Supermassive black hole formation at high redshifts

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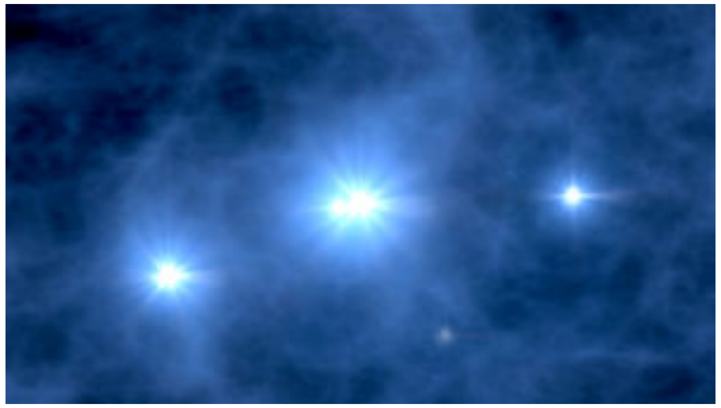
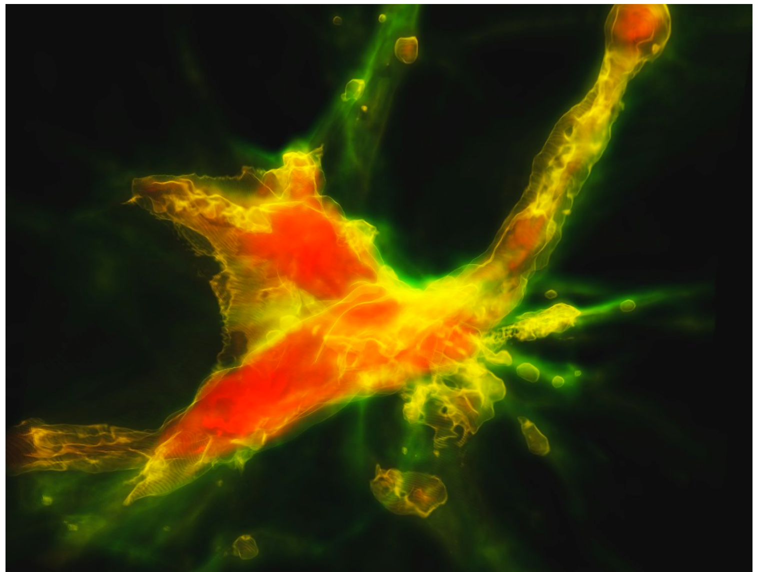
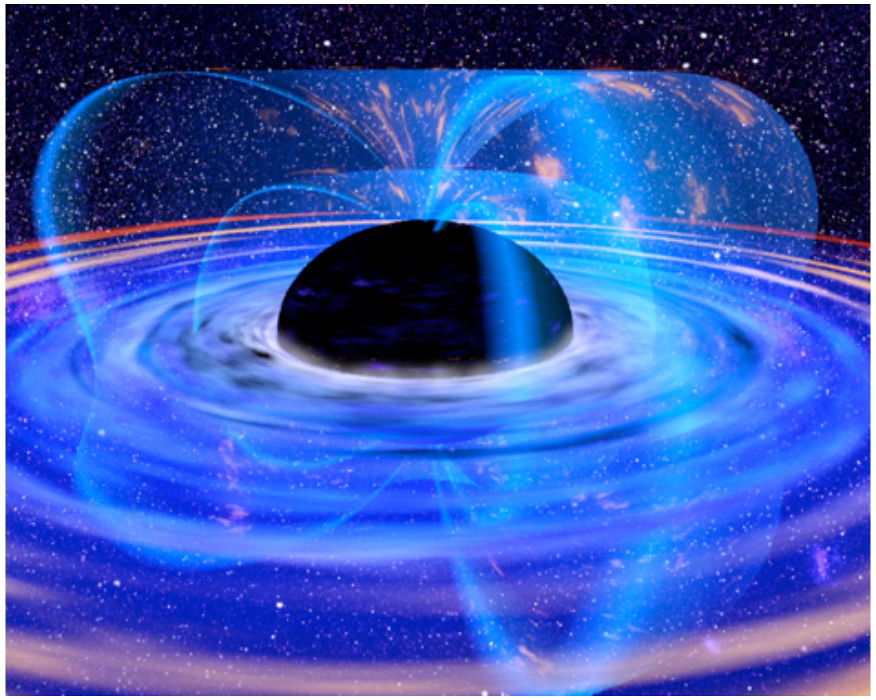
My research interests

- Black holes formation & evolution
- The birth of the first stars, low mass stars, metal poor stars
- Formation of the first galaxies (Lya alpha Emitters)
- Turbulence & magnetic fields
- Chemistry of ISM & IGM
- Stellar and AGN feedback





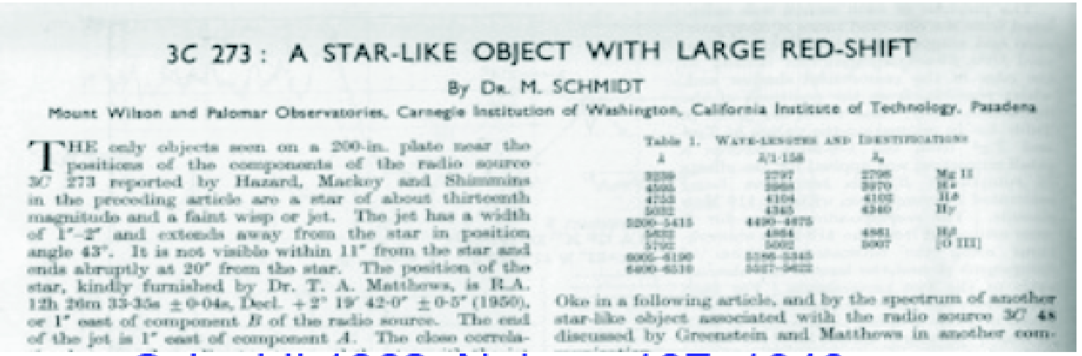
Outline



- Introduction
- Black hole formation scenarios
- Direct collapse model
- Feasibility of direct collapse scenario
- Alternatives to an isothermal collapse
- Observational constraints
- Summary

Milestones

- 1783 - 1795: John Michell and Pierre-Simon Laplace hypothesize existence of “dark stars” or “invisible bodies”
- 1915: Albert Einstein’s General Relativity
- 1916: Karl Schwarzschild finds the “black hole” solution for GR equations
- 1963: Maarten Schmidt, Jesse Greenstein & Thomas Matthews discover Quasars
- 1964: Edwin Salpeter and Yakov Zel’dovich independently hypothesize mass accretion onto a supermassive BH for quasars.
- 1968: John Wheeler coins the term “Black Hole”
- 1970s, beginning of: X-ray source Cygnus X-1 is the first BH candidate with $M_{BH} \sim 12\ M_\odot$
- 1978: Sargent et al. showed that images and spectra of the central region of M87 indicate the presence of a BH with $M_{BH} \sim 6 \times 10^9\ M_\odot$



3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

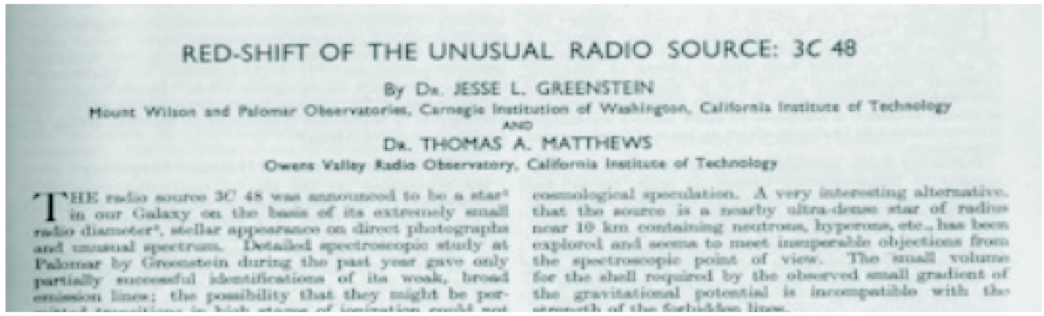
THE only objects seen on a 200-in. plate near the positions of the components of the radio source 3C 273 reported by Hazard, Mackey and Shimmins in the preceding article are a star of about thirteenth magnitude and a faint wisp or jet. The jet has a width of 1″–2″ and extends away from the star in position angle 43°. It is not visible within 11″ from the star and ends abruptly at 20″ from the star. The position of the star, kindly furnished by Dr. T. A. Matthews, is R.A. 12h 26m 33·35s ± 0·04s, Decl. + 2° 19′ 42·0″ ± 0·5″ (1950), or 1″ east of component B of the radio source. The end of the jet is 1″ east of component A. The close correla-

Table 1. Wave-lengths and Identifications

λ	λ/1·158	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	Hε
4753	4104	4102	Hδ
5032	4345	4340	Hγ
5200–5415	4490–4675		
5632	4864	4861	Hβ
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

Oke in a following article, and by the spectrum of another star-like object associated with the radio source 3C 48 discussed by Greenstein and Matthews in another com-

Schmidt 1963, Nature, 197, 1040



RED-SHIFT OF THE UNUSUAL RADIO SOURCE: 3C 48

By Dr. JESSE L. GREENSTEIN

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology

AND

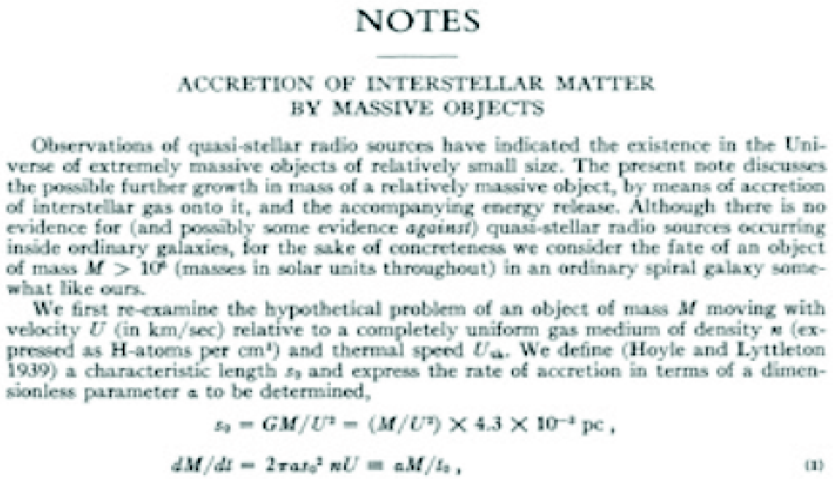
Dr. THOMAS A. MATTHEWS

Owens Valley Radio Observatory, California Institute of Technology

THE radio source 3C 48 was announced to be a star[1] in our Galaxy on the basis of its extremely small radio diameter[2], stellar appearance on direct photographs and unusual spectrum. Detailed spectroscopic study at Palomar by Greenstein during the past year gave only partially successful identifications of its weak, broad emission lines; the possibility that they might be per-

cosmological speculation. A very interesting alternative, that the source is a nearby ultra-dense star of radius near 10 km containing neutrons, hyperons, etc., has been explored and seems to meet insuperable objections from the spectroscopic point of view. The small volume for the shell required by the observed small gradient of the gravitational potential is incompatible with the strength of the forbidden lines.

Greenstein & Matthews 1963, Nature, 197, 1041



NOTES

ACCRETION OF INTERSTELLAR MATTER BY MASSIVE OBJECTS

Observations of quasi-stellar radio sources have indicated the existence in the Universe of extremely massive objects of relatively small size. The present note discusses the possible further growth in mass of a relatively massive object, by means of accretion of interstellar gas onto it, and the accompanying energy release. Although there is no evidence for (and possibly some evidence *against*) quasi-stellar radio sources occurring inside ordinary galaxies, for the sake of concreteness we consider the fate of an object of mass $M > 10^8$ (masses in solar units throughout) in an ordinary spiral galaxy somewhat like ours.

We first re-examine the hypothetical problem of an object of mass M moving with velocity U (in km/sec) relative to a completely uniform gas medium of density n (expressed as H-atoms per cm³) and thermal speed U_{th}. We define (Hoyle and Lyttleton 1939) a characteristic length s_0 and express the rate of accretion in terms of a dimensionless parameter α to be determined,

$$s_0 = GM/U^2 = (M/U^2) \times 4.3 \times 10^{-3}\ \text{pc}\ ,$$

$$dM/dt = 2\pi\alpha s_0^2\, nU = \alpha M/t_0\ , \qquad (1)$$

Salpeter 1964, ApJ, 140, 796

Black holes

Astrophysical black holes are described by two parameters only:

Mass

★**Stellar mass black holes**

(1-10 $M_\odot$)   Cygnus X-1

★**Intermediate mass black holes**

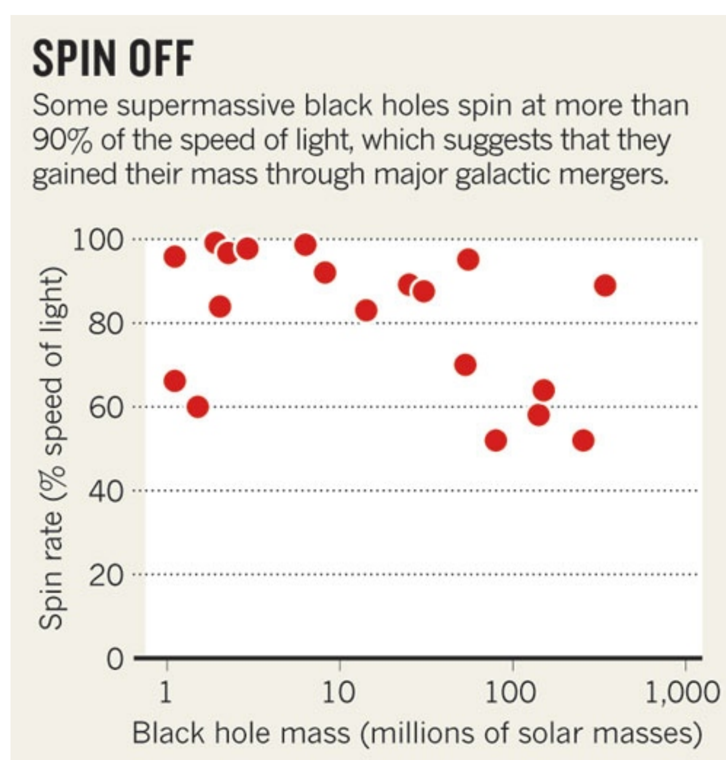
(100-10^5 $M_\odot$)

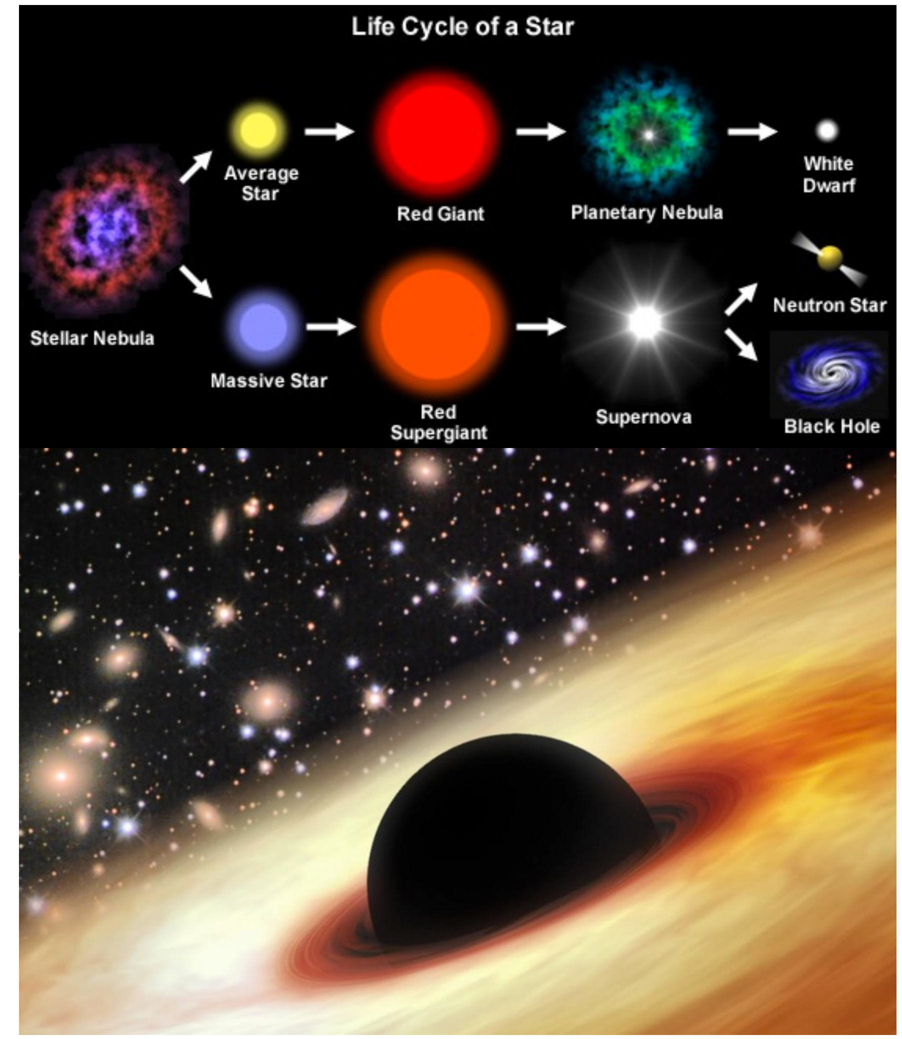
★**Supermassive black holes**

10^6-10^{10} $M_\odot$

Spin

speed ~40-90 %c





Risaliti et al. Nature 2013

Image credit: **Chris Reynolds**

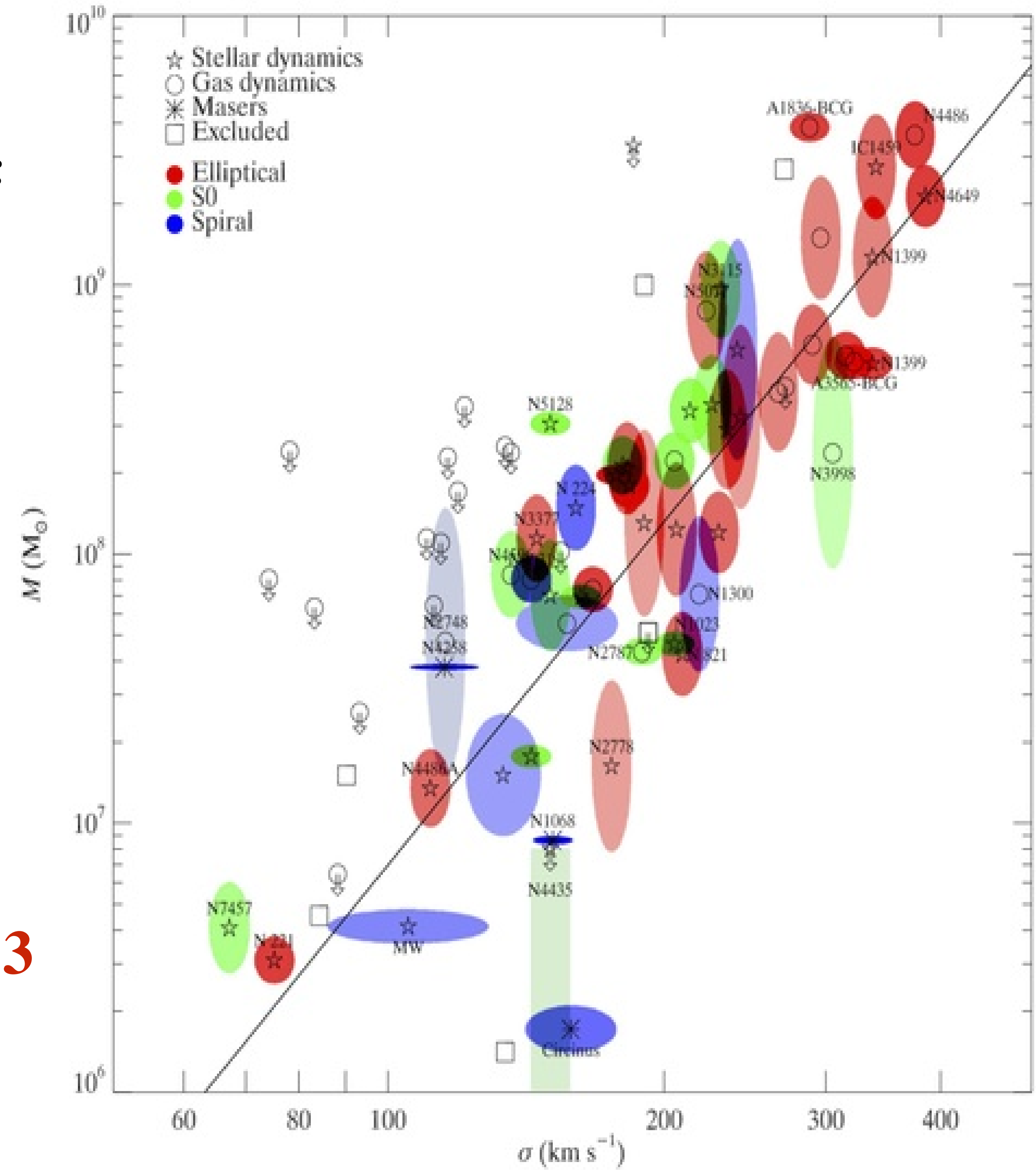
Co-evolution of BHs and Galaxies

★ **Common in the centres of present day galaxies**

★**M-Sigma Relation (Gultekin +09, Debatista+13)**

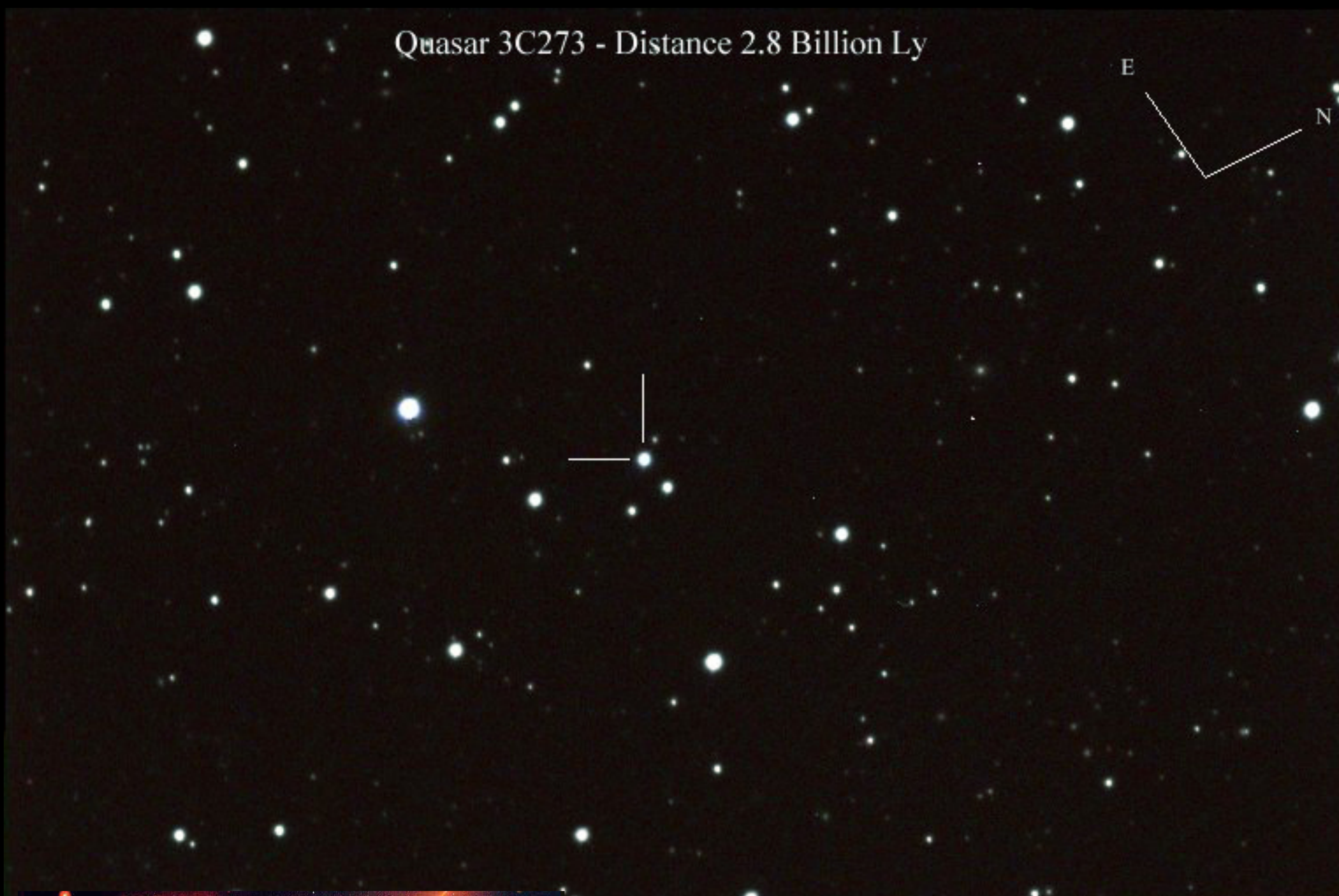
★**Co-evolution of BHs & host galaxies**

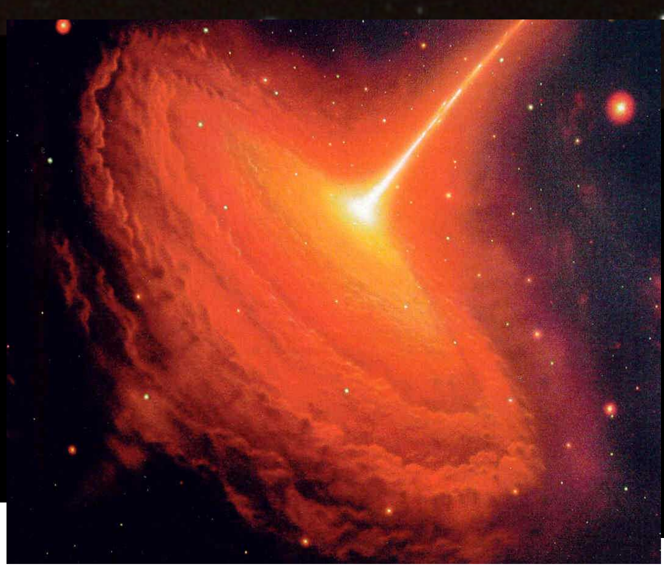
Co-evolution or not?
Review by Kormendy & Ho 2013



McConnell et al +13, Gultekin et al +9

Quasars





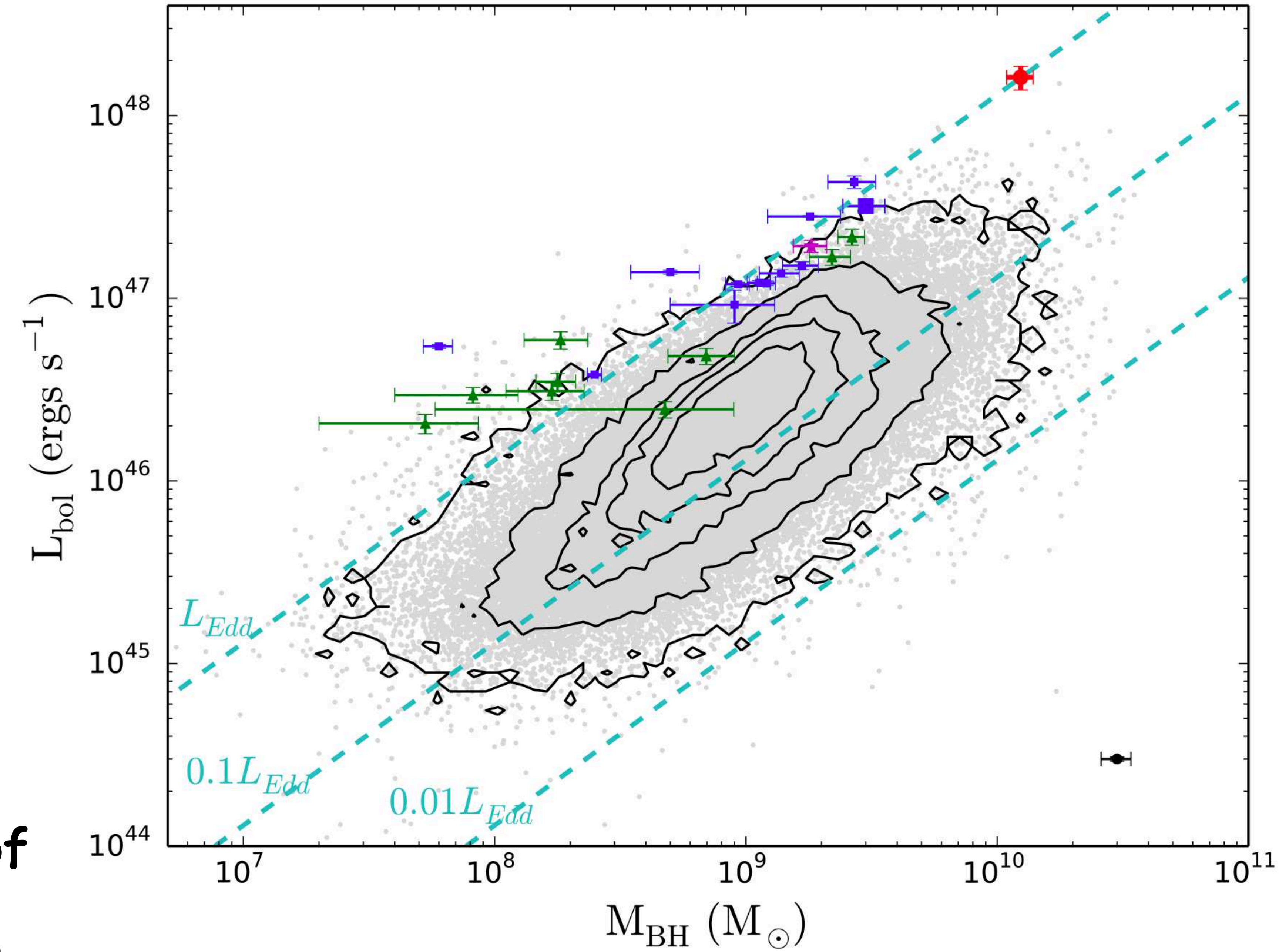
Point-like, or star-like, radio sources which varies rapidly: 'quasi-stellar' radio sources or quasars.

The quasar 3C273 is 640 Mpc~2.6 billion light years away.

The luminosity of 3C273 is more than 100 times the luminosity of our entire galaxy.

High z Quasars

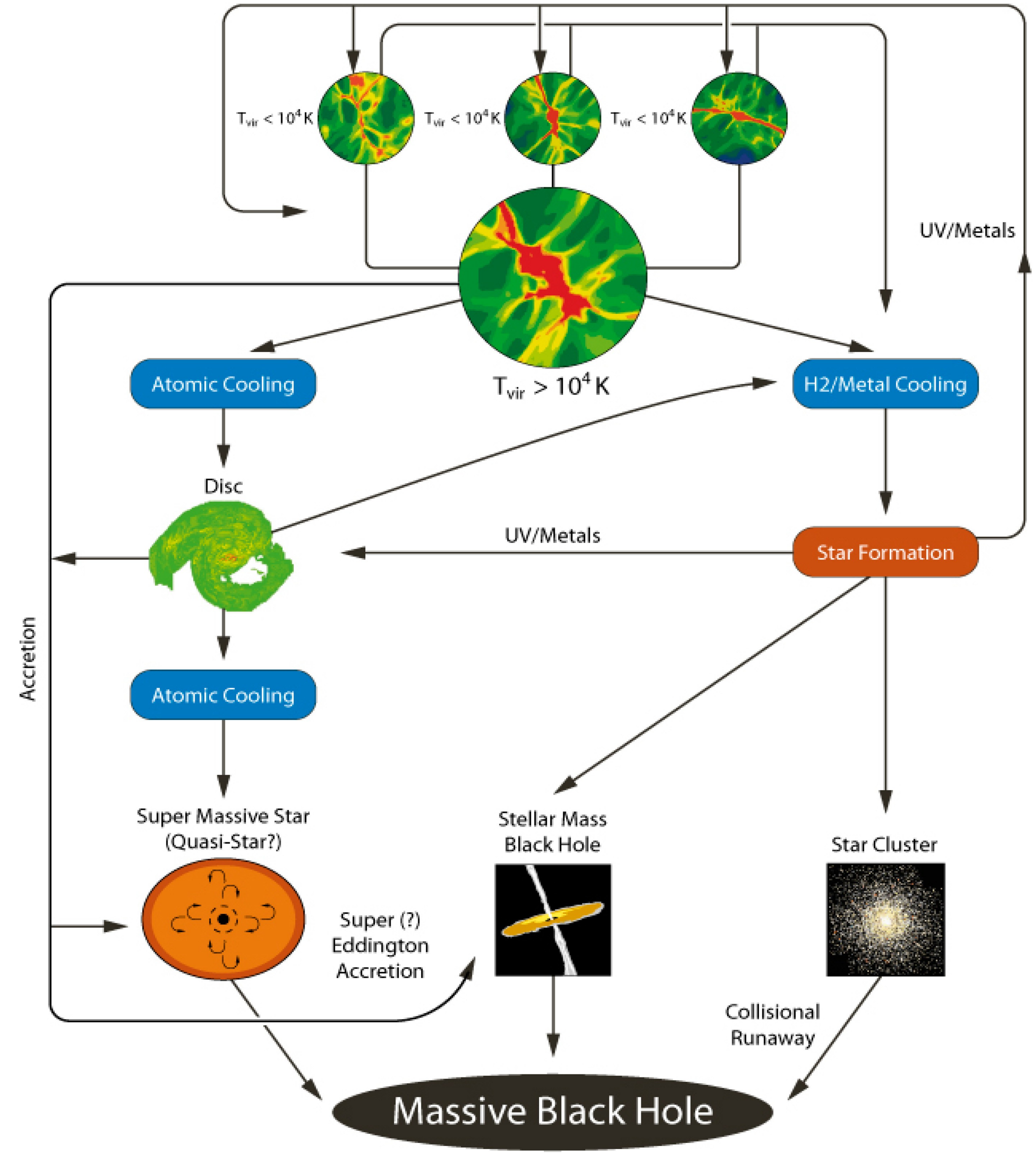
- Supermassive black holes with ~10^9 solar masses have been observed at z>6.
- The highest-redshift black hole currently observed is at z=7.085 and has $2x10^9 M_\odot$ (Mortlock et al. 2011).
- The most massive black of 1.3×10^{10} $M_\odot$ at z=6.3 (Wu et al. Nature 2015)



Wu et al. Nature 2015

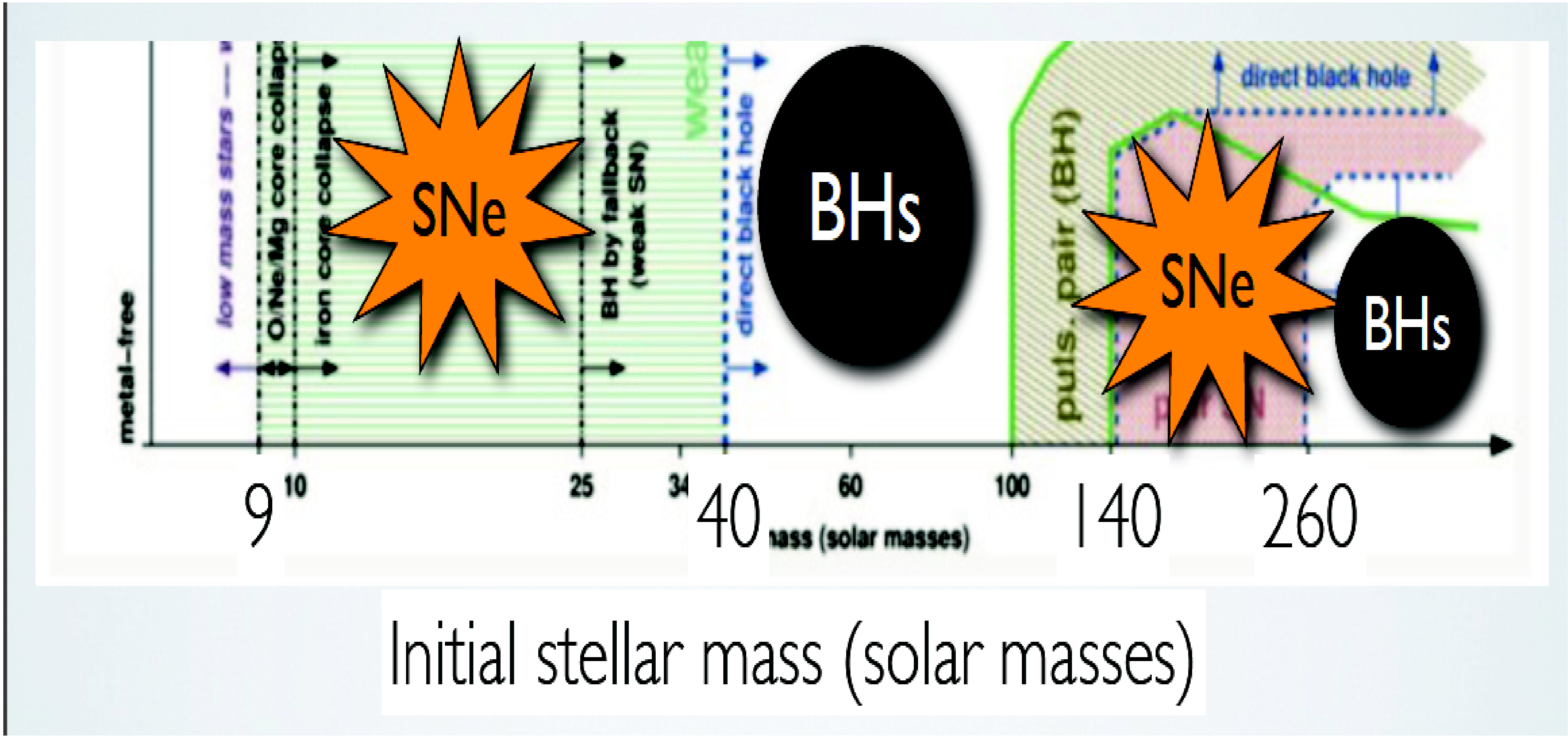
Black hole formation scenarios

- ★ Various ways to form massive black holes (Volonteri 2010, Haiman 2012)
- ★ Remnants of Pop III stars
- ★ Collapse of a dense stellar cluster via stellar dynamical processes
- ★ Monolithic collapse of a protogalactic gas cloud (Direct collapse)



Regan et al 2009

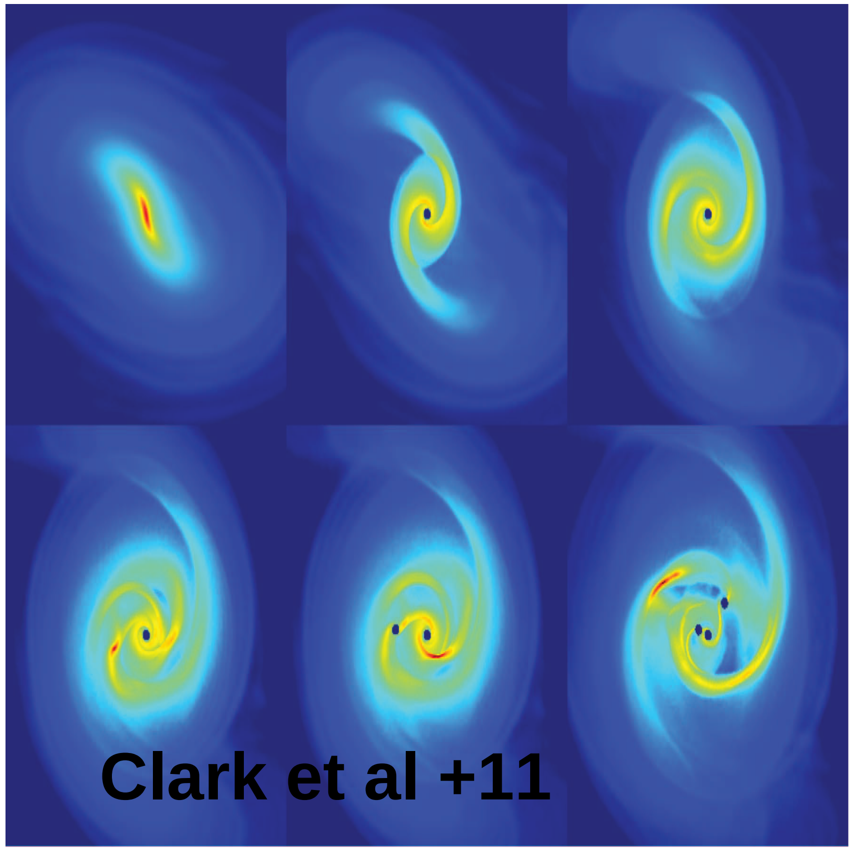
Black hole seeds from Pop III stars

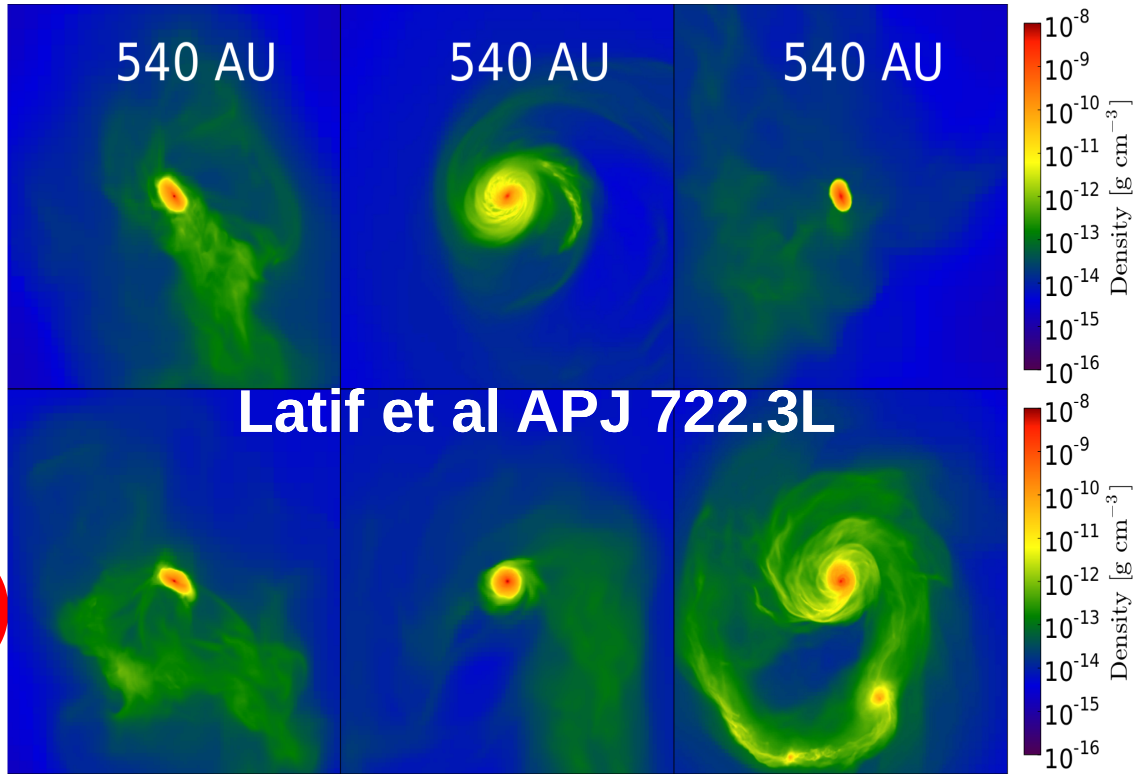


Heger et al. 2003

Black hole seeds from Pop III stars

- Form in minihalos of 10^5 -10^6 $M_\odot$ at z=20-30
- Collapse is triggered by molecular hydrogen cooling
- Very massive 200-300 $M_\odot$ (Bromm 2000. Abel 2002)
- Current simulations propose low mass stars (Clark+11, Greif +2012 Hosokawa +11, Latif +2013, Hirano +2014)

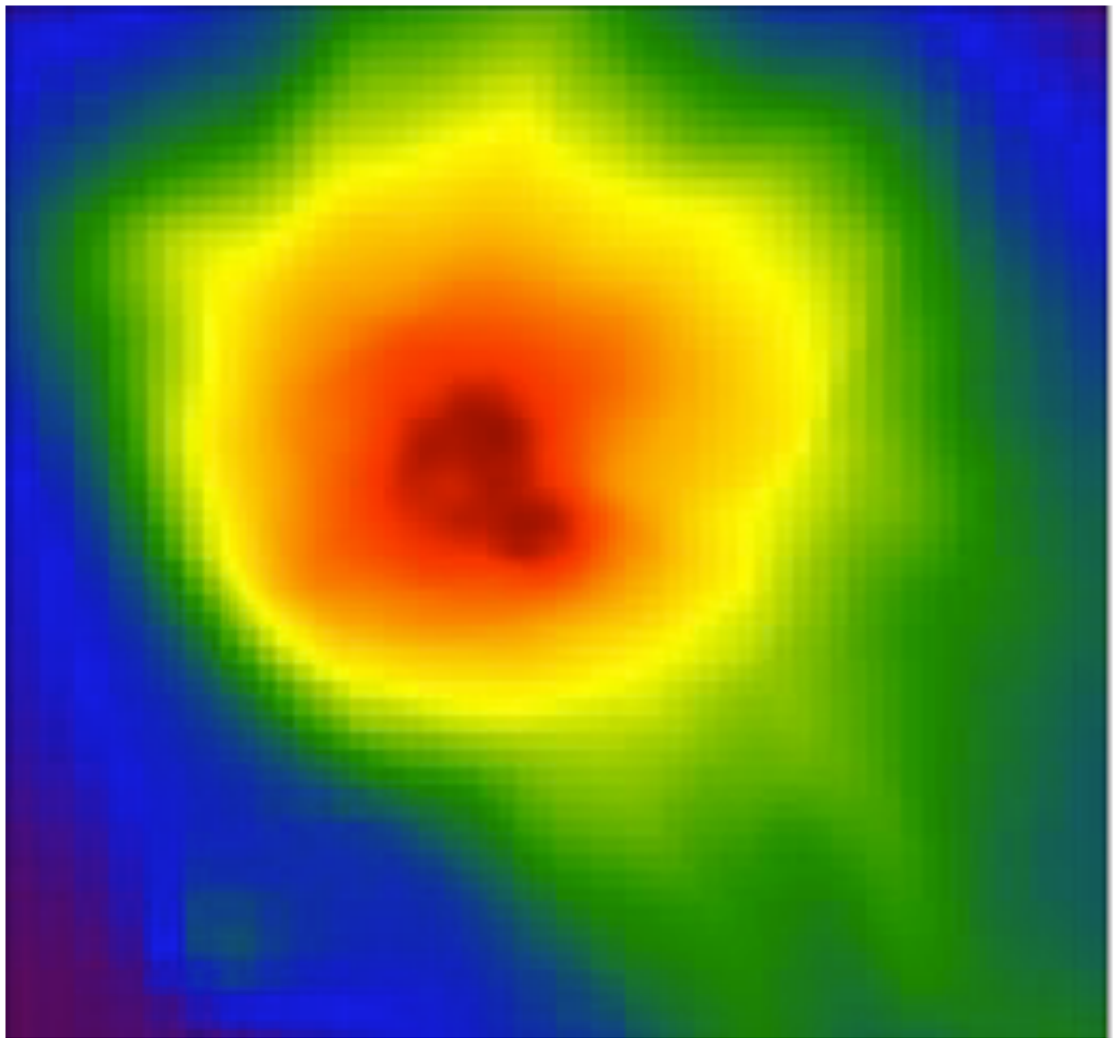




Fragmentation and clumps migration

- ★ Analytical model for disk fragmentation
- ★ Assumptions:
  Steady state condition
  Marginally stable (Q=1)
  Embedded in large inflow rates of 0.01-0.001 $M_{\odot}$/yr
- ★ Solve for thermal balance
- ★ Viscous Heating

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

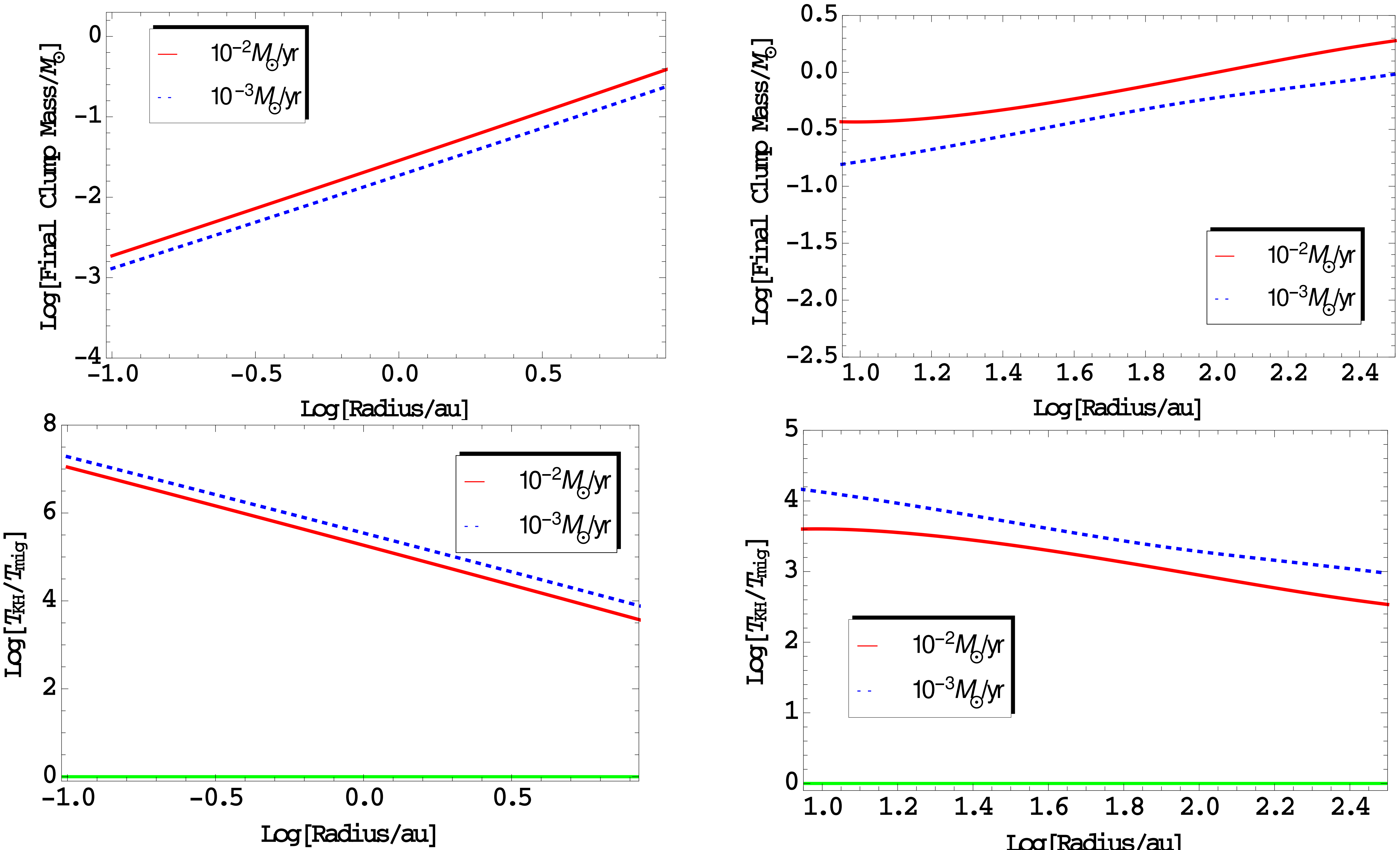


$$Q_+ = Q_-$$

Latif et al. 2013 ApJL

Latif & Schleicher 2015 MNRAS, 449, 77L

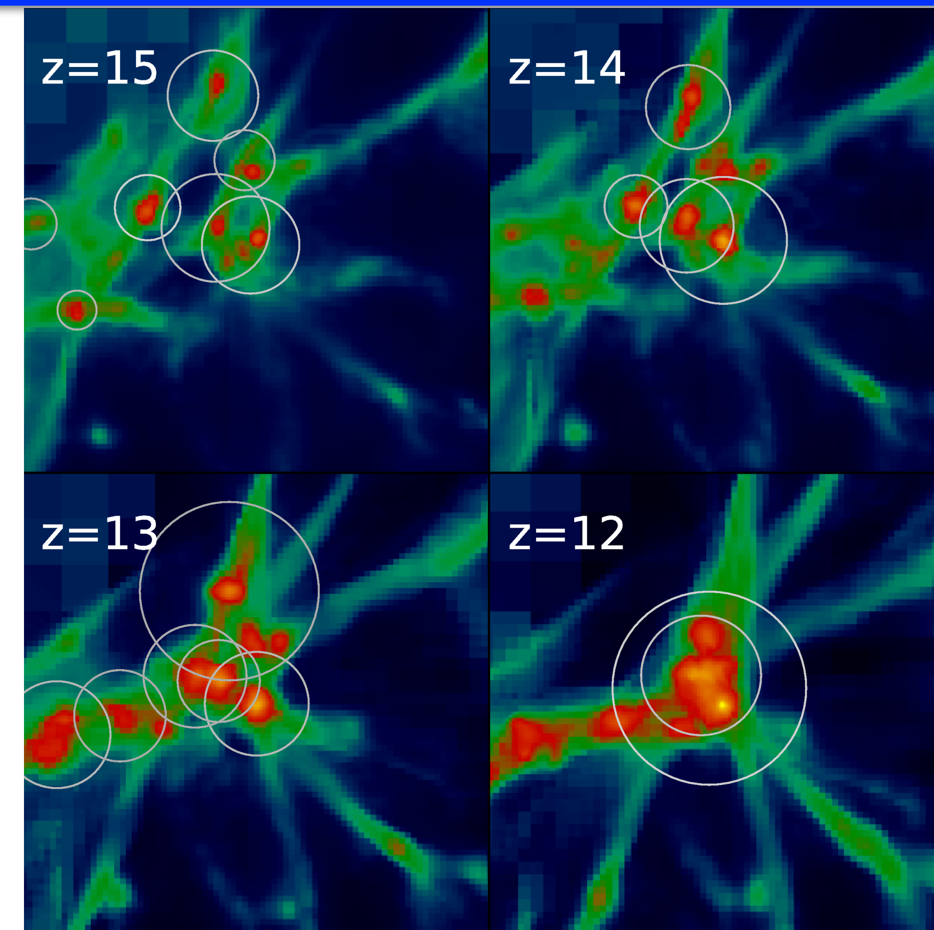
Clump masses & time scales comparison

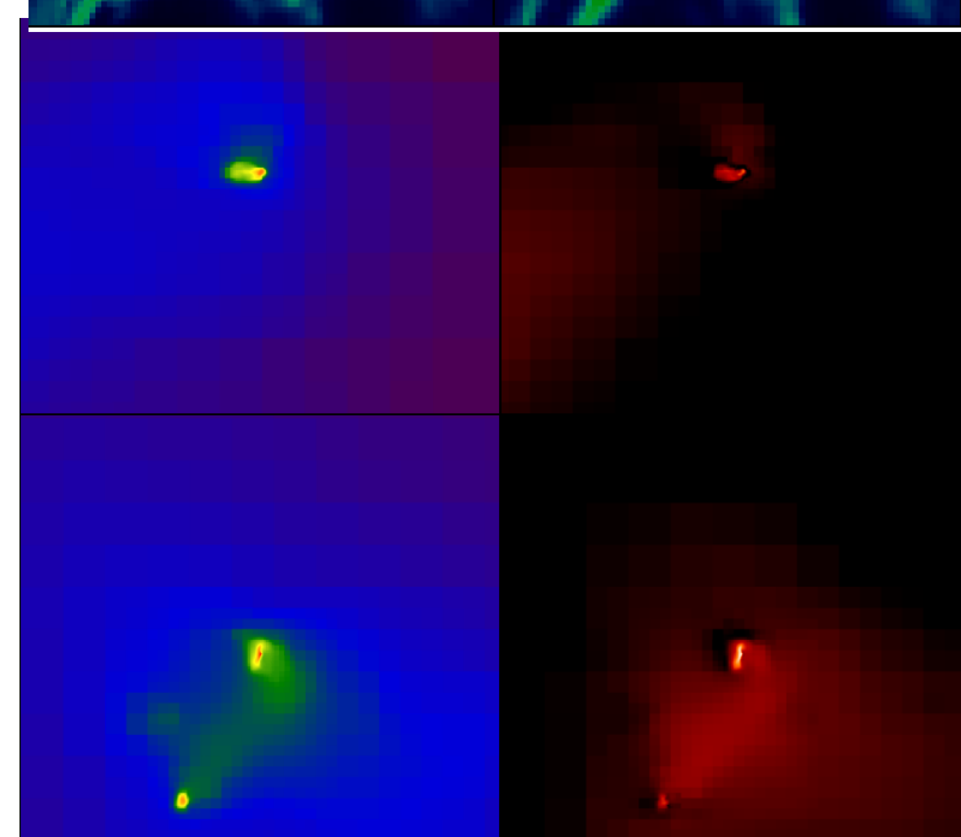


Latif & Schleicher 2015 MNRAS, 449, 77L

Formation of low mass stars

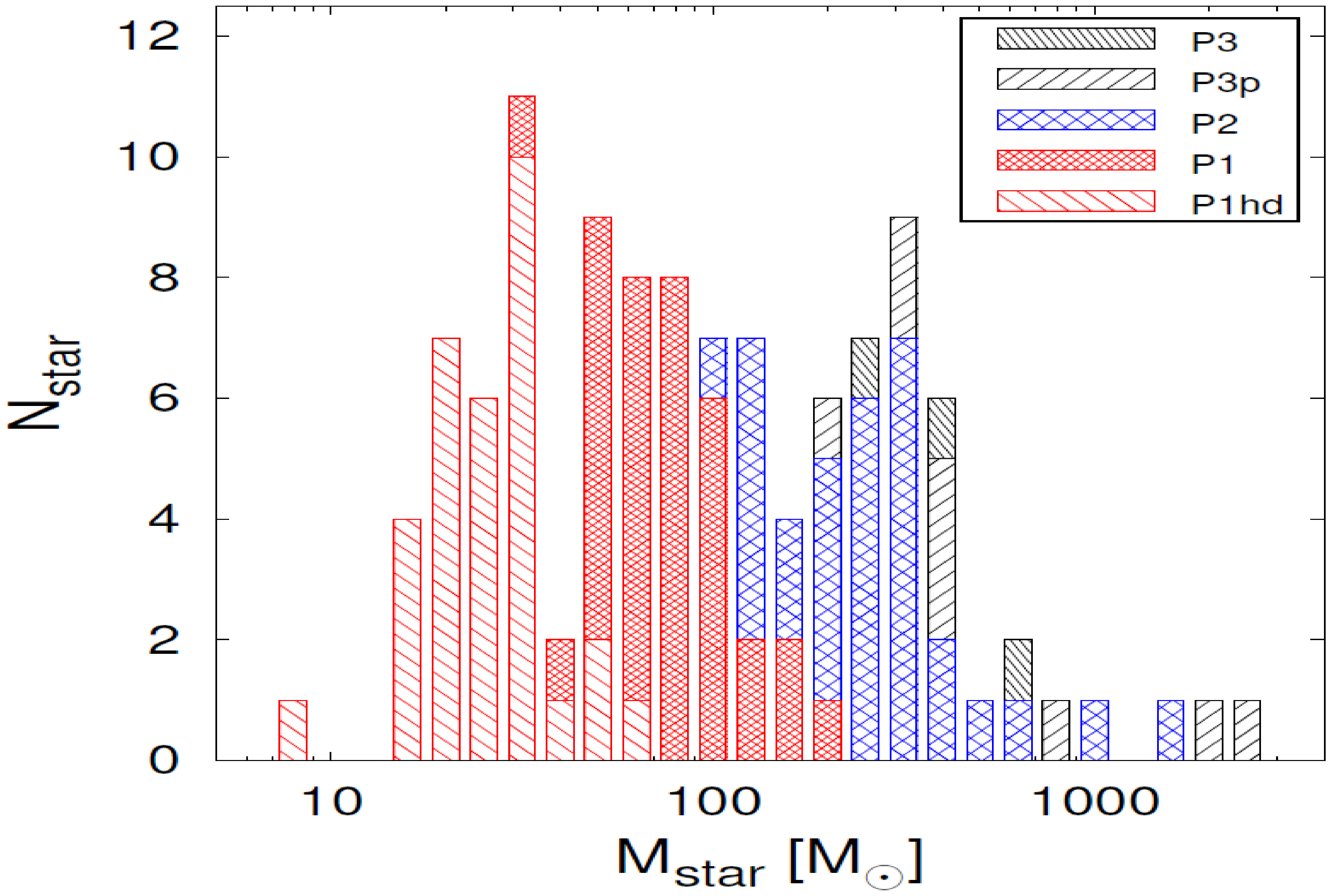
- ★ A possible route is enhanced HD cooling
- ★ Mergering of DM halos leads to a high ionization degree and catalyse the formation of HD
- ★ HD molecules cools the gas down to the CMB temperature ~60 K at z=12





Bovino, Latif, Schleicher, Grassi 2014 MNRAS

Black hole seeds from Pop III stars

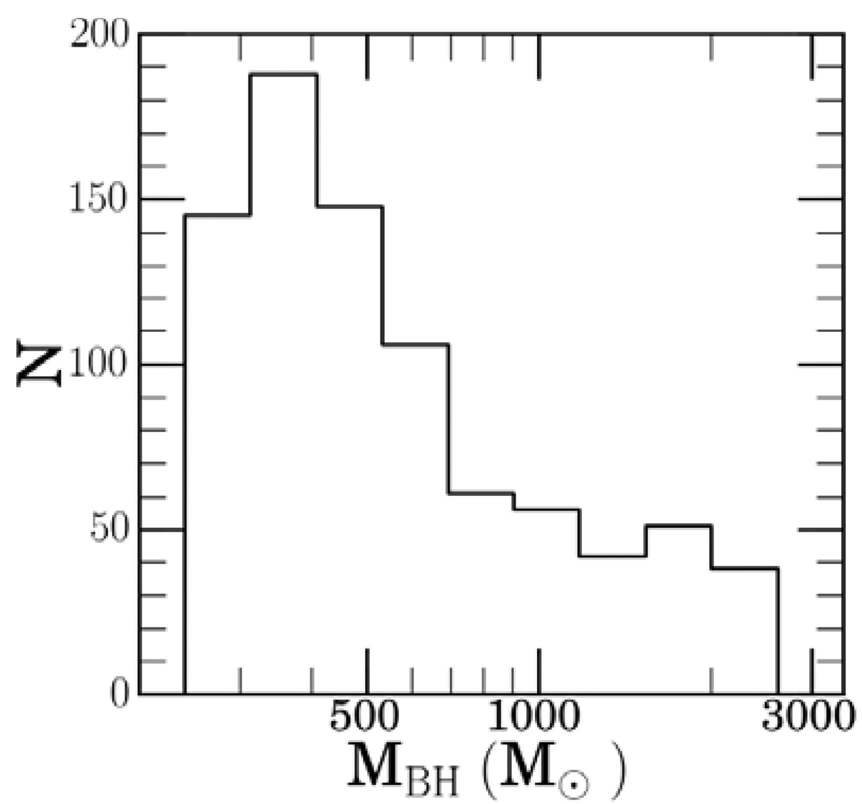


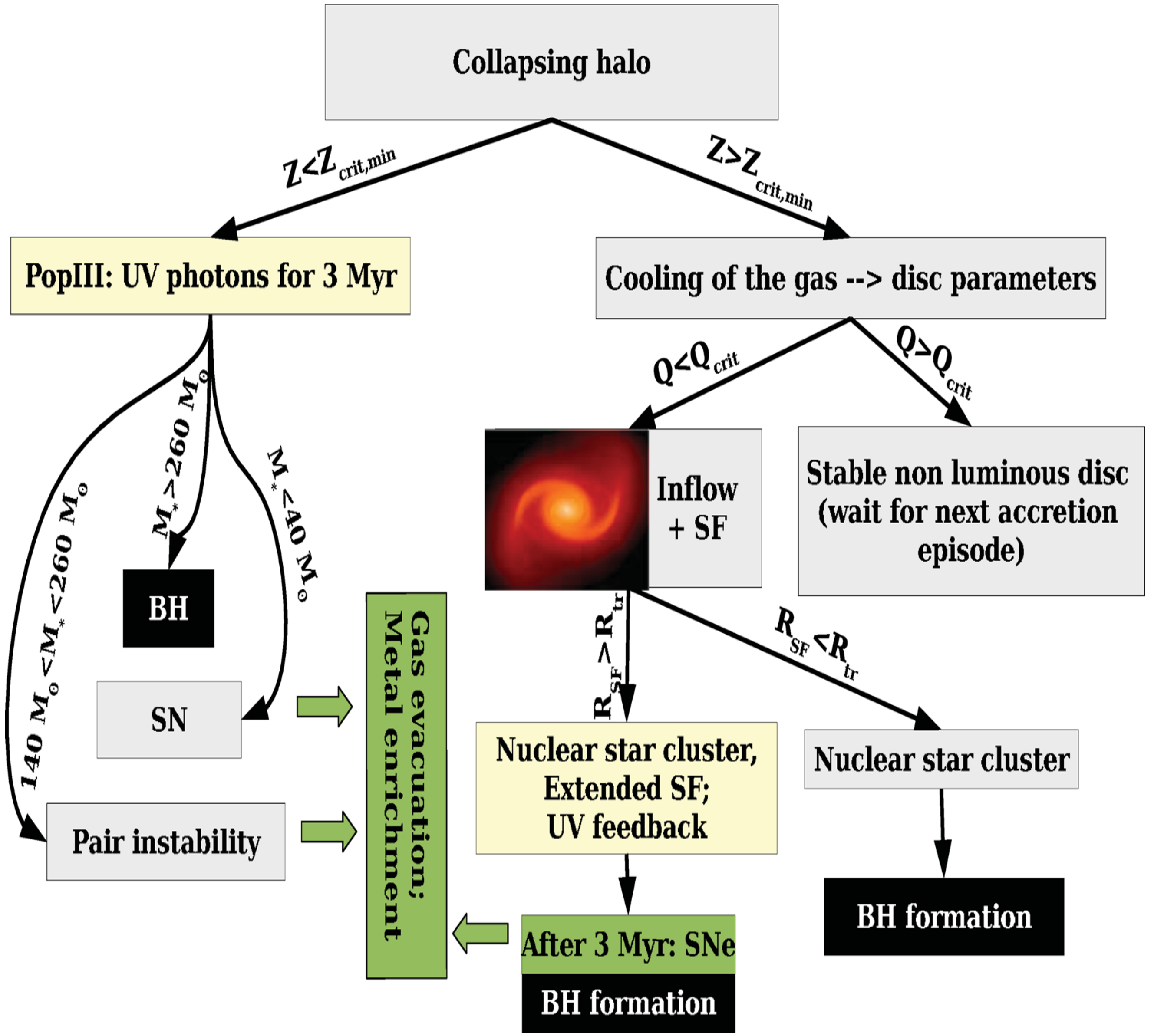
Hirano et al. 2014

Caution: This does not represent IMF of Pop III star

Black hole seeds from stellar dynamical processes

- Metal enrichment
- Nuclear star cluster
- Relativistic Instability





Devecchi et al +12

Also see Portegies Zwart et al. 1999, Omukai et al. 2008 and Latif et al. 2015

Direct collapse scenario

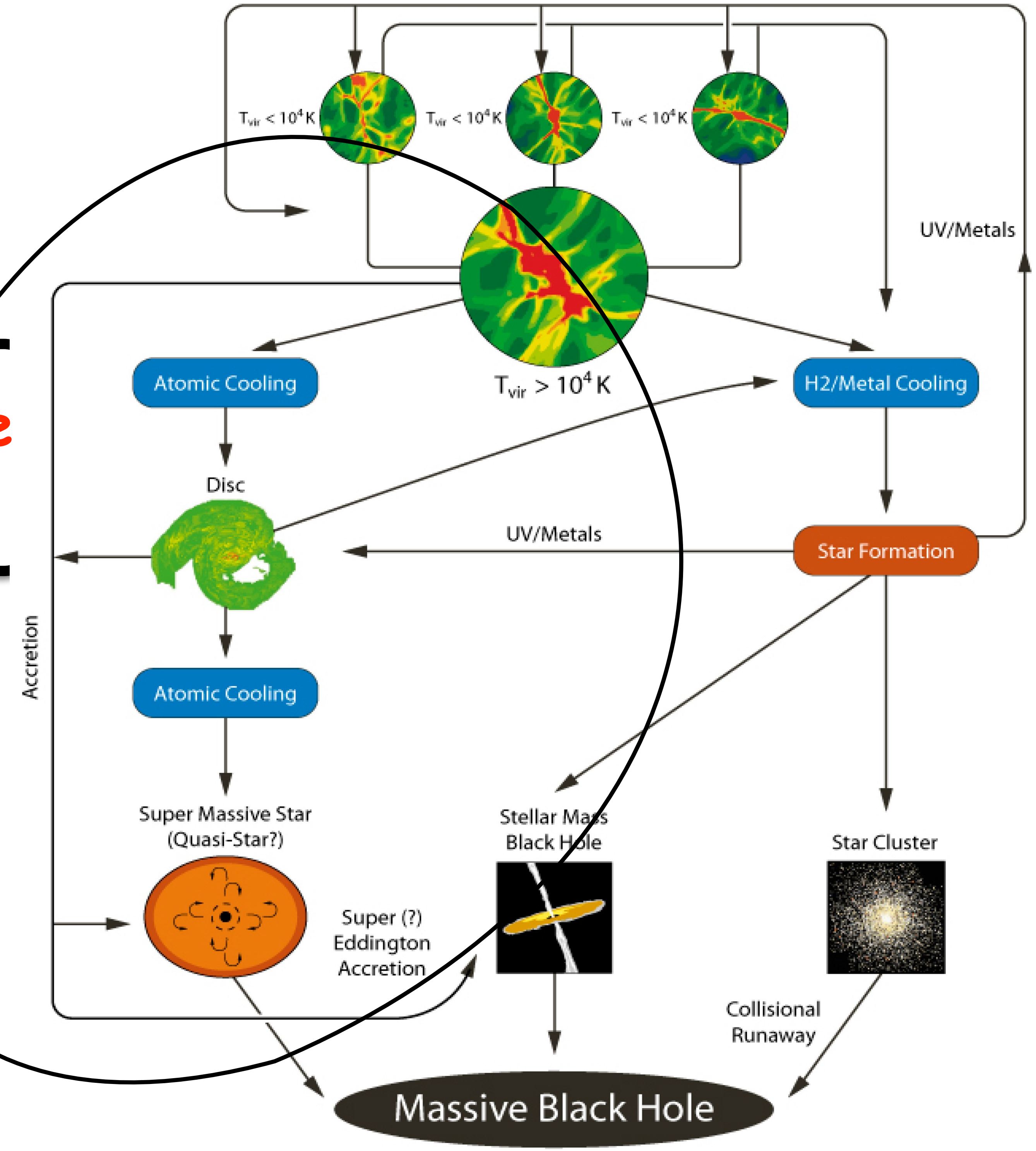
★ Provides massive seeds of 10^5-10^6 $M_\odot$

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

★ Isothermal direct collapse with T~ 8000 K

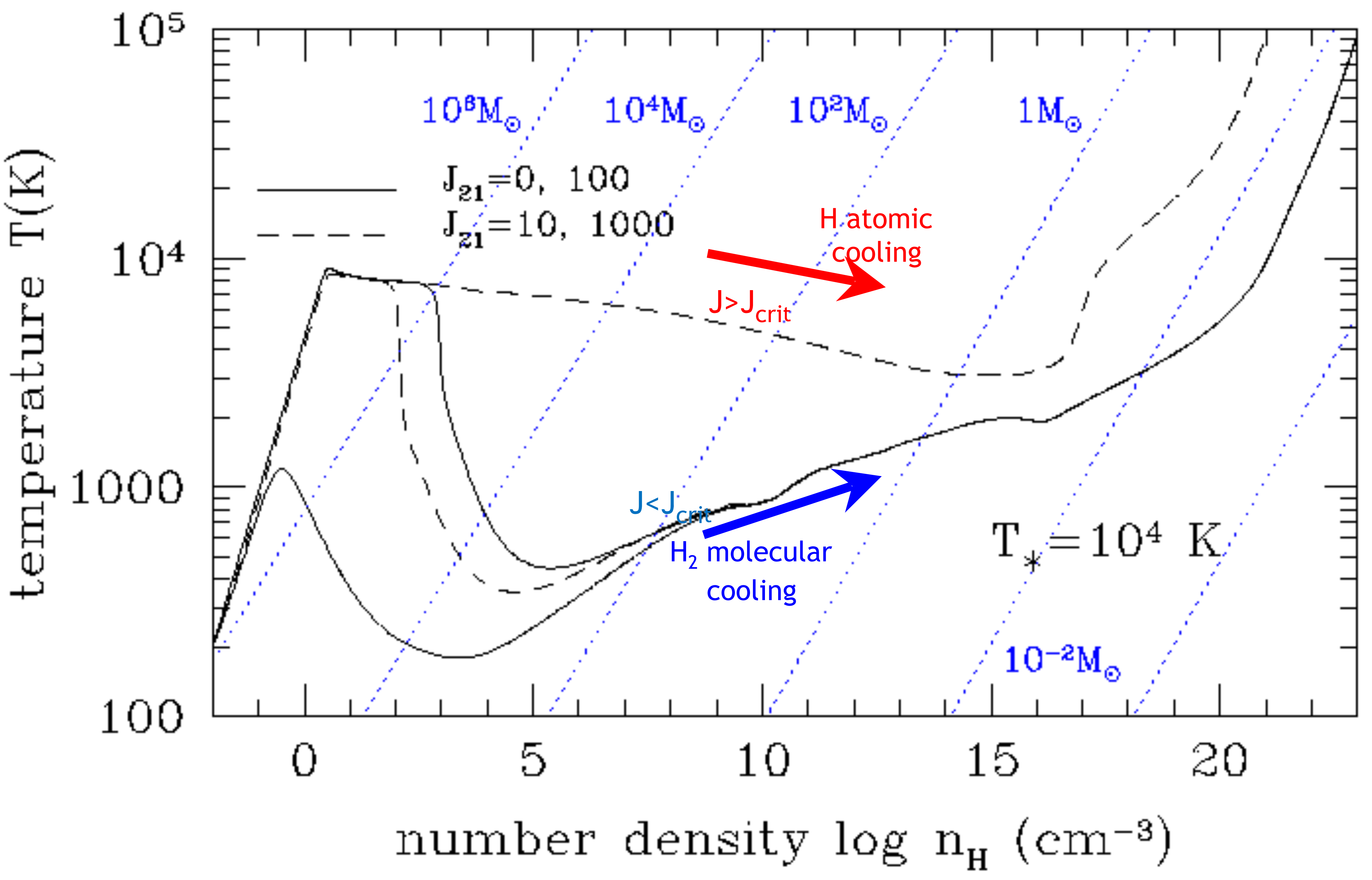
★ Primordial gas composition

★ Requires strong LW flux to quench H_2 formation



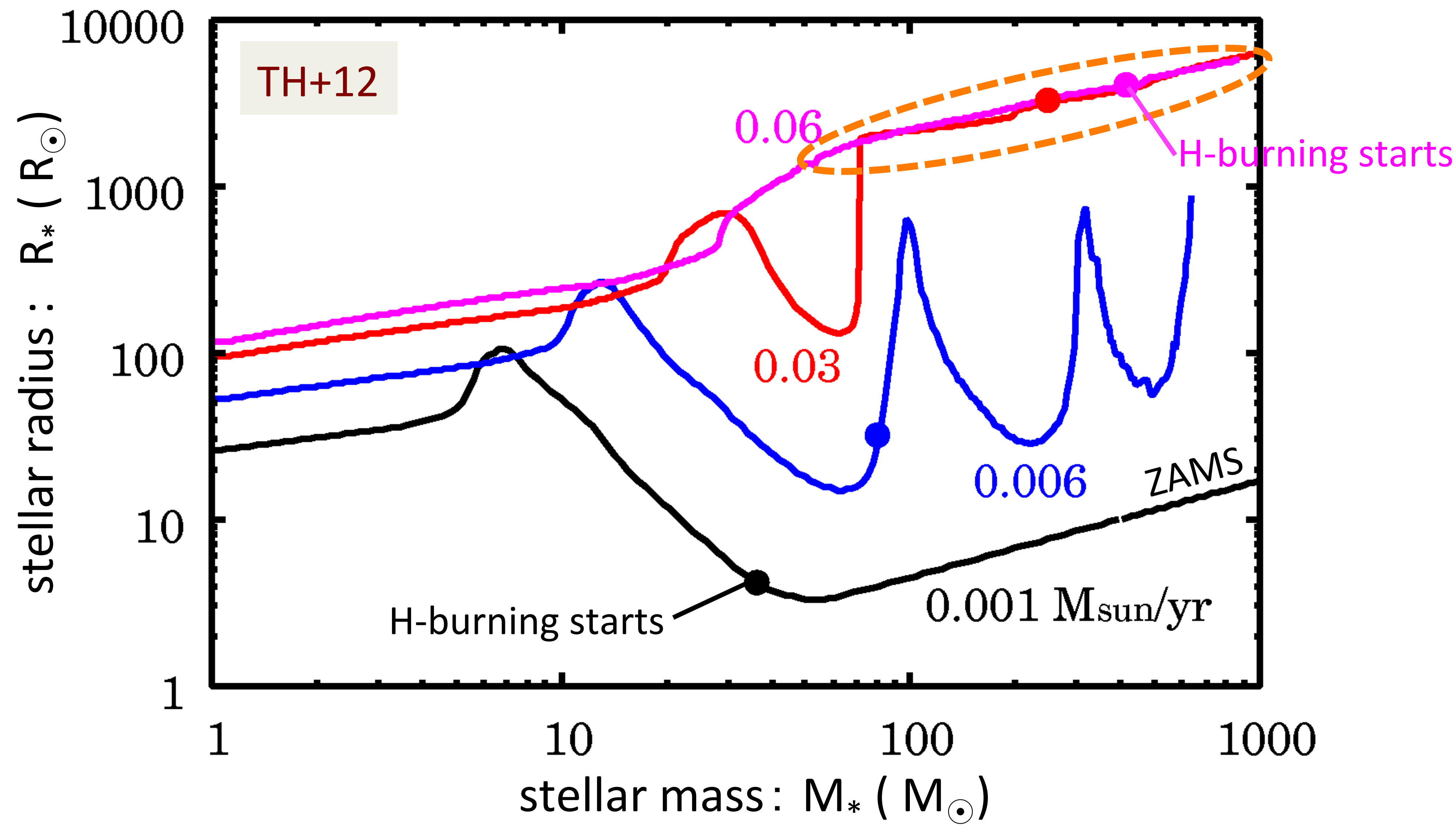
Regan et al 2009

Primordial gas chemistry



Omukai 01, See 3D results from Latif et. al 2014 MNRAS

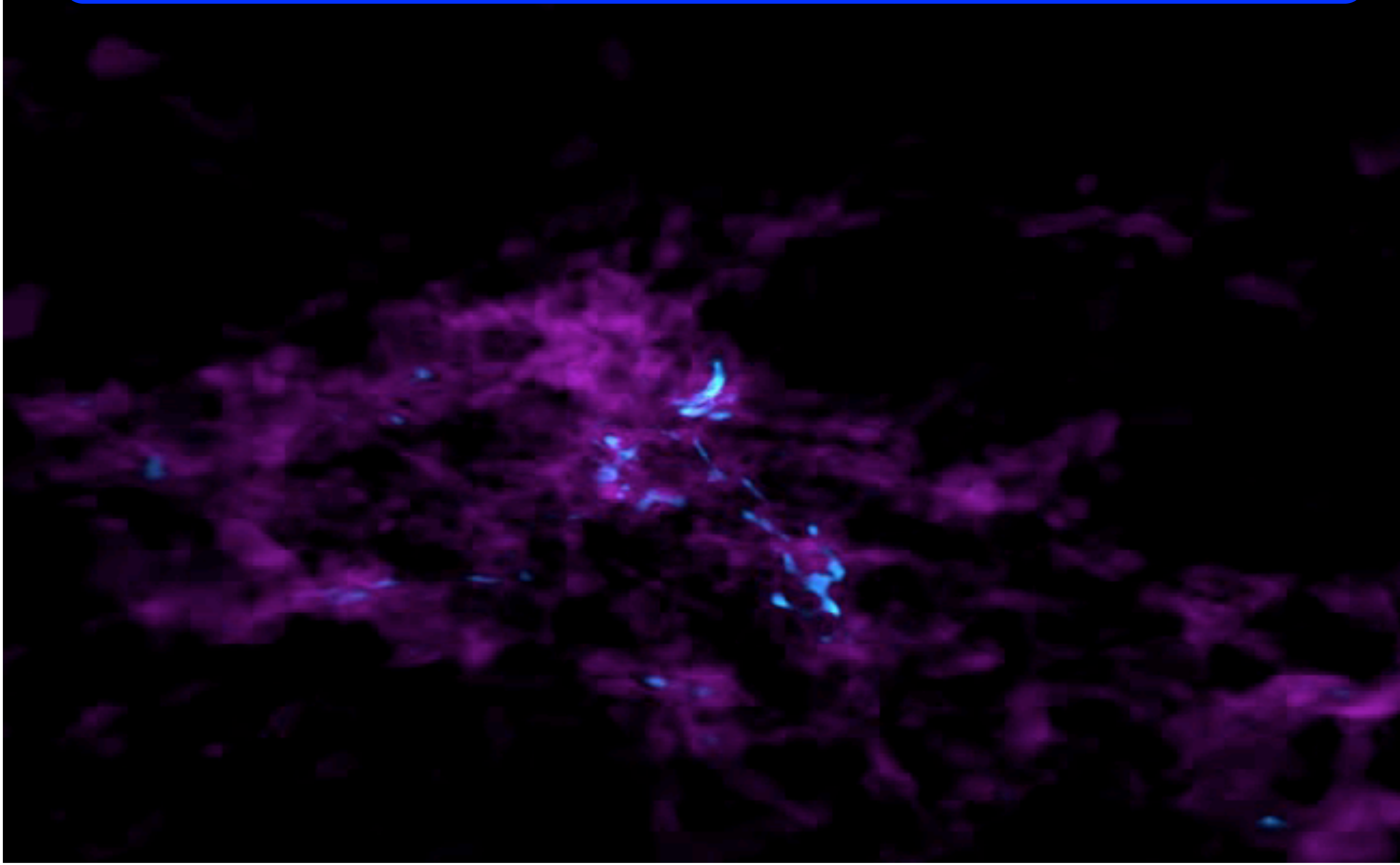
Supergiant protostar



- The protostar never contracts to reach the ZAMS stage, but largely expands with very rapid accretion, > 0.01 $M_\odot$/yr.
- large radius → low effective temperature → weak UV feedback

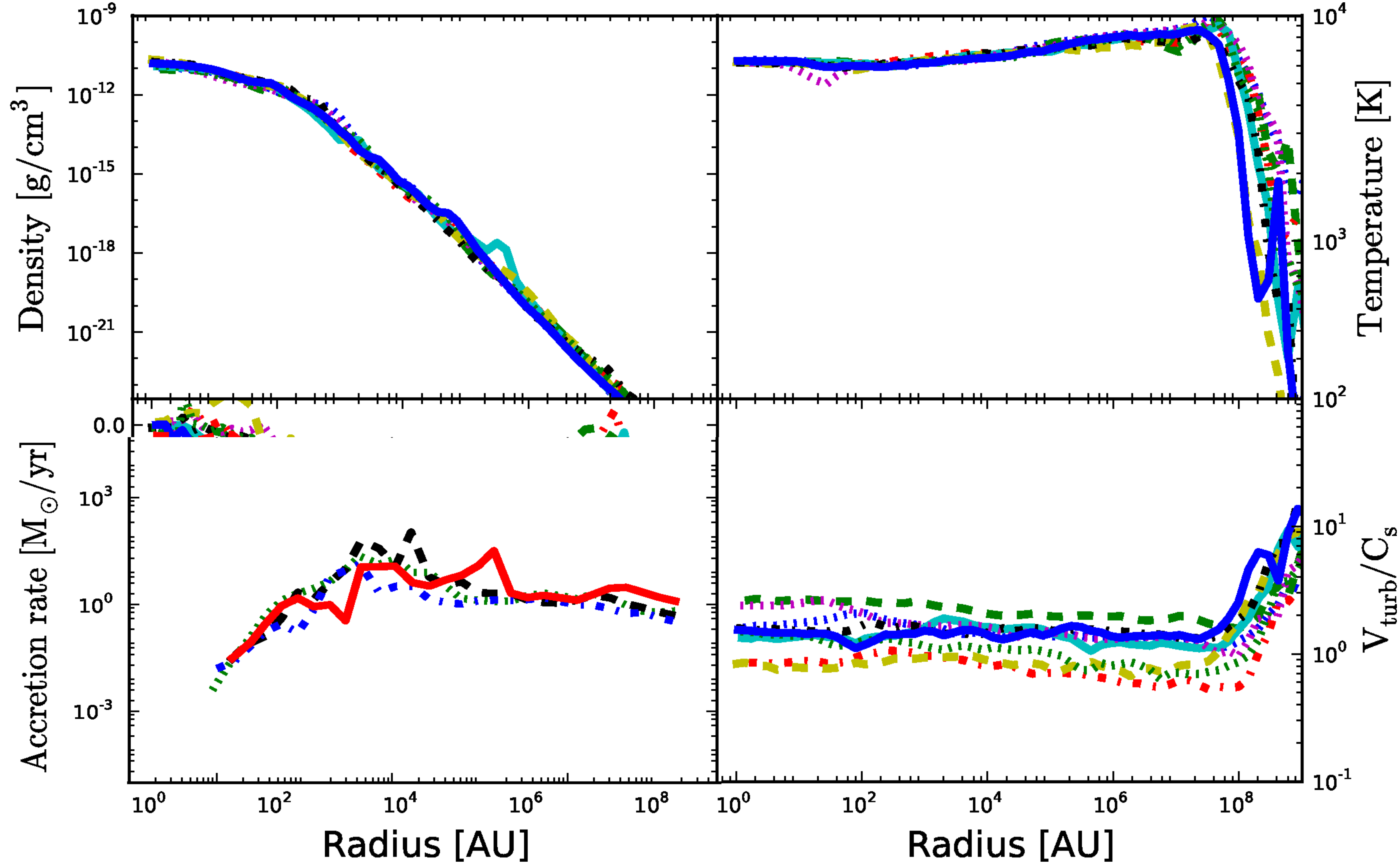
Hoskawa et al. 2012, Schleicher, ML et al. A&A 2013

Cosmological simulations



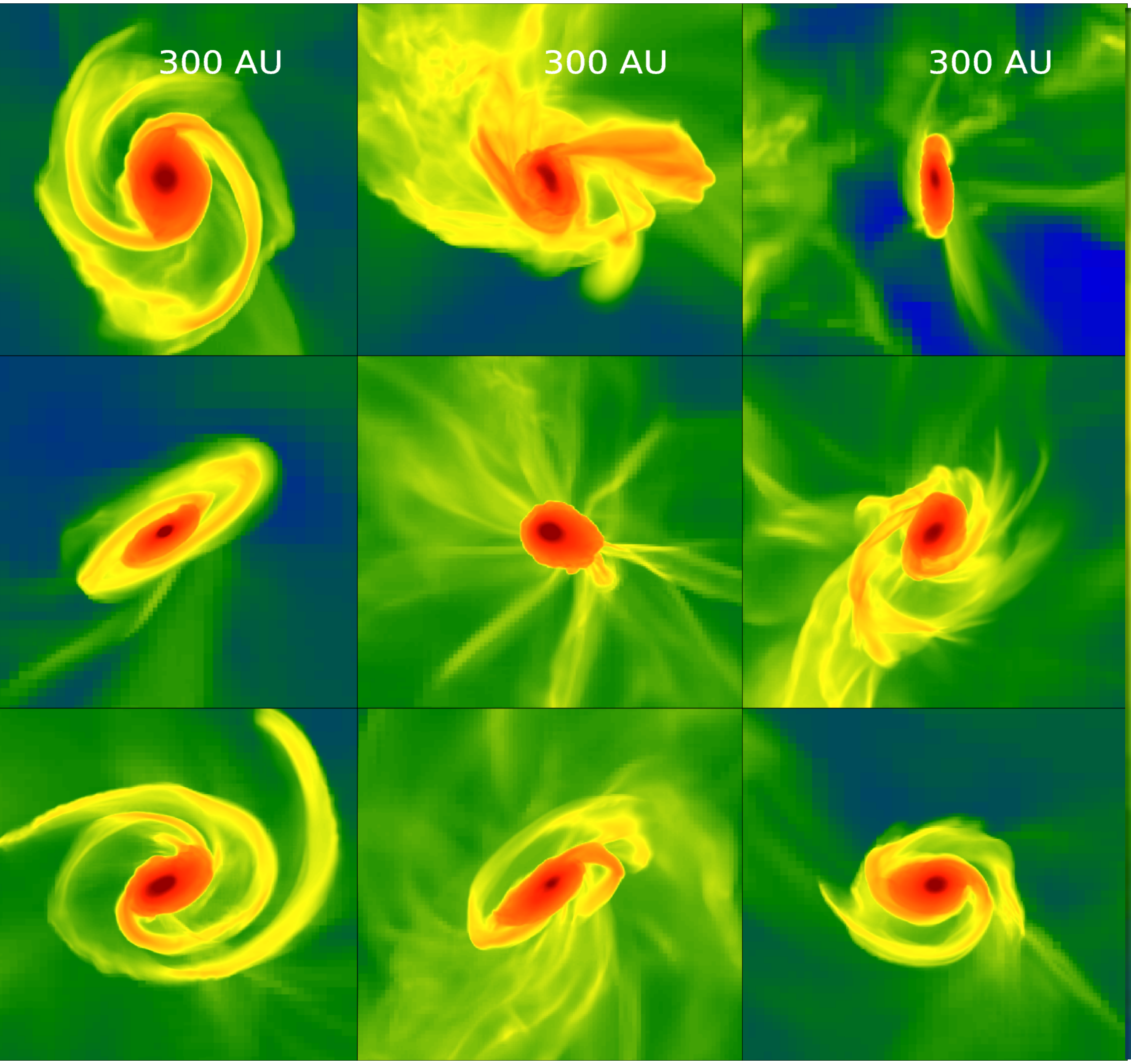
Latif et al. 2013, 2014, 2015

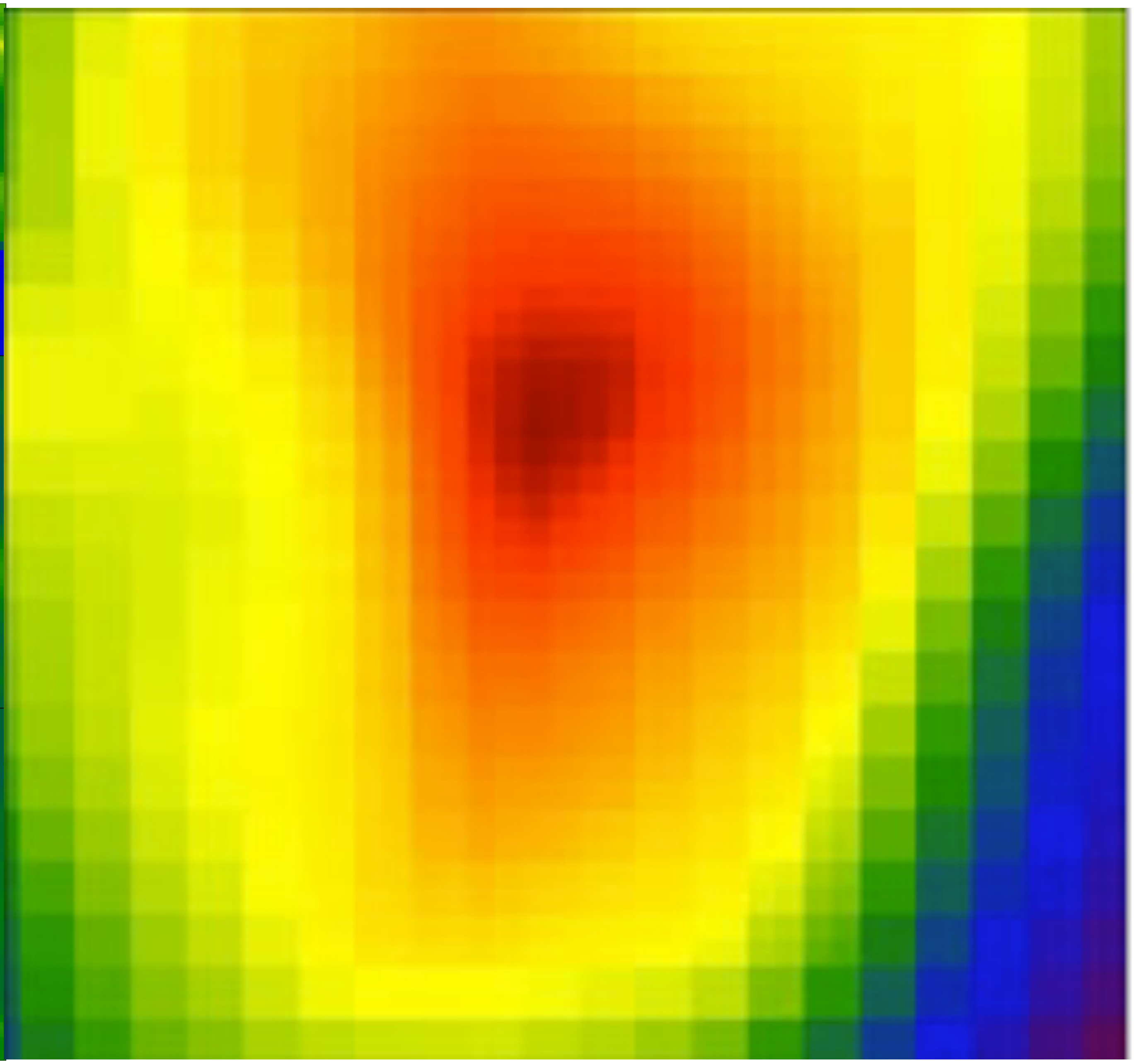
Global properties of simulated halos



Latif et al 2013 MNRAS 433 1607L

Simulations exploring the direct collapse



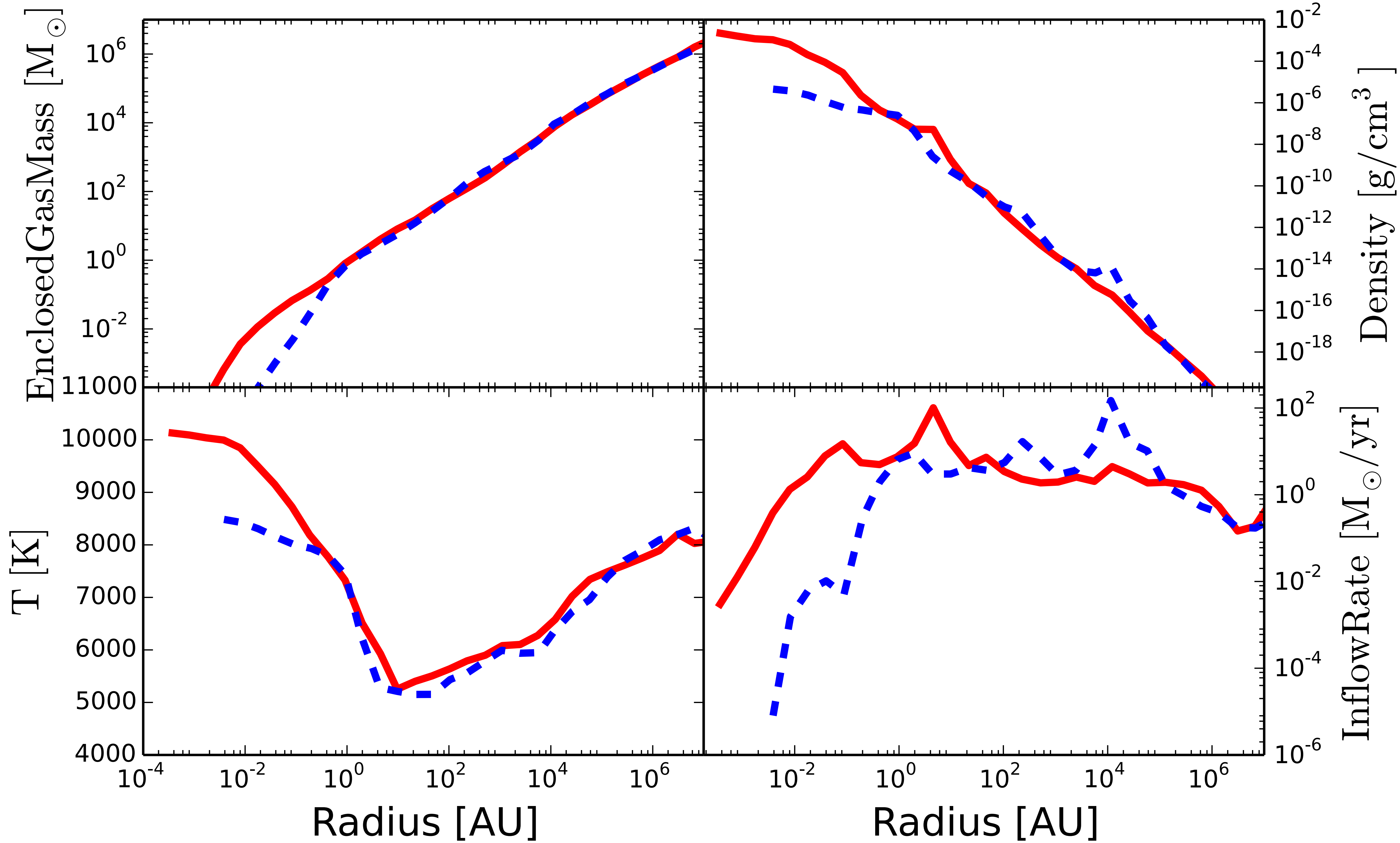


★Collapse occurs isothermally with T~ 8000 K

★Provides large inflow rates of ~1$M_{\odot}$/yr

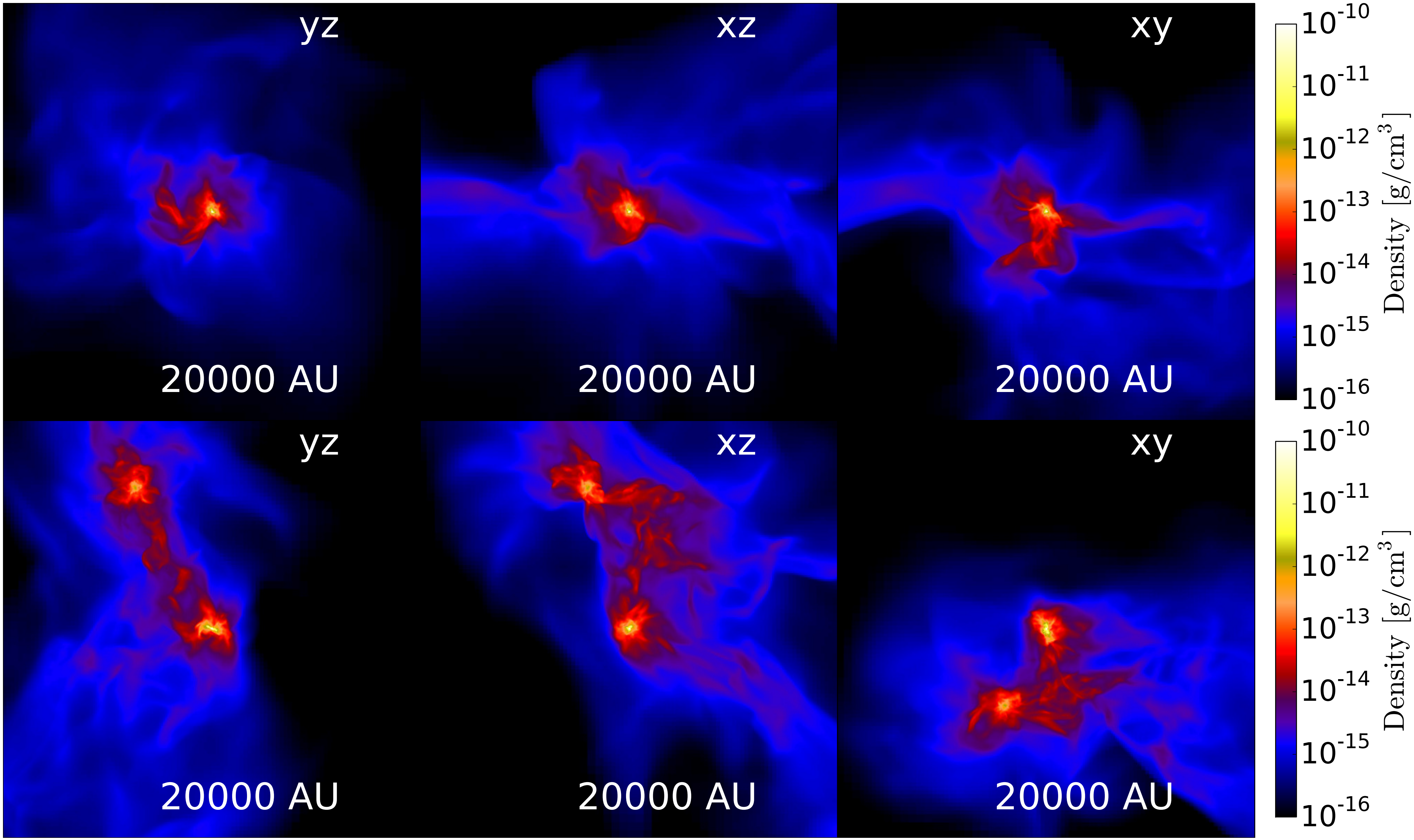
Latif et al. 2013 MNRAS 433 1607L

Impact of H⁻ cooling & Realistic opacities



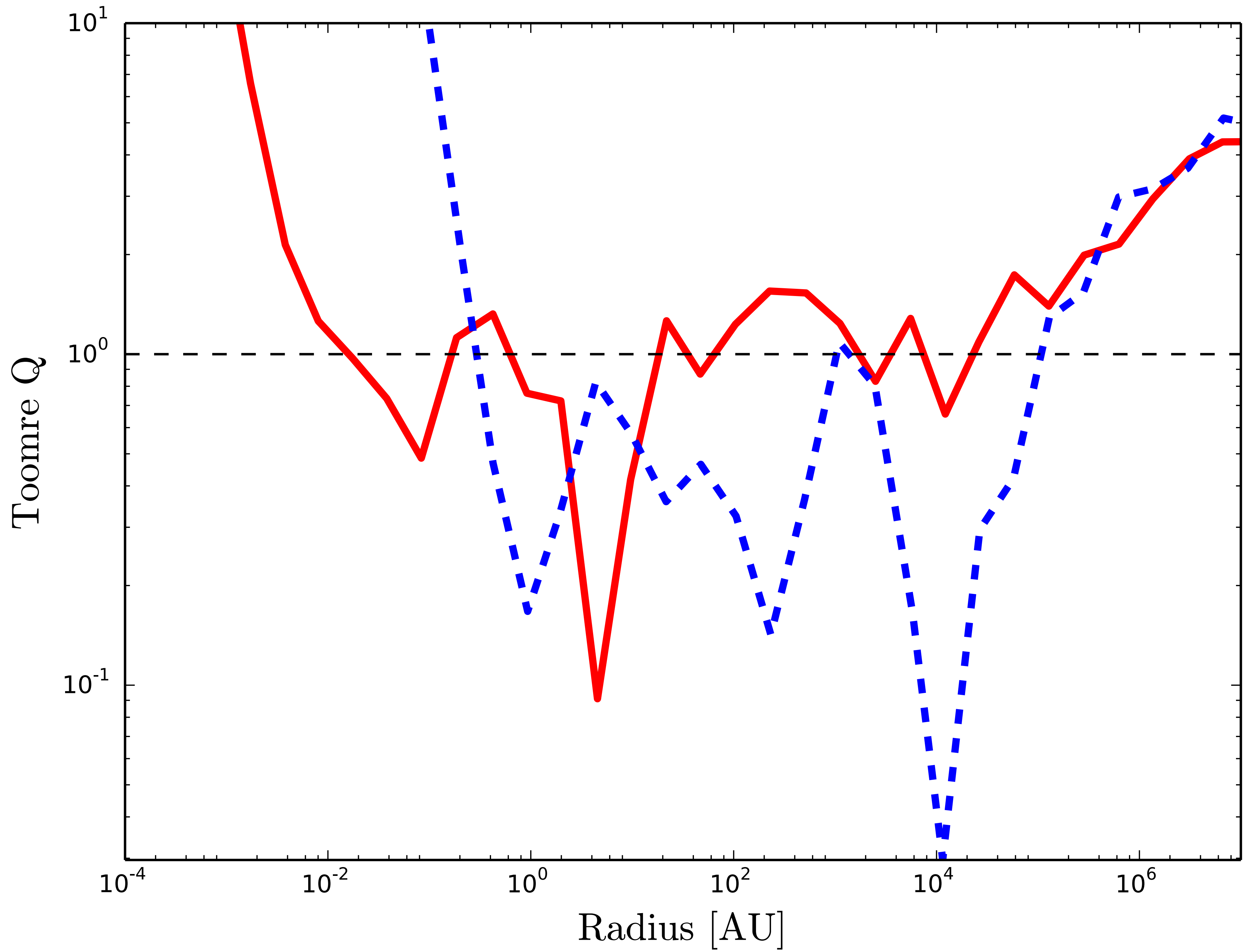
Latif, Schleicher & Hartwig 2015 (arXiv:1510.02788)

Impact of H⁻ cooling & Realistic opacities



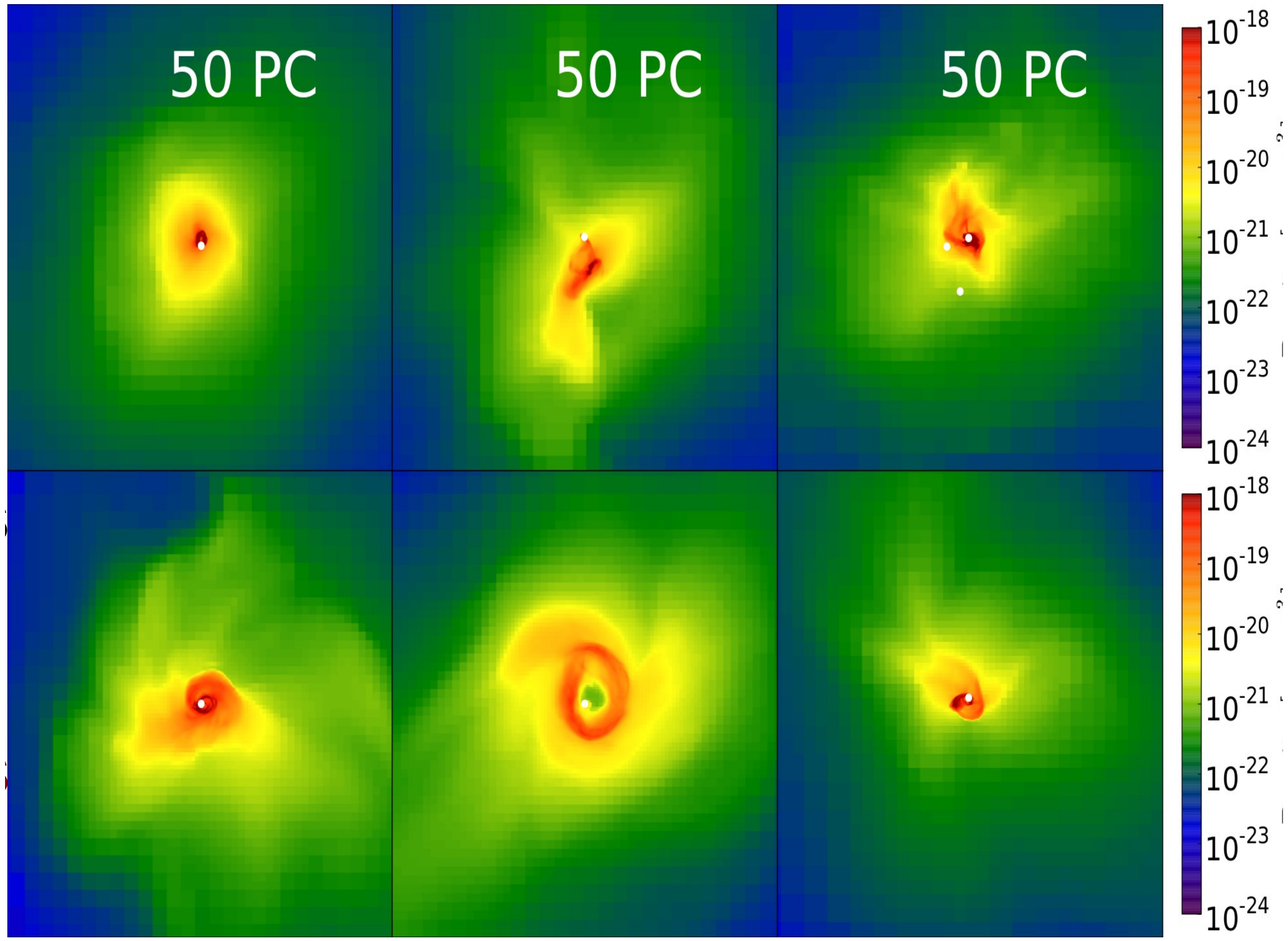
Latif, Schleicher & Hartwig 2015 (arXiv:1510.02788)

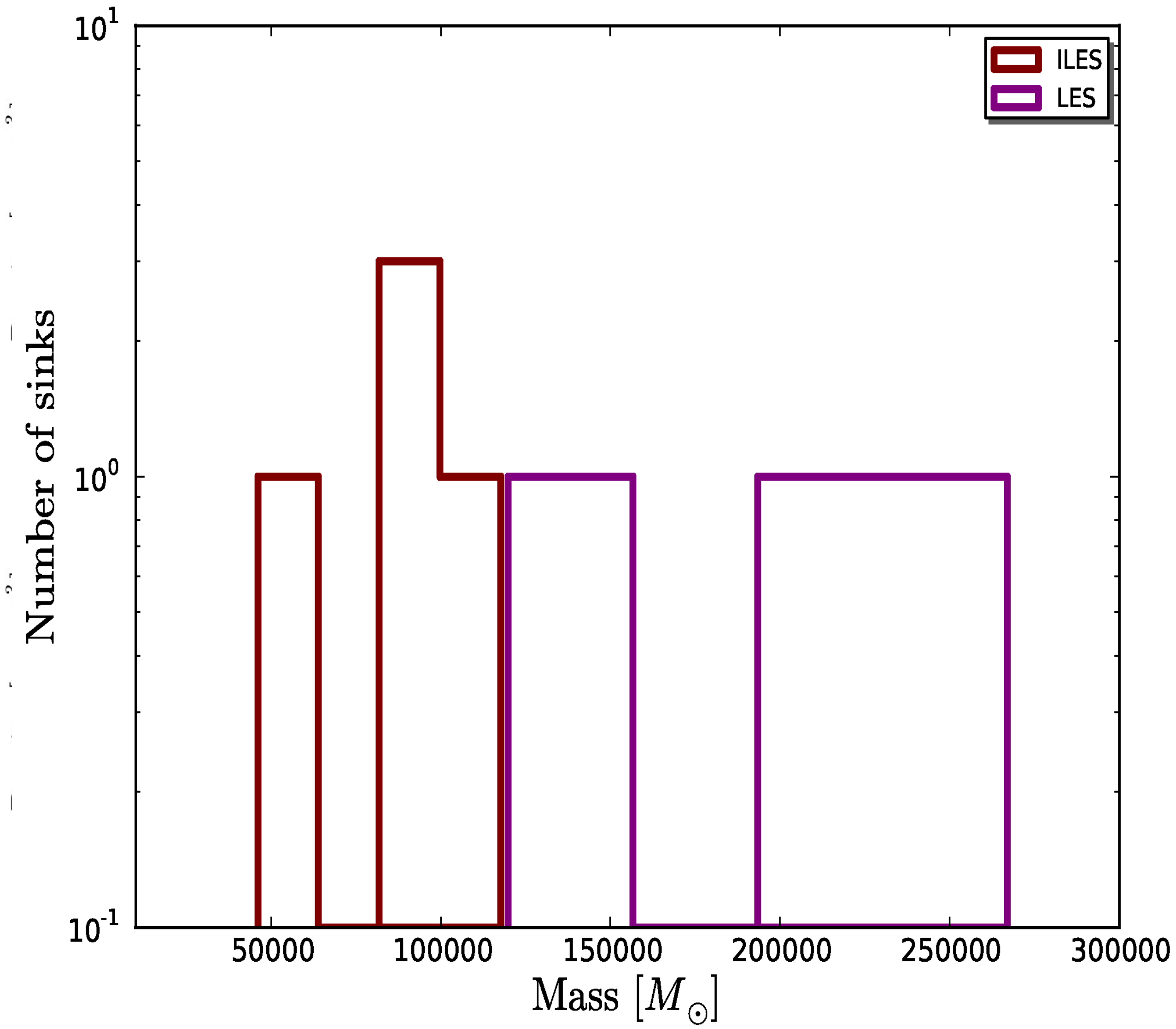
Impact of H^- cooling & Realistic opacities



Latif, Schleicher & Hartwig 2015 (arXiv:1510.02788)

Masses of protostars/sinks



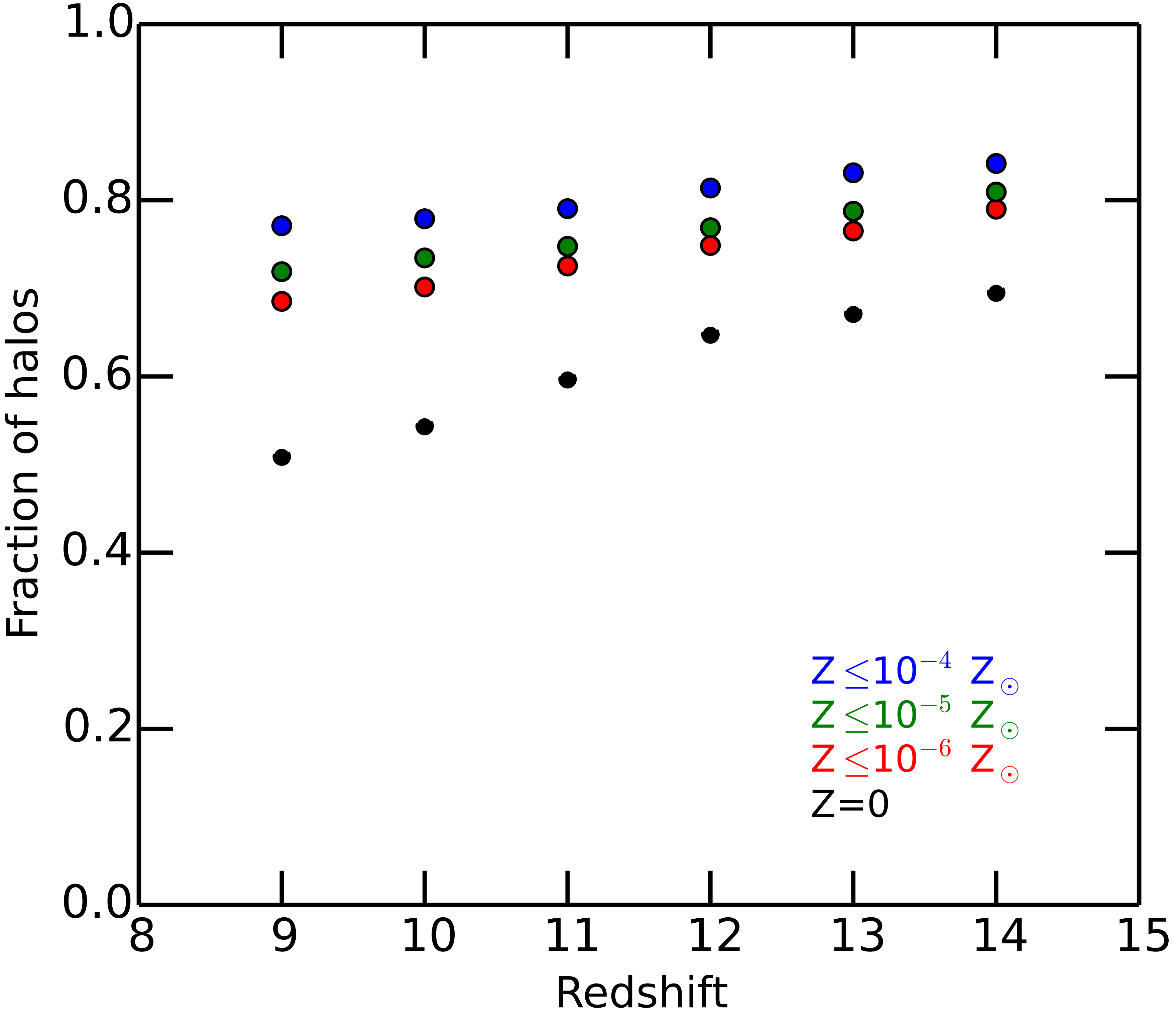


- Employed sink particles and followed the evolution for 200,000 yrs

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

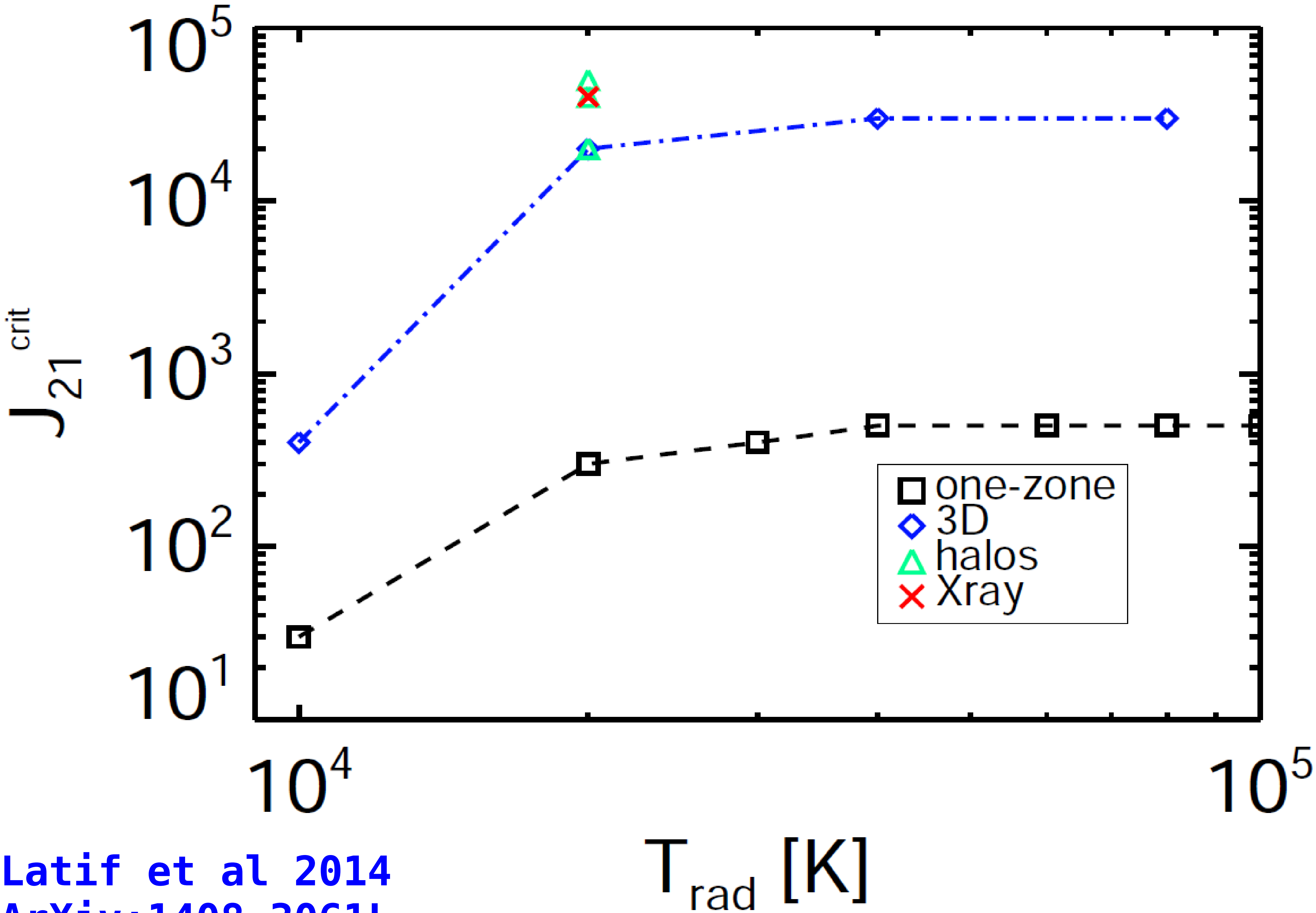
Latif et al. 2013 MNRAS 436 2989L

Fraction of metal free halos



Latif et al. 2015 submitted, Habouzit, ML et al 2016

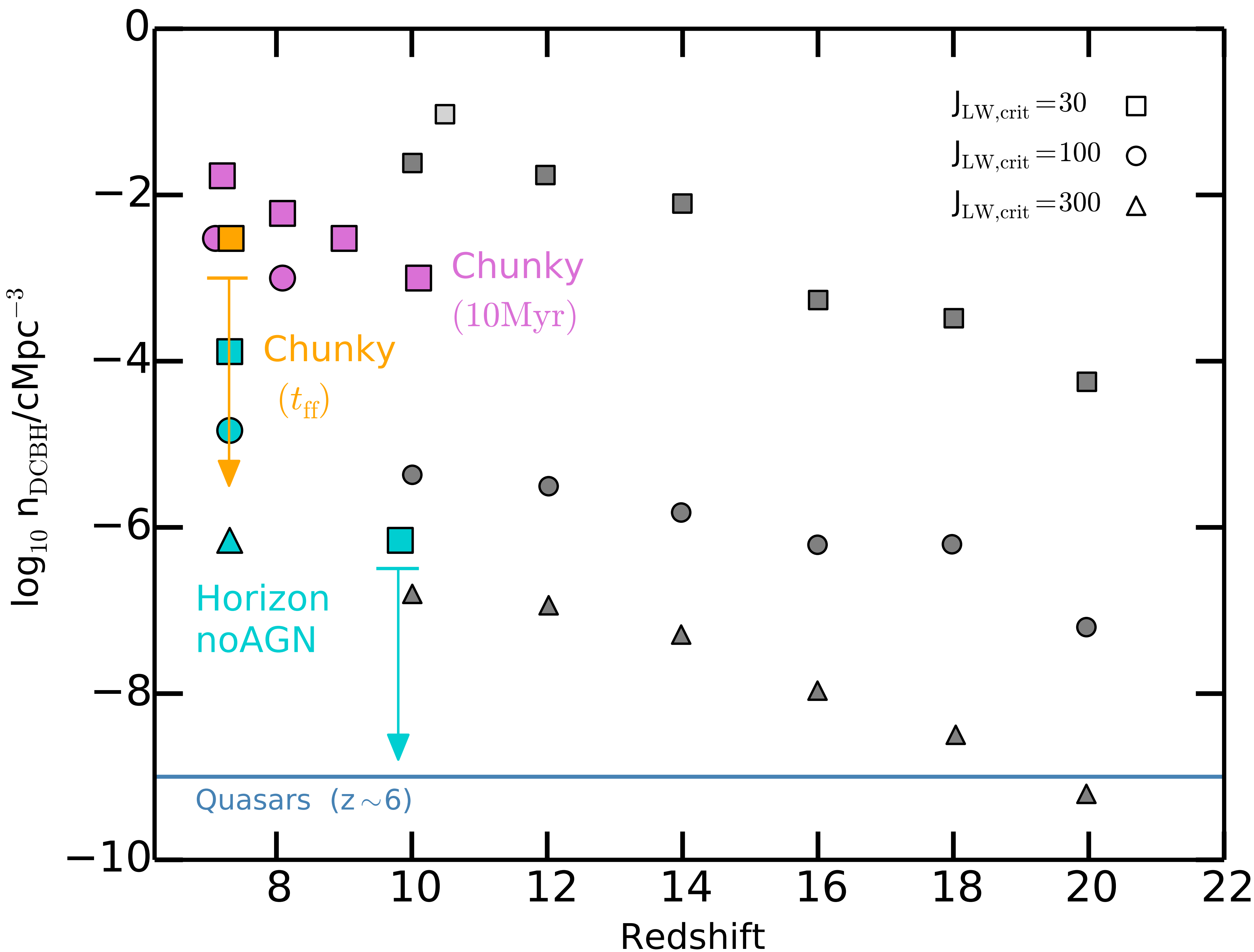
Estimates of J_{crit} from 3D simulations



Latif et al 2014
ArXiv:1408.3061L

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

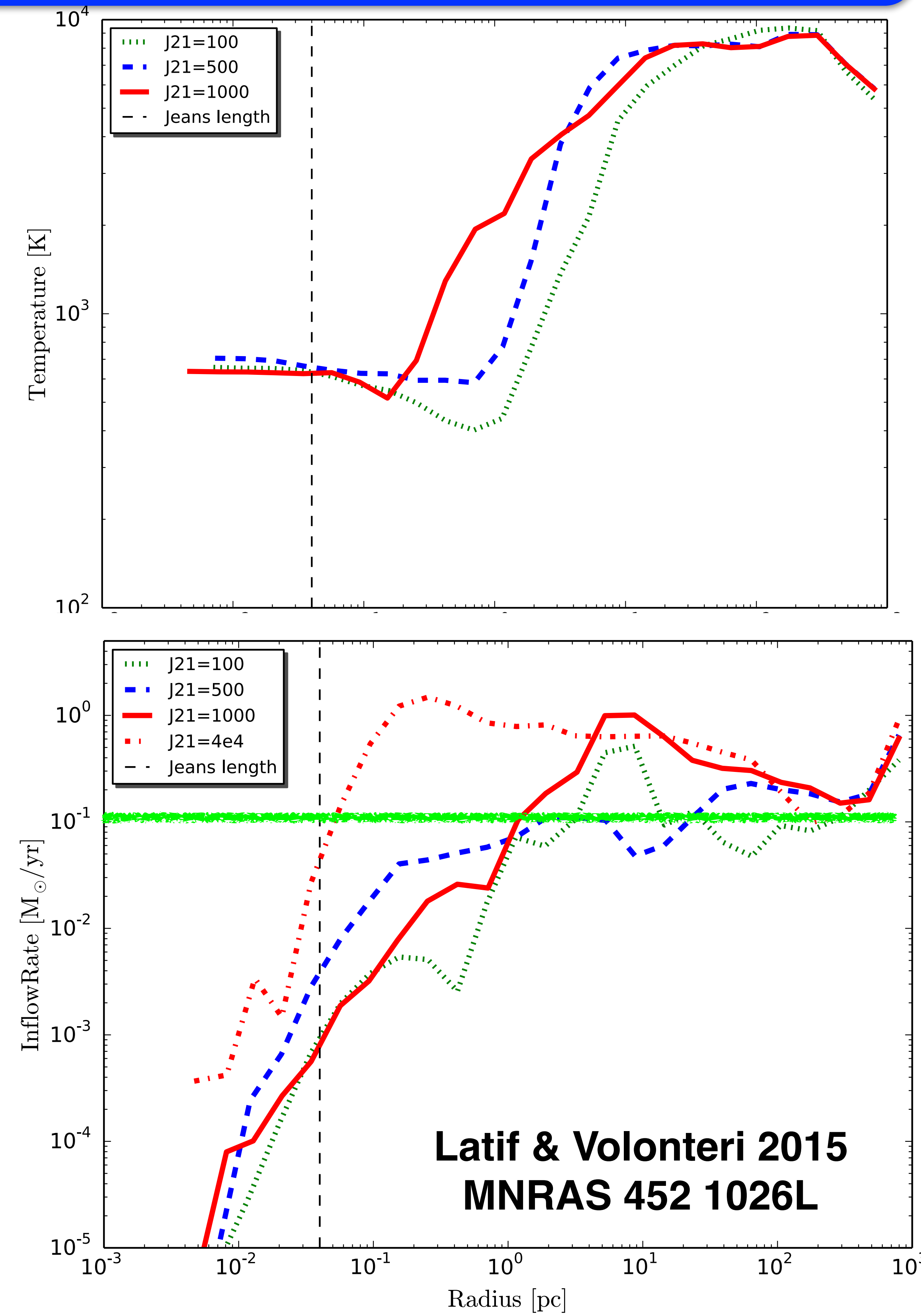
Number density of DCBHs



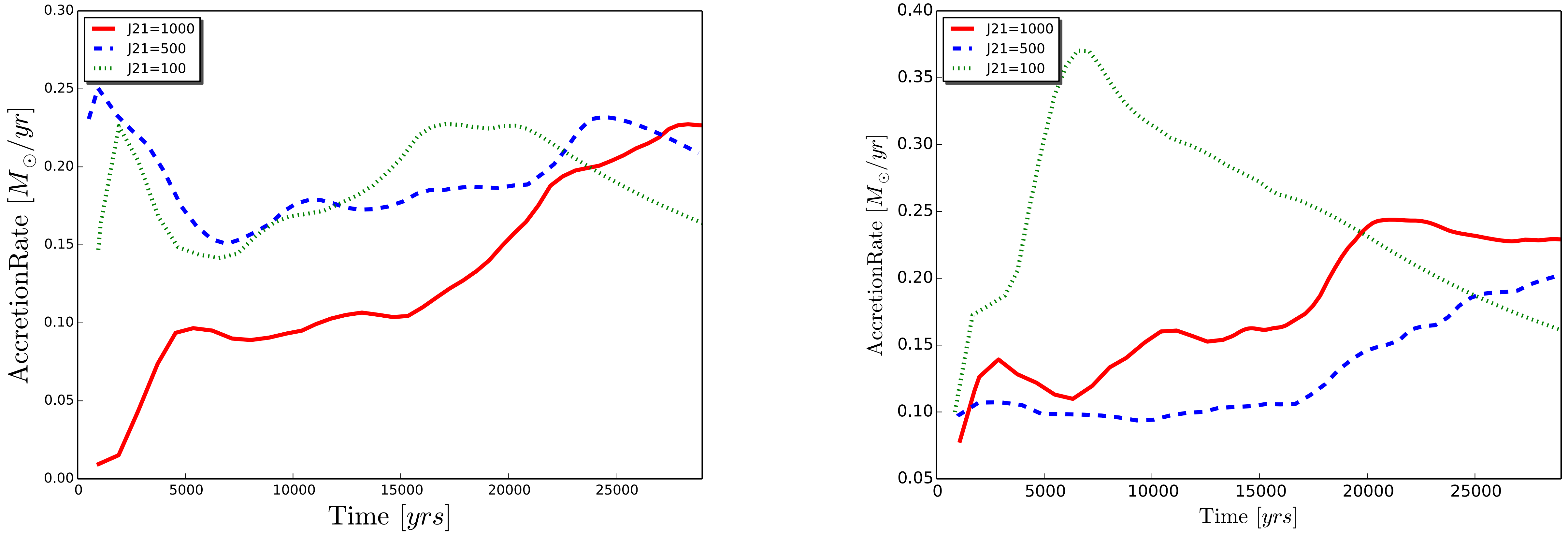
Habouzit, Volonteri, ML et al. 2016

What if there is a trace amount of H_2

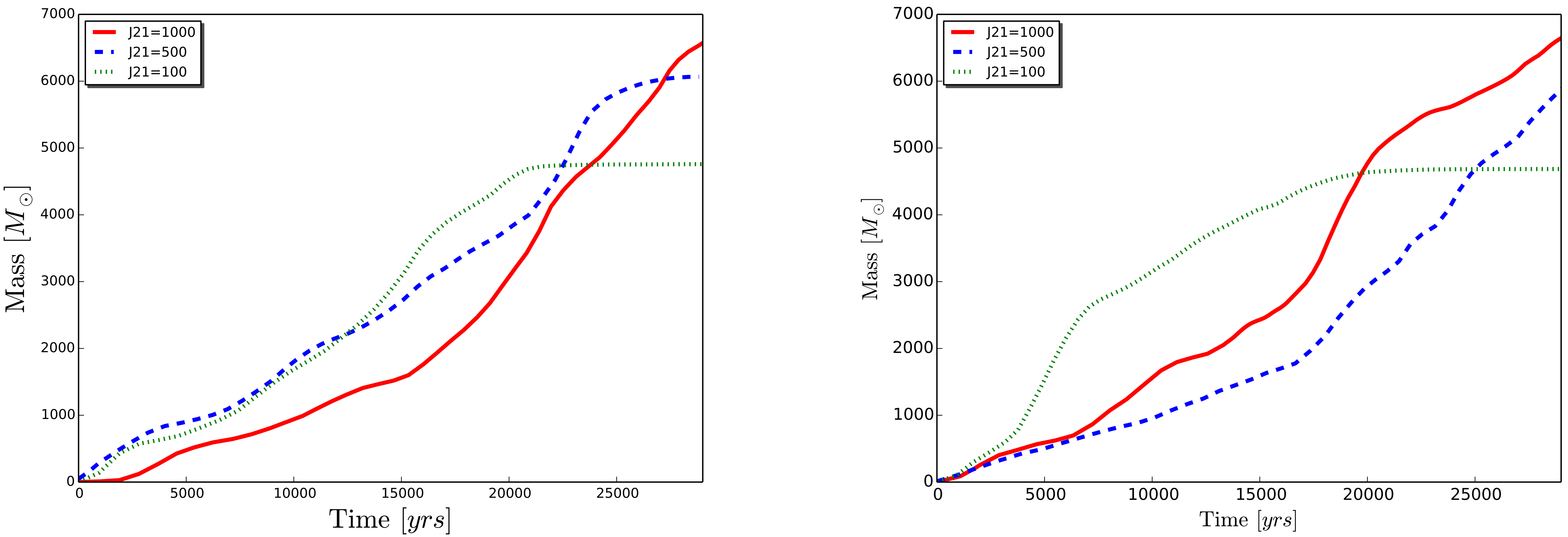
- Massive stars up to 1000 $M_\odot$ can be formed in minihalos (Hirano et al 2014, Latif & Schleicher 2015)
- LW flux helps in suppressing H_2 formation and keeps the gas warm with 8000 K down to ~ pc scales
- Key requirement for the formation of supermassive star is mass inflow rate of 0.1 $M_\odot$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



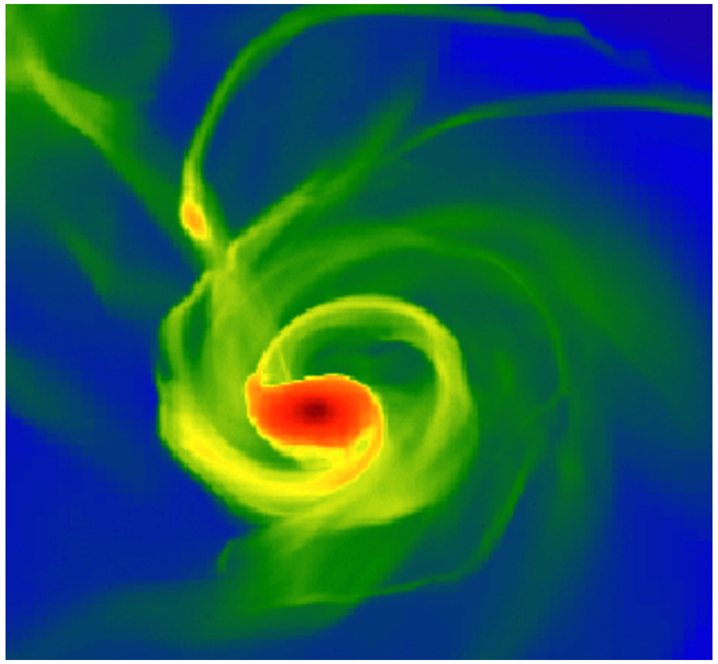
Sink Masses & accretion rates



Latif & Volonteri 2015 MNRAS 452 1026L



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

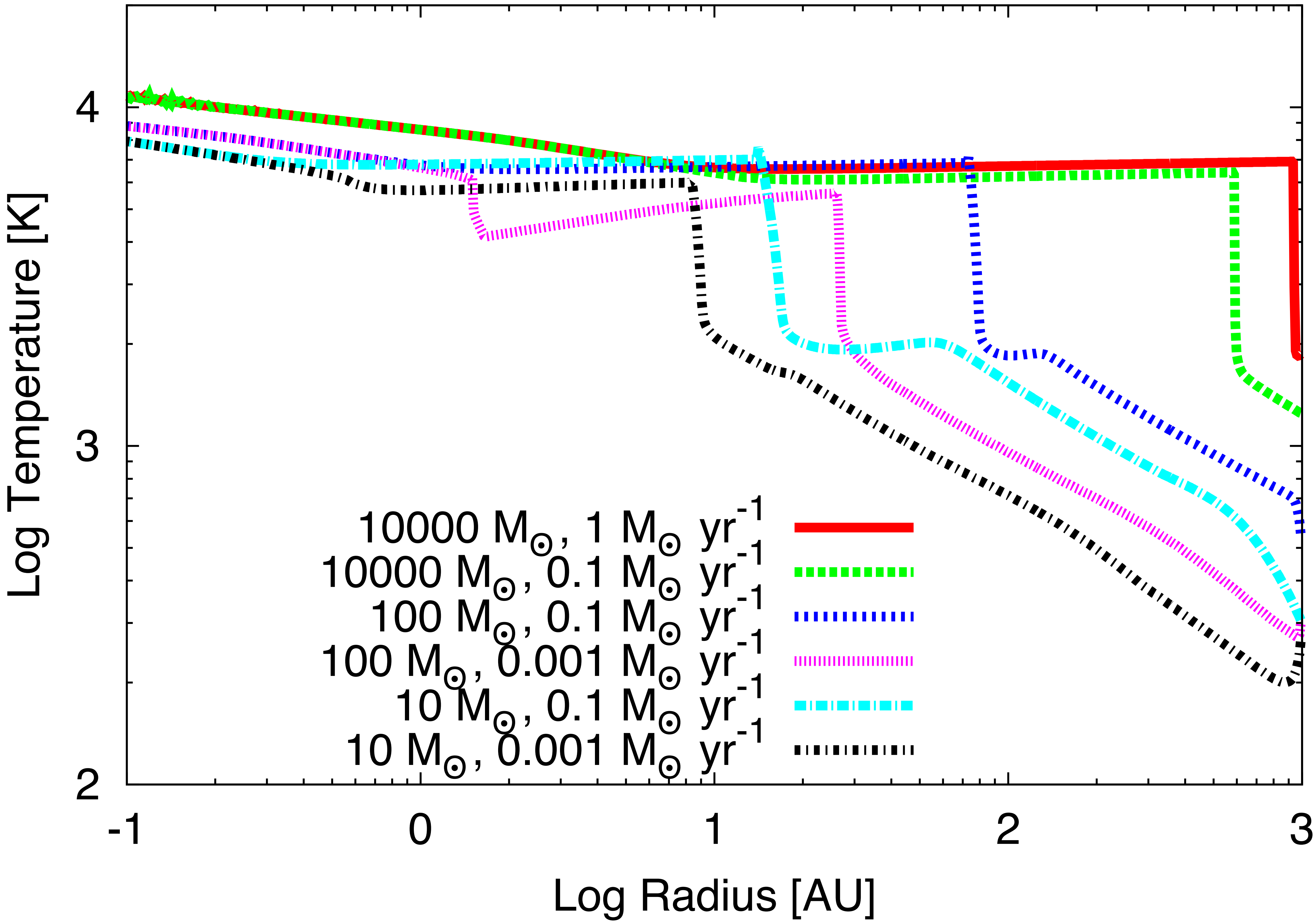
$$Q_+ = Q_-$$

- ★ Viscous Heating

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

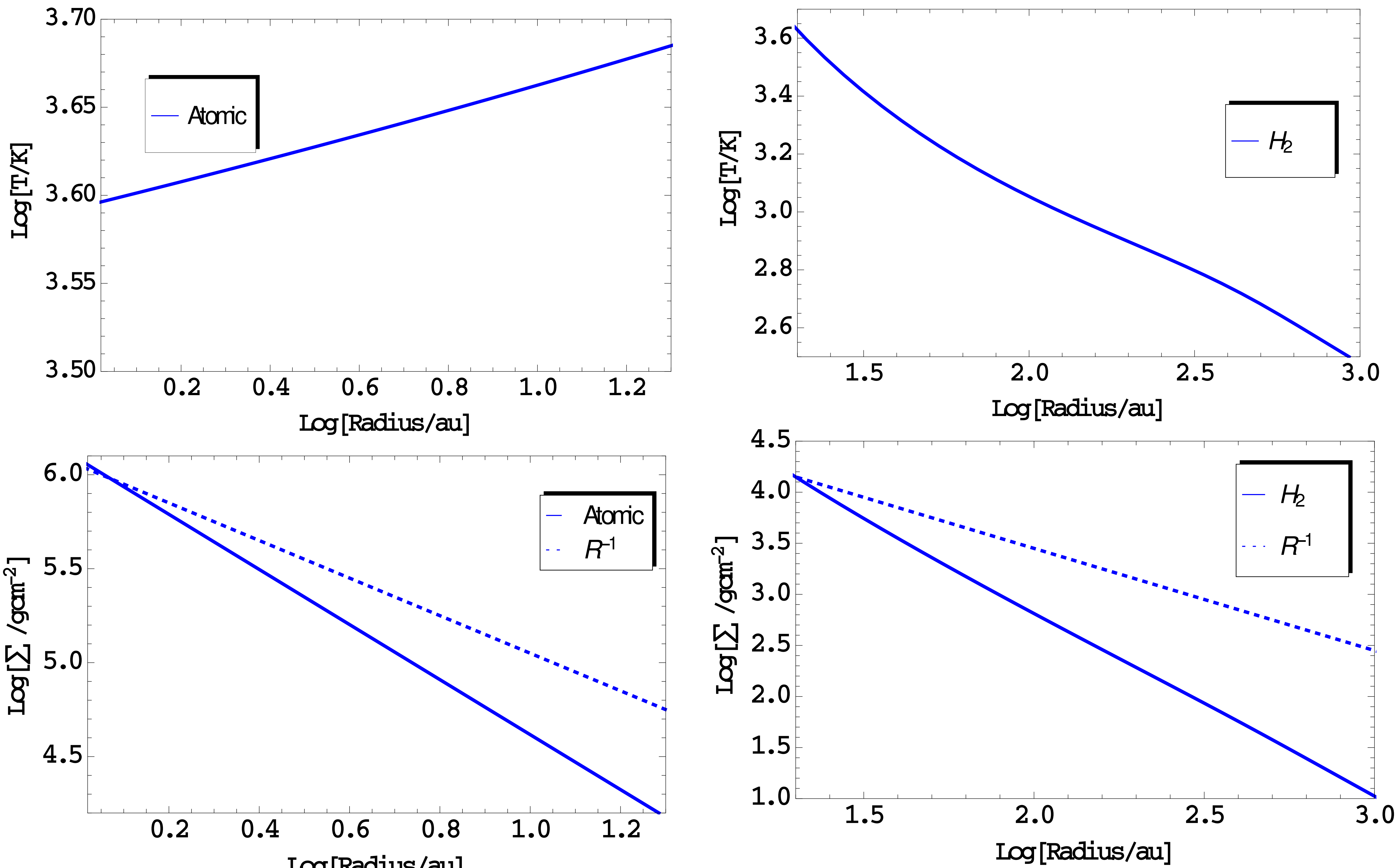
Latif & Schleicher 2015 A&A 578 A 118 L

Thermal properties of disk



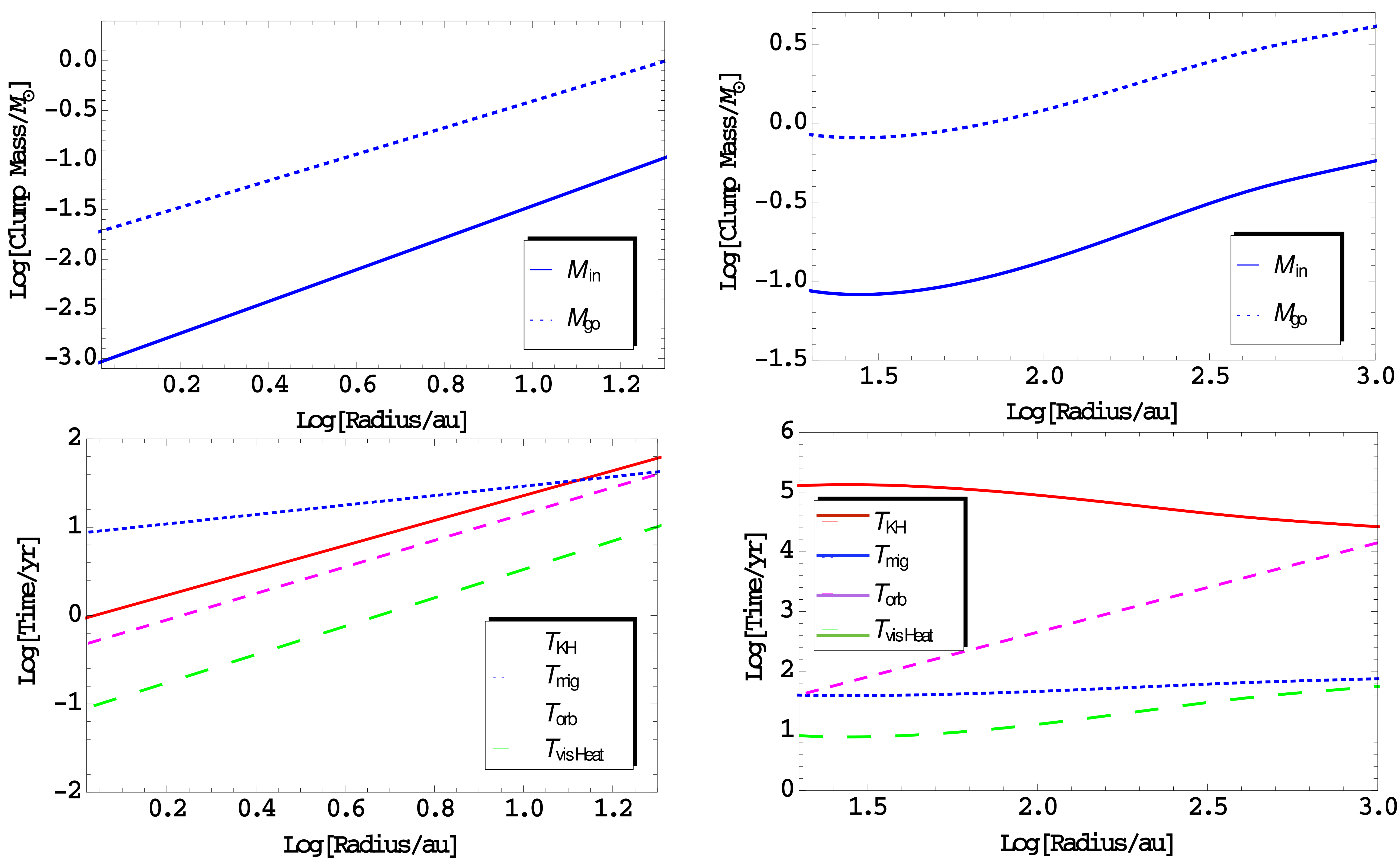
Schleicher, ML et al. A&A 2016

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



Latif & Schleicher 2015 A&A 578 A 118 L

Clump masses & time scales comparison



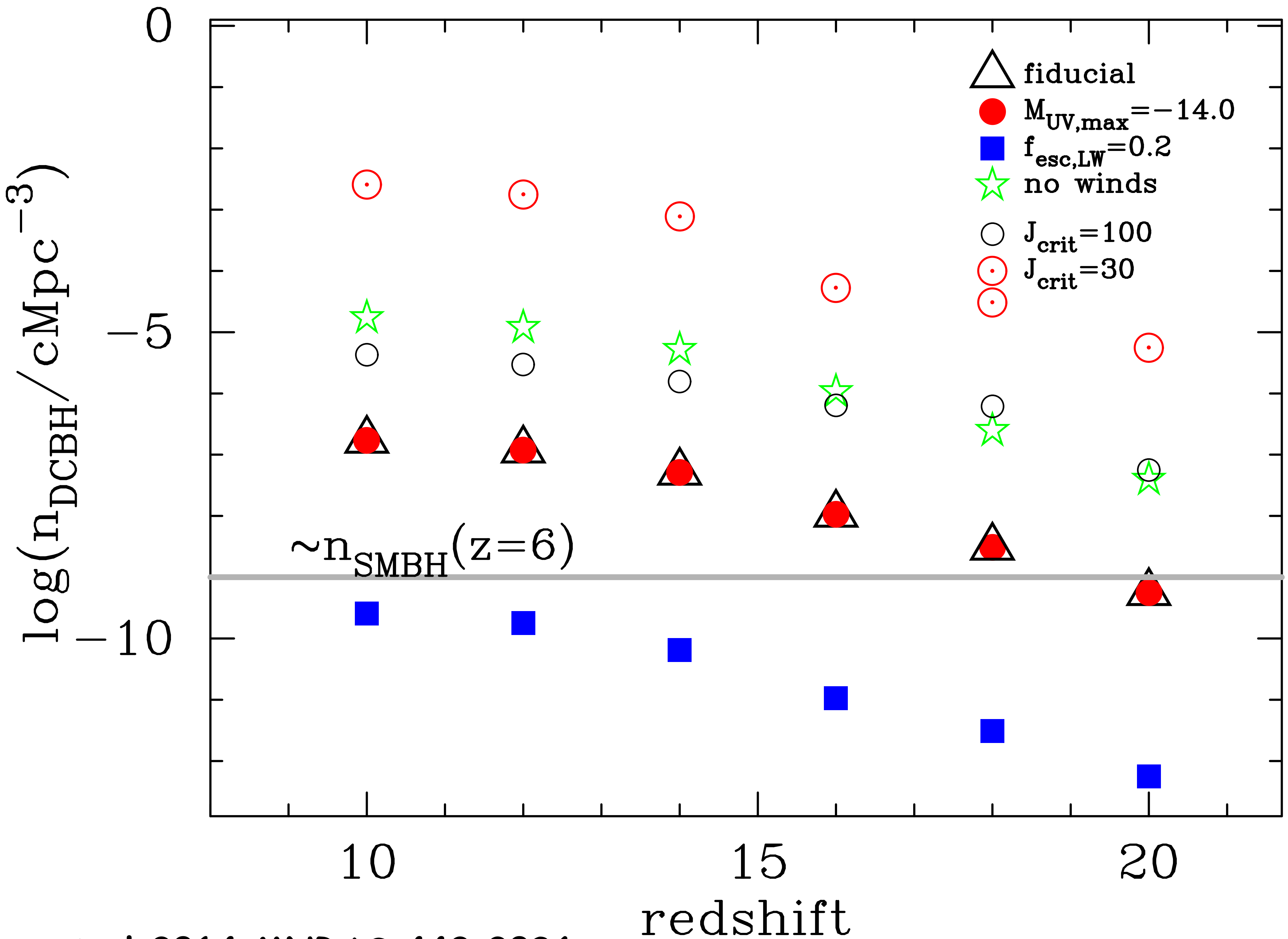
Latif & Schleicher 2015 A&A 578 A 118 L

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 2016)
- ★ 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 A&A 578 A 118 L

Number density of DCBHs

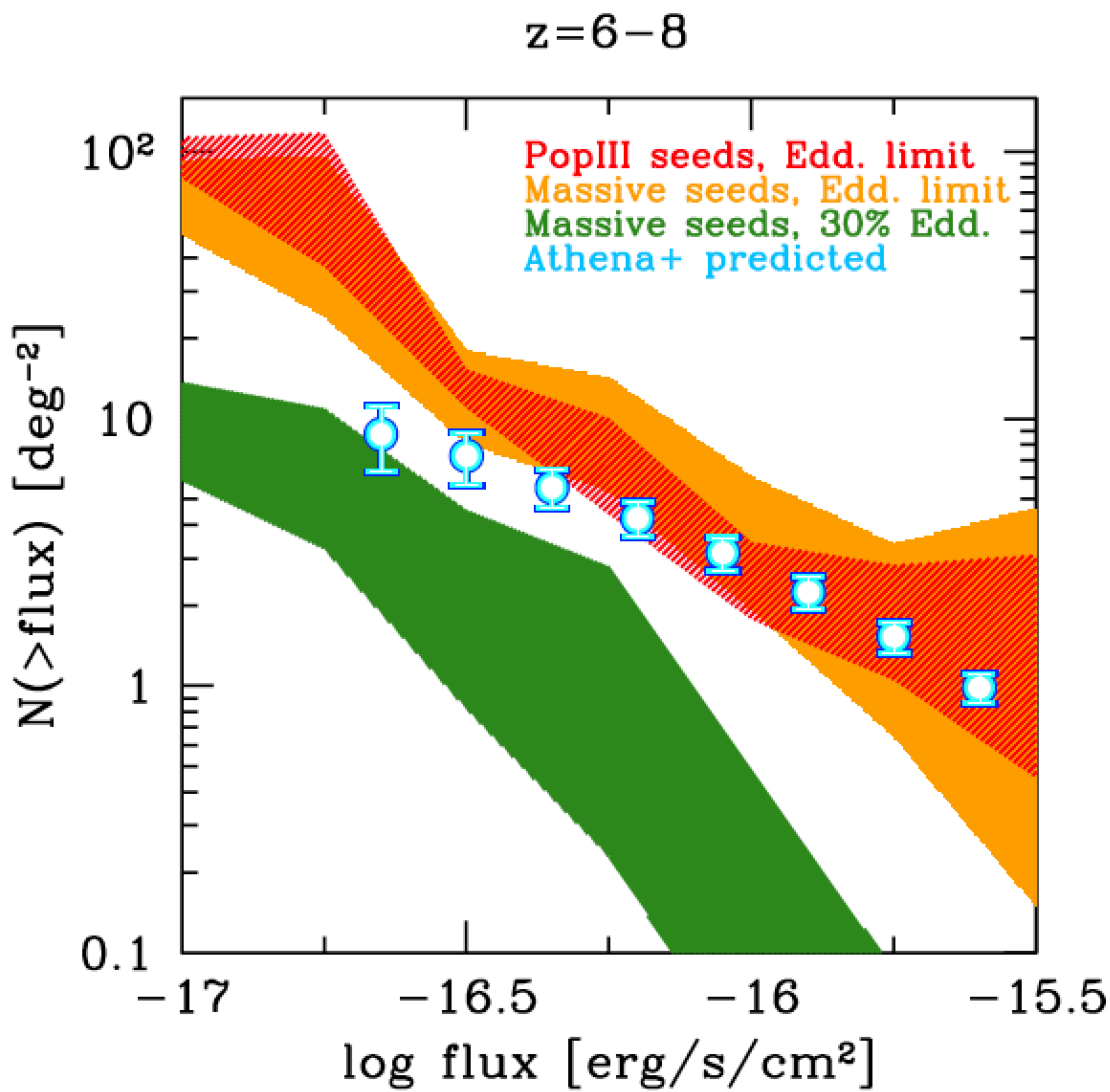


Dijkstra et al 2014 MNRAS 442 2036

Also see Habouzit,Volonteri, ML et al. 2015

Observational tests

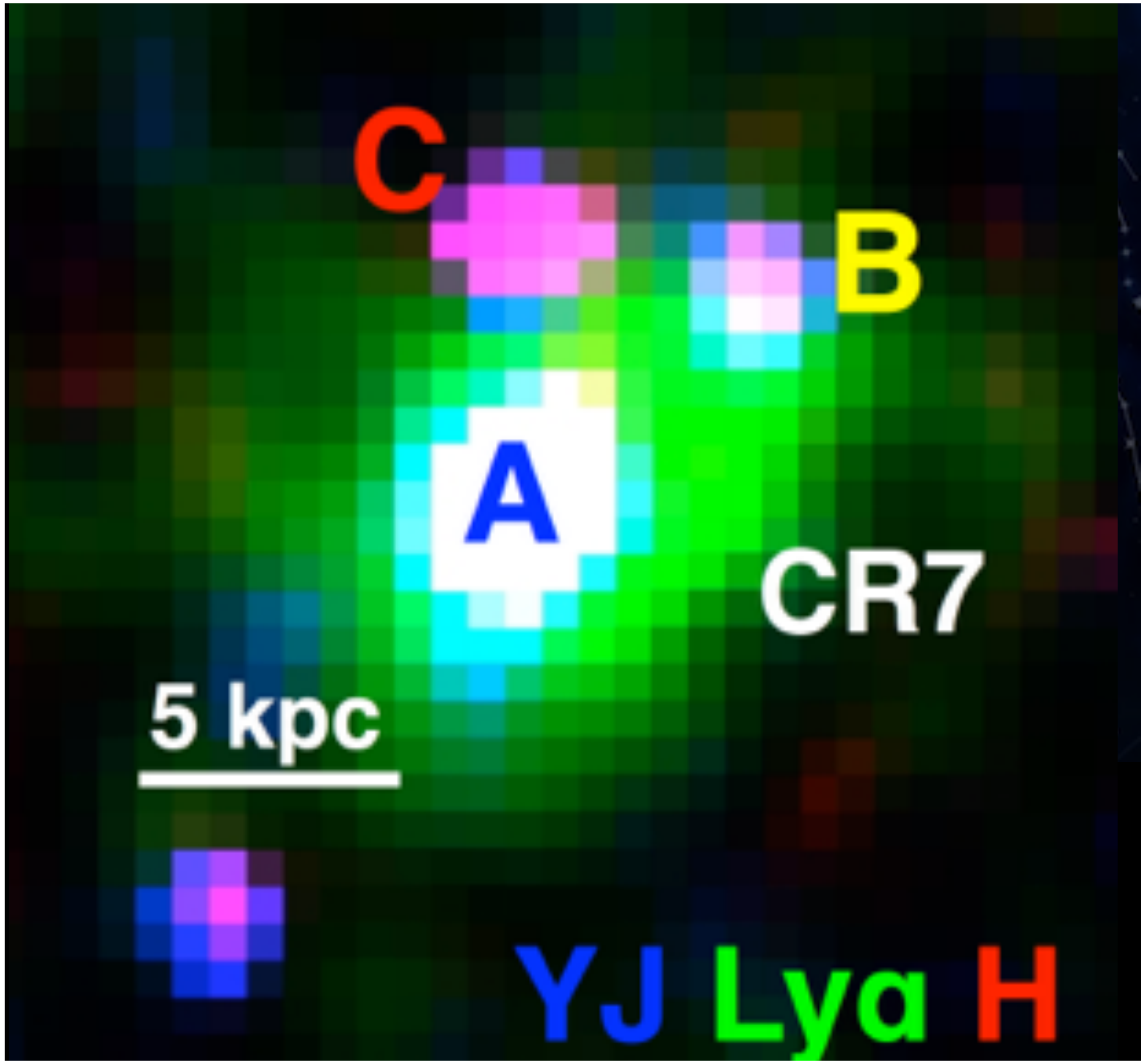
- ⋆ ATHENA X-ray observatory
- ⋆ Expected to probe a few hundred low luminosity AGNs at z>6
- ⋆ Provide direct constraints on BH seed formation mechanisms
- ⋆ Expected launch in late 2020s



Aird et al. Athena white paper, Volonteri & Begelman 2010

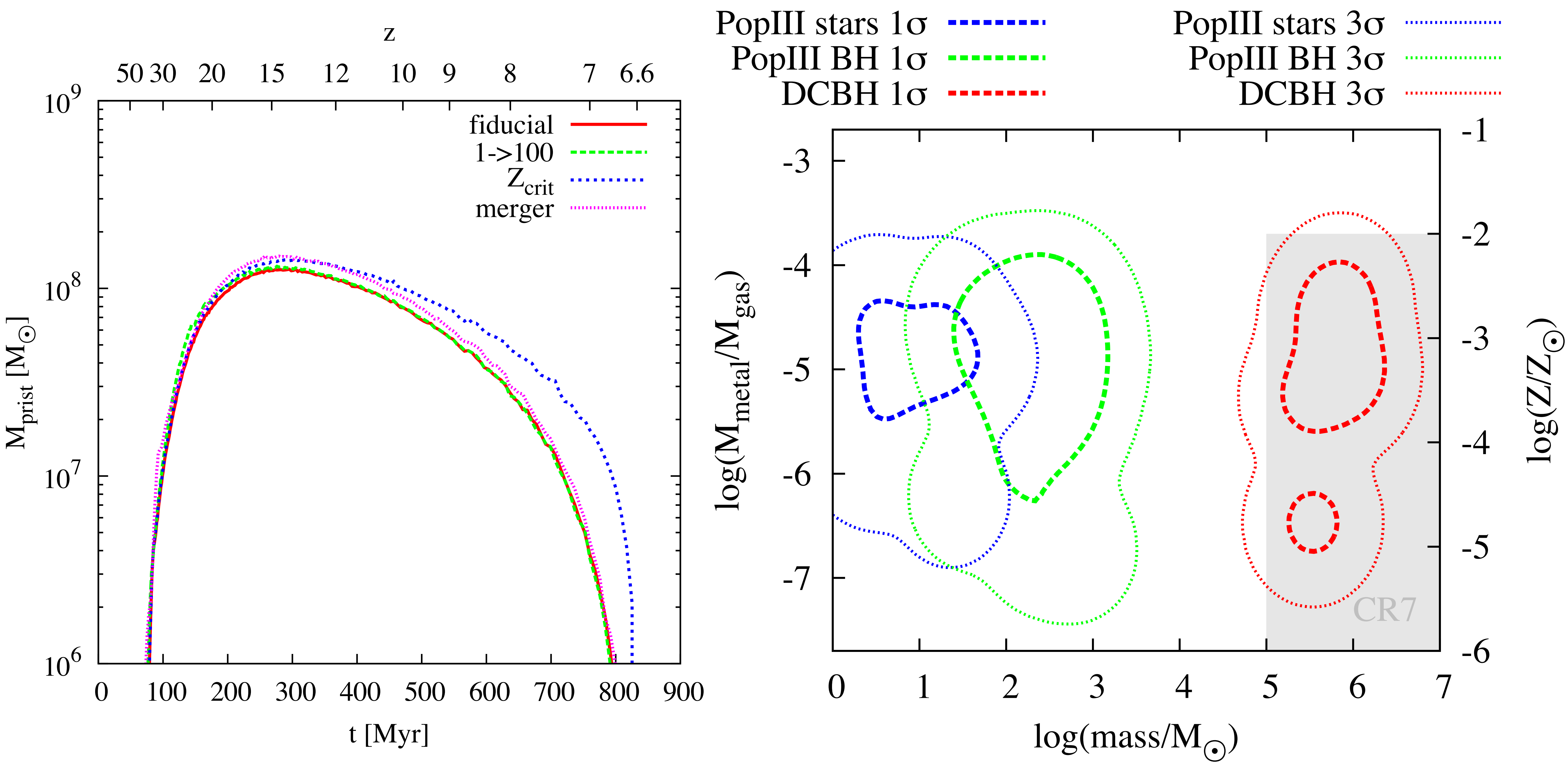
CR7: Potential host for a DCBH

- The brightest Lyman alpha emitter at z=6.6 (CR7)
- Shows strong Lyman alpha & He1640 emission
- No metal lines detected from UV to infrared
- Such strong line emission can be explained either via 10^7 $M_\odot$ in Pop III stars with top heavy IMF or a massive BH of 10^6 $M_\odot$ residing in metal poor environment



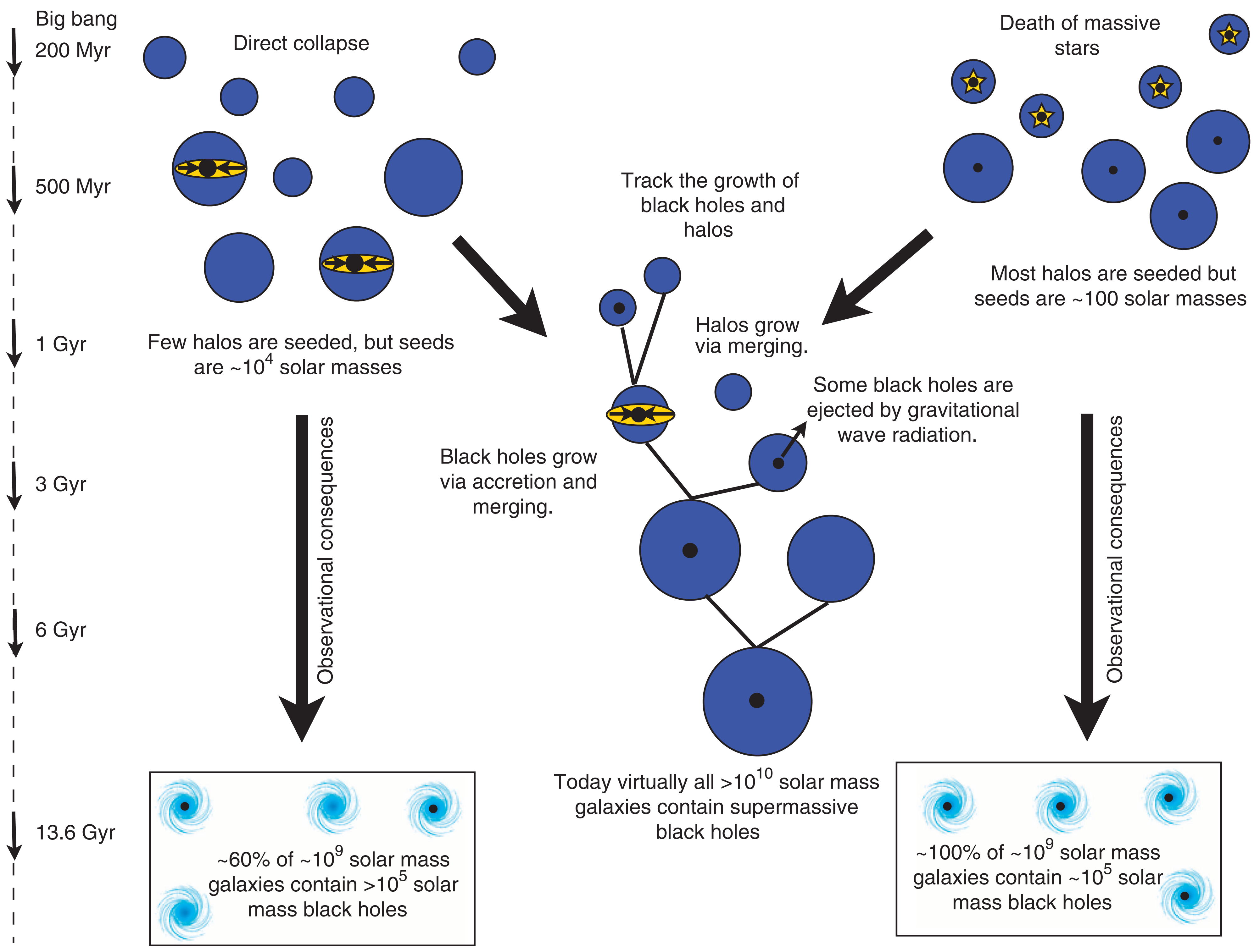
Sobral et al. 2015, Matthee et al 2014

CR7: Potential host for a DCBH



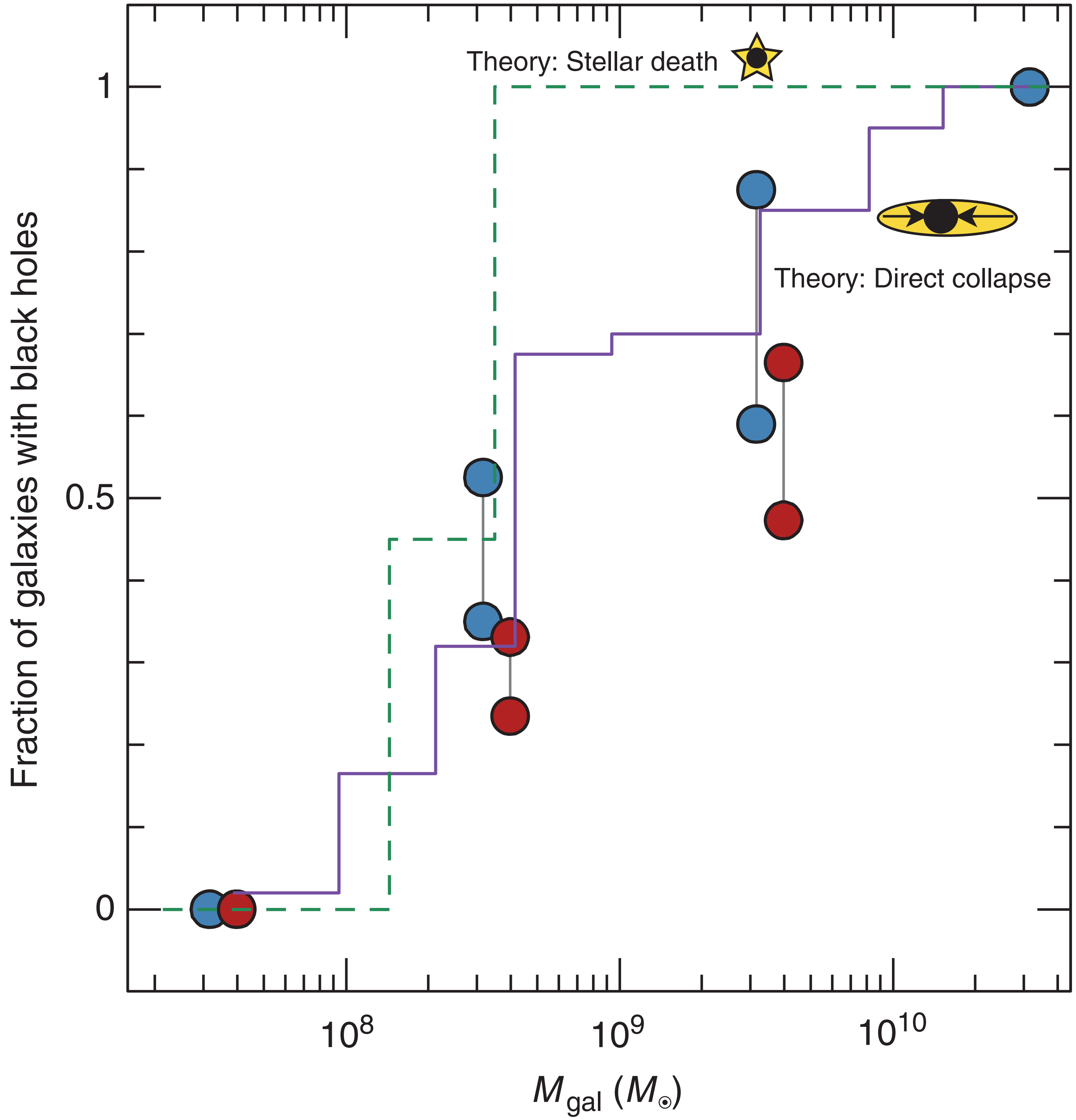
Hartwig, Latif et al. 2015 submitted to MNRAS

“Left over” seeds in low mass galaxies



Greene & Ho 2005, Greene 2012, Volonteri +08

“Left over” seeds in low mass galaxies



Greene 2012, Volonteri +08

Future plans

★The formation and evolution of supermassive BHs at high redshift

★ The formation of earliest quasars

★ Lyman alpha emission from first galaxies

★ Formation of the first and second generation of stars

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
- Fragmentation occurs occasionally but clumps migrate inwards
- 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 $M_\odot$

Thank you 谢谢

The formation and evolution of supermassive BHs at high redshift

- ★ Derive mass distribution of BHs to provide constraints on their masses and growth mechanisms
- ★ Make predictions for JWST, ATHENA, WFIRST and SKA
- ★ Provide recipes for BH formation in large cosmological simulations
- ★ Compute scaling relations between properties of hosting halo and BH mass
- ★ Build a statistical sample of high resolution simulations
- ★ Self-consistently investigate the impact of UV feedback from a supermassive star and X-ray feedback from BH itself by employing MORAY ray tracer

The formation of earliest quasars

- ⋆ Investigate in detail the origin of the first quasars

- ⋆ Compute typical black hole masses in high-z galaxies ($z>=5$) and understand under what conditions BHs can grow more efficiently (environment, mergers etc)

- ⋆ Derive Magorrian relation at high redshift

- ⋆ High resolution simulations of DM halos of 10^{11}-10^{13} $M_\odot$ including AGN feedback, In-situ star formation, supernova feedback, metal and dust cooling

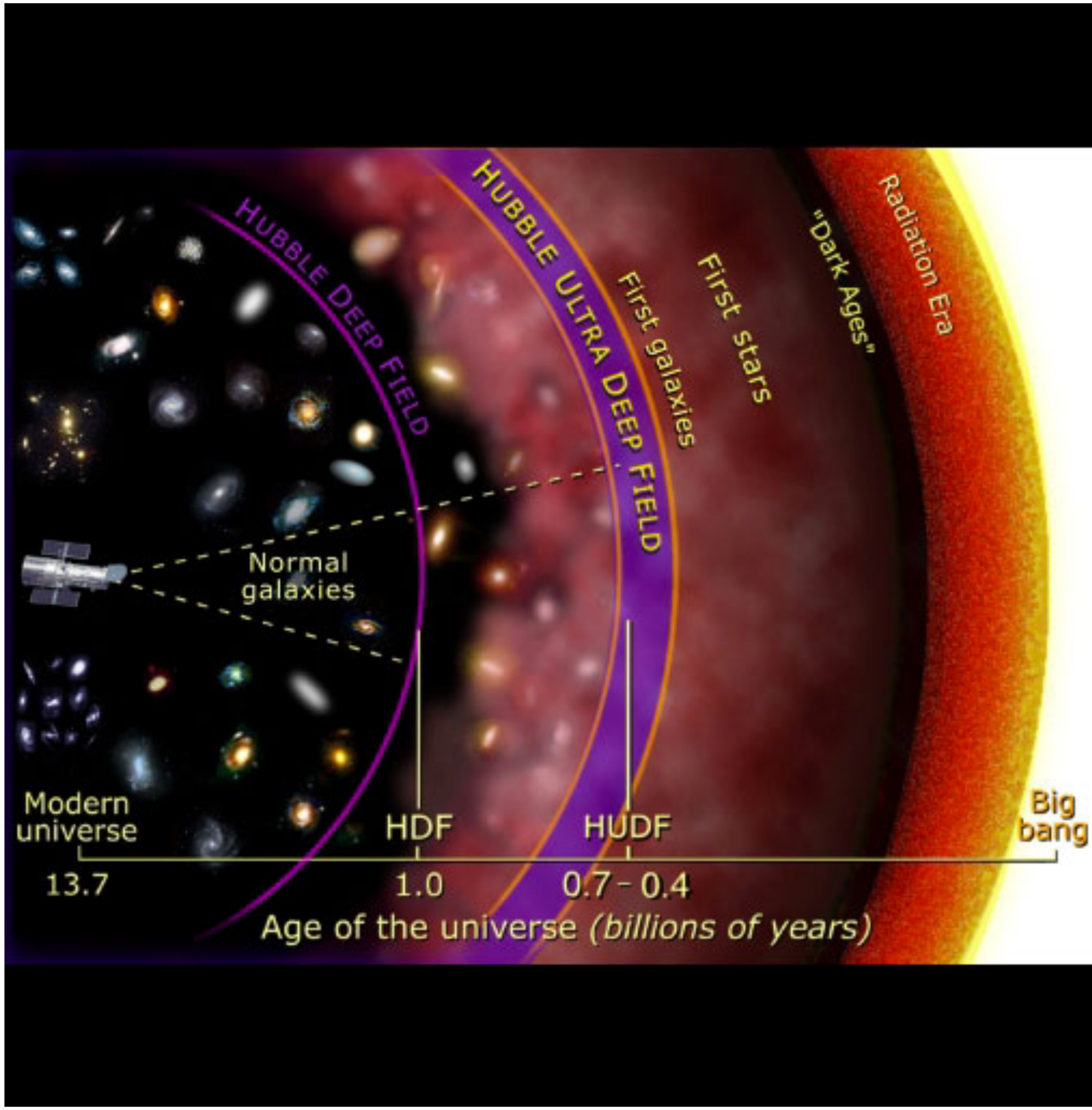
- ⋆ Employing the MORAY ray tracer for AGN feedback

Lyman alpha emission from first galaxies

- ★ Compute observational signatures of Lyman alpha emitting galaxies
- ★ Explore the origin of Lyman alpha emission
- ★ Investigate the number density of peculiar sources like CR7
- ★ Post-process cosmological simulations with and without AGN feedback with Lyman alpha radiative transfer code

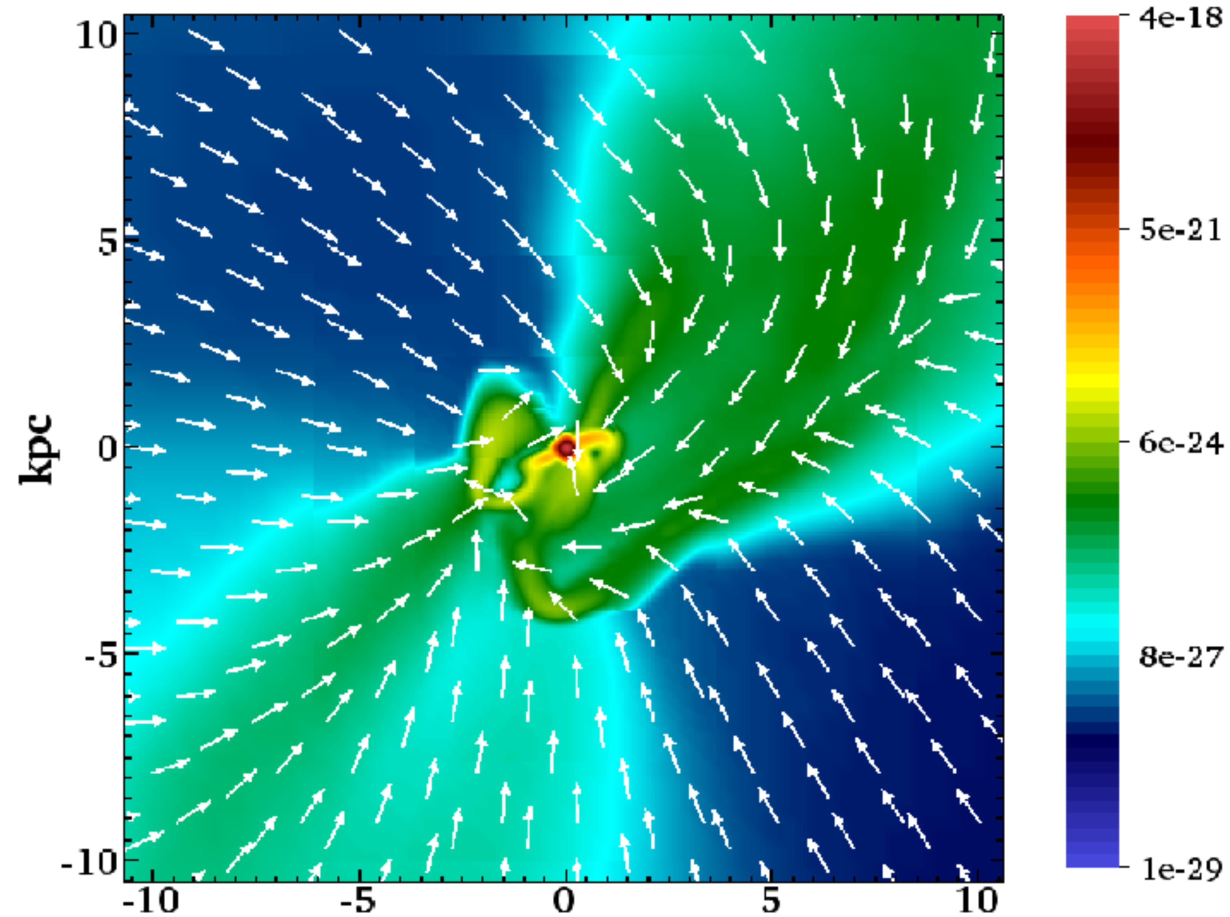
First galaxies

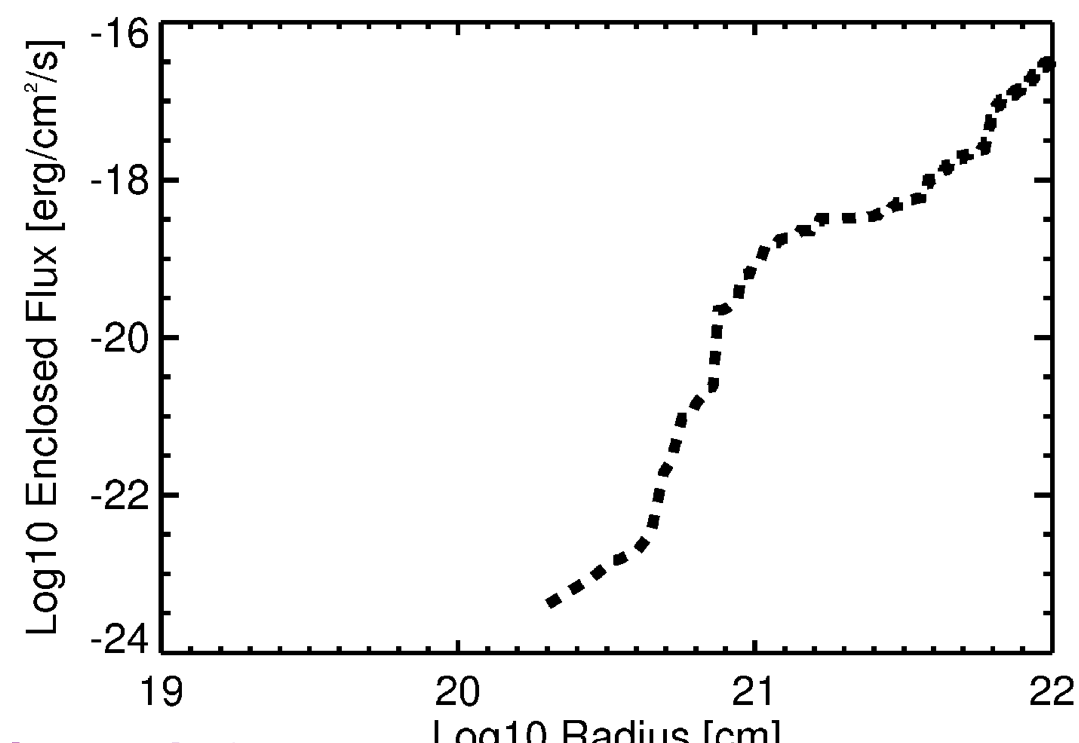
- ➡ Formed in massive halos at $z=10$ with $T_{vir} \geqslant 10^4$ K
- ➡ First galaxies likely comprise both Pop III and Pop II stars
- ➡ Observed at z >7 Bouwens + 2011, Ellis+13, Oesch +14
- ➡ First galaxies are known to be strong Lyman alpha emitters typical Lum~10^{42} erg/s, sizes ~ few kpc.
- ➡ Source & origin not completely known.



Origin of Lyman Alpha emission

- ➡ Baryons fall into the center of the galaxy through cold streams (~10^4 K, n=0.01-1 cm^3)
- ➡ Accretion flows and virialization shocks are the potential drivers of the observed LAEs
- ➡ Lyman alpha flux of 5×10^{-17} erg cm^{-2} s^{-1} is emerged from the envelope of the halo
- ➡ Emission of Lyman alpha photons is extended Such flux can be probed with JWST

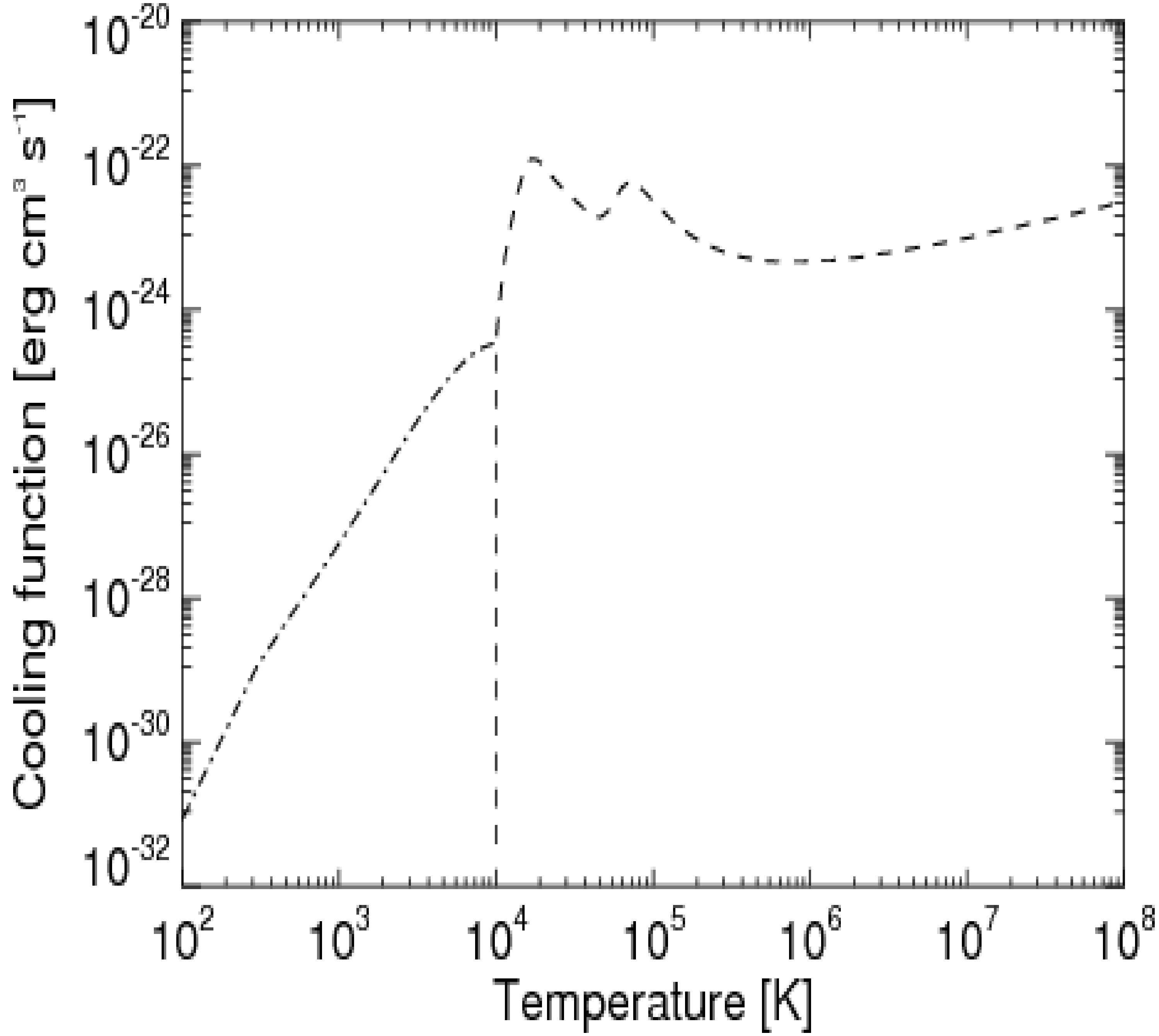




Latif et al 2011 b & c

Primordial gas chemistry

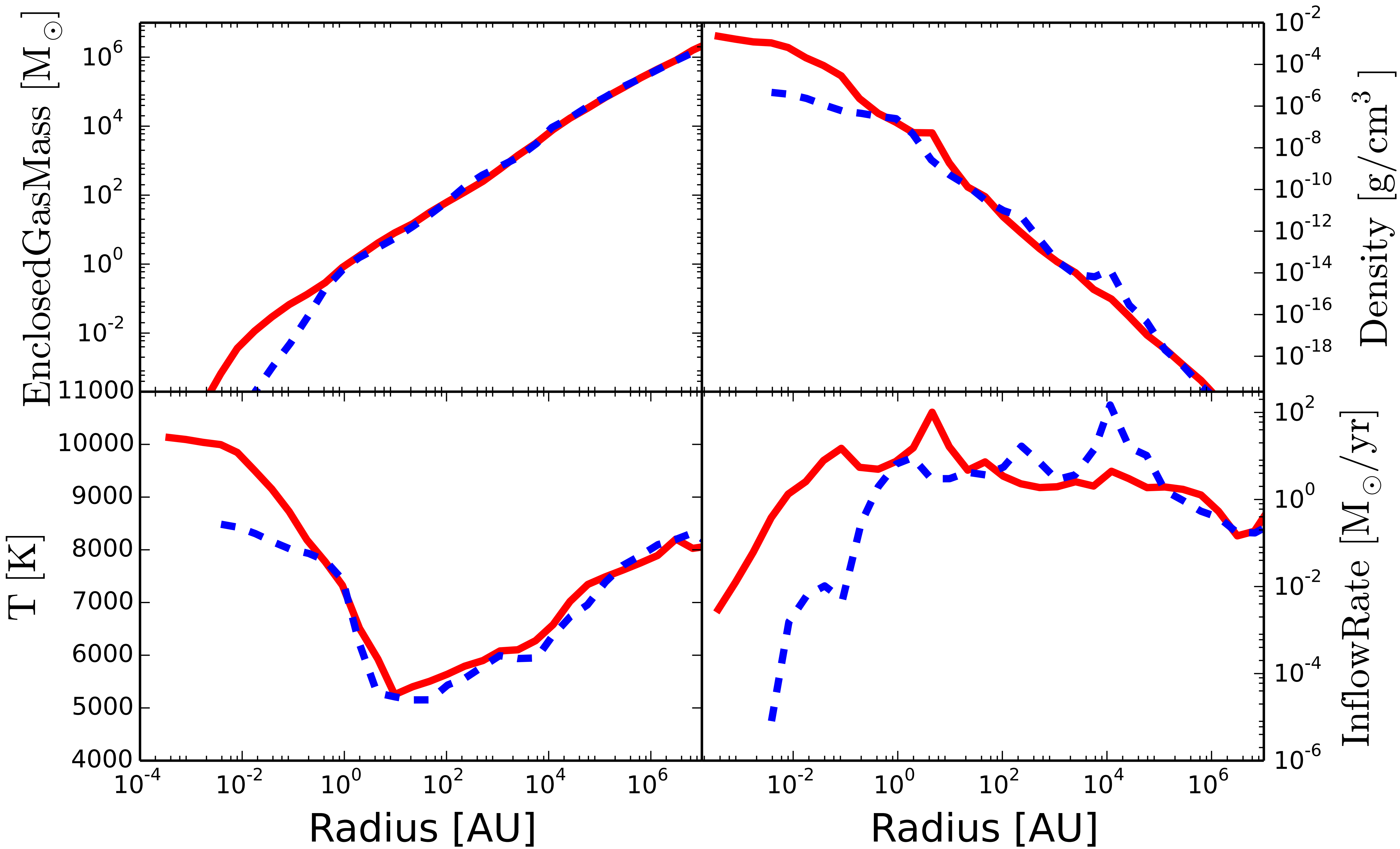
- ⋆ At T> 10^4 K, Lyman alpha is the main coolant in primordial gas
- ⋆ H_2 cooling becomes efficient at T<8000 K
- ⋆ In the presence of strong LW flux, H_2 gets dissociated



My work on BH formation

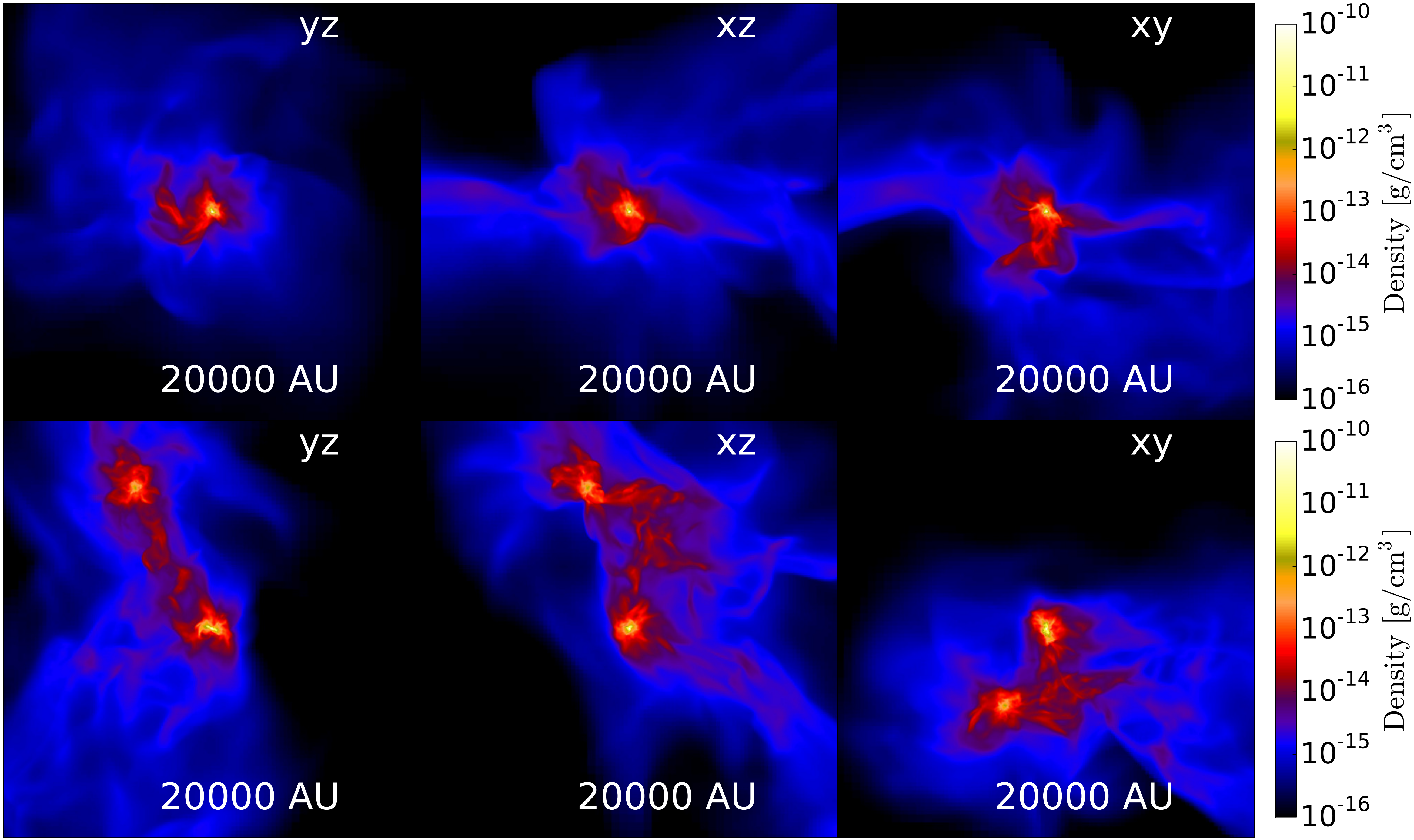
- Explored thermal, dynamical and physical properties
- Investigated the role of turbulence and magnetic fields
- Computed the expected masses of supermassive stars which later may collapse into mass black hole.
- Assessed the feasibility of direct collapse black holes by comparing their number density against quasars abundance at z=6

Global properties of simulated halos



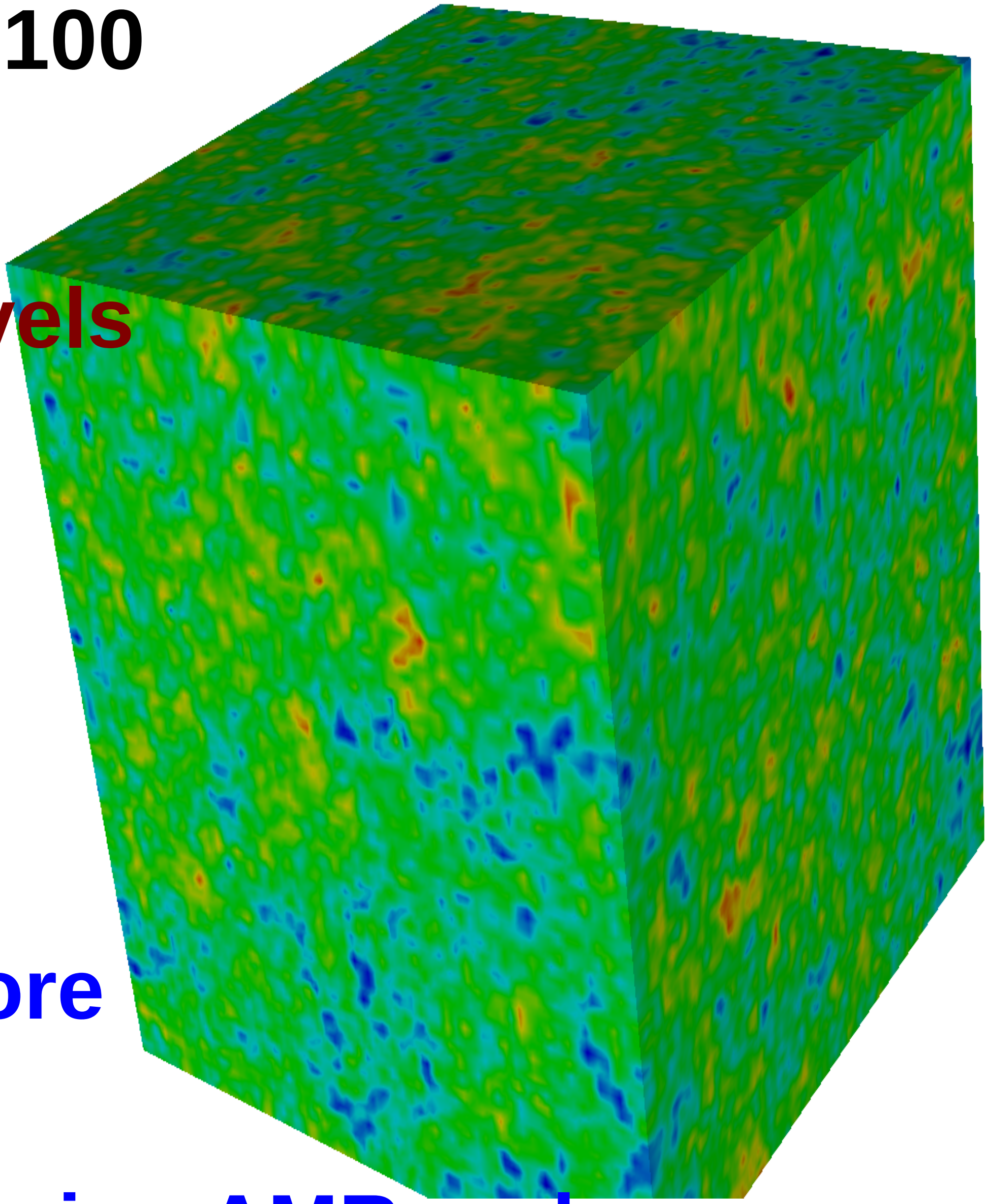
Latif, Schleicher & Hartwig 2015 (arXiv:1510.02788)

Impact of H^- cooling & Realistic opacities



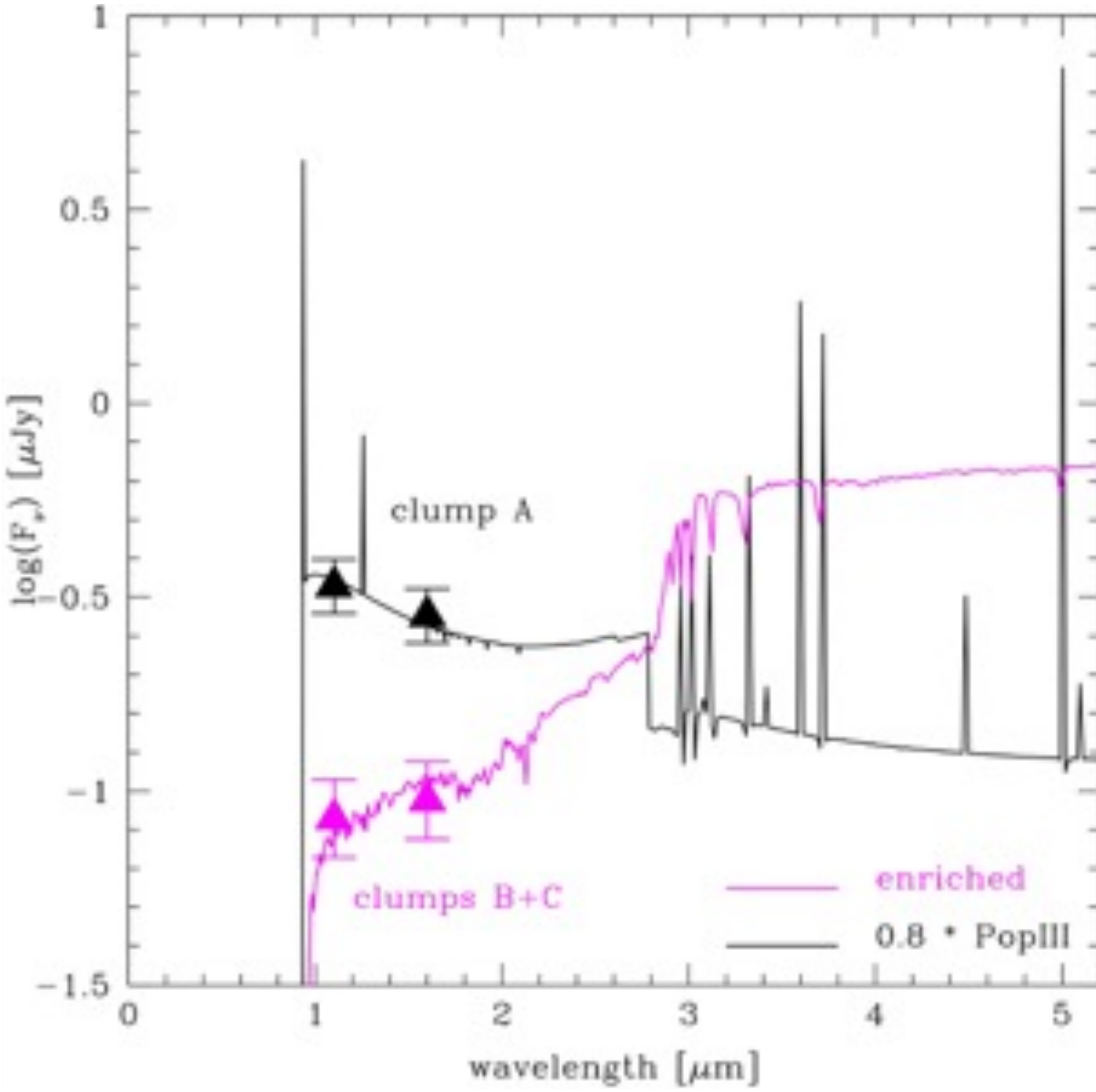
Latif, Schleicher & Hartwig 2015 (arXiv:1510.02788)

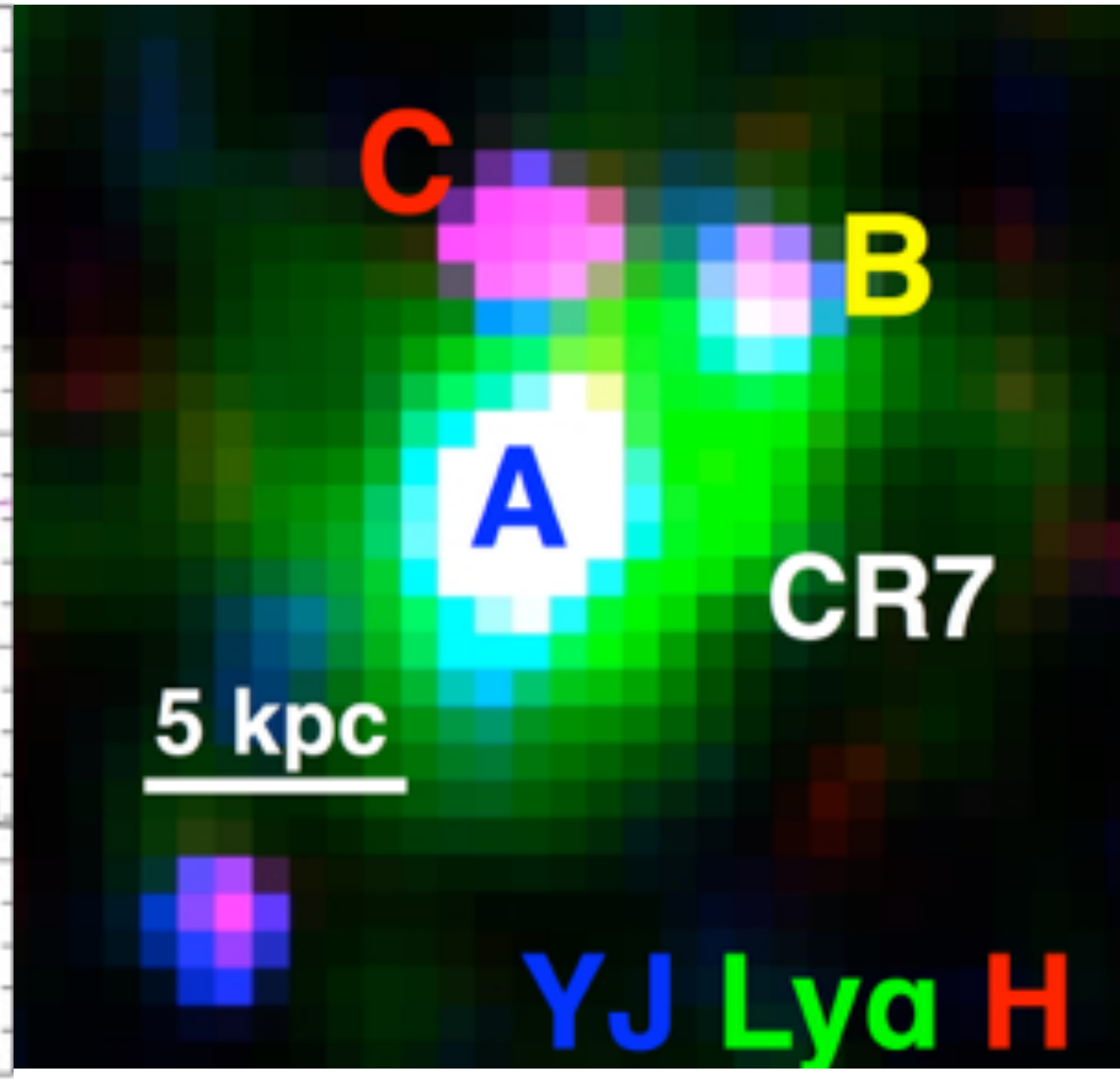
Simulation setup



- 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

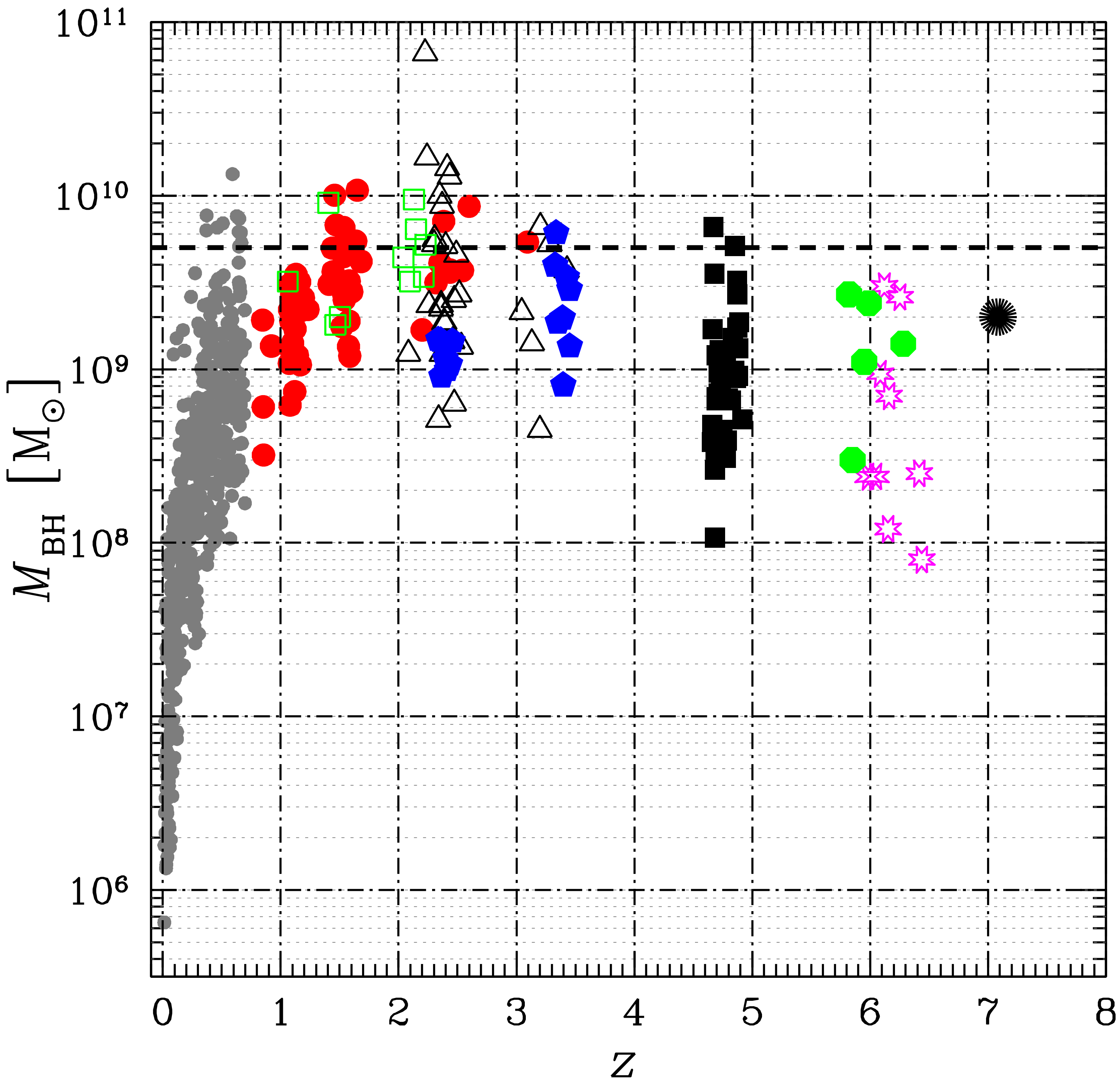
CR 7: Potential detection of DCBH





Sobral et al. 2015

Black holes mass distribution

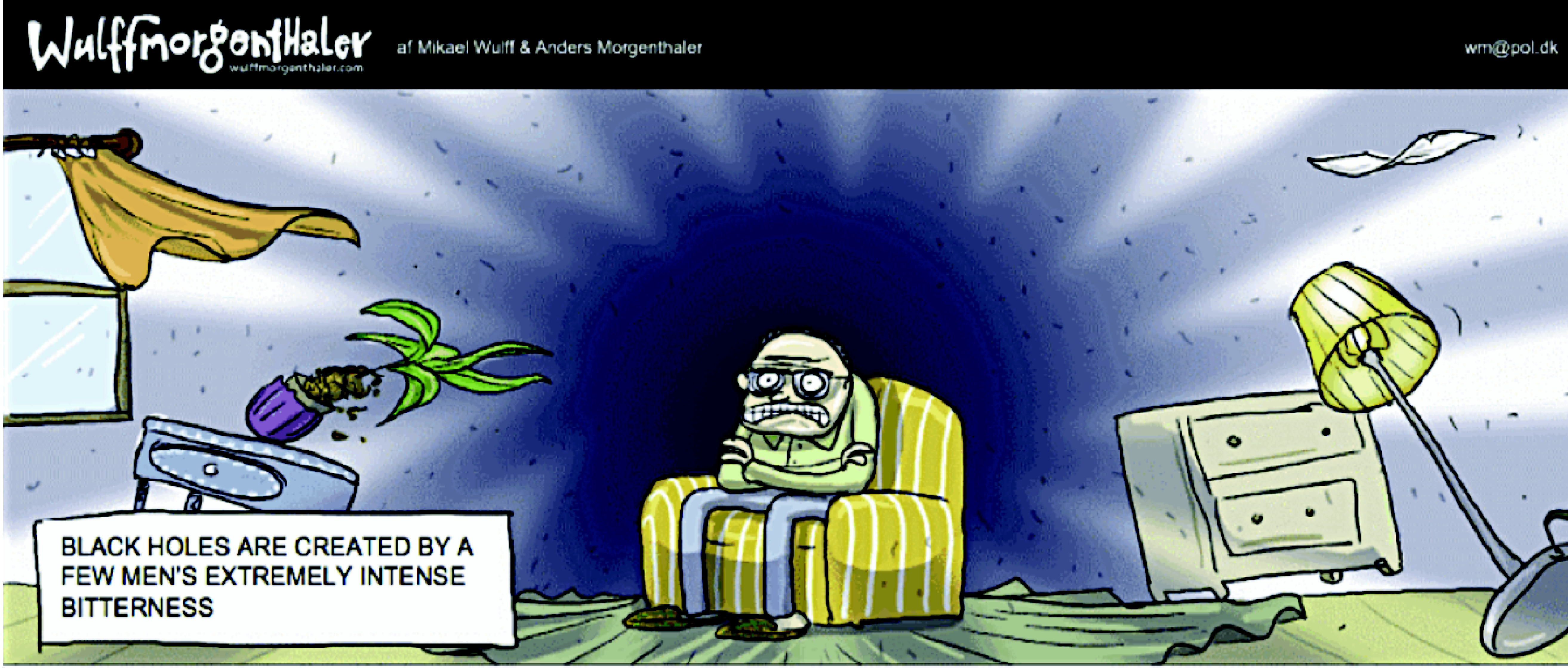


Mirziani & Sulentic 2012

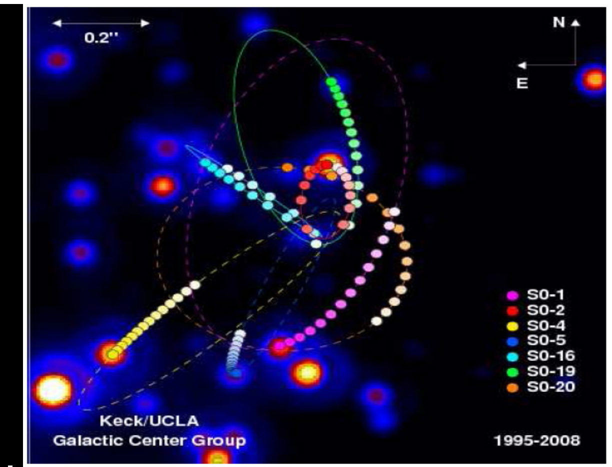
M. Volonteri, Brera 2013

HOW

can you make a massive black hole ‘seed’?



Mass measurements



Motions of *test particles*	
▪ Star proper motions and radial velocities	Milky Way
▪ Radial velocities of single gas clouds (masers)	Rare nearby galaxies/AGN with edge-on masers
Ensemble motions (spatially resolved)	
▪ Stellar Dynamics V from Stellar Absorption Lines	Quiescent/weakly active MBHs in nearby galaxies with bulges
▪ Gas Kinematics V from Gas Emission Lines	Quiescent/weakly active MBHs in nearby galaxies with circumnuclear discs
Ensemble motions (time resolved)	
▪ Reverberation Mapping V from line width, R from time variability	Nearby AGN
Virial estimates	
▪ V from line width, R from scaling relations	Distant quasars

Courtesy of A. Marconi

Brief Introduction

- **Marie Curie fellow at IAP, France (2015-present)**
  Project: The formation of supermassive black holes in the early universe

- **Postdoc at IAP, France (2014-2015)**
  Project: The formation and evolution of black holes across the cosmic time

- **Postdoc at University of Goettingen, Germany (2012-2014)**
  Project: MHD turbulence and the formation of supermassive BHs

- **Postdoc at Kapteyn Astronomical Institute**
  Project: The end of darkness: How the universe ionised its gas

- **PhD in Astrophysics from Kapteyn Astronomical Institute, University of Groningen, The Netherlands (2007-2011)**
  Thesis title: Cosmological Simulations of the first galaxies

- **Teaching Assistant at PIEAS, Islamabad, Pakistan (2003-2005)**