Star formation

WS24/25

High-mass star formation, clusters and the initial mass function (IMF)

Caroline Gieser
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Sternentstehung - Star Formation

Winter term 2024/2025

Henrik Beuther, Thomas Henning & Caroline Gieser

15.10 Today: Introduction & Overview (Beuther)
22.10 Physical processes I (Beuther)
29.10 --
05.11 Physcial processes II (Beuther)
12.11 Molecular clouds as birth places of stars (Beuther)
19.11 Molecular clouds (cont.), Jeans Analysis (Henning)
26.11 Collapse models I (Beuther)
03.12 Collapse models II (Beuther)
10.12 Protostellar evolution (Gieser)
17.12 Pre-main sequence evolution & outflows/jets (Henning)
07.01 Accretion disks I (Henning)
14.01 Accretion disks II (Henning)
21.01 High-mass star formation, clusters and the IMF (Gieser)
28.01 Extragalactic star formation (Henning), outlook & questions (Beuther, Gieser, Henning)
04.02 Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys
More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2425.html
beuther@mpia.de, henning@mpia.de, gieser@mpia.de

Cygnus X (d ~ 1.4 kpc)

Orion nebula (d ~ 400 pc)

credit: ESO/H. Drass et al.

credit: NASA

<u>Challenges of high-mass star formation:</u>

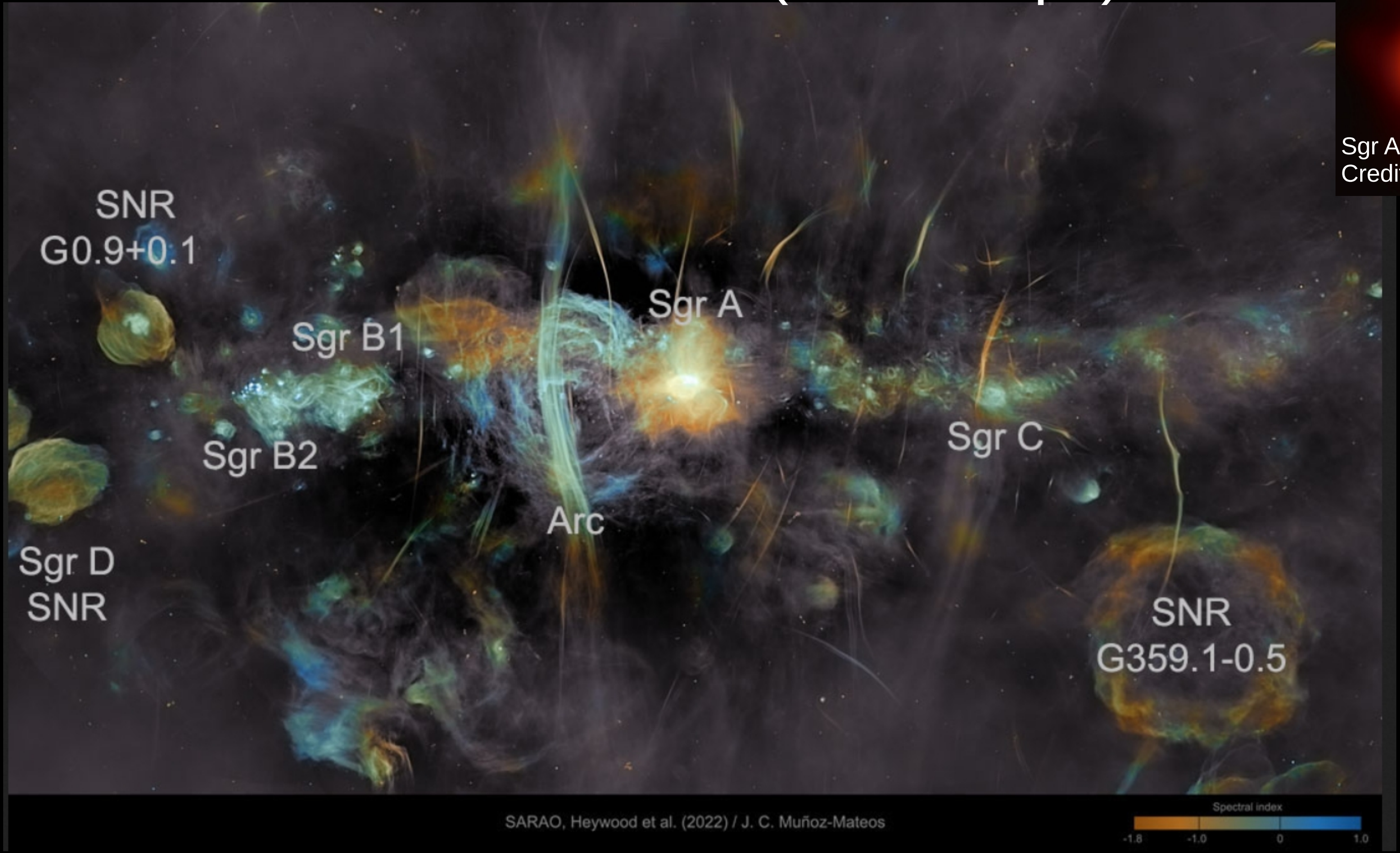
- most high-mass star-forming regions are located at **distances of several kpc**!
  → difficult to obtain high spatial resolution data (compared to nearby low-mass star forming regions)
- high-mass stars are **less common**
- high-mass star formation is **faster**

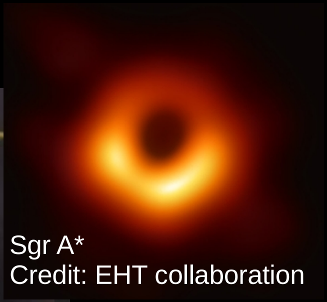
Carina nebula (d ~ 2.6 kpc)

→ cold molecular cloud material irradiated by massive stars

Credit: NASA, ESA, CSA, STScI

Galactic Center (d ~ 8.2 kpc)





→ active young star-forming regions close to the Galactic Center (e.g. Sgr B1/B2, C)!
→ many supernova remnants (SNR): endproducts of massive stars

Galactic Center (d ~ 8.2 kpc)

Galaxy's centre tastes of raspberries and smells of rum, say astronomers

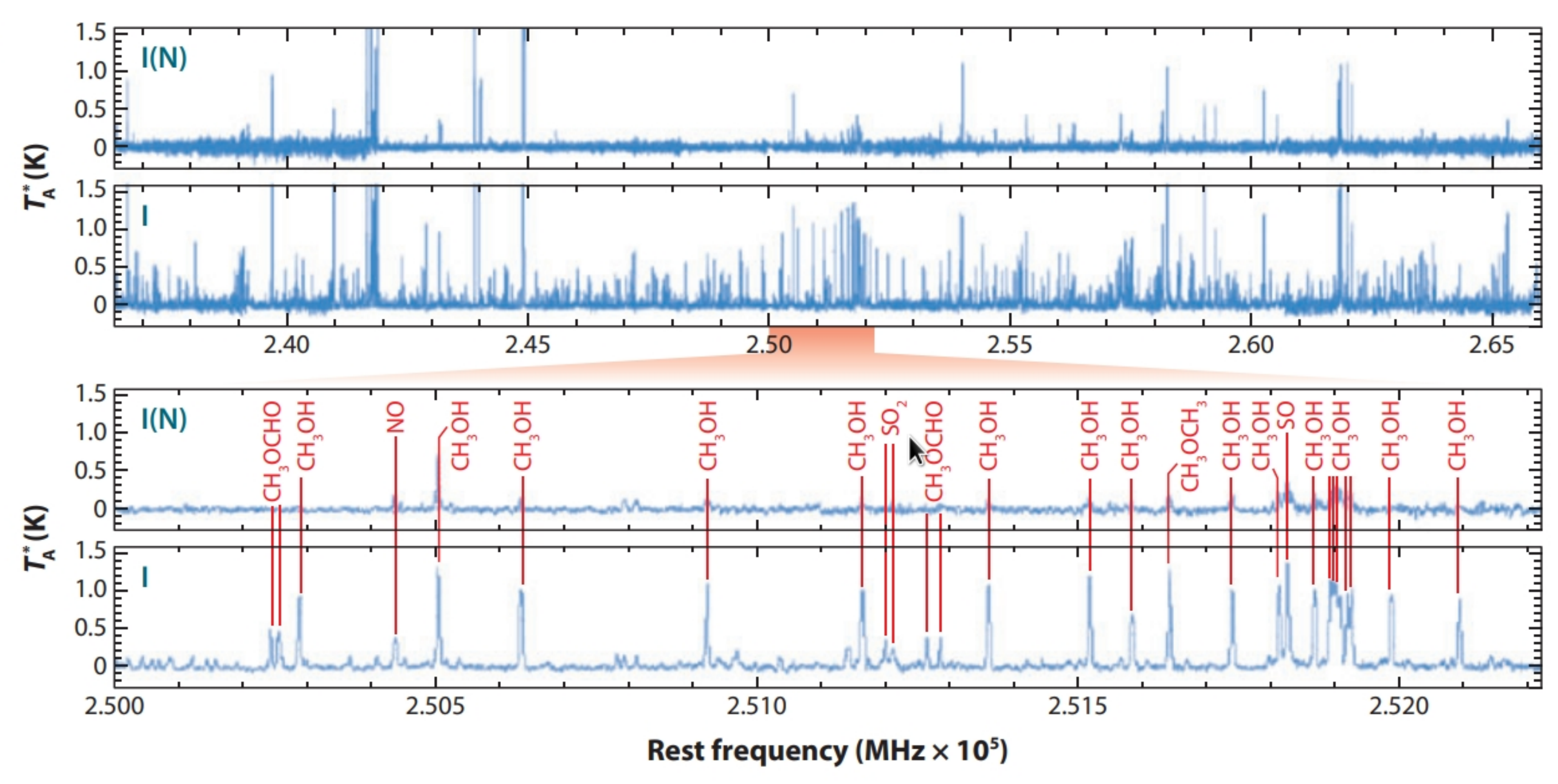
The hunt for chemicals in deep space that could seed life on other planets has yielded a large, fruity molecule

Ethyl formate, which gives raspberries their flavour and smells of rum, has now been found in deep space. Photograph: Tim Graham/Getty

→ large scale emission of
complex organic molecules (COMs)
in the Galactic center

https://www.theguardian.com/science/2009/apr/21/space-raspberries-amino-acids-astrobiology

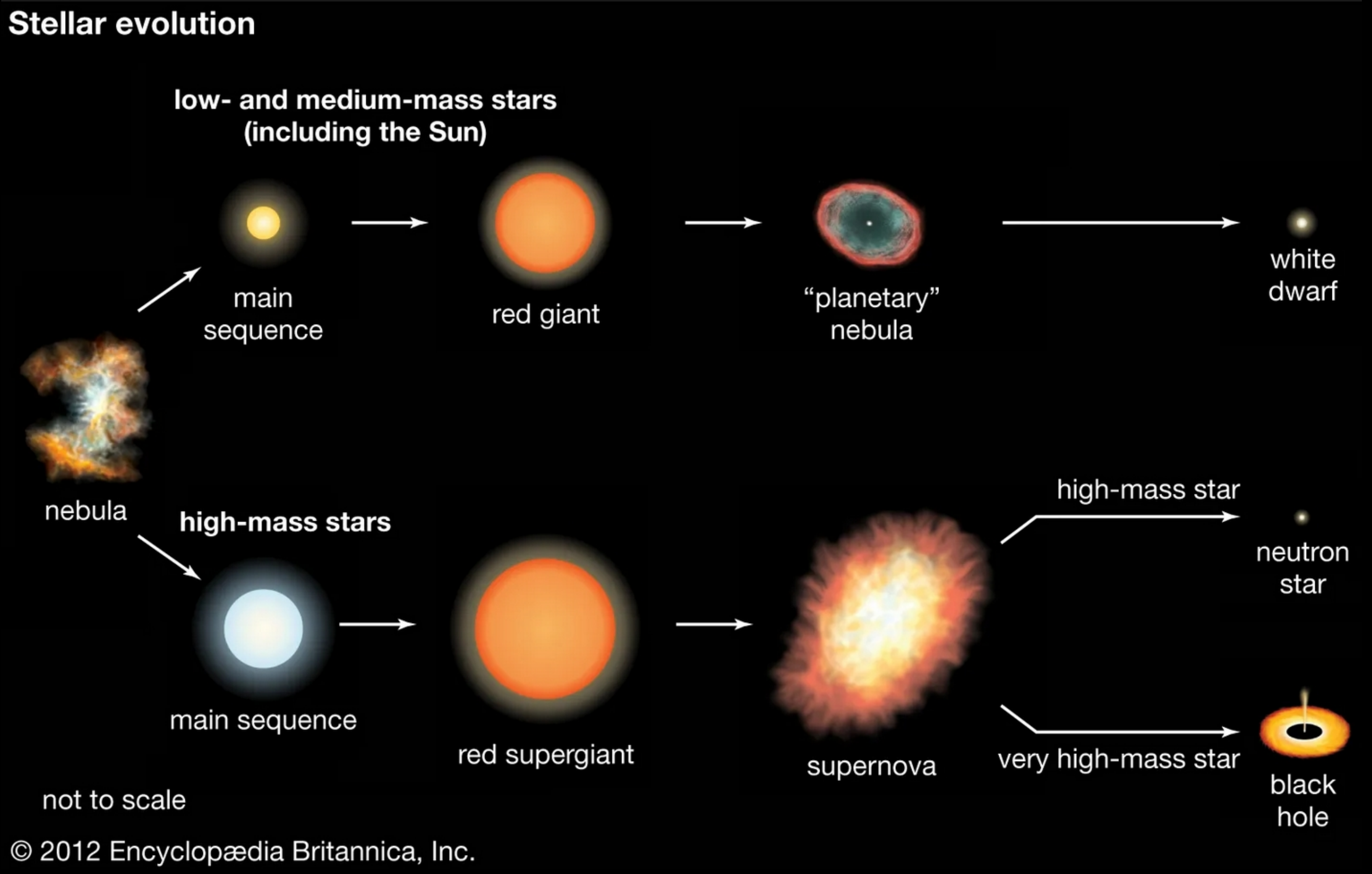
Chemical enrichment in high-mass star-forming regions



Herbst & van Dishoeck 2009

→ (sub)mm spectra of high-mass protostars reveal a rich & diverse chemical composition

Massive stars have final stellar masses $M_* > 8\ M_\odot$



Topics today

- **General concepts of massive star formation**
- Outflows in high-mass star-forming regions
- Rotation and disks
- Clusters and the IMF

General concepts of massive star formation

Credit: NASA, ESA, M. Robberto

Why are massive stars important?

- a few in numbers, but luminosity **$L \propto M^3$**

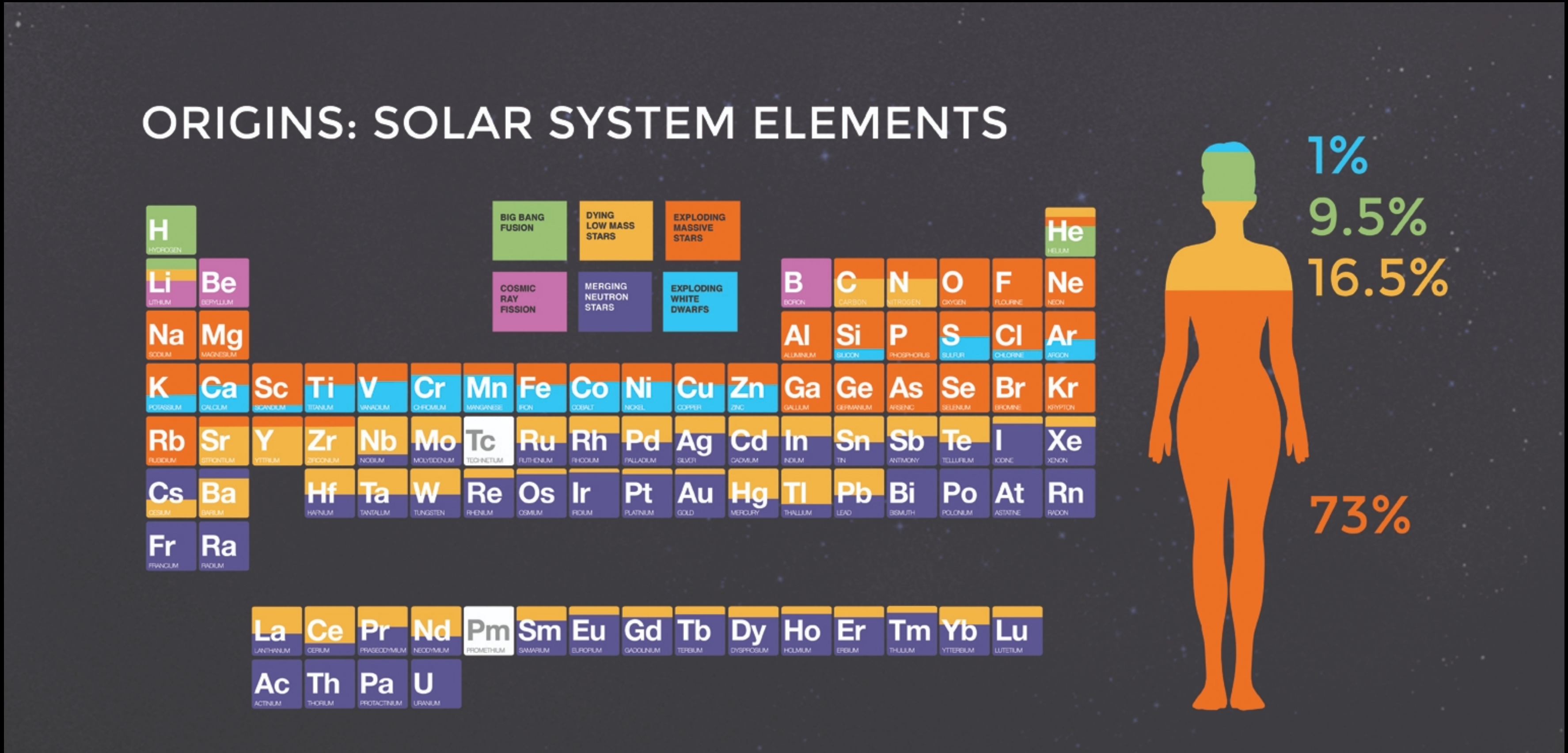
- inject significant amounts of energy into the interstellar medium (ISM) during their lifetime (**outflows, radiation, supernovae**)

- produce heavy elements

- massive stars form in **clusters**

  → low-mass star formation strongly influenced by massive stars in the cluster

General concepts of massive star formation



→ the majority of heavy elements in the Solar system was produced by massive stars!

Credit: NASA/CXC/SAO/K. Divona

General concepts of massive star formation

Kelvin-Helmholtz contraction time:

timescale in which all gravitational energy is radiated away

$$t_{\mathrm{KH}} \equiv \frac{G\,M_*^2}{R_*\,L_*}$$
$$= 3 \times 10^7\ \mathrm{yr} \left(\frac{M_*}{1\,M_\odot}\right)^2 \left(\frac{R_*}{1\,R_\odot}\right)^{-1} \left(\frac{L_*}{1\,L_\odot}\right)^{-1}$$

Recap:

for a low-mass protostar:

accretion onto protostar stops

→ pre-main-sequence (PMS) stage: energy released due to grav. contraction

Solar type star ($1M_\odot$, $5R_\odot$ and $7L_\odot$): **t_{KH} ~ 10^6 yr**

General concepts of massive star formation

Kelvin-Helmholtz contraction time:

timescale in which all gravitational energy is radiated away

$$t_{\mathrm{KH}} \equiv \frac{G\,M_*^2}{R_*\,L_*}$$
$$= 3 \times 10^7\ \mathrm{yr} \left(\frac{M_*}{1\,M_\odot}\right)^2 \left(\frac{R_*}{1\,R_\odot}\right)^{-1} \left(\frac{L_*}{1\,L_\odot}\right)^{-1}$$

for a massive protostar:

$60M_\odot$, $12R_\odot$ and $10^6L_\odot$

t_{KH} ~ 9000 yr

→ no observable pre-main sequence (PMS) phase

→ **due to high luminosity: radiation pressure important constraint**

General concepts of massive star formation

Eddington luminosity: upper luminosity limit before star is unstable

- assumptions: **spherical symmetry and fully ionized hydrogen**

→ radiation exerts force on free electrons via Thomson scattering

$\boldsymbol{\sigma_T=(q^2 / mc^2)^2}$ (σ_T: cross section, q: charge, m: mass)

- outward radial force equals rate at which electron absorbs momentum:

$\boldsymbol{F_{rad} = \sigma_T S/c}$ (S: energy flux)

- radiation pushes out electron-proton pairs against grav. force

$\boldsymbol{F_{grav} = GM(m_p+m_e) / r^2 \sim GMm_p / r^2}$

General concepts of massive star formation

Eddington luminosity: upper luminosity limit before star is unstable

- with flux $\mathbf{S = L / 4\pi r^2}$, the force equilibrium ($\mathbf{F_{grav} = F_{rad}}$) is:

$$\mathbf{GMm_p / r^2 = \sigma_T L / (4\pi r^2 c)}$$

- **Eddington luminosity:**

$$L_{Edd} = 4\pi GMc\,(m_p / \sigma_T) \qquad \text{(independent of r!)}$$

$$= 4\pi GMc / \kappa \qquad \text{(mass absorption coefficient } \boldsymbol{\kappa = \sigma_T / m_p}\text{)}$$

$$L_{\mathrm{Edd}} = 3.2 \times 10^4 \left(\frac{M}{M_\odot} \right) L_\odot$$

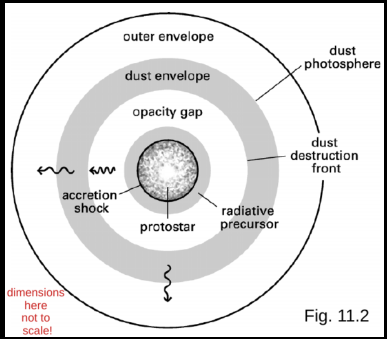


Fig. 11.2

- if $L > L_{Edd}$ then
  - accretion stops if L provided by accretion
  - gas layers pushed out and star unstable if L provided by nuclear fusion

- Scaling relation for massive (proto)stars: $L \propto M^a$ (with $2<a<4$)

General concepts of massive star formation

Radiation pressure of the central massive (proto)star on the surrounding dust cocoon

Same relation:

$$L / M = 4\pi G c / \kappa$$

- While κ is very low for ionized H plasma (**$\kappa \sim 0.3 cm^2 g^{-1}$**), at the dust destruction front (**T~1500K**) it is considerably larger with **$\kappa \sim 10 cm^2 g^{-1}$**.

$$\rightarrow L / M \sim 10^3 \ [L_\odot / M_\odot]$$

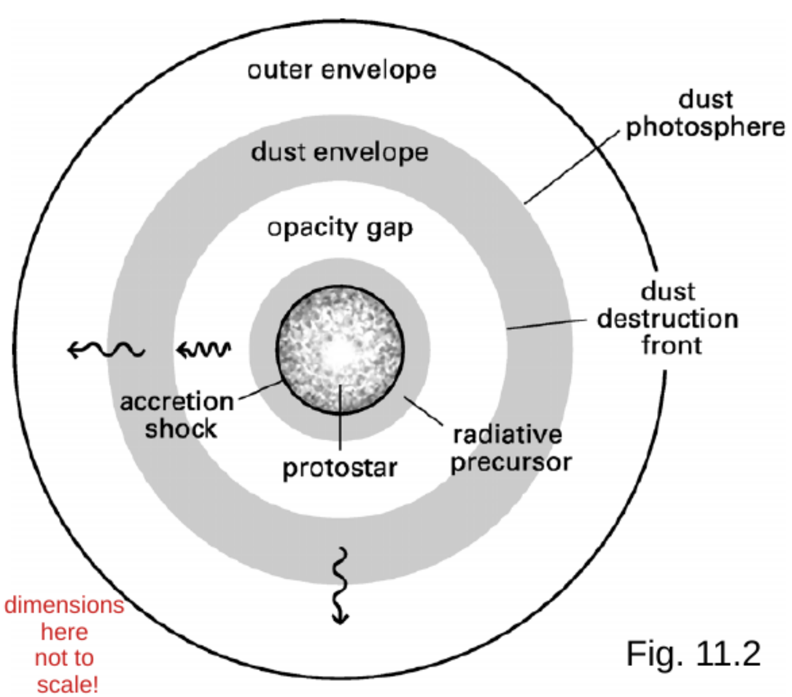


Fig. 11.2

General concepts of massive star formation

Radiation pressure of the central massive (proto)star on the surrounding dust cocoon

- **$L/M \sim 10^3$ $[L_\odot/M_\odot]$**

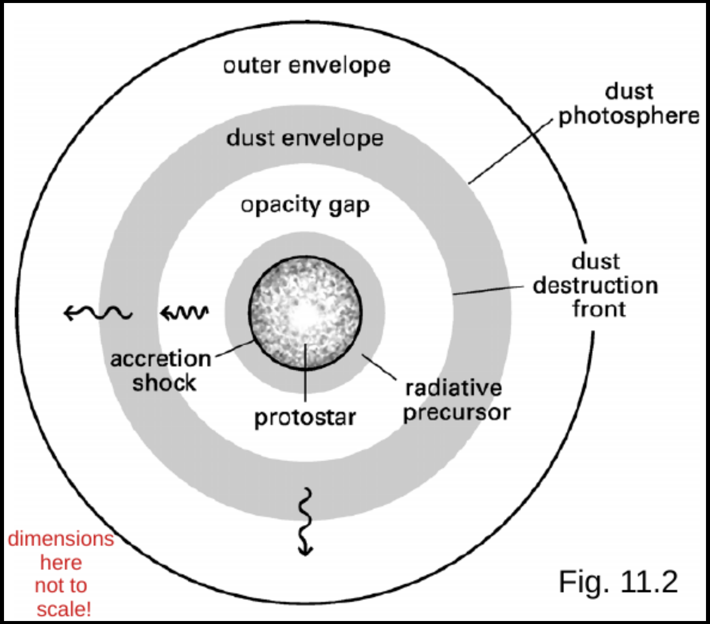
- In spherical symmetric accretion models, accretion is expected to stop as soon as the luminosity is approximately 1000 times larger than the mass of the protostar.

  → no problem for low-mass protostars (L much lower)

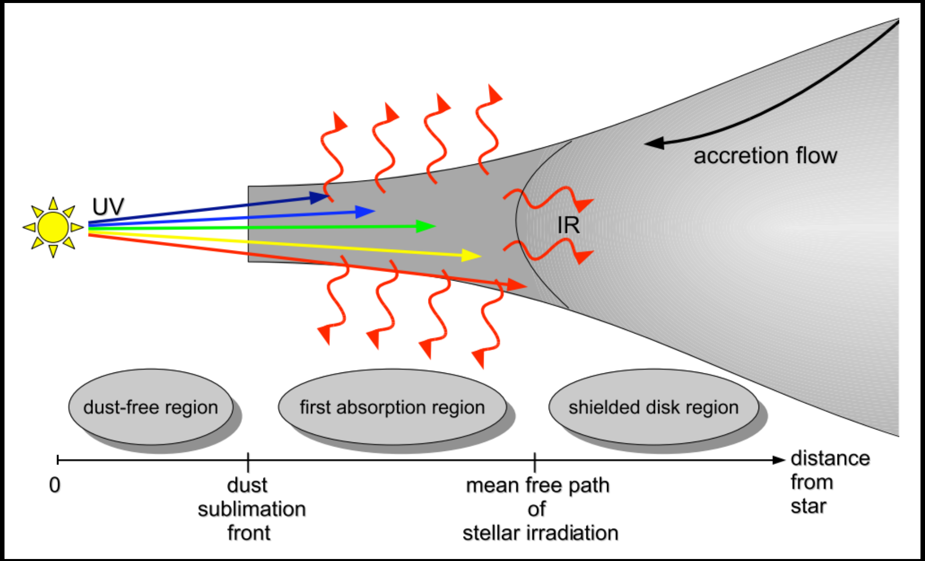
- The critical ratio is reached for stars of approximately **$10M_\odot$**:
  Since more massive stars are known, the assumption of spherical accretion has to be wrong and other processes are needed.

General concepts of massive star formation

Circumventing the radiation pressure issue:



spherical accretion



Kuiper+2010

disk accretion

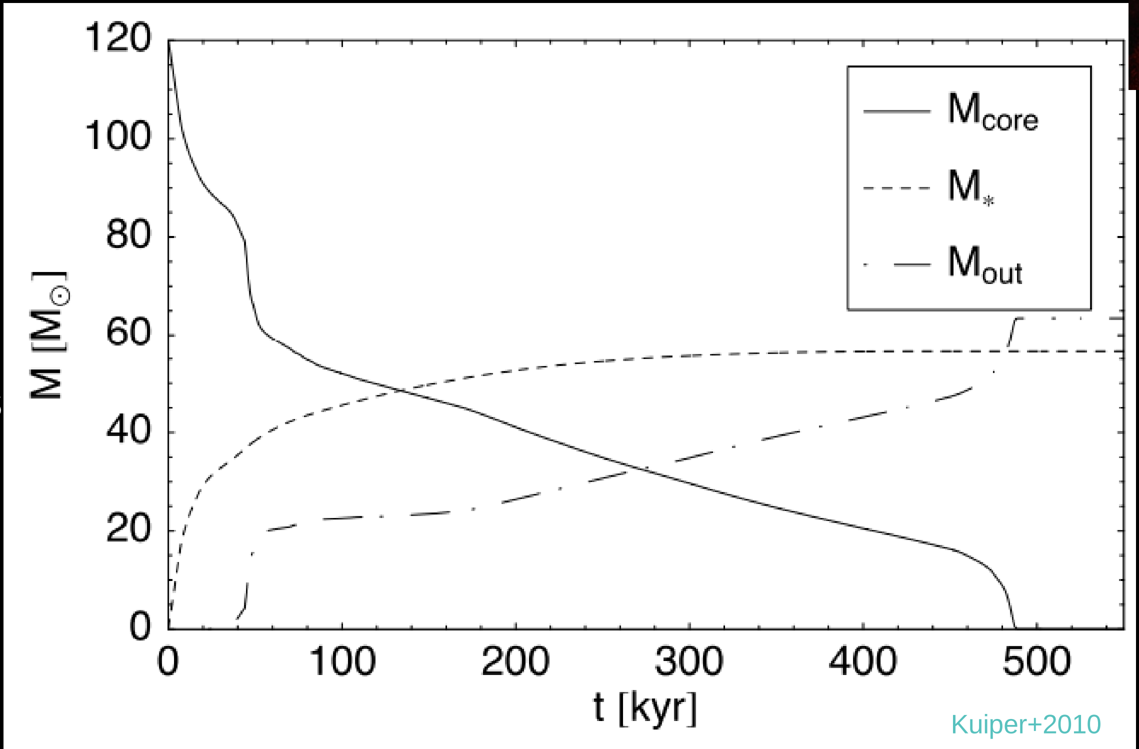
General concepts of massive star formation

Circumventing the radiation pressure issue:

spherical accretion (1D)
→ disk accretion (2D)

- Core (with mass M_{core}) collapses and matter is accreted onto protostar (with mass M_*)

- Protostar expells matter (M_{out}) through molecular outflow




Credit: ESO

General concepts of massive star formation

Massive star formation scenarios

I) Modified low-mass star formation:

- $100M_\odot$ star forms in $\sim10^5$yr
  → a**verage accretion rate: $\sim10^{-3}M_\odot$/yr**

(this is 2-3 order of magnitudes higher compared to a Solar type star!)

General concepts of massive star formation

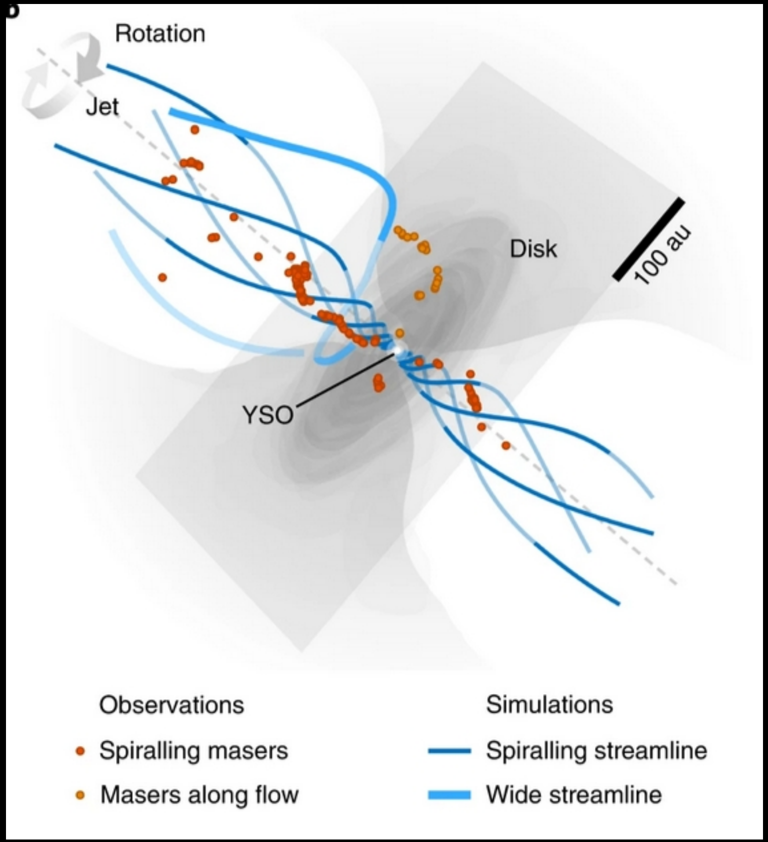
<u>**Massive star formation scenarios**</u>

I) Modified low-mass star formation:

- increased accretion rates of a few orders of magnitude

- 2D disk geometry helps accretion processes.

- radiation pressure can escape through outflow cavities
  → flashlight effect



Credit: Moscadelli+2022

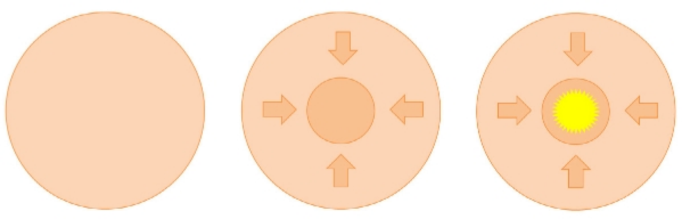
General concepts of massive star formation

<u>Massive star formation scenarios</u>

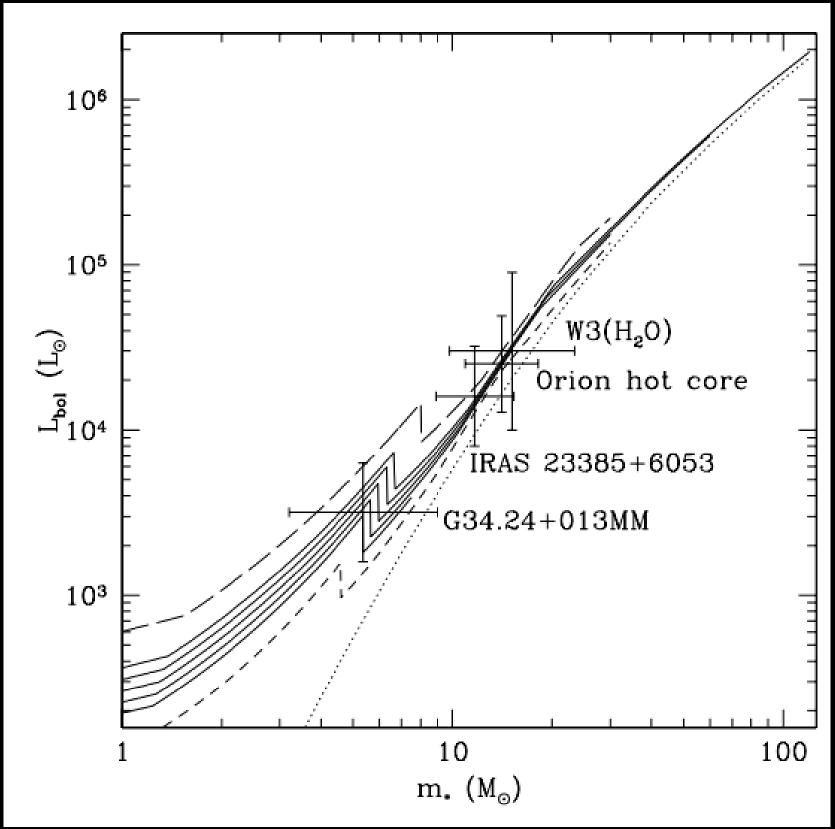
I) Modified low-mass star formation:

- “turbulent core model”:

  massive stars form within grav. bound cores supported by turbulence and magnetic fields



Credit: Rivilla+2013



McKee & Tan 2003

General concepts of massive star formation

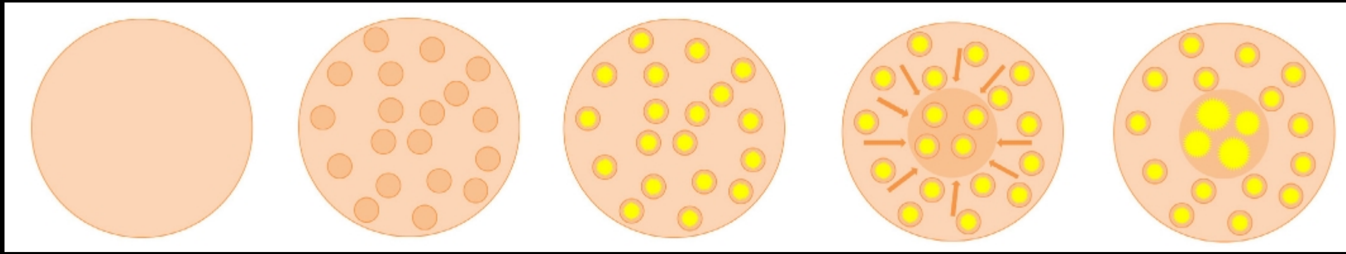
Massive star formation scenarios

II) Competetive accretion and coalescence:

- massive stars form only in clusters

- the cluster potential favours accretion toward objects in the center

- all kinds of protostellar entities may merge



Credit: Rivilla+2013

General concepts of massive star formation

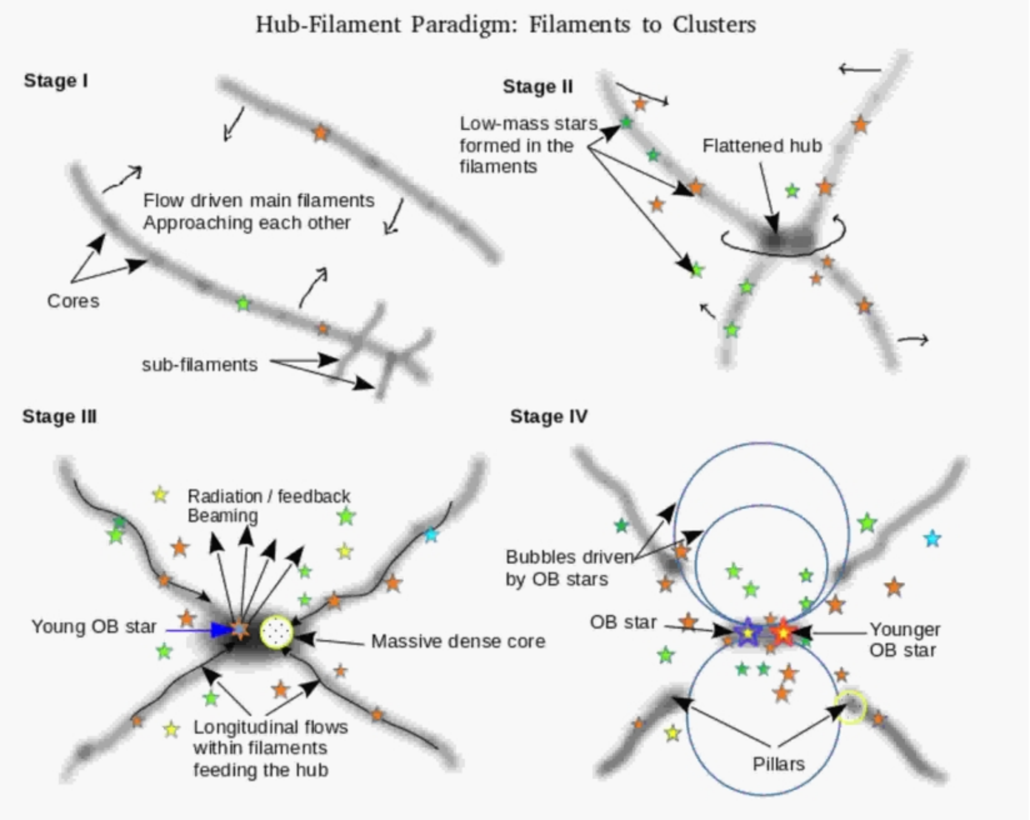
<u>Massive star formation scenarios</u>

III) Global star formation scenarios

- consider the hierarchical structures of molecular clouds

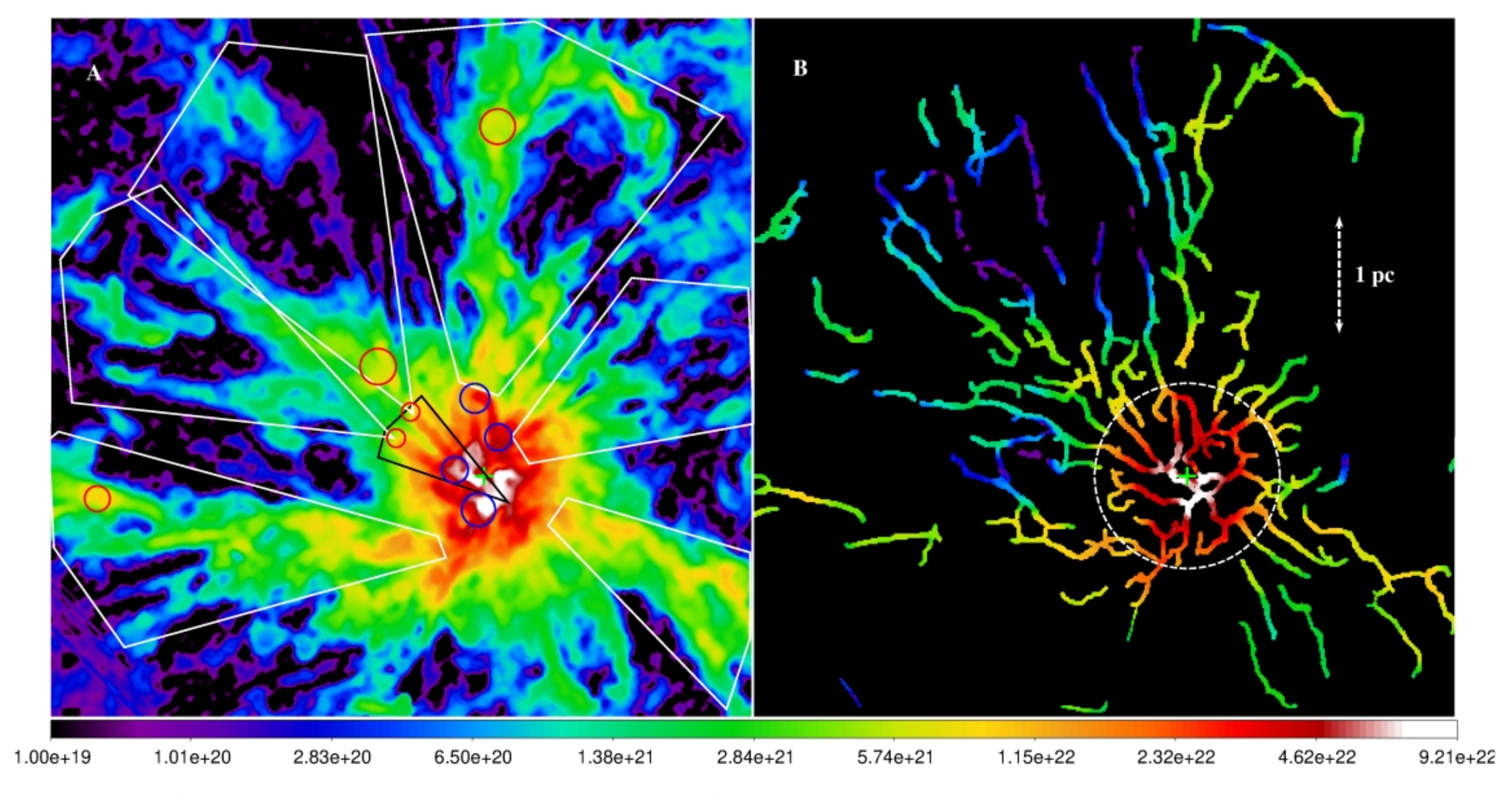
- low-mass star formation in filaments

- high-mass star formation in hub systems



Kumar+2020

Hub structure in Mon R2



Kumar+2022

General concepts of massive star formation

Evolutionary stages during high-mass star formation

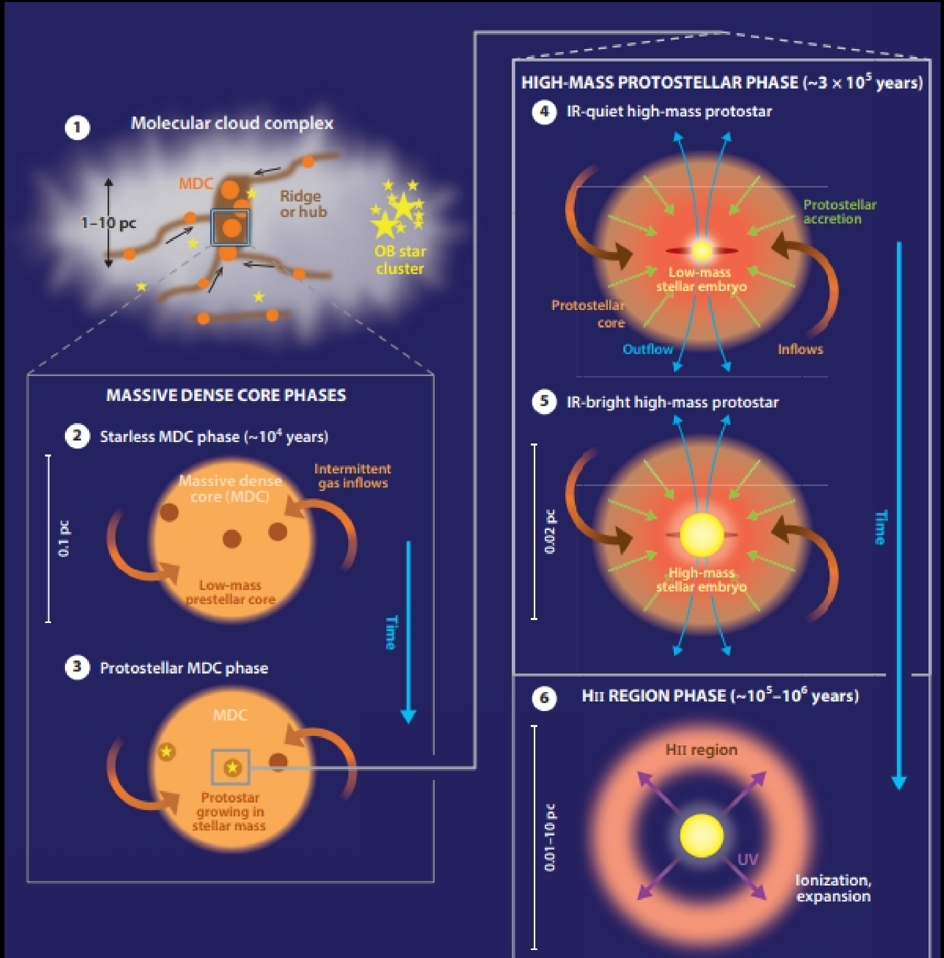
(the following is a crude classification motivated by observed properties)

Infrared dark cloud (IRDC):
- embedded protostar only visible in FIR/mm (cold gas/dust)

High-mass protostellar object (HMPO):
- protostar in main accretion phase
- large-scale energetic molecular outflows
- protostar becomes detectable in IR

Hot molecular core (HMC):
- at temperatures ~100 K:
  molecules frozen onto dust grains evaporate
  into the gas-phase revealing line rich spectra

HII region:
- protostellar radiation ionizes surroundingenvelope
  → free-free emission observed at low frequencies



Motte+2018

(HI: neutral hydrogen / HII: ionized hydrogen)

General concepts of massive star formation

Simulations of massive star formation:

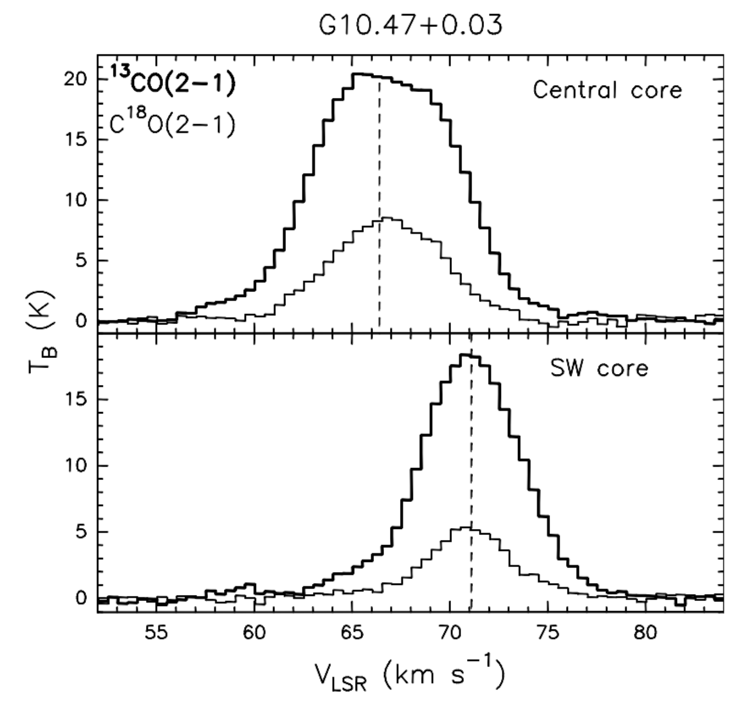
Massive stellar system forming out of turbulent core:
https://www.youtube.com/watch?v=SgYwNoPMmGE

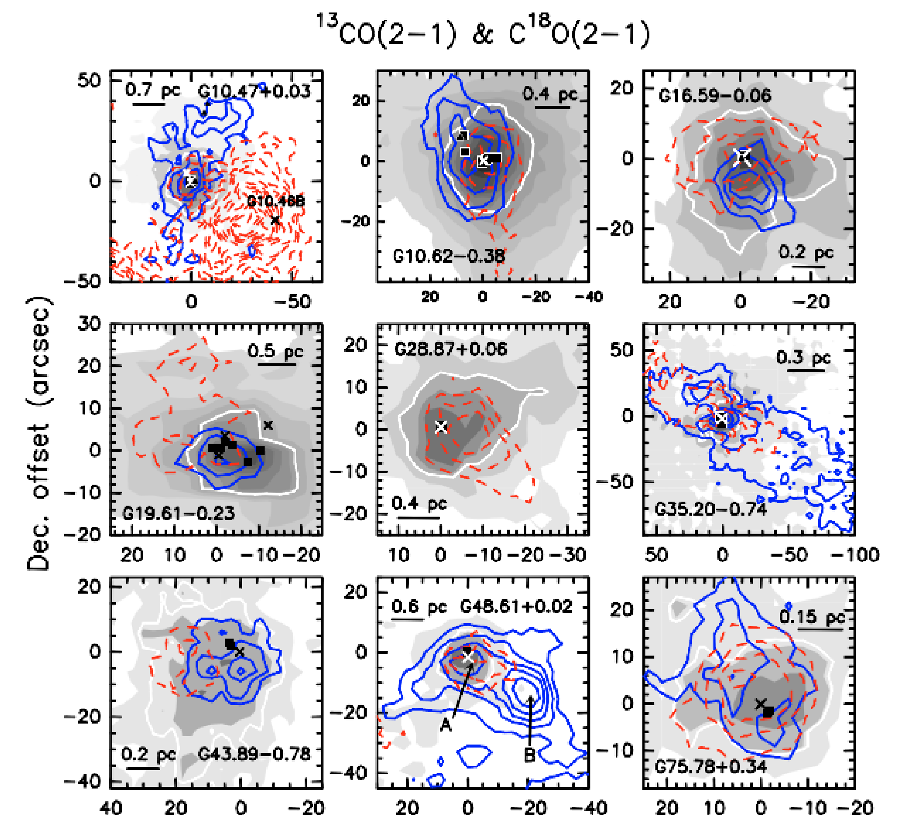
Formation of a massive protostar:
https://www.youtube.com/watch?v=IxrQoHu7W94

Topics today

- General concepts of massive star formation
- **Outflows in high-mass star-forming regions**
- Rotation and disks
- Clusters and the IMF

Outflows in high-mass star-forming regions





- common bipolar outflow tracers: CO isotopologues, SiO
- red- and blue-shifted line wings trace red- and blue-shifted outflow lobes

Lopez-Sepulcre+2009

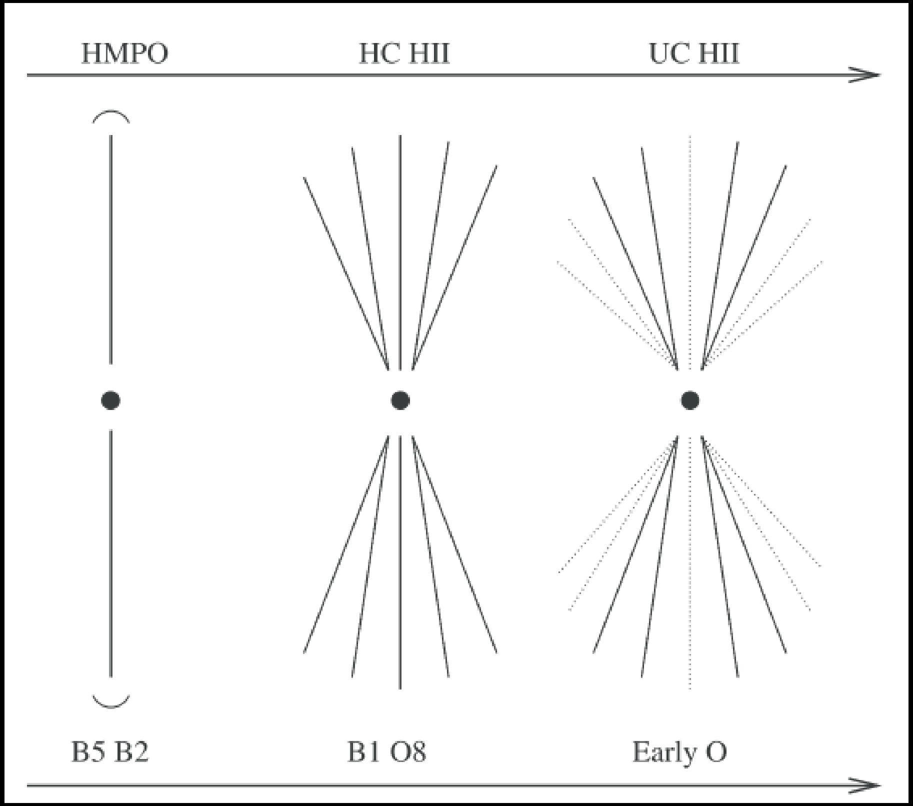
Outflows in high-mass star-forming regions

Outflow collimation related to evolutionary stage

HMPO: high-mass protostellar object
→ accretion through disk
→ system launches a collimated jet

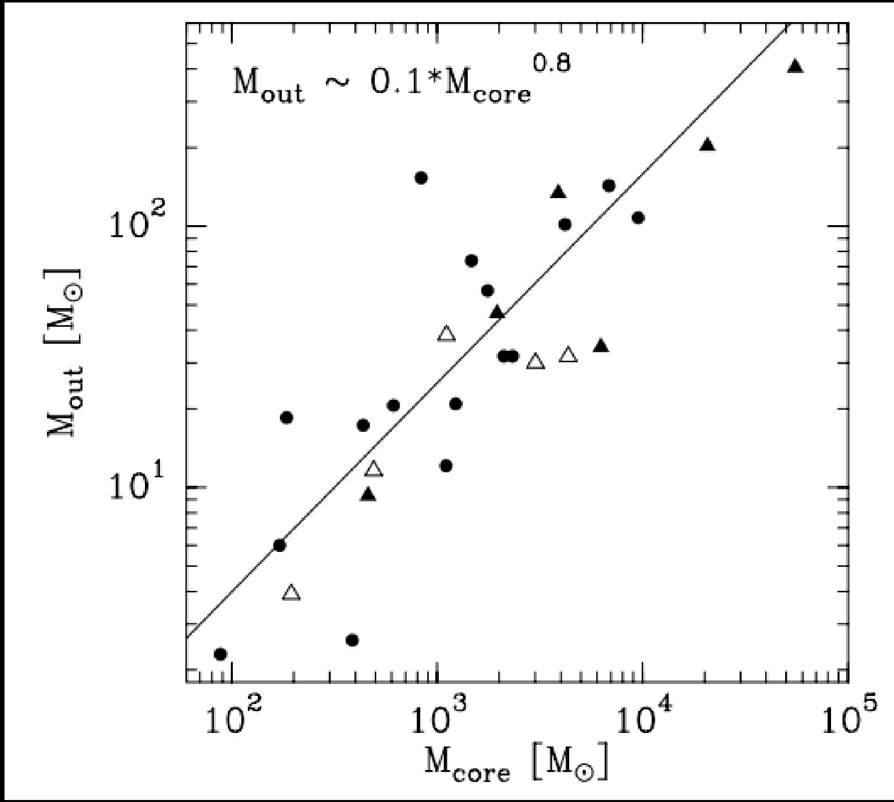
Hypercompact HII region (HC HII)
→ additional contributions from disk winds in HII region stage

Ultracompact HII region (UC HII)
→ strong contribution by disk winds



Beuther & Shepherd 2005

Outflows in high-mass star-forming regions



Beuther+2002

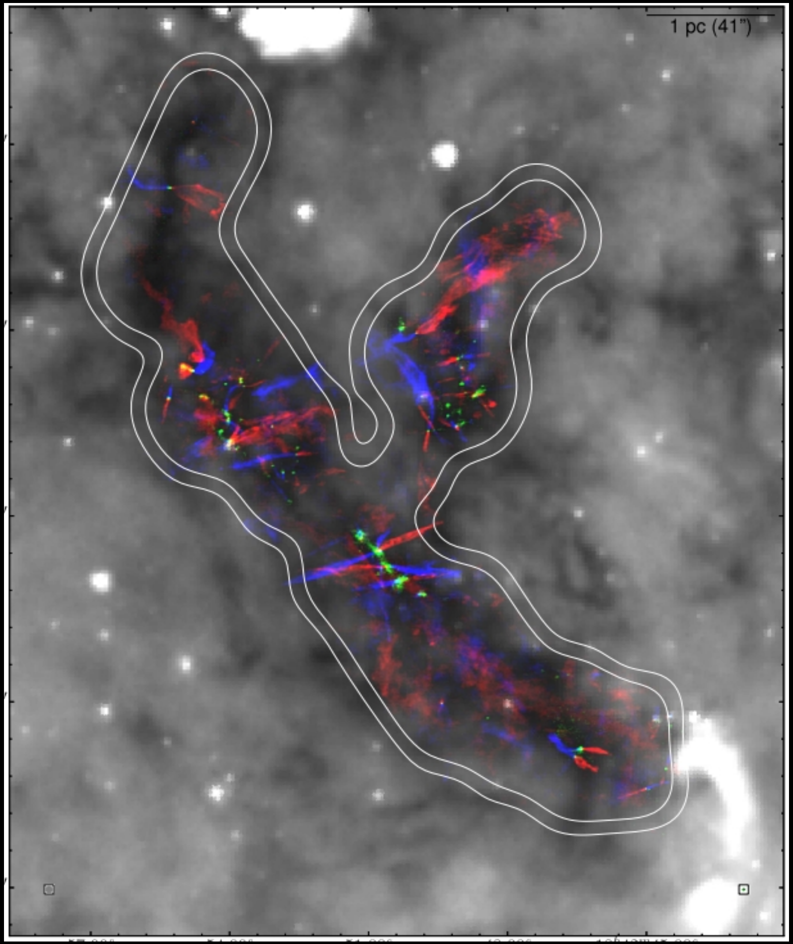
- Outflow-mass M_{out} scales with core mass M_{core}
  → High outflow rates imply high accretion rates

- Bipolar outflows are observed easily
  (although difficult to identify launching protostar
  in clustered regions)

- Accretion disks are challenging to resolve
  (high-mass protostars are much further away
  than low-mass protostars)

Outflows in high-mass star-forming regions

Molecular outflows in a young high-mass star-forming region



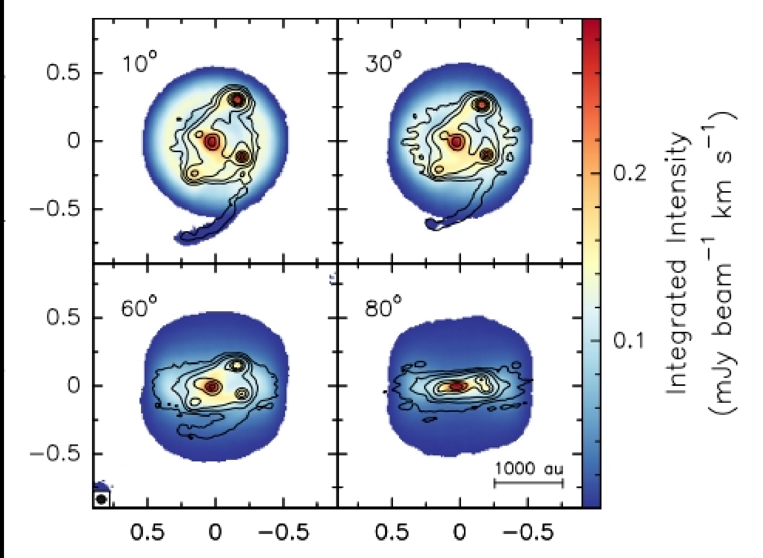
Kong+2019

At high spatial resolution: Bipolar molecular outflows show a complex morphology!

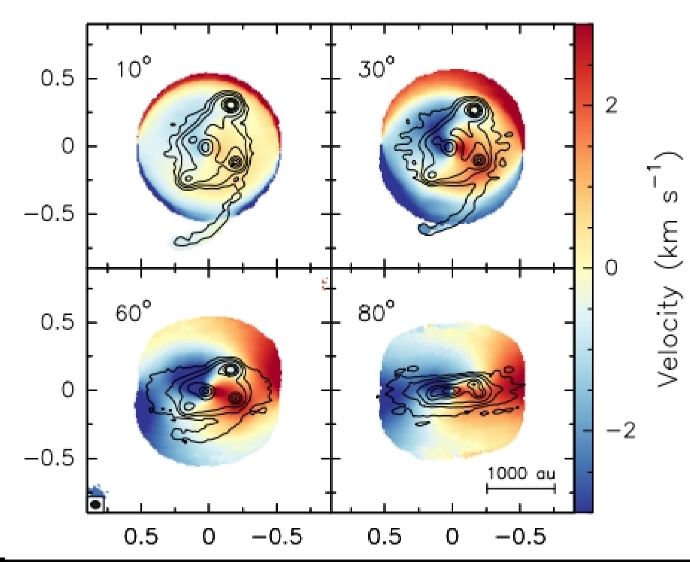
Topics today

- General concepts of massive star formation
- Outflows in high-mass star-forming regions
- **Rotation and disks**
- Clusters and the IMF

Rotation and disks



Velocity integrated intensity of a methyl cyanide (CH_3CN) line



Peak velocity of a methyl cyanide (CH_3CN) line

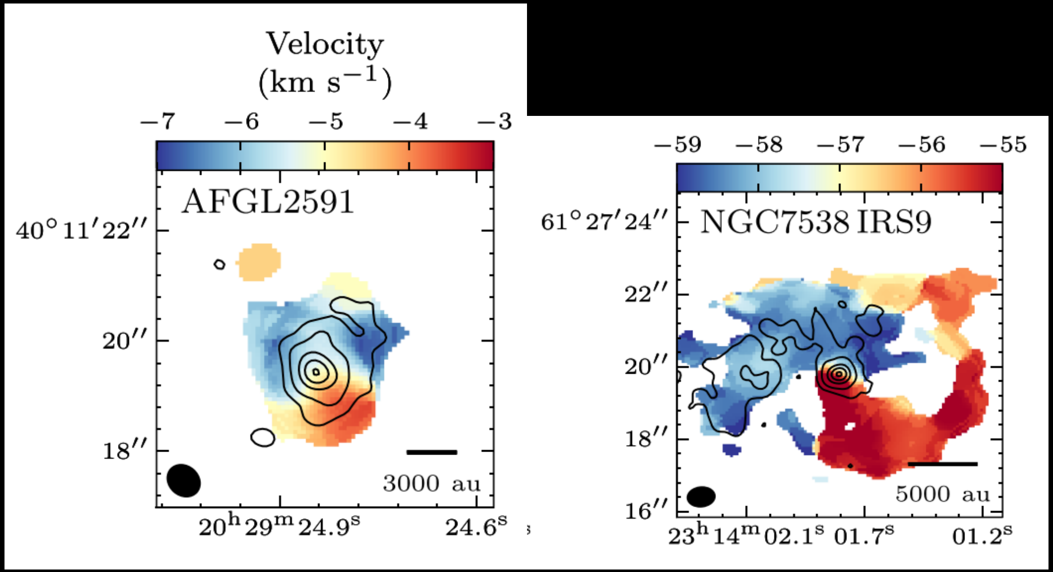
Ahmadi+2019

Credit: ALMA (ESO/NAOJ/NRAO), A. Marinkovic/X-Cam

Synthetic ALMA observations of a simulated fragmented massive disk at a distance of 2 kpc at different inclinations

→ signatures of disk rotation of molecules can be spectrally and spatially resolved with interferometers at very high angular resolution (0.08 arcsec)

Rotation and disks



Peak velocity of a
methyl cyanide (CH_3CN) line

Ahmadi+2023

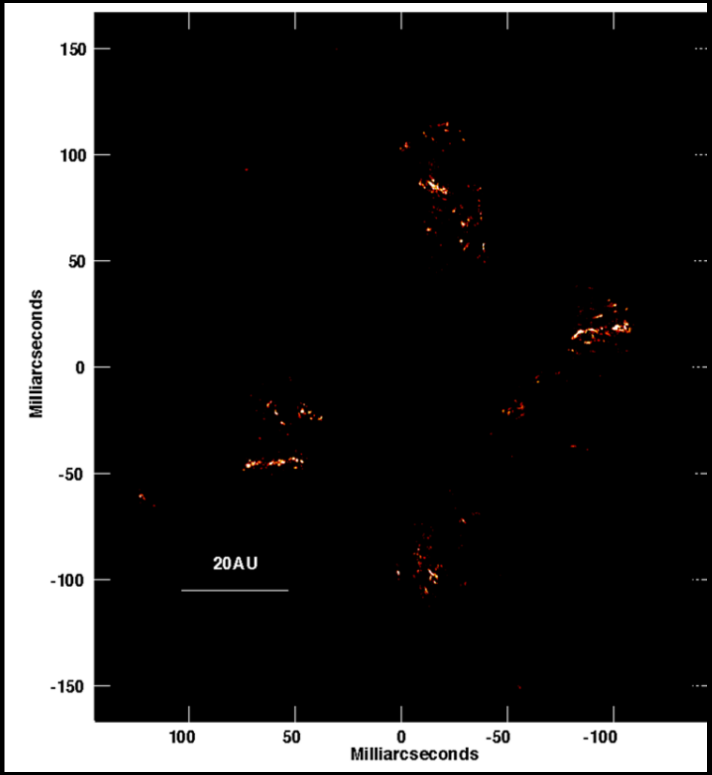
Credit: IRAM

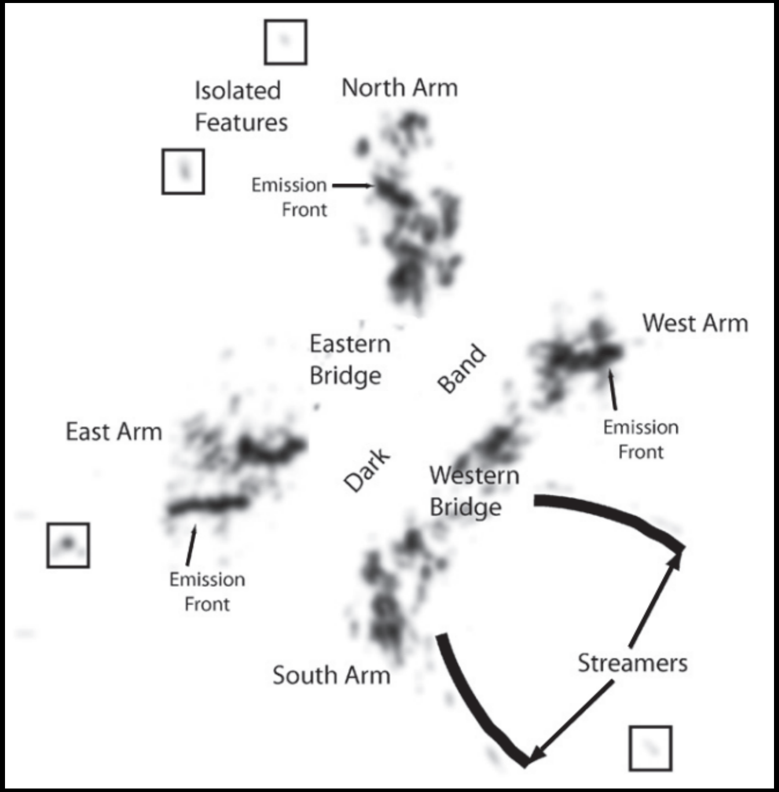
NOEMA observations
of high-mass
protostars
(0.4 arcsec resolution)

→ in real observations: complex morphology, additional contributions from, e.g., envelope rotation

Rotation and disks

A disk wind in Source I in the Kleinmann–Low (KL) nebula in Orion (d ~ 400 pc)





https://lweb.cfa.harvard.edu/kalypso/Figure5b.gif

Matthews+2010

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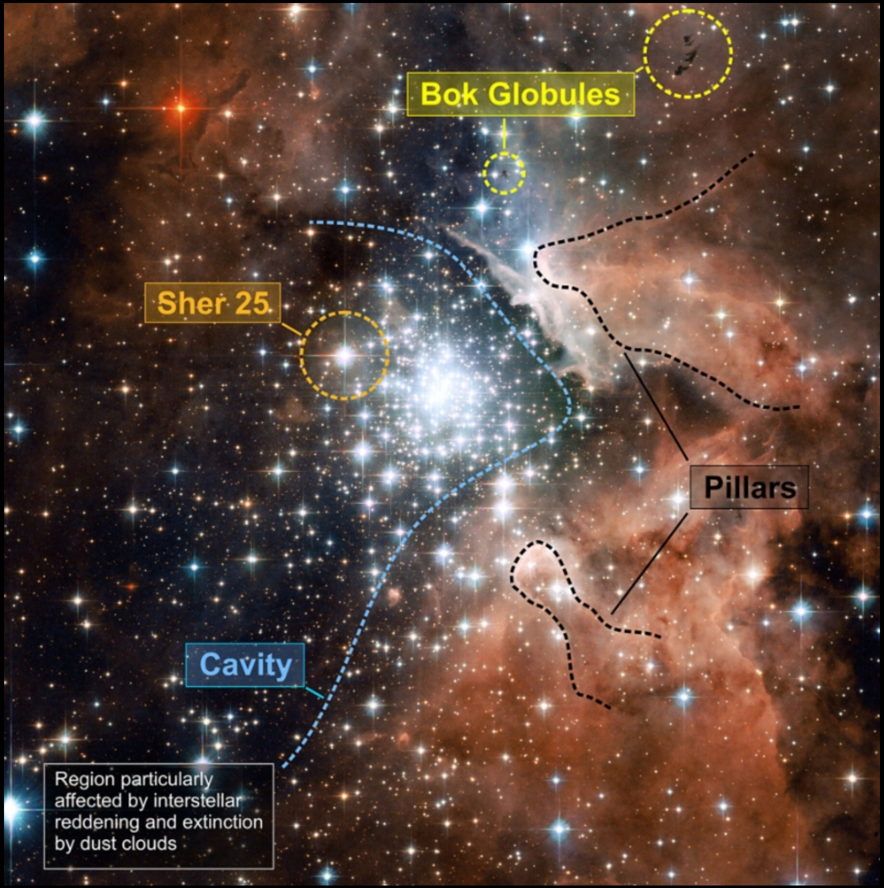
- Outflows in high-mass star-forming regions
- Rotation and disks
- **Clusters and the IMF**

Clusters and the IMF

Carina nebula



Credit: NASA/ ESA/ STScI/Aura

Almost all stars form not in isolation, but in clusters.

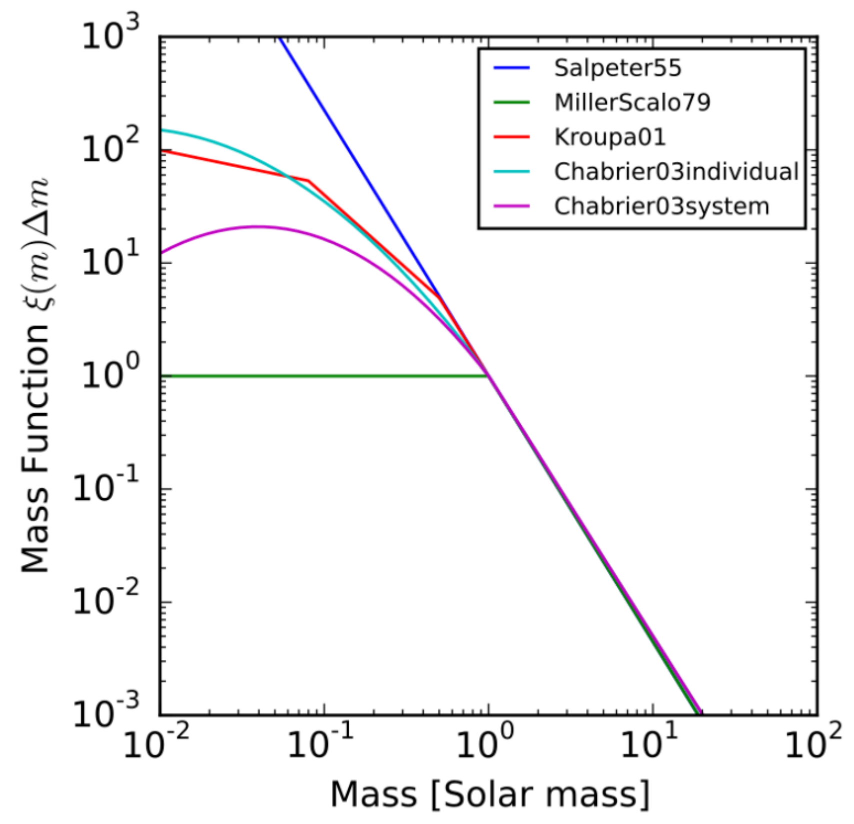
Initial mass function (IMF):
initial mass distribution for
a stellar population

(present day distribution may be different!)

Possible variations of the IMF:

- metallicity
- temperature of the collapsing molecular cloud
- magnetic field structure

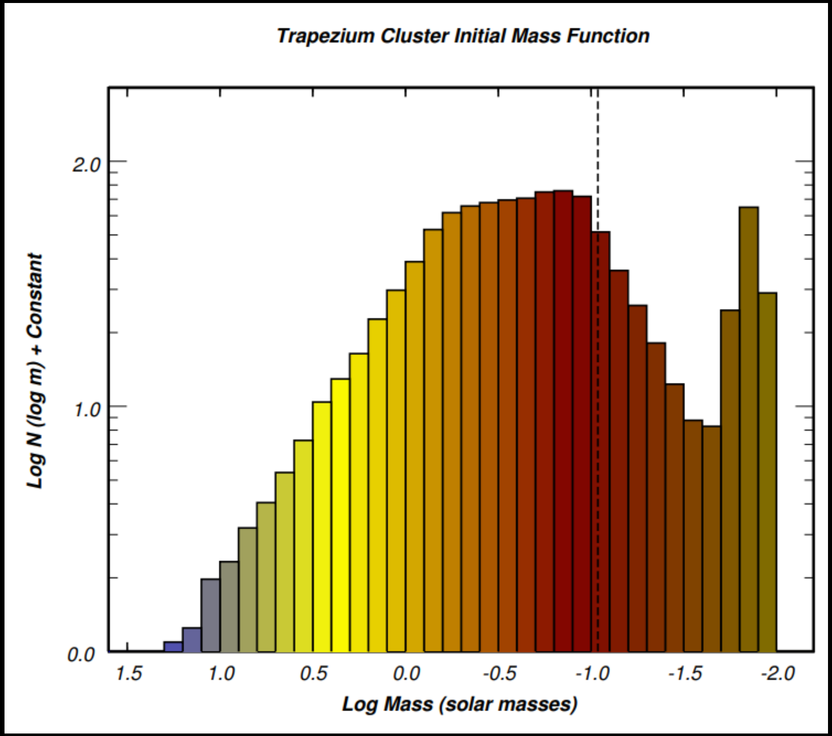
Clusters and the IMF



IMF described by
power-law approximations
for different mass regimes, e.g.:

$$\xi(M_*) = \begin{cases} C\ (M_*/M_\odot)^{-1.2} & 0.1 < M_*/M_\odot < 1.0 \\ C\ (M_*/M_\odot)^{-2.7} & 1.0 < M_*/M_\odot < 10 \\ 0.40\, C\ (M_*/M_\odot)^{-2.3} & 10 < M_*/M_\odot\ , \end{cases}$$

Clusters and the IMF

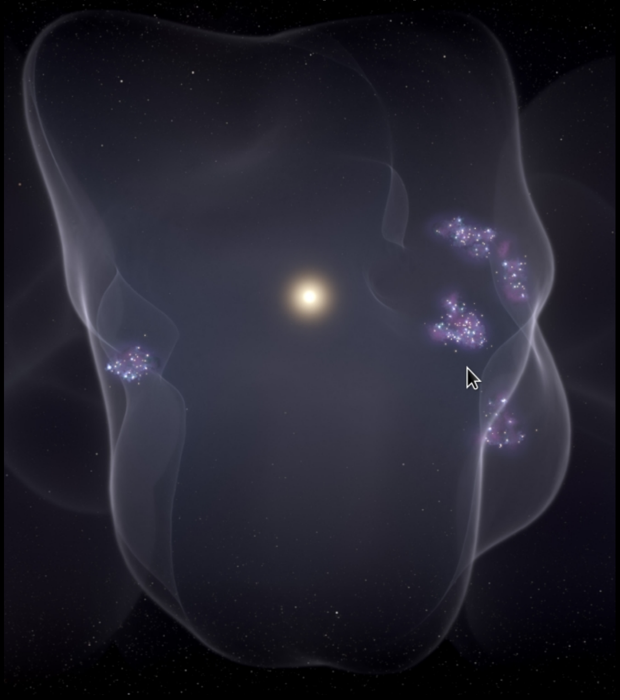


Muench+2002

Credit: NASA; K.L. Luhman (Harvard-Smithsonian CfA); and G. Schneider, E. Young, G. Rieke, A. Cotera, H. Chen, M. Rieke, R. Thompson

A Bubbly Origin for Stars Around the Sun

Credit: Leah Hustak (STScI)



https://www.youtube.com/watch?v=08UlpJBt5Ic

Bubbles in NGC 628 (M 74)

Credit: NASA / ESA / CSA / Judy Schmid

Summary

- Massive stars are very important for **energy budget and nucleosynthesis**

- They form exclusively in a **clustered mode**

- They have very short Kelvin-Helmholtz contraction times and hence no optically observable pre-main sequence evolution.

- Large radiation pressure has to be overcome.

Two main proposals:

(1) Scaled up low-mass star formation scenario (turbulent core model) with accretion disks and enhanced accretion rates.

(2) Turn more dynamical, competitive accretion, coalescence and merging.

→ Likely a combination of turbulent core and competitive accretion is solution

- Discussed outflows, disks, initial mass function, and clusters

Sternentstehung - Star Formation

Winter term 2024/2025

Henrik Beuther, Thomas Henning & Caroline Gieser

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Book: Stahler & Palla: The Formation of Stars, Wileys
More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2425.html
beuther@mpia.de, henning@mpia.de, gieser@mpia.de

Heidelberg Joint Astronomical Colloquium Winter Semester 2024/25

Tuesday January 21st Main Lecture Theatre, Philosophenweg 12, 16:30 CEST

Sylvia Ekström (University of Geneva)

Massive star evolution: Progress and challenges

https://www.physik.uni-heidelberg.de/hephysto/

Host: Andreas Sander (andreas.sander@uni-Heidelberg.de)

Image Credit: NASA/STScI