The formation of supermassive black holes via direct collapse at high redshift

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Outline

- Direct collapse scenario
- Feasibility of direct collapse scenario via high resolution cosmological simulations
- Role of turbulence and magnetic fields during seed BH formations
- Critical strength of UV flux and comparison of number density of DCBHs with observed quasar abundance
- Is complete isothermal collapse really necessary?

Direct collapse scenario

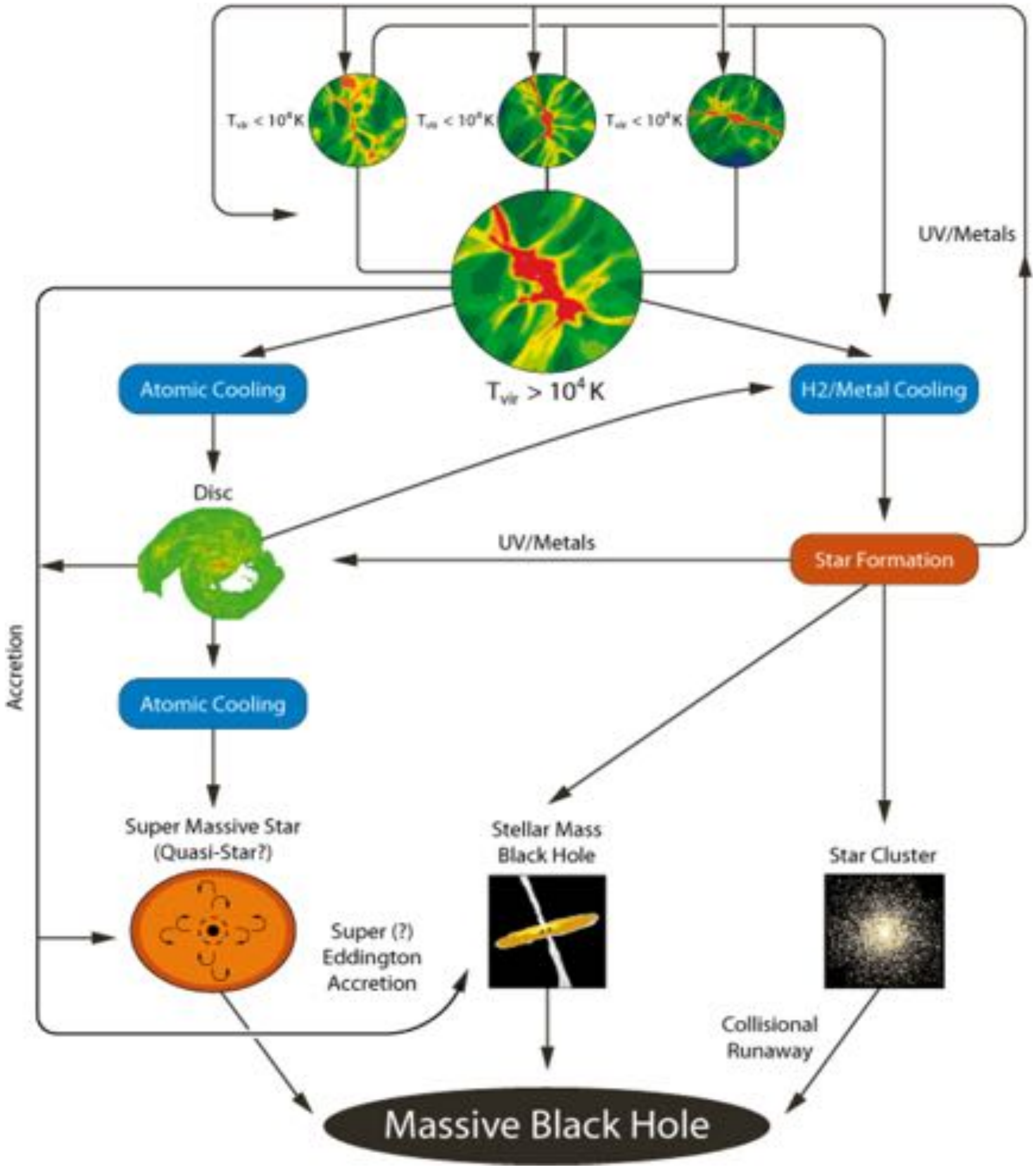
- Provides massive seed of 10^5-10^6 $M_\odot$

- Key requirement is to have large inflow rate of > 0.1 $M_\odot$/yr

- Isothermal direct collapse with T~ 8000 K

- Primordial gas composition

- Requires strong LW flux to quench H_2 formation



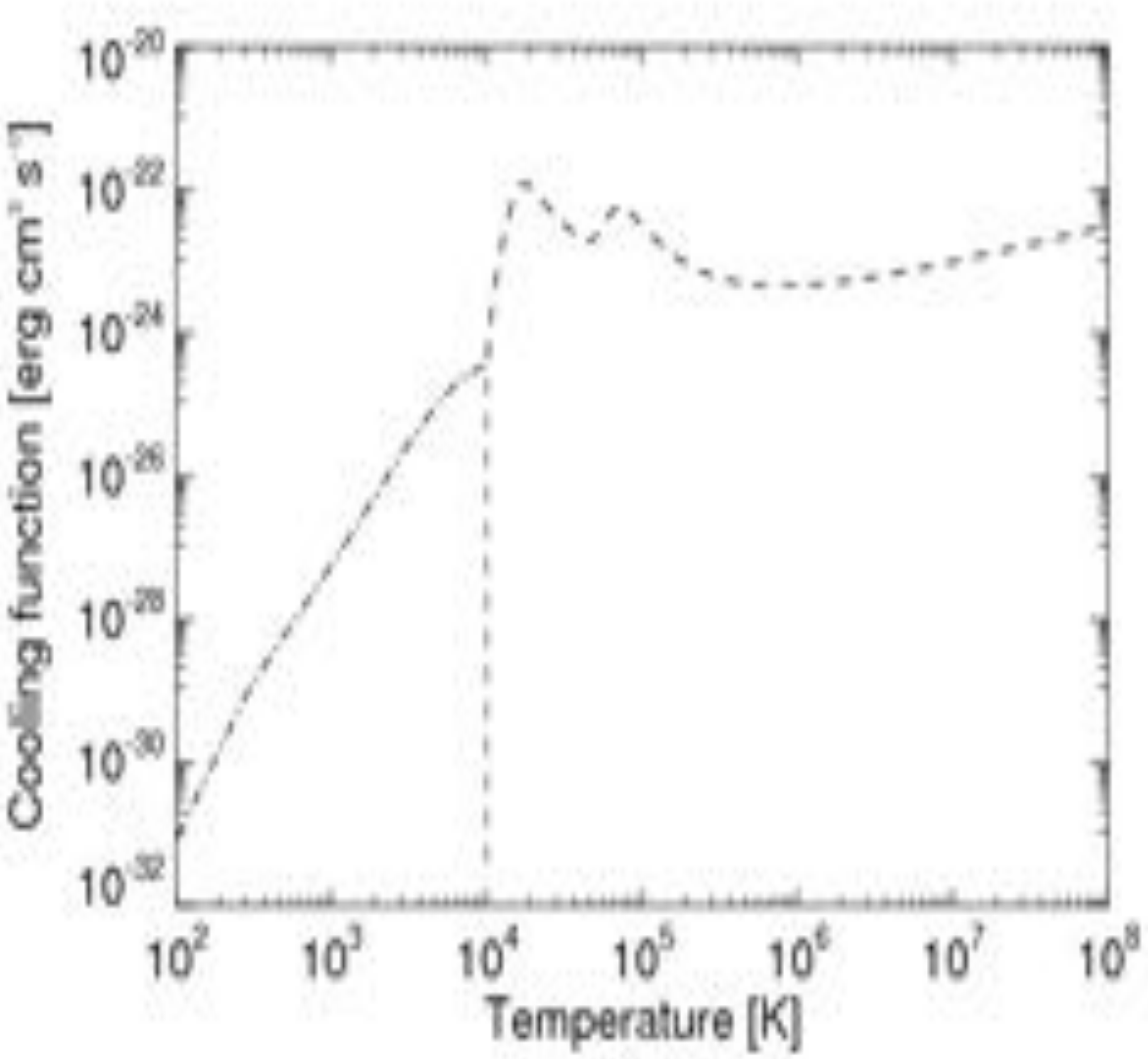
Regan et al 2009

Primordial gas chemistry

- Ly α is an efficient coolant

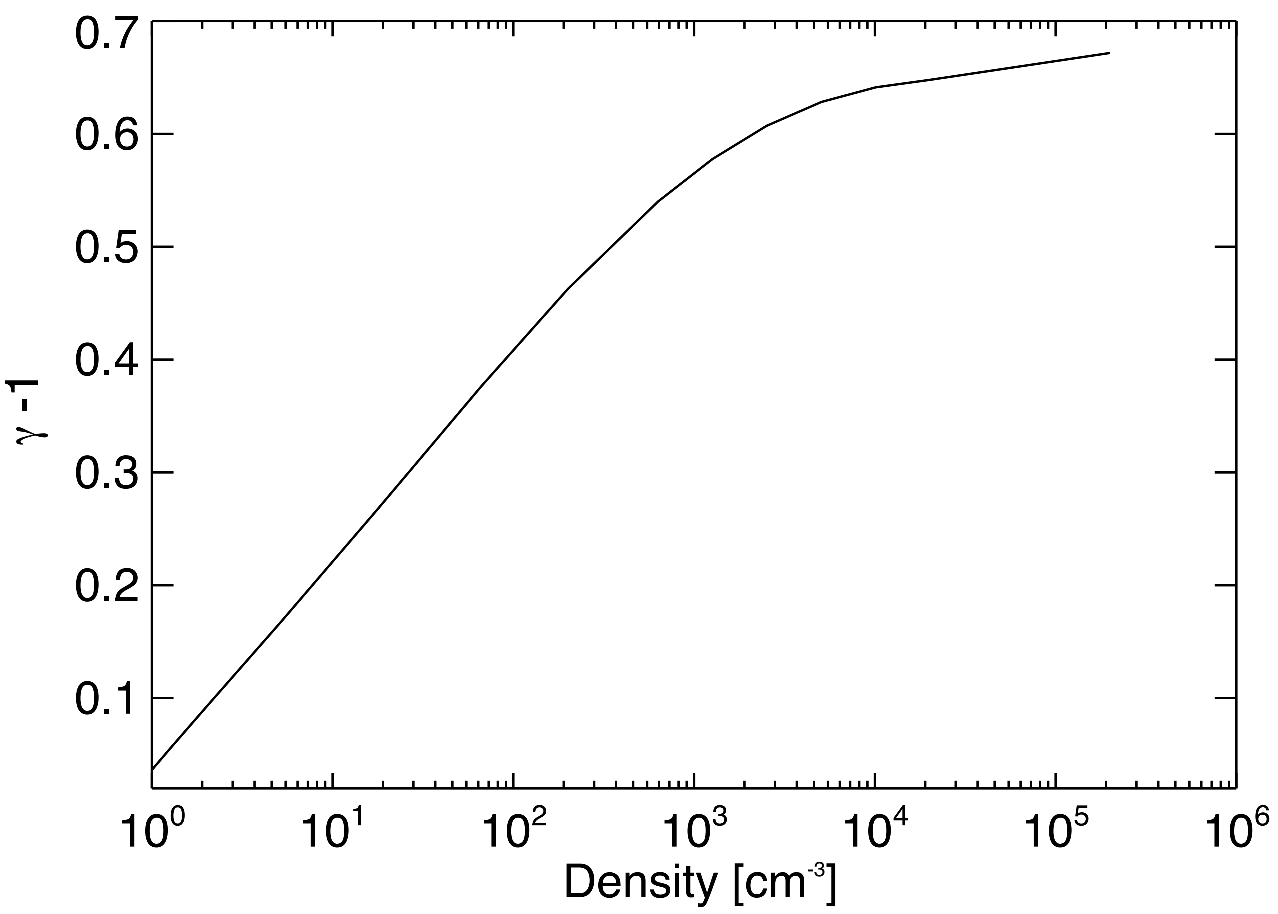
  for $T_{vir} > 10^4$ K halos

- At T<8000 K, H_2 cooling
- Cools the gas to 300 K
- Strong Lyman Werner flux
- Photodissociation of H_2



Lyman Alpha Trapping

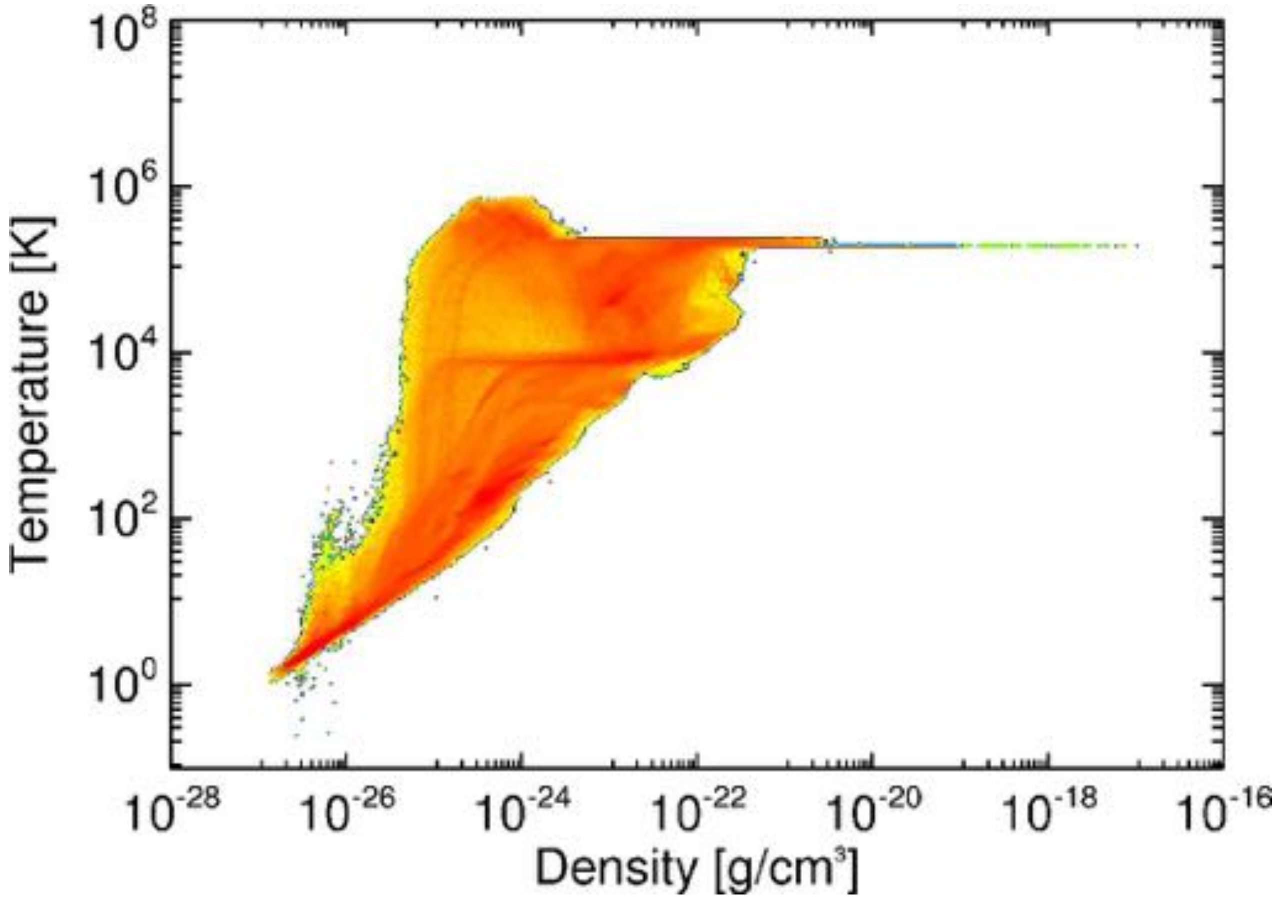
- ★ **Large columns of neutral gas make the gas optical thick**
- ★ **Photon escape time becomes larger than free fall time**
- ★ **Equation of state becomes stiff due to the trapping of Lyman alpha photons**

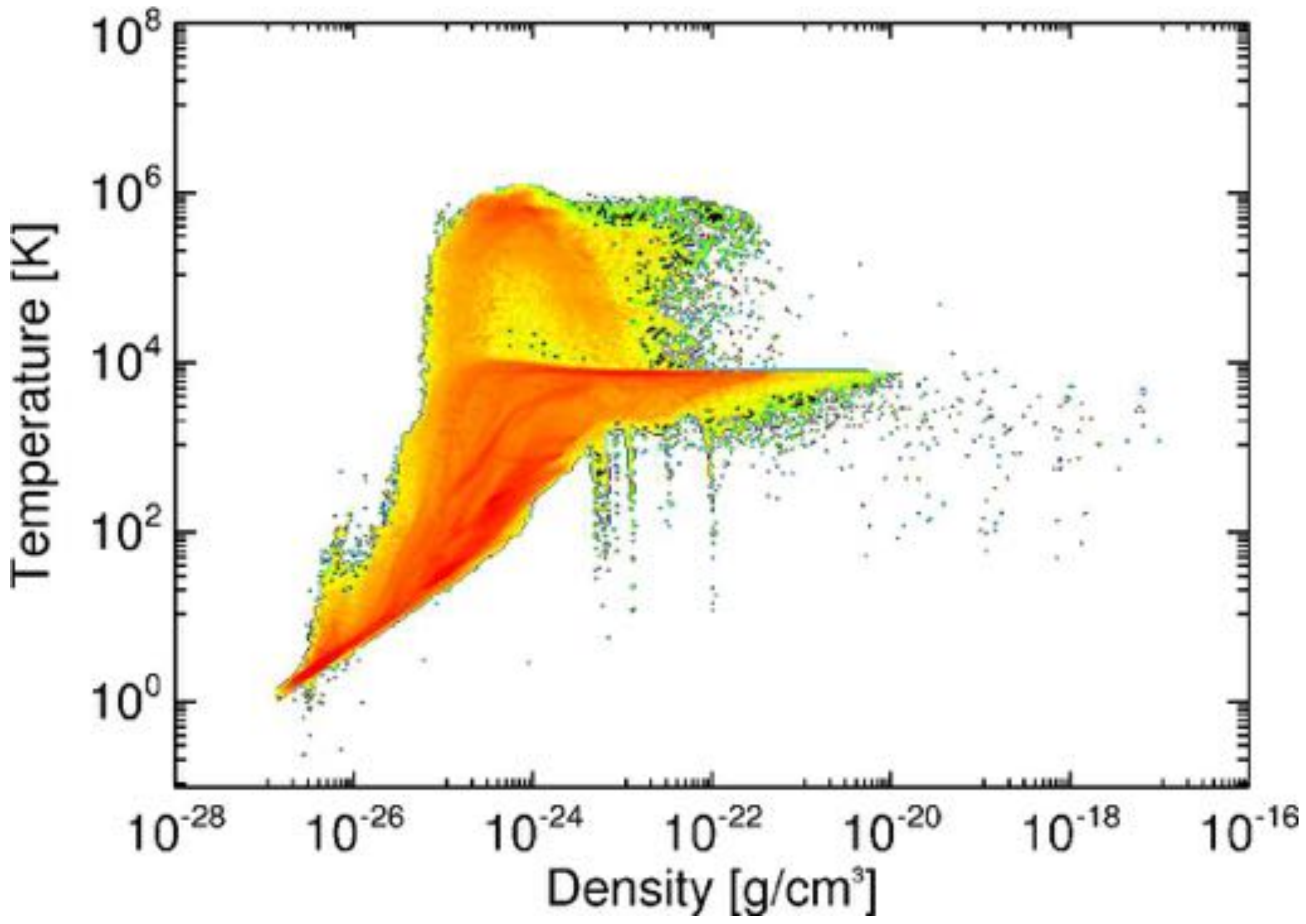


$$\gamma_{eff} = 1 + \frac{d\log T}{d\log\rho}$$

Spaans & Silk 2006, Latif et al. 2011

Thermal evolution

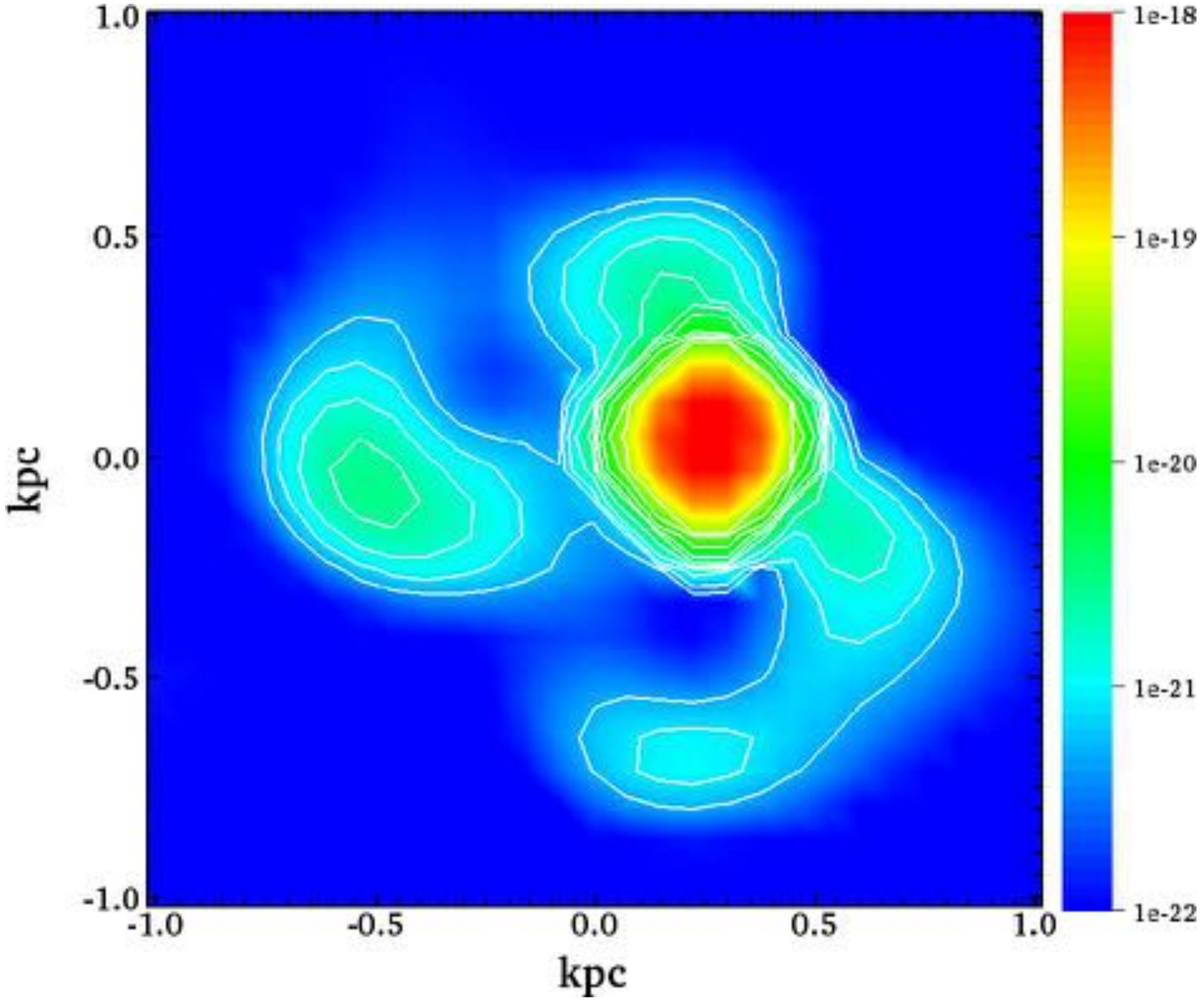




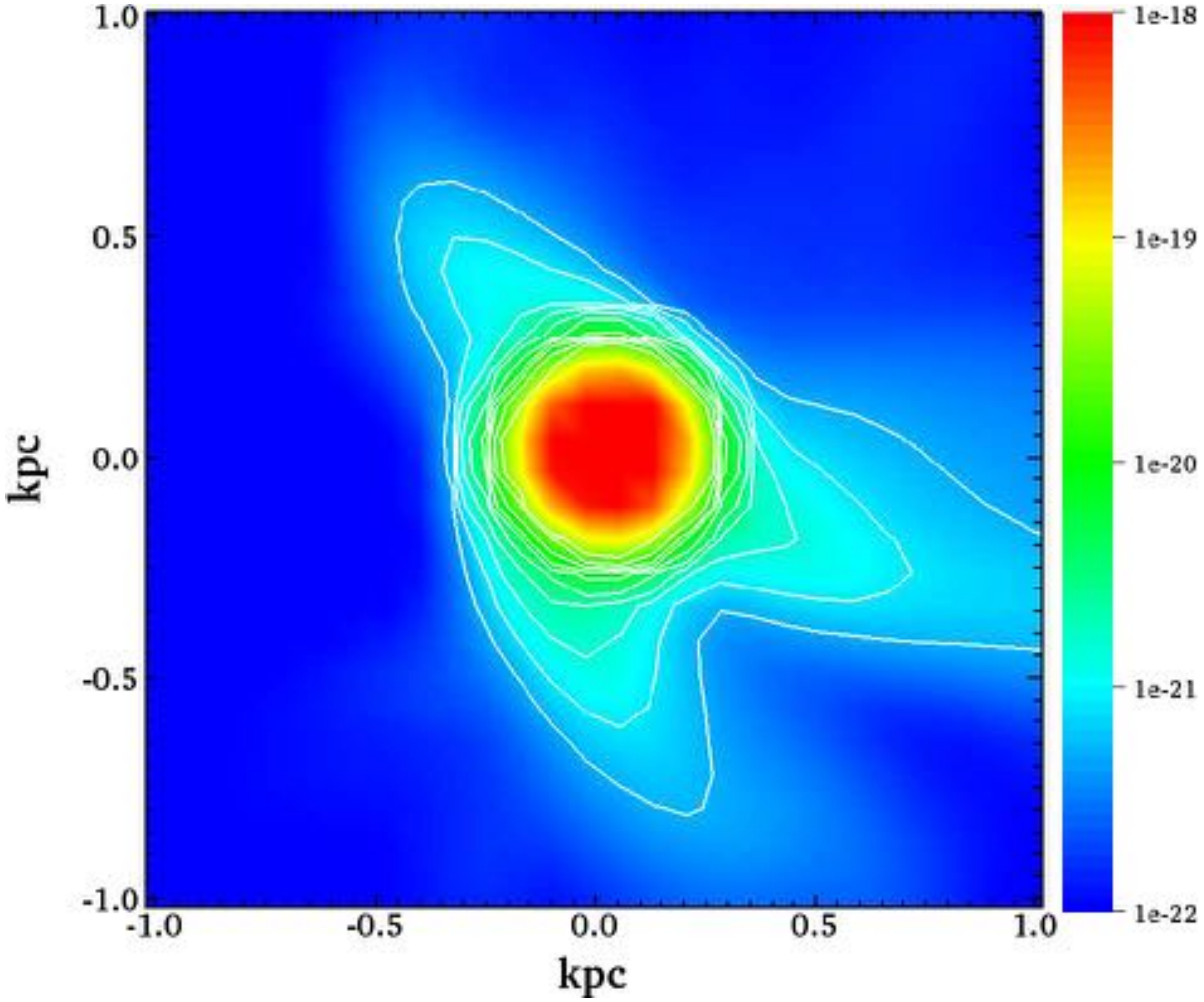
Lyman alpha trapping

Schleicher et al. 2010,Latif et al. 2011

Lyman alpha Trapping



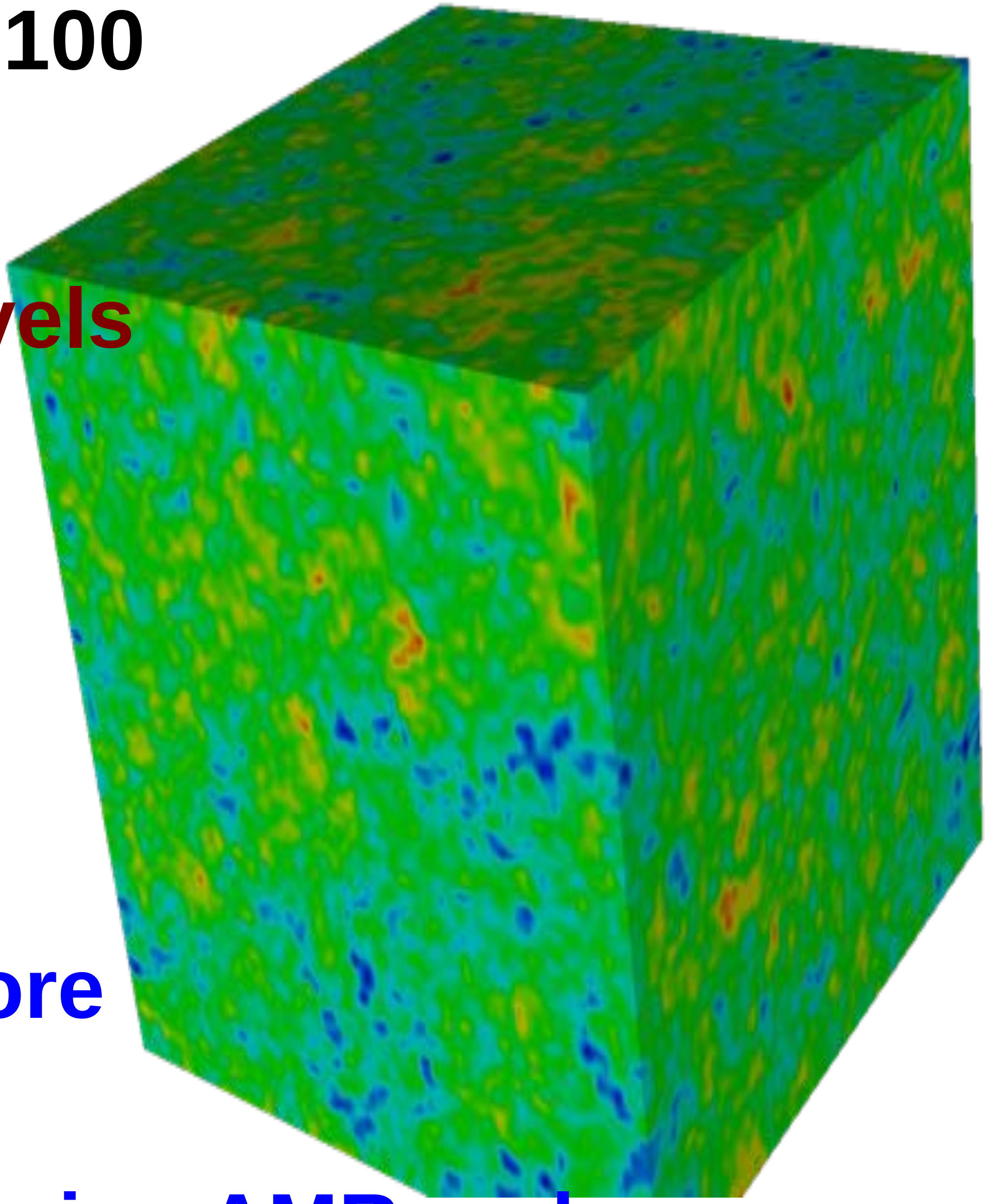
Isothermal case



Lyman alpha trapping

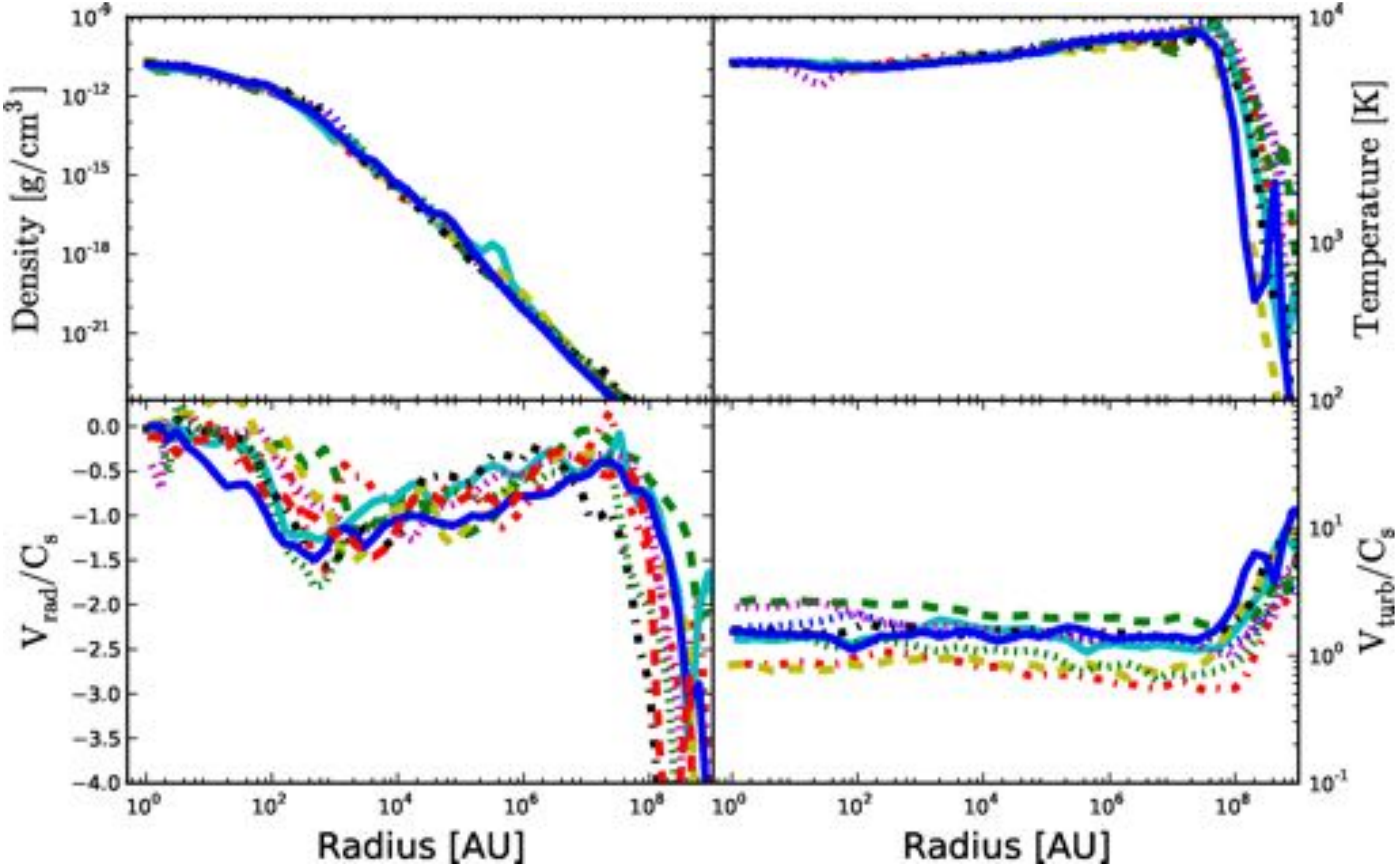
Latif et al. 2011

Simulation setup



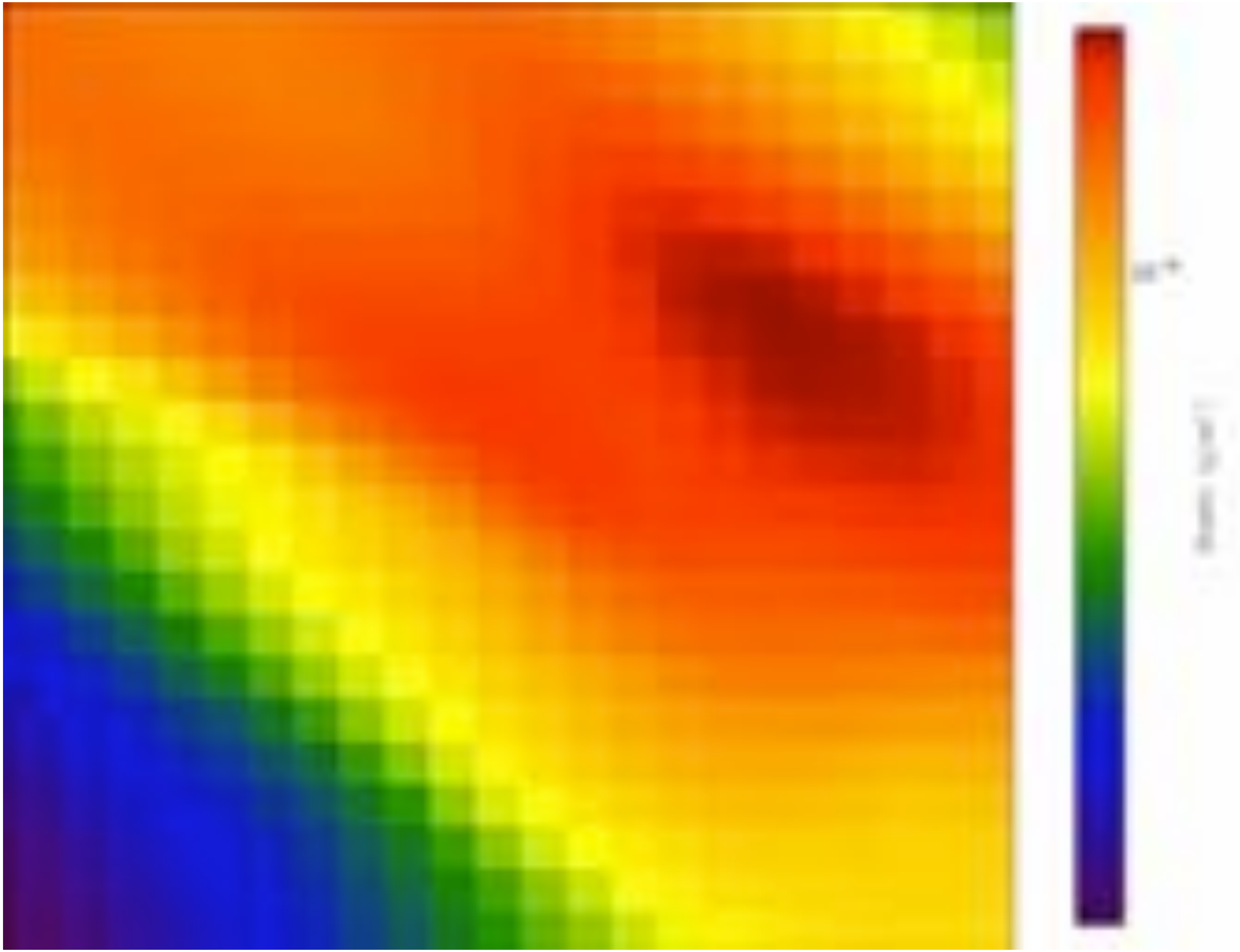
- **Comoving period box of 1 Mpc/h in size**
- **Cosmological Initial conditions at z=100**
- **6 Million MD particles**
- **Two nested grids + 27 refinement levels**
- **Halo masses of ~ $10^7 M_\odot$**
- **UV flux of various strengths in units of J_{21}**
- **X-rays**
- **First high resolution studies to explore the formation of seed BHs**
- **Perform Cosmological simulations using AMR code ENZO**

Global properties of simulated halos

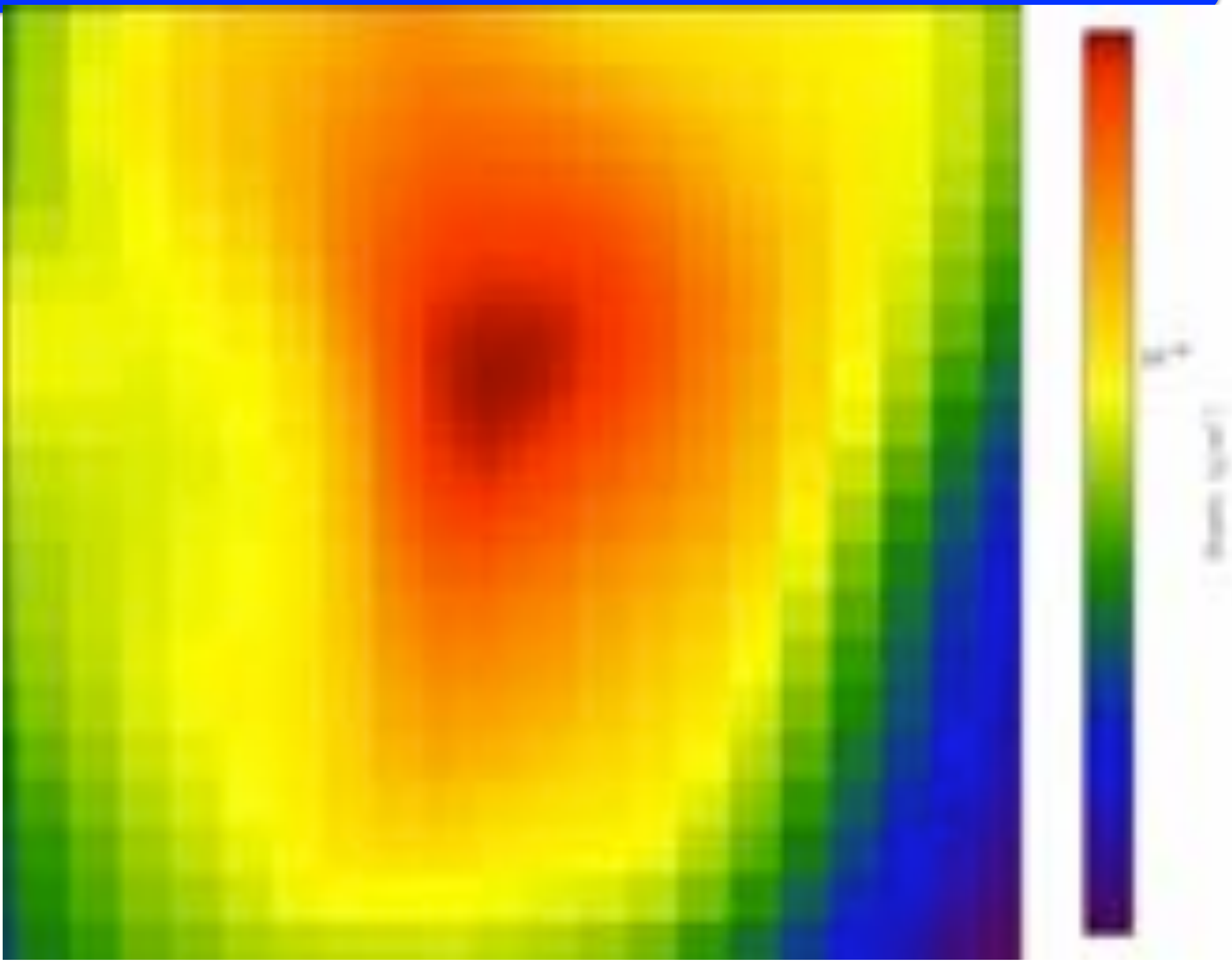


Latif et al 2013 MNRAS 433 1607L

Movie shows the collapse of central 1 pc

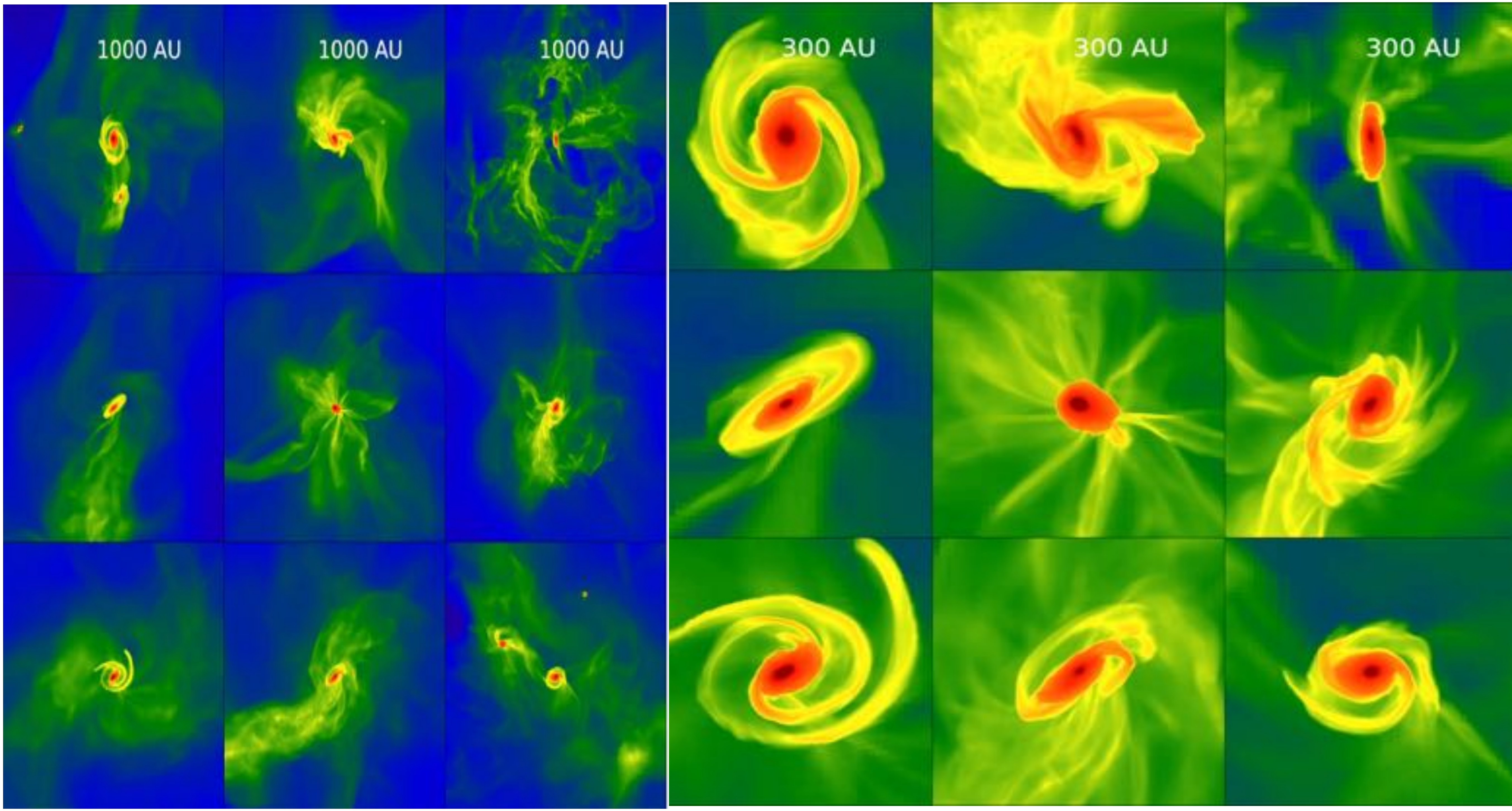


Movie shows the collapse of central 1 pc



Latif et al 2013 MNRAS 433 1607L

State of simulations



★Collapse occurs isothermally with T~ 8000 K

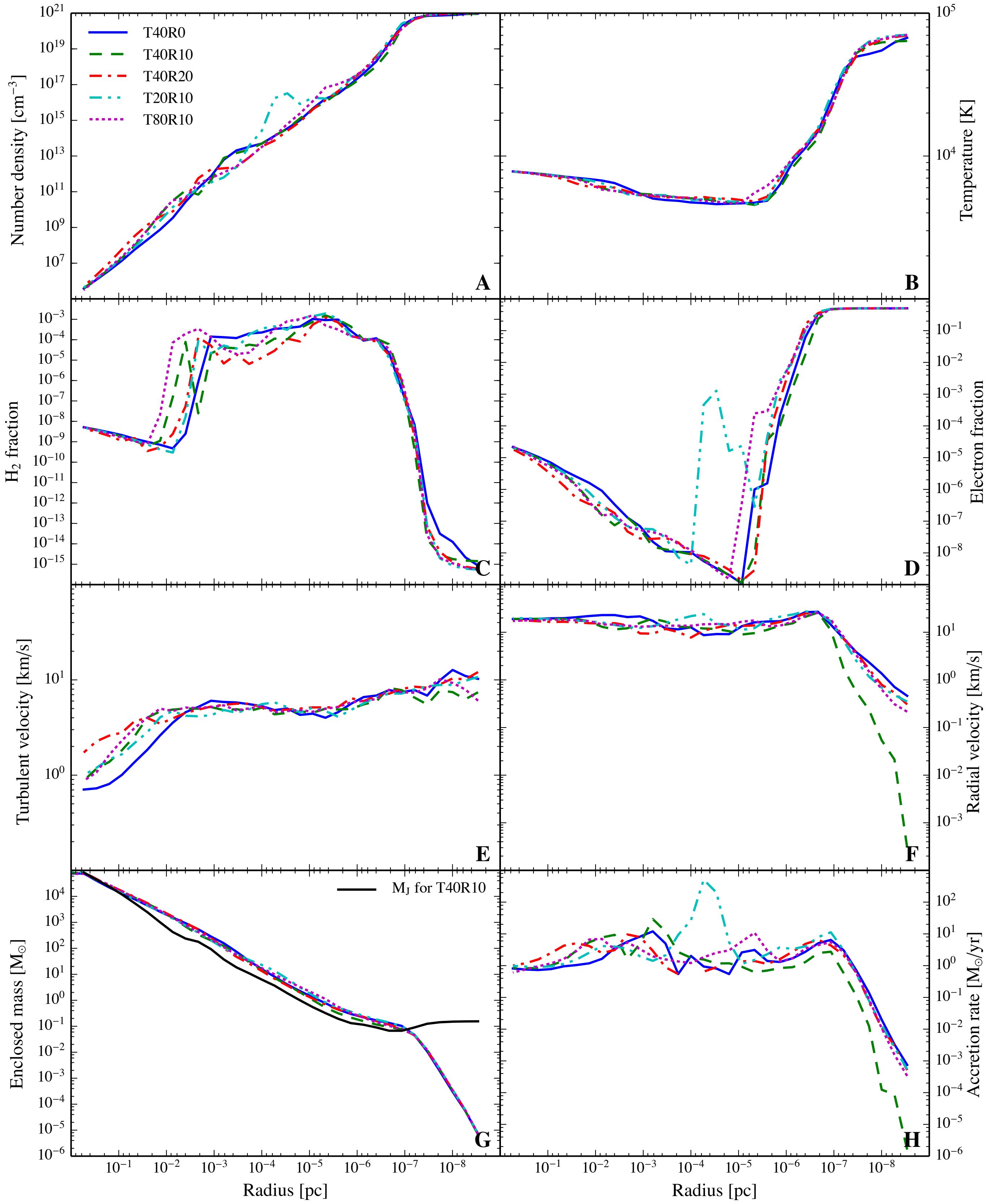
★Provides large inflow rates of $\sim 1 M_\odot$/yr

Latif et al. 2013 MNRAS 433 1607L

Impact of H⁻ cooling

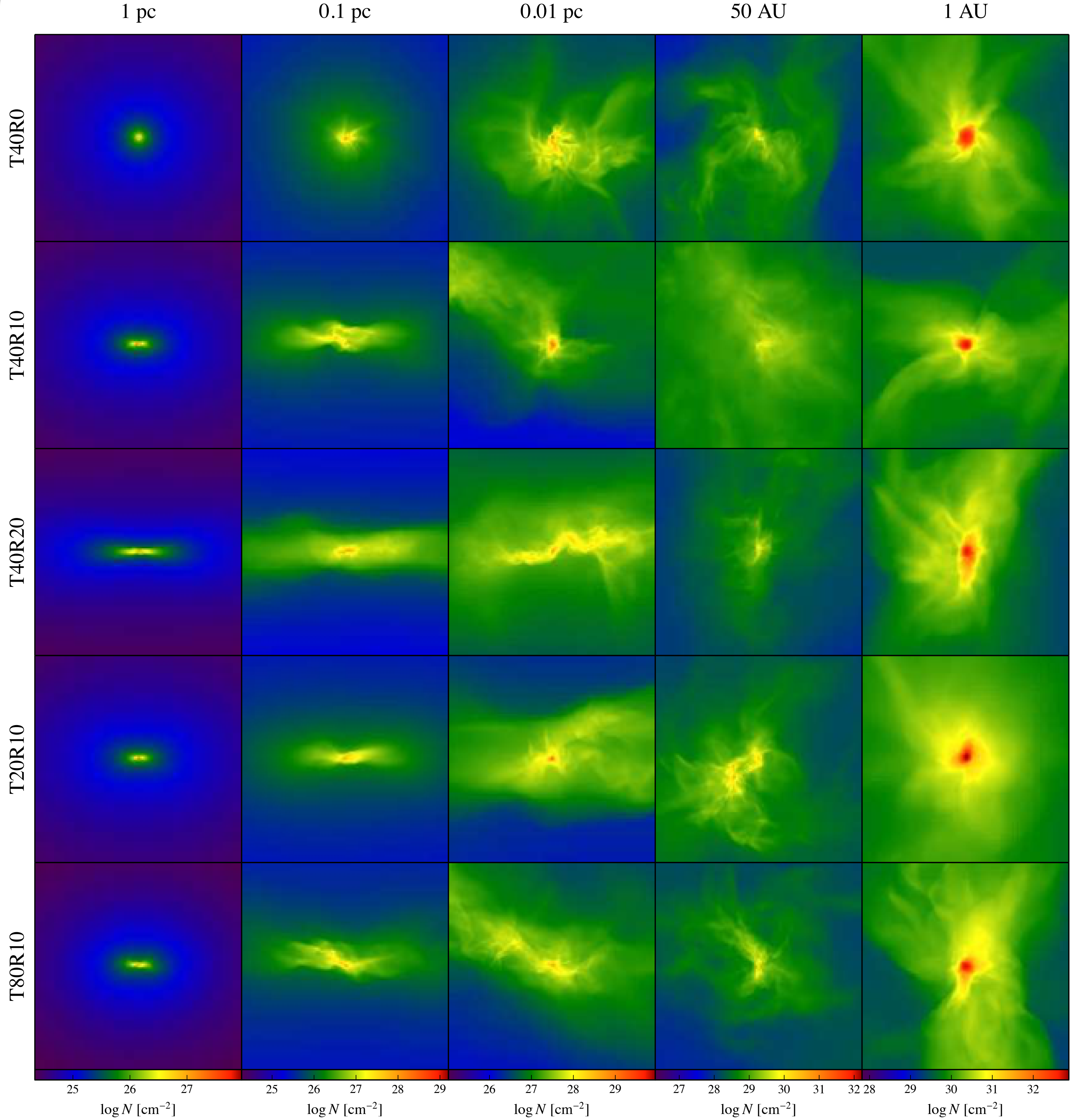
Simulations

Name	Turbulence (~ % of c_s)	Rotation (% of v_{Kep})
T40R0	40 %	0 %
T40R10	40 %	10 %
T40R20	40 %	20 %
T20R10	20 %	10 %
T80R10	80 %	10 %



Van Borm, Latif, Schleicher et al. 2014A&A...572A..22V

Impact of rotation & turbulence



Van Borm, Latif, Schleicher et al. 2014A&A...572A..22V

Impact of rotation & turbulence

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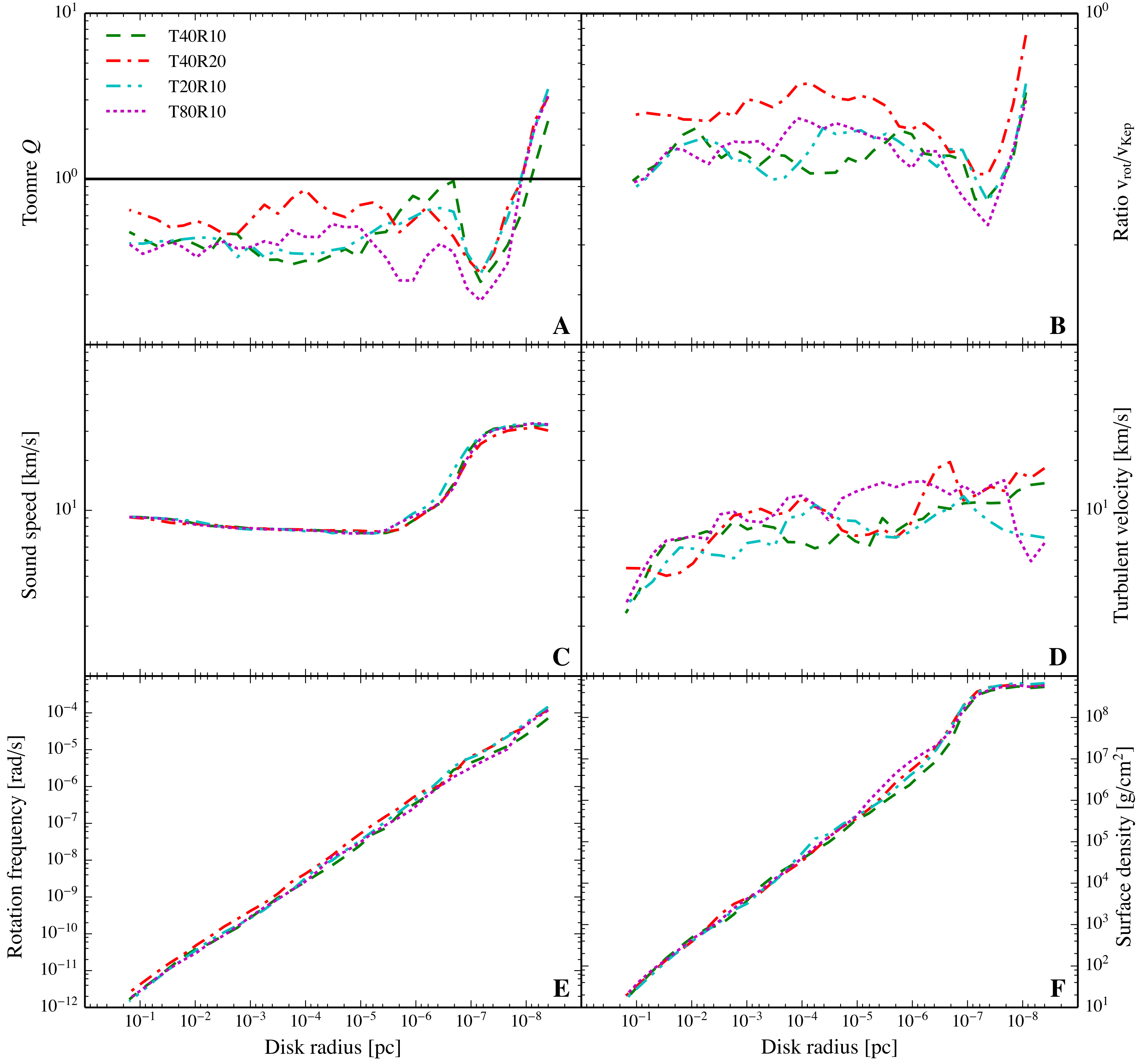
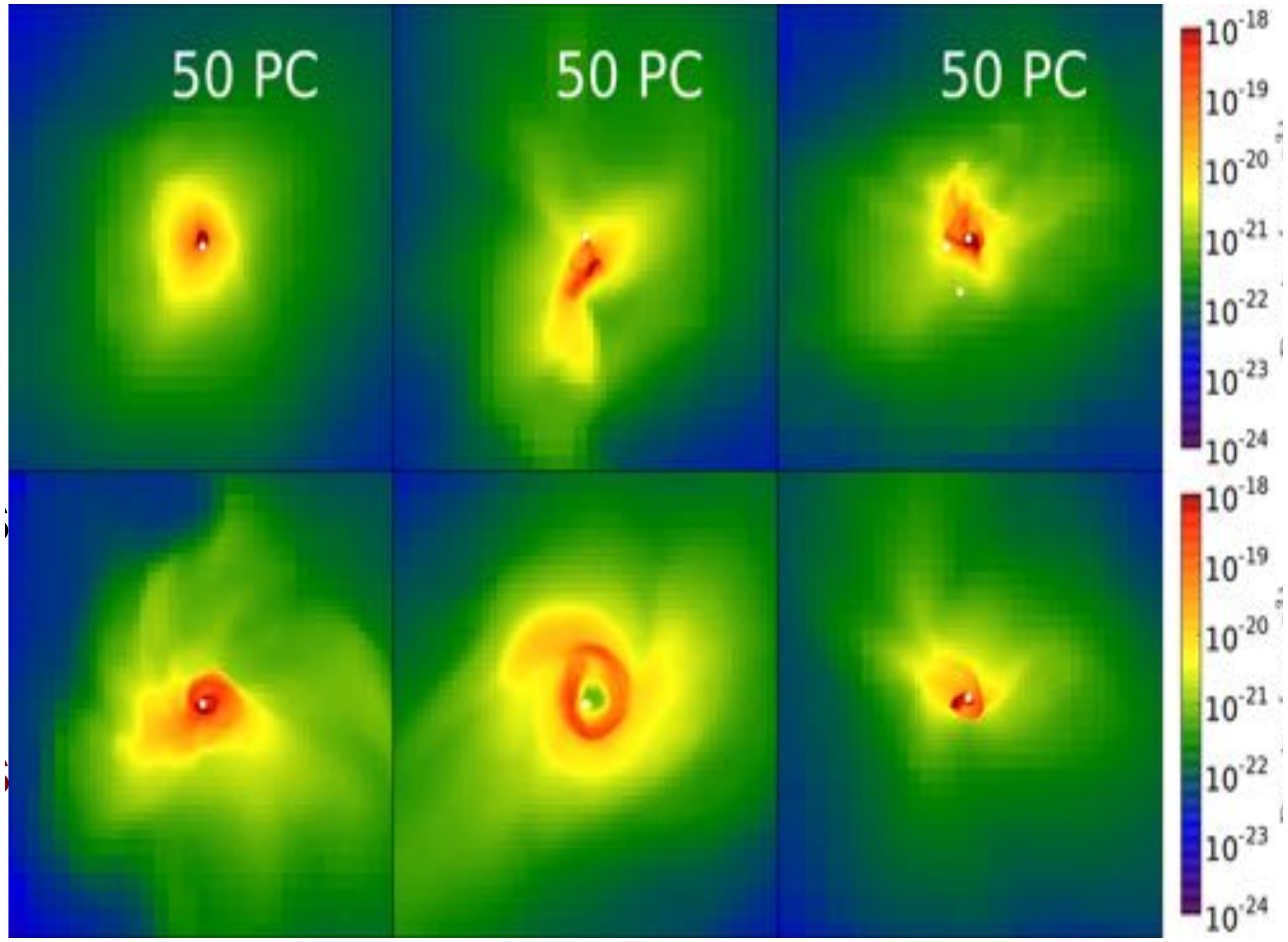
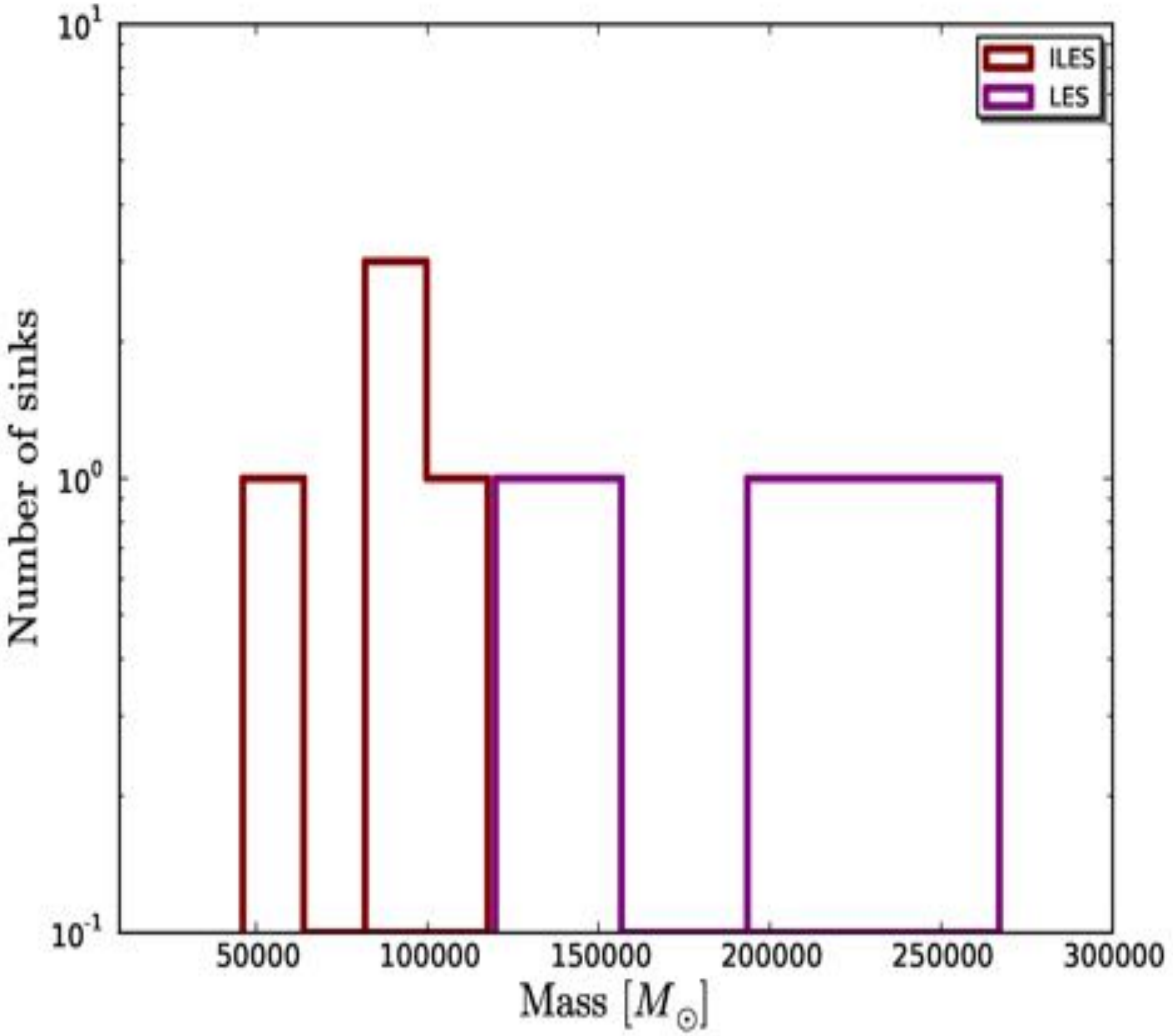


Masses of protostars





- Employed sink particles to follow the evolution for 20,000 yrs

- Massive protostars of about 10^5 $M_\odot$ are formed

Latif et al. 2013 MNRAS 436 2989L

Begelman et al. 2006, Volonteri 2010

What about Magnetic fields?
Are they important in BH formation?

Small scale dynamo

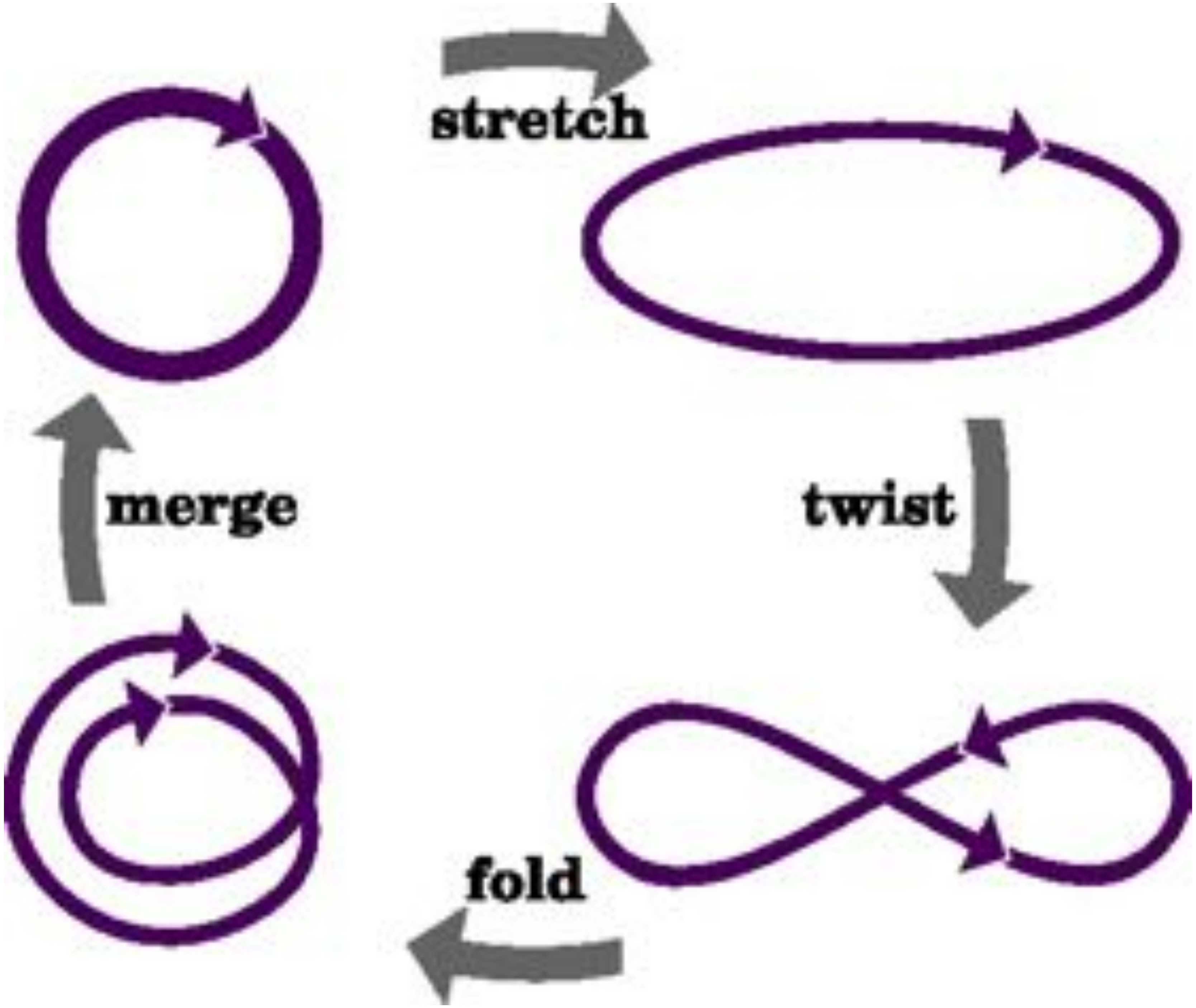
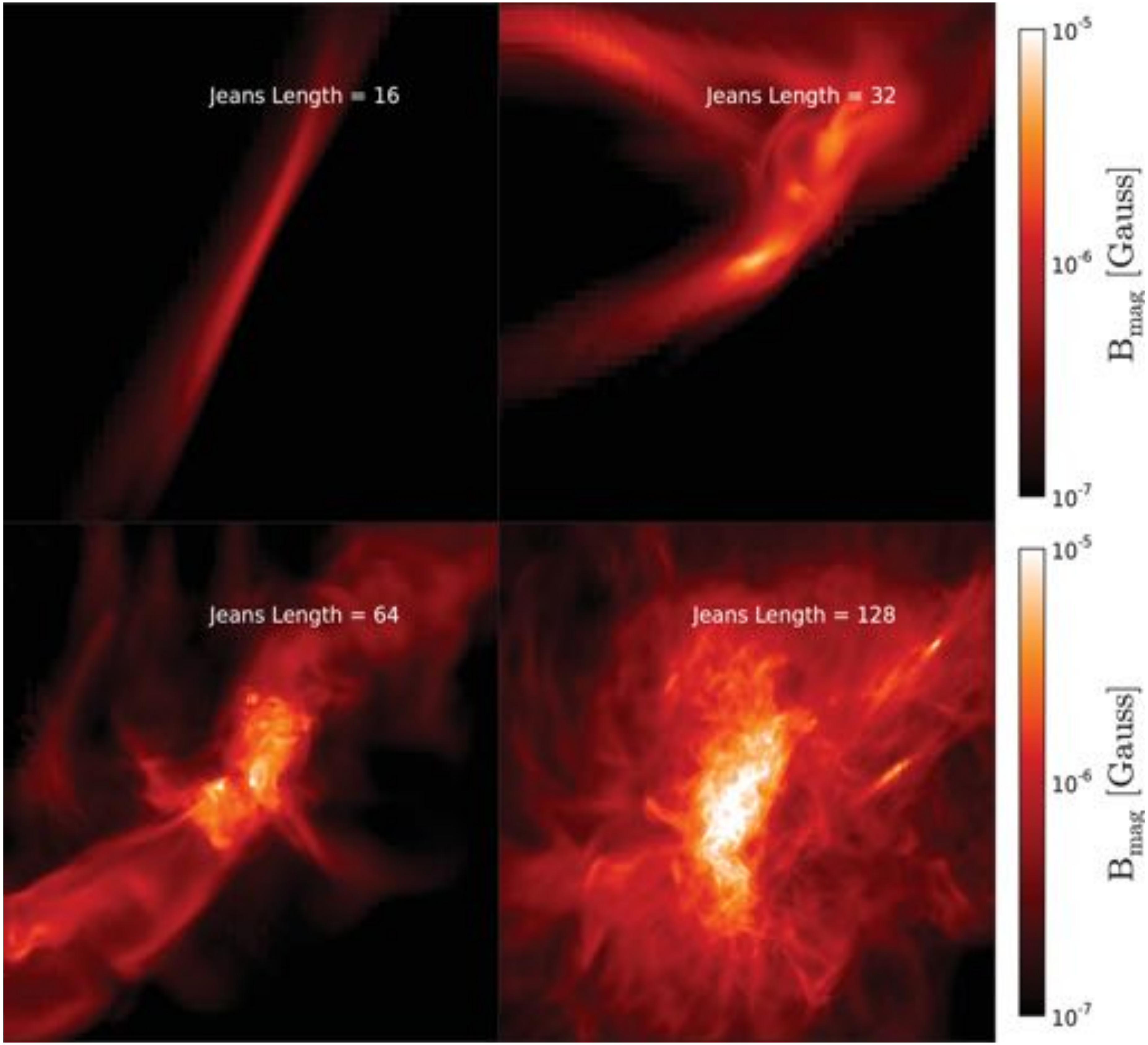


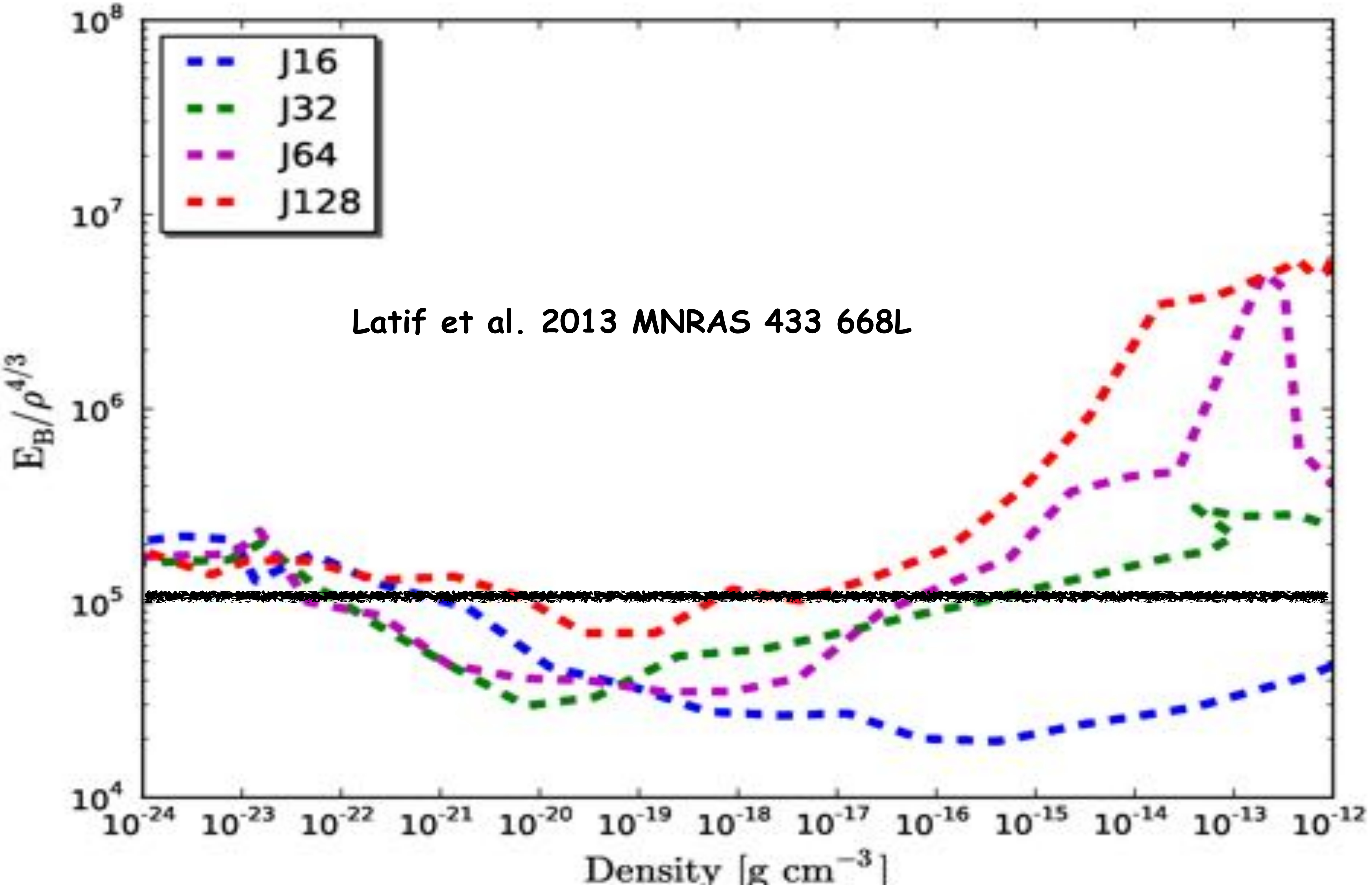
Image credit: Schober et al. 2012

Magnetic field Amplification

Latif et al. 2013 MNRAS 433 668L

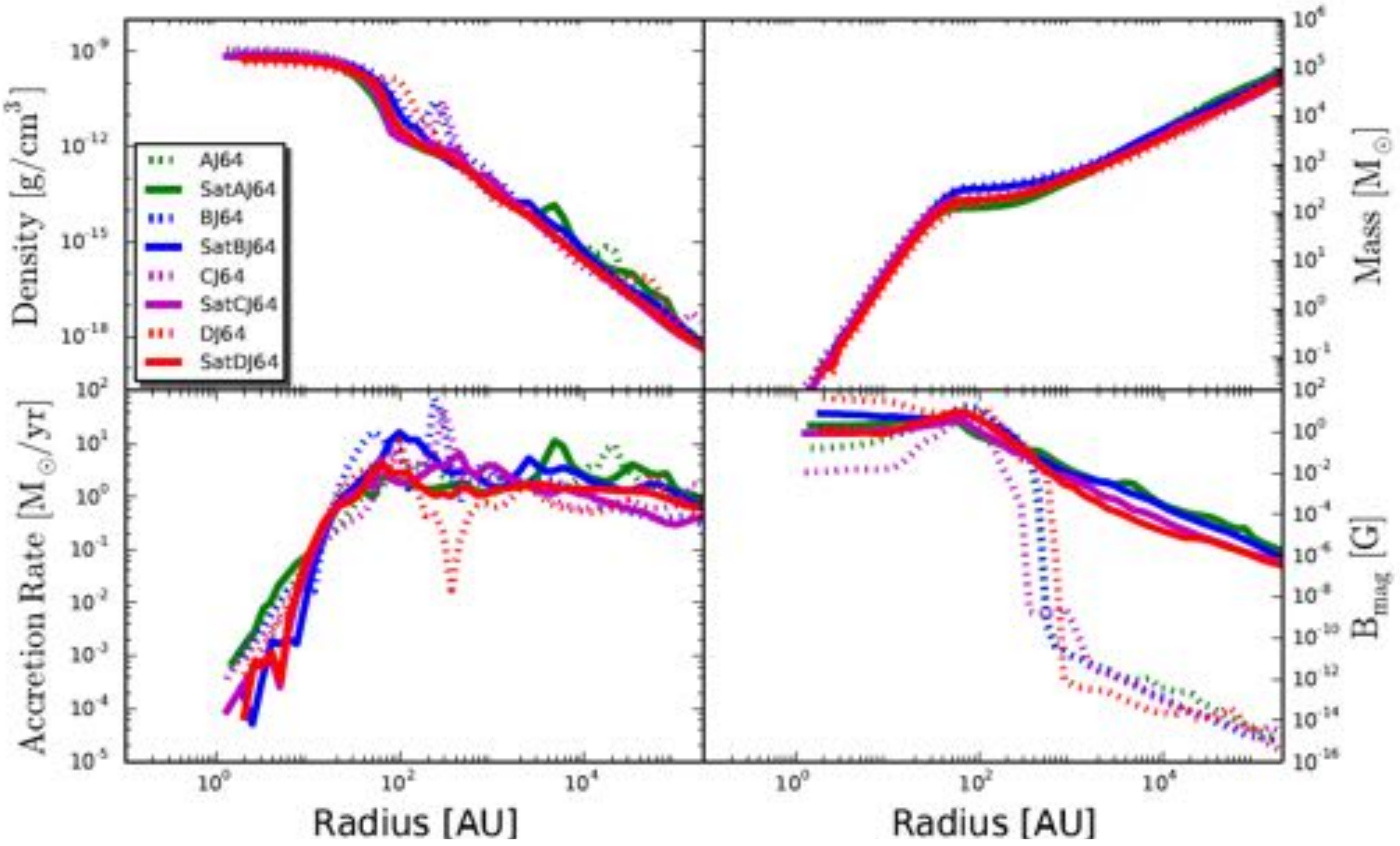


Magnetic field Amplification



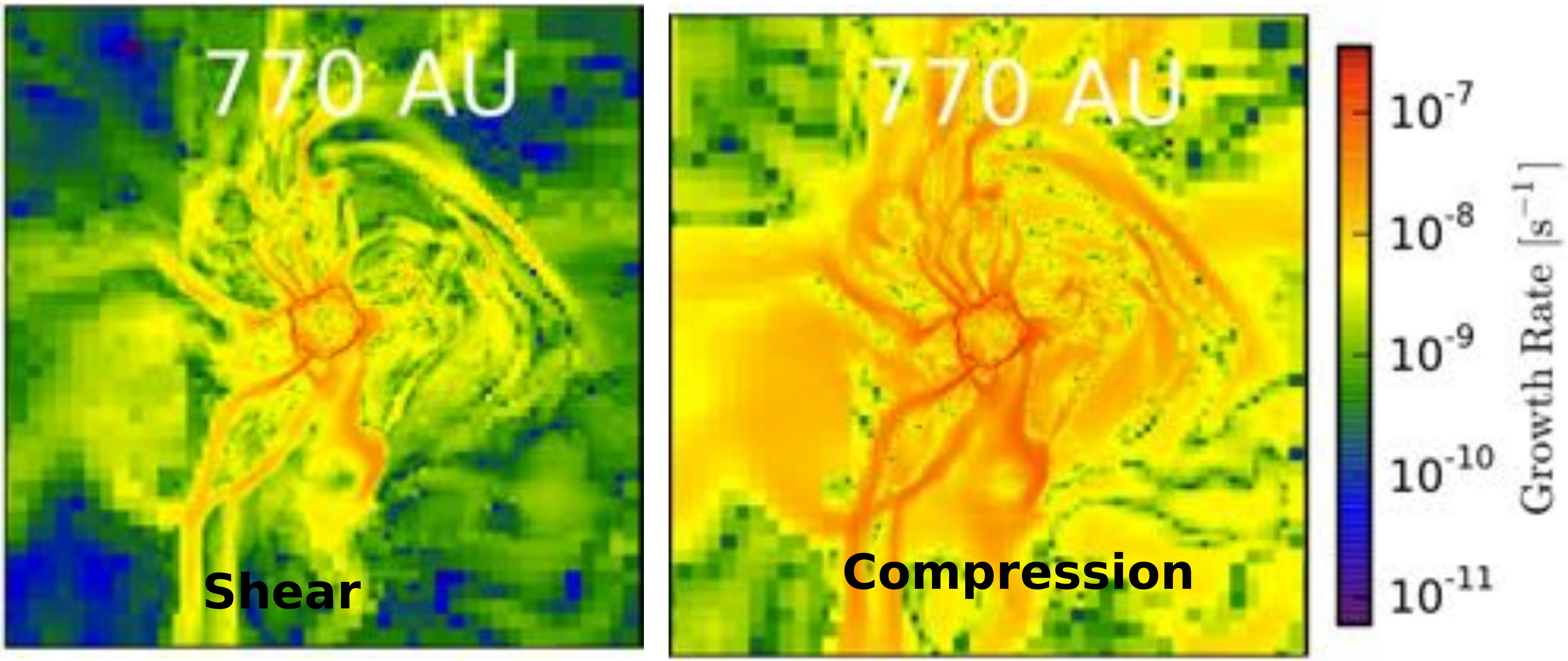
Latif et al. 2013 MNRAS 433 668L

Impact of Magnetic fields on Fragmentation



Latif et al. 2014 MNRAS 440 1551L

Impact of shear and compression

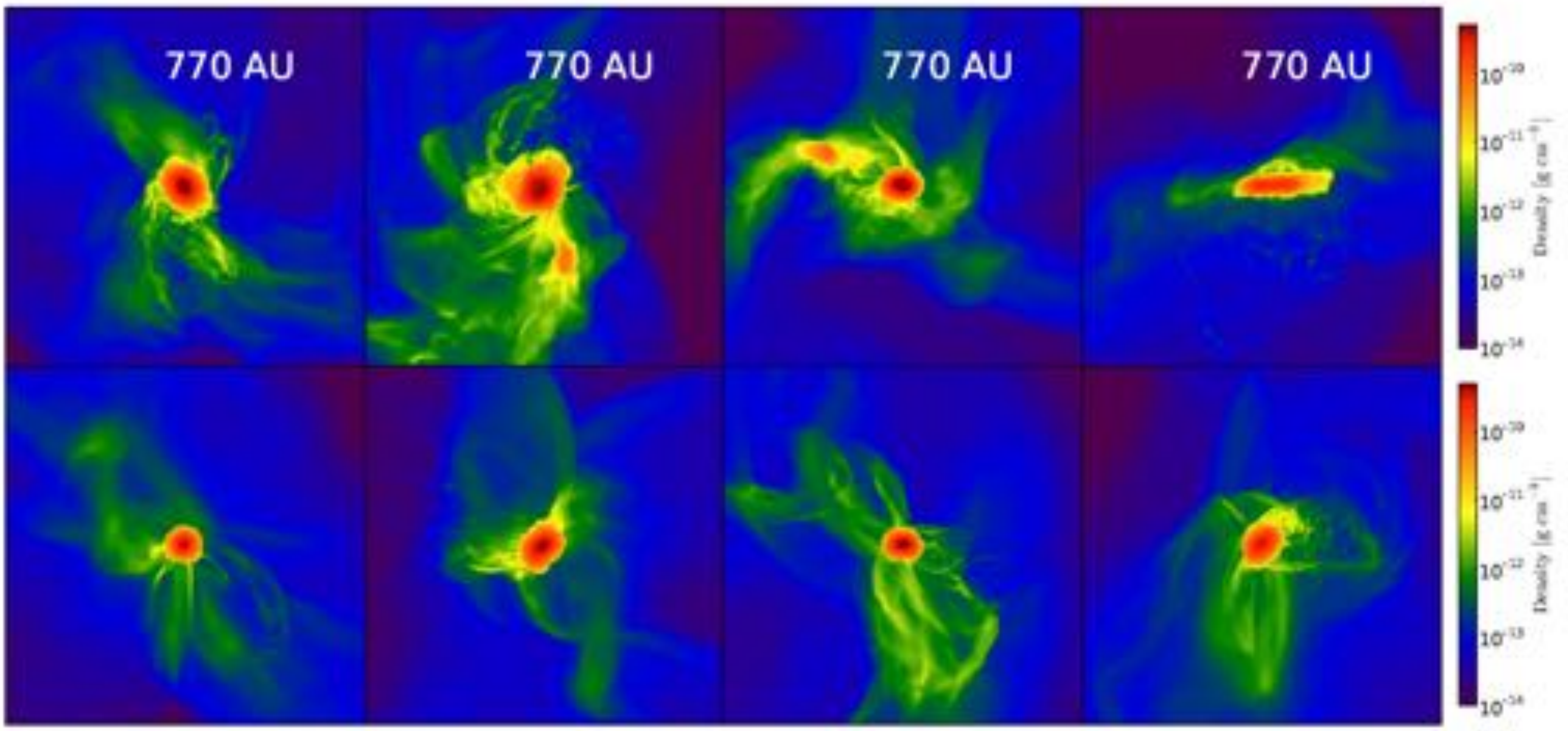


$$\frac{D}{Dt}\left(\frac{B^2}{8\pi}\right) = \frac{1}{4\pi}\left(B_i B_j S^{*}_{ij} - 2/3 B^2 d\right)$$

see Schmidt+13 **Shear** **Compression**

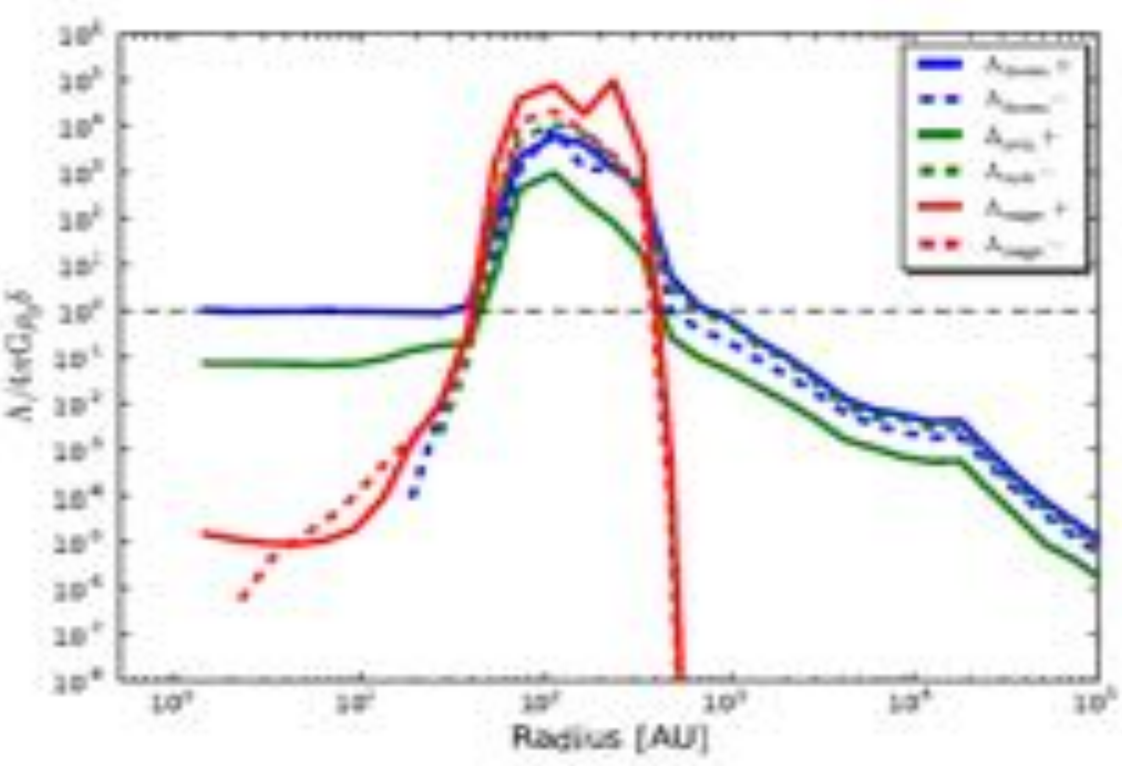
Latif et al 2013 submitted
Arxiv:1310.3680

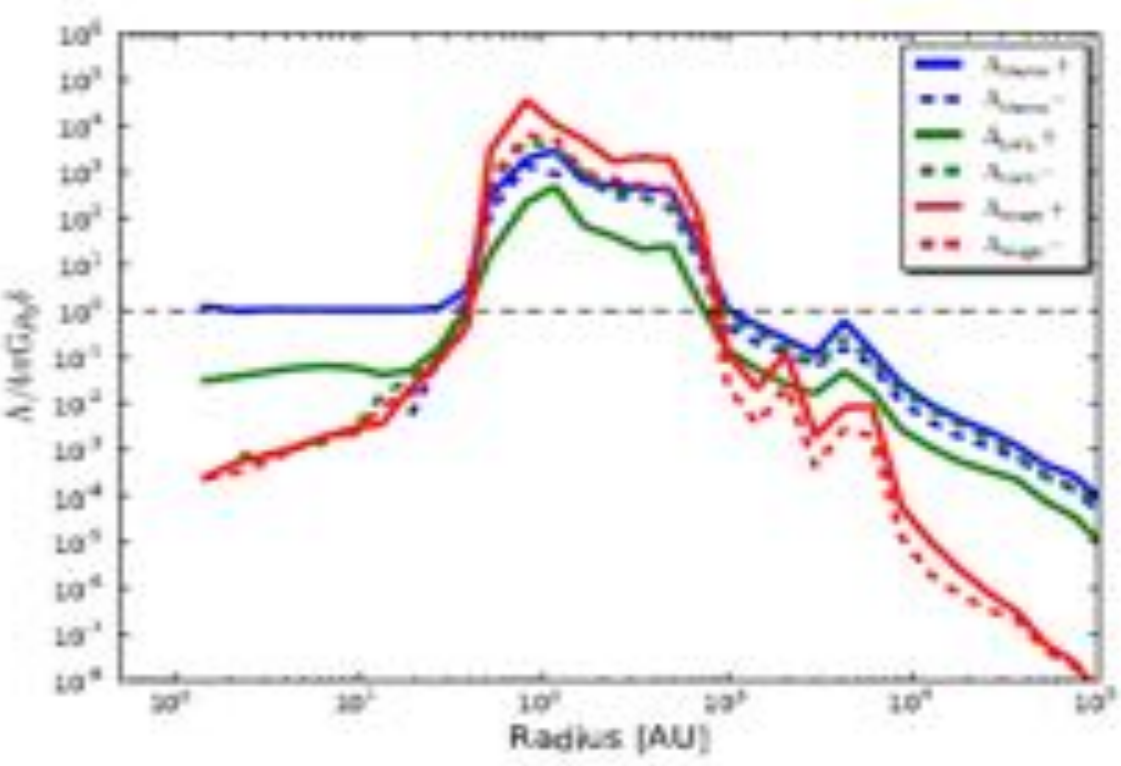
Impact of Magnetic fields on Fragmentation

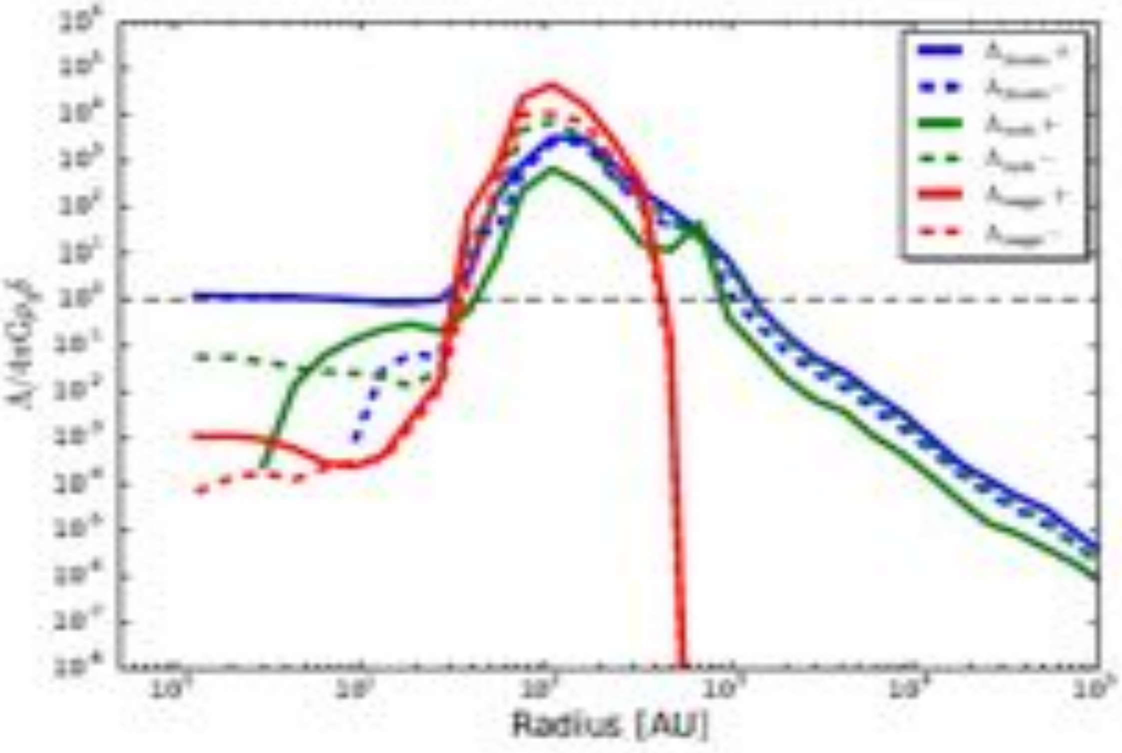


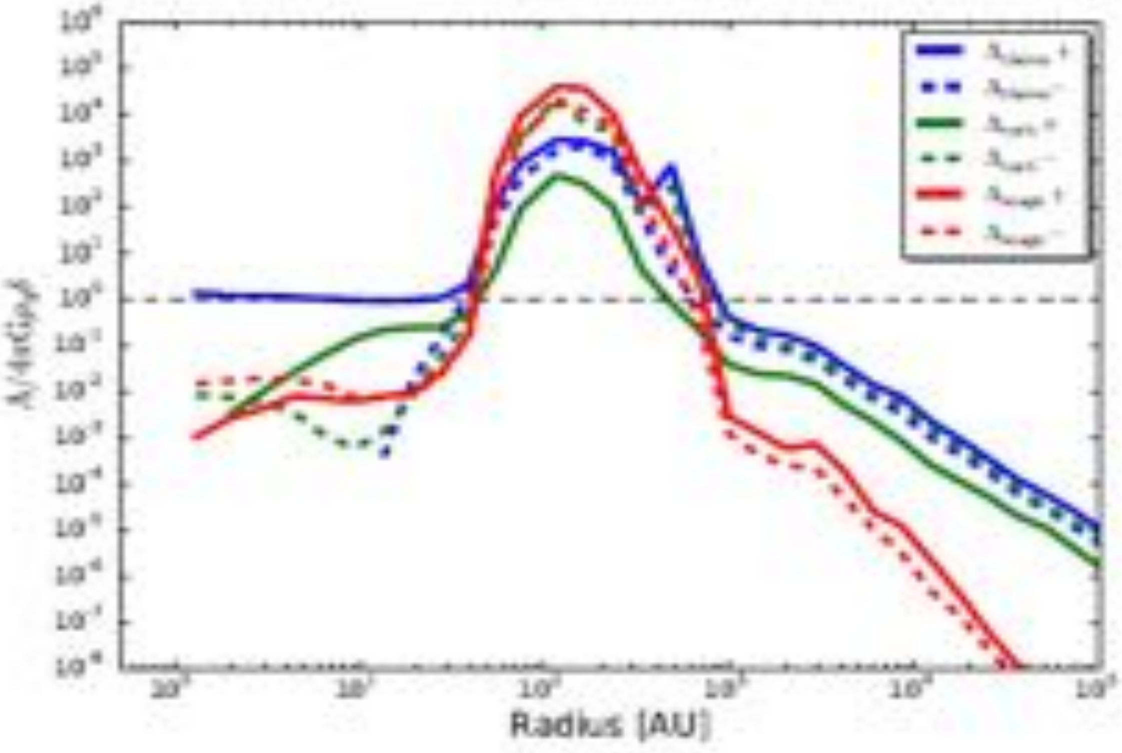
Latif et al. 2014 MNRAS 440 1551L

Magnetic Fields during the formation of SMBHs

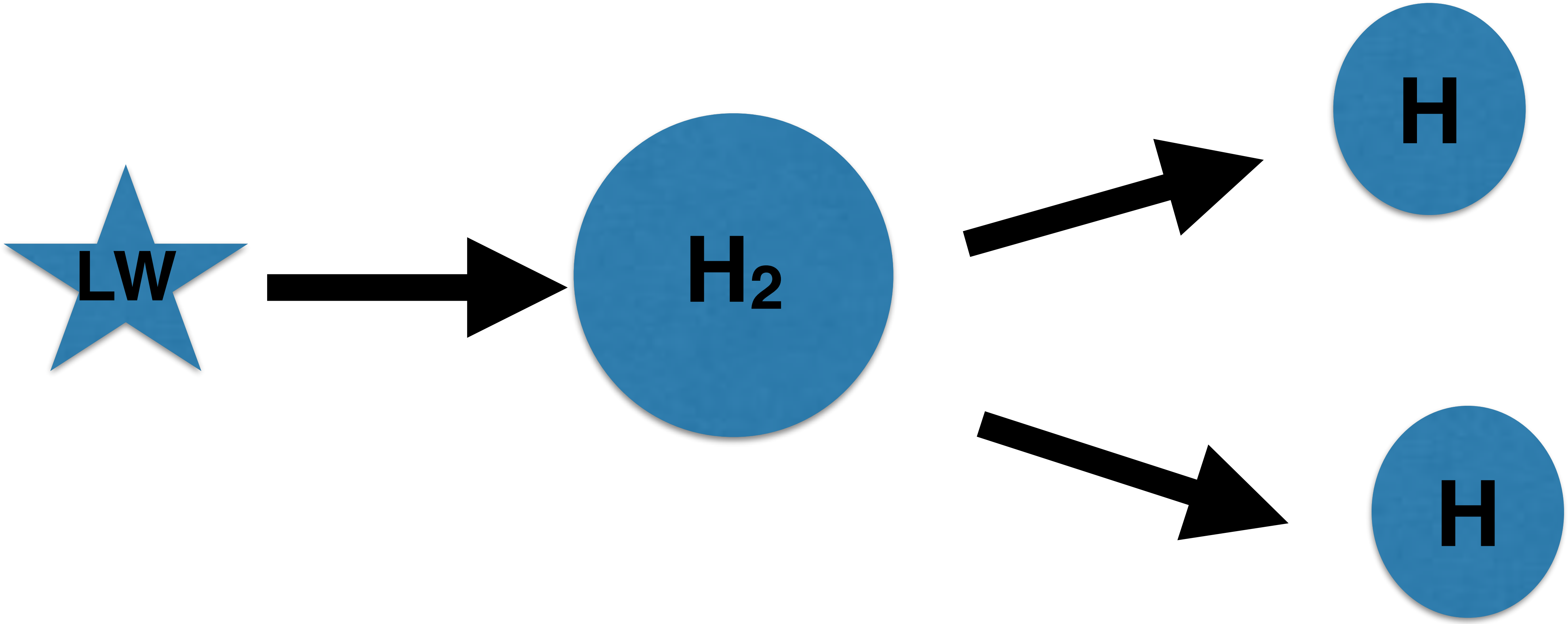




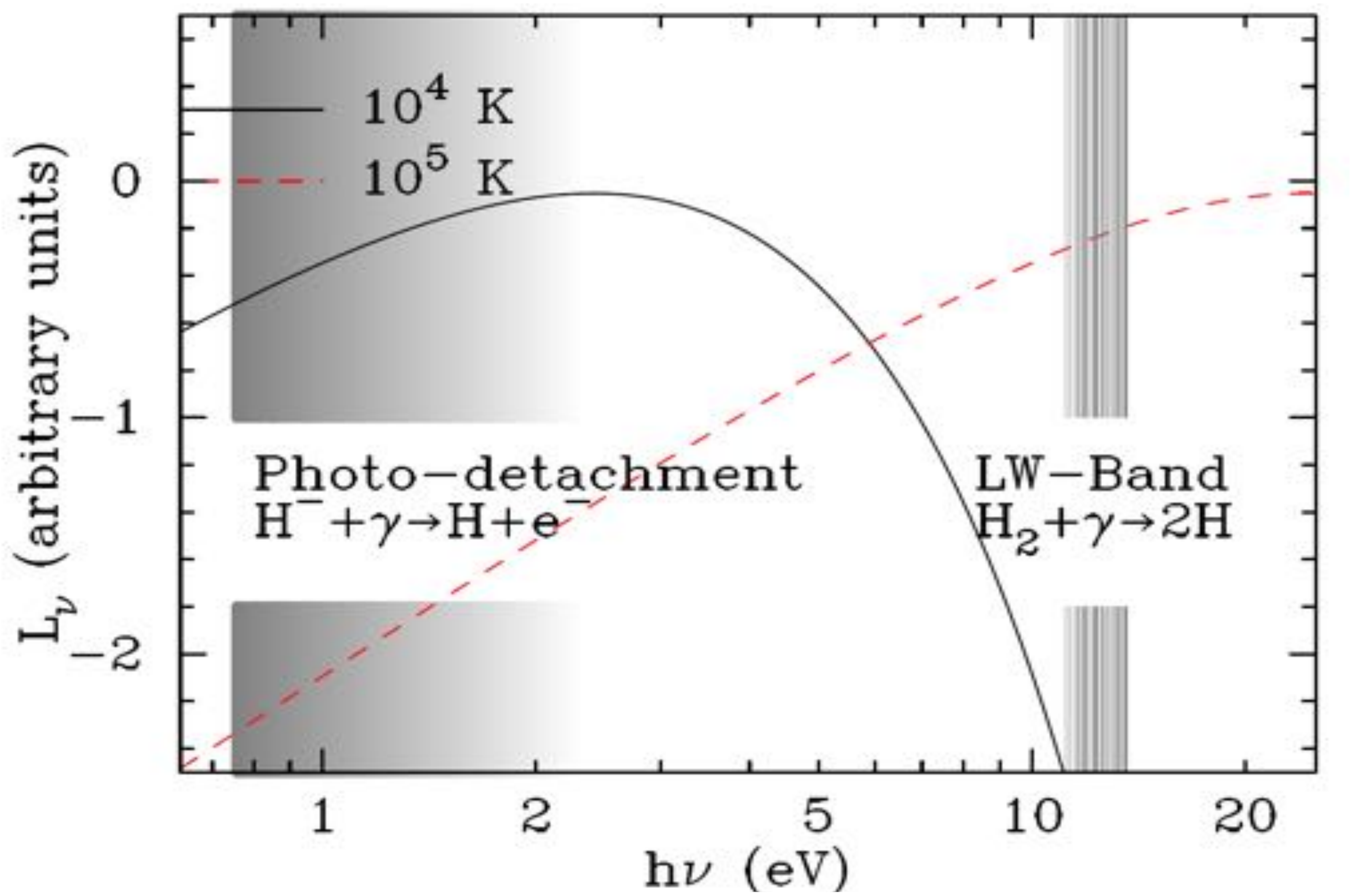




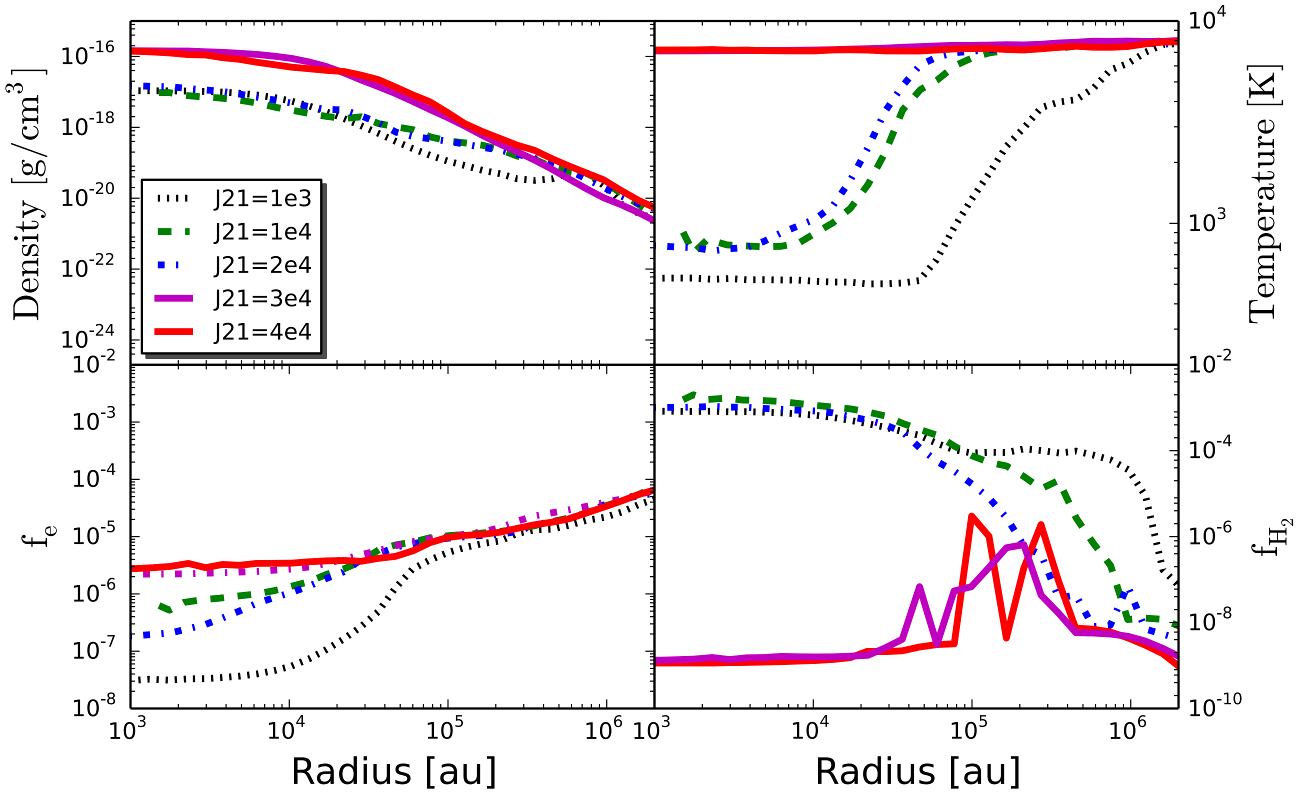
What is the critical value of Lyman Werner Flux?

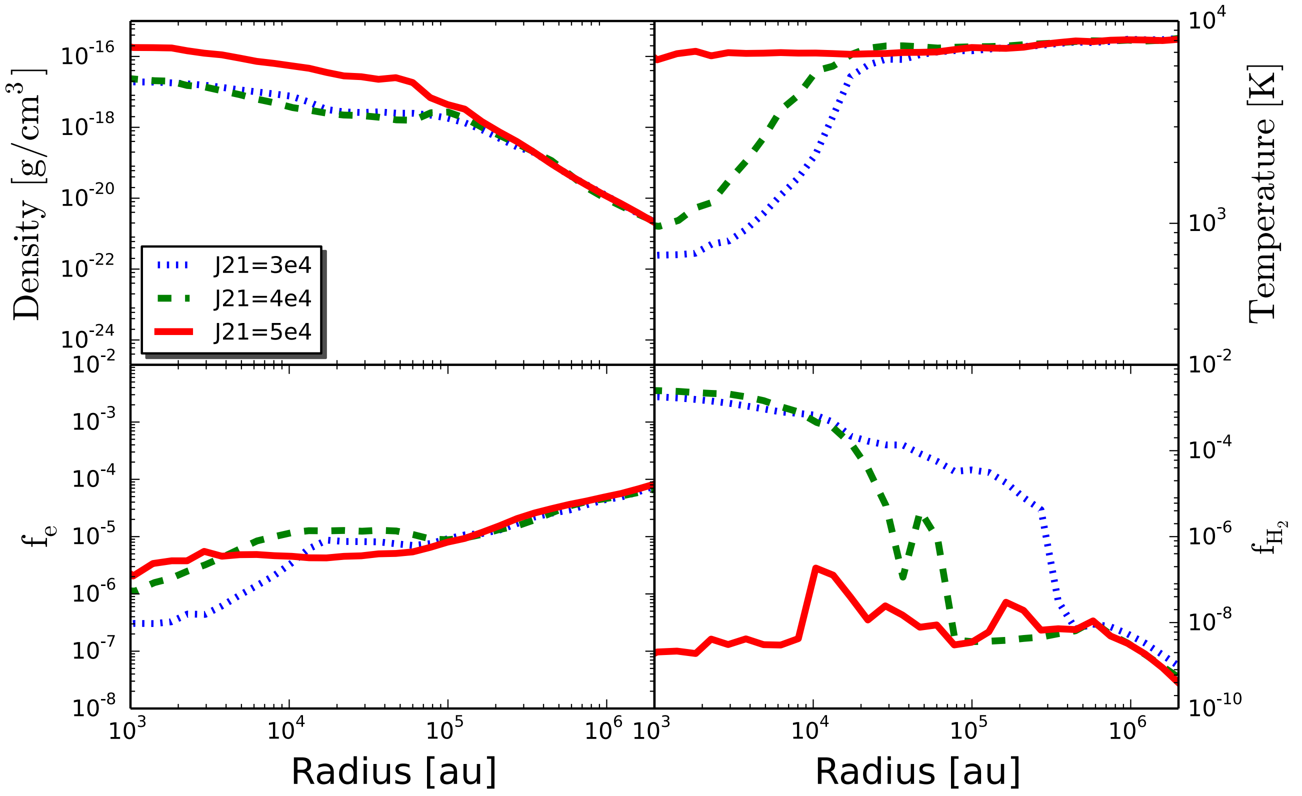


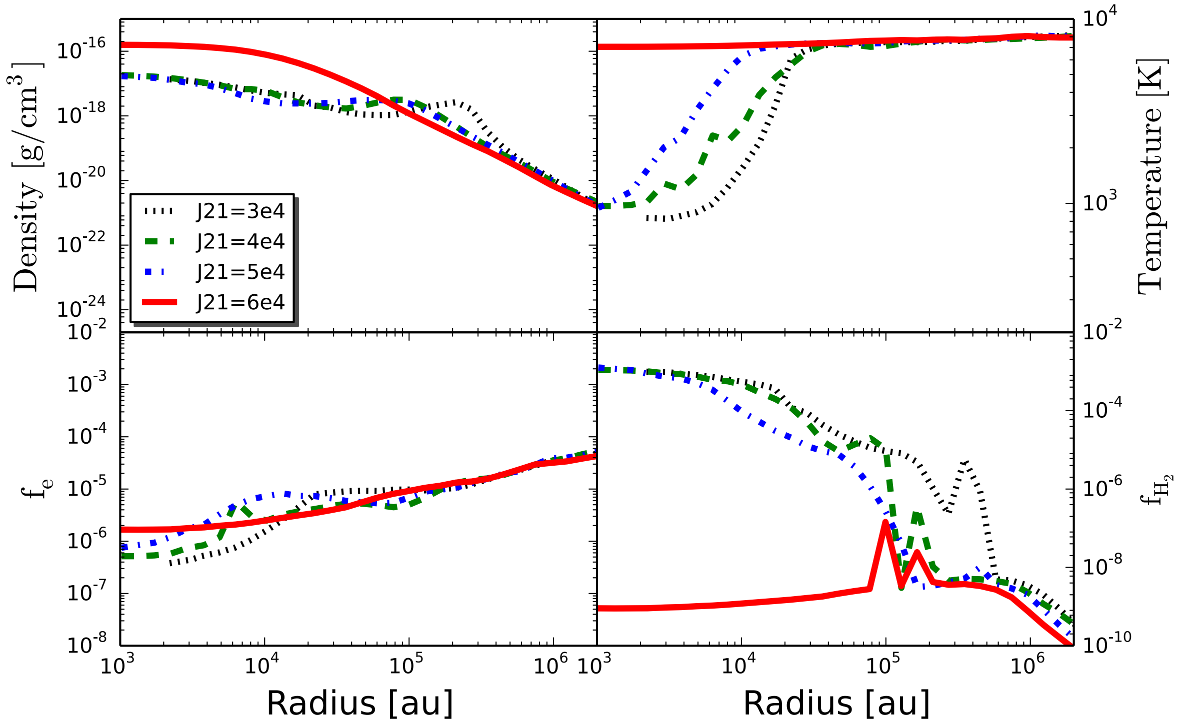
Dependence of J_{crit} on radiation spectra



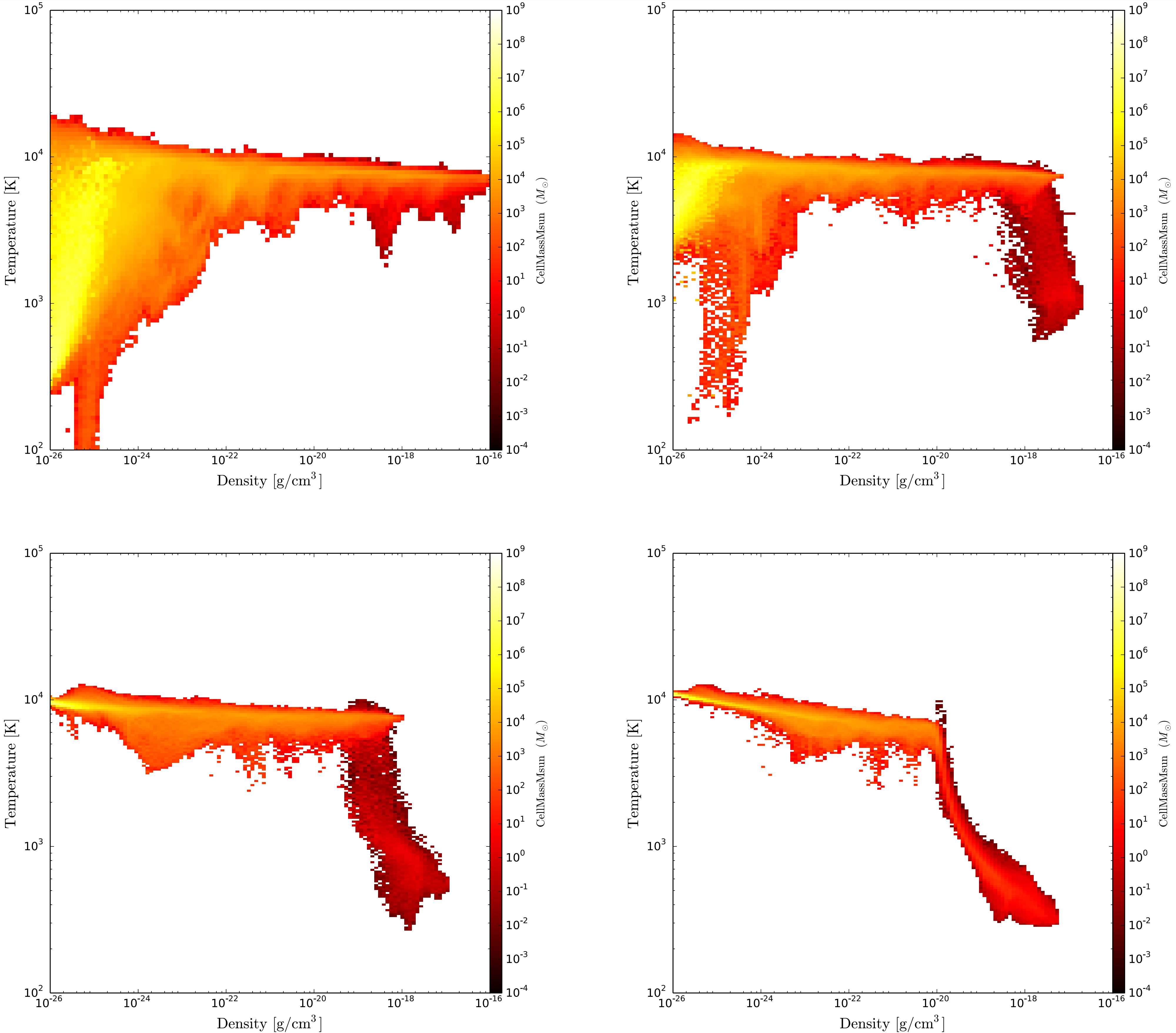
Dependence of J_{crit} on halo properties



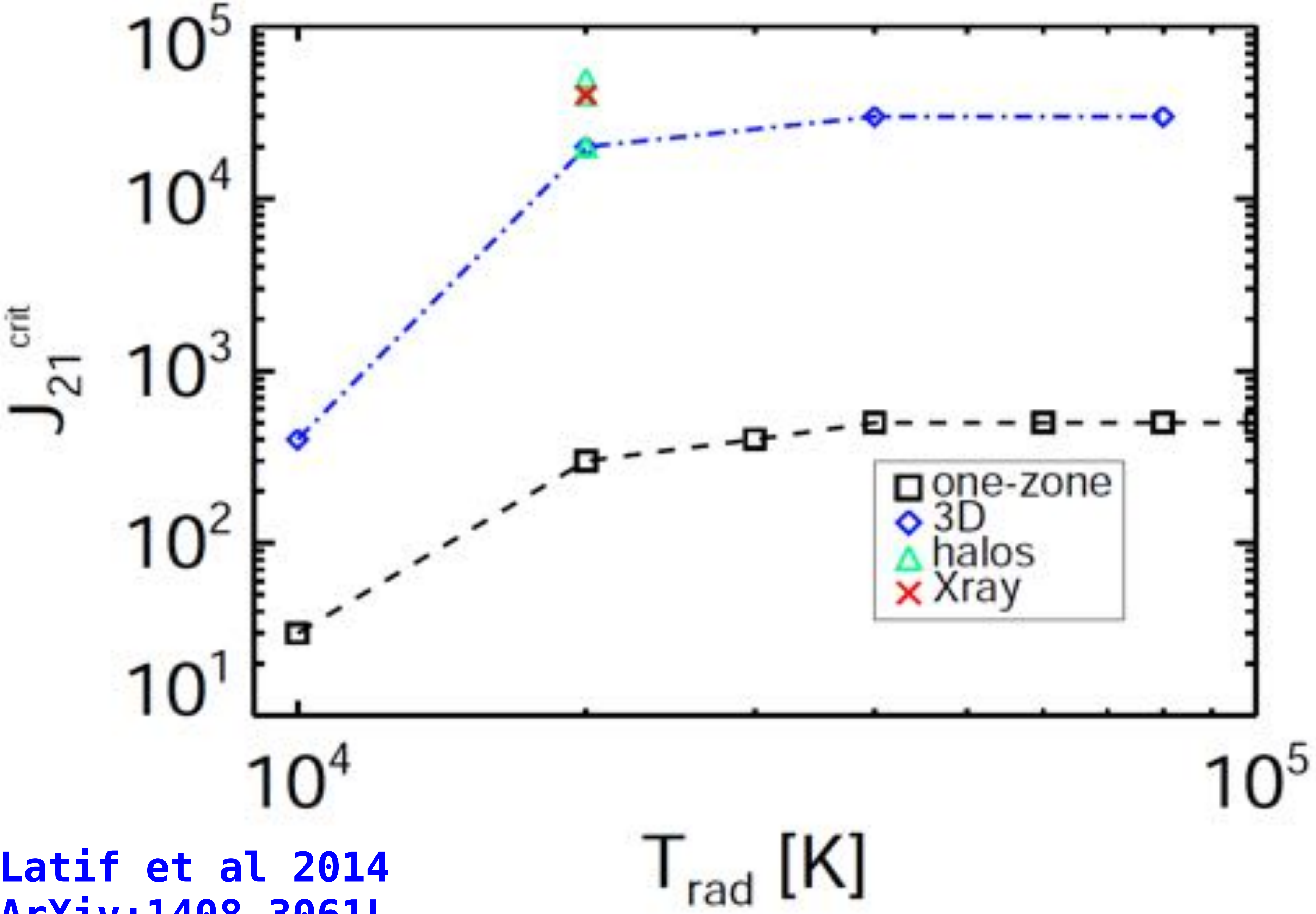




Impact of X-ray heating on J_{crit}



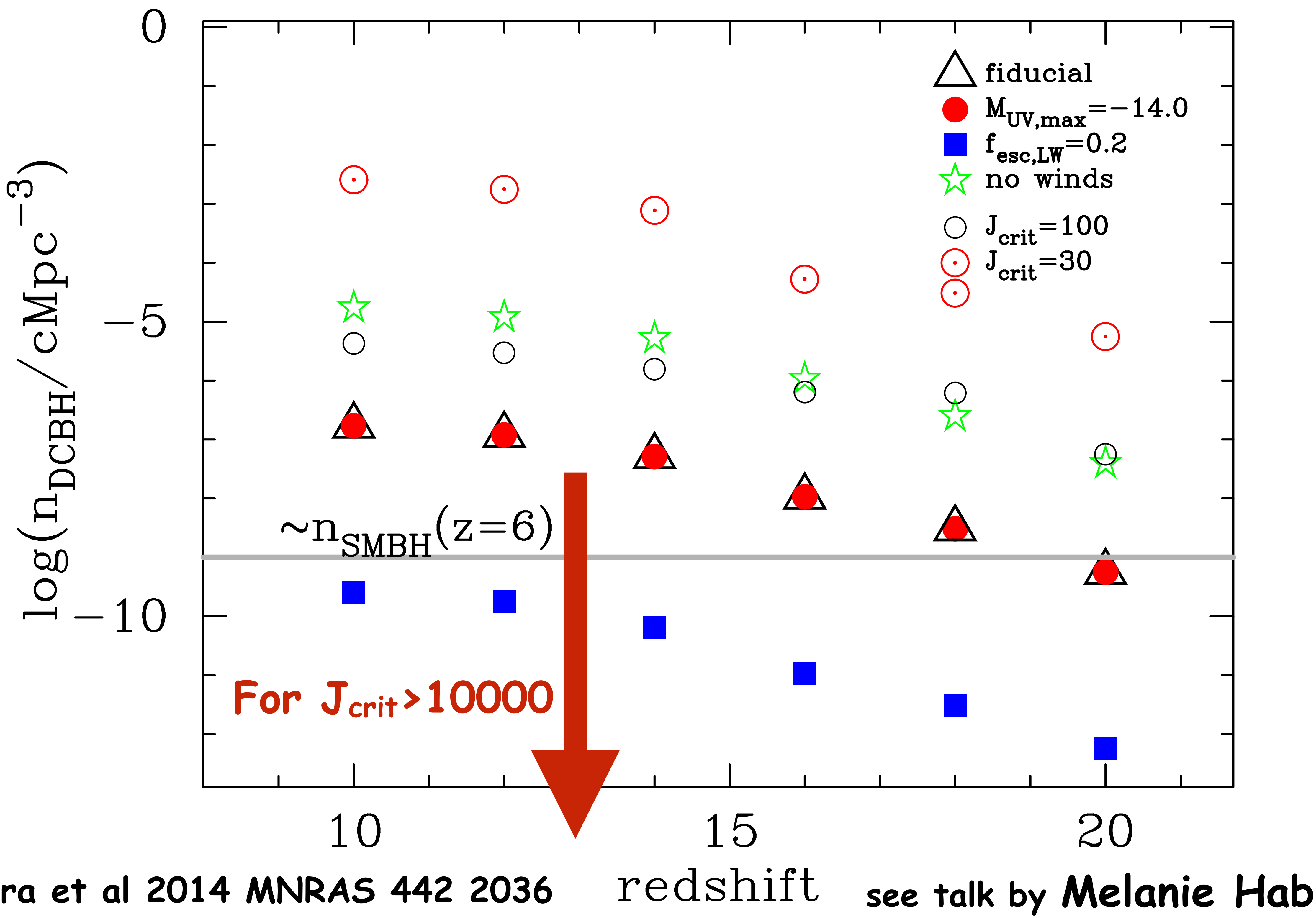
Estimates of J_{crit} from 3D simulations



Latif et al 2014
ArXiv:1408.3061L

Latif et al. MNRAS 2015 446 3136, Also see Hartwig et al. 2015

Number density of DCBHs

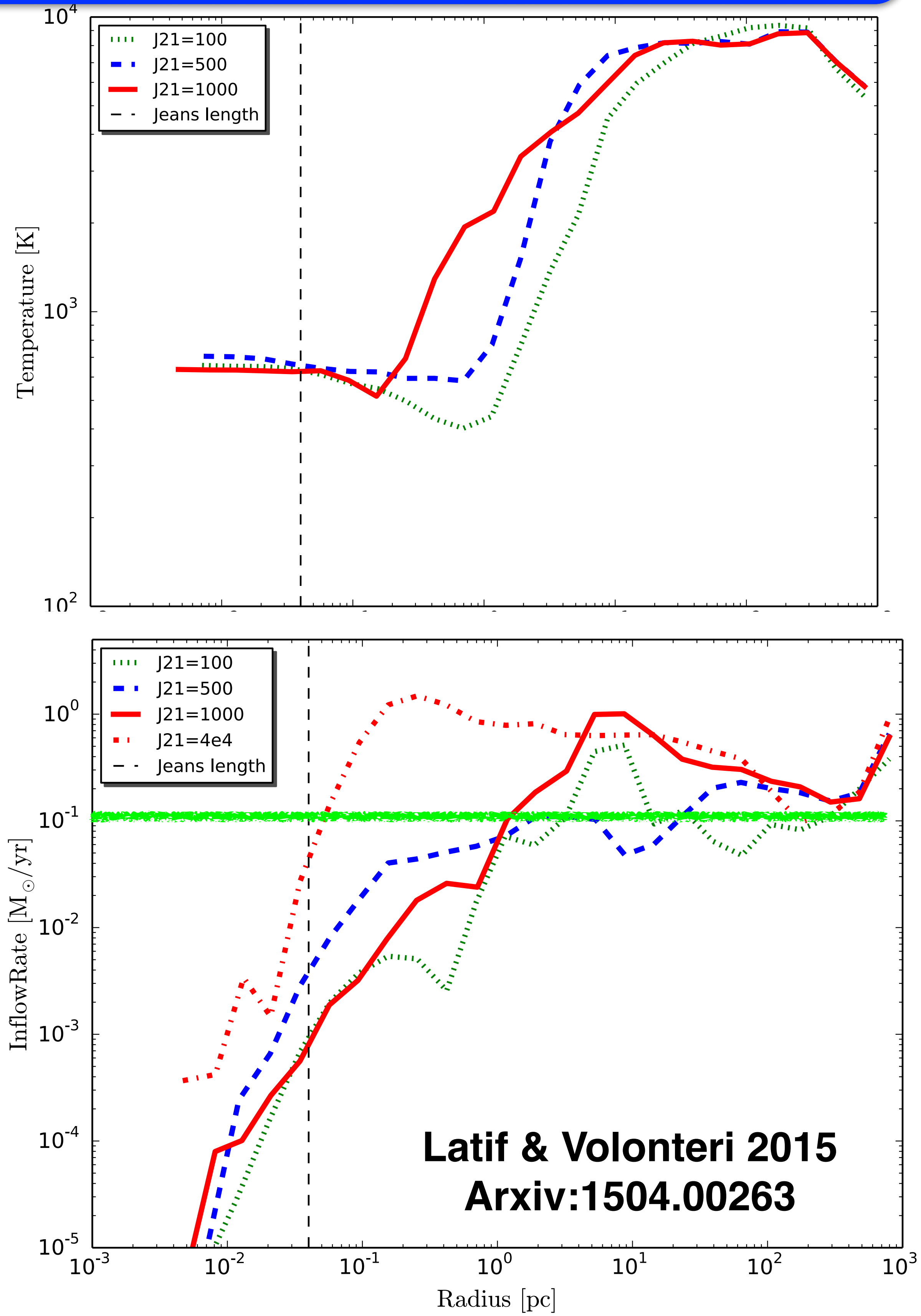


Dijkstra et al 2014 MNRAS 442 2036

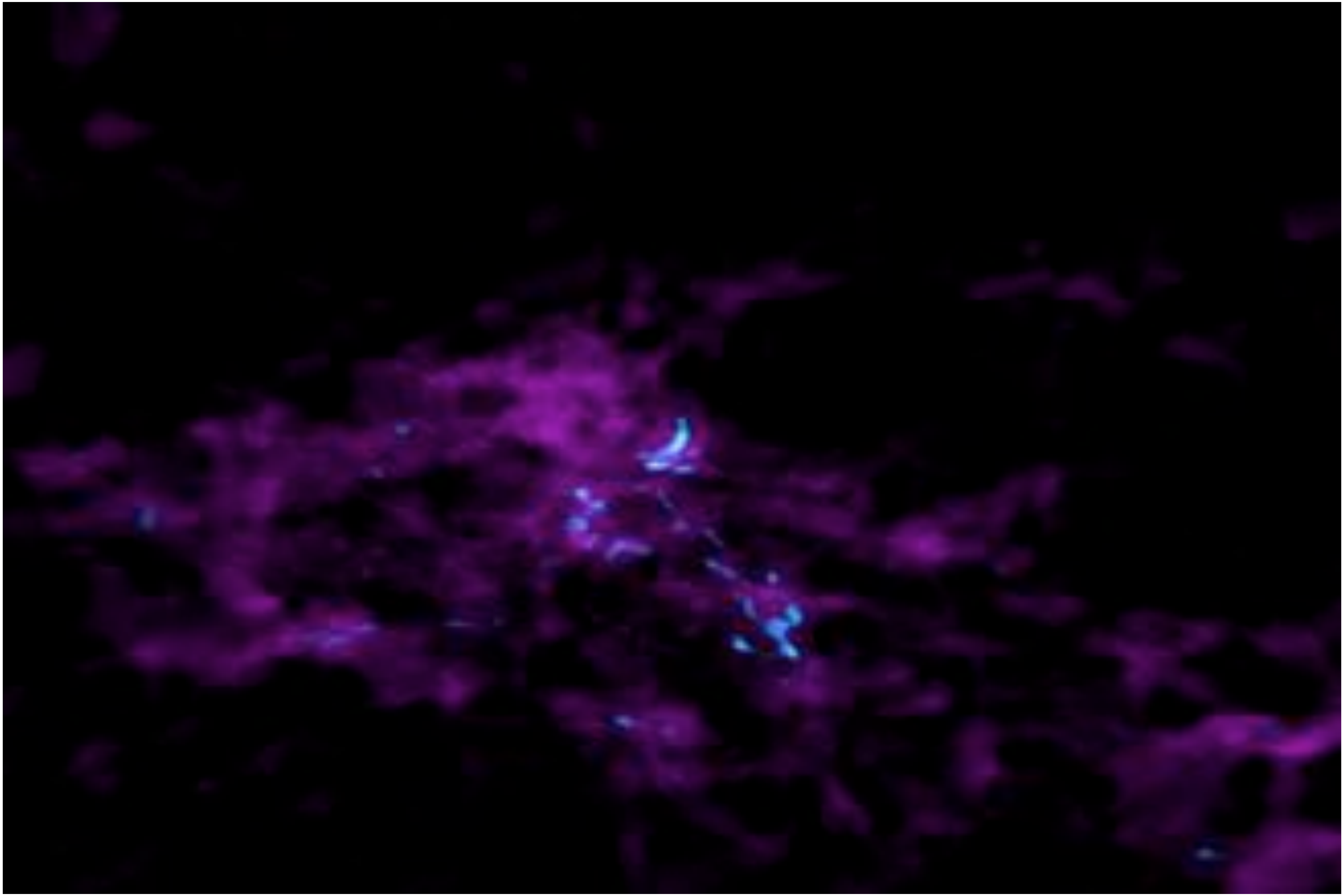
see talk by **Melanie Habouzit**

What if there is trace amount of H_2

- Massive stars up to 1000 $M_\odot$ can be formed in minihalos (Hirano et al 2014, Latif & Schleicher 2015)
- LW flux helps in suppressing H_2 formation and keeps the gas warm with 8000 K down to ~ pc scales
- Key requirement for the formation of supermassive star is mass inflow rate of 0.1 $M_\odot$ /yr

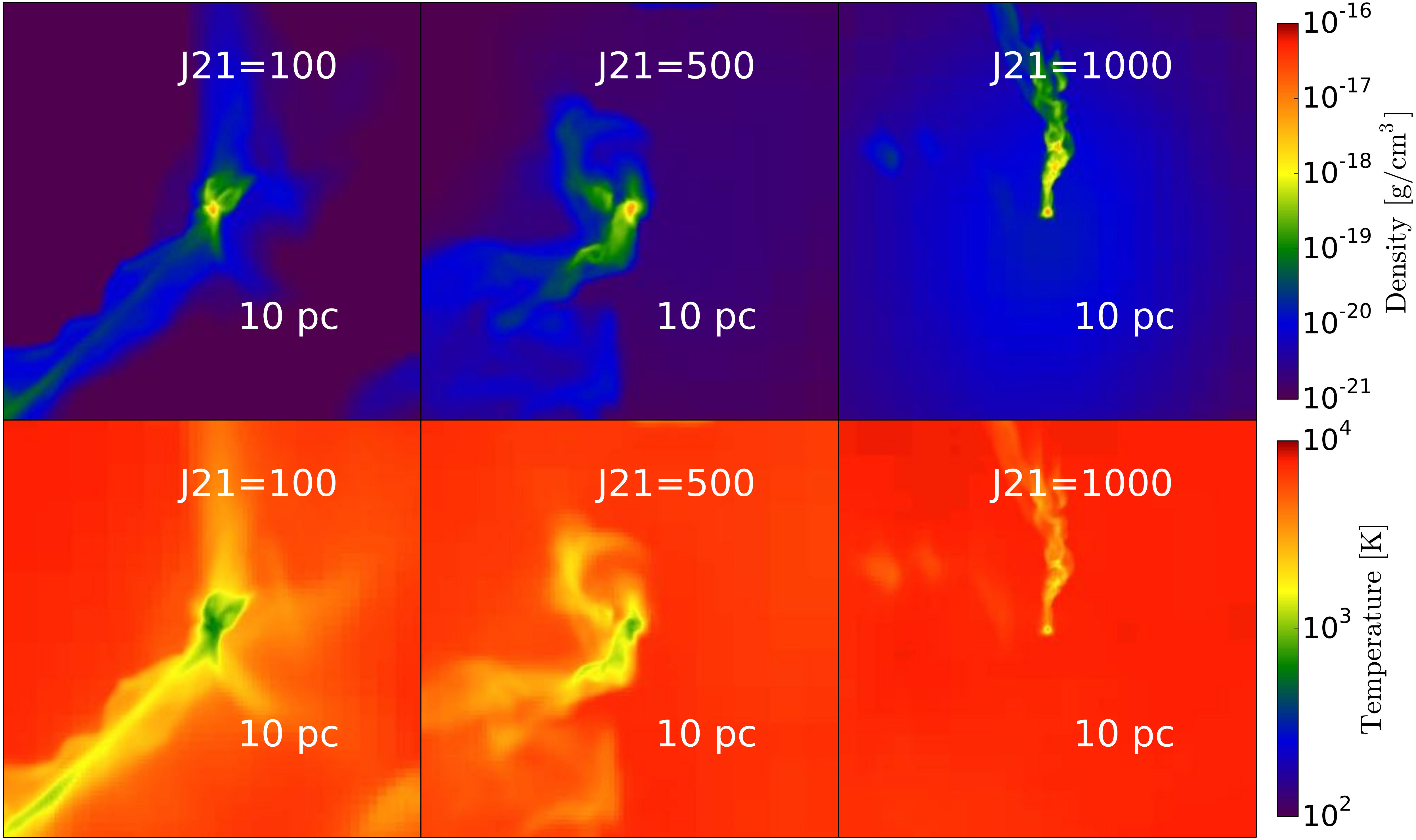


Latif & Volonteri 2015
Arxiv:1504.00263



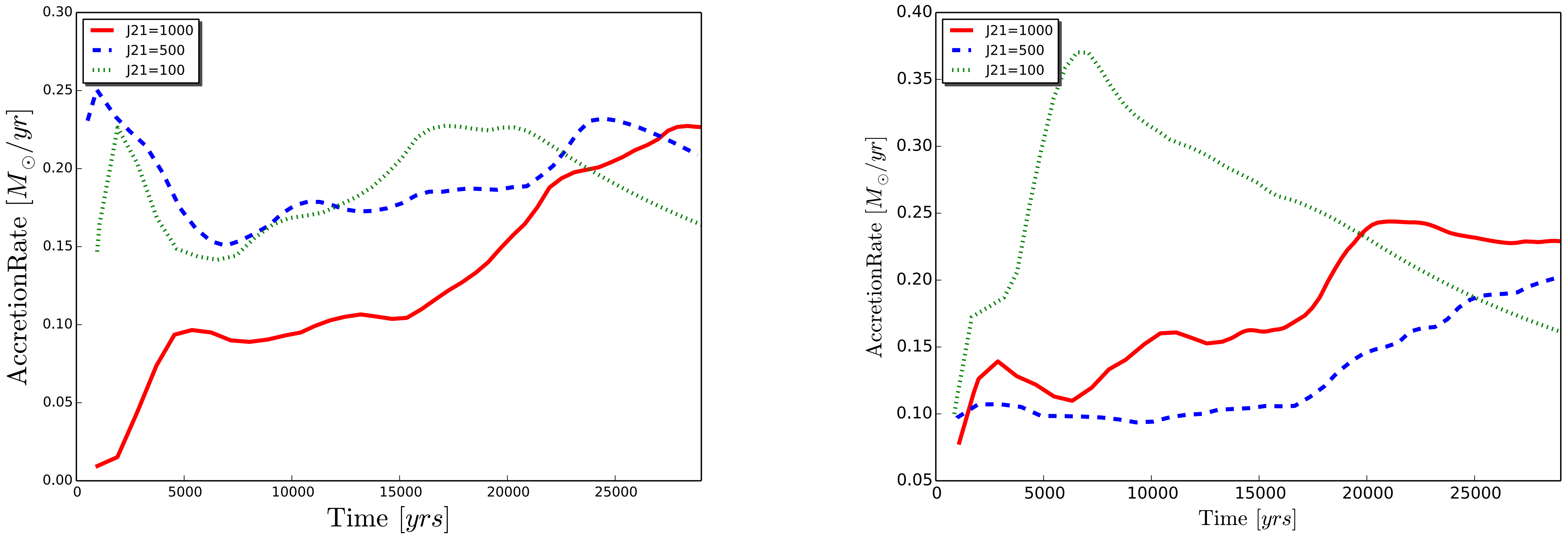
Latif & Volonteri 2015 Arxiv:1504.00263

Density structure in the halo

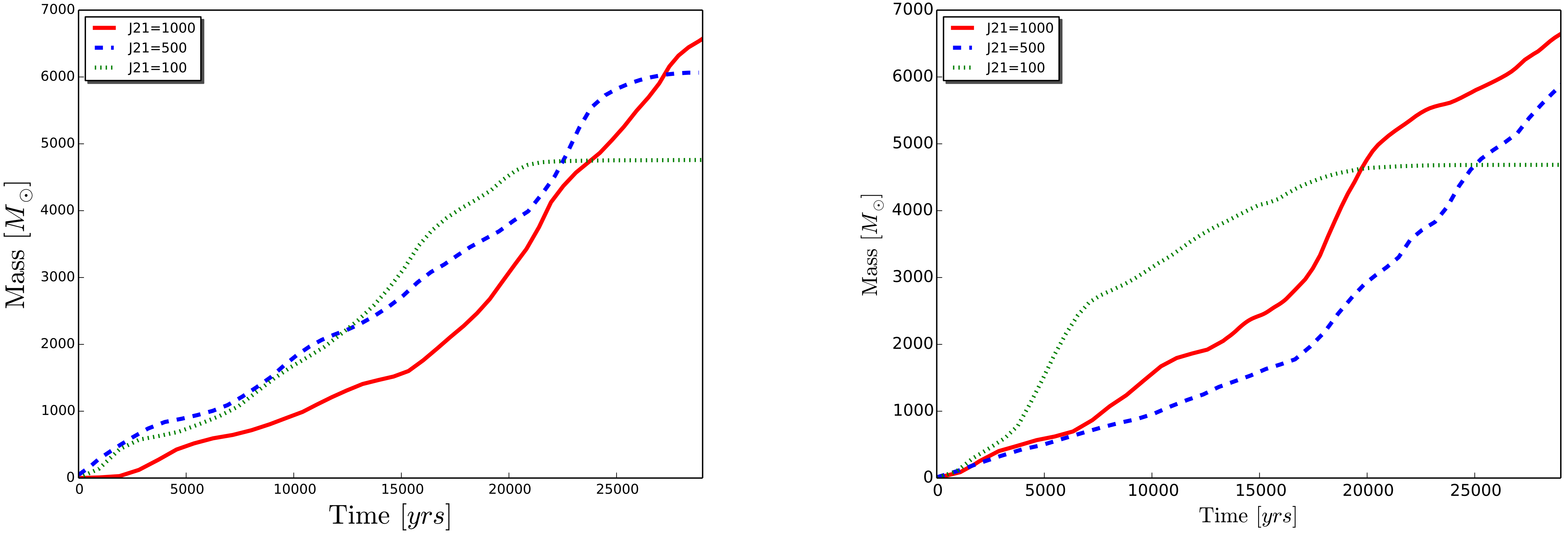


Latif & Volonteri 2015 Arxiv:1504.00263

Sink Masses & accretion rates



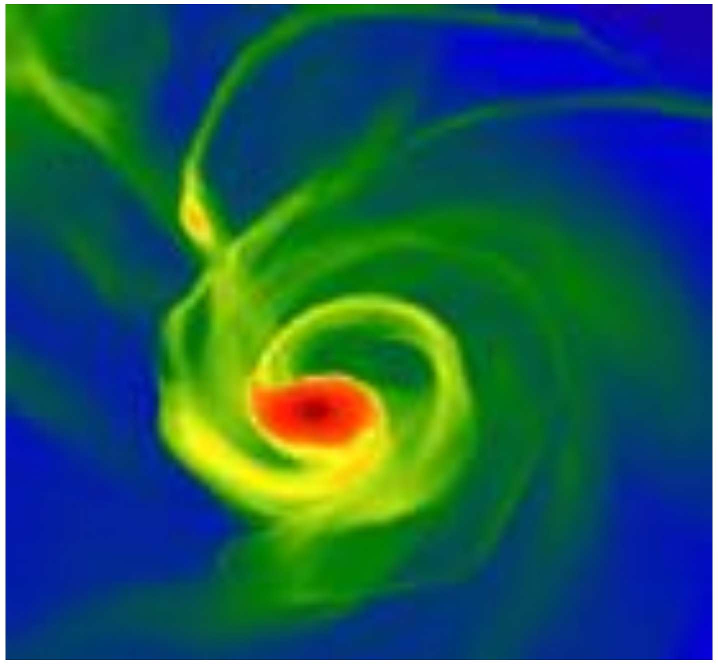
Latif & Volonteri 2015 Arxiv:1504.00263, to be published in MNRAS



What if fragmentation occurs at smaller scales

- ★ Analytical model for disk fragmentation
- ★ Assumptions:
  Steady state condition
  Marginally stable (Q=1)
  Embedded in large inflow rates of 0.1 $M_\odot$/yr
- ★ Solve for Thermal balance

- ★ Viscous Heating

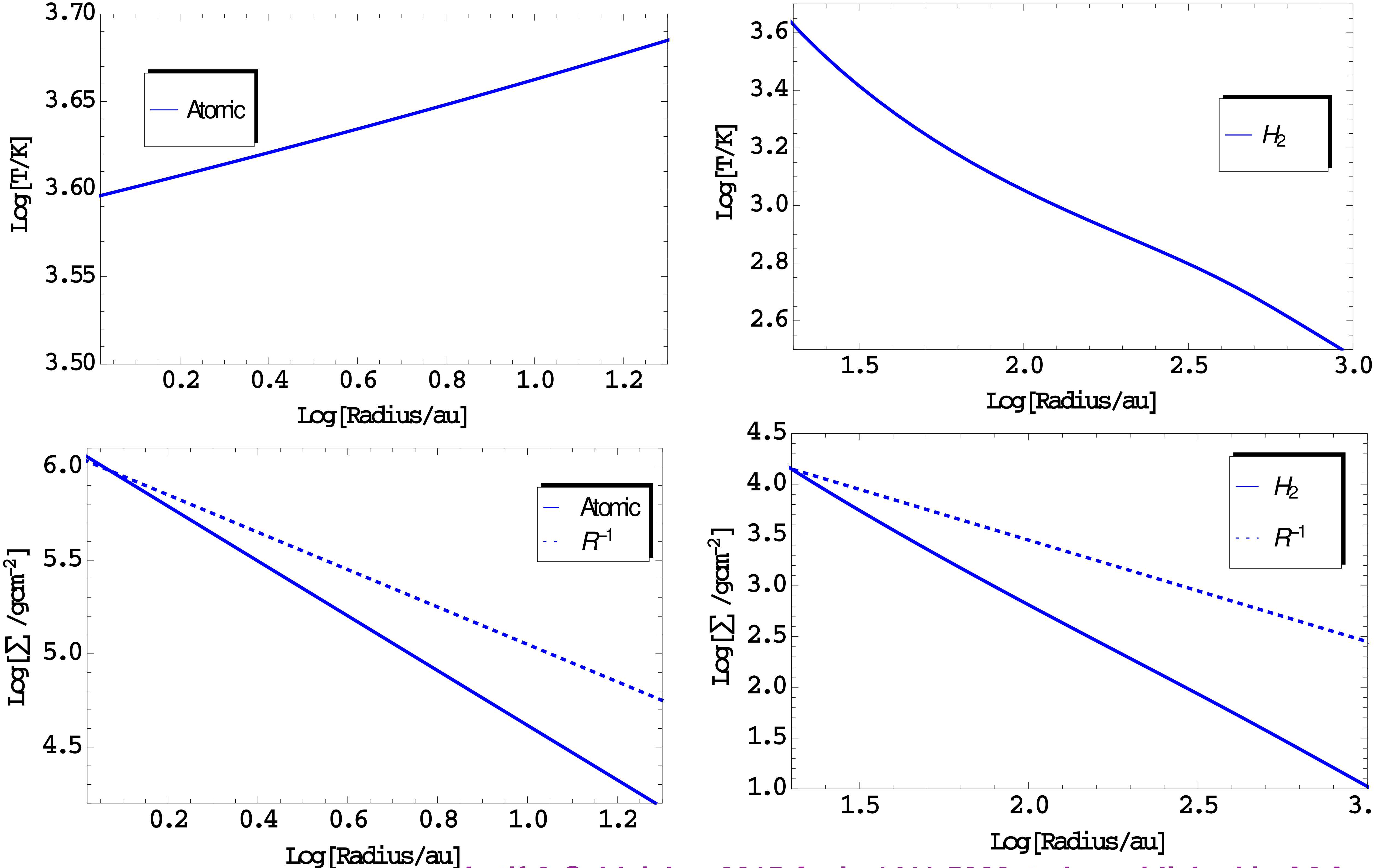


$$Q_+ = Q_-$$

$$Q_+ = \frac{9}{4}\nu\Sigma\Omega^2$$

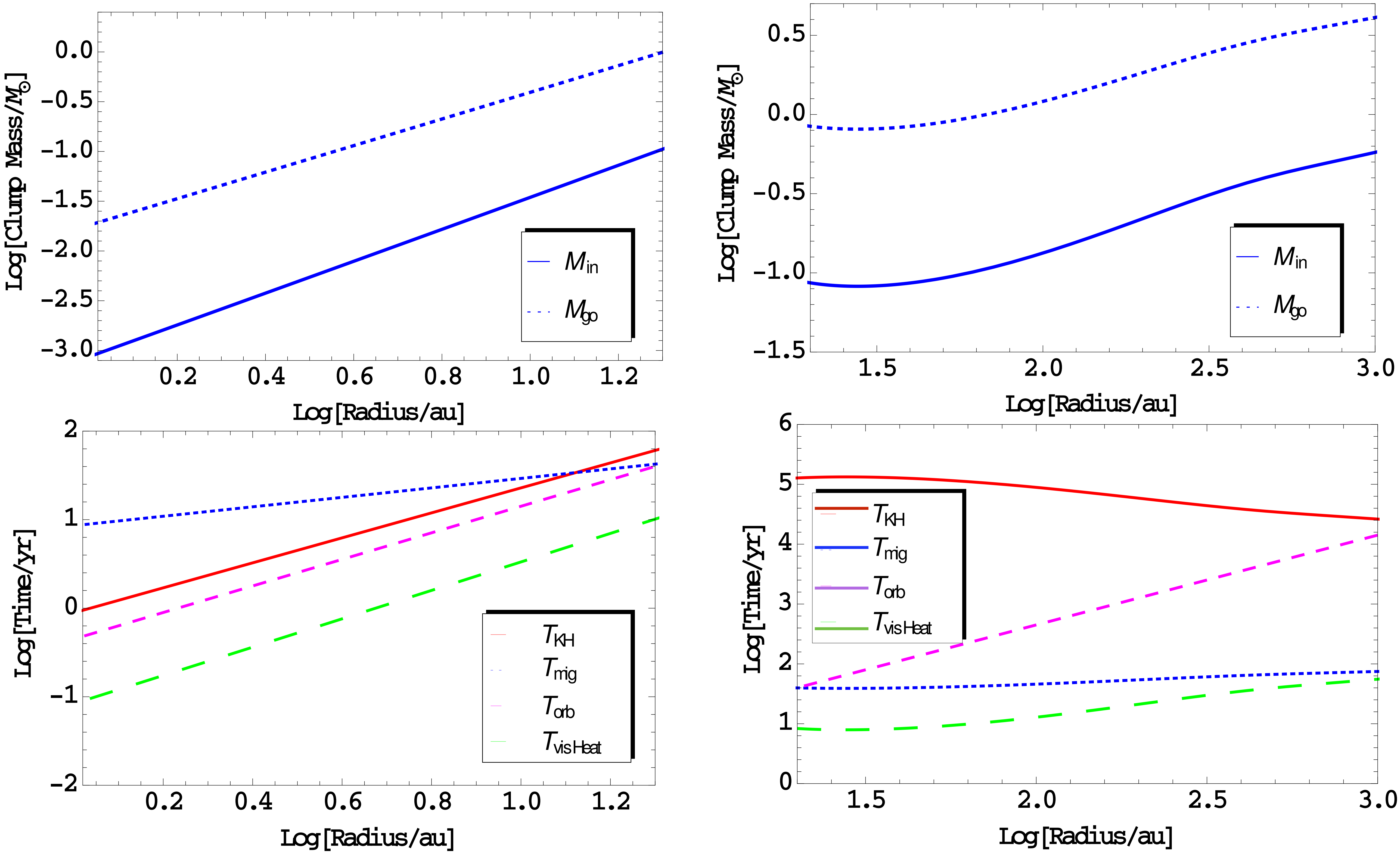
Latif & Schleicher 2015 Arxiv:1411:5902, published in A&A

Disk properties for central star of 10 $M_\odot$



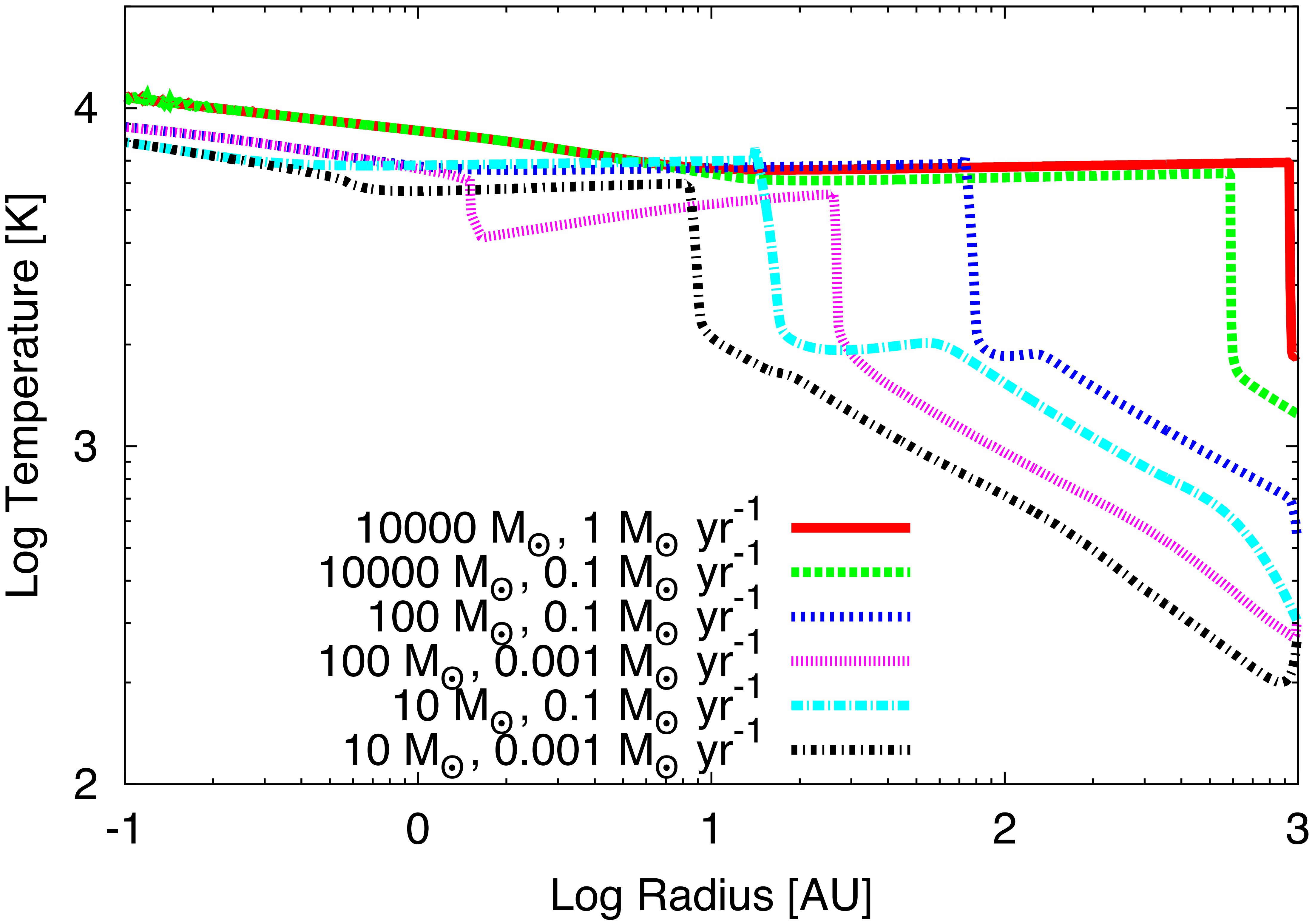
Latif & Schleicher 2015 Arxiv:1411:5902, to be published in A&A

Clump masses & time scales comparison



Latif & Schleicher 2015 Arxiv:1411:5902, to be published in A&A

Thermal properties of disk



Schleicher et al. 2015 Arxiv:1504:06296

Key findings of this model

- ★ Temperature of the disk increases due to viscous heating for higher accretion rates

- ★ H_2 gets collisionally dissociated (Also see Schleicher et al 2015)

- ★ Clumps are able to migrate inward on short time scales, even tidally disrupted within central 10 AU

- ★ Feedback from the central star only becomes important at later stages for $10^4\ M_\odot$

Latif & Schleicher 2015 Arxiv:1411:5902, to be published in A&A

Summary

- Direct isothermal collapse provides massive seeds of about $10^5\,M_{\odot}$ but sites are rare
- Large accretion rates of ~0.1 $M_{\odot}$/yr are found in simulations with moderate UV flux
- No vigorous fragmentation is observed in such cases
- Viscous heating leads to collisional dissociation of H_2 and help in stabilising the disk.
- Complete isothermal collapse may always not be necessary to form supermassive stars of about ~$10^5\,M_{\odot}$