Probing massive young stellar objects with long-baseline mid-infrared interferometry

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May 5, 2014
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Formation of massive stars

- Where? Dense molecular clouds

  => High extinction

- How long? ~1 Myr

  => Forming massive stars *extremely* rare

- How?
  - Stellar mergers?
  - Competitive accretion?
  - Spherical collapse?
  - *Non-spherical* collapse (accretion disk)?
    - What is the role of turblence, magnetic fields, composition of gas and dust, etc.?

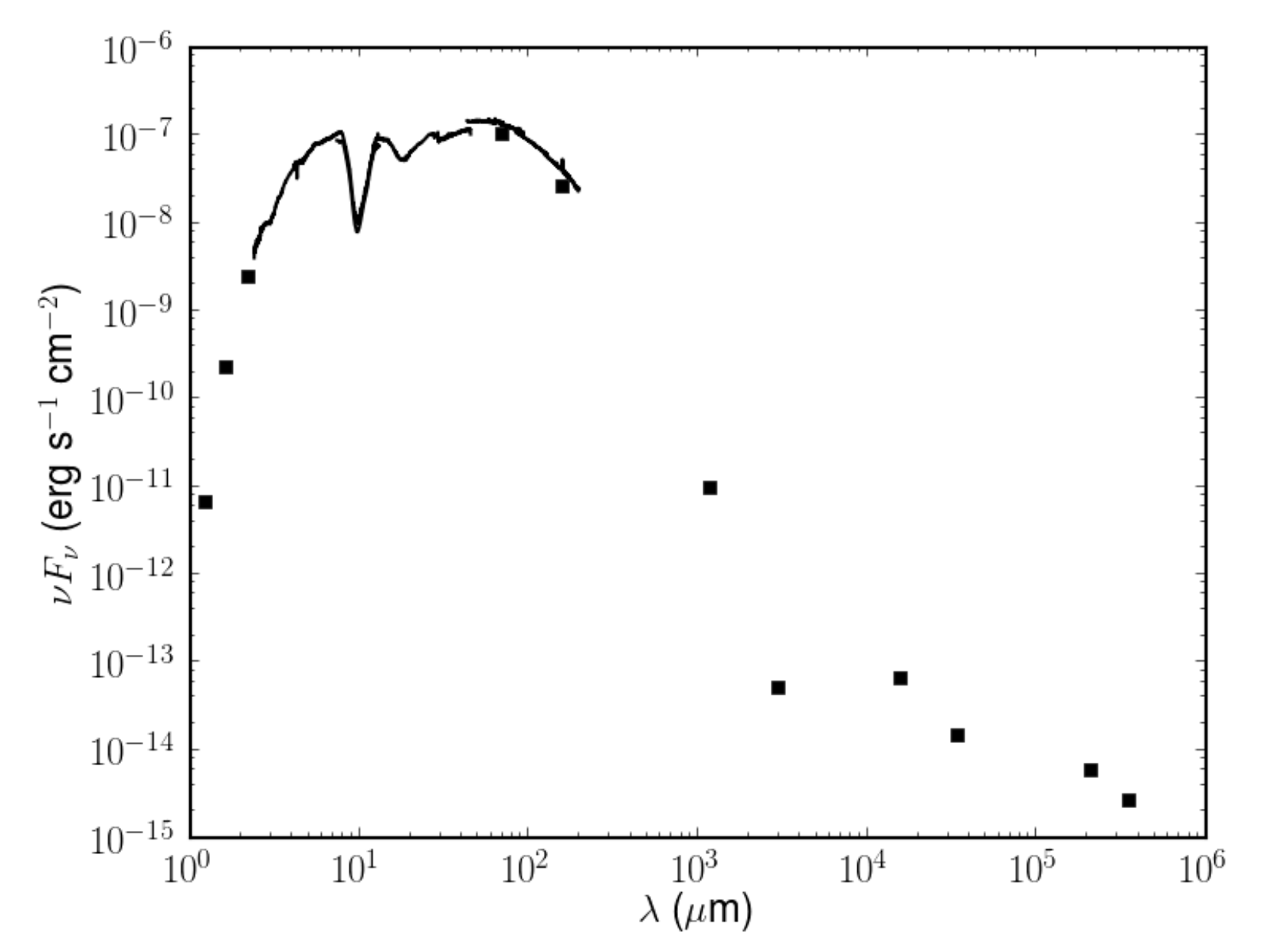
Massive young stellar objects

- Observationally-defined class
- Luminosity: 10^4 - 10^6 L⊙
  - Progenitors of “massive” stars (>8 M⊙)
- Deeply embedded: A_V ~ 20 - 100 mag

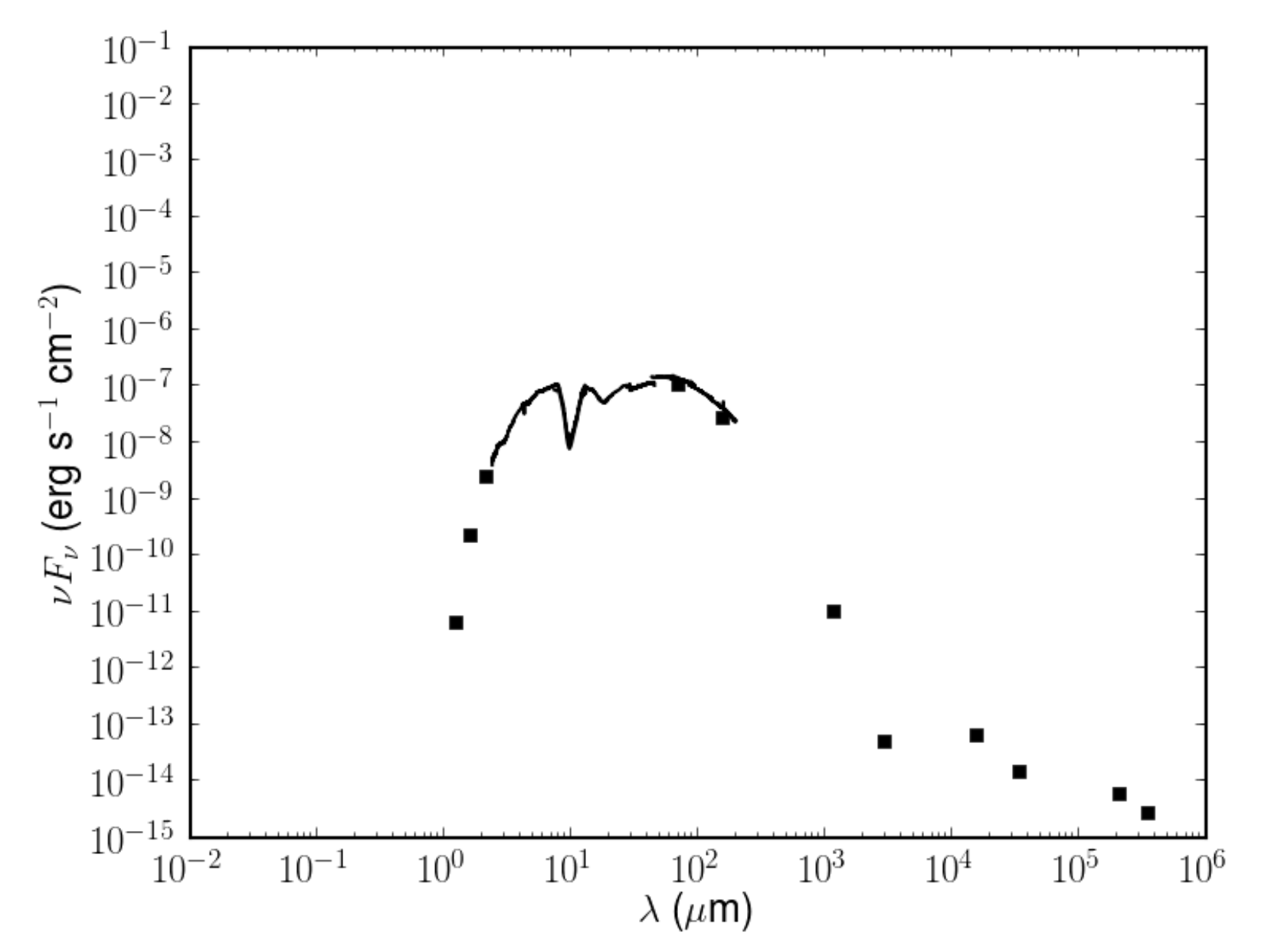
  => Generally invisible at optical wavelengths

  => Deep silicate absorption in *N* band (8-13 μm)
- Outflows, (compact) H II zones, masers
- Typical distances of 1 - 5 kpc
  - Resolution on VLTI: ~10 mas <=> tens of AU.
- SED is dominated by **envelope**
  - There are **indications** of dust disks (e.g. IRAS 13481-6124, AFGL 4176)

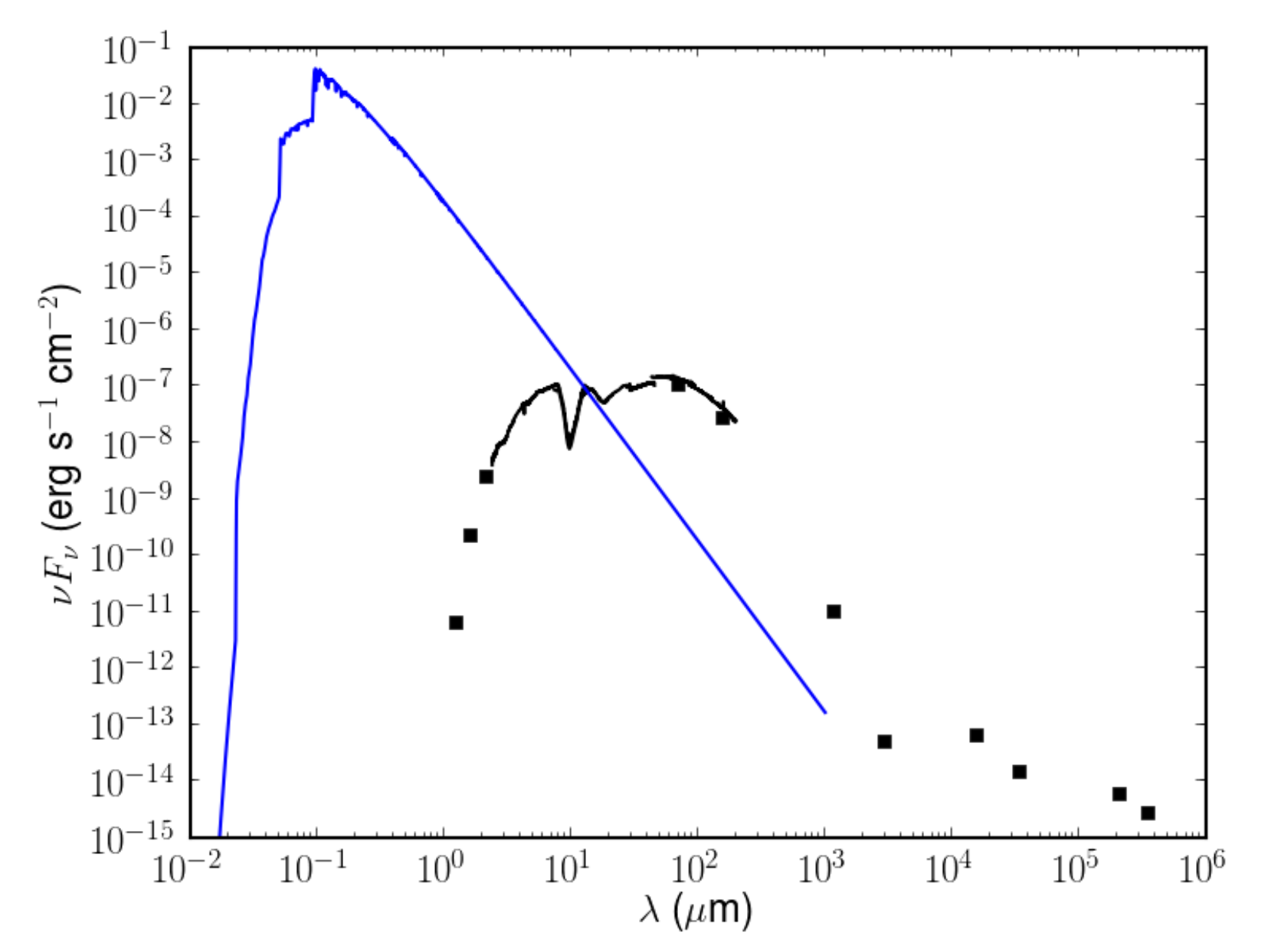
SED of AFGL 4176



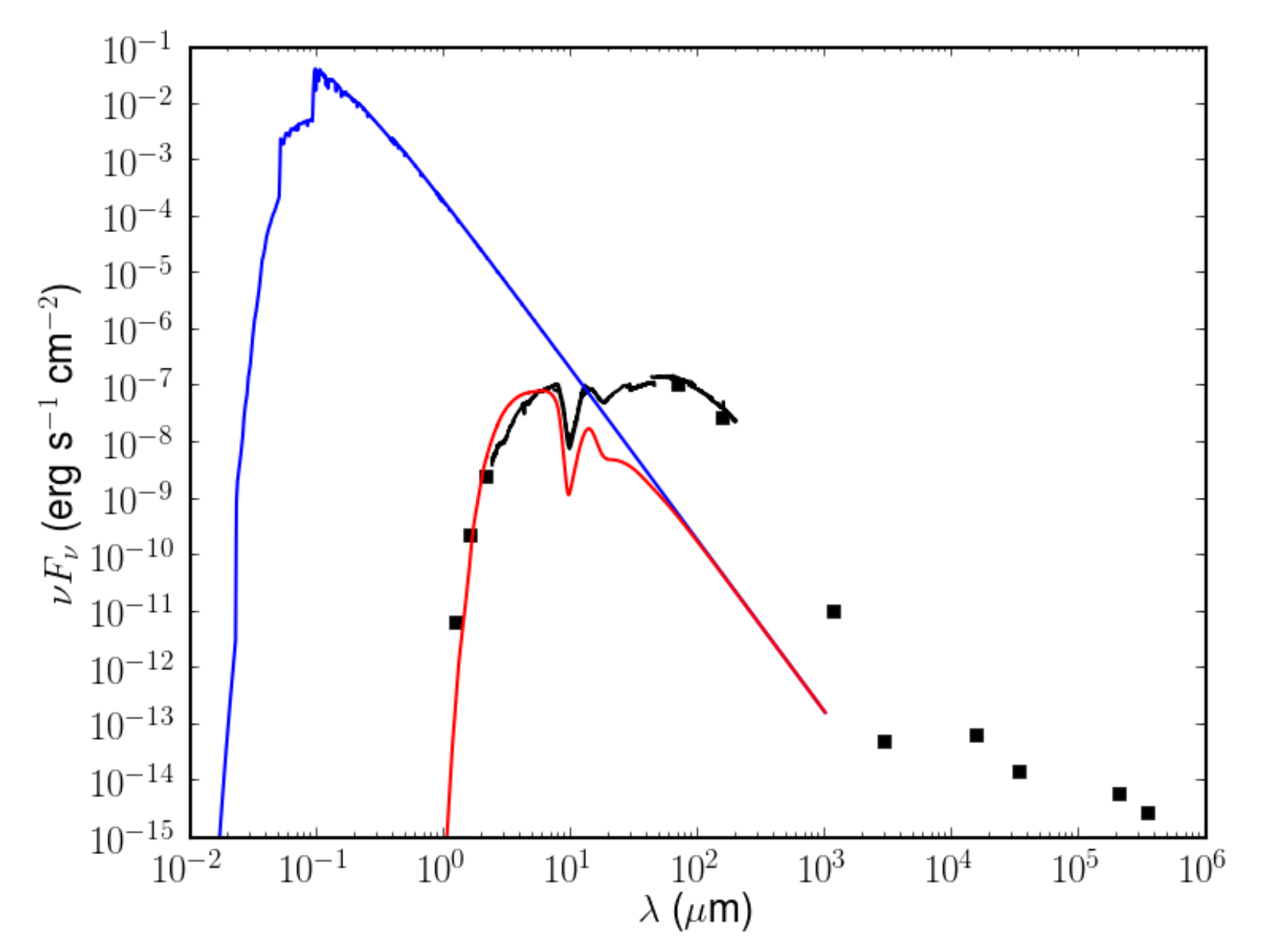
SED of AFGL 4176



SED of AFGL 4176



SED of AFGL 4176



Long-baseline infrared interferometric studies of MYSOs

To date, 100% of published works use VLTI

1) de Wit et al. 2007 (ApJ 671, L169): W33A
2) Acke et al. 2008 (A&A 485, 209): MWC 297
3) Linz et al. 2009 (A&A 505, 655): M8E-IR
4) de Wit et al. 2010 (A&A 515, A45): W33A
5) Vehoff et al. 2010 (A&A 520, A78): NGC 3603 IRS 9A
6) Follert et al. 2010 (A&A 522, A17): M17 SW IRS1 (KW)
7) Kraus et al. 2010 (Nature 466, 399): IRAS 13481-6124
8) de Wit et al. 2011 (A&A 526, L5): AFGL 2136
9) Grellmann et al. 2011 (A&A 532, A109): NGC 2264 IRS1
10) Boley et al. 2012 (A&A 547, A88): AFGL 4176
11) Boley et al. 2013 (A&A 558, A24): 20 MYSOs

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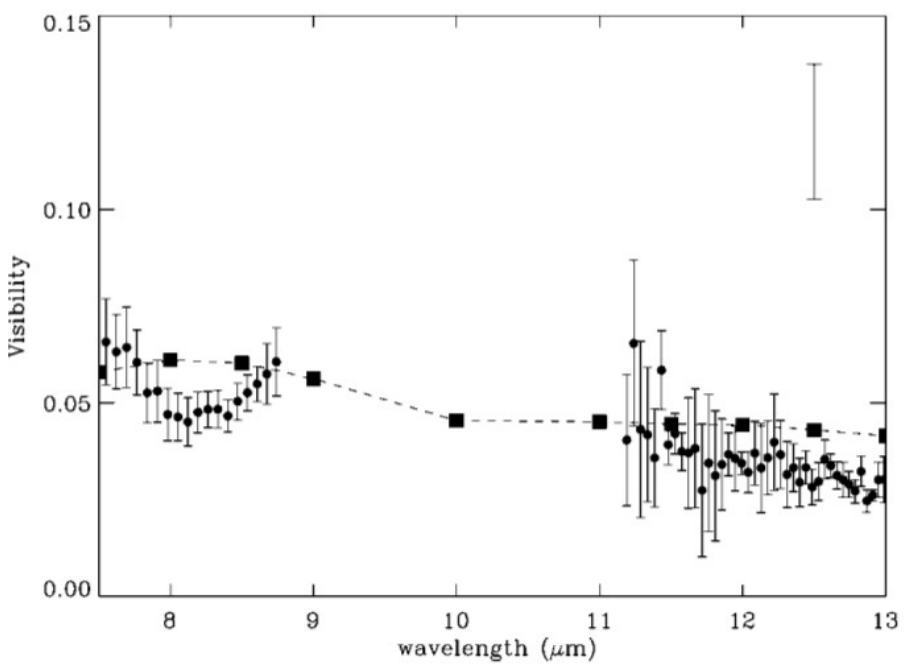
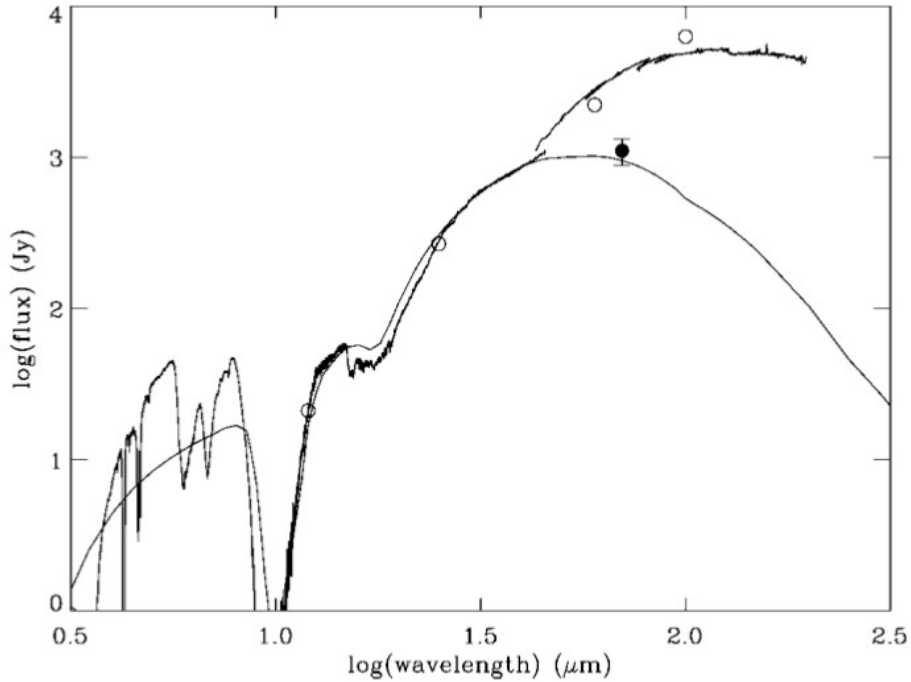
MIDI observations of W33A

de Wit et al. 2007 (ApJ 671, L169)



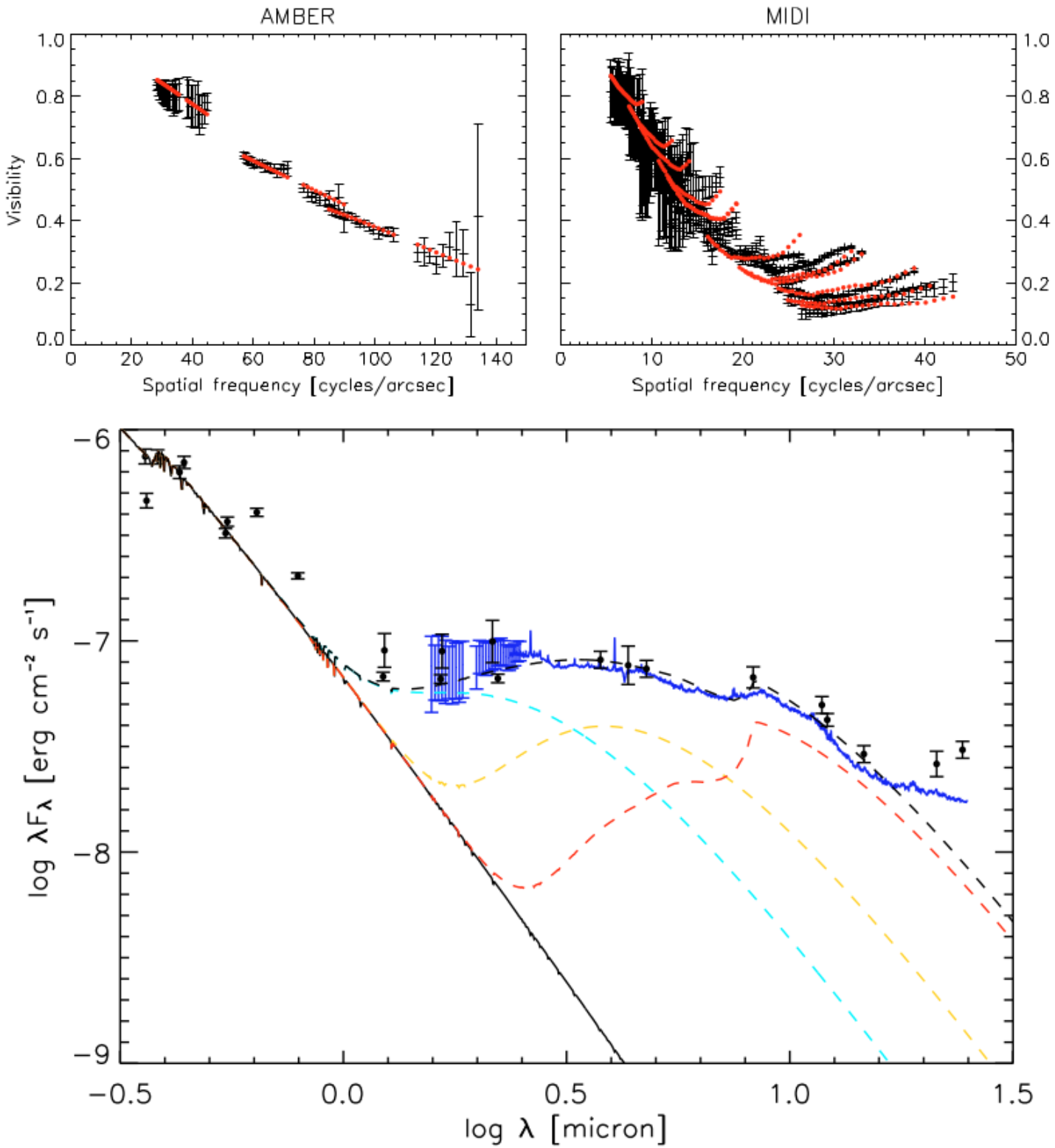


- Single *uv* point (46 m); 1D rad. tran. modeling
- First *direct confirmation* of warm dust around MYSO at scales of 100-200 AU

MWC 297: a young high-mass star rotating at critical velocity

Acke et al. 2008 (A&A 485, 209)

- AMBER + MIDI (6 and 13 *uv* points)
- Geometric (Gaussian) modeling of visibilities and SED


AMBER
MIDI
Visibility
Spatial frequency [cycles/arcsec]
Spatial frequency [cycles/arcsec]
log λF_λ [erg cm^-2 s^-1]
log λ [micron]

MWC 297: a young high-mass star rotating at critical velocity

Acke et al. 2008 (A&A 485, 209)

- AMBER + MIDI (6 and 13 *uv* points)
- Geometric (Gaussian) modeling of visibilities and SED
- Compact (~1 AU), elongated emission; attributed to circumstellar disk at 40 deg inclination

Evidence for a circumstellar disk surrounding the Kleinmann-Wright object

Follert et al. 2010 (A&A 522, A17)

- Five *uv* points with MIDI
- Fit SED (only) with Robitaille et al. grid; compare visibilities of best-fitting models

Evidence for a circumstellar disk surrounding the Kleinmann-Wright object

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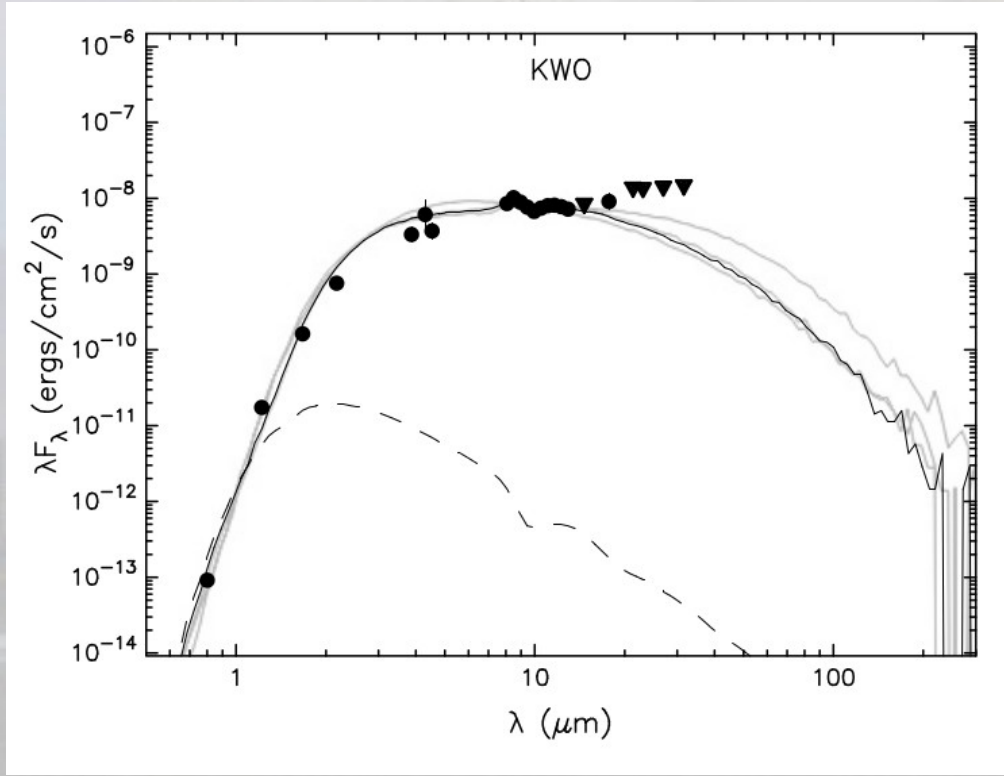
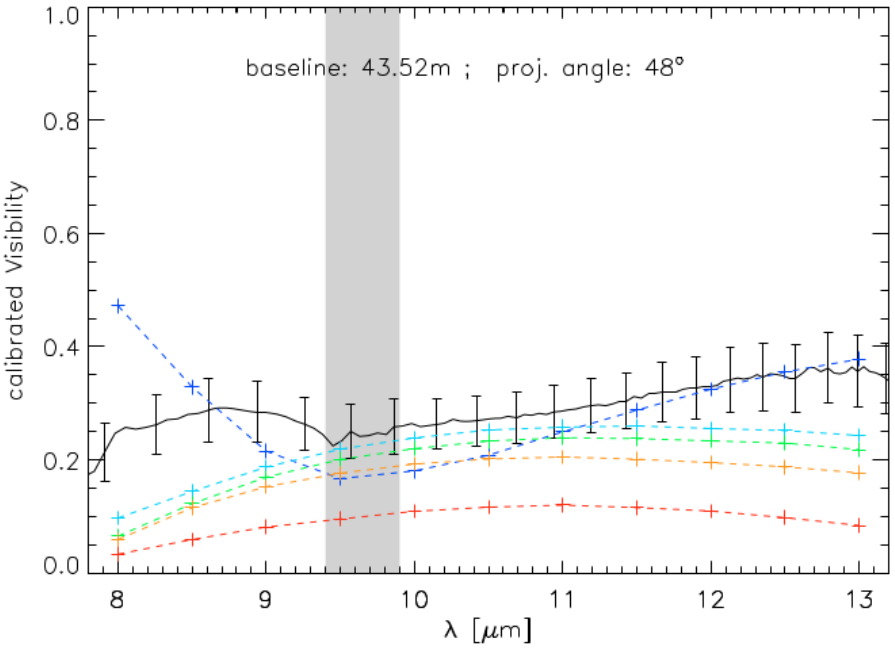
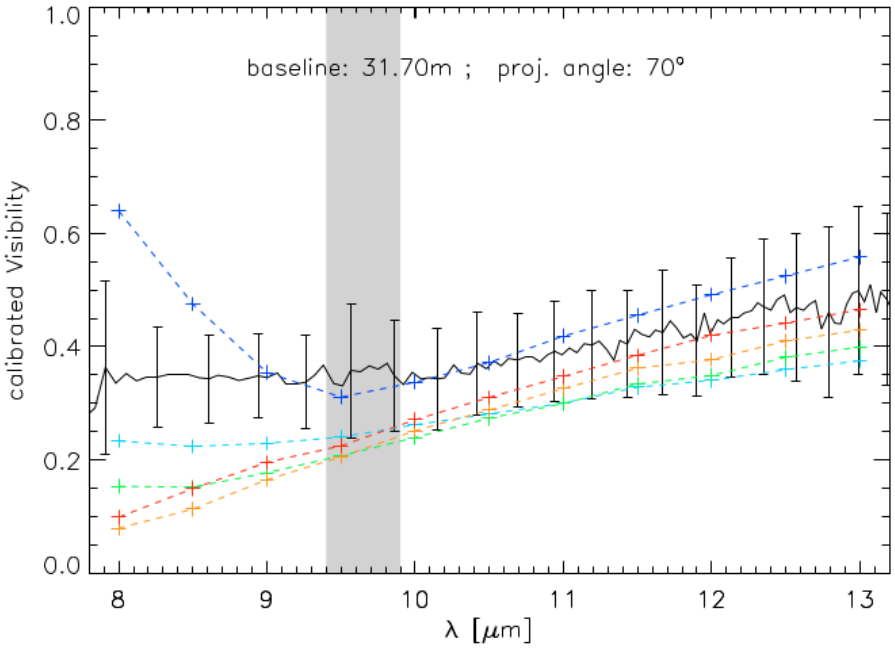
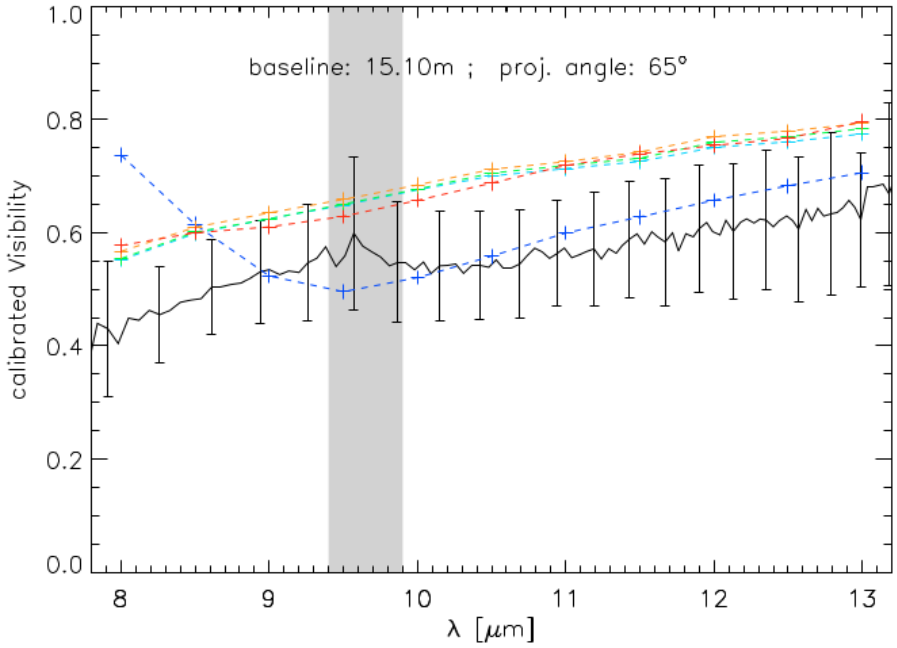
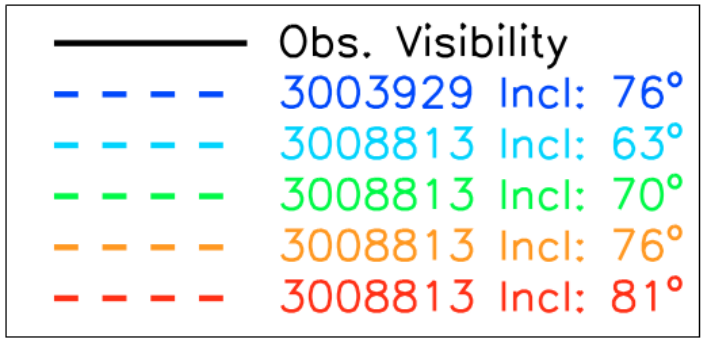



baseline: 43.52m ; proj. angle: 48°
calibrated Visibility
λ [μm]


baseline: 31.70m ; proj. angle: 70°
calibrated Visibility
λ [μm]


baseline: 15.10m ; proj. angle: 65°
calibrated Visibility
λ [μm]


Obs. Visibility
3003929 Incl: 76°
3008813 Incl: 63°
3008813 Incl: 70°
3008813 Incl: 76°
3008813 Incl: 81°

Evidence for a circumstellar disk surrounding the Kleinmann-Wright object

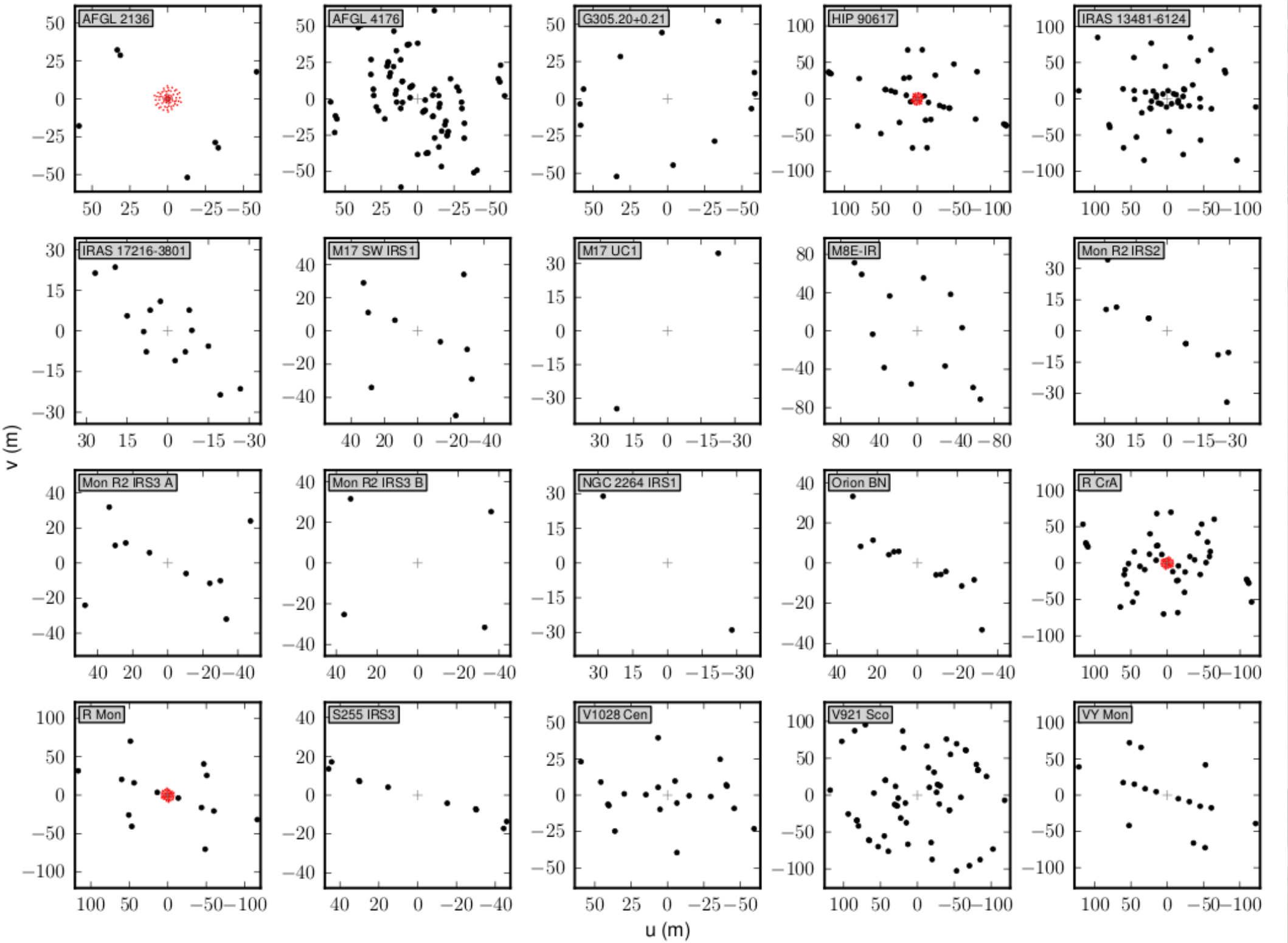
Follert et al. 2010 (A&A 522, A17)

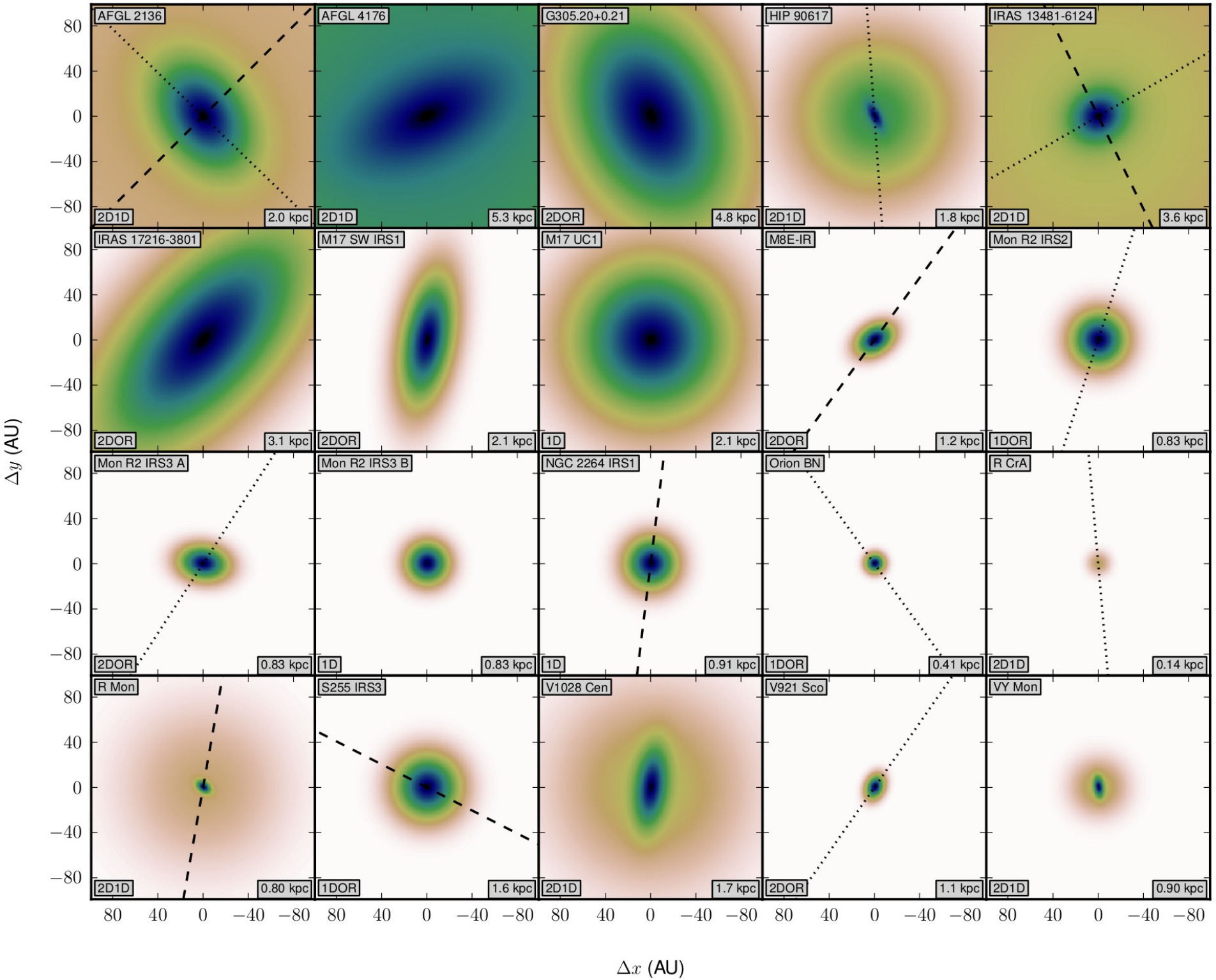
- Five *uv* points with MIDI
- Fit SED (only) with Robitaille et al. grid; compare visibilities of best-fitting models
- Inclined 0.1 $M_{\odot}$ disk without envelope consistent with SED and MIDI visibilities

VLTI/MIDI survey of massive young stellar objects

Boley et al. 2013 (A&A 558, A24)

- MIDI observations of 20 MYSOs (1-40 *uv* points per object)
- Fit visibilities with simple (Gaussian) geometric models
- Fit silicate absorption with lab opacities


AFGL 2136
AFGL 4176
G305.20+0.21
HIP 90617
IRAS 13481-6124
IRAS 17216-3801
M17 SW IRS1
M17 UC1
M8E-IR
Mon R2 IRS2
Mon R2 IRS3 A
Mon R2 IRS3 B
NGC 2264 IRS1
Orion BN
R CrA
R Mon
S255 IRS3
V1028 Cen
V921 Sco
VY Mon
v (m)
u (m)


AFGL 2136
2D1D
2.0 kpc
AFGL 4176
2D1D
5.3 kpc
G305.20+0.21
2DOR
4.8 kpc
HIP 90617
2D1D
1.8 kpc
IRAS 13481-6124
2D1D
3.6 kpc
IRAS 17216-3801
2DOR
3.1 kpc
M17 SW IRS1
2DOR
2.1 kpc
M17 UC1
1D
2.1 kpc
M8E-IR
2DOR
1.2 kpc
Mon R2 IRS2
1DOR
0.83 kpc
Mon R2 IRS3 A
2DOR
0.83 kpc
Mon R2 IRS3 B
1D
0.83 kpc
NGC 2264 IRS1
1D
0.91 kpc
Orion BN
1DOR
0.41 kpc
R CrA
2D1D
0.14 kpc
R Mon
2D1D
0.80 kpc
S255 IRS3
1DOR
1.6 kpc
V1028 Cen
2D1D
1.7 kpc
V921 Sco
2DOR
1.1 kpc
VY Mon
2D1D
0.90 kpc
80
40
0
−40
−80
Δy (AU)
Δx (AU)

VLTI/MIDI survey of massive young stellar objects

Boley et al. 2013 (A&A 558, A24)

- MIDI observations of 20/24 MYSOs (1-40 *uv* points per object)
- Fit visibilities with simple (Gaussian) geometric models
- Fit silicate absorption with lab opacities
- Warm dust at 10s of AU ubiquitous
- Emission can be aligned with disk or outflow (or neither)
- Absorption occurs at scales larger than those probed by MIDI

Conclusion: MIDI and MYSOs

- Warm circumstellar dust probed at ~10-100 AU scales for the first time by MIDI
  - Critical for testing/constraining massive star formation theories
- 24 MYSOs observed and published in
  - 10 refereed publications
  - 4 PhD theses
- Some idea of what to expect with e.g. MATISSE
- More to come
  - Survey data publically available!
  - P93/P94 observations