



The VLA Nascent Disk and Multiplicity (VANDAM) Survey: Protostellar Jets from the Centimeter to Far-Infrared

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VANDAM Team:

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Mike Dunham (CfA), Kaitlin Kratter (Arizona), Dominique Segura-Cox (Illinois), Sarah Sadavoy (MPIA),
Laura Perez (NRAO), Carl Melis (UCSD), Robert Harris (Illinois), Lukasz Tychoniec (Leiden/AMU-Poland)

<http://home.strw.leidenuniv.nl/~tobin/VANDAM/>

Image: Bill Saxton (NRAO)

Survey Details

- 264 hour VLA large program
 - 8 mm/1 cm (207 hours) and 4 cm/6.4 cm (57 hours)
 - A and B configurations, 0.06" (15 AU) resolution
 - Perseus region ($d \sim 230$ pc), 92 YSOs (79 detected)
 - 43 Class 0, 37 Class I sources, 12 Class II
 - Luminosities range $0.1 L_{\text{sun}}$ to $30 L_{\text{sun}}$
- Goals:
 - Measure multiplicity fractions down to 15 AU
 - Resolve disks in dust continuum, measure dust masses
 - Jet properties from centimeter emission (free-free)
 - Inner ~ 10 s AU of the jet

Star Formation Process

Protostellar Phase

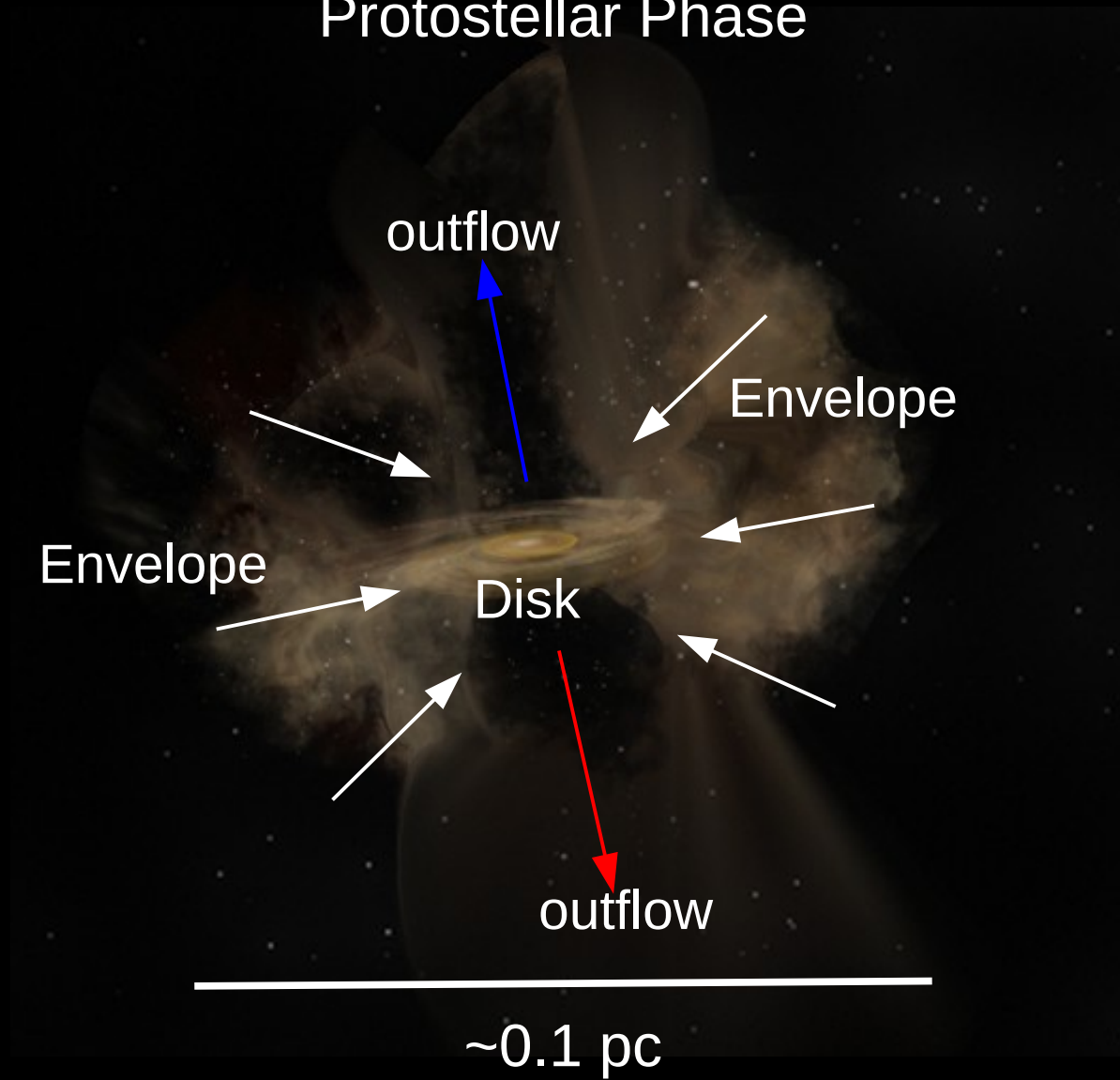


Image: Bill Saxton (NRAO)

Star Formation Process

Protostellar Phase

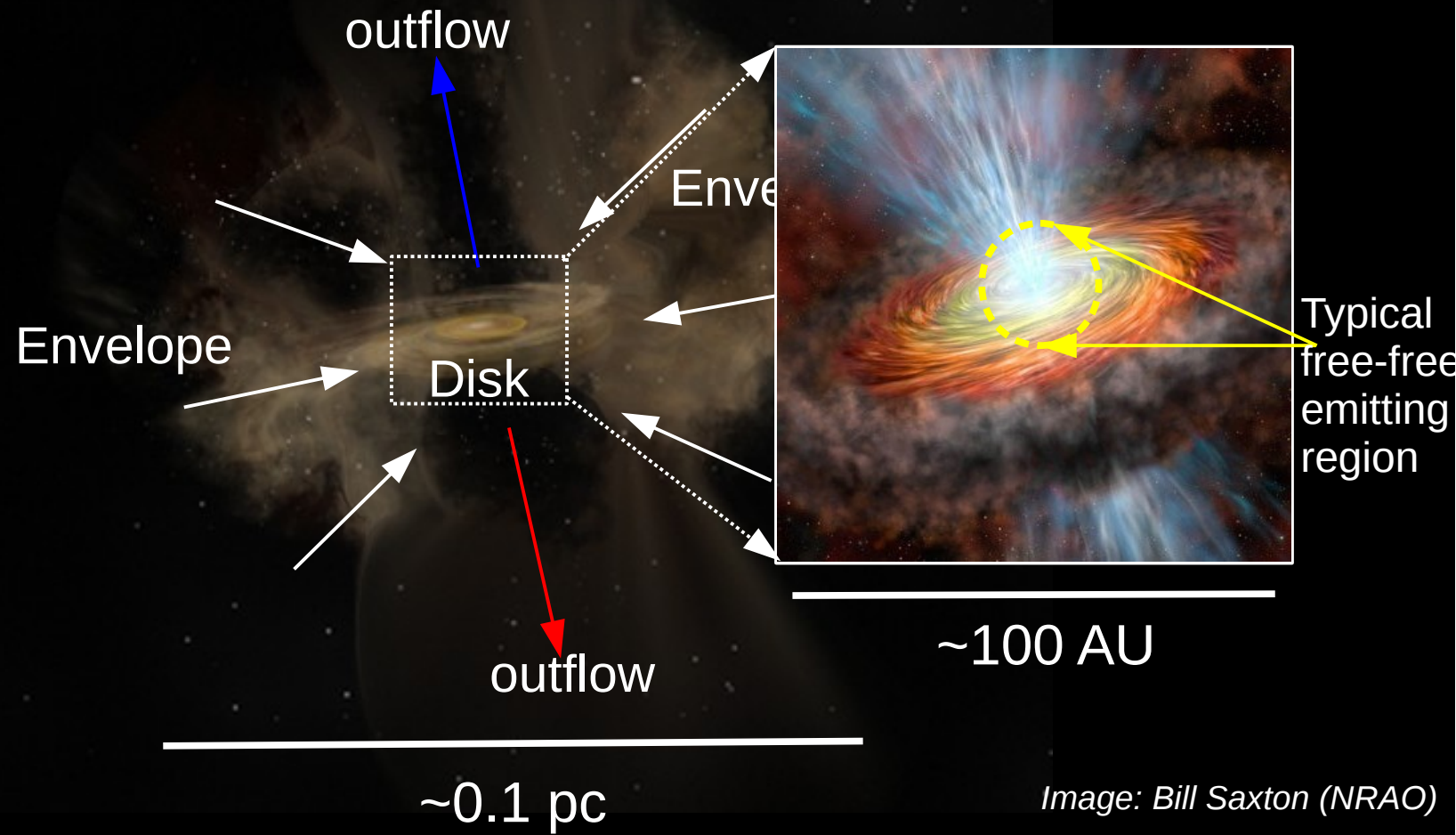
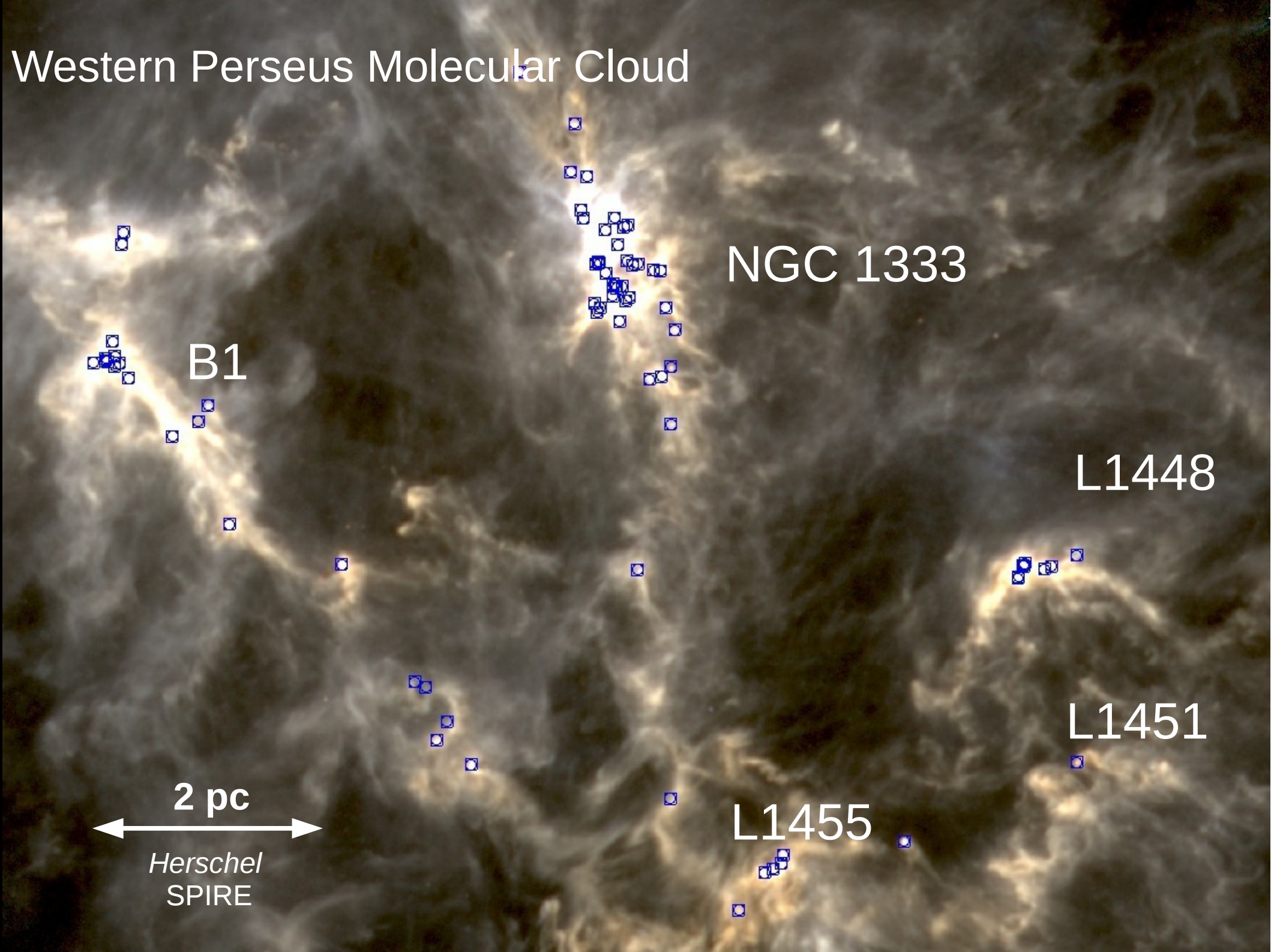


Image: Bill Saxton (NRAO)

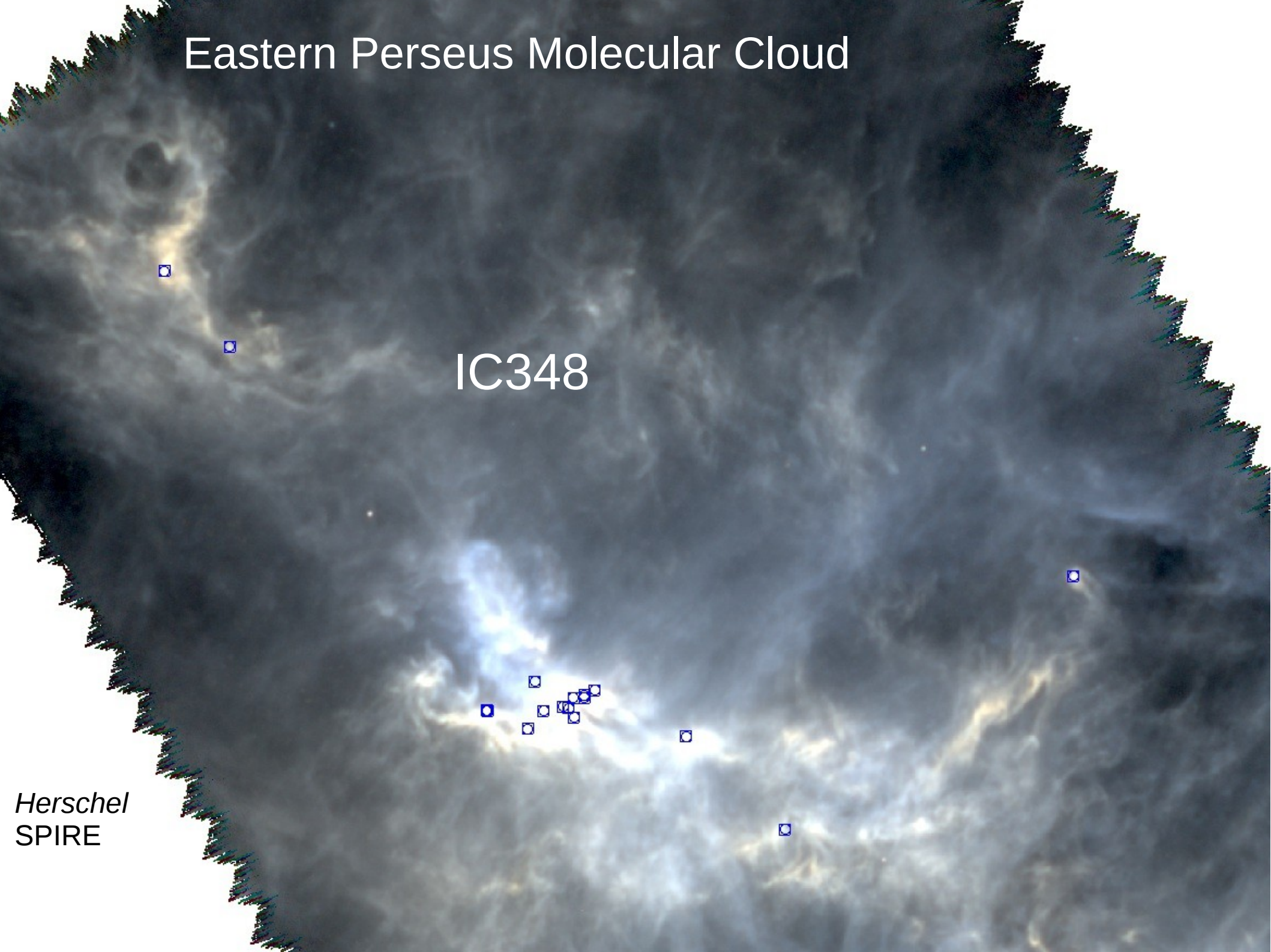
Western Perseus Molecular Cloud



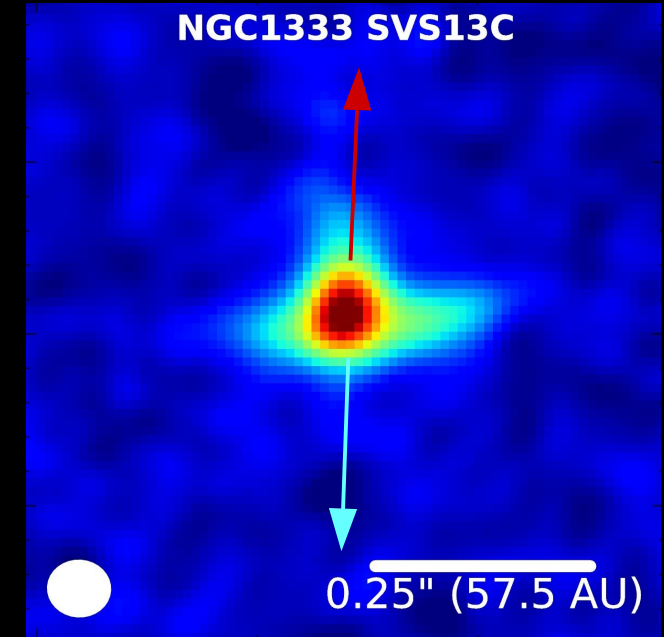
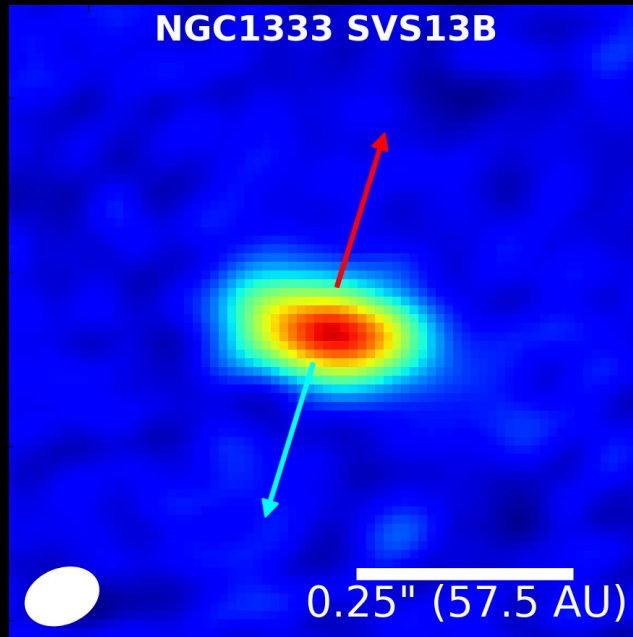
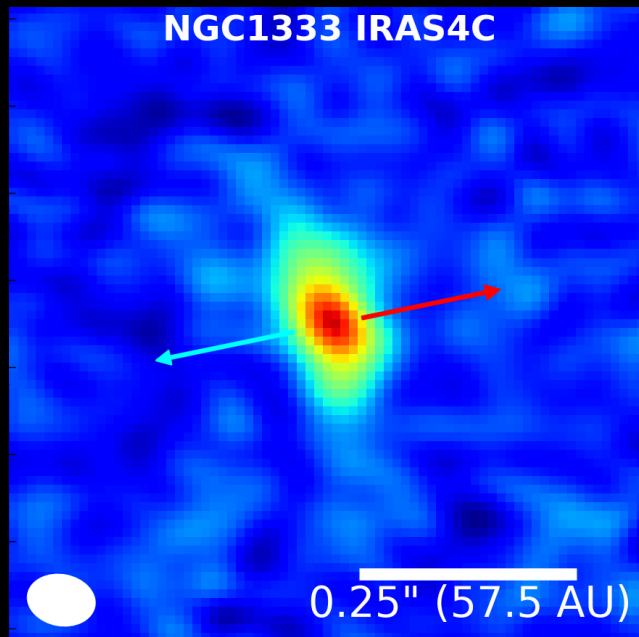
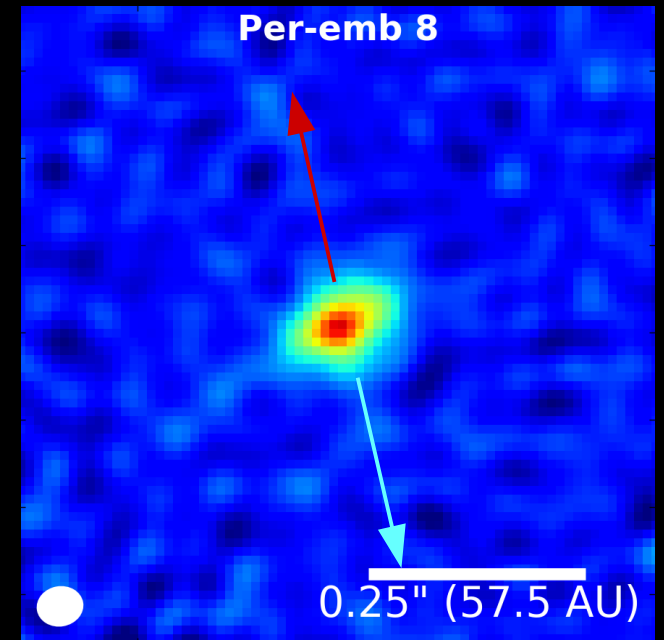
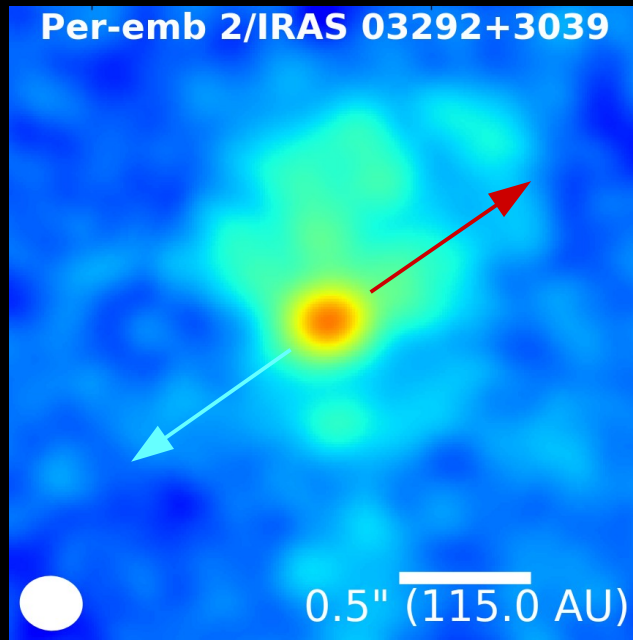
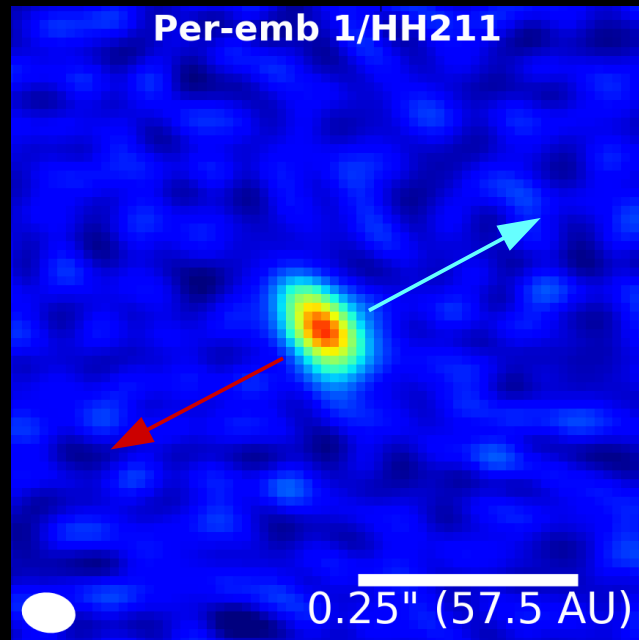
Eastern Perseus Molecular Cloud

IC348

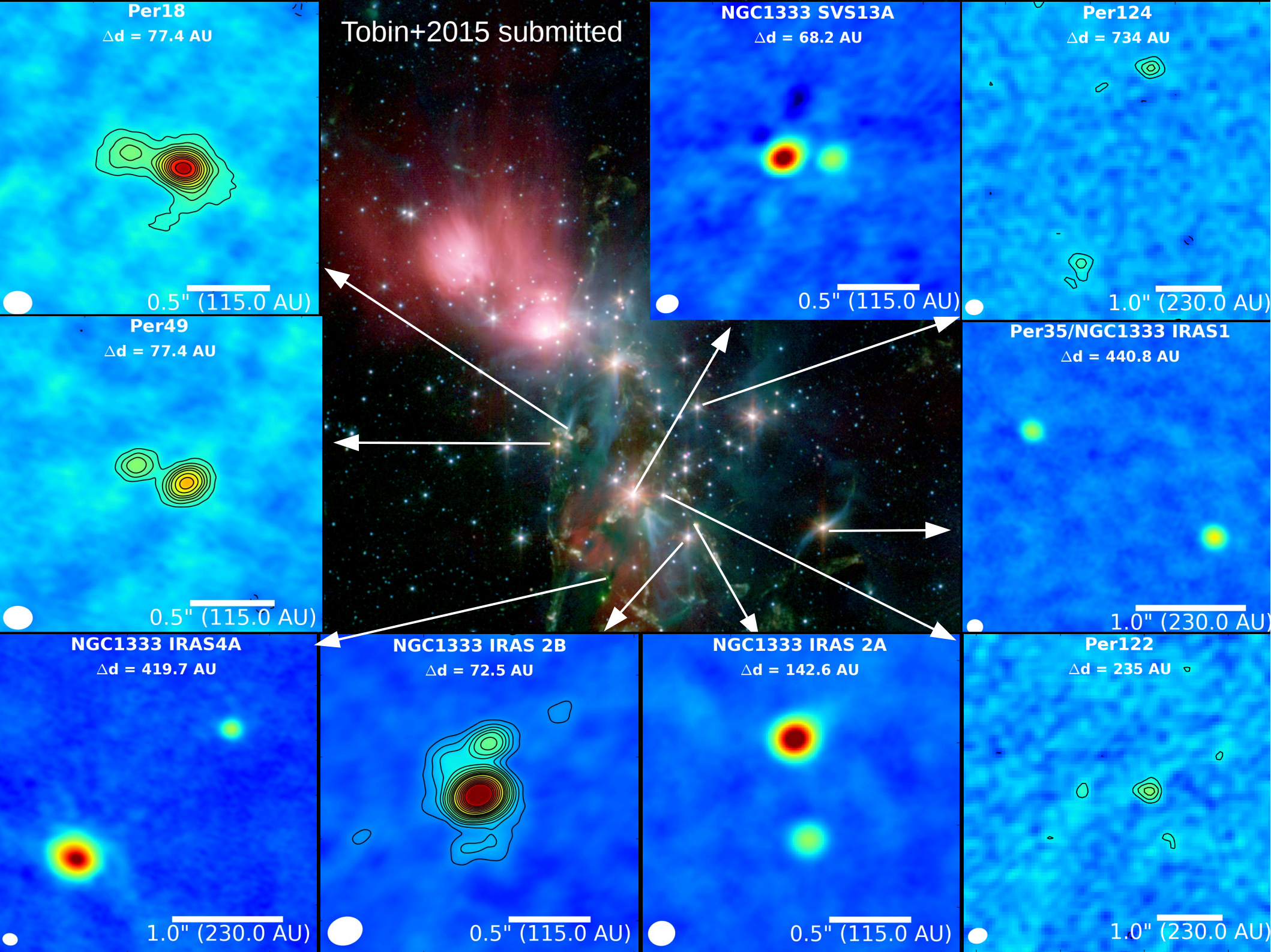
Herschel
SPIRE

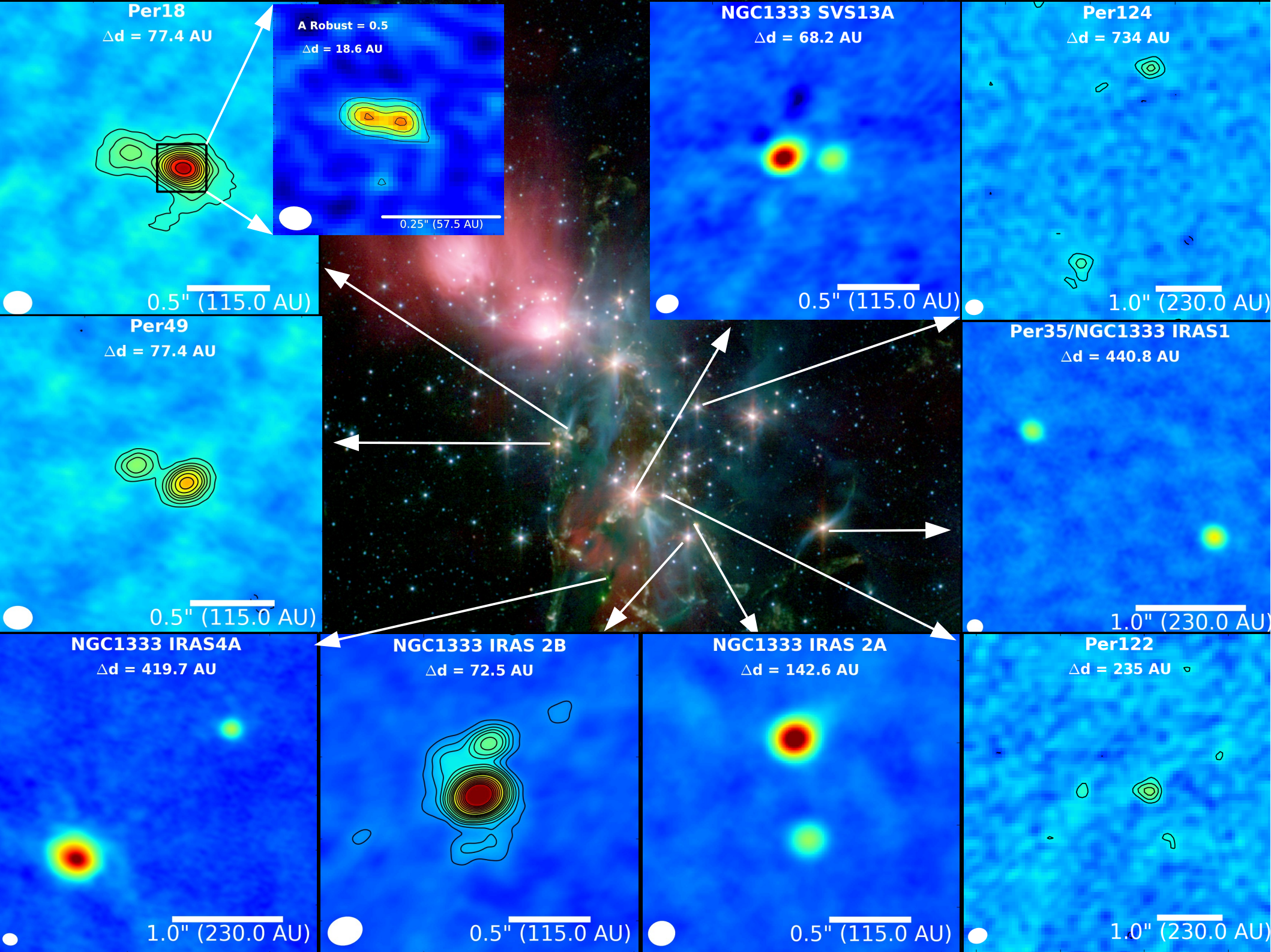


VANDAM Class 0 Disk Candidates

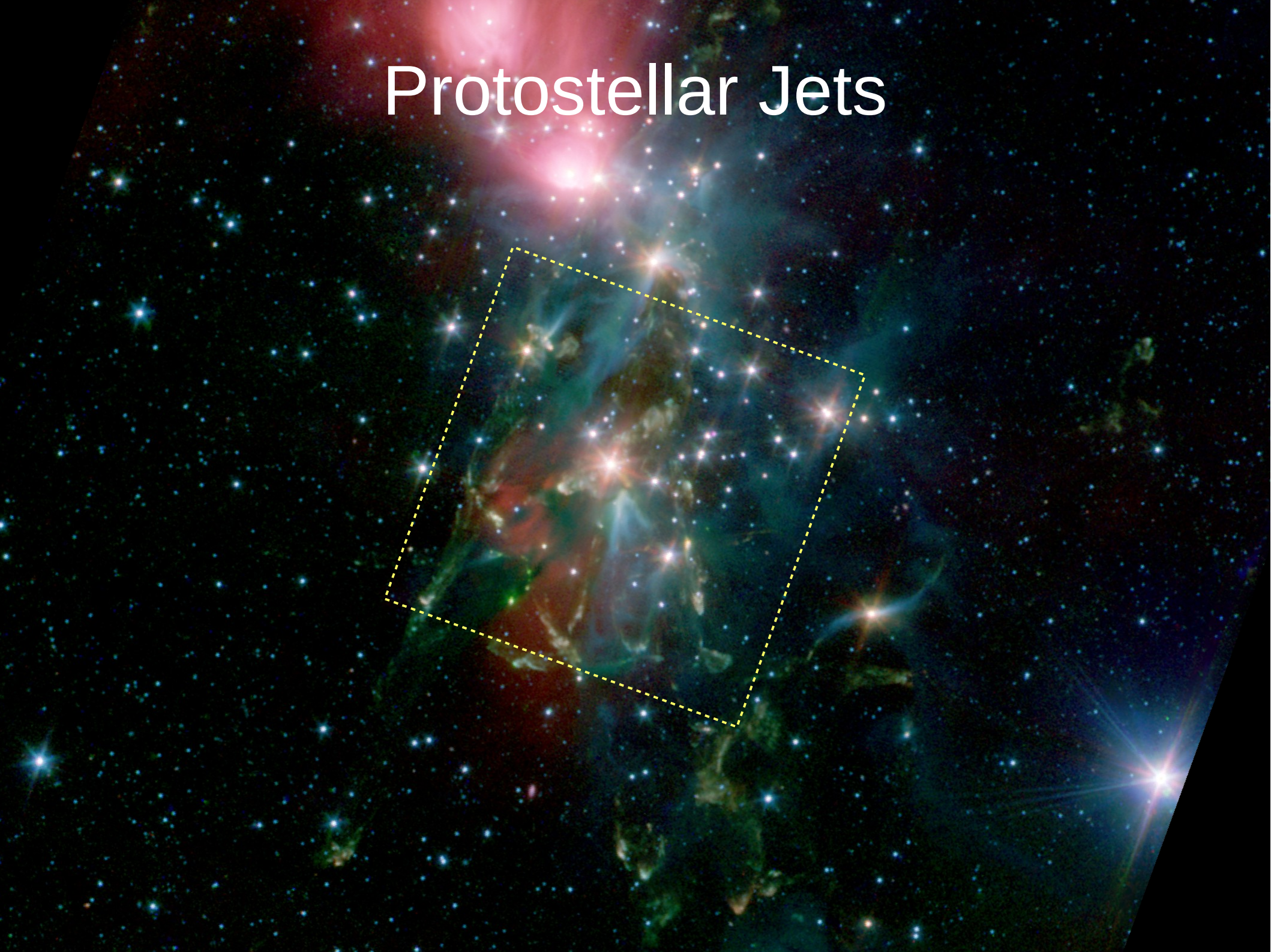




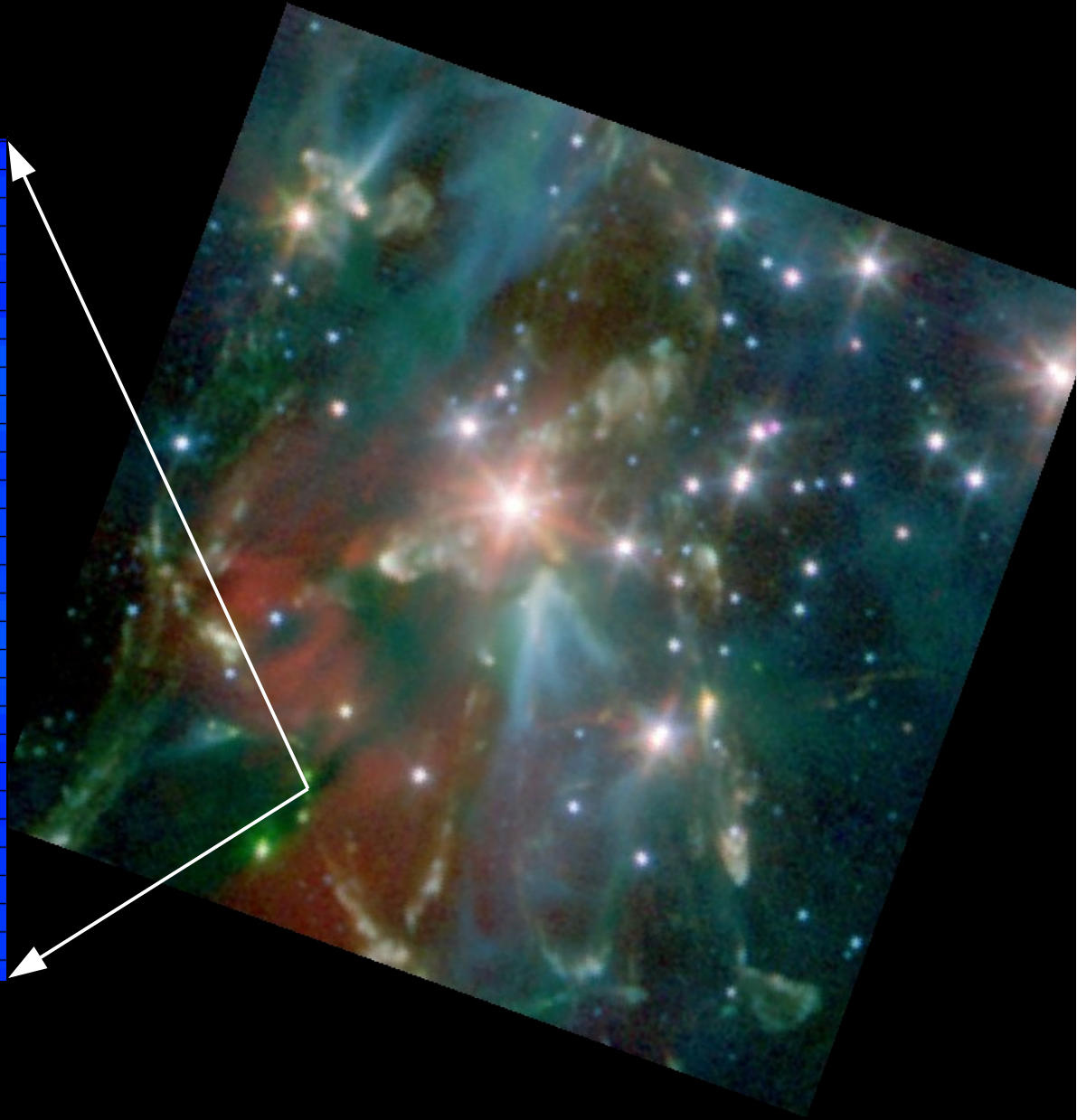
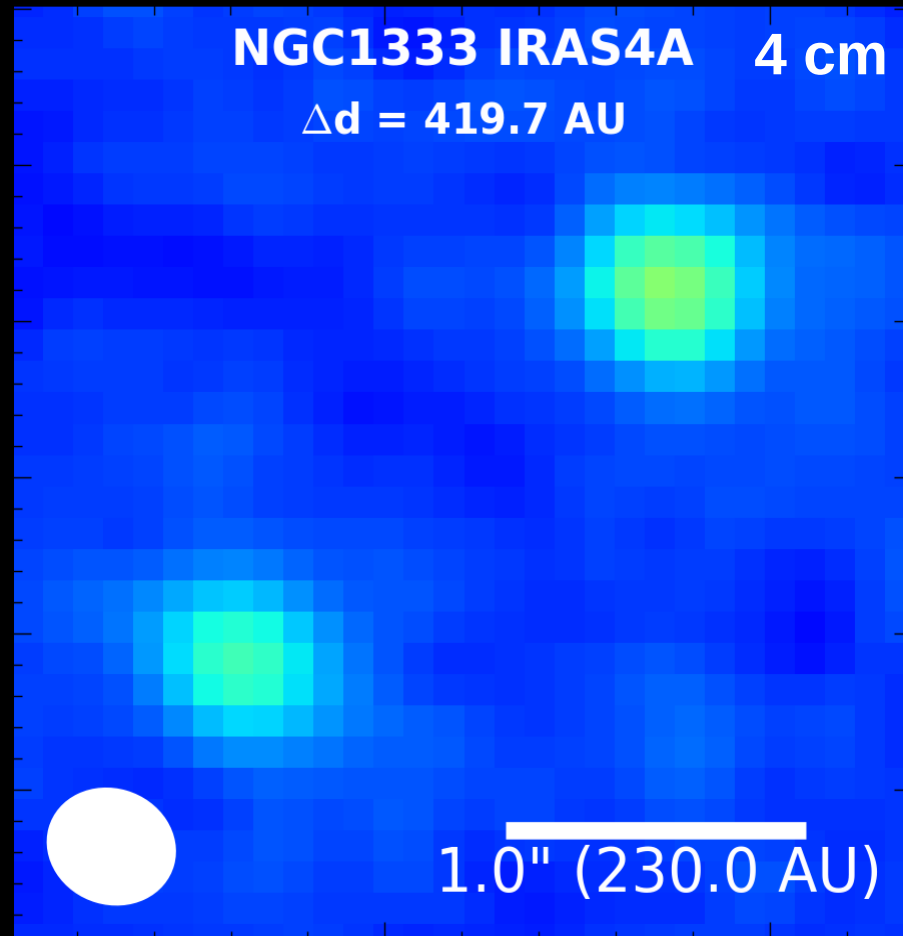




Protostellar Jets

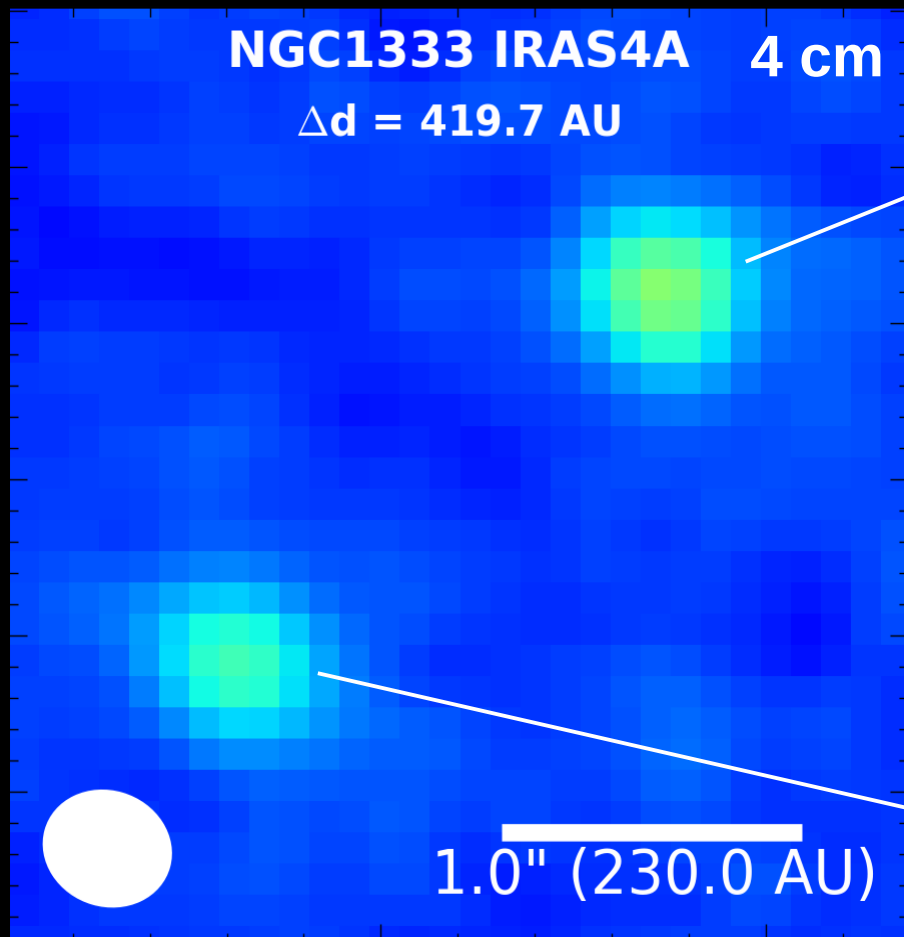


Protostellar Jets: IRAS4 A

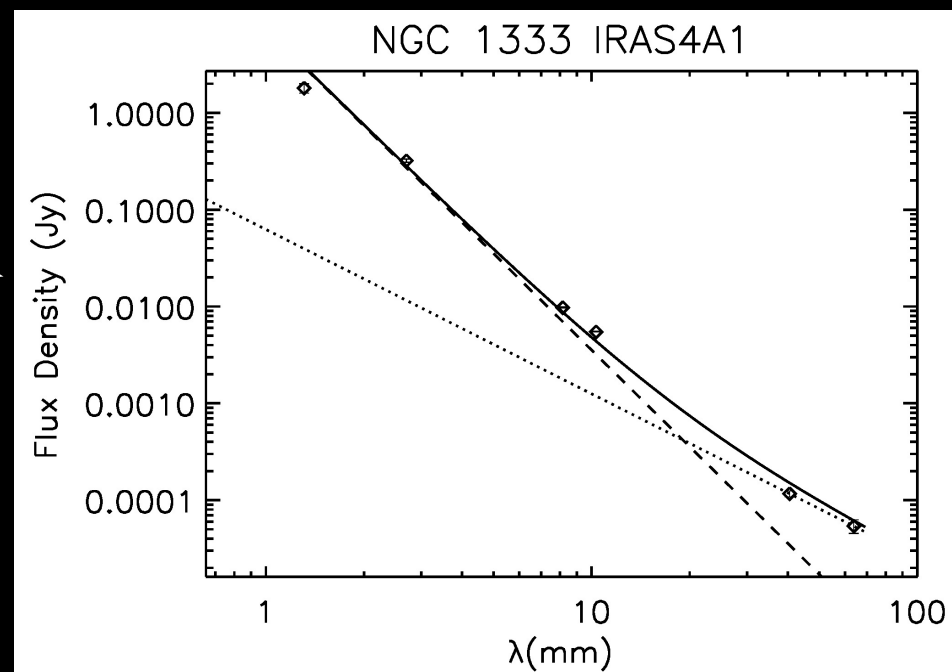
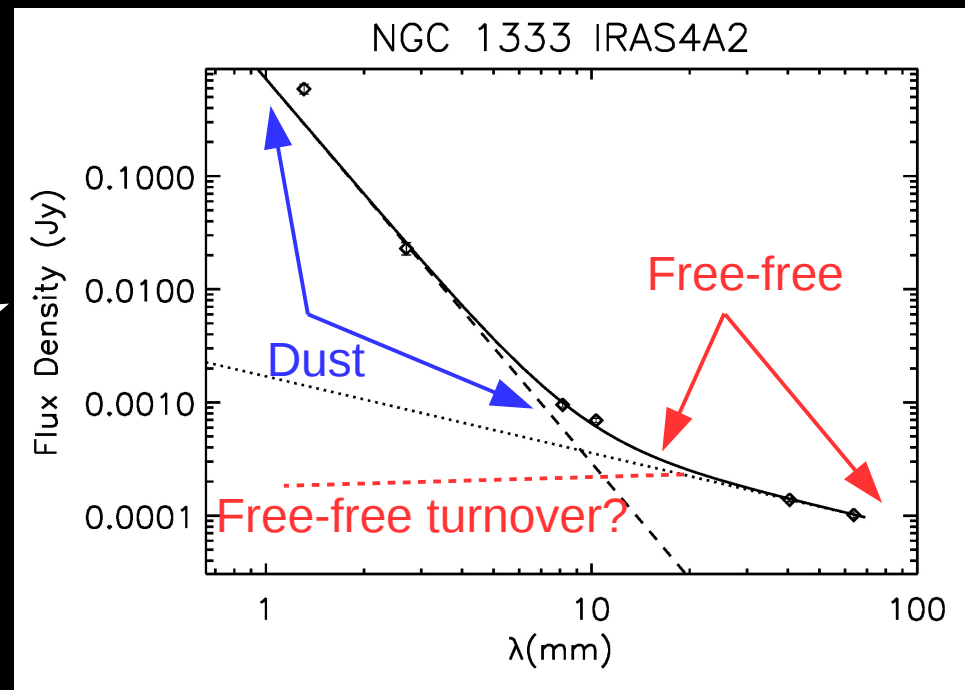


Tychoniec+2016 in prep.

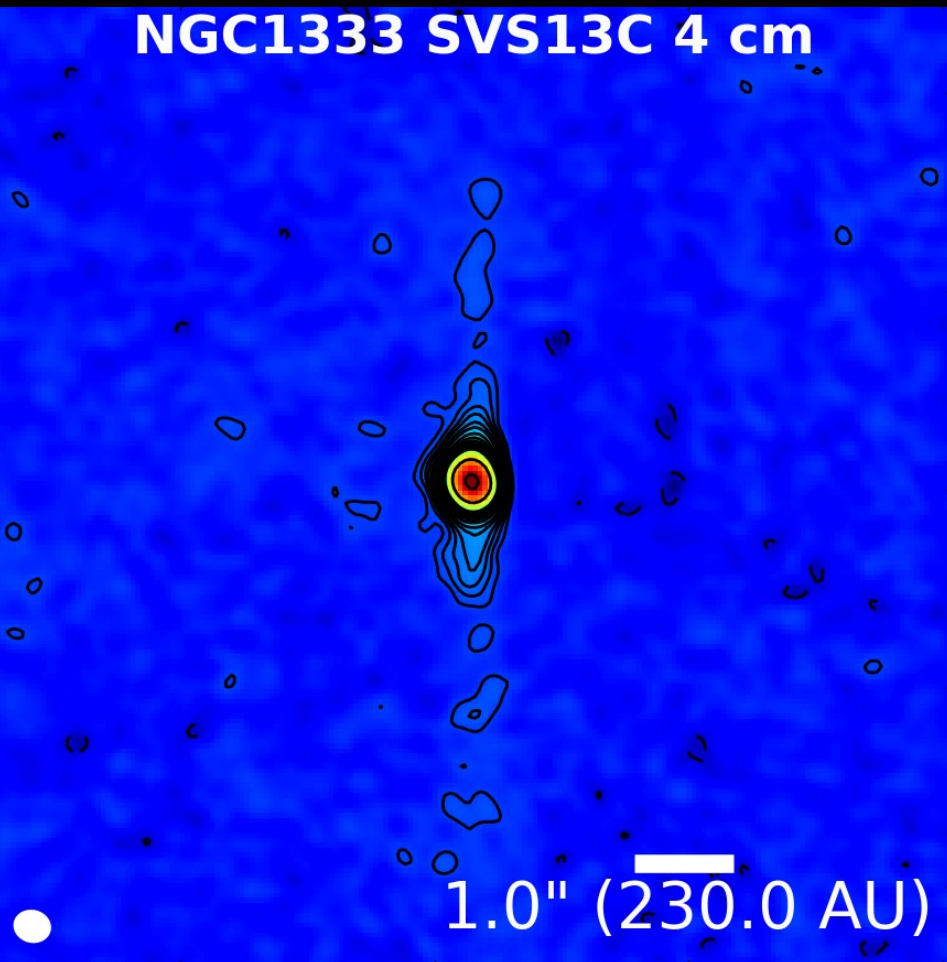
Protostellar Jets: IRAS4 A



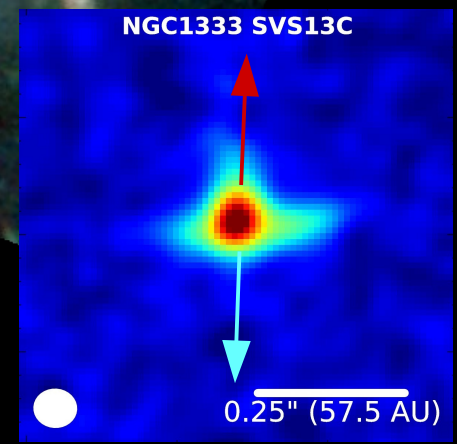
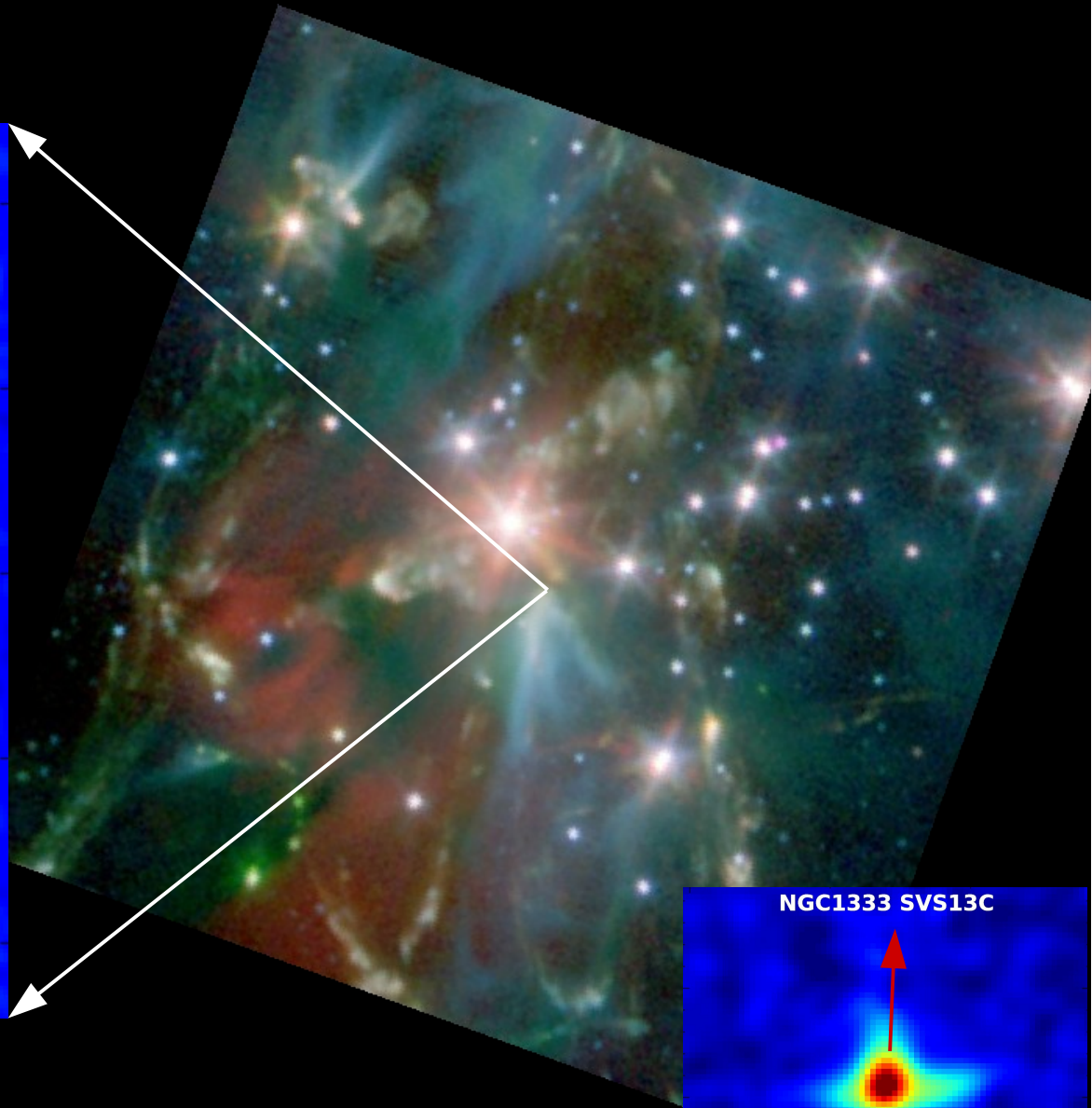
Tychoniec+2016 in prep.



Protostellar Jets: SVS13C



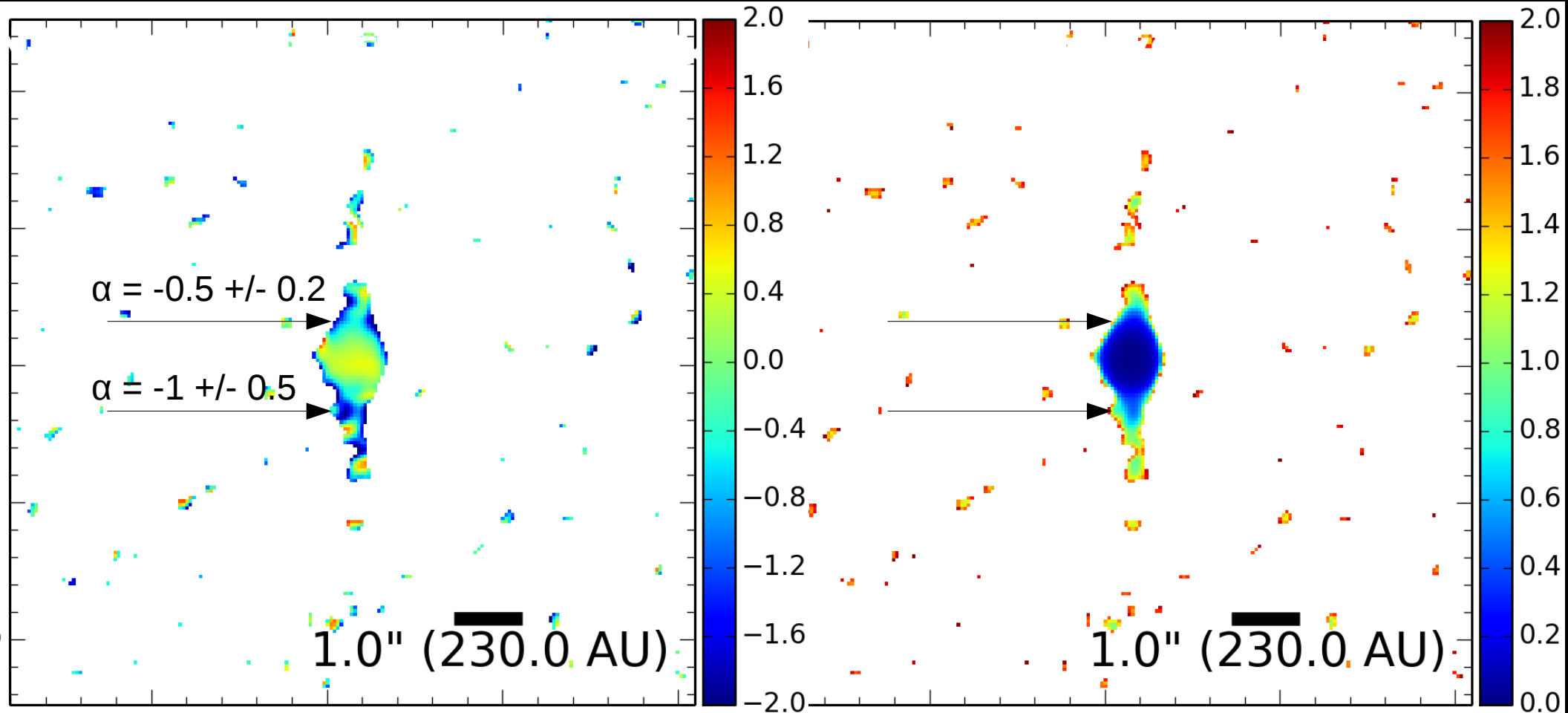
Tychoniec+2016 in prep.



Protostellar Jets: SVS13C

Spectral Index

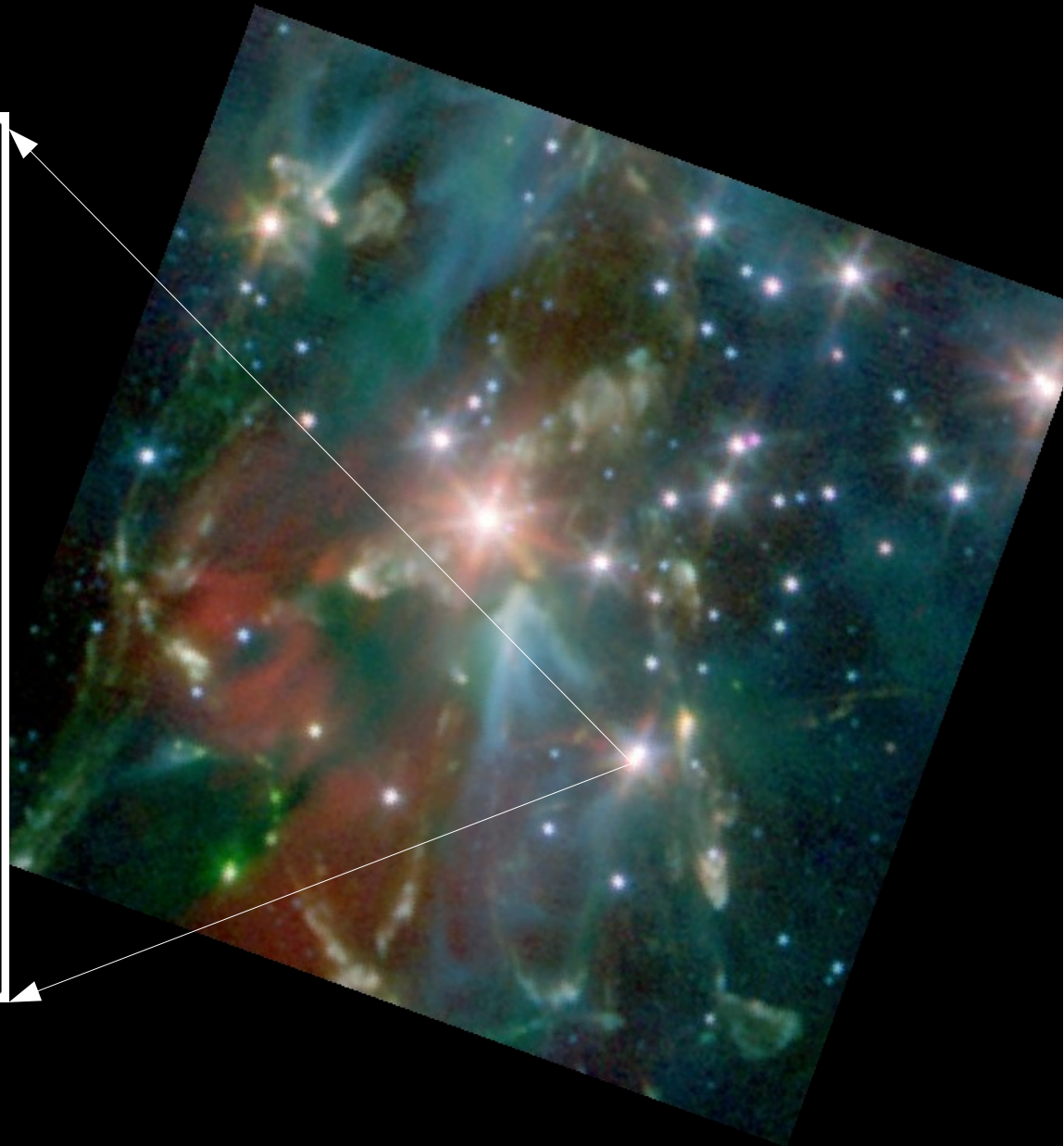
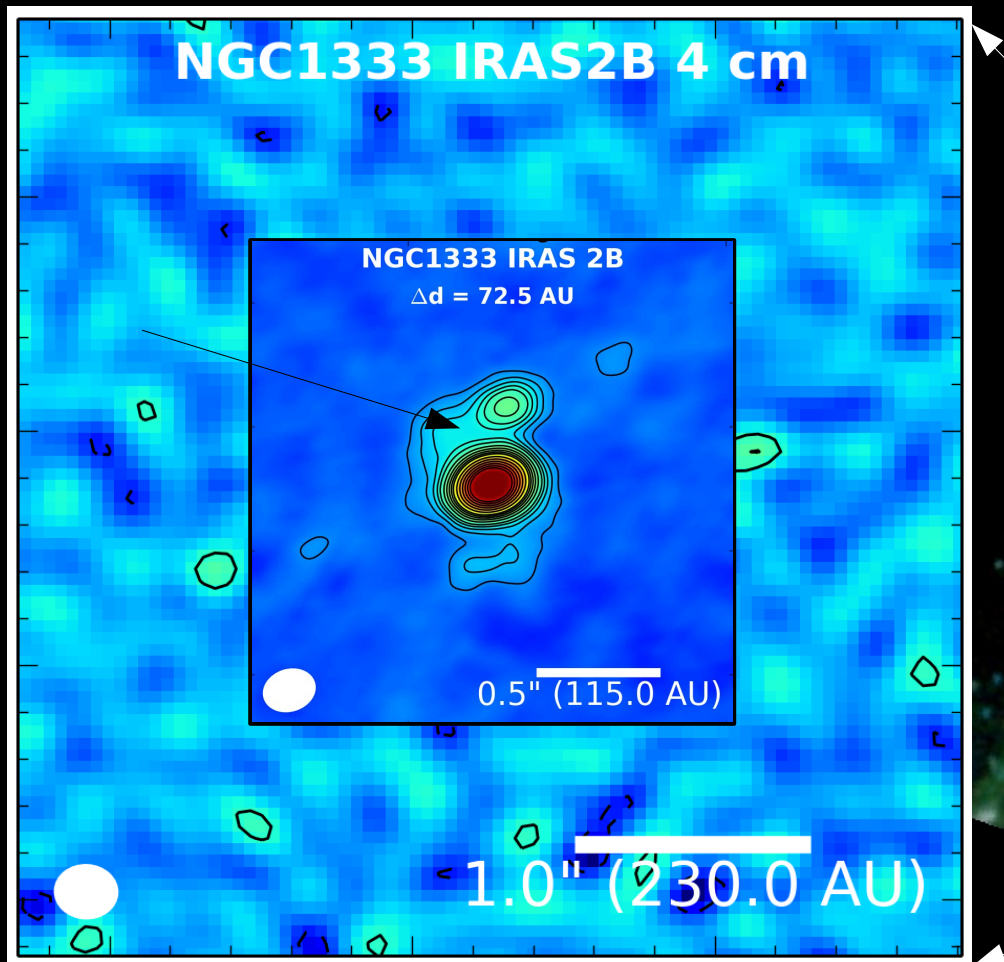
Spectral Index Error



Tychoniec+2016 in prep.

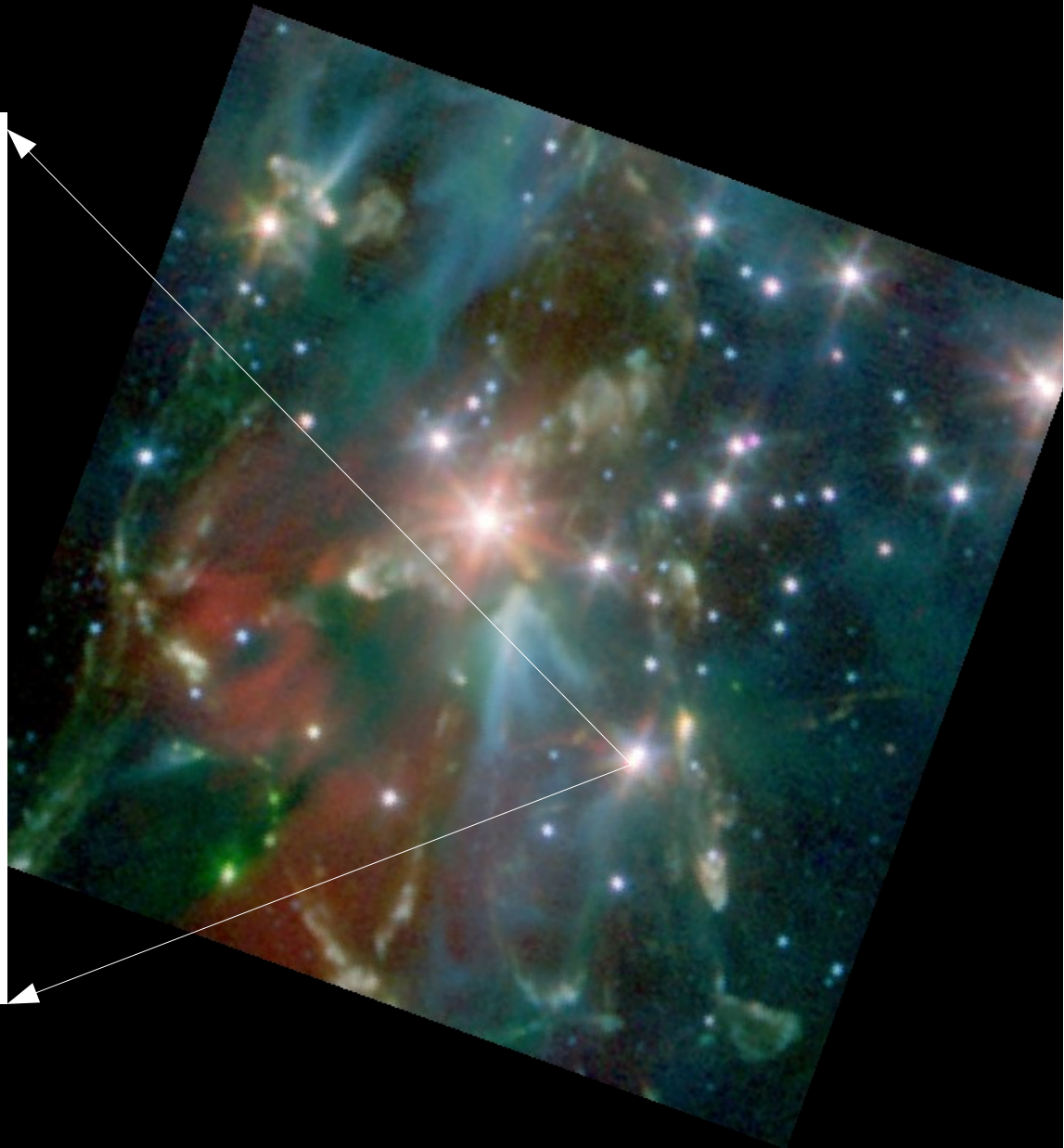
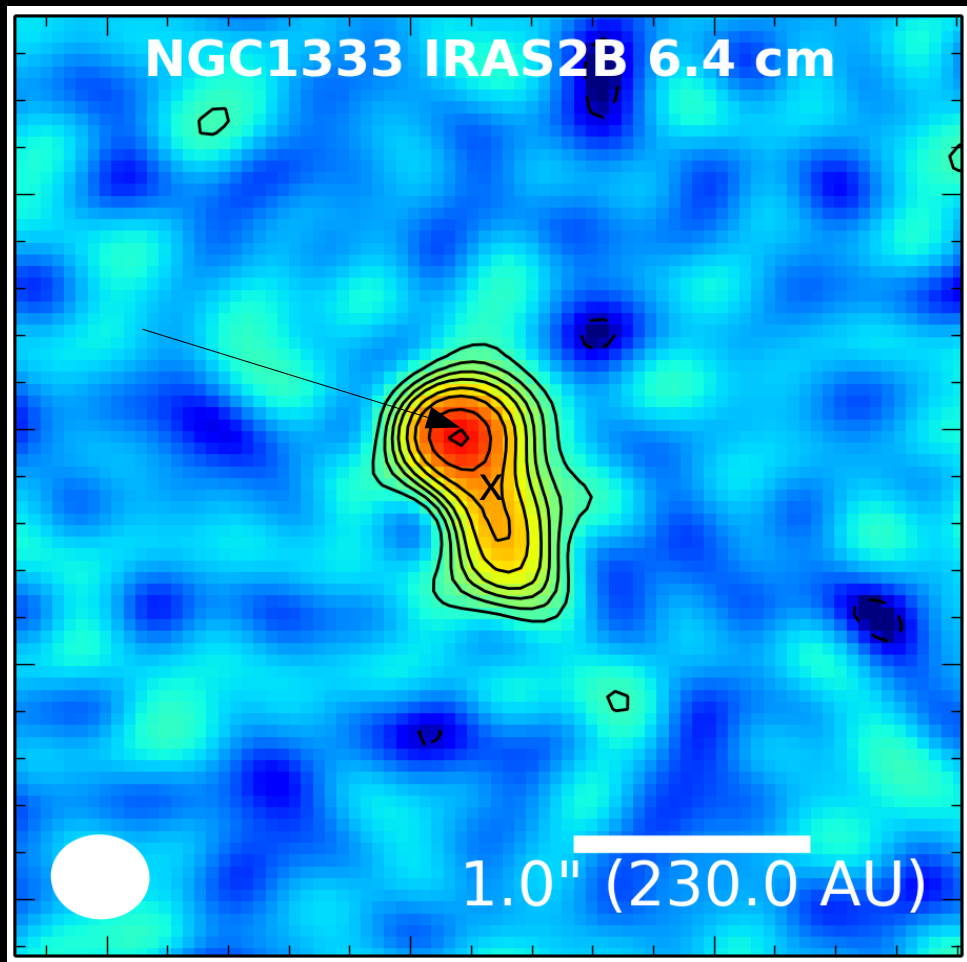
- No X-ray emission detected

Protostellar Jets: IRAS2B



Tychoniec+2016 in prep.

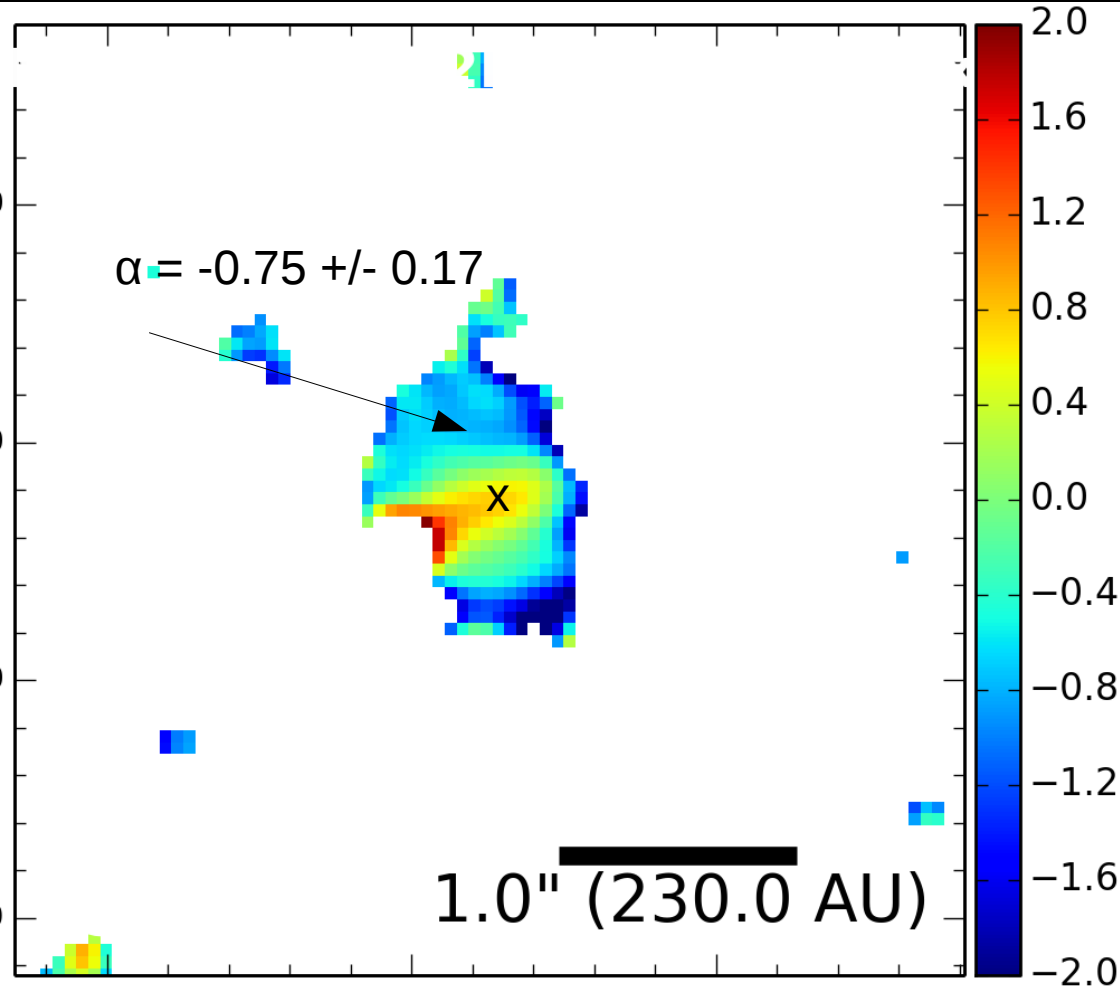
Protostellar Jets: IRAS2B



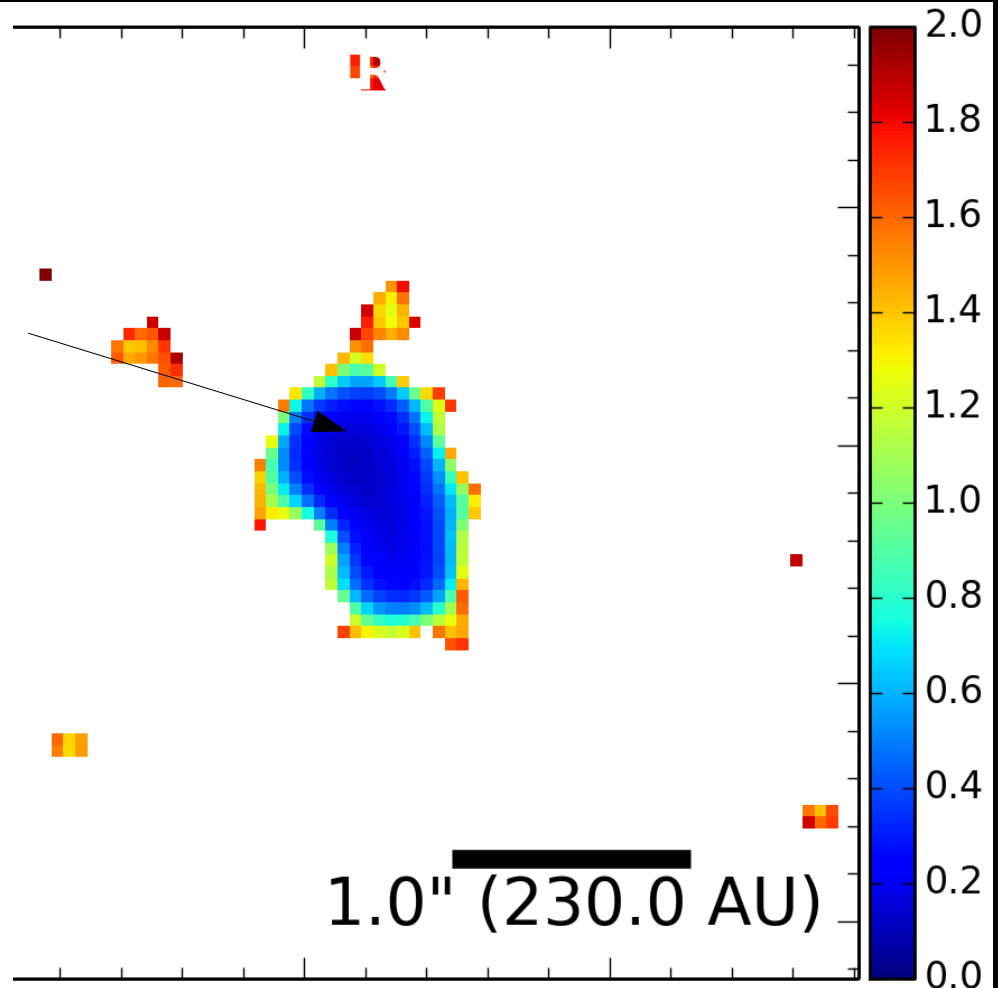
Tychoniec+2016 in prep.

Protostellar Jets: IRAS2B

Spectral Index



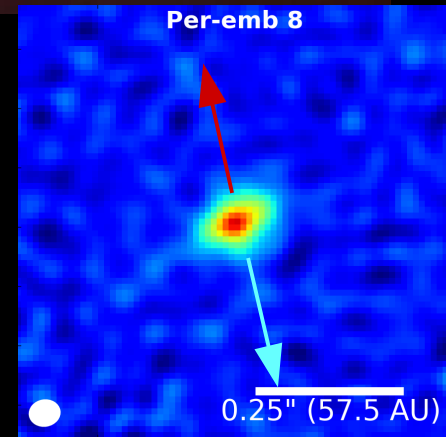
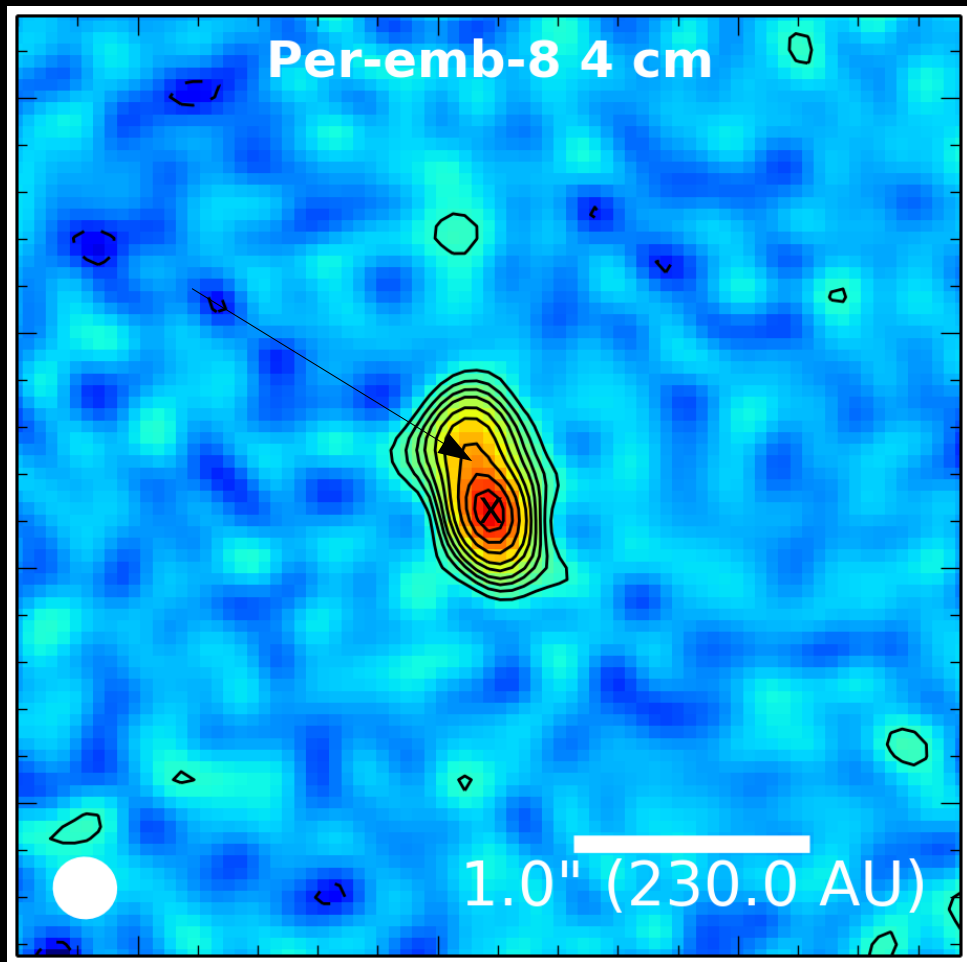
Spectral Index Error



Tychoniec+2016 in prep.

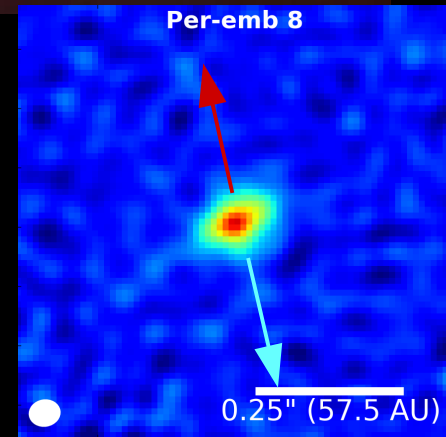
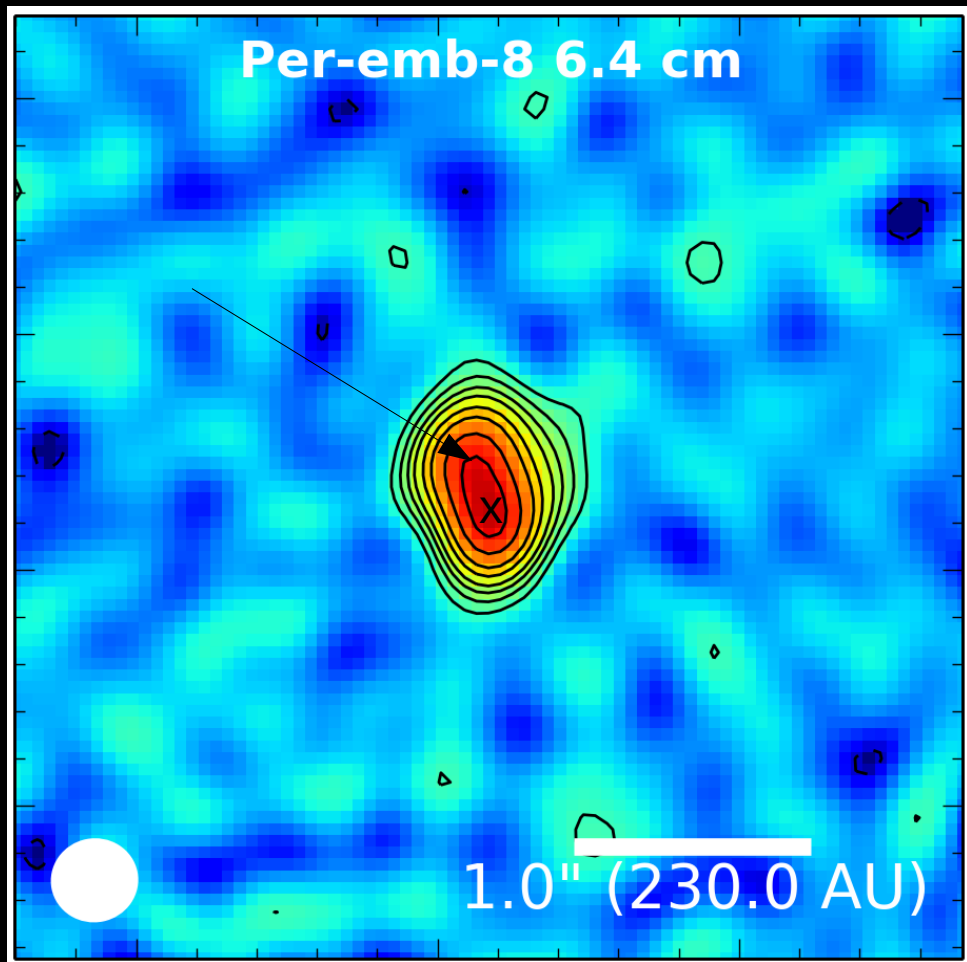
- X-ray emission possibly detected, blended with nearby Class III YSO
- Class III source has negative spectral index at 4 cm/6 cm

Protostellar Jets: Per-emb-8



Tychoniec+2016 in prep.

Protostellar Jets: Per-emb-8

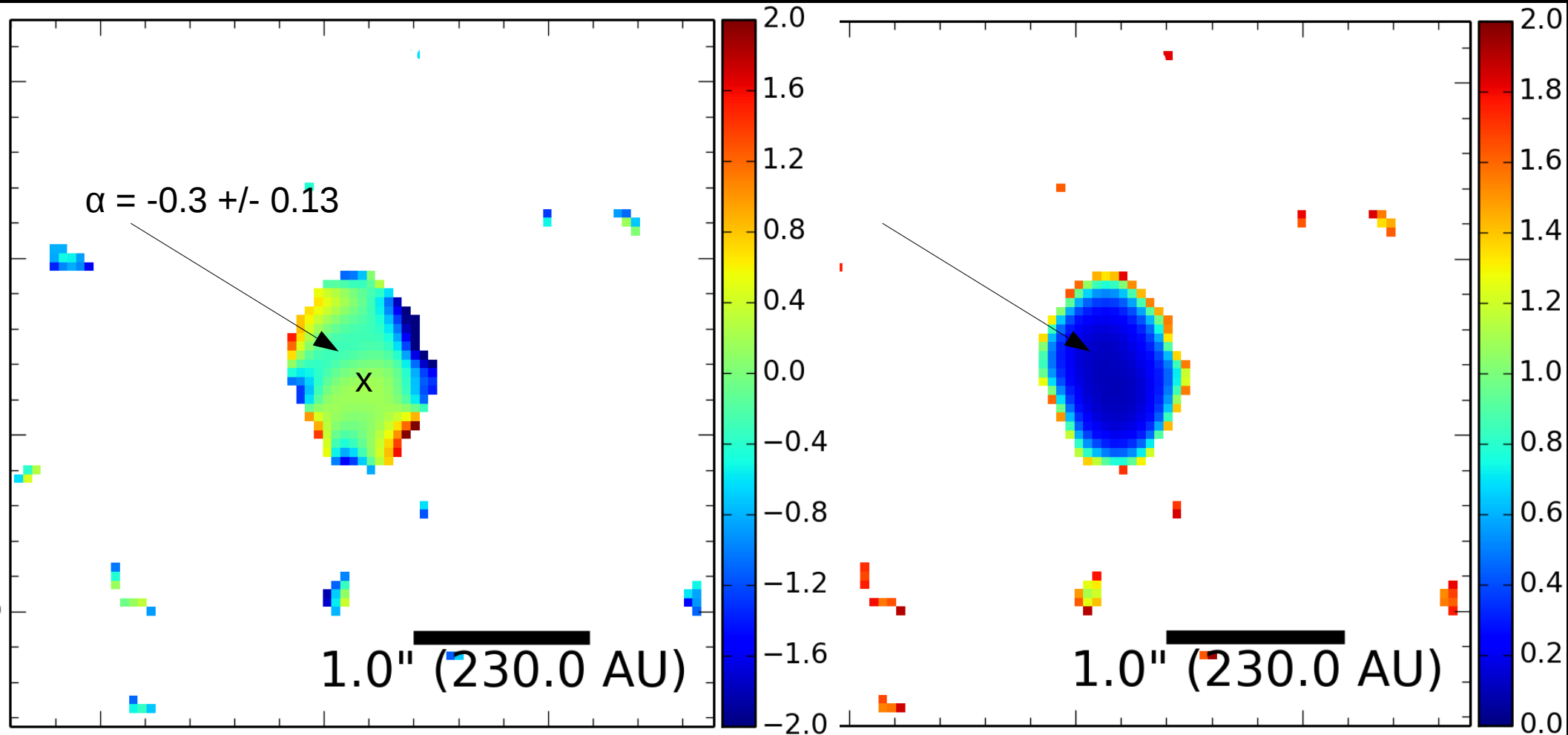


Tychoniec+2016 in prep.

Protostellar Jets: Per-emb-8

Spectral Index

Spectral Index Error

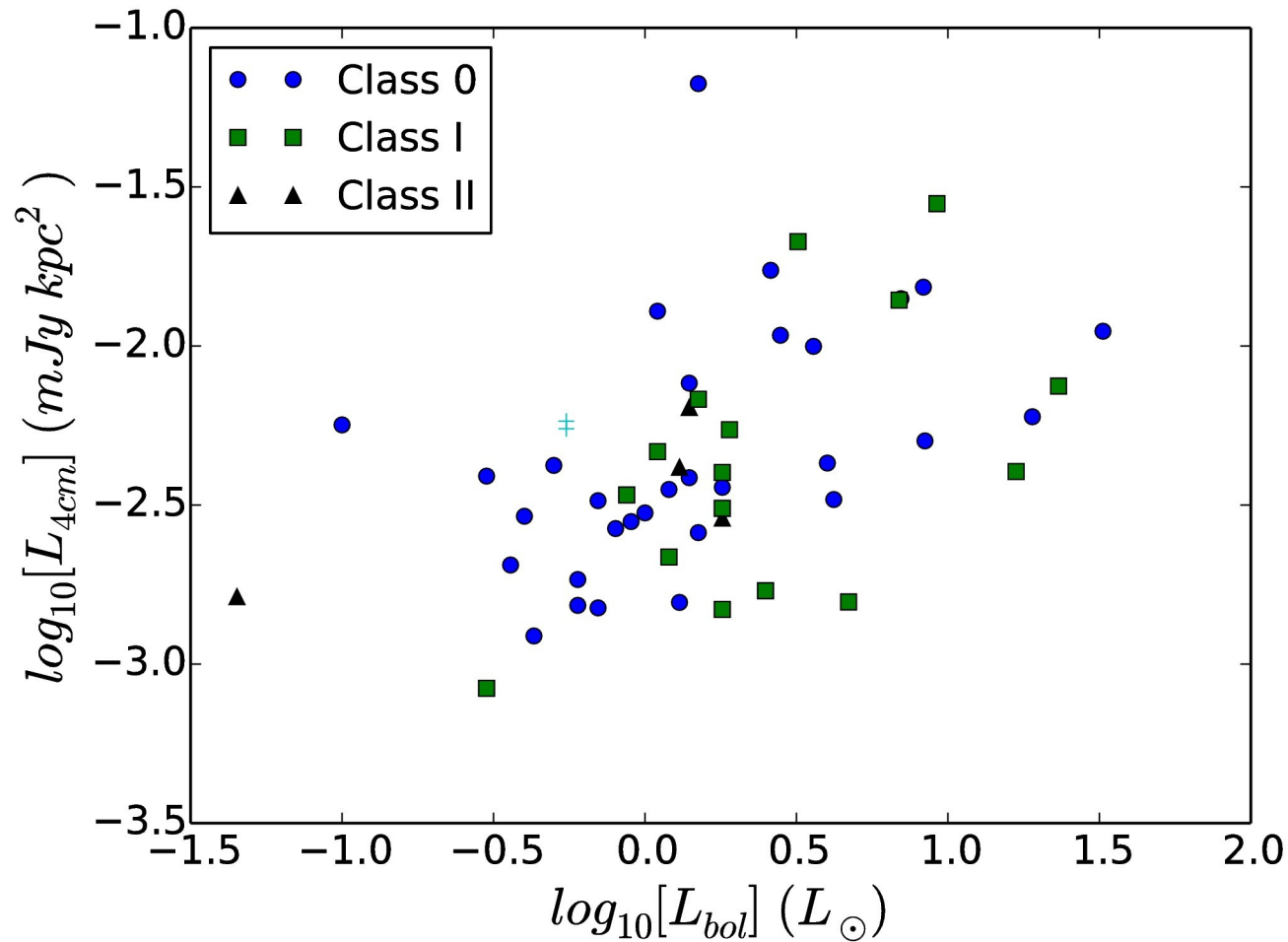


Tychoniec+2016 in prep.

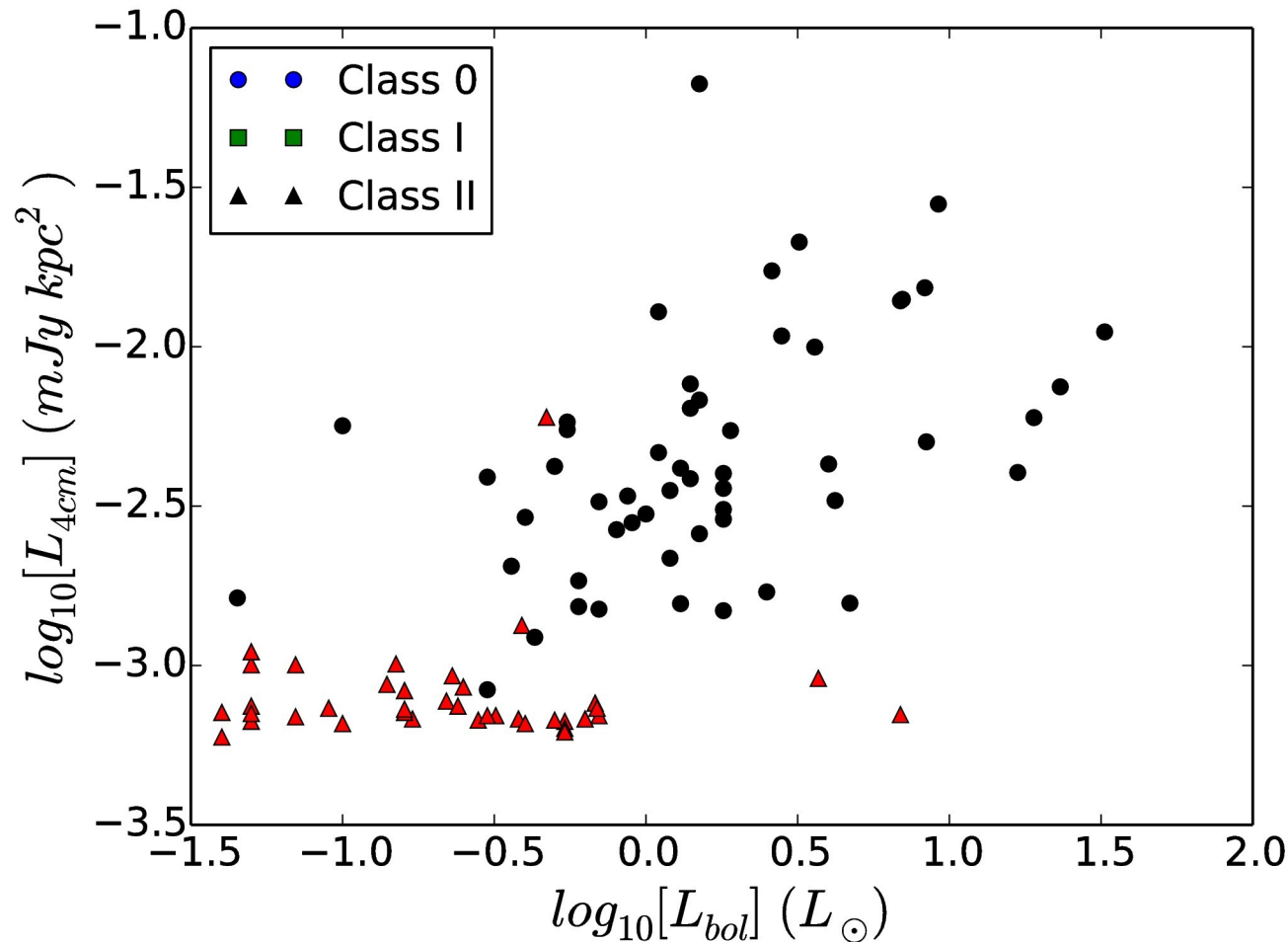
- No X-ray data

L_{cm} vs. Source Luminosity

L_{cm} vs. Source Luminosity

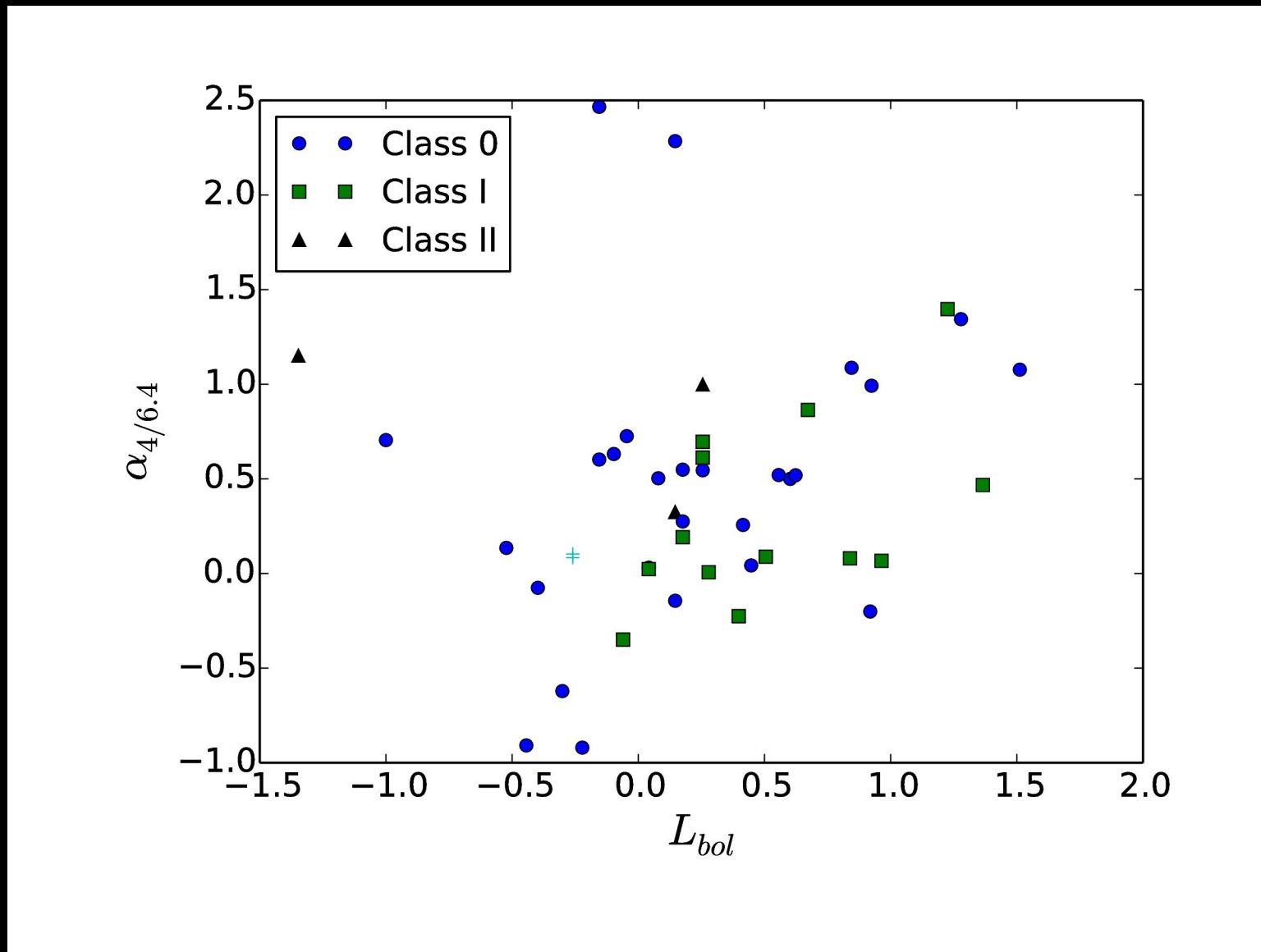


L_{cm} vs. Source Luminosity



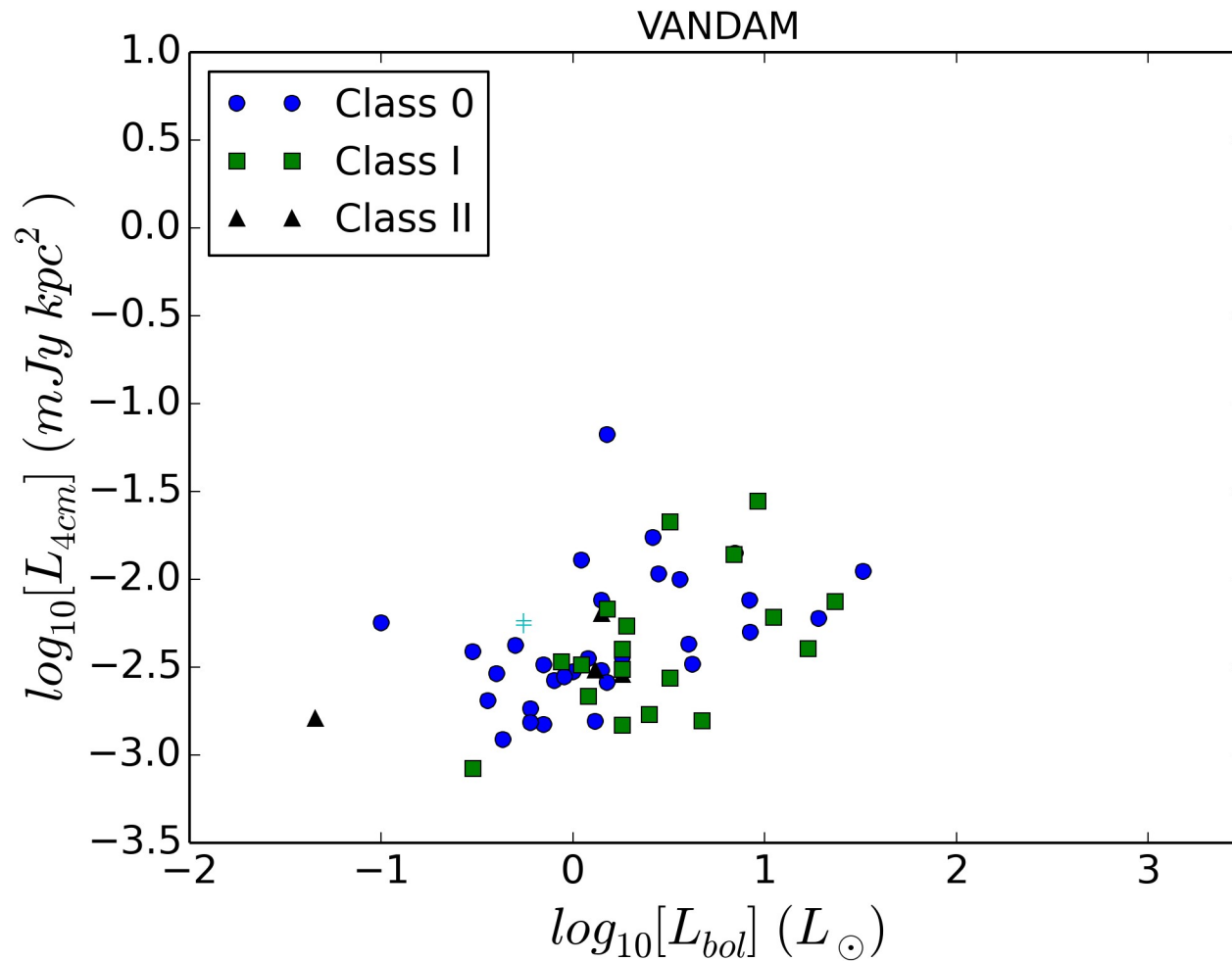
- 57% of protostars detected
- No detections toward FHSCs candidates

Spectral Index vs. Source Luminosity

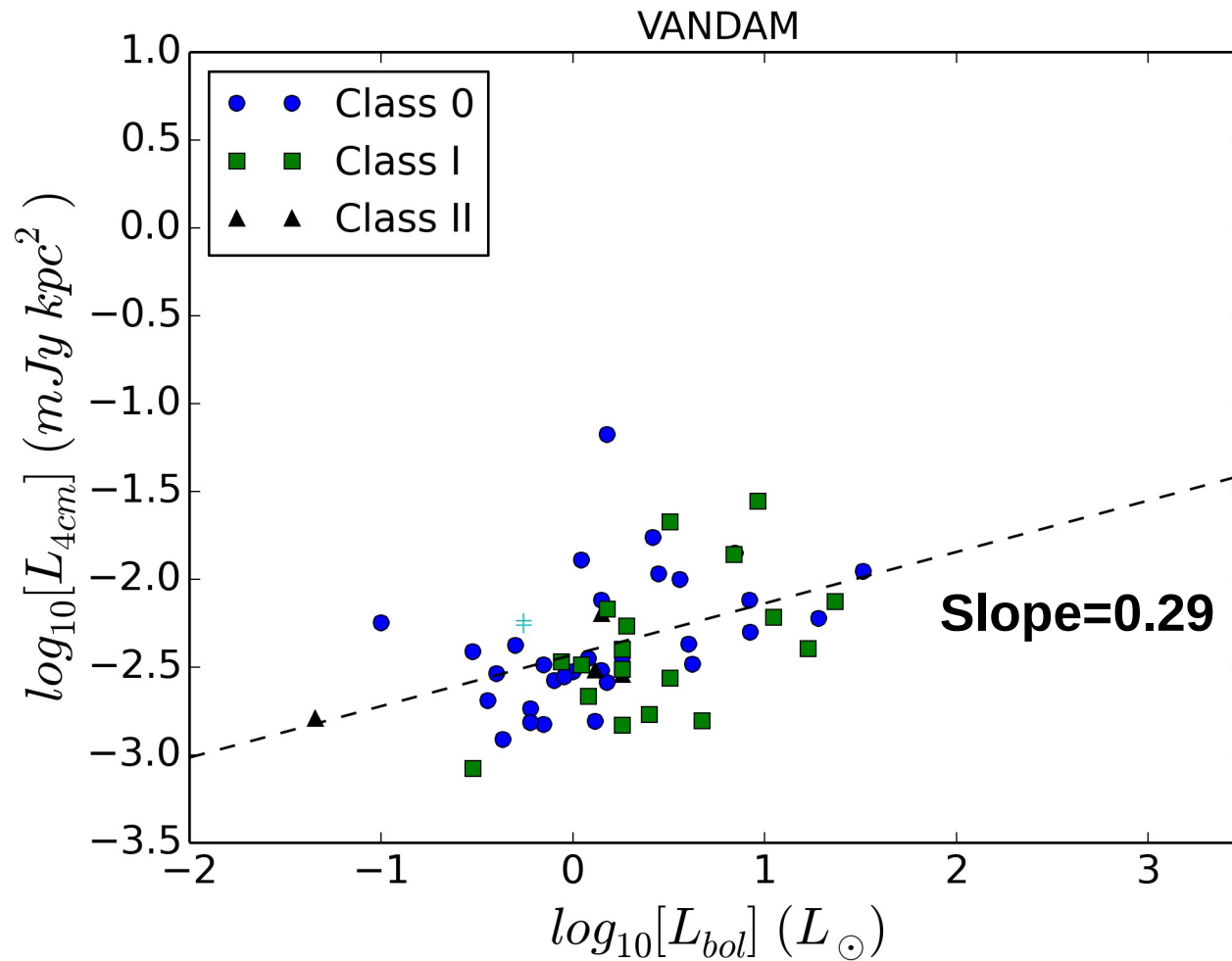


- Spectral index of ~ 0.25 'typical' for protostars with large scatter

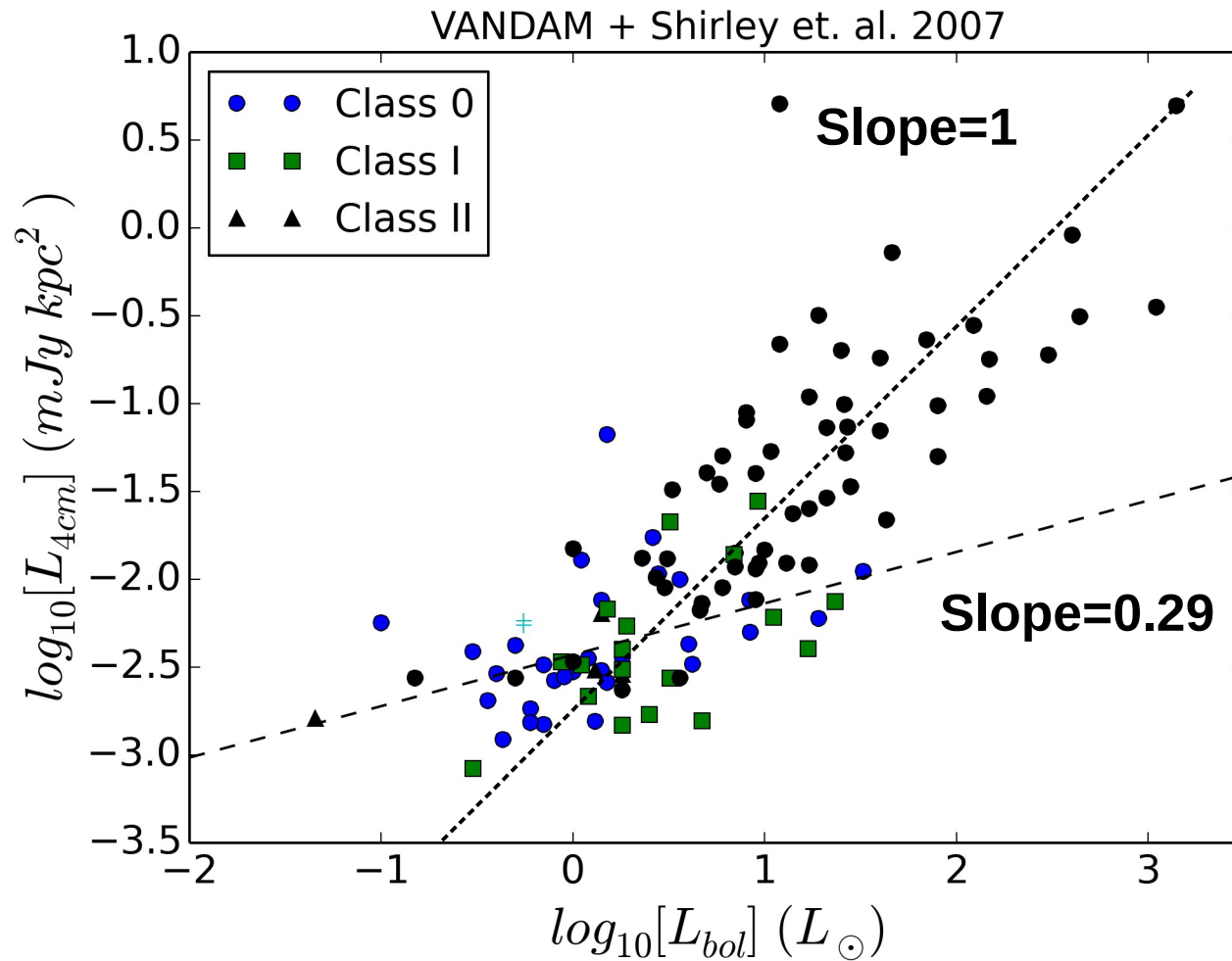
L_{cm} vs. Source Luminosity



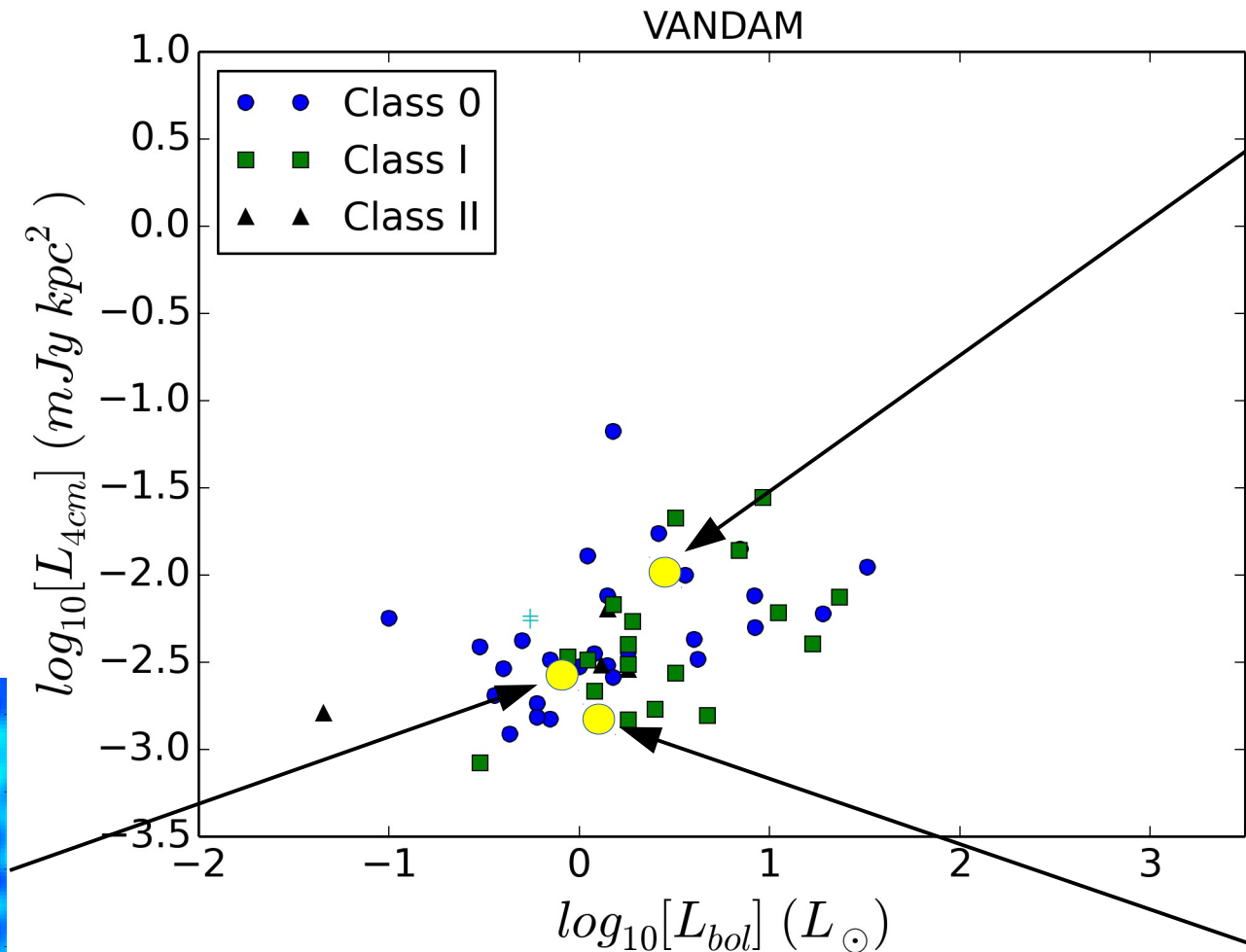
L_{cm} vs. Source Luminosity



L_{cm} vs. Source Luminosity

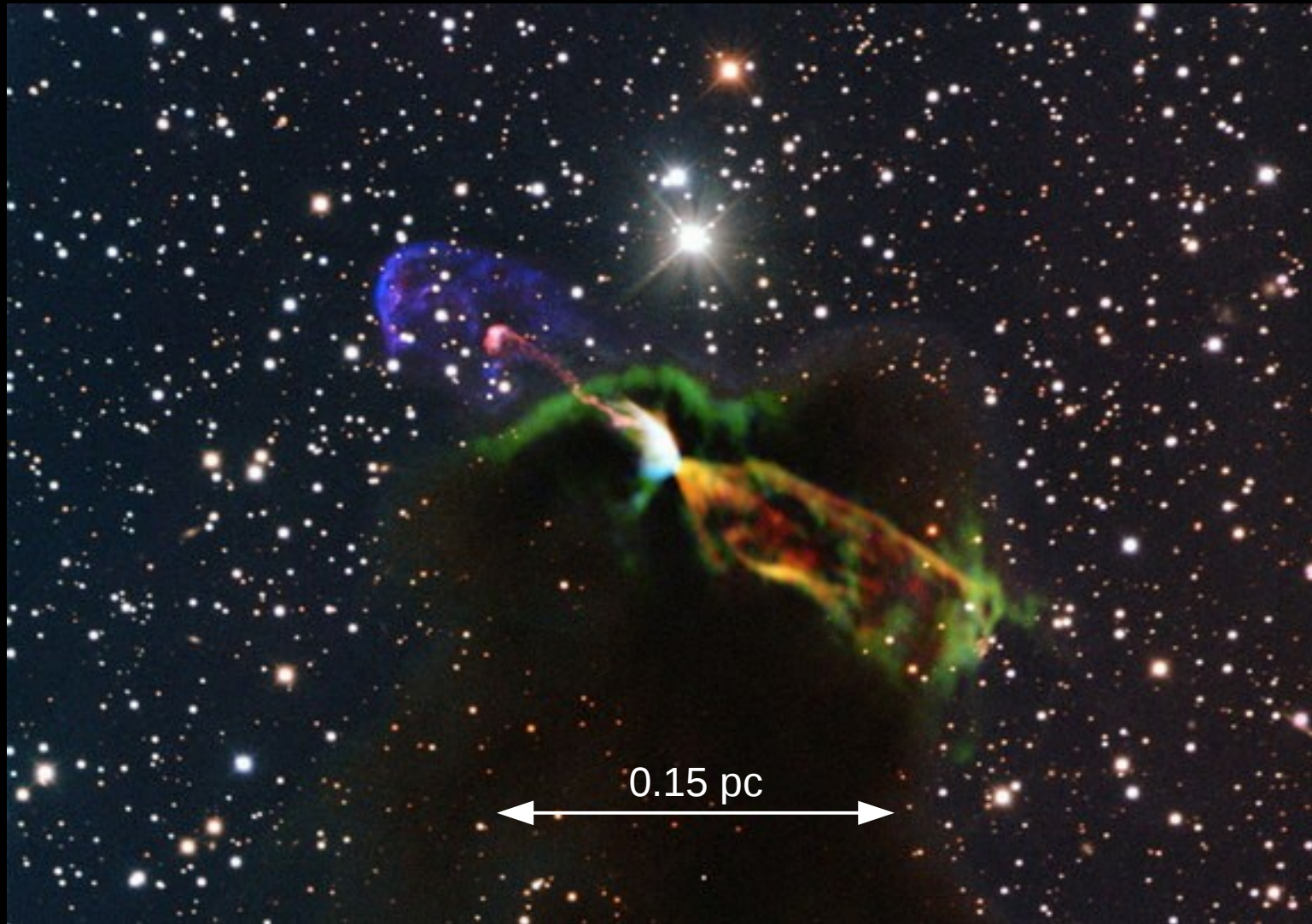


L_{cm} and Close Multiples



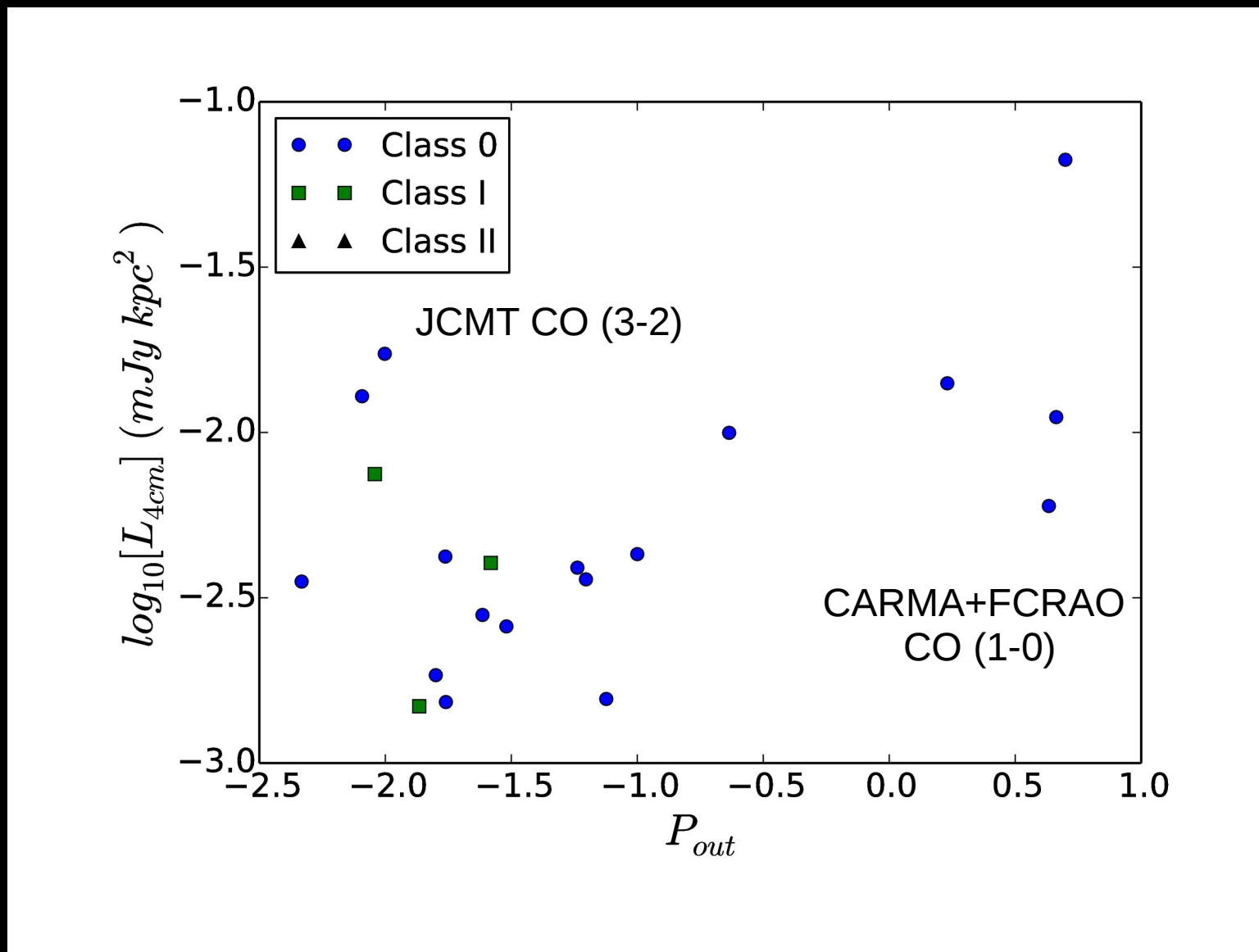
- Close multiples do not appear to affect production of free-free emission

L_{cm} vs. Molecular Outflow



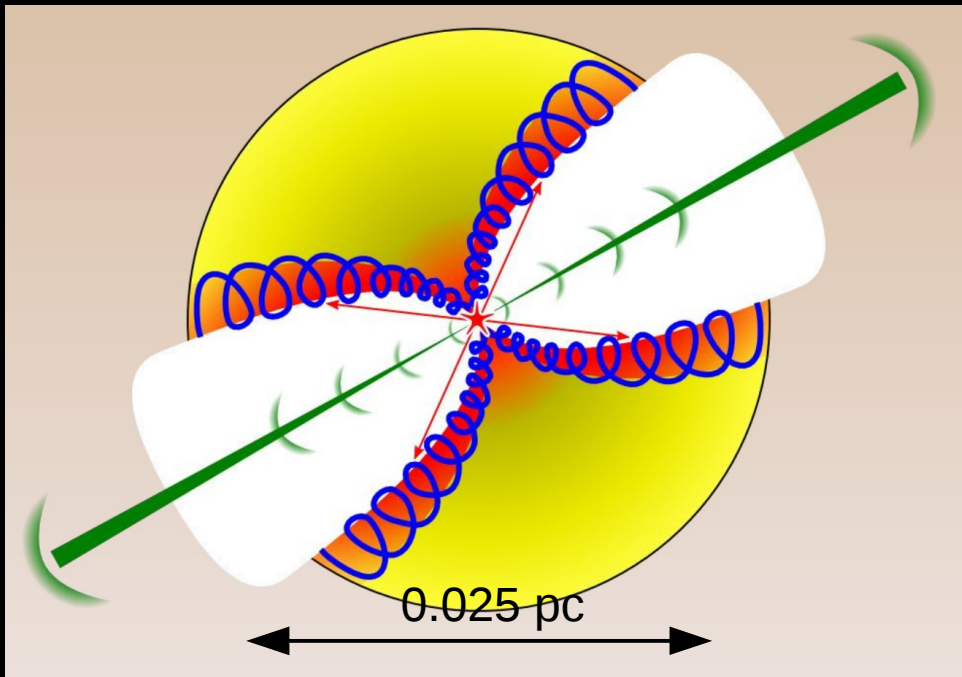
ALMA HH46/47; Arce+2014

L_{cm} vs. ^{12}CO

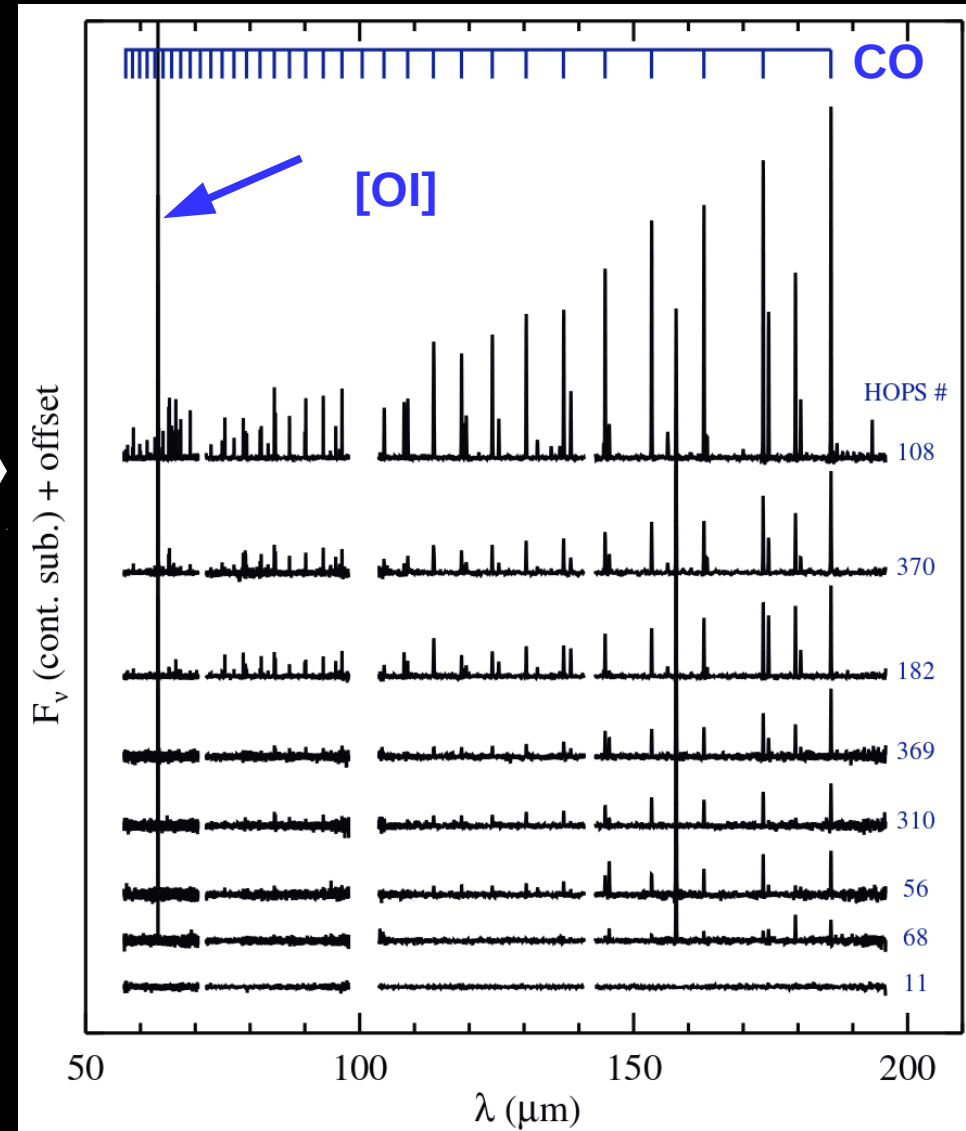


- Possible weak correlation with outflow momentum

L_{cm} vs. *Herschel*

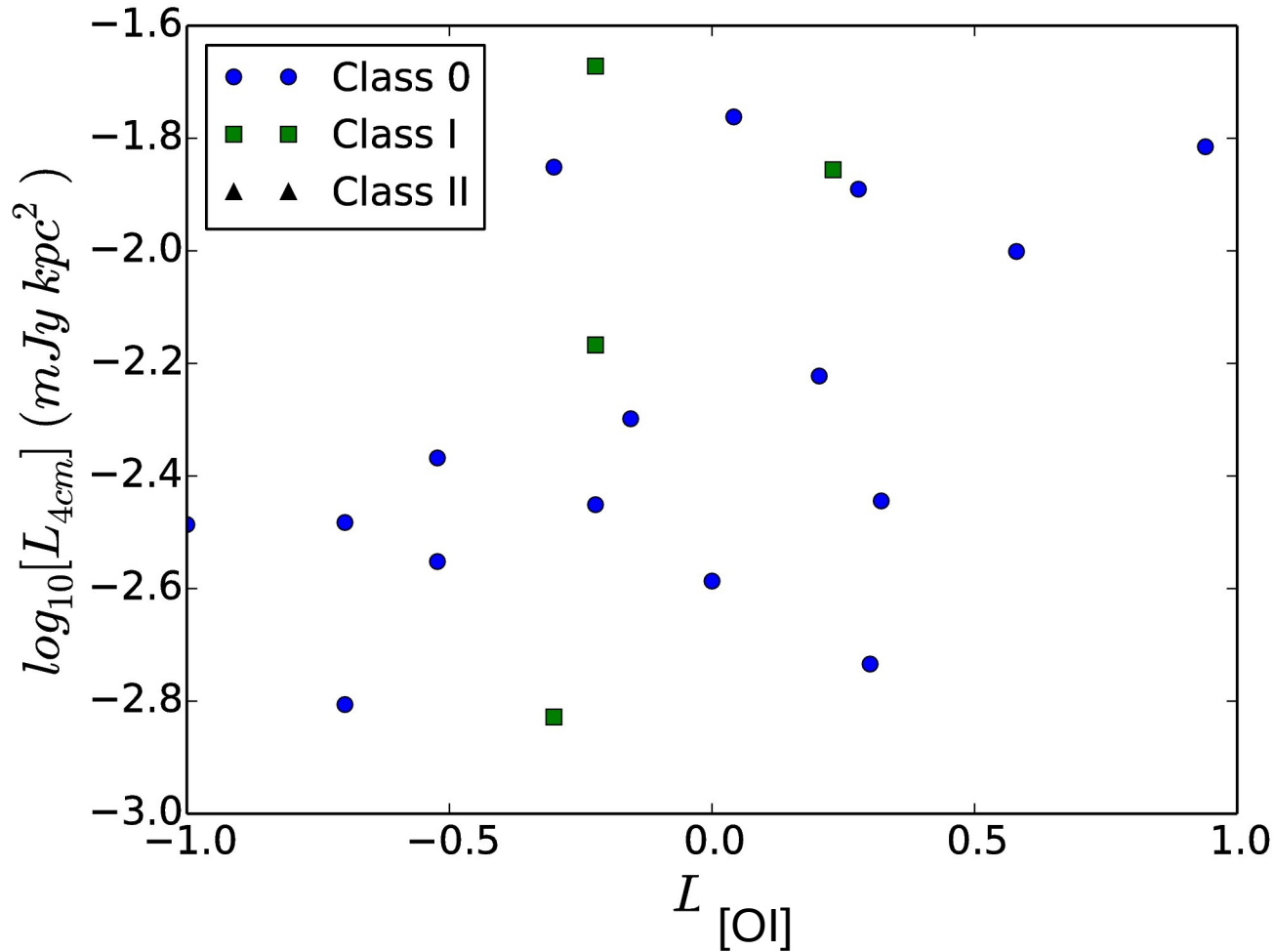


Credit: Ruud Visser



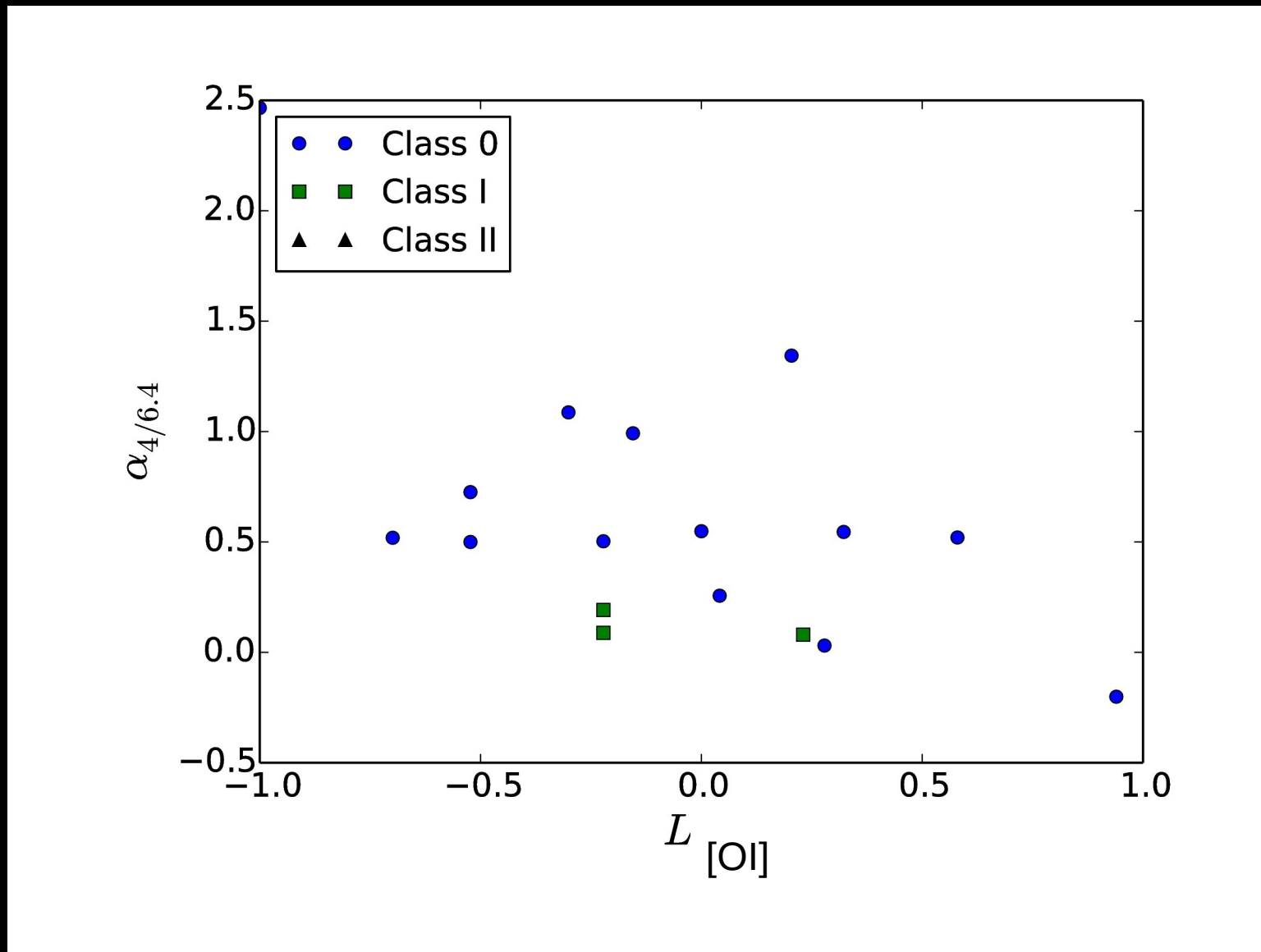
Manoj+2013; HOPS Survey

L_{cm} vs. *Herschel*: [OI]



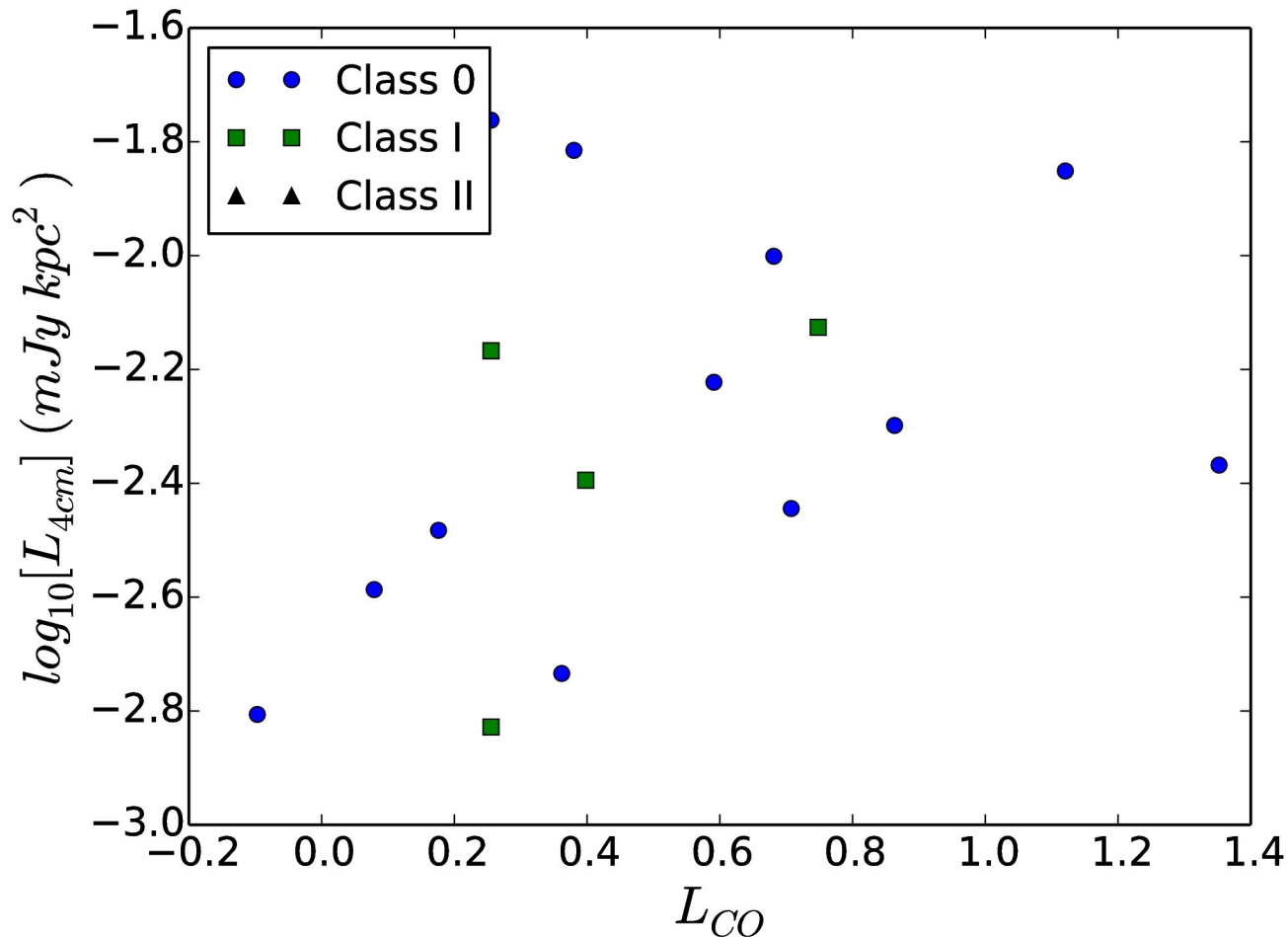
- Possible weak correlation with atomic jet probed with [OI]

Spectral Index vs. *Herschel*: [OI]



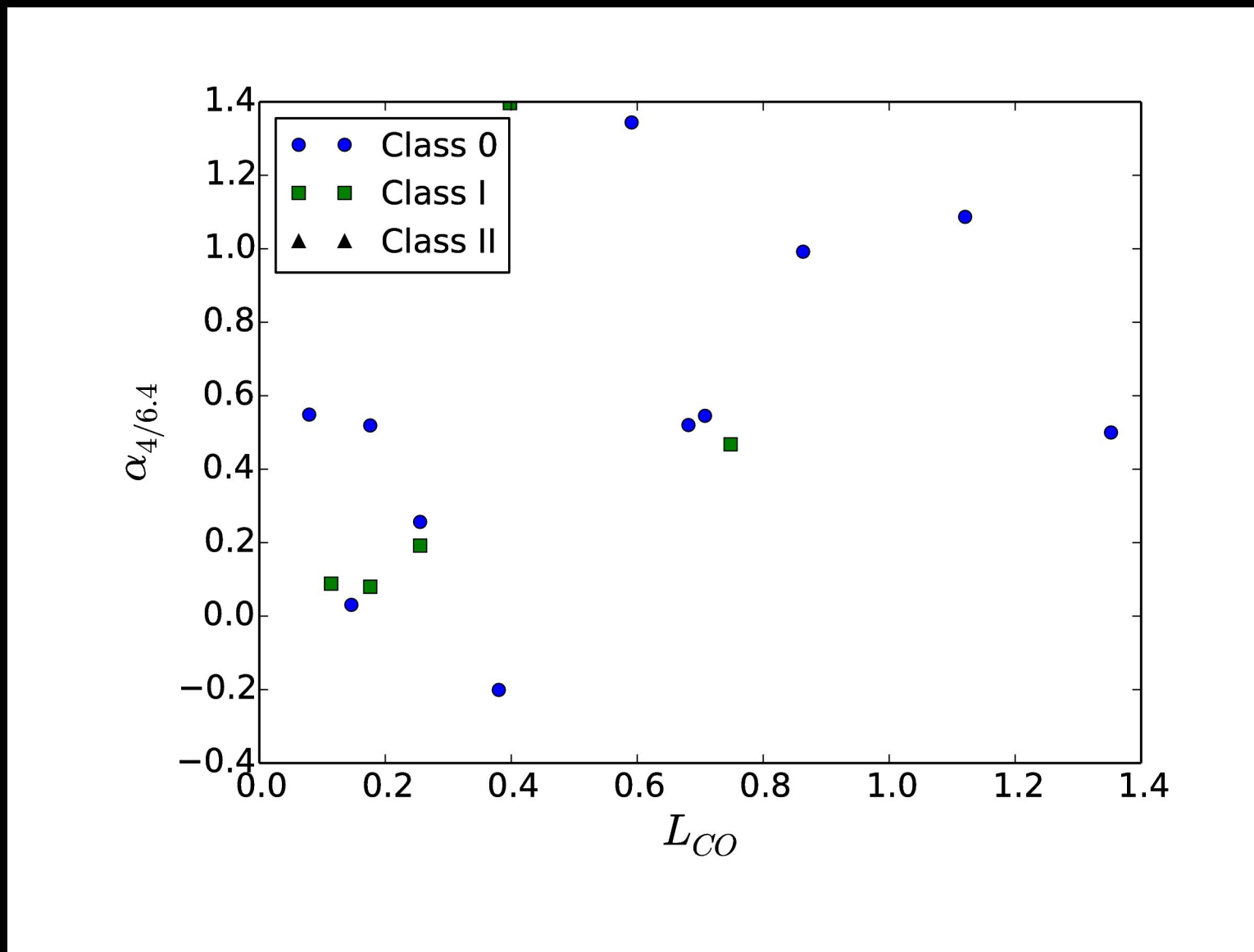
- No dependence of [OI] on cm-spectral index

L_{cm} vs. Herschel: L_{CO}



- Possible weak correlation with CO $J_{\text{up}} > 13$ luminosity

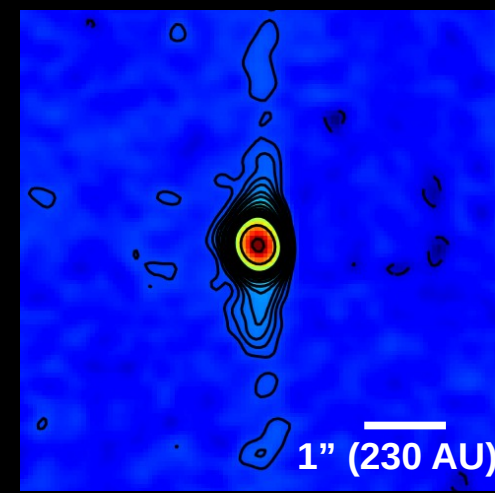
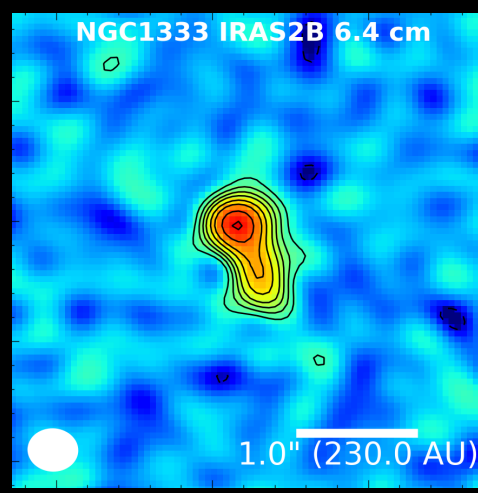
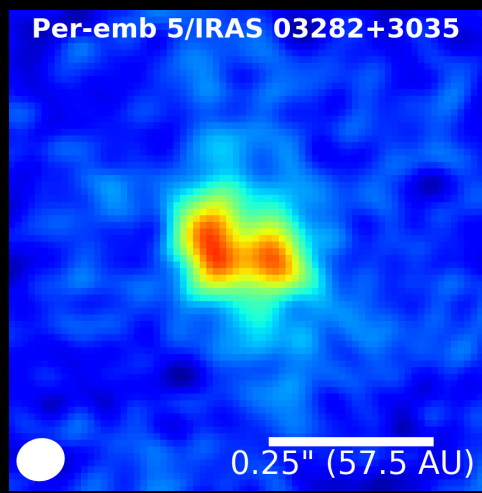
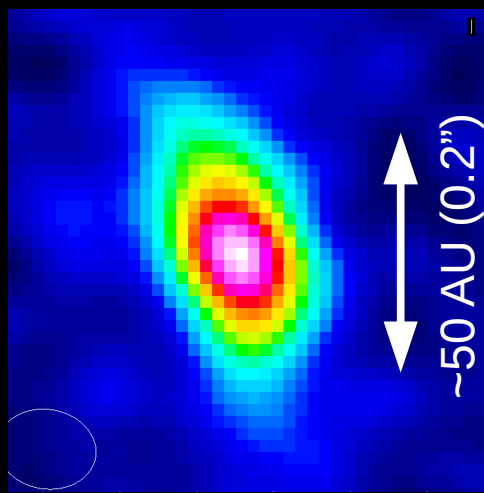
Spectral Index vs. Herschel: L_{CO}



- Possible weak correlation with CO $J_{up} > 13$ and cm-spectral index

Summary

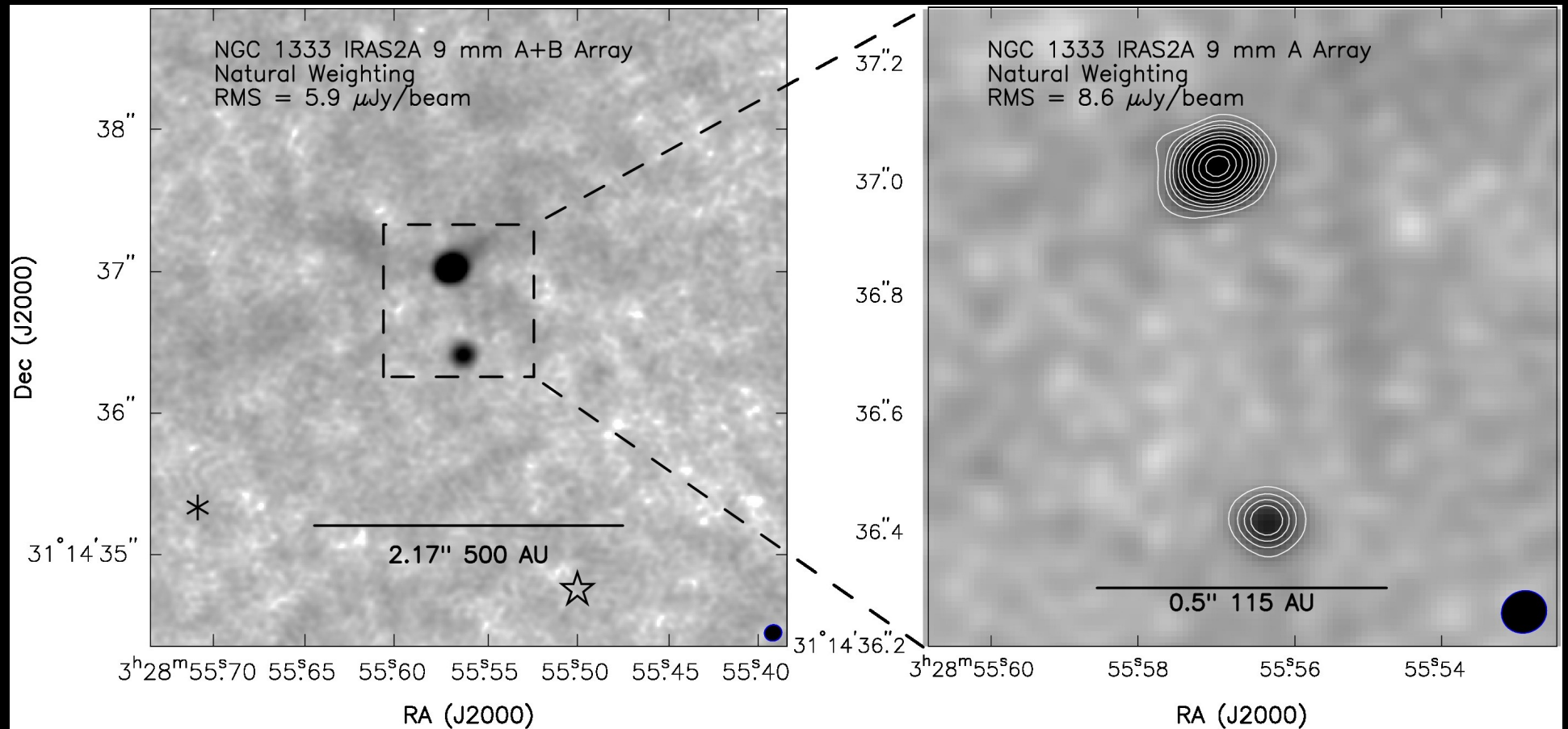
- Unbiased surveys crucial for disk, multiplicity, and jet studies
- New views of protostellar jets
 - Possible offset synchrotron shocks in some sources
 - DG Tau analogues?
- Weak correlations with luminosity
- Poor (if any) correlations of free-free jets and molecular outflow
- Similarly poor correlations of free-free jets and *Herschel* lines
- Weak correlations due to different scales/mechanisms?



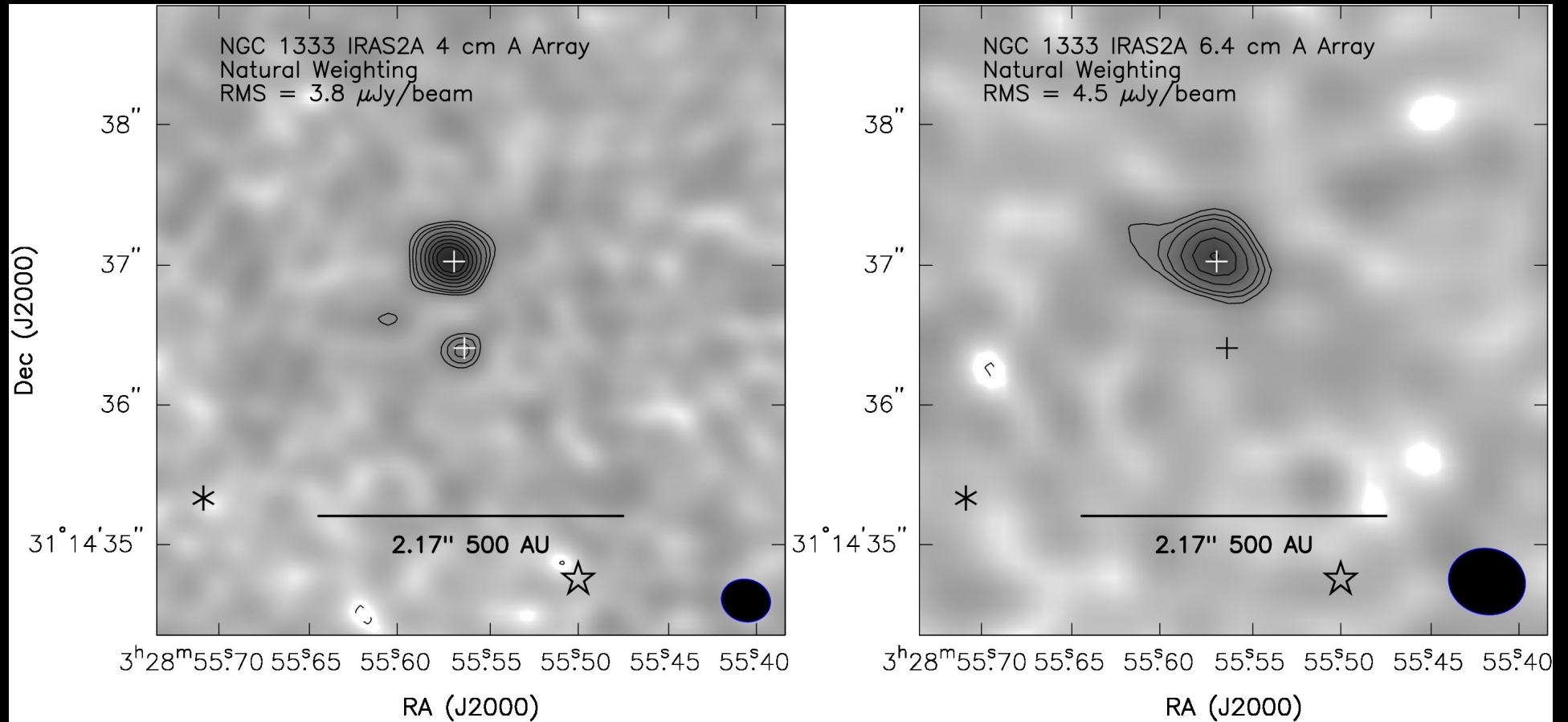
Research Supported By:

- NWO Veni Fellowship
- EU A-ERC Grant CHEMPLAN
- NASA Hubble Fellowship (formerly)
- NRAO funded by National Science Foundation

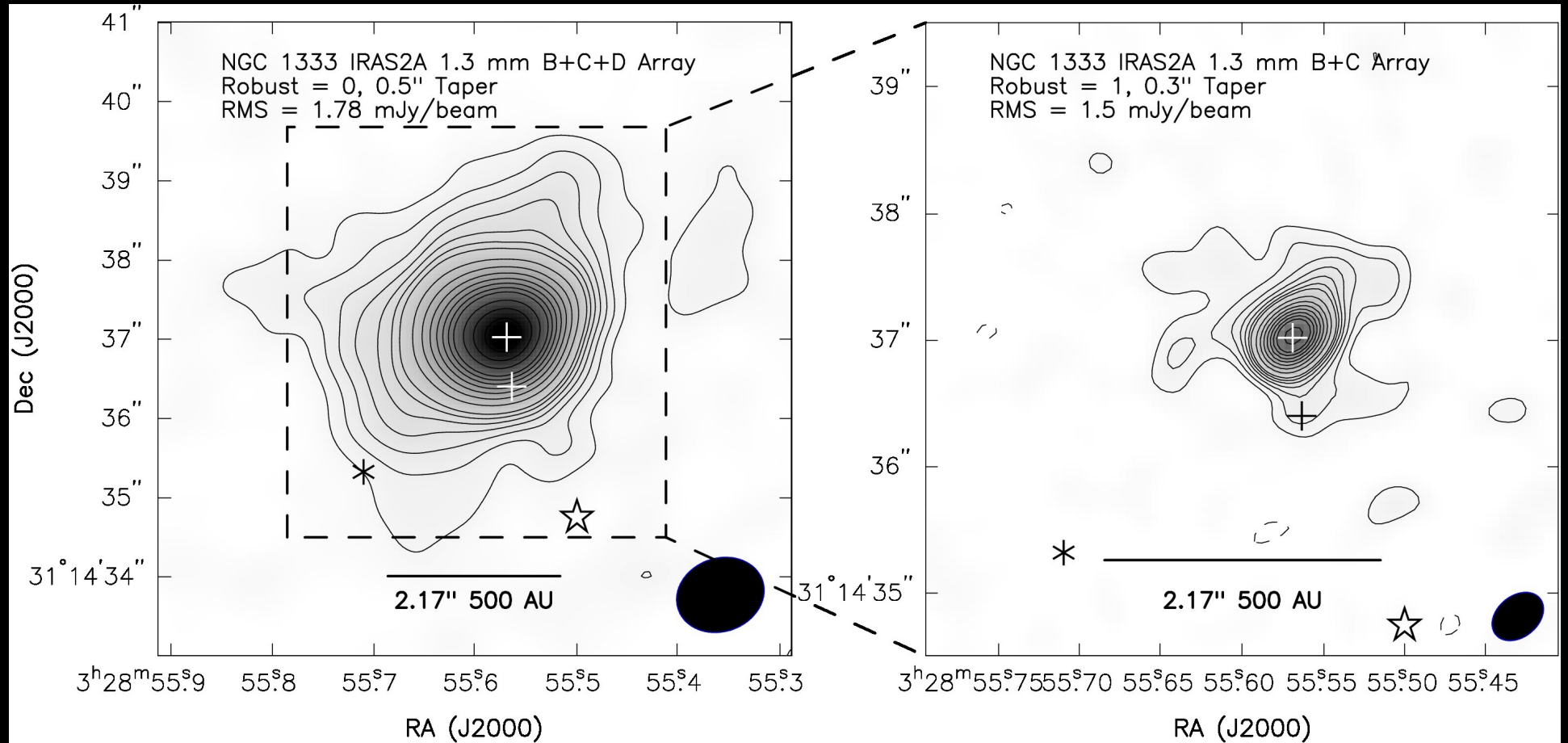
IRAS2A



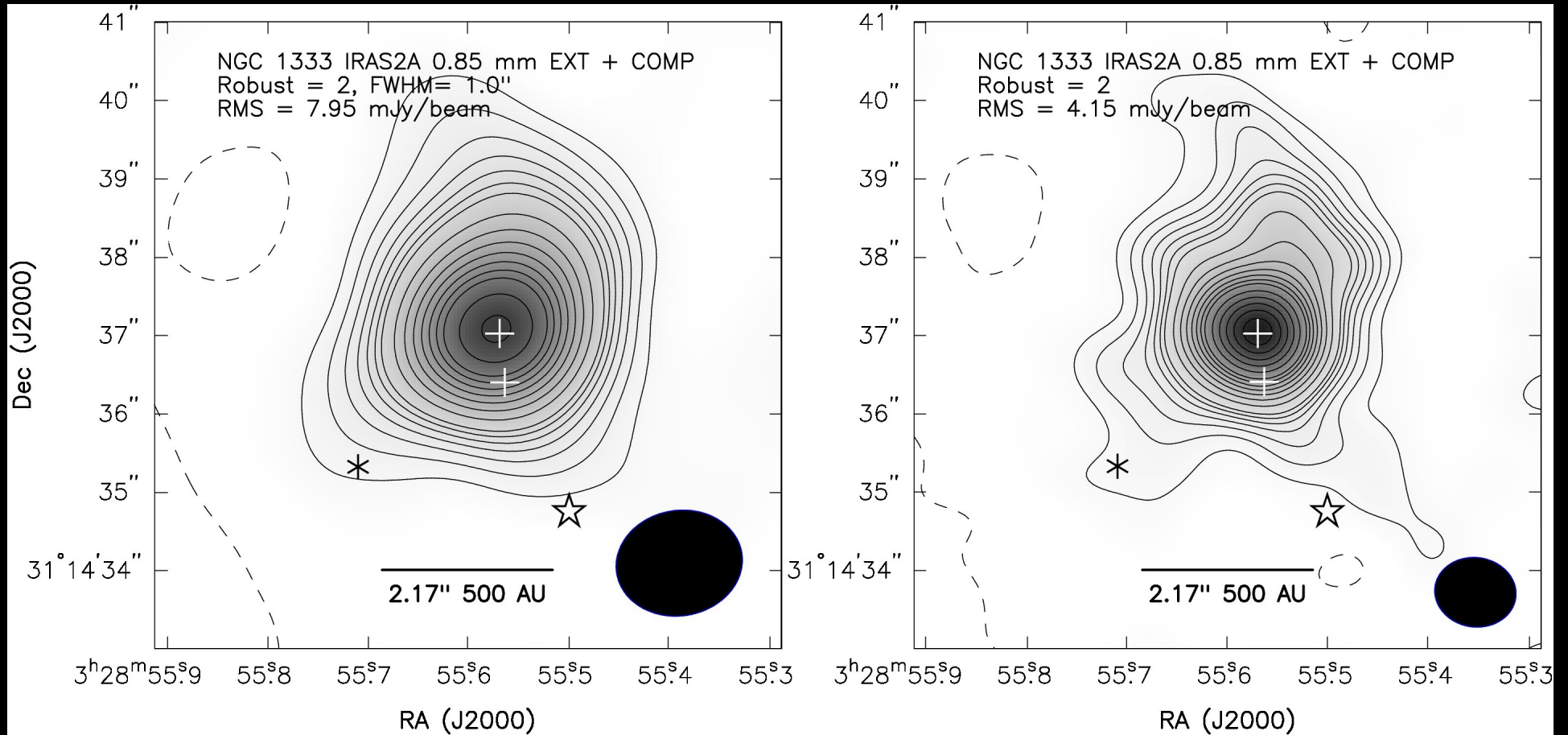
IRAS2A



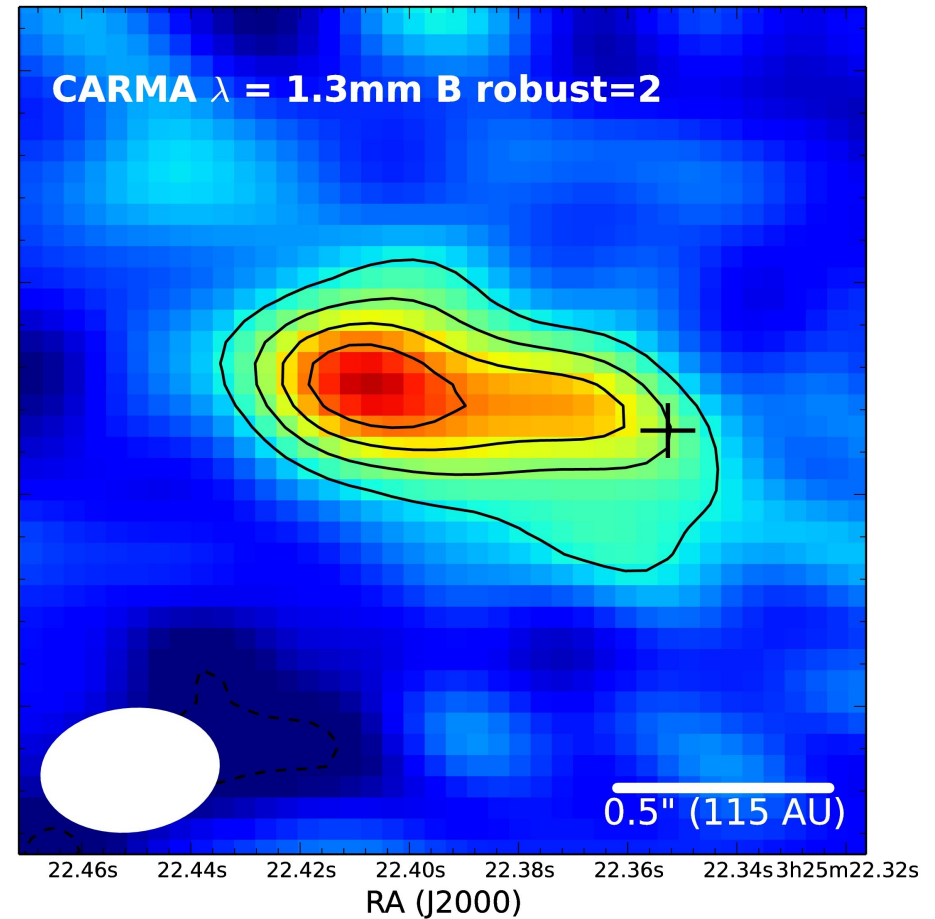
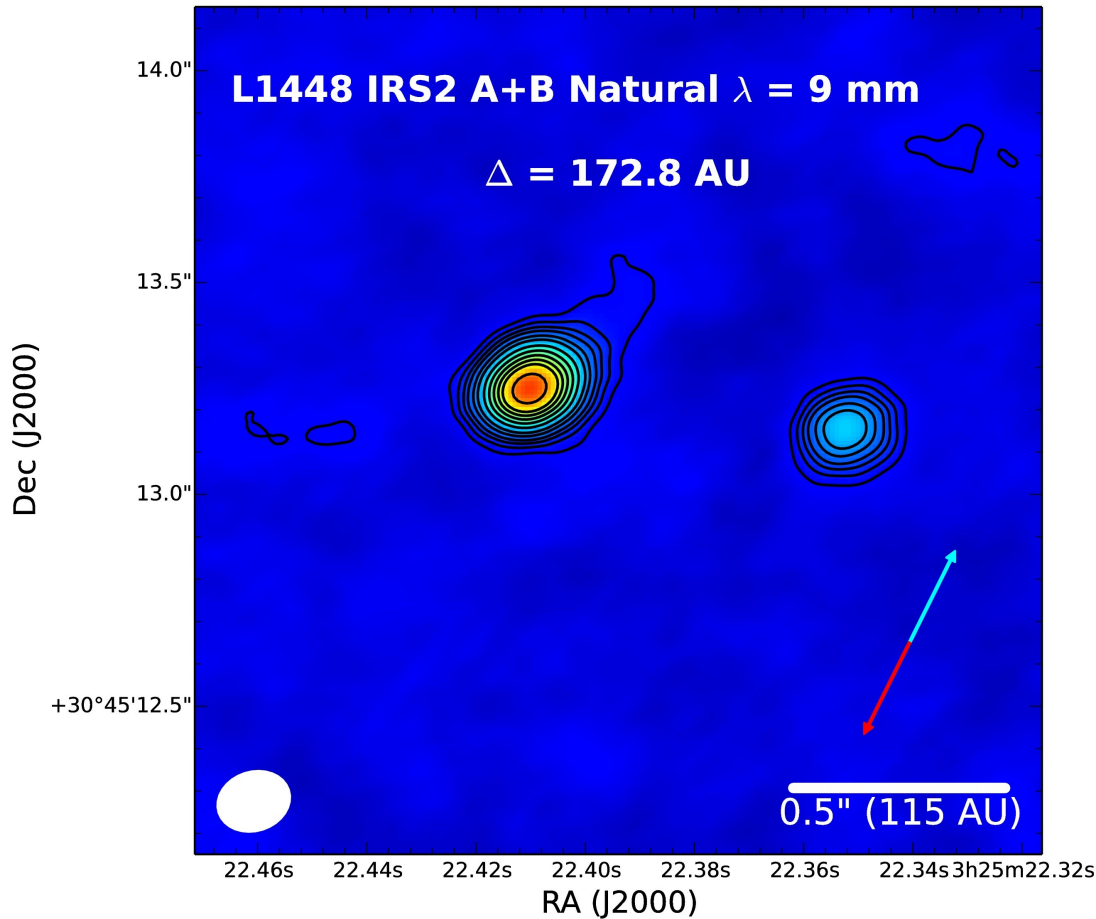
IRAS2A



IRAS2A

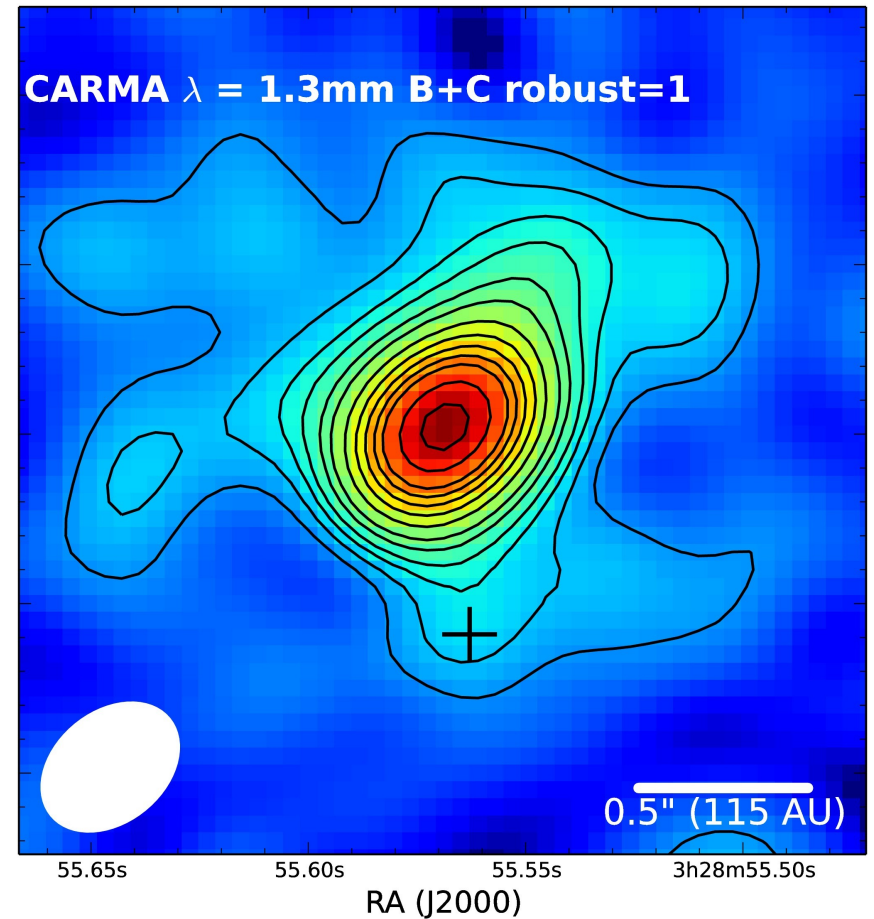
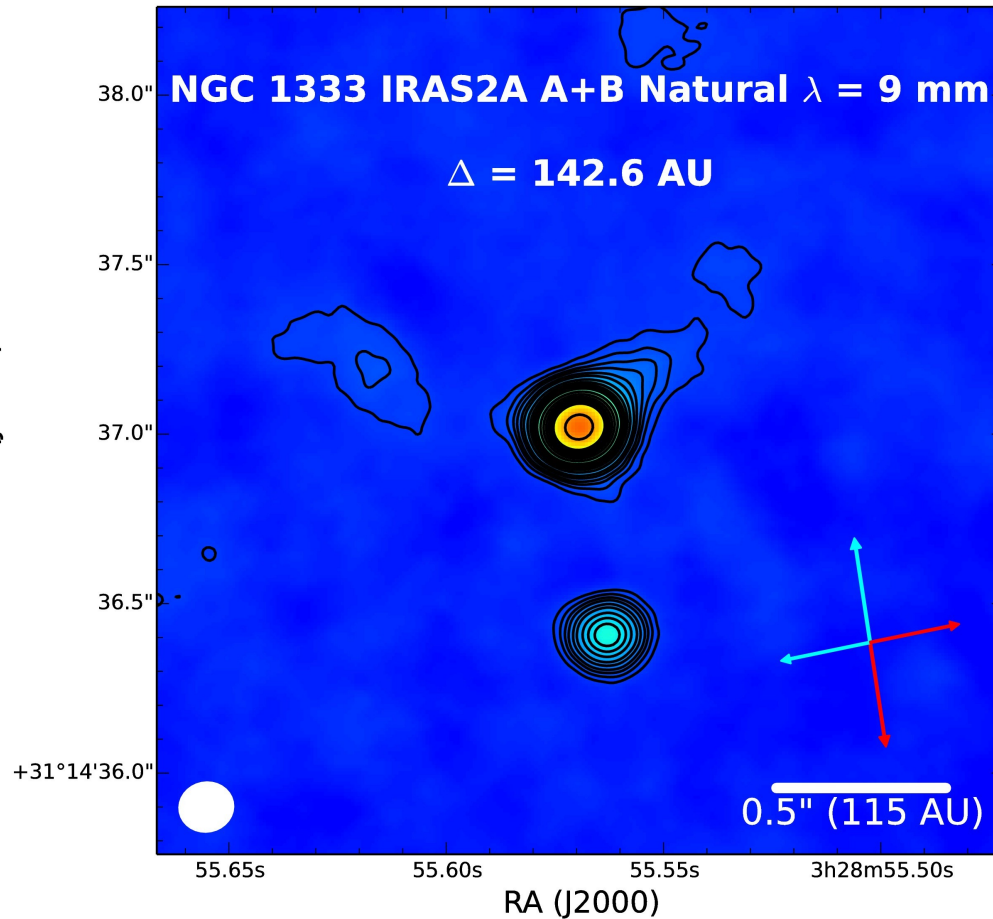


Why the VLA?



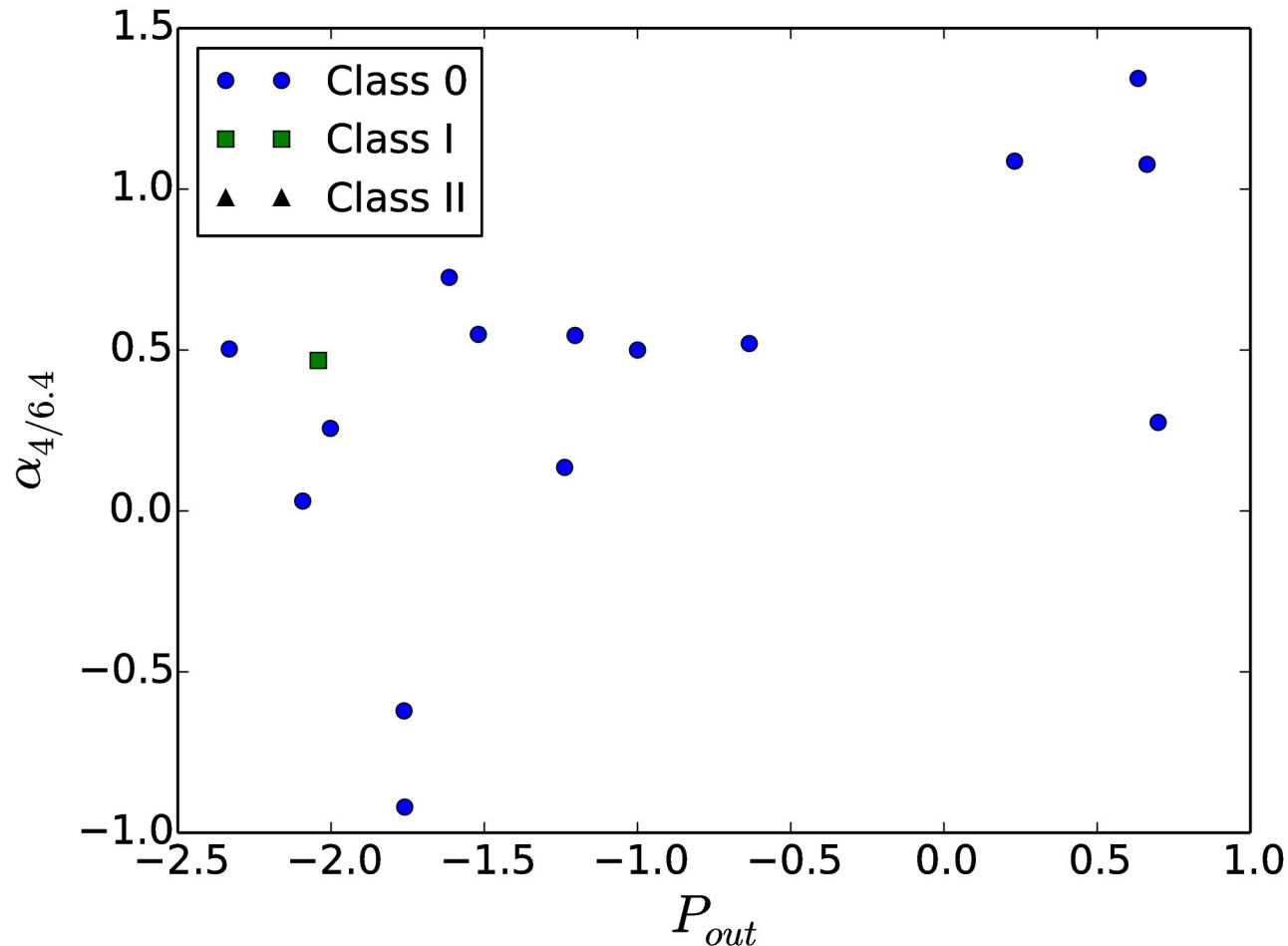
- Companions identified not always bright at 1.3 mm

Why the VLA?



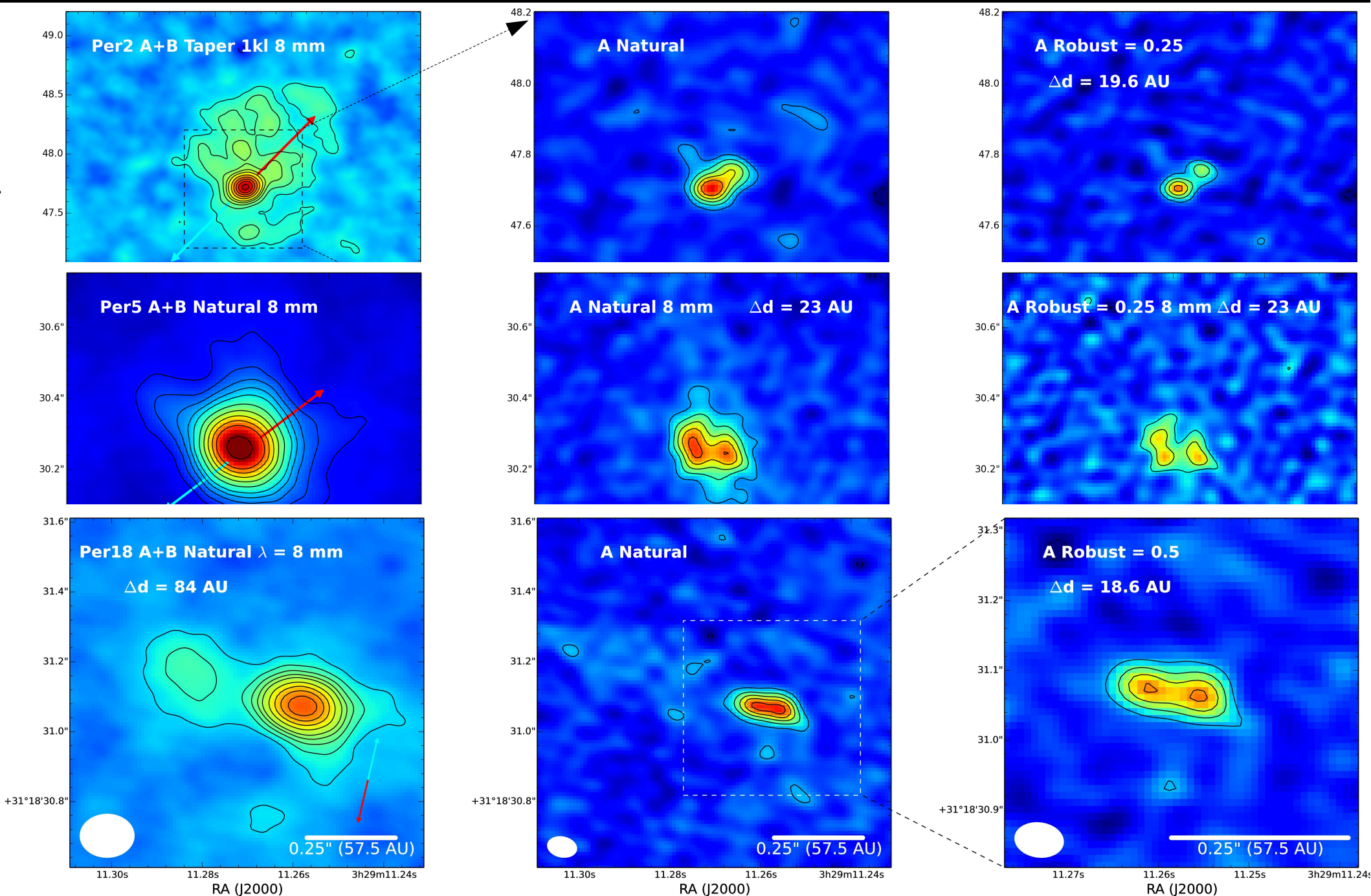
- Companions identified not always bright at 1.3 mm

Free-Free Jet vs. ^{12}CO



- No clear correlation of outflow momentum and cm-spectral index

Evidence for Fragmenting Disks

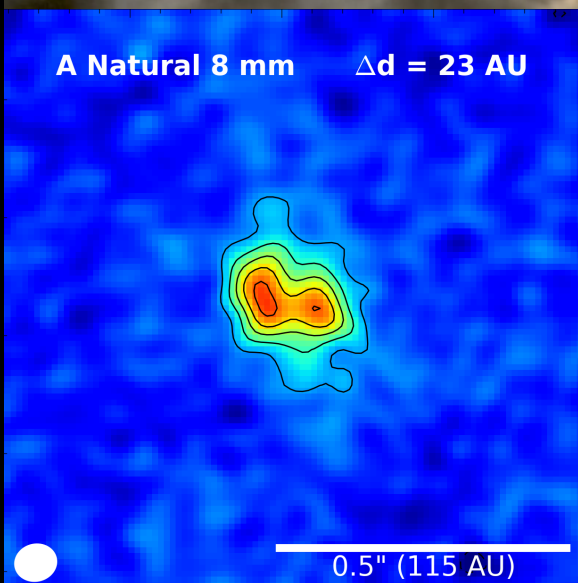
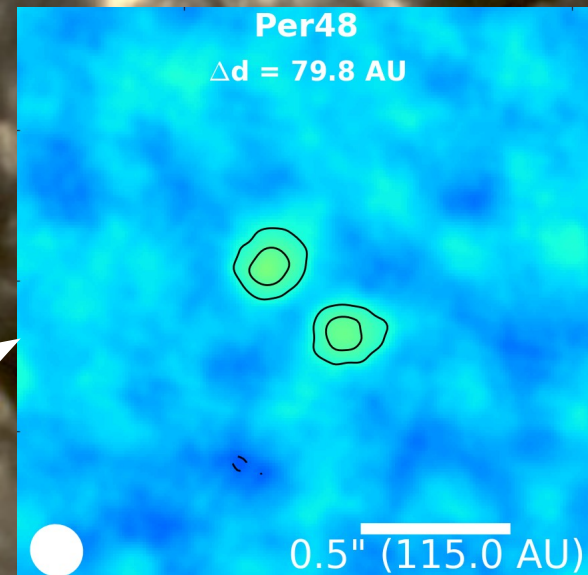
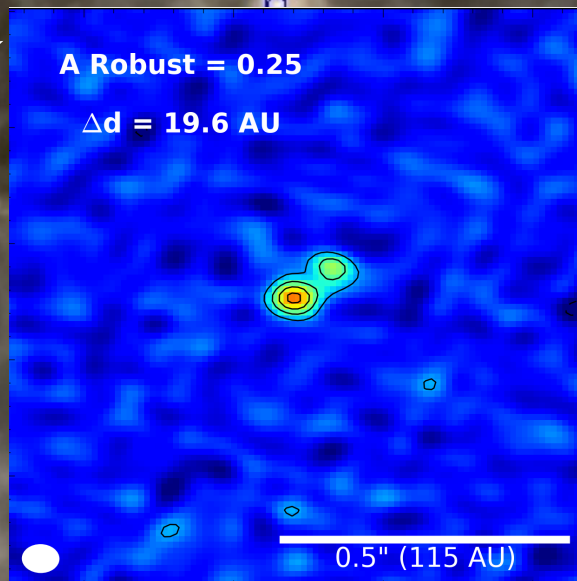
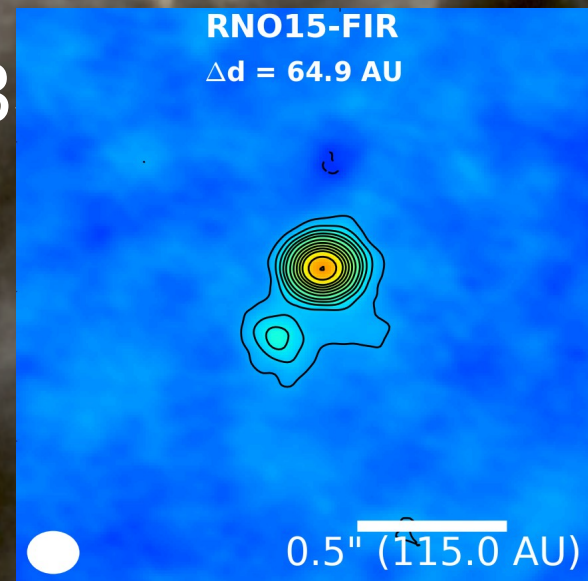
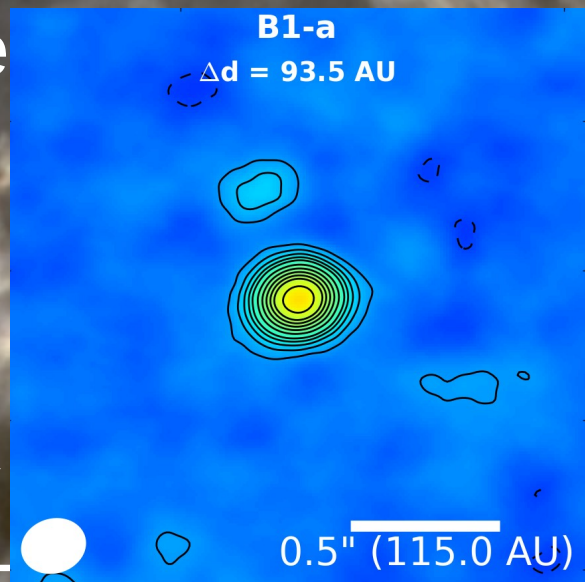


Western Pe Cloud

Cloud

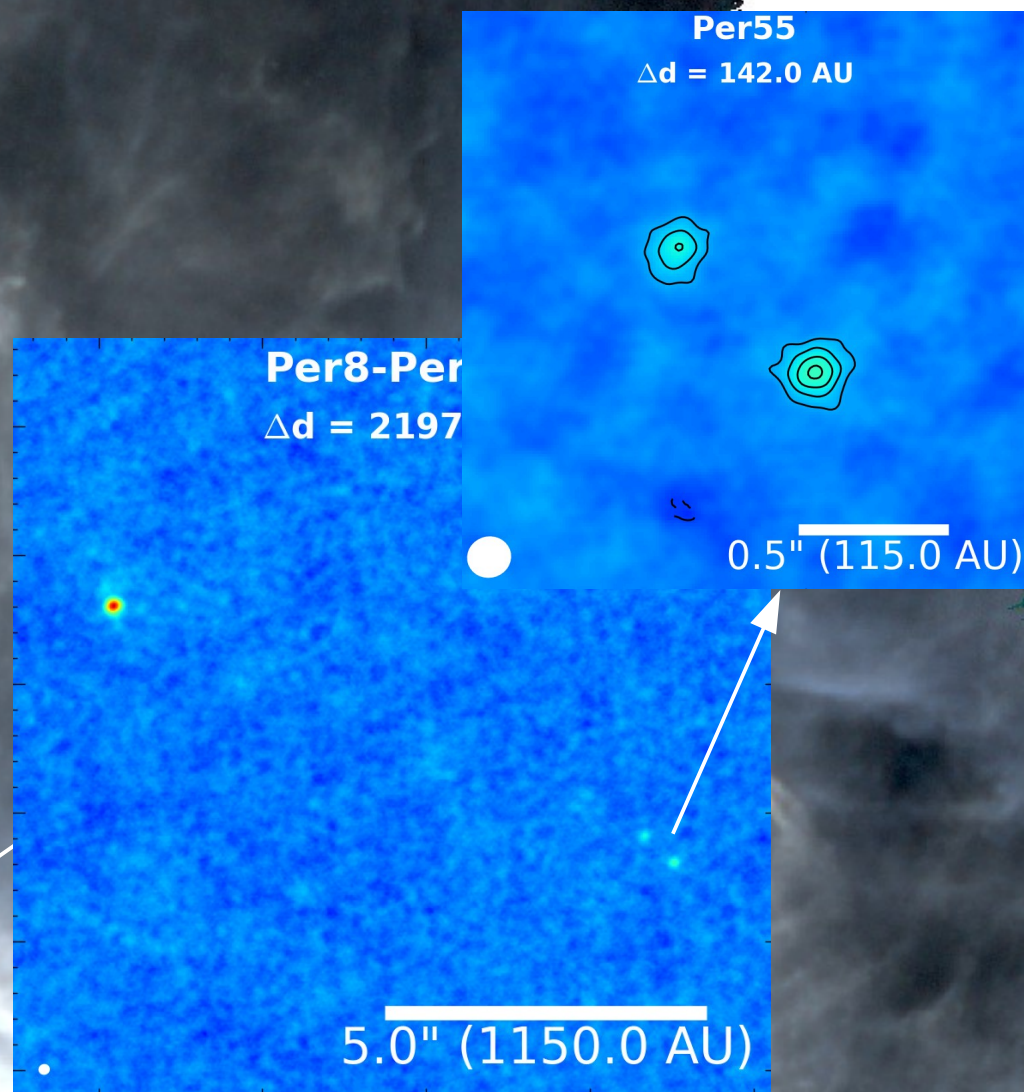
NGC 13

L1455



Eastern Perseus Molecular Cloud

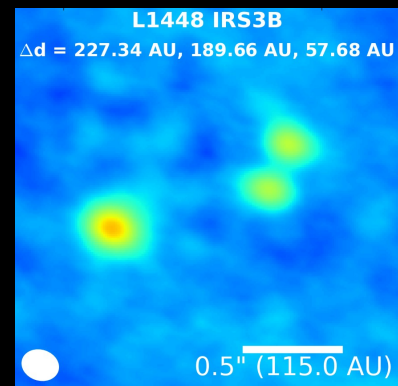
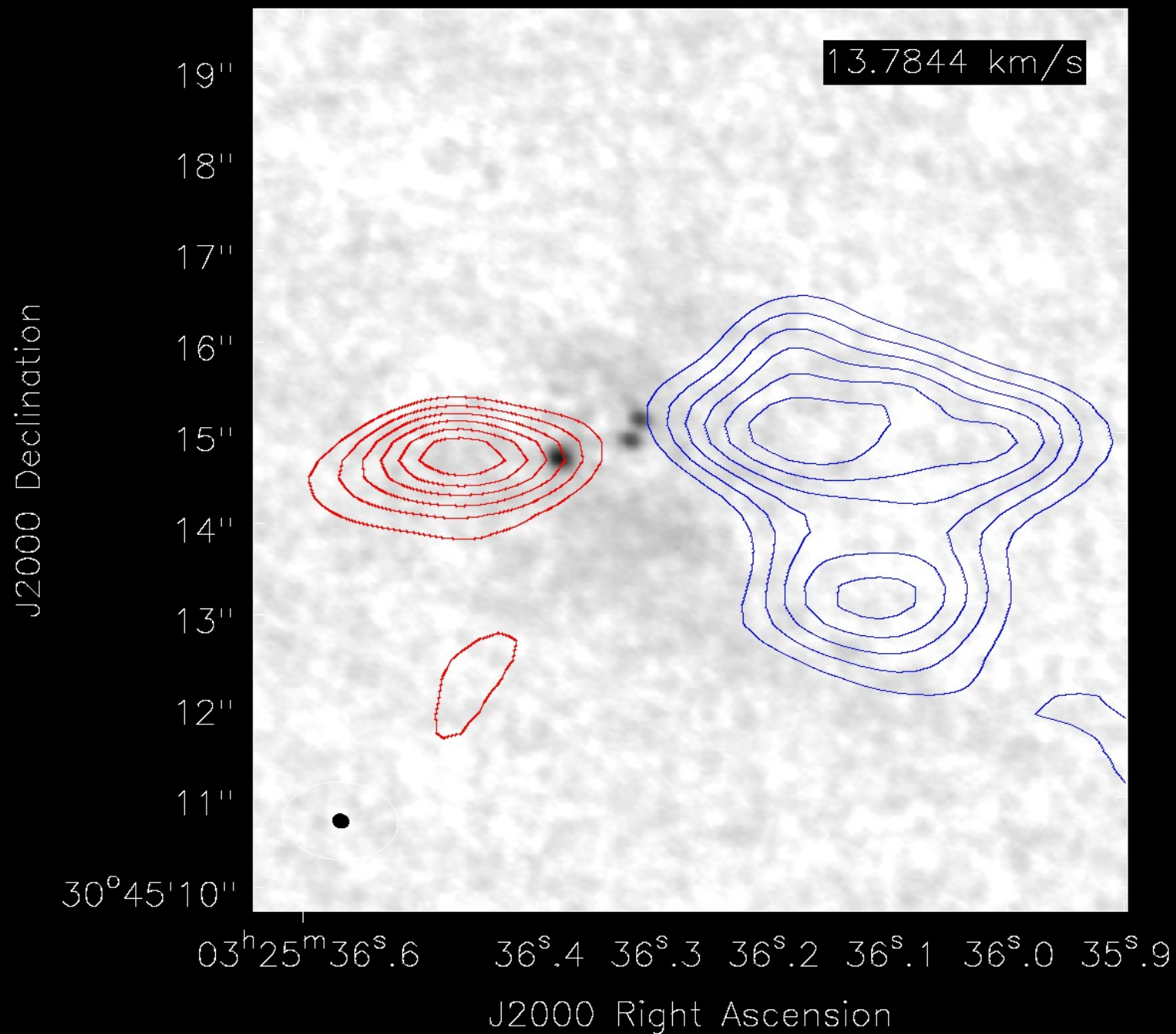
IC348



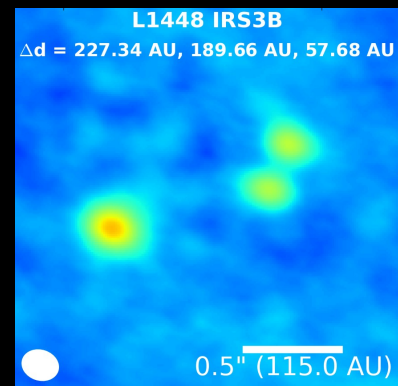
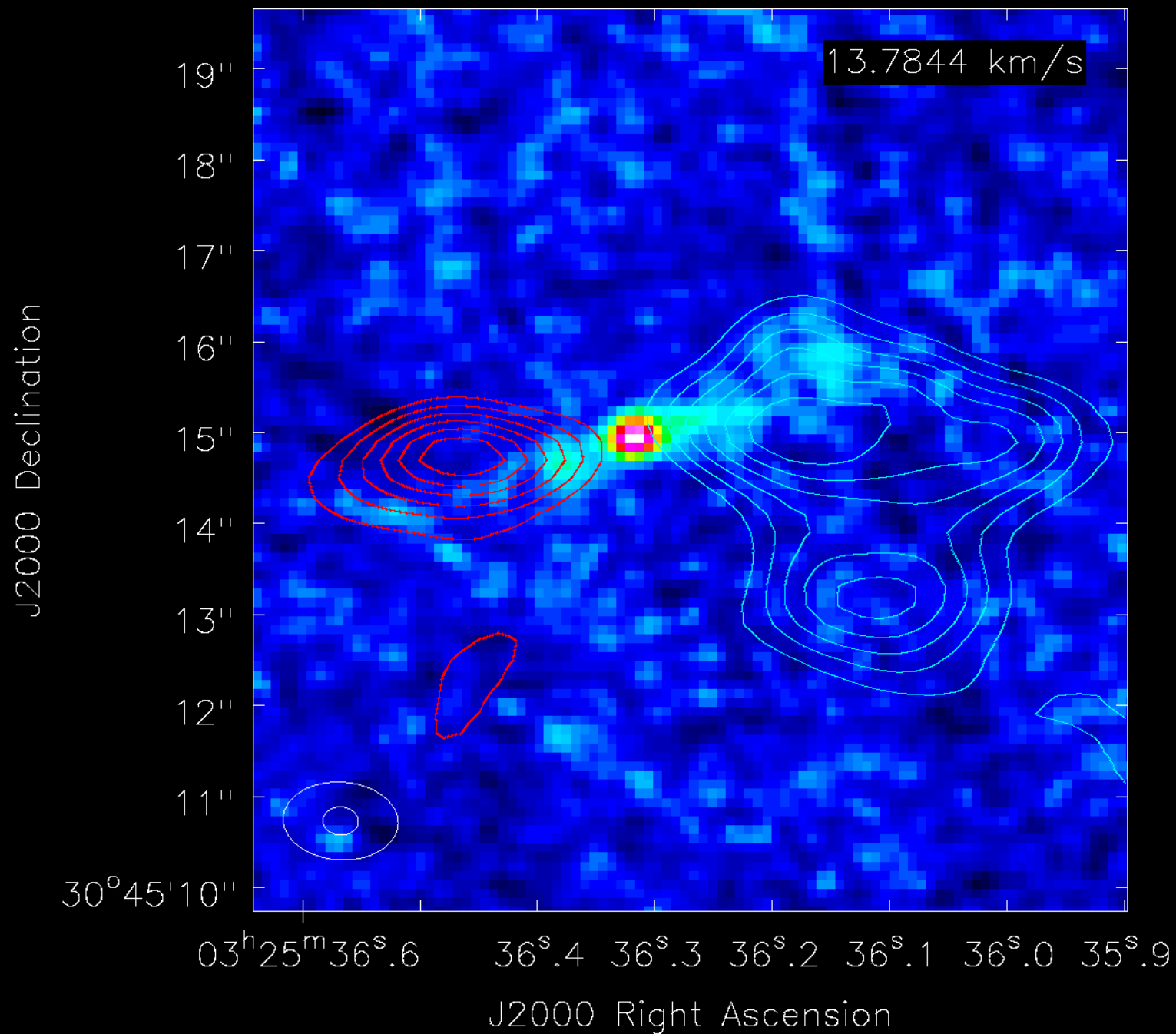
Herschel
SPIRE

Tobin+2015 in prep.

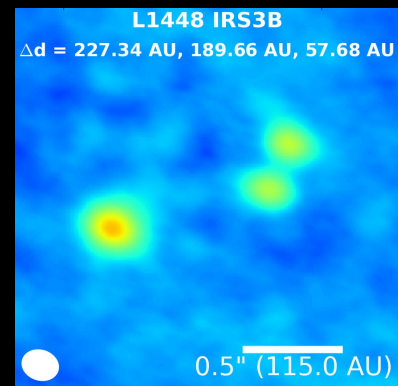
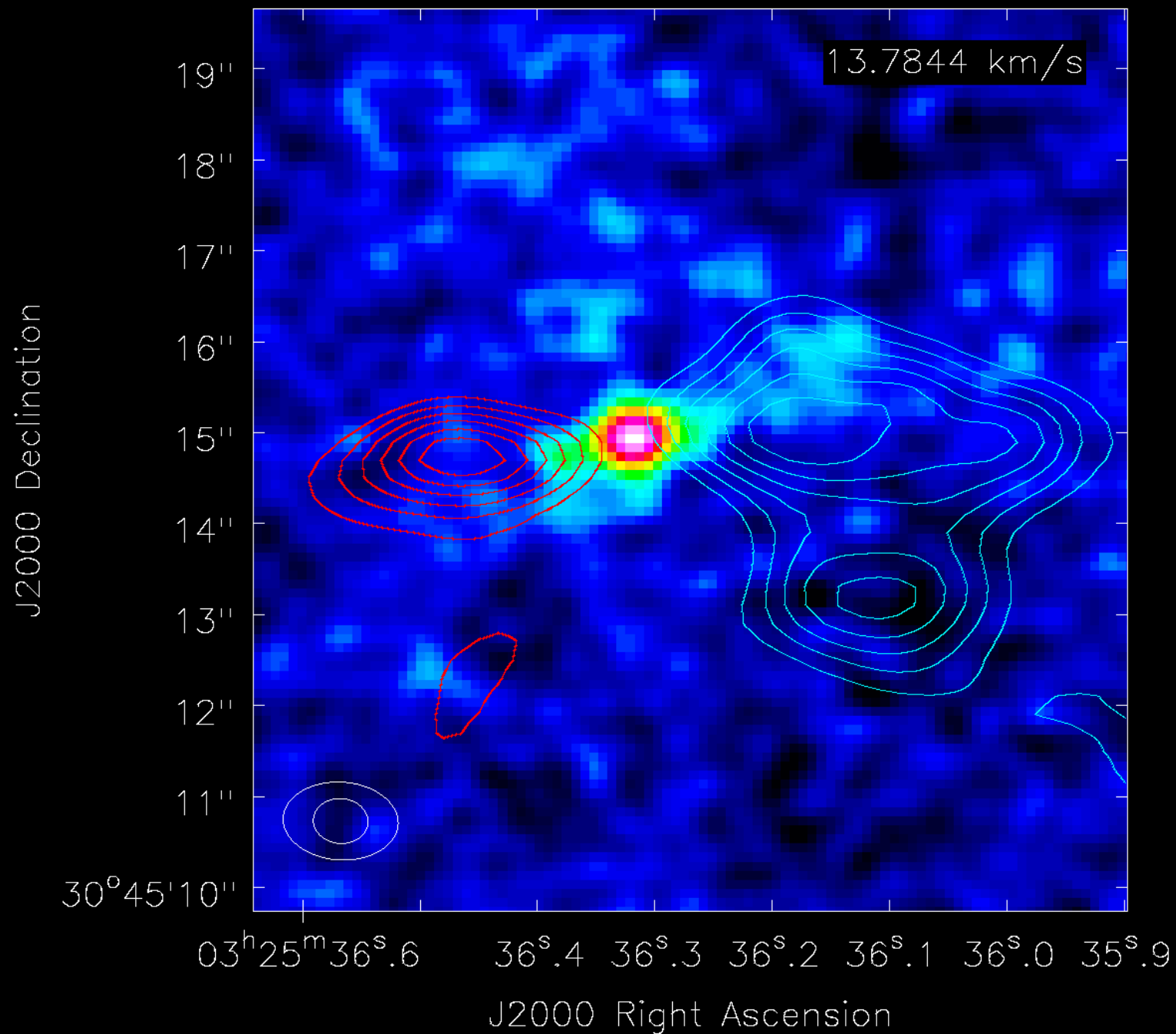
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PerC29.A.C.high.cont.image.fits-raster



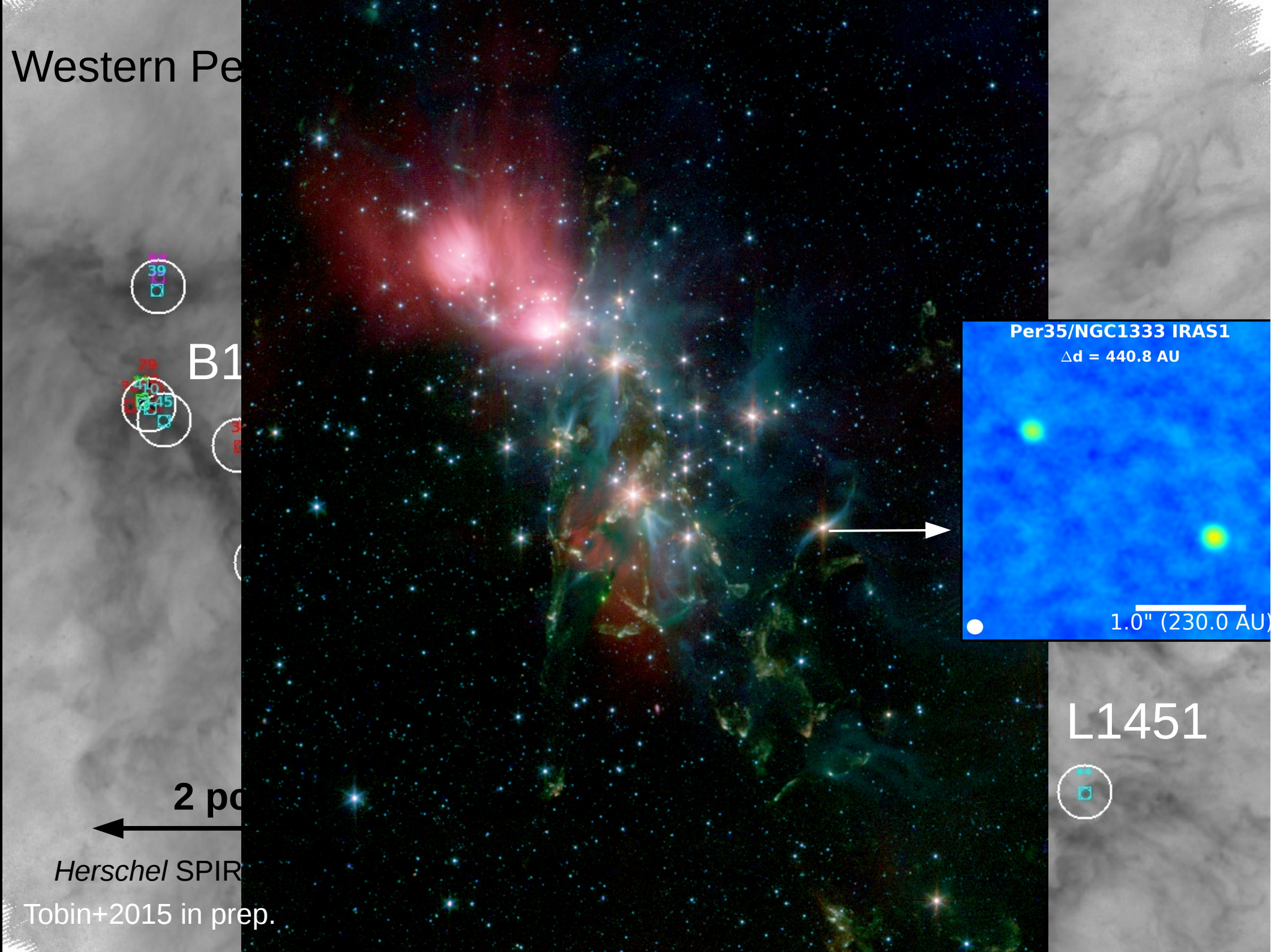
PerC29.A.C.low.cont.image.fits—raster



Known Class 0 Disks

- **L1527** – $R_d \sim 50\text{-}100 \text{ AU}$ – $M_{ps} \sim 0.2 - 0.3 \pm 0.02 M_{\text{sun}}$
 - Tobin+2012, Ohashi+2014; ^{13}CO , C^{18}O
- **VLA 1623** – $R_d \sim 150 \text{ AU}$ – $M_{ps} \sim 0.2 \pm 0.02 M_{\text{sun}}$
 - Murillo+2013, C^{18}O
- **HH212** – $R_d \sim 50 \text{ AU}$ – $M_{ps} \sim 0.3 \pm 0.1 M_{\text{sun}}$
 - Codella+2014, Lee+2014; ALMA C^{17}O and HCO^+
- **R CrA IRS 7B** – $R_d \sim 50 \text{ AU}$ – $M_{ps} \sim 2.3 \pm 0.1 M_{\text{sun}}$
 - Lindberg+2014; ALMA C^{17}O

Western Pe



B1

Per35/NGC1333 IRAS1
 $\Delta d = 440.8 \text{ AU}$

1.0'' (230.0 AU)

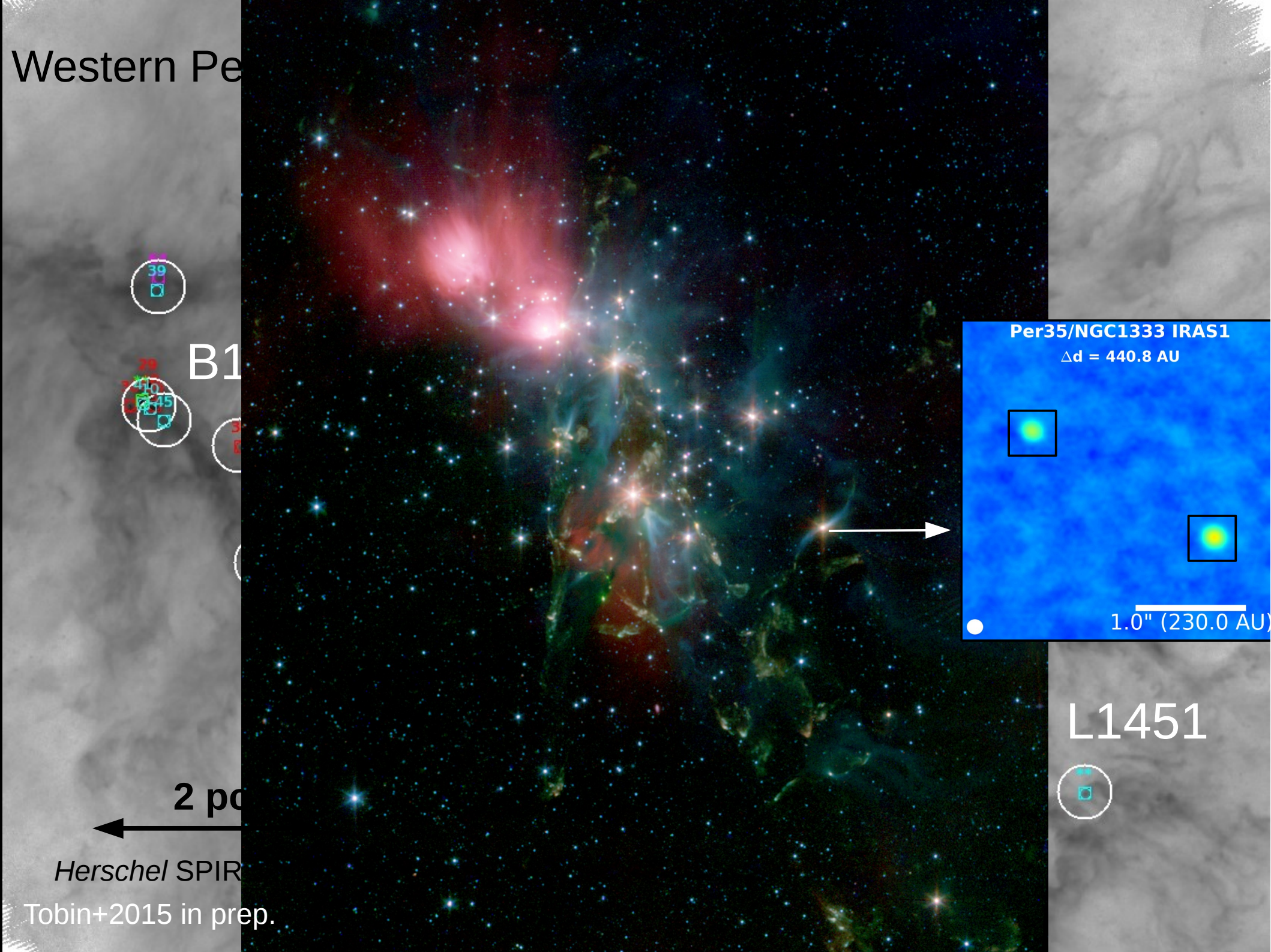
L1451

2 pc

Herschel SPIR

Tobin+2015 in prep.

Western Pe



B1

Per35/NGC1333 IRAS1

$\Delta d = 440.8 \text{ AU}$

1.0" (230.0 AU)

L1451

2 pc

Herschel SPIR

Tobin+2015 in prep.

Western Pe

B1

2 pc

Herschel SPIR

Tobin+2015 in prep.

Per-emb-35/NGC1333 IRAS1

0.25" (57.5 AU)

Per-emb-35/NGC1333 IRAS1

0.25" (57.5 AU)

Per35/NGC1333 IRAS1

$\Delta d = 440.8$ AU

1.0" (230.0 AU)

L1451

Western Perseus Molecular Cloud

NGC 1333

B1

L1448

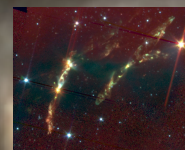
L1451

L1455

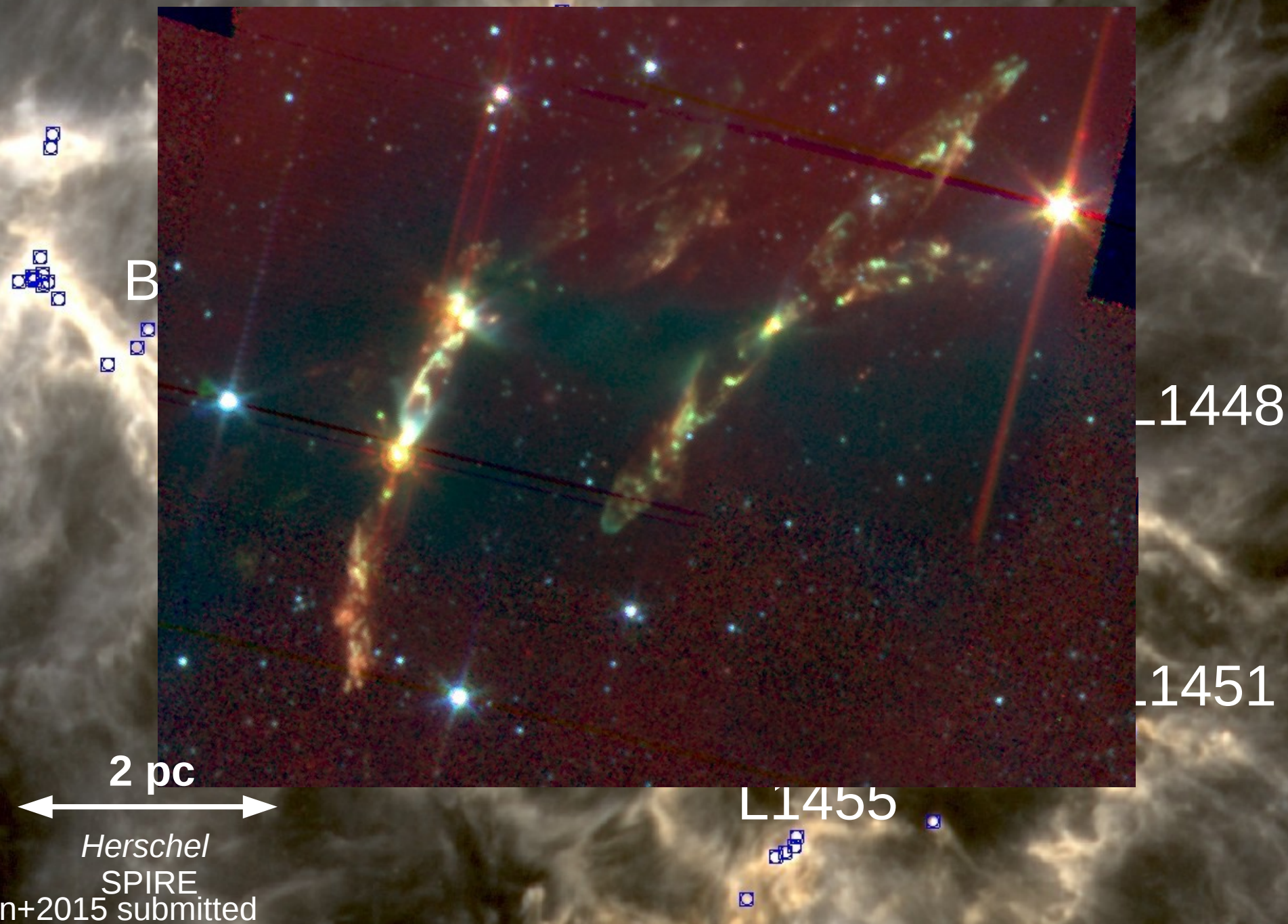
2 pc

Herschel
SPIRE

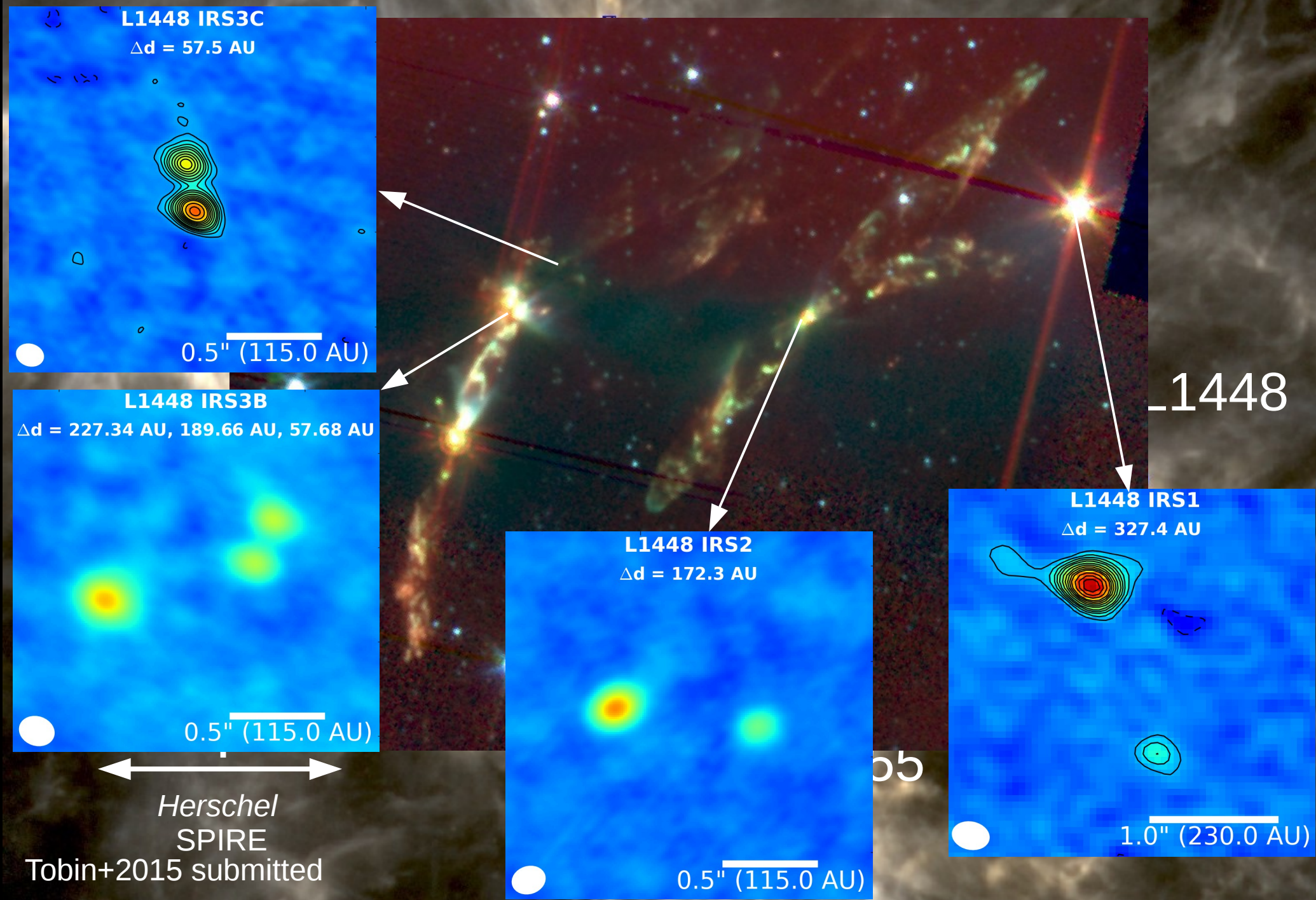
Tobin+2015 submitted



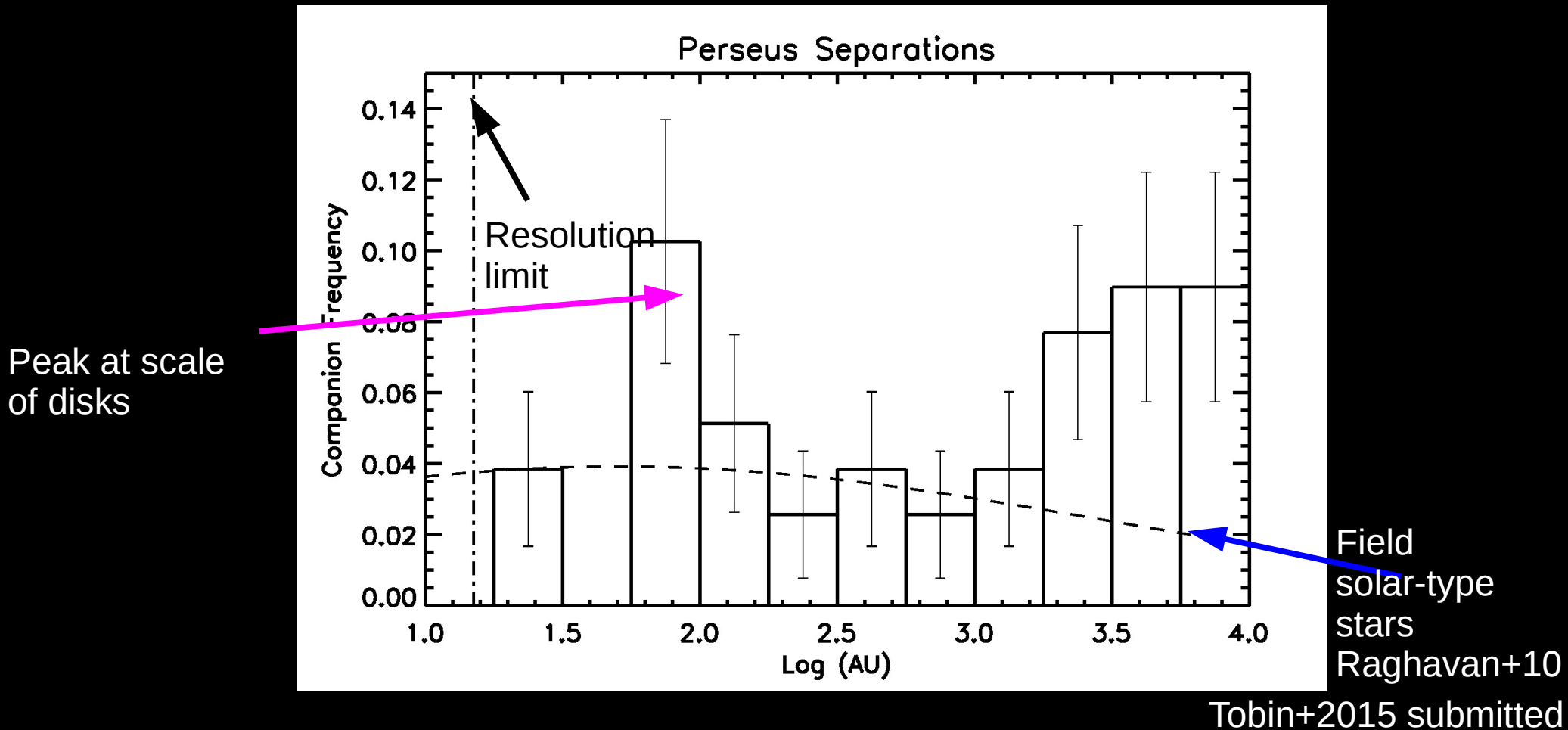
Western Perseus Molecular Cloud



Western Perseus Molecular Cloud

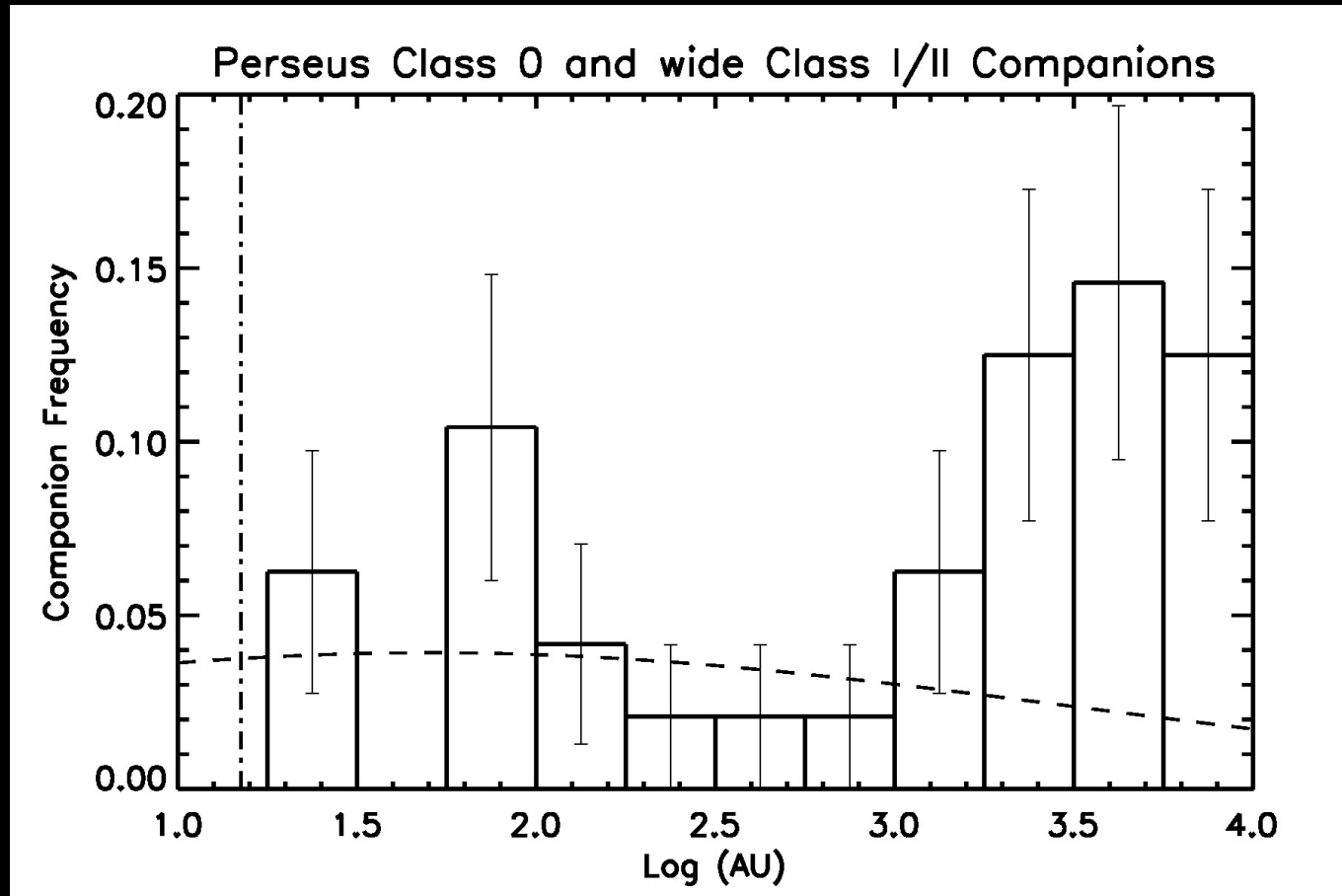


Perseus Separation Distribution



- Perseus Class 0 and Class I Separation Distribution
- Excess relative to field at ~ 75 AU and > 1000 AU

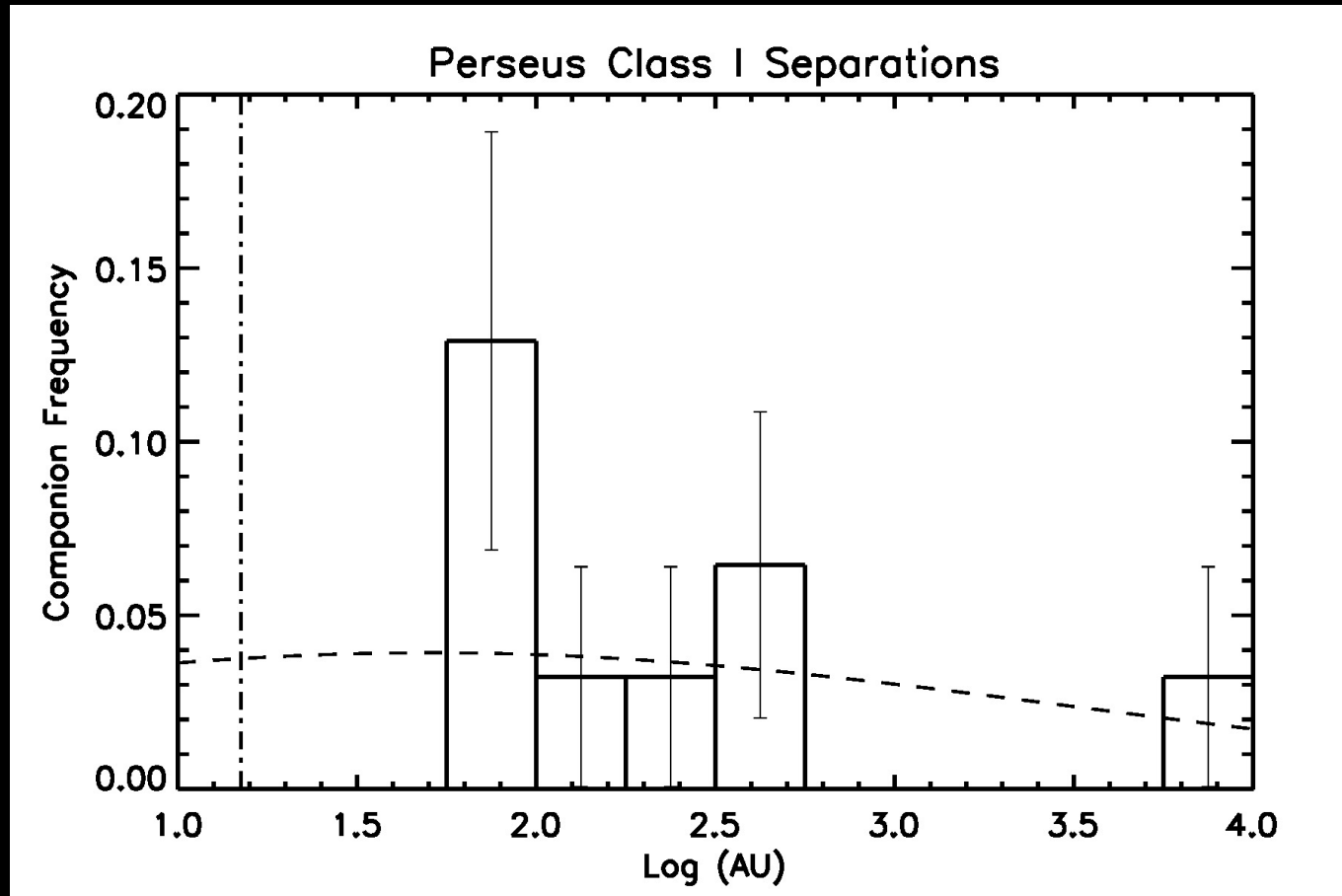
Perseus Separation Evolution



Tobin+2015 submitted

- Class 0 (youngest) sources still have two peaks

Perseus Separation Evolution



Tobin+2015 submitted

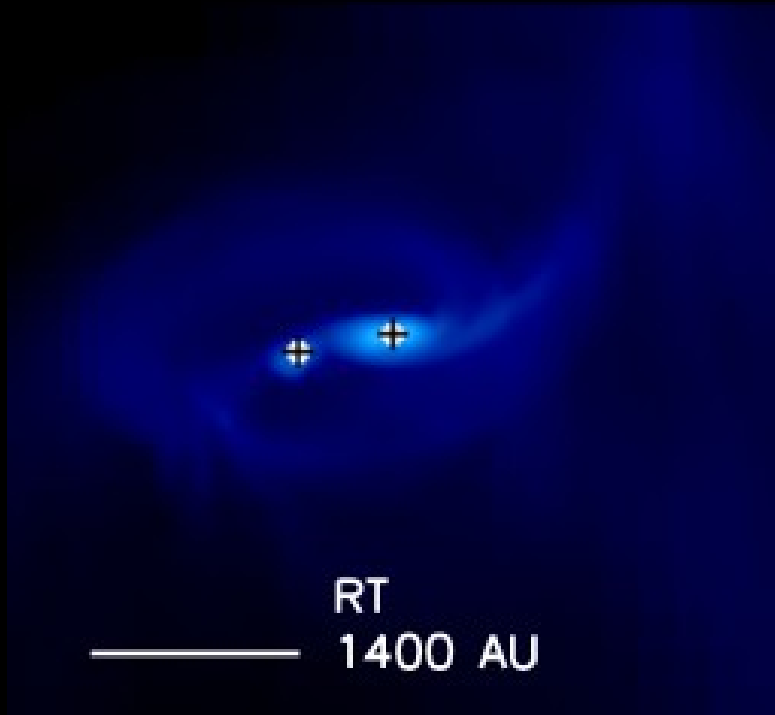
- Lack of wide multiples toward Class I (more-evolved) sources
- Evolution of separations?
 - Fraction of < 100 AU systems $\sim$ constant
 - Wide systems form unbound and disperse?

Multiplicity Statistics

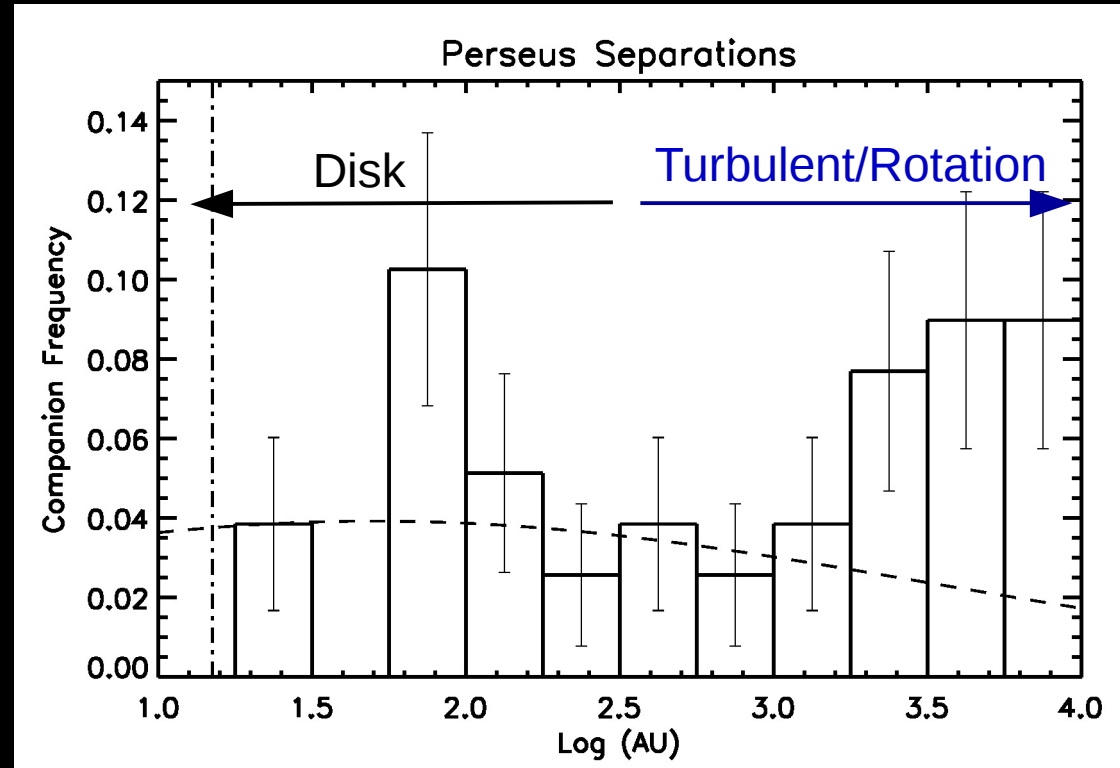
- Multiplicity Fraction (MF) and Companion Star Fraction (CSF) depend on scales of interest
- 15 AU to 10000 AU
 - Class 0 – MF = 0.58 – CSF = 1.13
 - Class I – MF = 0.23 – CSF = 0.23 – due to wide Class 0/I pairs
- 15 AU to 2000 AU
 - Class 0 – MF = 0.35 – CSF = 0.43
 - Class I – MF = 0.28 – CSF = 0.28
- 15 AU to 1000 AU
 - Class 0 – MF = 0.27 – CSF = 0.30
 - Class I – MF = 0.27 – CSF = 0.27

Multiple System Formation

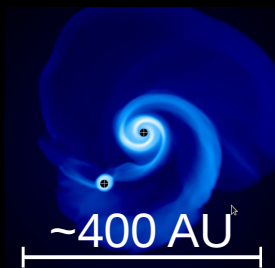
Turbulent Fragmentation



vs. Offner+2010



Disk Fragmentation



Kratter+2010

- Do close systems have circumbinary disks?
- Are wide systems bound or consistent with turbulent or order rotational fragmentation?

Why the VLA?

- High-sensitivity at 8 mm – 1 cm with 8 GHz bandwidth
- Routine observations with $< 0.1''$ resolution at 8 mm
- Probing to two emission processes at 8 mm/1 cm
 - Thermal free-free + thermal dust
 - Protostars stand out
- High optical depths at ~ 1.3 mm may hide close companions
- Jet emission enhances companion detectability