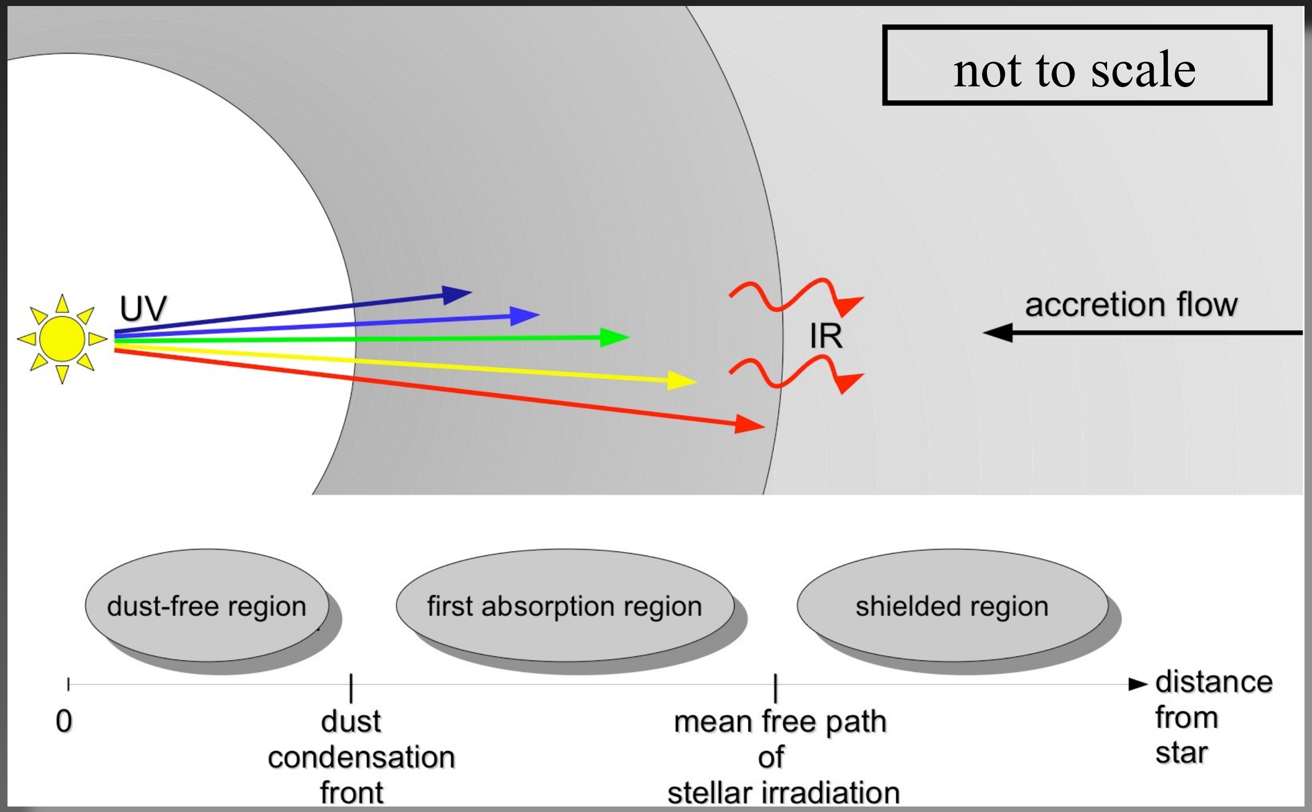
Formation of the Most Massive Stars

Spherical Infall

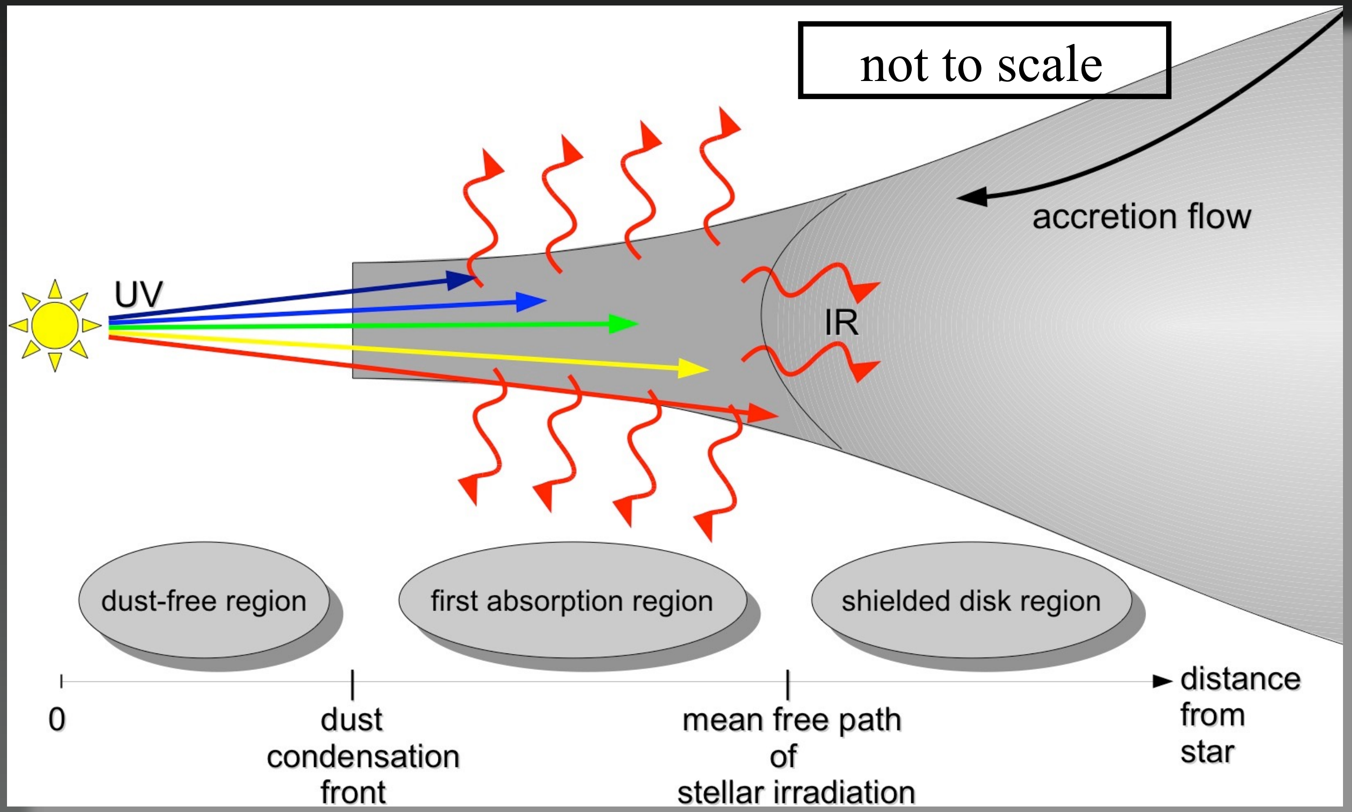


- **Radiation Pressure Barrier**

at $M_{star} \sim 40\ M_{sol}$

(Kahn 1974, Yorke & Krügel 1977)

Disk Accretion

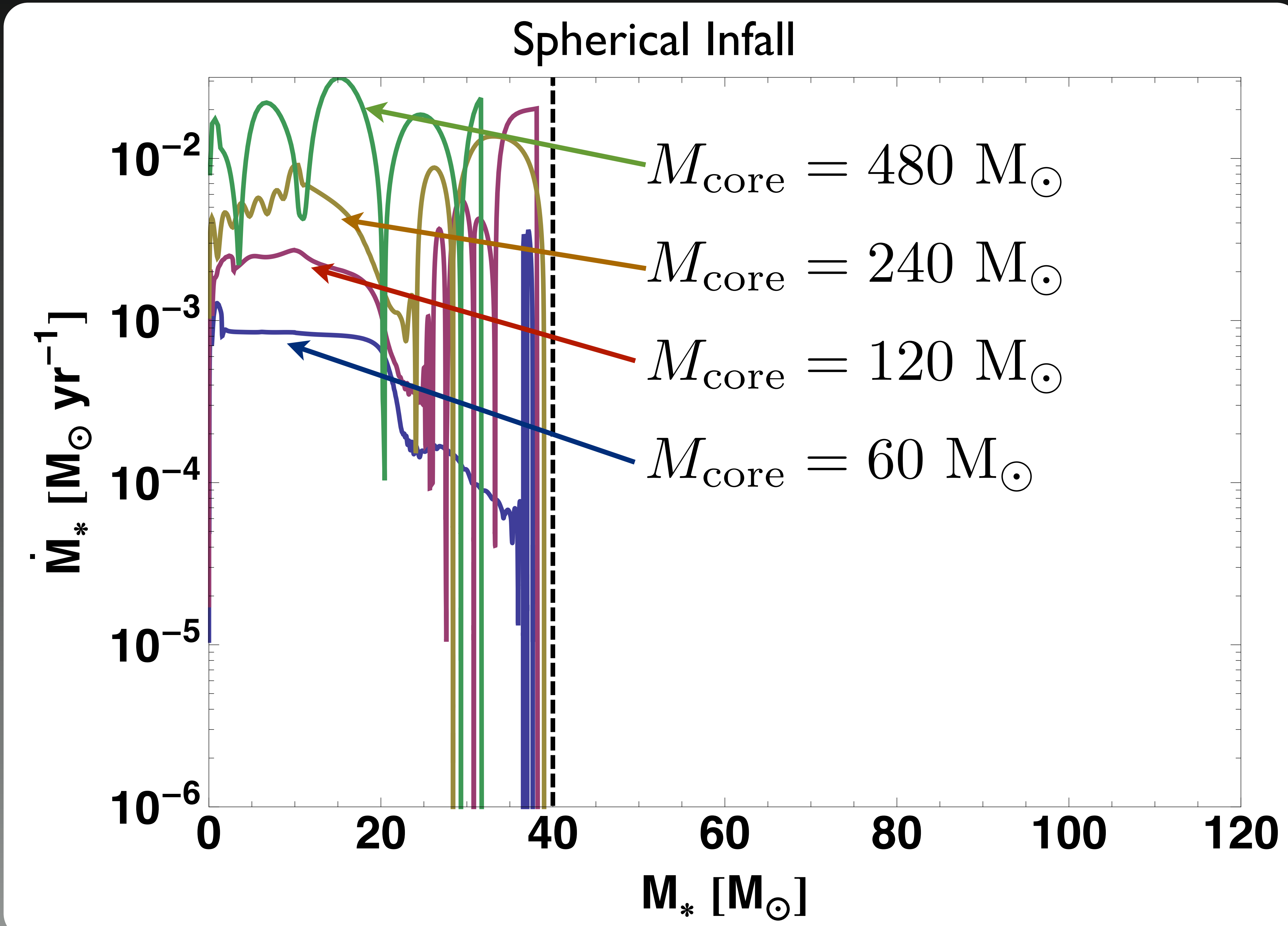


- Optically thick Disk
- Anisotropy of Infrared Radiation / **Disk Flashlight Effect**

(Nakano 1989, Yorke & Bodenheimer 1999)

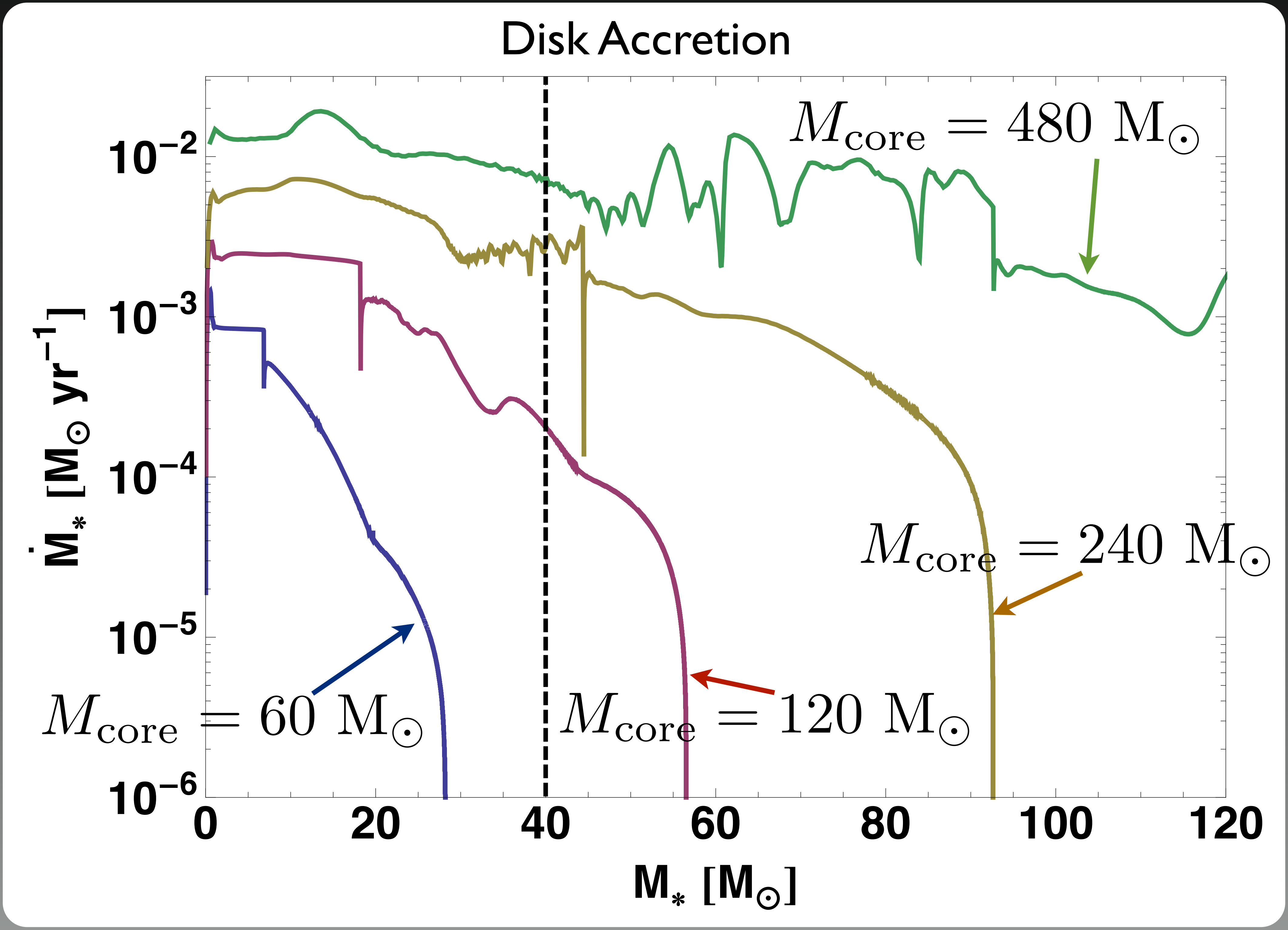
Kuiper et al. (2010)

Formation of the Most Massive Stars



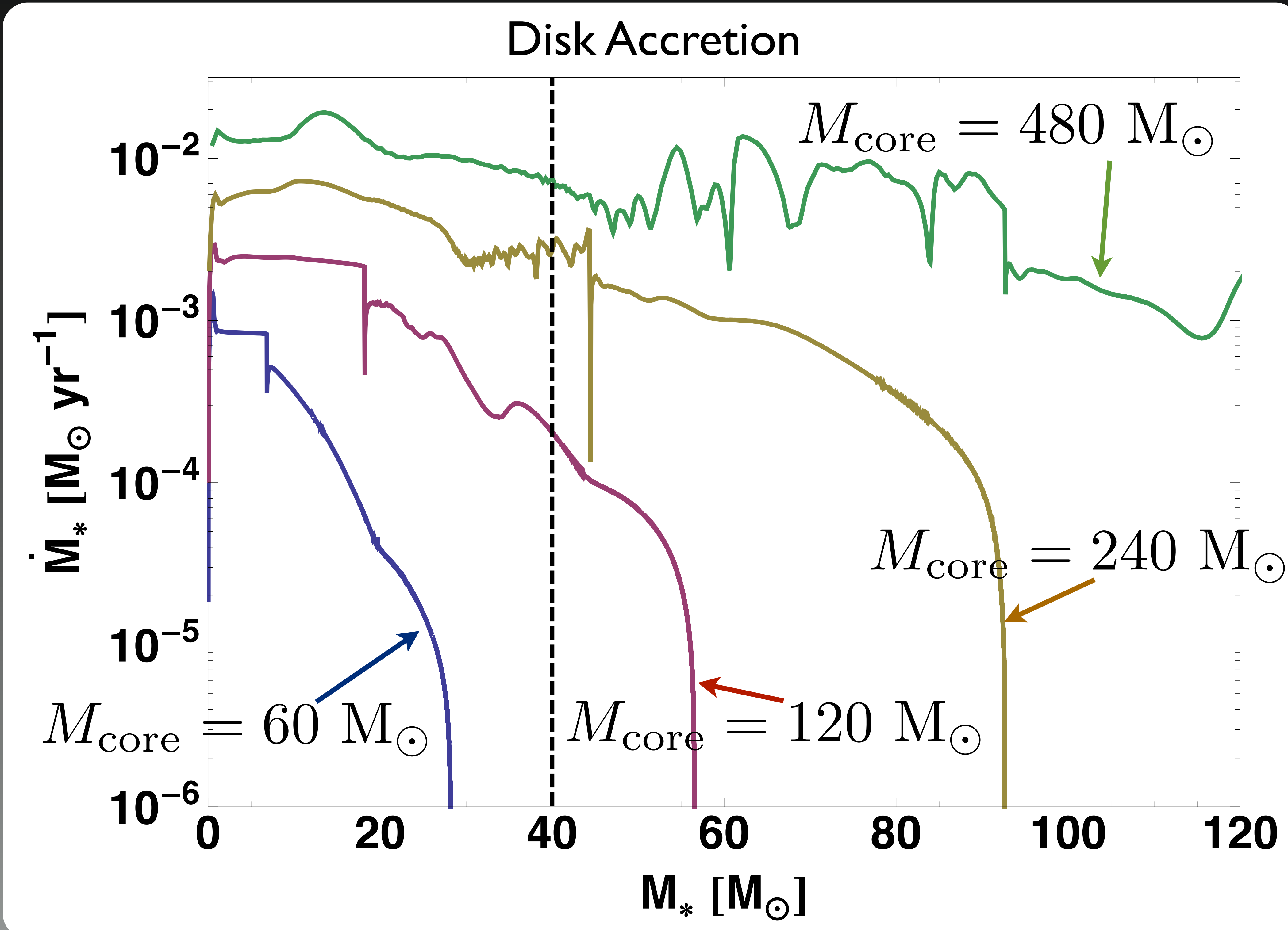
Kuiper et al. (2010)

Formation of the Most Massive Stars



Kuiper et al. (2010)

Formation of the Most Massive Stars



→ **Talks by Aida Ahmadi and Adam Ginsburg!**

Kuiper et al. (2010)

Is there a Stellar Upper Mass Limit due to Feedback?

What about Photo-Evaporation of the Disk?

Photoionization + Radiation Forces

Initial Condition:

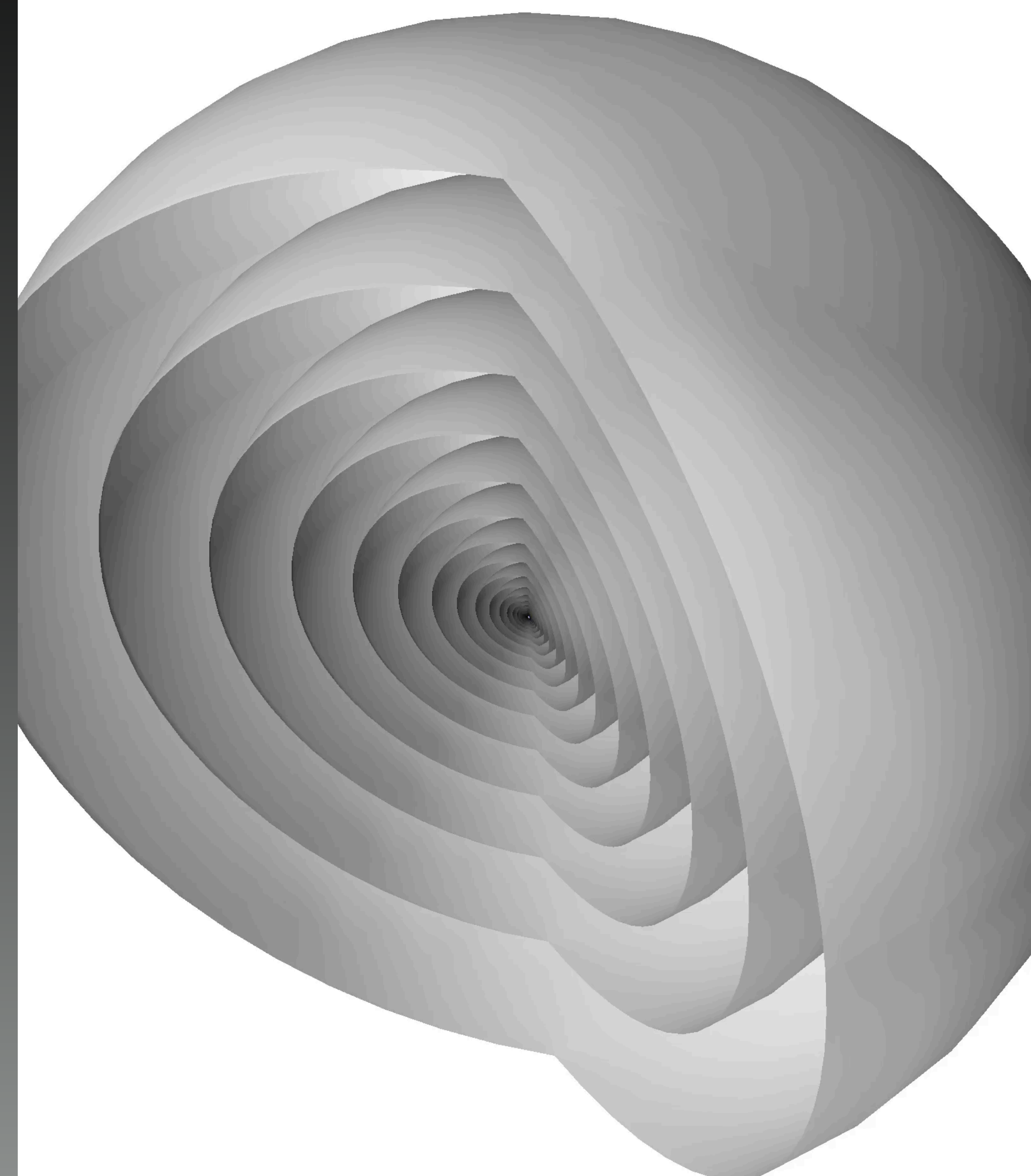
- 1000 $M_\odot$ mass reservoir (R = 1 pc) = 100 $M_\odot$ pre-stellar core fed by large-scales

Feedback Physics:

- Outflows
- Radiation Forces
- Photoionization / HII Regions

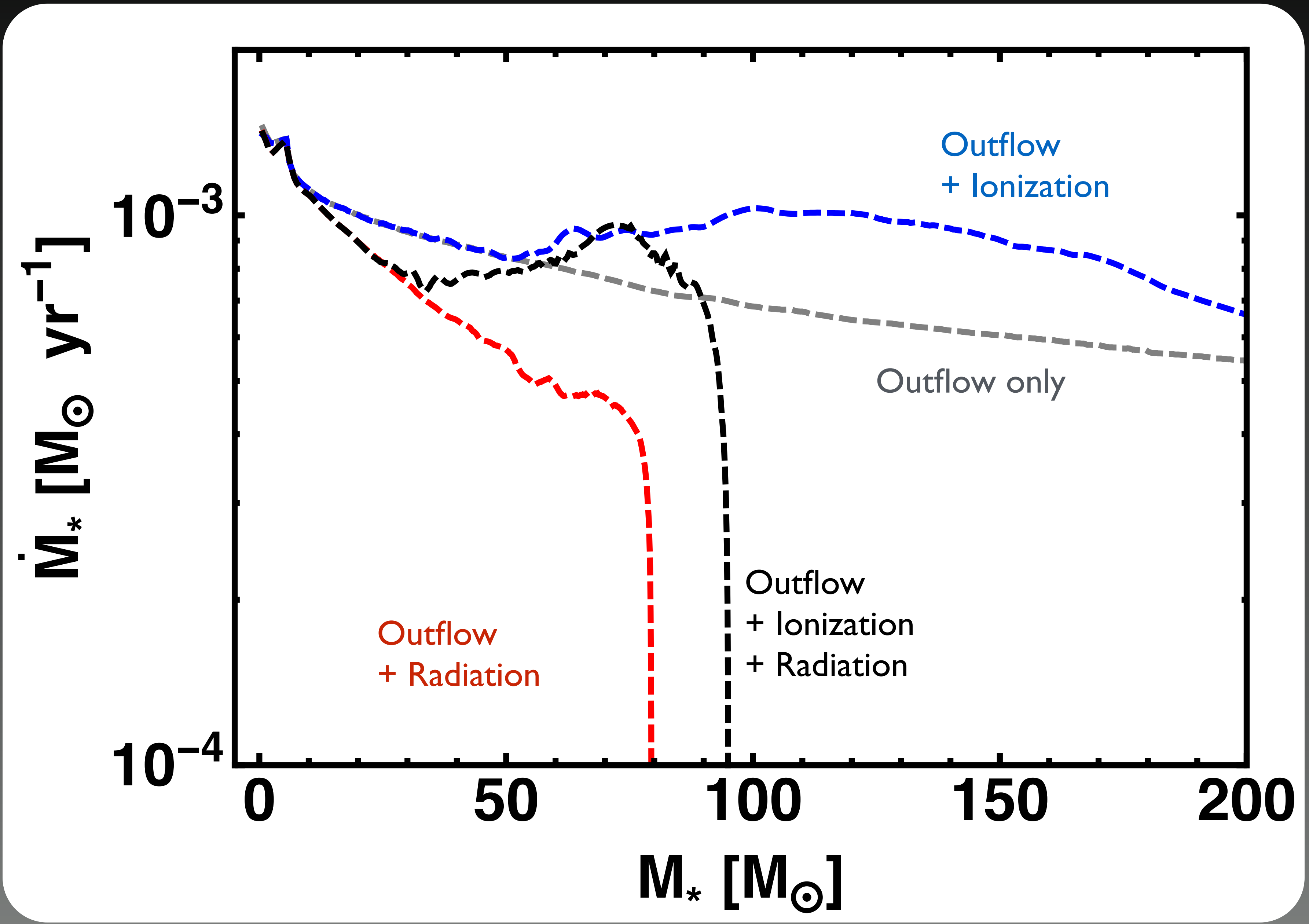
Grid:

- Axial and midplane symmetry (2D)
- R_{sink} = 3 au, Δx = 0.3 au



Kuiper & Hosokawa (2018)

Feedback and Star Formation Efficiencies



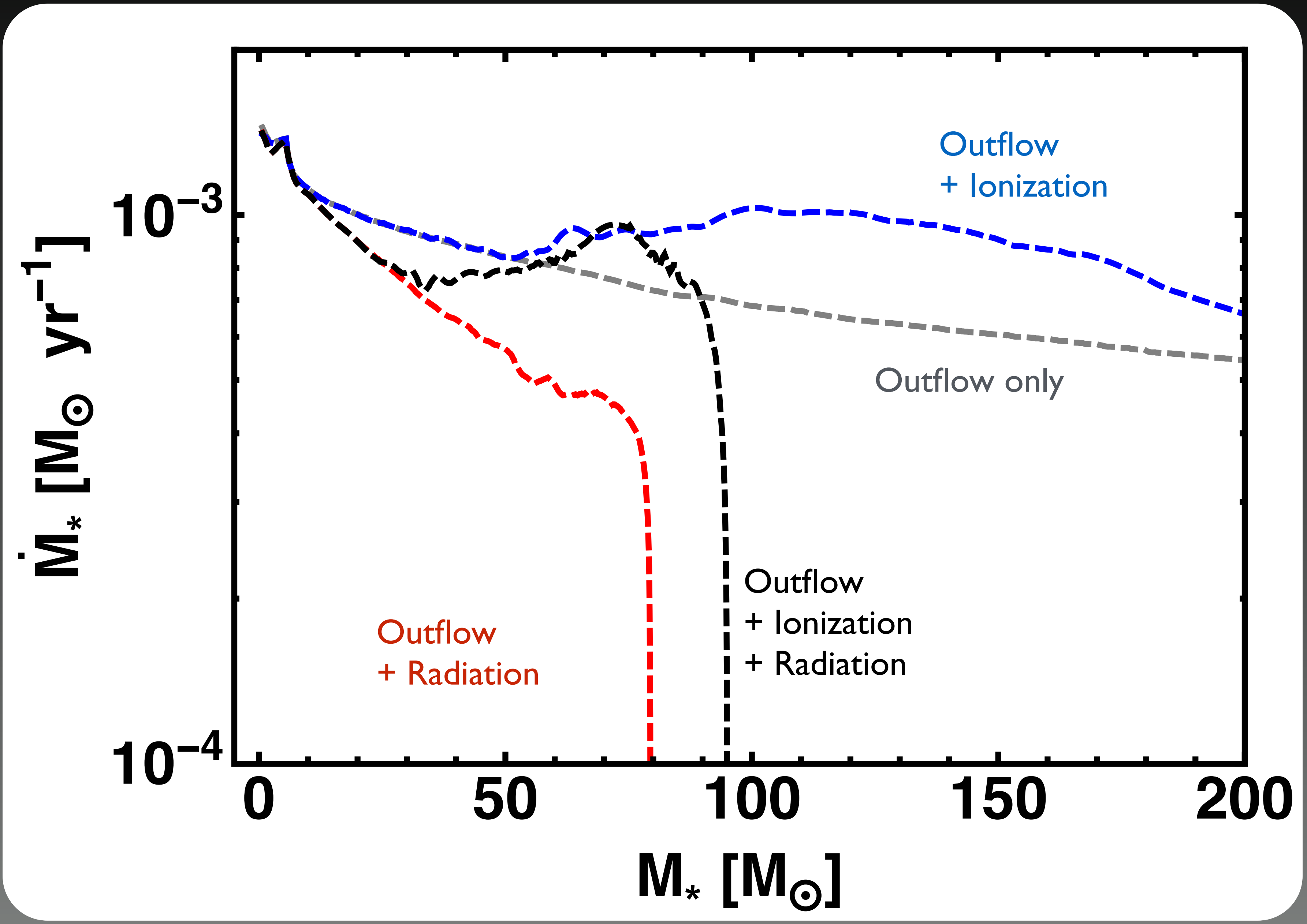
- ✘ Outflows
- ✘ Photoionization
- ✔ Radiation Forces

$M_{star} = 95 \; M_\odot$, $t_{acc} \sim 0.13$ Myr

$R_{res} \sim 0.24$ pc, $M_{res} \sim 240 \; M_\odot$

Kuiper & Hosokawa (2018)

Feedback and Star Formation Efficiencies



✘ Outflows

✘ Photoionization

✔ Radiation Forces

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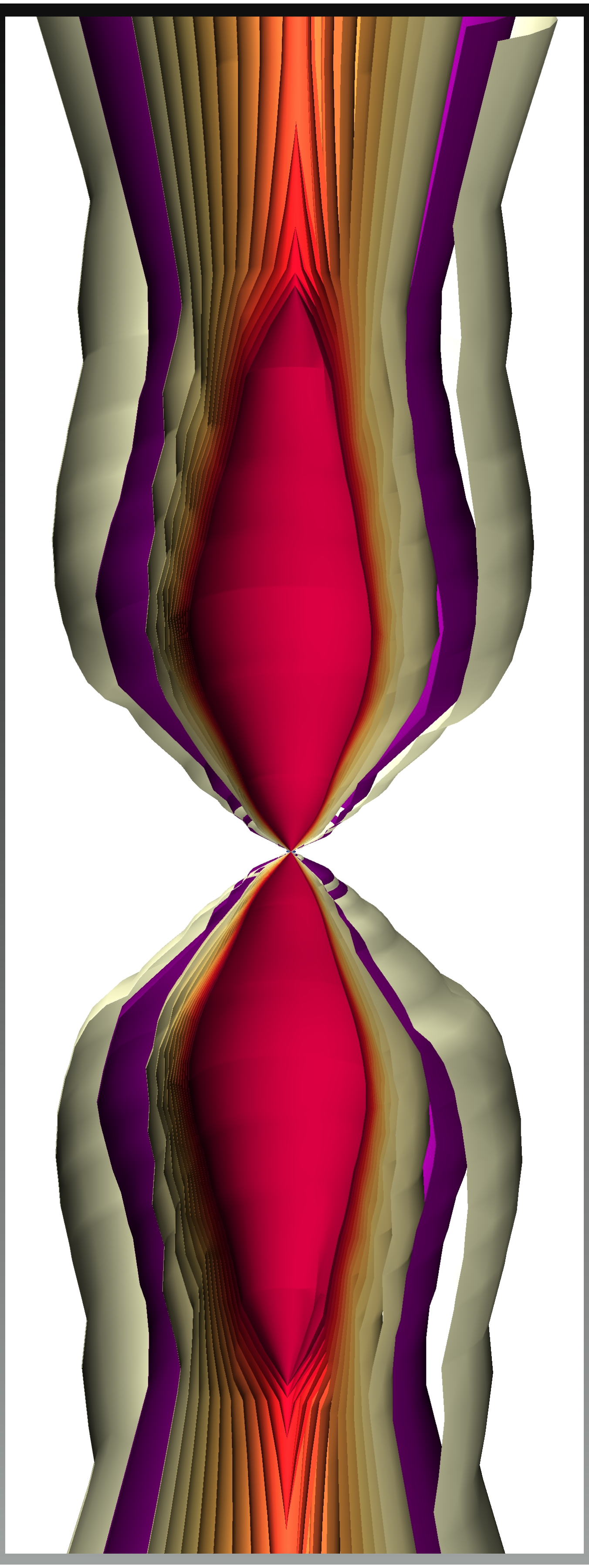
→ Talk by Alessio Traficante!

Kuiper & Hosokawa (2018)

Feedback and Outflow Broadening



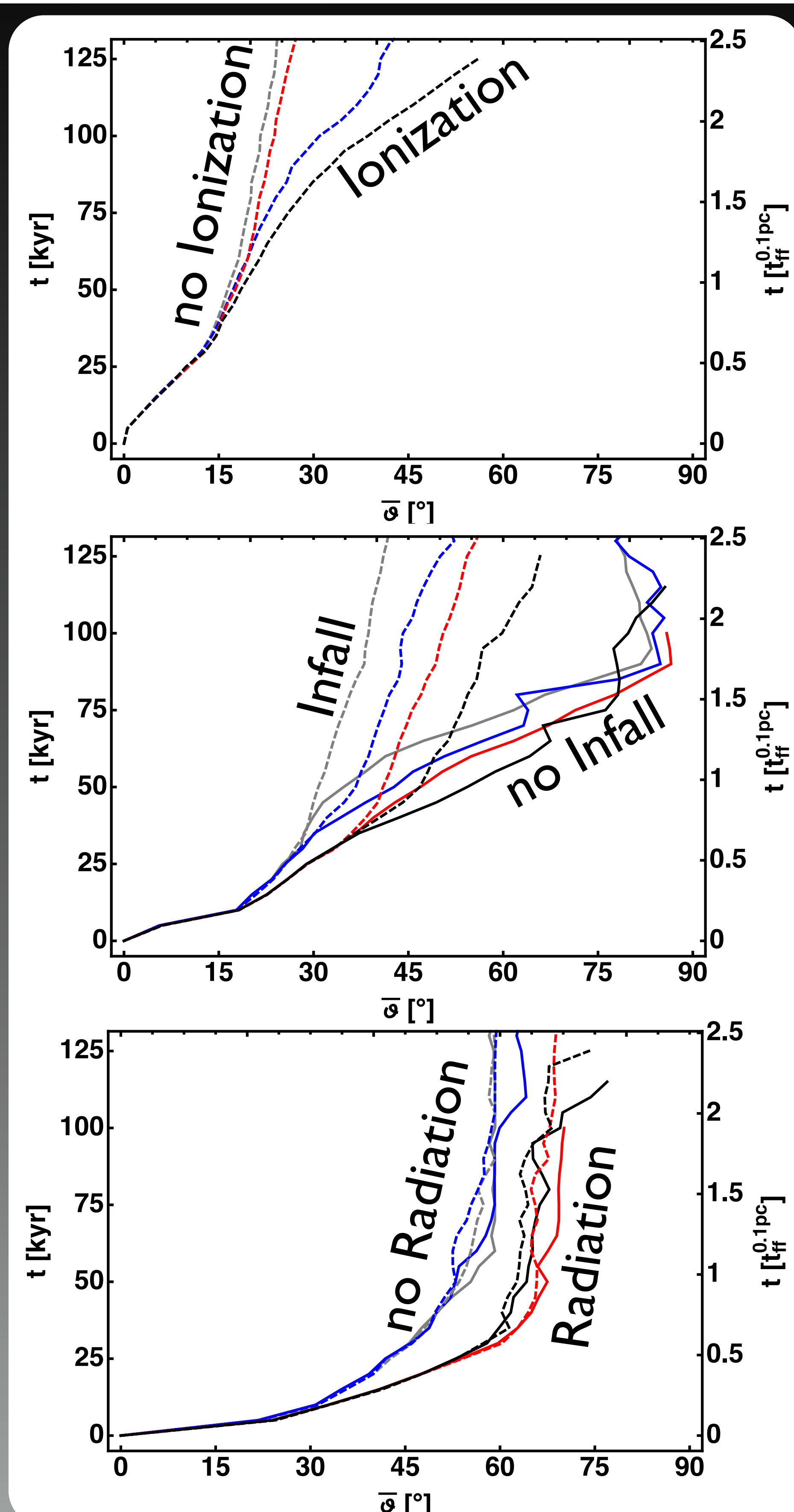
Kuiper & Hosokawa (2018)

Feedback and Outflow Broadening

Cluster
1.0 pc

Photoionization > Radiation Forces

HII Region Expansion decreases Infall by 50%



Core
0.1 pc

Ram Pressure from Infall collimates Outflow

Radiation Forces > Photoionization

Disk
0.01 pc
2000 AU

Disk Structure sets Opening Angle

✘ Photoionization

✔ Radiation Forces

Outflow only

Out + Ionization

Out + Radiation

Out + Ion + Rad

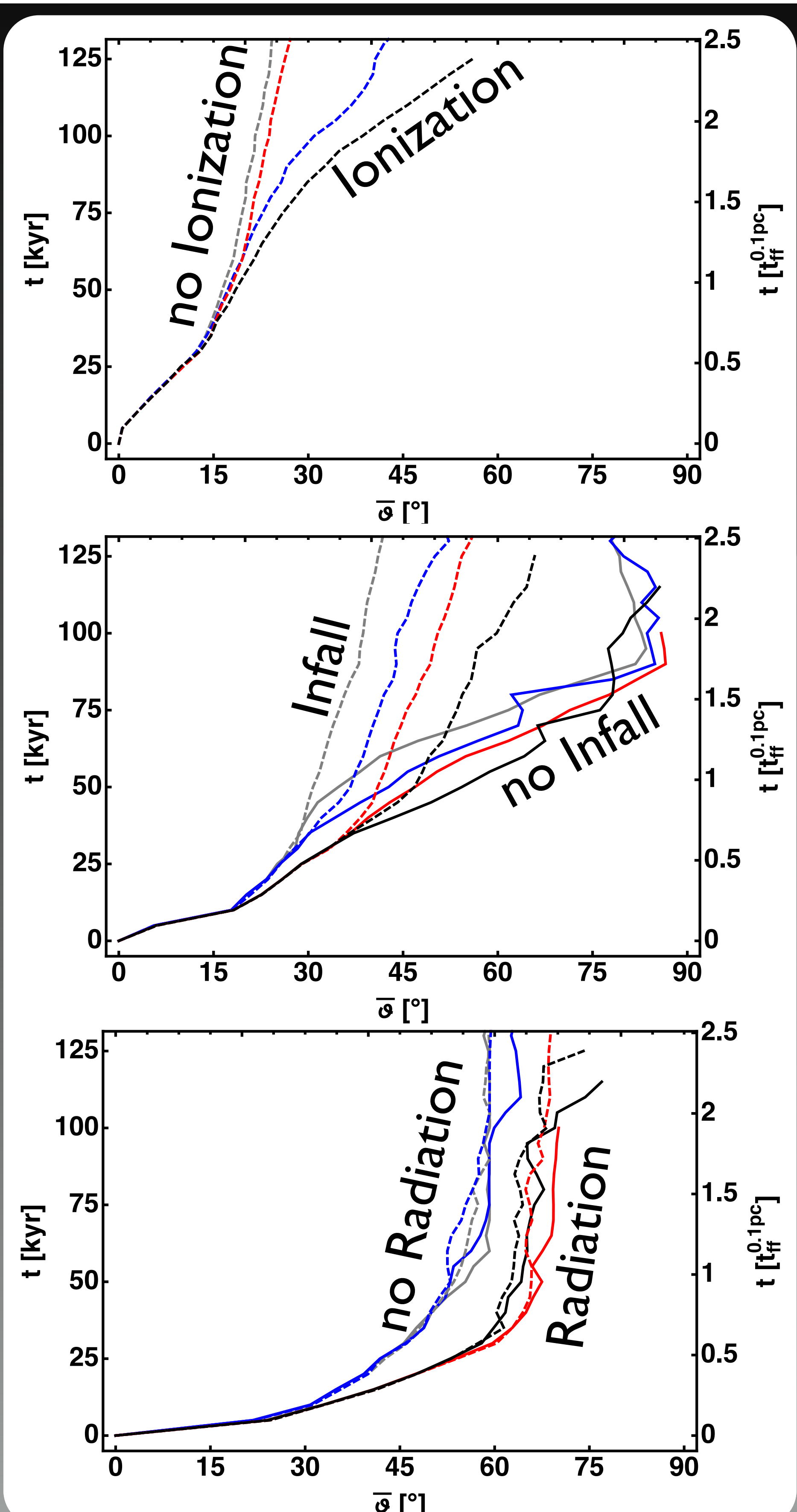
Kuiper & Hosokawa (2018)

Feedback and Outflow Broadening

Cluster
1.0 pc

Core
0.1 pc

Disk
0.01 pc
2000 AU



Outflow only
Out + Ionization
Out + Radiation
Out + Ion + Rad

Photoionization > Radiation Forces

HII Region Expansion decreases Infall by 50%

→ **Talks by Annie Zavagno and Jeong-Gyu Kim!**

Ram Pressure from Infall collimates Outflow

Radiation Forces > Photoionization

Disk Structure sets Opening Angle

✘ Photoionization

✔ Radiation Forces

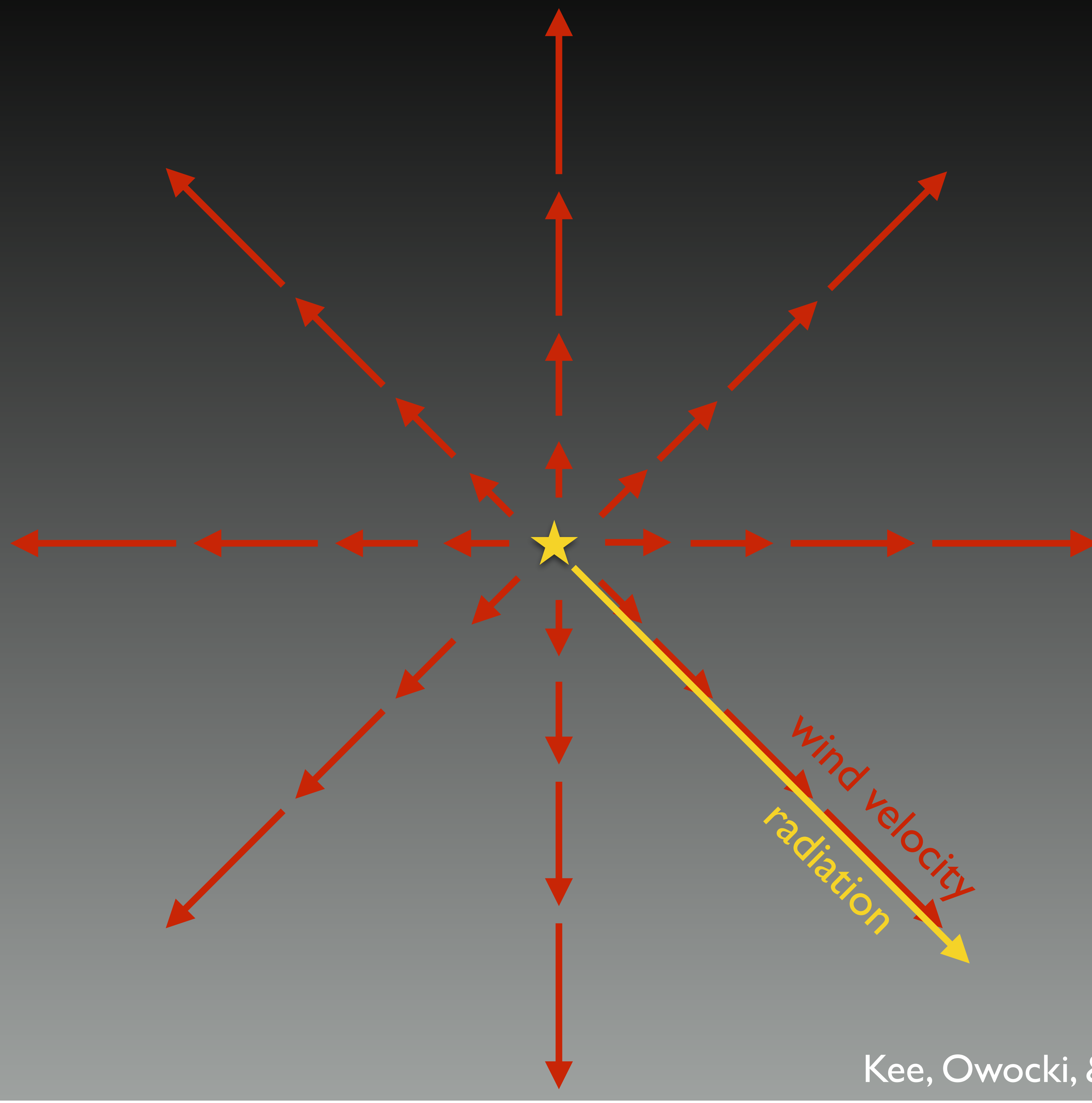
Kuiper & Hosokawa (2018)

Is there a Stellar Upper Mass Limit due to Feedback?

How is the gas accreted from the disk to the star ?

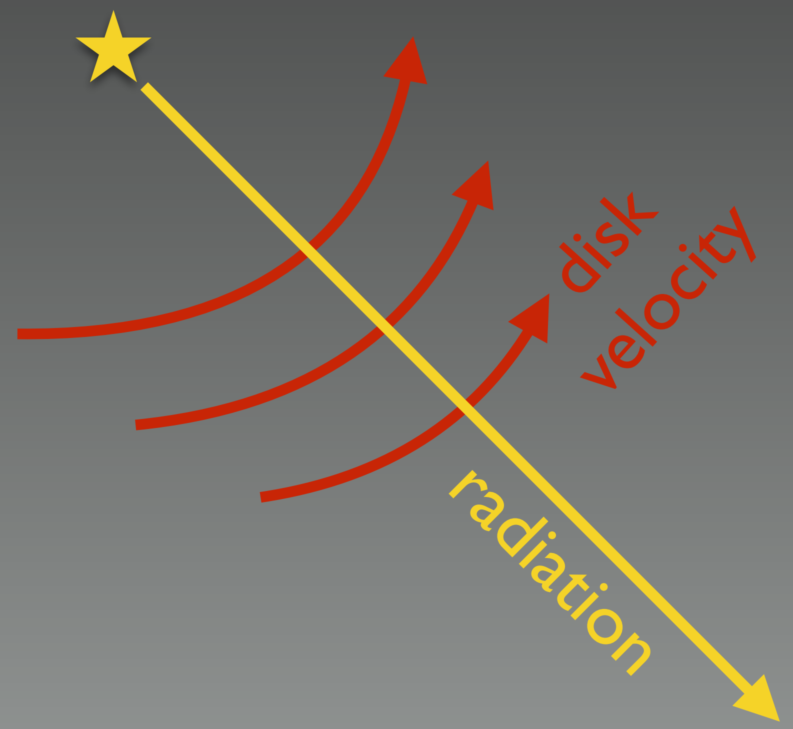
→ UV-Line Scattering Forces!

UV-Line Scattering Feedback



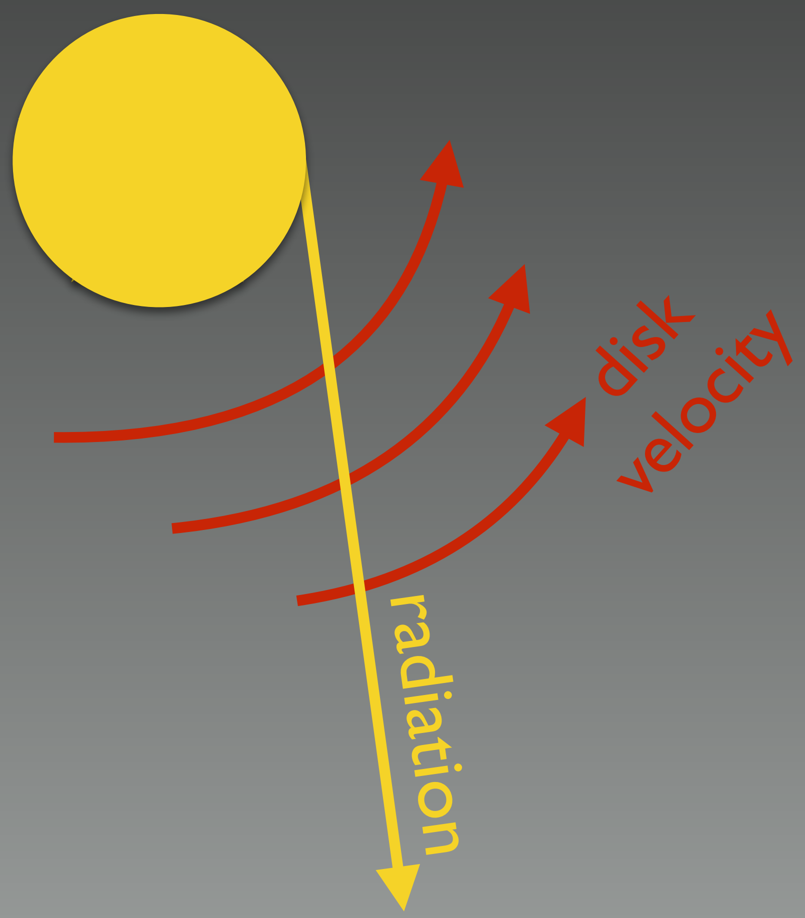
Kee, Owocki, & Kuiper (2018a,b)

UV-Line Scattering Feedback



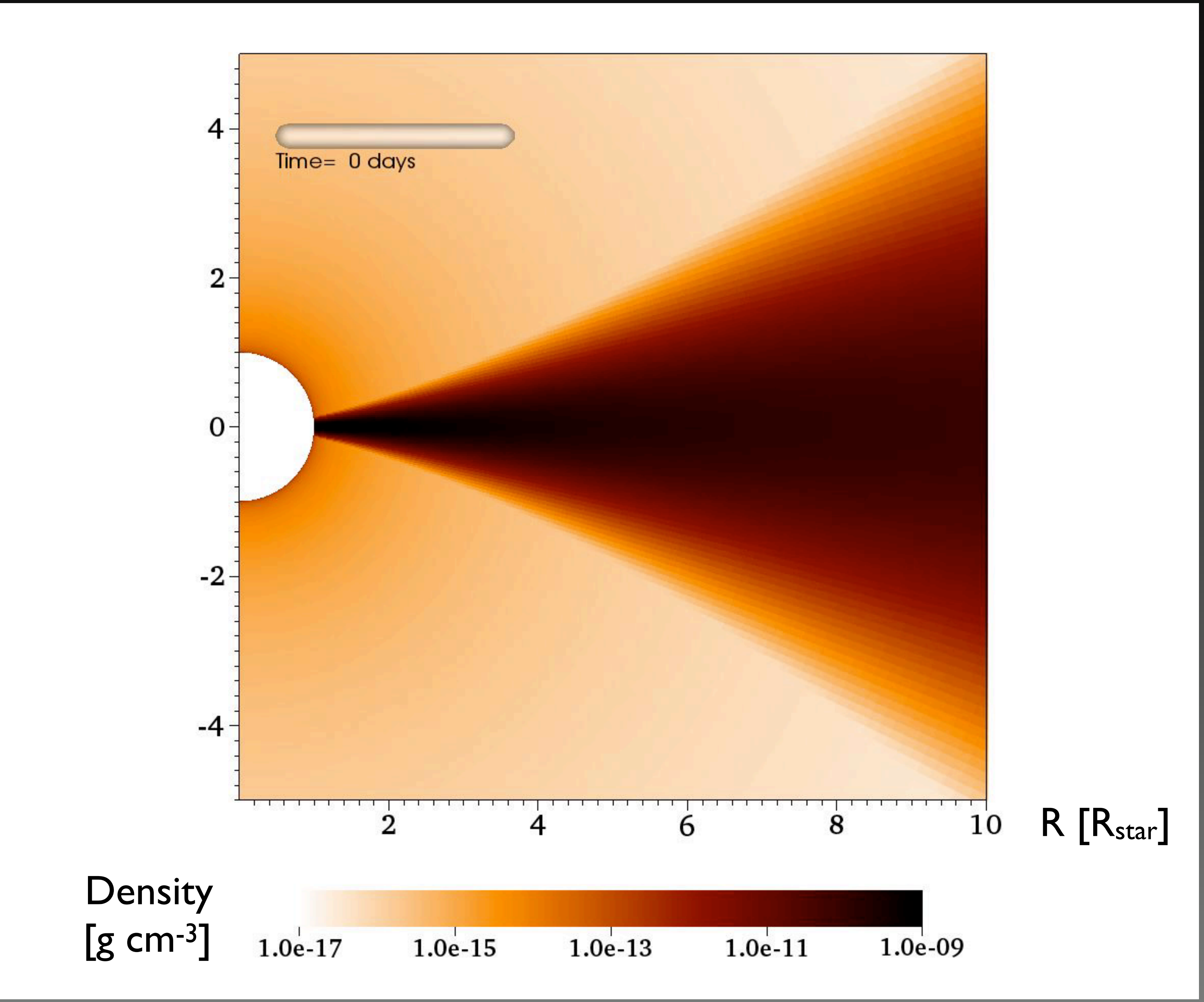
Kee, Owocki, & Kuiper (2018a,b)

UV-Line Scattering Feedback



Kee, Owocki, & Kuiper (2018a,b)

UV-Line Scattering Feedback

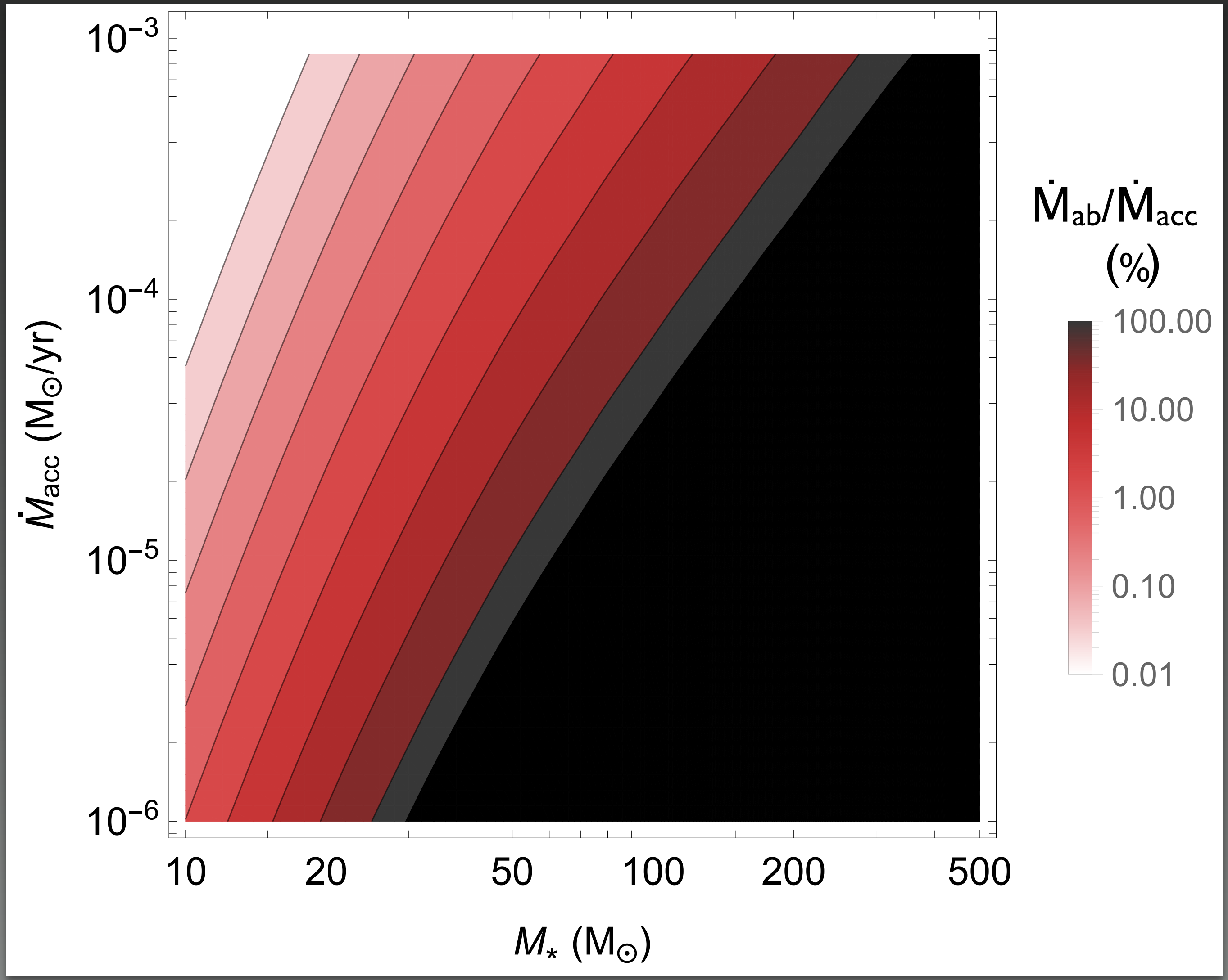


- resolved Stellar Photosphere
- 3D Ray-Tracing (> 2 million rays / timestep) using CAK theory
- ‣ Ablation rates (as function of stellar and disk parameters)

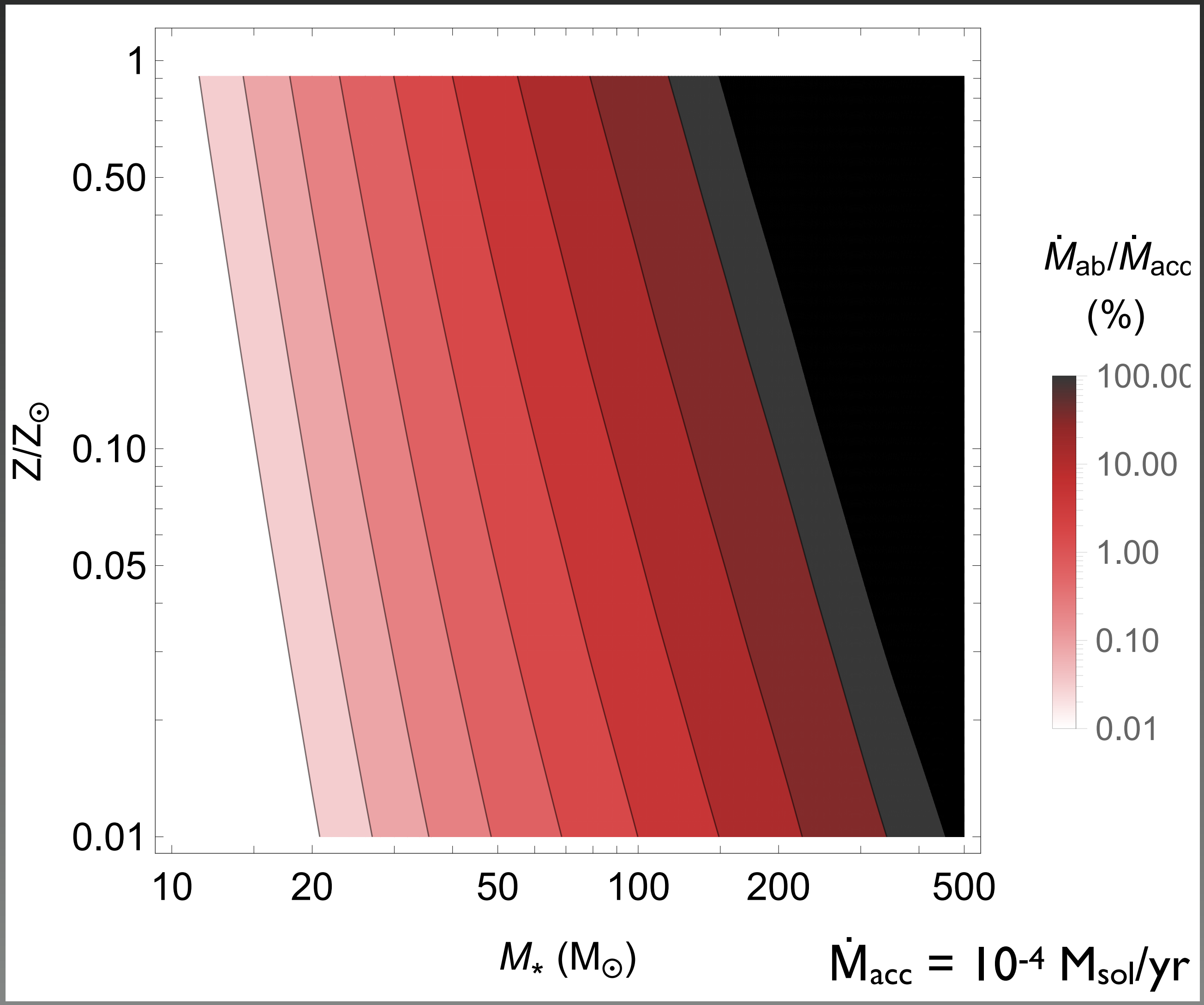
Kee & Kuiper (2018)

UV-Line Scattering Feedback

Stellar Upper Mass Limit



Metallicity-dependence

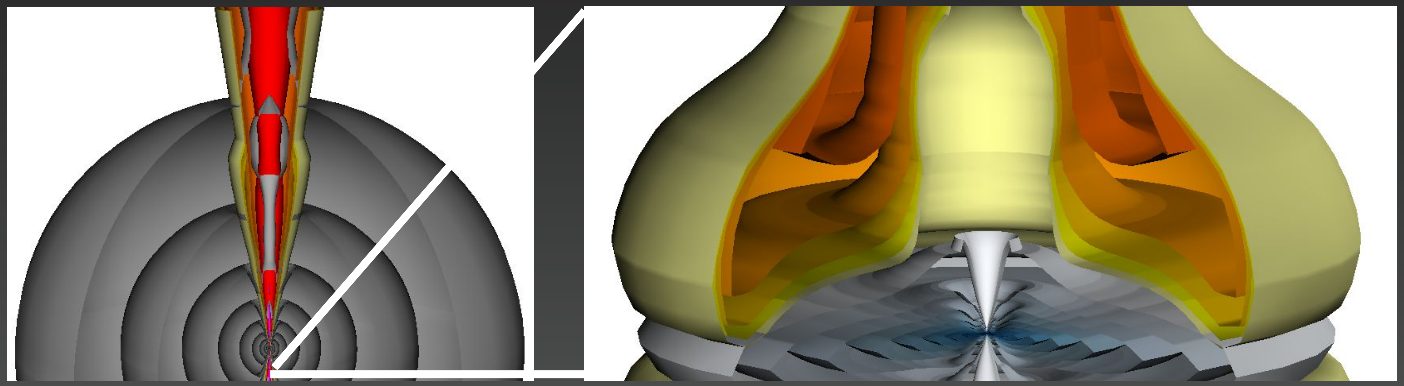


Kee & Kuiper (2018)

What else is new?

- **RMHD-driven Jets & Outflows** (Kölligan & Kuiper 2018, Nies & Kuiper, subm.)
  - Collimated Jets (magneto-centrifugally-driven à la Blandford & Payne 1982)
  - Disk Winds (magnetic-pressure-driven à la Lynden-Bell 2003)
  - Ejection/Accretion efficiency ~ 10%

→ Talks by Willice Obonyo and Patrick Koch!



- **Disk Fragmentation**
  - Spectroscopic Binaries / Multiplicity (Meyer et al. 2018)
  - Accretion Bursts (Meyer et al. 2017)

→ Talks by Igor Zinchenko, Johan van der Walt, and Aida Ahmadi!

- **1st and 2nd Larson Cores**
  - 1st Larson cores do not exist in high-mass star formation (Bhandare et al. 2018)
  - 2nd Larson cores are convective (Bhandare et al., in prep.)

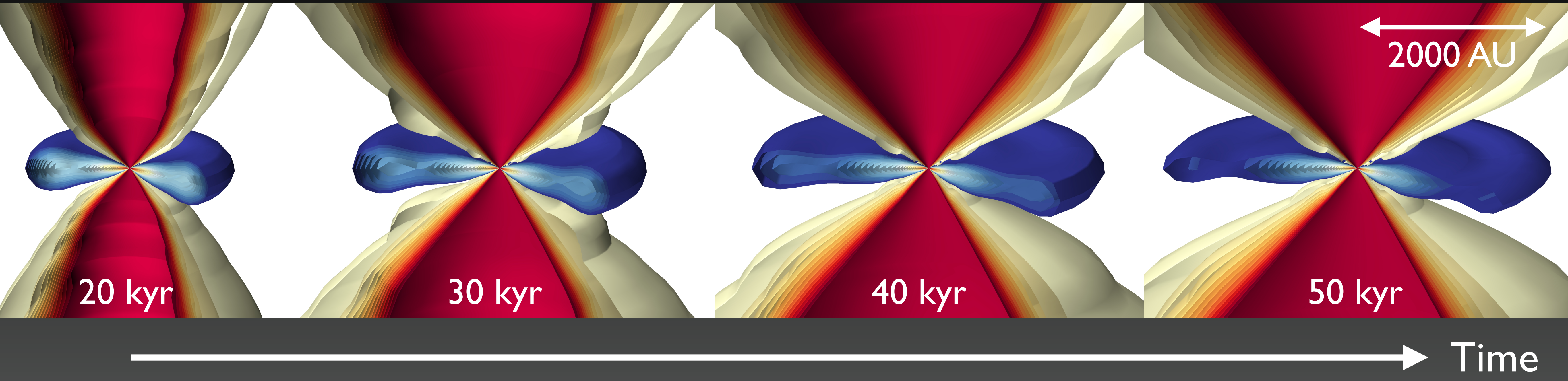
→ Poster #14 by Asmita Bhandare!

Is there a Stellar Upper Mass Limit due to Feedback?

- MHD-**Jets** remove ~10% of Accretion
- **Photoionization** (only) important on Cluster scales
- **Disk Fragmentation** yields Multiplicity and Accretion Bursts
- **Continuum Radiation** Forces set Disk Lifetime!
  + Large-scale Cloud Fragmentation → Upper Mass Limit
- **UV-Line Radiation** Forces stop Disk-to-Star Accretion!
  + Disk Accretion Physics → Upper Mass Limit

Thanks for your attention!

Photoionization feeding the Disk



- Protostar keeps bloated until ~30 kyr / ~30 M_{sol}
  (Hosokawa & Omukai 2009, Kuiper & Yorke 2013)

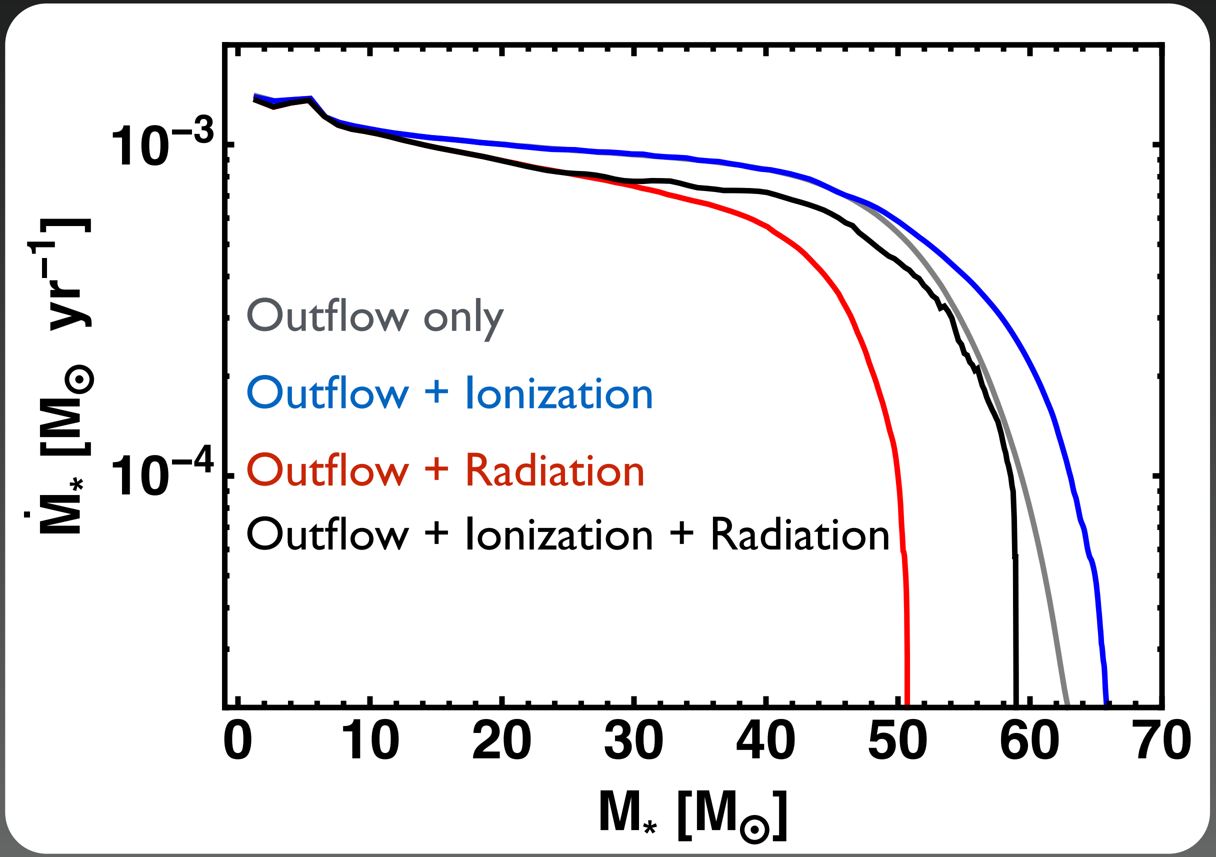
- HII Region fills Bipolar Outflow Cavity

- Thermal Pressure Feedback in the polar directions acts like Scissor Handles

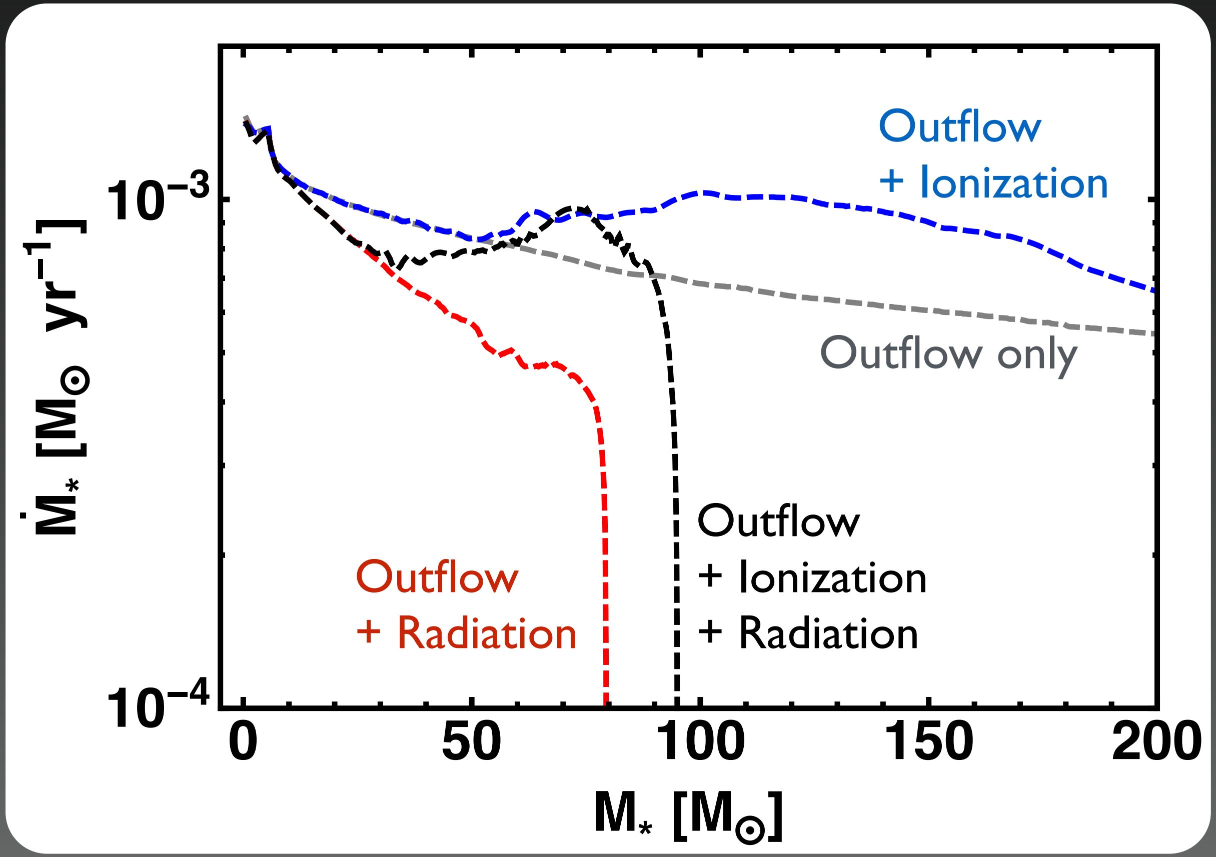
Kuiper & Hosokawa (2018)

Feedback and Star Formation Efficiencies

Finite Mass Reservoir



"Infinite" Mass Reservoir



✔ Outflows
✘ Photoionization
✔ Radiation Forces

→ see also Talk by Anna Rosen

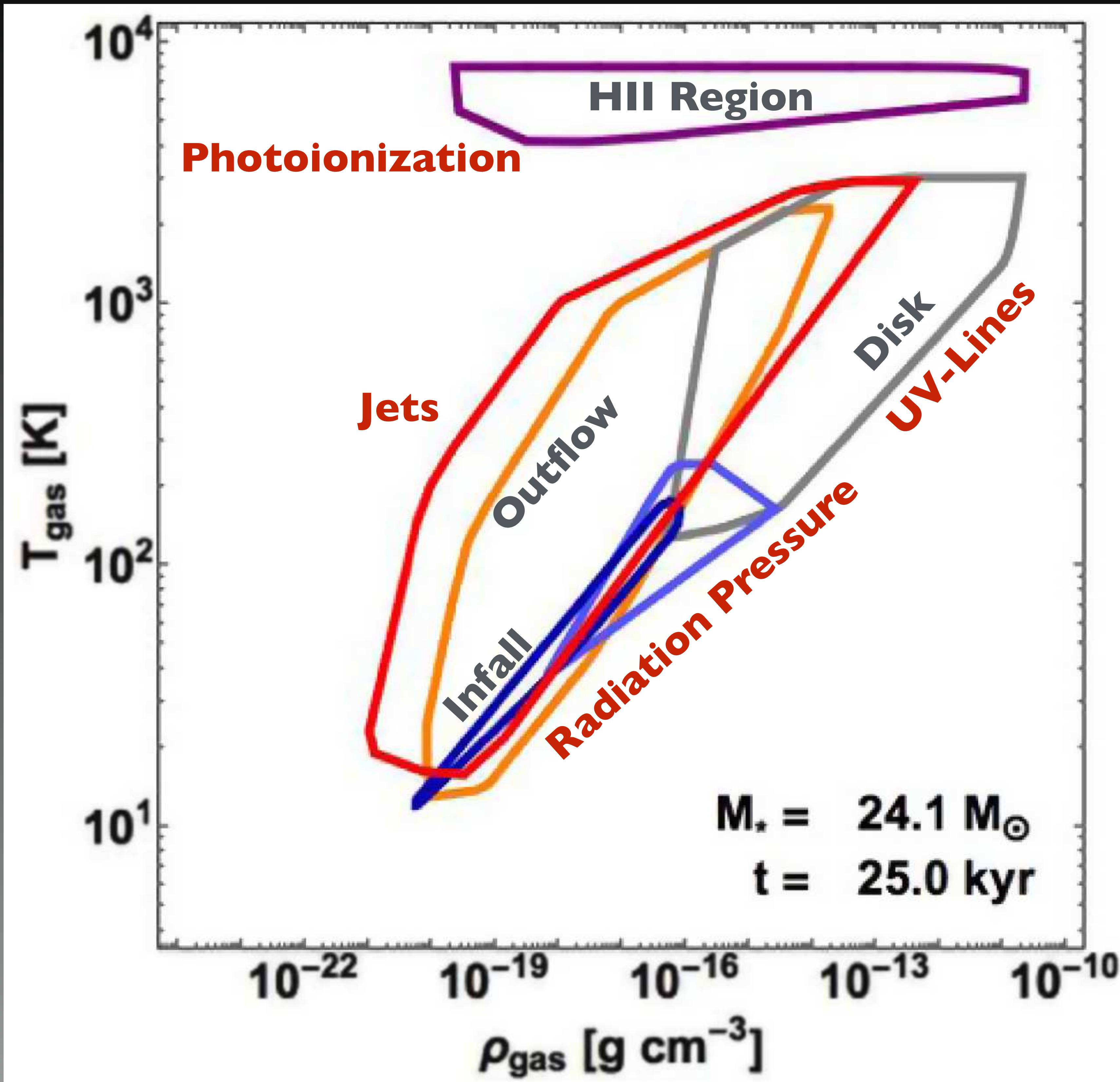
✘ Outflows
✘ Photoionization
✔ Radiation Forces

$M_{star} = 95 \, M_\odot$, $t_{acc} \sim 0.13$ Myr

$R_{res} \sim 0.24$ pc, $M_{res} \sim 240 \, M_\odot$

Kuiper & Hosokawa (2018)

Phase Diagram(s) of Feedback



Region	Selection Criterion	Color Code
Infall	$v_r < 0$ and $\|v_r\| > \|v_\phi\|$	Dark Blue
Torus	$v_r < 0$ and $\|v_r\| < \|v_\phi\|$	Light Blue
Disk	$v_\phi \approx v_{Kepler}$	Gray
Outflow	$v_r > 1$ km s^{-1}	Orange
Jet	$v_r > 100$ km s^{-1}	Red
HII	$x > 0.5$	Purple

Kuiper & Hosokawa (2018)

Software Development

- **Magneto-Hydrodynamics** PLUTO 4.1 (Mignone et al. 2007, 2012)
- **Self-Gravity** (Kuiper et al. 2010b)
- **Stellar Evolution** (Kuiper & Yorke 2013)
- **Dust Evolution**: Sublimation and Evaporation
- **Protostellar Outflows** (Kuiper, Yorke, & Turner 2015; Kuiper, Turner, & Yorke 2016)
    - **MHD-driven Jets & Outflows** (Kölligan & Kuiper 2018; Nies & Kuiper subm.)
- **Radiation**:
    - Hybrid Scheme: Stellar Irradiation + Continuum (Re-)Emission (Kuiper et al. 2010a)
    - now also in FLASH 4 (Klassen, Kuiper et al. 2014) & ORION (Rosen et al. 2017)
- **Variable Equation of State**: Thermal Dissociation and Ionization (Vaidya et al. 2015)
- **Photoionization**: Stellar Feedback + Recombination (Kuiper, Yorke, & Mignone, subm.)
- **UV-Line Scattering** (Kee, Owocki, & Kuiper 2018a,b; Kee & Kuiper 2018)

Log-spherical Grid Approach

General Properties:

- Resolution ~ Radius
- High Dynamic Range

Example:

- 234 x 64 x128 ≈ 2 mill.
- $R_{sink} = 10^0 \ldots R_{max} = 10^5$
- Δr @ $R_{sink} = 0.05$
  (≈ 22 levels of Cartesian AMR)