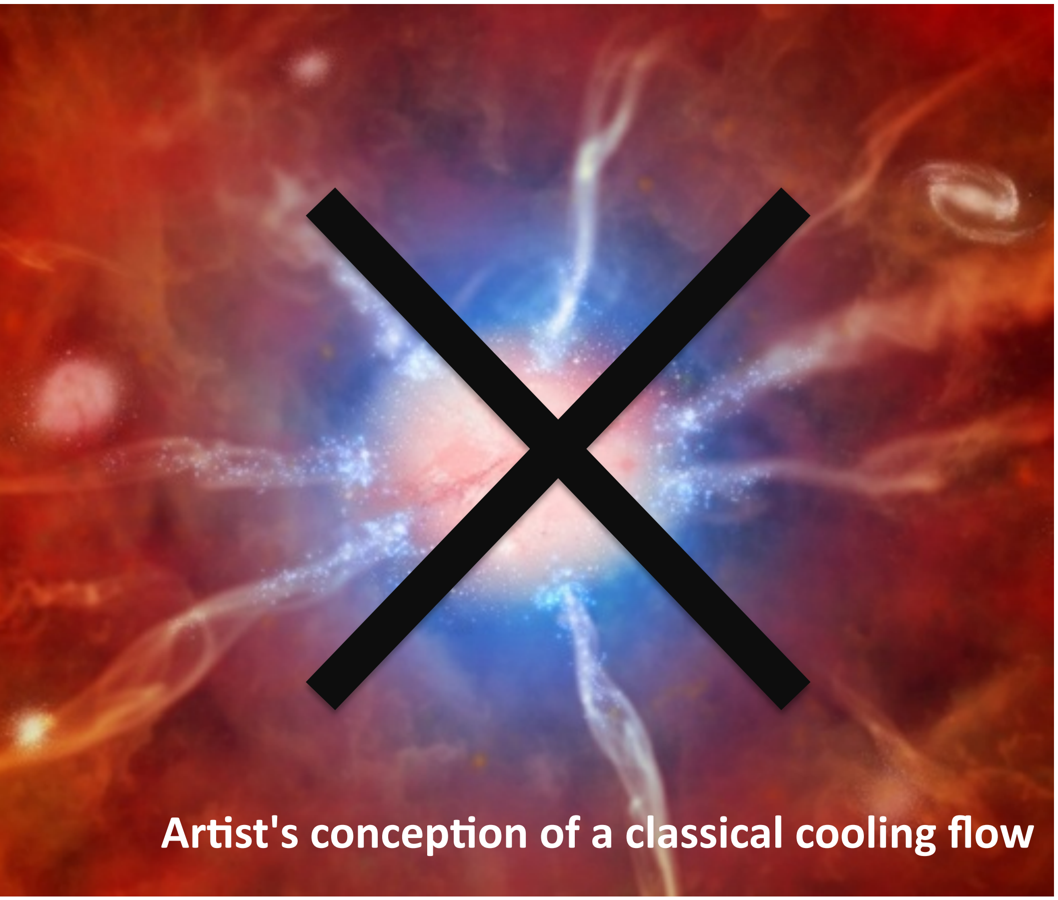
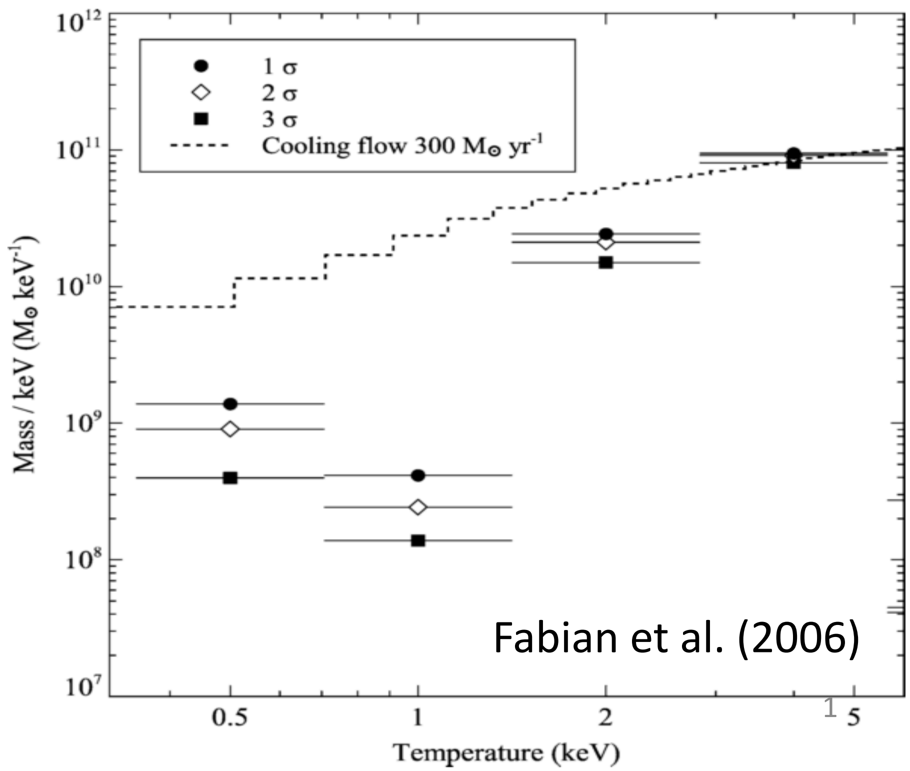
The Cooling Flow Problem



No Classical Cooling Flow!

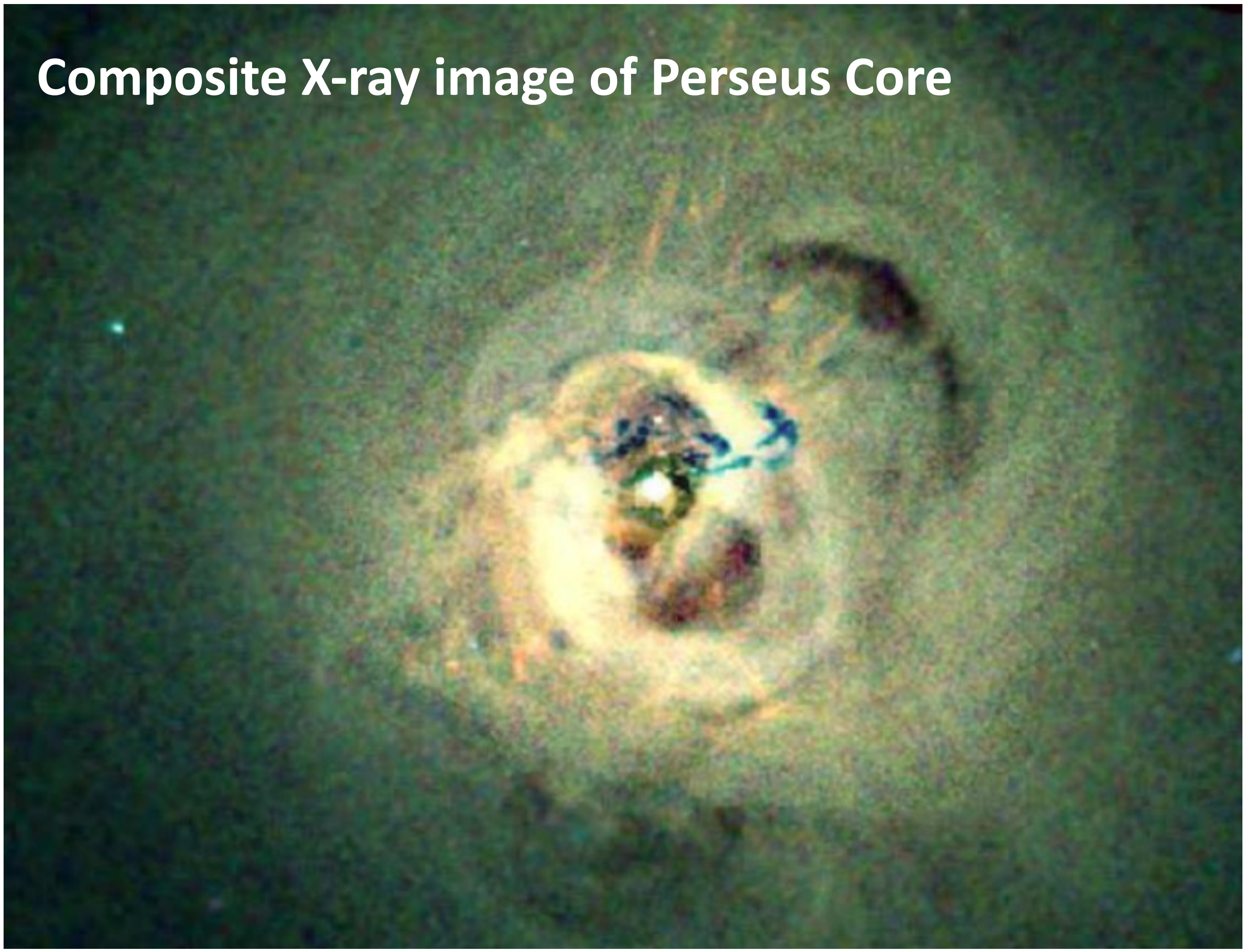
- **Observed SFR ~ 10 $M_\odot$/yr << 100s-1000 $M_\odot$/yr**
- **Lack of cool gas below 1-2 keV in the X-ray**



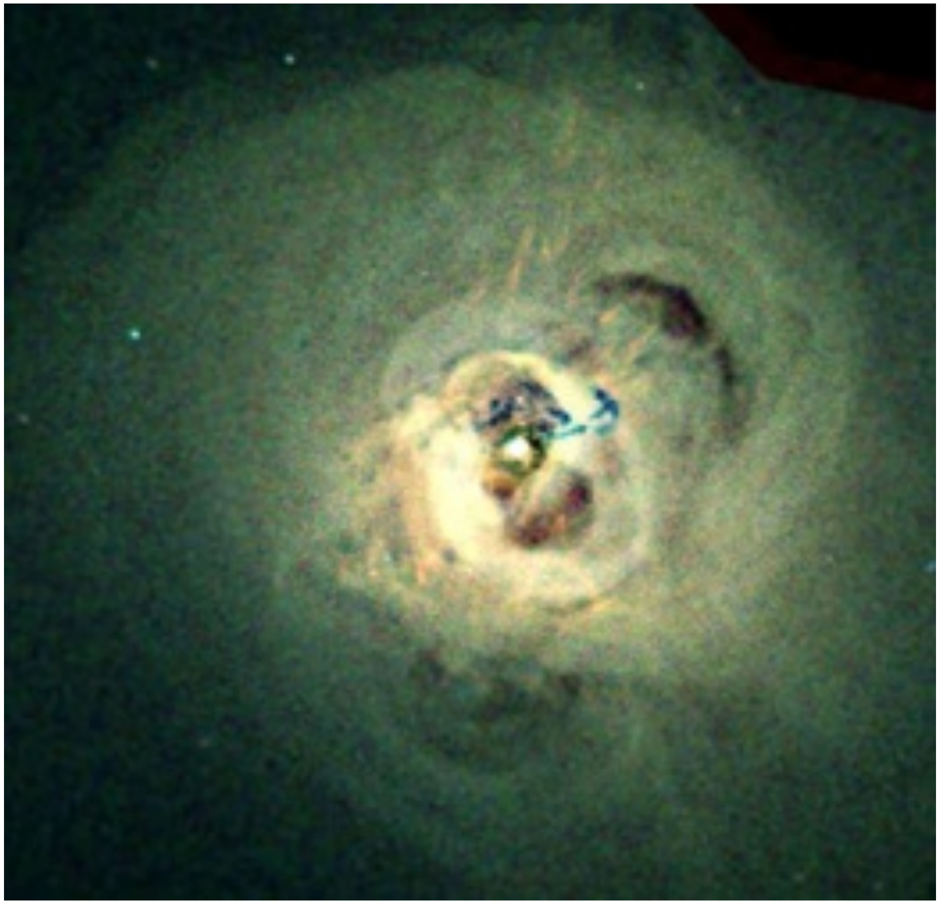
Yuan Li, University of Michigan

Can AGN Feedback Balance Cooling?

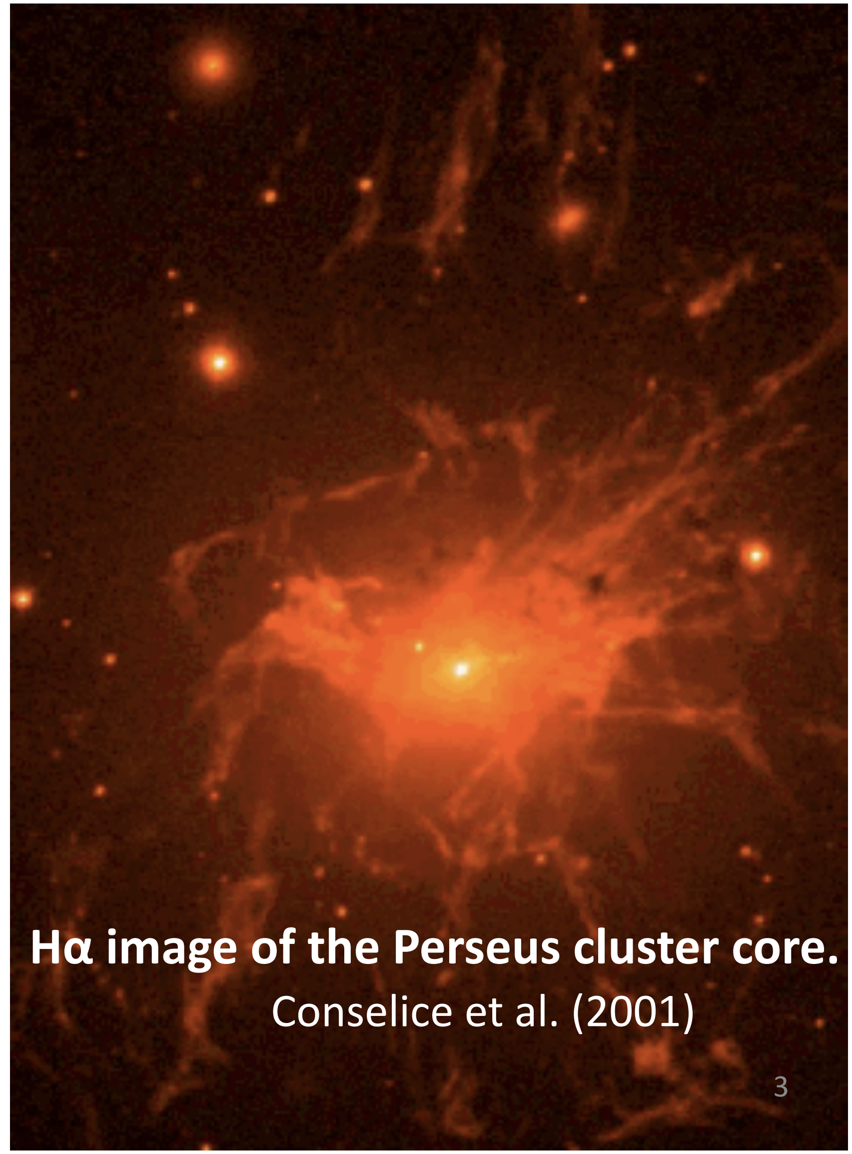
100 kpc



The Origin of the Cold Filaments



Composite X-ray image of Perseus Core
Fabian et al. (2006)



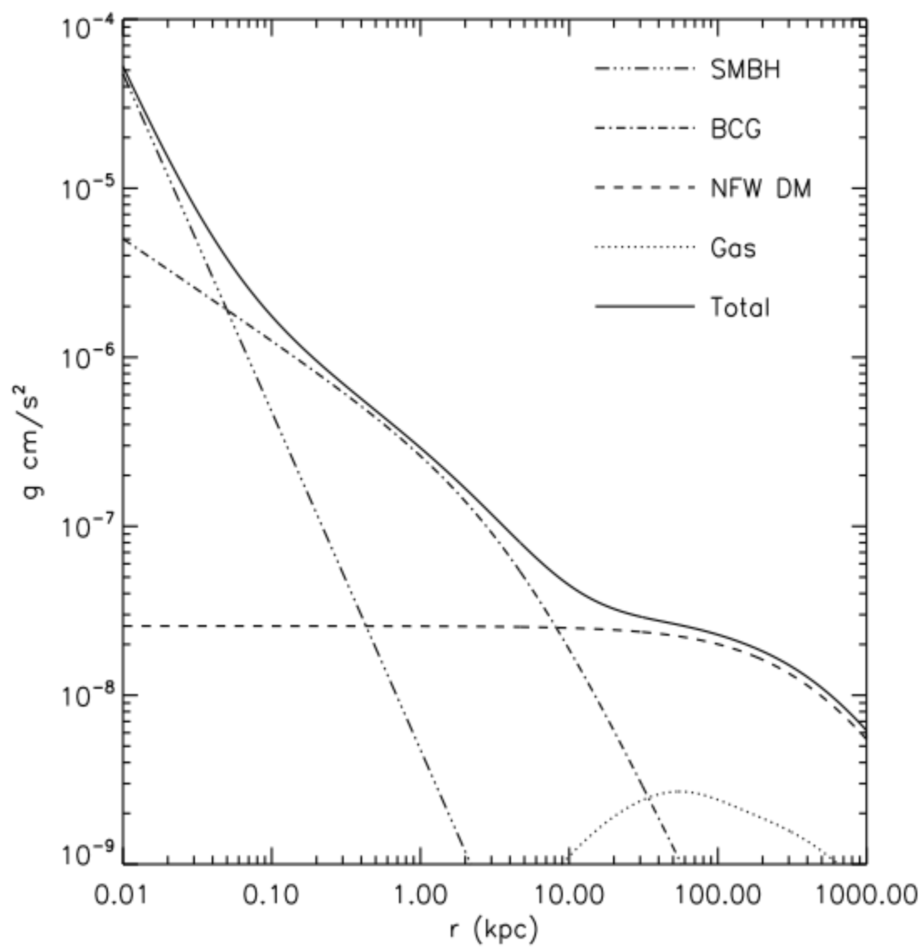
Hα image of the Perseus cluster core.
Conselice et al. (2001)

Key Questions

- **Can AGN feedback balance cooling?**

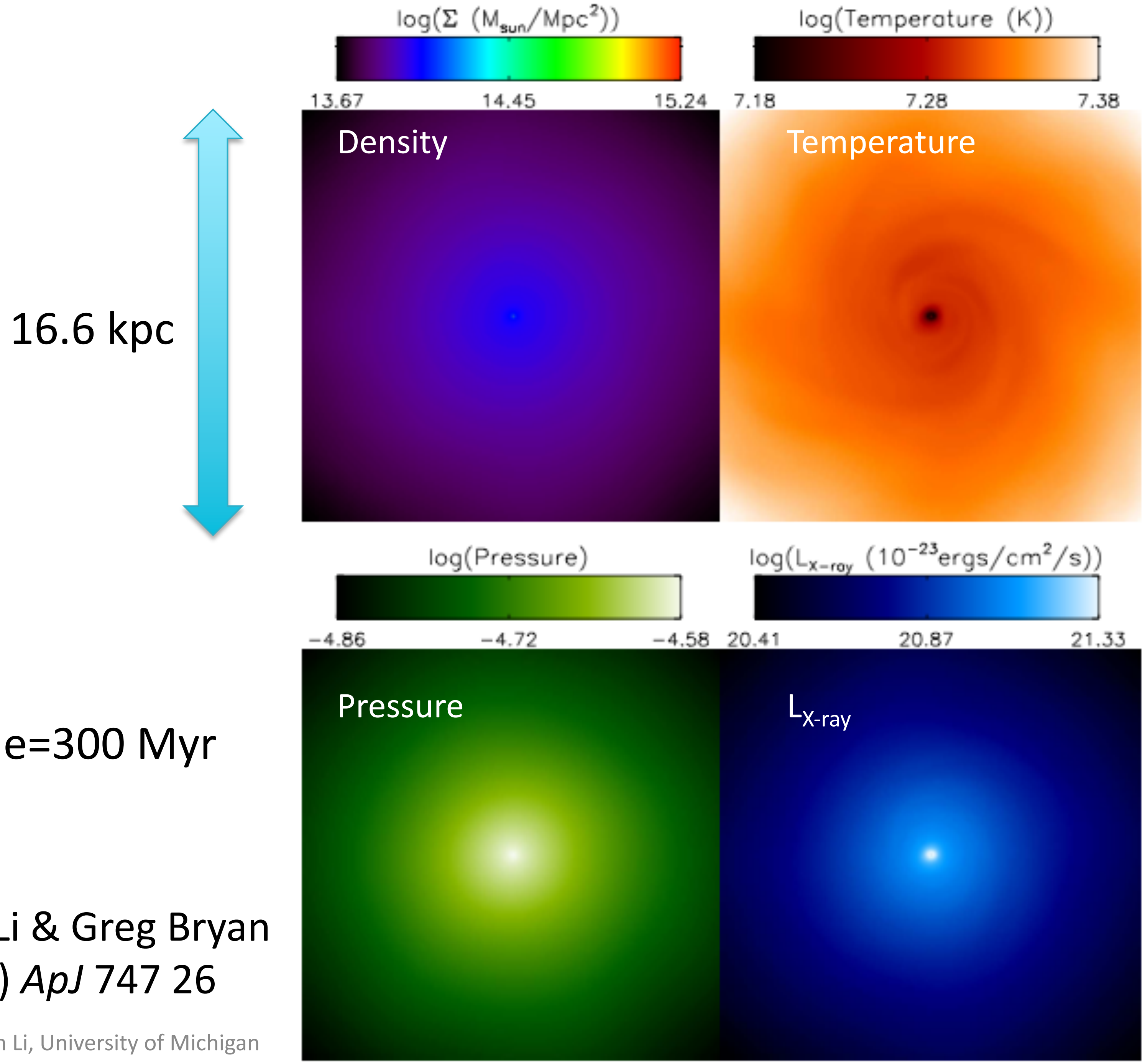
- **How does gas cool into filaments?**

Pure Cooling Flow Simulation



- Enzo (an AMR code)
- Box size **L = 16 Mpc/h**
- N_{root} = 256, l_{max} = 15
- → smallest cell ~ **2pc**.
- 3D, spherically symmetric
- Gravity: NFW Dark Matter + BCG + SMBH + gas
- Initial gas density and temperature: observations of the Perseus Cluster
- Initial pressure: Ideal Gas Law

10^6



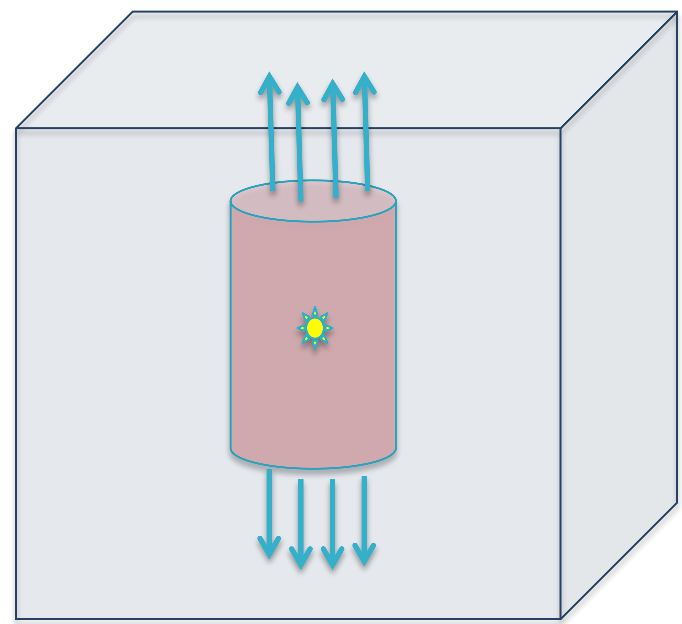
time=300 Myr

Yuan Li & Greg Bryan (2012) *ApJ* 747 26

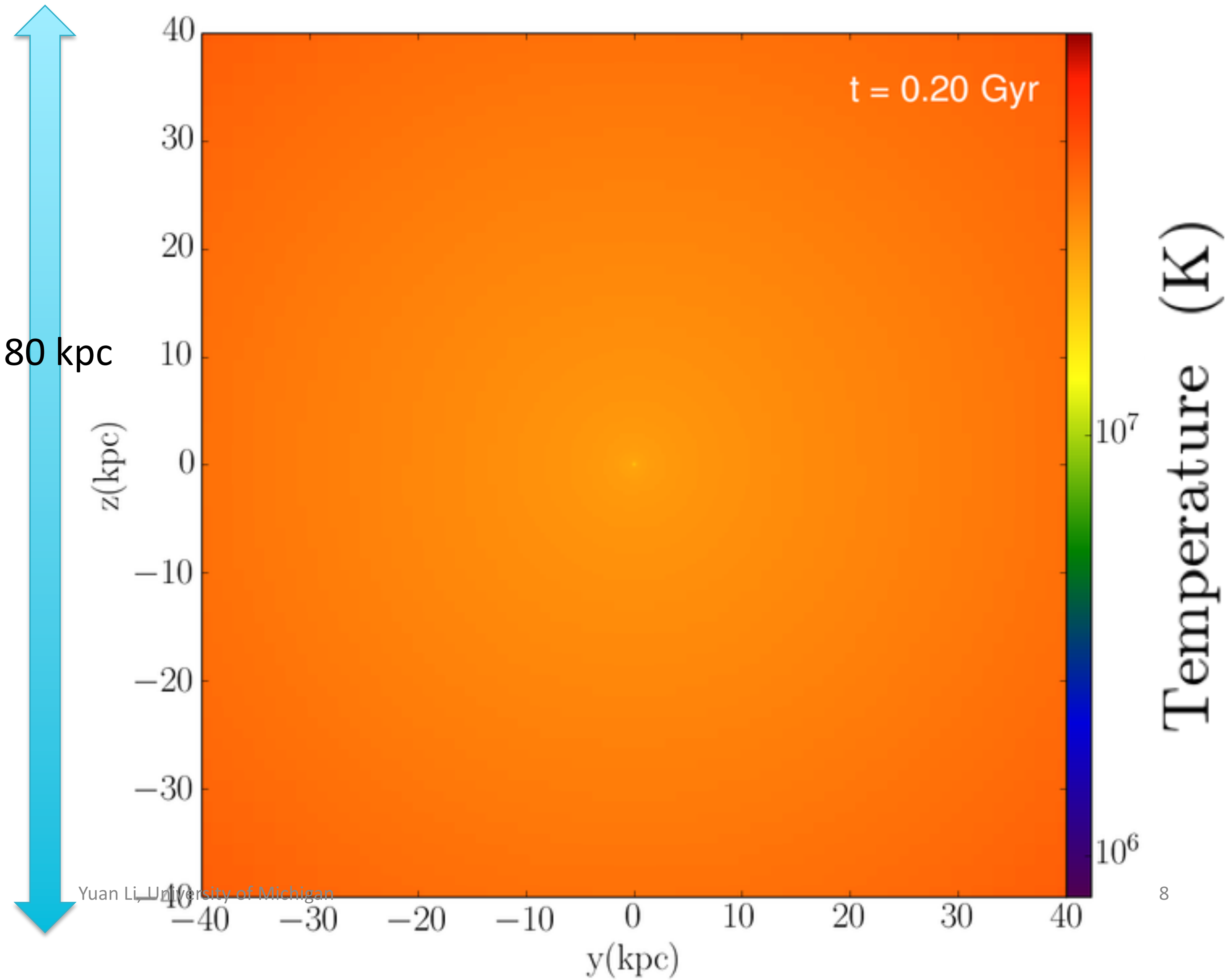
Jet Generation

- Add mass, momentum and energy to cells within the xy plane of the jet launching region (a cylinder with r = 100 pc and h = 300 pc) following Omma et al. (2004)
- Outflow rate (dM/dt) = accretion rate ($M_{cold}/t_{accretion}$)

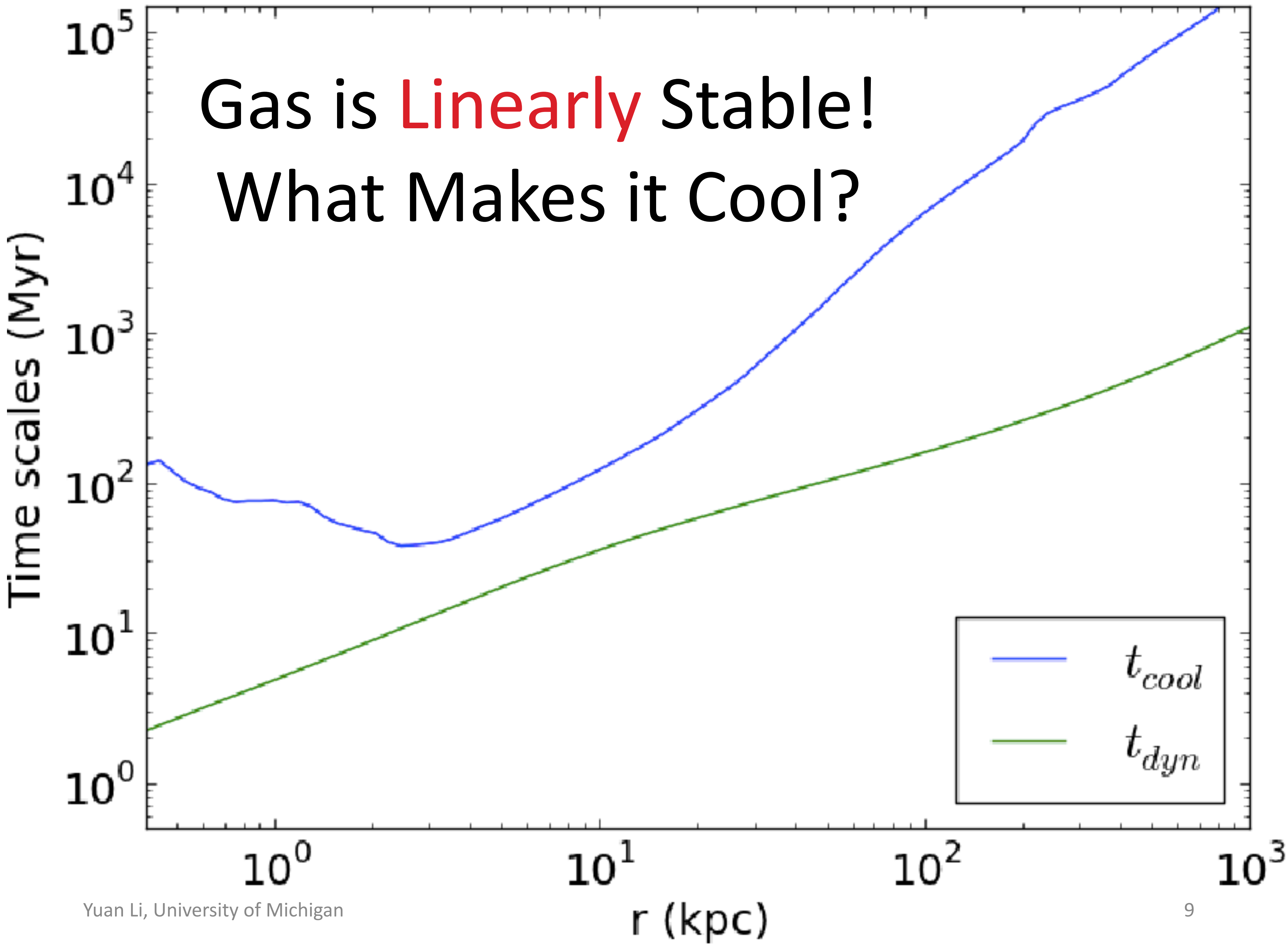
  Jet power dE/dt = $\varepsilon \times dM/dt \times c^2$
- Kinetic fraction: f = 0.5
- $V_{jet} \approx 10000$ km/s (ε=0.001)
- Precessing jets: P = 10 Myr
- $l_{max} = 12 \rightarrow$ smallest cell size ~ 15pc

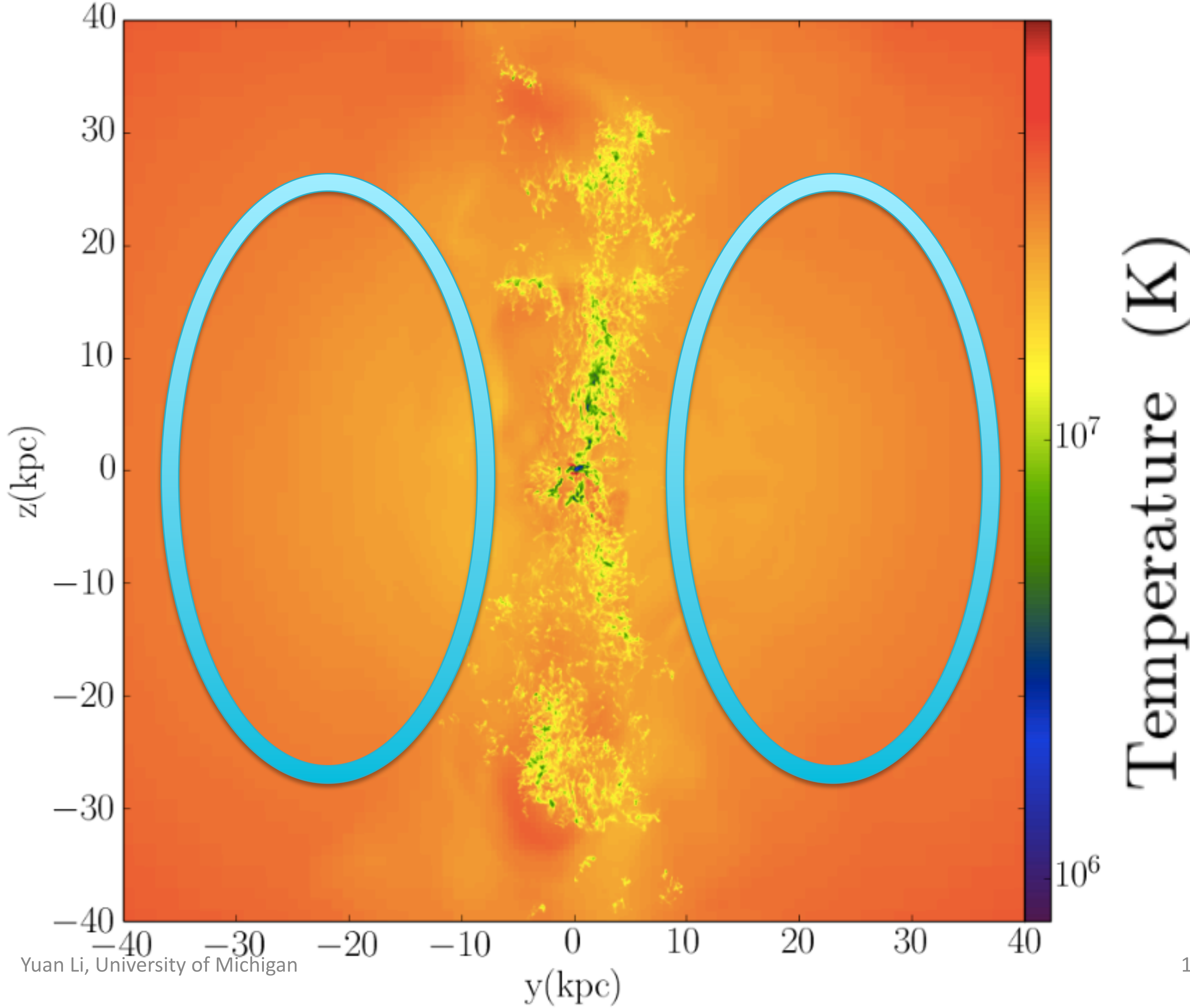


Li & Bryan (2014) *ApJ* 798 54 & 798 153


80 kpc
t = 0.20 Gyr
z(kpc)
y(kpc)
Temperature (K)
10^7
10^6
40
30
20
10
0
−10
−20
−30
−40

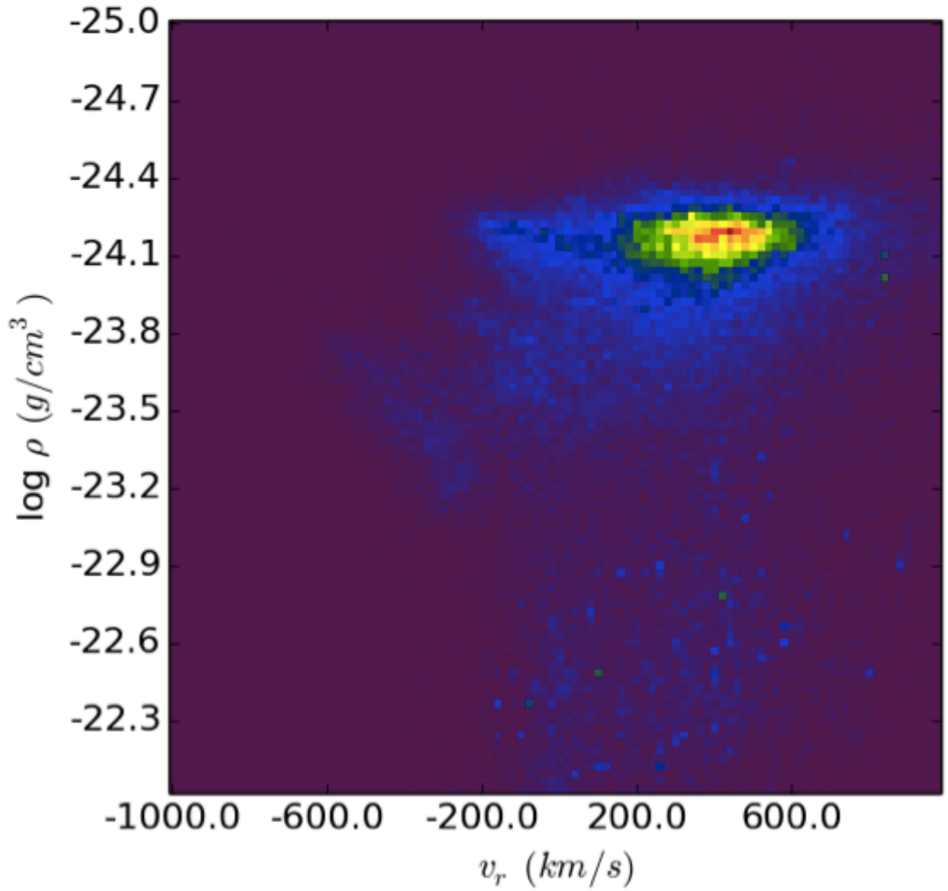
Gas is Linearly Stable! What Makes it Cool?



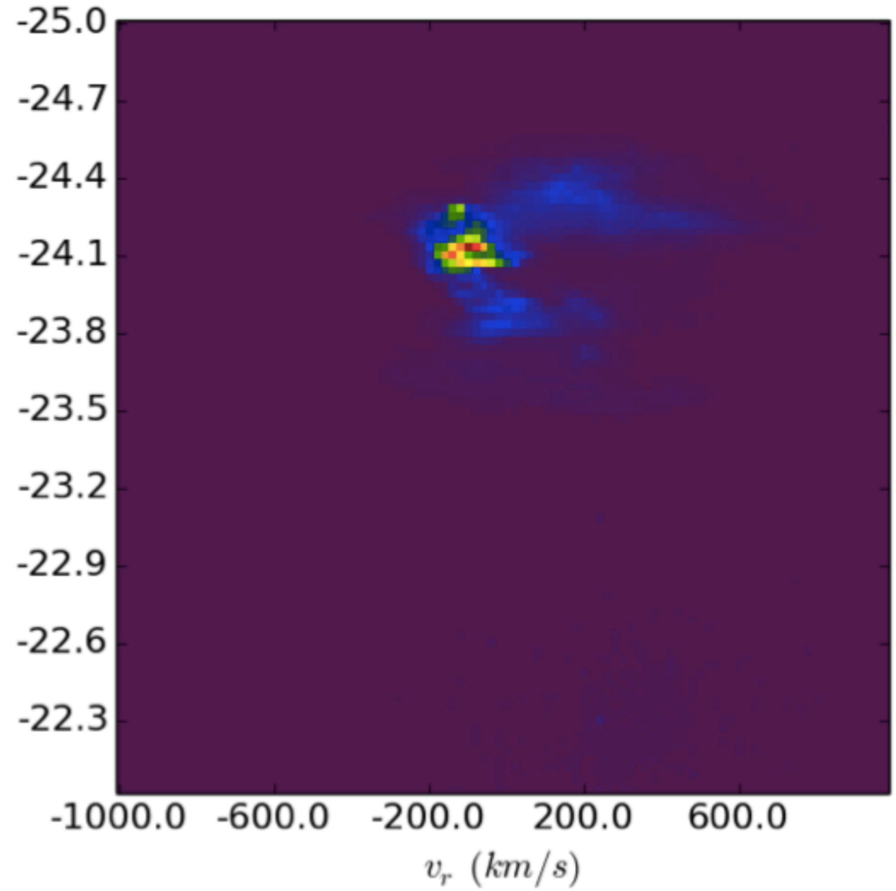

z(kpc)
y(kpc)
Temperature (K)
10^7
10^6
40
30
20
10
0
−10
−20
−30
−40

What is Special about the Gas that Cools into Clumps?

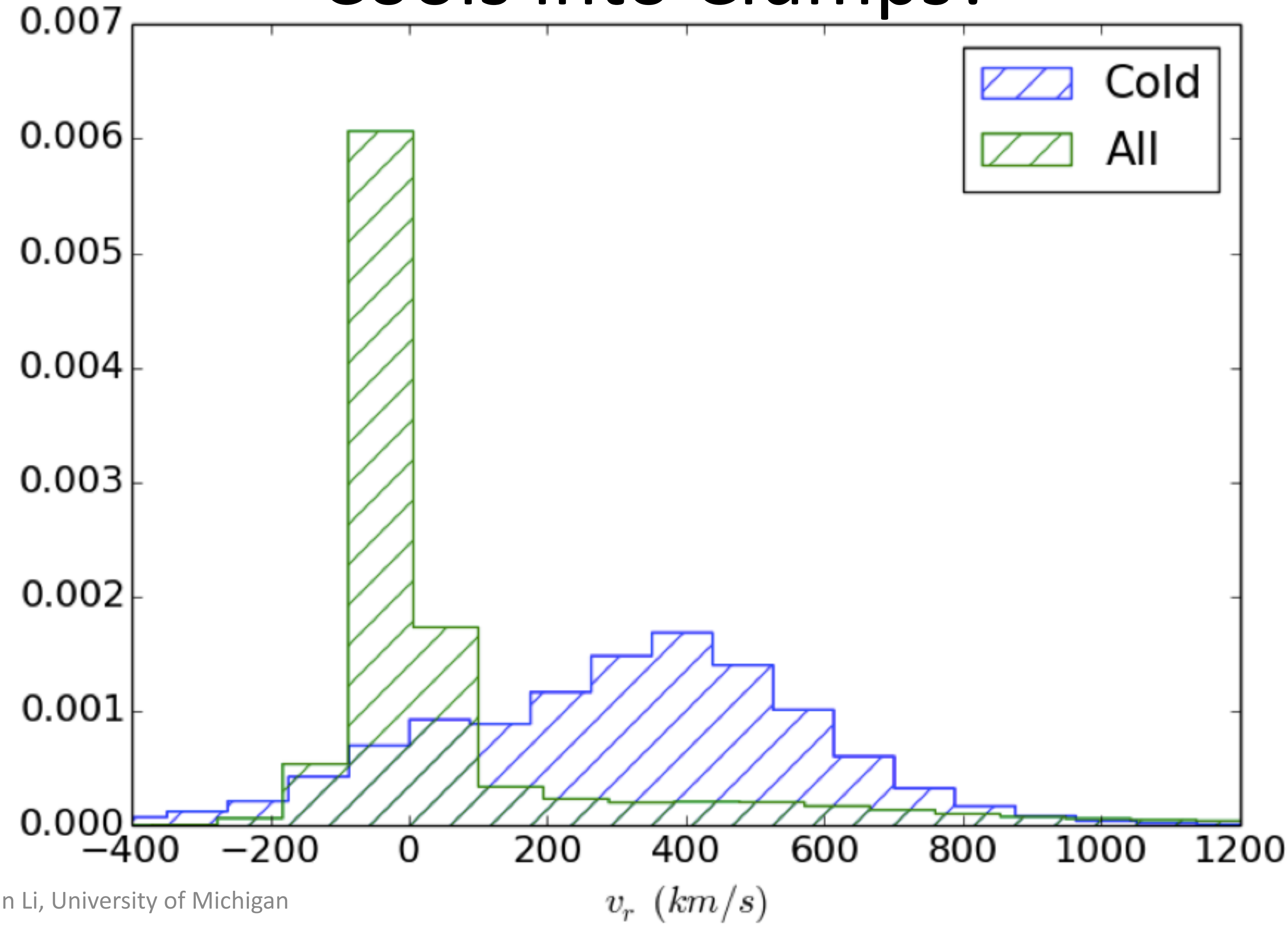
The "Cool Sample"



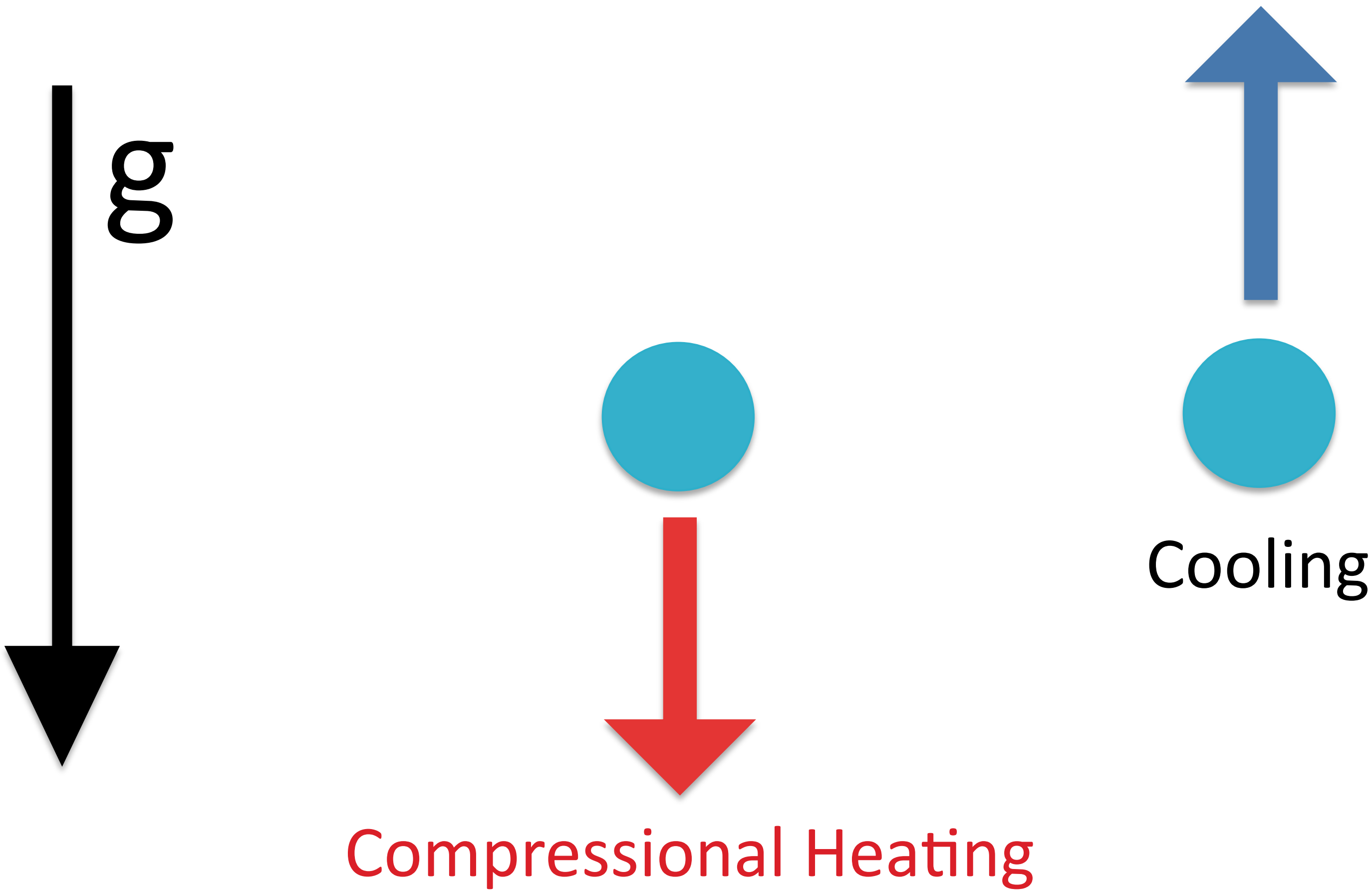
The Whole Sample

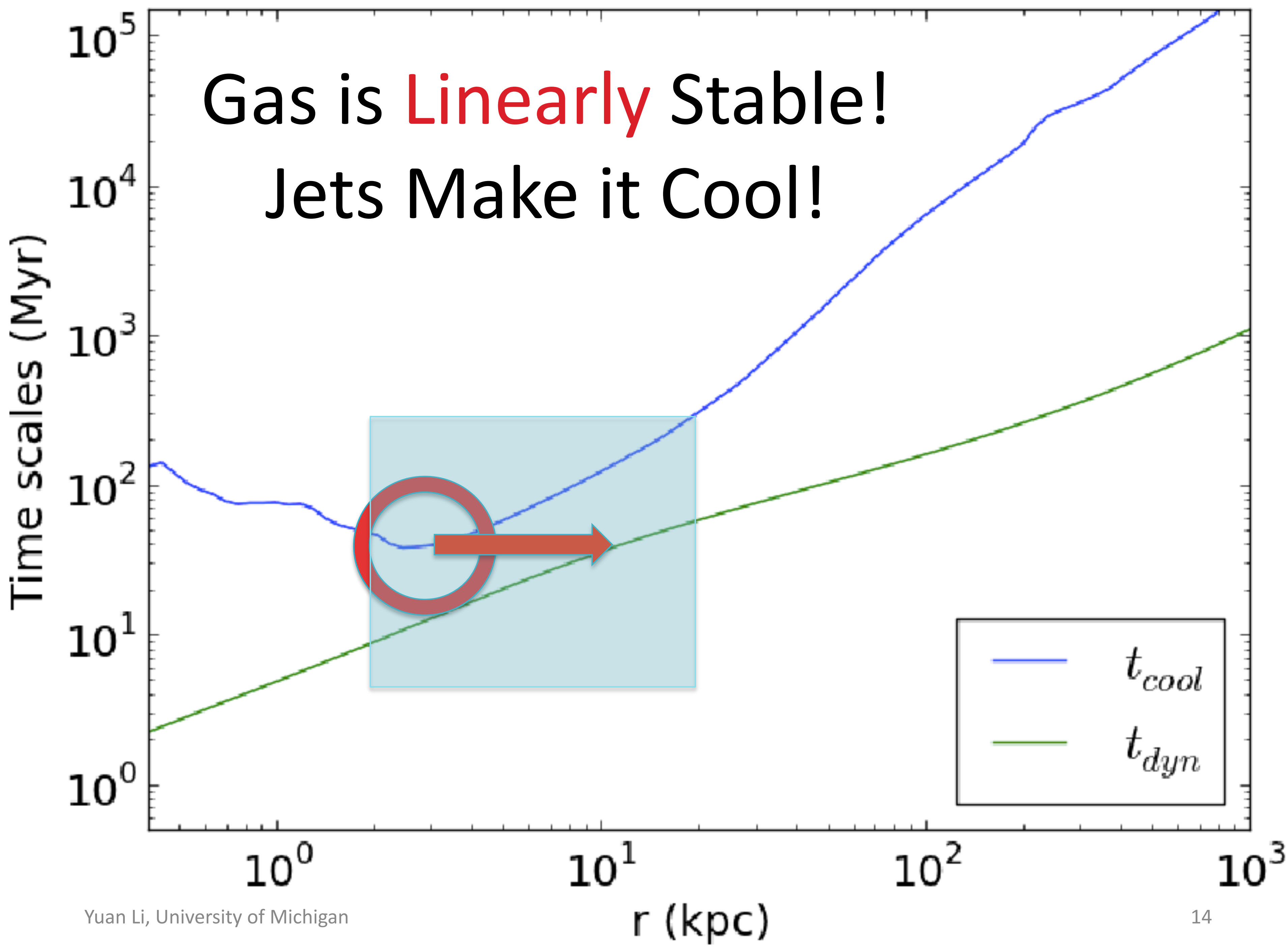


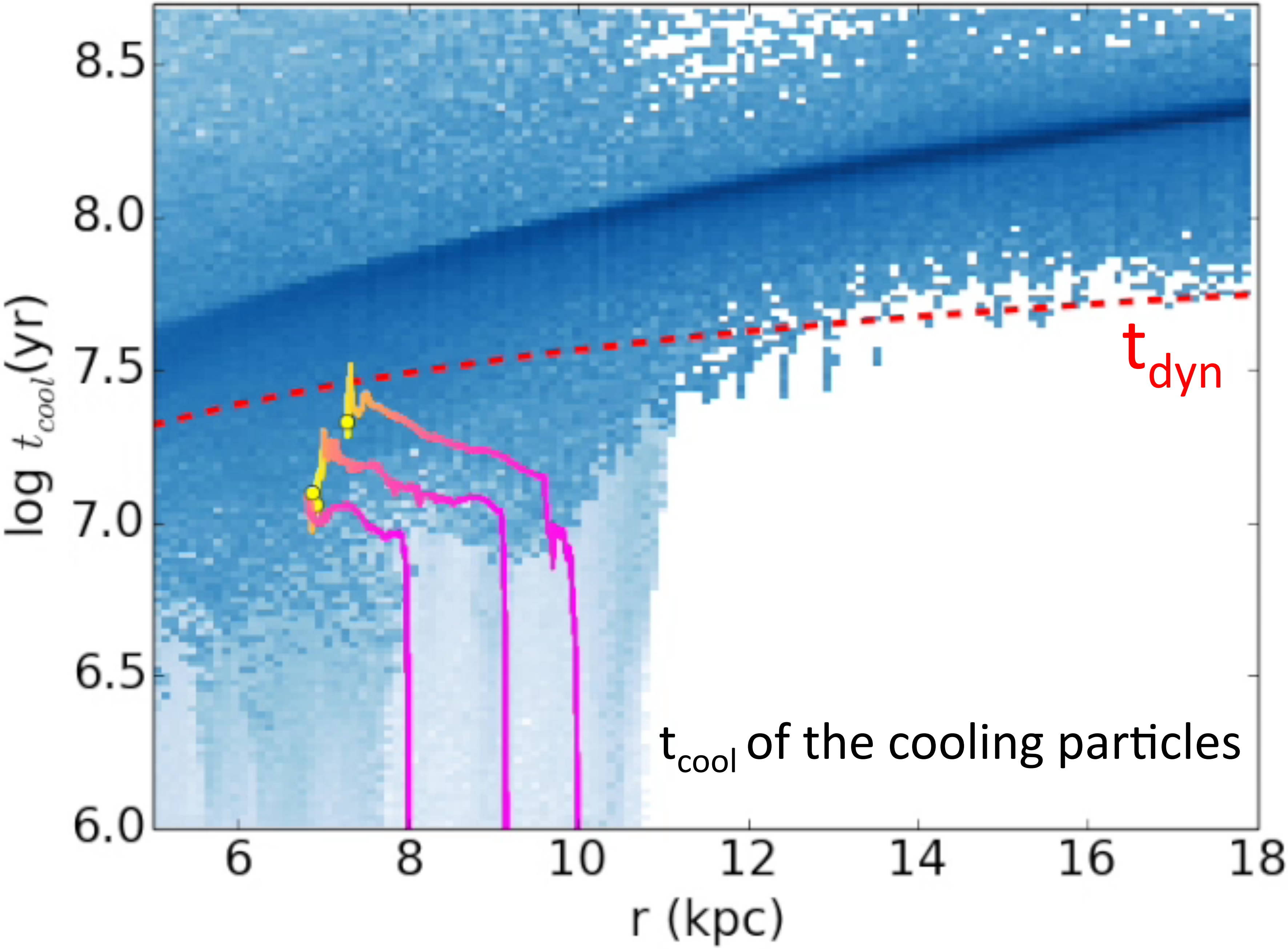
What is Special about the Gas that Cools into Clumps?



In a gravitationally-stratified medium




Gas is Linearly Stable!
Jets Make it Cool!
Time scales (Myr)
r (kpc)
t_{cool}
t_{dyn}



8.5
8.0
7.5
7.0
6.5
6.0
log t_{cool}(yr)
6
8
10
12
14
16
18
r (kpc)
t_{dyn}
t_{cool} of the cooling particles

The Origin of the Filaments

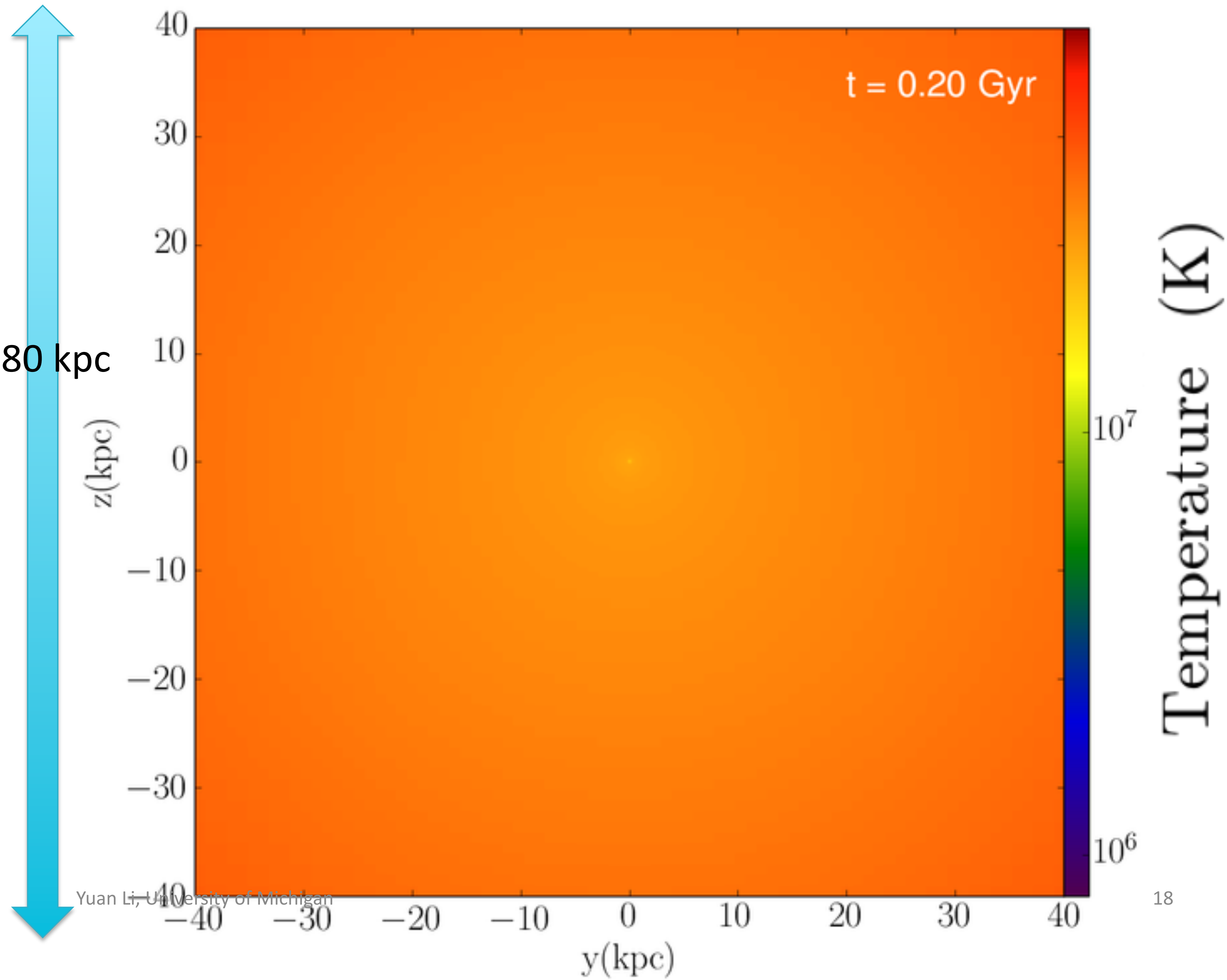
- Cooling => low entropy gas with short cooling time (but still linearly stable!)

+

- AGN jets (non-linear perturbation)

Key Questions

- **Can AGN feedback balance cooling?**
- **How does gas cool into filaments?**


80 kpc
t = 0.20 Gyr
z(kpc)
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10^7
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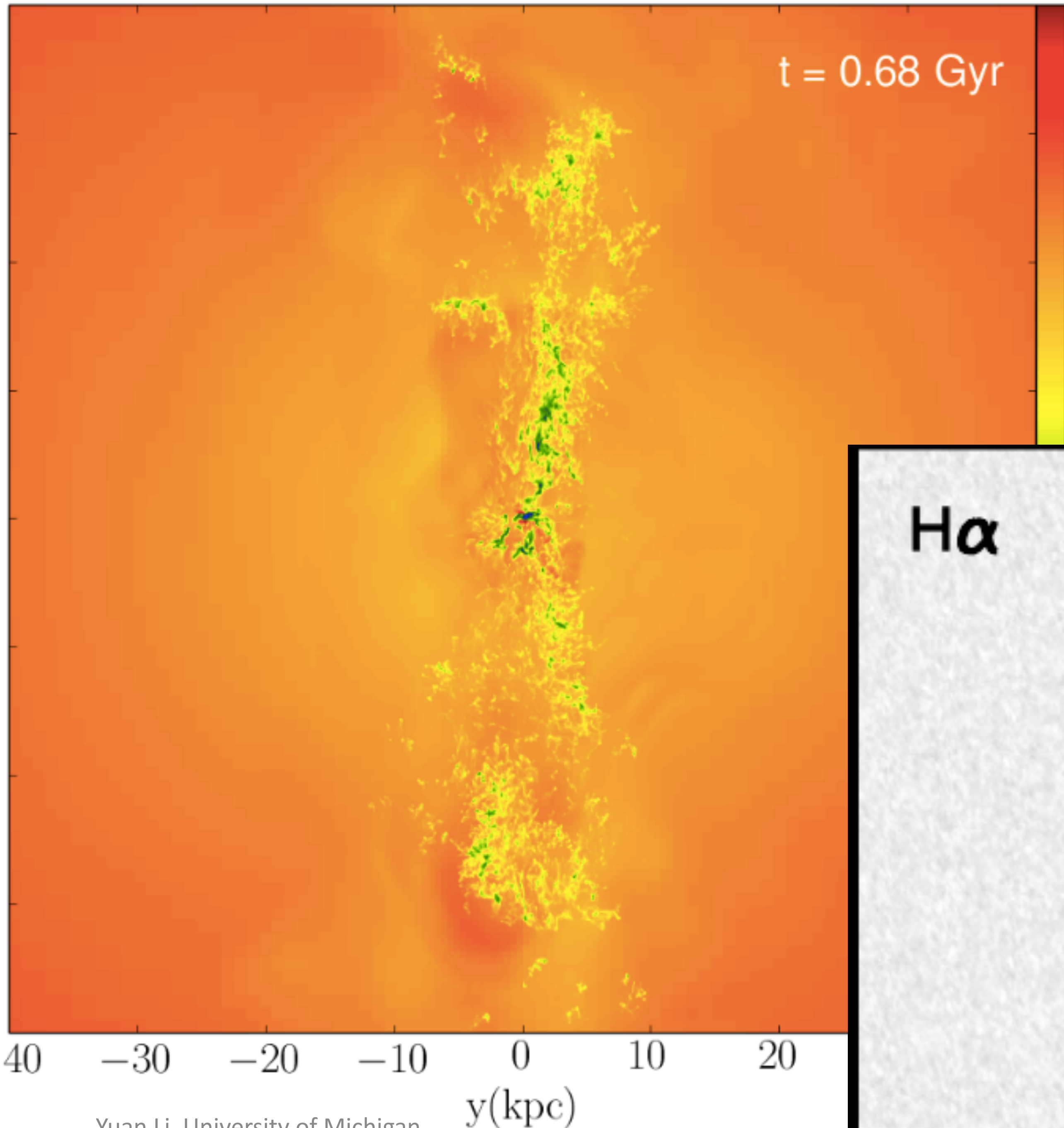

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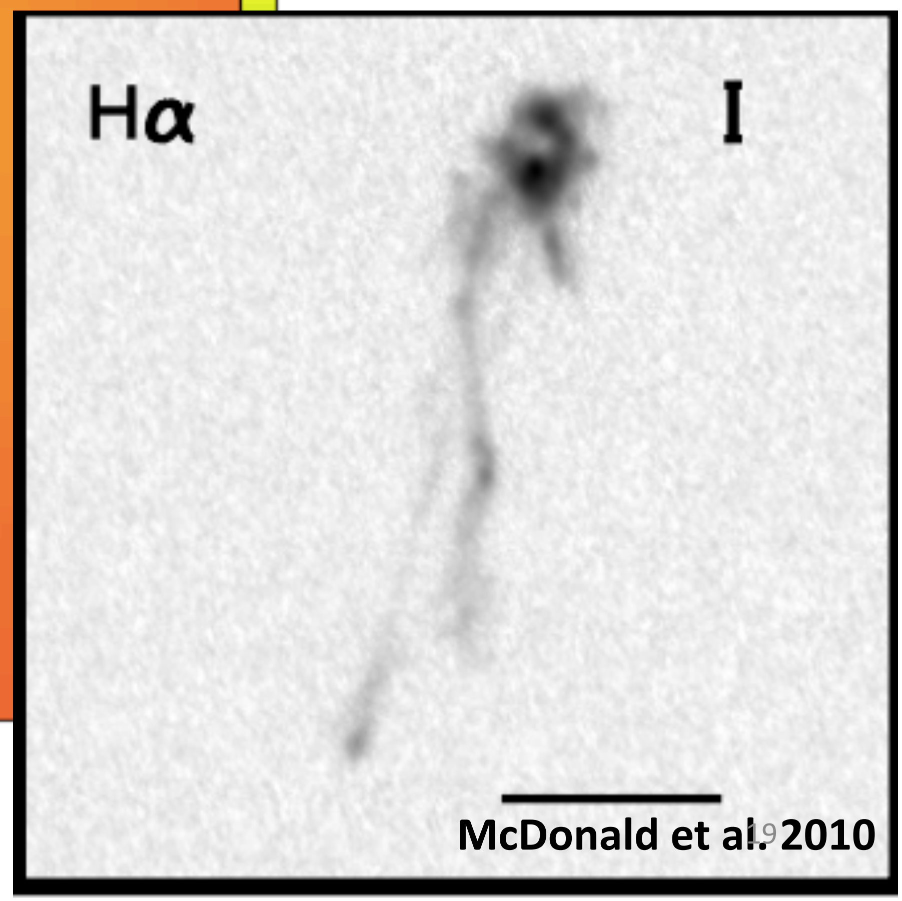
Filamentary Gas

Turbulence: low
Jet Power: low

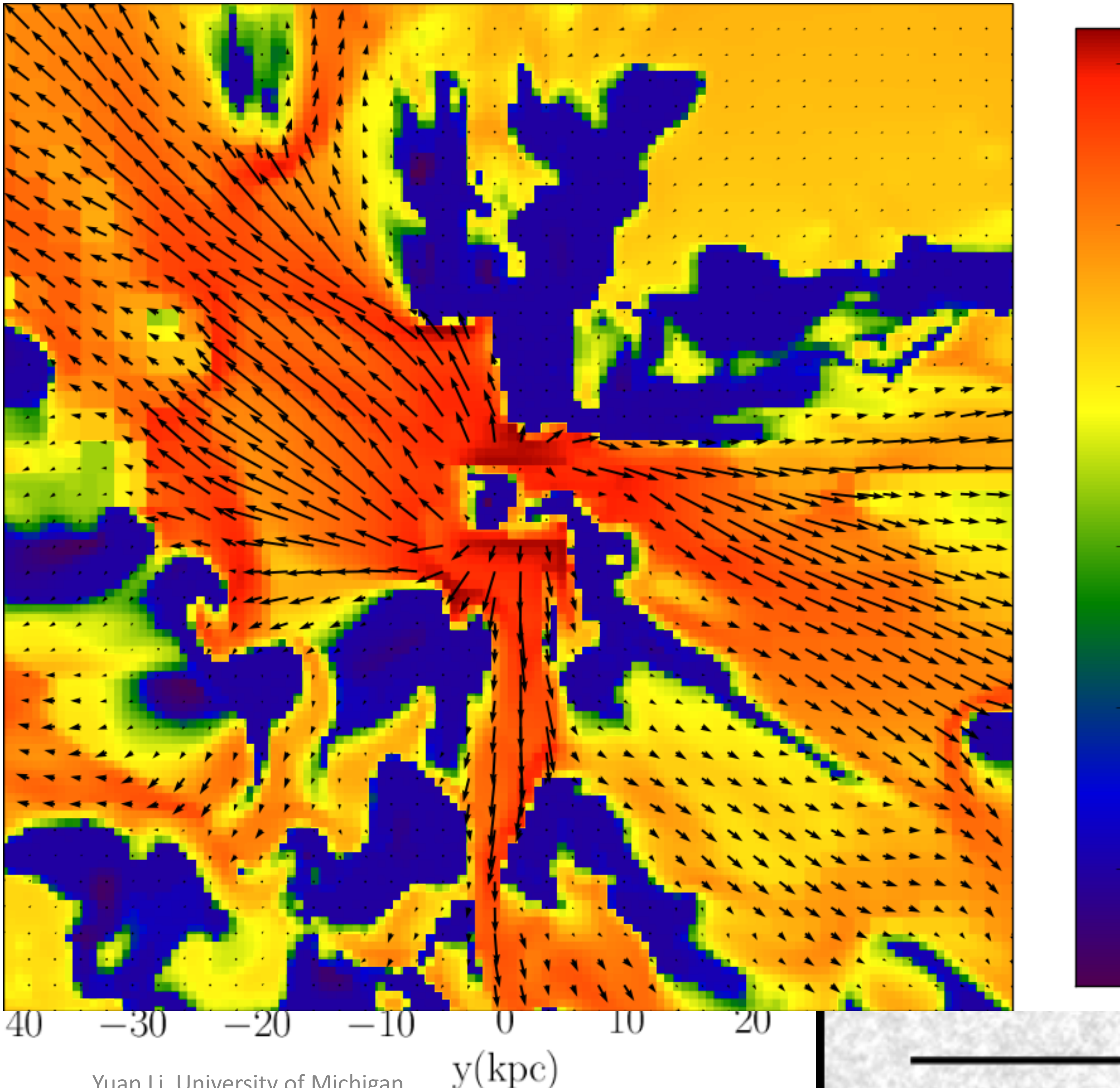


McDonald et al. 2010

l Cold Gas

ce: high

r: high



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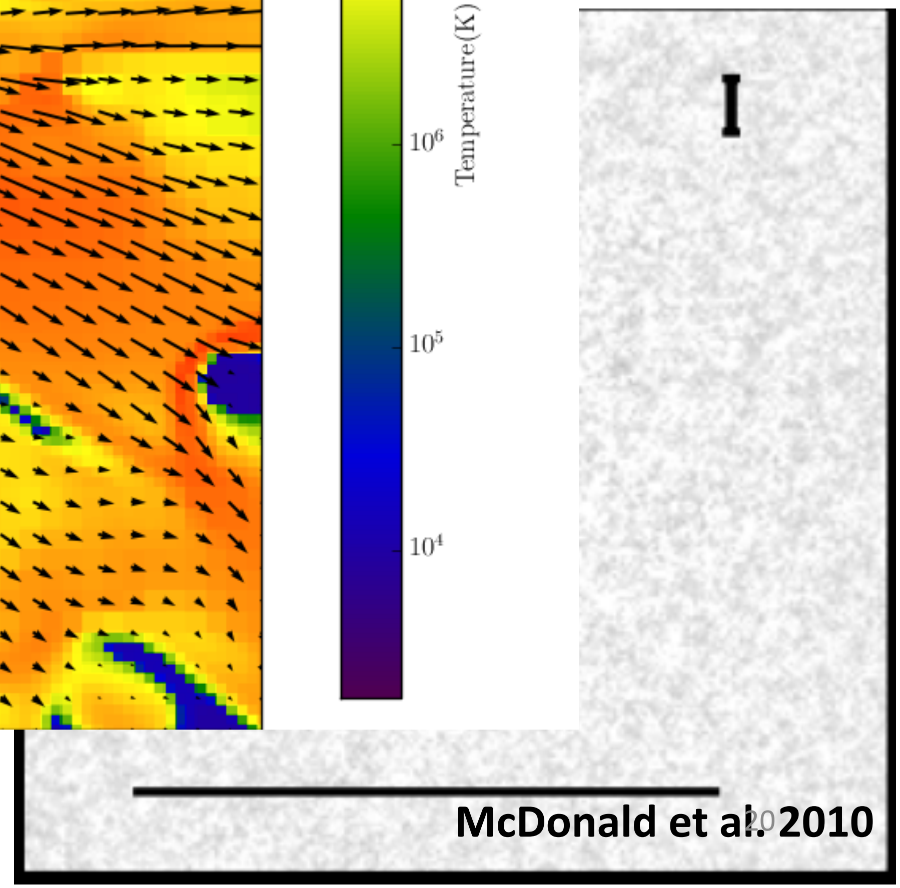
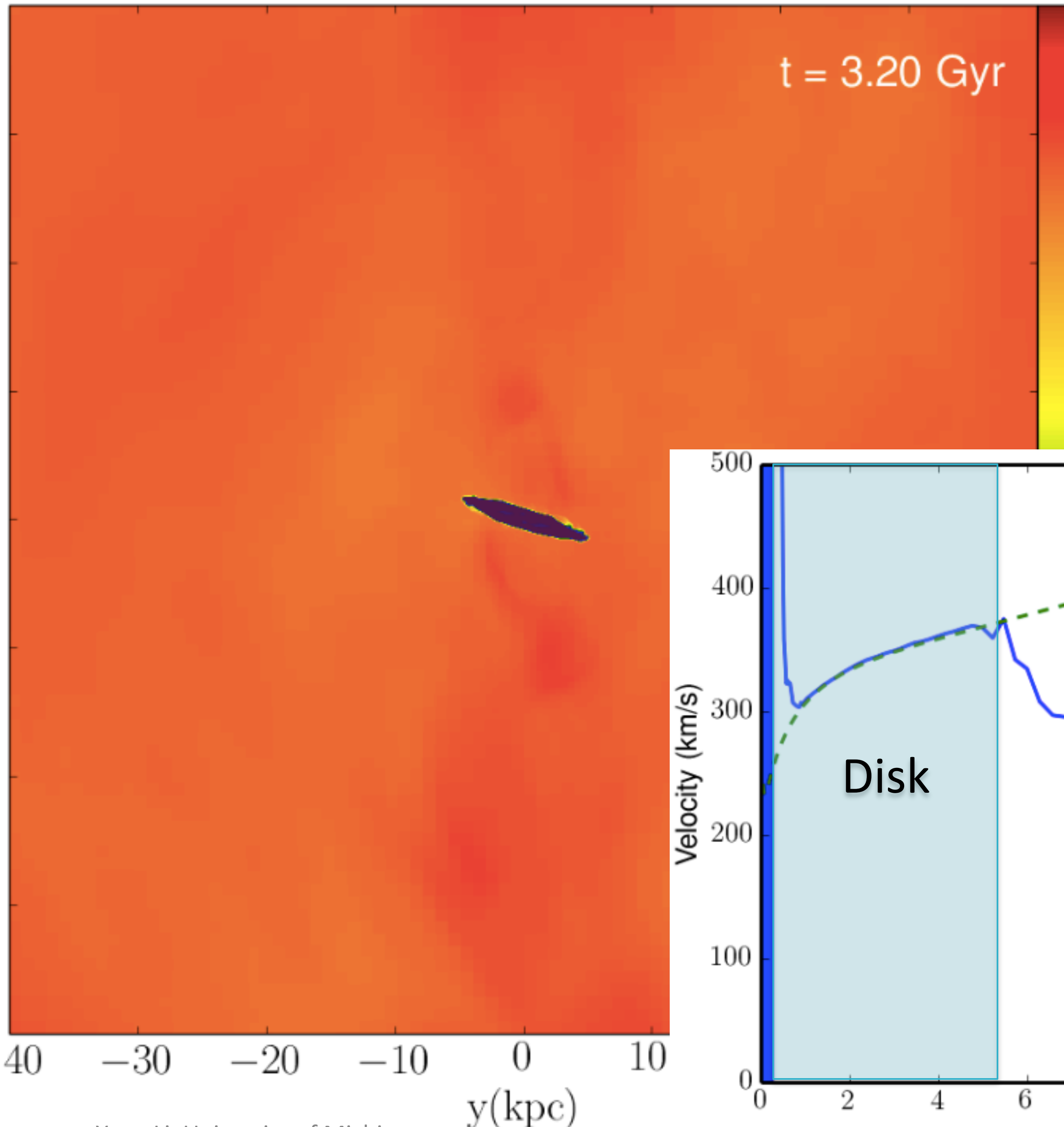
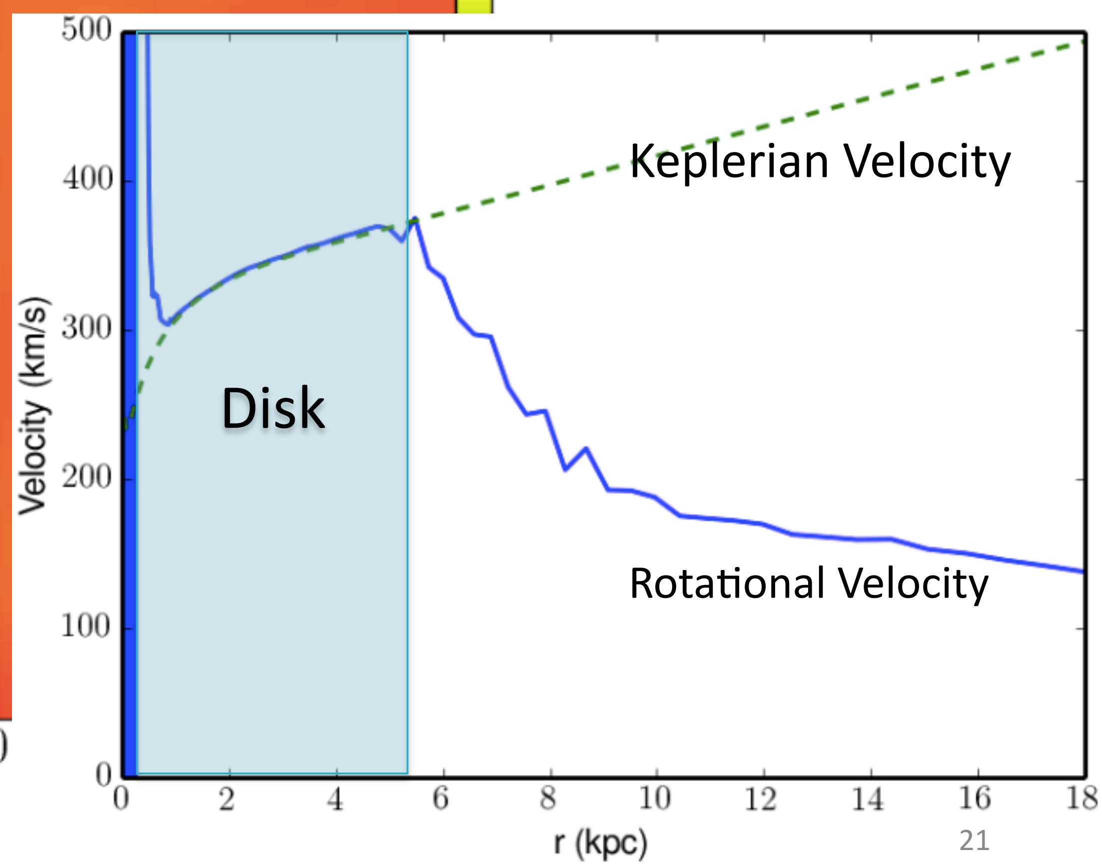


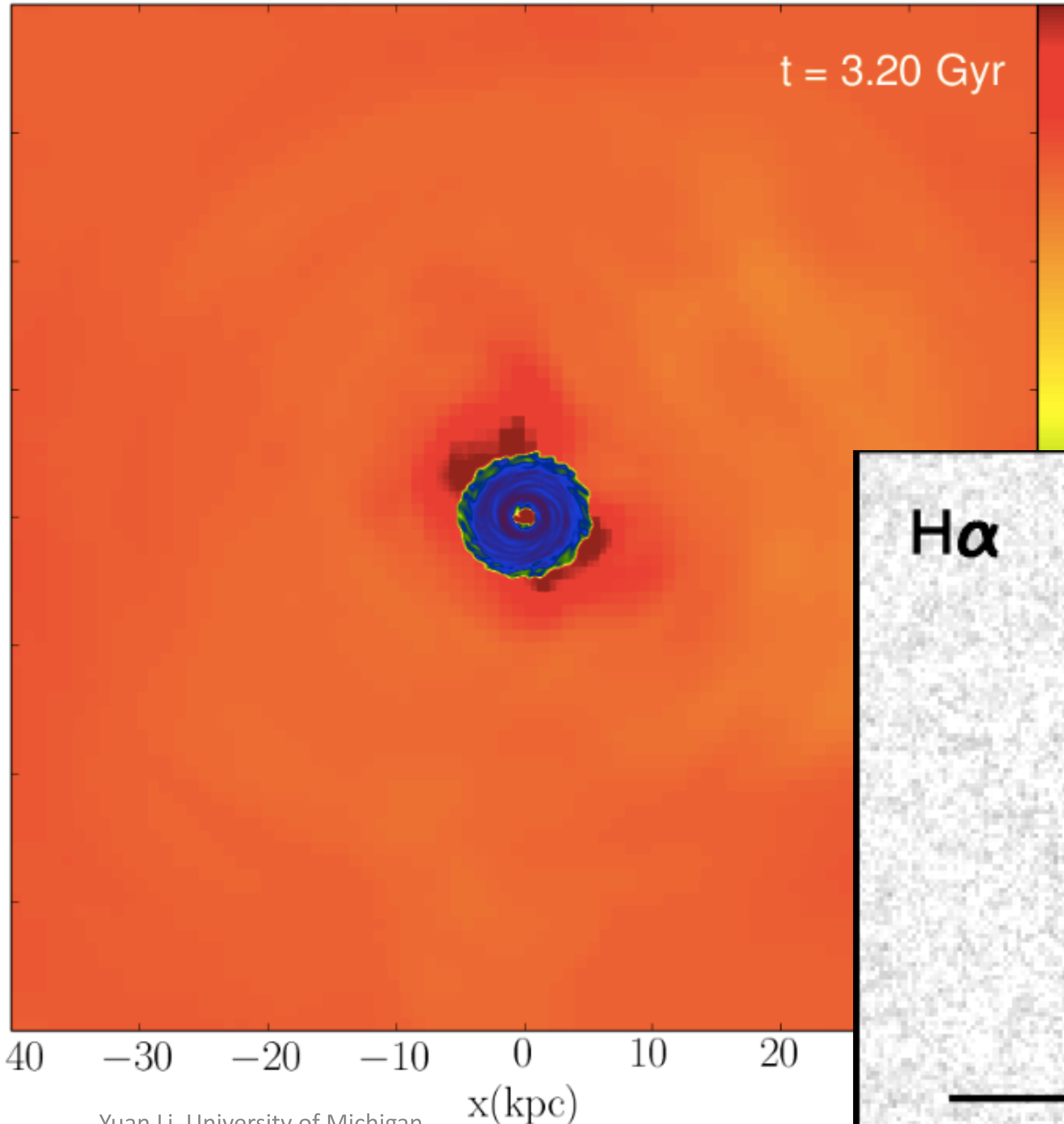
McDonald et al. 2010

Rotating Disk

Turbulence: high
Jet Power: Steady



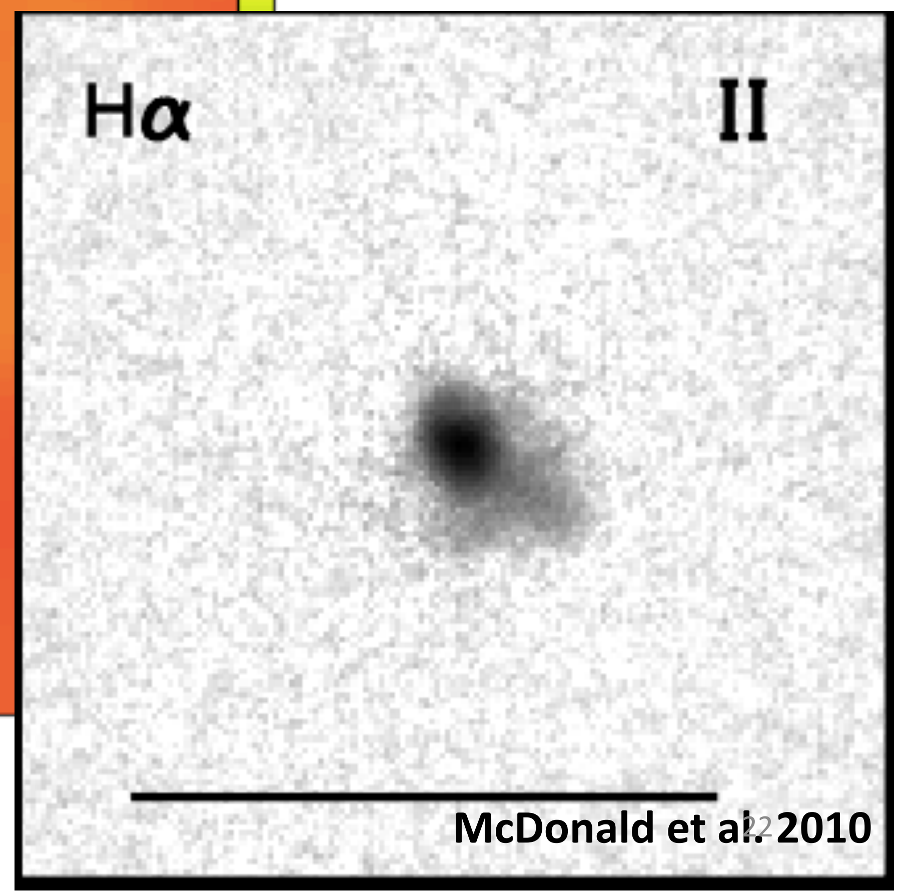




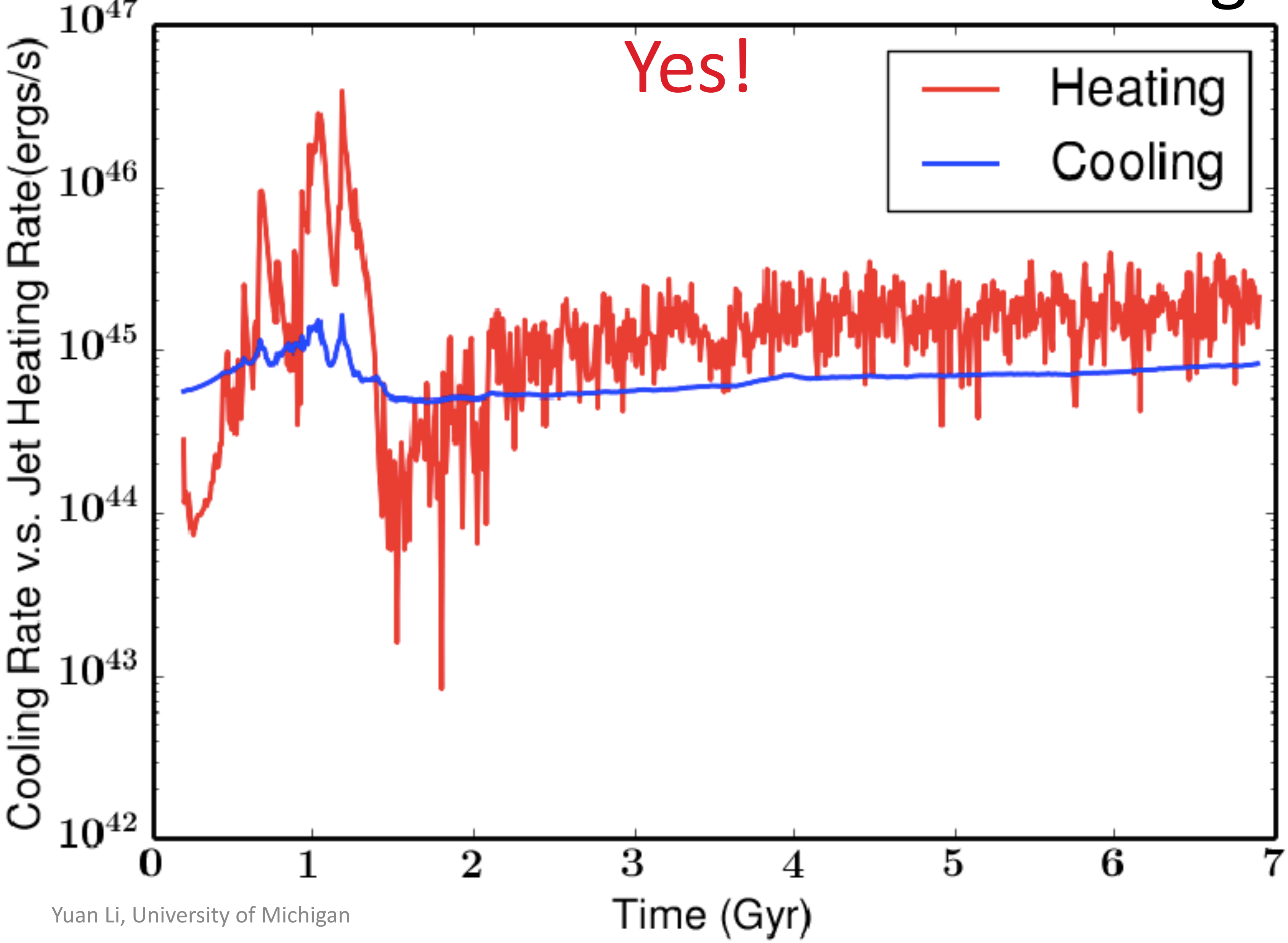
Rotating Disk

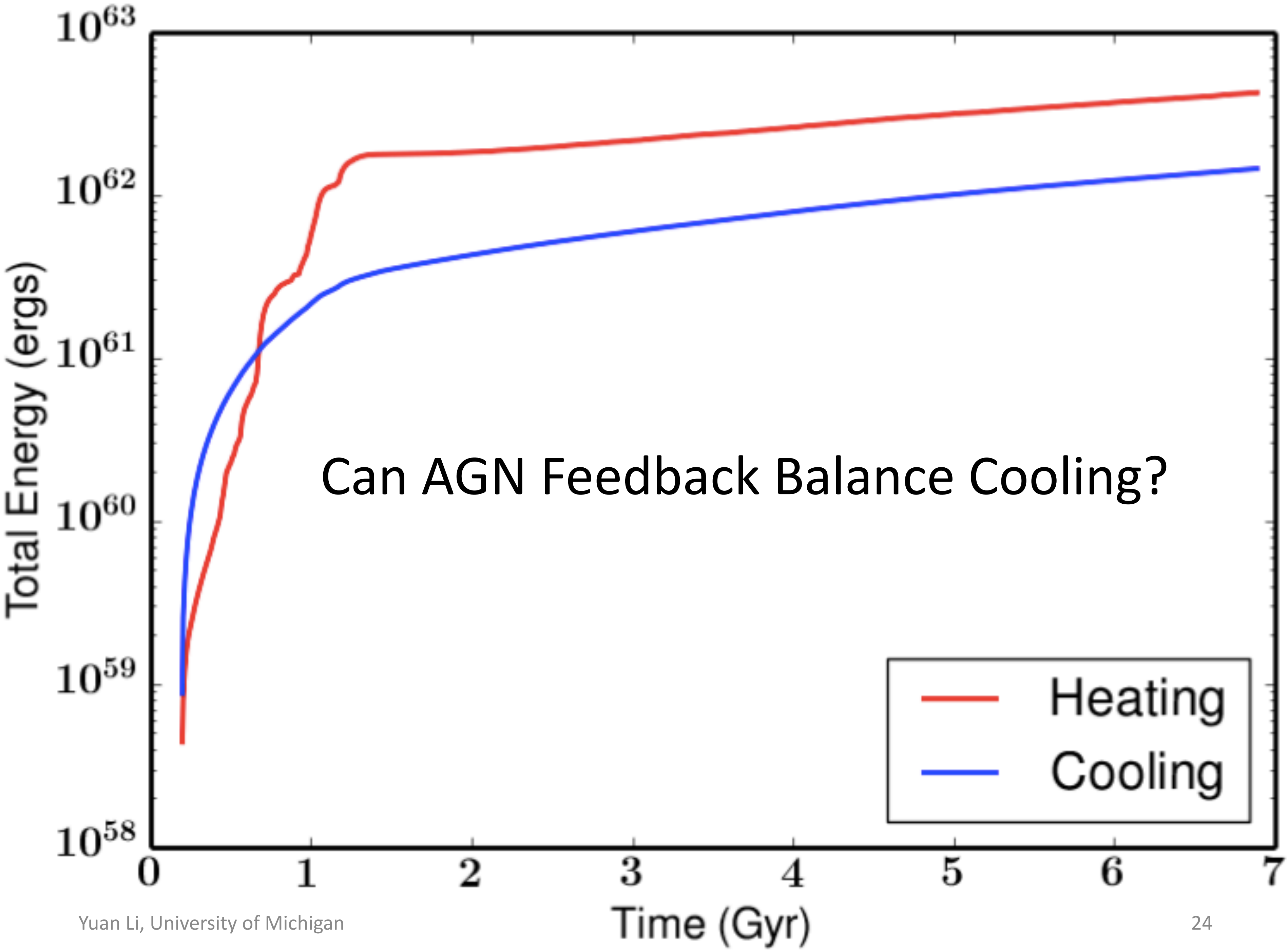
Turbulence: high

Jet Power: Steady



Can AGN Feedback Balance Cooling?





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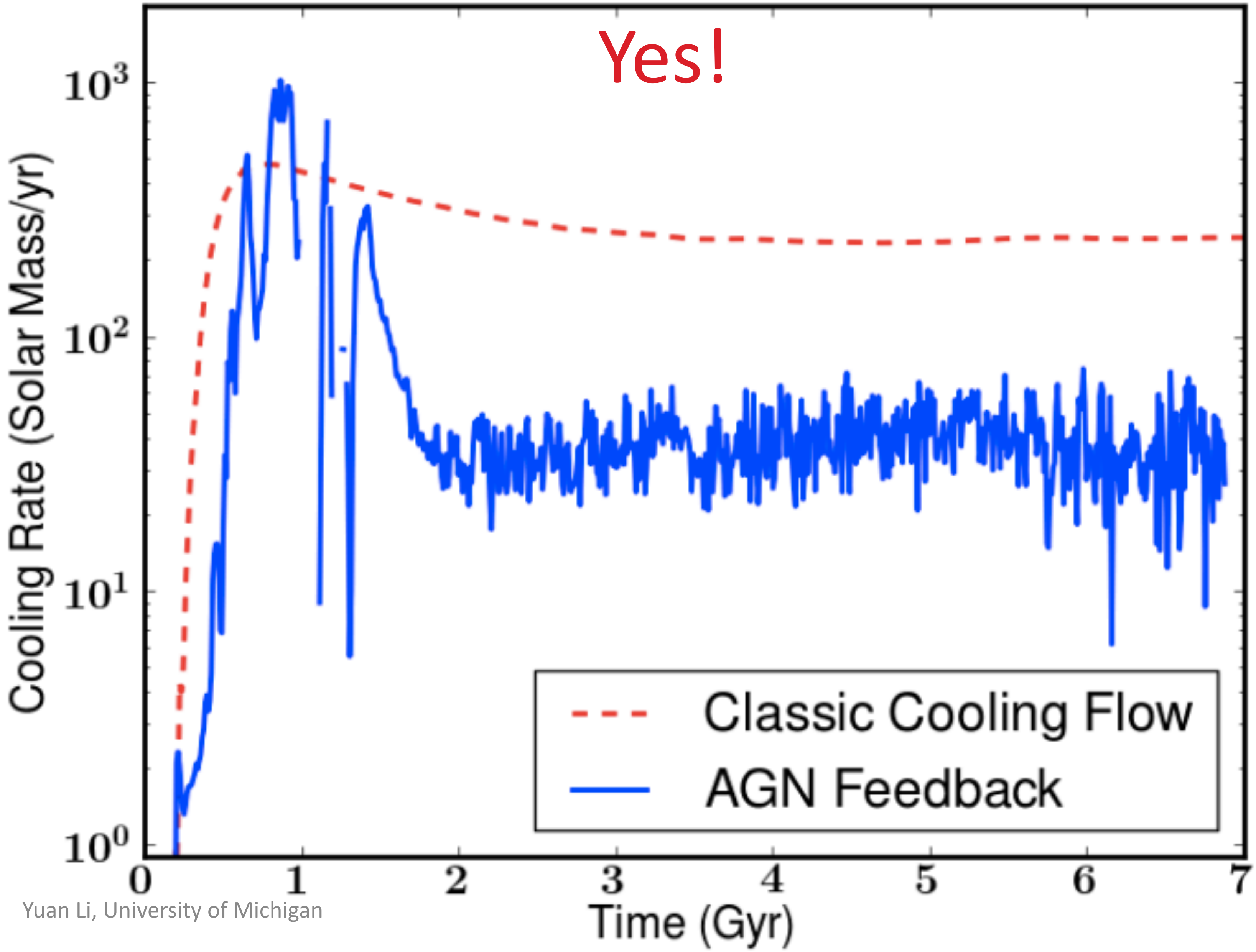
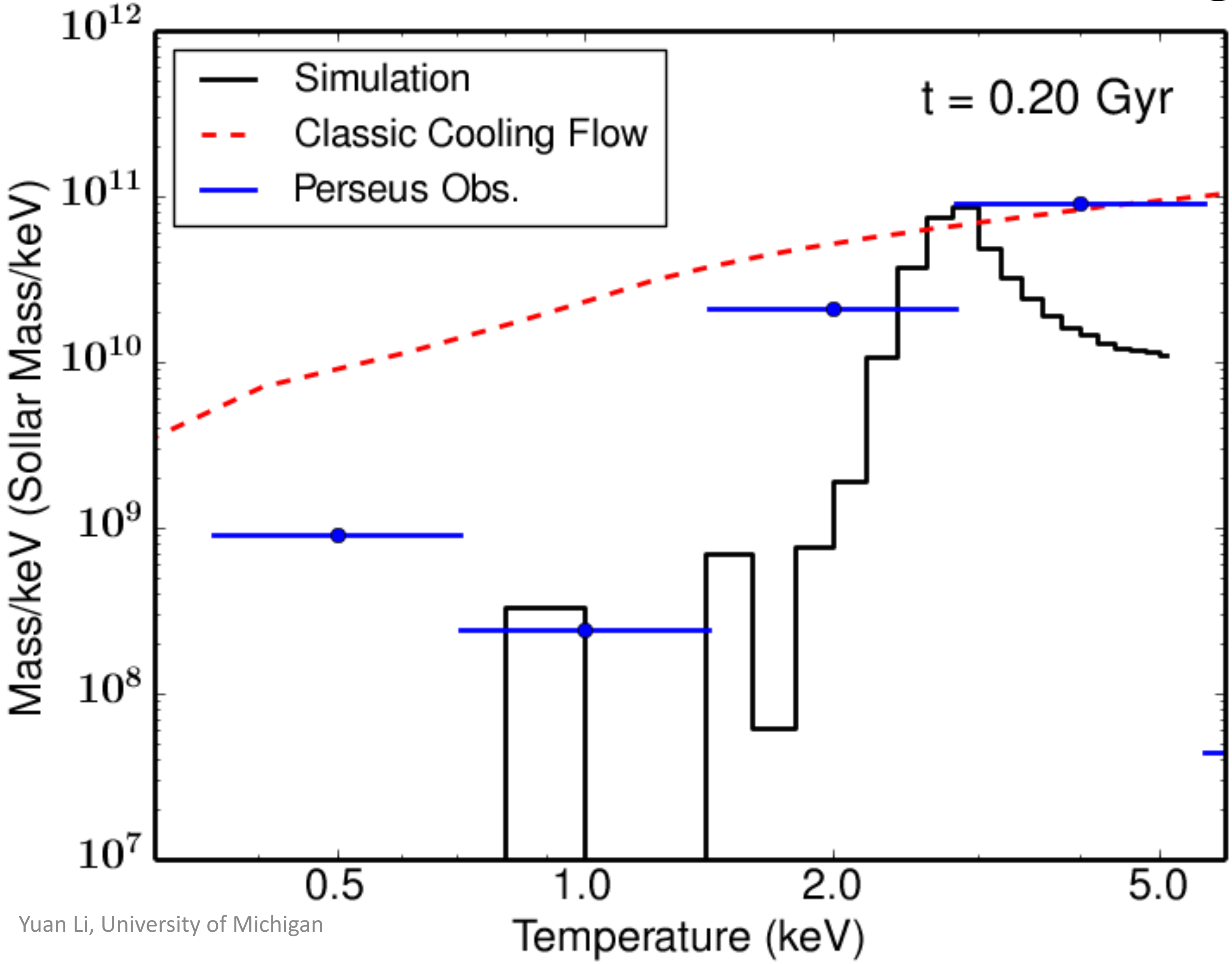


Can AGN Feedback Balance Cooling?



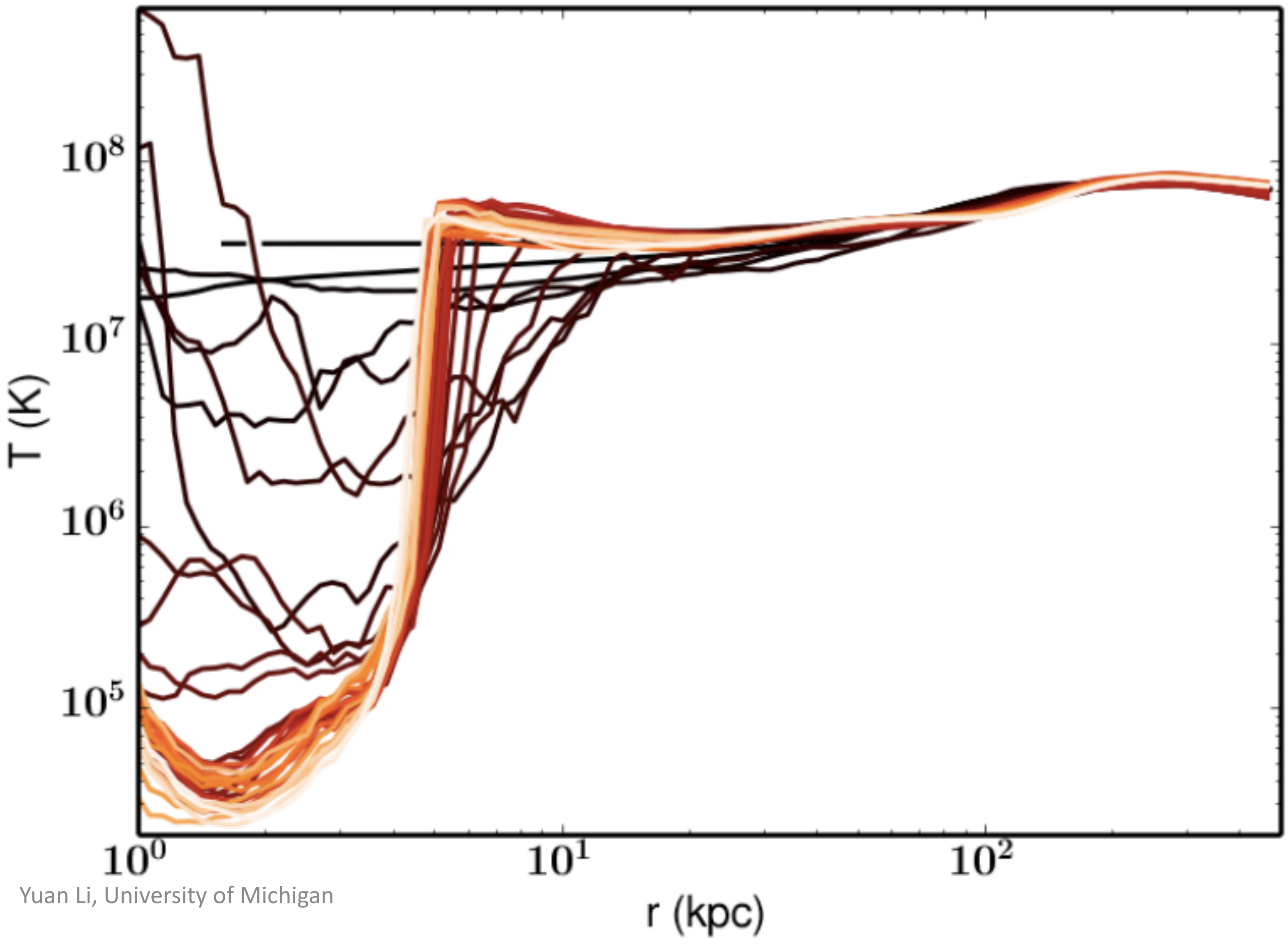
Success of the Model

- Balancing Cooling
- Consistent results when varying model parameters:

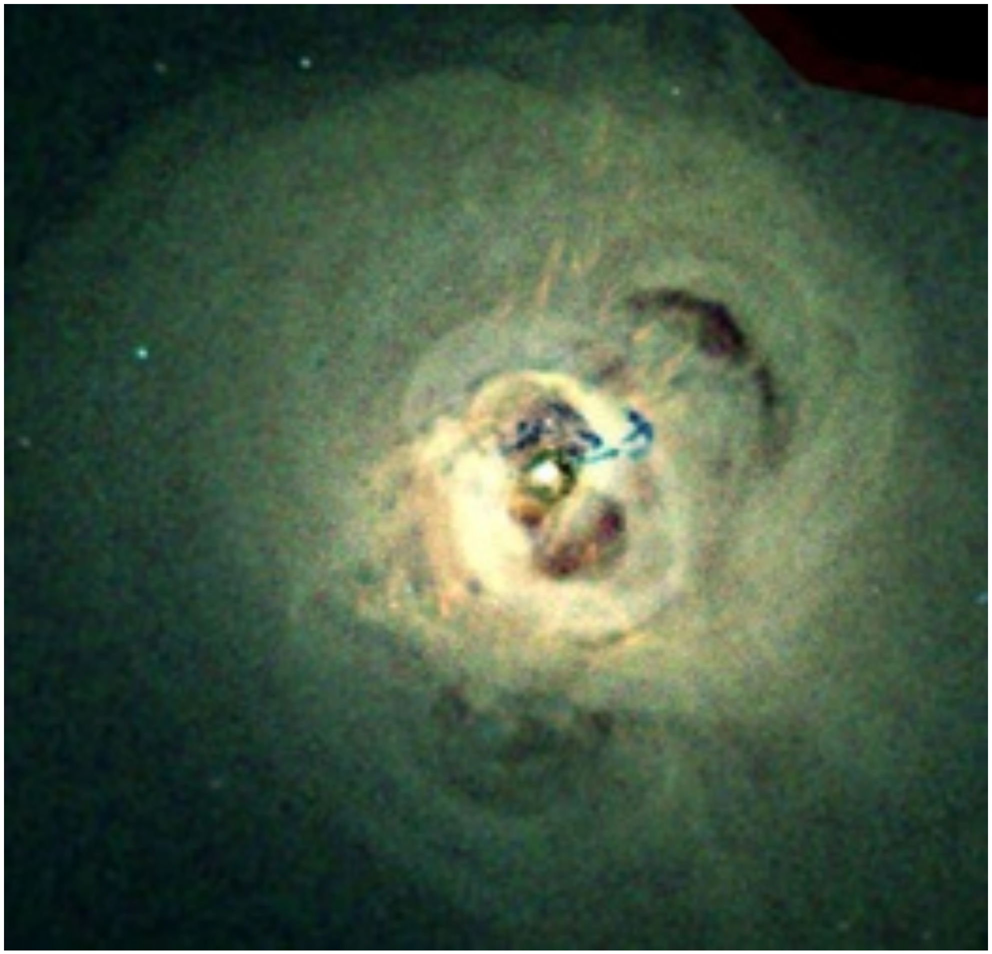
  kinetic fraction f (0.1-1)

  feedback efficiency ε (0.1%-1%)
- Converging results when smallest cell size < 500 pc

Maintaining a cool-core appearance

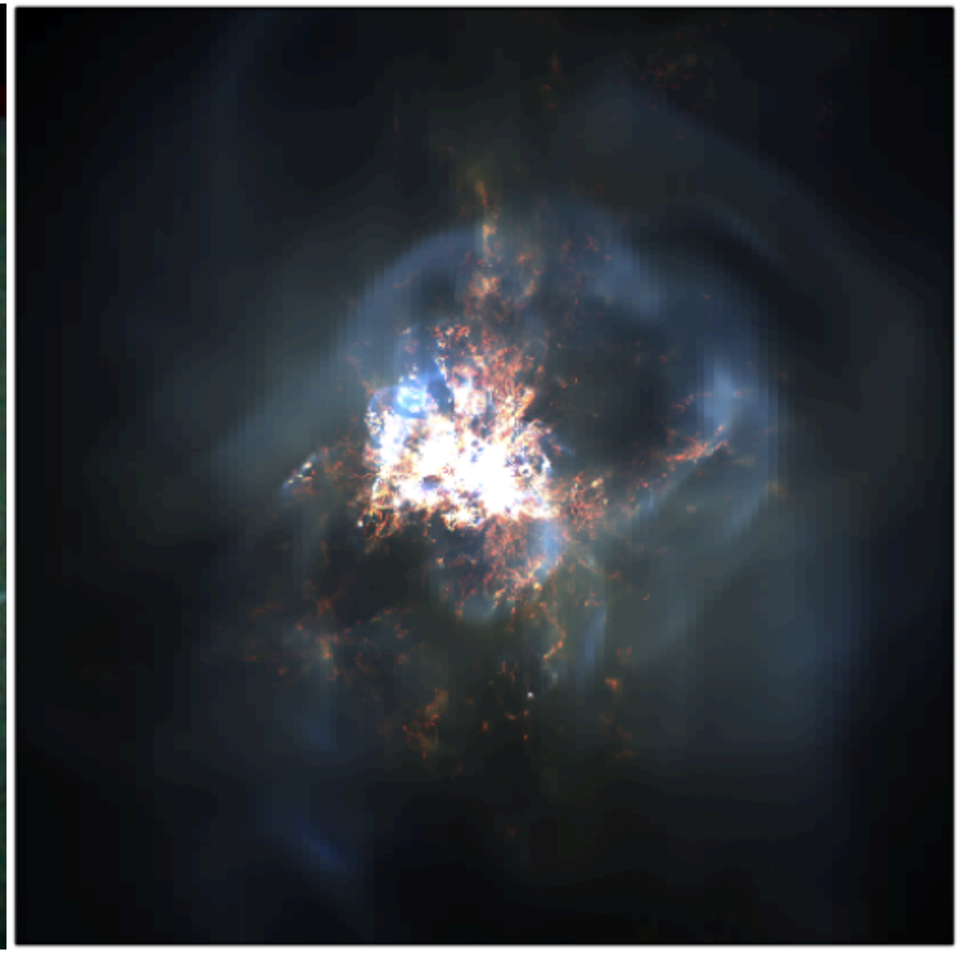


Comparison with Observations



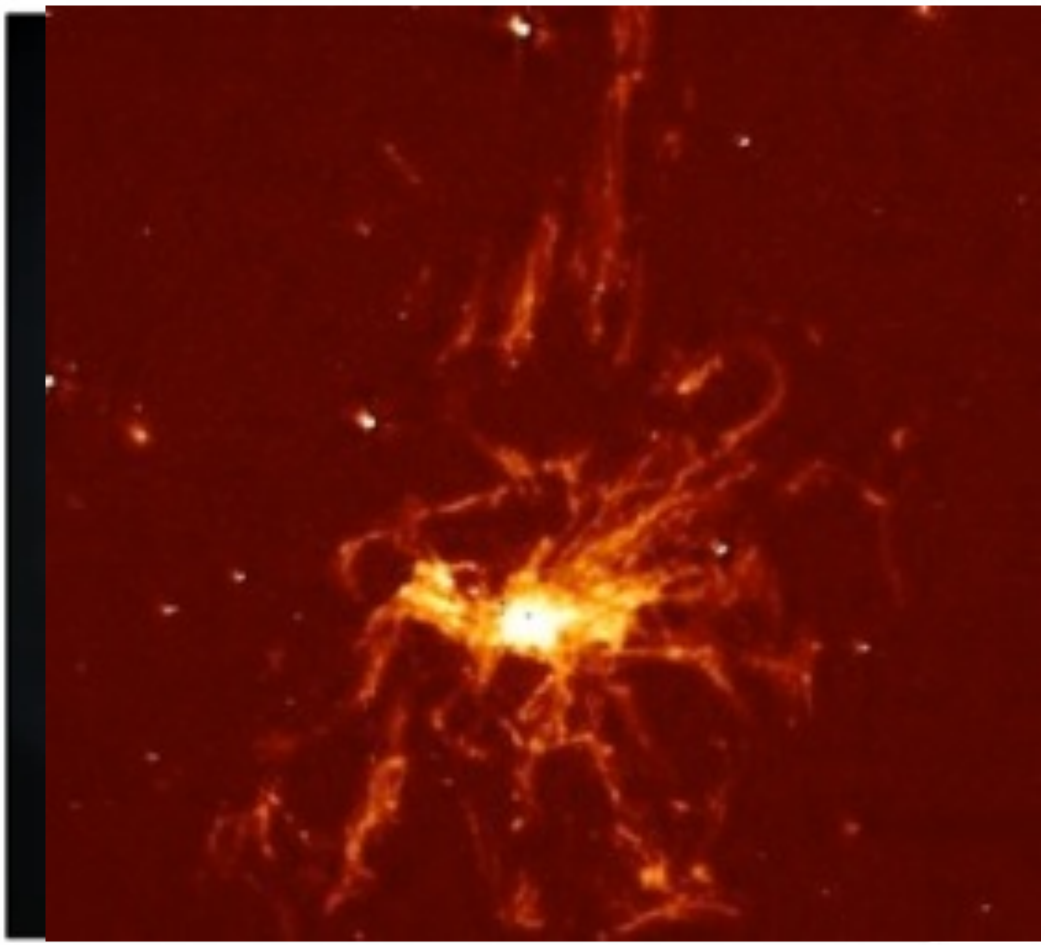
Composite X-ray image of Perseus Core

Fabian et al. (2006)

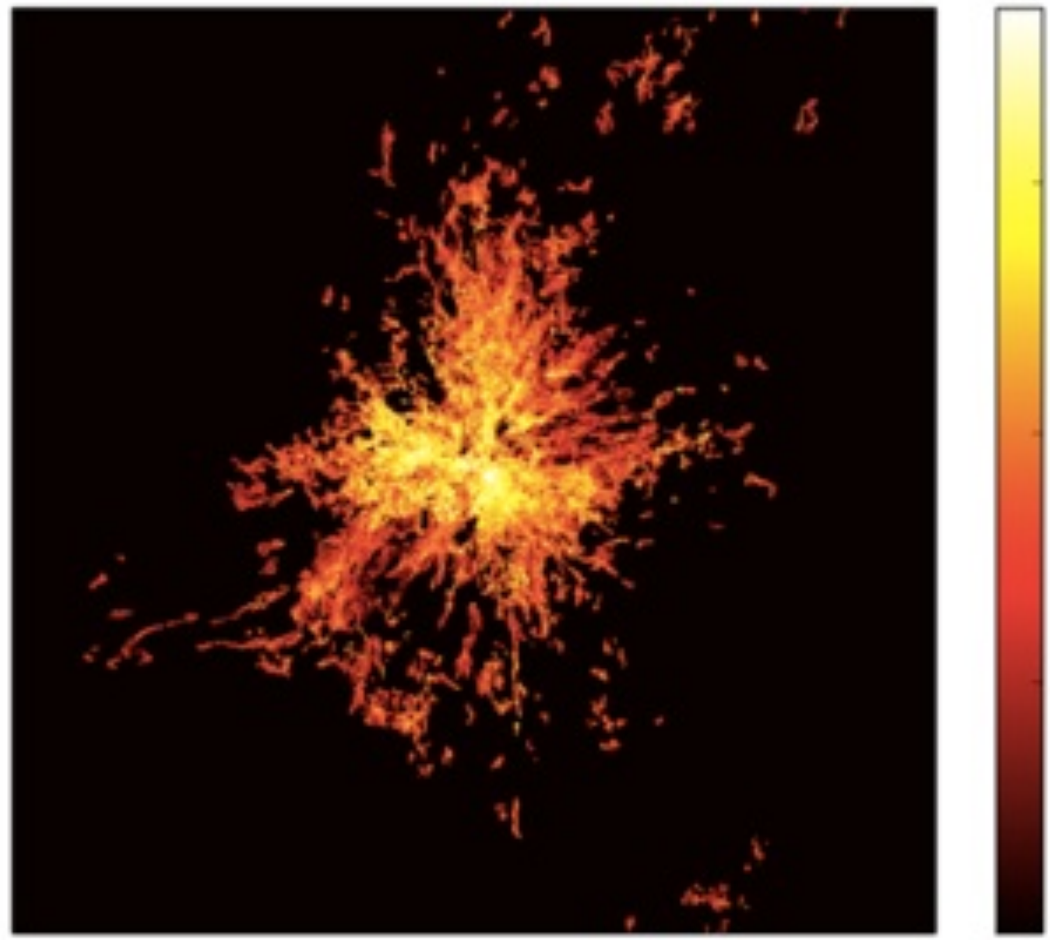


Synthetic X-ray image from the simulation

Comparison with Observations



Hα image of the Perseus cluster core.

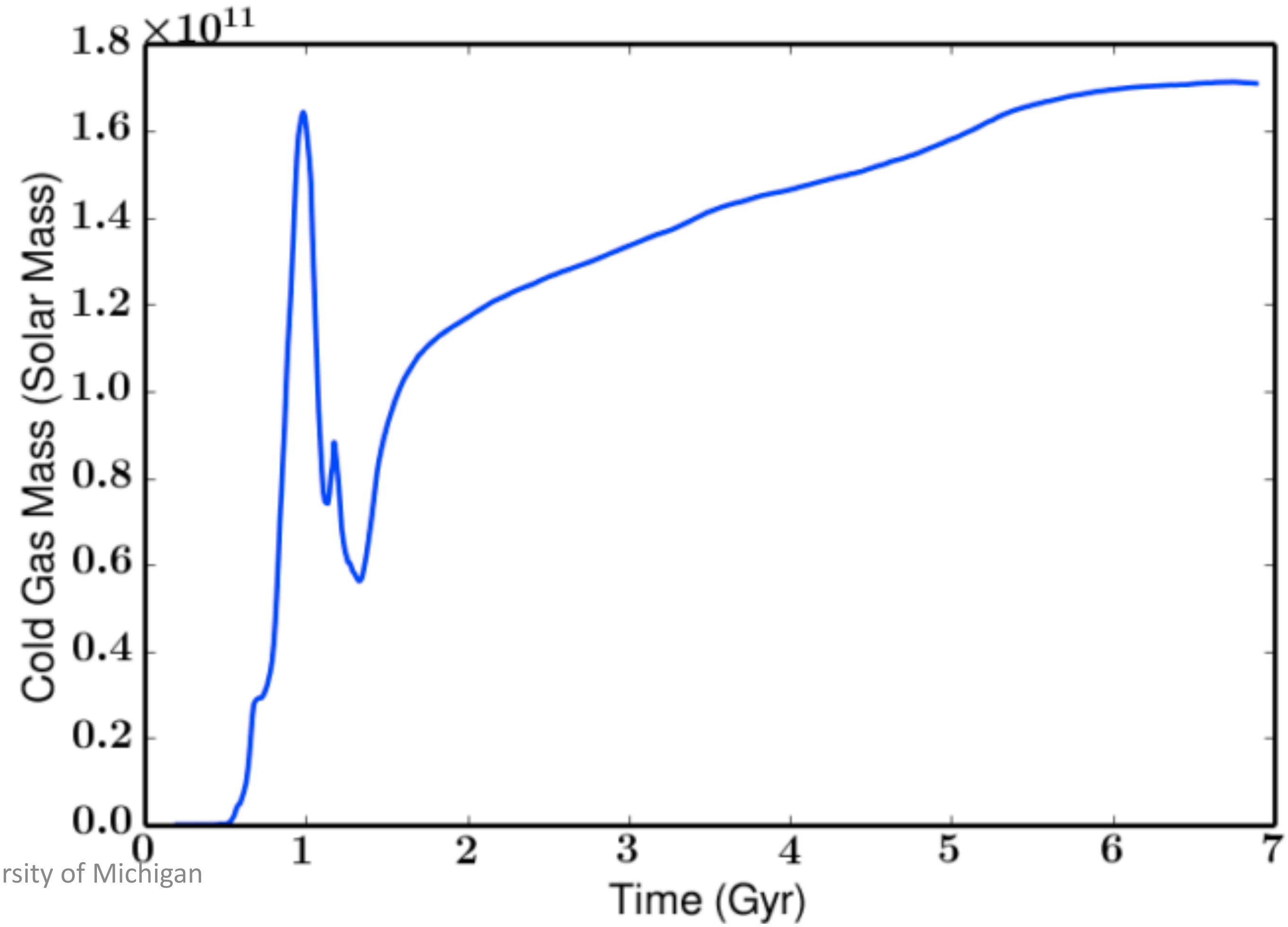


Synthetic Hα map from the simulation

But…

Disk is too large (~ $10^{11}\,M_\odot$) and stays forever

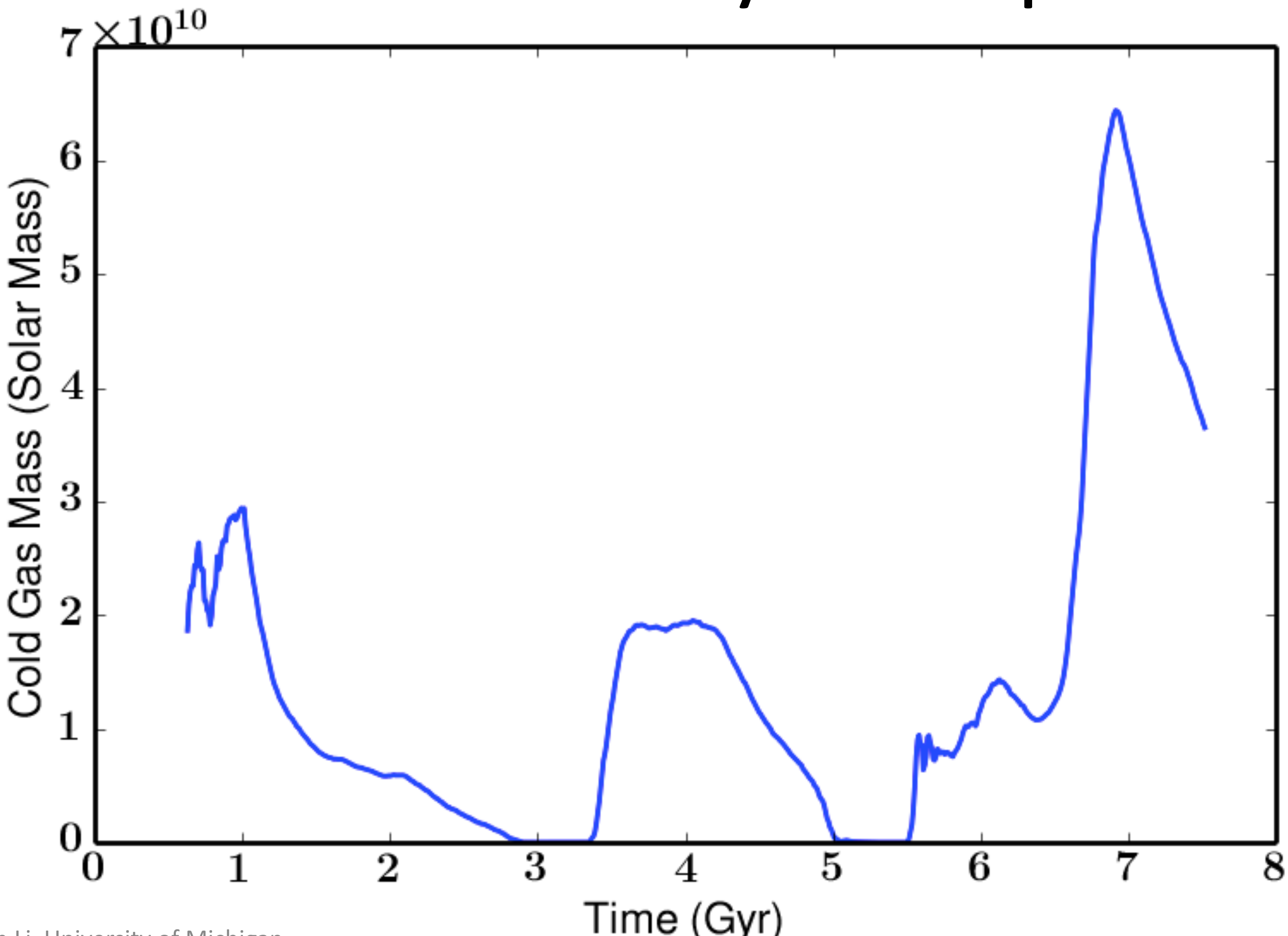
Consistent with simulations (Gaspari et al. 2012), but not the observations.



Missing Physics

- Self-gravity? – help accrete the disk
- Viscosity? – help accrete the disk
- Conduction? – dissolve the cold disk
- Magnetic Field? – complicated; support filaments?
- Star Formation? – consumes and locally heats up the cold gas

Star Formation May Be Important



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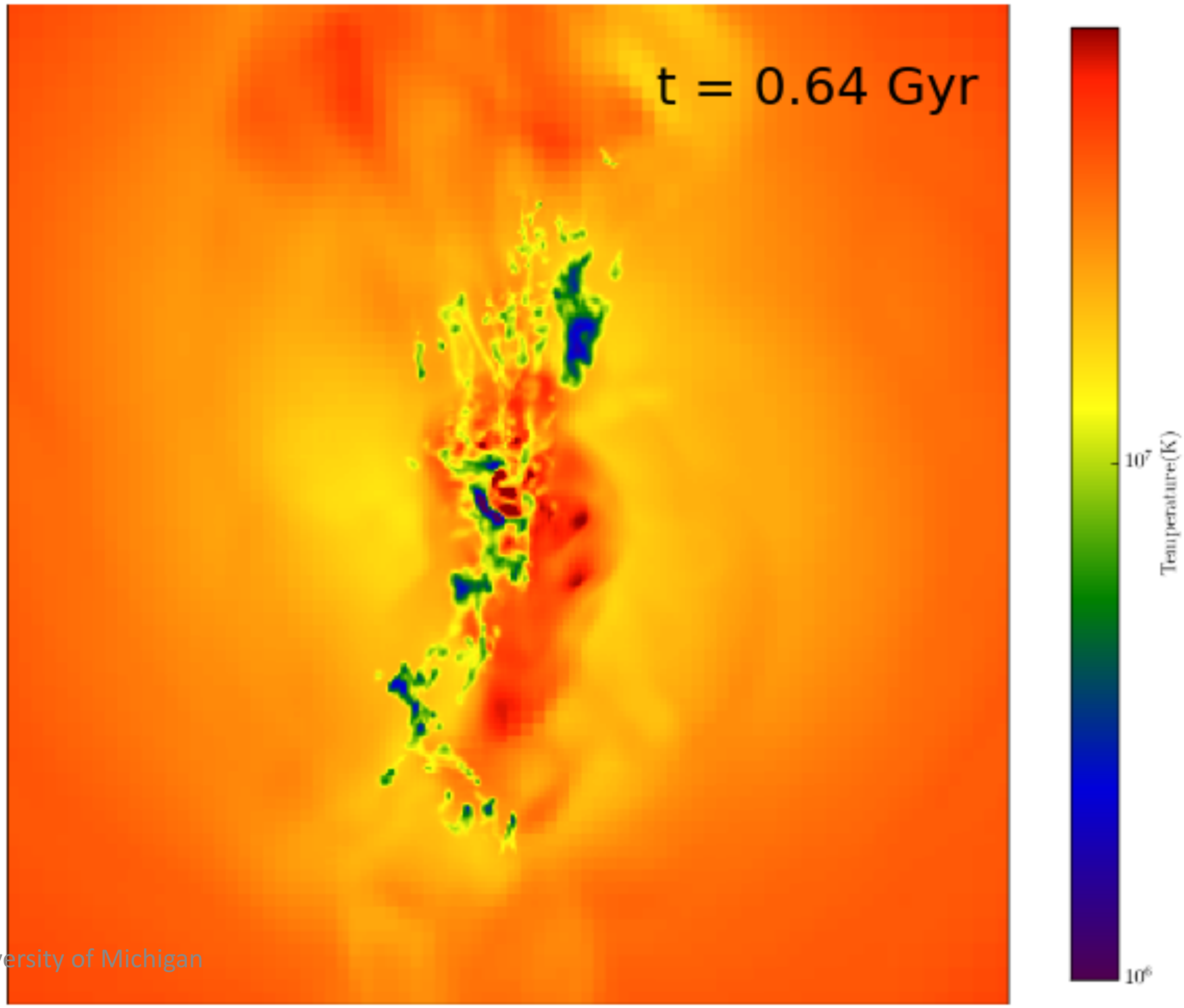

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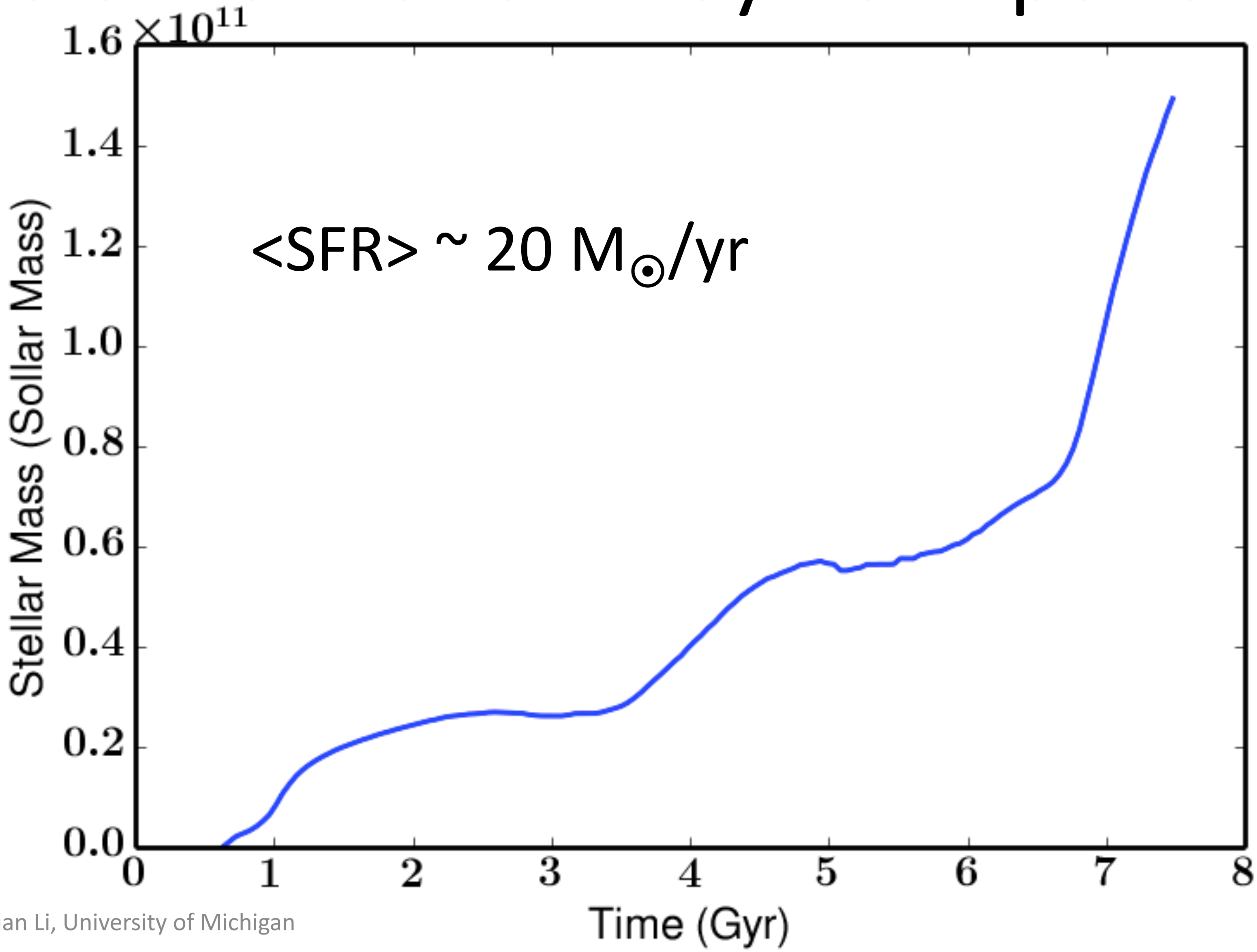

Conclusion

- Without AGN, cooling catastrophe happens only in the very center (r<50pc).
- AGN jets drive the formation of cold clumps/filaments when the gas is still (linearly) thermally stable.
- AGN feedback can balance cooling (over a few Gyr), but additional physics is needed to get the picture right.