Observations of outflows and angular momentum transport from the inner to the outer disk

R. Garcia Lopez (DIAS; MPIA)

K. Perraut (IPAG); A. Caratti o Garatti (DIAS); J. Sanchez-Bermudez (ESO); L. Labadie (Koeln Uni.); W. Brandner (MPIA); C. Dougados (IPAG); M. Benisty (IPAG); M.-K. Koutoulaki (DIAS); T. P. Ray (DIAS); and the GRAVITY-GTO team.

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MARIE CURIE ACTIONS

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Outline

- Introduction (talks: G. Rosotti; J. Simon)
- Observational constraints
  - Indirect tracers: HR spectroscopy
  - Direct tracers: spectro-interferometry
- Conclusions

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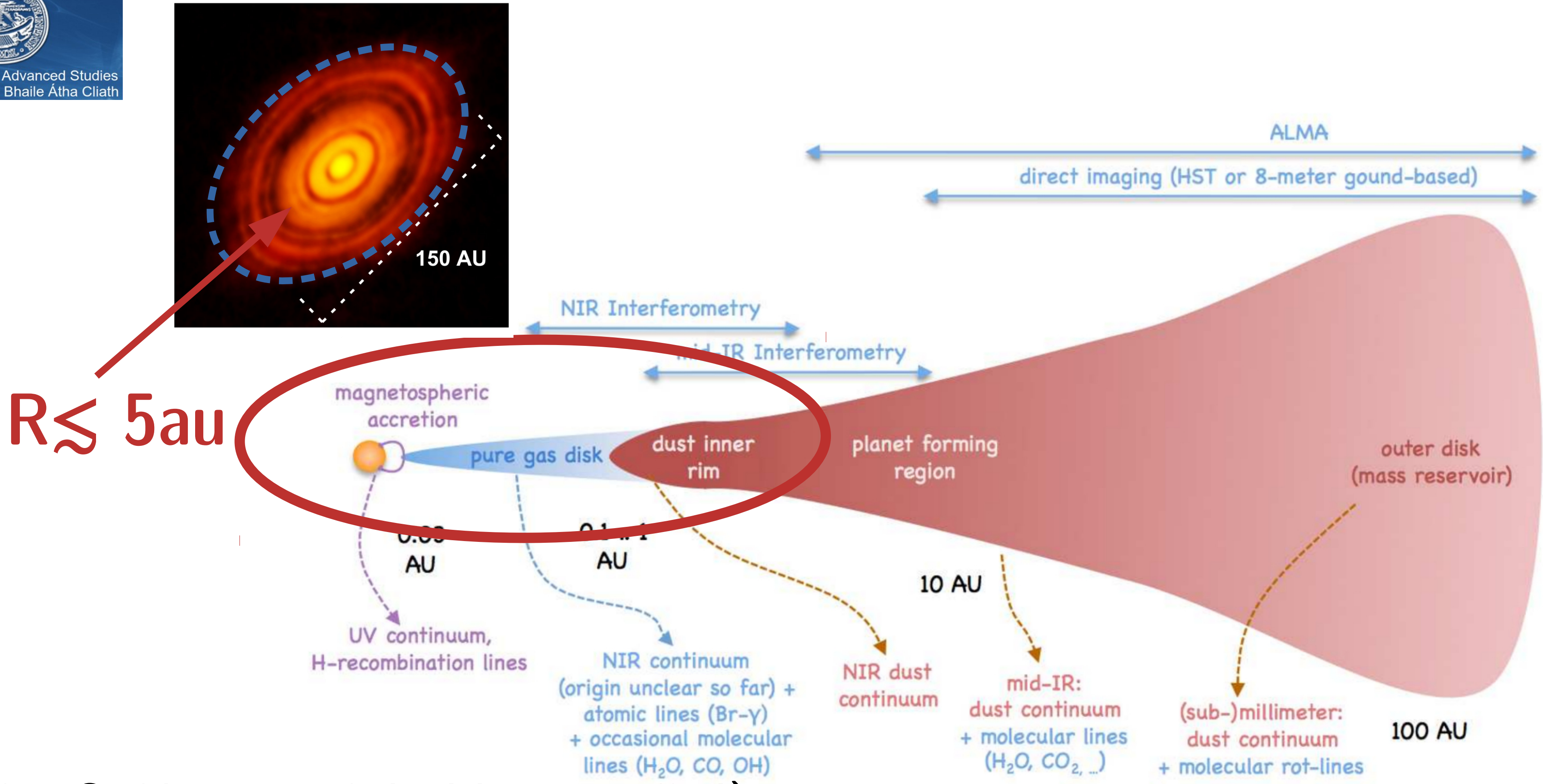
Introduction



(See also S. Kraus and A. Matter talks!)

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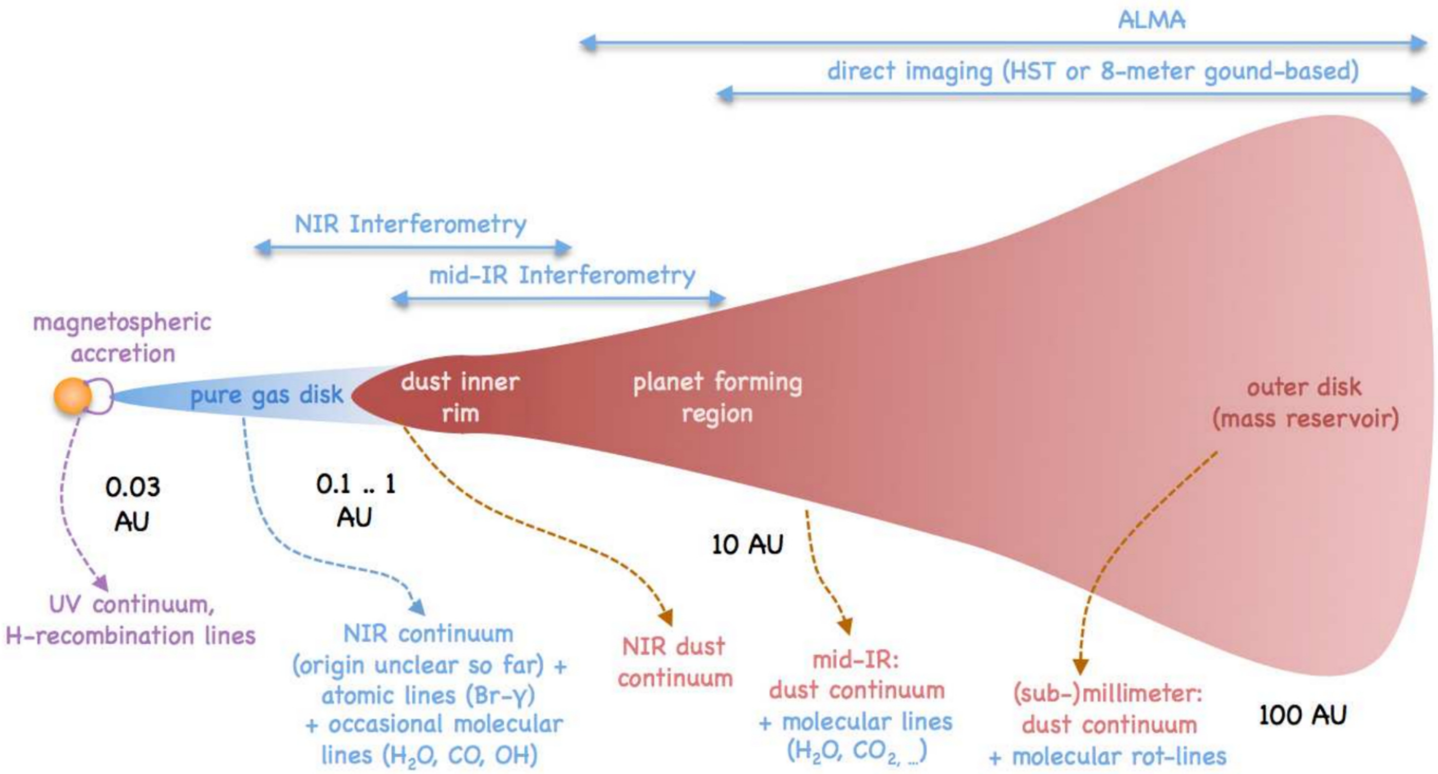
Introduction



(See also Stefan Kraus talk!)

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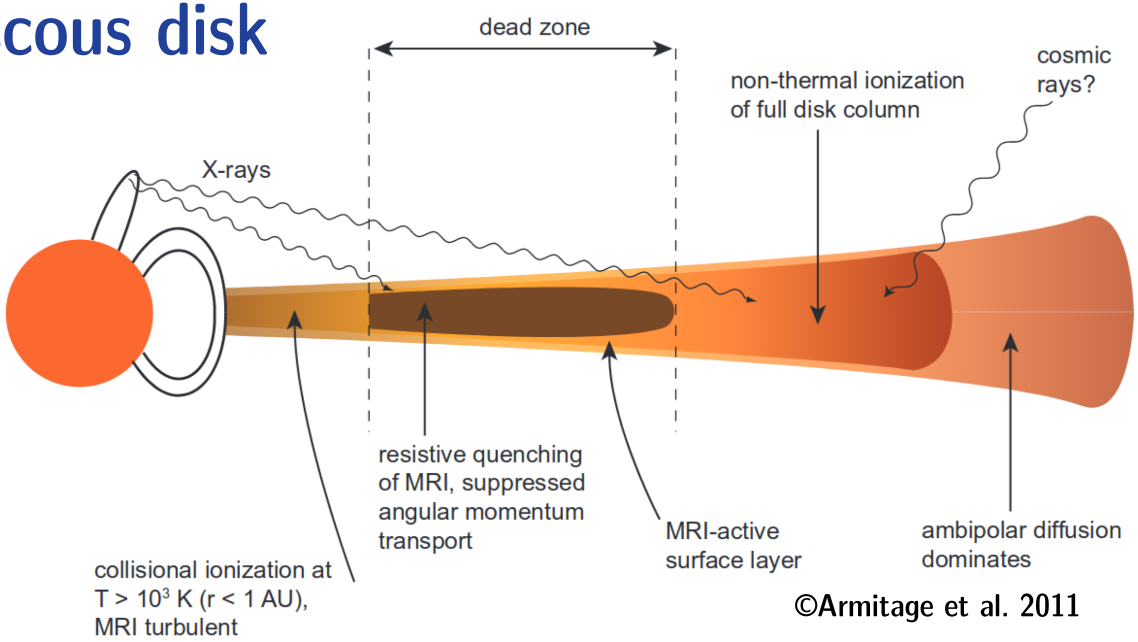
Introduction

Standard picture: viscous disk



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- Gas dynamics is dominated by accretion, followed by photoevaporation at later stages.
- Turbulence: MRI instability
- MRI disk "ingredients": weakly magnetised, angular velocity decreases with distance from the rotation centre, ionisation

(See e.g. Gammie et al. 1996; Ercolano et al. 2017; Najita et al. 2018,...)

Introduction

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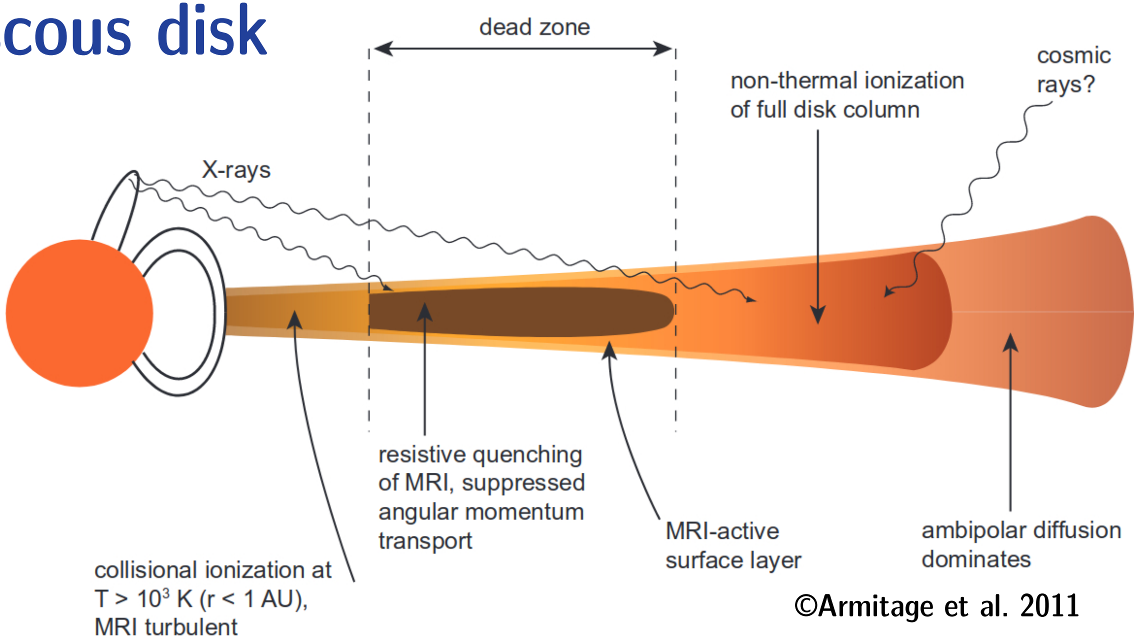

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- MRI disk “ingredients”: weakly magnetised, angular velocity decreases with distance from the rotation centre, ionisation ?

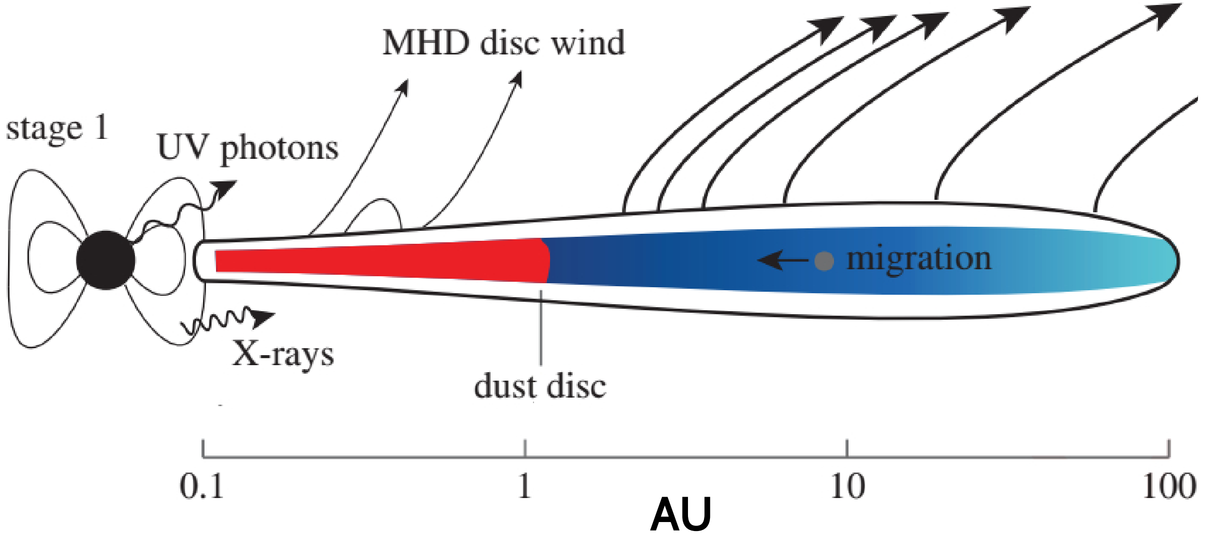
(See e.g. Gammie et al. 1996; Ercolano et al. 2017; Najita et al. 2018,...)

Introduction

New paradigm: MHD winds

- Non-ideal MHD simulations: MRI supressed, but strong MHD wind is generated.
- Efficiency of angular momentum transport depens on: ionization fraction, magnetic field strength.

(See e.g. Bai et al. 2017 and refs. there in)



Adapted from Ercolano et al. 2017

Introduction

New paradigm: MHD winds

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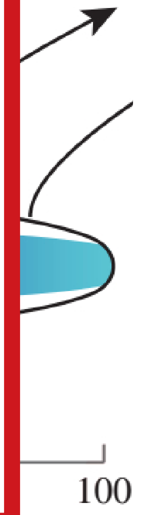
- Non-ideal MHD simulations: MRI supressed, but strong MHD
  w
- E
  m
  de
  fr
  strength.

(See e.g. Bai et al. 2017 and refs. there in)

Can we give observational constraints to distinguish between MRI and MHD-winds?



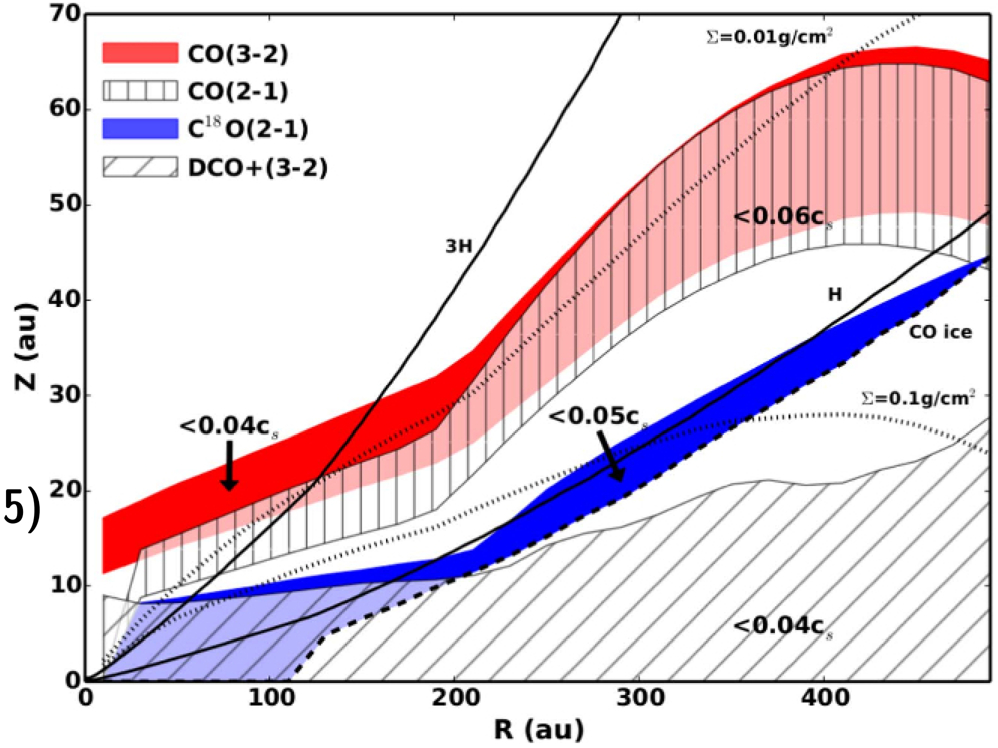
Adapted from Ercolano et al. 2017

Observational constraints

Turbulence

Talks by J. Simon and G. Rosotti

- HD163296: low turbulence level at $30\ \mathrm{au} < R < 300\ \mathrm{au}$ (Flaherty et al. 2015;2017)
- Inconsistent with MRI
  (0.3-$1\ c_s$ at $>3H$; 0.05-$0.1\ c_s$ at H)
  (e.g. Fromang & Nelson 2006; Simon et al. 2013, 2015)
- Consistent with ambipolar MHD damping ($\sim 0.01\ c_s$)
  (e.g. Simon et al. 2013, 2015; Bai 2015)



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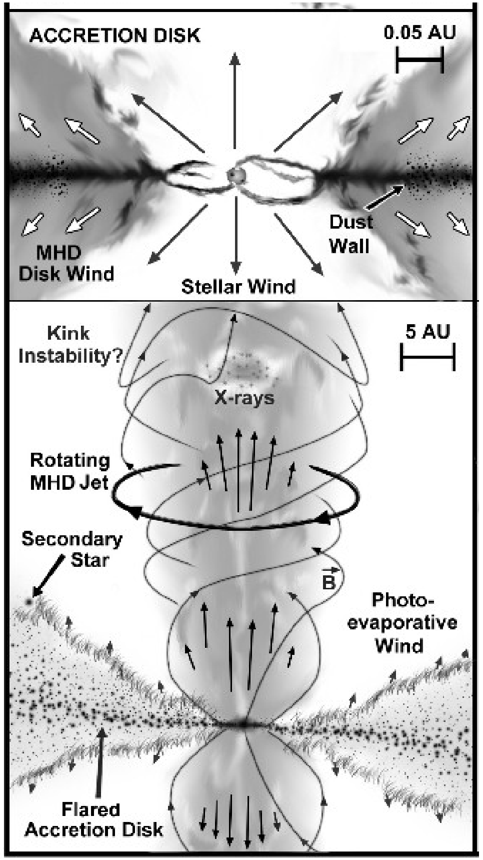
Observational constraints

MHD winds

- Wealth of literature on MHD disk winds to explain jets from YSOs (see e.g. PPVI Frank et al. 2014, Ferreira et al. 2006)
- MHD winds extract angular momentum



DISK SCALE

©Frank et al. 2014

Observational constraints

MHD winds

- Wealth of literature on MHD disk winds to explain jets from YSOs
  (see e.g. PPVI Frank et al. 2014, Ferreira et al. 2006)

(talk by C. Dougados)

- MHD winds extract angular momentum
- Jet rotation
  (Bacciotti+ 02;
  Coffey+ 04,07,12,15)
- Uncertain outcome:
  (entrainment material?, shocks?,...)

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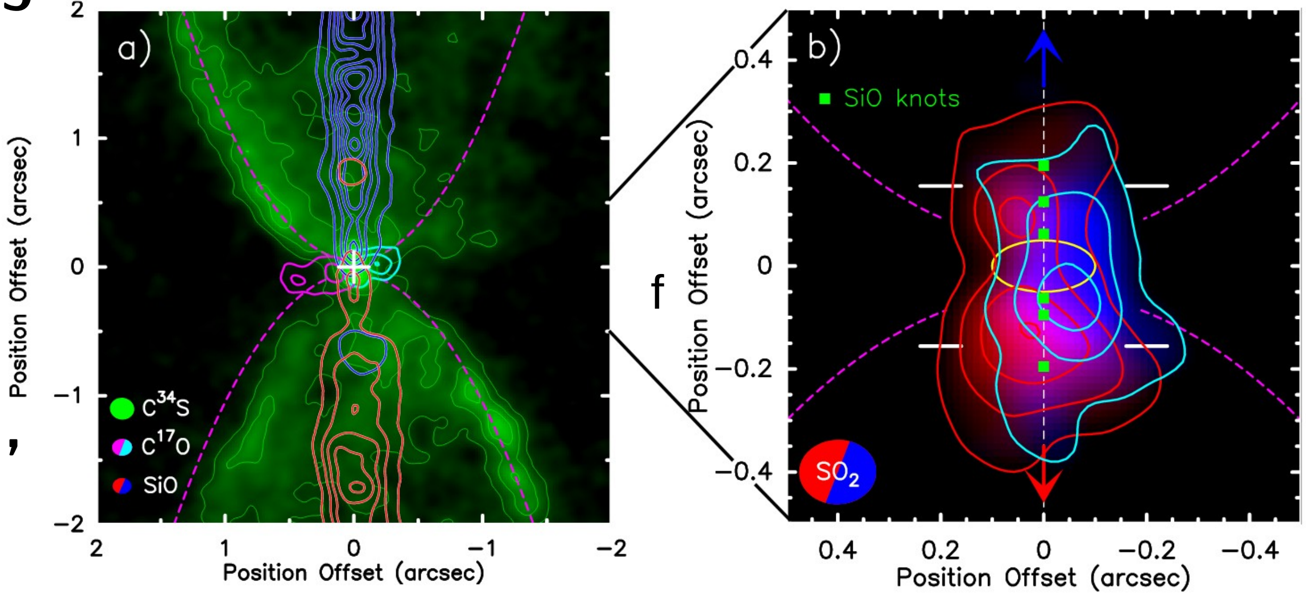
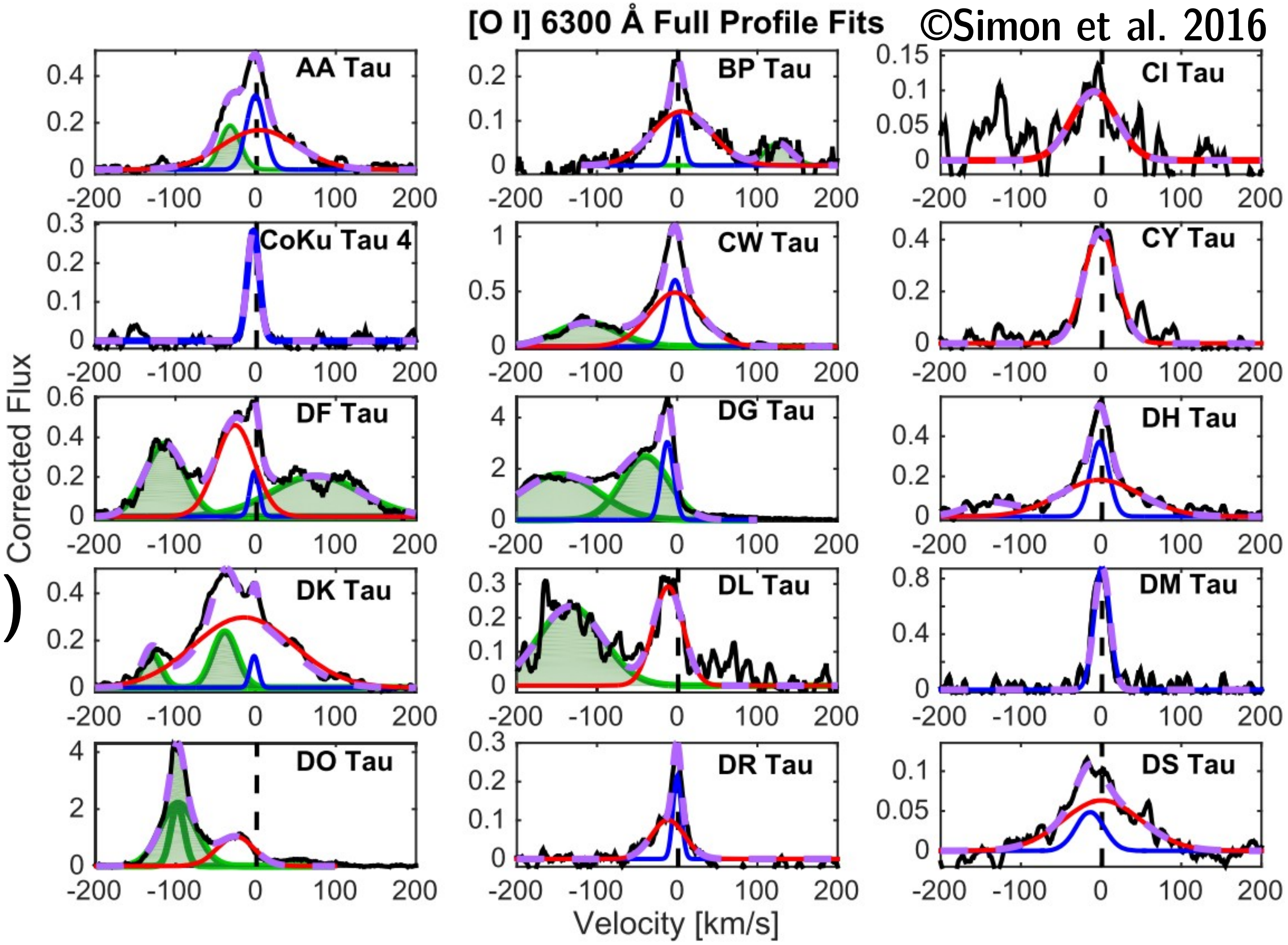


Observational constraints

MHD winds



- HVC, LVC
- LVC always observed

  Narrow componet (NC)

  Broad componet (BC)

(e.g. Rigliaco et al. 2013; Natta et al. 2014; Nisini et al. 2018)

Observational constraints

MHD winds

- HVC: Jet emission
- LVC-BC: R<0.5 au

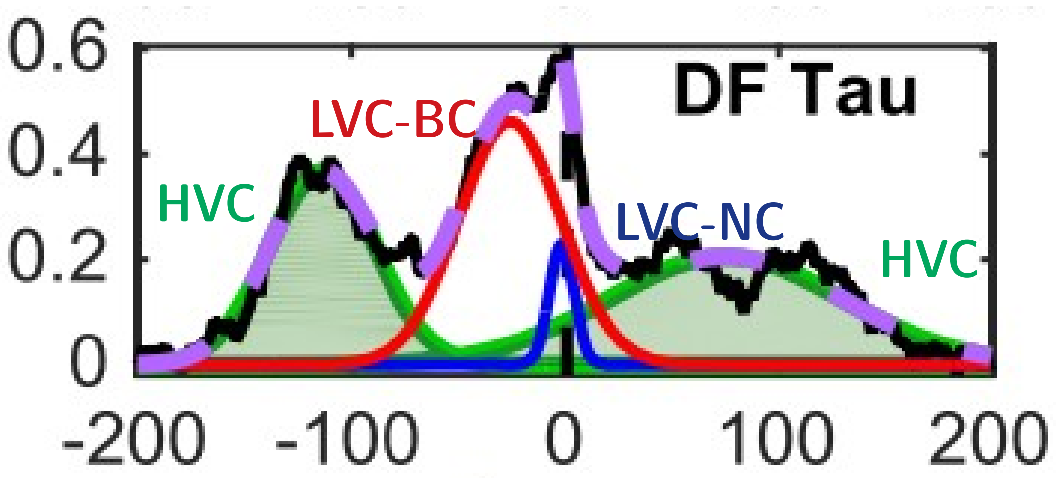
lower inclinations:

narrower+bluer line.

MHD-wind?

LVC-NC: R<5 au, always observed in TDs

photoevaporative wind?



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(e.g. Simon et al. 2016; McGinnis et al. 2018, Fang et al. 2018)

Observational constraints

MHD winds

- HVC: Jet emission
- LVC-BC:

lower inc

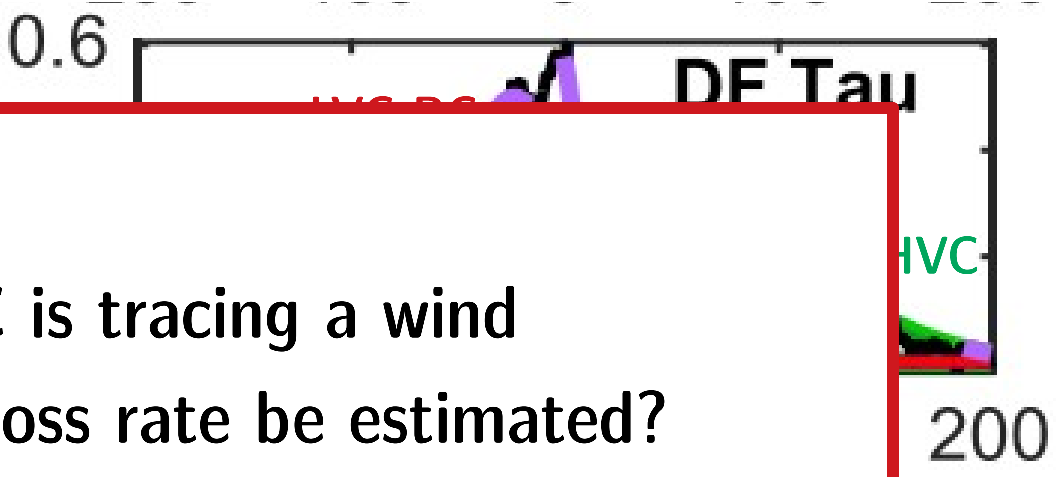
narrower

MHD-wi

LVC-NC:

If the LVC is tracing a wind

can the mass loss rate be estimated?



2016

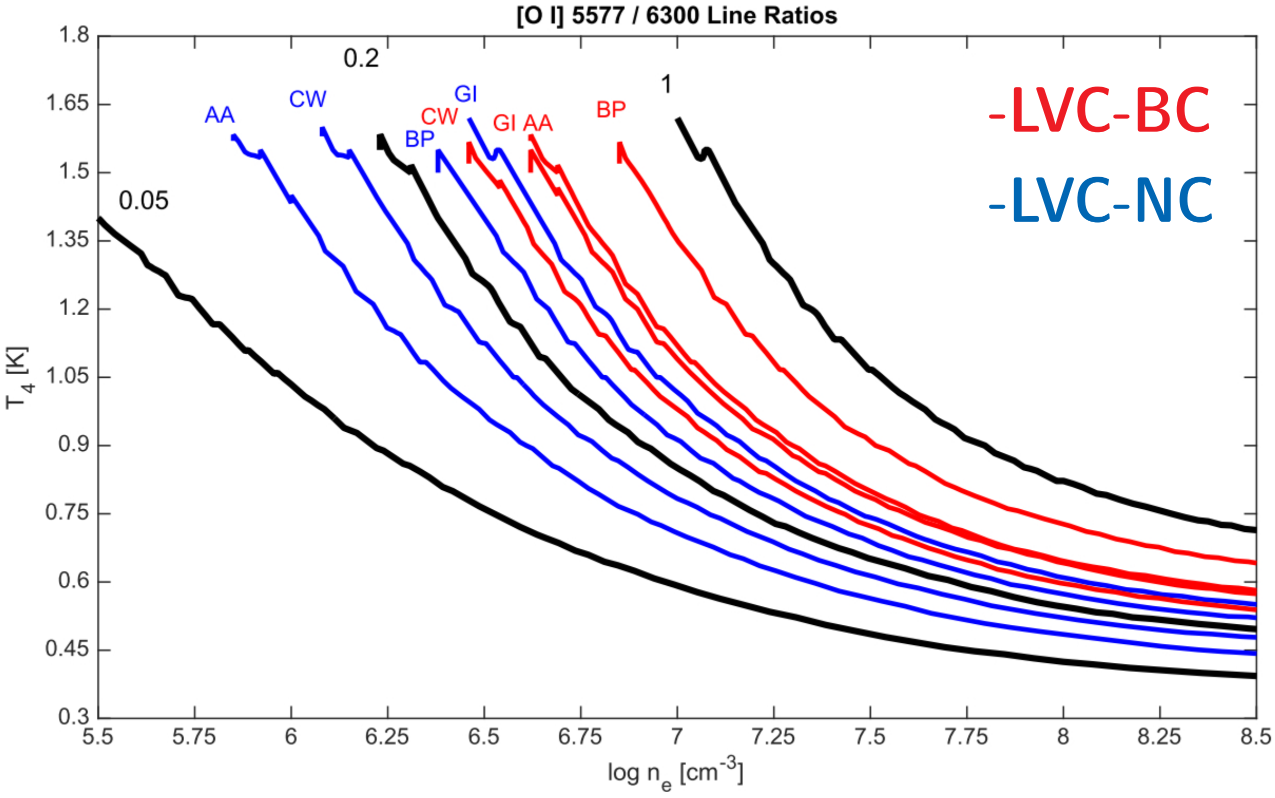
photoevaporative wind?

(e.g. Simon et al. 2016; McGinnis et al. 2018, Fang et al. 2018)

Observational constraints

MHD winds

- Line ratio diagnostics: [OI] λ5577/λ6300
  n_e (LVC-BC) > n_e (LVC-NC)
  (Natta et al. 2014; Simon et al. 2016)
- But photodisociation produce similar ratios in gas at T~1000 K
  (e.g. Gorti et al. 2011)



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Observational constraints

MHD winds

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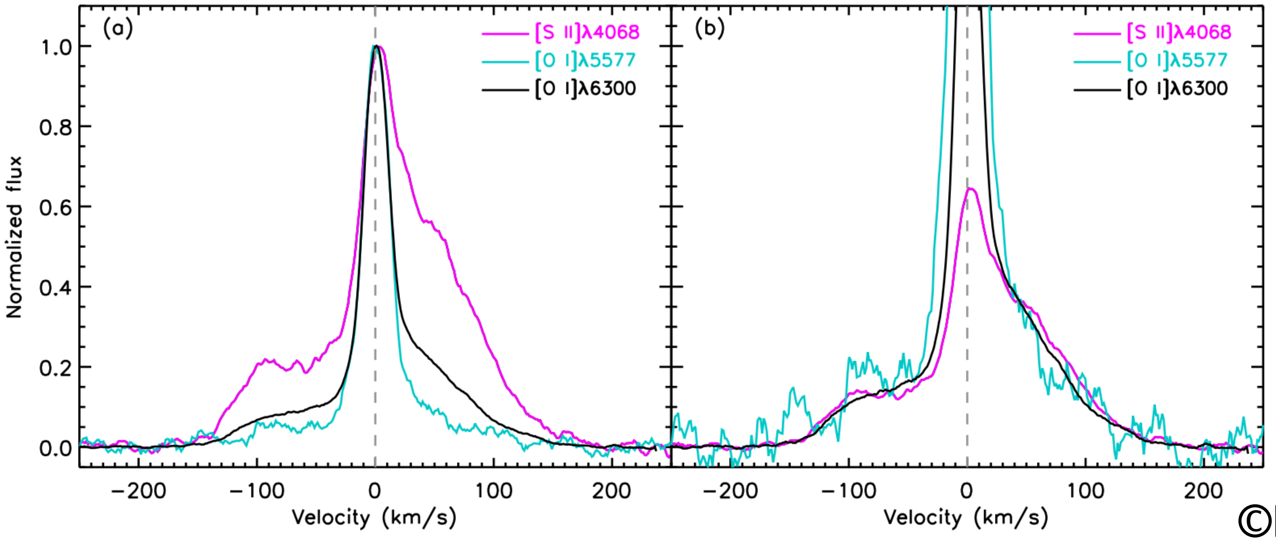
- [SII] λ4068 and [OI] λ6300 have similar critial density.
- [SII] thermaly excited -> [SII]/[OI] ratio to discern thermal vs nonthermal excitation (e.g. Natta et al. 2014, Fang et al. 2018)



Observational constraints

MHD winds

- From Fang et al. 2018:

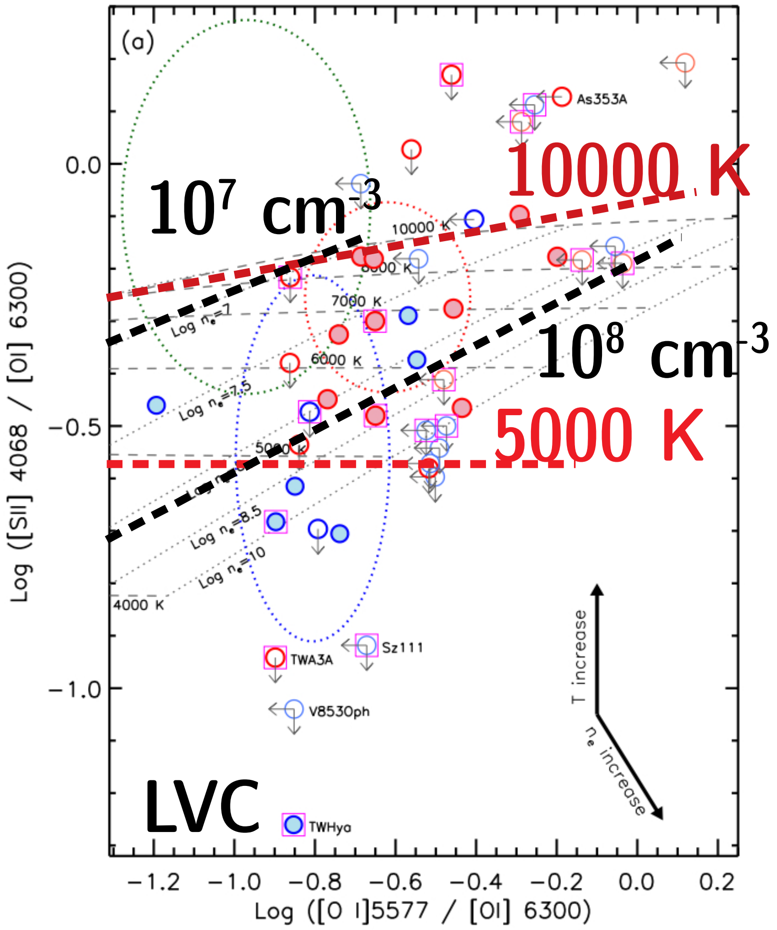
  $5000\ \mathrm{K} < T(\mathrm{LVC}) < 10000\ \mathrm{K}$

  $10^7\ \mathrm{cm^{-3}} < ne(\mathrm{LVC}) < 10^8\ \mathrm{cm^{-3}}$

  M_{wind}(LVC-BC) ~ $5xM_{wind}$ (LVC-NC)

M_{wind}/M_{acc}(LVC-BC) > M_{wind}/M_{acc}(LVC-NC)

(see also Suzan Edwards poster)



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Observational constraints

MHD winds

- From Fang et al. 2018:

5000 K <

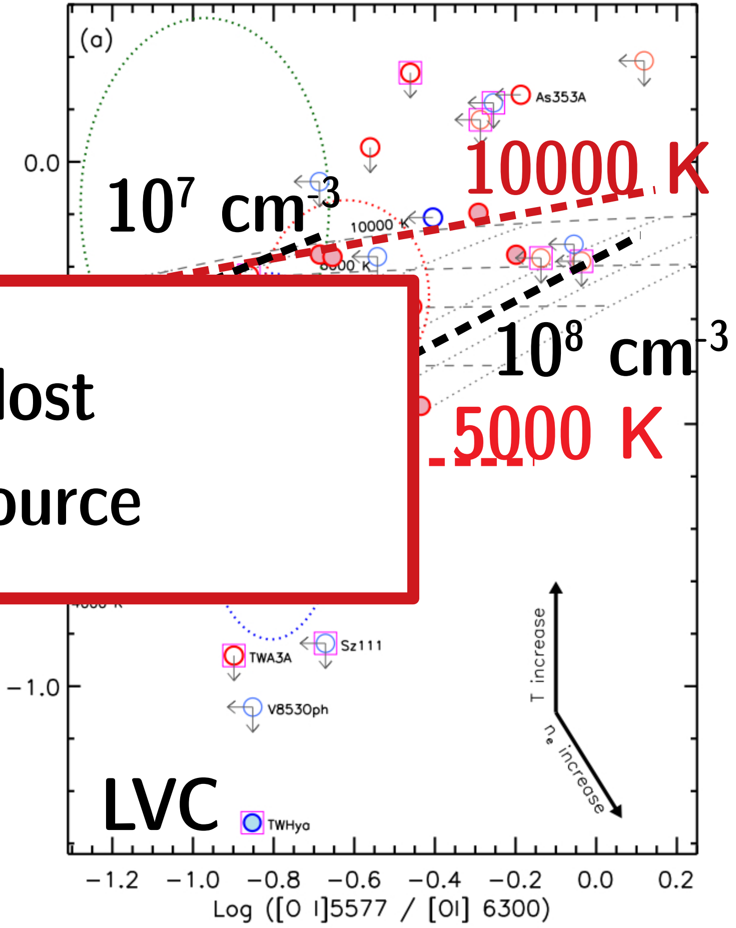
10^7 cm^{-3}

Most of the mass is lost close to the central source

M_{wind}(LVC-BC) ~ 5xM_{wind} (LVC-NC)

M_{wind}/M_{acc}(LVC-BC) > M_{wind}/M_{acc}(LVC-NC)

(see also Suzan Edwards poster)



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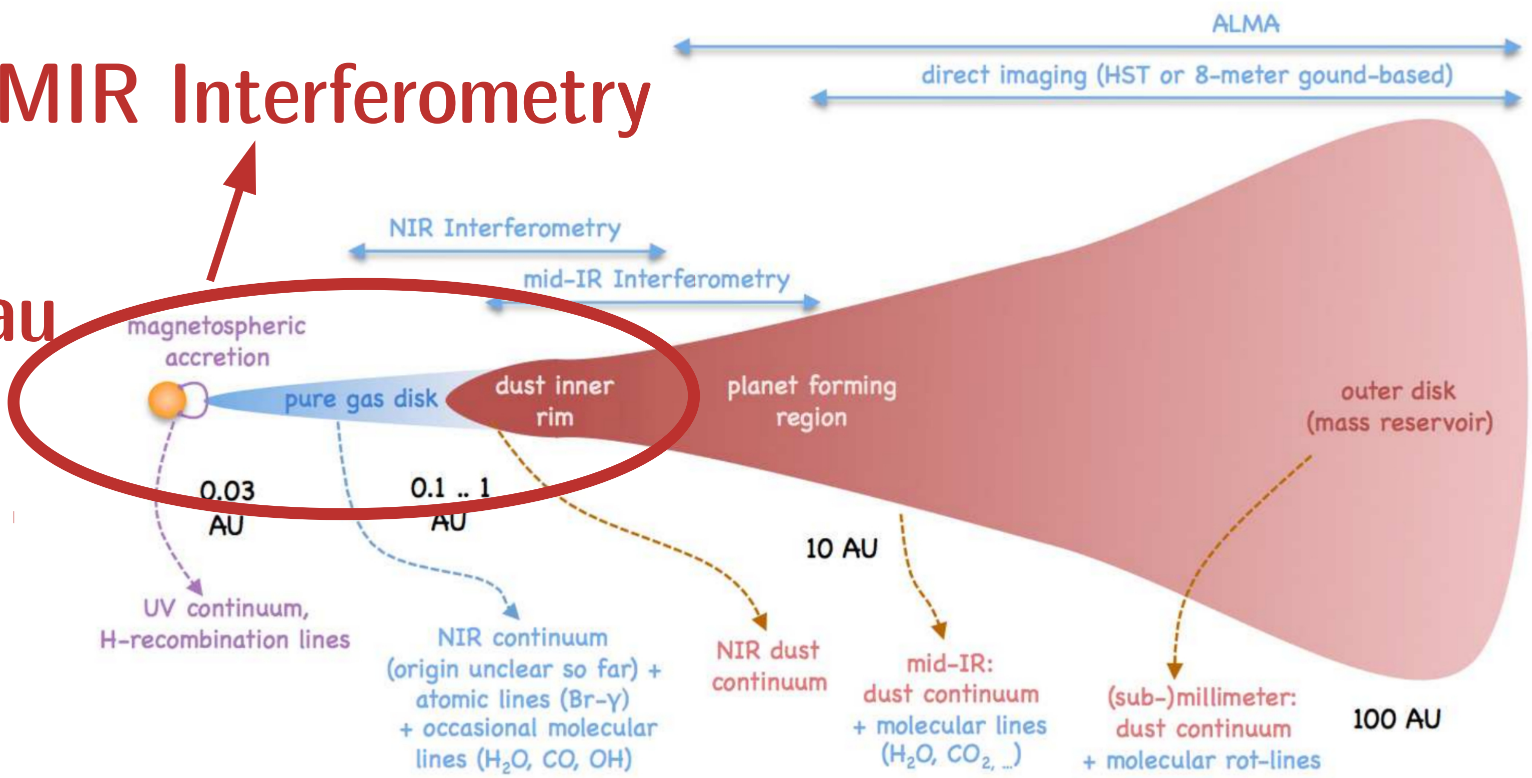
Observational constraints

Spatially resolved observations

NIR/MIR Interferometry

$R \lesssim 5$au



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Observational constraints

Spatially resolved observations

Most interferometers work in the K-band

+

YSOs are red objects

↓

Brγ is our favourite line!!

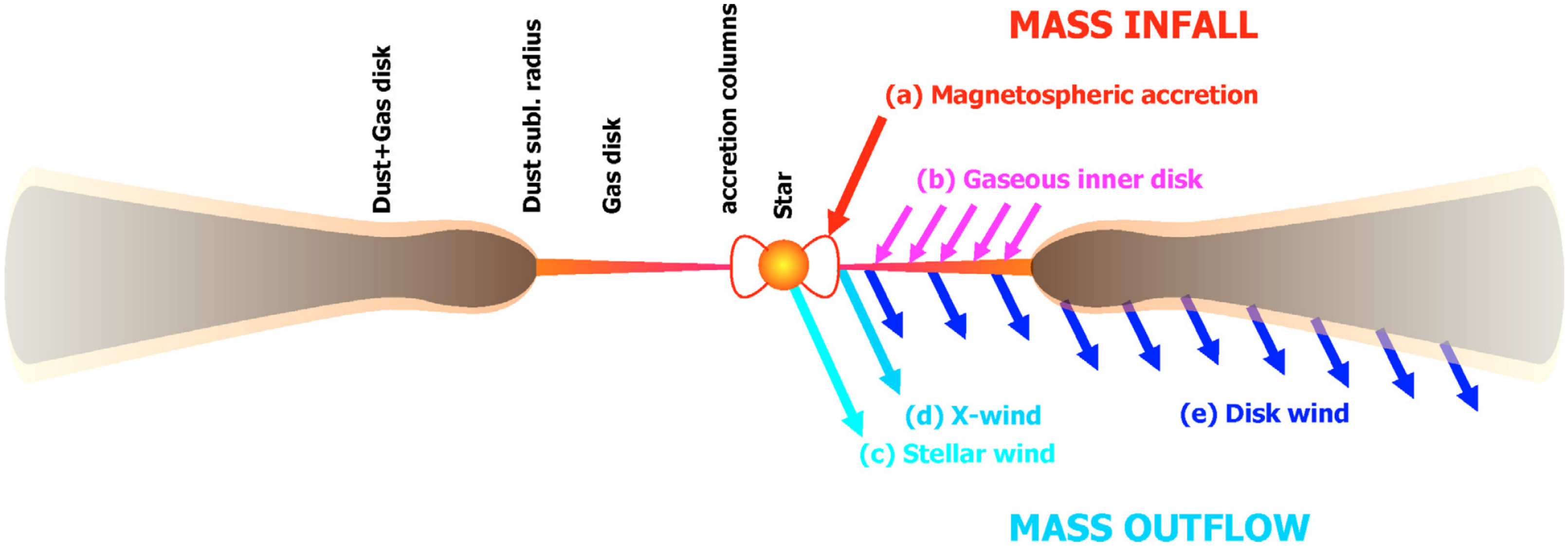
Can we constraint the origin of this line/associate it with winds/accretion?

Observational constraints

Spatially resolved observations

- Emitted in a compact region (few tenths of mas) within R_{dust}

  (see e.g. Kraus et al. 2008, Eisner et al. 2009)



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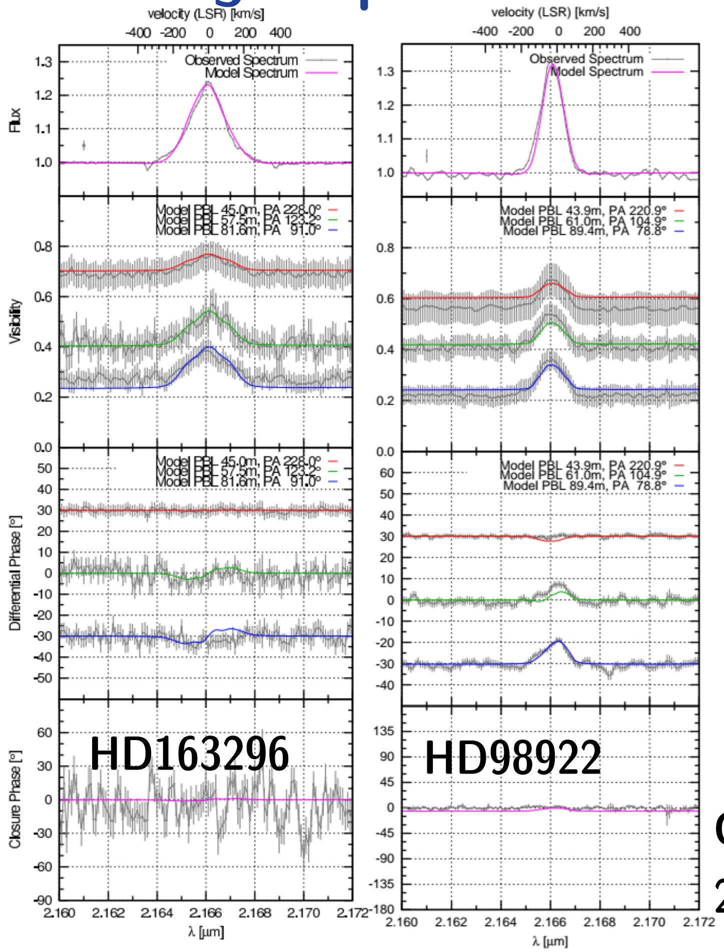
Spatially resolved observations

Modelling Brγ emission



$V_{line} > V_{cont}$:

$R_{line} < R_{cont}$

Photocenter shift of the line vs continuum

Garcia Lopez et al. 2015; Caratti o Garatti et al. 2015

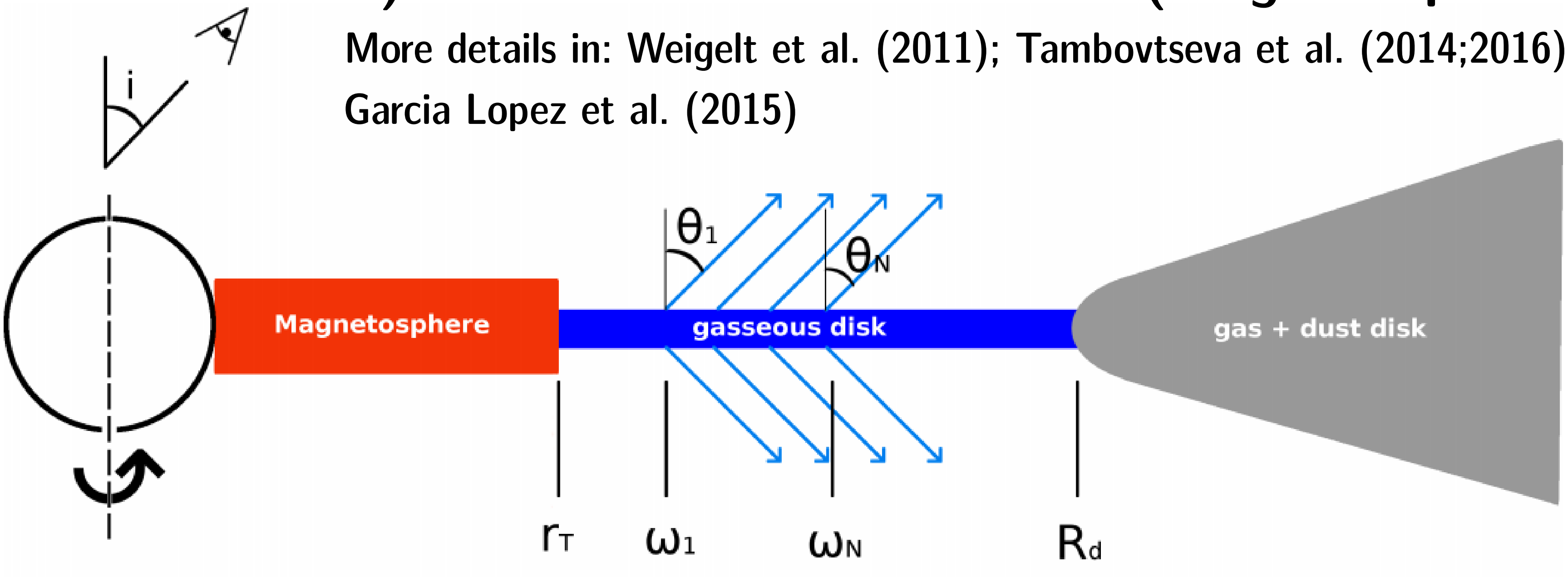
Spatially resolved observations

Modelling Brγ emission

Contributions: 1) continuum emission: star + disc

2) line emission: disc wind + (magnetosphere)

More details in: Weigelt et al. (2011); Tambovtseva et al. (2014;2016); Garcia Lopez et al. (2015)

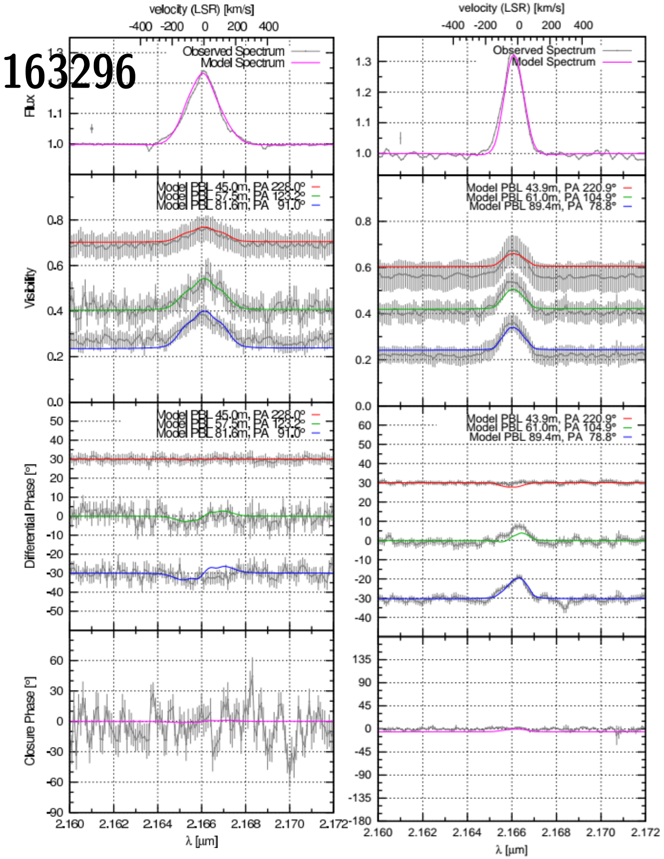


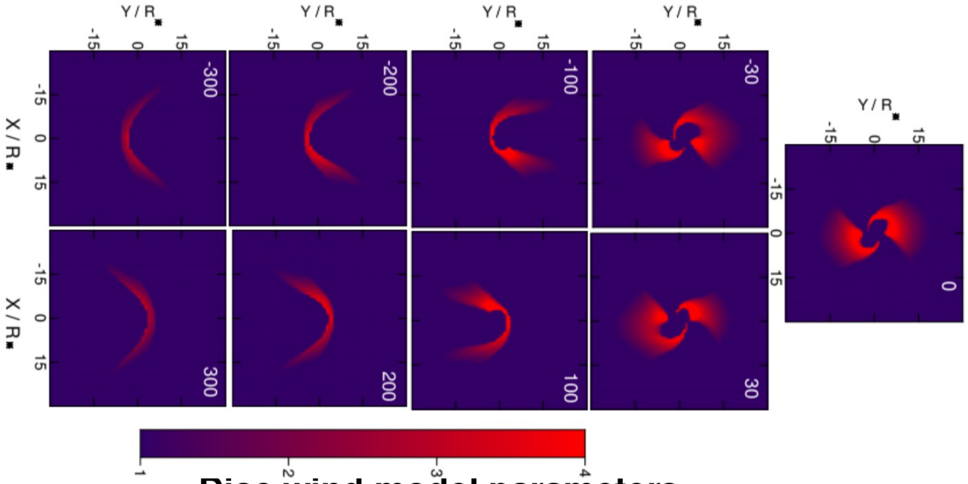
Spatially resolved observations

Modelling Brγ emission

HD98922

HD163296





Disc wind model parameters

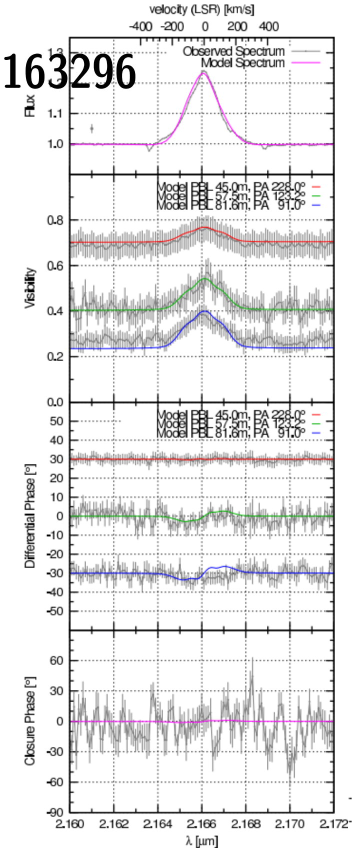
	HD163296	HD98922
Temperature (K)	10 000	10 000
Half opening angle (θ)	45°	30°
Inner radius (ω_1 (R_*))	2.0 (0.02 AU)	3.0 (0.1 AU)
Outer radius (ω_N (R_*))	4.0 (0.04 AU)	30.0 (1 AU)
Mass loss rate ($\dot{M}_w$ ($M_\odot$/yr))	5×10^{-8}	2×10^{-7}

Garcia Lopez et al. 2015; Caratti o Garatti et al. 2015

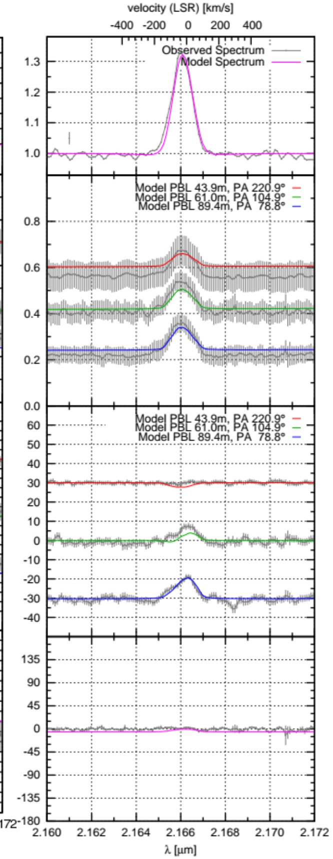
Spatially resolved observations

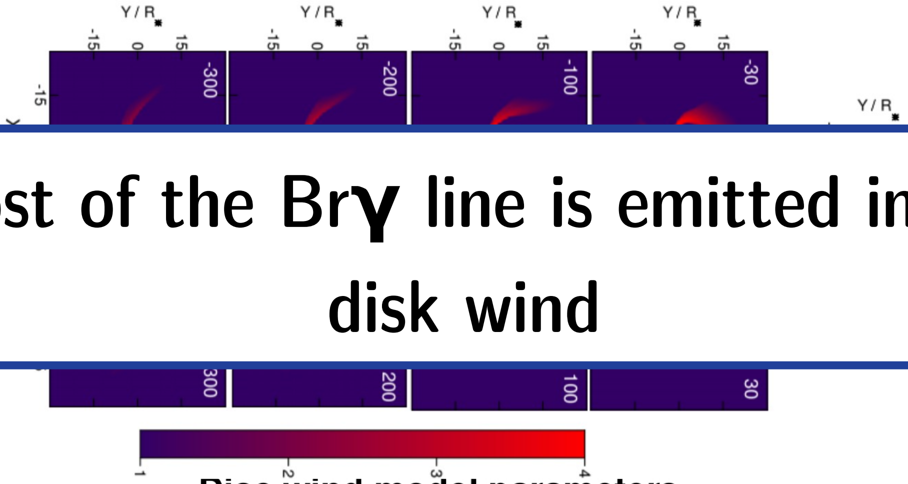
Modelling Brγ emission

HD163296



HD98922





Most of the Brγ line is emitted in a disk wind

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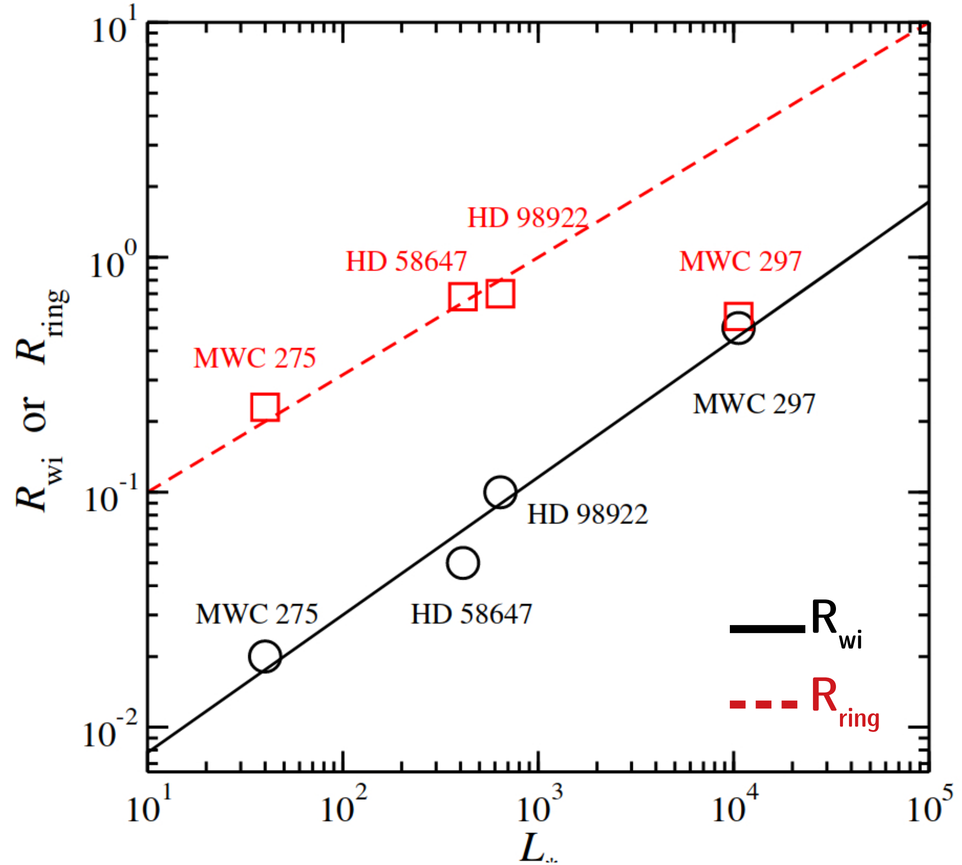
Spatially resolved observations

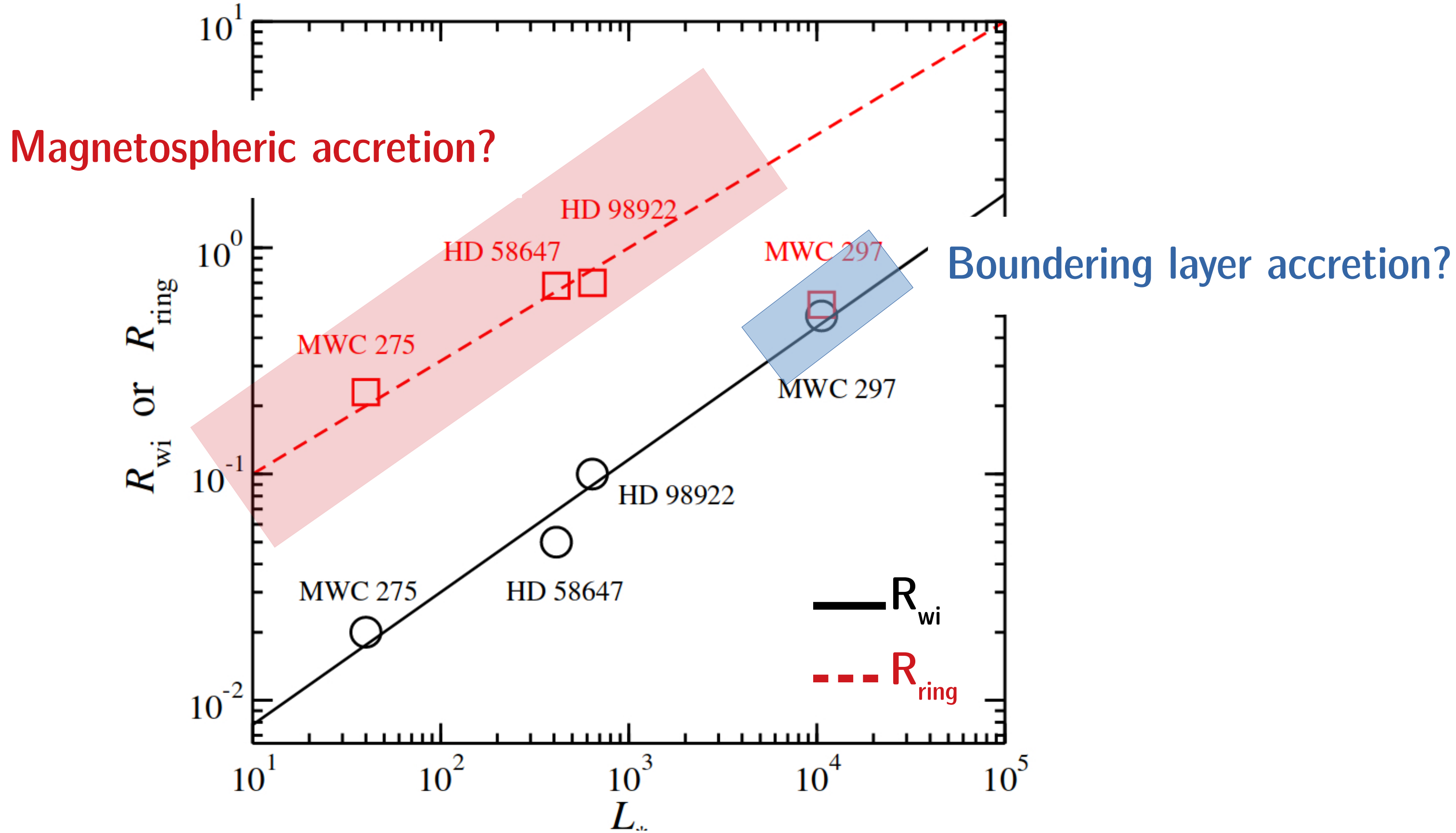
Modelling Brγ emission



Kurosawa et al. 2016

Spatially resolved observations

Modelling Brγ emission



Kurosawa et al. 2016

Spatially resolved observations

A statistical approach – VLTI-GRAVITY GTO program

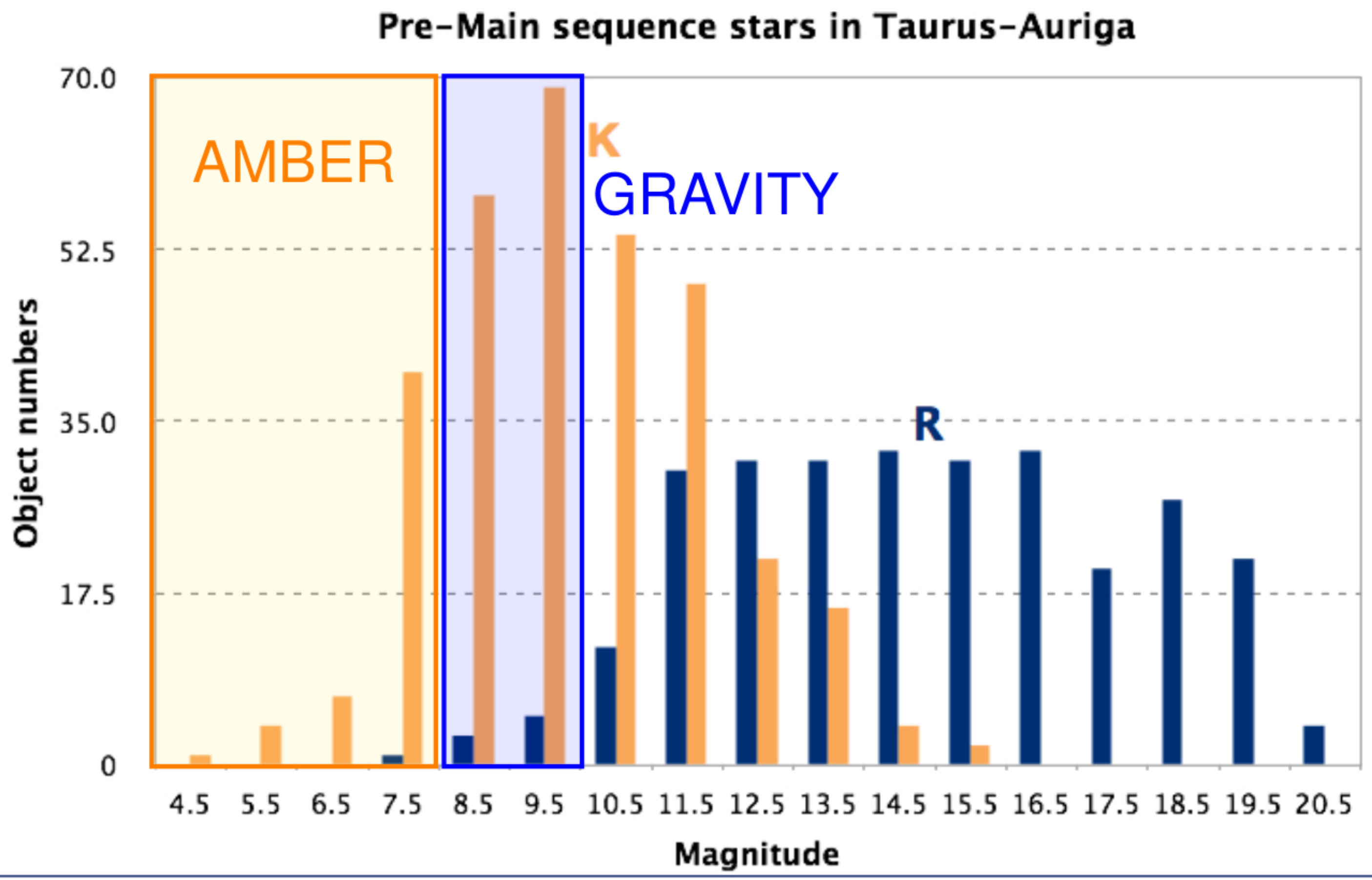
Can we study the presence of inner winds in a statistical and homogeneous ways accross the mass and age spectrum?

- Aim: Statistical study of the gas content in YSO disks to spatially resolve the hot (Brγ) and warm (CO) gas in disks.
- Large sample of YSOs (~100) spanning a wide range of stellar masses (very low-, high-mass), ages (10^4 -10^7) and disk properties (full and TDs).

(talk by K. Perraut)

Spatially resolved observations

A statistical approach



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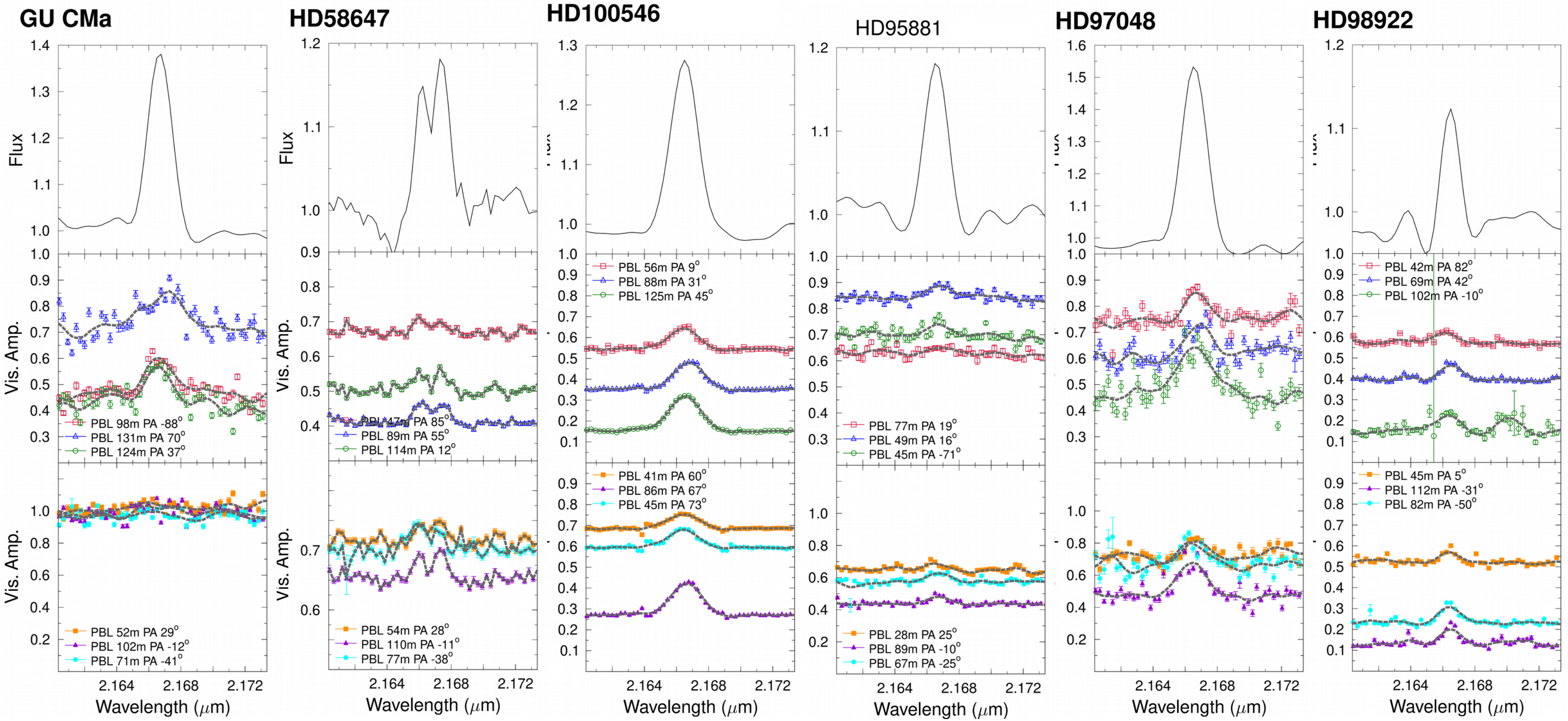
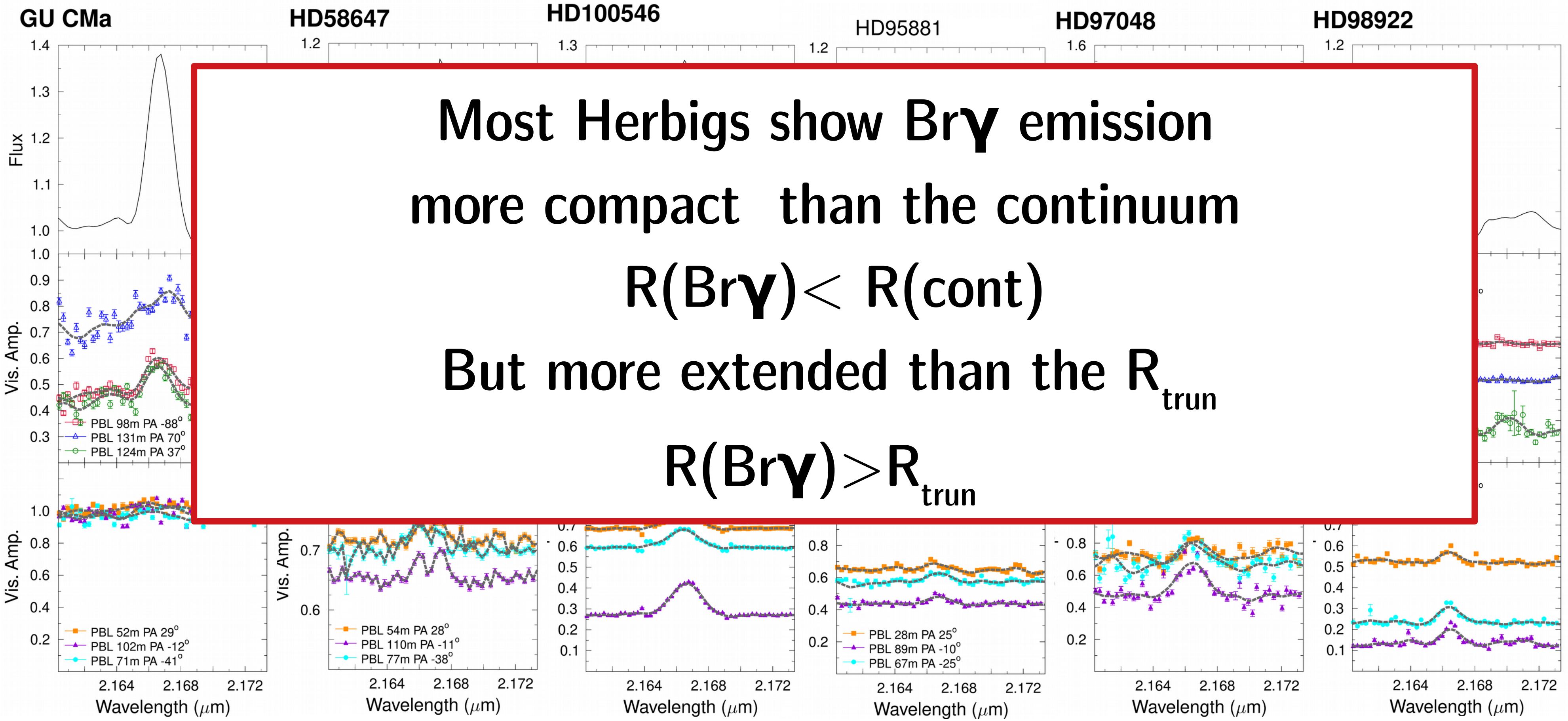
Spatially resolved observations

A statistical approach



Spatially resolved observations

A statistical approach



Most Herbigs show Brγ emission more compact than the continuum

R(Brγ) < R(cont)

But more extended than the R_{trun}

R(Brγ) > R_{trun}

Spatially resolved observations

A statistical approach

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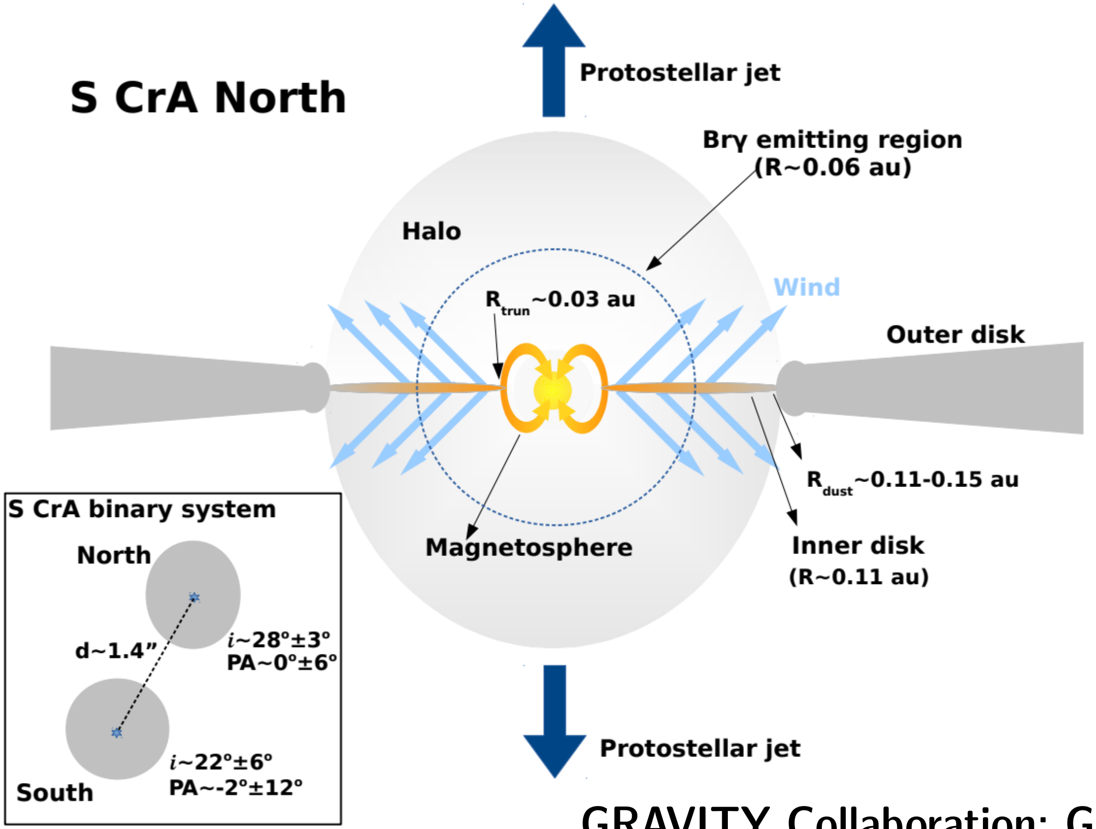
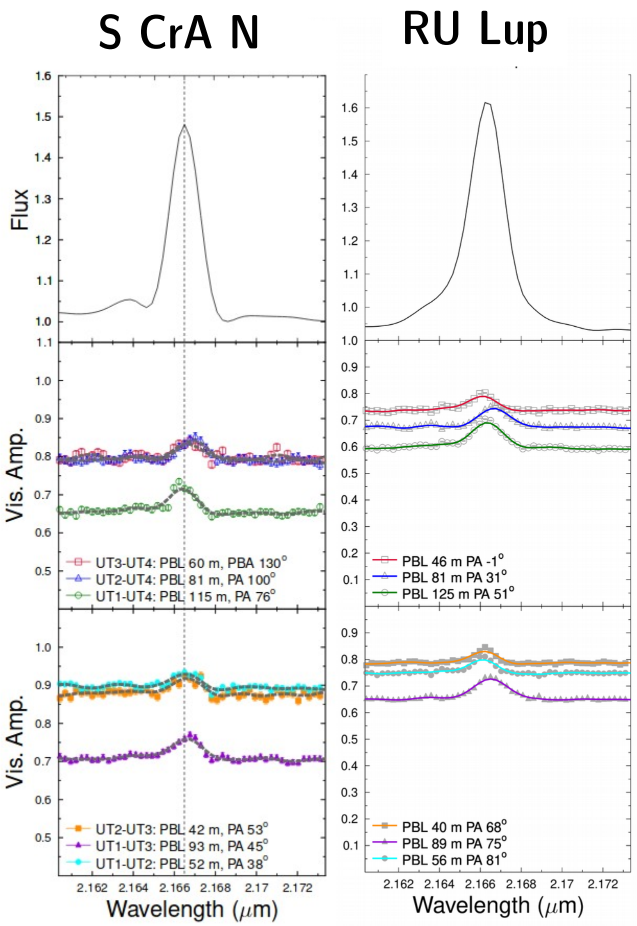
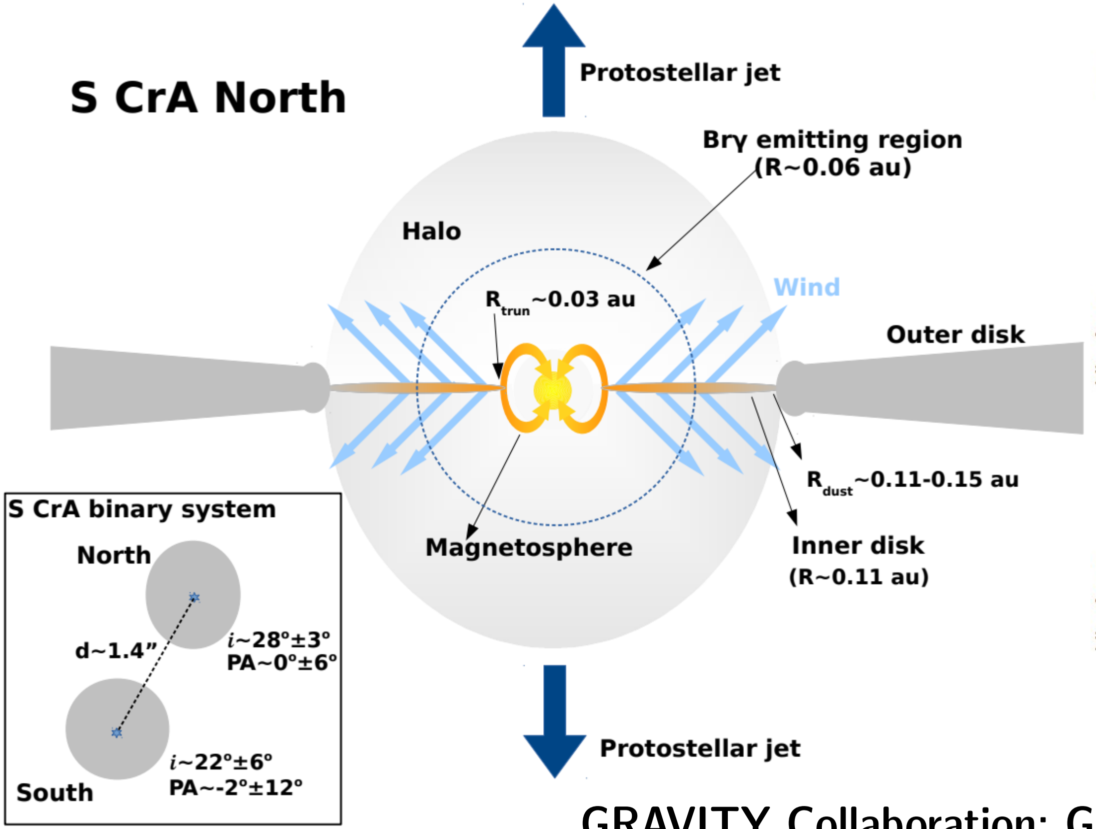


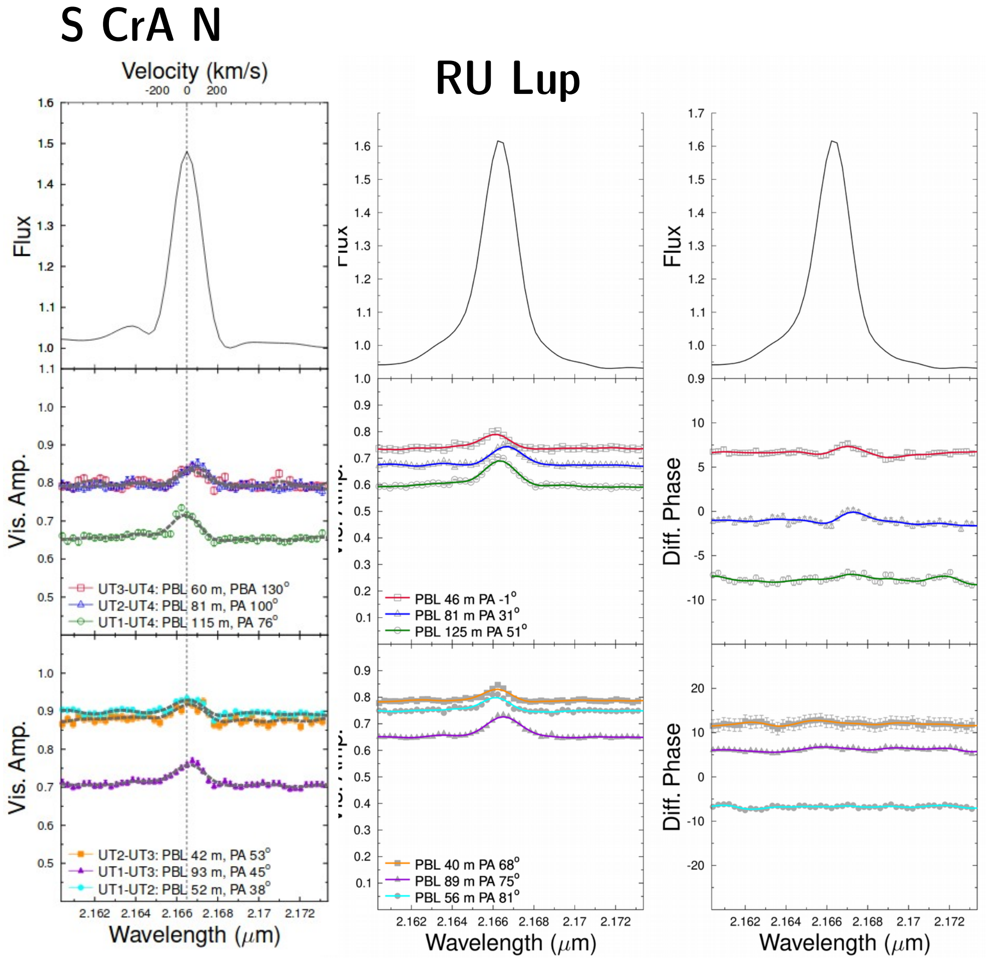


GRAVITY Collaboration: Garcia Lopez et al. 2017; Koutoulaki et al. in prep.

Spatially resolved observations

A statistical approach





GRAVITY Collaboration: Garcia Lopez et al. 2017; Koutoulaki et al. in prep.

Spatially resolved observations

A statistical approach

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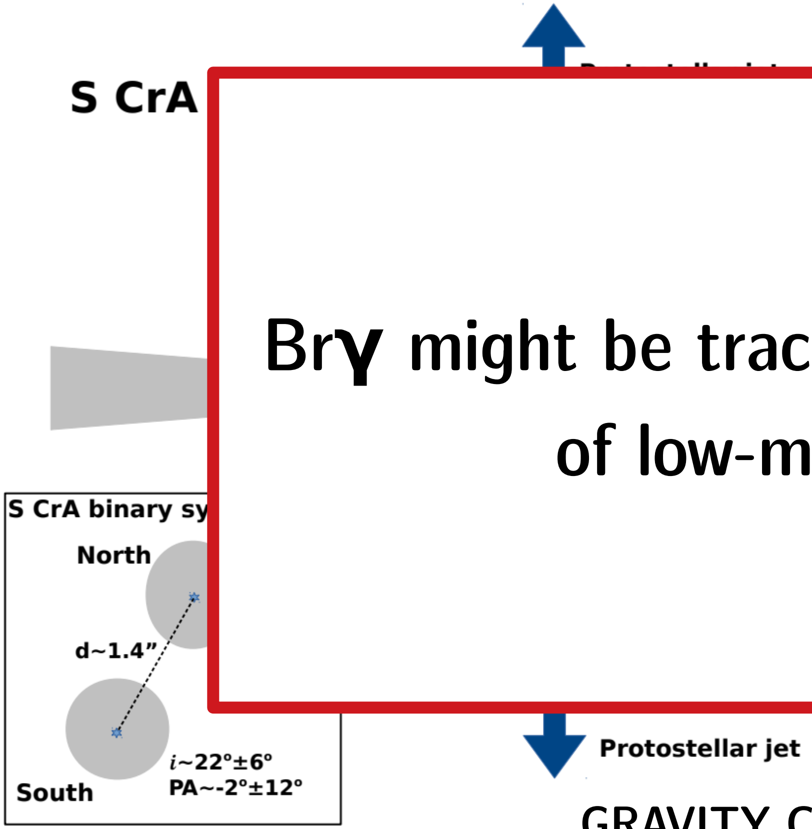
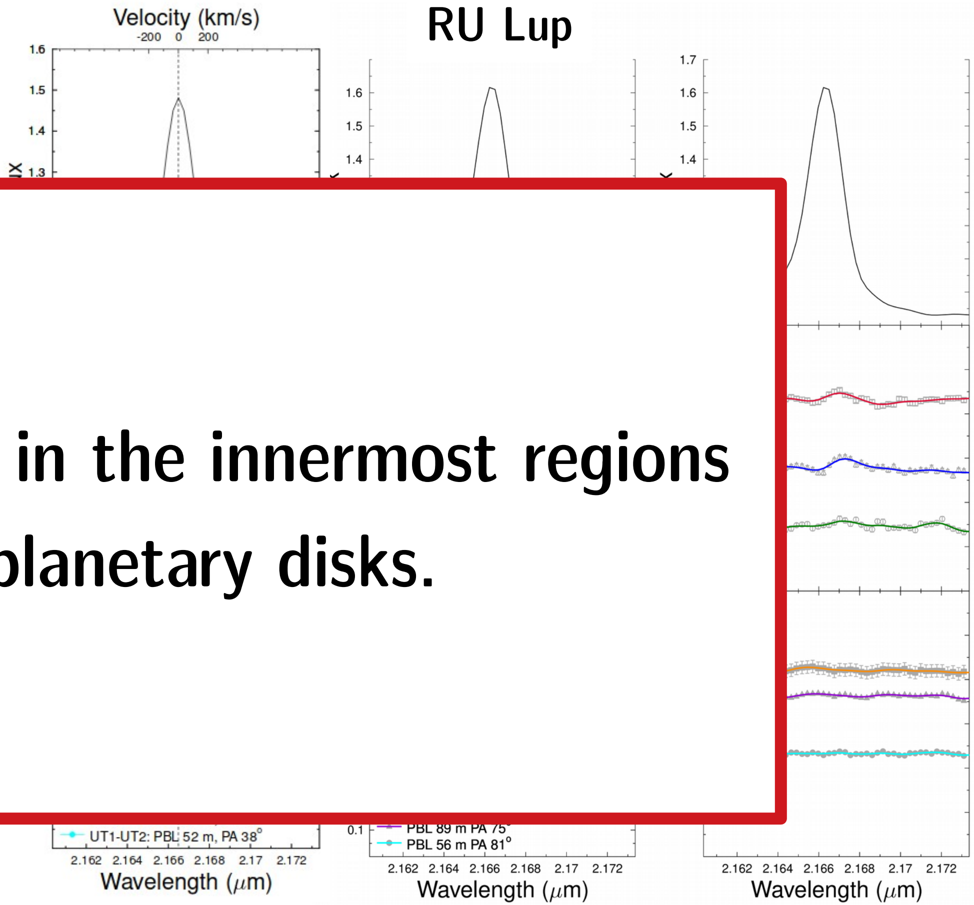


S CrA N



Brγ might be tracing winds in the innermost regions of low-mass protoplanetary disks.

GRAVITY Collaboration: Garcia Lopez et al. 2017; Koutoulaki et al. in prep.

Conclusions

- ALMA starts to probe turbulence in disks
  - Low levels of turbulence
- LVC-BC detected in forbidden lines might be tracing an inner MHD-wind.
  - First constraints on physical properties
- NIR interferometry has came to age.
  - Brγ might be mostly originated in a disk wind, tracing the presence of MHD-winds in the innermost disk region.

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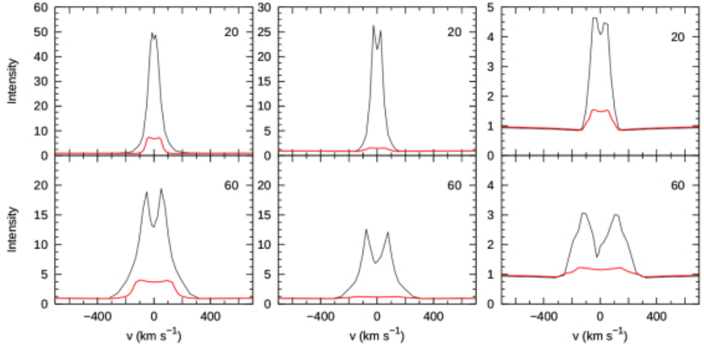
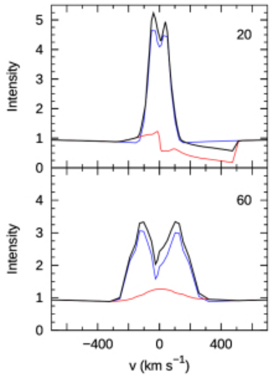
emission in the inner disk

Disk wind + accreting disk

M_{out} ($M_\odot$/yr) $= 1\times10^{-7}; 3\times10^{-7}; 1\times10^{-8}$
M_{acc} ($M_\odot$/yr) $= 1\times10^{-6}; 1\times10^{-7}; 1\times10^{-7}$



Disk wind + magnetosphere



$M_{out} = 1\times10^{-8}\ M_\odot$/yr
$M_{acc} = 1\times10^{-7}\ M_\odot$/yr

©Tambovtseva et al. 2016

Disk surface hot layers

p=9/8 p=5/4