Accretion and Feedback in the Formation of Massive Stars

Rolf Kuiper

Collaborators: T. Hosokawa, A. Kölligan, N.D. Kee, D. Meyer, A. Bhandare, S. Owocki, A. F. McLeod, M. Reiter, P. D. Klaassen, C. J. Evans, K. G. Johnston, W. Kley, E. Vorobyov, A. Ahmadi, H. Beuther, H.W. Yorke, N. J. Turner, …

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The Wonders of Star Formation
aka HansFest
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Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Image Credit: ESA/Herschel

Emmy Noether Research Group on Massive Star Formation

- **MHD-driven Jets & Outflows**: Launching, Acceleration, and Feedback
  (Kölligan & Kuiper 2018)

- **Radiation Forces** & **Photoionization**: Feedback in Time and Space
  (Kuiper & Hosokawa 2018)

- **UV-Line Scattering Forces**: Ablation, Disk Winds, and the Upper Mass Limit
  (Kee, Owocki, & Kuiper 2018a,b; Kee, Kuiper et al., in prep.)

- **Disk Fragmentation**: Variable Accretion, Luminosity Bursts and Binary Formation
  (Meyer, Kuiper et al. 2018; Kuiper et al., in prep.; Ahmadi, Kuiper et al., in prep.)

- **First Larson Cores** from Low-mass Stars to Massive Stars
  (Bhandare, Kuiper et al. 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)
- **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)

- Grids: log-radial **Spherical Coordinates** and Cartesian, Cylindrical, stacked, …
  - extremely high spatial resolution of the innermost object (disk, jet launching, first core)
  - 1D spherical symmetry, 2D axial symmetry, and 3D available
  - long-term runs & parameter studies

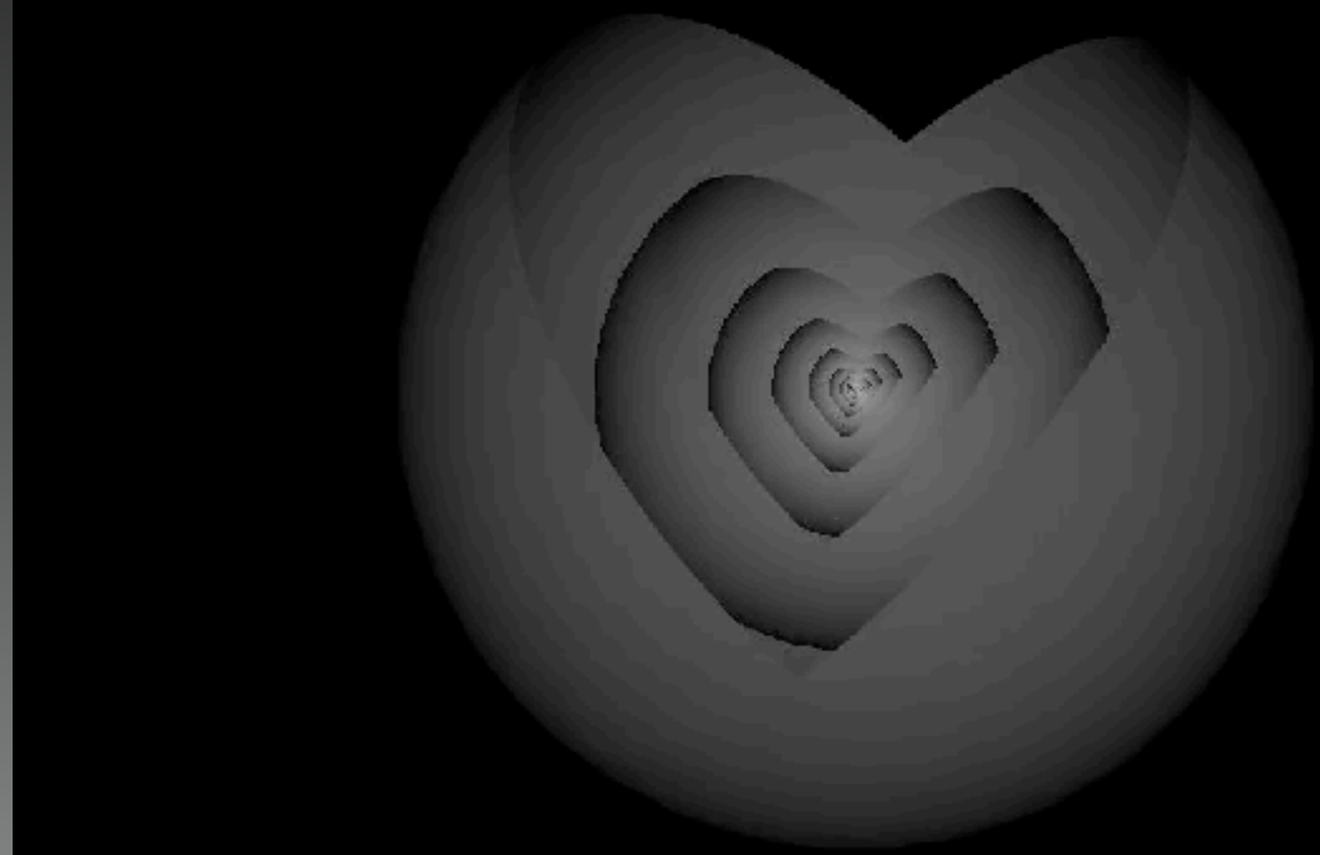
MHD-driven Jets & Outflows

- What is the driving source of observed large-scale outflows?
- Is jet launching an universal (mass-independent) process?
- Does magnetic braking prevent disk formation?
- What is the efficiency of the accretion-ejection process?
- Does the outflow carry angular momentum (enabling disk accretion)?
- What is the effect from/onto the stellar environment?

Kölligan & Kuiper (2018)

MHD-driven Jets & Outflows

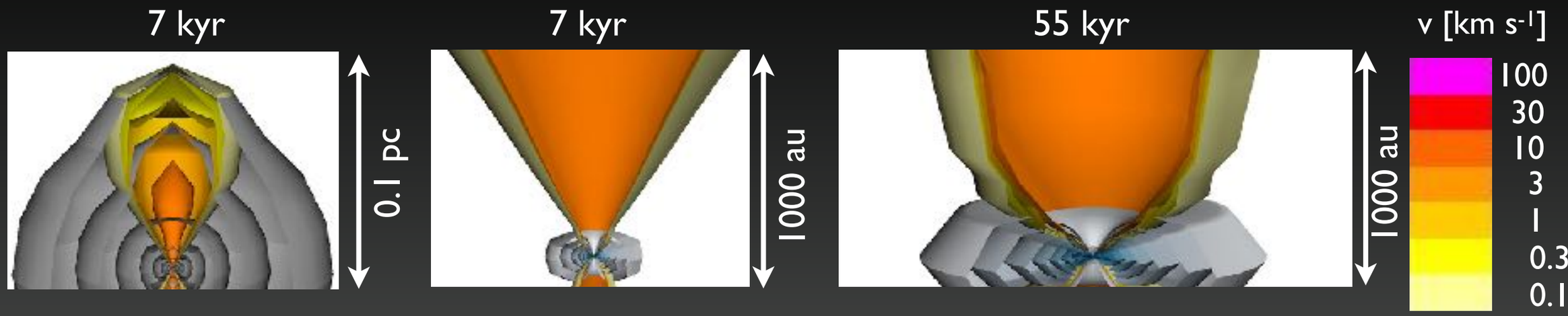
- non-ideal MHD
- isothermal
- axial and midplane symmetry (2D)
- high-resolution:
  R_{min} = 1 au, Δx = 0.1 au;
  in comparison: Cartesian AMR:
  sink particle 40 au, Δx = 10 au (Myers et al. 2013);
  see also Matsushita et al. (2017): nested grid down to Δx = 1 au



Kölligan & Kuiper (2018)

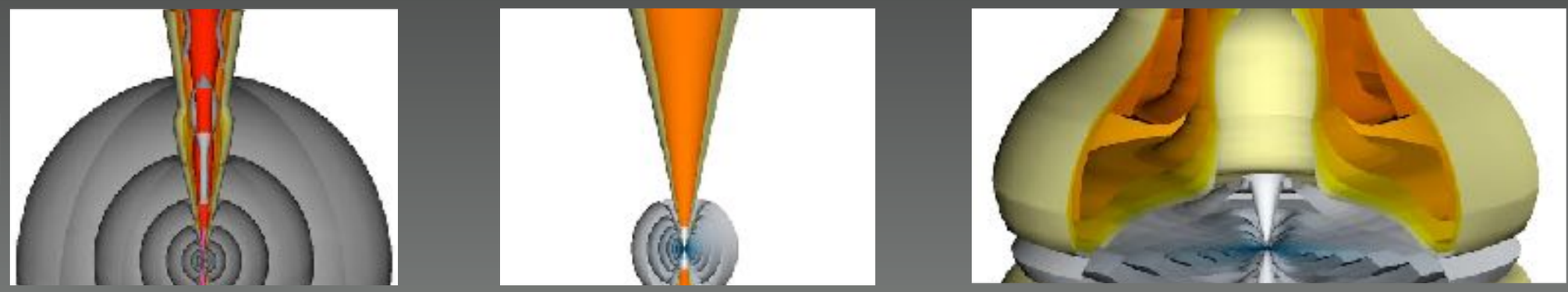
MHD-driven Jets & Outflows

low-res



- early, single, broad, and massive outflow (as in Banerjee & Pudritz 2008)

high-res



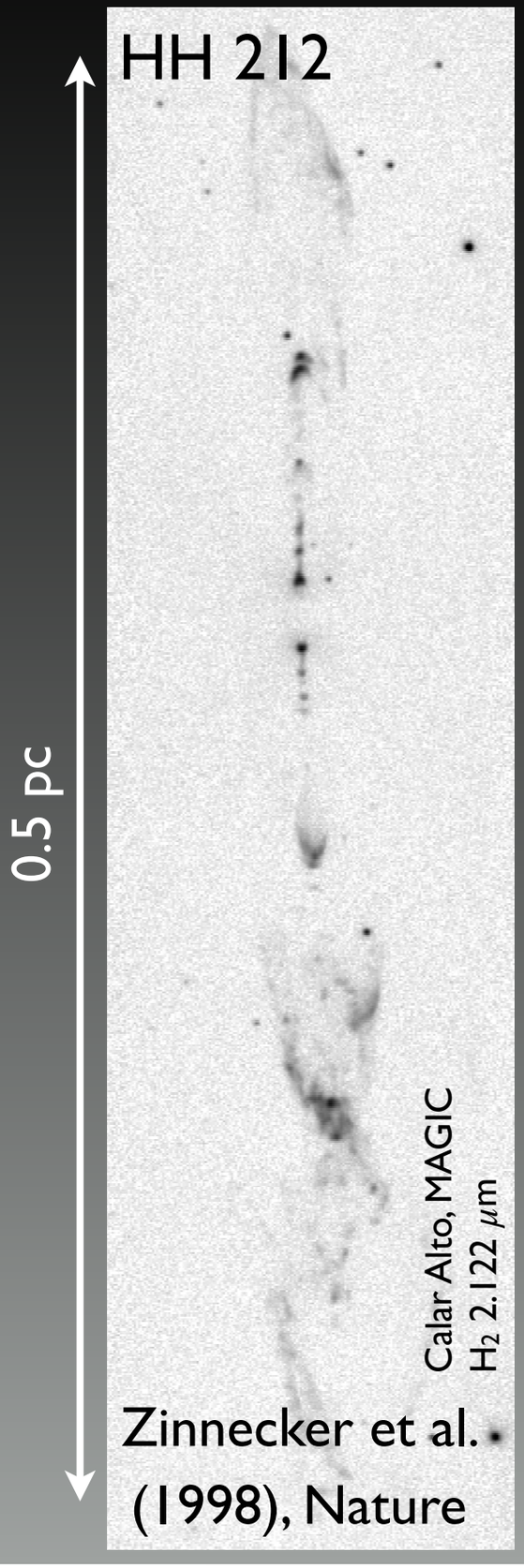
- two distinguished outflow components
  - early collimated magneto-centrifugal jet (Blandford & Payne 1982)
  - late disk-driven magnetic tower flow (Lynden-Bell 2003)

→ see Poster 4D by Anders Kölligan

Kölligan & Kuiper (2018)

But do collimated jets around massive proto stars exist?

A scaled-up view of star formation?!



Zinnecker et al. (1998), Nature

McLeod, Reiter, Kuiper, Klaassen, & Evans (2018), Nature

A scaled-up view of star formation?!

Zinnecker et al.
(1998), Nature

McLeod, Reiter, Kuiper, Klaassen, & Evans (2018), Nature

Radiation & Photoionization Feedback

- Does feedback stop stellar accretion?
- Is the upper mass limit of stars due to feedback?
- Which feedback components dominate?

  On what spatial scales? During which epochs?

Kuiper & Hosokawa (2018)

Radiation & Photoionization Feedback

Grid:

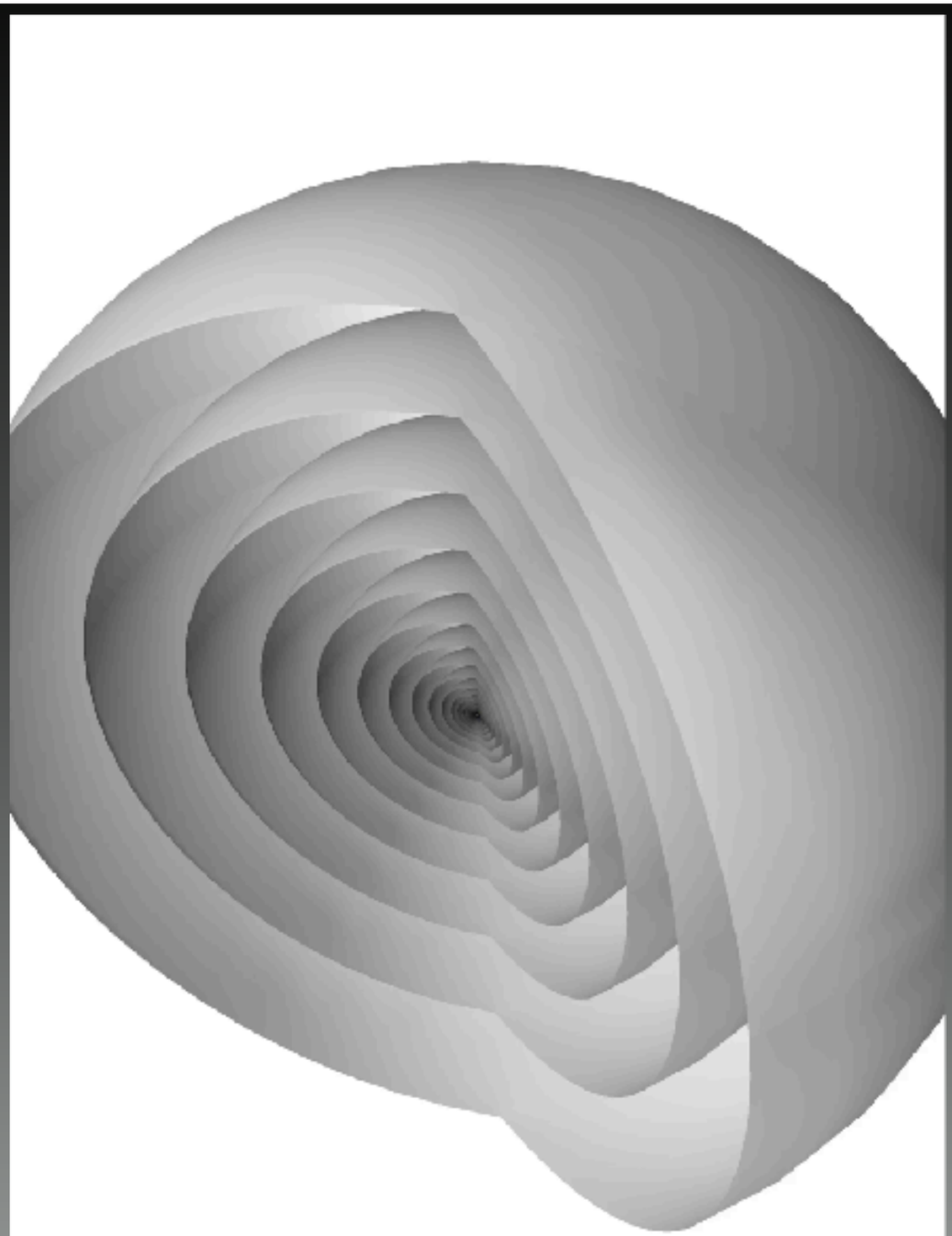
- Axial and midplane symmetry (2D)
- Δx = 0.3 au

Feedback Physics:

- Outflows (subgrid)
- Radiation Forces
- Photoionization → HII Region

Two different Initial Conditions:

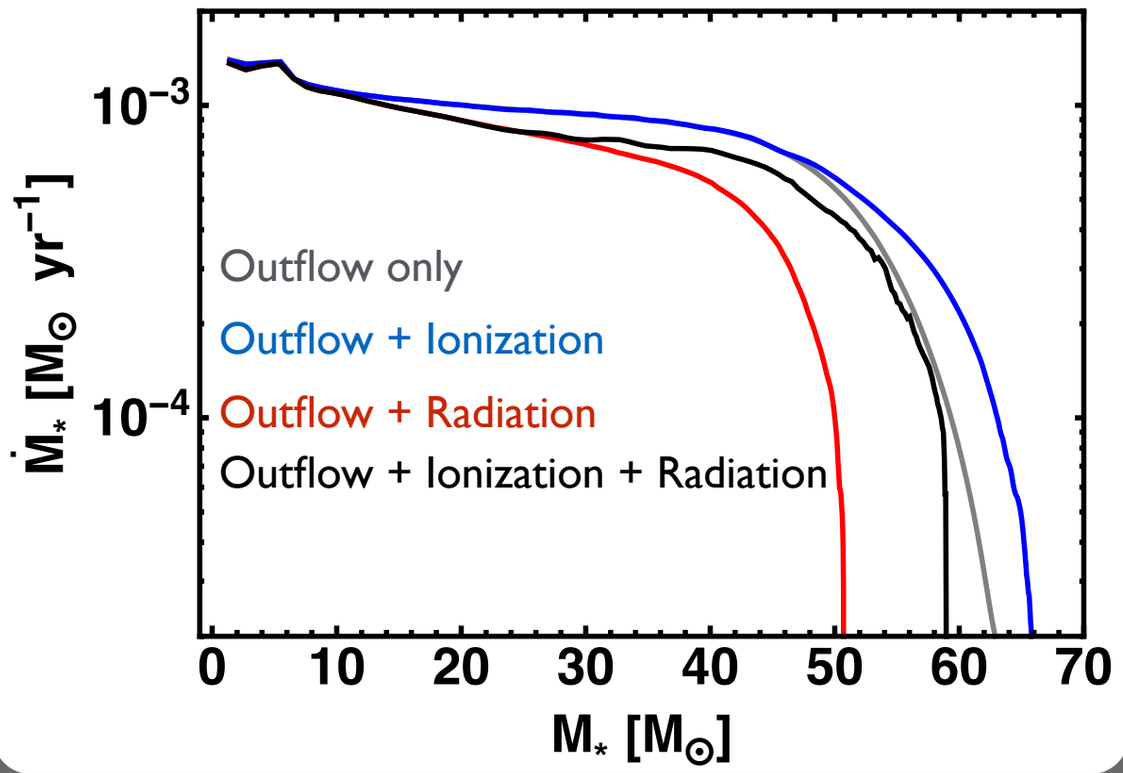
- Finite 100 $M_\odot$ pre-stellar core (R = 0.1 pc)
- „Infinite“ 1000 $M_\odot$ mass reservoir (R = 1 pc)
  = 100 $M_\odot$ pre-stellar core fed by large scales



Kuiper & Hosokawa (2018)

Radiation & Photoionization Feedback

Finite Mass Reservoir

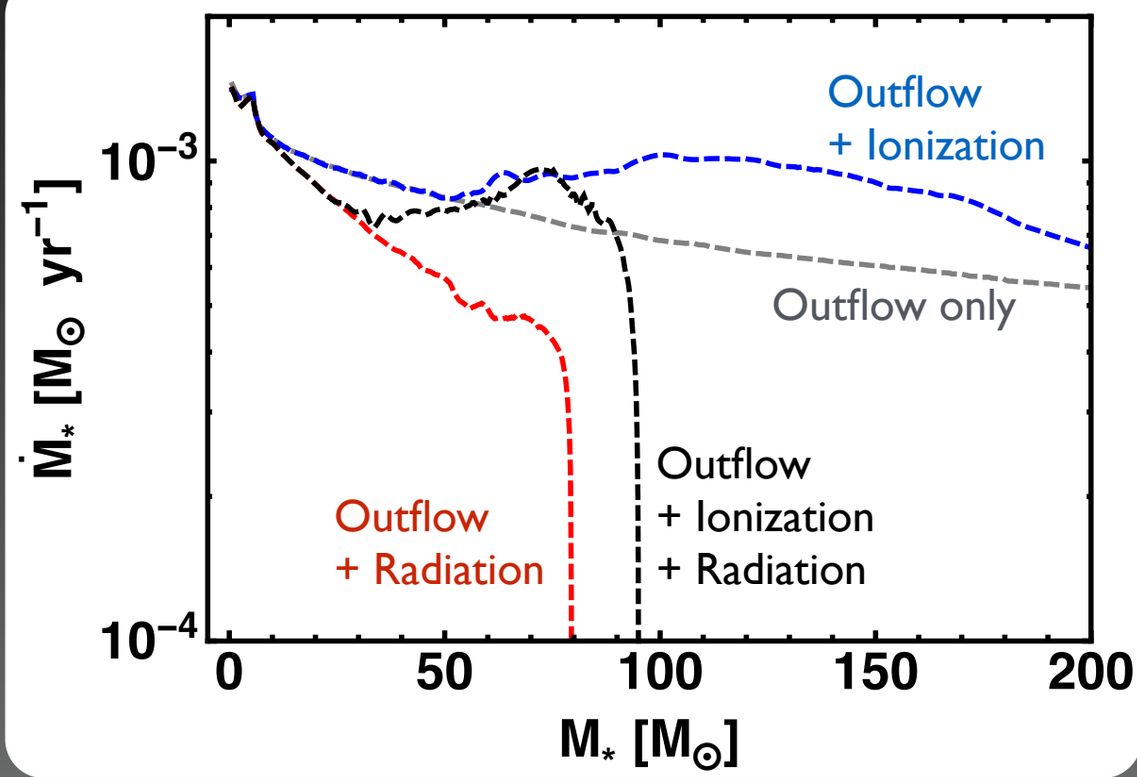


Controlled by mass loss of the reservoir:

✔ Outflows

→ **see also Talk by Anna Rosen**

"Infinite" Mass Reservoir



Controlled by radiation forces:

✘ Outflows

✘ Photoionization

✔ Radiation Forces

→ **see also Talk by Kei Tanaka**

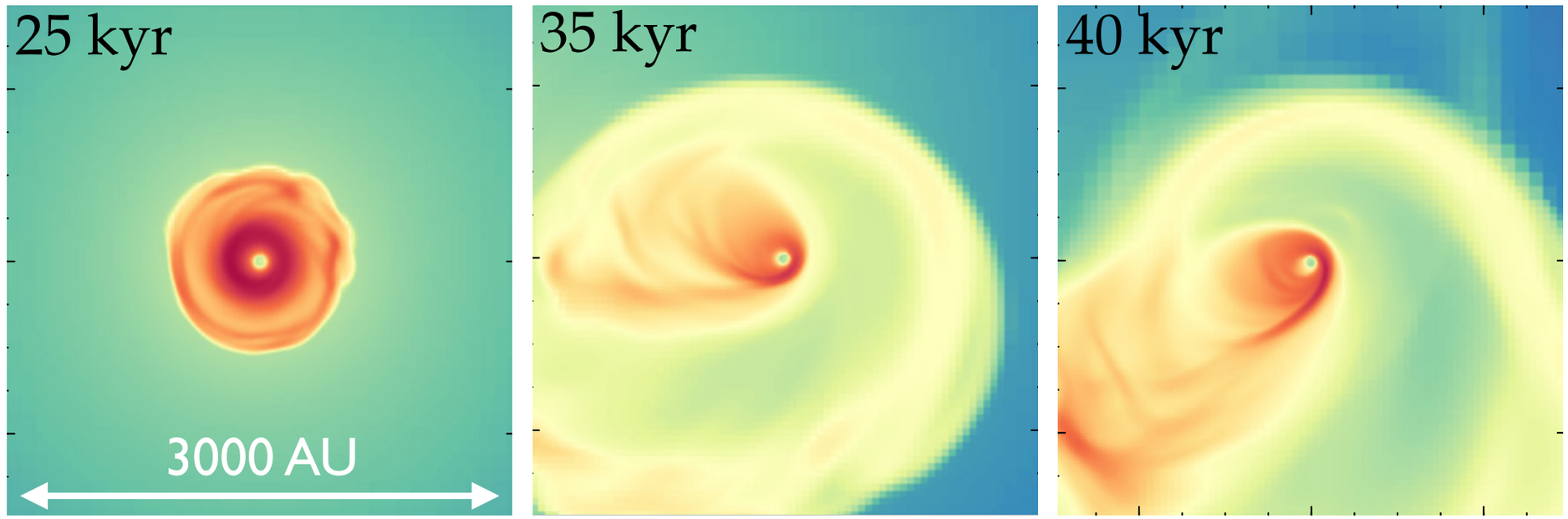
Kuiper & Hosokawa (2018)

Disk Fragmentation

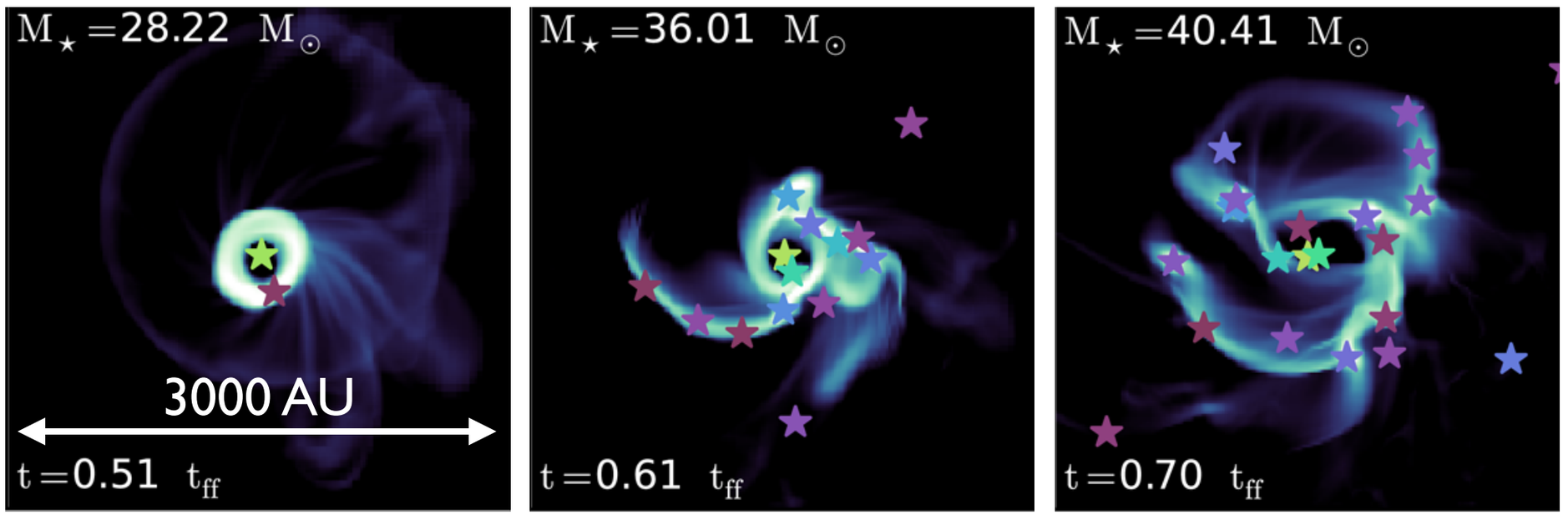
- Do massive accretion disks undergo fragmentation?
- Does disk fragmentation prevent/enhance stellar accretion?
- Does disk fragmentation yield multiplicity?

Previous Disk Fragmentation Studies

Klassen, Pudritz, Kuiper et al. (2016)



Rosen et al. (2016)



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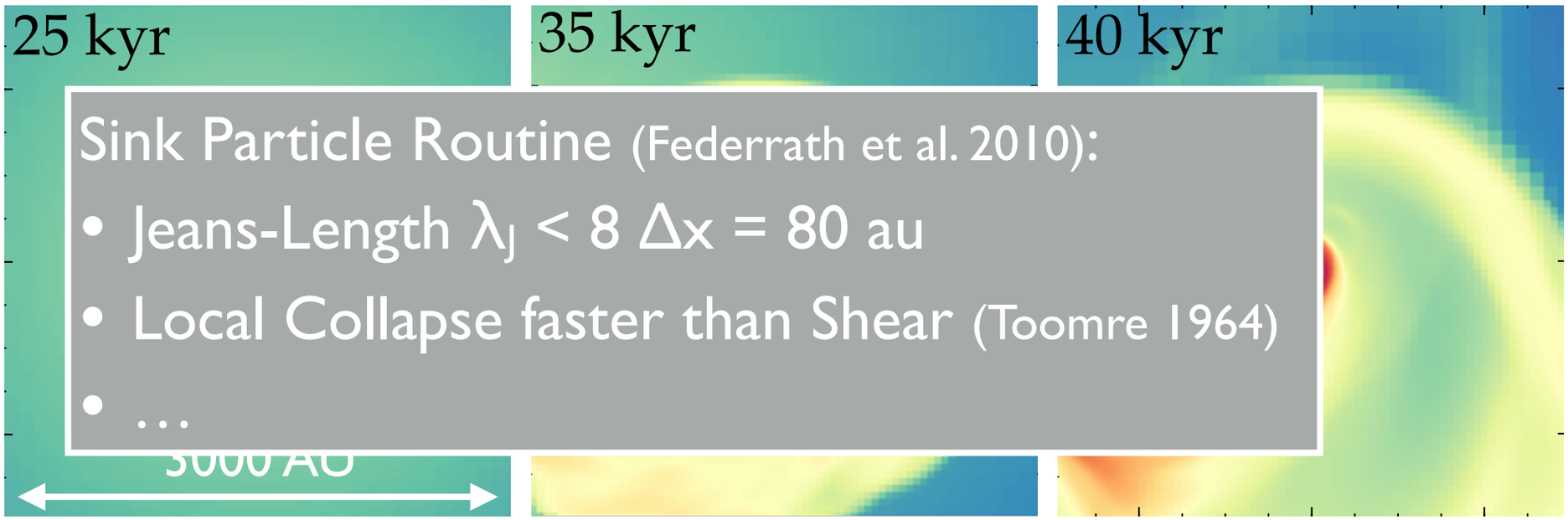

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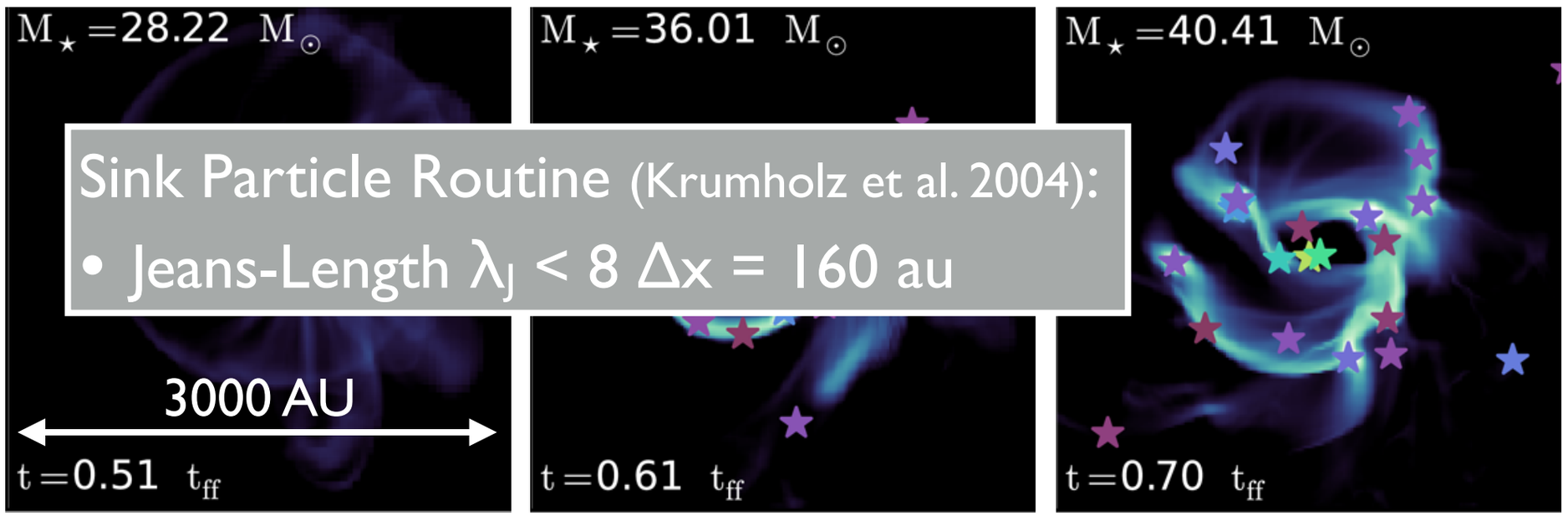


Disk Fragmentation

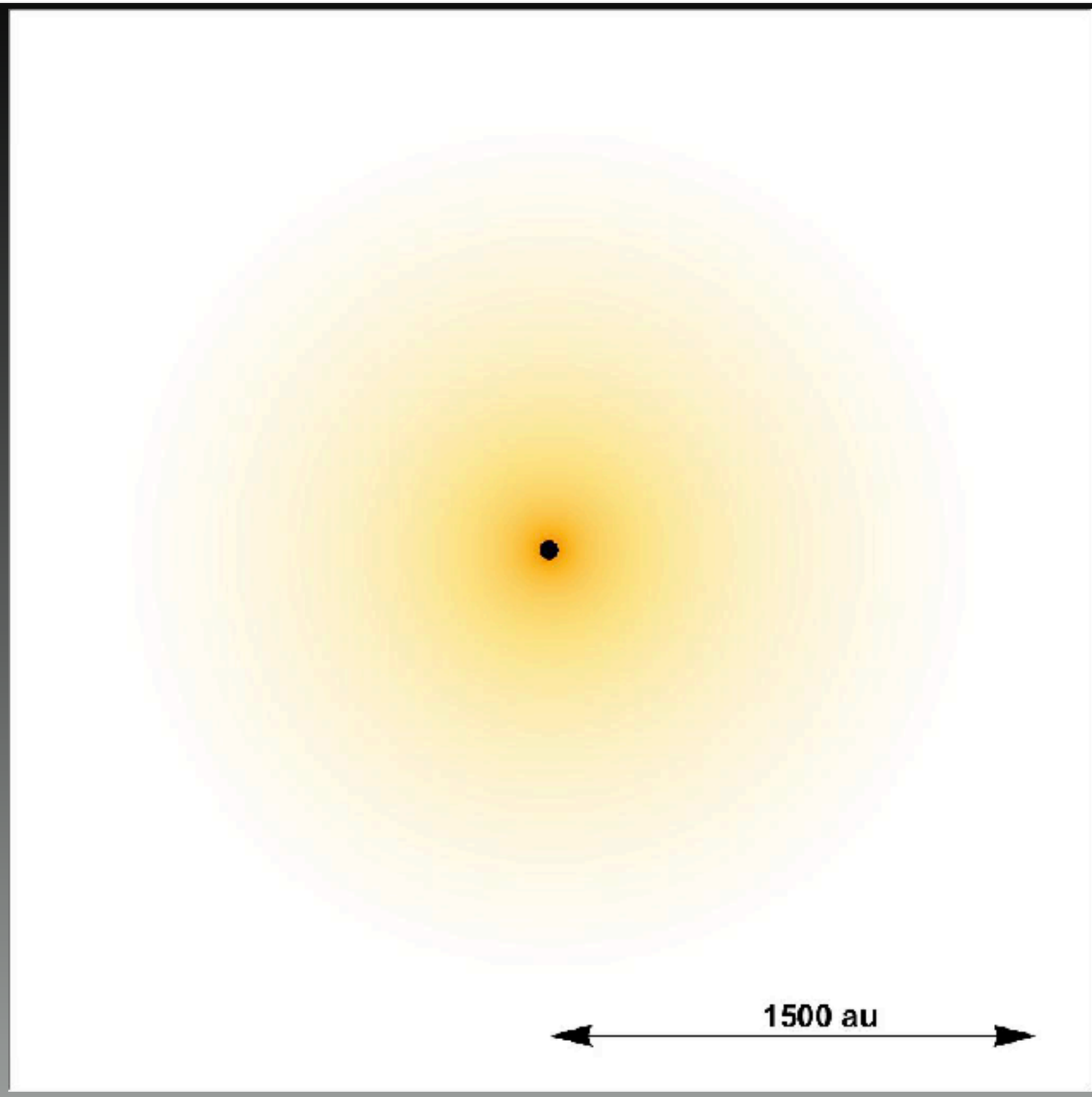
No sink particles!

- spatially resolve the disk's pressure scale height & Jeans length
- log-radial + cos-polar grid:
  - 4.4 x 10^7 grid cells total
  - 10^7 grid cells in the disk

    (dynamic range $V_{disk} / V_{cloud} \sim 10^{-5}$)

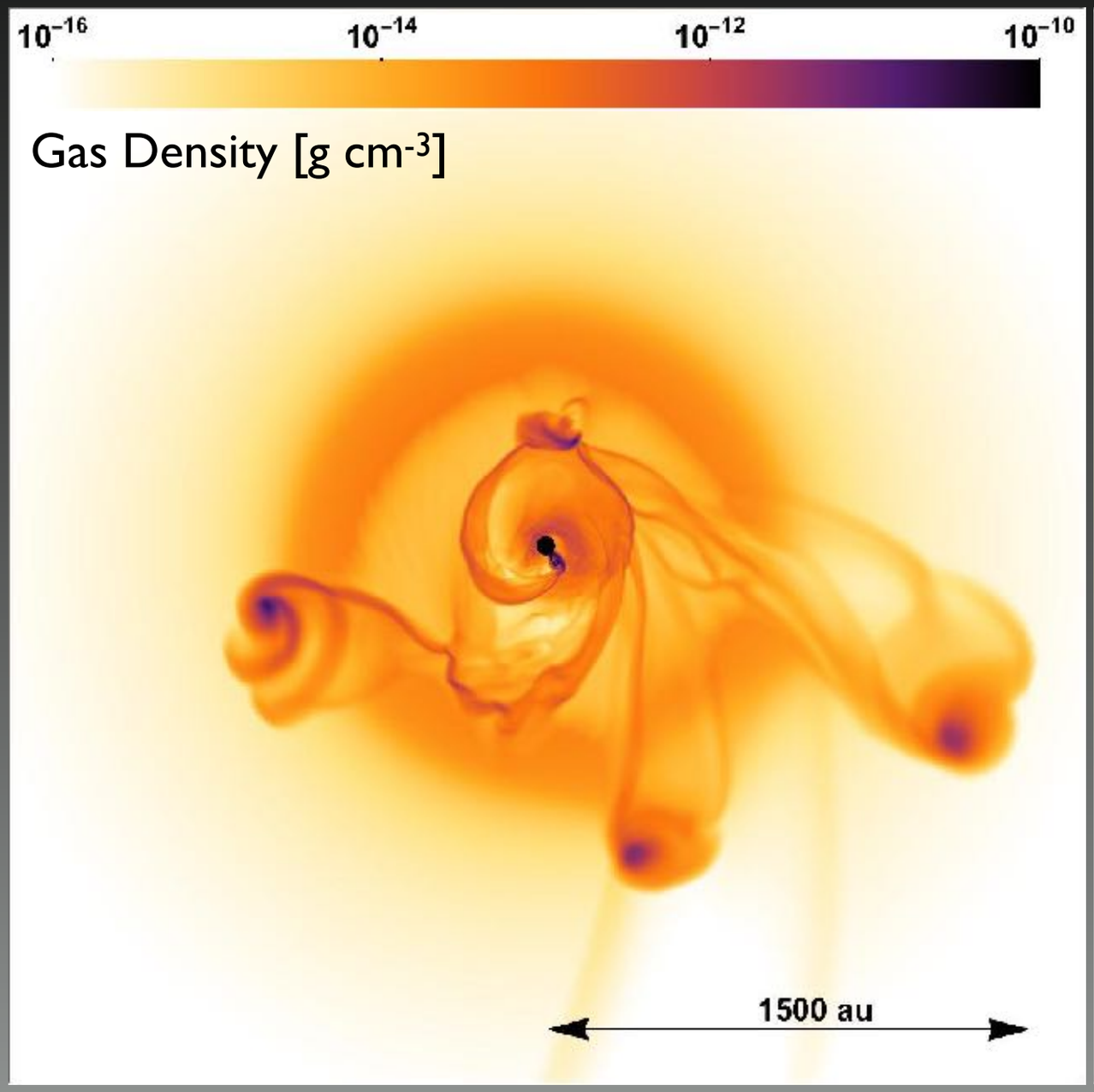
naturally includes ...

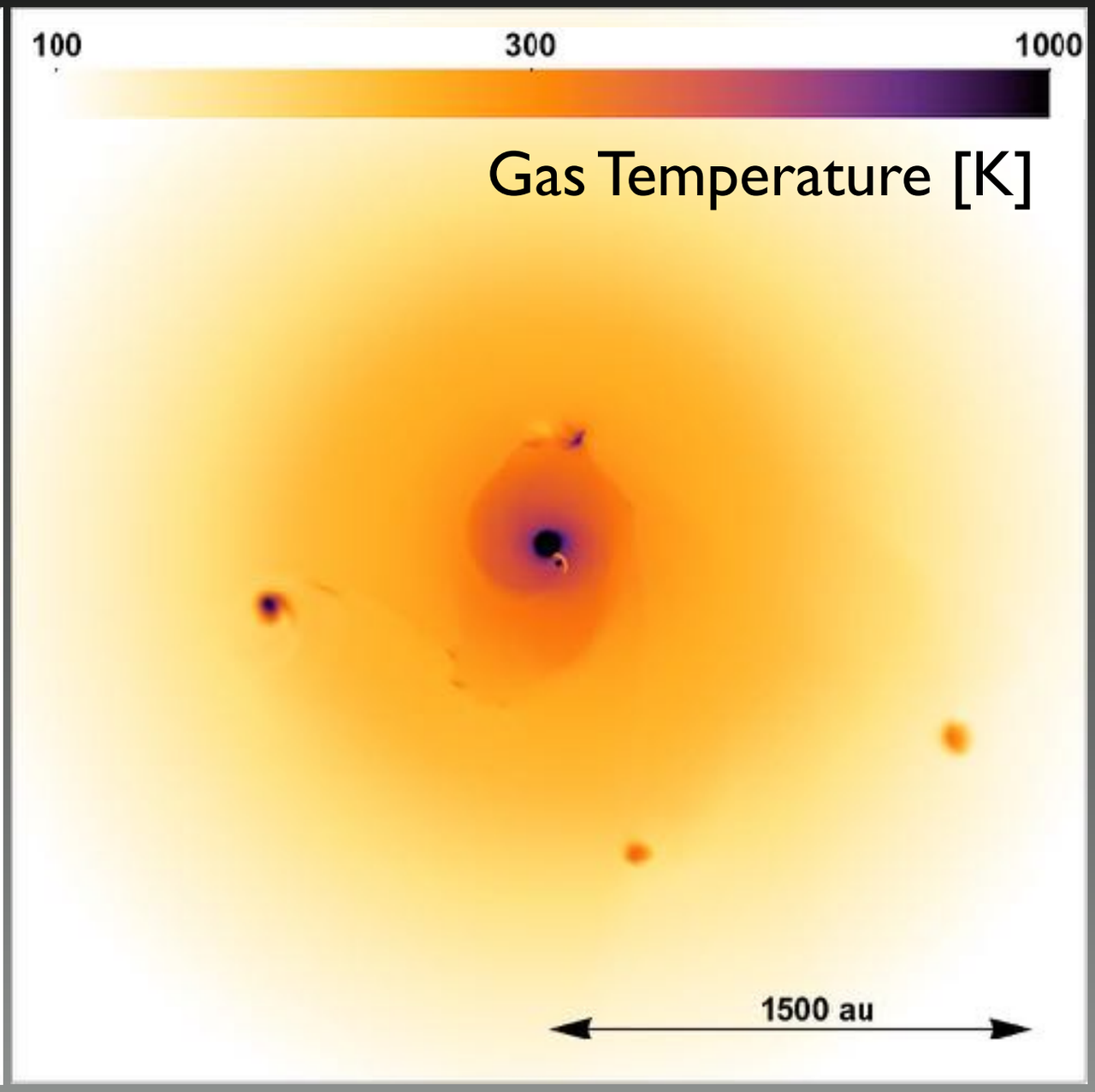
- fragmentation / local collapse
- shear
- migration / grav. torques
- merging
- orbital interaction
- mass transfer



Kuiper et al. (in prep.); Ahmadi, Kuiper et al. (in prep.)

Fragmentation & Star Formation

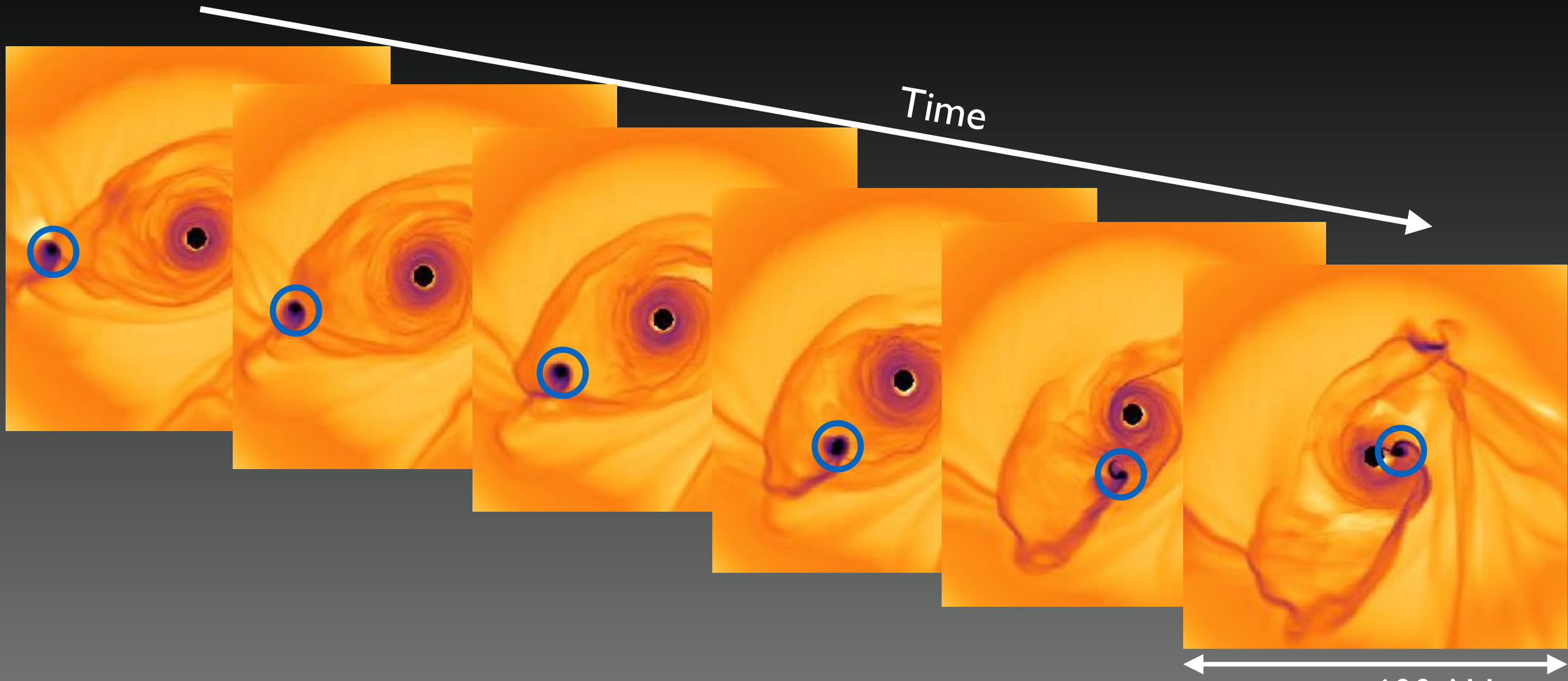




→ see Poster 1C by Aida Ahmadi

→ see Talks by Katharine Johnston & Henrik Beuther

Migration



- Accretion Bursts! (Meyer, Vorobyov, Kuiper, Kley 2017)

  observational counterpart: Caratti o Garatti et al. (2016) & Stecklum et al. (2017)

→ see Poster 7C by Bringfried Stecklum

- Formation of Spectroscopic Binaries! (Meyer, Kuiper, Kley, Johnston, Vorobyov 2018)

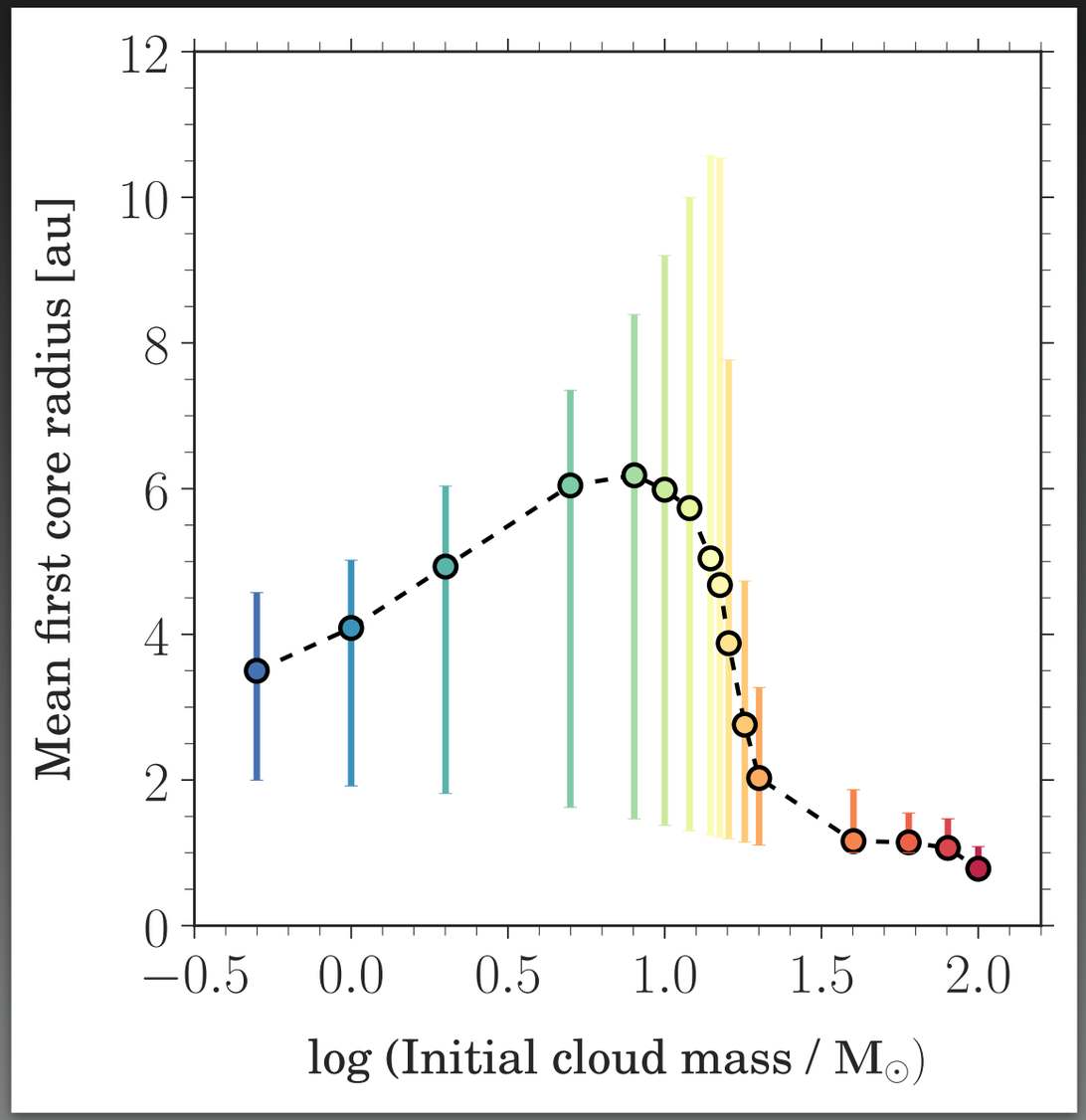
→ see Talk by Stefan Kraus

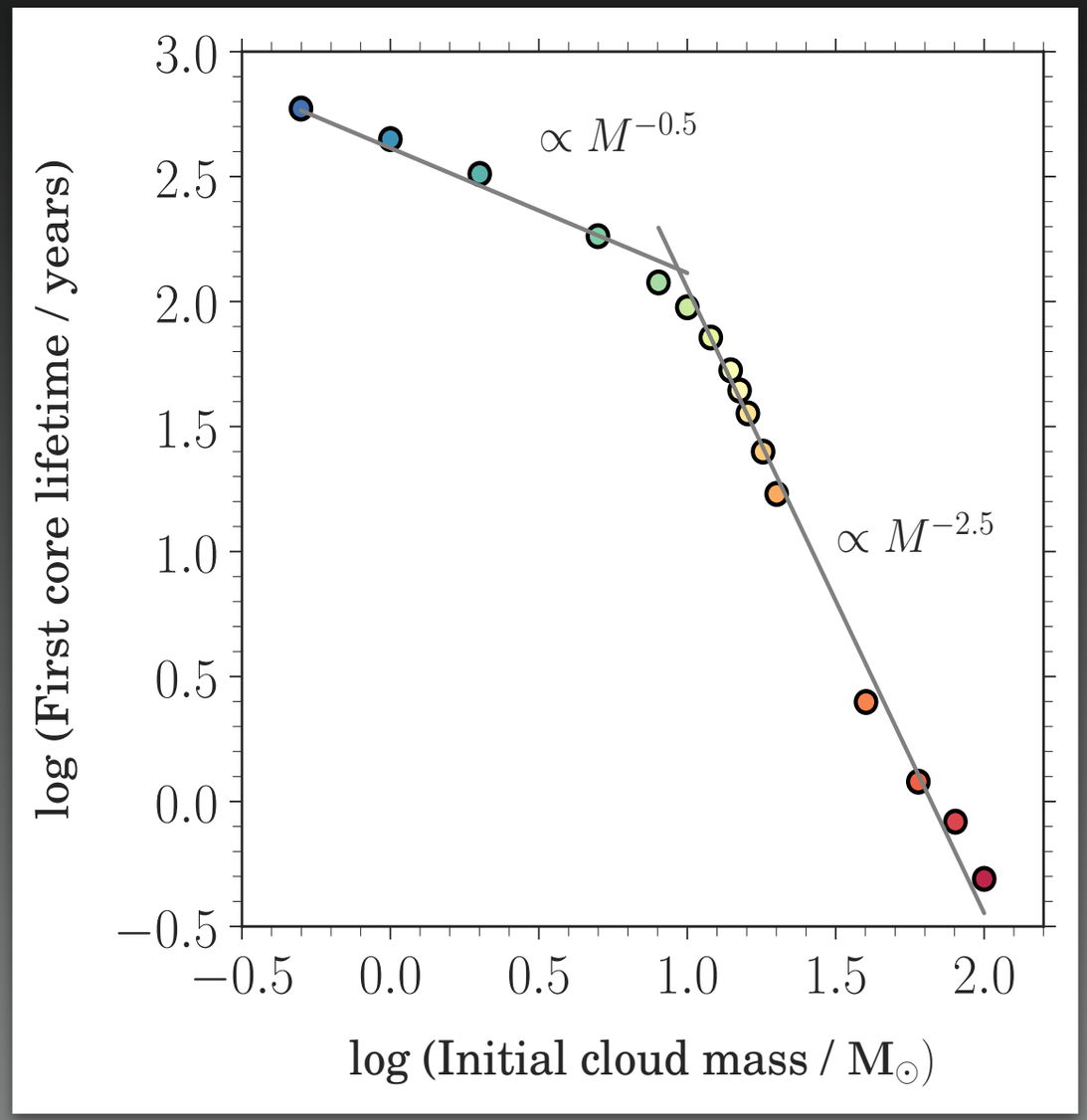
First Larson Cores

- Mass dependence of first Larson core properties
- How important is rotation?
- How important are magnetic fields?

Bhandare, Kuiper et al. (2018)

First Larson Cores





→ see Poster 3A by Asmita Bhandare

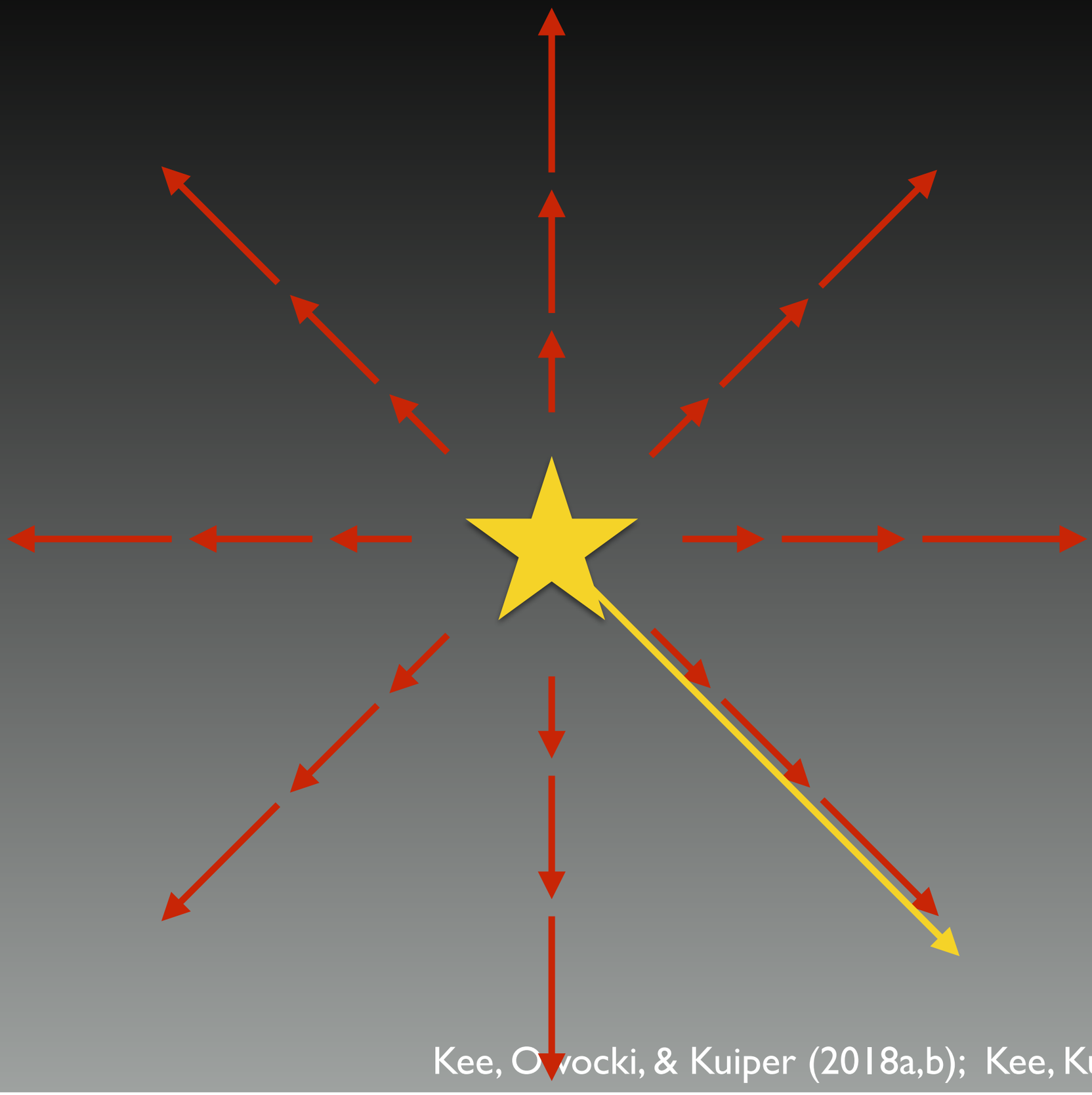
Bhandare, Kuiper et al. (2018)

UV-Line Scattering Feedback

- How is the gas accreted from the disk onto the stellar surface?
- How important is feedback on these smallest accretion scales?
- Boundary layer vs. magneto-spheric accretion?

Kee, Owocki, & Kuiper (2018a,b); Kee, Kuiper et al, in prep.

UV-Line Scattering Feedback



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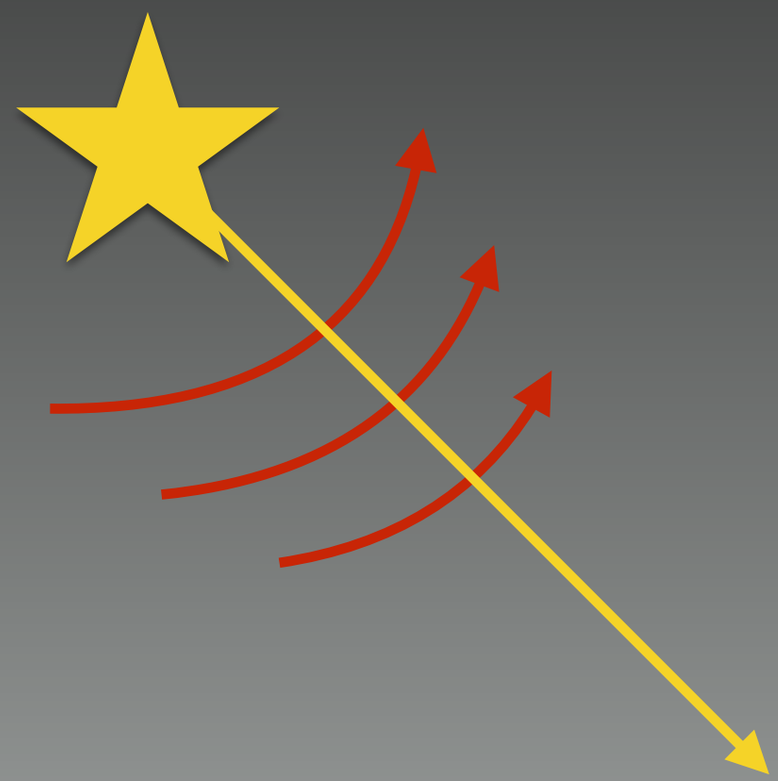

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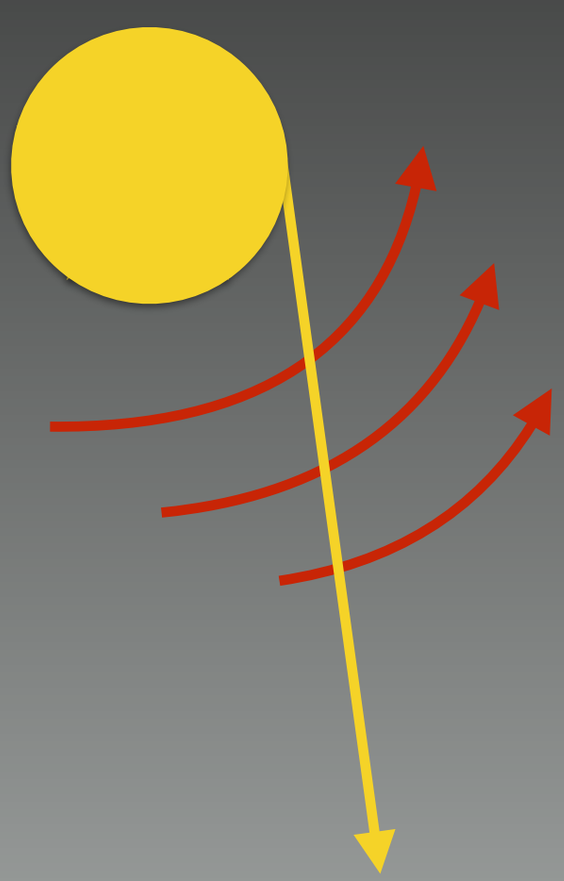

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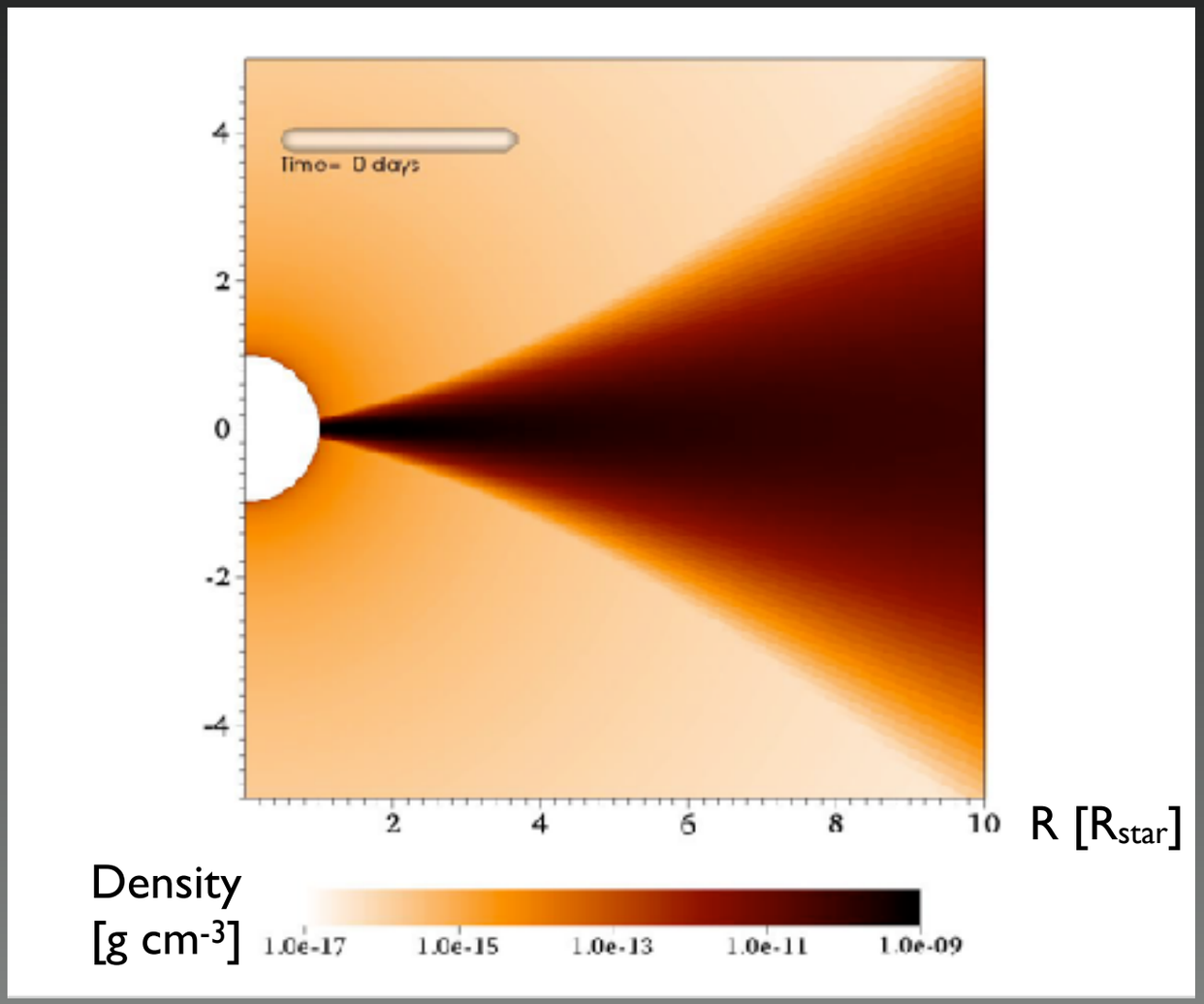
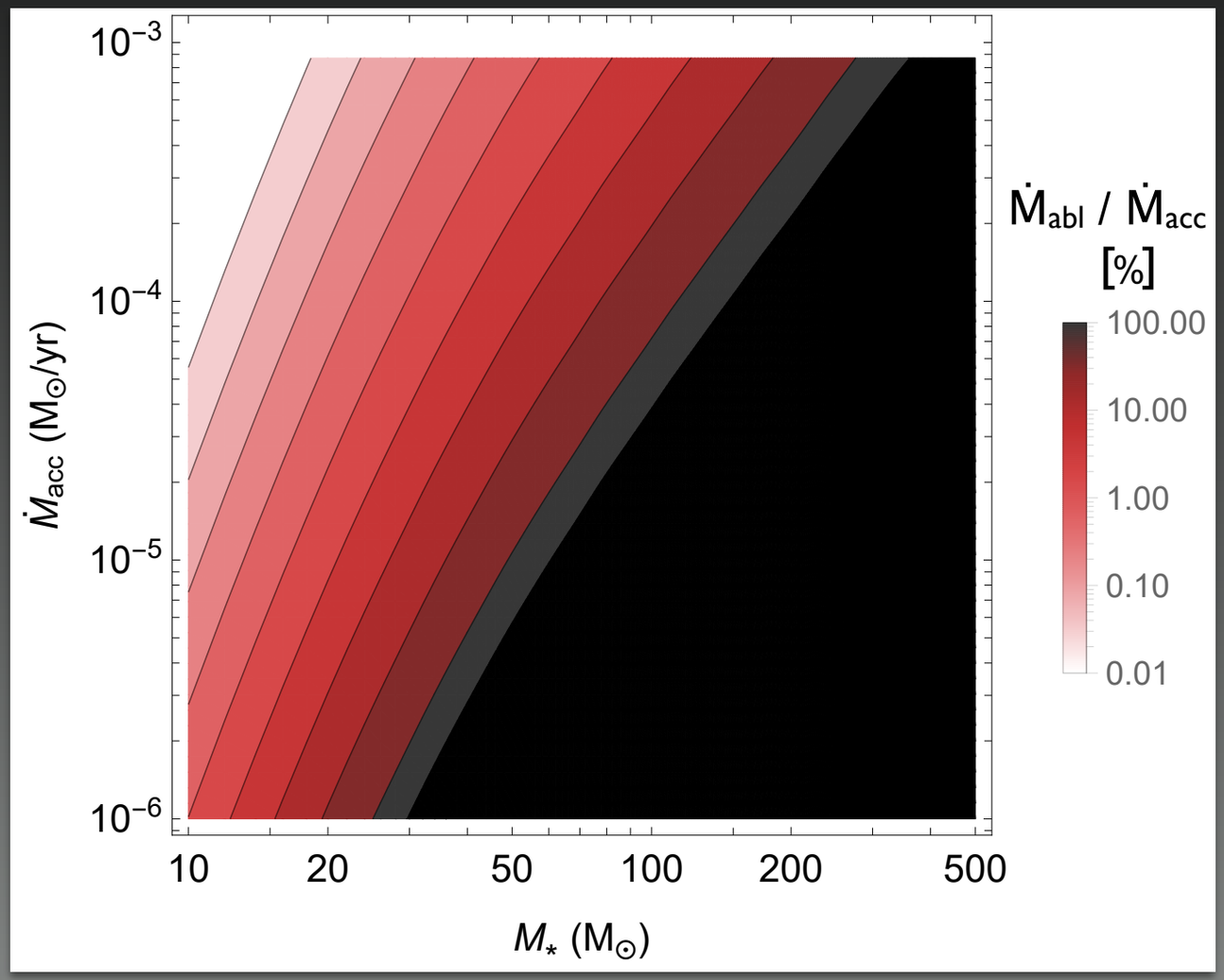


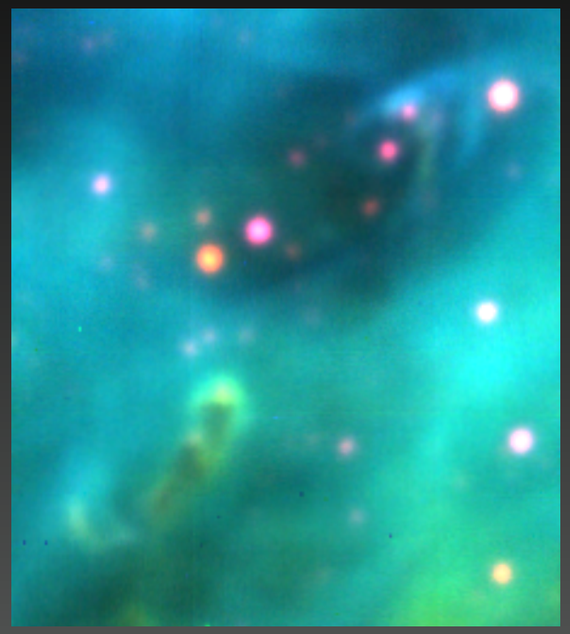


→ see Poster 2C by Nathaniel Dylan Kee

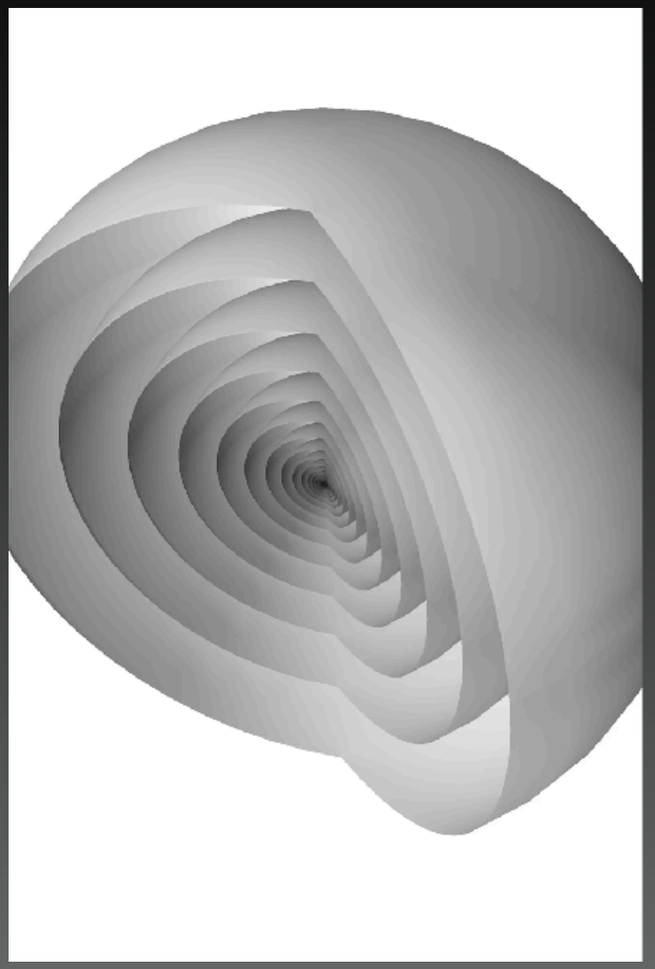
Kee, Owocki, & Kuiper (2018a,b); Kee, Kuiper et al, in prep.

Summary / Overview

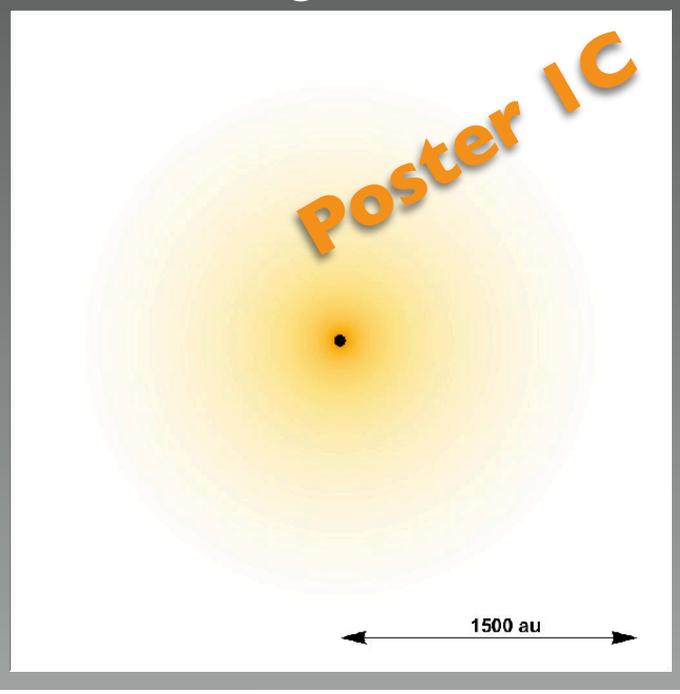
MHD-driven Jets & Outflows



Radiation & Photoionization Feedback



Disk Fragmentation



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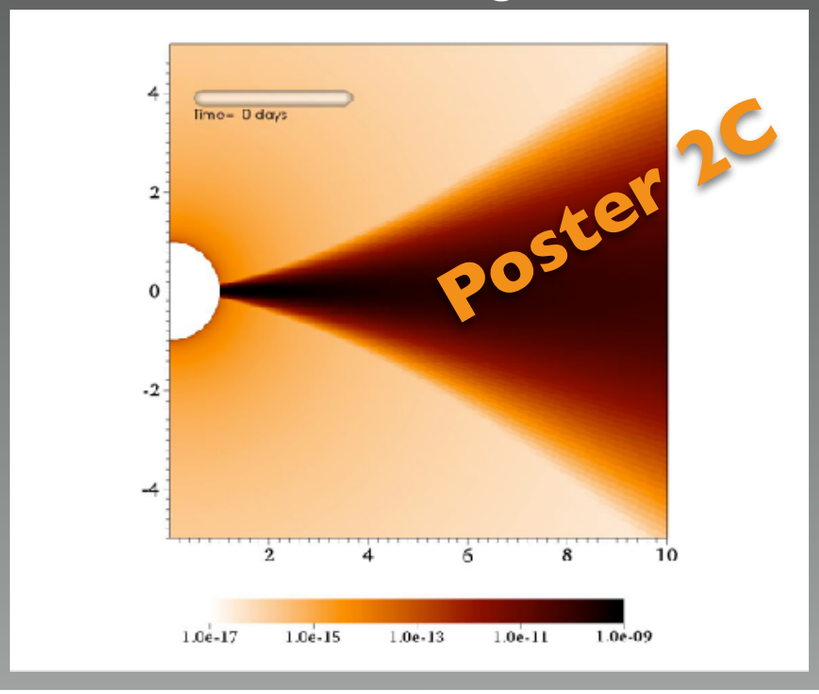
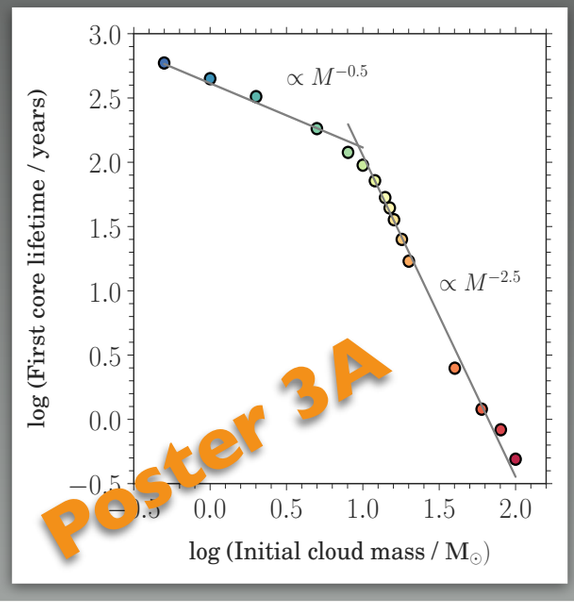


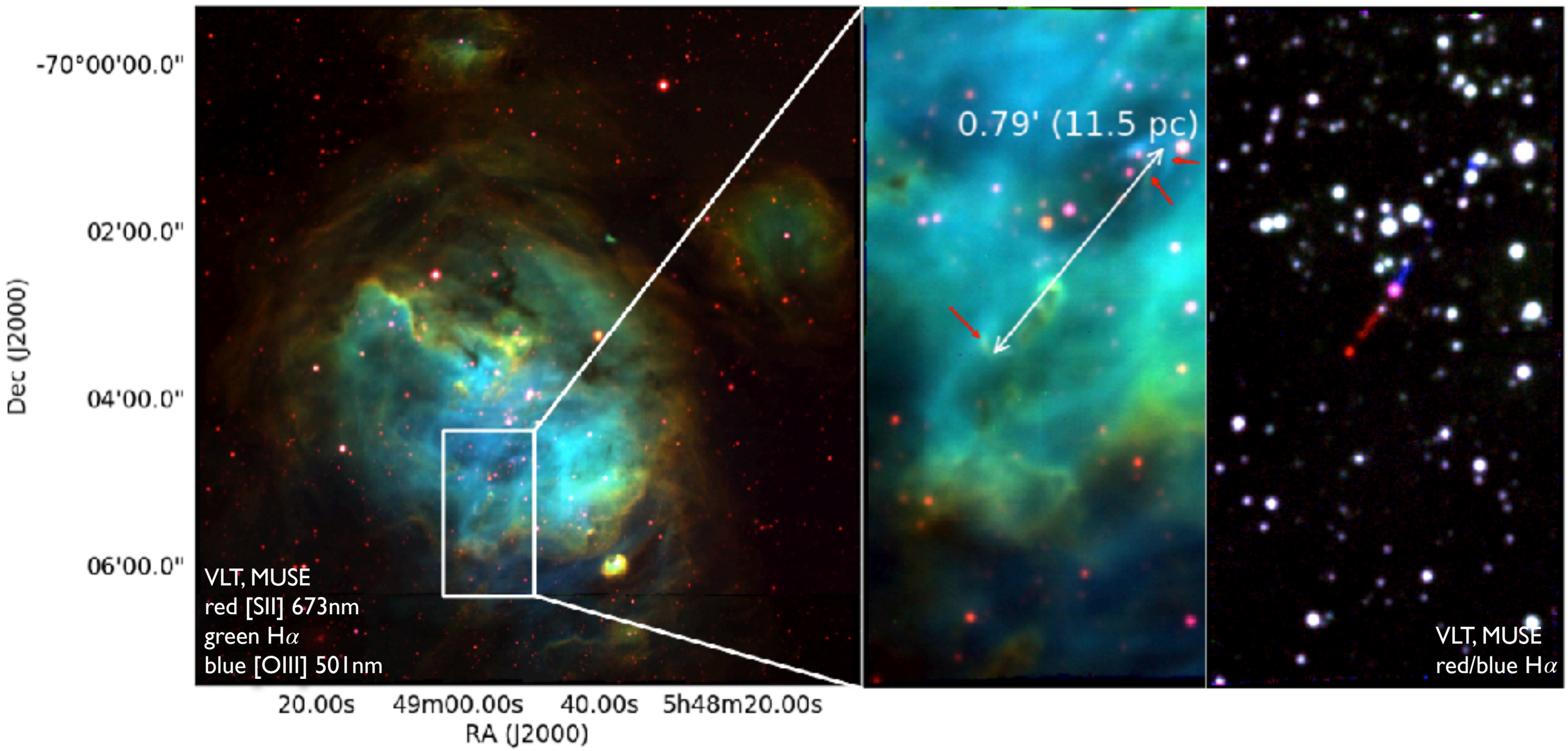
First Larson Cores



A parsec-scale Jet from a Massive Young Star

Large Magellanic Cloud - N180

HH 1177



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