Clouds in the circumgalactic medium

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Theoretical Physics Colloquium

Outline

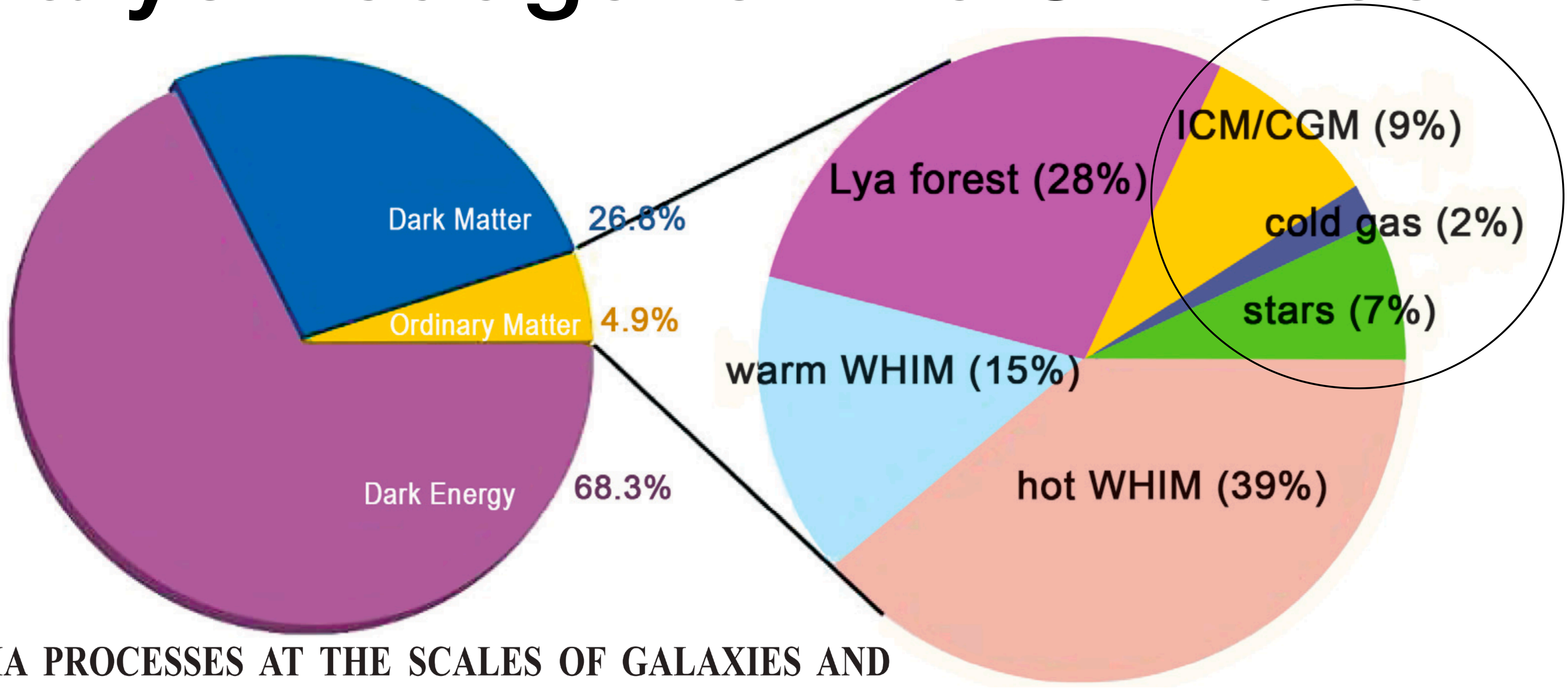
- CGM (~ Mpc): the middle world of cosmological galaxy formation (observable Universe ~10^{10} pc, galaxy disk height ~100 pc)

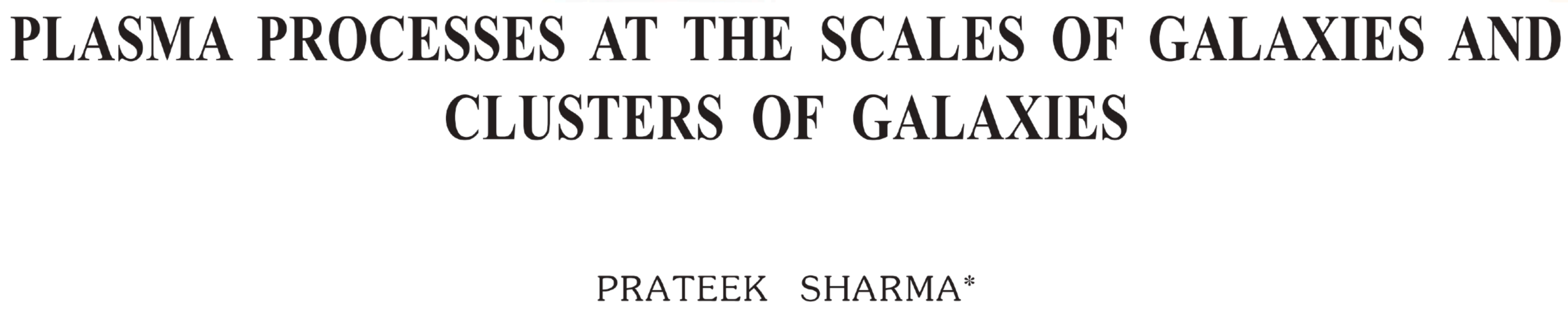
- Why study the CGM (δ~$10^{2\text{-}5}$, n~10^{-5}–1 cm^{-3})? New absorption/emission observations; not as nonlinear as stars (δ~10^{30}, n~10^{24} cm^{-3}), easier to understand

- CGM is multiphase (gas at different n,T coexist)! How to explain this?

- Some idealised models: thermal instability & condensation, galactic outflows, cloud crushing

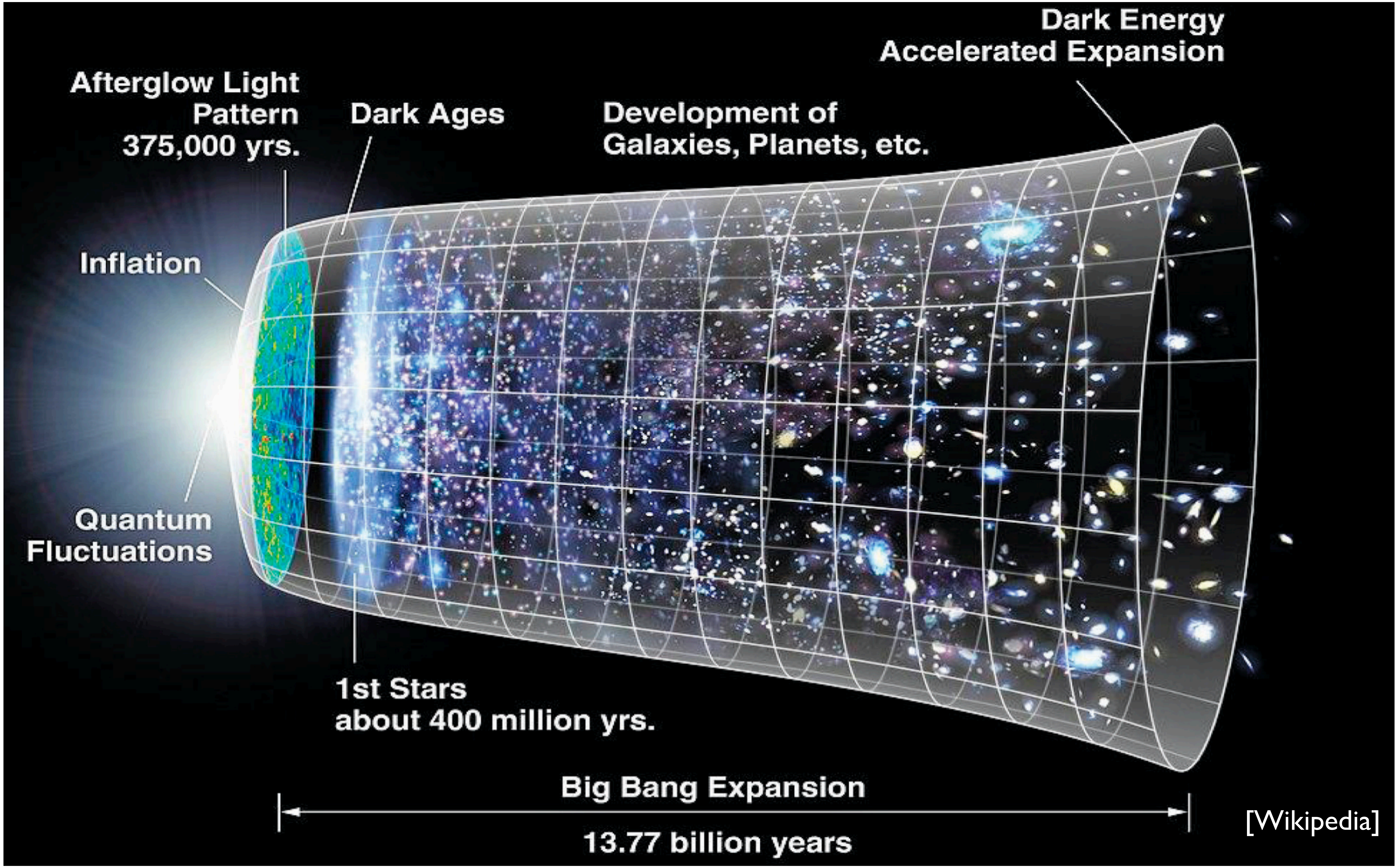
Baryon budget of the Universe





arXiv:1811.12147

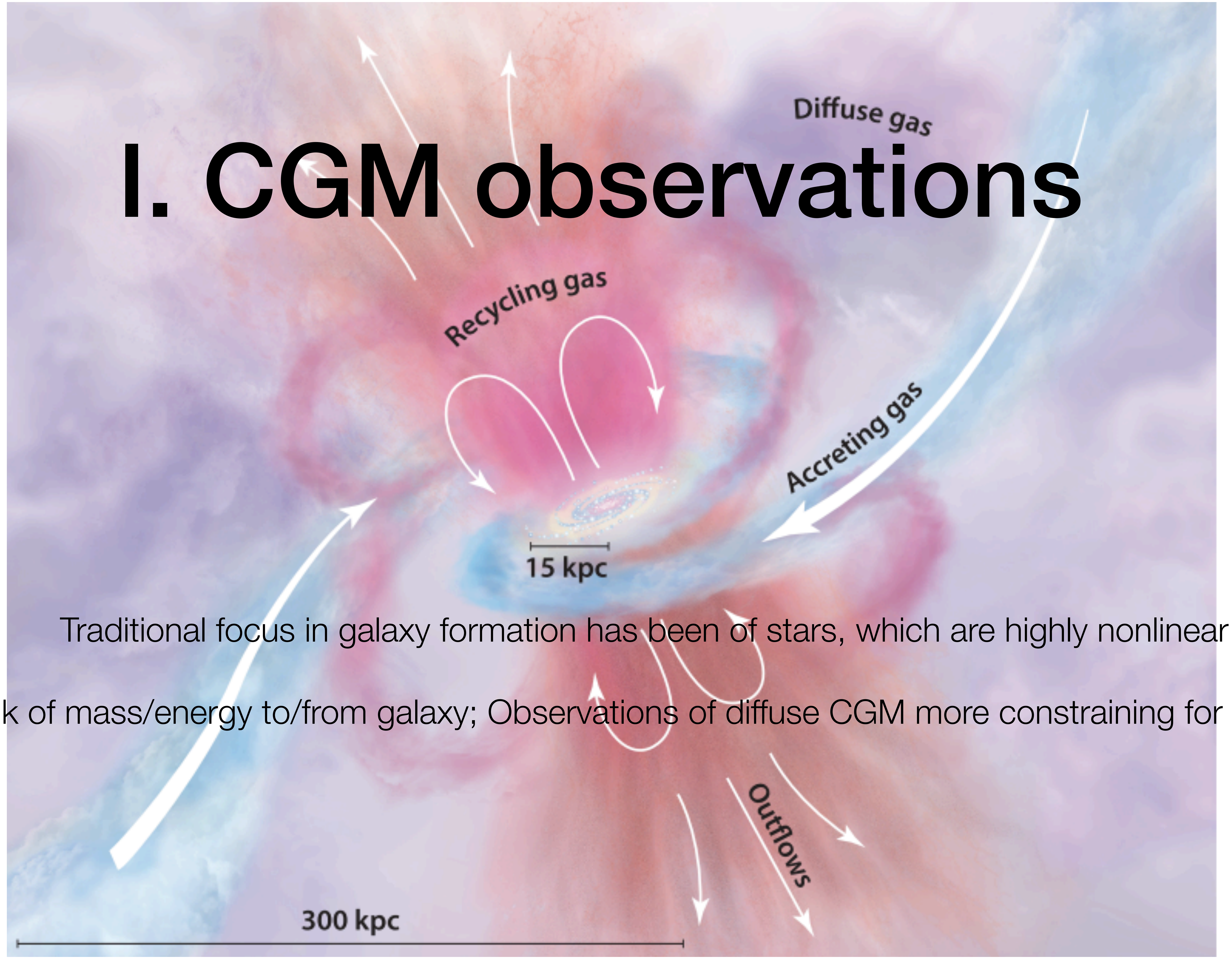
Evolution of the Universe



Universe had
a beginning
&
it evolves with time

focus on z~0,
nearby Universe

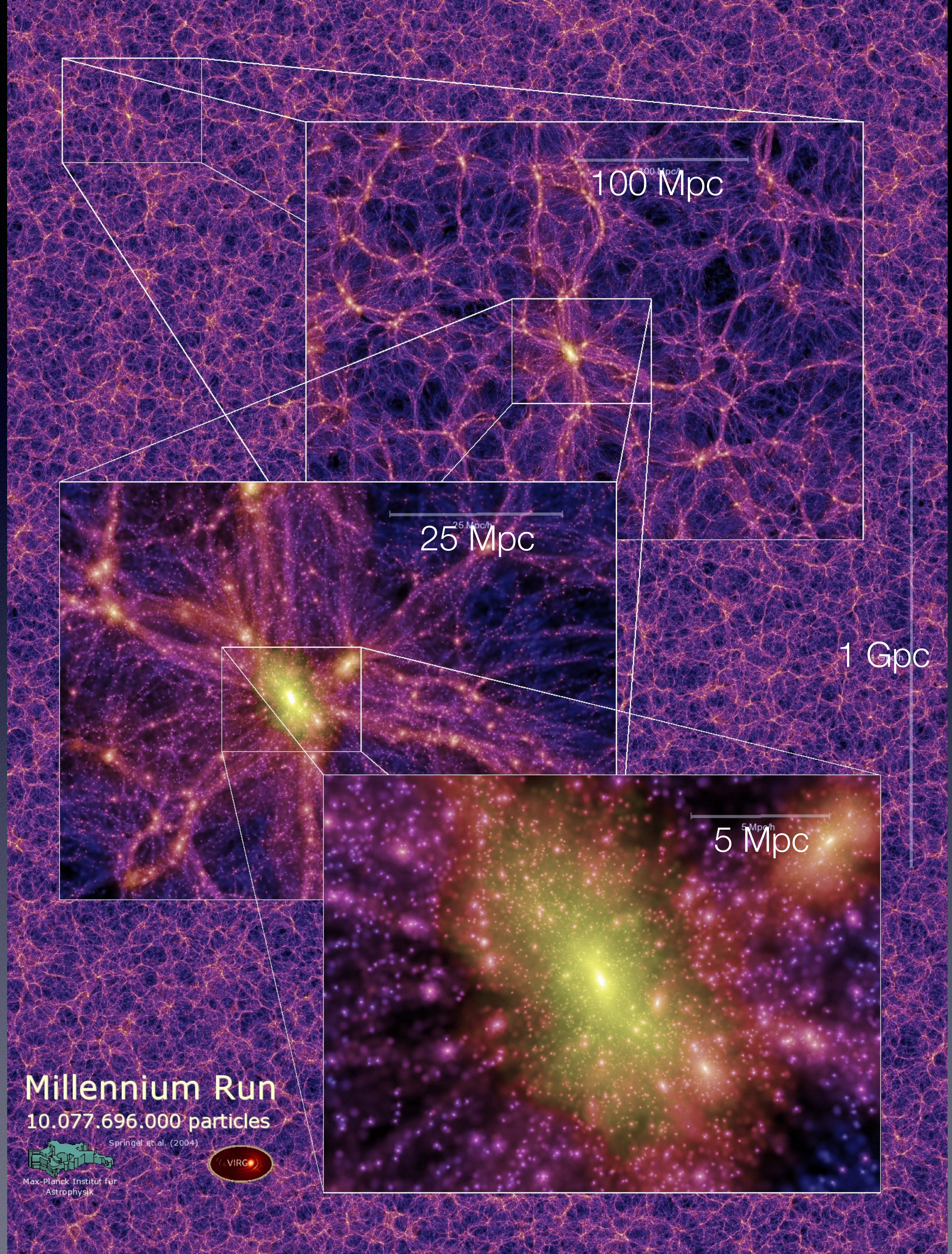
I. CGM observations

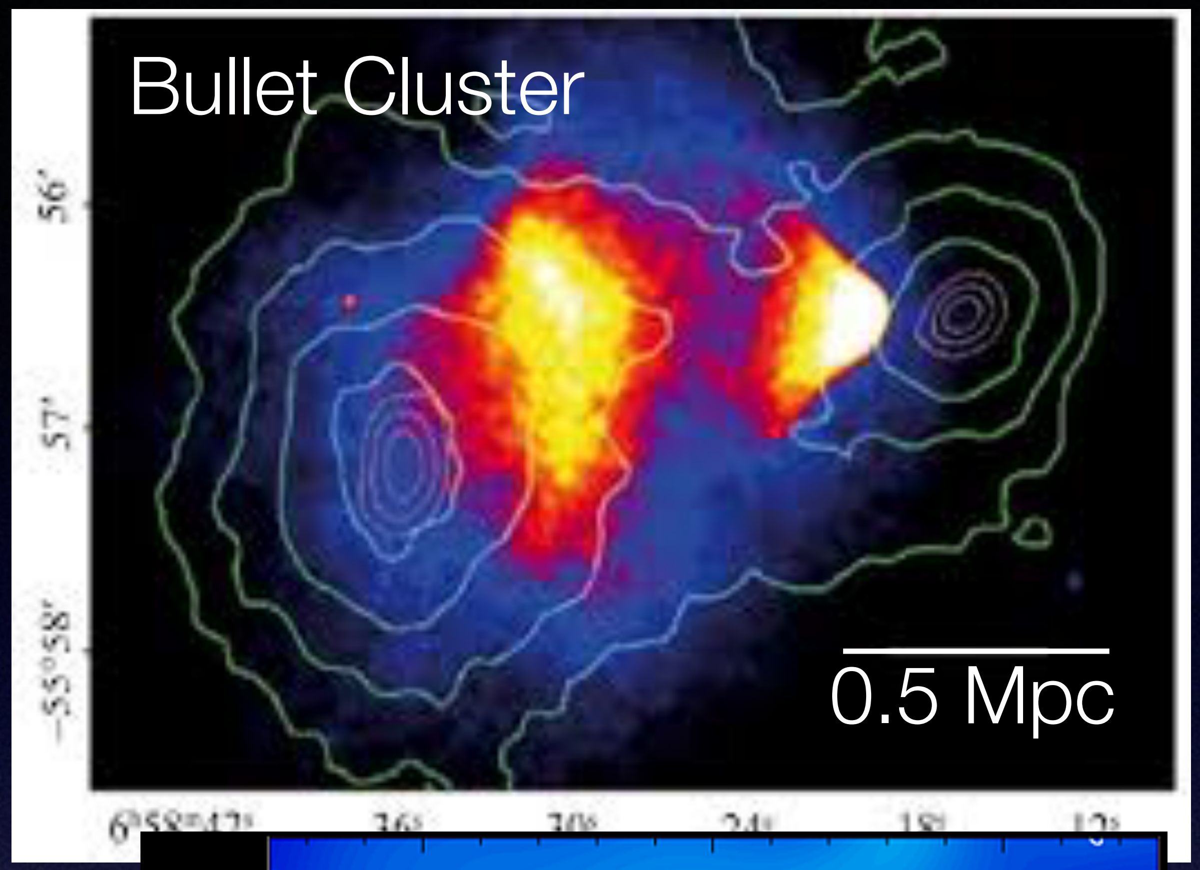


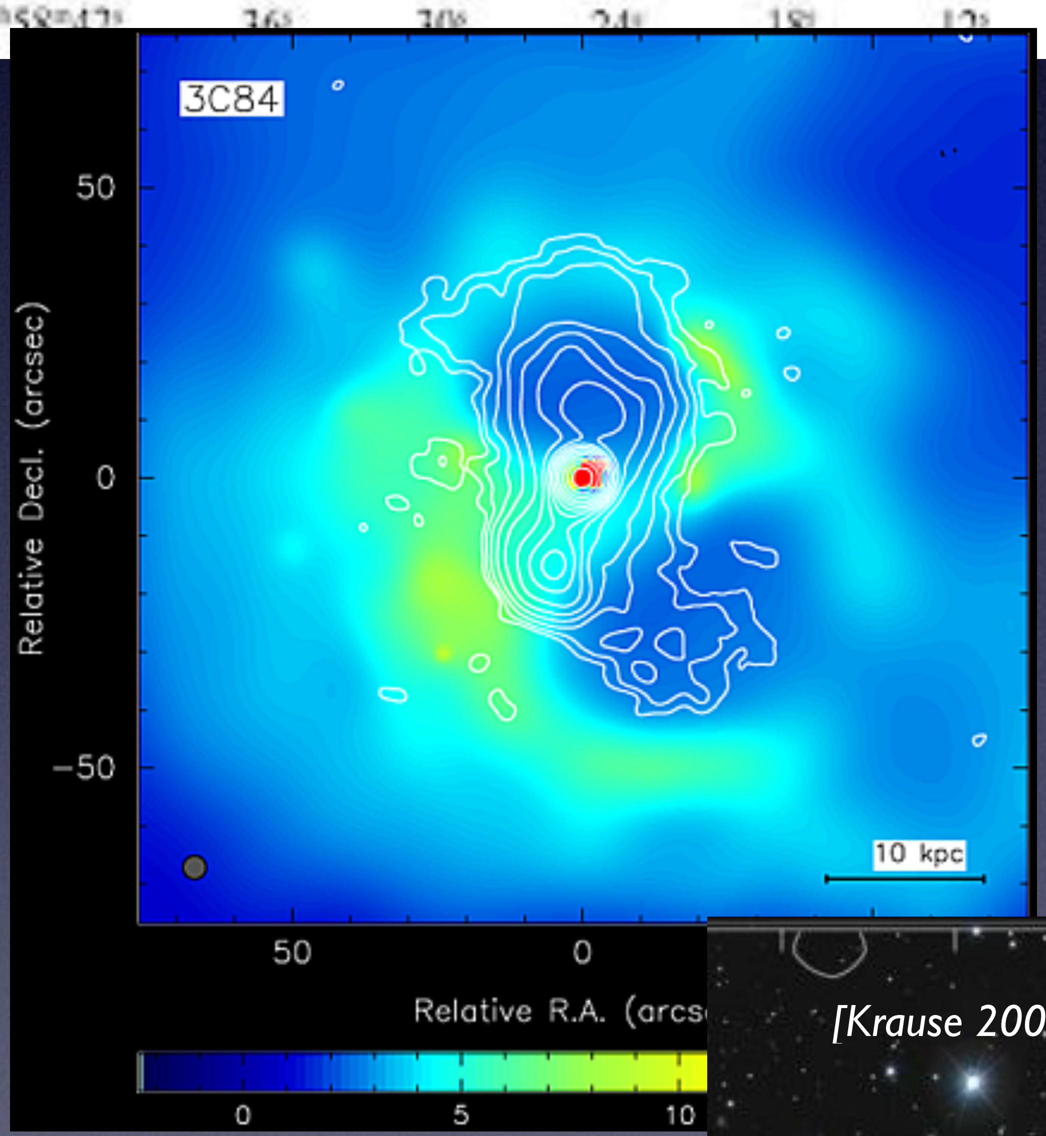
Traditional focus in galaxy formation has been of stars, which are highly nonlinear

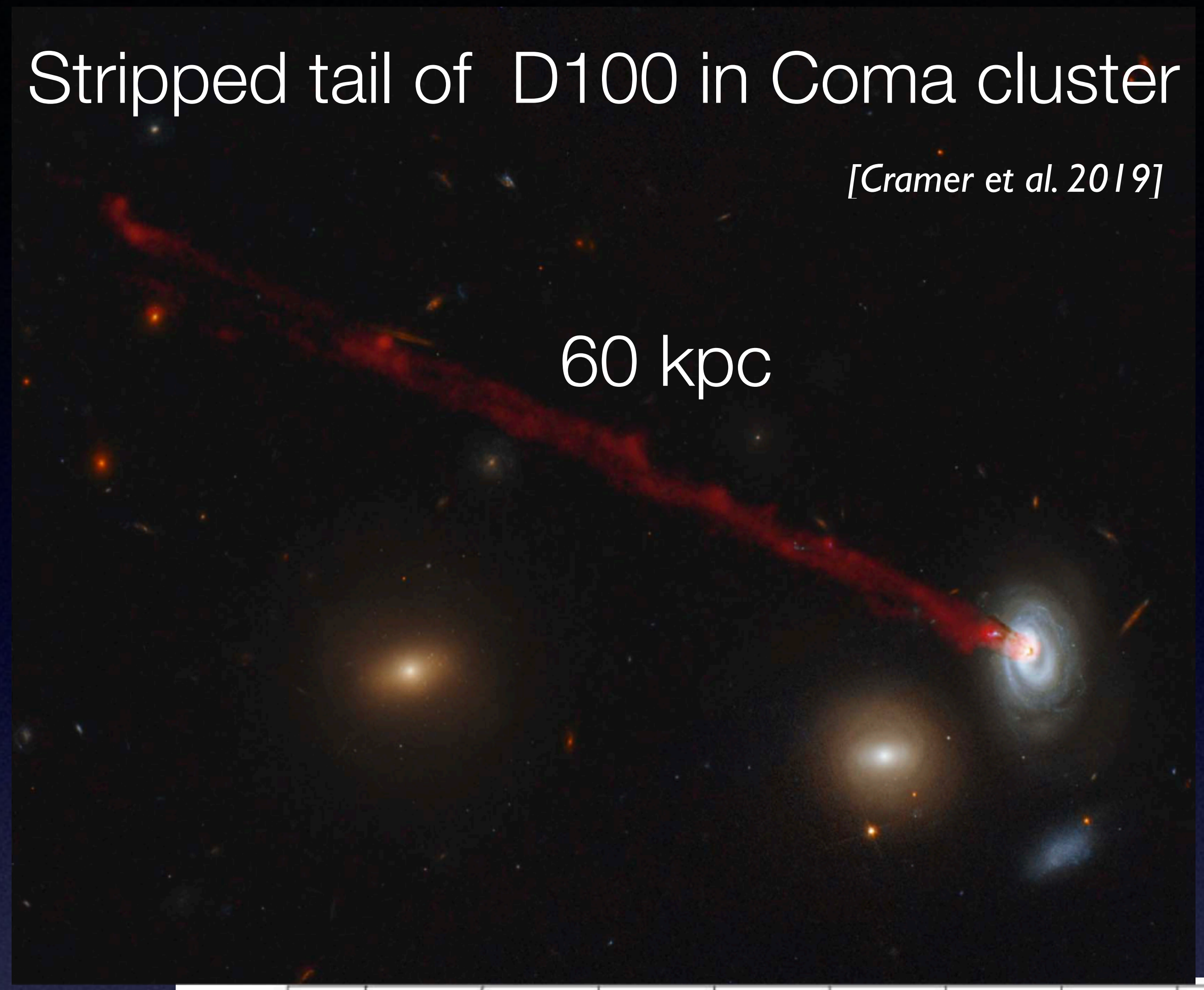
Source & sink of mass/energy to/from galaxy; Observations of diffuse CGM more constraining for galaxy formation

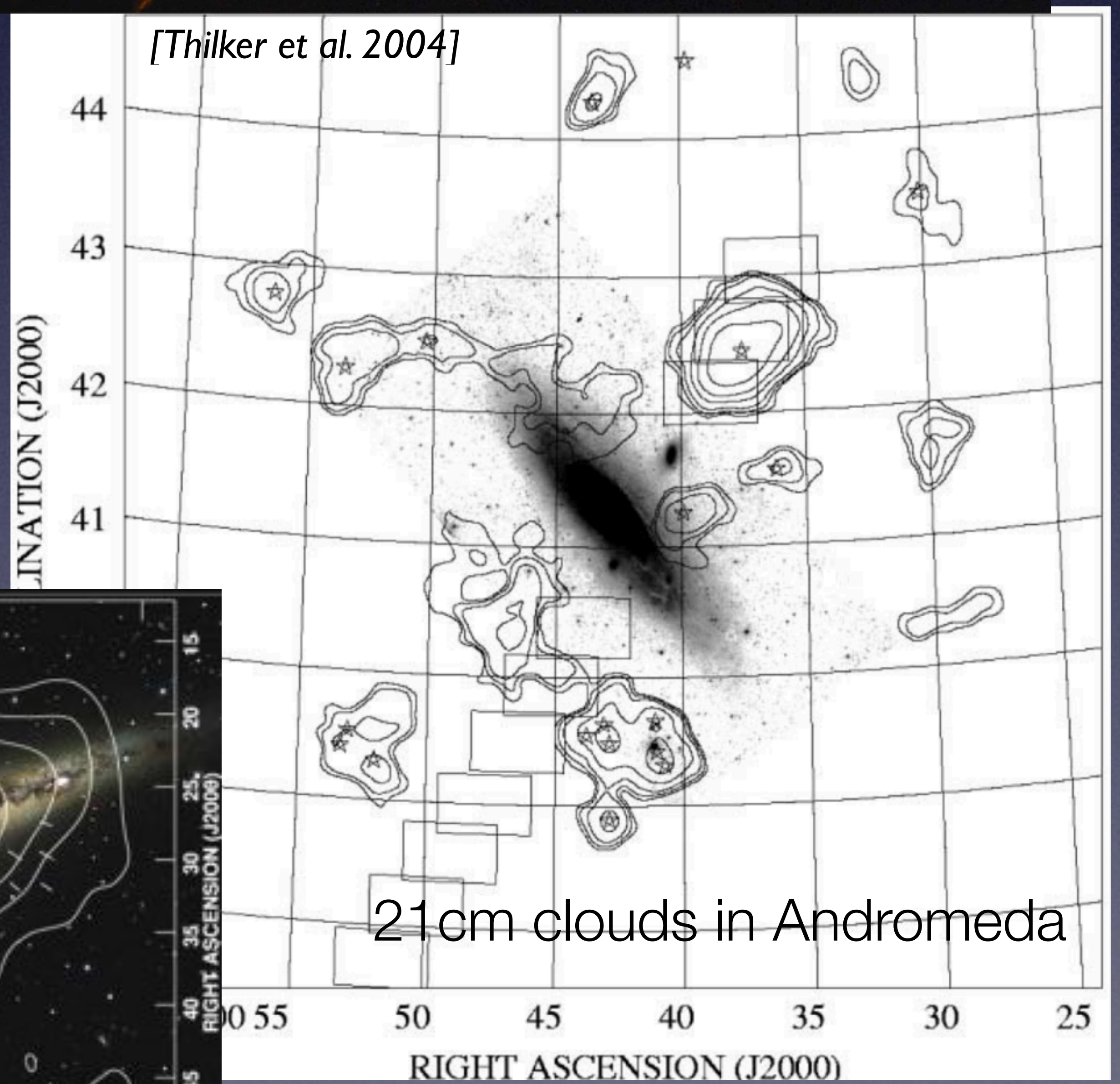
Scales

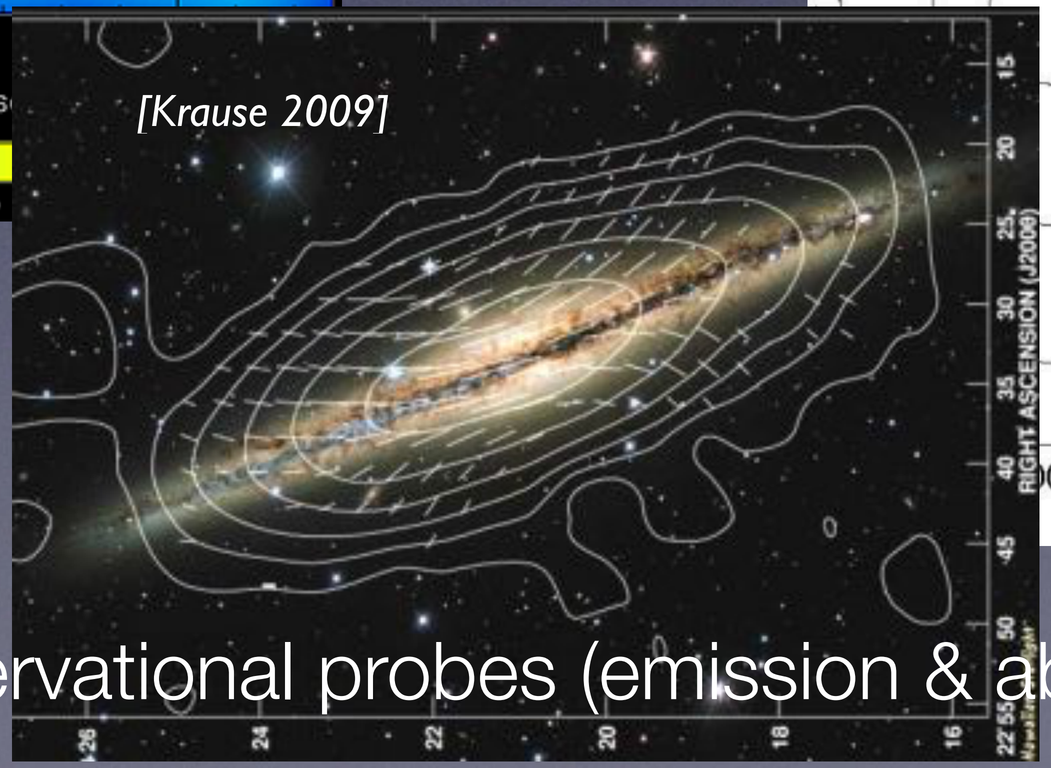










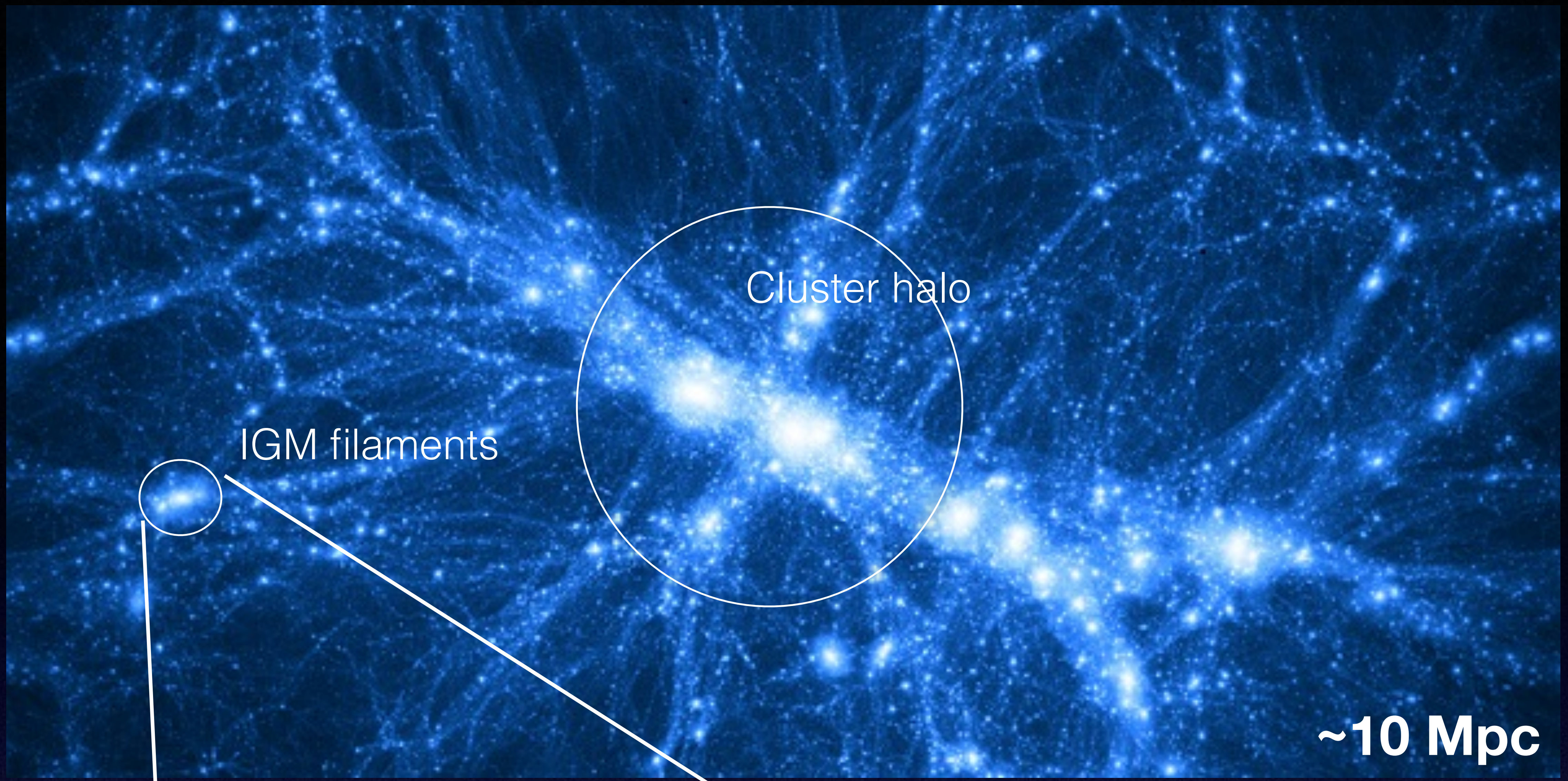


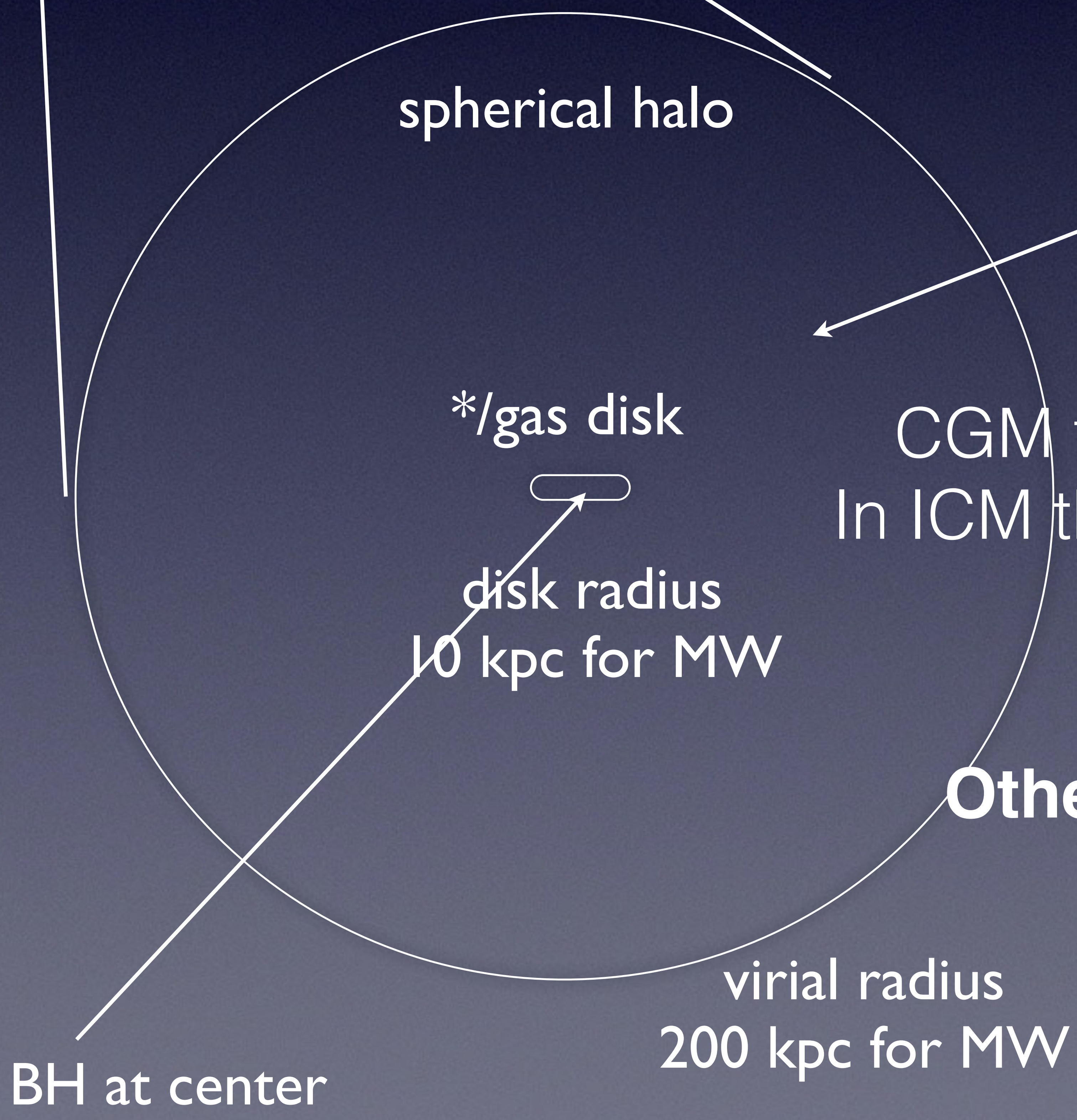
Many more observational probes (emission & absorption) going to high z!

CGM/ICM

circumgalactic/intracluster medium

LCDM

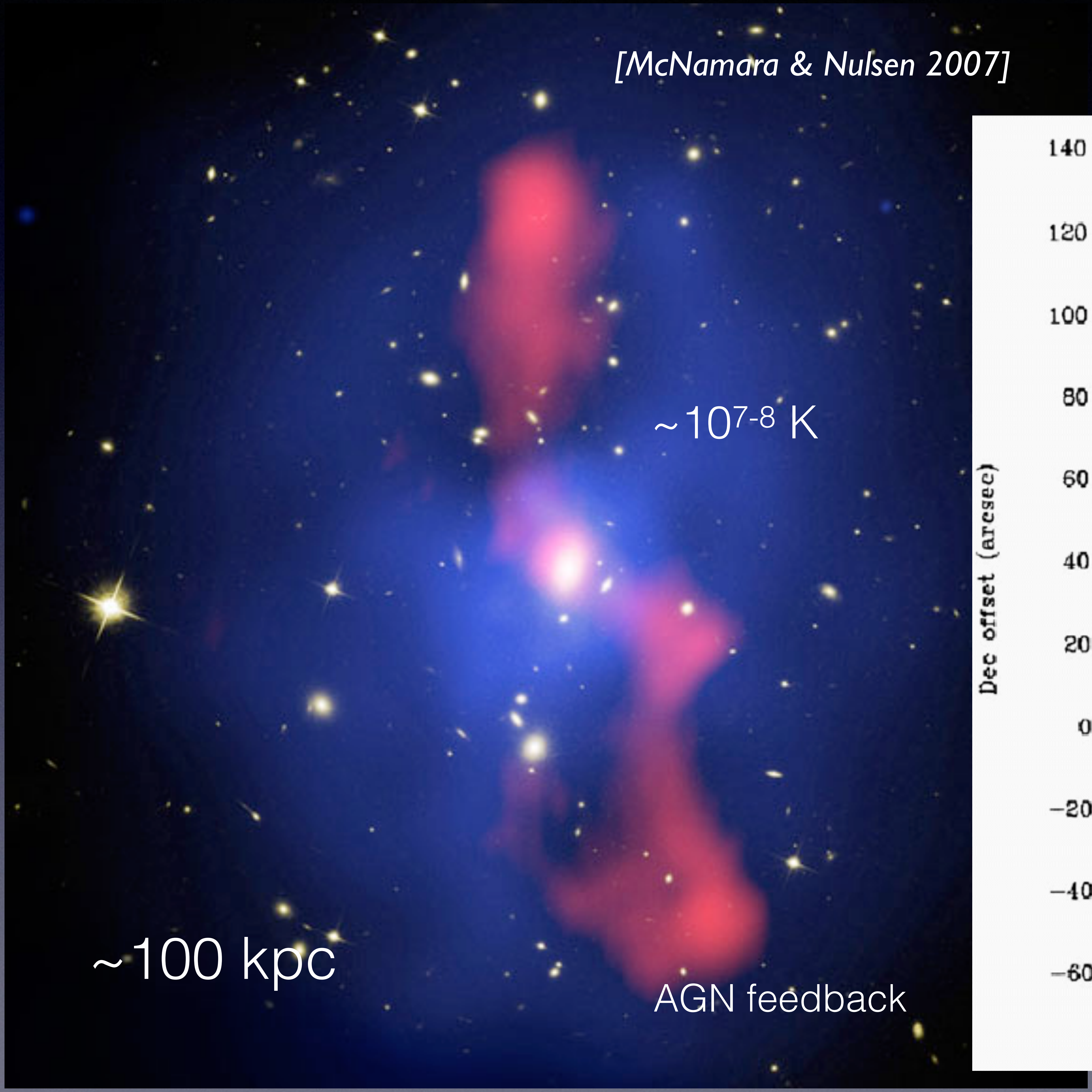




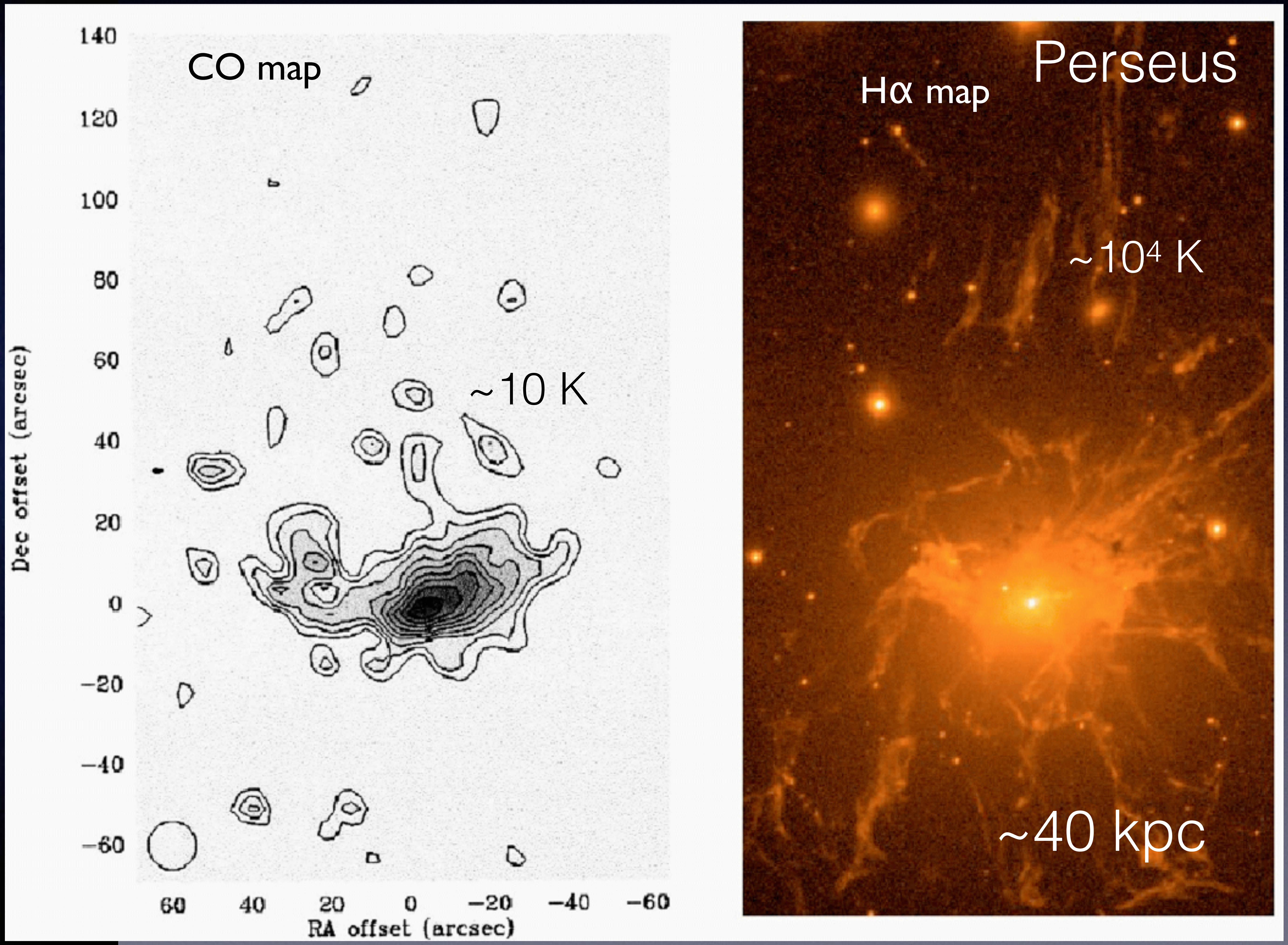
CGM typically unobservable in emission but in quasar absorption line studies
In ICM the hot gas is dense and observable in emission through X-ray telescopes
Therefore, ICM is better understood than CGM

Other probes: SZ effect (distortion of CMB by halo e^-s), FRBs pulse dispersion

Clusters in emission

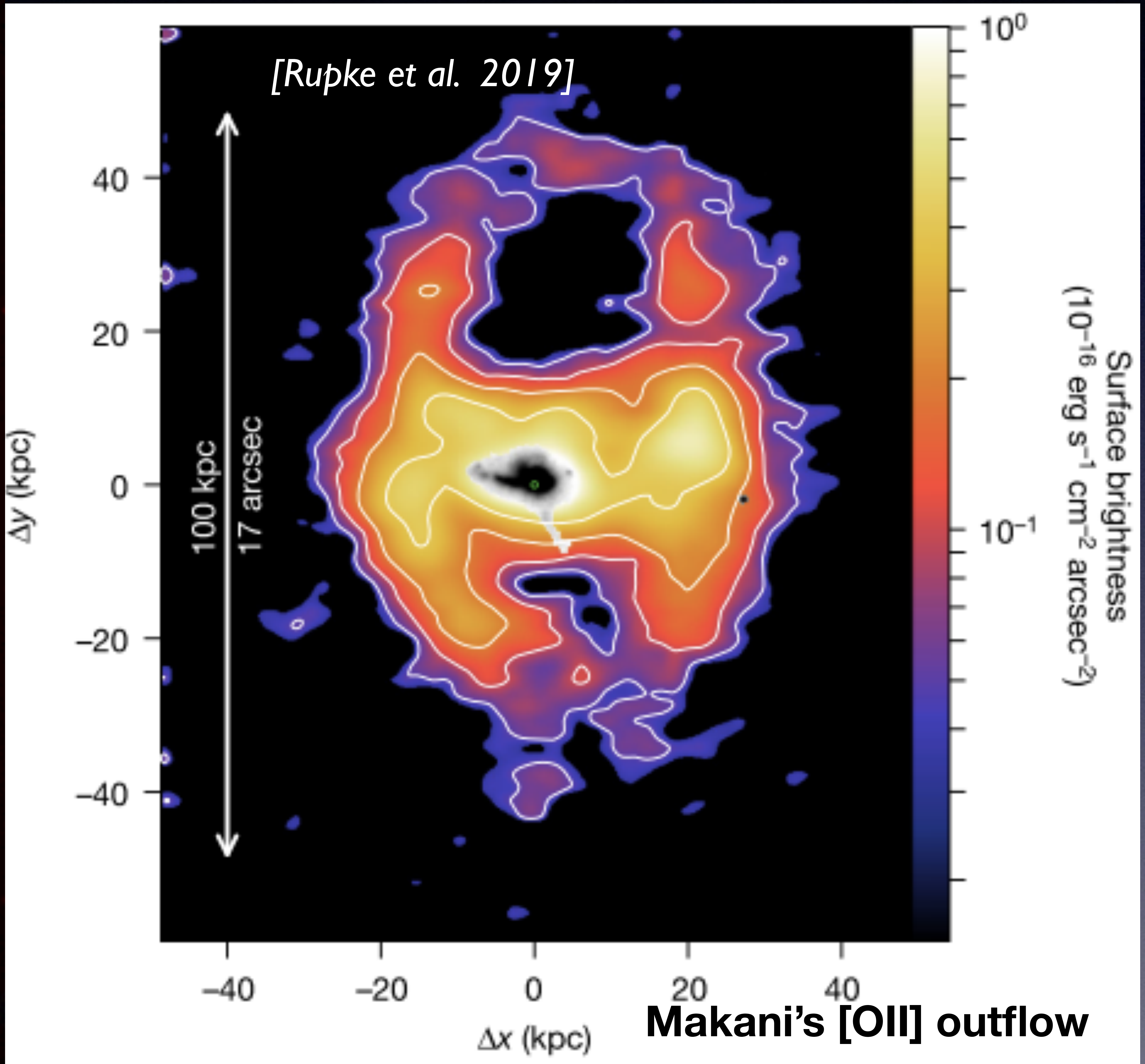


[Salome et al 2006]



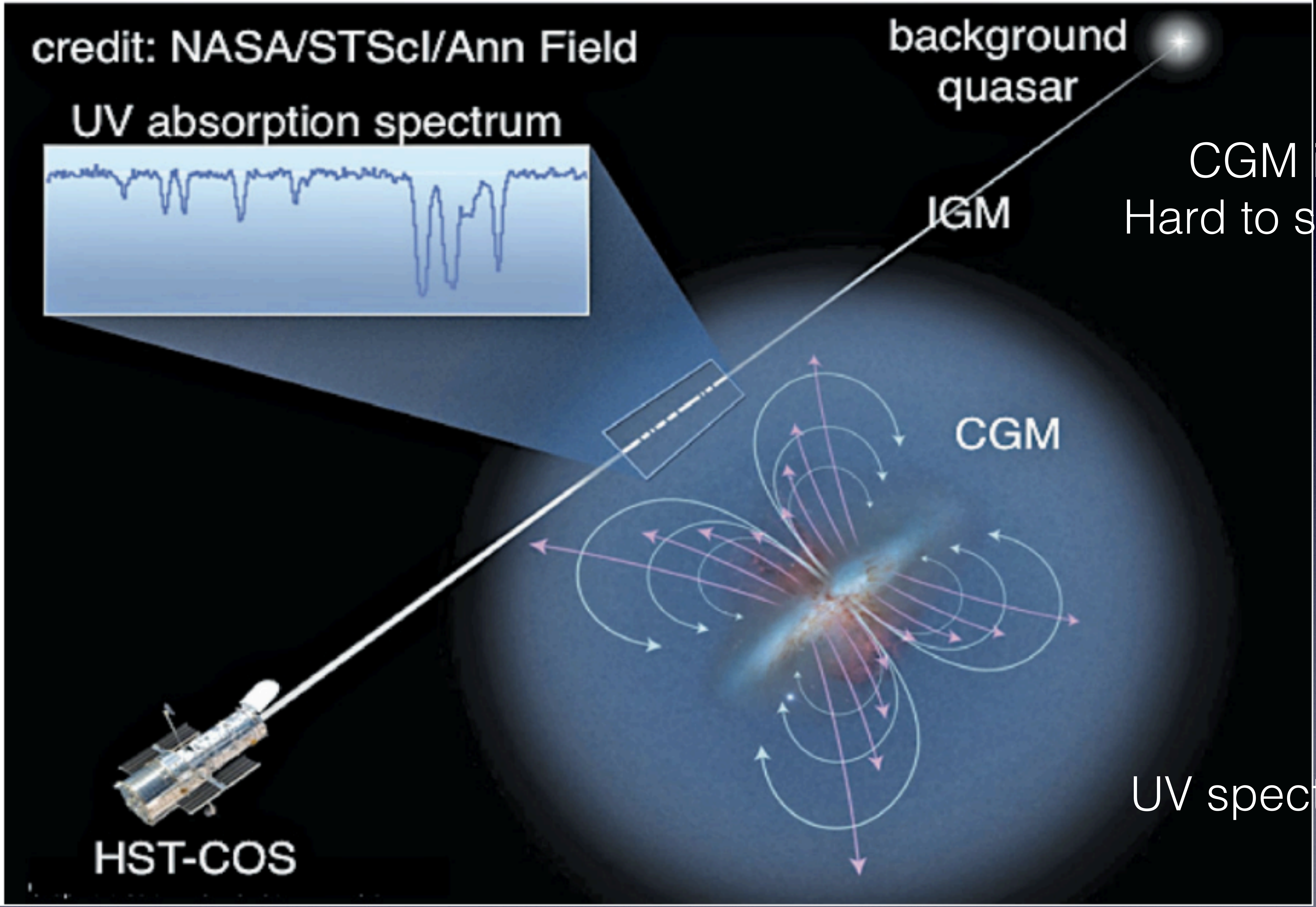
Galactic outflows

Credit: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht



Largest imaged galactic outflow in nearby Universe

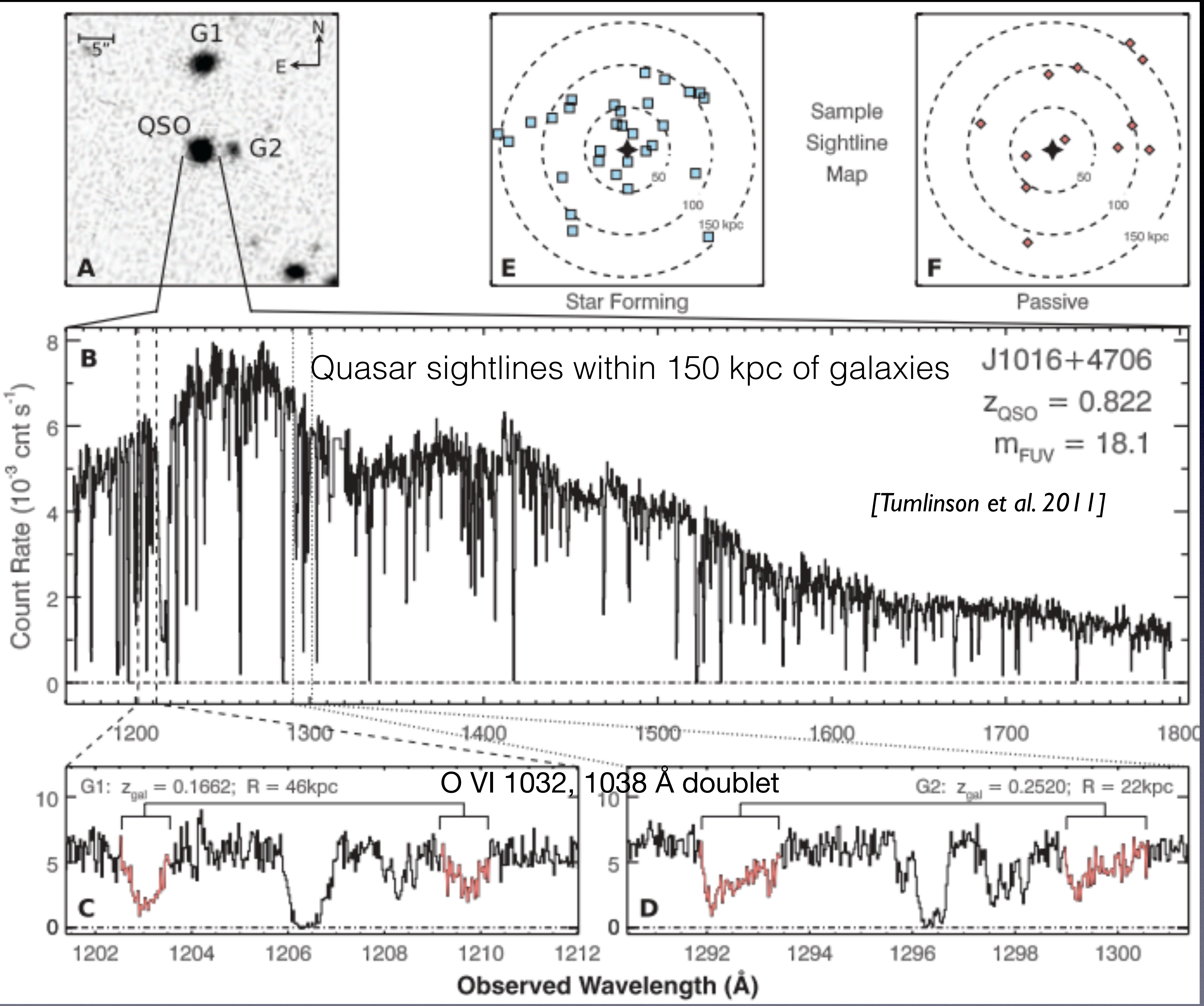
CGM probed in absorption



CGM is so dilute!
Hard to see in emission

UV spectra must for z~0

COS-Halos

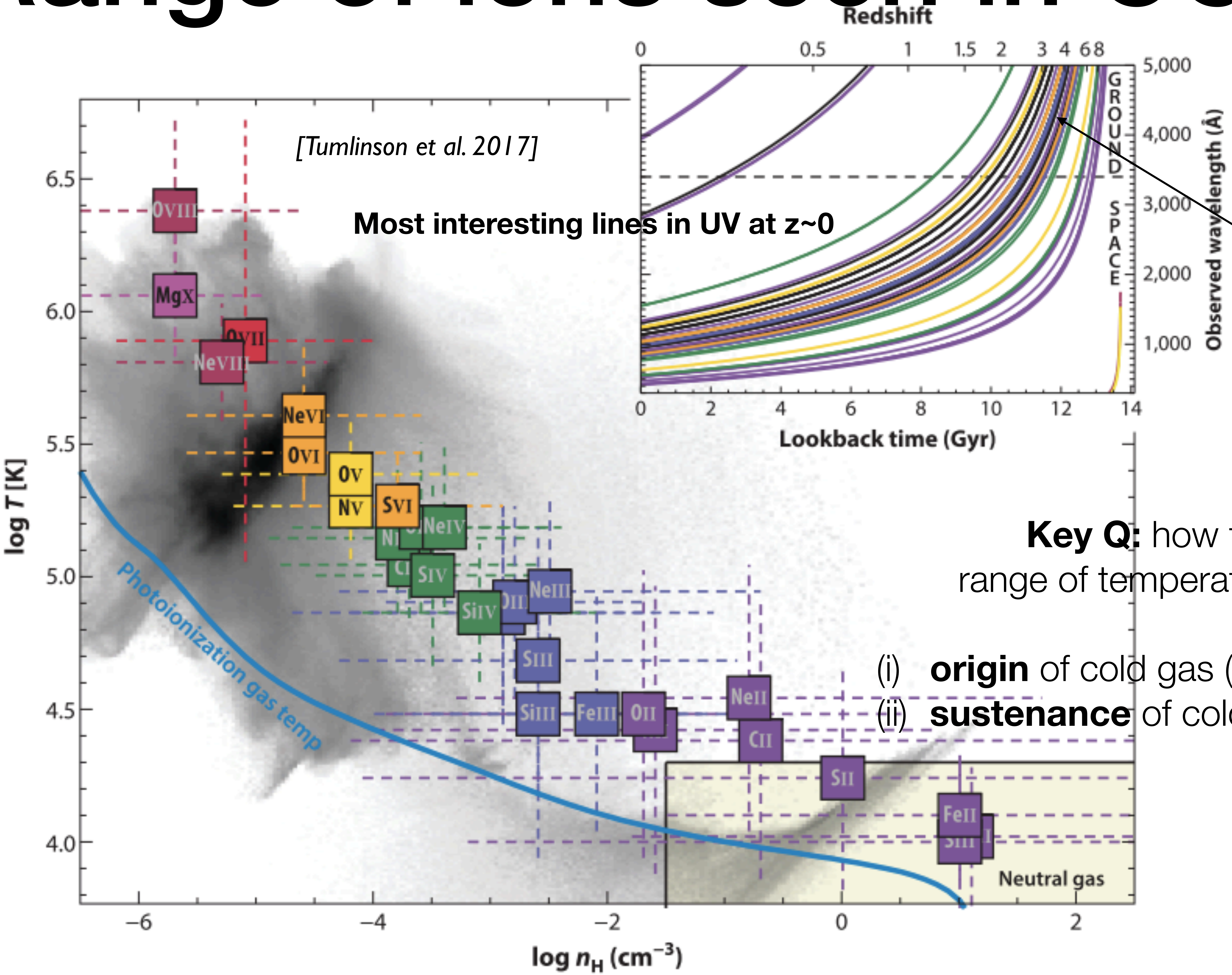


$\lambda_{obs} = \lambda_{em}(1+z)$

lines redshift due to cosmological expansion

Several surveys:
COS-Dwarfs, COS-LRG,
COS-DISK, CGM²…

Range of ions seen in CGM



Most interesting lines in UV at z~0

$\lambda_{obs} = \lambda_{em}(1+z)$

cosmological expansion

know a lot about z≳2

Key Q: how to explain the range of temperatures & densities?

(i) **origin** of cold gas (condensation, uplift)

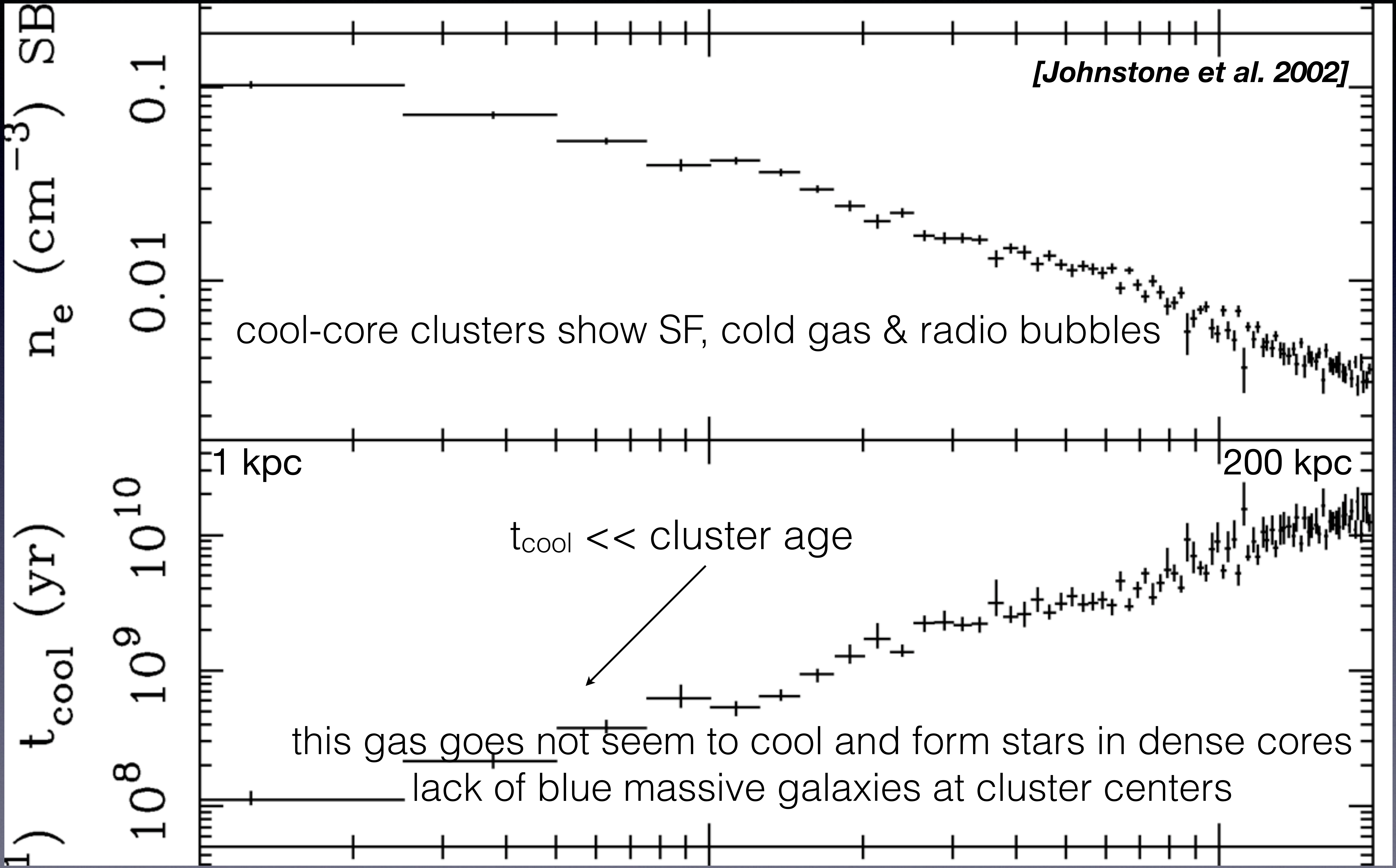
(ii) **sustenance** of cold gas (Cloud Crushing)

III. The origin of multiphase gas

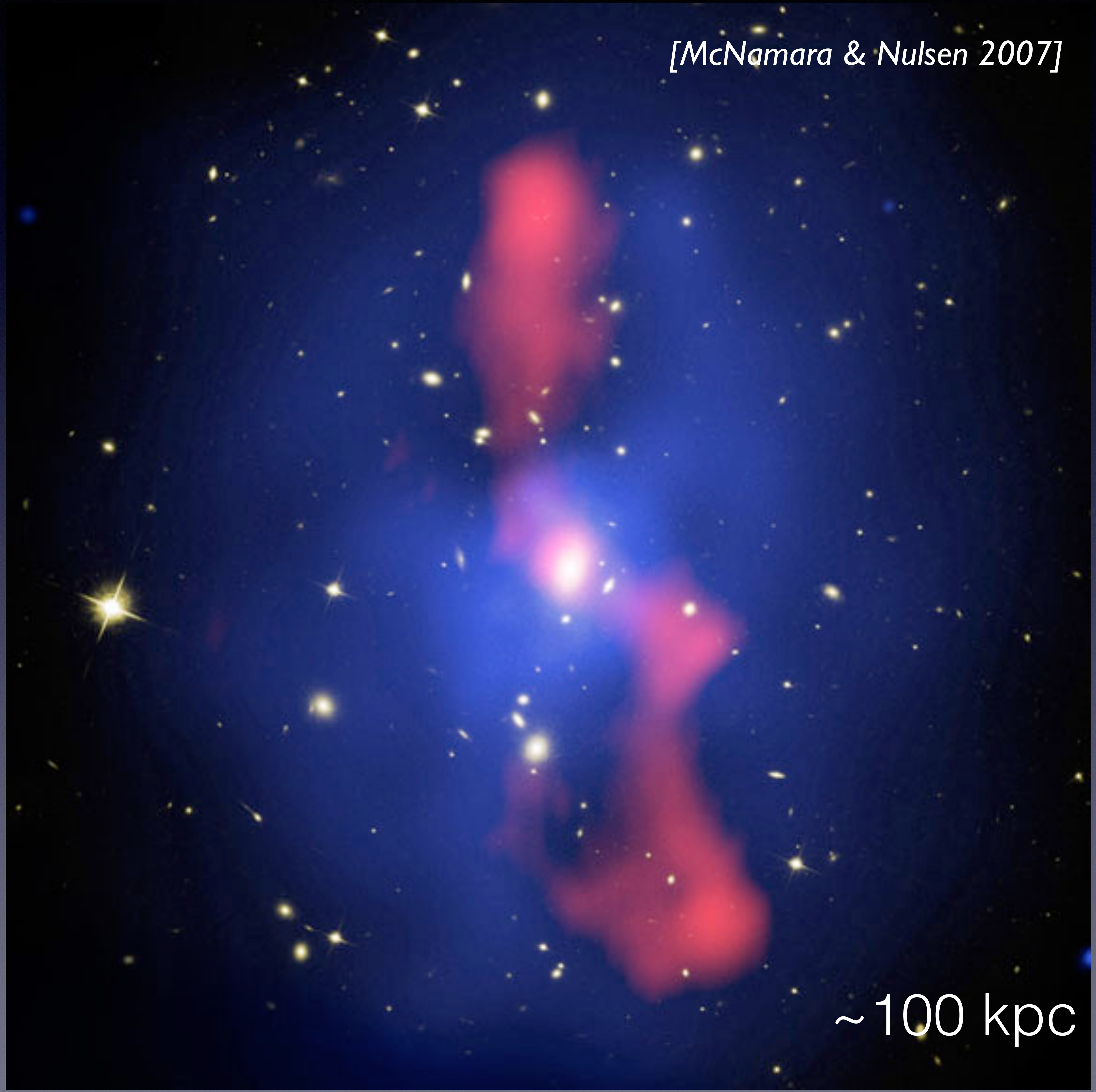
How is cold gas produced in the CGM/ICM?

(i) TI & condensation from the hot phase;
(ii) seeding by galaxy wakes, IGM filaments
(iii) uplift of dense gas by distributed outflows

Cluster cooling flow problem



AGN Heating?



cooling ICM can power SMBH

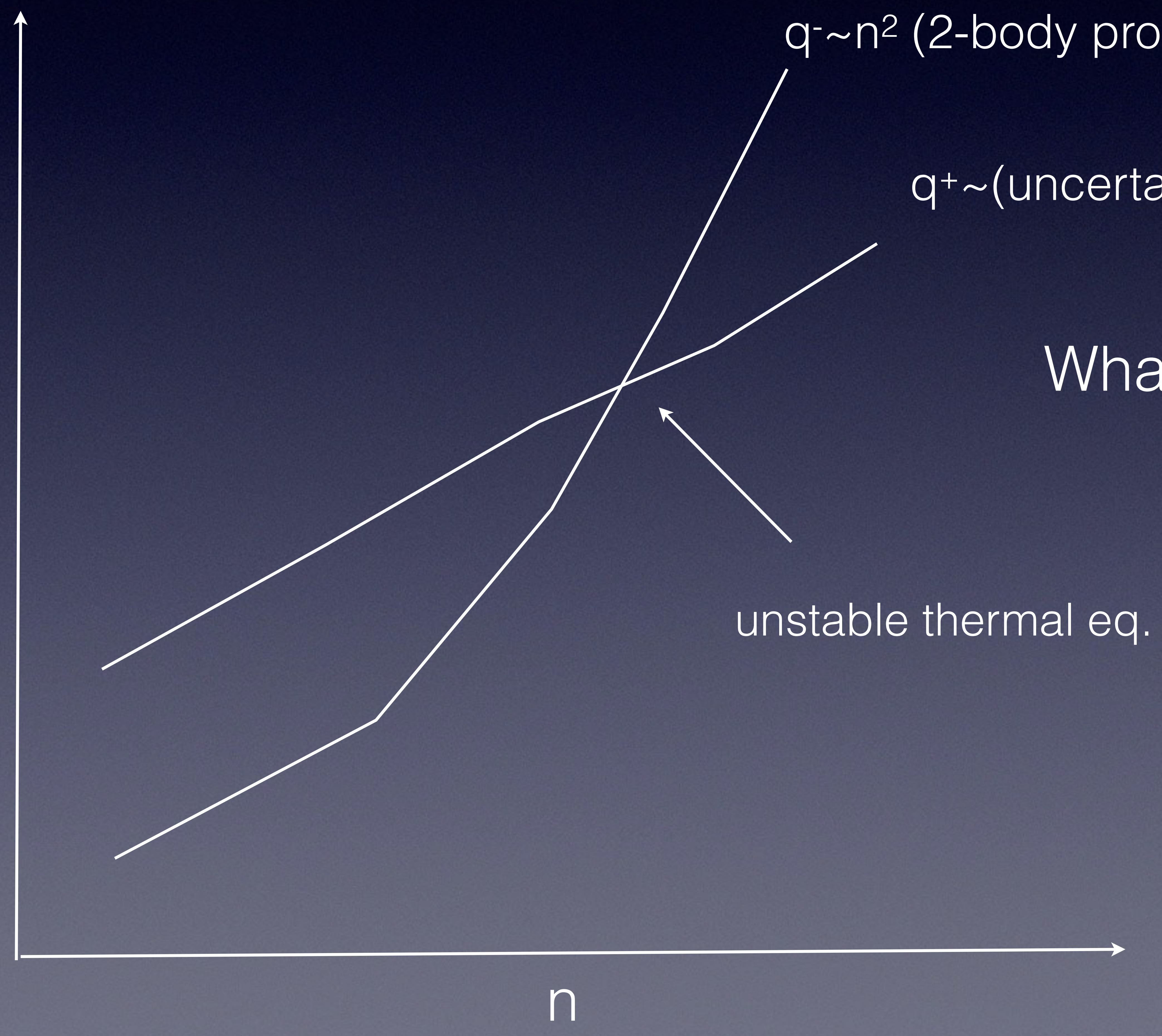
negative feedback loop prevents catastrophic cooling

jet/cavity power ~ X-ray luminosity & lack of cooling

=> rough thermal balance

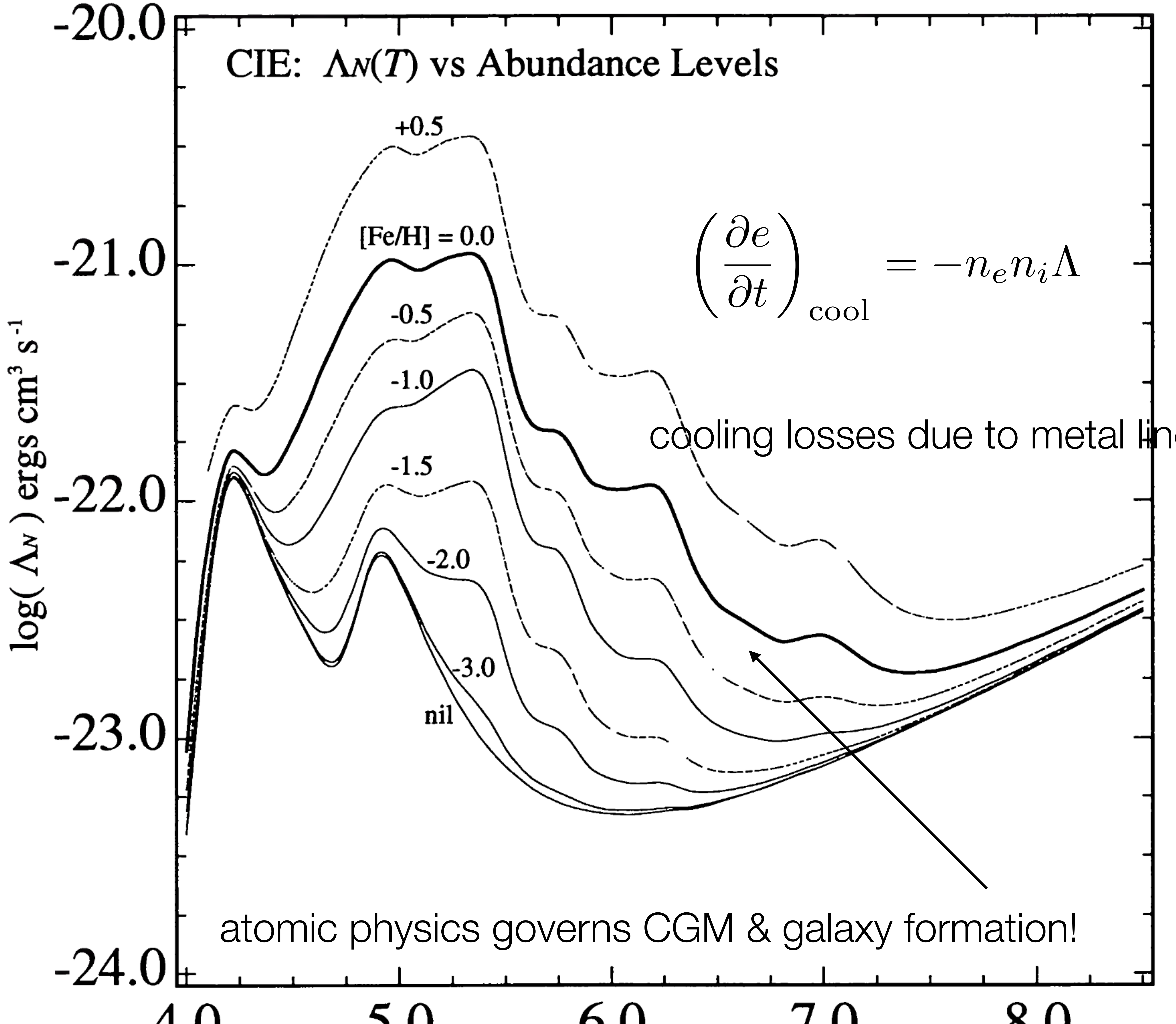
Thermal instability

AGN heating can balance cooling globally



What about local thermal stability?

Radiative cooling



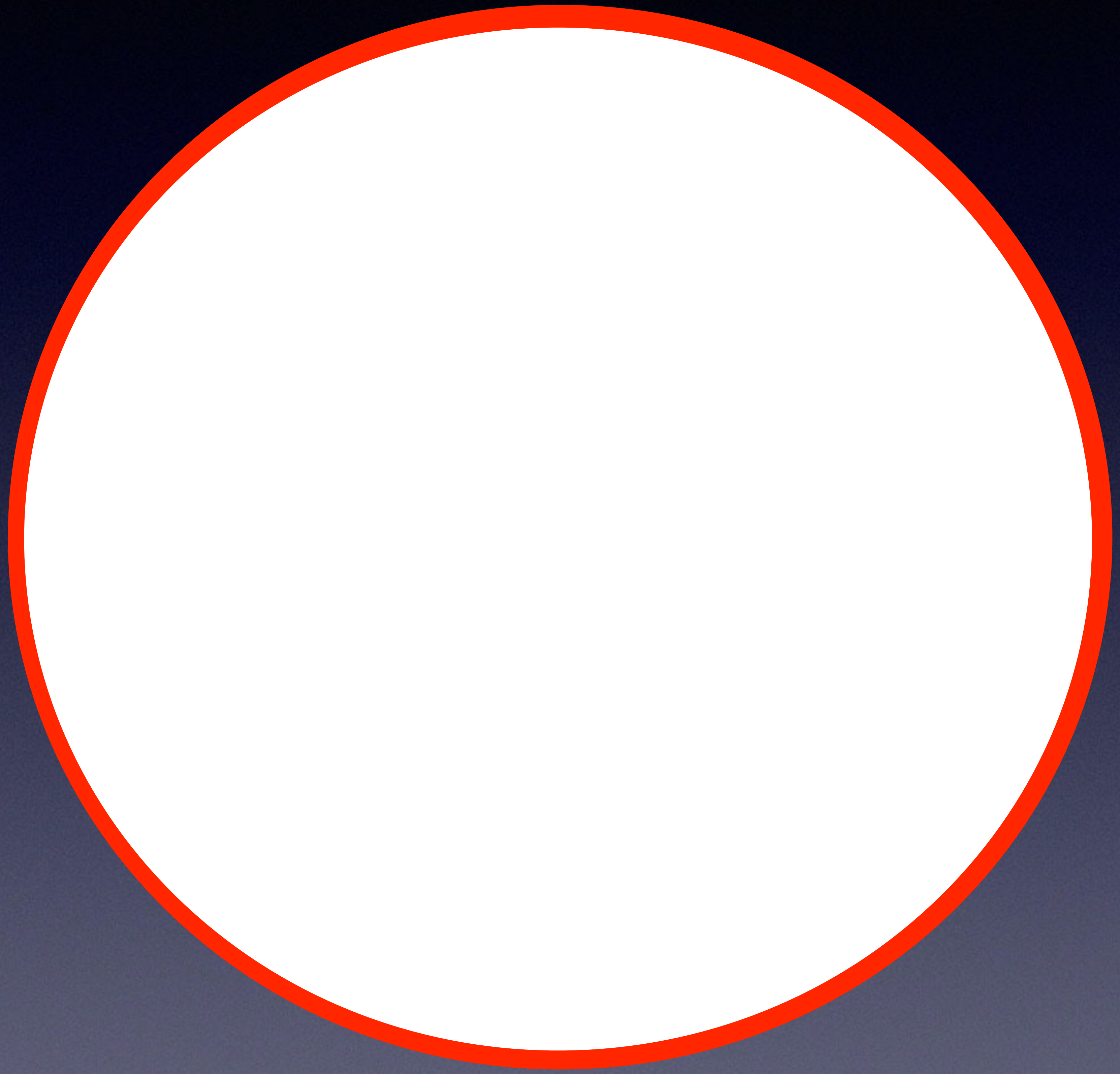
$$\left(\frac{\partial e}{\partial t}\right)_{\rm cool} = -n_e n_i \Lambda$$

cooling losses due to metal line & ff emission

atomic physics governs CGM & galaxy formation!

$\log_{10}[T(K)]$

Toy model



heating~cooling at every radius
(to explain lack of cooling flows)

hydrostatic equilibrium: $dp/dr = -\rho g$
gravity due to dark matter

how far can we go with
this simple model?

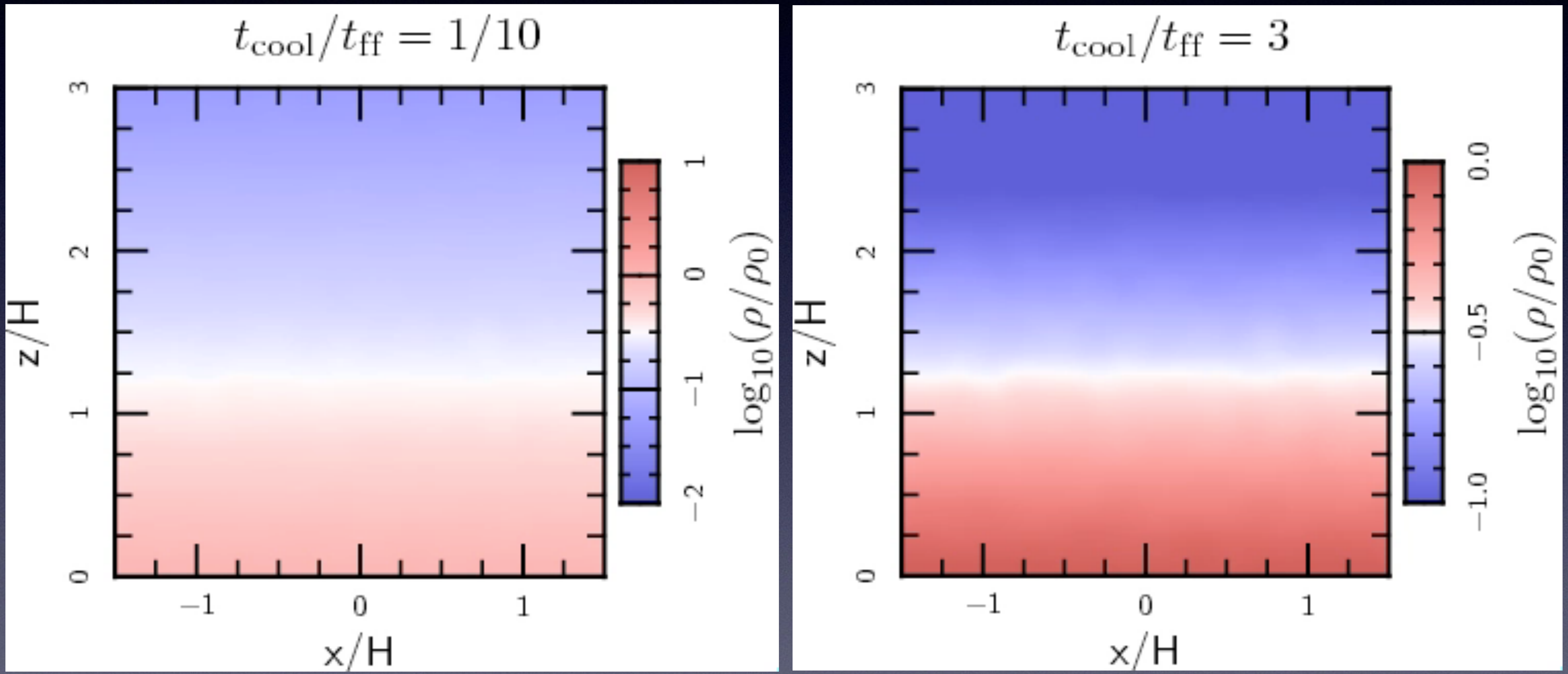
TI with gravity

-ansatz: heating = <cooling> at each ht. small density perturbns

-we know this is true globally

[McCourt et al. 2012]

gravity



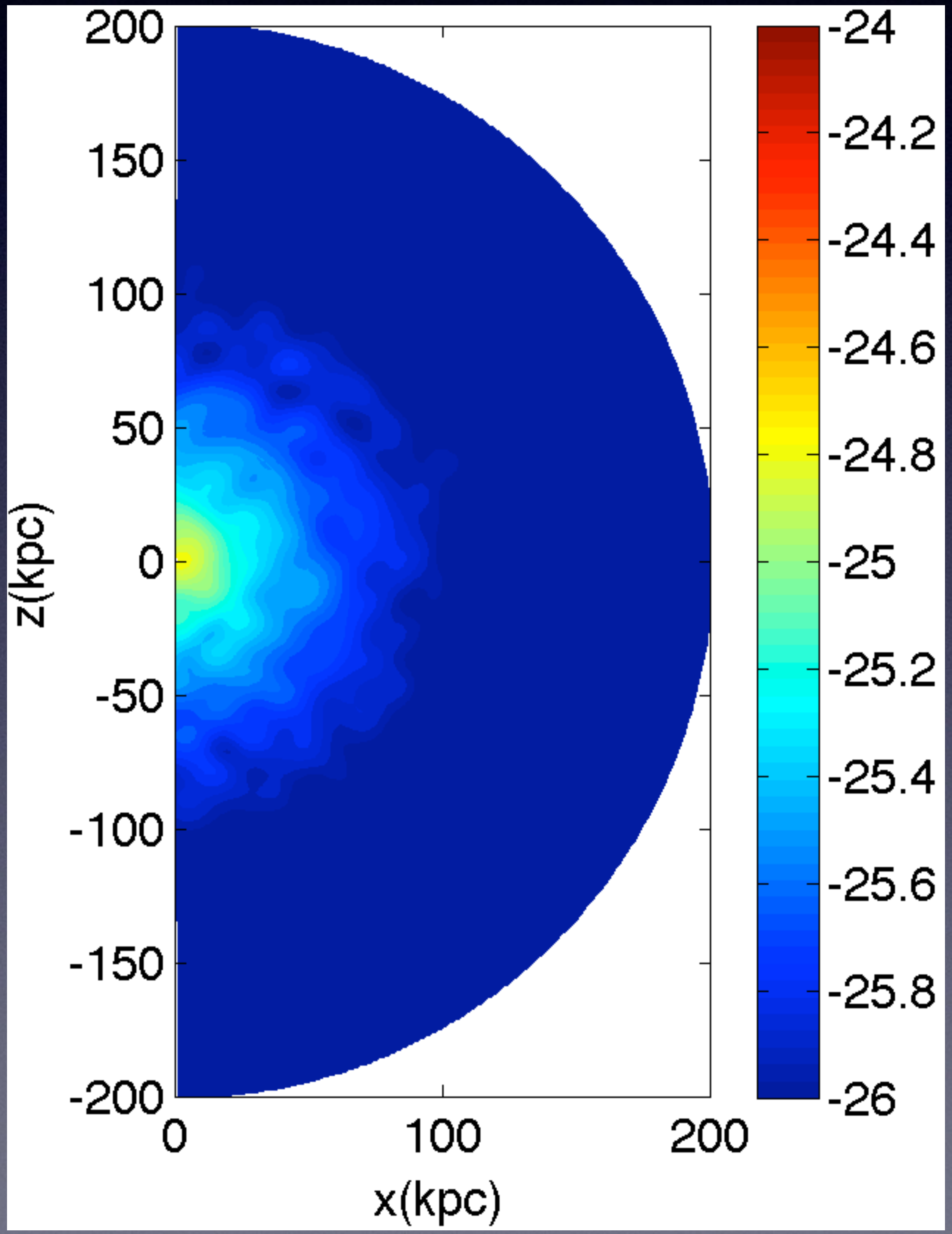
in-situ multiphase only when $t_{cool}/t_{ff} < 1$ (crucial parameter)

$$t_{\rm cool} = \frac{1.5 n k_B T}{n_e n_i \Lambda[T]}$$

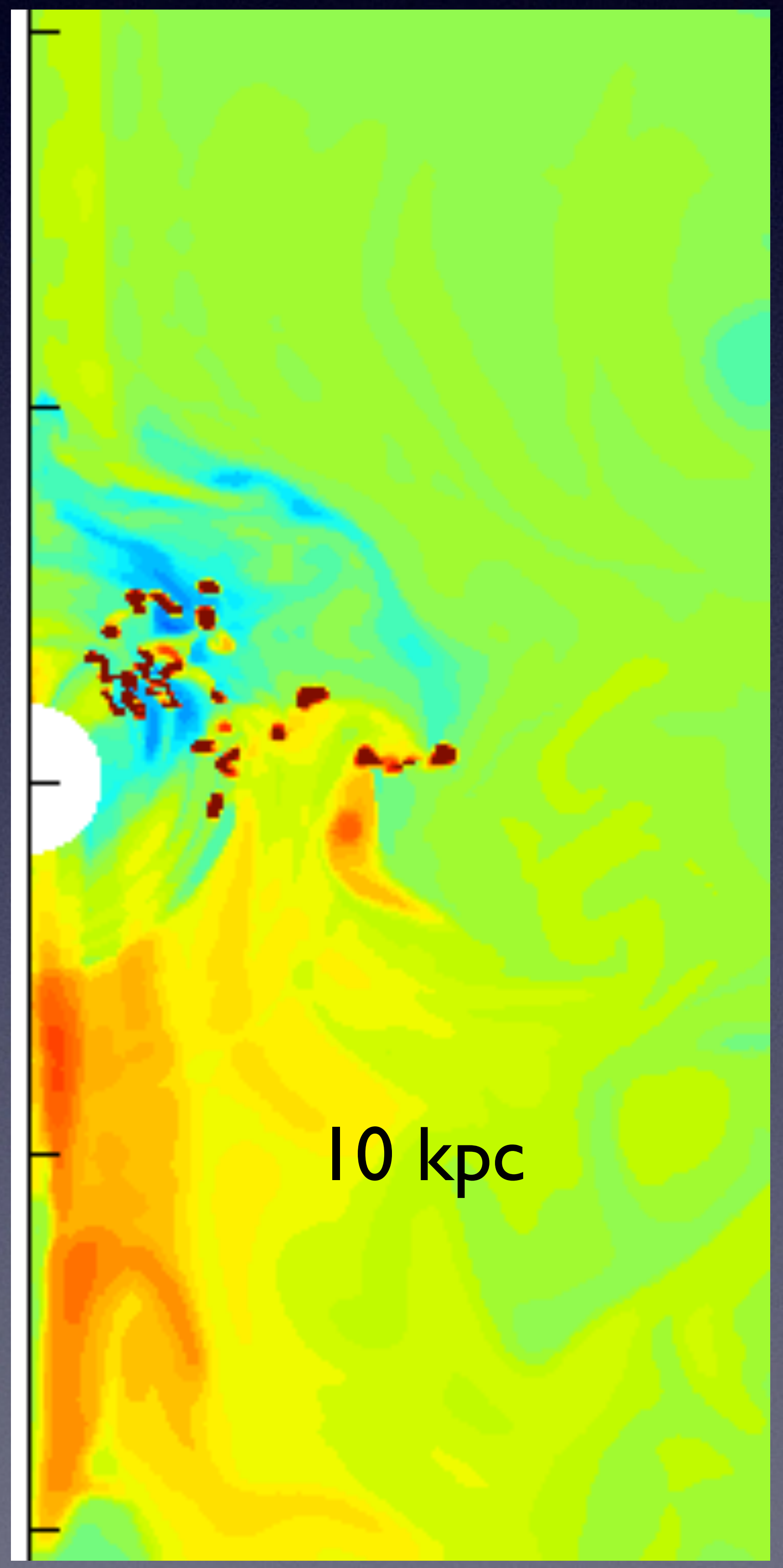
$$t_{\rm ff} = \sqrt{\frac{2r}{g(r)}}$$

Spherical sims. clusters

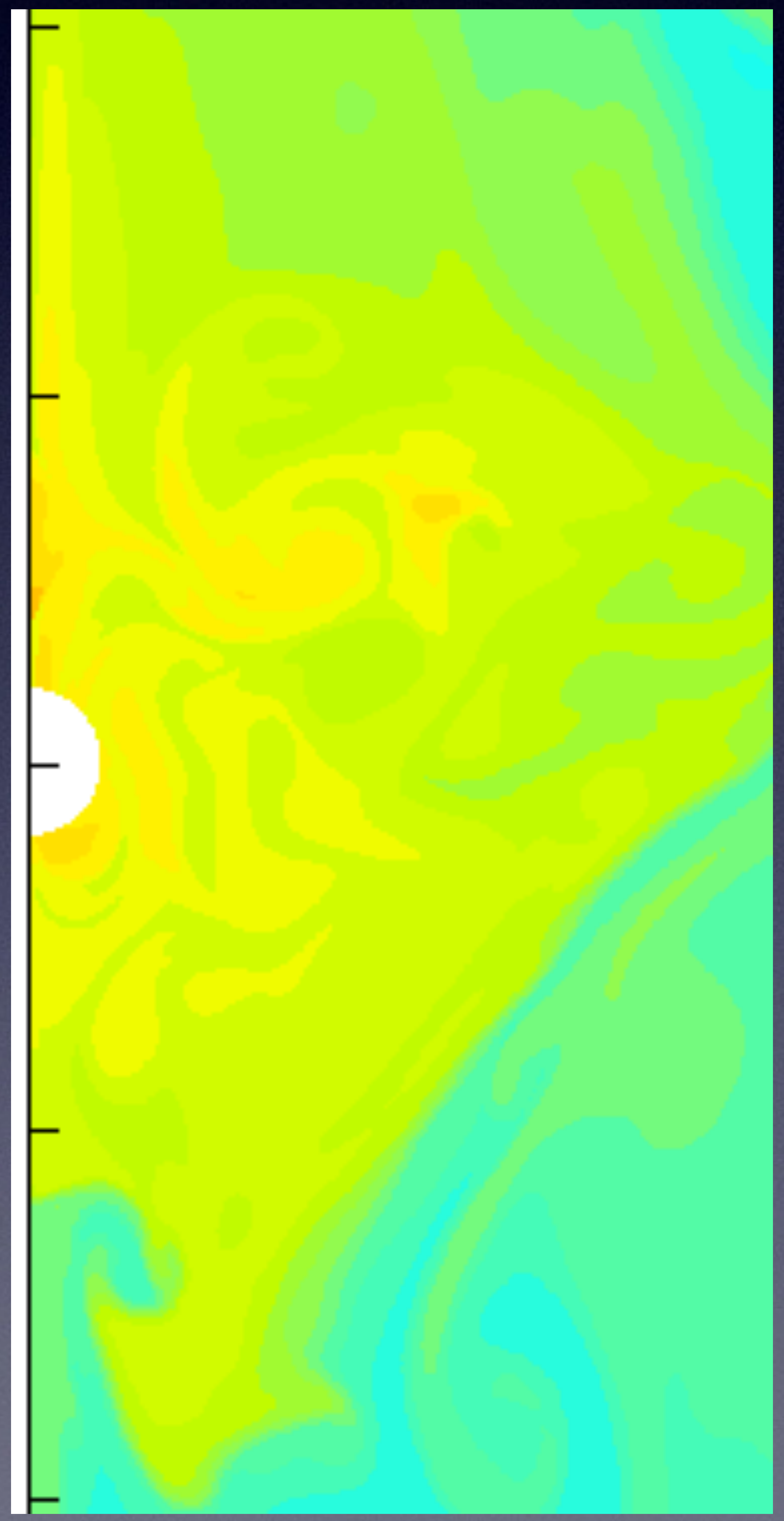
Log$_{10}$ density



multiphase
if t_{cool}/t_{ff} small!



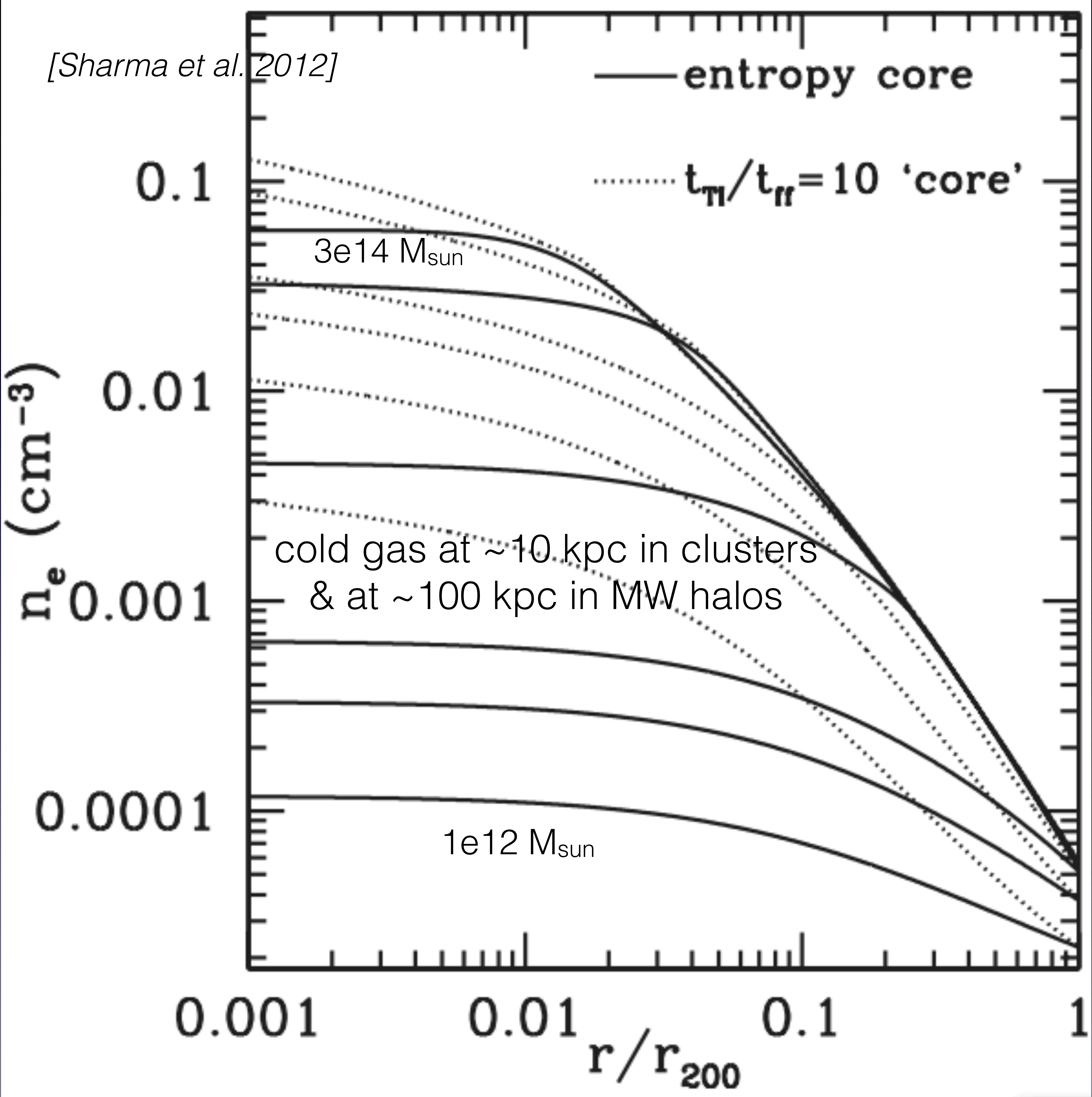
only hot phase
if t_{cool}/t_{ff} big!



[Sharma et al. 2012]

cool filaments when $t_{TI}/t_{ff} < 10$

ICM vs CGM



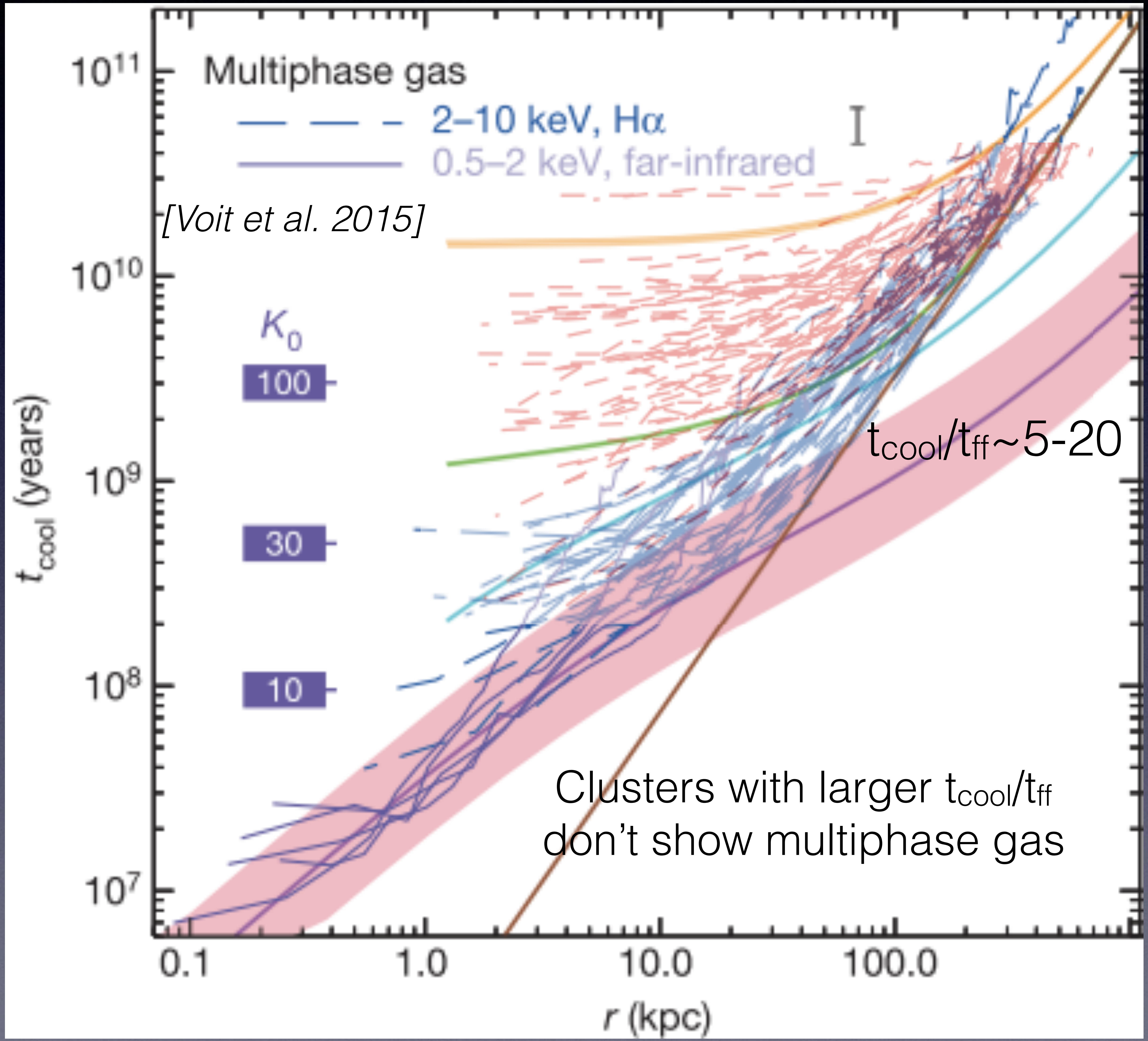
cooling/heating breaks self-similarity of hot gas!

t_{cool}/t_{ff}~10 threshold for hot CGM

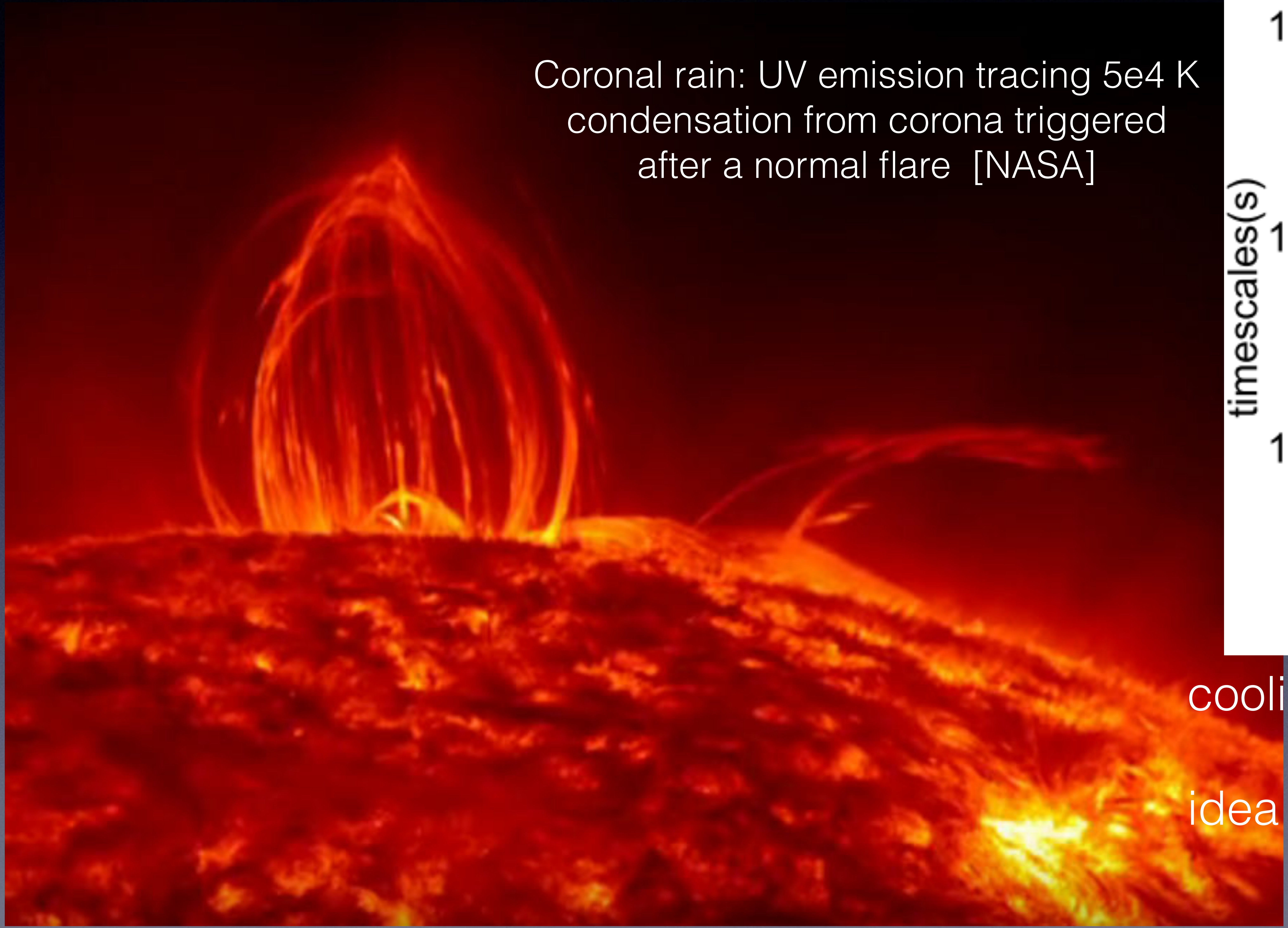
lower mass halos lower density

beware: cooling time for MW halos at viral radius ~ Hubble time; non-equilibrium effects!

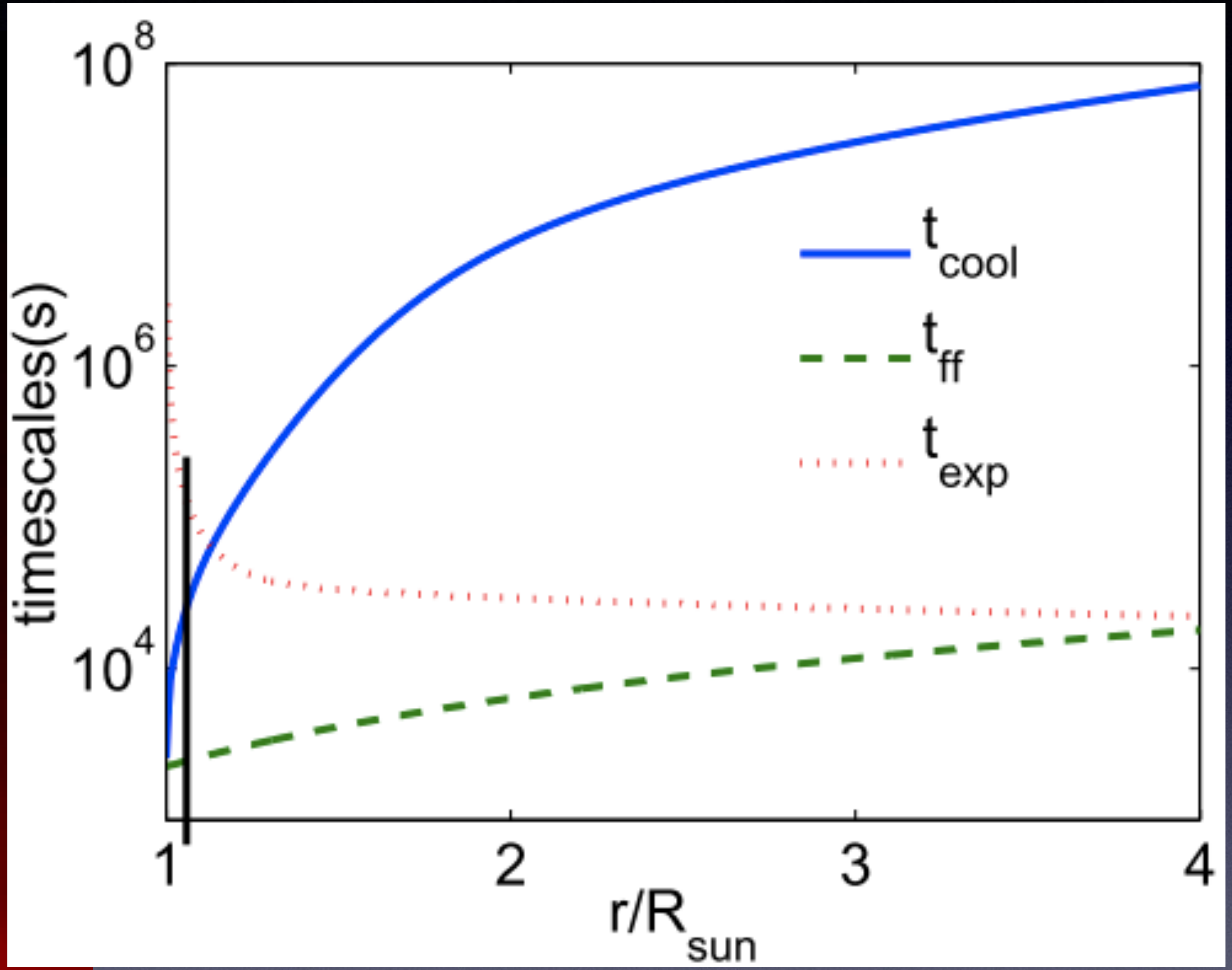
Observations & t_{cool}/t_{ff}



Ideas apply to smaller scales!



Coronal rain: UV emission tracing 5e4 K condensation from corona triggered after a normal flare [NASA]



cooling time ~ few hrs instead of 100 Myr

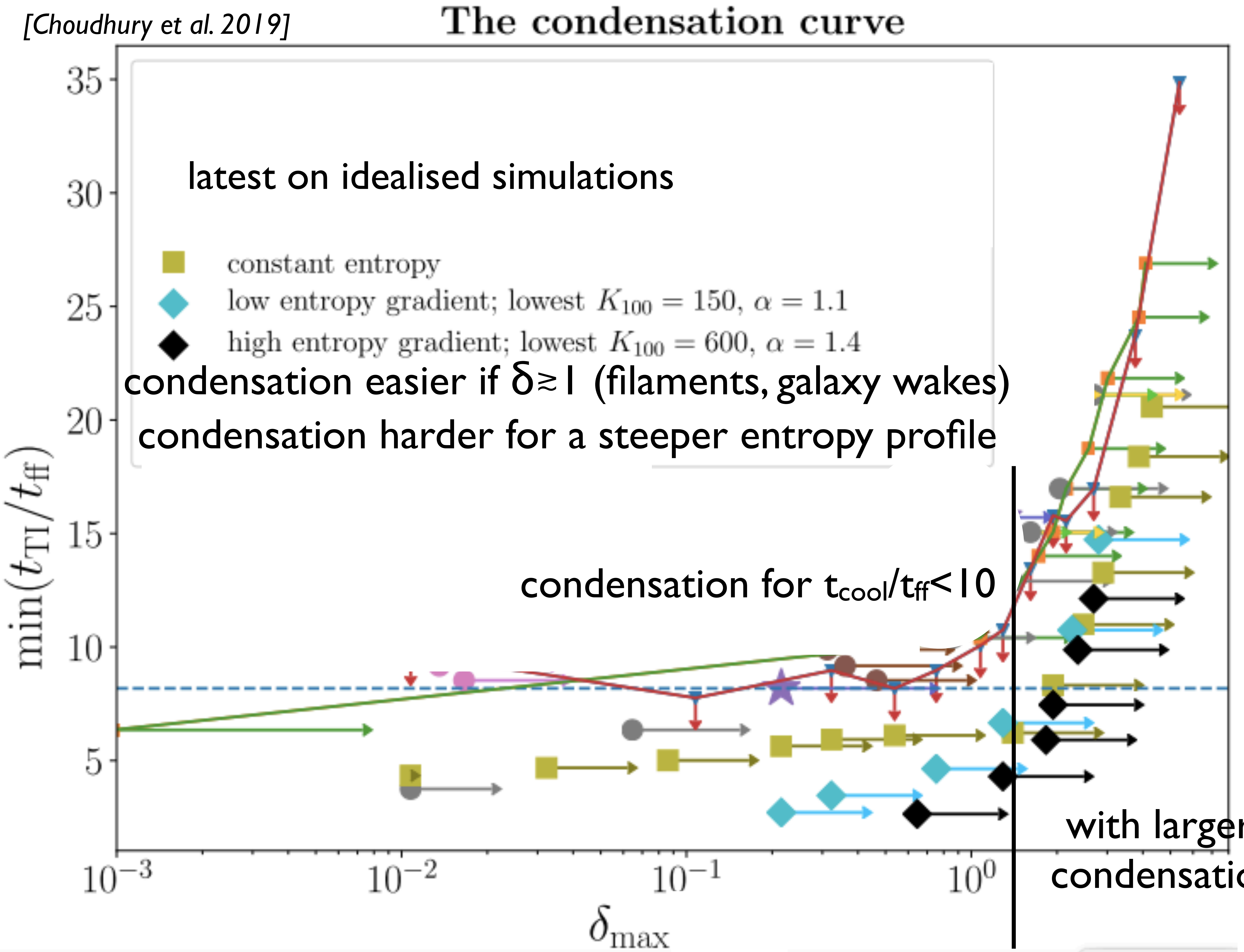
yet t_{cool}/t_{ff} similar!

idea generally applicable to ALL coronae

arXiv:1304.2408

Larger density perturbations

[Choudhury et al. 2019]



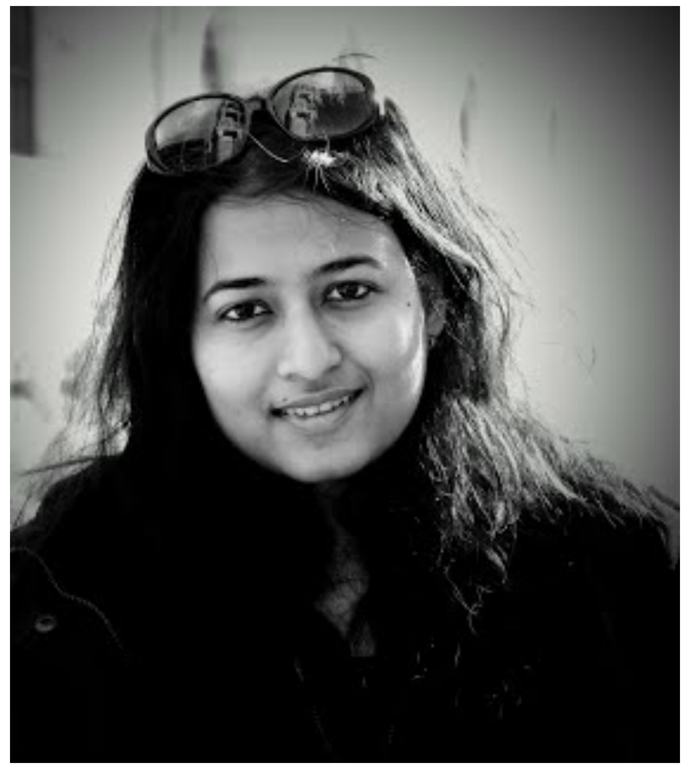
latest on idealised simulations

condensation easier if δ≳1 (filaments, galaxy wakes)

condensation harder for a steeper entropy profile

condensation for $t_{cool}/t_{ff}<10$

with larger density perturbations, condensation for lower bkg density

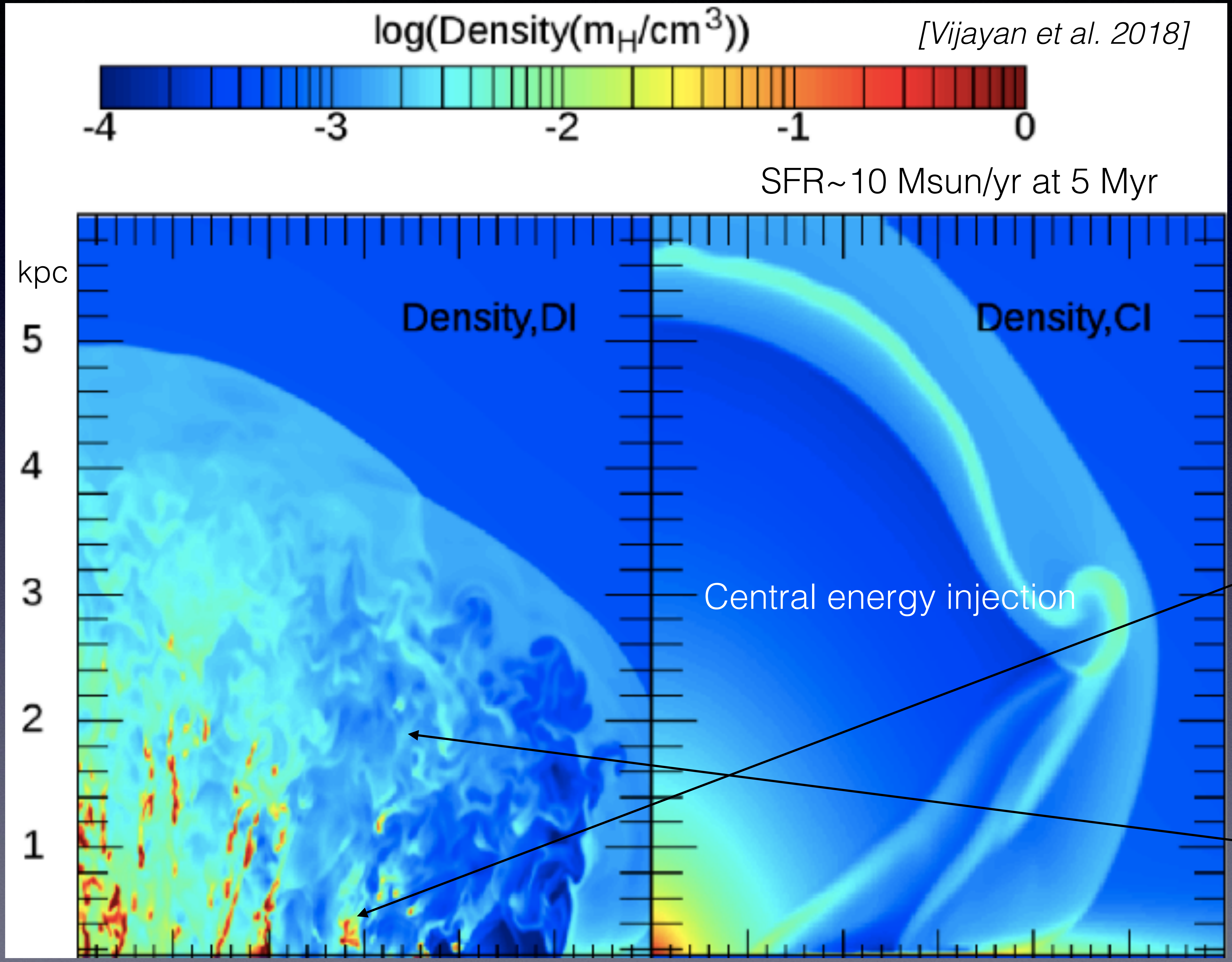


Prakriti Pal Choudhury

real galaxies have perturbations!
galaxy wakes & IGM filaments

dense gas column density in 1e13-14 halos [TNG50]

MP gas in galactic outflows



Aditi Vijayan

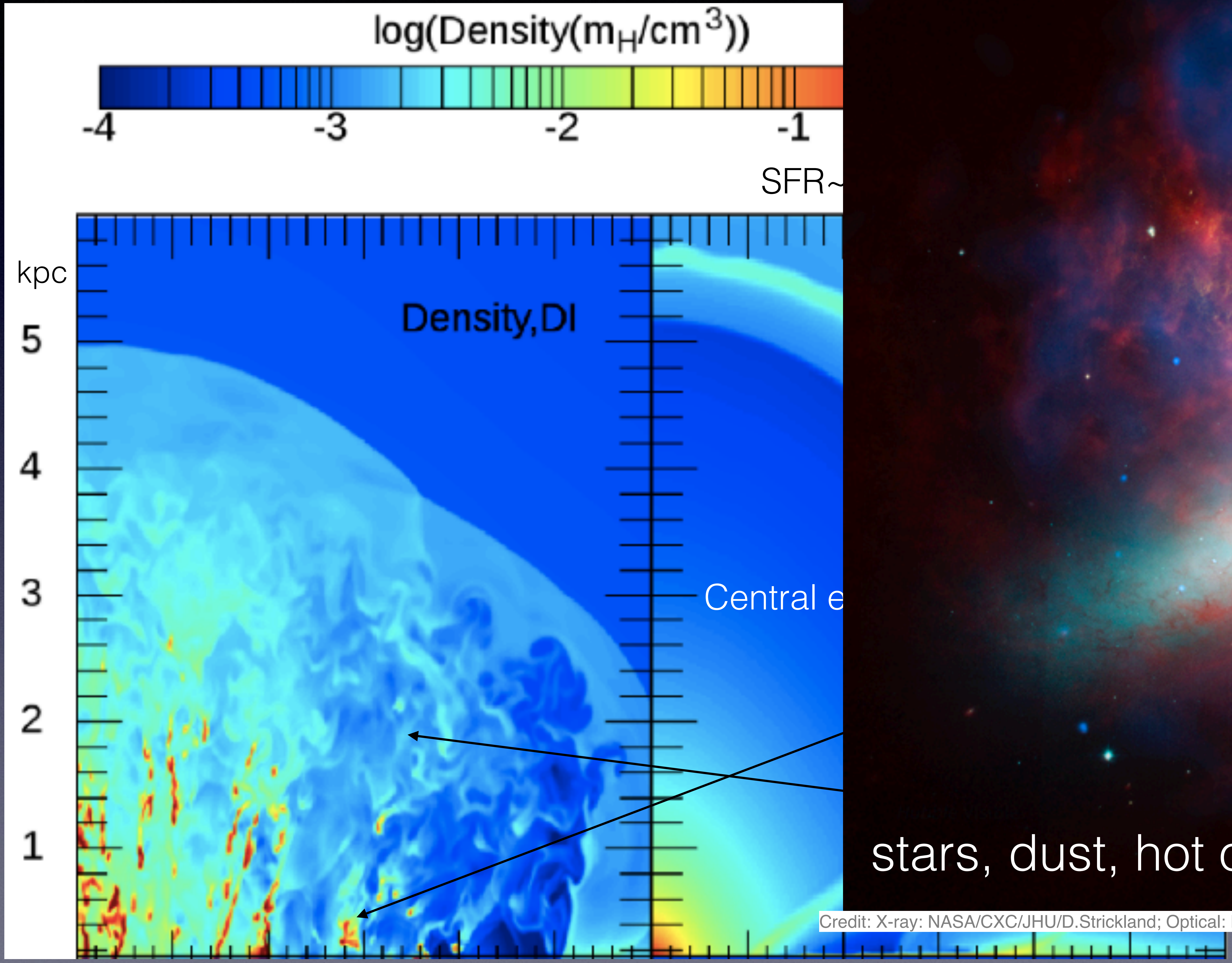
central injection doesn't give MP clouds

similar conclusions from Schneider et al. 2018

multiple *SN spread throughout* disc throw up cold clouds

Clouds cannot grow indefinitely in an expanding wind. How is growth stopped?

MP gas in galactic outflows



Credit: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

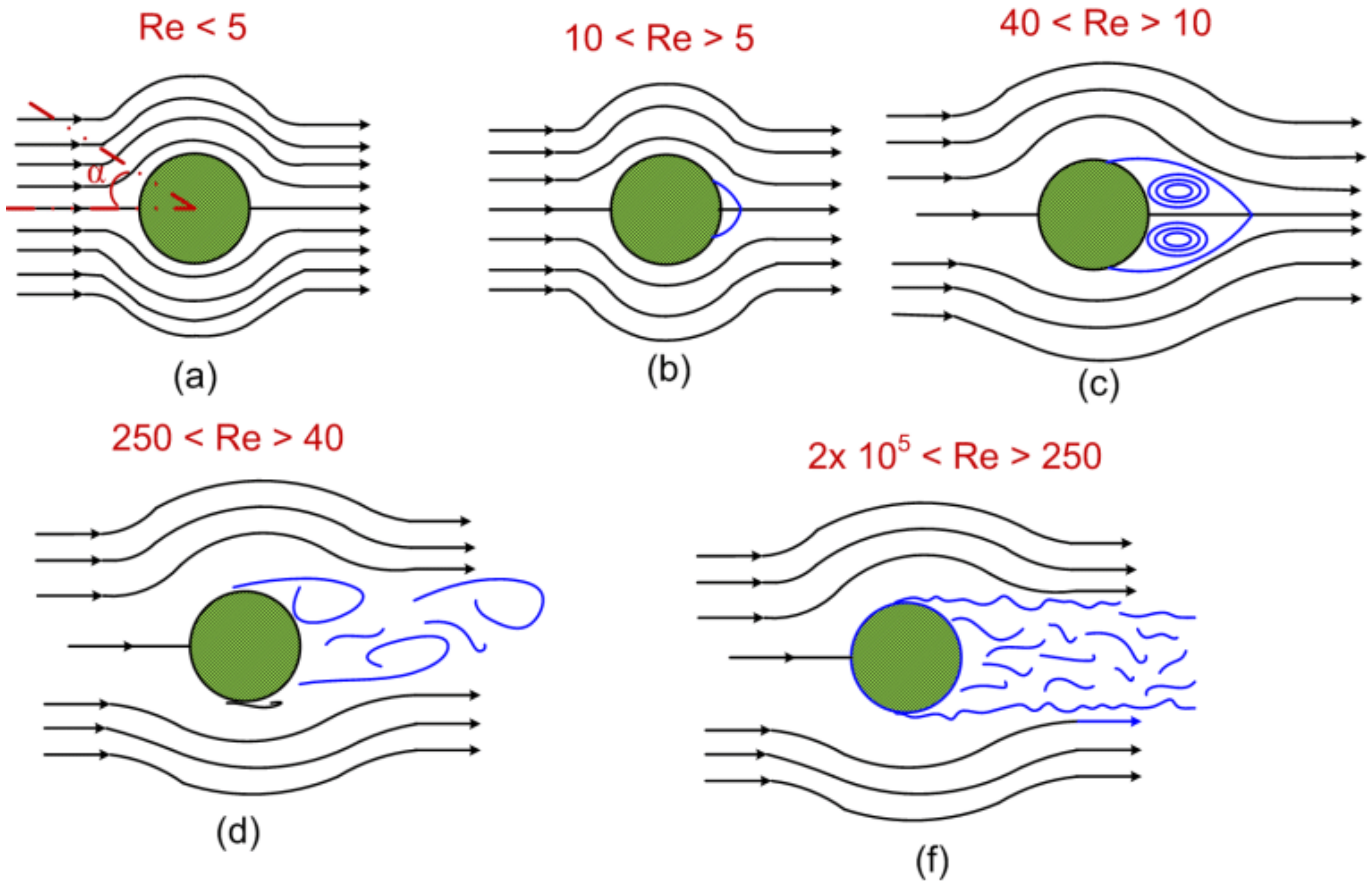
ın

expanding wind. How is growth stopped?

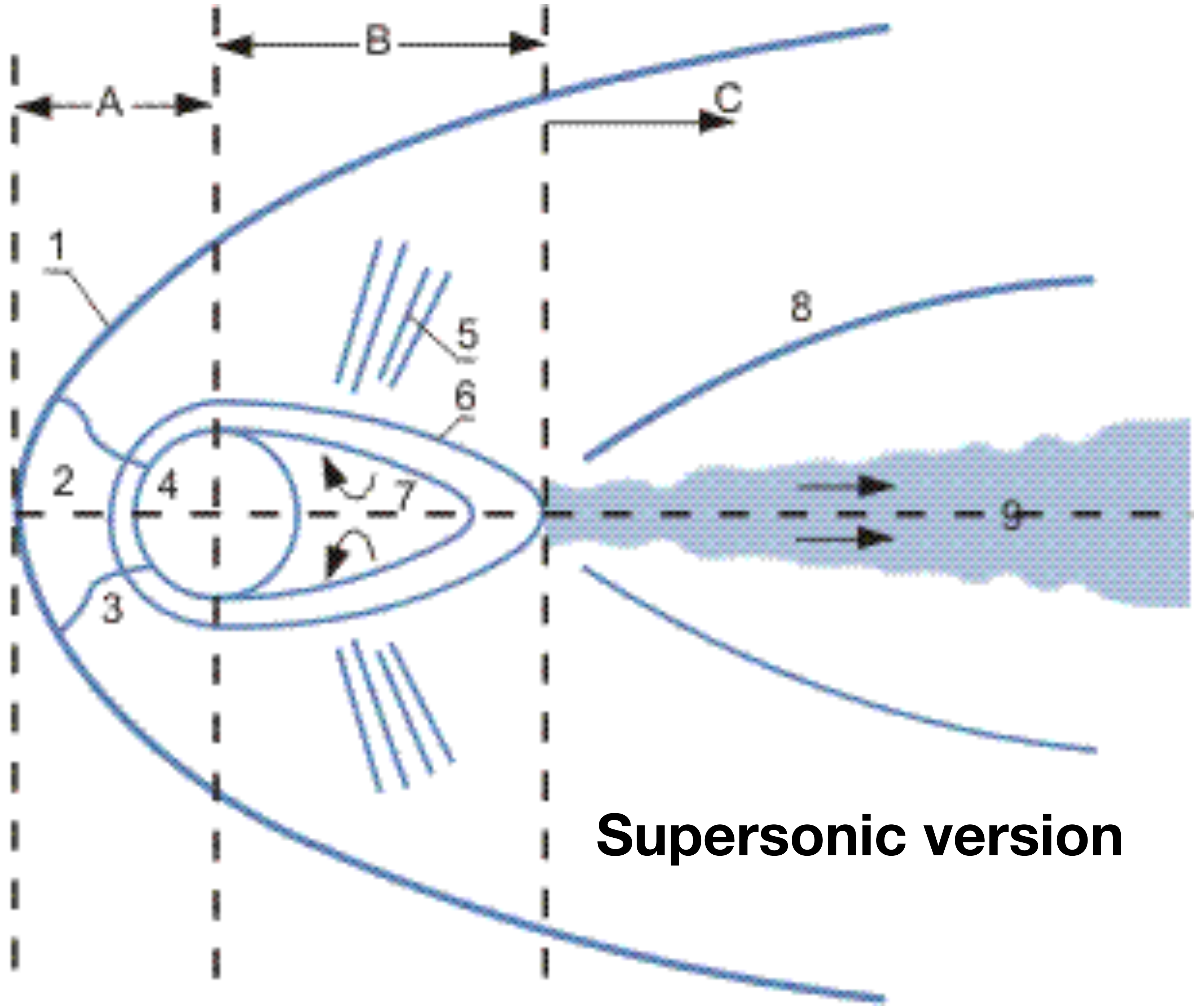
III. The cloud-crushing problem

Once cold gas is produced, it moves relative to the hot/diffuse background either due to gravity or as it is lifted by hot outflow
What is its fate? Small-scale problem

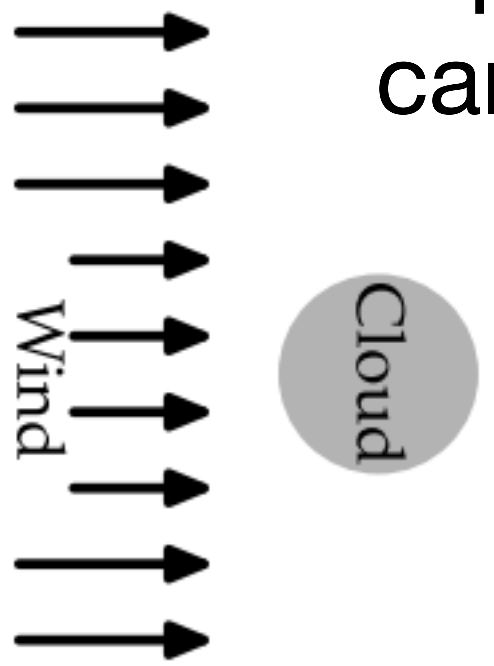
The cloud crushing problem



classic incompressible flow past a cylinder

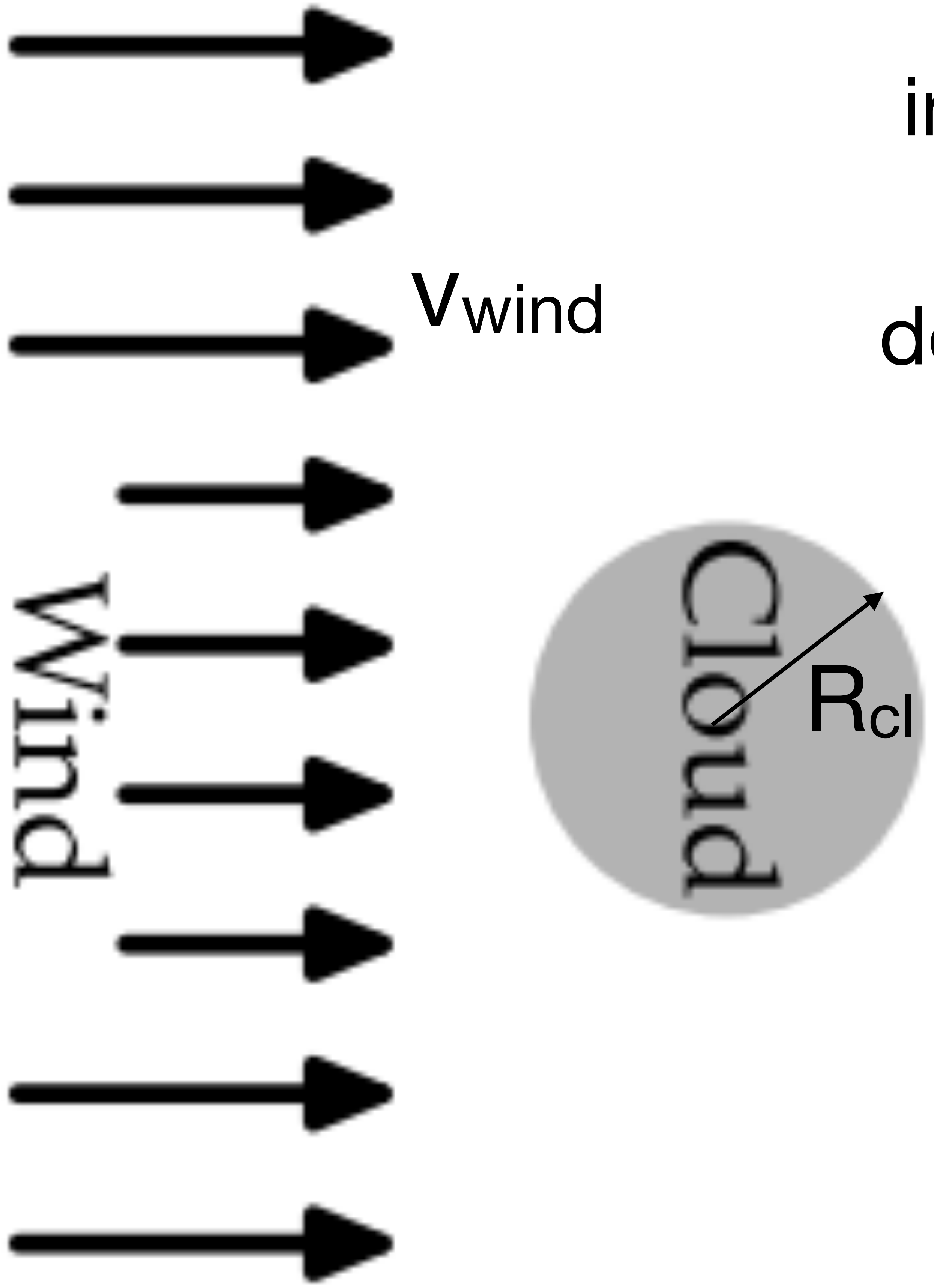


Supersonic version



except the dense cloud material can **mix with diffuse wind & be moved by it**

CCP: timescales



in pressure balance initially

density contrast $\chi = \rho_{\rm cl}/\rho_{\rm hot} = T_{\rm hot}/T_{\rm cl}$

Mach number $\mathcal{M} = v_{\rm wind}/c_{s,\rm hot}$

$$t_{\rm cross} = R_{\rm cl}/v_{\rm wind} = R_{\rm cl}/(\mathcal{M} c_{s,\rm hot})$$

$$t_{\rm cc} = \chi^{1/2} t_{\rm cross}$$

Kelvin-Helmholtz timescale
time for mixing dense cloud into wind

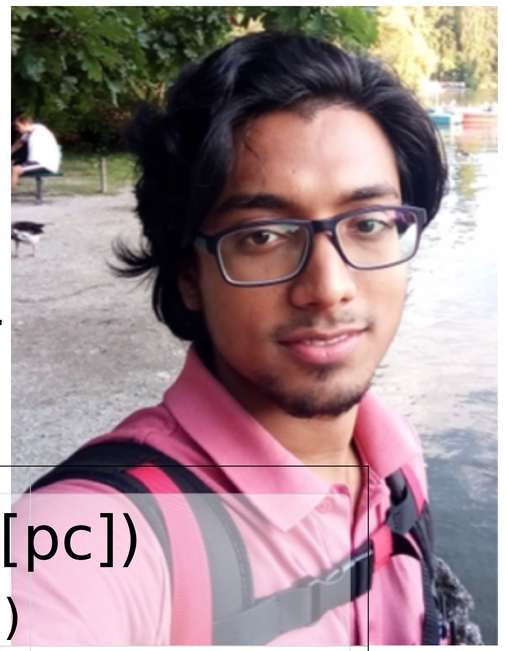
$$t_{\rm drag} = \chi t_{\rm cross}$$

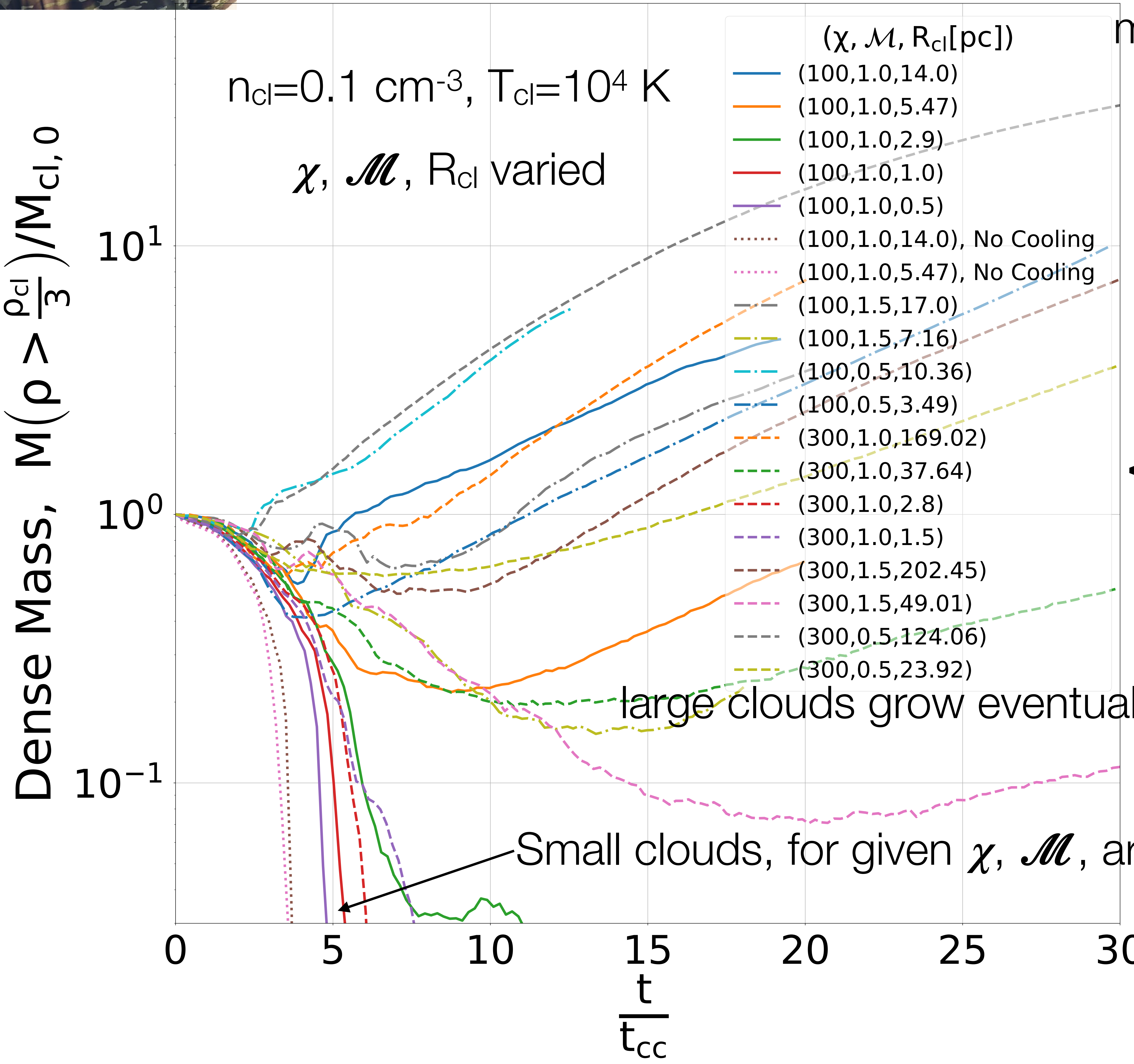
time over which hot wind pushes cloud
longer than CC time by $\chi^{1/2}$
=> cloud mixed before it can be pushed!

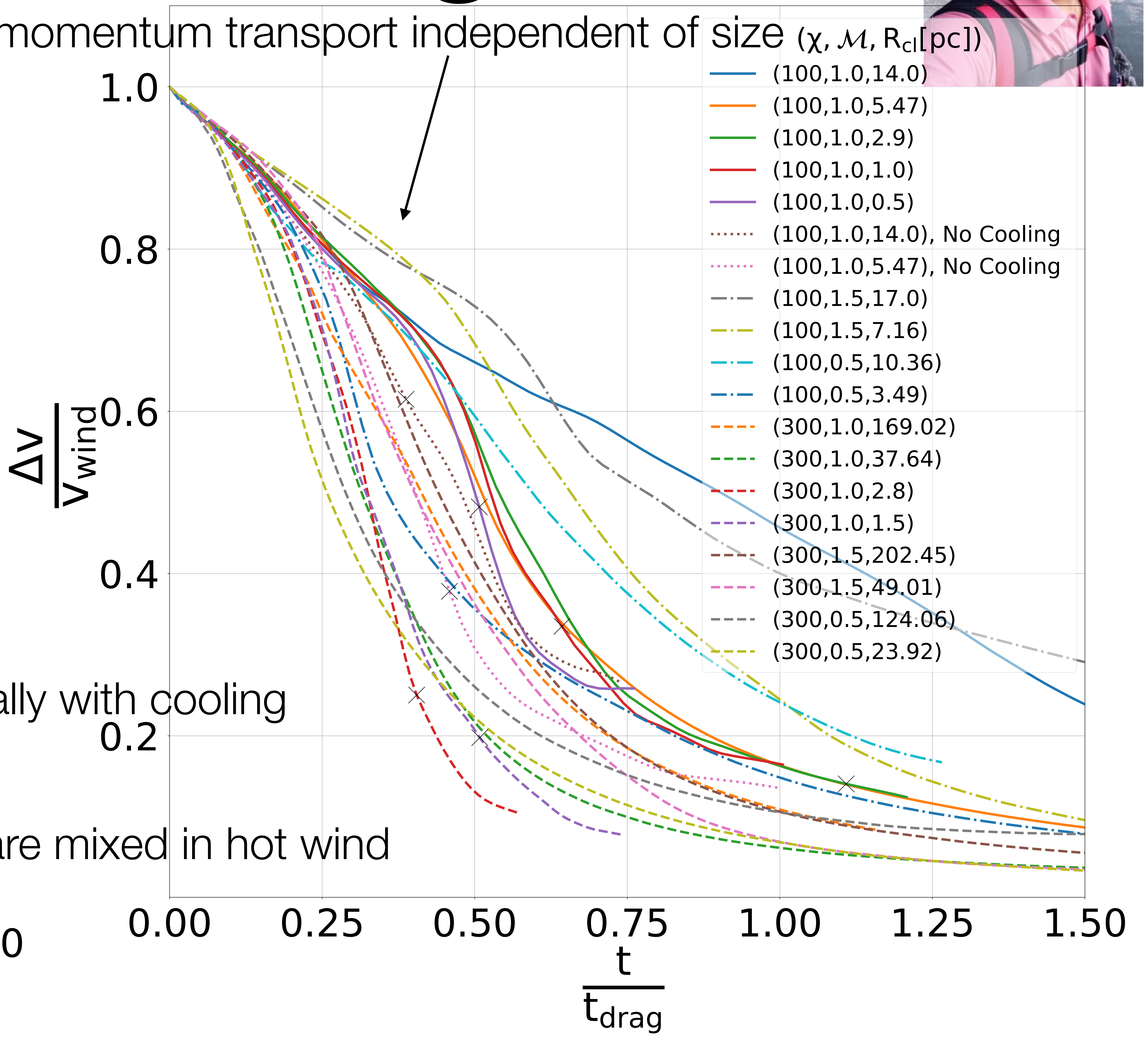
Vijit Kanjilal

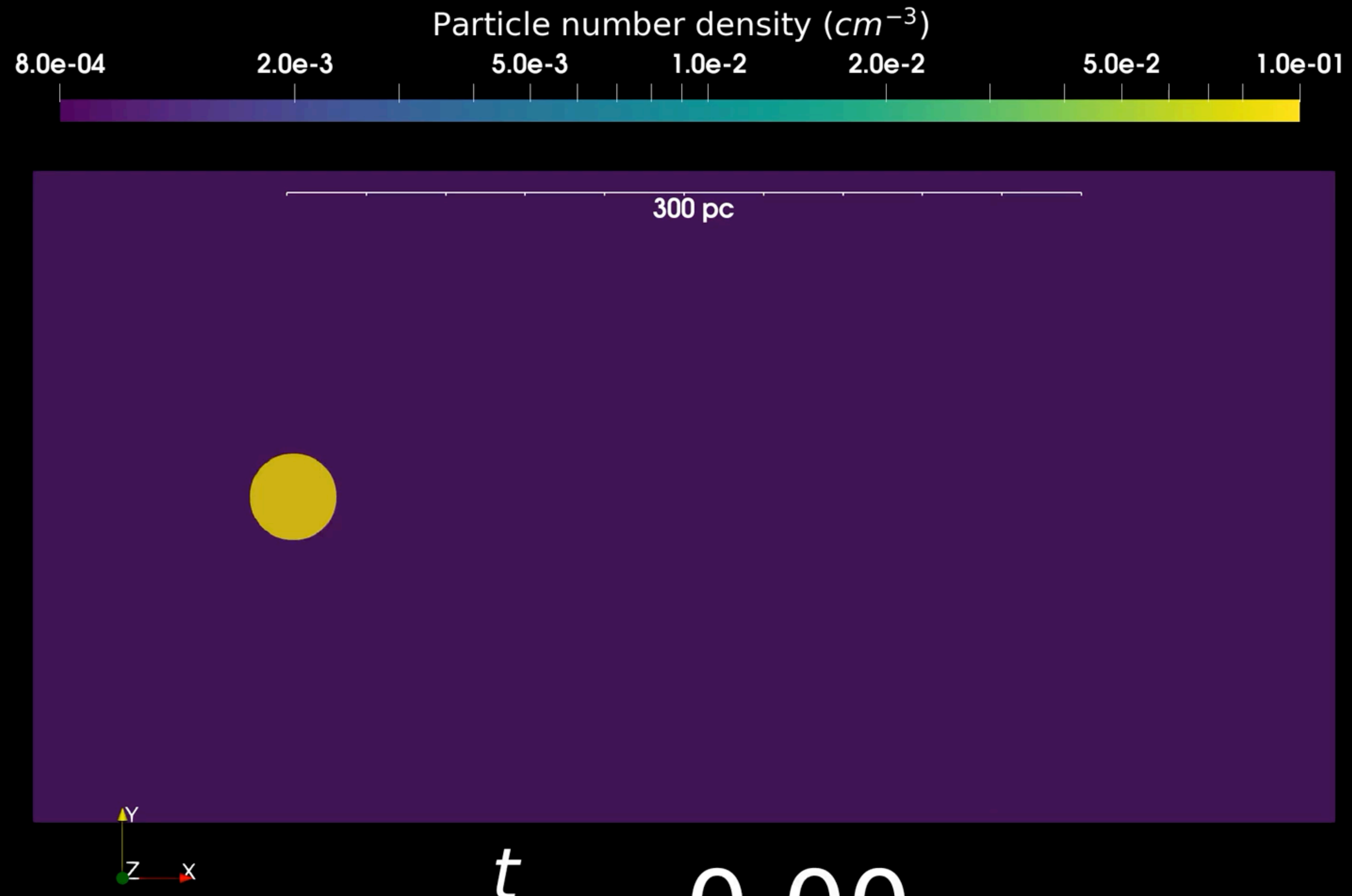
CC with cooling

Alankar Dutta









$$\frac{t}{t_{cc}} = 0.00$$

Parameters

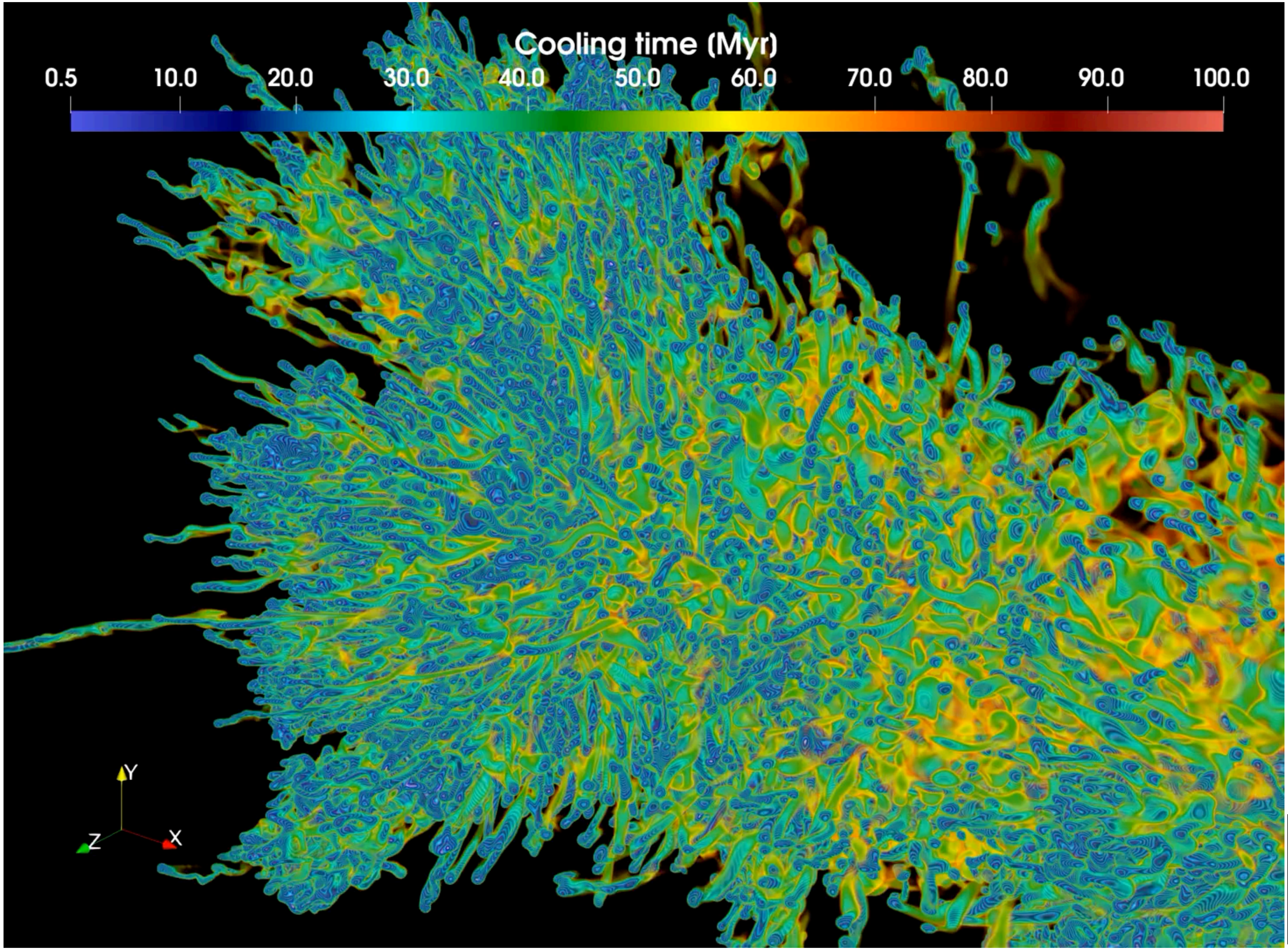
n_{cl}=0.1 cm^{-3}, T_{cl}=10^4 K

χ=100, $\mathcal{M}$=1, R_{cl}=14 pc

Box-size (30,15,15)R_{cl},
resolution R_{cl}/d_{cell}=64

PLUTO hydrodynamics code
Eqs. solved in a frame moving with cloud material

CIE cooling function for Z_{sun}
No cooling below 10^4 K



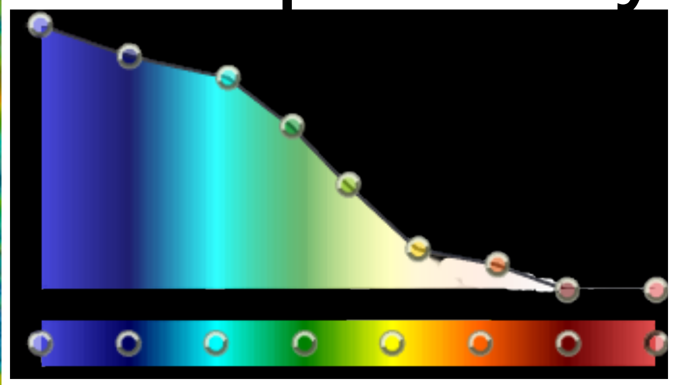
Volume rendering of cooling time

$$t \approx 14 t_{\rm cc}$$

Paraview+NVIDIA IndeX on GPU cluster SahasraT@IISc

Surfaces highly irregular!

Transparency



Growth criterion

$t_{\rm cool,mix}/t_{\rm cc} \lesssim 1$ with $T_{\rm mix} \approx \sqrt{T_{\rm cl} T_{\rm hot}}$

Gronke-Oh criterion [2018]

$$R_{\rm GO} \approx 2\,{\rm pc}\frac{T_{\rm cl,4}^{\frac{5}{2}}\mathcal{M}}{P_3 \Lambda_{\rm mix,-21.4}}\frac{\chi}{100} = 2\,{\rm pc}\frac{T_{\rm cl,4}^{\frac{3}{2}}\mathcal{M}}{n_{\rm cl,0.1}\Lambda_{\rm mix,-21.4}}\frac{\chi}{100}$$

$R > R_{\rm GO}$ implies cloud growth
smaller clouds destroyed

Other groups question this, but our simulations are consistent with this!

$t_{\rm cool,hot}/(\bar{f} t_{\rm cc}) \lesssim 1$ Li et al. [2020]: *hot gas* cooling time instead of *mixed-gas* cooling time!

$$R_{\rm Li} \approx 15.4\,{\rm pc}\frac{T_{\rm cl,4}^{\frac{12}{13}}\mathcal{M}^{\frac{4}{13}}}{n_{\rm cl,0.1}\Lambda_{\rm hot,-21.4}^{\frac{10}{13}}}\left(\frac{\chi}{100}\right)^{\frac{20}{13}}$$

Li radius is more than 10 times larger!

We resolve this apparent discrepancy: arXiv:2009.00525

Concluding Thoughts

- CGM can be studied in great detail with **so many observational probes**
- Where does the **cold gas** come from **in the first place**? Condensation due to thermal instability, perhaps seeded with large density fluctuations, uplift by outflows
- **Cloud-crushing problem:** a prototype of multiphase gas in CGM; turbulent boundary layers have gas at a range of Ts/ns.
- How do we stop dense mass growth? Size of cold clouds?

Thank You!