First Hydrodynamics Simulations of Radiation Forces and Photoionization Feedback in Massive Star Formation

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Emmy Noether-Programm
DFG

Motivation

Motivation

Jets & Outflows

Photoionization
&
HII Regions

Radiation Forces

Stellar Winds

Supernova

I Kuiper et al. (2010, 2011, 2013ab, 2015, 2016)

II Tan et al. (2014), PPVI:

„… a few caveats are in order.

First, no code yet includes all of these physical processes.“

III Eric Keto, EPoS 2014:

„If it does not form an HII region, it is not a massive star.“

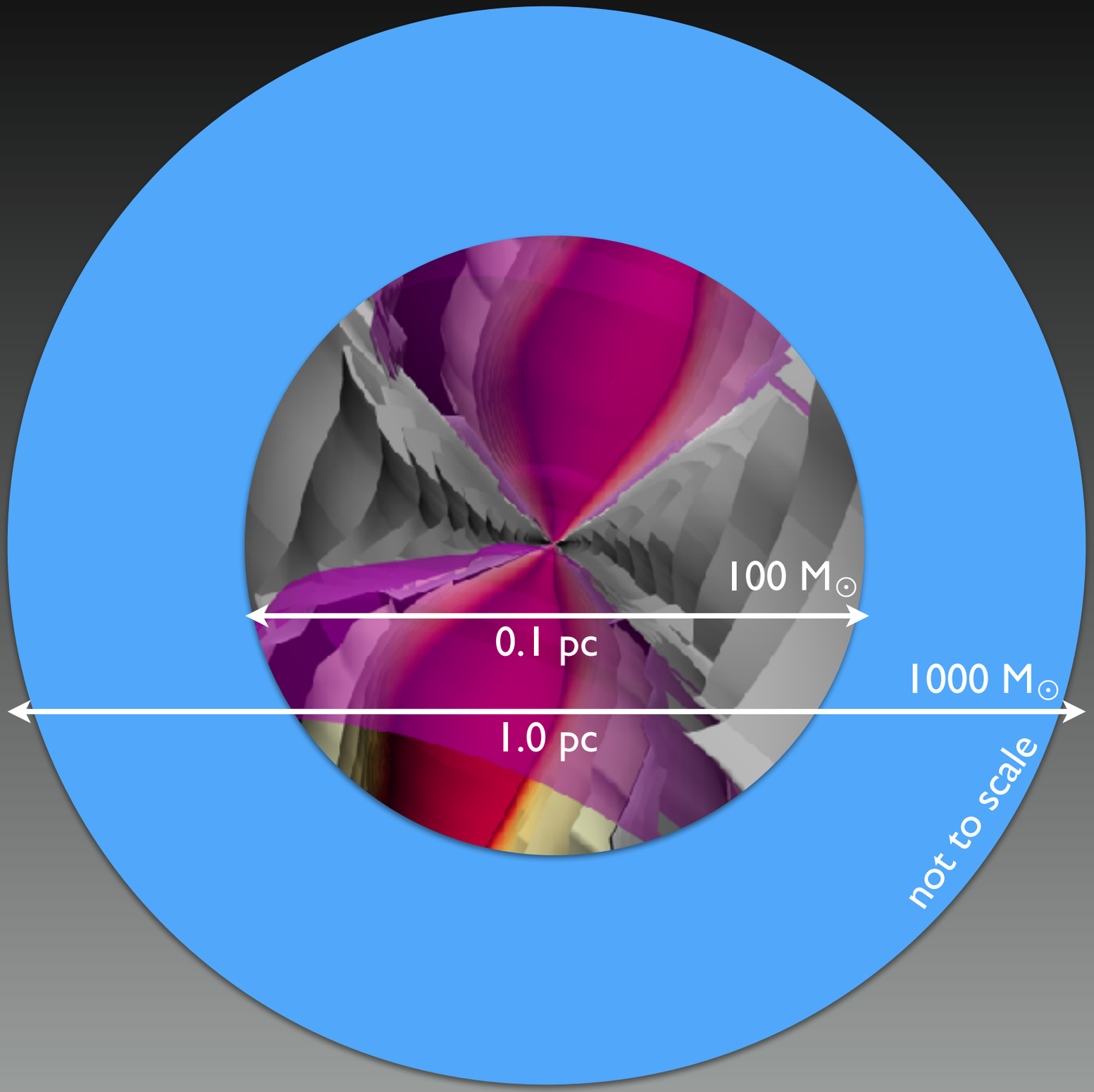
Physics

Code Development:

- Hydrodynamics (Pluto; Mignone et al. 2007, 2012)
  - log-radial spherical grid; axial and midplane symmetry
- Self-Gravity (Kuiper et al. 2010b)
- Stellar Evolution (Hosokawa & Omukai 2009)
  - Stellar Atmosphere (Kurucz 1979)
- Radiation Transport (Kuiper et al. 2010b, 2018 subm.)
  - Dust Evaporation and Sublimation (Bhandare et al. 2018 subm.)
- Protostellar Outflows (Kuiper et al. 2015, 2016)
- Photoionization (Kuiper, Yorke, & Mignone 2018 subm.)

Feedback Physics:	Simulation Series:			
• Protostellar Outflows	✔	✔	✔	✔
• Photoionization	✘	✔	✘	✔
• Radiation Forces	✘	✘	✔	✔

Two Accretion Scenarios



$$\rho \propto r^{-2}$$

$$t_{\rm ff} = 52.4 \text{ kyr} \quad (524 \text{ kyr})$$

$$\dot{M}_{\rm ff} = 2 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1}$$

$$\Omega \propto R^{-1}$$

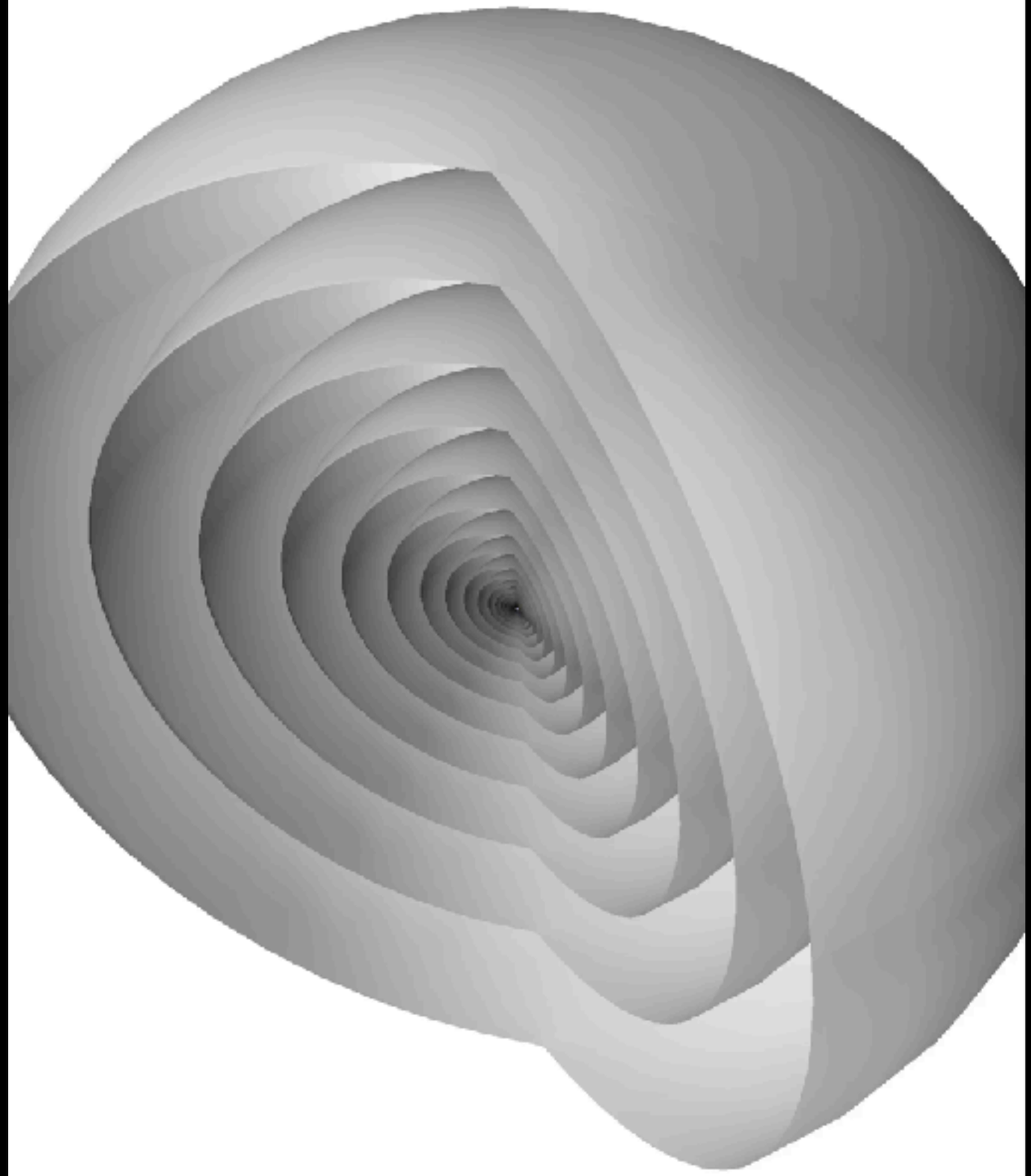
$$E_{\rm rot}/E_{\rm grav} = 2\%$$

Finite Mass Reservoir:

- "archetype" of a monolithic pre-stellar core

"Infinite" Mass Reservoir:

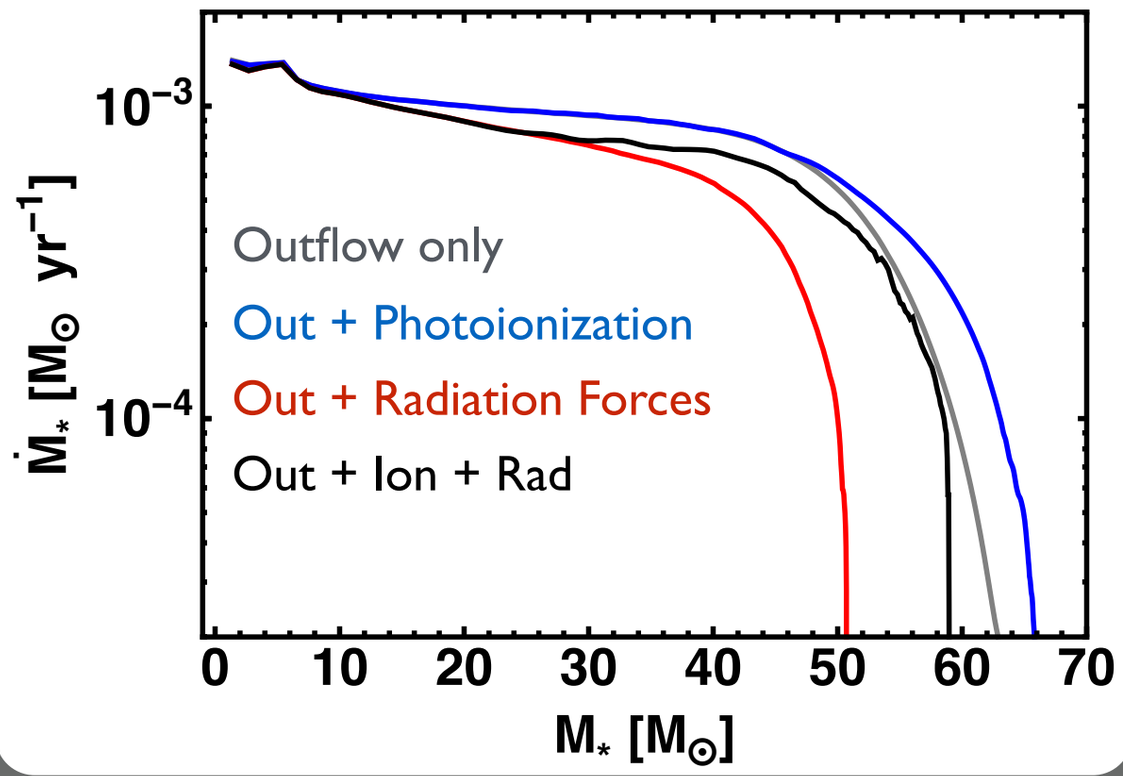
- sustained accretion
- ram pressure



Kuiper & Hosokawa (2018)

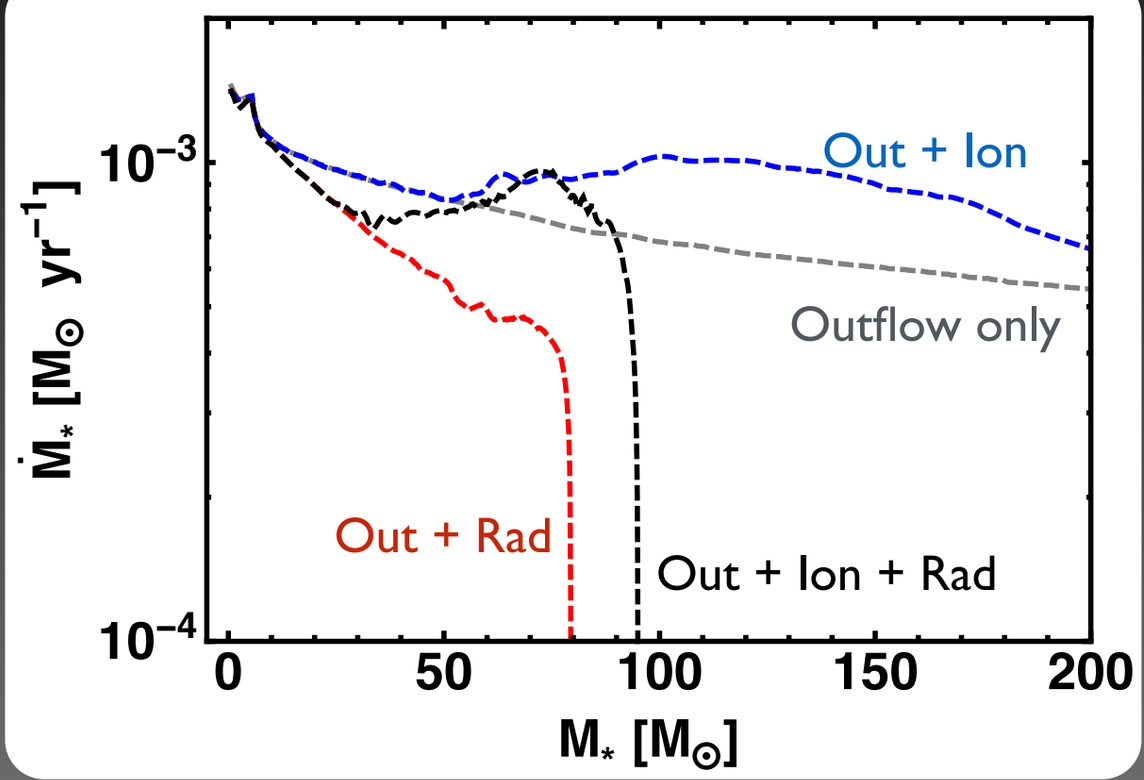
Result: Stellar Mass

Finite Mass Reservoir



- controlled by mass loss of the reservoir

"Infinite" Mass Reservoir



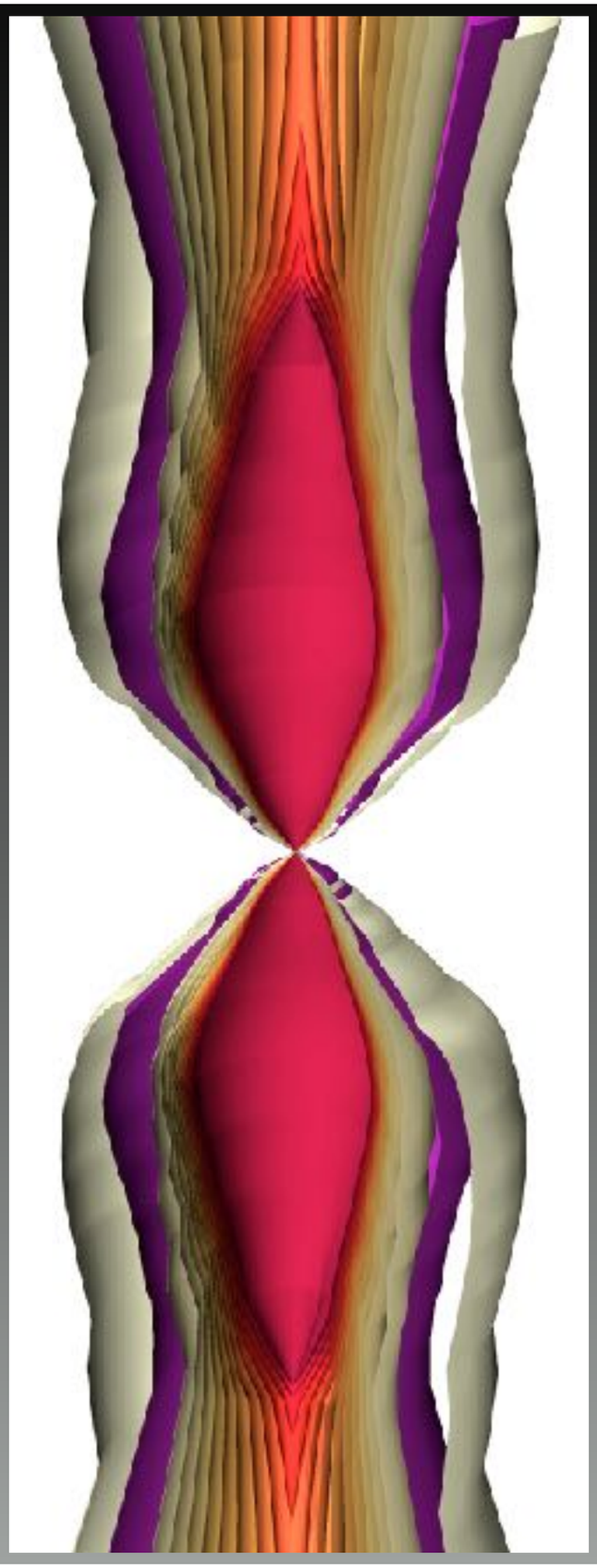
✘ Outflows
✘ Photoionization
✔ Radiation Forces

M_{star} = 95 $M_\odot$, t_{acc} ~ 126 kyr

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

Kuiper & Hosokawa (2018)

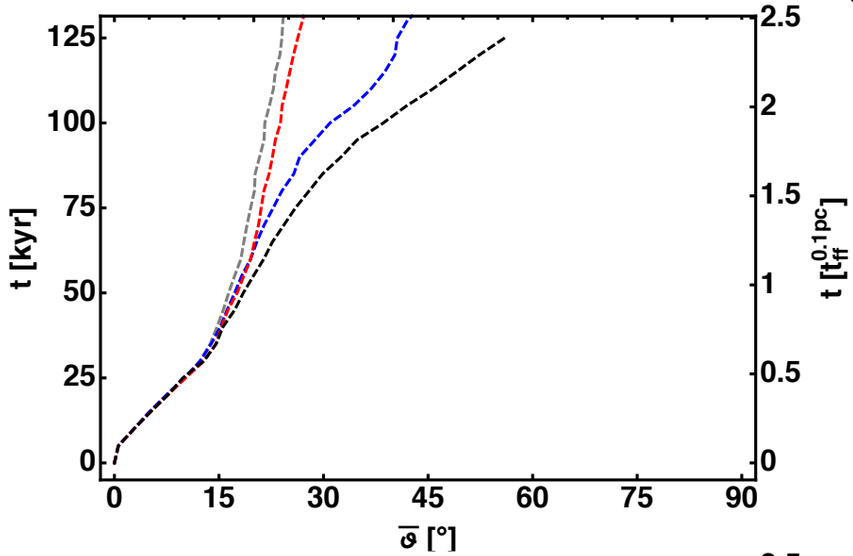
Result: Outflow Broadening



Kuiper & Hosokawa (2018)

Result: Outflow Broadening

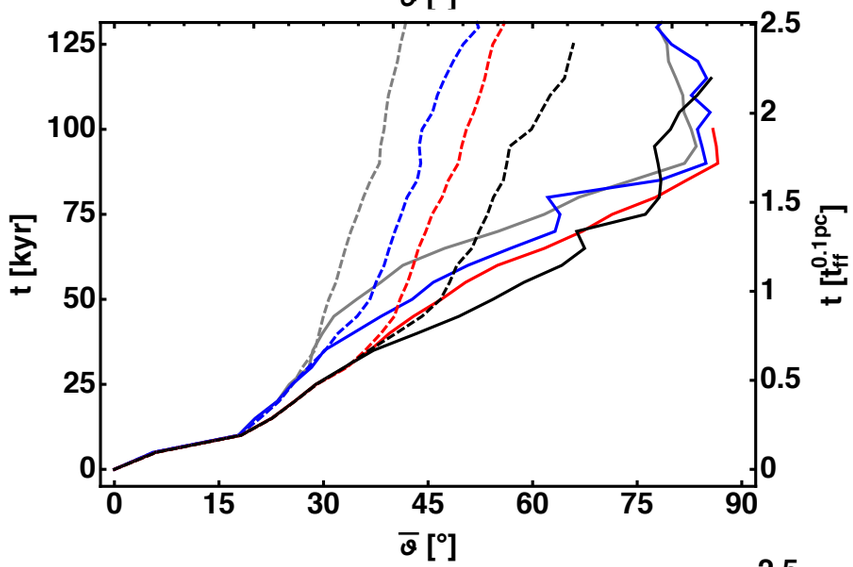
Cluster
1.0 pc



Photoionization > Radiation Forces

HII Region Expansion decreases Infall by 50%

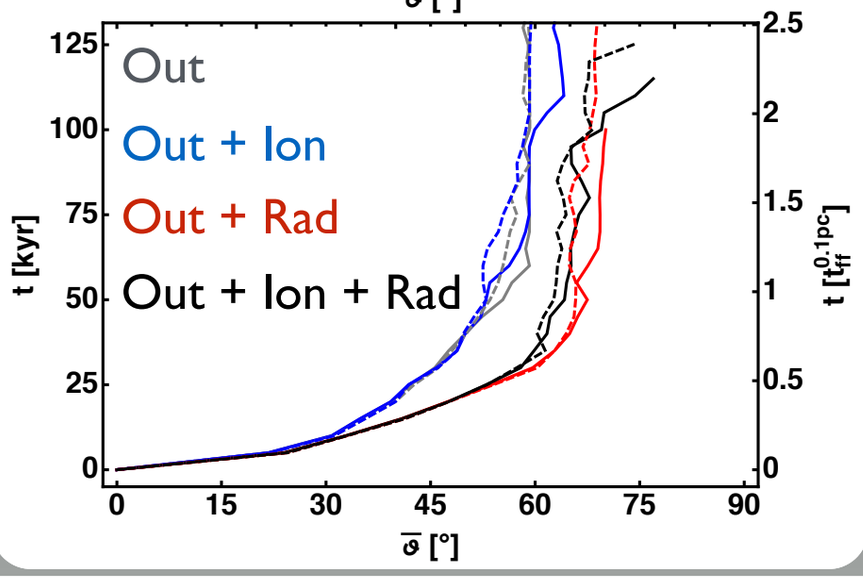
Core
0.1 pc



Ram Pressure collimates Outflow Cavity

Radiation Forces > Photoionization

Disk
0.01 pc
2000 AU



Disk Structure sets Opening Angle

✘ Photoionization

✔ Radiation Forces

Kuiper & Hosokawa (2018)

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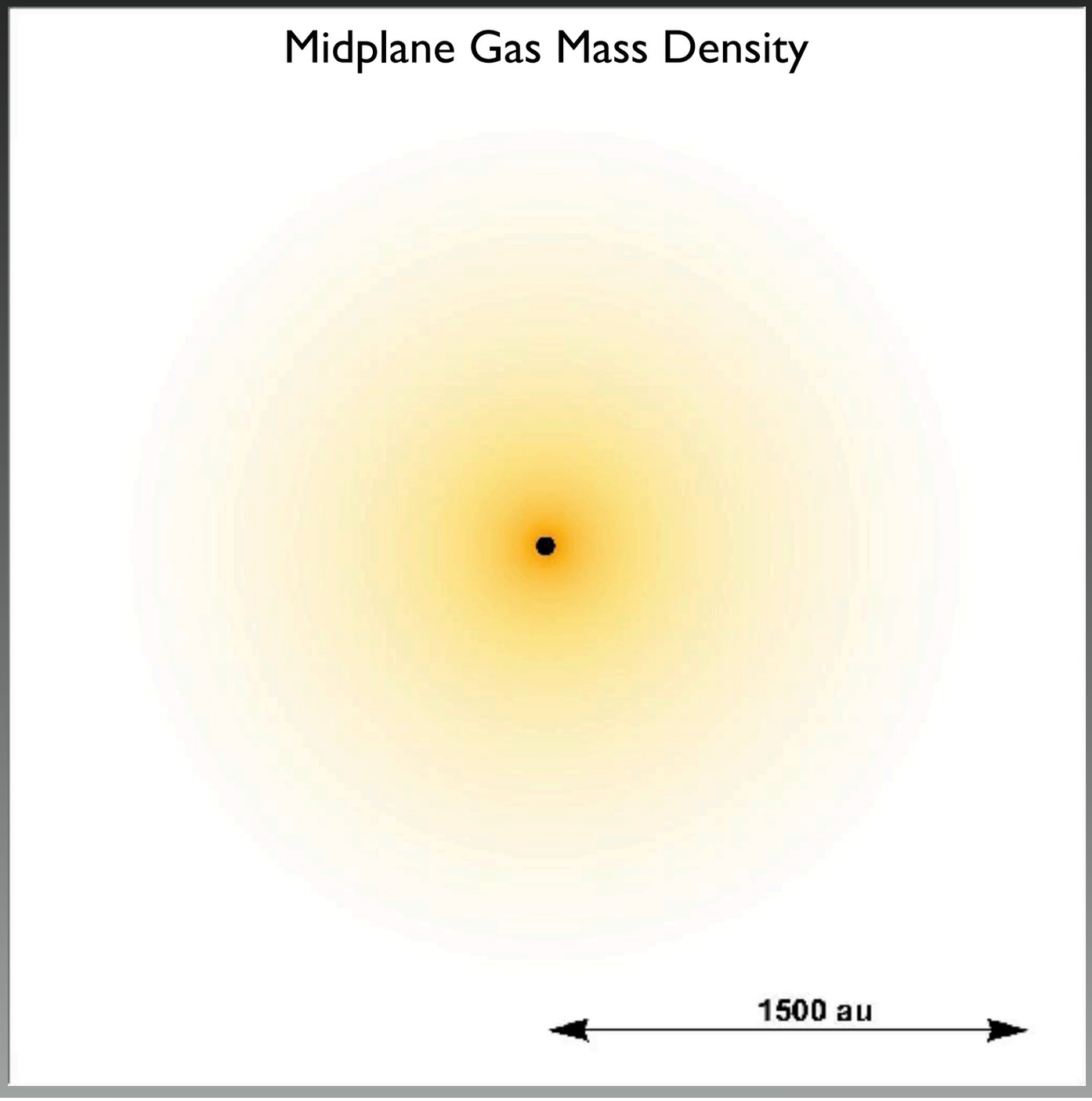
- Disk Fragmentation (Meyer et al. 2017, 2018)

  → see Poster by Rolf Kuiper



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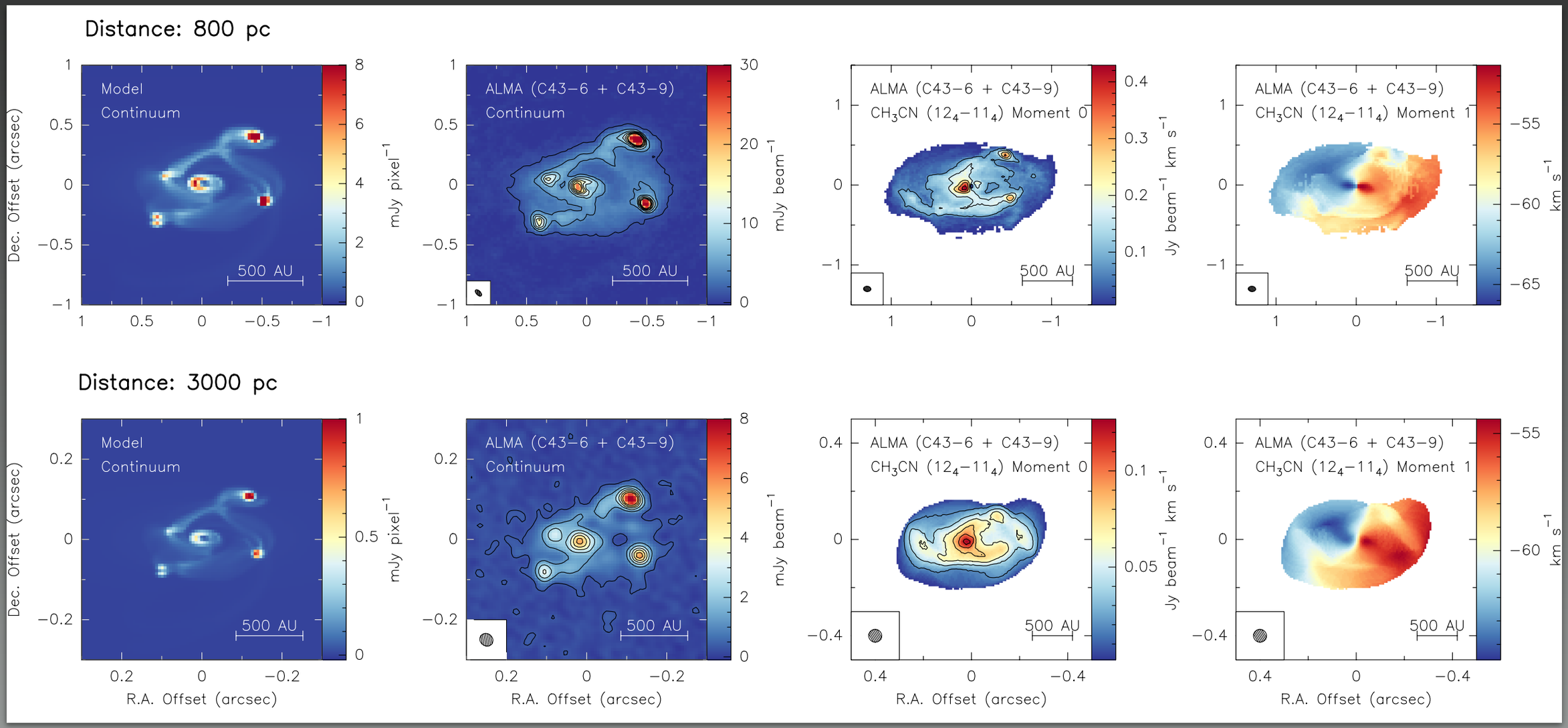
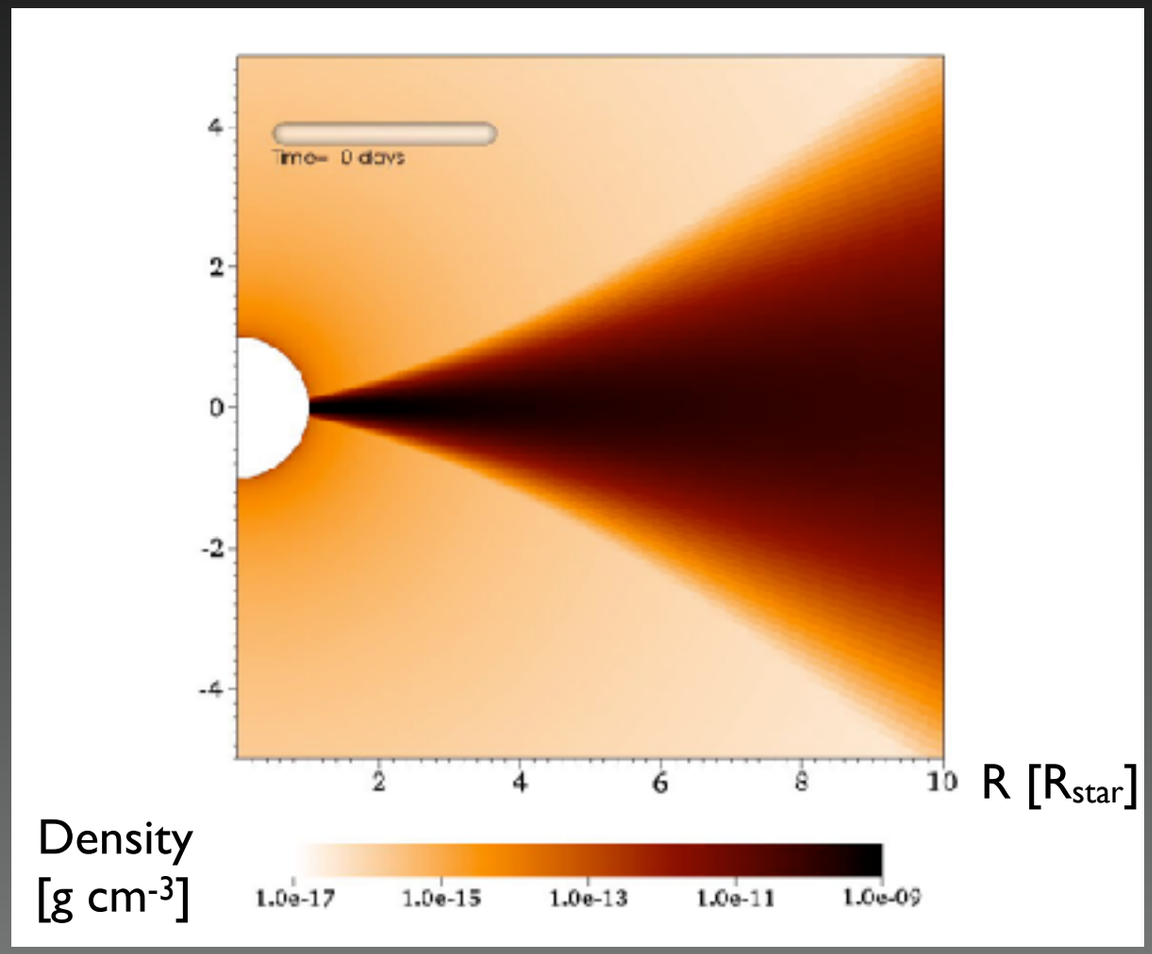
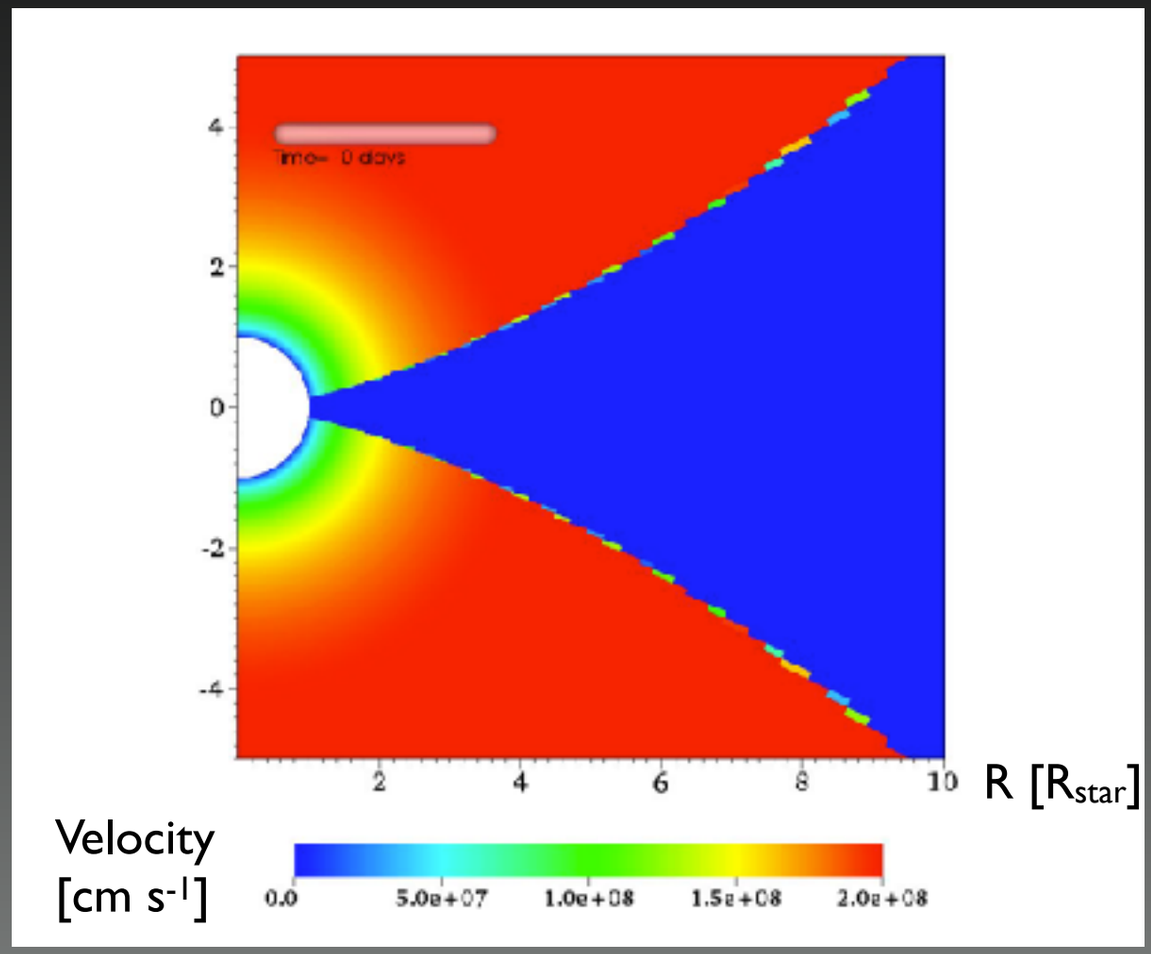
  - Observational Comparison / CORE (Ahmadi, Kuiper et al., in prep.)

  → see Poster by Aida Ahmadi #P2

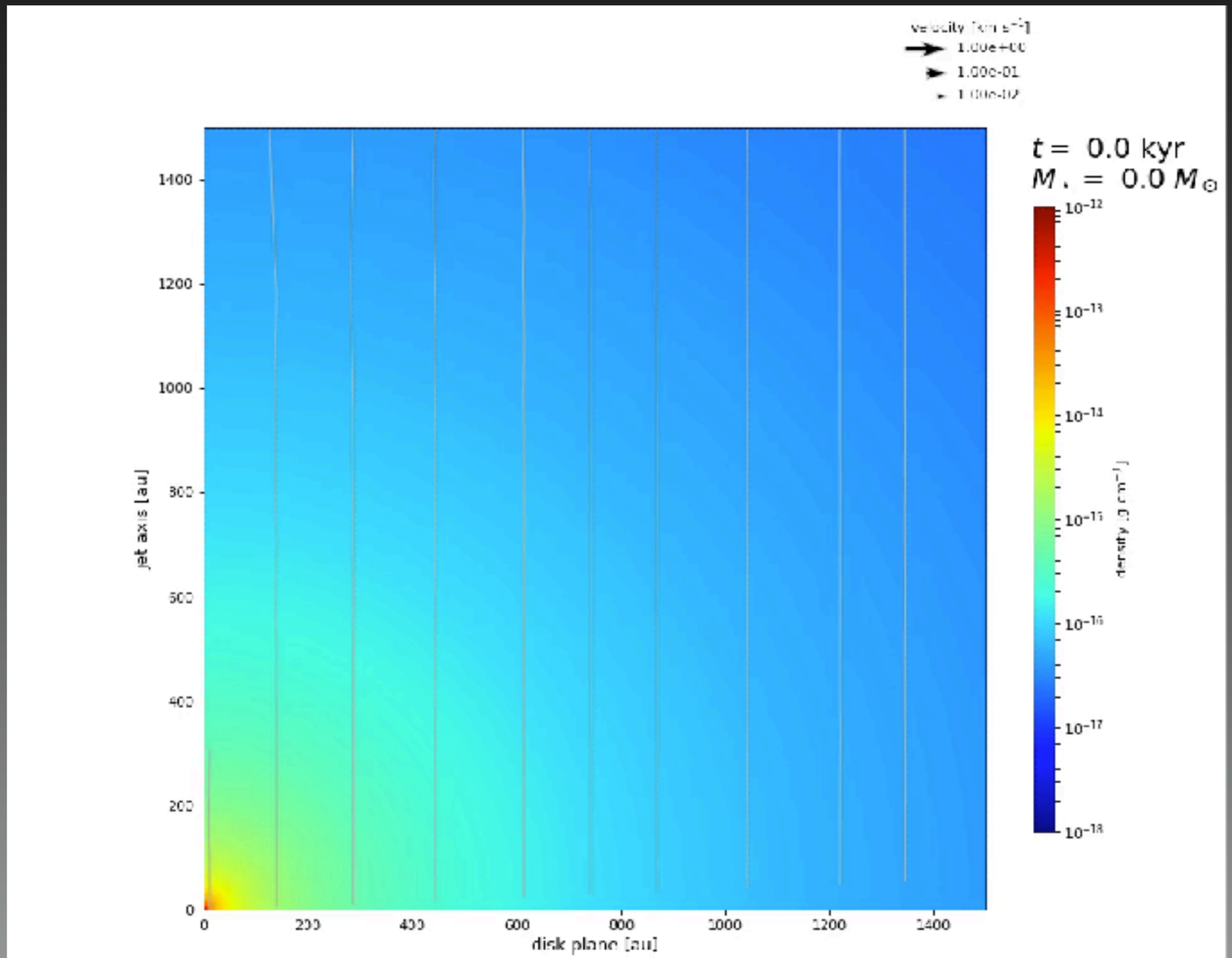


- UV-line Scattering Feedback onto the near-star Disk (Kee et al. 2018, + subm.)





- MHD-driven Jets and Outflows (Kölligan & Kuiper, in prep.)



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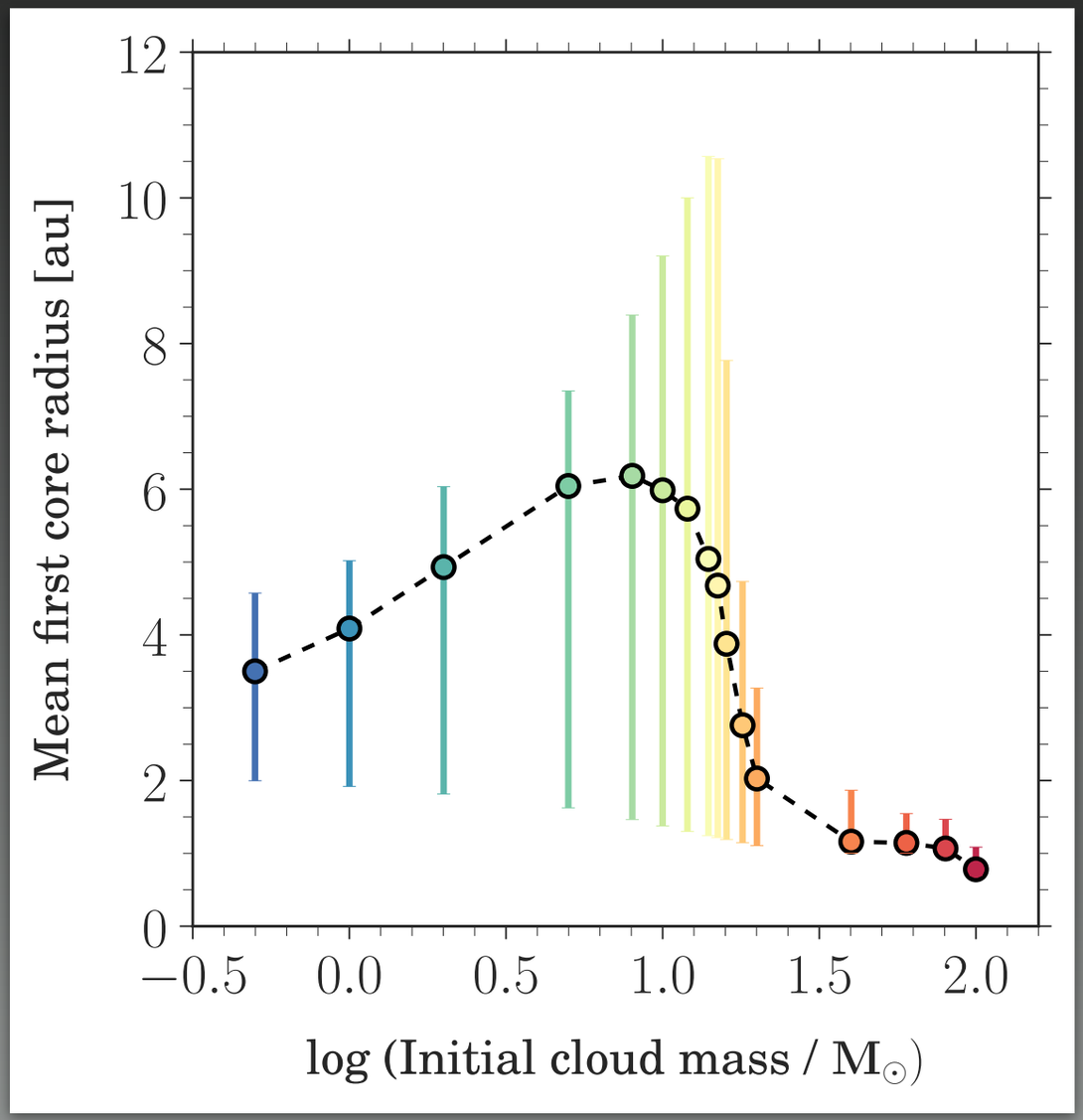
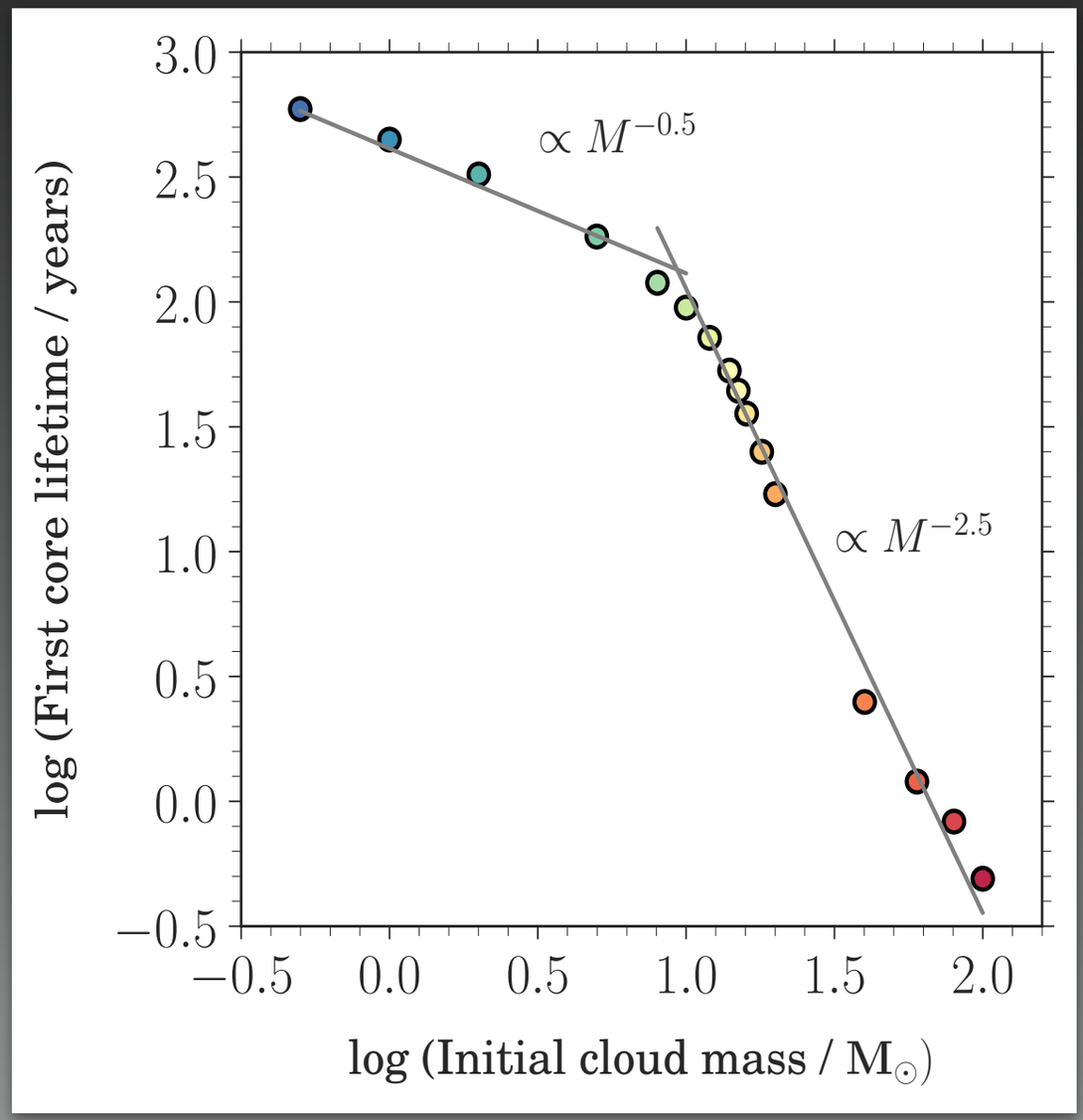
- First Larson Cores (Bhandare, Kuiper, Henning, Fendt, Marleau, Kölligan, subm.)

  → see Poster by Asmita Bhandare #P5





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Summary

Photoionization & HII Regions

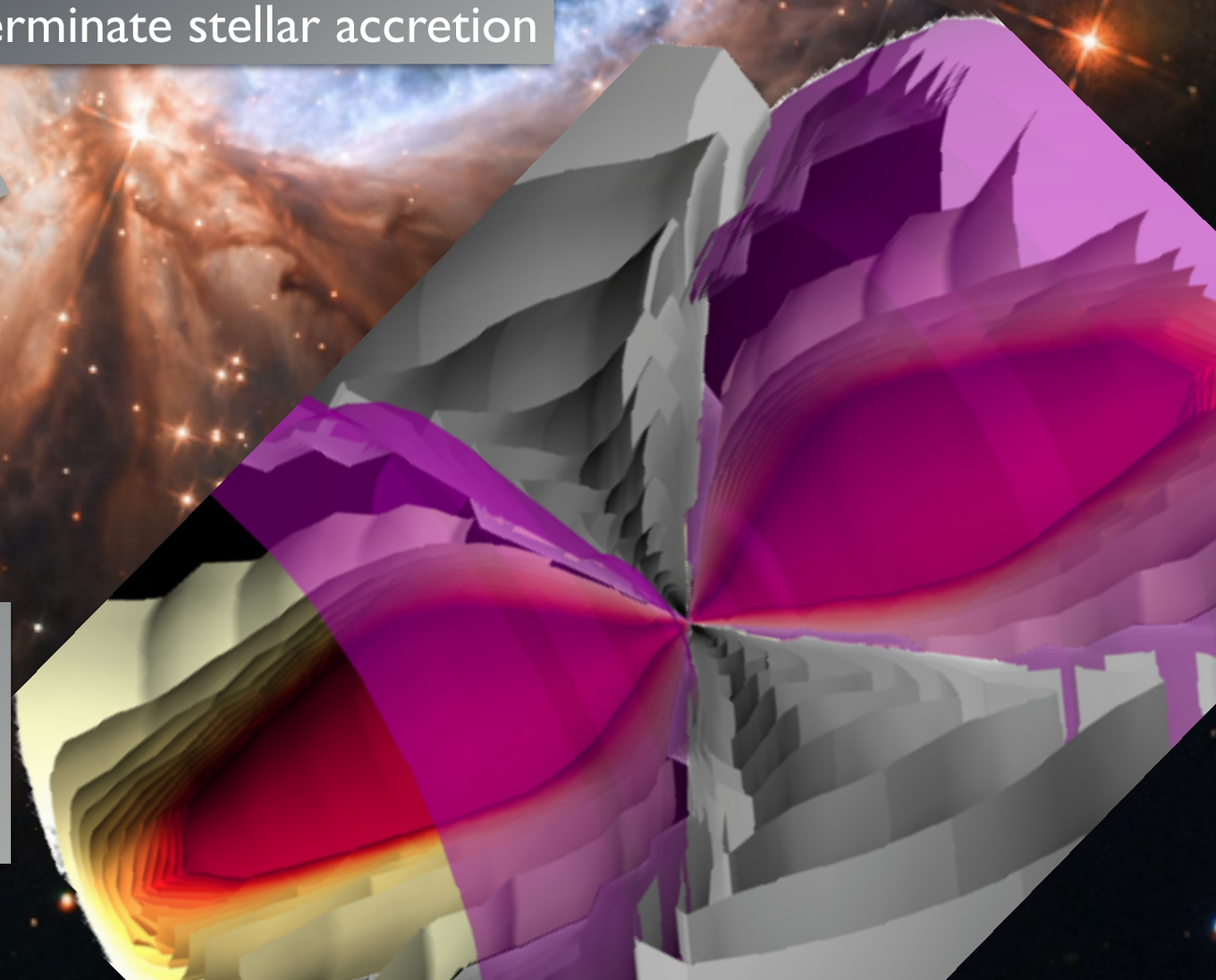
→ late epochs + large scales

Radiation Forces

→ terminate stellar accretion

Jets & Outflows

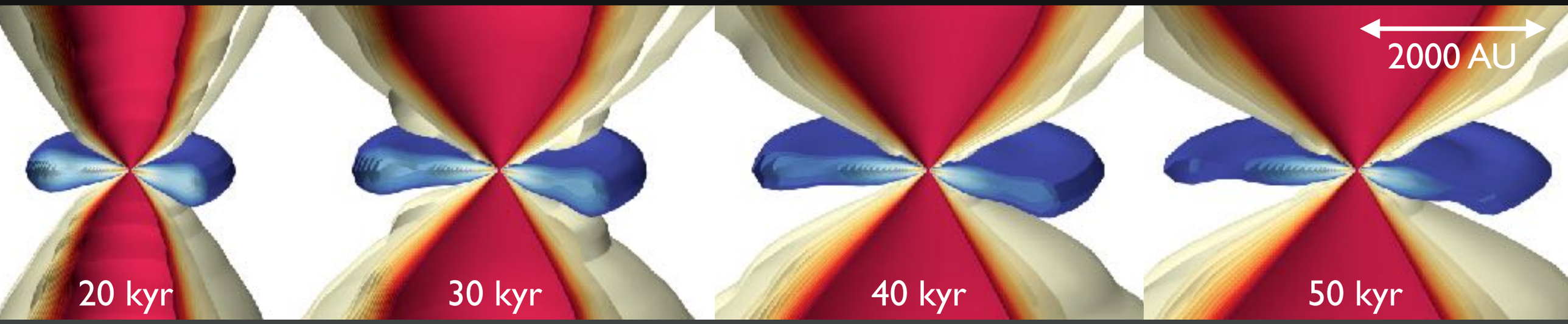
→ finite mass reservoirs



Obstacles / Open Questions:

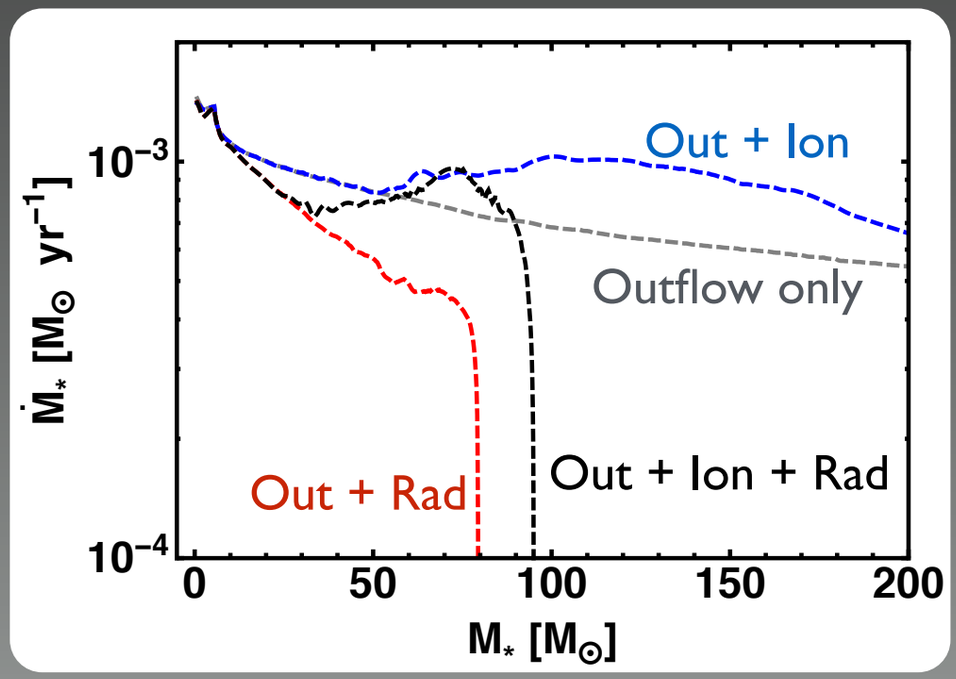
- 2D long-timescale vs. 3D high-resolution
- broad parameter space / initial conditions

Photoionization feeding the Disk



Photoionization's positive Feedback:

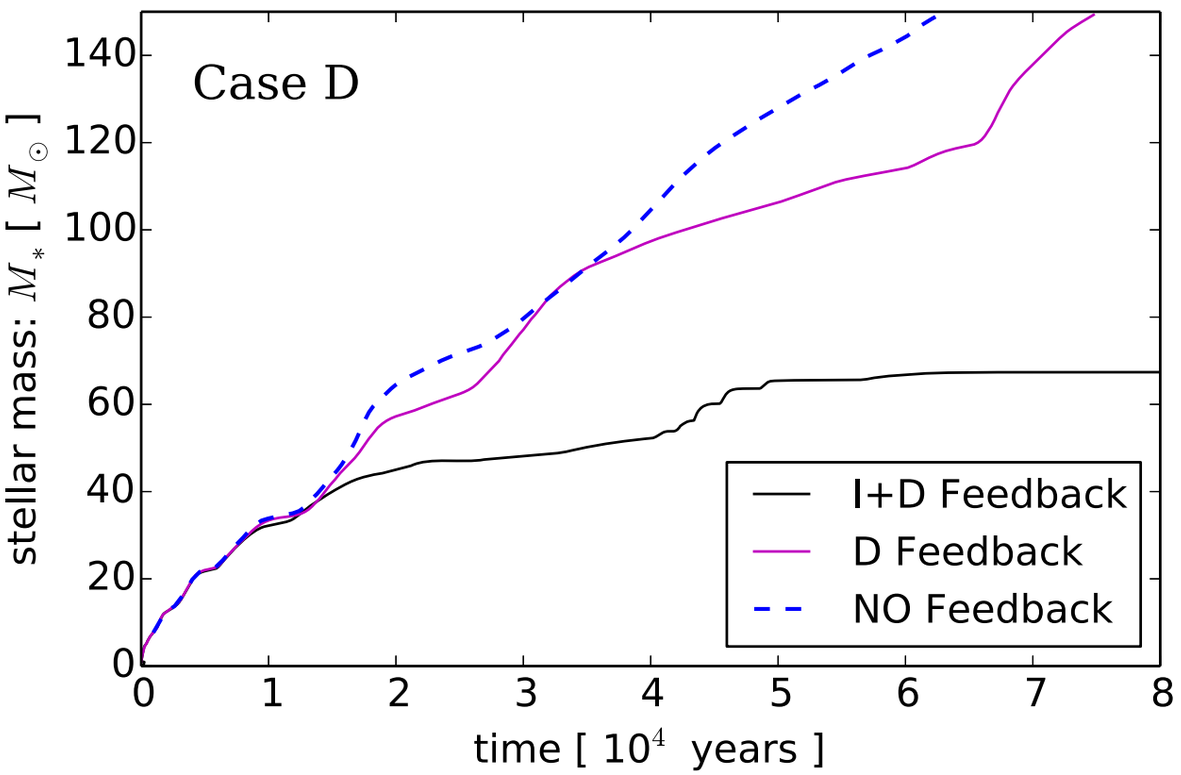
- Protostar keeps bloated until ~30 M_{sol} (~30 kyr)
  (Hosokawa & Omukai 2009, Kuiper & Yorke 2013)
- HII Region fills Bipolar Outflow Cavity
- Thermal Pressure Feedback
  acts like Scissor Handles



Kuiper & Hosokawa (2018)

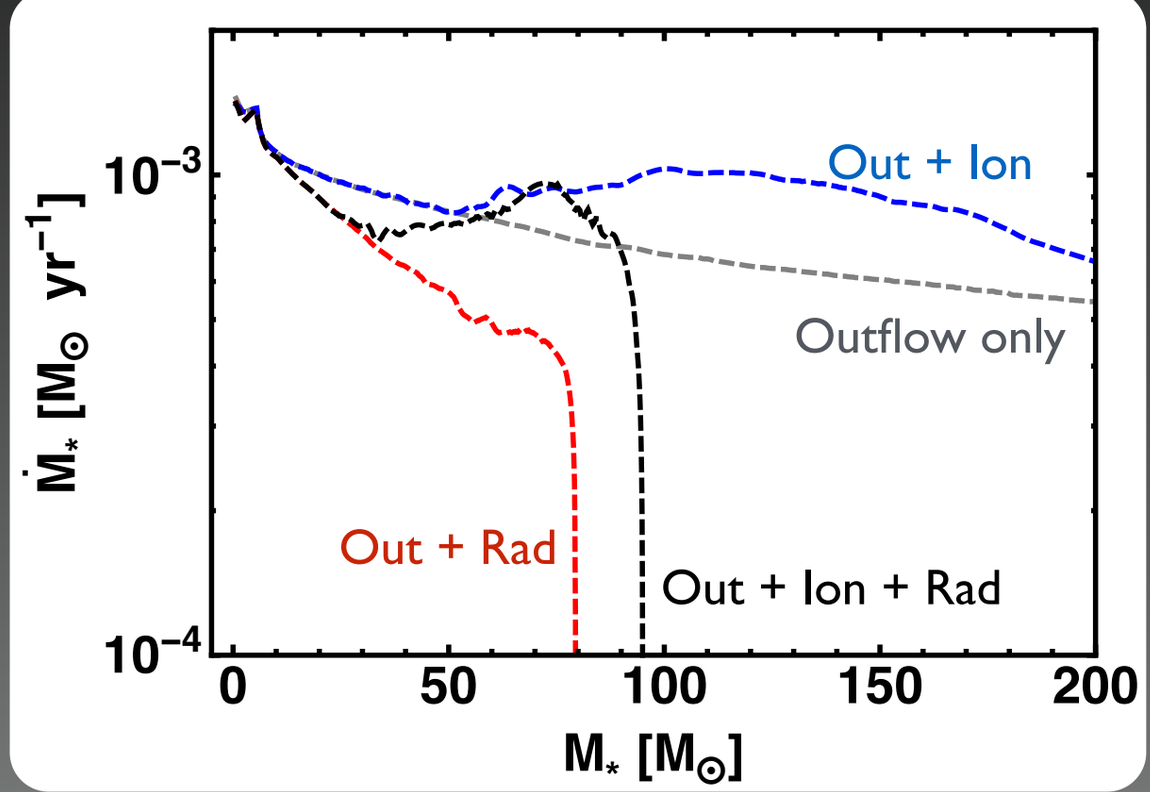
Feedback from First Stars

First Stars



Hosokawa, Hirano, Kuiper, et al. (2016)

Present-Day Star Formation

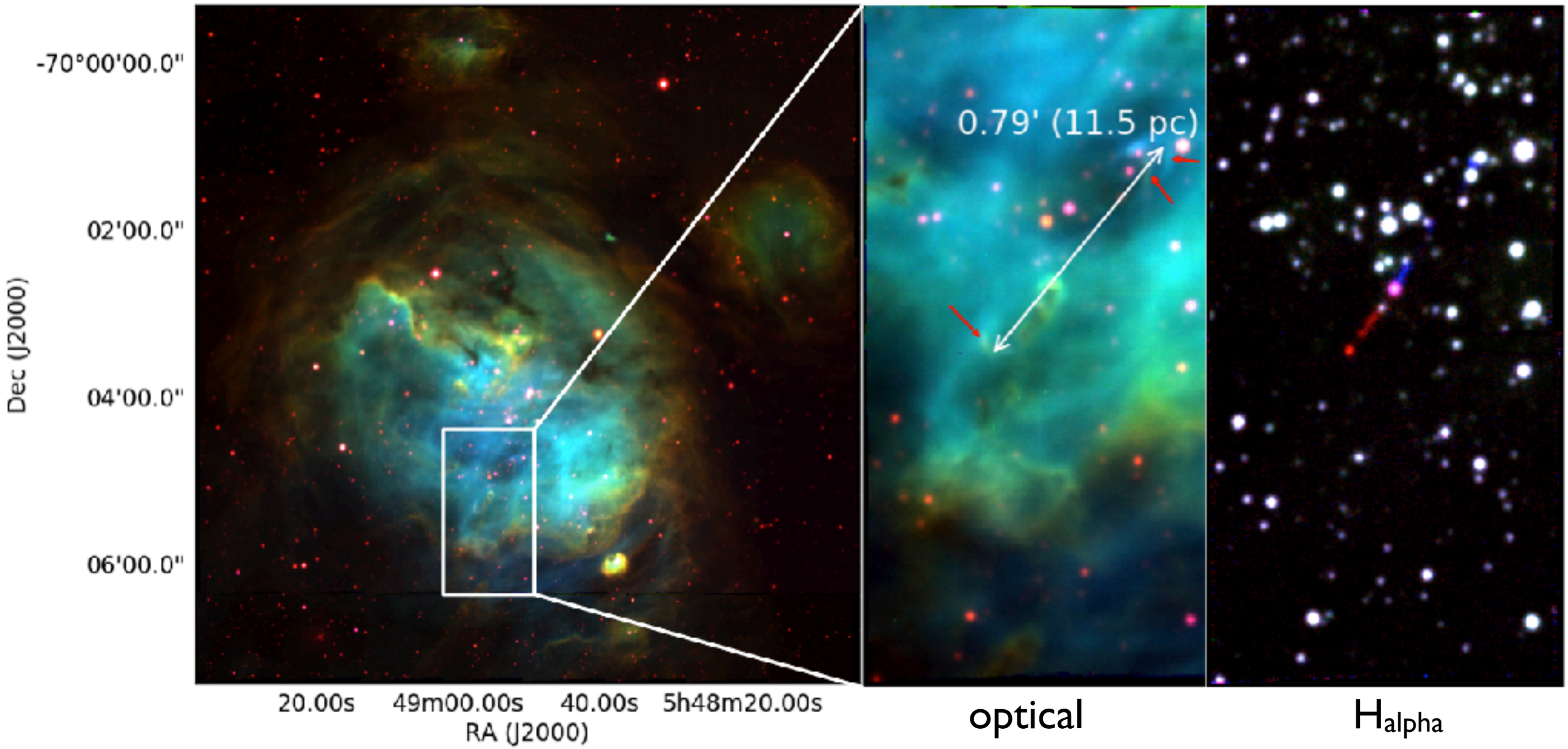


Kuiper & Hosokawa (2018)

A parsec-scale Jet from a Massive Young Star

Large Magellanic Cloud - N180

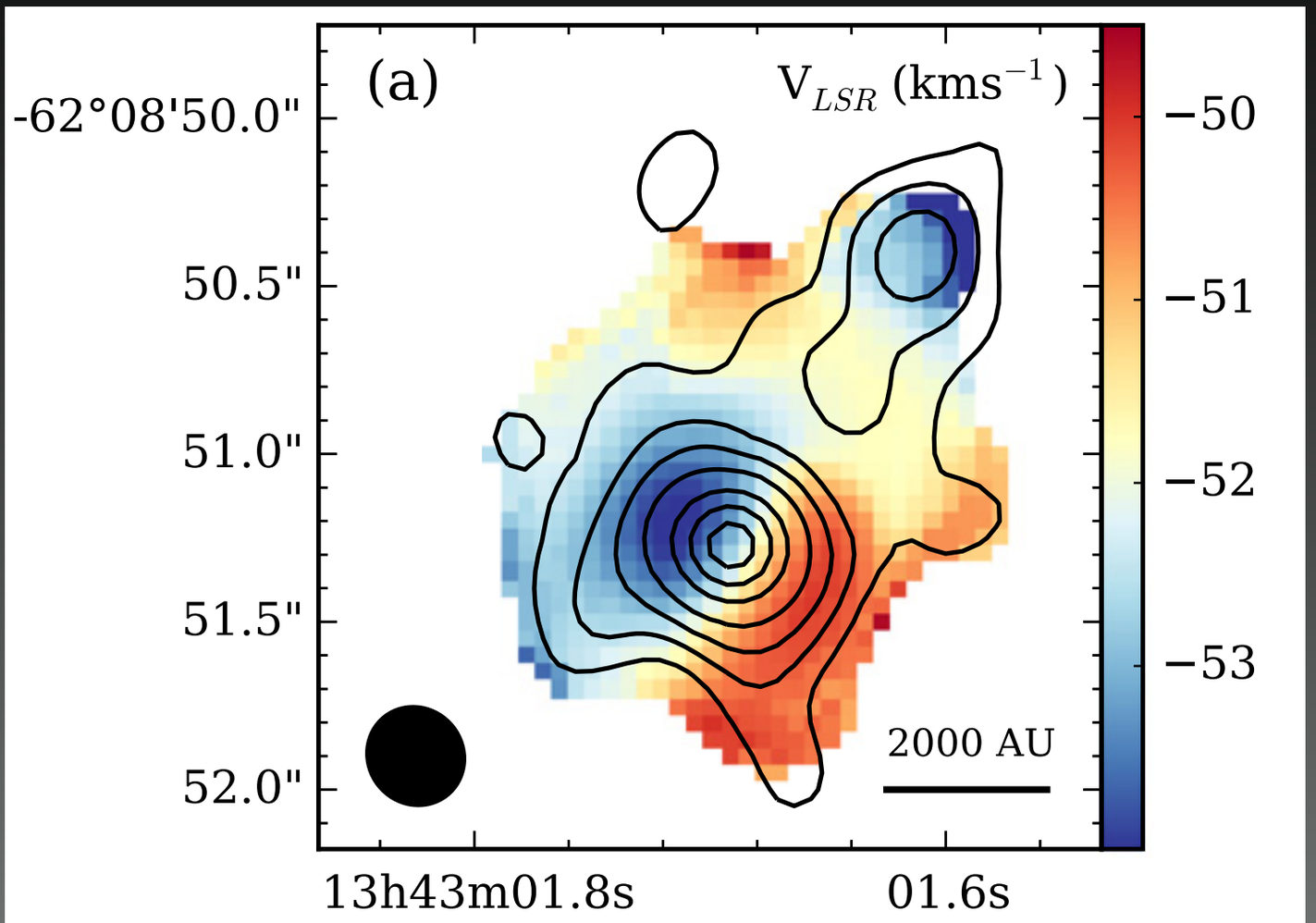
HH 1177



McLeod, Reiter, Kuiper, Klaassen, & Evans, Nature

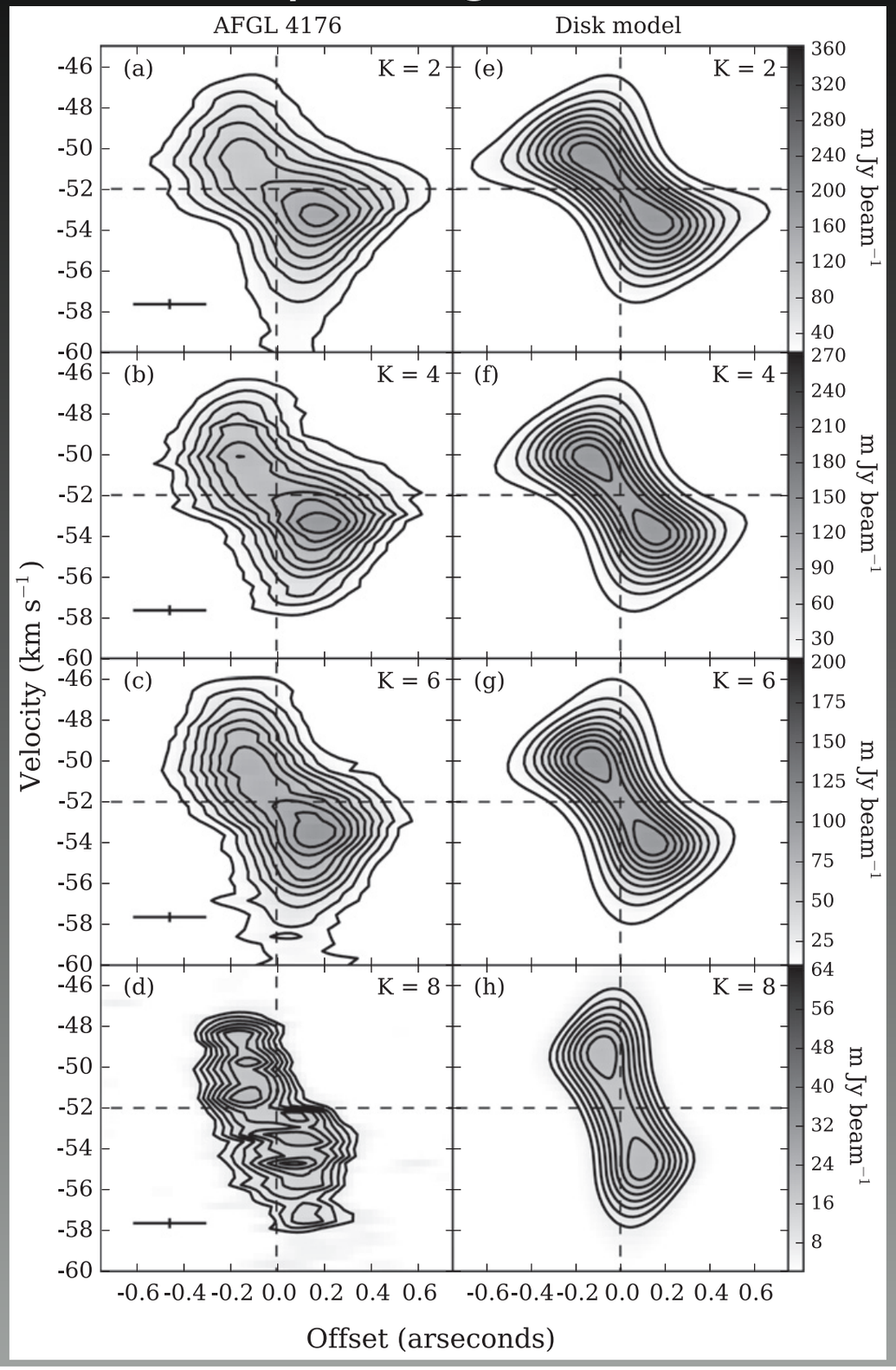
A Disk around a Massive Young Star

AFGL 4176



CH_3CN

p-V diagrams



Johnston, Robitaille, Beuther, Linz, Boley,
Kuiper, Keto, Hoare, & van Boekel (2015)