Protostellar Variability and the Assembly of Stars and Planets

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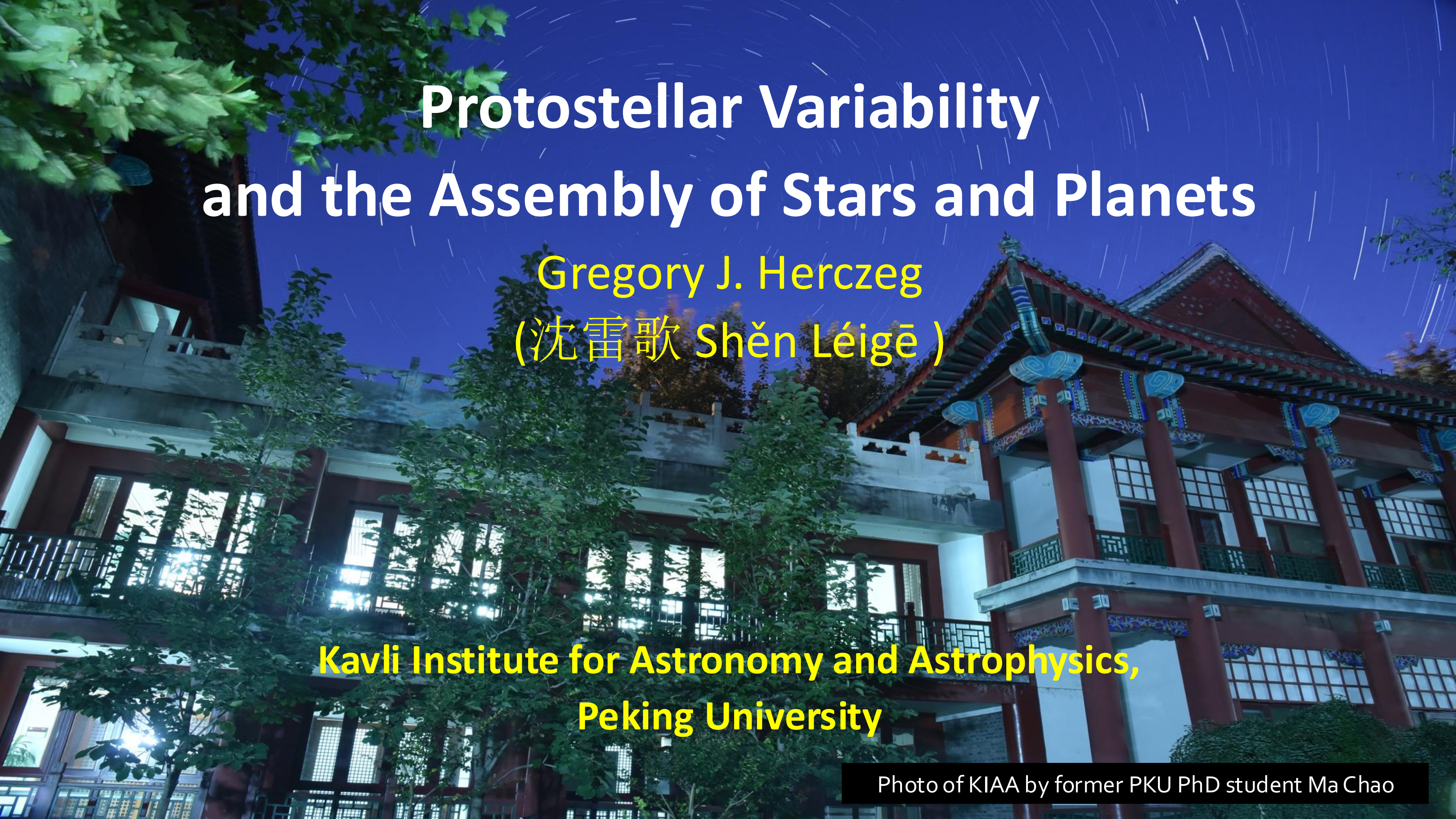
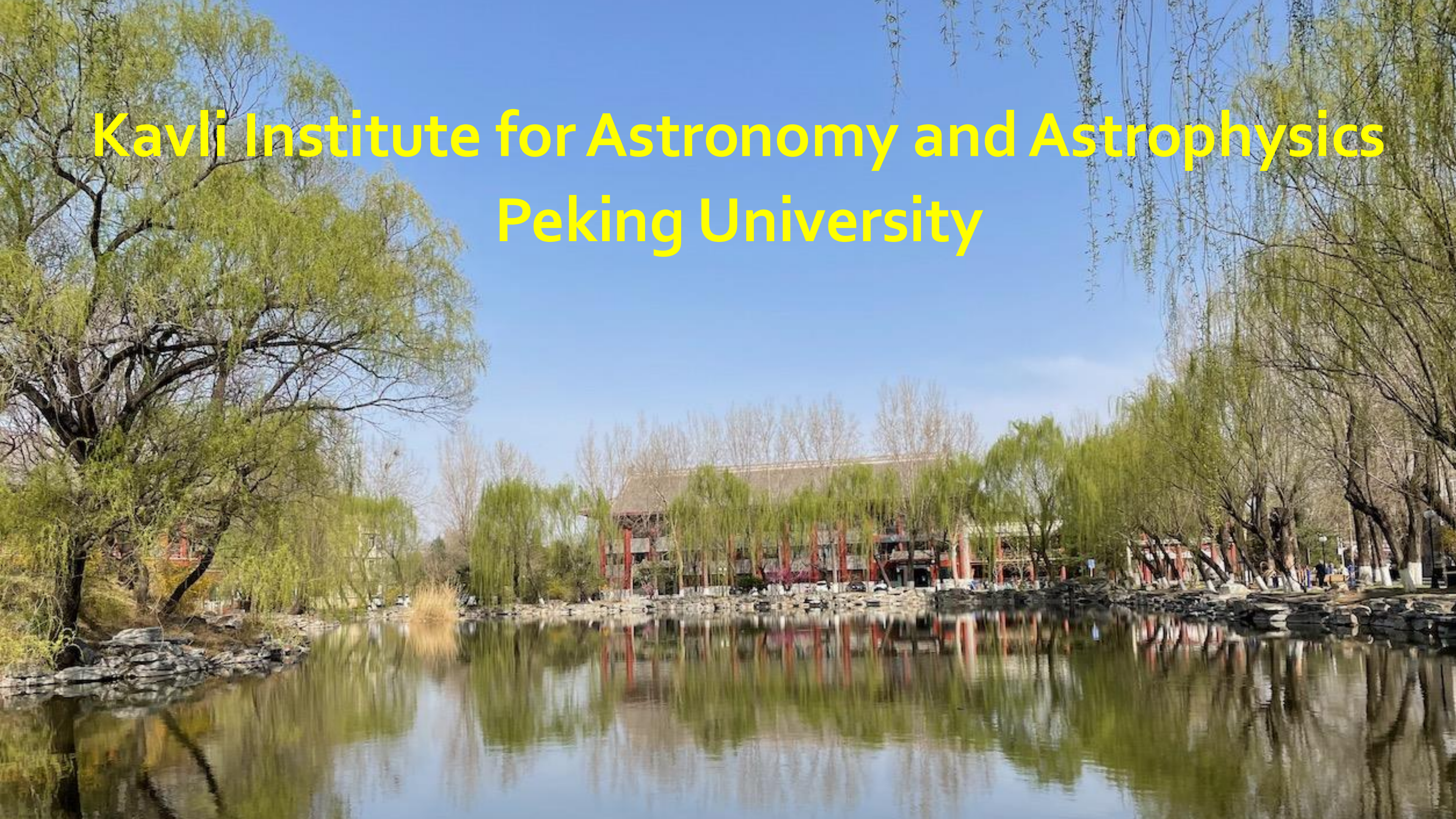


Photo of KIAA by former PKU PhD student Ma Chao


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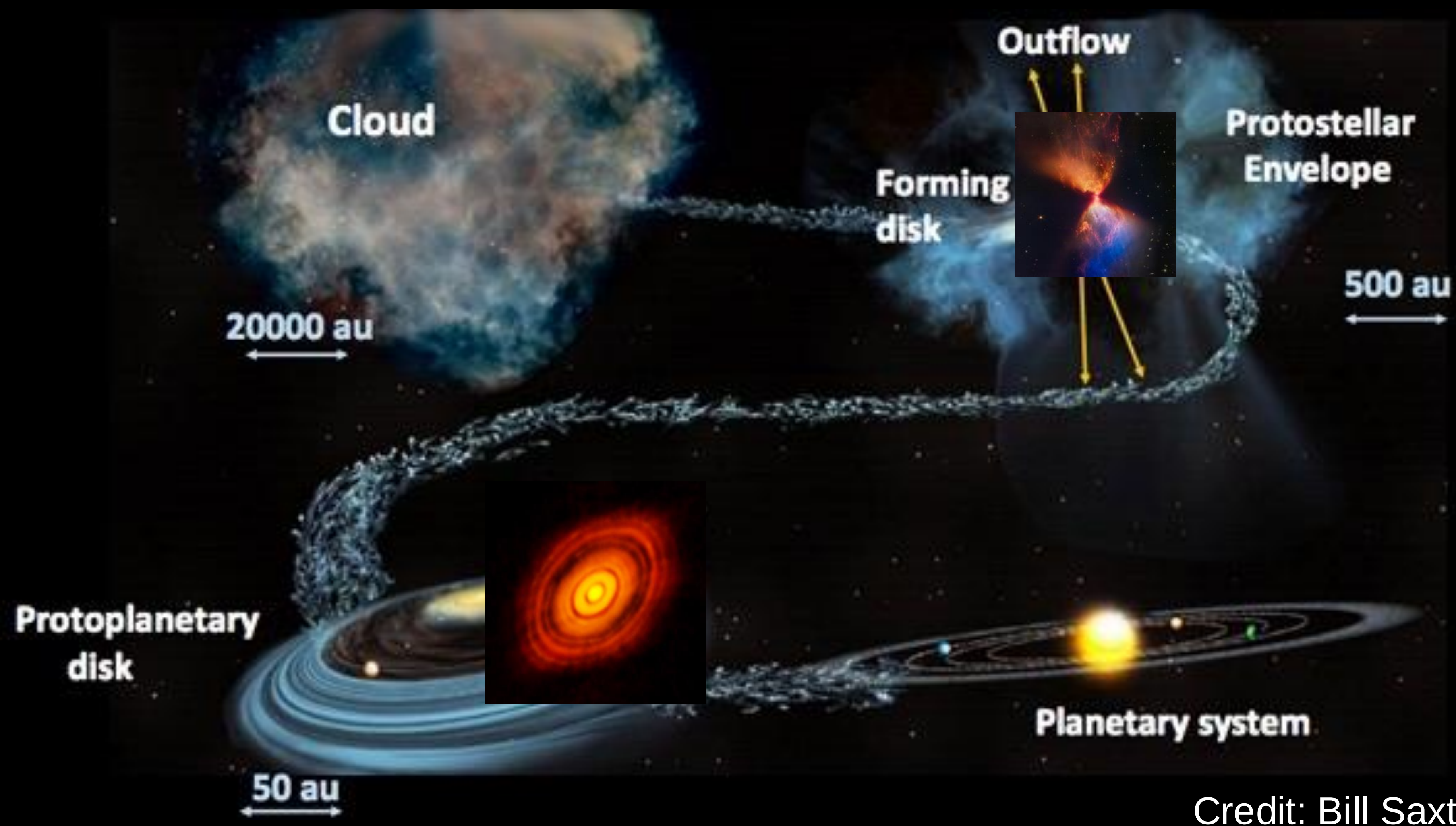
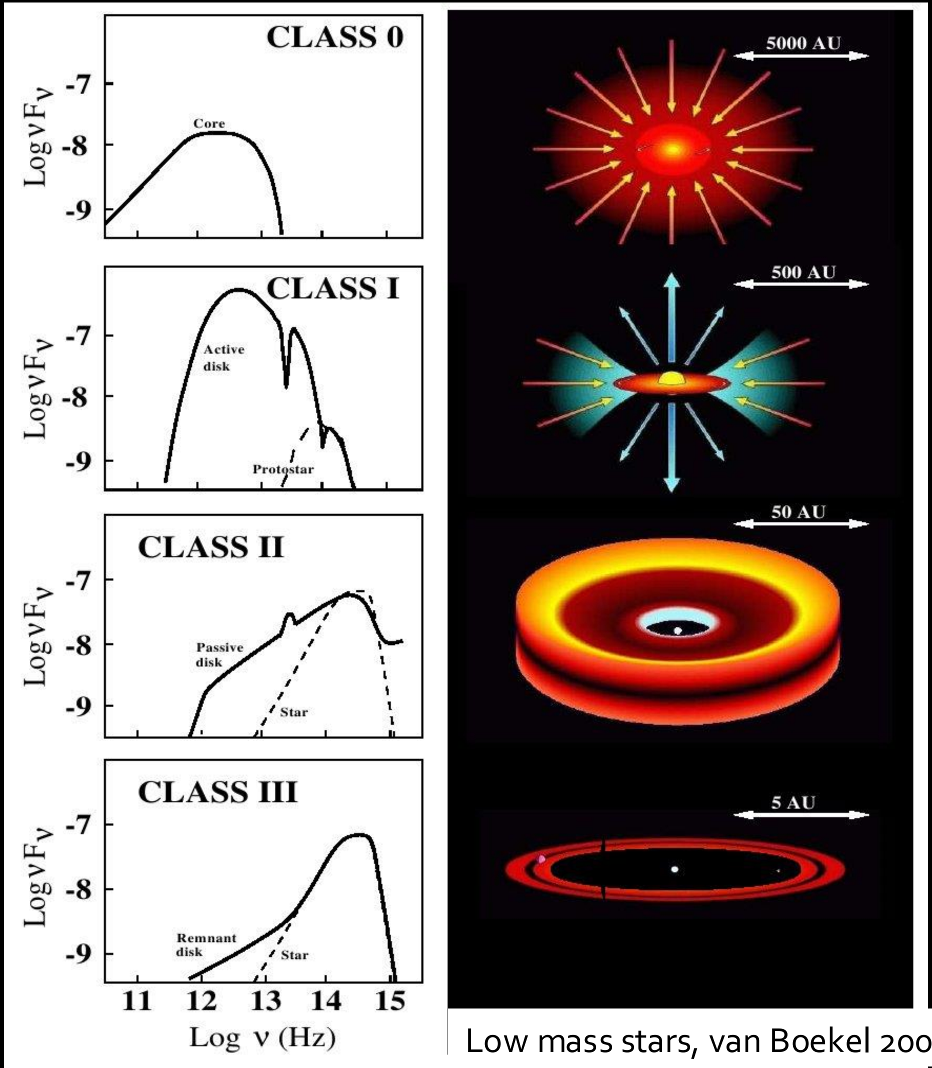
科维理天文与天体物理研究所
Kavli Institute for Astronomy and Astrophysics
Peking University Astronomy Family Photo
October 26, 2018



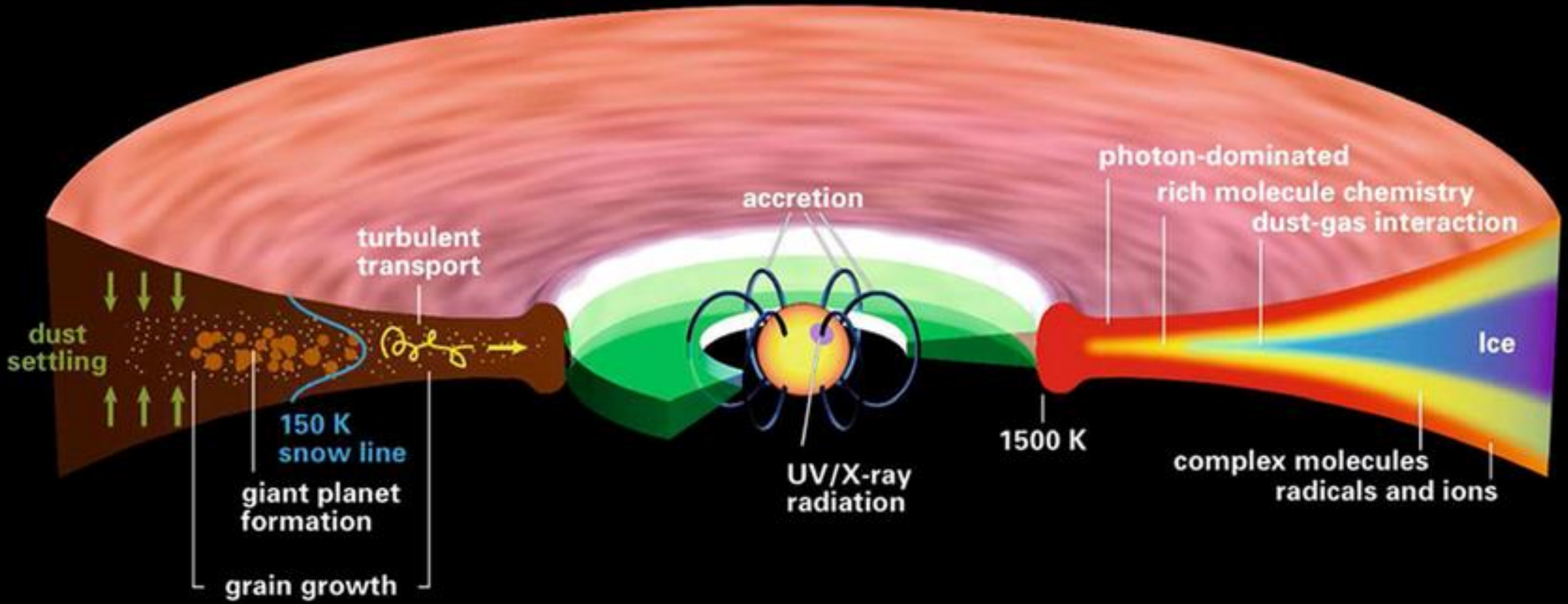
Credit: Bill Saxton



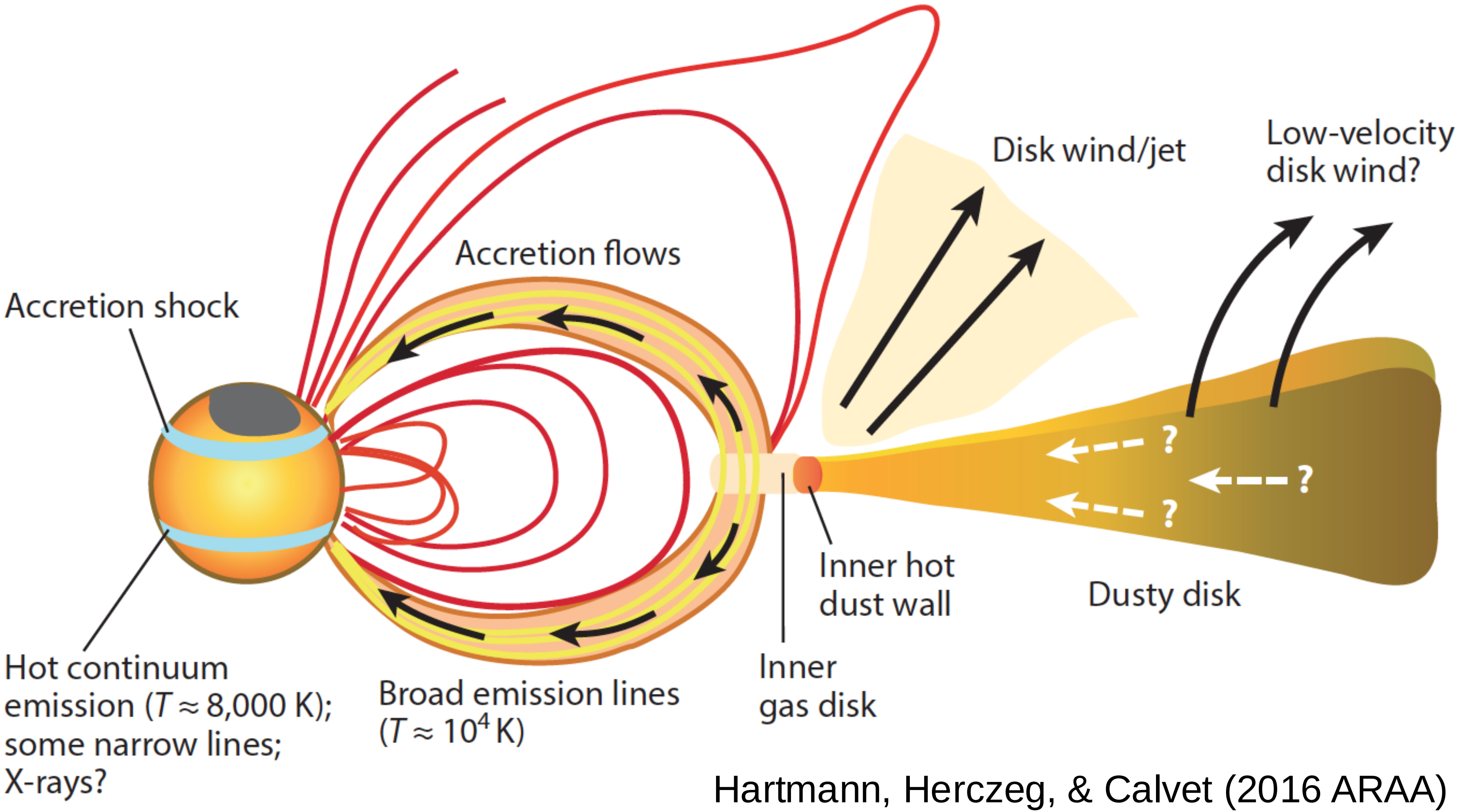
Low mass stars, van Boekel 2005

Protostars:
~few 10^5 yr
Stellar growth

Disks
~few 10^6 yr
Planet formation



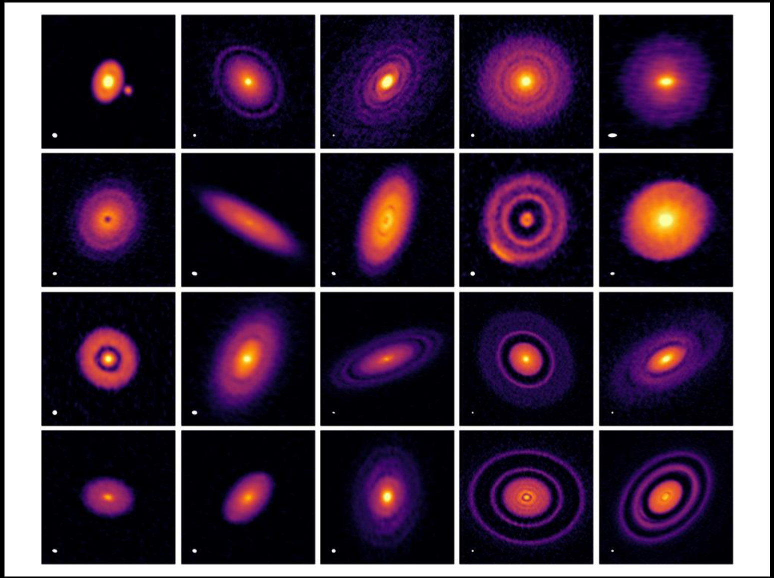
Henning & Semenov (2013)



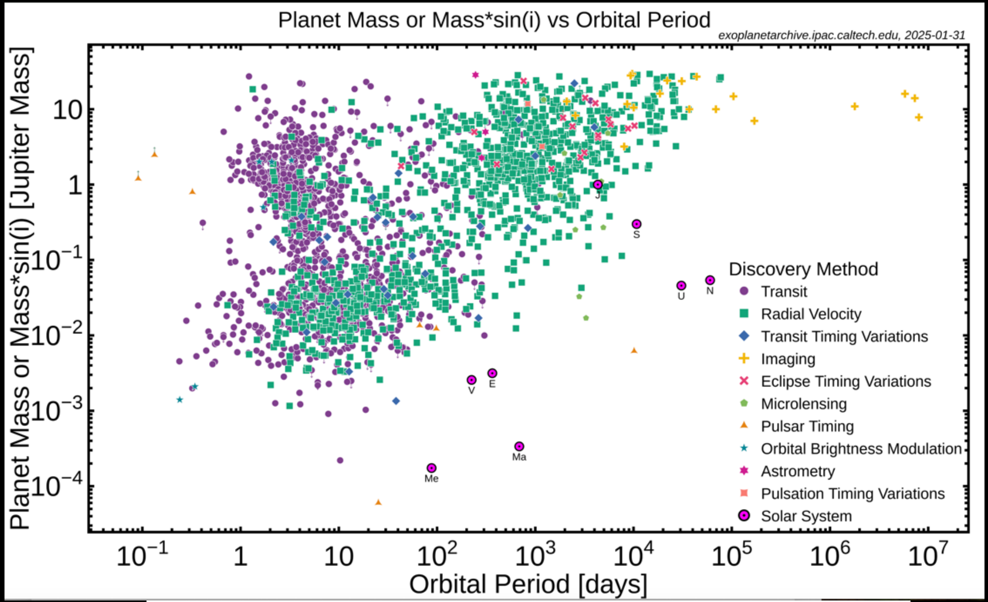
Hartmann, Herczeg, & Calvet (2016 ARAA)

Diversity in star and disk outcomes:

Accretion physics is instability physics: variability



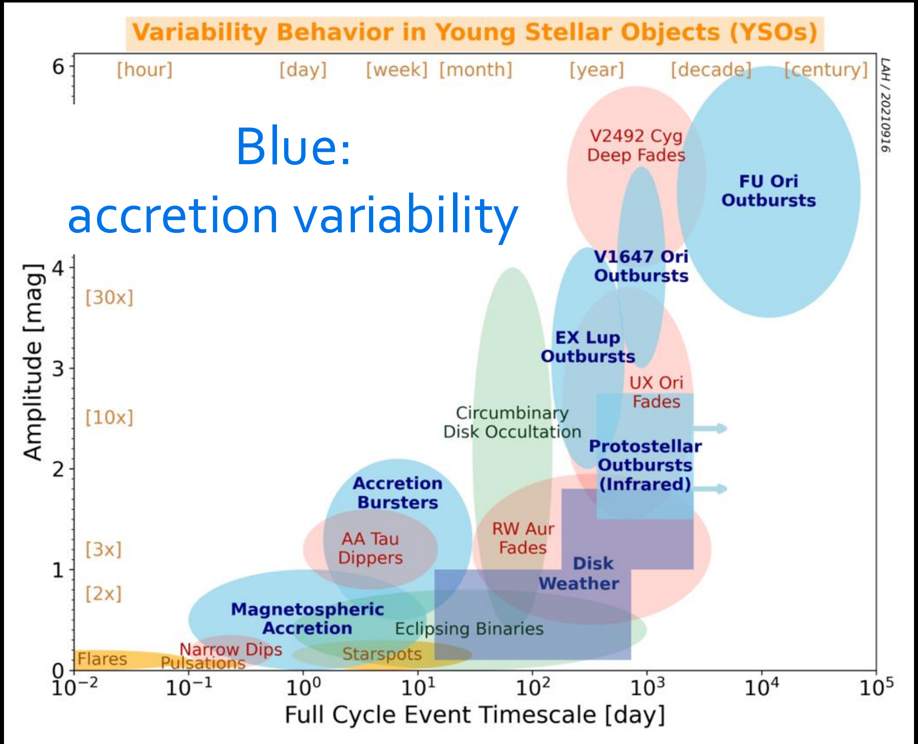
ALMA DSHARP, Andrews+2018:
brightness-selected disks
See also, e.g., Long+2018



NASA Exoplanet Archive

Diversity in star and disk outcomes:

Accretion physics is instability physics

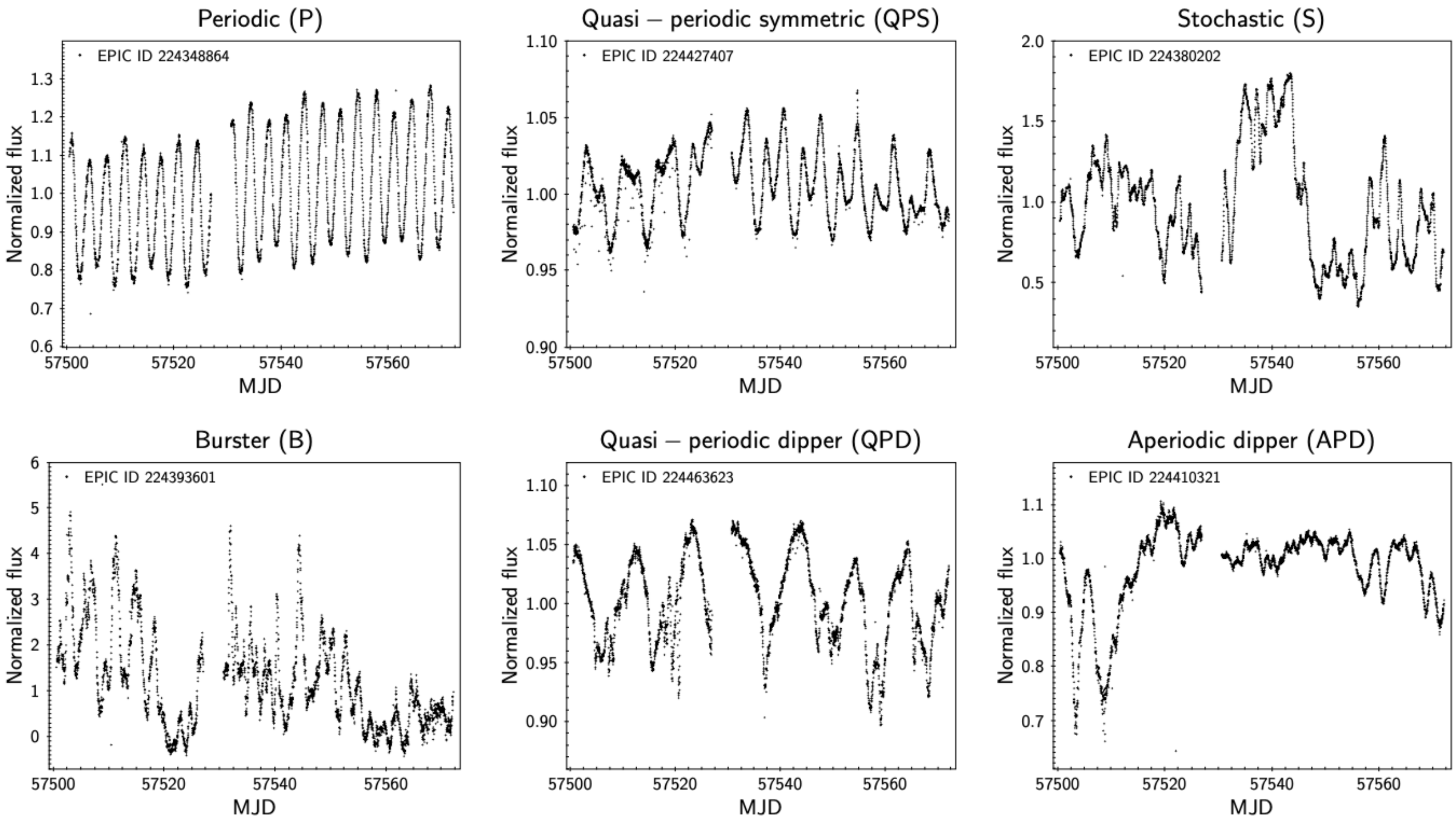


Hillenbrand & Findeisen (2015)

What is the role of variability in stellar mass assembly?

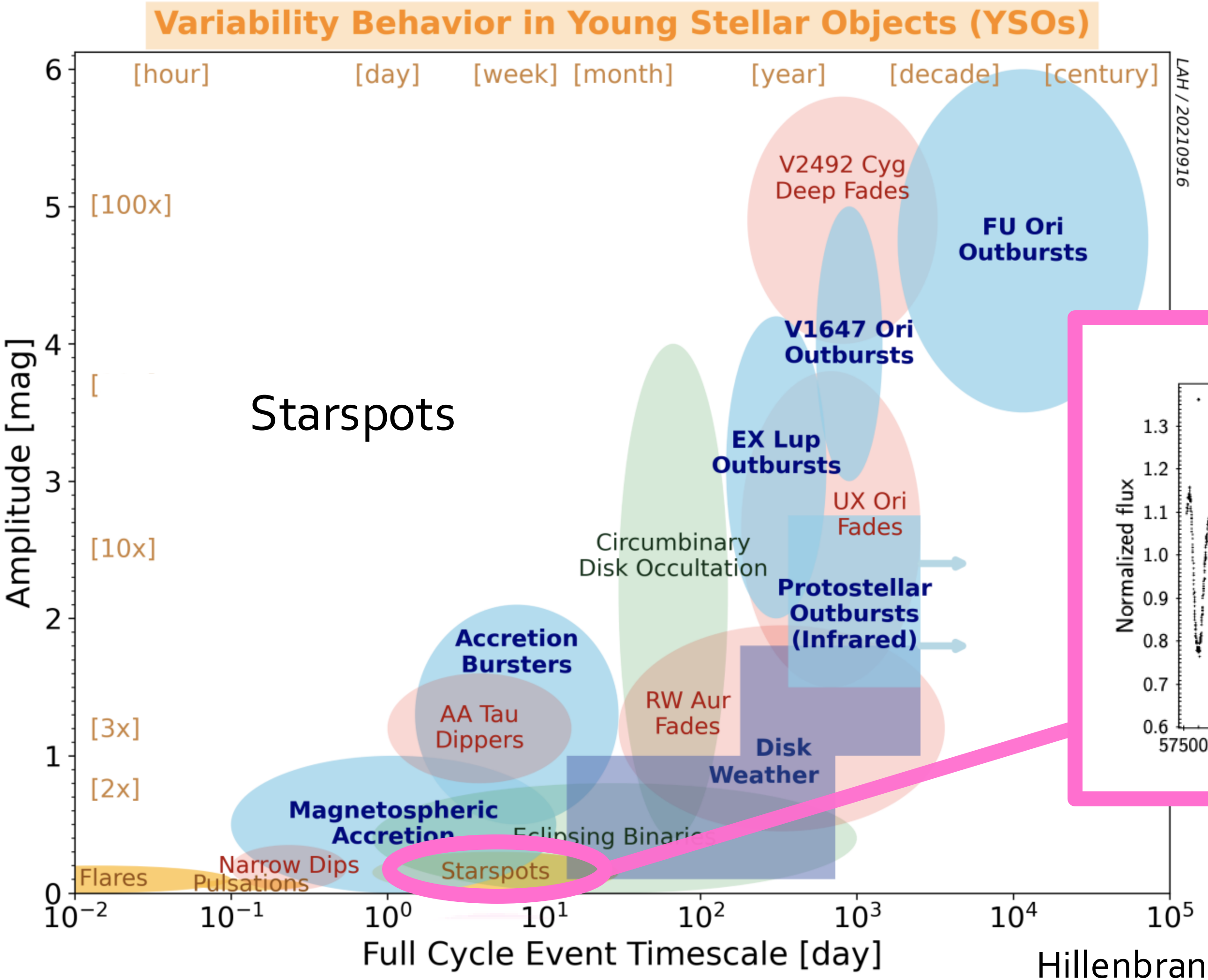
PPVII Review
Will Fischer
Lynne Hillenbrand
Gregory Herczeg
Doug Johnstone
Agnes Kospal
Mike Dunham

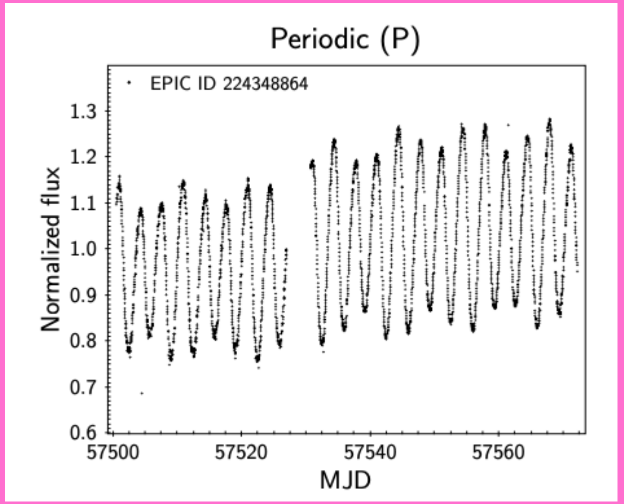
Will Fischer, 1980-2024



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)

Starspots





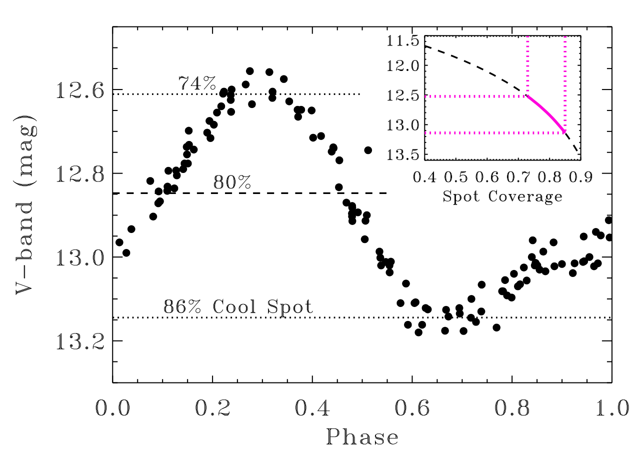
Hillenbrand & Findeisen (2015)

Placing the spotted young star LkCa 4 on the HR diagram

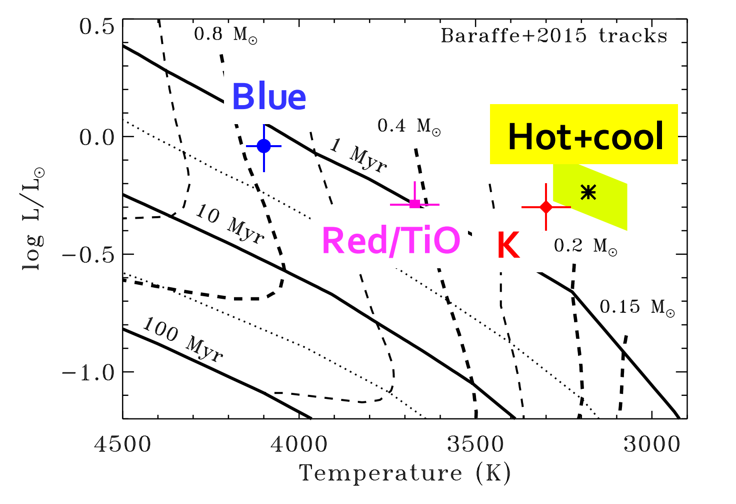
(Gully-Santiago, Herczeg, et al. 2017, using the STARFISH code from Czekala+2015)

<u>IGRINS high-res H&K spectra</u>

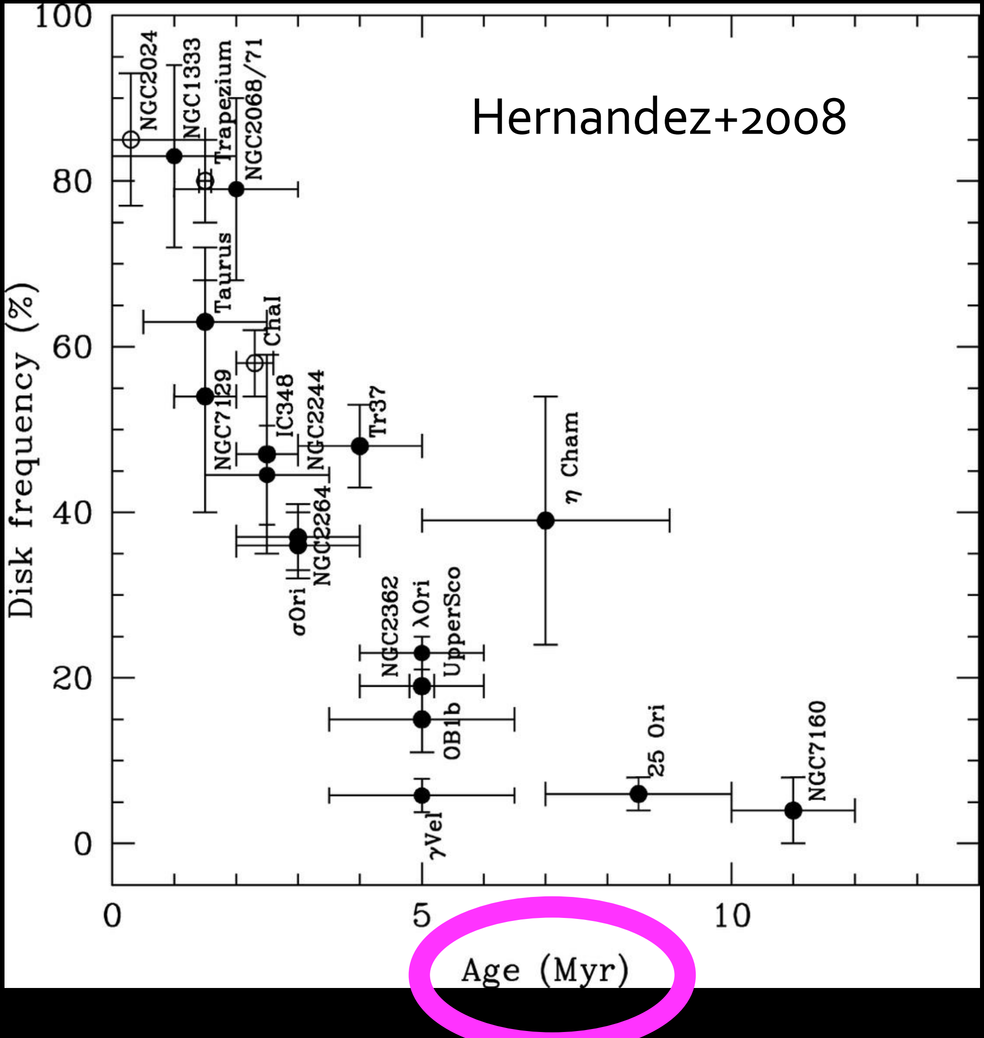
Two temperature fit:	4000, 2750 K
Fill factor of cool component:	80%



Large amplitude: filling factor must be high



Extreme case but spots are universal for convective stars: See, e.g., Fang et al. 2016, Cao et al. 2022

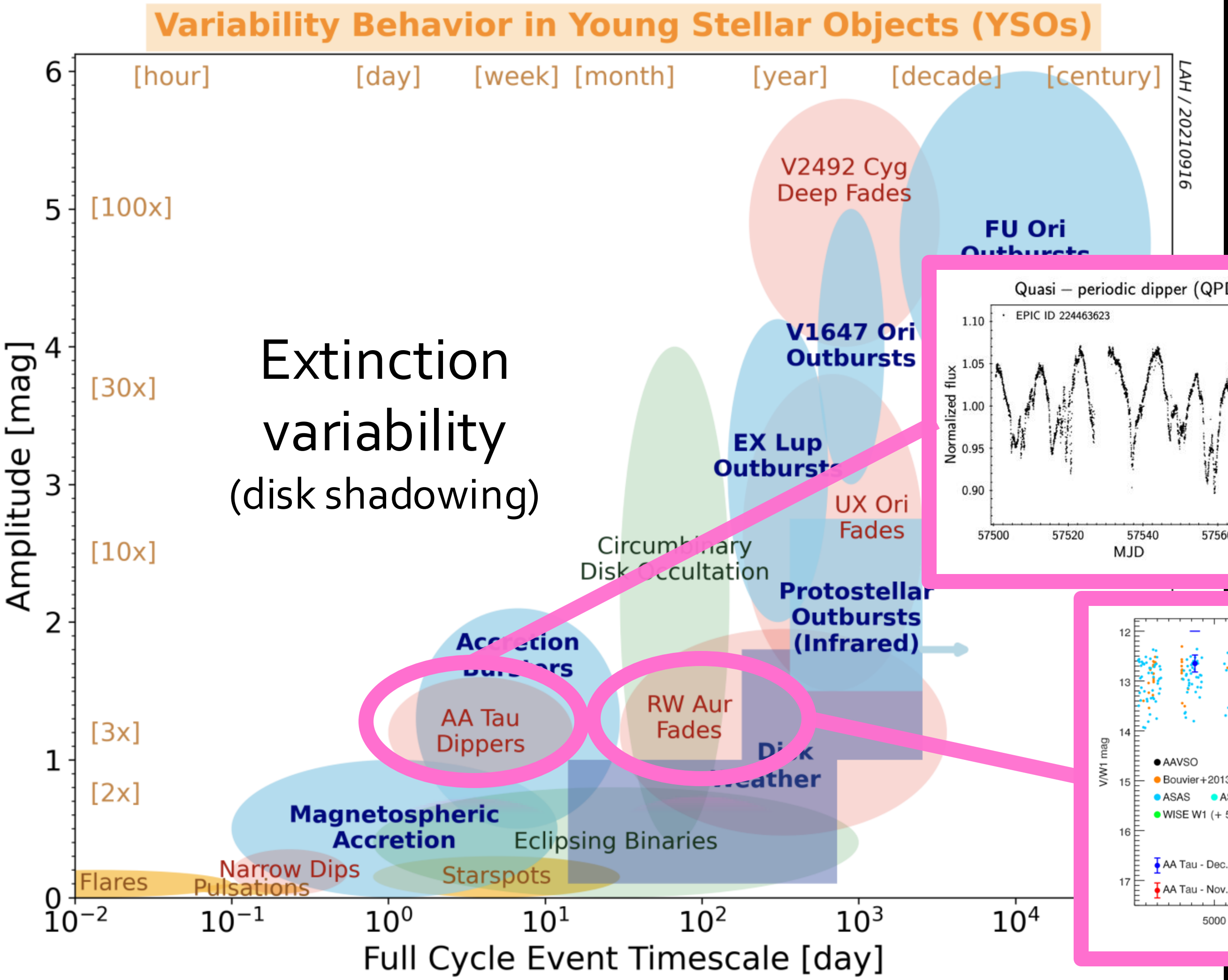


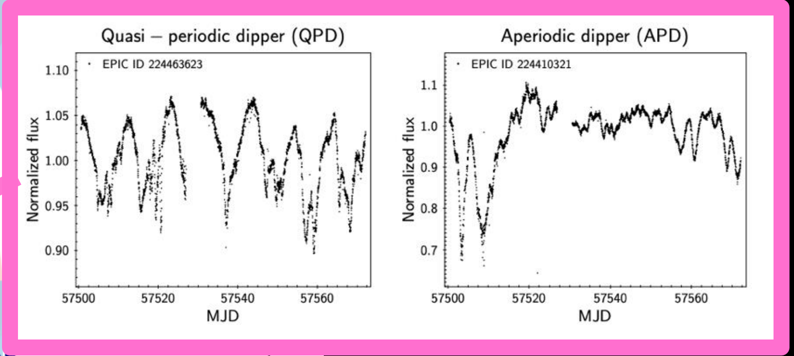
Spots affect ages

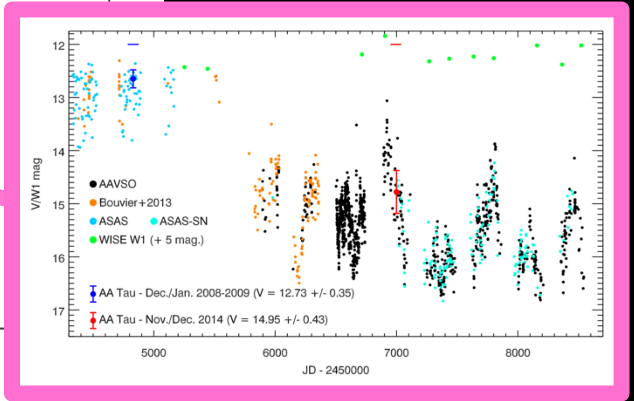
Age from HR diagram: Luminosity and Teff

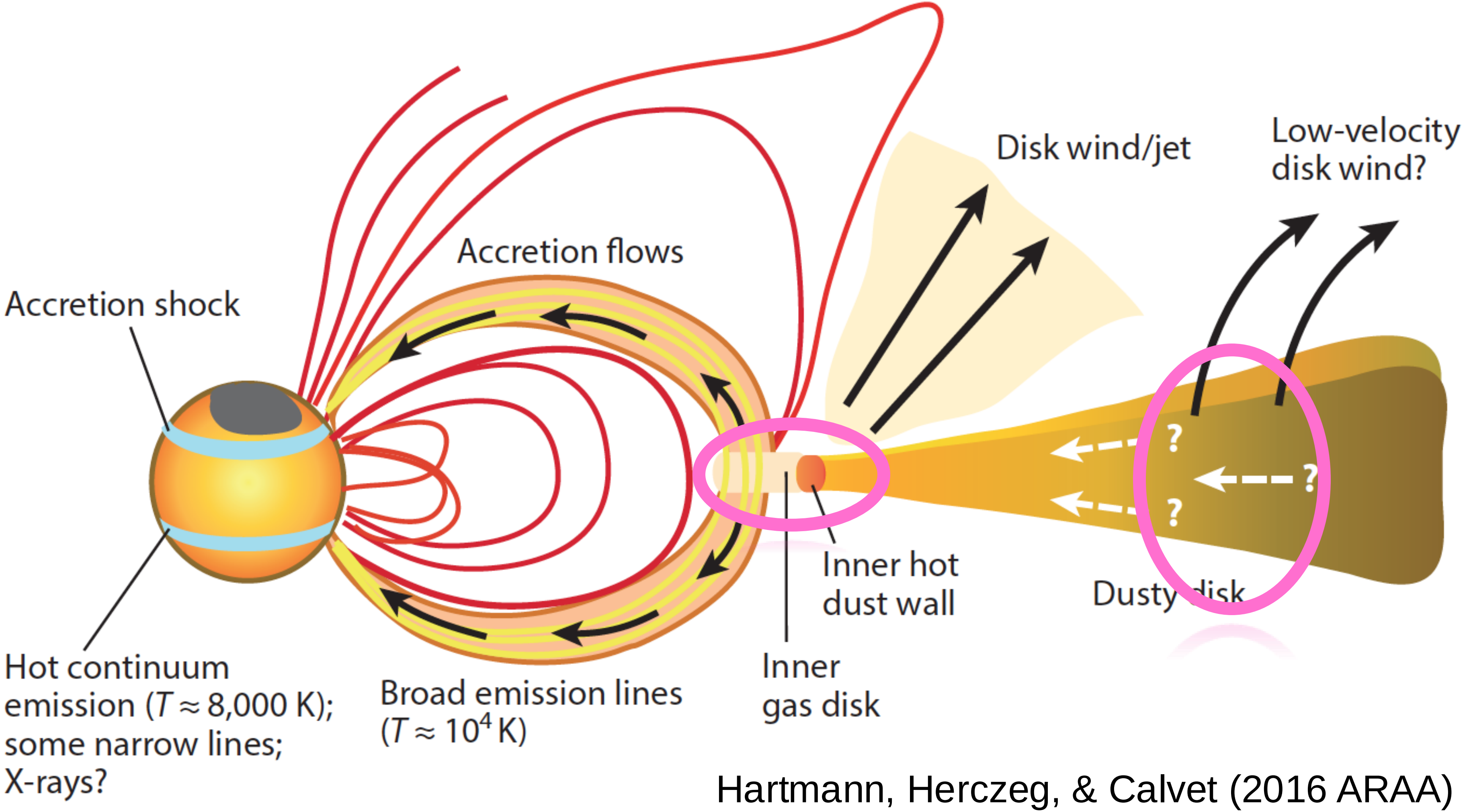
- Factors of 2 uncertainty in disk (and envelope) lifetimes
- Spotted evolutionary models (Somers+2020)
- Spot measurements in many young regions (Cao+2023)

Extinction variability
(disk shadowing)

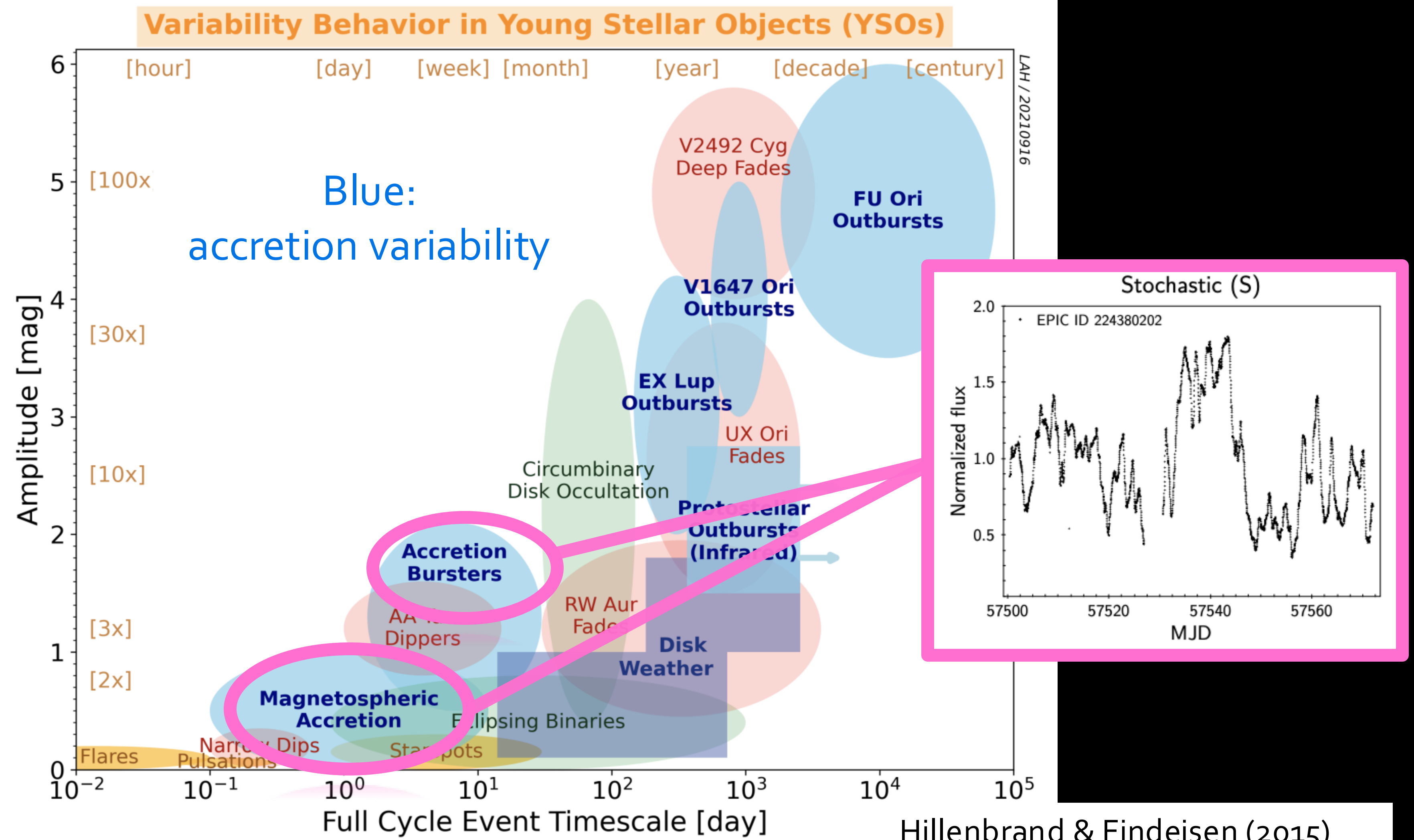








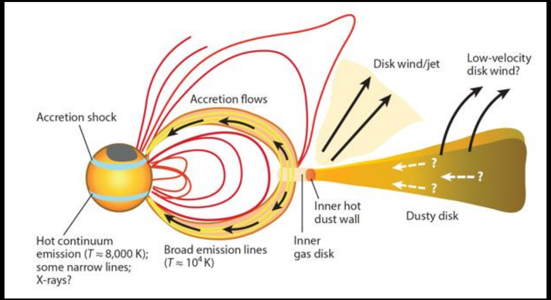
Hartmann, Herczeg, & Calvet (2016 ARAA)

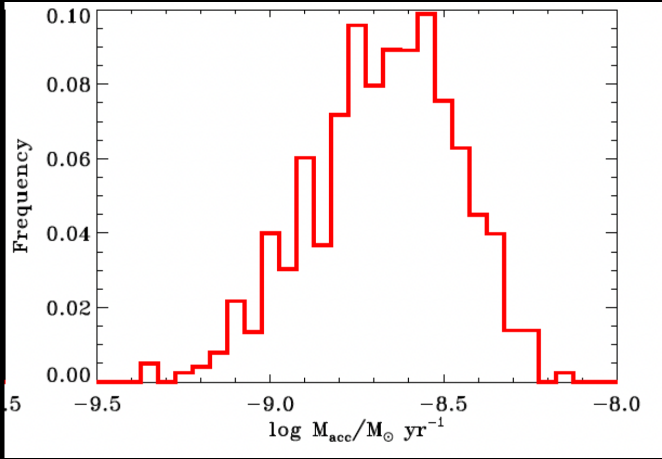


Hillenbrand & Findeisen (2015)

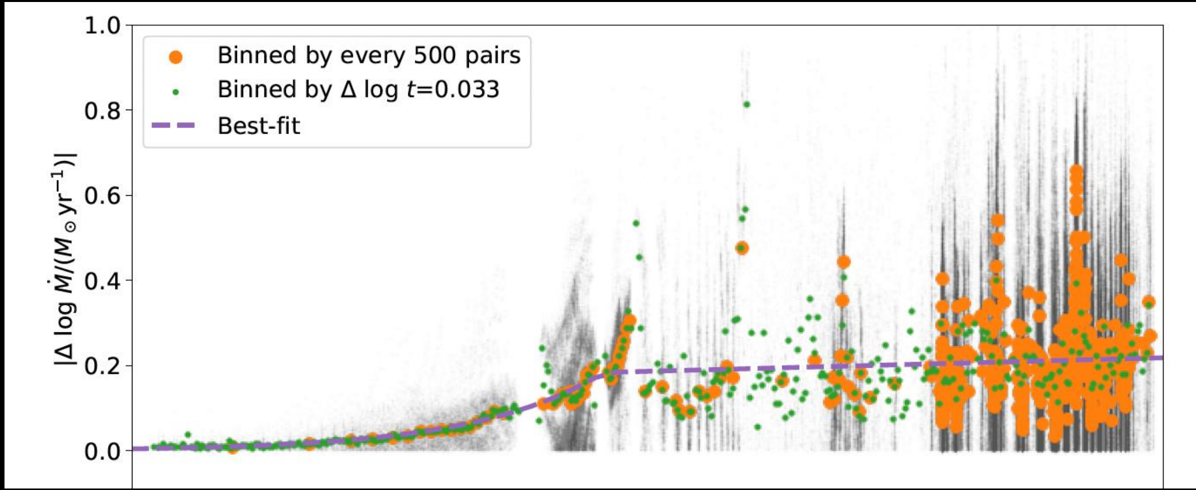
Variability of accretion onto TW Hya

(Herczeg, Yuguang Chen, et al., 2023)



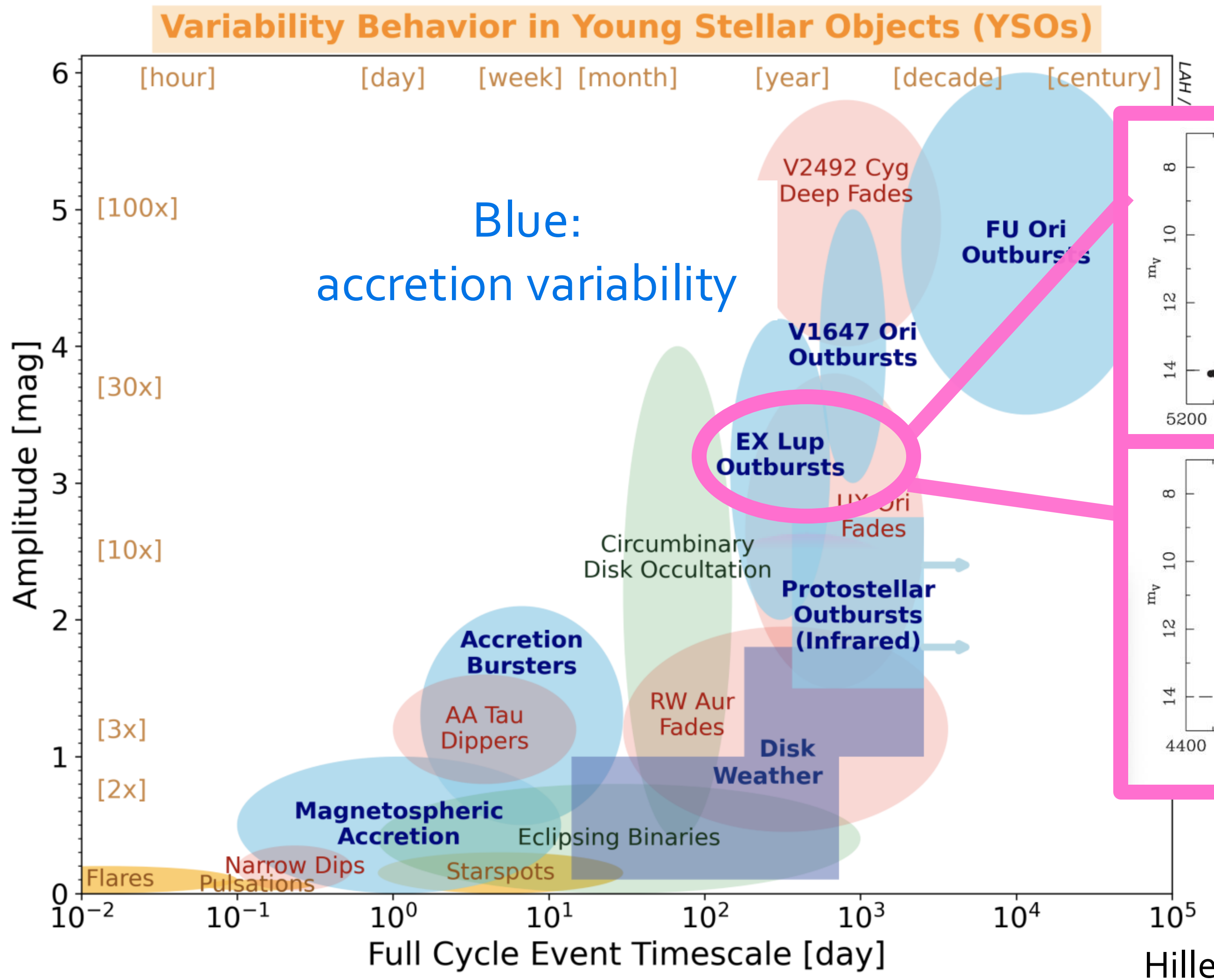


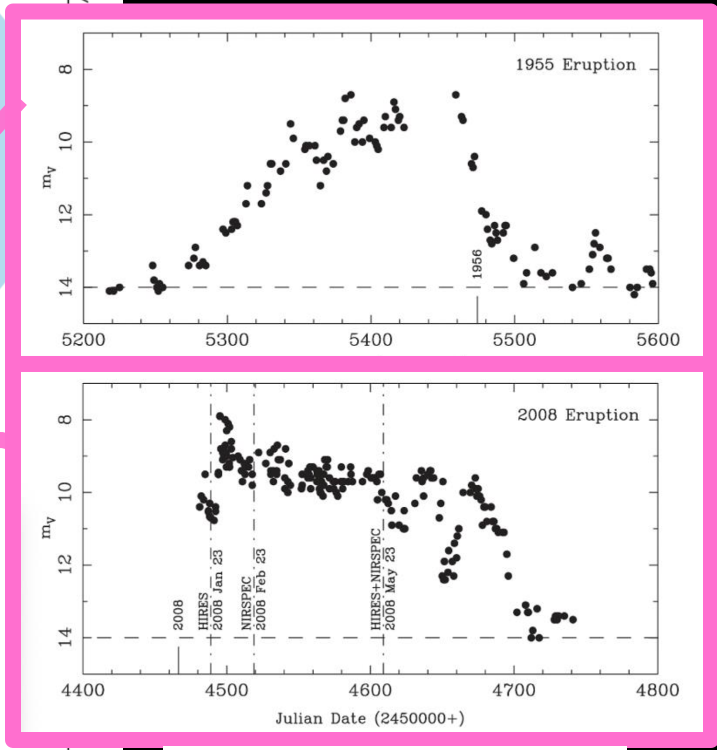
Accretion rates from
1168 high-resolution spectra(!)



Structure function:

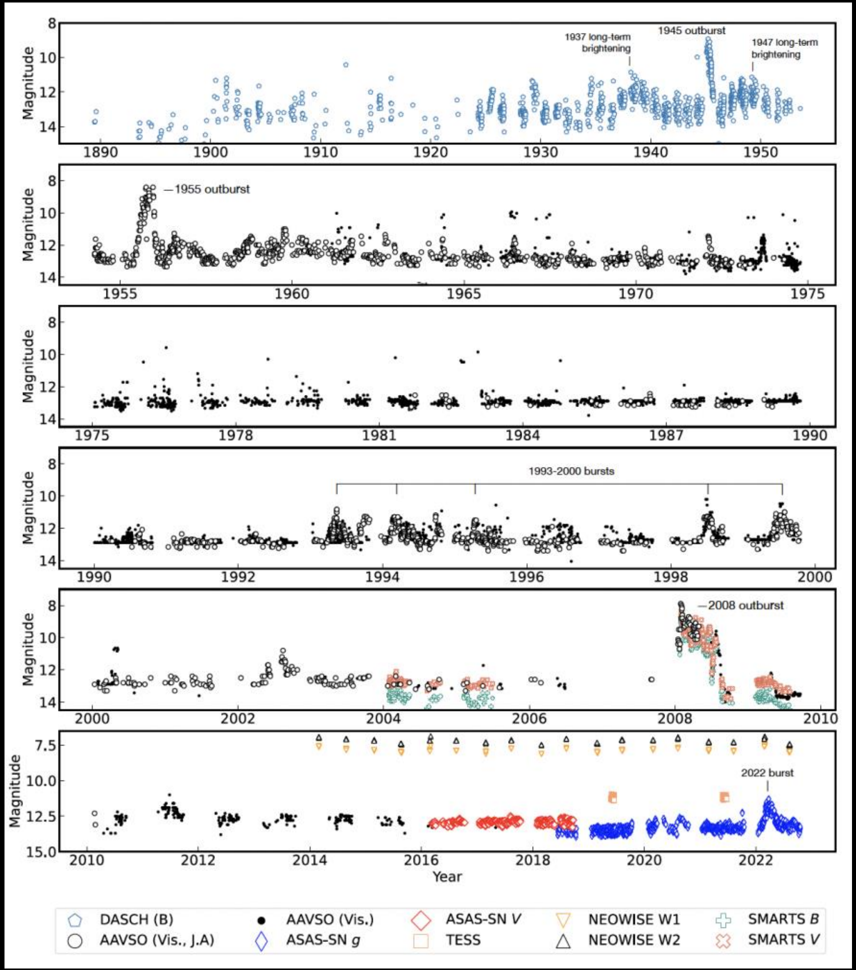
- reset timescale of 1.6 days
- Variability of ~0.2 dex





EX Lup (Aspin et al. 2010)

Hillenbrand & Findeisen (2015)



A century of accretion bursts onto EX Lup

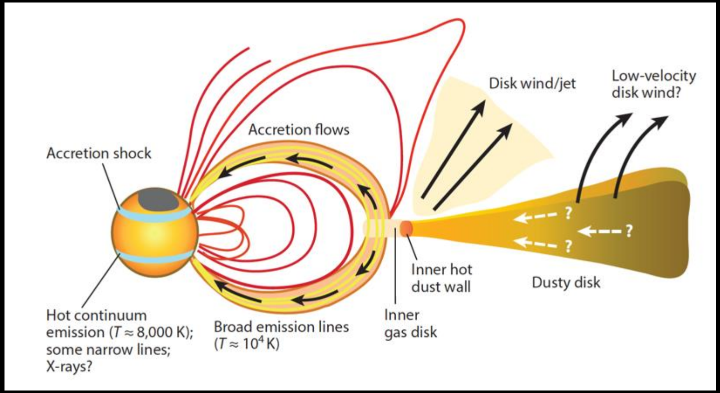
Wang Mu-Tian, Herczeg, et al. 2023;

see also Cruz Saenz de Miera et al. 2023, Sicilia-Aguilar et al. 2023)

- Archetype of EX Lup-type bursts
  - Herbig 1951; 2008
- Small and large bursts
- Roughly half of mass accreted during bursts

“Weather” of Young Stellar Objects

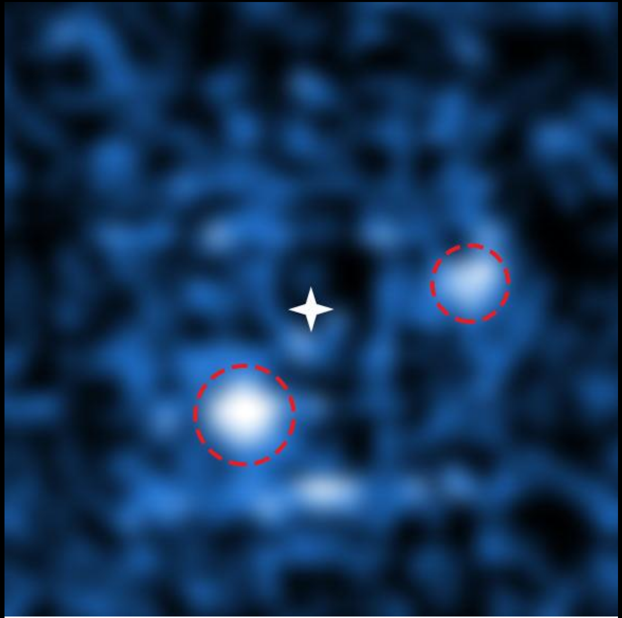
- Diskless (often older): starspots
- Disks: accretion, extinction, winds



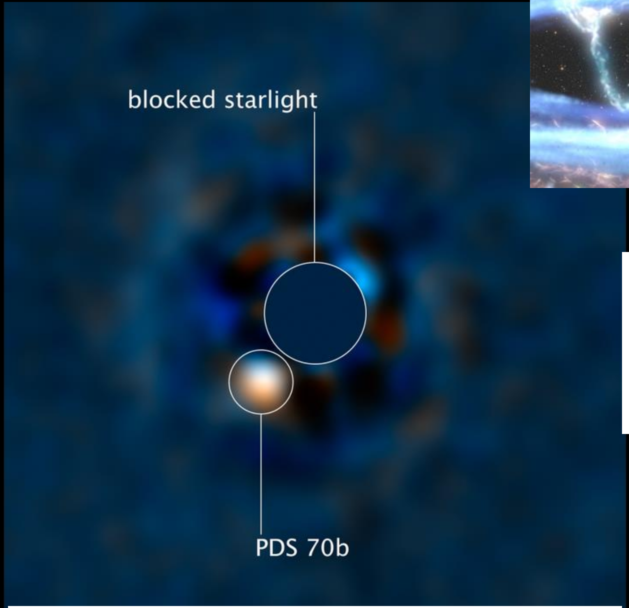
<u>Not stellar mass assembly!</u>

- Average accretion: 1e-8 Msun/yr
- Disk timescale: 3e6 yr
- 0.03 Msun: negligible mass

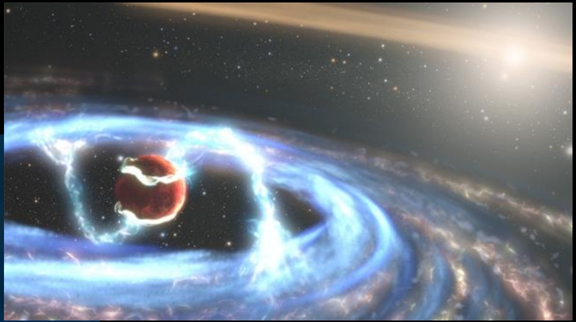
Watching young planets grow!



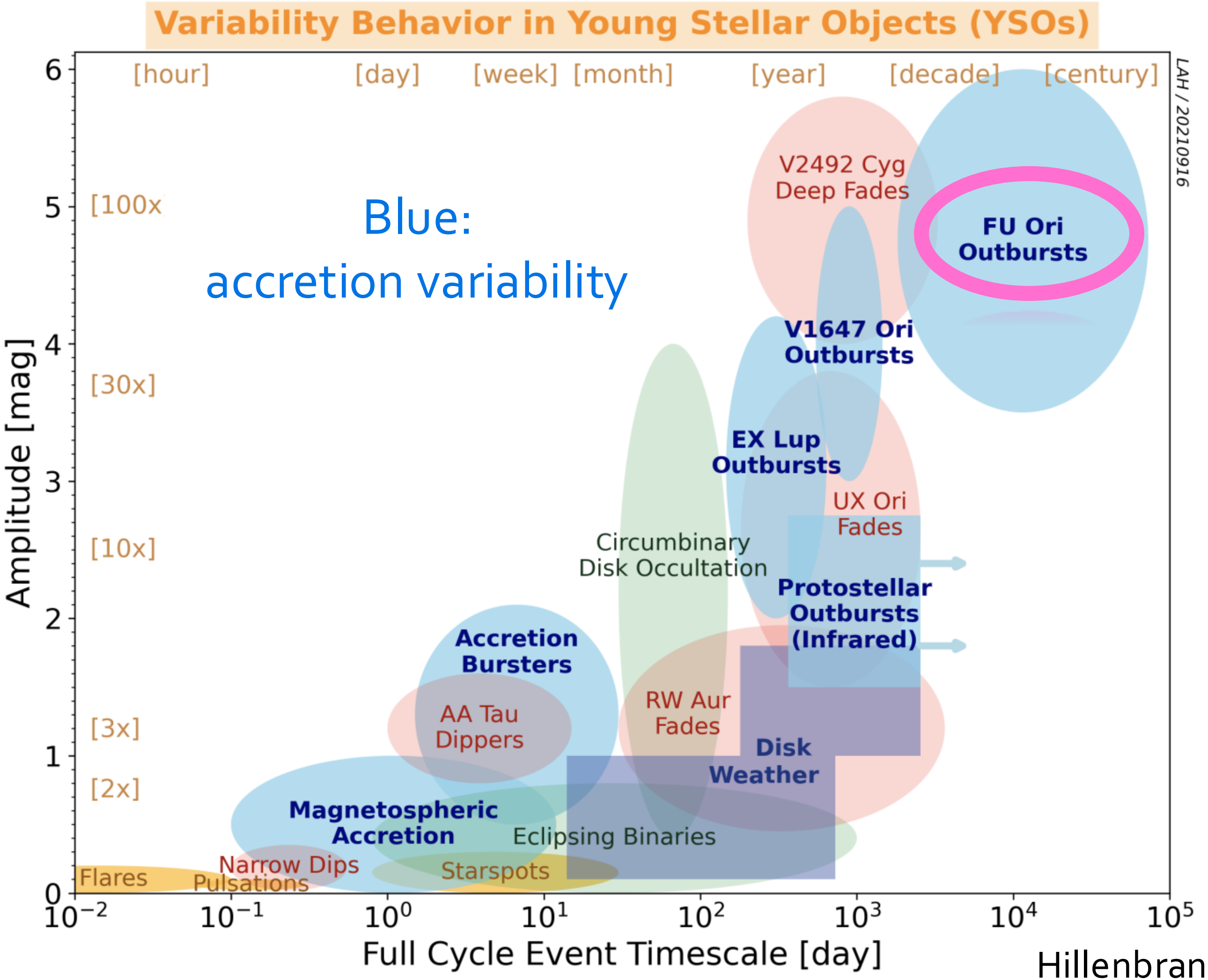
VLT MUSE H-alpha images
Haffert et al. 2019



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



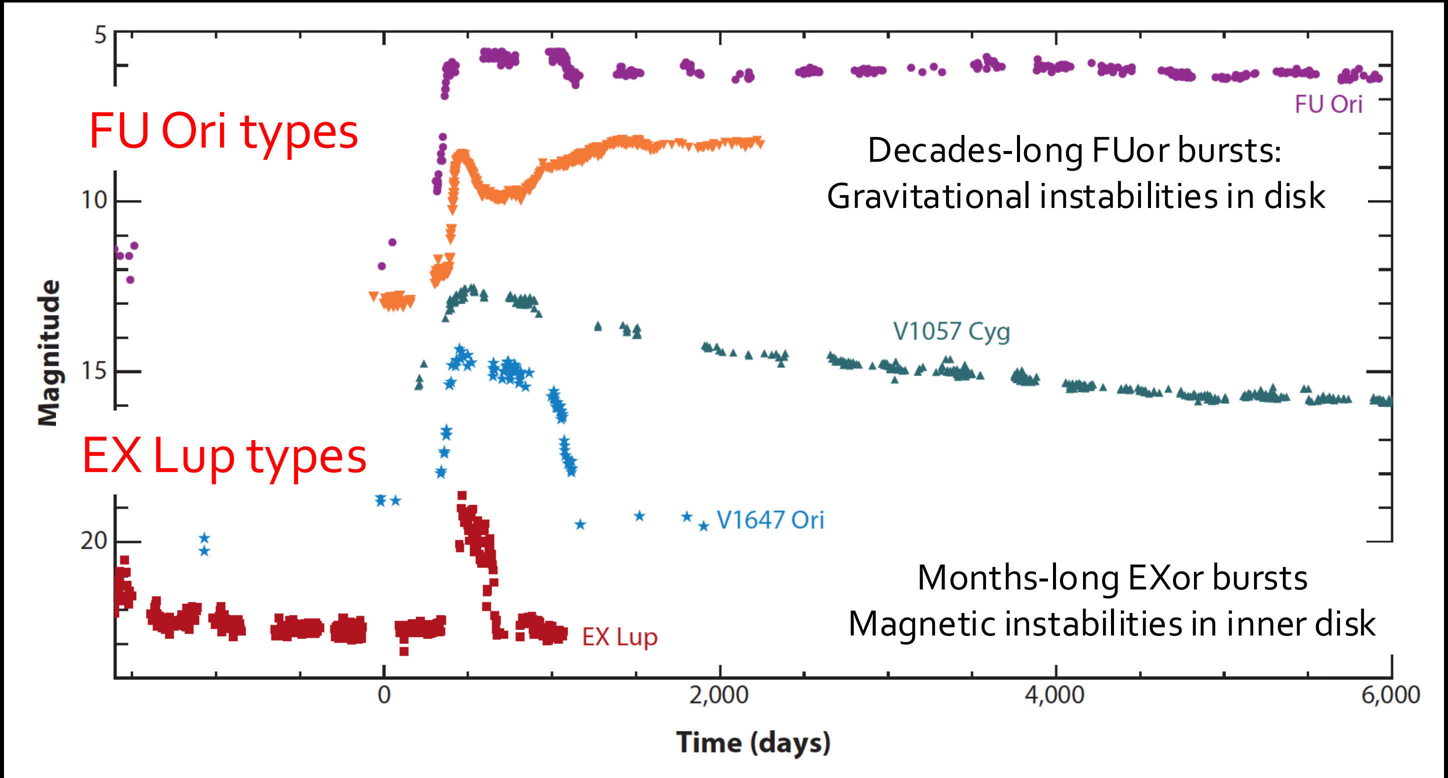
Planets in disk around PDS 70



Hillenbrand & Findeisen (2015)

FU Ori type outbursts

(adapted from Kospal+2011)

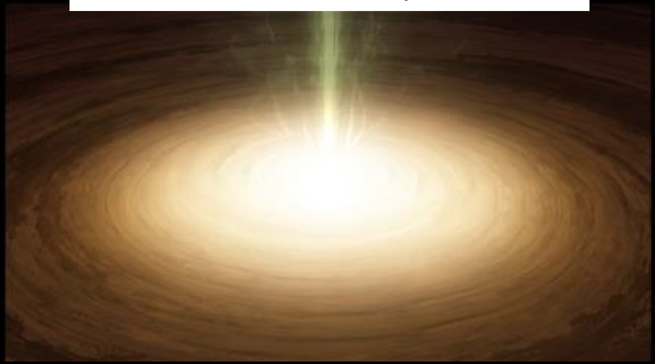


Most recent bursts are found by PTF/ZTF and Gaia

FU Ori type outbursts

- Accretion crushes stellar magnetosphere
- Disk viscously heated to ~10000 K
- Disk emission overwhelms stellar photosphere
- Viscous timescales: 0.1-1 AU
- Causes: disk instabilities

- <u>**May play major role in stellar assembly**</u>
  - Macc/outburst: 1e-5 * 1e2 = 1e-3 Msun per burst



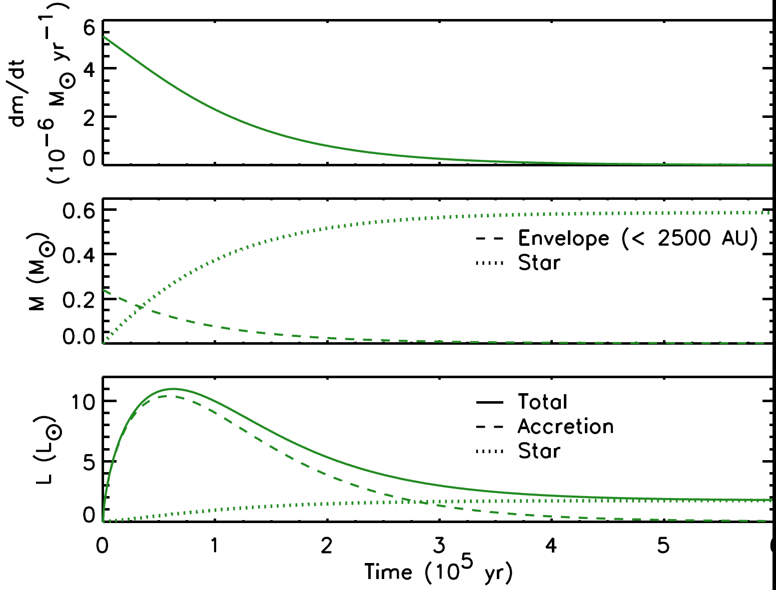
Cartoon from Fischer+2023 review

Role of bursts in stellar assembly is uncertain

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

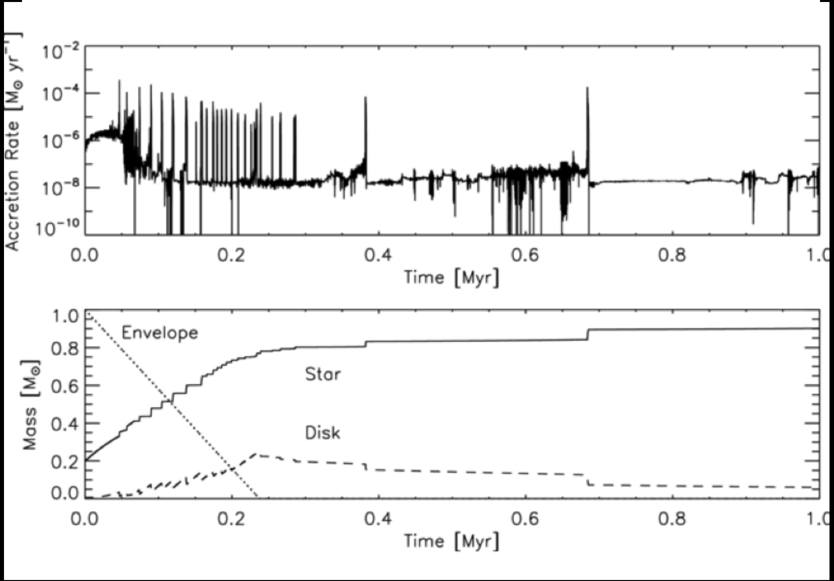
Smooth accretion:

Fischer+2017



Accretion bursts:

models by Zhu+2010; Bae+2014



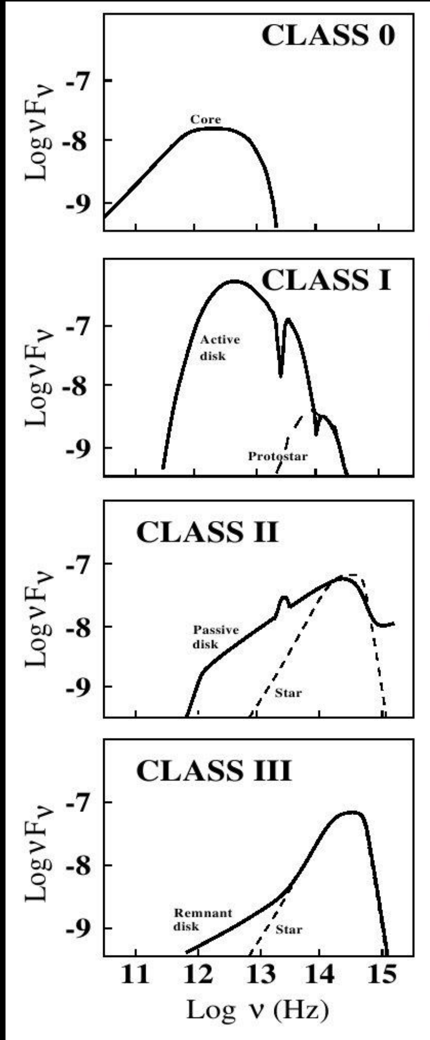
If occur early and radiative, affects initial radius (age estimate) of star

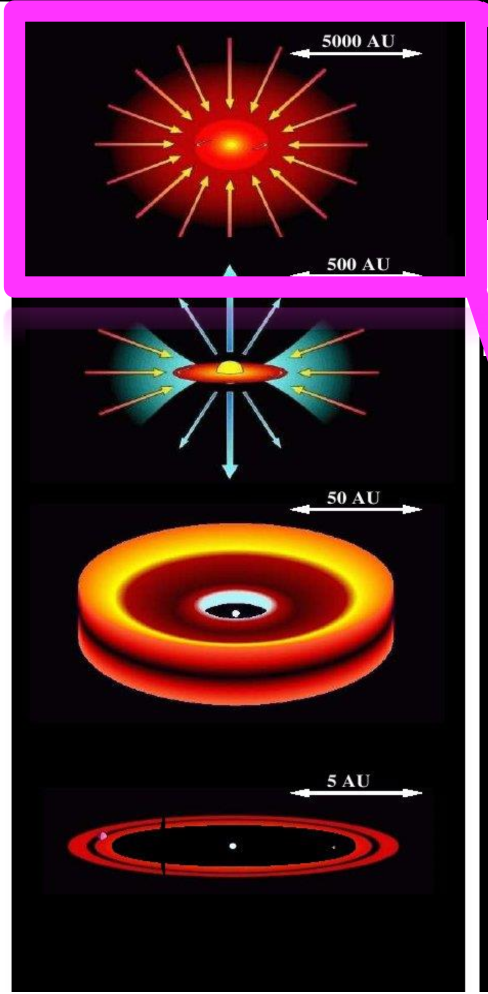
(e.g., Baraffe et al. 2009; Hosokawa et al. 2011; Kunitomo et al. 2017)

Stellar assembly occurs during protostellar phase

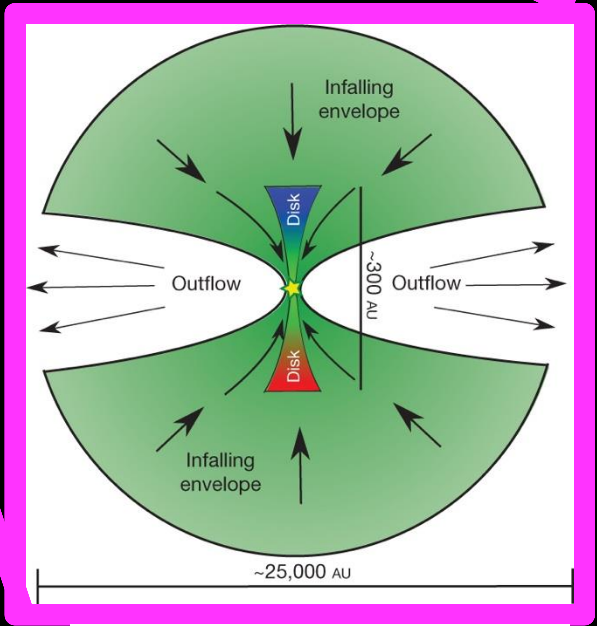
$L_{tot}=L_{acc}+L_{phot}$

Buried in envelope, Scattered by dust





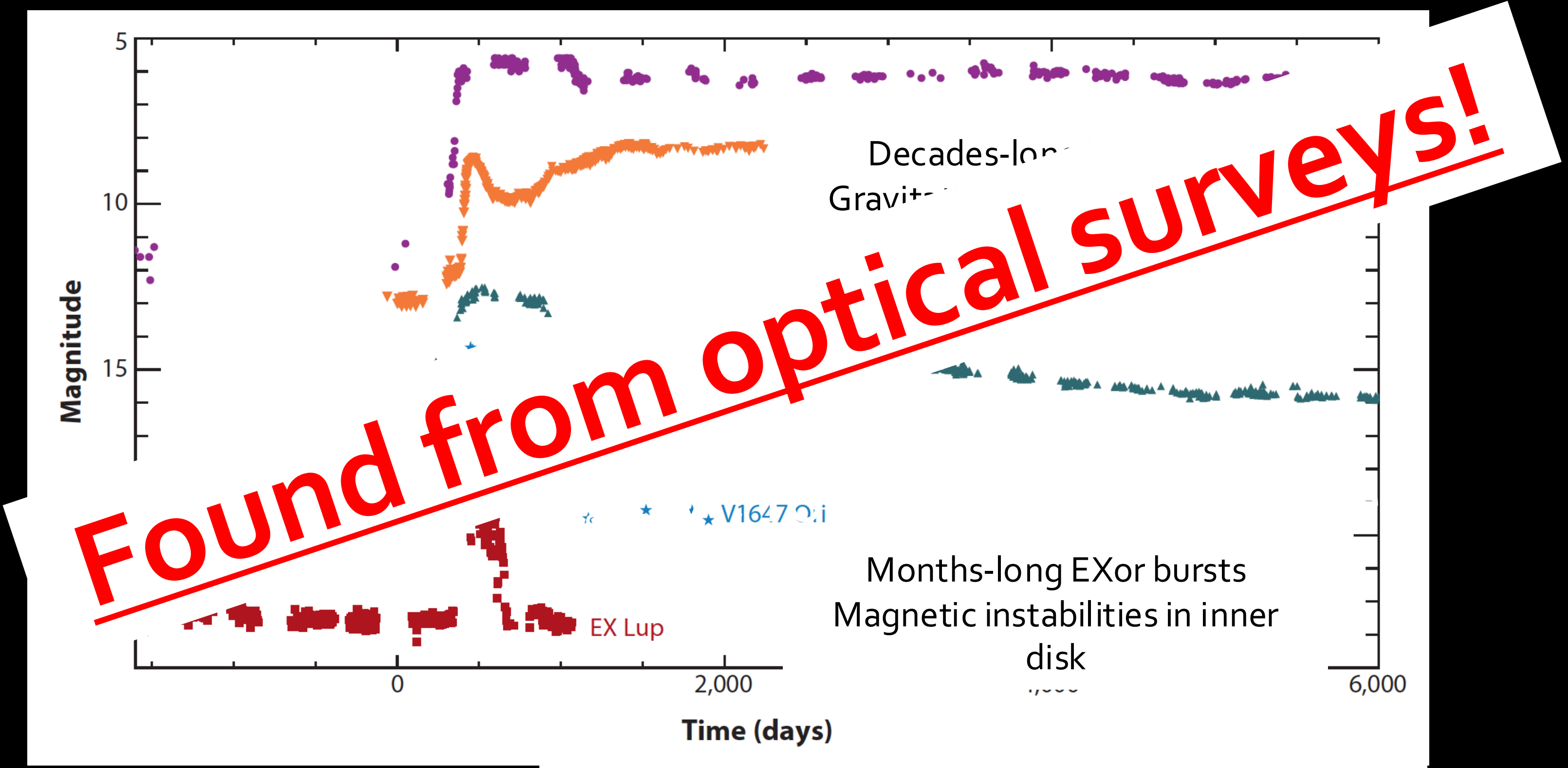
Low mass stars, van Boekel 2005



Cartoon from Tobin+2012

FU Ori type outbursts

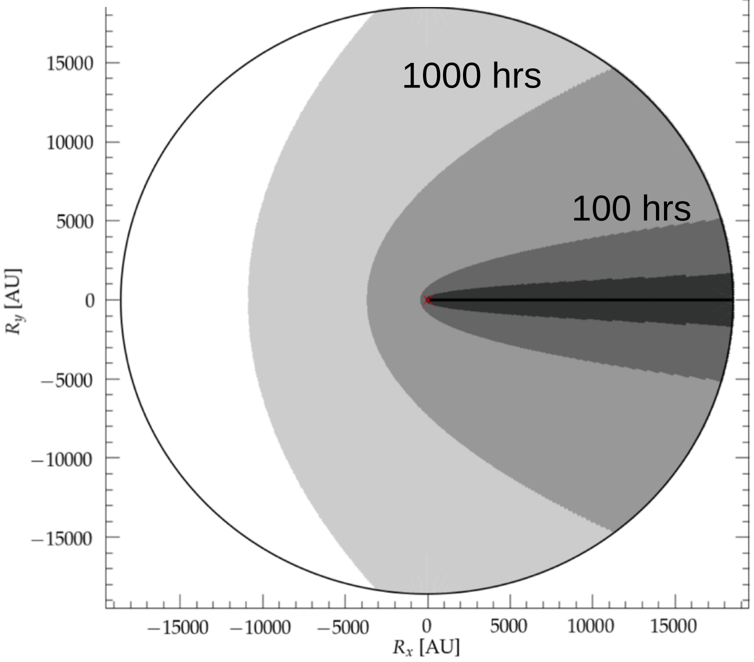
(adapted from Kospal+2011)



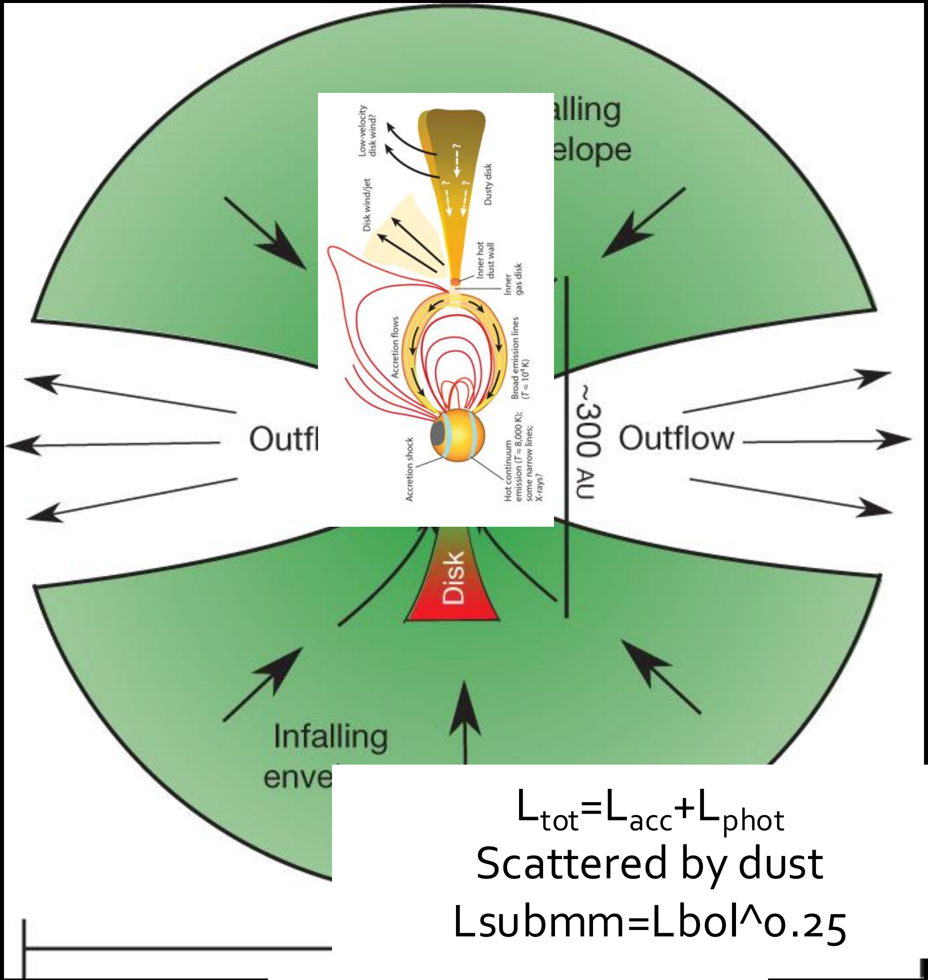
Most recent bursts are found by PTF/ZTF and Gaia

Stars grow during protostellar phase

Timescale for dust scattering



Johnstone+2013: envelope as a calorimeter



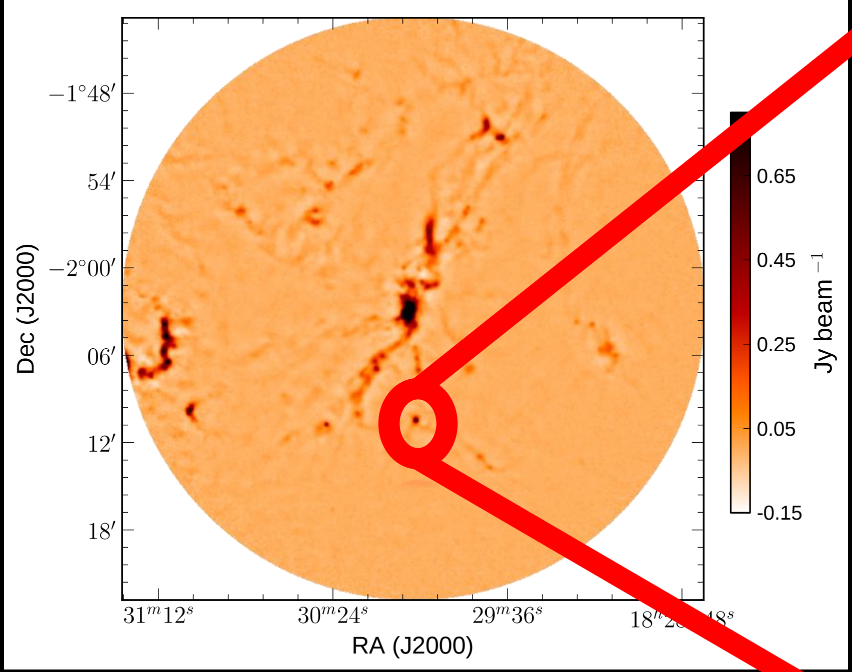
$L_{tot} = L_{acc} + L_{phot}$

Scattered by dust

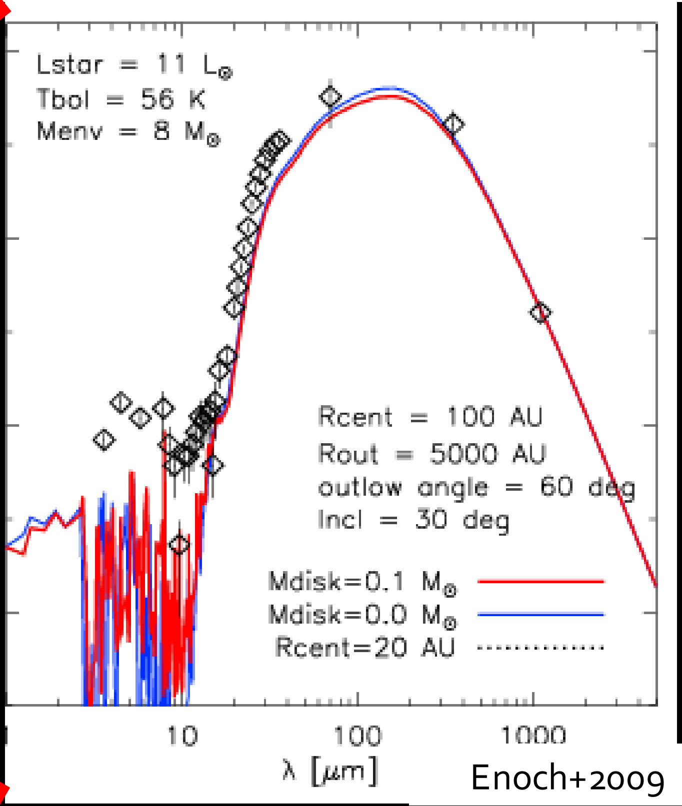
Lsubmm=Lbol^0.25

Cartoon from Tobin+2012

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



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



Enoch+2009

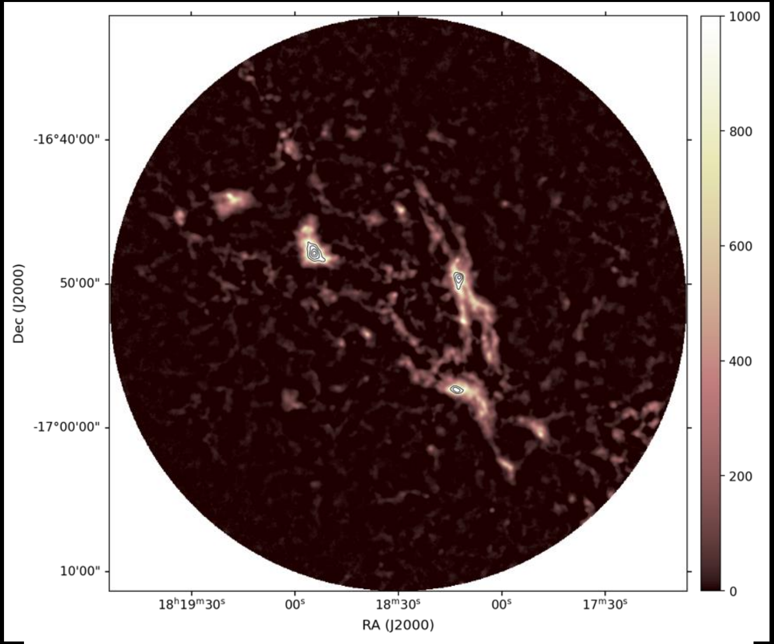
The East Asian Observatory JCMT-Transient Survey: the first long-term sub-mm monitoring program (Herczeg+2017)

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)

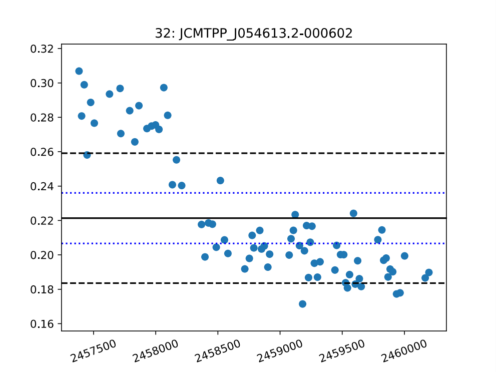
Yong-hee Lee (KHU), Wooseok Park (KHU), Jenny Hatchell (Exeter), Geoff Bower (ASIAA), Zhiwei Chen (PMO), Xu Zhang (NJU), Sheng-Yuan Liu (ASIAA/NTU), Yuri Aikawa (Tokyo), Graham Bell (EAO), Mizna Ashraf (IISER-Tirupathi), Sung-Yong Yoon (KASI), many others

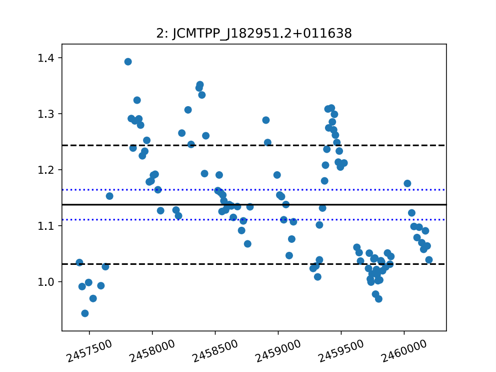
JCMT Transient: sample 850-micron light curves

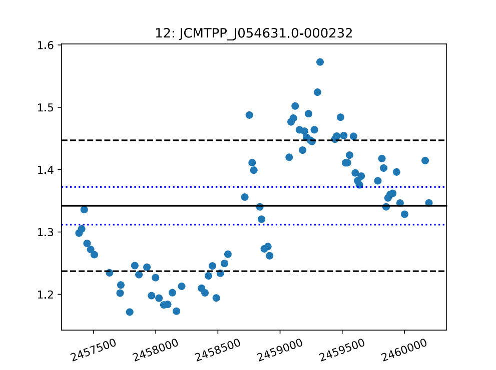
(523 hrs from 2016-2024; Mairs+2017ab; Johnstone+2018; Lee et al. 2021; Mairs+2023)

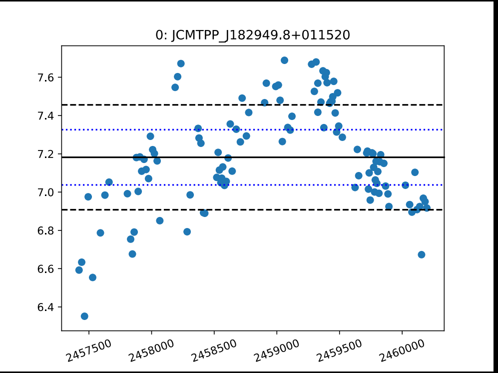


M17SWex: Chen et al. in prep





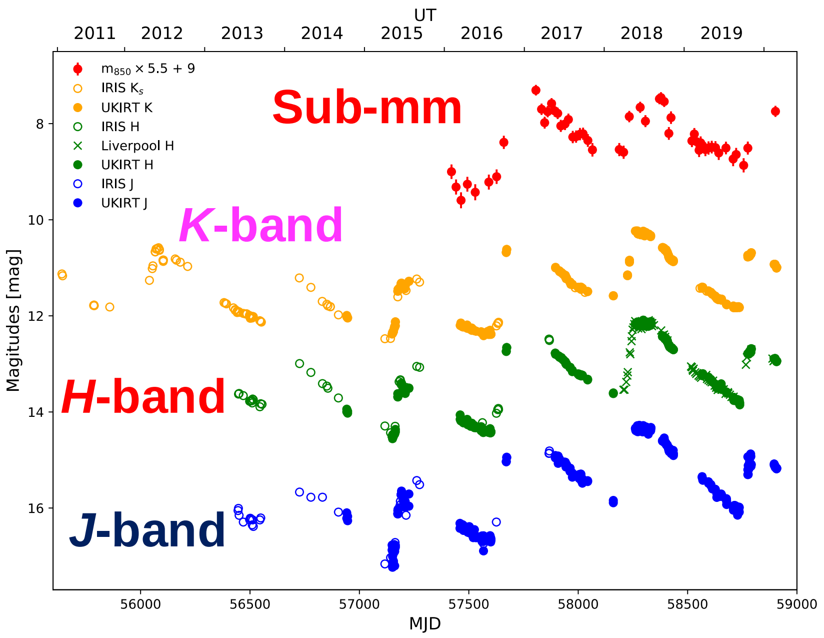




Precision of ~1% from “differential photometry” (Mairs+2023)

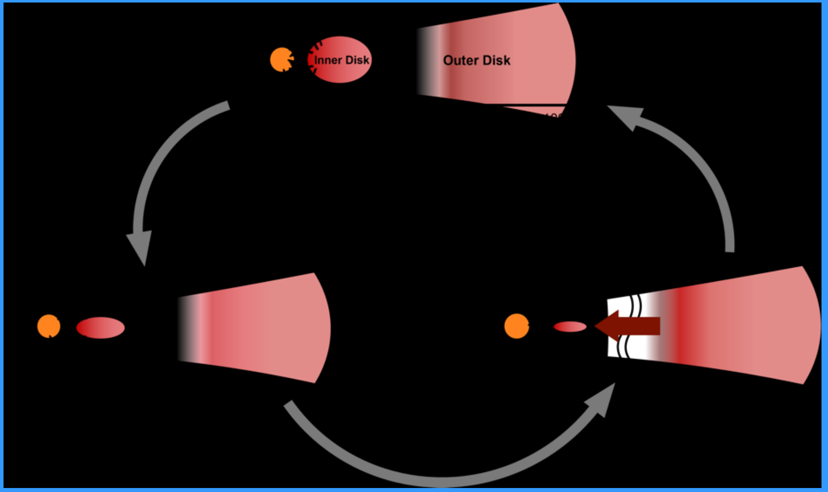
EC 53 (V371 Ser): Young Faithful

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



Near-IR periodicity discovered by Hodapp 2012;
Source similar to Muzerolle+2011; Dahm & Hillenbrand 2020

Cycles of filling and draining the disk



Timescale (e-folding):

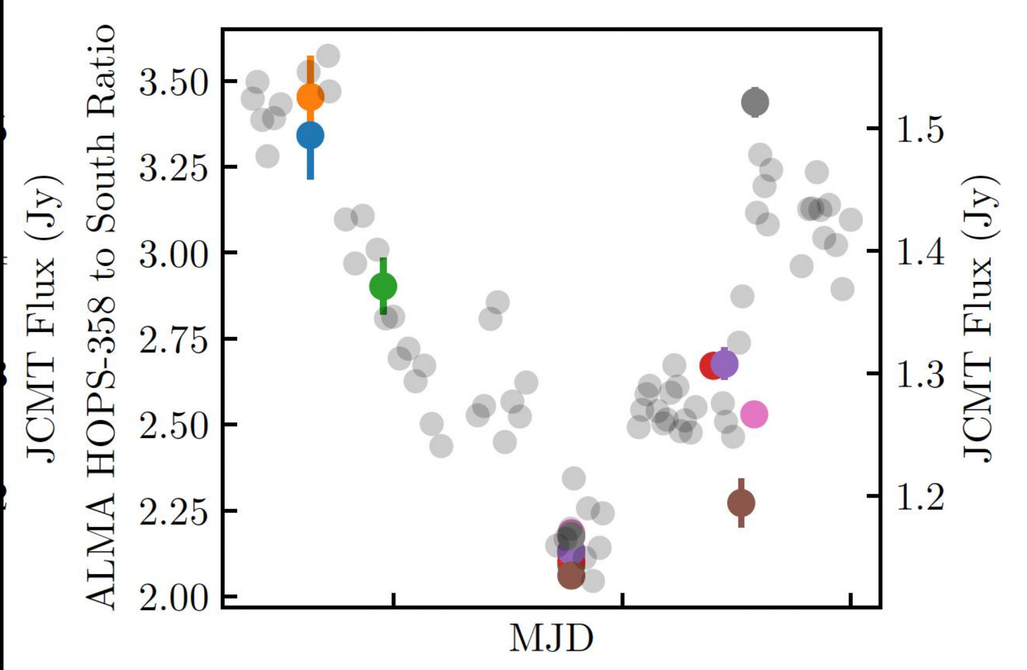
- Decay ~ 0.75 yr
- Rise ~ 0.10 yr

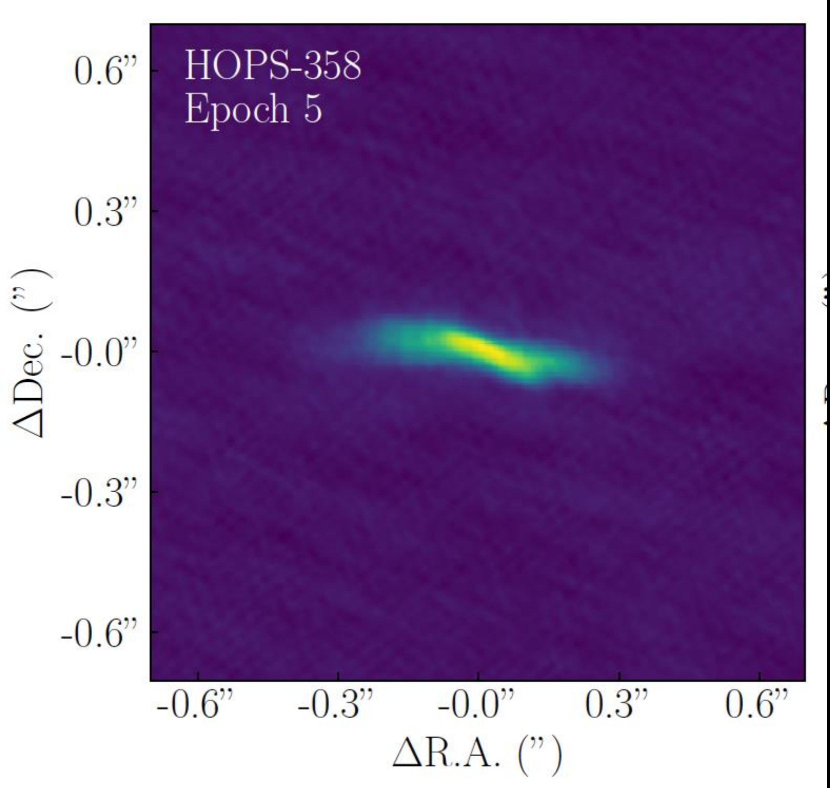
Accretion rate: ~2.5 to 8 x 10^{-6} M_{sun}/yr

HOPS 358: variability with JCMT and ALMA

(Sheehan et al. 2024; see also Francis+2020, 2022)

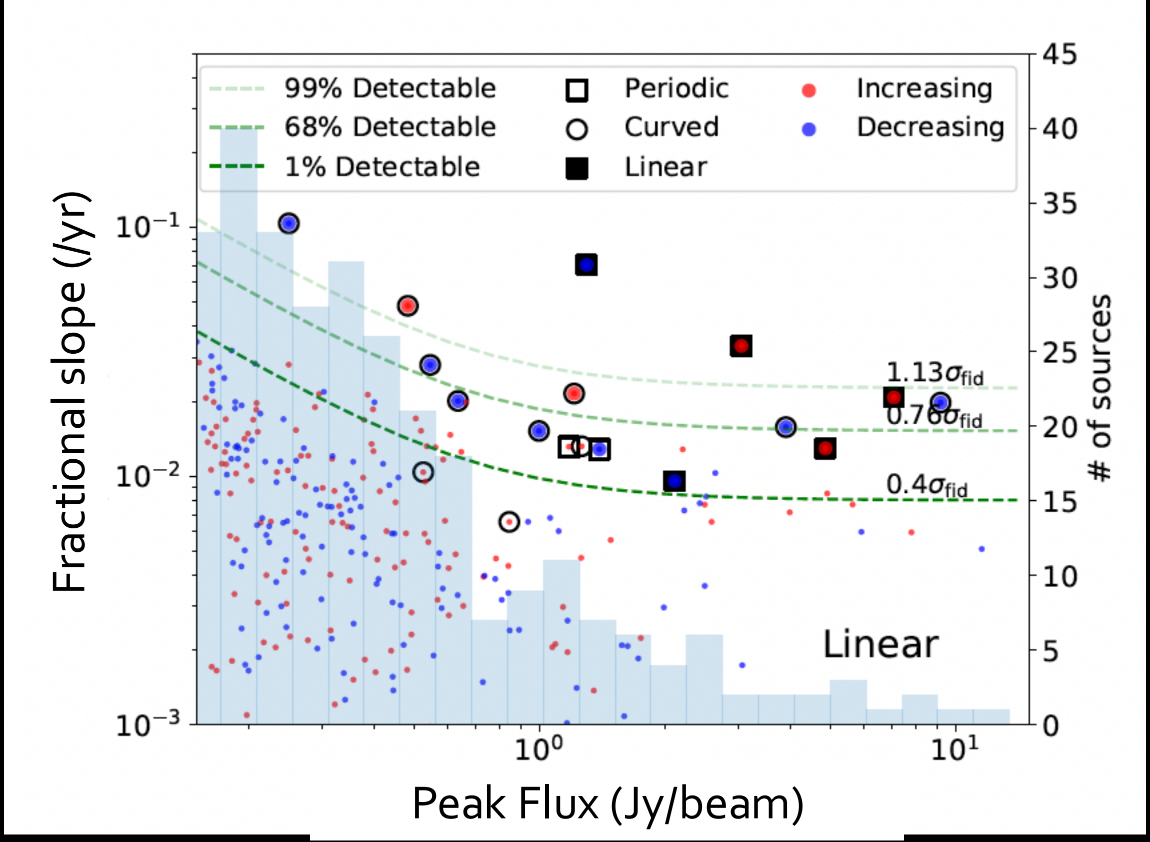
Different beam sizes: reverberation mapping





Summary of sub-mm variability over 4 years

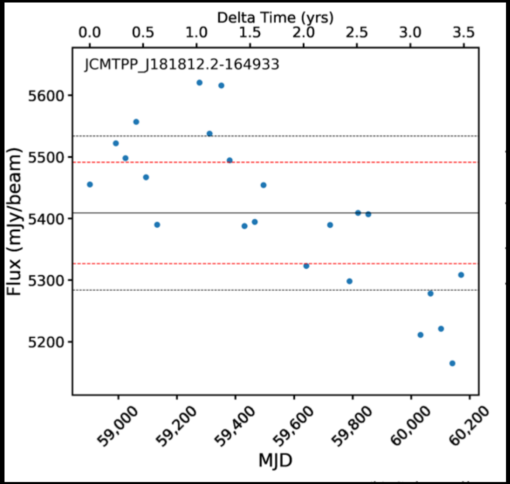
(Y-H Lee, Johnstone, JE Lee, et al. 2021; Johnstone et al. 2023)

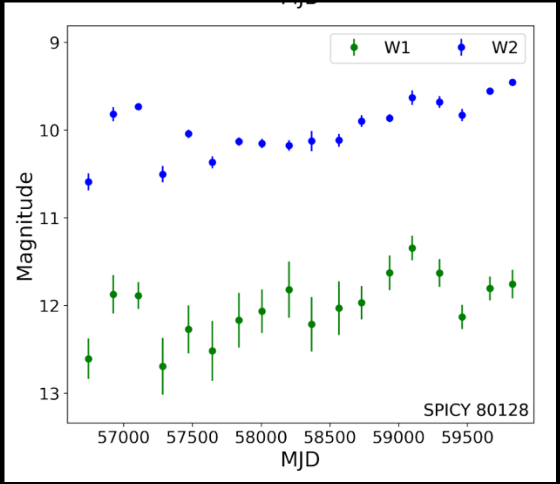


- Protostars are variable!
  - About half by 5-10% per year
  - L^0.25, so modest changes
- Many interesting case studies
- Not enough time/number to detect largest bursts
- Expanding to more distant intermediate-mass star-forming regions

Monitoring Intermediate Mass Star-Forming regions

(Mairs+2024; Park et al. 2024; ZW Chen et al. in prep)

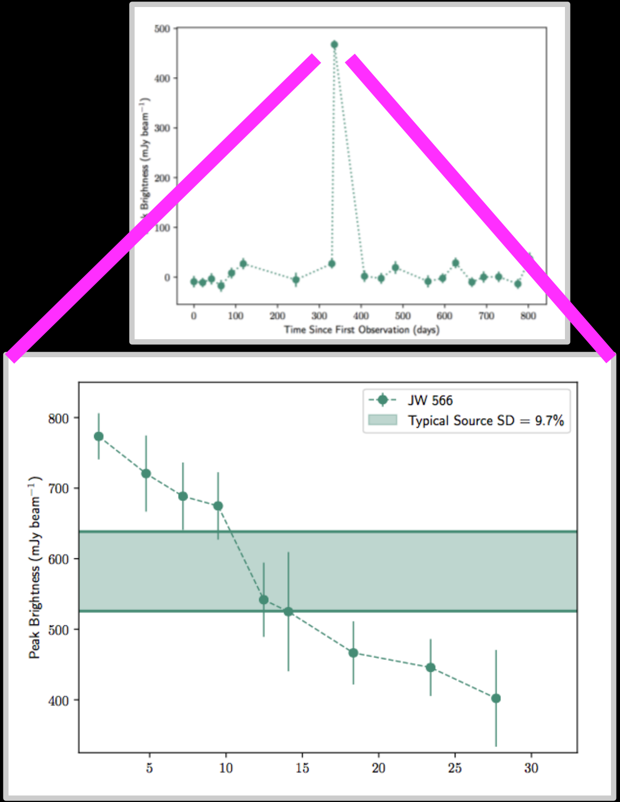




- Increase in source numbers
- Source confusion
- Source characterization
- Less survey time
- Complement with NEOWISE

The sub-mm variable sky

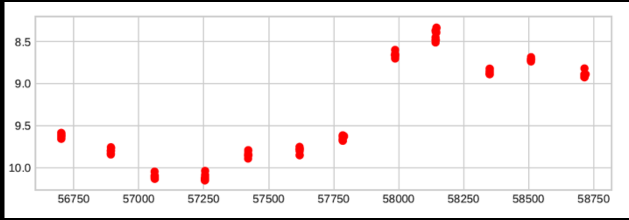
- Coronal flare on a YSO
  - Strongest ever recorded?
  - Mairs et al. 2019; Johnstone et al. 2023
- Two variable AGNs
- Sub-mm flux calibration techniques
  - Previously ~10% unquantified errors

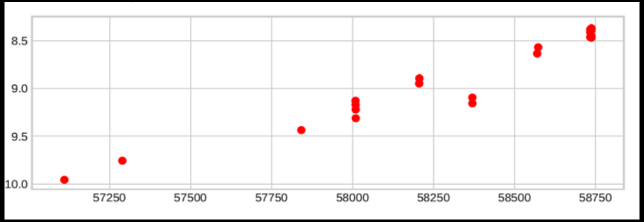


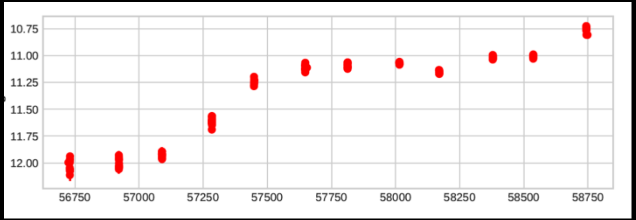
Decay during 30-min integration

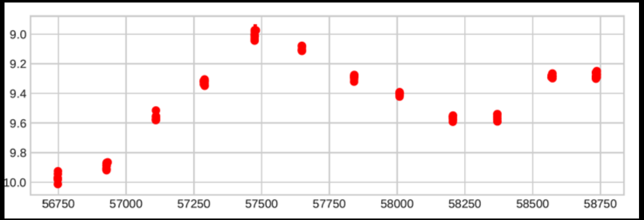
Essential for CMB-S4 Cosmology Experiment (2020 US Decadal)

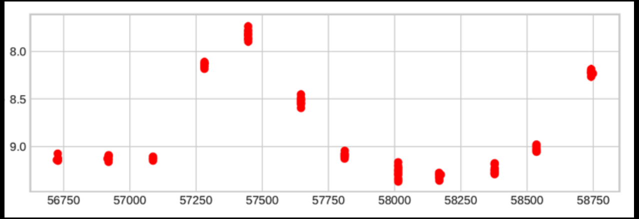
NEOWISE: mid-IR variable sky

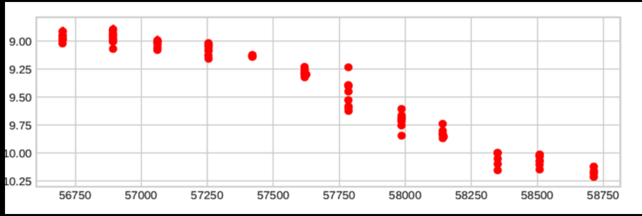


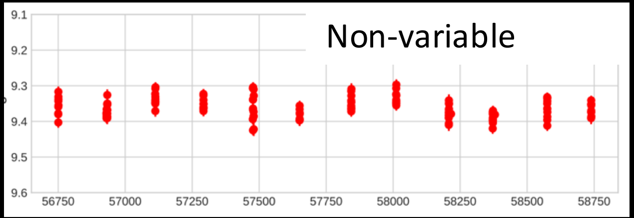


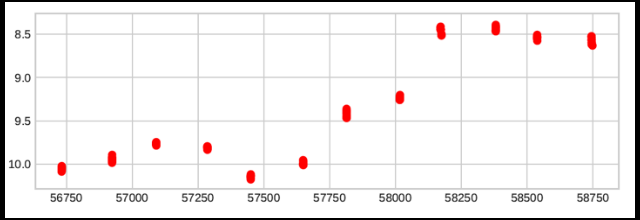












- NEOWISE mission:
- All-sky, 3.6, 4.5 microns
- 2 epochs/year
- statistical analysis of variability

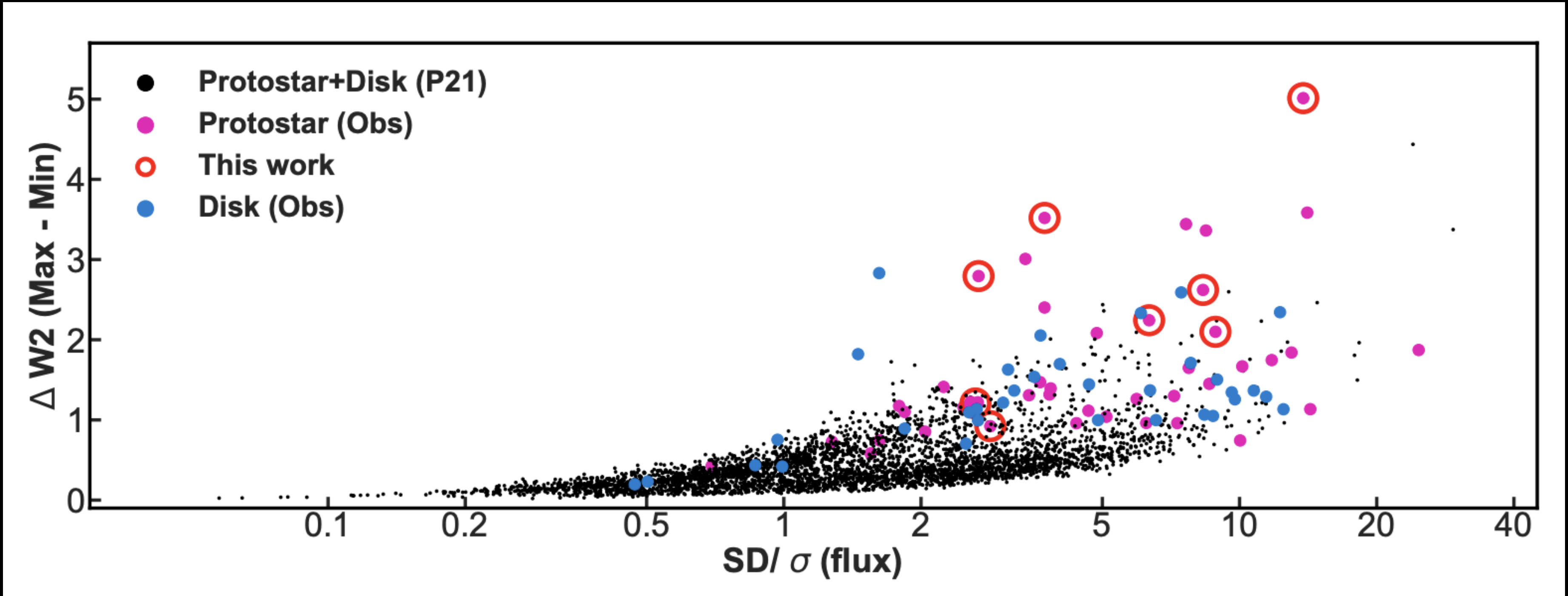
Long-term goal:
frequency of FUor outbursts

Park, JE Lee, et al. 2021
Contreras Pena et al. 2023

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

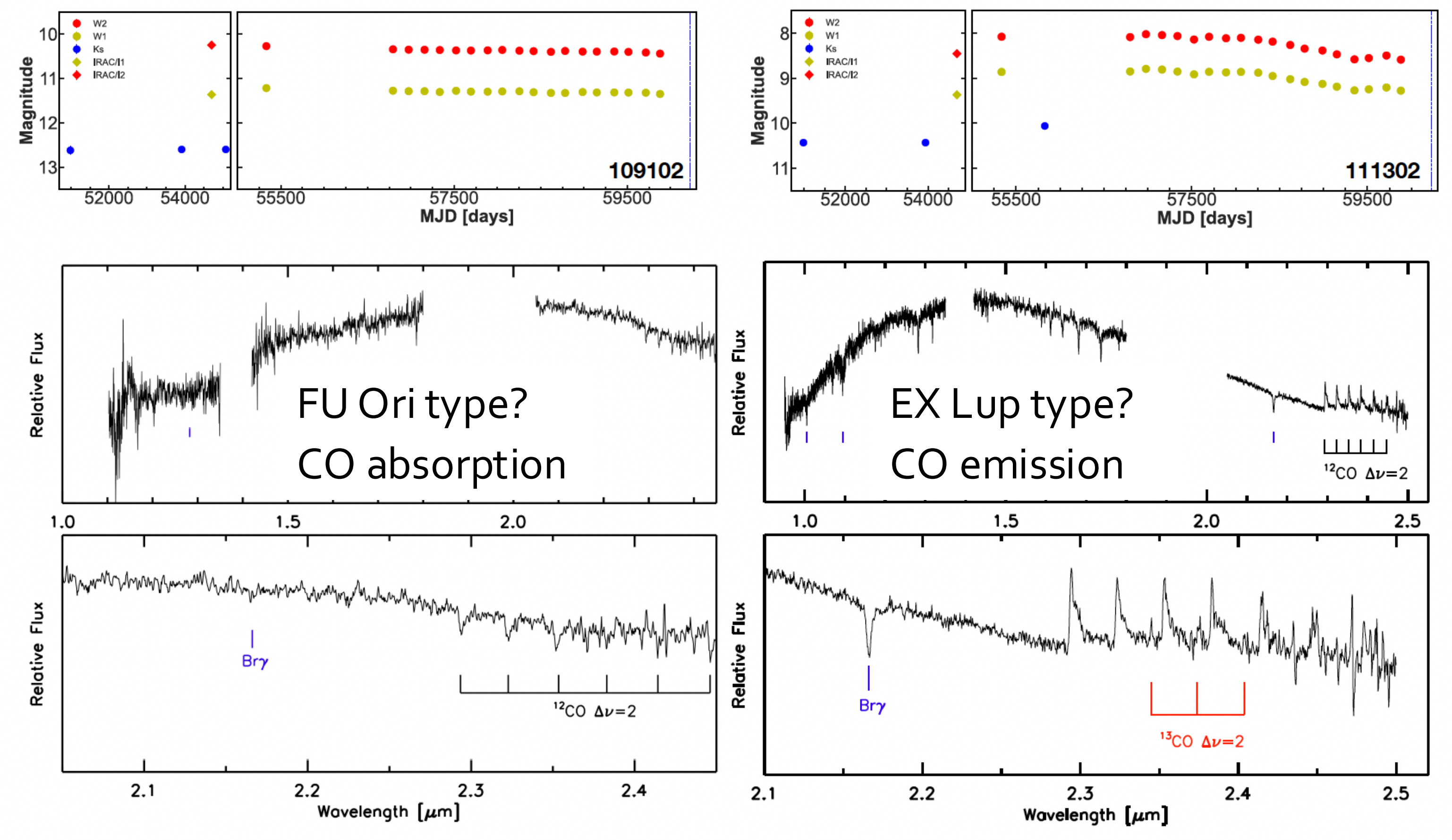
NEOWISE: from case studies to population statistics

(Contreras Pena et al. 2024; in prep)



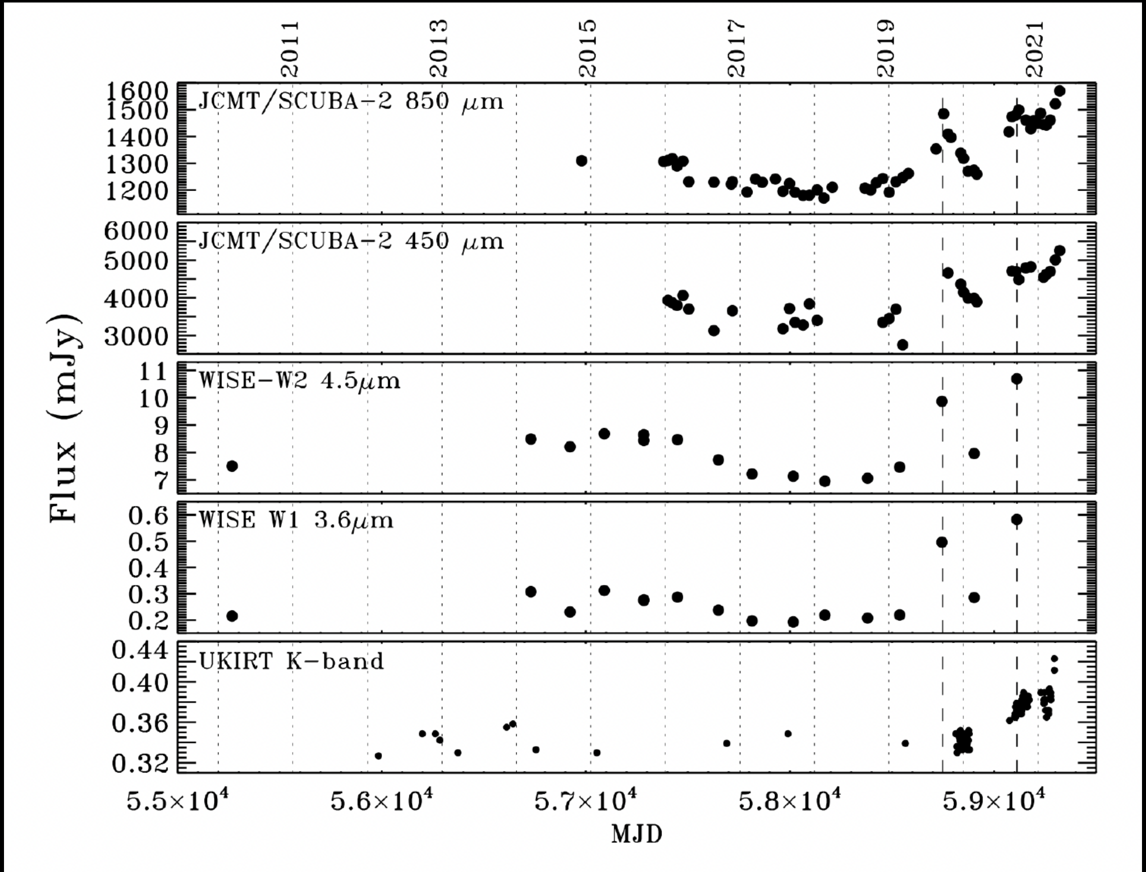
Searching for fading FU Ori-like objects

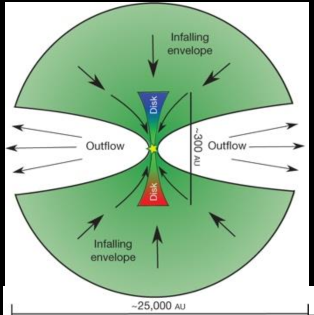
(Contreras Pena et al. in prep)



HOPS 373: a modest accretion burst found with JCMT

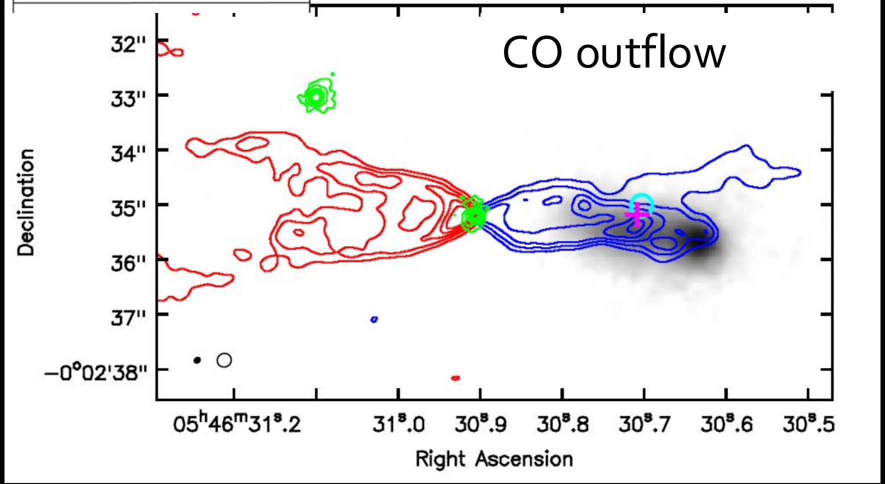
(Yoon, Herczeg, JE Lee, et al., 2022)

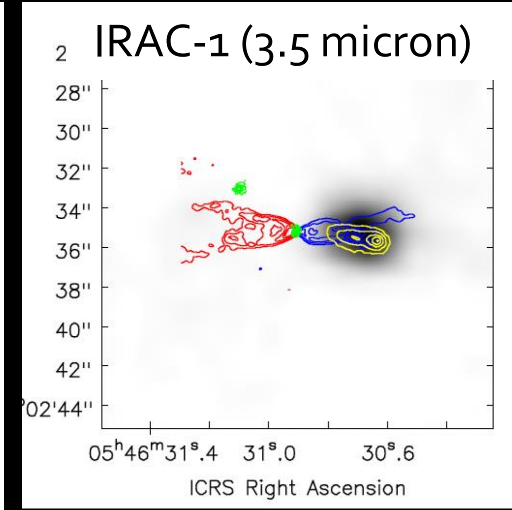


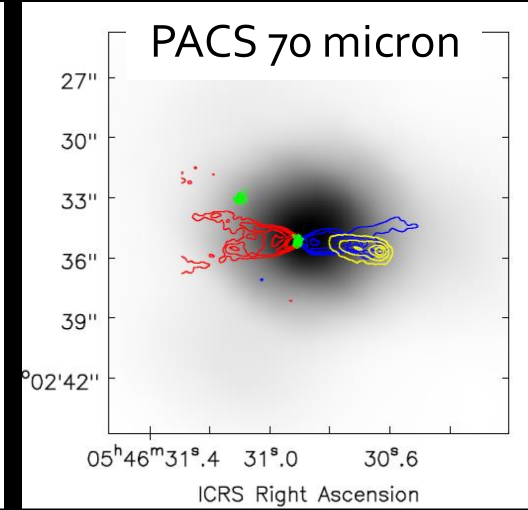


HOPS 373: a modest accretion burst

Yoon, Herczeg, JE Lee, et al. 2022





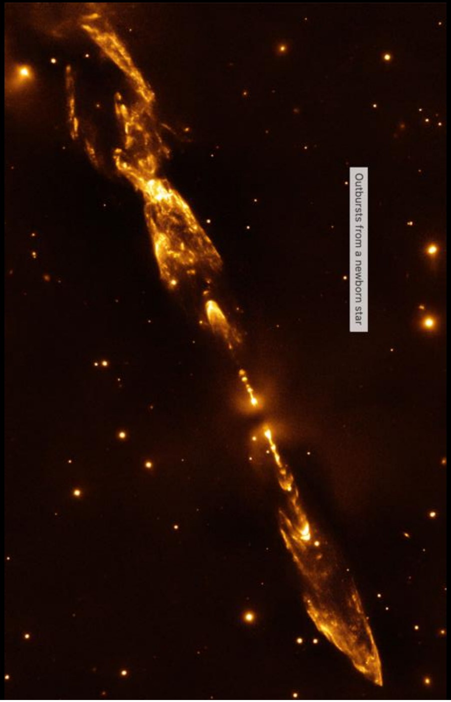


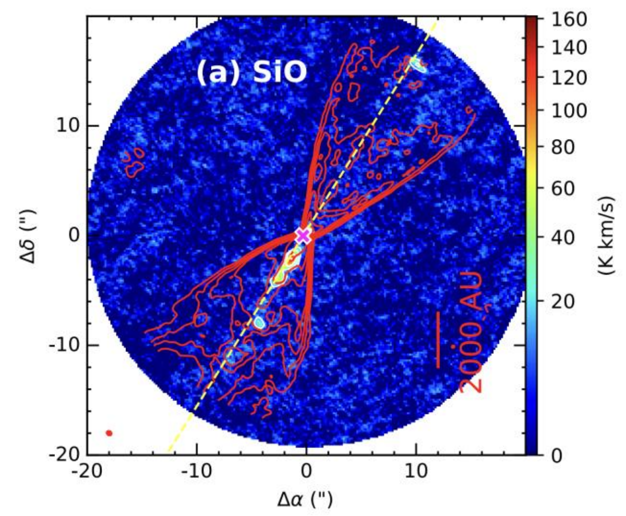
Near- and mid-IR emission: emission reflected and escapes out of cavity walls

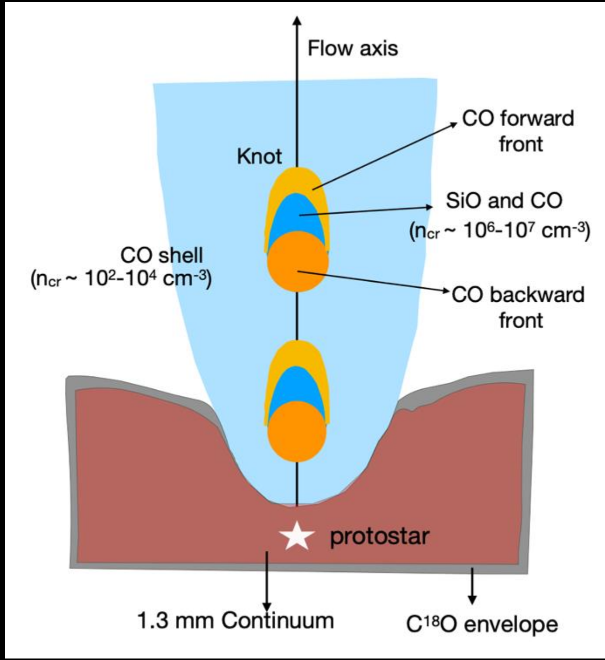
W2/IRAC-2, K-band variability: suppressed by H2, CO

Outflows as a pre-historic record of outbursts

(e.g., Dutta+2024)



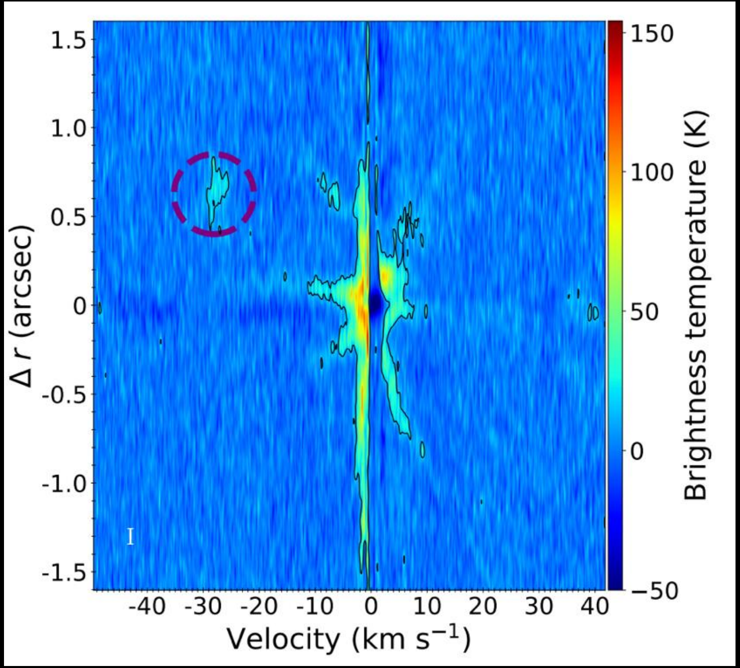


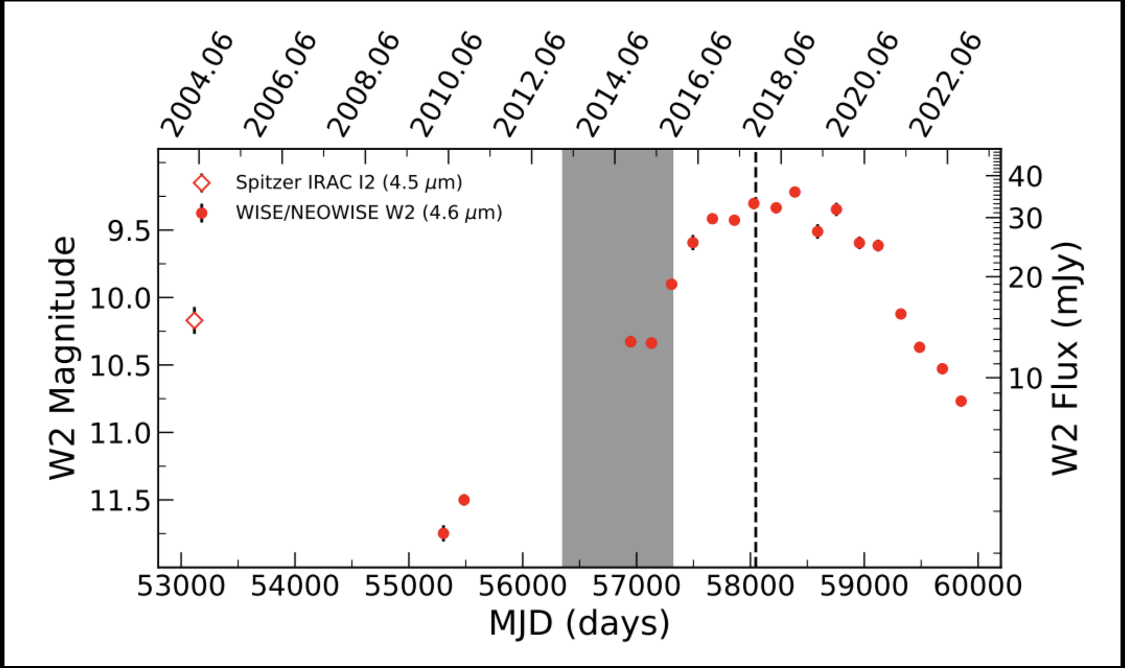


ESO/McCaugheran; see also Raga+ papers

Challenge: relationship still speculative

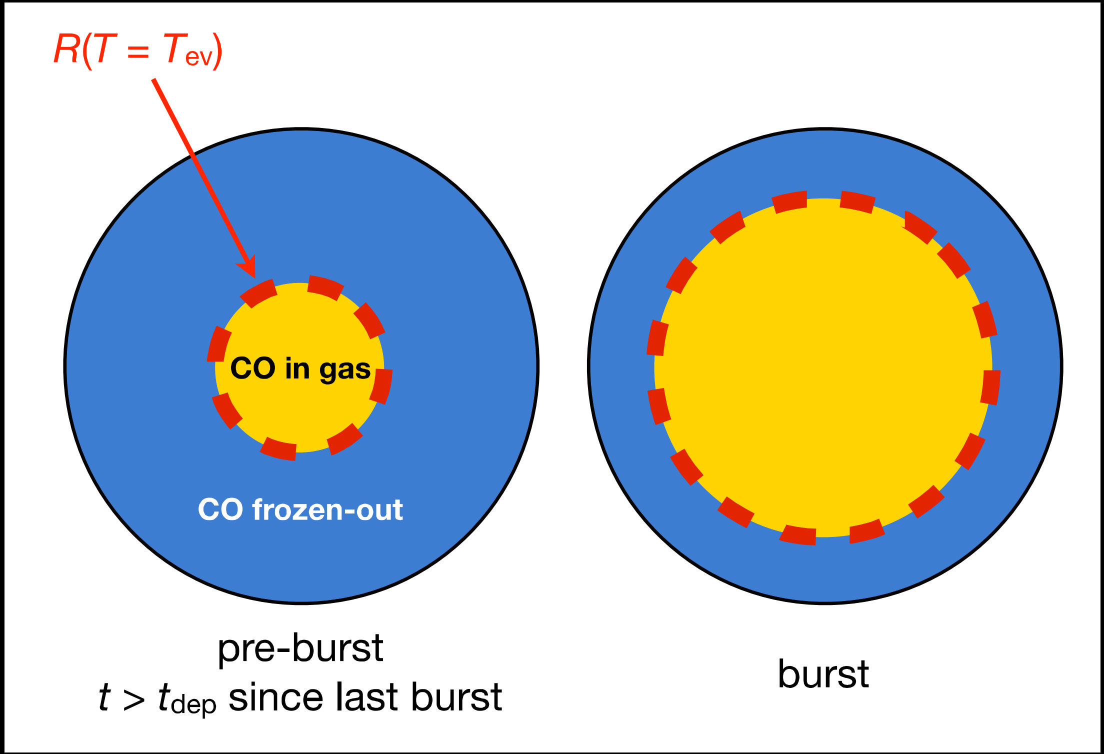
Outflows as a pre-historic record of outbursts
The case of B335 (Kim et al. 2024)





Envelope heating by stellar luminosity

freeze-out timescale longer than sublimation timescale



e.g., Lee 2007; Jørgensen+2015; Hsieh+2019

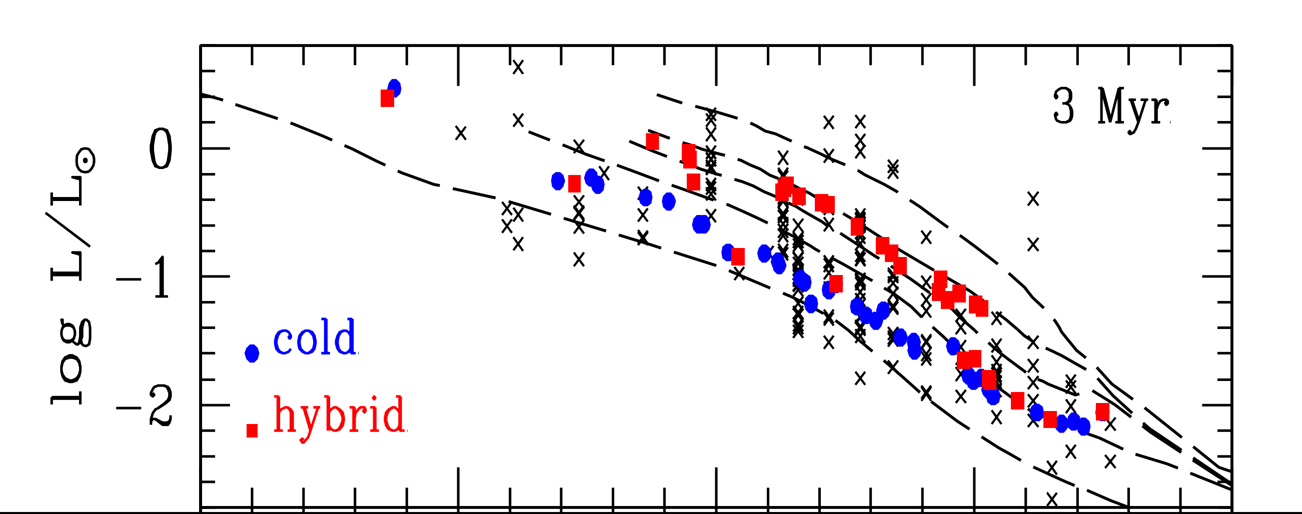
What is the role of variability in stellar assembly?

- Optical: 1 large outburst every 50,000 years
  - Contreras Pena & Naylor 2019, see also Hillenbrand & Findeisen 2015
  - Insufficient
- JCMT Survey (sub-mm): lacks number of sources and time duration
- Mid-IR (Spitzer and NEOWISE):
  - 1 large outburst every 2000 years for protostars, with large uncertainties
  - Roughly consistent with outflow shocks, envelope chemistry
  - Scholz et al. 2013; Park et al. 2021; Zakri et al. 2022; Contreras Pena et al. 2025

Role of stellar variability is still unclear!

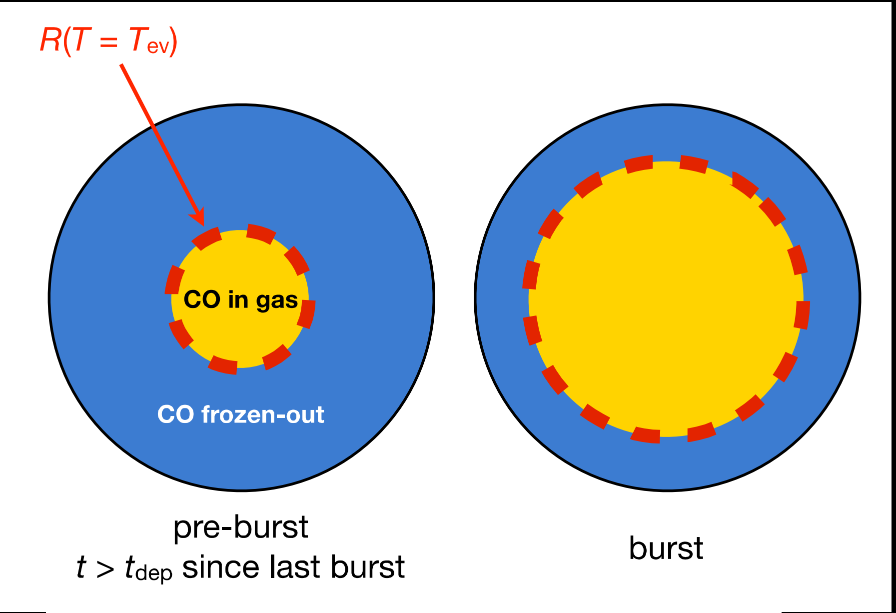
Initial Radius (Entropy): affects birth line and ages

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

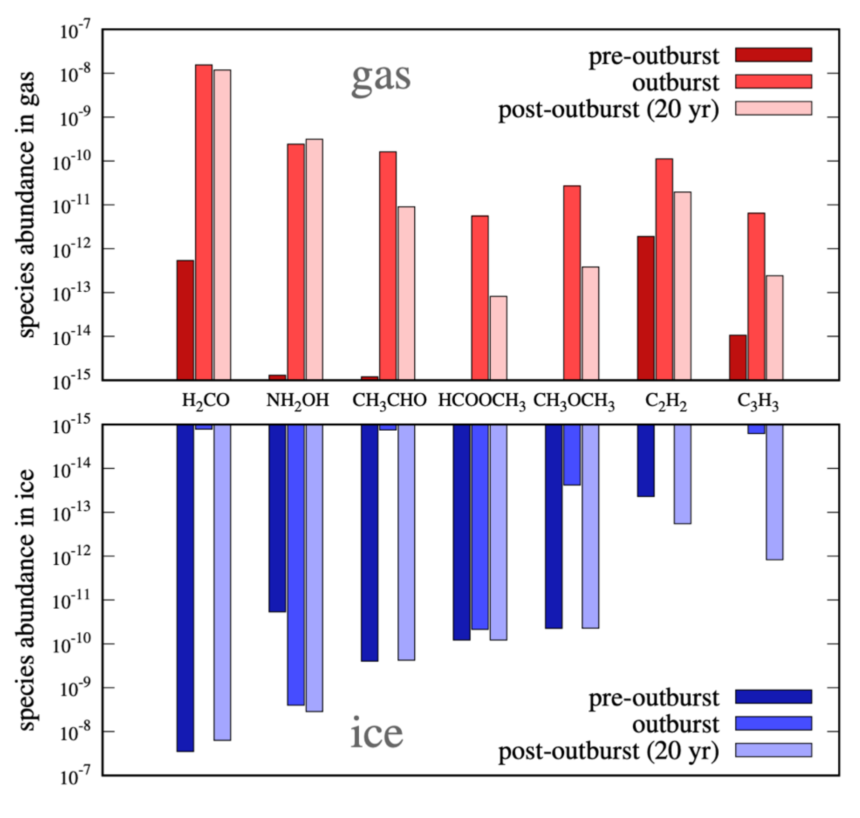


- Need accretion history of the star + initial core size
- Modest affects/outliers are possible
  - Some age spread (smaller radii)
  - Brown dwarfs appear too young: larger initial core
  - Intermediate mass stars too old: same initial core, more cold accretion

Chemistry: heating in the disk and envelope



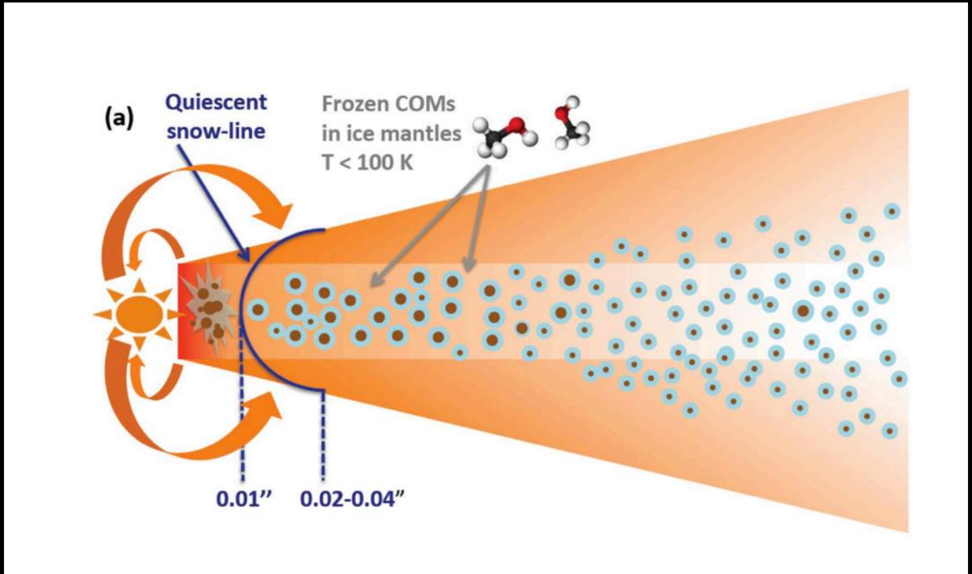
Jørgensen+2015; Lee 2007; Hsieh+2019; Molyarova+2018; others

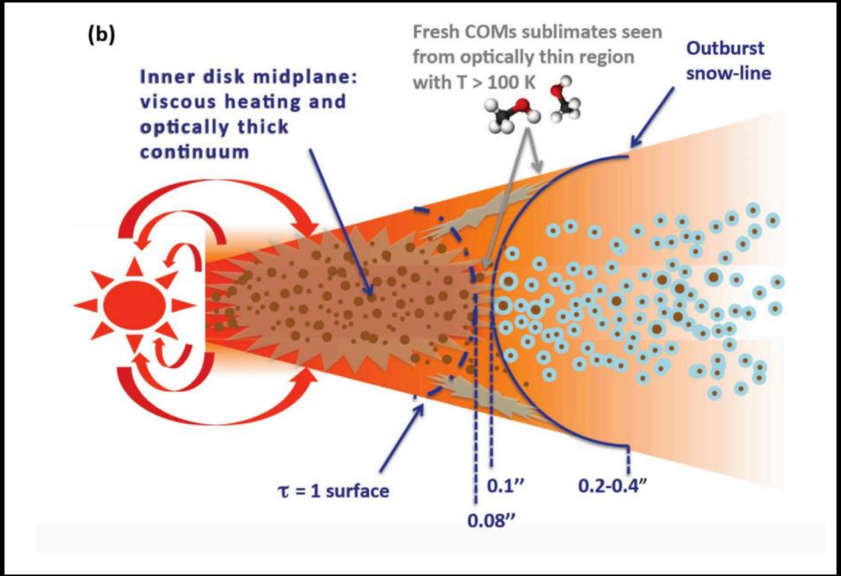


Molyarova et al. 2019

Outbursts as a probe of COMs abundances

(eg, JE Lee et al. 2019; see also van 't Hoff et al. 2019)

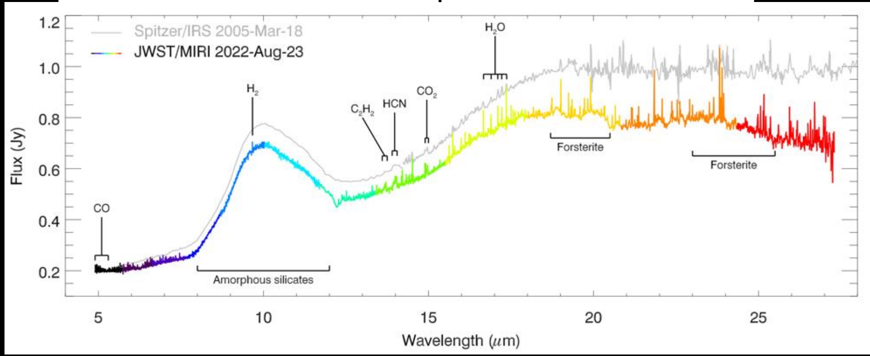


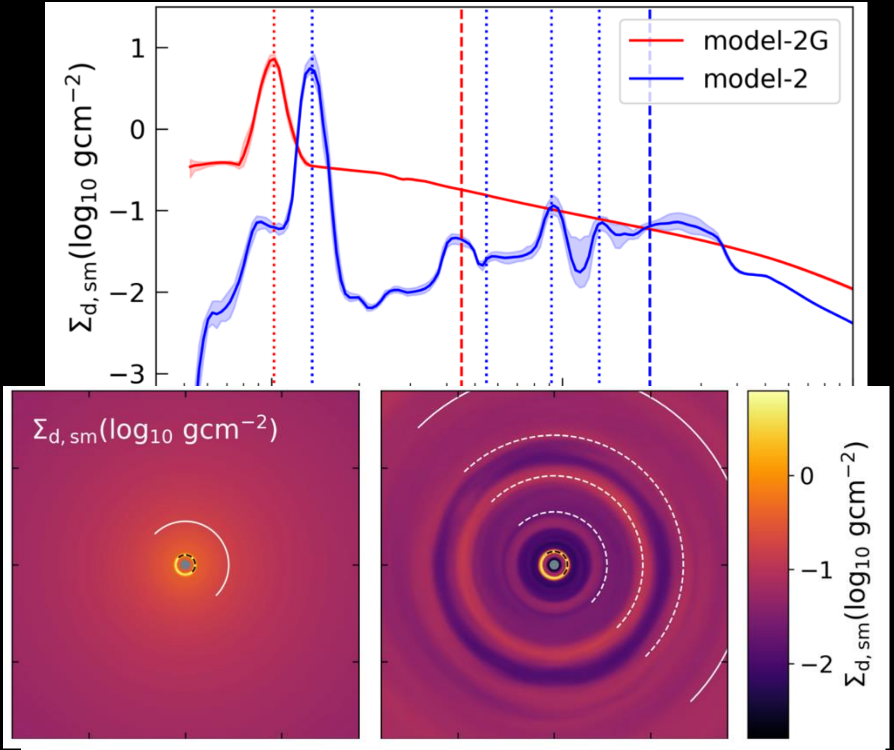


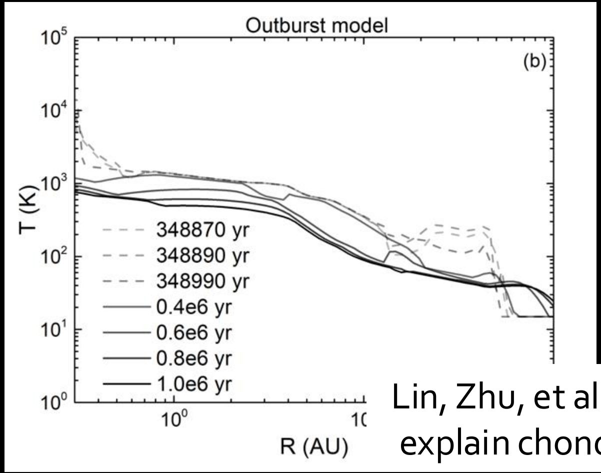
Snow line moves to larger radius: COMs sublimate
Provide comparison to cometary compositions

Outbursts and dust

Kospal+2023: crystalline grains formed in outburst then transported outward







Lin, Zhu, et al. 2023: outbursts can explain chondrites & CAIs at 1 AU

Kadam+2024: outbursts can create and change ring locations (affect streaming instability)

Following the mass flows: the assembly of stars and planets

The era of the transient sky is here (ASAS-SN, ZTF, LSST) and gone (NEOWISE, Gaia)

Variability and Stellar Mass Assembly

- 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: some fraction during outbursts
  - Need to pierce through envelope: long wavelengths
  - JCMT Transient, NEOWISE; future far-IR mission?

Future for Protostar Variability

- Far-IR Space Telescope (eg, PRIMA)
  - Ideal wavelength but limited monitoring
- Mid-IR Monitoring (eg, SPHEREx)
  - Geometry/interpretation issues
- Ground-based sub-mm monitoring
  - eg, CCAT, AtLAST, PMO-15m

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