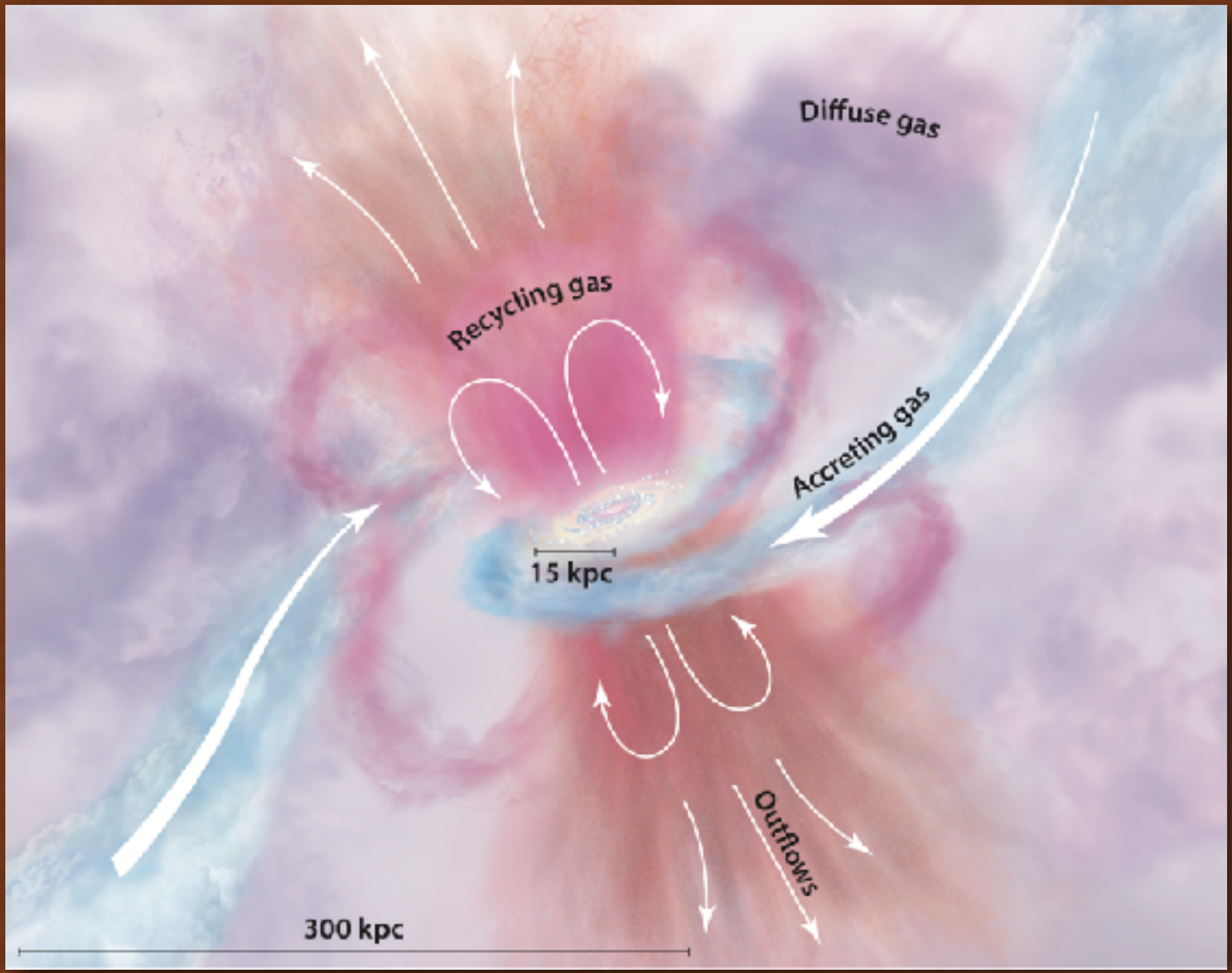


Tumlinson, Peeples & Werk (2017)

COLD GAS IN HOT HALOS

CHARGE FROM THE ORGANIZER

"a short stimulating or controversial (10min) talk to set the stage"

"challenge their main-stream thoughts"

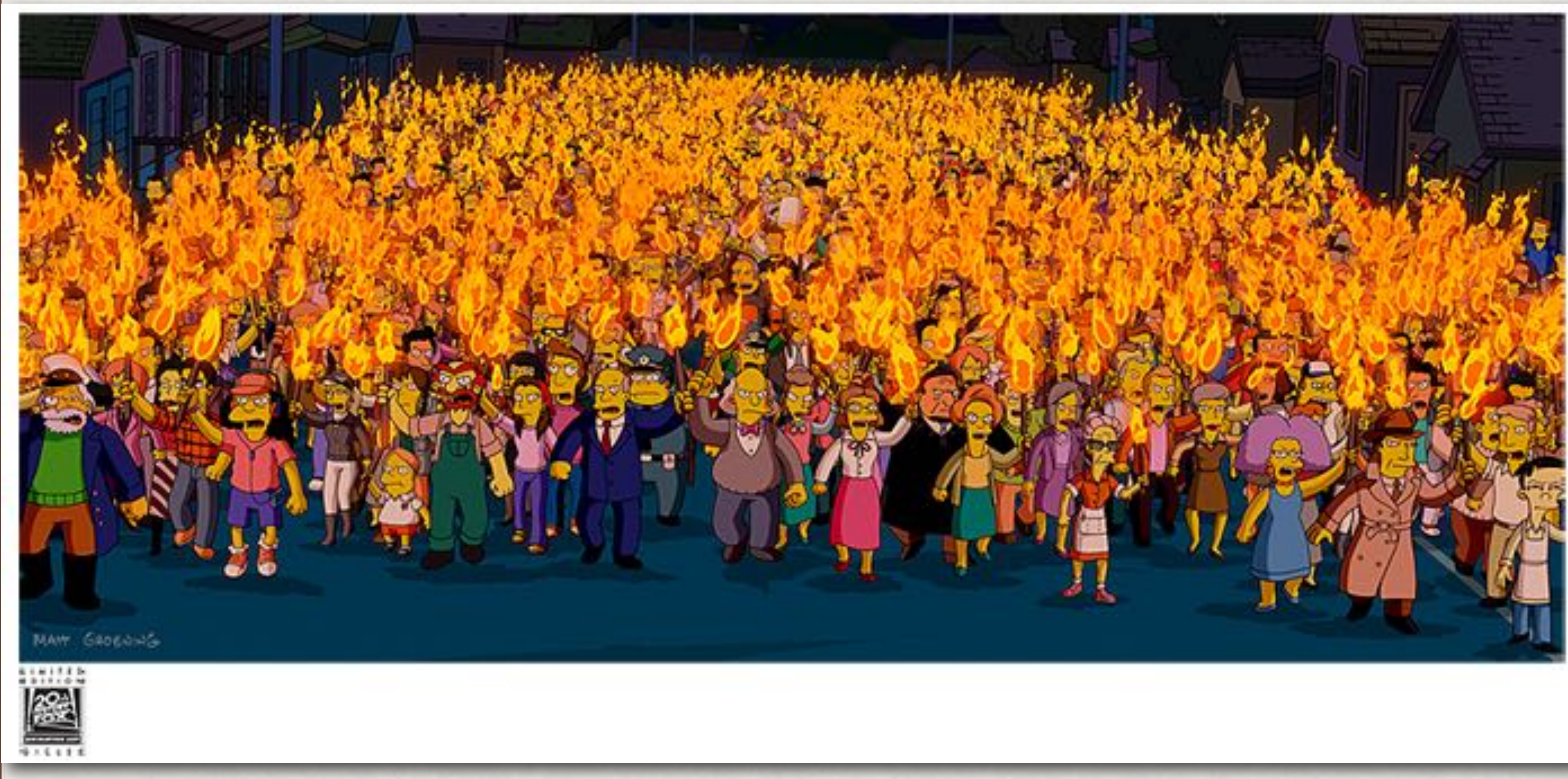
"food for thought to move towards a more physically oriented galaxy formation approach"

"a pedagogical introduction or pose a controversial statement"

"cover …the "fundamental scale of cold gas" etc"

CONCLUSION

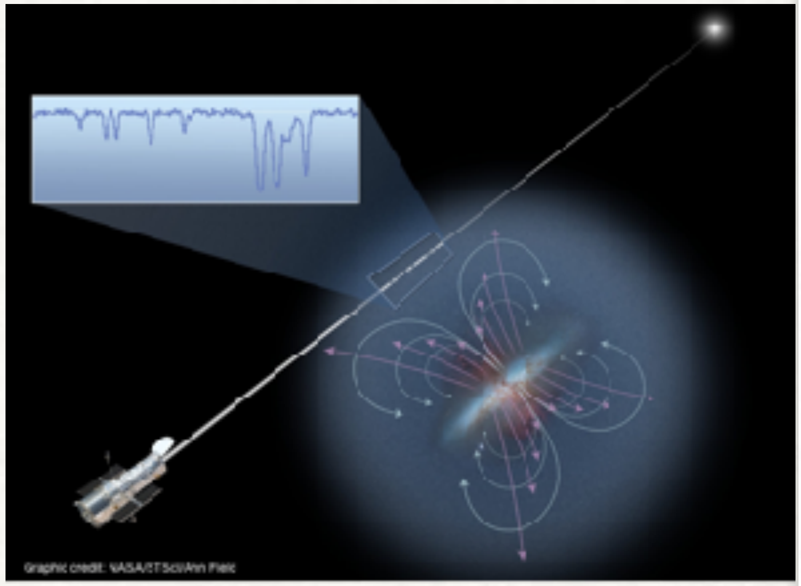
CHRISTOPH THINKS IT WOULD BE AMUSING IF I GOT LYNCHED

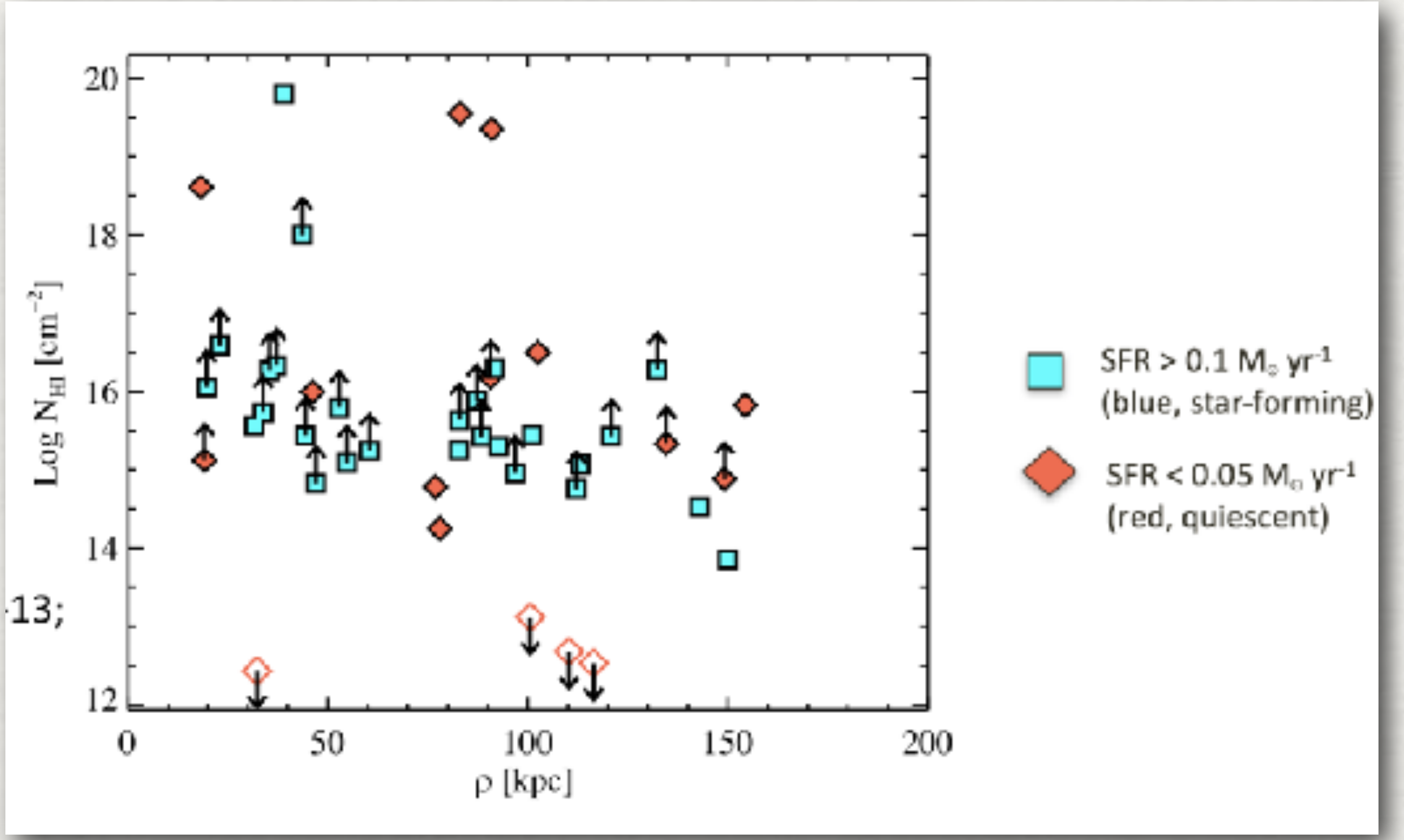


LET'S TALK ABOUT THE COLD GAS IN THE CGM

WHY?

It's what we can see



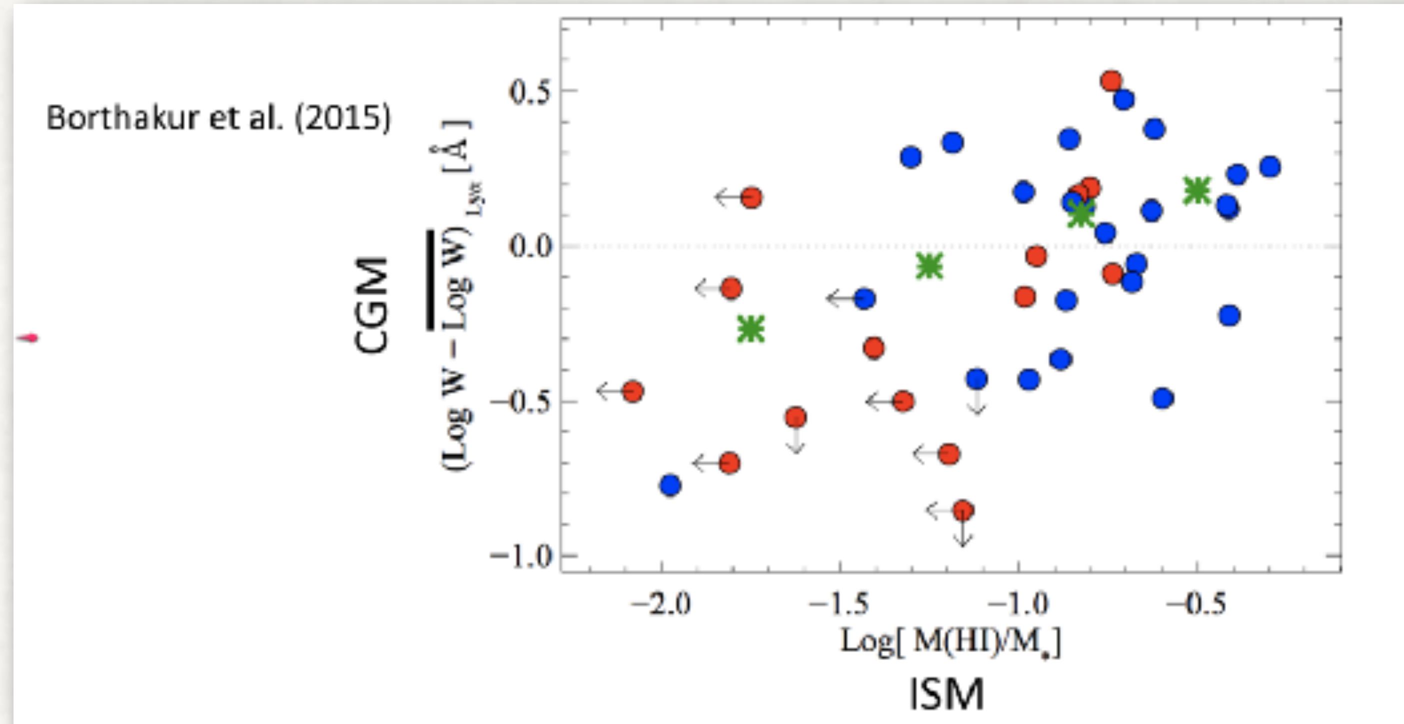


Werk (2018), adapted from Prochaska et al (2017)

It's everywhere
(even in passive galaxies)

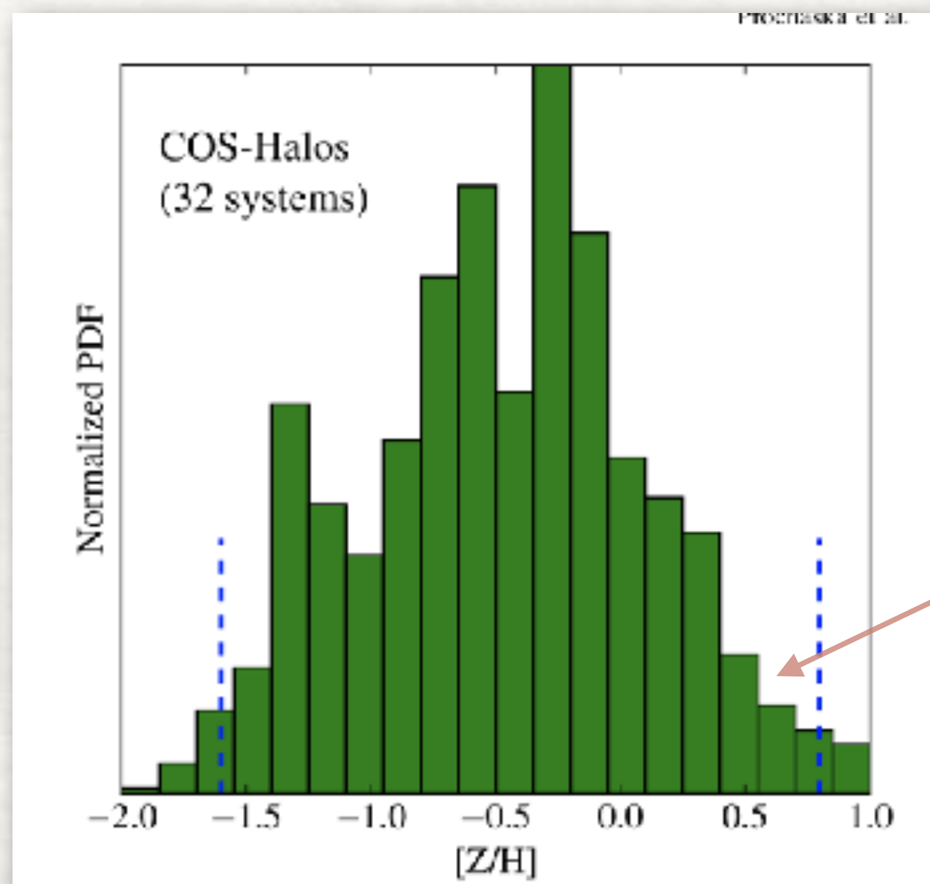
WHY?

Fuel for star formation



(Correlation between CGM cold gas and ISM cold gas)

Signpost of feedback

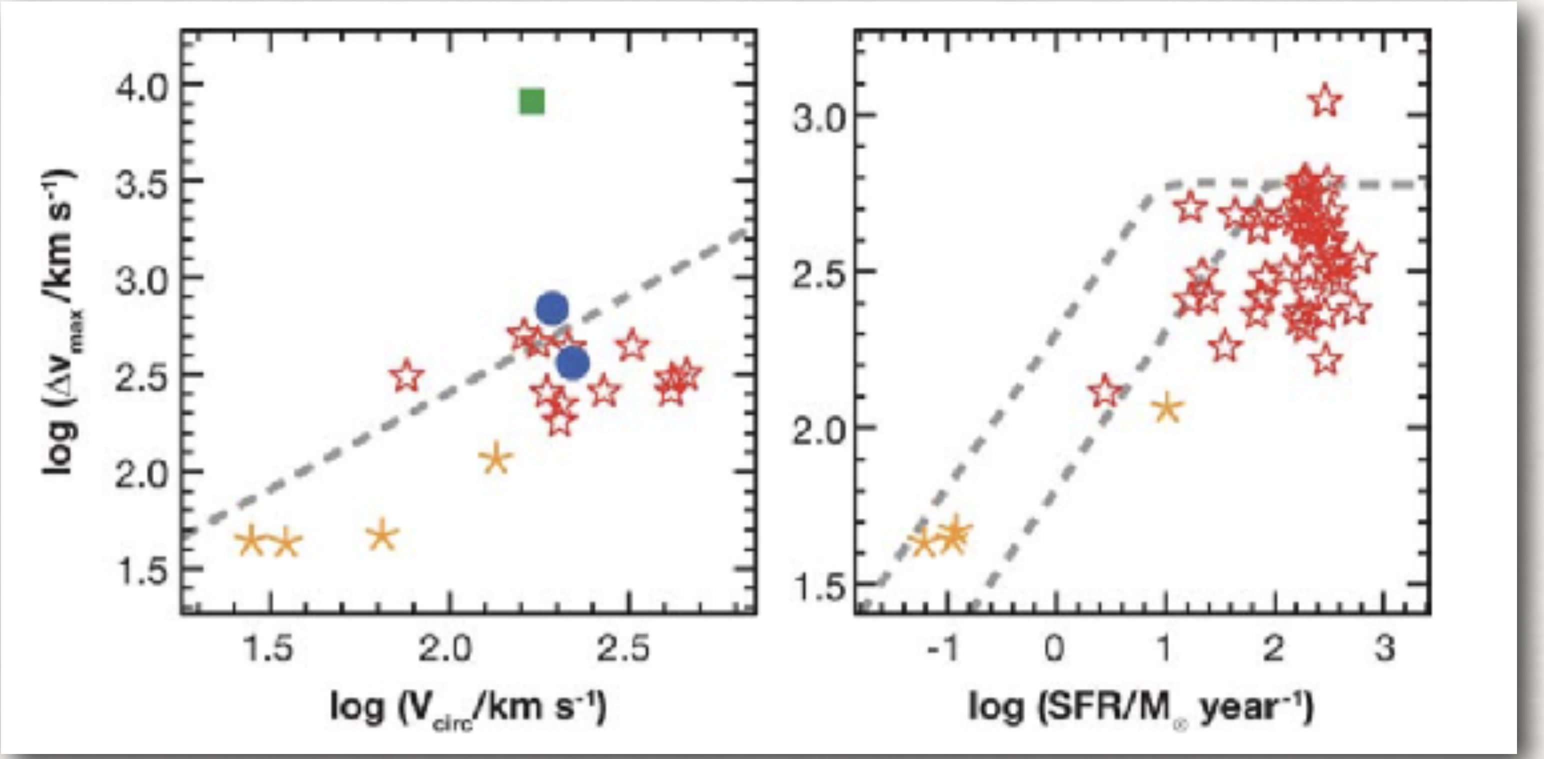


i) Metallicity

check out this supersolar gas!

Prochaska et al (2017)

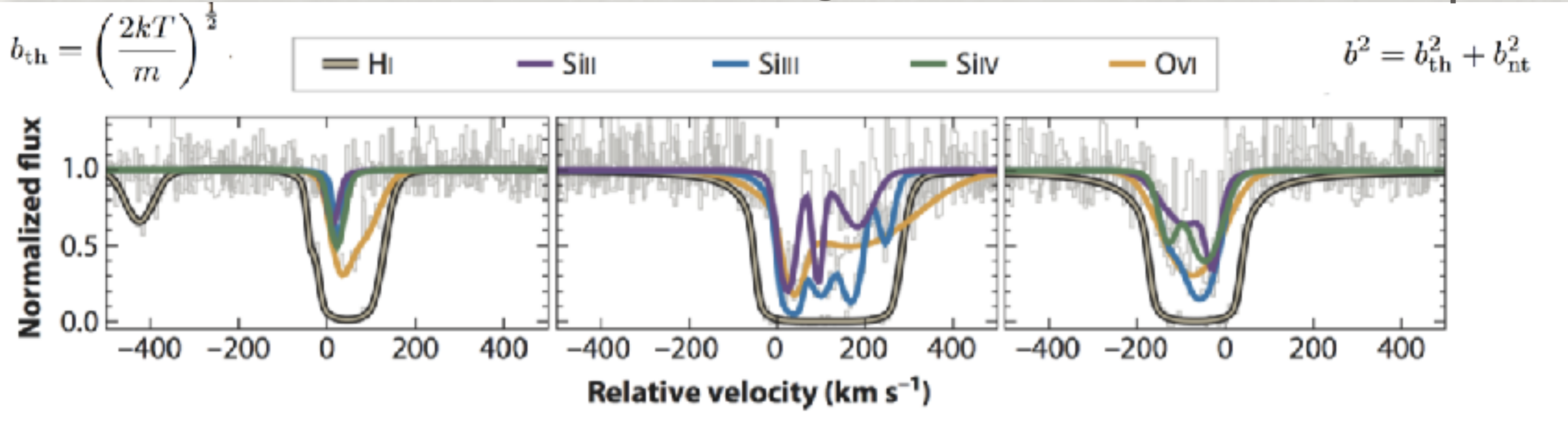
ii) Kinematics



Outflows

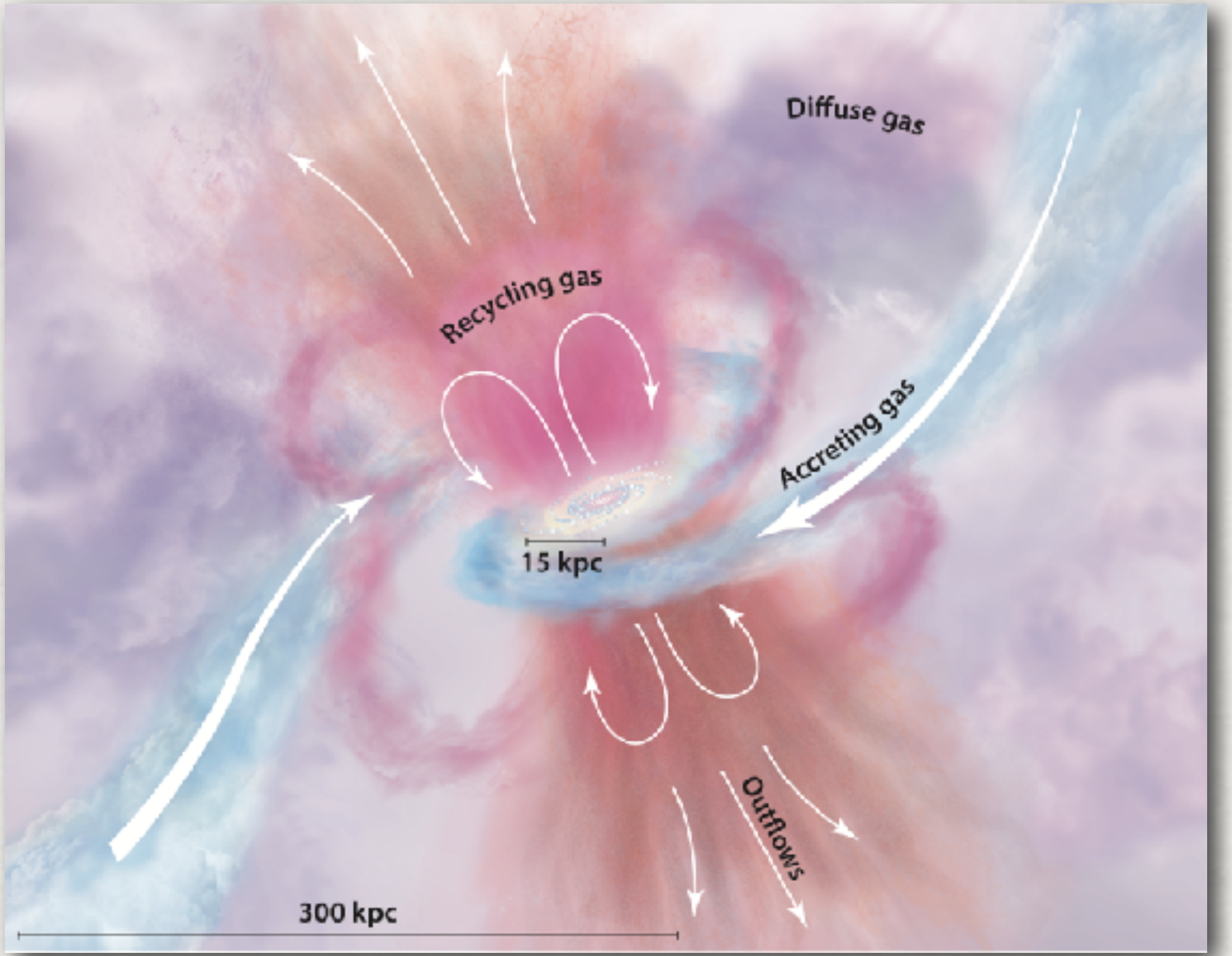
Veilleux et al 2005

Enigmatic Kinematic Correspondences



McQuinn & Werk (2018); Werk et al. (2016), Tripp et al. (2008), Muzahid et al. (2012), Savage et al. (2014), and more

Werk (2018)



Tumlinson, Peeples & Werk (2017)

"The CGM is a galactic ..

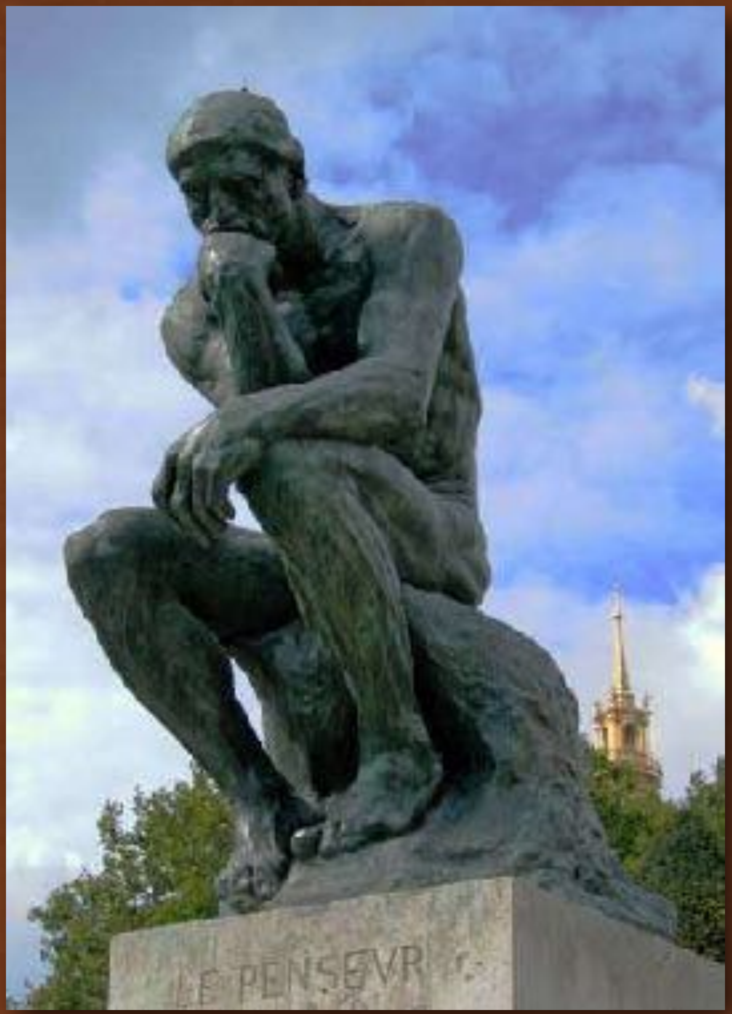
Fuel tank

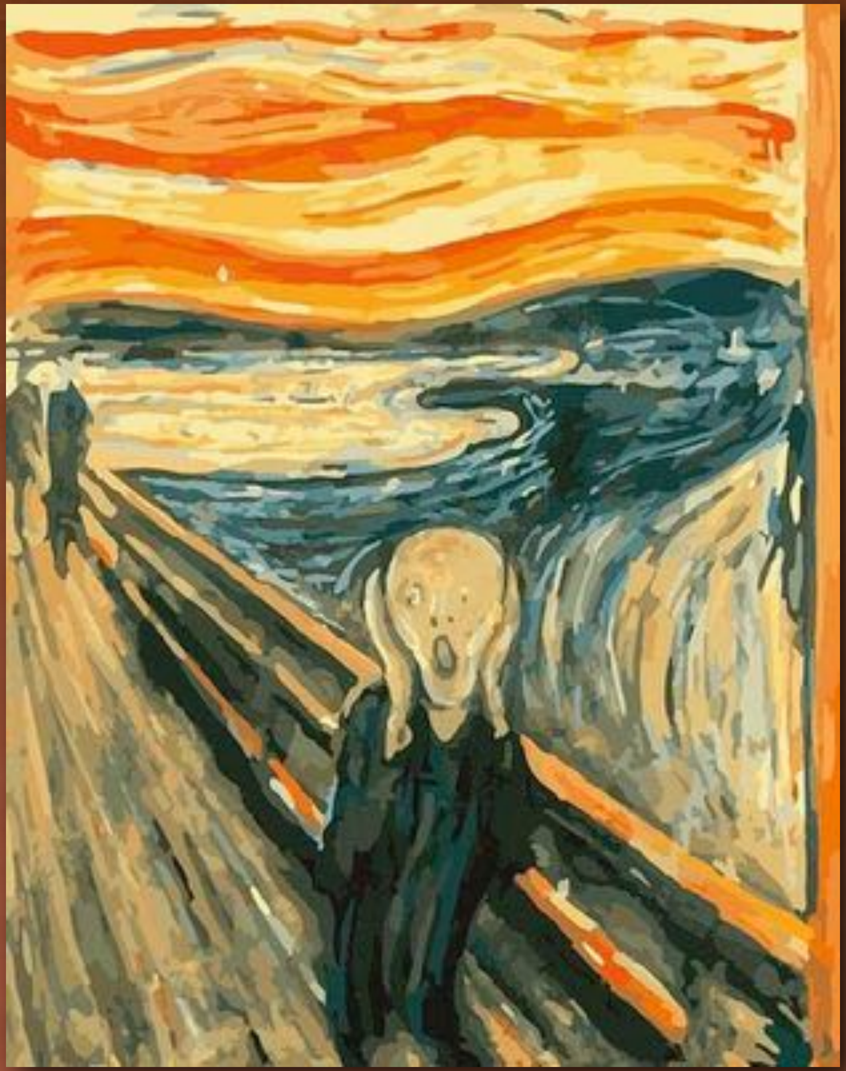
Waste Dump

Recycling Center"

YOUR MISSION, SHOULD YOU CHOOSE TO ACCEPT IT...

Understand physics of cold gas so we can interpret what we are seeing

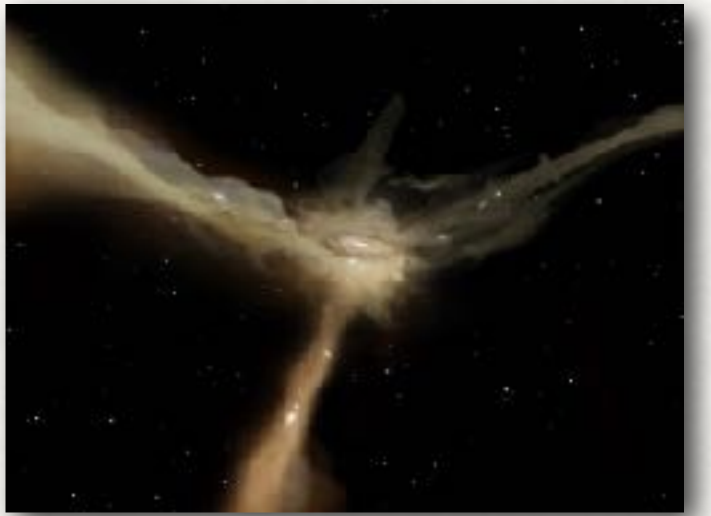




OPEN QUESTIONS

WHERE DOES IT COME FROM?

Cosmological Accretion?



But cold flows have small covering factor in sims

Also wrong velocity sign

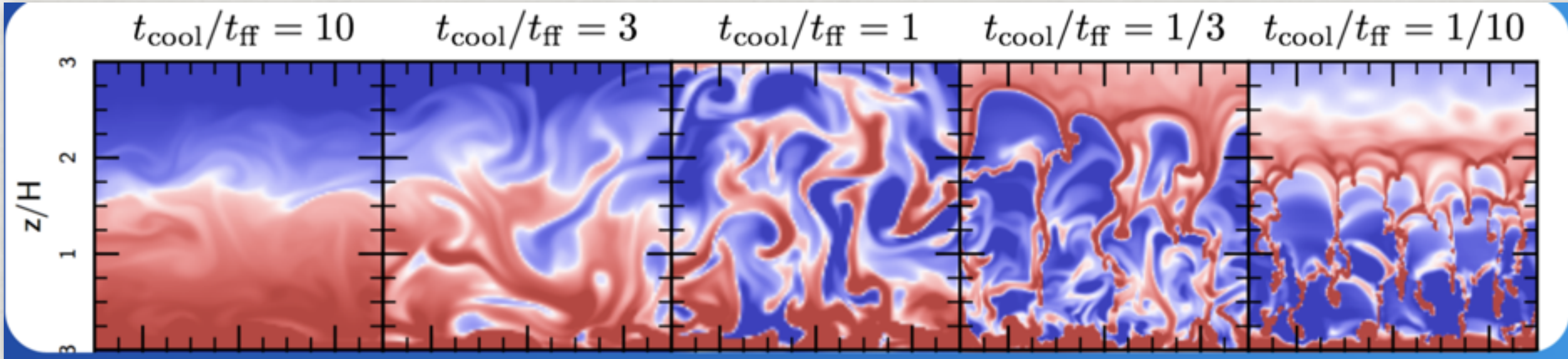
Ejected in outflows

Agrees with fact that we see dust

But entraining dense cold gas is hard! (more later)

Made in situ by thermal instability ('rain'; 'precipitation')

McCourt+12

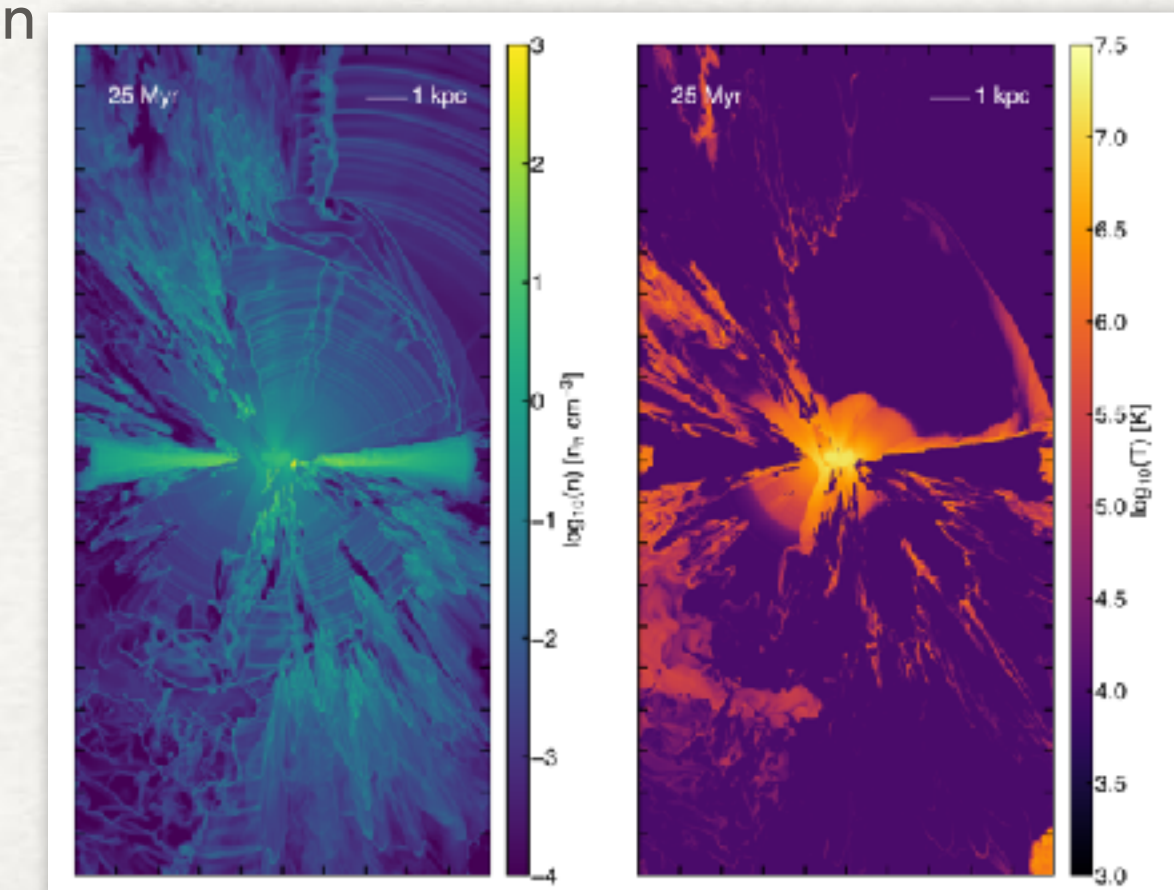


Arise as a result of competition between driving (by cooling) and damping from motions driven by buoyancy forces

Schneider+18

Are these models relevant? — galaxy CGM not in hydrostatic/thermal equilibrium

Buoyancy forces less relevant — reduced by B-fields, flat entropy profiles



Made by cooling of galactic wind

Adiabatic, then radiative cooling (Thompson+16)

Automatically solves entrainment problem

All of the above??

HOW DOES IT ENTRAIN AND SURVIVE?

Basic reason

Acceleration time:

$$t_{\rm acc} \sim \left(\frac{\rho_{\rm c}}{\rho_{\rm h}}\right)\frac{R}{v_{\rm h}}$$

is longer than destruction time

$$t_{\rm cc} \sim \left(\frac{\rho_{\rm c}}{\rho_{\rm h}}\right)^{1/2}\frac{R}{v_{\rm h}}$$

$$\frac{t_{\rm acc}}{t_{\rm cc}} \sim \left(\frac{\rho_h}{\rho_c}\right)^{1/2}$$

THE 'FAST AND FURIOUS' LIFE OF COLD GAS...

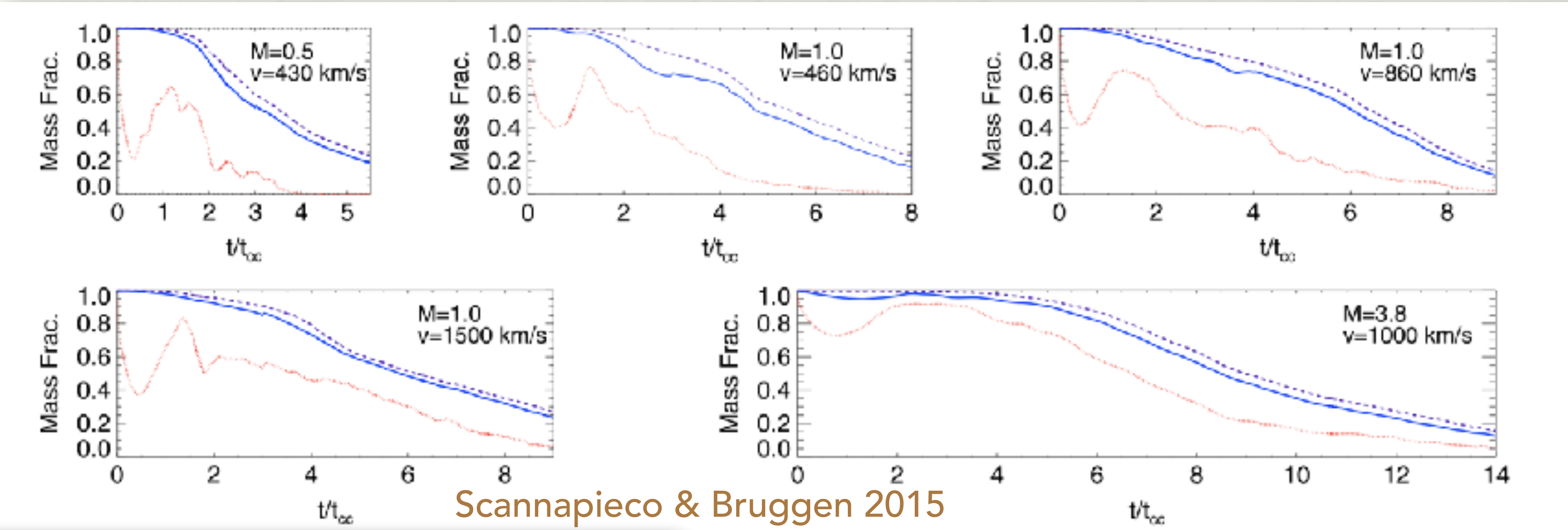
Entrainment is hard!

Entrainment in trouble: cool cloud acceleration and destruction in hot supernova-driven galactic winds

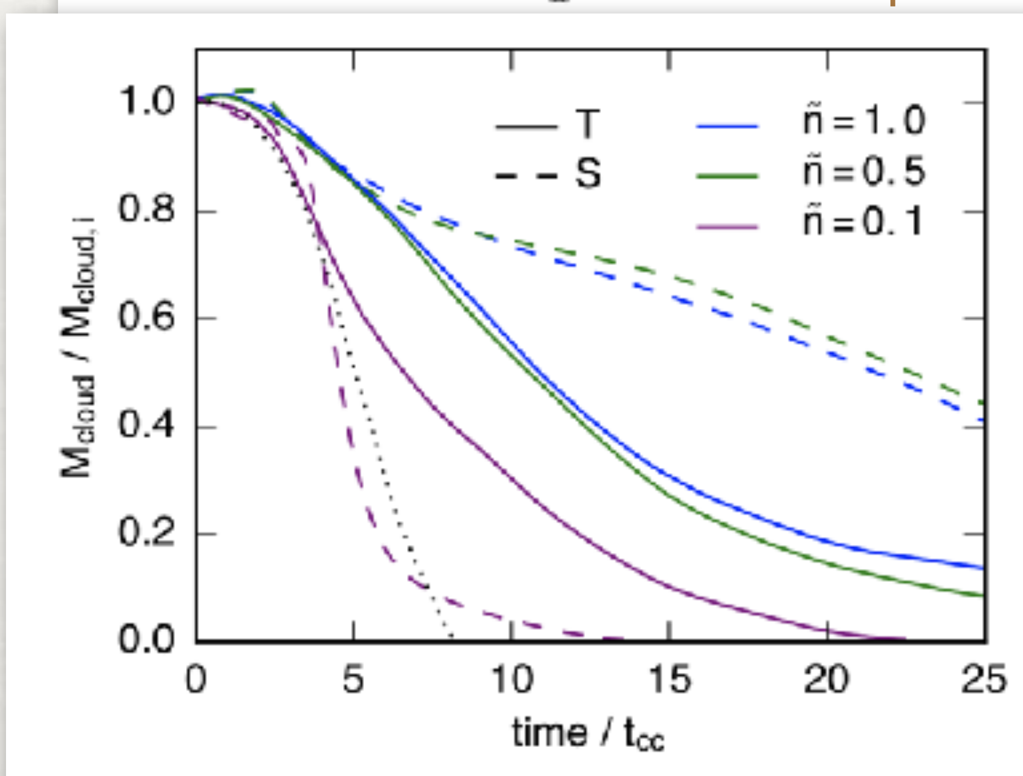
Dong Zhang,[1,2,3★] Todd A. Thompson,[2,3] Eliot Quataert[4] and Norman Murray[5†]

CLOUDS ERODE IN WIND TUNNEL SIMULATIONS

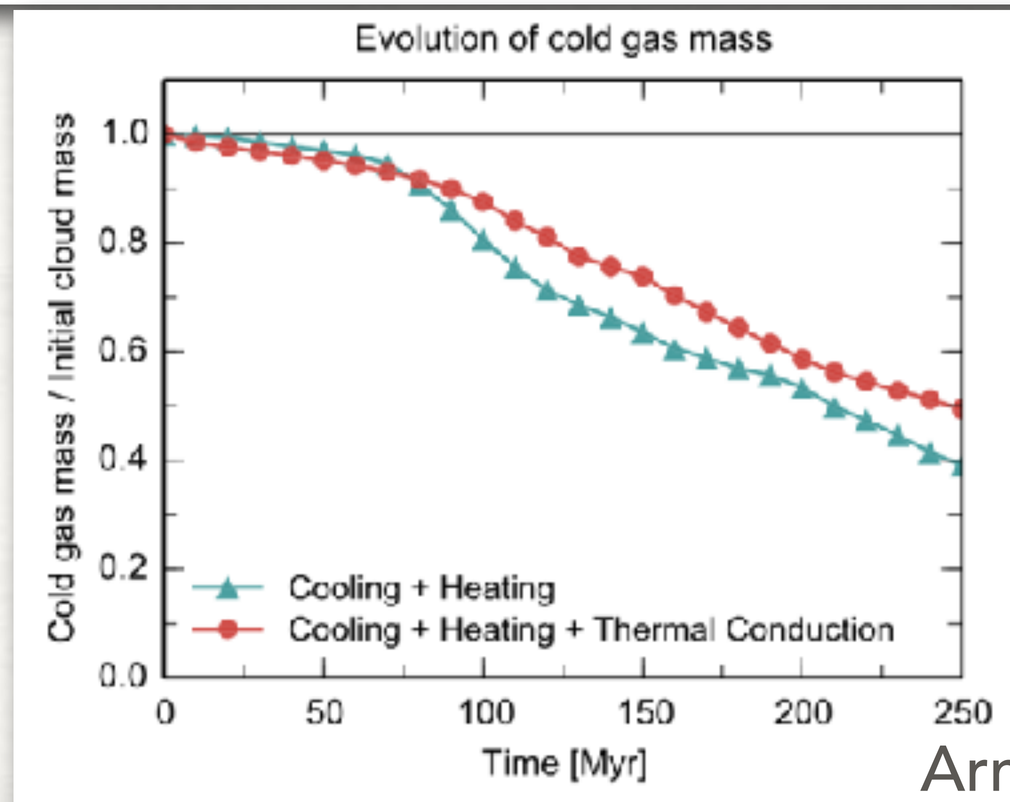
EVEN WHEN HAVE RADIATIVE COOLING...



Scannapieco & Bruggen 2015



Schneider & Robertson 2017



Armillotta et al 2017

THE PROBLEM

Schneider et al 2017

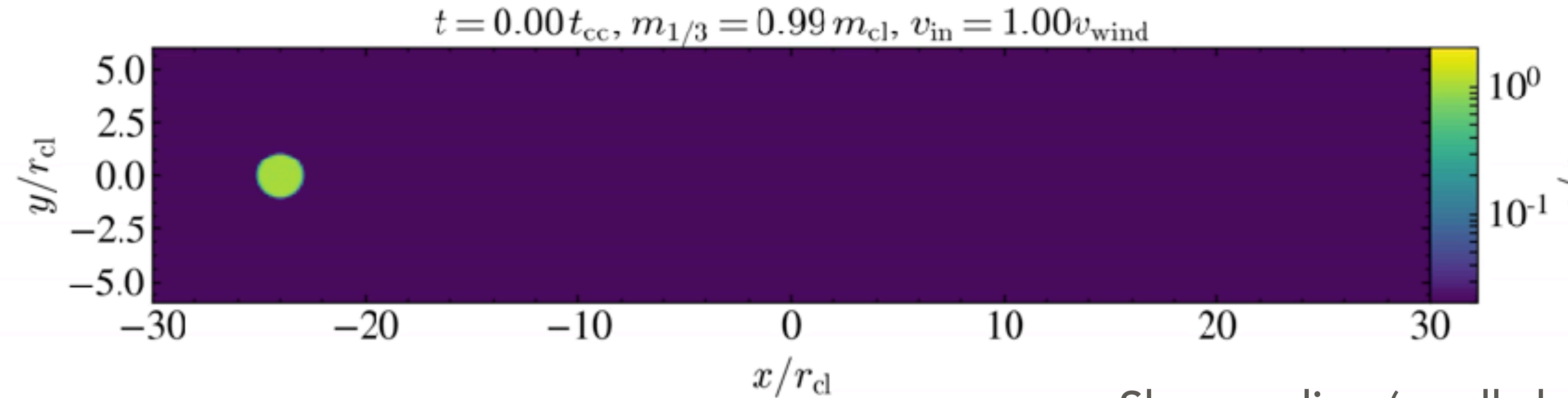
> billion grid cell sim!

Break up and KH away…

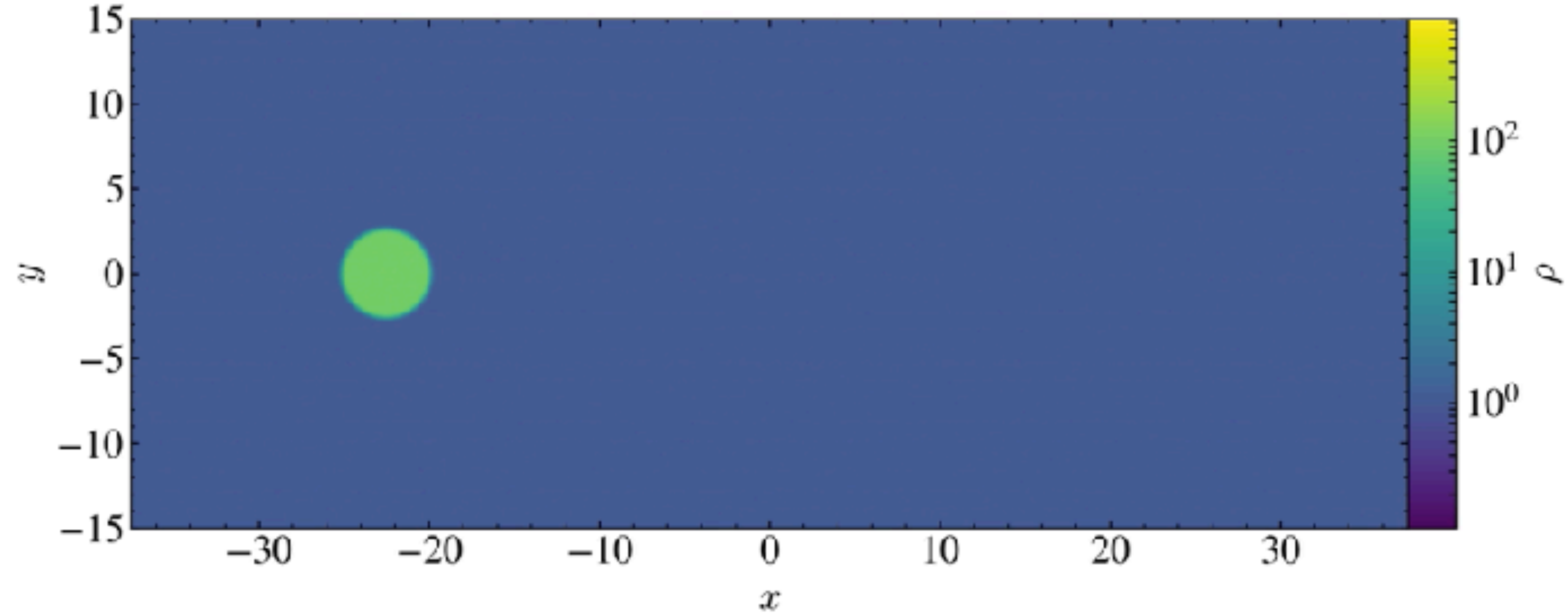
Possible solutions: 1) Make cold gas out of wind (but what about dust?)
2) B-fields (stabilizes interface, increases drag force…but doesn't work in detail)
3) Non-hydro forces (radiation pressure, cosmic rays…)

Gronke & Oh (2018)

MY TWO CENTS: MIXED GAS CAN COOL



Slow cooling (small cloud)

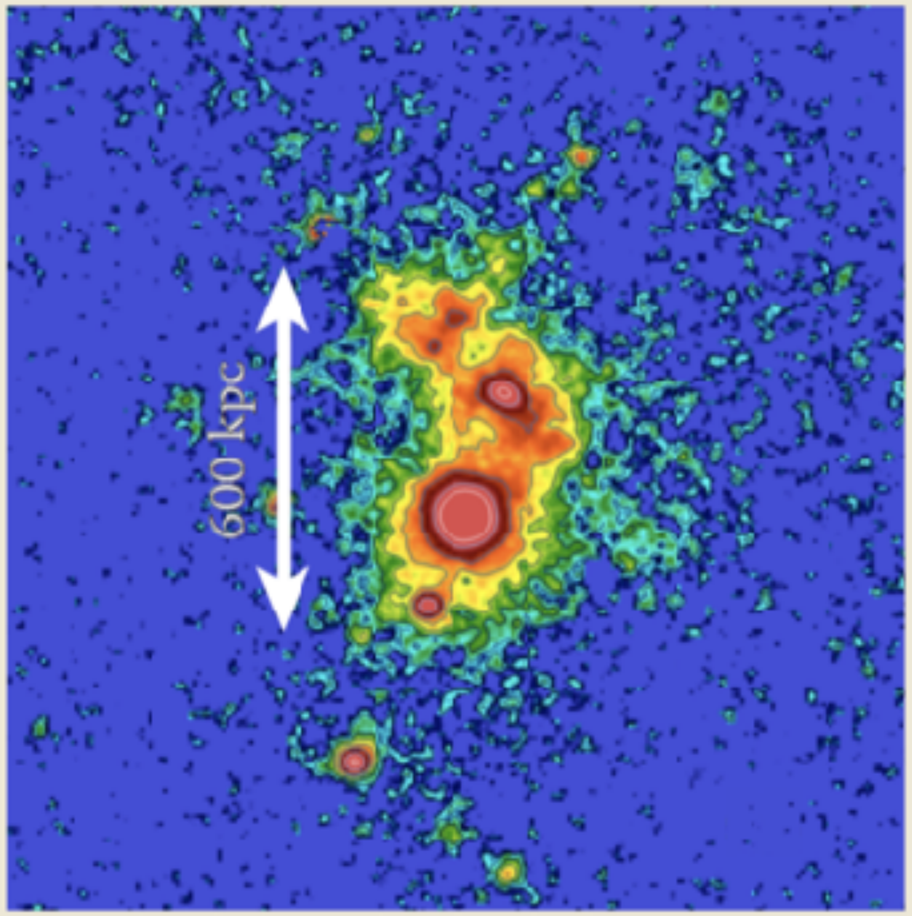


Fast cooling (large cloud)

Cold gas grows in mass (from hot gas cooling out) and becomes comoving (since hot gas has high momentum)

WHAT IS THE MORPHOLOGY OF THE COLD GAS?

And how dense gas with a very small volume filling factor blanket the entire halo?



Hennawi et al. 2015

"Joe's Cluster:"

$z \sim 2$

$M \sim 3 \times 10^{14} M_{\odot}$

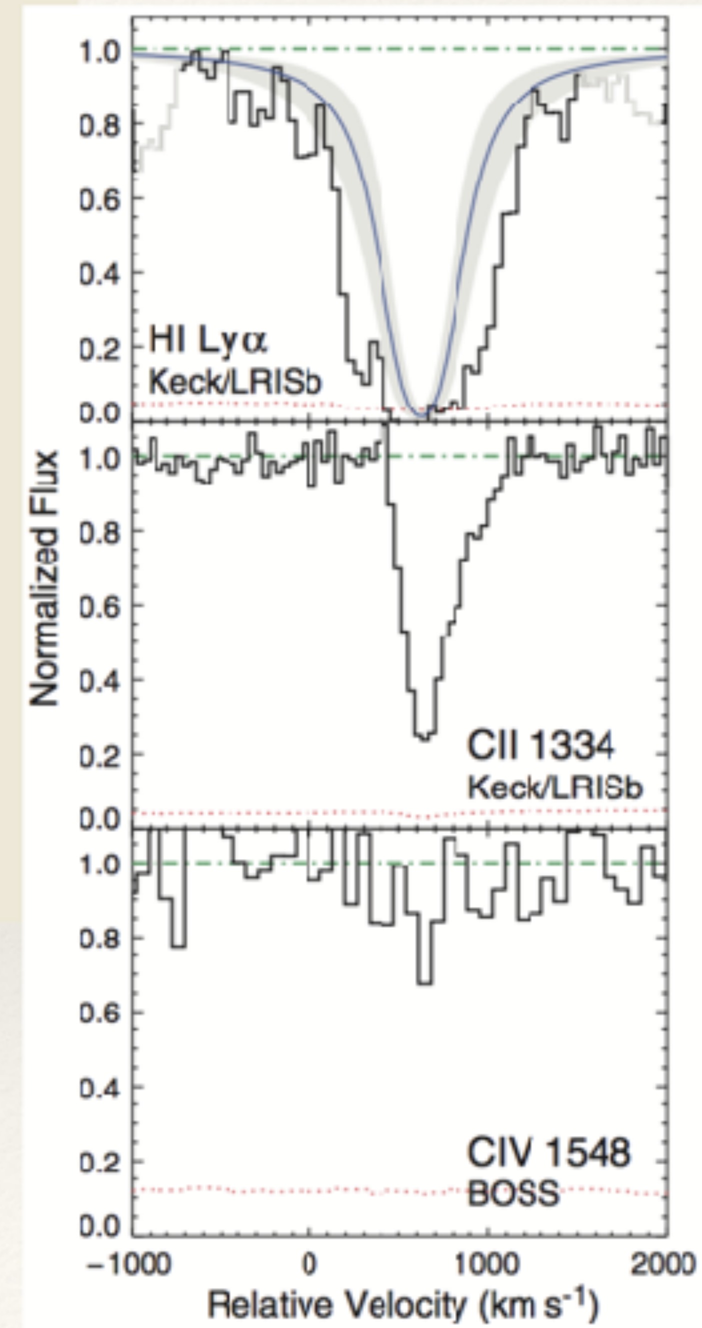
Ly_{α} in absorption *and* emission

Problems

$M_{cold} \sim 10^{11} M_{\odot}$

$n_{cold} \sim 1 \text{ cm}^{-3}$

$\ell_{cold} \equiv N/n \sim 40 \text{ pc}$



Warm gas should fall in ballistically and get shredded!
Small volume fraction (f_v ~ 10^-4). Why area covering?
High turbulent velocities?!

McCourt+18

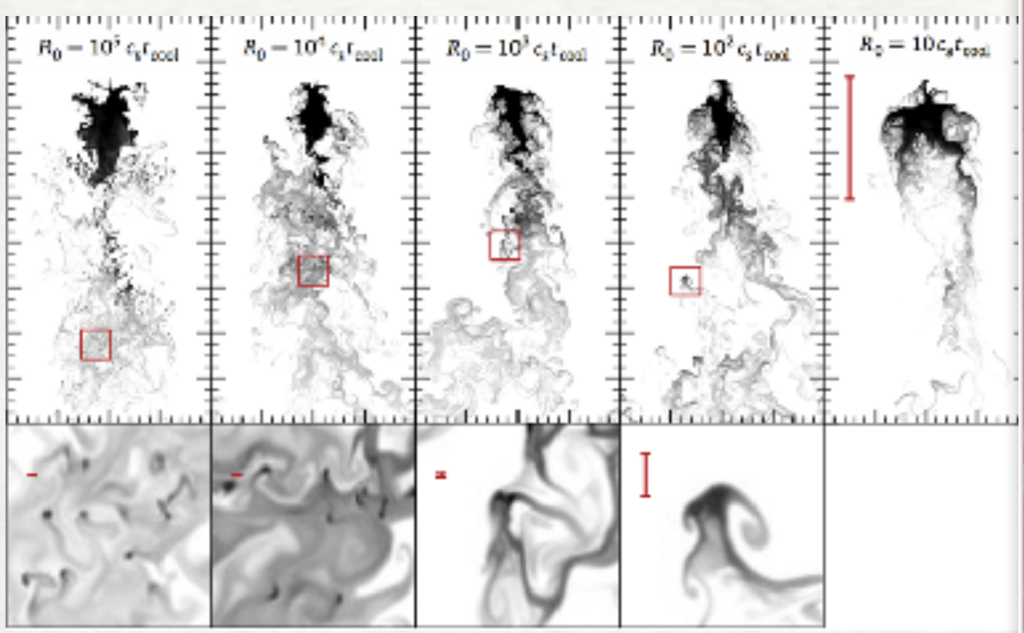
MY TWO CENTS

COLD GAS HAS SMALL SCALE STRUCTURE

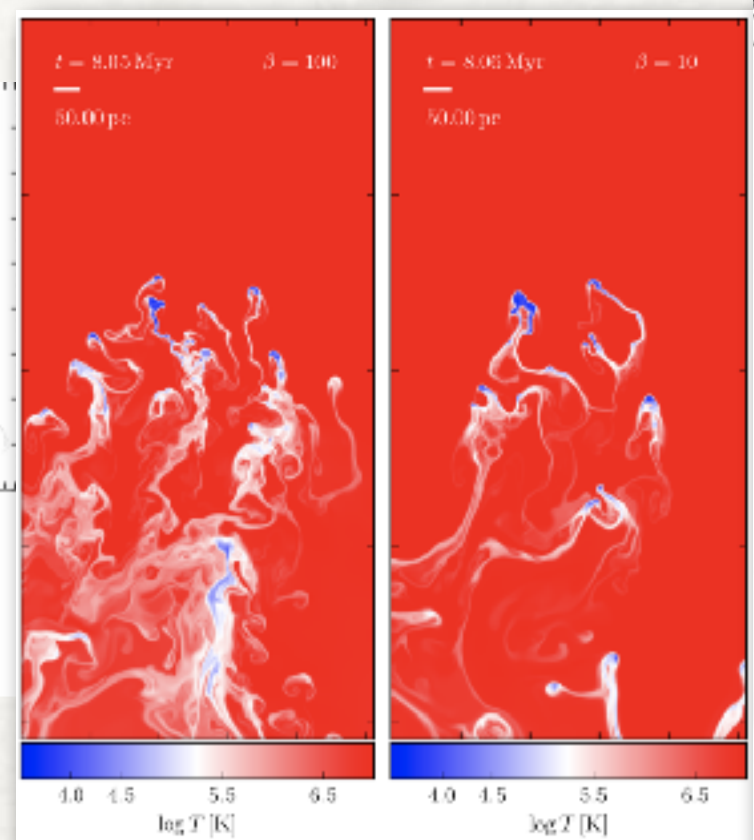
Rapid cooling does not mean isobaric —> isochoric cooling

Instead, there is a 'shattering' instability, breakup into fragments

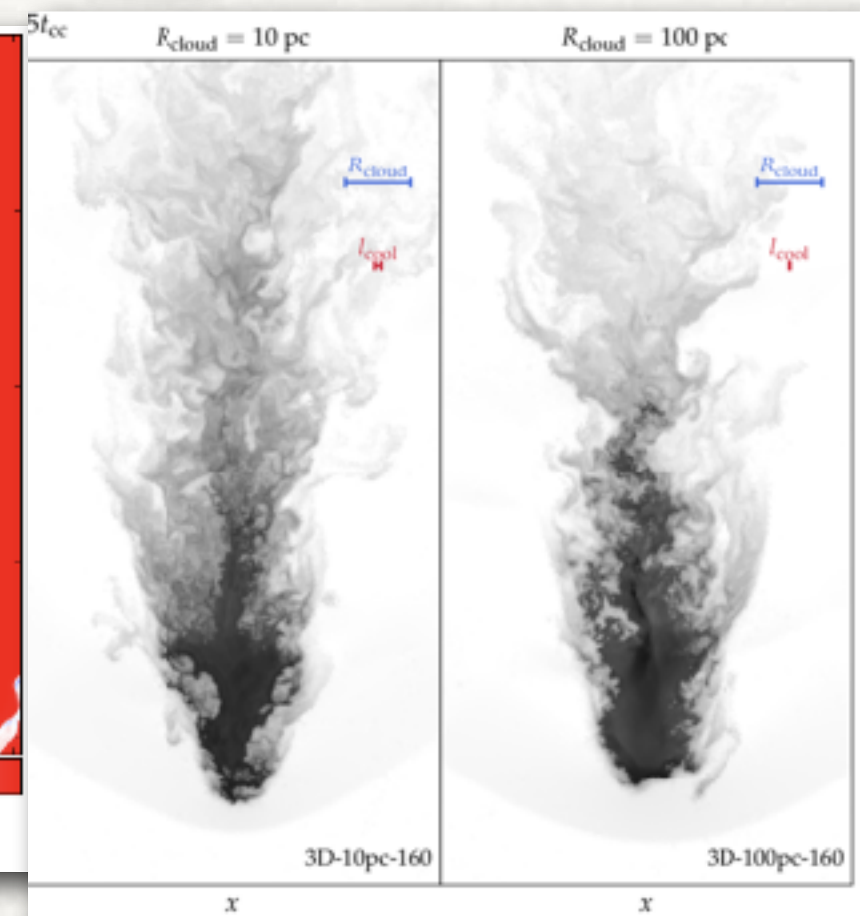
$$\lambda \sim c_s t_{\rm cool} \sim 0.1 n^{-1} \text{ pc} \qquad N_{\rm H} \sim 10^{17} \text{ cm}^{-2}$$



2D hydro (McCourt+18)

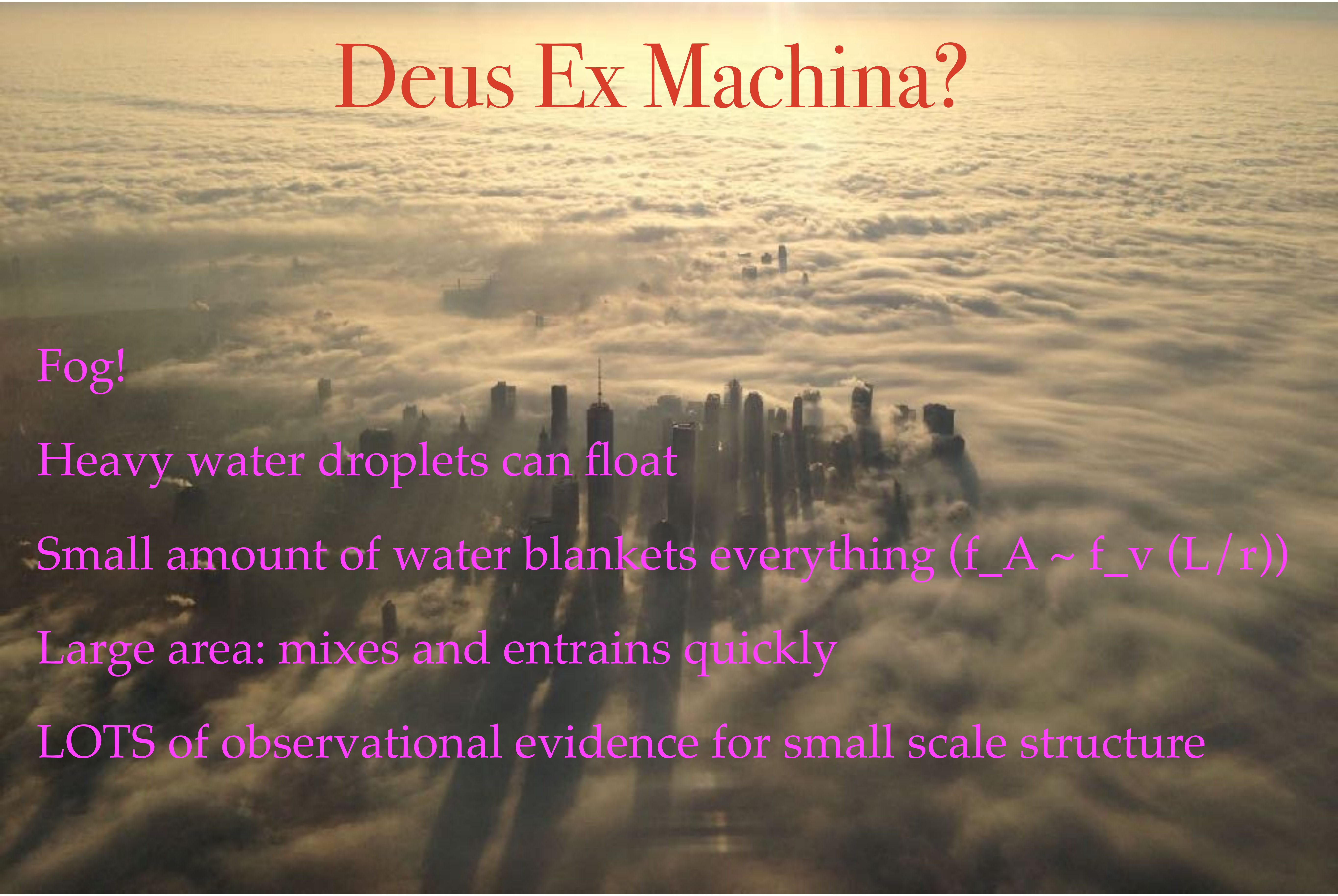


2D MHD (Liang & Remming 18)



3D hydro (Sparre+18)

Deus Ex Machina?



Fog!

Heavy water droplets can float

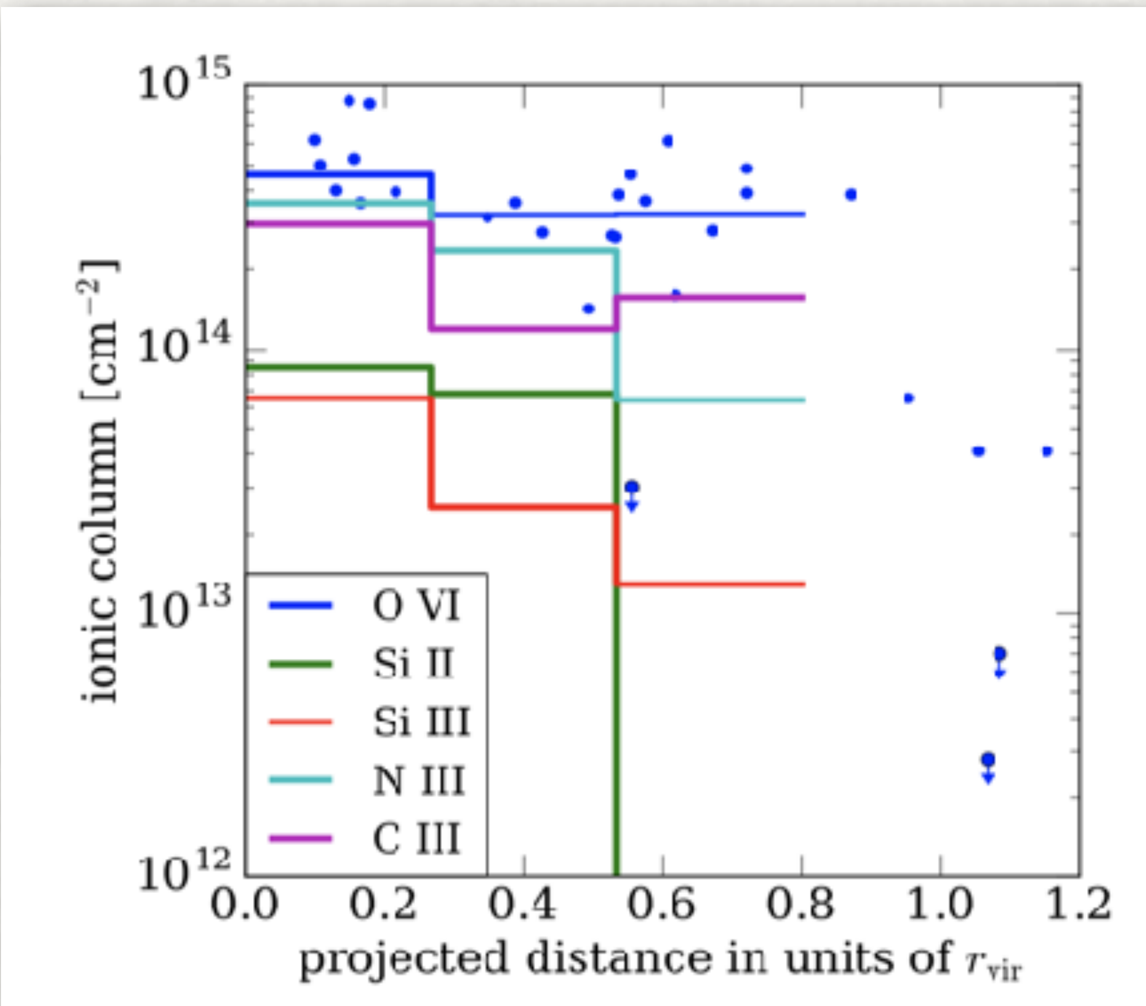
Small amount of water blankets everything ($f_A \sim f_v (L/r)$)

Large area: mixes and entrains quickly

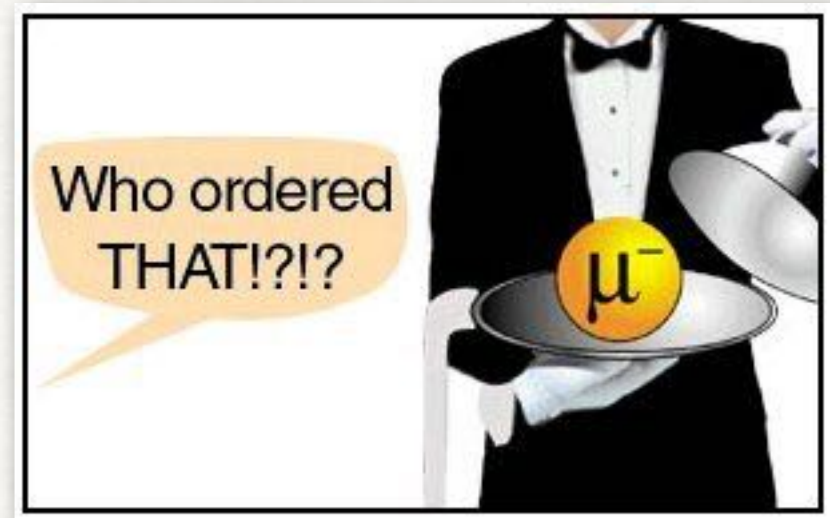
LOTS of observational evidence for small scale structure

SOME OTHER PUZZLES

Why is there all this OVI?



McQuinn & Werk (2018)

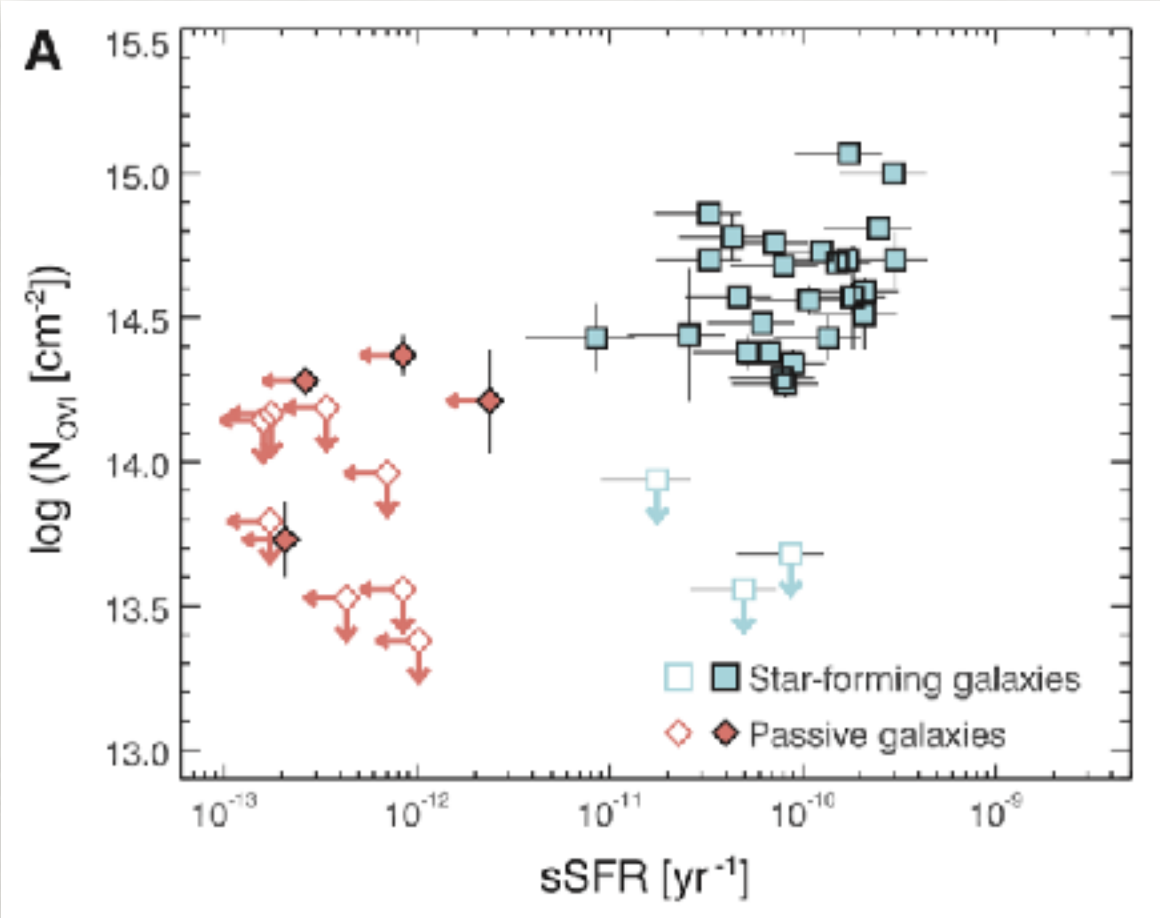


I.I Rabi's reaction to discovery of mu meson

Implies a mass in warm gas of:

$$M = 8 \times 10^9 M_\odot \left(\frac{0.1}{f_{\rm OVI} Z}\right) \left(\frac{N_{\rm OVI}}{10^{14.5}{\rm cm}^{-2}}\right) \left(\frac{R}{200{\rm kpc}}\right)^2, \quad (1)$$

If collisionally ionized, need gas to sit at unstable part of cooling curve.
If photoionized, need low-pressure shell (Stern+18)



Tumlinson et al 2011

Interesting clue: OVI is only seen in star-forming galaxies

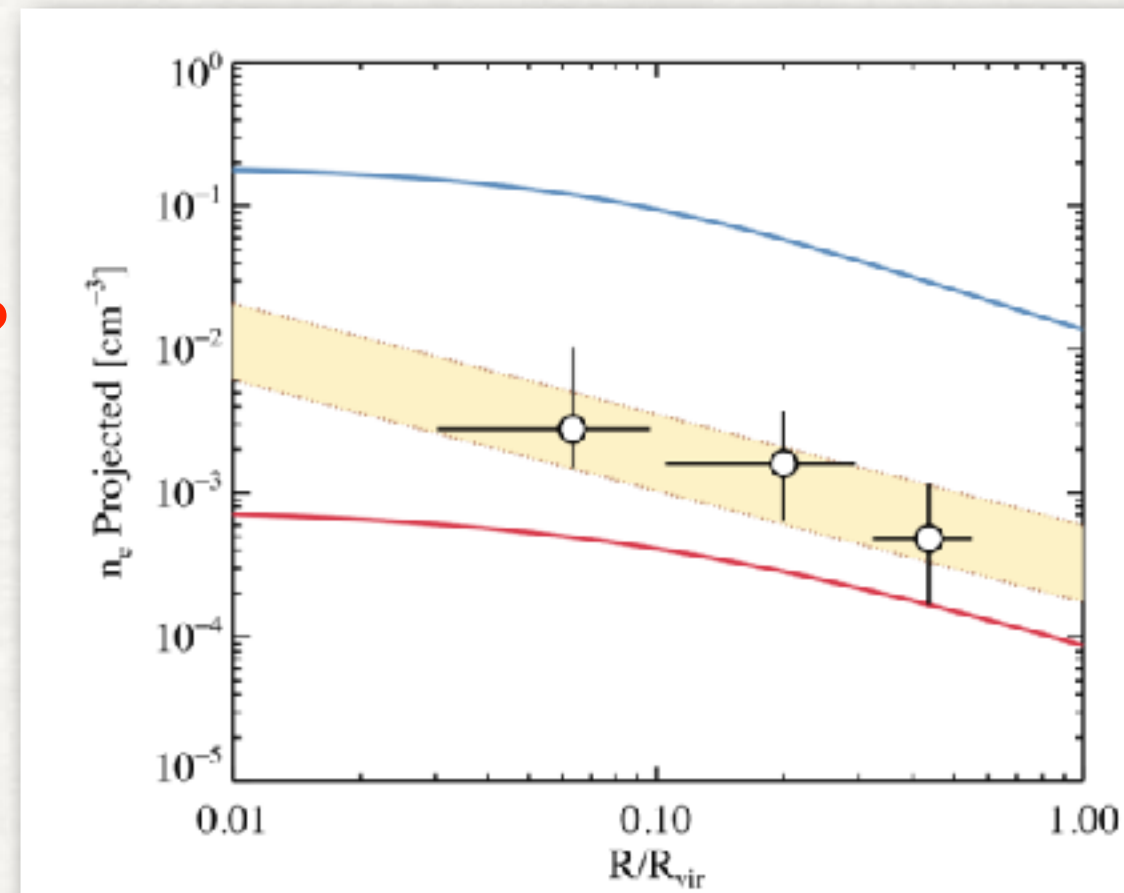
Due to correlation of SFR with halo mass?
Or do winds produce OVI?

Why is T ~10^4 K gas so low density?

At least an order of magnitude less dense than expected.

Non-thermal pressure support?

Don't see this problem at high z

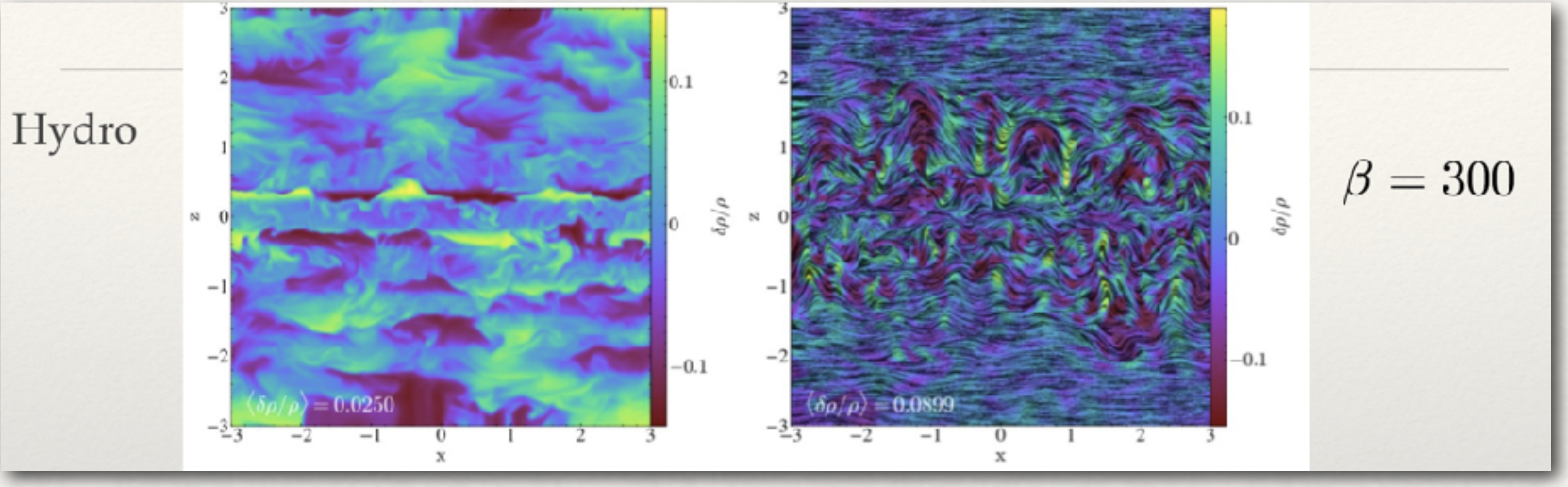


Werk+14 (corrected HM01)

SOME CHALLENGES

GOING BEYOND HYDRO

Gentle reminder: MHD forces make a difference



Thermal instability, Ji+18

This is (relatively) easy, just have to do it

Radiation: Numerically challenging

Cosmic Rays: Numerically challenging, physics uncertain

(Ellen's discussion)

HOW MUCH NUMERICAL RESOLUTION DO WE NEED?

Cosmological simulations of the circumgalactic medium with 1 kpc resolution: enhanced H I column densities

Freeke van de Voort,[1,2*] Volker Springel,[3,1] Nir Mandelker,[2,1] Frank C. van den Bosch[2] and Rüdiger Pakmor[3,1]

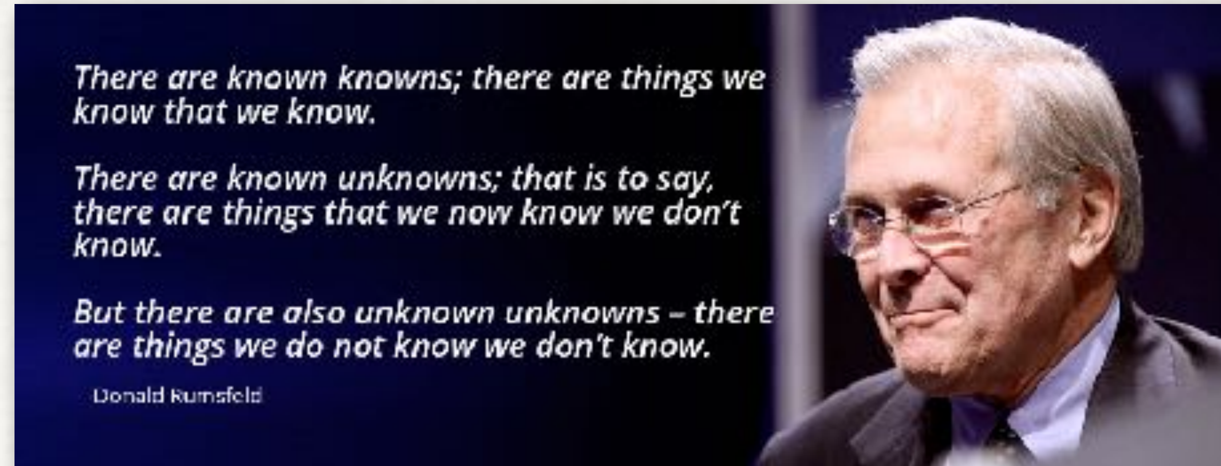
The CGM is still not yet numerically converged.

Do we have to go to sub-pc resolution?

Should we treat cold gas in a subgrid manner?

(treat as separate fluid w/ coupling terms just like CRs)

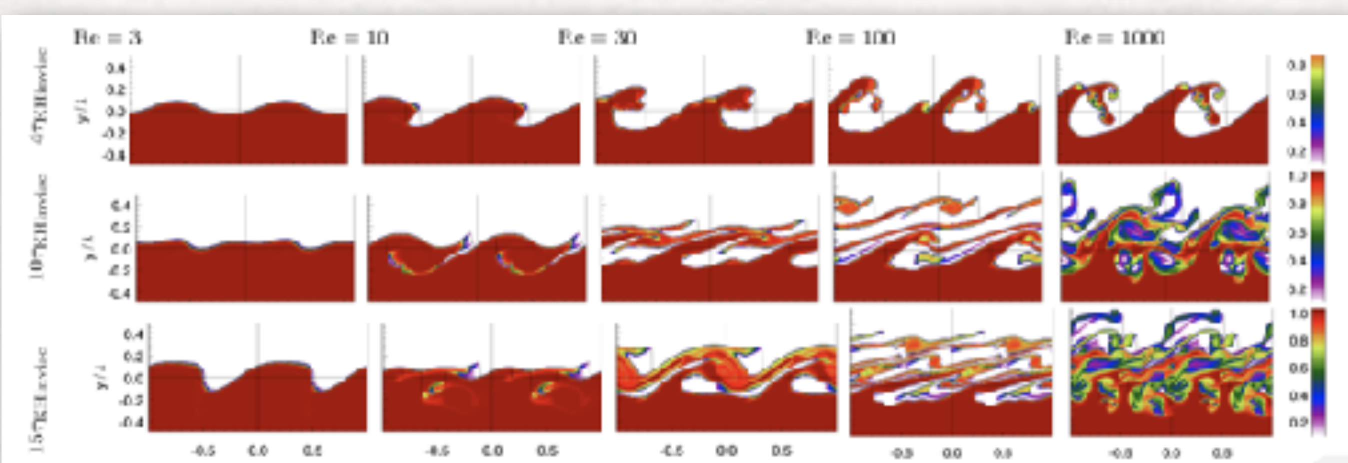
WHAT PHYSICS ARE WE MISSING?



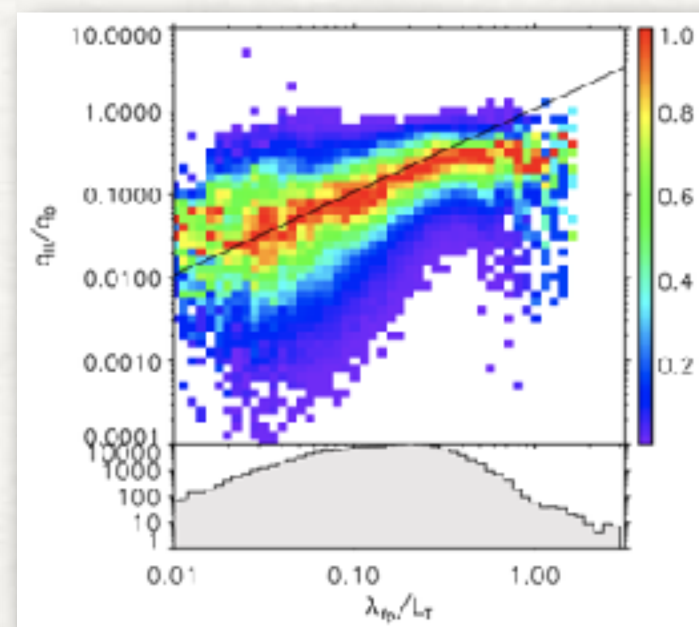
What are the diffuse transport coefficients for energy, momentum?

Conduction, viscosity will significantly change boundary layers, hydro instabilities

They could be anything from zero to Spitzer-Braginskii



Roediger+13



Bale+13

Spitzer-like conduction only seen in solar wind

Reynolds number matters!

On what scales does hydrodynamics break down?

$$\sigma \equiv \frac{\lambda_{\rm mfp}^{\rm (hot)}}{\ell_{\rm cloudlet}} \sim 300 \times \left(\frac{T}{10^6\,{\rm K}}\right)^2,$$

Coulomb mean free path of ions in hot gas
much larger than 0.1 pc scales

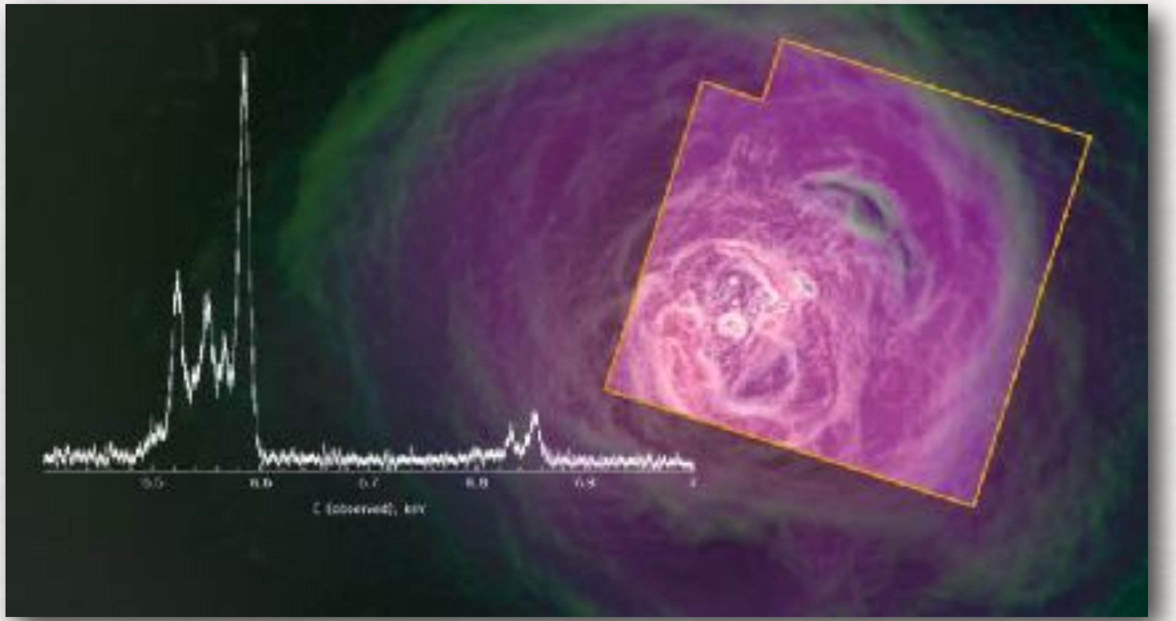
Same problem in galaxy clusters — MHD is poor approx on small scales (mfp ~ 20 kpc)

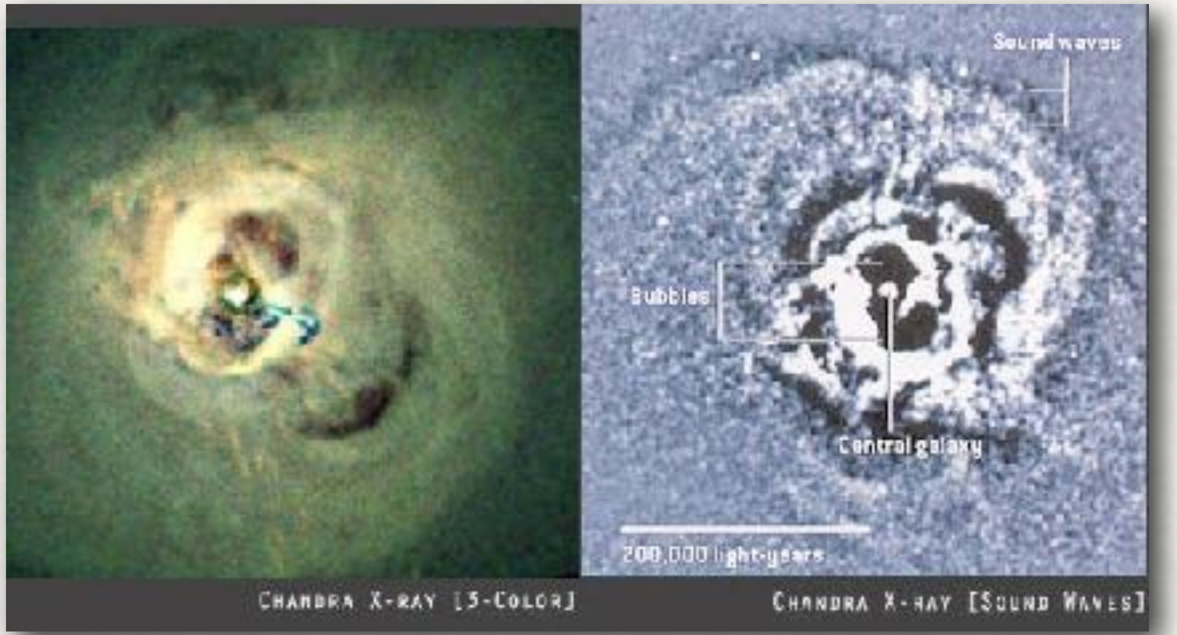
Does observational evidence for small scale structure suggest other scattering processes? (plasma instabilities)

When do we need to start doing kinetic theory?

OBSERVATIONAL COMPARISONS

WHAT'S GOING TO DISTINGUISH BETWEEN DIFFERENT FEEDBACK MODELS?





A party pooper:

the ICM, the CGM's big brother

We see the hot gas, in X-ray and SZ

No need to guess from cold gas properties!

We see the energy source: bubbles from radio mode feedback

But still no consensus solution: thermal conduction, cosmic rays, turbulent dissipation & diffusion, weak shocks, sound waves, etc etc …

How to avoid this fate??