Stellar Mass Assembly with PRIMA

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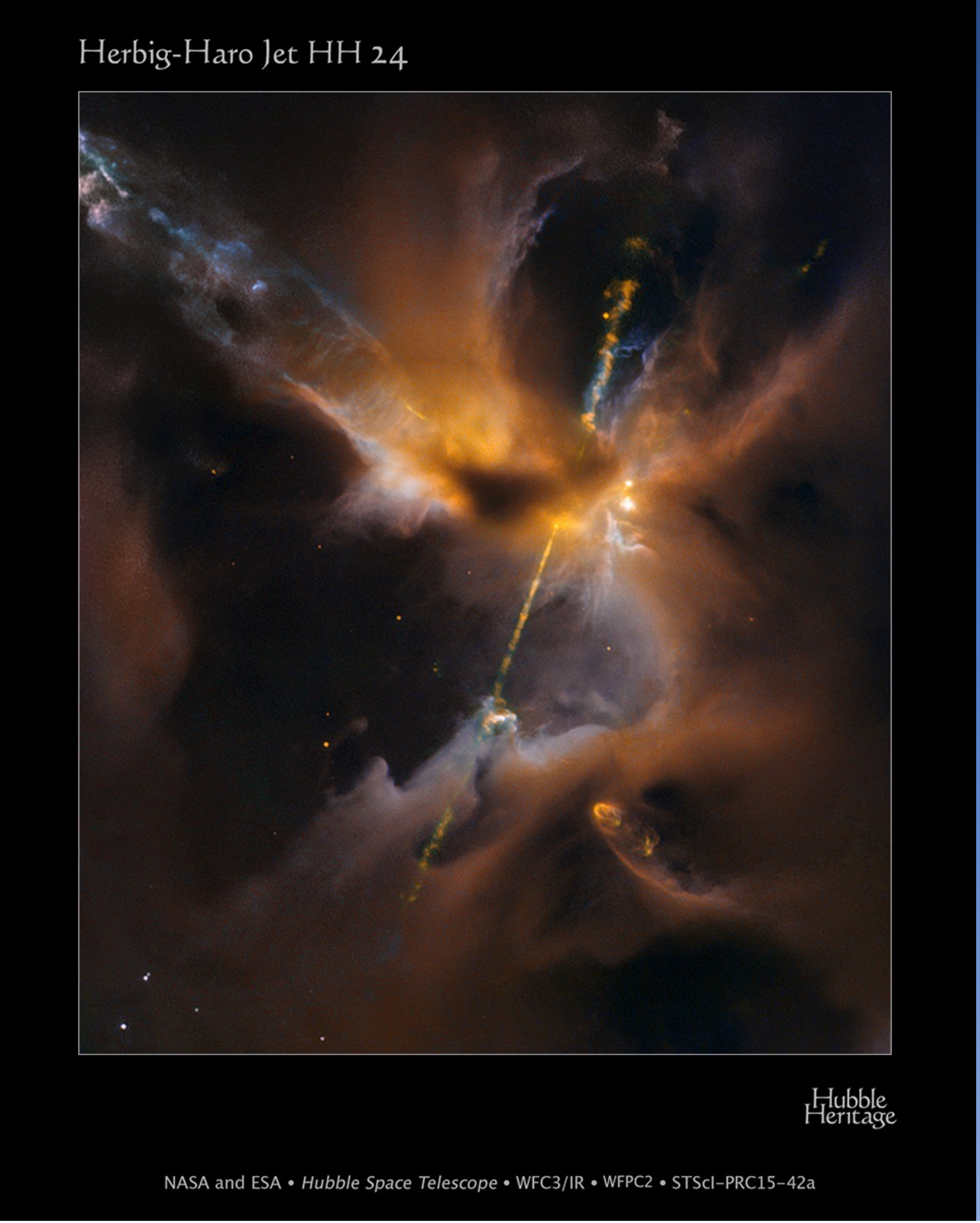


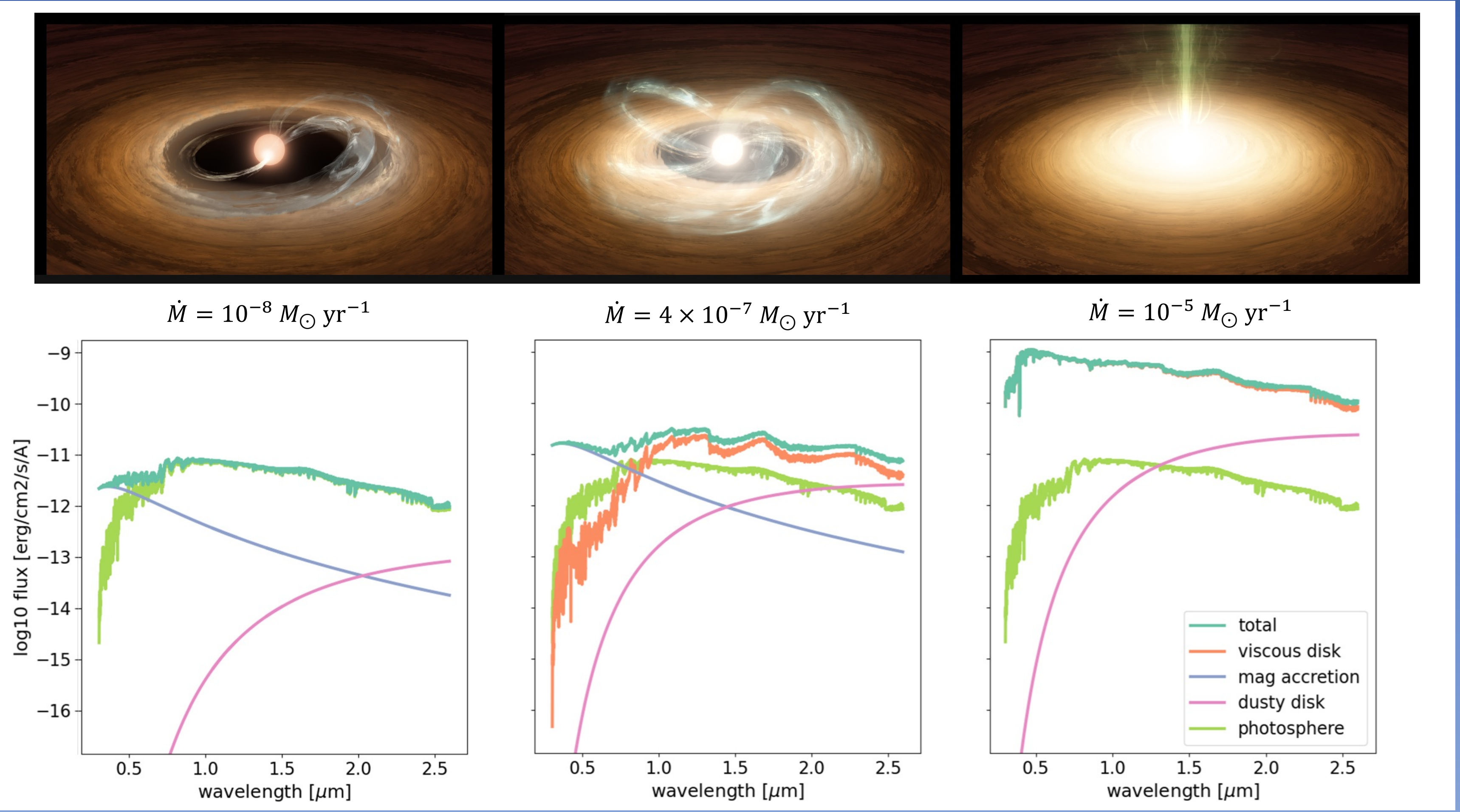
Protostars reveal the origins of solar systems

- A dense, infalling circumstellar envelope is still present
- Outflows are clearing the envelope
- A protoplanetary disk is in the earliest stage of its evolution
- The majority of the stellar mass is being assembled
- Protostellar lifetime: ~0.5 Myr

Variability: a guide to stellar mass assembly

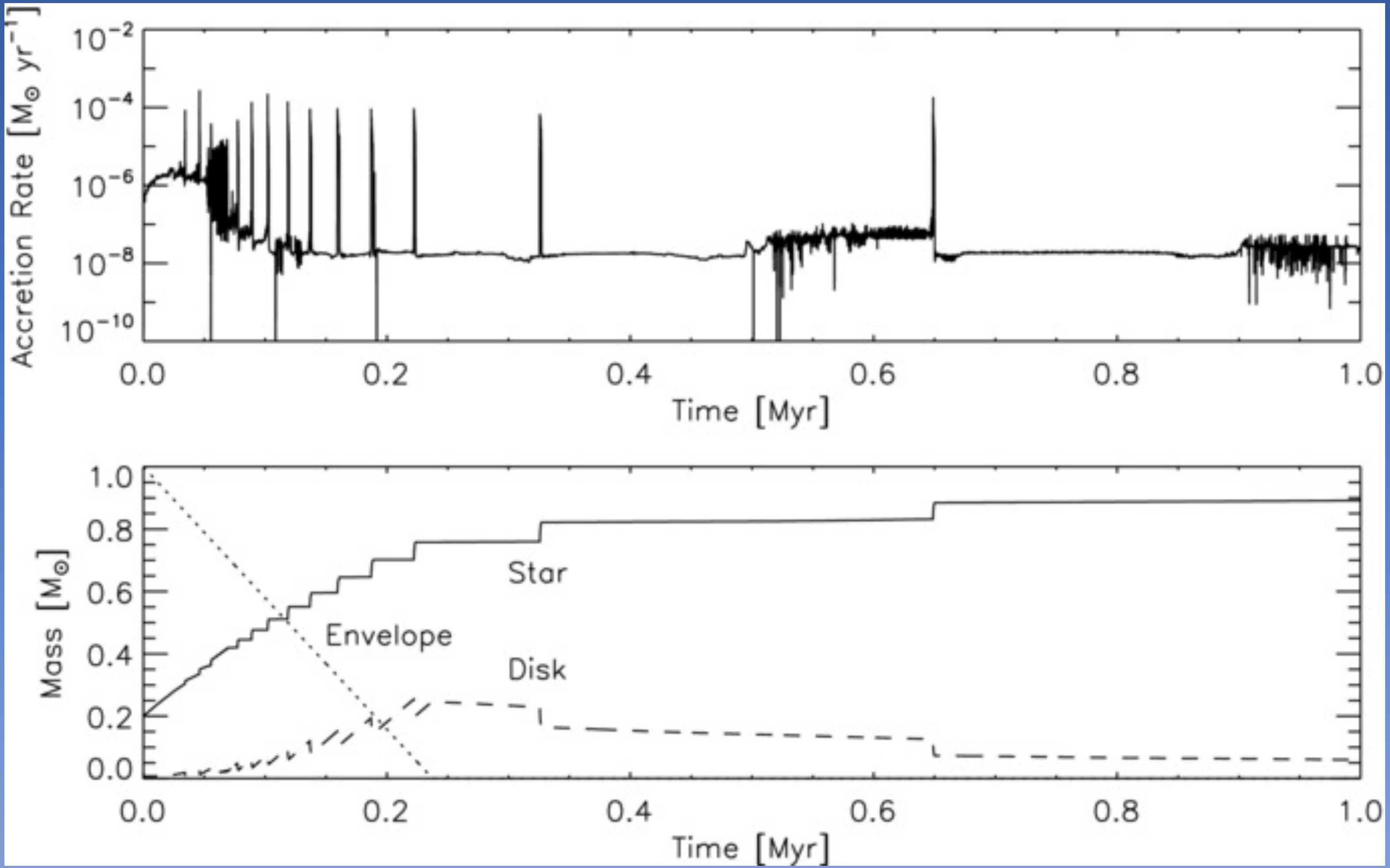
$$L = L_{\rm phot} + L_{\rm acc} = L_{\rm phot} + G\dot{M}M_*/R_*$$

- Many causes of variability (extinction, rotation, etc.)
- Luminosity changes are primarily due to changes in the accretion rate
- Luminosity changes affect disk conditions



Art by T. Pyle (Caltech/IPAC)
Models from Liu et al. (2022)

Variability can be gradual or sudden

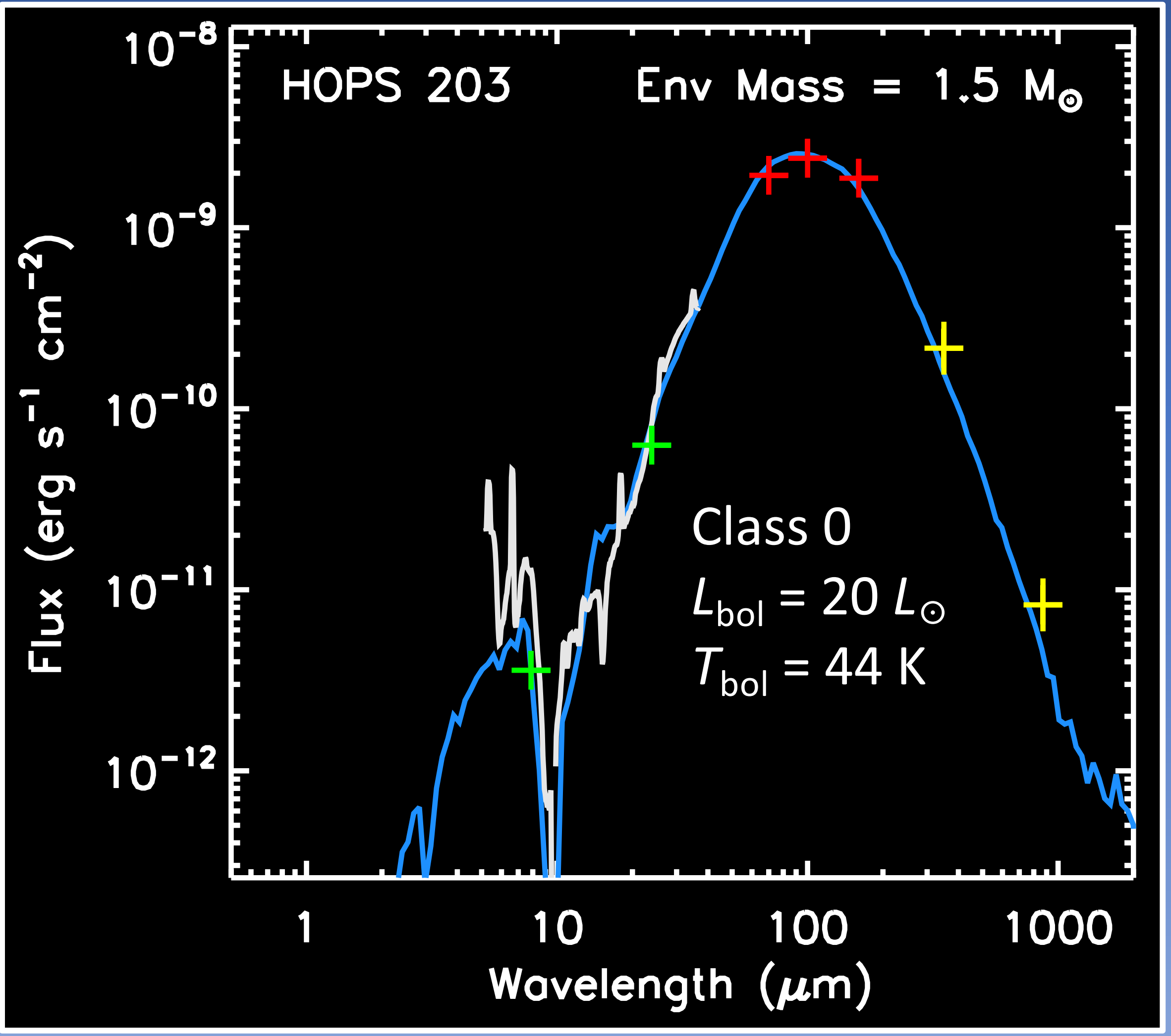


One model of the evolution of accretion rate and stellar mass (Bae et al. 2014)

- Several types of accretion variability
  - Long-term decline in luminosity as the envelope depletes
  - Short-term low-amplitude changes
  - Sudden, short-lived bursts
- Which of these are most important for mass assembly?

Embedded protostars present observing challenges

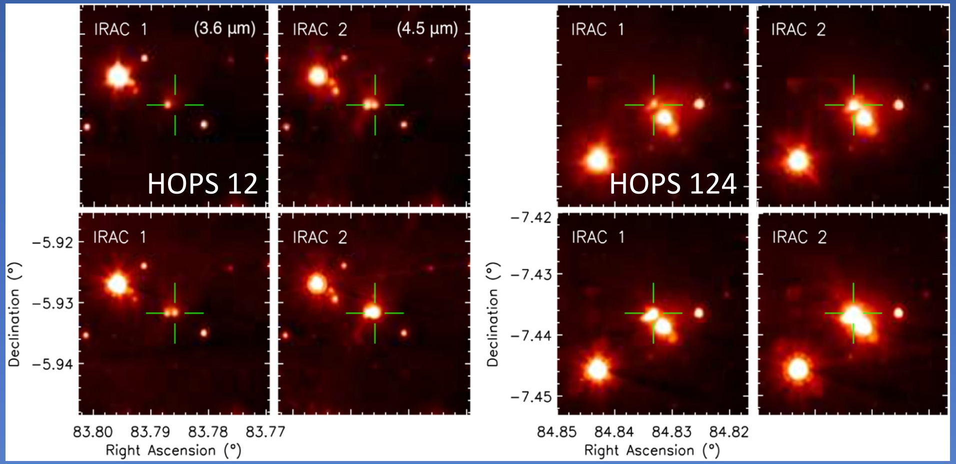
- Optical/NIR spectroscopy tells us about accretion processes in more evolved young stellar objects – impossible for younger, embedded protostars that are still forming
- Mid-IR is strongly affected by extinction
- Sub-mm responds to temperature changes



SED and model from Furlan et al. (2016)

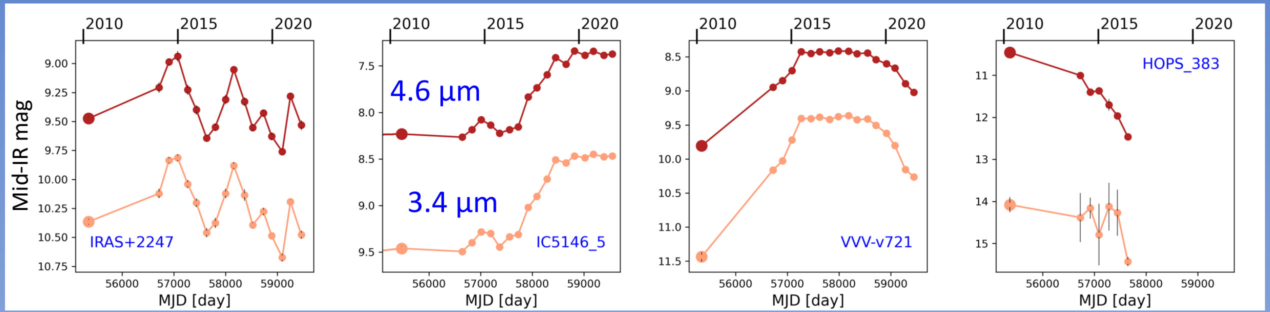
Mid-IR and sub-mm campaigns set the stage

Protostellar bursts in Spitzer images (Zakri et al. 2022)



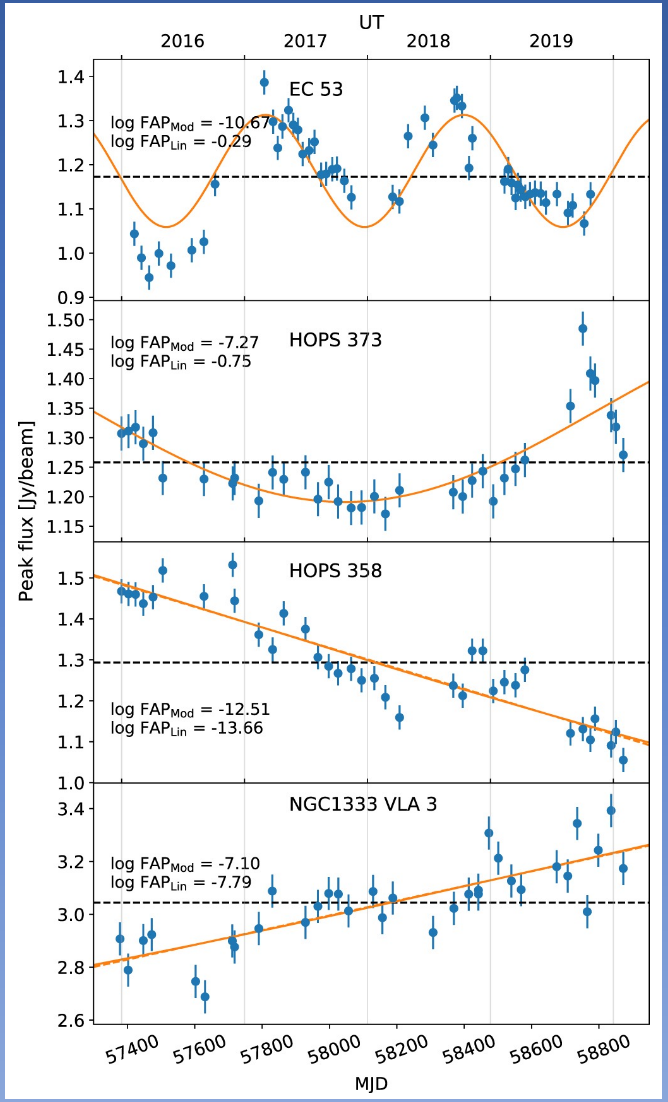
Top row: 2004; Bottom row: 2017 (Δt = 13 yr)

Variability, including bursts, is well documented on both sides of the SED peak, but flux changes translate only ambiguously to luminosity changes



WISE protostellar light curves (Fischer et al. 2023; Δt = 12 yr)

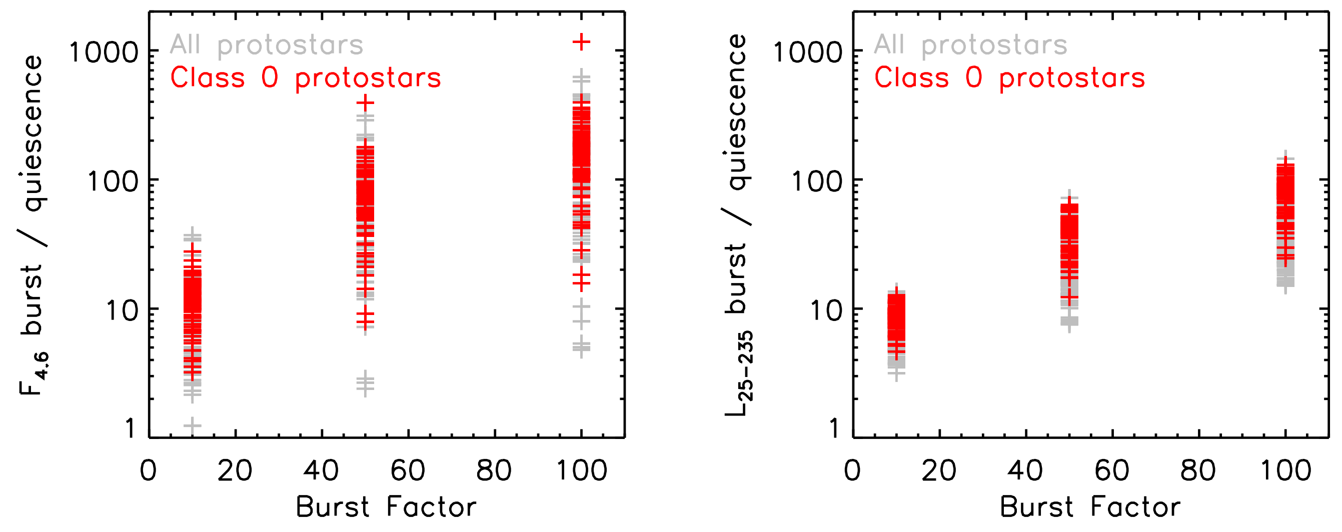
Right: JCMT protostellar light curves (Lee et al. 2021; Δt = 4 yr)



Far IR is needed to track mass assembly

- Starting with SED models for 319 protostars, we increased the luminosity by 10x, 50x, or 100x
- Evaluated the effect on
  - 4.6 μm flux density (WISE)
  - 25 – 235 μm luminosity (PRIMA)
- Without far-IR monitoring, hard to estimate $\Delta\dot{M}$ from ΔL
- Youngest protostars are not even visible in the mid IR (Stutz et al. 2013)

Dispersions shrink by factors of ~ 3 – 4

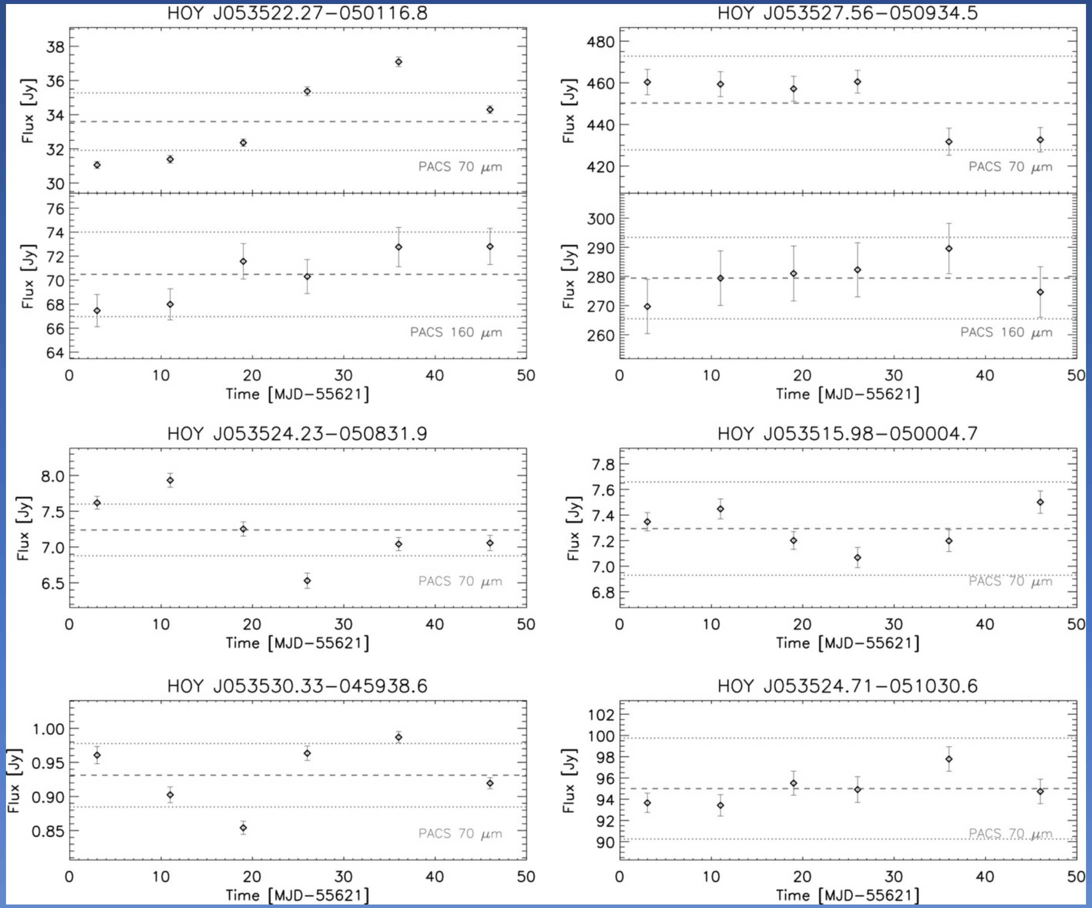


Mid-IR ΔF has a high dispersion; depends on cavity geometry, extinction

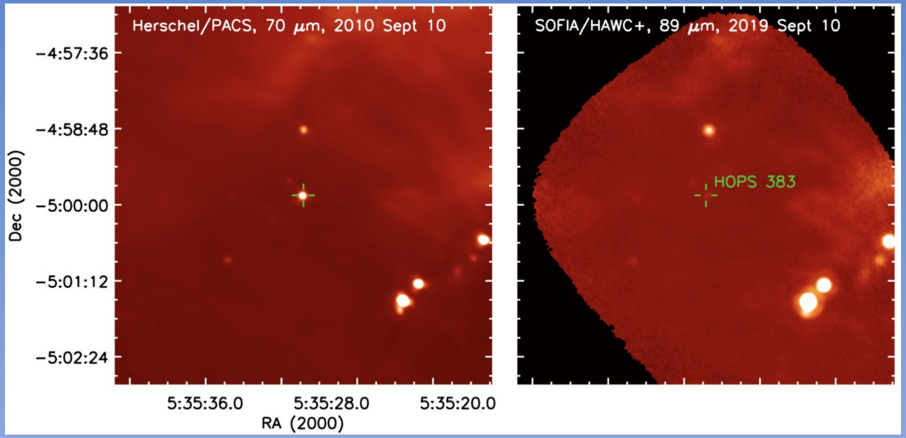
Far-IR ΔL is more tightly clustered around the input ΔL, more so for young Class 0 protostars

Herschel & SOFIA showed the value of the far IR

- Herschel
  - Limited time coverage due to 3 yr mission lifetime, lack of emphasis on time domain
  - Provided a critical epoch 0
- SOFIA
  - No capacity for surveys
  - Important for follow-up of known bursts



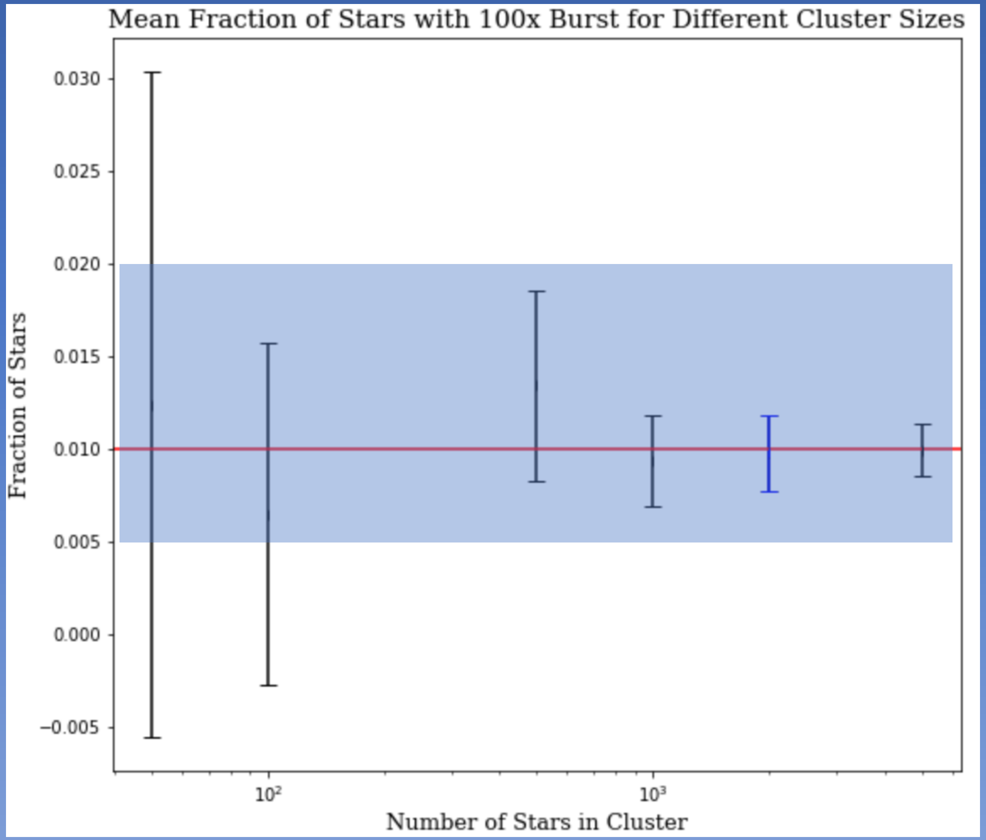
Herschel 70 μm and 160 μm light curves of protostars (Billot et al. 2012; Δt = 6 wk)



A SOFIA 89 μm image from 2019 shows the end of a protostellar burst seen in a Herschel 70 μm image from 2010 (Zakri et al. 2022)

Key Question for PRIMA: Do protostars accrete the majority of their masses in >100x bursts?

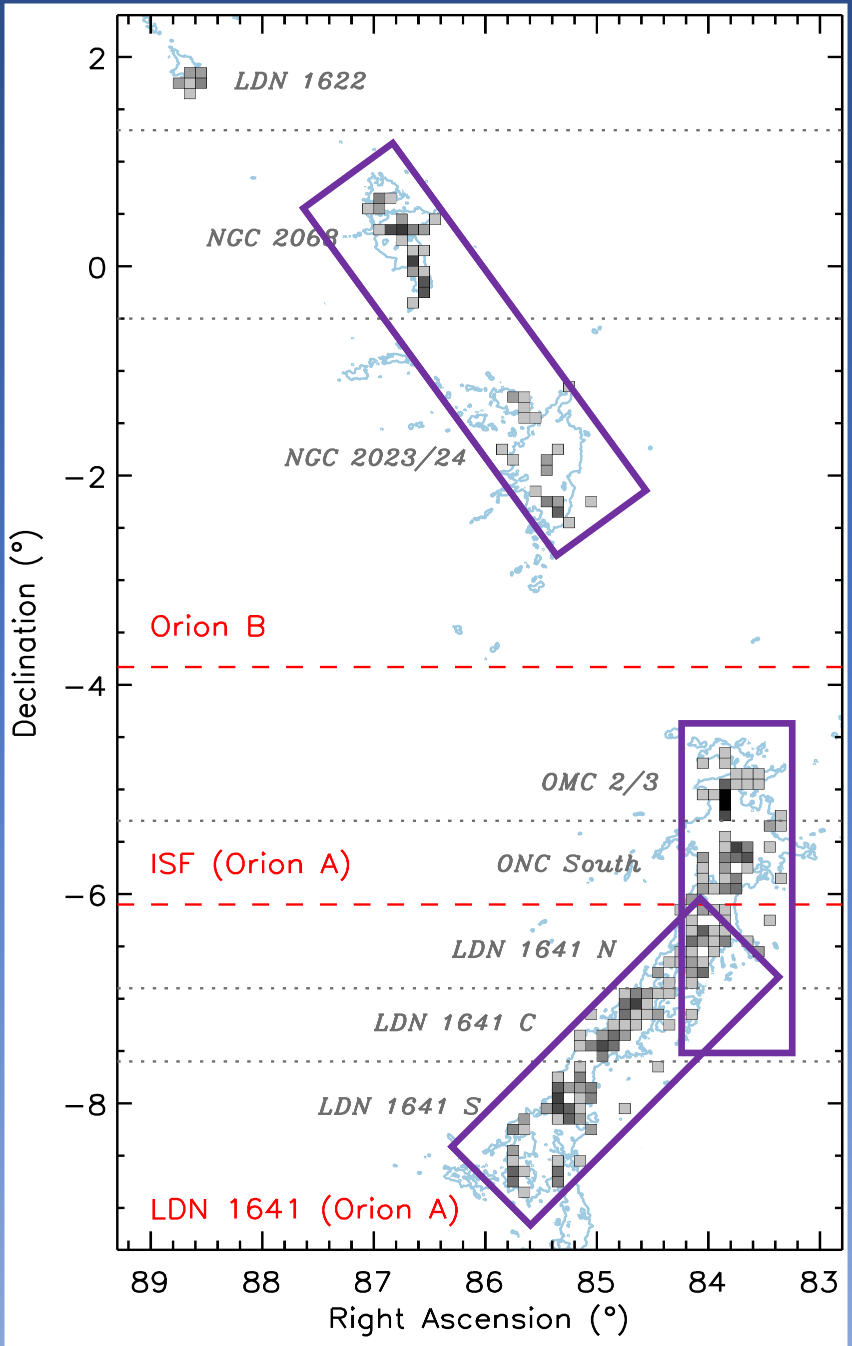
- About 1000 yr between major mid-IR bursts of a given protostar (Fischer et al. 2019; Park et al. 2021)
- Monitor 2000 protostars for 5 yr
  - Discover ~10 major bursts
  - Determine durations of bursts
- Answer additional questions with protostellar light curves
  - What is the burst power spectrum?
  - How do burst amplitudes and durations depend on evolutionary state? Mass of the central object? Disk mass and radius?



Monte Carlo simulations by Rachel Lee (UConn)
Observe ~few × 10^3 protostars for good statistics

Variability survey

- Repeatedly image about 2000 protostars in the nearest 1.5 kpc
  - 30% are Class 0 (youngest)
  - Distributed across ~55 deg^2 of various molecular clouds (Cygnus X, Orion, Mon R2, Aquila, Perseus, etc.)
- Long maps are most efficient
  - Convenient for protostars, which tend to be clustered along filaments



Example: Mapping Orion (~10 deg^2)

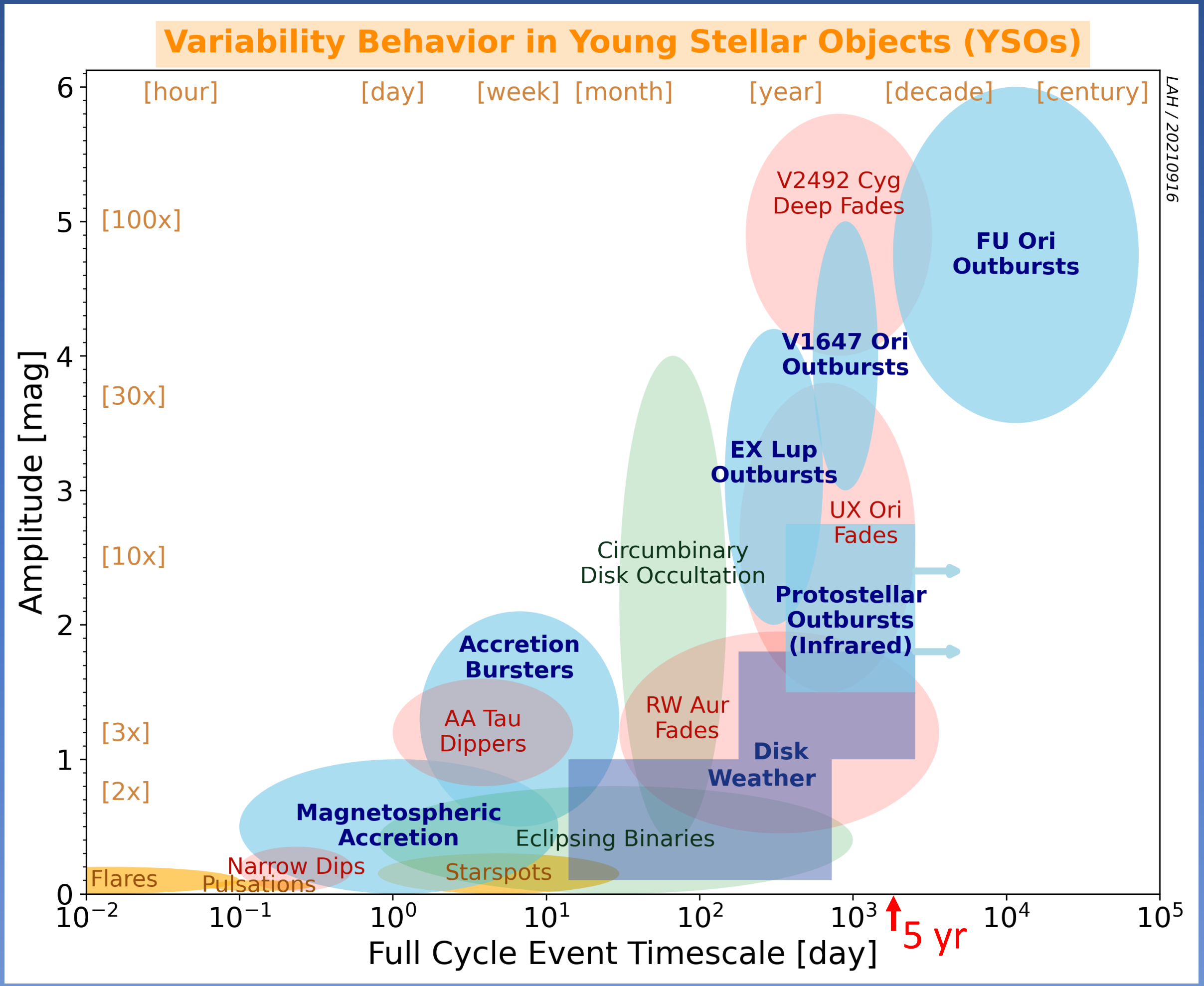
Blue contours: 500 μm Herschel map (Stutz & Kainulainen 2015)

Gray boxes: Locations of 319 protostars (darker boxes contain more; Fischer et al. 2020)

Purple boxes: Tentative PRIMA mapping areas

Cadence

- If mapping speed is 1 deg²/hr, need ~55 hr to map nearest 2000 protostars
- Multiple visits per year
  - Sample a range of timescales from ~8 wks to the full five-year mission
  - Combining PRIMA (~2035) with Herschel (~2010) extends Δt to 25 yr
  - Explore structure in light curves to constrain physical mechanisms
- Repeat a ~55 hr survey ~10 times for ~550 total hours



Blue shading denotes accretion-related variability (Fischer et al. 2023)

Time-domain mapping with PRIMA will show us how stars get their masses

Collaborators on this science case include

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