The VLA Nascent Disk and Multiplicity (VANDAM) Survey of Perseus

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), Erin Cox (Illinois), Lukasz Tychoniec (Leiden/AMU-Poland)

Posters: Segura-Cox – 236.09 and Cox – 236.08 (both Wednesday)
Talk: Tobin – 205.3 (10:30 Wednesday)

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

Image: Bill Saxton (NRAO)

Star Formation Process

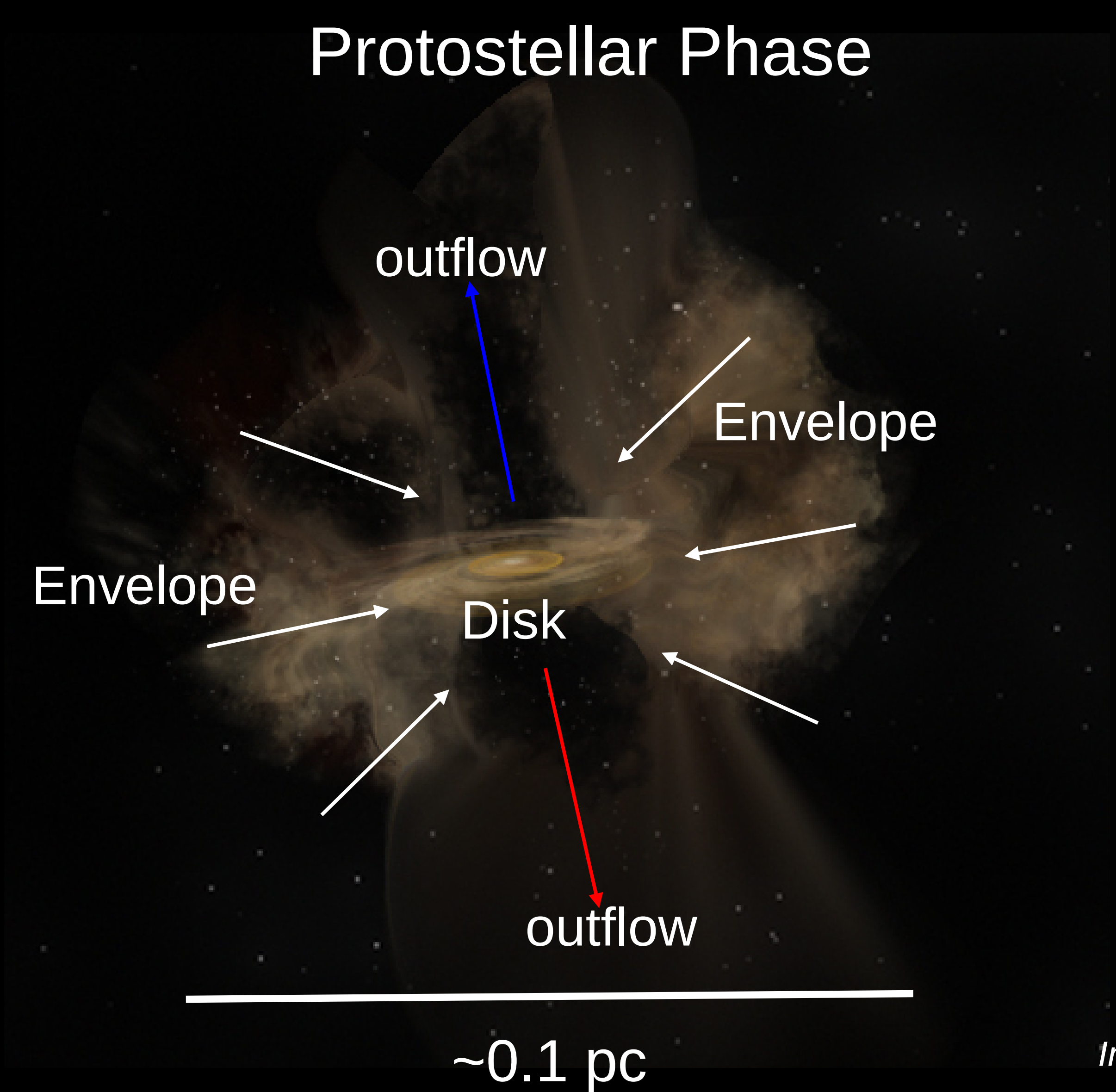


Image: Bill Saxton (NRAO)

Star Formation Process

Protostellar Phase

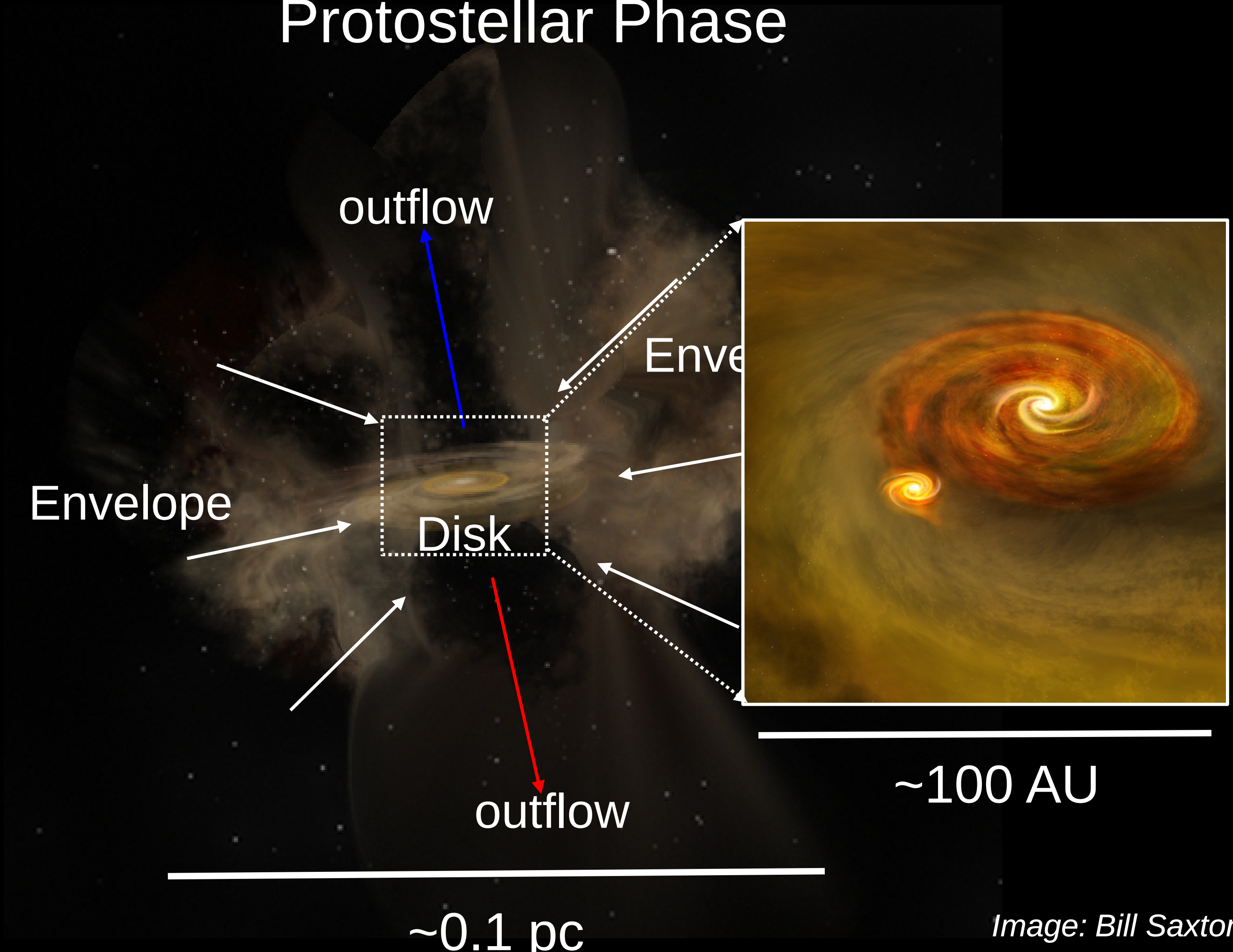
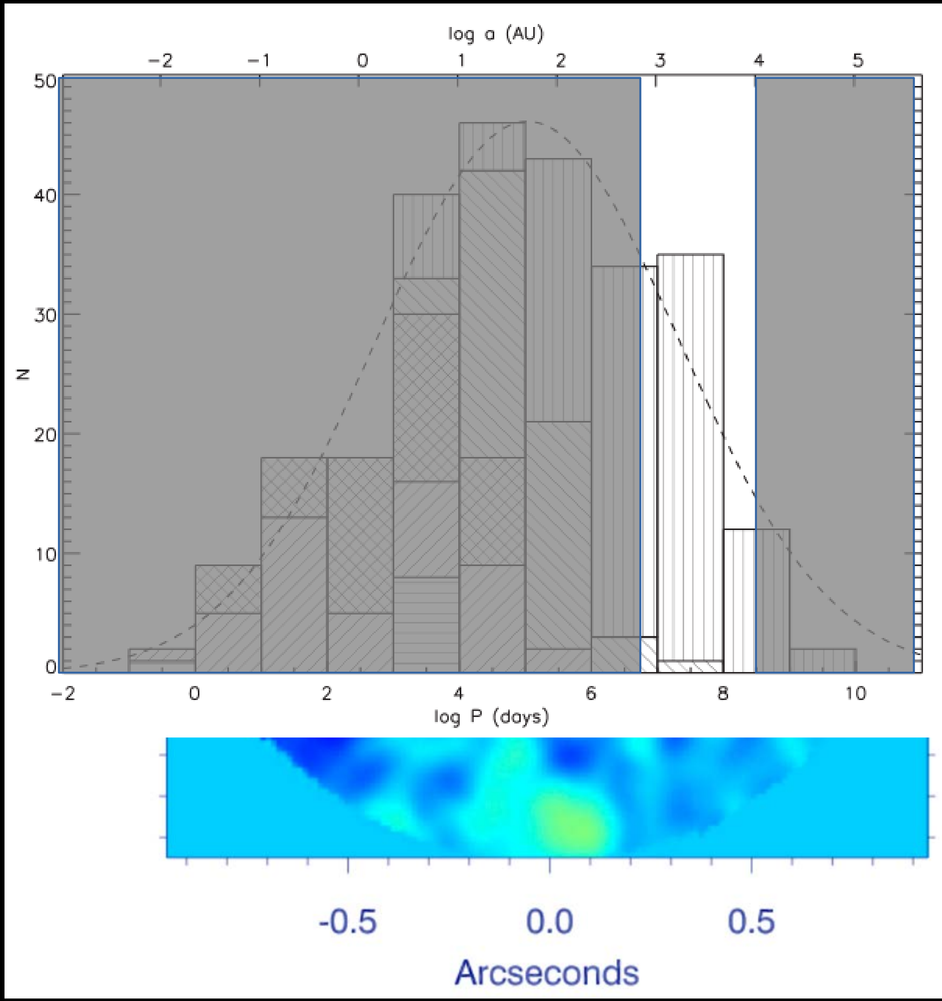


Image: Bill Saxton (NRAO)

Early Disks and Multiplicity

- About ~46% of solar-type stars in multiple systems
  - ~35% for M-stars
  - Observed distribution must have significantly evolved
  - Protostars 3x higher multiplicity
- Initial cond's of proto-planetary disks
  - Disk masses
  - Density profiles
  - Early grain growth
- Companion/planet formation via GI?
  - Disk must be massive
- 'Typical' protostellar disk is unknown



Quanz+2015

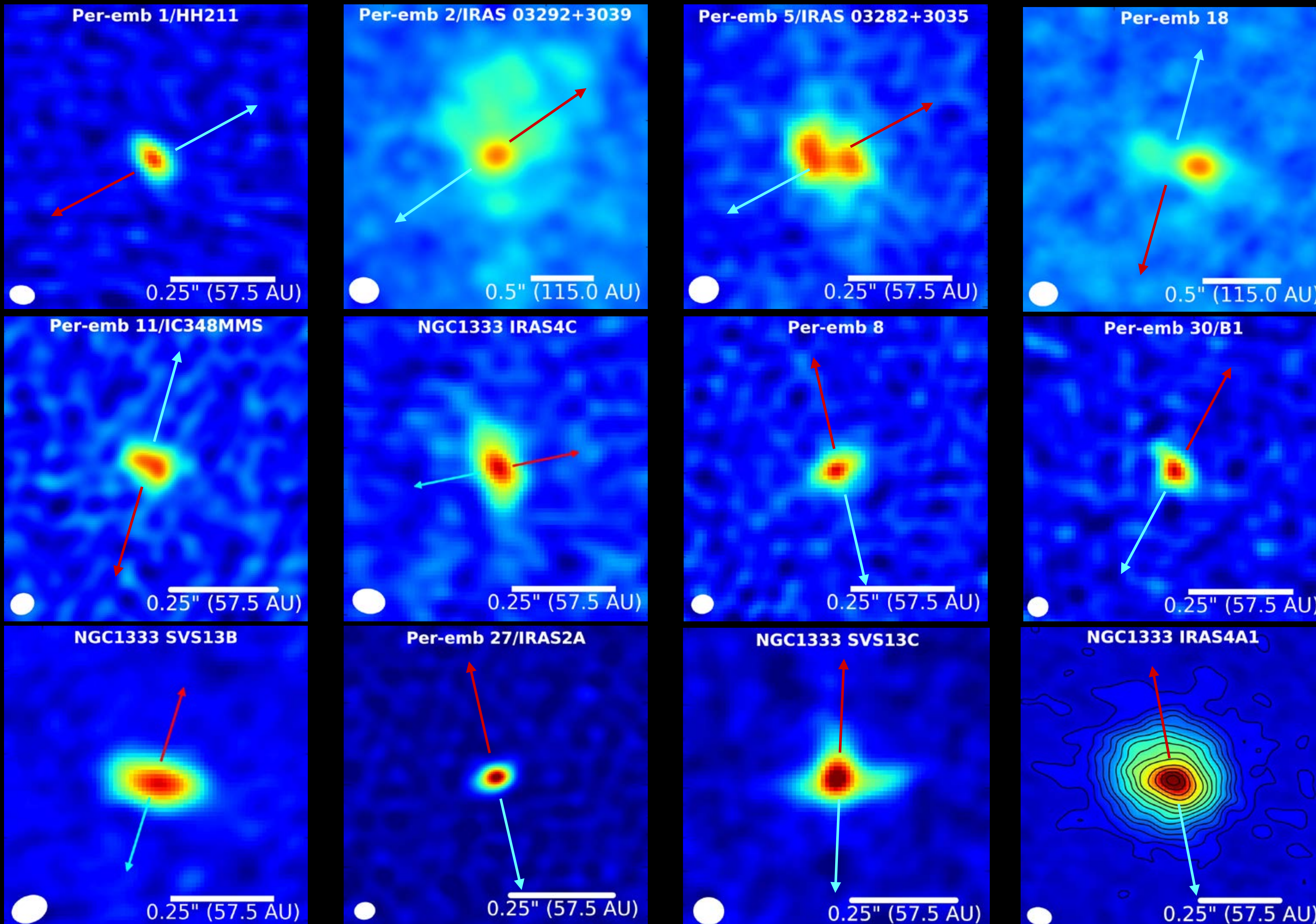
VLA Nascent Disk And Multiplicity (VANDAM) Survey

- 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 (ng)VLA?

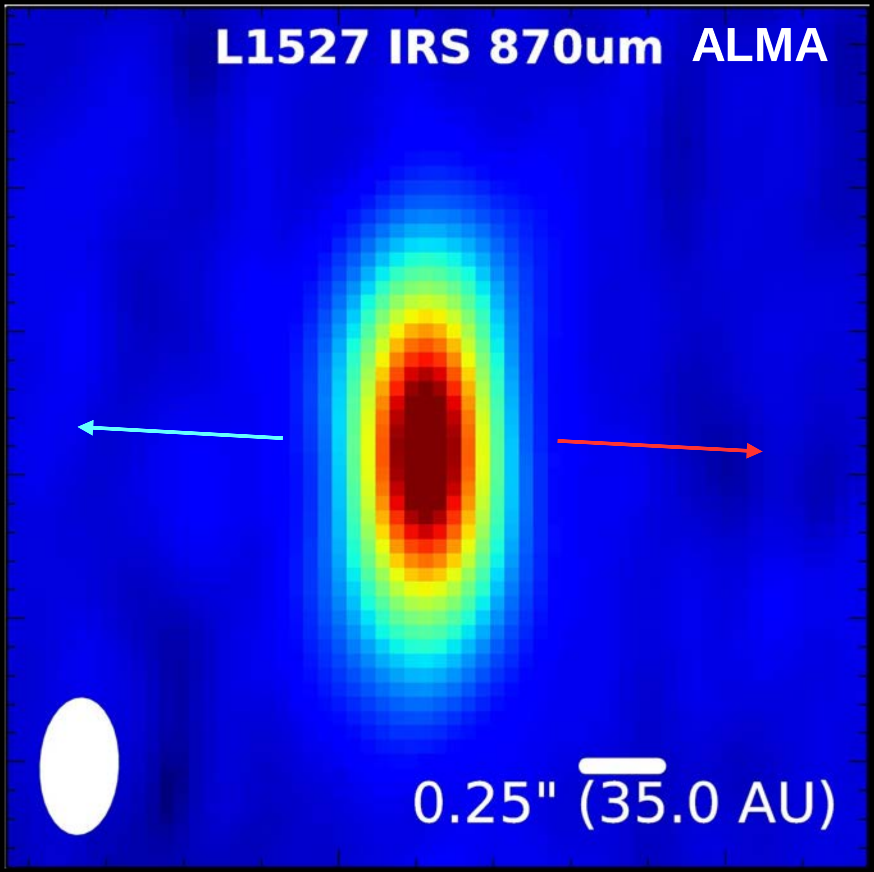
- High-sensitivity at 8 mm – 1 cm with 8 GHz bandwidth
- Routine observations with < 0.1” resolution at 8 mm
- Probing to two emission processes at 8 mm
  - Thermal free-free + thermal dust
  - Protostars stand out
- High optical depths at λ~1.3 mm may hide close companions
- 8 mm traces densest regions, i.e. disks
  - Envelope contribution minimal

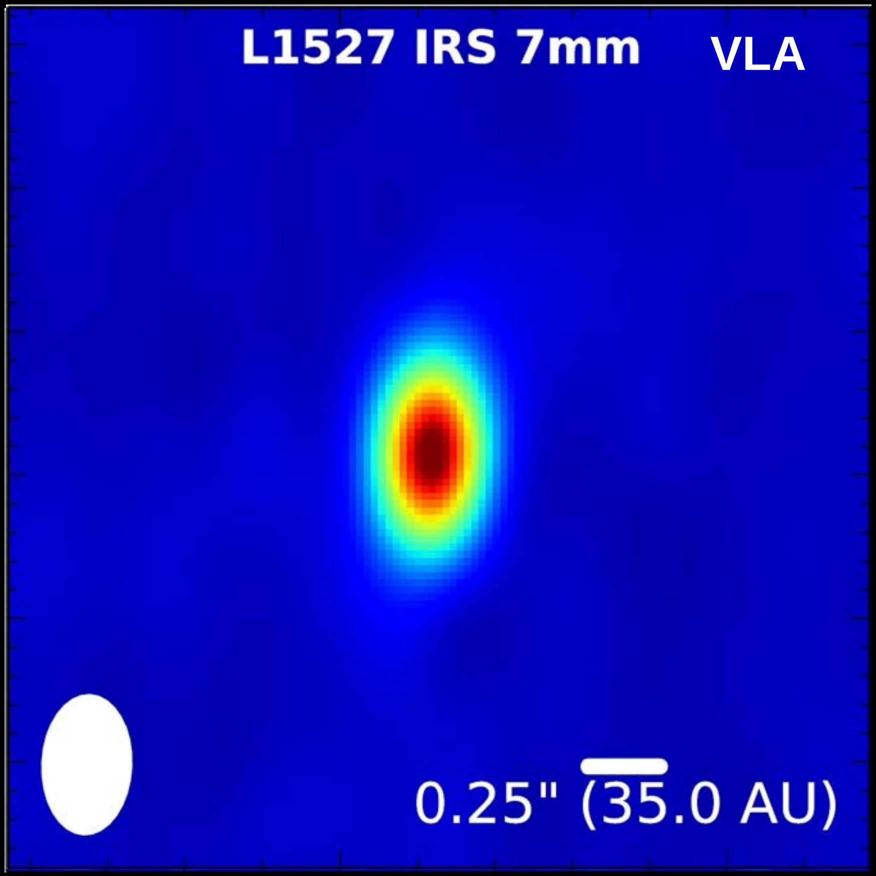
VANDAM Class 0 Disk Candidates



Segura-Cox+2016 submitted – Poster 236.09

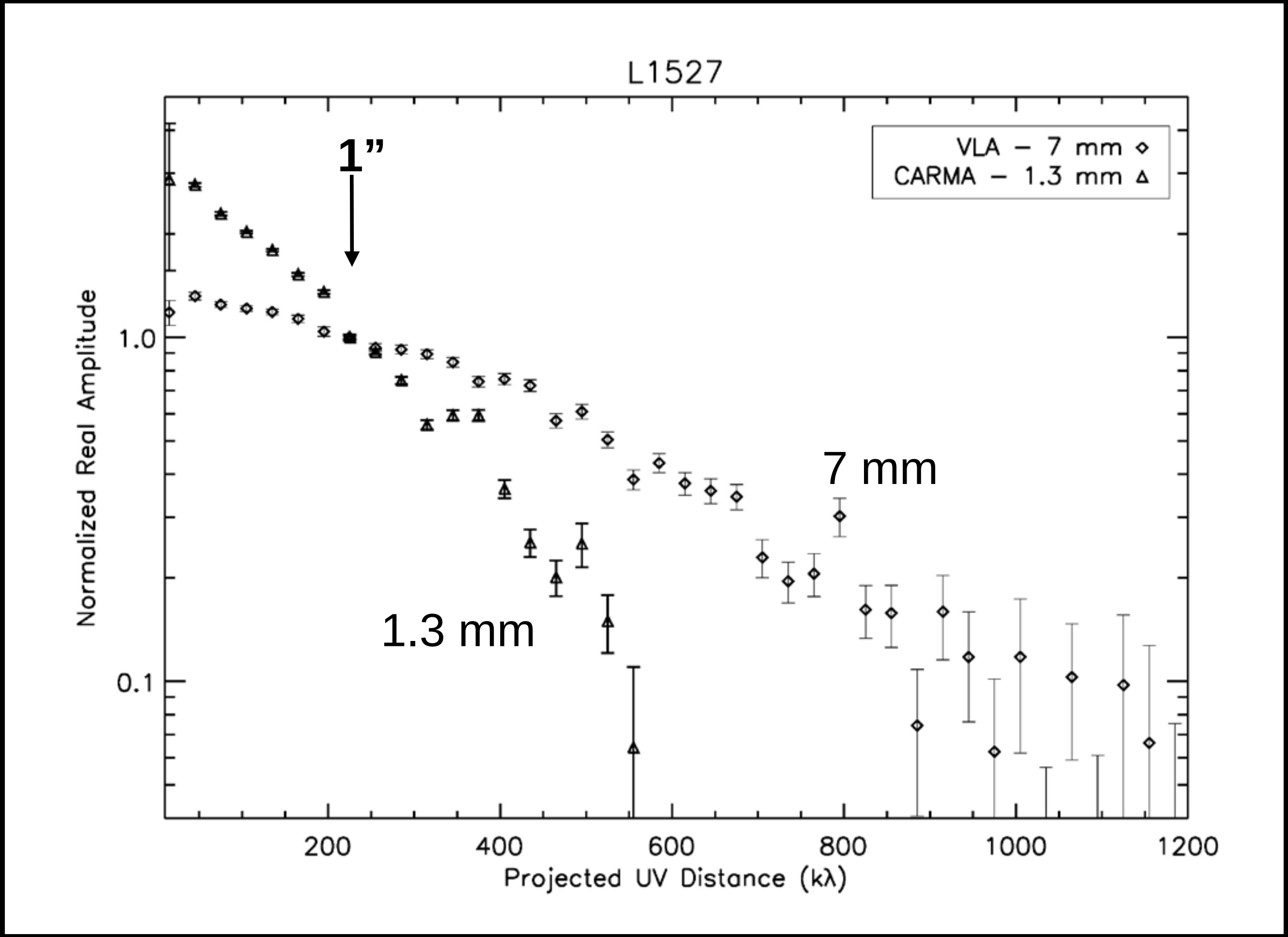
VANDAM Disk Candidates Sizes





- 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

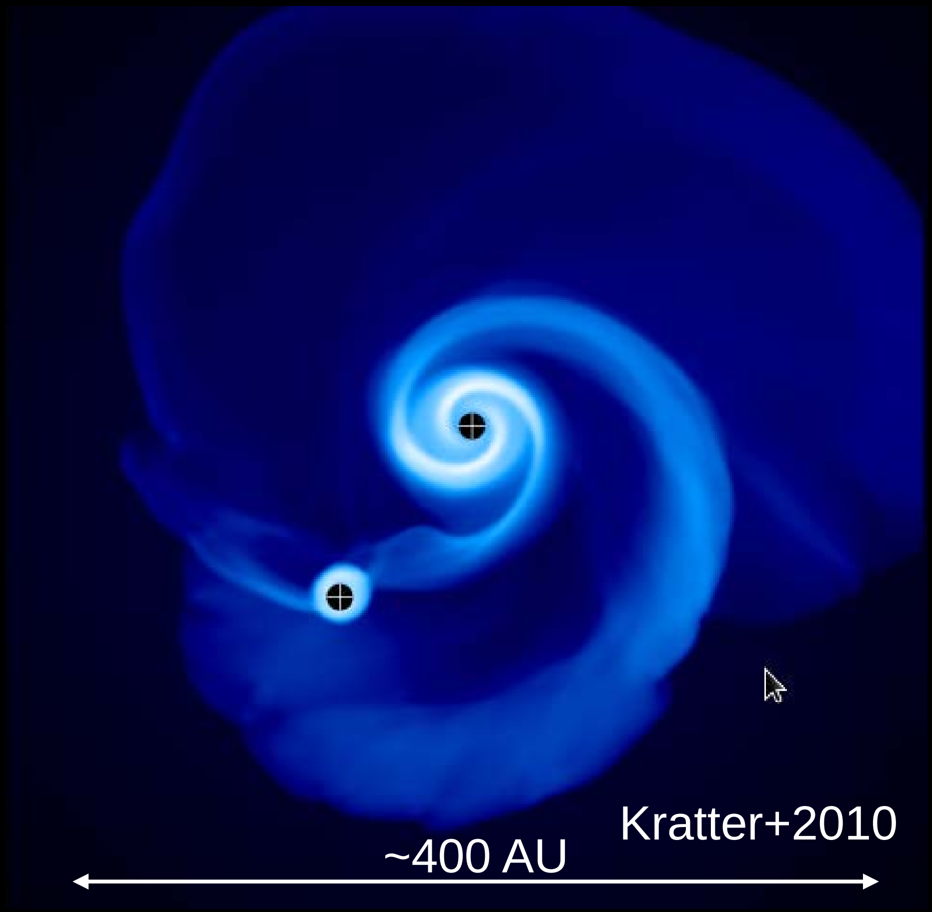
Radial Distribution of Dust



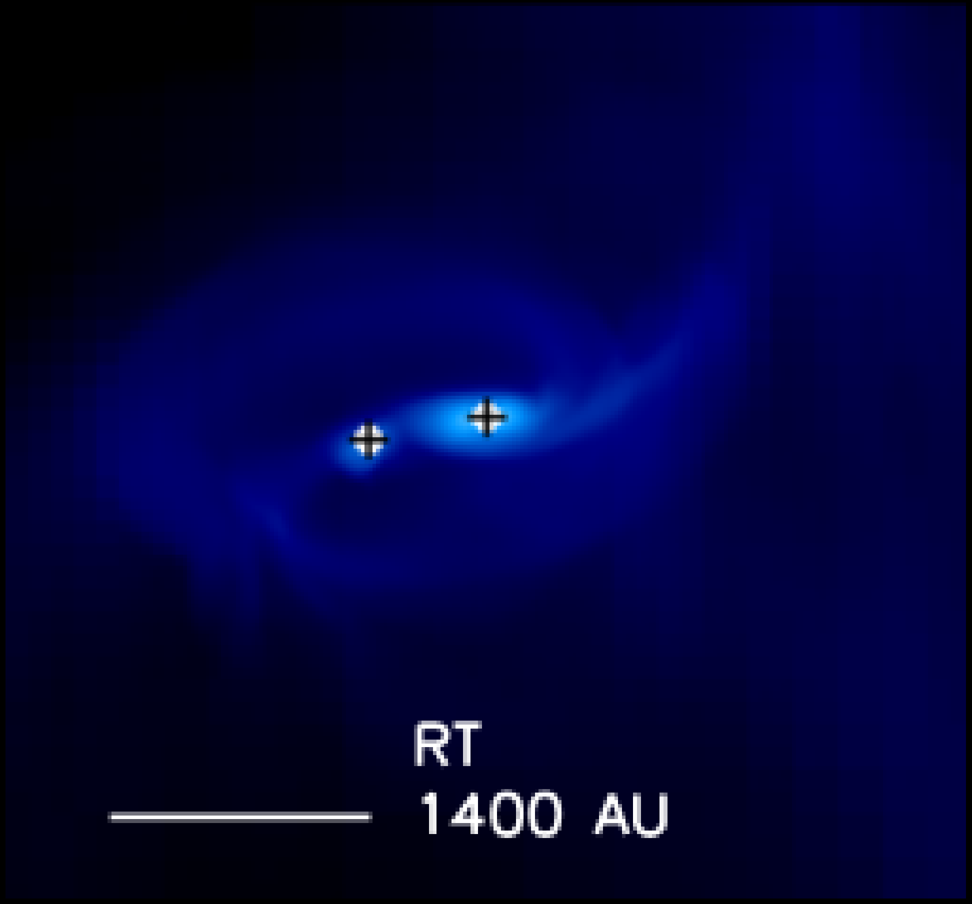
- Compare visibility amplitude data at 1.3 mm and 8.1 mm
  - Normalized at 200 kλ ~ 1”
  - 1.3 mm data drop faster, more spatially extended than 8.1 mm

Multiple System Formation

Disk Fragmentation



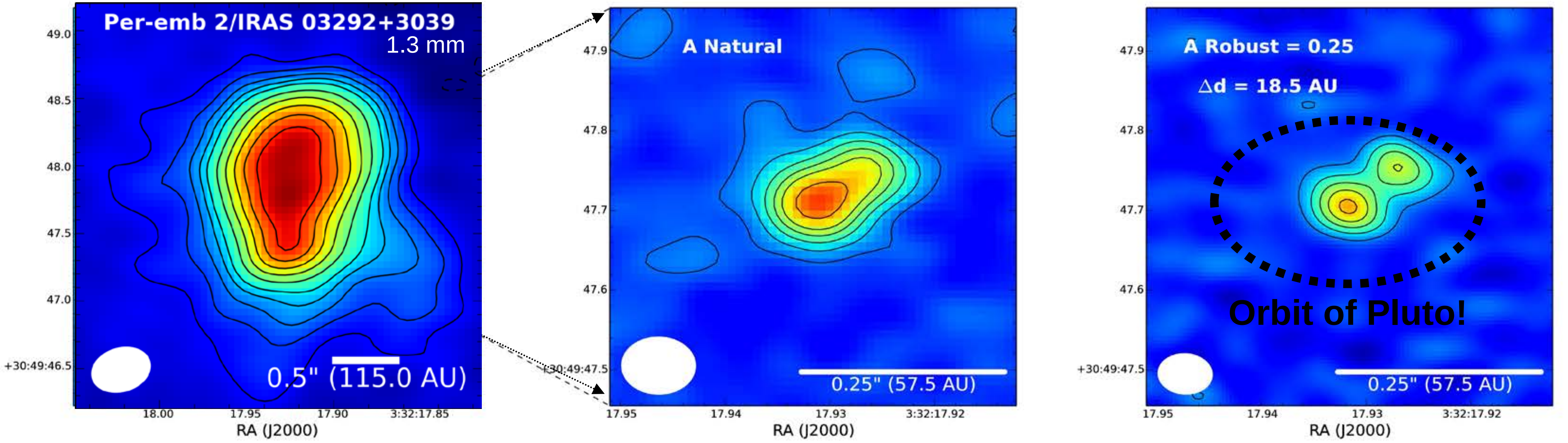
Turbulent/Rotational Fragmentation



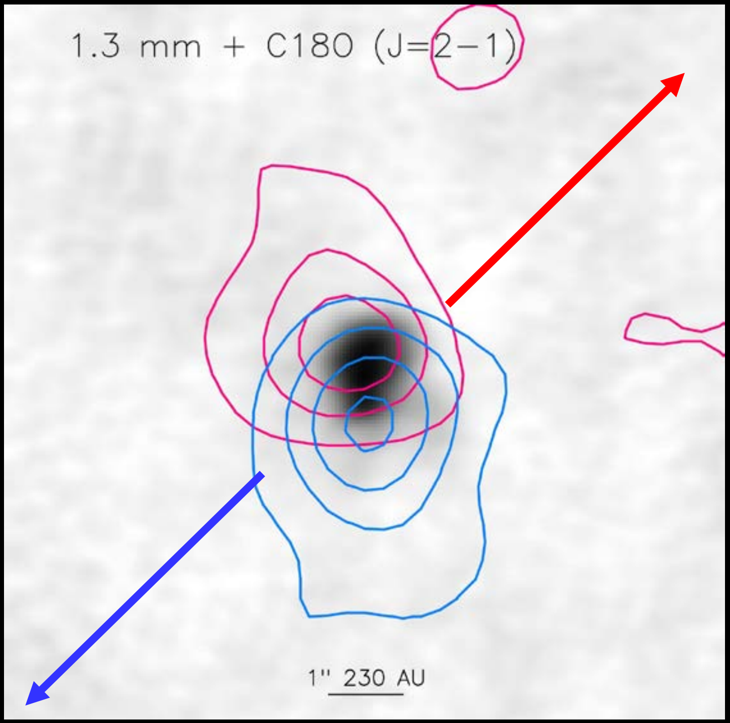
Offner+2010

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

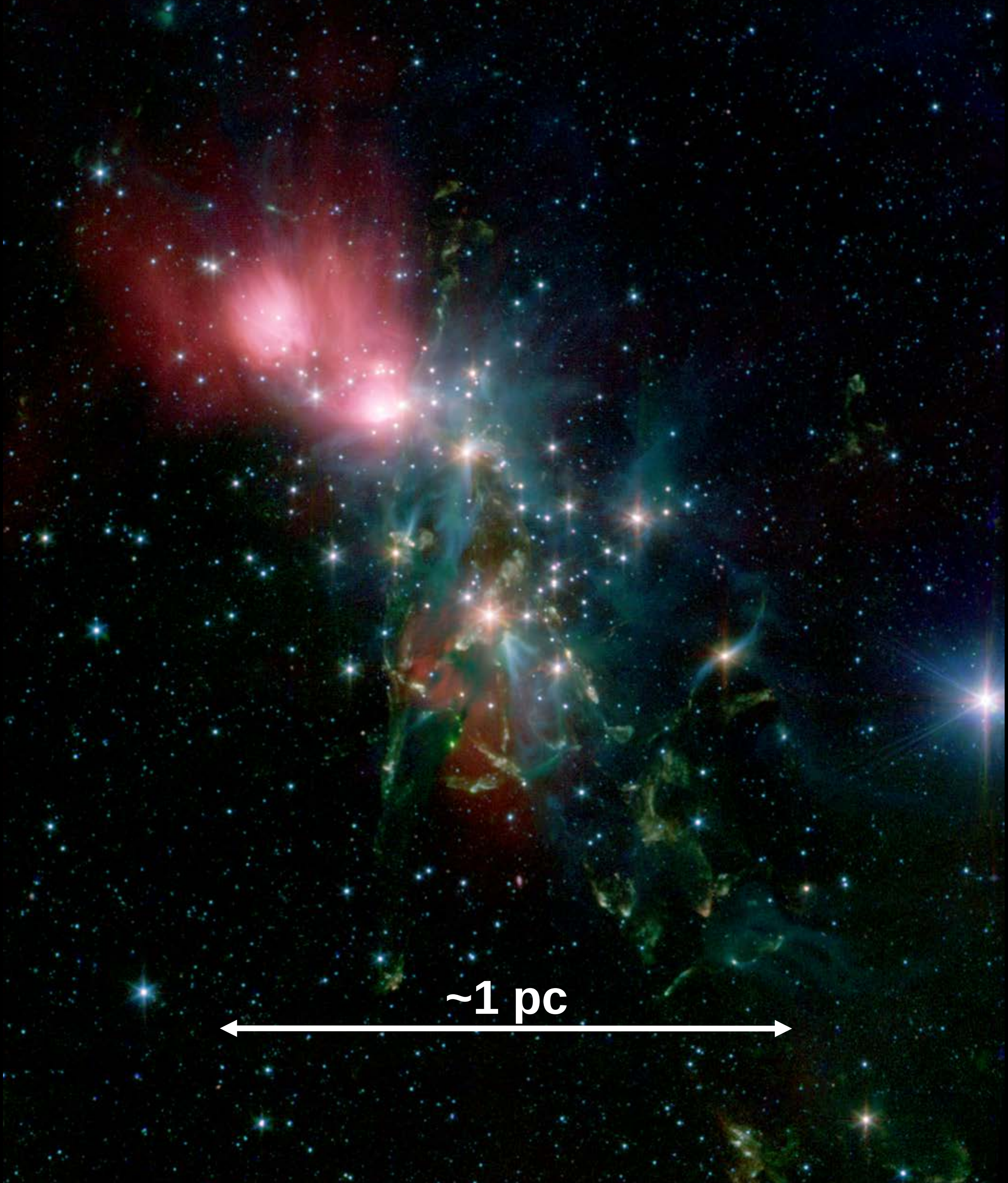
Evidence for Fragmenting Disks



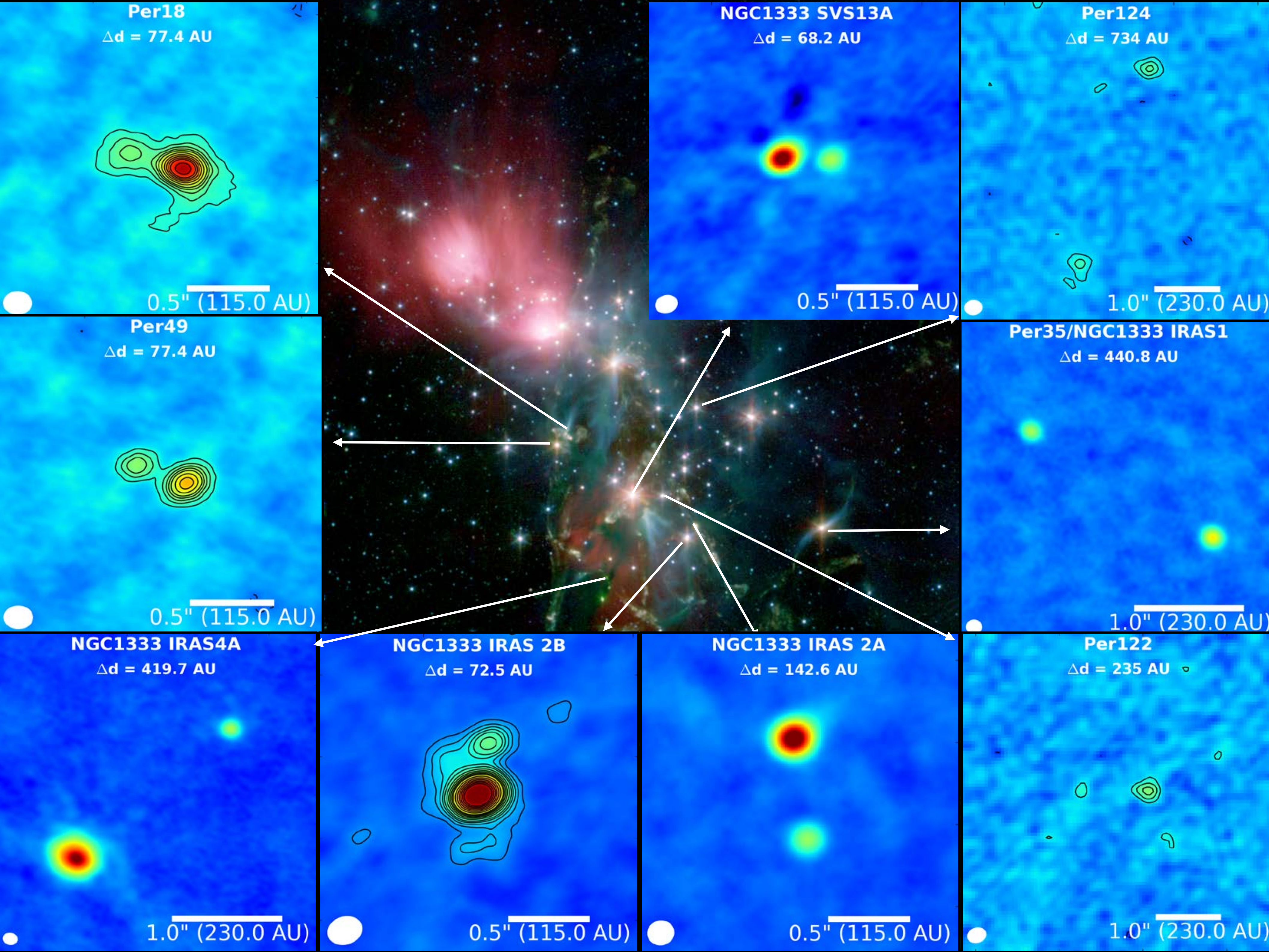
- Evidence of fragmentation within 'disks'
  - 3/43 Class 0 systems
- Gravitationally unstable disks likely transient
  - Appear unstable ~30 kyr (Stamatellos+2009)
- Candidate ~0.3 M_{sun} disk
  - Possibly optically thick at 1.3 mm
  - Rotation observed on outer scale of structure



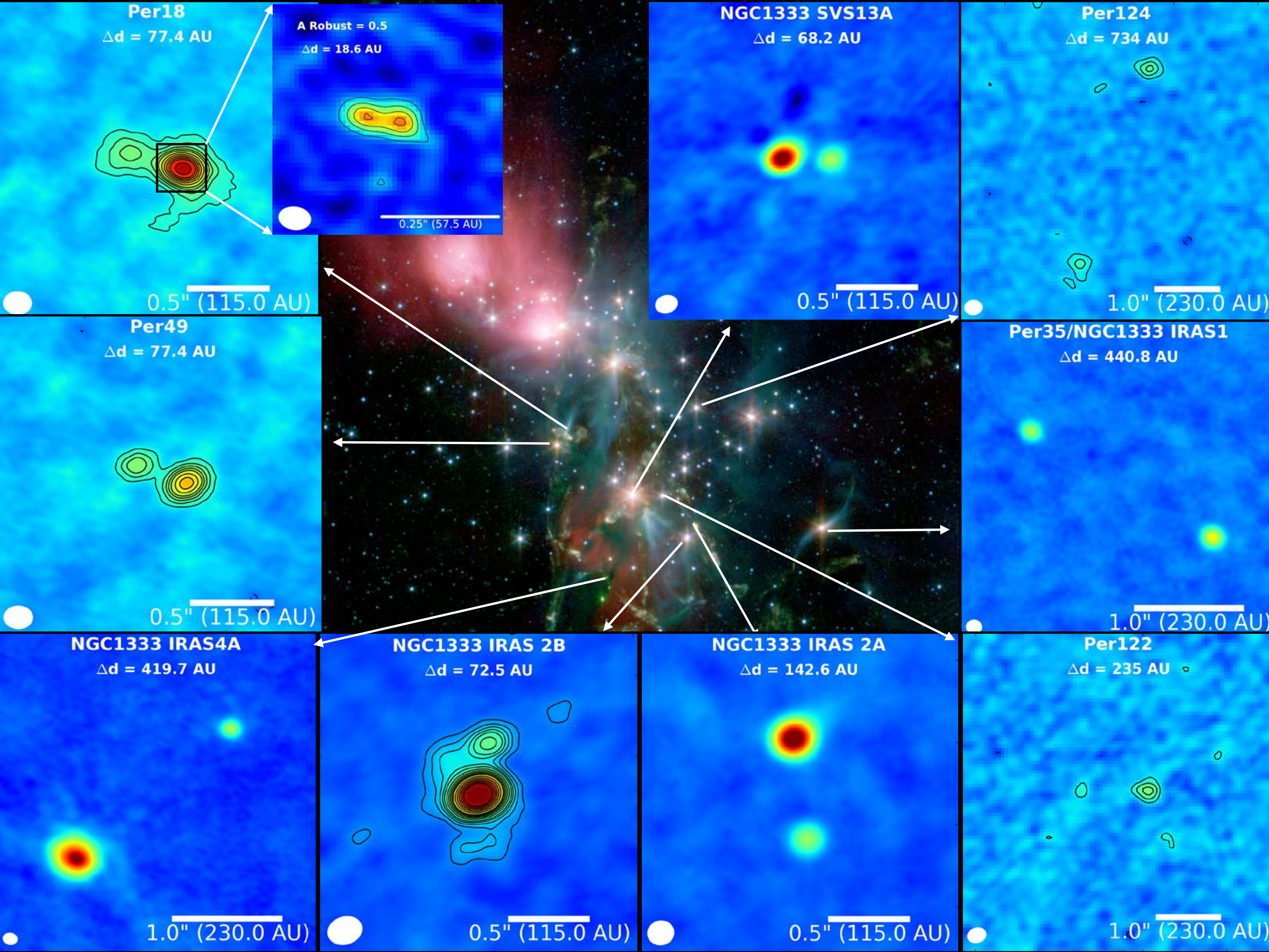
NGC 1333



Tobin+2016



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
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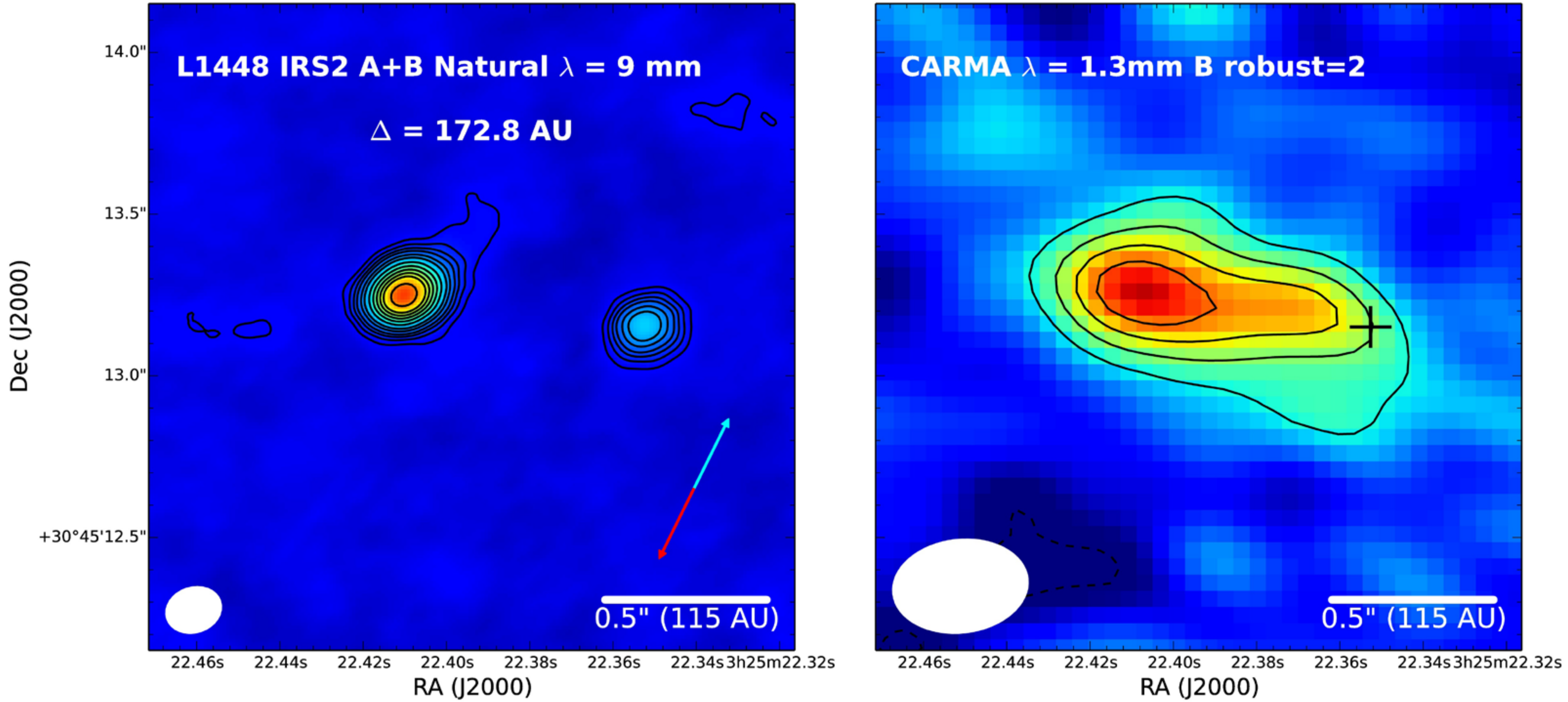
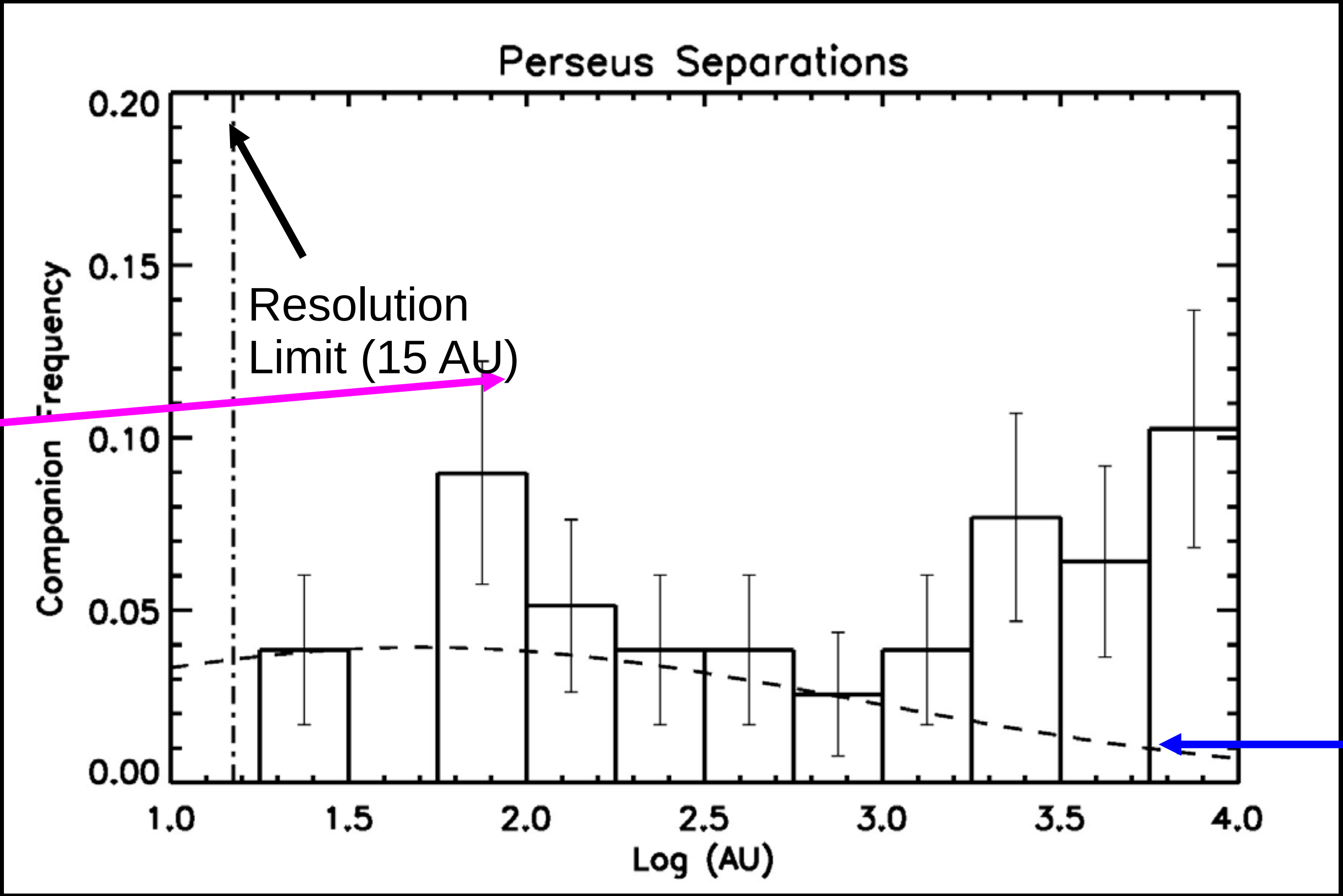
9 mm vs 1.3 mm



- Companions identified not always bright at 1.3 mm

Perseus Separation Distribution



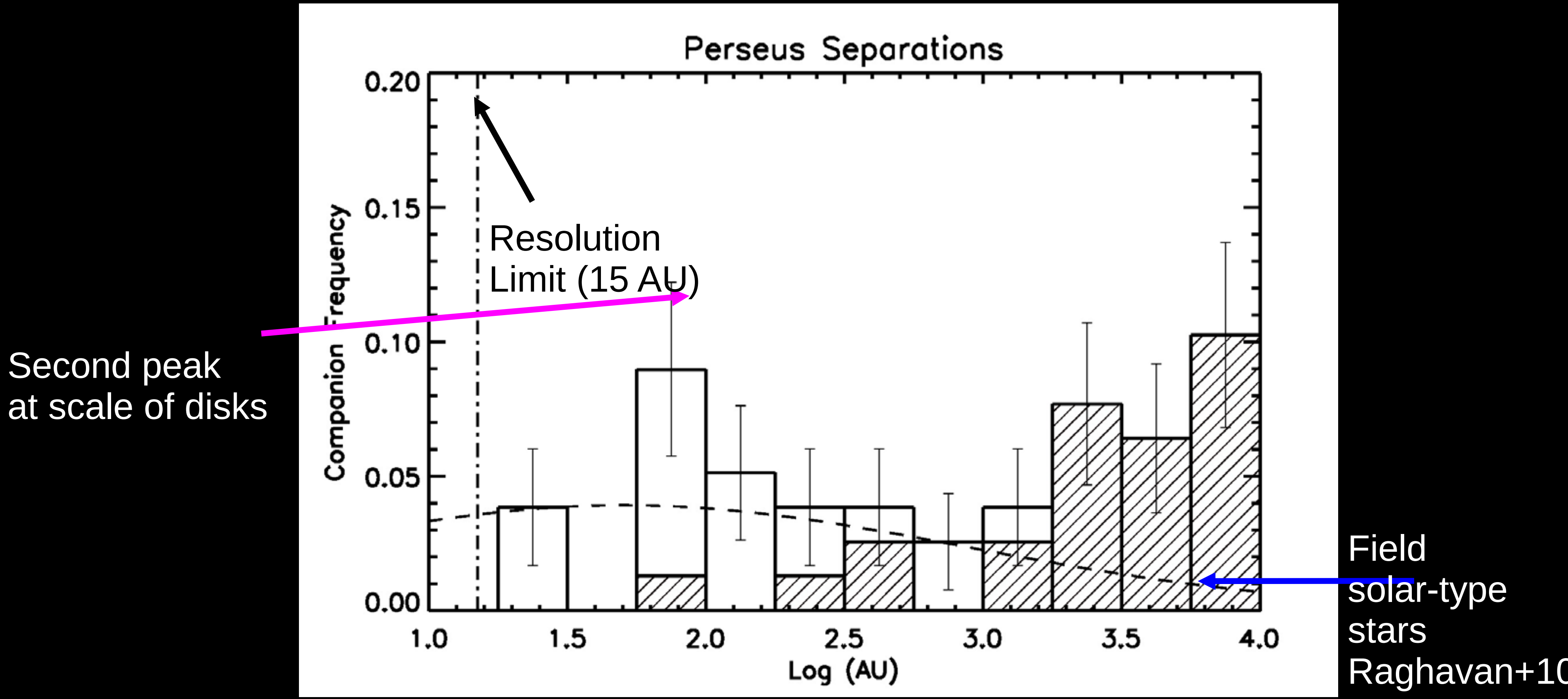
Second peak
at scale of disks

Field
solar-type
stars
Raghavan+10

Tobin+2016

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

Perseus Separation Distribution

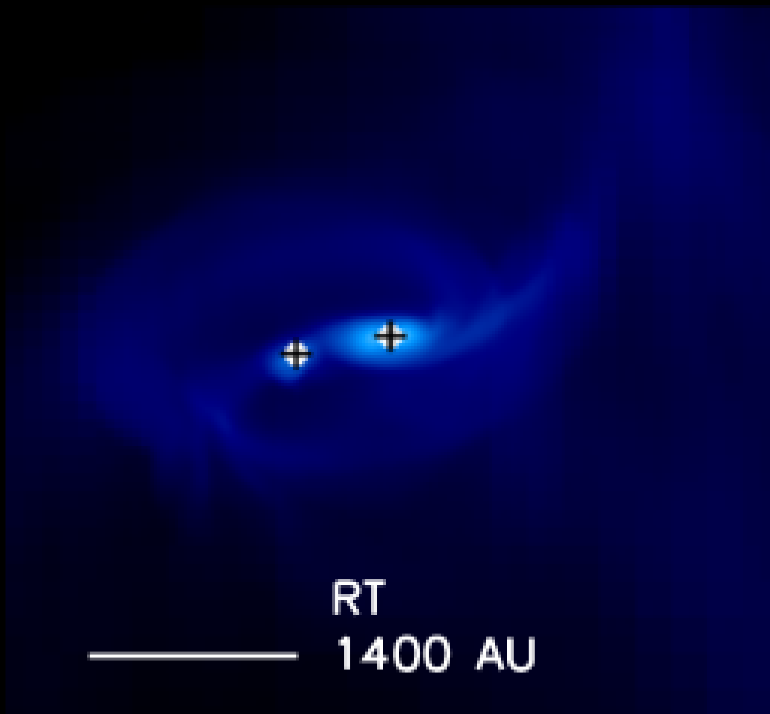


Tobin+2016

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

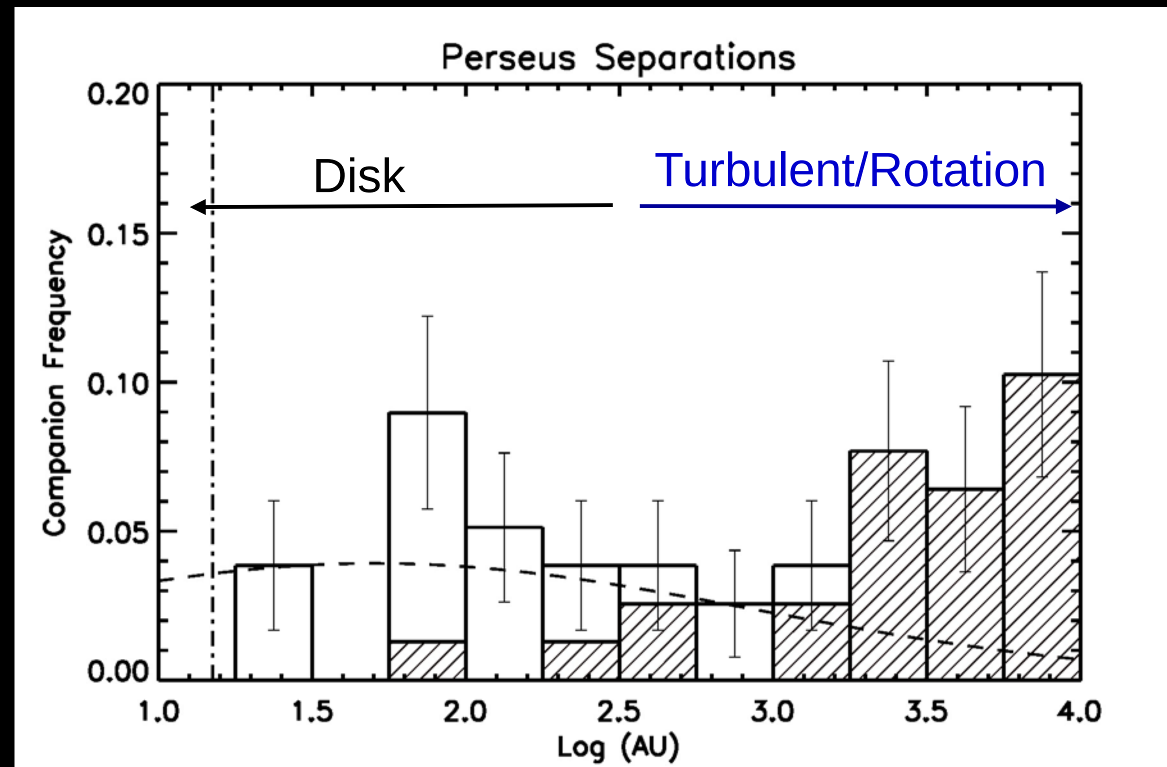
Multiple System Formation

Turbulent Fragmentation

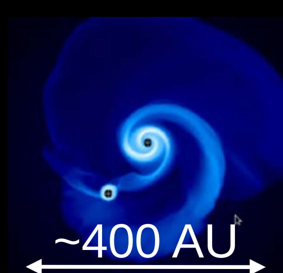


vs.

Offner+2010



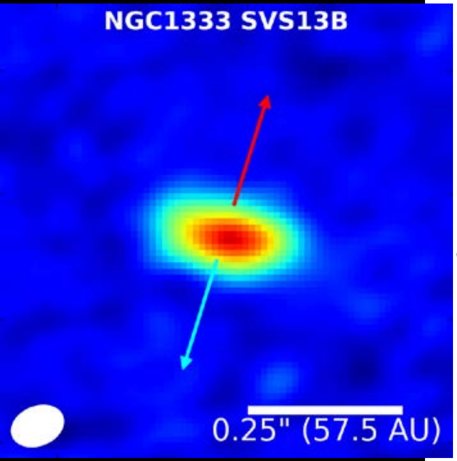
Disk Fragmentation

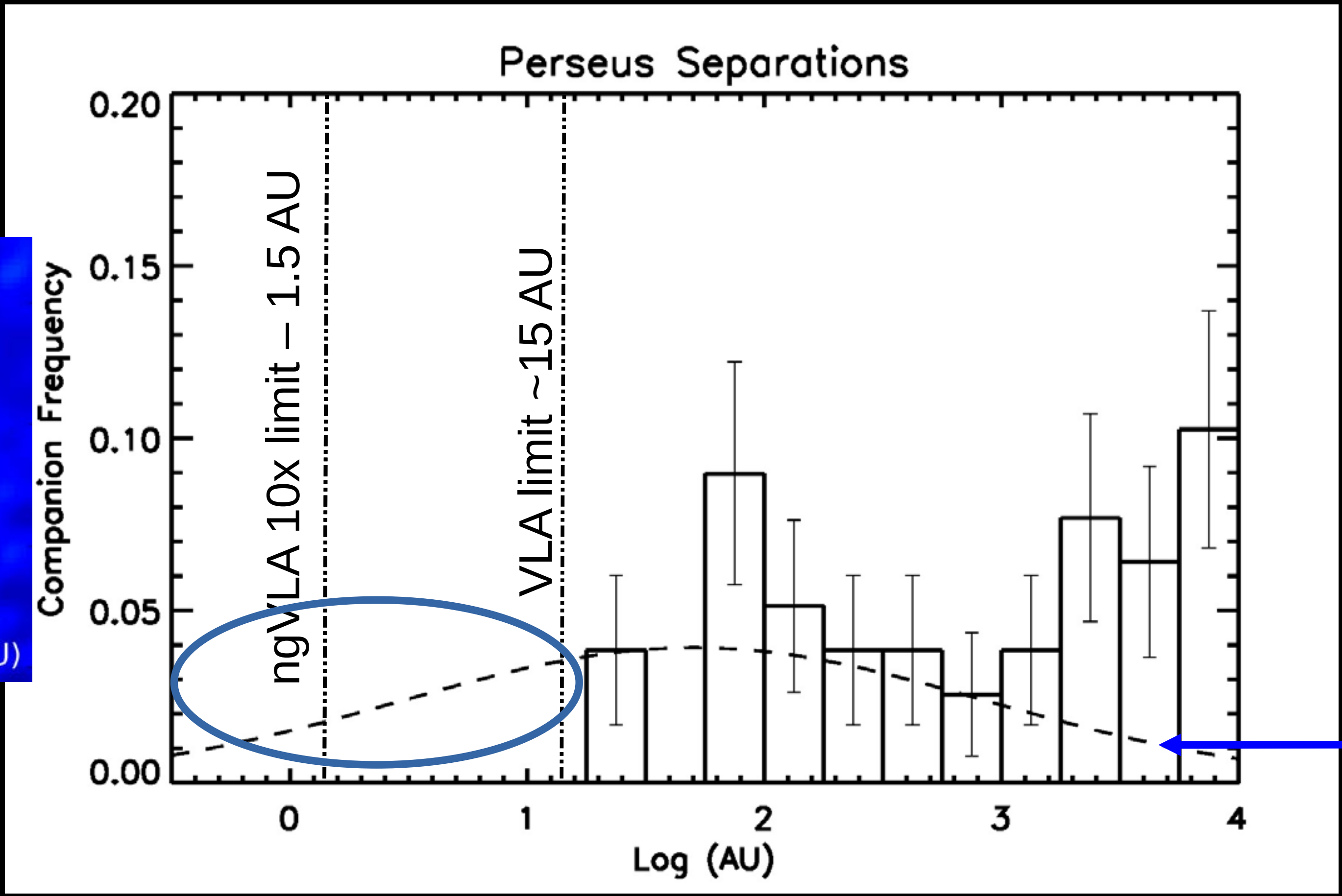


Kratter+2010

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

Perseus Separation Distribution

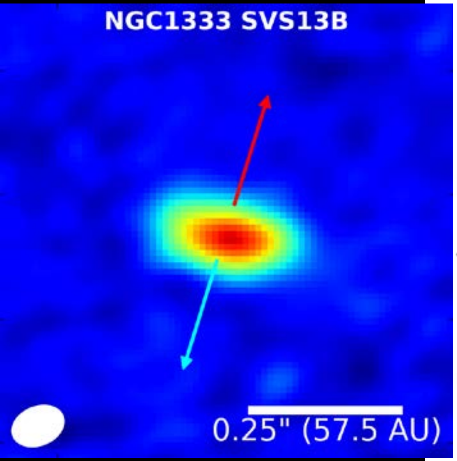


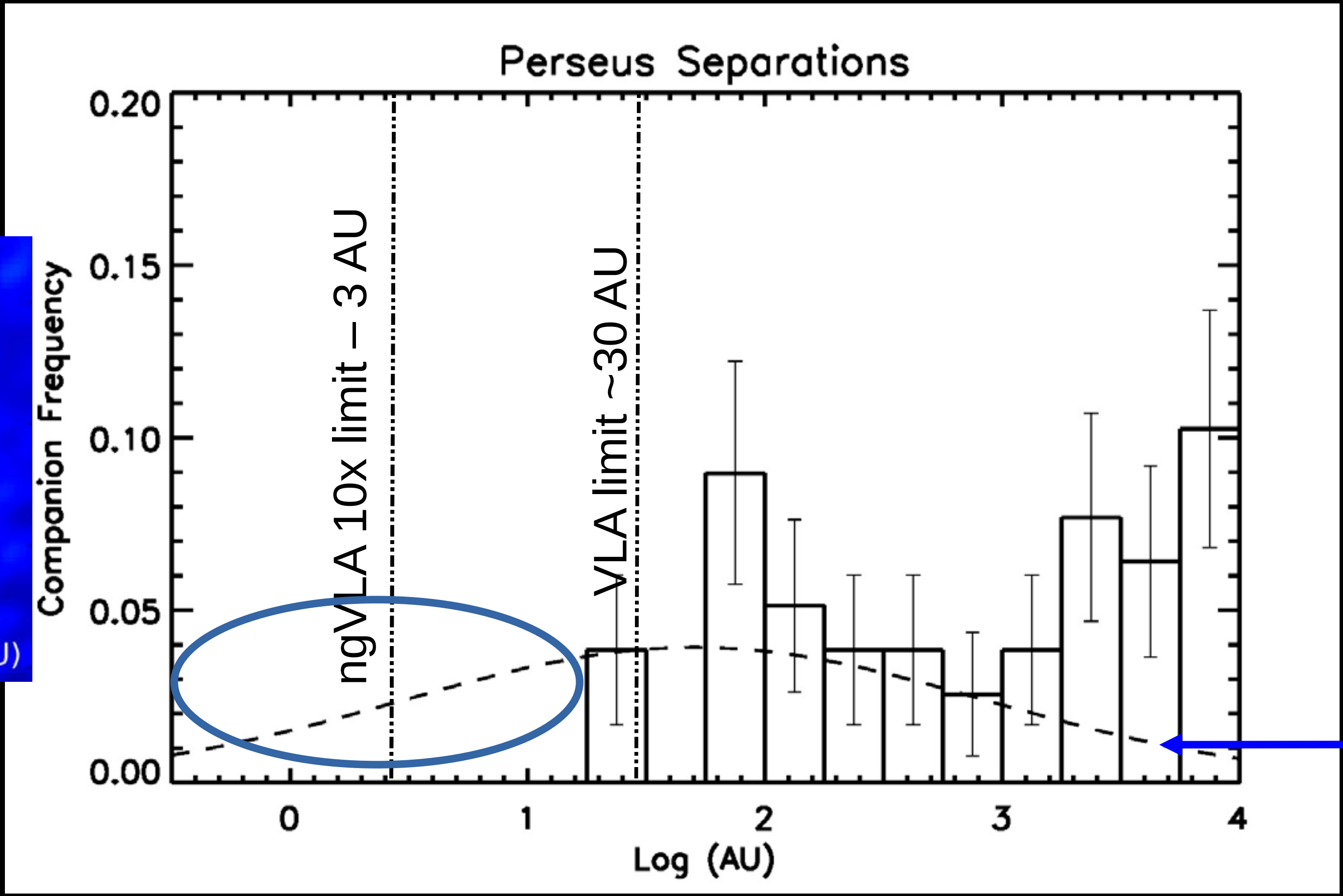


Field solar-type stars Raghavan+10

- Number of protostars at d < 300 pc is limiting for statistics

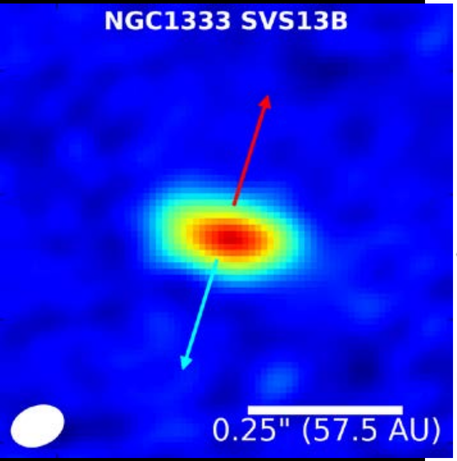
Orion Separation Distribution

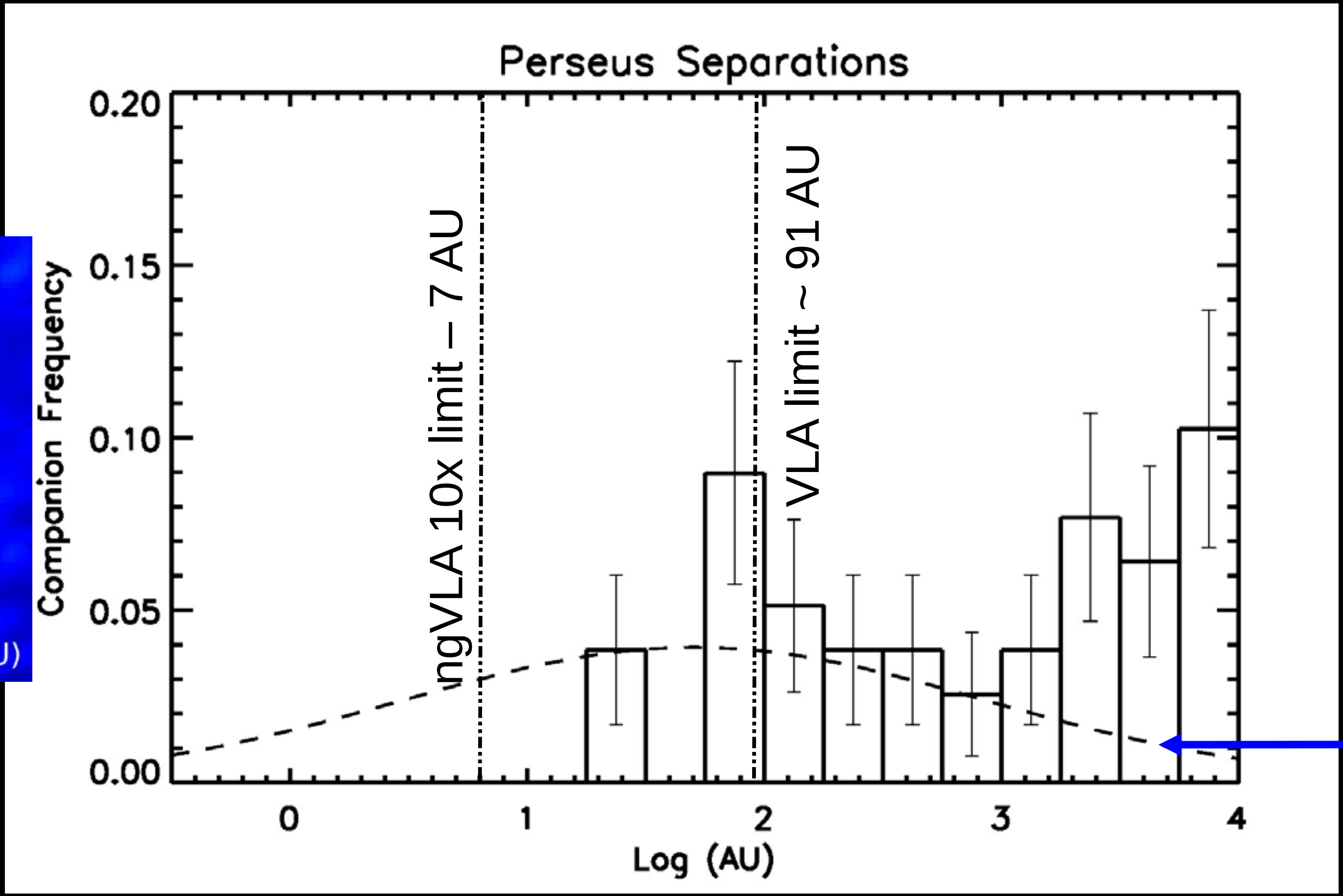




- Number of protostars at d < 300 pc is limiting for statistics
  - Orion @ 420 pc has ~ 400 protostars
  - Closest systems found in Perseus unresolved in Orion with VLA
    - ngVLA needed

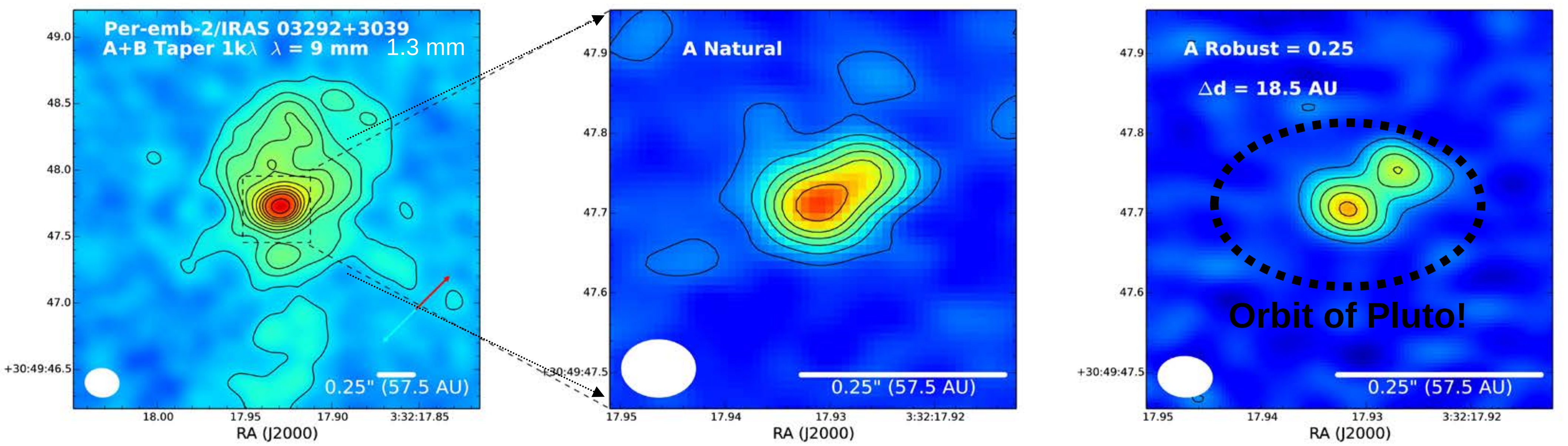
Cygnus - X Separation Distribution





- Number of protostars at d < 300 pc is limiting for statistics
  - Orion @ 420 pc has ~ 400 protostars
  - Closest systems found in Perseus unresolved in Orion
  - ngVLA can open door for SF regions at d ~ 0.5 – 1.5 kpc

IRAS 03292- A Benchmark System



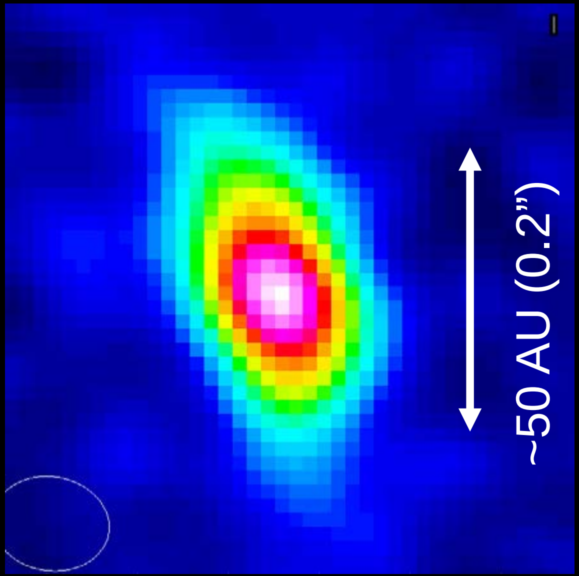
- F_{v} (9 mm) ~ 170 μJy/bm (S/N ~ 17), 130 μJy/bm (S/N ~ 13)
  - @ Orion/Serpens: F_{v} ~ 51 μJy/bm, 39 μJy/bm, σ ~ 3 μJy/bm
  - ~1 hr on-source in Perseus → 11 hr on-source in Orion (3 μJy/bm)
  - For A_{eff} ~ 10x VLA and Δv ~ 2x VLA (Q + Ka) → 0.5 hr on-source
  - Need at least 2x VLA Max. baseline to resolve
    - Look for orbital motion around similar or more compact systems
      - Protostar masses!

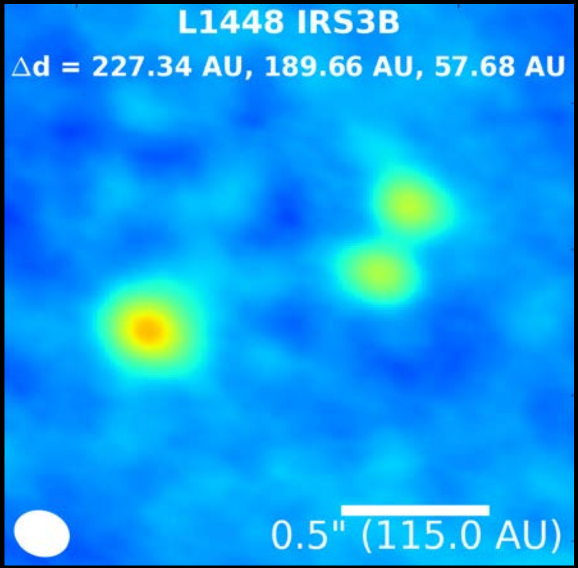
Sensitivity Reference

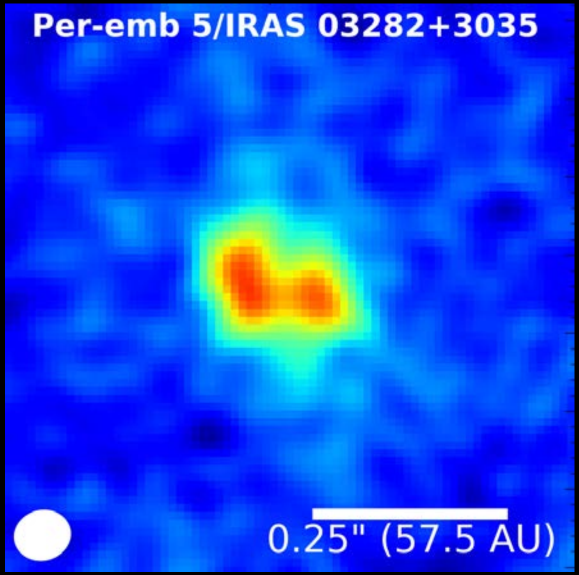
- $\Delta t \sim 1 / (\Delta v\ A) * (d_x/d_{per})^4$
  - Orion/Serpens: d ~ 420 pc; $\Delta t/\Delta t_{per}$ ~ **11x**
  - MonR2/NGC2264/Cepheus: d ~ 800 pc; $\Delta t/\Delta t_{per}$ ~ **144x**
  - Cygnus-X: d ~ 1400 pc; $\Delta t/\Delta t_{per}$ ~ **1400x**
- 10x ngVLA + 2x bandwidth (Q + Ka)
  - Orion/Serpens: d ~ 420 pc; $\Delta t/\Delta t_{per}$ ~ **0.5x**
  - MonR2/NGC2264/Cepheus: d ~ 800 pc; $\Delta t/\Delta t_{per}$ ~ **7x**
  - Cygnus-X: d ~ 1400 pc; $\Delta t/\Delta t_{per}$ ~ **70x**
- Primary Beam area increases with d^2
  - Remaining time penalty offset by covering more sources
    - Assuming 18 m dishes, 2x lower for 25 m dishes

Summary

- Unbiased surveys crucial for disk and multiplicity studies
- Large sample of protostellar disk candidates revealed by VLA
- Multiplicity of protostars characterized, hints of evolution?
  - Closest known Class 0 protostellar multiples identified
- ngVLA will greatly expand capability to characterize multiplicity and disks out to more populous regions of star formation
  - Will enable robust constraints on multiplicity and disk evolution



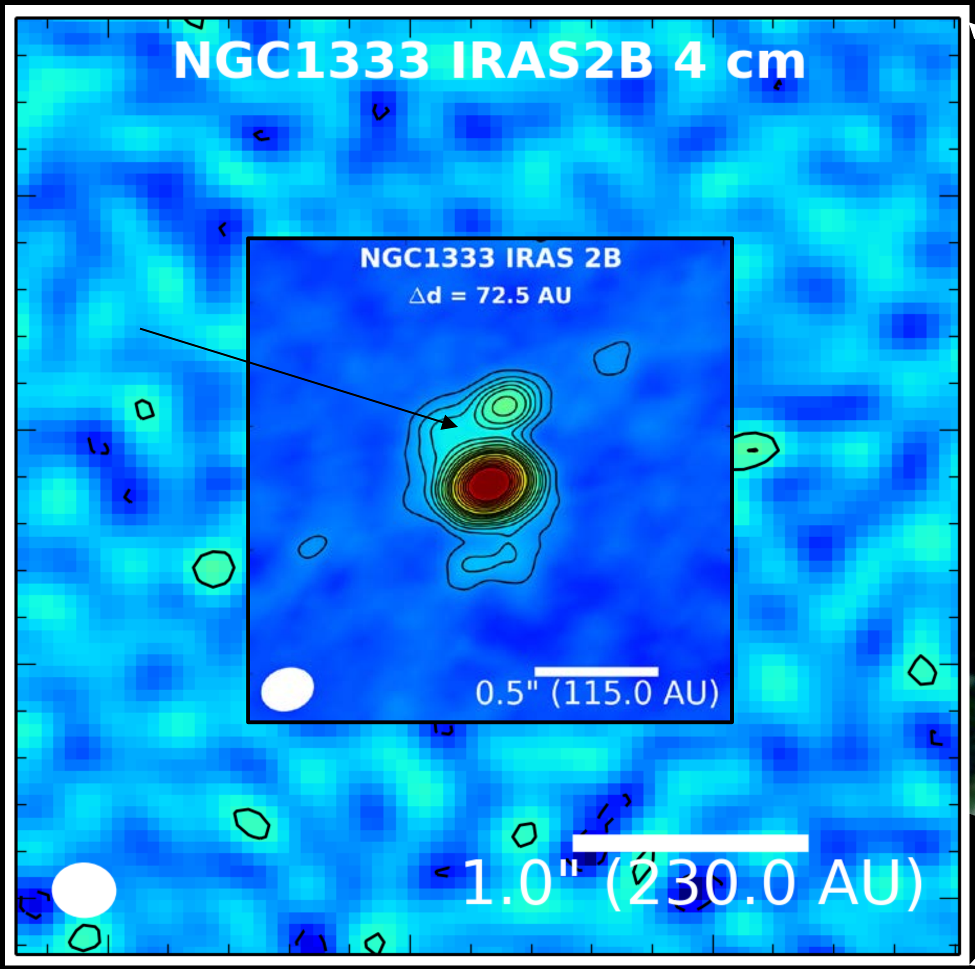


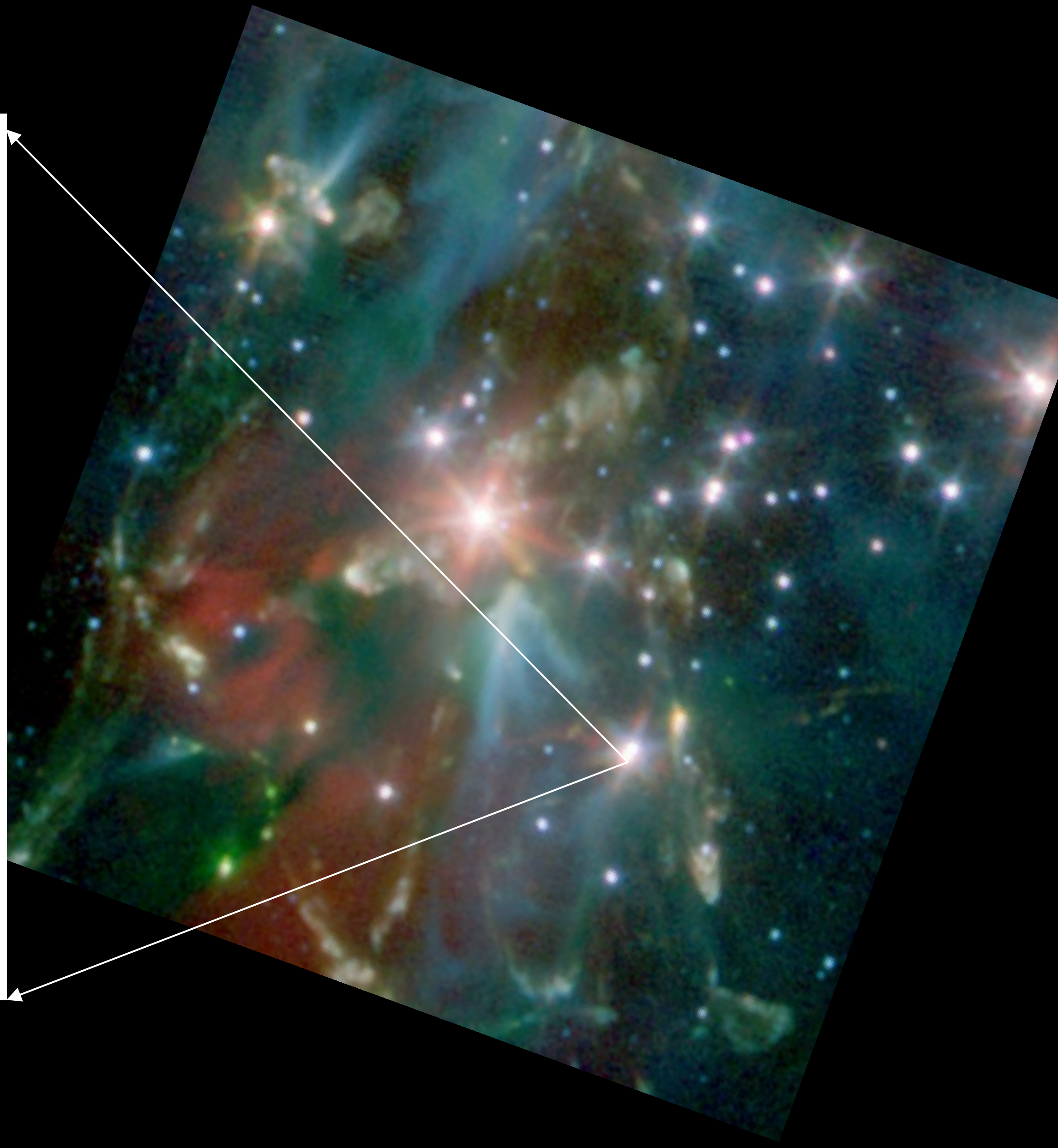


Research Supported By:

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

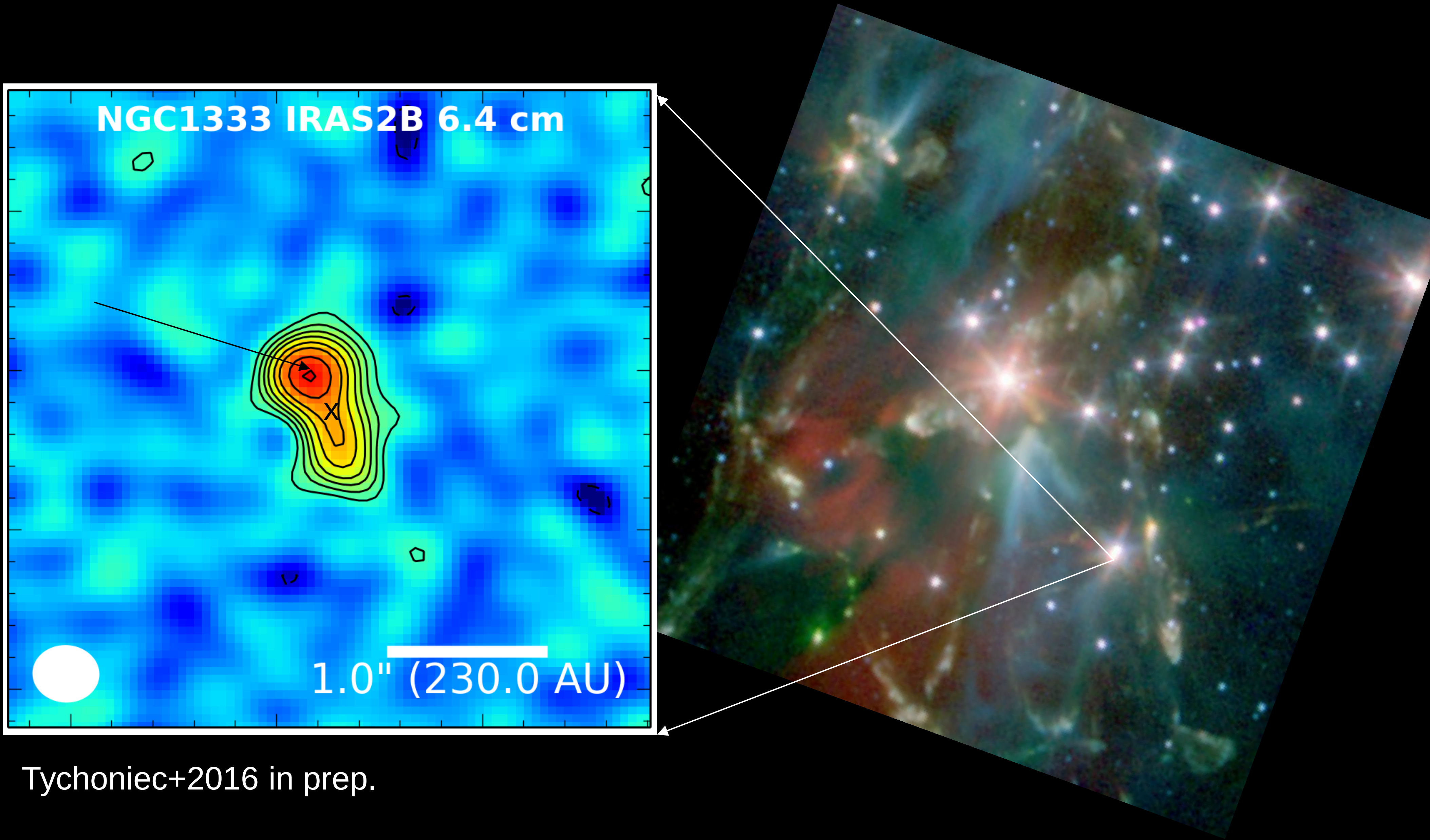
Protostellar Jets: IRAS2B





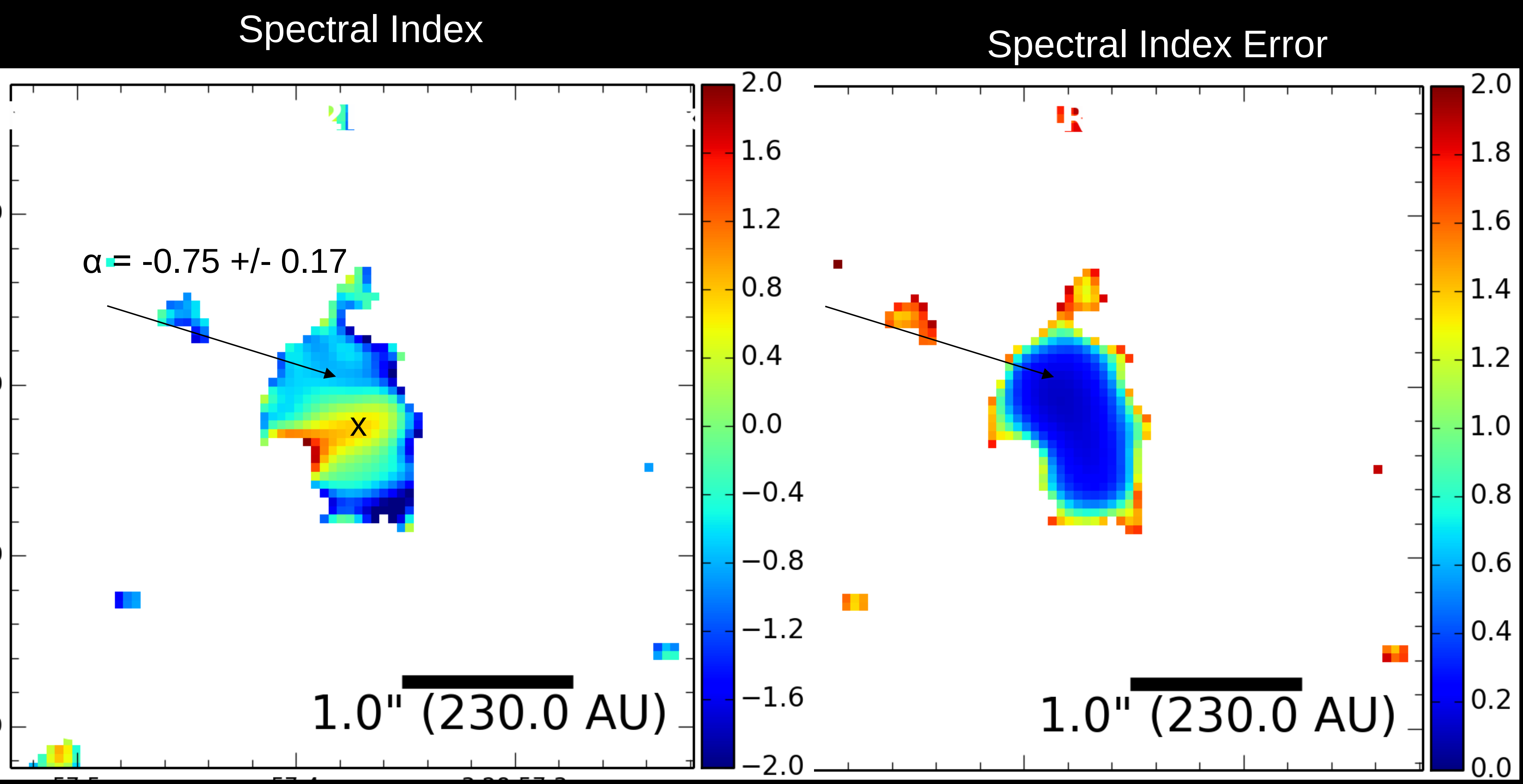
Tychoniec+2016 in prep.

Protostellar Jets: IRAS2B



Tychoniec+2016 in prep.

Protostellar Jets: IRAS2B

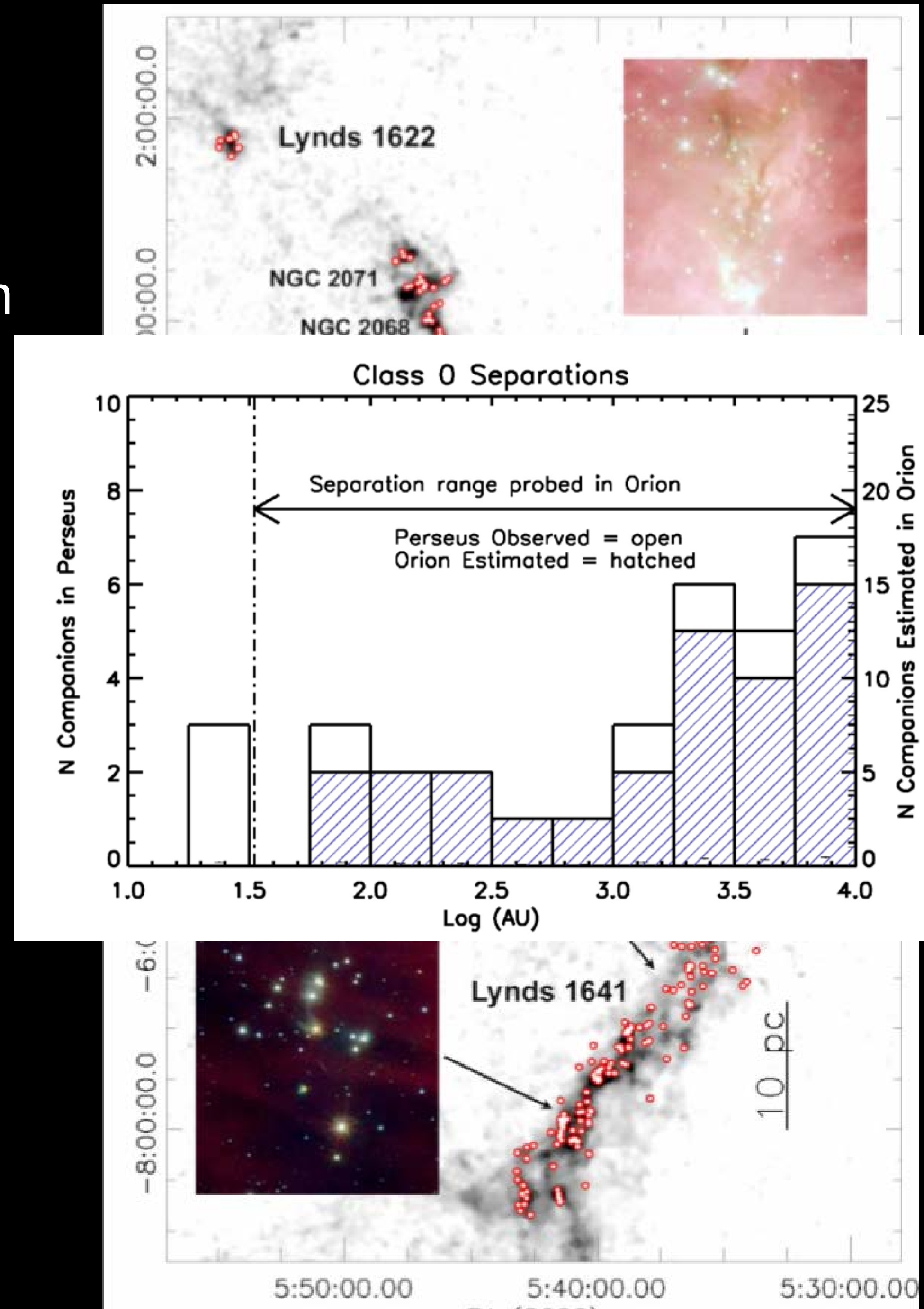


Tychoniec+2016 in prep.

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

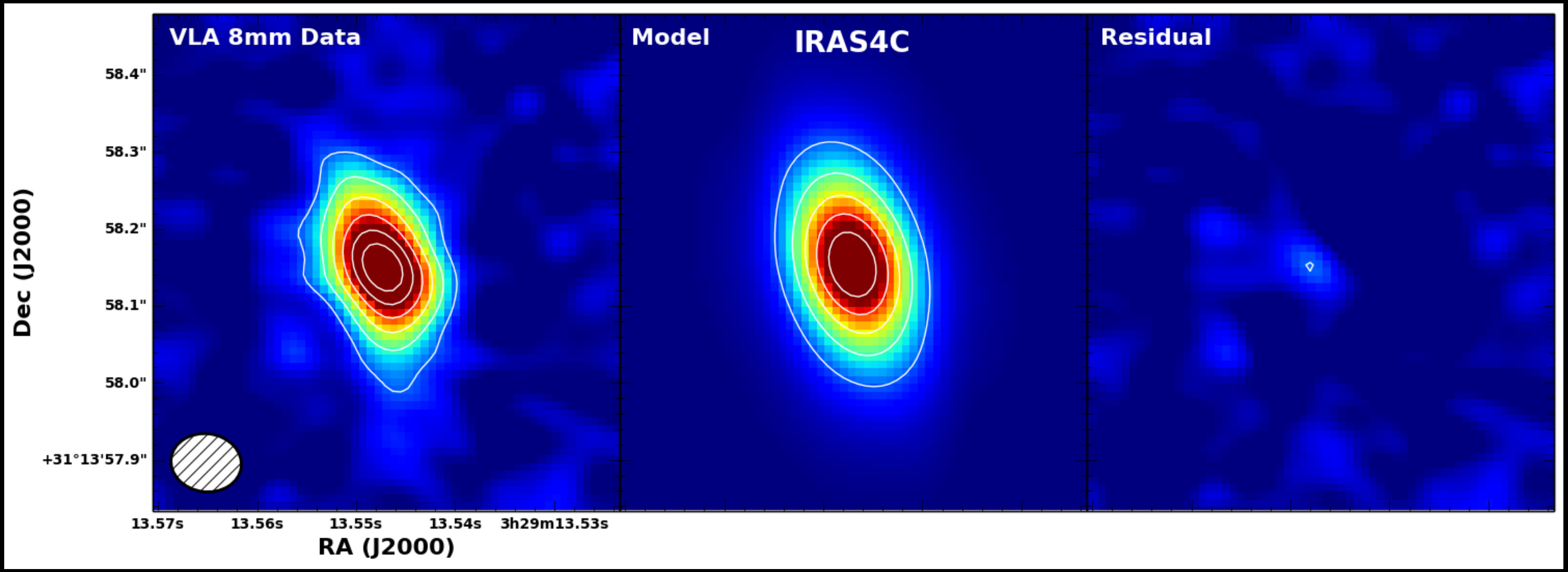
Orion: The Great Frontier

- Most populous star forming region within 500 pc
  - Nearest region actively forming high and intermediate mass stars
- Approved ALMA Cycle 3 Survey
  - 330 Orion protostars
  - 0.85 mm, 30 AU resolution (0.08")
  - begins 2016
- VLA large program (340 hr) approved
  - 110 Class 0
  - 8 mm, 30 AU resolution (<0.08")
  - Begins 2016



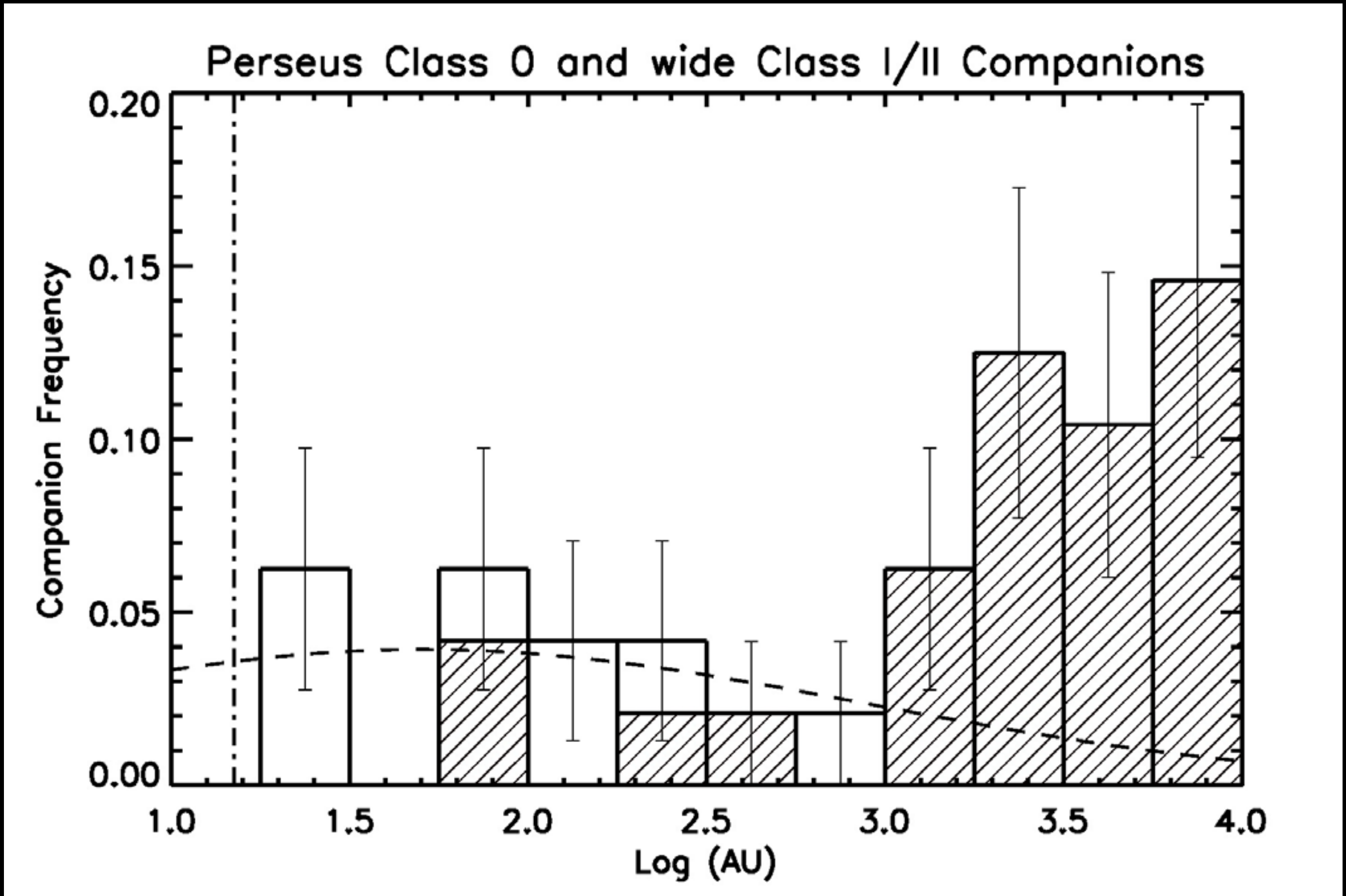
VANDAM Disk Candidates

- Resolved structures consistent with disks for 17/80 Class 0/I
  - ~12/43 for Class 0 (youngest) sources; 5/37 Class I
- Power-law disk models indicate 8 mm radii 10 AU – 30 AU
  - Masses ~0.1 M_{sun}
  - Need to be confirmed kinematically
  - Poster 236.09 by D. Segura-Cox (Wednesday)



Segura-Cox+2016 submitted

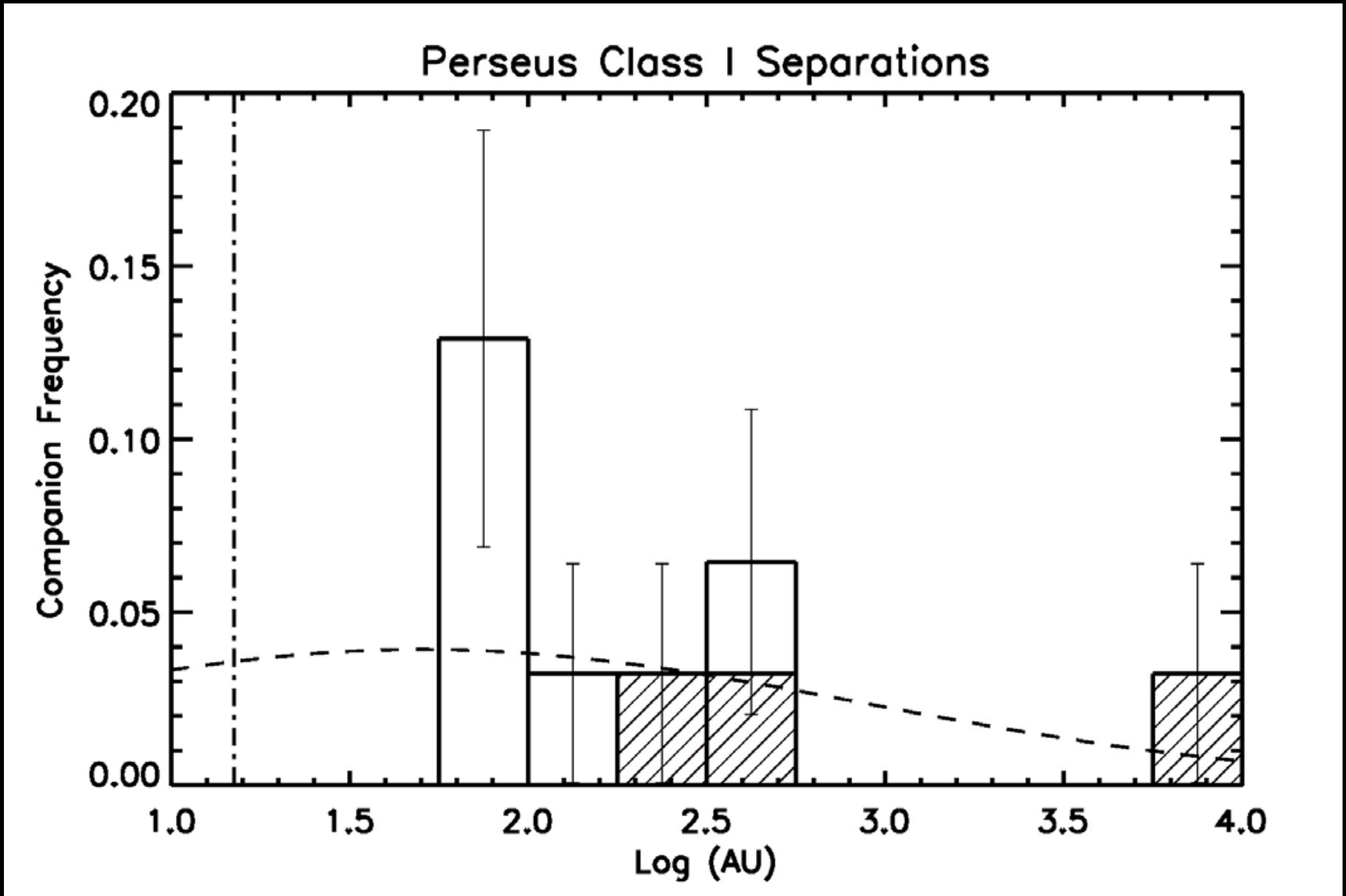
Perseus Separation Evolution



Tobin+2016

- Class 0 (youngest) sources still have many at < 300 AU

Perseus Separation Evolution



Tobin+2016

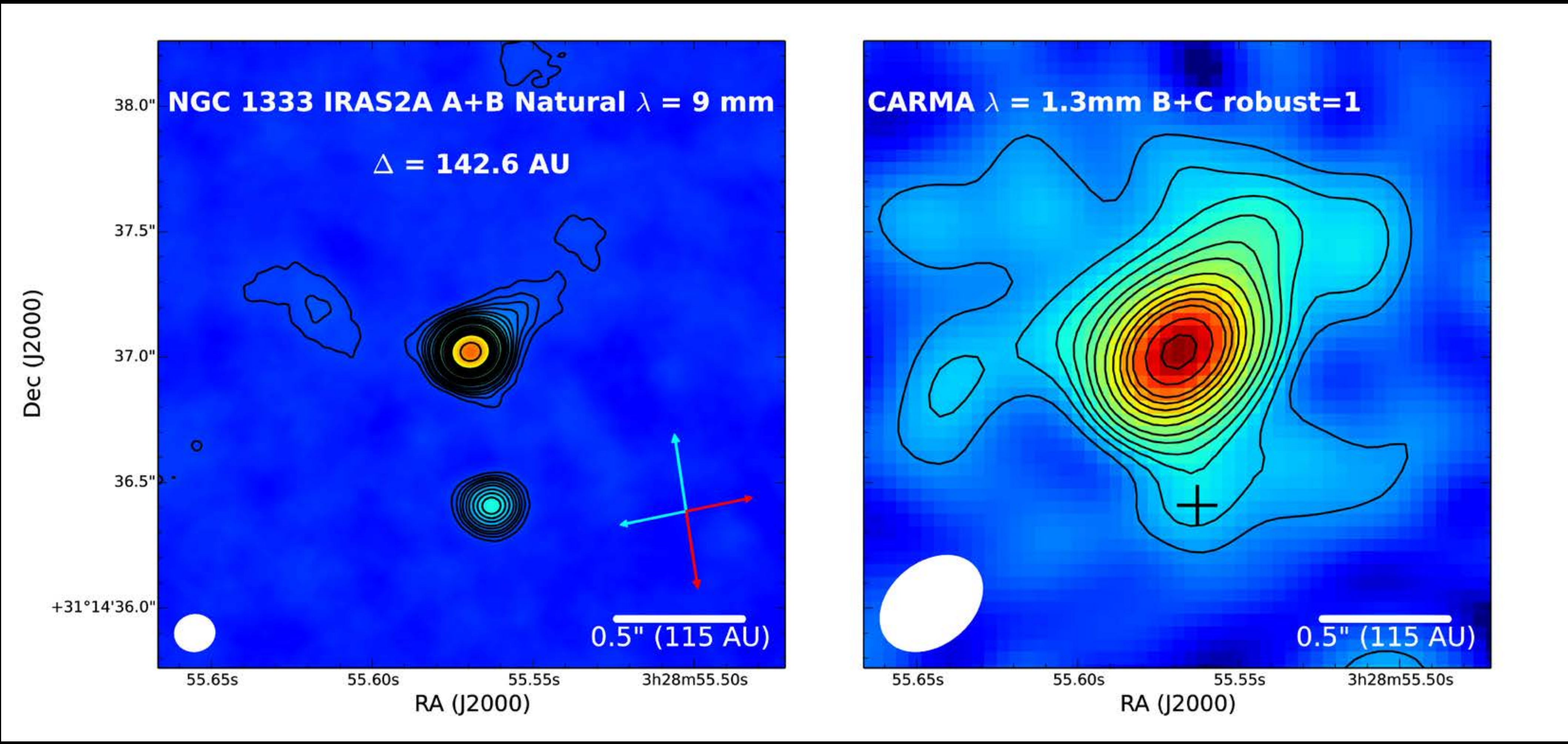
- Lack of wide multiples toward Class I (more-evolved) sources
  - Evolution of separations?
    - Fraction of < 300 AU systems ~constant
    - Wide systems form unbound and disperse?

Multiplicity Statistics

- Multiplicity Fraction (MF) and Companion Star Fraction (CSF) depend on scales of interest
- 15 AU to 10000 AU
  - Class 0 – MF = 0.57 – CSF = 1.21
  - 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
- Most stars are born in wide multiple systems that rapid dissolve
  - Smaller fraction have closer companions

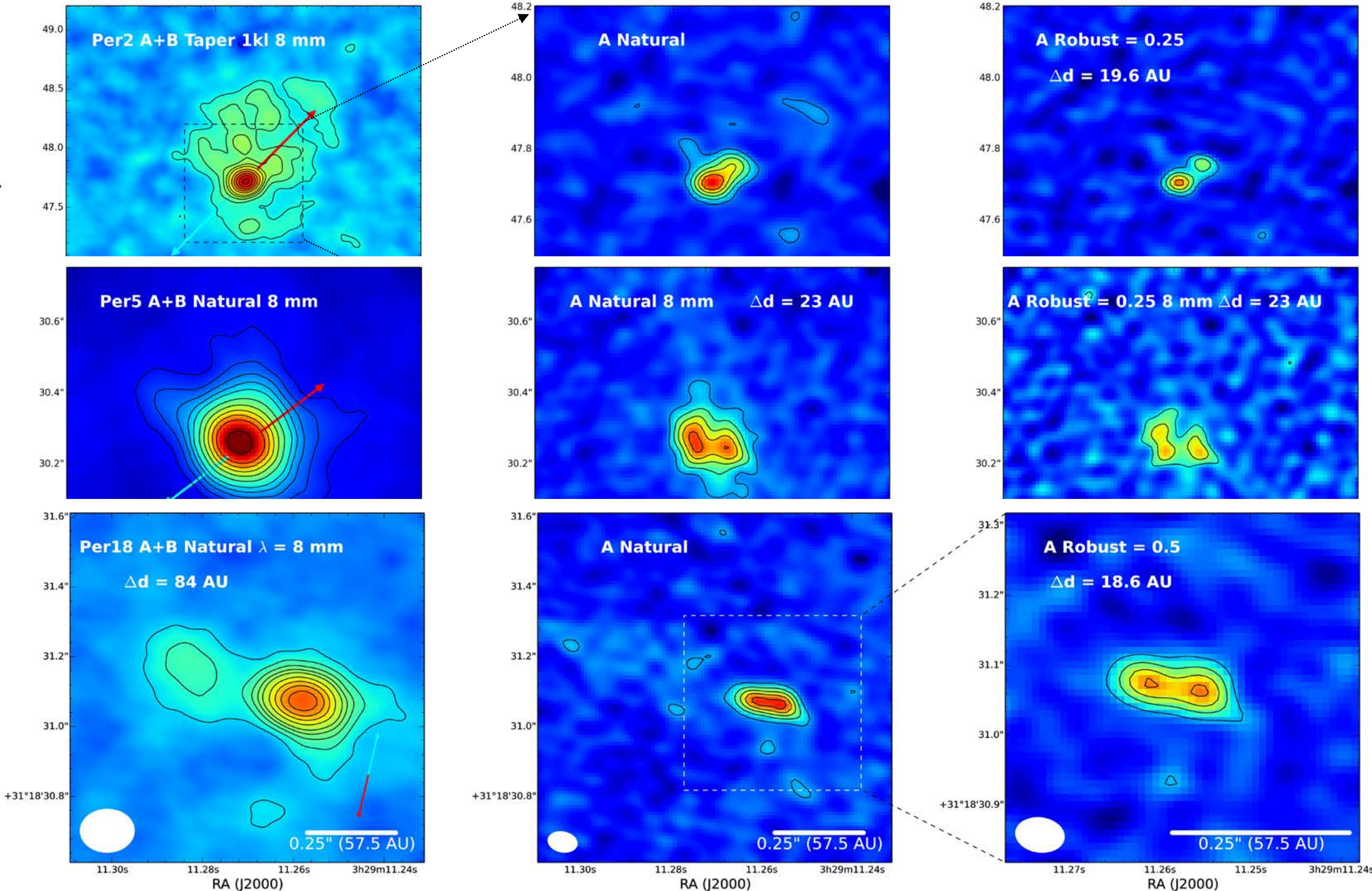
Tobin+2015 submitted

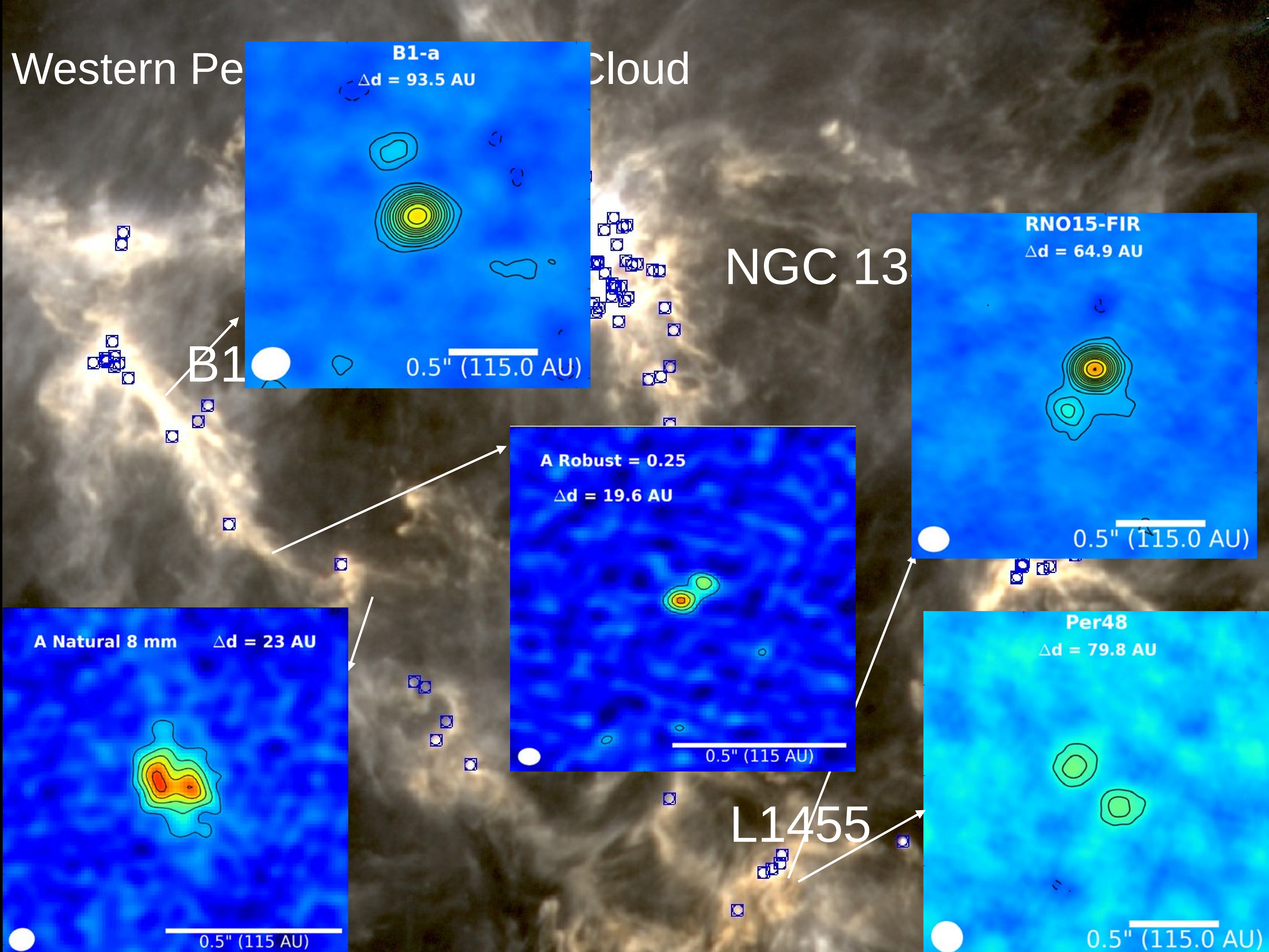
Why the VLA?



- Companions identified not always bright at 1.3 mm

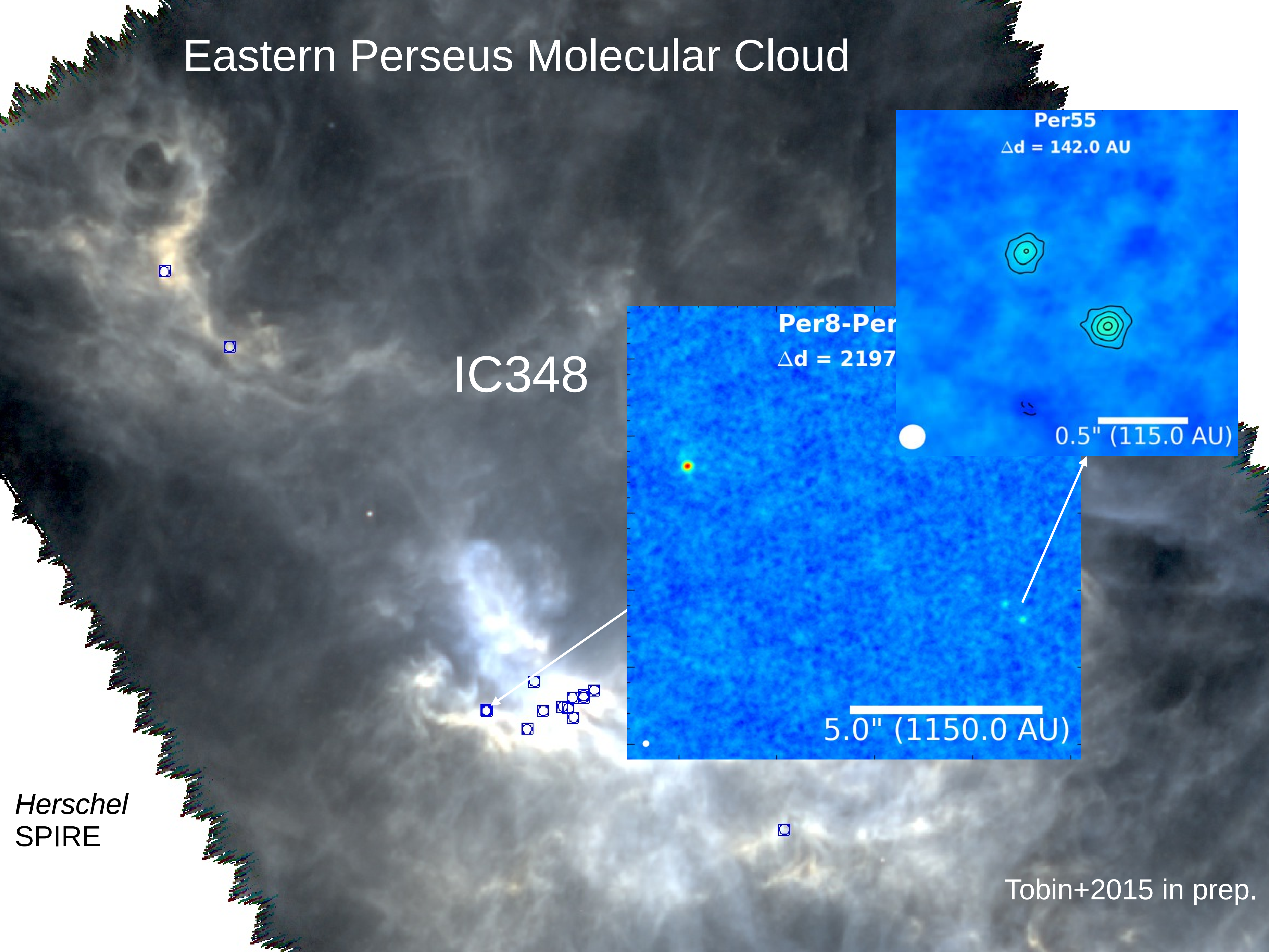
Evidence for Fragmenting Disks





Western Pe
Cloud
B1-a
Δd = 93.5 AU
0.5" (115.0 AU)
B1
NGC 13
RNO15-FIR
Δd = 64.9 AU
0.5" (115.0 AU)
A Robust = 0.25
Δd = 19.6 AU
0.5" (115 AU)
A Natural 8 mm
Δd = 23 AU
0.5" (115 AU)
Per48
Δd = 79.8 AU
0.5" (115.0 AU)
L1455

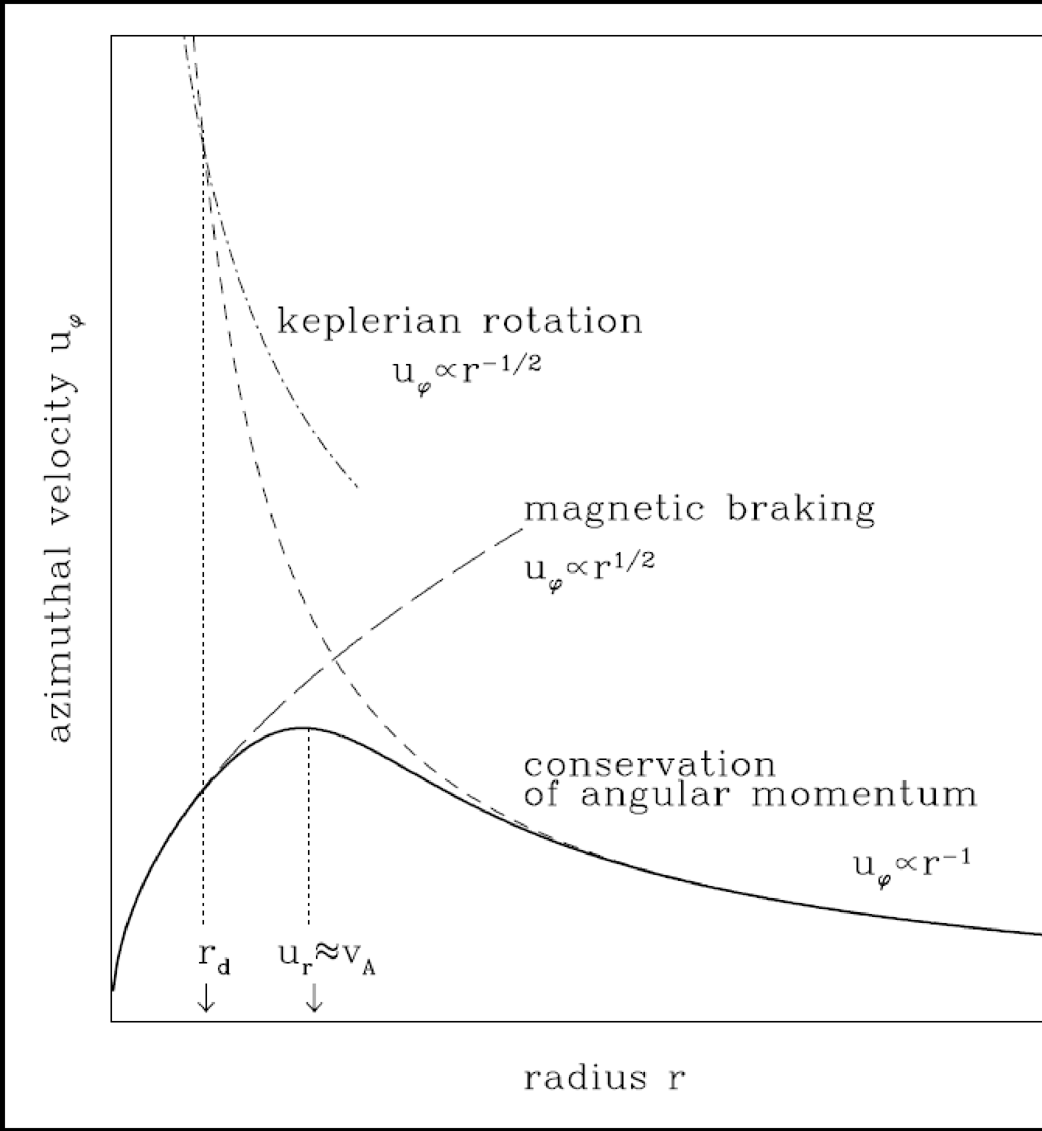
Eastern Perseus Molecular Cloud



Tobin+2015 in prep.

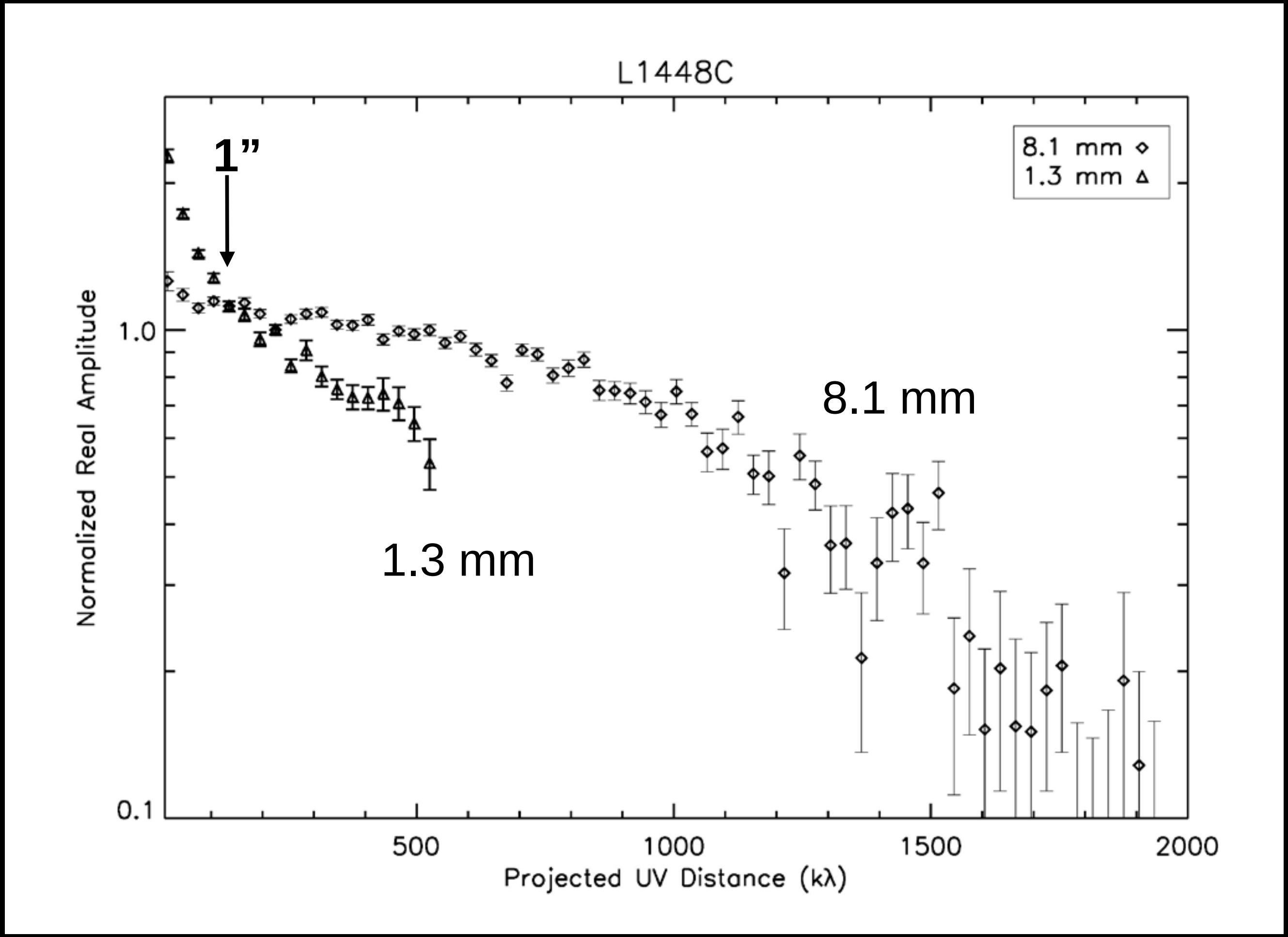
Problems for Disk Formation?

- Disks form due to conservation of angular momentum
- Magnetized clouds pose some complications
  - Angular momentum removed
  - 'Magnetic braking catastrophe'
  - Prediction of ideal MHD
- Several potential remedies
  - Non-ideal MHD – Ohmic Diss. (Dapp & Basu 2010)
  - Misaligned rotation and magnetic field (Joos+2010)
  - Magnetic mirroring of Cosmic Rays (Padovani+2013)

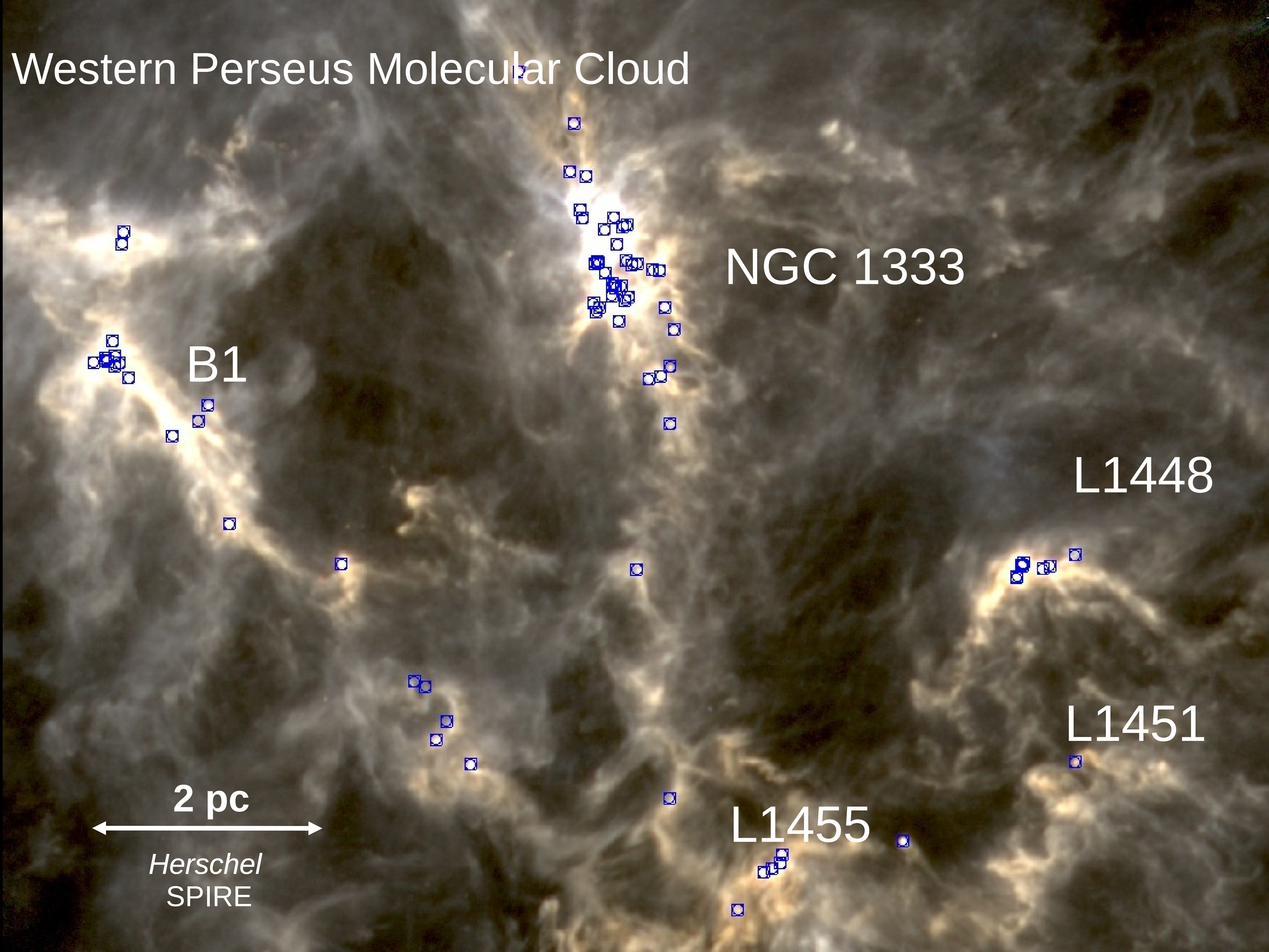


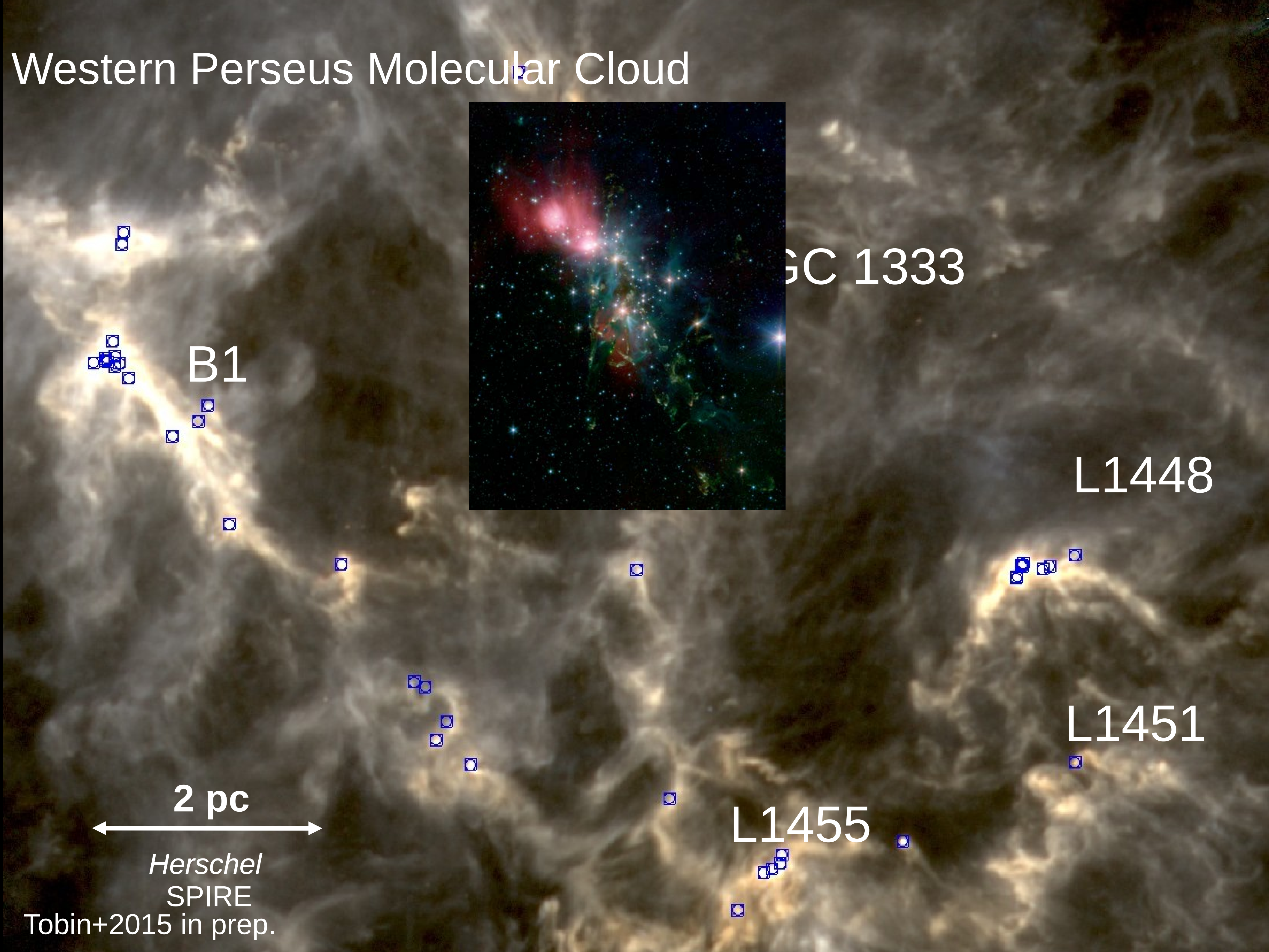
Galli 2009

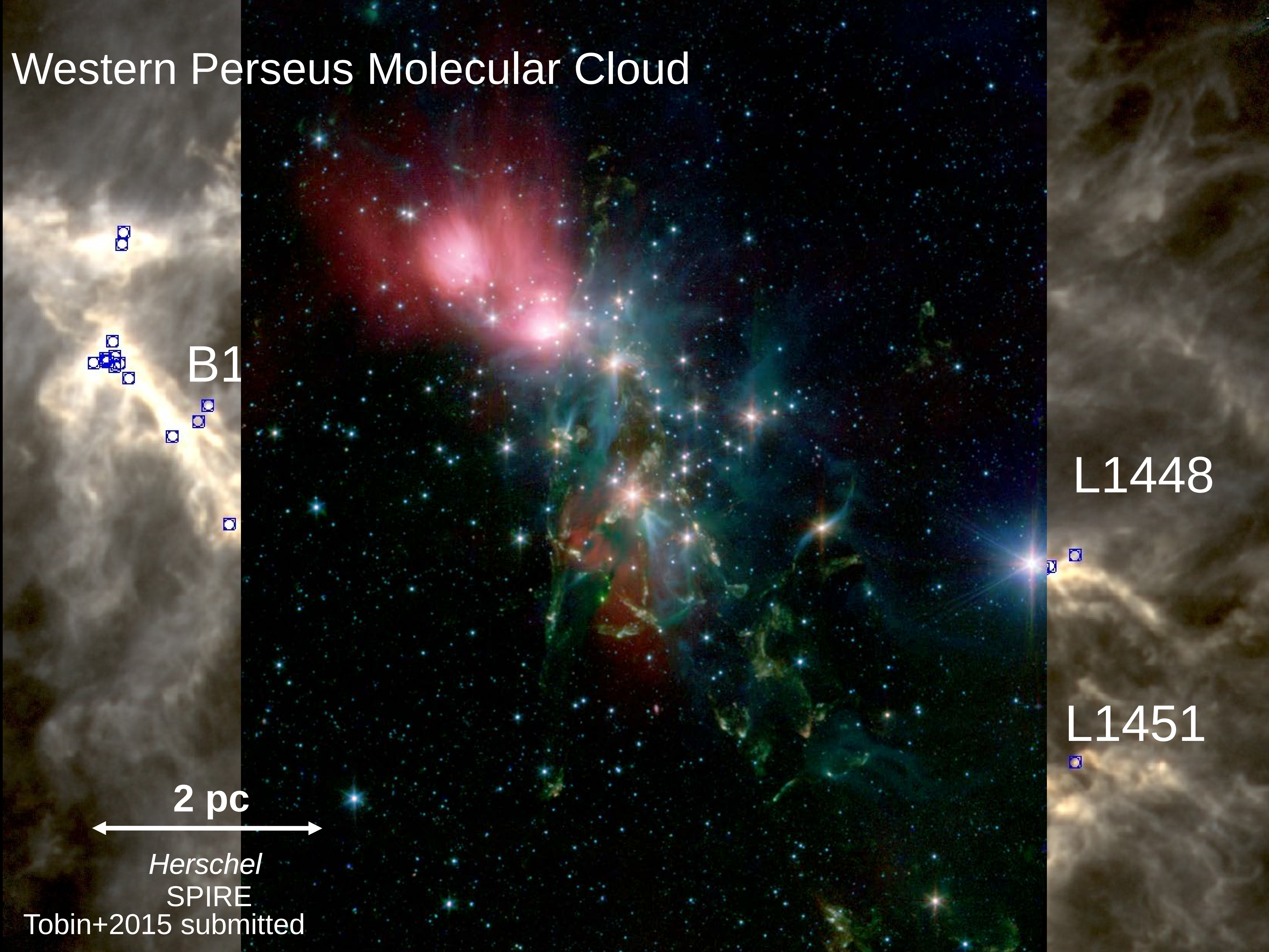
Radial Distribution of Dust

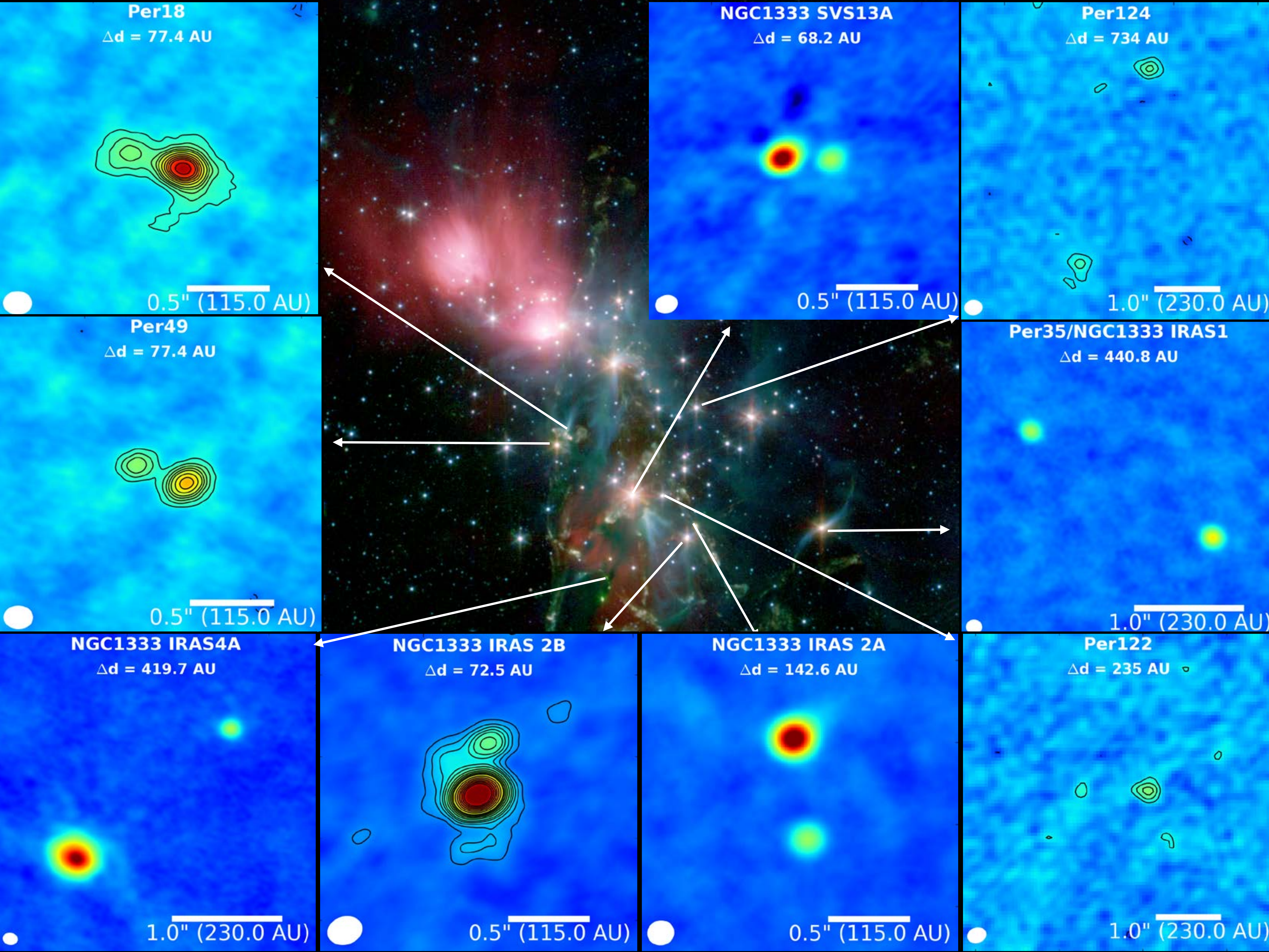


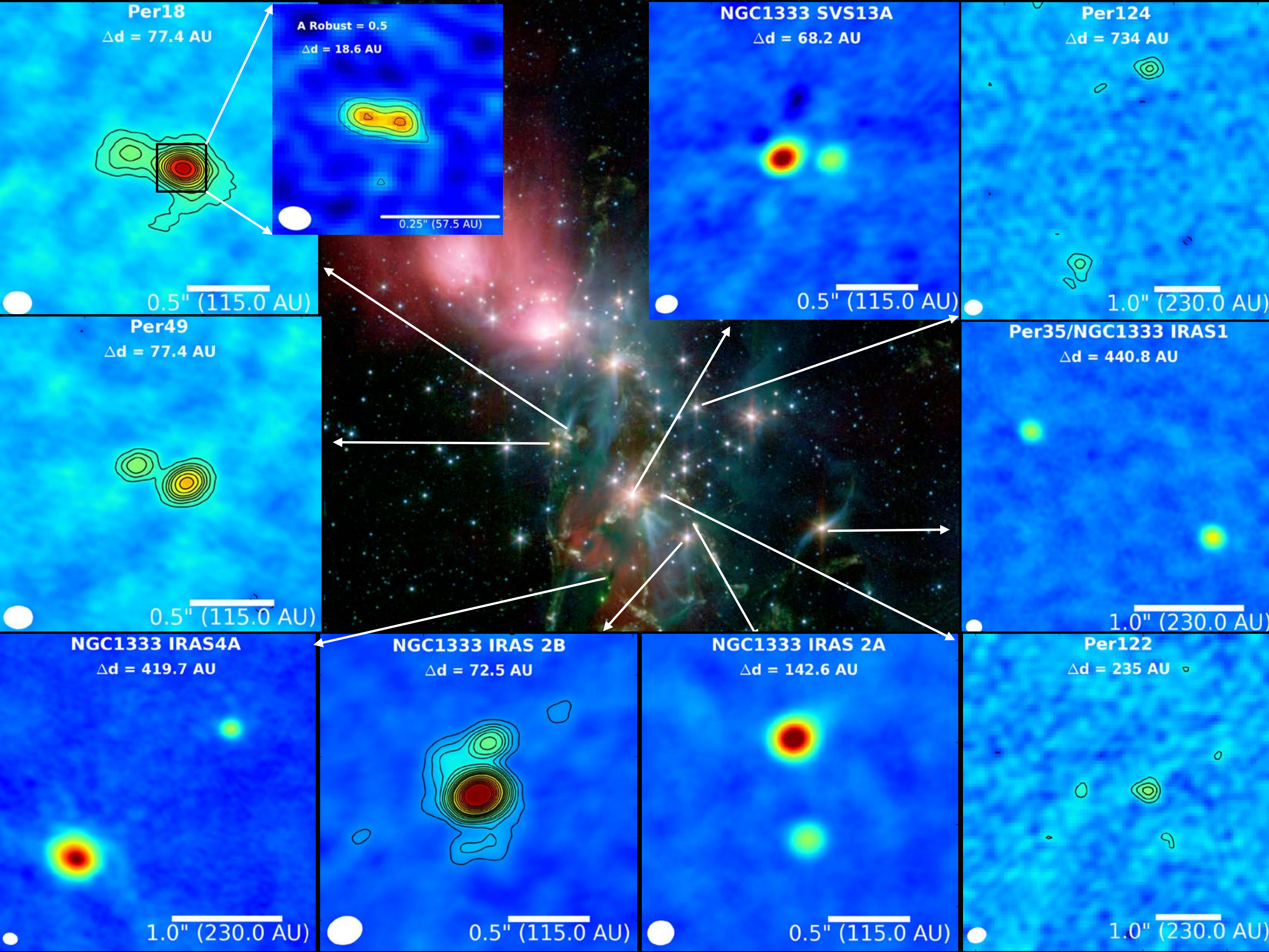
- Compare visibility amplitude data at 1.3 mm and 8.1 mm
  - Normalized at 200 kλ ~ 1"
  - 1.3 mm data drop faster, more spatially extended than 8.1 mm
  - Evidence for grain growth and radial drift early, Class 0 phase


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)
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)


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
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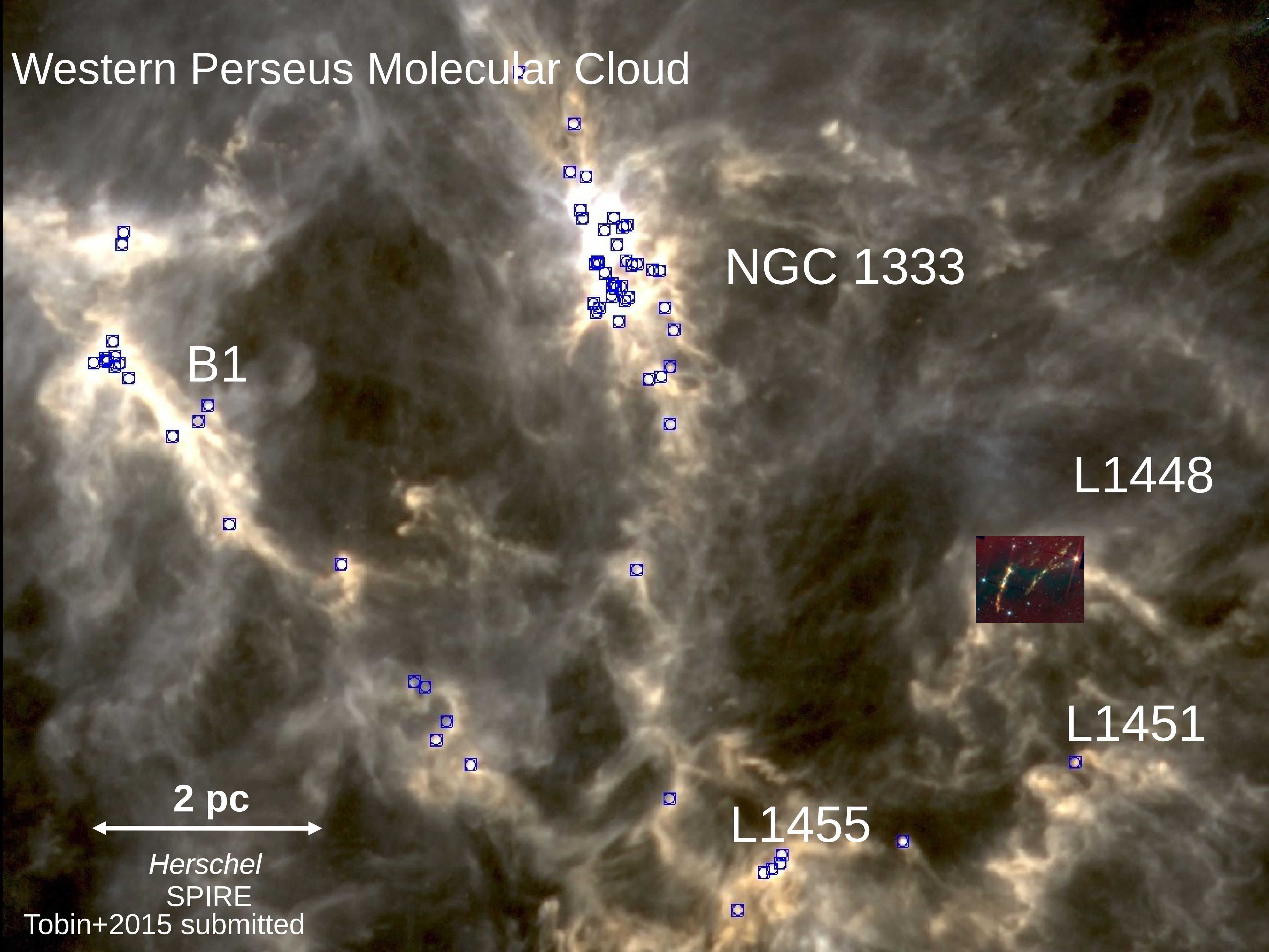

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NGC 1333
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L1448
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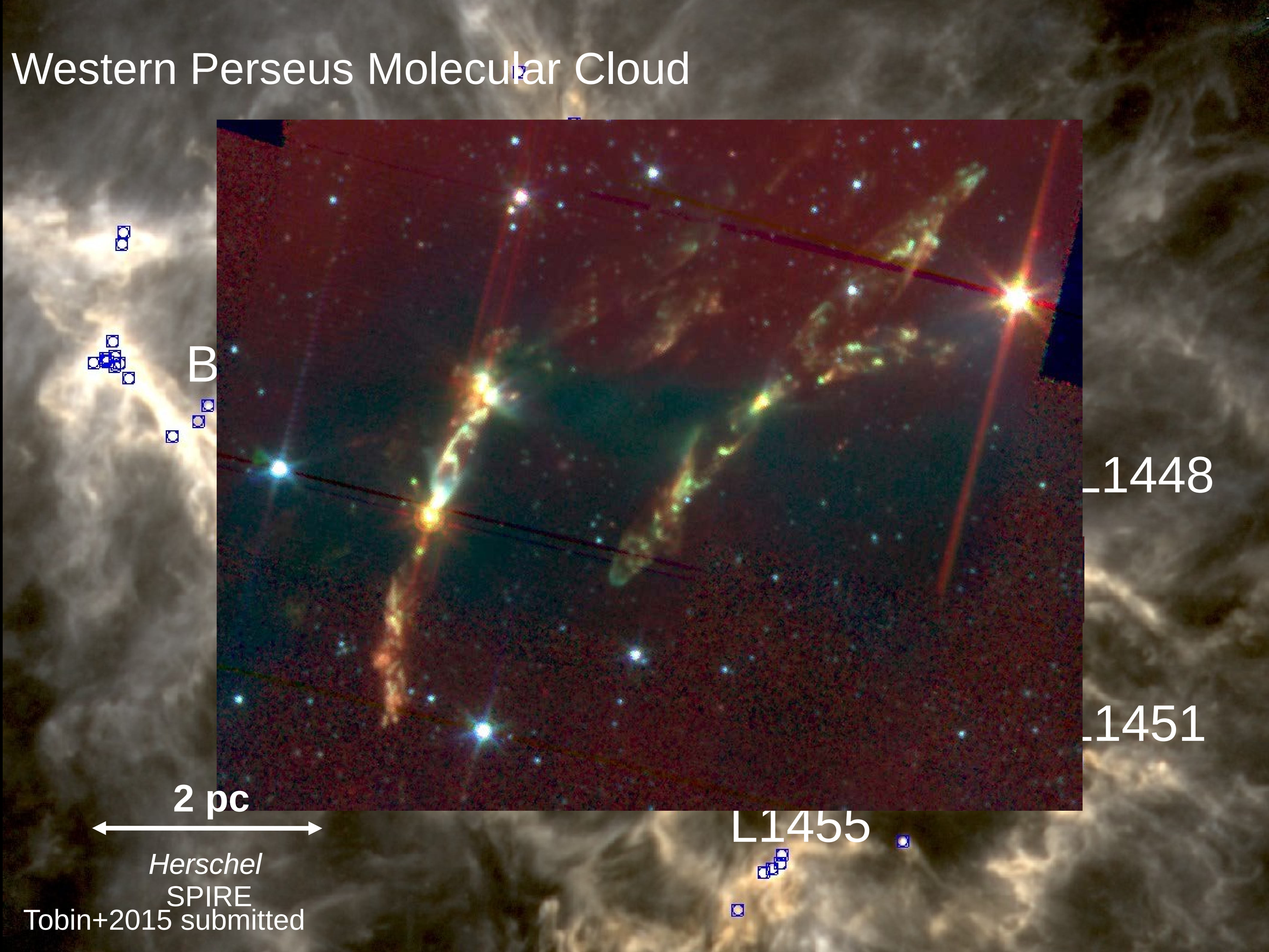
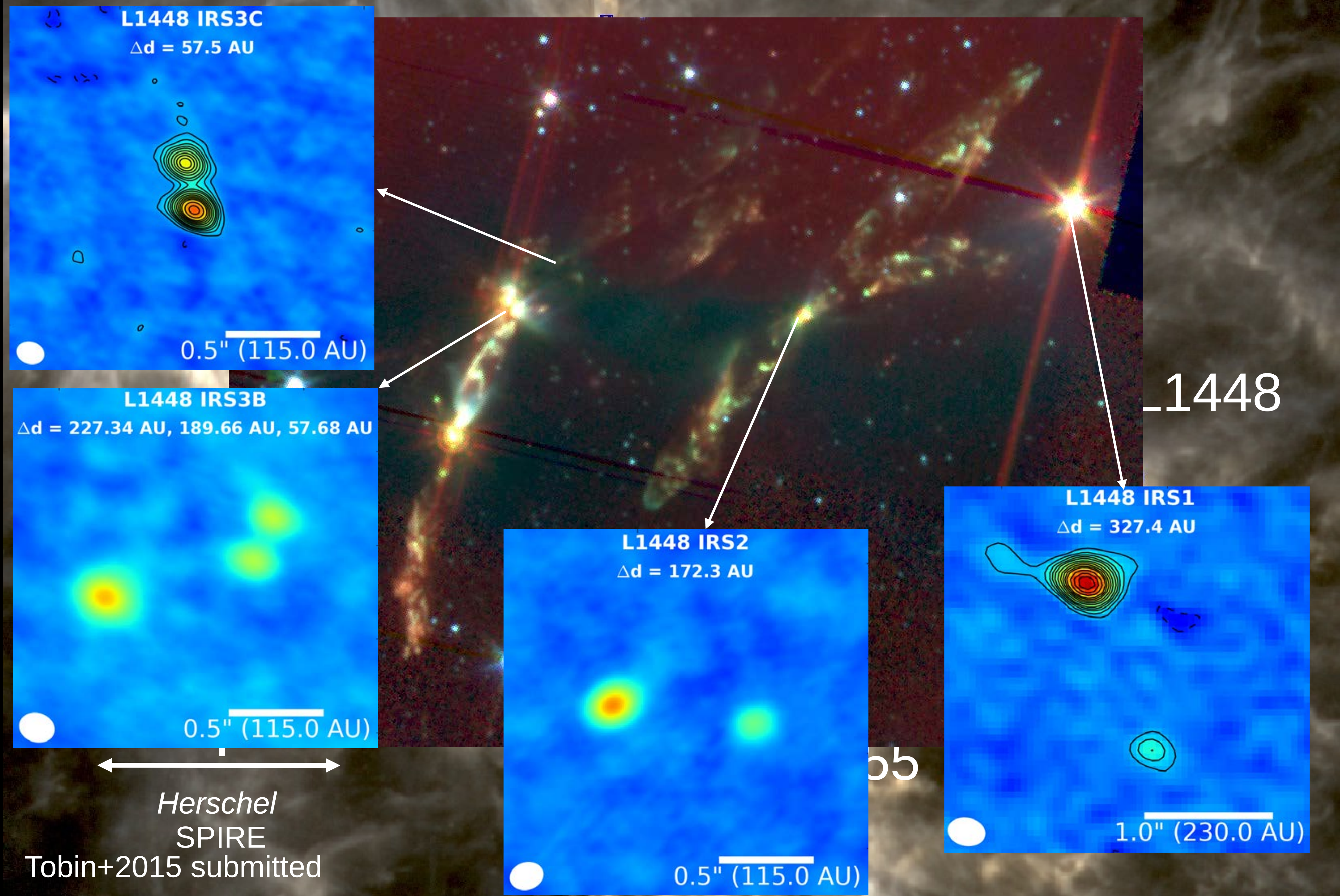
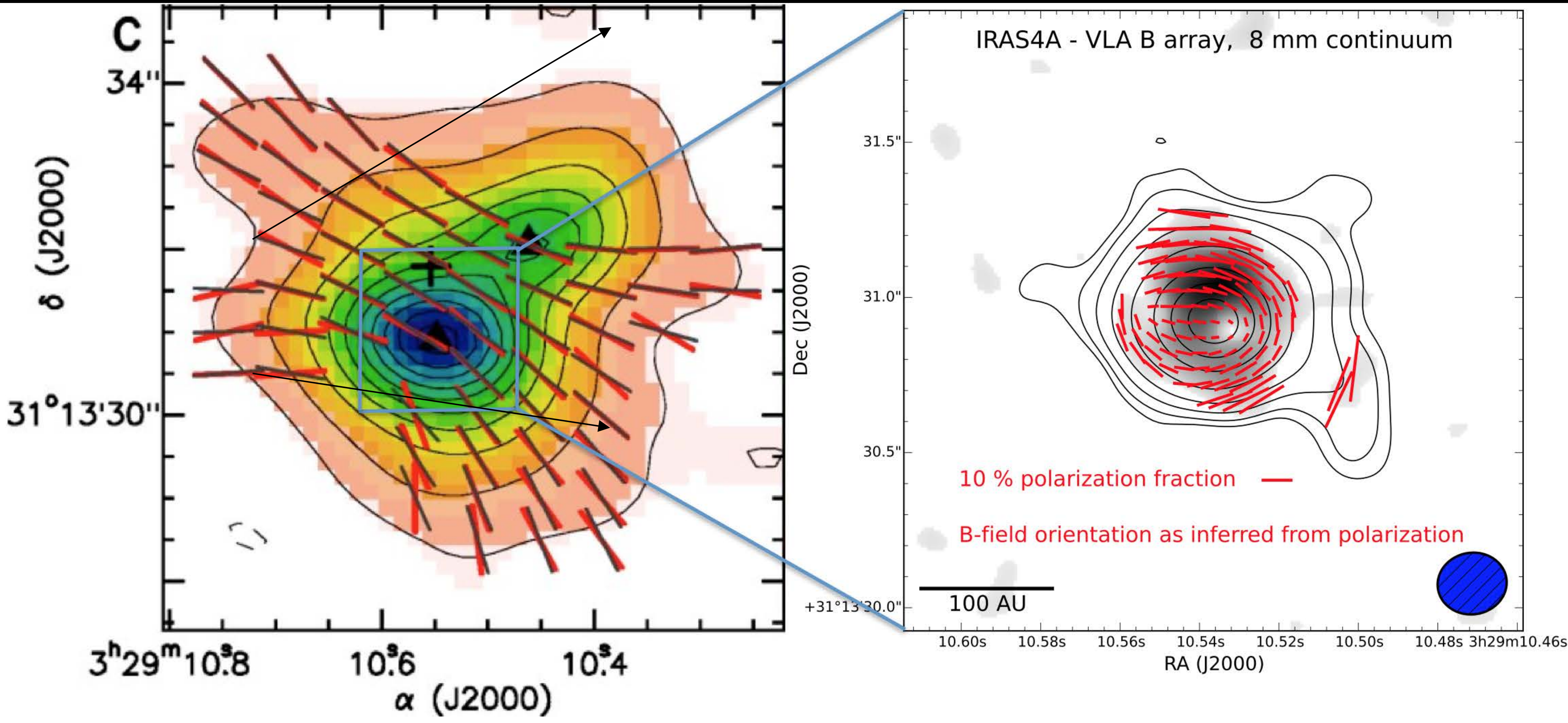

Western Perseus Molecular Cloud
B
1448
1451
L1455
2 pc
Herschel
SPIRE
Tobin+2015 submitted

Western Perseus Molecular Cloud



Herschel
SPIRE
Tobin+2015 submitted

A Brief Aside: 8 mm Polarization

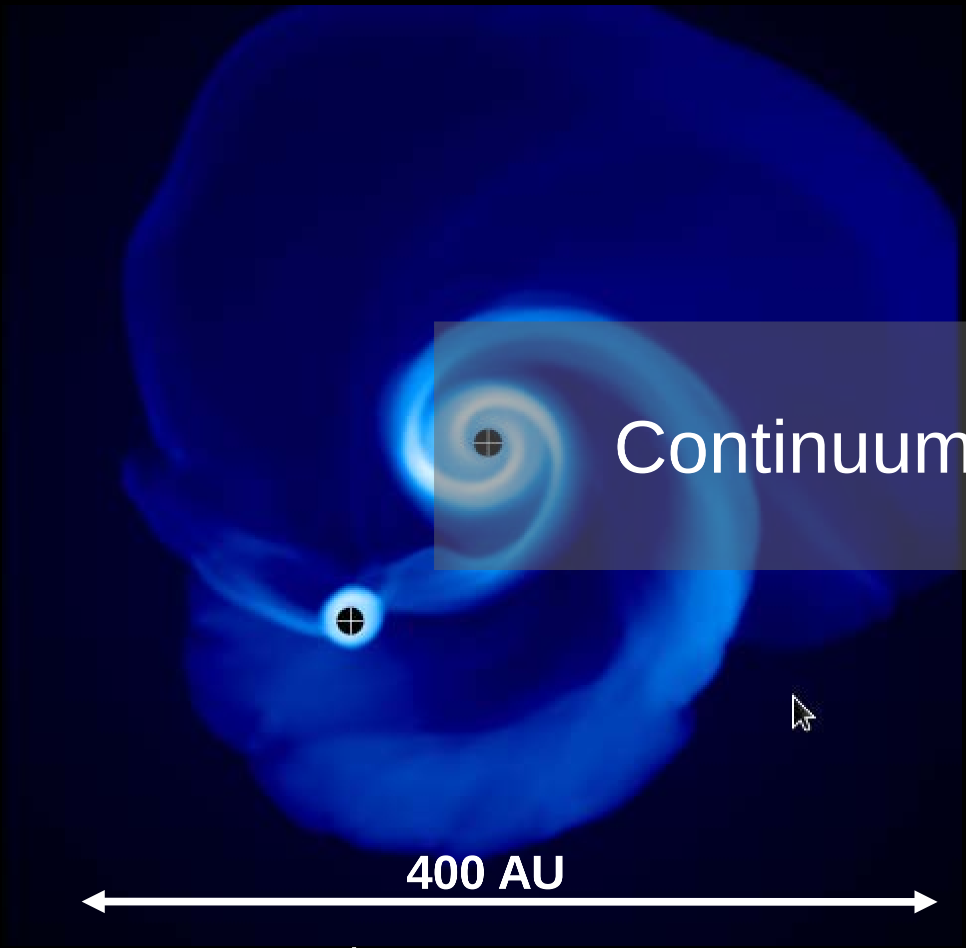


Cox et al. submitted

Protostellar Disks: Big or Small?

Large, massive – Gravitaitionally Unstable

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



Continuum of disk sizes?

Adapted from Kratter+2010

e.g., Vorobyov 2010, Kratter+2010

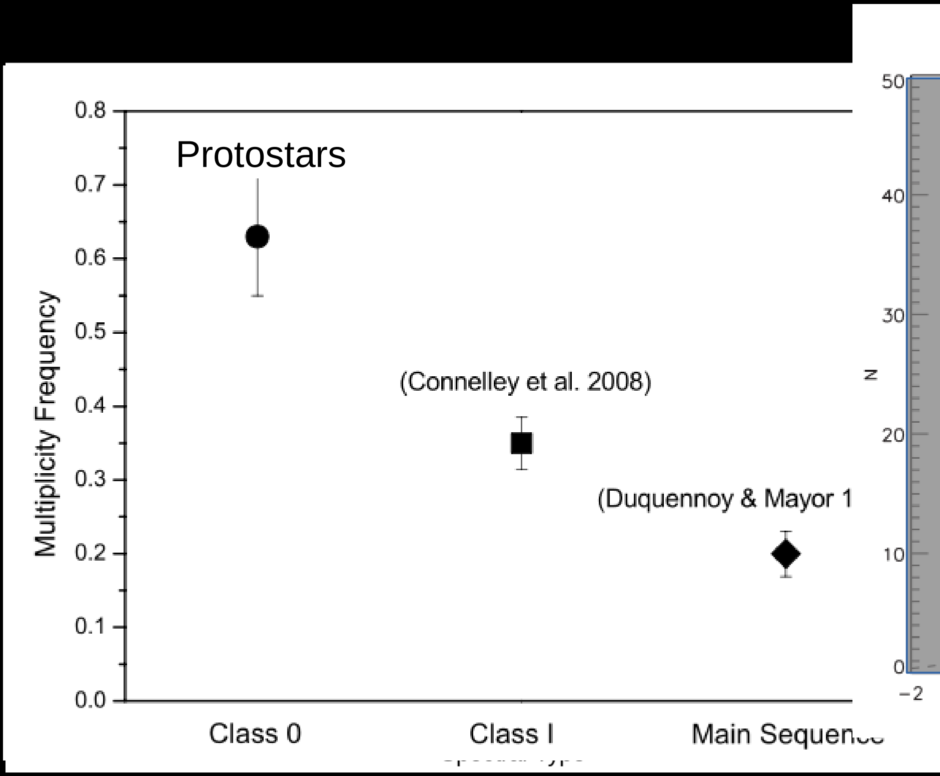
Little or no magnetic braking (e.g. TSC 1984)

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

- Youngest protostellar disks have long eluded direct observation

Multiple Star Formation

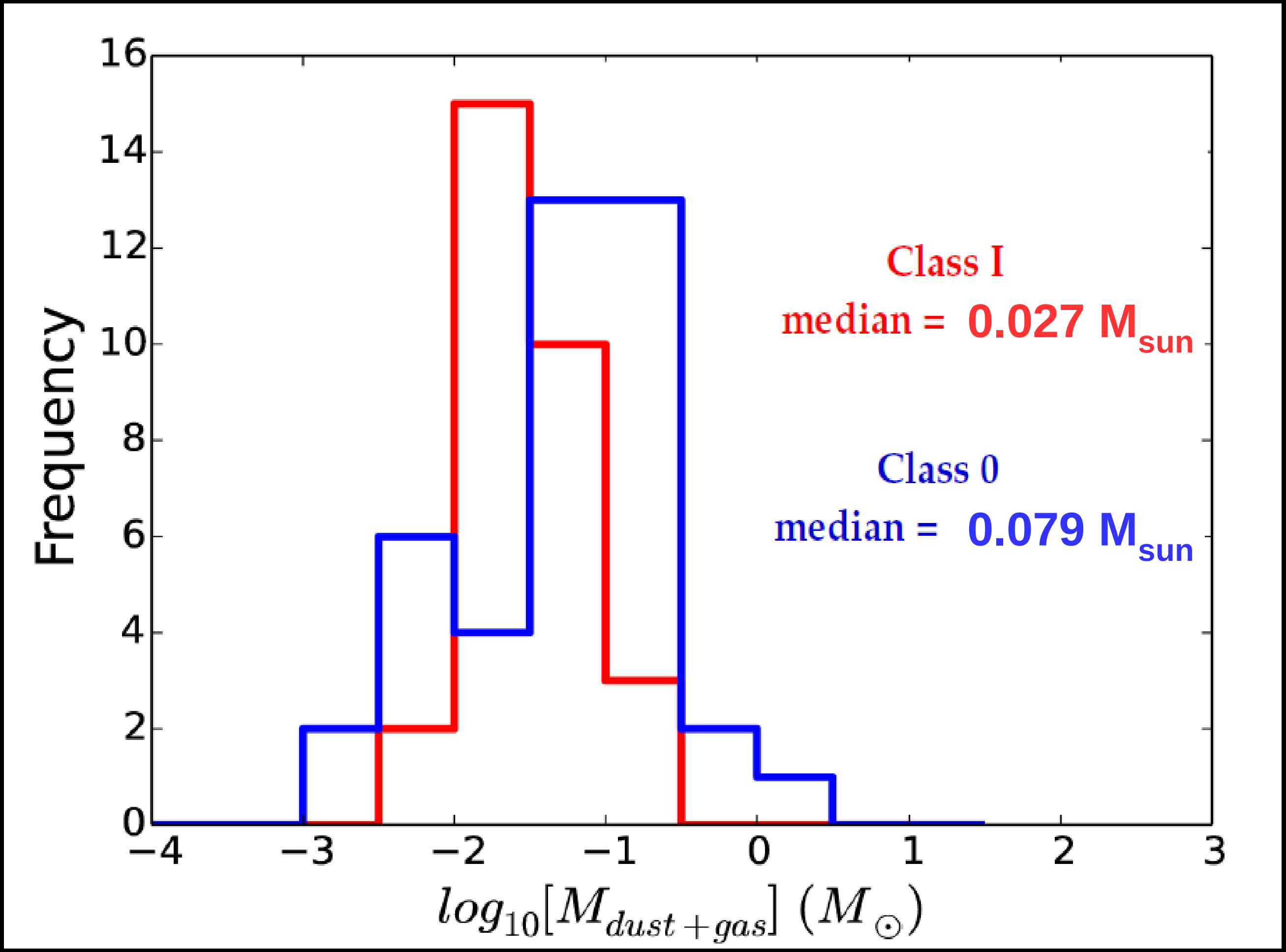
- Multiplicity key component of star and planet formation
  - Star formation efficiency
  - Stable planetary systems
  - Evolution of multiples different?



- 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

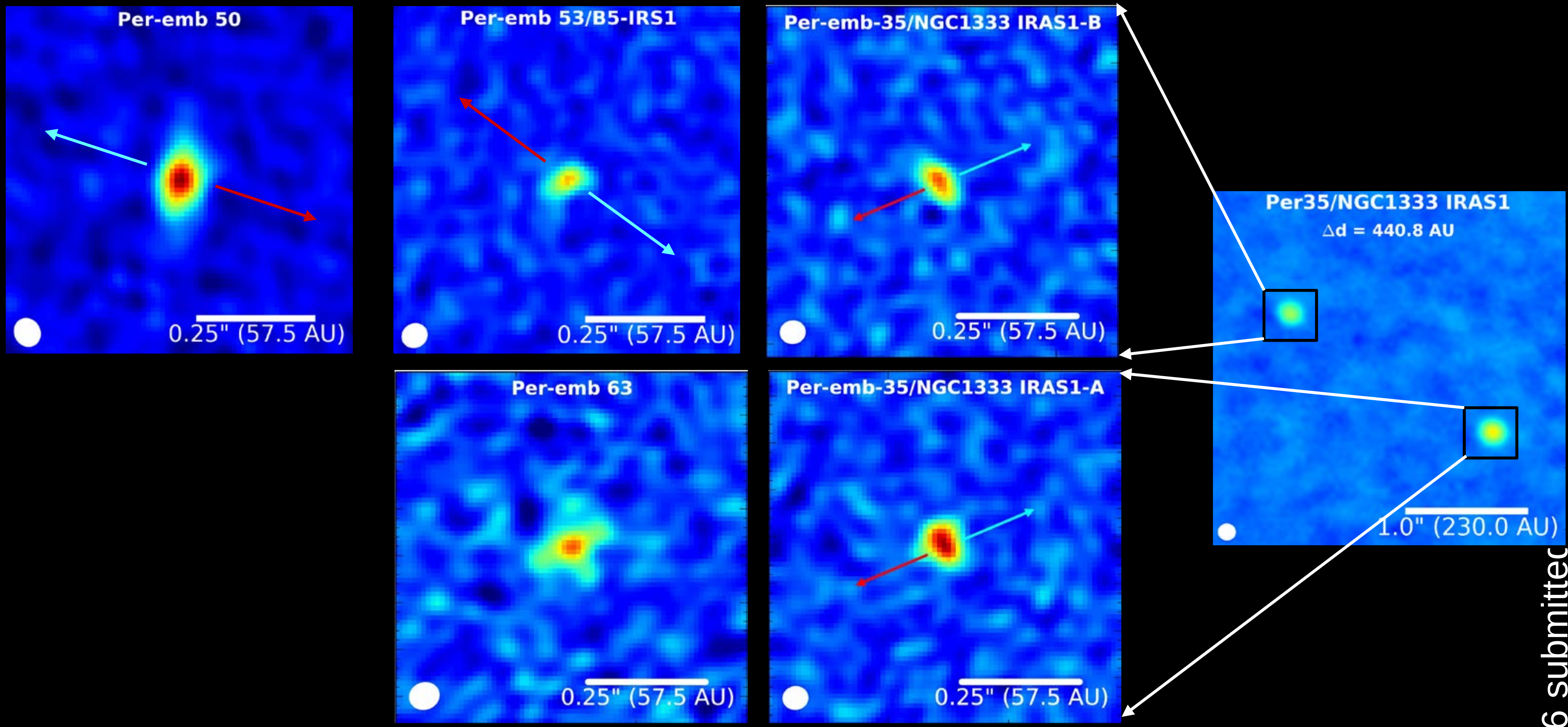
VANDAM 'Disk' Masses



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

VANDAM Class I Disk Candidates



Segura-Cox+2016 submitted