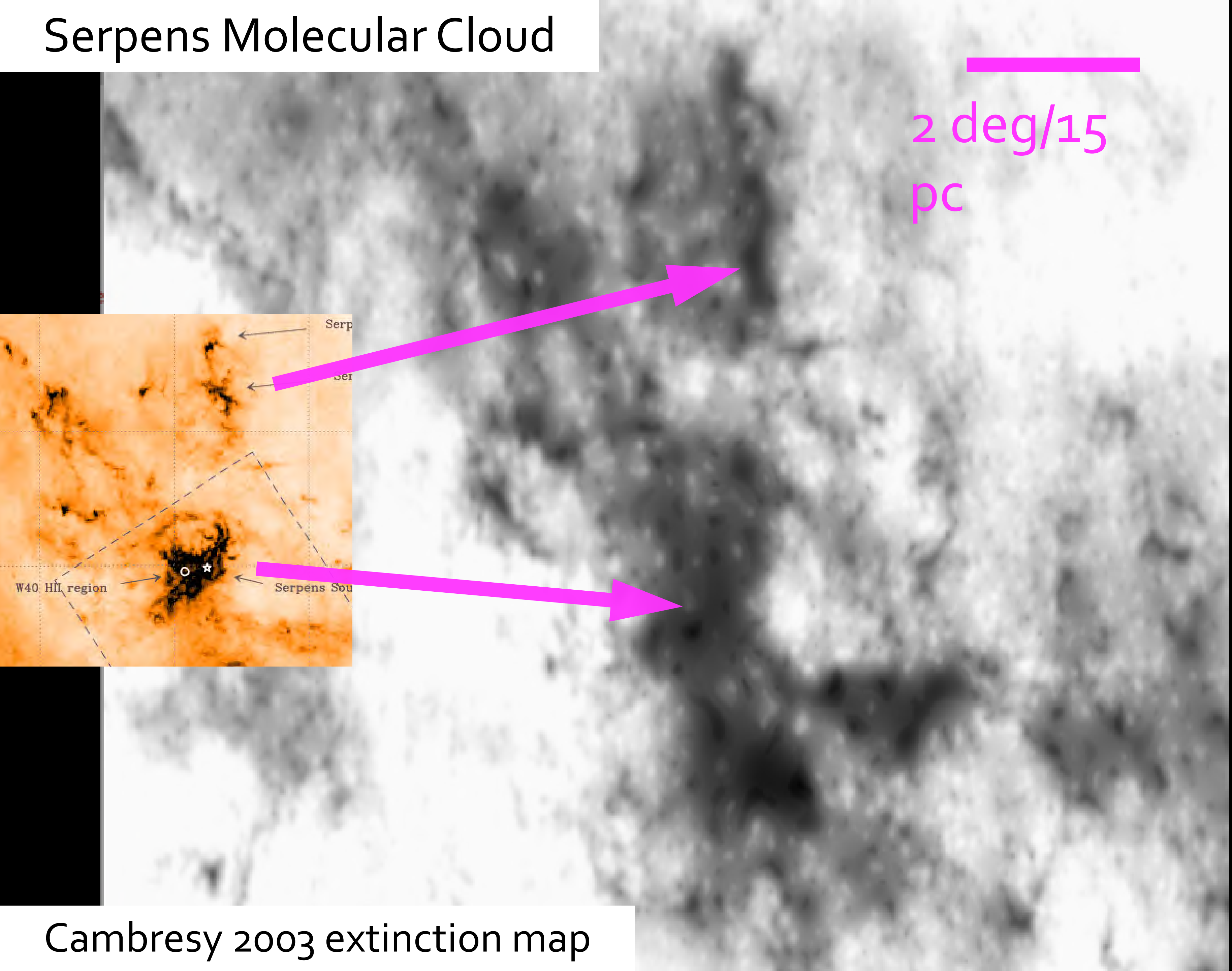
Serpens star-forming region and Aquila Rift
Courtesy Adam Block via APOD

Far-IR/sub-mm: emission from dust and protostars



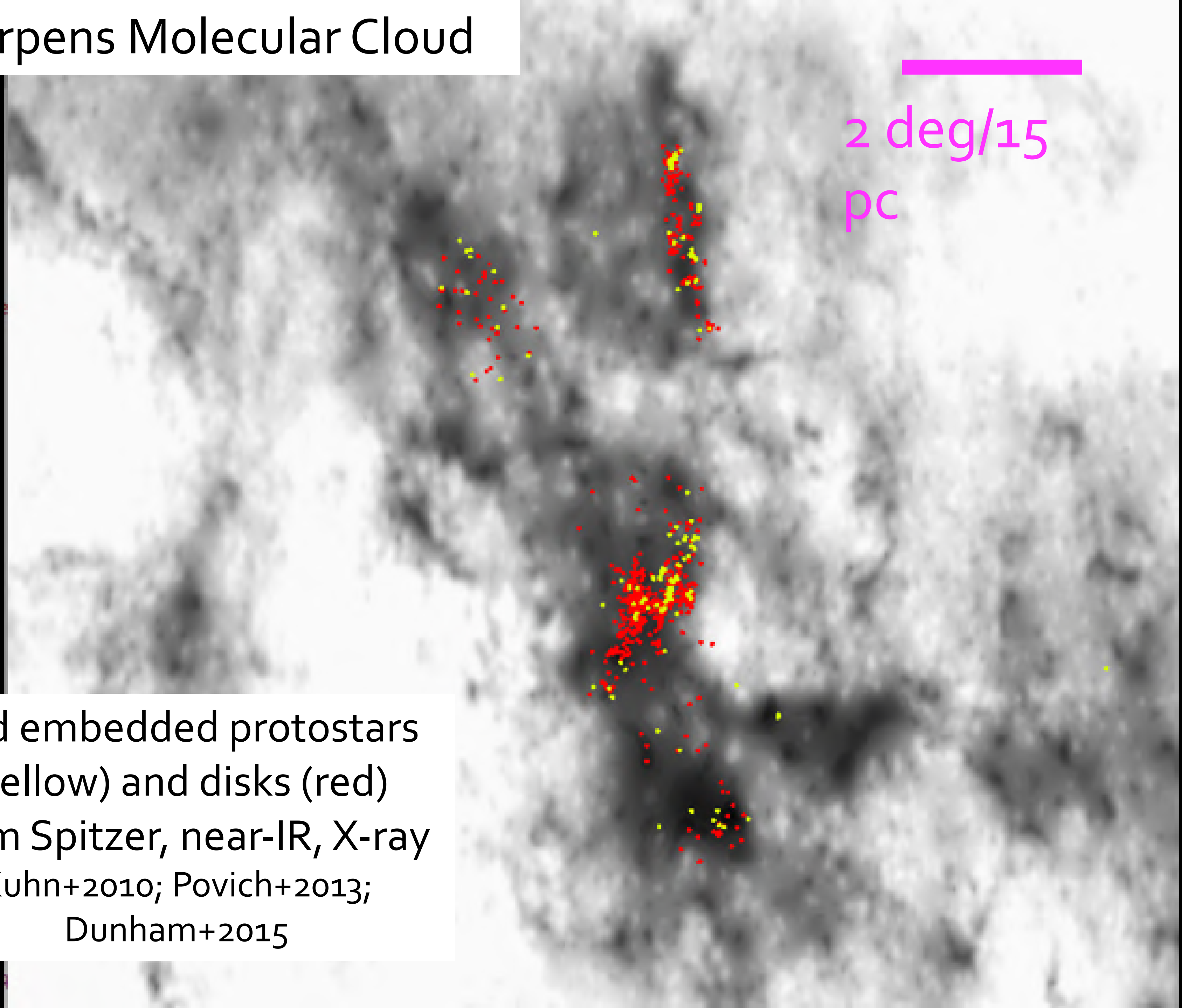
Herschel far-IR dust image,
Bontemps et al. 2010

Serpens Molecular Cloud



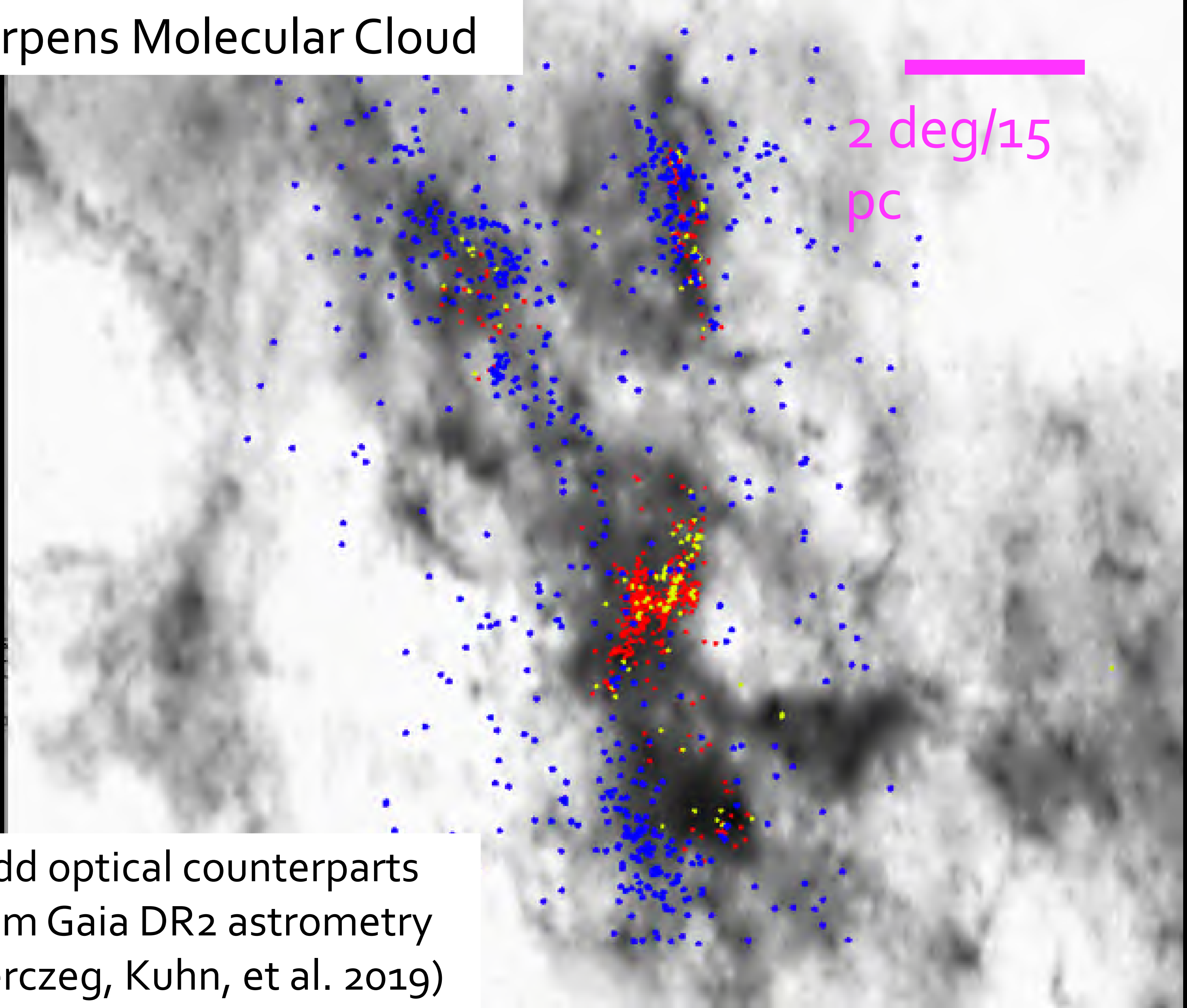
Cambresy 2003 extinction map

Serpens Molecular Cloud

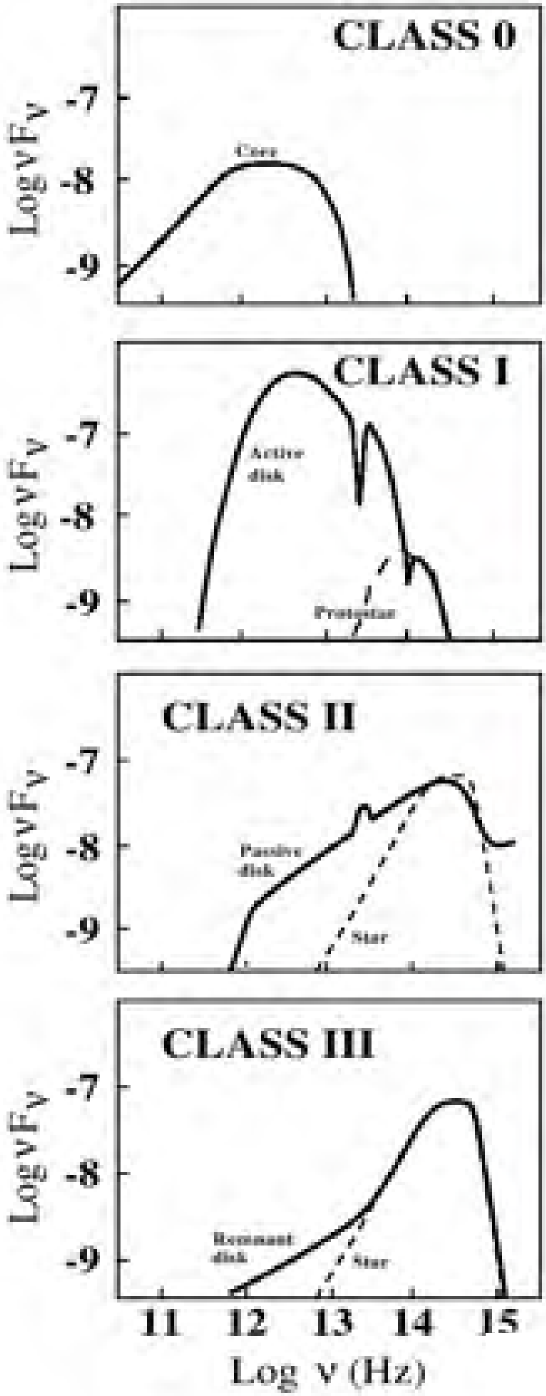


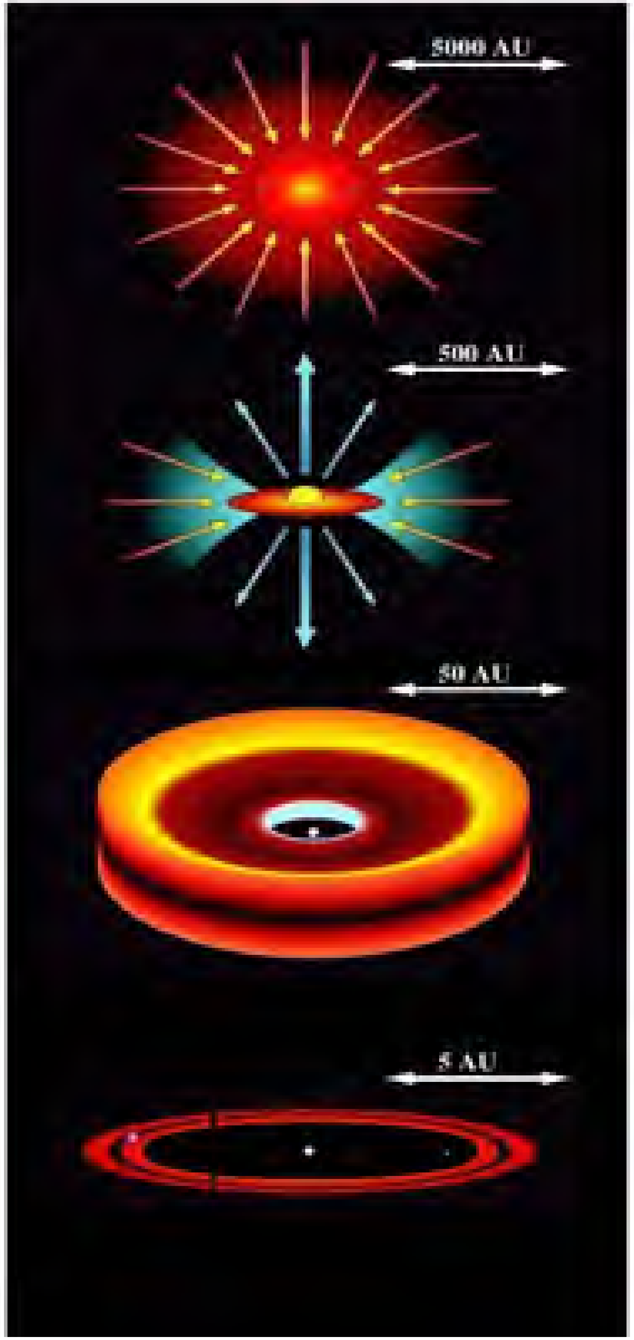
Add embedded protostars (yellow) and disks (red) from Spitzer, near-IR, X-ray
Kuhn+2010; Povich+2013; Dunham+2015

Serpens Molecular Cloud



Add optical counterparts from Gaia DR2 astrometry (Herczeg, Kuhn, et al. 2019)





Low mass stars, van Boekel 2005

Protostars:

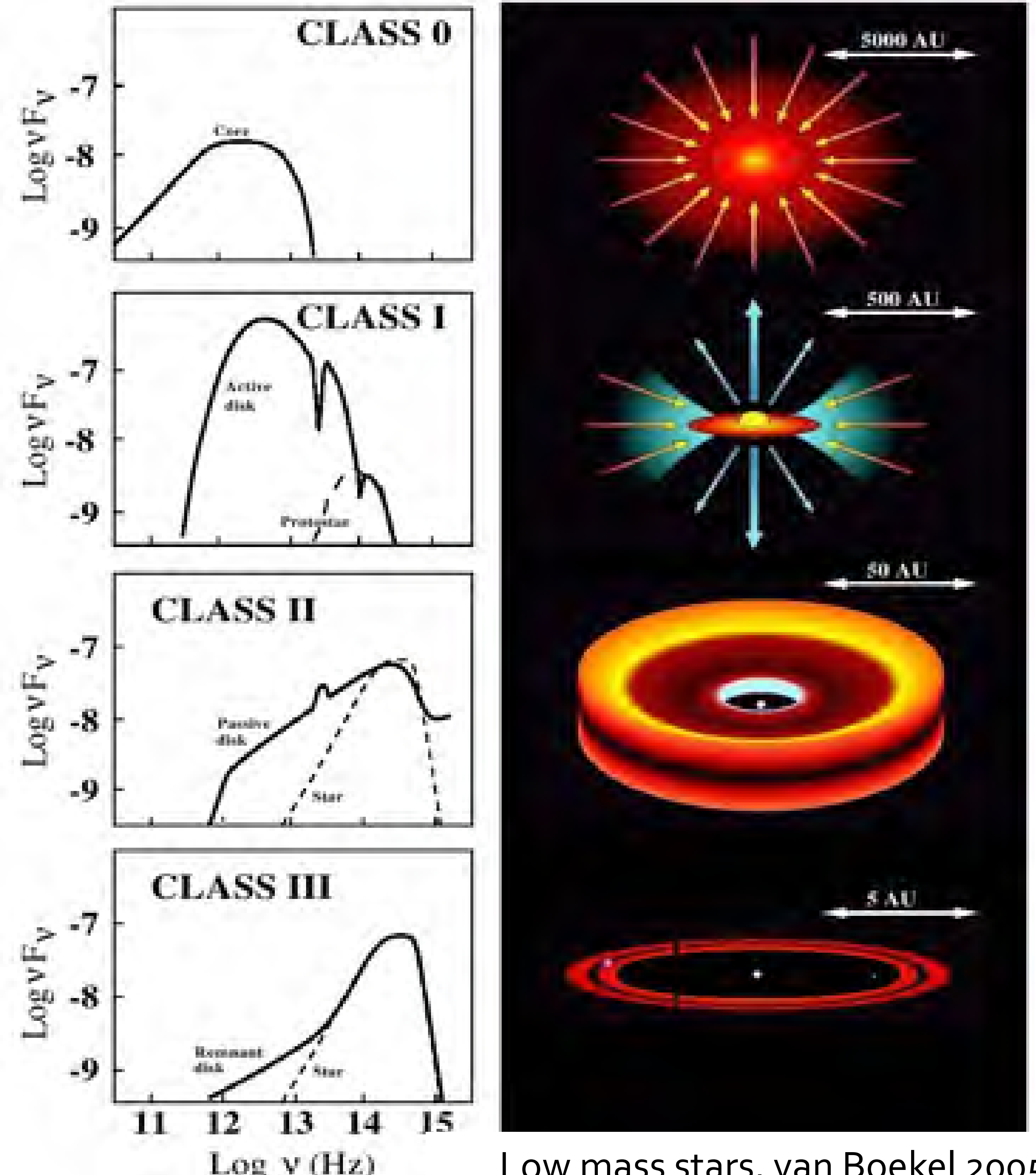
~few 10^5 yr

Stellar growth

Disks

~few 10^6 yr

Planet formation



Low mass stars, van Boekel 2005

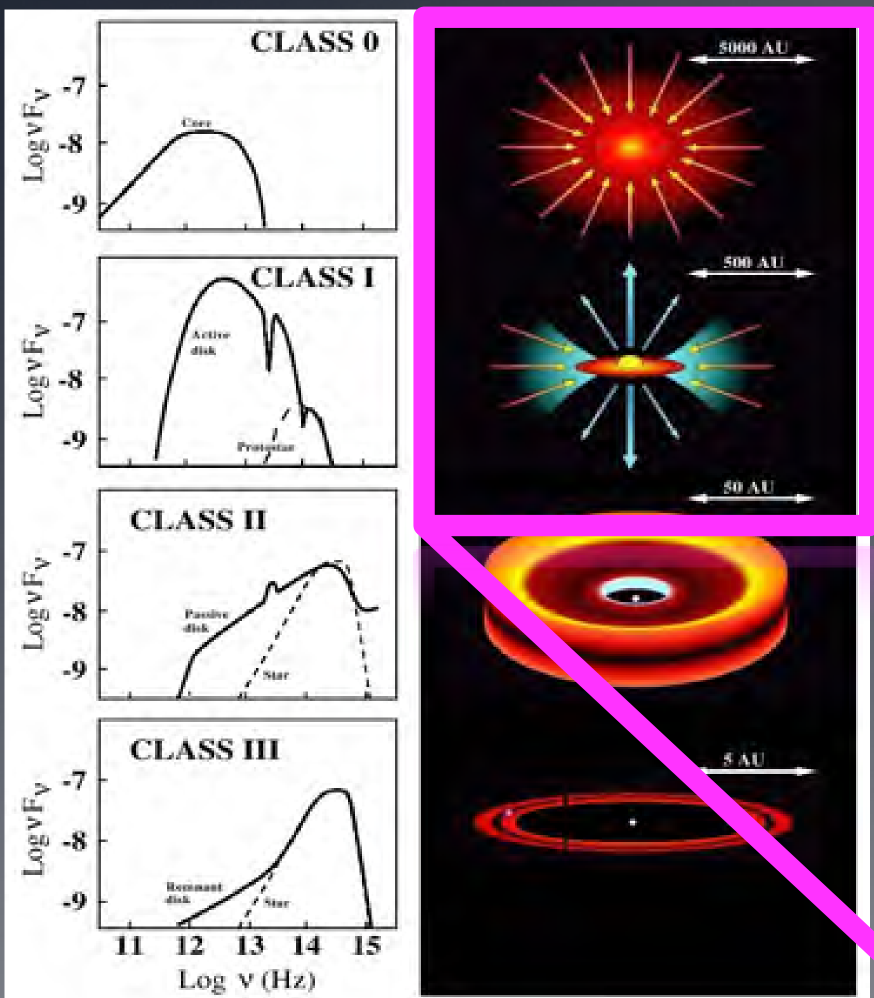
Luminosity problem: how do stars grow?
(JCMT Transient)

Looking for planets inside disks

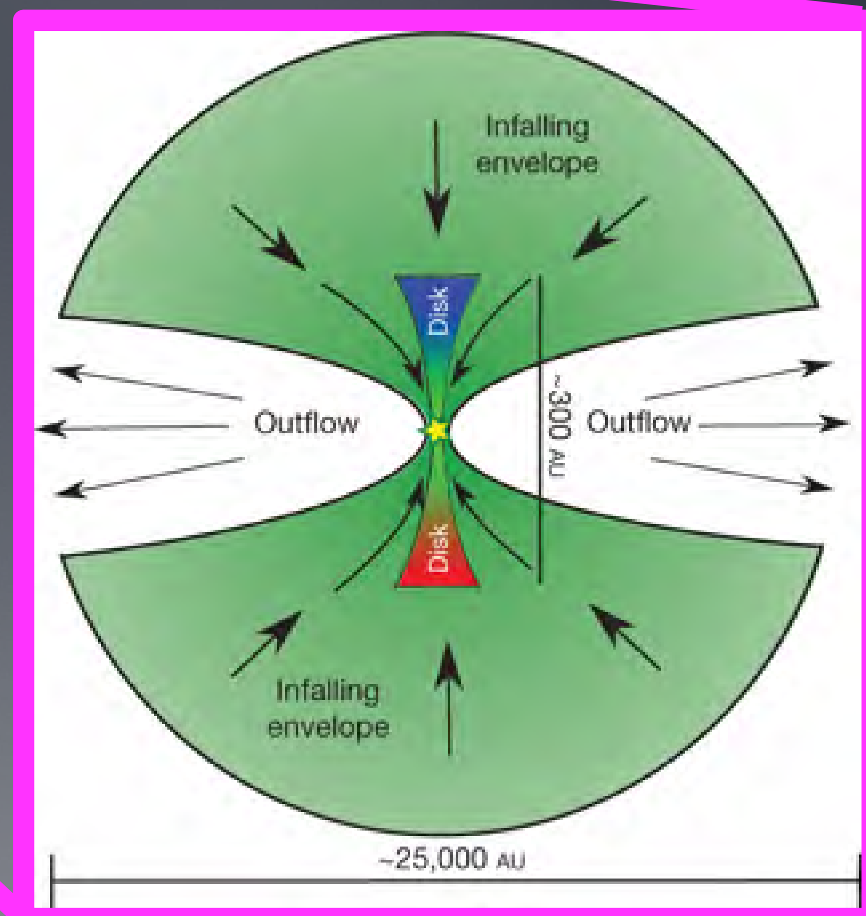
Uncertainties in pre-main sequence stellar evolution

Stars grow during protostellar phase

$L_{tot}=L_{acc}+L_{phot}$
Buried in envelope,
Scattered by dust



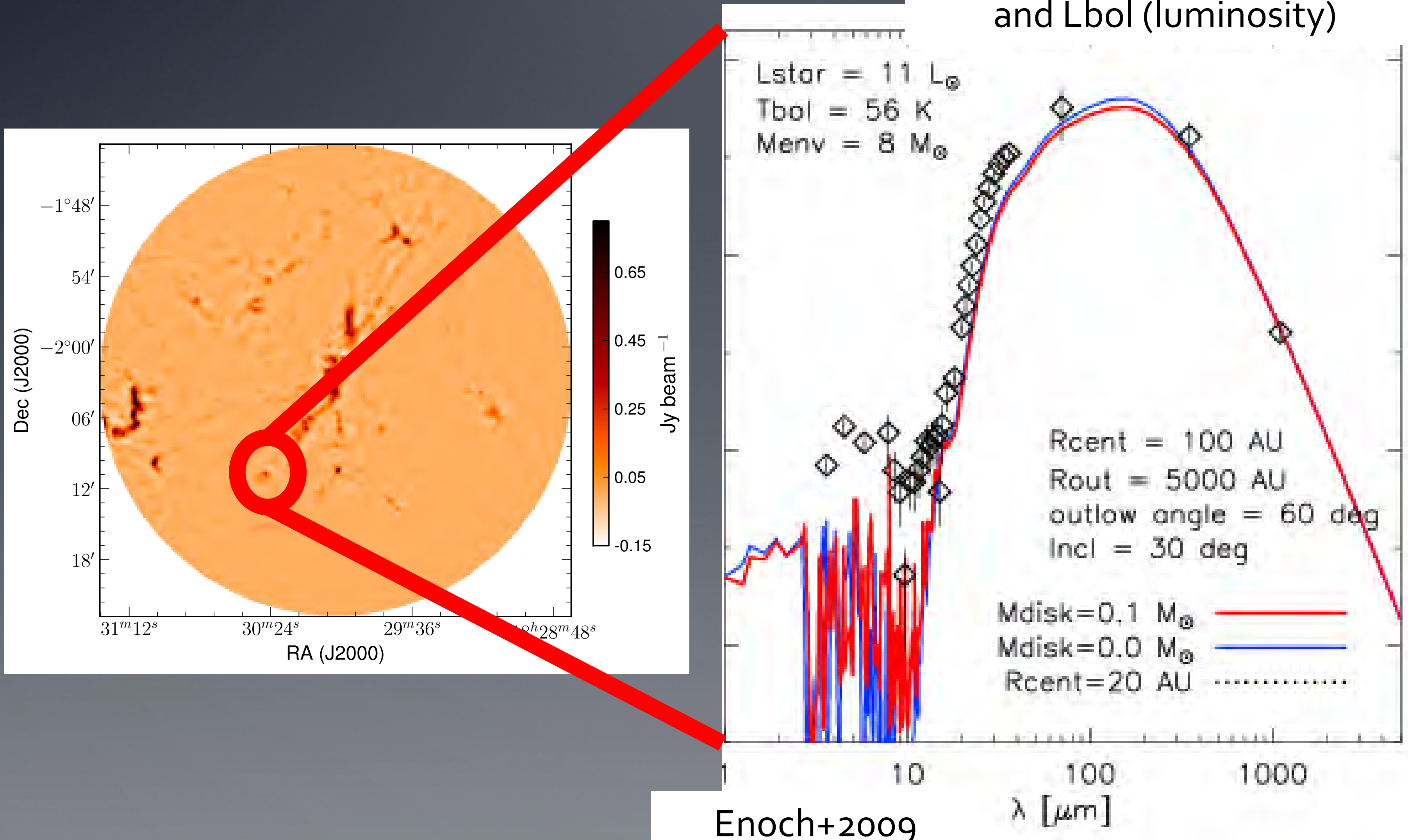
Cartoon from Isella 2006



Cartoon from Tobin+2012

Measure: T_{bol} (SED peak) and L_{bol}

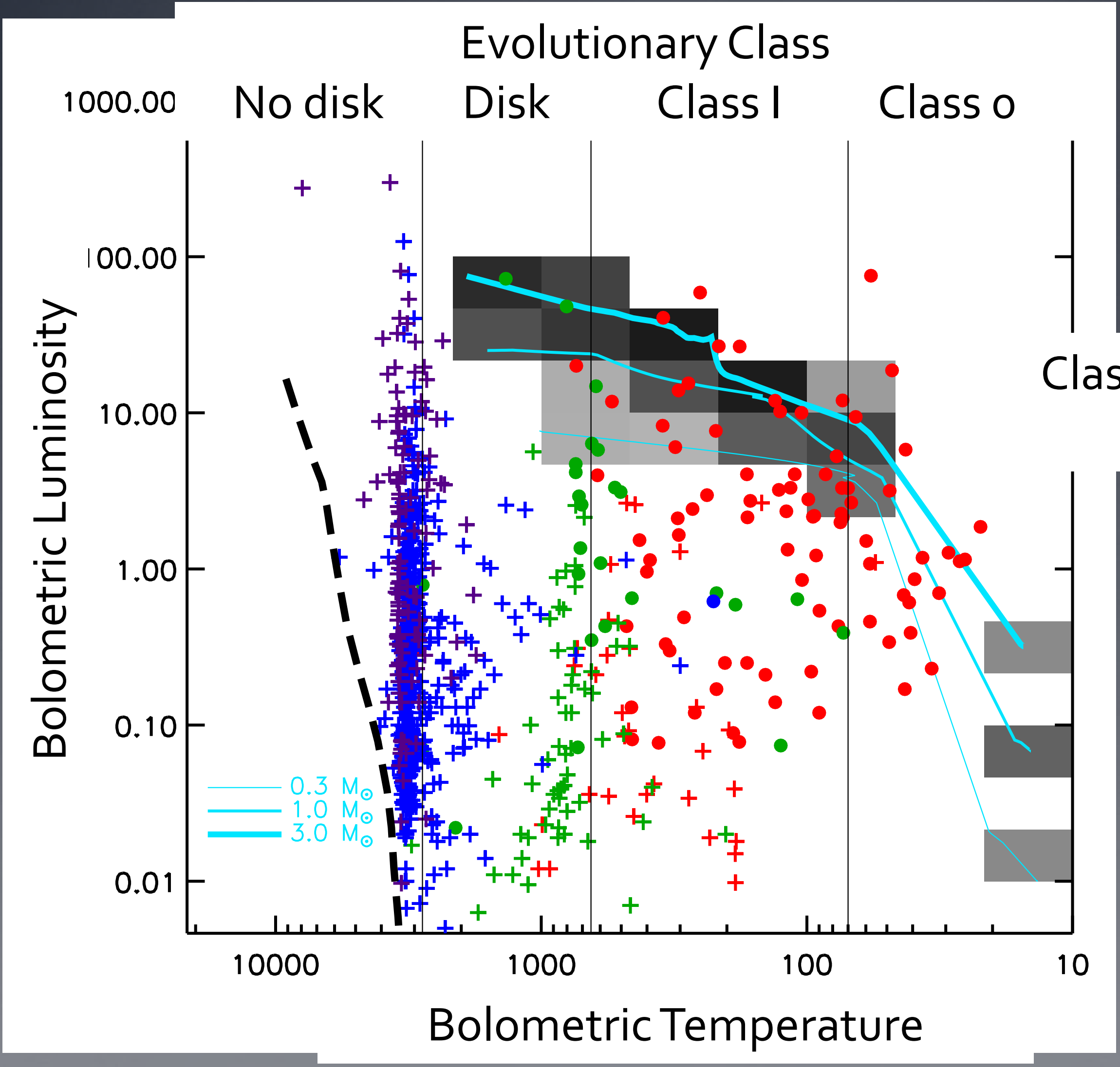
Measure Tbol (~peak of SED) and Lbol (luminosity)



Enoch+2009

Luminosity Problem

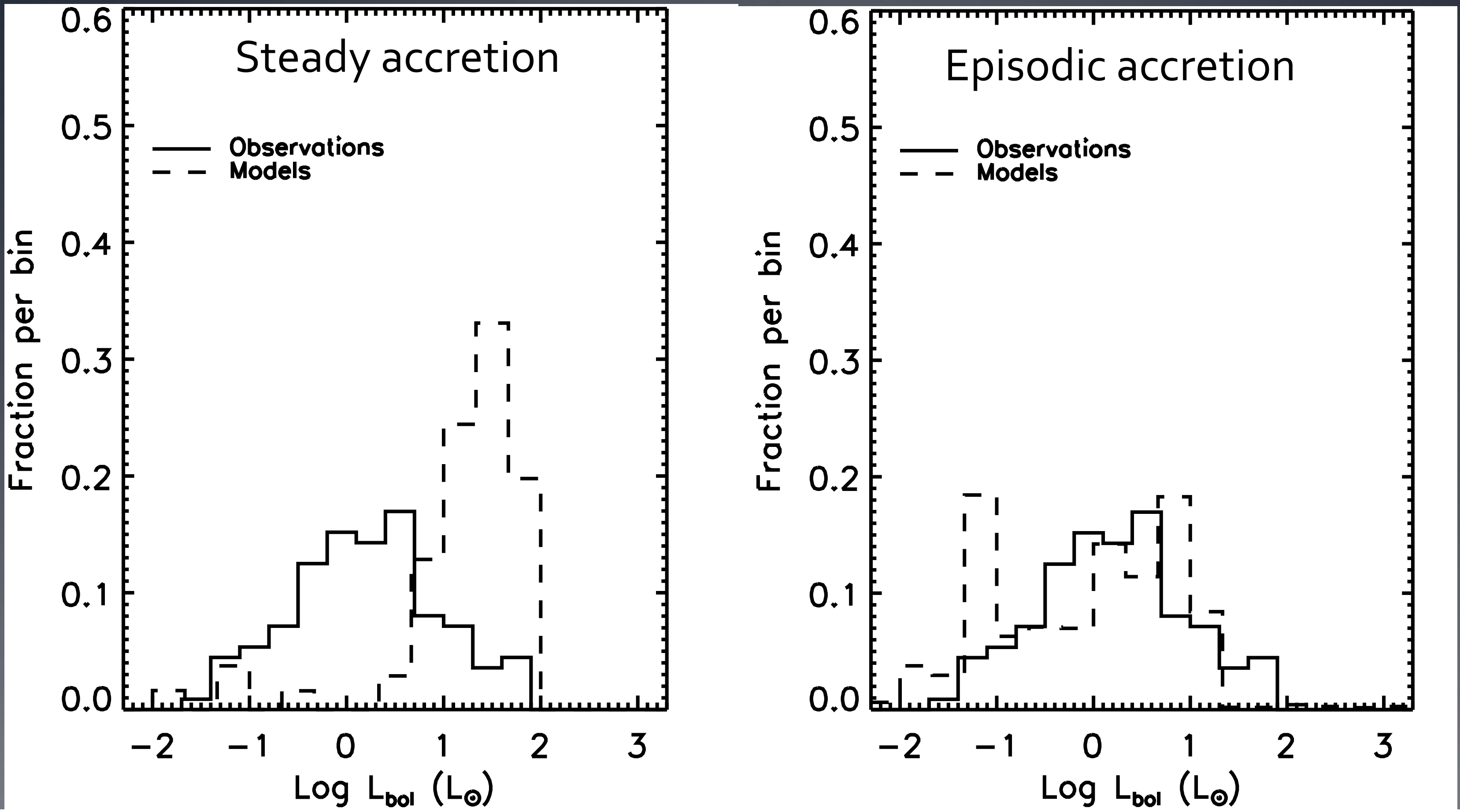
(Kenyon et al. 1990; Dunham et al. 2010)



Classical infall models: shaded region

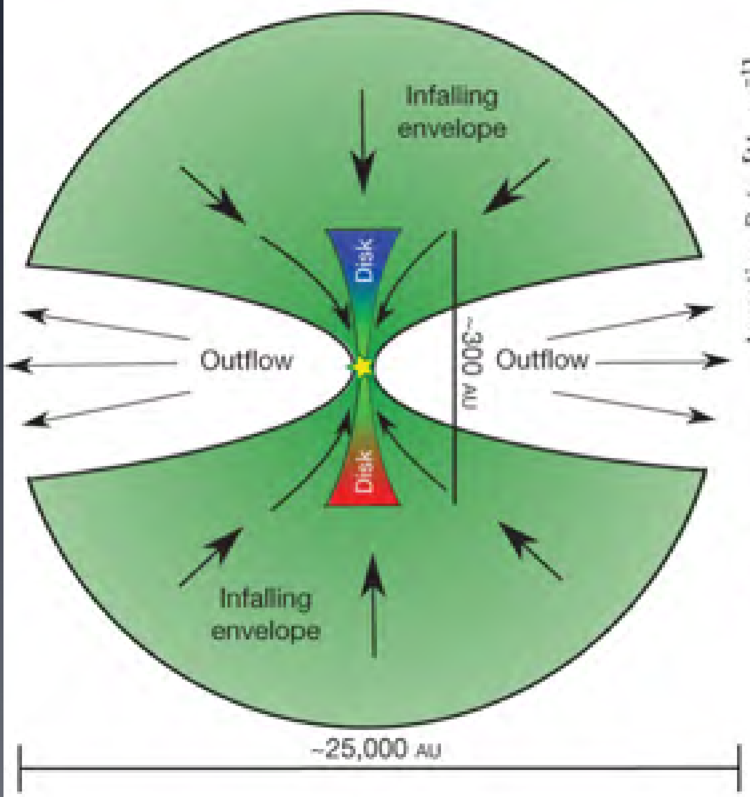
Episodic bursts of accretion?

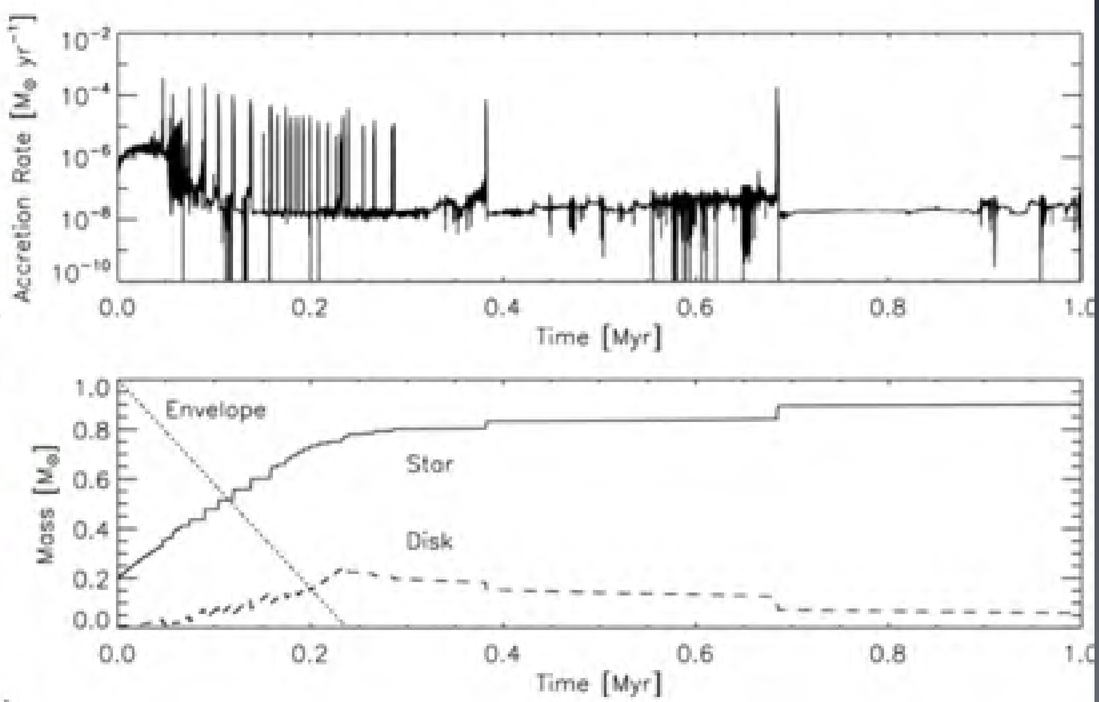
(Kenyon et al. 1990; Dunham, Evans, et al. 2009)



Time dependence needed; episodic accretion is likely (but not only) solution (e.g., Offner & McKee for different assumptions; Fischer+2017 for exponential decay)

Stars grow during bursts at young ages



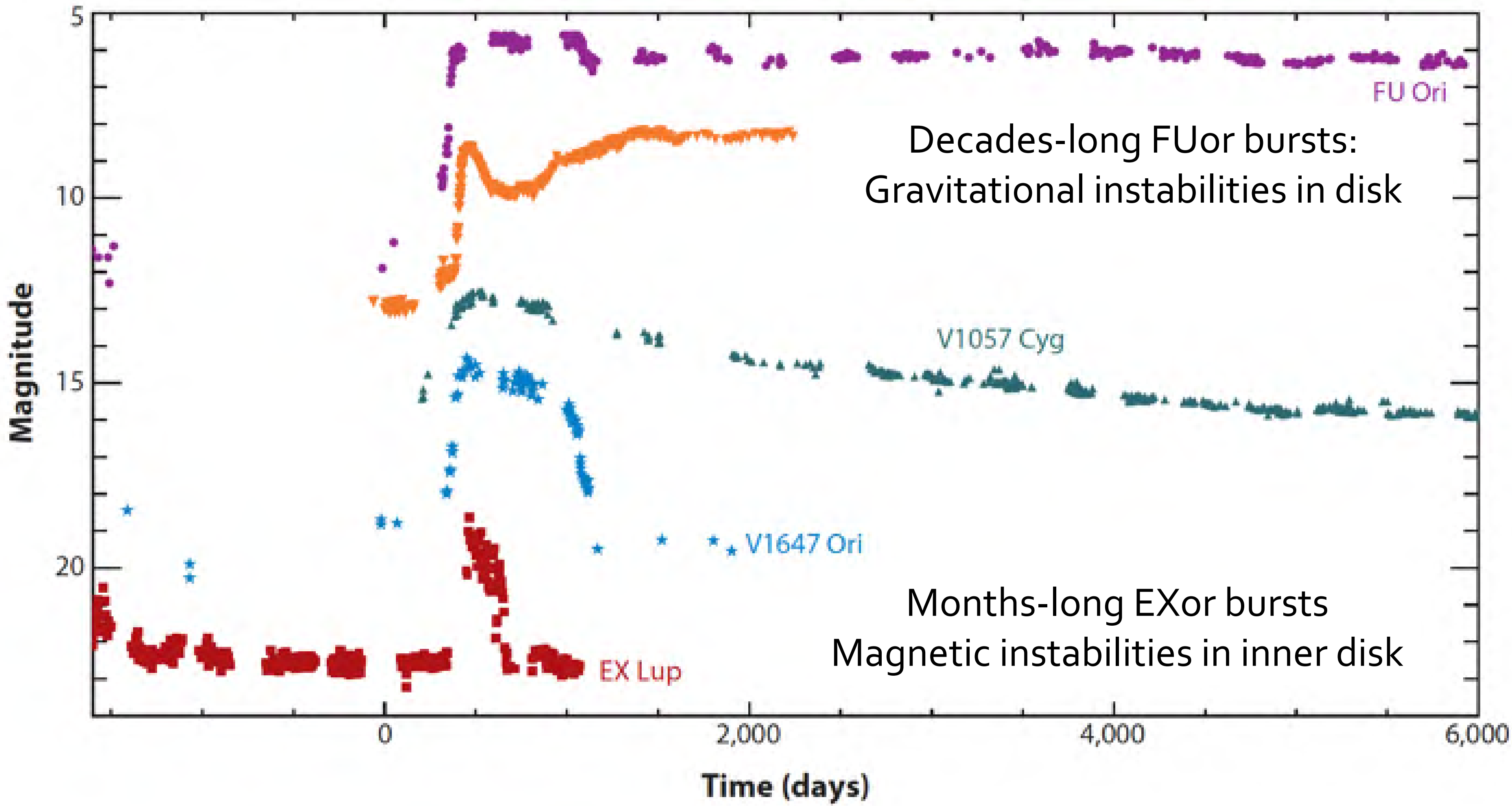


Tobin+2012

Zhu+2010; Bae+2014

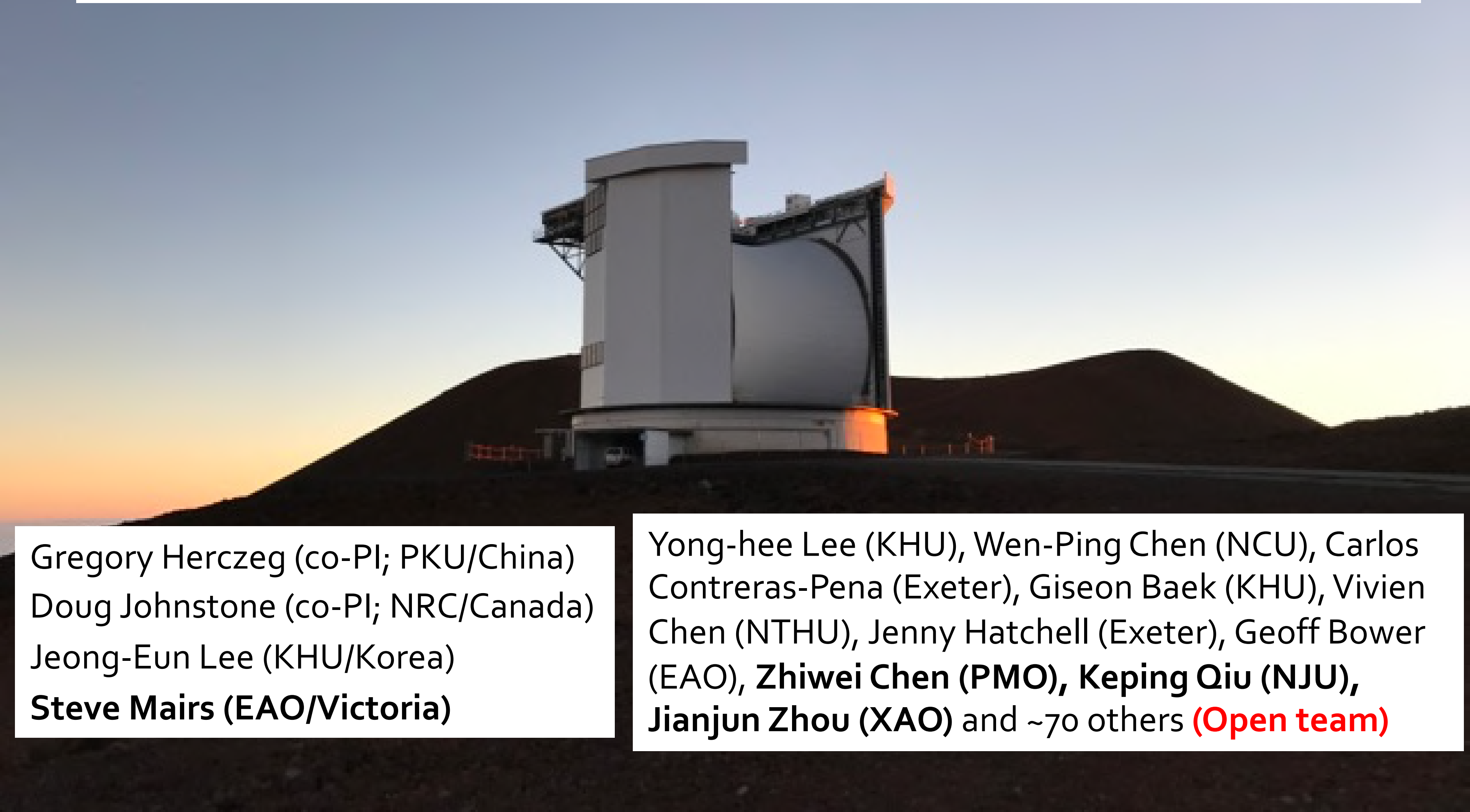
FUor and EXor outbursts: discovered from optical monitoring

(adapted from Kospal+2011)



Most recent bursts found by PTF/ZTF and Gaia

The East Asian Observatory JCMT-Transient Survey: the first long-term sub-mm monitoring program (Herczeg+2017)



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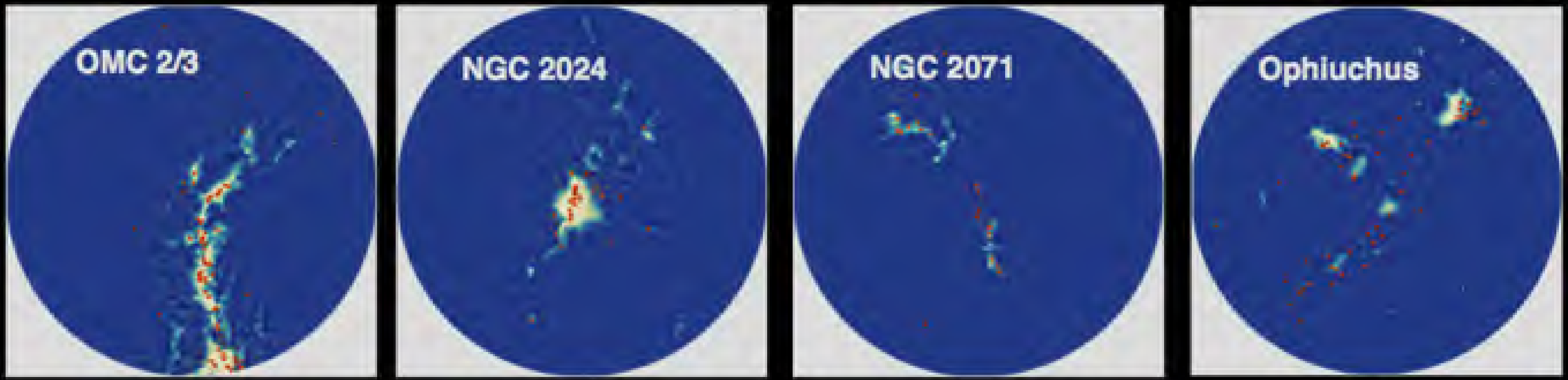
Doug Johnstone (co-PI; NRC/Canada)
Jeong-Eun Lee (KHU/Korea)
Steve Mairs (EAO/Victoria)

Yong-hee Lee (KHU), Wen-Ping Chen (NCU), Carlos Contreras-Pena (Exeter), Giseon Baek (KHU), Vivien Chen (NTHU), Jenny Hatchell (Exeter), Geoff Bower (EAO), **Zhiwei Chen (PMO), Keping Qiu (NJU), Jianjun Zhou (XAO)** and ~70 others **(Open team)**

The EAO/JCMT Transient Survey

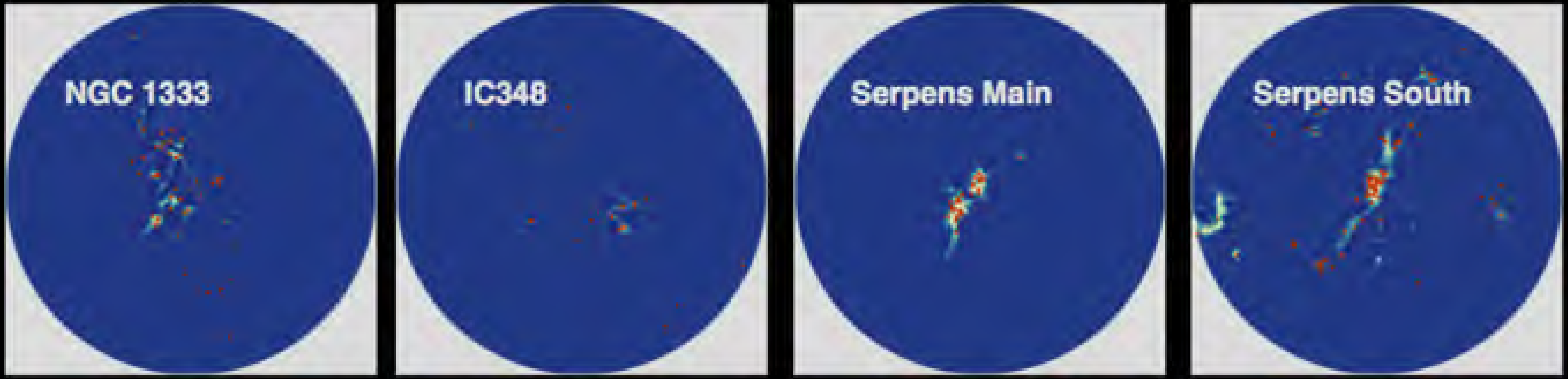


8 Regions < 500 pc (GBS)

7 ~~3~~ Year Survey

182 Protostars, 800 Disk sources

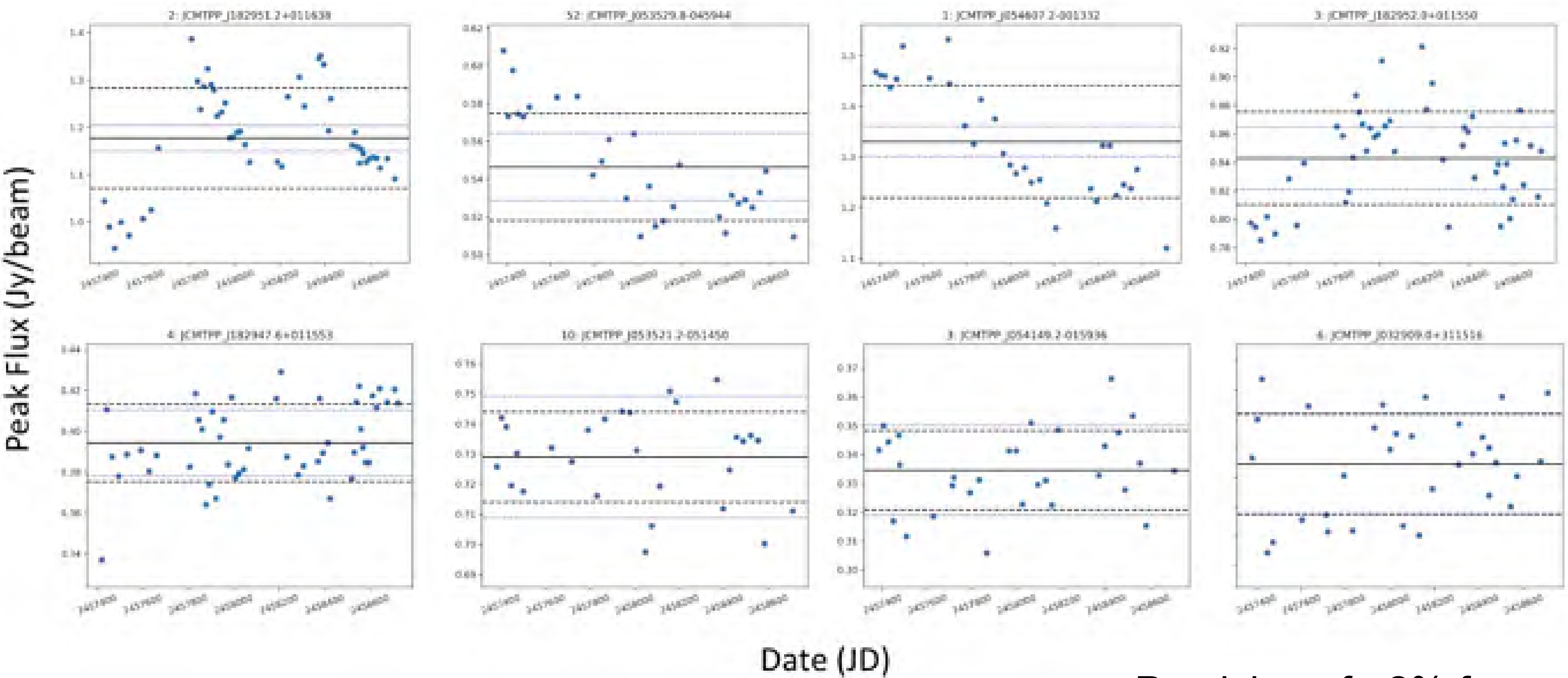
One Month Cadence



Expansion in 2020 to include 6 intermediate mass regions

JCMT-Transient Light Curves

(Mairs+2017ab; Johnstone+2018; Lee et al. in prep)

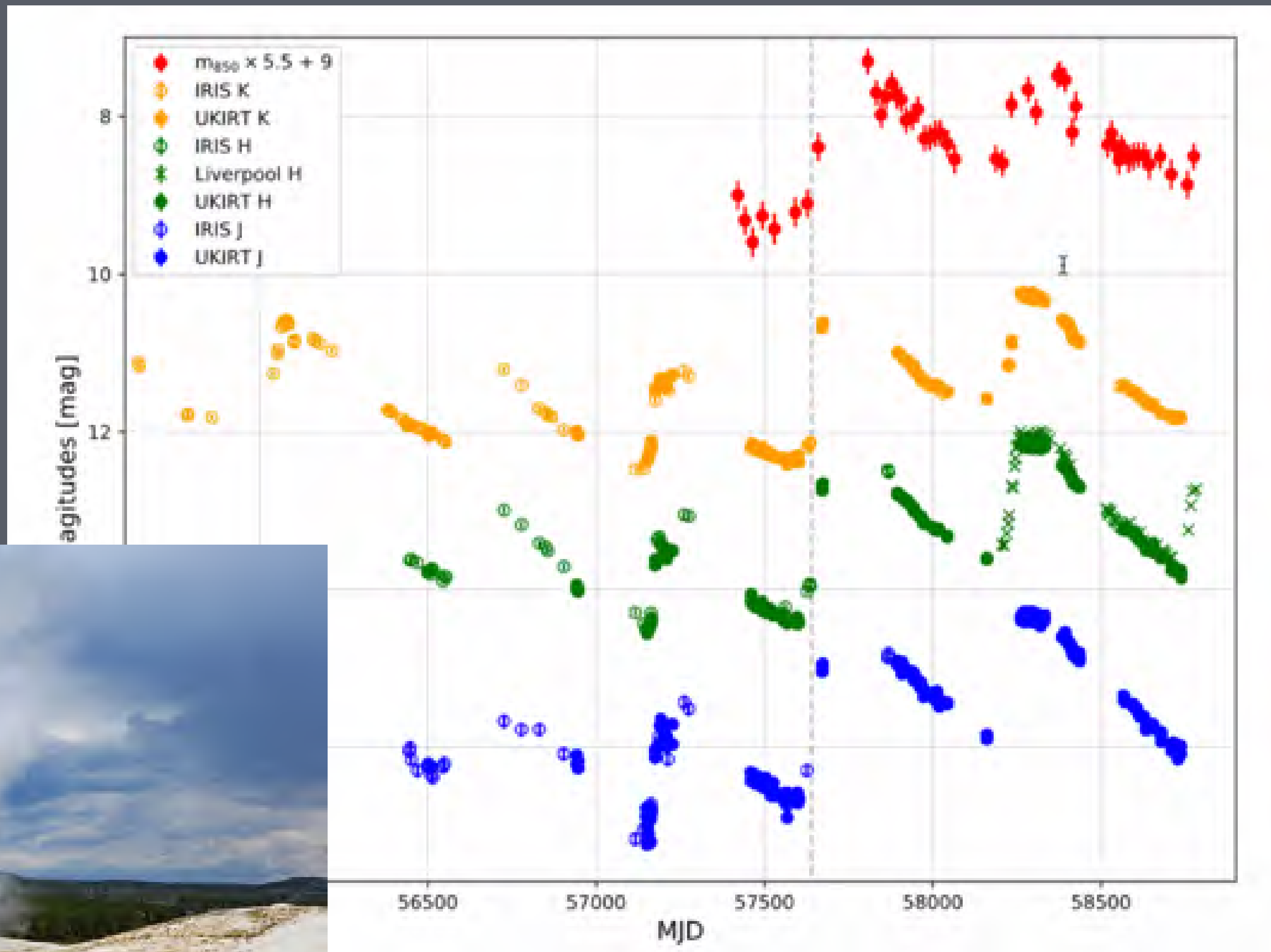


Precision of ~2% from "differential photometry"

Analysis of light curves

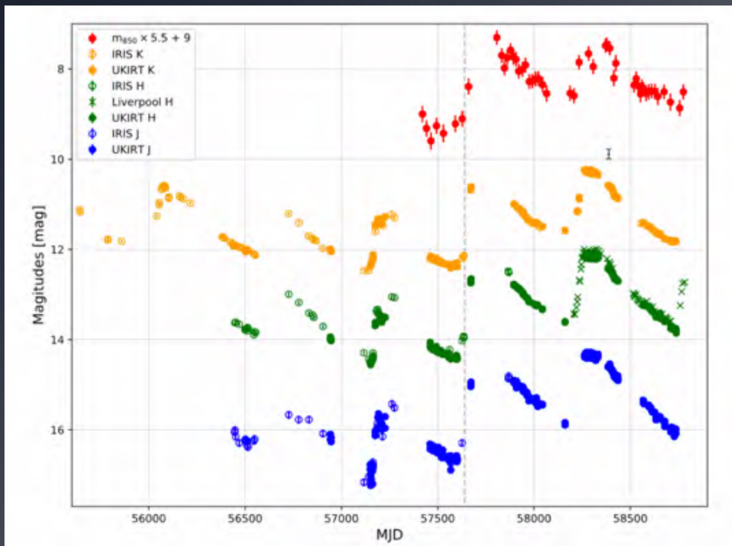
stochastic (random); secular (linear); and periodic

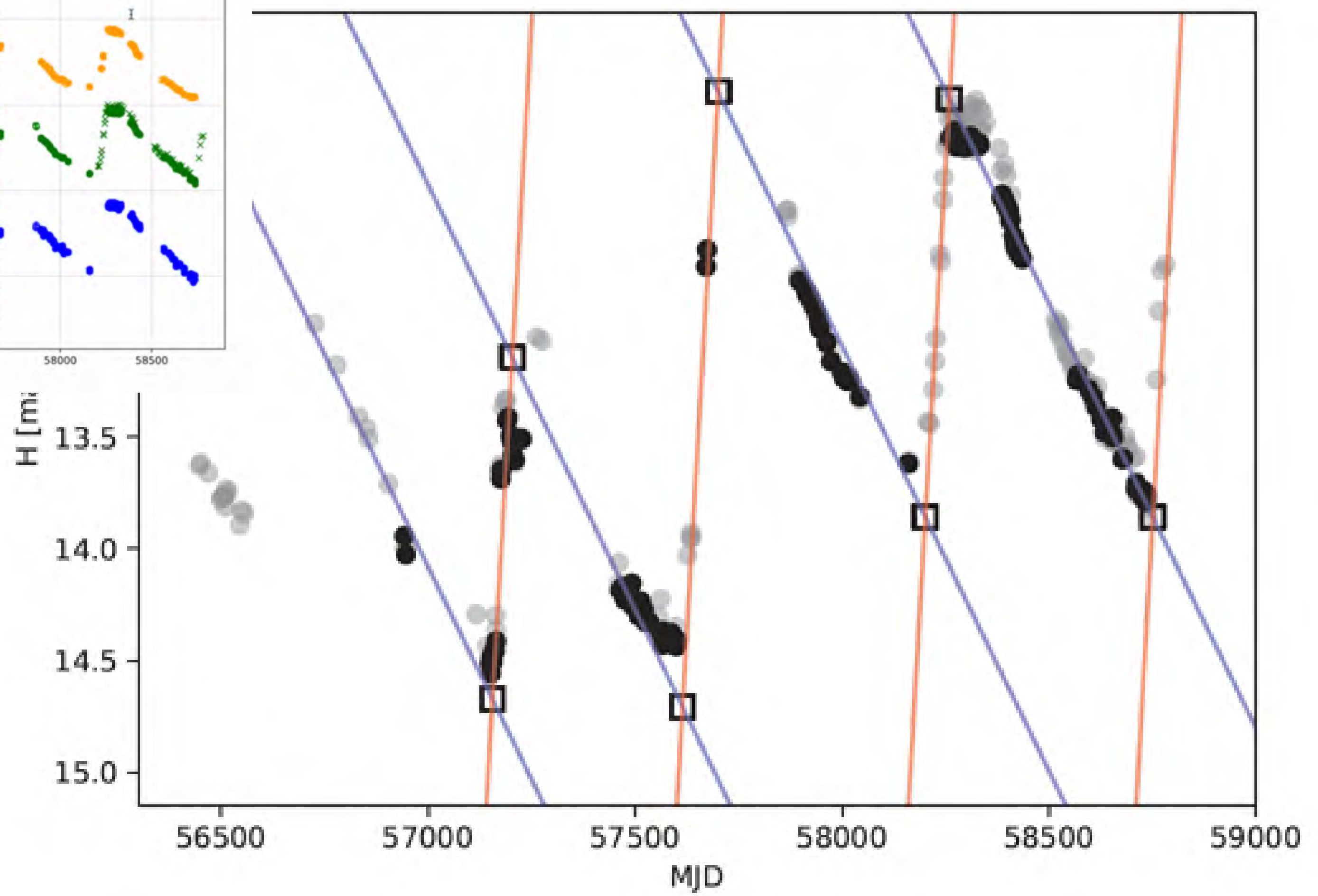
Young Faithful: bursts and decays
(Y-H Lee, Johnstone, et al. 2020; Contreras-Pena et al. 2020)



Decay of accretion bursts

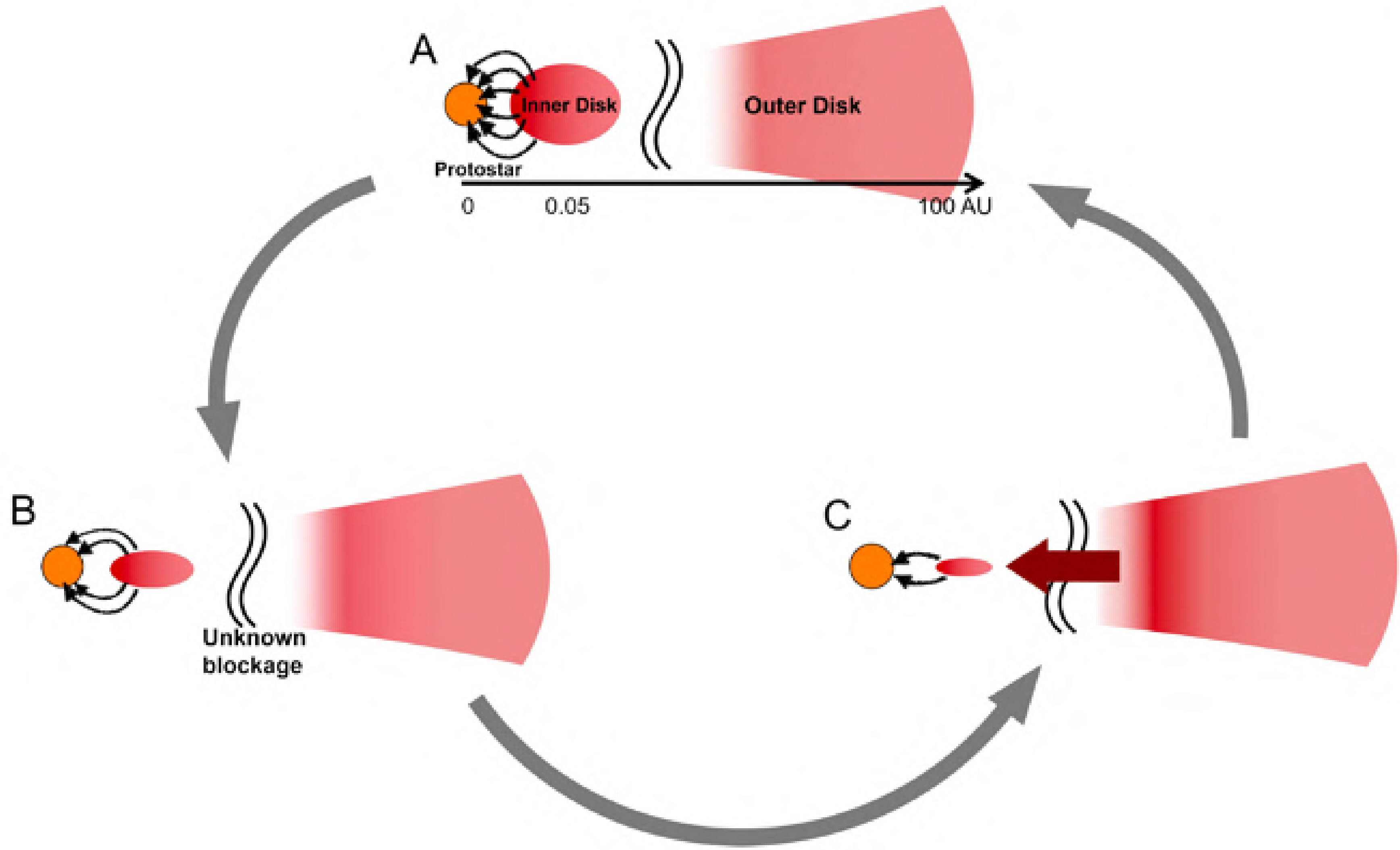
(Y-H Lee, Johnstone, et al. 2020)





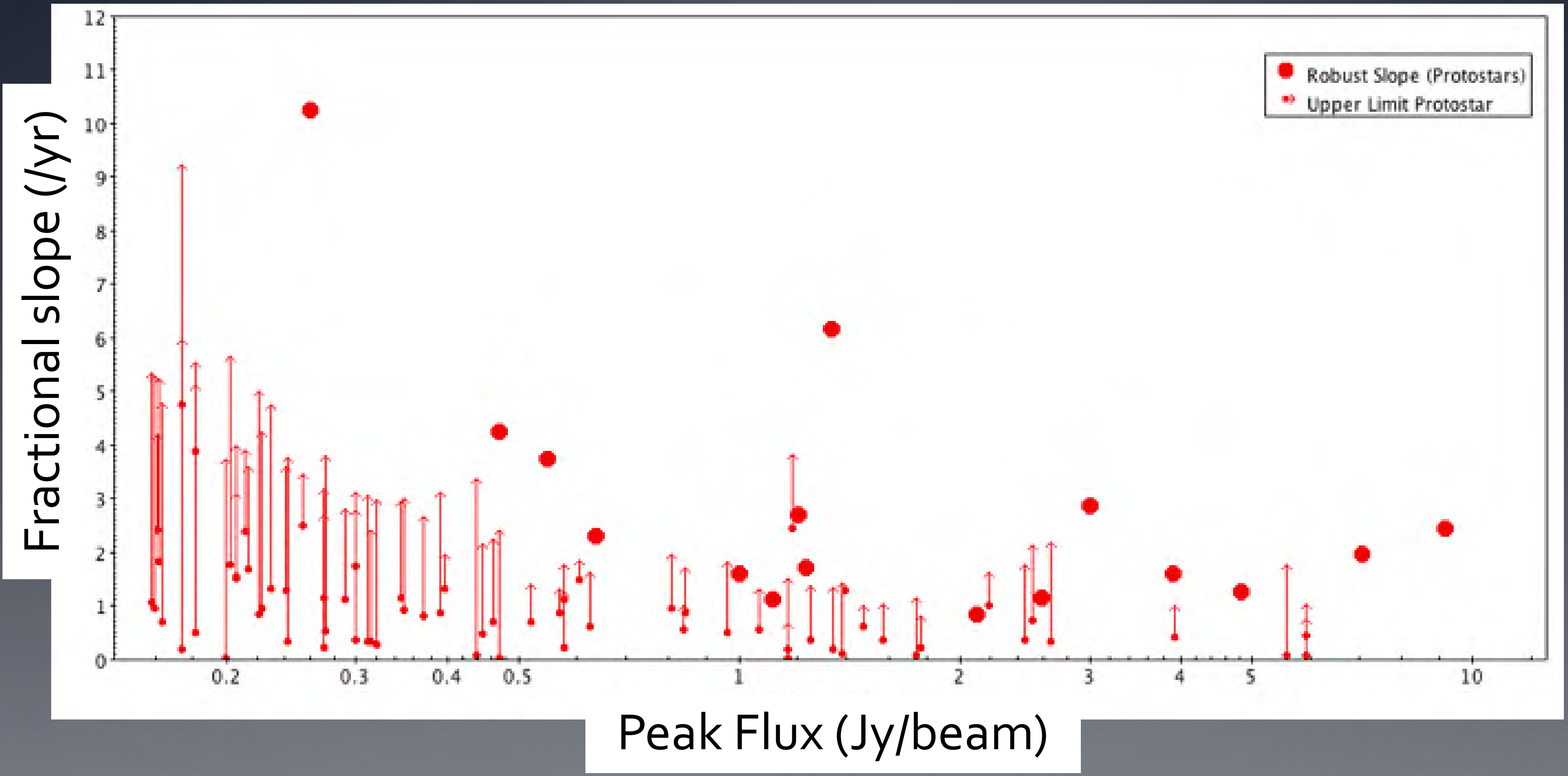
Rise: 0.1 yr

Decay: 0.75 yr


A
Inner Disk
Outer Disk
Protostar
0
0.05
100 AU
B
Unknown
blockage
C

Summary of variability over 4 years

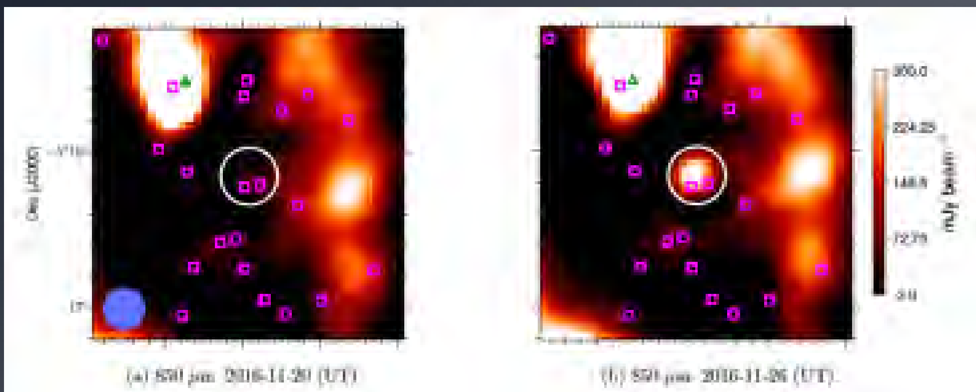
(Y-H Lee, Johnstone, et al. in prep)



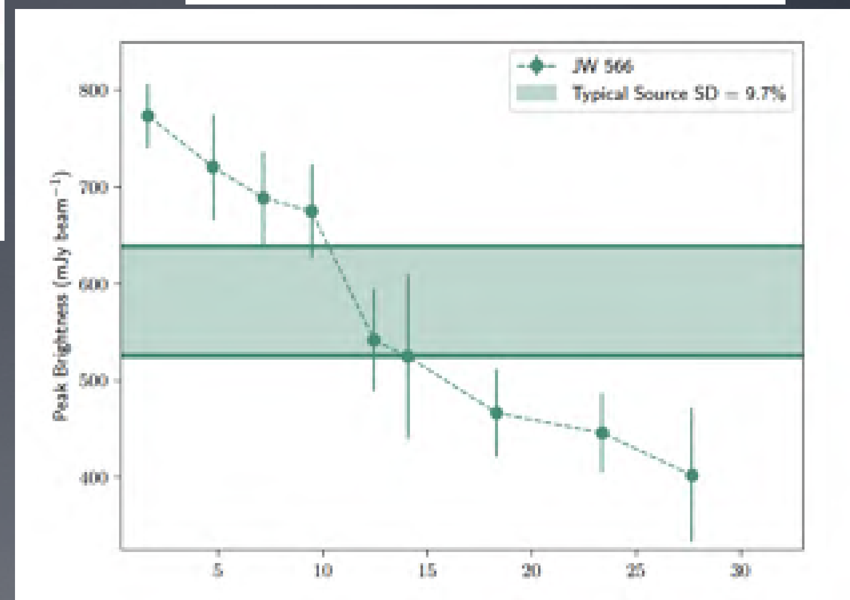
Follow-up with NEOWISE mid-IR monitoring and Gemini spectroscopy

Most luminous coronal radio flare ever detected?

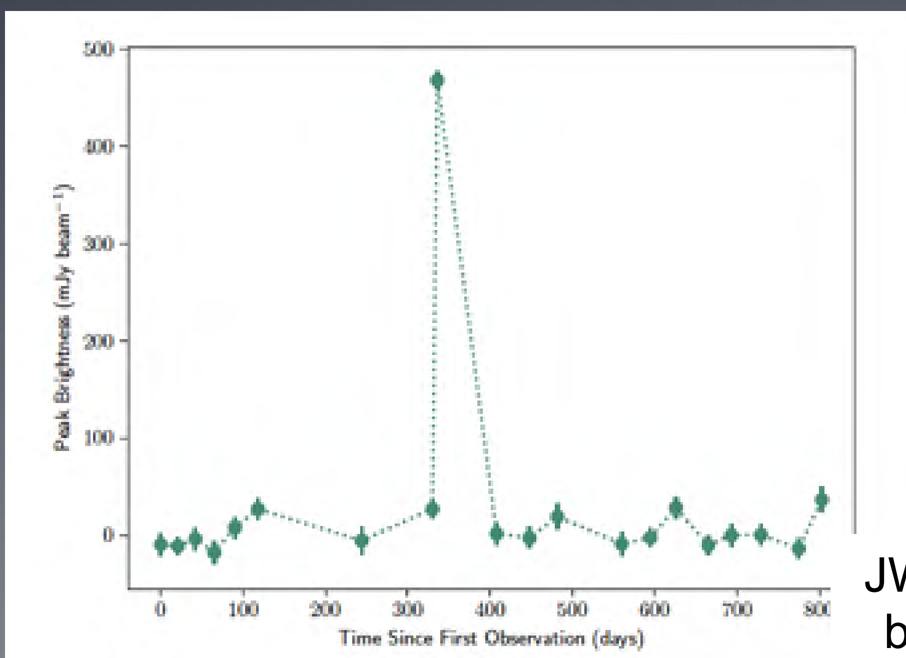
(Mairs+2019; Lalchand+ in prep for statistics)



First coronal flare detected in sub-mm



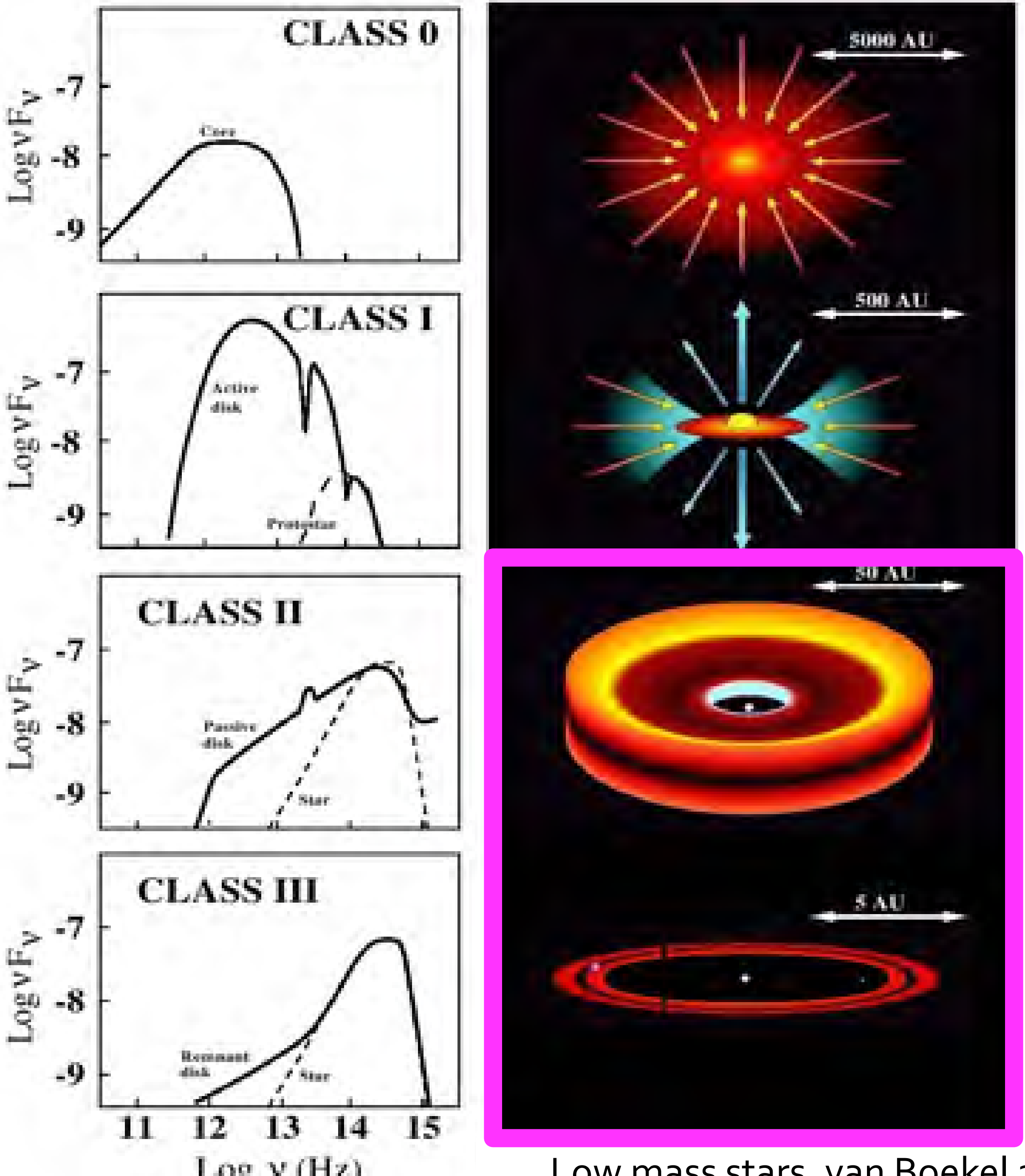
Decay detected during 30-min integration



JW 566 (binary) in Orion: bright in a single epoch

Future of JCMT-Transient

- Continued monitoring of eight primary regions
- Added 6 intermediate-mass star-forming regions
  - Many more sources; confusion
- Only current method to detect protostellar variability on youngest protostars (Yoon, Herczeg, et al. in prep)

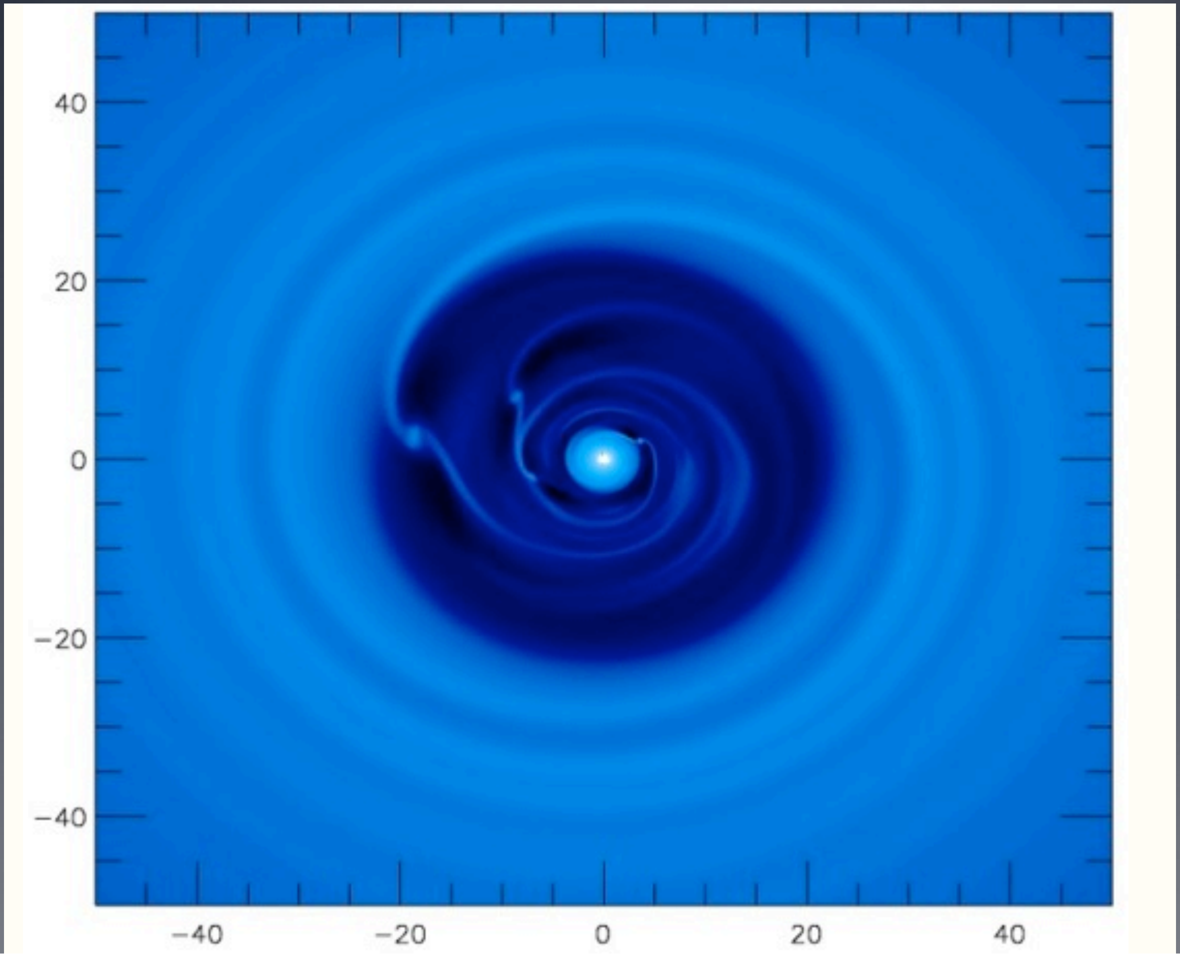


Low mass stars, van Boekel 2005

Disk evolution and planet formation

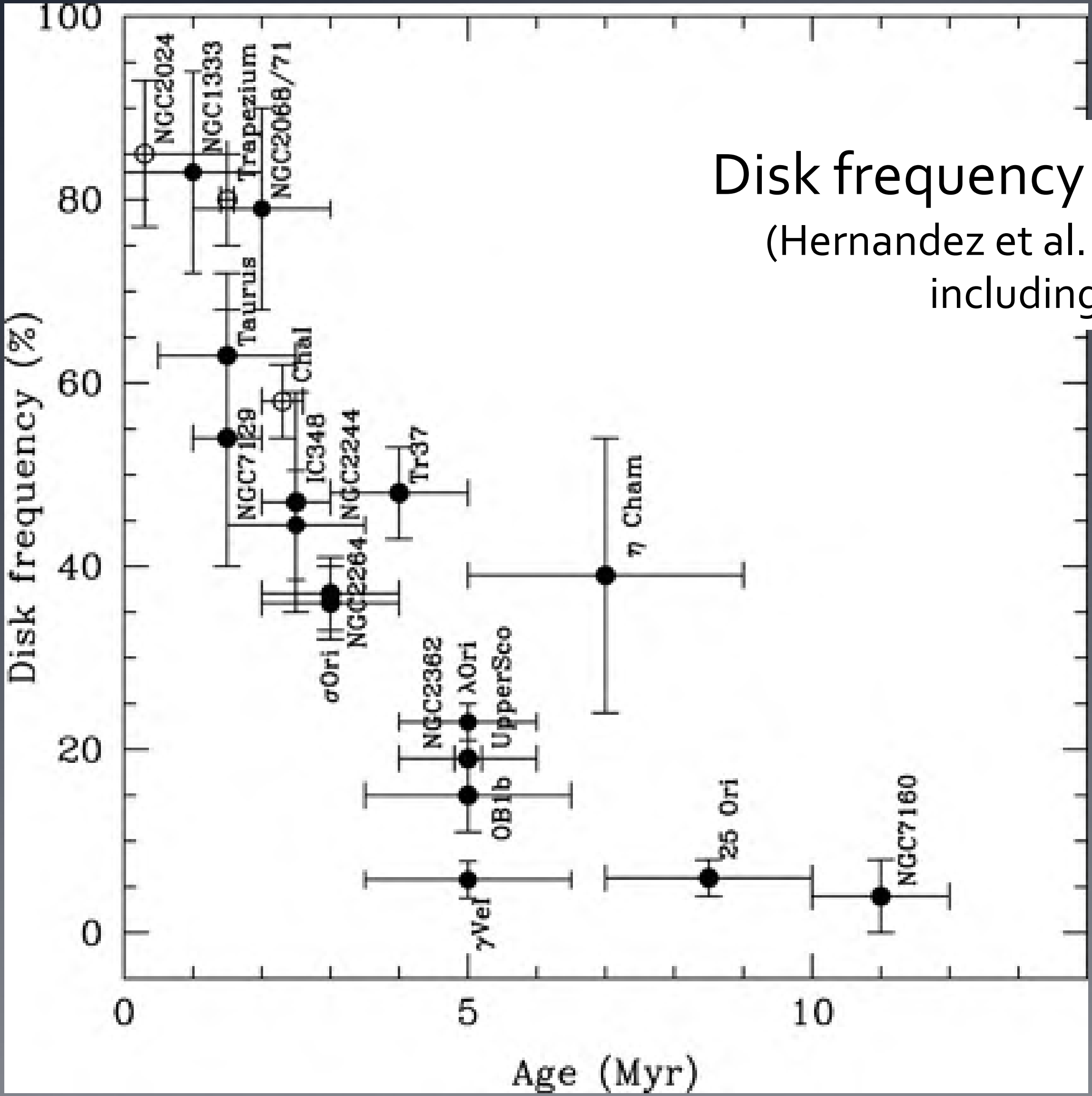
How would a forming planet affect a disk?

(e.g., Lin & Papaloizu 1986; Zhu+2011)



Competition between gas accretion; gap/hole formation

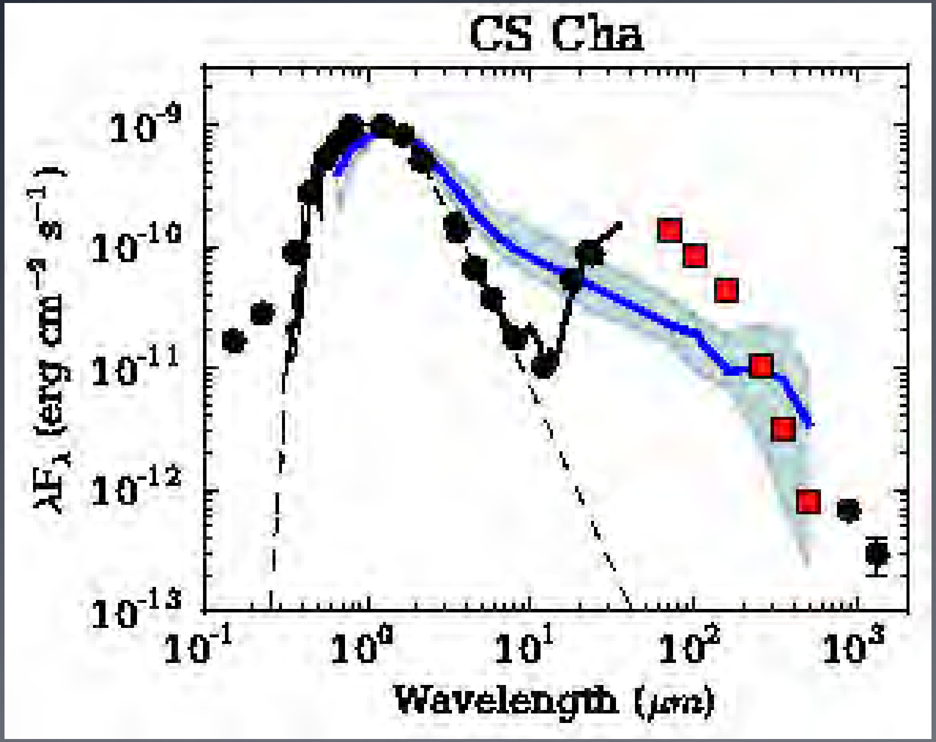
Dust and gas disk timescales:
planet formation must occur within ~3 Myr



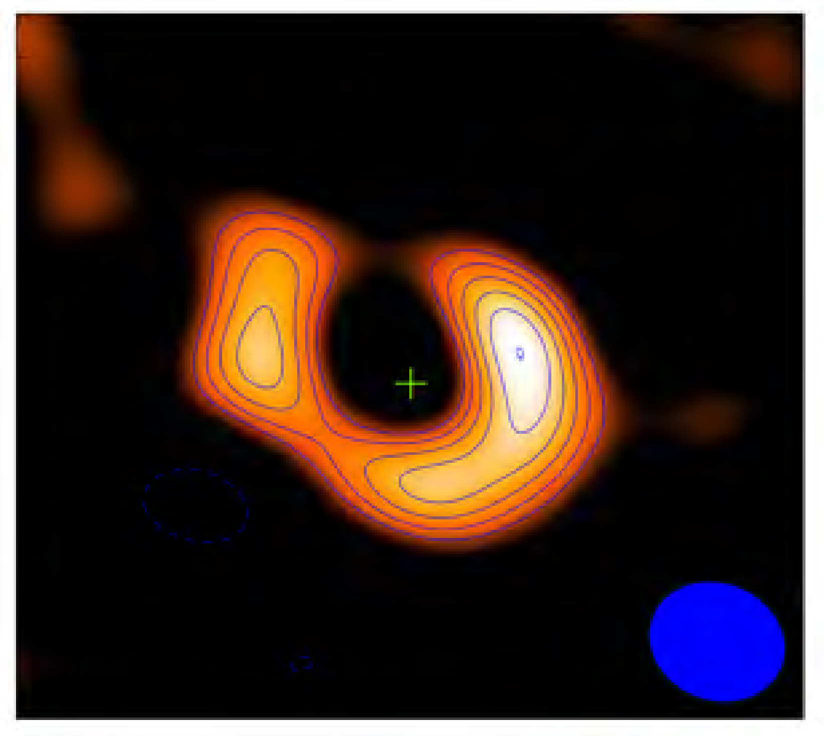
Disk frequency in different clusters

(Hernandez et al. 2008 and many others, including Haisch+2001)

Do disks show evidence of planet formation? Inner holes in dust

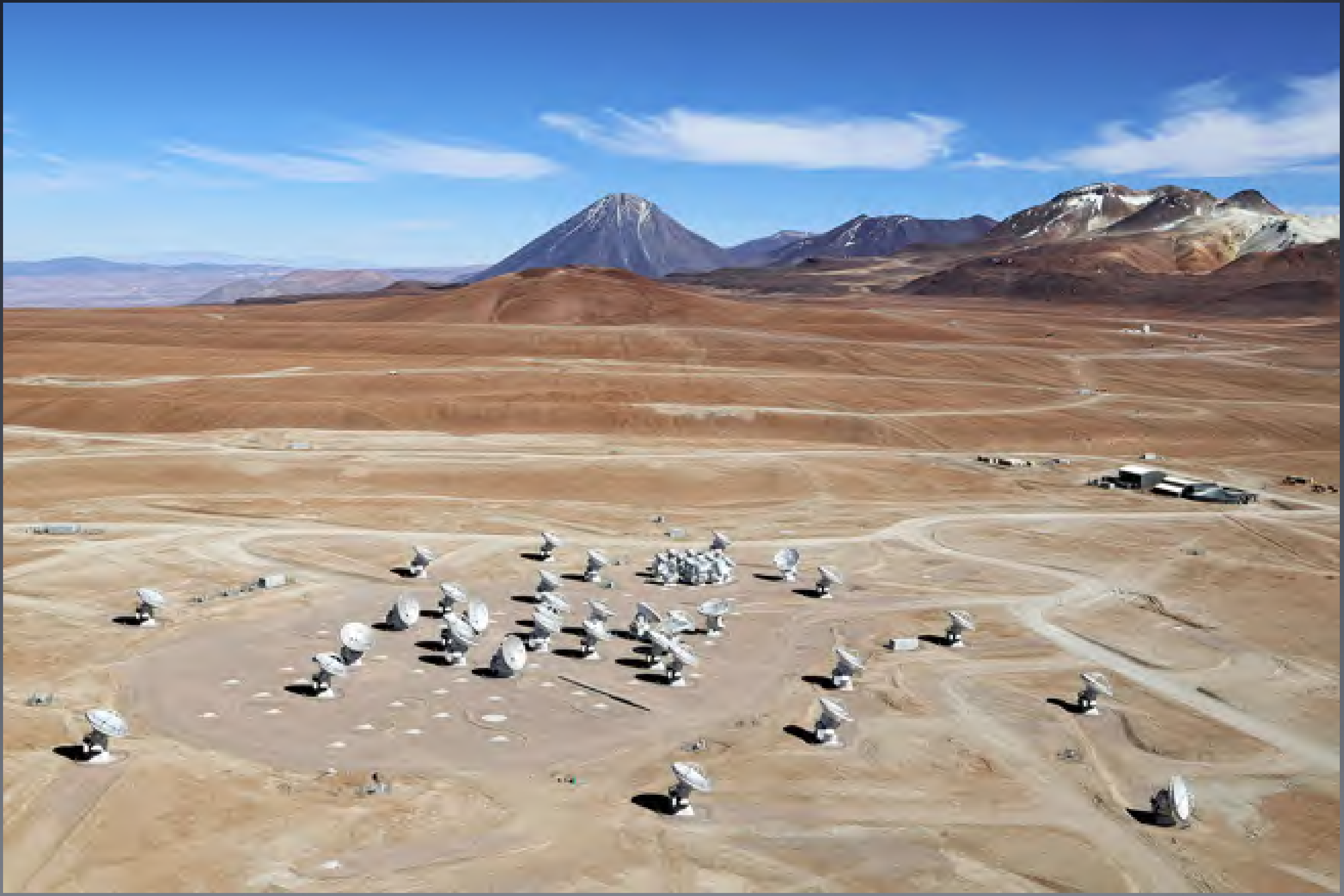


Espaillat+2007; see also, eg Strom+1989, Calvet+2002, D'Alessio+2005, Furlan+2006; Kim+2009, Merin+2010



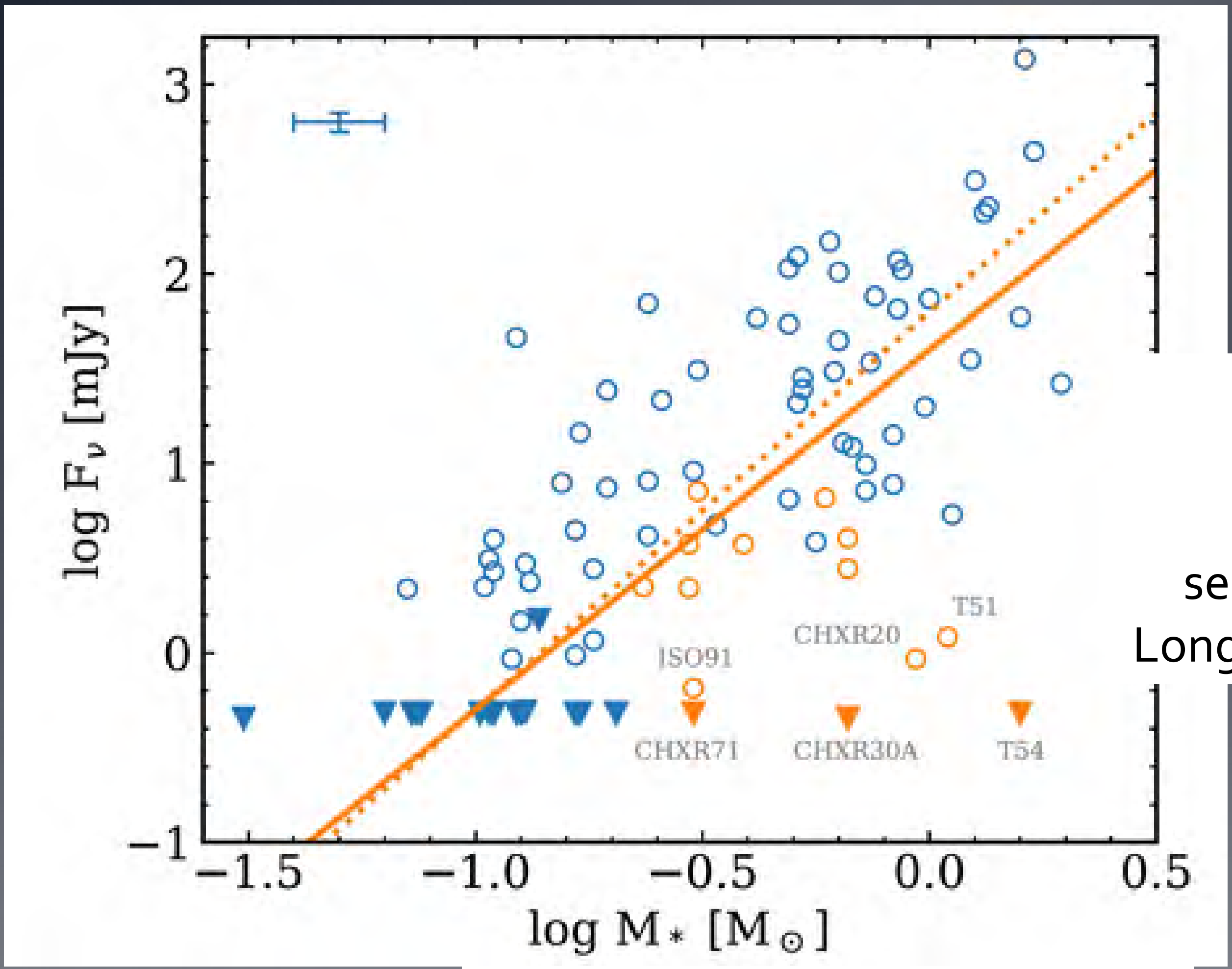
Brown et al. 2008

Atacama Large Millimeter Array (ALMA)



Sub-mm interferometer, 5000m high plateau in Chile

Complete surveys of disk flux (~mass)



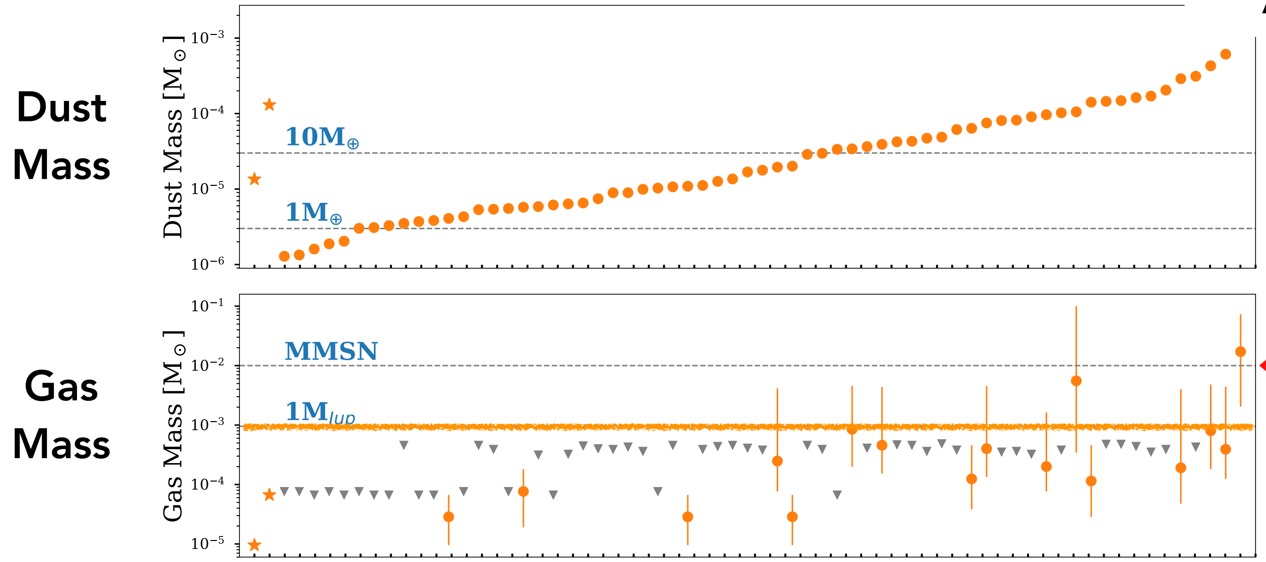
From Long+2018a

e.g., Ansdell+2016;
Pascucci+2016;
Barenfeld+2016;
see also Miotello+2017 and
Long, Herczeg+2017 for CO flux

Complete surveys of disk flux (~mass)

Cha I : 2 Myr-old star-forming region

Long+2018a; see also, eg, Ansdell+ and Miotello+

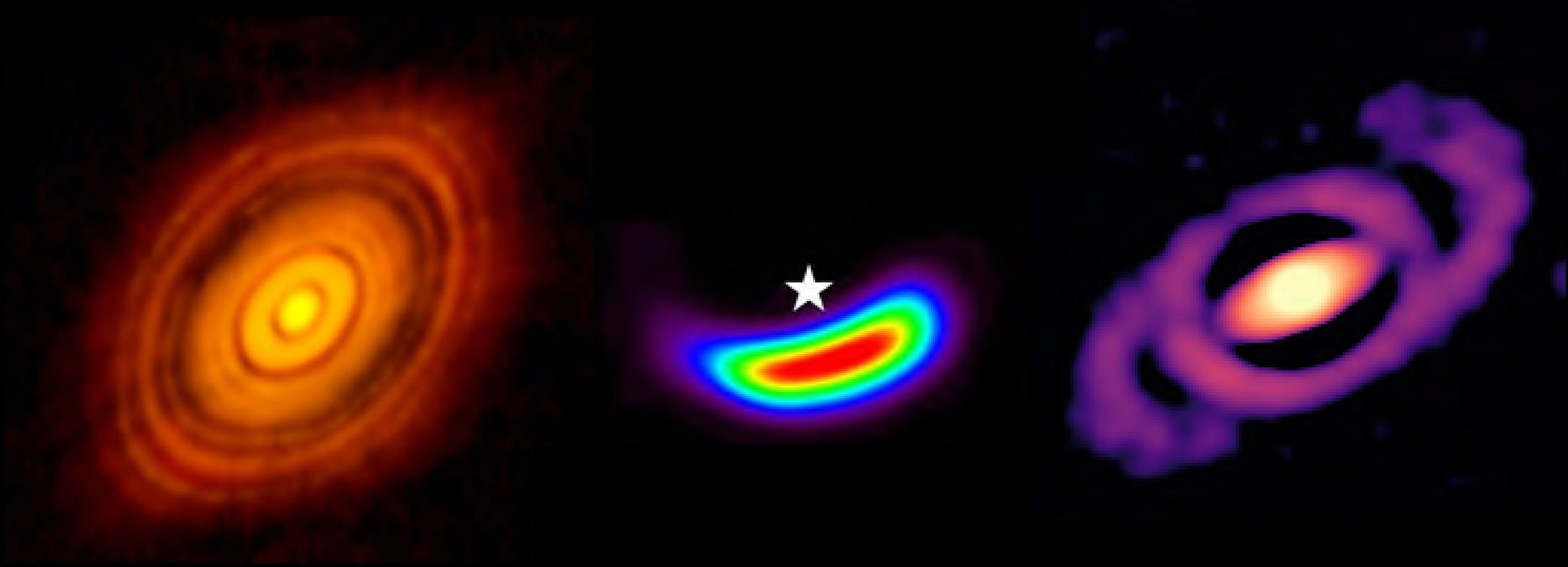


Minimum mass solar nebula

Not enough disk mass to grow more giant, terrestrial planets and to drive accretion (see also Manara+; Mulders+)

depends on dust opacities/scattering (Kataoka+2015; Zhu+2019)

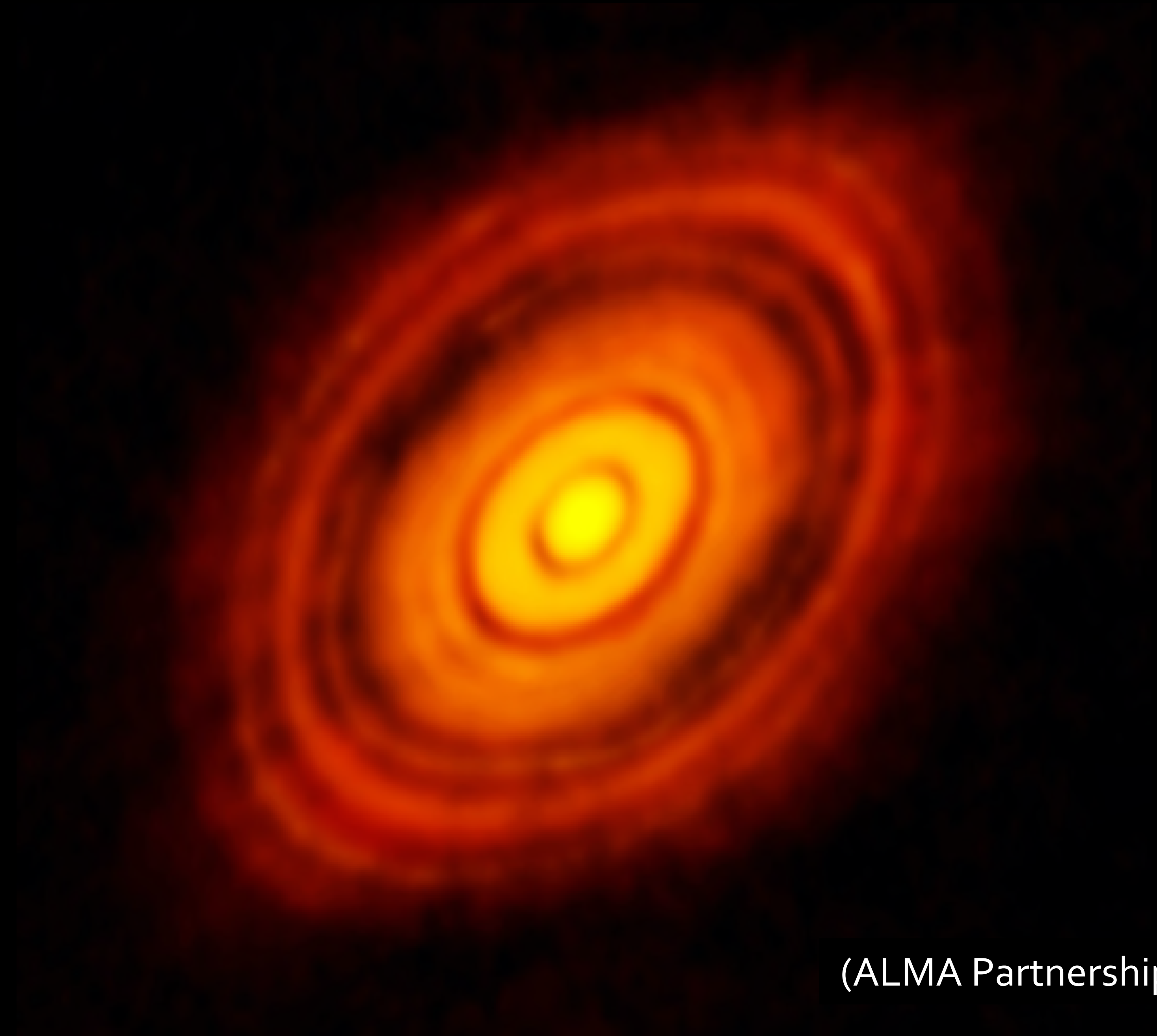
The ALMA revolution: Dust structures in protoplanetary disks



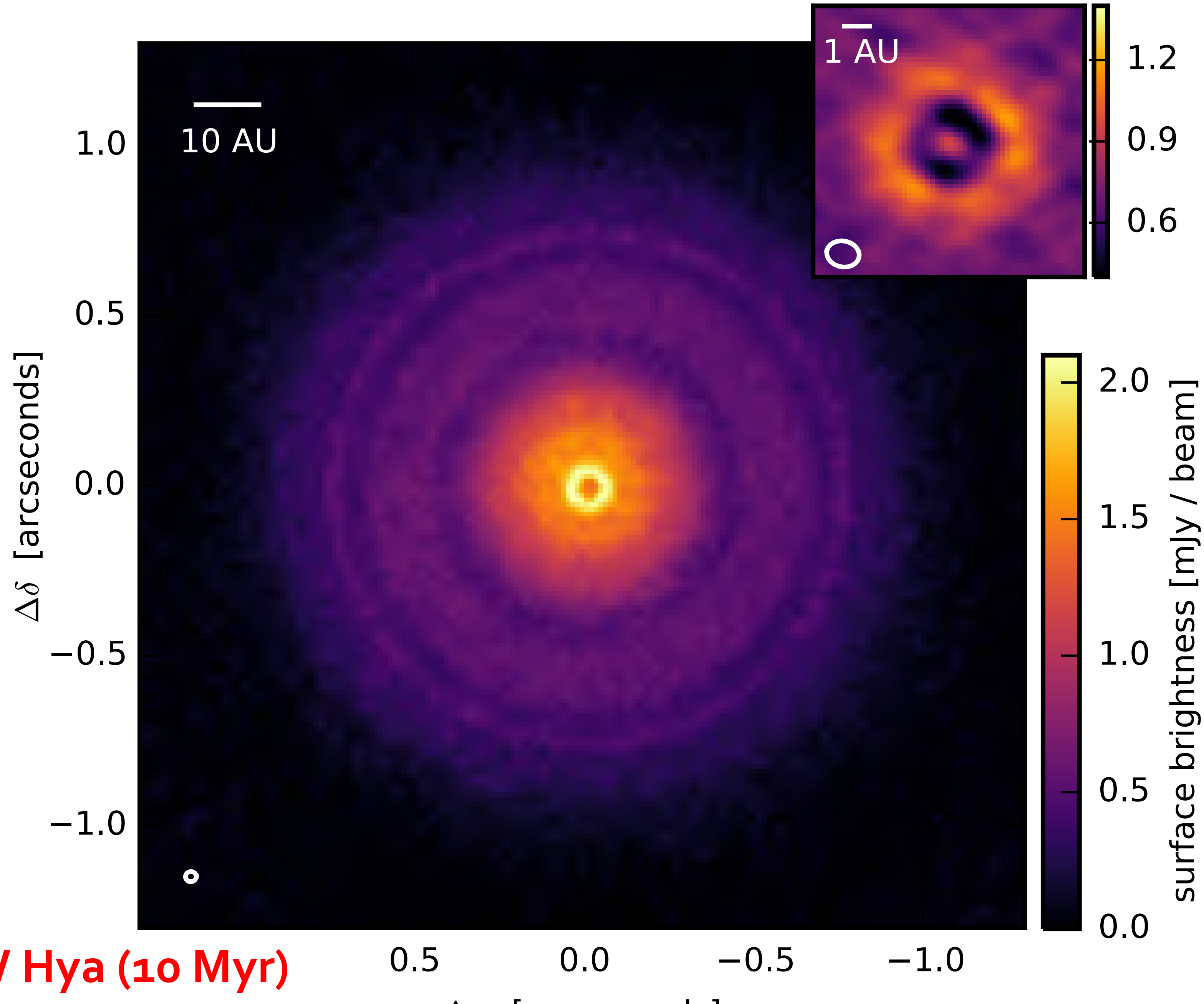
Large dust grains drift to local pressure maxima

(e.g., Weidenschilling 1977; Pinilla+2015)

ALMA Image of HL Tau disk (0.5-1 Myr)

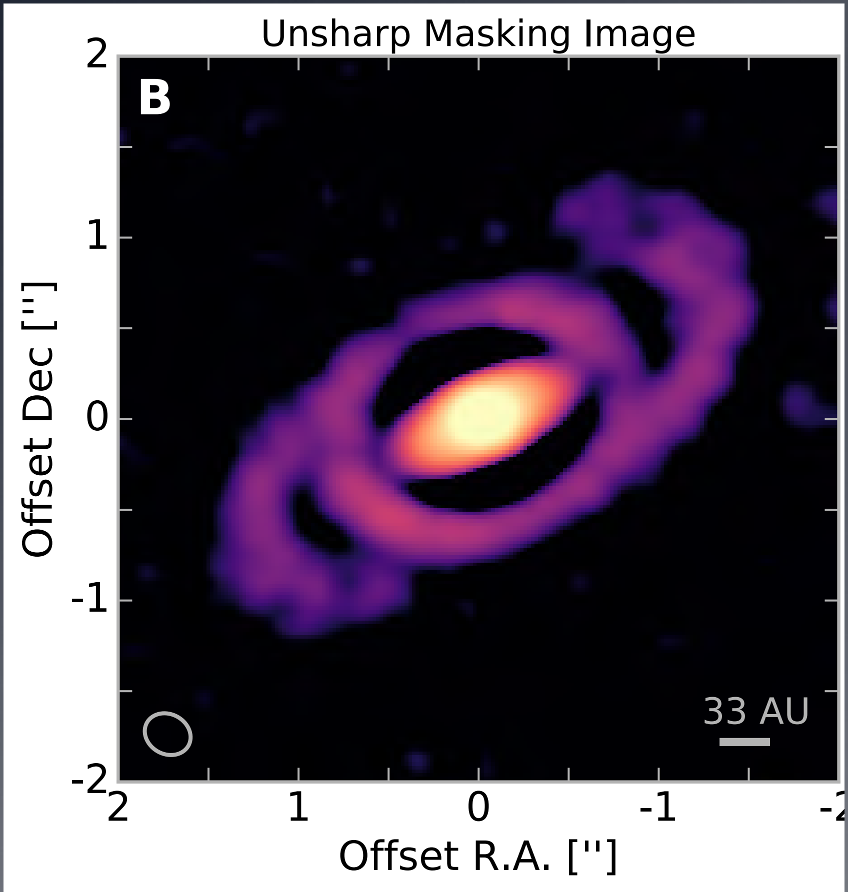


(ALMA Partnership+2015)

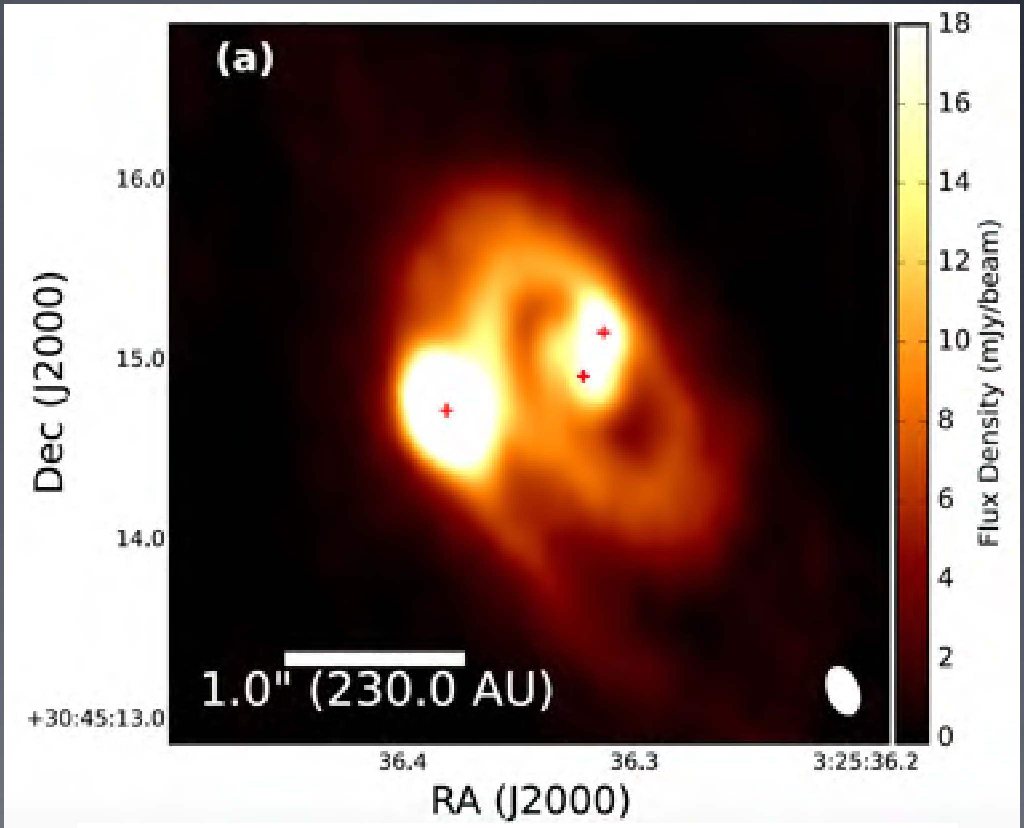


TW Hya (10 Myr)
Andrews+2016

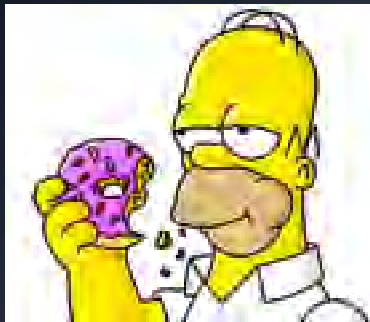
Spirals in young protoplanetary disks



Companion? spiral density waves (e.g., Perez+2016)

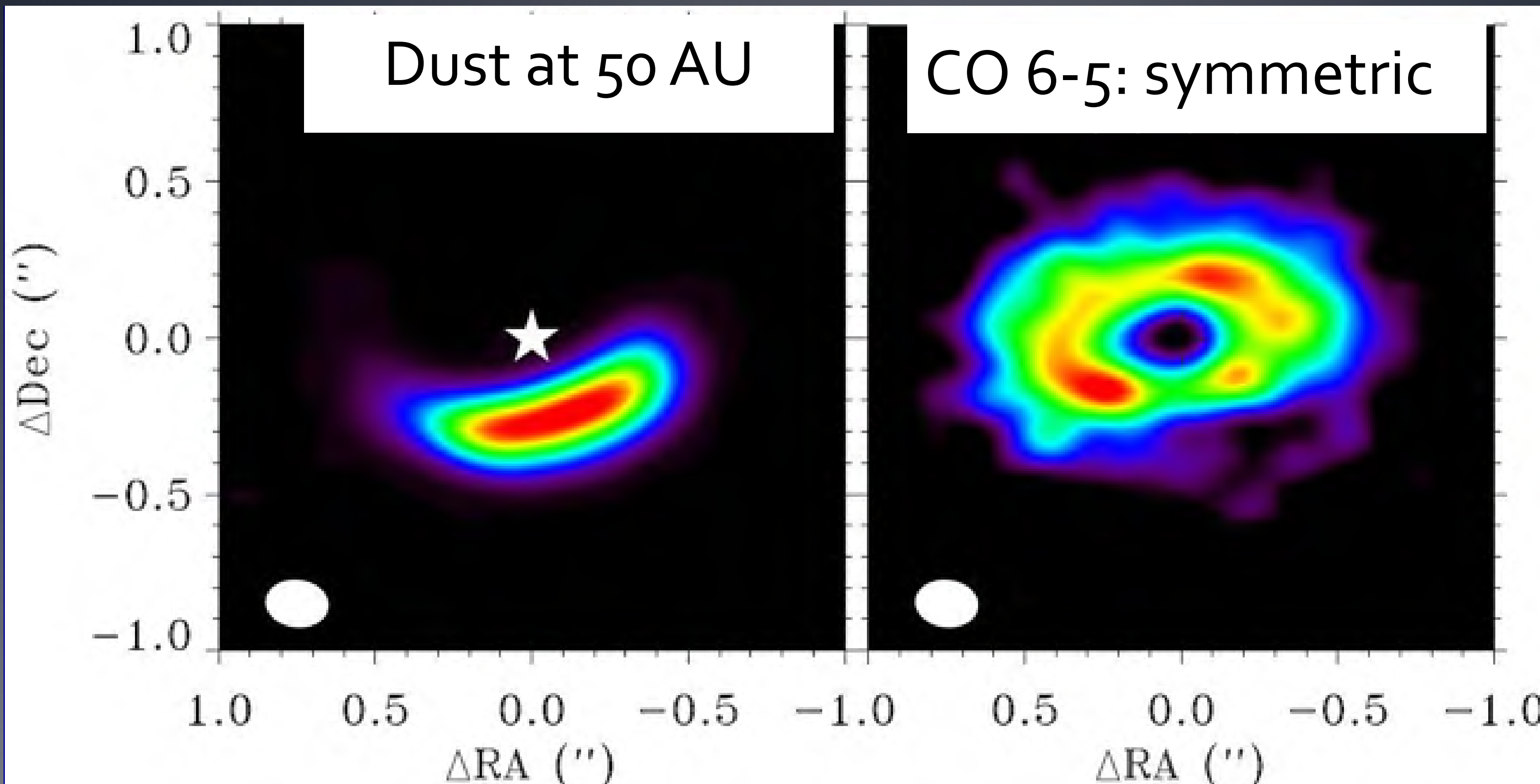


Binary formation in young, gravitationally unstable disk? (e.g., Tobin+2016)

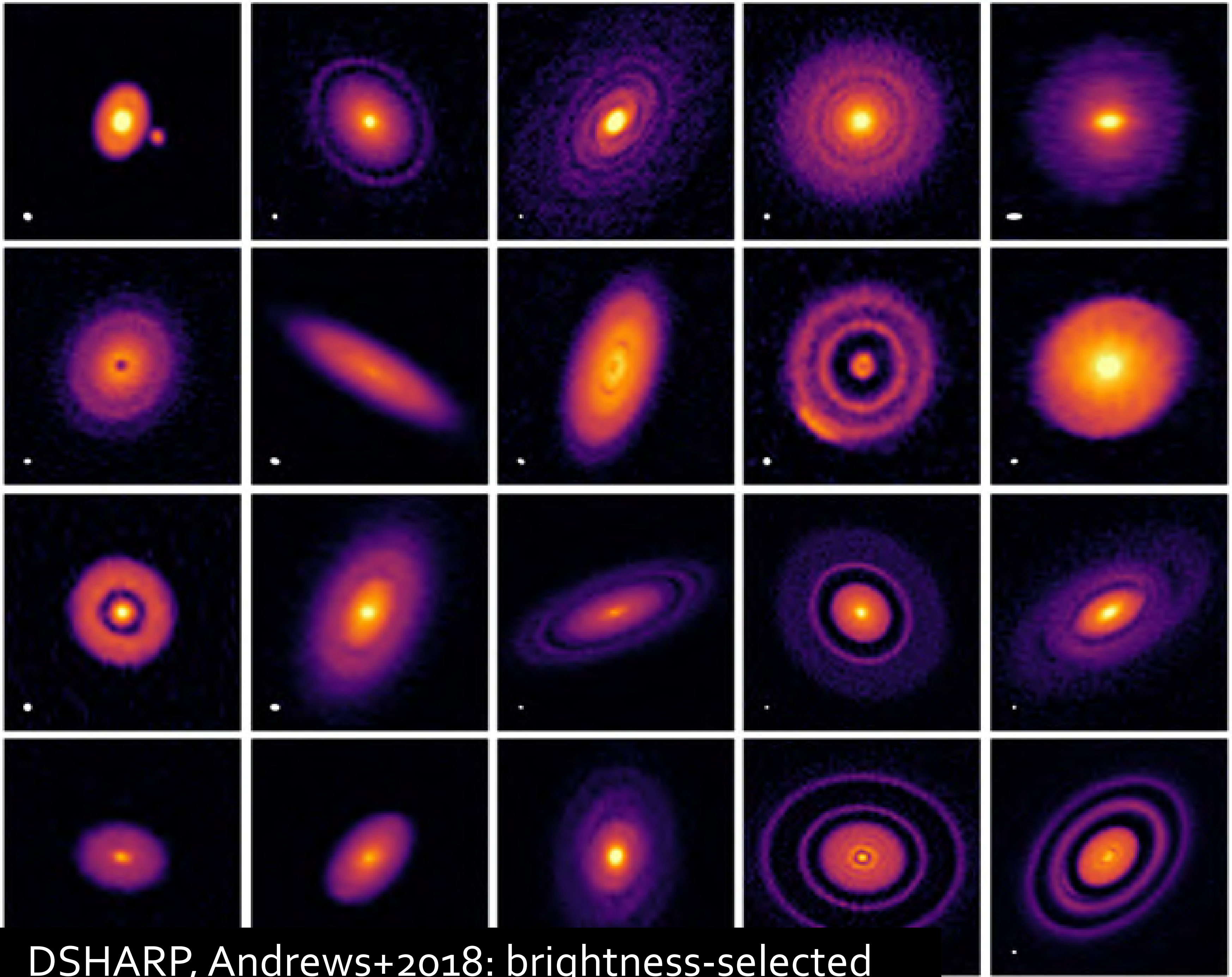


Dust trap in a transition disks

(e.g., van der Marel+2013, 2015)



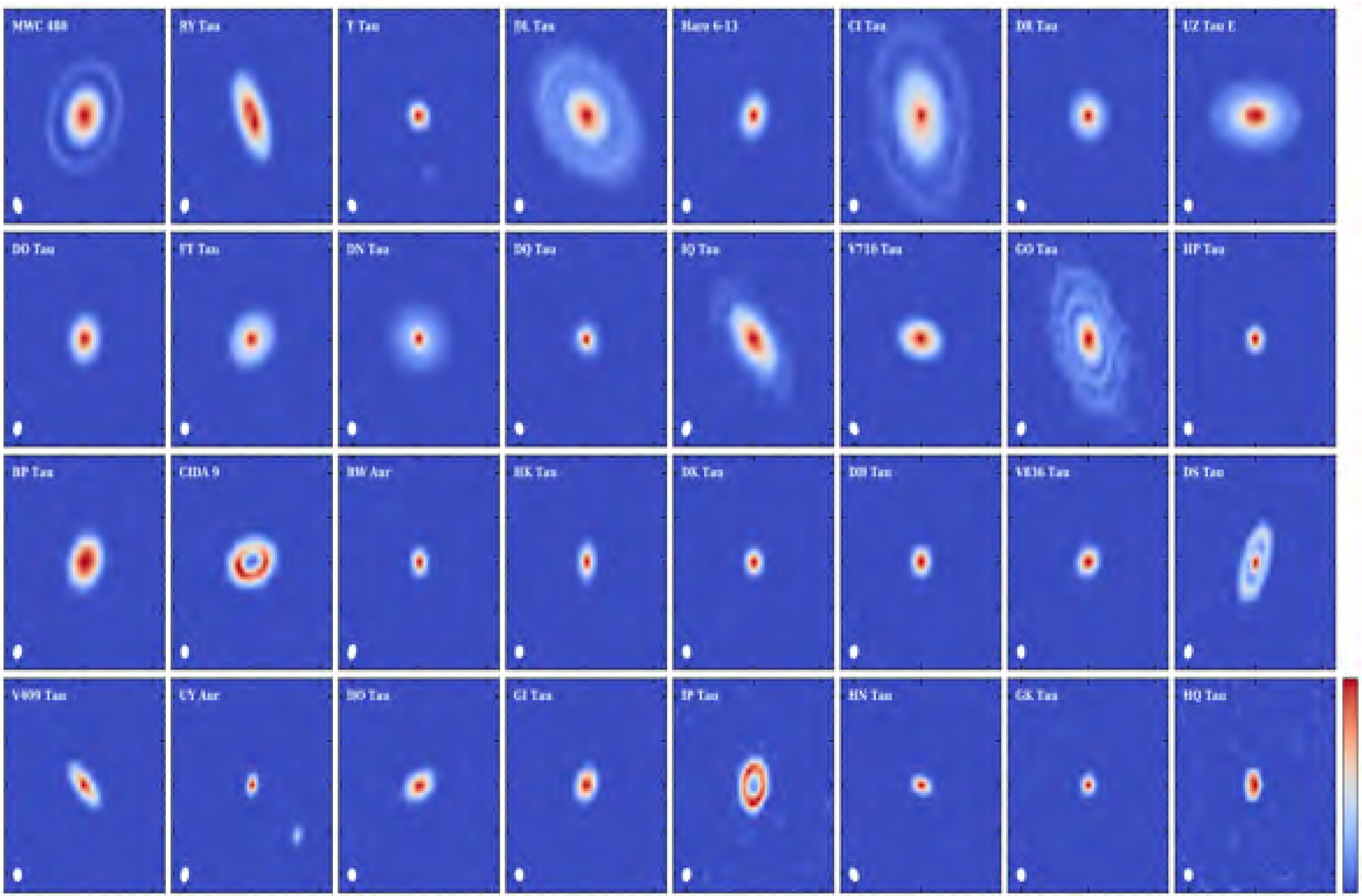
Planet inside hole: Vortex? Comet/KBO factory?



DSHARP, Andrews+2018: brightness-selected

Unbiased-ish ALMA survey of Taurus disks (0.1"/14 AU)

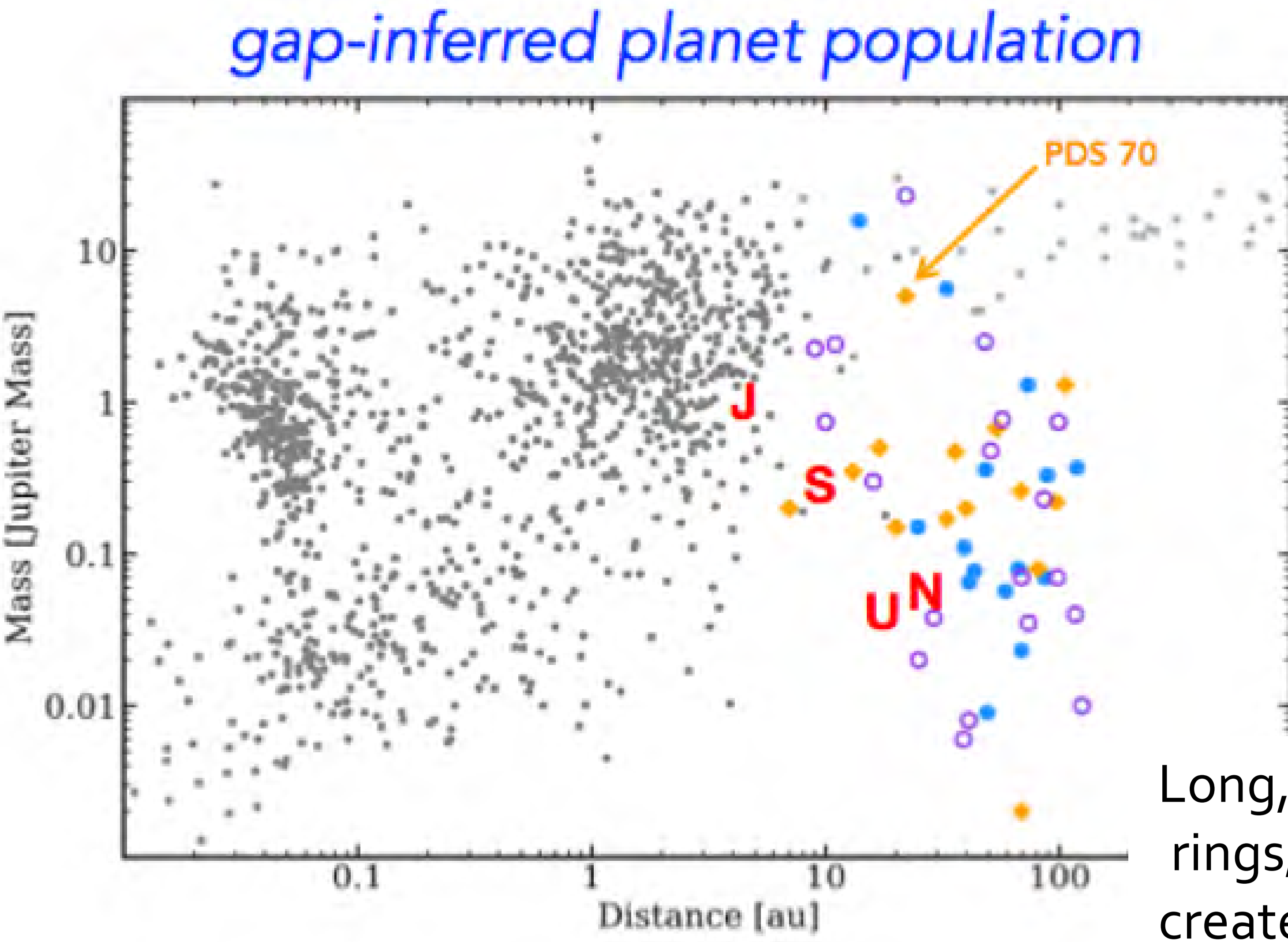
Long et al. 2018/2019, Yao Liu et al. 2018; Lodato+2019, Manara et al. 2019; includes Herczeg (PI), Pinilla, Harsono, Ragusa, Dipierro, Tazzari, and ~10 others



2.4'' (350 AU) on each side

What if the gaps are carved by young planets?

(Lodato et al. 2019)

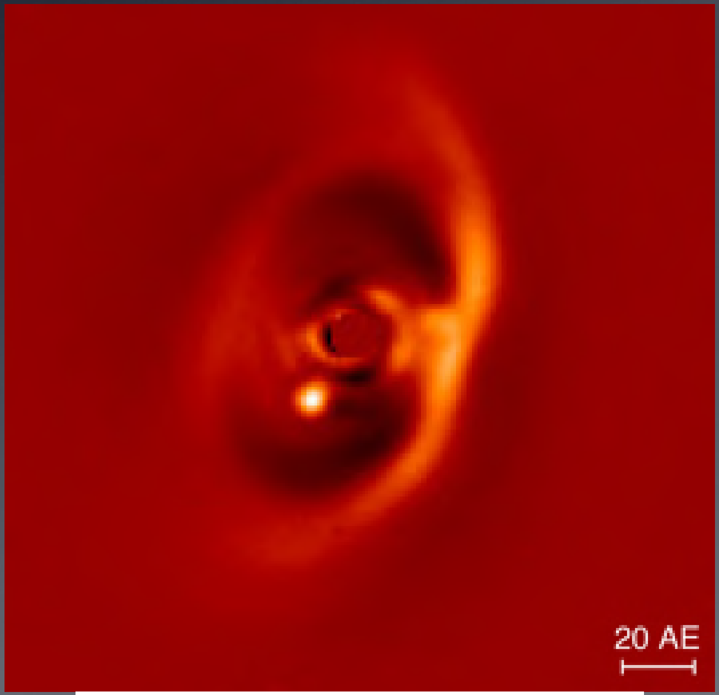


Long, Pinilla+2018: rings/gaps are not created by ice lines

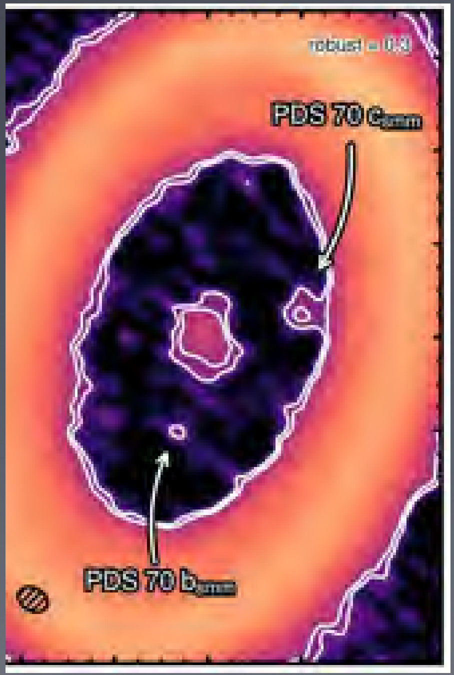
Zhang+2018 (DSHARP); Bae+2018 (archival)

Planet(s) in a disk around the star PDS 70!

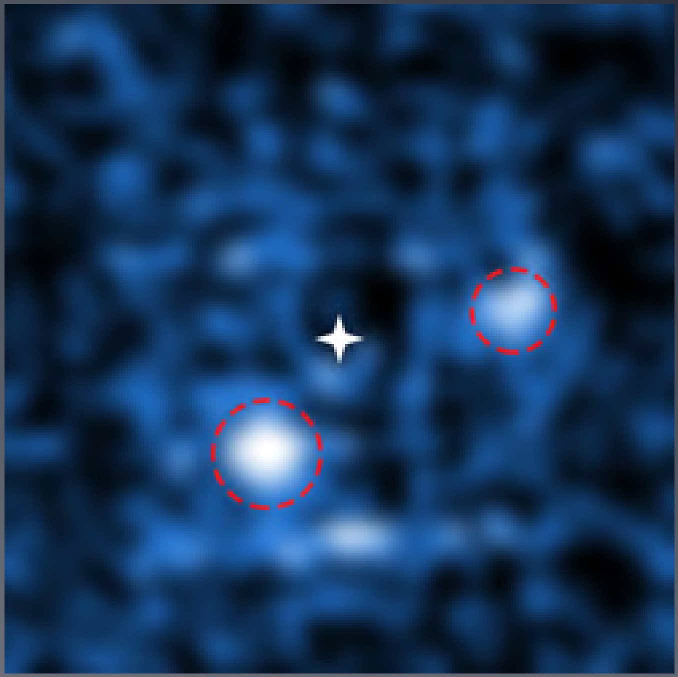
(Keppler et al. 2018)



VLT/Sphere



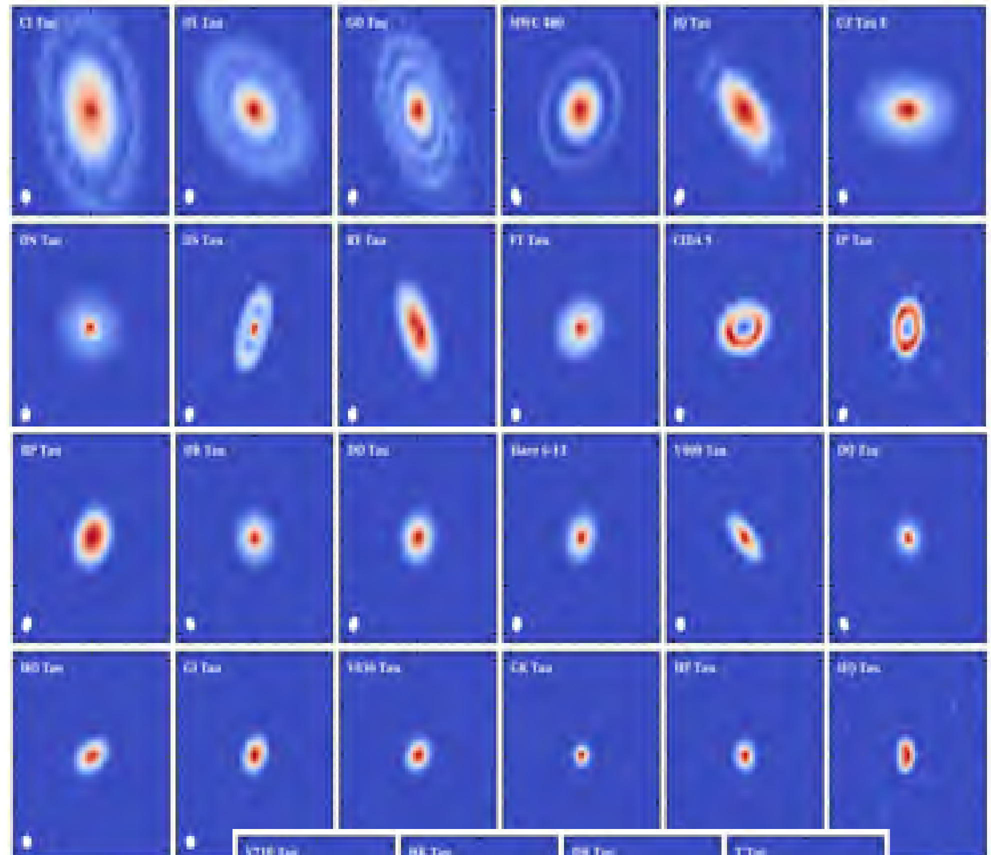
ALMA/dust,
Isella+2019



MUSE/H-alpha accretion,
Haffert+2019
See also Zhou, Herczeg, et al. 2014

Other evidence for planets in rings: from kinks in CO channel maps, Pinte+2018

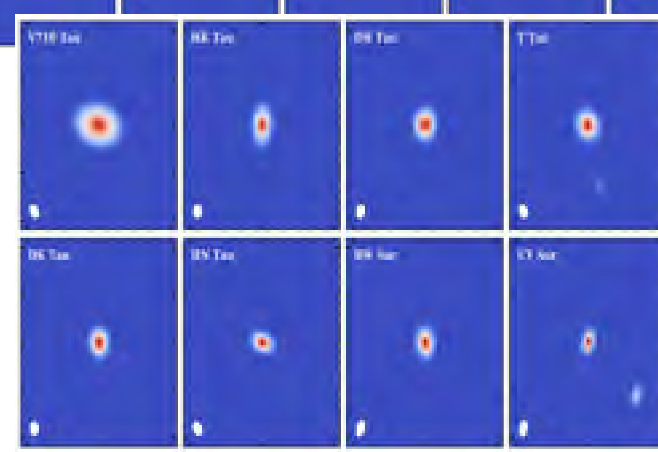
Unbiased survey of Taurus disks (Long et al. 2018/2019)



12 large disks with substructures

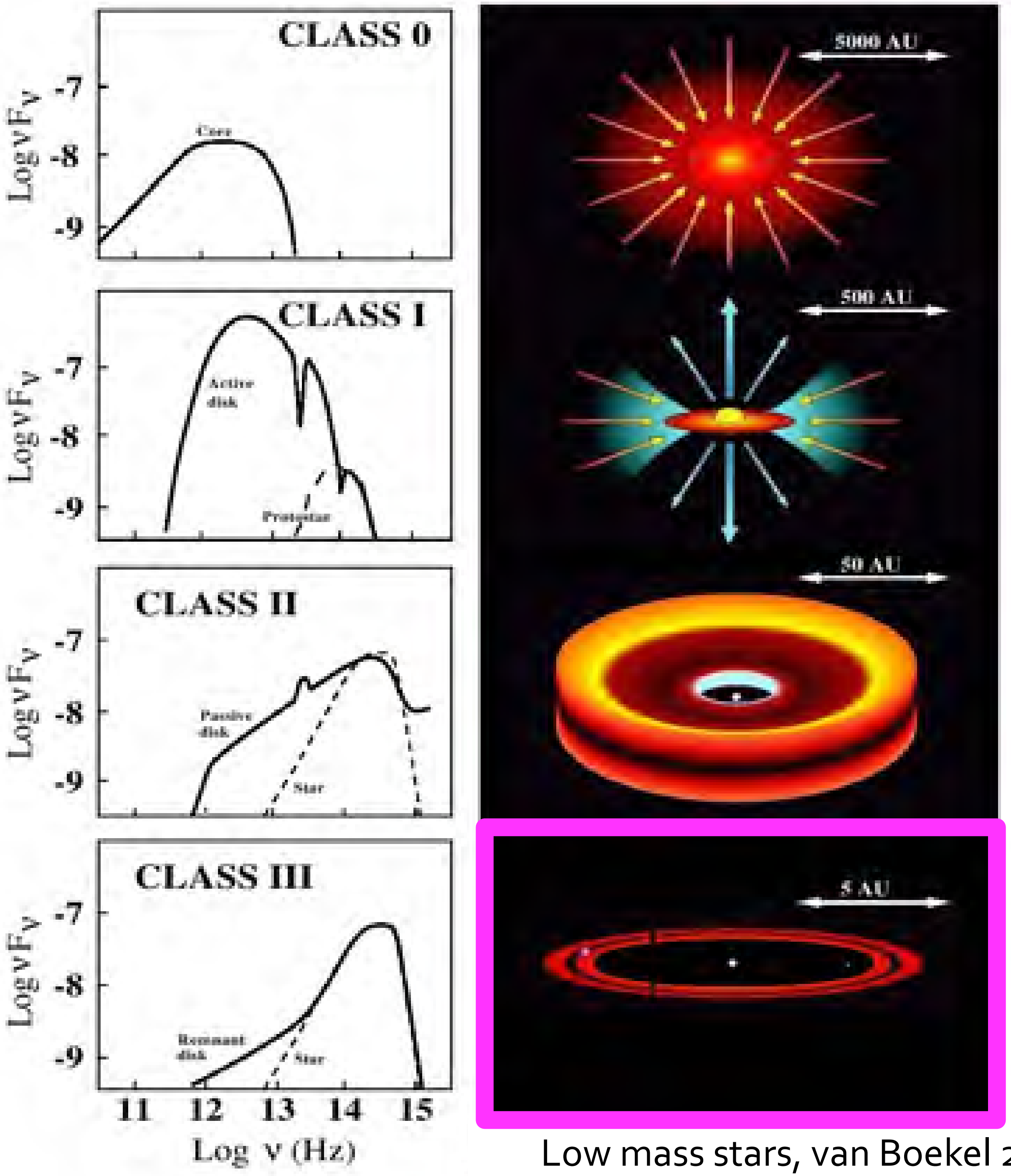
12 smooth (?), compact disks (~20-40 AU; not fainter)

Truncated disks: smooth disks in binaries (0.7″ — 4″; Manara+2019)



Disks and Planets with the Thirty Meter Telescope

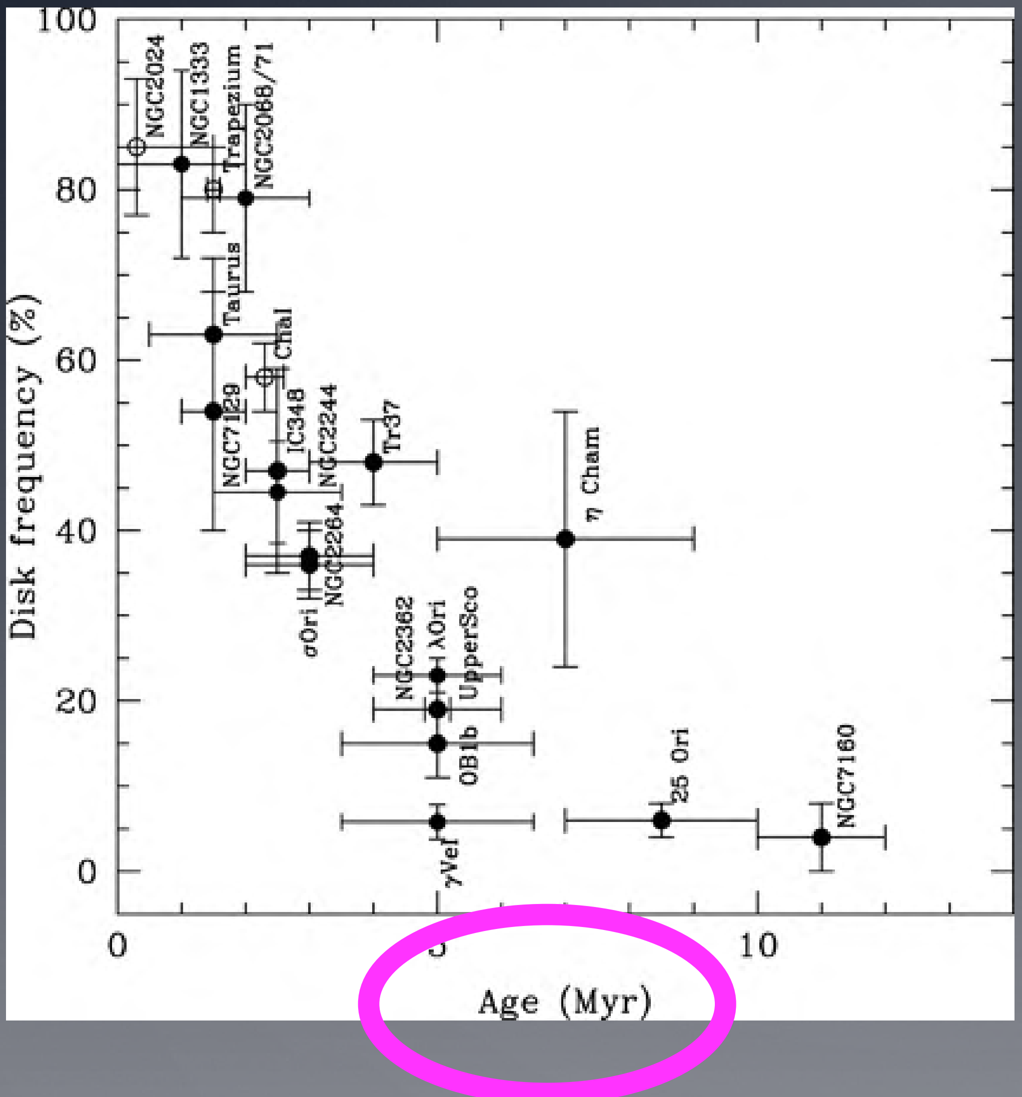
10 mas resolution = 1 AU for nearest disks



Low mass stars, van Boekel 2005

Ages of young stars

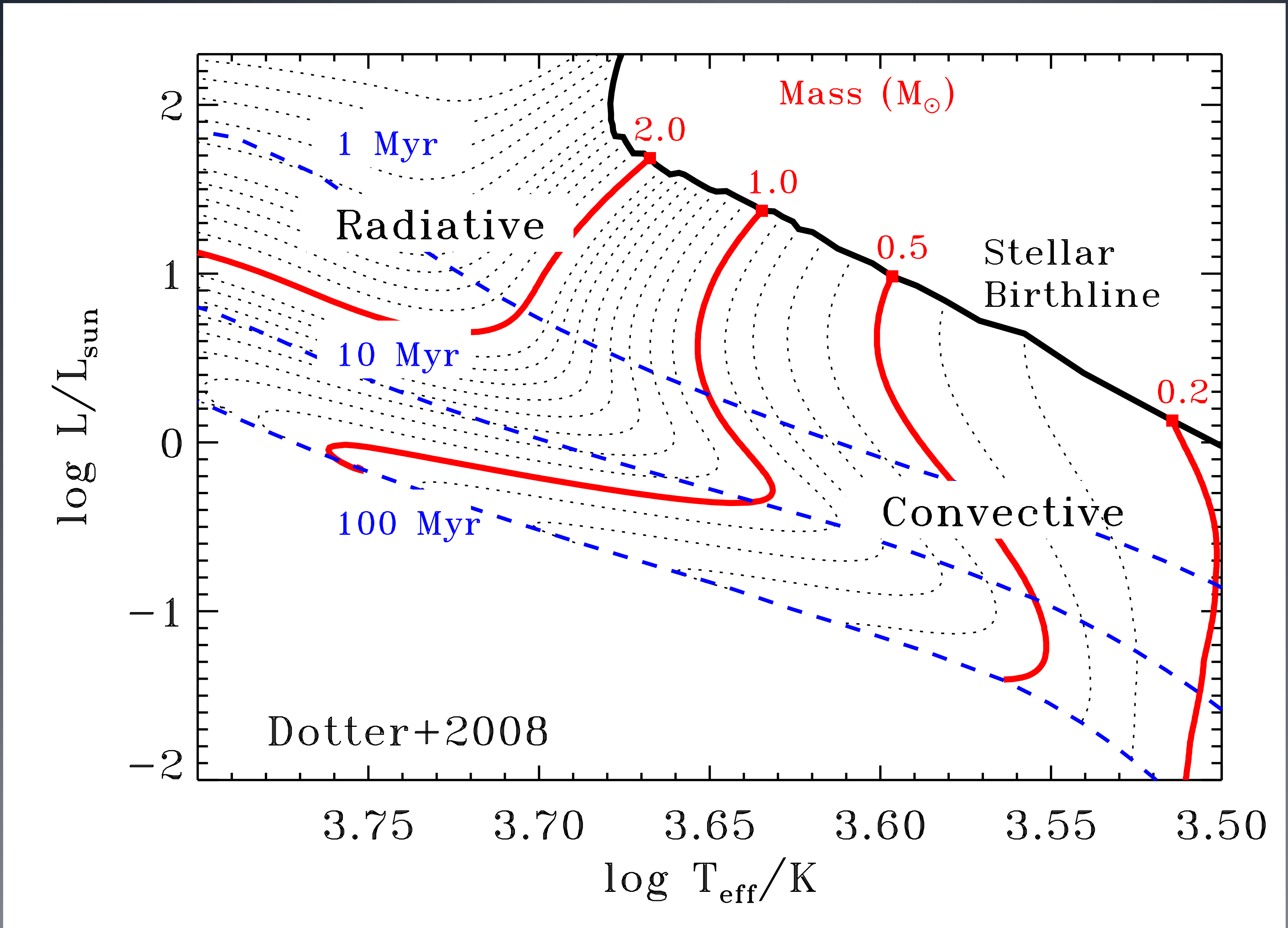
How to place disk properties on an evolutionary sequence?



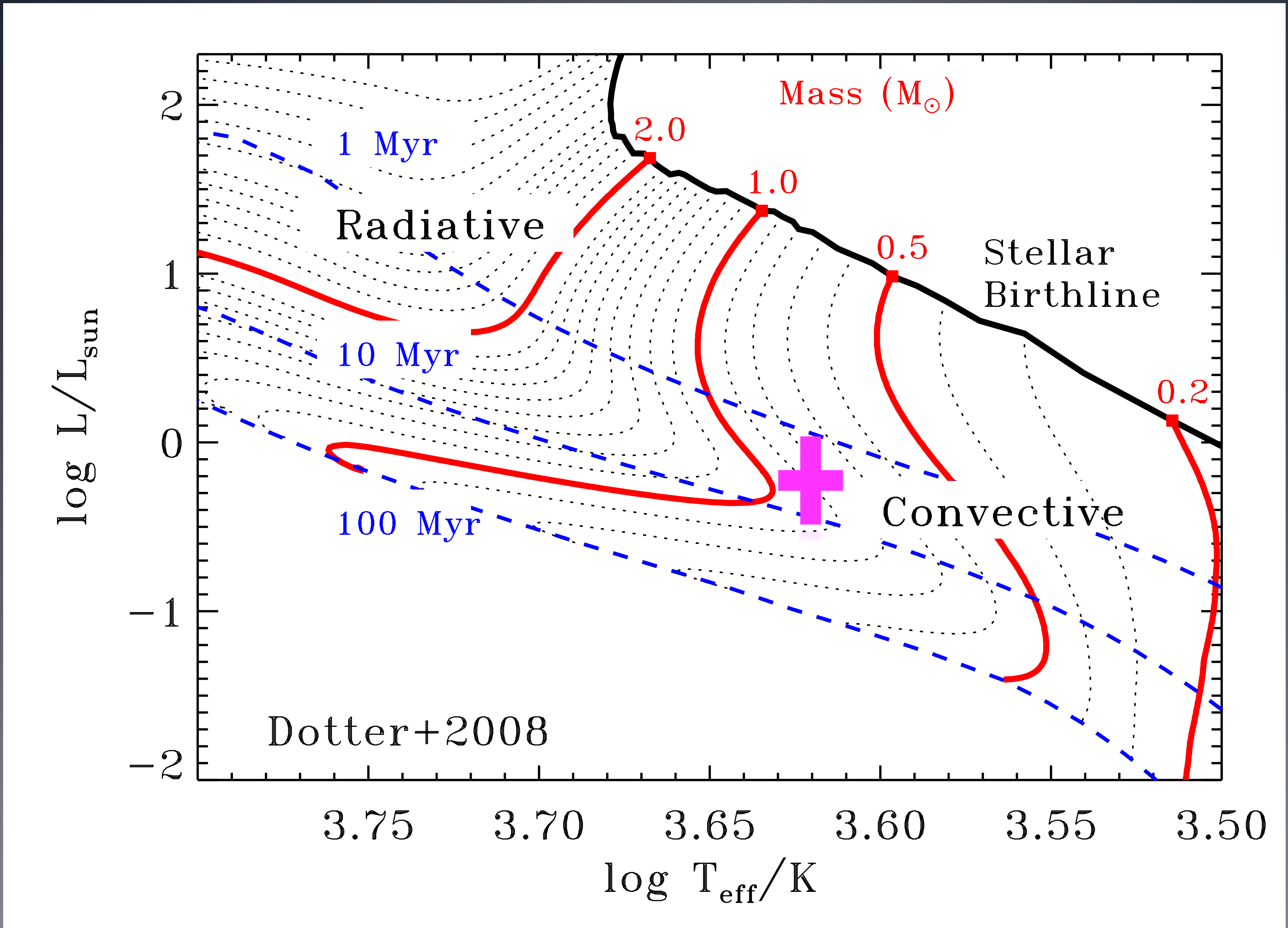
Properties we wish to relate to stellar ages

- Star formation history
- Disk mass (gas and dust)
- Mass accretion rate
- Outflow rate
- Disk size (gas and dust)
- **Disk substructures**

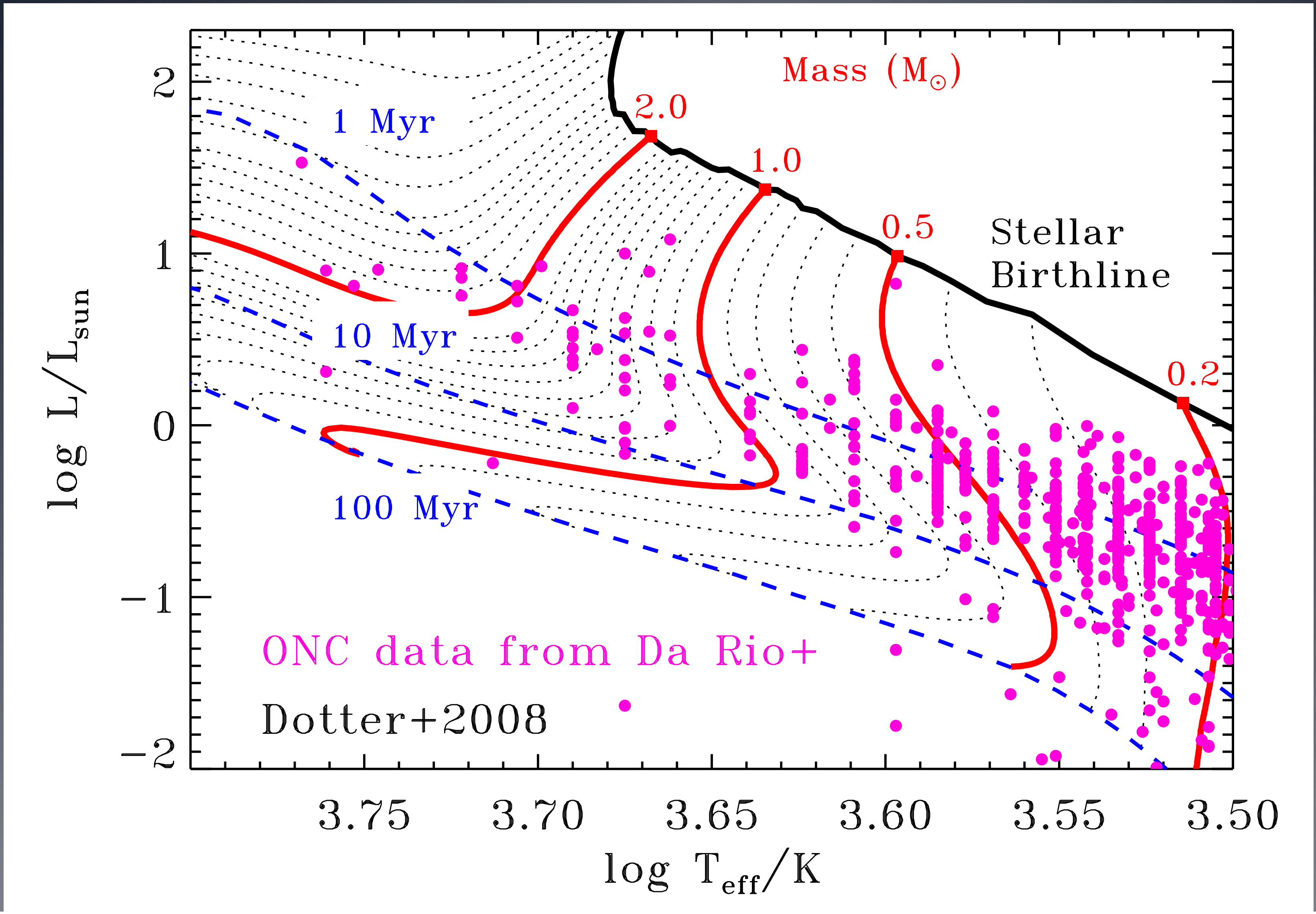
Basics of pre-main sequence evolution



Basics of pre-main sequence evolution

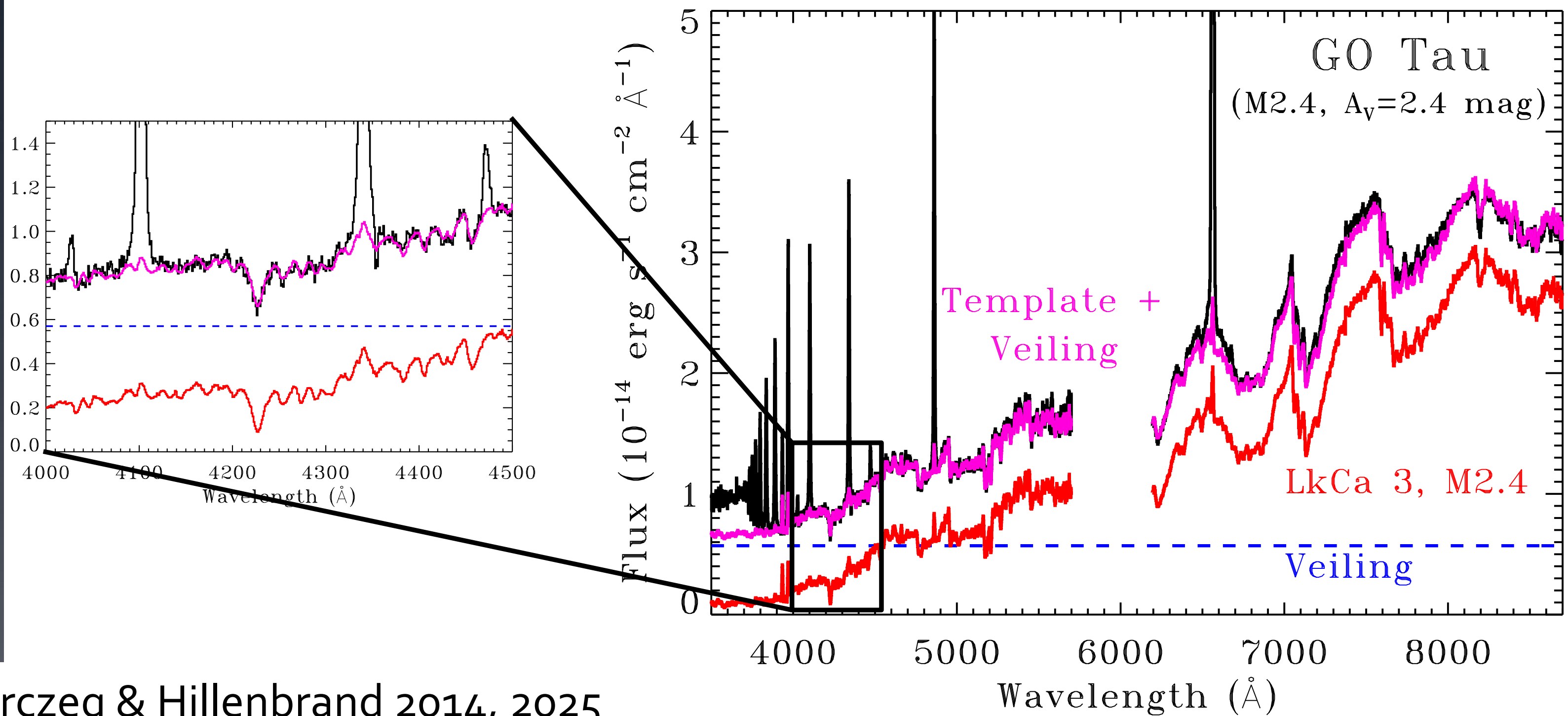


Age spreads in young clusters



Some spread is real (see, eg, Liu Jiaming: older clusters in Taurus), but how much?

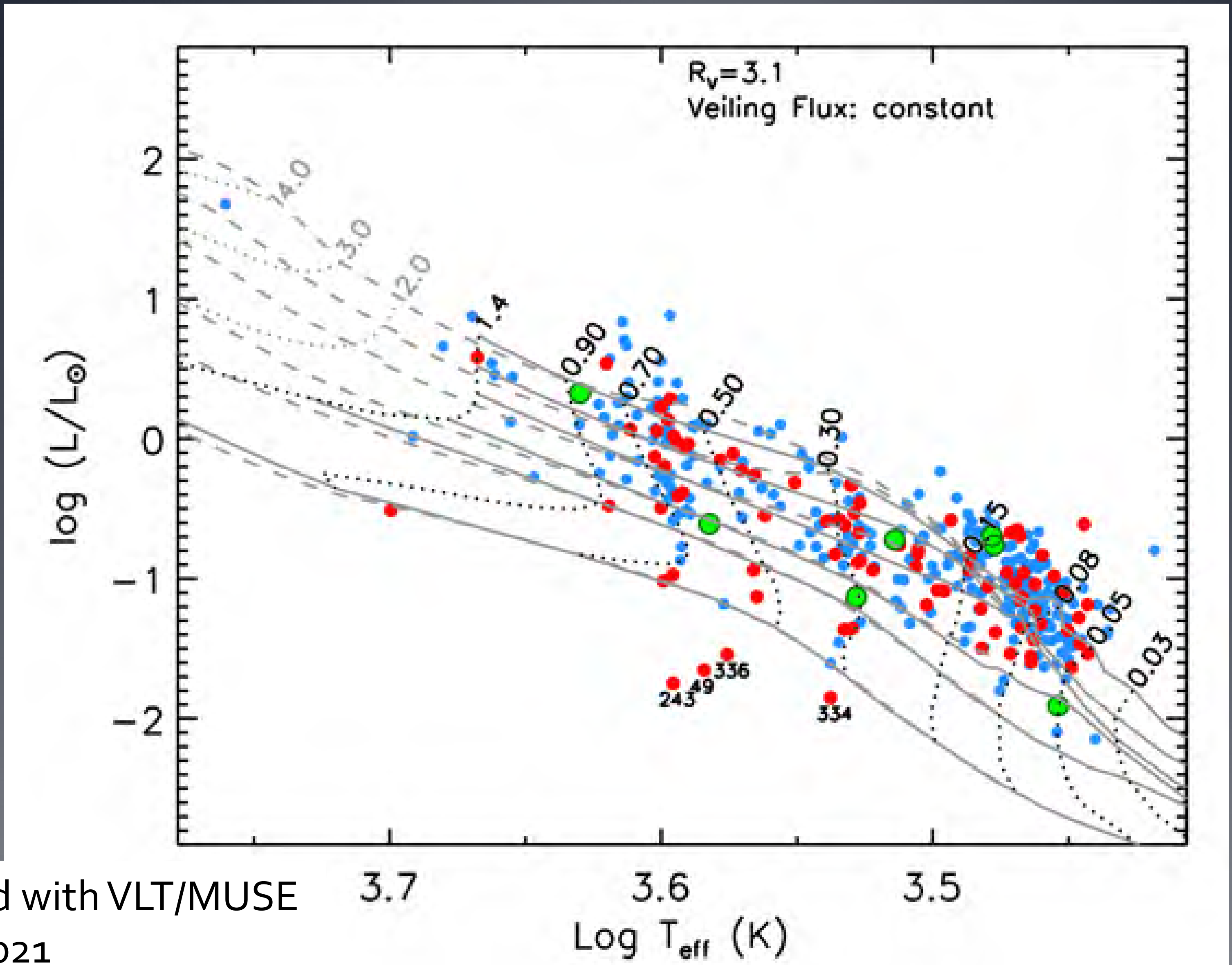
Empirical improvements in HR diagrams



Herczeg & Hillenbrand 2014, 2025

- Measure stellar properties with flux-calibrated optical spectroscopy
    - Simultaneous fit for Teff, Av, accretion rate, photospheric luminosity
    - Herczeg & Hillenbrand 2014/2024; Manara/Alcala+2010s; Fang+2009/2013
- Spreads in HR diagrams persist!

Age spreads in young clusters

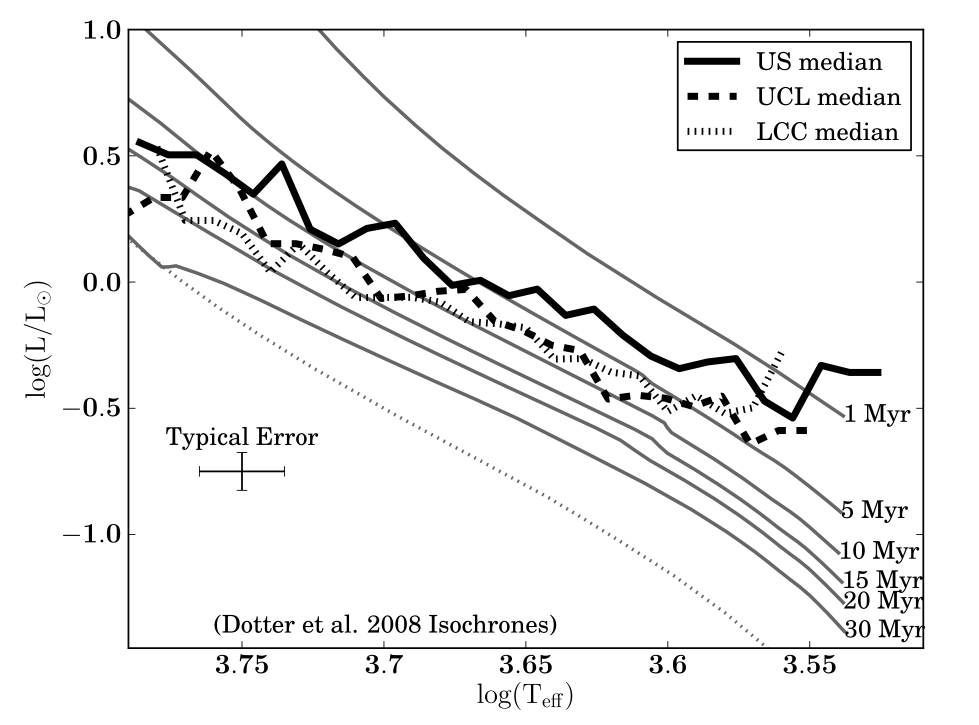


Updated with VLT/MUSE
Fang+2021

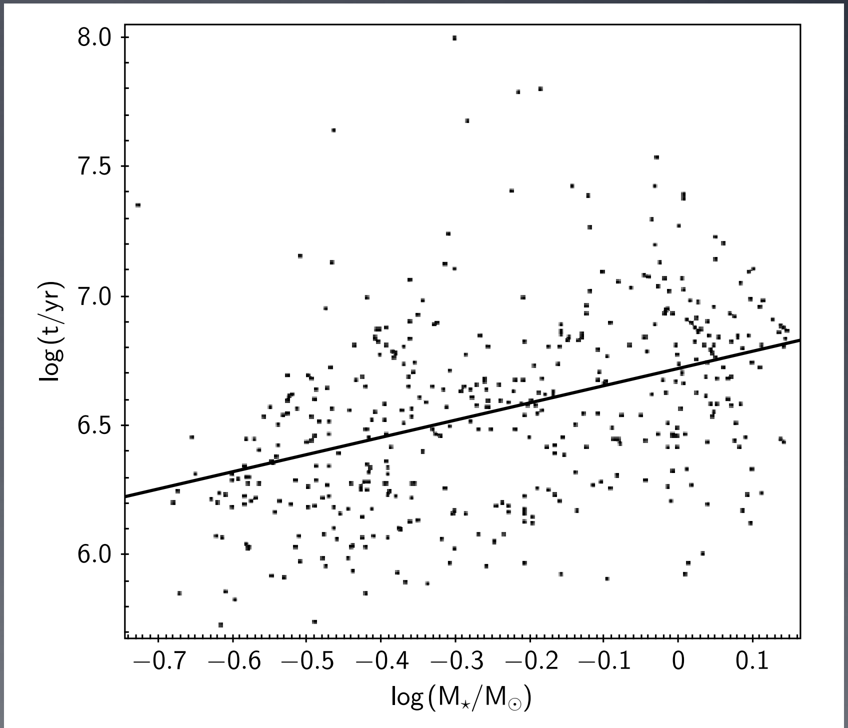
Discrepancies in ages v SpT

Intermediate/high mass stars older than low-mass stars

(e.g., Hillenbrand 1997; Preibisch 2002; Murphy+2013; Herczeg & Hillenbrand 2015)

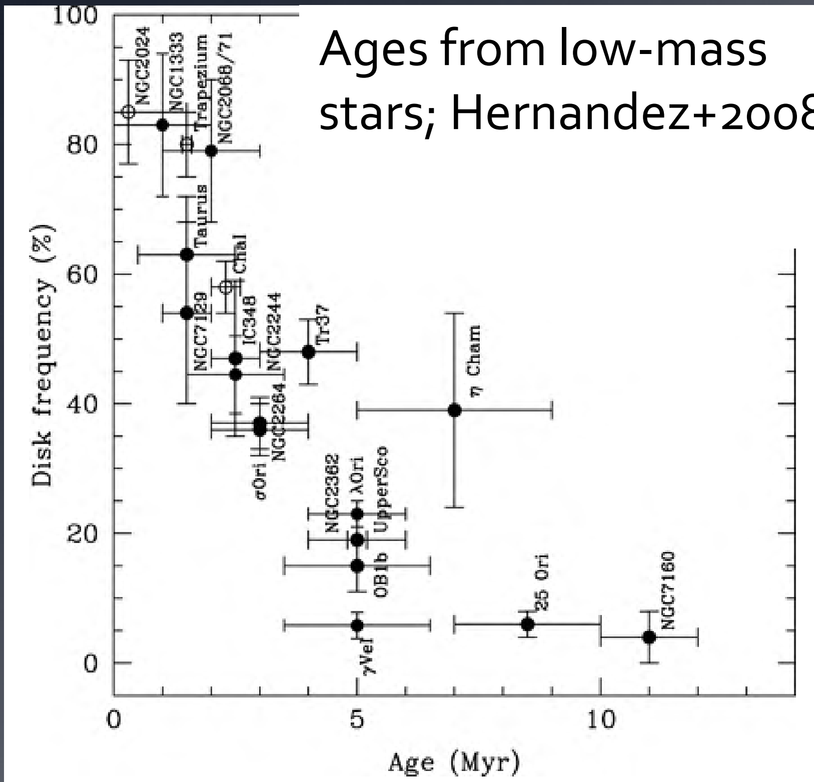


Pecaut+2016

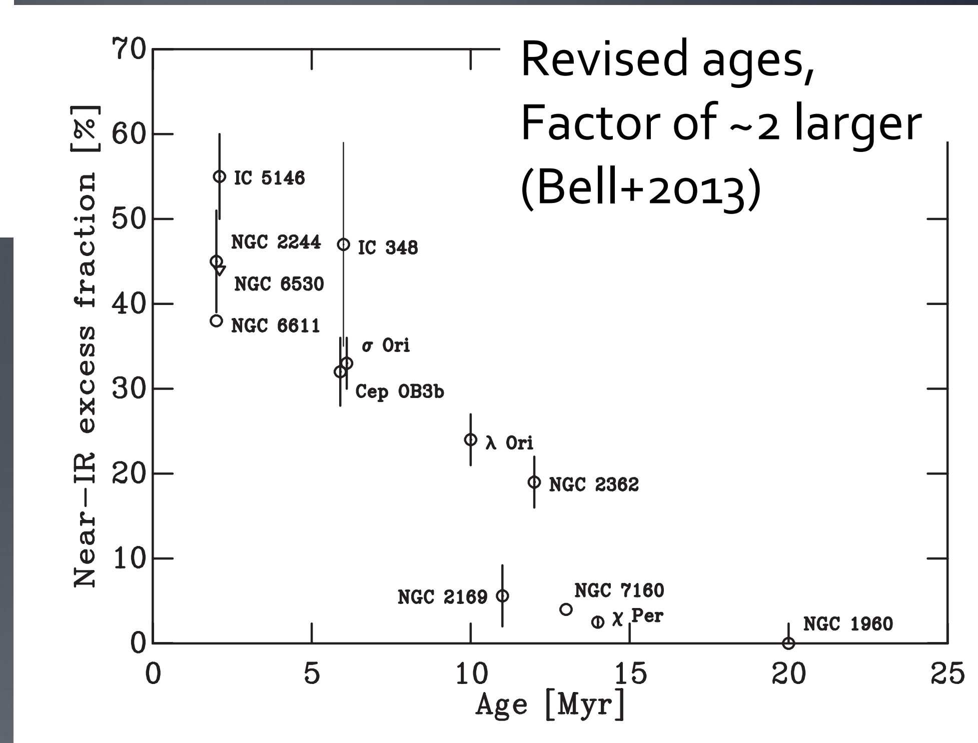


Venuti+2017, Gaia-ESO

Disk survival timescale: 3 Myr or 10 Myr?



Ages from low-mass stars; Hernandez+2008

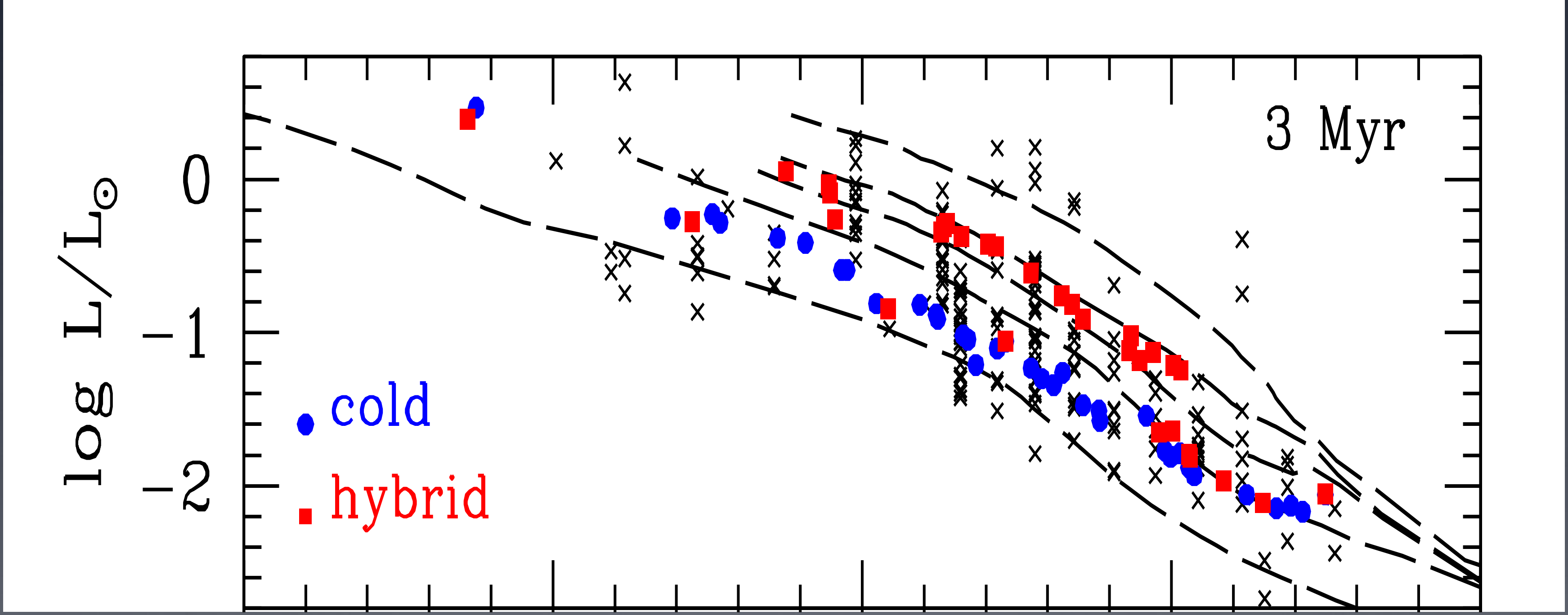


Revised ages, Factor of ~2 larger (Bell+2013)

- Timescale for envelope dispersal
- Star formation history
- Rotational evolution
- Masses of directly-imaged planets

Entropy of star depends on initial size+accretion

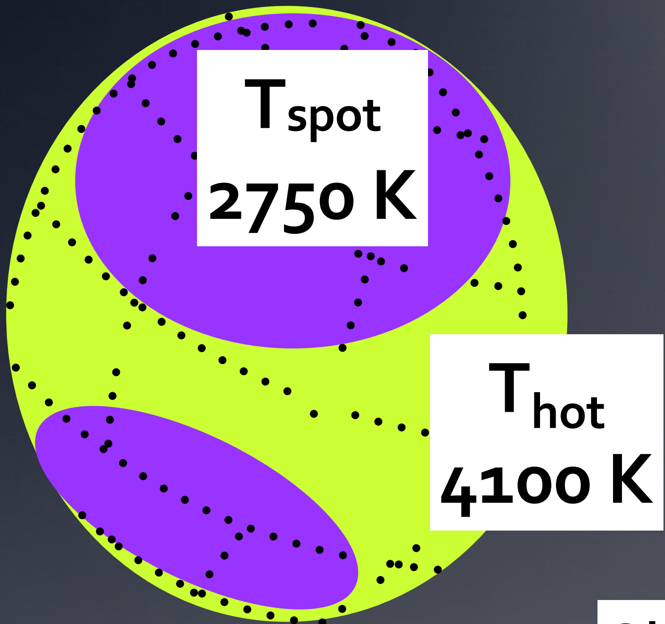
(e.g, Stahler+1980s; Hartmann+1997; Baraffe+2009/2017; Hosokawa+2011; Kunitomo+2017)



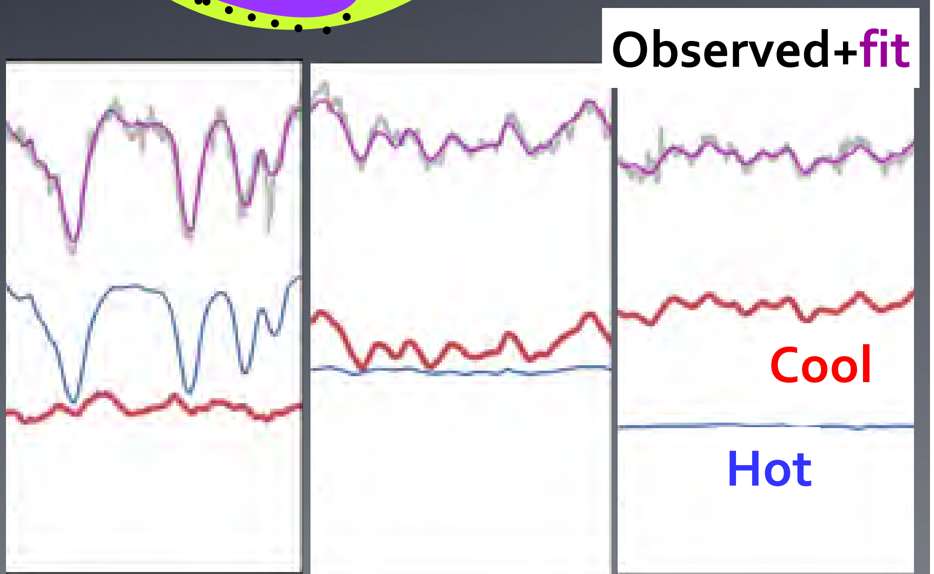
- Need accretion history of the star (JCMT-Transient survey!) + initial core size
- Modest affects/outliers are possible
  - Some age spread (smaller radii)
  - Brown dwarfs appear too young: larger initial core
  - Intermediate mass stars too old: same initial core, more cold accretion

Placing the spotted young star LkCa 4 on the HR diagram

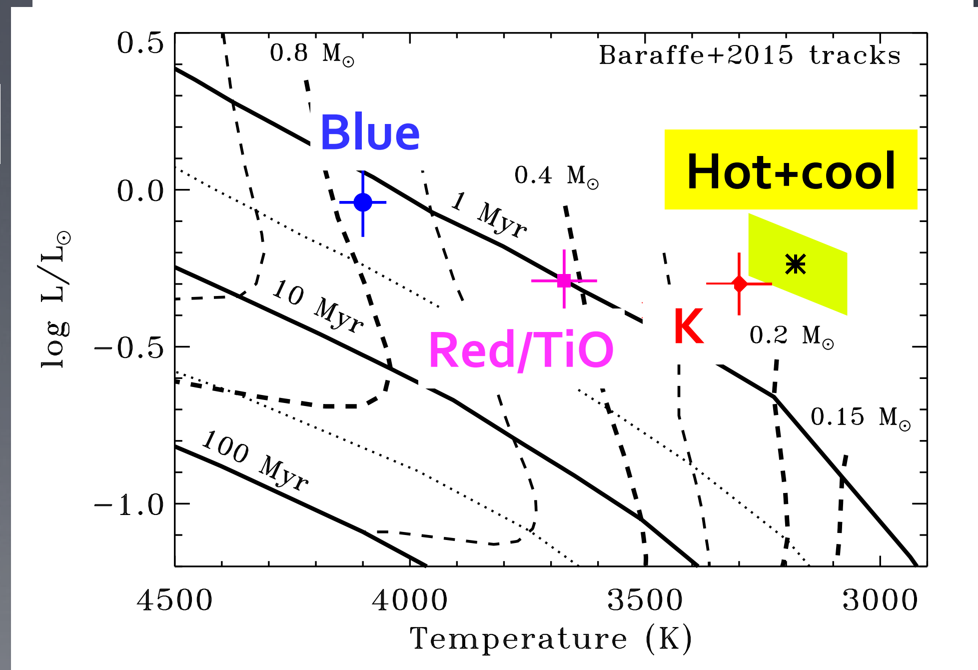
(Gully-Santiago, Herczeg, et al. +2017 TAP result, using STARFISH from Czekala+2015)



Two temperature fit: 4000, 2750 K
Fill factor of cool component: 80%

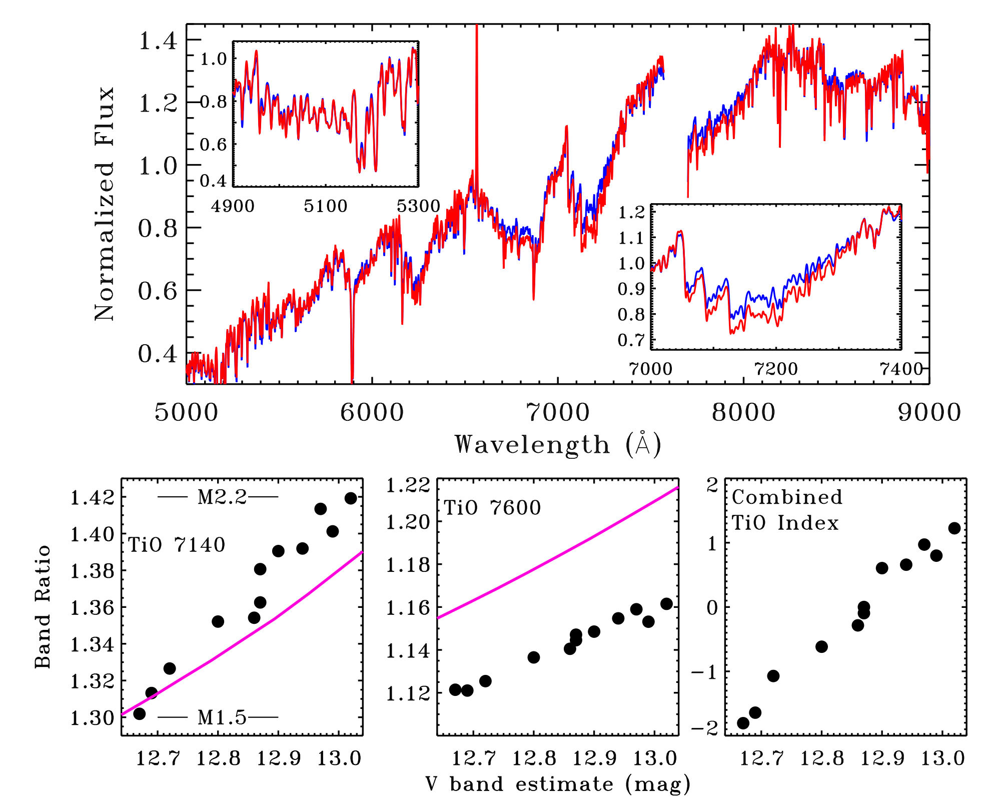


Example fits to segments of high-res IGRINS H+K spectra

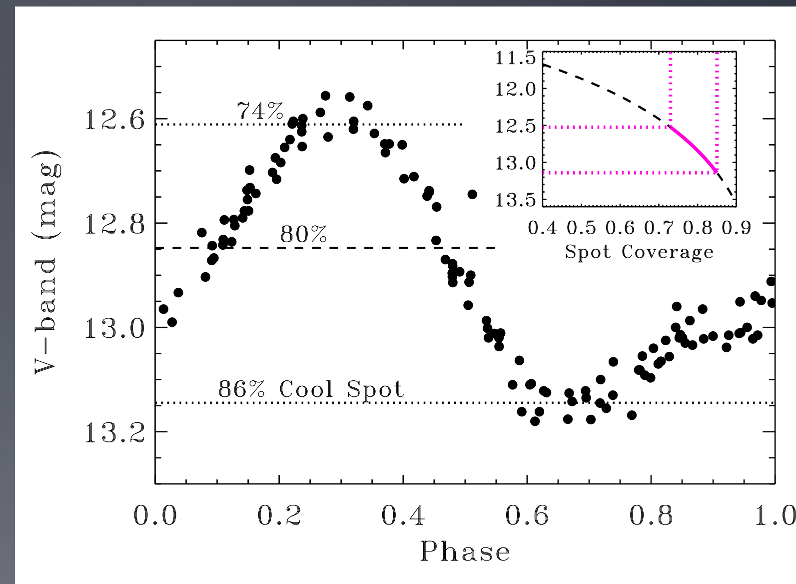


What does Teff mean?
Are we getting them all wrong?

Optical spectroscopic and photometric variability: confirms large spots (Gully-Santiago, Herczeg+2017; TAP)



CFHT/ESPaDOnS spectra
Supported by TAP



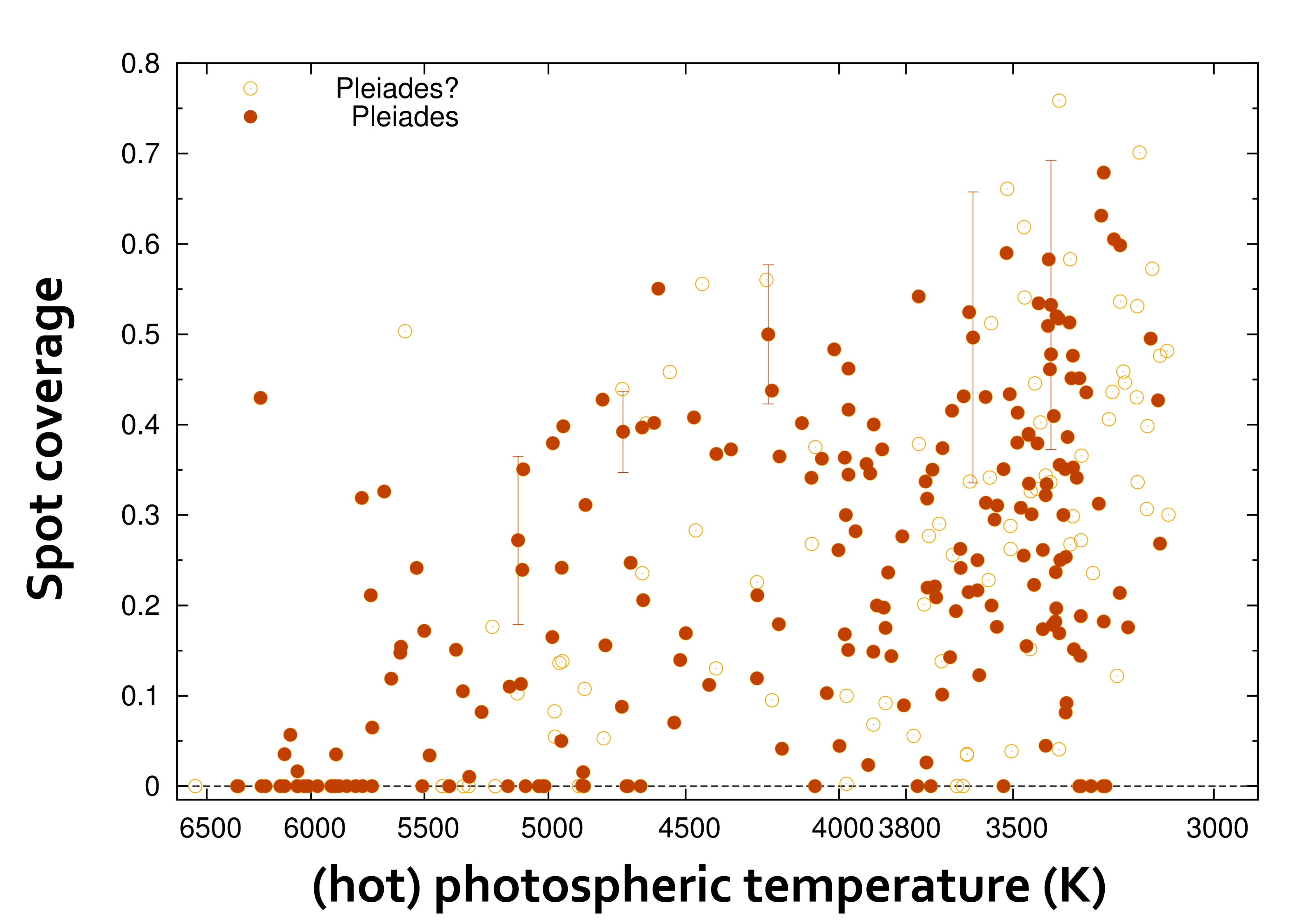
ASAS-SN lightcurve

TiO variability versus V (simulated, not fit)

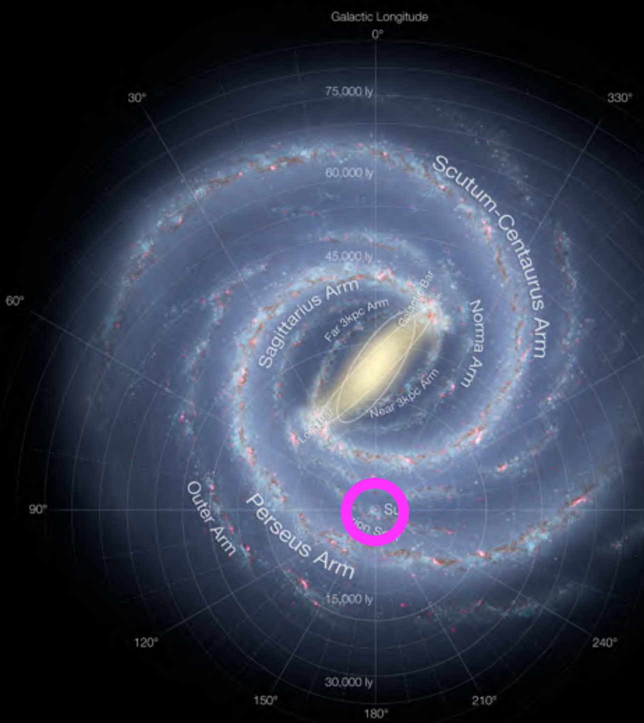
See also, Bouvier+1992; Herbst+1994; Petrov+1994; Grankin+2008; Debes+2013; Jackson & Jeffries 2014; Bary+2014; others

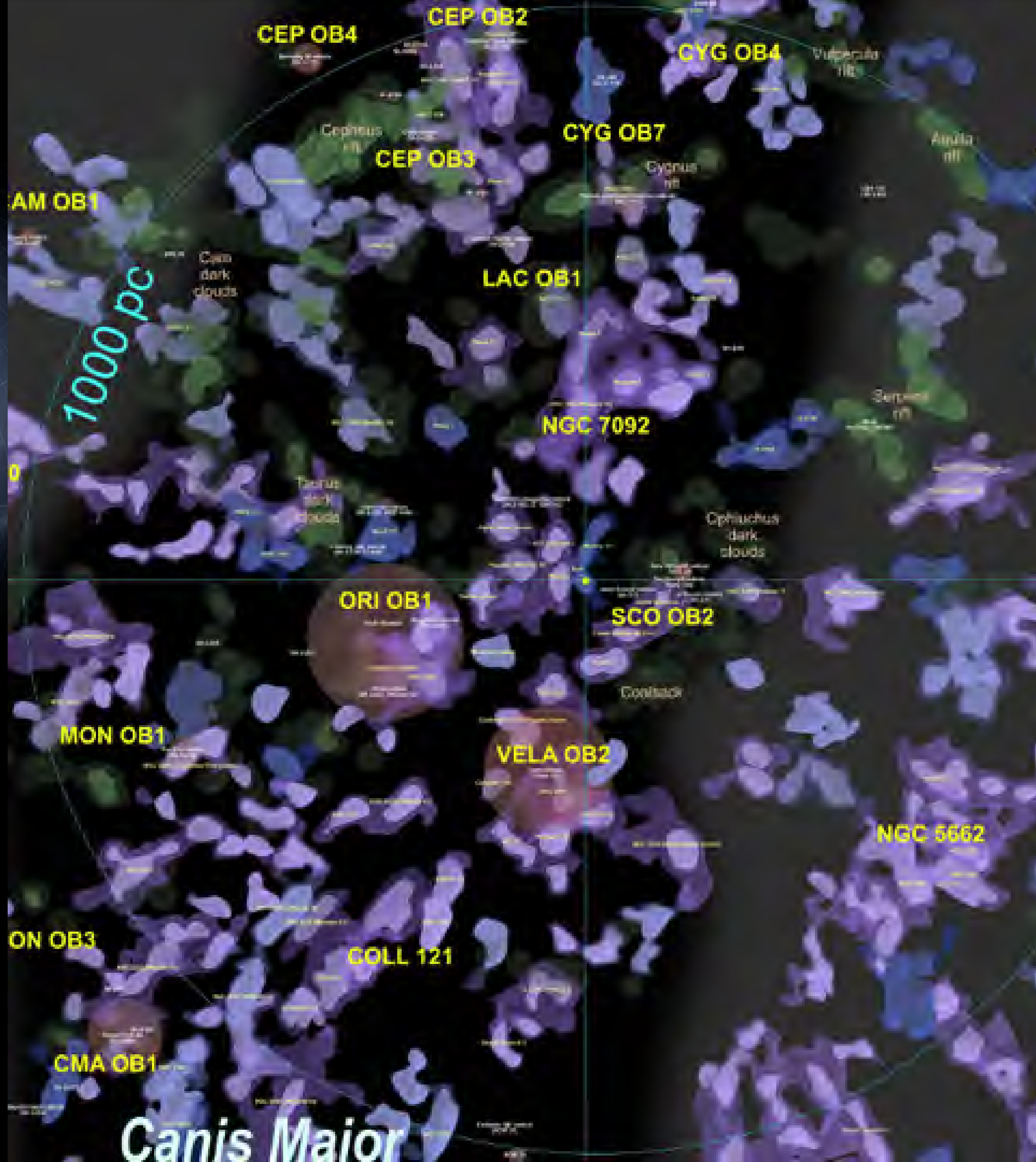
LAMOST: Spots in the 125 Myr Pleiades

(Fang et al. 2016)

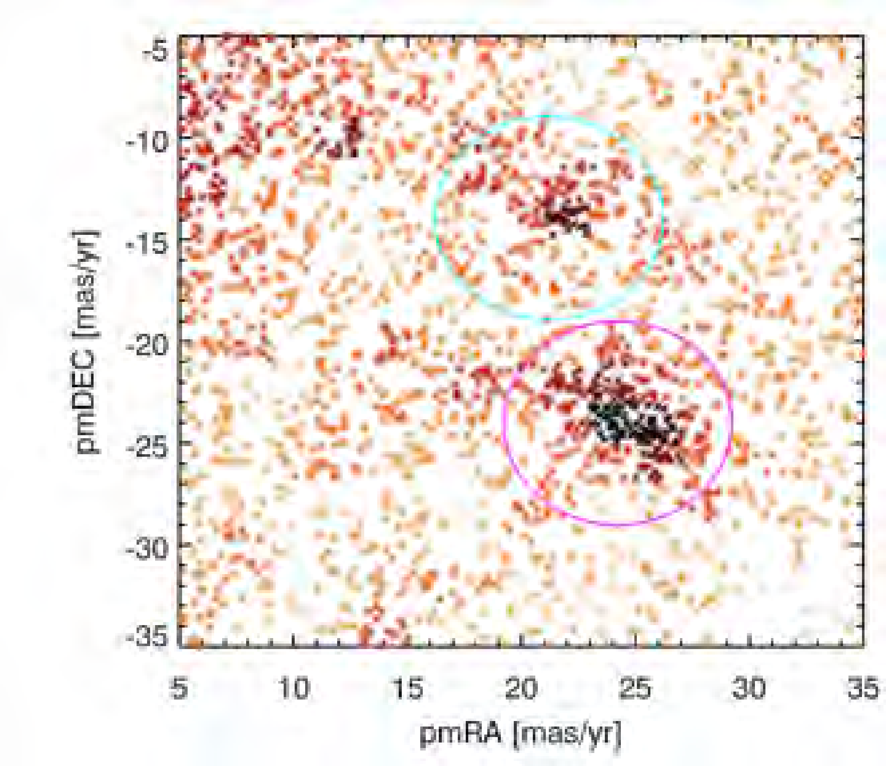


Gaia and prospects for pre-main sequence evolution and our local star formation history

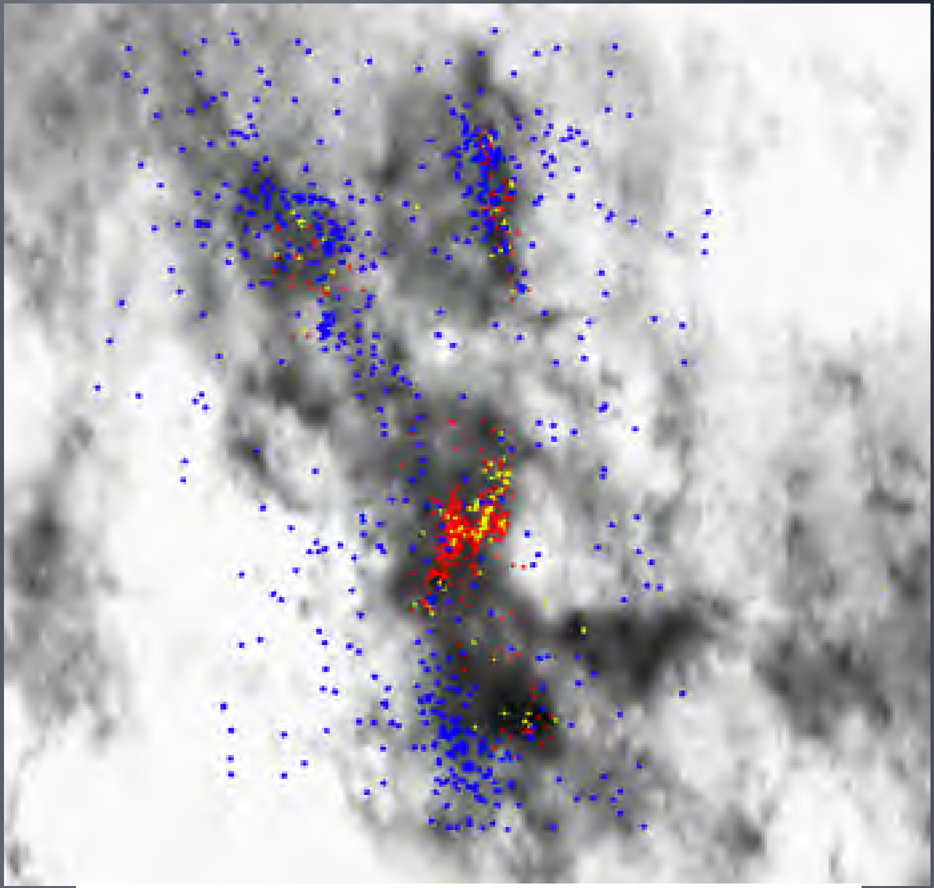




GalaxyMap plus
dozens of papers,
eg, Cantat-Gaudin+2018
Kounkel+2019



Liu, Jiaming, et al. 2020: new young clusters in Taurus, past epoch of star formation?



Herczeg, Kuhn+2019 in Serpens: several bursts over ~100 pc

<u>In addition to our local star formation history</u>

Masses: dynamical orbits of binaries

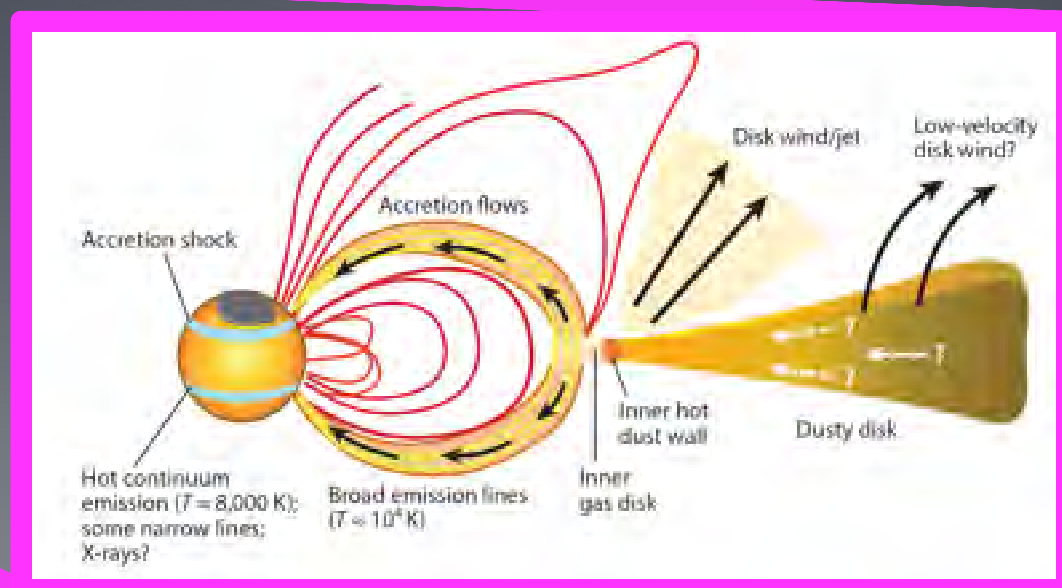
Ages: dynamical evolution of clusters

ODYSSEUS: archival HST program to analyze UV spectroscopy of accretion young stars from ULLYSES Legacy program

(PI Herczeg, co-PI Espaillat)

ULLYSES: DDT Legacy Program from HST

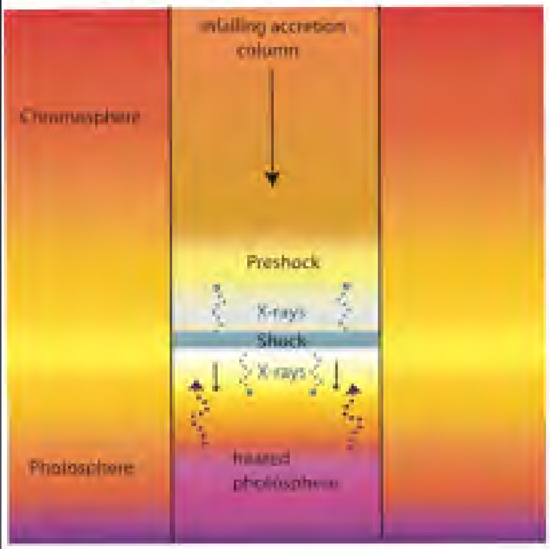
- 500 orbits, FUV-optical spectroscopy of young stars
- Disk accretion, accretion-driven winds, disk surface



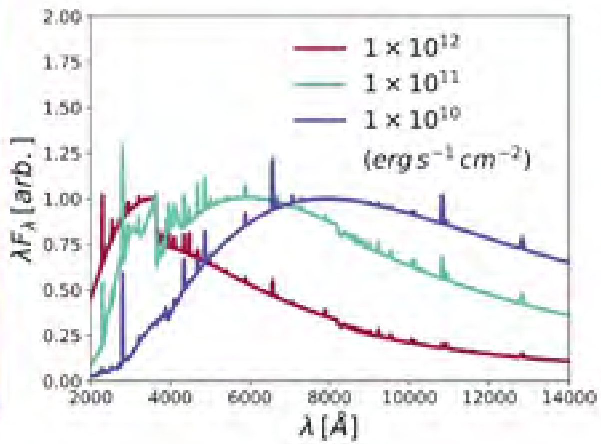
ODYSSEUS: archival HST program to analyze UV spectroscopy of accretion young stars from ULLYSES Legacy program

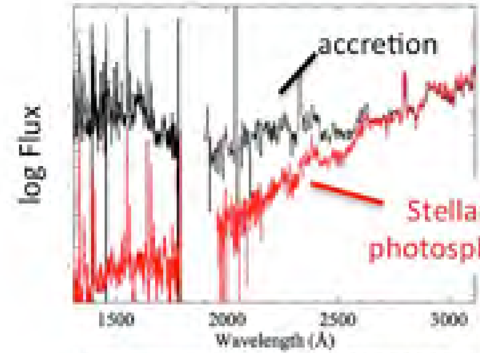
(PI Herczeg, co-PI Espaillat)

Shock structure

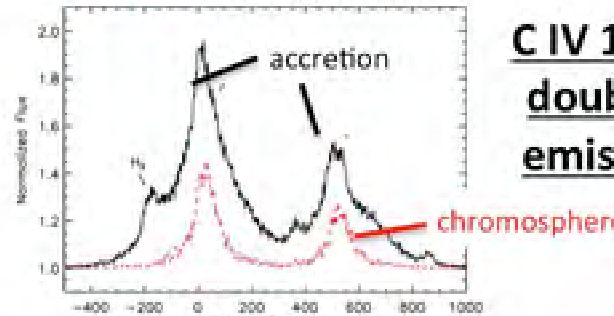


Model spectra of multi-column accretion flows

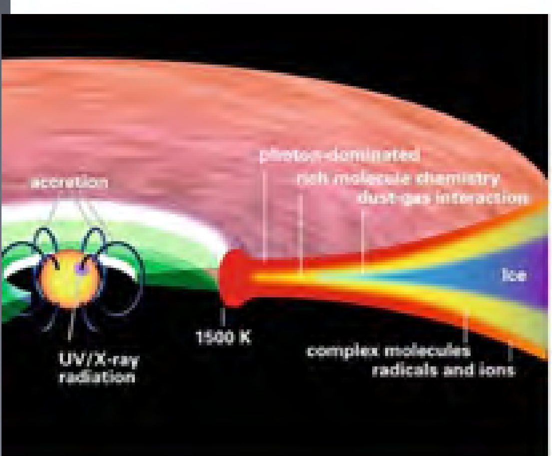


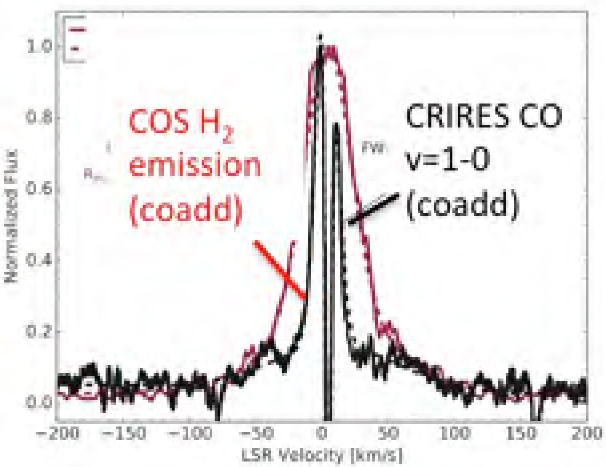


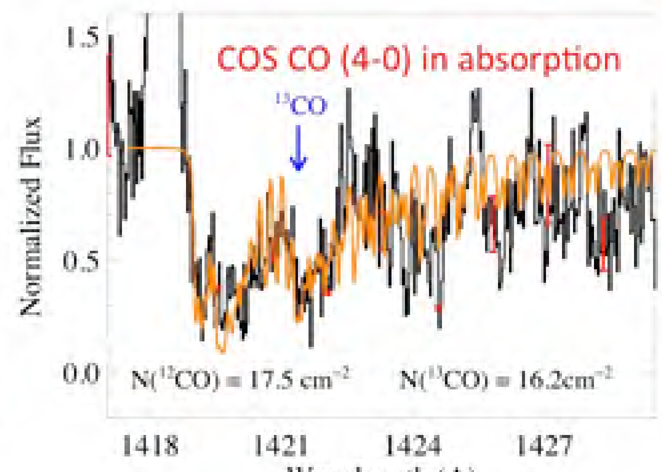
Accretion continuum



C IV 1548 doublet emission

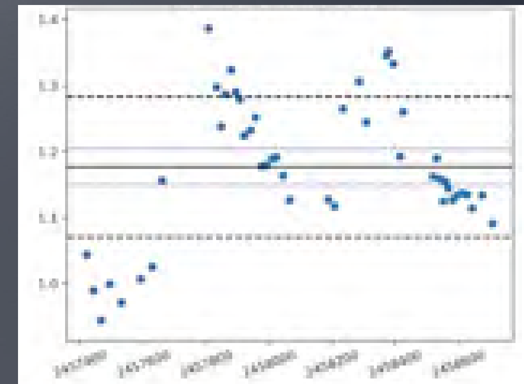


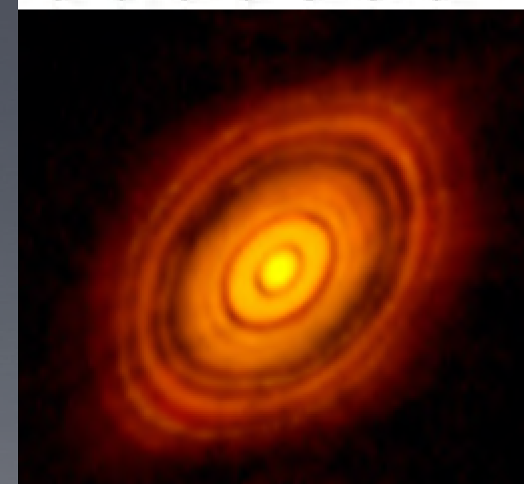


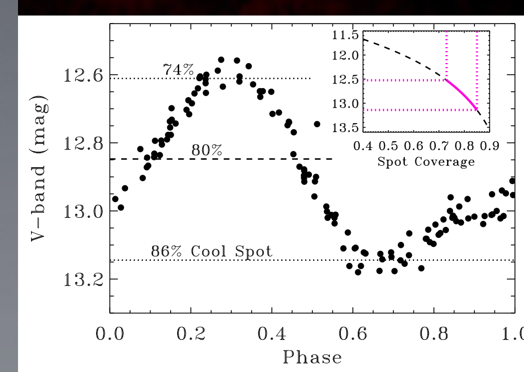


Protostars, disks, spots, and star formation histories

- First long-term sub-mm monitoring program
  - Variable sub-mm emission from protostars
- ALMA: driving an amazing revolution in disk physics and planet formation
  - We may be detecting planets in formation!
- Pre-main sequence evolutionary models are uncertain (mass, age)
  - Limits understanding of disk evolution and star formation history
  - Spots: uncertainty for low-mass stars







gherczeg1@gmail.com