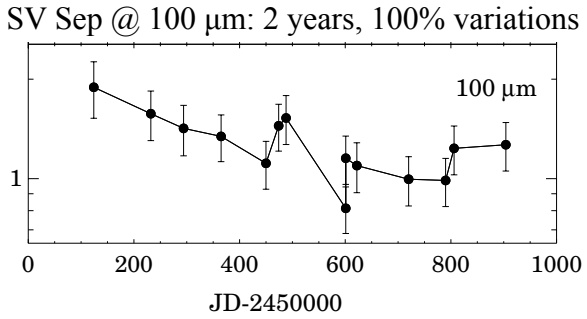
Far-IR Photometric Monitoring of Protostars in Orion Molecular Clouds

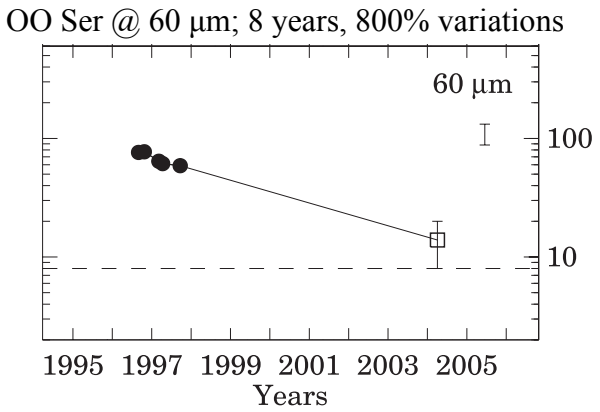
Nicolas Billot (IRAM)

M. Morales-Calderón, J. Stauffer (IPAC), T. Megeath (U. of Toledo), B. Whitney (SSI)

Protostellar Variability

- ***Variability*** is a defining characteristic of Young Stellar Objects (Joy 1945)
- *Optical / Near-IR*: accretion shocks – hot spots (e.g. Carpenter et al 2001)
- *Mid-IR*: Inner disk structure (warped disks, variable scale height)
  - YSOVAR (Morales-Calderón et al. 2009), LRLL 31 (Flaherty et al. 2011), etc.
- *Far-IR (>50μm)*: Only sparse and rare time series yet observed…
  - KAO: Harvey et al. (1998)
  - ISOPHOT: Juhász et al. (2007), Kóspál et al. (2007)

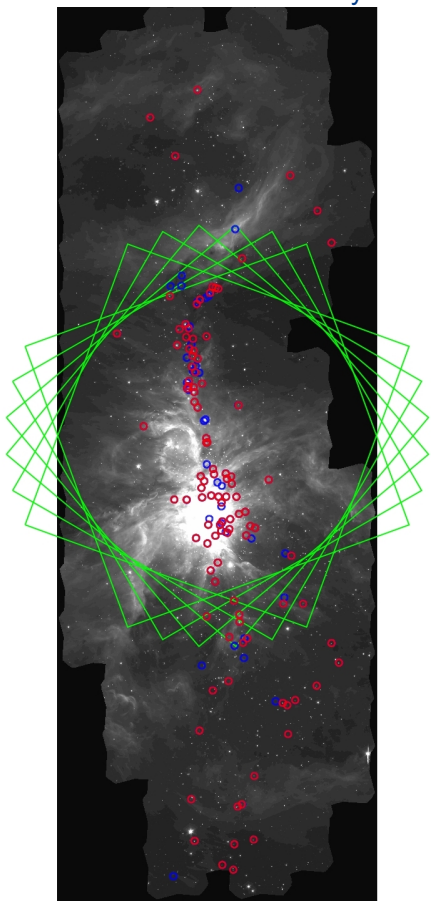




- 70 μm flux good proxy to protostellar total luminosity (Dunham et al. 2008)

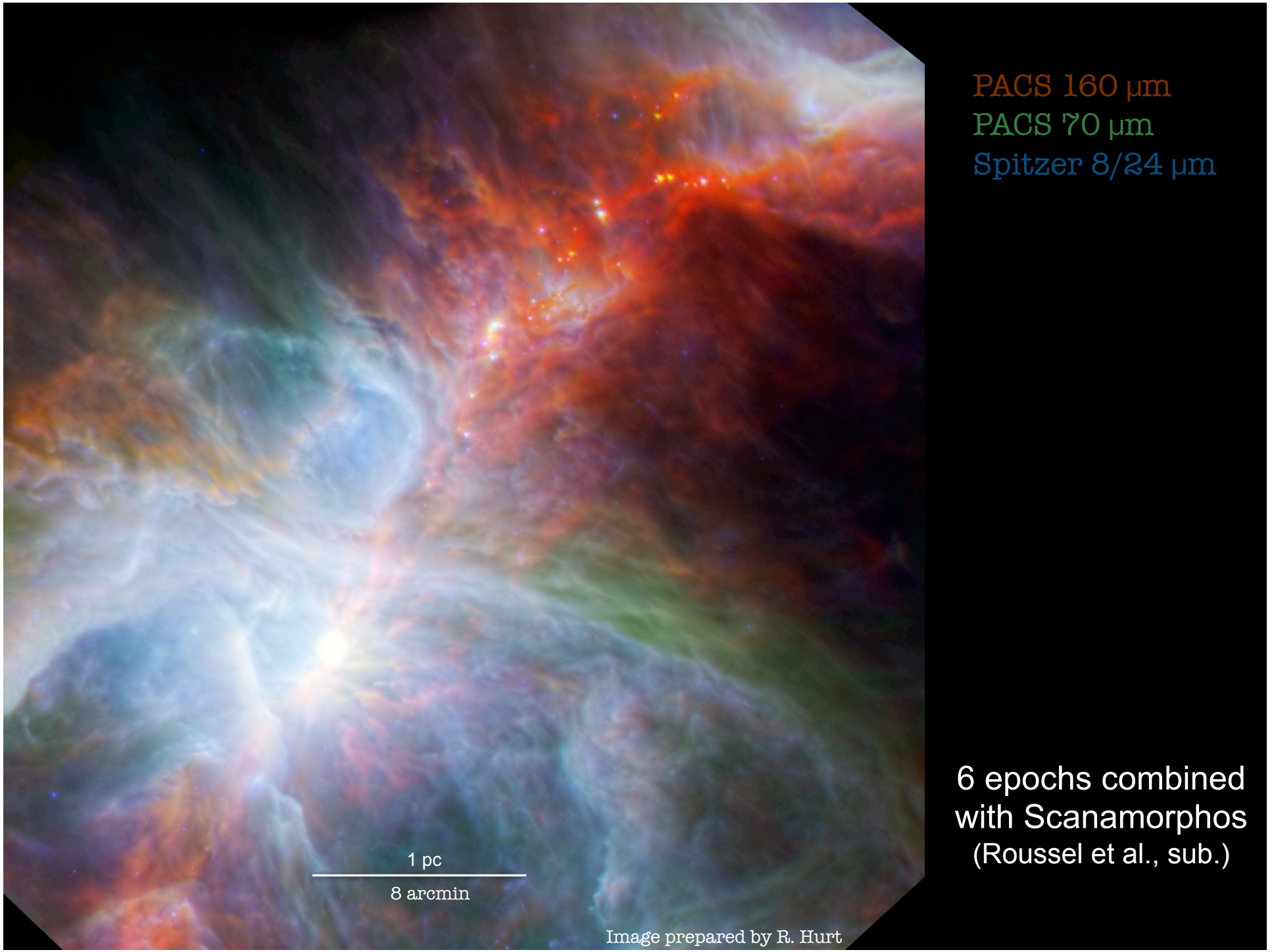
Far-IR photometric monitoring

Herschel AORs overlay

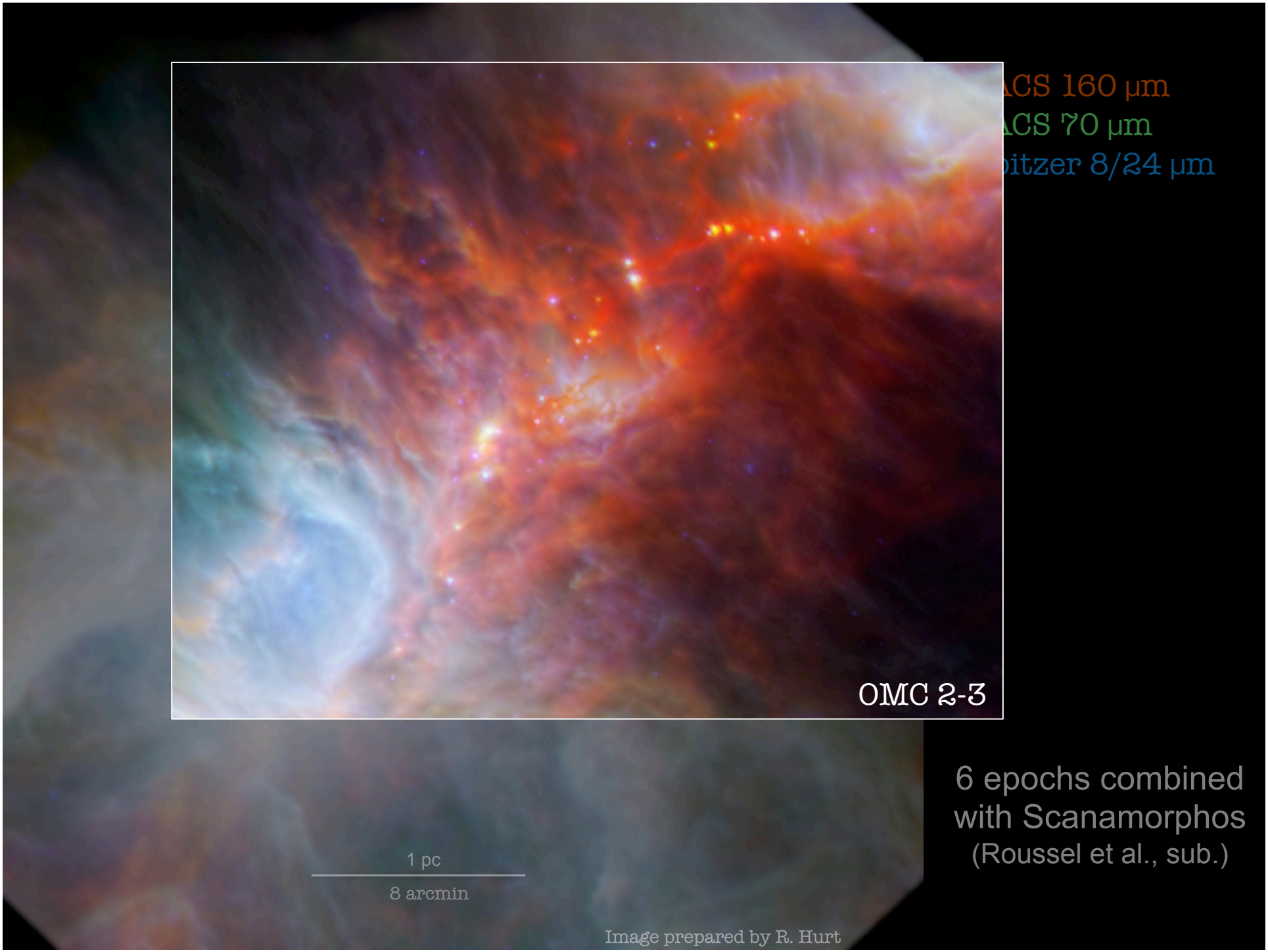


IRAC 4.5 μm + Class I/0
From YSOVAR

- Herschel PACS/Photometer 70 + 160 μm (10h obs. time)
- 18 epochs through 4 visibility windows (first 6 epochs are observed & analyzed)
  Sampling ~week ~months ~1.5 years
- Large maps (35'x35') preferred to pointed observations
  Covering OMC-1 to 3 which contain 100+ Spitzer-identified Class I/0 protostars
- High redundancy of scan directions
  Secular spacecraft rotation + orthogonal consecutive scans



6 epochs combined
with Scanamorphos
(Roussel et al., sub.)

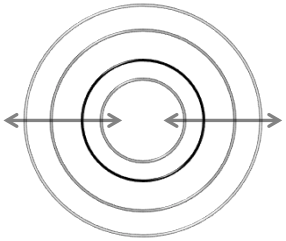

ACS 160 μm
ACS 70 μm
pitzer 8/24 μm
OMC 2-3
1 pc
8 arcmin
6 epochs combined
with Scanamorphos
(Roussel et al., sub.)
Image prepared by R. Hurt

Source Photometry

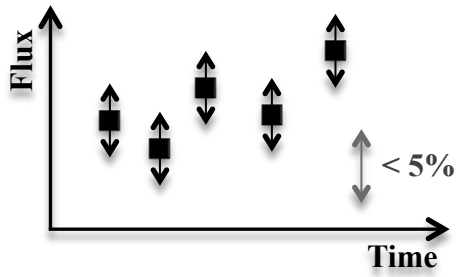
- Search for point sources in the 70 μm 6-epoch **combined map**
  - Automated source-finding algorithms gave unsatisfactory results
    - ➔ Visual inspection
- Photometry measured on individual **single-epoch maps**
  - Small apertures encircling the PSF core (4”/8’ radius @ 70/160 μm)
  - Aperture corrections applied (based on measured PACS PSF)
- Results:
  - 43 point-like sources at 70 μm with flux 0.4 – 500 Jy
  - 34 have counterparts at 160 μm
    - 13 are point like with fluxes 15 – 300 Jy
    - 21 are resolved/extended sources
- Most sources are Class I/0 protostars
  - (Morales-Calderón et al. 2009, following presentation by T. Megeath)

Building Reliable Light Curves

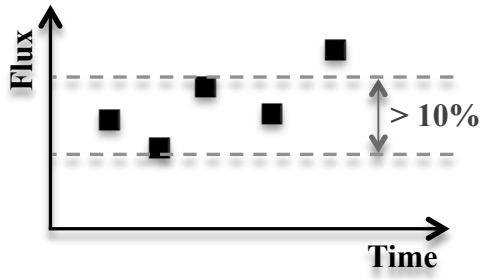
- Photometric errors on **single-epoch maps**
  - Standard deviation in background annulus inappropriate
  - Flux uncertainty estimated from varying aperture radii
    - ➔ ~5% uncertainty at 70 μm (up to 20% in crowded/ structured regions), ~20+% uncertainty at 160 μm



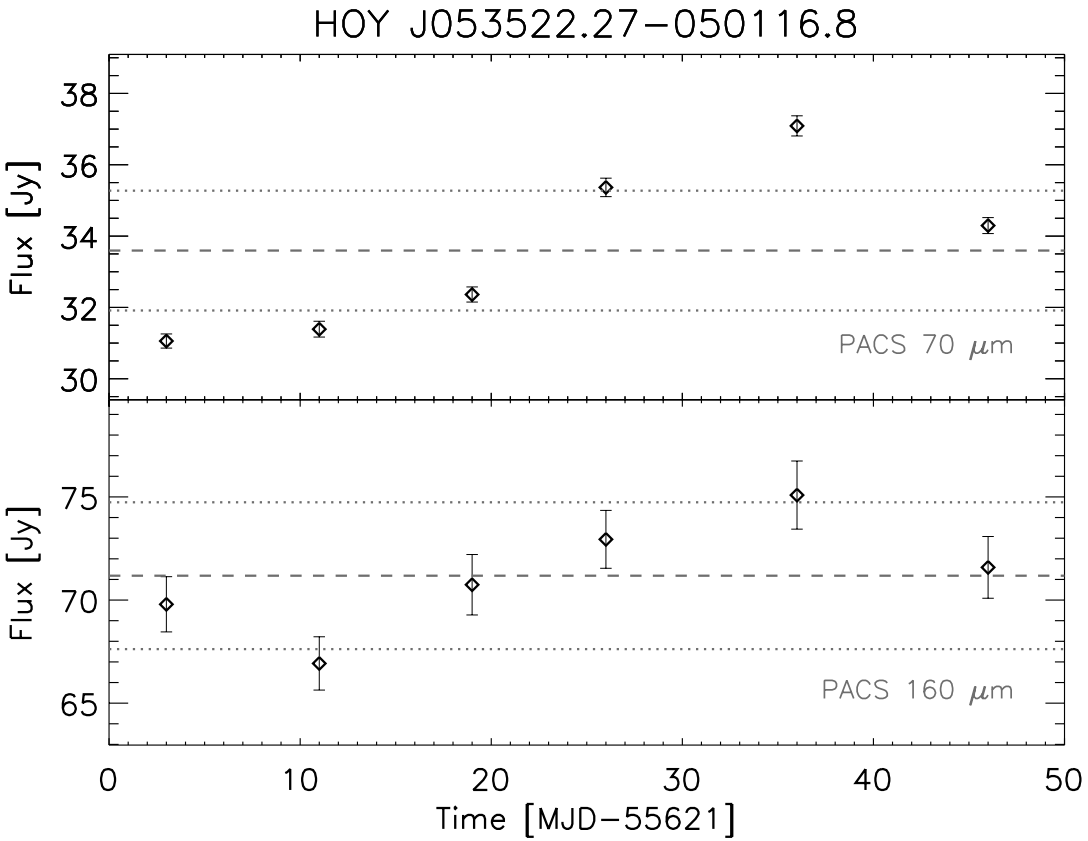
- Relative uncertainties:
  - Same approach with varying aperture radii
  - Light curve deemed unreliable if any single-epoch flux varies by > 5% for various aperture radii



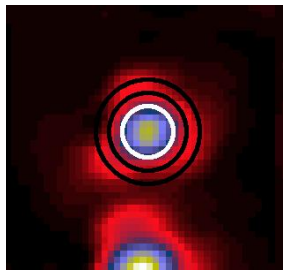
- 17 sources have reliable light curves
  - Variability detection: peak-to-peak variations > 10%



Rapid far-IR variability



- **20%** variation @ 70 µm over 6 weeks
- Phased light curve @ 160 µm
- High S/N detection (relatively isolated source with smooth background)



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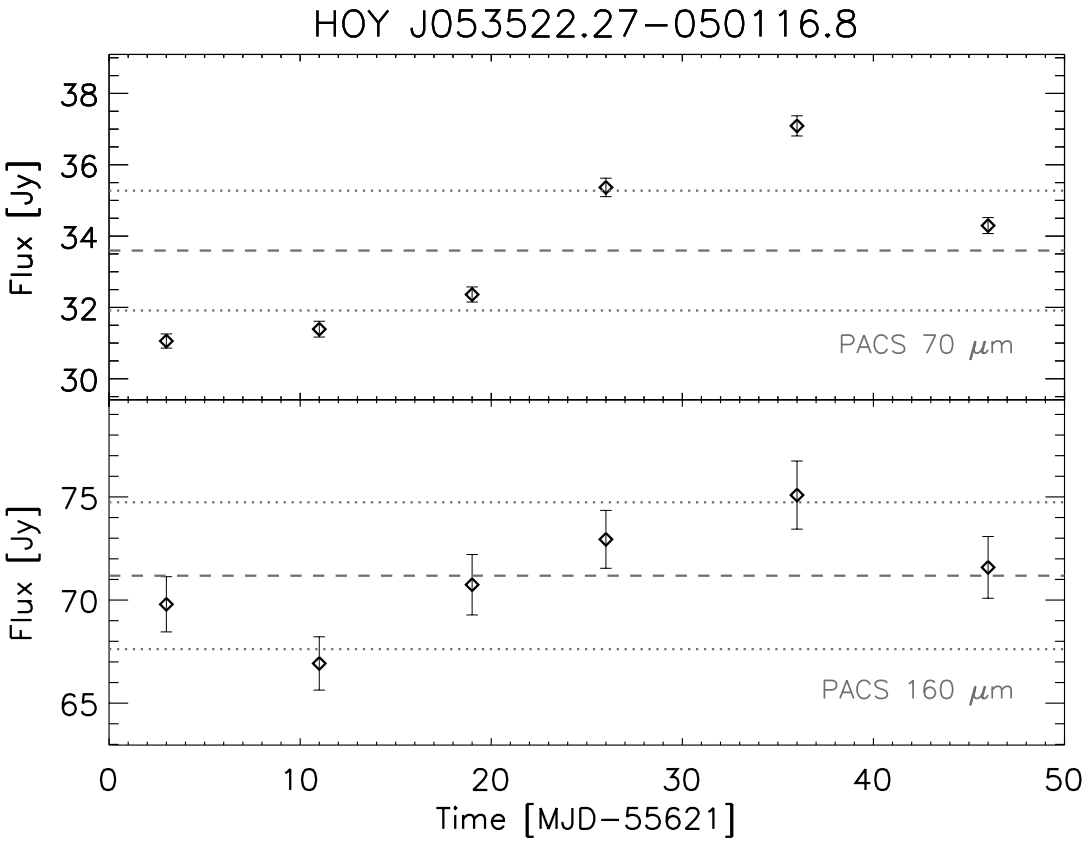

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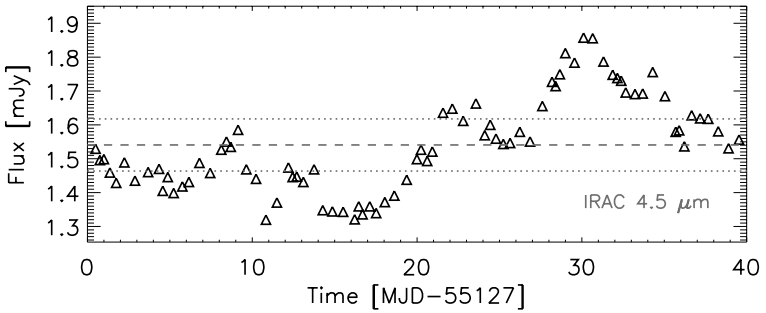
- Mid-IR variability, 30% (YSOVAR)

Non-contemporaneous IRAC 4.5 μm light curve



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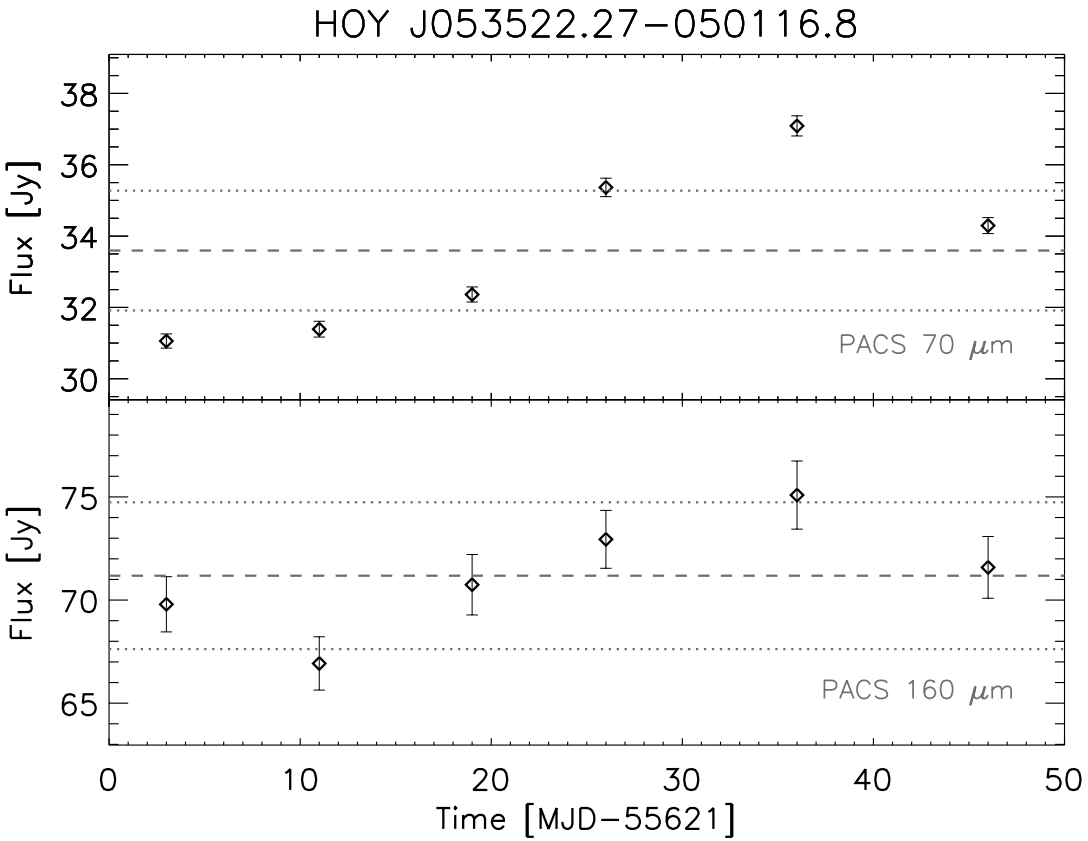

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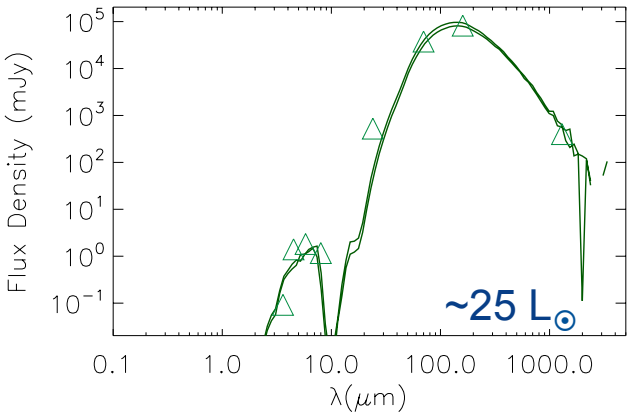
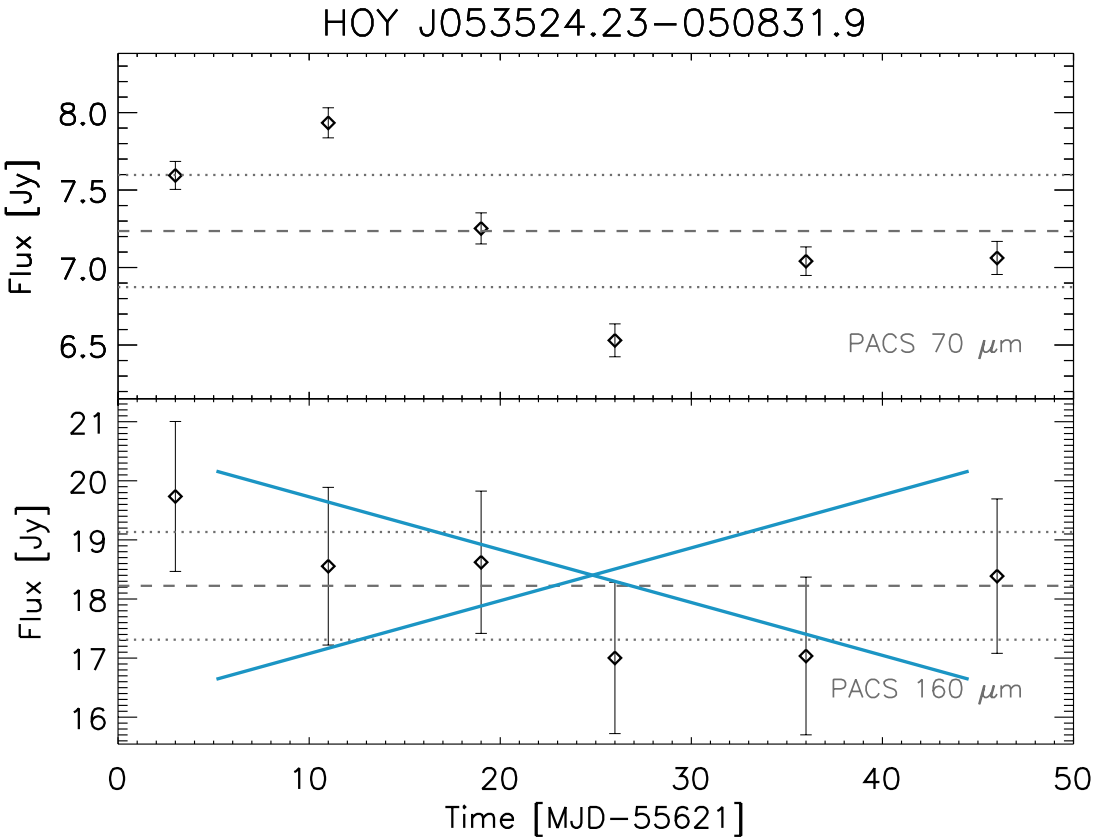
- Accretion rate ~ 3.10^{-4} $M_{\odot}$/yr



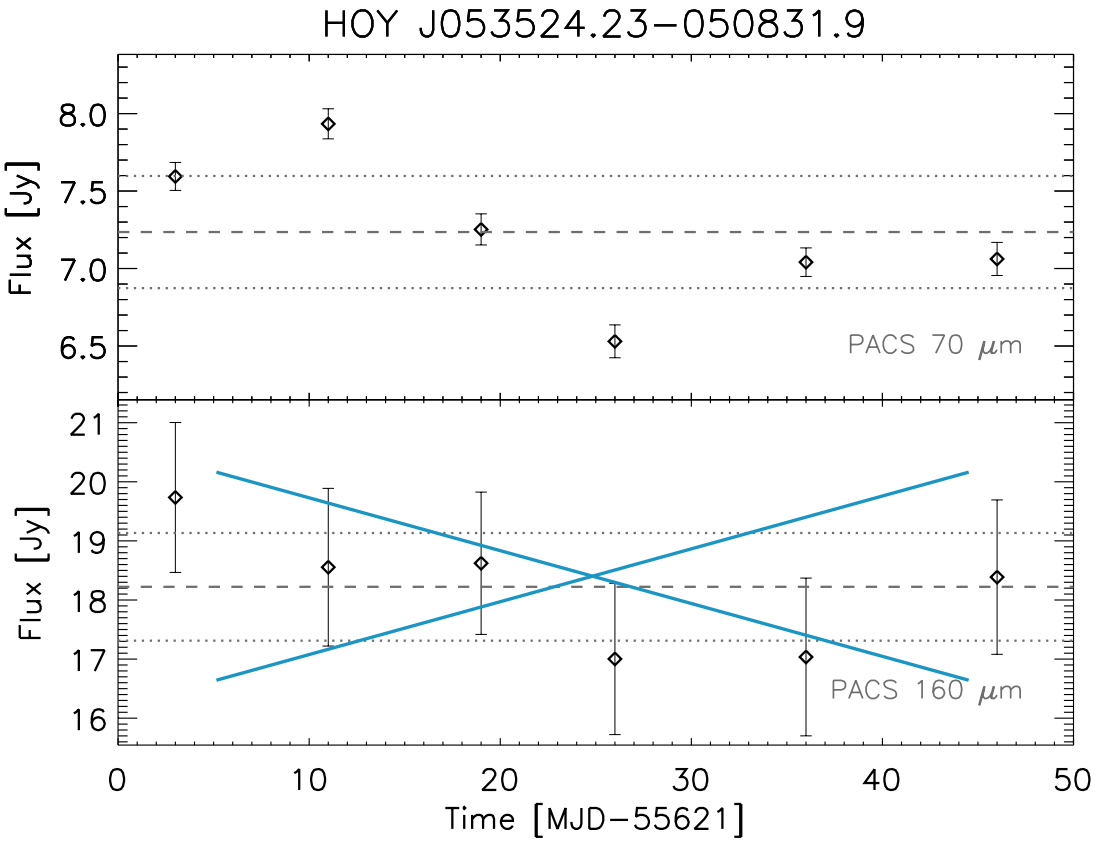
Likely variable mass accretion…

Rapid far-IR variability



- **20+%** variation @ 70 µm
- Same trend at 160 µm, but noisy photometry

Rapid far-IR variability



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- 50% variability at 4.5 μm

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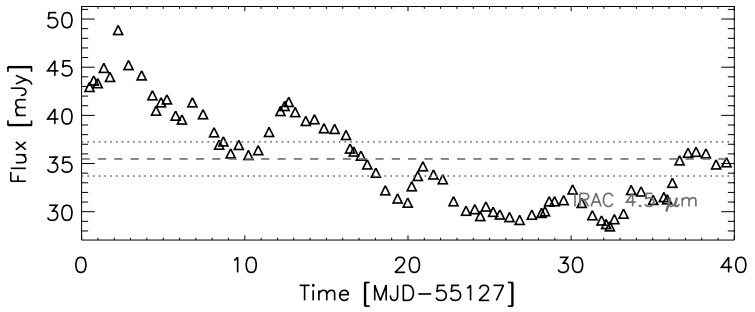

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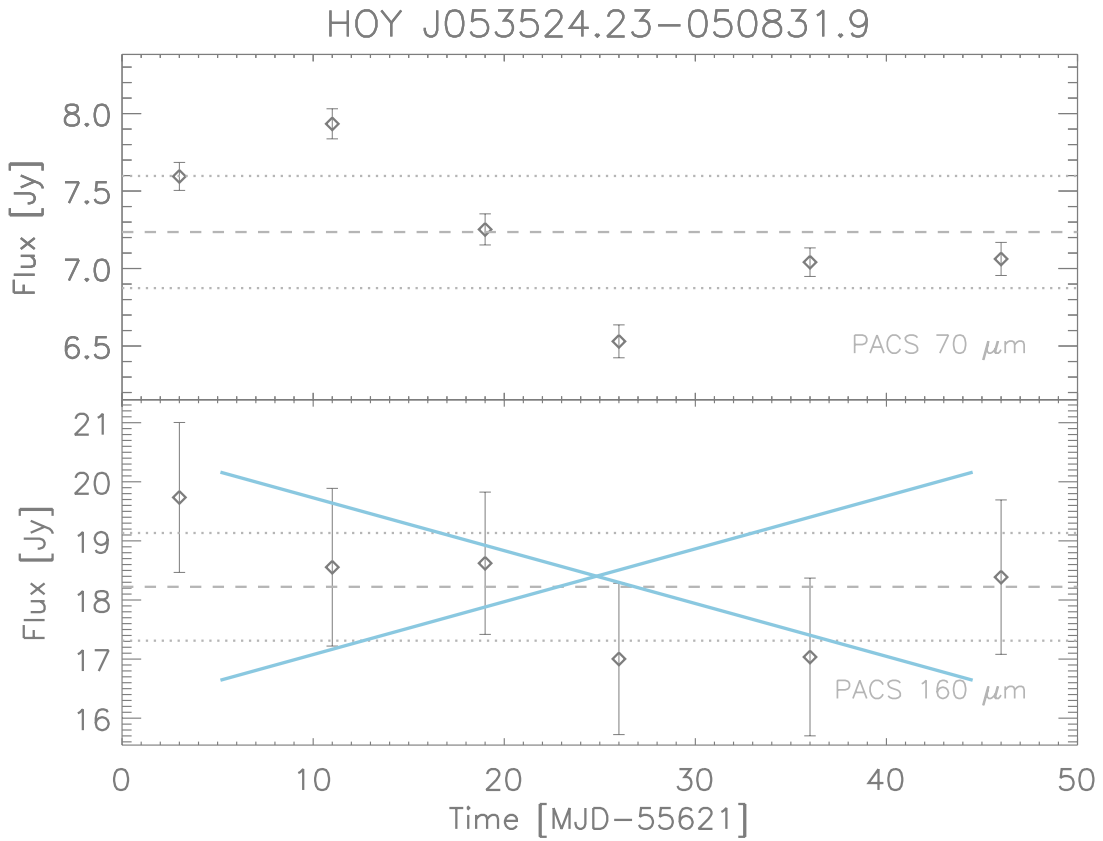

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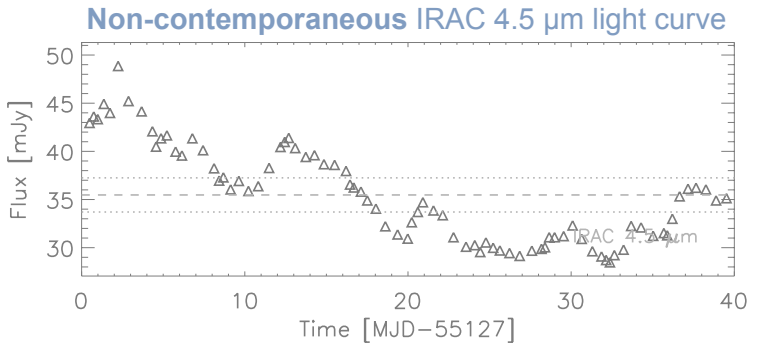
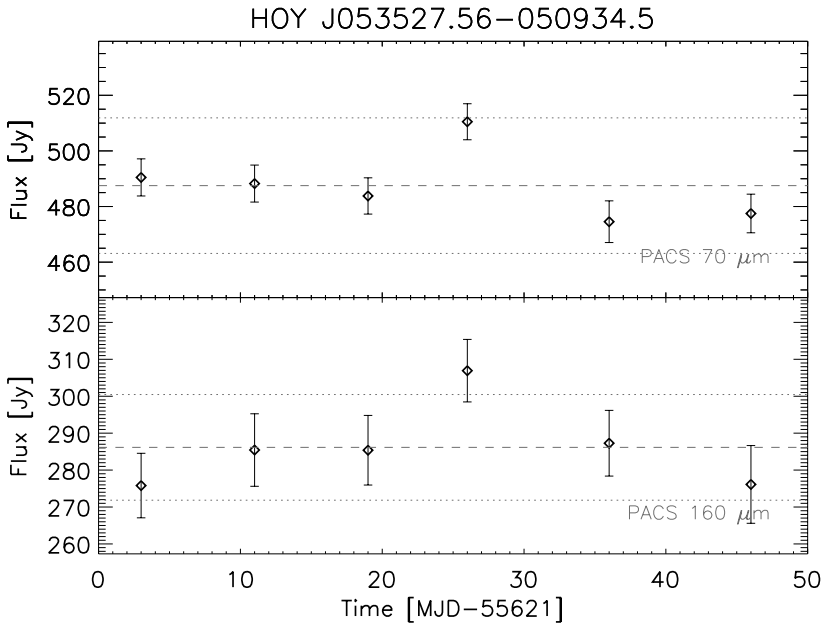
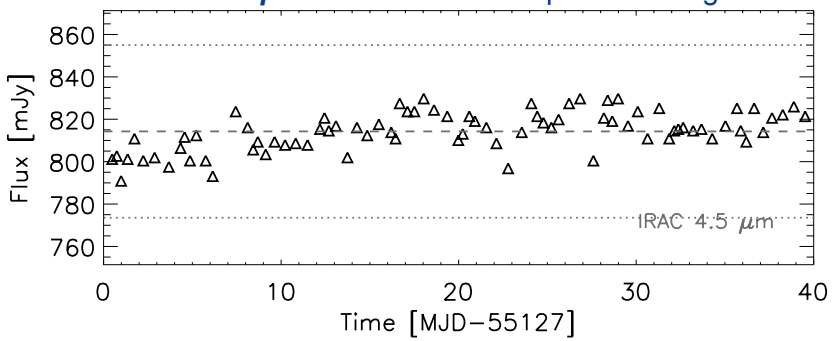


8 protostars out of 17 show 10+% variability at 70 μm

Inconclusive variability detections…



Non-contemporaneous IRAC 4.5 μm flat-ish light curve



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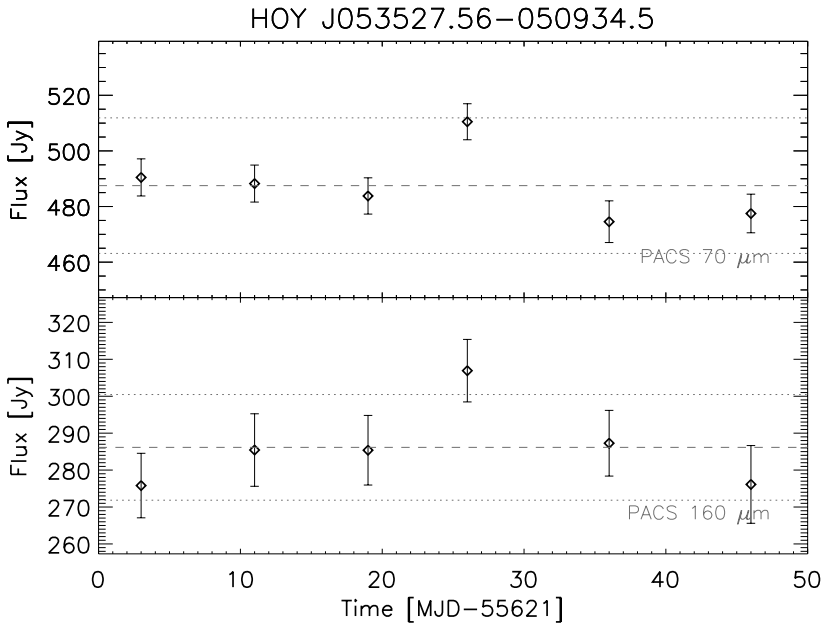

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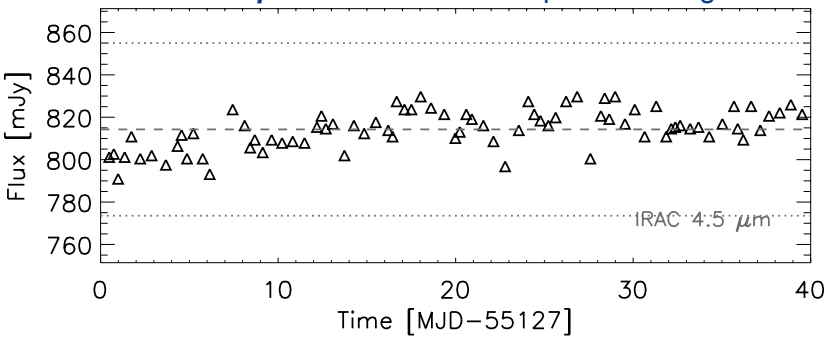

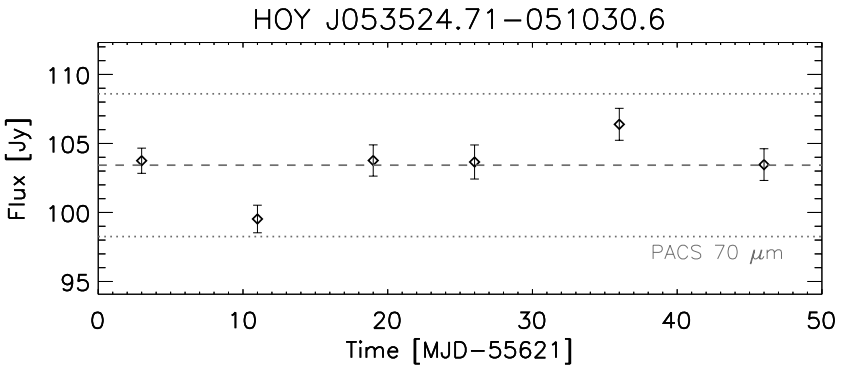

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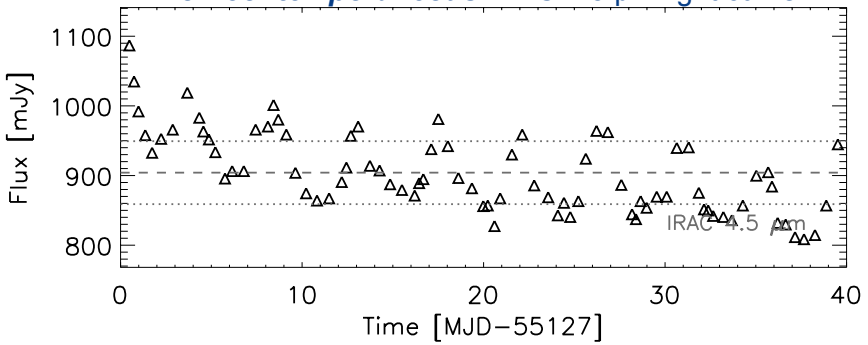
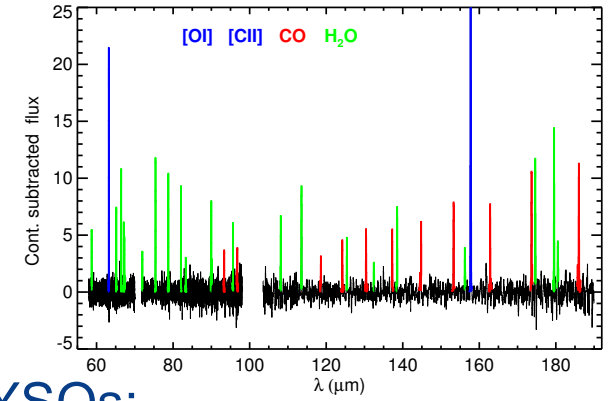


One-week cadence does not sample faster/slower periodic variations

Future Work…

- SED modeling of variable sources
- Extended emission, PDR (data are public, volunteers?)
- Improved photometry with PSF fitting
- 12 epochs remain to be observed/analyzed
- PACS spectrometer monitoring just started on selected sources
  - See poster by Manoj Puravankara

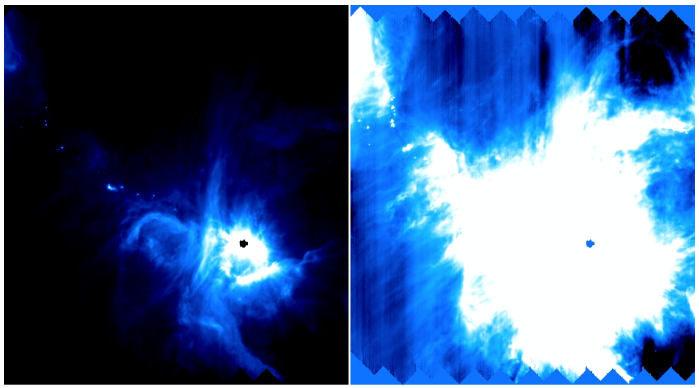


- More Herschel projects to monitor YSOs:

  GT2_zbalog_2, OT2_jforbric_3, OT2_nbillot_2, OT2_pabraham_4, OT2_rvisser_1, OT2_zbalog_3

Data reduction

- HIPE Standard pipeline up to calibrated data cubes (Level1 frames) including non-linearity corrections
- Single-epoch maps (single-direction scan map) are produced with the standard masked high-pass filtering scheme + projection



Same map (PACS 70), different color scale stretch

- Large spatial scales are affected to some extent by the high-pass filter
- Small spatial scales (point sources) are NOT affected

- First 6 epochs combined with the IDL-based mapmaker Scanamorphos (Roussel et al. 2012) to preserve extended emission…