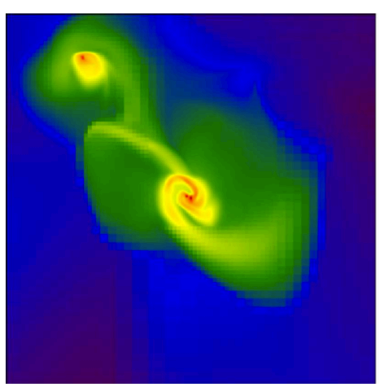
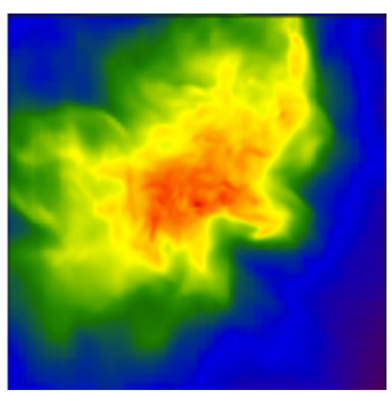
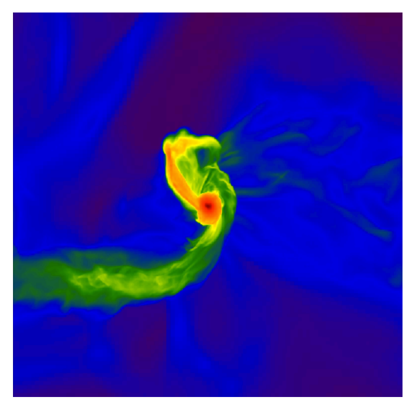
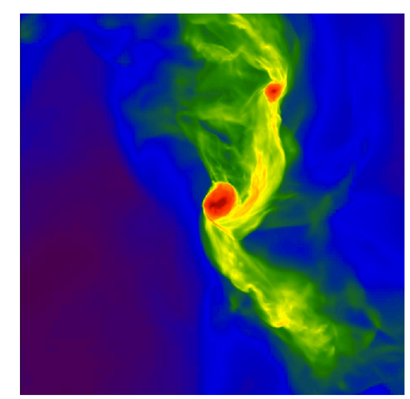
# Formation of Supermassive Black Holes via Direct Collapse: Successes and Problems

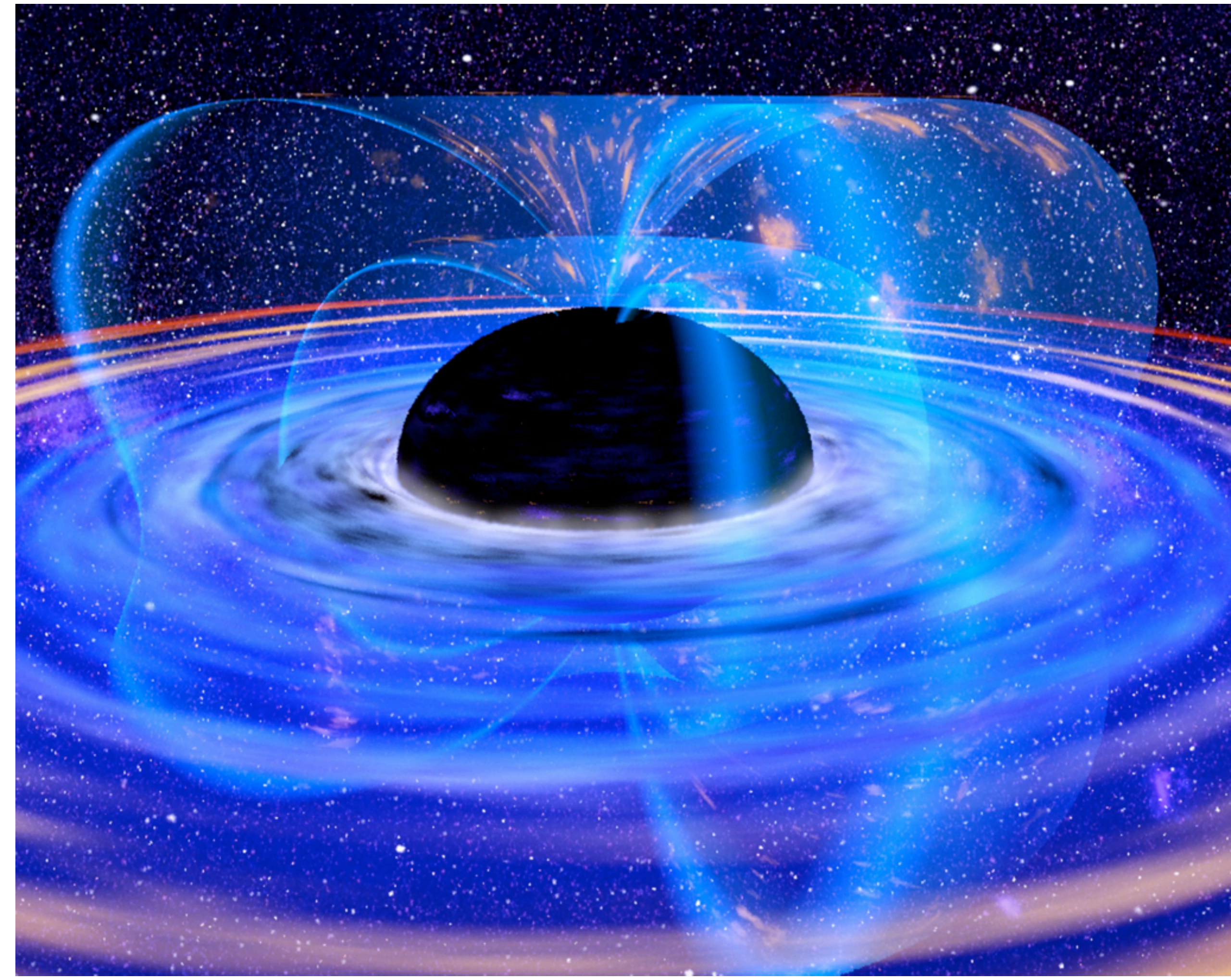
Dominik Schleicher
Departamento de Astronomía
Universidad de Concepción

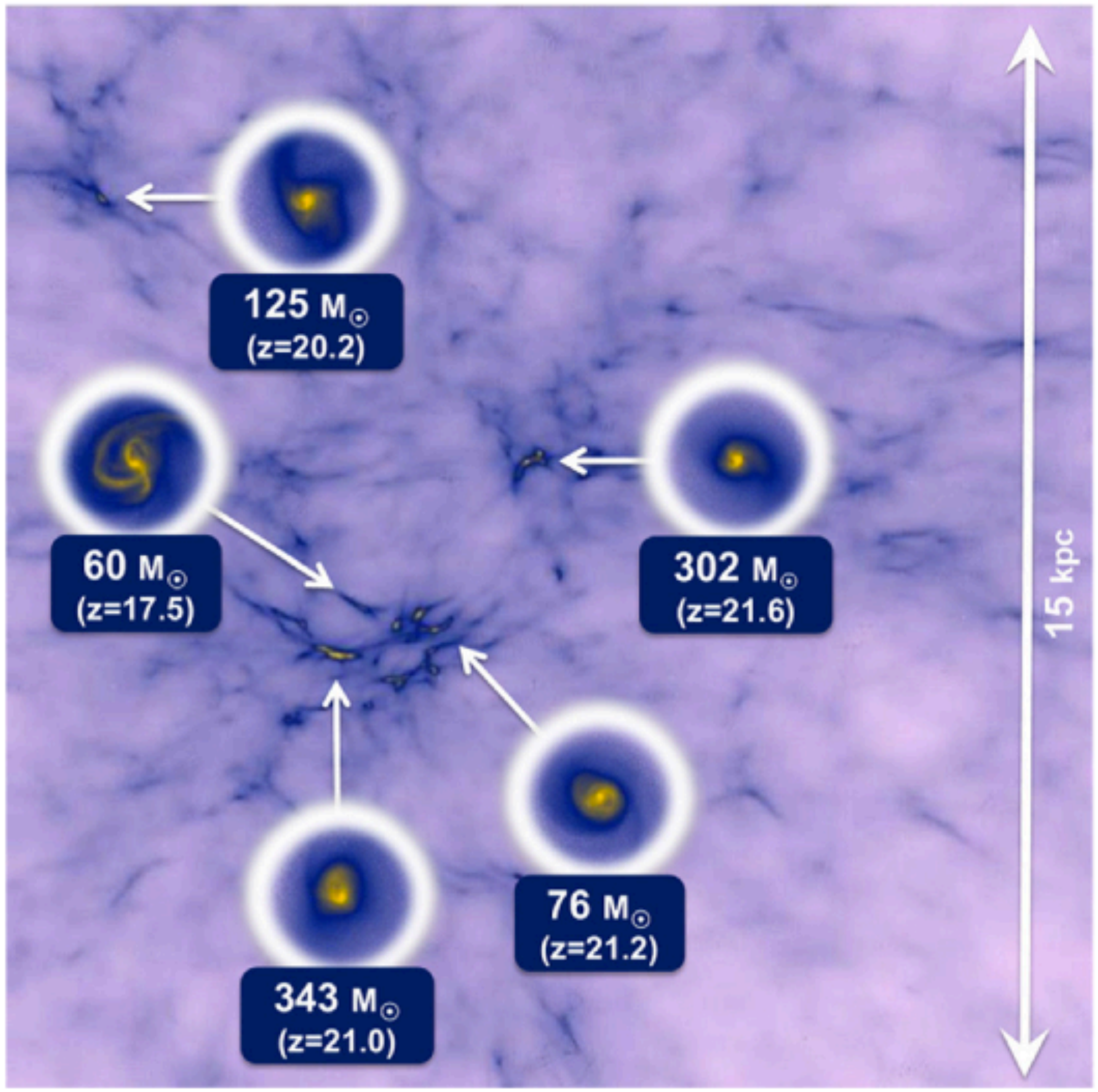
Collaborators:
Stefano Bovino (Hamburg), Pedro Capelo (Zürich), Stephanie Dörschner (Göttingen), Andrea Ferrara (Pisa), Tommaso Grassi (Copenhagen), **Muhammad Latif (Paris)**, Jens Niemeyer (Göttingen), Francesco Palla (Florence), Wolfram Schmidt (Hamburg), Marco Spaans (Groningen), Caroline Van Borm (Groningen)

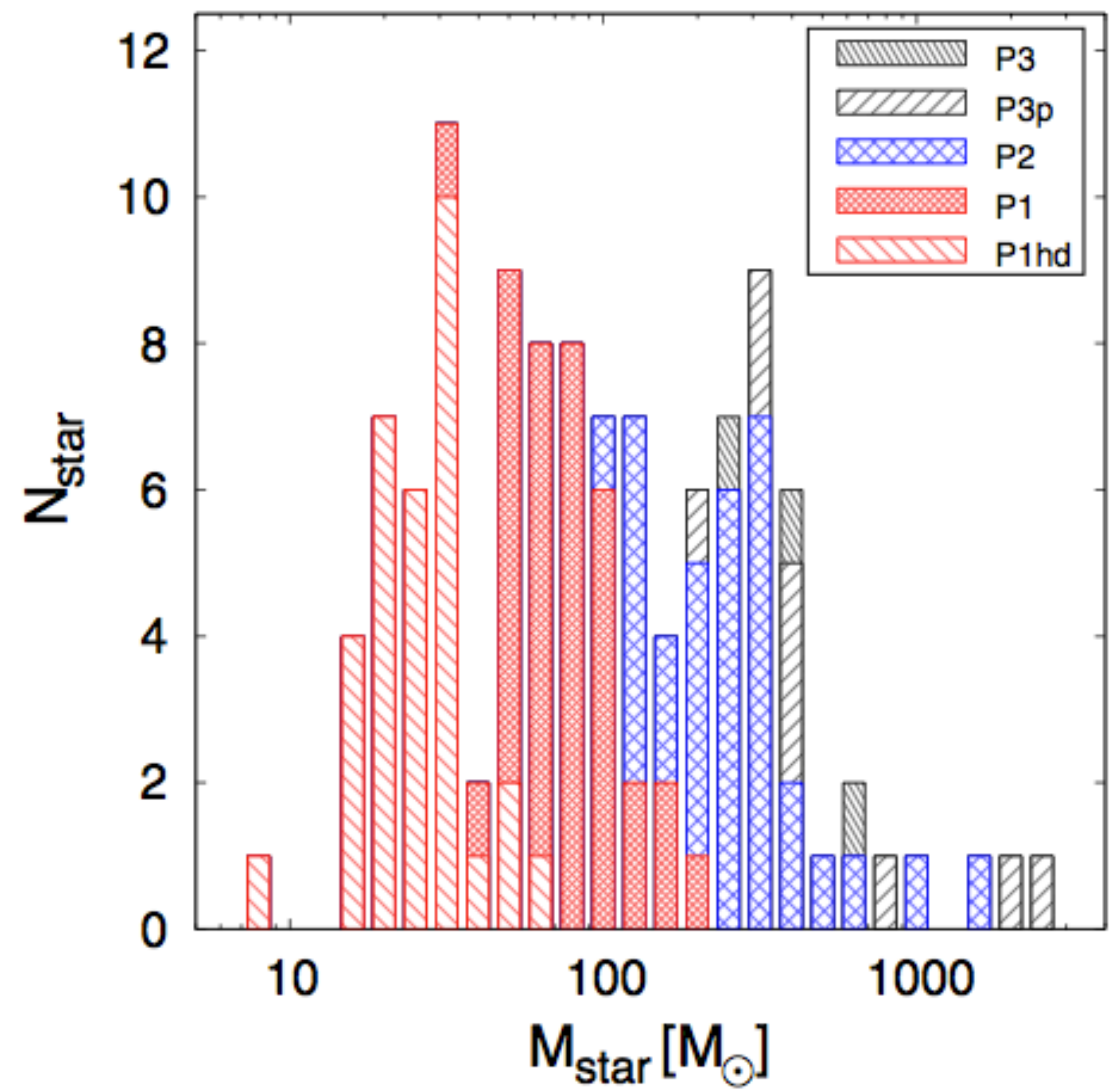
# Supermassive black holes at high redshift

- The highest-redshift black hole observed is at z=7.085 with $2 \times 10^9$ solar masses (Mortlock et al. 2011).
- A supermassive black hole with 12 billion solar masses has been observed at z=6.3 (Wu et al. 2015).
- Total accreted mass at z~6 $<1000\ M_{solar}\ Mpc^{-3}$ (Treister et al. 2013).



# Progenitors as massive primordial stars?

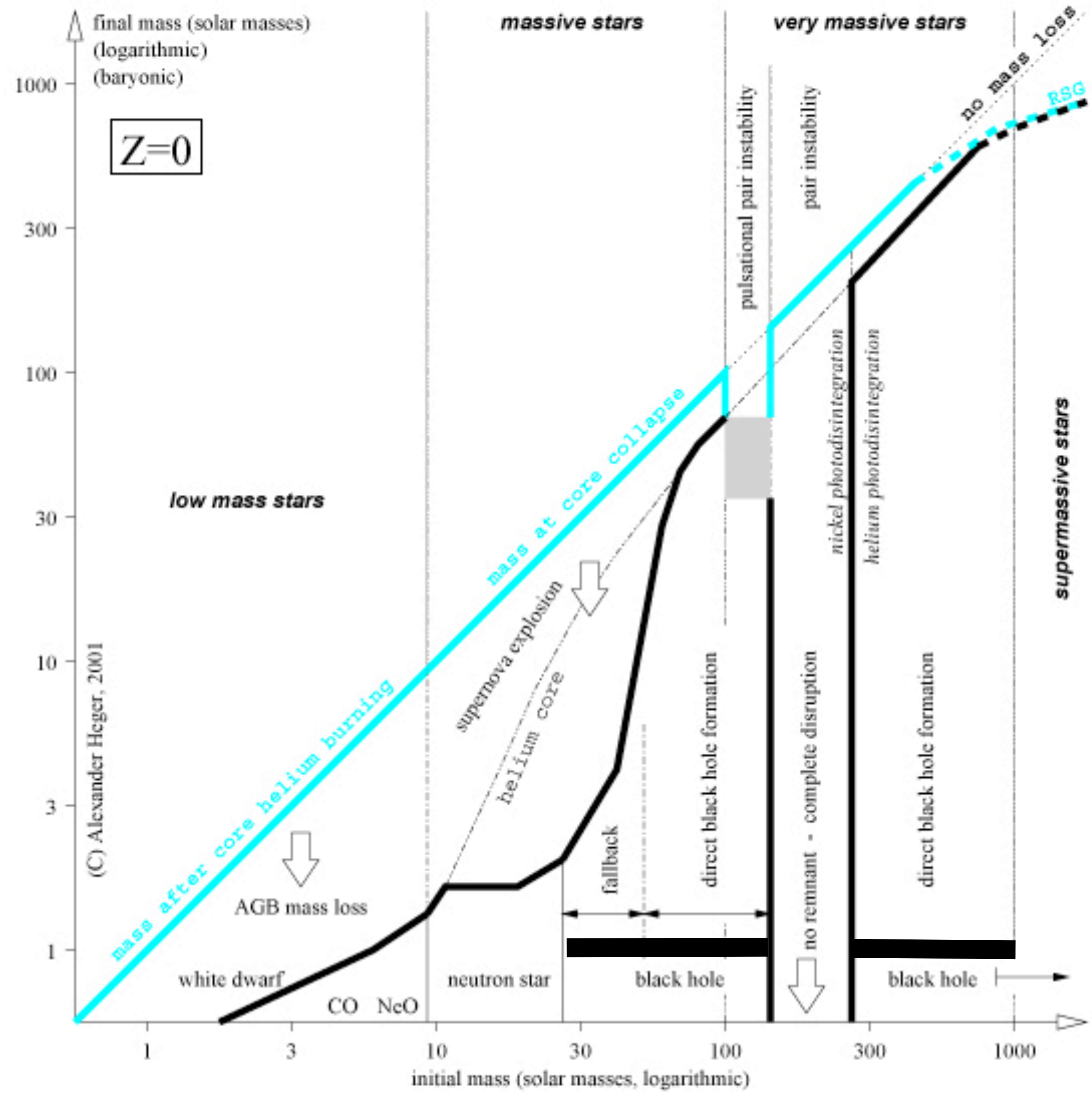



Hirano et al. (2014): Potentially stars more than 1000 solar masses.

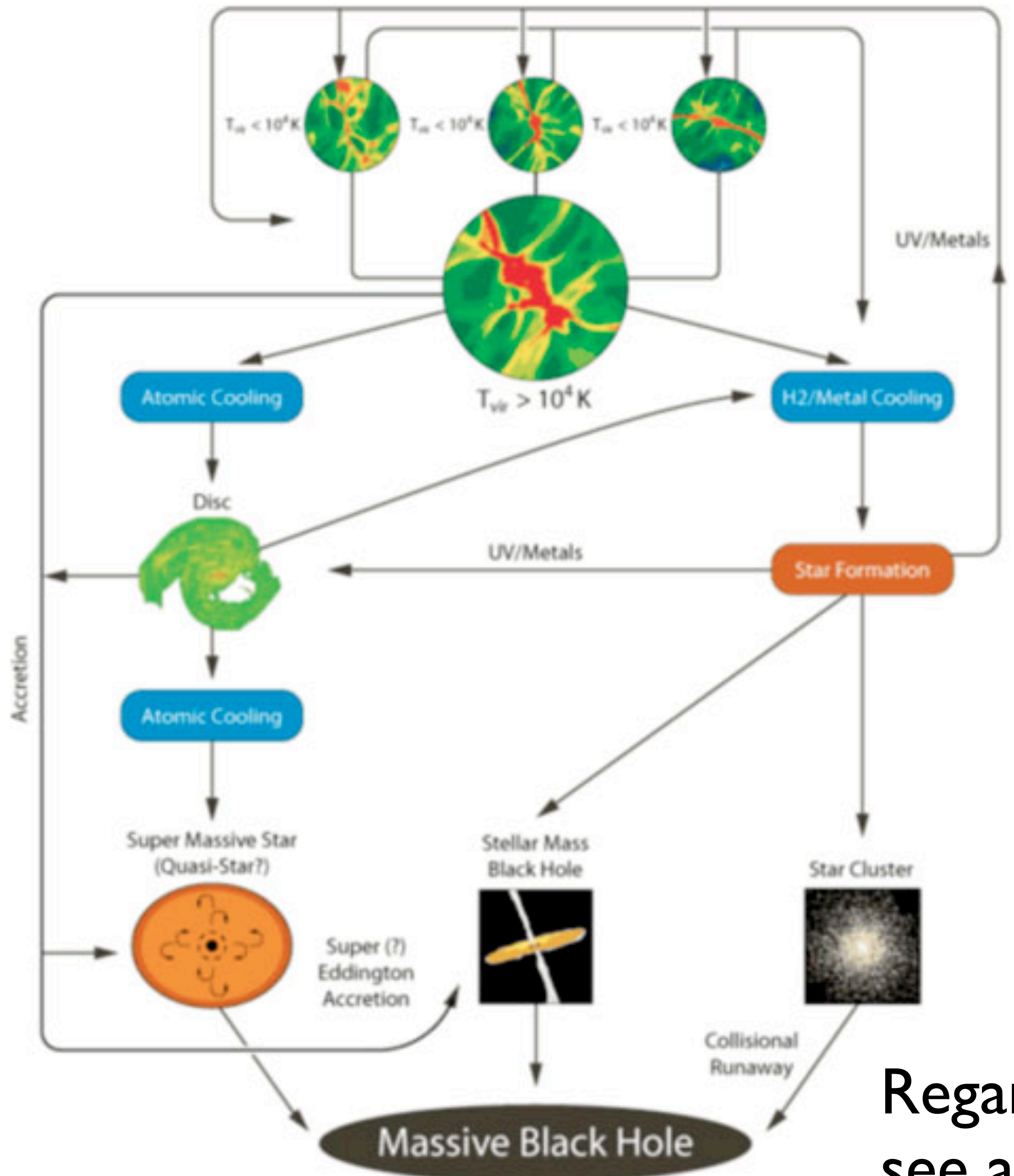
# Black holes from the first stars

- Stellar black holes could form between 30-100 or 300 to 1000 solar masses.
- Recent simulations show fragmentation and reduced masses (Clark et al. 2011, Greif et al. 2012, Latif et al. 2013).



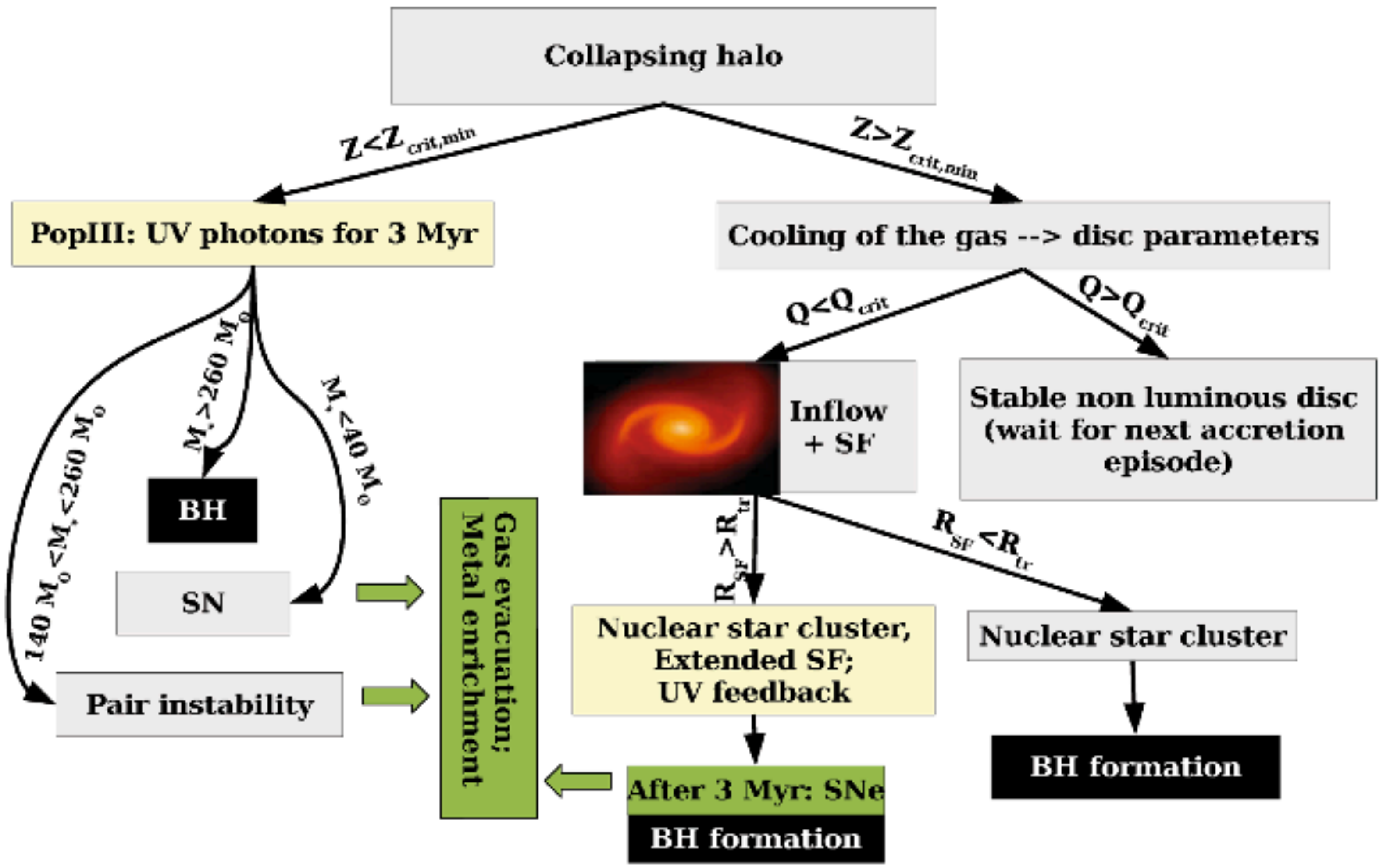

Heger et al. (2002)

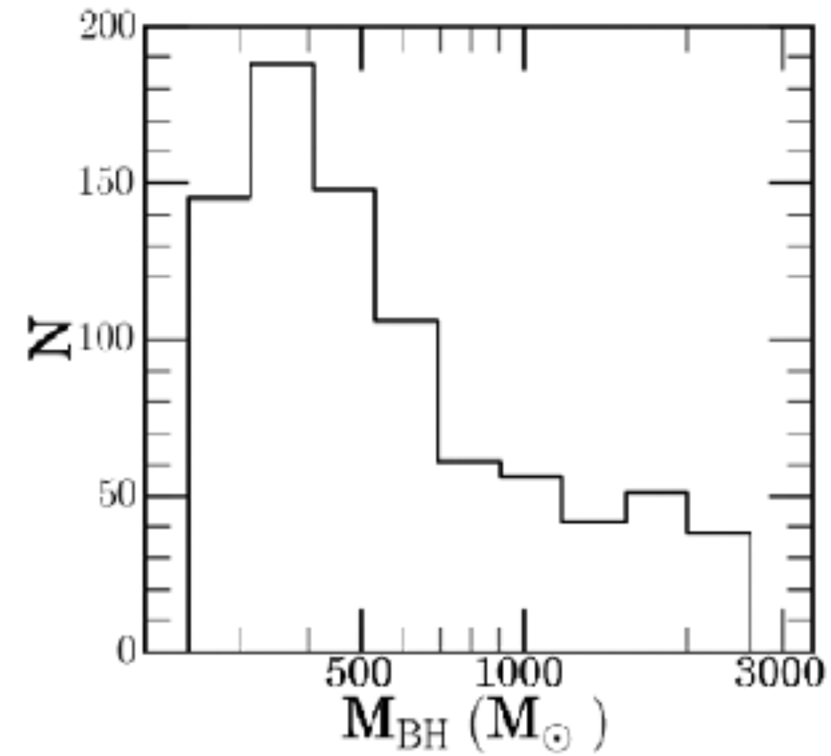
# Pathways to black hole formation




Regan et al. (2009),
see also M. Rees (1978)

# Black holes from stellar clusters

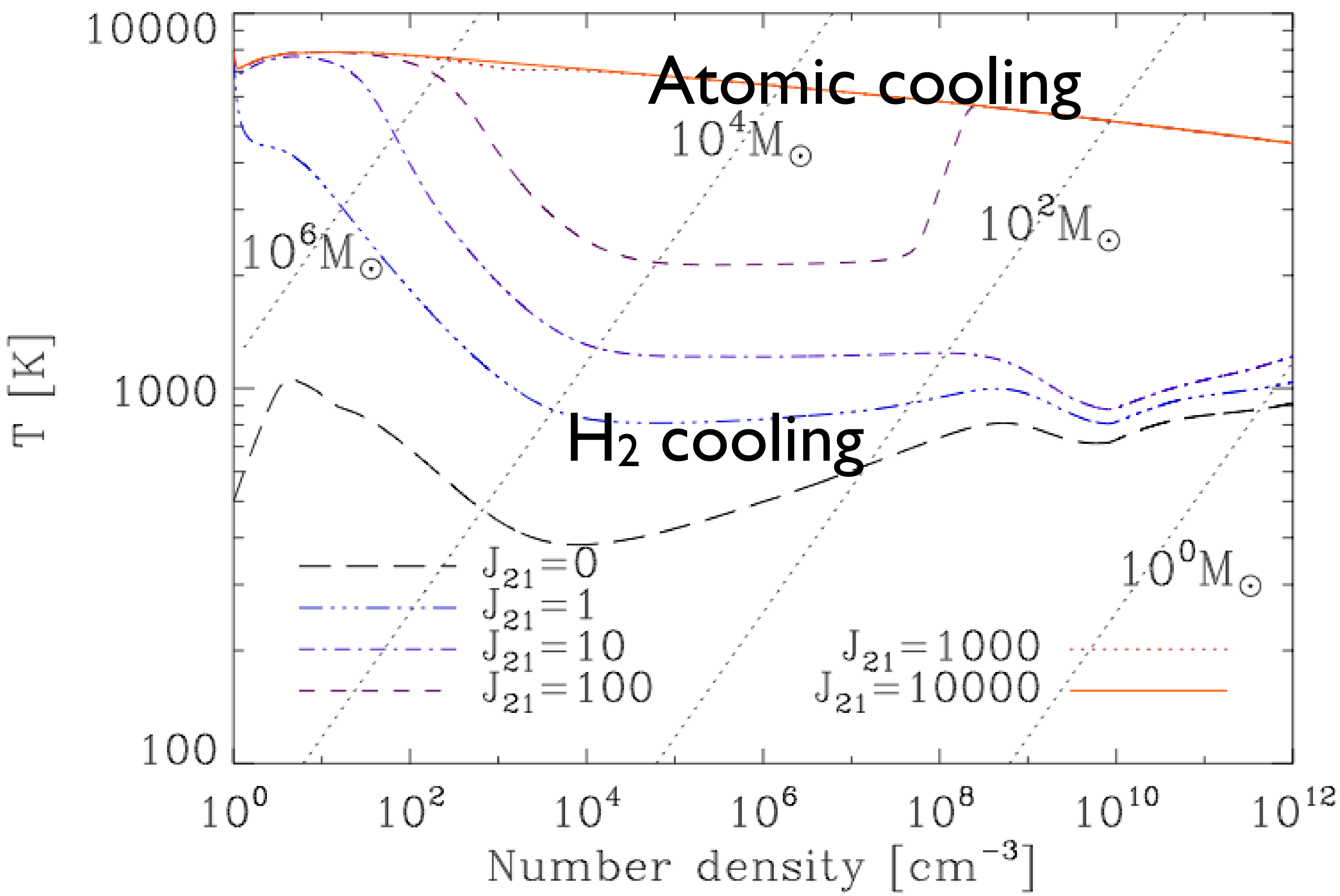



~1000 $M_{solar}$ mass black holes from stellar clusters

Devecchi et al. (2012)

# Thermodynamics in primordial gas

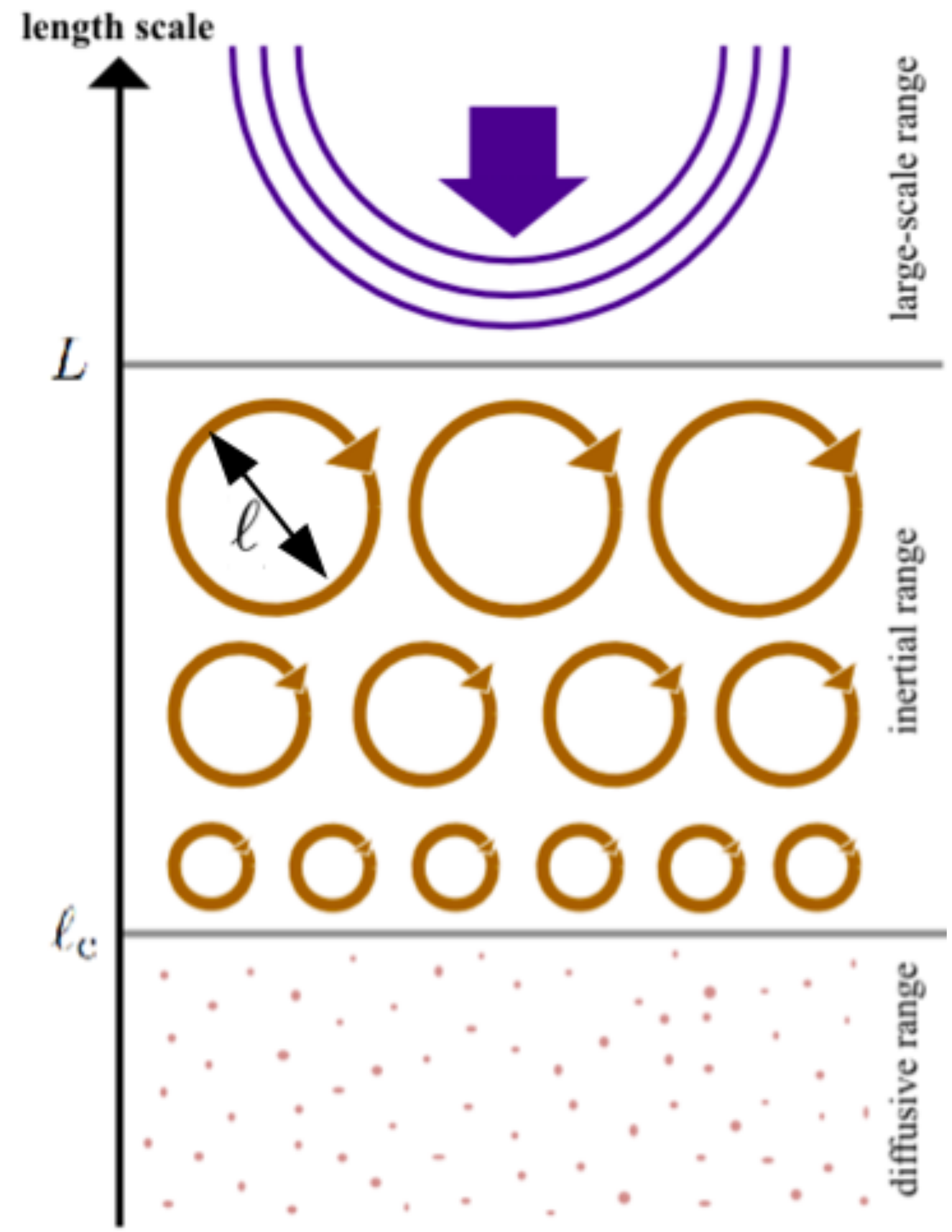



UV radiation: $J(\nu) = J_{21} \times 10^{-21} \frac{B_\nu(T_r)}{B_{\nu,H}(T_r)}\ erg\ s^{-1}\ cm^{-2}\ sr^{-1}\ Hz^{-1}$

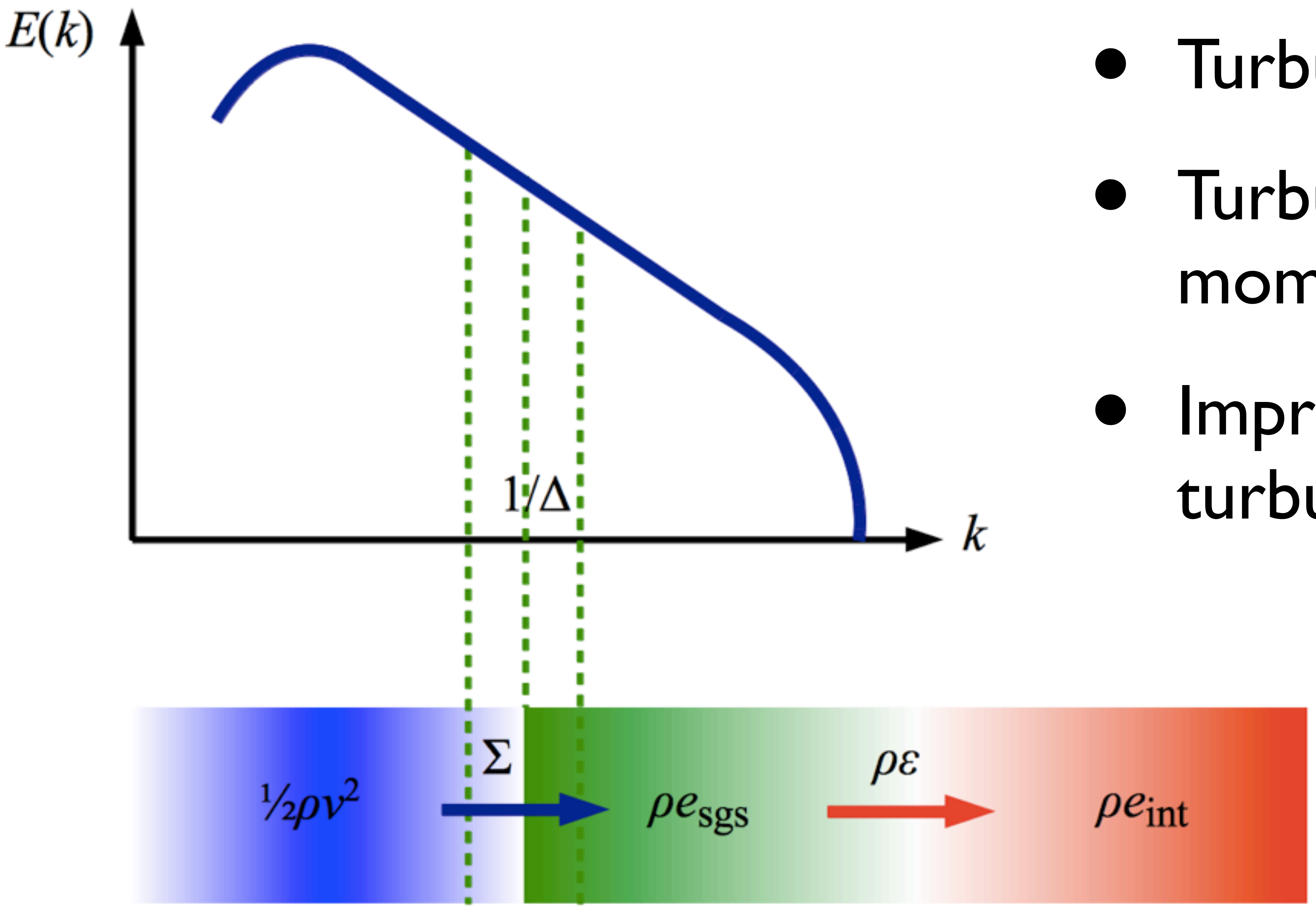
Schleicher, Spaans & Glover (2010)

# Impact of turbulence

- During gravitational collapse, turbulence is driven on the Jeans scale.
- Typical simulations resolve the Jeans length with 4-16 cells (Truelove 1997).
- Resolving turbulent eddies requires a numerical resolution of at least 32 cells per eddy! (Federrath et al. 2011, Latif et al. 2013).



# Resolution limits: Turbulence on unresolved scales



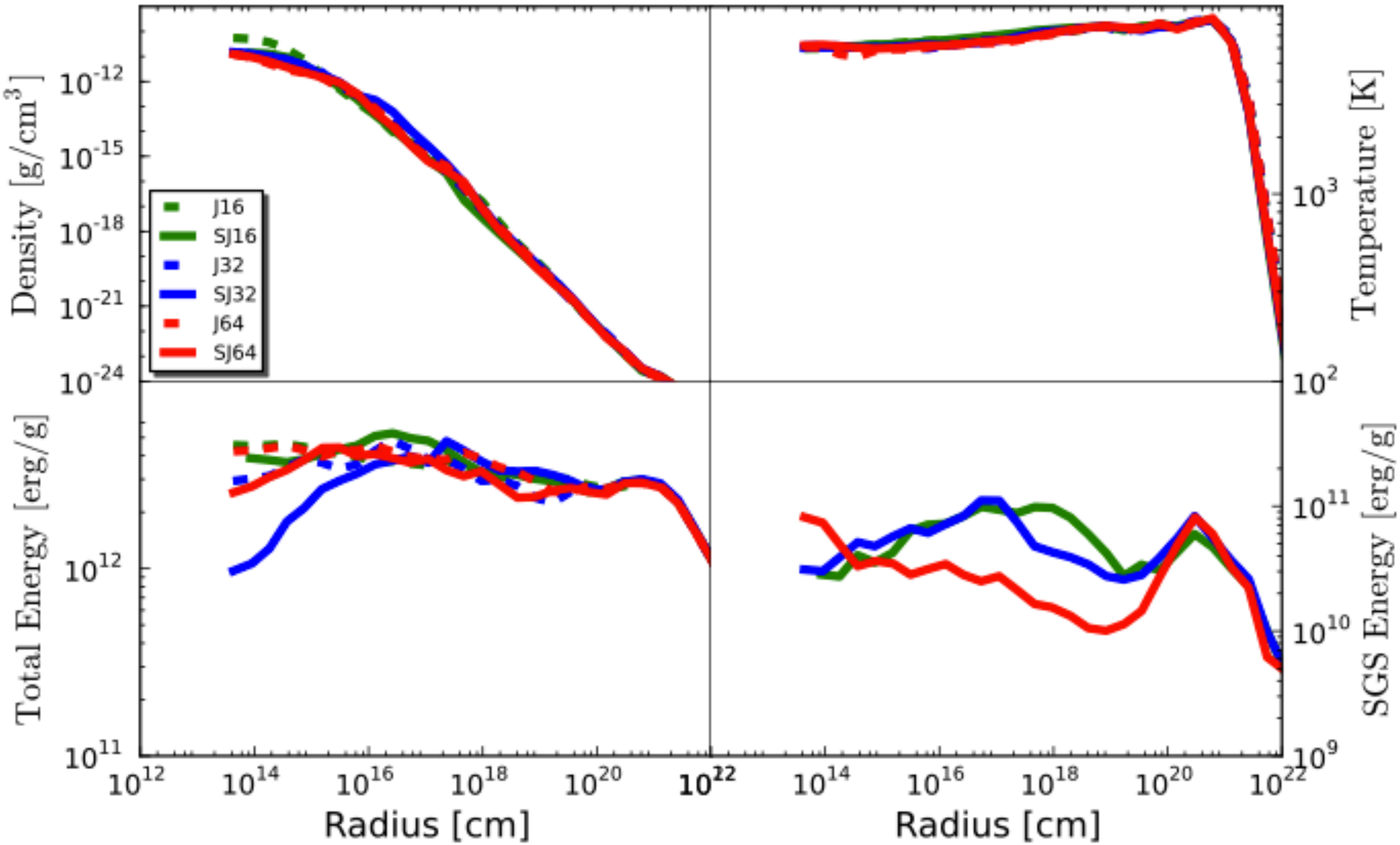

- Turbulent pressure
- Turbulent angular momentum transport
- Improved treatment of turbulent dissipation.

Schmidt & Federrath (2011)

# Simulations of black hole formation

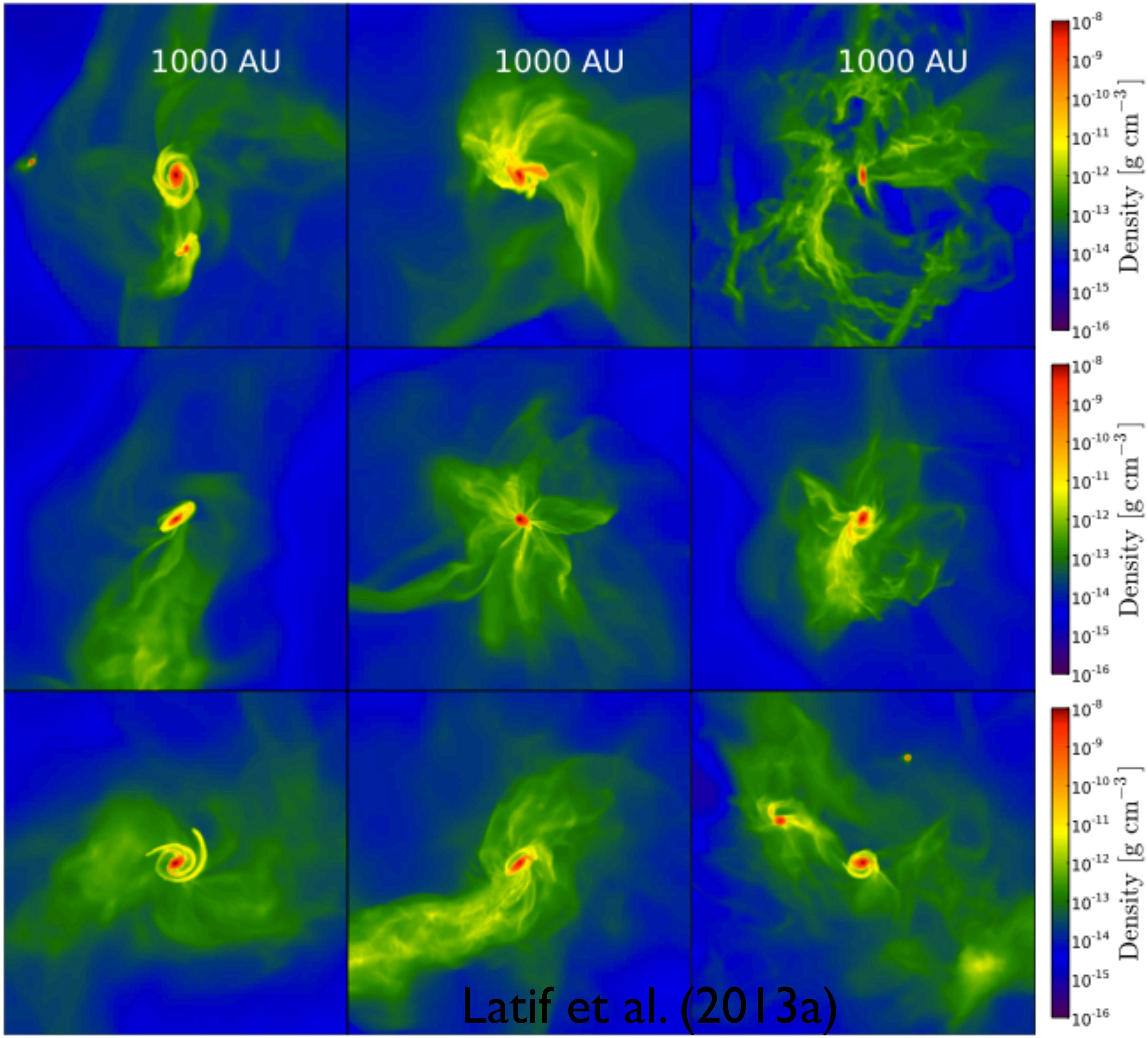
- Cosmological simulations with the adaptive mesh refinement code Enzo.
- Physics modules: dark matter, hydrodynamics, SGS turbulence and primordial chemistry.
- Focus on gravitational collapse in $10^7$ solar mass halos.
- The evolution becomes adiabatic at densities $>10^{-10}$ g cm$^{-3}$ to mimic the formation of protostellar cores.
- We will initially consider a strong radiation background to dissociate molecular hydrogen.

# Halo structure after the initial collapse

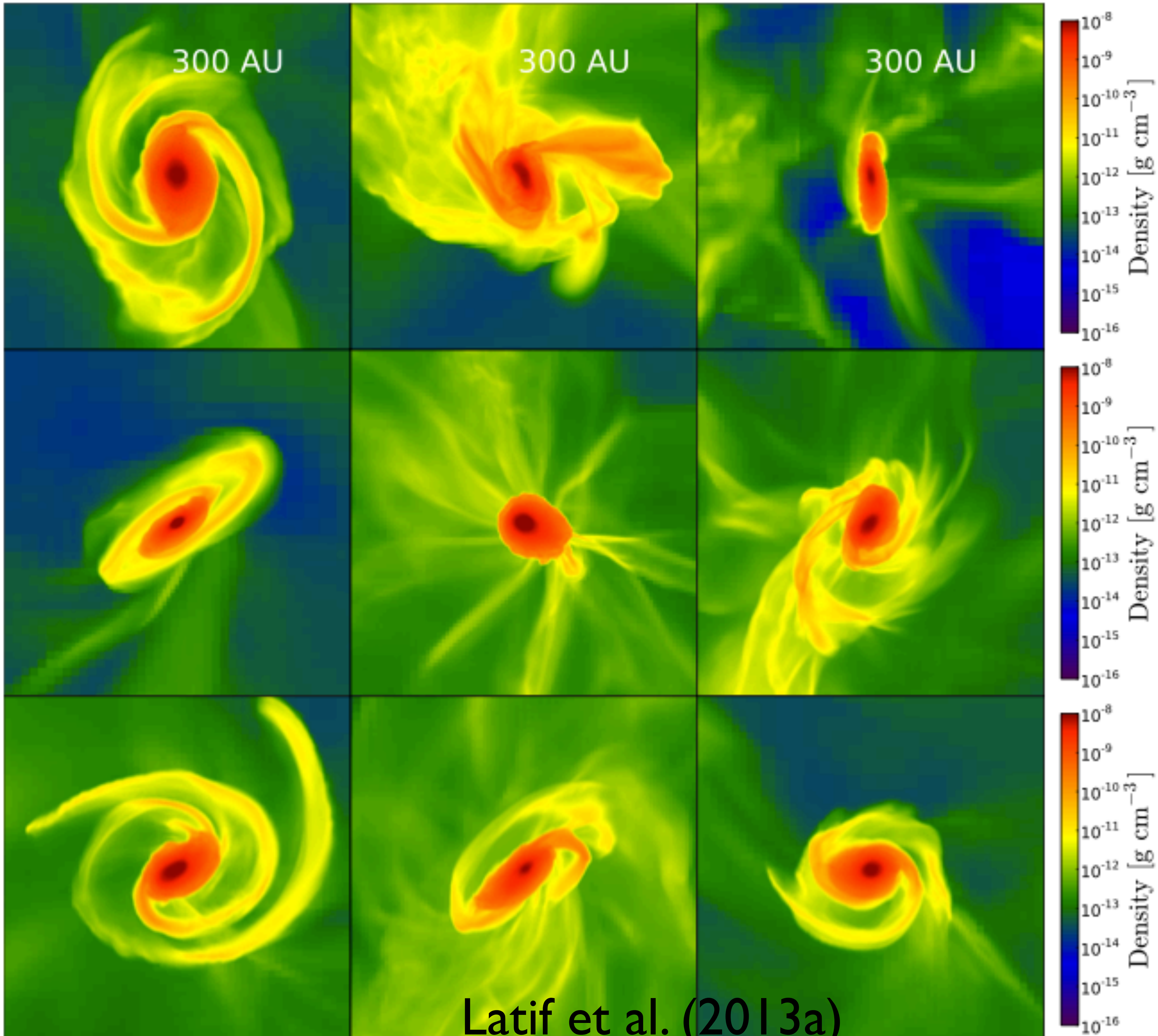



Latif, Schleicher, Schmidt & Niemeyer (2013a)

# The central region after four free-fall times

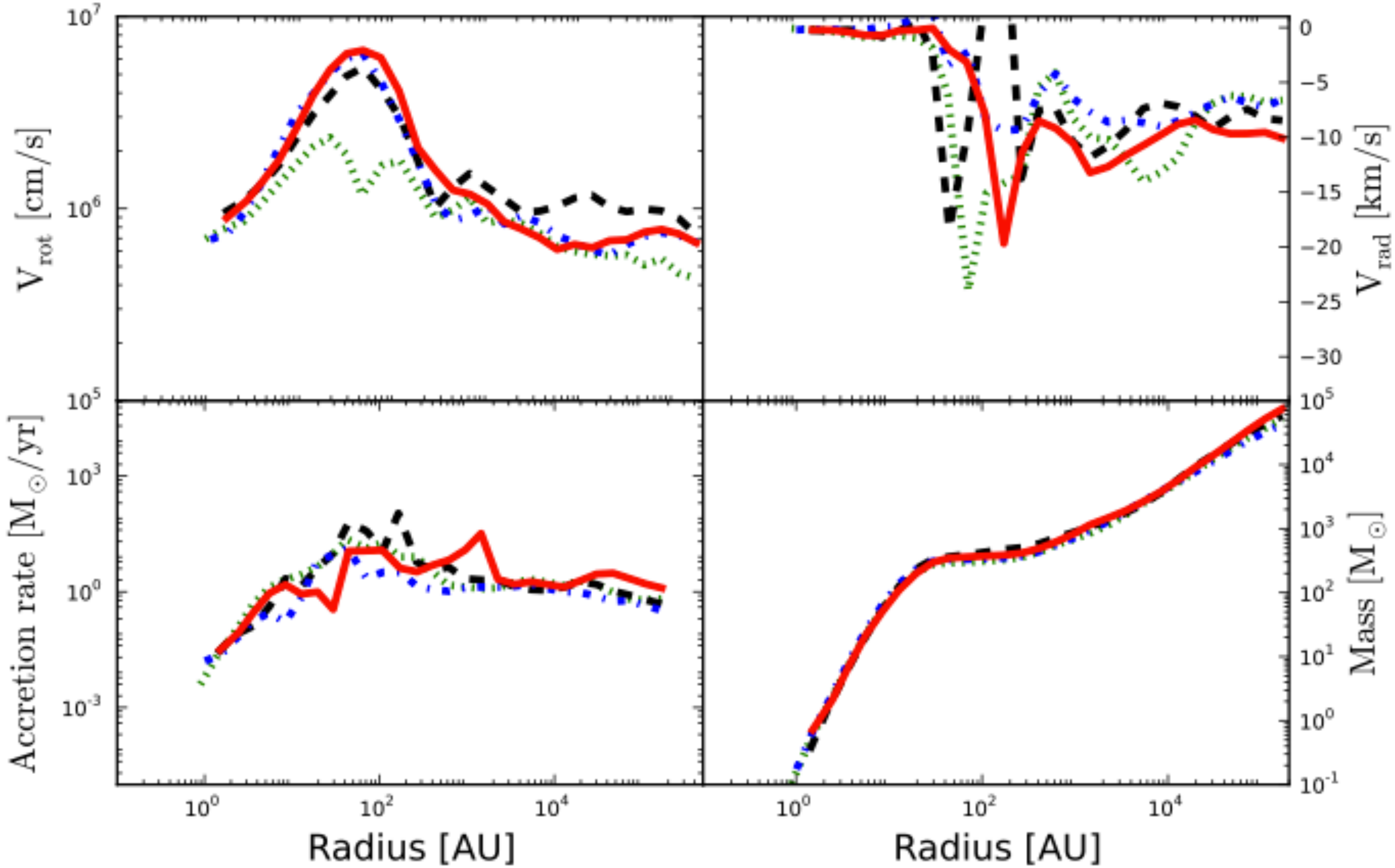


# Formation of self-gravitating disks



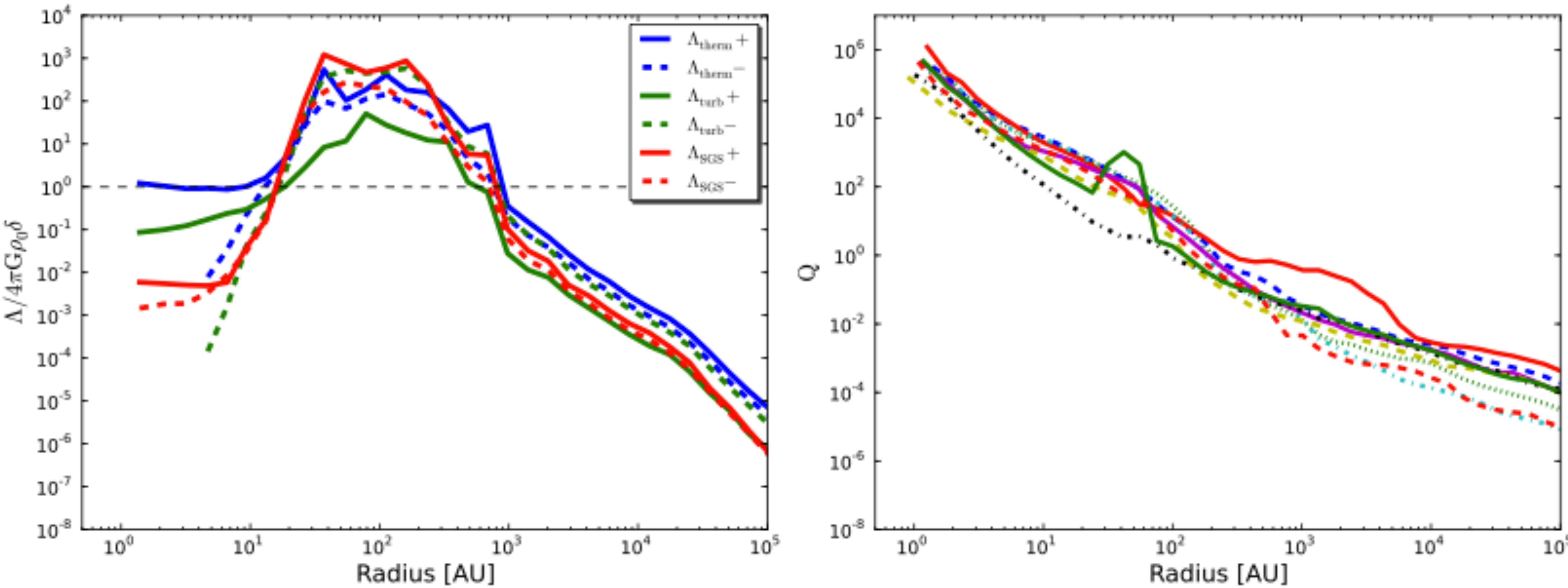

Latif et al. (2013a)

# Radial profiles after four free-fall times




Latif, Schleicher, Schmidt & Niemeyer (2013a)

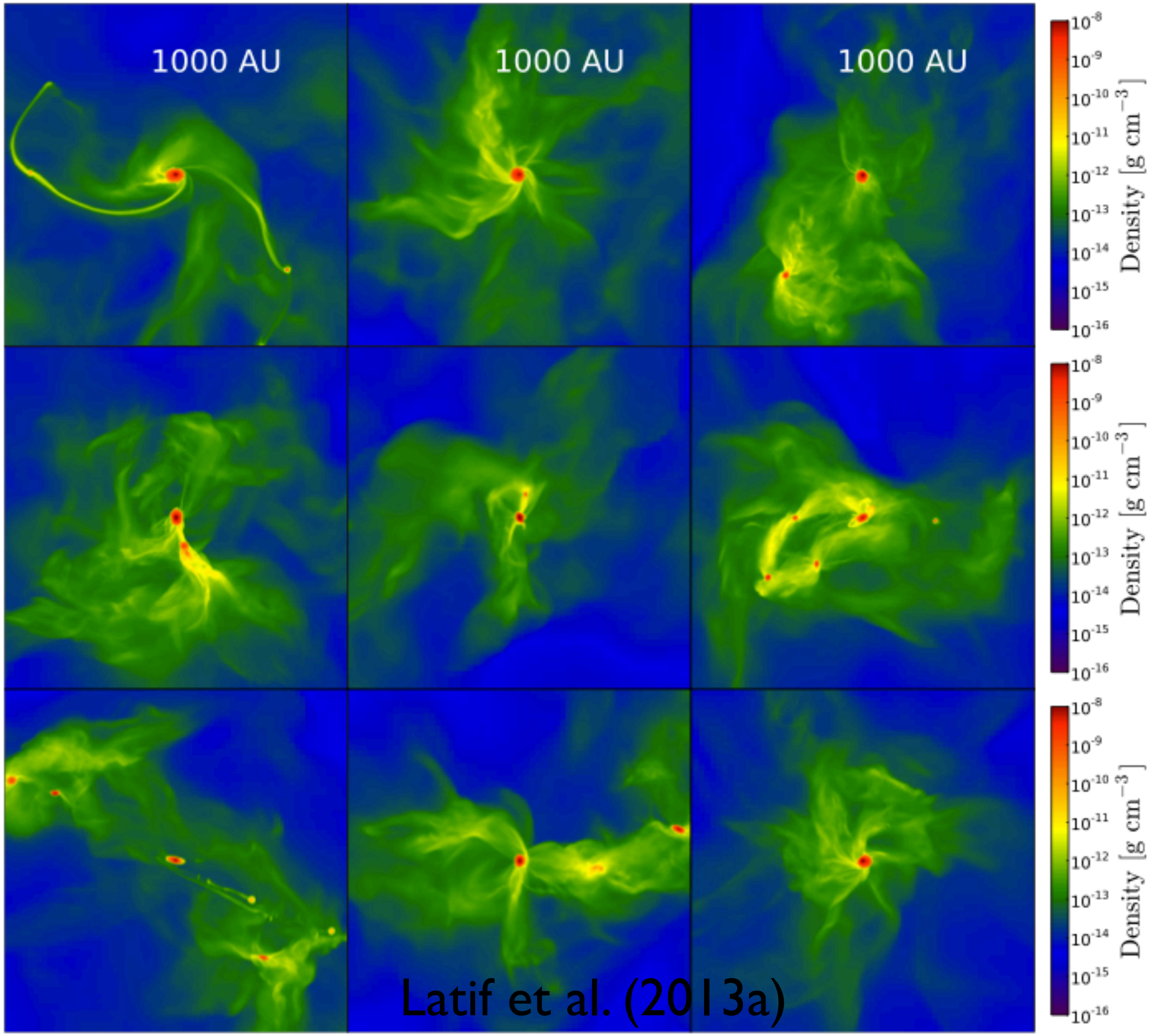
# Disk stability and support against gravity




Left: Support against gravity by thermal pressure, resolved turbulence and unresolved turbulence.
Right: Toomre-Q parameter for disk stability.

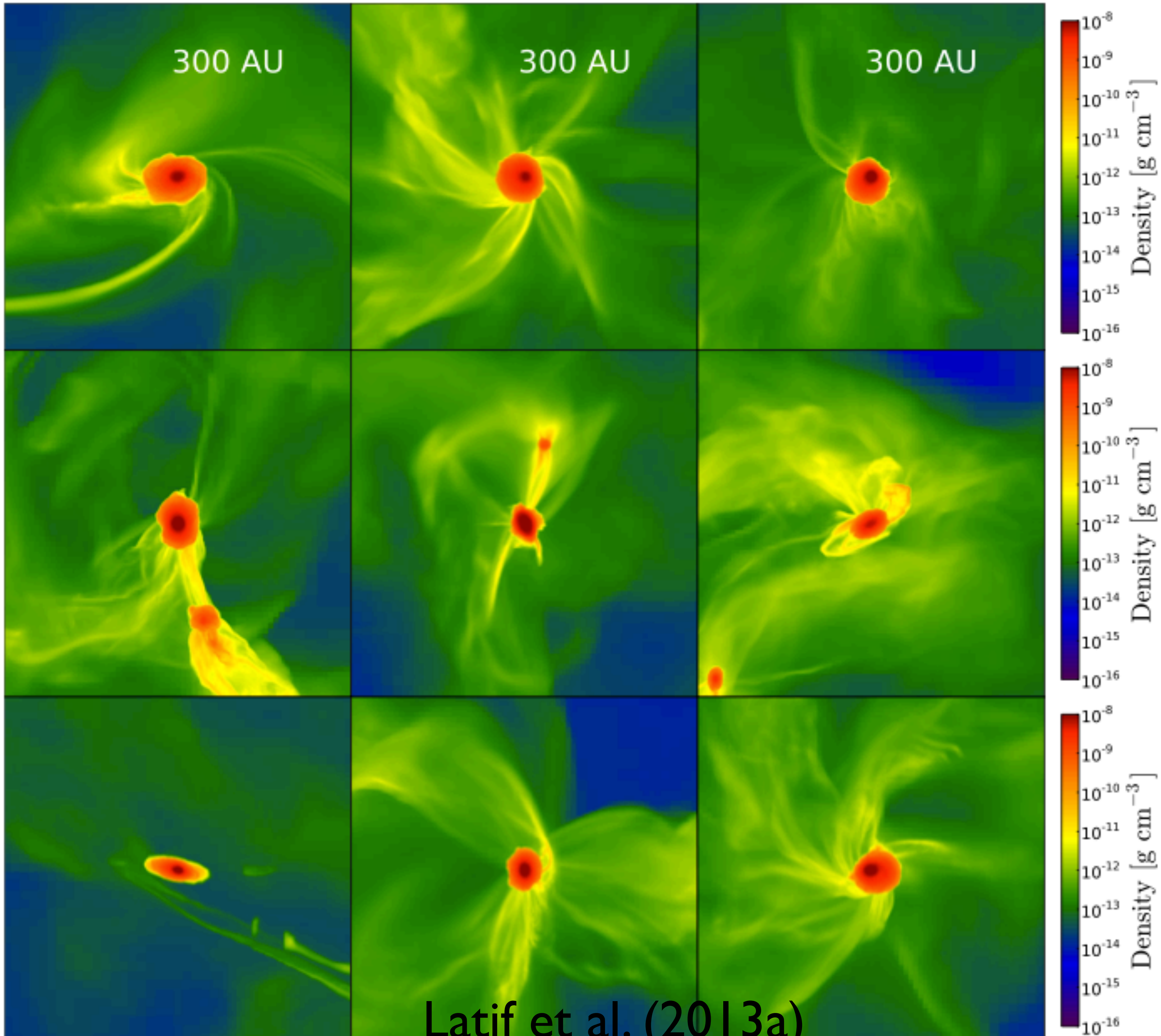
Latif, Schleicher, Schmidt & Niemeyer (2013a)

# Comparison run: no SGS model




Latif et al. (2013a)

# Comparison run: no SGS model




Latif et al. (2013a)

# Central clump masses

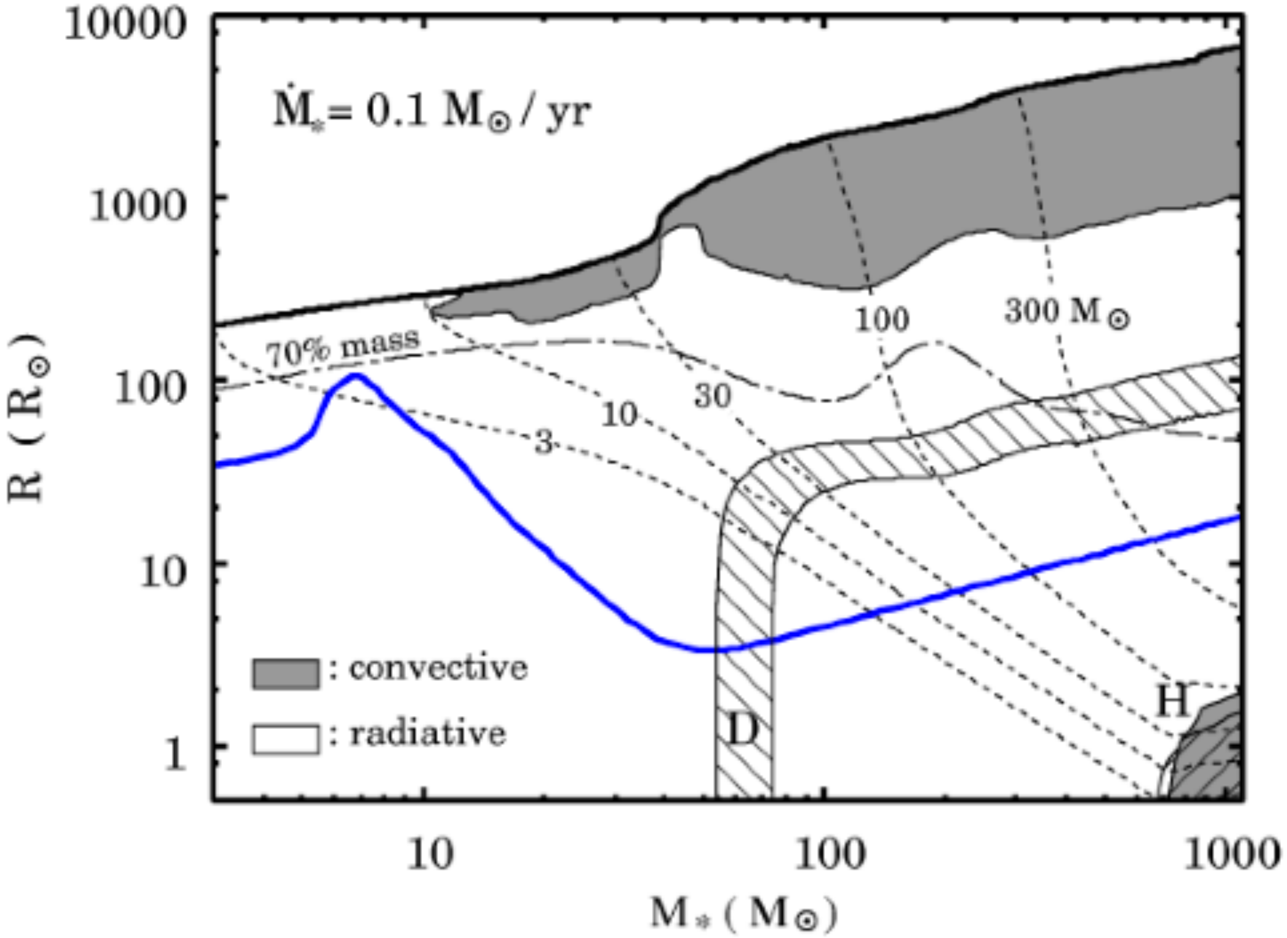
Table 1: Properties of the simulated halos are listed here

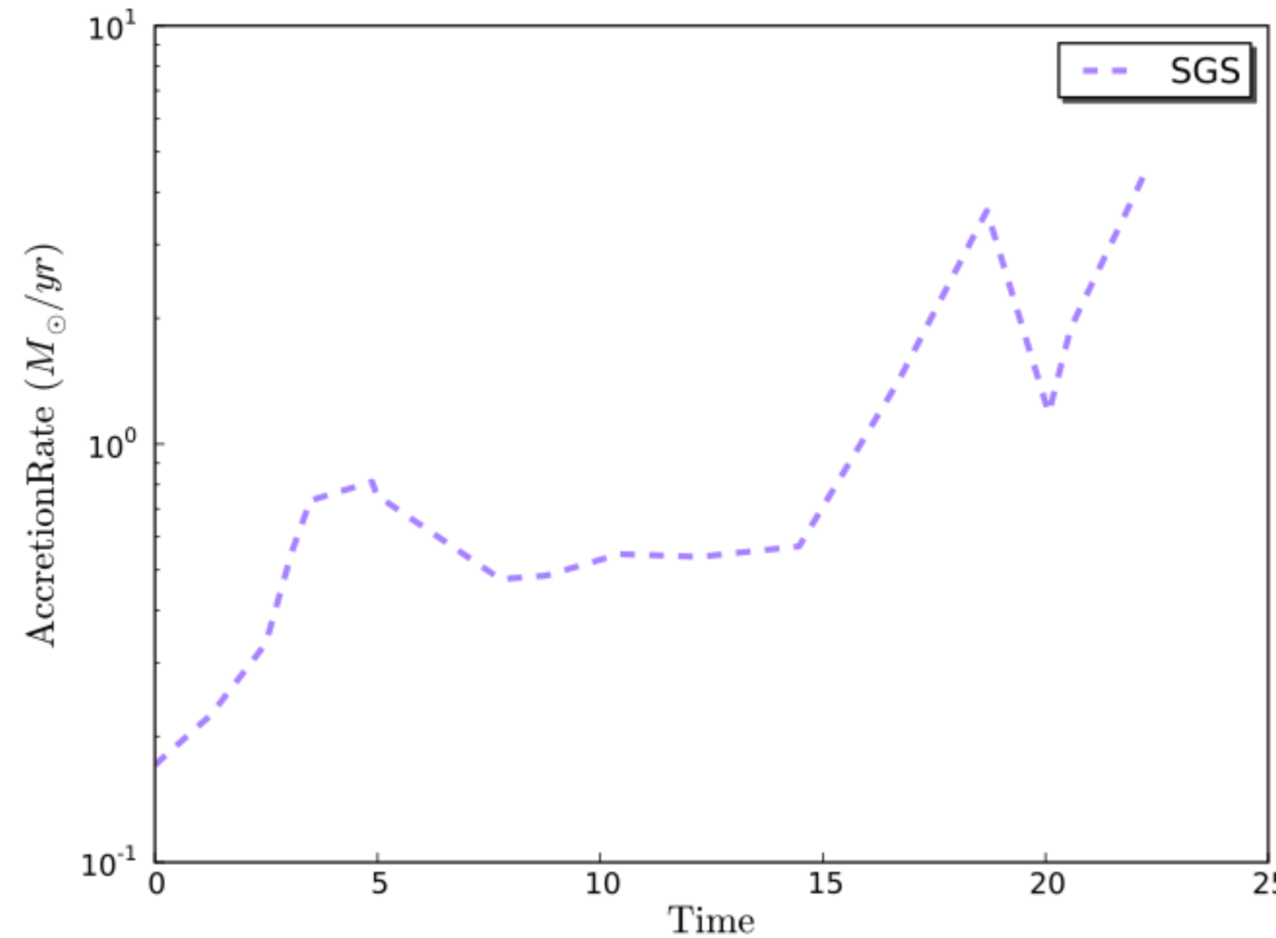
| Model | Mass $M_\odot$ | spin parameter $\lambda$ | Collapse redshift z | Clump Masses LES ($M_\odot$) | Clump Masses ILES ($M_\odot$) |
|---|---|---|---|---|---|
| A | $8.06 \times 10^6$ | 0.0347468 | 12.06 | 950 | 460 |
| B | $4.3 \times 10^6$ | 0.0309765 | 11.3 | 850 | 850 |
| C | $2 \times 10^7$ | 0.0178532 | 12.6 | 800 | 611 |
| D | $1.0 \times 10^7$ | 0.0338661 | 12.8 | 850 | 842 |
| E | $1.9 \times 10^7$ | 0.0084786 | 13.7 | 1200 | 741 |
| F | $4.5 \times 10^7$ | 0.0294066 | 18.1 | 800 | 588 |
| G | $2.3 \times 10^7$ | 0.021782 | 15.9 | 800 | 815 |
| H | $9.7 \times 10^6$ | 0.0099387 | 13.5 | 900 | 1522 |
| I | $8.2 \times 10^6$ | 0.0252206 | 15.0 | 556 | 1000 |

Characteristic mass scales are similar for hydro and SGS runs, but much more variation in standard hydro results!

Latif et al. (2013a)

# Implications of high accretion rates

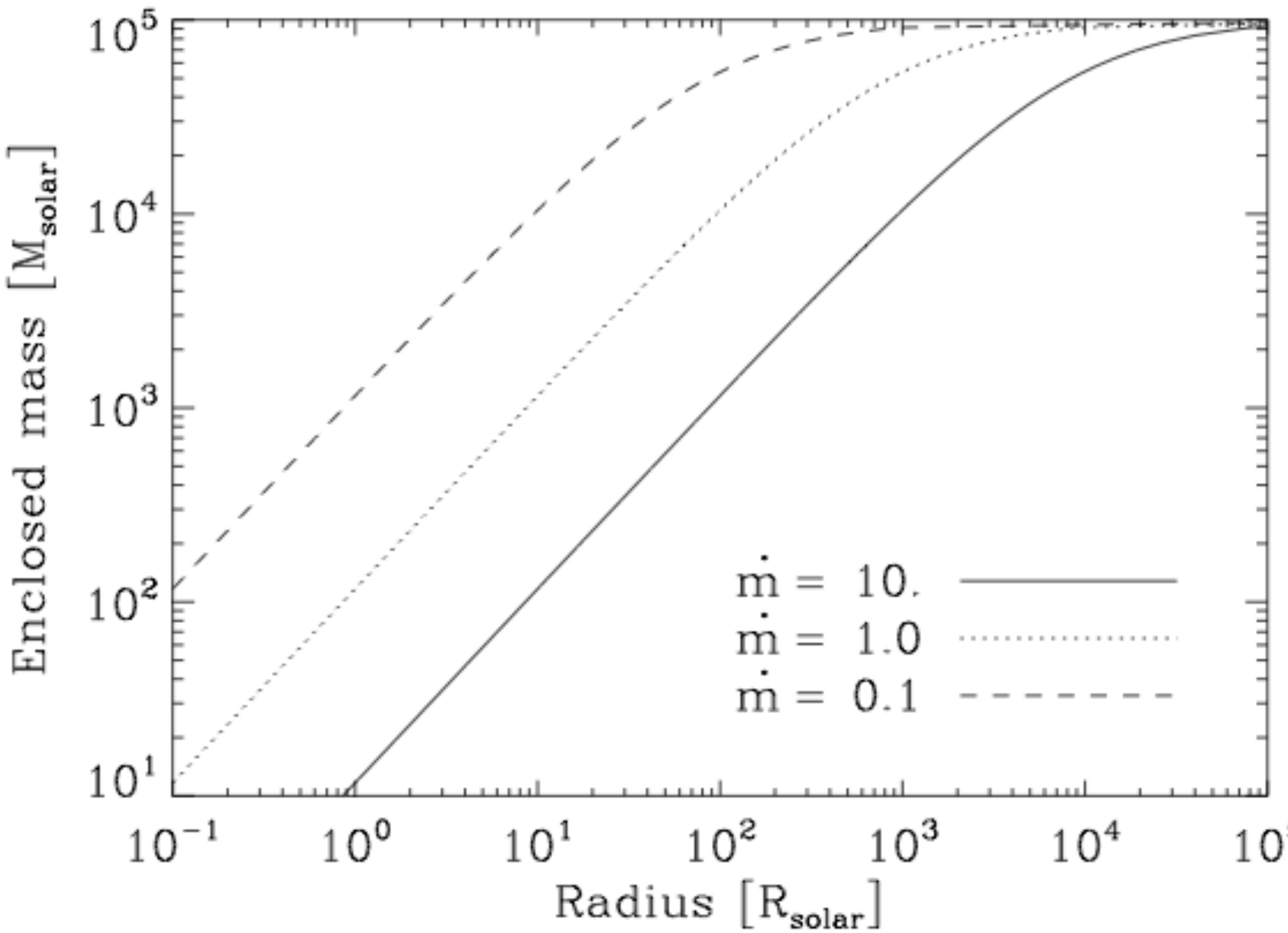



Hosokawa et al. (2012):
Very extended protostellar envelopes at high accretion rates (>0.006 $M_{solar}$ per year).

Latif et al. (2013a):
Accretion rates of order 1 $M_{solar}$ per year in the first four free-fall times.

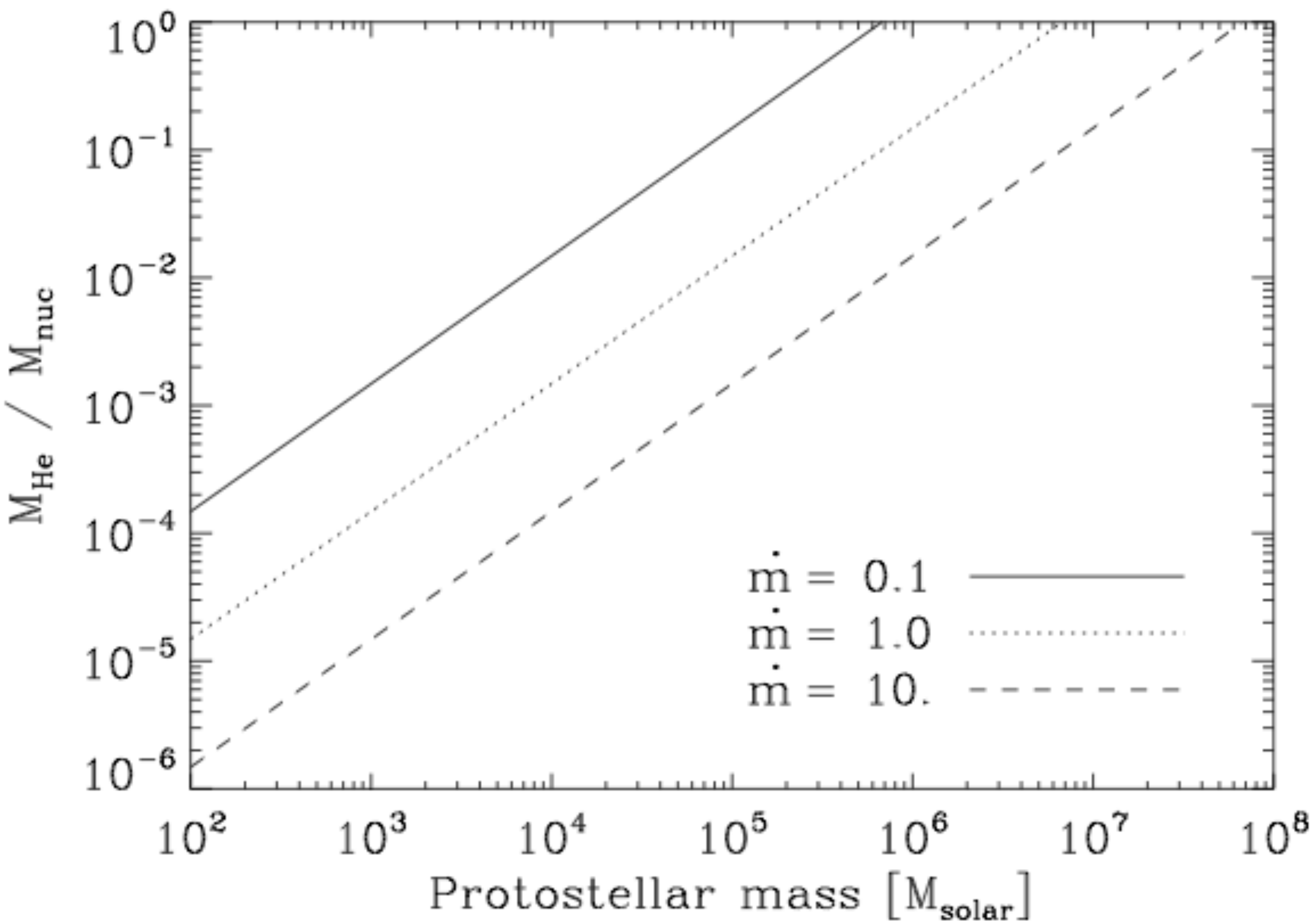
# Interaction of accretion and contraction




Timescale to transport mass in the nuclear core >> Kelvin-Helmholtz time until $M \geq 3.6 \times 10^8 \, \dot{m}^3 M_\odot$

Schleicher, Palla, Ferrara, Galli & Latif (2013)

# Supermassive stars or quasi-stars?




The helium core is exhausted after

$$t_{\mathrm{He,CNO}} = 2.25 \times 10^5 \epsilon_{\mathrm{fill},-1}^{-1}\ \mathrm{yr}$$

Result: Core collapses to a black hole -> quasi-star.

The core mass is then

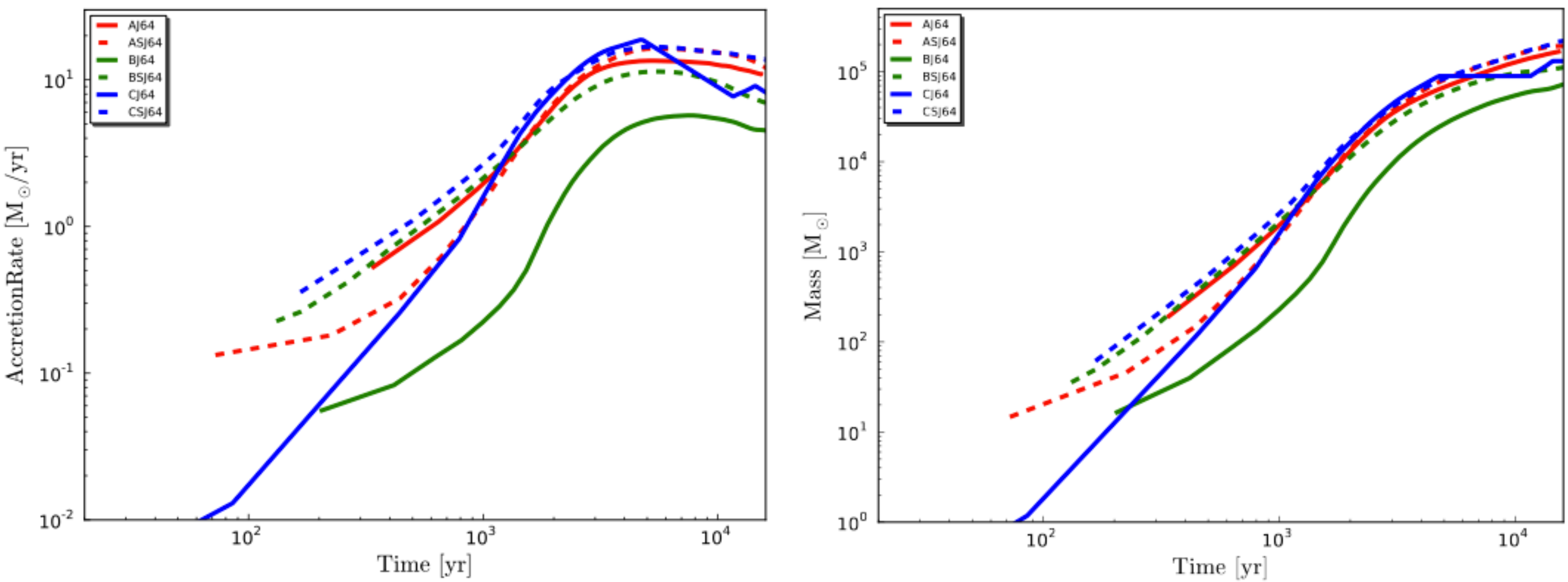
$$M_{\mathrm{He,CNO}} = 1.0 \times 10^{-3} \epsilon_{\mathrm{fill}}^2\, t_{710}^{7/2}\, M_\odot$$

However, this stage is only reached for

$$\dot{m} \gg 0.14$$

Schleicher, Palla, Ferrara, Galli & Latif (2013)

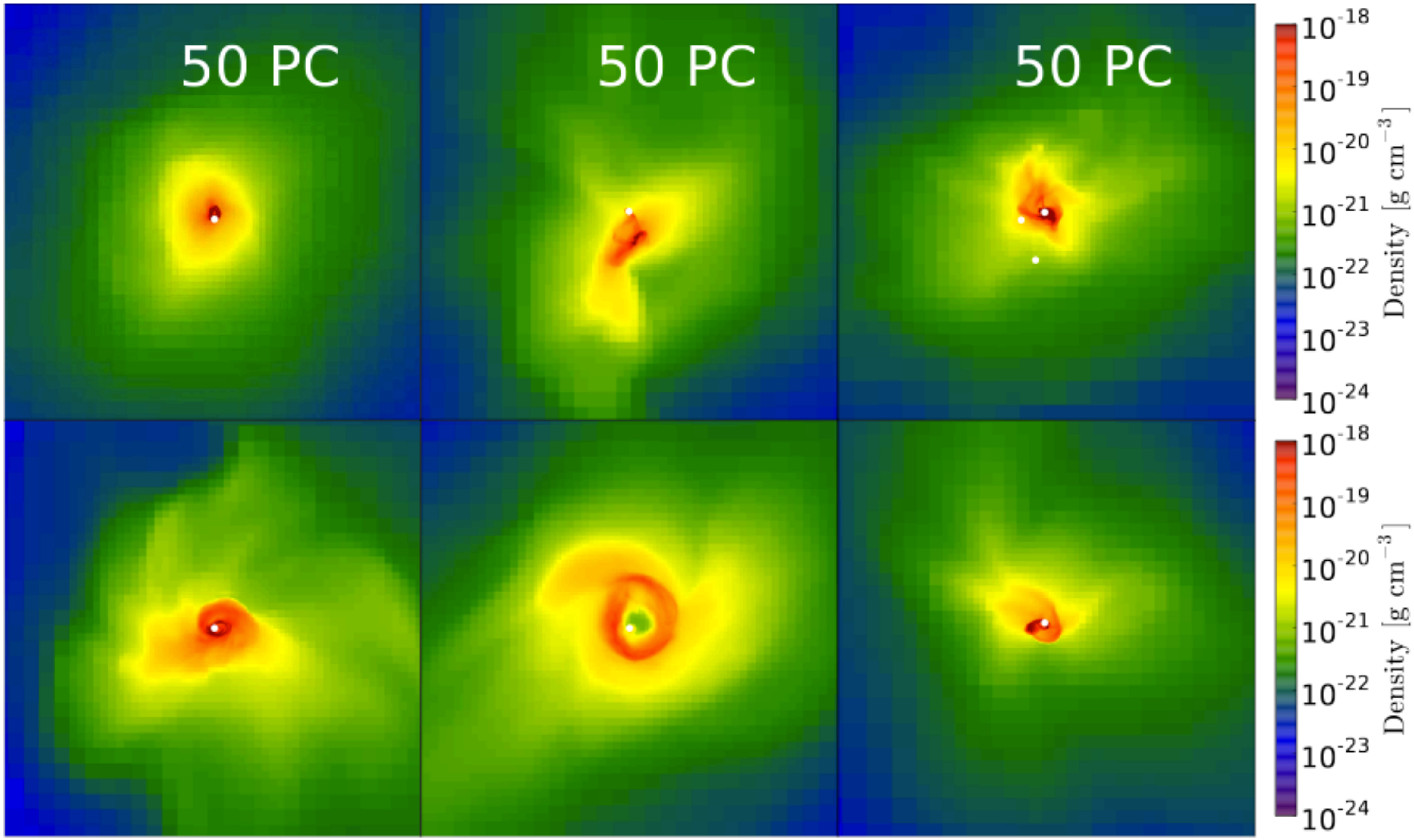
# The longer-term evolution




Characteristic time evolution of the accretion in four different halos

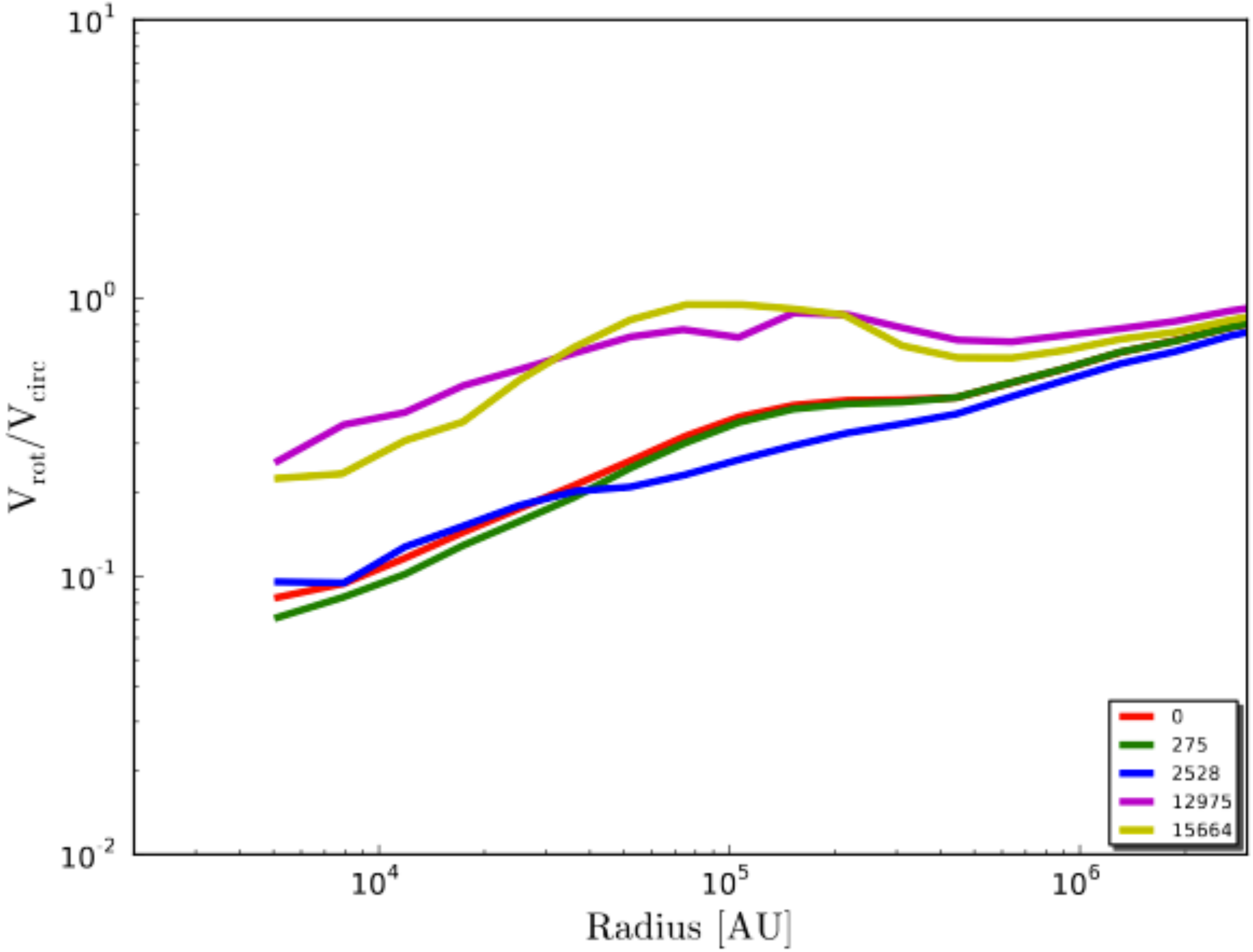
Latif, Schleicher, Schmidt & Niemeyer (2013b)

# Density distribution after 20000 years



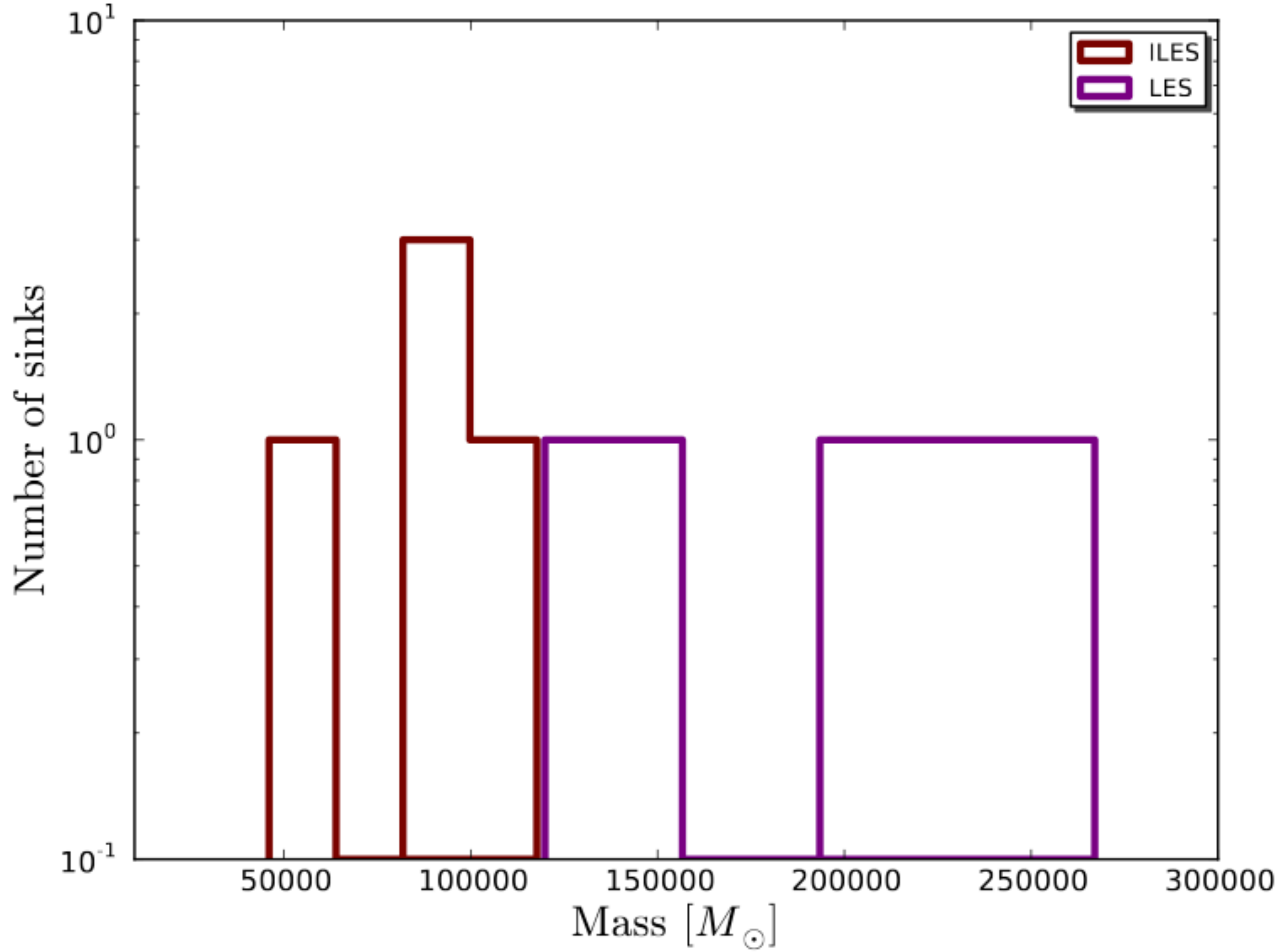

Latif, Schleicher, Schmidt & Niemeyer (2013b)

# Stabilization via angular momentum



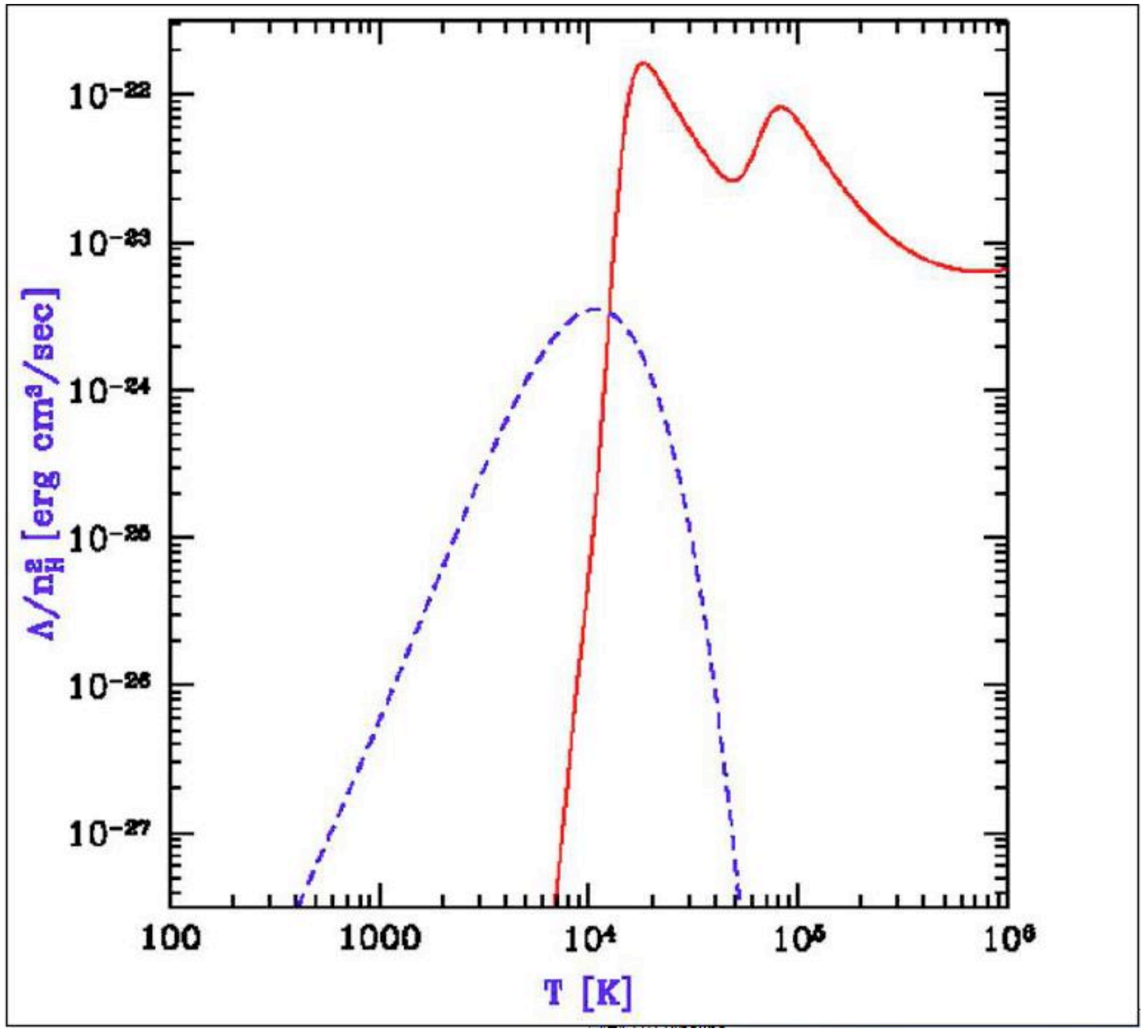

Latif, Schleicher, Schmidt & Niemeyer (2013b)

# The characteristic mass scale



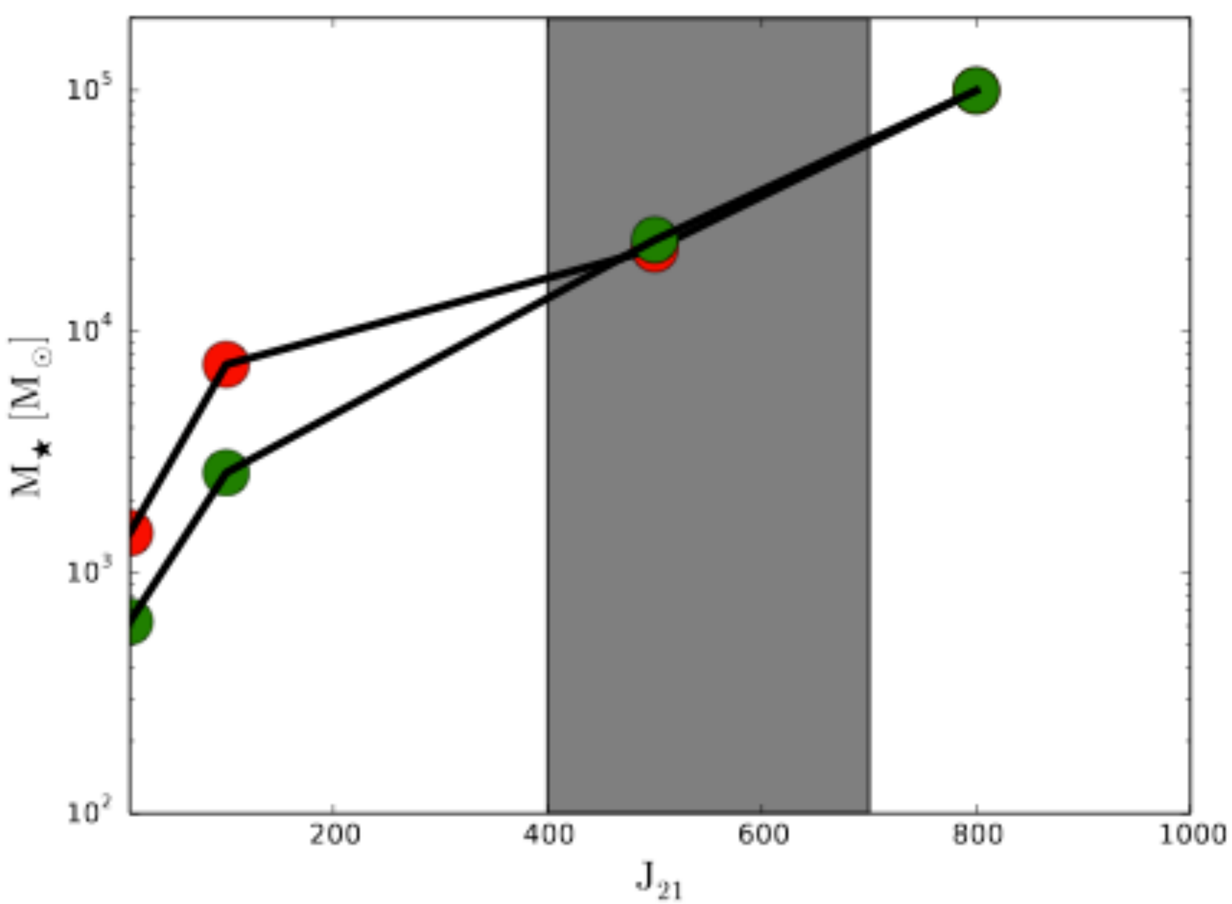

Latif, Schleicher, Schmidt & Niemeyer (2013b)

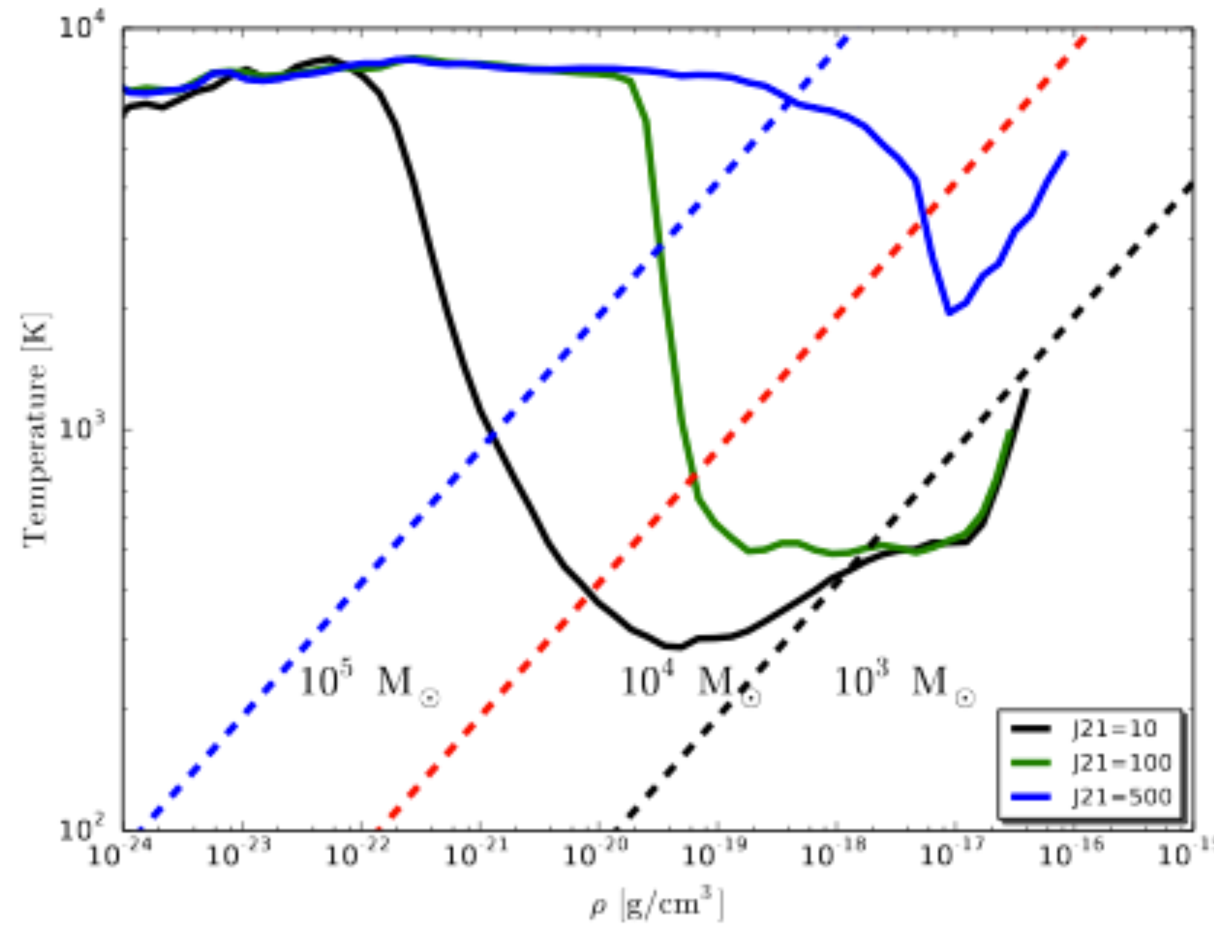
# Important caveats




- The simulations so far assume a very strong UV background to dissociate molecular hydrogen.
- The required value is however very high, the process thus extremely rare (e.g. Dijkstra et al. 2014, Latif et al. 2015).
- Realistic scenarios of black hole cooling should therefore consider $H_2$ cooling in self-gravitating disks.
- The long-term evolution of such disks is currently just marginally understood -> further investigation.

# Dependence of the central mass on the UV background - Do we need an isothermal collapse?

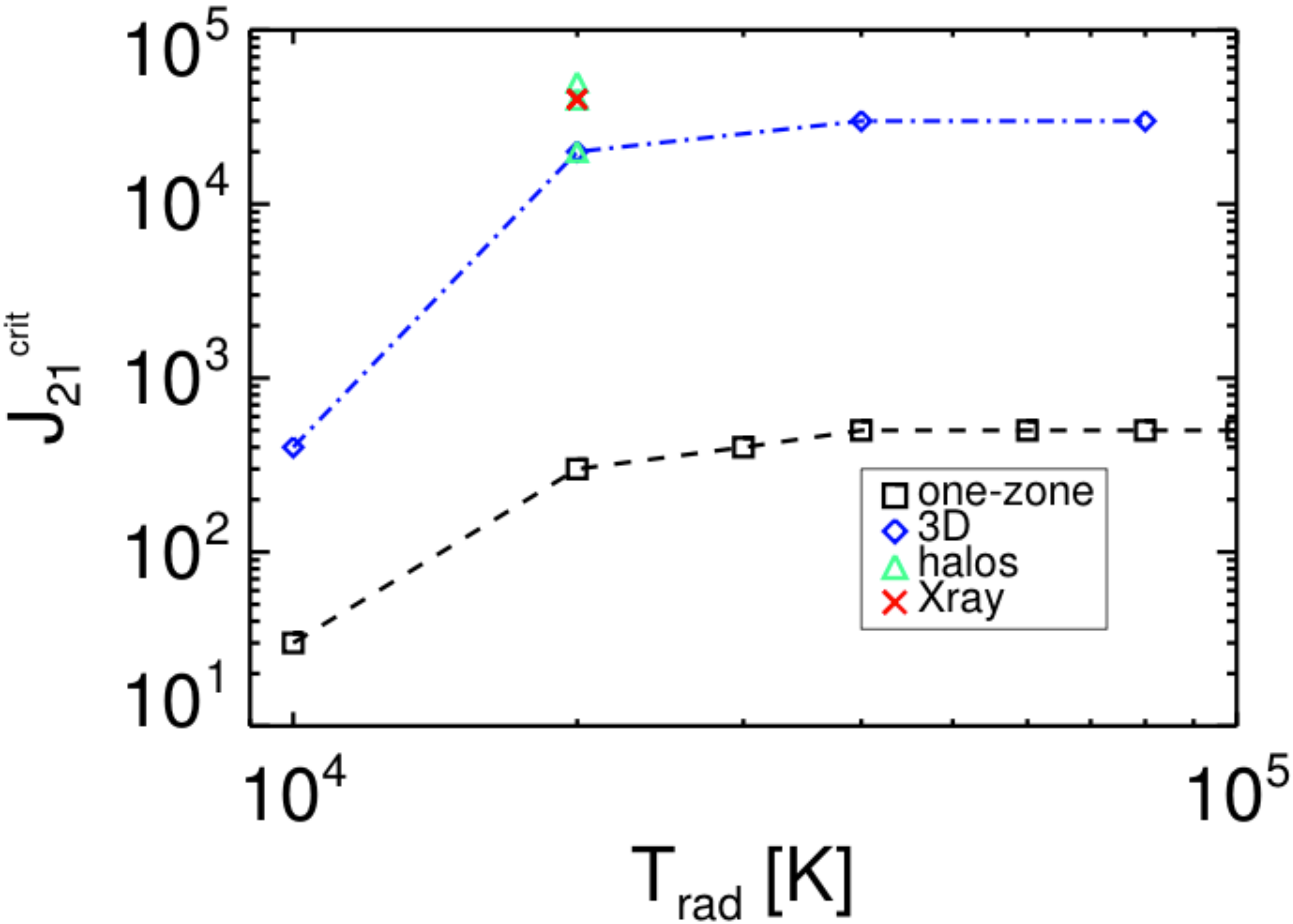



UV radiation field: $J(\nu) = J_{21} \times 10^{-21} \frac{B_\nu(T_r)}{B_{\nu,H}(T_r)}\ erg\ s^{-1}\ cm^{-2}\ sr^{-1}\ Hz^{-1}$

Latif, Schleicher, Bovino, Grassi & Spaans (2014)
see also Latif & Volonteri (2015)

# Uncertainties in the critical UV field strength for atomic cooling




Latif, Bovino, Grassi, Schleicher & Spaans (2014)

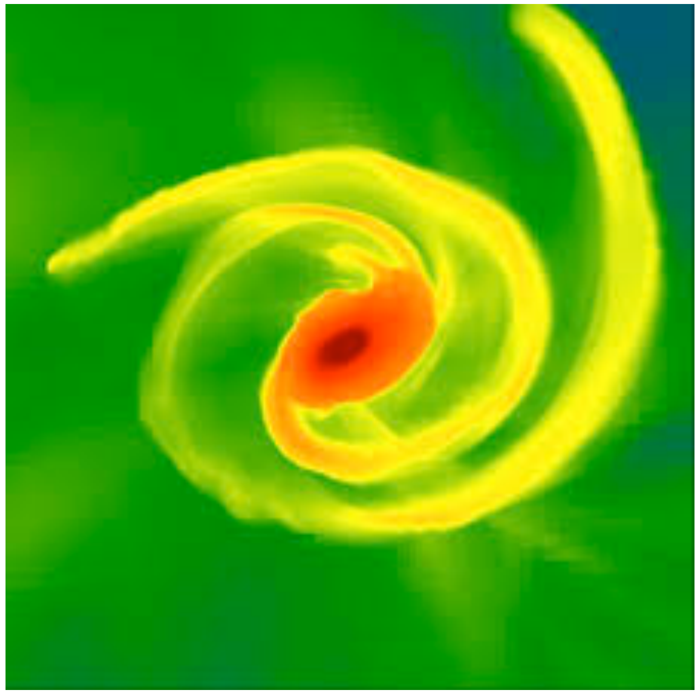
# Self-gravitating stationary disk model

Toomre Q parameter: $Q = \frac{c_s \Omega}{\pi G \Sigma}$

self-regulation: Q~1

stationarity plus mass conservation:

$$\Sigma = \frac{\dot{M}_{tot}}{3\pi\nu}$$



heating=cooling

Kepler rotation:

$$\Omega_K = \sqrt{\frac{GM_*}{R^3}}$$

viscous heating:

$$Q_+ = \nu\Sigma(R\Omega')^2$$

surface cooling:

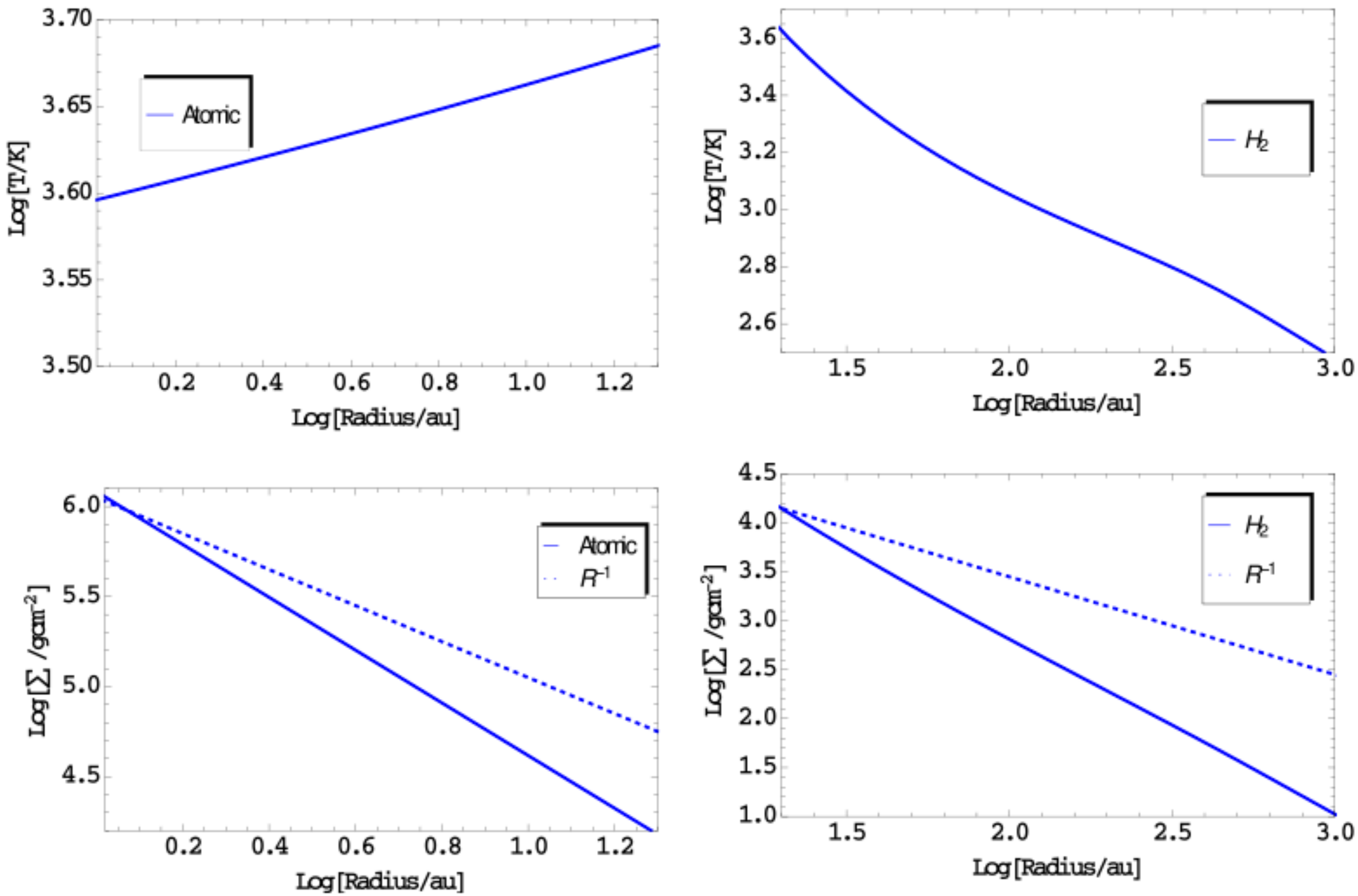
$$Q_- = 2H\Lambda_{\mathrm{H/H_2}}$$

disk height:

$$H = \frac{c_s}{\Omega}$$

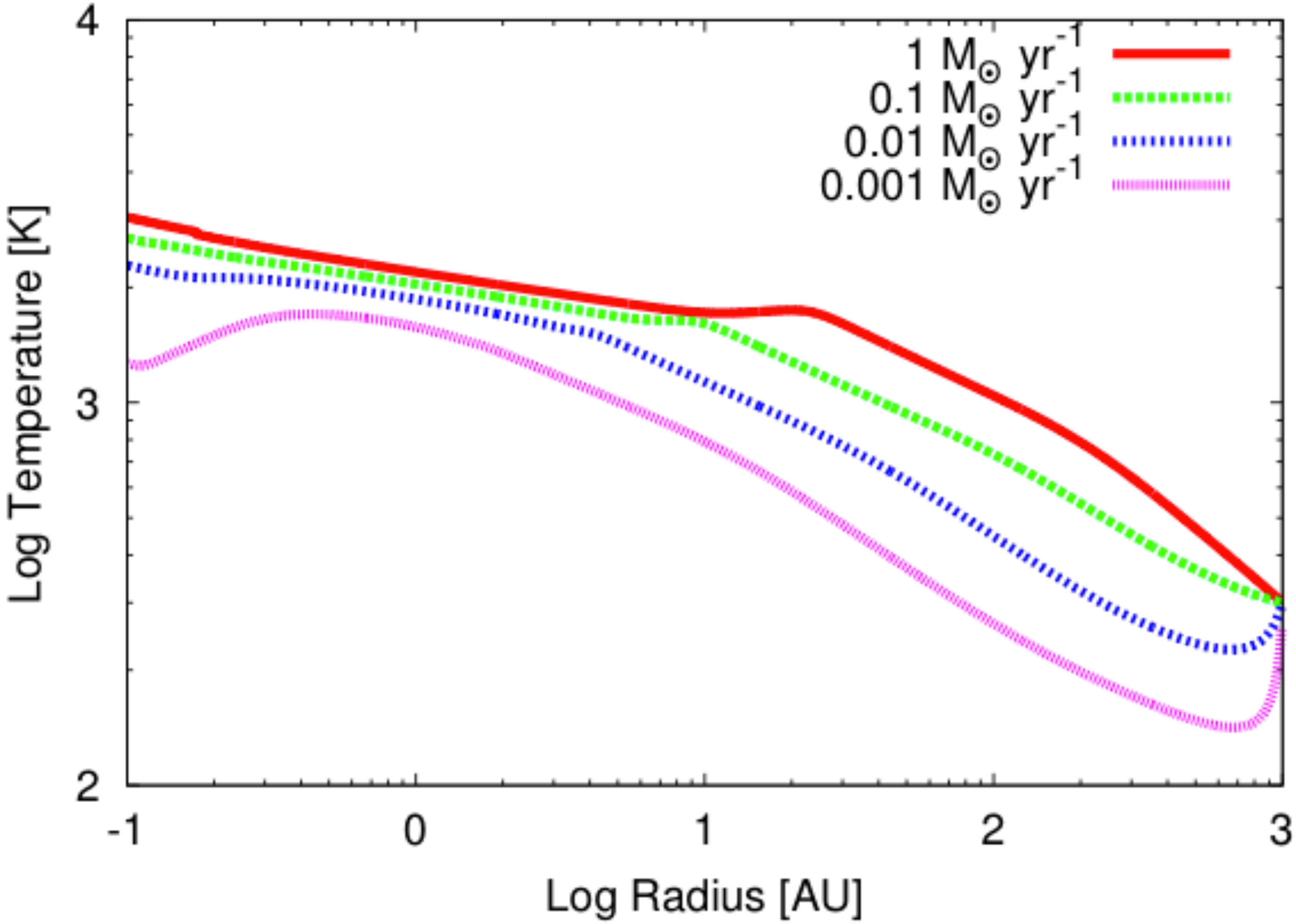
Latif & Schleicher (2015)

# Impact of viscous heating in self-gravitating disks




Latif & Schleicher (2015)

# Viscous heating in a full chemical model




$$\dot{R} = -\frac{R}{t_{vis}},$$

$$\dot{\Sigma} = \frac{\Sigma}{t_{vis}},$$

$$\dot{M} = 3\pi\nu\Sigma$$

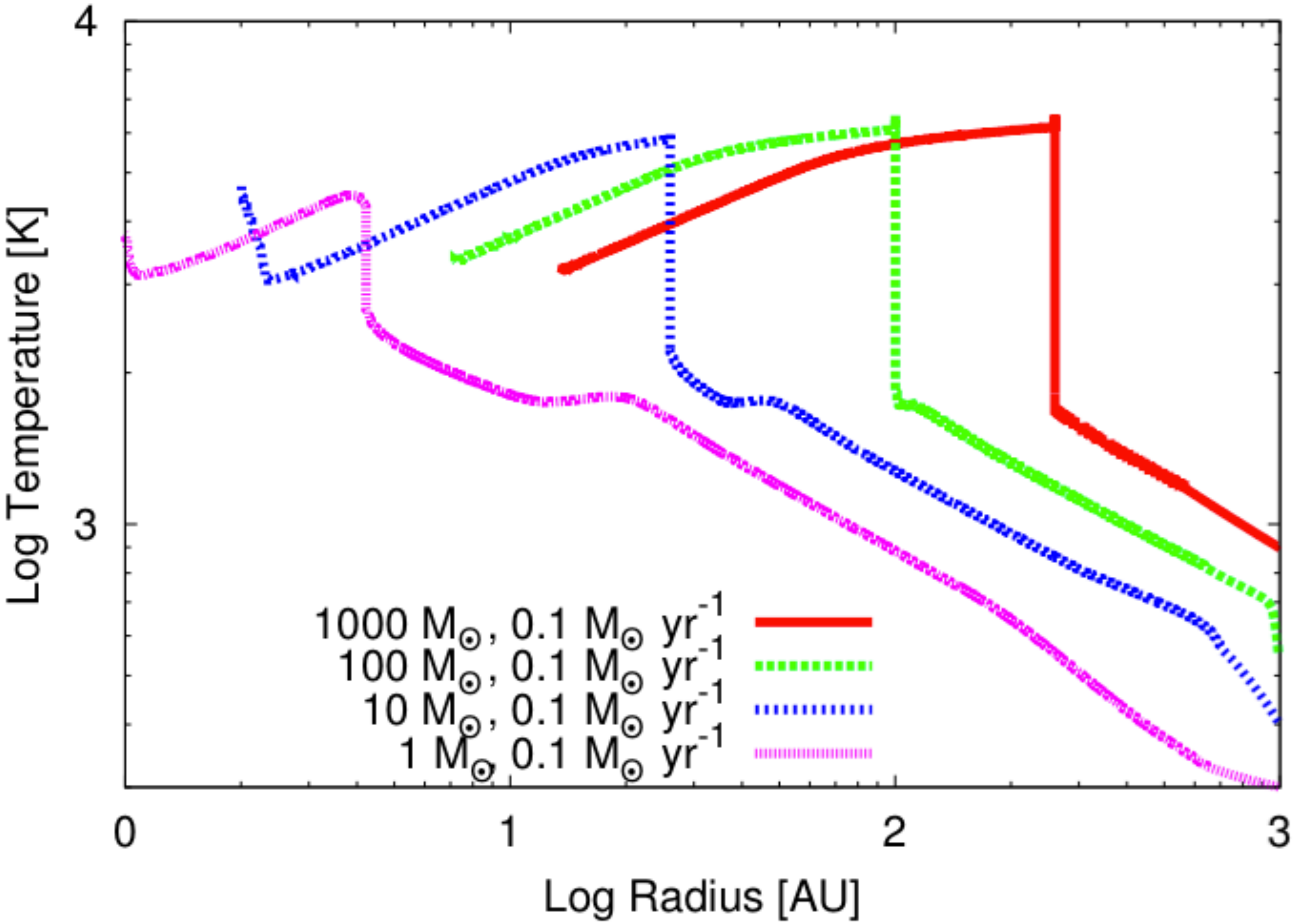
$$\nu = \frac{\dot{M}}{3\pi\Sigma}$$

$$H = \frac{c_s}{\Omega}$$

self-gravitating disk, no central sources

Schleicher et al., (2015)

# Viscous heating in a full chemical model




$$\dot{R} = -\frac{R}{t_{vis}},$$

$$\dot{\Sigma} = \frac{\Sigma}{t_{vis}},$$

$$\dot{M} = 3\pi\nu\Sigma$$

$$\nu = \frac{\dot{M}}{3\pi\Sigma}$$

$$H = \frac{c_s}{\Omega}$$

self-gravitating disk, central sources
plus high accretion rate

Schleicher et al., (2015)

# Summary

- Massive black holes with $10^5$ solar masses can form if molecular hydrogen is fully dissociated.
- Large-scale simulations indicate the formation of $10^3$-$10^4$ solar mass objects for moderate amounts of H2.
- Large uncertainties in the determination of $J_{crit}$ -> importance of 3D simulations!
- On scales of 10-100 AU, viscous heating can stabilize the disk and support the formation of very massive objects.
- The impact of metals and dust needs to be further explored in the future.