A Survey of Atomic Outflows from Massive Protostars

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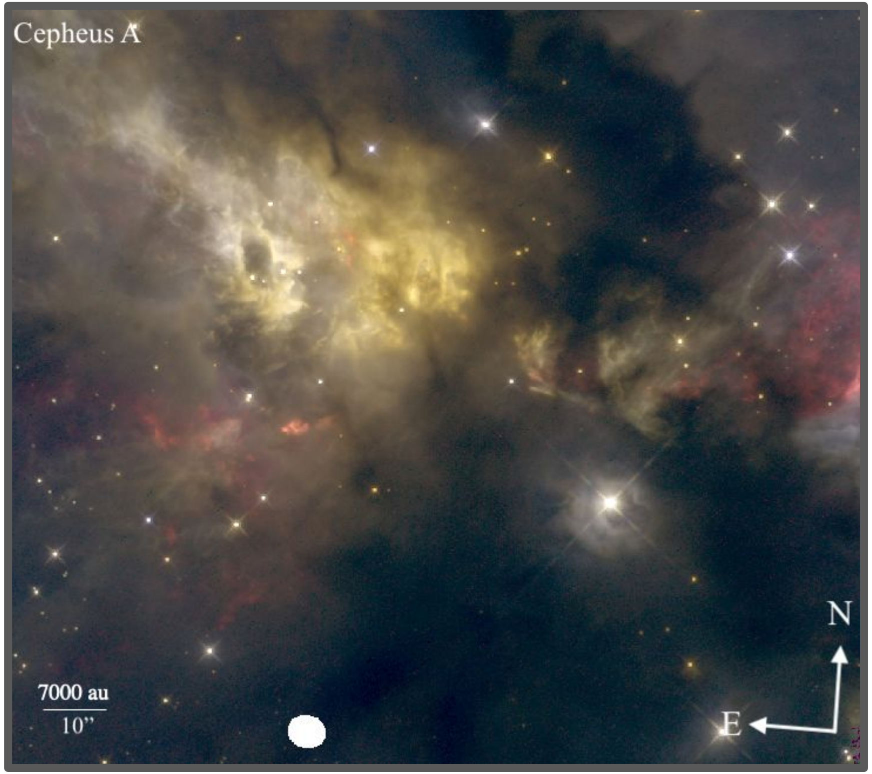
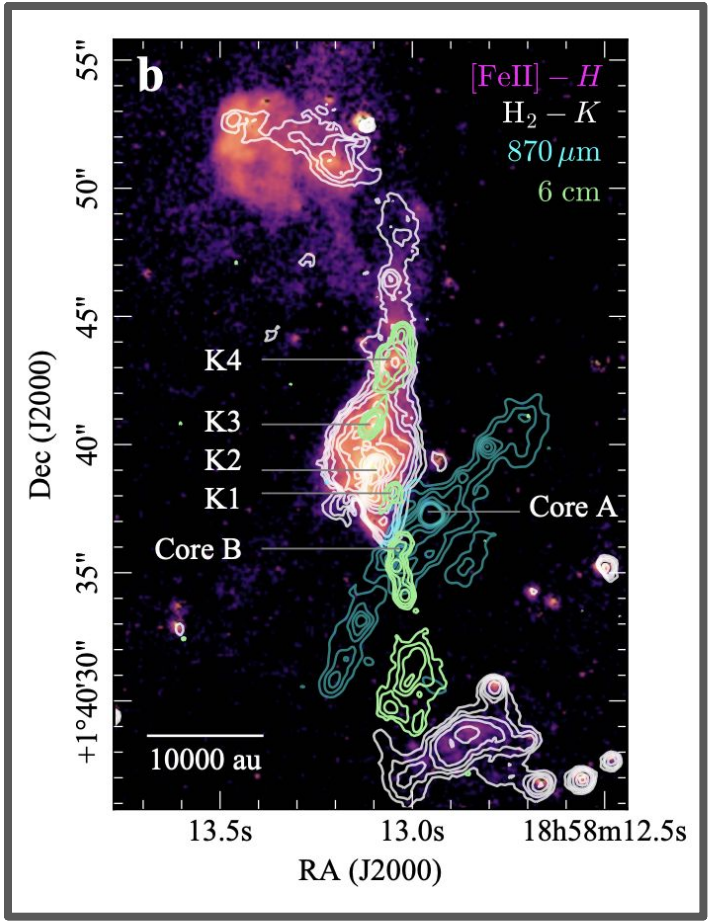


Fedriani et al. (in preparation)

Introduction

- Massive ($M_* > 8M_{\odot}$) protostars deeply embedded in dense molecular clouds with complex structures
- Outflows as a probe of massive star formation environments
- Handful of excellent outflow tracers in the far infrared ([Fe II], [OI], OH, H_2O, CO)
    - Trace shocks, outflow-envelope interactions, photodissociation regions (PDRs)



Fedriani et al. (2019)

Core Accretion Model

- Model for massive star formation
  - Suggests isolated core evolution
  - Scaled-up low-mass star formation

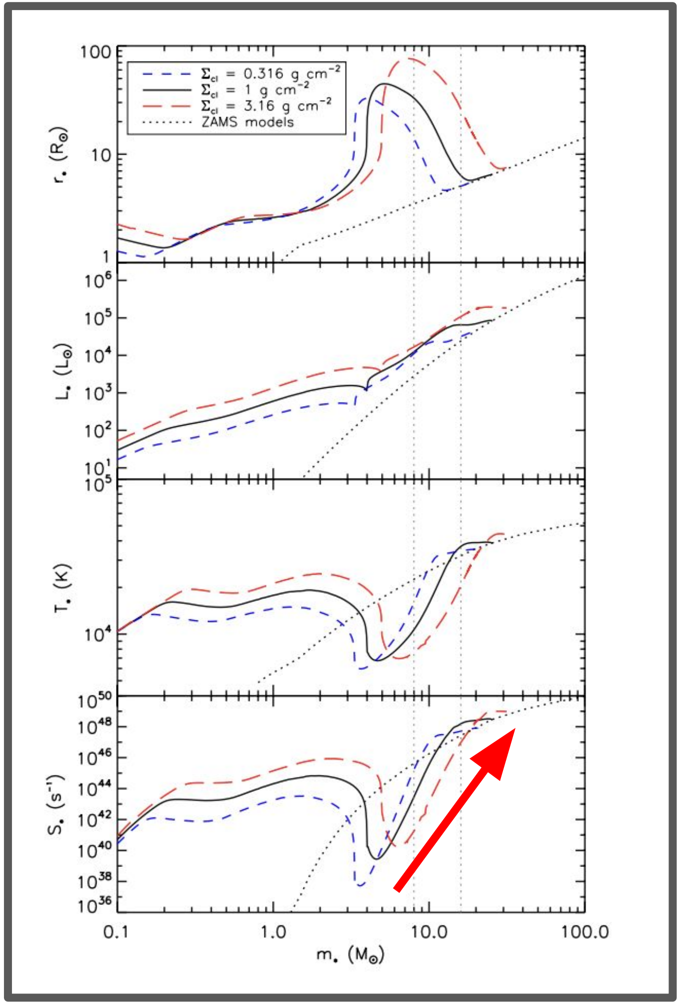
- Accretion along the main sequence towards the end of the protostellar stage

Protostellar radii

Protostellar luminosity

Temperature

Ionization rate

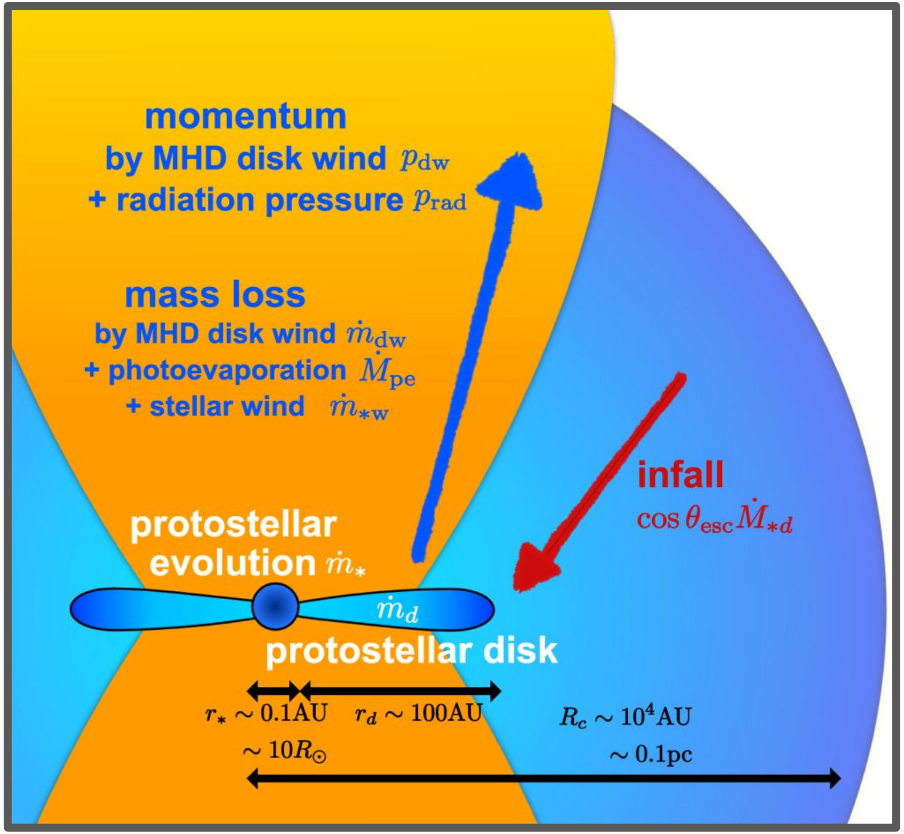


Tan et al. (2014)

Highly Irradiated Outflows

- Surge in ionization rate in late-stage massive protostars, developing PDRs in outflow

- High ionization rate is prediction of Core Accretion model



Tanaka et al. (2017)

Highly Irradiated Outflows

- Post-processing of numerical MHD simulation from Staff et al. (2019)

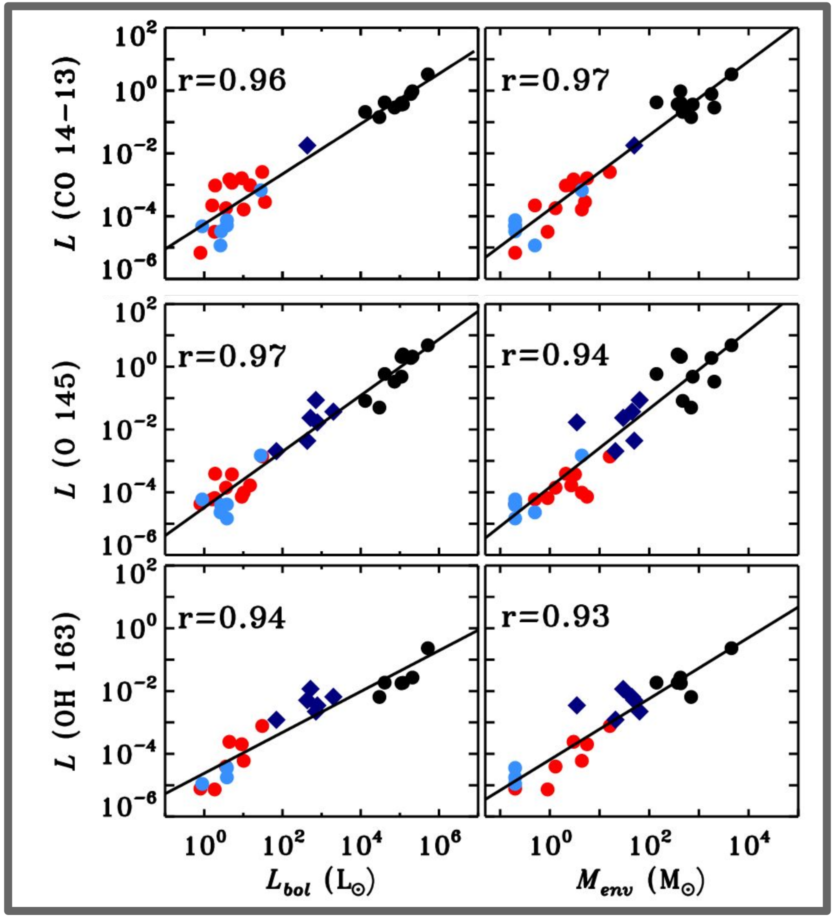
- Synthetic line intensities that can be compared with observational data

- Ionized regions nested within atomic and molecular regions

Obolentseva et al. (in preparation)

Previous Work on Atomic Outflows

- Certain tracers are poorly represented in literature; few sources have [OI] emission mapped

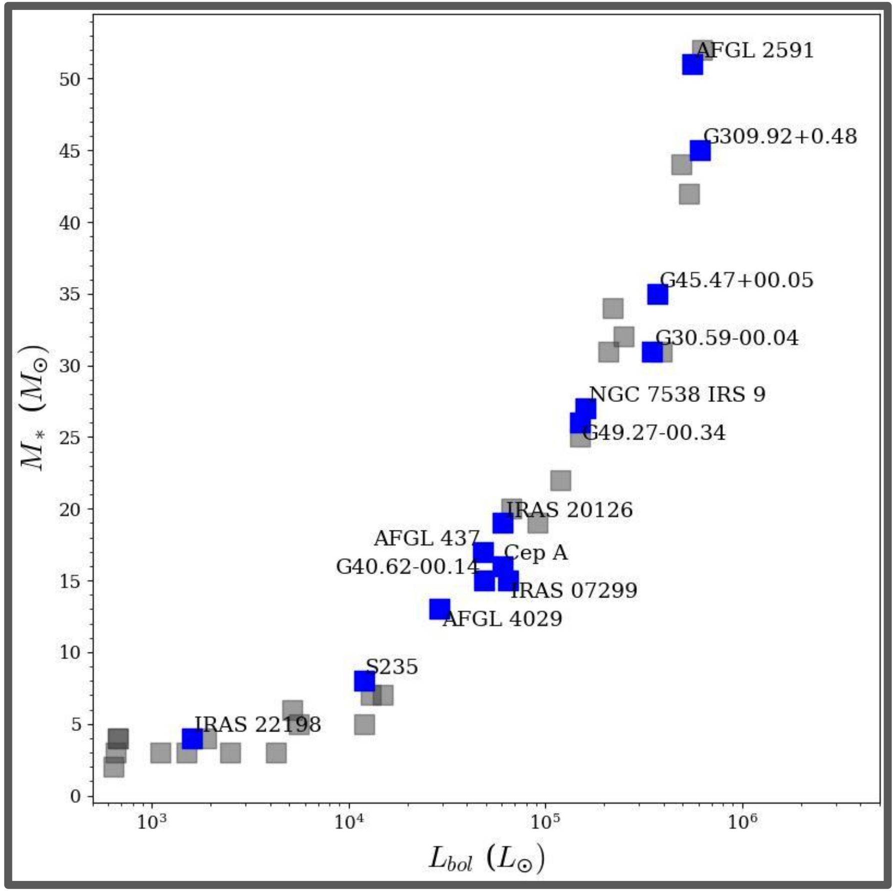


Karska et al. (2014)

High-mass - Class 0 low-mass - Class 1 low-mass - intermediate-mass

SOMA Atomic Outflow Survey

- **PI Yao-Lun Yang (RIKEN)**
- **17 sites of massive star formation sampled from the SOFIA Massive Star Formation Survey (SOMA)**
  - **Full presentation on Wednesday by SOMA PI Jonathan Tan**
- **SOFIA FIFI-LS observations in four bands — [OIII] 52 µm, [OI] 63 and 145 µm, CO 14-13 186 µm**
- **Complementary FIR data from SOFIA FORCAST, Herschel PACS, and Spitzer IRAC, used for constructing SEDs**



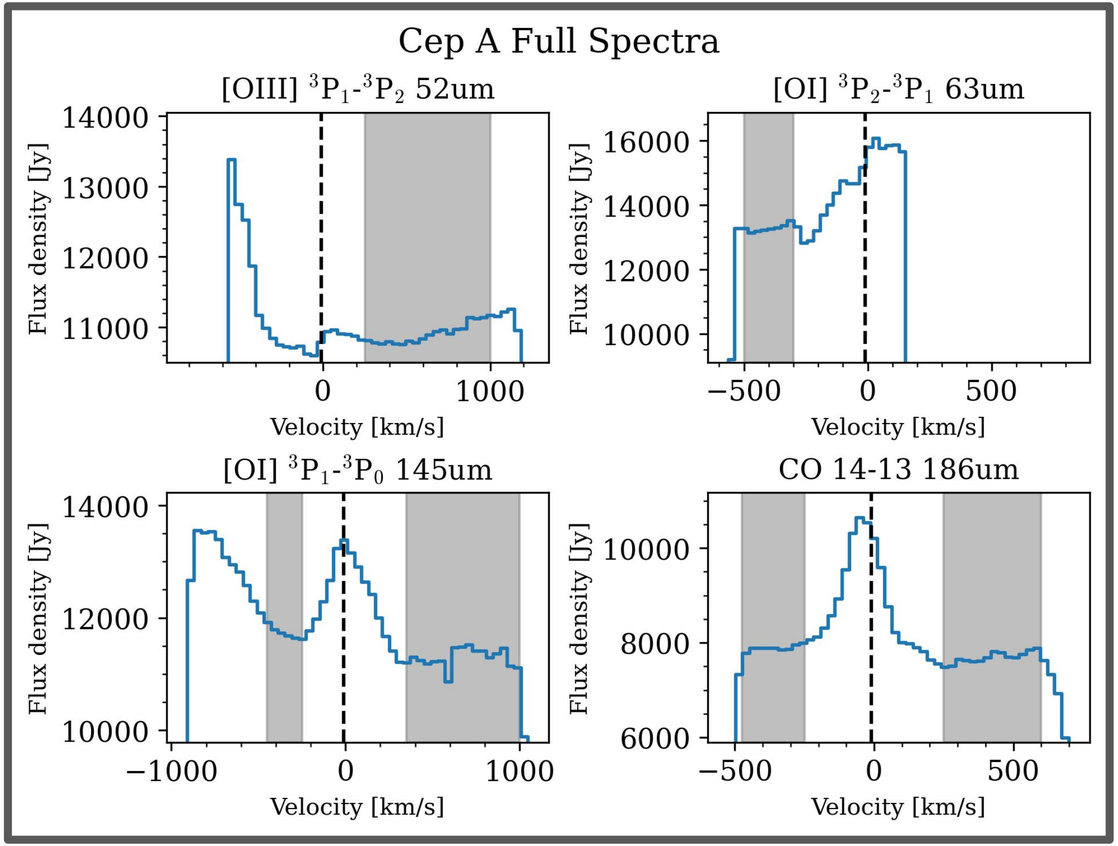
Oakey et al. (in preparation)

Objectives

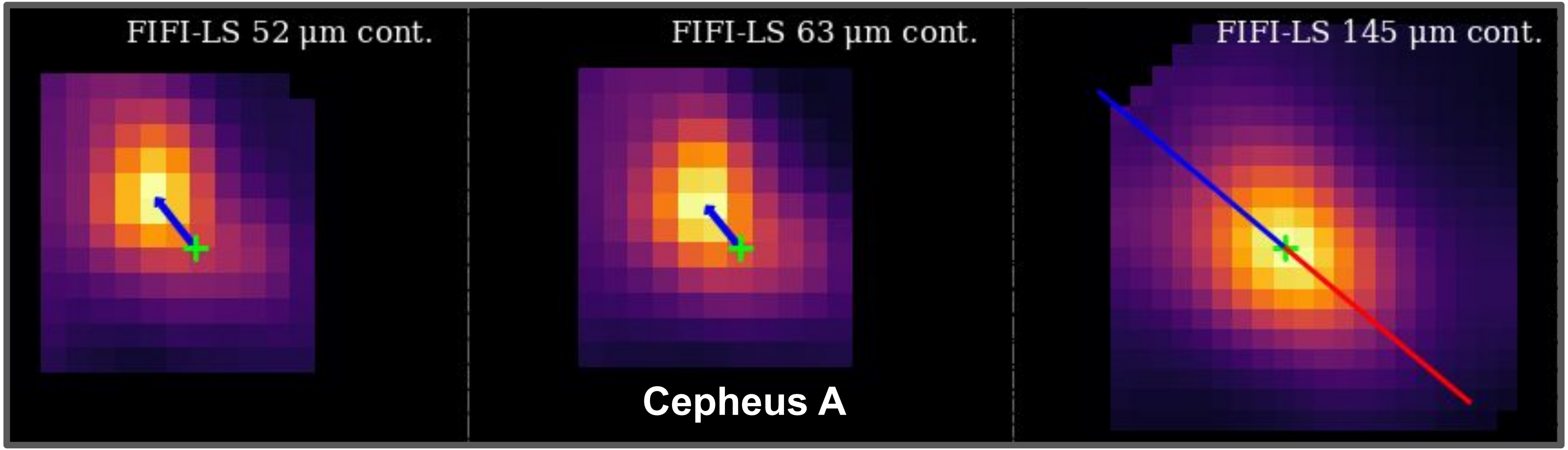
- Categorize outflow morphology
- Measure total line flux and compare with intrinsic protostellar properties
  - [OI] flux should trace both accretion and mass loss rate, also UV radiation (PDRs)
- Calculate CO/[OI] line flux ratios
- Comparison with PDR and shock models

Data - Continuum

- Spectral cubes with ranges ~ ± 500-1000 km s^{-1}, spectral resolution ~ 200-300 km s^{-1}
- Simultaneous LW/SW channel observations through dichroic, SW images have smaller FOV
- Astrometric correction performed upon LW continuum image, mapped to Herschel 160 μm peak
    - Color gradient measured

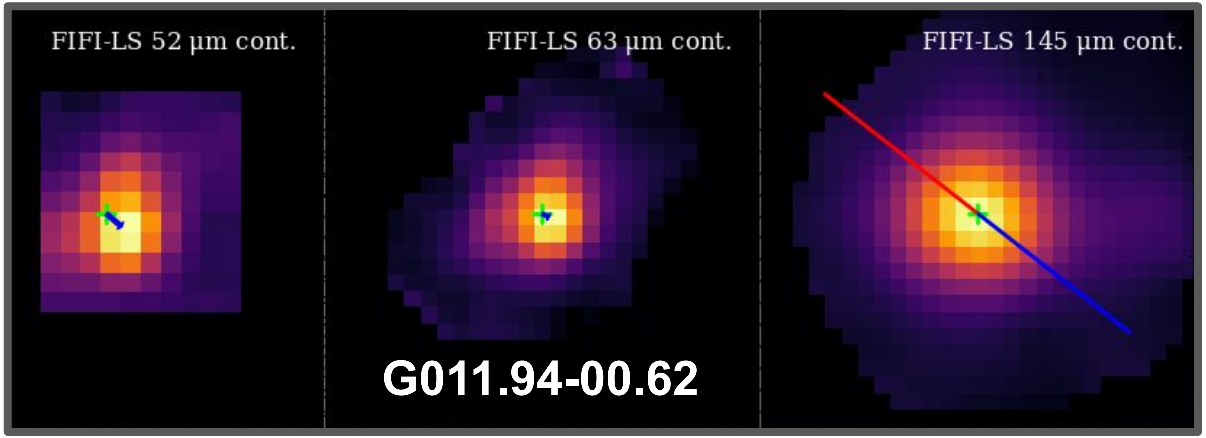


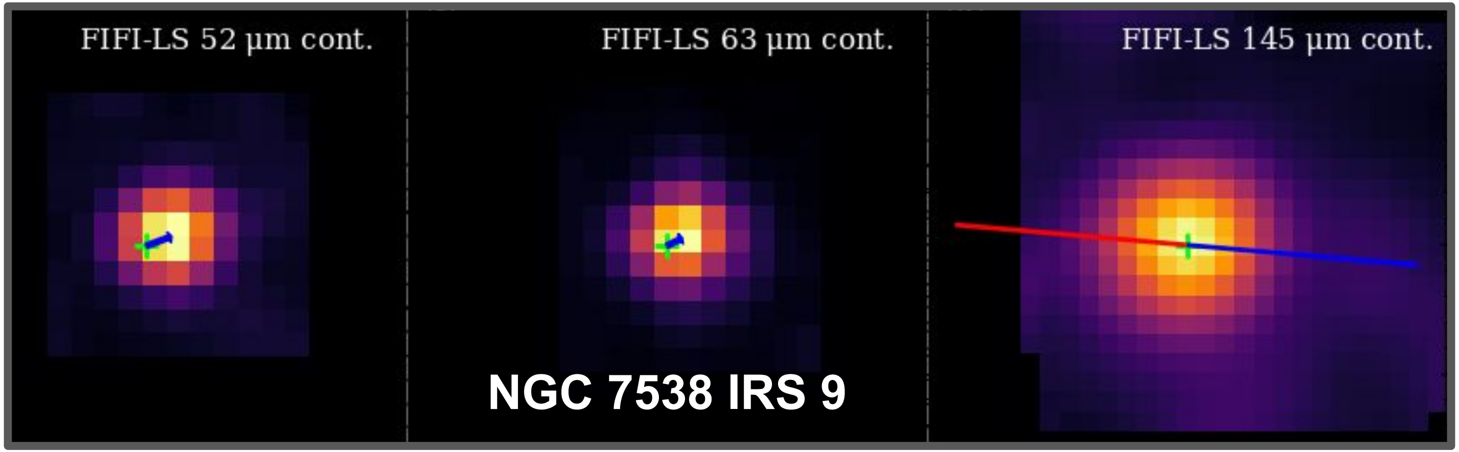
Color Gradient



- Core Accretion predicts alignment of blue-shifted outflow cavity with short-wavelength peak
- Outflow P.A. from CO observations (Rodriguez et al. 1980, 1994)

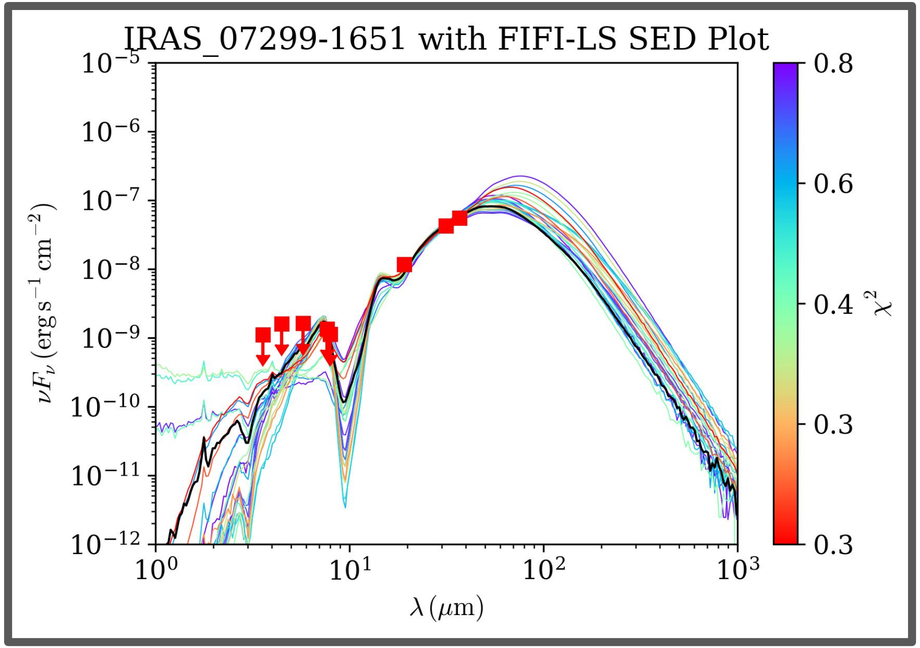
Color Gradient

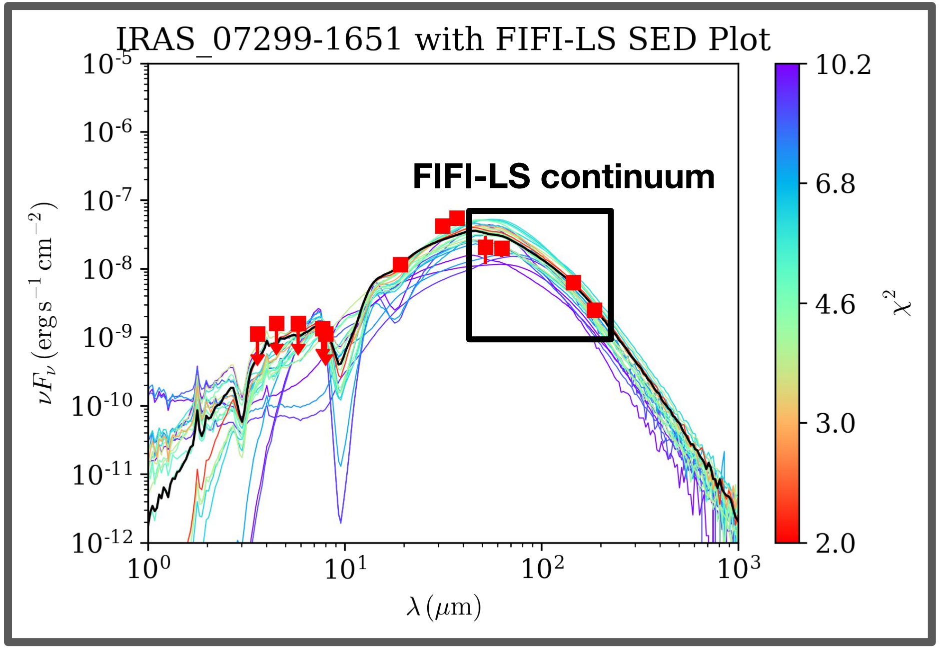




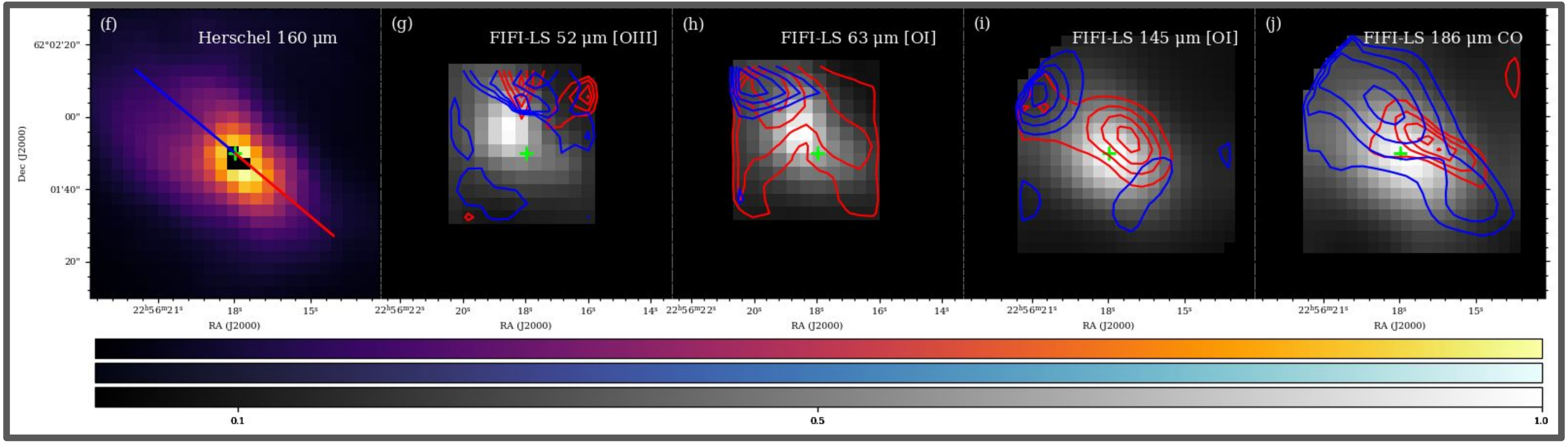
SED Improvement

- FIFI-LS data added to SOMA IV spectral energy distribution (SED) fits
- 3 sources lack LW Herschel data and are better constrained with FIFI-LS data





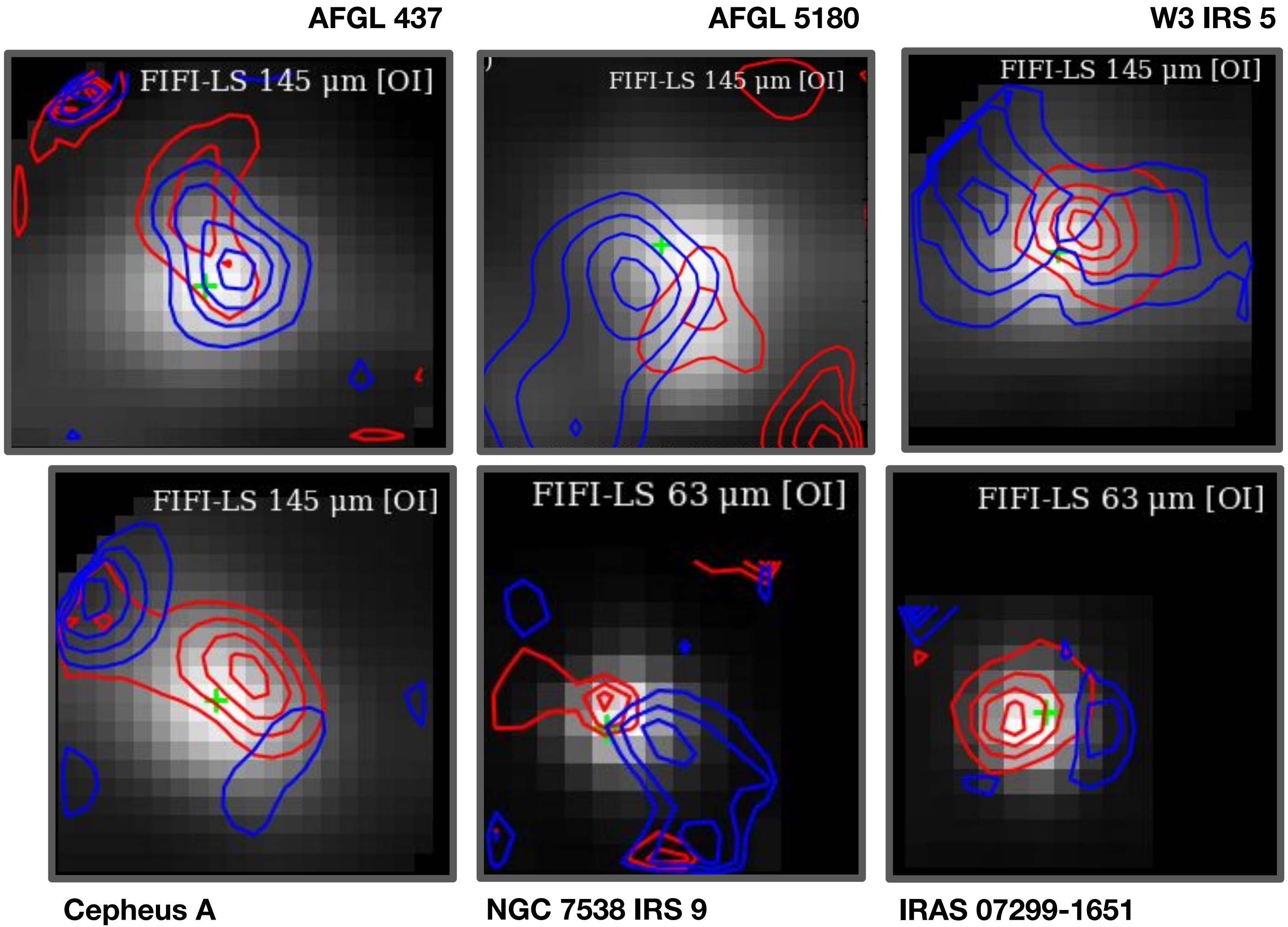
Outflows



- Strong 145 µm [OI] and CO emission are most usual outflow indicators from our survey
- 63 µm [OI] contaminated by absorption

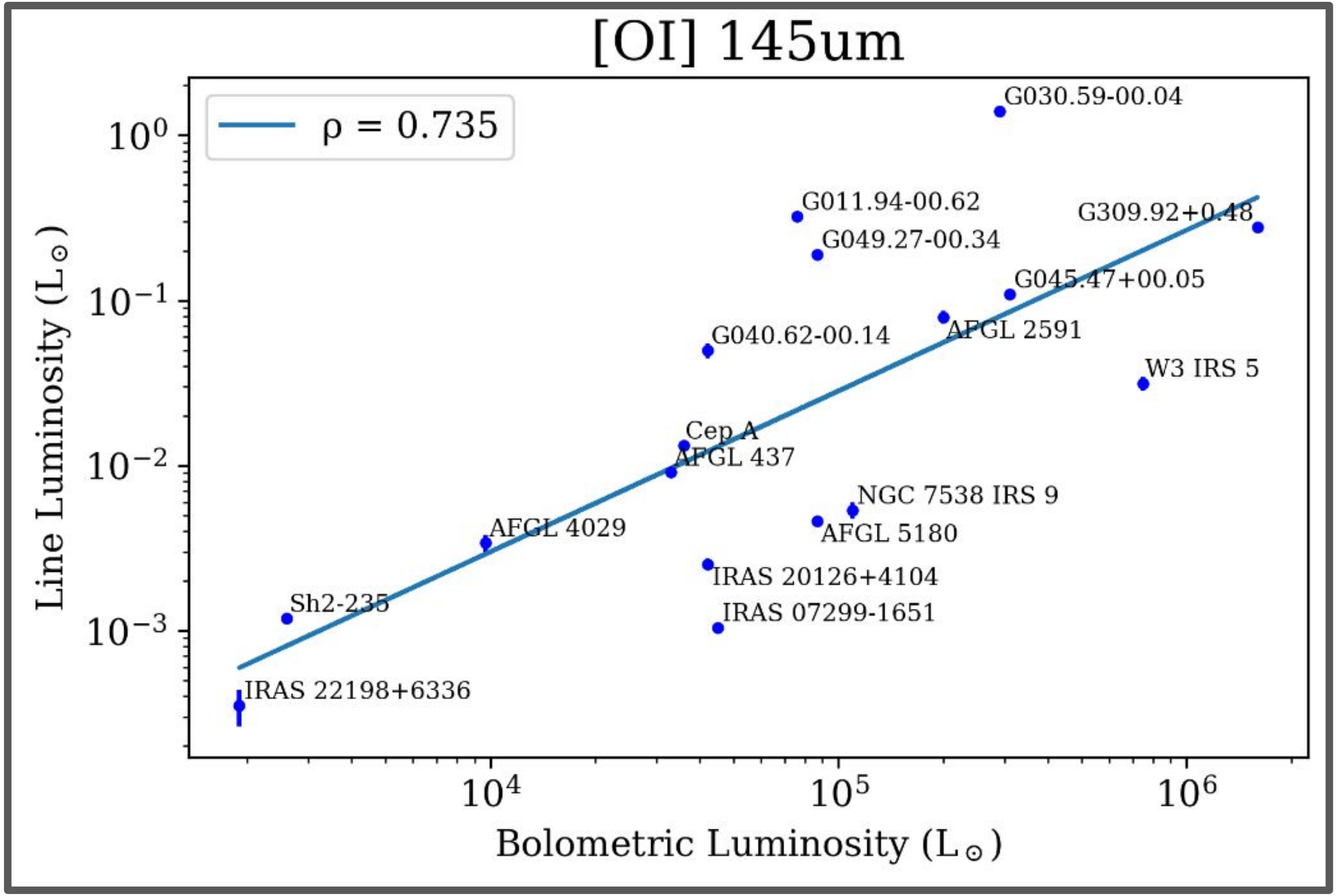
Outflows

- In all 17 sources we detect [OI], six display outflow morphology confidently
- Three other tentative detections
- Eight display no obvious detection



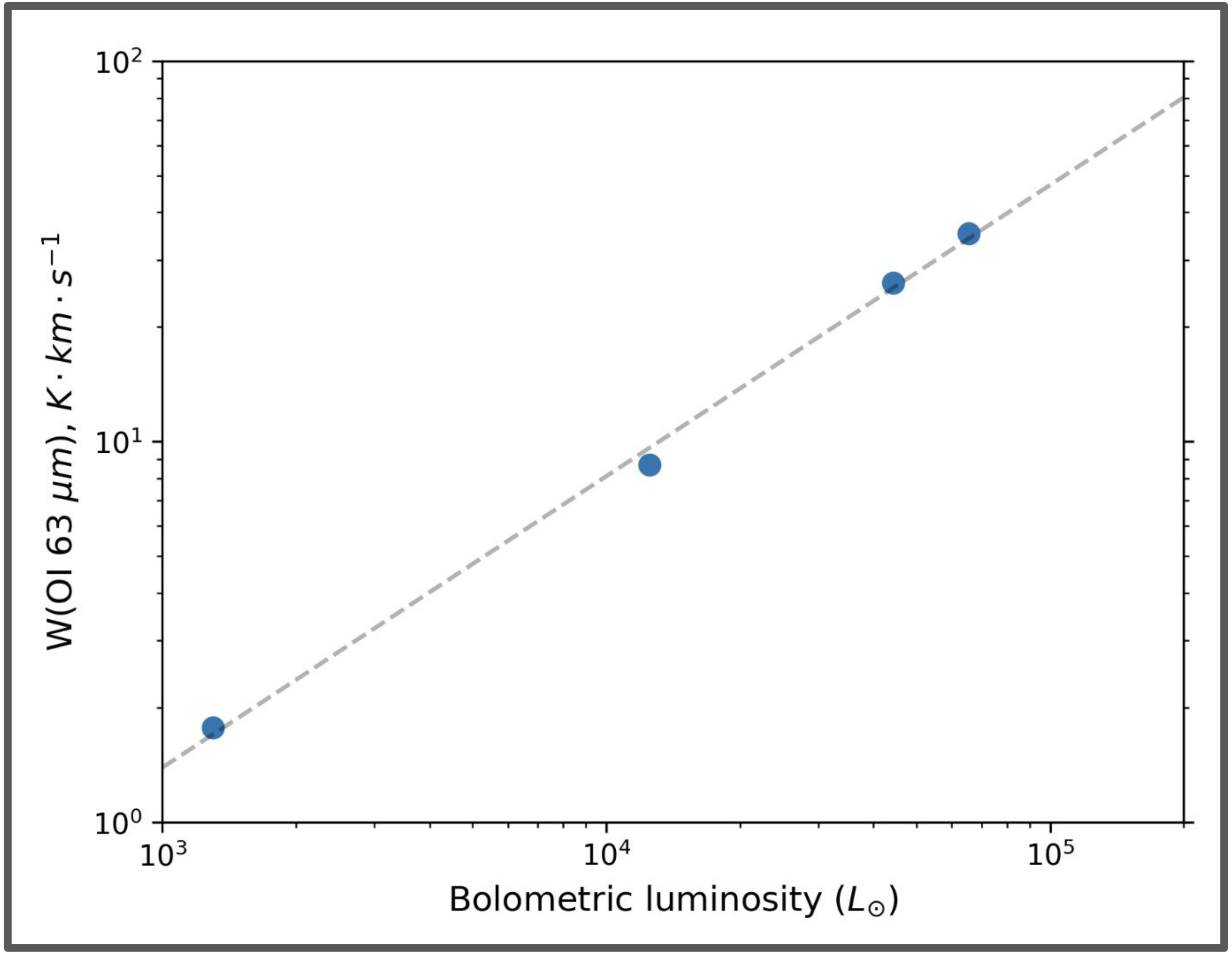
Line Flux

- Strong correlation in all bands except [OI] 63 μm, which is tainted by absorption
- This is expected if oxygen traces mass loss, accretion, and UV flux



Line Flux

- **Models predict α ~ 0.81, observations show α = 0.86**



Obolentseva et al. (in preparation)

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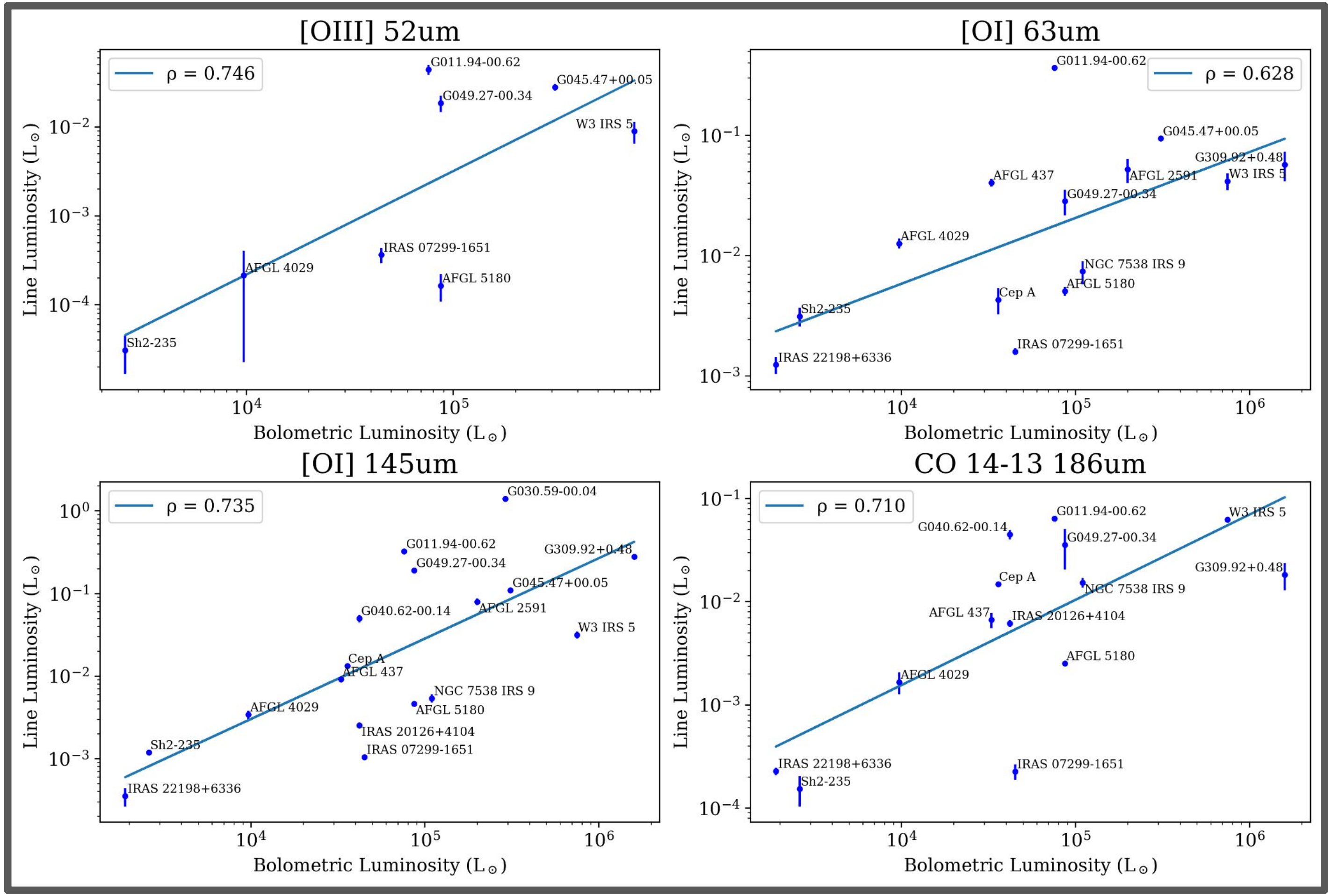
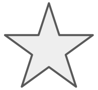
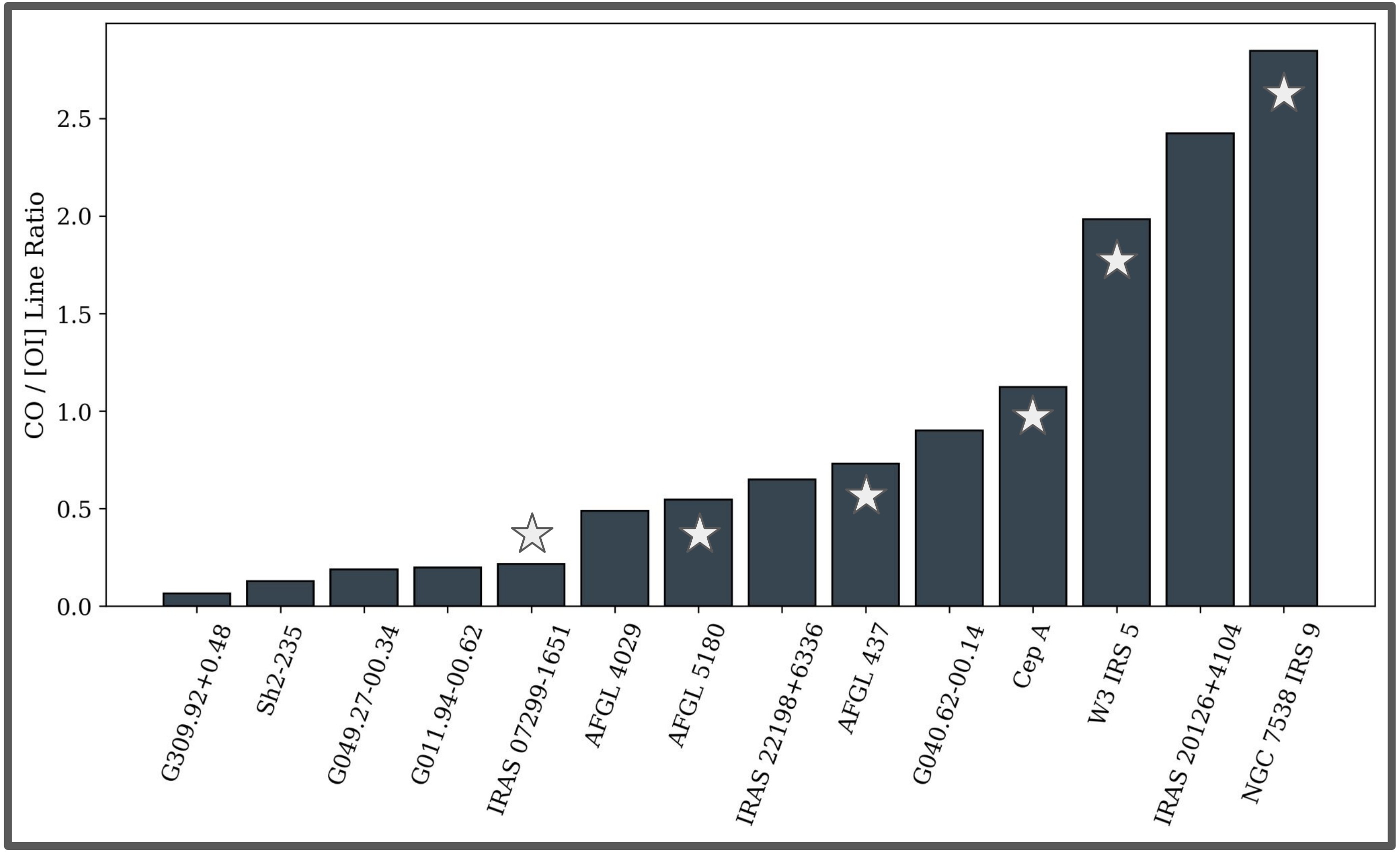


CO/[OI] Ratios

- Will be applying these to shock and PDR models
- Wide range of values, diverse survey of environments


: Denotes sources with observed outflows in FIFI-LS

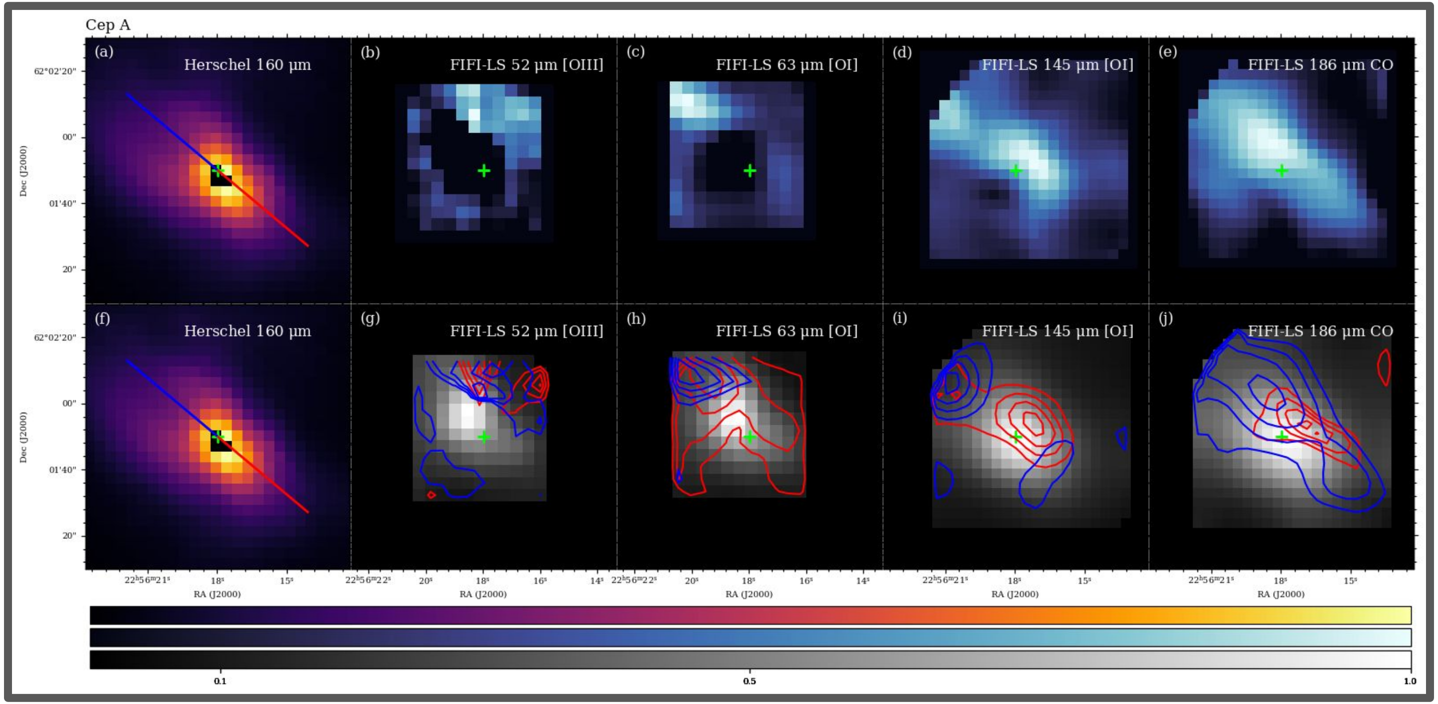


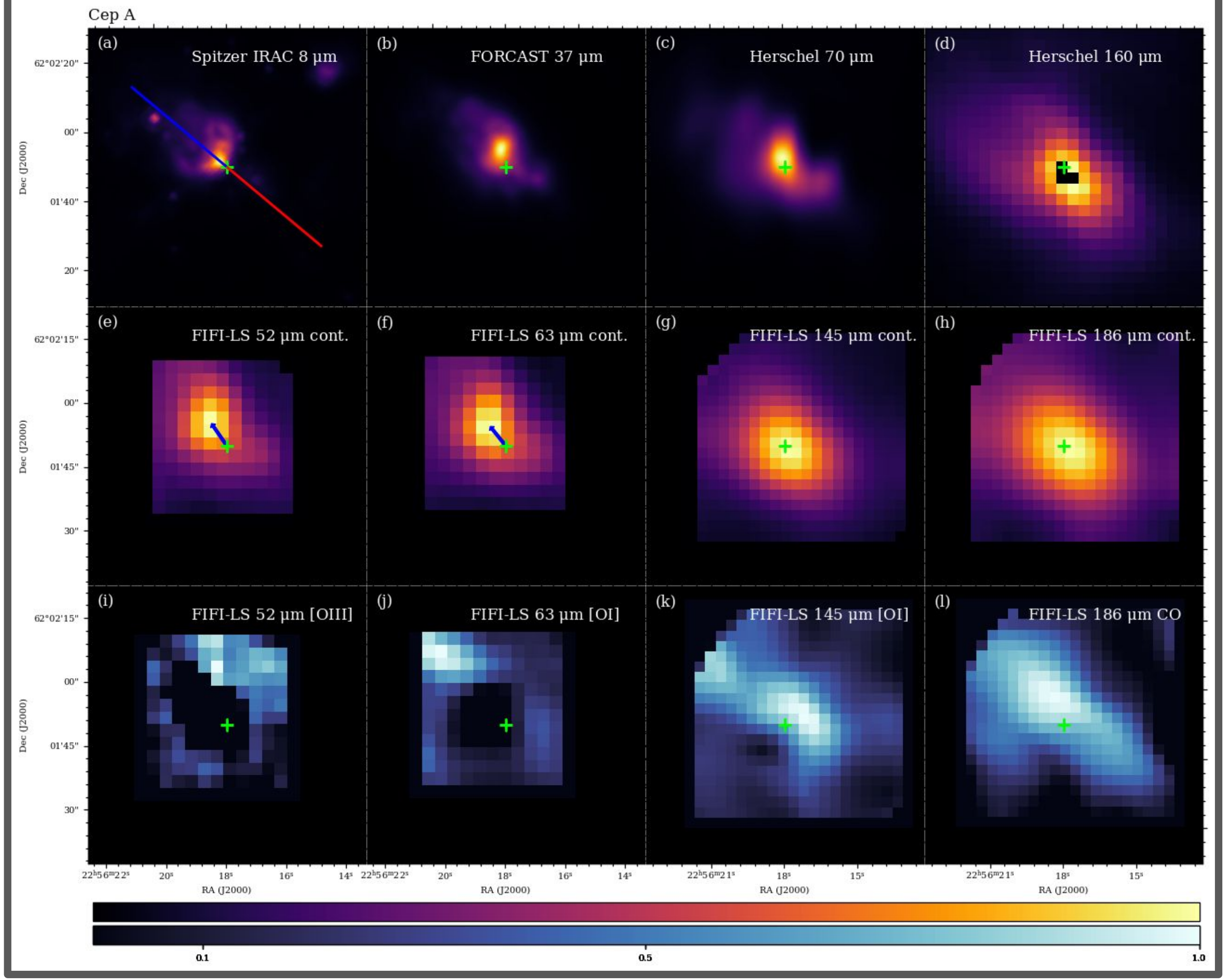
Summary

- Successfully mapped 17 massive star forming regions in [OI], [OIII], and CO, detected [OI] in all sources, [OIII] in very few, and generally CO is detected
- Improved SED constraints, better models for protostellar characteristics
- Measured color gradients, find weak or non-existent correlation with outflow axes
- Detected at least six outflows, with potential others
- Correlated intrinsic luminosity with integrated line emission in almost every band
    - Observed a range of CO to [OI] ratios, indicating transitions from molecular- to atomic-dominated outflows

Future

- Compare with shock models
- Apply CO/[OI] ratios
- Investigate kinematic features in the spectra
- Establish an evolutionary sequence for atomic outflows

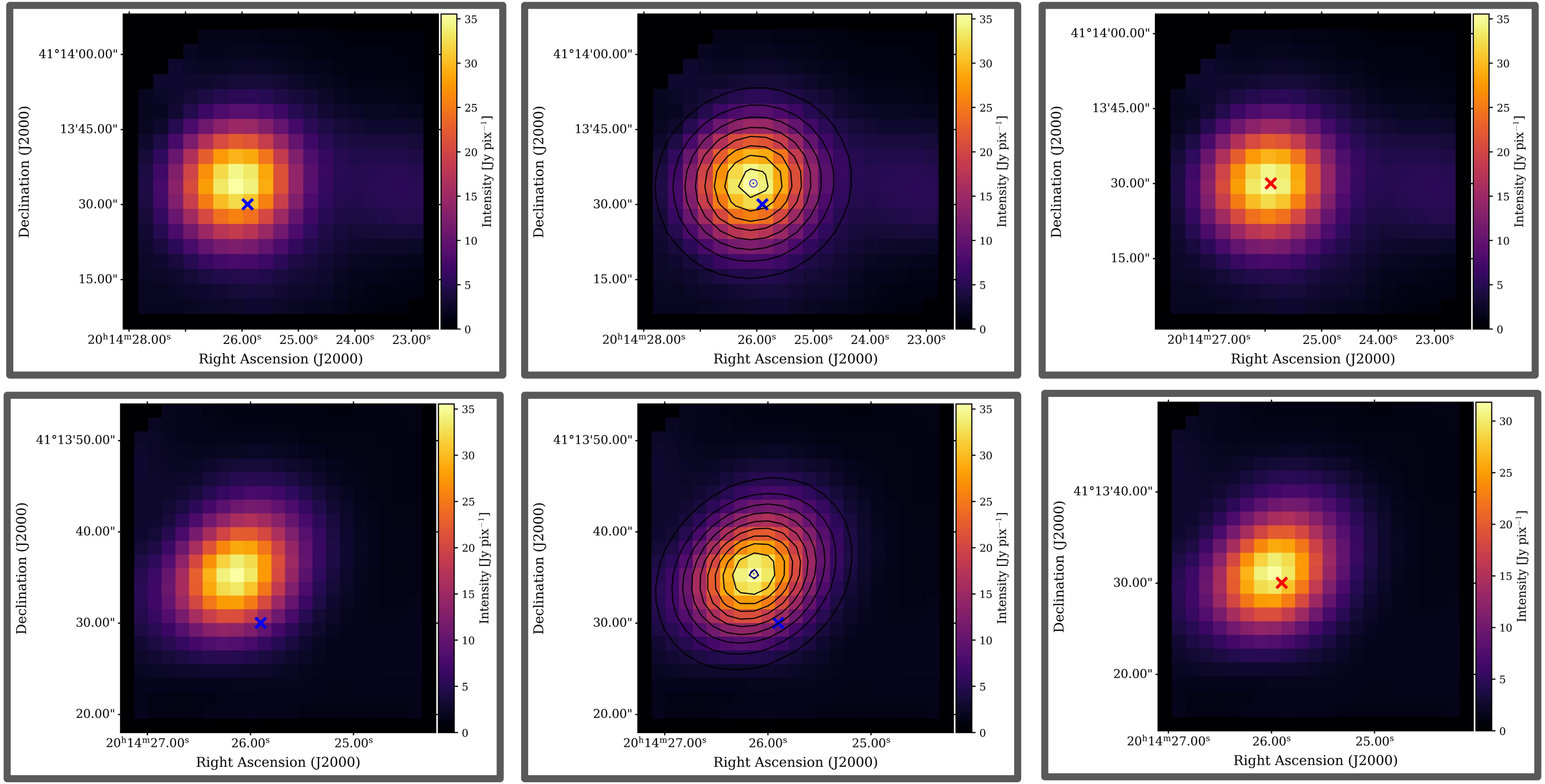



Cep A
(a) Spitzer IRAC 8 μm
(b) FORCAST 37 μm
(c) Herschel 70 μm
(d) Herschel 160 μm
(e) FIFI-LS 52 μm cont.
(f) FIFI-LS 63 μm cont.
(g) FIFI-LS 145 μm cont.
(h) FIFI-LS 186 μm cont.
(i) FIFI-LS 52 μm [OIII]
(j) FIFI-LS 63 μm [OI]
(k) FIFI-LS 145 μm [OI]
(l) FIFI-LS 186 μm CO
Dec (J2000)
RA (J2000)
62°02'20"
00"
01'40"
20"
62°02'15"
01'45"
30"
22h56m22s
20s
18s
16s
14s
22h56m21s
15s
0.1
0.5
1.0

Astrometric Correction

LW image

SW image

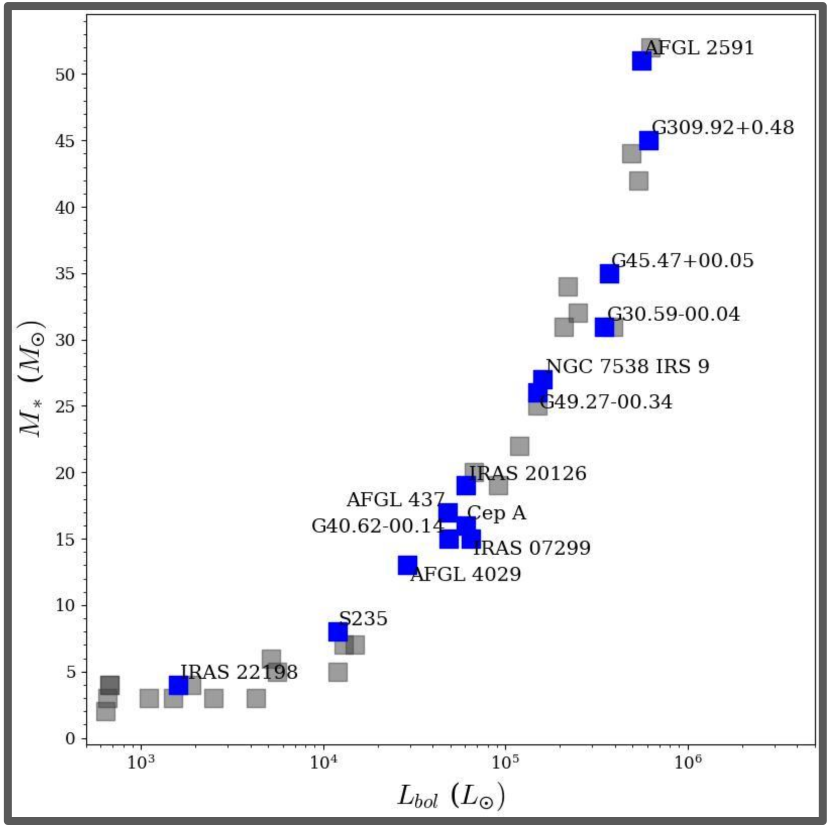


Color Gradients

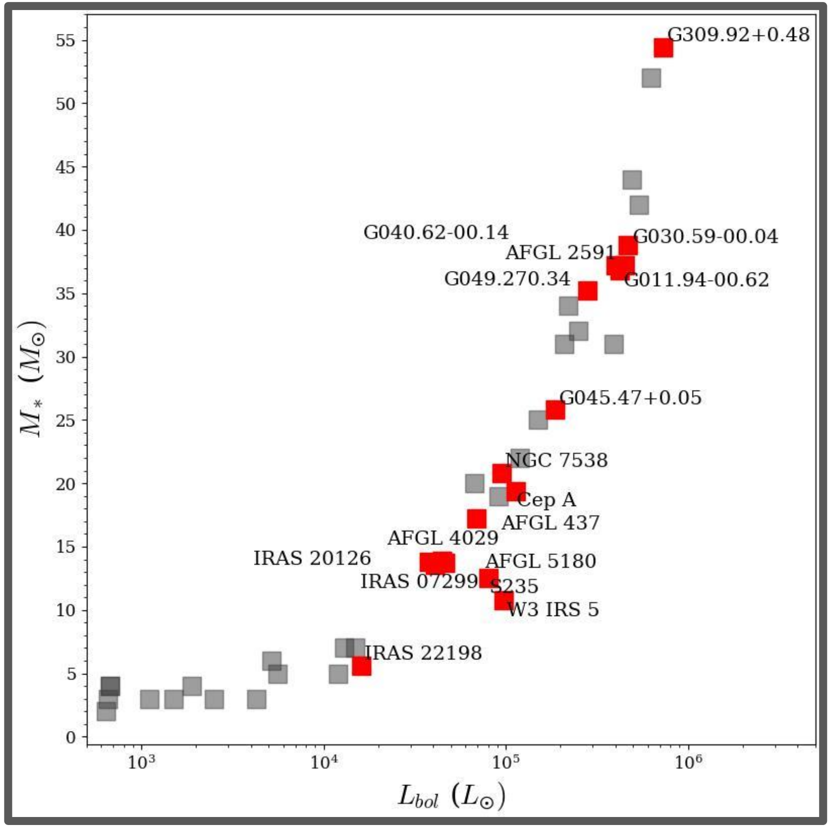
	Offset [arcsec]		Position Angle [deg]		Average		Outflow
Source	145 μm	186 μm	145 μm	186 μm	Offset	P.A.	P.A.
G045.47+00.05	1.0 ± 0.4	3.1 ± 0.7	-23.3 ± 23.4	161.8 ± 12.9	2.1 ± 0.8	69.2 ± 26.8	5
IRAS 07299-1651	2.2 ± 0.2	4.6 ± 0.4	119.7 ± 5.1	171.0 ± 4.6	3.4 ± 0.5	145.3 ± 6.8	...
AFGL 437	4.0 ± 0.7	4.6 ± 1.0	-59.4 ± 7.9	-81.1 ± 9.4	4.3 ± 1.2	-70.3 ± 12.3	-175
IRAS 20126+4104	1.6 ± 0.3	3.4 ± 0.8	35.0 ± 8.5	50.8 ± 14.0	2.5 ± 0.9	42.9 ± 16.4	115
G030.59-00.04	1.6 ± 0.8	2.0 ± 0.7	-26.8 ± 29.4	-70.6 ± 19.5	1.8 ± 1.1	-48.7 ± 35.3	...
Sh2-235	...	...	...	...	...	...	...
G040.62-00.14	0.6 ± 0.2	1.8 ± 0.3	-58.5 ± 15.9	171.5 ± 11.5	1.2 ± 0.4	56.5 ± 19.6	...
AFGL 4029	2.4 ± 0.5	5.9 ± 1.5	170.0 ± 11.2	-155.6 ± 12.5	4.1 ± 1.6	7.2 ± 16.8	-95
G309.92+0.48	1.2 ± 0.1	2.2 ± 0.2	-81.8 ± 5.0	-119.4 ± 4.8	1.7 ± 0.2	-100.6 ± 6.9	...
AFGL 2591	1.0 ± 0.2	...	-25.6 ± 11.2	...	1.0 ± 0.2	-25.6 ± 11.2	-100
Cep A	6.7 ± 0.3	8.0 ± 0.3	38.3 ± 2.4	38.1 ± 2.0	7.3 ± 0.4	38.2 ± 3.2	50
AFGL 5180	...	...	...	...	...	...	90
IRAS 22198+6336	12.3 ± 1.4	0.1 ± 1.0	-93.4 ± 4.0	-72.7 ± 483.7	6.2 ± 1.7	-83.0 ± 483.7	-133
NGC 7538 IRS 9	2.0 ± 0.2	2.9 ± 0.3	-71.2 ± 4.2	-83.8 ± 5.2	2.5 ± 0.3	-77.5 ± 6.7	-95
G011.94-00.62	1.0 ± 0.3	2.7 ± 0.3	-69.4 ± 14.9	-127.5 ± 6.6	1.9 ± 0.4	-98.5 ± 16.3	-128
G049.27-00.34	1.9 ± 0.7	1.6 ± 1.5	-35.3 ± 19.5	-114.9 ± 50.0	1.8 ± 1.6	-75.1 ± 53.7	...
W3 IRS 5	4.4 ± 0.3	4.5 ± 0.3	82.5 ± 4.5	104.0 ± 4.4	4.4 ± 0.5	93.2 ± 6.3	38

Weak association, but does not account for angle of outflow or uncertainty in outflow P.A.

SED Modelling (Average of Top 20 Fits)



SOMA IV values



SOMA IV + FIFI-LS values