School of Physics and Astronomy
FACULTY OF MATHEMATICS AND PHYSICAL SCIENCES

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Star Formation

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(Leeds, UK)

VLTI School 2013 Barcelonnette

Outline

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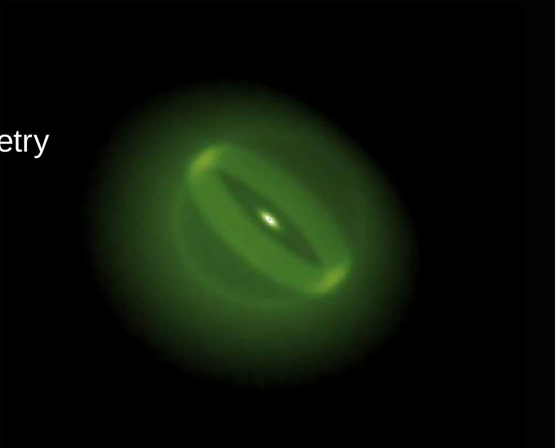
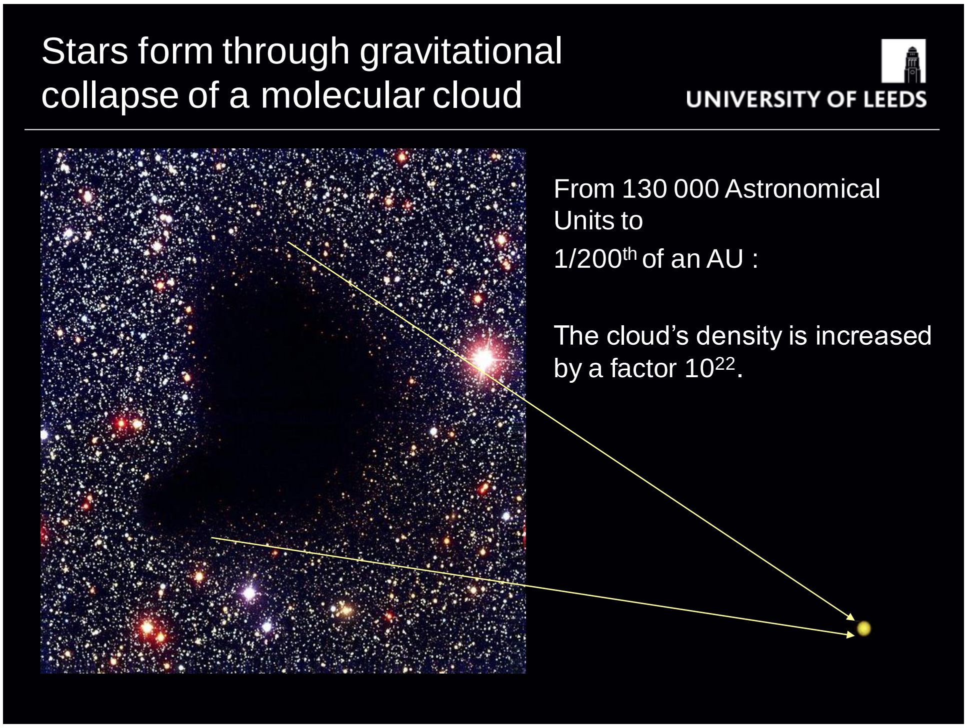
- Star Formation 101
- Current questions
- Optical /NIR interferometry to date



de Wit et al 2011

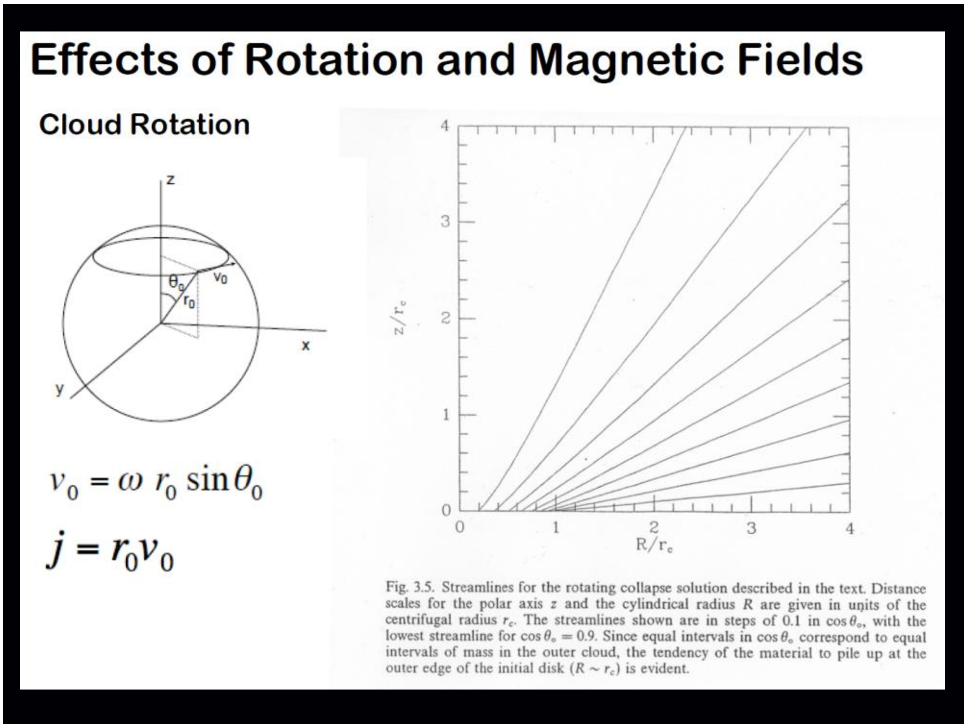


Stars form through gravitational collapse of a molecular cloud

From 130 000 Astronomical Units to

1/200th of an AU :

The cloud's density is increased by a factor 10^{22}.



Effects of Rotation and Magnetic Fields

Cloud Rotation

$$v_0 = \omega\, r_0 \sin\theta_0$$

$$j = r_0 v_0$$

Fig. 3.5. Streamlines for the rotating collapse solution described in the text. Distance scales for the polar axis z and the cylindrical radius R are given in units of the centrifugal radius r_c. The streamlines shown are in steps of 0.1 in $\cos\theta_o$, with the lowest streamline for $\cos\theta_o = 0.9$. Since equal intervals in $\cos\theta_o$ correspond to equal intervals of mass in the outer cloud, the tendency of the material to pile up at the outer edge of the initial disk ($R \sim r_c$) is evident.

Effects of Rotation and Magnetic Fields

Cloud Rotation

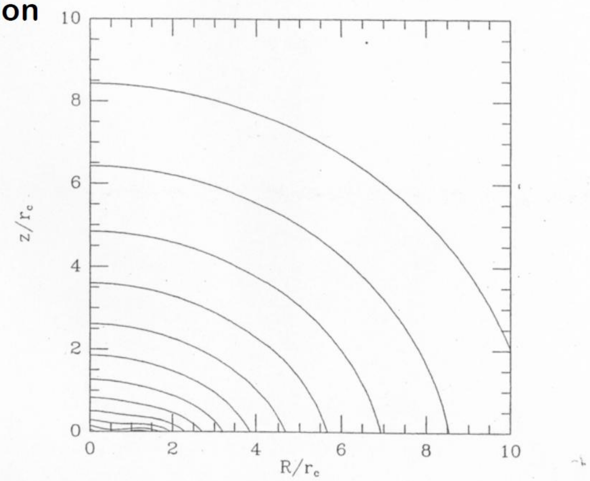
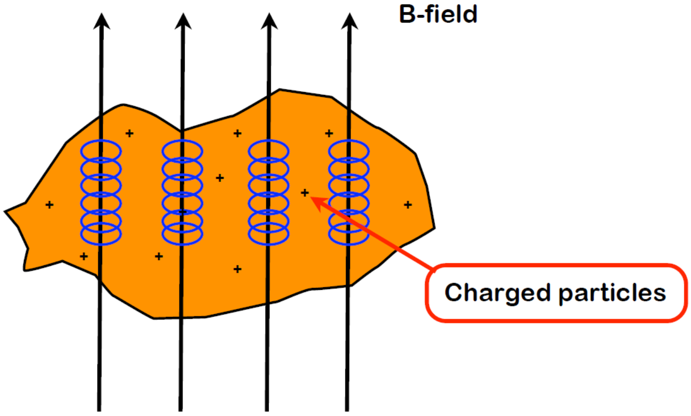


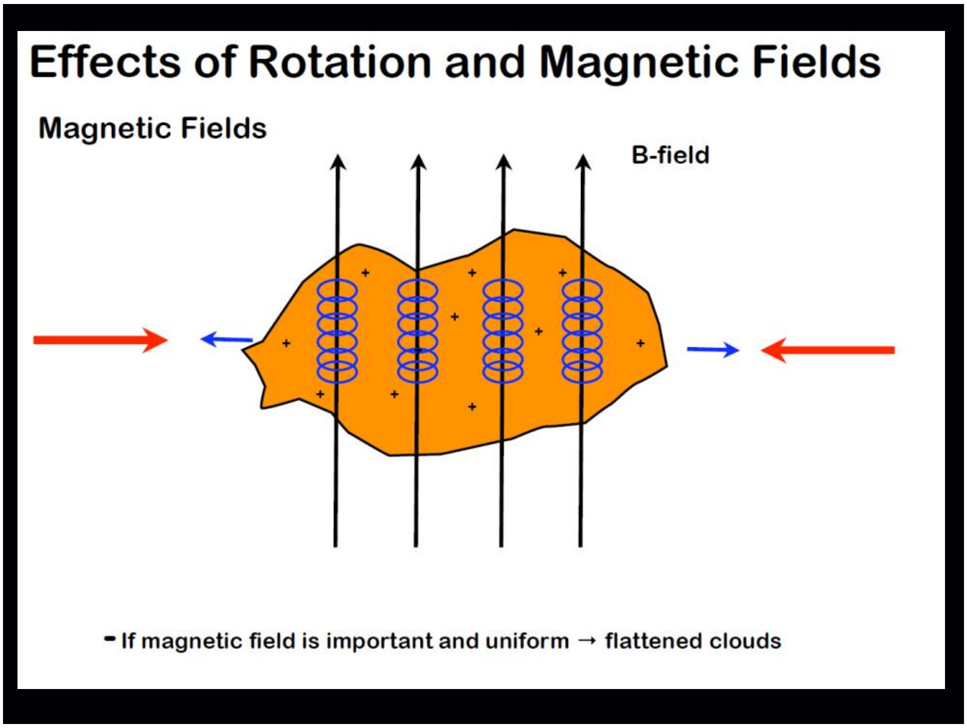
Fig. 3.6. Contours of constant density for the rotating collapse solution. Distance scales for the polar axis z and the cylindrical radius R are given in units of the centrifugal radius r_c. Each contour represents a factor of $2^{1/2}$ difference in density, with the outer contours representing the lowest densities. The flattening of the density distribution near the disk is evident.

Effects of Rotation and Magnetic Fields

Magnetic Fields



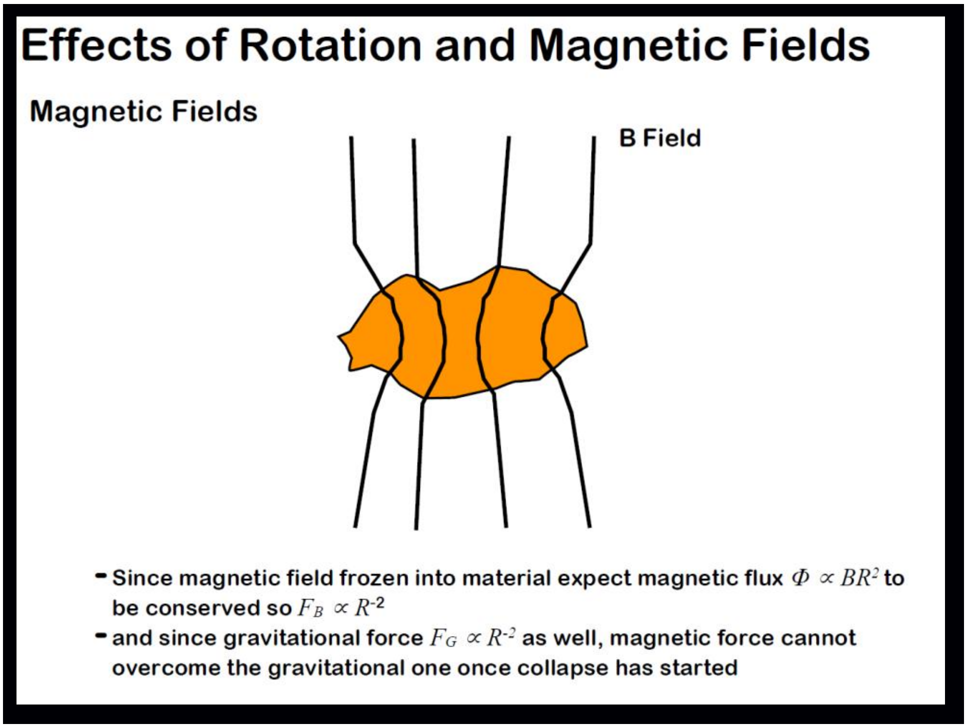
- Force due to a magnetic field $F_B \propto R^2B^2$
  - c.f. force on a wire $F_B = Il \times B$ and $I \propto lB$
- Charged particles spiral around field lines effectively freezing in the magnetic field into the material



Effects of Rotation and Magnetic Fields

Magnetic Fields

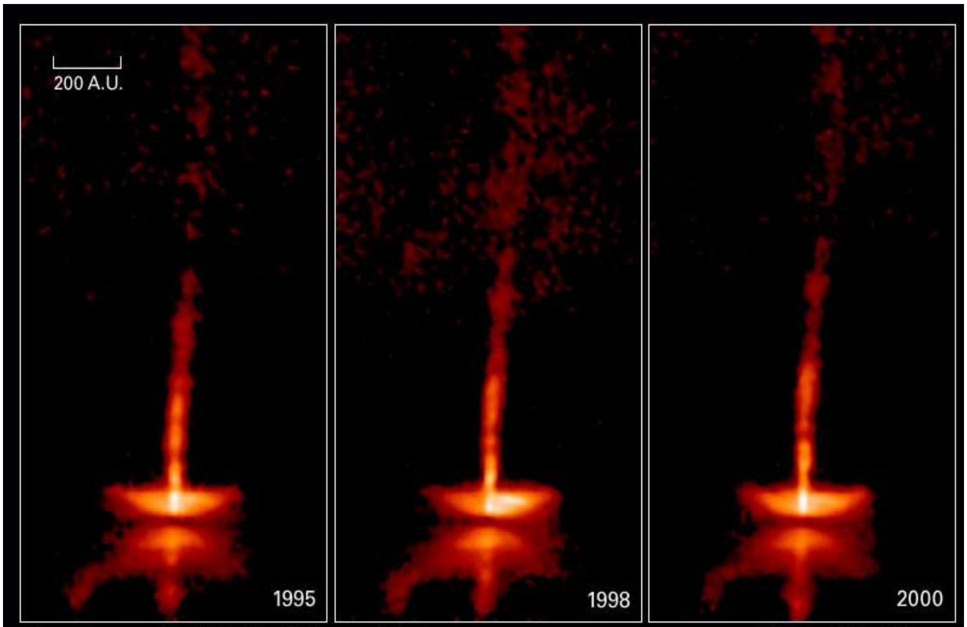
- If magnetic field is important and uniform → flattened clouds



Effects of Rotation and Magnetic Fields

Magnetic Fields

- Since magnetic field frozen into material expect magnetic flux $\Phi \propto BR^2$ to be conserved so $F_B \propto R^{-2}$
- and since gravitational force $F_G \propto R^{-2}$ as well, magnetic force cannot overcome the gravitational one once collapse has started



The Dynamic HH 30 Disk and Jet HST • WFPC2

NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b

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Modern picture :

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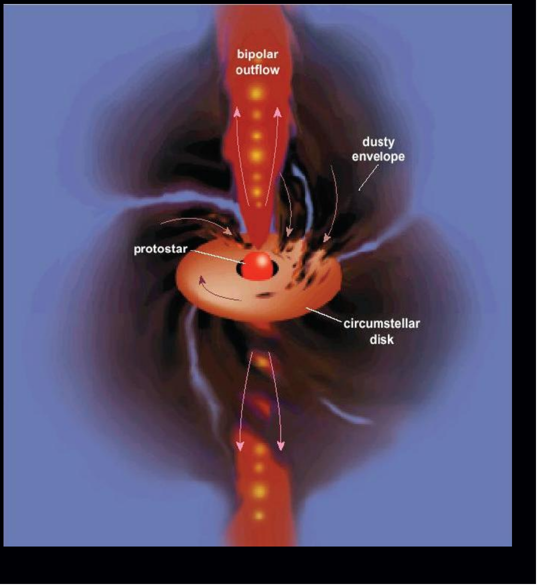
- Jets :
- A lot of matter injected into interstellar gas "stirring it up" - turbulence

- Last many thousands of years

- Signature of accretion (!)

- Rotate slightly



Star Formation in a nutshell

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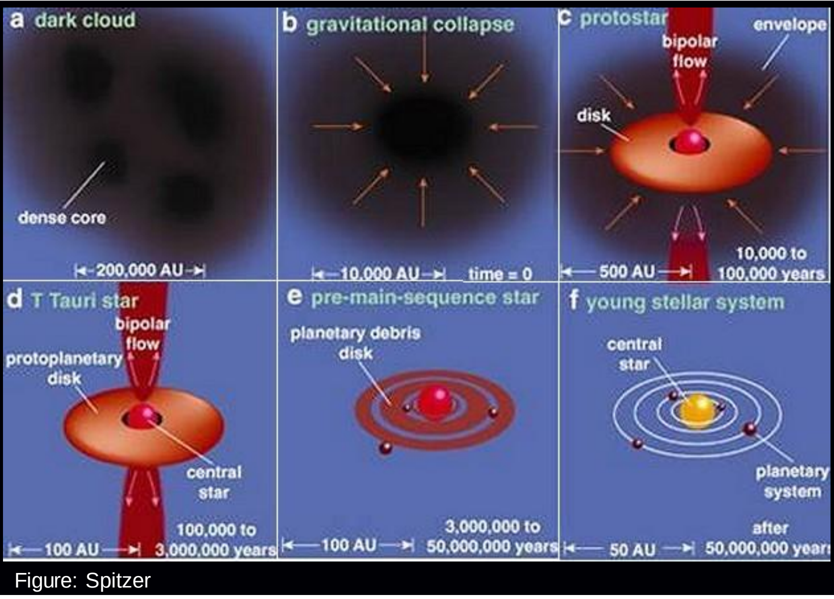
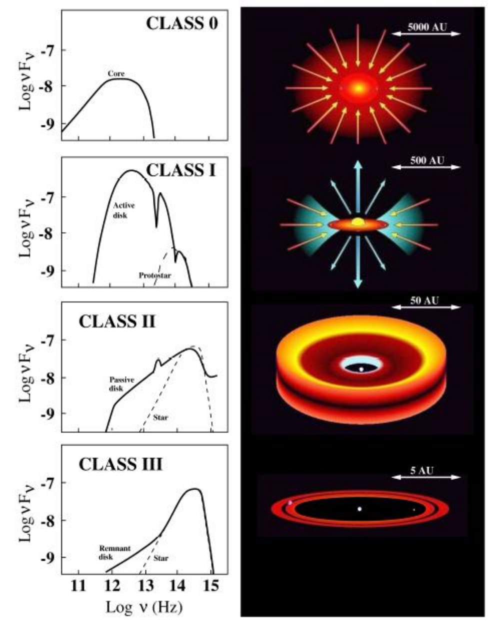


Figure: Spitzer

Evolution of spectral energy distribution (SED)

- In early stages of formation the dusty envelope is very optically thick even in IR
- Therefore spectrum peaks in Far-IR
- As envelope clears peak shift to shorter wavelengths until light from the star and accretion disk is revealed
- Eventually the disk is ‘dispersed’ leaving just the star



Van Boekel et al 2006

OIR interferometry exquisite to study “Class II/III” objects

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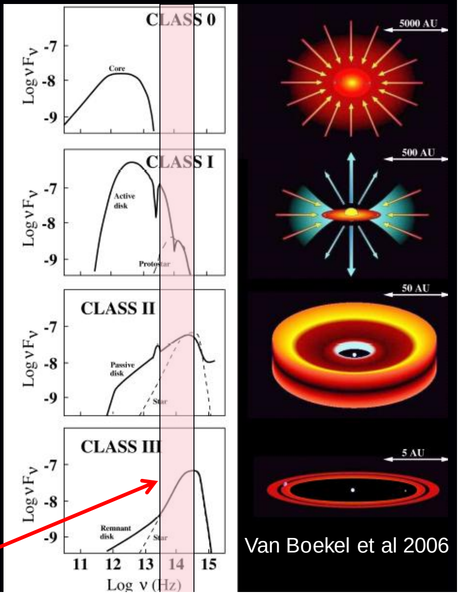
- **T Tauri stars** : solar mass, magnetically controlled accretion, veiling, optically visible
- **Herbig Ae/Be stars** : intermediate mass, accretion by infall, optically visible
- **Massive Young Stellar Objects** : massive, rare, elusive, obscured



OIR range

Van Boekel et al 2006

Problems solved !?

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The “bi-polar outflows” are too strong...

Massive stars not even supposed to form…

Disk accretion might be the answer

Problems, problems...

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The stars are predicted to rotate faster than the speed of light...

Angular momentum problem

Introducing a disk surrounding
the star may help

As would a rotating outflow

Presence disks difficult to establish

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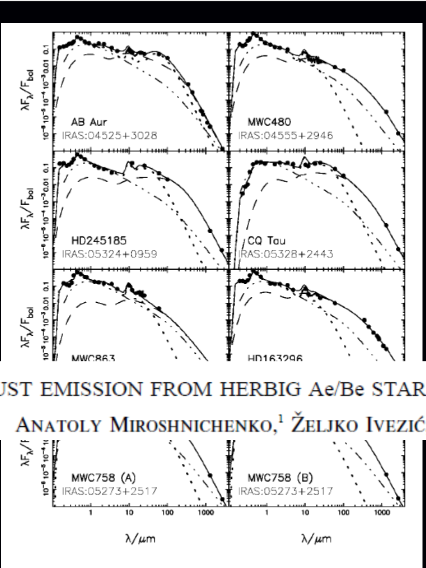

FIG. 1.—Fits to the SEDs of the MS sources with models comprised of geometrically thin, optically thick disks embedded in spherical dusty envelopes.

Existence disks often inferred from indirect data

Herbig Ae/Be stars :
Spectral Energy Distribution
Disk or Envelope?

DUST EMISSION FROM HERBIG Ae/Be STARS: EVIDENCE FOR DISKS AND ENVELOPES

ANATOLY MIROSHNICHENKO,[1] ŽELJKO IVEZIĆ,[2] DEJAN VINKOVIĆ,[3] AND MOSHE ELITZUR[3,4]

THE ASTROPHYSICAL JOURNAL, 520:L115–L118, 1999 August 1
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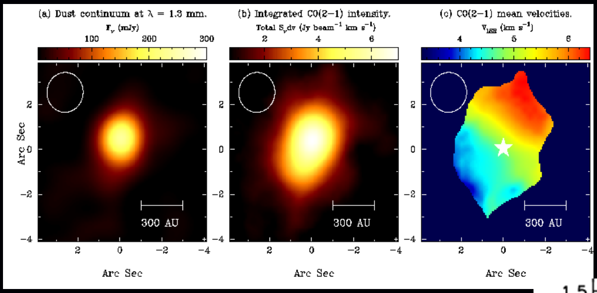
Detecting (accretion) disks not trivial

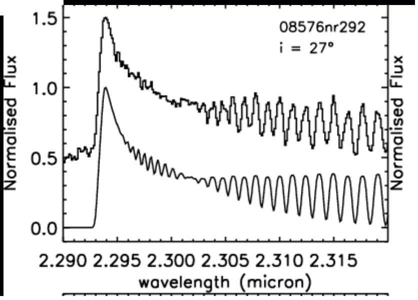


Very large scales

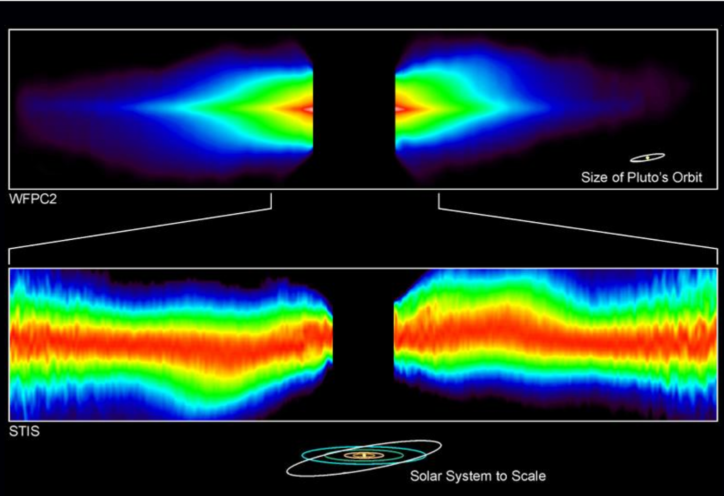
Mannings et al 1997

Indirect evidence

Bik and Thi 2004



Evidence for larger scale disks for few targets

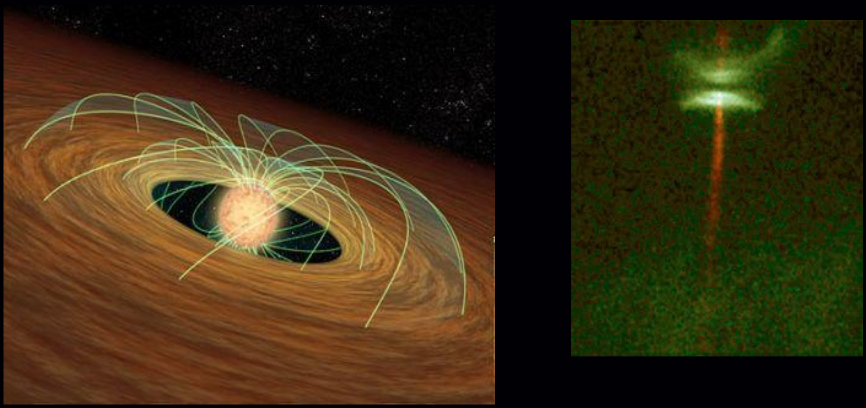


Beta Pictoris HST • WFPC2 • STIS

PRC98-03 • January 8, 1998 • ST ScI OPO

A. Schultz (Computer Sciences Corp.), S. Heap (NASA Goddard Space Flight Center) and NASA

Pre-Main Sequence Stars



Formation low mass (T Tauri) stars best understood: magnetospheric accretion

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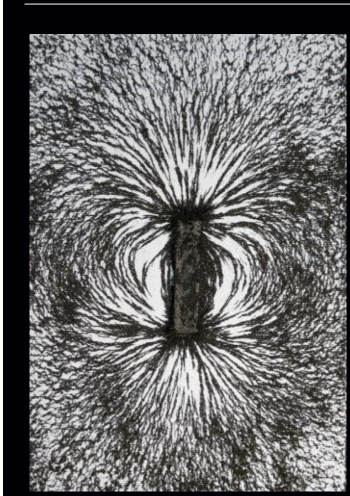
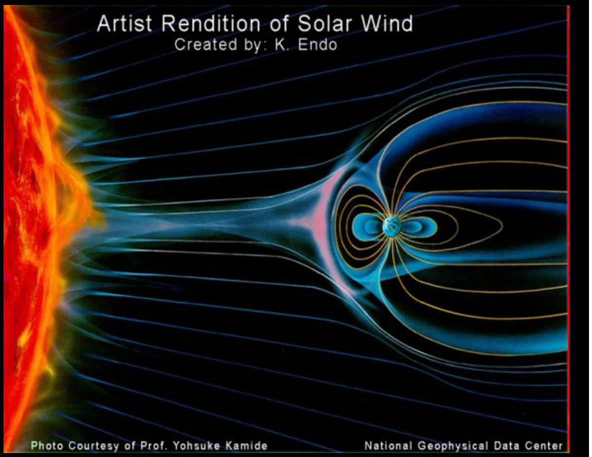
Intermezzo : Magnetic fields :





Magnetic fields now found:

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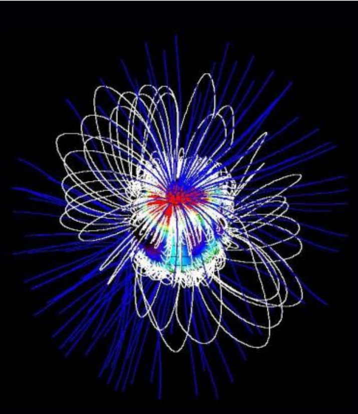

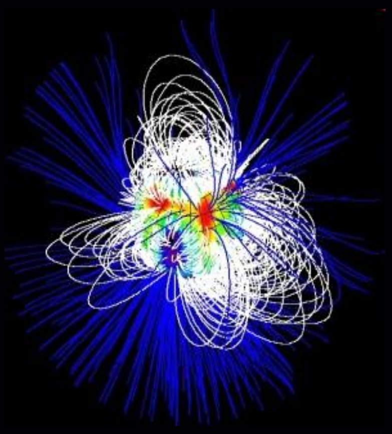

Material falls on star via
the field lines, and *FAST*

(Donati et al)

Low mass stars: magnetospheric accretion

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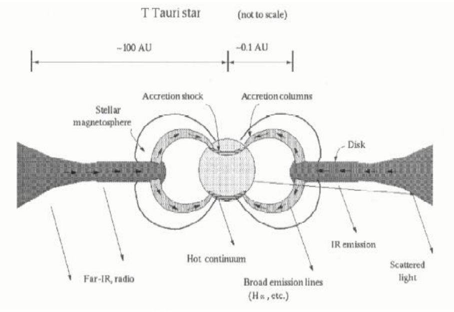

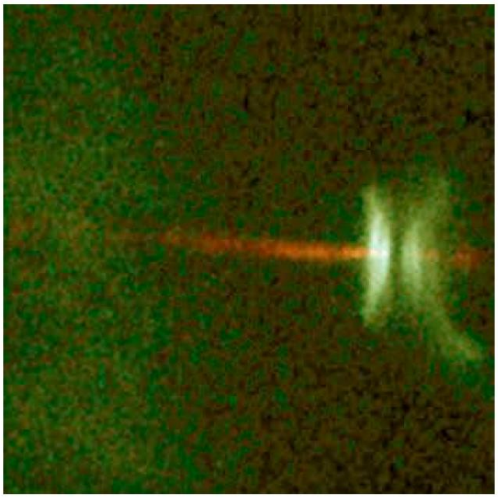

Pre-main sequence stars

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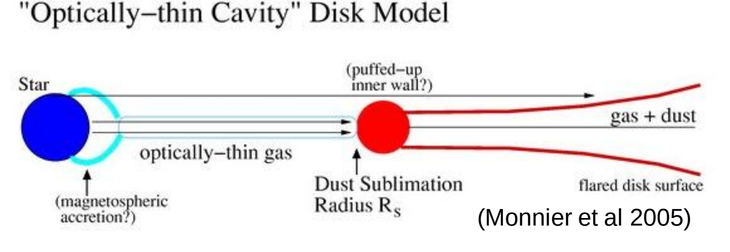
- Higher mass stars have radiative envelopes, so no magnetic fields, accretion process has to be different.
- However, Herbig Ae stars found to be similar to T Tauri stars (eg Vink et al. 2003)



(Monnier et al 2005)

Questions: what is accretion mechanism? what are structure and properties Herbig Ae/Be disks!?

Herbig Ae/Be Disks

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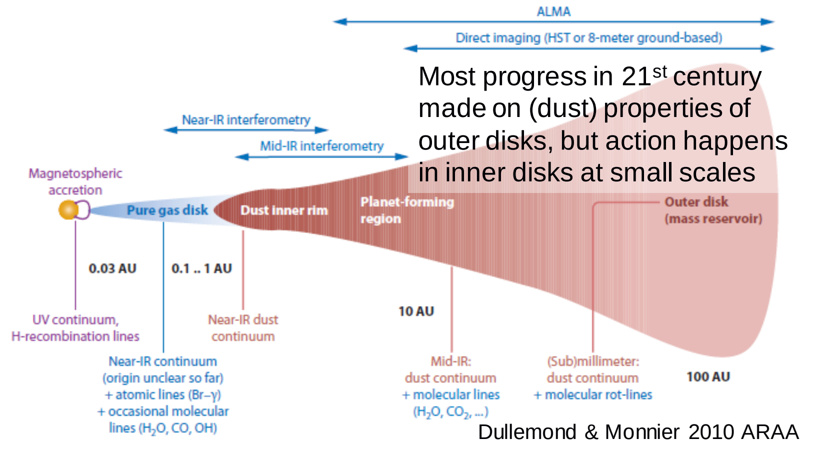
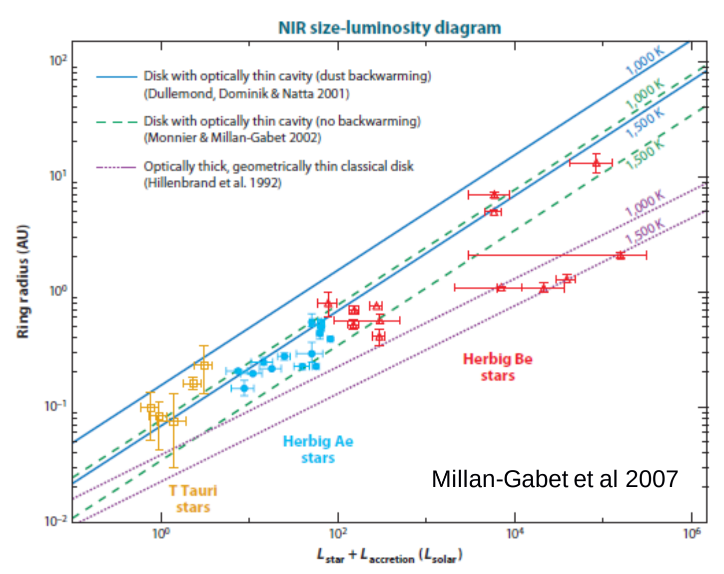
Presence of disks around Herbig Ae/Be stars now established, challenge to understand their properties and structure



Most progress in 21st century made on (dust) properties of outer disks, but action happens in inner disks at small scales

Dullemond & Monnier 2010 ARAA

OIR interferometry:
Continuum visibilities: sizes; provide info on structure



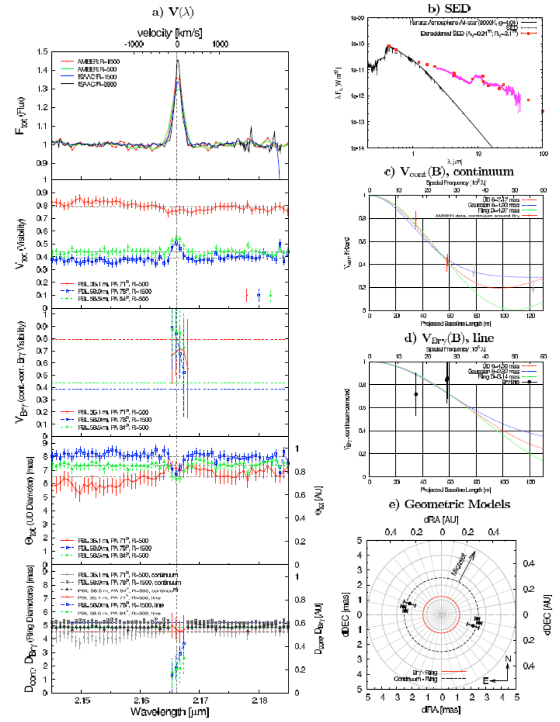
Millan-Gabet et al 2007

Emission line visibilities, probe accretion and winds

Survey of 5 Herbig Ae/Be stars in 2008 (Kraus et al.) found both compact (infall) and extended (wind) Brγ emission

NB: limited number of baselines

NB2: number of observable targets small!



Interferometric imaging now possible for limited number of objects

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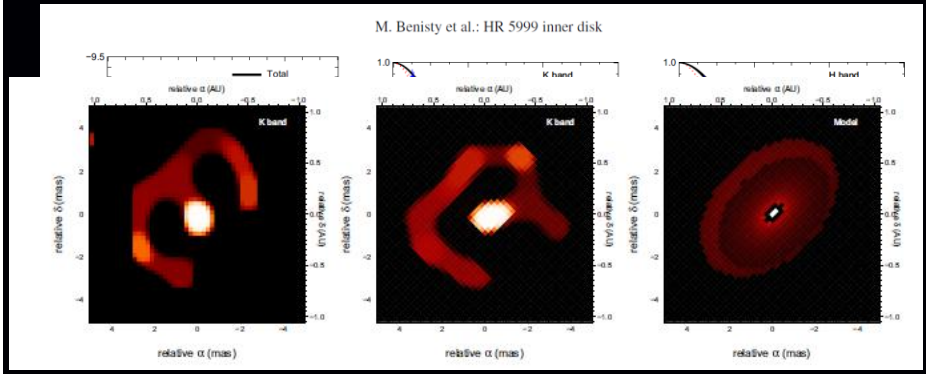


K band

H band

Model image

Benisty et al 2011

: evidence for refractory grains in

Herbig Ae type star HR 5999 (see also poster by Kluska)

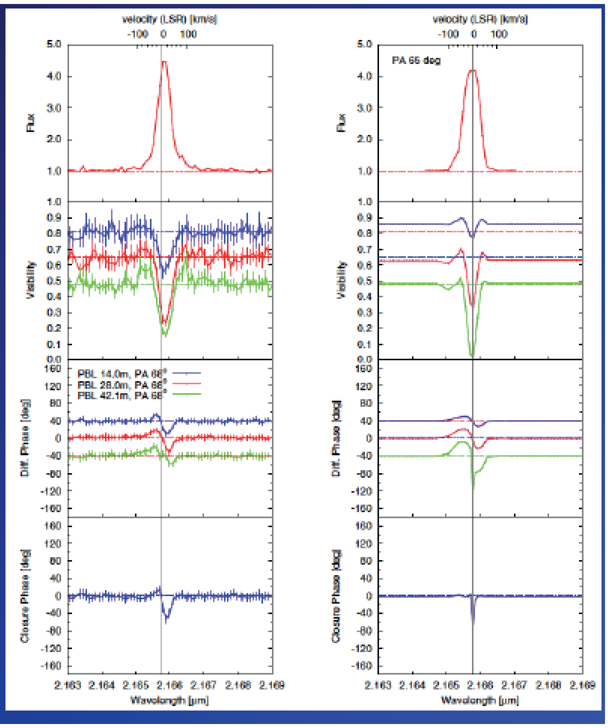
Interferometry at high spectral resolution:

B-type Herbig MWC 297

(Brγ forms outside continuum)

Left: observations,
Right: disk wind model

Weigelt et al. 2011



Cautionary Note

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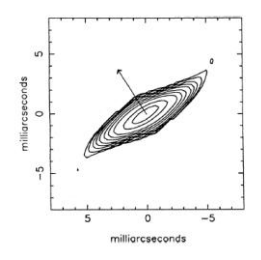
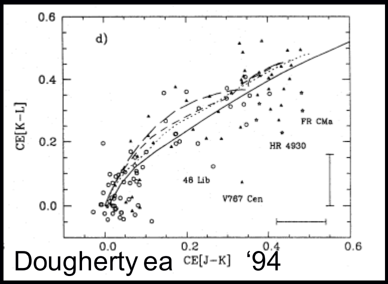
High resolution techniques (spectral, spatial, temporal) mostly limited to small numbers of bright objects



Map of Hα emission of ζ tau (*Quirrenbach et al. 1994*).



Dougherty ea '94

In-depth studies of individual targets inform follow-on studies employing lower resolution but larger, statistical, samples

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The direct detections also underpin statistical studies

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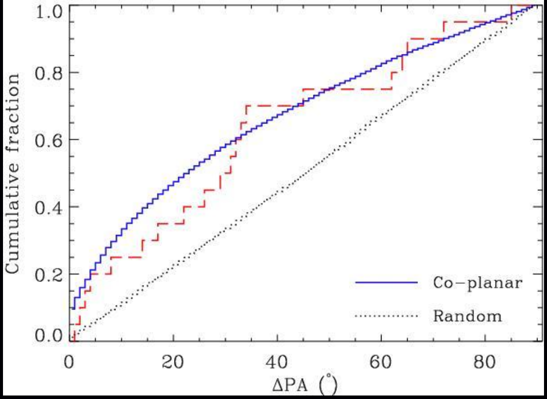
Compilation disk orientations and binary statistics of Herbig Ae/Be stars:

Primary disks are co-planar with binary orbits



⟶ Disk fragmentation, not capture, is route to high mass stars/binaries (cf. Kumholz et al 2009)

Wheelwright et al 2011

The Kelvin-Helmoltz Timescale ($t_{K\text{-}H}$)

Herbig Ae/Be stars span range up to 10-15 $M_\odot$

Let's move to more massive stars, these are not visible in optical:

- The protostar can only contract by radiating away the released gravitational energy.
- The timescale for contraction can be derived from:

$$t_{K-H} \sim \frac{\text{Gravitational Energy}}{\text{Luminosity}}$$

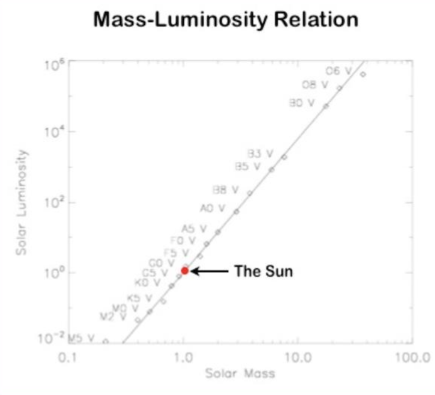
$$t_{K-H} \sim \frac{GM^2}{RL}$$

The Kelvin-Helmoltz Timescale

Fitting a line to the data:

$$L \propto M^4$$

$$t_{K-H} \sim \frac{GM^2}{RL} \rightarrow t_{K-H} \propto M^{-2}$$



For massive stars:

$$t_{K-H} << t_{ff}$$

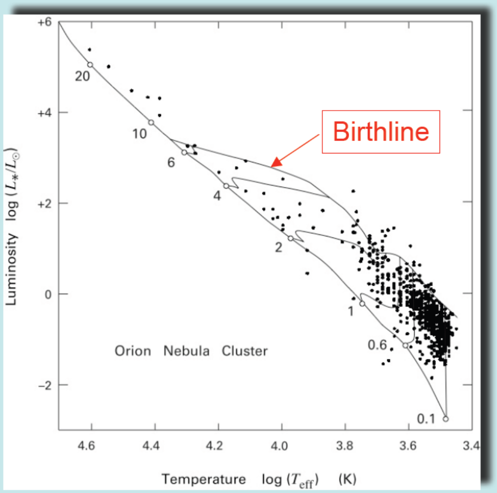
$$t_{ff} = \sqrt{\frac{3\pi}{32G\mu m_H n}}$$

Therefore, **massive stars arrive on the Main Sequence (MS) whilst still embedded in their molecular clouds.**

Comparison with low-mass stars

Massive stars reach the MS while still accreting material.
↓

- Massive stars have invisible Pre-Main-Sequence (PMS) phase.
- Luminous IR sources
- HII regions



Evolutionary Outline

Hot Core → MYSO → UCHII → OB Star

SED:

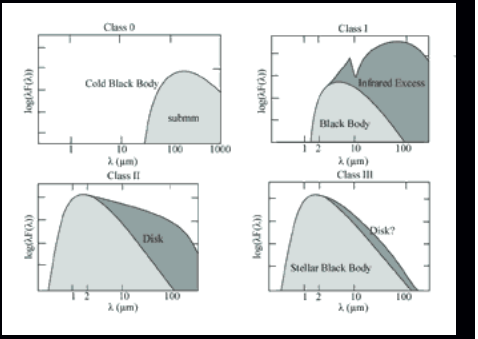
Sub-mm → Mid-IR → Mid/Near-IR → Near-IR/Visual

Radio:

No radio → Weak Radio → Strong Radio

Masers:

CH_3OH → H_2O → OH



Massive Young Stellar Objects

- Luminous (>10^4 $L_\odot$) IR source
- Bipolar molecular outflow
- Compact, ionised wind, v~100 km/s
- Distances of order kpc
- OIR faint

- How do they form?
- Accretion (disk) properties?
- Outflow and envelope properties?

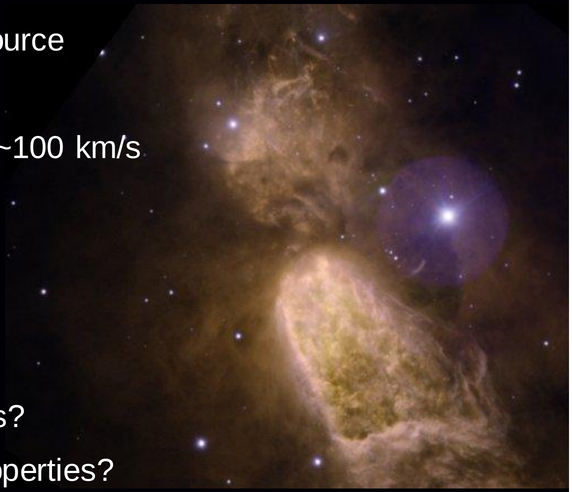
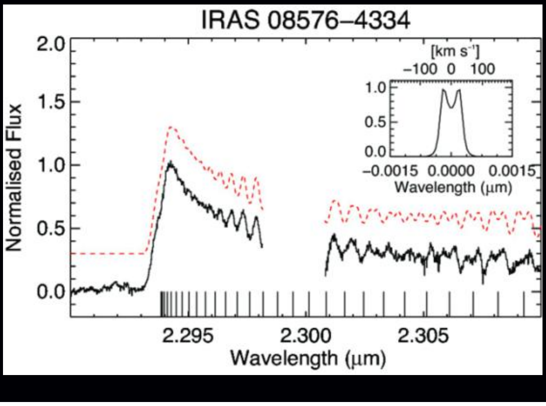


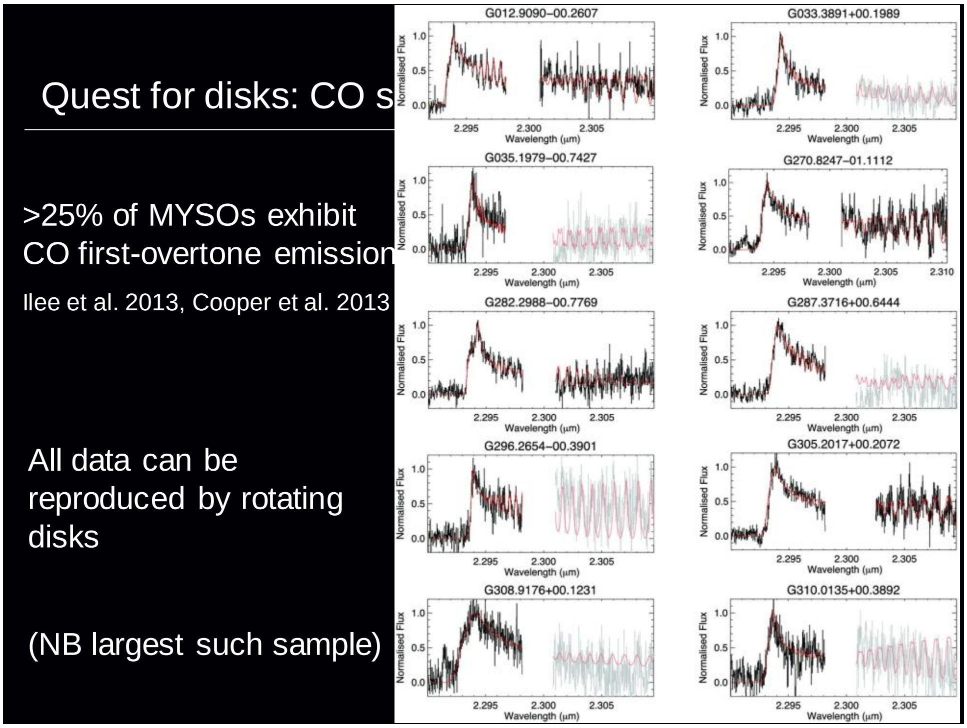
Image: Gemini

Quest for disks: CO spectroscopy at 2.3 µm

>25% of MYSOs exhibit
CO first-overtone emission

Ilee et al. 2013, Cooper et al. 2013





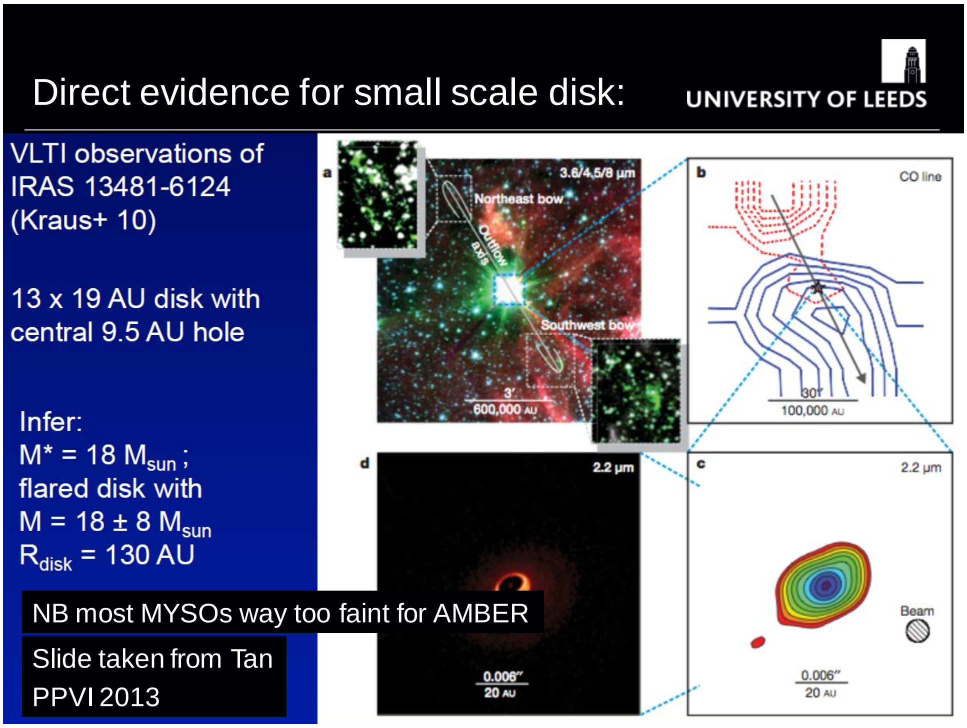
Quest for disks: CO s

>25% of MYSOs exhibit CO first-overtone emission

Ilee et al. 2013, Cooper et al. 2013

All data can be reproduced by rotating disks

(NB largest such sample)



Direct evidence for small scale disk:

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VLTI observations of IRAS 13481-6124 (Kraus+ 10)

13 x 19 AU disk with central 9.5 AU hole

Infer:
$M^* = 18\ M_{sun}$;
flared disk with
$M = 18 \pm 8\ M_{sun}$
$R_{disk} = 130$ AU

NB most MYSOs way too faint for AMBER

Slide taken from Tan PPVI 2013

Mid IR MIDI interferometry in 2013:

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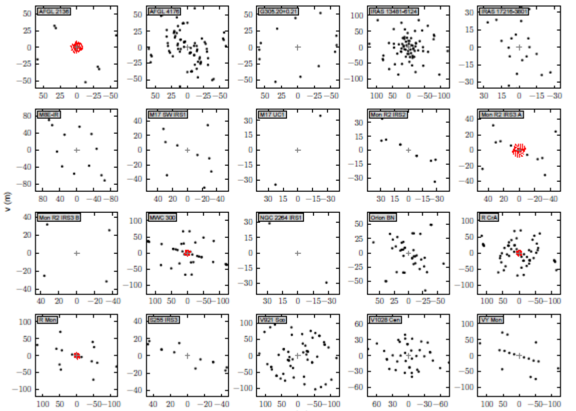
Massive Young Stellar Objects:
emphasis on dusty mid-infrared emission
Largest sample of MYSOs, Boley et al.: *uv* coverage



Mid IR MIDI interferometry in 2013:

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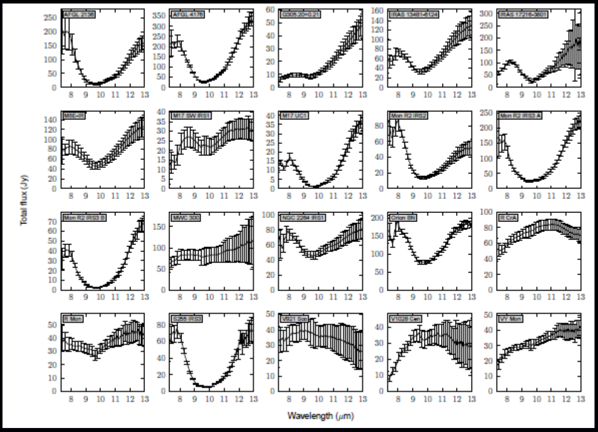
Largest sample of MYSOs, Boley et al: Flux



Mid IR MIDI interferometry in 2013:

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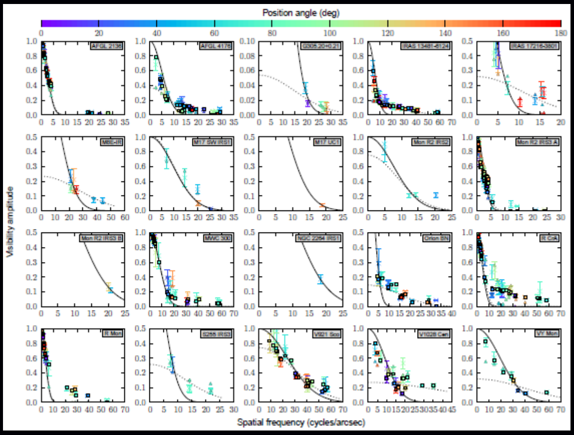
Largest sample of MYSOs, Boley et al: Visibilities



Mid IR MIDI interferometry in 2013:

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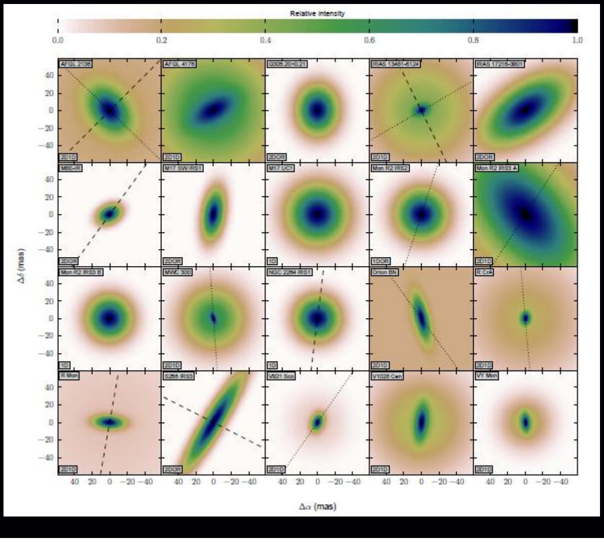
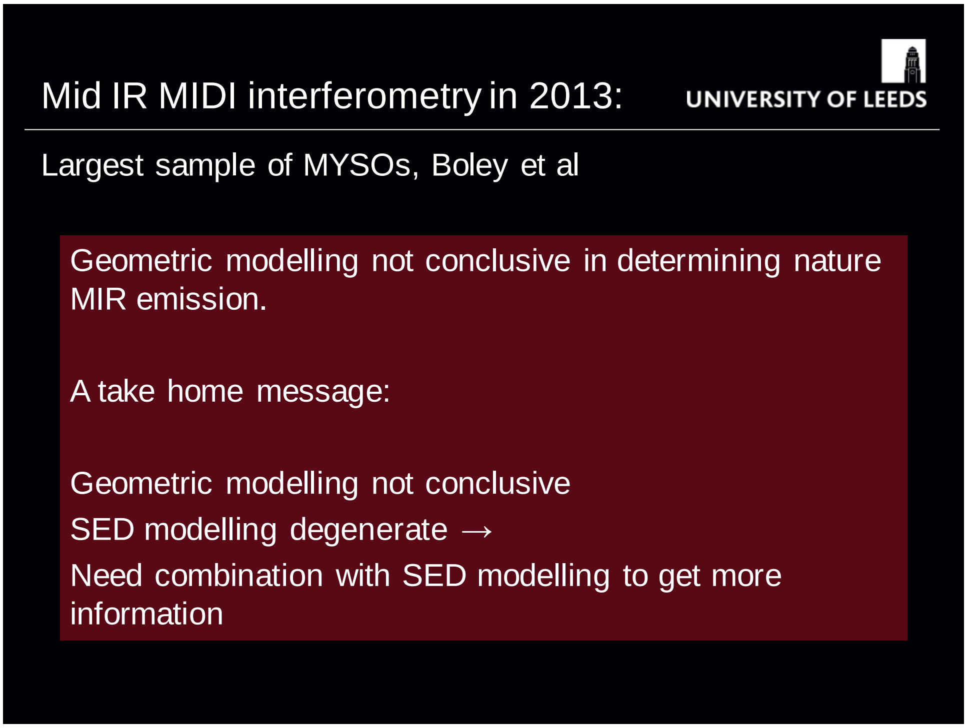
Largest sample of MYSOs, Boley et al: Geometric models





Mid IR MIDI interferometry in 2013:

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Largest sample of MYSOs, Boley et al

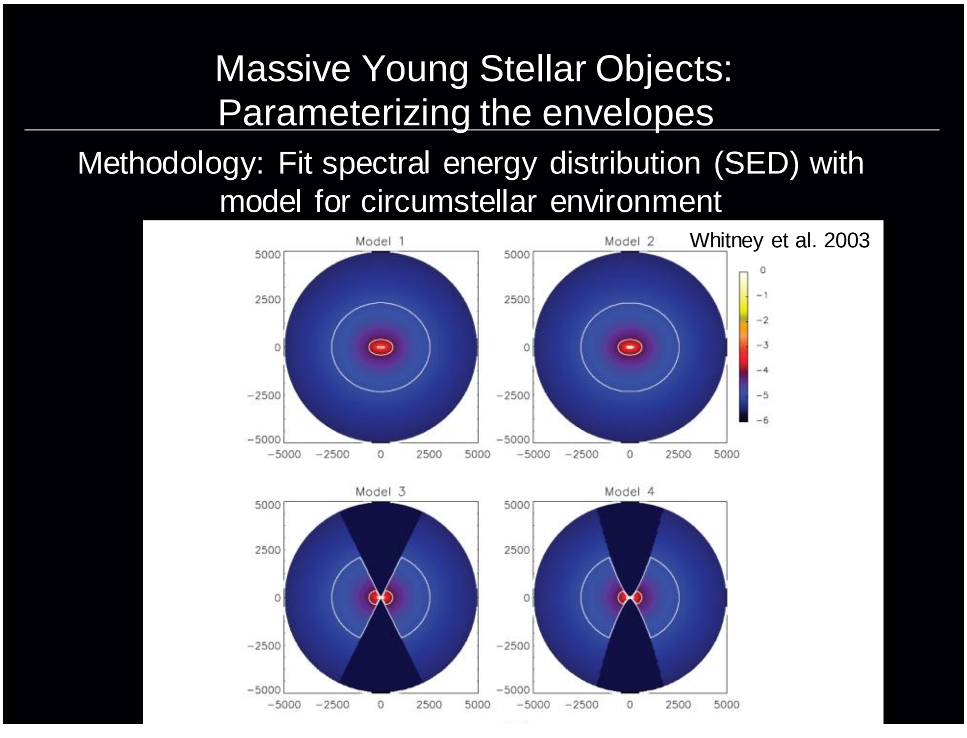
Geometric modelling not conclusive in determining nature MIR emission.

A take home message:

Geometric modelling not conclusive

SED modelling degenerate →

Need combination with SED modelling to get more information



Massive Young Stellar Objects: Parameterizing the envelopes

Methodology: Fit spectral energy distribution (SED) with model for circumstellar environment

Whitney et al. 2003

Massive Young Stellar Objects: Parameterizing the envelopes

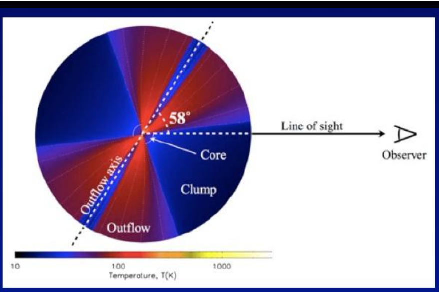
Methodology: Fit spectral energy distribution (SED) with model for circumstellar environment

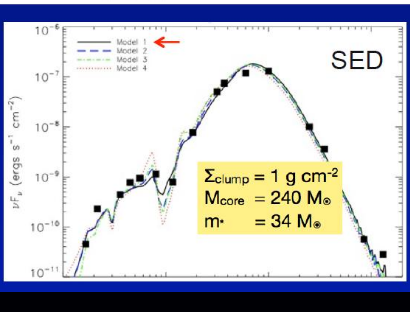
Free parameters:

- *Density (accretion rate)*
- *Opening angles*
- *Disk properties*
- *Etc*

Need imaging for better constraints

Zhang et al. 2013





Diffraction limited Mid-IR imaging

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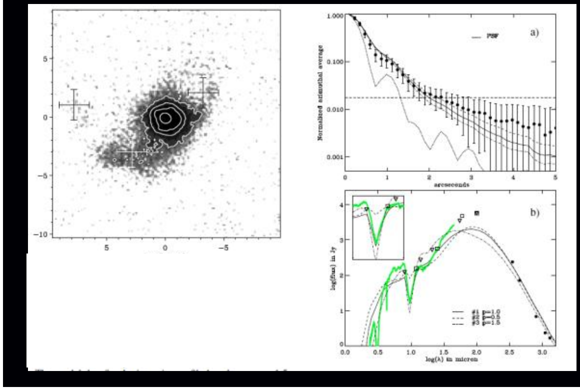
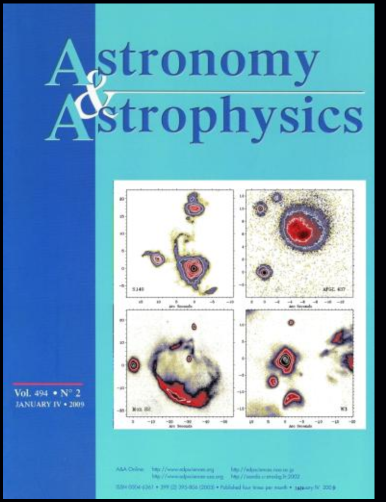
VISIR 20μm diffraction limited VLT Grantecan & SUBARU imaging

MIR emission cavity walls

Arcsec resolution





De Wit et al 2009;
Wheelwright et al. 2012

Example W33A: MIDI interferometry
SED Fitting alone not sufficient

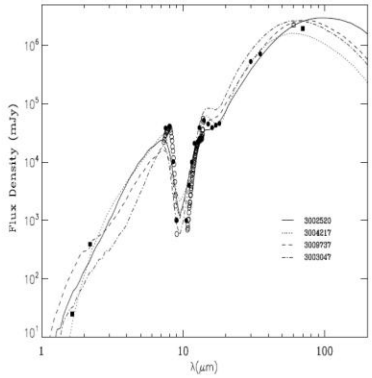
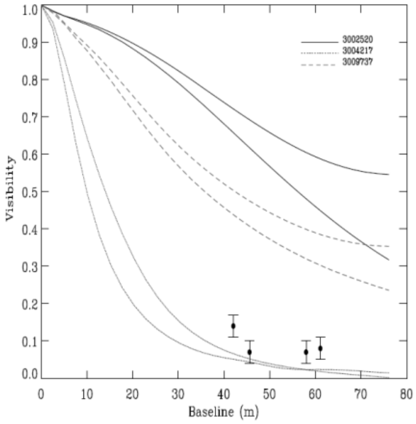


Fig. 12. Predicted SEDs of the discussed models obtained from the SED web fit procedure listed in Table 3.

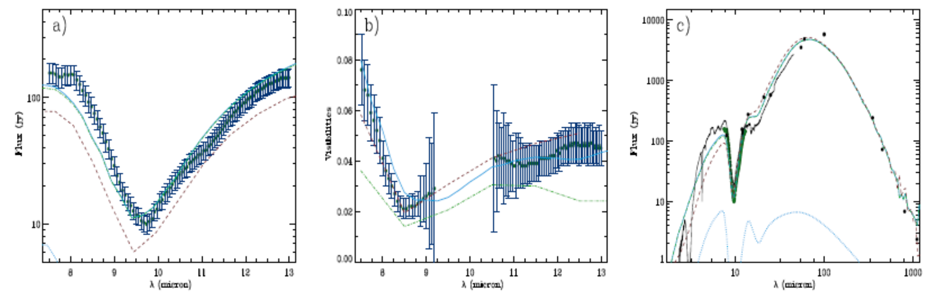


De Wit et al. 2010; Model grid by Robitaille et al. 2006

Mid IR MIDI interferometry:

CRL 2136, de Wit et al., 2011, A&AL – 42m baseline

Axi-symmetric dust radiative transfer code Whitney et al. 2003



Simultaneous fitting SED and spatial information

Mid IR Interferometry

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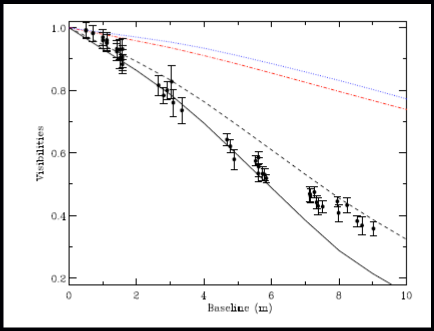

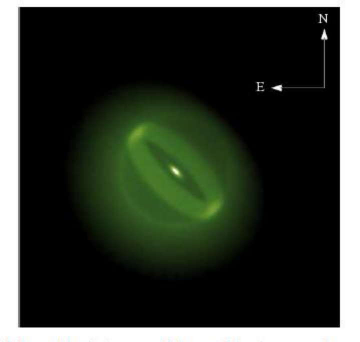

Envelope well characterized

Compact source in center – bloated star or accretion disk

Morale : need spatial information

Multi-baseline, 2D, fitting, W33A:

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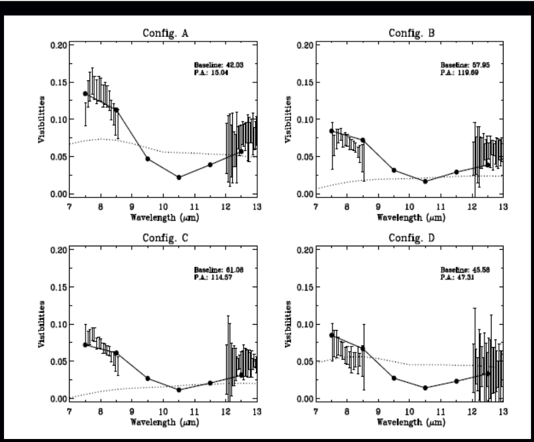
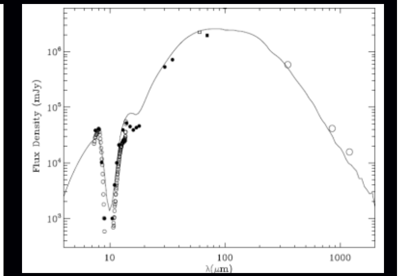
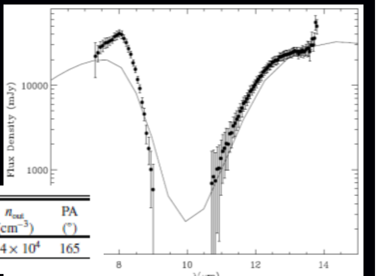
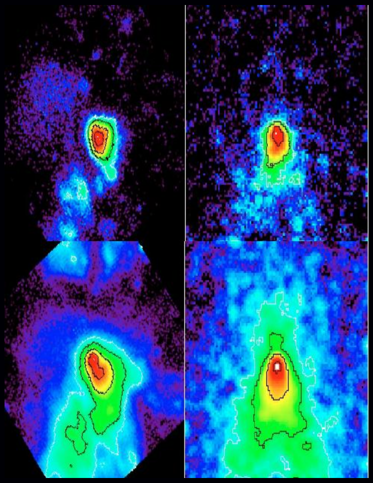




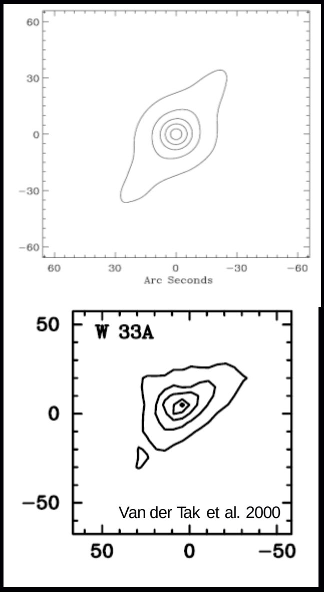


M_* ($M_\odot$)	R_* ($R_\odot$)	$T_{\rm eff}$ (K)	$M_{\rm env}$ ($M_\odot$)	$\dot{M}_{\rm infall}$ ($M_\odot\,{\rm yr}^{-1}$)	i (°)	$R_{\rm env}$ (AU)	$R_{\rm sub}$ (AU)	$A_V^{\rm for}$	$A_V^{\rm env}$	$n_{\rm out}$ (cm^{-3})	PA (°)
25	8.4	35 000	9.7×10^3	7.5×10^{-4}	60	5×10^5	25	8	230	1.4×10^4	165

Result of multi-wavelength approach:


H and *K* data and model

350 μm data and model



Van der Tak et al. 2000

Mid-IR interferometry

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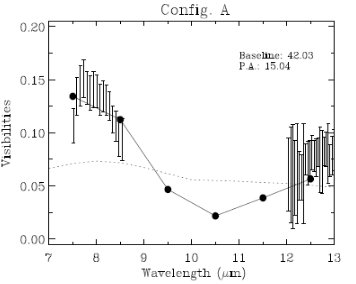
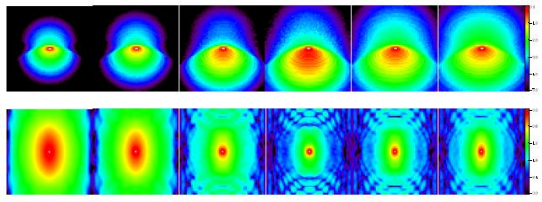
- VLTI MIDI 8-13 micron observations of the warm dust from the inner envelope/outflow cavity wall region
- Looking inside the cavity



De Wit et al 2010

Images 7.5-12.5 μm:



uv coverage

W33A and disk emission

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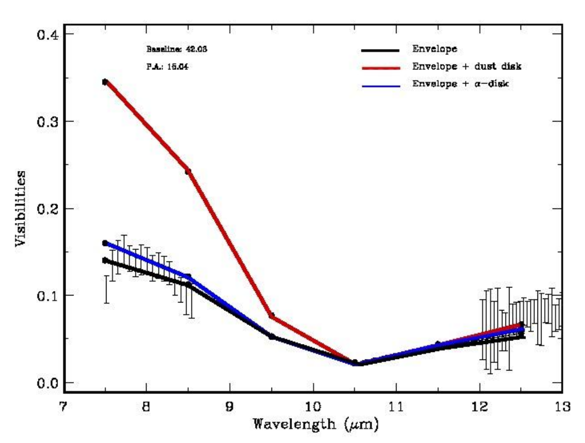
Disk limits from N-band interferometry:

Dust disk : $M < 0.01 M_\odot$, implies low accretion rate?

Gas (accretion) disk can be hidden: $M_{acc} < 10^{-3}\ M_\odot/yr$



De Wit et al. 2010

Davies et al. 2010

OIR Interferometry & Star Formation

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- Continuum and line interferometry has come of age in this century
- Results promising, but have scratched the surface
- Improved sensitivities will allow larger samples to be observed
- And imaging to be done
- (All in conjunction with sophisticated models)

Epilogue: Probing at very small scales: Prospects for spectro-astrometry

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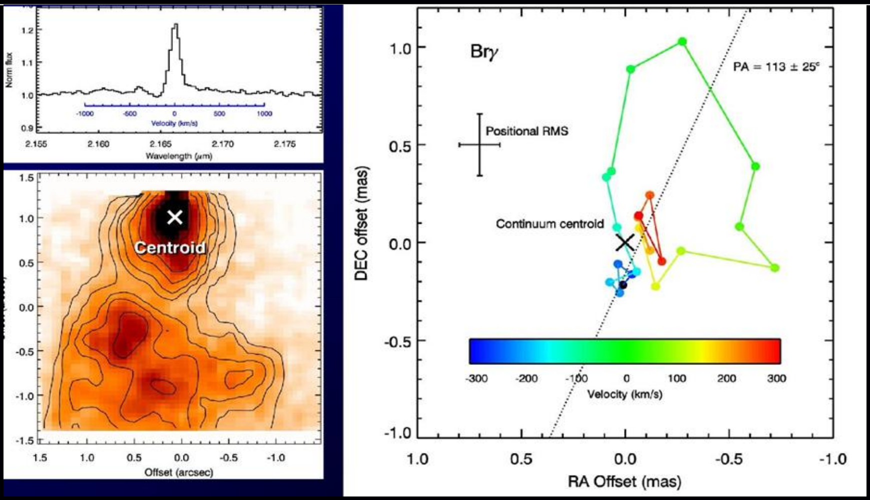

mas precision traces of Brγ in IFU data – tracing the first base of a bi-polar flow in a massive young star (Davies et al. 2010)

Prospects for spectro-astrometry

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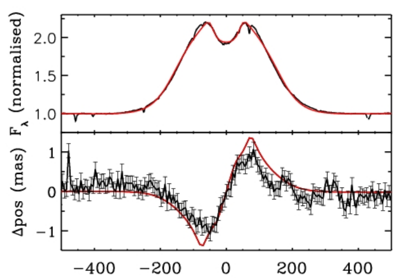
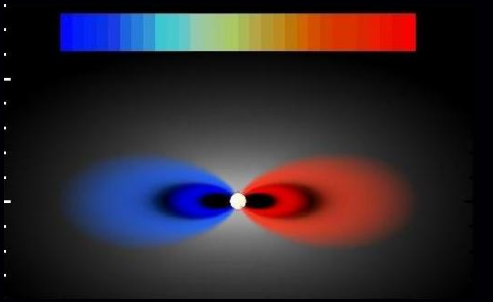
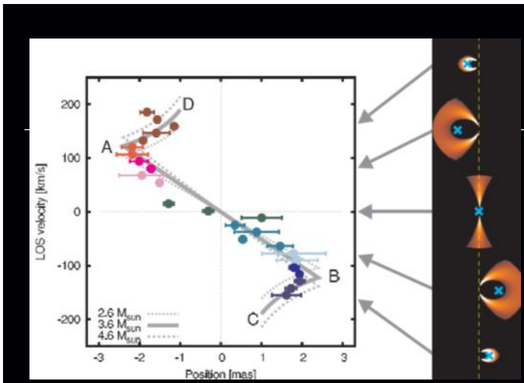




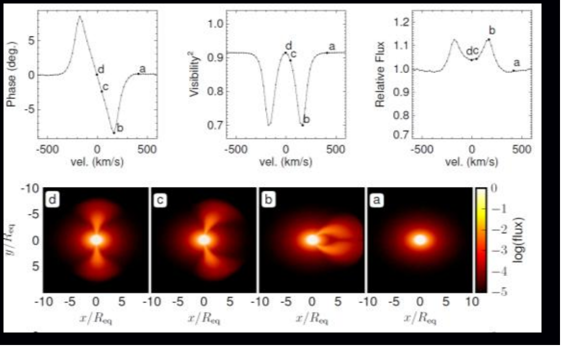
Sub-mas precision traces of Hα in Be stars, fit by 3D non-LTE models → disk parameters
(Wheelwright et al. 2012, MNRAS Let.)

Application to AMBER



Kraus et al. 2012

Faes et al. 2013



Prospects for spectro-astrometry

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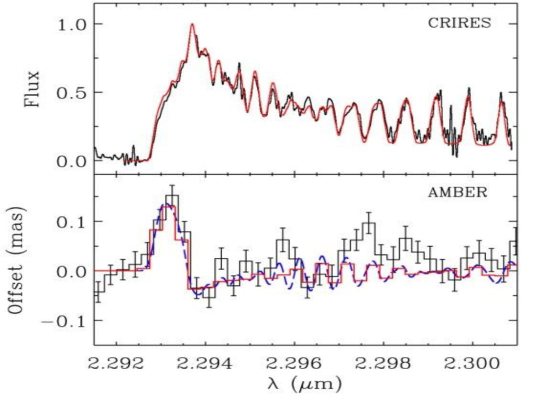

Micro-arcsec precision traces of CO in a B[e] star (AMBER, Wheelwright et al. 2012)

Probing at very small scales: Prospects for spectro-astrometry

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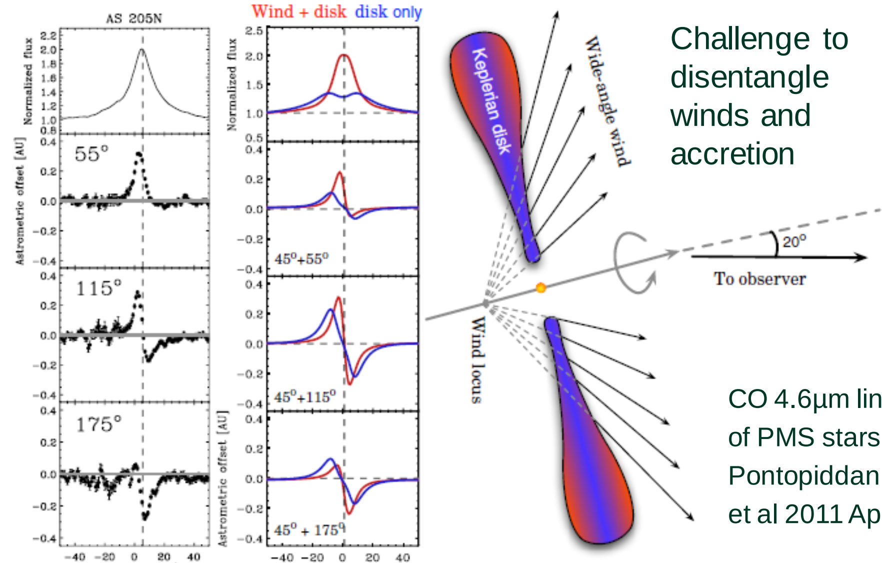

Challenge to disentangle winds and accretion

CO 4.6µm line of PMS stars
Pontopiddan et al 2011 ApJ

Future bright!

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- Improved sensitivities
- New beamcombiners
- New instruments
- New interferometers

Magdalena Ridge Observatory Interferometer
10 elements – 340m baseline, optical,NIR