Star Formation studies with the NOT

Anlaug Amanda Djupvik

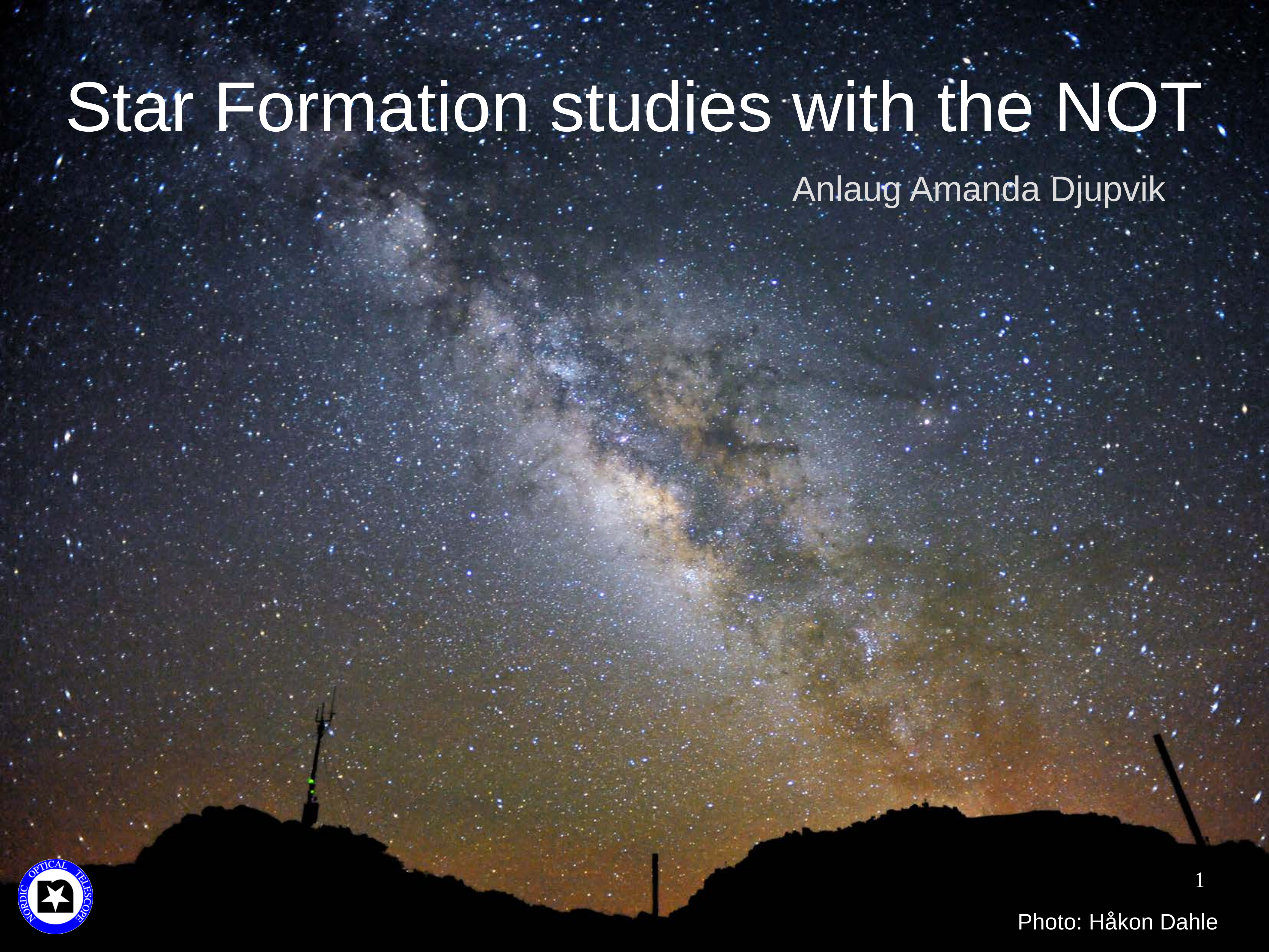


Photo: Håkon Dahle


La Palma
Lanzarote
Tenerife
La Gomera
Fuerteventura
Gran Canaria
El Hierro

Overview of this talk

- Short presentation of the Nordic Optical Telescope
- Young stellar objects and their evolution
- Protostellar jets and

    results from a near-IR kinematic study with NOT
- What drives UX Ori type of variability - some results

    from spectroscopic monitoring with NOT

Photo: Jens Jessen-Hansen

Some NOT history

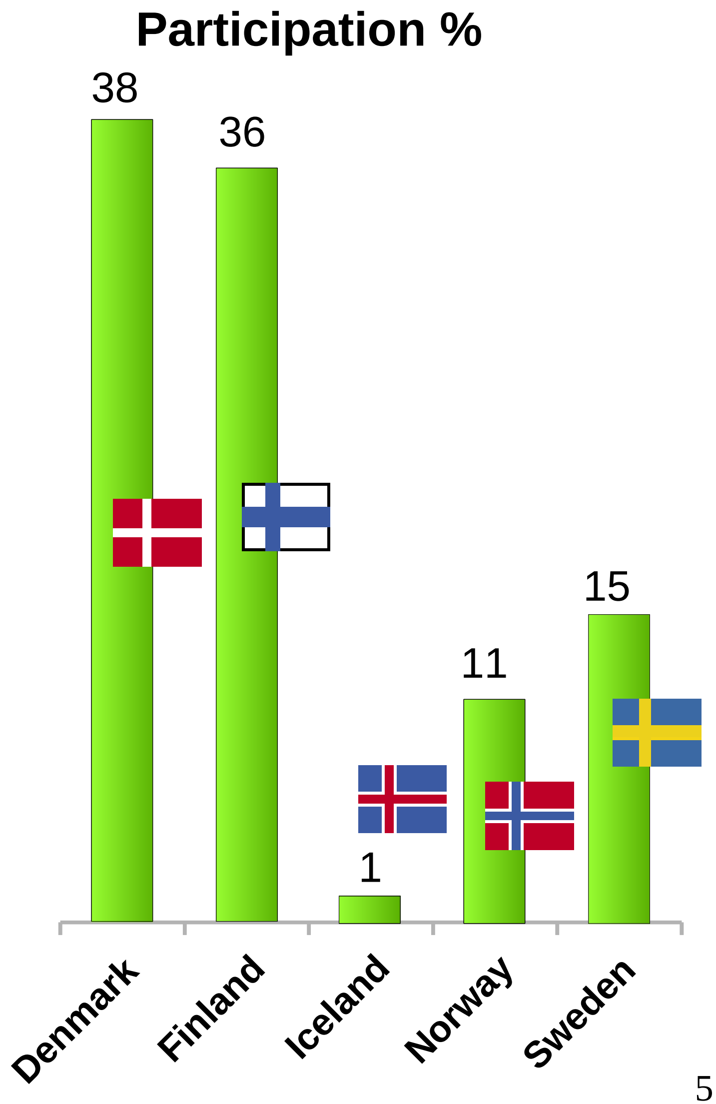
- 1984 NOT Scientific Association (NOTSA)
- Torben Andersen feasibility study (1981)
- 1989 NOT inaugurated
- Funding from national research councils
- Directors: Arne Ardeberg, Vilppu Piirola, Johannes Andersen, Thomas Augusteijn (now)
- NOT Council
- NOT Scientific and Technical Committee
- NOT Observing Program Committee

(new)NOT

New Structure (since 2020):

- Consortium of Nordic Universities
- Hosting organizations:
    * Telescope: University of Turku (FI)
    * Operations: Aarhus University (DK)
- National funding (DK,FI,IS,NO) through Nordic Universities
- Stockholm University new member
- Shares of observing time according to contribution

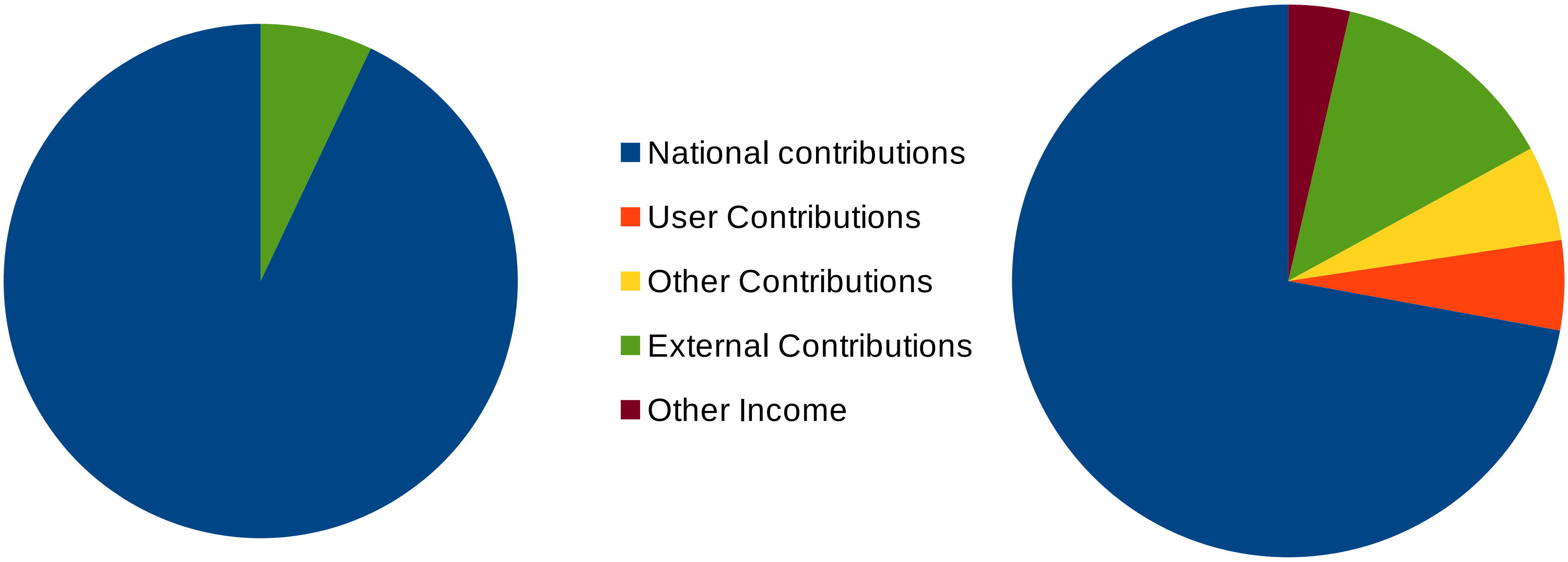
Executive body:
NOT Board & Council
Director & Executive Committee
Observing Programmes Committee (OPC)



What has changed

Annual Budget

2012 **2022**



~1.75M€ **~1.5M€**


Photo: Magnus Gålfalk

The telescope

- Alt/az mount, compact dome, low cost, no dome seeing
- Exceptional elevation limit (6.4 deg)
- F/11 Ritchey-Chretien optical system
- 2.56 m diameter main mirror (Korhonen, Turku)
- Telescope Control System, safe & flexible, linked to weather station with automatic closing for bad weather
- Operated 365 days/yr

Down time:	
Weather (summer)	~10 %
(winter)	~35 %
Technical problems:	~0.5-1 %

Instrumentation

StanCam
Standby 1k x 1k
CCD
UBVRI+Hα

FIES
High-resolution fiber
spectrograph

Stand-by

One of these
in Cassegrain
focus.

NOTCam
Near-IR camera
and spectrograph

ALFOSC
Optical camera
and
spectrograph

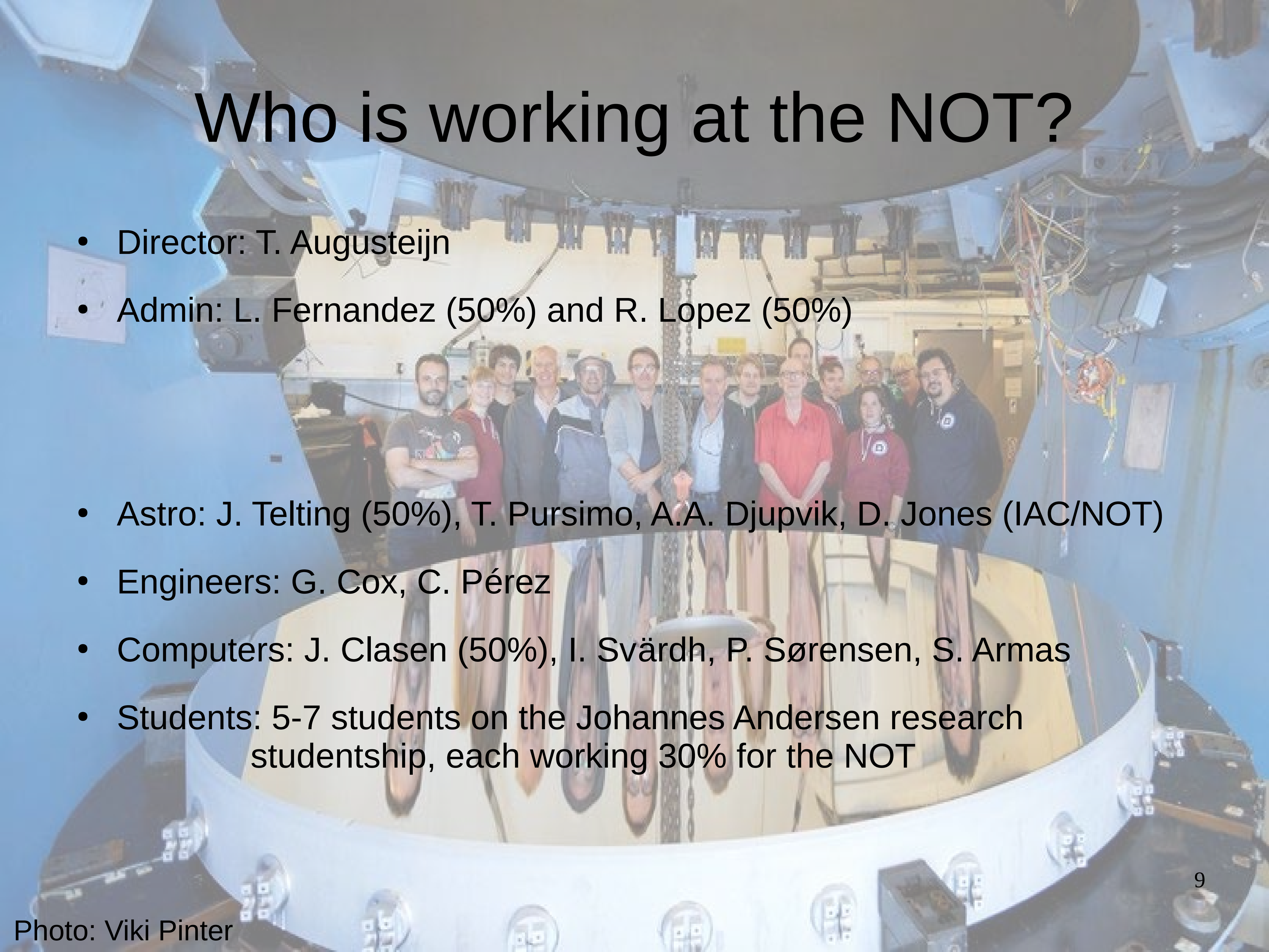
MOSCA
4 x (2k x 2k)
CCDs
Direct imager

SOFIN
High-resolution
spectrograph
PI: T. Hackman

DIPol-UF
BVR imaging
polarimeter
PI: A. Berdyugin

NB! Visitor
instruments.

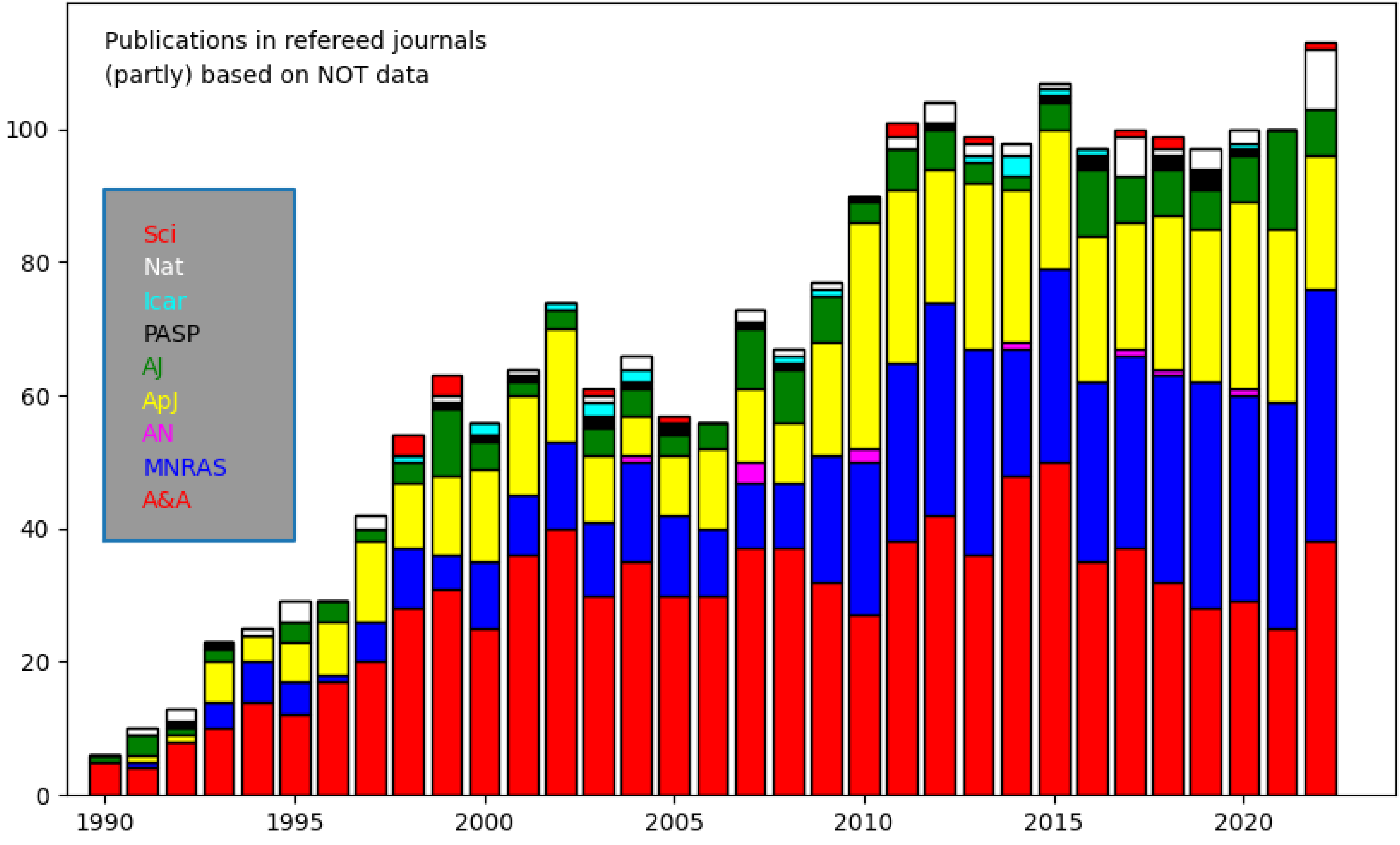
Who is working at the NOT?



- Director: T. Augusteijn
- Admin: L. Fernandez (50%) and R. Lopez (50%)
- Astro: J. Telting (50%), T. Pursimo, A.A. Djupvik, D. Jones (IAC/NOT)
- Engineers: G. Cox, C. Pérez
- Computers: J. Clasen (50%), I. Svärdh, P. Sørensen, S. Armas
- Students: 5-7 students on the Johannes Andersen research studentship, each working 30% for the NOT

Photo: Viki Pinter

Refereed publications



Types of observing modes:

Target of Opportunity (ToO)
- trigger based OBs
- Soft/Hard ToO
- can have hard override

Monitoring
- scheduled OBs

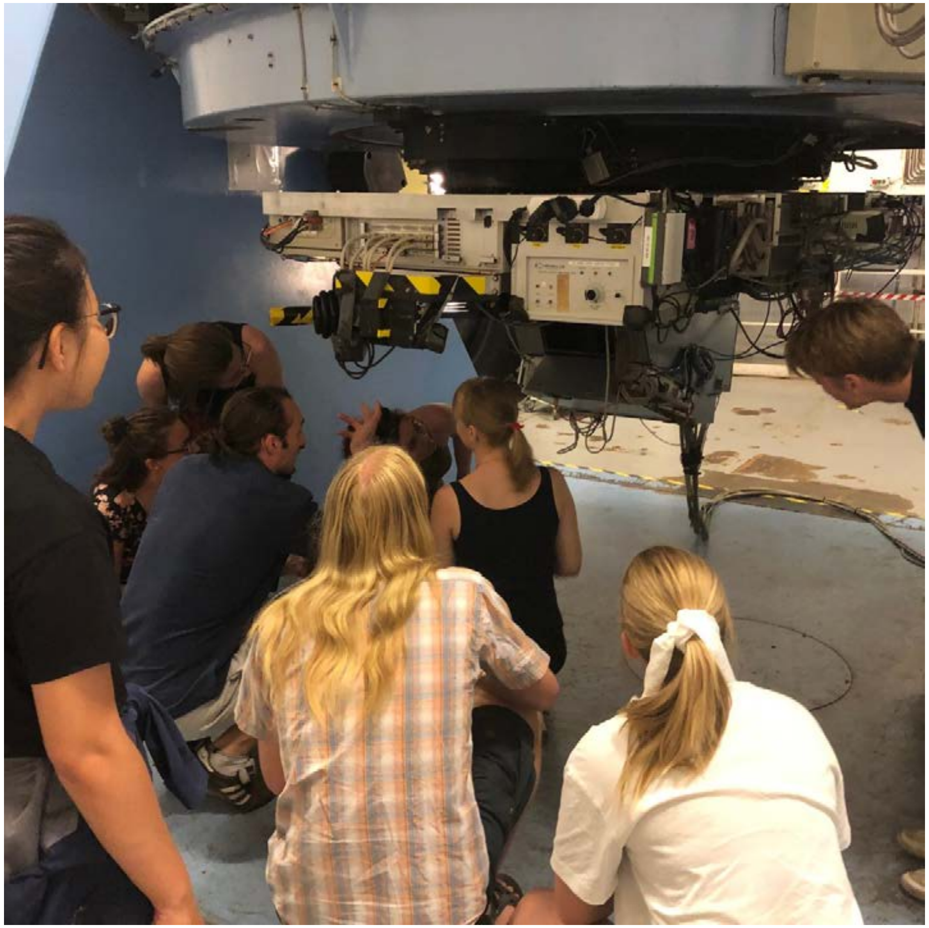
Fixed service mode
- pre-scheduled

Fast-track + Payback
- queued OBs
- requirement on sky conditions

Remote observing (schools)

Visiting observers

The educational role



From the latest on-site observing course, NBI (Denmark), August 2023
The NOT is giving unique hands-on experience for students

Schools/Courses

On-site courses or remote observing courses (VNC)
10 nights/semester dedicated to observational courses

- International schools: ChETEC-INFRA,
  NEON schools
  NORDFORSK schools
  NOT/Onsala Optical/NIR/Radio school
  Nordic Astrobiology Network

- University courses: Stockholm University
  NBI institute Copenhagen
  FINCA Turku & Helsinki Universities
  NTNU in Trondheim
  Tartu University, Estonia

- Horten videregående skole (research line)

Studentships at NOT:

“Johannes Andersen Student Programme”

- at any time we have 6-7 students stationed at the NOT

- astronomy students enrolled in MSc or PhD studies

- stay at the NOT 12 (+ 6) months as part of the team

- 30% of the time dedicated to NOT

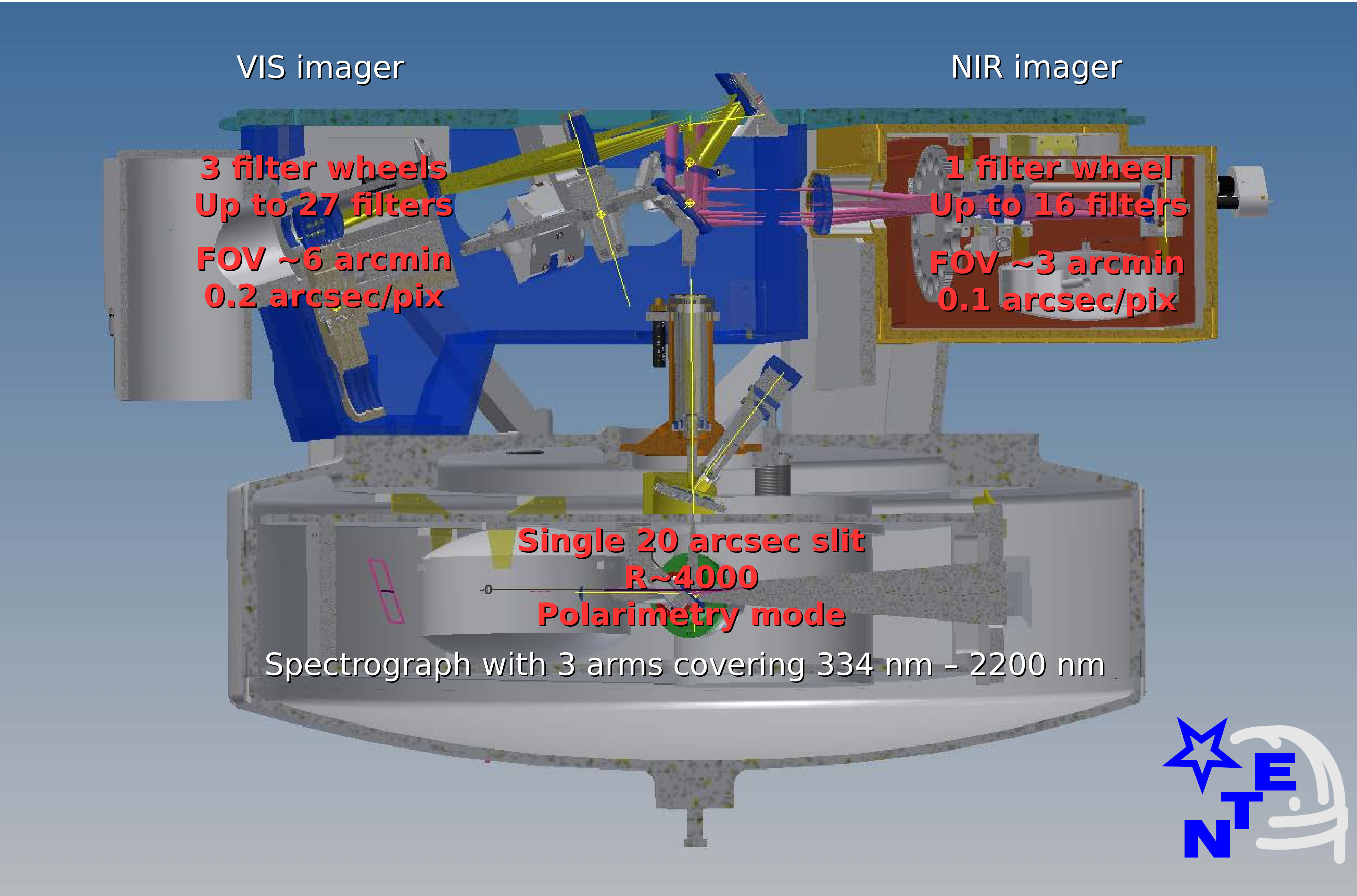
Over the years from 1990-2023:

110 NOT students

Photo: D. Juncher


NOT - a telescope for the future
2022 Jun 7-10
INVITED SPEAKERS
Michael Andersen, University of Copenhagen
Thomas Augusteijn, Nordic Optical Telescope
Andrei Berdyugin, University of Turku
Lars Buchhave, Technical University of Denmark
Frédéric Courbin, Swiss Federal Institute of Technology in Lausanne
Håkon Dahle, University of Oslo
Jesús Falcón Barroso, Instituto de Astrofísica de Canarias
Johan Fynbo, University of Copenhagen
Terese Hansen, Stockholm University
Hans Kjeldsen, Aarhus University
Jari Kotilainen, University of Turku
Jyri Lehtinen, University of Helsinki
Tiina Liimets, Czech Academy of Sciences
Yannis Liodakis, University of Turku
Jane Luu, University of Oslo
Daniele Malesani, Radboud University
Isabel Márquez, Instituto de Astrofísica de Andalucía
Marco Micheli, ESA NEO Coordination Centre, Frascati
Semeli Papadogiannakis, FOI, Swedish Defence Research Agency
Nikolai Piskunov, Uppsala University
Jesper Sollerman, Stockholm University
Max Stritzinger, Aarhus University
H10 Hotel
Taburiente Playa
La Palma Spain
In memoriam
Johannes Andersen
SCIENTIFIC ORGANIZING COMMITTEE
Simon Albrecht, Aarhus University
Anlaug Amanda Djupvik, NOT
Mikael Granvik, University of Helsinki
Kasper Elm Heintz, University of Copenhagen
Erkki Kankare, University of Turku (Chair)
Ragnhild Lunnan, Stockholm University
Kari Nilsson, University of Turku
Birgitta Nordström, University of Copenhagen
Mia Sloth Lundkvist, Aarhus University
Ása Skúladóttir, University of Firenze
Luc Rouppe van der Voort, University of Oslo
Coming together to explore science, instrumentation and education with the Nordic Optical Telescope.
Local Organizing Committee:
Sergio Armas, Thomas Augusteijn, Enrico Biancolini, Jacob Clasen, Rosa Clavero, Graham Cox, Anlaug Amanda Djupvik (Chair), Loida Fernandez, Anni Kasikov, Raquel López, Peter Meldgaard Sørensen, Carlos Perez, Tapio Pursimo, Ingvar Svärdh, John Telting, Angela Toledo (Designer), Akke Viitanen
Photo: Joonas Viuho and Giovanni Tessicini
AARHUS UNIVERSITET
UNIVERSITY OF TURKU
workshop2022@not.iac.es
https://indico.not.iac.es/e/workshop2022/
La Palma

NOT Transient Explorer



Star formation studies with the NOT

Two “portals” into learning about accretion/ejection processes in young stars

a) Low mass stars – infrared imaging & spectroscopy using **NOTCam**

Kinematic study of embedded protostellar jets

T. Liimets (Tartu Observatory) , H. Zinnecker (SOFIA Science Center), Nordforsk summer school 2009 students

b) Intermediate mass stars – optical high-resolution spectroscopy using **FIES**

Spectral variability in fading UX Orionis stars

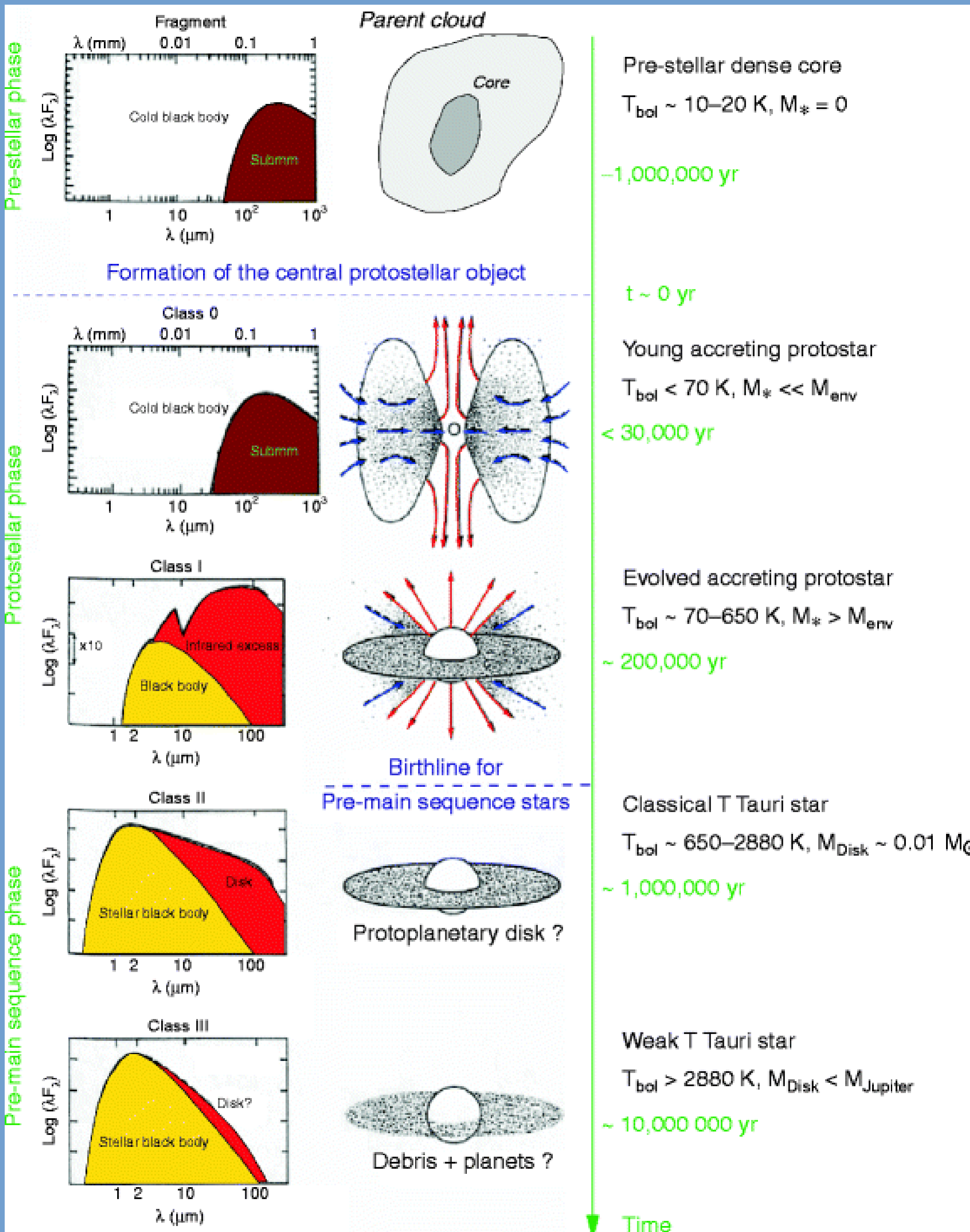
G. Gahm (Stockholm Observatory),

H. Weber, T. Grenman (Luleå University of Technology)

V. Grinin, L. Tambovtseva (Pulkovo Astronomical Observatory)

Svensk Amatör Astronomisk Förening - observers

M16 (credit: H. Uthas)



YSO evolution

Lada 1987
Shu et al. 1987
Adams et al. 1987
André et al. 1993
Myers et al. 1998

Defined for low-mass stars:
0.3 – 1.5 M_{sun}

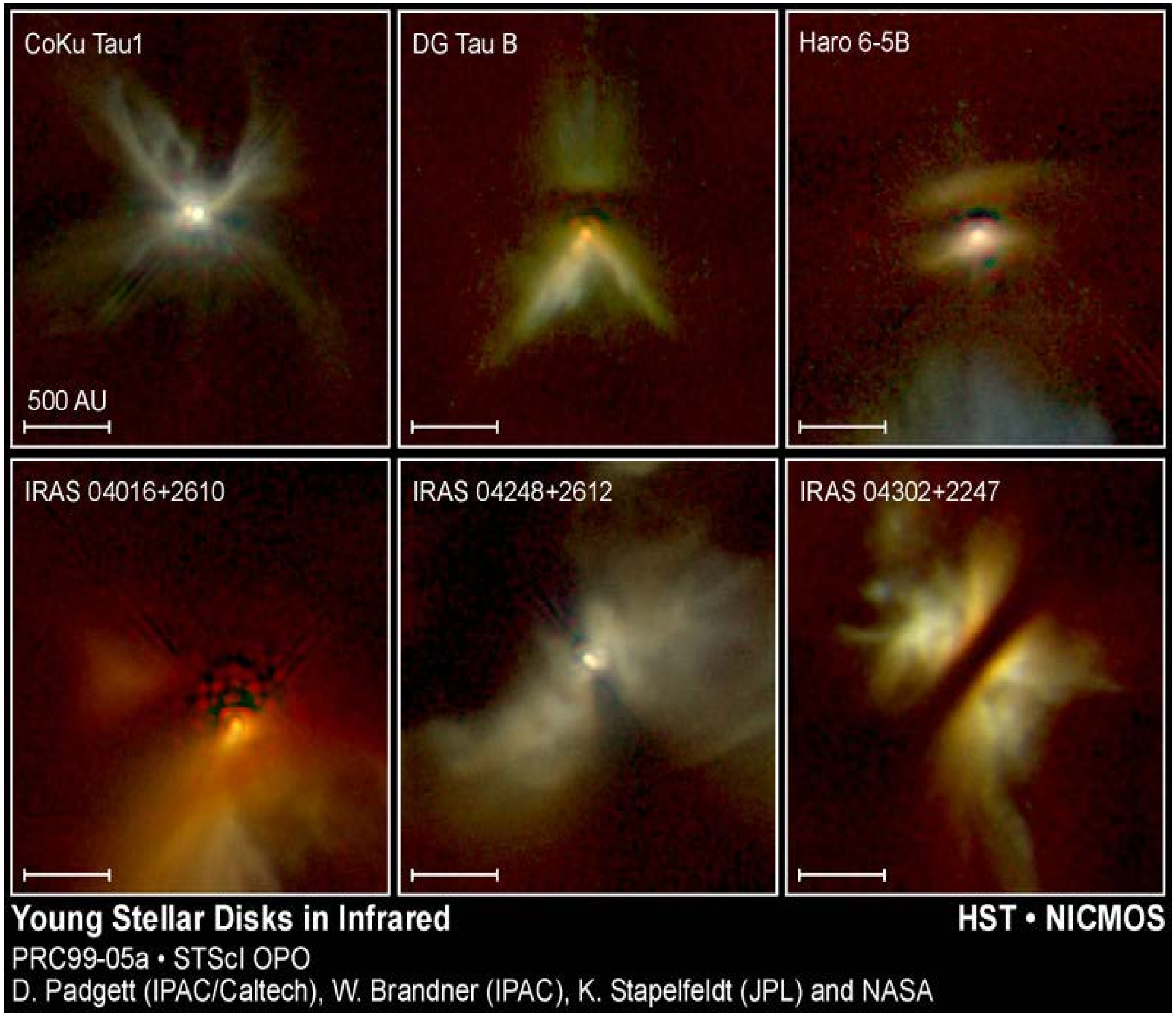
Likely holds for < 0.3 M_{sun}
(Luhman, 2012)

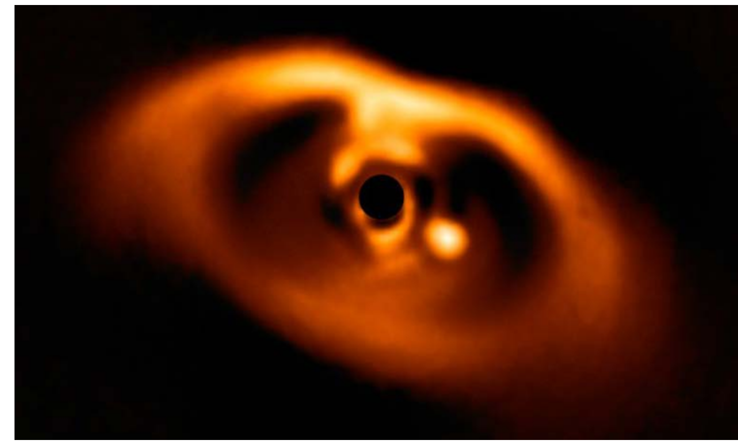
Intermediate to massive:
1.5 - 8 M_{sun} Herbig Ae/Be

Also YSOs 8 – 30 M_{sun}
have disks (Kraus et al. 2010)

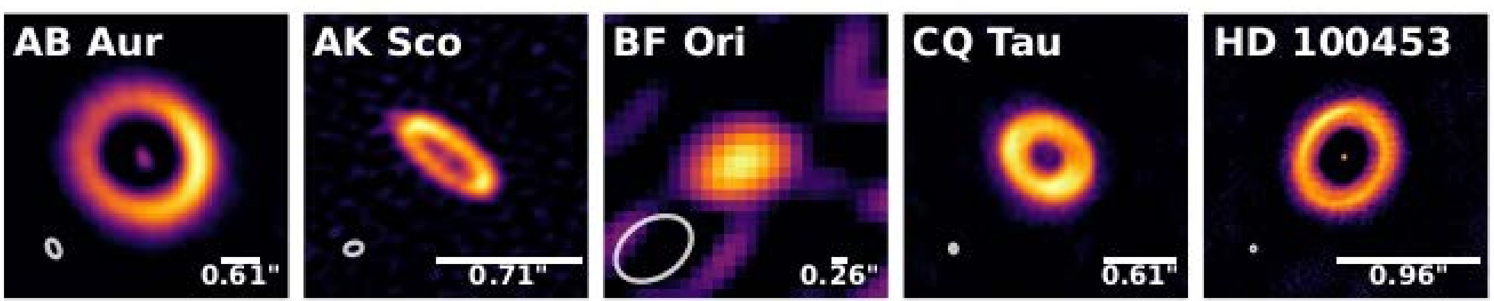
P. André, 2011

Young stellar objects and their protoplanetary disks





PDS70b SPHERE/ESO
Keppler et al. 2018, A&A 617, A44

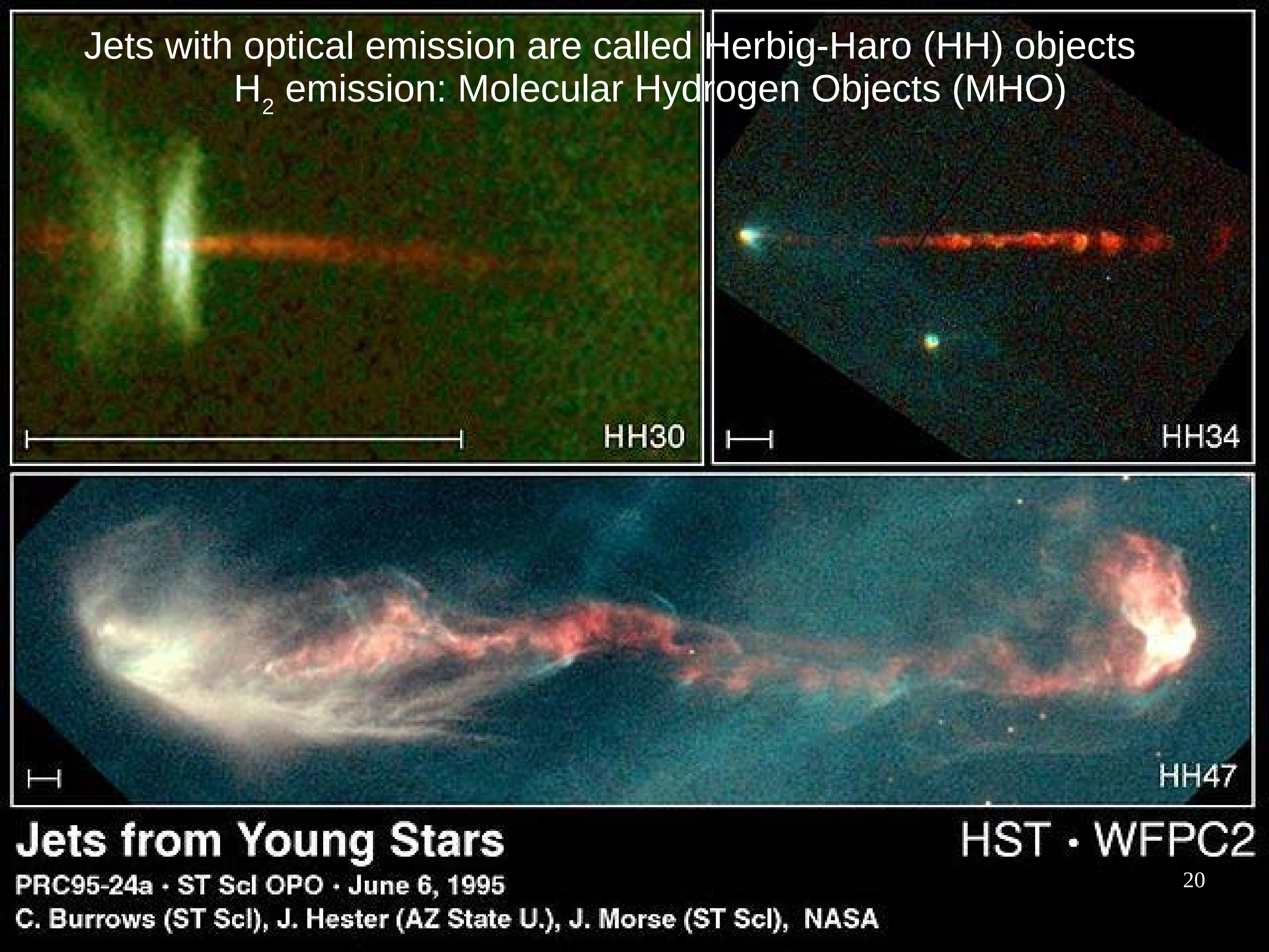


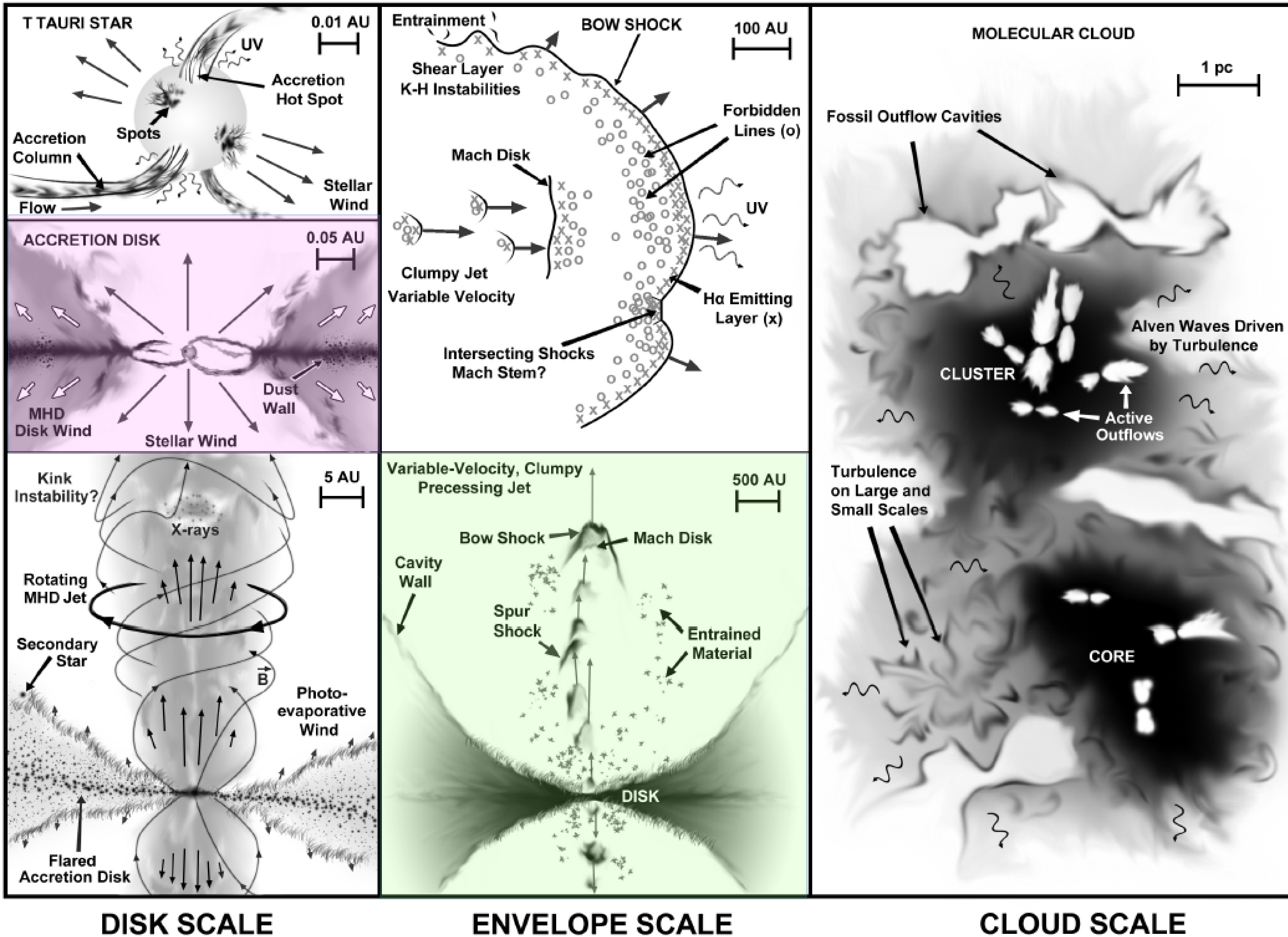
ALMA study of 36 Herbig disks

Stapper et al. 2022, A&A 658, 112

Jets with optical emission are called Herbig-Haro (HH) objects

H_2 emission: Molecular Hydrogen Objects (MHO)

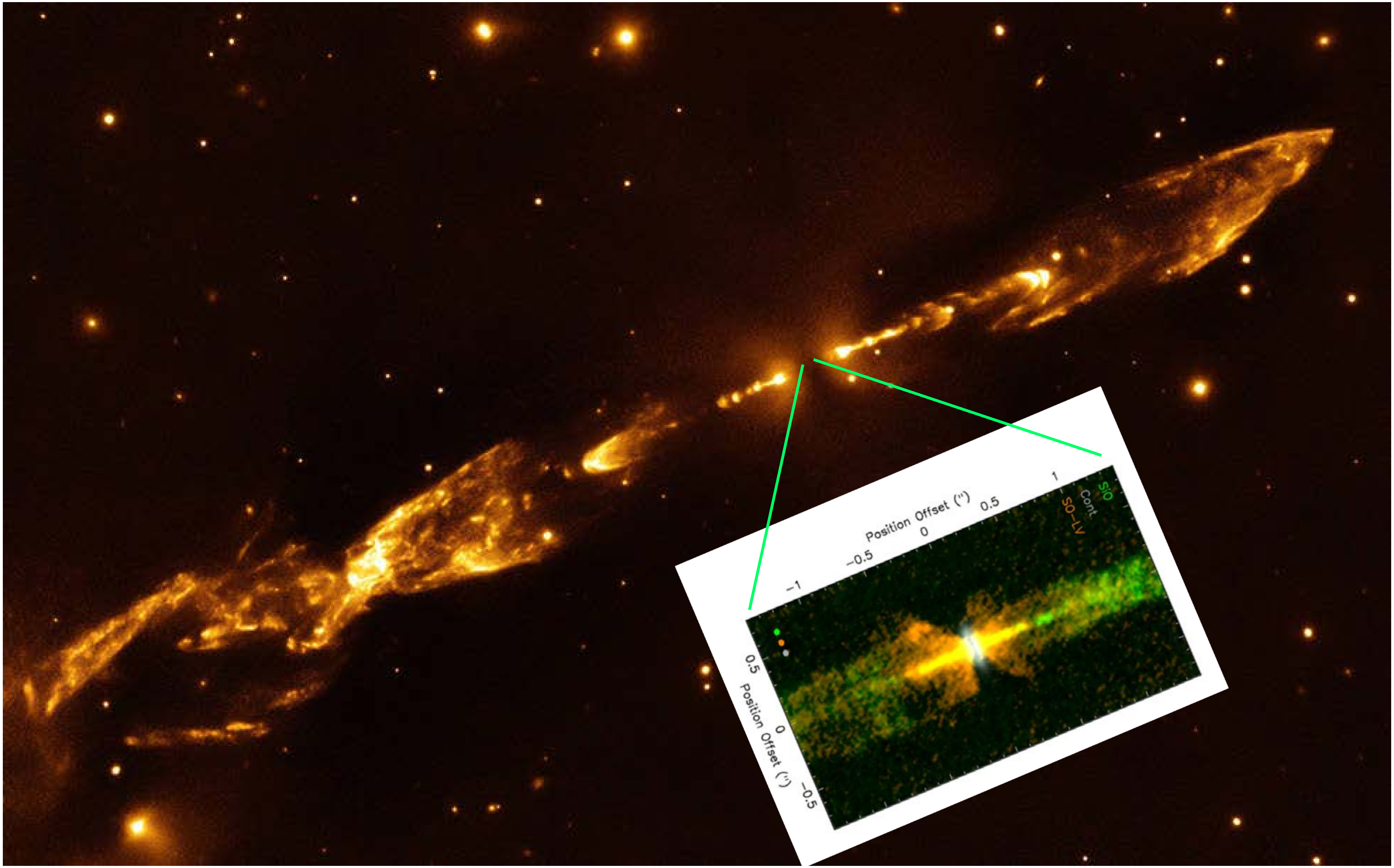




Frank et al. 2014, Protostars and Planets VI

Protostellar jets, outflows, accretion

- Jets exist in accreting systems: Young Stellar Objects (YSOs), evolved binaries, Active Galactic Nucleis (AGNs)
- Jet launching mechanism? Magneto-centrifugal disk wind?
- Bipolar flows remove mass and angular momentum from system
- How much energy is injected into the surrounding cloud?
- What can the jet tell us about the accretion history of the star?
- What is the relation between jet power and evolution stage?
- What about binary (or planet) formation?



Credit: McCaughrean, ESO
Zinnecker, McCaughrean, Rayner, 1998, Nature 394, 862

Lee et al. 2021 ApJL 907, L41

HH 212

A multi-wavelength census of star formation activity in the young embedded cluster around Serpens/G3-G6⋆,⋆⋆

A. A. Djupvik[1,⋆⋆⋆], Ph. André[2,5], S. Bontemps[3], F. Motte[2,5], G. Olofsson[4], M. Gålfalk[4], and H.-G. Florén[4]

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[4] Stockholm Observatory, Roslagstullsbacken 21, 10691 Stockholm, Sweden
[5] AIM – Unité Mixte de Recherche CEA – CNRS – Université Paris VII – UMR 7158, France

Received 3 May 2006 / Accepted 6 July 2006

NOTCam discovery

Discovery of embedded protostellar jets!

NB filter on H_2 line v=1-0 S(1) 2.122 µm

2003 data was to become first epoch
of a later proper motion study.

MHO 2233, MHO 2234, MHO 2235

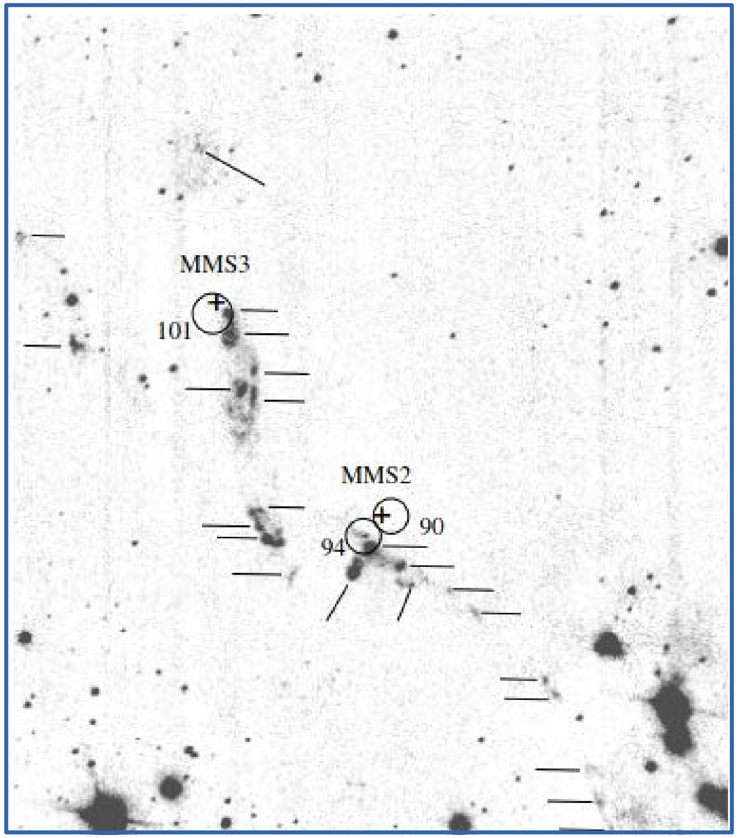
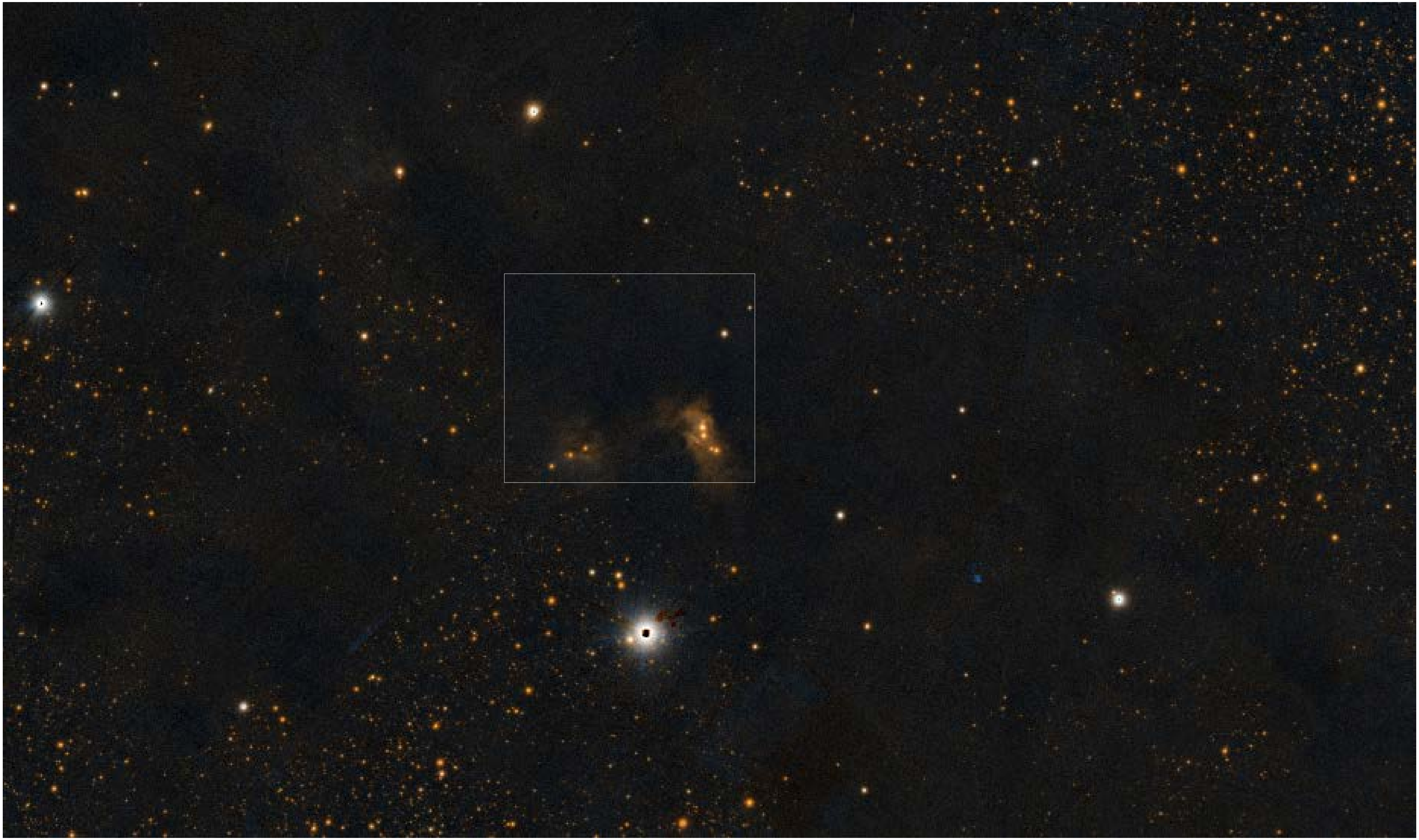


Fig. 13. NOTCam H_2 line image (2.122 μm) of Ser/G3-G6NE. Pure line emission features are arrowed (cf. the continuum image in Fig. 14). The locations of the two bright mm sources MMS2 and MMS3 are marked with plus signs. The Class I candidates ISO-90 and 94, as well as ISO-101, probably a hot spot in the jetlike emission, are encircled.

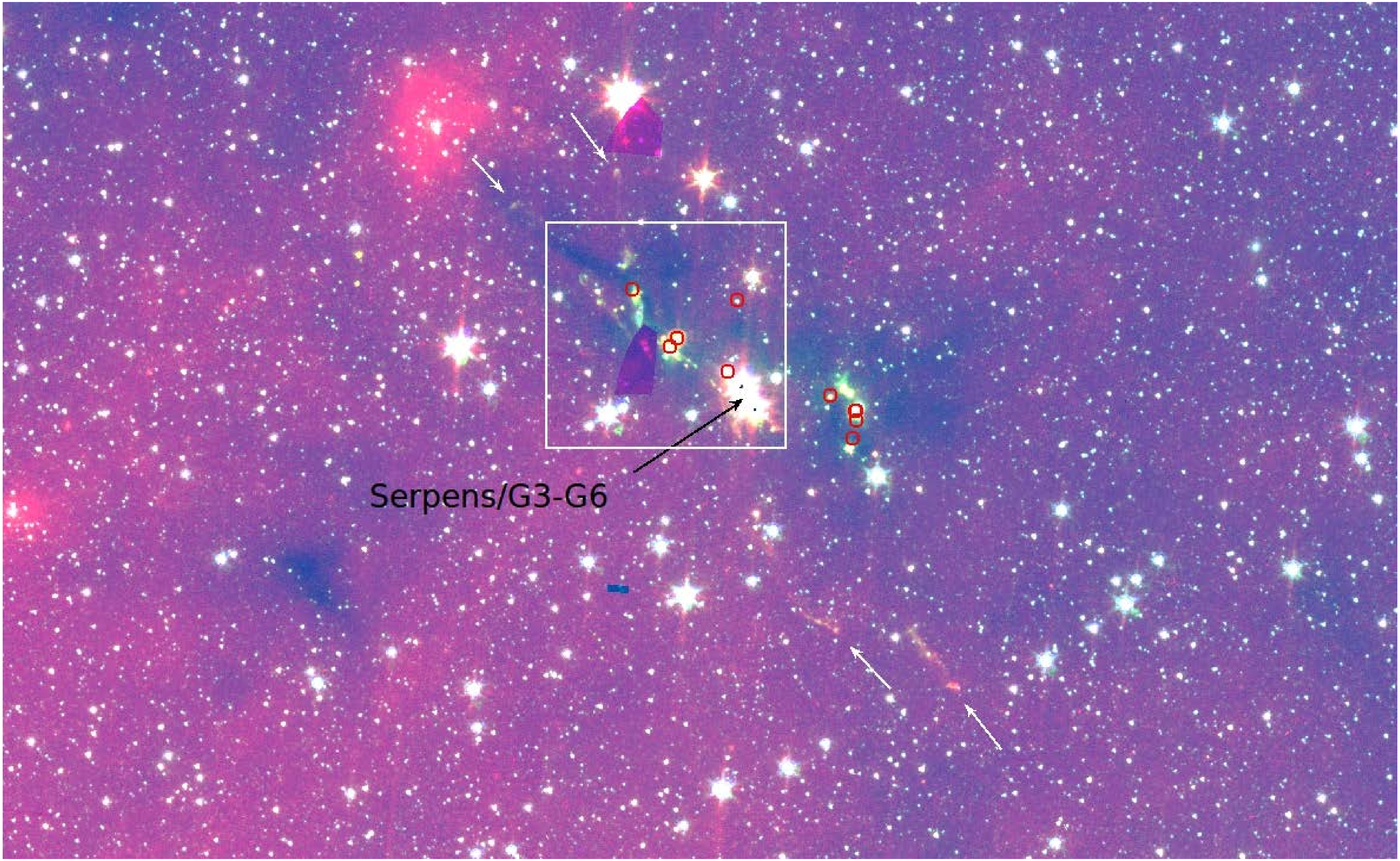
Djupvik et al. 2006, A&A 458, 789

Optical image - Serpens/G3-G6



PanSTARRS DR1 g’ (4800 Å) and z’ (8300 Å)

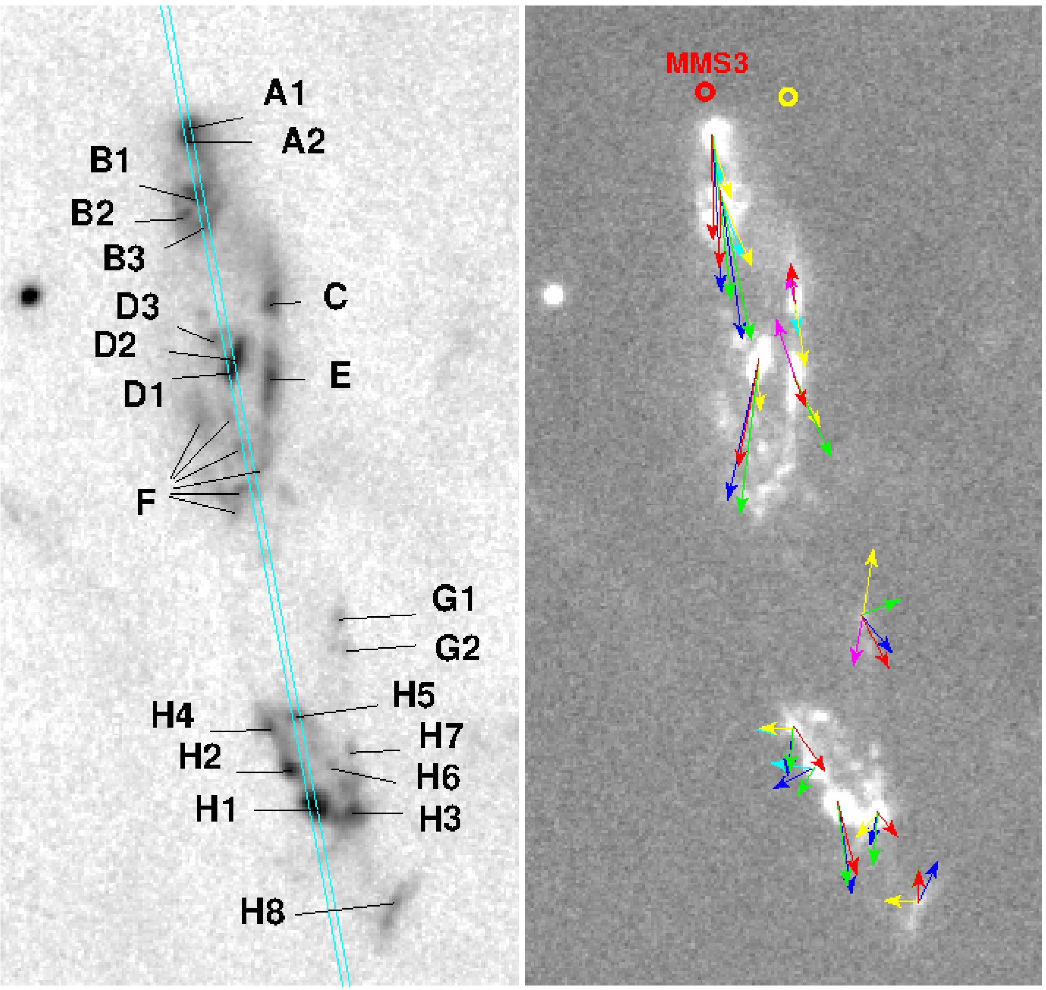
INFRARED!



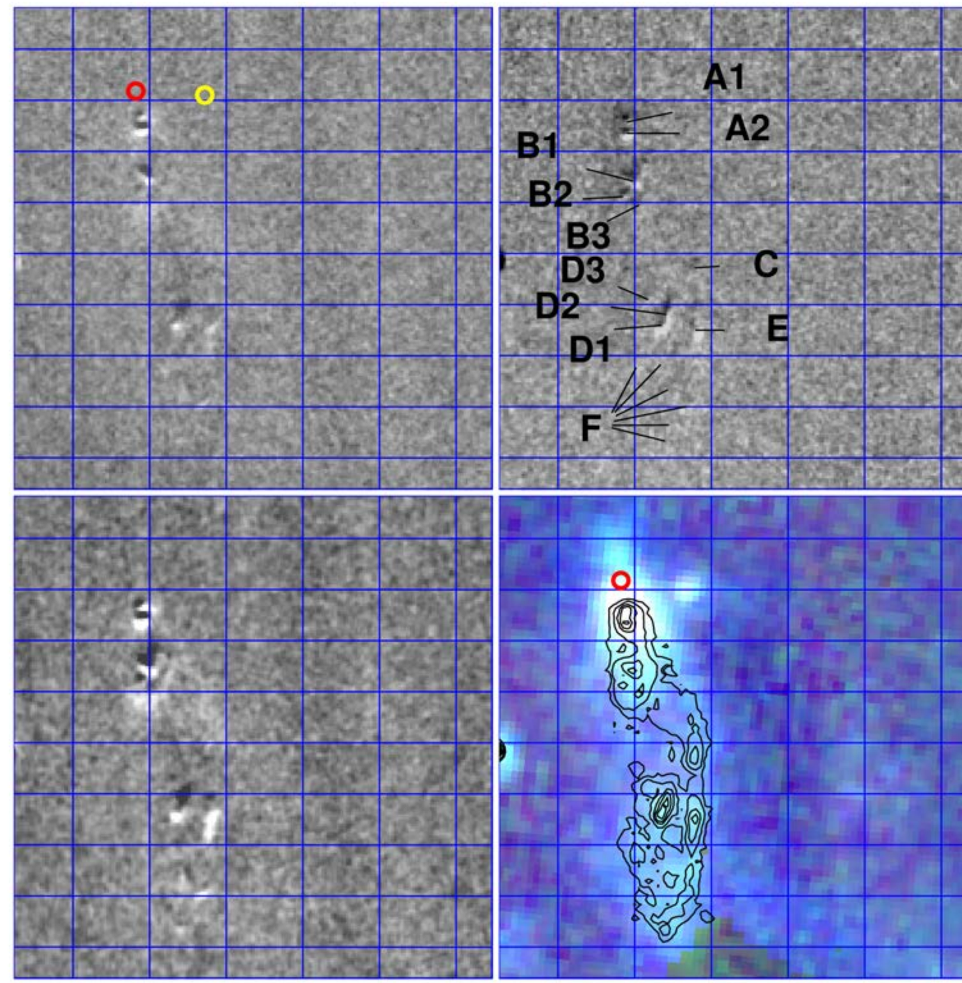
Spitzer IRAC image (3.6, 4.5, and 8.0 µm bands).

Deep NOTCam H2 line imaging at four epochs: 2003, 2009, 2011, 2013:

- Identified 57 knots, reliable positions and fluxes for 31 knots
- images matched globally using 60 stellar PSFs, gave positional accuracy of 0.06”
- Over 10 years baseline 17 knots have measurable proper motions



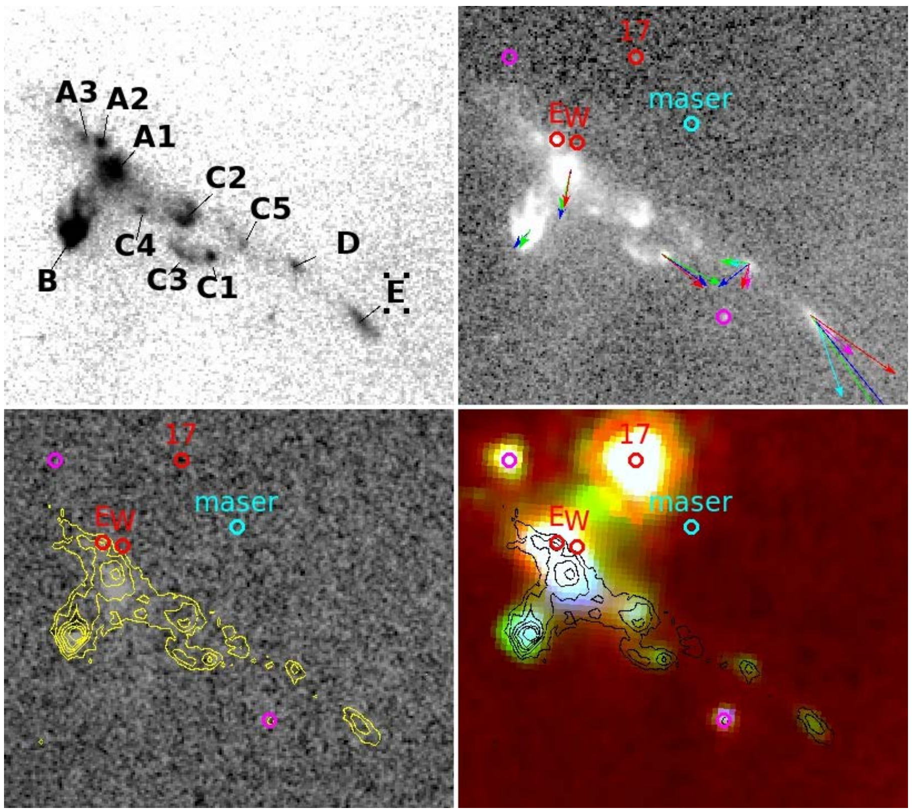
Southern part of Class 0 flow. Class 0 is MMS3. Coloured arrows refer to different baselines used.

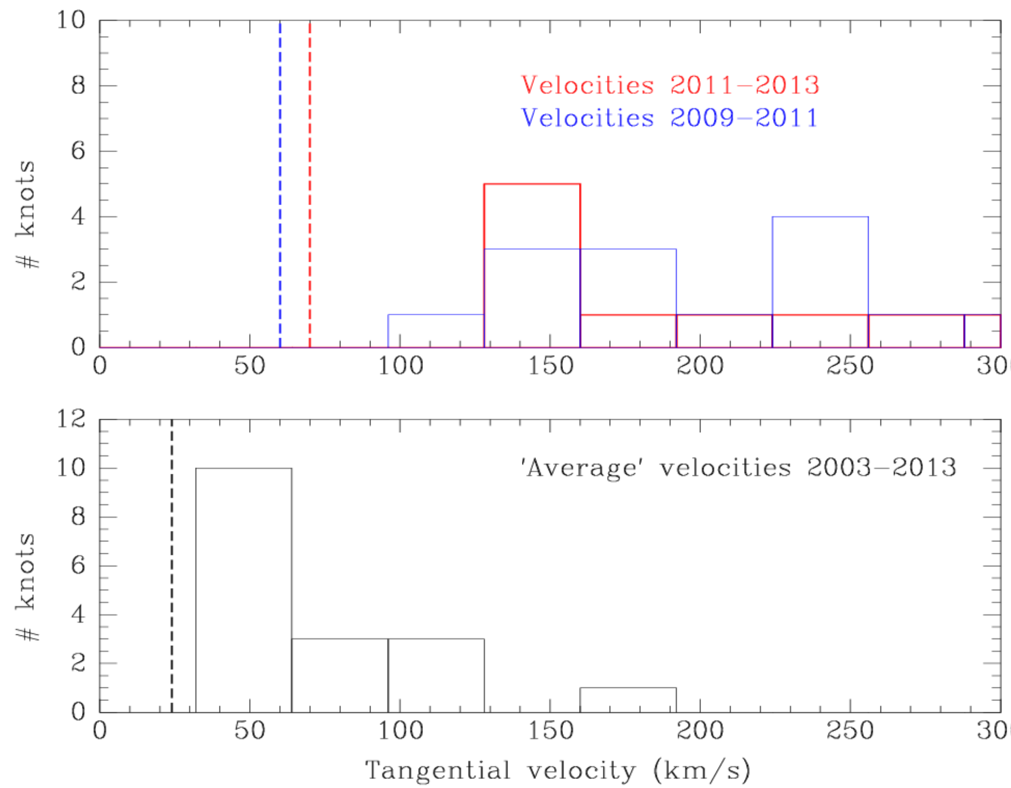


Difference images. Upper left: 2009-2003, right:2011-2009. Lower left: 2013-2003. Lower right: Spitzer 4.5 μm image.

NOTCam multi-epoch proper motion study finds:

- tangential velocities up to 190 km/s, median: 50 km/s, over 10 year baseline
- over 2-year baselines, very high velocities! → time-variable knot velocities!





Central part of two Class I flows.

Ser-emb-11EW Class I binary, and Ser-emb-17 classified by Enoch et al. 2009)

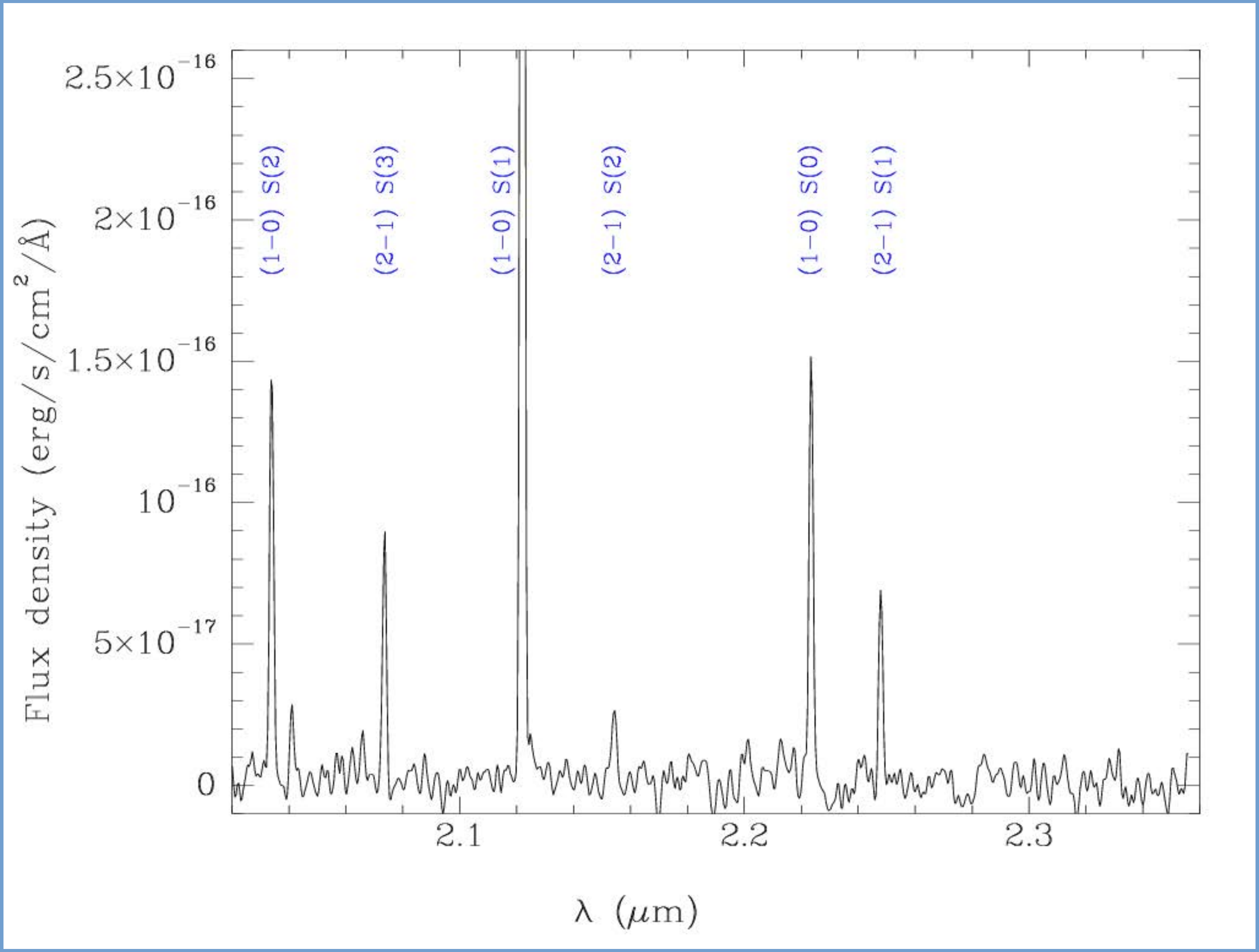
Accelerated and decelerated motion.

Also noted in HH 154 (Bonito et al. 2008), and in HH 52 and 54 (Caratti o Garatti et al. 2009)

NIR spectroscopy of knots

NOTCam K-band spectra (R = 2100 or 140 km/s) of the brightest knots

Radial velocities range from -32 km/s to +16 km/s (relative to the cloud) +- 4 km/s



Space velocities → Identification of flows and driving sources (protostars)

Dynamical ages: $t_{dyn} = L / v$

NOTCam deep H_2 narrow-band image

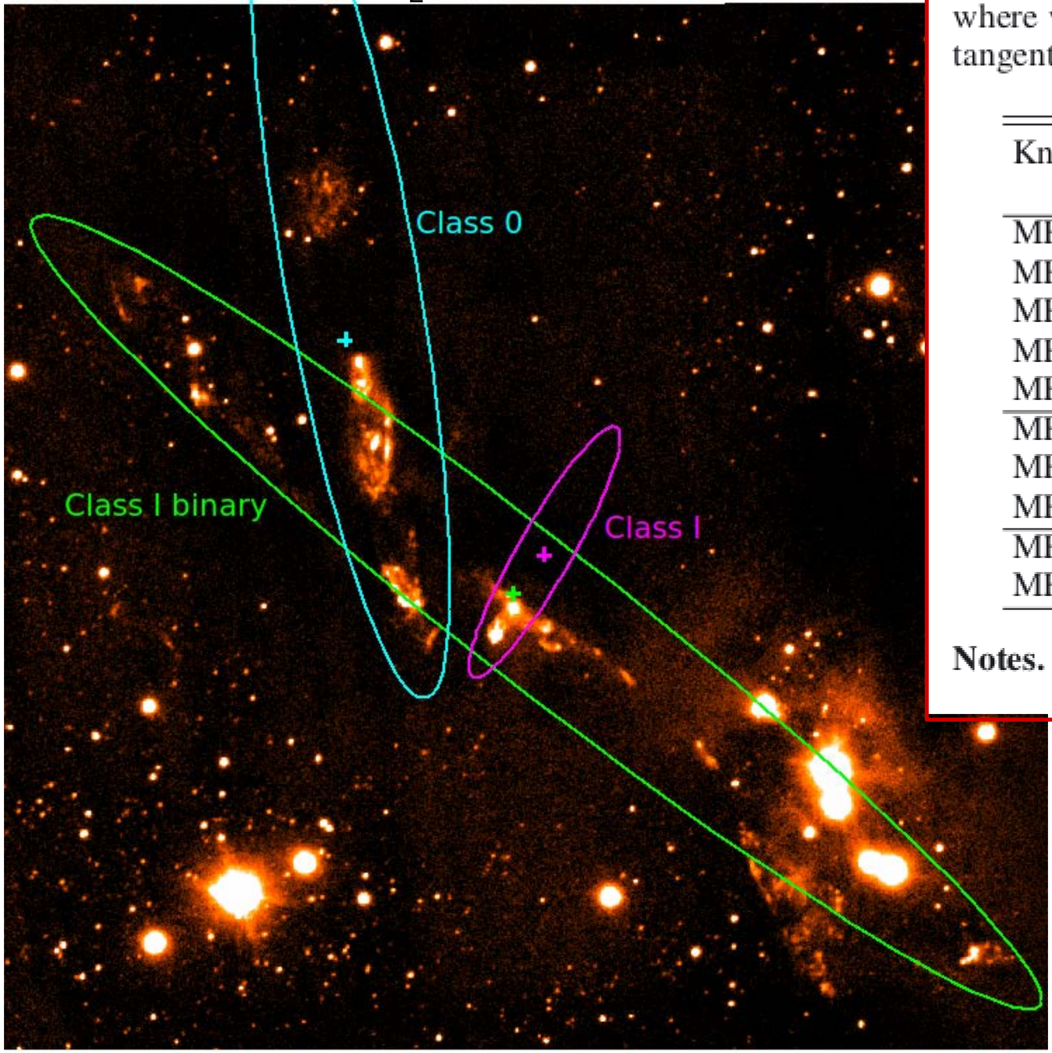


Table 9. Dynamical ages of the knots based on their jet lengths, i.e. separation from the candidate driving source, and their current velocities, v, where we adopt the space velocities when available, and otherwise the tangential velocities on the longest timescale available.

Knot	F	Driving YSO candidate	Length (pc)	v (km s^{-1})	τ_{dyn} (yr)
MHO 2234-A2	1	MMS3	0.009	125	70
MHO 2234-B1	1		0.019	116	160
MHO 2234-D1+D2	1		0.048	110	420
MHO 2234-H1	1		0.123	72	1680
MHO 2234-I1	1		0.078	40	1900
MHO 2233-N	2	Ser-emb-11	0.174	42	4050
MHO 2235-I2	2		0.208	74	2750
MHO 2235-M4	2		0.264	44	5860
MHO 2235-A1	3	Ser-emb-17	0.028	54	507
MHO 2235-B	3		0.044	26	1650

Notes. The flow for each knot is given in Col. 2.

Youngest feature ~ 70 yr !

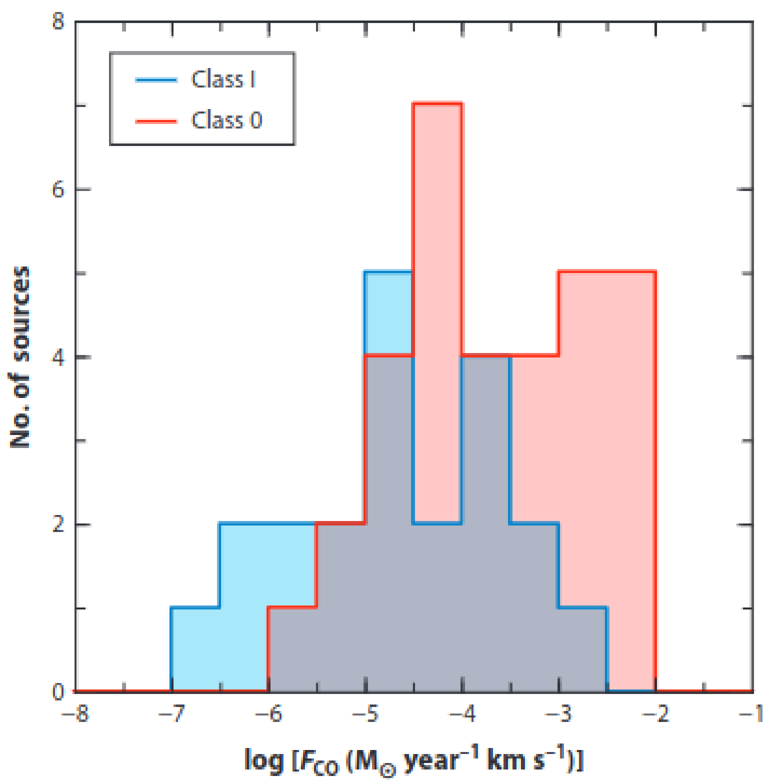
Table 10. Estimates of total H_2 luminosity, mass, mass flow rate, and momentum flux in each flow, as obtained by summing over the individual knots.

Flow	L_{bol} ($L_\odot$)	L_{H_2} ($L_\odot$)	M_{H_2} ($M_\odot$)	$\dot{M}_{out}$ ($M_\odot$ yr^{-1})	$\dot{P}_{H_2}$ ($M_\odot$ km s^{-1} yr^{-1})
1	4.1	0.3	8.7×10^{-5}	1.0×10^{-6}	1.3×10^{-4}
2	4.8	0.02	2.0×10^{-6}	2.0×10^{-9}	2.6×10^{-7}
3	3.8	0.04	8.6×10^{-6}	3.3×10^{-9}	1.9×10^{-7}

Notes. L_{bol} of the driving source are from Enoch et al. (2009, 2011).

Mass-loss rate
Momentum flux

Class 0



Are Class 0 jets stronger in general? Evolution?

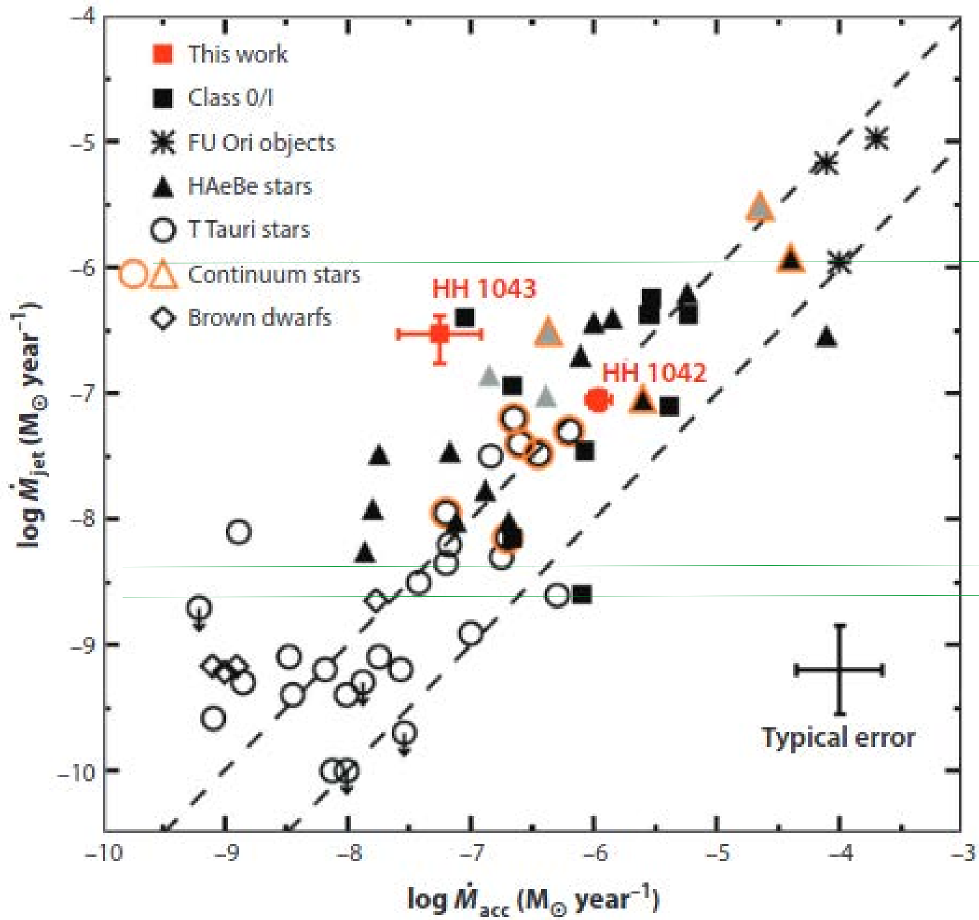
CO outflows in Class 0s are higher than in Class Is (Bontemps et al. 1996). But not so clear for jets.

Or partly due to an episodic event?

Most momentum carried by two knots close to the Class 0 source. Episodic nature of ejection/accretion.

Adopted from Mottram et al. 2017, A&A 600, A99, see Annual Review A&A by Bally 2016 on “Protostellar Outflows”

Relation between mass loss and mass accretion



Compilation from Ellerbroek et al. 2013, A&A 551, 5

$\dot{M}_{jet}/\dot{M}_{acc}$ ~ 0.01 – 0.1

Class 0

$$\dot{M}_{acc} \sim 10^{-4}\ M_\odot\ yr^{-1}.$$

Class I

$$\dot{M}_{acc} = \left(1 - \frac{R_*}{R_{in}}\right)^{-1} \frac{L_{acc} R_*}{G M_*}$$

Gullbring et al. 1998, ApJ 492, 323

We can not measure L_{acc} in the deeply embedded driving source. Use above relation.
A generally higher mass accretion rate? A recent (70 yr ago) burst of mass accretion.

Conclusions 1

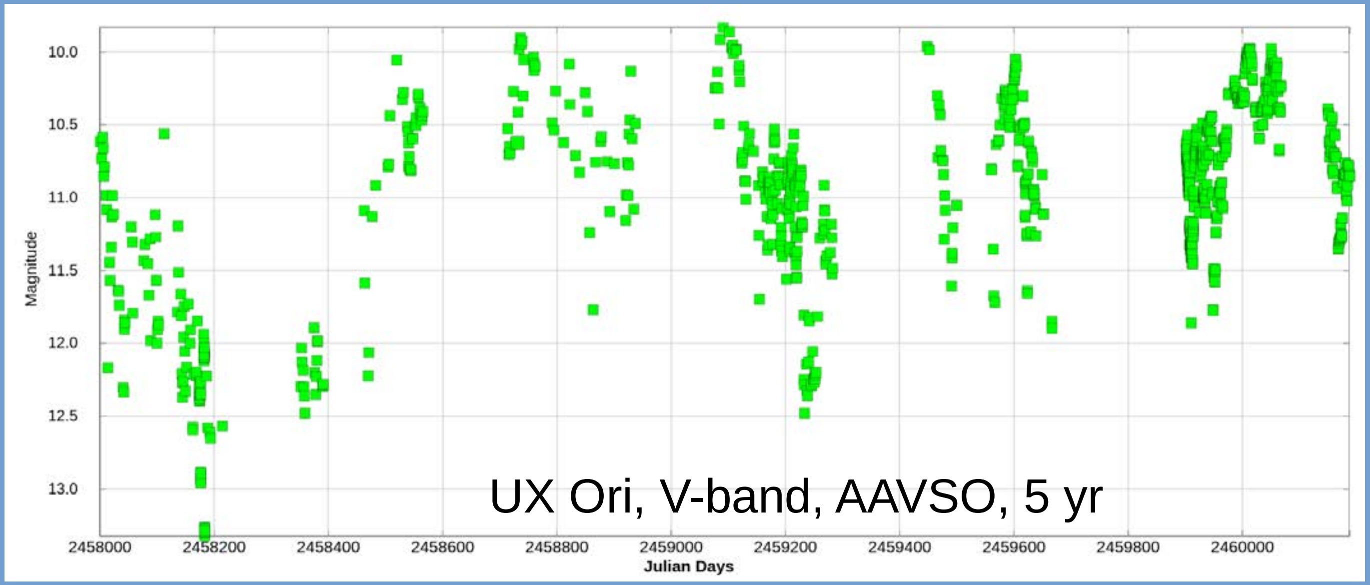
- Multi-epoch NOTCam images high precision proper motions
- K-band spectra → physical properties and radial velocities
- Kinematics of 3 new protostellar jets (+ time-variable velocities)
- Locate the driving sources (Class 0, Class I, binary Class I)
- Estimate mass-loss rate and momentum flux
- Jet power strongest in the youngest protostar
- Transient/episodic nature, a recent burst of accretion?
- TBD: larger field and more epochs
- Thanks to excellent image quality at the NOT

Djupvik, Liimets, Zinnecker et al. 2016, A&A 587,75

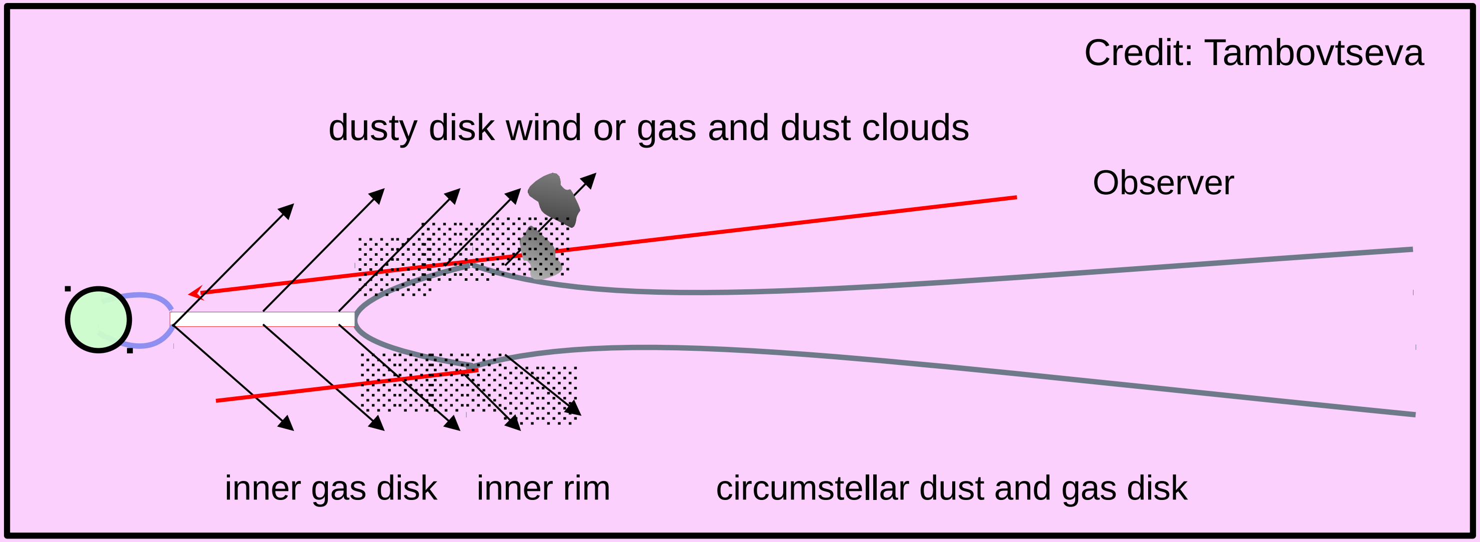
The UXOR phenomenon

This particular behaviour gives insight into the inner disk region

- About 25% of Herbig Ae/Be stars have UXOR variations
- Irregular brightness variations, ΔV ~ 2-4 mag
- duration from days to weeks, sometimes long-lasting minima
- the fainter the redder and stronger polarisation, then a “blueing effect”



Suggested mechanism:



UXORs are viewed through the dusty atmosphere of their accretion disks.

Variability caused by variable circumstellar extinction in the protoplanetary disk.
Based on linear polarization (Grinin et al. 1991), confirmed by near-IR interferometry (Kreplin et al. 2016, A&A 590, 96).

What causes disk material to be lifted up out of the disk?
How can observations with the NOT help?

The moving “dust clouds” obscure the star and part of the emission line region.

The inner disk region

the importance of magnetic fields

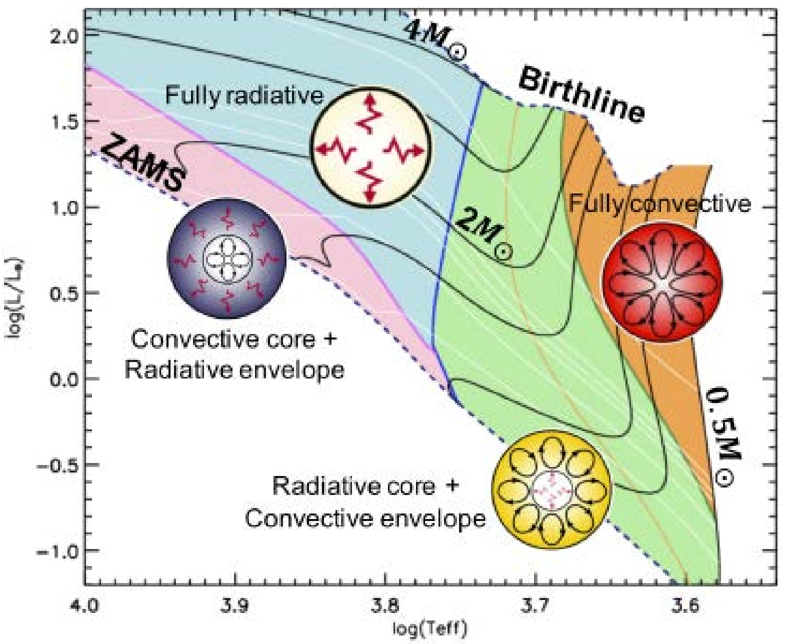
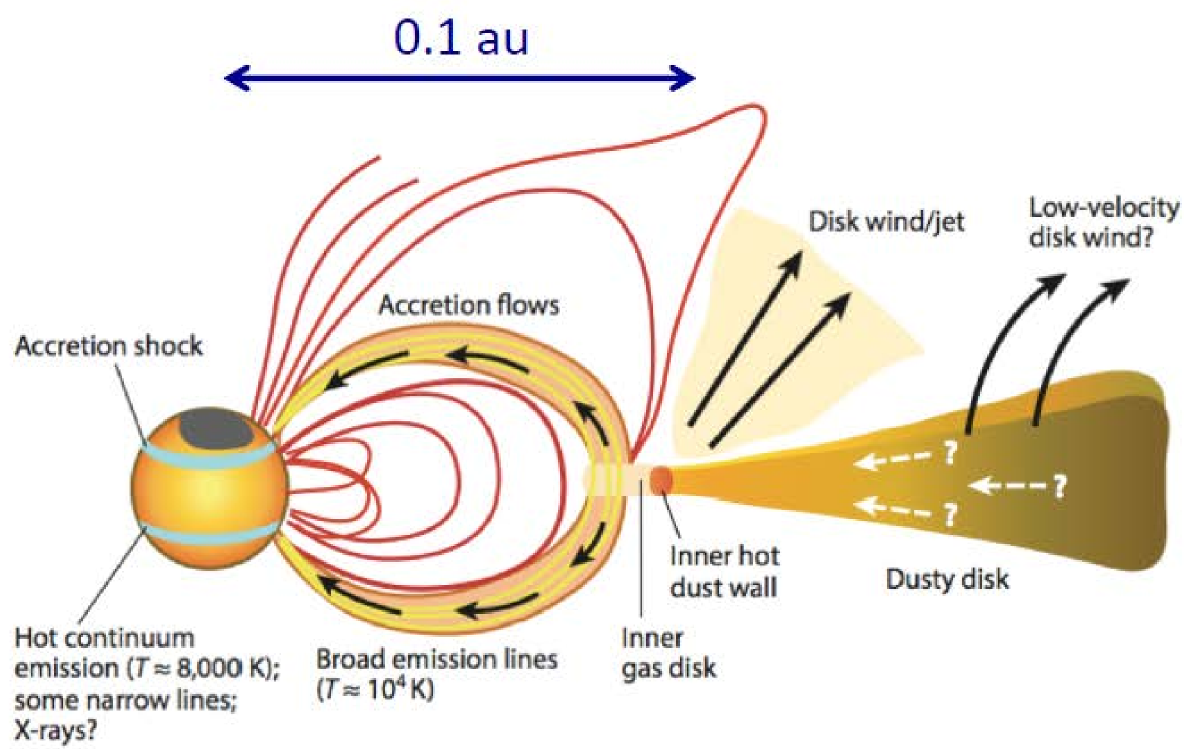


Fig. 1.6 Hertzsprung-Russell diagram of the optical phase of the star formation evolutionary sequence from the birthline to the zero age main sequence (ZAMS). Different colours trace different stellar interiors as indicated by the depictions. Evolutionary tracks appear in black (0.5, 0.8, 1, 1.5, 2, 3, and 4 $M_\odot$) and isochrones appear in white (1, 4, 5, 6, 10, and 20 Myr). The orange line indicates the location where 40% of the radius of the star is a convective envelope. Figure adapted from Alecian et al. (2013) and Villebrun et al. (2019).



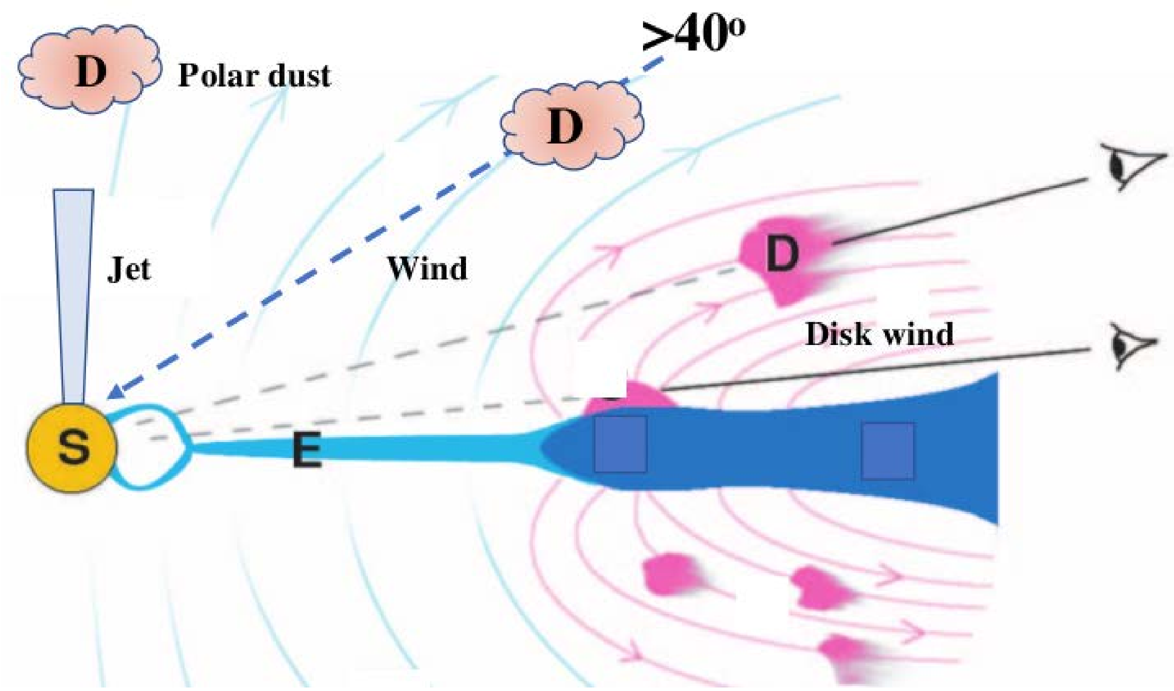
Camenzind (1990) Shu et al. (1994), Hartmann et al. (1994) Kurosawa et al. (2006,2011), Lima et al. (2010), Hartmann et al. (2016)

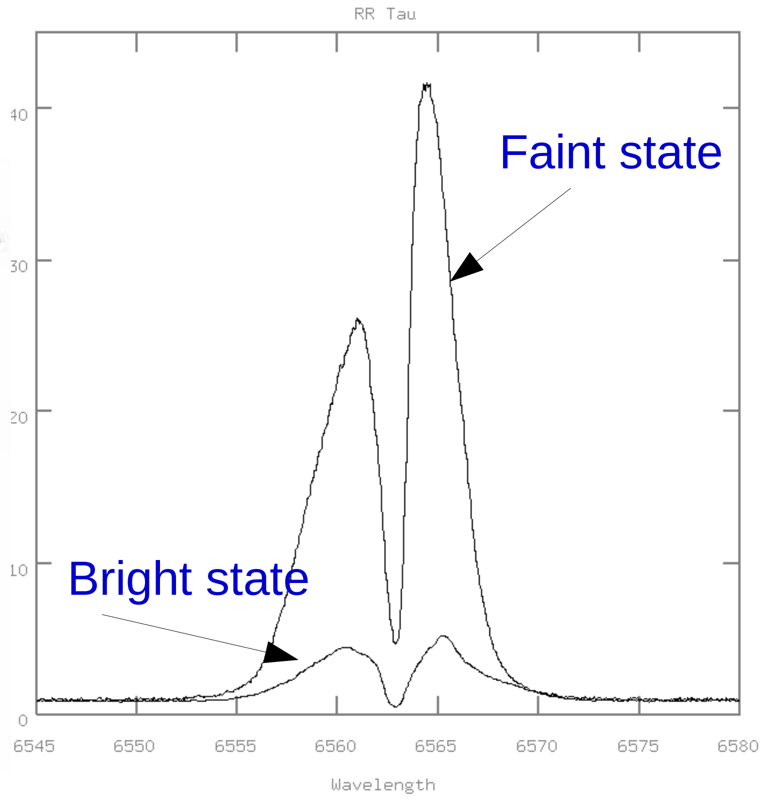
Modern telescopes are not able to resolve the region near the star < 0.1 AU even for nearest stars

How can we study those regions with the NOT?

FIES spectroscopy during eclipses

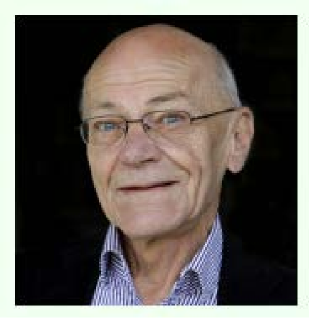
- The dust clouds eclipsing the star act as a natural coronagraph
- Emission line formation region is extended and less eclipsed
- Double-peaked Hα profile





The NOT study of UXORs

Project initated 2019 by the late Prof. G. Gahm, Stockholm



- High-resolution spectroscopic monitoring of fading events
- Instrument: FIES (**FI**ber **E**chelle **S**pectrograph) in low resolution mode R=25000 to ensure a sufficient S/N in 30 min also when fading
- Need spectra when target is fading → require ToO time

62-404 (PI: Gahm) "UX Ori stars caught in the act"

64-018 (PI: Djupvik) "Probing the strongly variable inner surroundings of UX Orionis stars"

66-410 (PI: Djupvik) "Catching a candidate binary UXOR in its dim phase"

68-012 (PI: Djupvik) "Probing the strongly variable inner surroundings of UX Orionis stars"

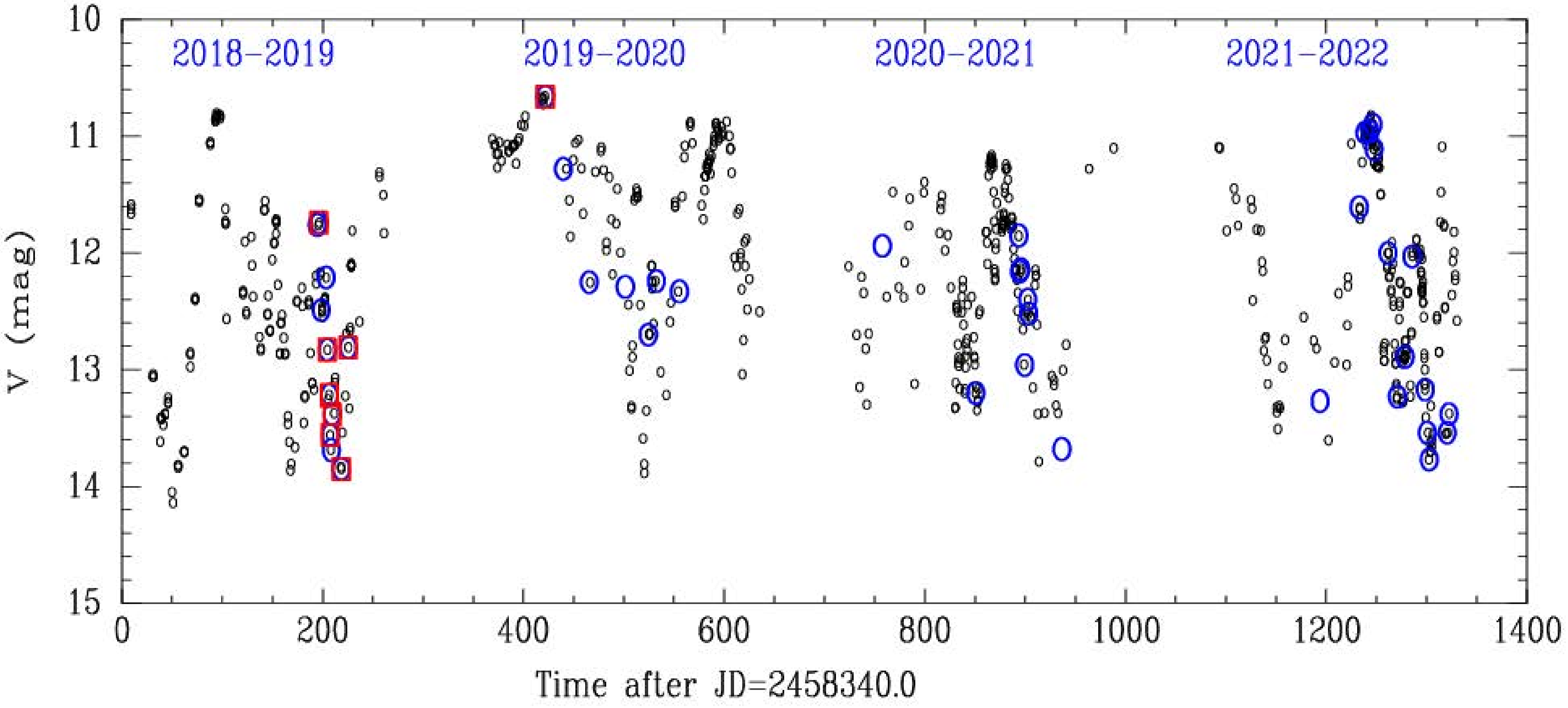
- Needs frequent V-band monitoring and rapid communication of alerts in order to know when to trigger spectroscopic observations → amateur astronomers
- Why NOT? Demanding observational task – flexible schedule and ToO time

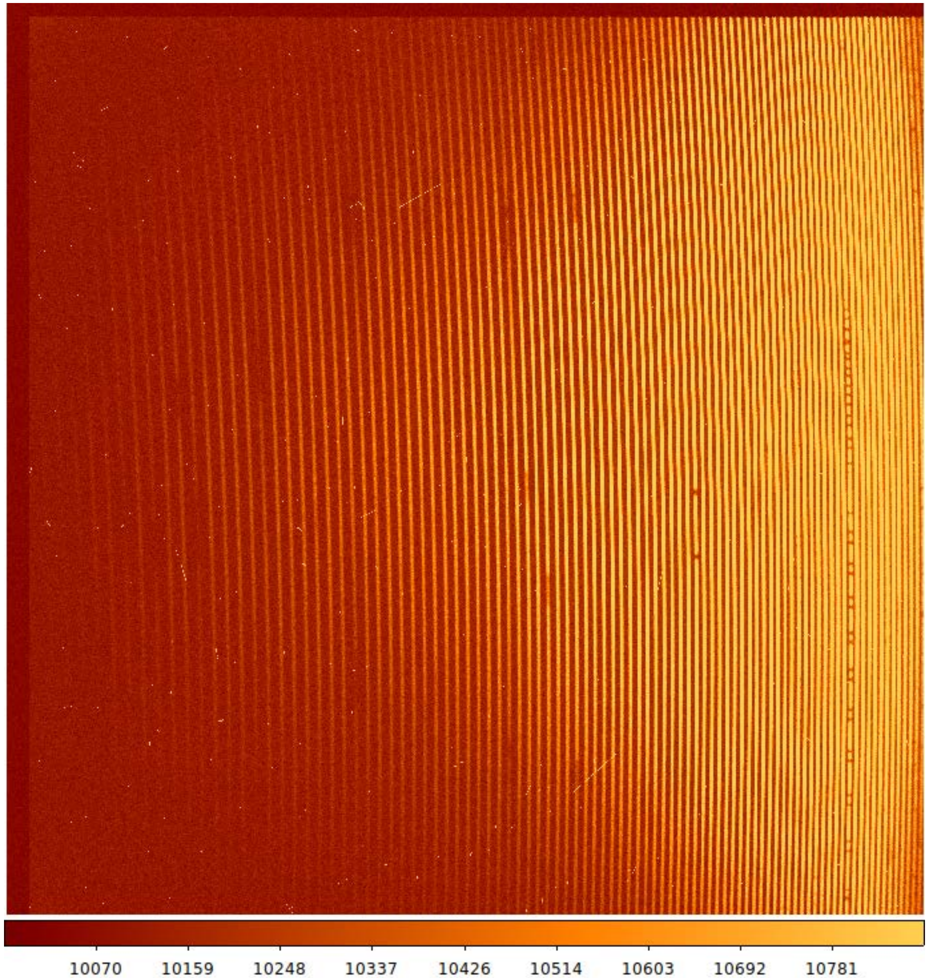
Amateur astronomers needed!

SAAF (Svensk AmatörAstronomisk Förening), collaboration initiated by G. Gahm
Variable star group: (9 observers, reporting to us, coordinated by H. Bengtsson)

Jan Qvam (Horten Astronomiske Observatorium, 68cm)

RR Tau





FIES

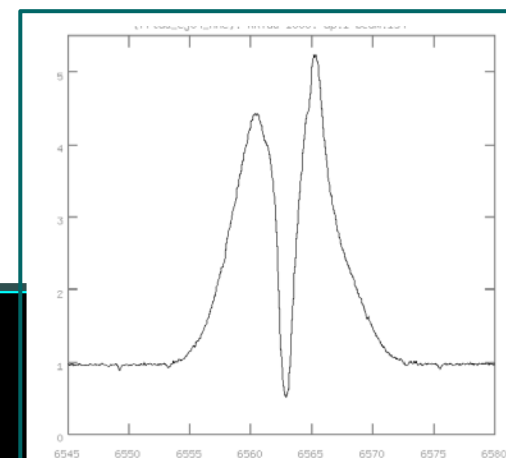
Fiber-fed, isolateded for stability in its own building next to the telescope

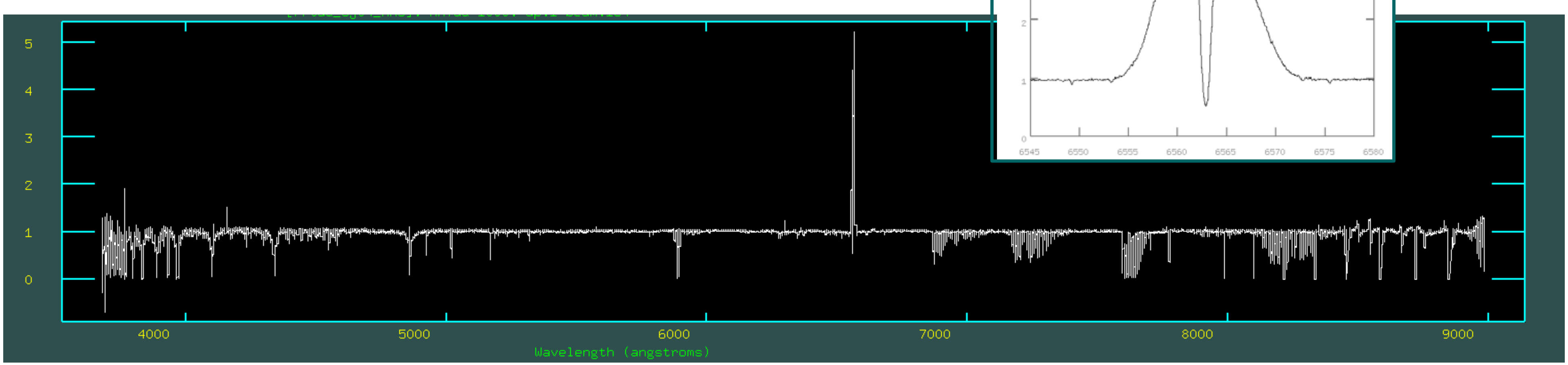
Cross-dispersed echelle spectrograph

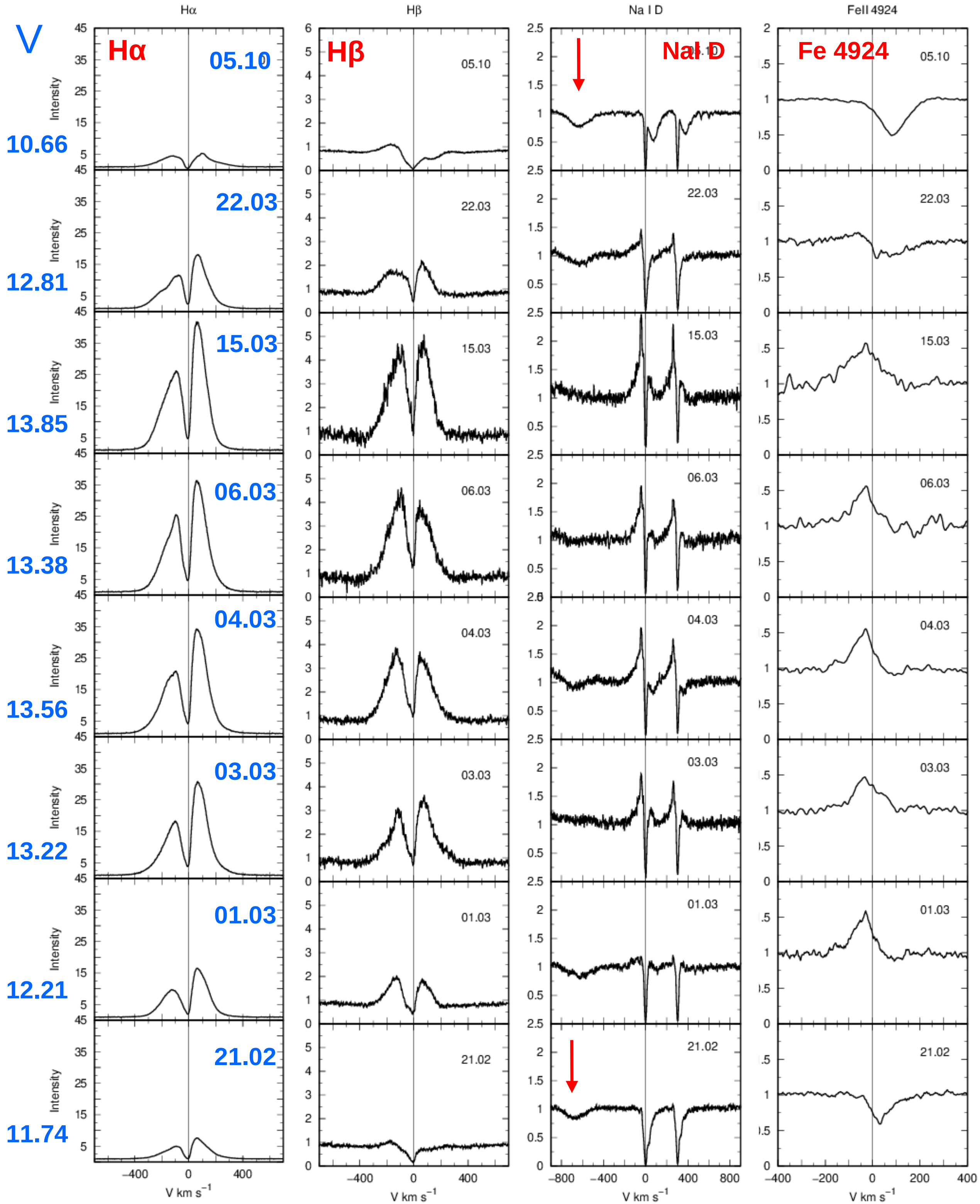
3 fibers: R=25000, R=46000, R=67000

93 orders distributed on the CCD

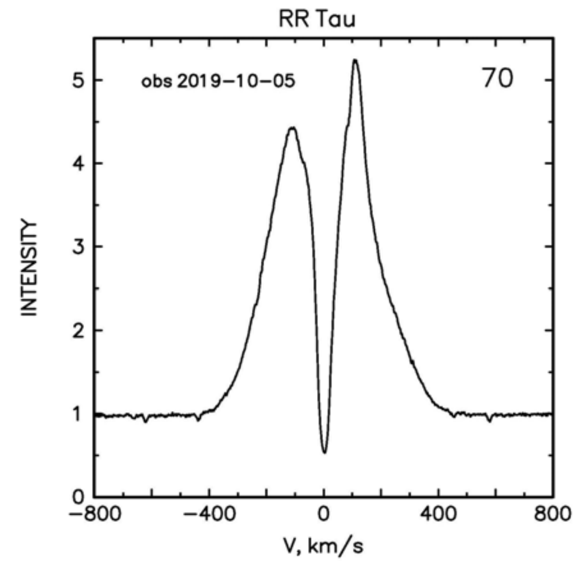
Wavelength range: 3700 – 9000 Å







2019



Hα	6563 Å
Hβ	4861 Å
NaI D1	5895,9 Å
D2	5889,9 Å
FeII	4924 Å

↓ He I 5876 Å

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **524**, 4047–4061 (2023) https://doi.org/10.1093/mnras/stad2108

Modelling UX Ori star eclipses based on spectral observations with the Nordic Optical Telescope – I. RR Tau

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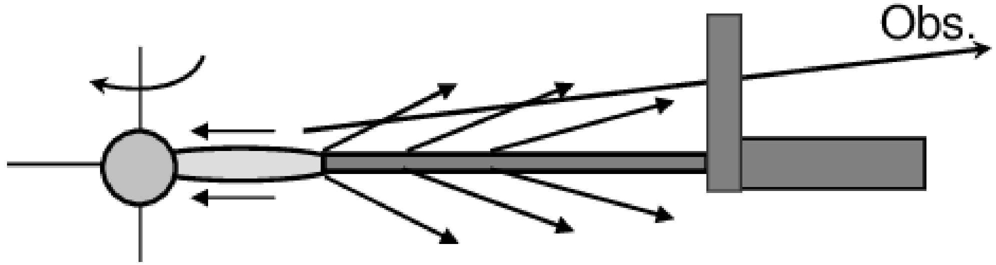
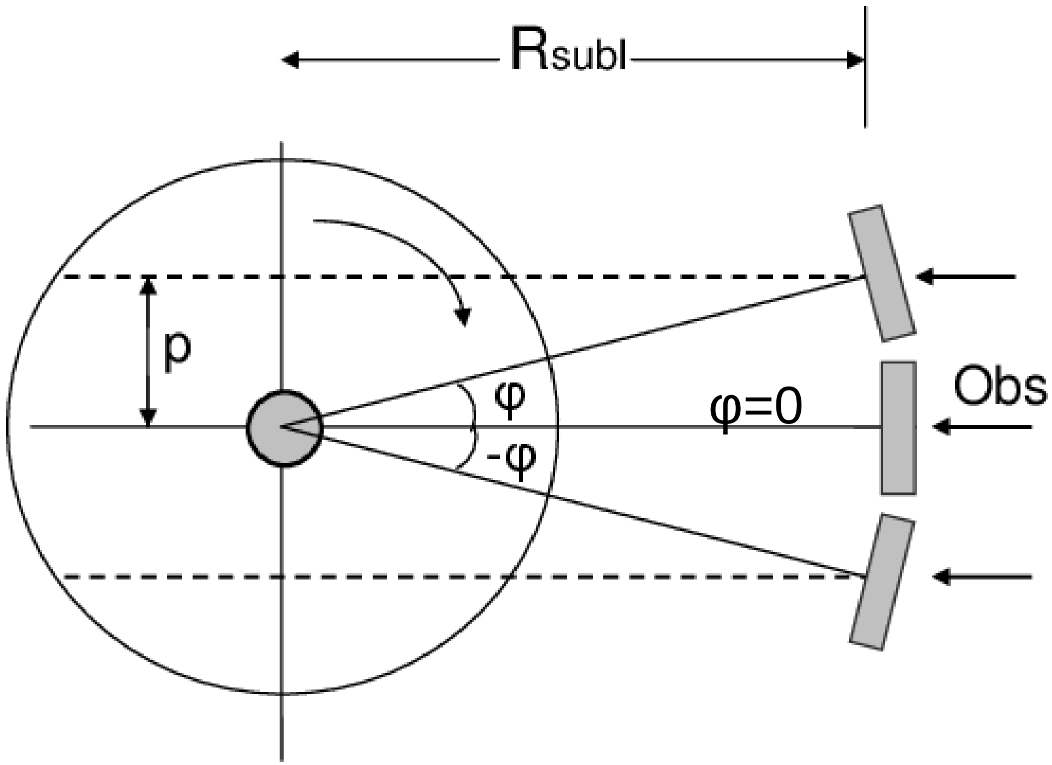
- 45 spectra of the RR Tau from Feb 2019 to Jan 2023
- Line profile parameters measured: EW, Flux, V/R, W_{10} (blue), W_{10} (red)
- Hybrid models of accretion and wind (Tambovtseva et al. 1999,2001,2014,2020)
- Adding obscuration scenarios and calculate hydrogen line profiles



Edge-on



Pole-on

Sublimation zone:
0.3 – 0.5 AU
Tannirkulam + (2007)
Flock + (2017)

0.45 AU ~ 46 R_*

Position of the screen relatively the system “star + disk”.
φ = 0 - «a central eclipse»

From Grinin, Tambovtseva, Djupvik et al. 2023, MNRAS 524, 4047

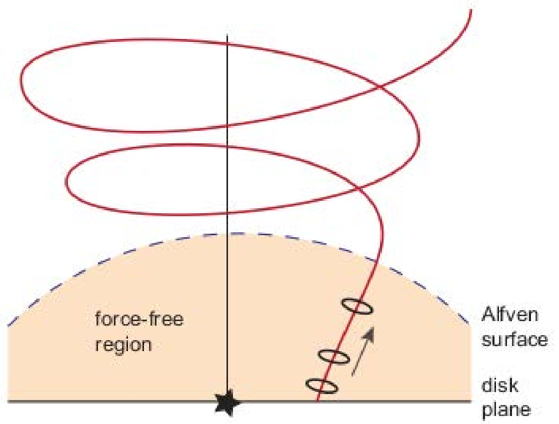
Modelling of hydrogen lines

Disk wind model based on magneto-centrifugal disk winds (Blandford & Payne, 1982), applied to young stellar objects by Pudritz & Norman (1986)

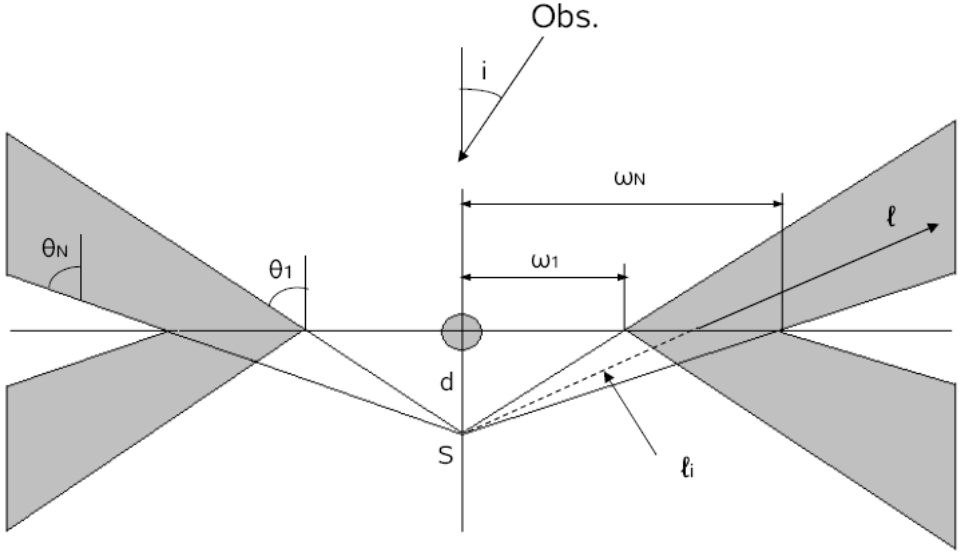
Algorithm used presented in Tambovtseva et al. (2014) based on Kurosawa et al. (2006)
For all emitting volumes non-LTE modelling of the radiative transfer is performed considering 15 hydrogen levels (Grinin & Tambovtseva 2011).

Accretion model is using magnetospheric accretion model with a more compressed stellar magnetosphere than for T Tauri stars due to weak B-fields and fast rotation .

Scattered light causes the brightness drop to reach a limit due to scattered light by disk and/or disk wind.

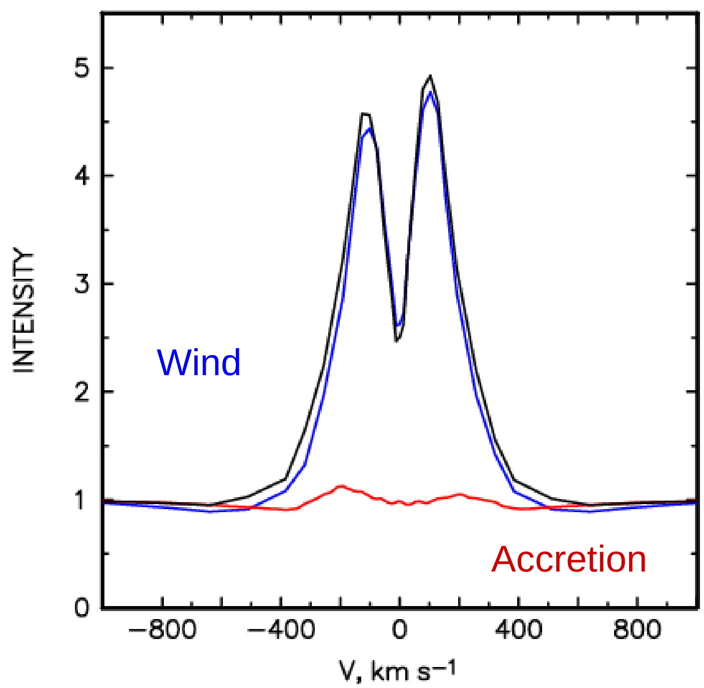


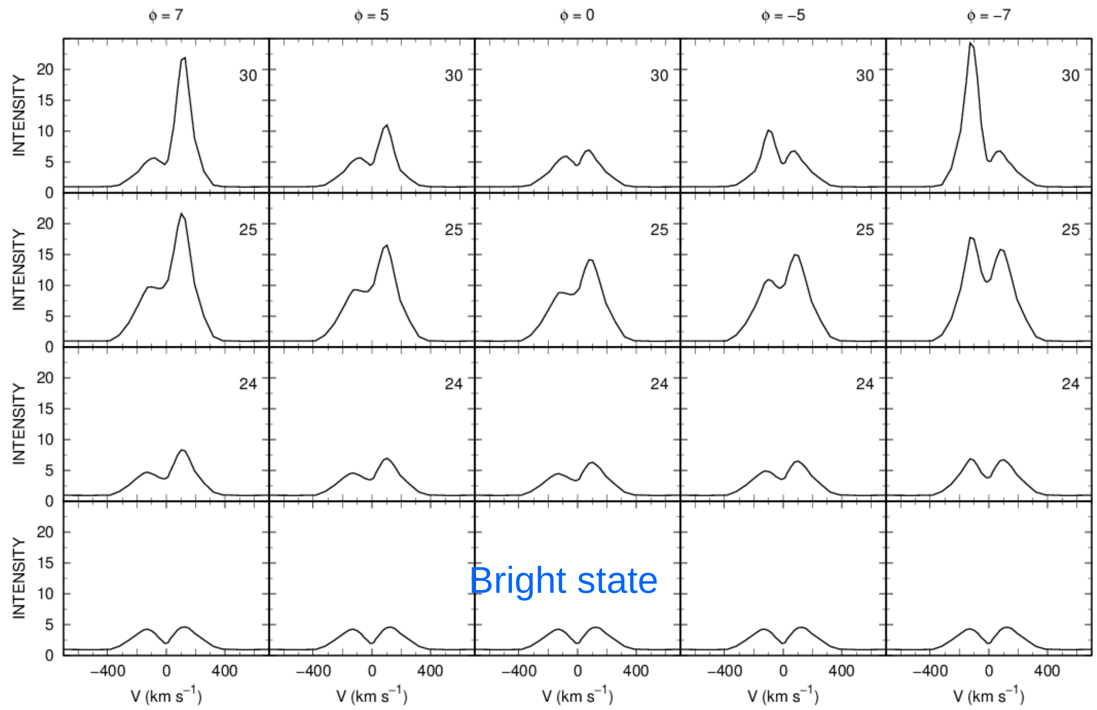
From Spruit, 1996 review



From Tambovtseva et al. 2014, A&A 562, 104

H-alpha profile model results for RR Tau





Vertical obscuration scenario and screen width is $20R_*$

- Hybrid models (MA + extended DW), where the disk wind dominates, fit the Hα profile well. For Hβ and Hγ: the role of MA increases, but DW dominates even Hβ for RR Tau
- Hα profile constrains the inner DW launching region to 2-3 R_* , dm/dt = 2-5E-09 M_{sun}/yr
- All Hα line profile parameters (EW, flux, V/R, $W10_B$, $W10_R$) are best fitted with the vertical obscuration scenario

Conclusions and future prospects

- RR Tau eclipses can be explained by a vertical rise of dust above the disk, most likely lifted by a structured, dusty disk wind
- [O I] 6300/6363 Å lines have constant luminosity during eclipses → they are formed beyond the screening material, probably in the photoevaporated disk wind. Because EW anti-correlates with flux, this confirms that the variability is caused by an external effect (obscuration) and not by accretion
- More UXOR stars are currently being analysed
- More observing time allocated at NOT

Concluding remarks

- High-spatial resolution near-IR images → jet morphology
- Timing FIES spectroscopy → disk wind signatures
- The NOT is competitive and productive
- Not only size, but image quality & reaction time matters
- Flexible modes are increasingly popular
- The new instrument NTE is aimed at this
- The NOT has a future – if funded

https://www.not.iac.es