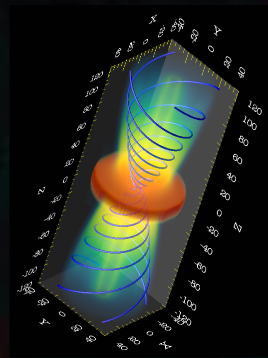
Accretion-ejection processes in Herbig Ae/Be stars



Catherine Dougados

UMI-FCA Dept. Astronomia, Universidad de Chile Santiago
& Institut de Planétologie et d'Astrophysique de Grenoble

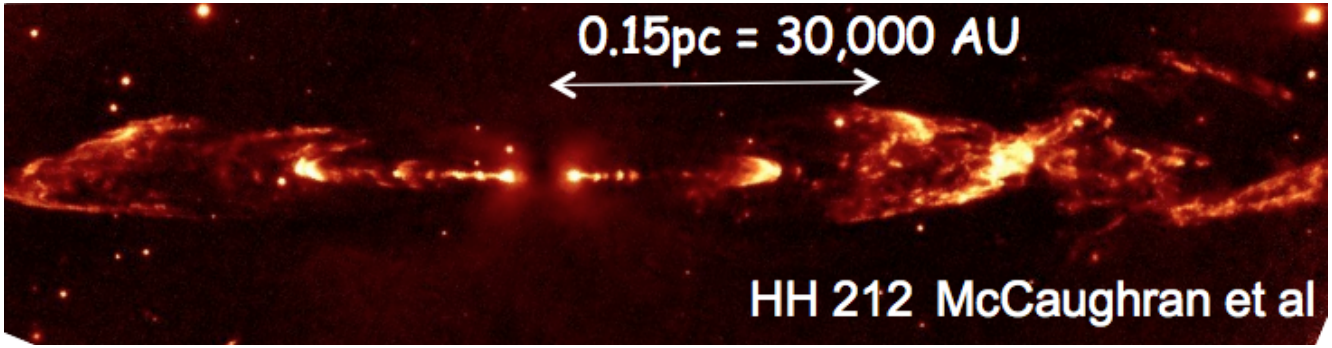
IPAG Institut de Planétologie et d'Astrophysique de Grenoble

DEPARTAMENTO DE ASTRONOMÍA
Facultad de Ciencias Físicas y Matemáticas
UNIVERSIDAD DE CHILE

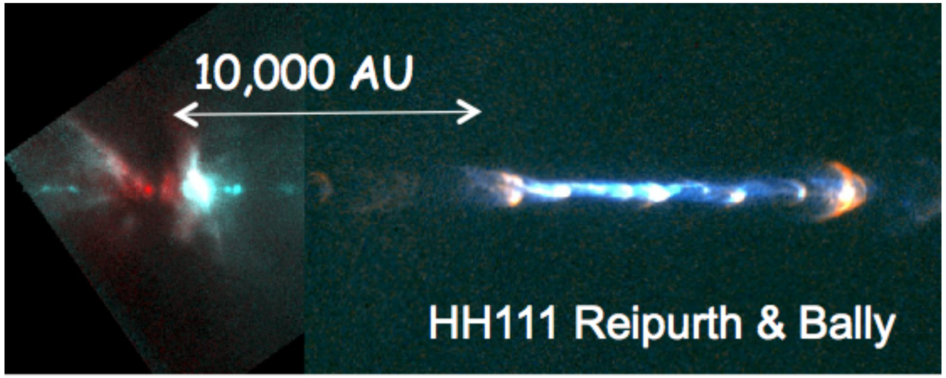
Cerro Calán Observatorio Astronómico Nacional

fcfm

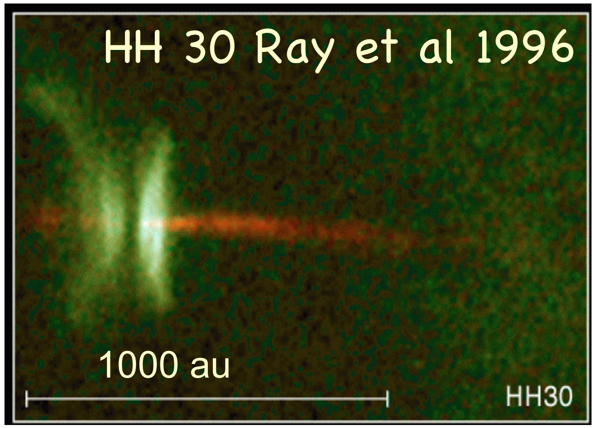
The Accretion-Ejection connexion



Class 0 Protostar



Evolved Class I Protostar



Class II
Disk only

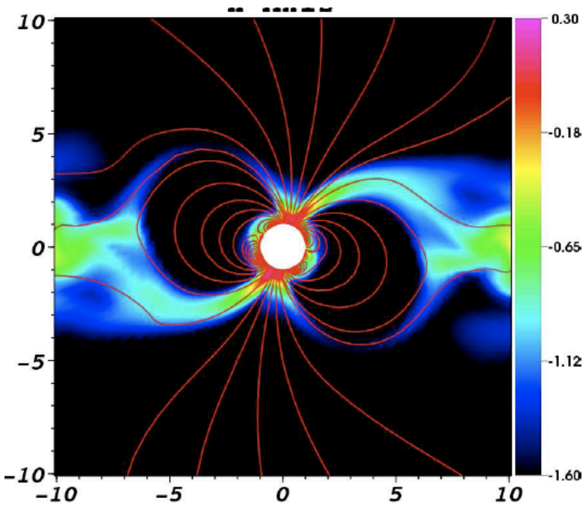
- Universal accross evolutionary stages dMjet/dt/dMac/dt ≈ 0.1

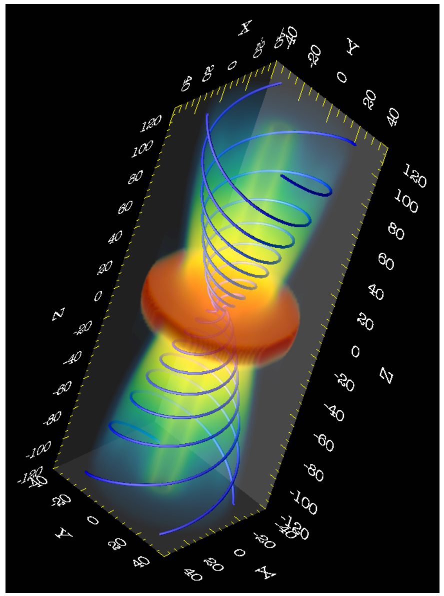
  Accretion-Powered

  Hartigan et al. 1995; Antoniucci et al. 2008

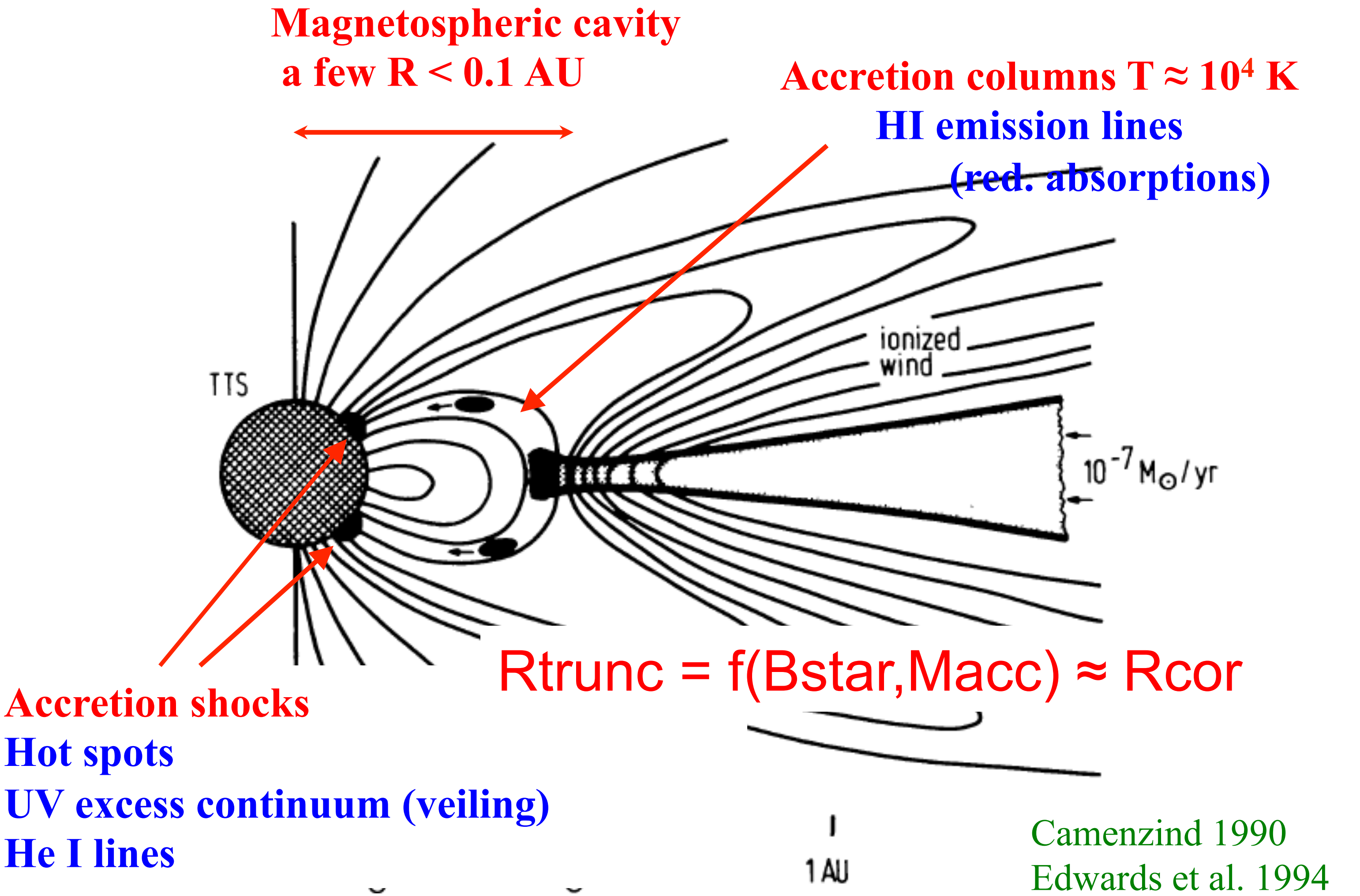
- **Universal in Mstar**: from 24 Mjup to 20 $M_{\odot}$

I- What do we (think we) know about Accretion-Ejection in T Tauri stars



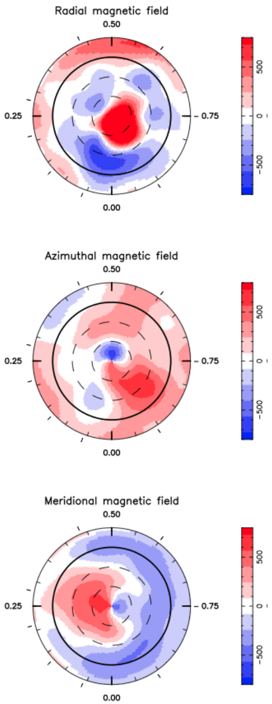


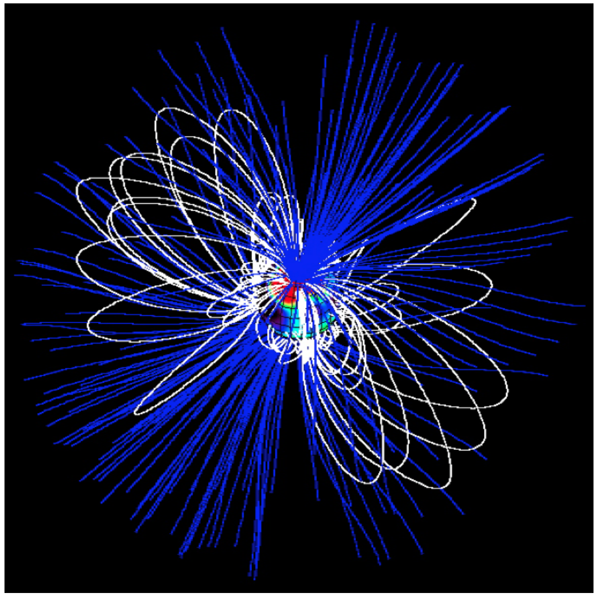
Magnetospheric accretion in T Tauri stars

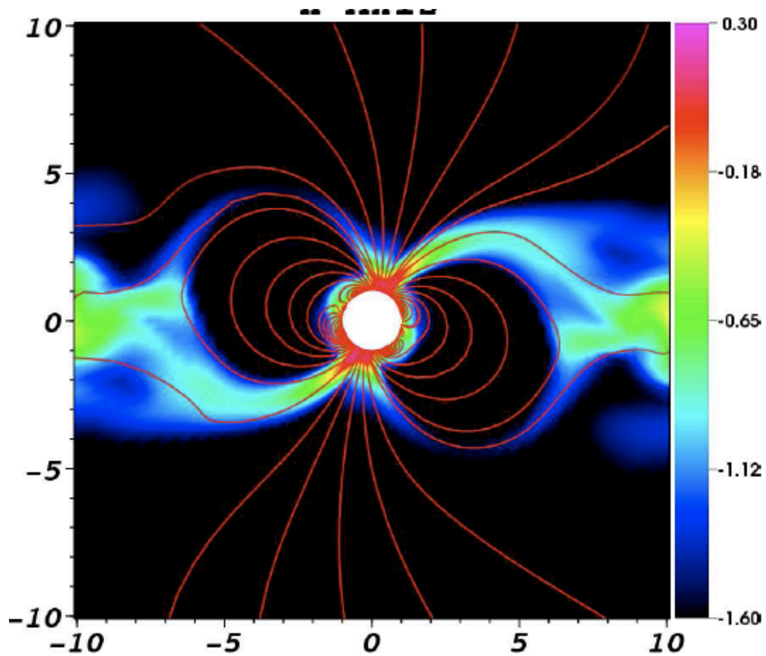


Camenzind 1990
Edwards et al. 1994
Hartmann et al. 1994

Accretion onto a complex magnetic field







- Strong kGauss large-scale B*

  Yang et al. 2011, Johns-Krull et al. 2013

- Complex geometry (≠ pure aligned dipole)

Donati et al. 2012, Gregory et al. 2012, Johnstone et al. 2014 Dynamo origin ?

- Octupole modifies accretion shock

But dipole dominates star-disc interaction

Long, Romanova et al. 2007, 2008

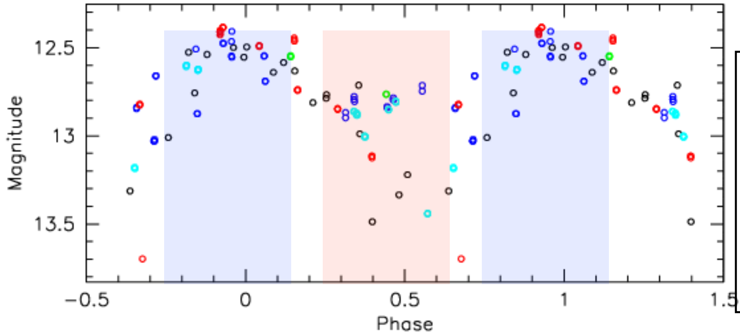
Alencar et al. 2012

statistical relations: Cauley et al. 2012

A dynamic star-disk interaction

- Inner disc warp resulting from inclined magnetosphere

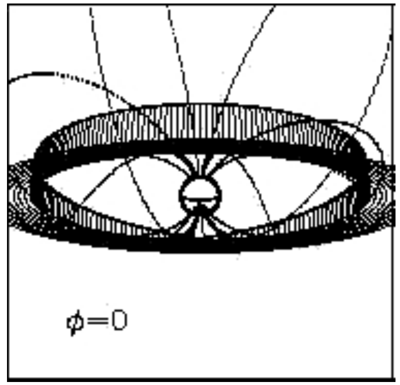
AA Tau   Bouvier et al. 2003,2007



Periodic eclipses

(disk warp)

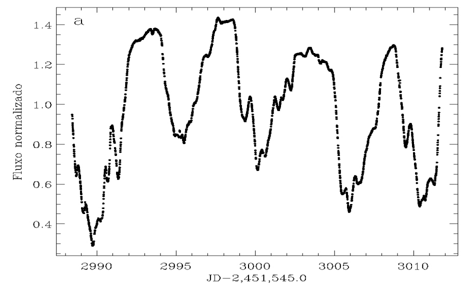
(P=8.22d)

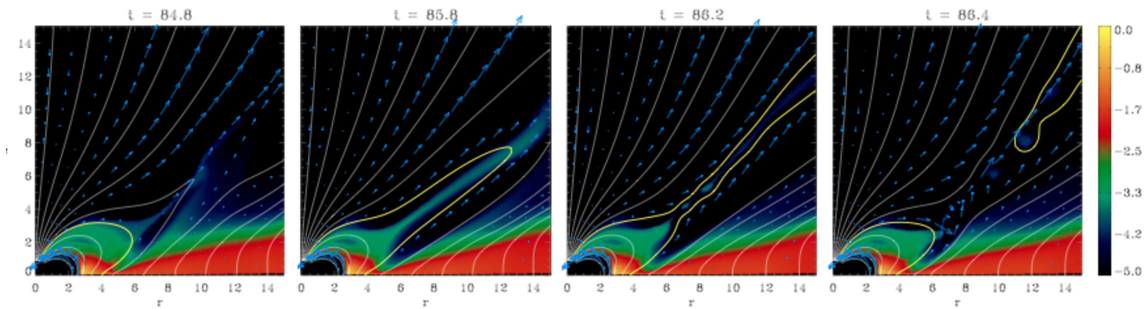


- CoRoT studies of NGC2264   Alencar et al. 2010, Cody et al. 2014, Stauffer et al. 2014

30 % AA Tau lightcurves / 20 % bursters

Different accretion regimes ?





- Cyclic inflation/reconnection with Magnetospheric Ejections
  Zanni & Ferreira 2013

Magnetic ejection processes

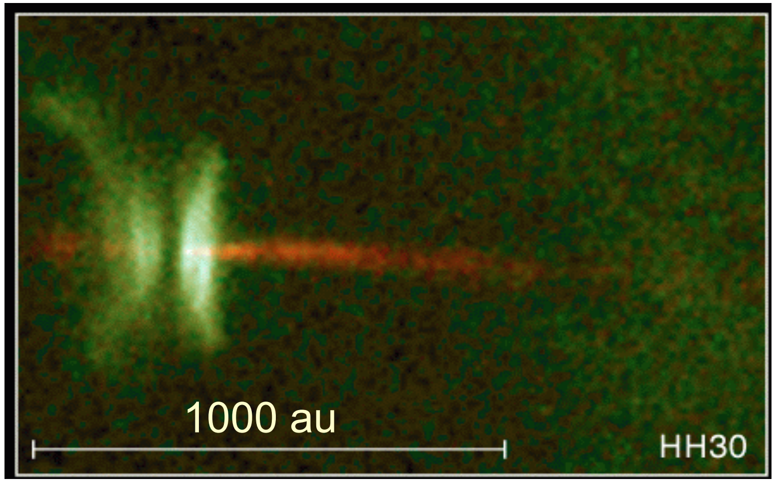
- Collimation scale z= 30-50 UA

  r < 5 AU Ray, Dougados et al. PPV
- Supersonic ejection velocities:

  $V_{jet} \approx$ 200-400 km/s   ($V_{esc,*} \approx$ 100 km/s)

  Mach number= $V_{jet}/C_s \approx 30$
- High efficiencies:

  $\mathbf{(dM/dt)_{jet} \approx 0.1\ (dM/dt)_{acc}}$

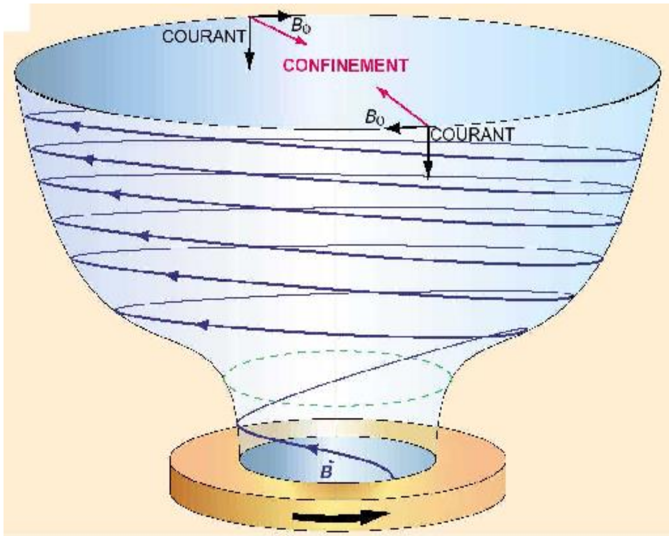


Magneto-centrifugal ejection process

$J_z \times B_\varphi$: self-collimation

Blanford & Payne 1982

see Cabrit et al. 2007 (JETSET I school proceedings)



Different flow components ?

Accretion Powered Stellar Winds

- $T=10^5$-10^6 K V > 500 km/s ?
- Mass flux ?
- Stellar braking ?

Matt & Pudritz 2005

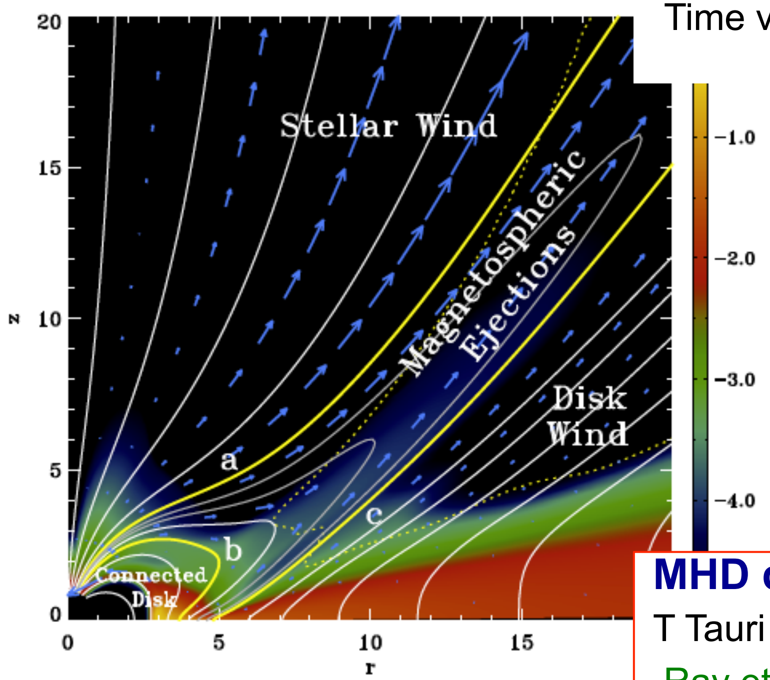
Magnetospheric Ejections (ME)

Conical Winds Romanova et al. 2009

Zanni & Ferreira 2013

Low collimation and velocities

Time variability, stellar braking ?



Zanni & Ferreira 2013

MHD disk winds (DW) 0.1- a few AUs

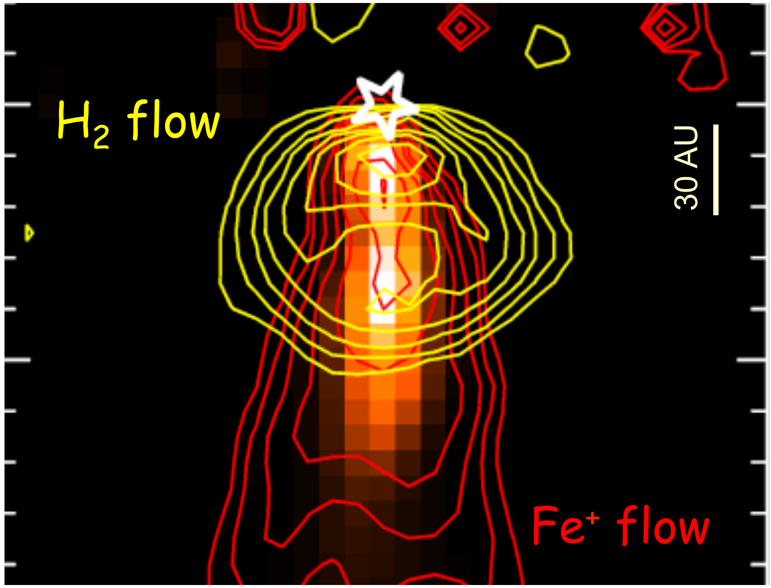
T Tauri Atomic Jets V=30-300 km/s

Ray et al, 2007 PPV

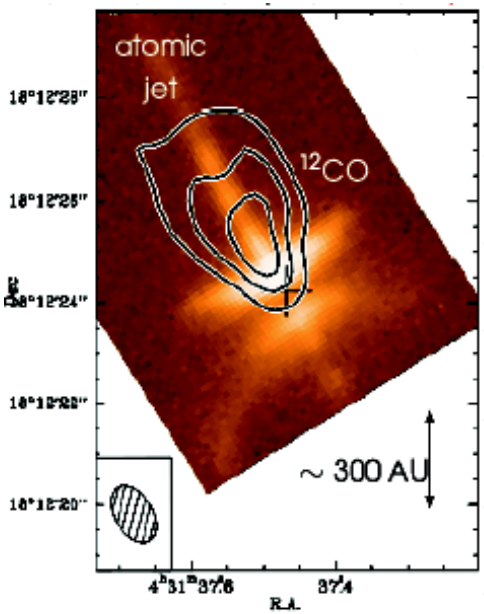
Strong impact on disk magnetisation

See Ferreira, Dougados, Cabrit 2006

Small scale molecular flows ?



DG Tau Agra-Amboage, Cabrit, Dougados 2014



HH 30 Pety et al. 2006

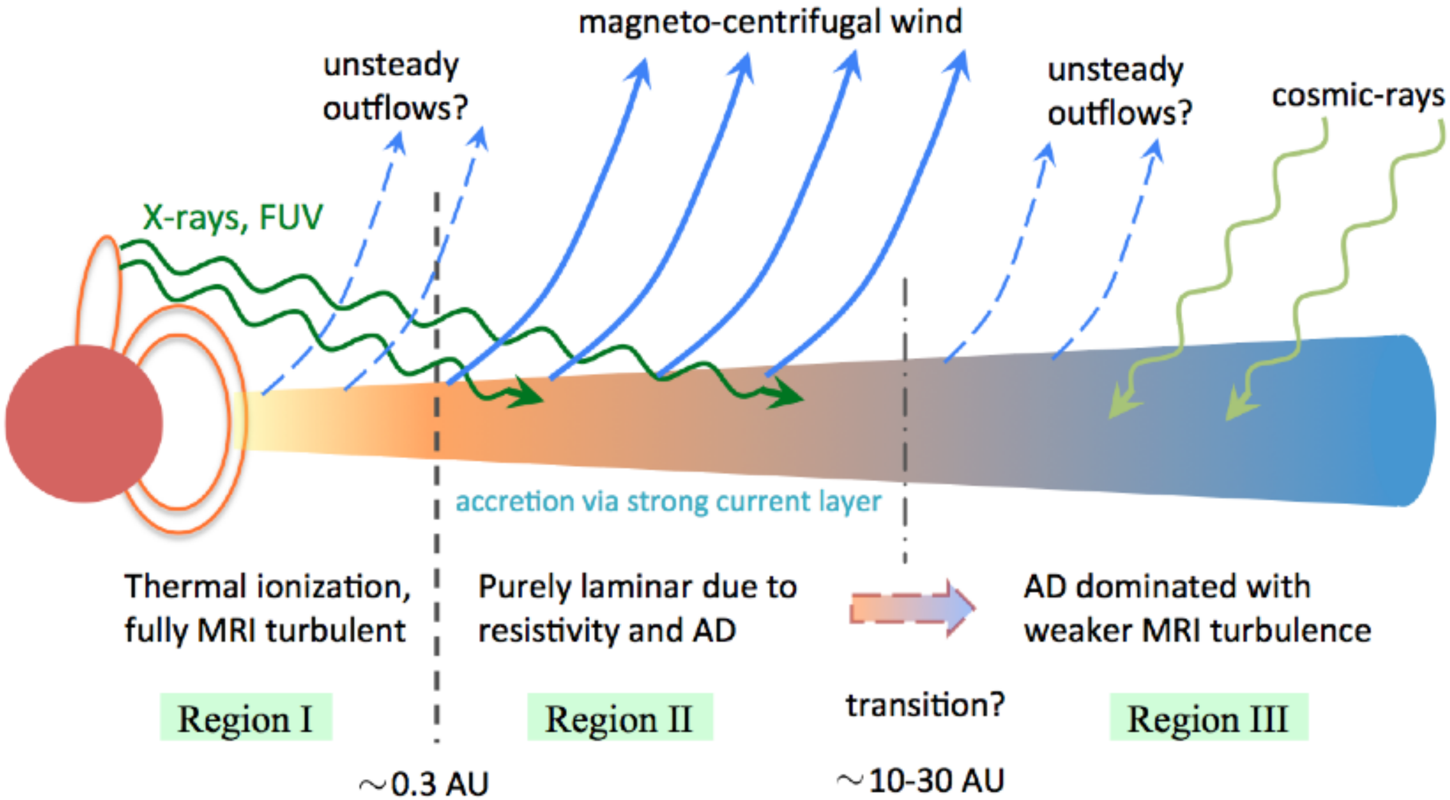
Slowly expanding (V < 20 km/s) CO (mm) , H_2 (NIR) wide-angle winds surrounding atomic jet:

- **Outer streamlines of MHD disc wind** r_0=10 AU Panoglou et al 2011
- OR **photo-evaporated wind** (FUV+X-ray irradiated disc surface)

Crucial tests to be performed with ALMA

non-ideal MHD simulations of proto-planetary discs

Magneto-centrifugal wind can play a major role in angular momentum transport from r= 0.3-5-10 AU Bai et al. 2013, Bai & Stone 2011 see also Fromang et al. 2013, Lesur & Ferreira 2013



II - Accretion diagnostics in Herbig stars

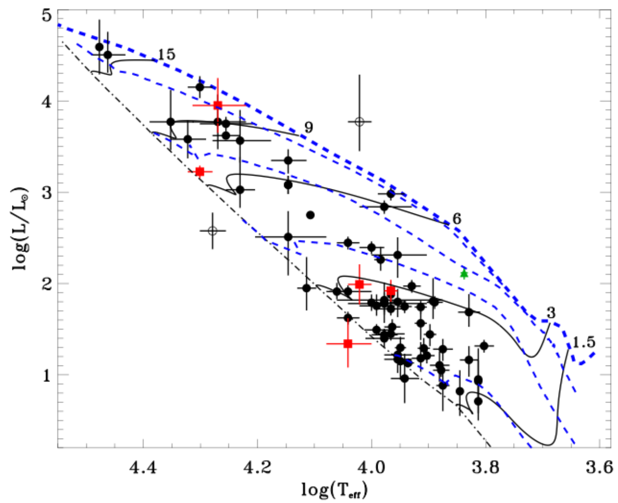
Magnetic Field in Herbig Stars ?

- **< 10 % of Herbig Ae/Be** stars with strong large scale and stable magnetic fields

Alecian et al. 2013, Hubrig et al. 2009,2013

similar to MS Ap/Bp stars Fossil field ?

≈ 1kG dipolar field required to allow accretion at 10^{-8} Msun/yr Bessolaz et al. (2008)



Alecian et al 2013

- Chromospheres and hot stellar winds:

Bouret & Catala (2000), Martin-Zaidi et al. (2004)

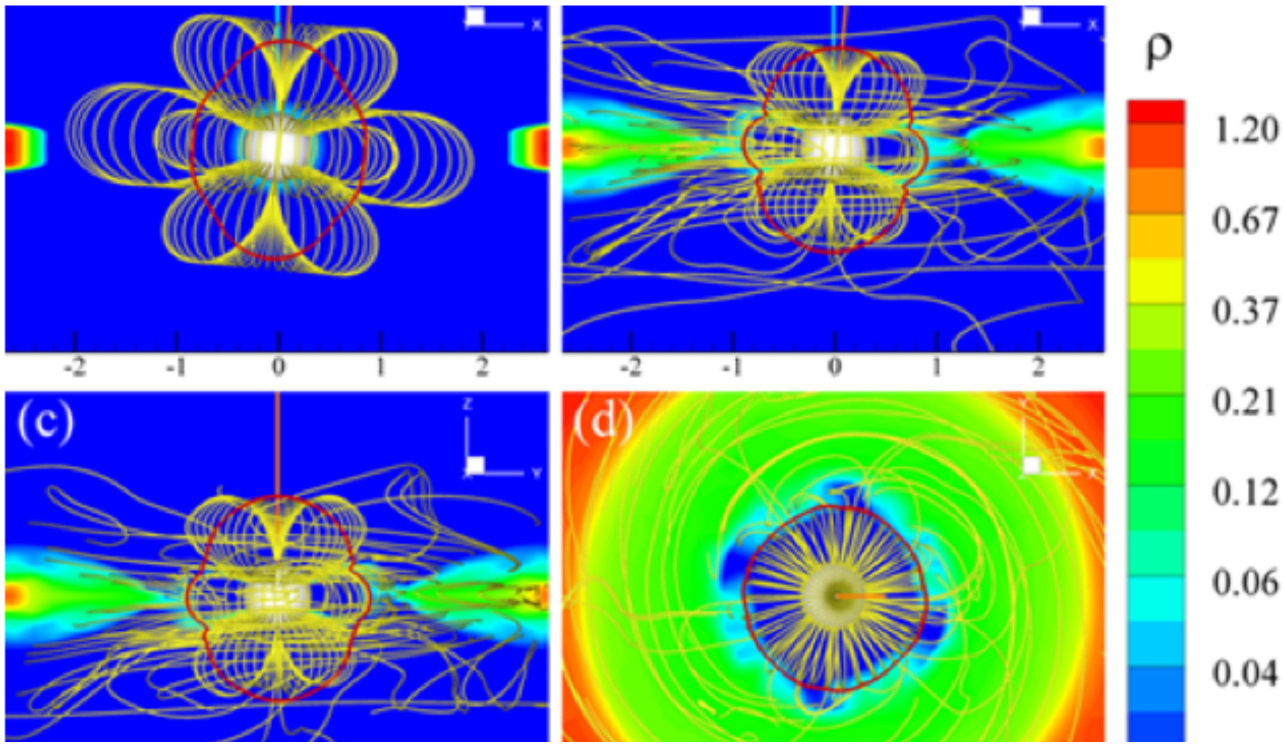
- Strong ubiquitous X-ray emission:
  - Late-type Companions ?

    Stelzer et al. 2006
  - MWC 480: $N_{H,X} >> N_{H,V}$ accretion column

    Grady et al. 2010

-> **Complex B (multipolar) ?**

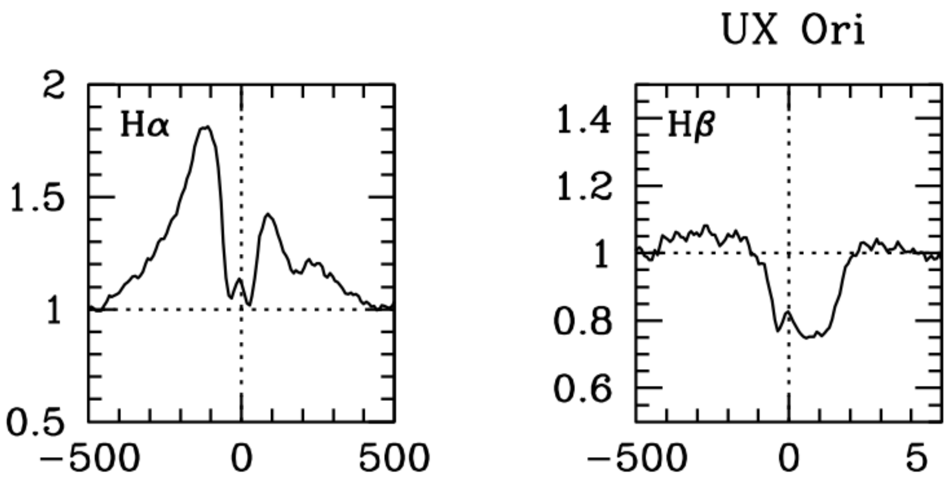
Magnetospheric accretion on complex fields ?



Long, Romanova et al. 2012

But will not sustain high accretion rates ? cf Mohanty & Shu 2008

Accretion signatures

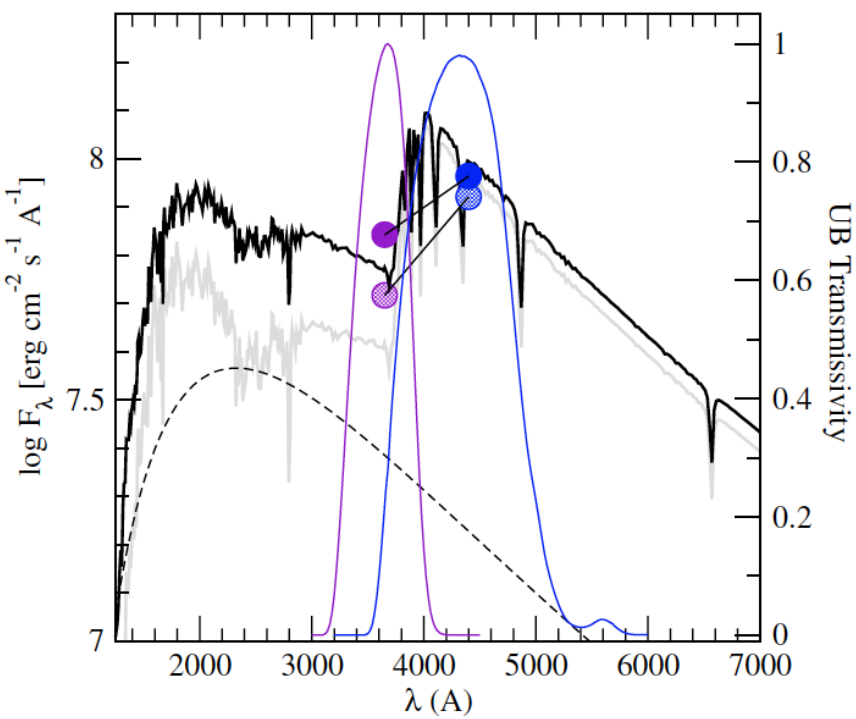


- Ballistic Infall signatures in permitted emission lines
  HI NaD CaII (+UV)

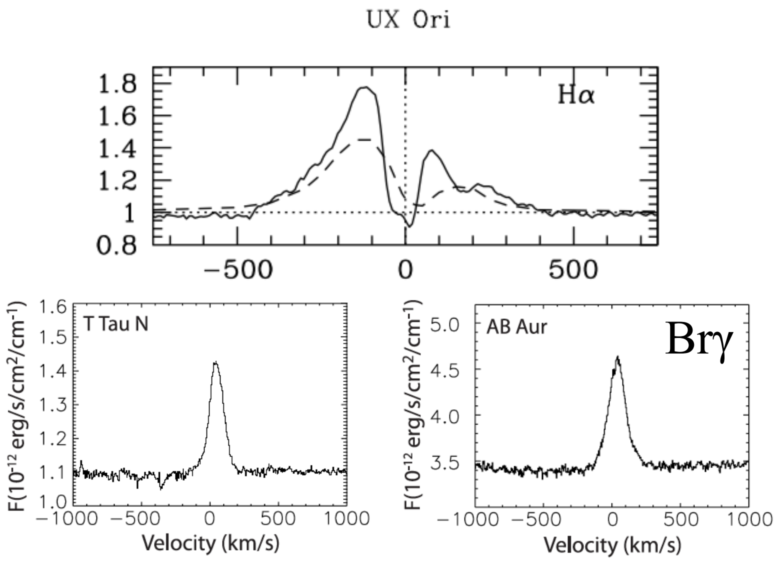
Sorelli et al. 1996, Natta et al. 2000, Deleuil et al. 2004, Muzerolle et al. 2004

- Balmer jump excesses well fitted by MA shock models

Muzerolle et al 2004, Mendigutia et al. 2011, 2013



HI lines as accretion tracers ?

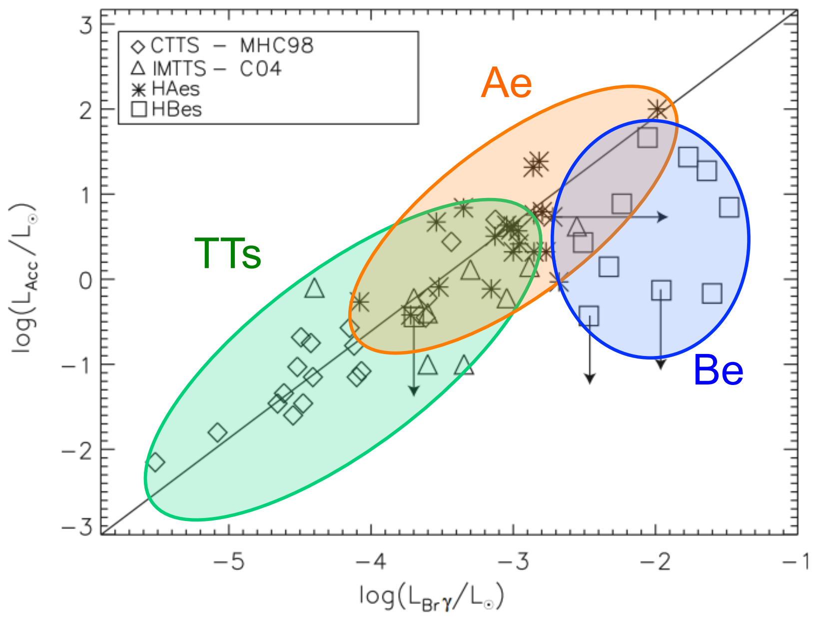


- MA accretion models reproduce HI line profiles
  - Muzerolle et al. 2004 (UX Ori)
  - centrally peaked HI Brγ profiles 50 % in Brittain et al. 2007

- HI Brγ - Macc correlation

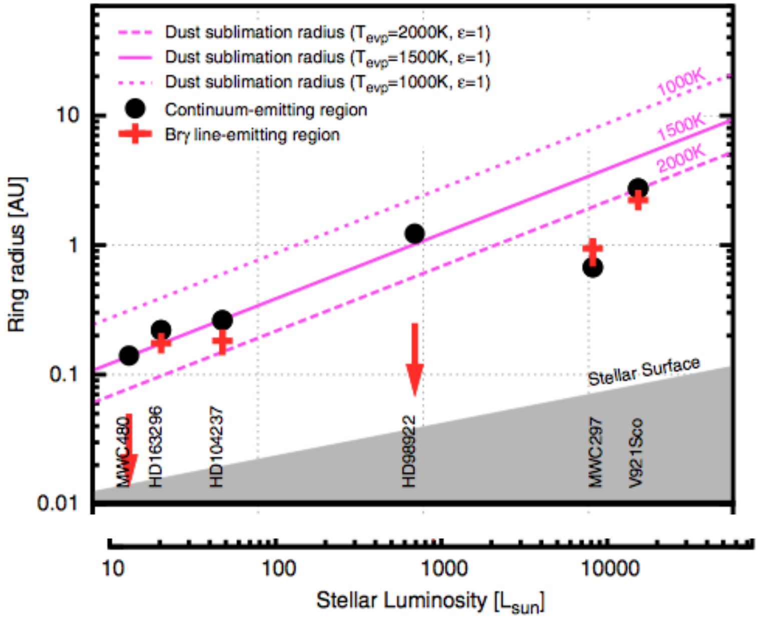
van den Acker 2005, Garcia-Lopez et al. 2006 Donehew & Brittain 2011

Break at A0/B9 SpT ?



The formation of HI lines

- Hα linear spectro-polarimetric and variability studies Vink et al. 2002, 2005 Costigan et al. 2014



- Hα/Brγ Optical Interferometric
  - Kraus et al. (2008): R > 0.1 AU
  - Eisner et al. (2010) smaller Brγ sizes derived (x 10)
  - Inner rotating disk in MWC 1080
    Eisner et al. 2010 MWC 1080
    Kraus et al. 2012 V921 Scorpii
  - Bipolar jet/disk winds
    ZCMA-Be Benisty et al. 2010
    MWC 297 (B0V): Malbet et al 2007, Weigelt et al. 2011
    AB Aur (A0V) Rousselet et al. 2010

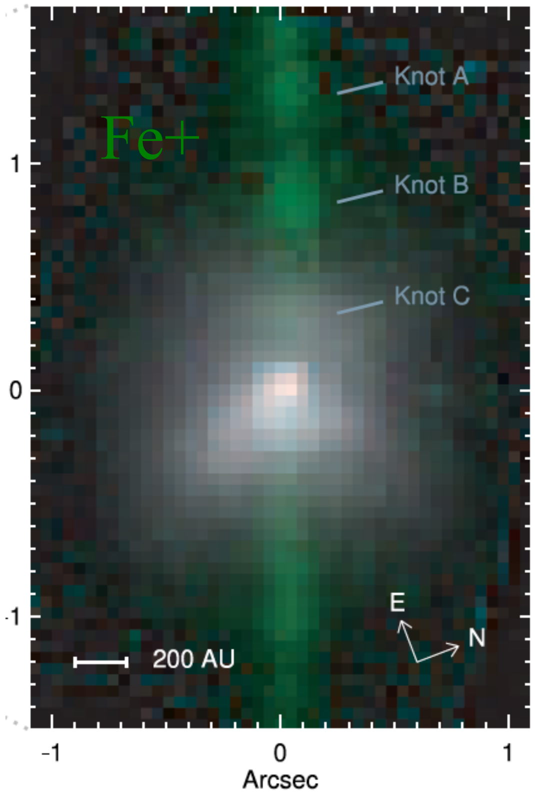
- Spectro-astrometry with AO: Ramirez et al. in prep HD100546 (B9) not compatible with disc emission but infall/outflow
  rms=0.01mas also VV Ser (cf Sean brittain presentation)

III – Winds/Jets in Herbig stars

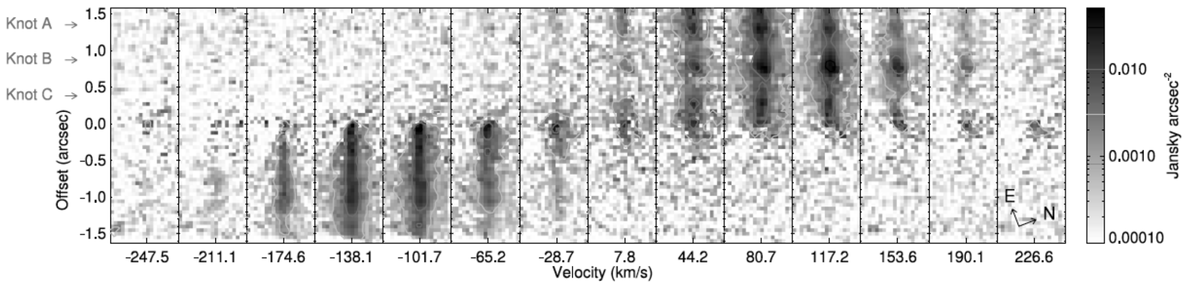
Jets in Herbig Stars: atomic lines

- Spectroscopic evidence for atomic jets rarer than in T Tauri stars:
< 10 % with [O I] 6300 Angs emission at |V| > 55 km/s (≈ > 50% in cTTS)
Catala & Bohm 1994, Corcoran & Ray 1997,1998 Observational Bias ?

- Jets clearly detected around ≈ 10 Herbig stars and sometimes out to pc scales
Mc Groarty et al. 2004



Similar collimation as TTs Jets

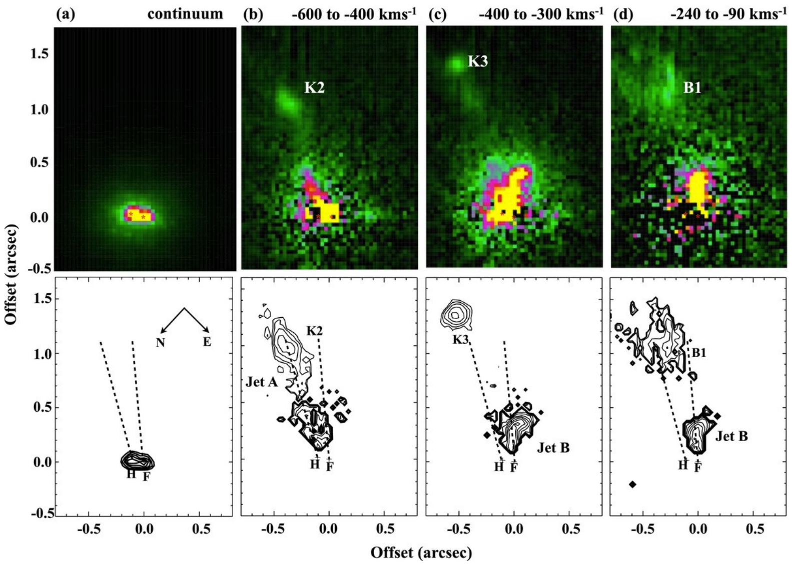


LkHa 233 (A5) Perrin et al. (2007) see also Corcoran & Ray 1998 Melnikov et al. 2008

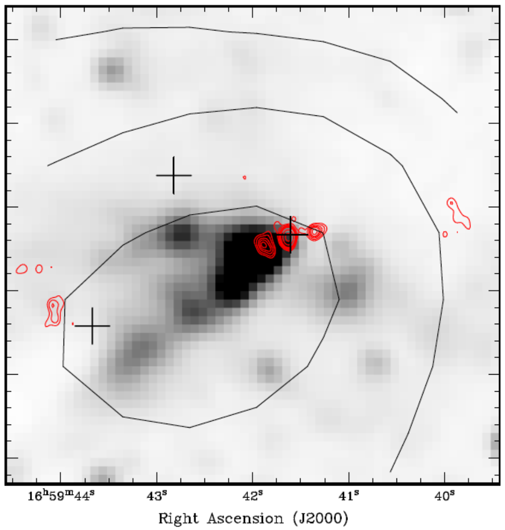
Massive stars also drive collimated jets

Bipolar outflows/Jets observed in:

- B stars e.g. Ray et al. 1990 Whelan et al. 2010
- Intermediate mass YSOs e.g. Ellerbroek et al. 2013, Reiter & Smith 2013
- Massive (> 10 $M_{\odot}$) YSOs up to L = a few 10^4-10^5 $L_{\odot}$ (20 $M_{\odot}$ ZAMS) e.g. Kraus et al. 2010 Cesaroni et al. 2007 Guzman et al. 2010, 2012



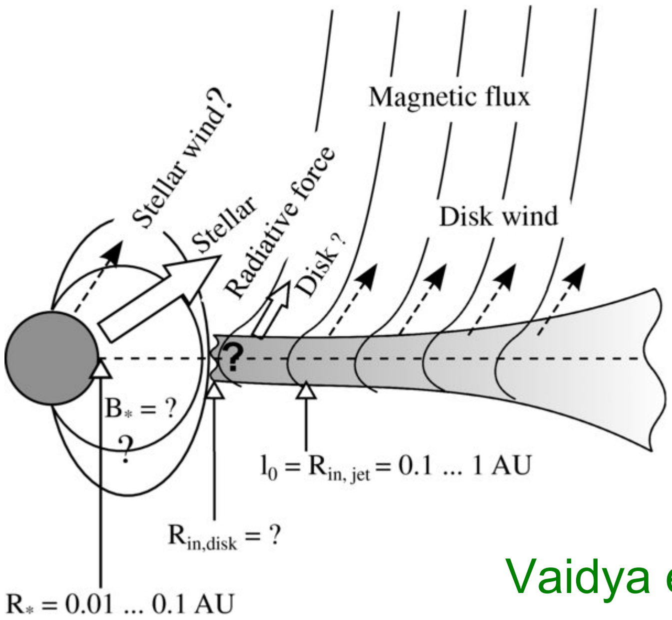
ZCMA-Be Whelan et al. 2010
Fe+ emission maps

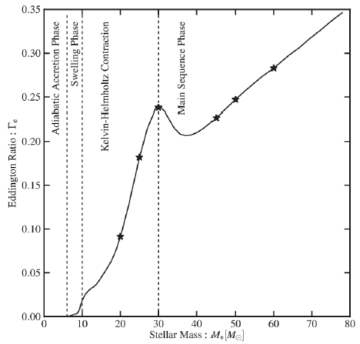


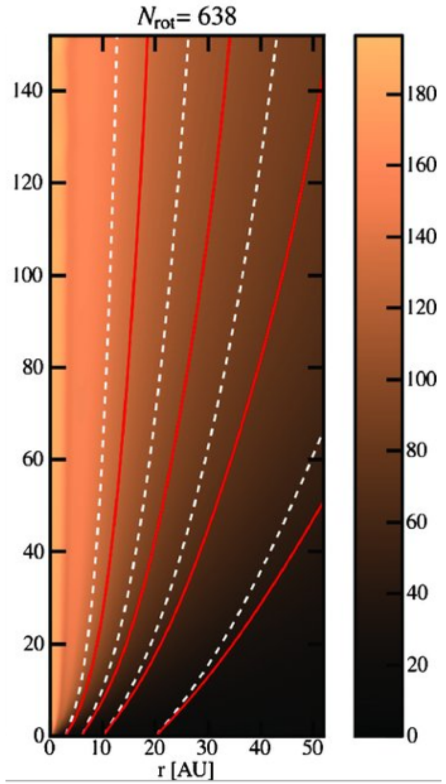
Guzman et al. 2010 7x10^4 $L_{\odot}$
Background: 8 μm SPITZER
Red contours: 8.6 GHz emission

Effect of radiation pressure on Jets

- Disk gravitationnally stable around massive stars (20-60 $M_\odot$) Vaidya et al. 2009
- Radiation pressure expected to decollimate flow for $M > 30\ M_\odot$

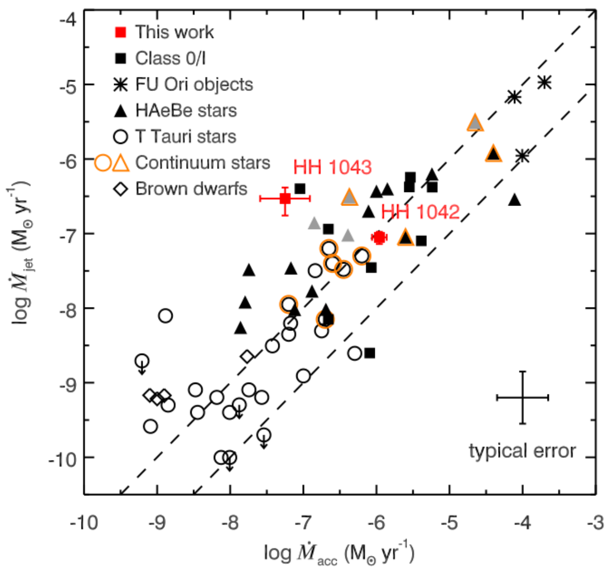




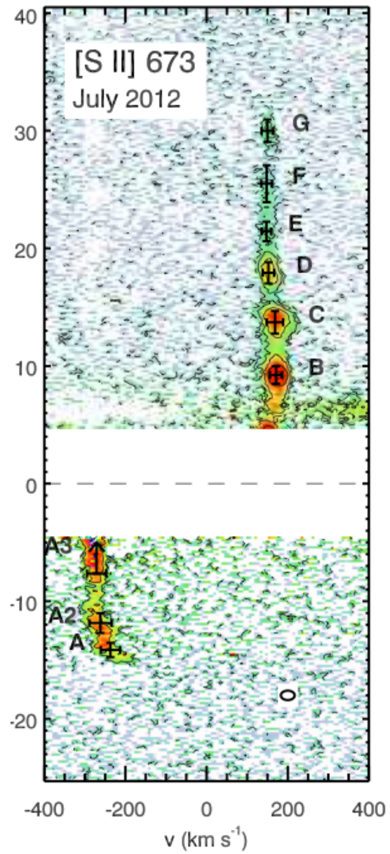


Vaidya et al. 2011

Properties very similar to T Tauri Jets



- **dMjet/dt ≈ 0.1 dMac/dt**
  Ellerbroek et al. 2013



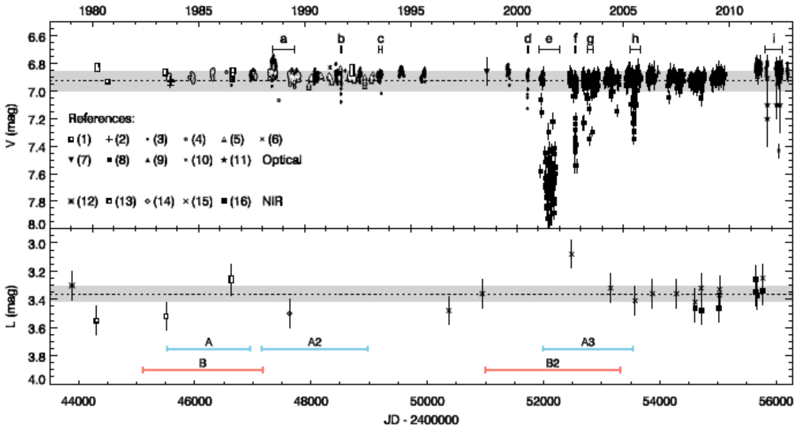
HD163296

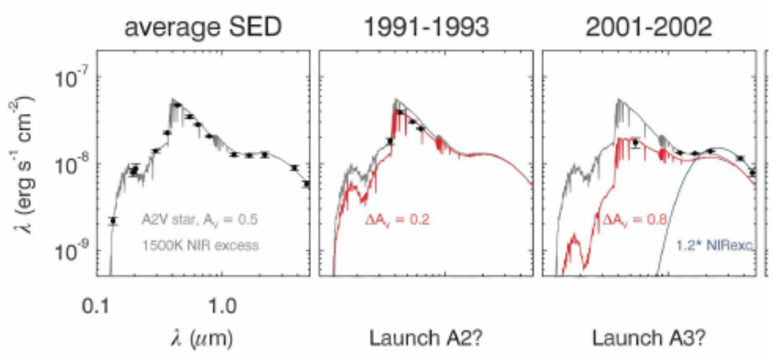
Ellerbroek et al. 2014

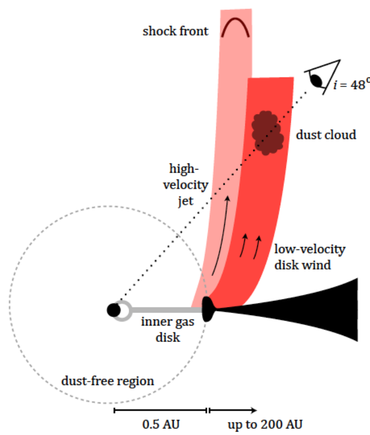
- Variable ejection   Δt ≈ 16 yrs
- Red/Blue asymetries BUT synchronized ejection and similar mass-flux.
- X-ray emission Gunther & Schmitt 2009 soft emission

Similar mechanism likely at work !

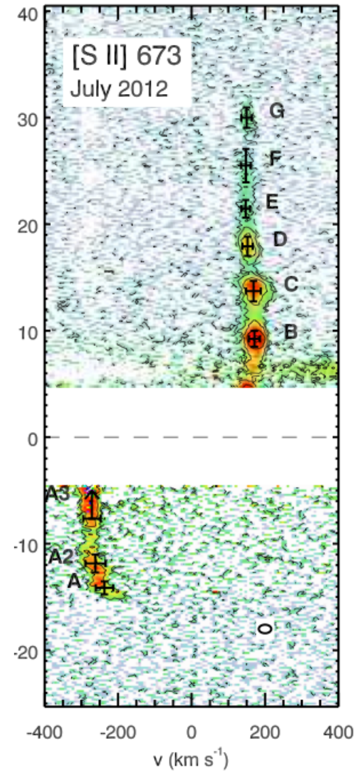
The jet from HD 163296





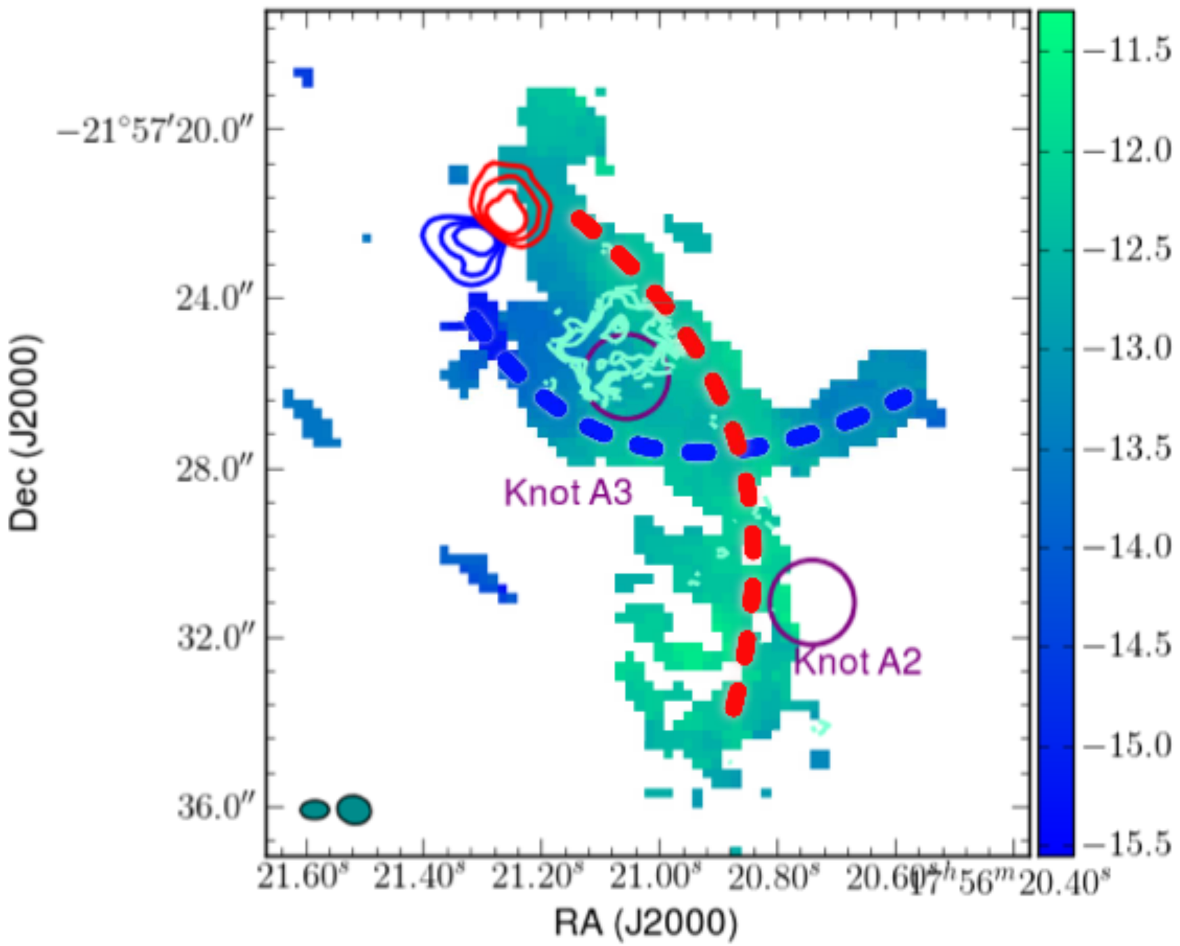


Ellerbroek et al. 2014



- Jet launch accompanied by dust occultation events and NIR flares akin to EX Ori events ? cf PV Ceph Caratti o Garatti 2013
- Bans & Konigl (2012) :
- No B* detected → **Origin in disk wind ?**

Molecular Disk wind in HD 163296 ?



Klaassen et al. 2013

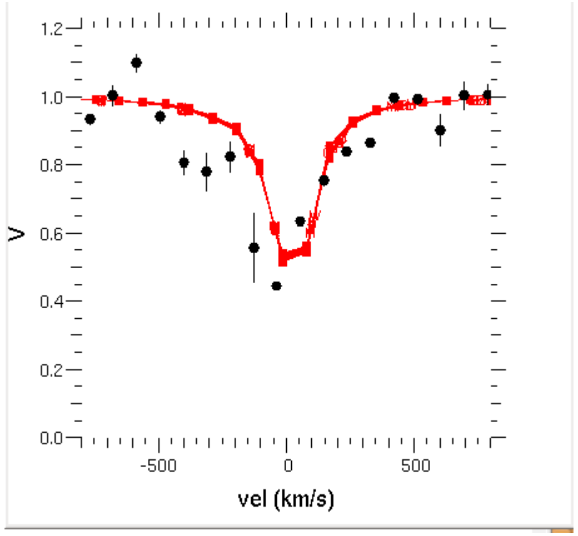
The origin of HI line in AB Aur

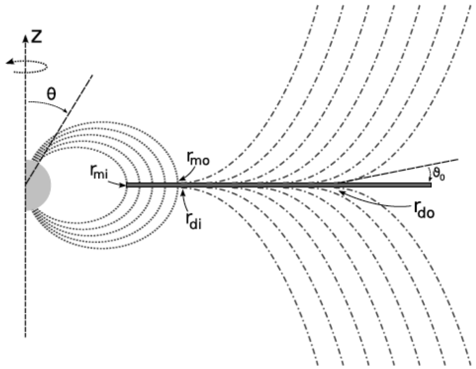
For Macc > 10^{-7} $M_{\odot}$/yr Disc Wind (DW) can contribute significantly to HI profiles Lima et al. 2010, Alencar et al. 2005

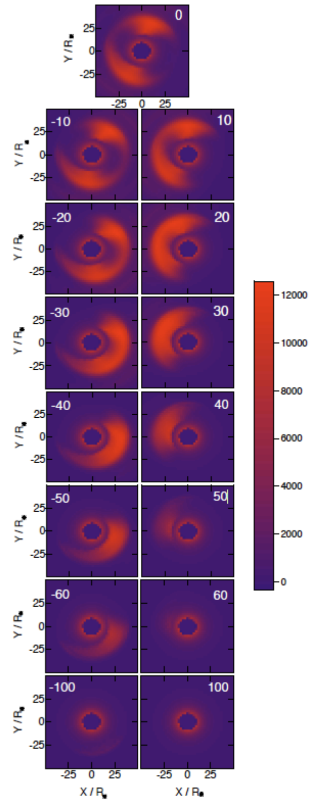
VEGA/CHARA observations in AB Aur (A0V)

Hα more extended than continuum, size ≈ 0.05-0.15 AU > Rcor

MA+ MHD Disc wind model 5-10 $R_{\star}$



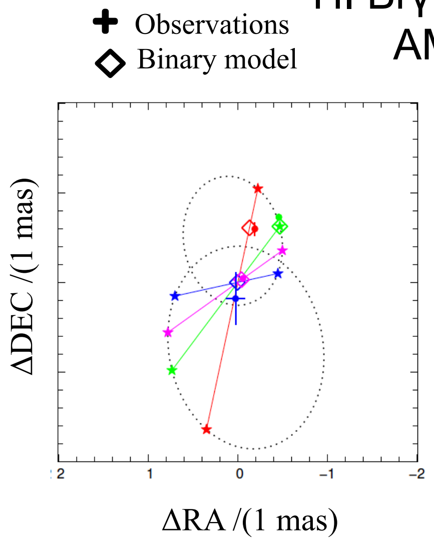


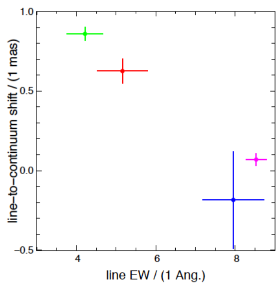


Rousselet-Peraut K. et al 2010,
Lima, Rousselet, Dougados et al. in prep

Tidally disrupted accretion/ejection in HD 104237

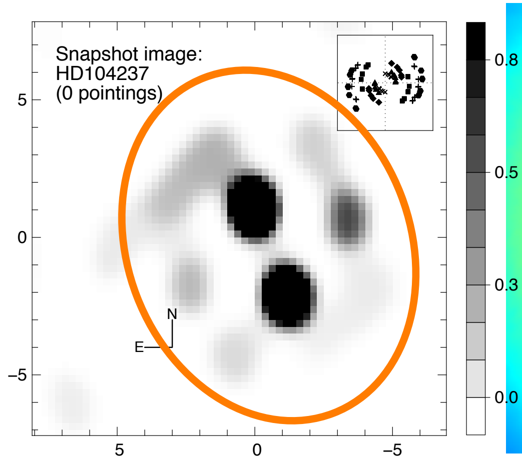
HI Brγ Spectro-astrometry
AMBER/VLTI



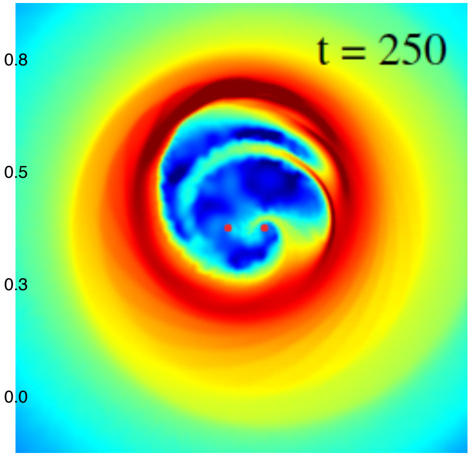


Garcia, Benisty, Dougados et al. 2013

PIONIER/VLTI
H band



Hydro-dynamical modelling



Garcia et al. in prep, Dunhill et al. in prep

Close eccentric system: a=0.22 AU e=0.64

- Compact Brγ and enhanced accretion on both components at periastron
- System driving **large scale jet** Grady et al. 2004

- This situation may not be uncommon: spectroscopic binary fraction of 35% in Herbig stars Corporon et al. 1999, See G. Duchene talk
- Frequent Wiggling in jets: dynamical cf Reipurth et al. 2013 (V 380 Ori)

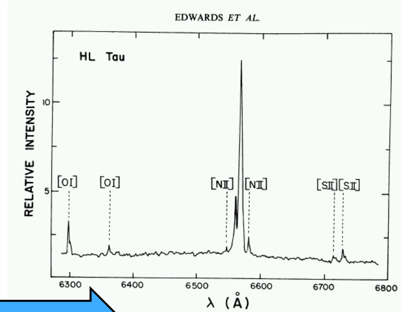
Summary

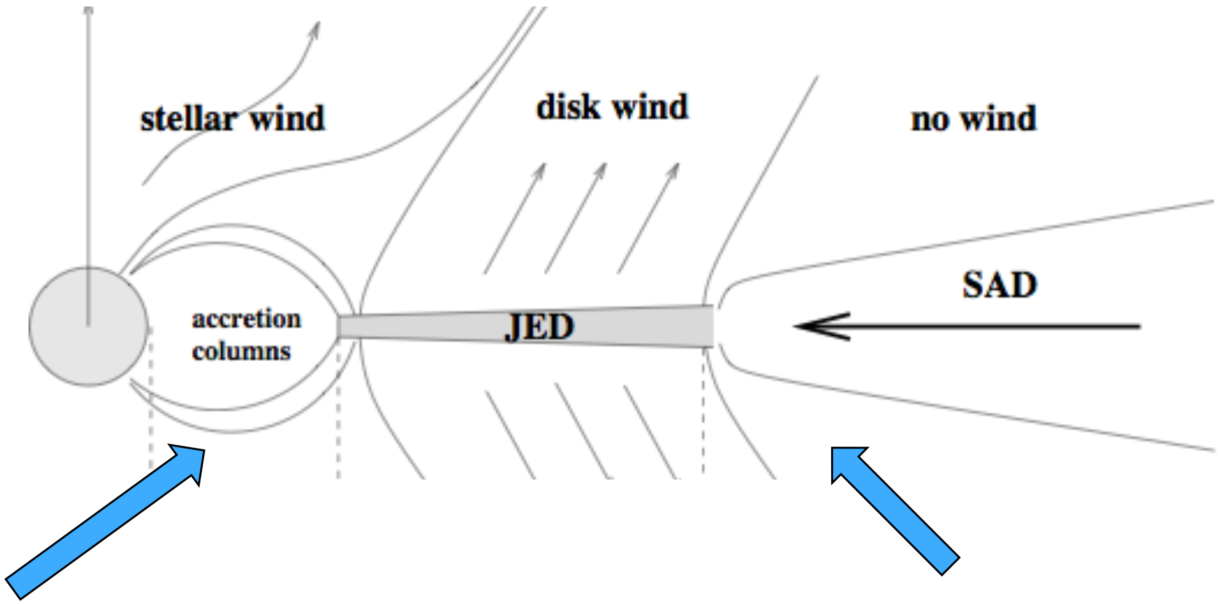
- T Tauri stars:
  - strong observational/theoretical support for magnetospheric accretion
  - Atomic jets launched from inner AU regions: MHD disc winds most promising scenario
- Accretion processes in Herbig stars, Puzzle 1
  - MA scenario reproduces Balmer jump excess + HI line profiles (≈ 50%)
  - BUT not strong Bstar detected in 90 % Herbig stars !
  - Indication of a transition of accretion regime at A0/B9 SpT but no clear compelling evidence of direct disk accretion so far
- Jets from Herbig stars, Puzzle 2
  - more rare than T Tauri case (observational bias)
  - very similar properties to TTs jets: **similar ejection mechanism up to 20 Msun ?**
  - influence of Bstar, close companion ?
- Next:
  - Statistical studies of jet signatures vs stellar/disk properties
  - Linking all scales on a few sources

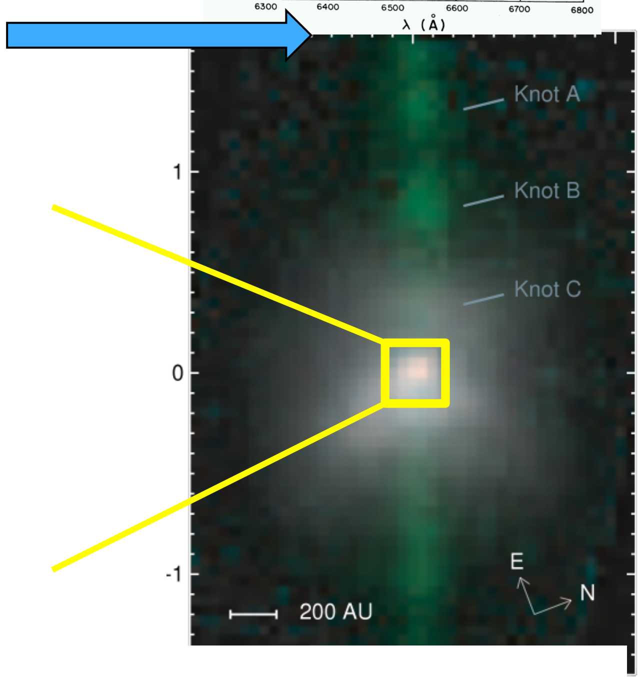
Towards a global picture

1- **Collimation regions of Jets** (z= 10-1000 AU)

Opt-NIR-mm spectro-imaging SINFONI/VLT MUSE/VLT ALMA







3- **B$_\star$ and the accretion flow** (1-10 $R_\star$)

spectro-polarimetry HarpsPol ESPADONS

Monitoring studies

2- **Inner (sub-AU) regions** (0.1-1 AU)

Opt/NIR interferometry, spectro-astrometry

GRAVITY, AMBER, PIONIER

Many Thanks to

R. Ramirez, S. Casassus, D. Mardones, G. Garay (Dept. astronomia Universidad de Chile) A. Dunhill, J. Cuadra (PUC Santiago) A. Hales (Alma-Santiago)

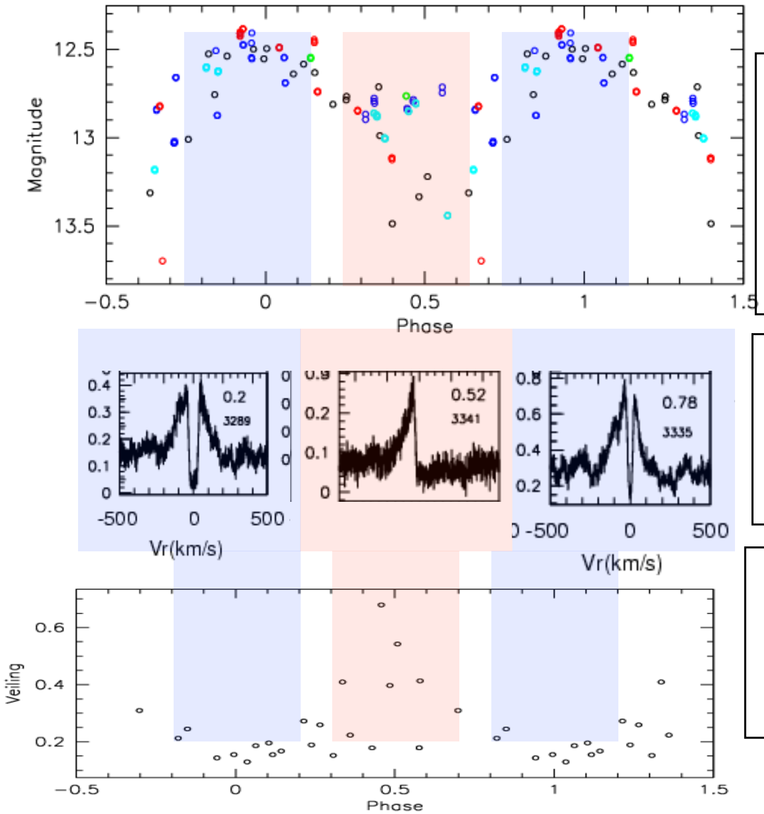
P. Garcia, V. Agra-Amboage (Porto)   E.Whelan (Tubingen) S. Brittain, C. Adams (Clemson Univ. USA) S. Alencar, G. Lima (Belo Horizonte Brasil) M. Bonnefoy (MPIA-Heidelberg) L. Ellerbroek (Amsterdam)

S. Cabrit (LERMA/Obs. Paris)   J. Ferreira, J. Bouvier , M. Benisty, K. Rousselet-Perraut, J. Bouvier (IPAG)   J.F. Donati (OMP)

A dynamic star-disk interaction

Inner disc warp resulting from inclined magnetosphere

AA Tau Bouvier et al. 2003,2007



Periodic eclipses

(disk warp)

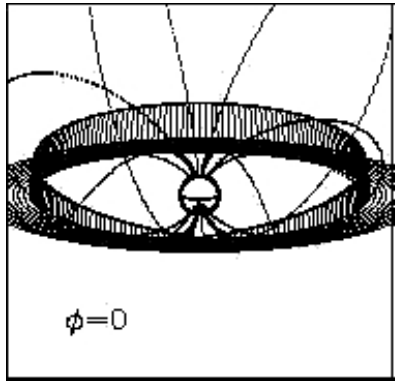
(P=8.22d)

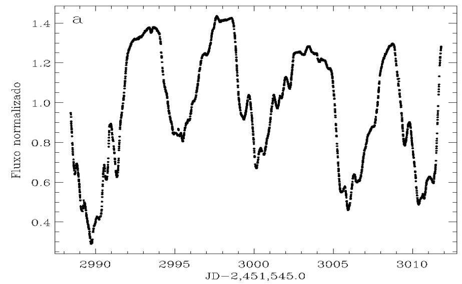
Balmer lines

(accretion funnel)

Veiling

(accretion shock)



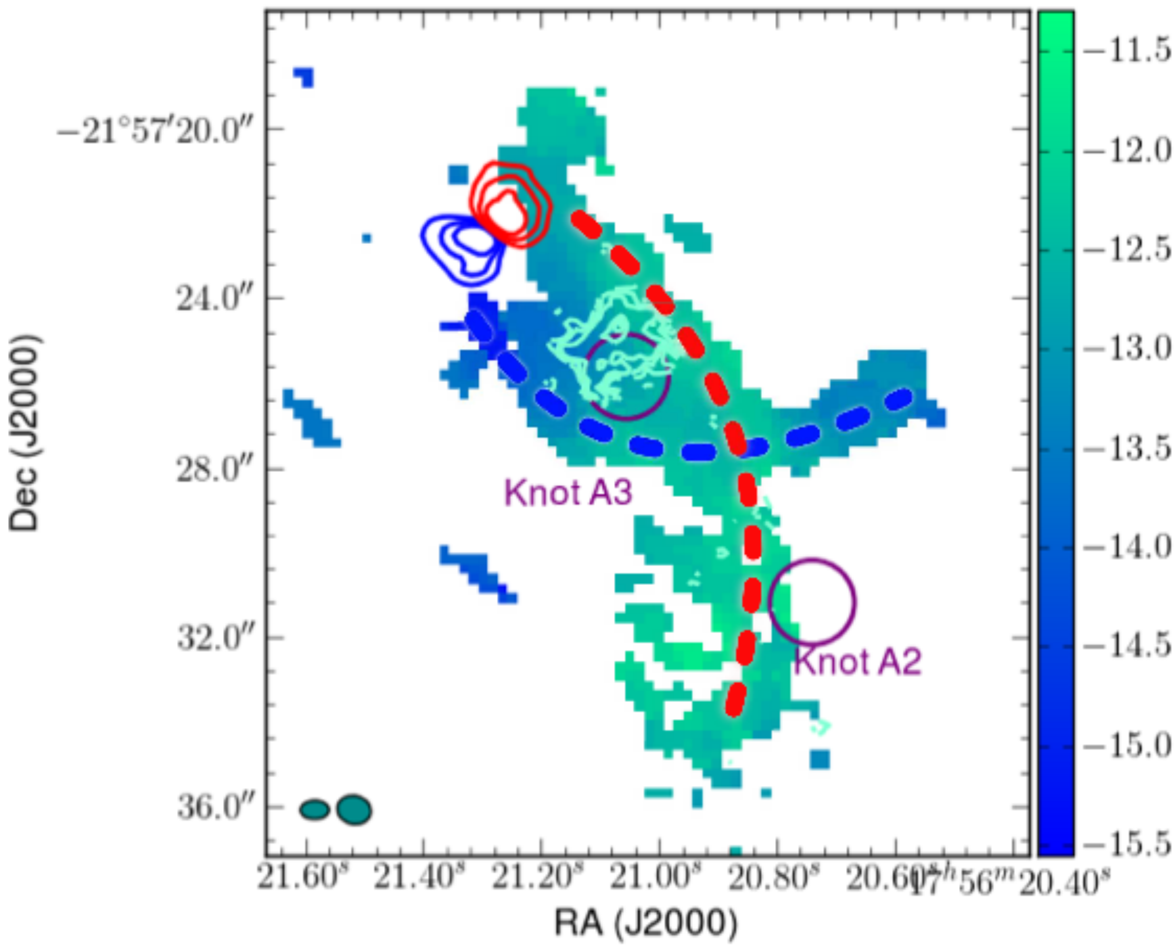


CoRoT studies of NGC2264

Alencar et al. 2010, Fonseca et al. 2014

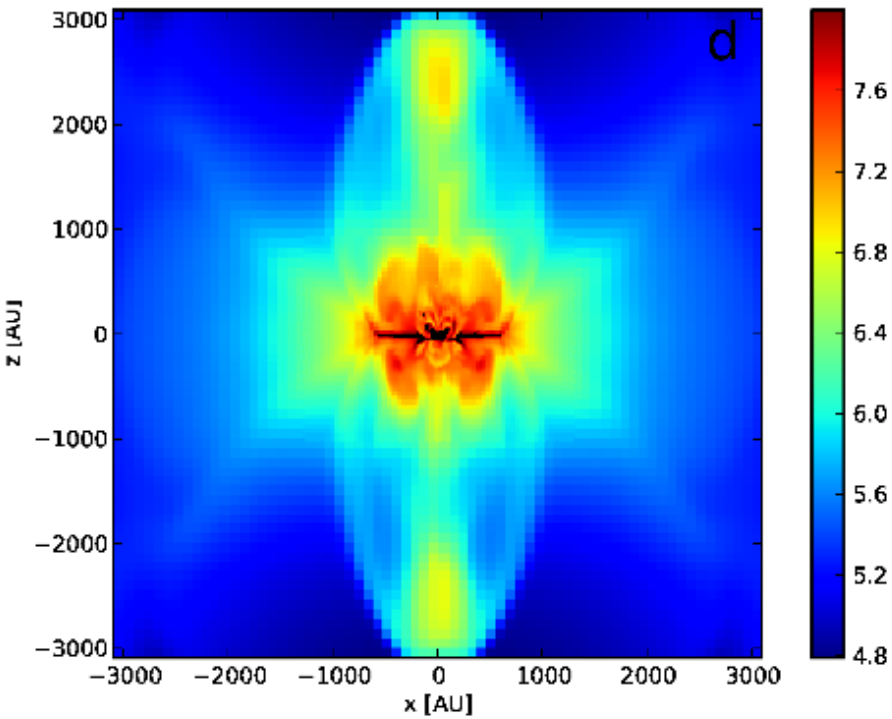
30 % AA Tau lightcurves

Molecular Disk wind in HD 163296 ?

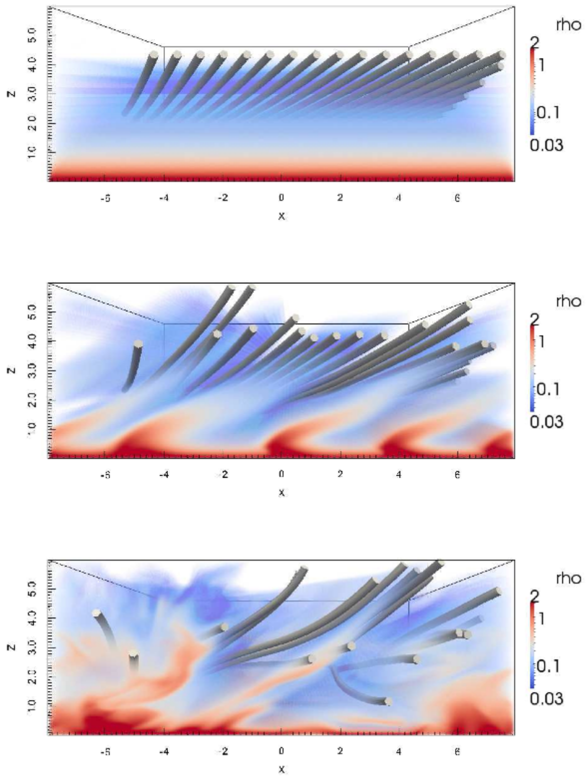


MHD Disk winds: A natural outcome of star formation ?

- Expectations from both numerical simulations of collapse and of MRI in disks (→ disk wind)
- MHD DW can play a major role in angular momentum transport from r=0.3-5-10 AU Bai et al. 2013



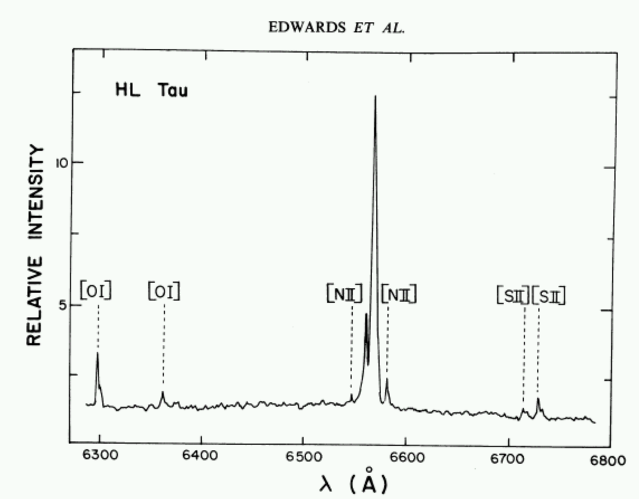
Ciardi & Hennebelle 2010



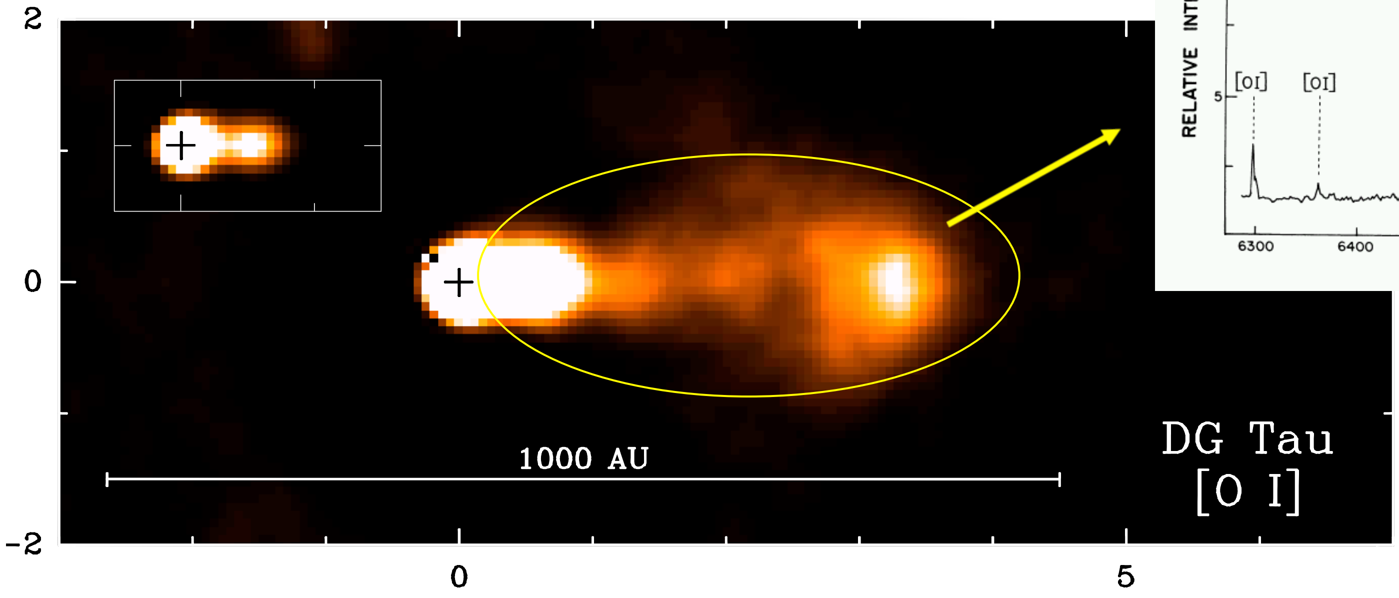
Lesur & Ferreira 2013

Microjets from T Tauri stars

Optical spectrum



Dougados et al. 2000   PUEO at CFHT



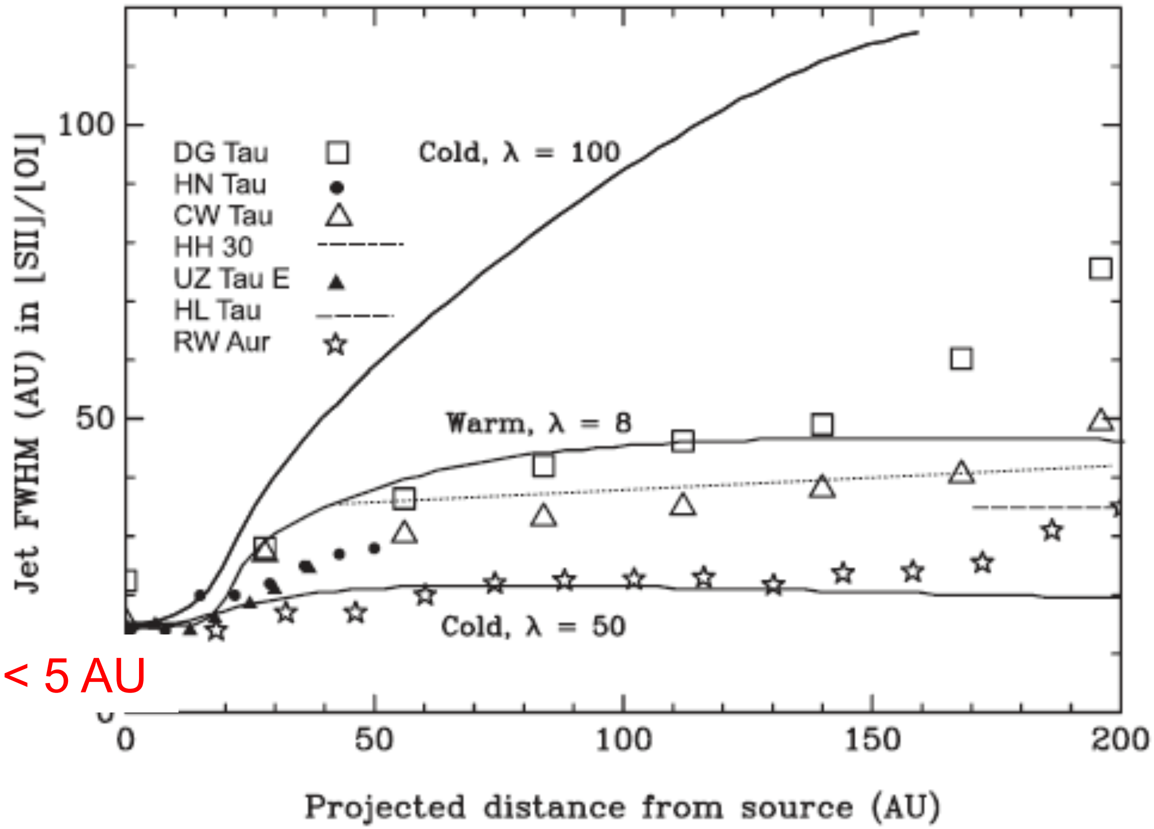
« Old » Young stars: ages a few Myrs, $M_\star$=0.5-2 $M_\odot$

→ Detailed studies of the collimation regions of jets (z=10-1000 AU)

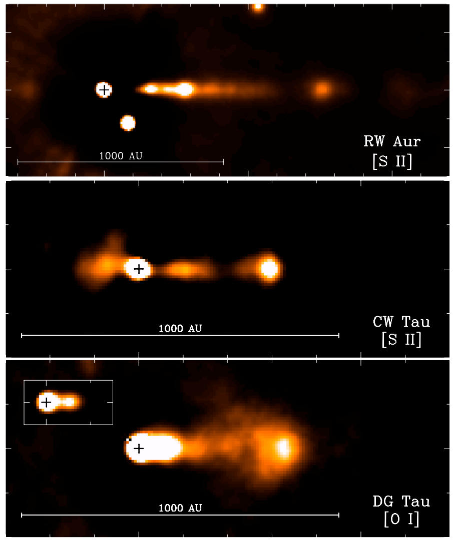
Properties best compatible with Disk wind models (Ferreira, Dougados, Cabrit 2006)

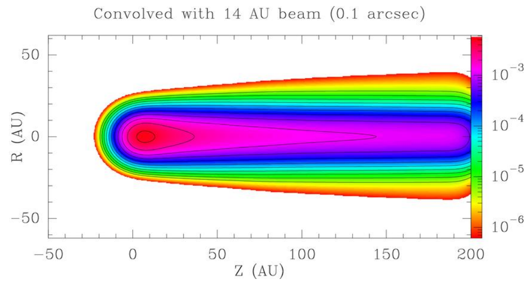
Collimation properties of T Tauri Jets

Jet radius: Observations (Symbols) vs disk wind models (full lines)



$R_0 < 5$ AU





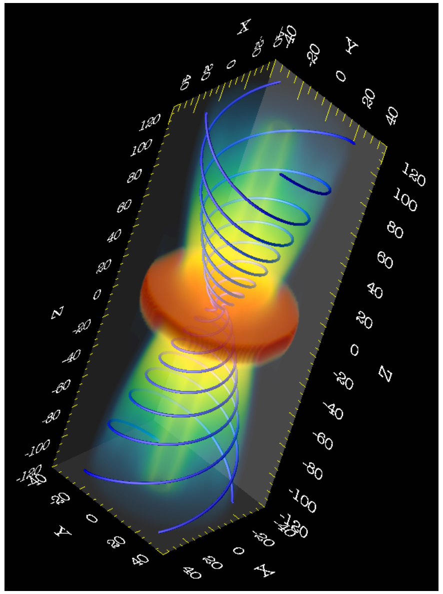
✓ $R_0 < 5$ AU Collimation scale 30-50 AU Ray, Dougados et al. 2007 PPV

✓ does not depend on evolutionary status Cabrit et al. 2007

✓ Compatible with expectations from MHD disk winds

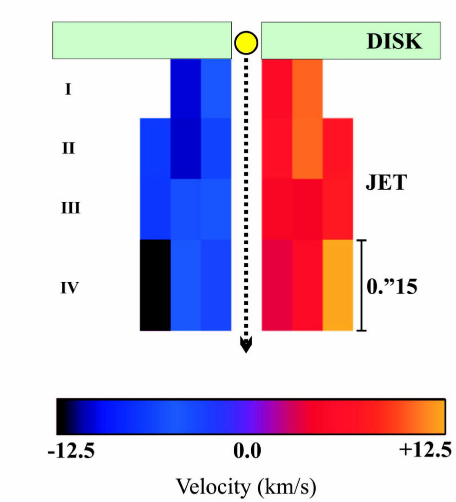
Magnetic disc winds

MODELS



OBSERVATIONS

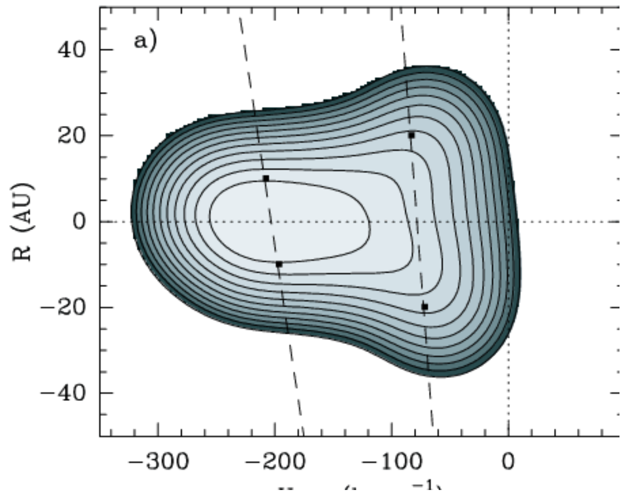
Bacciotti et al. (2002)



HST/STIS

Disc wind model predictions

Pesenti et al 2004

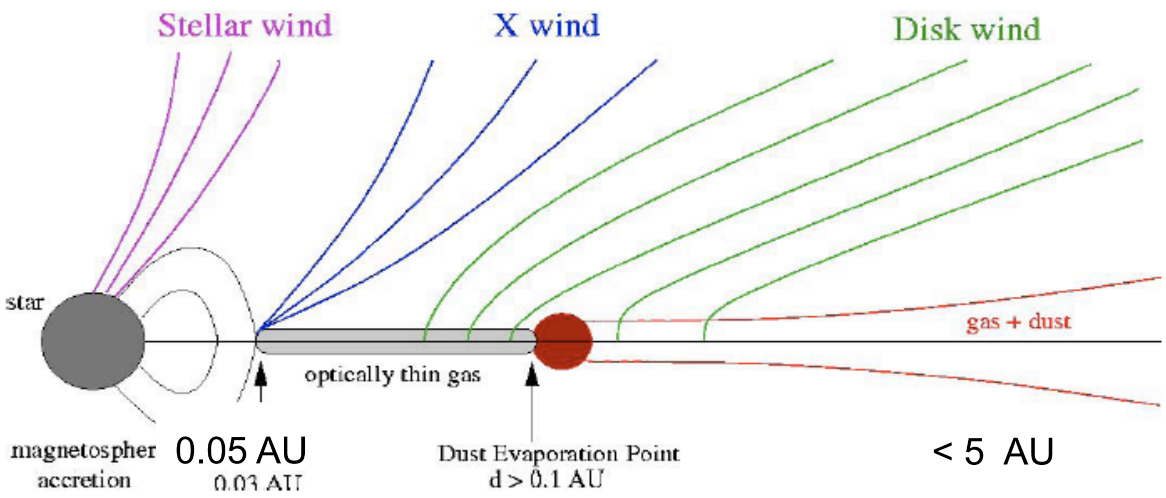


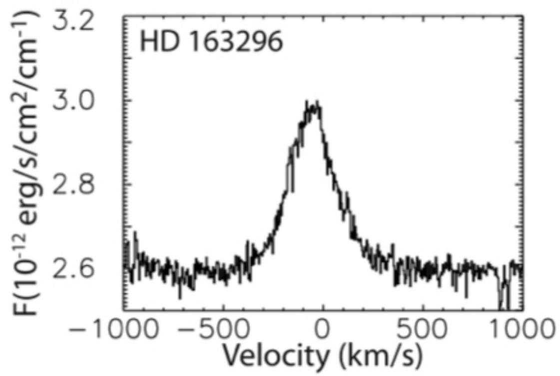
Overall properties (morphology, kinematics, mass-flux) best reproduced by steady MHD disk wind models launched from inner disk with r_0=0.1- 3 AUs

Strong magnetisation of inner disk (B=B_{eq})

cf Ferreira, Dougados, Cabrit 2006 A&A

2- Direct constraints on jet launching regions





r_0 < a few AUs requires mas angular resolution

spectrally resolved near-infrared interferometry (AMBER/VLTI)

spectro-astrometry applied to high-angular resolution data

✧ HI lines most prominent tracer of hot gas in Young Stars but exact origin still unknown (accretion columns, wind, hot disc surface ?)

in collaboration with M. Benisty & K. Perraut