School of Physics and Astronomy
FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

UNIVERSITY OF LEEDS

Winds and outflows from massive pre-Main Sequence Stars

René Oudmaijer


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UNITED KINGDOM
National capital
Const. country capital
City, town
International airport
International boundary
Motorway
Main road
N
10°
8°
6°
4°
2°
0°
2°
60°
58°
56°
54°
52°
50°
Shetland Islands
Lerwick
Orkney Islands
Hebrides
Sea of the Hebrides
Moray Firth
Inverness
Aberdeen
Scotland
Ben Nevis
1,345 m (4,413 ft)
Dundee
Perth
NORTH ATLANTIC OCEAN
North Sea
Great Britain Is.
Glasgow
Edinburgh
Arran Is
Ayr
North Channel
Dumfries
Stranraer
Carlisle
Newcastle upon Tyne
Middlesbrough
Scarborough
Londonderry
Northern Ireland
Omagh
Lough Neagh
Belfast
Strangford Lough
Island of Ireland
Isle of Man
Douglas
York
Bradford
Leeds
Hull
Blackpool
Preston
Irish Sea
Liverpool
Manchester
Grimsby
Sheffield
Dublin
Holyhead
Bangor
Chester
England
Galway
Rep. of IRELAND
Nottingham
Stoke-on-Trent
Shrewsbury
Leicester
Norwich
Wolverhampton
Peterborough
Limerick
Aberystwyth
Newtown
Birmingham
Coventry
Worcester
Northampton
Waterford
Cambridge
Ipswich
Cork
St George's Channel
Wales
Colchester
Swansea
Newport
Gloucester
Oxford
St Albans
Cardiff
Southend on-Sea
London
Bristol
Bath
Reading
Canterbury
Bristol Channel
Dover
Celtic Sea
Folkestone
Channel Tunnel
Calais
BELGIUM
Hastings
Southampton
Brighton
Bournemouth
Exeter
Poole
Portsmouth
Plymouth
Torquay
English Channel
FRANCE
Penzance
United Kingdom
0
50
100
150
200 km
100 mi
Ferry

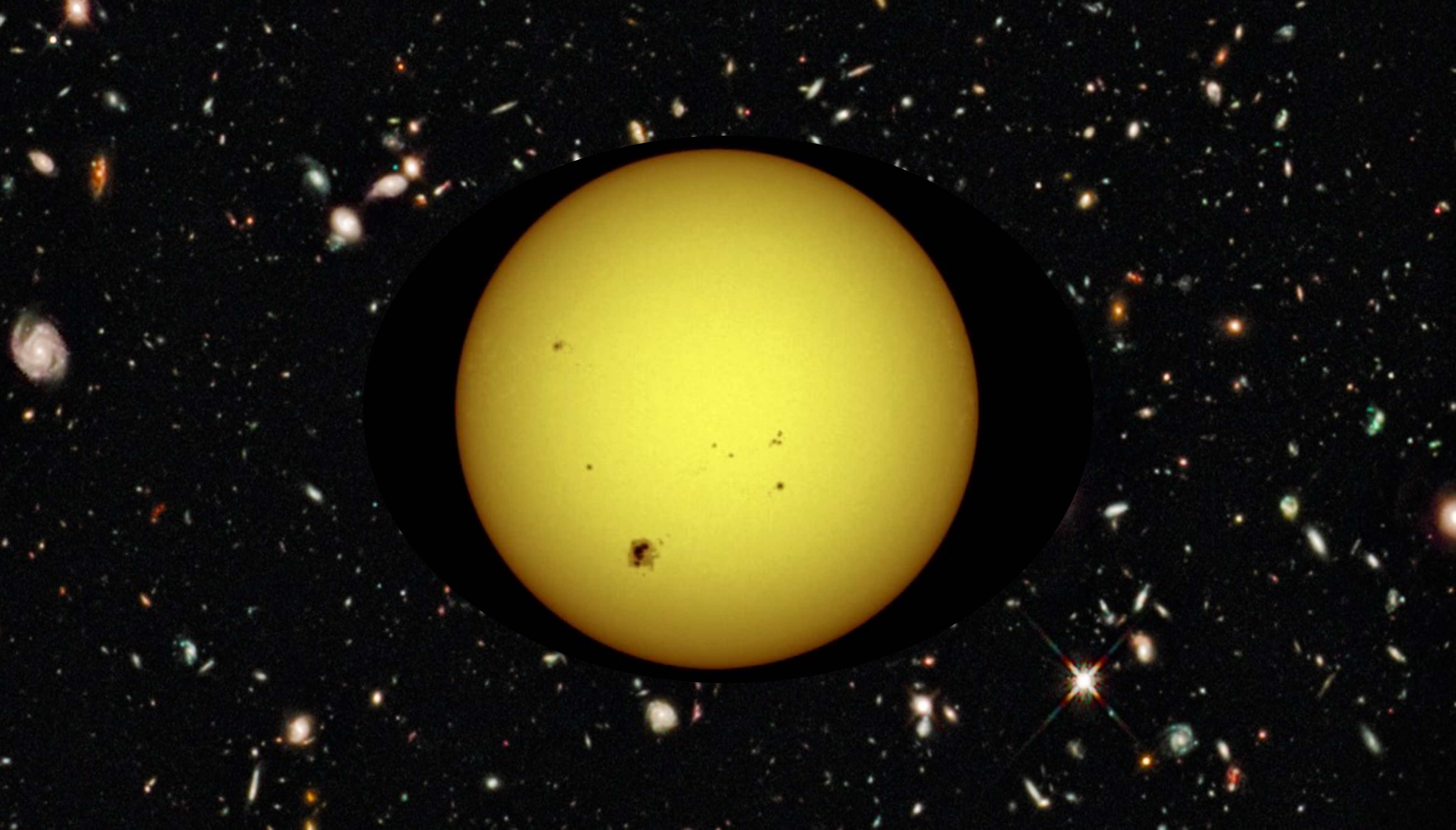

60°
58°
56°
54°
52°
50°
Douglas
Irish Sea
Blackpool
Preston
Bradford
Leeds
Hull
Manchester
Liverpool
Sheffield
Galway
Rep. of IRELAND
Dublin
Holyhead
Bangor
Chester
England
Nottingham
Stoke-on-Trent
Limerick
Shrewsbury
Wolverhampton
Leicester
Aberystwyth
Newtown
Birmingham
Coventry
Waterford
Worcester
Northampton
Cork
St George's Channel
Wales
Gloucester
Swansea
Newport
Oxford
Cardiff
Bristol
Bath
Reading
Bristol Channel
Celtic Sea
Southampton
Bournemouth
Exeter
Poole
Portsmouth
Plymouth
Torquay
Penzance
English Channel
0 50 100 150 200 km
0 50 100 mi
10°
8°
6°
4°
2°
0°

Outline

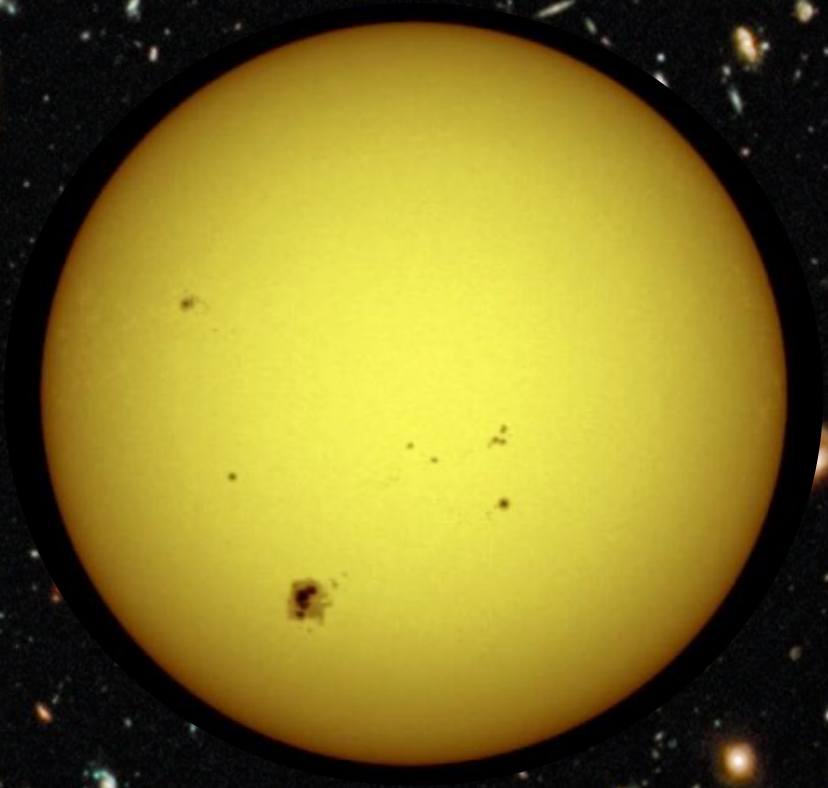
- Star Formation
- Winds/Outflows
- Jets and their formation
- Winds and Star Formation

Credit: ESA/Hubble

What is a star?



It's a hot ball of gas, with a furnace in the center



As does a “molecular” cloud :

Embedded Outflow in HH 46/47

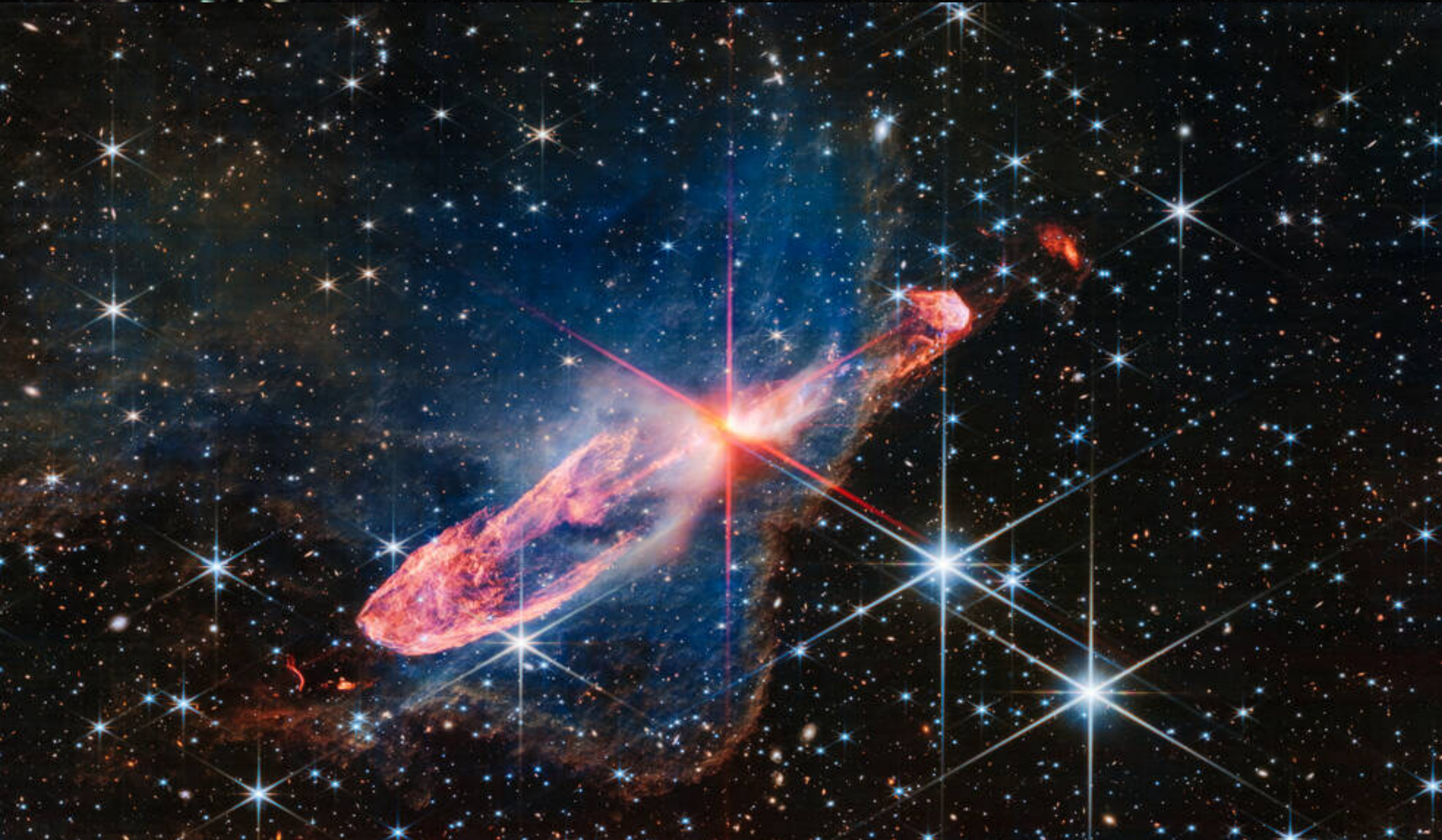
Spitzer Space Telescope • IRAC

Inset: visible light (DSS)

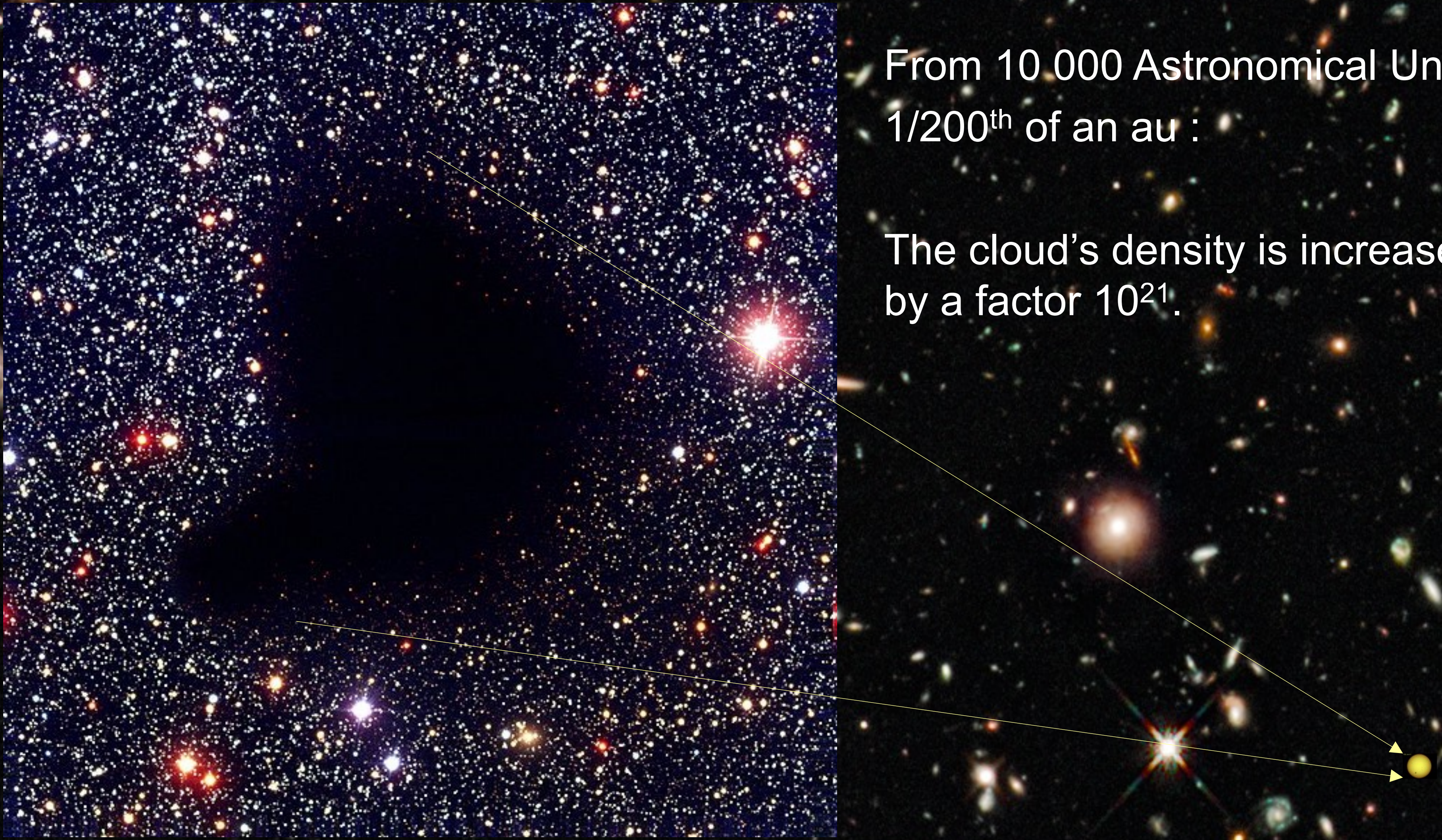
NASA / JPL-Caltech / A. Noriega-Crespo (SSC/Caltech)

ssc2003-06f

JWST of same object (July 2023!)



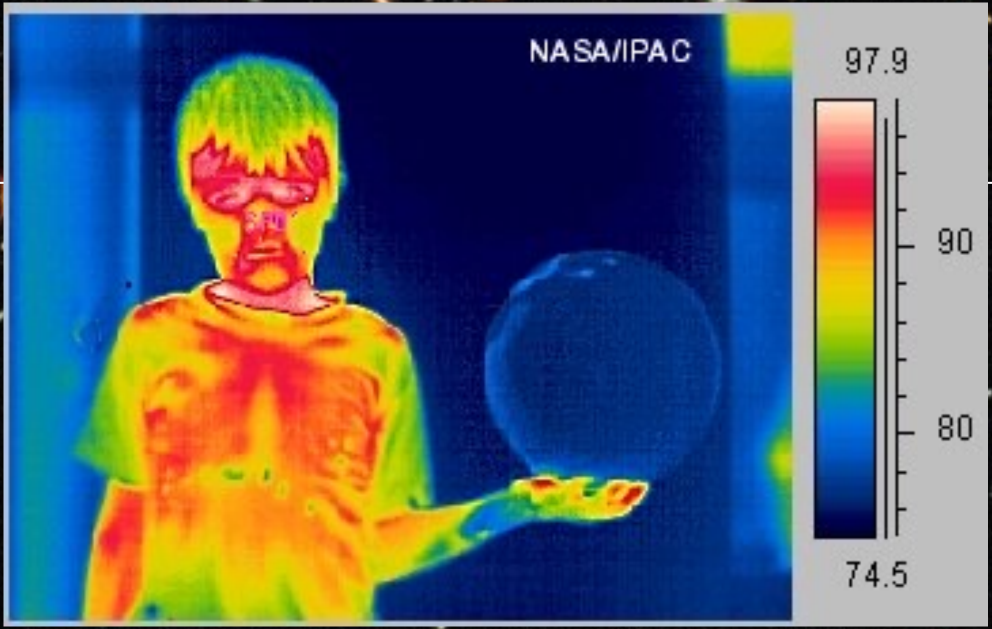
So what can happen?



From 10 000 Astronomical Units to $1/200^{th}$ of an au :

The cloud’s density is increased by a factor 10^{21}.

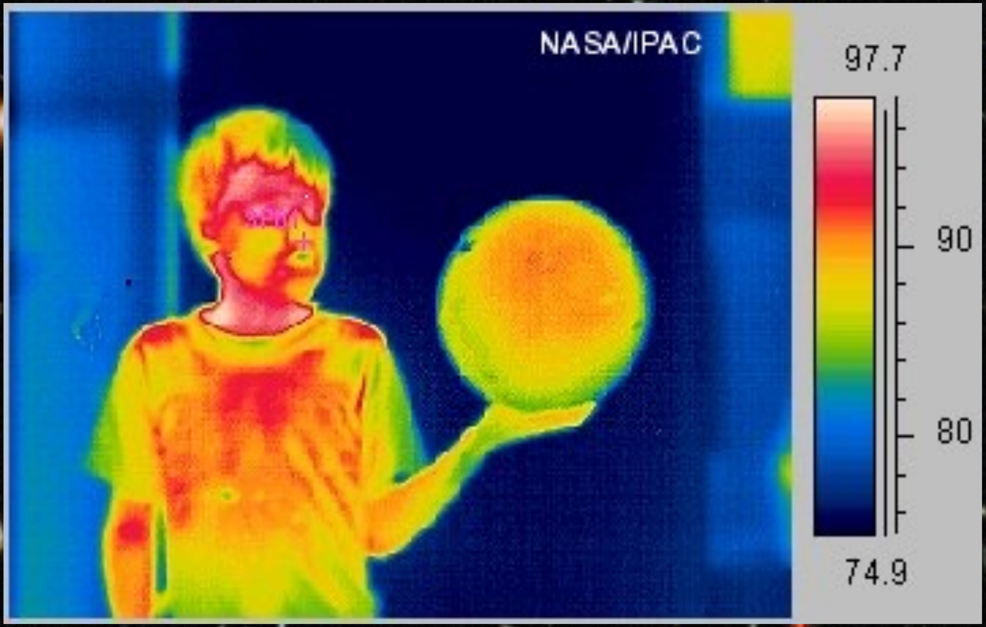
What happens if matter falls on star?



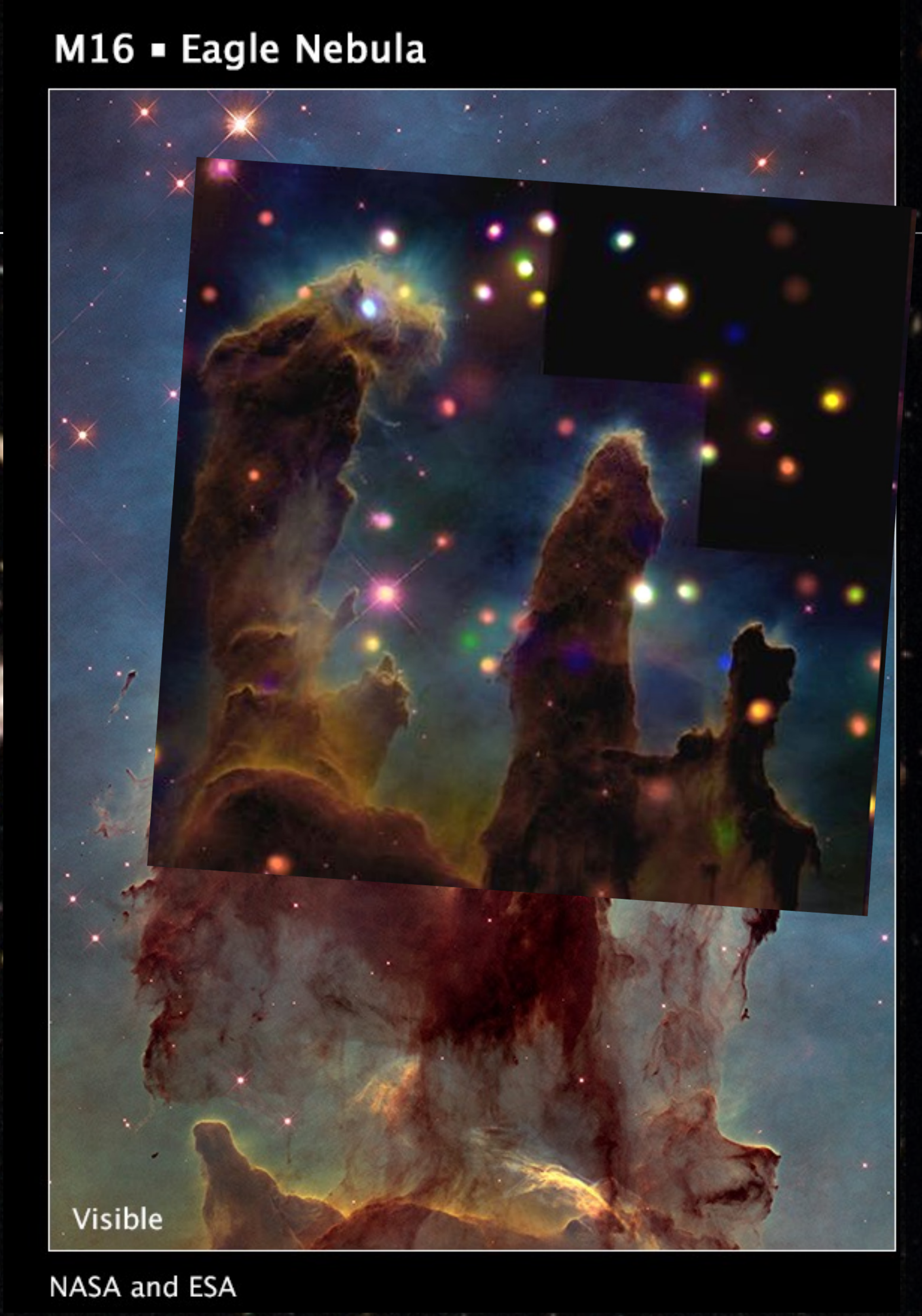
Ball heats up after falling

Similarly, accretion material heats up, but terminal velocity much, much higher than the ball

Star + accretion very ***bright*** and ***hot***



Hubble Space Telescope data of Messier 16 at optical wavelengths and James Webb at NIR:



Hubble Space Telescope data of Messier 16 at optical wavelengths

Chandra X-data

So what else will happen?

From 10 000 Astronomical Units to 1/200th of an au :

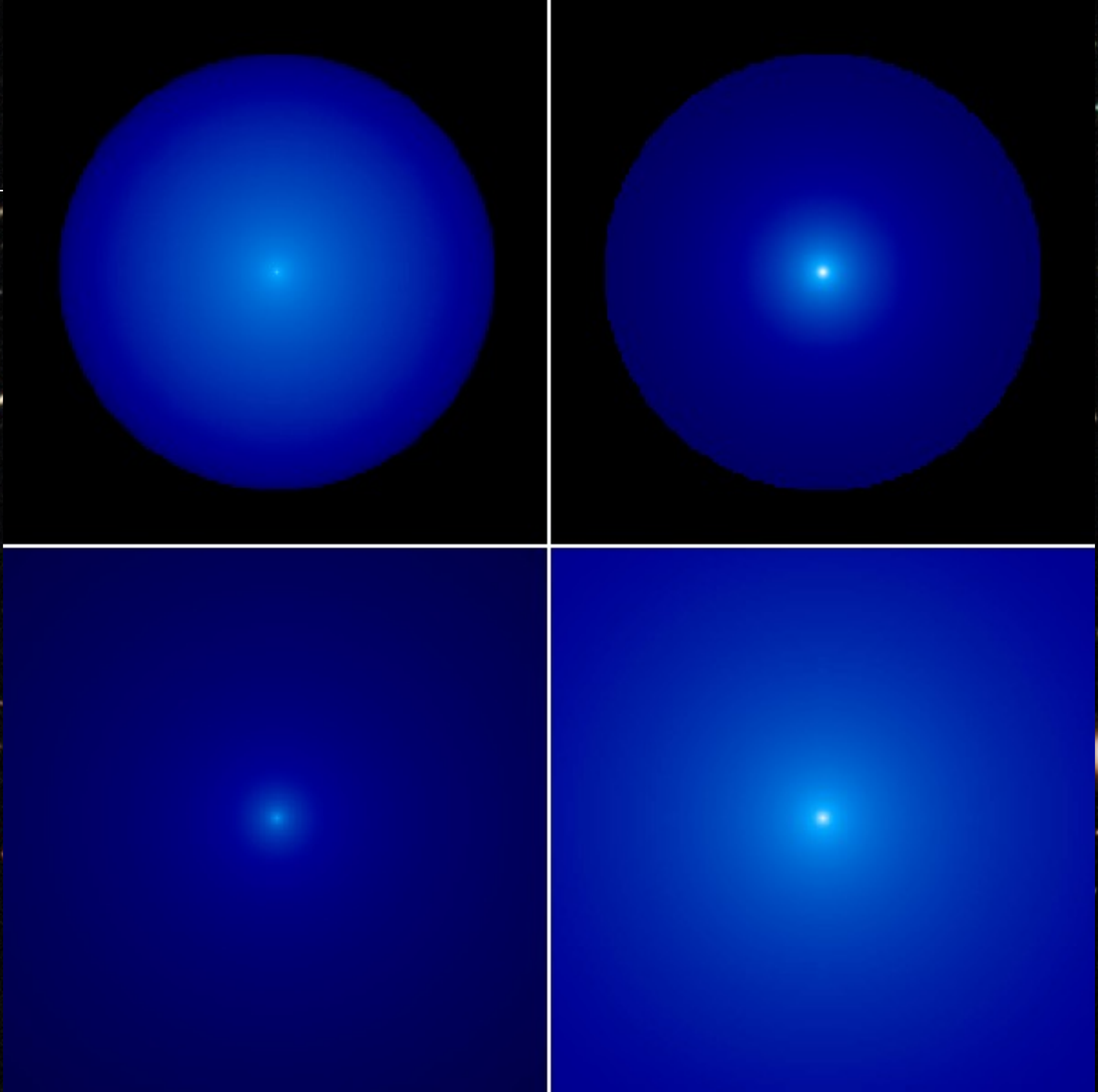
The cloud’s density is increased by a factor 10^{21}. That is 1000 000 000 000 000 000 000 times!

What happens if this cloud rotates?

Conservation of angular momentum

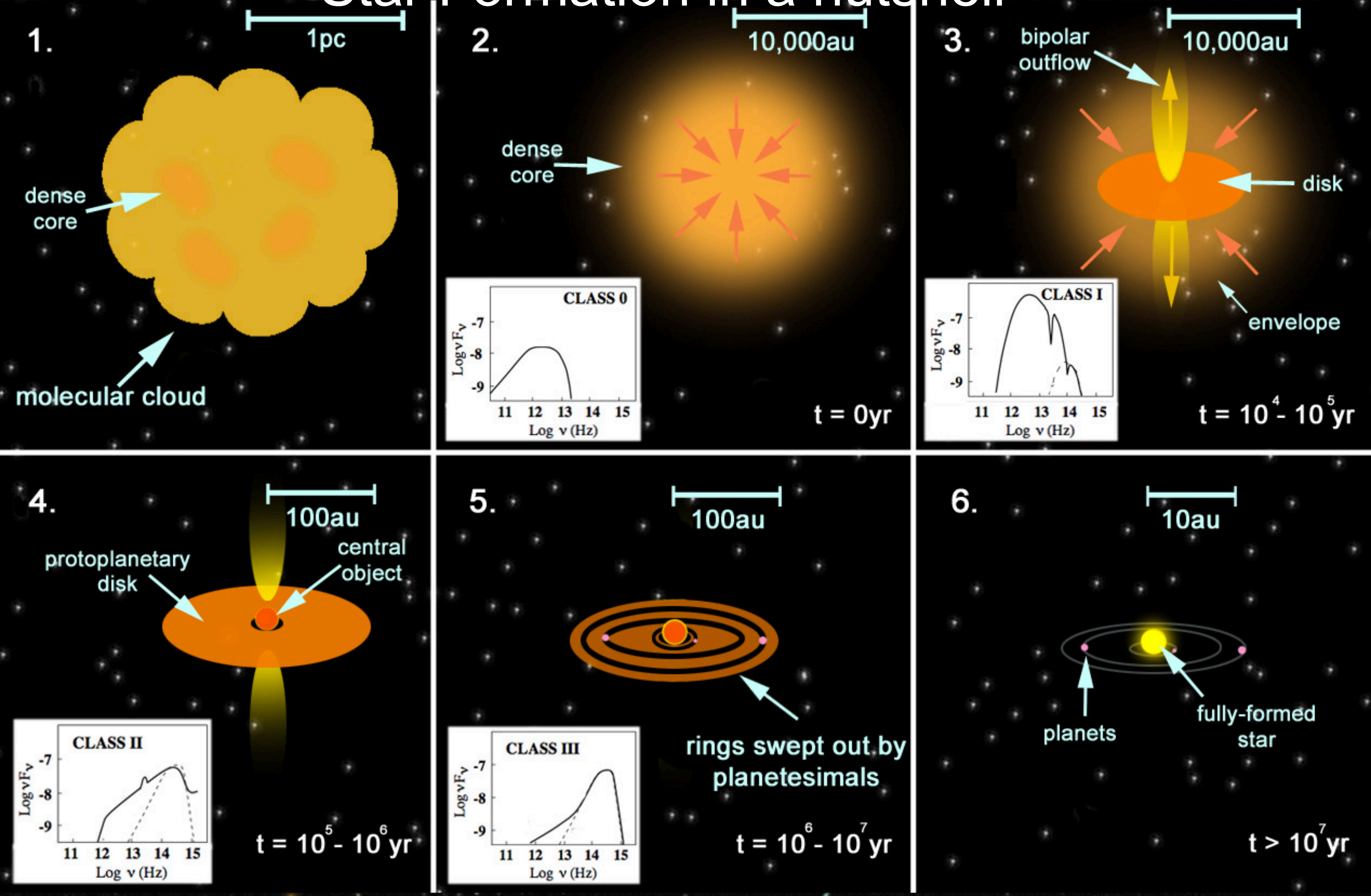
Making of a ~~planetary system~~ pizza

Forming a star: a computer simulation



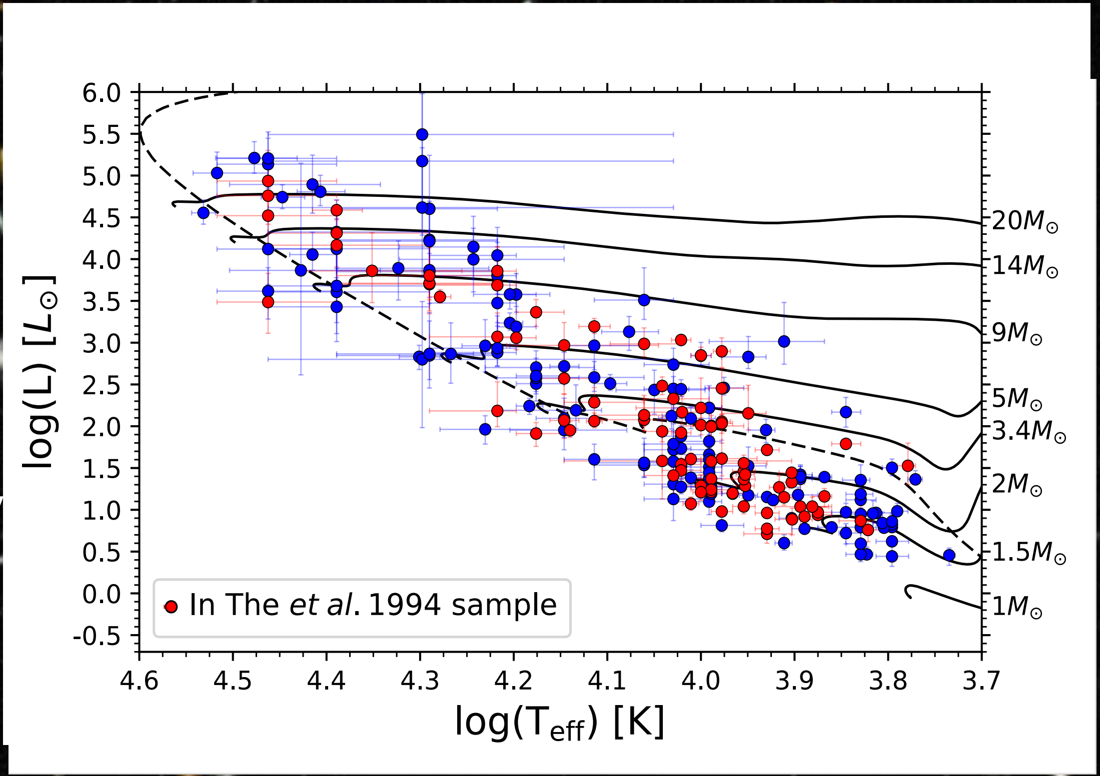
Credit: Krumholz

Star Formation in a nutshell



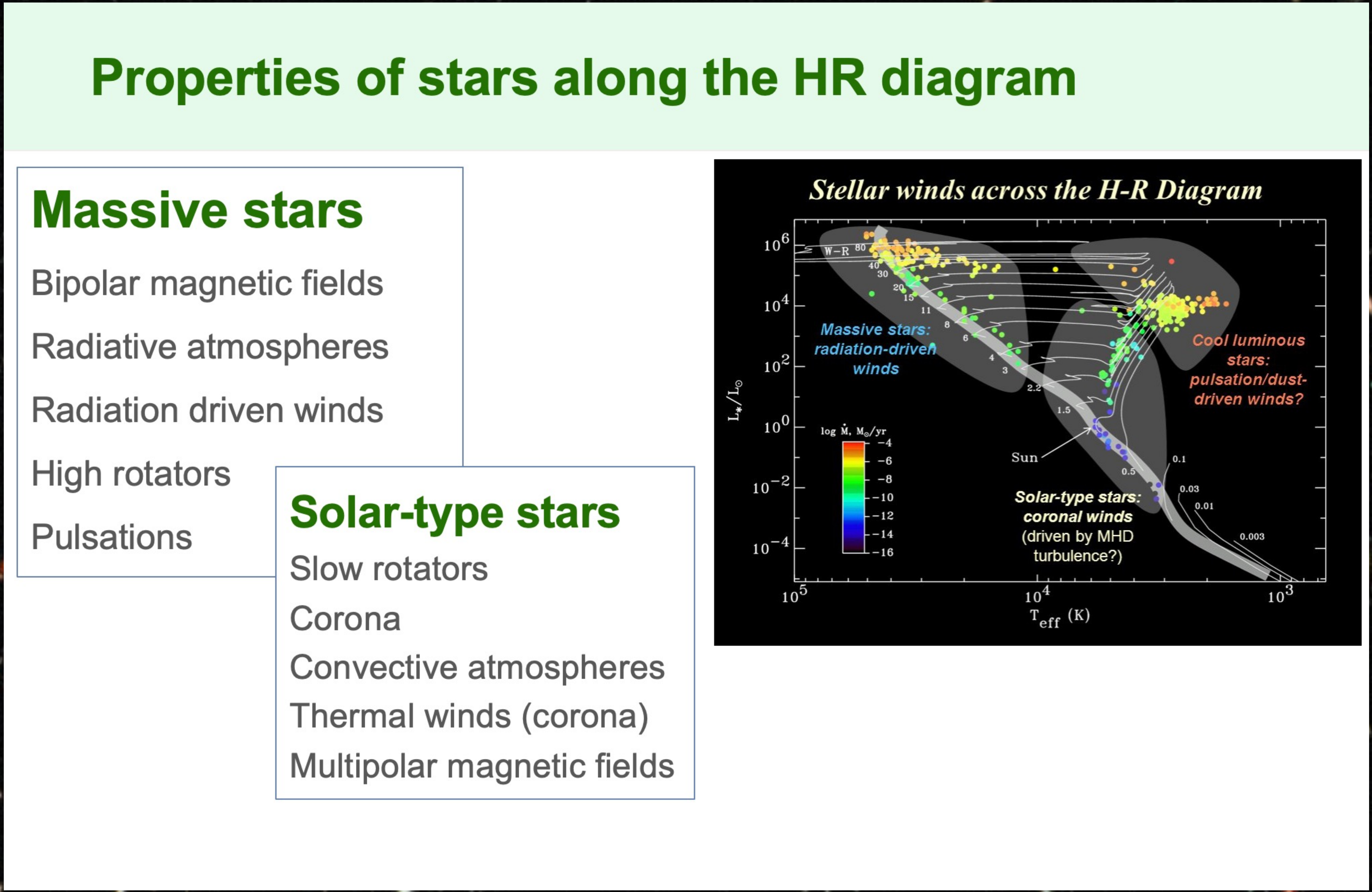
Pre-main sequence stars

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



Gaia DR2 Vioque+ 2018

Olya & Lydia- Last week



Properties of stars along the HR diagram

Massive stars

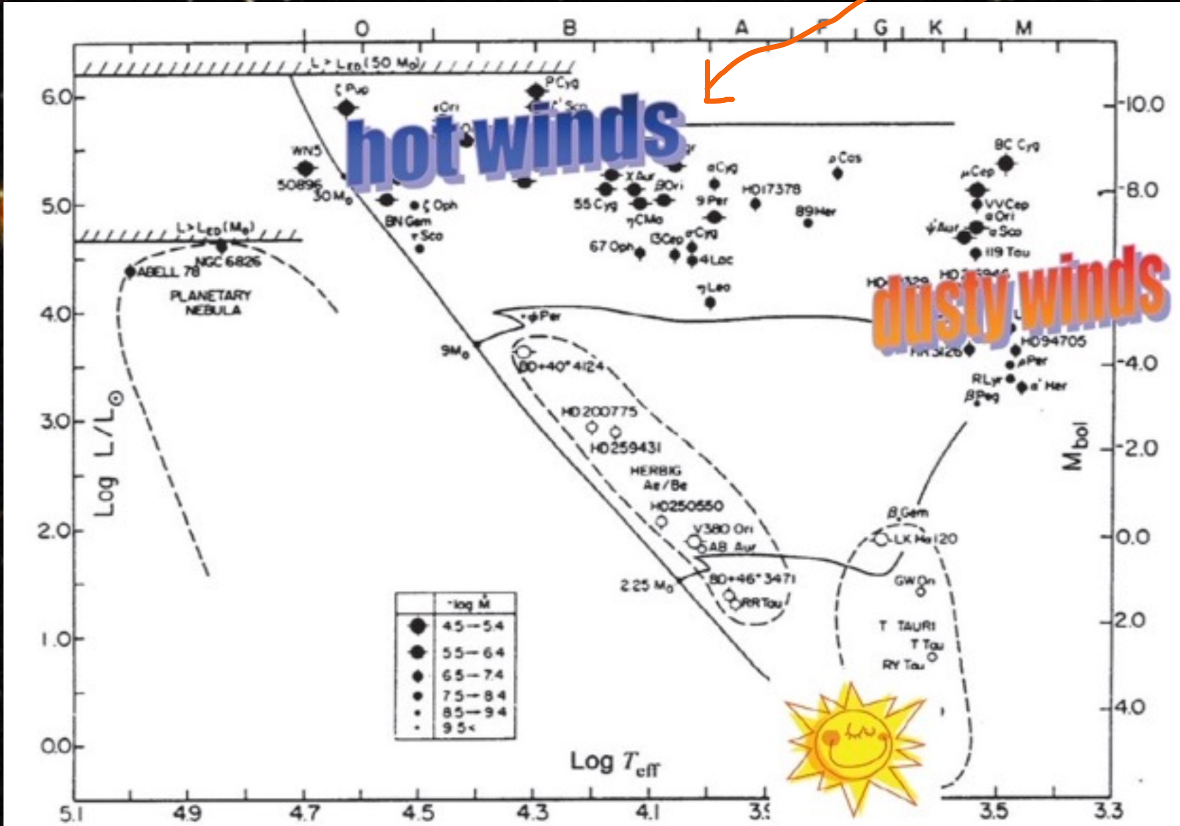
- Bipolar magnetic fields
- Radiative atmospheres
- Radiation driven winds
- High rotators
- Pulsations

Solar-type stars

- Slow rotators
- Corona
- Convective atmospheres
- Thermal winds (corona)
- Multipolar magnetic fields

Michel – last week

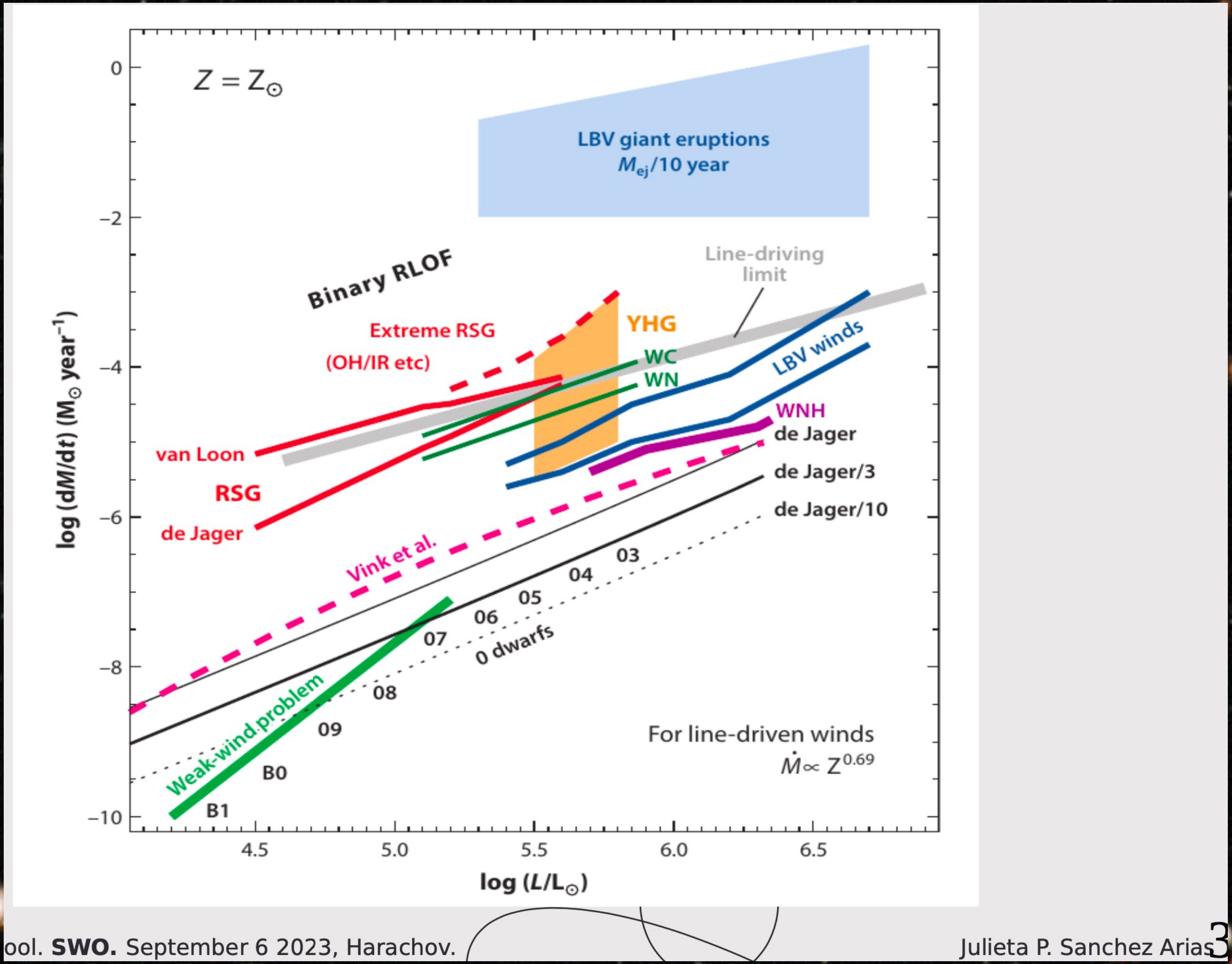
Peter – last week



ubiquitous phenomenon

- solar type stars (incl. the sun)
- red supergiants ("normal" + Mira Variables)
- hot stars (OBA supergiants, Luminous Blue Variables, OB-dwarfs, Central Stars of PN, sdO, sdB, Wolf-Rayet stars)
- T-Tauri stars
- and many more

Julieta – Last week



ool. **SWO.** September 6 2023, Harachov.

Julieta P. Sanchez Arias 3

Winds from an A-type pre-Main Sequence Object AB Aur

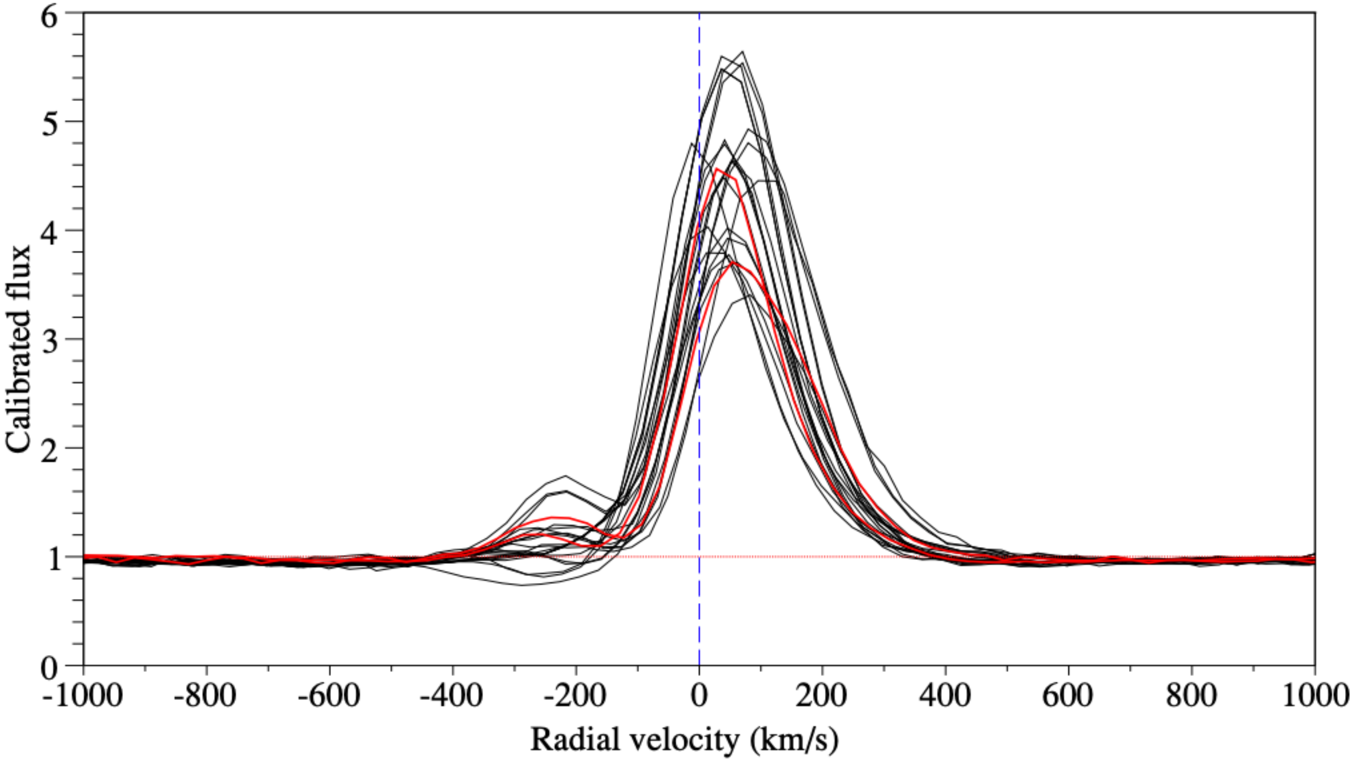
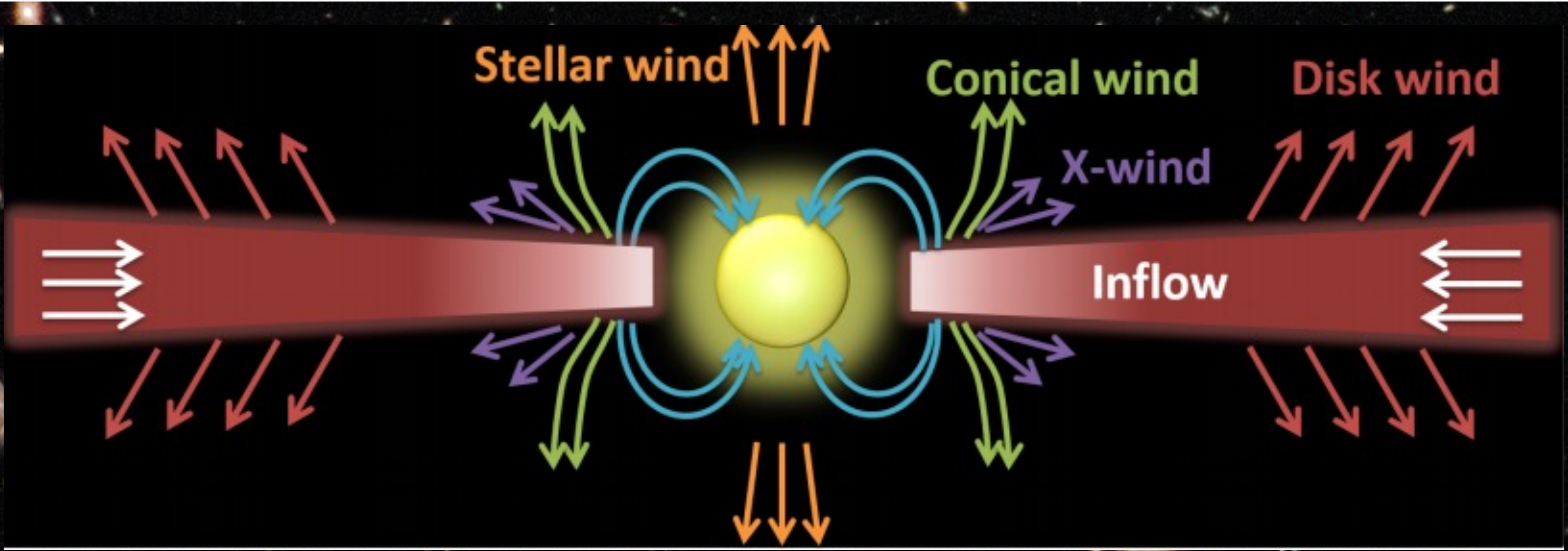


Fig. 1. Hα emission line of AB Aur recorded with VEGA from 2010 October to 2013 December. Spectra corresponding to the data set used for the detailed modeling are displayed in red.

Perraut+ 2016

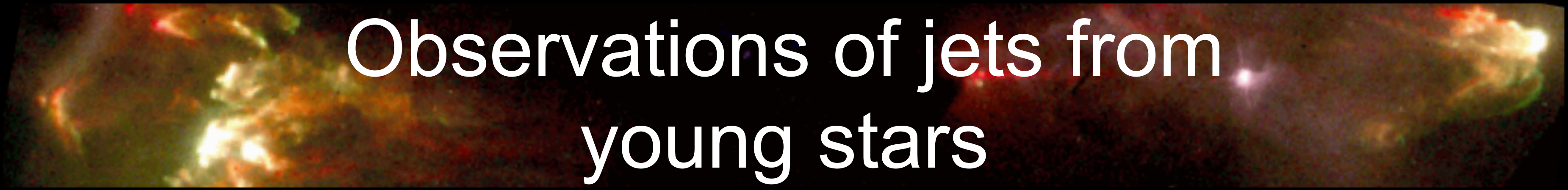
Low mass vs. high mass star formation



- Stars of spectral type A and earlier have radiative envelopes, so no magnetic dynamo expected
- Only about 10% of intermediate mass stars found to have *B*-fields (Alecian+ 2013) but much indirect evidence for “Magnetospheric Accretion” occurring.
- Let us discuss jets…

Observations of jets from young stars

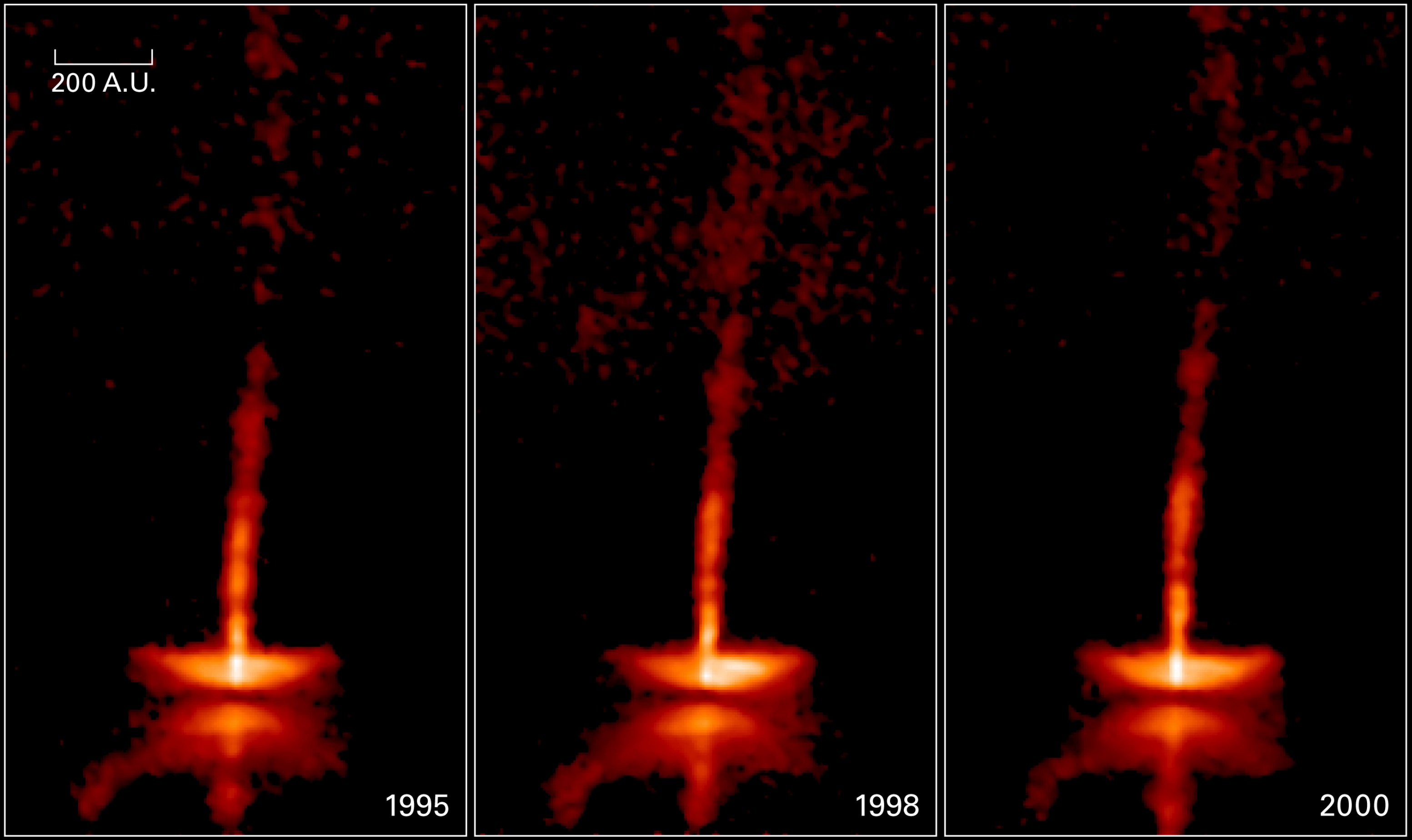
Image: ESO/Bo Reipurth/NTT



Observations of jets from young stars

Image: ALMA (ESO/NAOJ/NRAO)/ESO/H. Arce. Acknowledgements: Bo Reipurth

Optical jets



The Dynamic HH 30 Disk and Jet

Hubble Space Telescope • WFPC2

Image: NASA (A Watson)

Optical jets

Properties of optical jets:

✳ Shocked ionised gas (H-α, [SII])

✳ Low ionisation fraction (~ 10%)

✳ Highly collimated (~ 100:1)

✳ Dense (~ 10^9 cm^{-3})

✳ Fast (~ 300 km/s)

✳ Knots along the jet

✳ Some evidence of precession

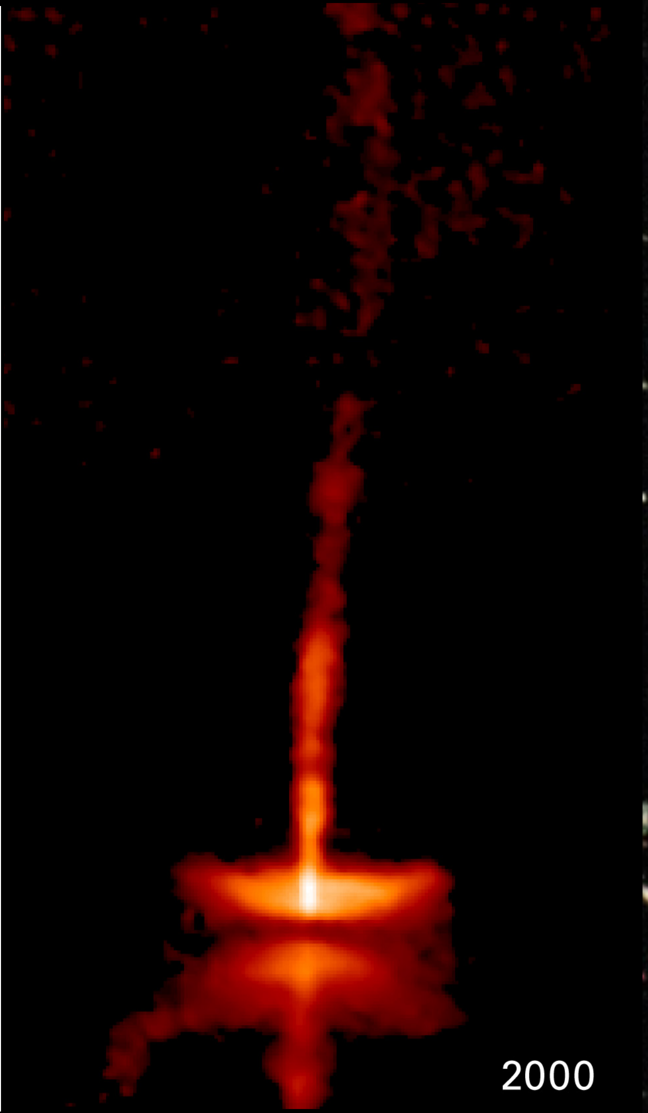
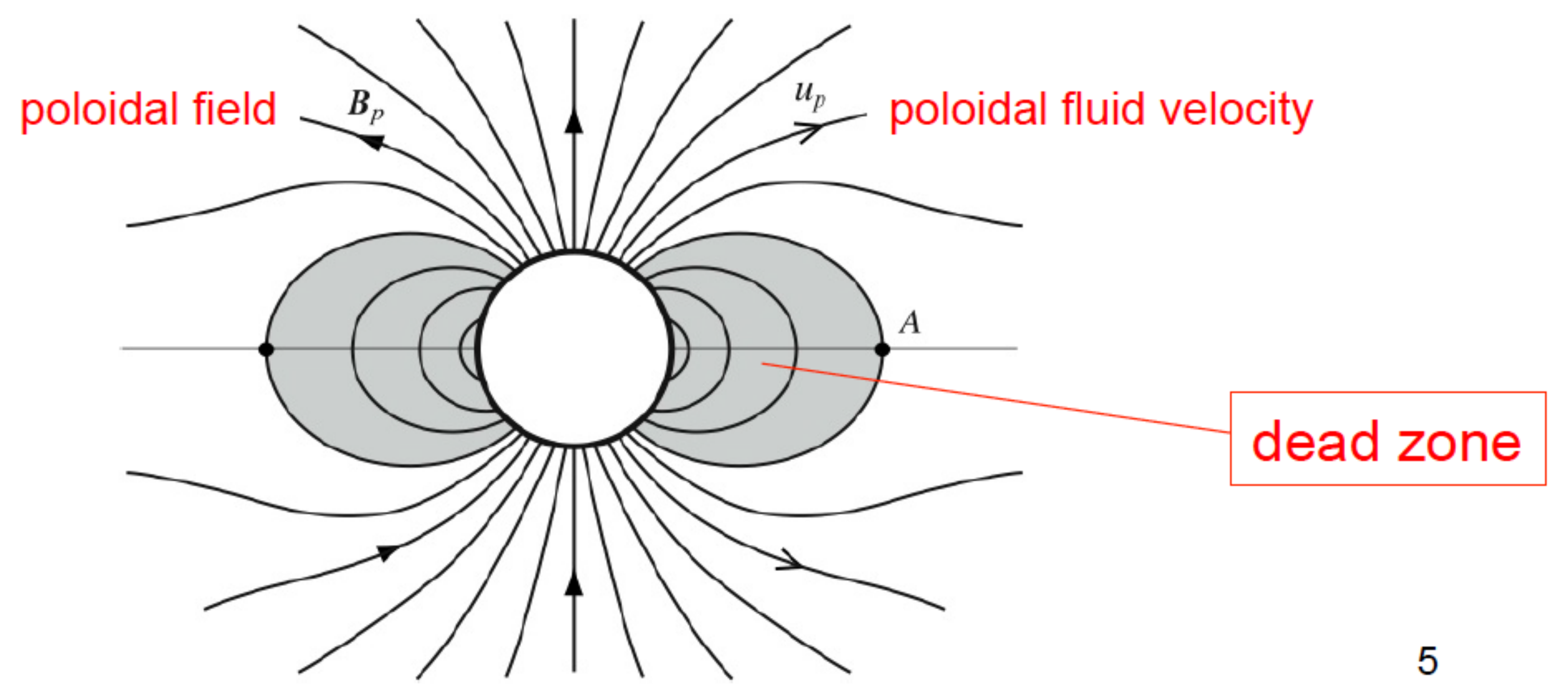


Image: NASA (A Watson)

Driving mechanism: magnetohydrodynamics

In certain geometric configurations, rotating magnetic fields can accelerate gas



The magnetic field could arise in the star or in the disk

Generated dynamo (or fossil)

Driving mechanism: magnetohydrodynamics

Magneto-centrifugal acceleration
(c.f., “beads on a wire”)

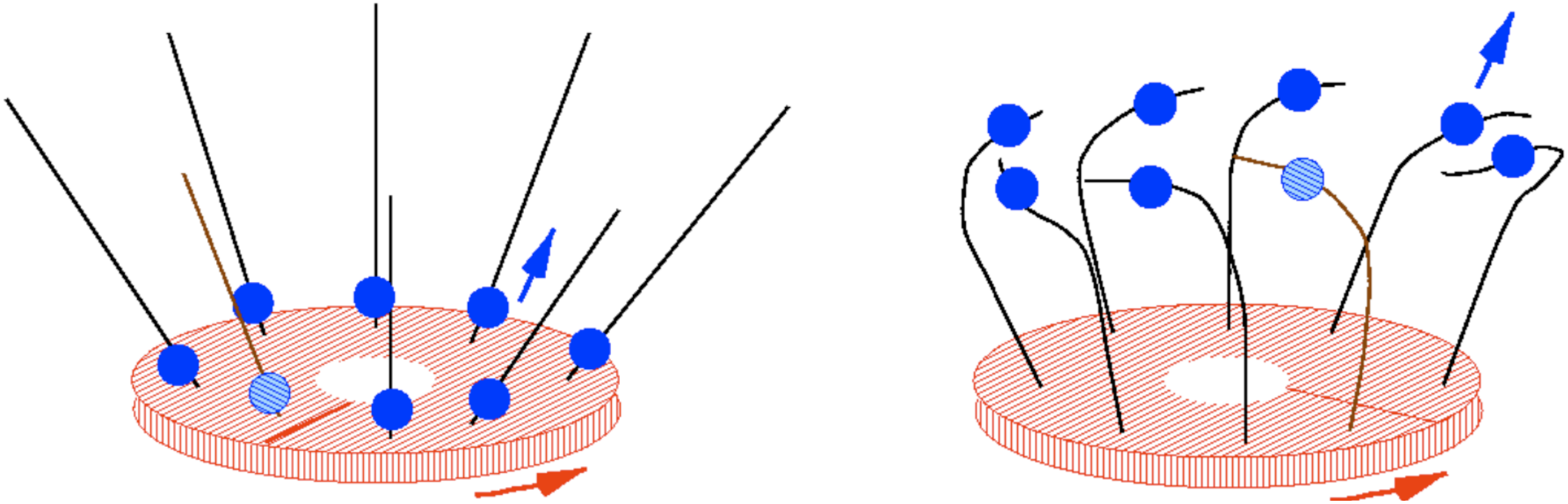


Image: Blandford & Payne1982, MNRAS, 199, 883

Driving mechanism: magnetohydrodynamics

Magnetohydrodynamics (MHD) can also generate an MHD disk wind

Field lines are anchored in the disk

Rotating field lines enforce co-rotation of the material in the atmosphere of the disk

Recall "beads on a wire" picture

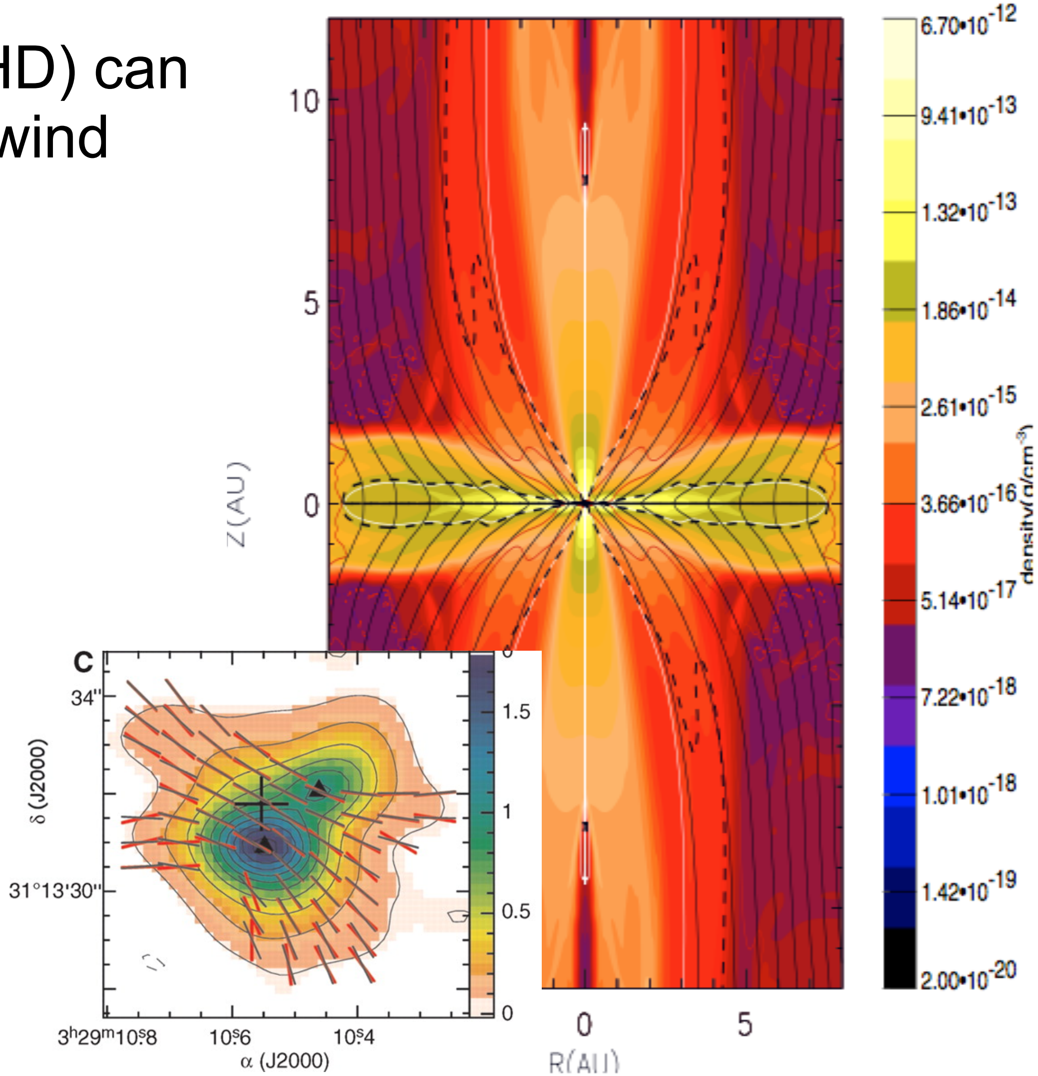


Image: Melanie et al. 2006, A&A, 460, 1; Girart et al. 2006, Science, 313, 812

Collimation

How are jets collimated?

- Expect a flattened distribution in the cloud surrounding the young star
- A wind will expand most rapidly in the direction of lowest density ⇒ bipolar flow
- Thus, a wind cannot produce the highly collimated jets observed from young stars

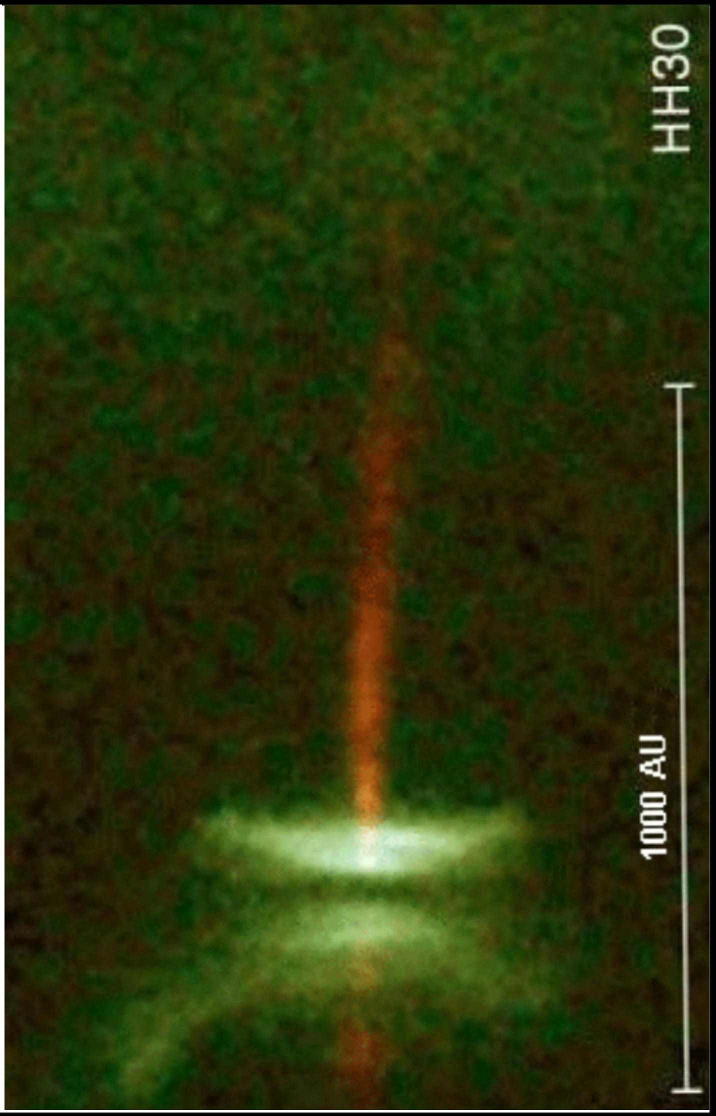


Image: ESO

Collimation

The jets are also thought to be magnetohydrodynamic in origin

- Even if an initial toroidal component could collimate the outflow, it is hard to imagine that this B-field would still be wound up at ~ parsec distances from the star
- Need another, more sustained mechanism

~ 1 pc

HH34 in Orion

Image: ESO

Collimation

Let’s consider the analogous process in electromagnetic theory

A magnetic field will be induced by a current-carrying wire:

$$B = \frac{\mu_0}{4\pi}\frac{2I}{R}$$

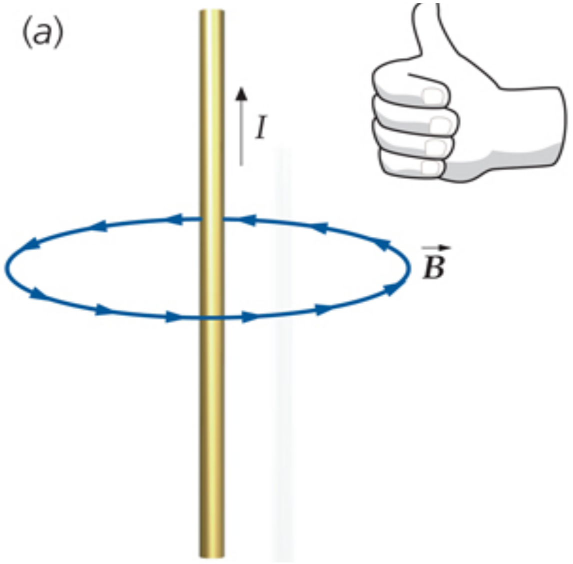
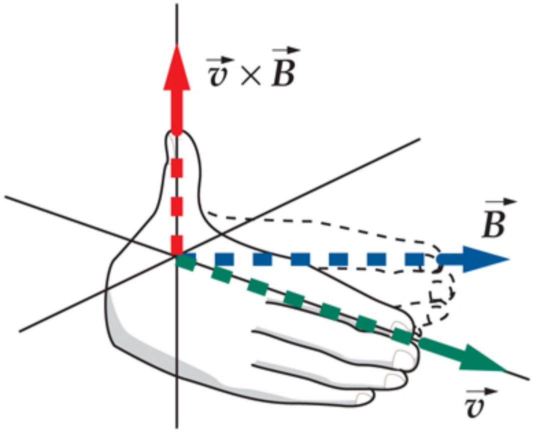


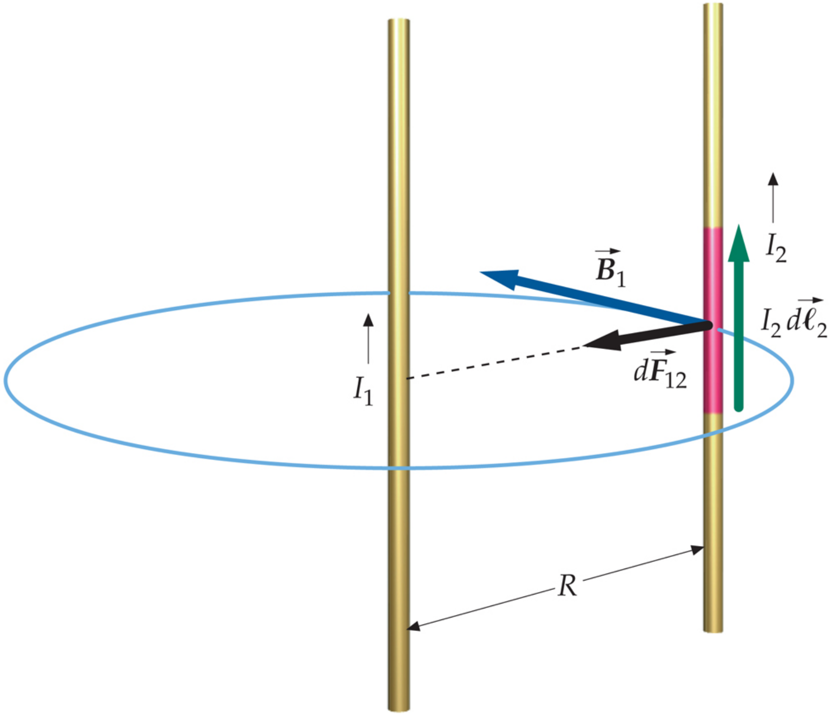
Image: Tipler

Collimation

The magnetic field exerts a force on another charge, e.g., in a nearby wire:

$$\frac{dF_{12}}{dl_2} = \frac{\mu_0}{2\pi}\frac{I_1 I_2}{R}$$





If the currents are parallel, the force is attractive: a natural way to self-collimate an ionised outflow

Image: Tipler

The jets rotate – not only mass loss, but angular momentum loss

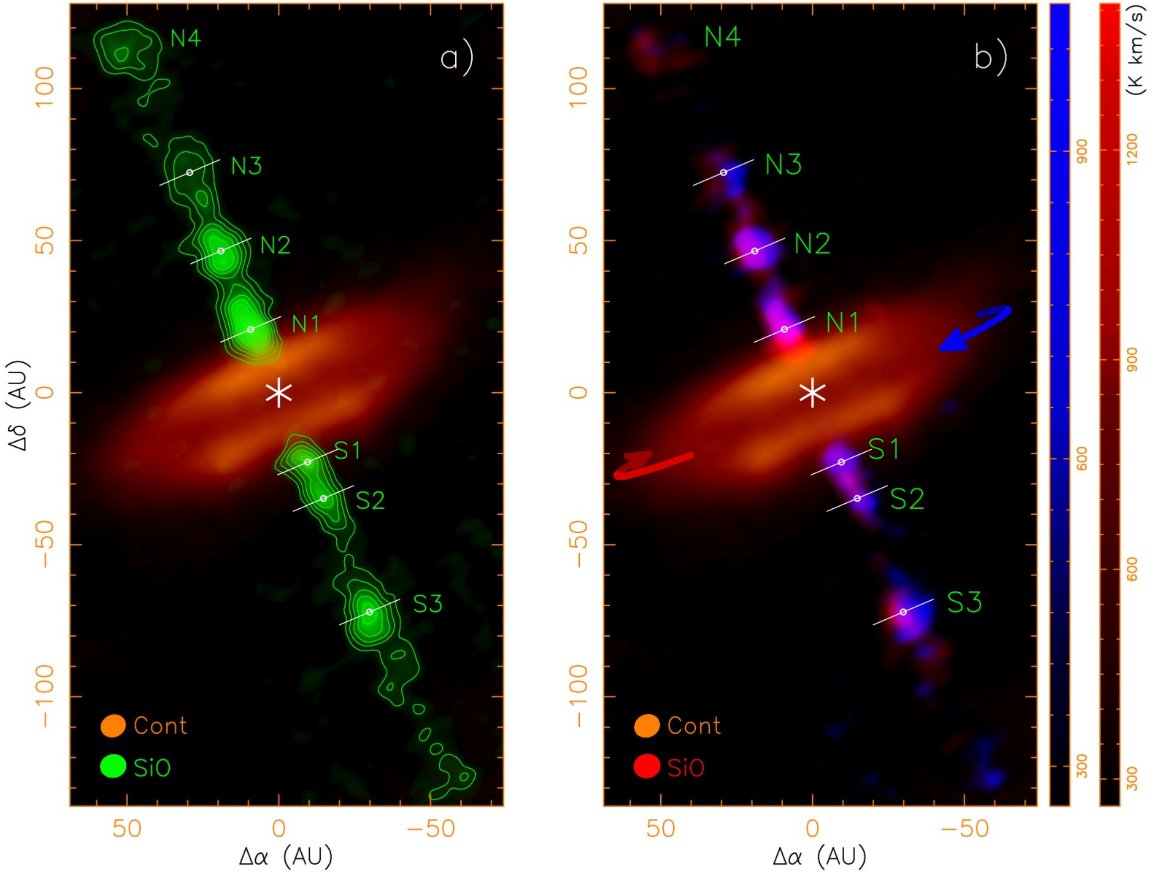


Fig. 3 ALMA results of the SiO jet in HH 212 within 100 au of the central source, adopted from Lee et al. (2017c). The orange image shows the dusty disk observed at 850 μm (Lee et al. 2017a). In (a), the green image shows the SiO jet. In (b), blueshifted emission and redshifted emission are plotted separately to show the jet rotation around the jet axis. The blue and red arrows show the disk rotation.

Lee 2017, 2020

The final picture

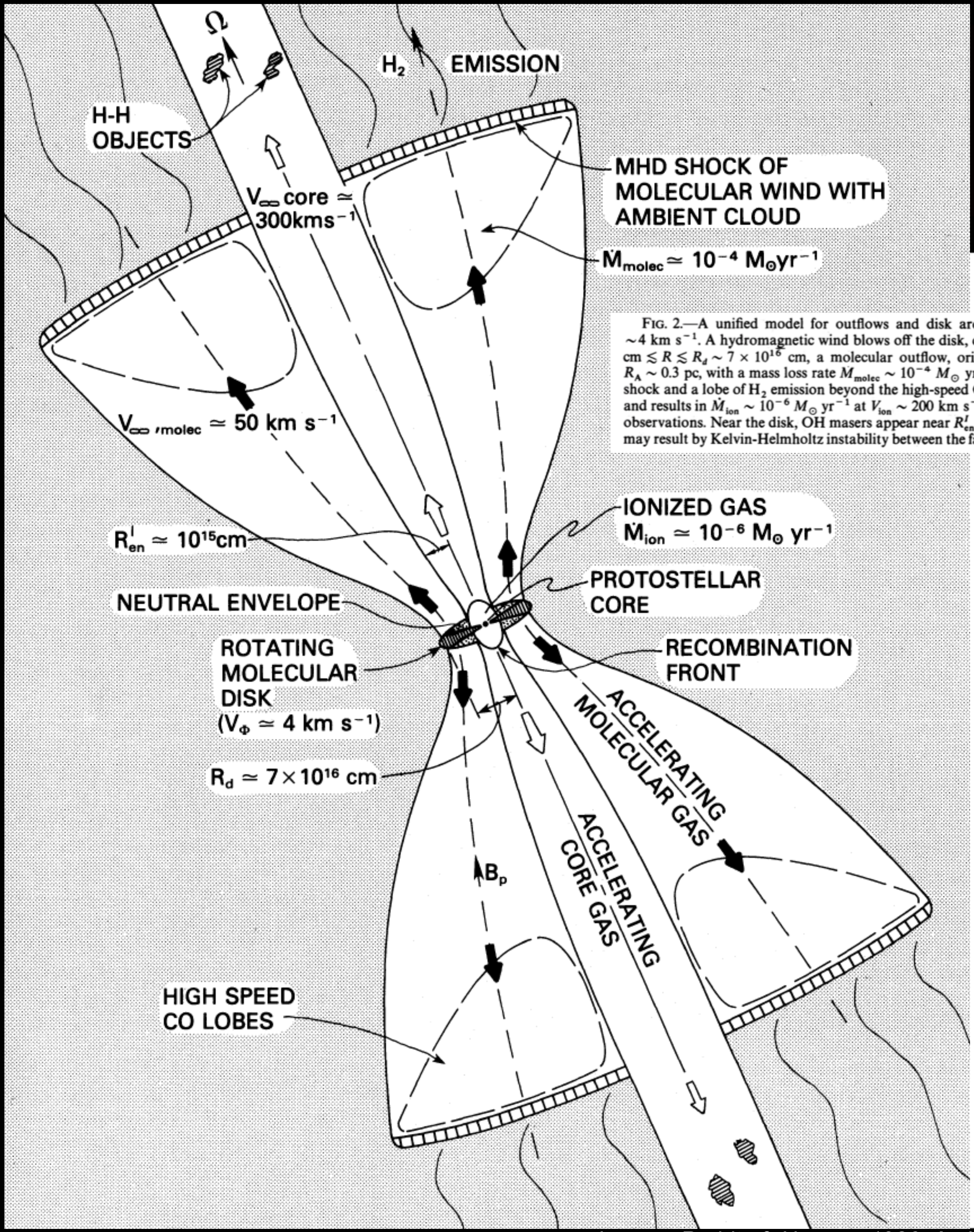
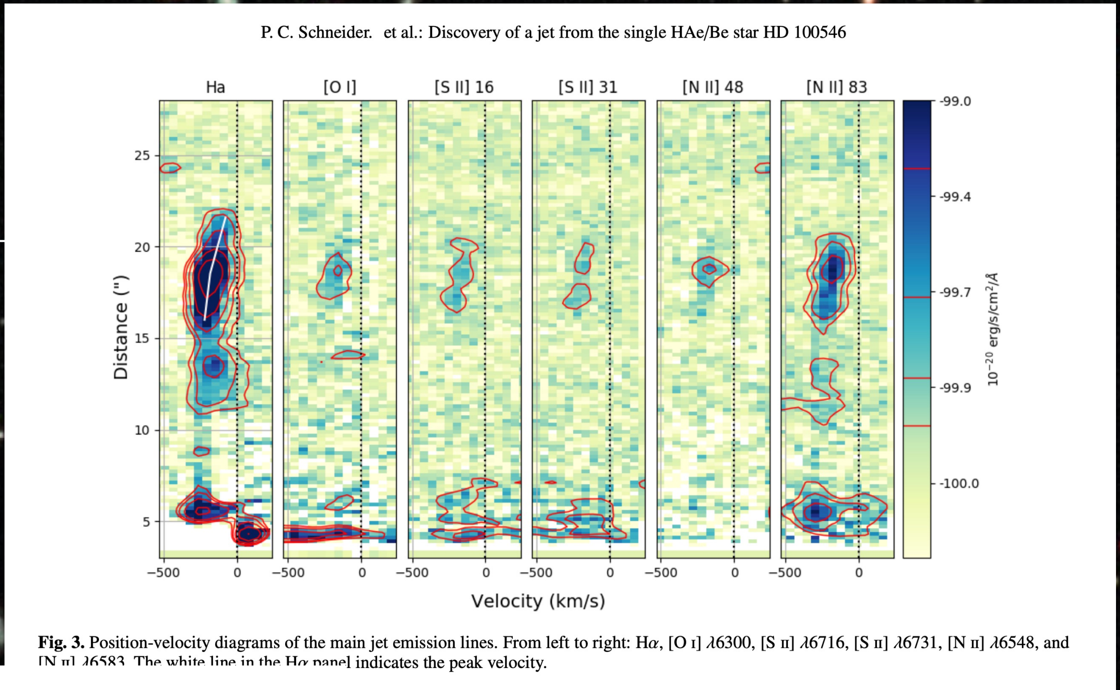


FIG. 2.—A unified model for outflows and disk around protostars. A massive protostar is forming in a massive ($\sim 10^2\ M_\odot$) molecular disk, rotating at $\sim$4 km s^{-1}. A hydromagnetic wind blows off the disk, carrying away its angular momentum and driving accretion onto the protostellar core. At radii $R^I_{en} \sim 10^{15}$ cm $\lesssim R \lesssim R_d \sim 7 \times 10^{16}$ cm, a molecular outflow, originating from a cool neutral envelope, is accelerated up to terminal speed of $\sim$50 km s^{-1} at a scale $R_A \sim 0.3$ pc, with a mass loss rate $\dot{M}_{molec} \sim 10^{-4}\ M_\odot$ yr^{-1}. This molecular wind collides with ambient molecular cloud material (*shaded region*), causing an MHD shock and a lobe of H_2 emission beyond the high-speed CO lobe. Inside disk radii $r \leq 10^{15}$ cm, Lyman continuum from the accretion shock ionizes a core envelope and results in $\dot{M}_{ion} \sim 10^{-6}\ M_\odot$ yr^{-1} at $V_{ion} \sim 200$ km s^{-1}. This outflow remains ionized for low mass loss rates and is the component identified by VLA and optical observations. Near the disk, OH masers appear near R^I_{en}; and far down the flow, HH objects are driven by the core component of the overall disk wind. HH objects may result by Kelvin-Helmholtz instability between the fast core gas and the slower-moving molecular outflow.

Image: Pudritz & Norman 1986, ApJ, 301, 571

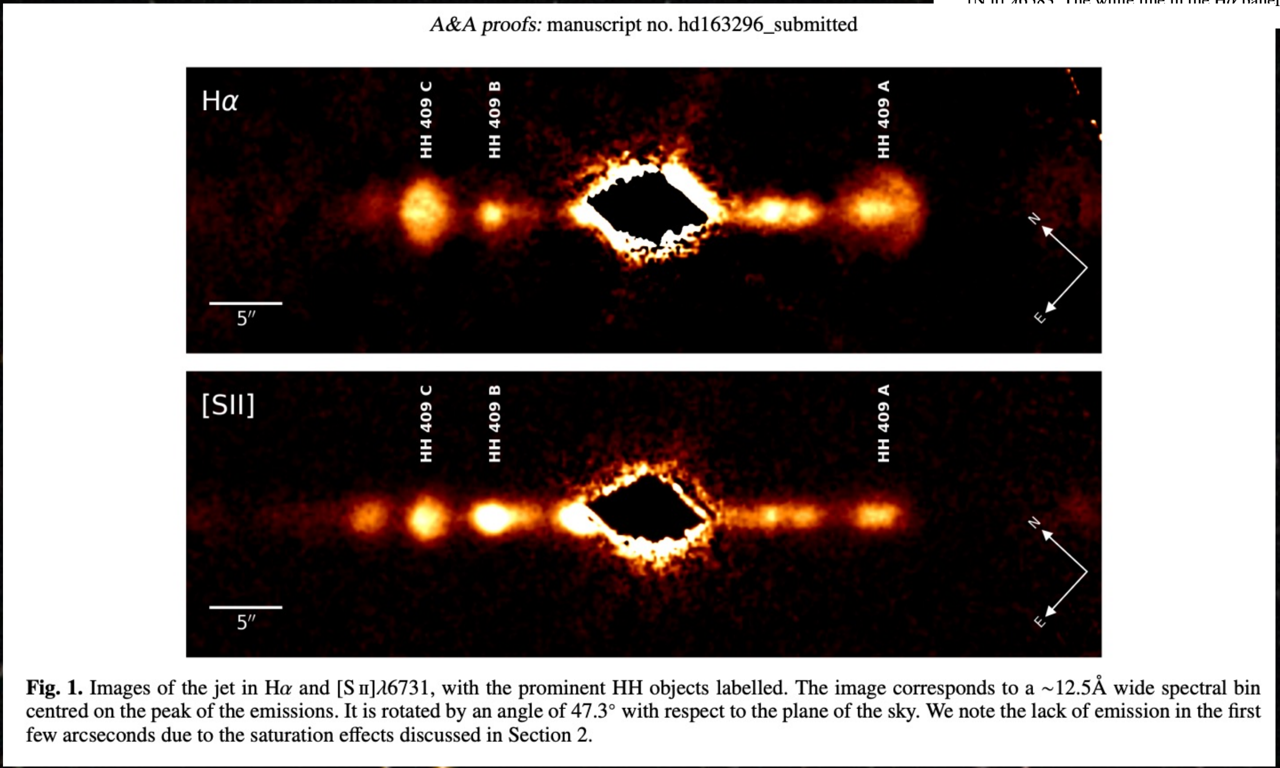
Jets and bi-polar flows only recently identified in higher mass young stars!

Herbig Ae/Be stars



P. C. Schneider. et al.: Discovery of a jet from the single HAe/Be star HD 100546

Fig. 3. Position-velocity diagrams of the main jet emission lines. From left to right: Hα, [O i] λ6300, [S ii] λ6716, [S ii] λ6731, [N ii] λ6548, and [N ii] λ6583. The white line in the Hα panel indicates the peak velocity.



A&A proofs: manuscript no. hd163296_submitted

Fig. 1. Images of the jet in Hα and [S ii]λ6731, with the prominent HH objects labelled. The image corresponds to a ∼12.5Å wide spectral bin centred on the peak of the emissions. It is rotated by an angle of 47.3° with respect to the plane of the sky. We note the lack of emission in the first few arcseconds due to the saturation effects discussed in Section 2.

Schneider+ 2020

Kirwan+ 2022

Massive Young Stellar Objects Purser+ 2017, 2021

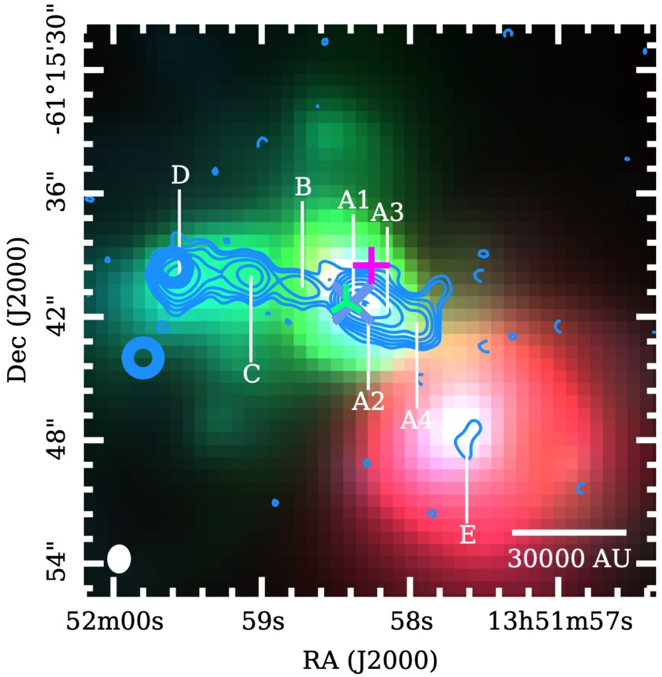


Figure B3. The 9GHz radio contours overlaid on an RGB (8.0μm, 4.5μm and 3.6μm) composite image of existing GLIMPSE data for G310.1420+00.7583A. Contours step up from 4σ by a factor of $\sqrt{3}$ per level and negative (-4σ) contours are dashed. Other annotations have the same meanings as in Figure C1.

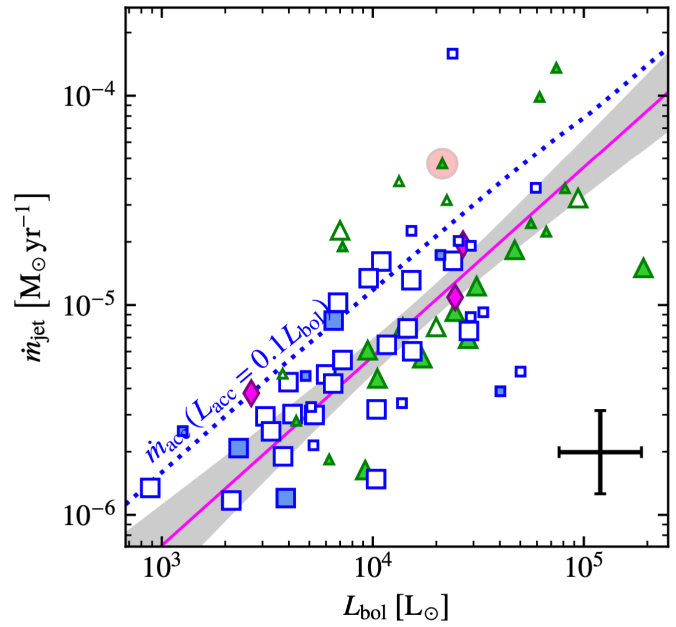
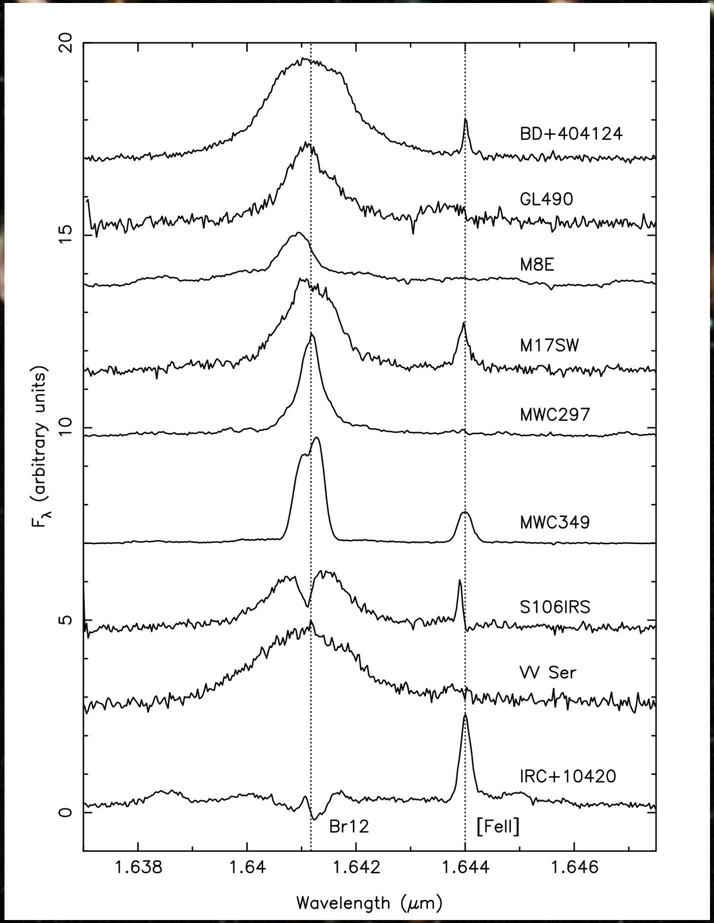


Figure 11. A plot of the jet mass loss rate against bolometric luminosity for jet-like sources detected. Symbols have the same meaning as in Figure 4 and the magenta line is the fit (Equation 6) to both the data presented here and that of P16 with the corresponding 1σ confidence interval shaded in light grey. The dotted line represents the accretion rate (using Equation 7 and assuming $L_{acc} = 0.1\, L_{bol}$, Cooper et al. 2013).

Inferred mass loss rate smaller than accretion rate

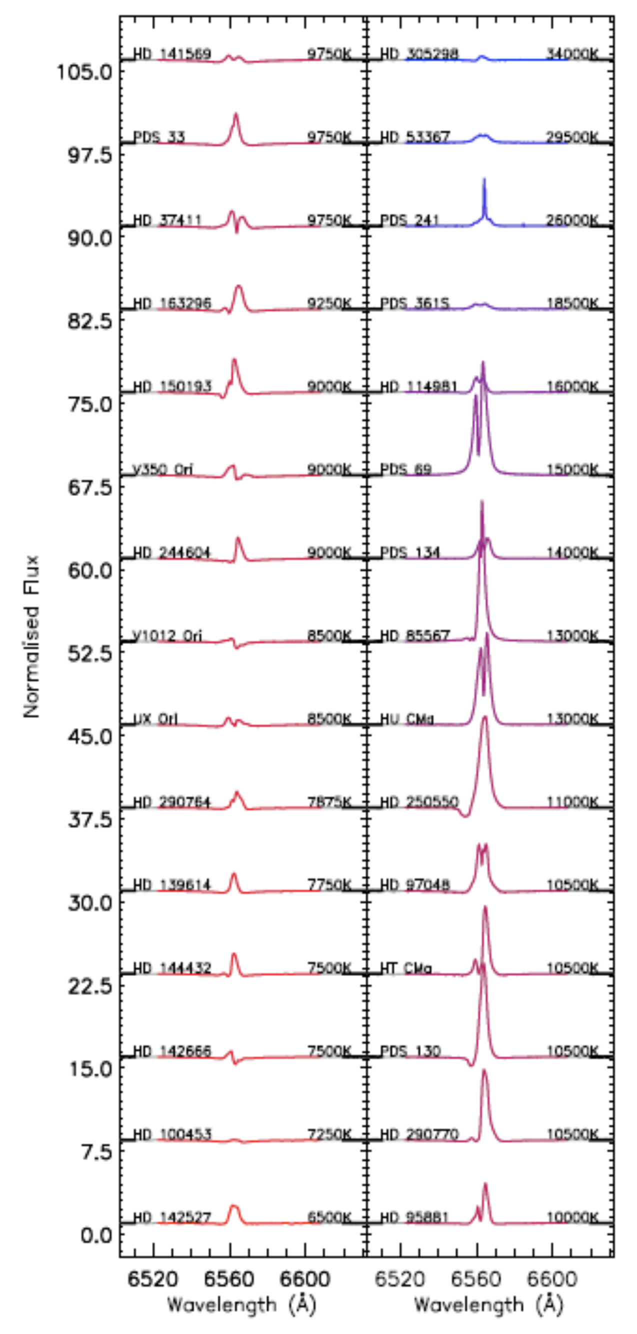
Winds, Outflows from Massive pre-Main Sequence stars

- Jets
- Disk Winds
- Stellar Winds
- Polar Winds



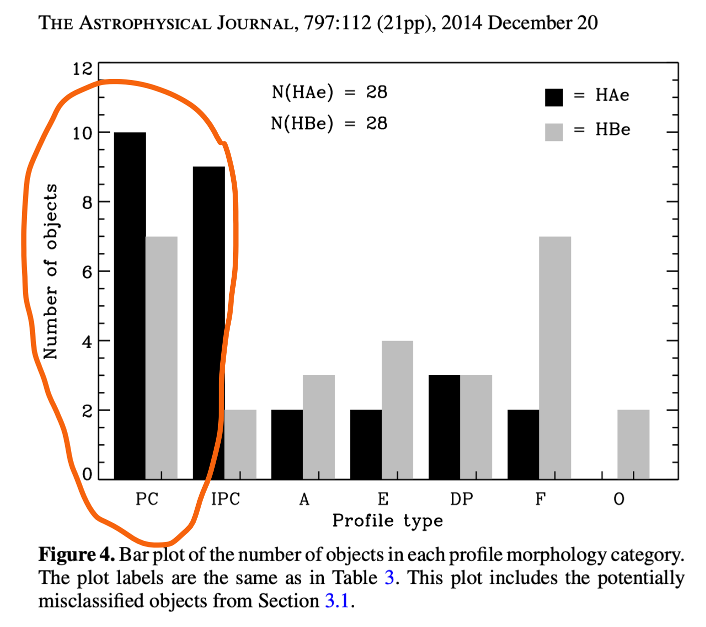
← MYSOs
Lumsden+ 2012

Herbig Ae/Be stars →
Fairlamb+ 2015



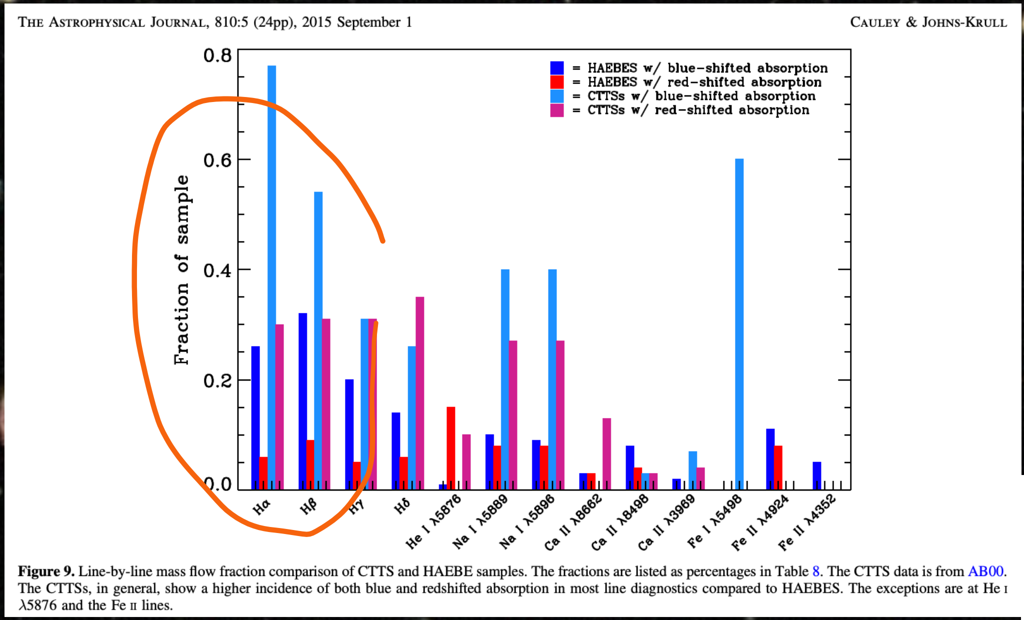
Differences between T Tauri – Herbig Ae – Herbig Be – MYSO

Cauley & Wilson 2014, 2015 Pomohaci+ 2017



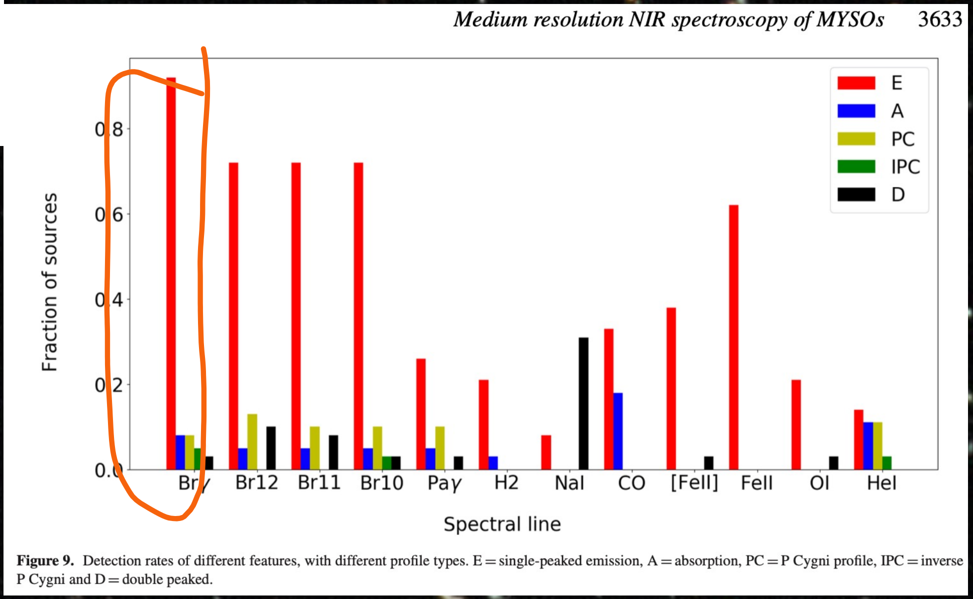
THE ASTROPHYSICAL JOURNAL, 797:112 (21pp), 2014 December 20

Figure 4. Bar plot of the number of objects in each profile morphology category. The plot labels are the same as in Table 3. This plot includes the potentially misclassified objects from Section 3.1.



THE ASTROPHYSICAL JOURNAL, 810:5 (24pp), 2015 September 1 CAULEY & JOHNS-KRULL

Figure 9. Line-by-line mass flow fraction comparison of CTTS and HAEBE samples. The fractions are listed as percentages in Table 8. The CTTS data is from AB00. The CTTSs, in general, show a higher incidence of both blue and redshifted absorption in most line diagnostics compared to HAEBES. The exceptions are at He I λ5876 and the Fe II lines.



Medium resolution NIR spectroscopy of MYSOs 3633

Figure 9. Detection rates of different features, with different profile types. E = single-peaked emission, A = absorption, PC = P Cygni profile, IPC = inverse P Cygni and D = double peaked.

Inverse P Cygni:

Accretion in edge-on disks

P Cygni : Polar Winds

Lowest mass stars more

Inverse P Cygni.

Round-up 1 : About the Winds & Outflows

- Every star produces an outflow for the first 10^5 - 10^6 years of its YSO (young stellar object) phase

- Outflows interact with their surrounding gas, injecting energy and momentum into the cloud: this is thought to help drive turbulence in clouds

- Energy from shocks can dissociate molecules, heat gas, sputter the dust, thereby triggering chemical reactions that do not (and cannot) occur in the quiescent gas

- They can modify their parent cloud structure, even at great distances from the source

- The interaction between the outflow and the circumstellar envelope may help end the infall stage

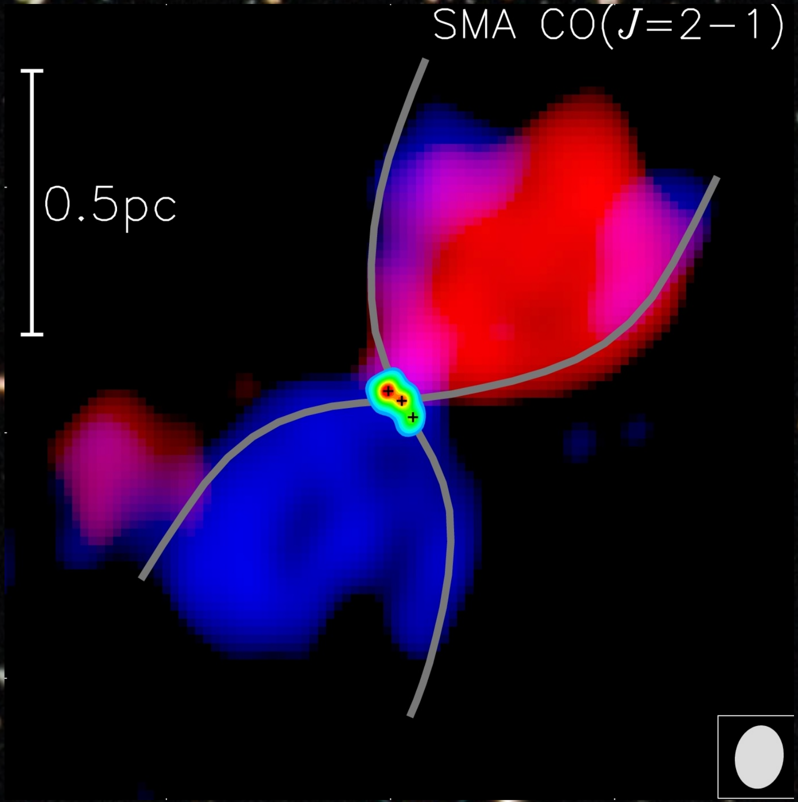
Round-up : About the Winds & Outflows

What is the mechanism?

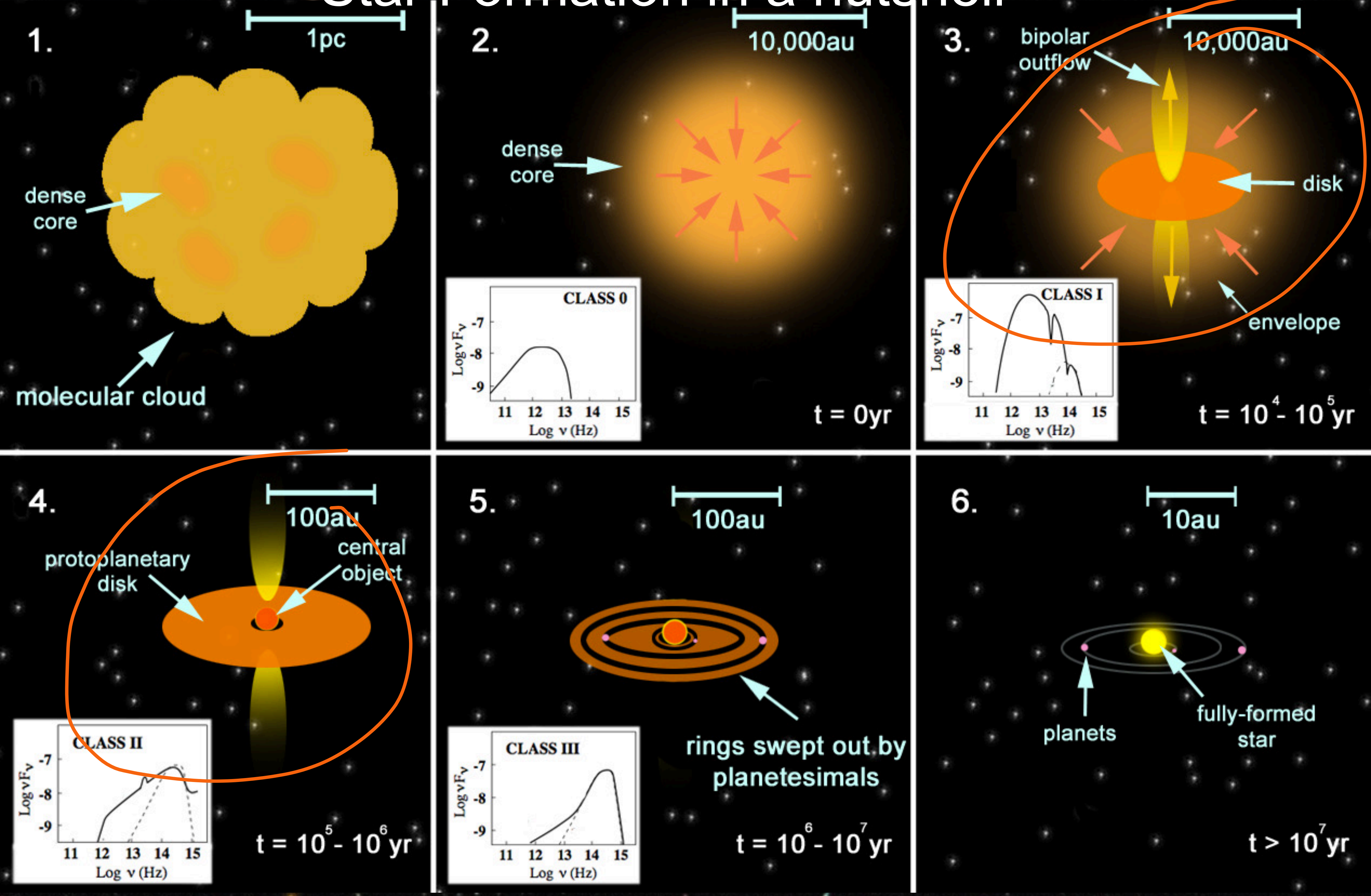
What powers the outflows?

How large is mass loss rate?

Wind velocities?



Star Formation in a nutshell



Round-up : About the Winds & Outflows

What is the mechanism?

- up until at least mid-B type:

MHD mechanisms inferred

Higher mass: still matter of debate

What powers the outflows?

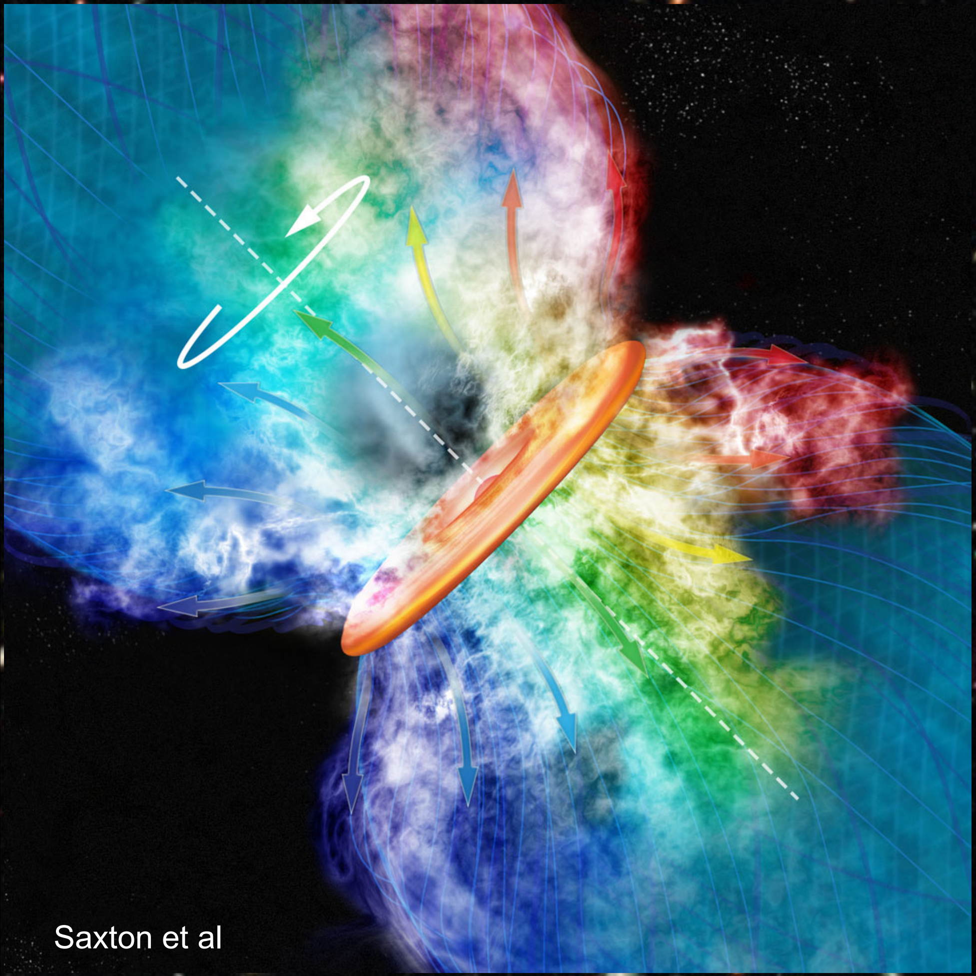
- accretion

How large is mass loss rate?

- 10% of accretion rate

Wind velocities?

- typically not much more than escape speed



Saxton et al

Conclusions

- Radiation pressure from the young star is not sufficient to drive the jet and/or outflow (exercise class)

- Both are likely generated via magnetohydrodynamic processes

- A rotating magnetic field (either in the star and the disk) can accelerate gas, if in the correct geometry

- Centrifugal acceleration overcomes gravity that then generates a “disk wind”

- Jets consist of fast moving charged particles: this can induce a magnetic field that leads to sustained self collimation

- Recent progress into jets around massive objects allow studies into star forming mechanism for massive stars

Thank you !