From protostars to adolescence: A tour of young stellar systems

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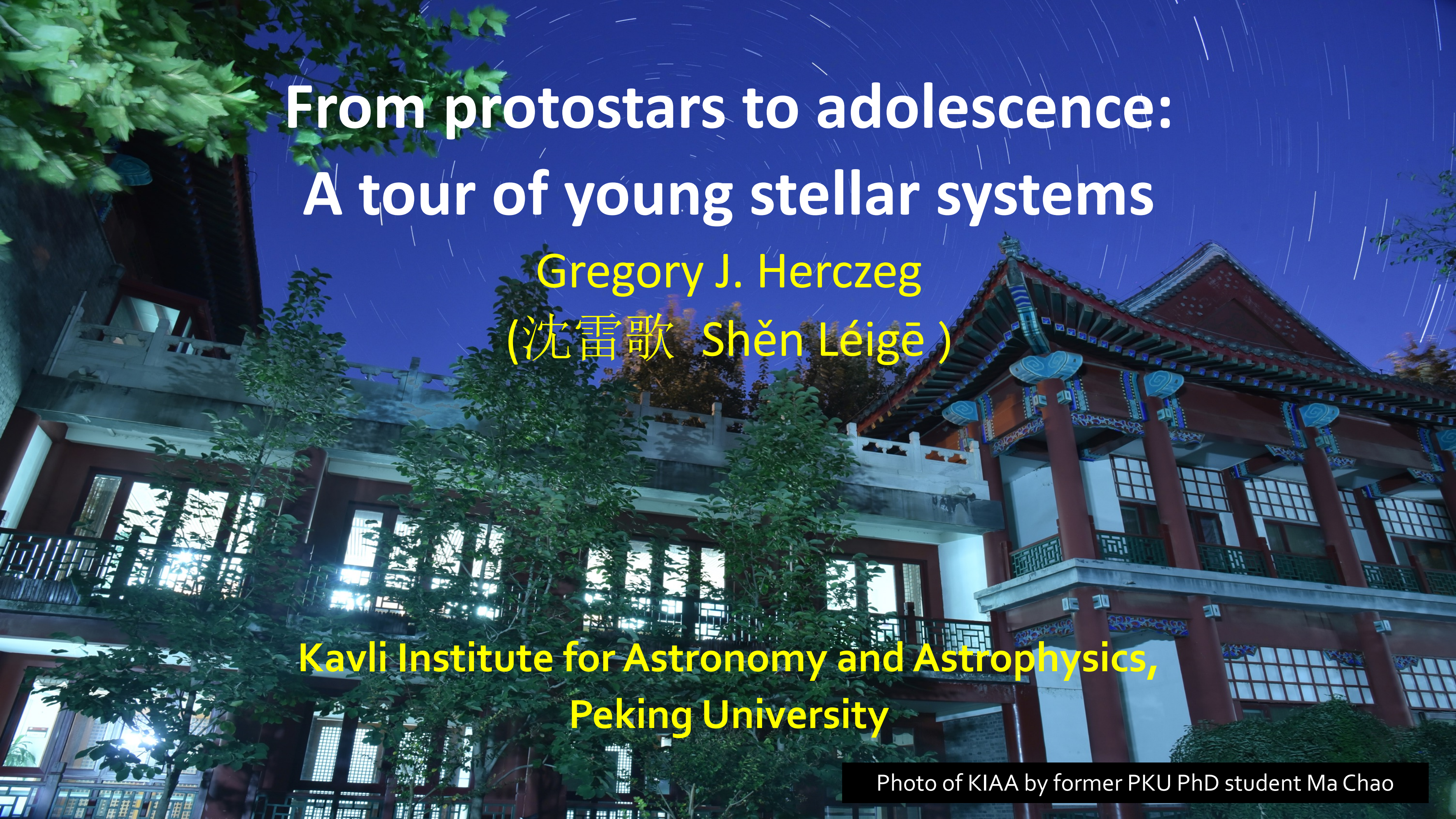

Photo of KIAA by former PKU PhD student Ma Chao


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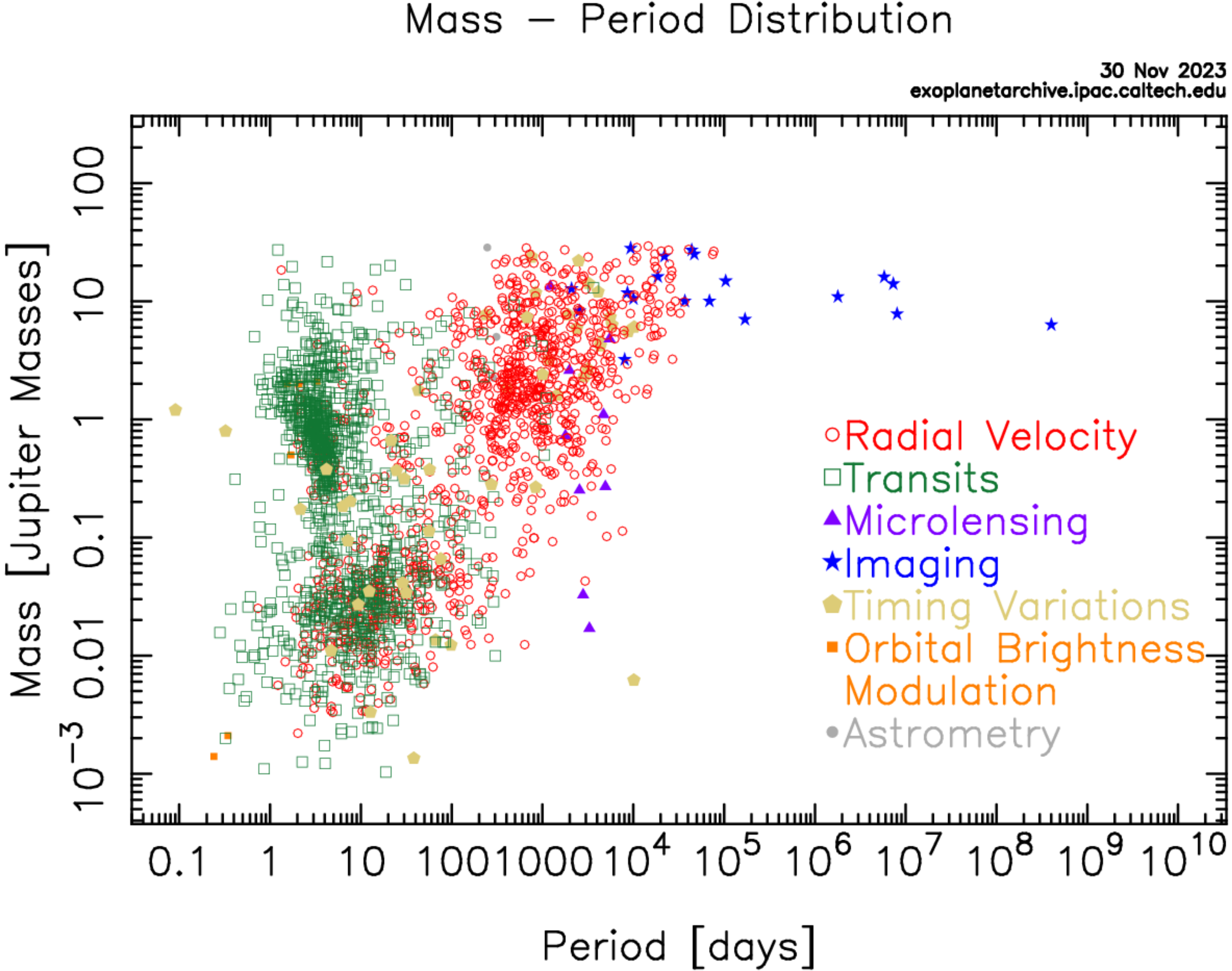
科维理天文与天体物理研究所
Kavli Institute for Astronomy and Astrophysics
Peking University Astronomy Family Photo
October 26, 2018

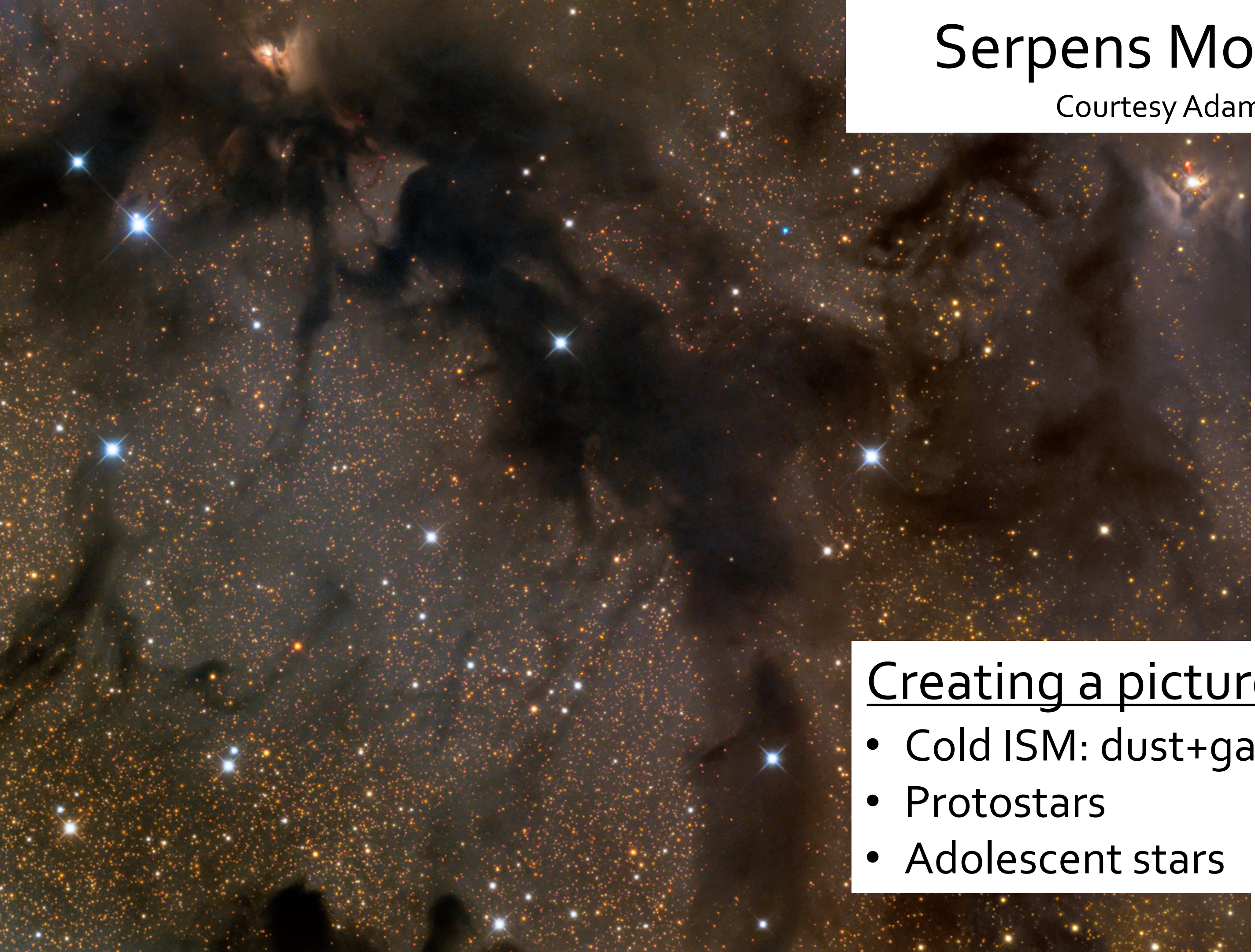


NASA exoplanet archive

The last astrophysical step of our origins

Serpens Molecular Cloud

Courtesy Adam Block via APOD



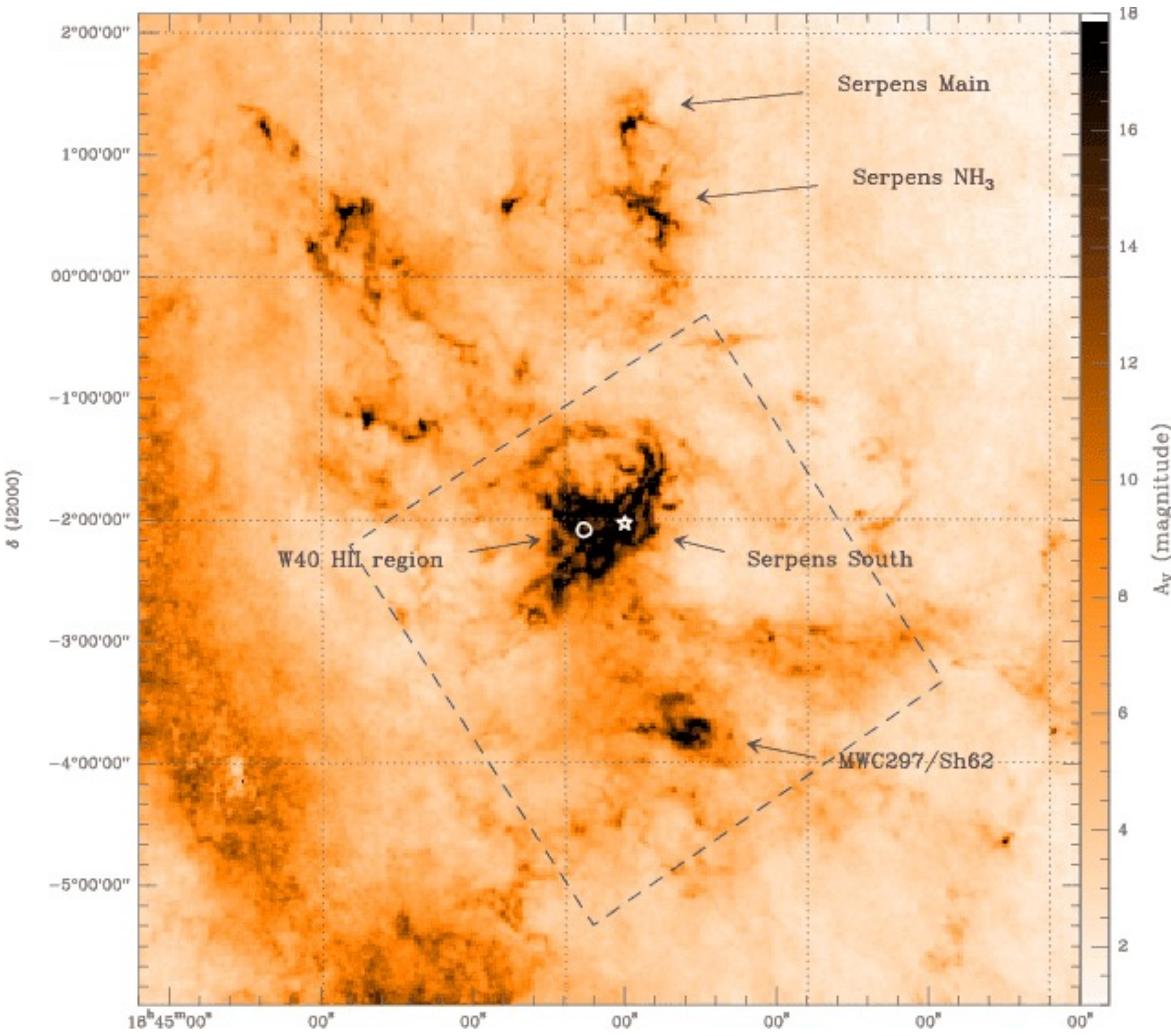
Creating a picture of star formation

- Cold ISM: dust+gas
- Protostars
- Adolescent stars

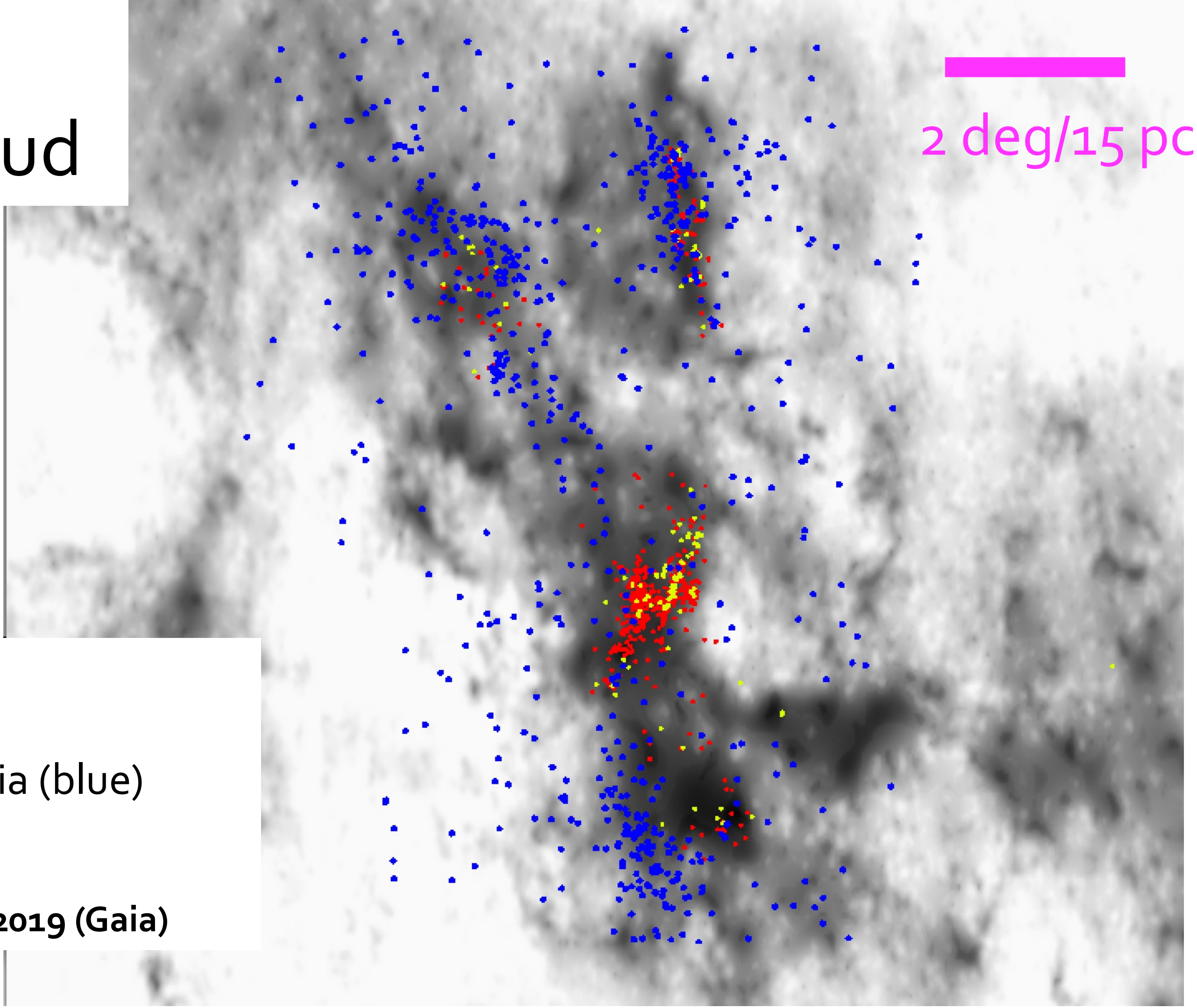
Serpens Molecular Cloud

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

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

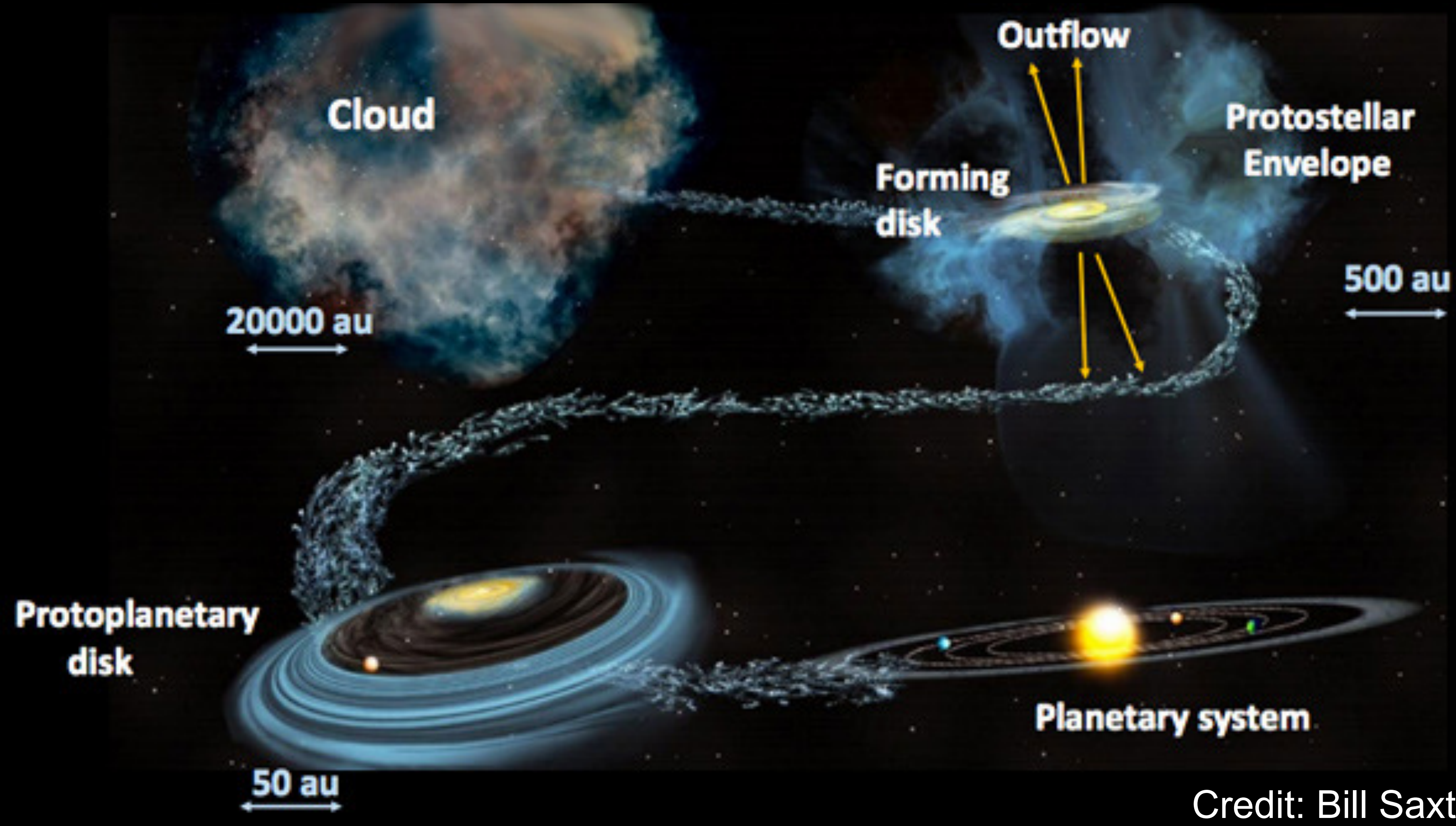


Serpens Molecular Cloud



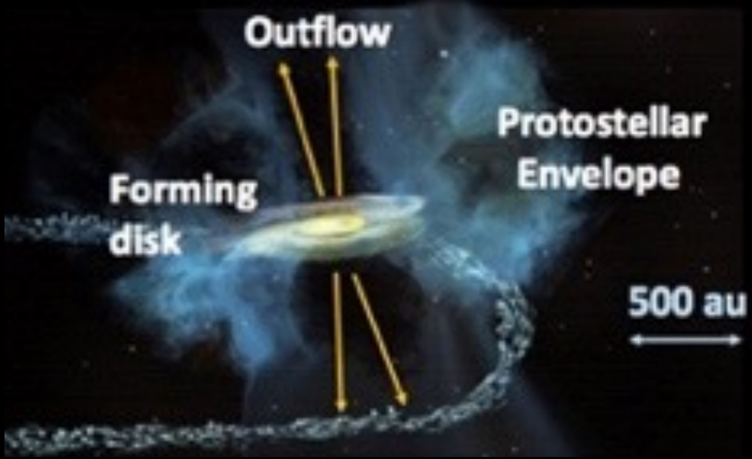
Protostars (yellow)
disks (red)
Optical members from Gaia (blue)

Kuhn+2010; Povich+2013;
Dunham+2015, **Herczeg et al. 2019 (Gaia)**



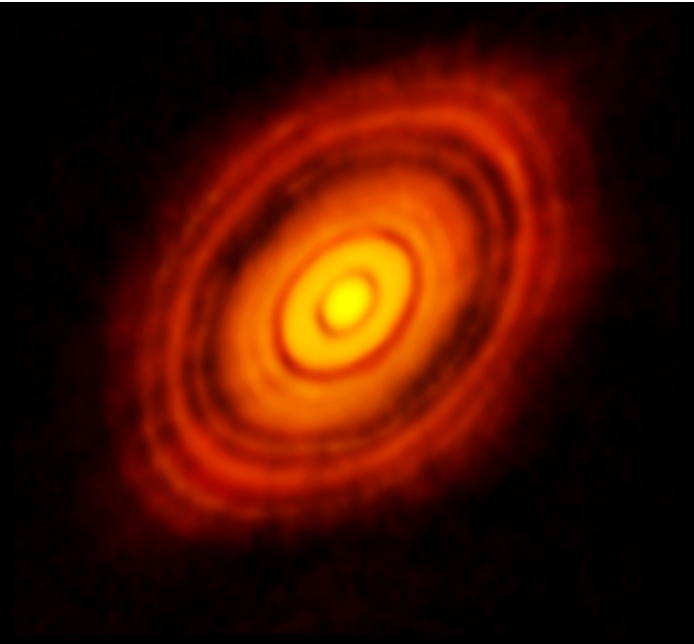
Credit: Bill Saxton

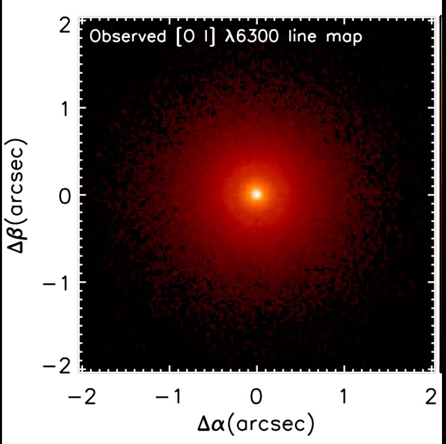
JWST image of protostar L1527



ALMA Image of HL Tau disk

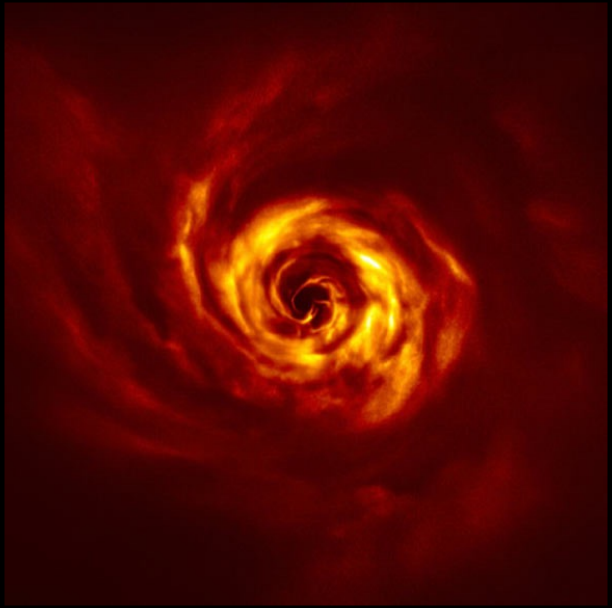
(cold dust, ALMA Partnership et al. 2015)





VLT MUSE image of [O I] in a disk

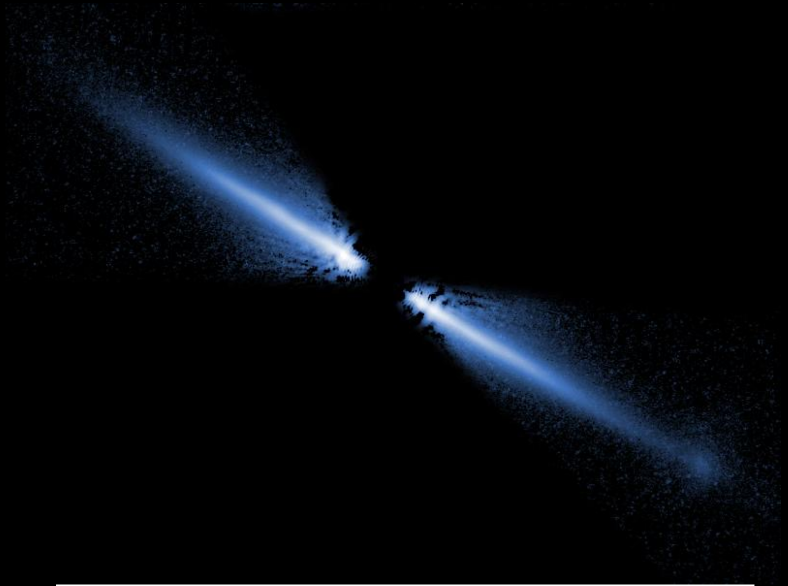
Fang, Wang, Herczeg, et al., NatAs, 2023



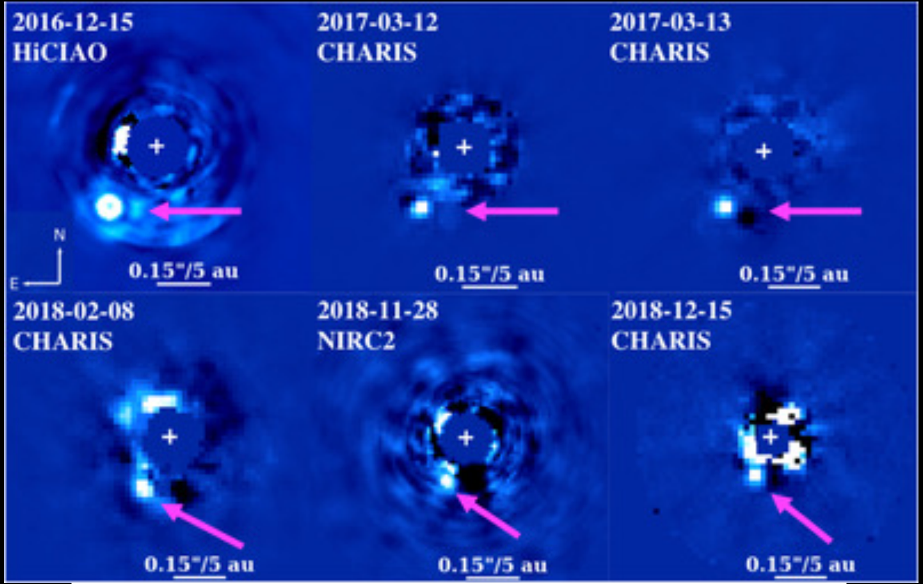
VLT/SPHERE image of scattered light;

Boccalletti+2019

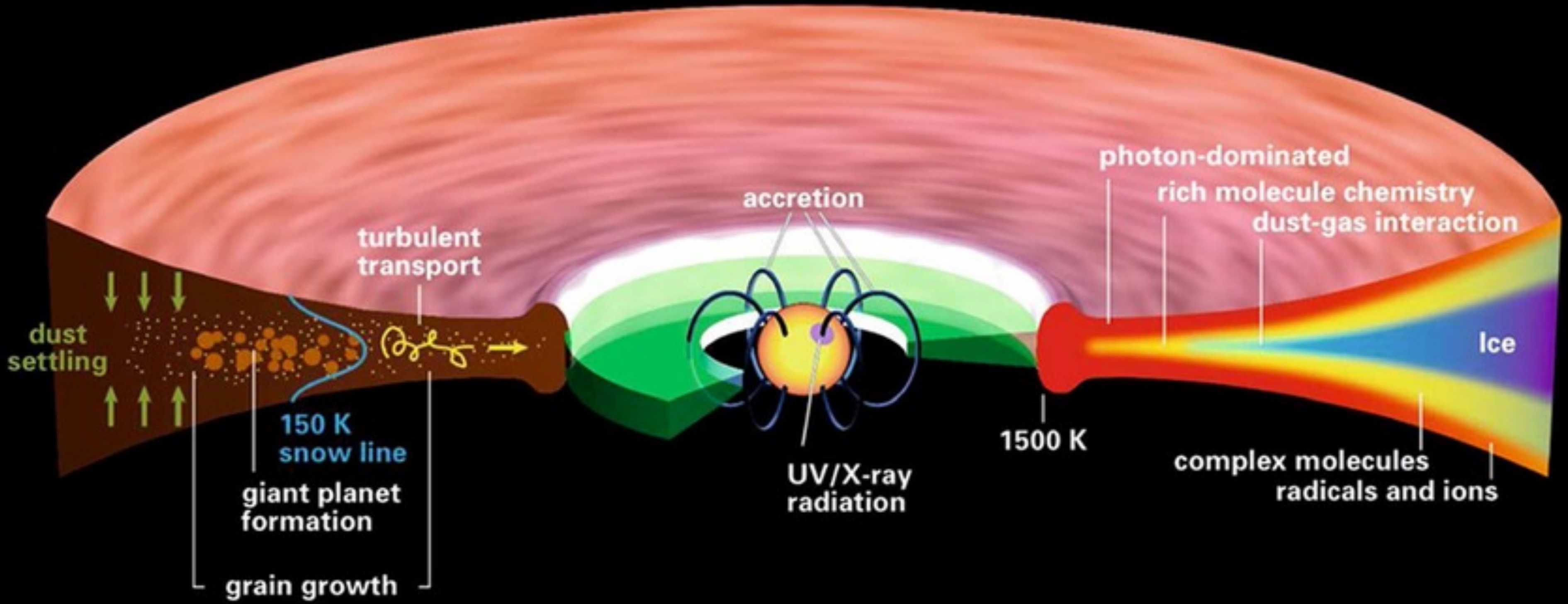
Young stars after disk dissipation: debris disks and targets for giant planet searches



HST scattered light image of AU Mic
Kalas et al. 2004

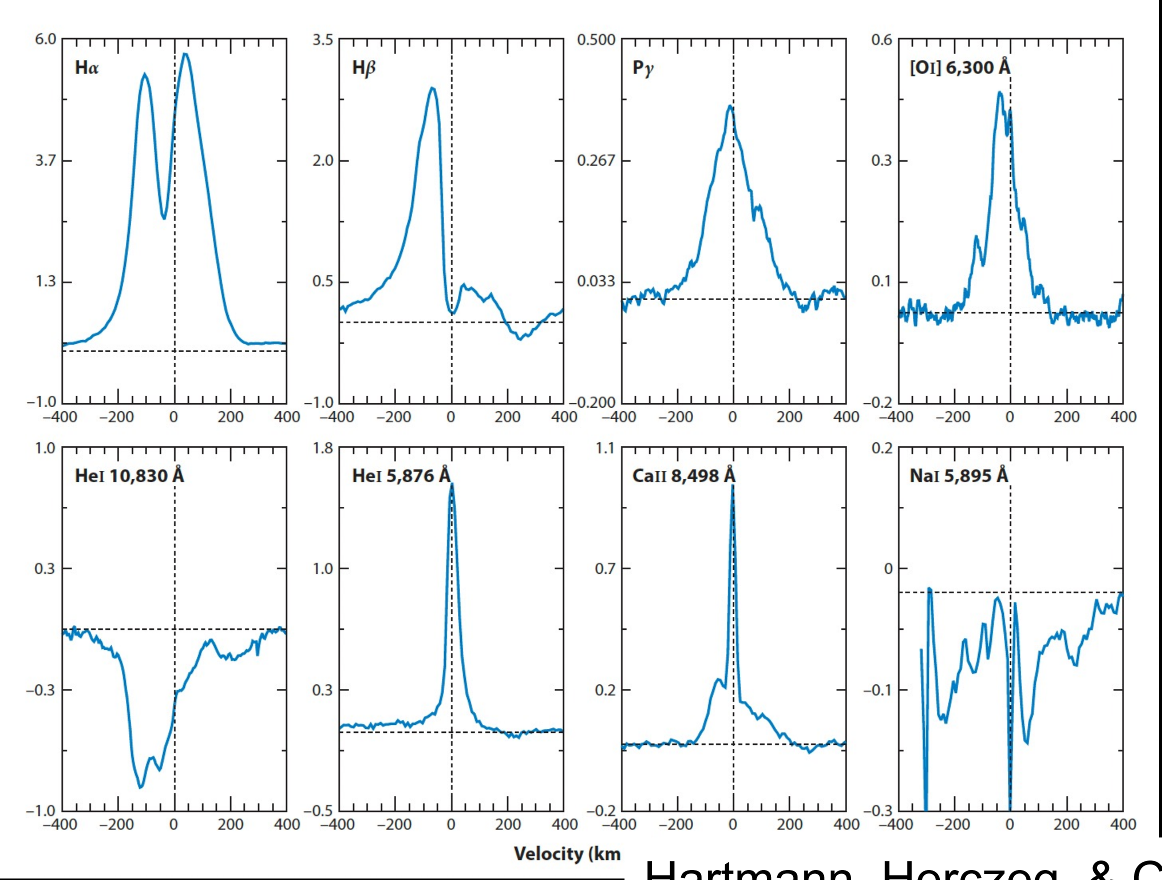


Chilcote et al. 2021:
searching for exoplanets with direct imaging

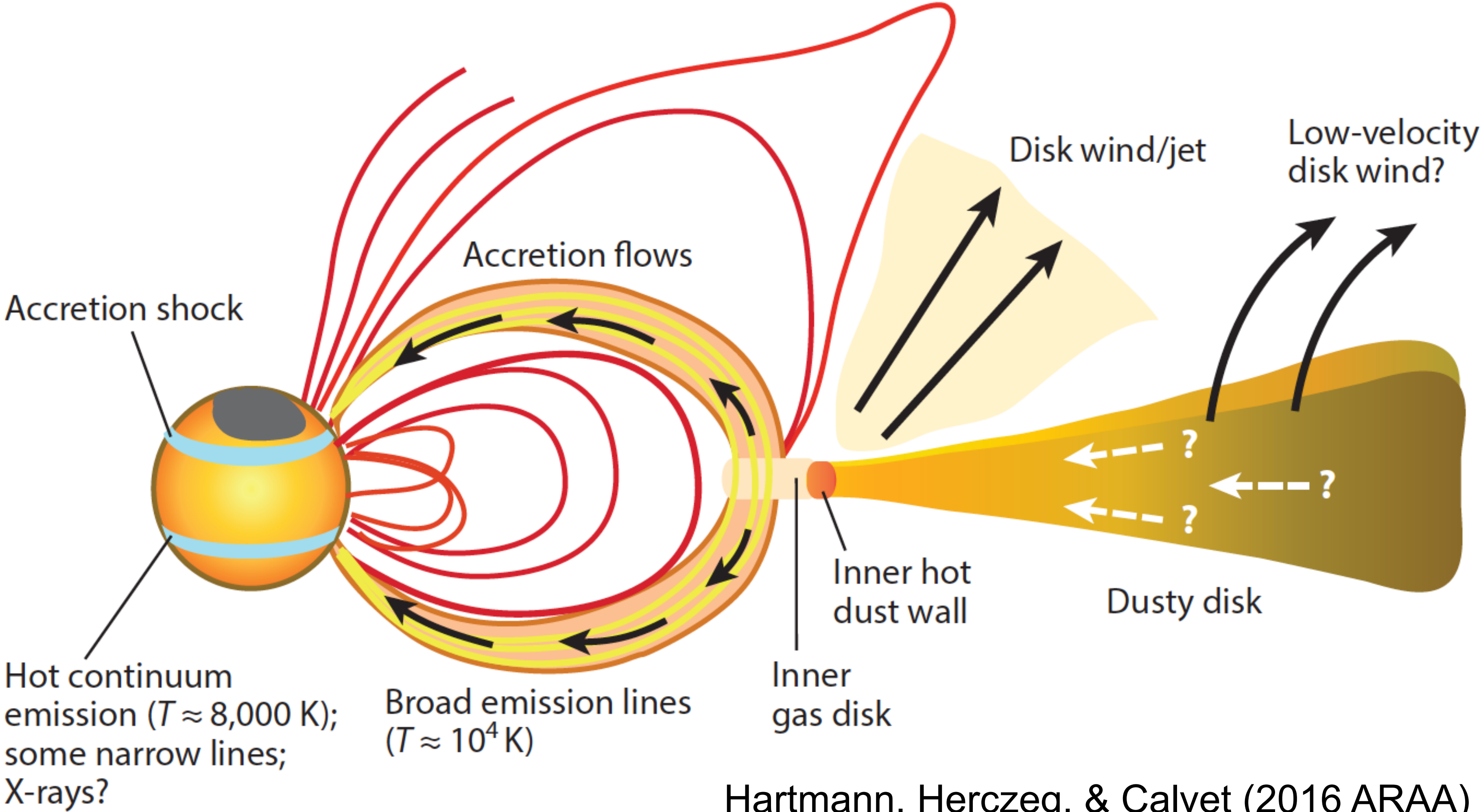


Henning & Semenov (2013)

Spectroscopy: structures from dynamics

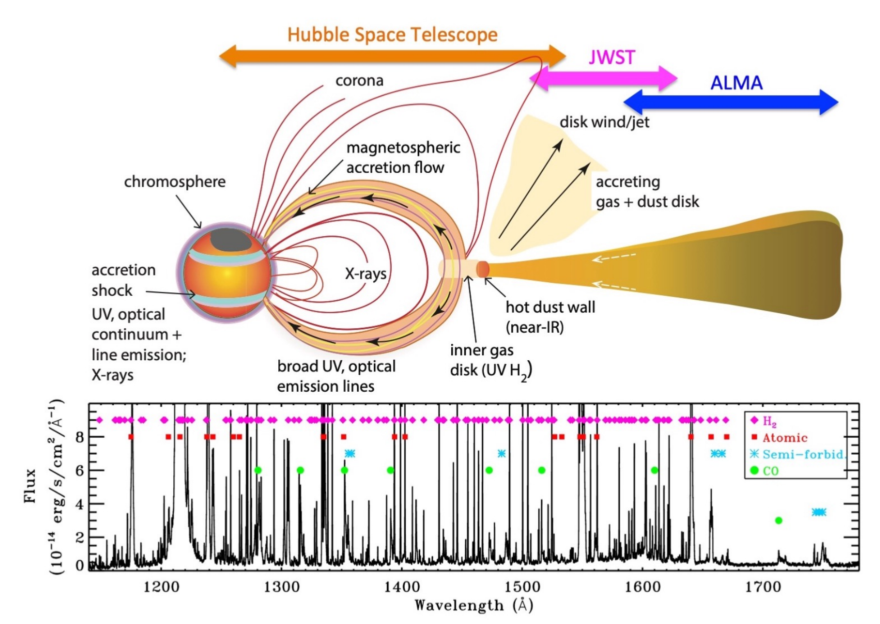


Hartmann, Herczeg, & Calvet (2016 ARAA)



Hartmann, Herczeg, & Calvet (2016 ARAA)

ODYSSEUS



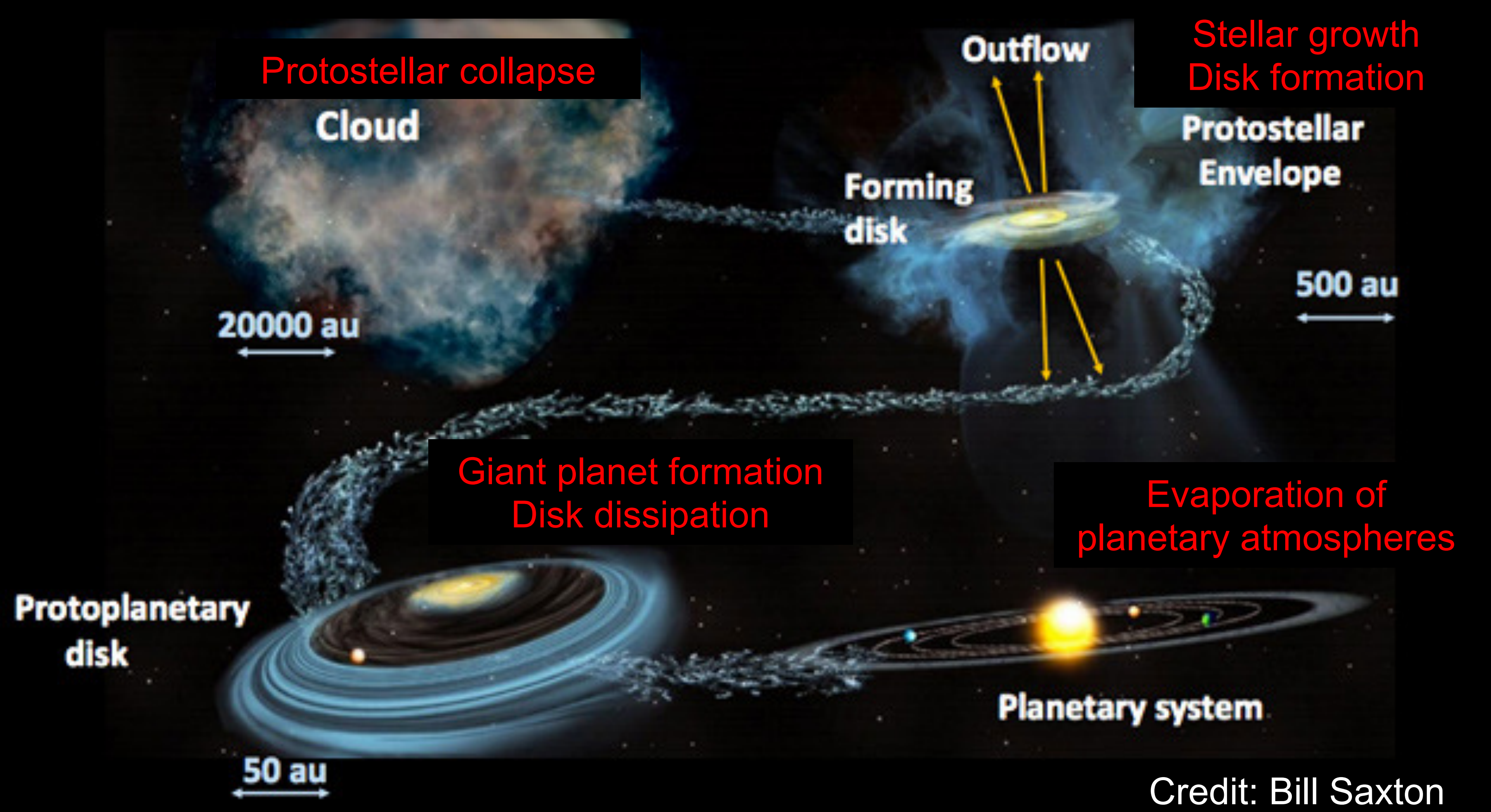
ODYSSEUS: archival HST program to analyze ULLYSES UV spectra of accreting young stars

(PI Herczeg, co-PI Espaillat)

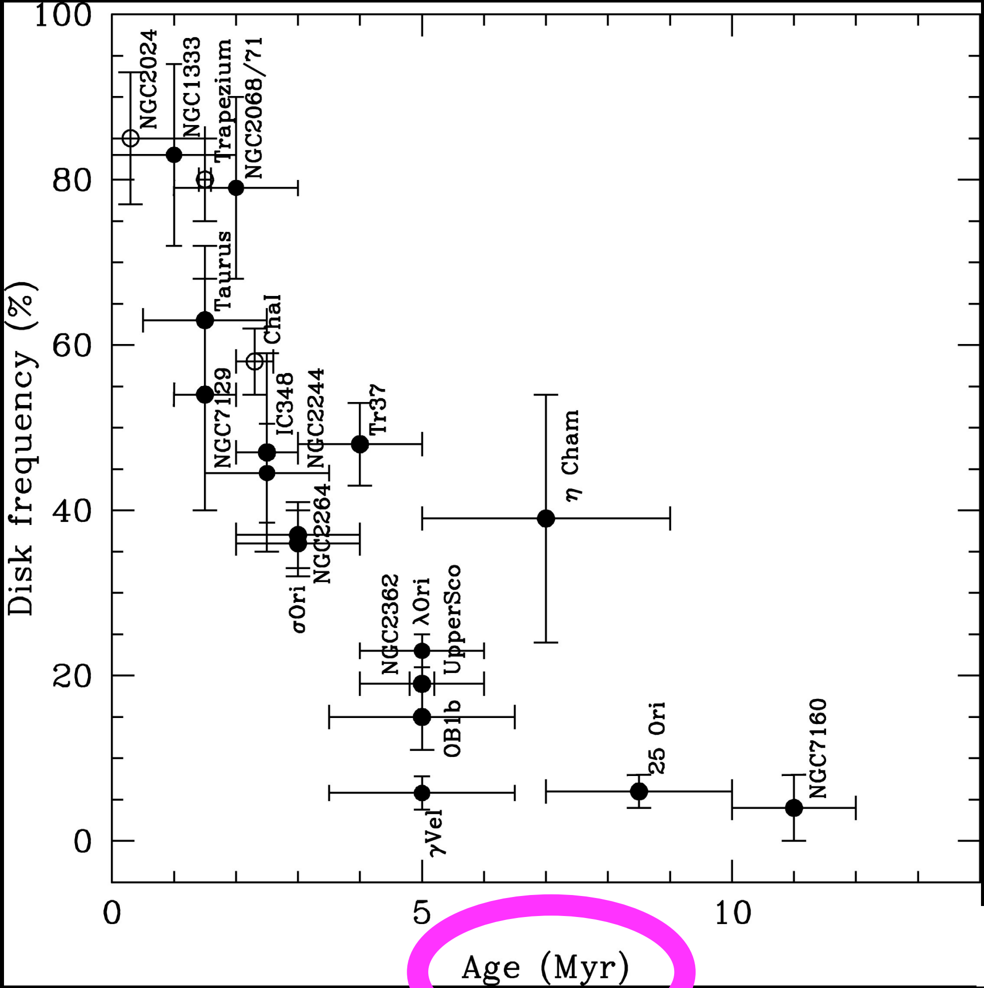
VLT Large Program PENELLOPE (PI Manara)

ULLYSES: DDT Legacy Program from HST

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



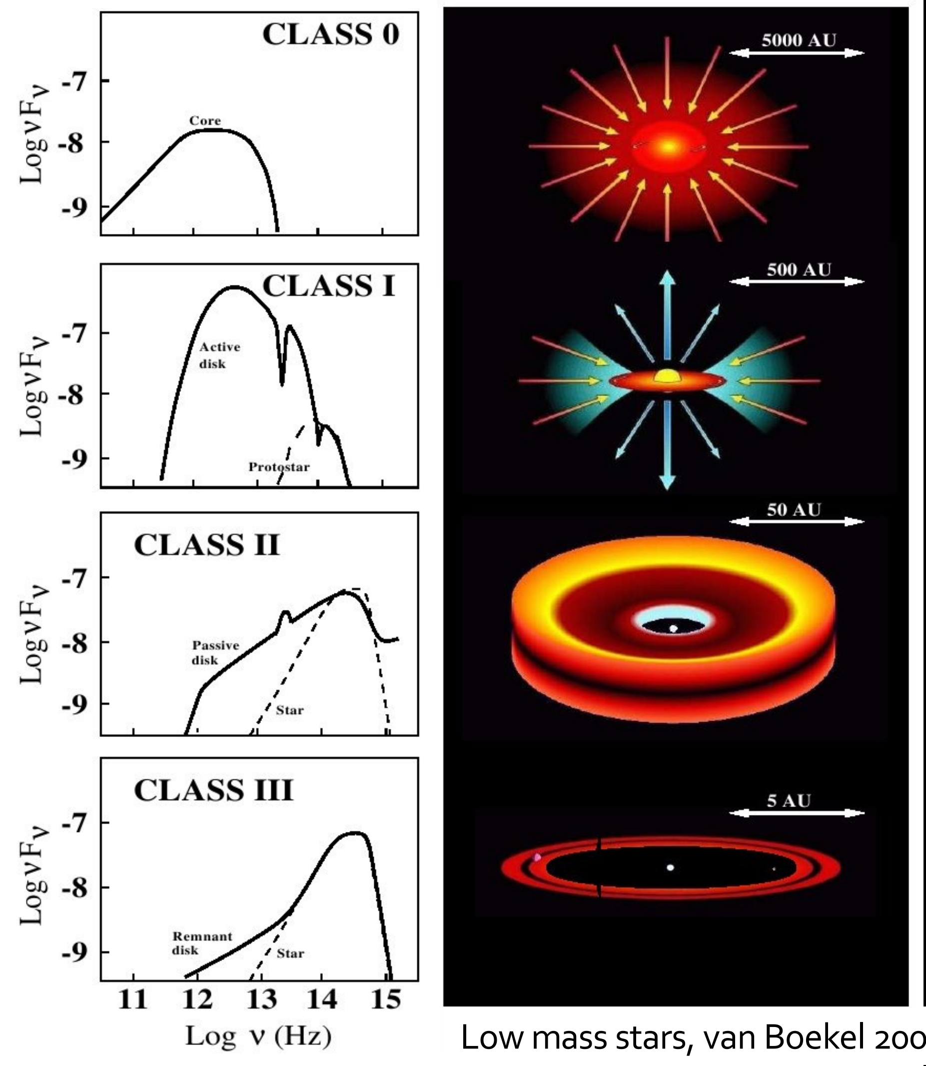
Credit: Bill Saxton



Disk survival timescales

- Measure disk fraction in many region
- Average dissipation: 3 Myr

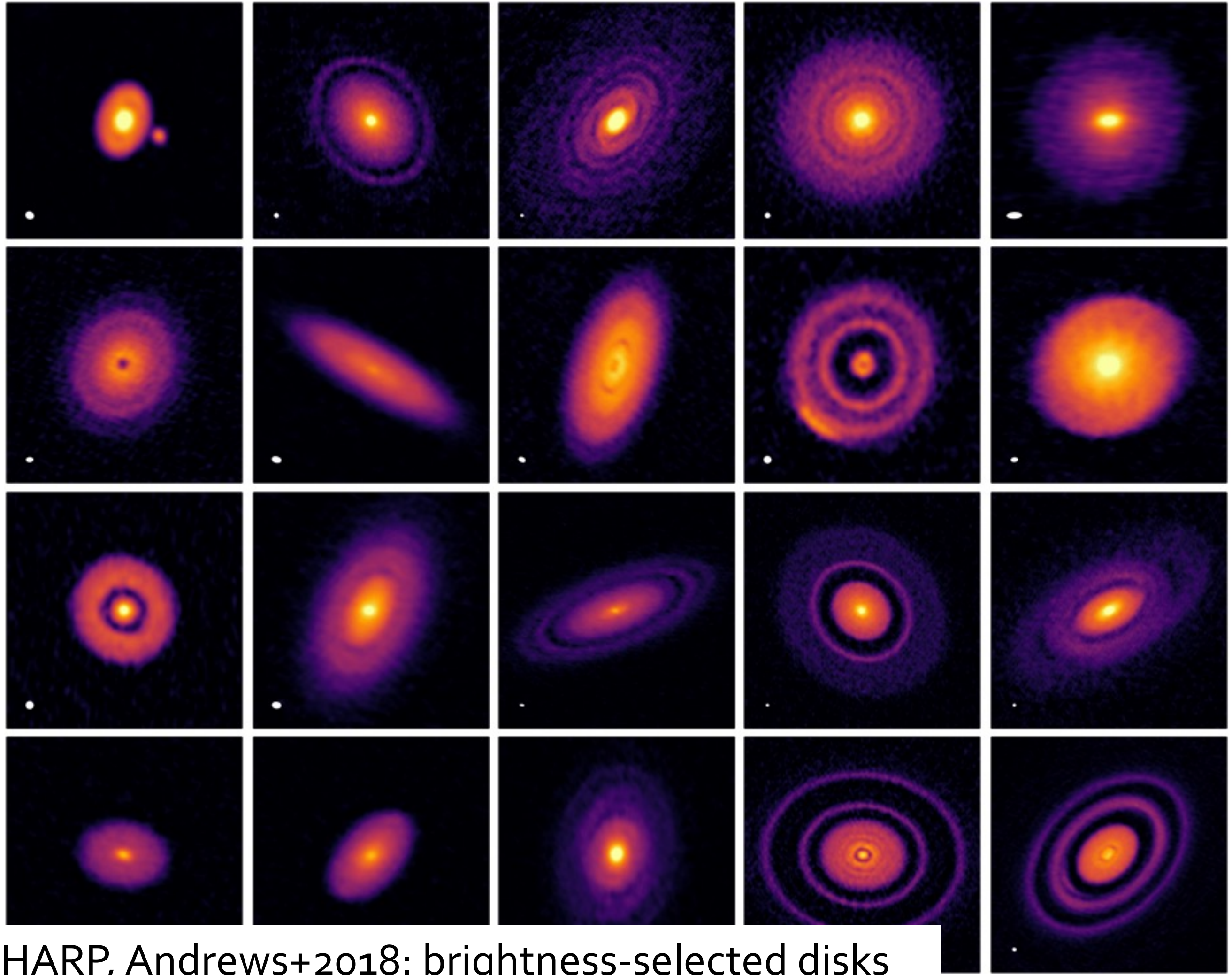
Hernandez+2008



Low mass stars, van Boekel 2005

Protostars:
~few 10^5 yr
Stellar growth

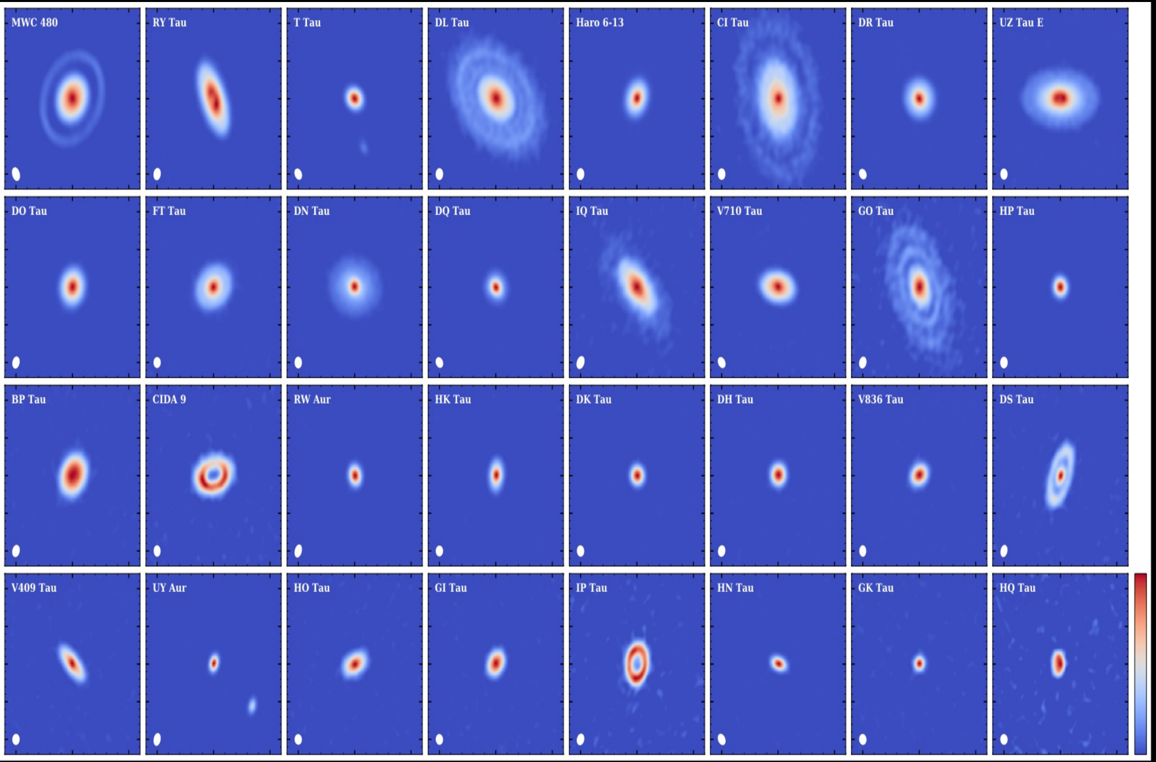
Disks
~few 10^6 yr
Planet formation



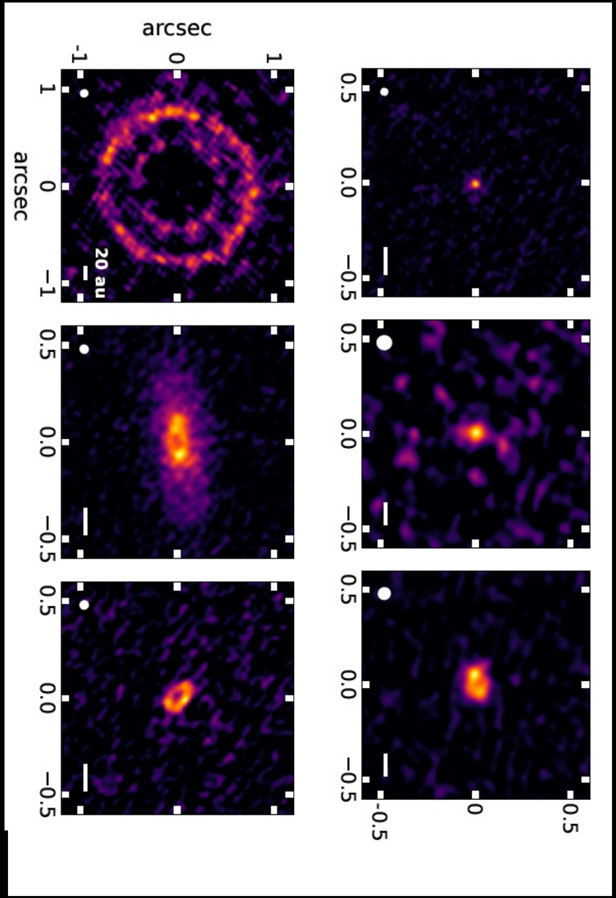
ALMA DSHARP, Andrews+2018: brightness-selected disks

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

Diversity in disk size and substructures
Long et al. 2018/2019 (left); Shi et al. subm (right)



2.4" (350 AU) on each side

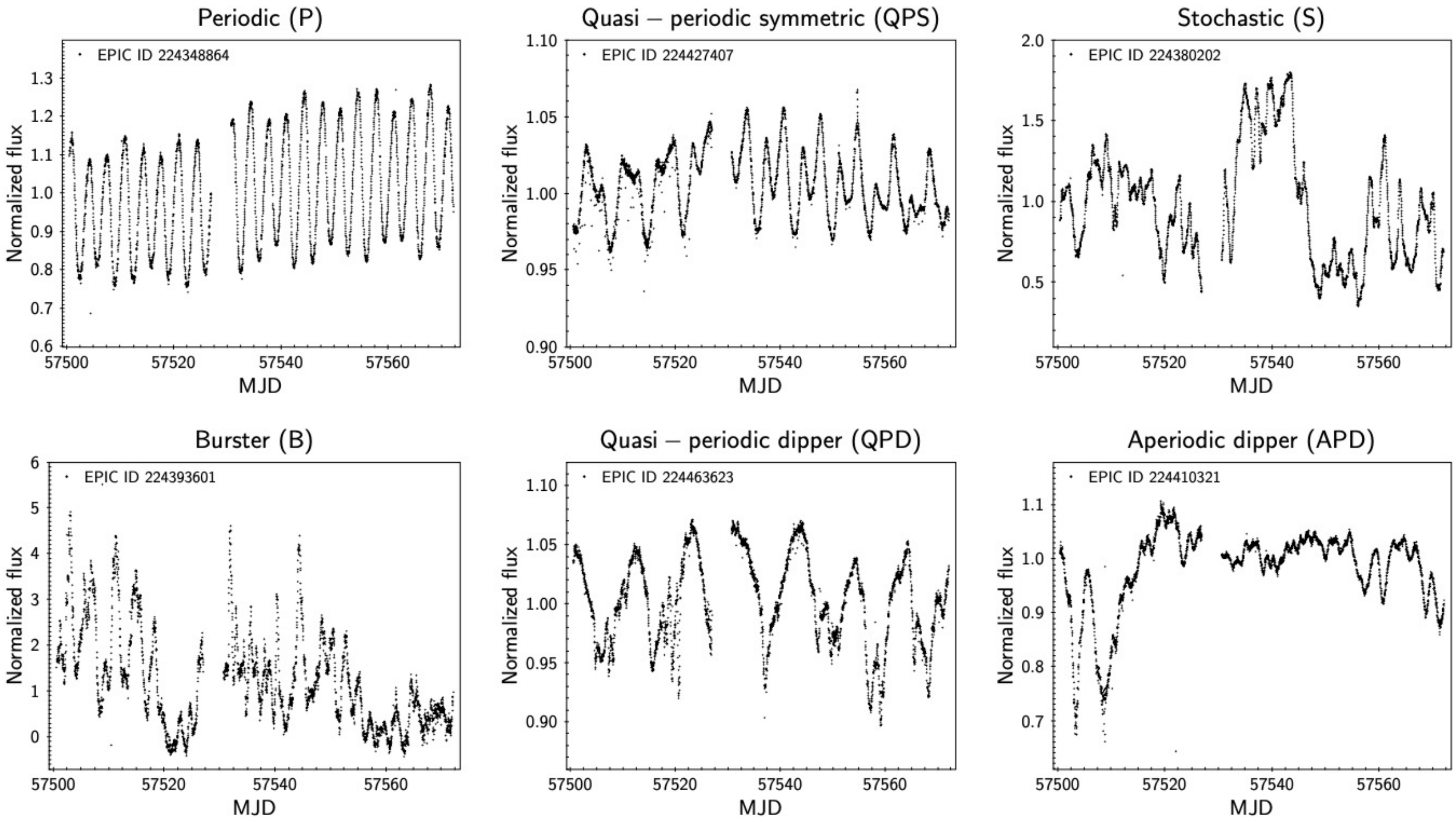


Diversity in disk outcomes: mass flows versus time

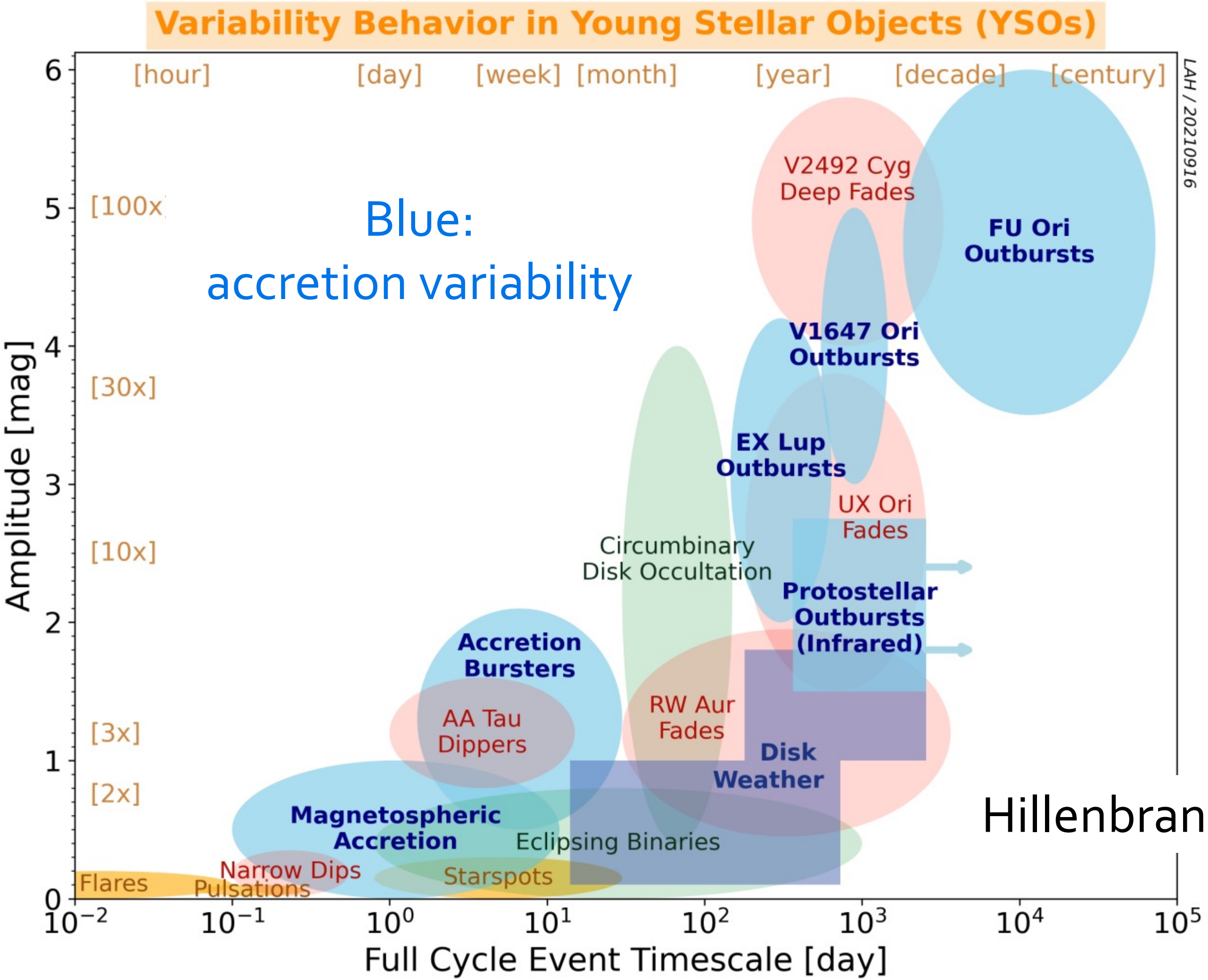
Accretion/ejection physics

- Non-ideal MHD through the disk
- Microphysics: impossible to measure
- Assume accretion through disk = accretion onto star

Fischer+2023 (incl Herczeg) and Manara+2023 PPVII reviews



Venuti+2021 from K2, see also, YSOVar and K2 from Cody, Stauffer, et al.; COROT (Alencar et al. 2010); TESS (e.g., Serna et al. 2023)

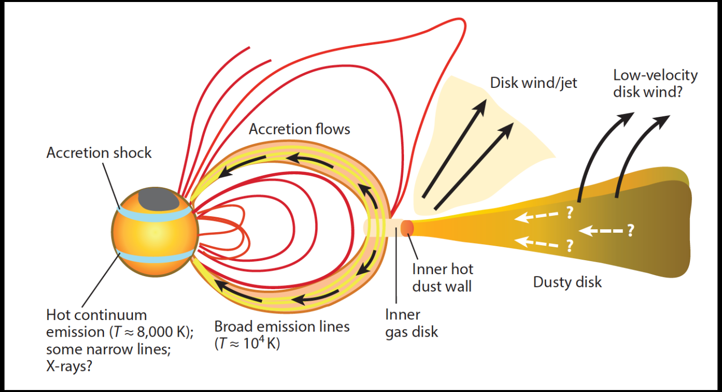


Blue:
accretion variability

Hillenbrand & Findeisen (2015)

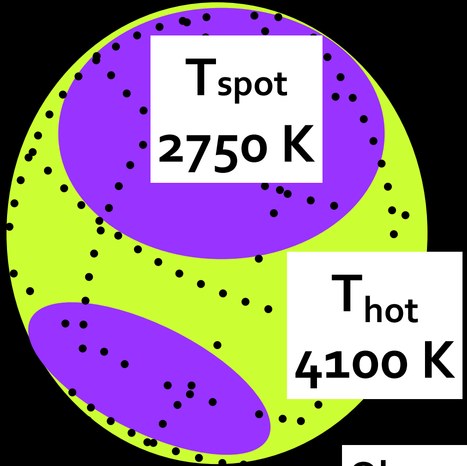
Variability of Young Stellar Objects

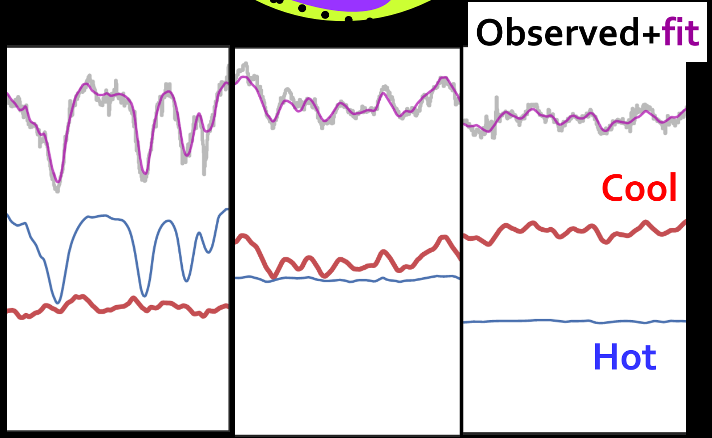
- Diskless (often older): starspots
  - Ages of young stars
  - Extreme examples to evaluate spots in exoplanet transits
- Disks: accretion, extinction, winds
  - Instabilities lead to planet formation
  - Accretion astrophysics
- Protostars: stellar mass assembly
  - Disk and envelope chemistry
  - Initial conditions for stellar evolution



Placing the spotted young star LkCa 4 on the HR diagram

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

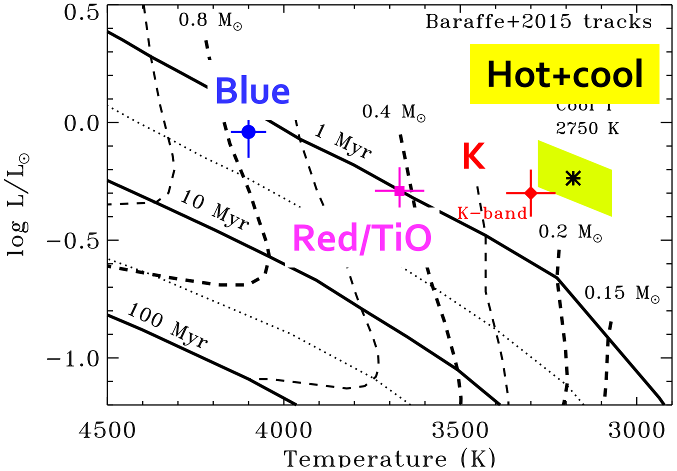




Example fits to segments of high-res IGRINS H+K spectra

Two temperature fit: 4000, 2750 K

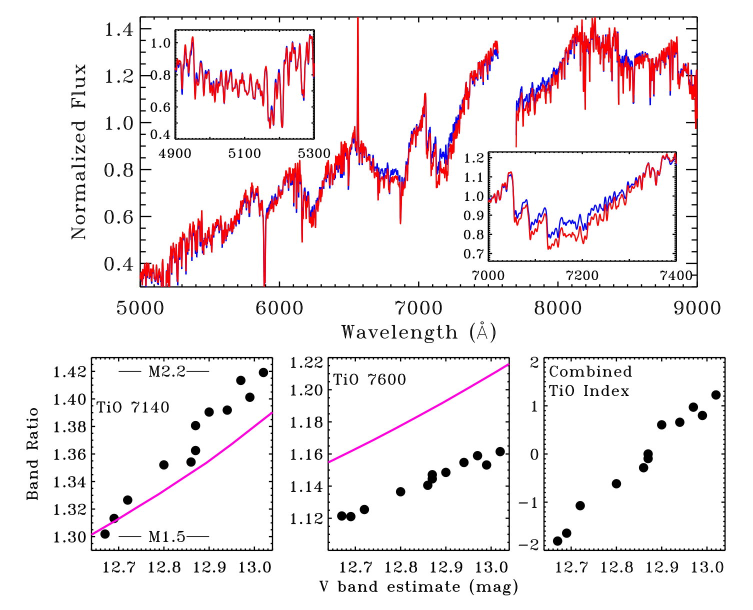
Fill factor of cool component: 80%



Extreme case but common:

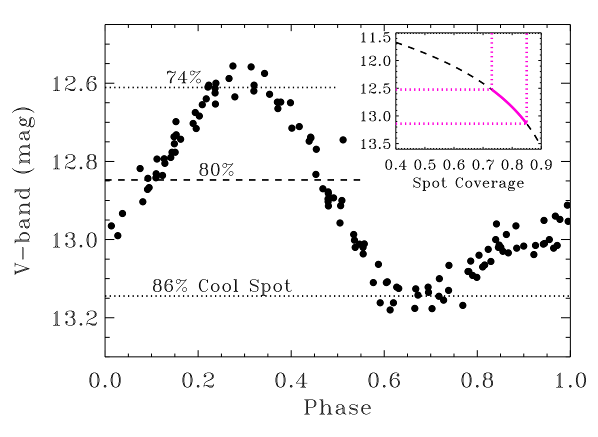
See, e.g., Fang et al. 2016, Cao et al. 2022

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



CFHT/ESPaDOnS spectra

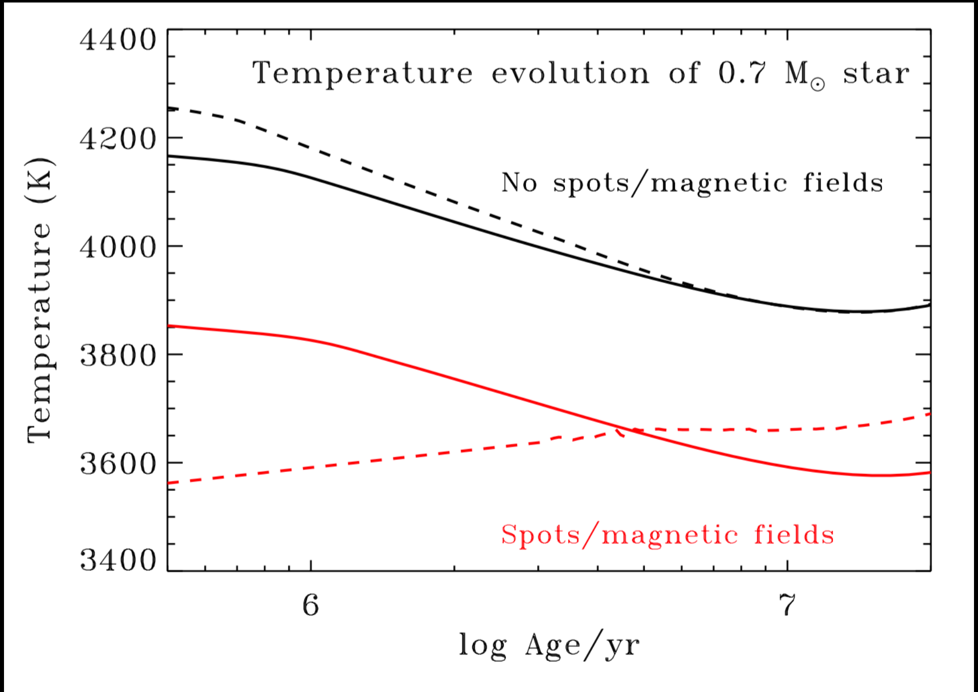
TiO variability versus V (simulated, not fit)



ASAS-SN lightcurve

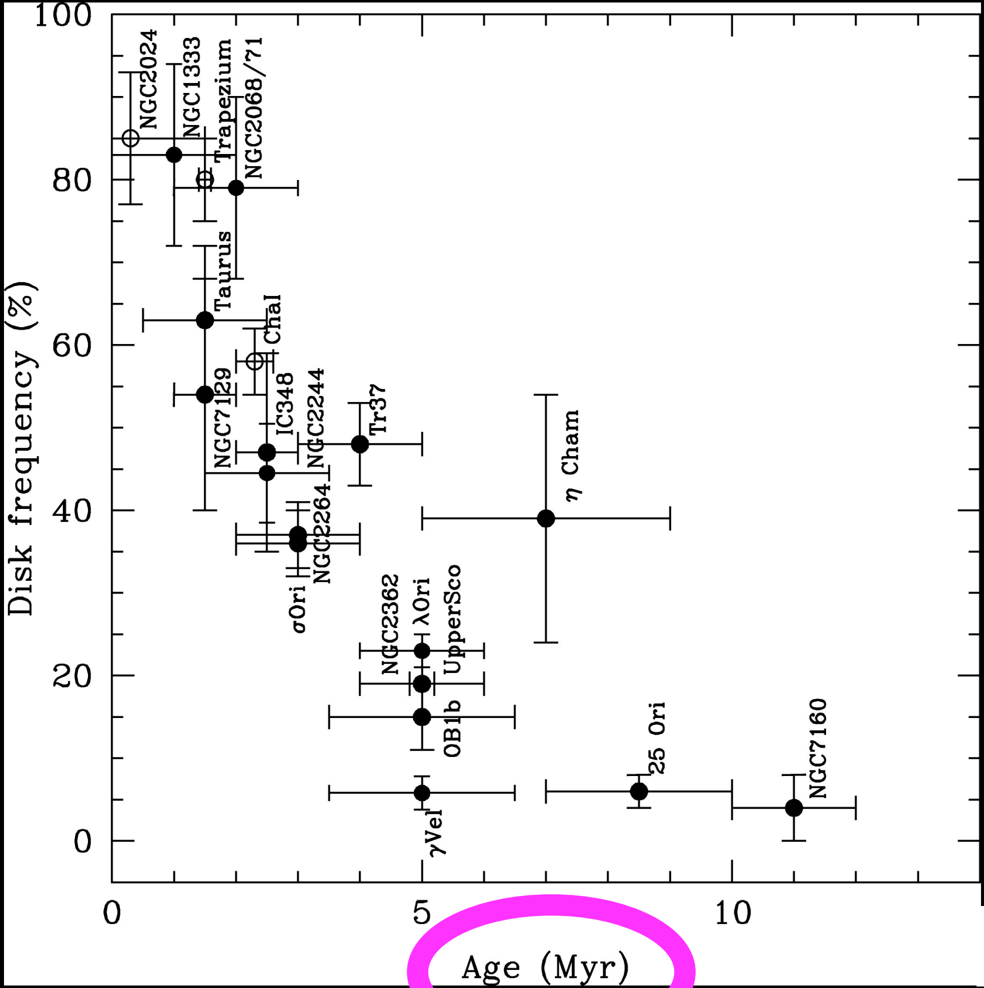
See also, Bouvier+1992; Herbst+1994; Petrov+1994; Grankin+2008; Debes+2013; Jackson & Jeffries 2014; Bary+2014; others

New evolutionary models incorporate spots
(Somers et al. 2020)



Significant changes in Temperature, Radius => differences in inferred ages, masses

Spots affect ages



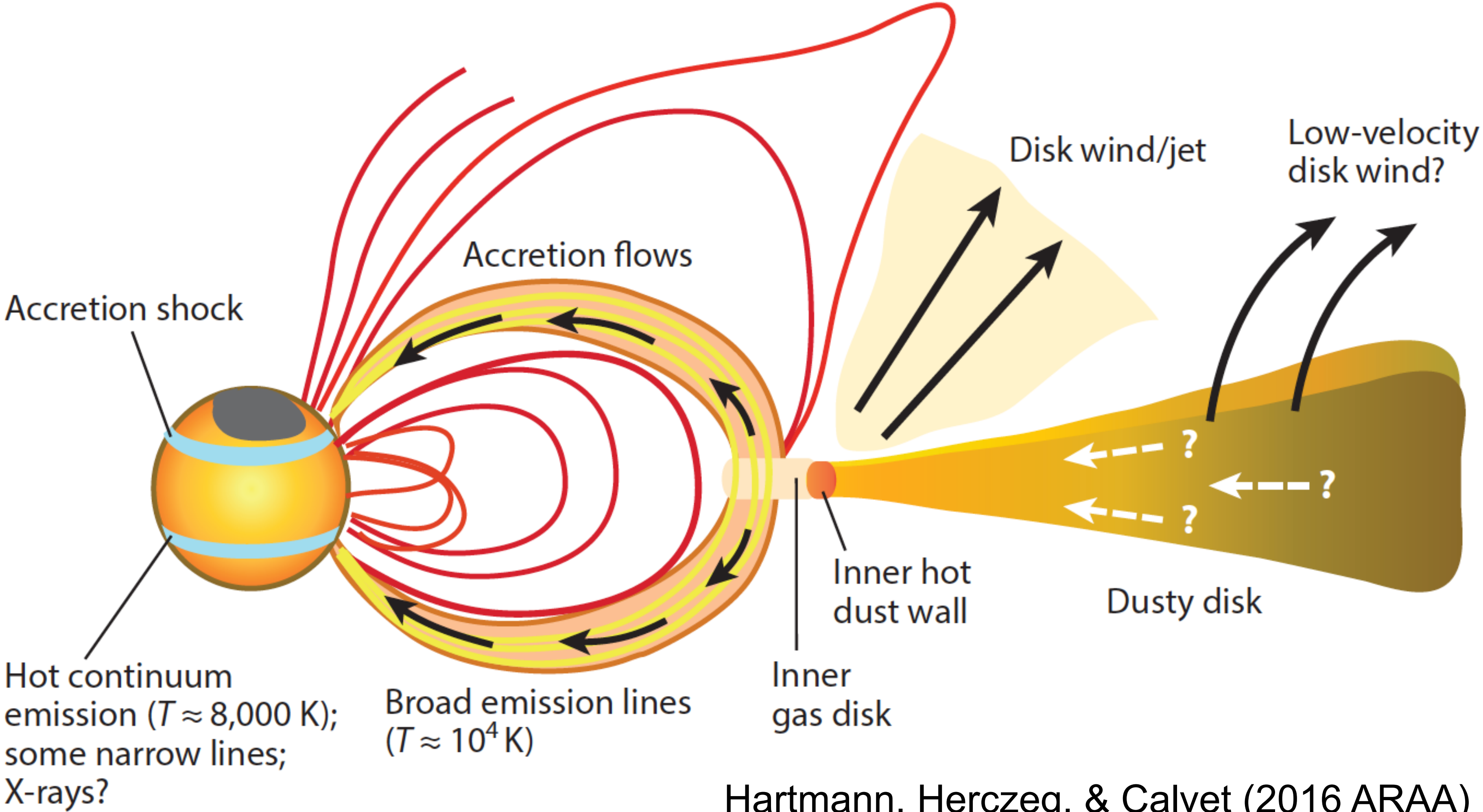
Age from HR diagram: Luminosity and Teff

Factor of ~2 uncertainty;

individual stellar ages uncertain

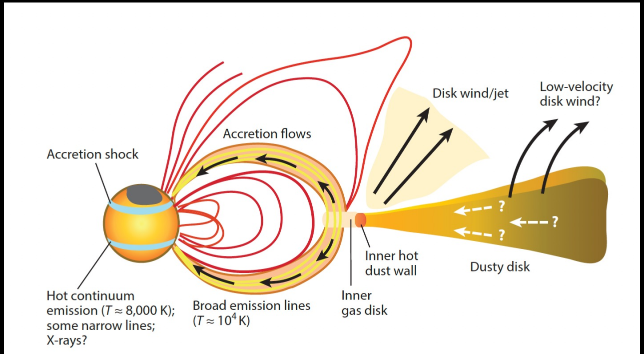
- Star formation history
- Stellar assembly
- Disk evolution
  - Size, substructures, etc

Hernandez+2008

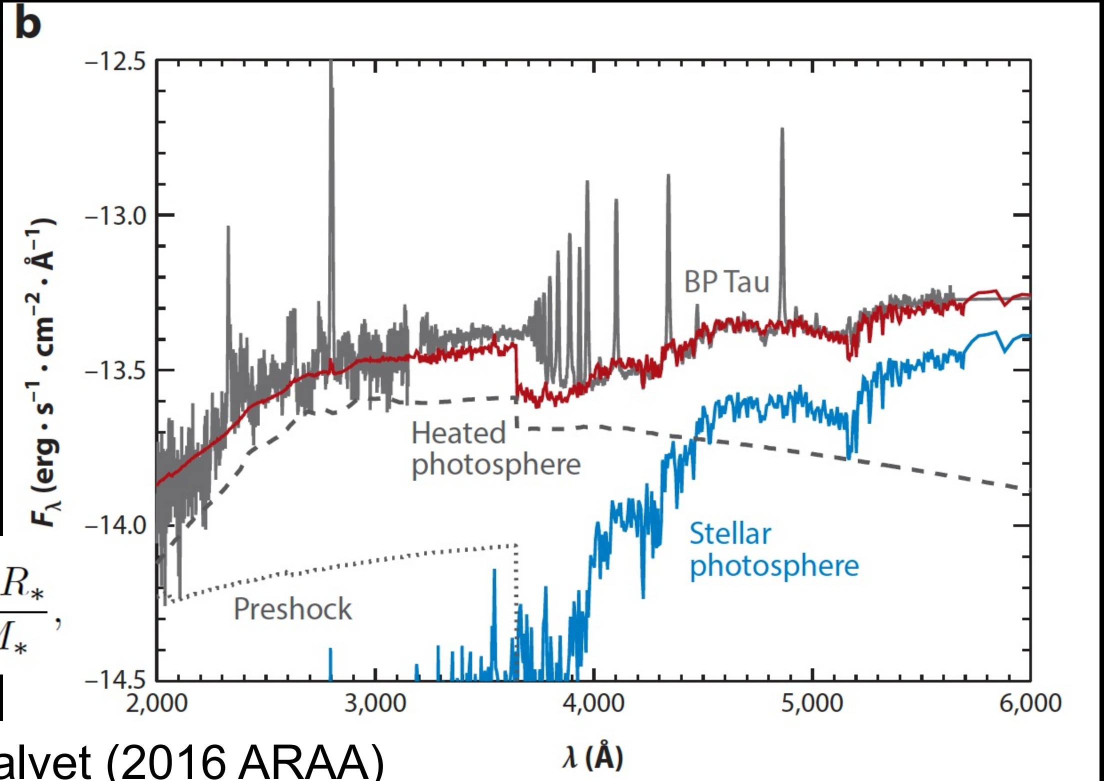


Hartmann, Herczeg, & Calvet (2016 ARAA)

Accretion disks: spots, accretion, and extinction



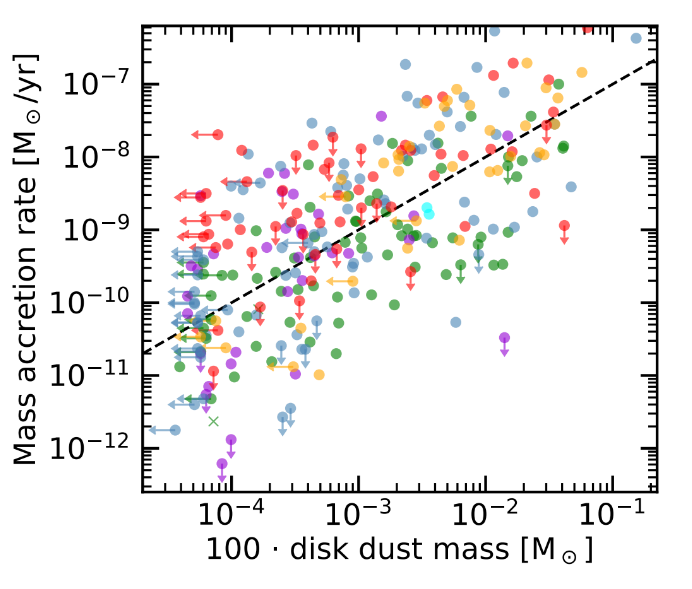
$$\dot{M}_{\rm acc} = (1 - \frac{R_*}{R_{\rm in}})^{-1}\frac{L_{\rm acc}R_*}{GM_*} \sim 1.25\frac{L_{\rm acc}R_*}{GM_*},$$

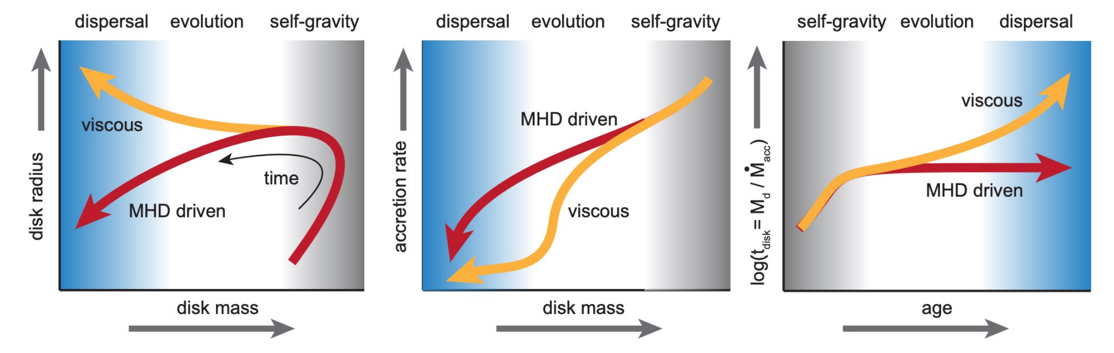


Hartmann, Herczeg, & Calvet (2016 ARAA)

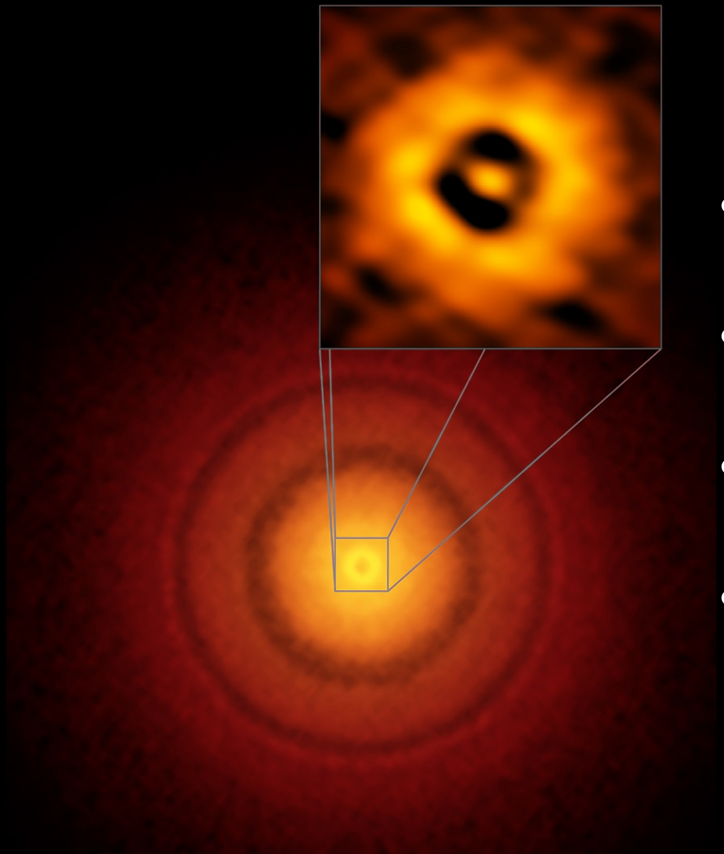
Accretion rates: how do stars evolve?

(see Manara+2023 PPVII review)





Diversity versus mass, age: role of variability?



Andrews+2016: 1 au cavity

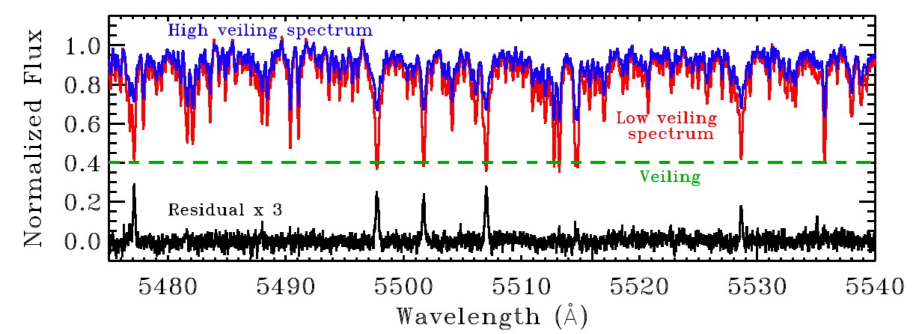
TW Hya: a remarkable disk

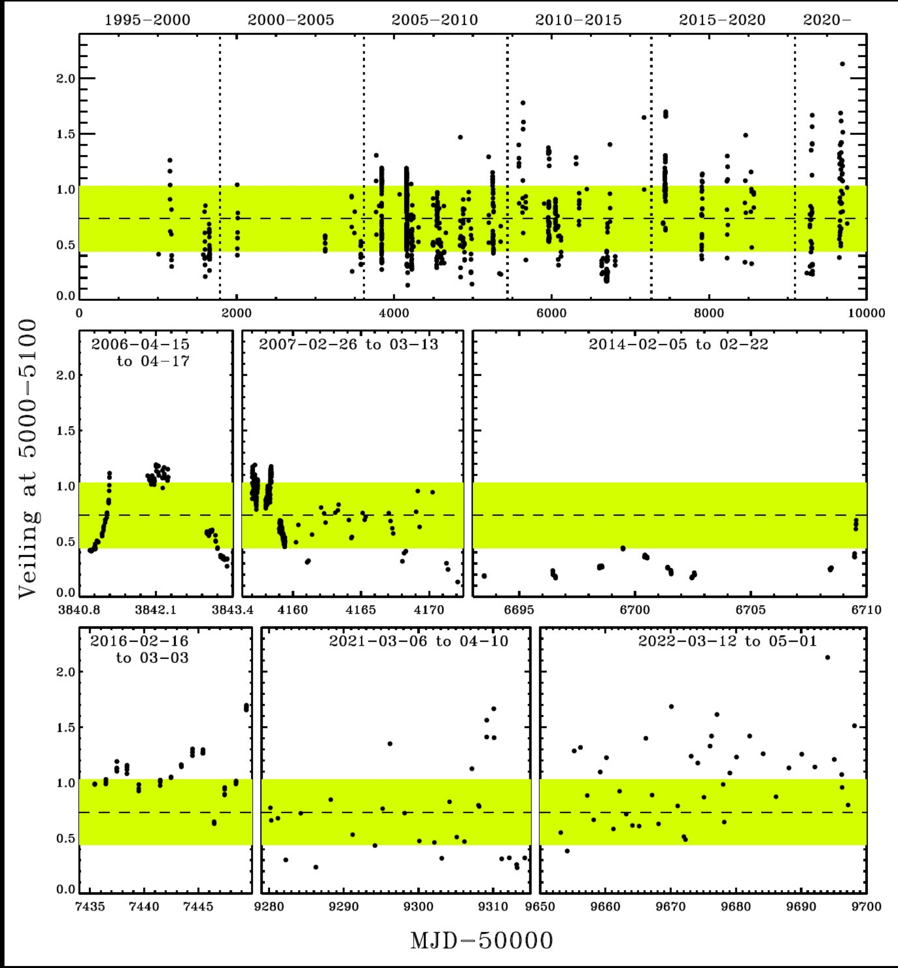
- closest (60 pc) disk around solar mass star
- ~10 Myr old: how did the disk survive?
- Face-on
- No extinction

Twenty-five years of variable accretion onto TW Hya

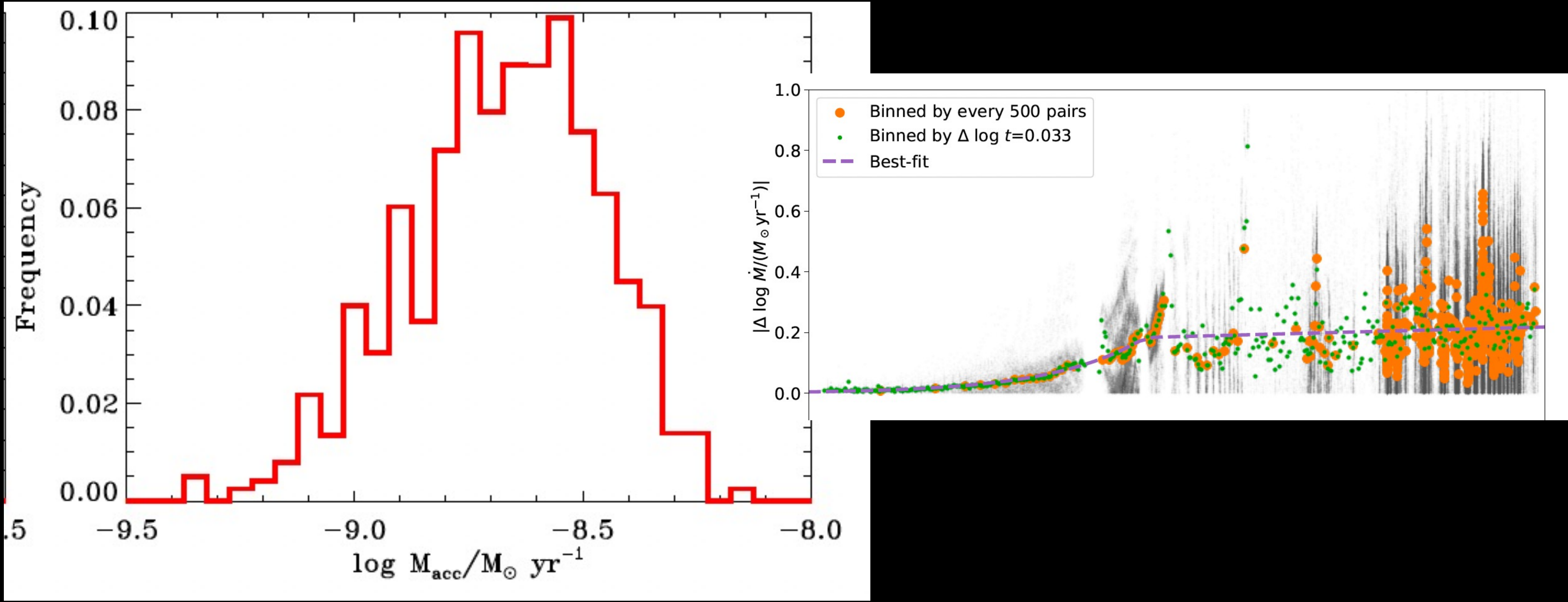
(Herczeg, Chen Yuguang, et al. 2023)

- Veiling (accretion) from 1177 high-res spectra
  - TW Hya is a "normal" accretor with 0.2 dex variability (weather)



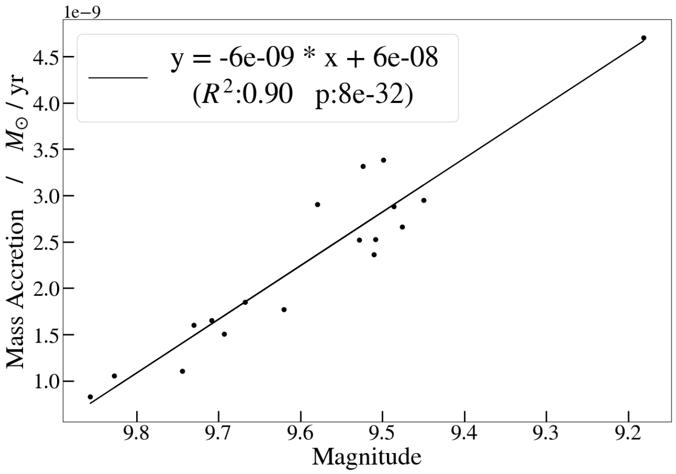


Variability of accretion rate

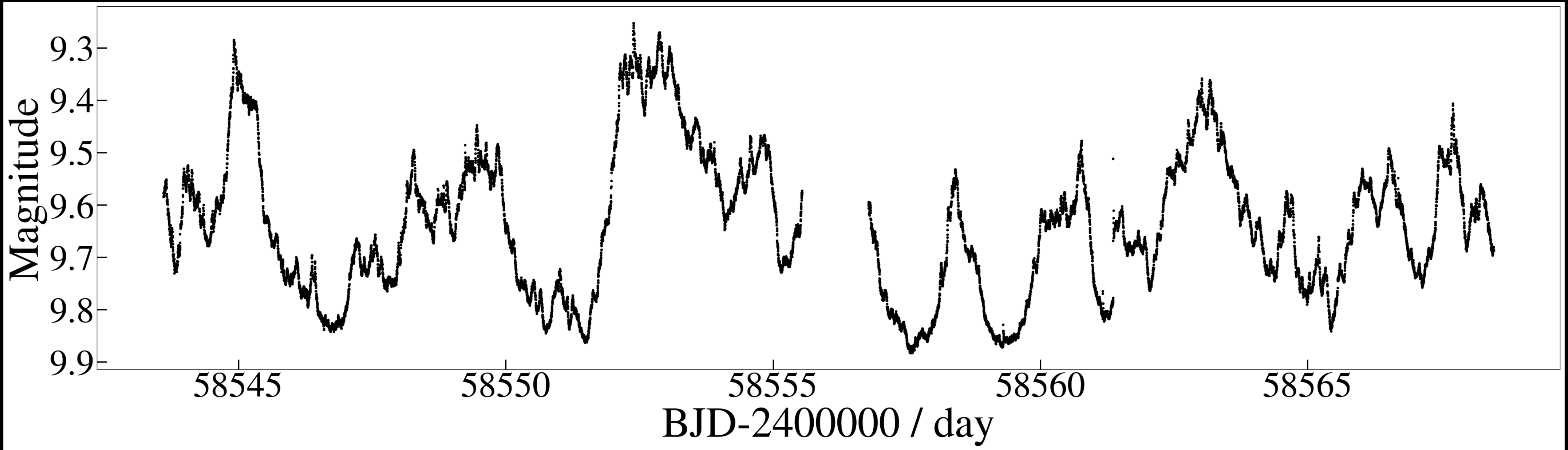


Log (average accretion rate): -8.65 +/- 0.22

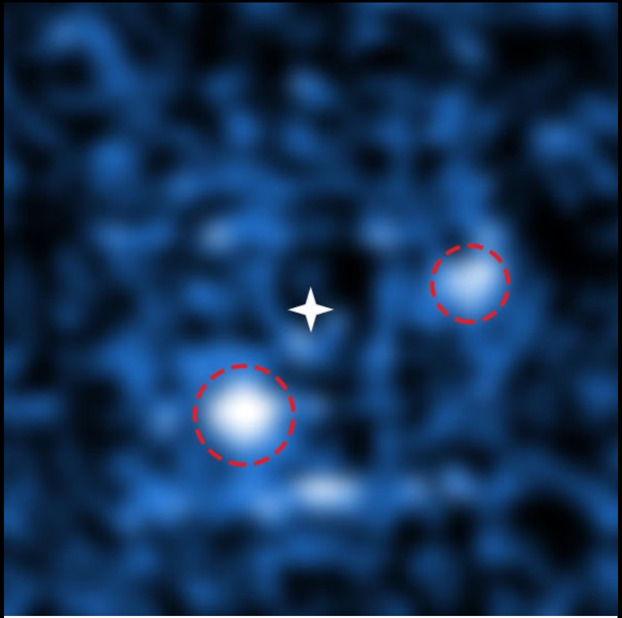
Scaling photometry to accretion (JI Tao et al., in prep)



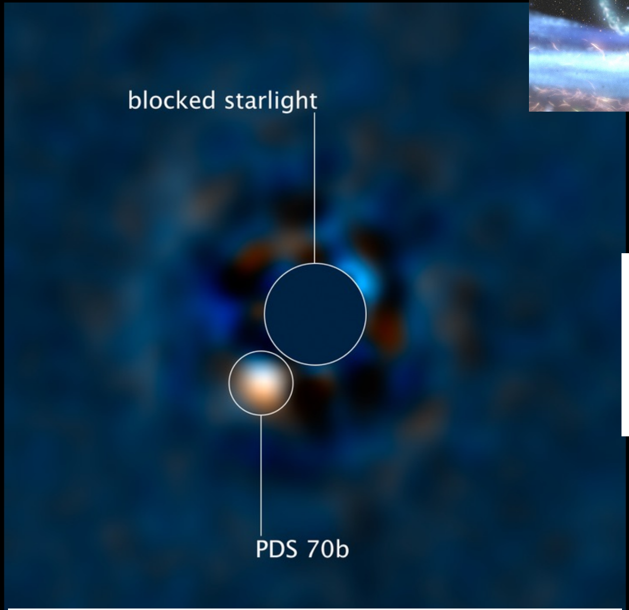
- TESS, ASAS-SN, other surveys+amateurs (AAVSO)
  - high time resolution
  - consistent cadence



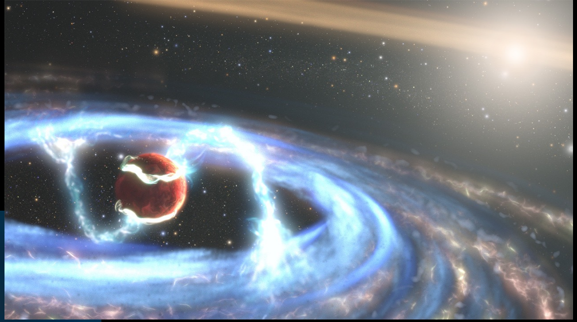
Watching young planets grow!



VLT MUSE H-alpha images
Haffert et al. 2019



Hubble Space Telescope: H-alpha and U-band imaging
(Zhou et al. 2021; see also Zhou, Herczeg, et al. 2014)



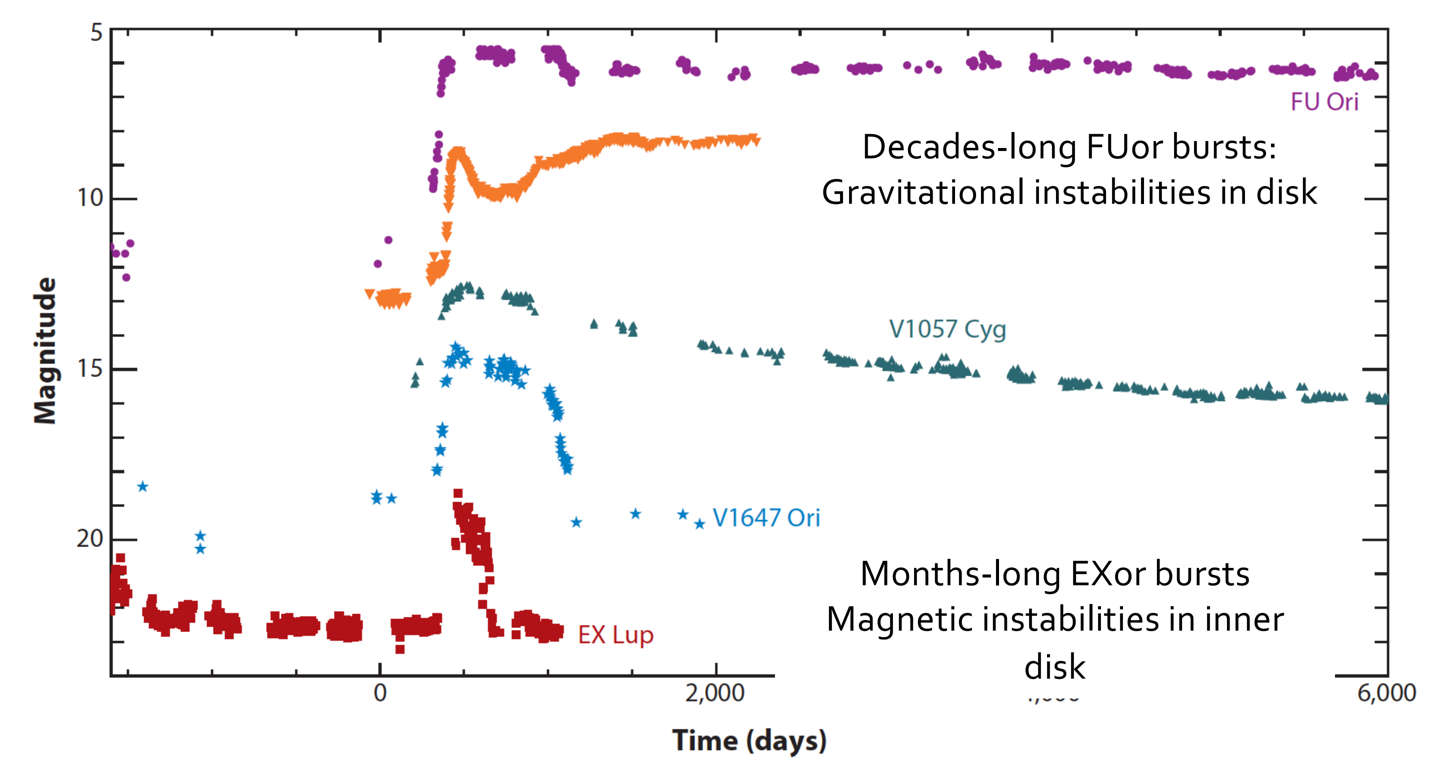
Planets in disk around PDS 70

ALMA Image of PDS 70c

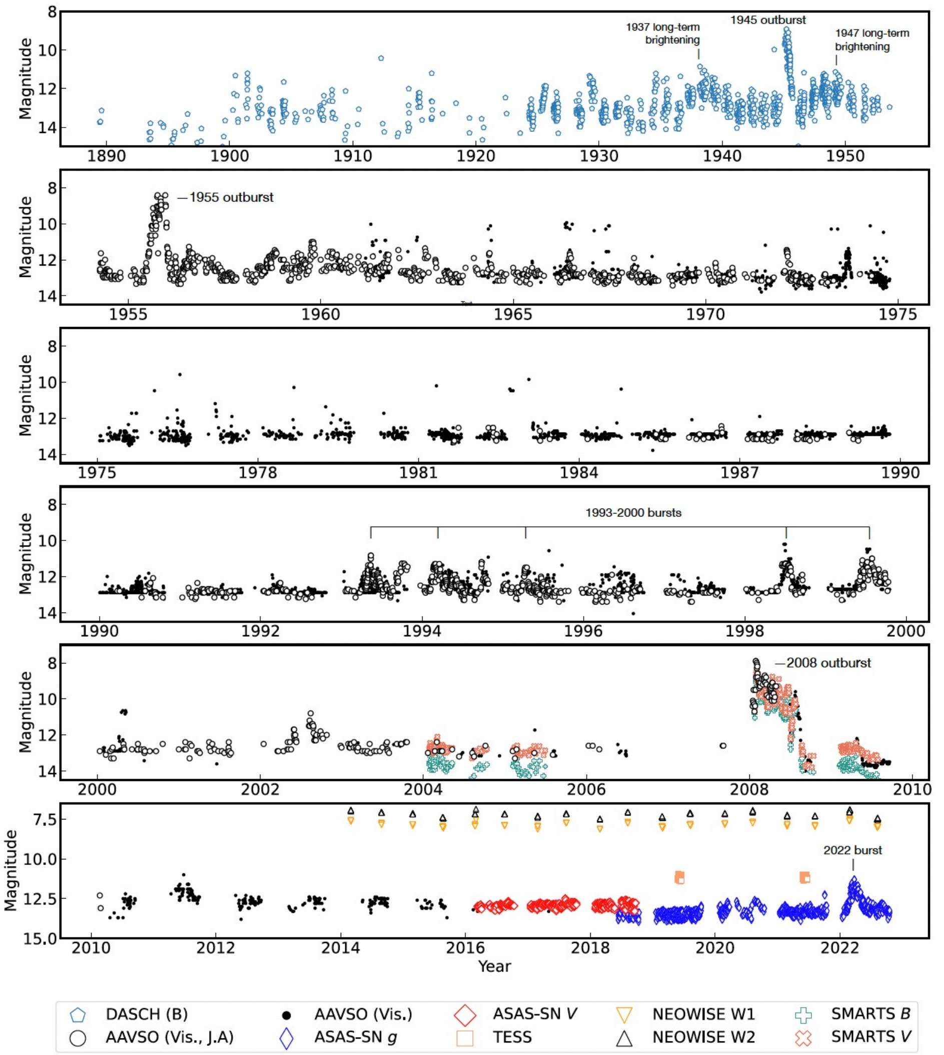
(Benisty et al. 2021; see also Isella+2019)

EX Lup and FU Ori type outbursts

(adapted from Kospal+2011)



Most recent bursts are found by PTF/ZTF and Gaia

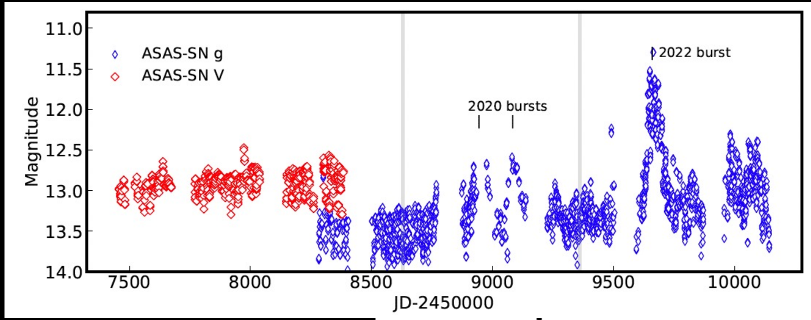


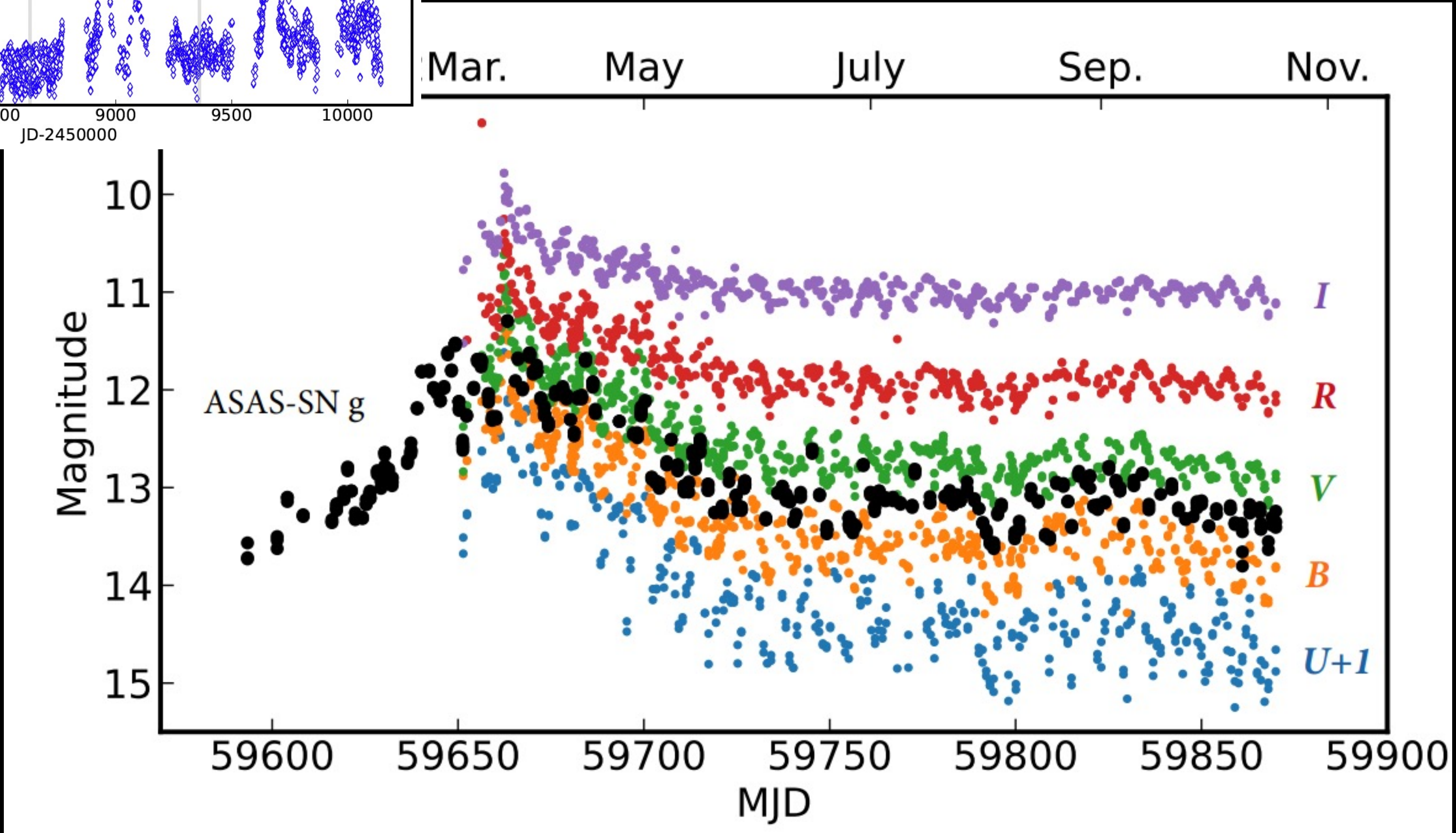
A century of accretion bursts onto EX Lup

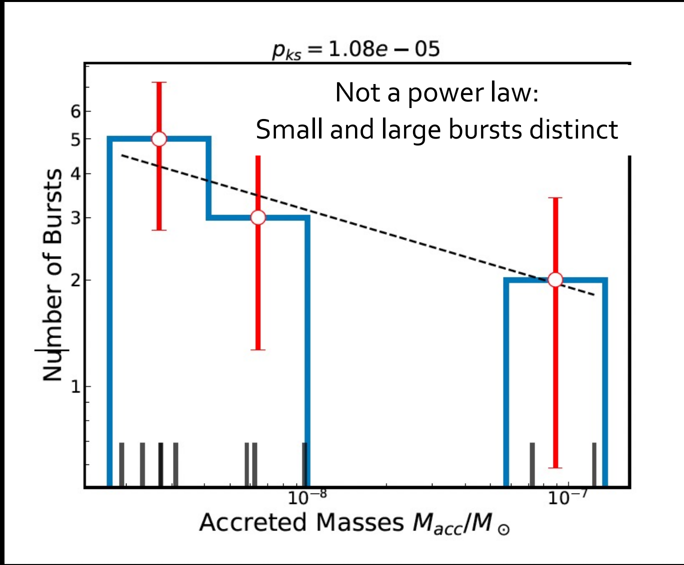
Wang Mu-Tian, Herczeg, et al. 2023; see also Cruz Saenz de Miera et al. 2023)

- Archetype of EX Lup-type bursts
  - Herbig 1951; 2008
- 160 pc, few Myr old
- Long history of photometry
  - How to interpret?

Burst in 2022: leverage amateur photometry to interpret past photometry





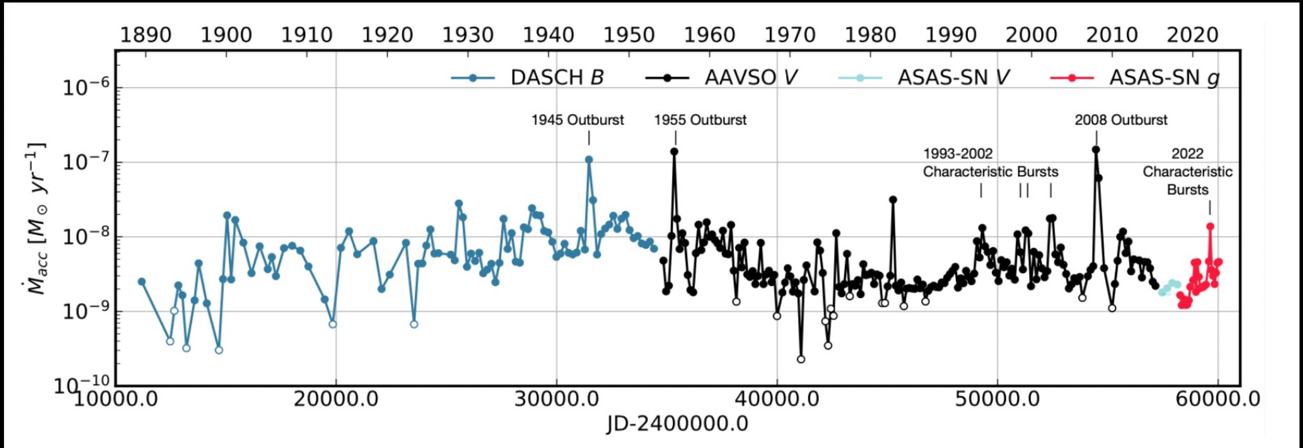


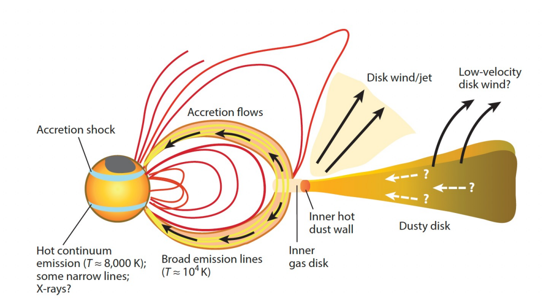
A 100-year picture of accretion onto EX Lup

- Similar mass accreted in quiescence and bursts
- Large bursts are more important than small bursts
- Important for disk chemistry; irrelevant in building star

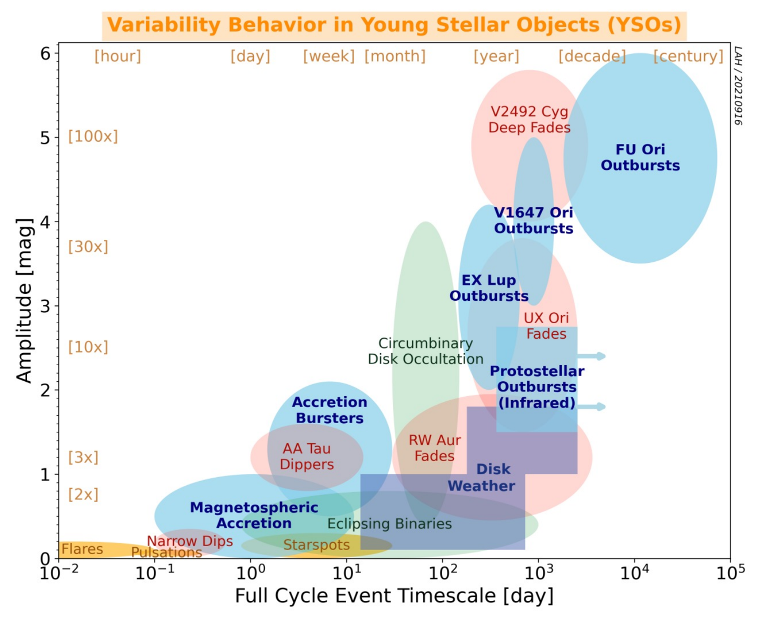
Magnetospheric Instability (D'Angelo & Spruit 2010)?

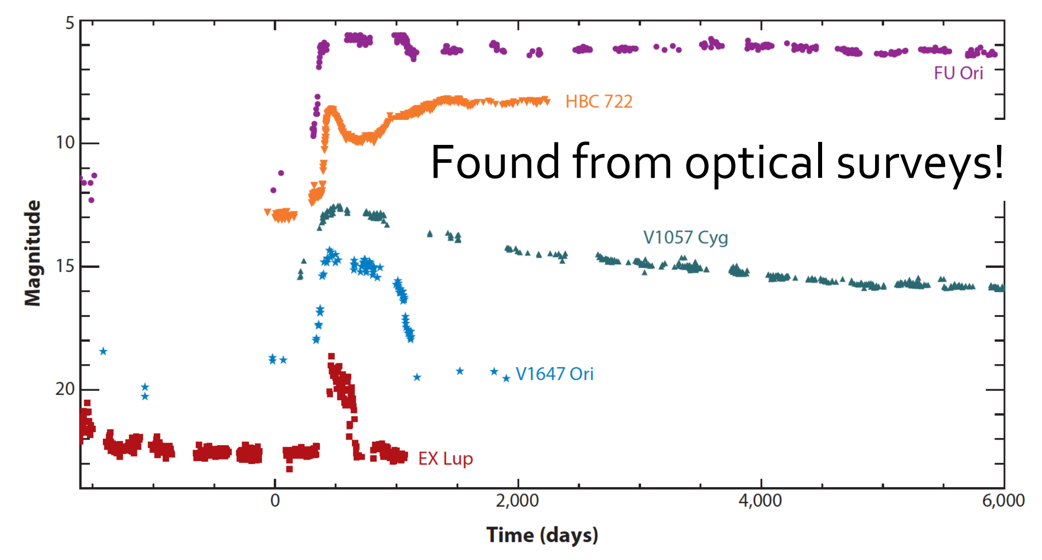
- Truncation radius >> corotation: little accretion
- Gas builds up until the dam breaks





The largest and rarest bursts:
FU Ori-type objects (FUors)

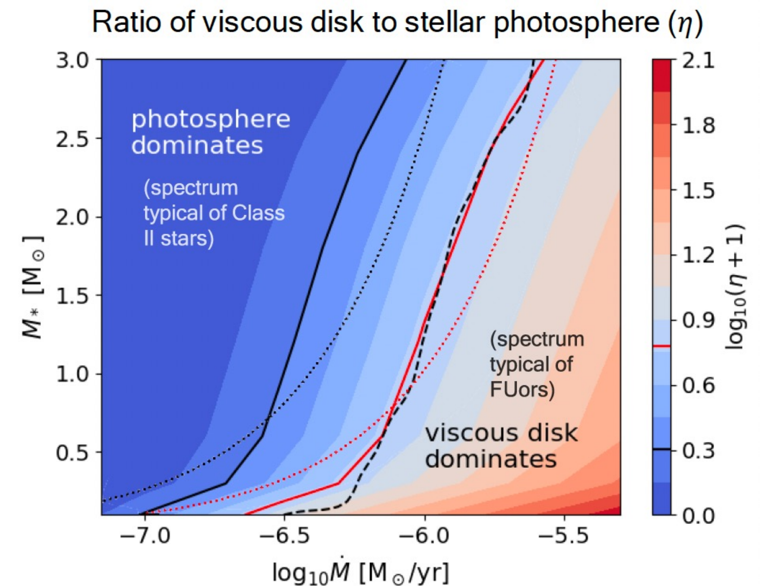




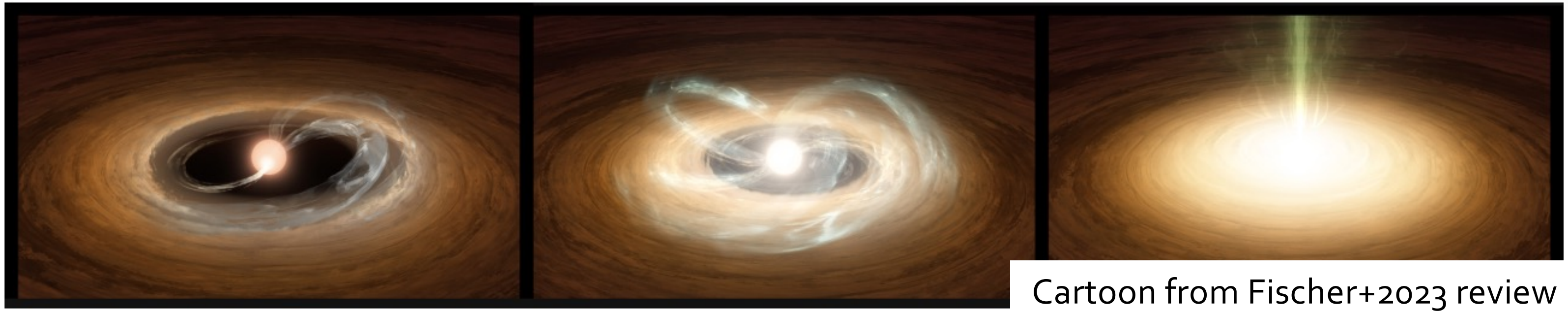
Accrete 10^{-5} M_{sun}/yr, for decades-centuries

FU Ori type outbursts

- Accretion crushes stellar magnetosphere
- Disk viscously heated to ~10000 K
- Disk emission overwhelms star
- **May play major role in stellar assembly**
  - Mass: 1e-5 * 1e2 = 1e-3 Msun



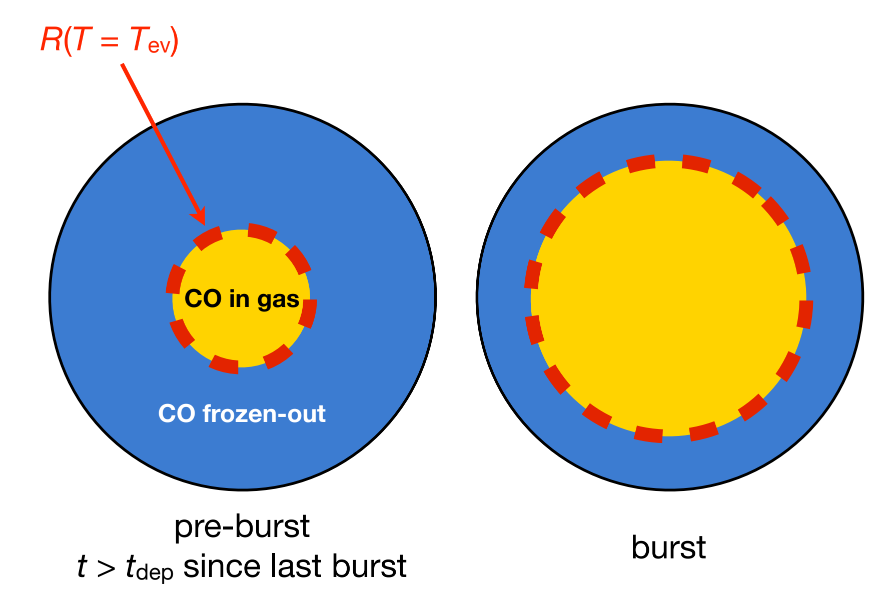
Liu, Herczeg, et al. 2022; see also, eg, Calvet 1990; Zhu et al. 2007, Rodriguez & Hillenbrand 2022



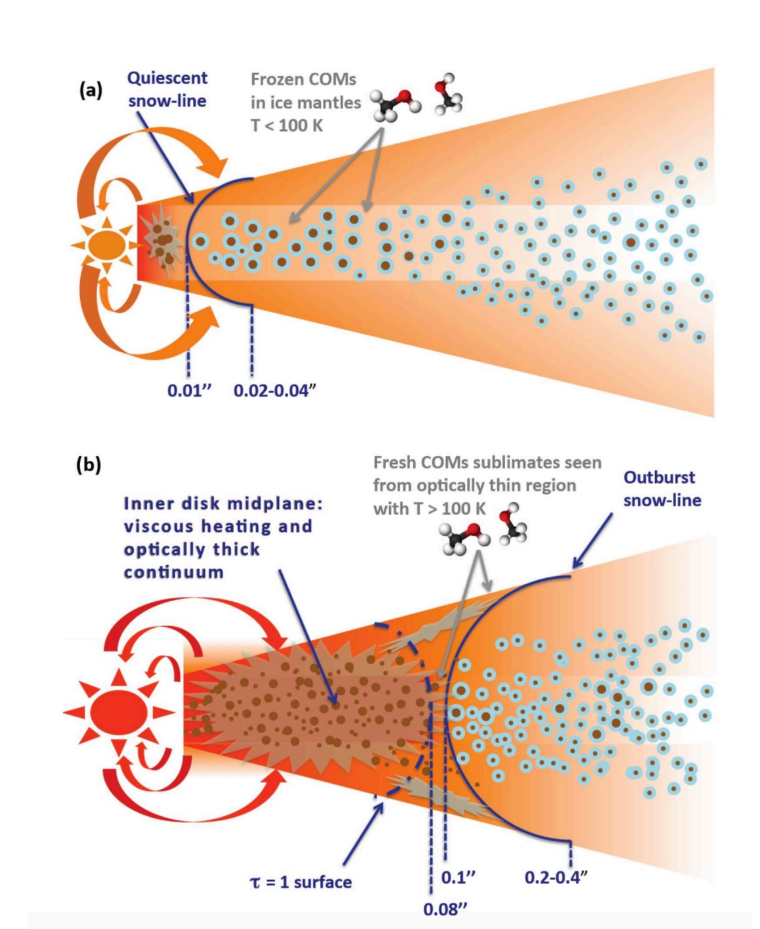
Cartoon from Fischer+2023 review

Disk and envelope heating:

Ices sublimate at larger radii



Jørgensen+2015; Lee 2007; Hsieh+2019; Molyarova+2018; others



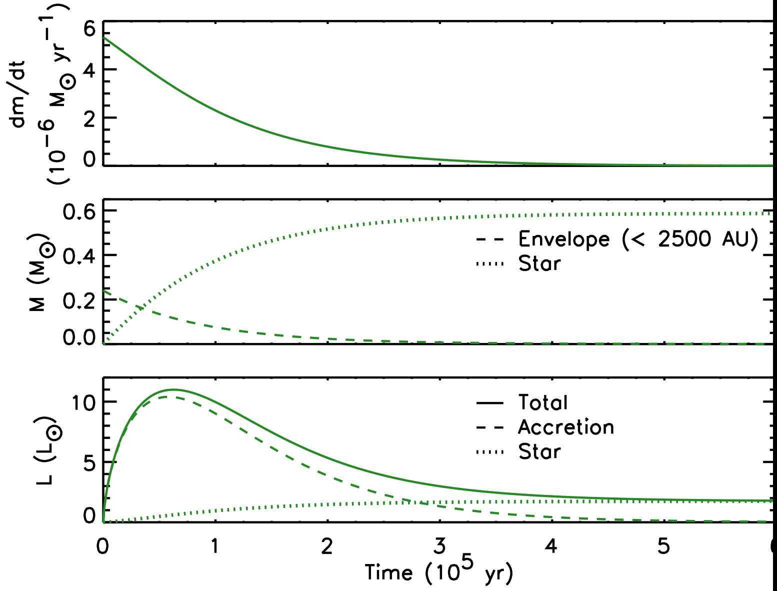
Lee JE et al. 2019 NatAs, includes Herczeg

Role of bursts in stellar assembly is uncertain

(Fischer, Hillenbrand, Herczeg, et al., 2023, PPVII review)

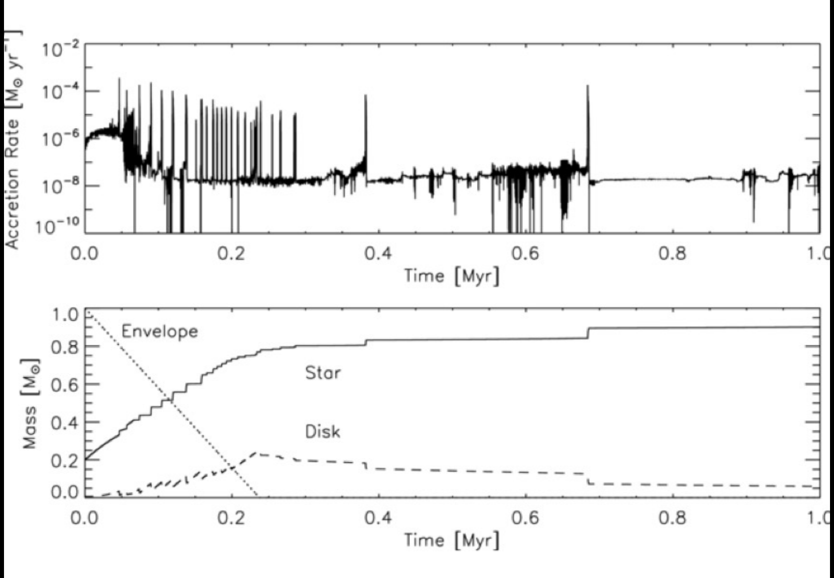
Smooth accretion:

Fischer+2017



Accretion bursts:

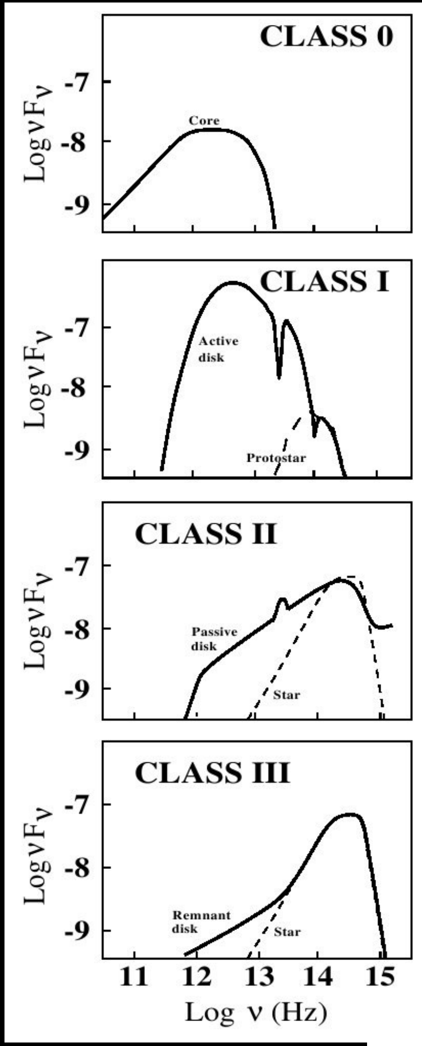
models by Zhu+2010; Bae+2014

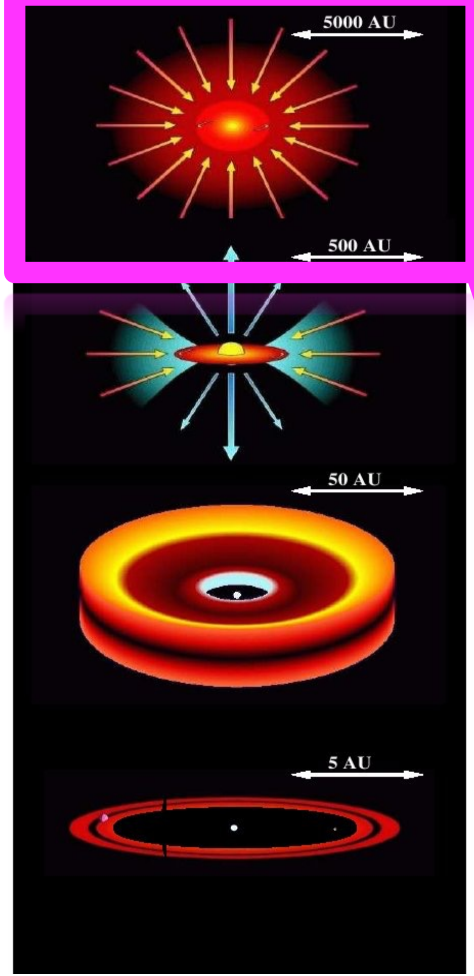


Stellar assembly occurs during protostellar phase

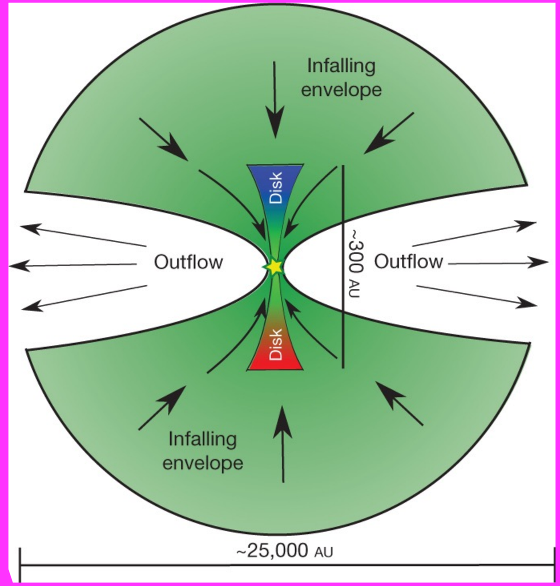
$L_{tot}=L_{acc}+L_{phot}$

Buried in envelope, Scattered by dust





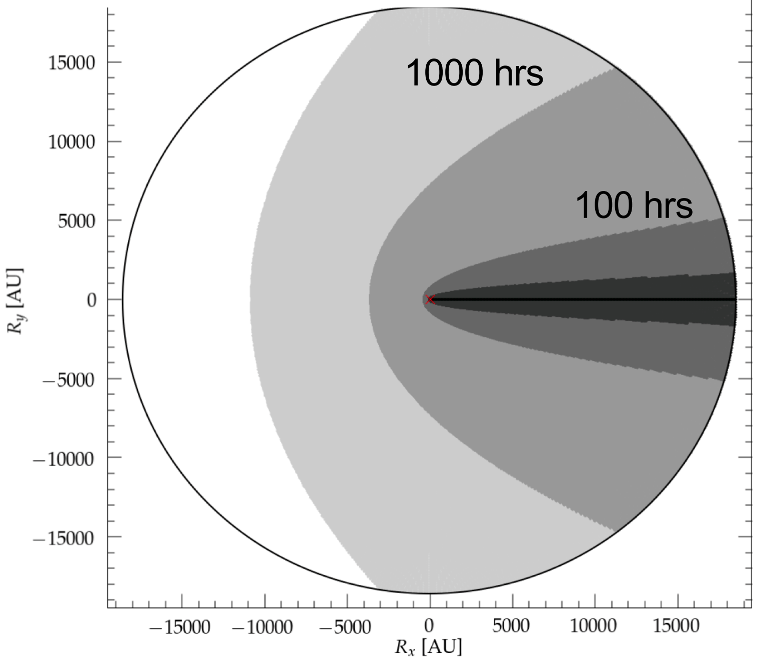
Low mass stars, van Boekel 2005



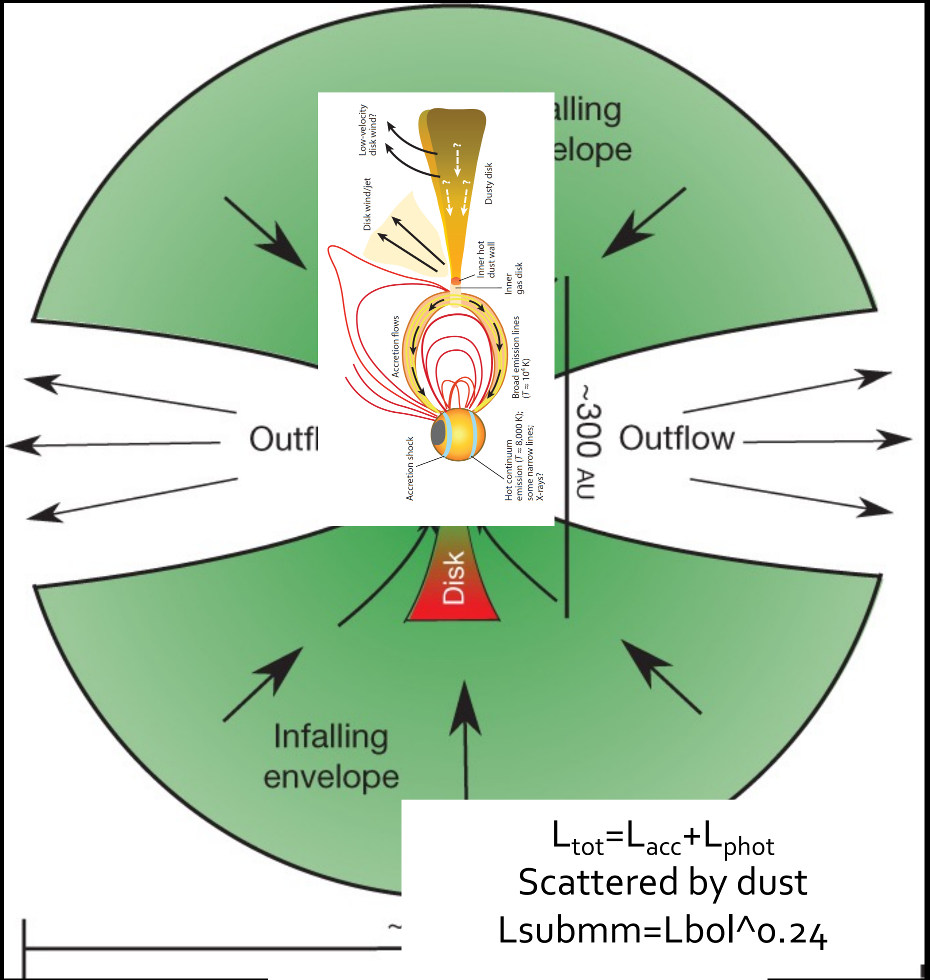
Cartoon from Tobin+2012

Stars grow during protostellar phase

Timescale for dust scattering



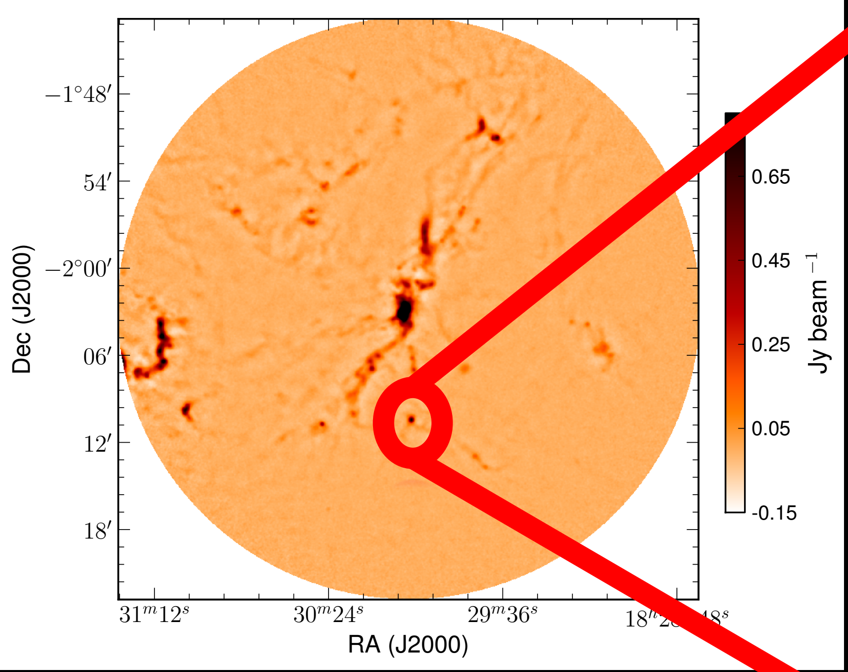
Johnstone+2013: envelope as a calorimeter



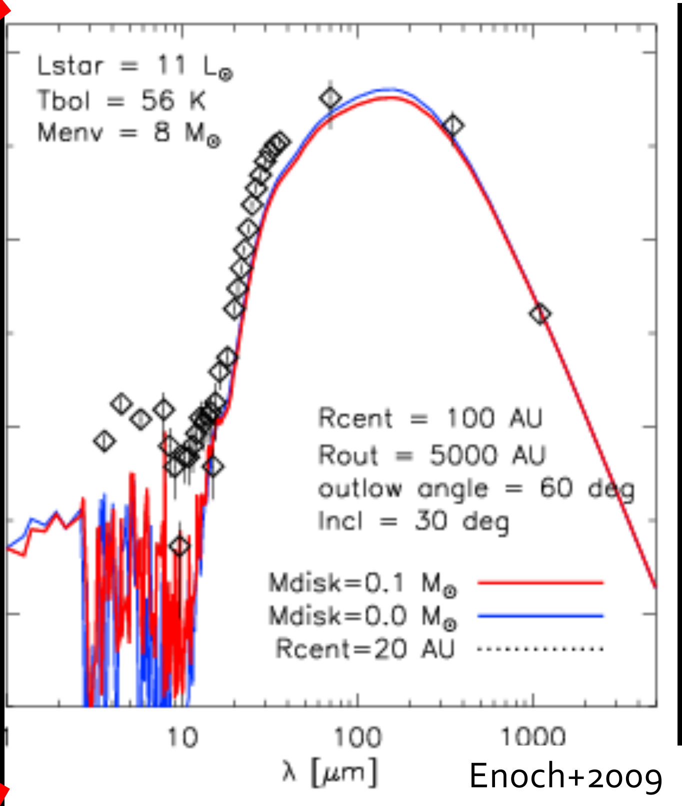
$L_{tot}=L_{acc}+L_{phot}$
Scattered by dust
Lsubmm=Lbol^0.24

Cartoon from Tobin+2012

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



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



Enoch+2009

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

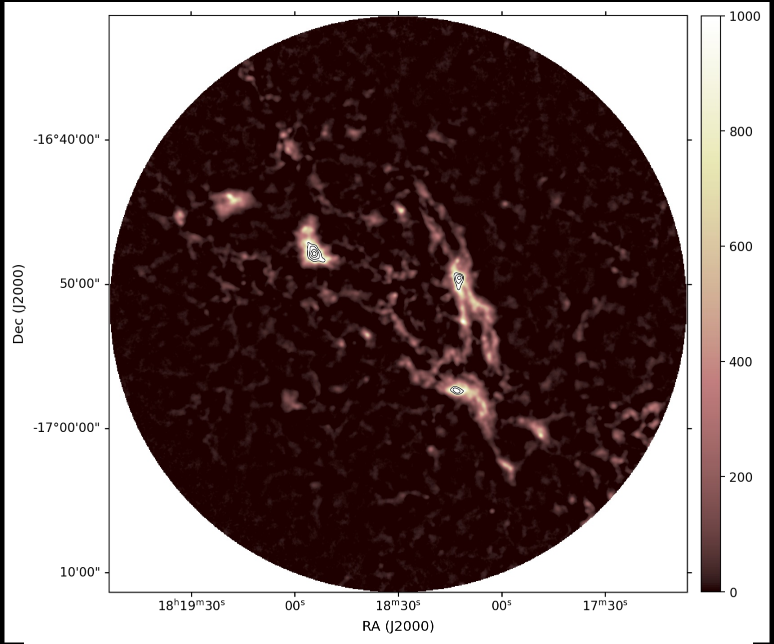
Gregory Herczeg (co-PI; PKU/China)
Doug Johnstone (co-PI; NRC/Canada)
Jeong-Eun Lee (co-PI; SNU/Korea)
Steve Mairs (UBC/EAO/BC Health Care)
NEOWISE+follow-up: Carlos Contreras Pena (SNU)

Yong-hee Lee (KHU), Wooseok Park (KHU), Jenny Hatchell (Exeter), Geoff Bower (ASIAA), Zhiwei Chen (PMO), Xu Zhang (NJU), Sheng-Yuan Liu (ASIAA/NTU), Yuri Aikawa (Tokyo), Graham Bell (EAO), Mizna Ashraf (IISER-Tirupathi), Sung-Yong Yoon (KASI), many others

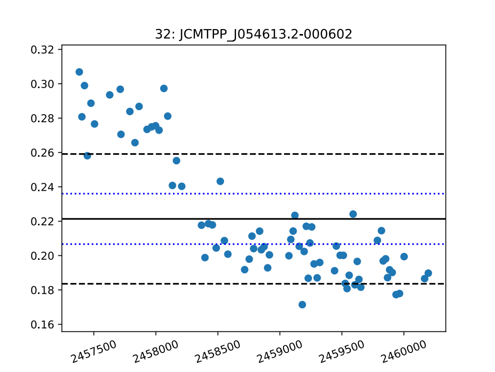
JCMT Transient Survey: 523 hrs allocated from 2016.02-2024.01

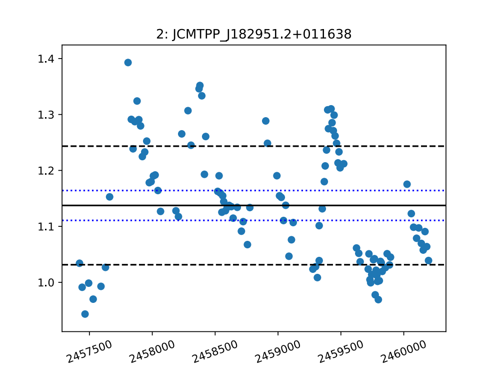
JCMT Transient: sample 850-micron light curves

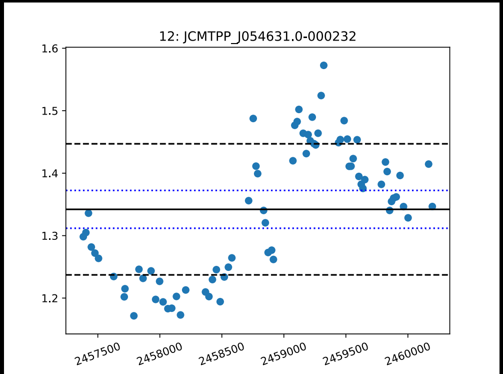
(Mairs+2017ab; Johnstone+2018; Lee et al. 2021; Mairs+2023)

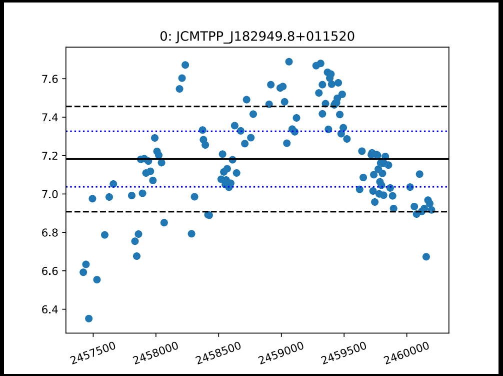


M17SWex: Chen et al. in prep





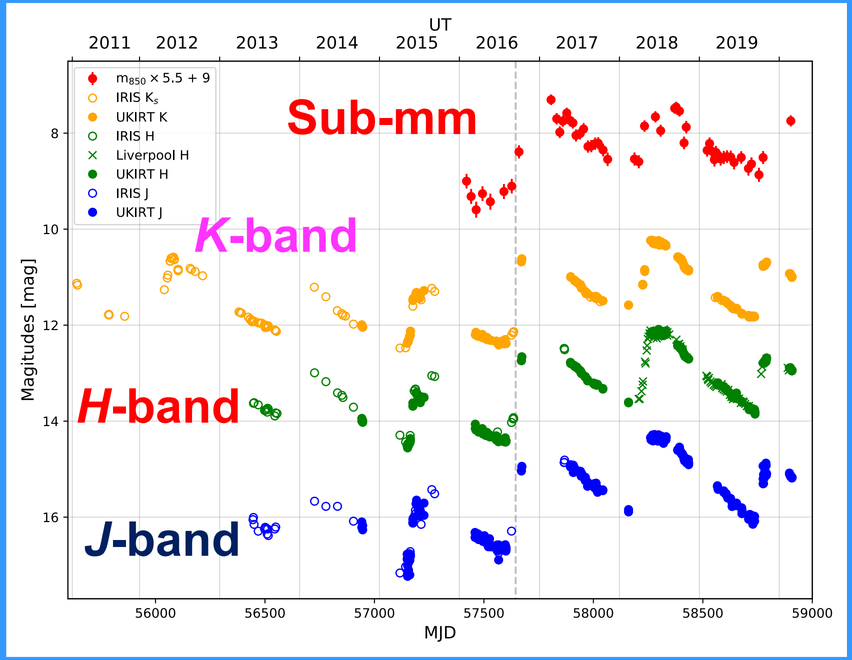




Precision of ~1% from "differential photometry" (Mairs+2023)

EC 53 (V371 Ser): Young Faithful

(YH Lee, Johnstone, JE Lee, et al. 2020)

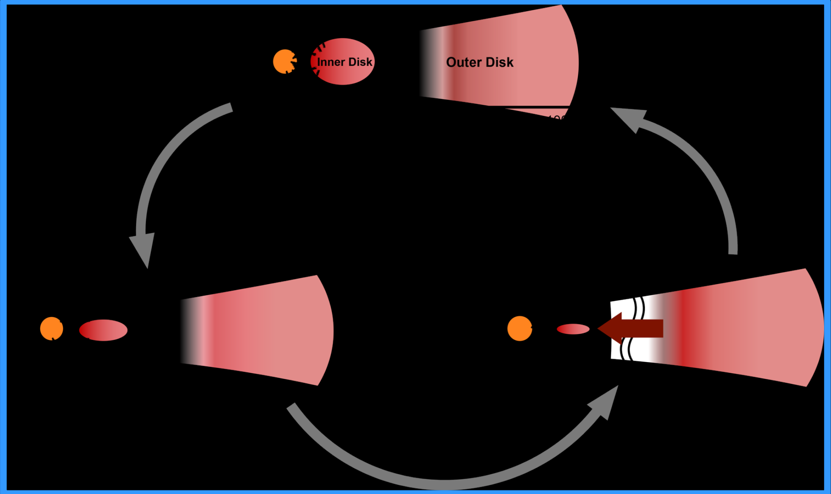


Near-IR periodicity discovered by Hodapp 2012;

Source similar to Muzerolle+2011; Dahm & Hillenbrand 2020

Approved JWST program (PI Lee) timed for faint and bright epochs!

Cycles of filling and draining the disk



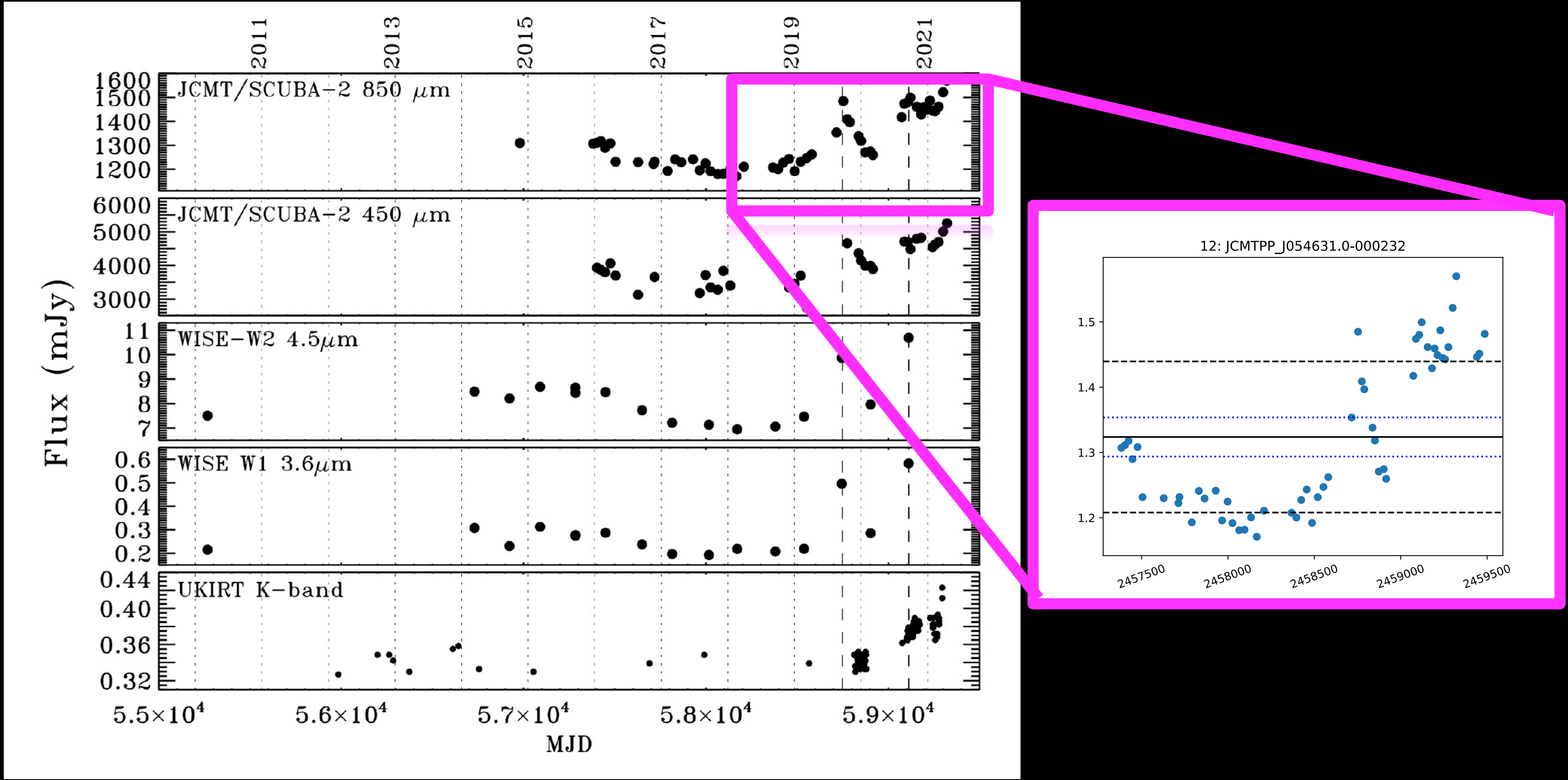
Timescale (e-folding):

- Decay ~ 0.75 yr
- Rise ~ 0.10 yr

Accretion rate: ~2.5 to 8 x 10^{-6} M_{sun}/yr

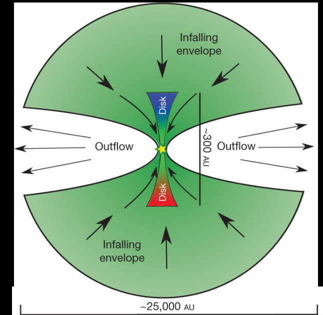
HOPS 373: a modest accretion burst

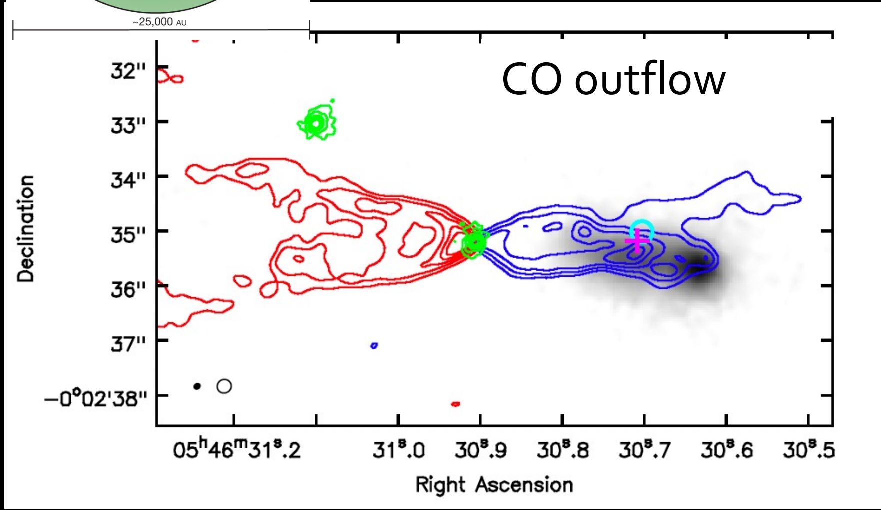
(Yoon, Herczeg, JE Lee, et al., 2022)

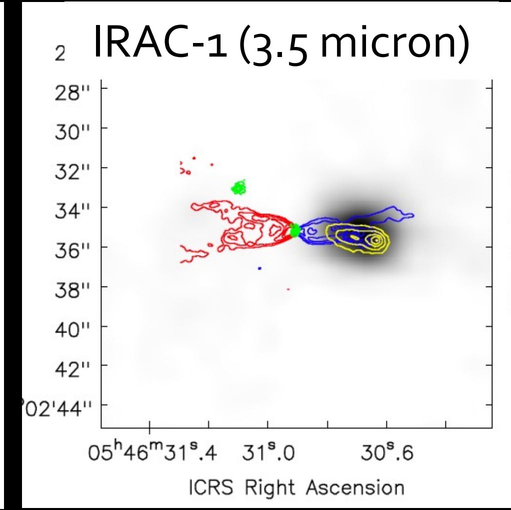


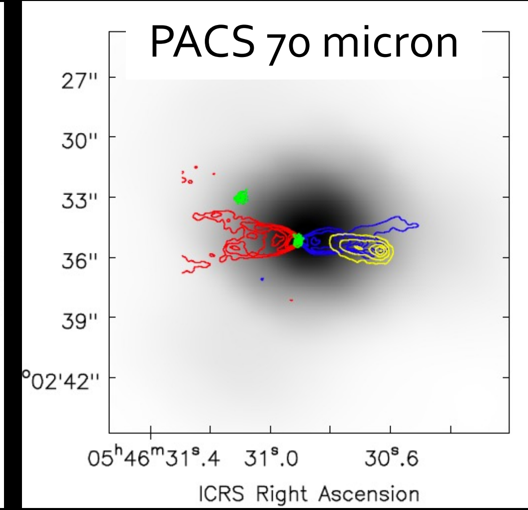
HOPS 373: a modest accretion burst

Yoon, Herczeg, JE Lee, et al. 2022





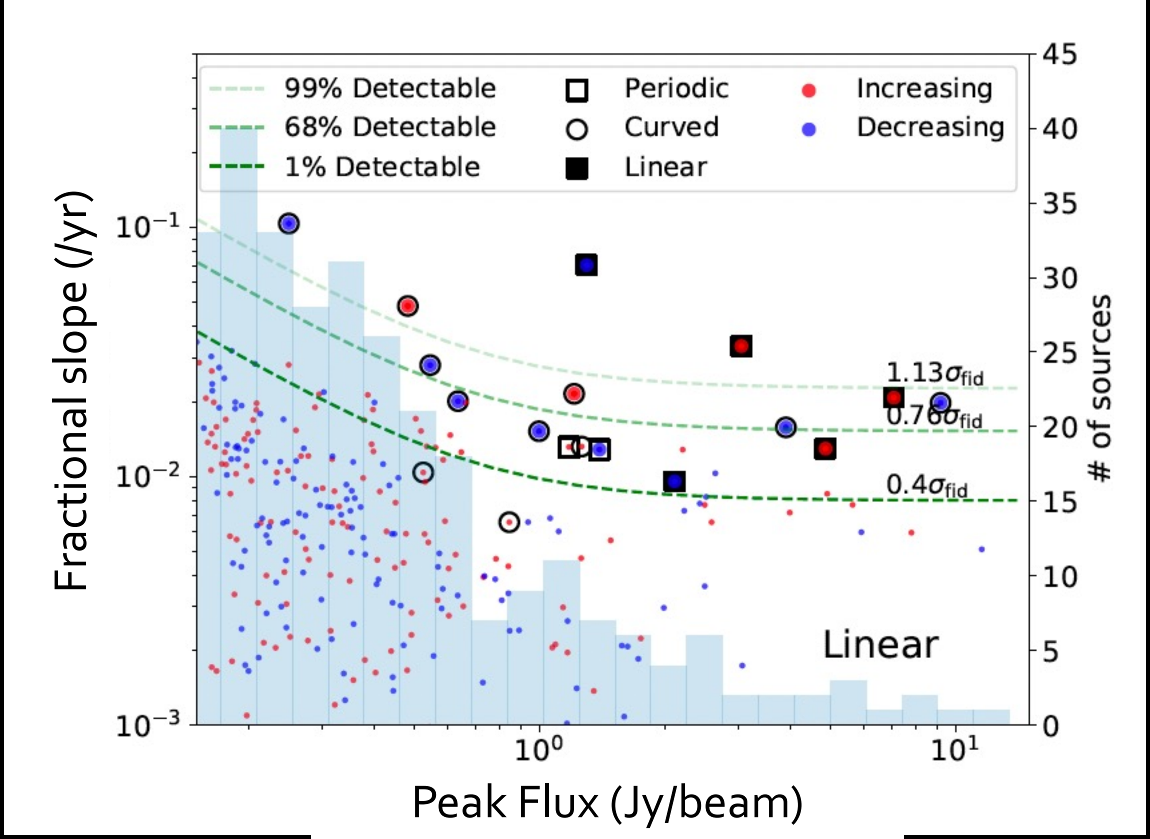




Near- and mid-IR emission: emission reflected and escapes out of cavity walls
IRAC-2, K-band variability: suppressed by H2, CO?

Summary of sub-mm variability over 4 years

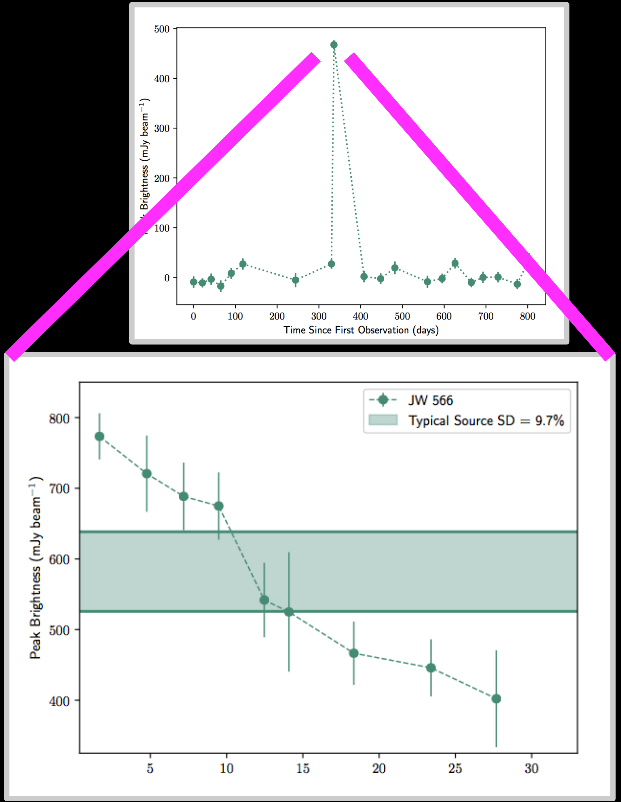
(Y-H Lee, Johnstone, et al. 2021; Johnstone et al. 2023)



- Protostars are variable!
  - About half by 5-10% per year
  - L^0.25, so modest changes
- Many interesting case studies
- Not enough time/number to detect largest bursts
- Expanding to more distant intermediate-mass star-forming regions

The sub-mm variable sky

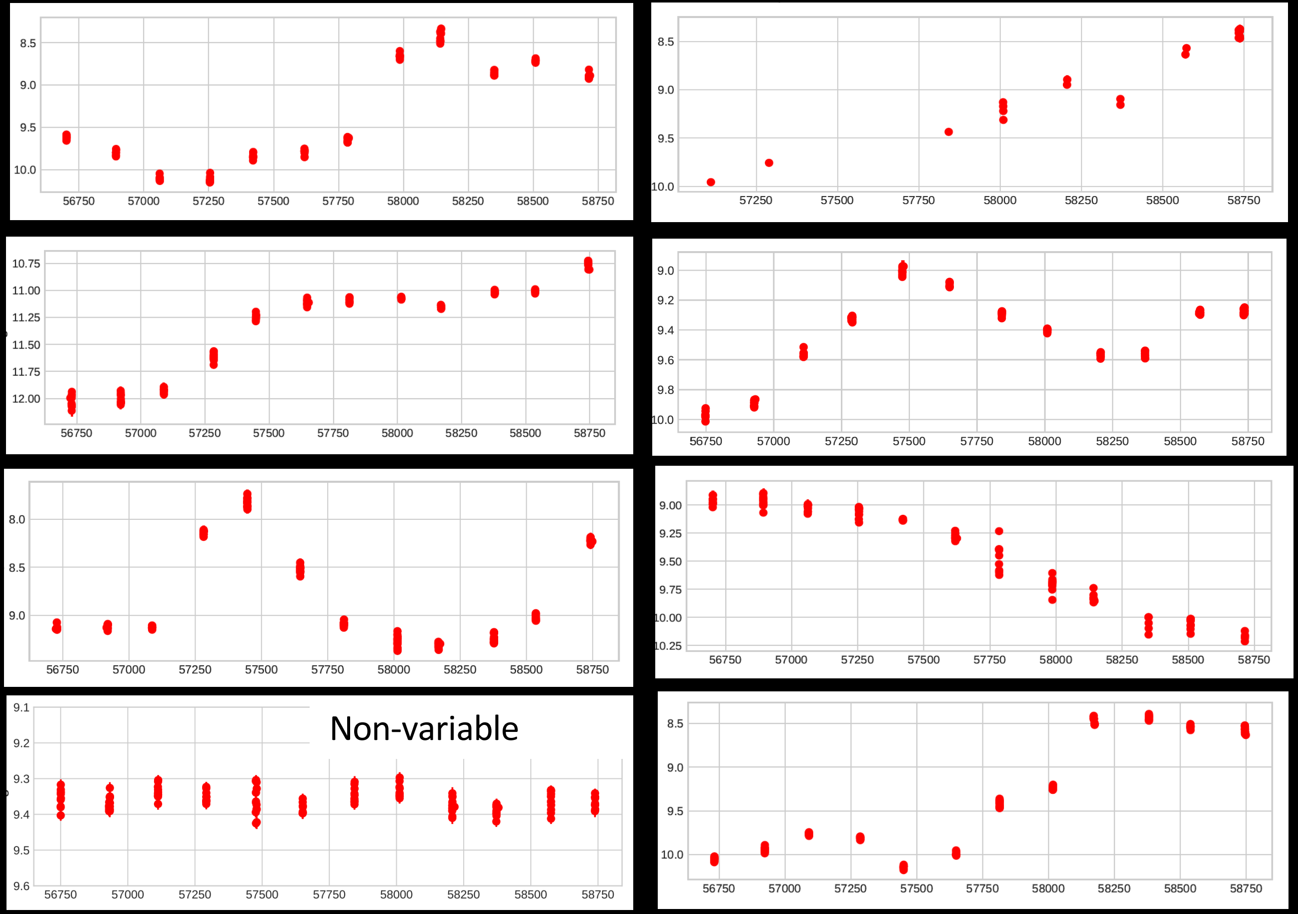
- Coronal flare on a YSO
  - Strongest ever recorded?
  - Mairs et al. 2019; Johnstone et al. 2023
- Two variable AGNs
- Sub-mm flux calibration techniques
  - Previously ~10% unquantified errors



Decay during 30-min integration

Essential for CMB-S4 Cosmology Experiment (2020 Decadal)

NEOWISE: mid-IR variable sky



- NEOWISE mission:
- All-sky, 3.6, 4.5 microns
- 2 epochs/year

- statistical analysis of variability

- Long-term goal: frequency of FUor outbursts

Park, JE Lee, et al. 2021

Follow-up spectroscopy (Gemini, IRTF, Palomar) by Contreras Pena, others

Following the mass flows: the assembly of stars and planets

The era of the transient sky is here (ASAS-SN, ZTF, NEOWISE, others; soon LSST)

gherczeg1@gmail.com

- Weather
  - frequent changes in star-disk connections
  - Spots on accreting, non-accreting stars can affect ages
- Climate
  - major changes in accretion rate
- Stellar mass assembly: "climate" of protostars
  - Need to pierce through envelope: long wavelengths
  - JCMT Transient, NEOWISE; future far-IR mission?
- ALMA: driving an amazing revolution in disk physics and planet formation
  - We may be detecting planets in formation!
  - Hopefully JWST will drive a similar revolution in direct detection of exoplanets