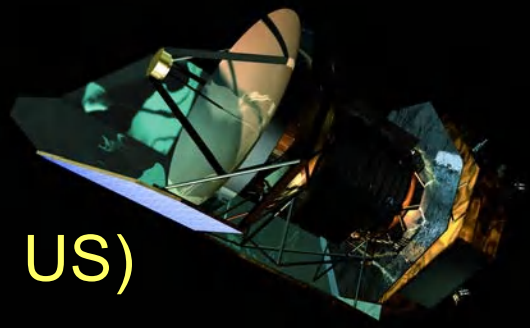
HERSCHEL ORION PROTOSTAR SURVEY (HOPS) @10 years

Mayra Osorio
(IAA-CSIC, Spain)

PI: Tom Megeath (U. Toledo, US)



Co-Is: Will Fischer (STScI), Nicole Karnath, Wafa Zaire (U. Toledo, US), A. Stutz (U. Concepcion, Chile), Beatriz González-García (ESA, Spain), Babar Ali (NHSC), Elise Furlan (IPAC, Caltech US), Manoj Puravankara (Tata Institute, India), Thomas Stanke (ESO), John Tobin (NRAO, US), Dan Watson (U. of Rochester, US), Nuria Calvet, Lee Hartmann (U. Michigan US), Ana Karla Díaz-Rodríguez, Guillem Anglada, José F. Gómez (IAA-CSIC, Spain)

HOPS: 200 h Open-Time Key Program with Herschel

With Herschel, we imaged the Spitzer-identified Orion protostars in the far IR, where they are brightest.

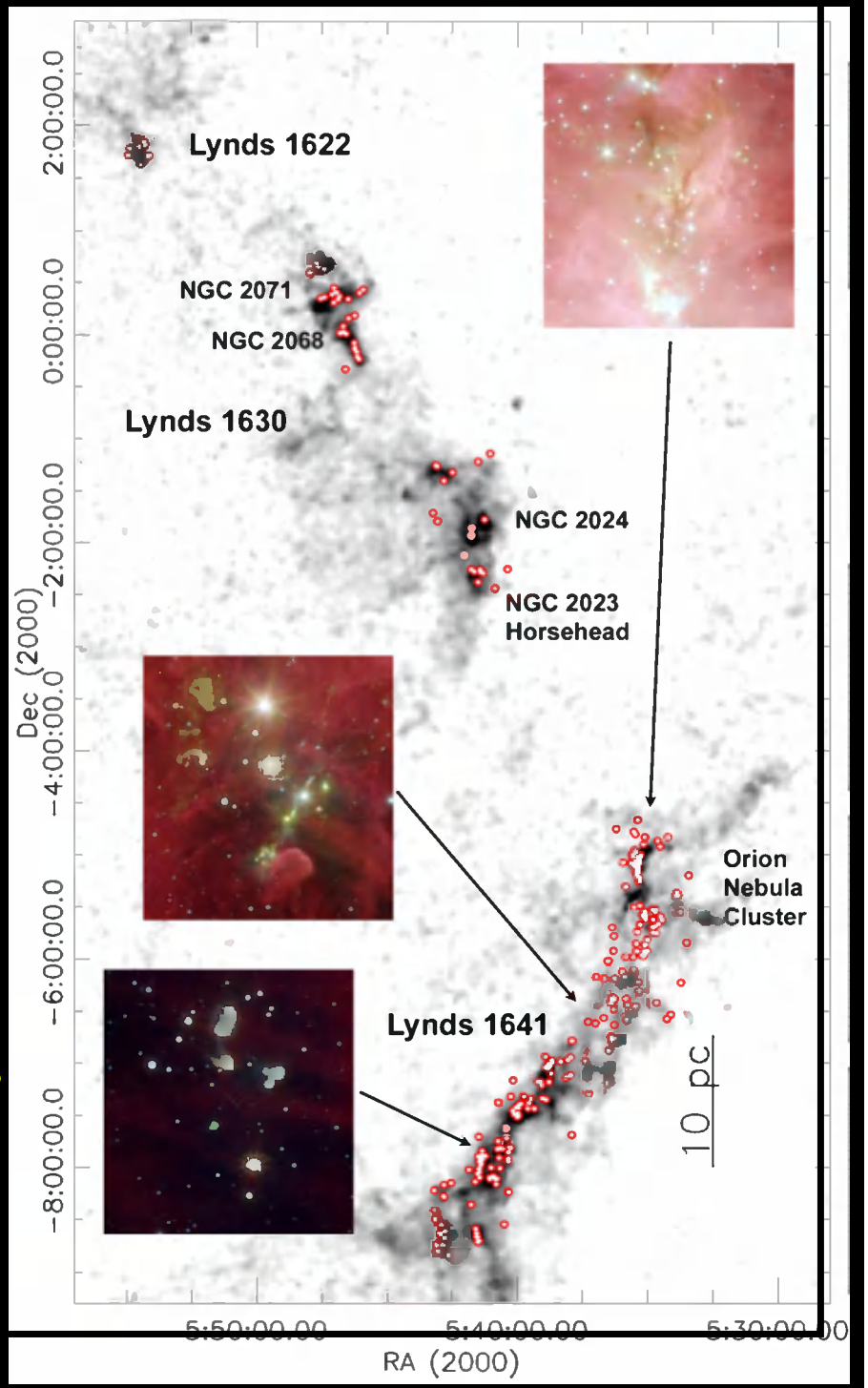
Why Orion?

- Orion Molecular Cloud contains the largest sample of protostars in the nearest 420 pc.
- Orion protostars have a wide range of luminosities, different evolutionary stages, and they are forming in diverse environments

PACS imaging at 70, 160 μm of >300 protostars

PACS spectroscopy (55-200μm) of 33 protostars

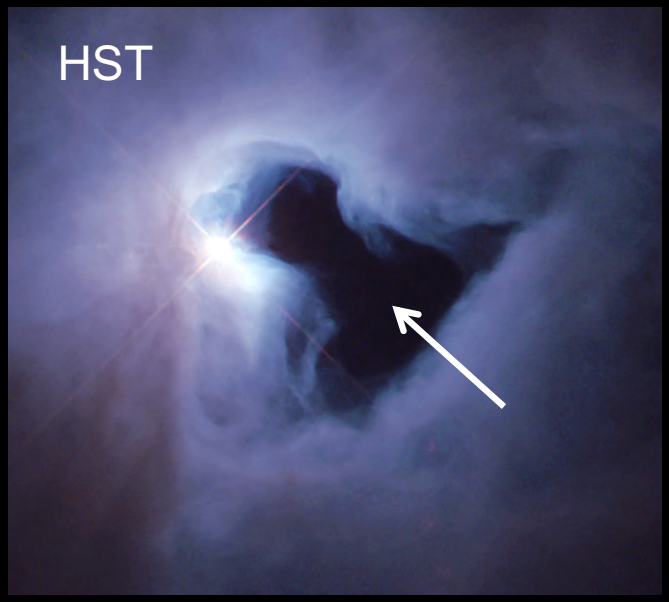
Red dots = HOPS targets
Gray scale = extinction

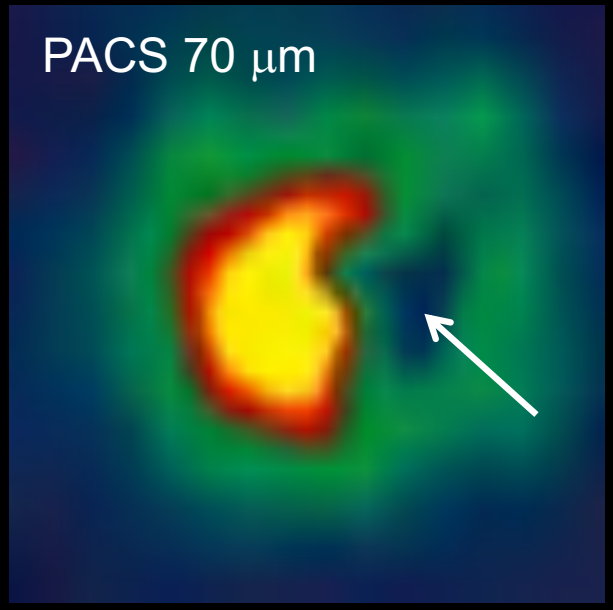


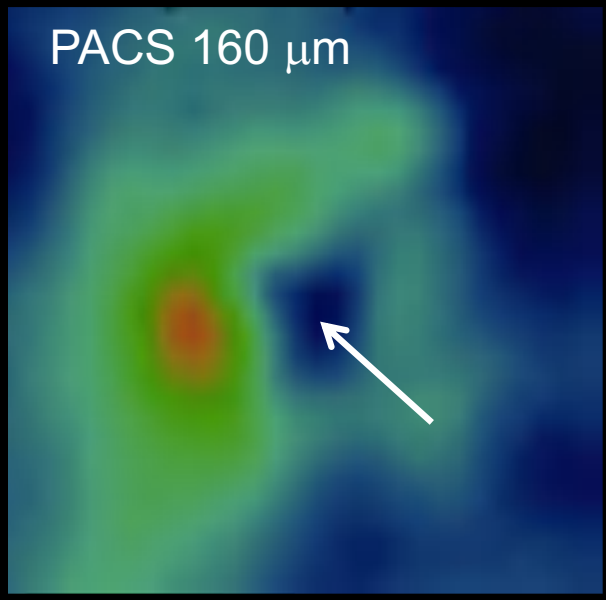
Some HOPS results:

- Clarification of the nature of NGC 1999: Dark Cloud or Hole in the Sky?
- Building of well-sampled SEDs (HOPS + SOFIA, Spitzer, APEX) and detailed modeling of 330 Orion protostars.
- Discovery of PBRS: Extremely young Orion protostars.
- Identification of four outbursting Orion protostars.
- Established correlation between bolometric luminosity and the luminosity of the far-IR CO lines generated by outflow shocks.
- Imaging of a far-IR protostellar jet with strong shocks in an intermediate luminosity protostar of the sample.
- Signs of triggered star-formation by outflow (HOPS + VLA).

Is NGC 1999 (V380 Ori) nebula a Dark Cloud?







The cloud remains dark in the far-IR, suggesting a high extinction.

A strong submm emission is expected.

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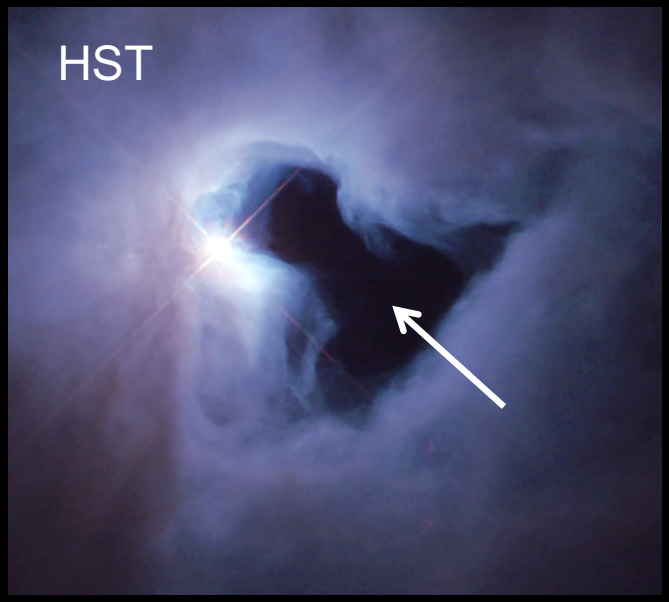
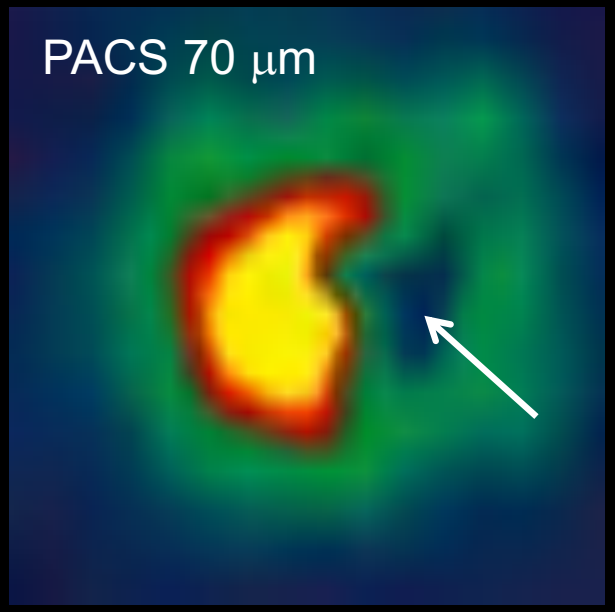
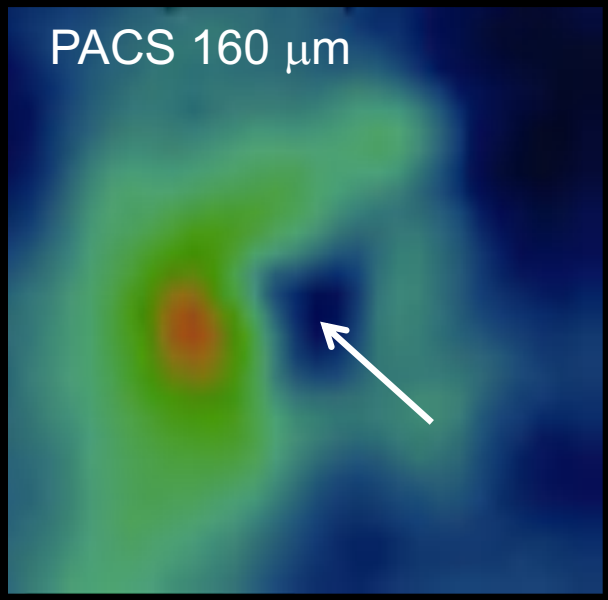


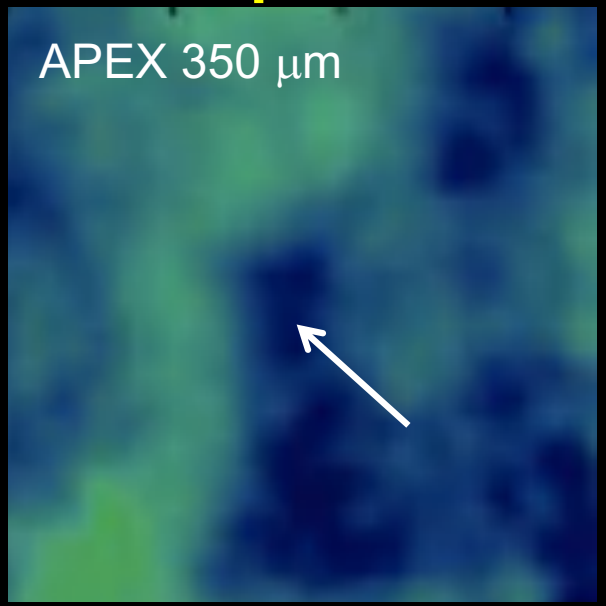


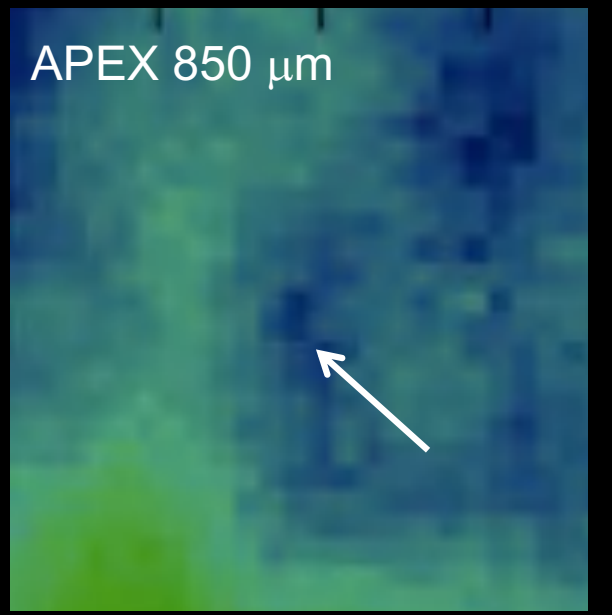


The cloud remains dark in the far-IR, suggesting a high extinction.
A strong submm emission is expected.

No submm emission of the cloud is detected. This is not a dark cloud but a genuine ***hole*** *in the nebula* -- Carved by outflows?

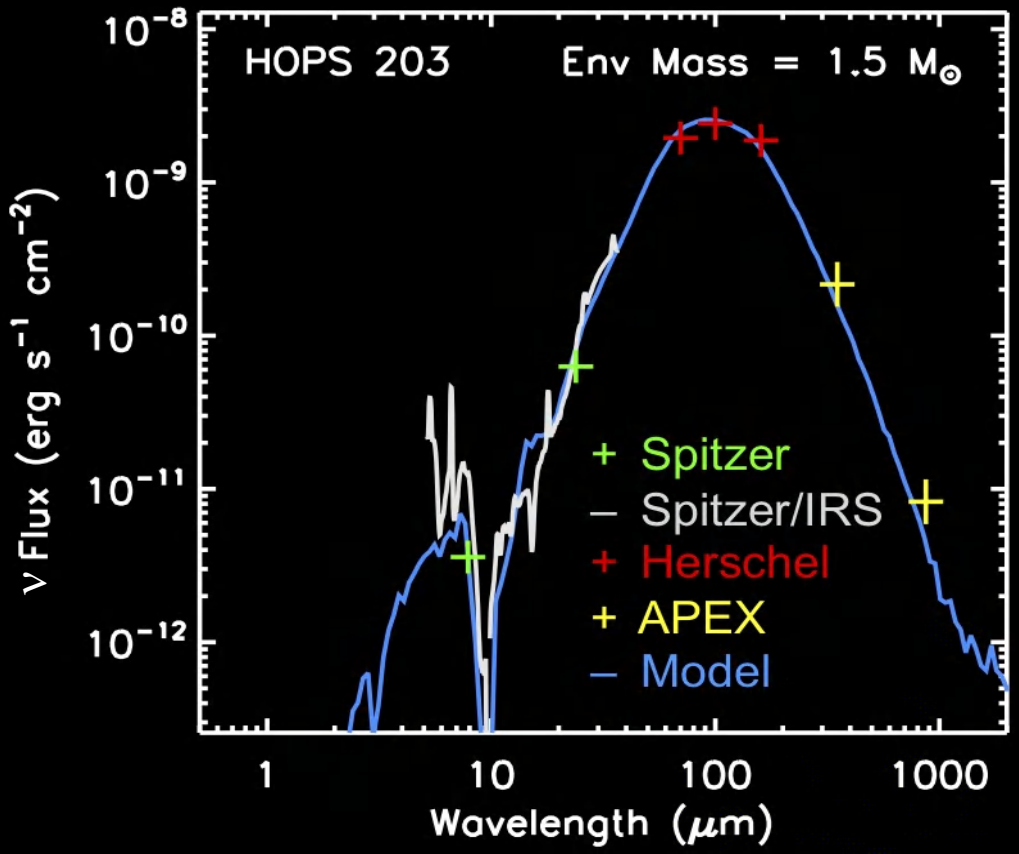
(Stanke+2010)

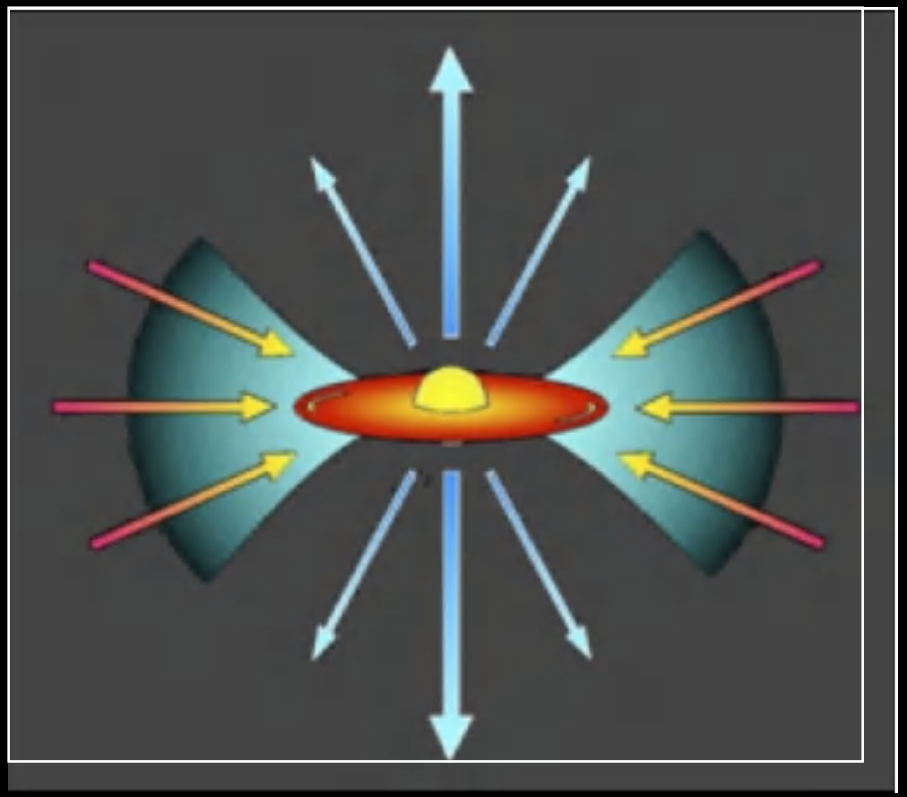




SED fitting of 300 protostars in Orion

SED constructed with 2MASS, Spitzer, Herschel, and APEX data

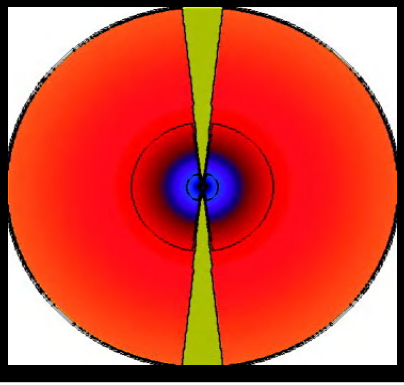




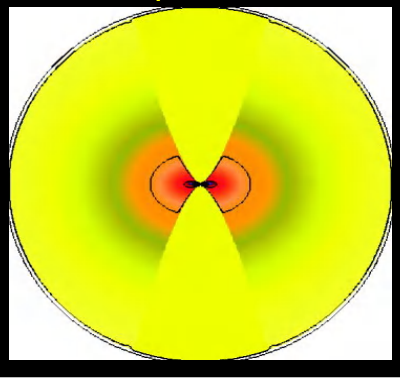
Modeling of the SED as dust thermal emission + scattered light from a circumstellar envelope and a disk (Furlan +2016)

Far-IR Herschel data enable accurate measurement of luminosity, and bolometric temperature of the protostars, and help to constrain the envelope mass

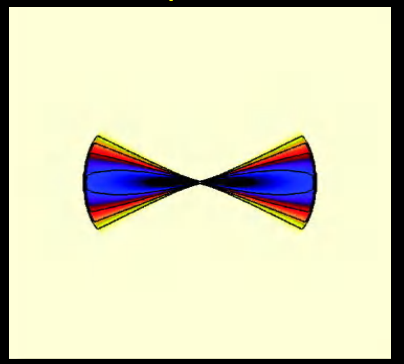
Class 0 (92 in Orion)

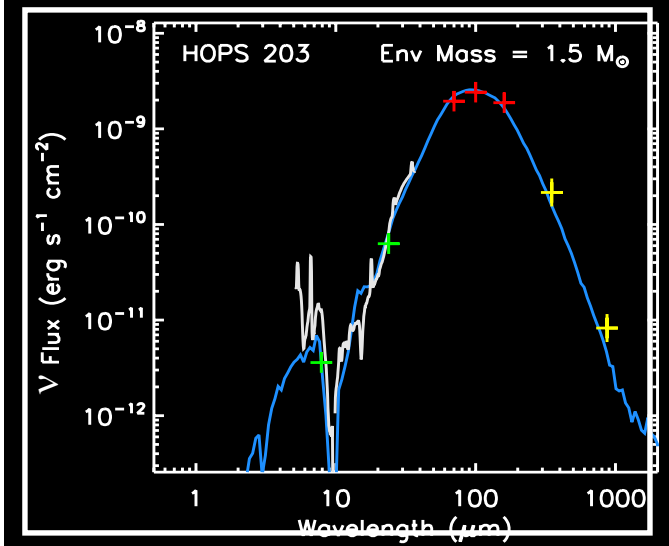


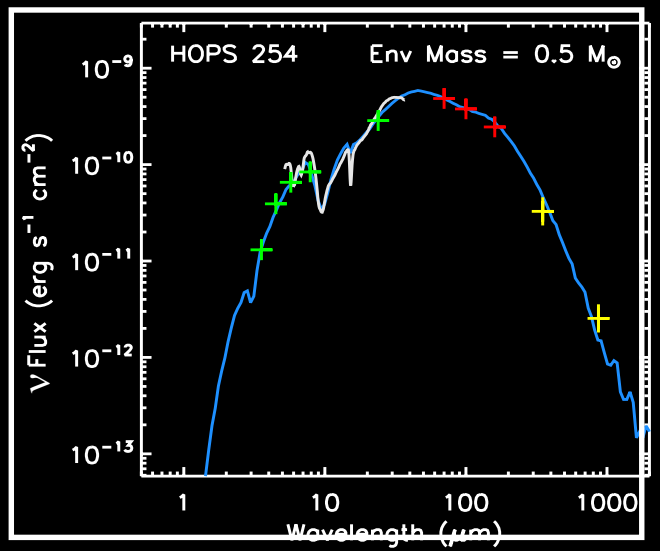
Class I (125 in Orion)

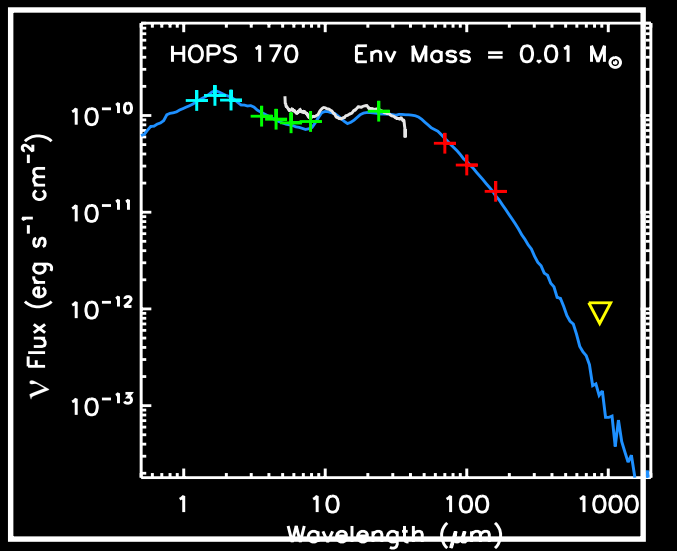


Class II (11 in Orion)









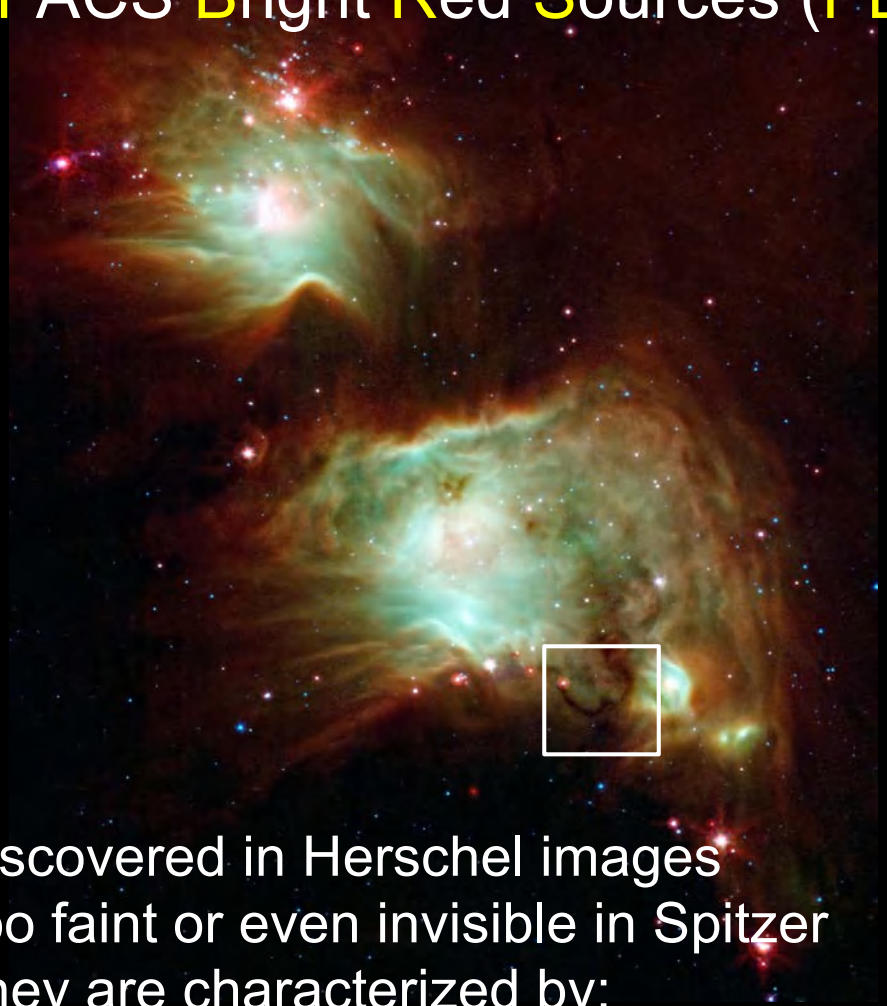
Furlan+2016

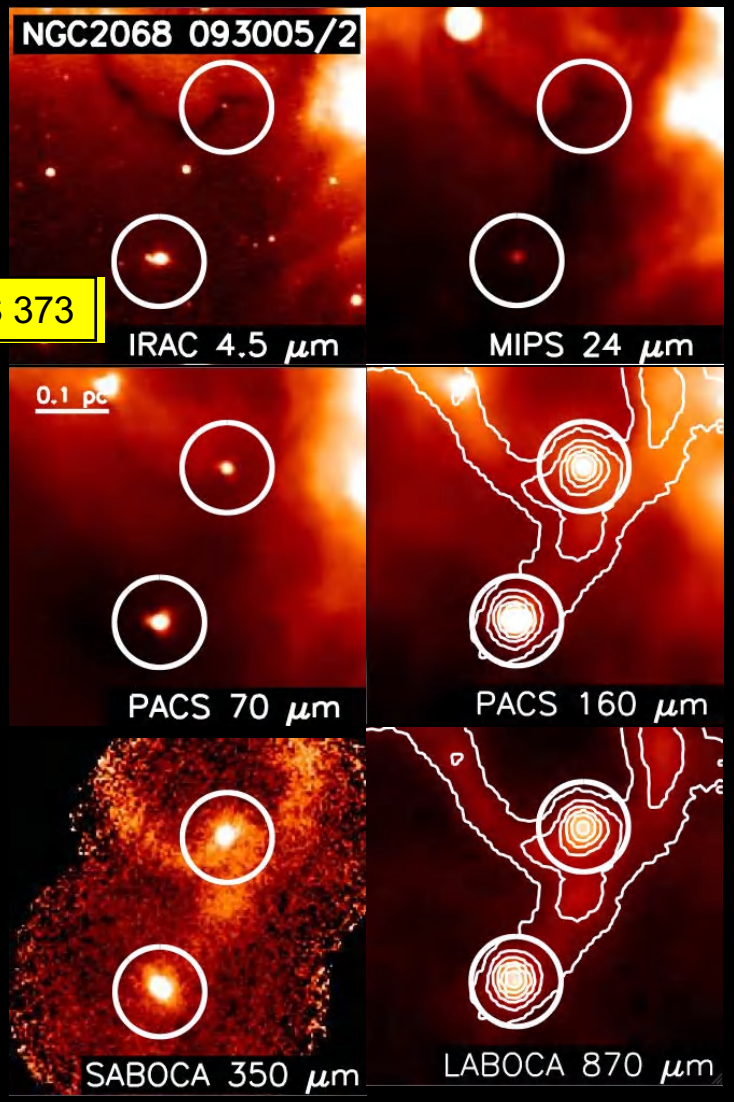
time

Extreme Class 0 protostars in Orion

PACS Bright Red Sources (PBRS)

(Stutz+2013)





- Discovered in Herschel images
- Too faint or even invisible in Spitzer
- They are characterized by:
  - Very red SEDs
  - Strong submm emission (M=0.5-2 $M_{\odot}$)

Extremely young stars: might have formed only 25,000 years ago

PRESS RELEASE

MAX PLANCK INSTITUTE FOR ASTRONOMY
HOUSE OF ASTRONOMY

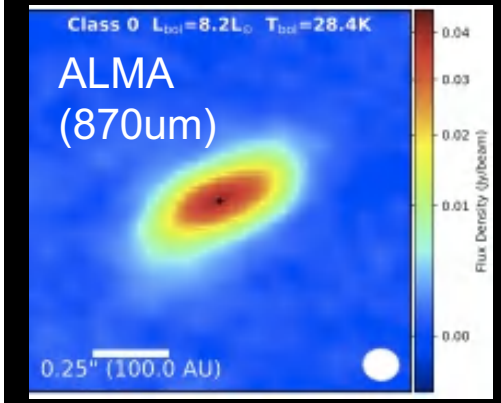
In Orion, Herschel finds the youngest stars yet

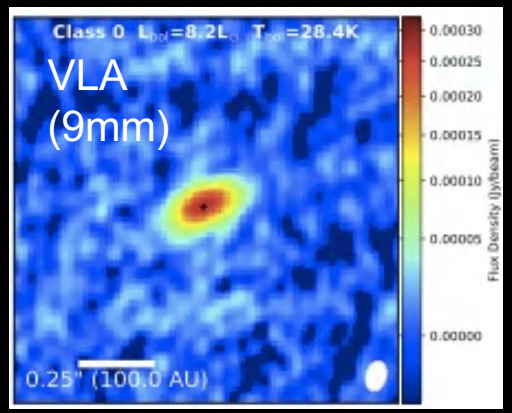
ALMA + VLA follow-up observations of PBRs

(Karnath et al. in prep) from VANDAM Orion Survey of all HOPS sources, J. Tobin P.I.

DISKS

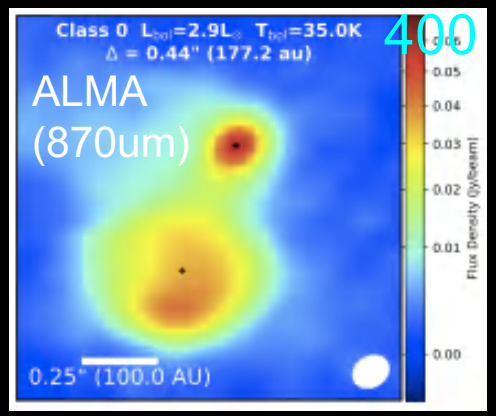
HOPS 409

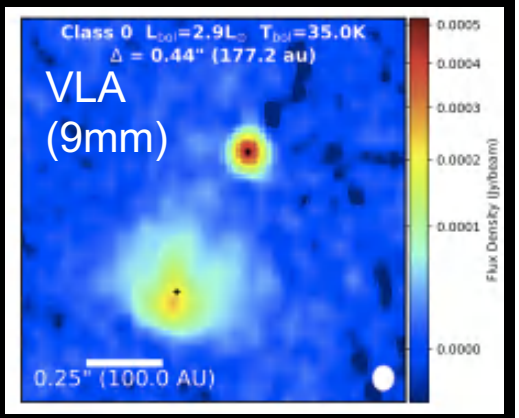




BINARIES

HOPS 400

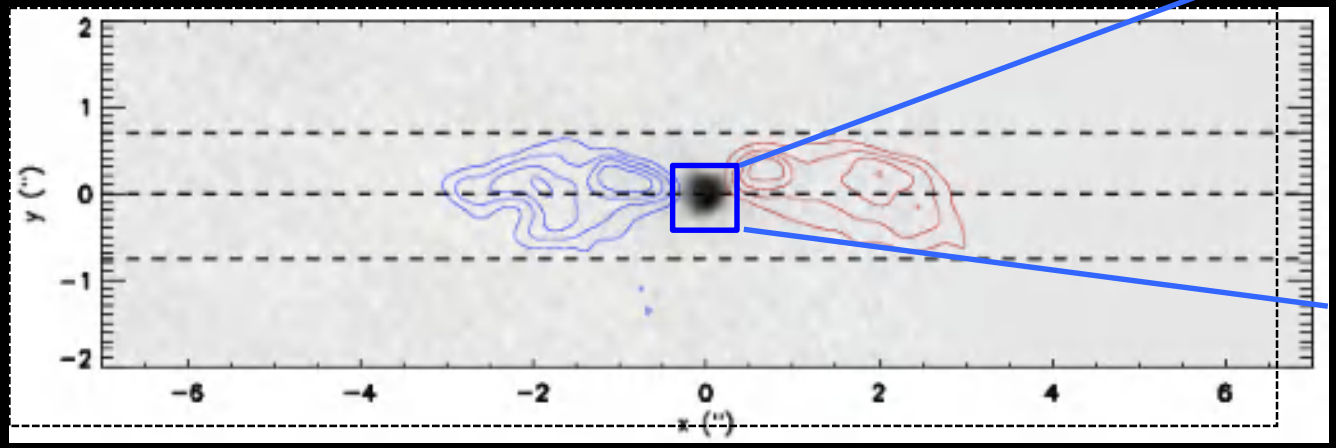


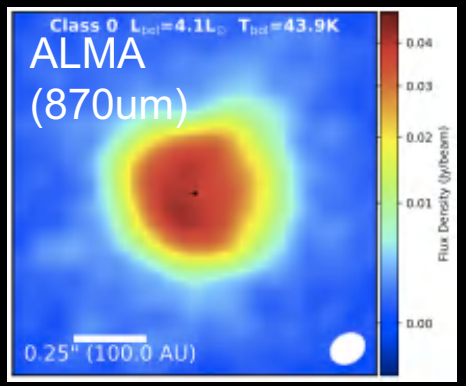


OUTFLOWS

HOPS 403

Tobin+2015, 2016

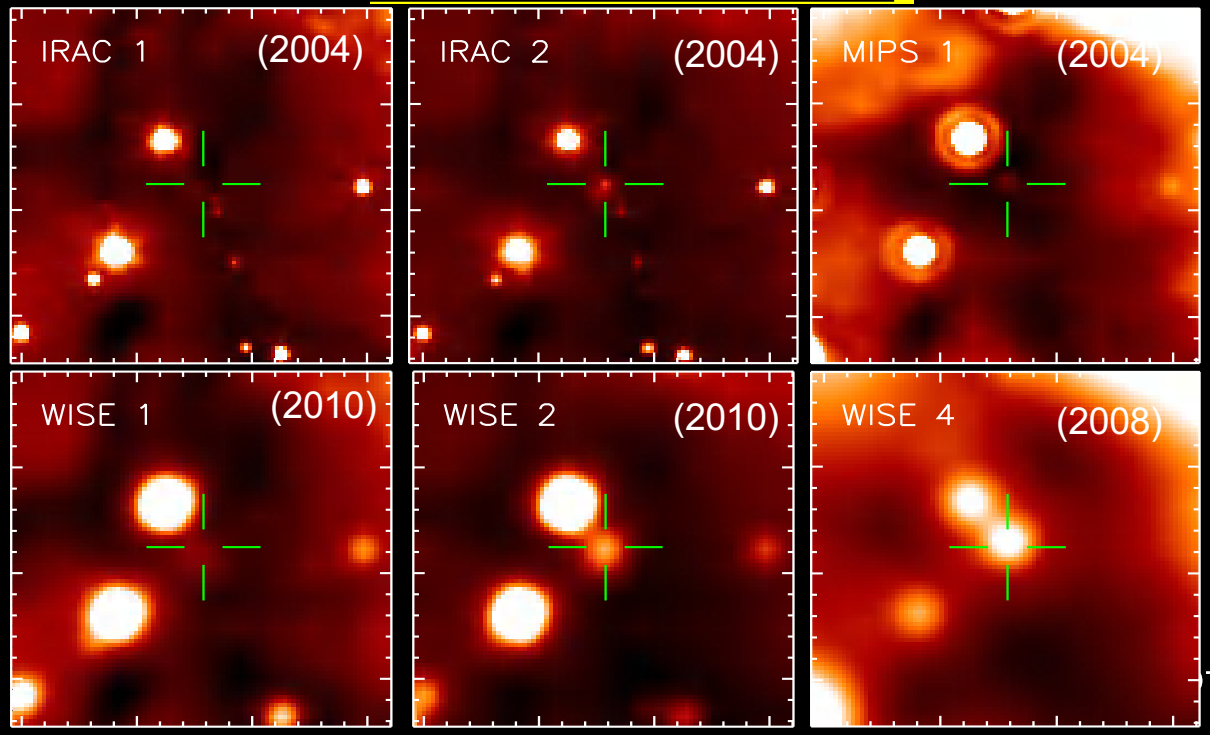




Outbursting HOPS protostars:

HOPS 383: Class 0

Also Fischer+2012

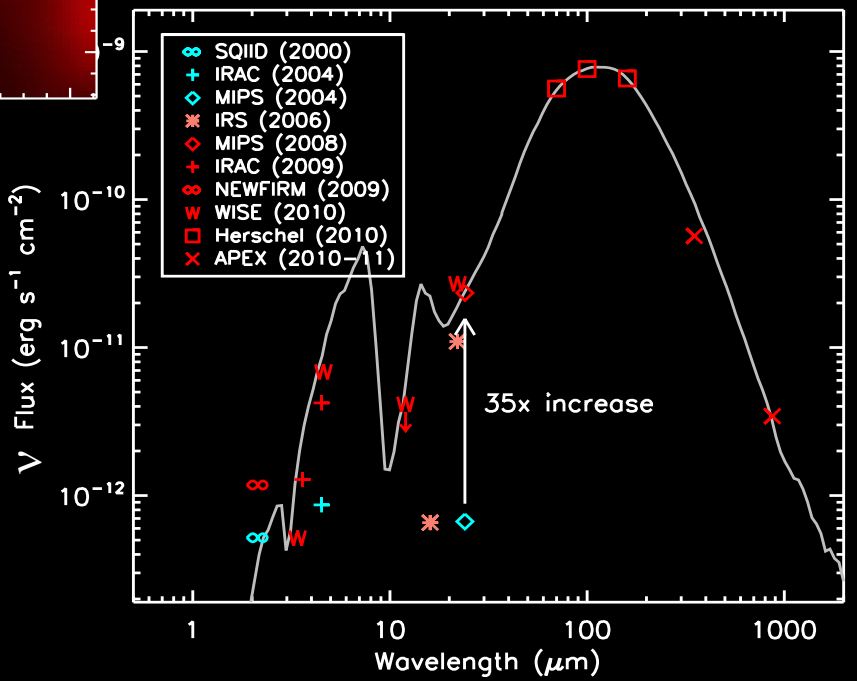


Before

After

Safron+2015

Herschel enables us to infer the post-outburst luminosity (2-4 Lsun)



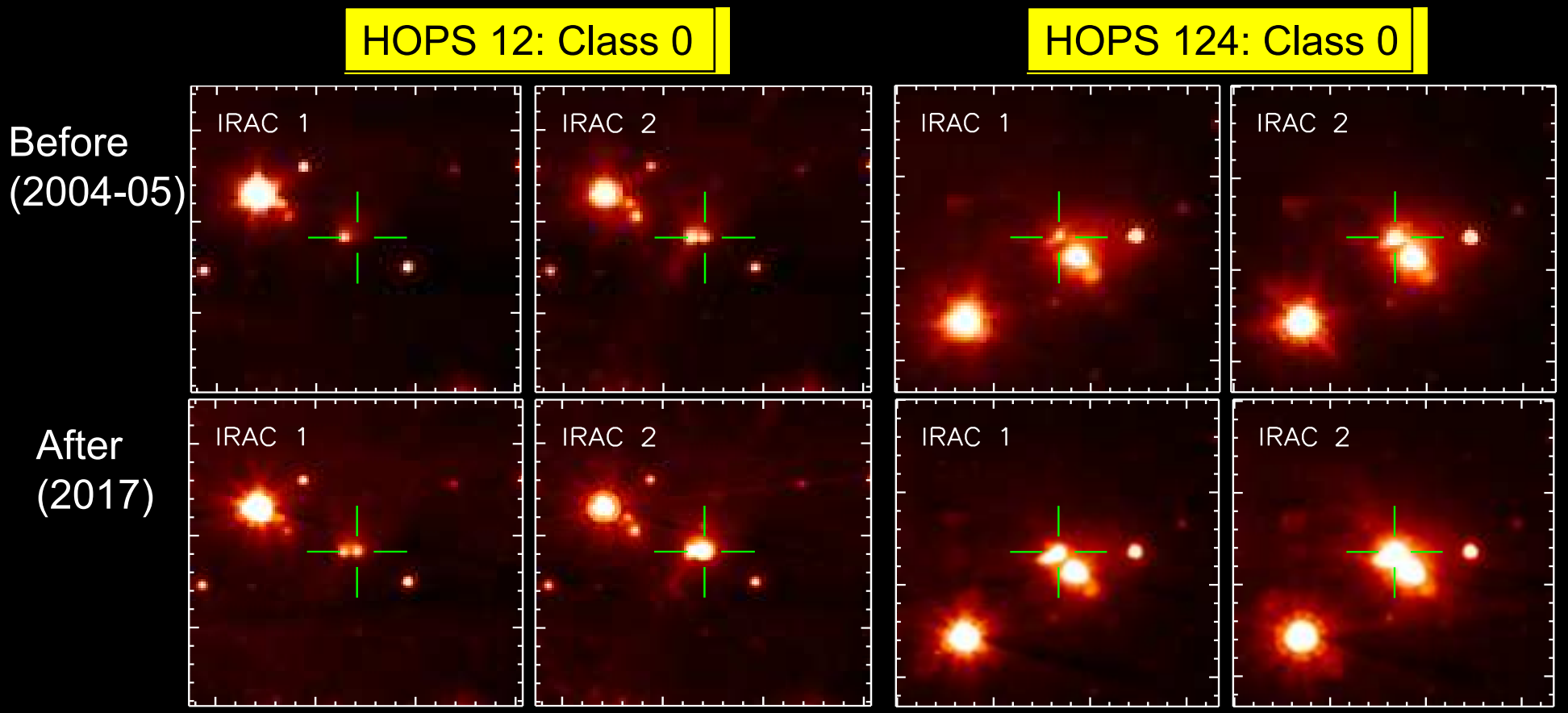
Jet Propulsion Laboratory
California Institute of Technology

PRESS RELEASE

NEWS | MARCH 23, 2015

NASA Satellites Catch a 'Growth Spurt' from a Newborn Protostar

Outbursting HOPS protostars:

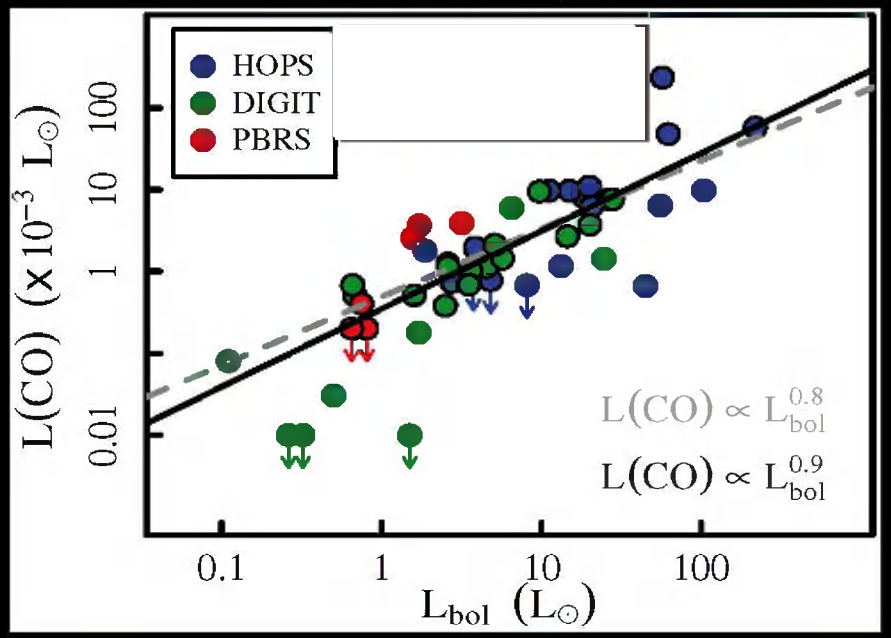


Four protostars have burst since the 2004-05 Spitzer maps of Orion
* HOPS 383 was the first Class 0 outburst discovered
* Four outbursts in 319 protostars in 13 years suggests that each protostar bursts every ~1000 yrs on average. Also see Fischer+2019

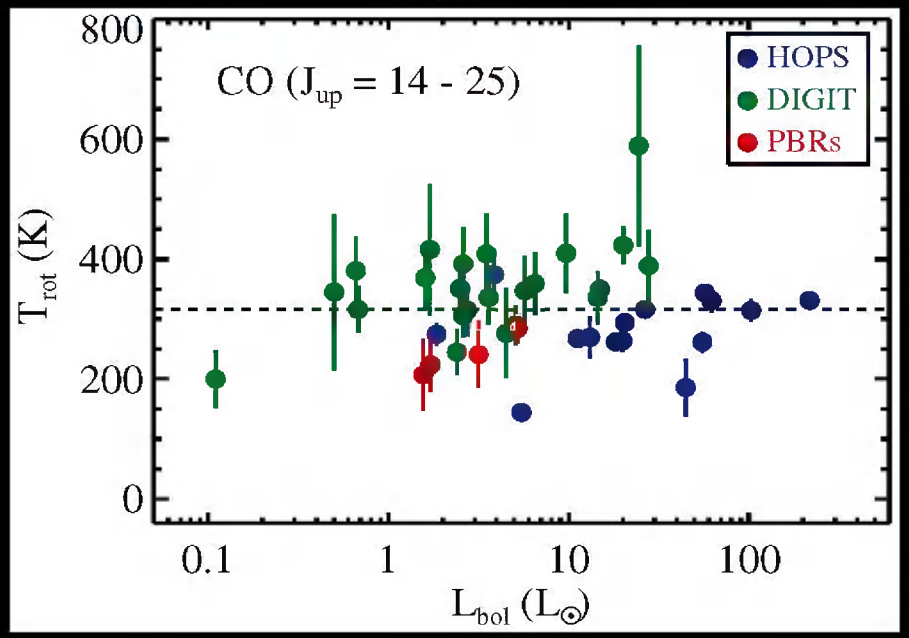
CO Emission from Accretion-Driven Outflows

(Manoj et al. 2013; DIGIT data provided by J. Green & N. Evans)

Absolute line fluxes L(CO) scale with L_{bol}



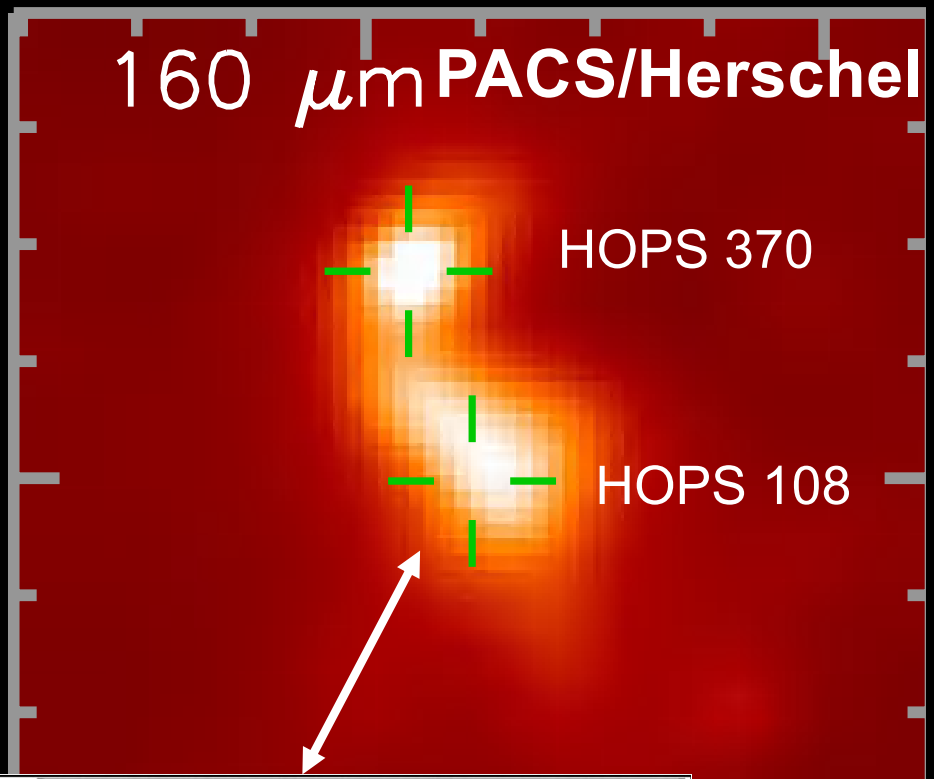
Line ratios (T_{rot}) remain ~ constant

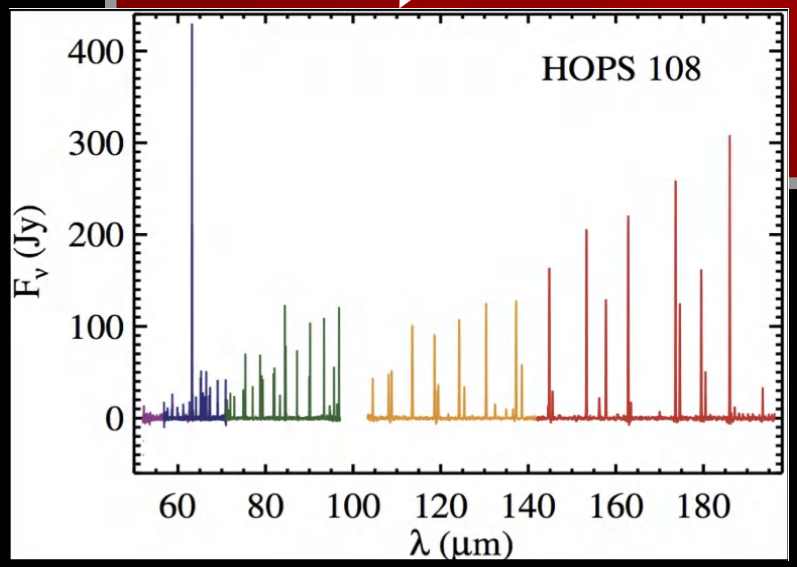


T_{rot} curve for CO is independent of source luminosity and envelope density; most likely explanation is that emission is from shock-heated material in outflow.

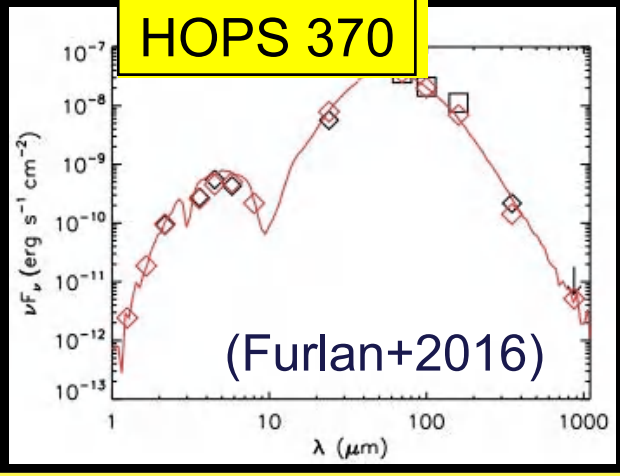
More luminous sources have more CO luminosity; suggests momentum and mass flow rates of the outflows correlate with bolometric luminosity: sources with high L_{bol} have higher accretion and outflow rates

The most luminous protostars in the OMC 2 region



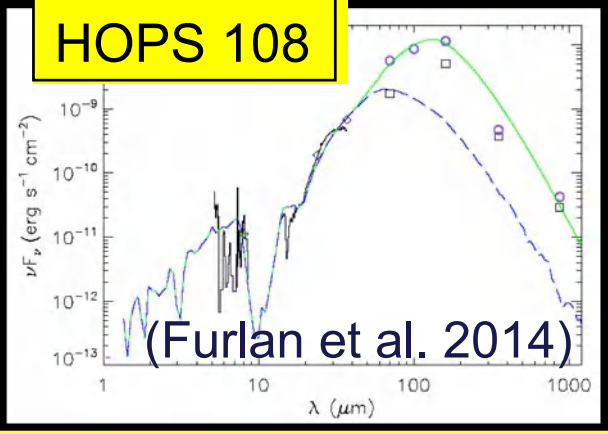


HOPS 370



HOPS 370: Class I intermediate-mass star with L~500Lsun

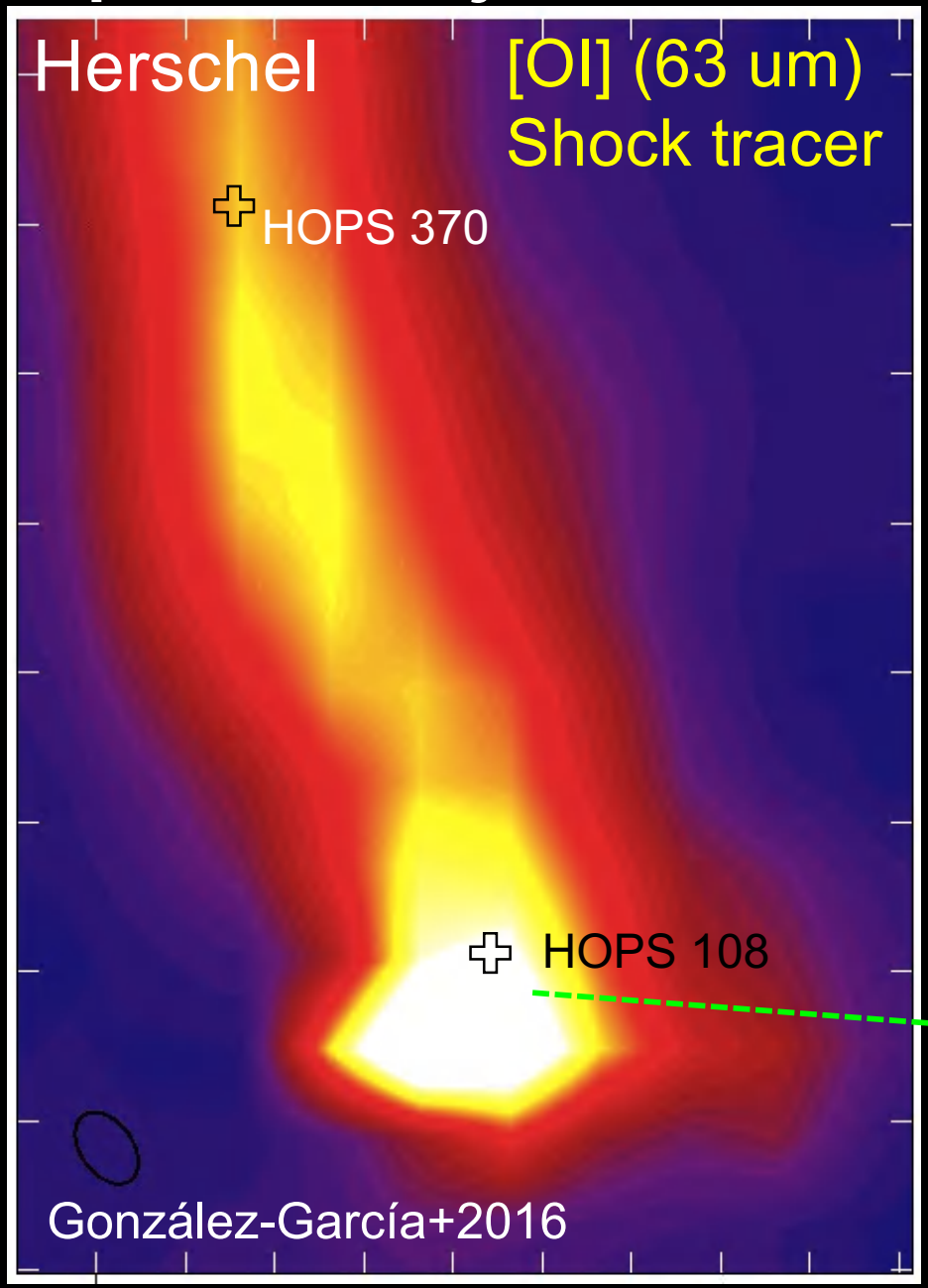
HOPS 108



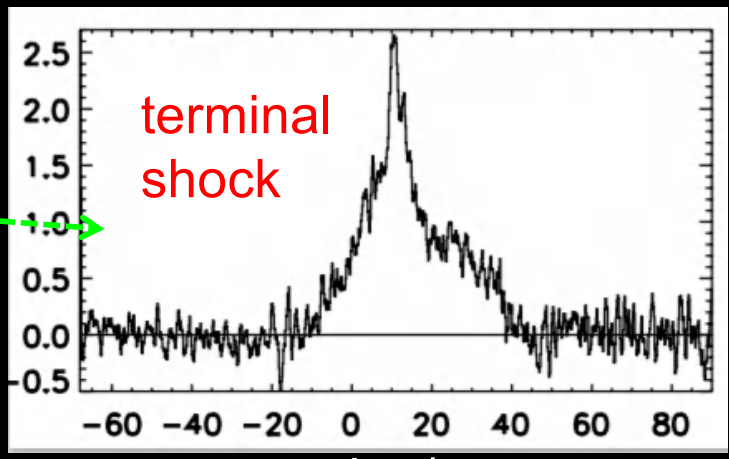
HOPS 108: Class 0 protostar with L< 120Lsun

FIR shock tracers such as: high excitation CO, H_2O, OH lines have been detected near HOPS 108 (Manoj+2013, 2018).

The formation of a HOPS protostar triggered by the impact of the jet of another protostar?



SOFIA GREAT [OI] spectrum
(Megeath et al in prep).



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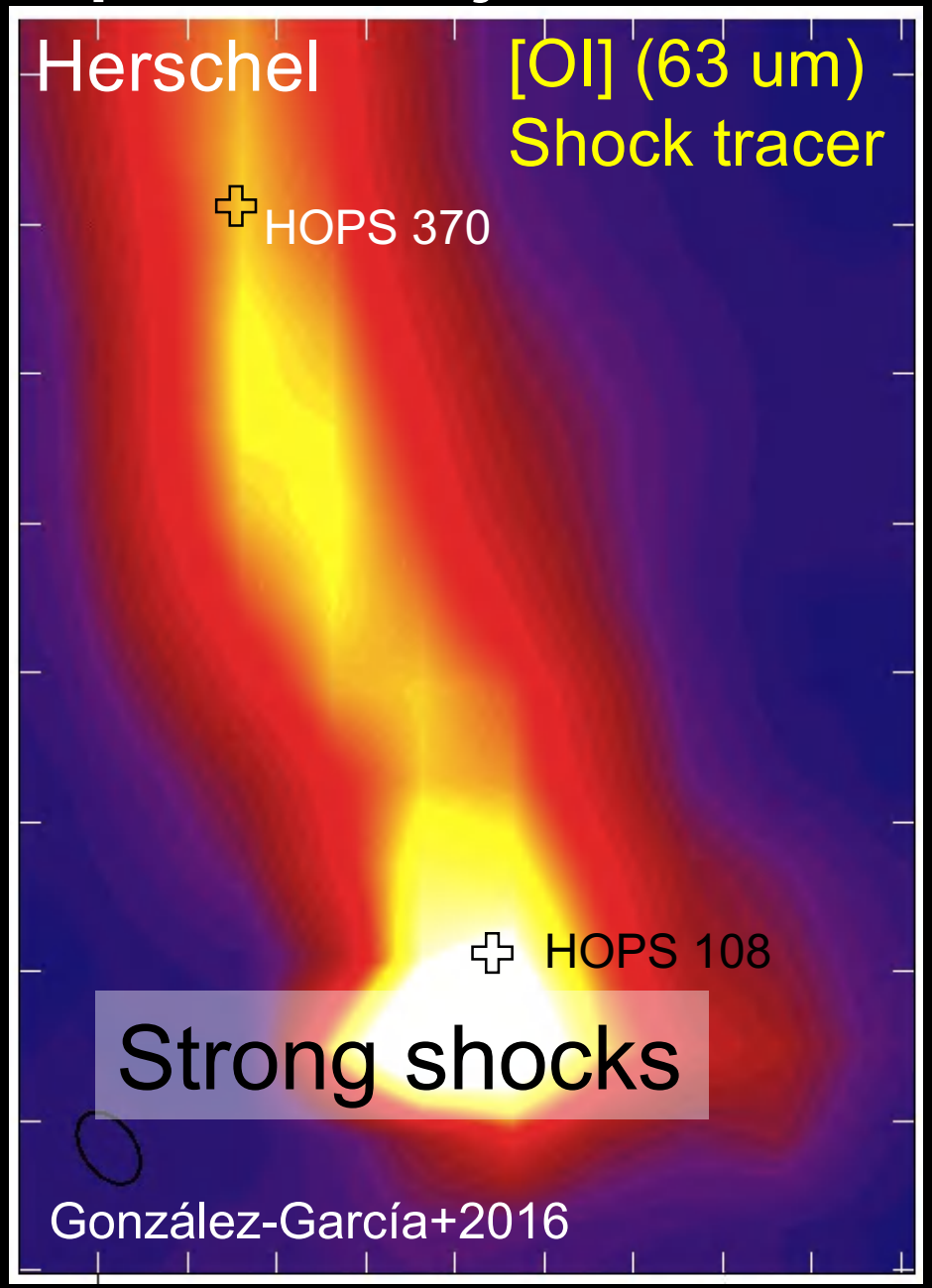

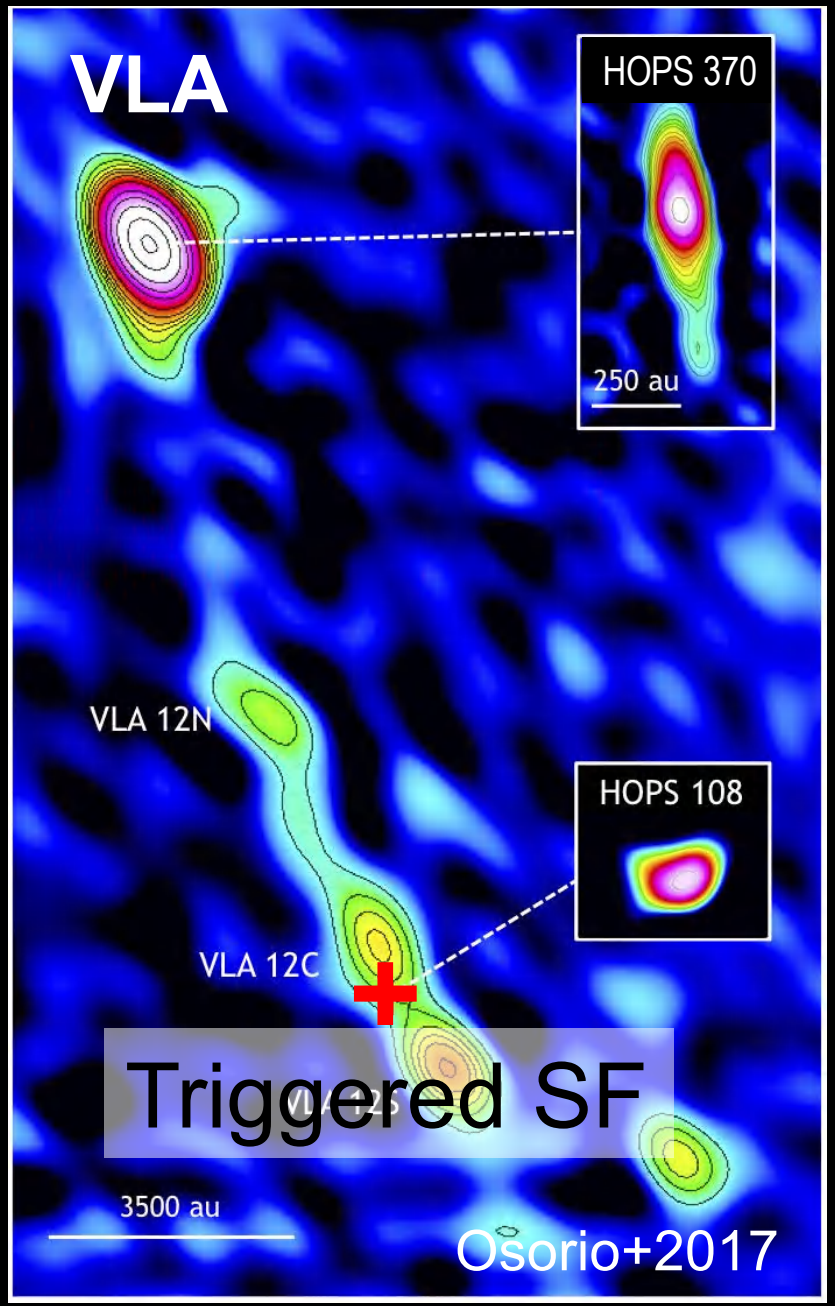

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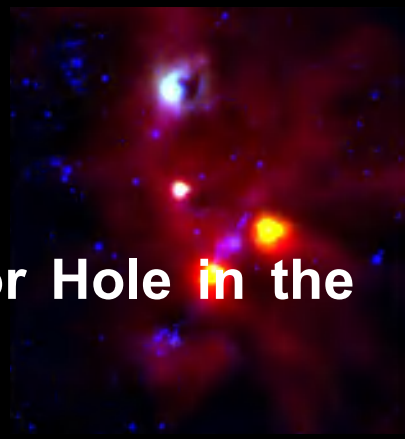

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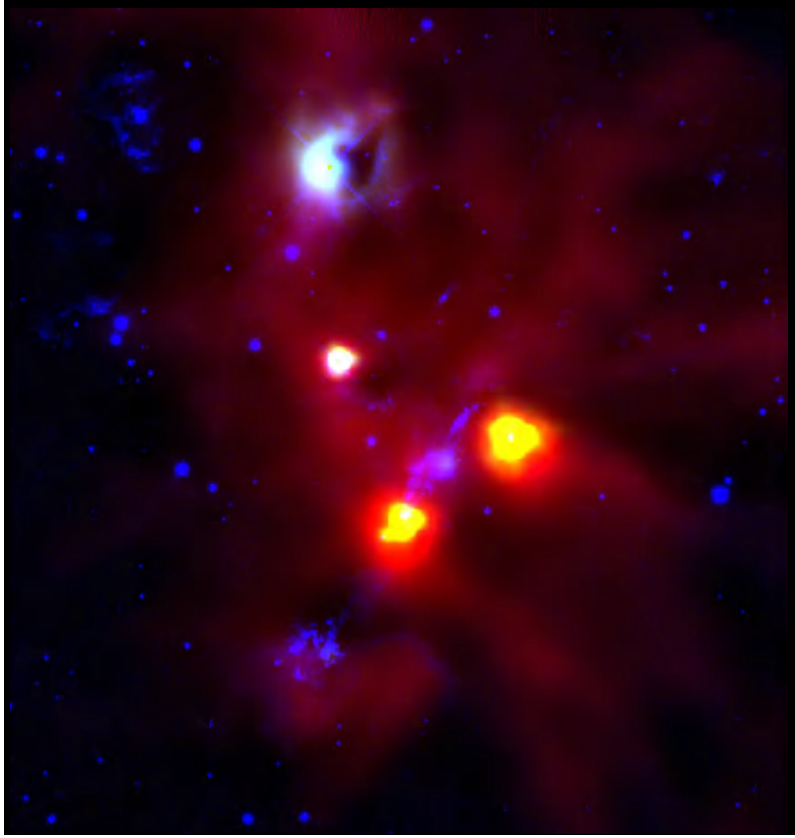

Thanks!