The VLA Nascent Disk and Multiplicity (VANDAM) Survey: The Perseus Molecular Cloud

John Tobin

NWO Veni Fellow
Leiden Observatory
Leiden, The Netherlands

VANDAM Team:
John Tobin (PI), Leslie Looney (Illinois), Zhi-Yun Li (Virginia), Claire Chandler (NRAO), 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) also with Steven Bos (Leiden), Katherine Lee (CfA), Tyler Bourke (SKA), and MASSES team

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

Image: Bill Saxton (NRAO)

VLA Nascent Disk And Multiplicity (VANDAM) Survey

- 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~230 pc), 92 YSOs (79 detected)
    - 43 Class 0, 37 Class I sources, 12 Class II
  - Luminosities range 0.1 L_{sun} to 30 L_{sun}
- Goals:
  - Measure multiplicity fractions down to 15 AU
  - Resolve disks in dust continuum, measure dust masses
  - Protostellar jet properties
    - ...and changes with evolution

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
  - Thermal free-free + thermal dust
  - Protostars stand out
- High optical depths at ~1.3 mm may hide close companions
- 8 mm traces densest regions, i.e. disks
  - Envelope contribution minimal

Star Formation Process

Protostellar Phase

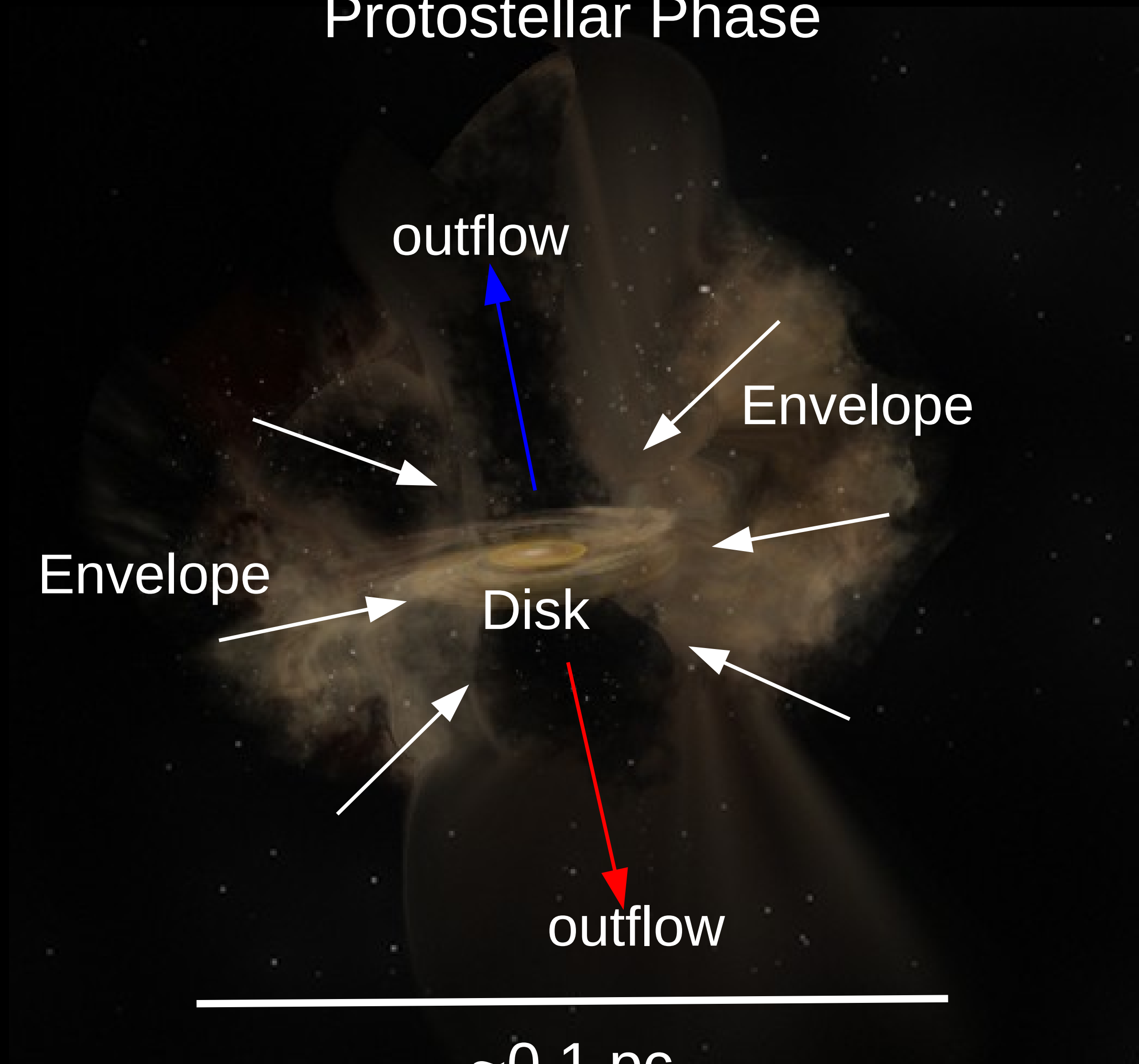


Image: Bill Saxton (NRAO)

Star Formation Process

Protostellar Phase

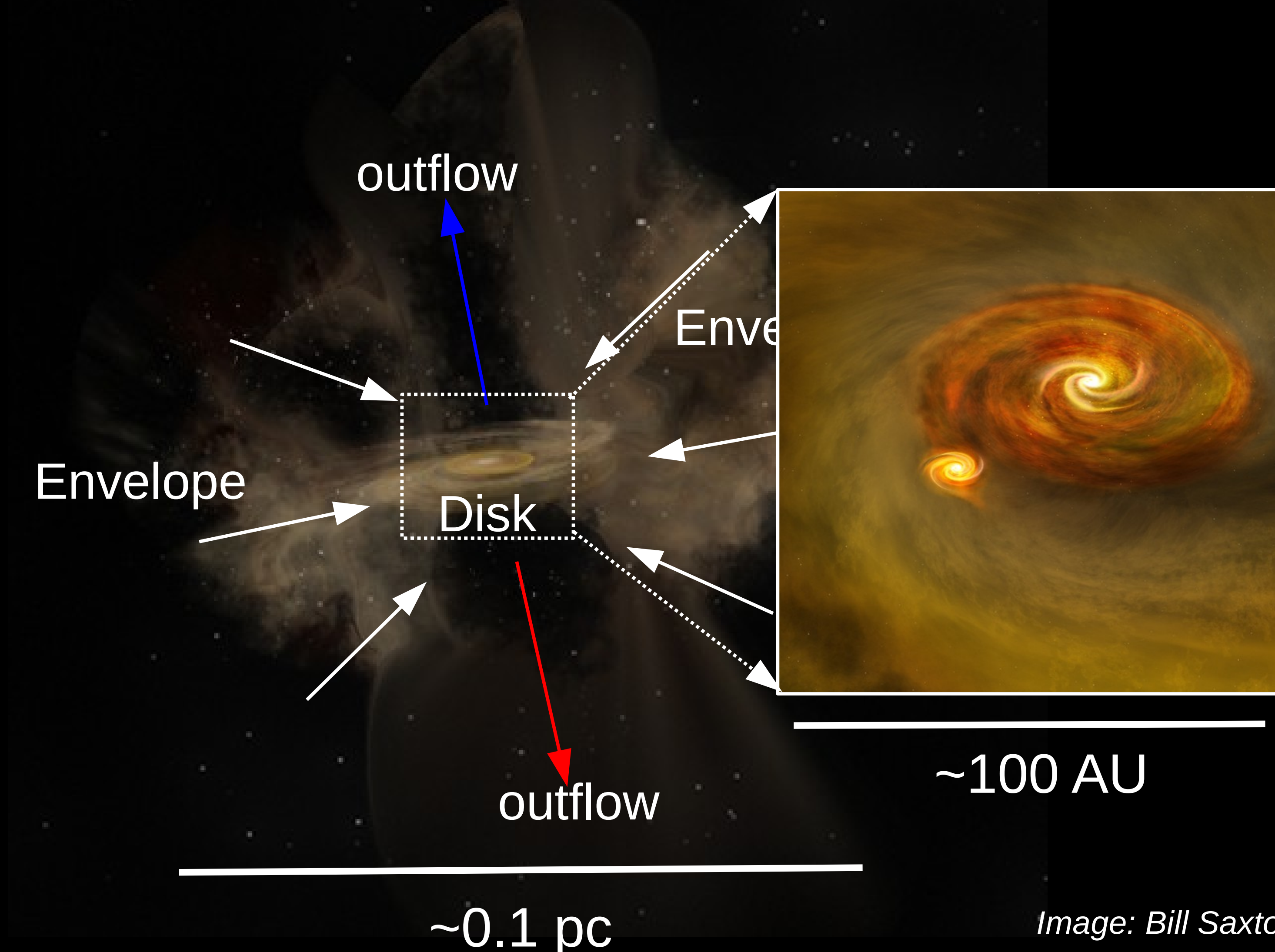
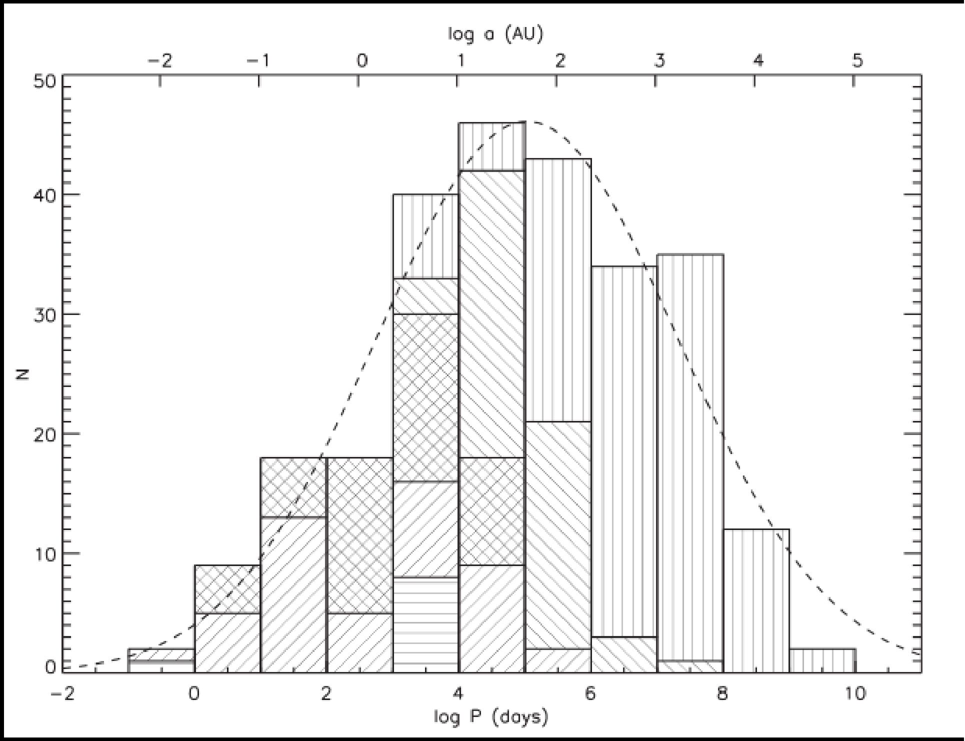


Image: Bill Saxton (NRAO)

Multiple Star Formation

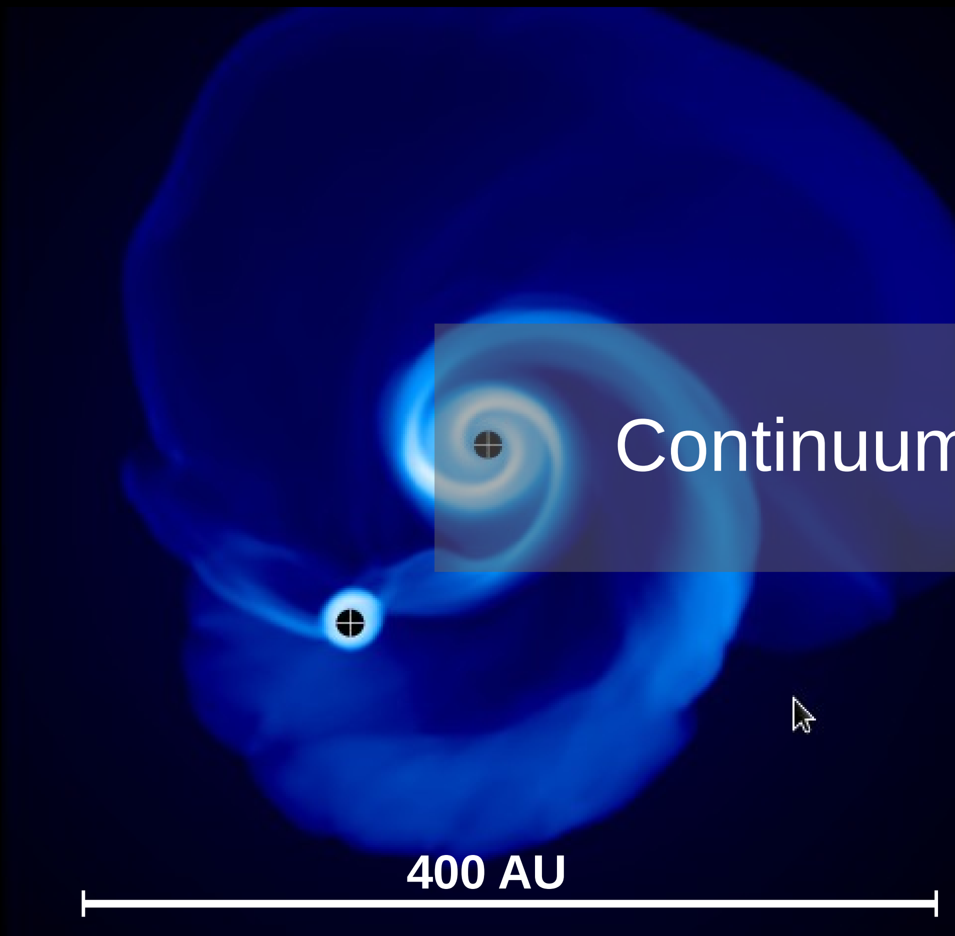
- Multiplicity key component of star and planet formation
  - CMF → IMF scaling
  - Stable planetary systems
  - Evolution of multiples different?
- Large fraction of MS stars are multiple
- Most protostars form as multiples
  - Typically found at R > 600 AU
- Field star separations must have evolved
  - Where/how are the companions born?
- Few proto-binaries known to have separations < 500 AU
  - Lack of multiplicity suggested (Maury+2010)
  - Observations with enough resolution lacking



Lada 2006
Raghavan+10
50 < R < 5000 AU Chen+13

Protostellar Disks: Big or Small?

Large, massive – Gravitaitionally Unstable



e.g., Vorobyov 2010, Kratter+2010
Little or no magnetic braking (e.g. TSC 1984)

Continuum of disk sizes?

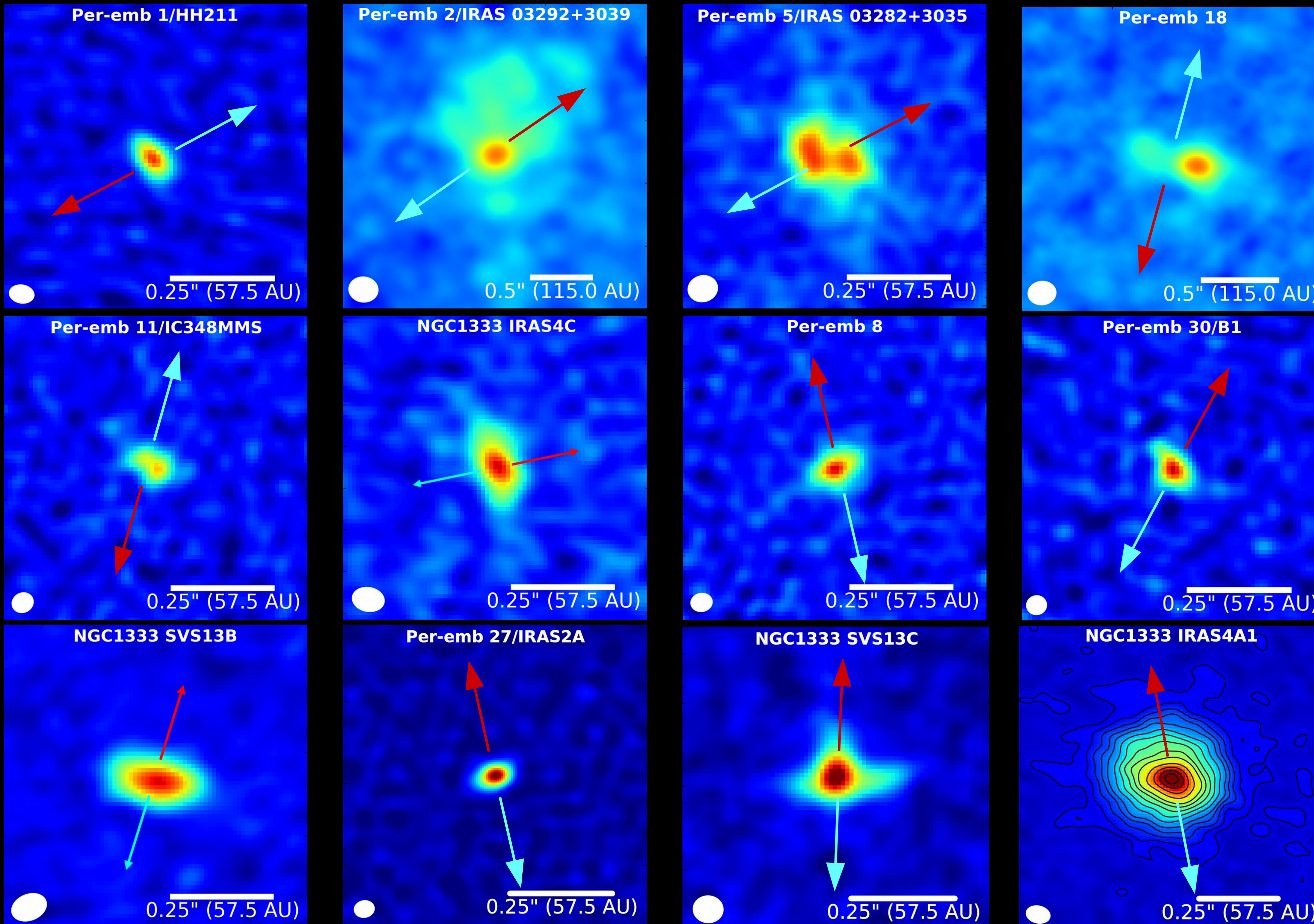
Small, low-mass, and/or no rotational support

Adapted from Kratter+2010

Significant magnetic braking? Allen+2003, Galli2006, Mellon & Li 2008, et al.

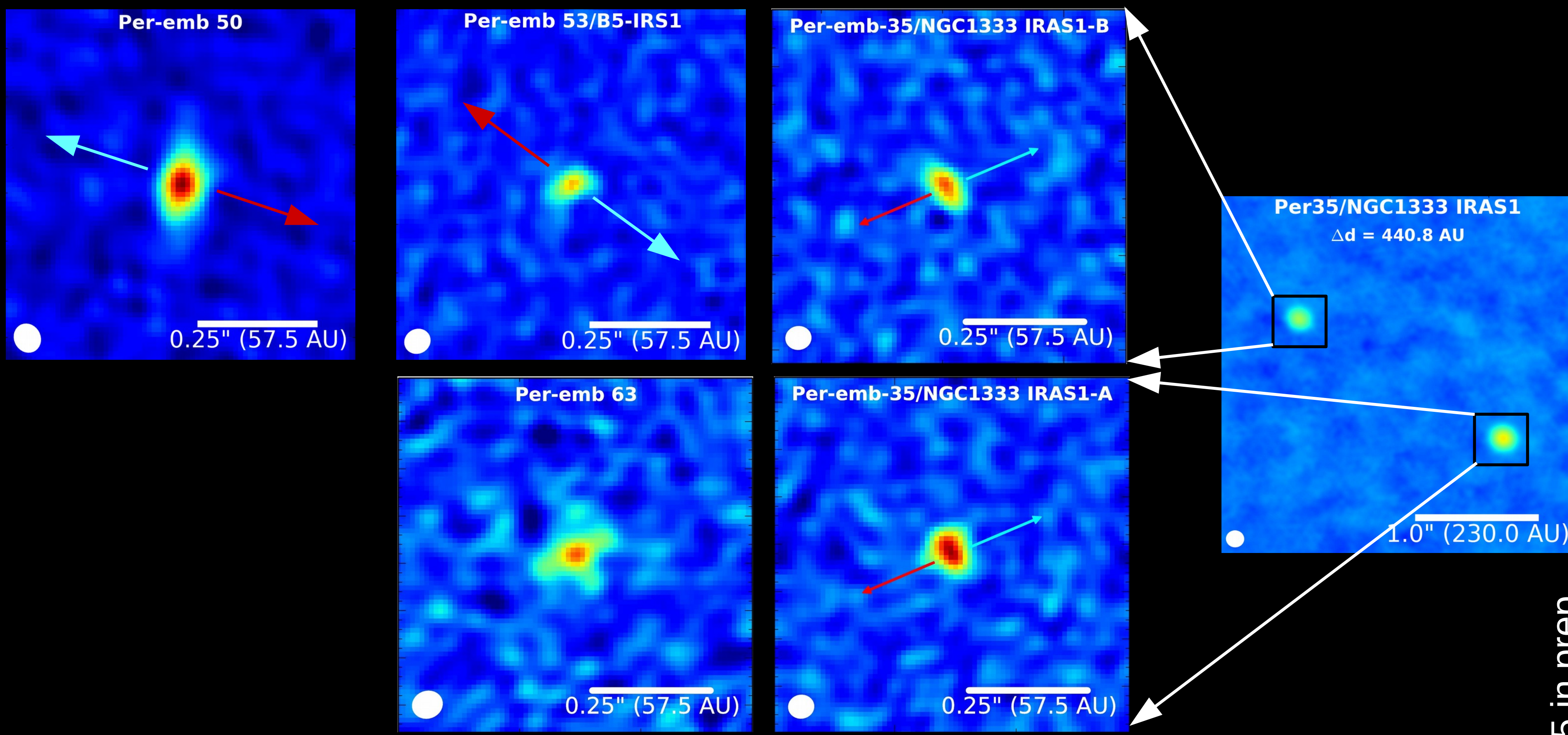
- Youngest protostellar disks have long eluded direct observation
  - Only four known Class 0 disks: L1527, VLA 1623, HH212, RCrA IRS7B

VANDAM Class 0 Disk Candidates



Segura-Cox+2015 in prep.

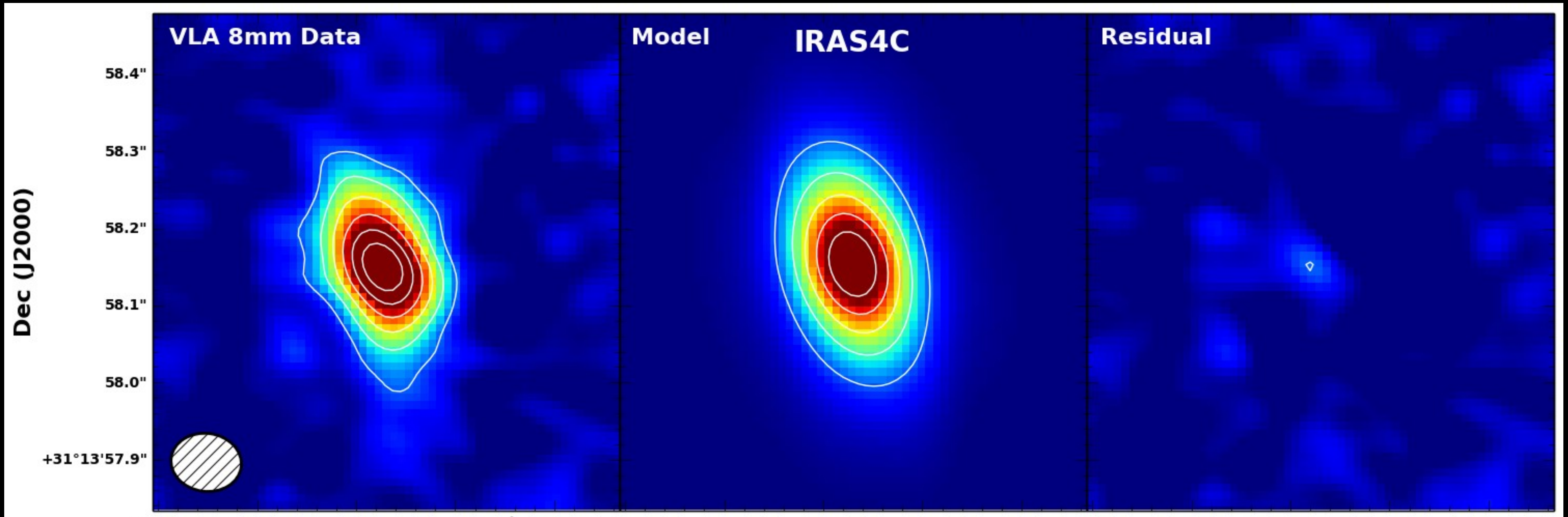
VANDAM Class I Disk Candidates



Segura-Cox+2015 in prep.

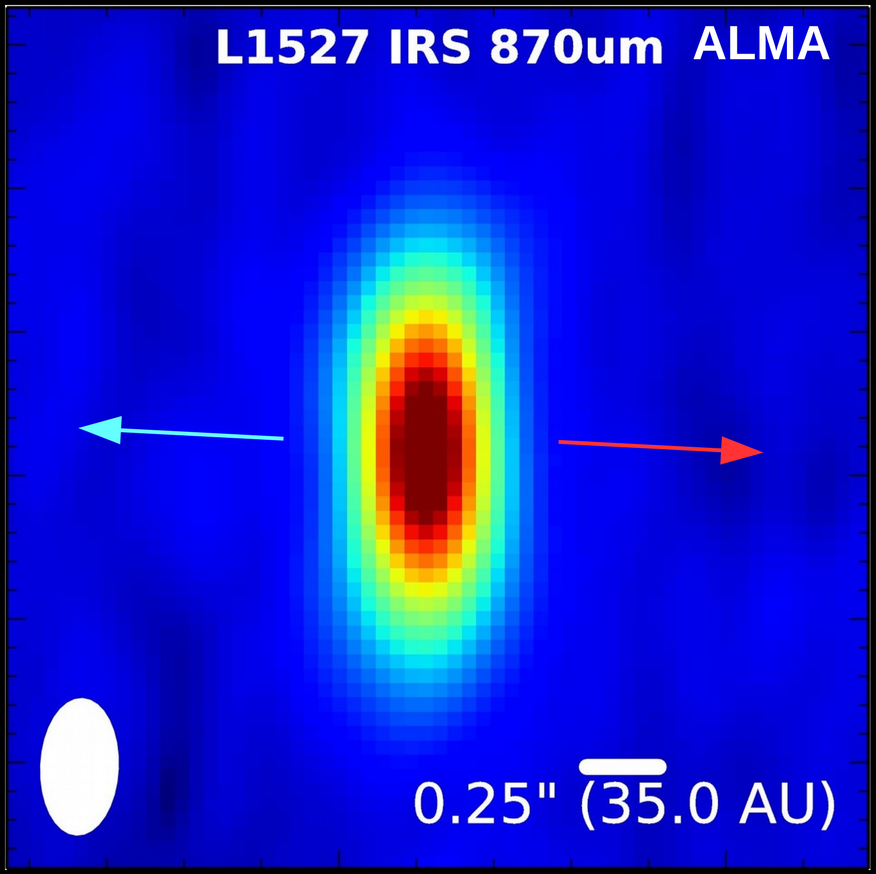
VANDAM Disk Candidates

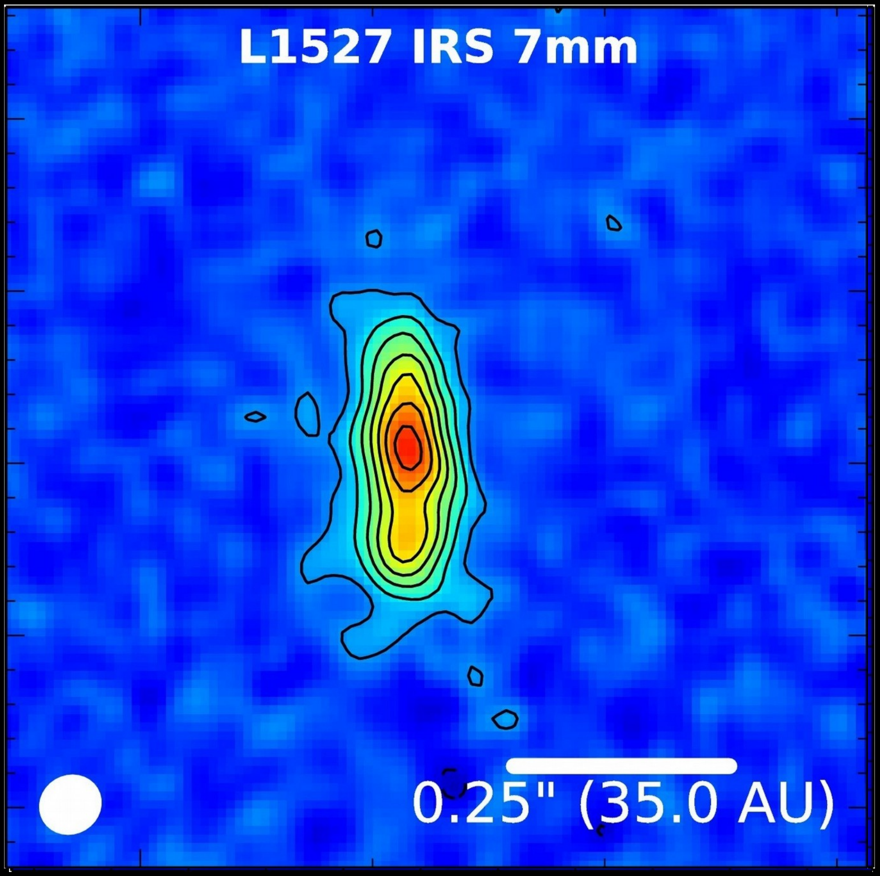
- Resolved structures consistent with disks for 16/70 Class 0/I
  - ~11/43 for Class 0 (youngest) sources; 6/37 Class I
- Power-law disk models indicate 8 mm radii 10 AU – 30 AU
- Need to be confirmed kinematically
- Multi-wavelength dust continuum and molecular line needed
  - MASSES survey with SMA (PI: Mike Dunham)
  - Molecular line complement to VANDAM



Segura-Cox+2015 in prep.

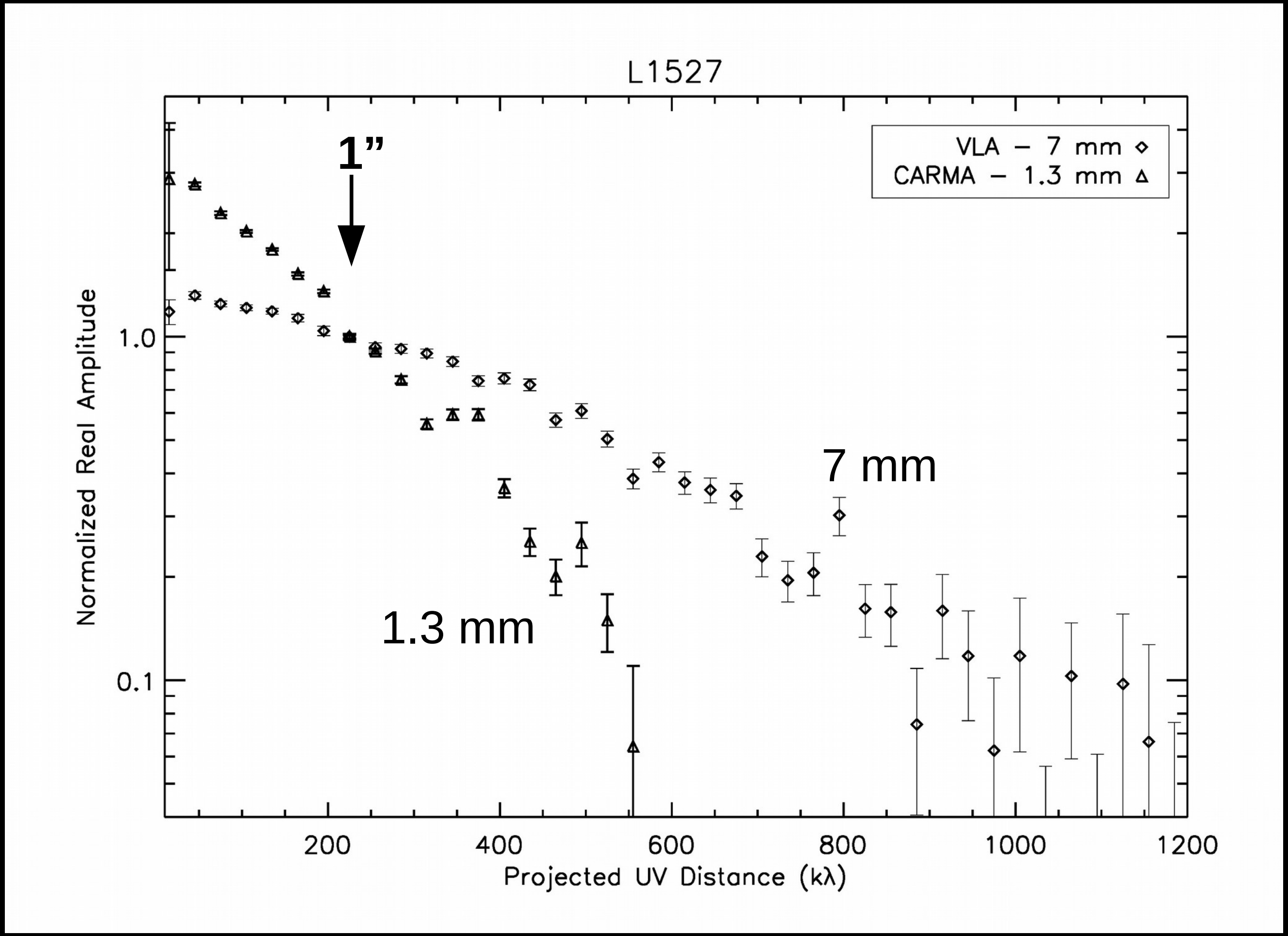
VANDAM Disk Candidates Sizes





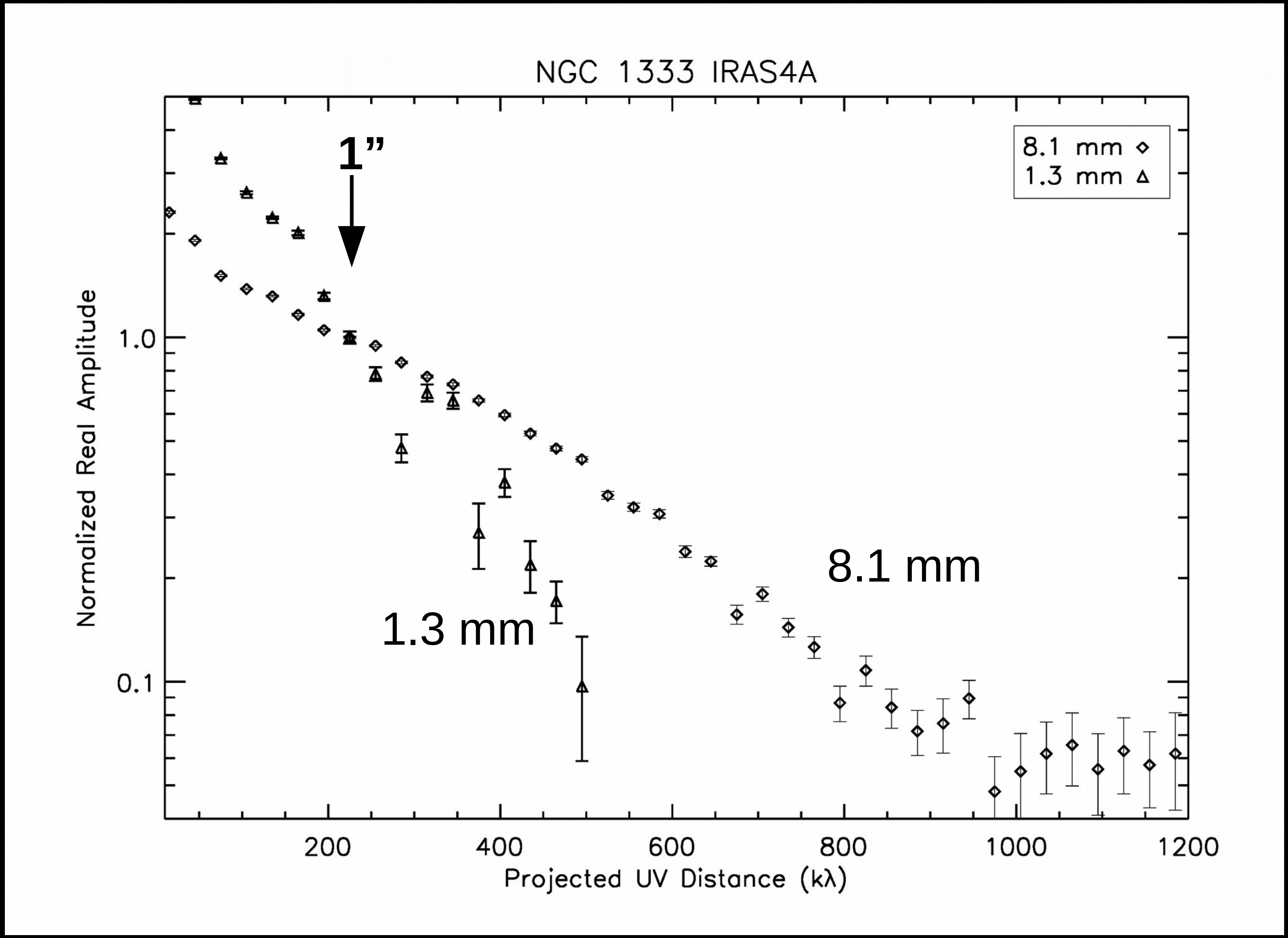
- Dust emission more compact at 8 mm vs 870 micron; 0.26” vs 0.62”
  - Surface brightness sensitivity limit/radial drift of dust grains
  - Also seen in Class II disks (e.g., Perez+2012)
- Disk candidates likely larger than apparent size

Radial Distribution of Dust



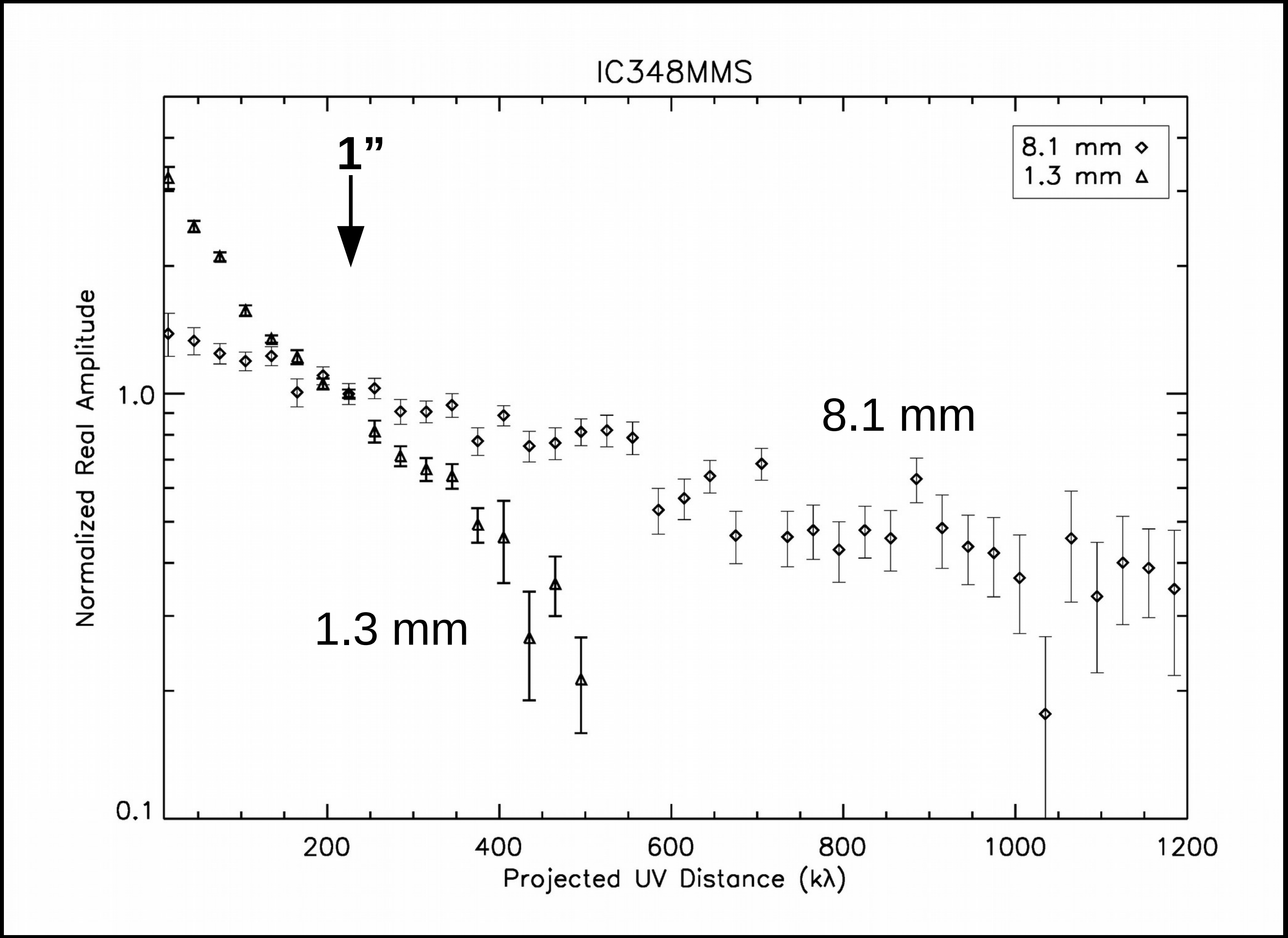
- Compare visibility amplitude data at 1.3 mm and 8.1 mm
  - Normalized at 200 kλ ~ 1”
  - 1.3 mm data drop faster, more spatially extended than 8.1 mm

Radial Distribution of Dust



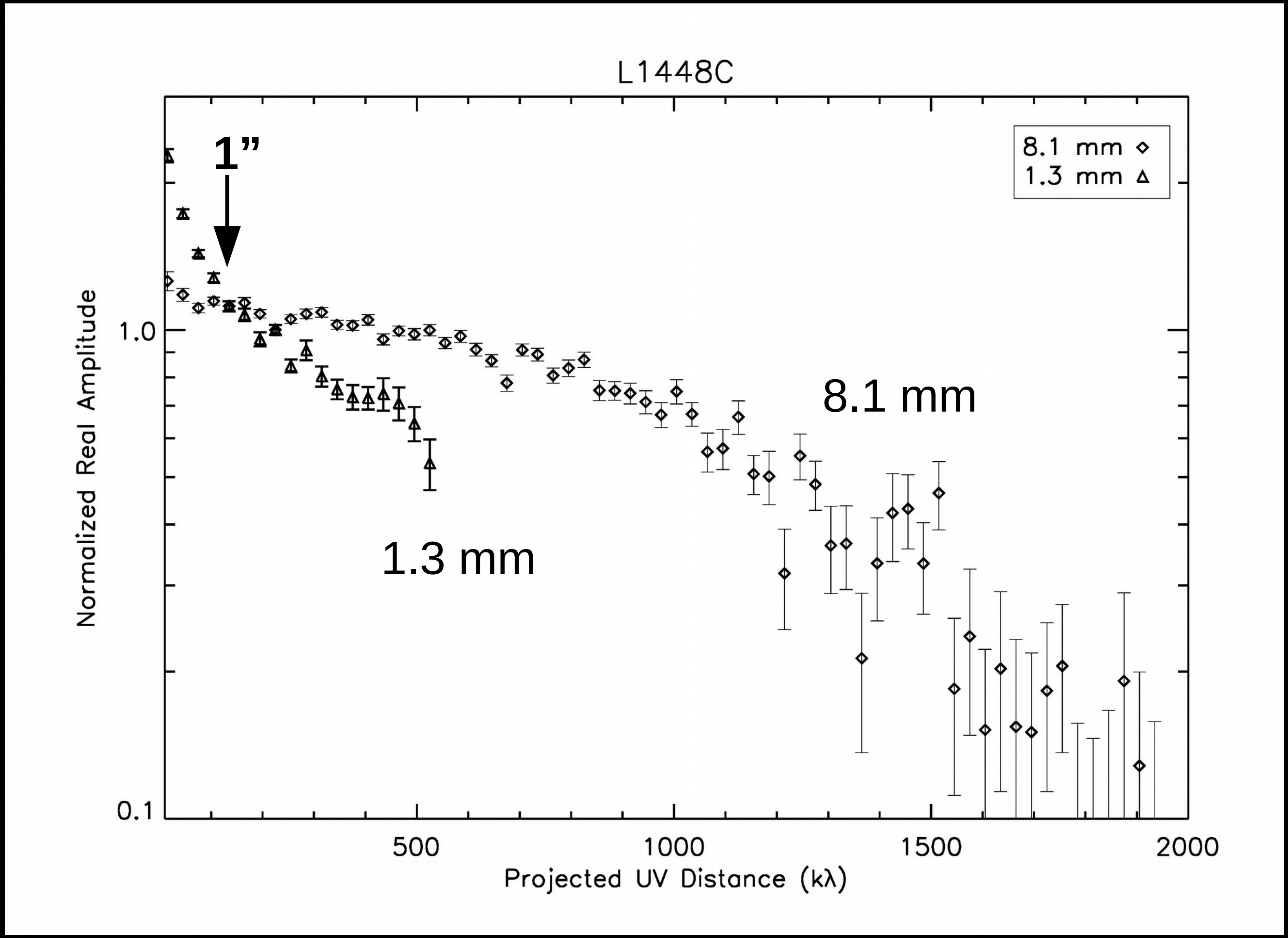
- Compare visibility amplitude data at 1.3 mm and 8.1 mm
  - Normalized at 200 kλ ~ 1”
  - 1.3 mm data drop faster, more spatially extended than 8.1 mm

Radial Distribution of Dust



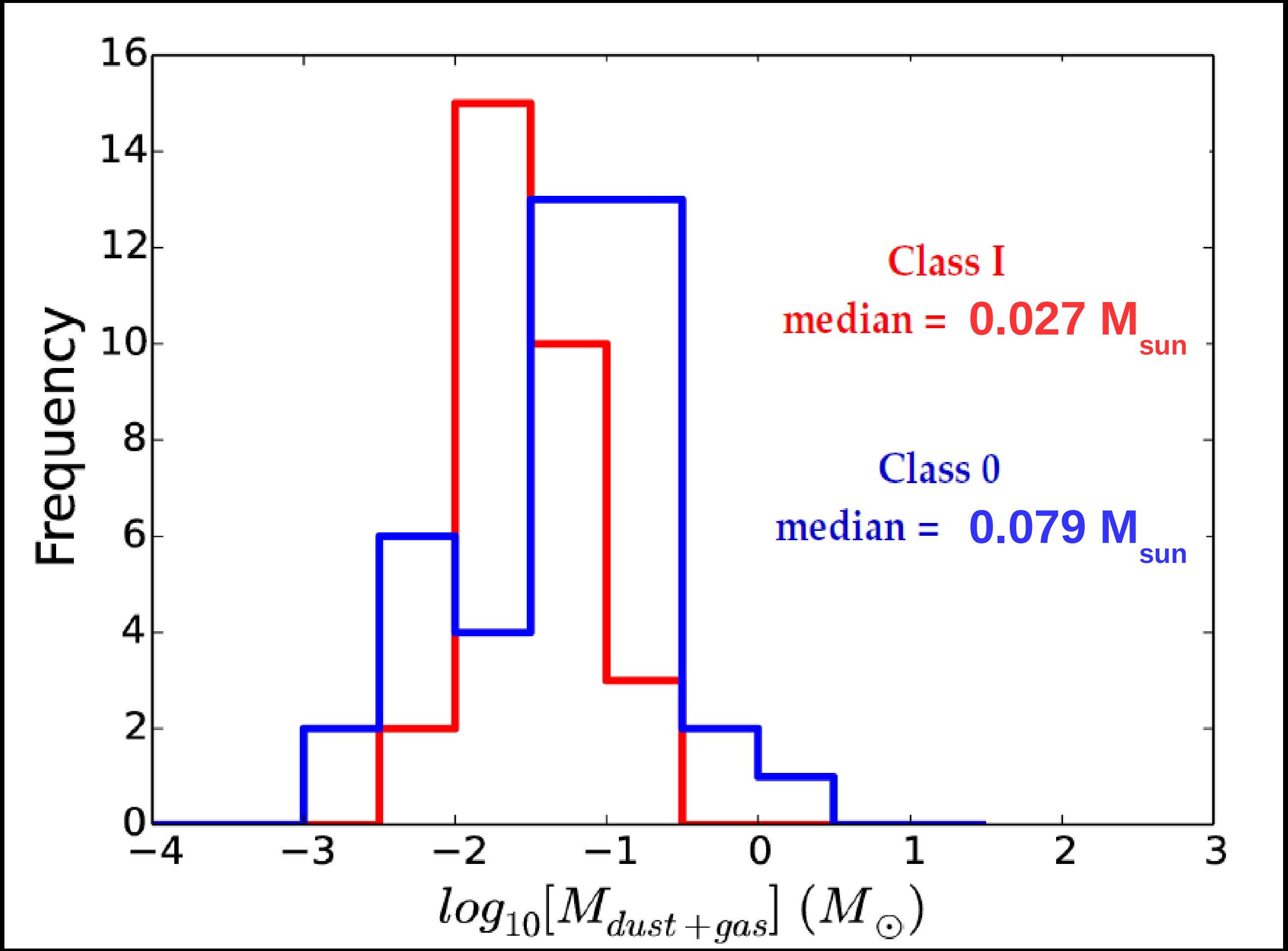
- Compare visibility amplitude data at 1.3 mm and 8.1 mm
  - Normalized at 200 kλ ~ 1”
  - 1.3 mm data drop faster, more spatially extended than 8.1 mm

Radial Distribution of Dust



- Compare visibility amplitude data at 1.3 mm and 8.1 mm
  - Normalized at 200 kλ ~ 1"
  - 1.3 mm data drop faster, more spatially extended than 8.1 mm
  - Evidence for grain growth and radial drift early, Class 0 phase

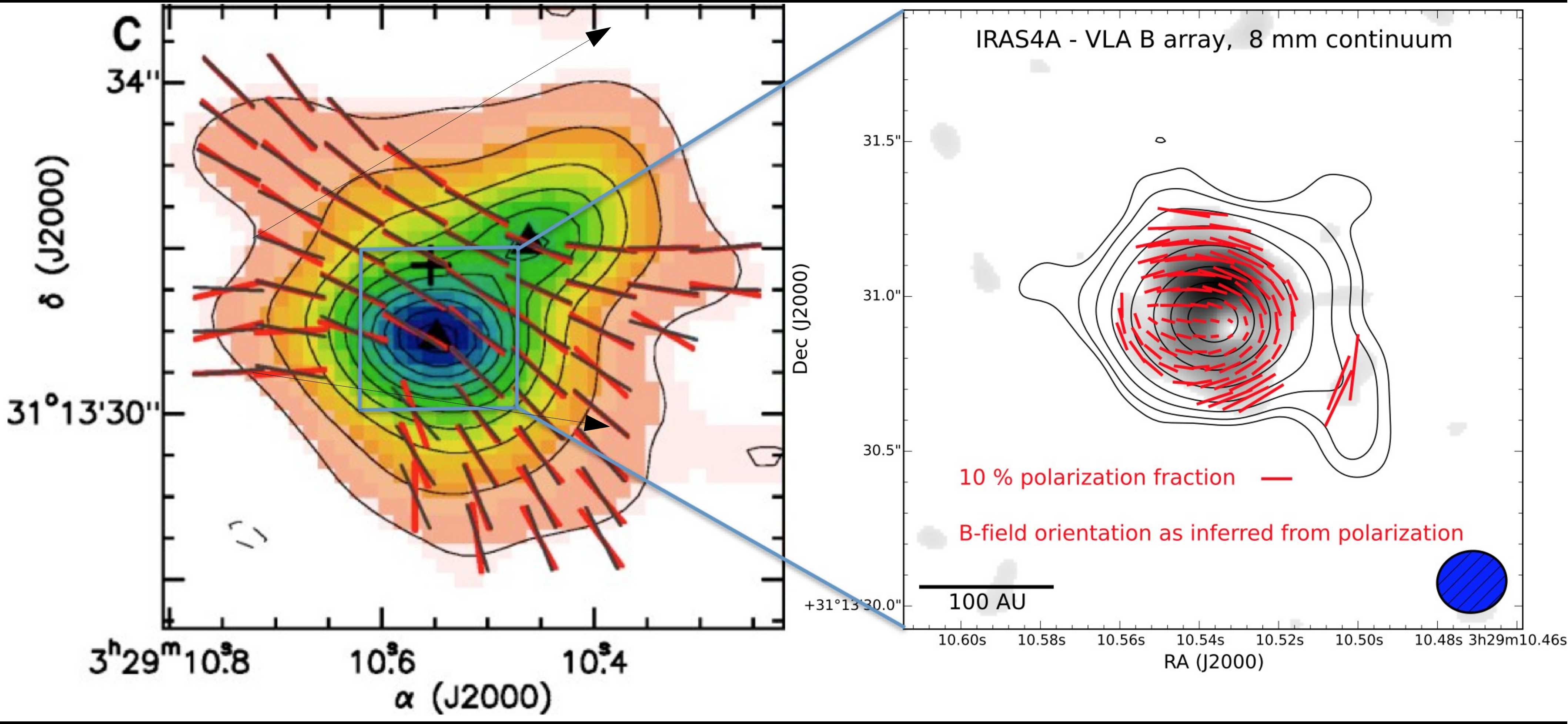
VANDAM 'Disk' Masses



Tobin+2016 in prep.

- Masses from 8 mm emission corrected for free-free contribution
  - Extrapolation from 4 cm and 6.4 cm data
  - Assume Ossenkopf & Henning 1994 at 1.3 mm, β = 1 to 8 mm

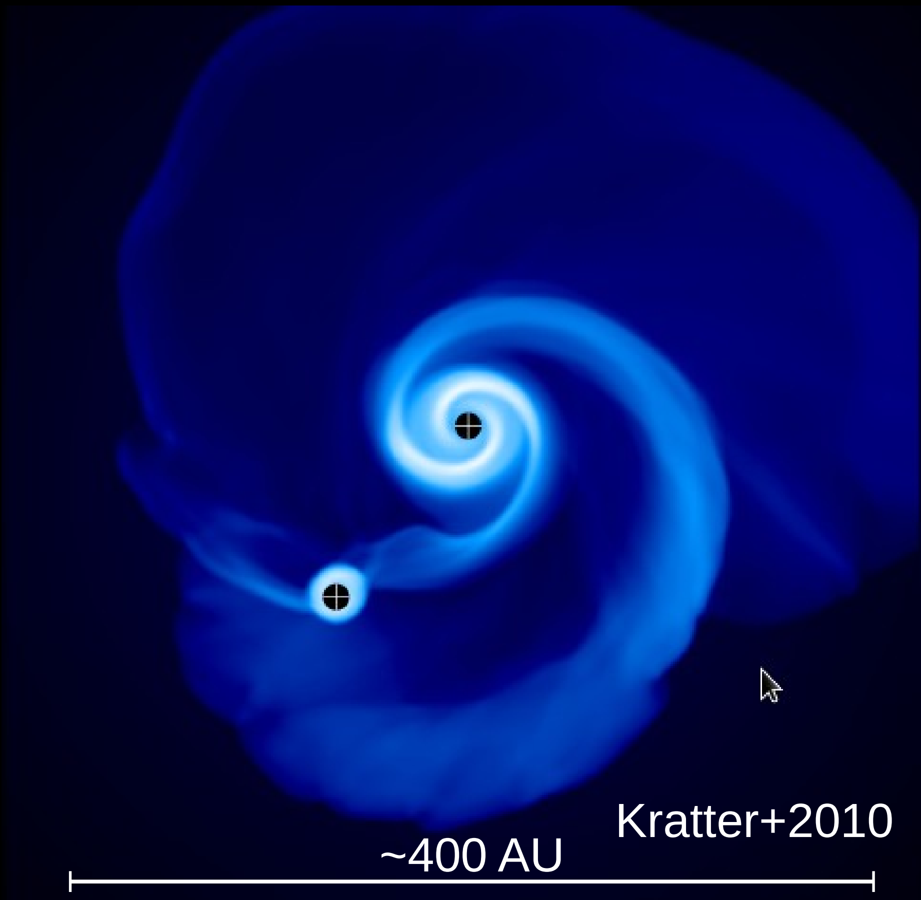
A Brief Aside: 8 mm Polarization



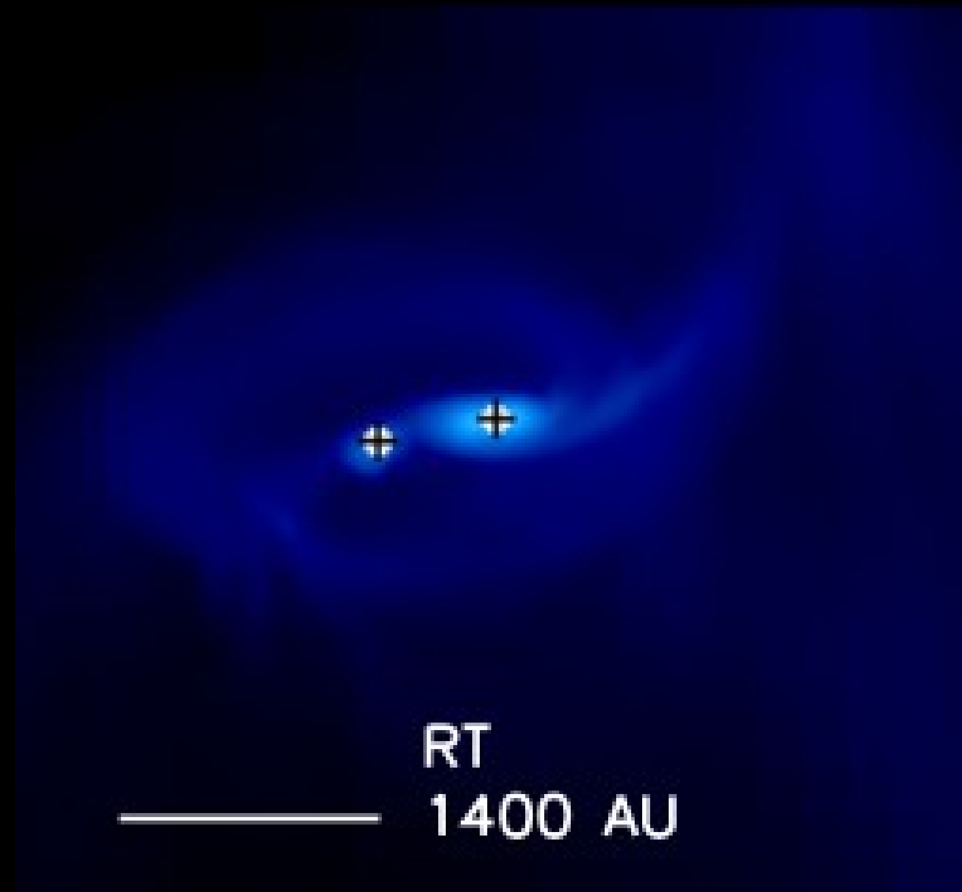
Cox et al. submitted

Multiple System Formation

Disk Fragmentation



Turbulent Fragmentation

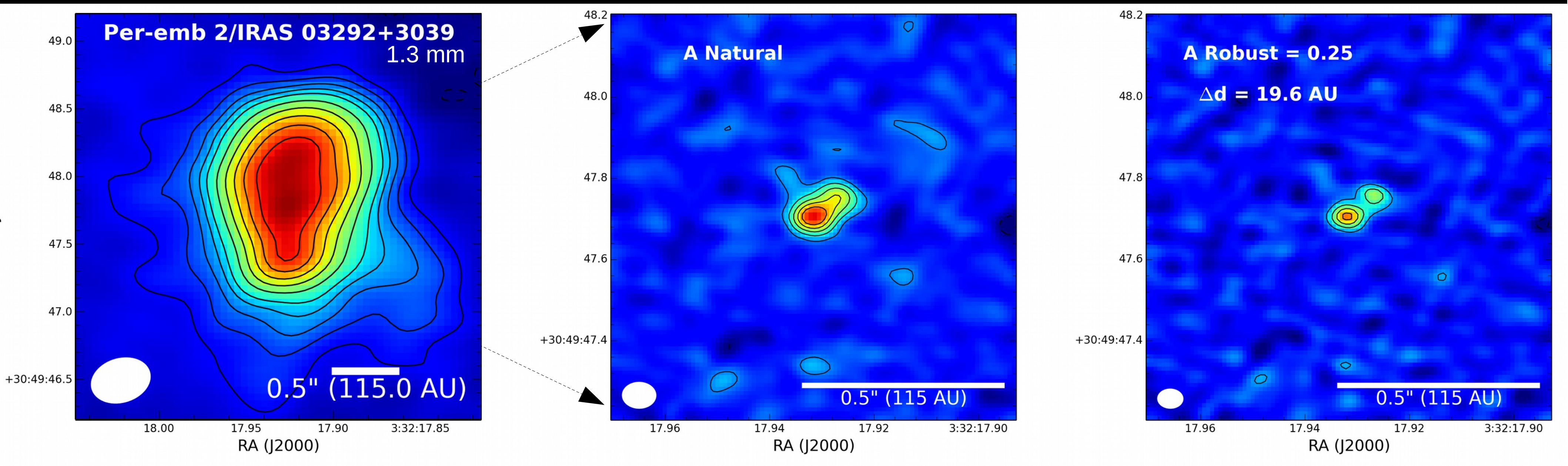


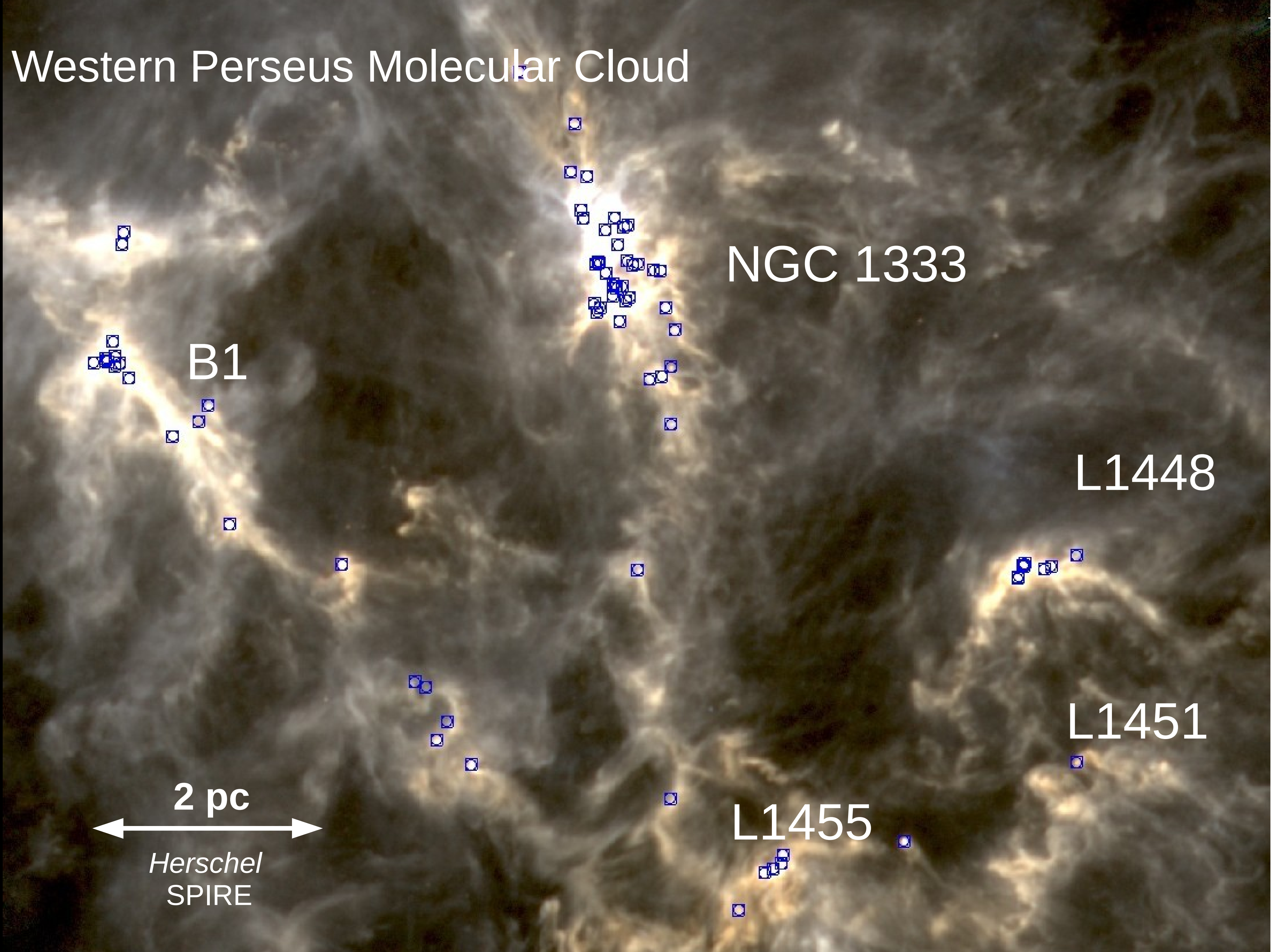
Offner+2010

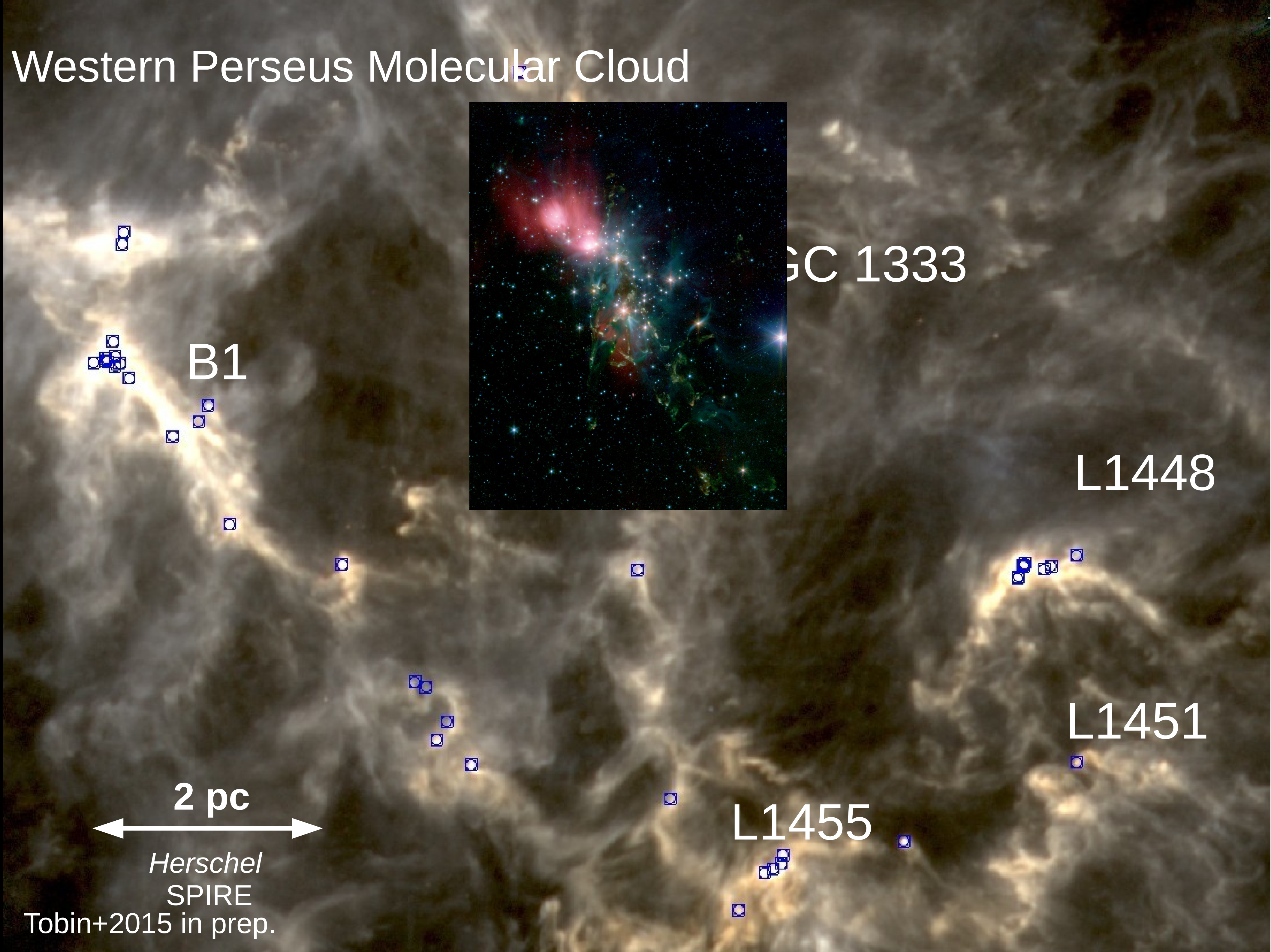
- Disk fragmentation – form in disk directly
  - Replenishment needed to grow companion – early formation
- Turbulent fragmentation – form in cloud and migrate in
  - Rapid migration needed – 2000 AU → 200 AU in 10 kyr

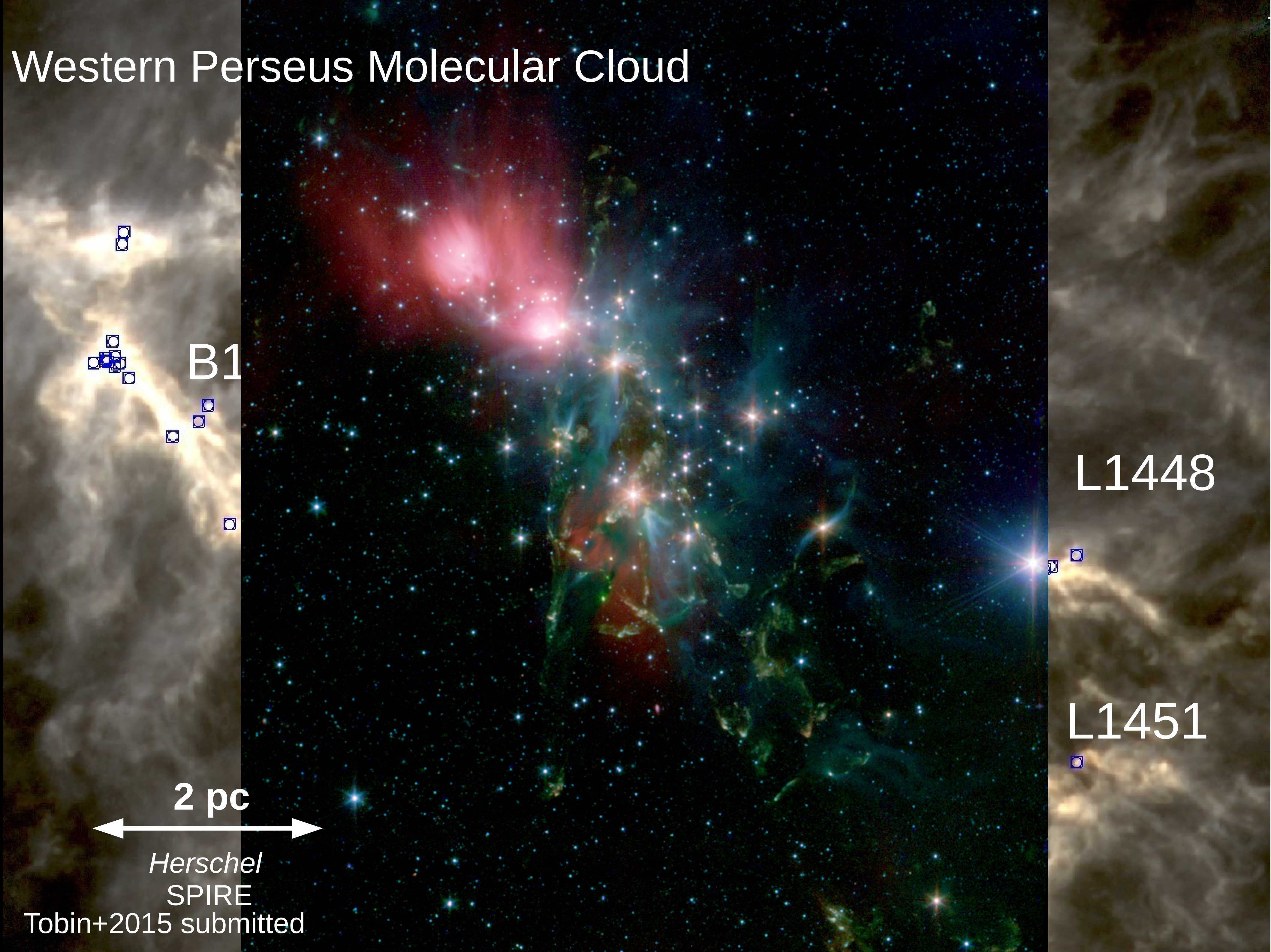
Evidence for Fragmenting Disks

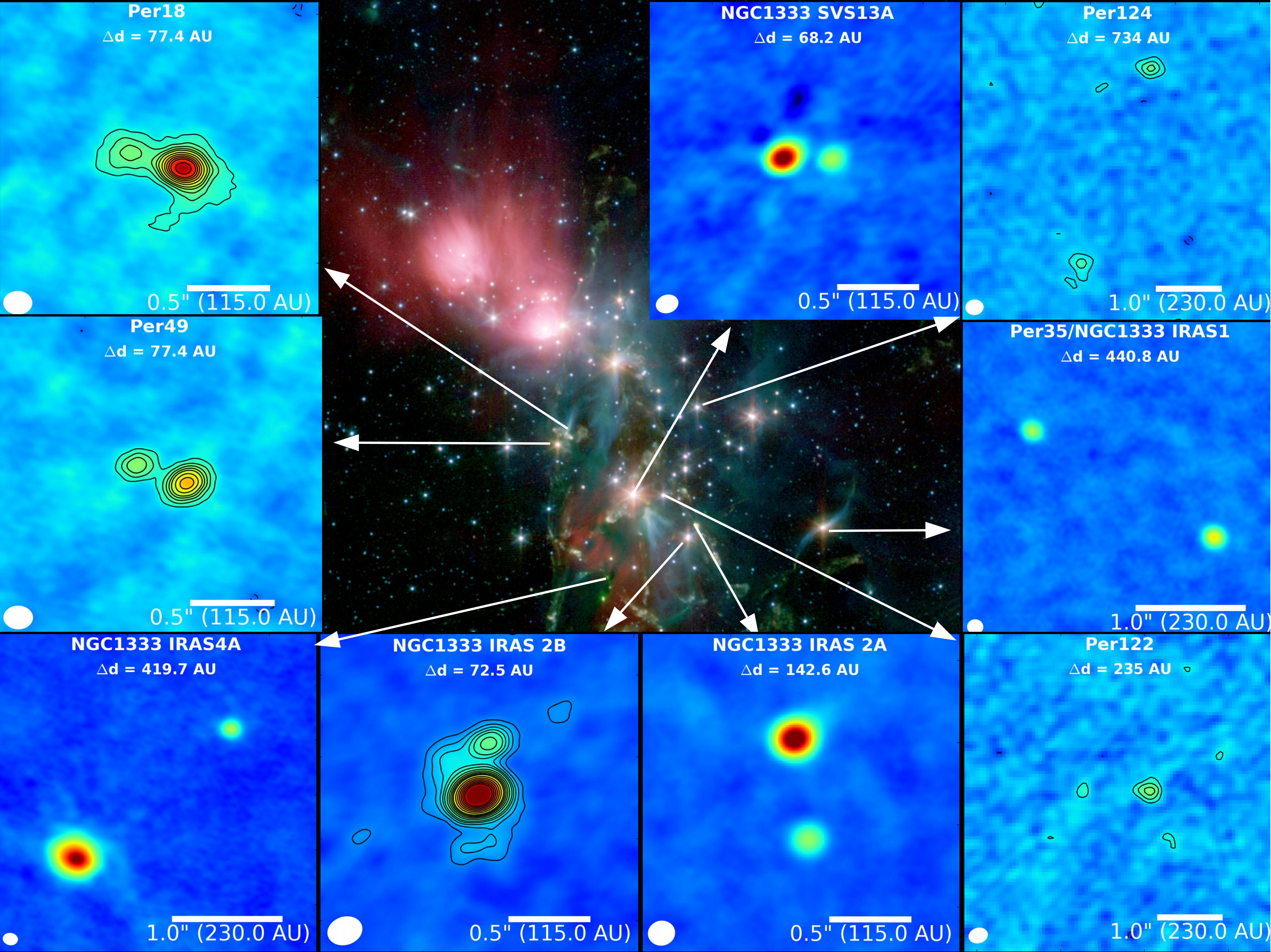
- Evidence of fragmentation within resolved structures found
  - 3/43 Class 0 systems
- Gravitationally unstable disks likely transient (Stamatellos+2009)
  - Fragmentation greatly reduces disk mass
  - Unstable disks only last ~30 kyr
- Candidate ~0.3 M_{sun} disk, with rotation observed
  - Evidence for substantial optical depth at 1.3 mm

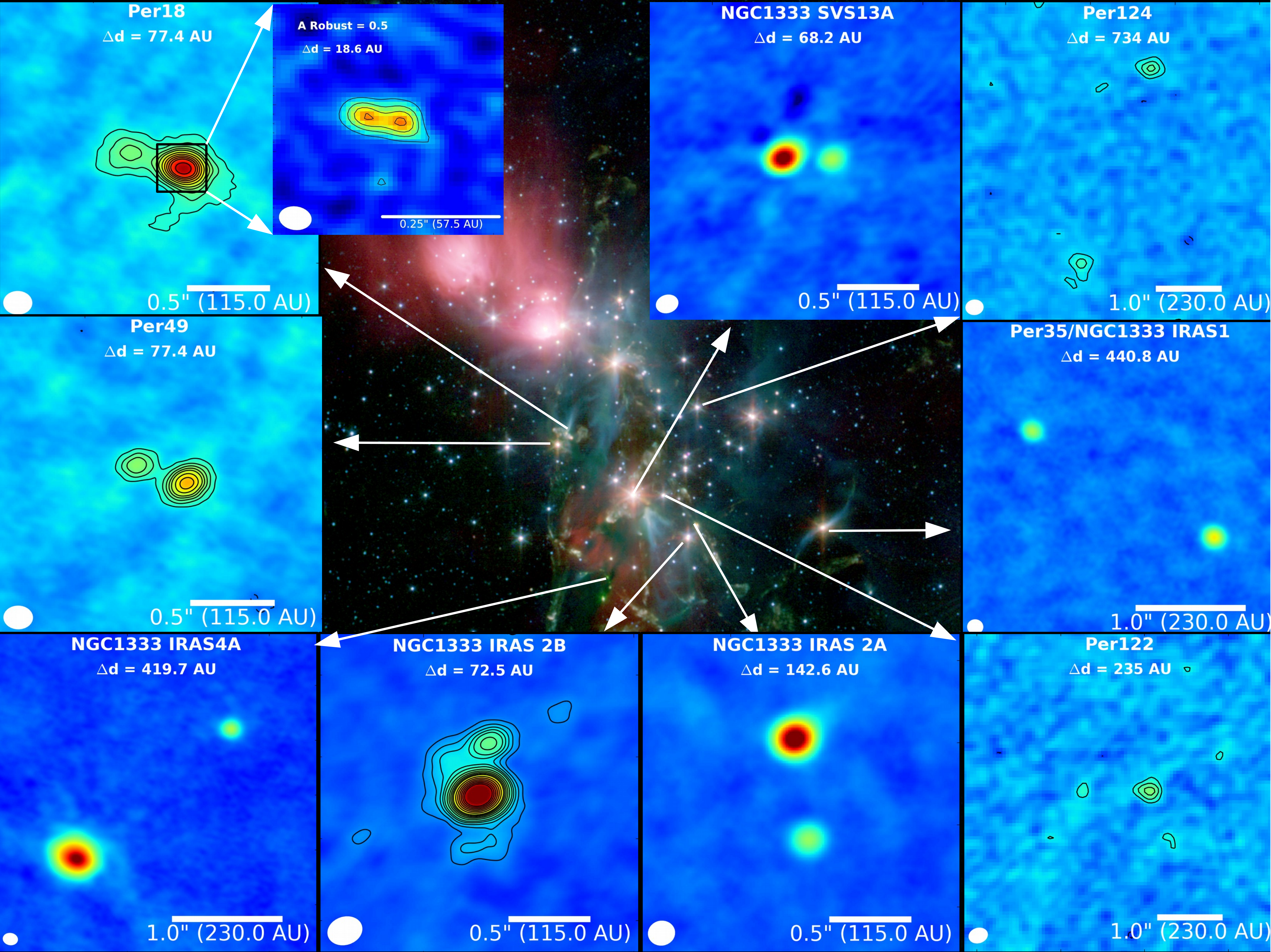



Western Perseus Molecular Cloud
NGC 1333
B1
L1448
L1451
L1455
2 pc
Herschel
SPIRE

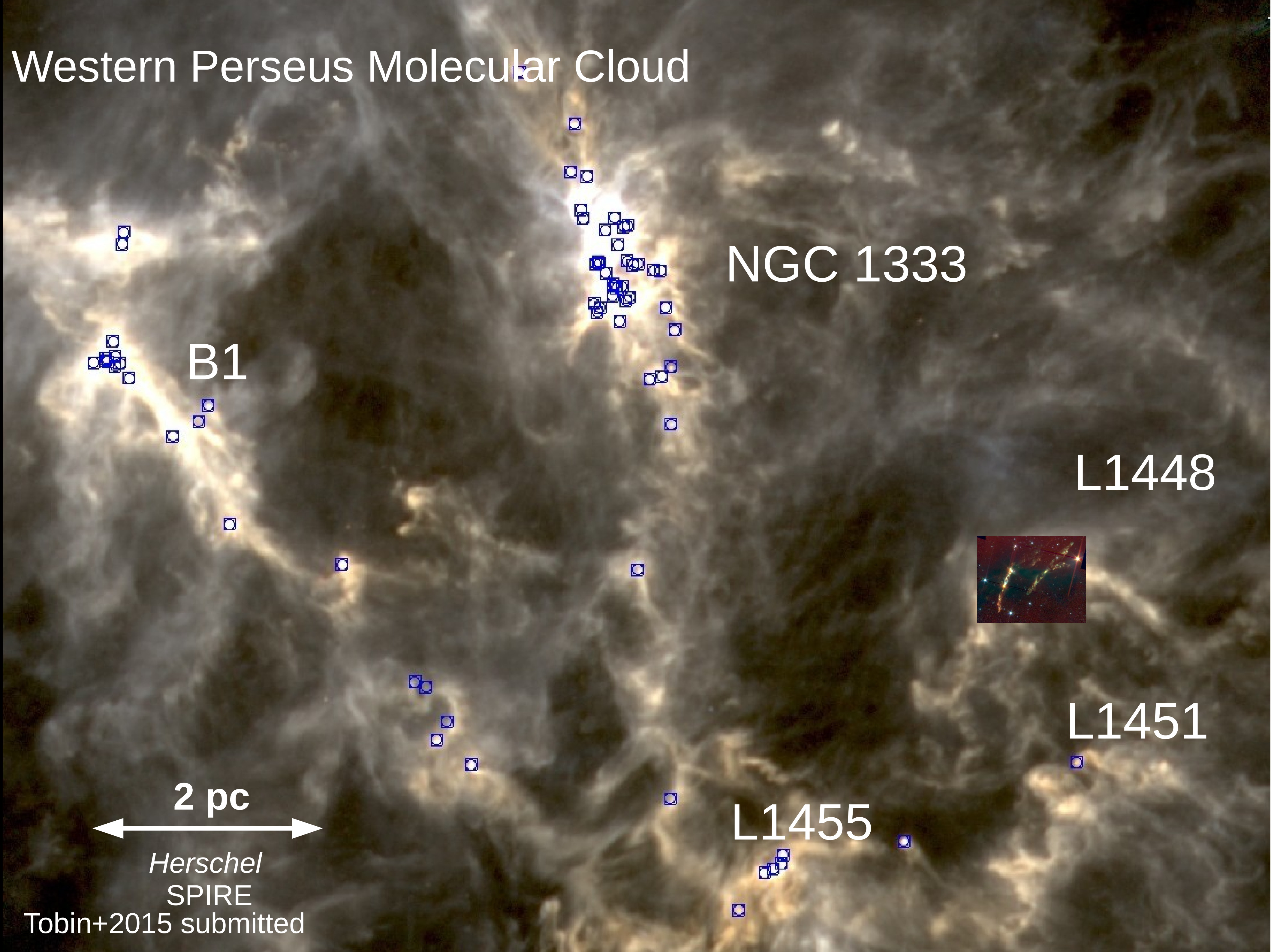

Western Perseus Molecular Cloud
GC 1333
B1
L1448
L1451
L1455
2 pc
Herschel
SPIRE
Tobin+2015 in prep.

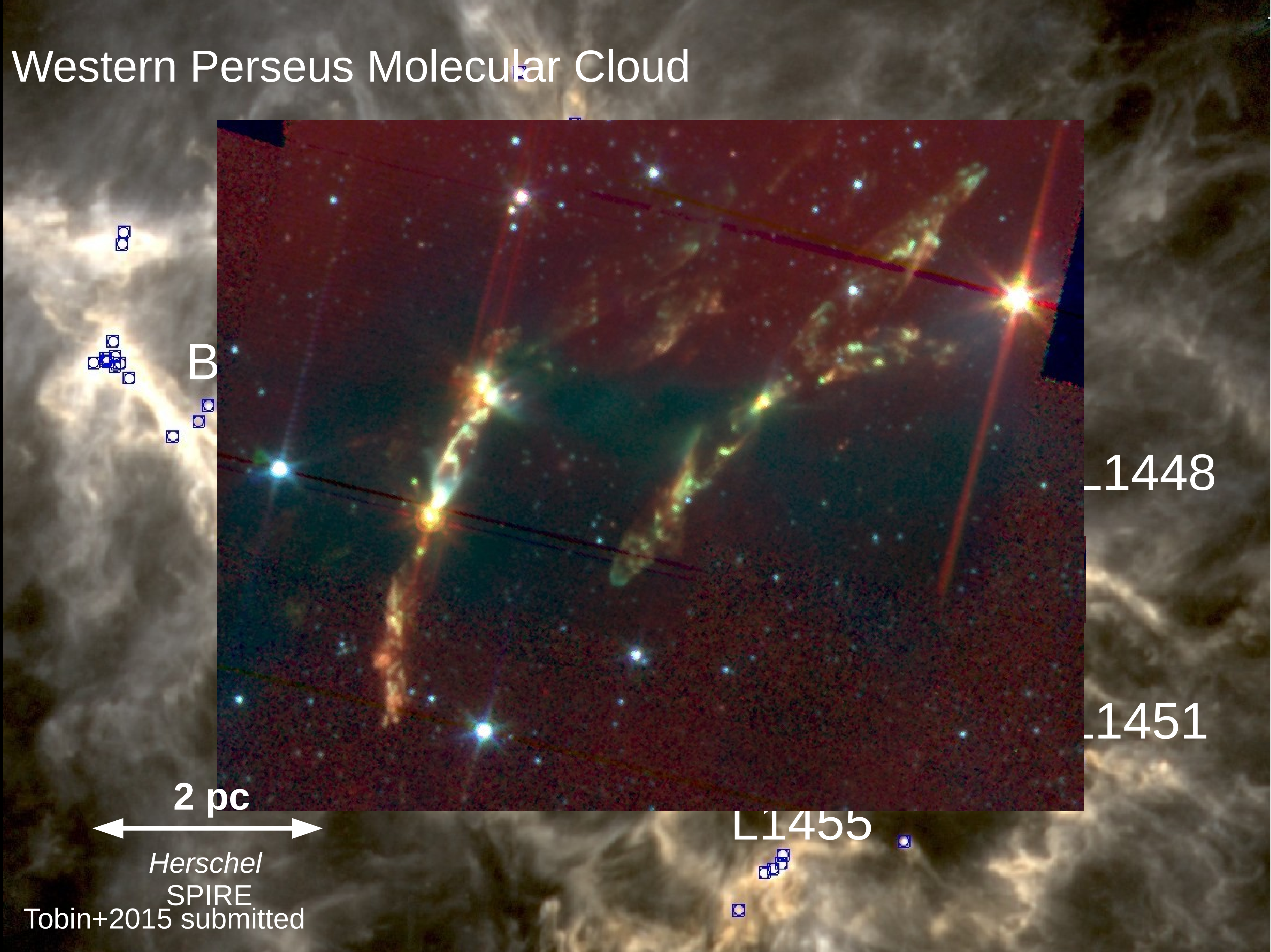

Western Perseus Molecular Cloud
B1
L1448
L1451
2 pc
Herschel
SPIRE
Tobin+2015 submitted

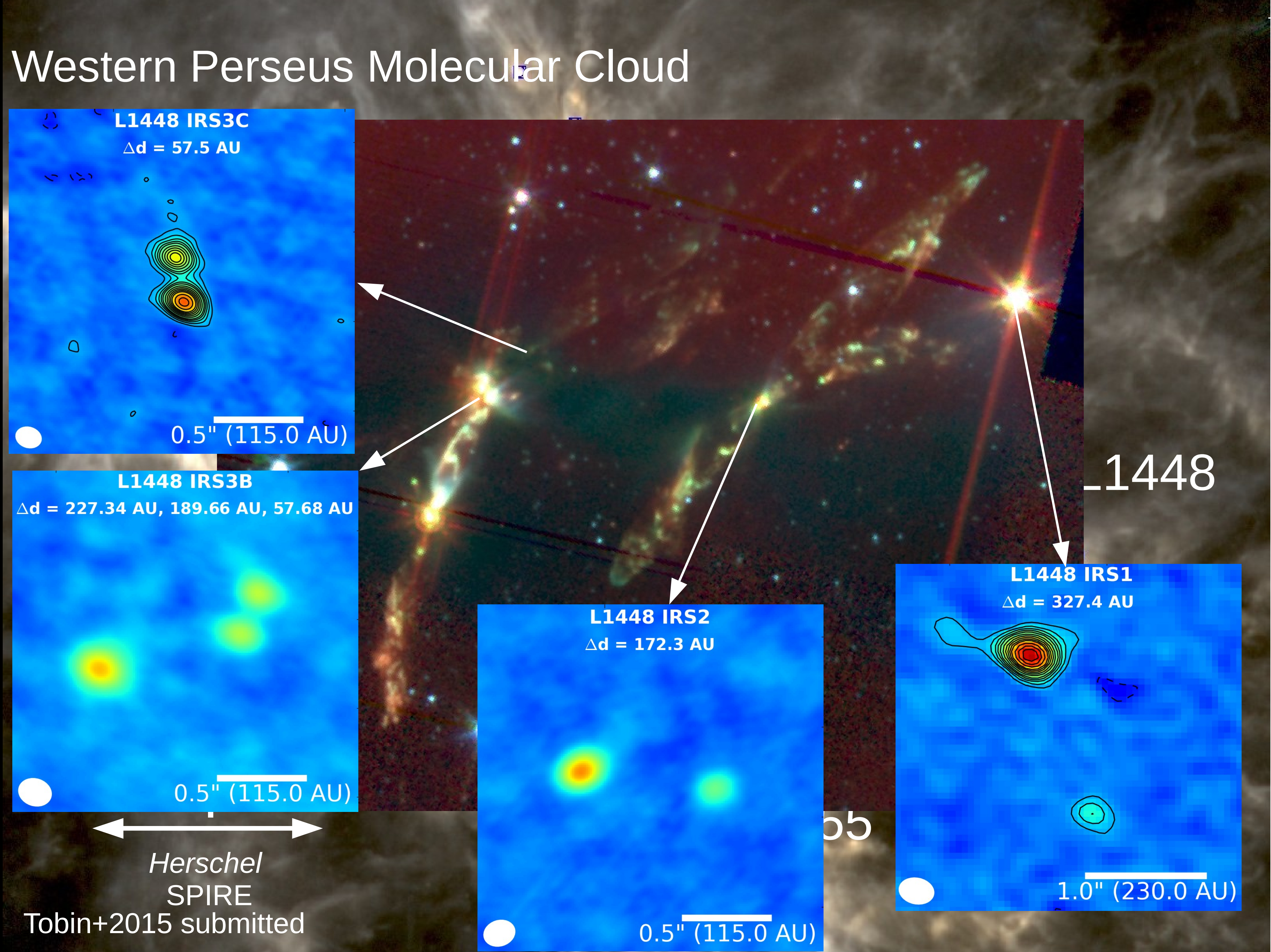

Per18
Δd = 77.4 AU
0.5" (115.0 AU)
Per49
Δd = 77.4 AU
0.5" (115.0 AU)
NGC1333 SVS13A
Δd = 68.2 AU
0.5" (115.0 AU)
Per124
Δd = 734 AU
1.0" (230.0 AU)
Per35/NGC1333 IRAS1
Δd = 440.8 AU
1.0" (230.0 AU)
NGC1333 IRAS4A
Δd = 419.7 AU
1.0" (230.0 AU)
NGC1333 IRAS 2B
Δd = 72.5 AU
0.5" (115.0 AU)
NGC1333 IRAS 2A
Δd = 142.6 AU
0.5" (115.0 AU)
Per122
Δd = 235 AU
1.0" (230.0 AU)



Per18
Δd = 77.4 AU
0.5" (115.0 AU)
A Robust = 0.5
Δd = 18.6 AU
0.25" (57.5 AU)
NGC1333 SVS13A
Δd = 68.2 AU
0.5" (115.0 AU)
Per124
Δd = 734 AU
1.0" (230.0 AU)
Per49
Δd = 77.4 AU
0.5" (115.0 AU)
Per35/NGC1333 IRAS1
Δd = 440.8 AU
1.0" (230.0 AU)
NGC1333 IRAS4A
Δd = 419.7 AU
1.0" (230.0 AU)
NGC1333 IRAS 2B
Δd = 72.5 AU
0.5" (115.0 AU)
NGC1333 IRAS 2A
Δd = 142.6 AU
0.5" (115.0 AU)
Per122
Δd = 235 AU
1.0" (230.0 AU)

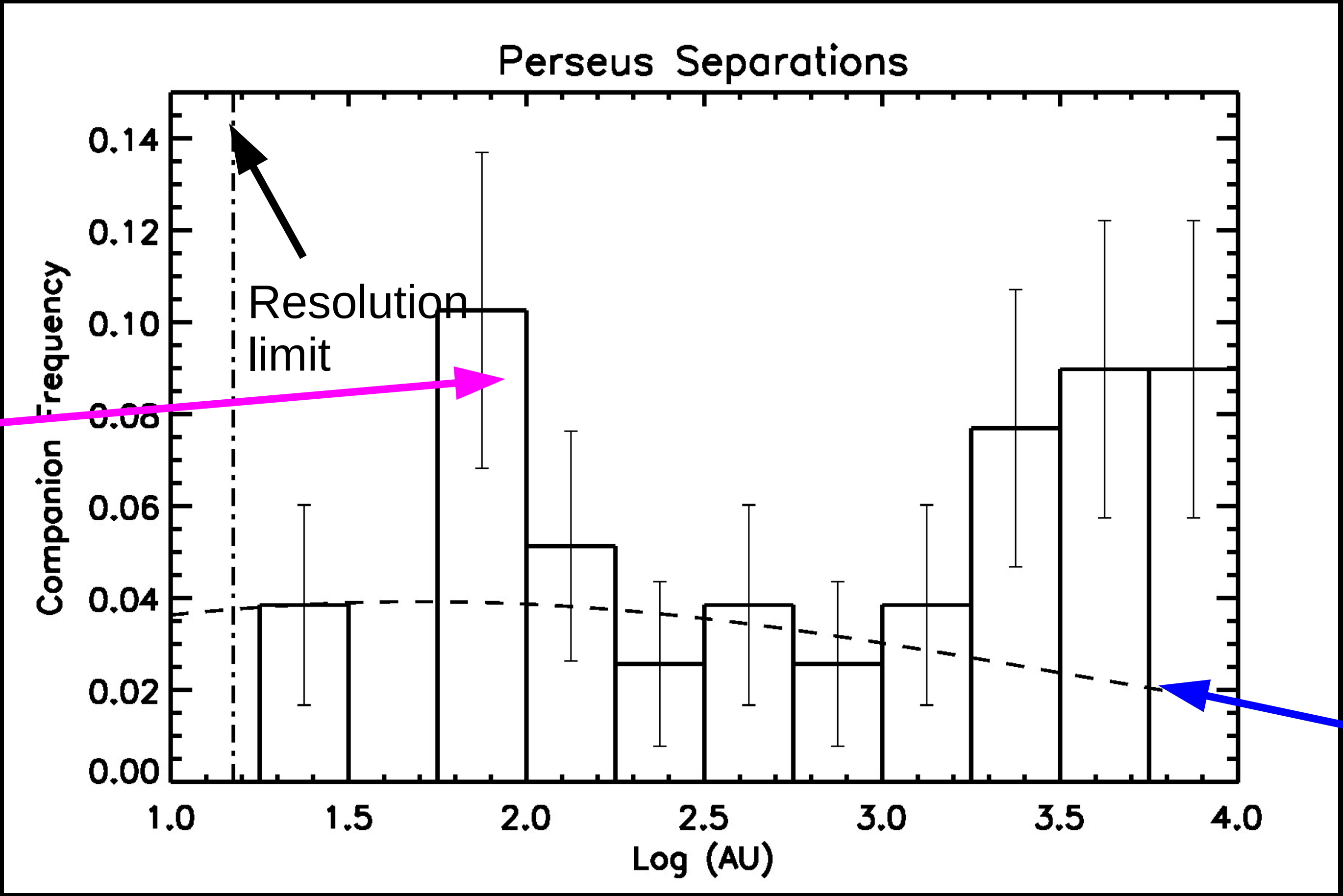

Western Perseus Molecular Cloud
NGC 1333
B1
L1448
L1451
L1455
2 pc
Herschel
SPIRE
Tobin+2015 submitted


Western Perseus Molecular Cloud
B
1448
1451
L1455
2 pc
Herschel
SPIRE
Tobin+2015 submitted


Western Perseus Molecular Cloud
L1448 IRS3C
Δd = 57.5 AU
0.5" (115.0 AU)
L1448 IRS3B
Δd = 227.34 AU, 189.66 AU, 57.68 AU
0.5" (115.0 AU)
L1448 IRS2
Δd = 172.3 AU
0.5" (115.0 AU)
L1448 IRS1
Δd = 327.4 AU
1.0" (230.0 AU)
Herschel
SPIRE
Tobin+2015 submitted

Perseus Separation Distribution

Peak at scale of disks

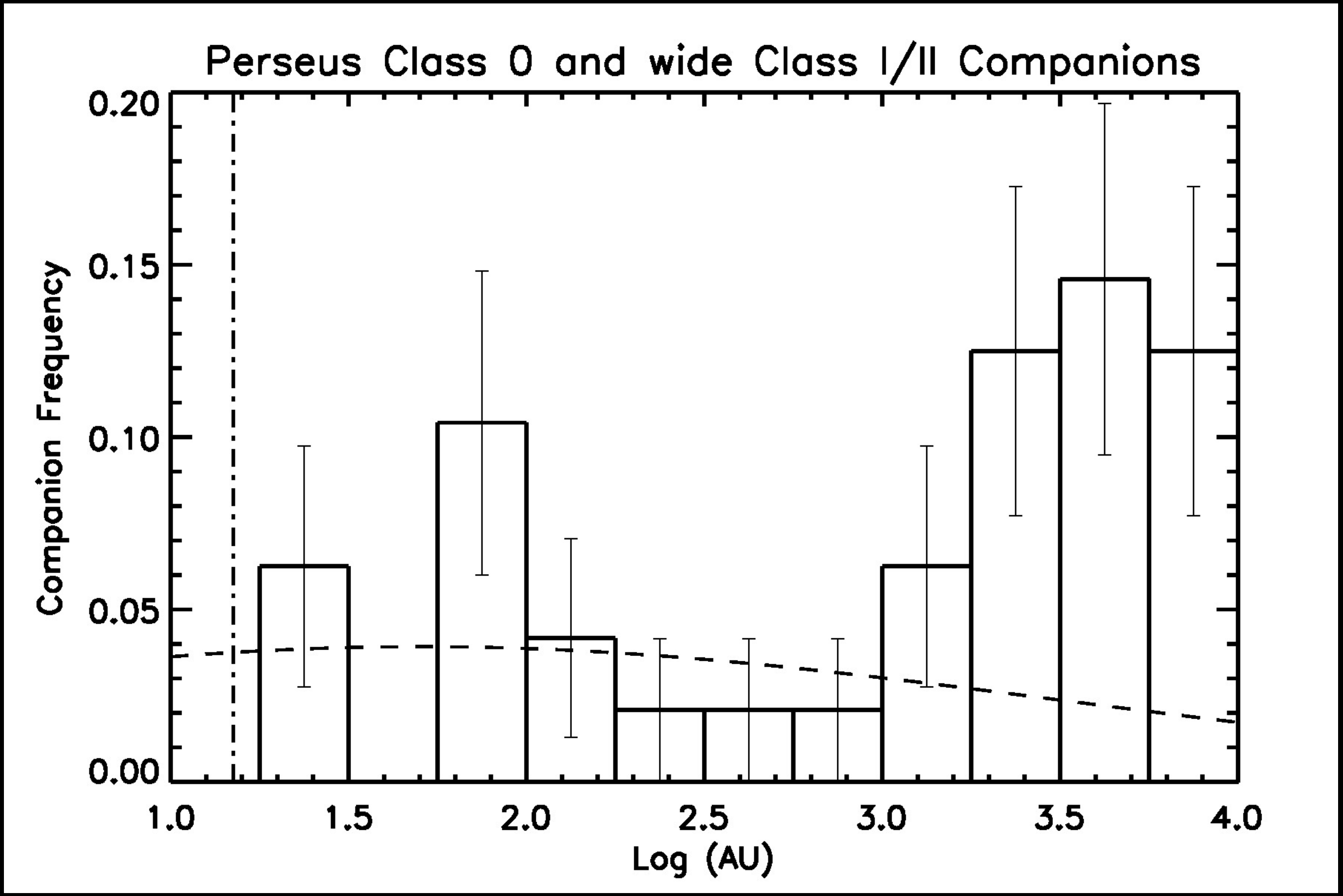


Field solar-type stars Raghavan+10

Tobin+2015 submitted

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

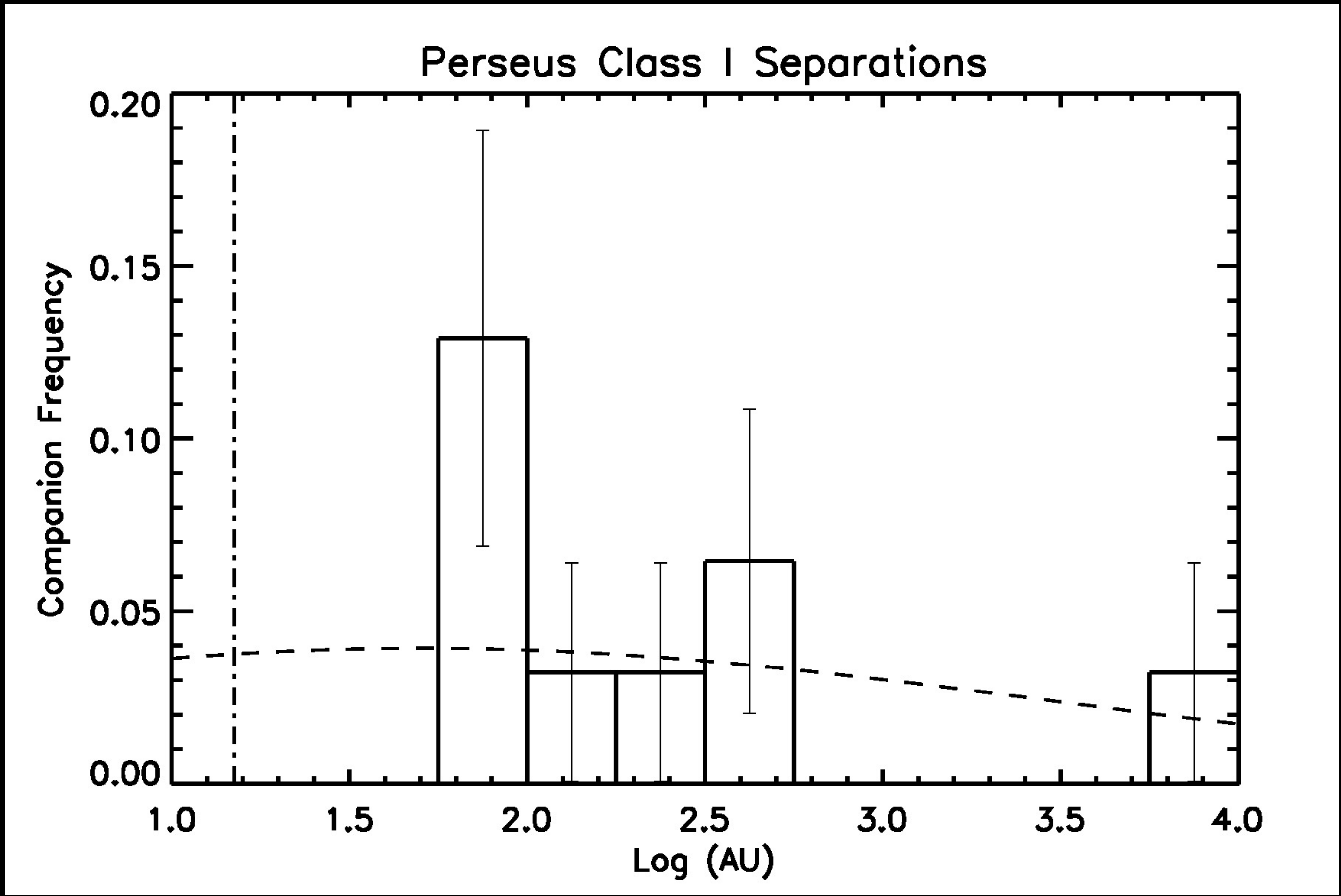
Perseus Separation Evolution



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 ~constant
    - Wide systems form unbound and disperse?

Multiplicity Statistics

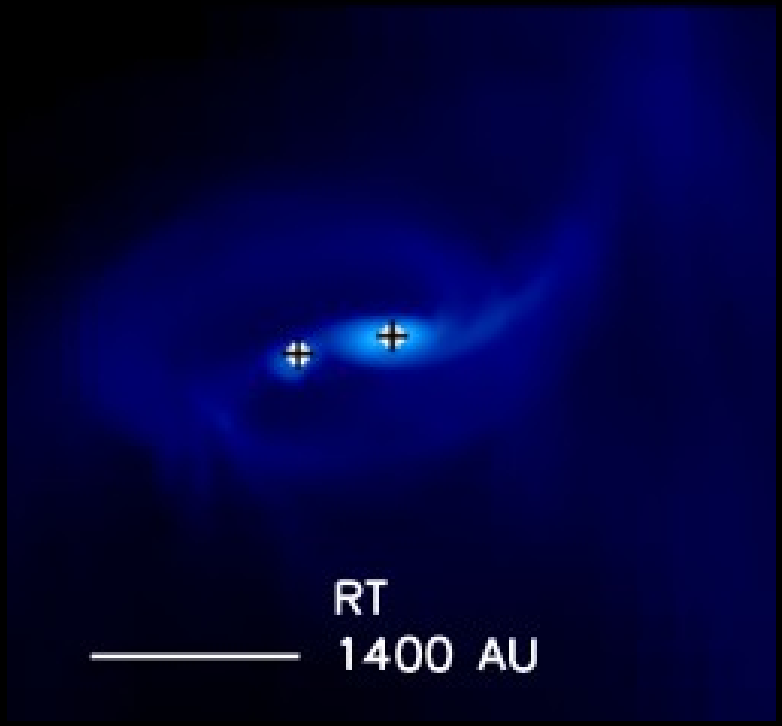
- Multiplicity Fraction (MF) and Companion Star Fraction (CSF) depend on scales of interest

- 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

Tobin+2015 submitted

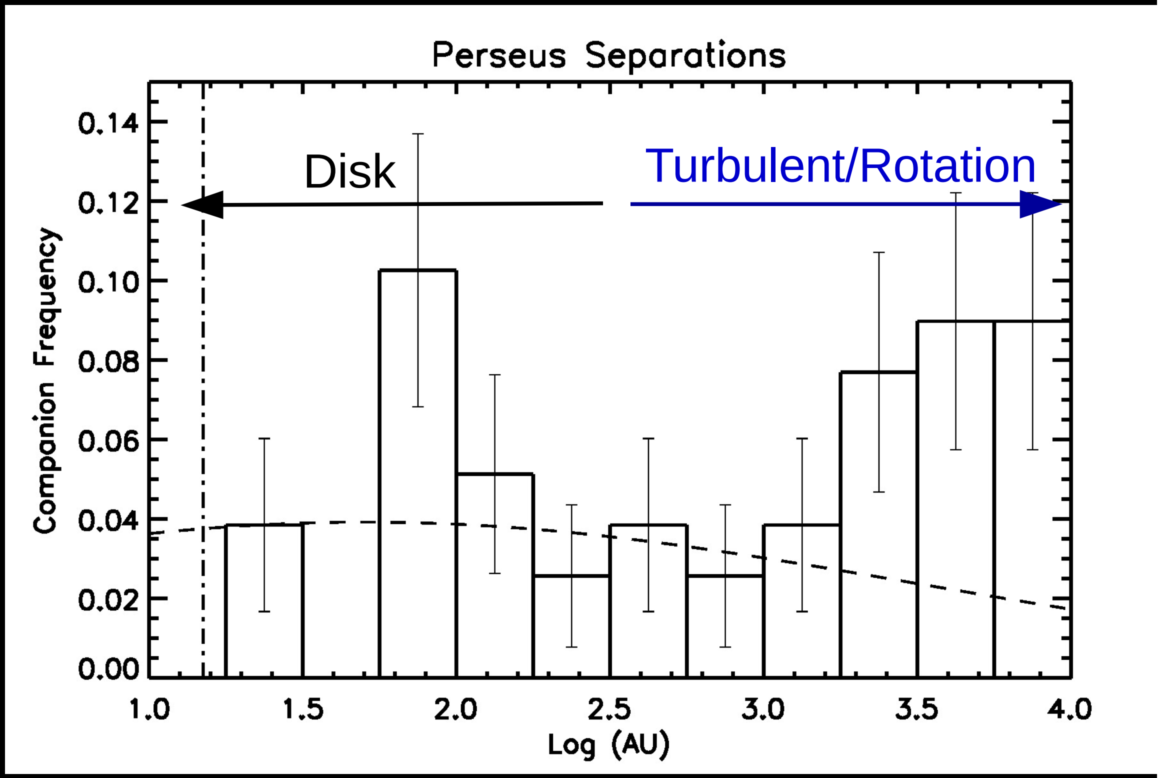
Multiple System Formation

Turbulent Fragmentation

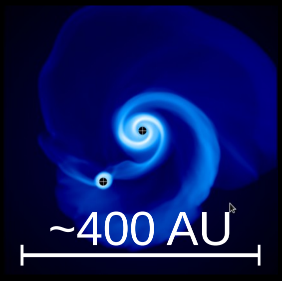


Offner+2010

vs.

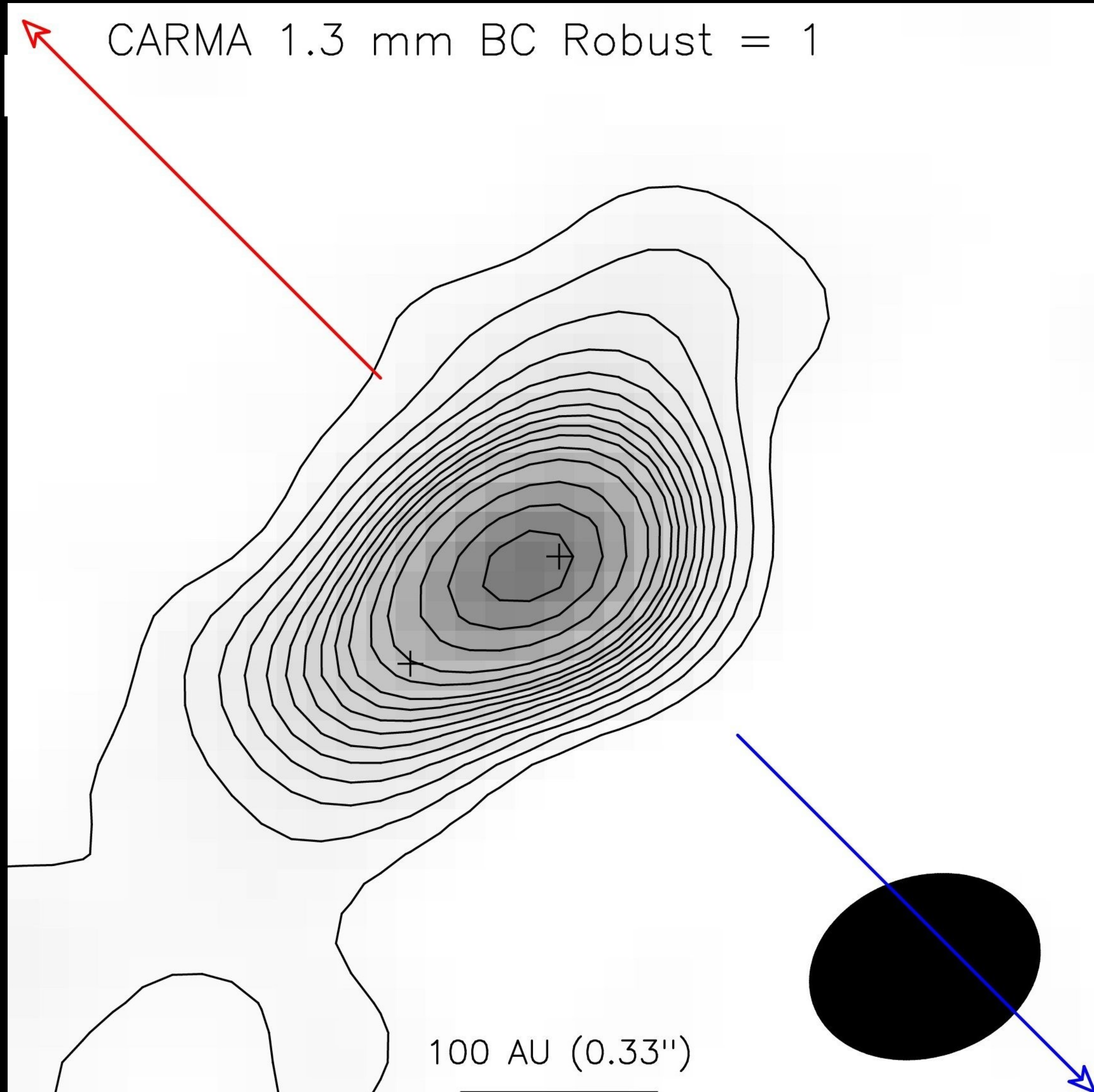


Disk Fragmentation



Kratter+2010

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

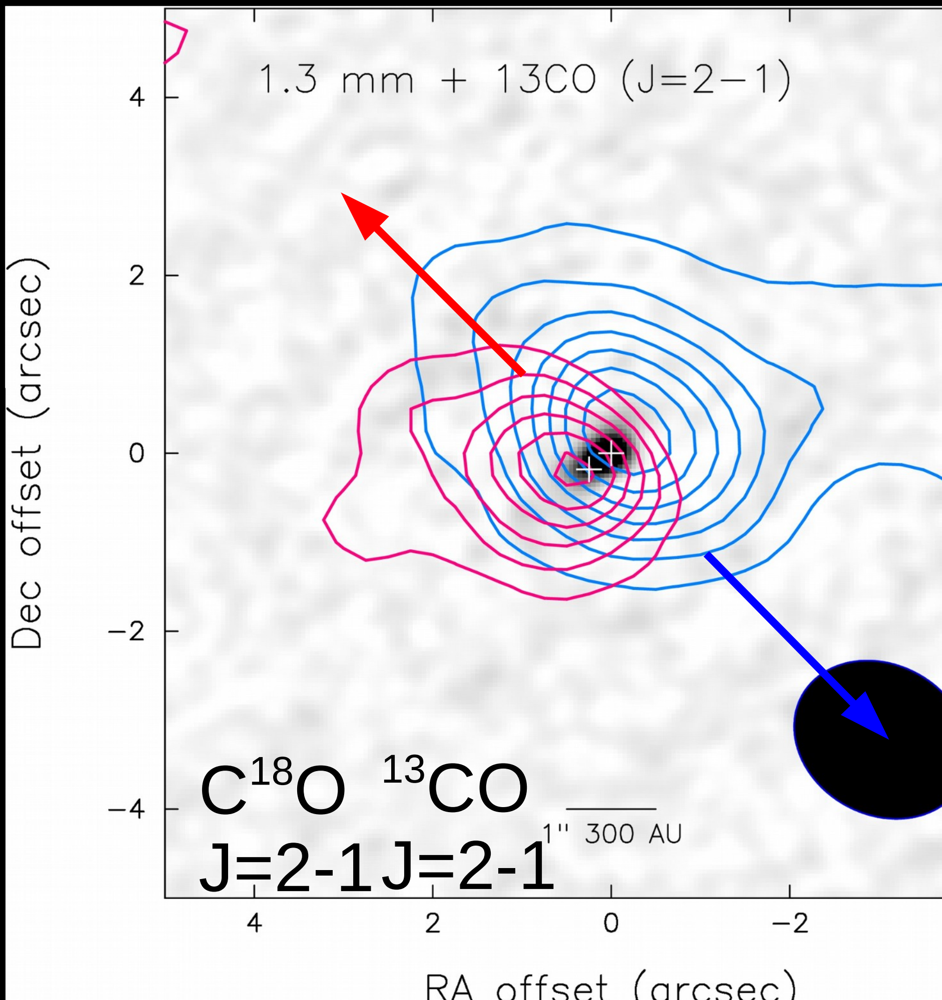


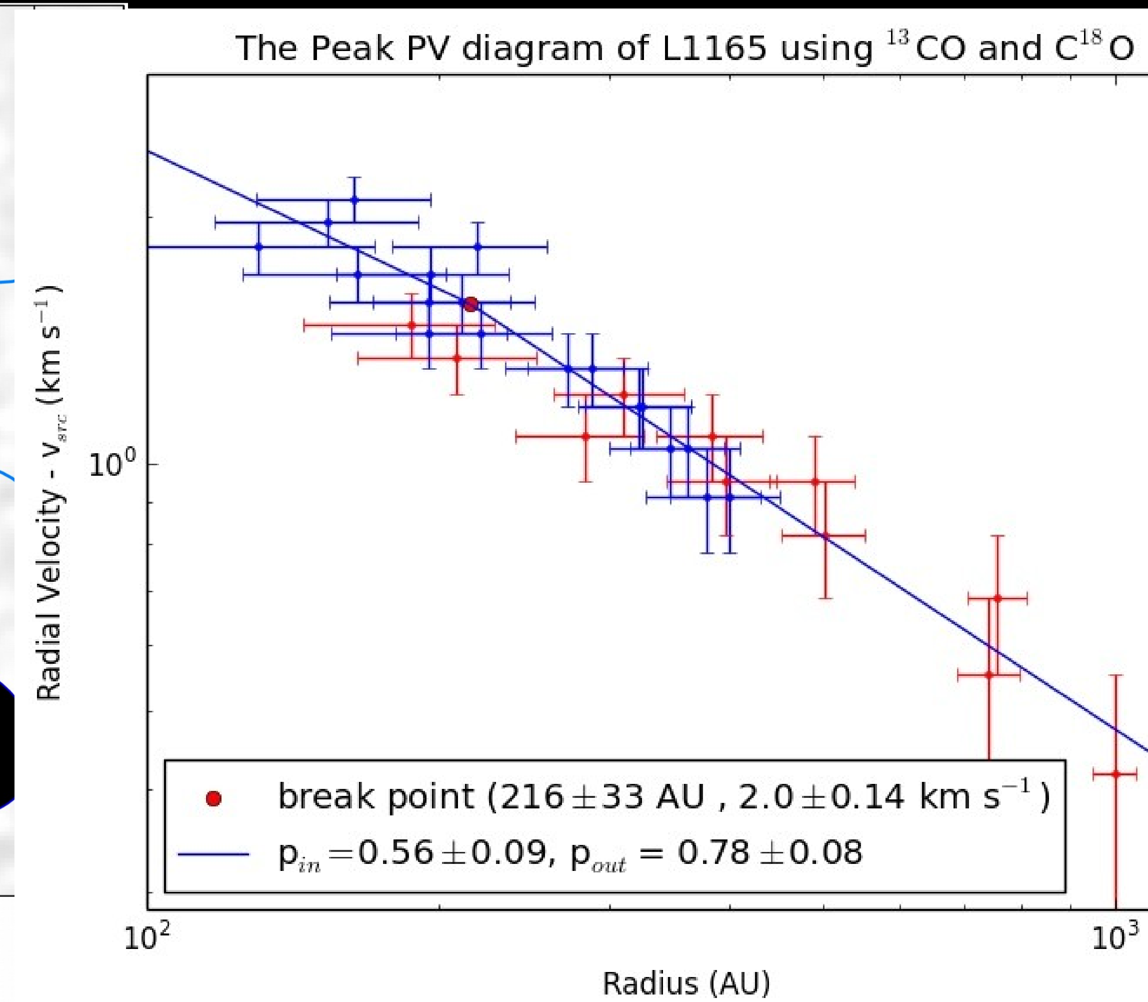
CARMA
1.3 mm

VLA
7 mm

Tobin+2013

Rotating, Circumbinary Disk

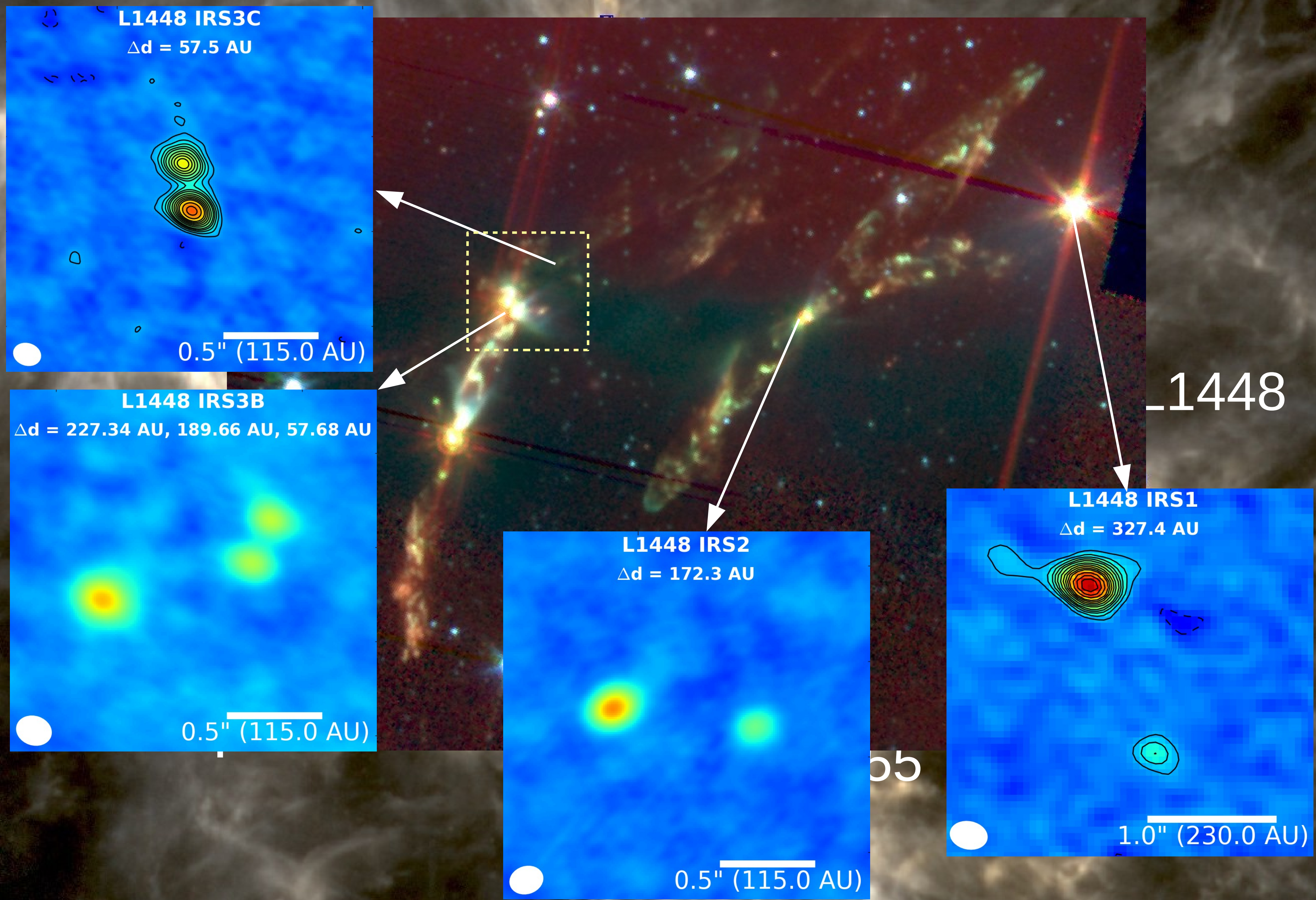




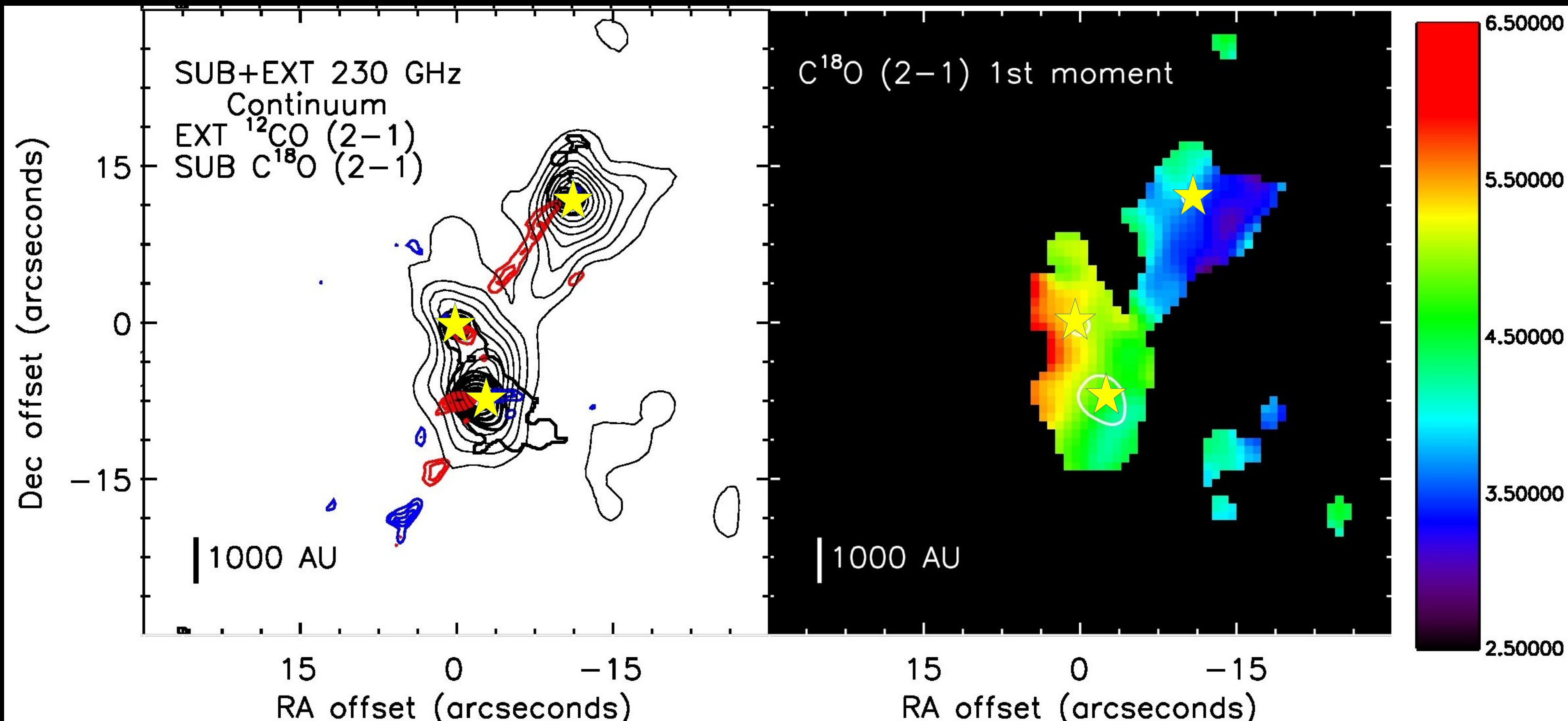
Tobin/Bos+ in prep.

- Near-Keplerian rotation observed
  - Total mass of protostars ~ 0.6 – 0.8 M_{sun}
- Disk fragmentation plausible

Western Perseus Molecular Cloud

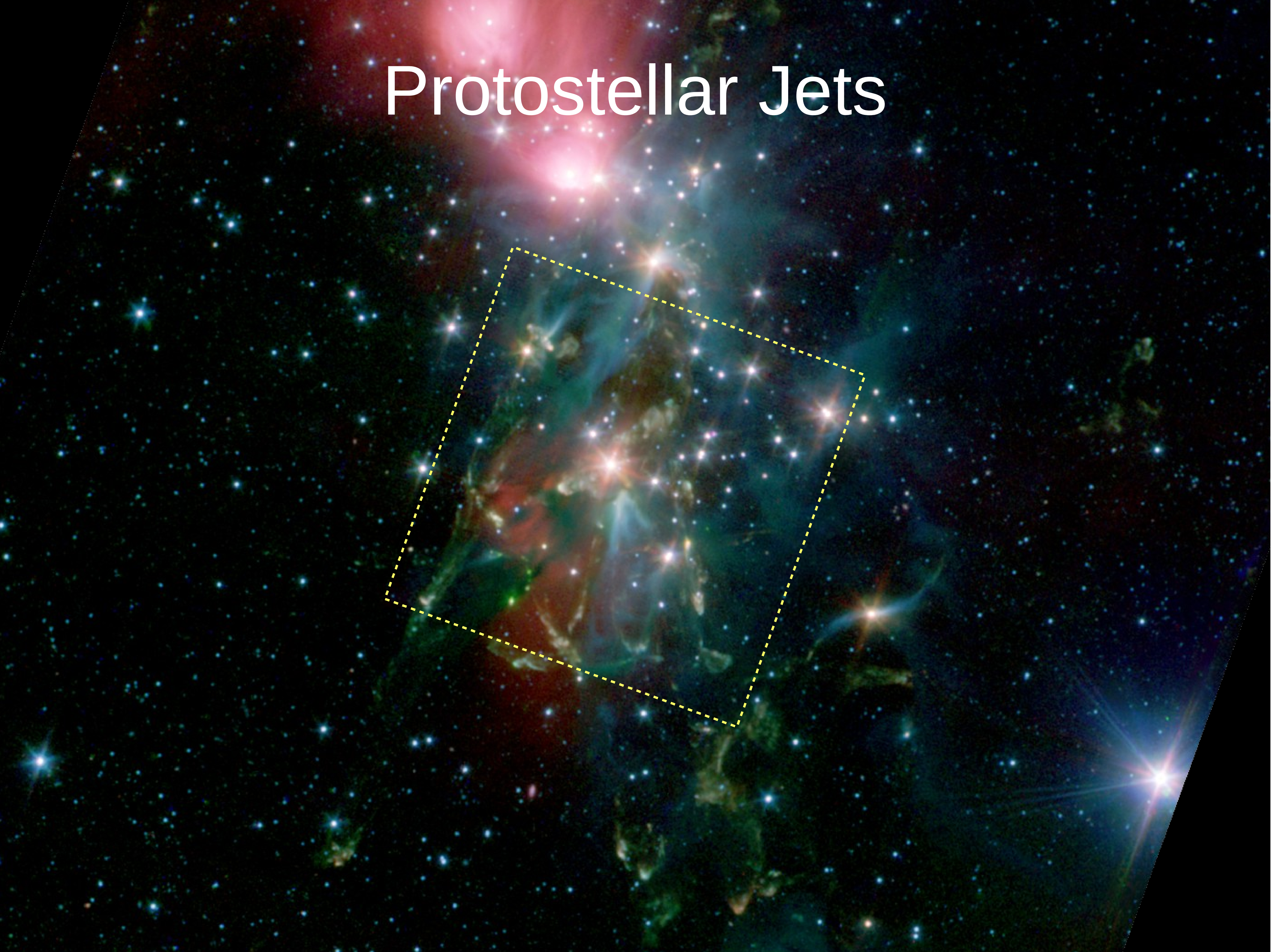


L1448N Kinematics from MASSES

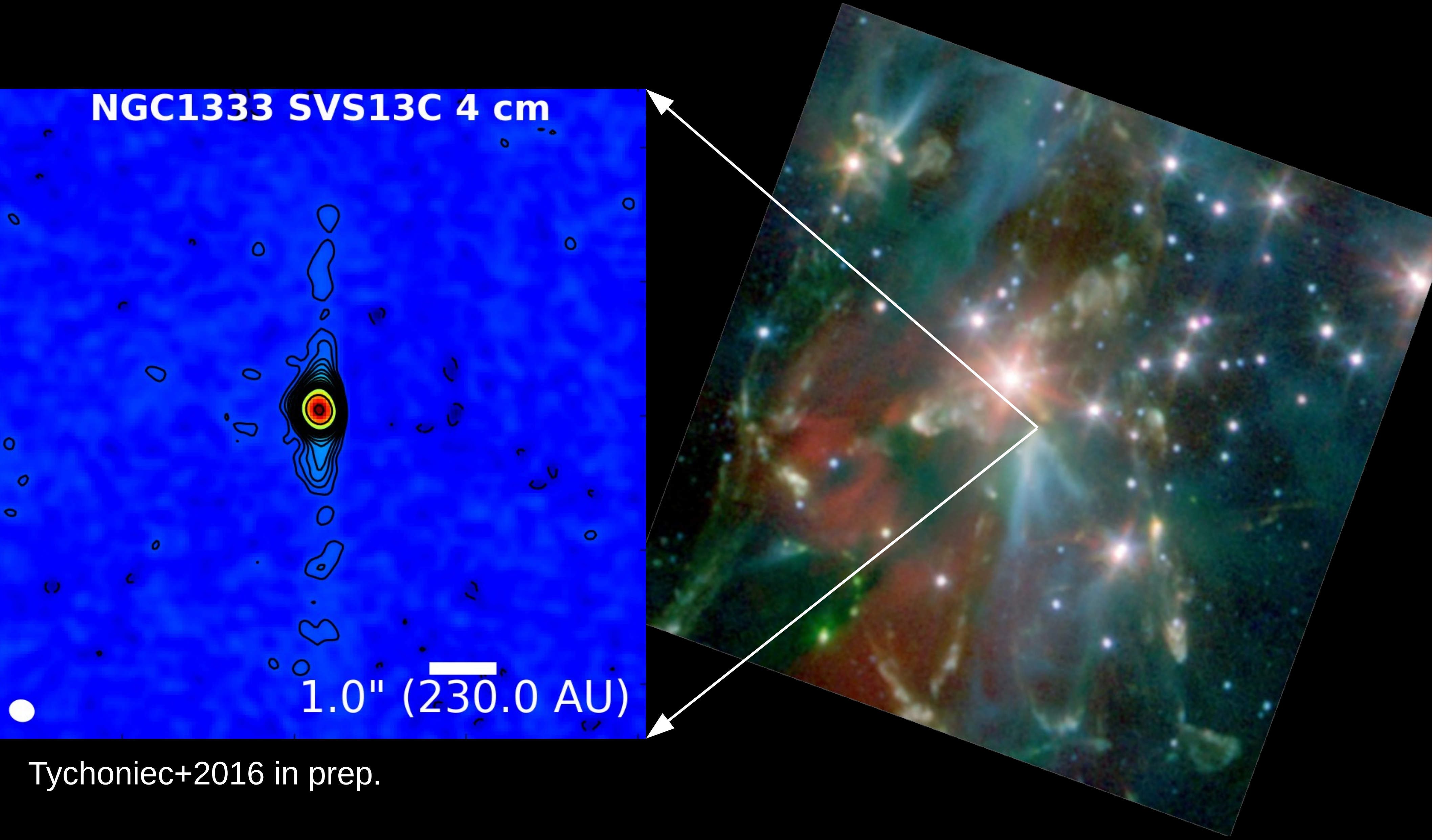


Lee, Dunham, Tobin+2015 submitted.

Protostellar Jets

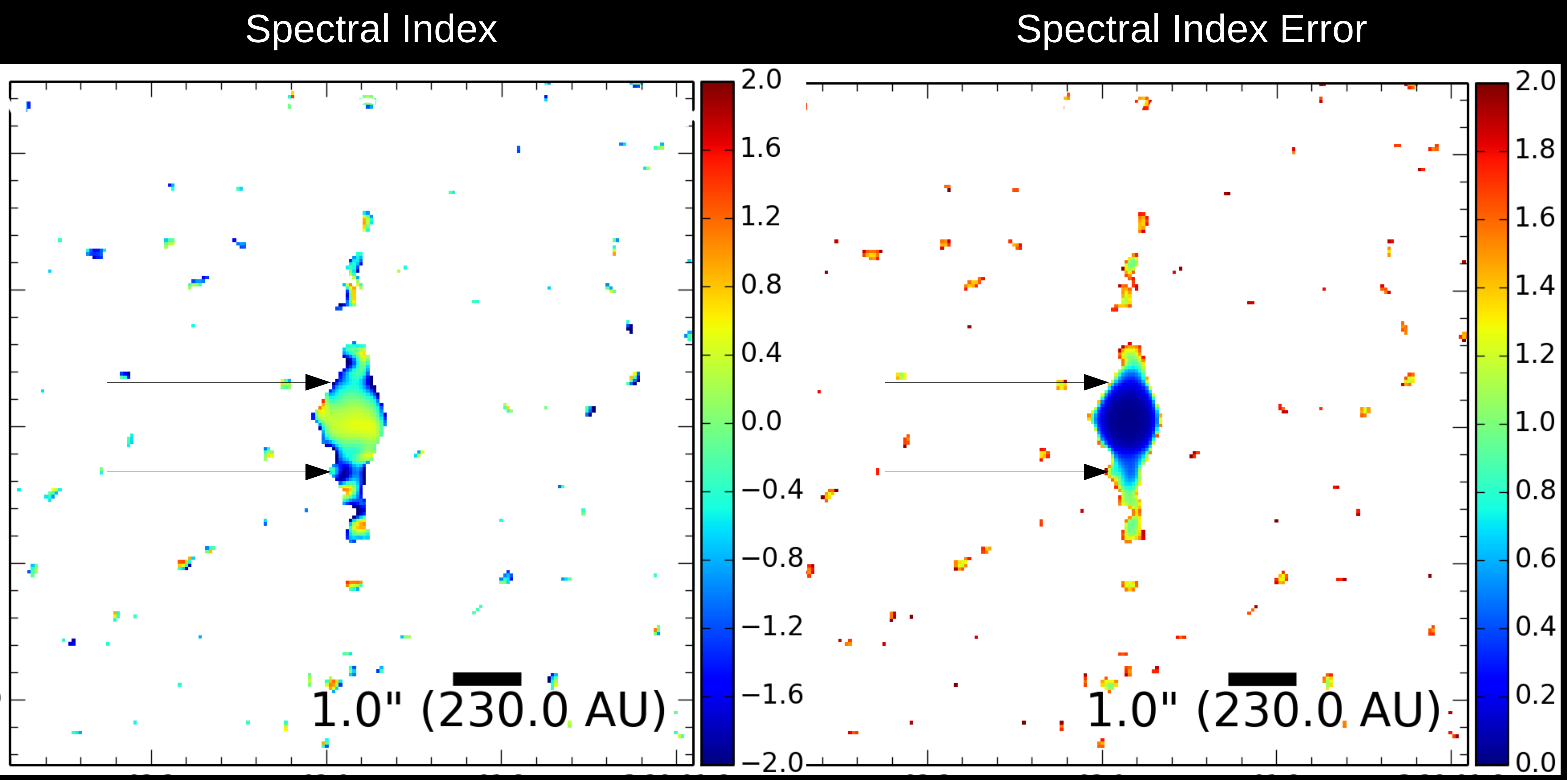


Protostellar Jets: SVS13C



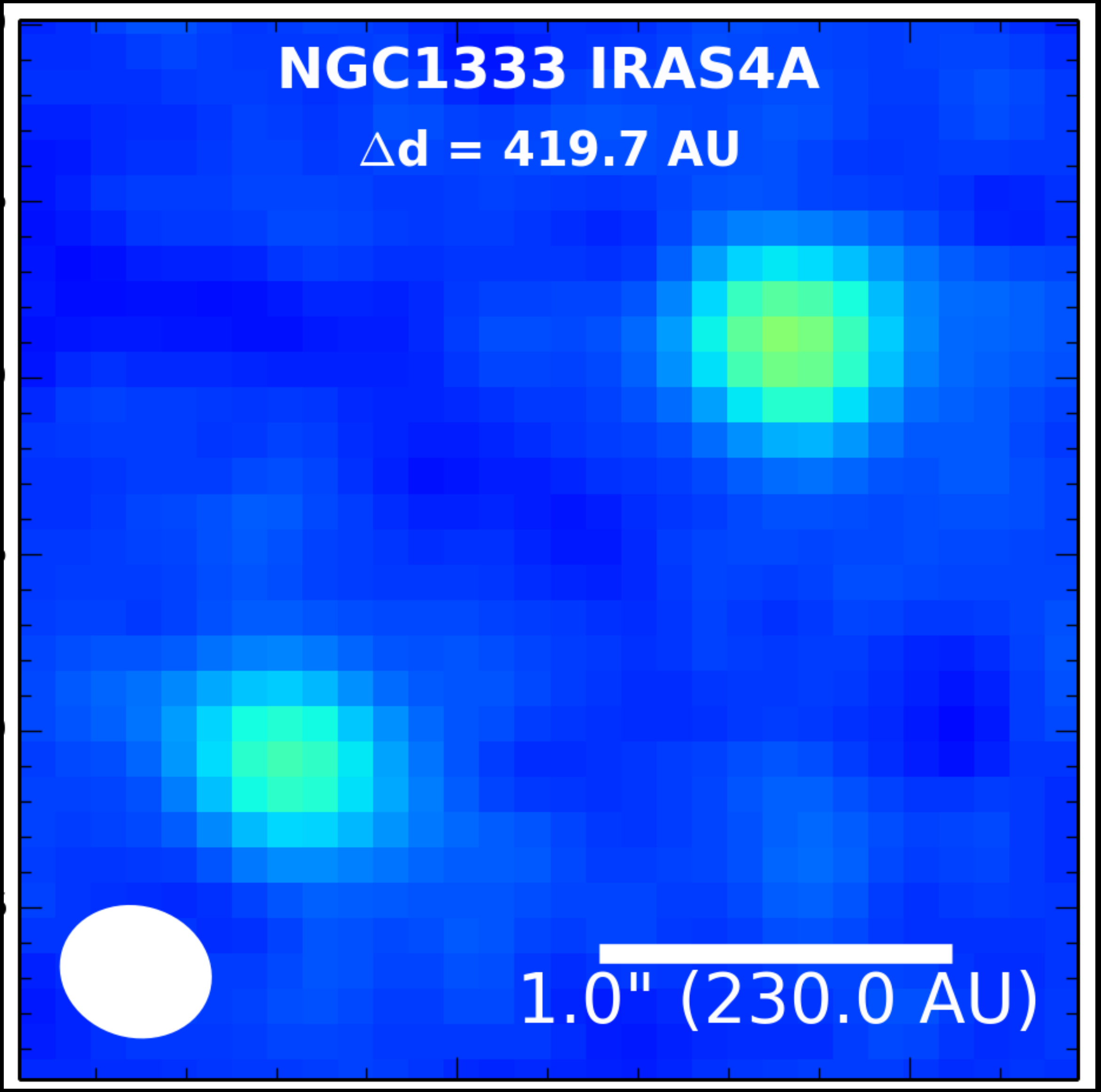
Tychoniec+2016 in prep.

Protostellar Jets: SVS13C



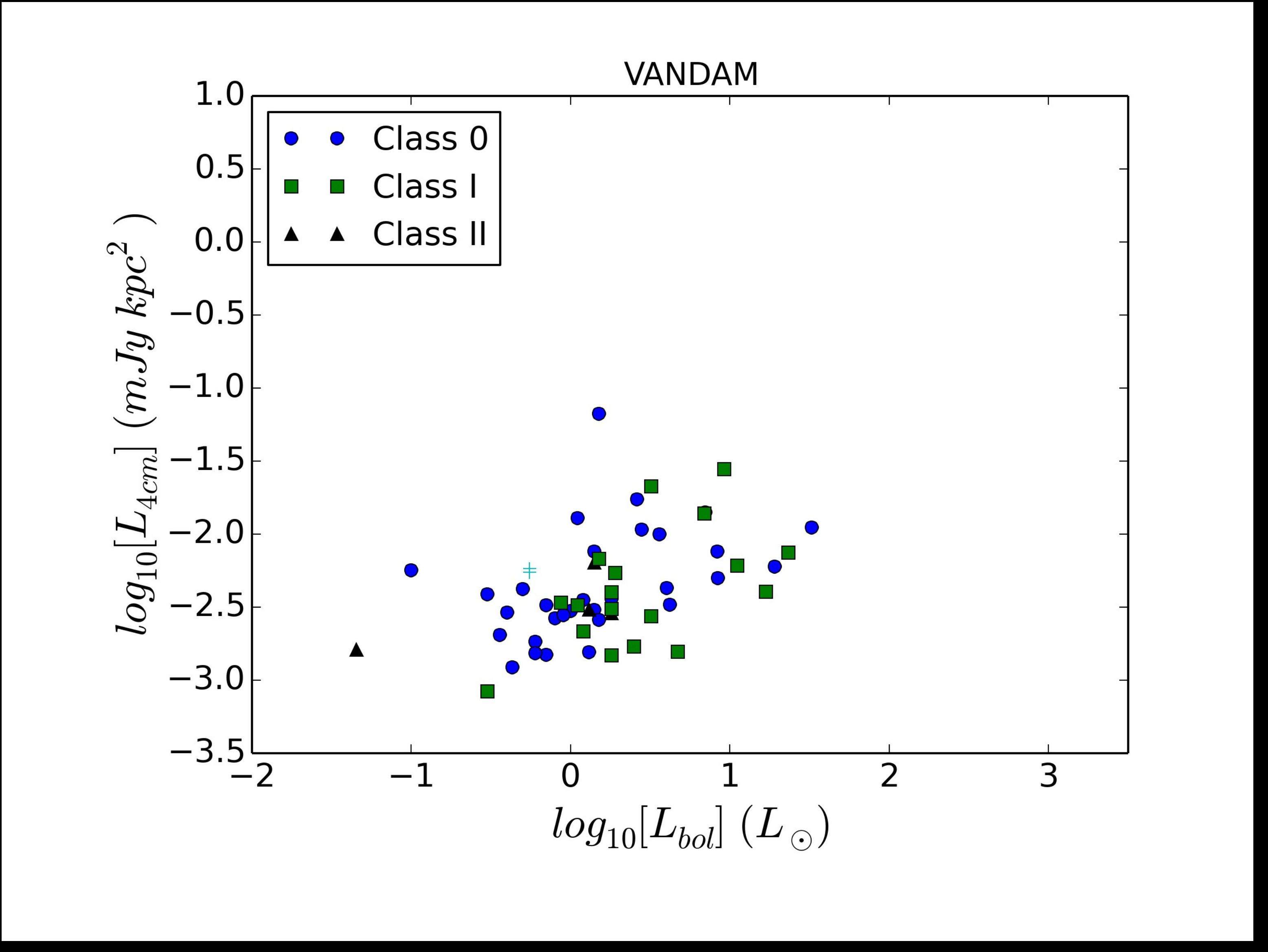
Tychoniec+2016 in prep.

Protostellar Jets: IRAS4A



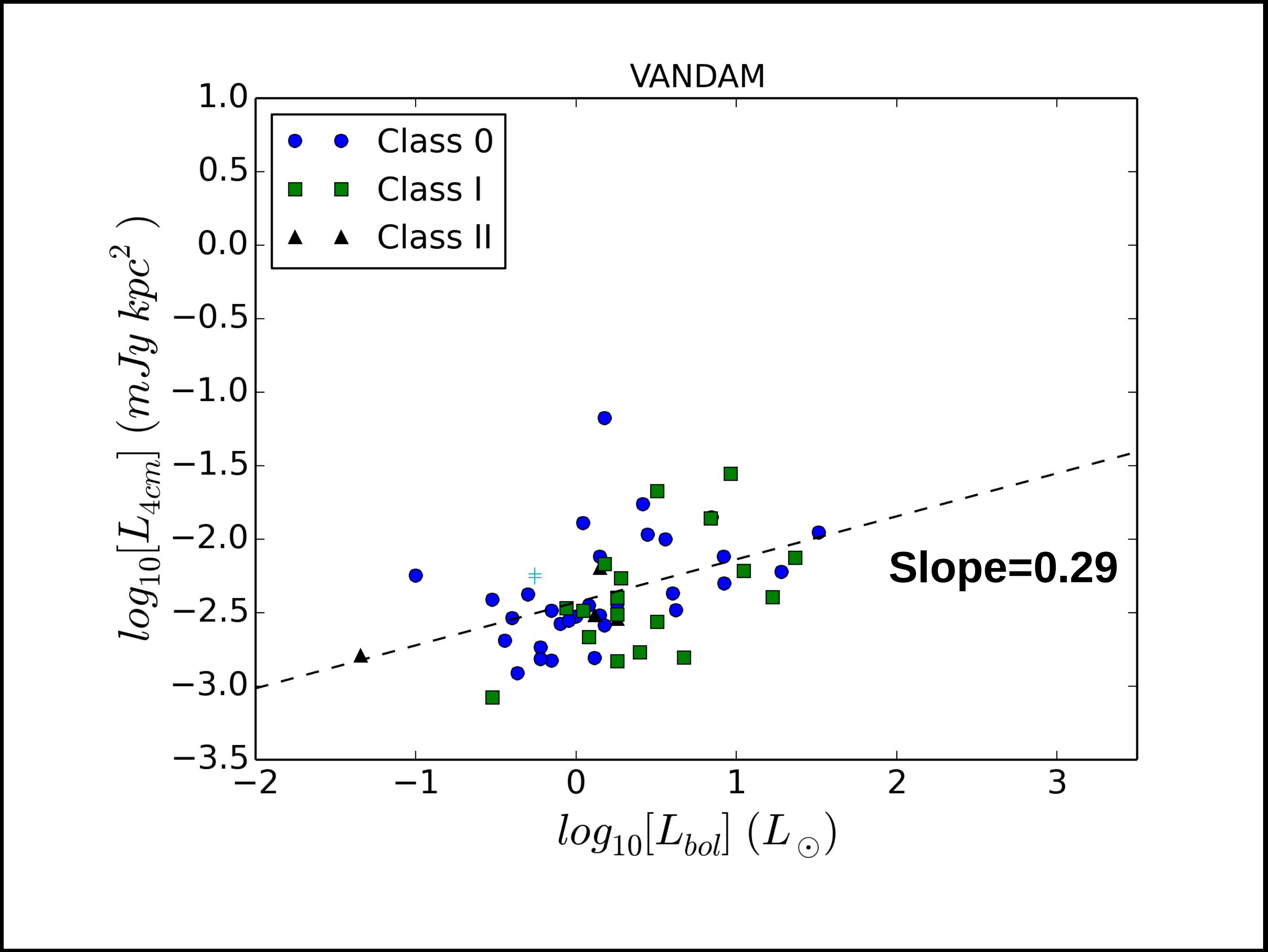
Tychoniec+2016 in prep.

Free-Free Jet vs. Source Properties



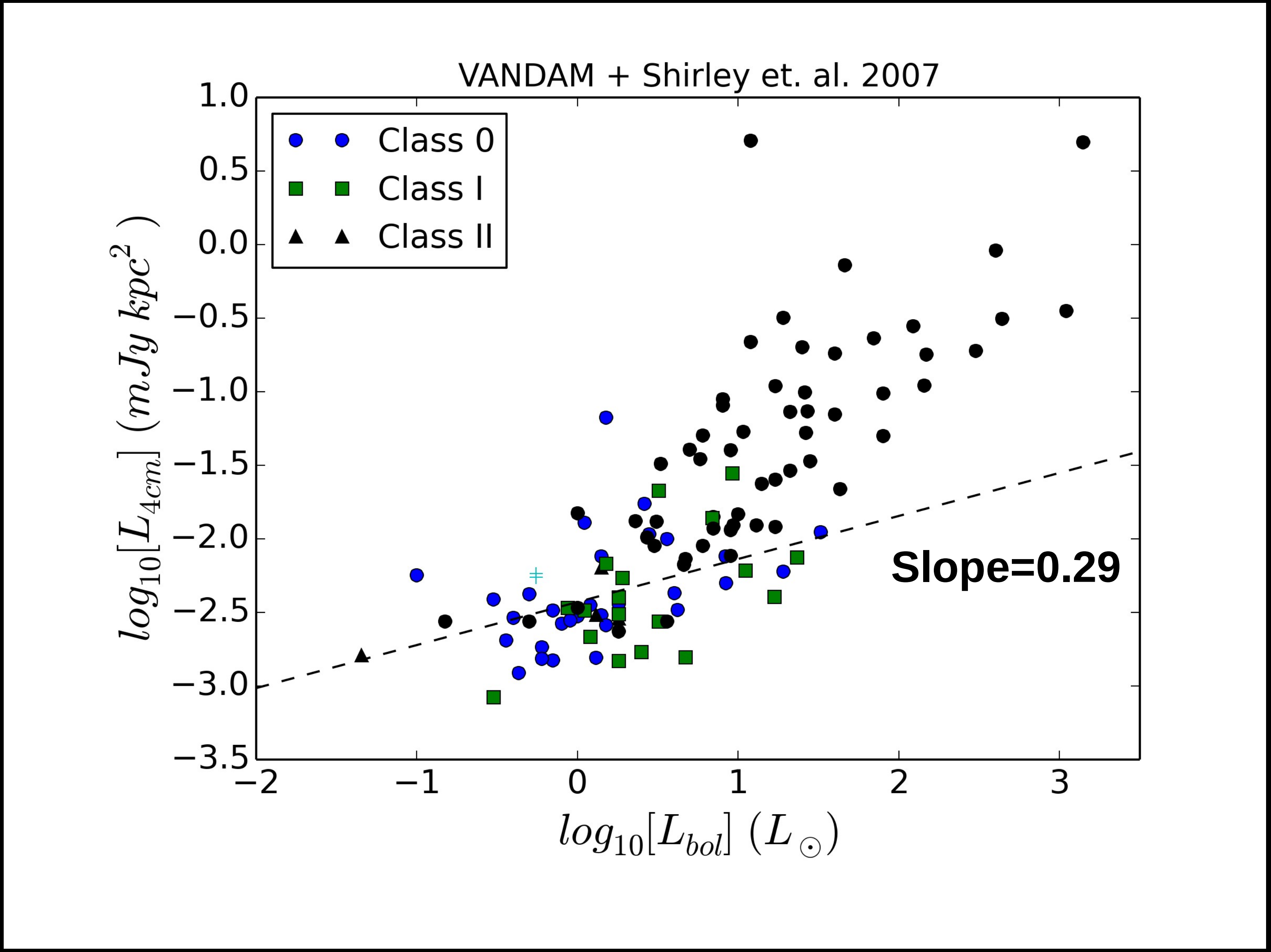
Tychoniec+2016 in prep.

Free-Free Jet vs. Source Properties



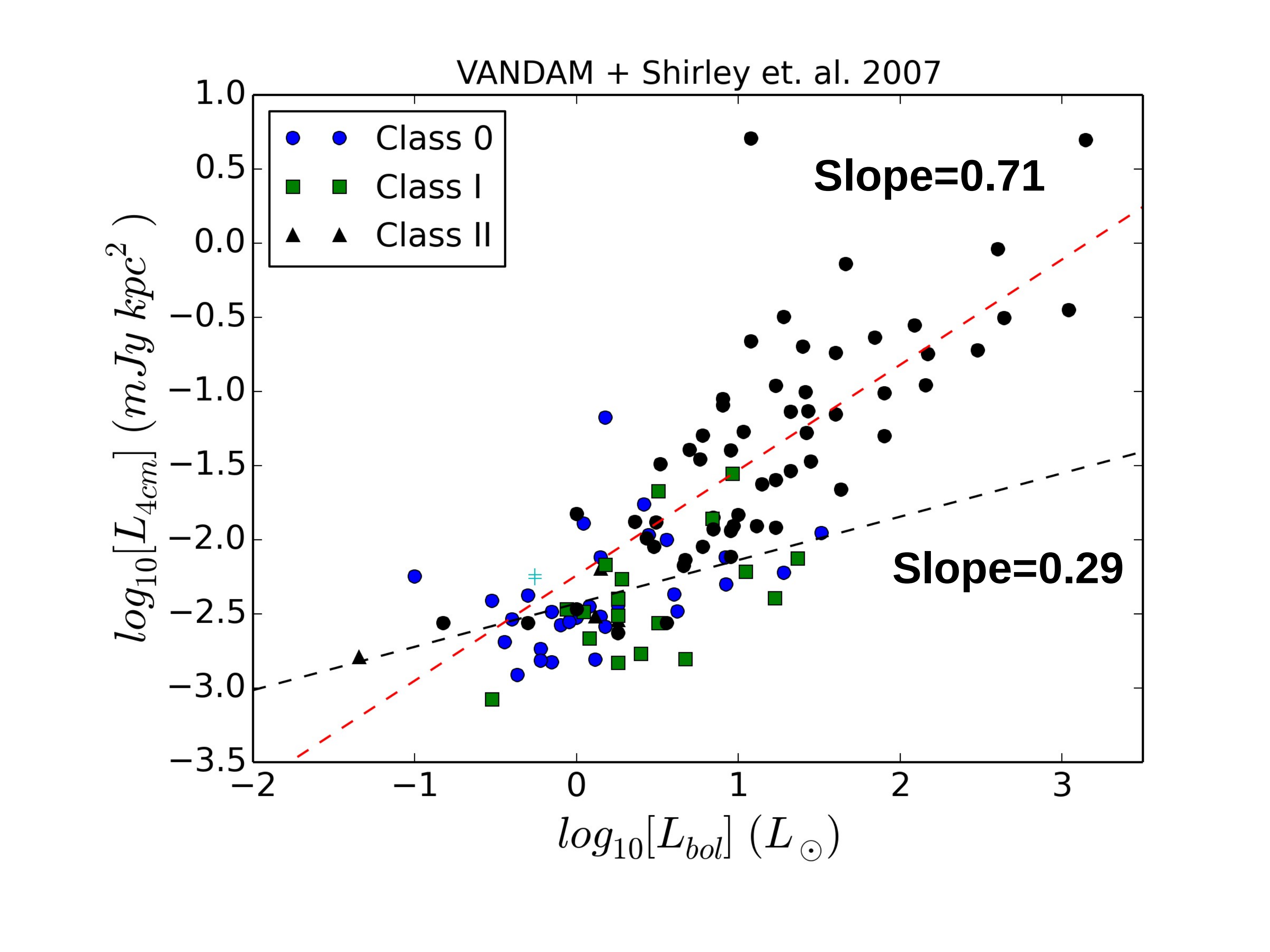
Tychoniec+2016 in prep.

Free-Free Jet vs. Source Properties



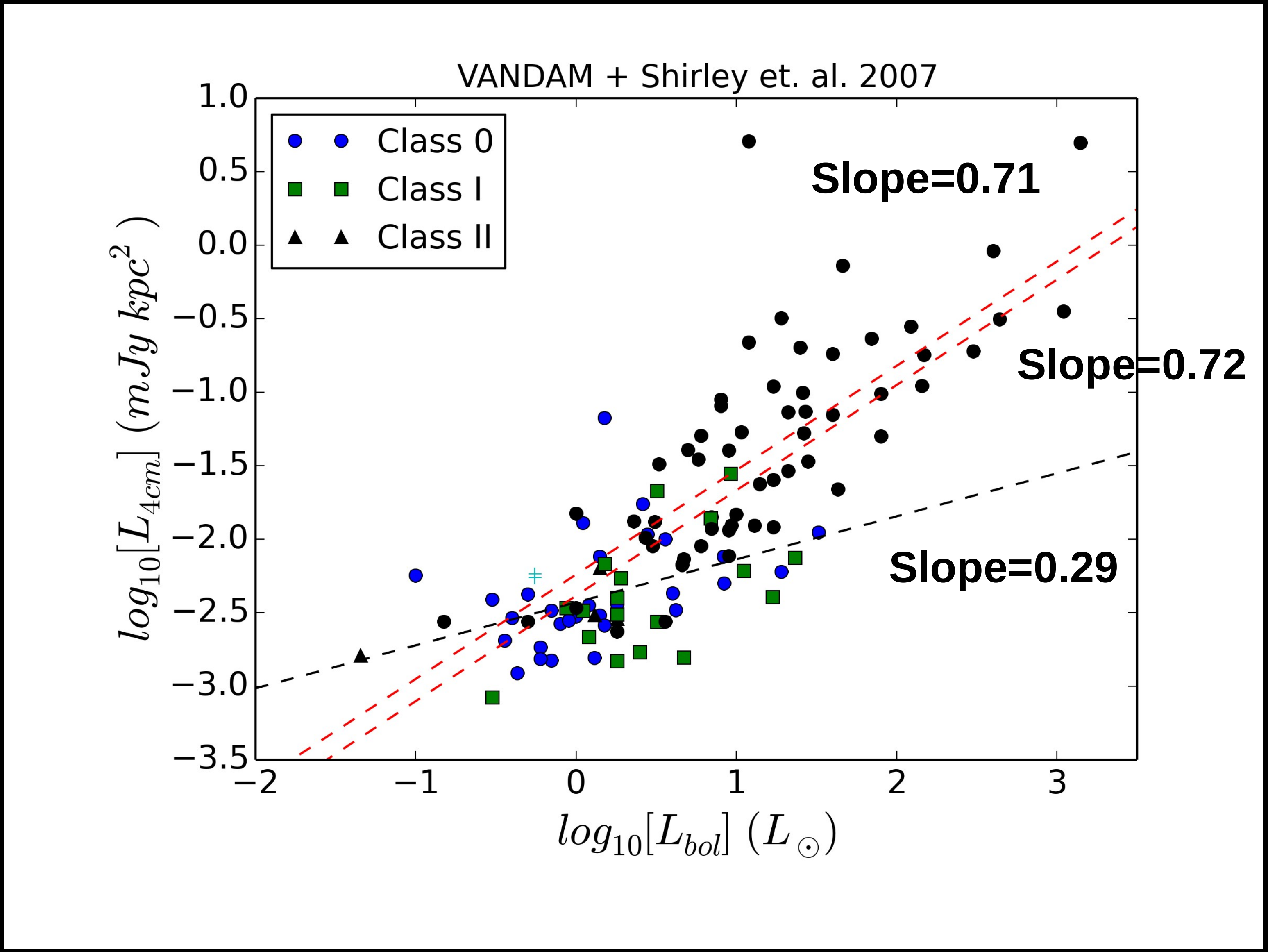
Tychoniec+2016 in prep.

Free-Free Jet vs. Source Properties



Tychoniec+2016 in prep.

Free-Free Jet vs. Source Properties

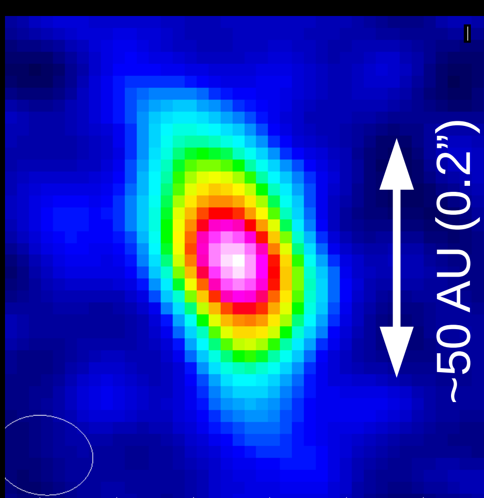


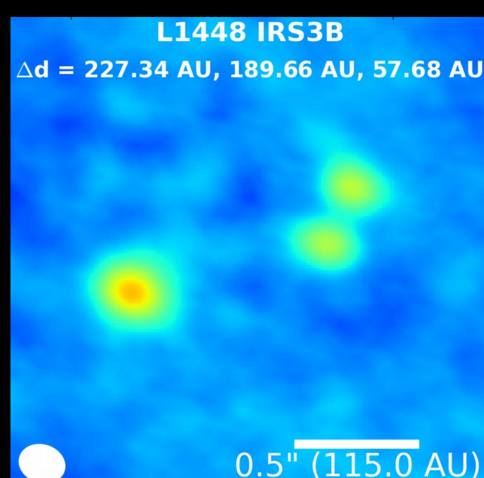
- No detections toward FHSCs candidates, cf. L1014 Shirley+2007

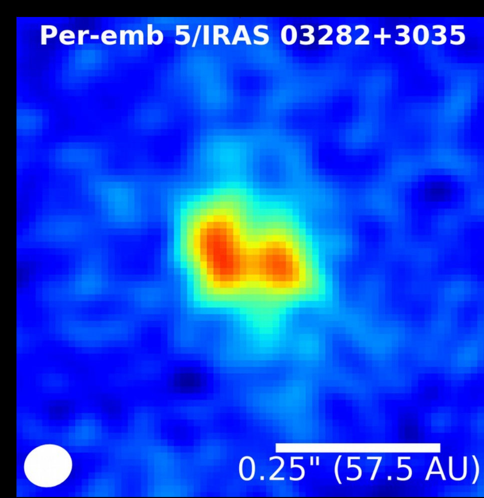
Tychoniec+2016 in prep.

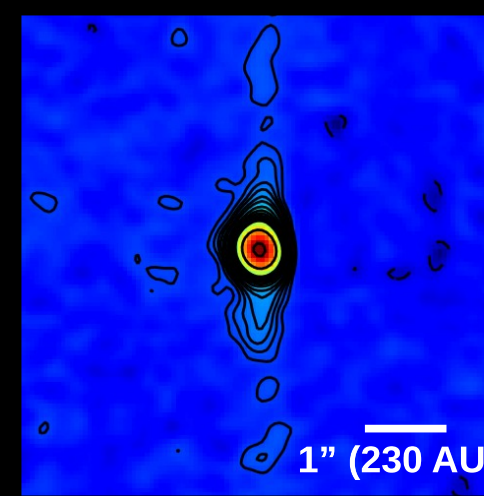
Summary

- Unbiased surveys crucial for disk and multiplicity studies
- Large sample of protostellar disk candidates revealed by VLA
- Multiplicity of Class 0/I protostars well-characterized
  - Closest know Class 0 protostellar multiples identified
  - Molecular lines important for characterizing formation routes
- New views of protostellar jets, a few possible synchrotron shocks
- ALMA Survey of 330 Orion protostars approved (0.85 mm/30 AU)
  - VLA proposed for 100 Class 0 (8 mm/30 AU)









Research Supported By:

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