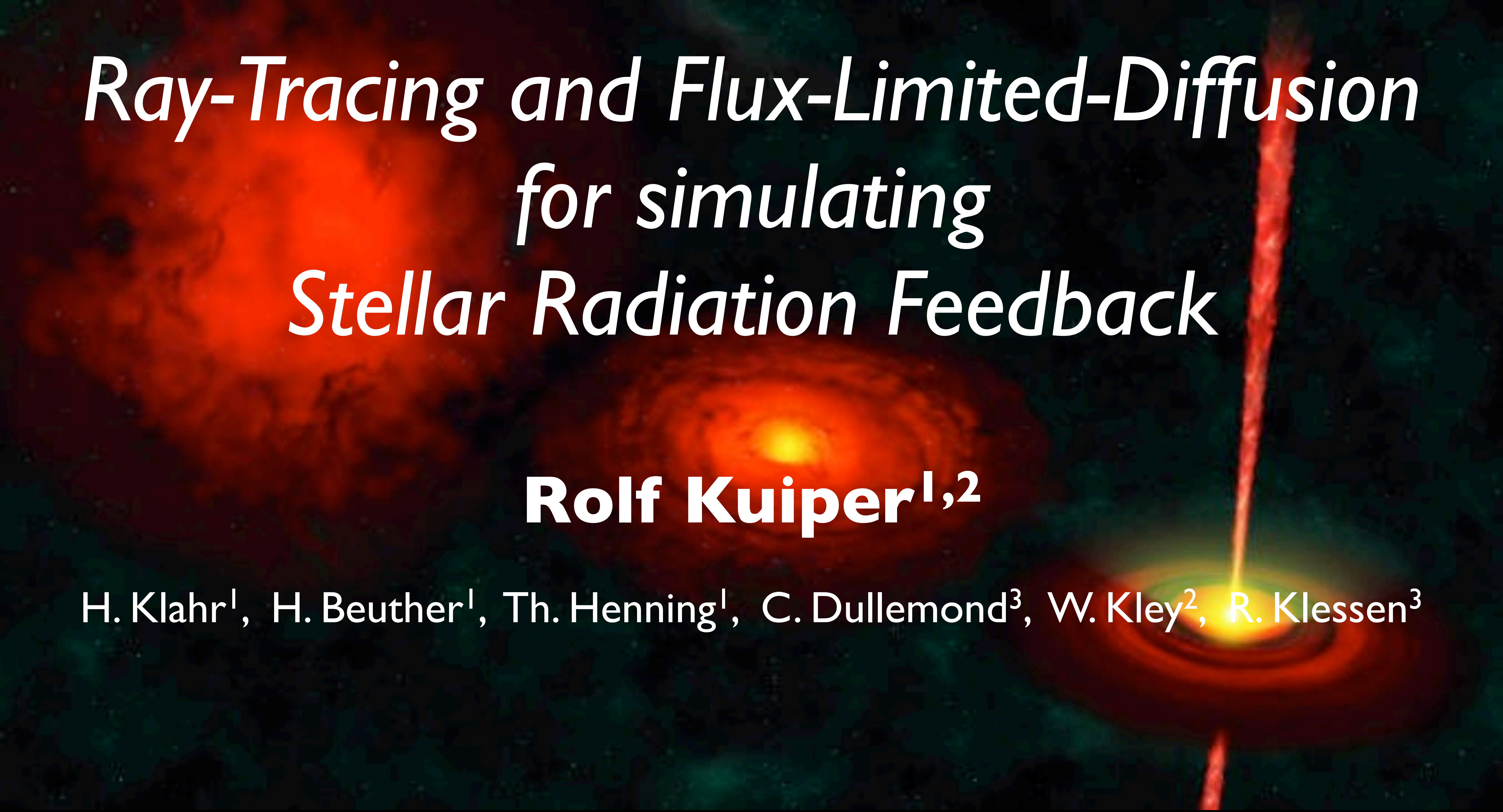


Ray-Tracing and Flux-Limited-Diffusion for simulating Stellar Radiation Feedback

Rolf Kuiper[1,2]

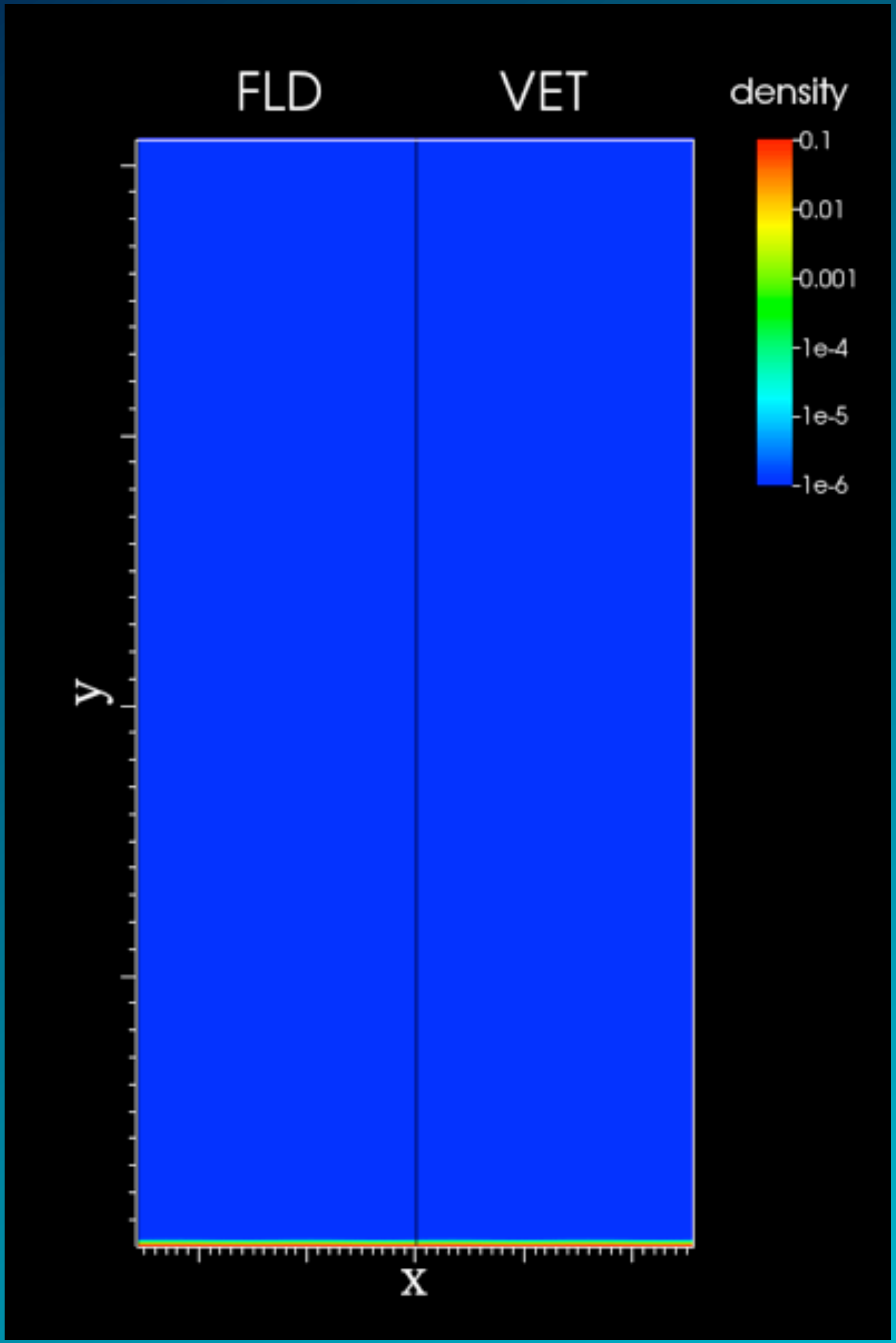
H. Klahr[1], H. Beuther[1], Th. Henning[1], C. Dullemond[3], W. Kley[2], R. Klessen[3]

1 - Max Planck Institute for Astronomy Heidelberg, Germany
2 - Computational Physics, Tübingen University, Germany
3 - Institute for Theoretical Astrophysics, Heidelberg University, Germany

Fire Down Below - The Impact of Feedback on Star and Galaxy Formation
Kavli Institute for Theoretical Physics, Santa Barbara, CA, USA
April 17, 2014

Radiative Rayleigh-Taylor Instability in ULIRGs

E = 0.5



Davis et al. (2014, submitted)

Shane Davis (on Tuesday):
Flux-Limited-Diffusion vs. Variable Eddington Tensor for *Thermal* Radiation Feedback (T ~ 80 K).

This talk:
Flux-Limited-Diffusion vs. Ray-Tracing for *Stellar* Radiation Feedback

Ray-Tracing (RT)

Radiation Transport Equation:

$$\frac{1}{c}\frac{\partial I}{\partial t} + \vec{\Omega}\vec{\nabla} I + \sigma_{\mathrm{ext}} I = \frac{c}{4\pi}\left(\sigma_{\mathrm{abs}} B - \sigma_{\mathrm{scat}} E\right)$$

Radiative Flux and Radiation Energy Density:

$$\vec{F} = \int_{4\pi} d\Omega \; \vec{\Omega} \; I(r, \Omega, t)$$

$$E = \frac{1}{c}\int_{4\pi} d\Omega \; I(r, \Omega, t)$$

Flux-Energy Relation:

$$\vec{F} = \frac{\int_{4\pi} d\Omega \; \vec{\Omega} \; I(r, \Omega, t)}{\int_{4\pi} d\Omega \; I(r, \Omega, t)} c \; E$$

Flux-Limited-Diffusion (FLD)

Radiation Transport Equation:

$$\frac{1}{c}\frac{\partial I}{\partial t} + \vec{\Omega}\vec{\nabla} I + \sigma_{\mathrm{ext}} I = \frac{c}{4\pi}\left(\sigma_{\mathrm{abs}} B - \sigma_{\mathrm{scat}} E\right)$$

Approximations:

- *Locally Isotropic*, mean angular values (integral over full solid angle):

$$\frac{\partial E}{\partial t} + \vec{\nabla}\vec{F} = c\sigma_{\mathrm{abs}}(B - E)$$

Conservation equation

- *FLD* approximation:

$$\vec{F} = -D\vec{\nabla}E$$

Flux-Energy Relation

$$\frac{\partial E}{\partial t} - \vec{\nabla}(D\vec{\nabla}E) = c\sigma_{\mathrm{abs}}(B - E)$$

Diffusion equation

- *Gray* approximation:
  - *Opacity* is computed from *local* conditions: $\kappa(\vec{x}) = \kappa_{\mathrm{P/R}}(T_{\mathrm{rad}}(\vec{x}))$

The Hybrid Scheme (RT+FLD)

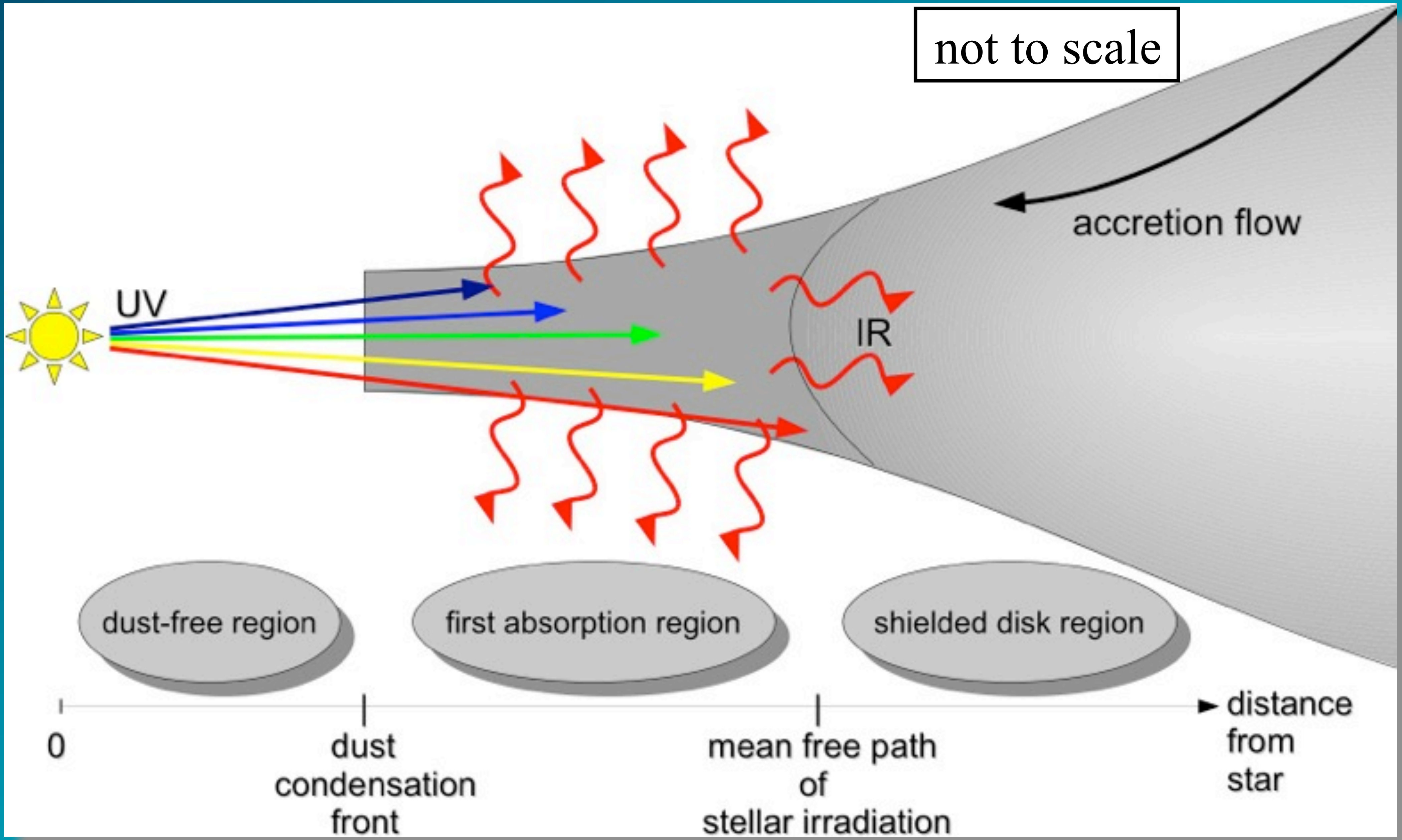
Split Radiation Fields:

- Stellar Irradiation
- Thermal dust (re-)emission

Different Solvers:

➡ Ray-Tracing (RT)

➡ Flux-Limited-Diffusion (FLD)



Kuiper et al. (2010), A&A 511

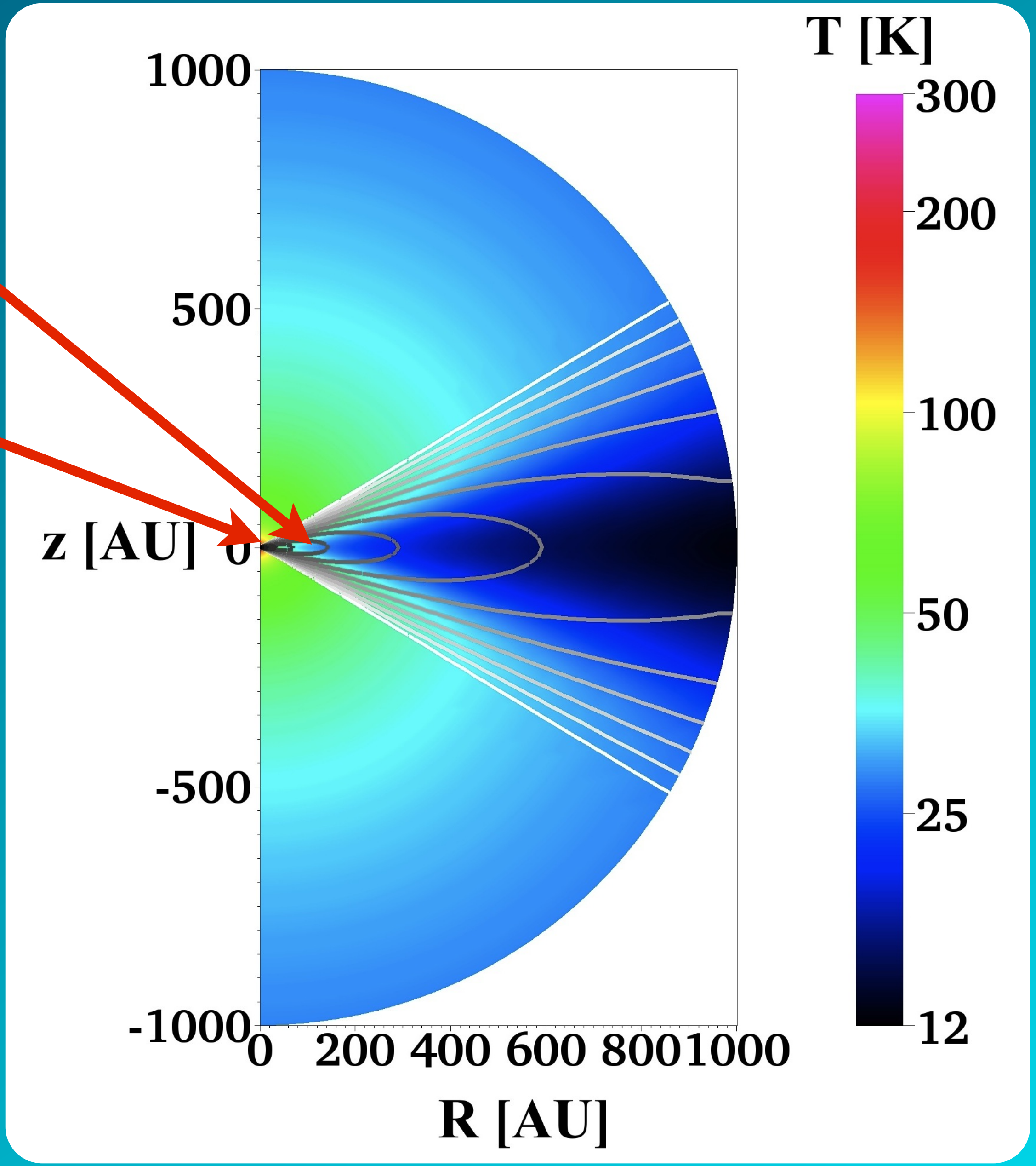
Outline

A. Radiation Transport Problem: Circumstellar Disk Temperatures
  - Setup from Pascucci et al. (2004) benchmark test
  - Setup from Pinte et al. (2009) benchmark test

B. Radiation-Hydrodynamics:
  (1) Stellar Radiative Feedback
  (2) Radiative Rayleigh-Taylor Instability
  (3) The Science case:
  „A Solution to the Radiation Pressure Problem in the Formation of the Most Massive Stars“

Circumstellar Disk Temperatures

Setup:	Star	Disk (flared)
Pascucci et al. (2004)	T_{star} = 5800 K $R_{star} = 1\ R_\odot$	Tau = 0.1 ...10^2 at 550 nm
Pinte et al. (2009)	T_{star} = 4000 K $R_{star} = 2\ R_\odot$	Tau =10^3 ...10^6 at 810 nm



Methods/Codes:

- „MC": Monte-Carlo code RADMC as reference (scattering is neglected)
- „Hybrid": ν-dependent RT for Stellar + Gray FLD for Thermal Radiation
- „FLD": Gray FLD approximation for both - Stellar and Thermal - Radiation

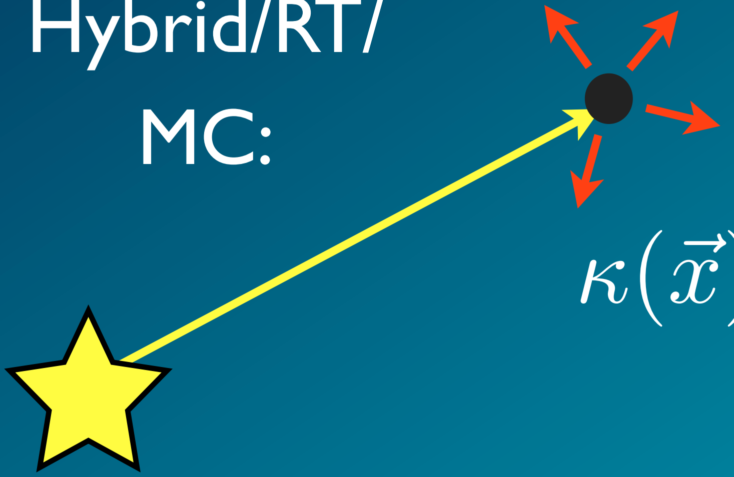
Kuiper & Klessen (2013), A&A 555

Results

Optically thin (Tau$_{550nm}$ = 0.1):

- Hybrid accurate up to *3%*
- FLD yields *wrong Temperature slope*

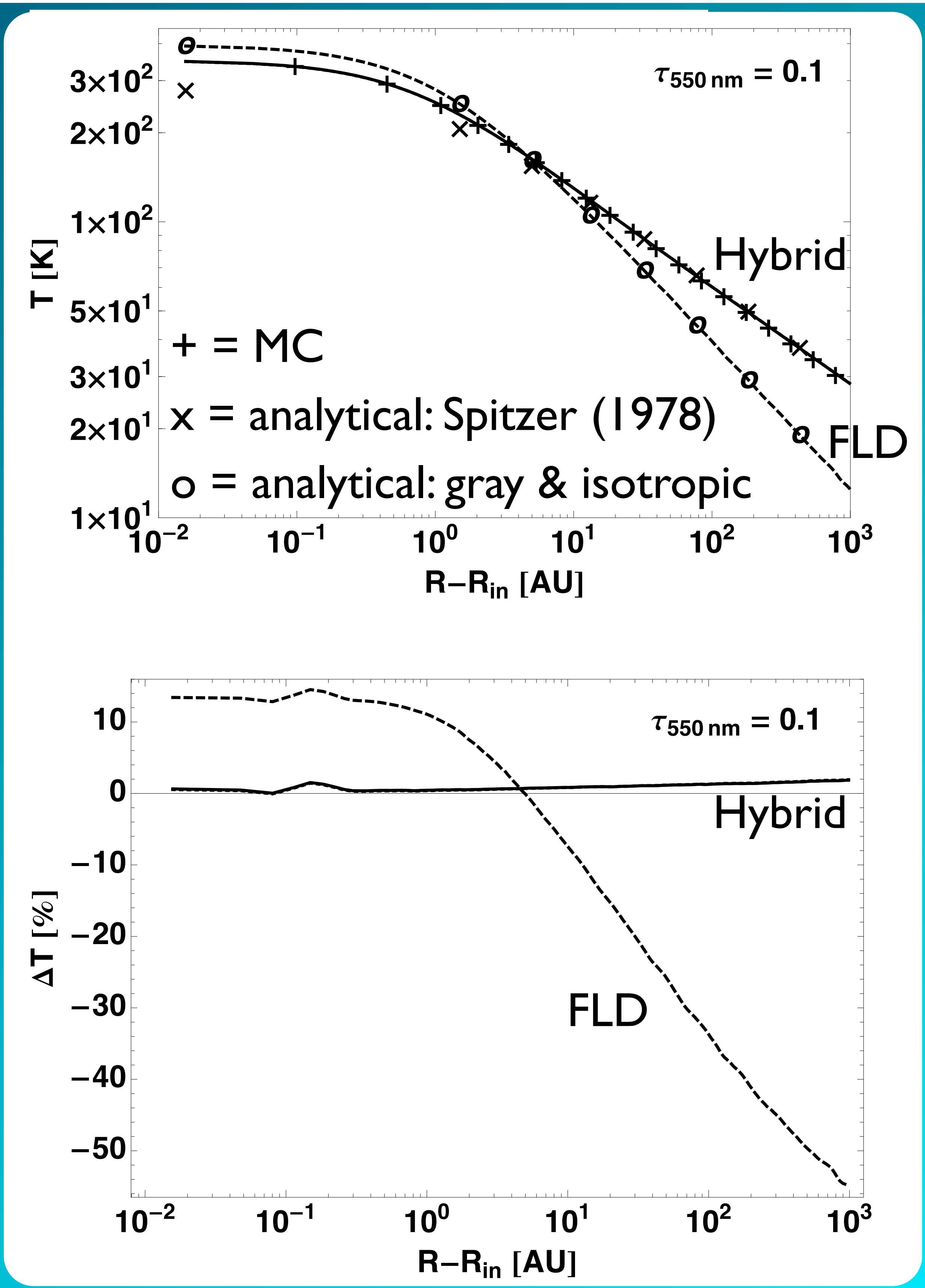
Hybrid/RT/MC:



$$\kappa(\vec{x}) = \kappa_\nu \approx \kappa_P(T_*)$$

FLD:

$$\kappa(\vec{x}) = \kappa_{\mathrm{P}}(T_{\mathrm{rad}}(\vec{x}))$$

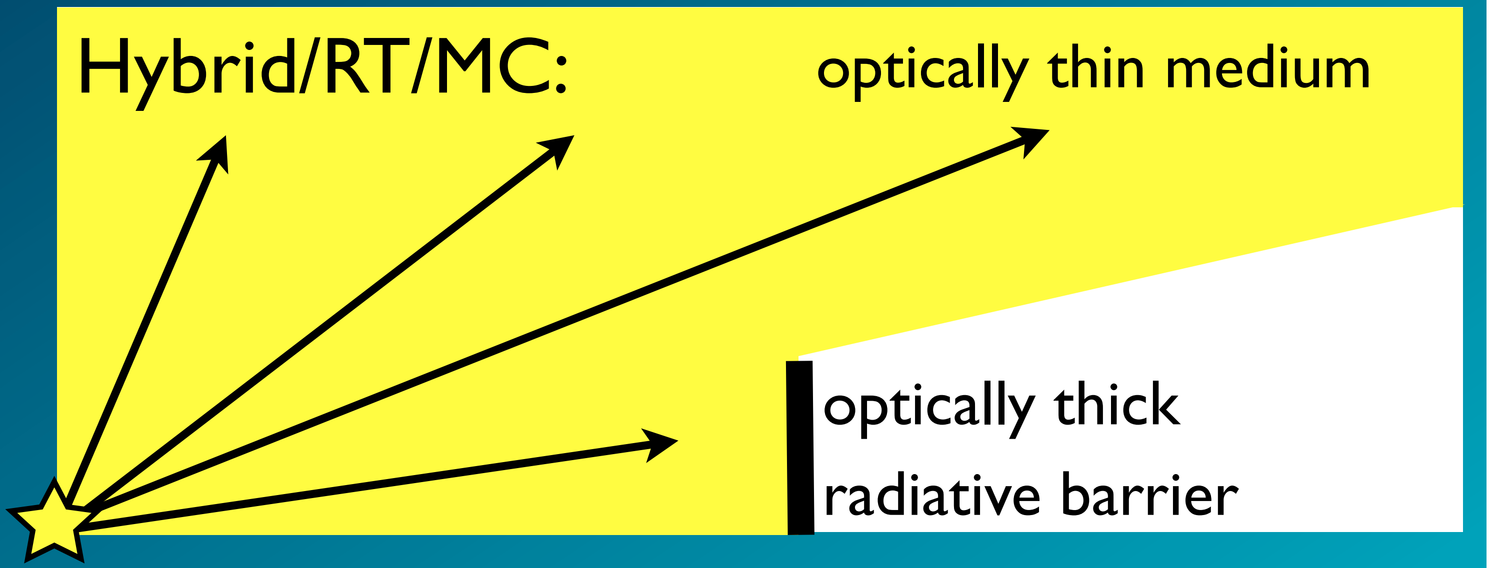


Kuiper & Klessen (2013), A&A 555

Results

Optically thick (Tau$_{810nm}$ = 10^4):

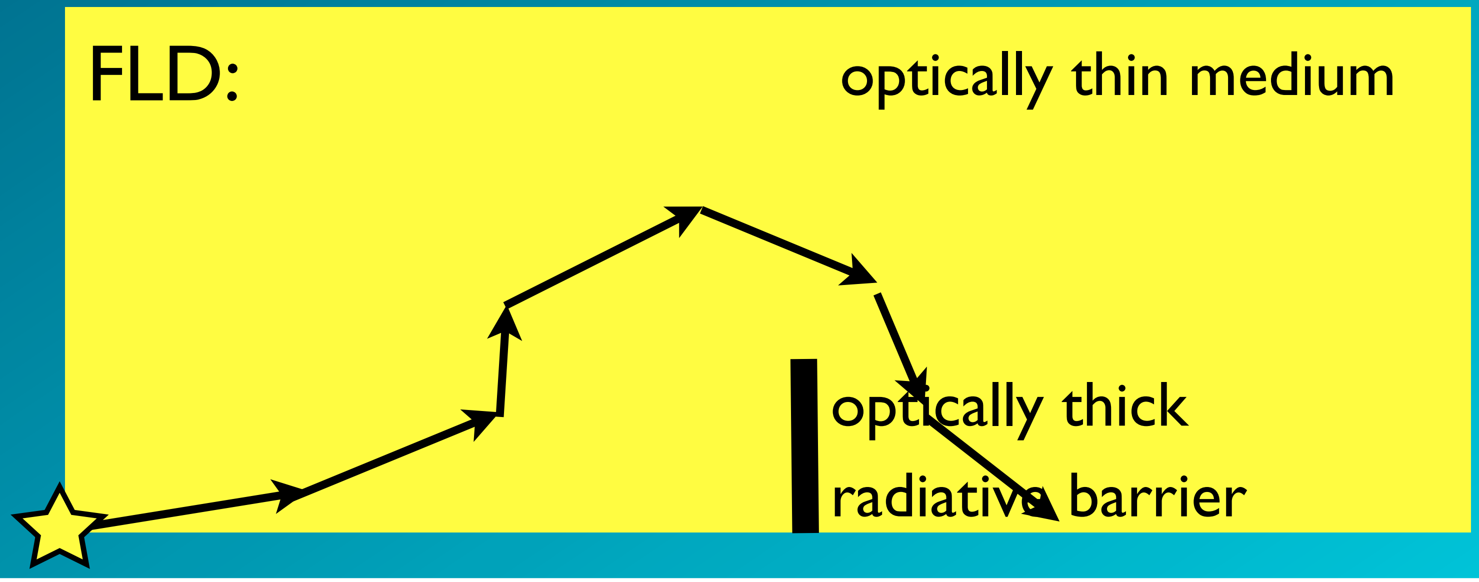
- Hybrid accurate up to *46%*
- FLD misses *Shadowing* effects



Hybrid/RT/MC:

optically thin medium

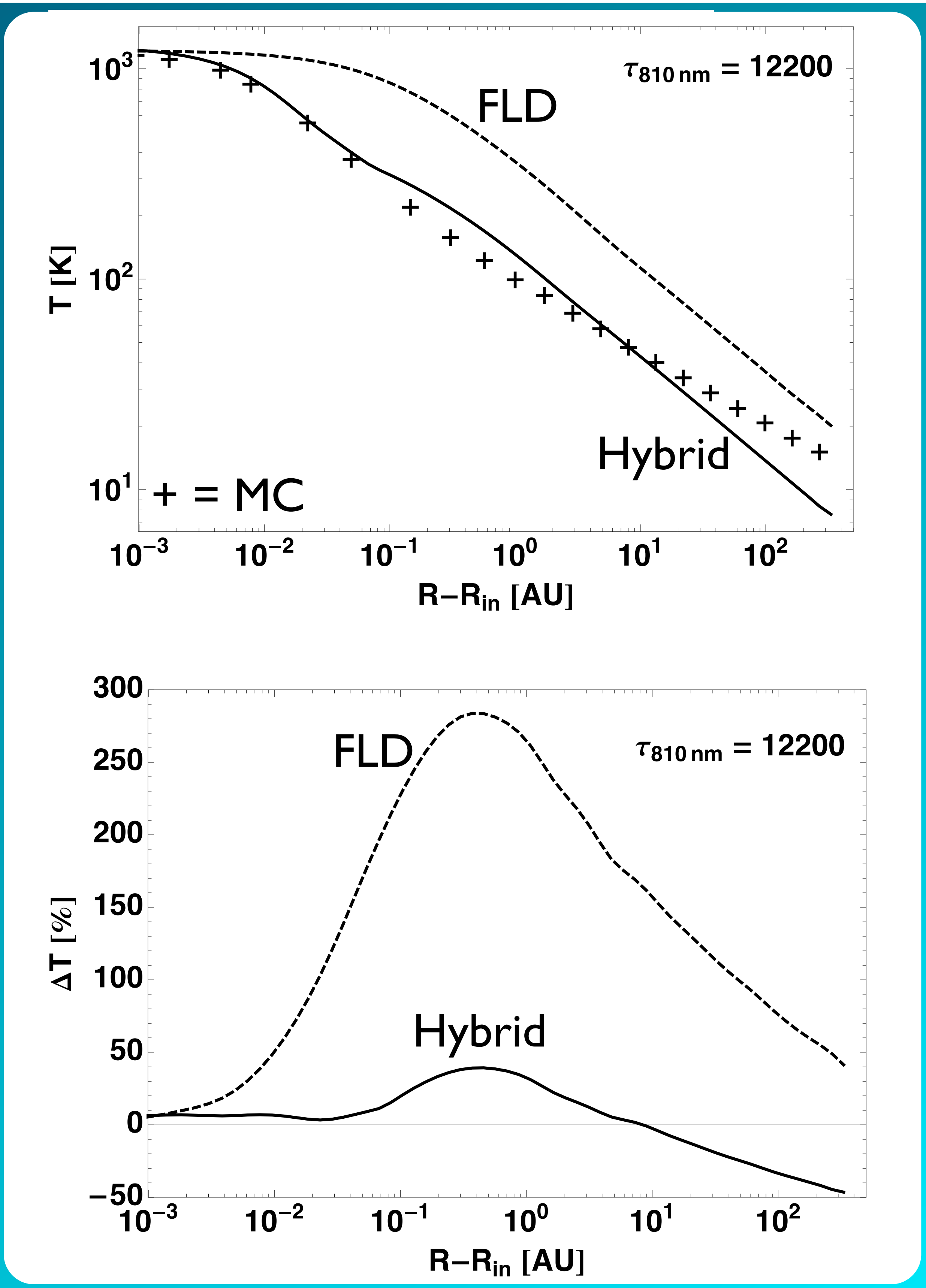
optically thick radiative barrier



FLD:

optically thin medium

optically thick radiative barrier

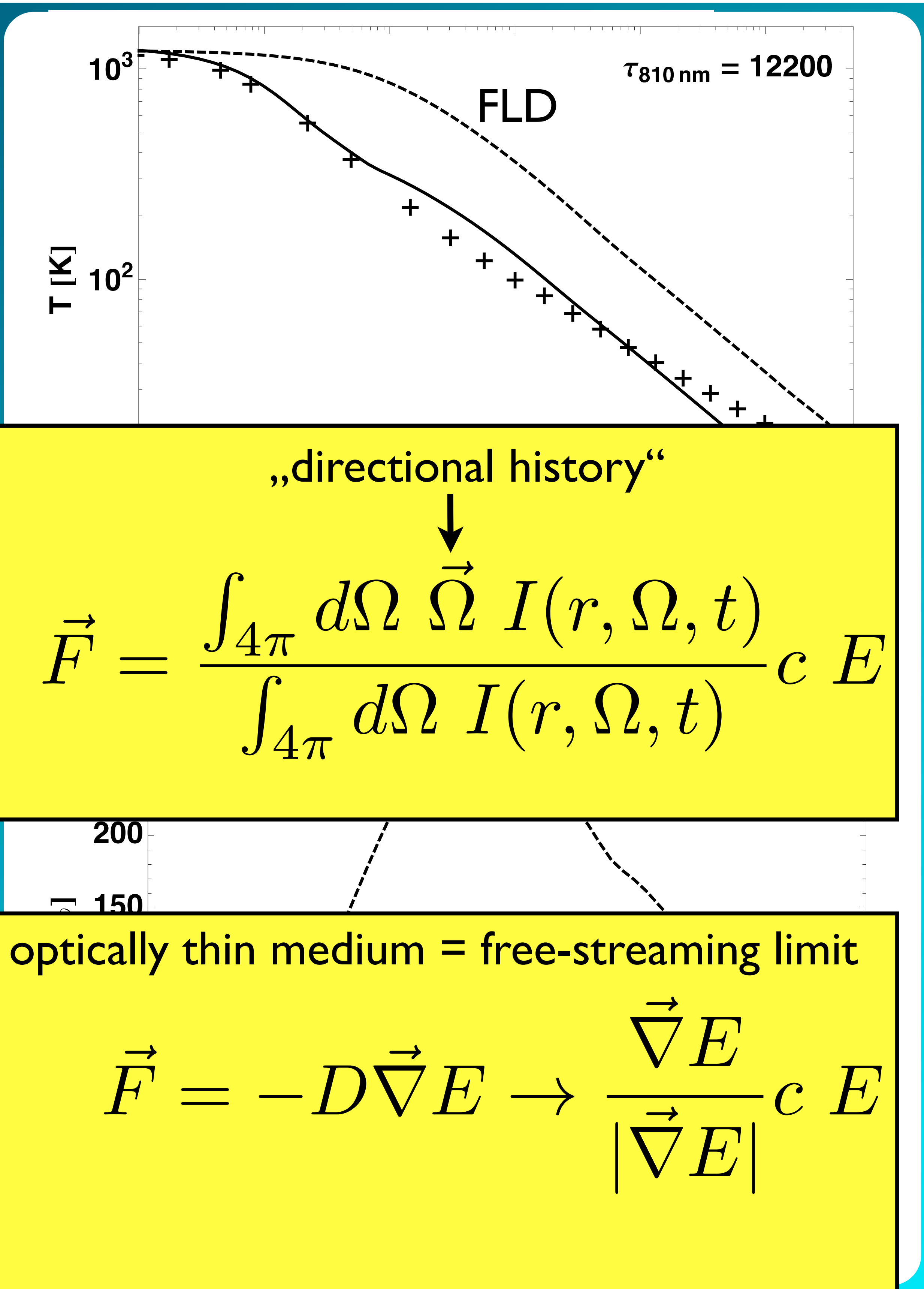


Kuiper & Klessen (2013), A&A 555

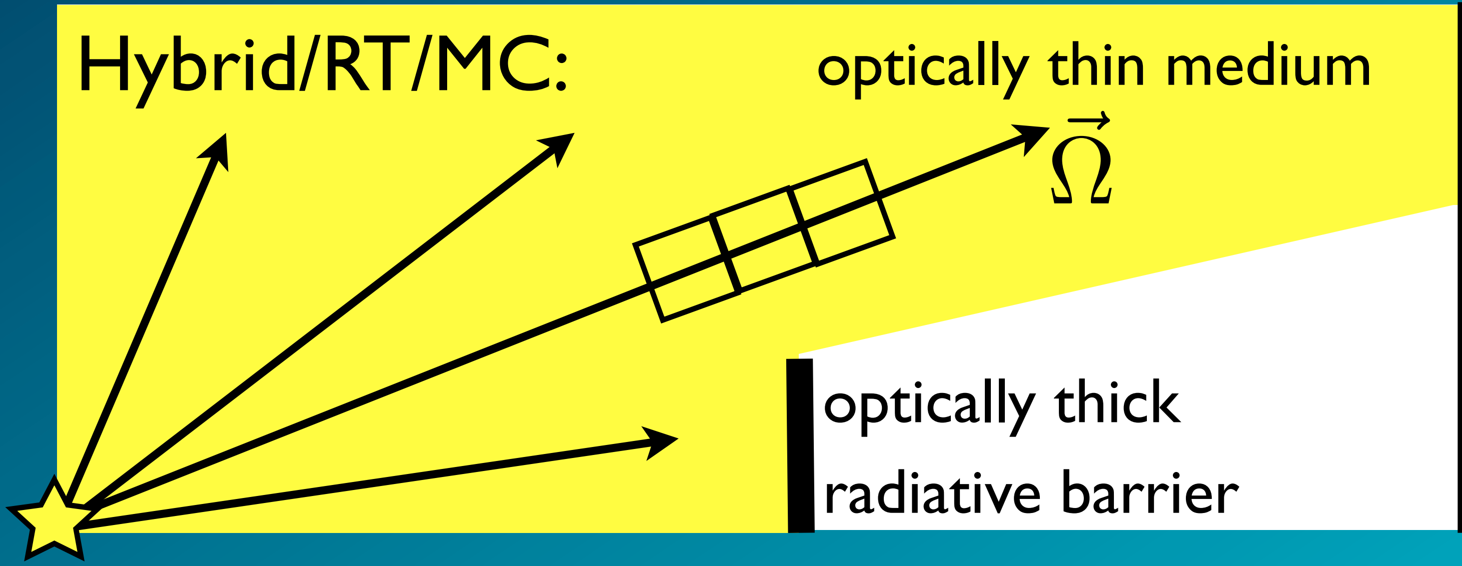
Results

Optically thick ($\mathrm{Tau}_{810\mathrm{nm}} = 10^4$):

- Hybrid accurate up to 46%
- FLD misses *Shadowing* effects



Kuiper & Klessen (2013), A&A 555



Hybrid/RT/MC:

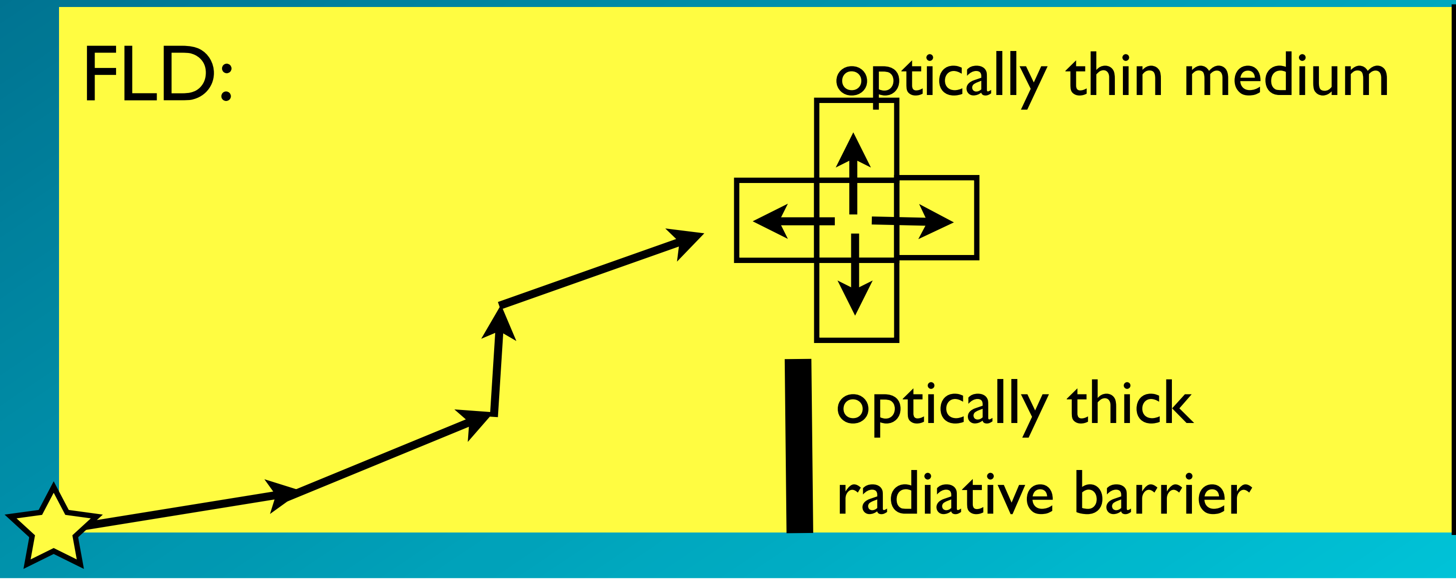
optically thin medium

$\vec{\Omega}$

optically thick
radiative barrier

„directional history“

$$\vec{F} = \frac{\int_{4\pi} d\Omega\; \vec{\Omega}\; I(r,\Omega,t)}{\int_{4\pi} d\Omega\; I(r,\Omega,t)}\, c\, E$$



FLD:

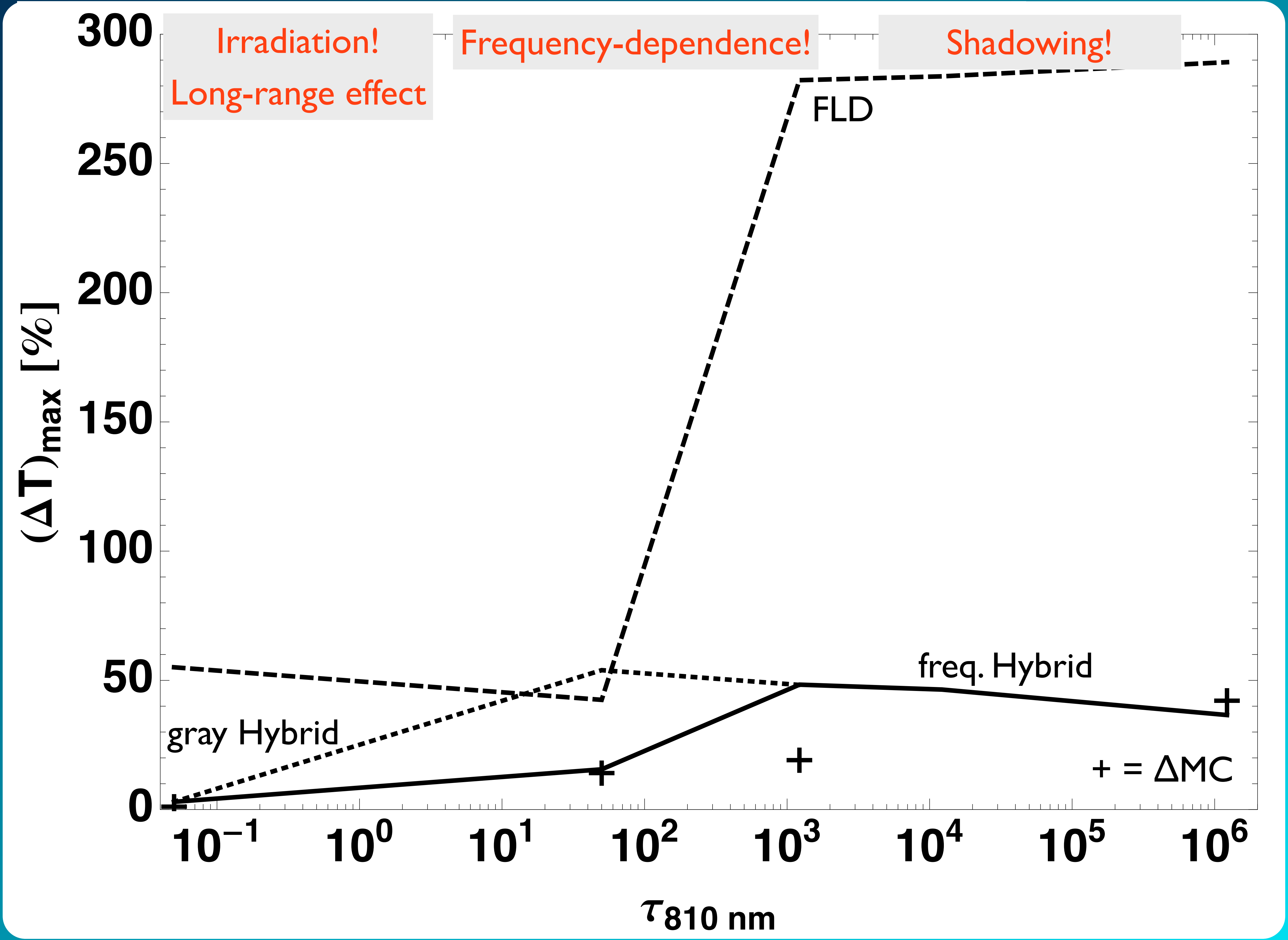
optically thin medium

optically thick
radiative barrier

optically thin medium = free-streaming limit

$$\vec{F} = -D\vec{\nabla}E \rightarrow \frac{\vec{\nabla}E}{|\vec{\nabla}E|}\, c\, E$$

Conclusion



Irradiation!

Long-range effect

Frequency-dependence!

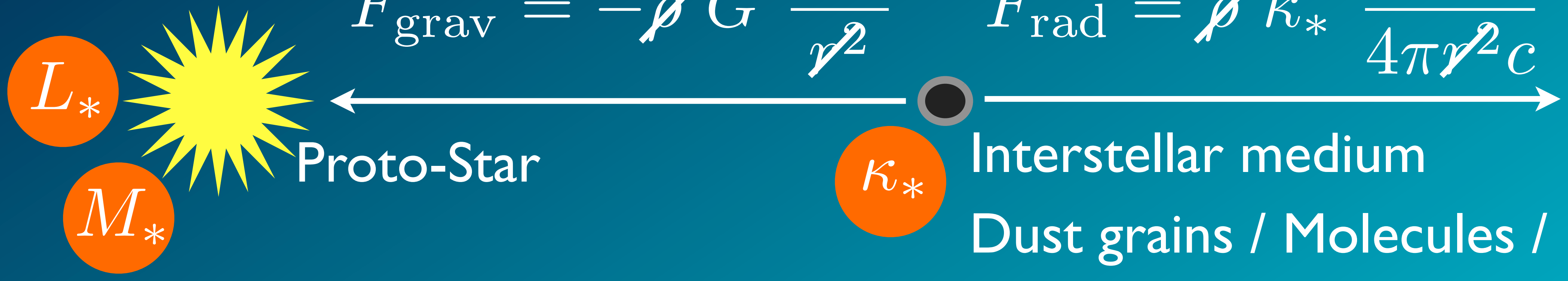
Shadowing!

Kuiper & Klessen (2013), A&A 555

Radiation-Hydrodynamics: Stellar Feedback

Eddington limit:

$$F_\mathrm{grav} = -\cancel{\rho}\, G \frac{M_*}{\cancel{r^2}} \qquad F_\mathrm{rad} = \cancel{\rho}\, \kappa_* \frac{L_*}{4\pi \cancel{r^2} c}$$



Interstellar medium

Dust grains / Molecules / Ionized gas

Radiative Force overcomes Gravity:

$$F_\mathrm{rad} > F_\mathrm{grav}$$

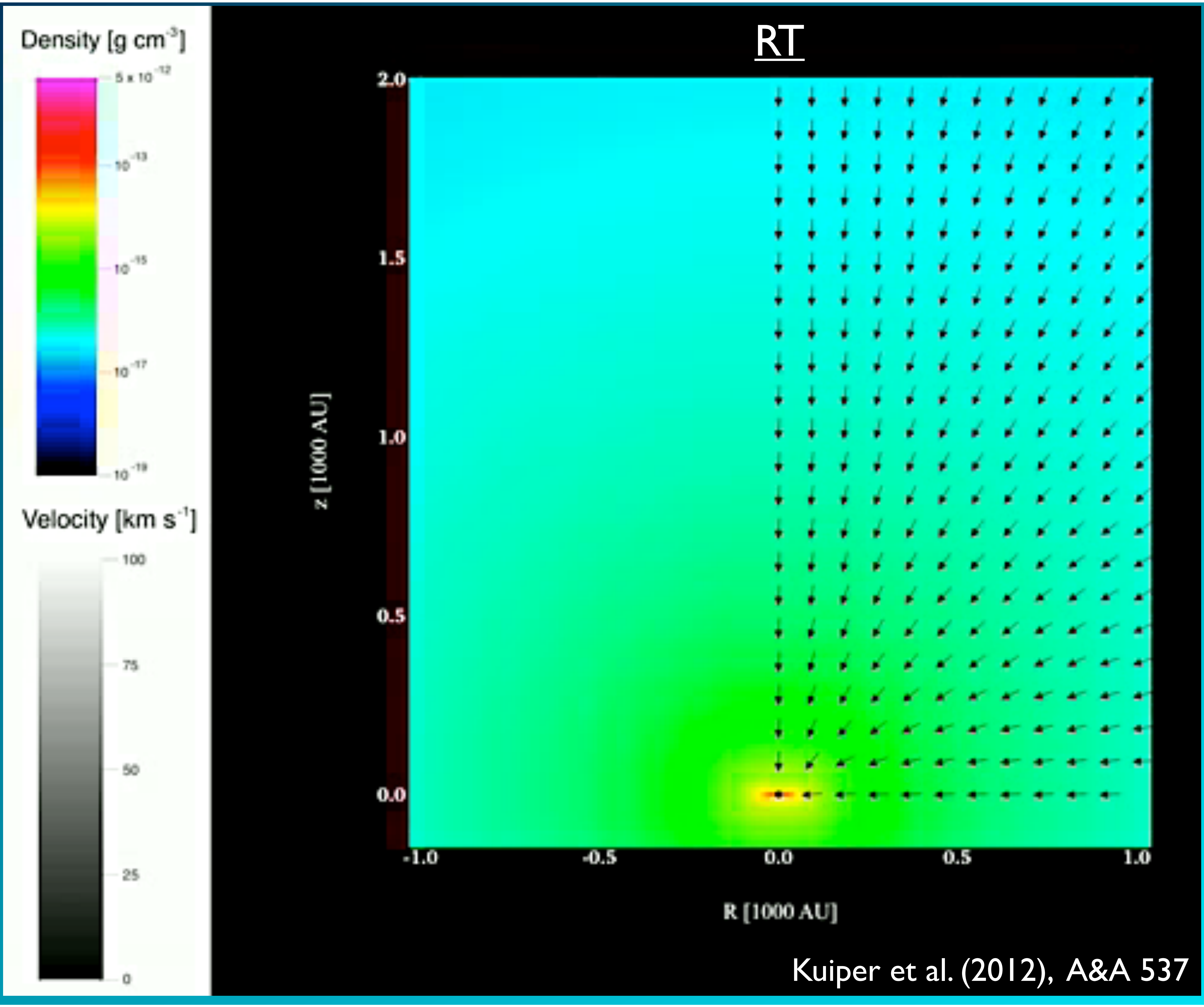
$$\frac{L_*}{M_*} \geq \frac{4\pi G c}{\kappa_*}$$

Scale-free!

RT: $\kappa(\vec{x}) = \kappa_\nu \approx \kappa_P(T_*)$ ☺ Scale-free!

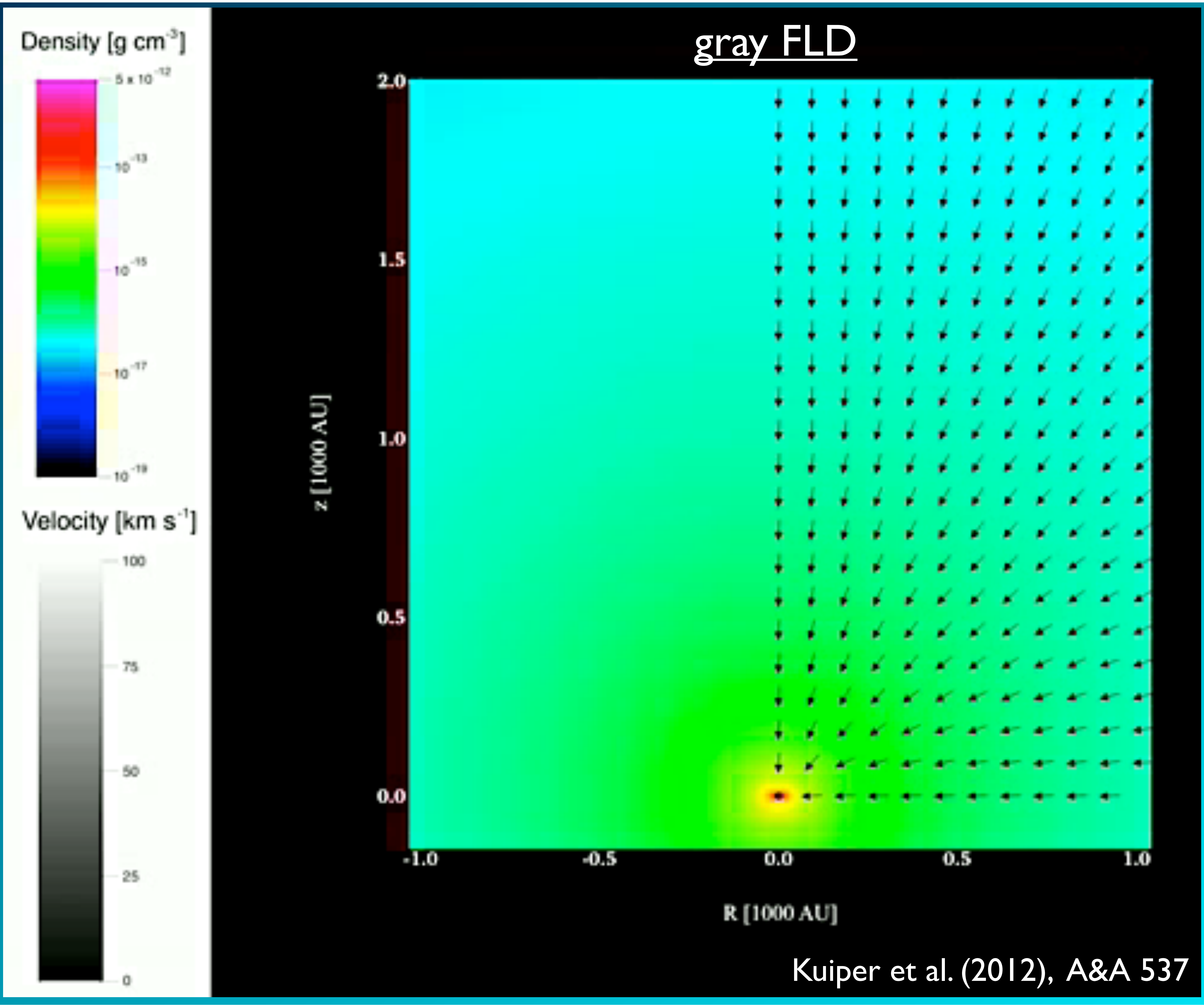
FLD: $\kappa(\vec{x}) = \kappa_\mathrm{P}(T_\mathrm{rad}(\vec{x}))$ ⚠ Eddington ratio decreases with distance to Star!

Radiation-Hydrodynamics: Stellar Feedback



Kuiper et al. (2012), A&A 537

Radiation-Hydrodynamics: Stellar Feedback

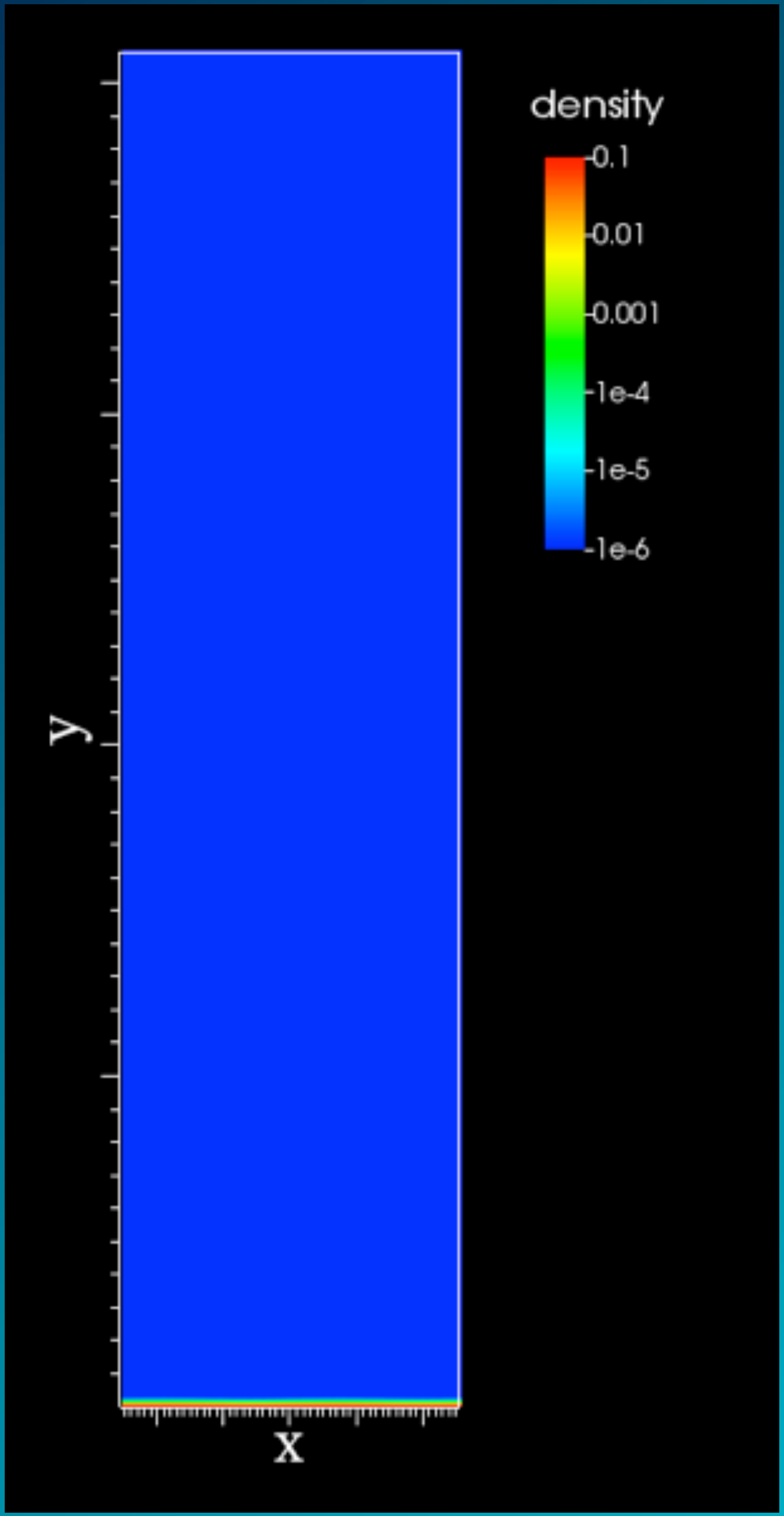


gray FLD

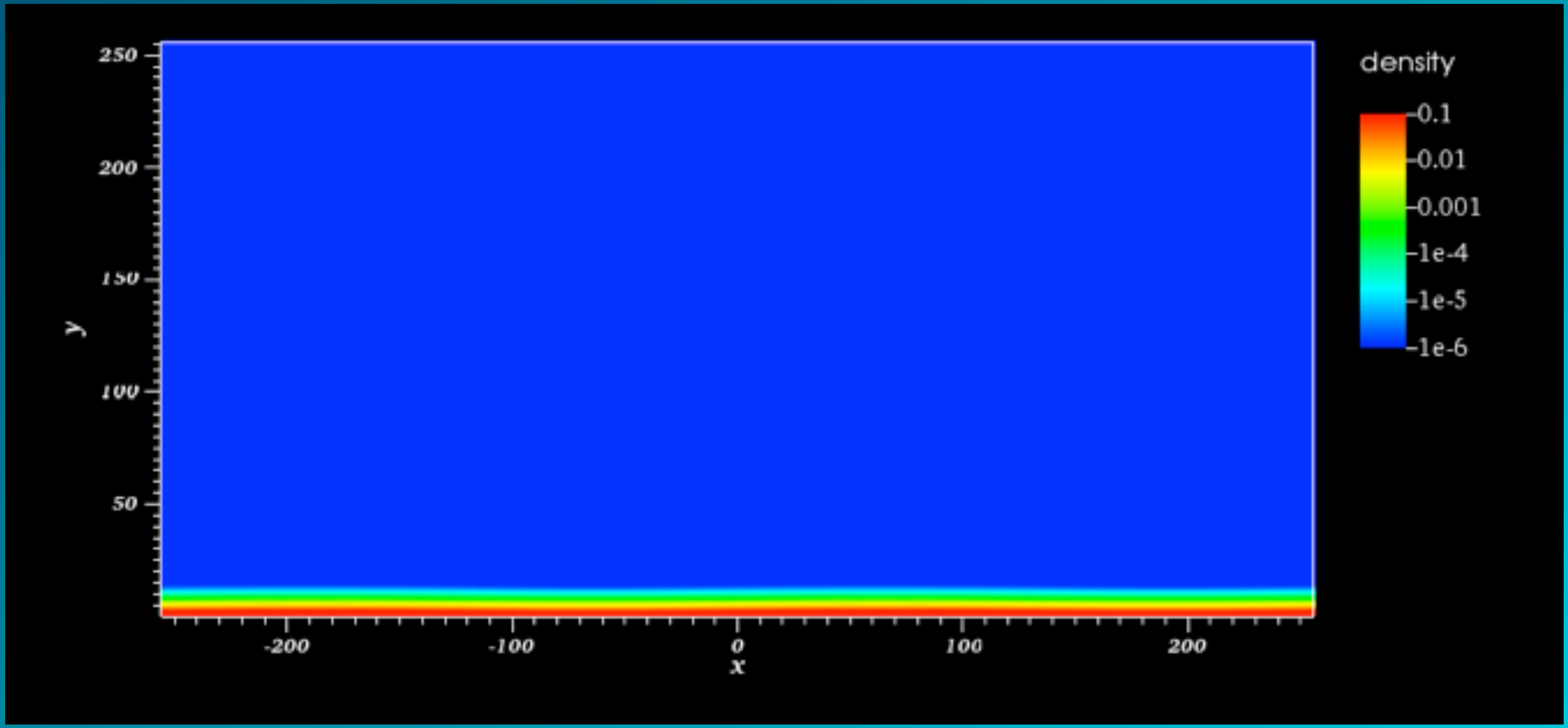
Kuiper et al. (2012), A&A 537

Radiative Rayleigh-Taylor Instability

E = 0.5: $F_{grav} \sim F_{rad}$



E = 0.02: $F_{grav} >> F_{rad}$



Davis et al. (2014, submitted)

E = 2.0: $F_{rad} = 2*F_{grav}$

„In this case, the shell is accelerated efficiently and reaches the upper boundary of the domain before the RTI has time to grow appreciable."

Jiang, Davis, & Stone (2013)

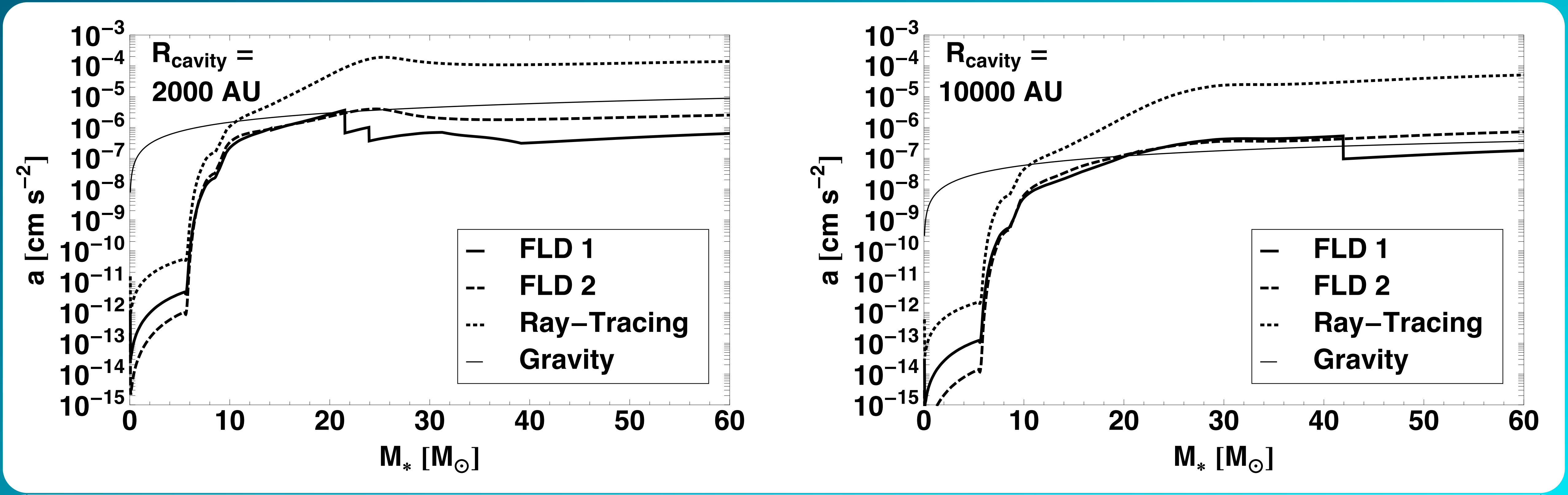
Radiative Rayleigh-Taylor Instability

Analytically:

- Opacity / Radiative force is actually 1-2 orders of magnitude higher than computed within the gray FLD approximation

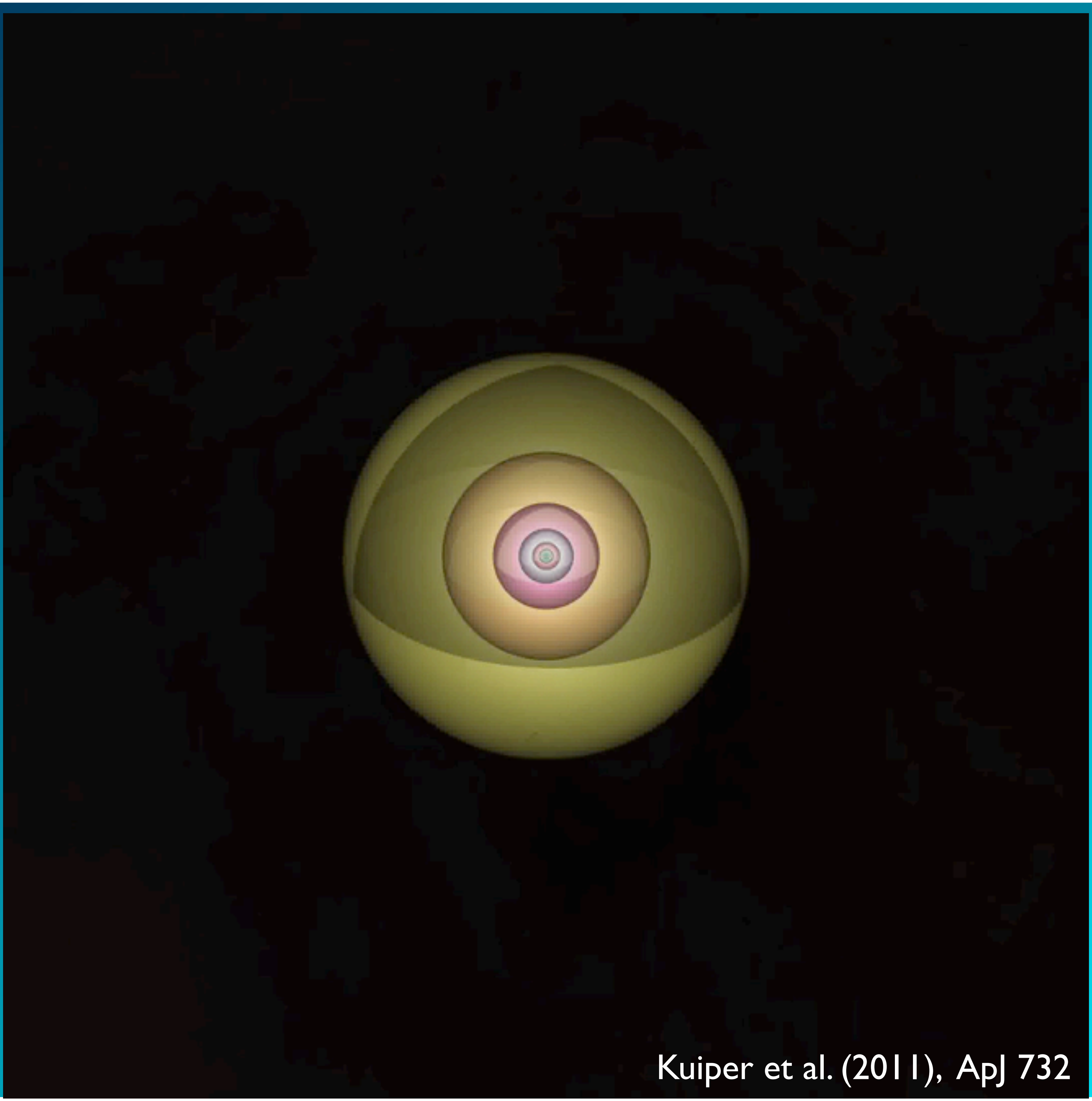
‣ Radiation-pressure-dominated cavities remain *stable*

‣ Massive Stars do not form via Radiative Rayleigh-Taylor Instability



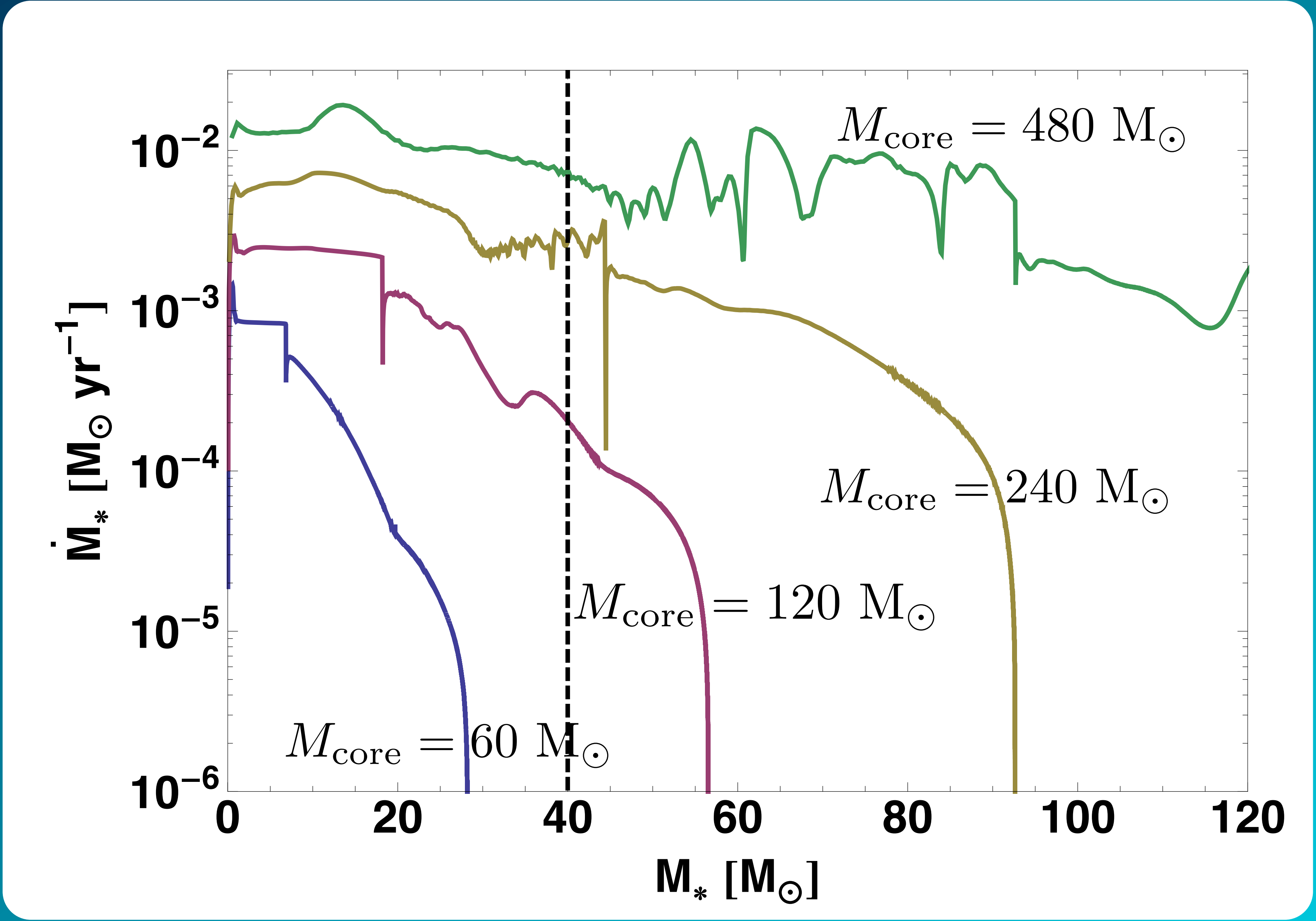
Kuiper et al. (2012), A&A 537

Scientific Application: Radiation Pressure Problem



Kuiper et al. (2011), ApJ 732

Solving the Radiation Pressure Problem!



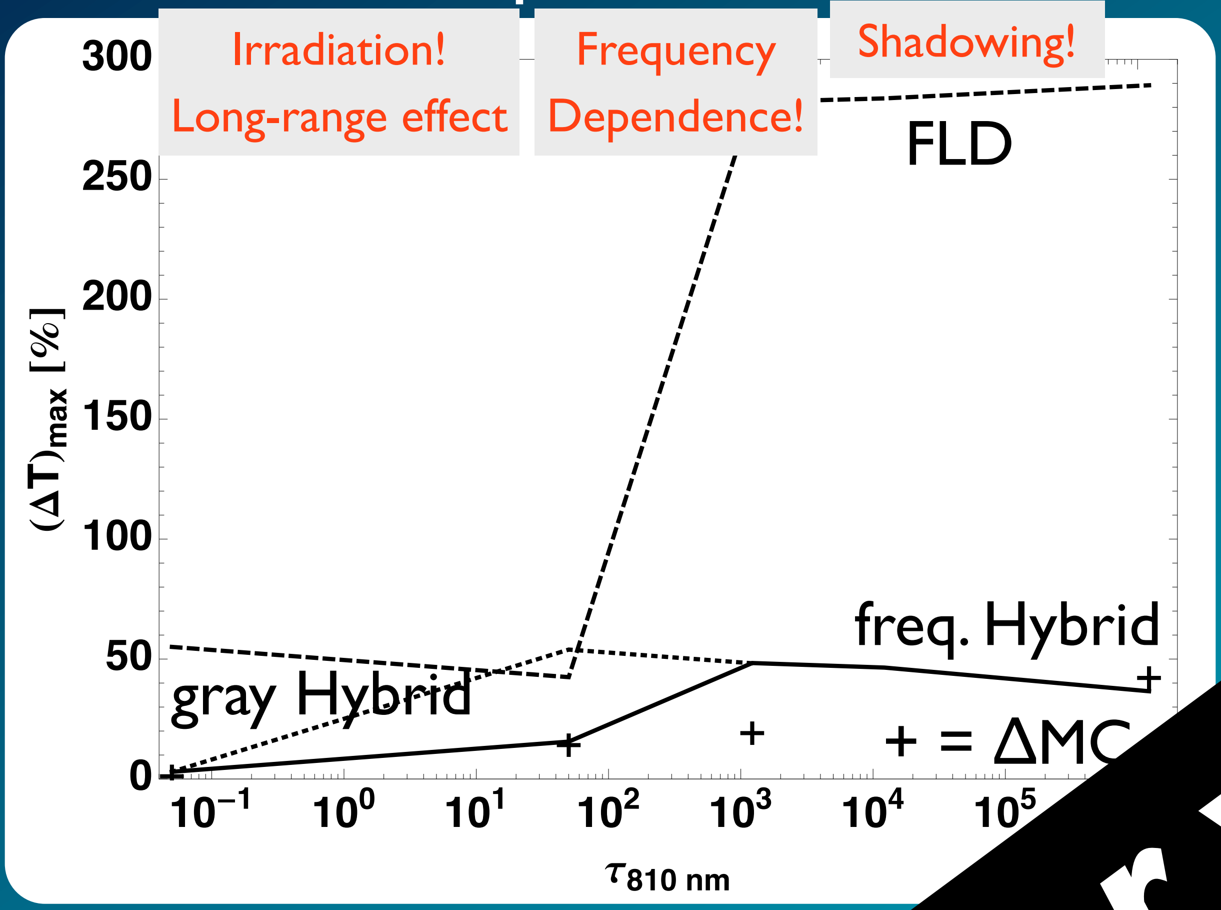
Kuiper et al. (2010), ApJ 722

First simulations ...

- Including *Radiation Pressure Feedback*
- Forming stars *far* beyond the *Radiation Pressure Barrier*!
- mostly up to the observed upper mass limit $M_* \rightarrow 140\ {\rm M}_\odot$

Summary

Radiation Transport Benchmark:

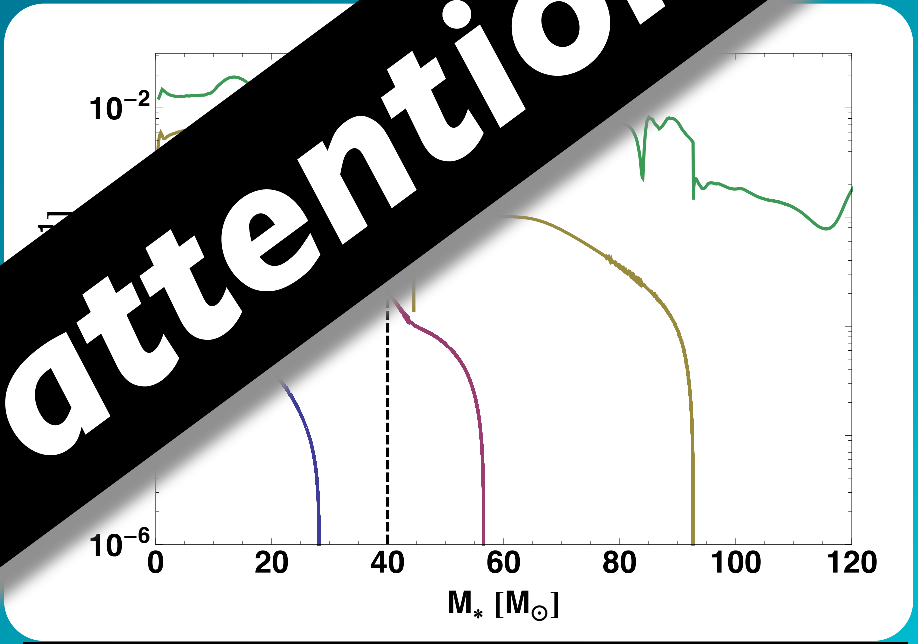

Irradiation!
Long-range effect

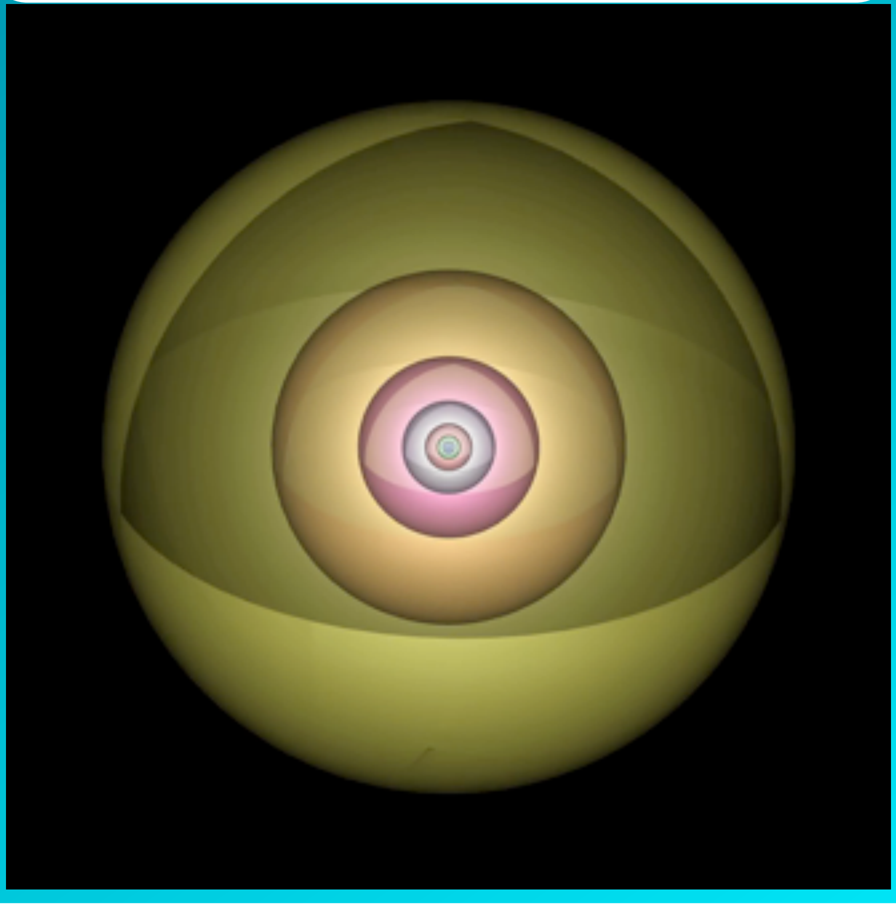
Frequency
Dependence!

Shadowing!

Radiation Pressure blem:

- Solved via D on!





Radiative Stellar Feedba

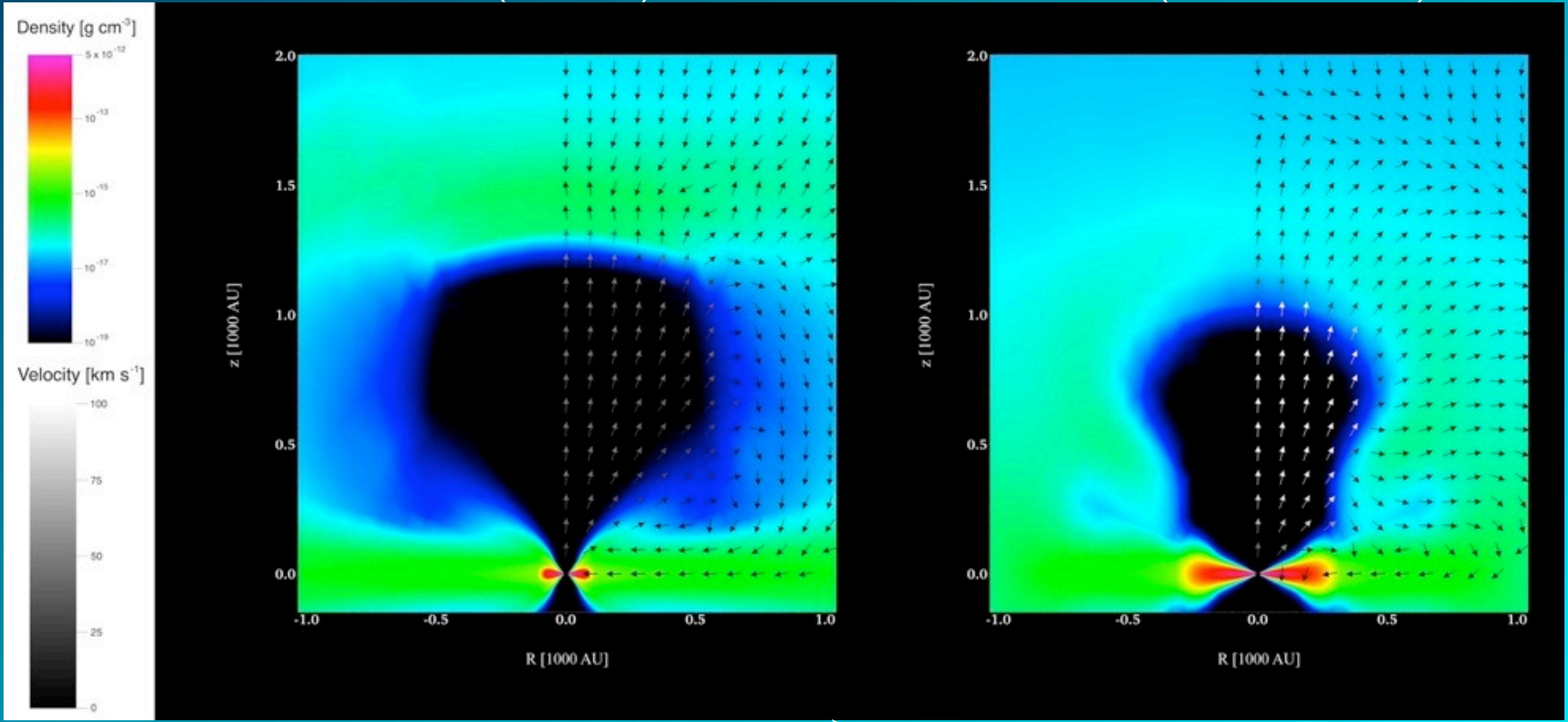
Hybrid / RT

Thanks for your attention!

Stability of radiation-pressure-dominated cavities

Shell morphology:

- Frequency-dependent RT: pre-acceleration of layers on top of the cavity shell



FLD (E ~ 1.0)

RT (E ~ 20 ... 200)

2000 AU

Kuiper et al. (2012), A&A 537

Double-Check

Kuiper et al. (2012):

- „In the RT cases, the radiation pressure exceeds gravity by 1–2 orders of magnitude.“

Owen, Ercolano, & Clarke (2012):

- FLD, Hybrid, and MC Radiation Transport
  - „[...] we find the FLD method significantly underestimates the radiation pressure by a factor of ~100.“

Harries, Haworth, & Acreman (2012):

- MC-Radiation-Hydrodynamics
  - “The development and speed of the cavities is similar to that found by Kuiper et al.“