Protostellar Outflows and Radiation Feedback in Massive Star Formation

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The Early Phases of Star Formation (EPoS 2014)
June 3, 2014

Feedback in Massive Star Formation

- Feedback mechanisms in *chronological* order:
  - Protostellar Outflows
  - Radiation Pressure feedback

    „Early Phases“
  - Ionization feedback
  - Stellar winds / mass loss
  - Supernova

- How to form (the most) massive stars?
  - *Core* formation: Fragmentation problem
    - Radiative heating & Magnetic Fields
    - Global collapse & dynamic feeding
  - *(Proto-)Star* formation:
    - Radiation Pressure problem
    - Disk Formation
    - Stellar Evolution
    - Protostellar Outflows

„Small Scales“

The Radiation Pressure Problem

Forces:

F_{grav} ← ● → F_{rad}

(Proto)-Star — Interstellar Medium

Static force balance: F_{rad} > F_{grav} $\quad M_* \rightarrow \sim 20\ \mathrm{M}_\odot$

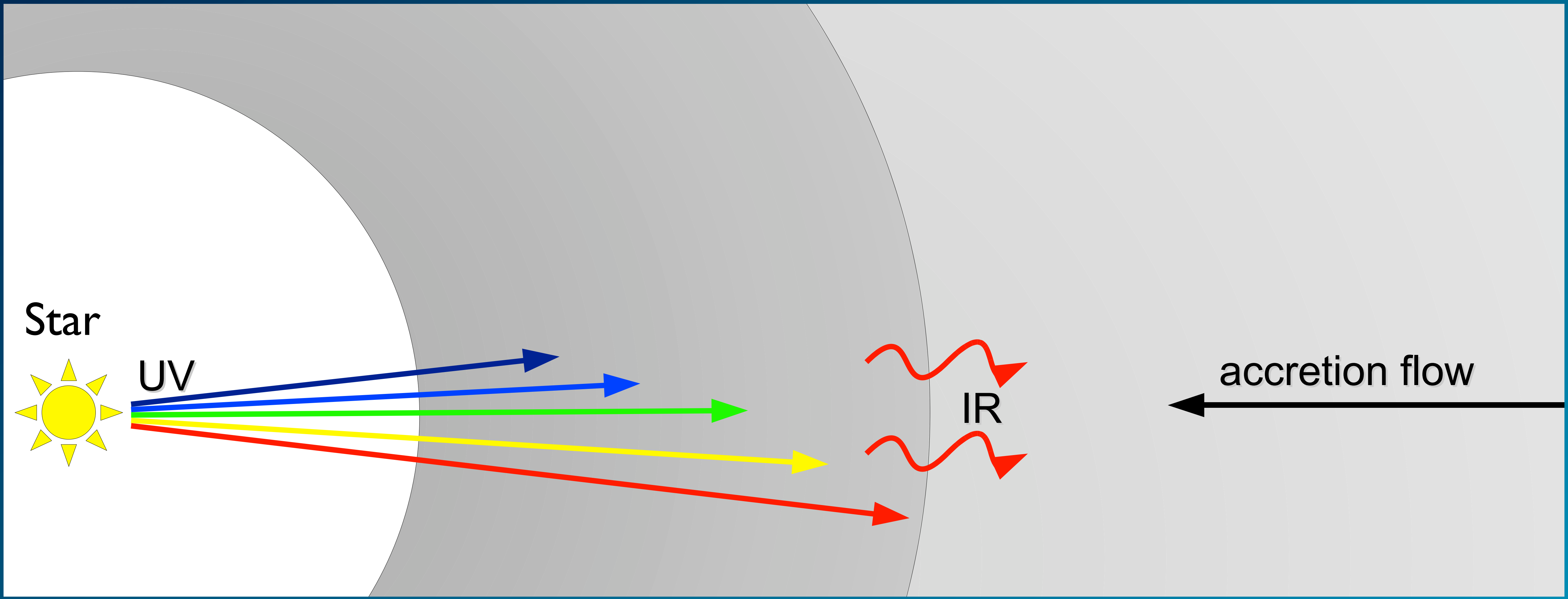
Dynamical 1D RHD Collapse: Accretion stalled $\quad M_* \rightarrow \sim 40\ \mathrm{M}_\odot$

Observed upper mass limit of stars $\quad M_* \rightarrow \sim 150\ \mathrm{M}_\odot$

Anisotropy of the Radiation Field

Nakano (1989)

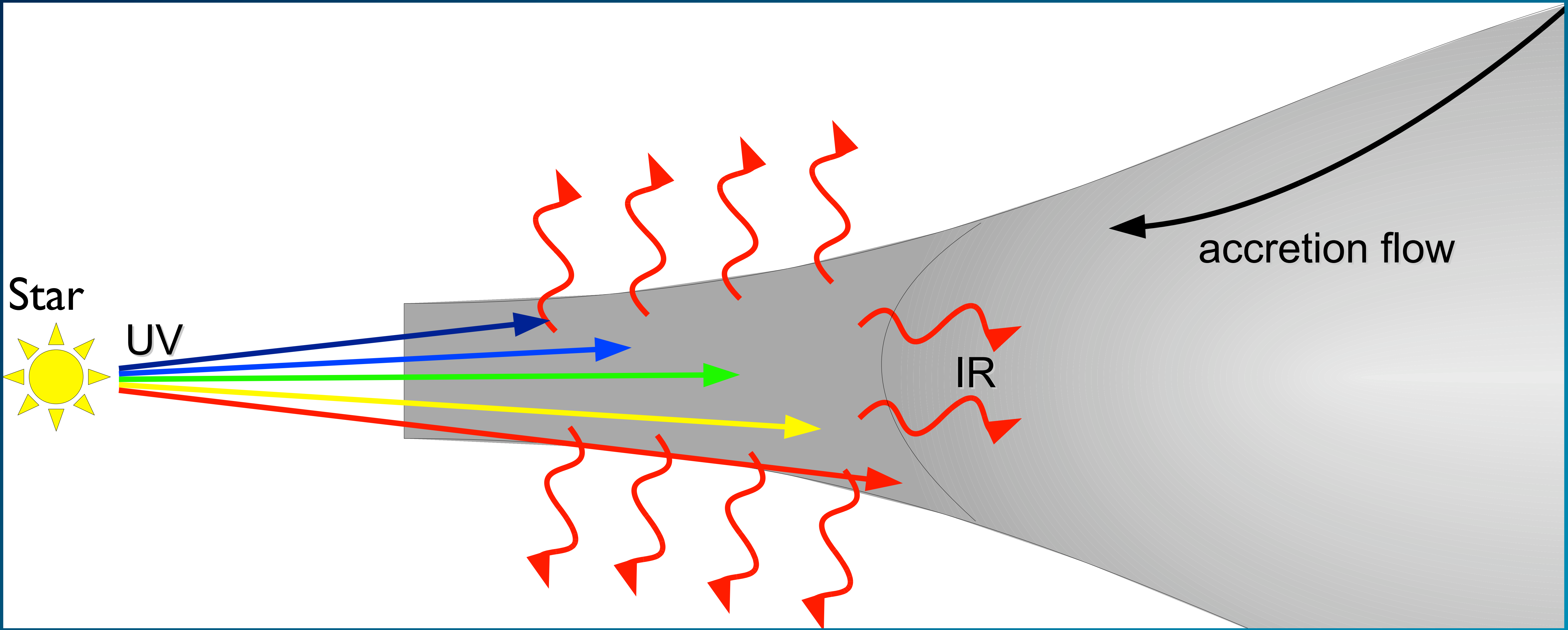
Spherical free-fall:



Anisotropy of the Radiation Field

Nakano (1989)

Disk accretion:



The Radiation Pressure Problem

Forces:

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Static force balance: $F_{rad} > F_{grav}$ $M_* \to \;\sim 20\ \mathrm{M}_\odot$

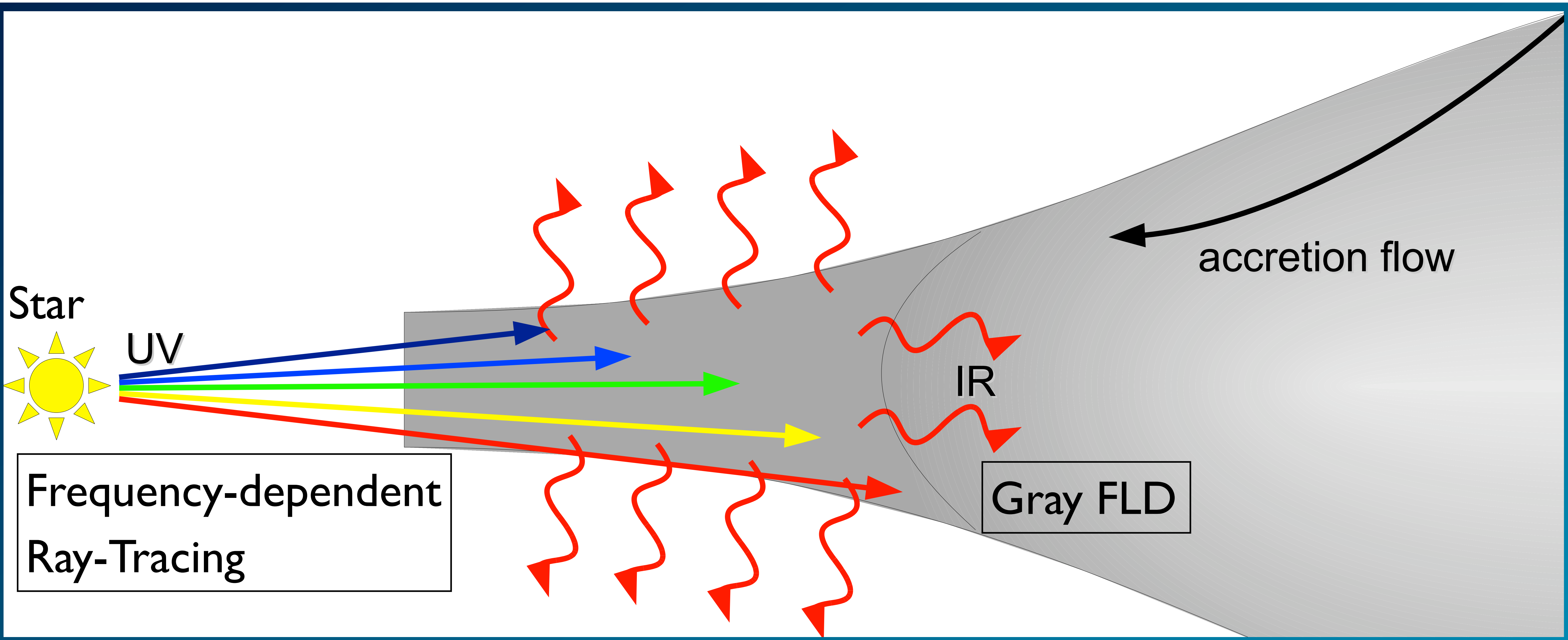
Dynamical 1D RHD Collapse: Accretion stalled $M_* \to \;\sim 40\ \mathrm{M}_\odot$

Dynamical 2D RHD (Yorke & Sonnhalter 2002): $M_* \to 43.0\ \mathrm{M}_\odot$

Dynamical 3D RHD (Krumholz et al. 2009): $M_* \to 41.5\ \mathrm{M}_\odot$

Observed upper mass limit of stars $M_* \to \;\sim 150\ \mathrm{M}_\odot$

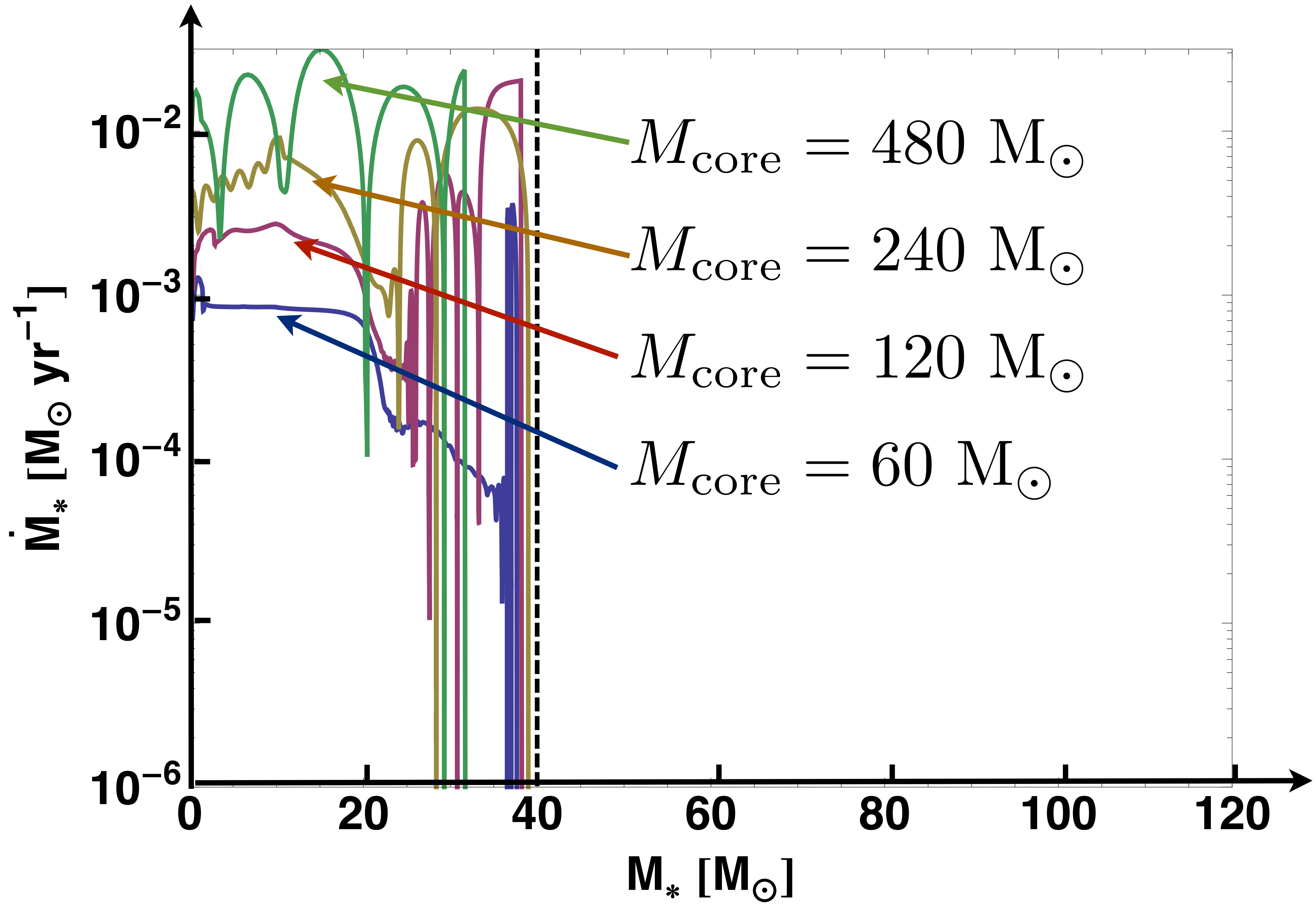
Numerics (adapted to the Problem)



Highlights:

- Fast and *accurate* 3D *Hybrid* Radiation Transport (***Kuiper*** et al. 2010, A&A)
- *Resolving* the disk's scale height (down to ~1 AU, convergence study!)
- Complete coverage of the *accretion phase* (10^5 ...10^6 yrs) for the first time
- First comprehensive scan of the *parameter space* (> 50 simulations published)

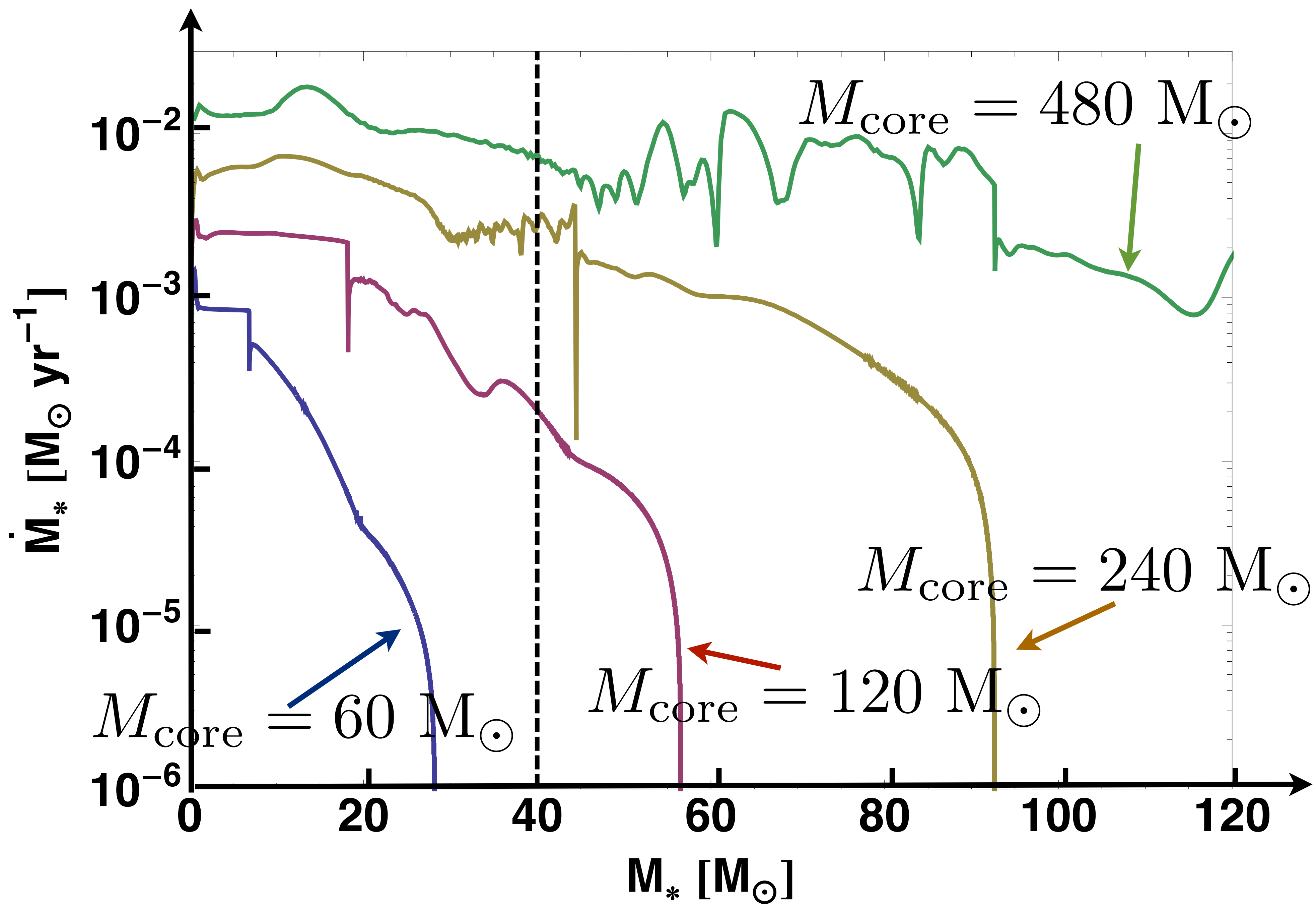
The Radiation Pressure Problem revisited



Kuiper et al. (2010), ApJ 722

- Reconstruction of the early 1D Models (e.g. Yorke & Krügel 1977)

Solution of the Radiation Pressure Problem!



Kuiper et al. (2010),
ApJ 722

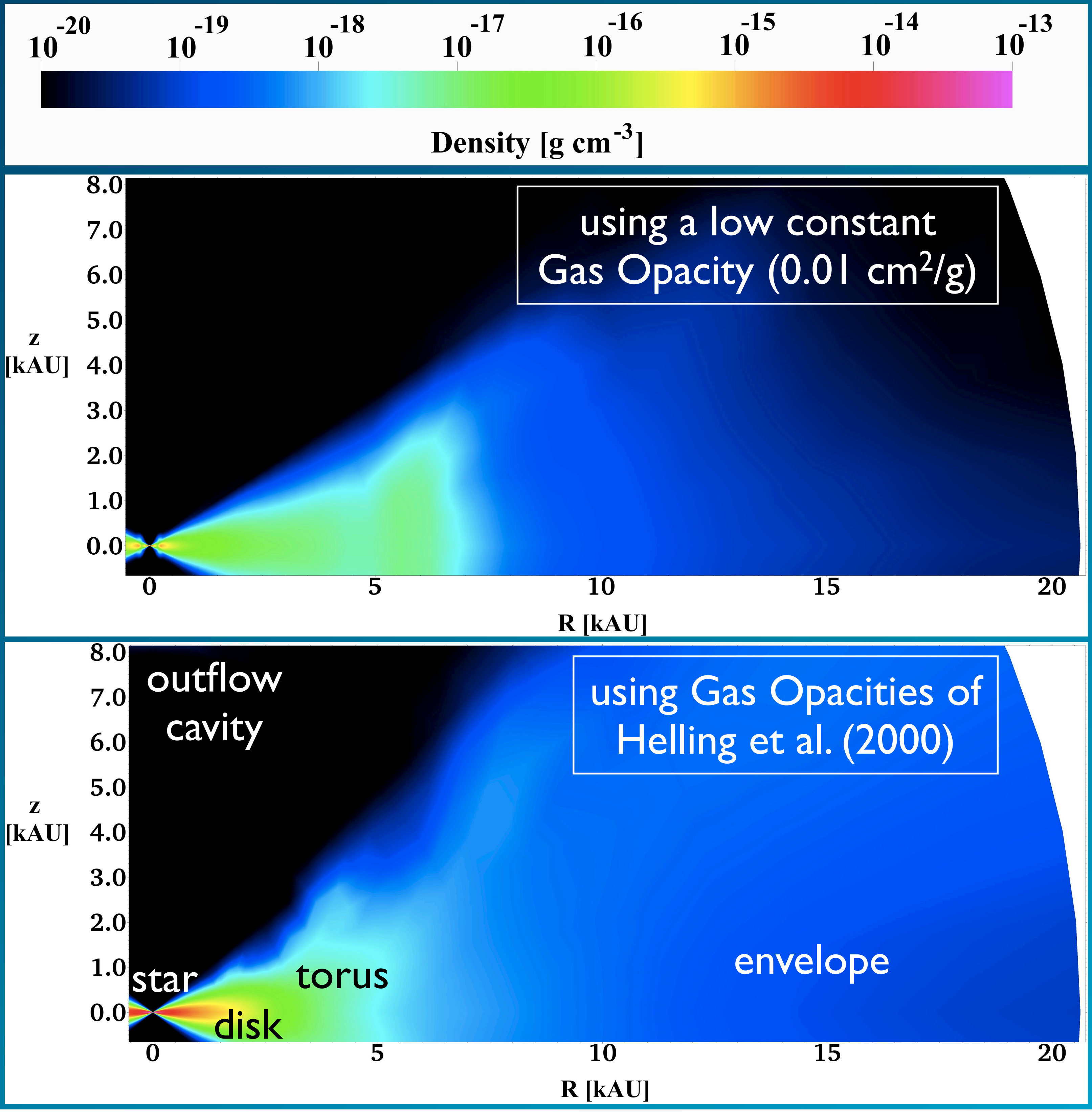
- *First* Simulations of the Formation of the most *Massive* Stars!
  - Resolving the Disk Scale Height (→Anisotropy of Radiation)
  - Accurate Treatment of the Stellar Irradiation Feedback

Optically thick gas (disks)

Results:

- Inner dust-free gas disk is *optically thick*
  - Further *shielding* of the radiative acceleration on large scales
  - Sustained *feeding* of the accretion disk
  - Enhancement of the *flashlight effect* / anisotropy of thermal radiation field

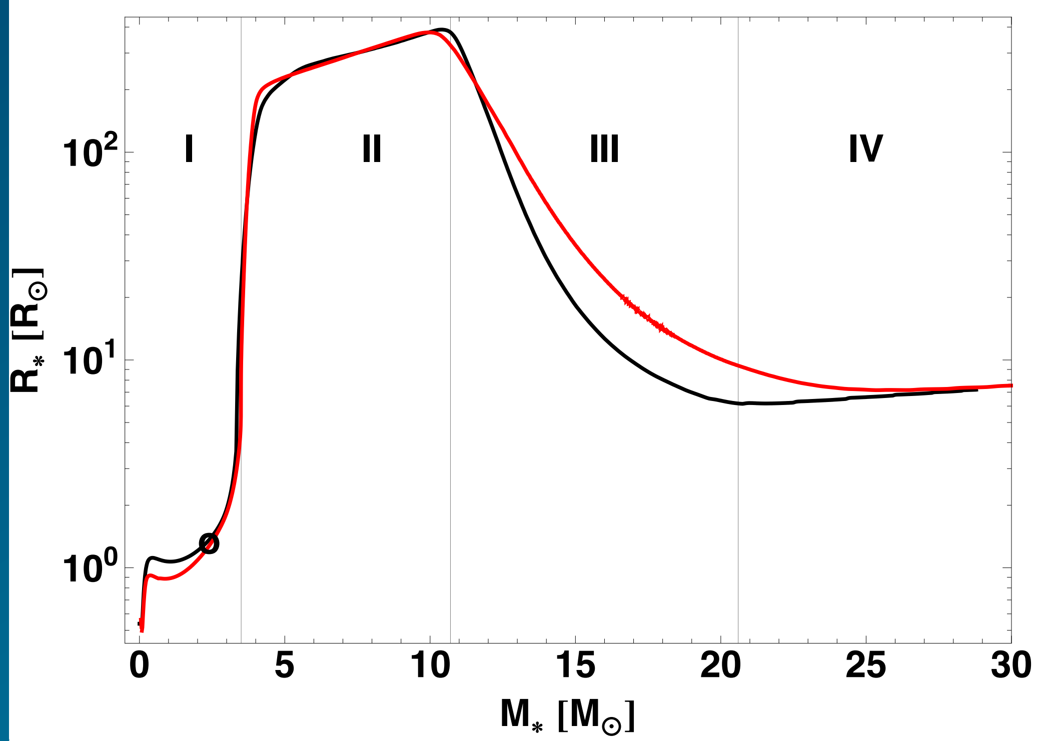
Kuiper & Yorke (2013a), ApJ 763

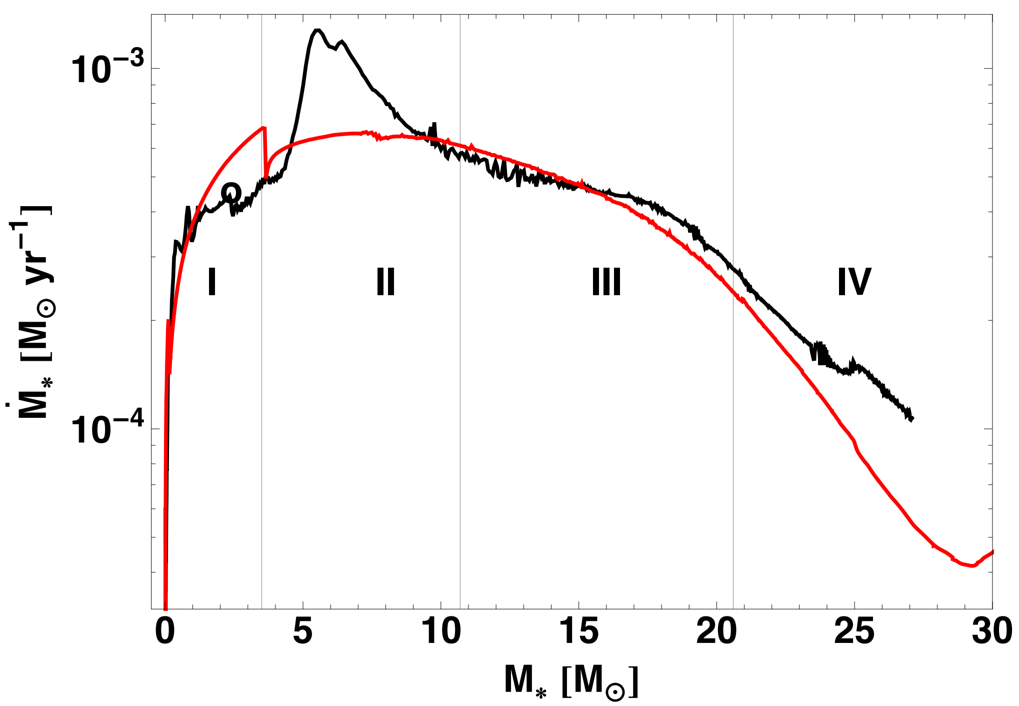


(Proto-) Stellar Evolution

<u>Results:</u>

- Robust features / phases (of all runs):
  - I. Initially $L_{\rm acc} \gg L_*$
  - II. *Bloating* phase of Proto-Star
  - III. Transition to zero-age main sequence
  - IV. Main sequence evolution
- Diverse features on *small timescales* $t \leq 5$ kyr
  - *Proto-Star - Disk* interaction





Kuiper & Yorke (2013), ApJ 772

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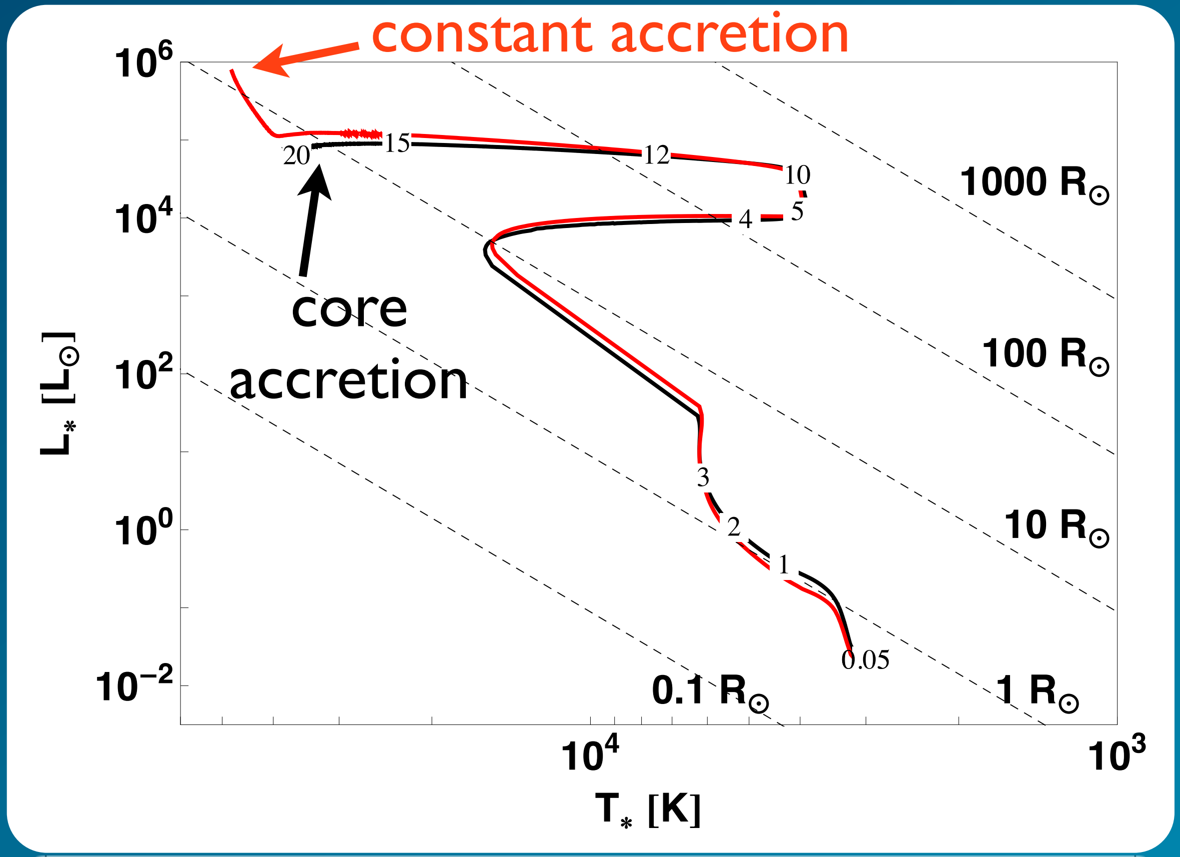
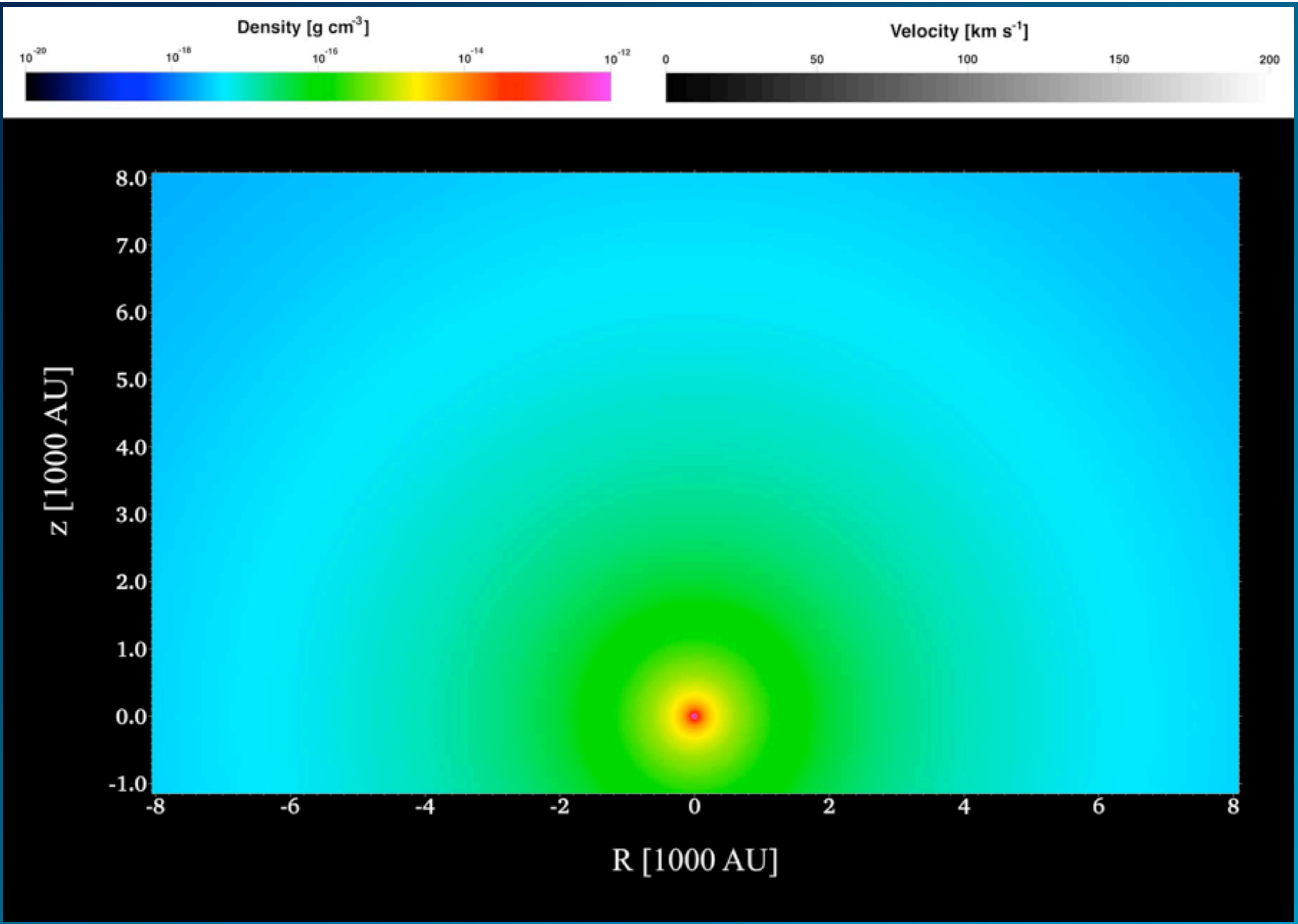
- Diverse features on *small timescales* $t \leq 5\ \rm kyr$
  - *Proto-Star - Disk* interaction
- Evolution on *larger timescale* similar to tracks assuming constant accretion



Kuiper & Yorke (2013), ApJ 772

Investigating 3D Effects

Protostellar Outflows



Kuiper, Yorke, & Turner (submitted to ApJ)

Protostellar Outflows

Numerical approach:

- Disk Formation yields MHD driven Outflows
- Inject Outflow ‚artificially' (without computing MHD)
- Adopt basic injection equations from Cunningham et al. (2011), based on Matzner & McKee (2000)

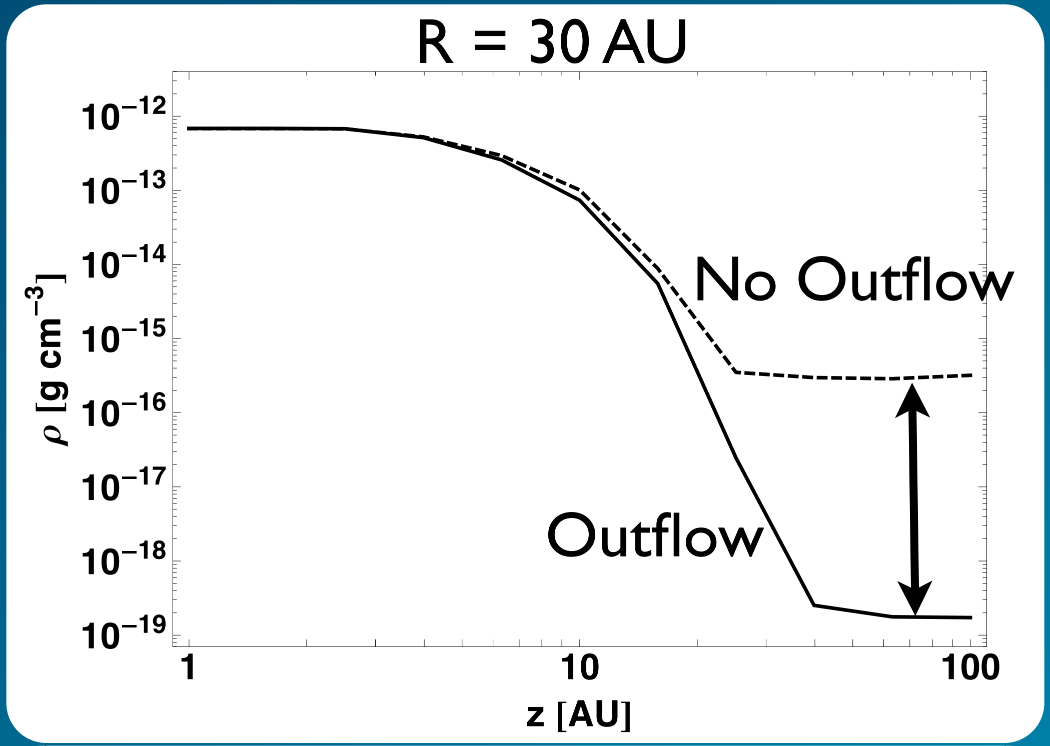
- Differences:
  - *Long-term* evolution (7 instead of 0.8 free-fall times!)
    - ▸ *Radiation Pressure* feedback phase
  - *Scale Height* of the accretion disk is spatially resolved
    - ▸ Kinematic Feedback from *Outflow* onto *Disk Accretion Flow*

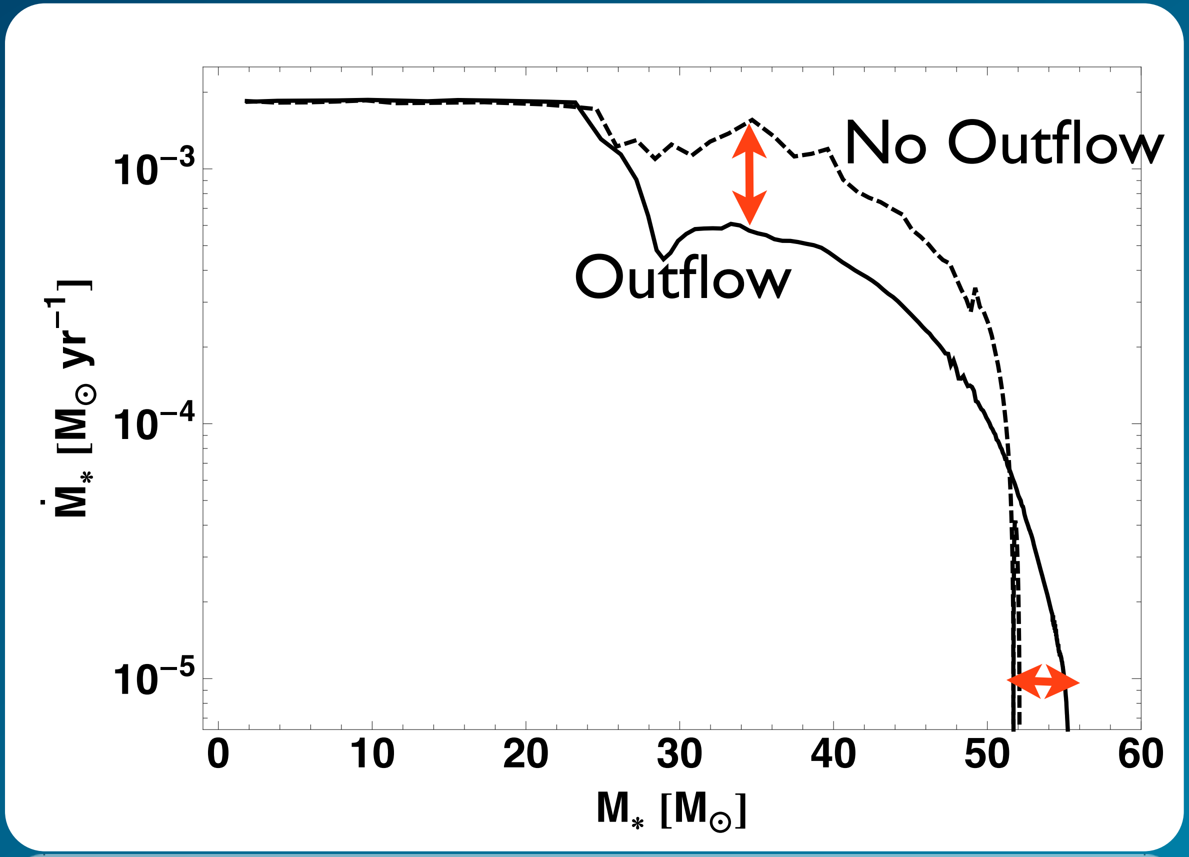
Kuiper, Yorke, & Turner (submitted to ApJ)

Protostellar Outflows

<u>Results:</u>

- *Kinematic* feedback
- ▸ Accretion rate decreases
- Enhancement of the *Disk's* Flashlight Effect
- *Core* Flashlight Effect due to global anisotropy
- ▸ Accretion epoch increases





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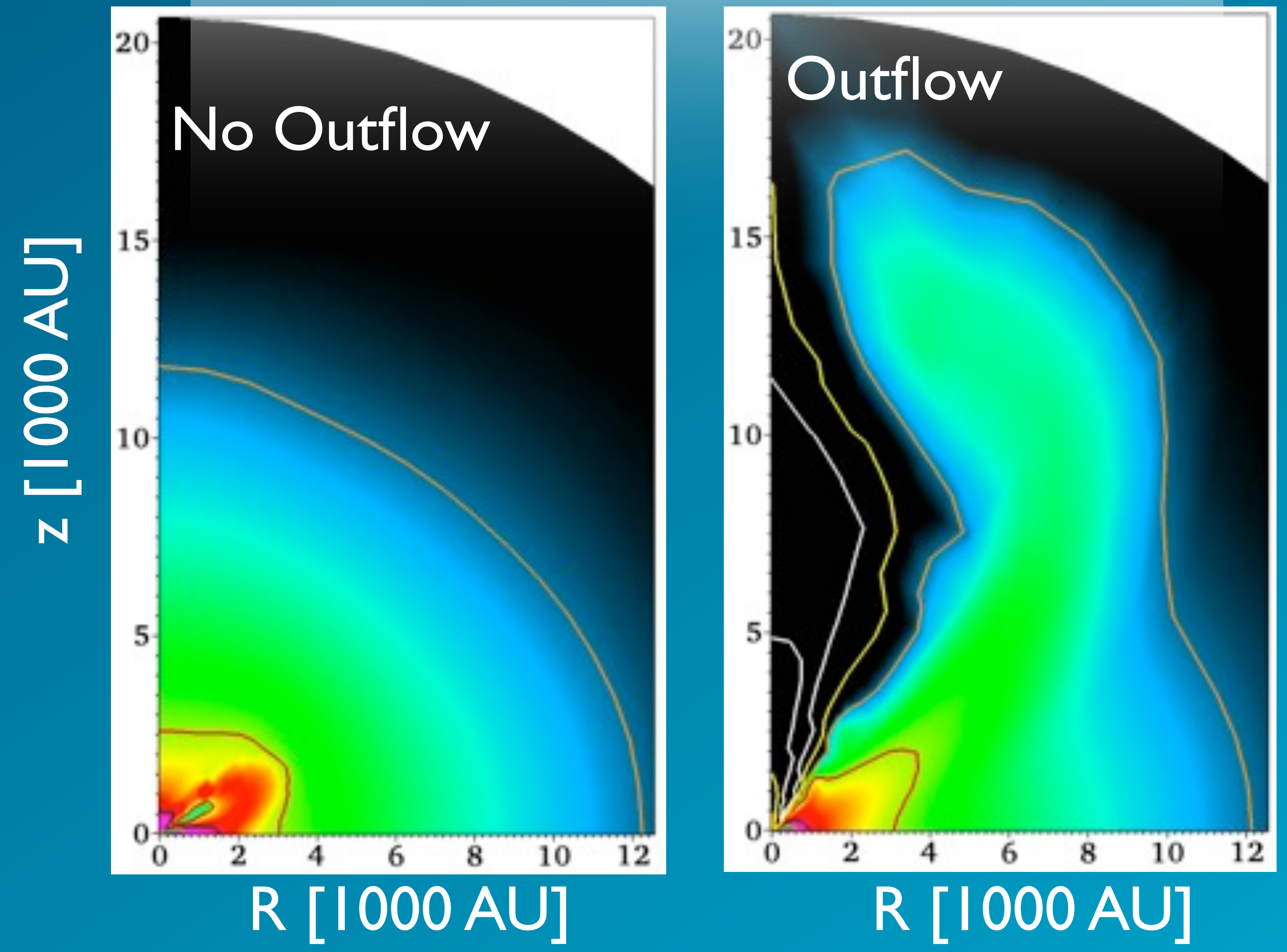
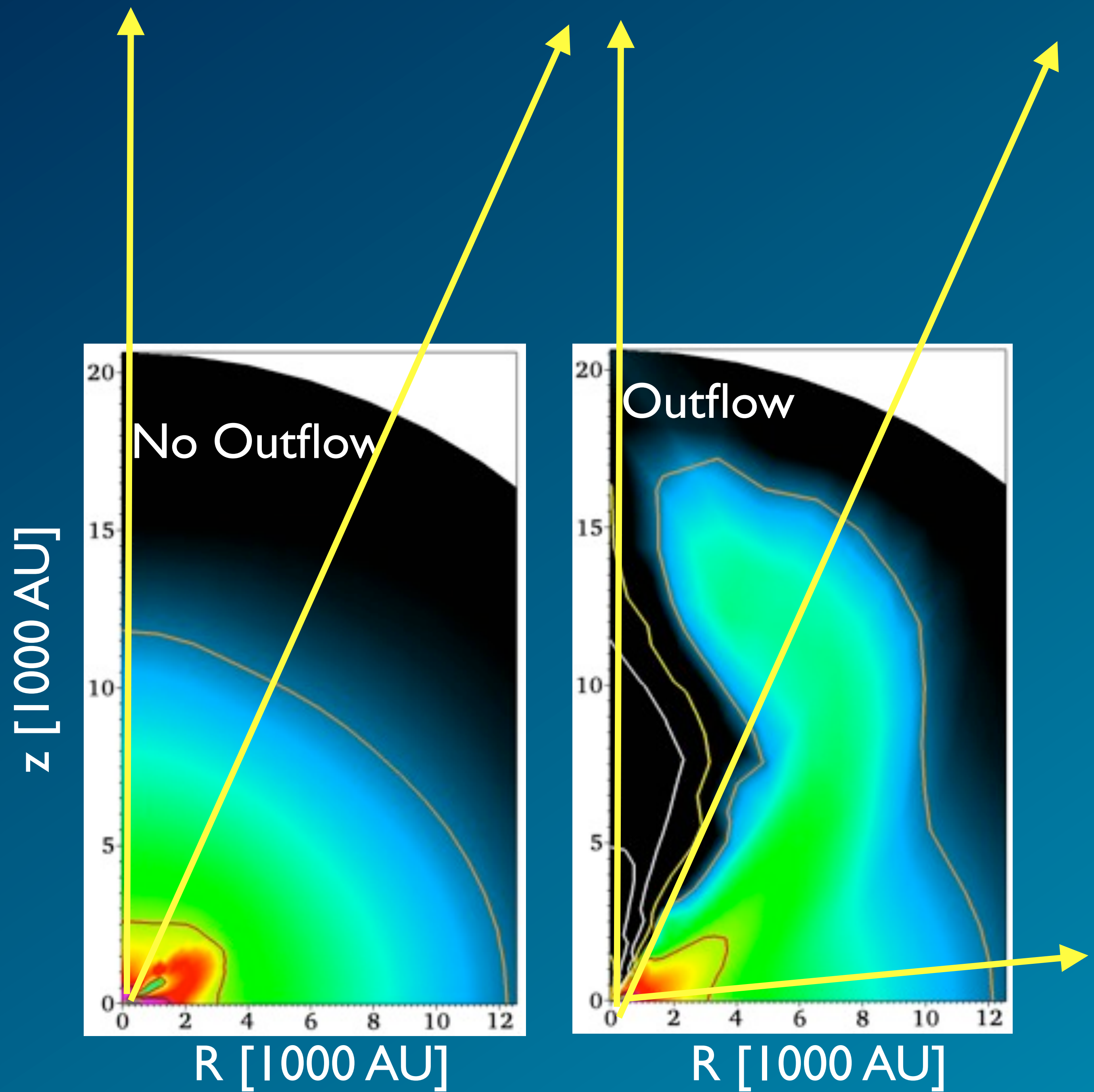
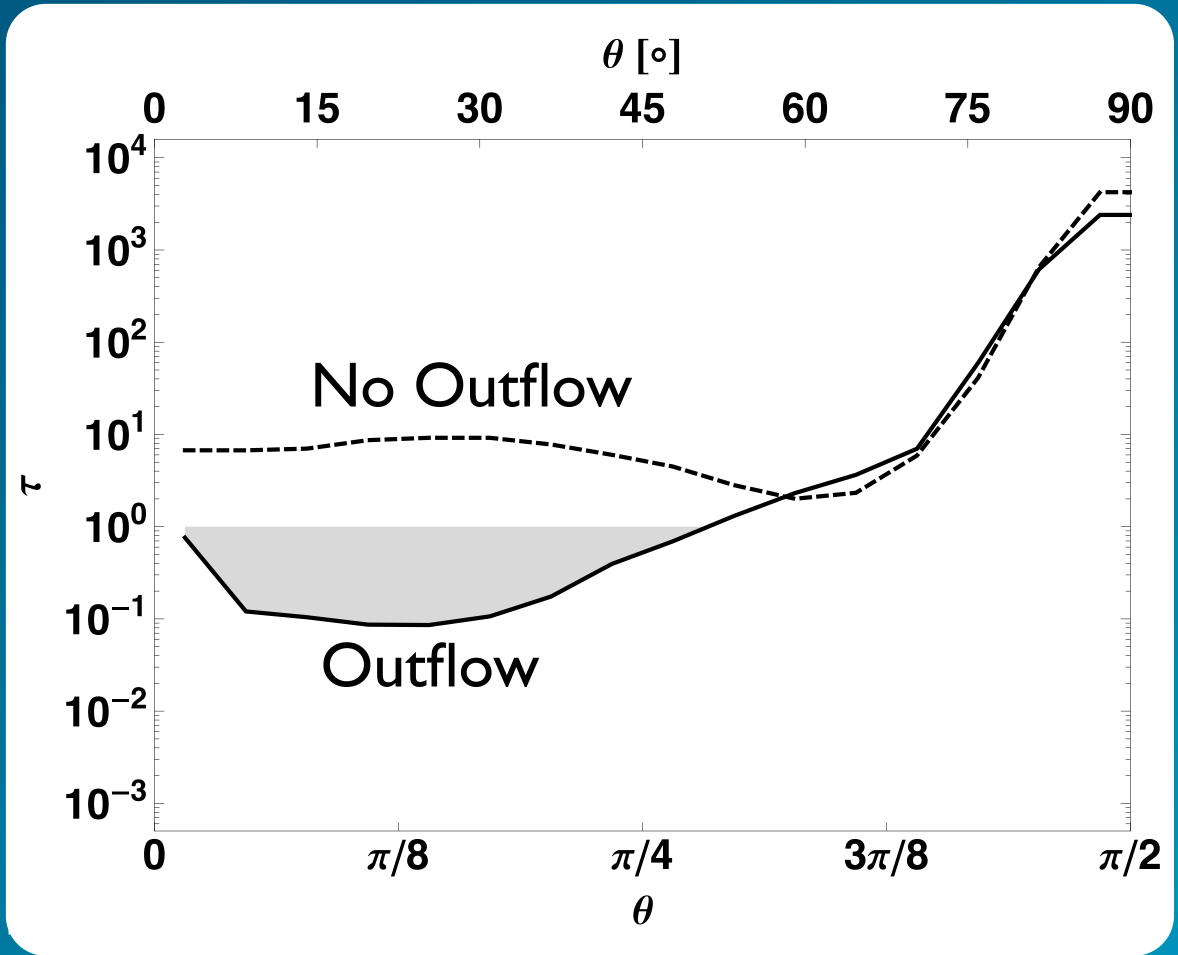


Protostellar Outflows

<u>Analysis:</u>

- *Core* flashlight effect





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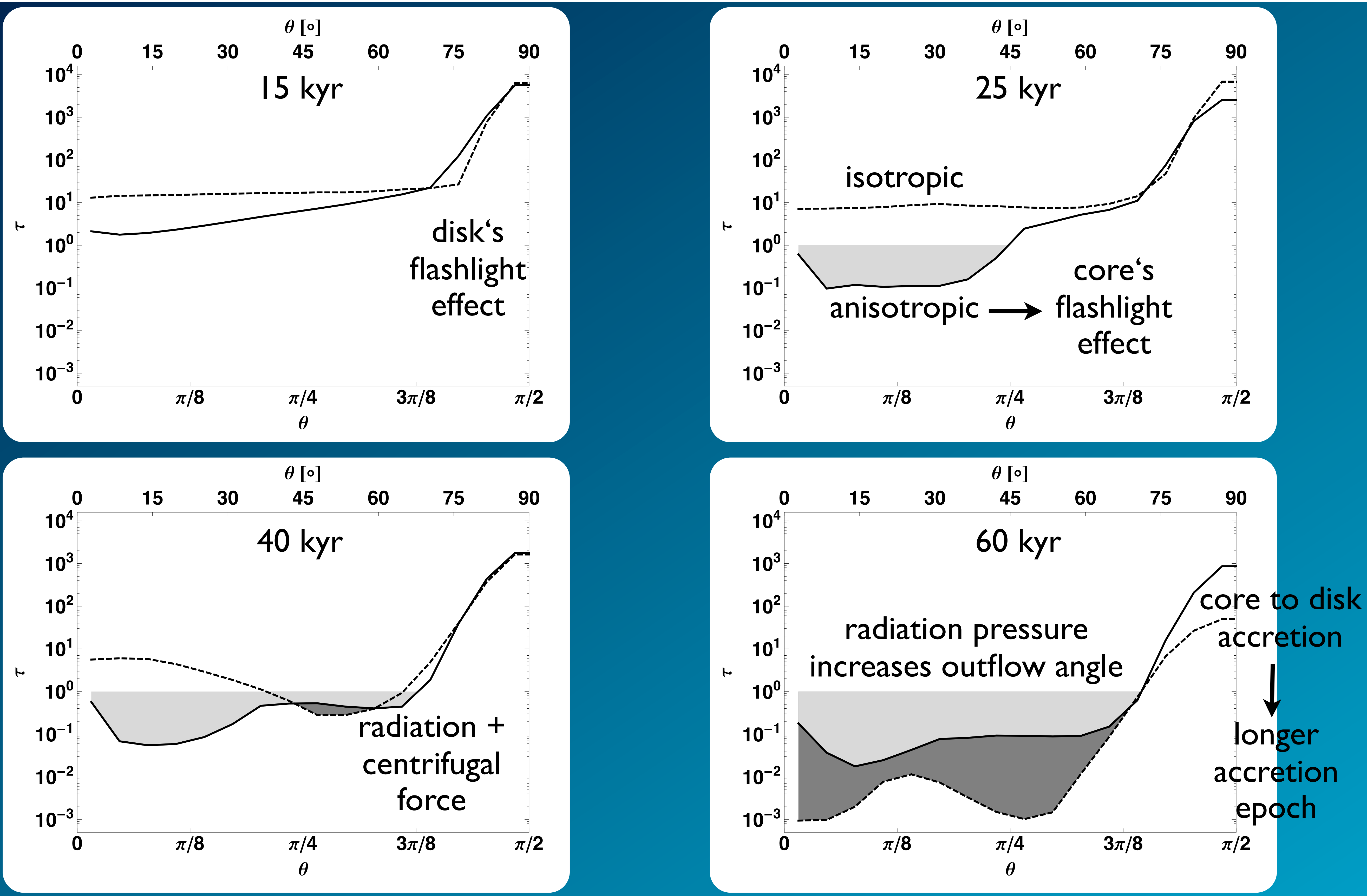
Protostellar Outflows



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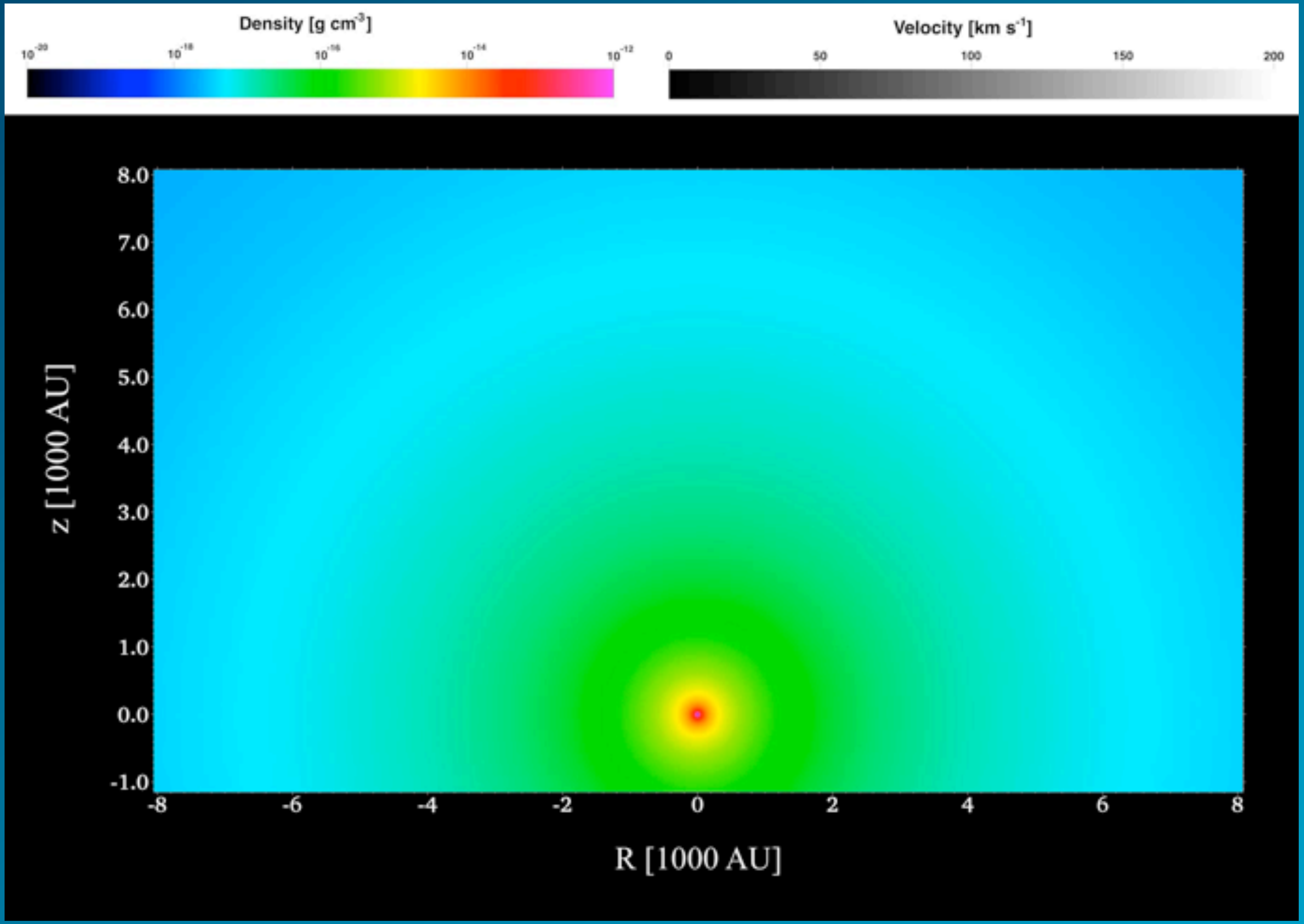
Protostellar Outflows

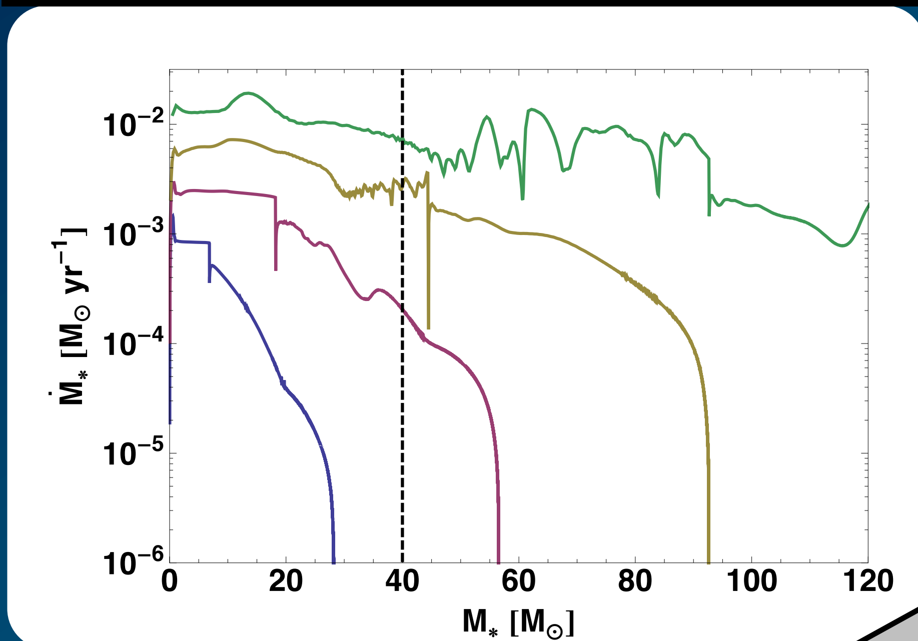
Ongoing parameter studies:

- Dependence on
  - Accretion-Outflow efficiency
  - Launching time
  - Collimation
  - Launching velocity

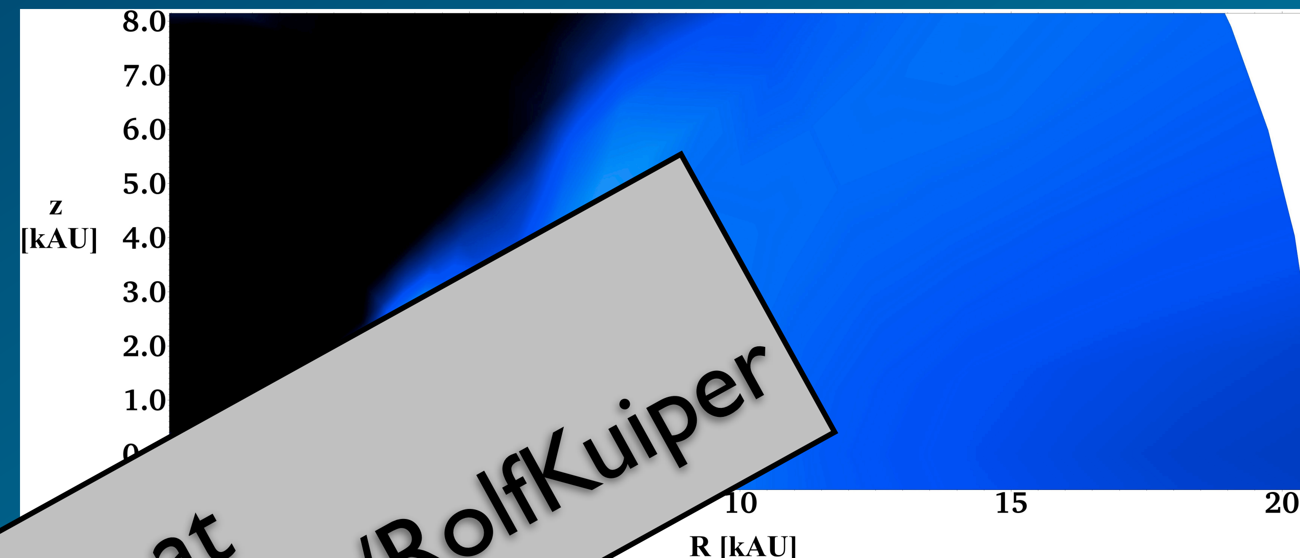


Summary

Radiation Pressure Problem solved via Disk Accretion!



Inner gas disks can be optically thick!



Animations at http://www.youtube.com/user/RolfKuiper

otostellar Outflows yield a „Core Flashlight Effect“