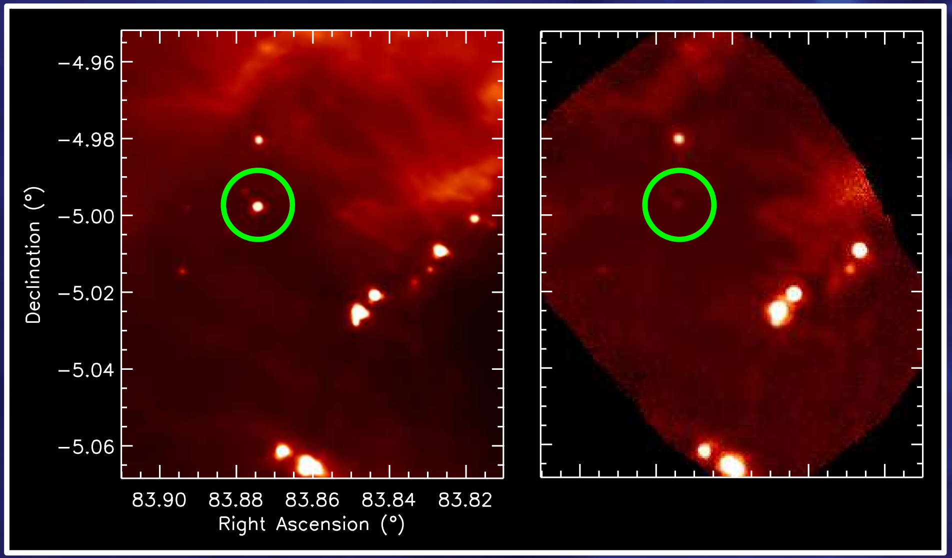


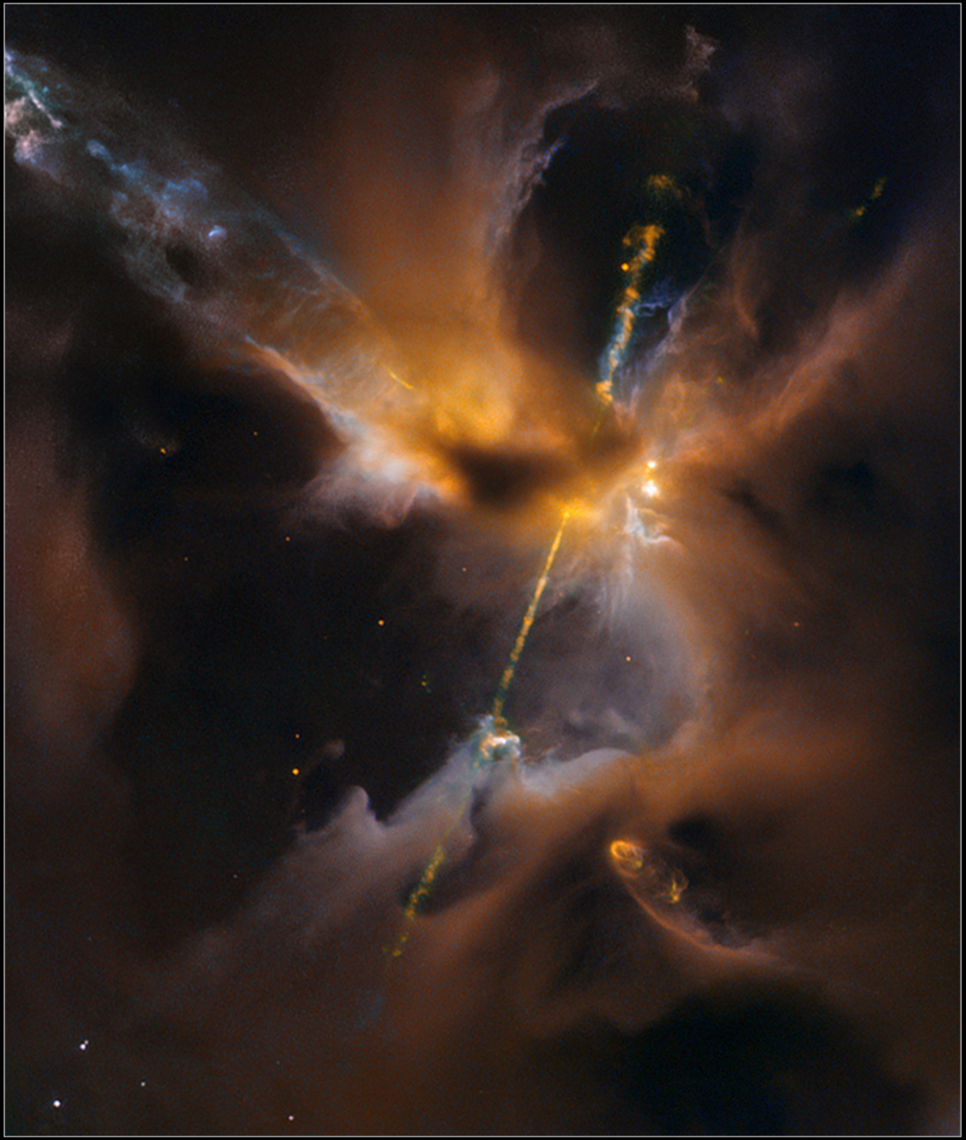
Tracking Protostellar Luminosity Outbursts with SOFIA

Will Fischer

Space Telescope Science Institute

Protostars reveal the origins of solar systems

Herbig-Haro Jet HH 24



Hubble Heritage

NASA and ESA • *Hubble Space Telescope* • WFC3/IR • WFPC2 • STScI-PRC15-42a

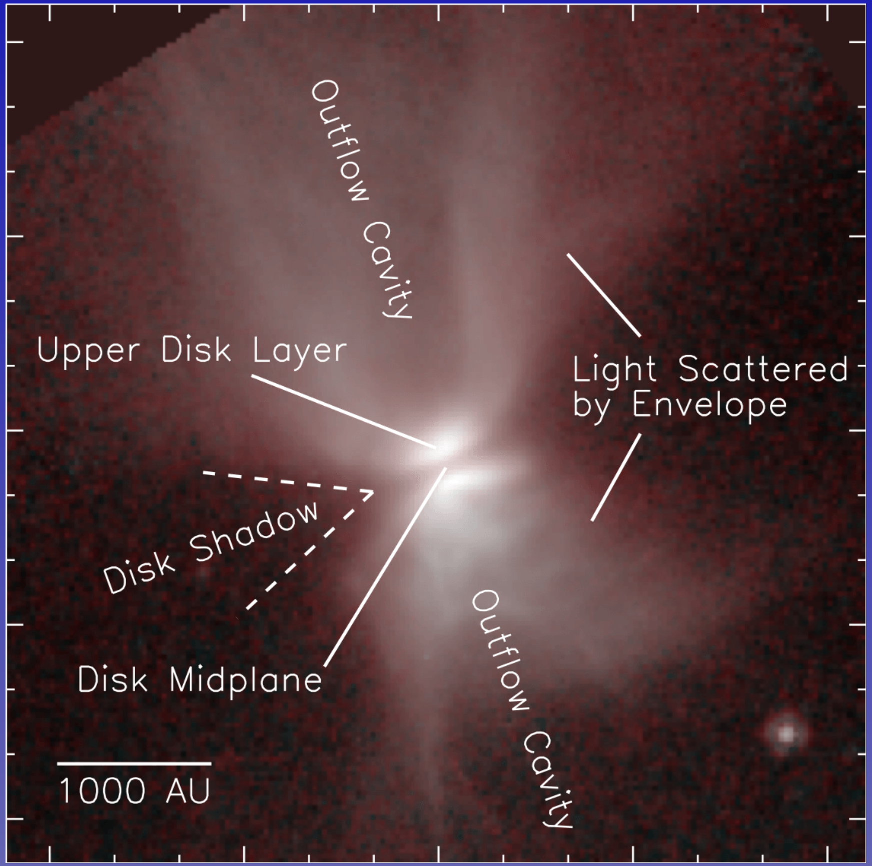
- A dense, infalling circumstellar envelope is still present
- A protoplanetary disk is in the earliest stage of its evolution
- Ages are < 500,000 yr
- The majority (> 90%) of the stellar mass is being assembled

How do stars get their masses?

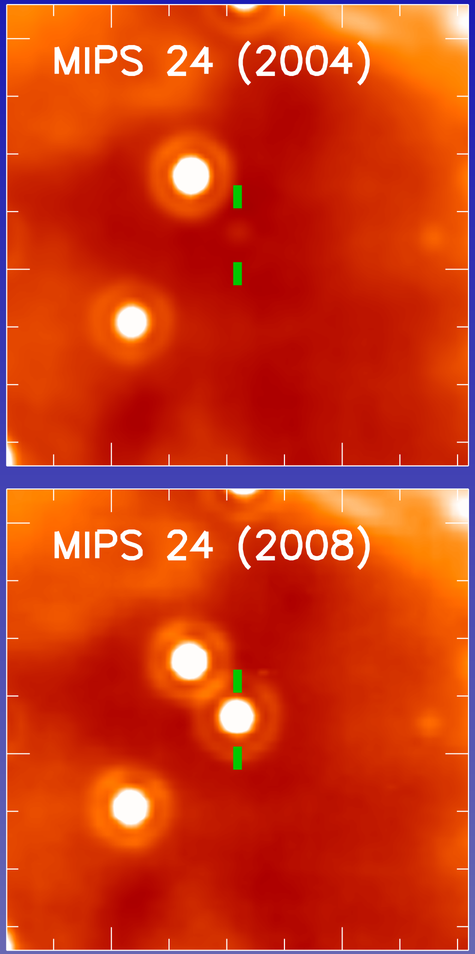
Secular or stochastic processes?

Stochastic:
A sudden luminosity outburst
due to rapid disk accretion

Secular:
Gradual envelope
infall onto a disk, then
accretion onto the star



HOPS 136 (NICMOS)

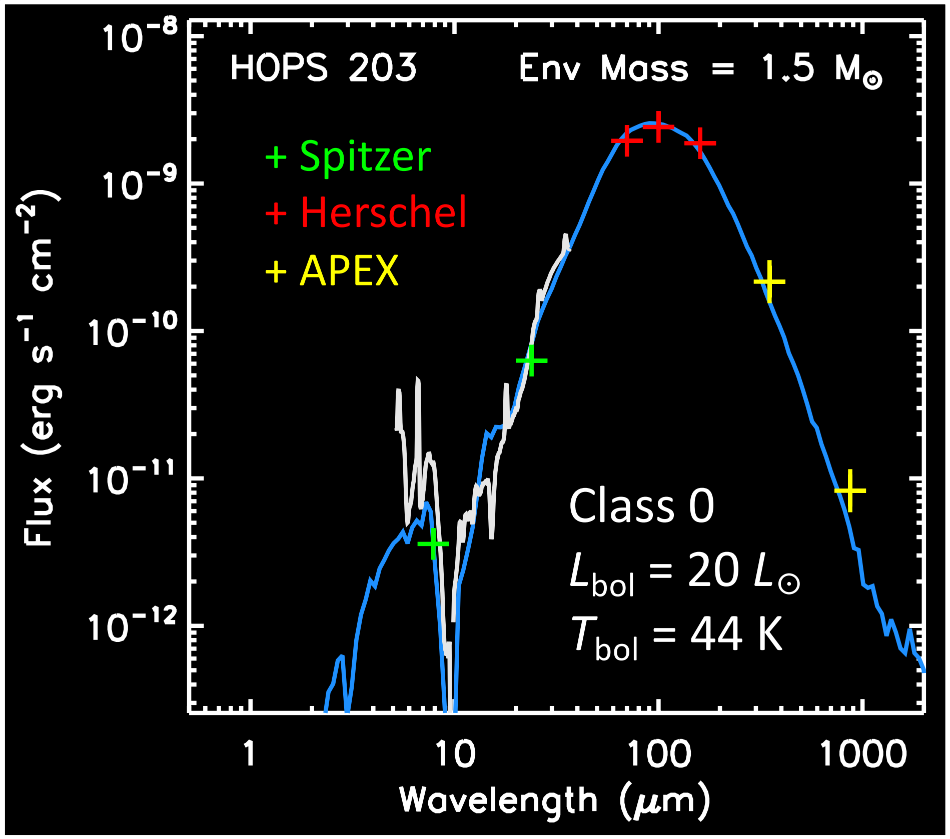


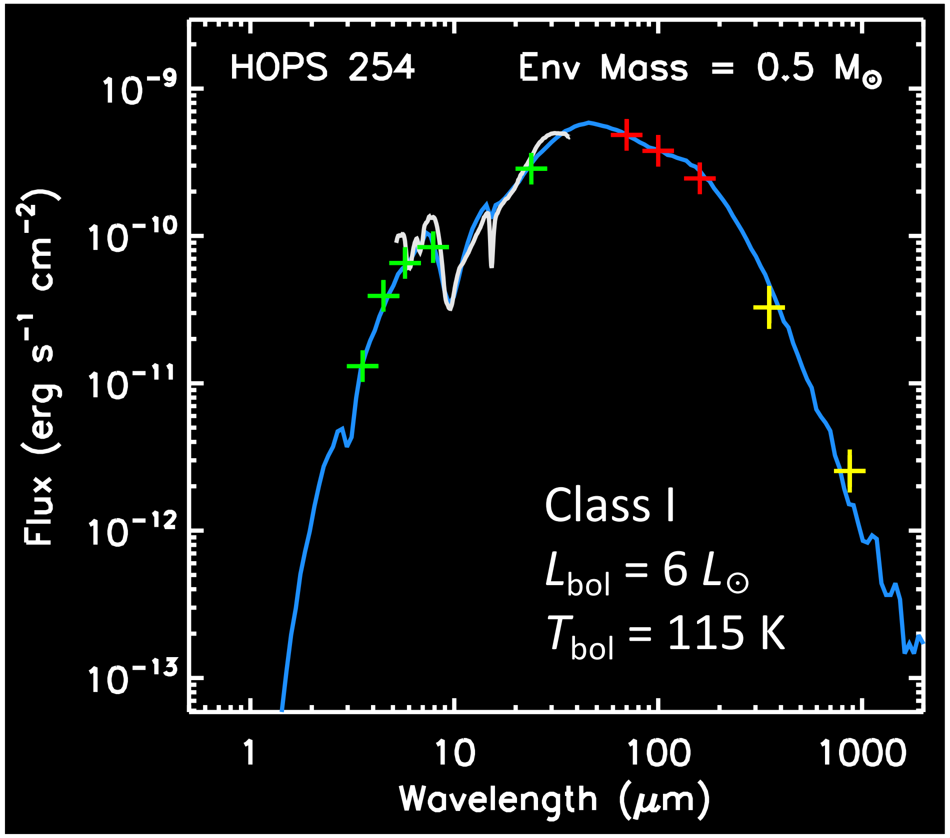
HOPS 383 (MIPS)

Determining how stars get their masses requires mid- and far-IR photometry for accurate protostellar properties

- luminosities
- evolutionary states (redder ≈ younger)

HERSCHEL ORION PROTOSTAR SURVEY



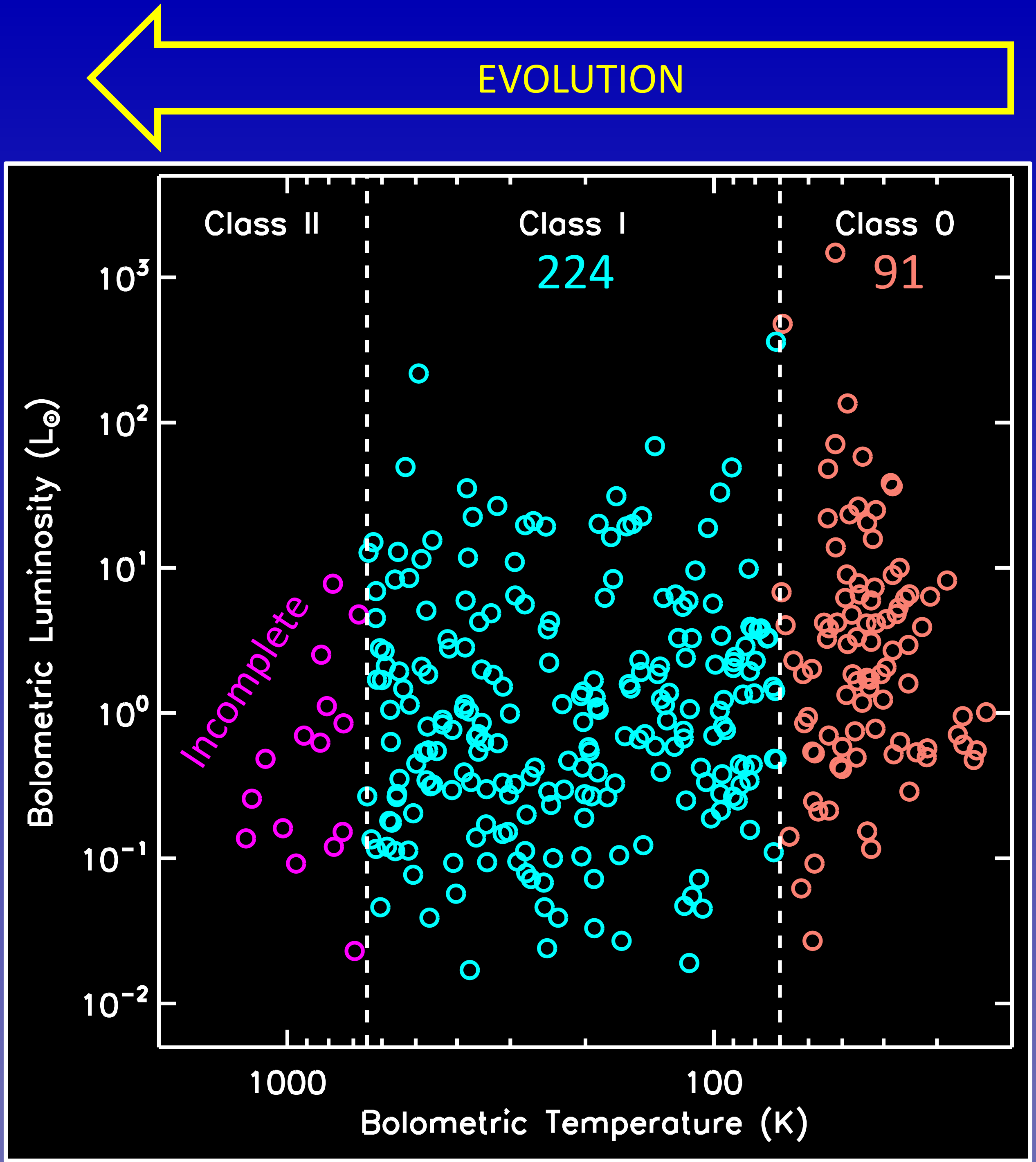


SEDs from the Herschel Orion Protostar Survey (PI Tom Megeath; Furlan et al. 2016)

FORCAST and HAWC+ allow time-domain studies of protostars first characterized with Spitzer and Herschel

The Orion BLT Diagram

Fischer et al. (2017)



Like an HR diagram for protostars

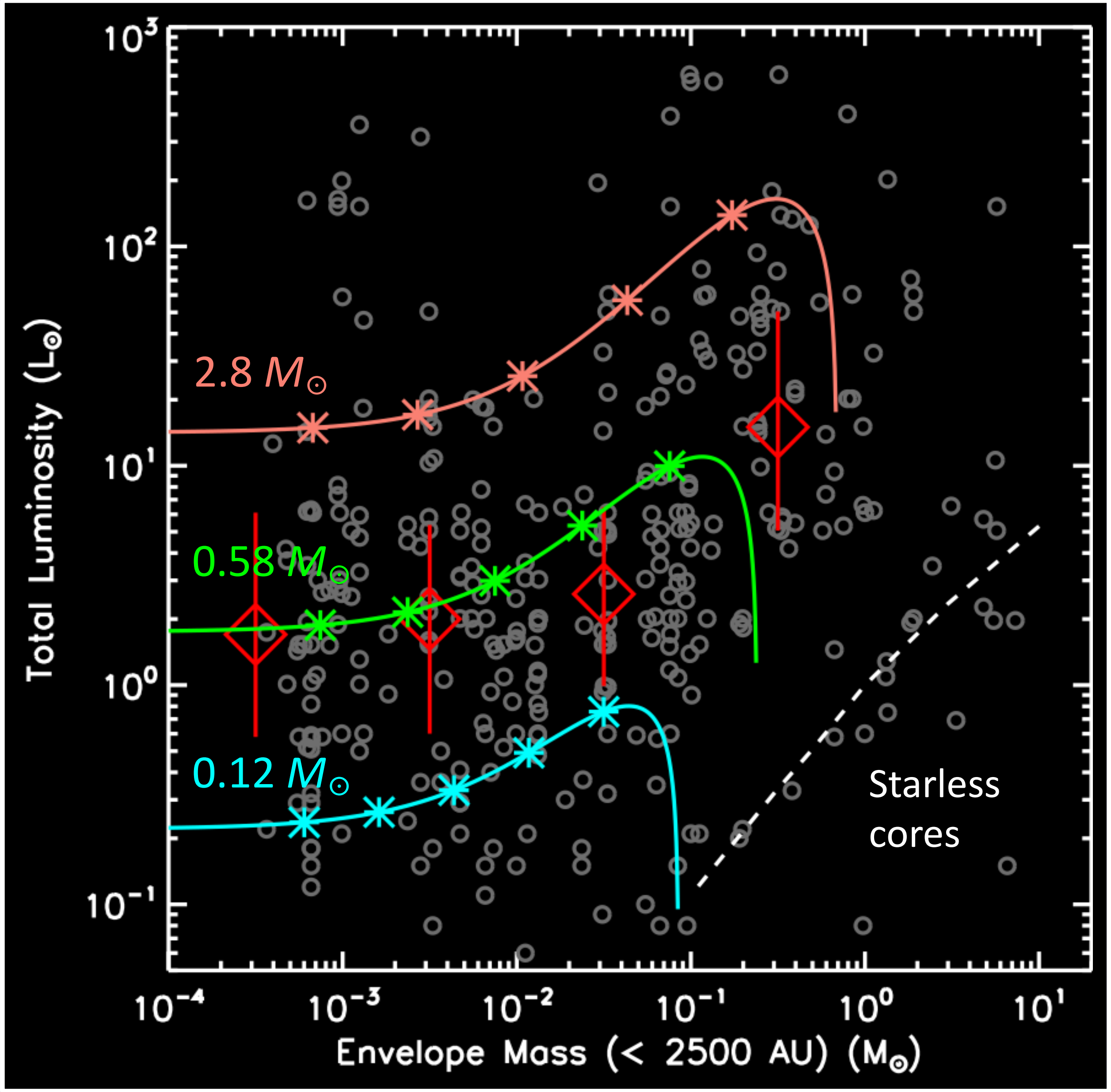
Three main features:

- Large spread in L_{bol}
- Similar # of protostars at each T_{bol}
- Lower L_{bol} at late times

Can these be explained with slowly changing infall rates over the star-formation period? (secular evolution)

Or do we need rapid bursts of accretion? (stochastic evolution)

Evolutionary diagrams are consistent with secular processes

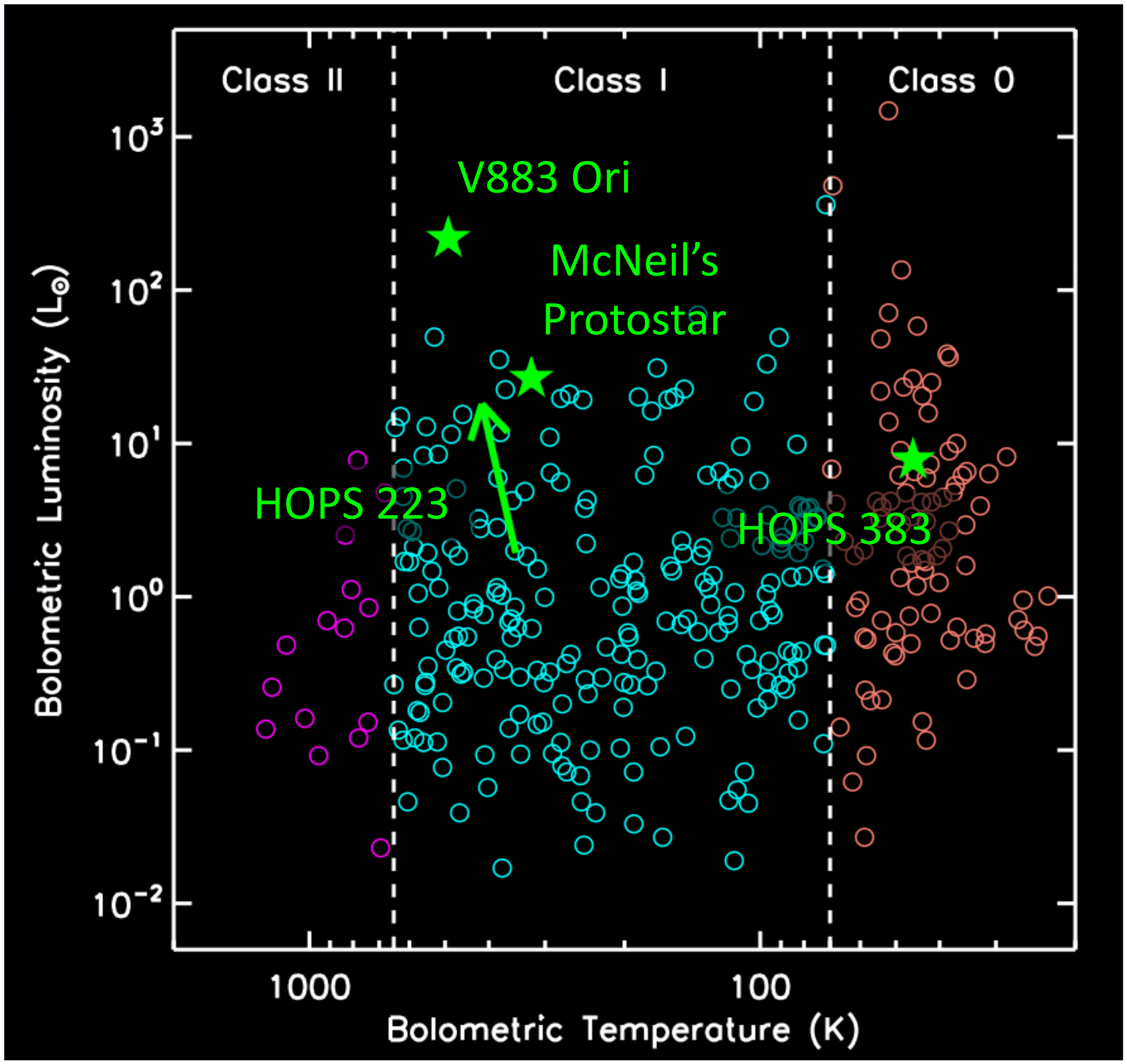


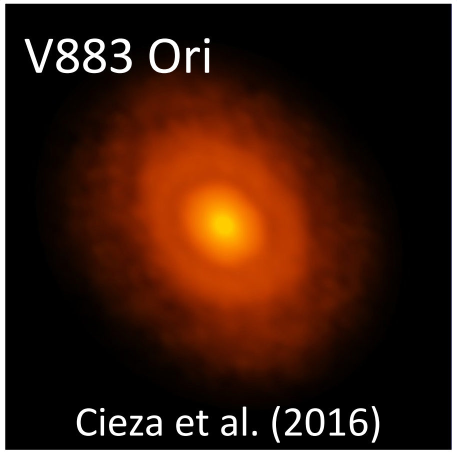
Converting T_{bol} to envelope mass with models, we showed that the main features of this diagram can be explained with

- An initial range of envelope masses
- Accretion rates that are large early and decline exponentially and smoothly

- Tracks show example protostars that reach the main sequence at 0.12, 0.58, 2.8 $M_\odot$
- Asterisks: models at 1, 2, …, 5 × 10^5 yr

But outbursts clearly influence evolutionary diagrams




V883 Ori

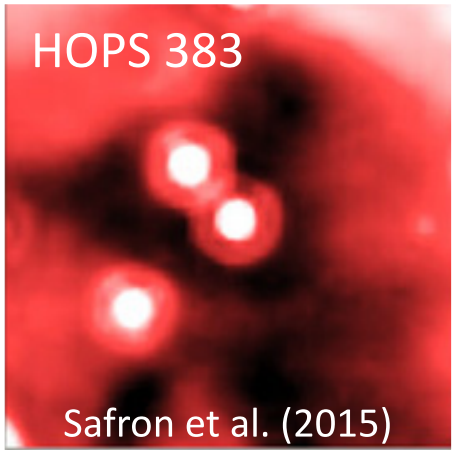
Cieza et al. (2016)


McNeil's Protostar

Reipurth & Aspin (2004)


HOPS 223

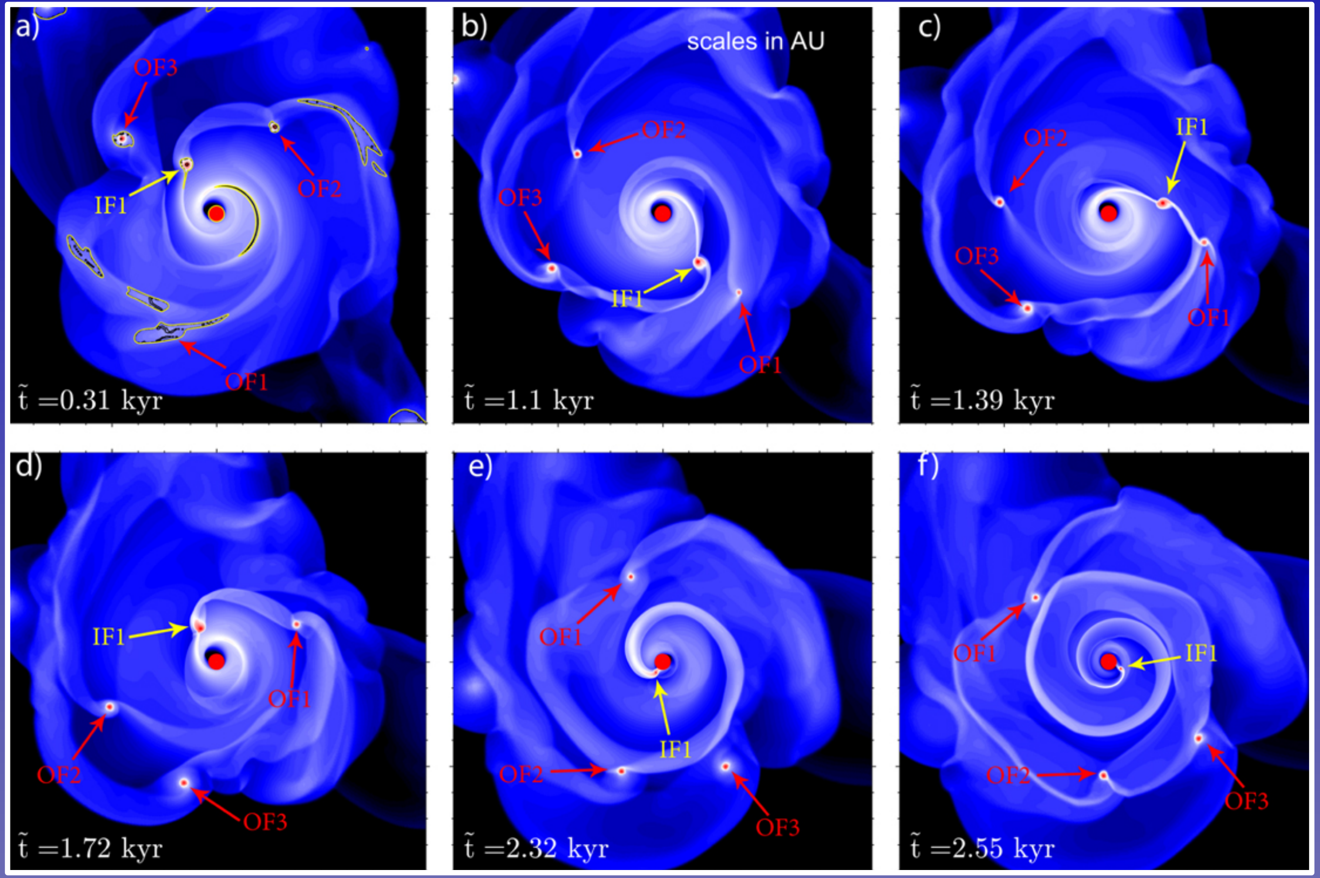
Fischer et al. (2012)


HOPS 383

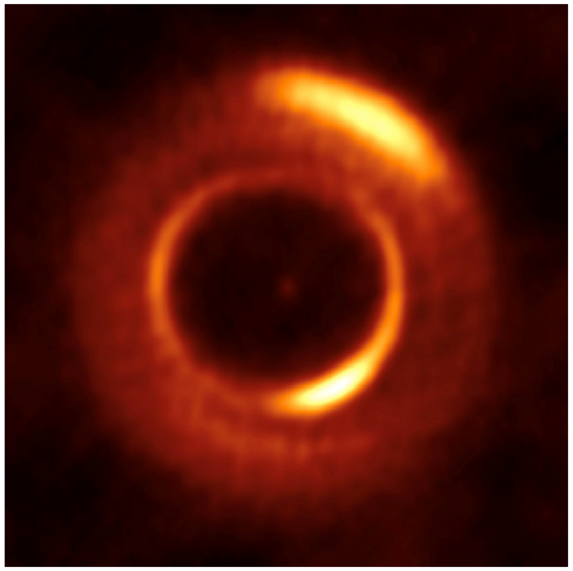
Safron et al. (2015)

Outbursts are likely due to disk instabilities

- Can arise due to the interplay between gravitational and magneto-rotational instabilities in the disk, mediated by envelope infall
- Clumps at large radii may appear as structure in images



Simulation by Vorobyov & Elbakyan (2018)



ALMA image of MWC 758
(Dong et al. 2018)

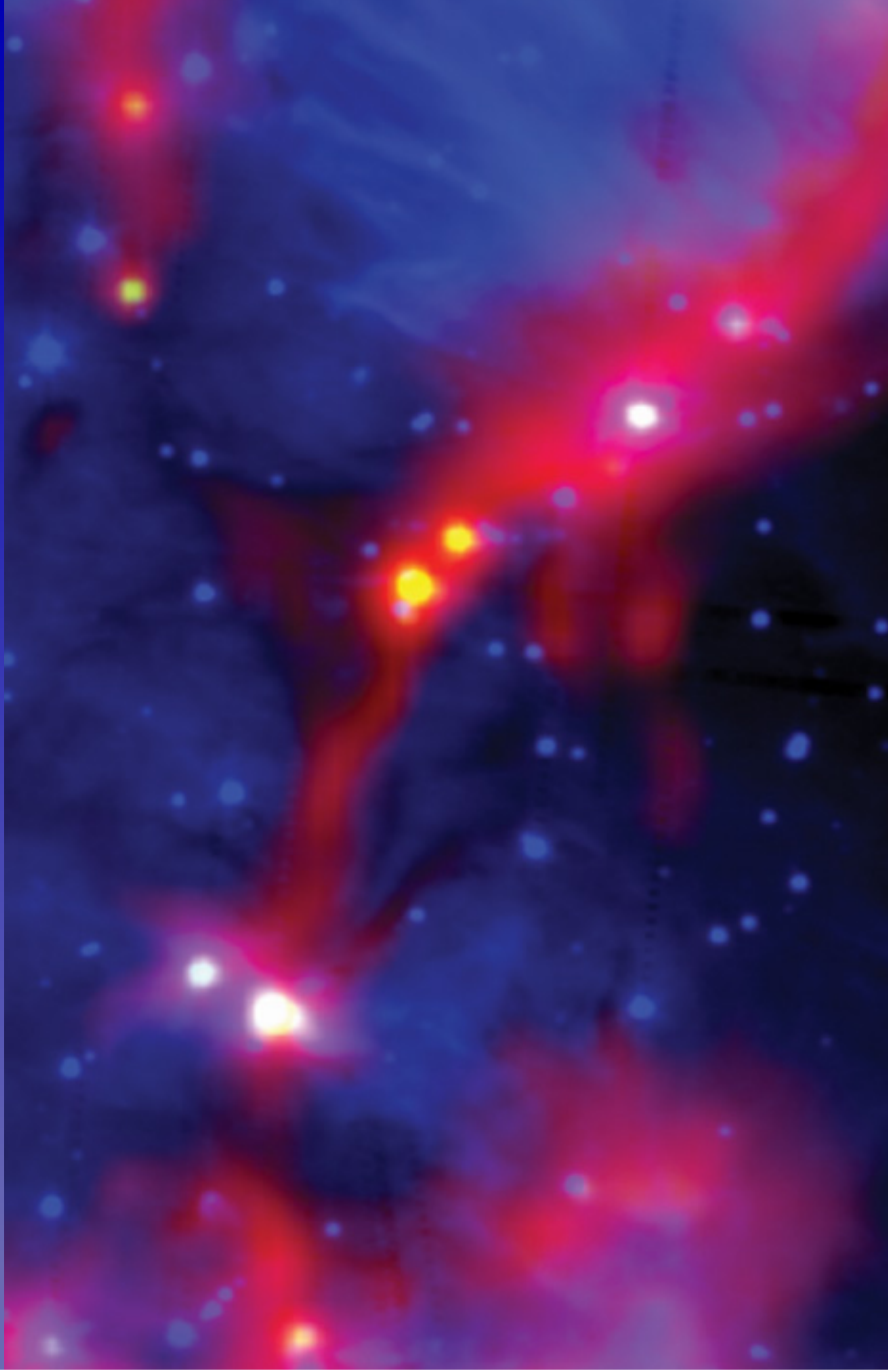
Quantifying the Role of Outbursts

- How much of a star's ultimate main-sequence mass is accumulated in bursts?

$$M_b = \dot{M}_b \times N_b \times t_b$$

  - $\dot{M}_b$: typical accretion rate in bursts; related to luminosity
  - N_b: number of bursts experienced while the star forms
  - t_b: typical duration of each burst

- SOFIA is essential to measure t_b

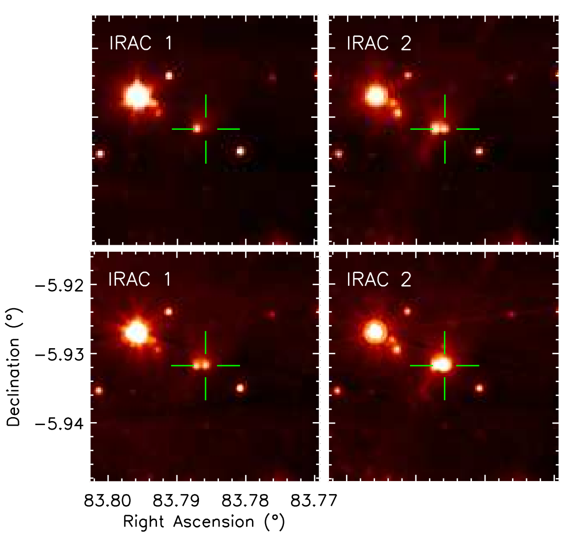


Four Orion Outbursts in Spitzer and WISE

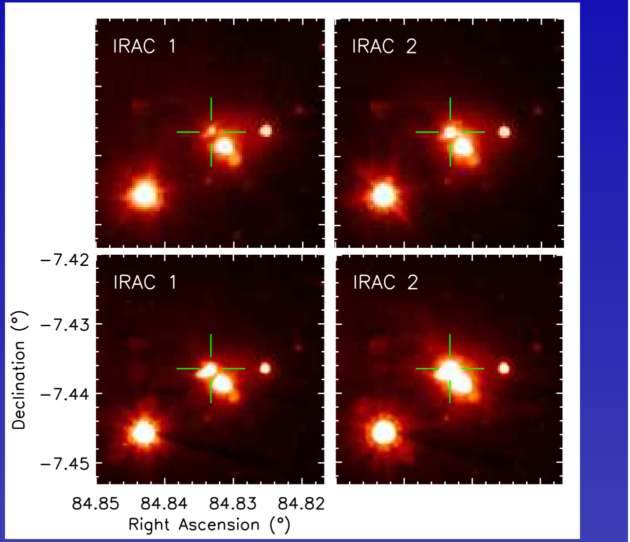
Finding outbursts requires wide surveys

- Spitzer cryo mission (3.6, 4.5, 24 µm)
- WISE (3.4, 4.6, 22 µm)
- Spitzer warm mission (3.6, 4.5 µm)
- NEOWISE (3.4, 4.6 µm)

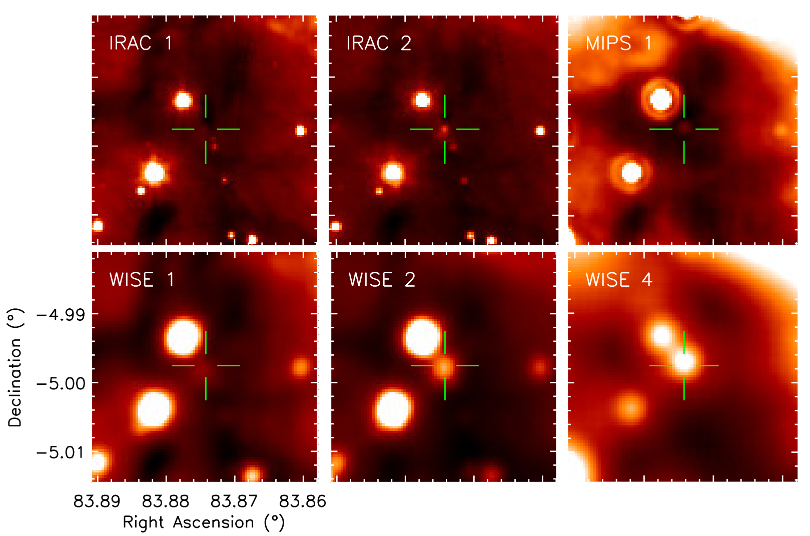
HOPS 12



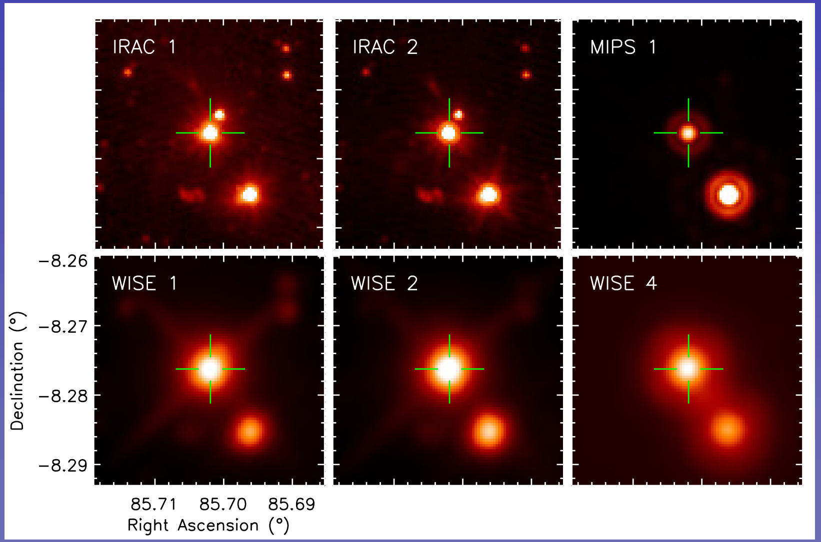
HOPS 124



HOPS 383



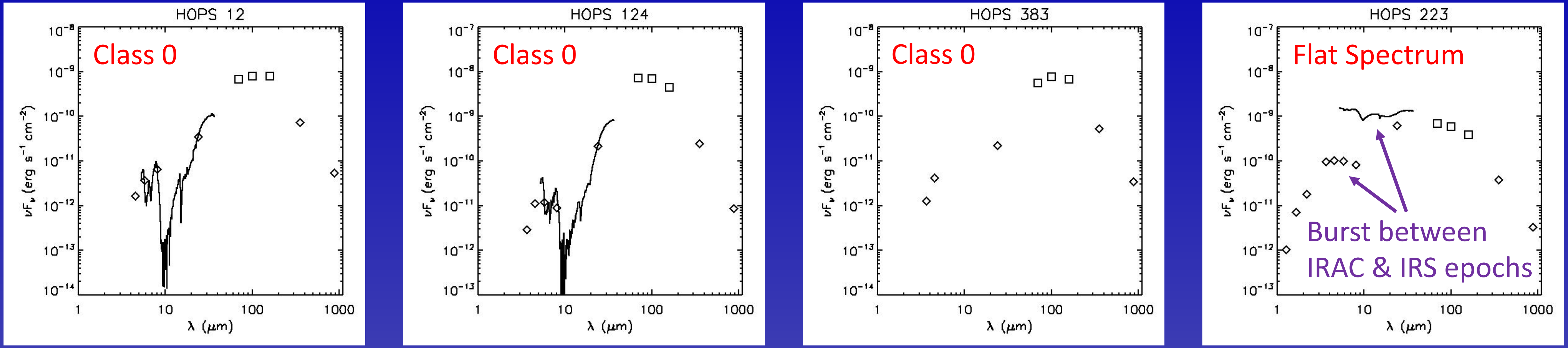
HOPS 223



From Spitzer cryo / warm comparison
(Orion: The Final Epoch,
W. Zakri PhD thesis, in prep)

From Spitzer / WISE comparison
(Safron et al. 2015;
Fischer et al. 2019)

Four Orion Outbursts in Spitzer and WISE



SEDs from the IRSA HOPS Archive
https://irsa.ipac.caltech.edu/data/Herschel/HOPS/overview.html

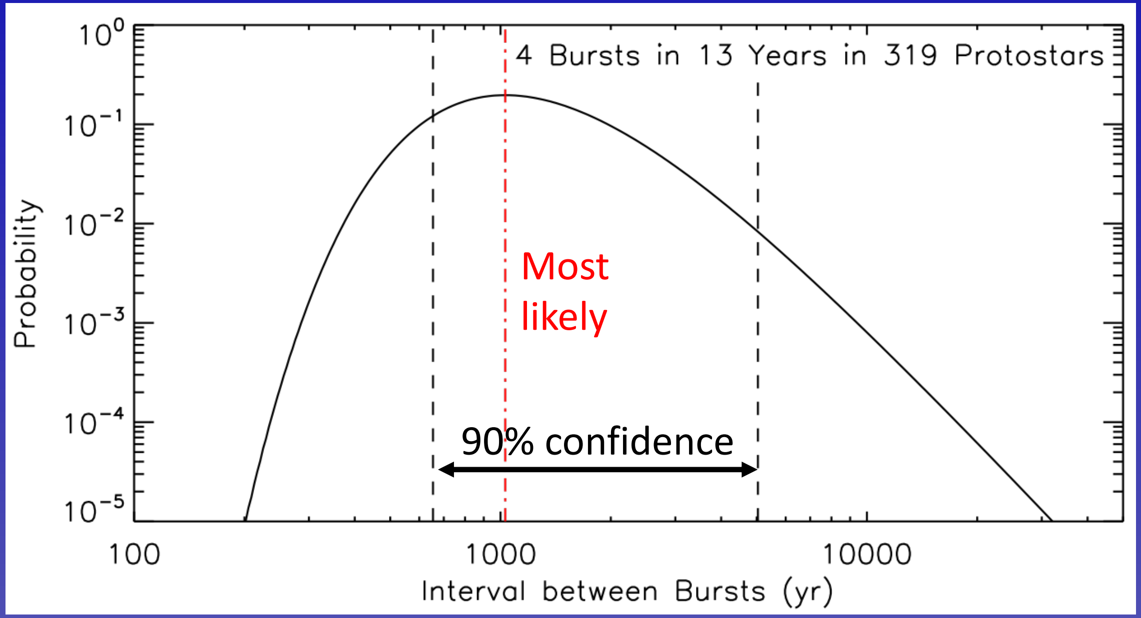
◇ 2MASS, Spitzer, APEX
— IRS
□ Herschel

- Three of the outbursts are Class 0 protostars (deeply embedded, young)
- They may be analogous to the more evolved FU Ori or EX Lup outbursts, but this is not yet clear
- SOFIA is essential to track their decay times

How many bursts does a protostar experience?

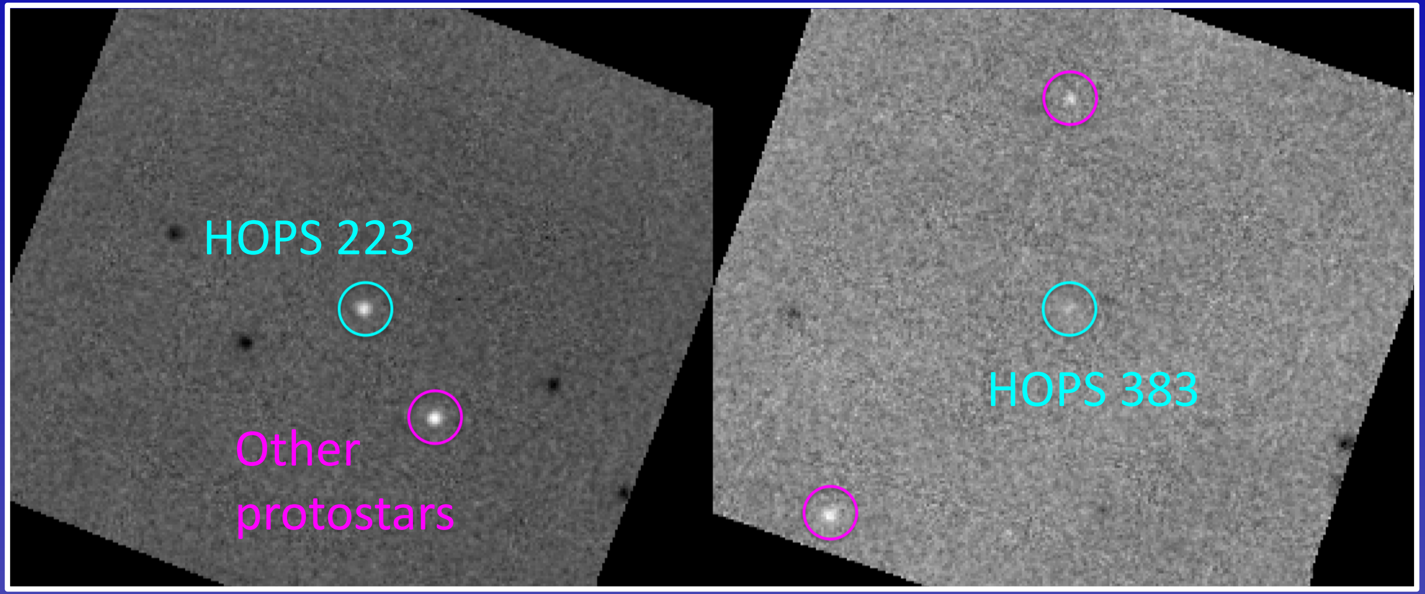
- We found 4 in 319 protostars in 13 years
- Suggests that every protostar should burst in 13 yr / 4 × 319 ~ 1040 yr with 90% confidence between 650 and 5000 yr
- Protostellar burst interval is < than ~ 10^4 yr found for pre-main-sequence stars with disks (Scholz et al. 2013; Contreras Peña et al. 2019; Zakri et al. in prep.)
- 1000 yr between bursts means N_b ~ 500 bursts per protostar over the 500,000 yr protostellar phase

Burst Interval Probability



~ 25% of a star’s main sequence mass may be accumulated in bursts

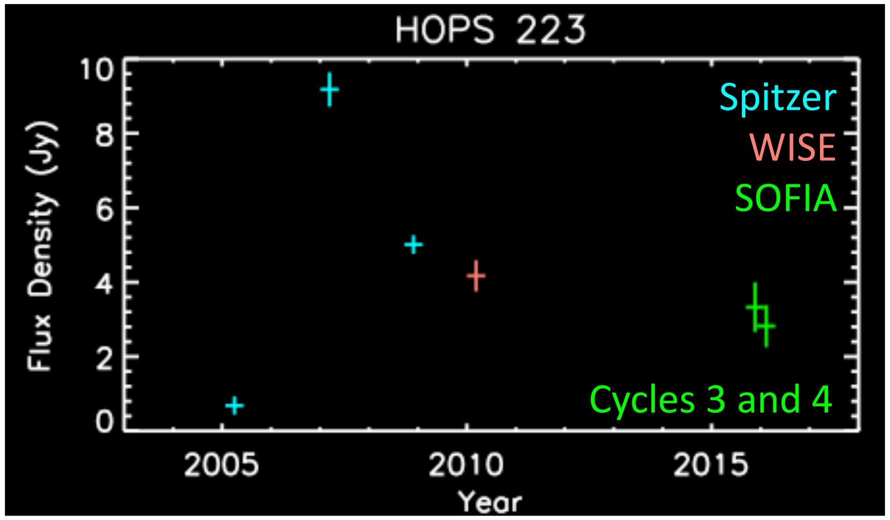
Estimating the outburst time scale

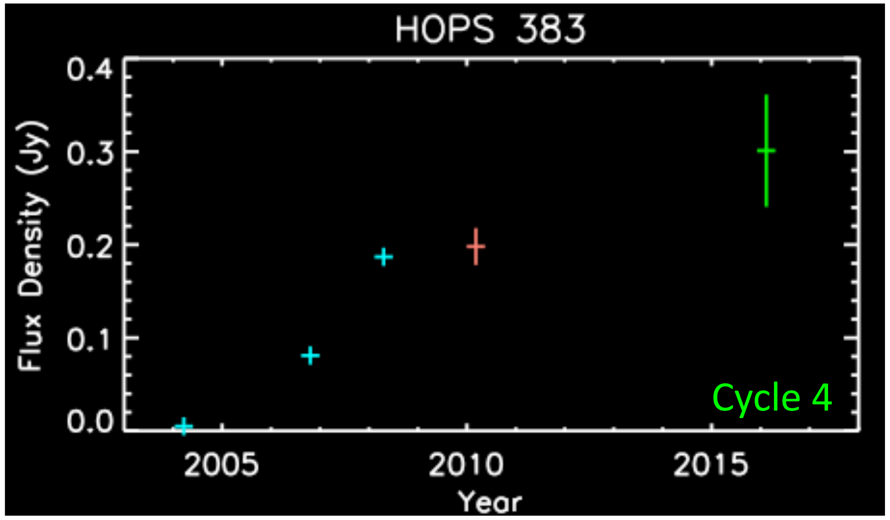


FORCAST 37 µm images

(HOPS 383 is deeply embedded and nearly invisible even at 37 µm)

24 µm Light Curves



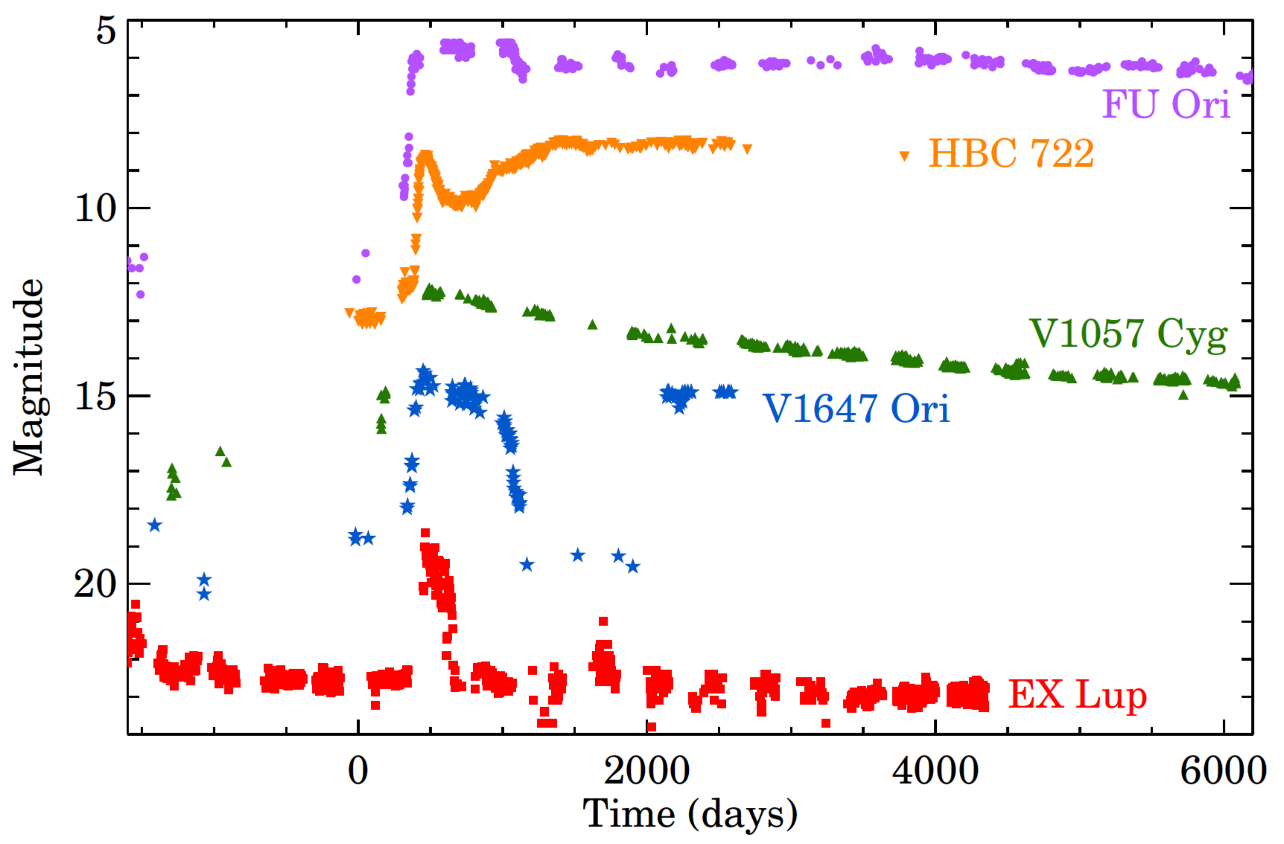


Cycle 3+4 FORCAST photometry shows that both HOPS 223 and HOPS 383 have persisted on decade timescales

Bursts may have long decay times

- Decay times vary (~ 1 to > 80 yr), but we do not require fine time sampling
- Monitoring each burst a few times per year is sufficient
- SOFIA could facilitate time-domain proposals to observe a given bright target multiple times per cycle
- E.g., in recent cycles there have been 2 HAWC+ flight series out of Palmdale separated by ~ 6 months, enabling multiple yearly visits

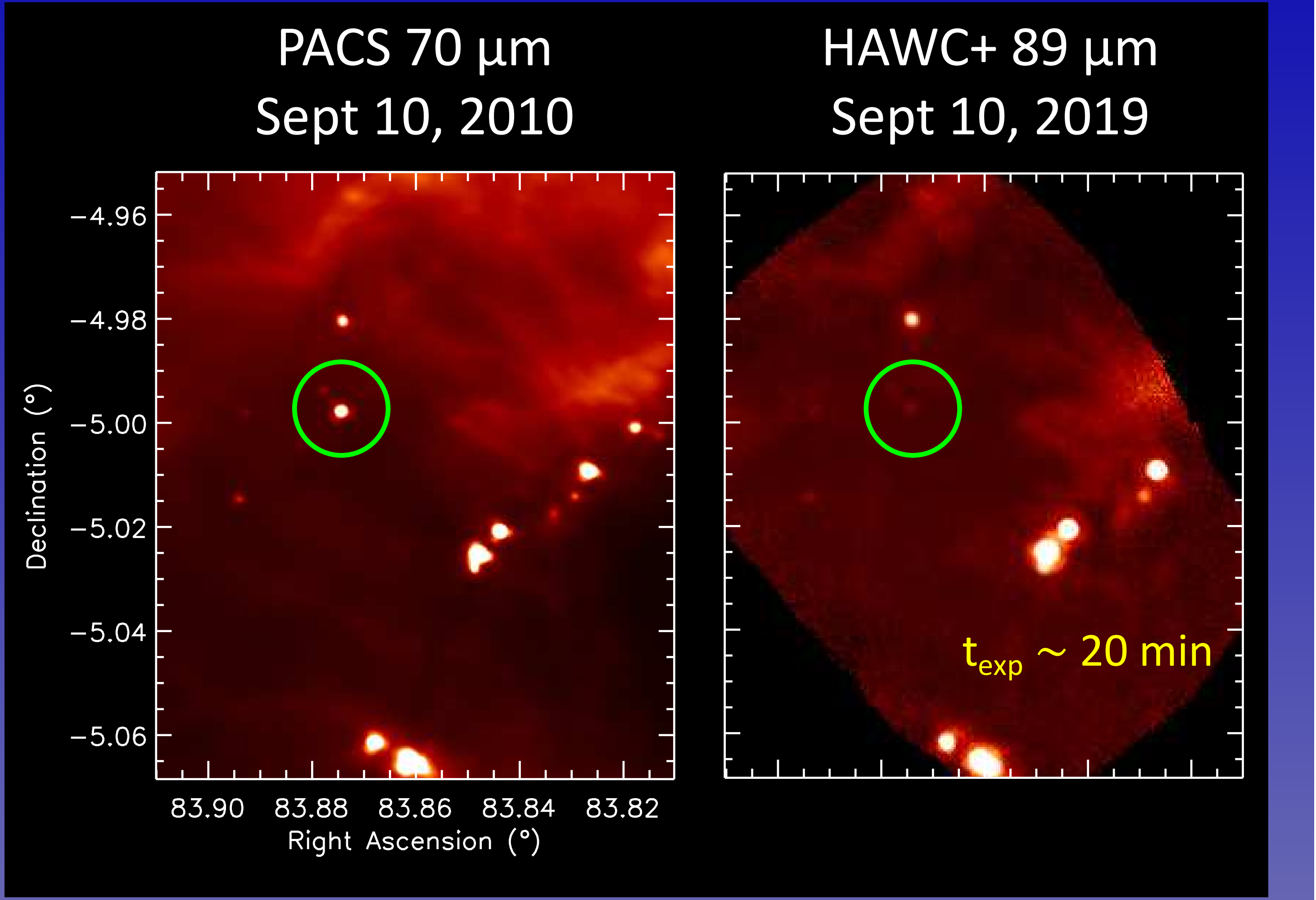
Light curves of famous bursts



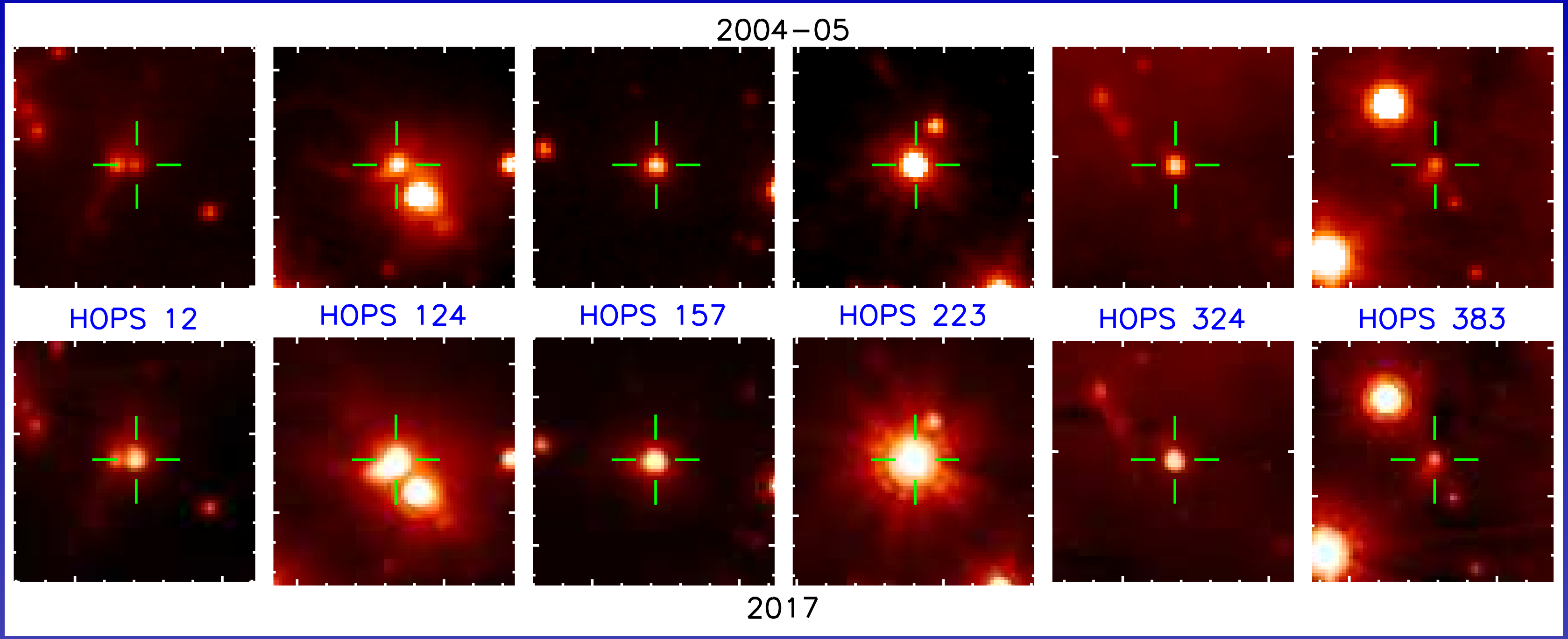
Adapted from Kóspál et al. (2011)

The HOPS 383 outburst has ended!

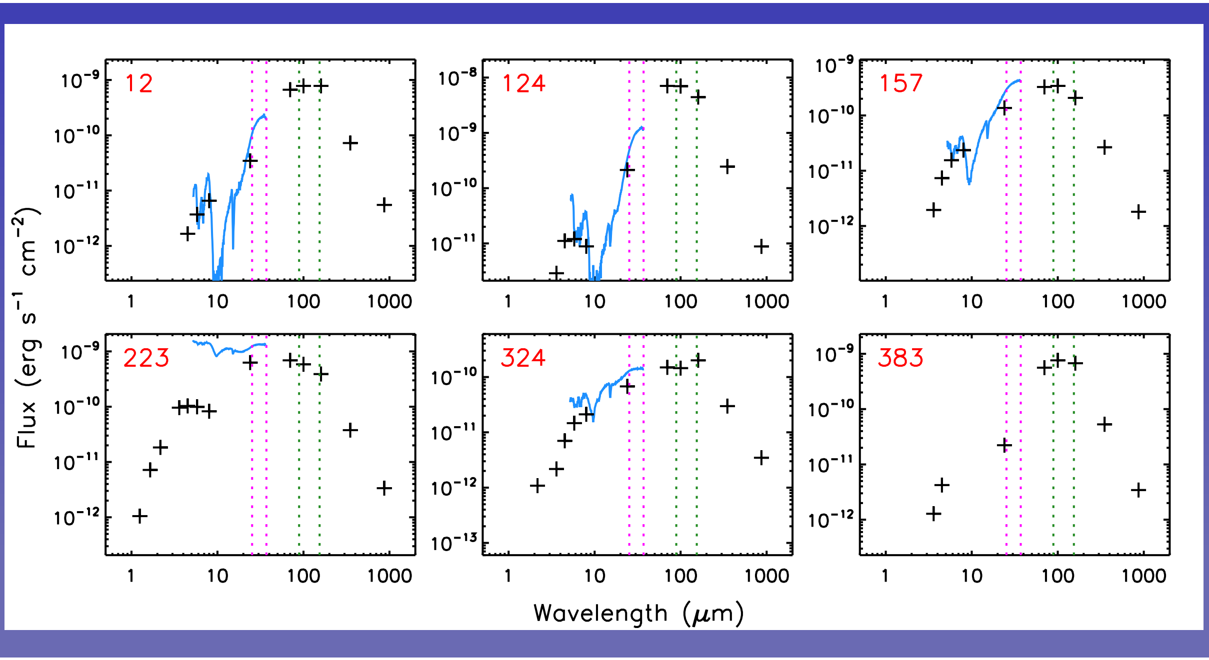
- We have begun using HAWC+ for far-IR monitoring to track the luminosity of outbursts
- In Sept 2019, HAWC+ revealed a dramatically fainter HOPS 383
- Total mass accumulated in burst:
  - Accretion rate ~ 10^{-6} $M_\odot$ yr^{-1}
  - Duration ~ 10 yr
  - Even 1000 of these would account for 0.01 $M_\odot$, not much
- Also see Grosso et al. (2020) for a similar conclusion from NEOWISE data



Before (top) and After (bottom) with Spitzer 4.5 μm



2MASS / Spitzer / Herschel SEDs (SOFIA bands: dotted lines)

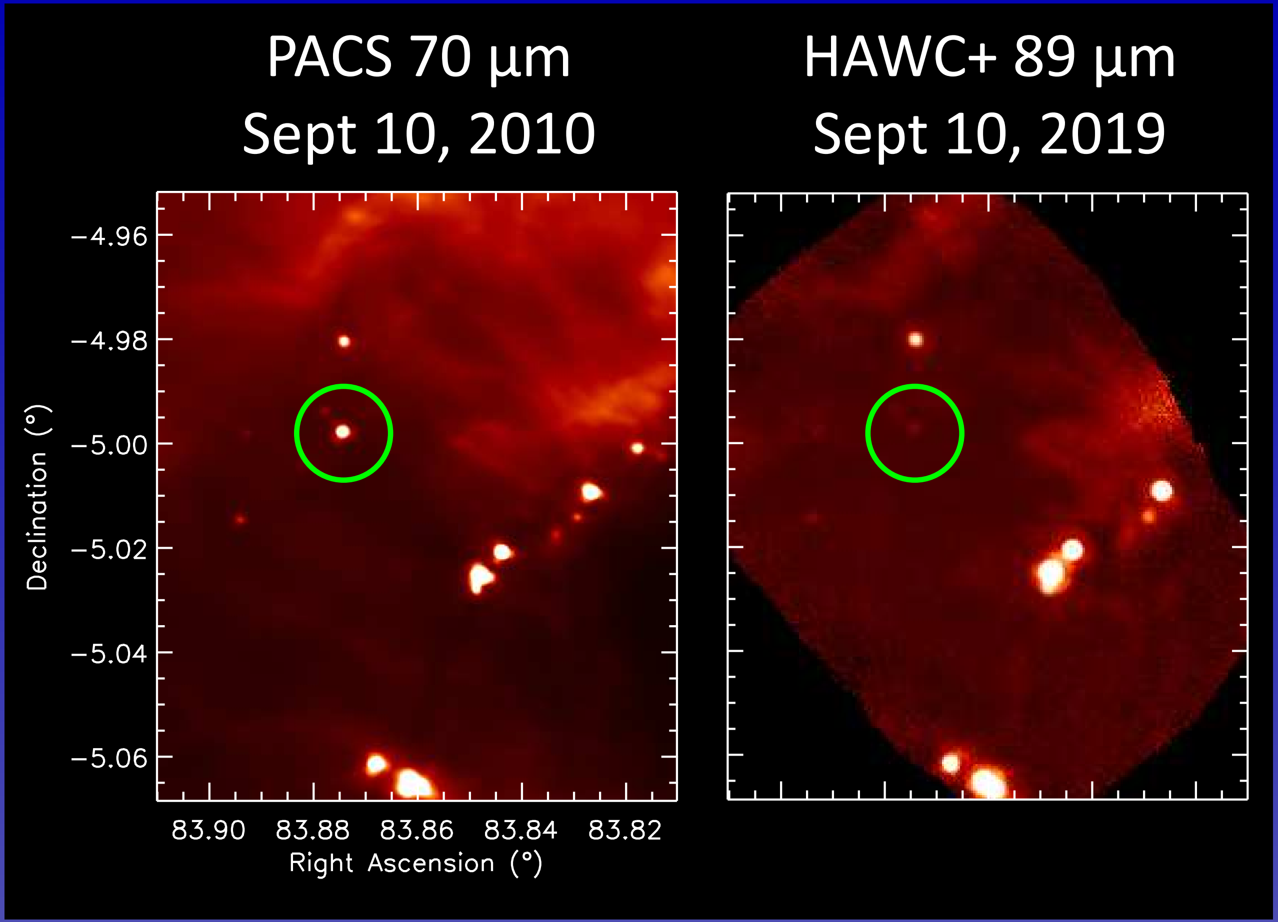


Future Monitoring

- For Cycle 8, we have been approved for imaging of six Orion outbursts
  - FORCAST: 25.3 + 37.1 μm
  - HAWC+: 89 + 154 μm
- All this in only ~ 2 hrs
- These bands surround the SED peaks and correspond roughly to wavelengths available with previous instruments

Conclusions

- An important fraction of a star's main sequence mass may be assembled by enhanced accretion during luminosity outbursts
- SOFIA tracks luminosity over time for deeply embedded outbursts discovered in wide surveys
- What we need:
  - FORCAST & HAWC+ photometry
  - Enhanced time-domain capacity
  - Enhanced synergy with other observatories, e.g., joint targets of opportunity (HAWC+ for luminosity; HST/WFC3 for imaging of environmental scattered light)



- Spectroscopy? Items of interest discussed on Monday include
  - FORCAST gratings
  - HAWC+ narrow-band filters, e.g., [O I] 63 µm
  - FIR line mapping: accretion / outflow connection