Understanding the fountain-corona interaction

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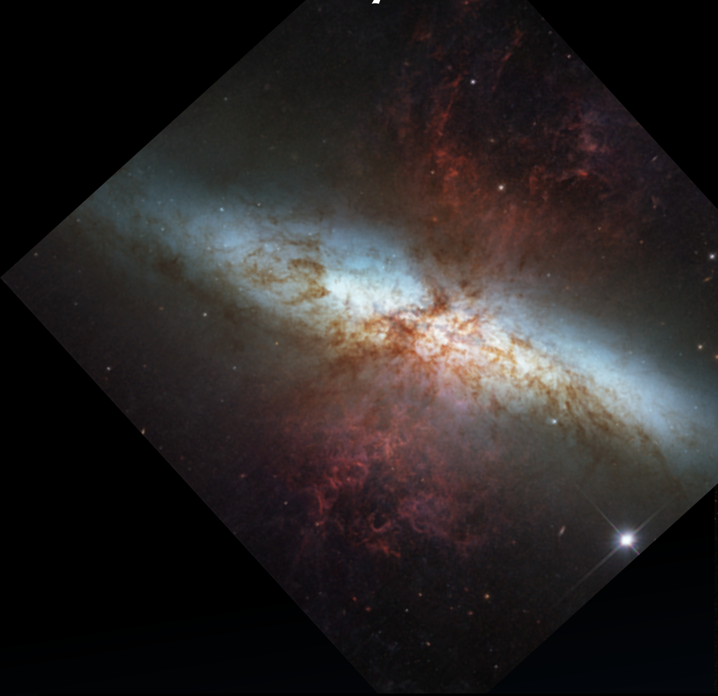
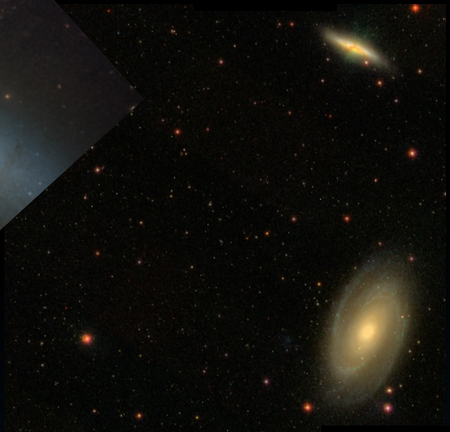
Why is everybody showing M82?

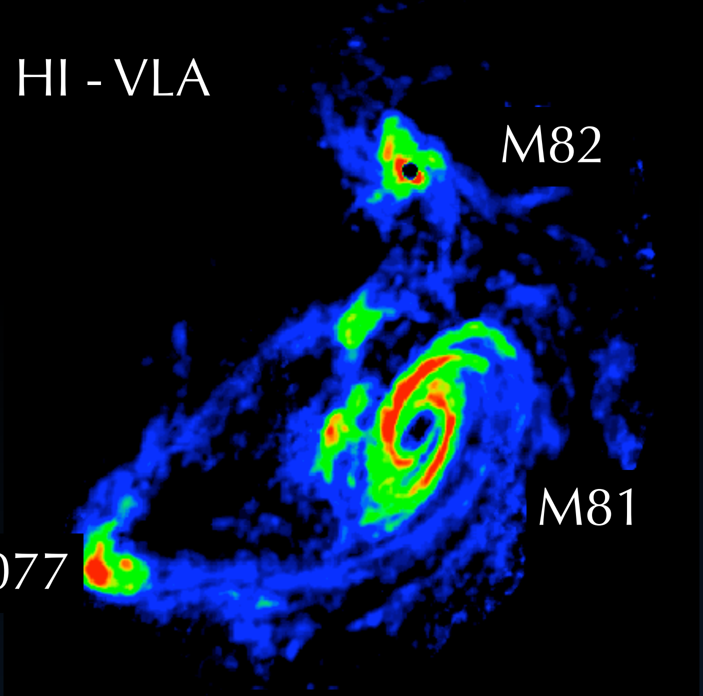
Because it is an "exceptional" galaxy!



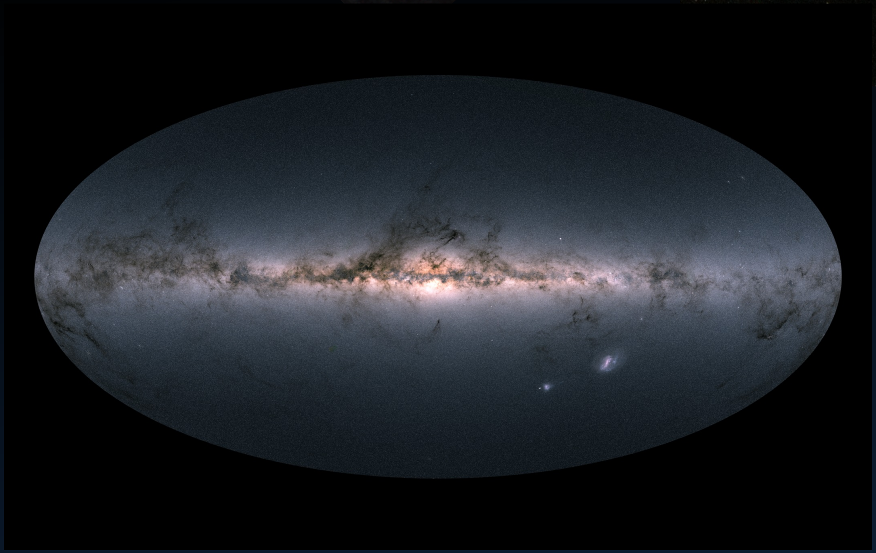
SDSS



HI - VLA

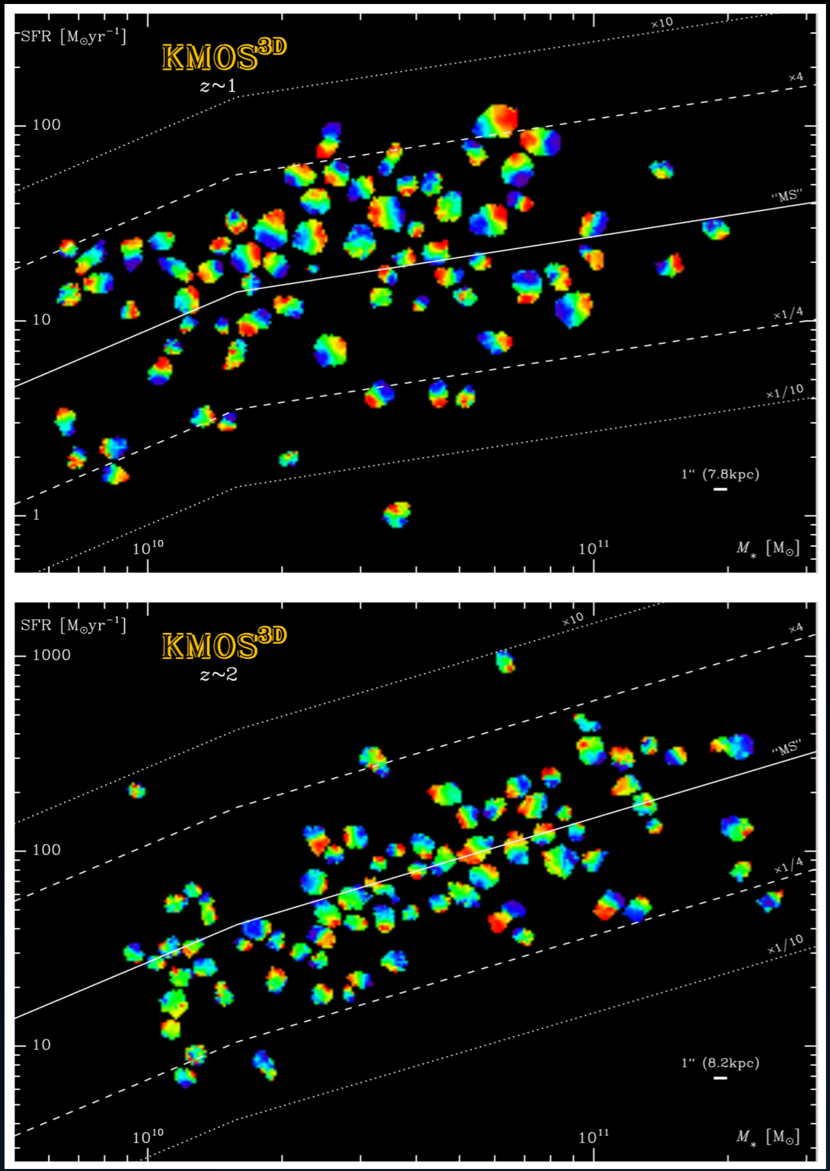


Yun et al. 1997



Milky Way
Gaia collaboration 2018

Galaxies at z=1 and z=2

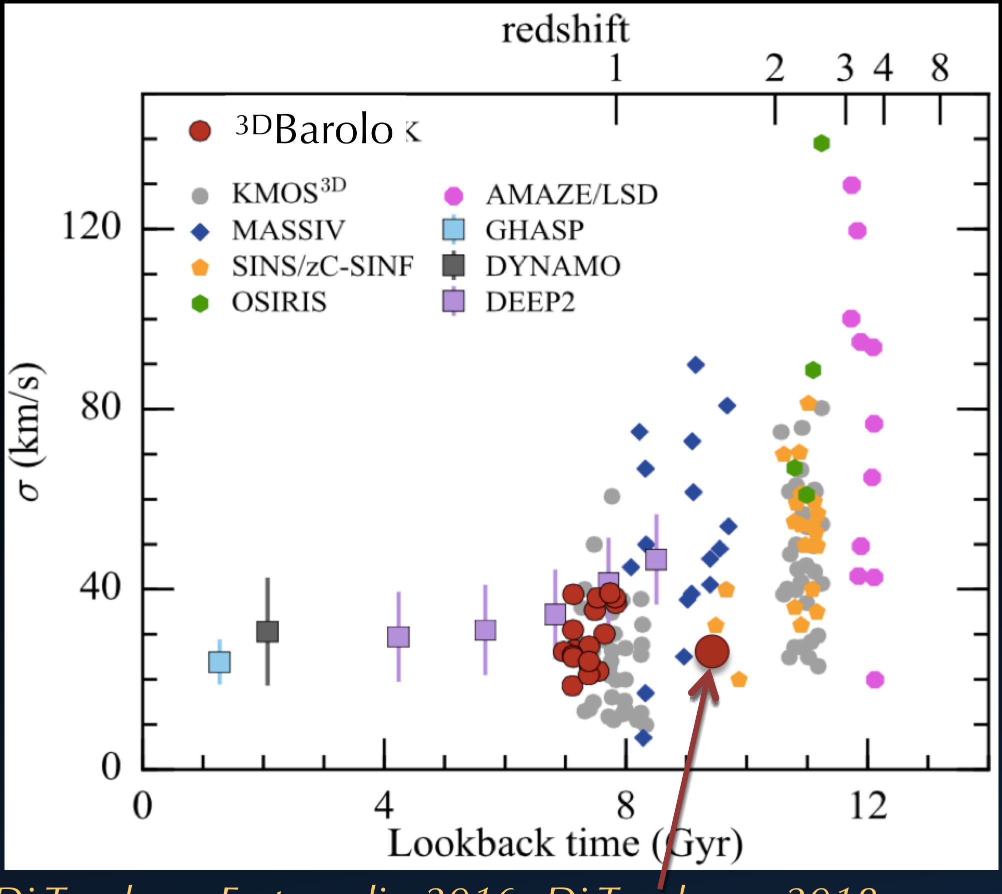


Wisnioski et al. 2015

Hα observations

93% of galaxies (z~1), 74% (z~2) rotationally supported

Velocity dispersion vs redshift

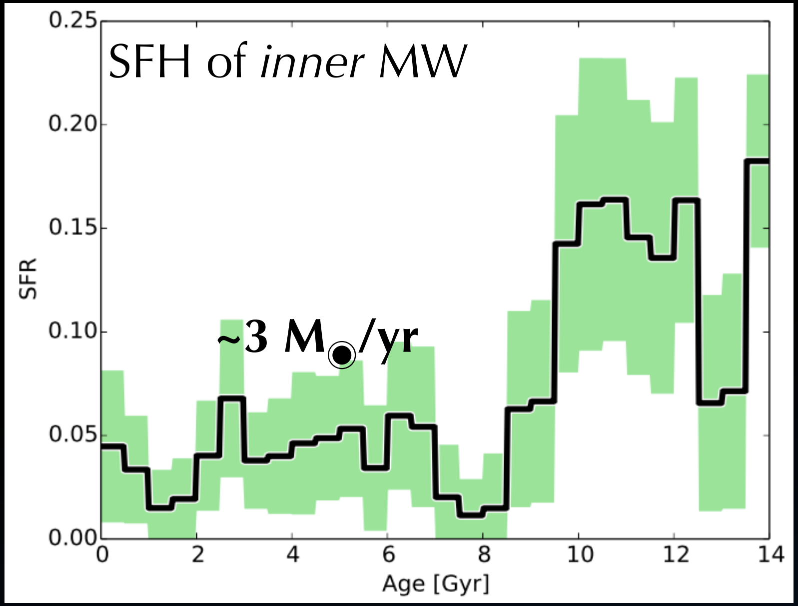


Di Teodoro, Fraternali+ 2016; Di Teodoro+ 2018

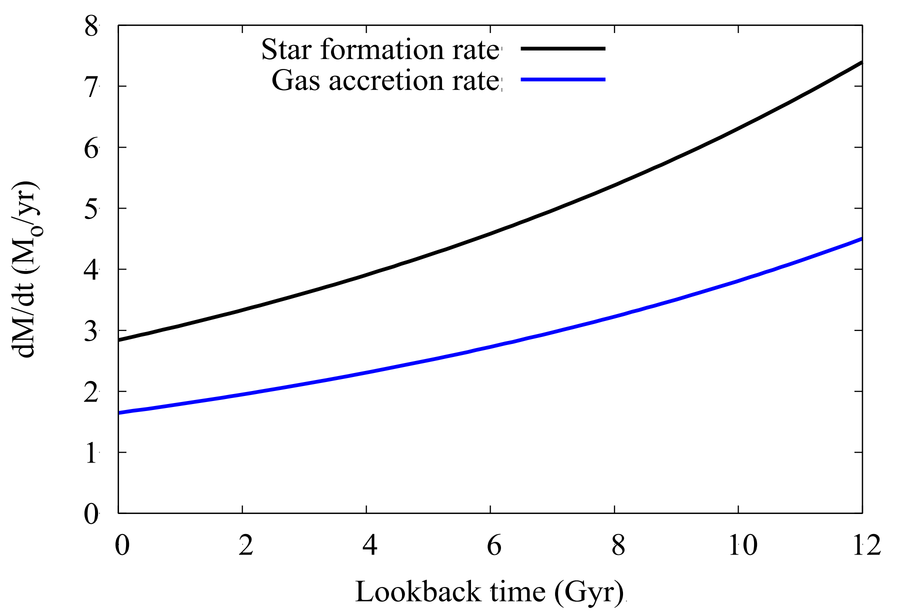
Growth of the Milky Way's disc

Chemical evolution models
G-dwarf problem
Larson 1972; Tynsley 80; Tosi 1988; Chiappini et al. 1997, 2001; Boissier & Prantzos 1999; Matteucci+ 2009; Schoenrich & Binney 2009

Need for metal-poor gas accretion at ~ 1 $M_{\odot}$/yr



Snaith et al. 2015



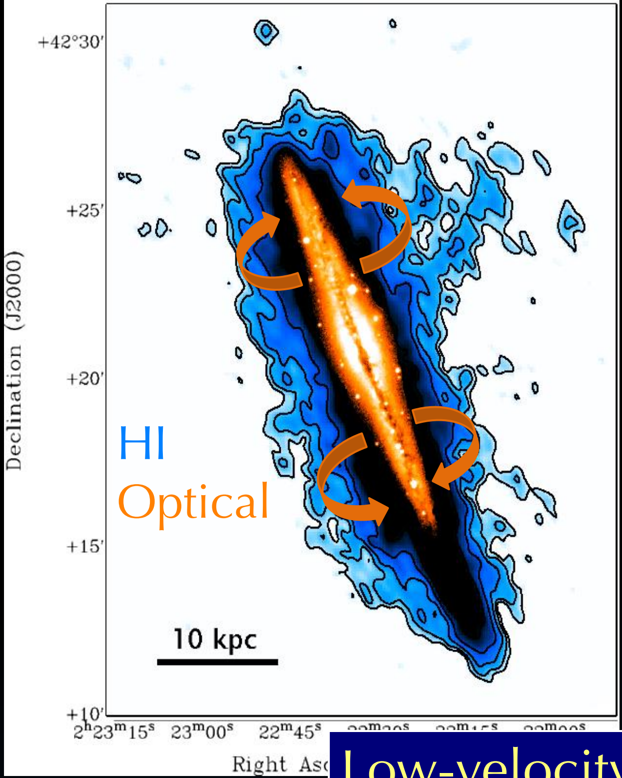
Pezzulli & Fraternali 2016

Galactic fountain and corona condensation

Fraternali F., "Gas accretion via condensation and fountains", 2017, ASSL - Springer, 430, 323 – review chapter

Massive local circulation

NGC 891



Oosterloo, Fraternali,
Marasco et al. 2011

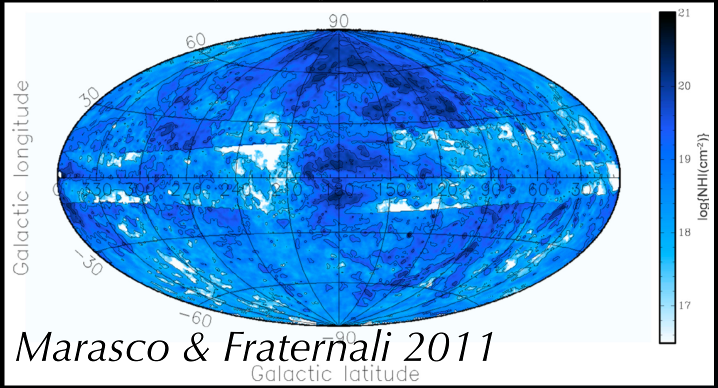
Low-velocity
produces a m
circulation

Extraplanar HI
h ~ 1-2 kpc, M~4x10⁸ M$_\odot$

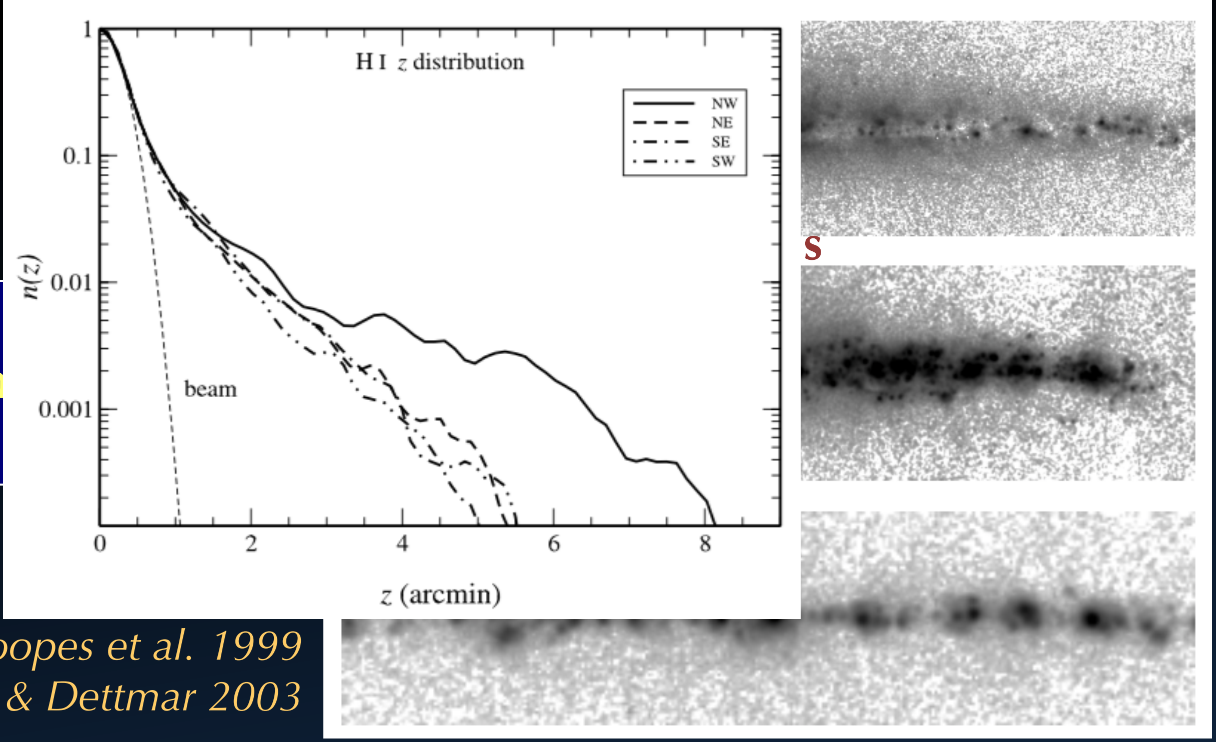
Falls in few x 10⁷ yr
-> galactic fountain
circulates ~ 10 M$_\odot$/yr

Typical velocities v~70 km/s
≤1% of SN energy

Milky Way's extraplanar HI



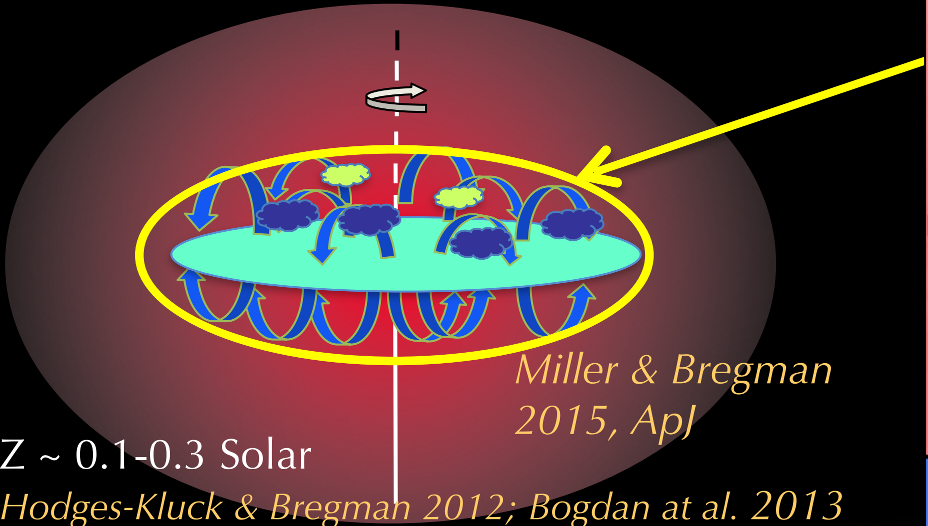
Marasco & Fraternali 2011



See simulations e.g.
Kim & Ostriker 2018

Hoopes et al. 1999
Rossa & Dettmar 2003

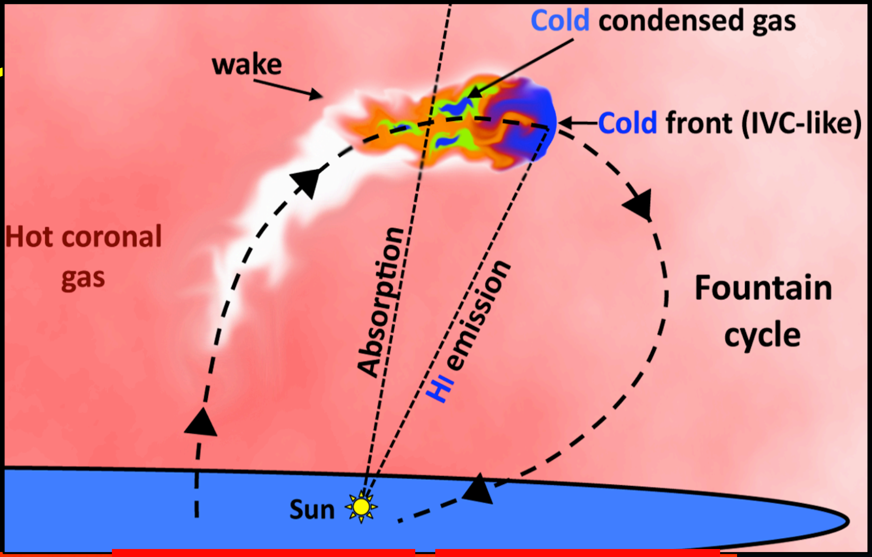
Mixing promotes corona condensation/accretion

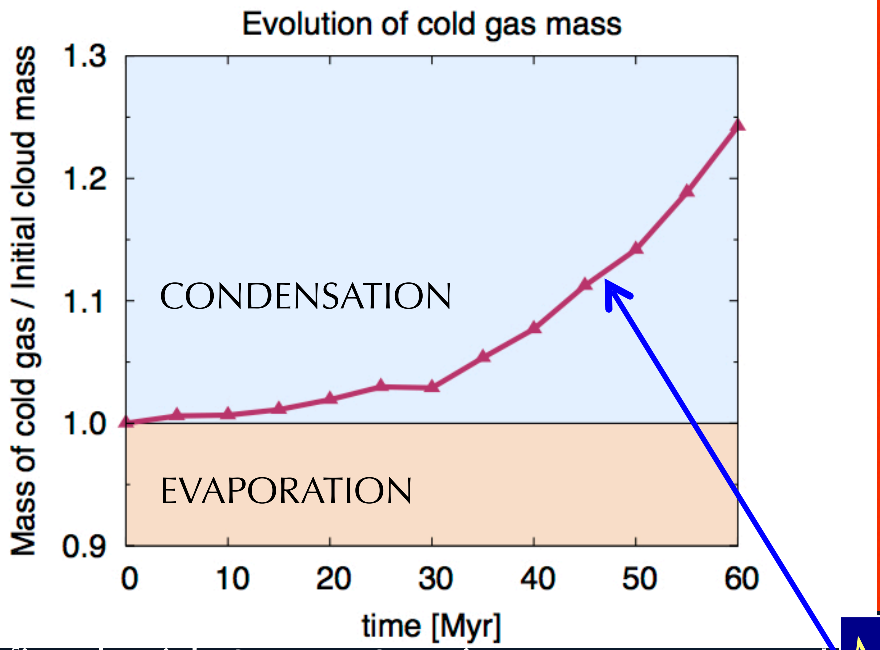


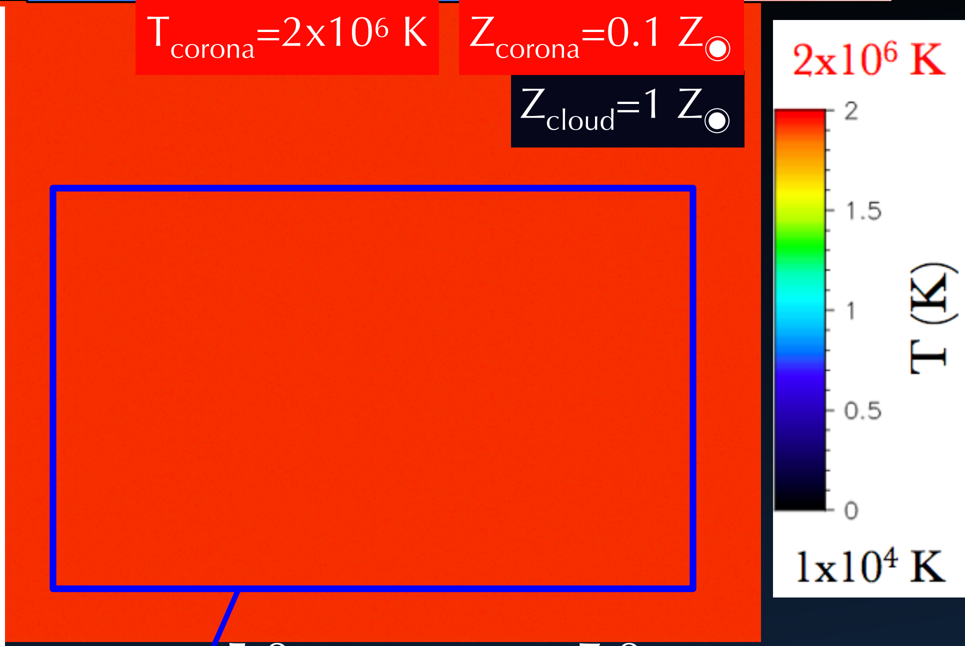
Miller & Bregman 2015, ApJ

$Z \sim 0.1-0.3$ Solar

Hodges-Kluck & Bregman 2012; Bogdan at al. 2013







$T_{\mathrm{corona}}=2\mathrm{x}10^6$ K

$Z_{\mathrm{corona}}=0.1\ Z_{\odot}$

$Z_{\mathrm{cloud}}=1\ Z_{\odot}$

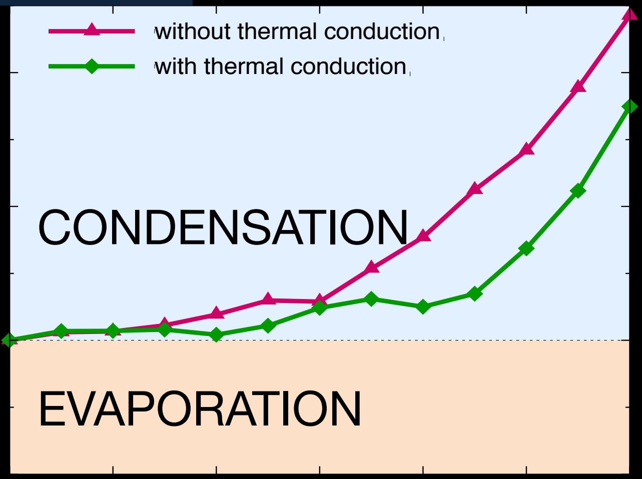
Mass of cold gas increased by ~20%!

2D fixed grid, 2 pc x 2 pc!

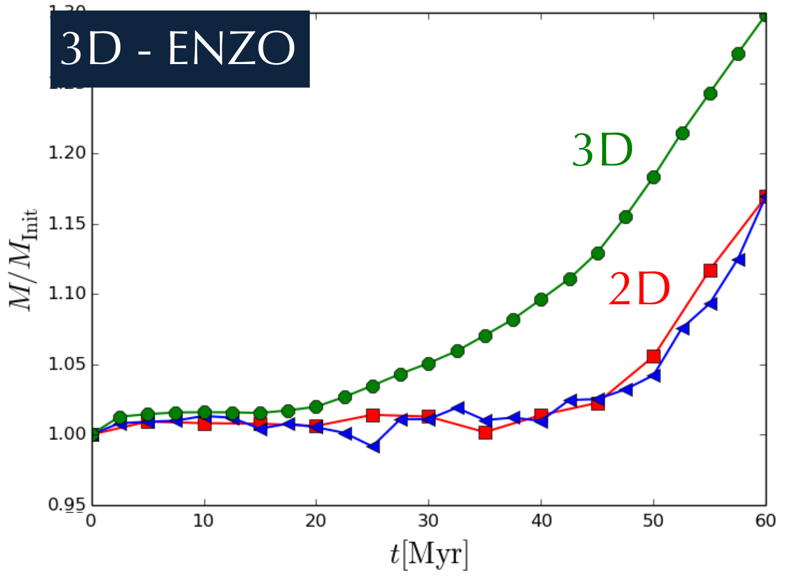
X (k

Condensation is persistent

Thermal conduction

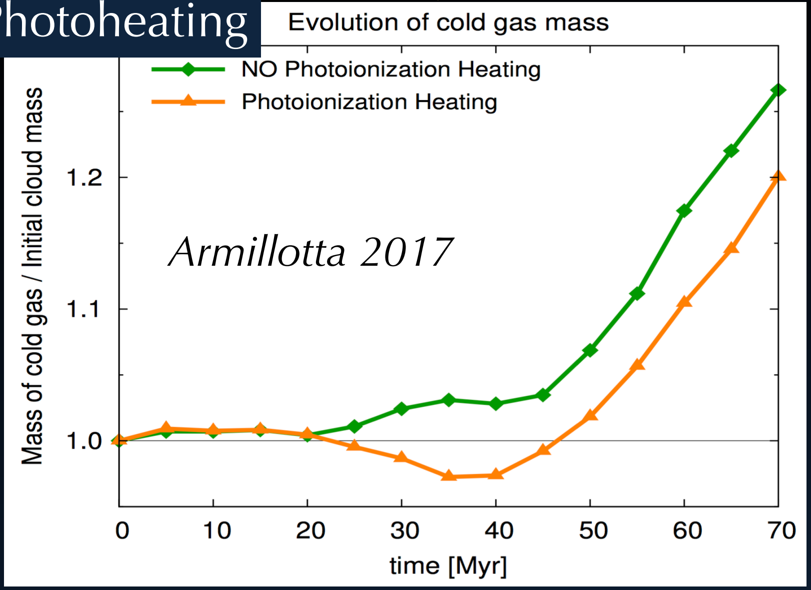


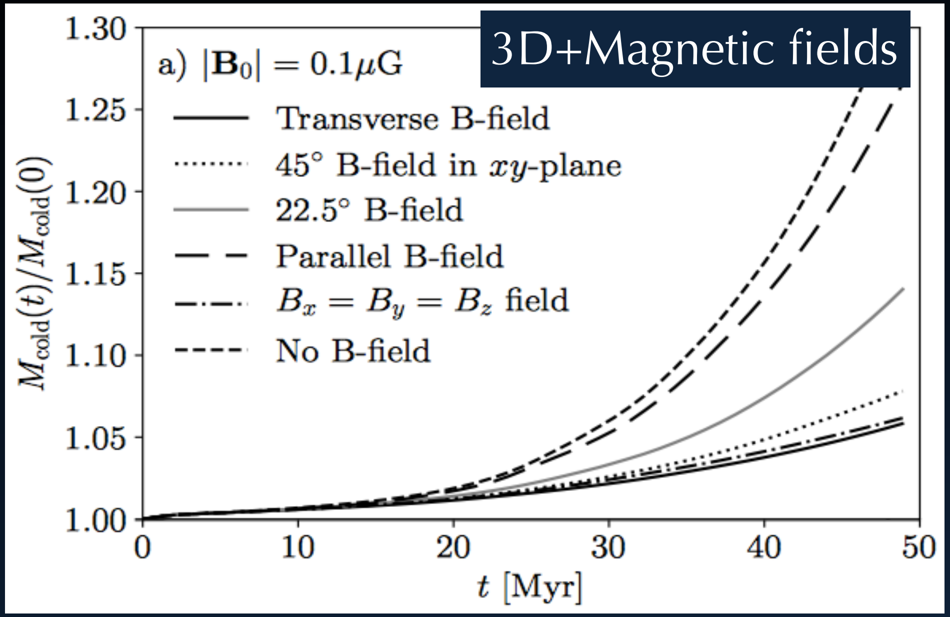
Armillotta, Fraternali et al. 2016



M. Canducci

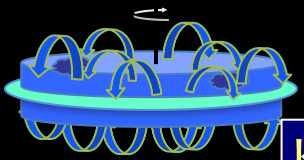
Photoheating

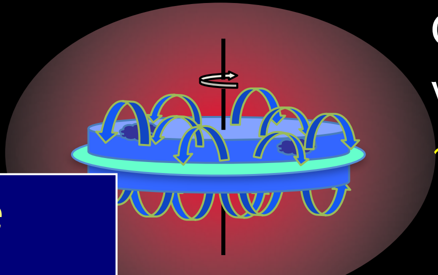




Gronnow, Tepper-Garcia & Bland-Hawthorn 2018

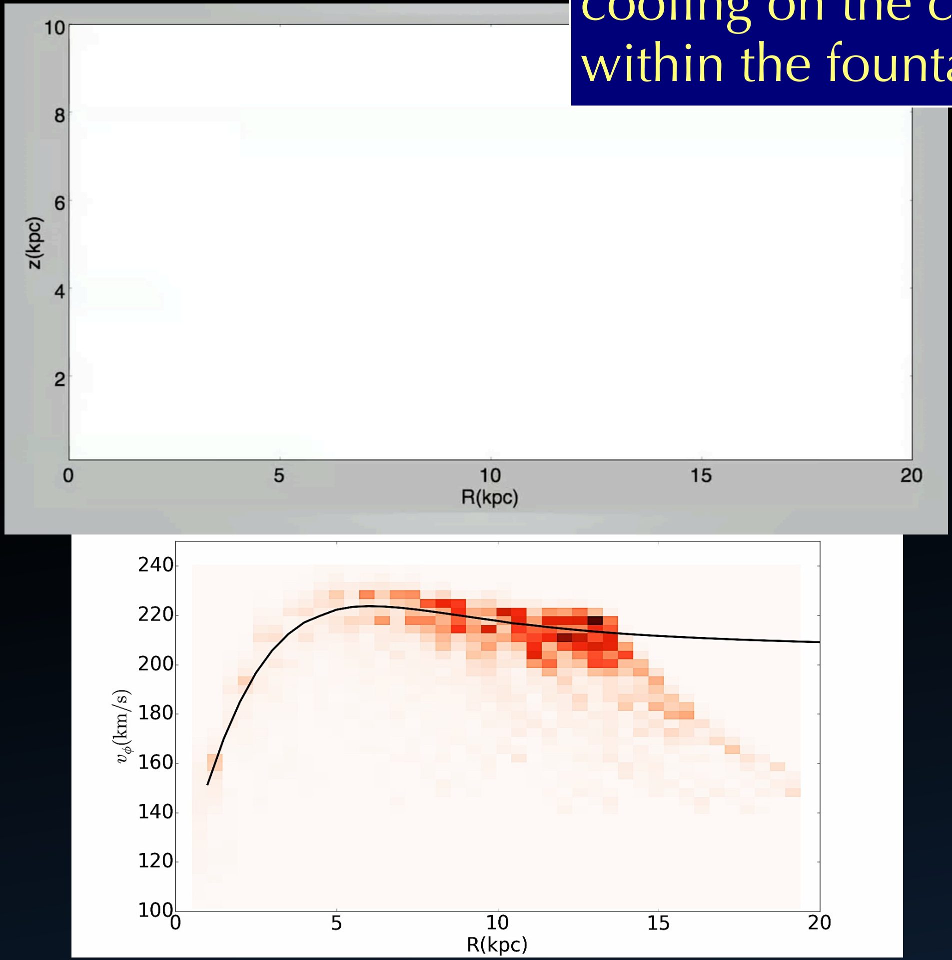
Modification of orbits

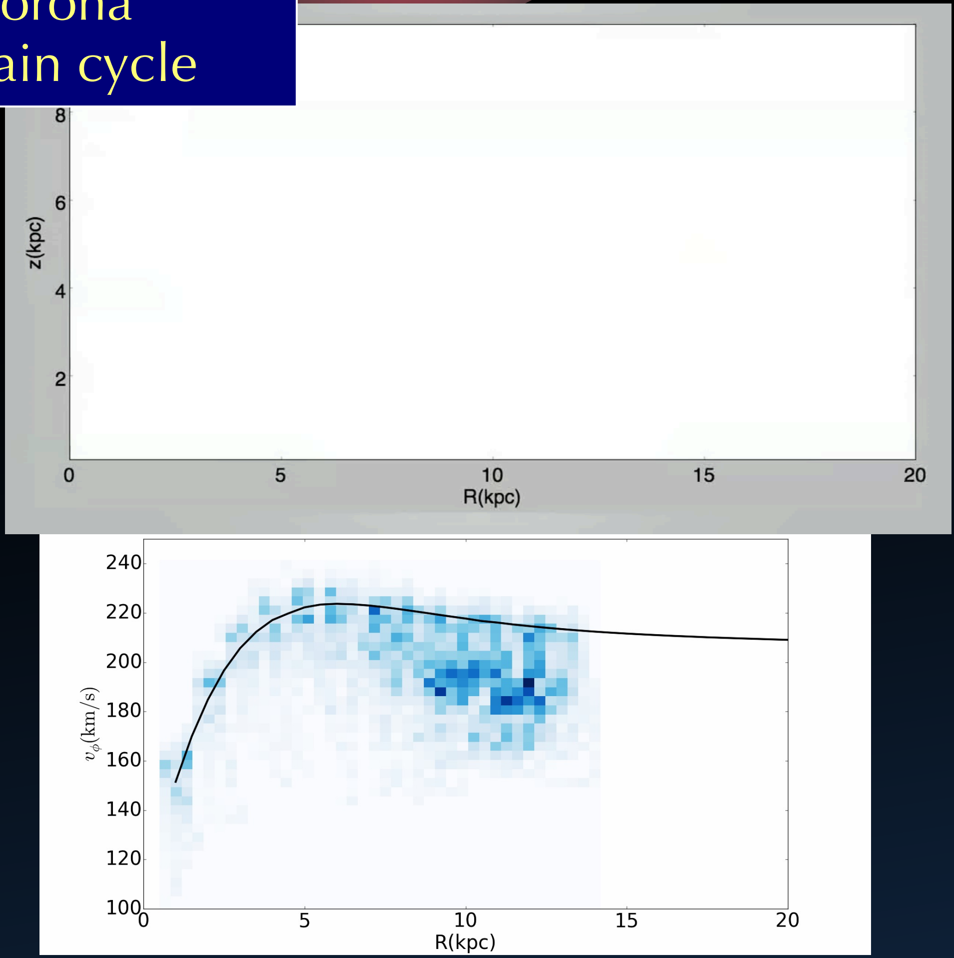




Corona rotates with a lag of ~ 75 km/s

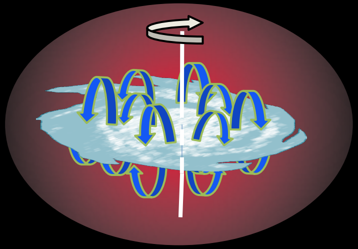
Kinematic imprint of the cooling on the corona within the fountain cycle





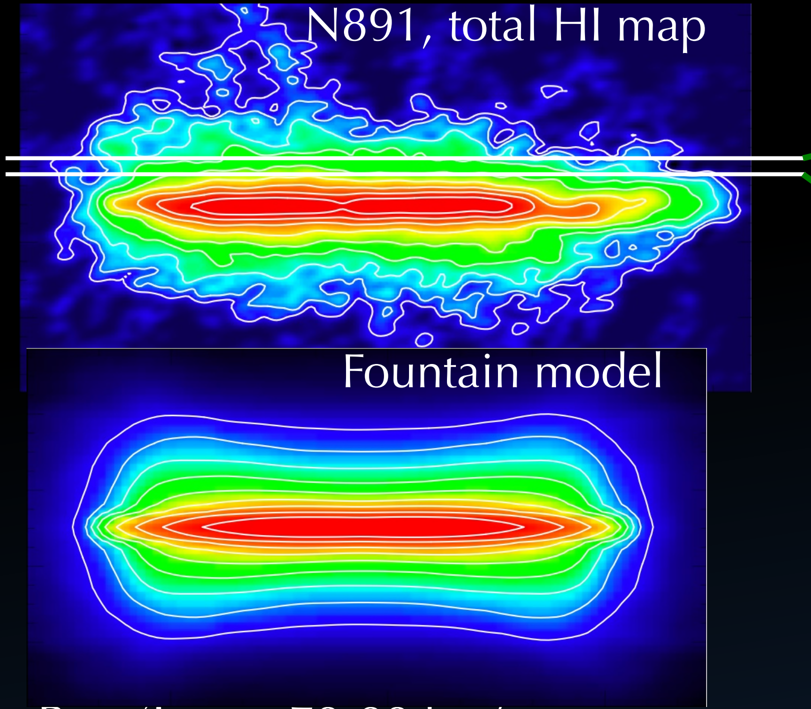
Rotation of the corona from (*Marinacci, Fraternali et al. 2011, MNRAS*)

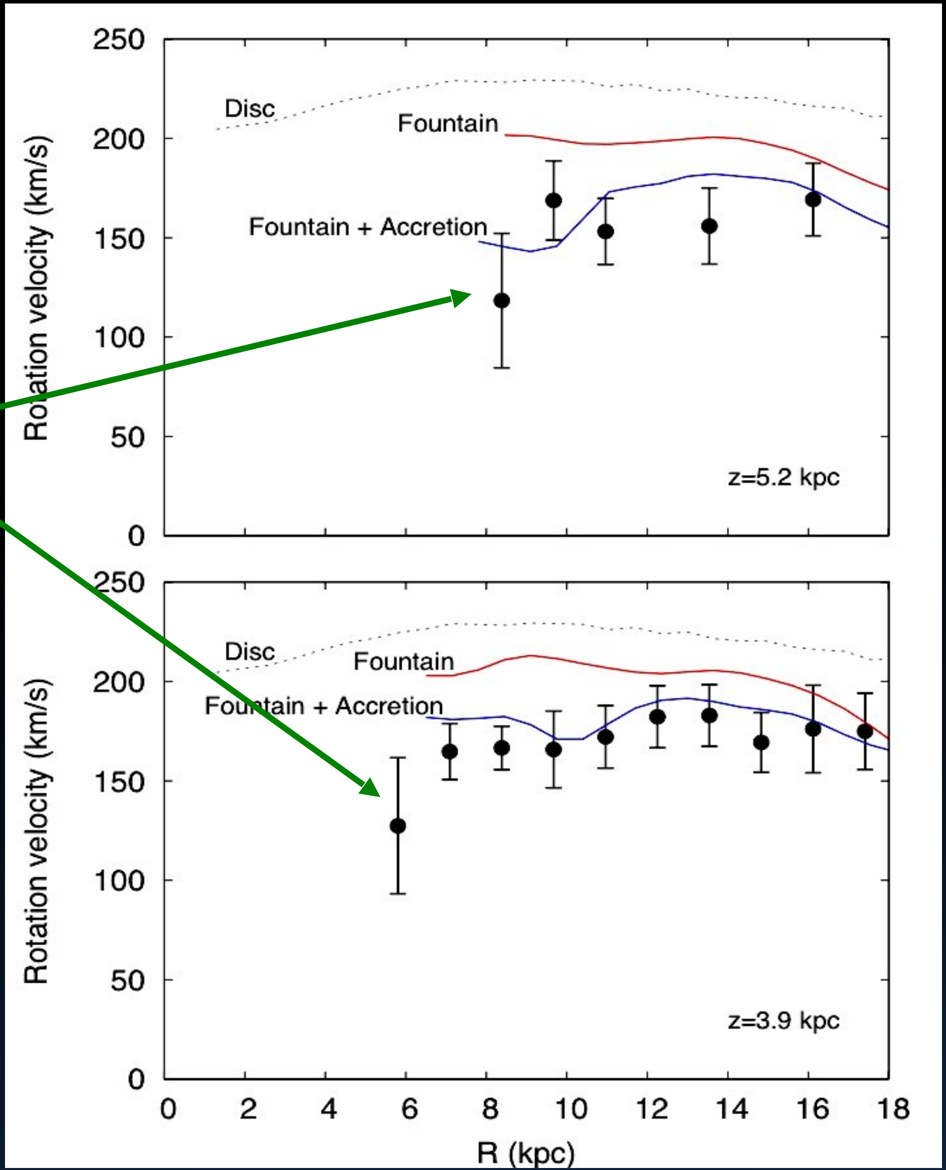
Data require fountain accretion



Kick velocities (v_k)

Accretion rate (dM/dt)





Best-fit v_k = 70-80 km/s

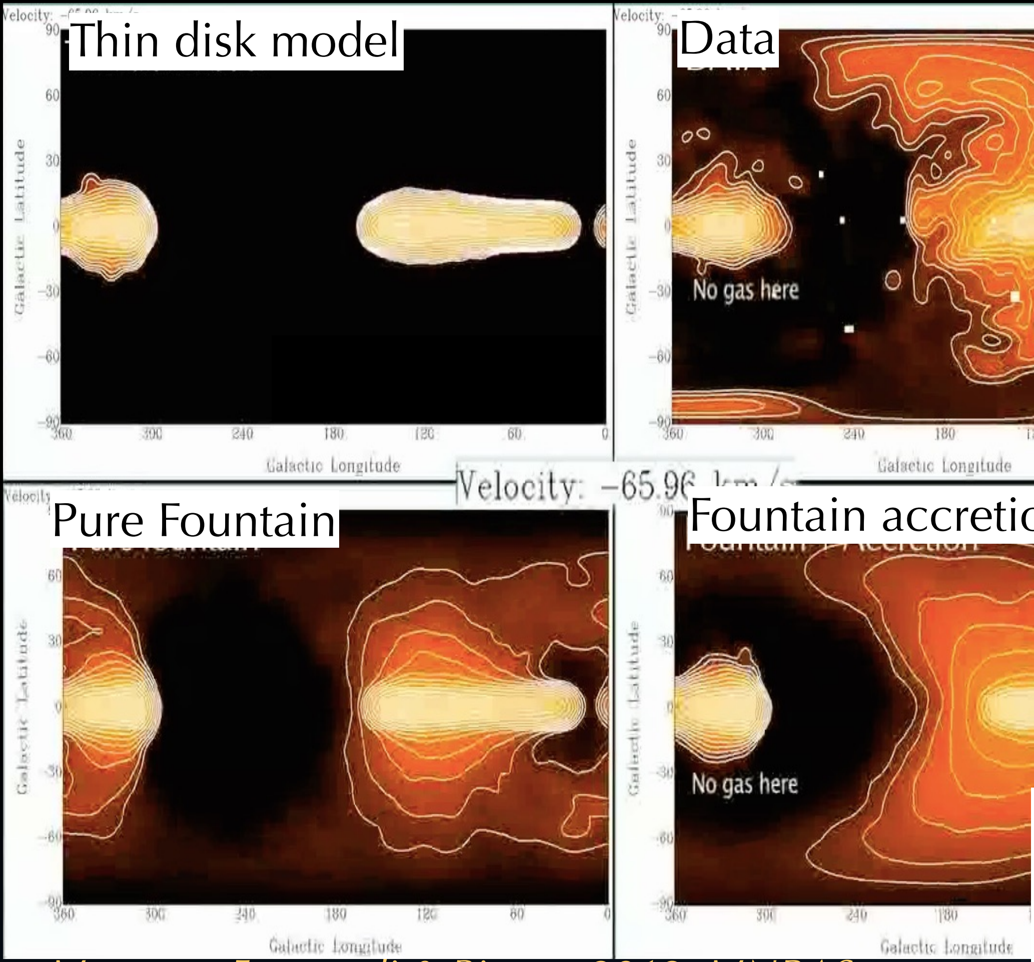
Best-fit Accretion Rate ~ 3 $M_\odot yr^{-1}$

Compare to SFR ~ 4 $M_\odot yr^{-1}$

80-90% of the gas from the disc, rest from condensation

Fraternali & Binney, 2008

Fountain accretion in the Milky Way



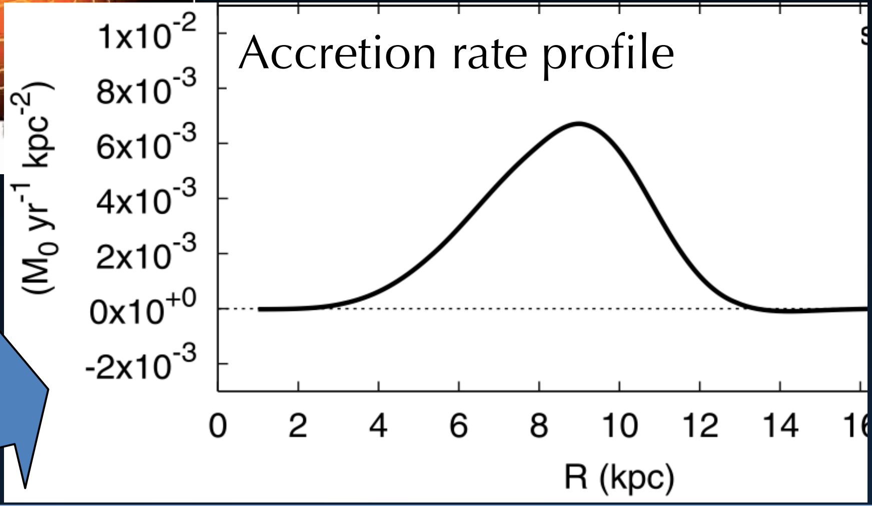
Corona rotates with a lag of 75 km/s
-> ~170 km/s

Marasco, Fraternali & Binney 2012, MNRAS

Movie in www.filippofraternali.com

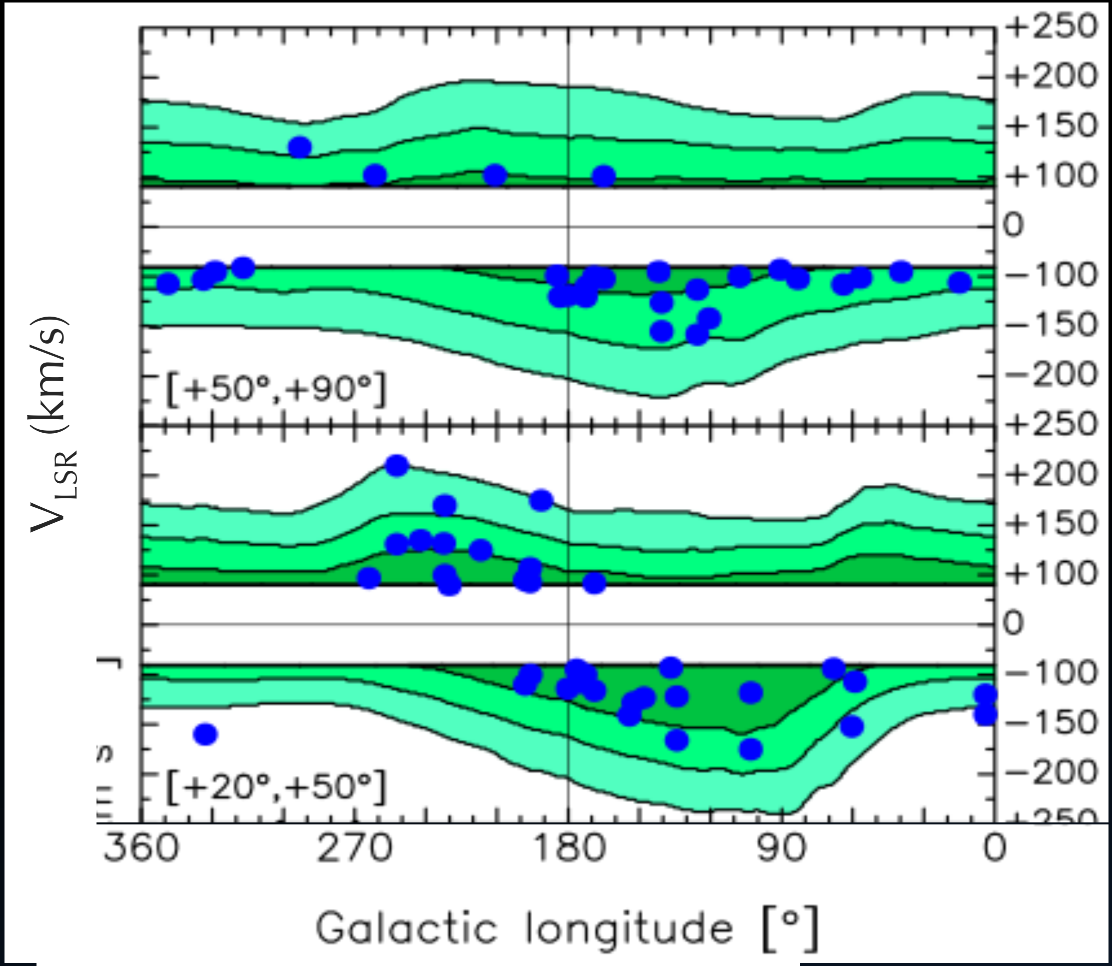
Best-fit Accretion Rate ~ 2 $M_\odot yr^{-1}$

Compare to SFR ~ 1-3 $M_\odot yr^{-1}$

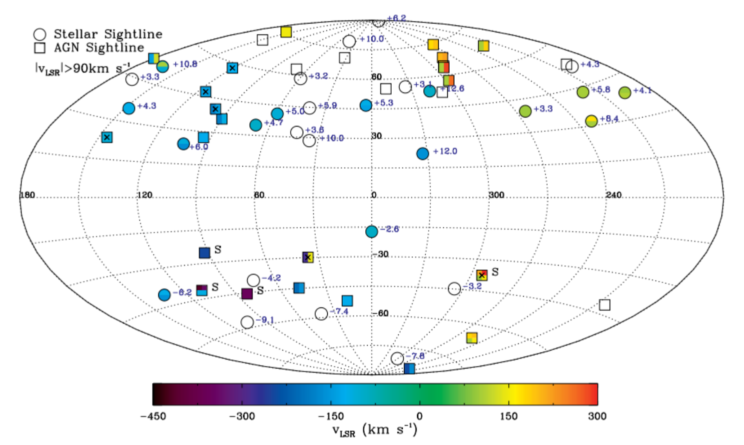


Ionized gas around the MW

Marasco, Marinacci & Fraternali 2013, MNRAS



● *Data from Lehner et al. 2012, MNRAS*

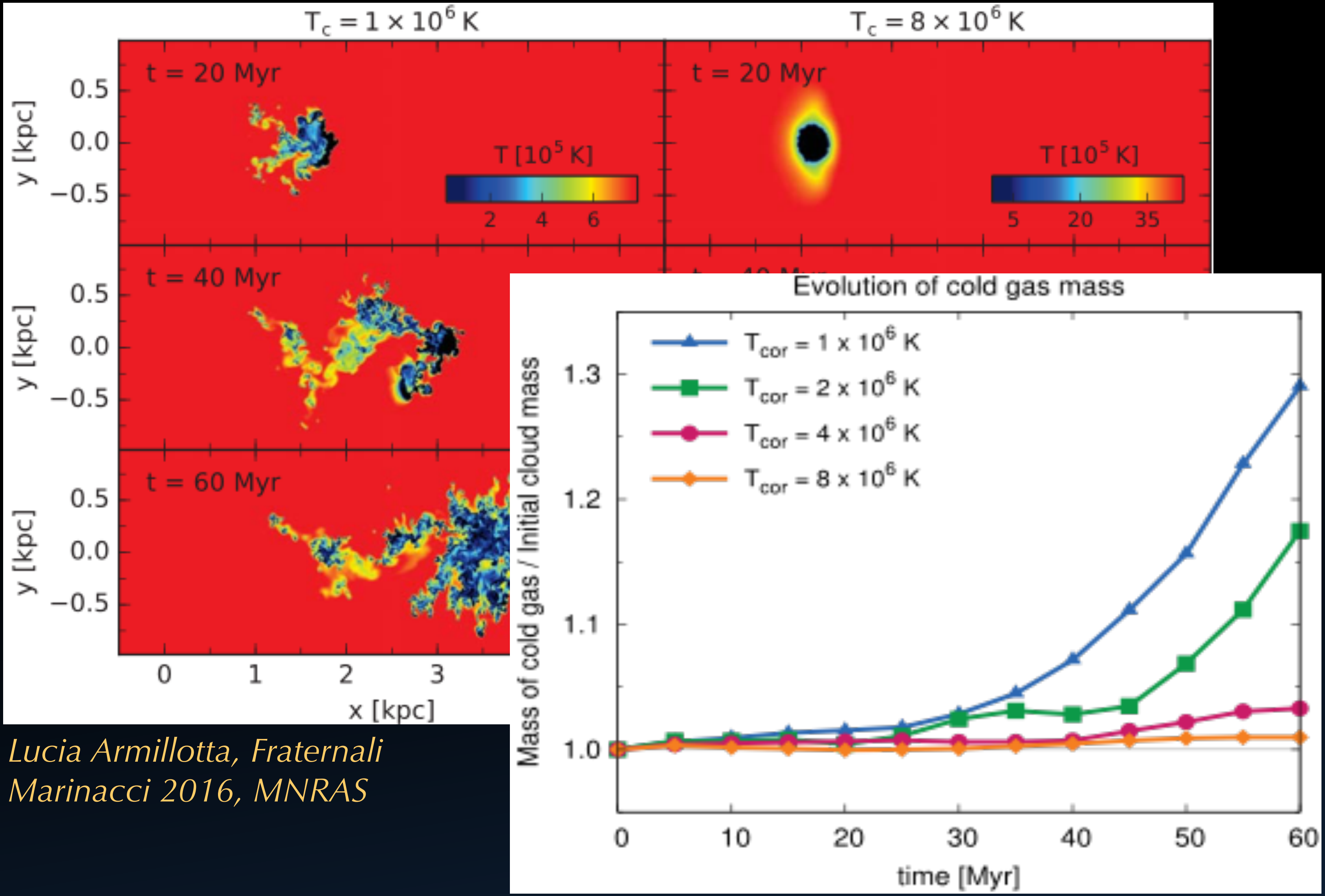


This model reproduces:

- Positions & velocities of 95% absorbers
- Average column density
- Number of absorbers along the l.o.s.
- High velocity dispersions of absorbers

'Warm' accretion: ~1 $M_\odot$/yr

Condensation: different temperatures



*Lucia Armillotta, Fraternali
Marinacci 2016, MNRAS*

Smaller halos

↑

MW

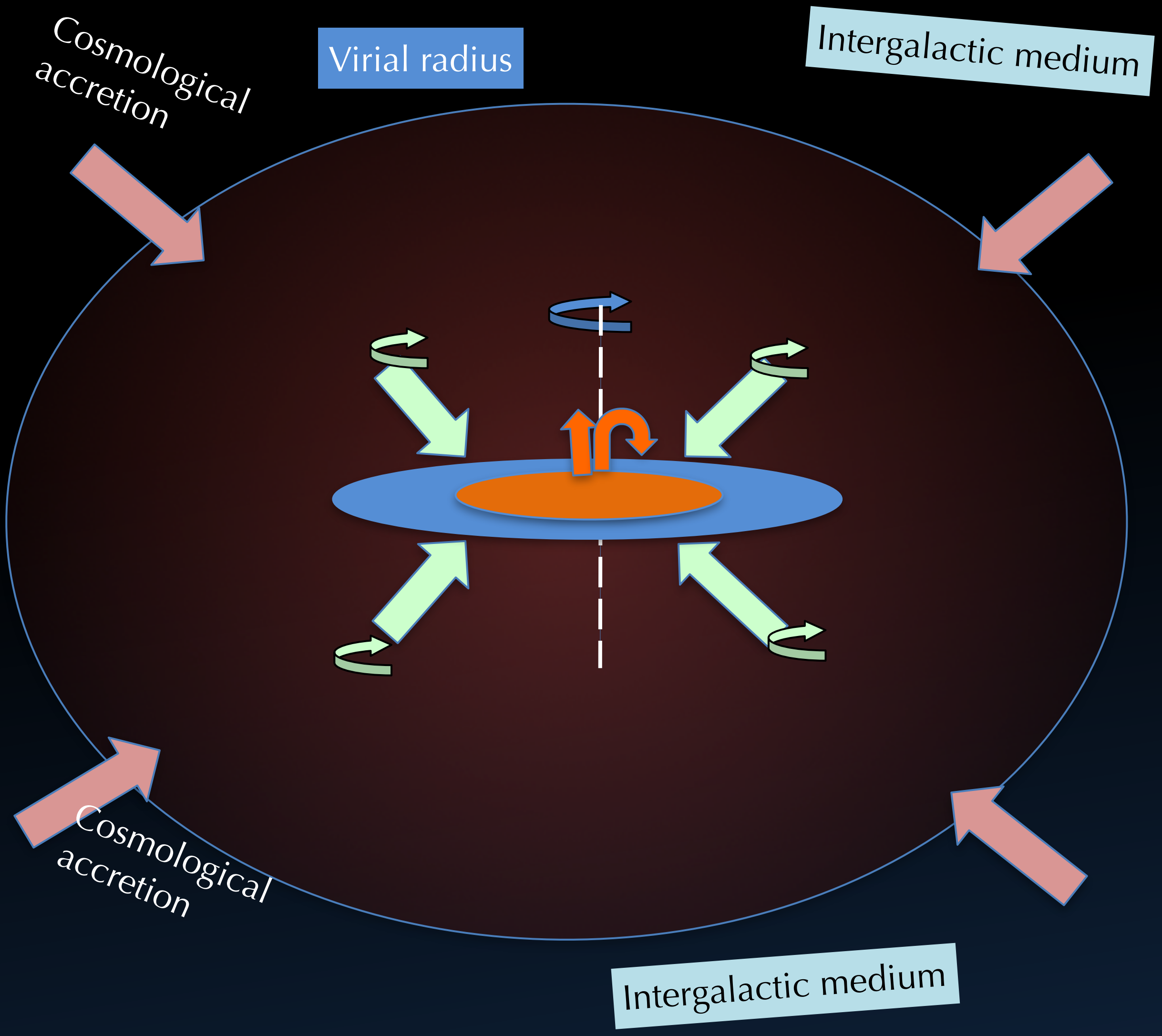
↓

Larger halos

Role in "halo" quenching?

Angular momentum of the accreting gas

Disc growth

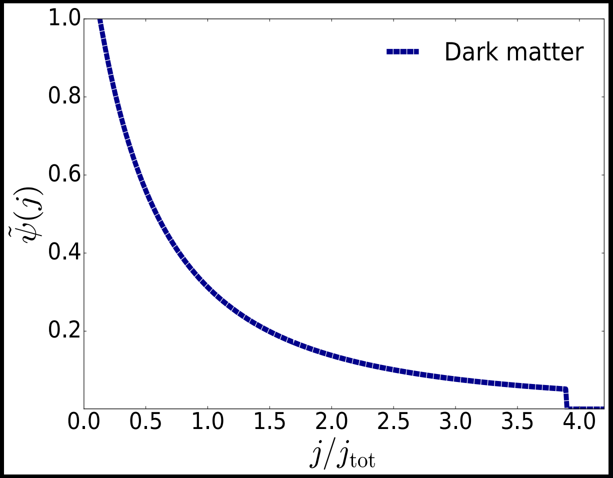

Cosmological accretion
Virial radius
Intergalactic medium
Cosmological accretion
Intergalactic medium

A cosmologically motivated corona

Starting points:

1. Angular momentum distribution (ψ) $\psi \equiv \frac{\mathrm{d}M}{\mathrm{d}j}$

Key assumption: AMD of baryons = AMD of dark matter



From Tidal Torques

Peebles 1969; Bullock et al. 2001; Sharma & Steinmetz 2005

2. Galactic potential
3. Barotropic corona (e.g. isothermal)

Rotating equilibrium

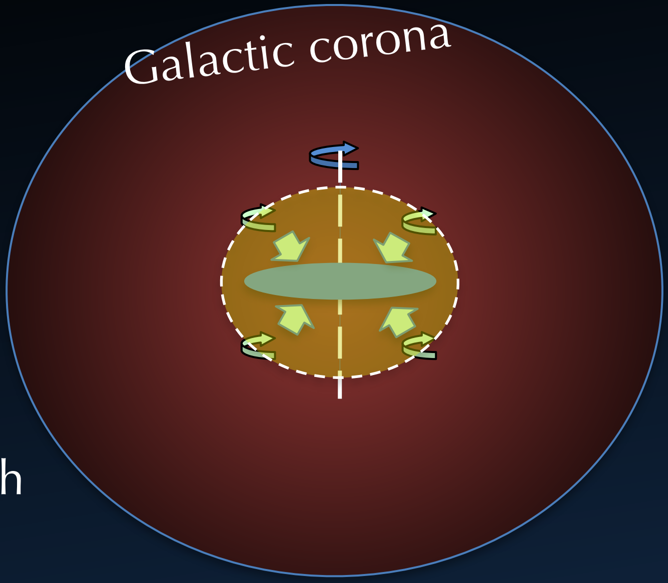
Analytical method

Pezzulli, Fraternali & Binney 2017, MNRAS

Density & rotation of the corona functions of temperature

If the corona in contact with the disc has $j_{\rm cor} > j_{\rm disc}$

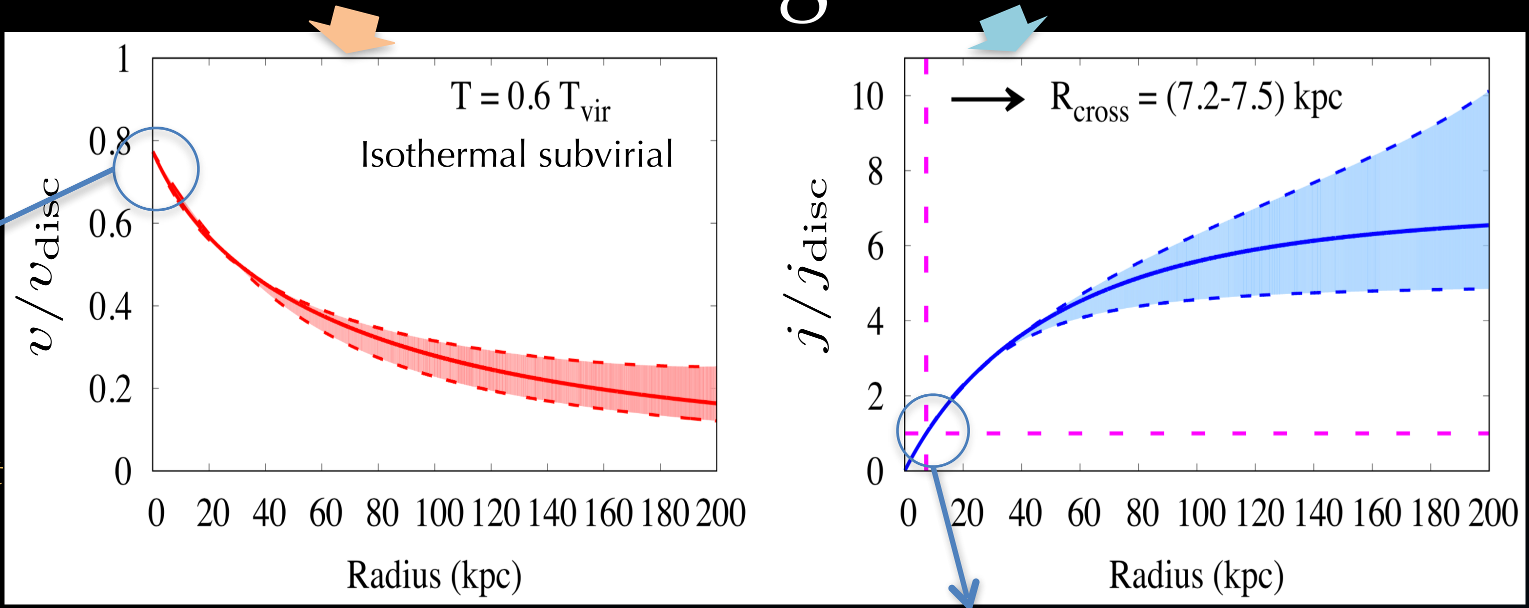
Inside-out growth



Corona rotation & angular momentum

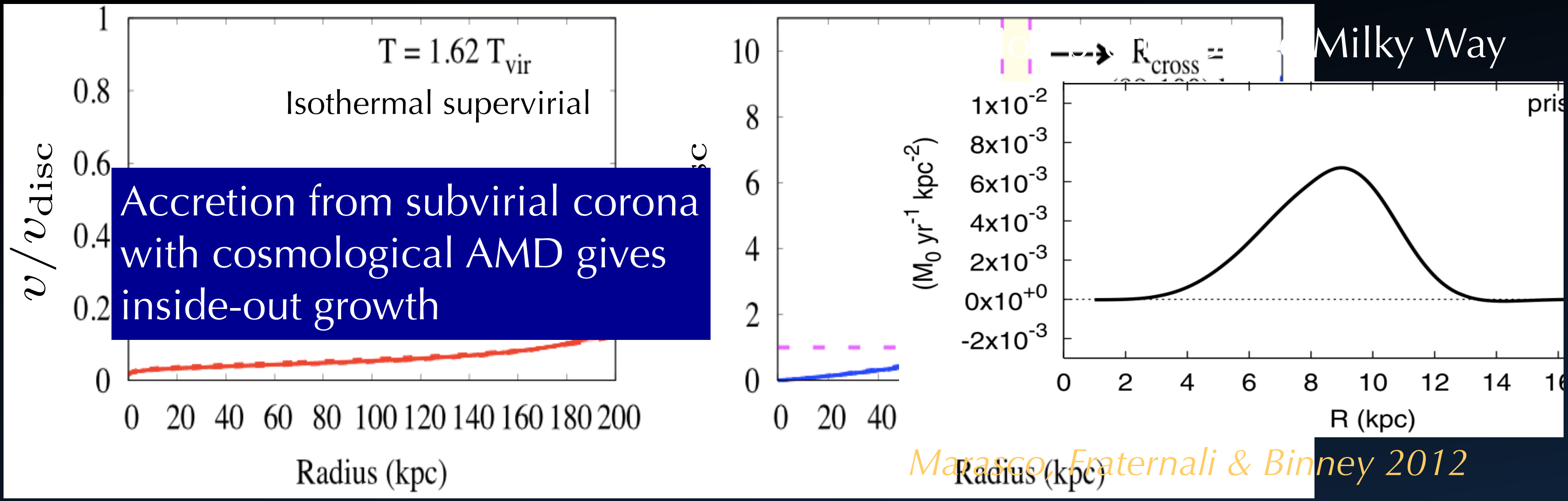
Consistent with Fountain!

And pioneering measure: 183+-41 km/s *Hodges-Kluck et al. 2016, ApJ*



Pezzulli, Fraternali & Binney 2017, MNRAS

High angular momentum accretion -> inside-out growth possible!



Milky Way

Accretion from subvirial corona with cosmological AMD gives inside-out growth

Marasco, Fraternali & Binney 2012

How to reconcile this with strong feedback

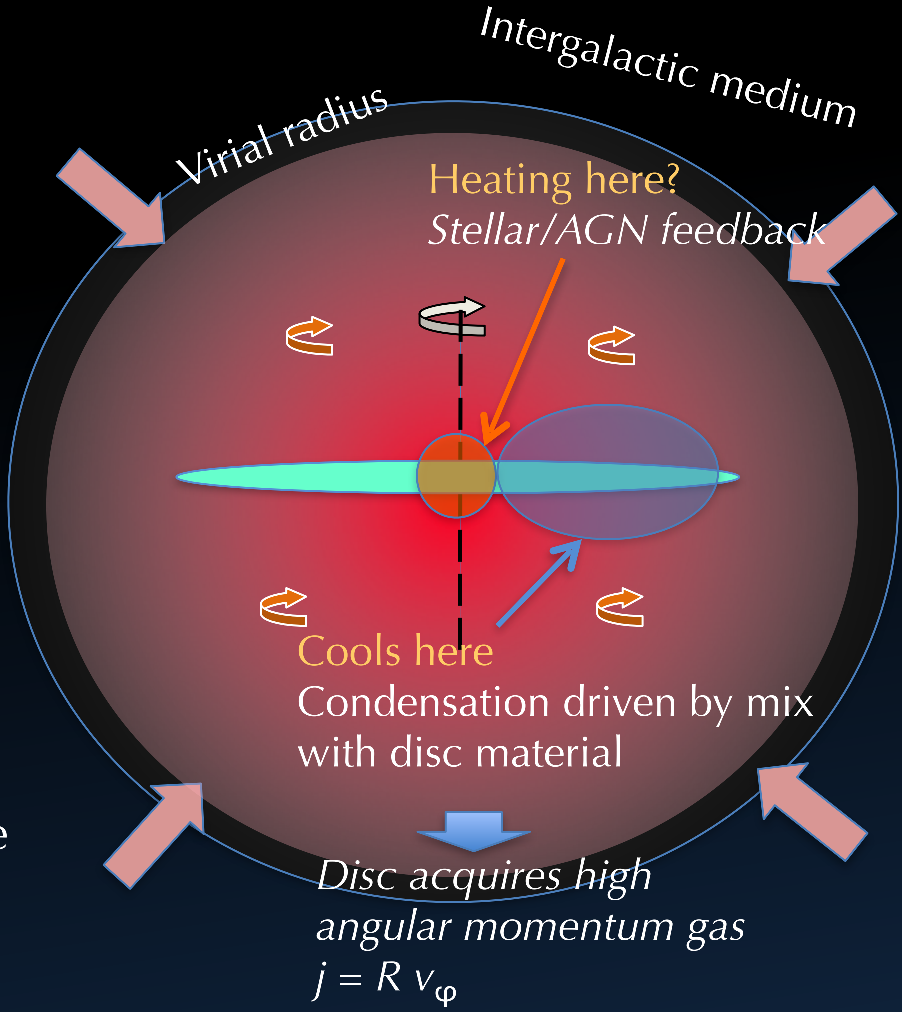
How to make a disc galaxy

z> 2 Cold gas accretion phase -> disc formation
Feedback very effective
Mergers -> thick discs, bulges

z~1-2 Mass threshold reached
-> corona formation

z< 1 Corona cooling phase -> growth of disc
Feedback -> can keep inner corona hot?
Fountain -> corona accretion

Merger / infall into cluster
YES -> cold gas ends -> quenching
NO -> SF keeps going on until T too large



Heating here?
Stellar/AGN feedback

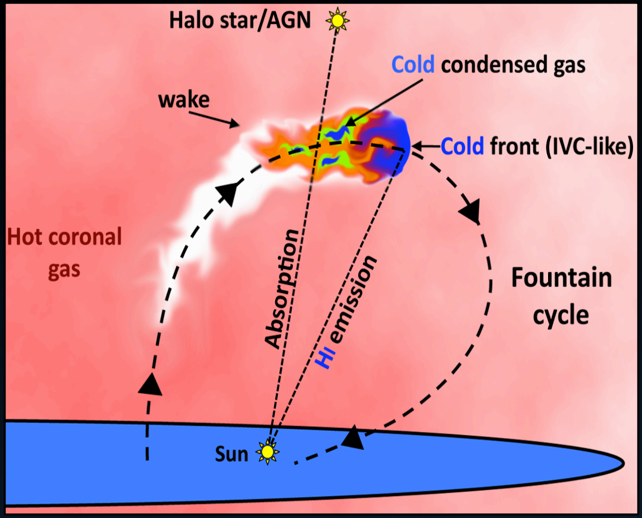
Cools here
Condensation driven by mix with disc material

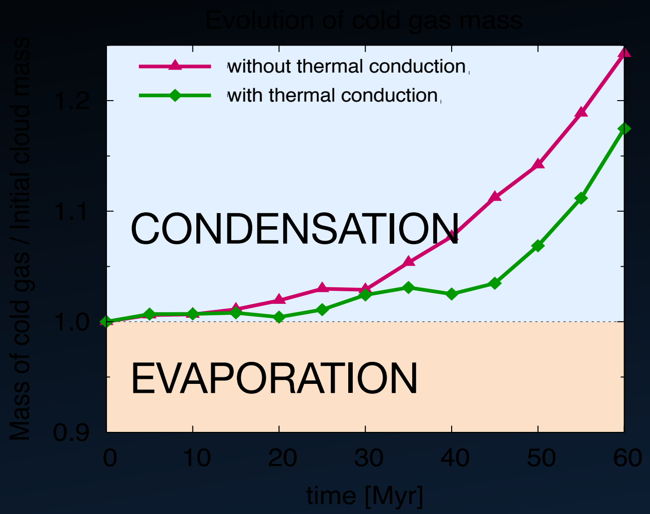
Disc acquires high angular momentum gas
$j = R\, v_\varphi$

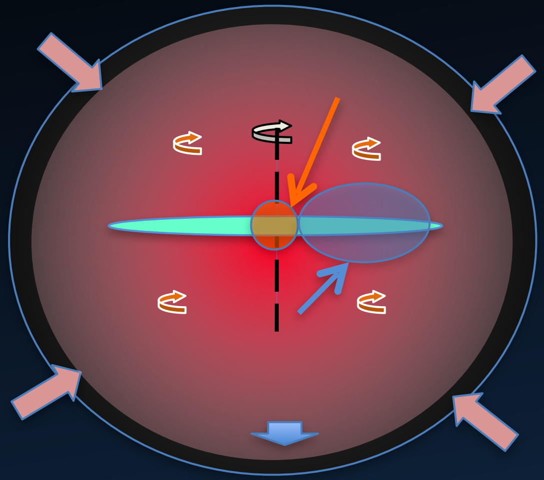
Conclusions

1) Galactic fountain
   Circulates a large mass (more than winds)
   Triggers the condensation of lower corona
   Many observable reproduced, how do we incorporate with the rest?

2) Angular momentum
   Accretion must occur at high *j*
   Corona can be consistent with inside-out growth



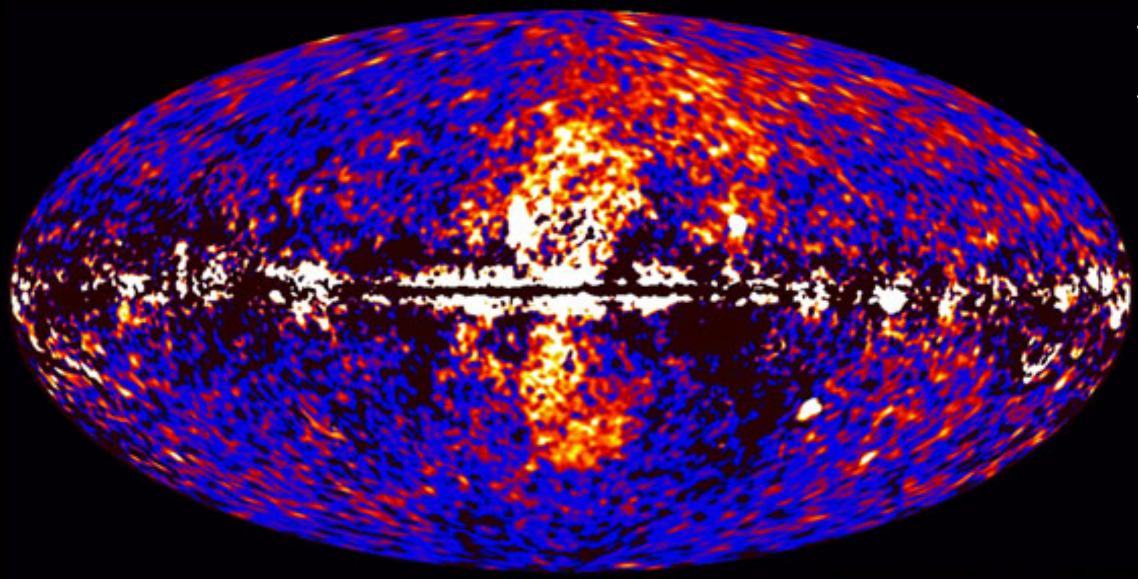




Thanks!

Do galaxies keep the heating high?

1)



What is the effect of this on the corona cooling and gas accretion?

Bland-Hawthorn+ 2013
Su et al. 2015

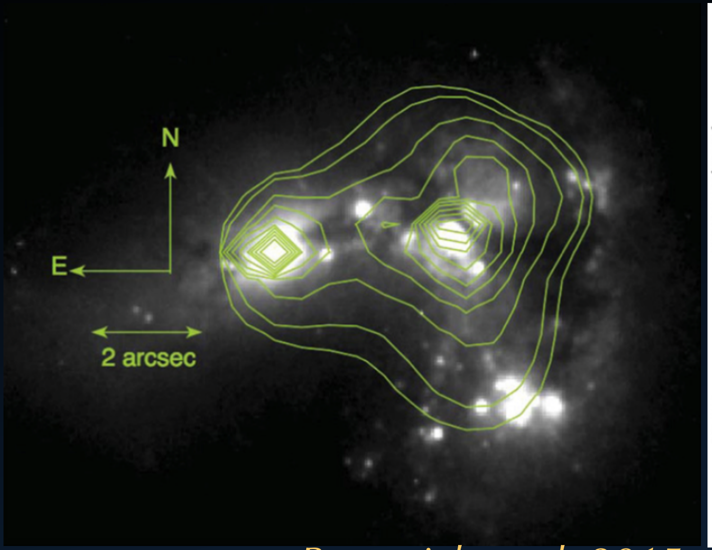
3) Local sources
Cantalupo et al. 2010

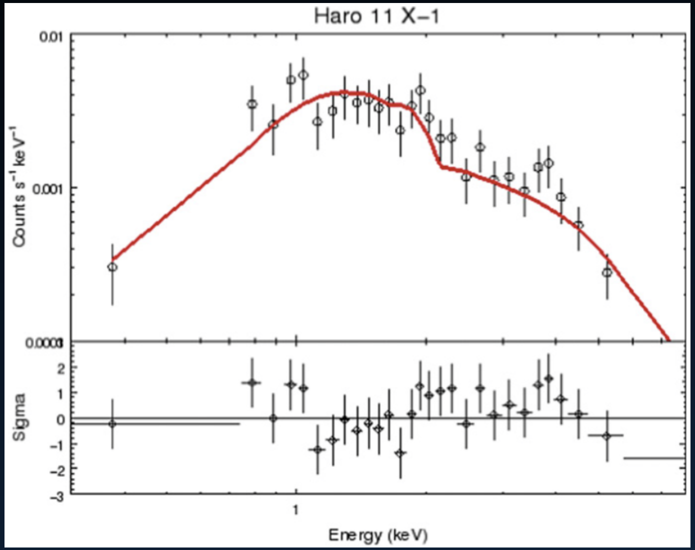
2)

Ultra-luminous X-ray sources

Insane luminosity
$L_X \sim 10^{40}$-10^{41} erg s^{-1}

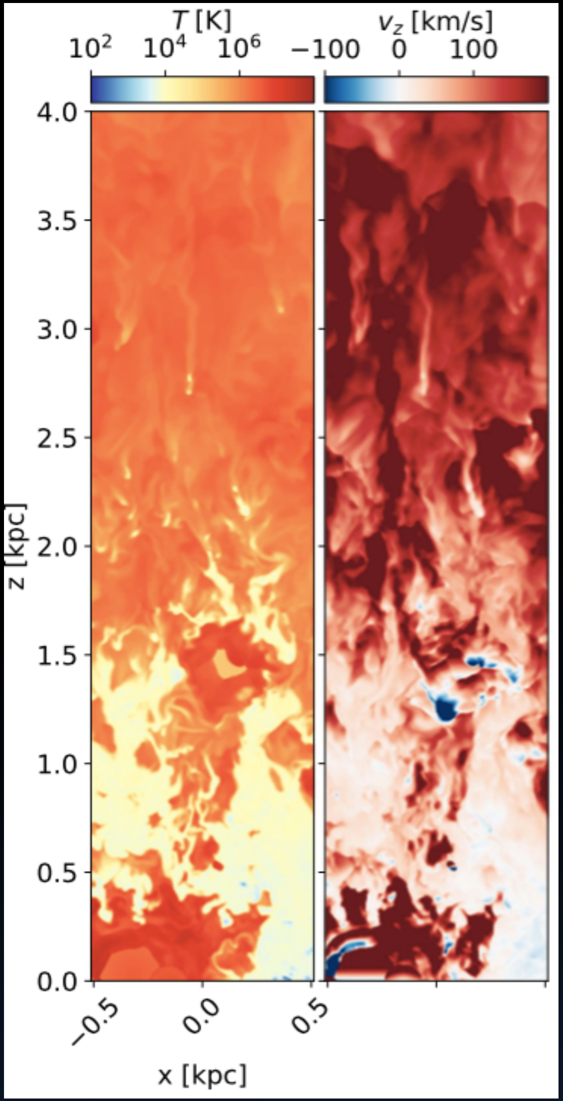
This is L_X of M87 BH!

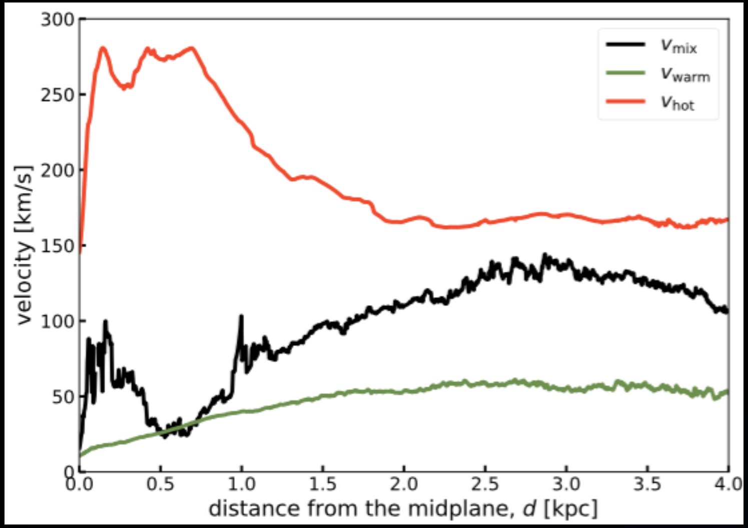


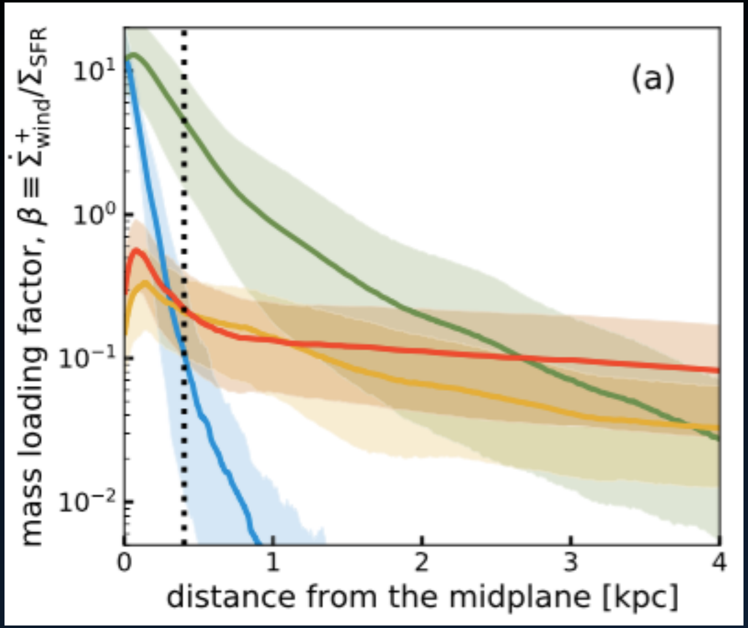


Prestwich et al. 2015

High-res simulations

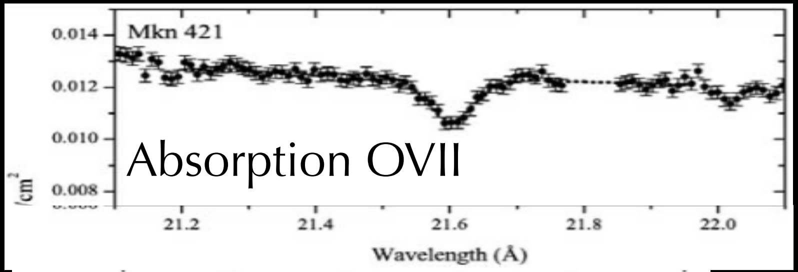




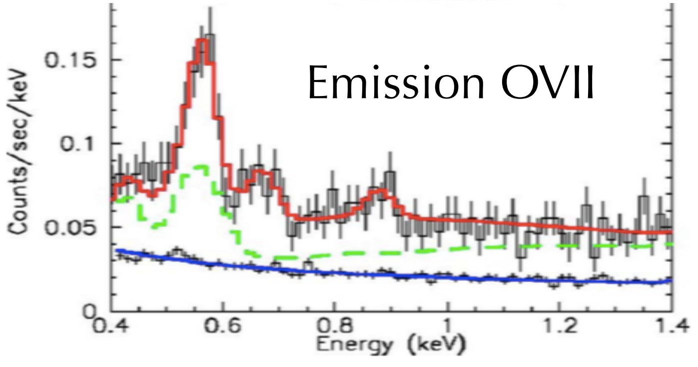


Kim & Ostriker 2018

HOT gas around galaxies

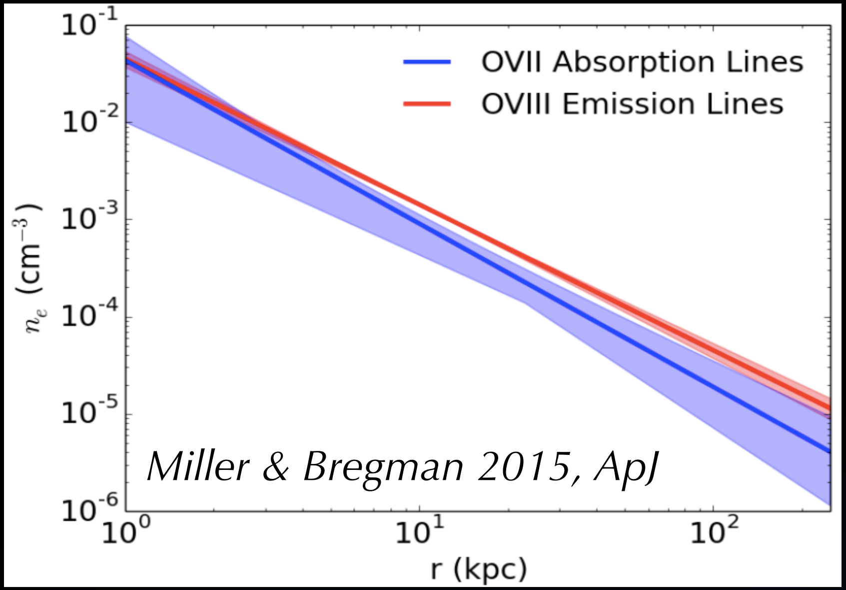


Absorption OVII

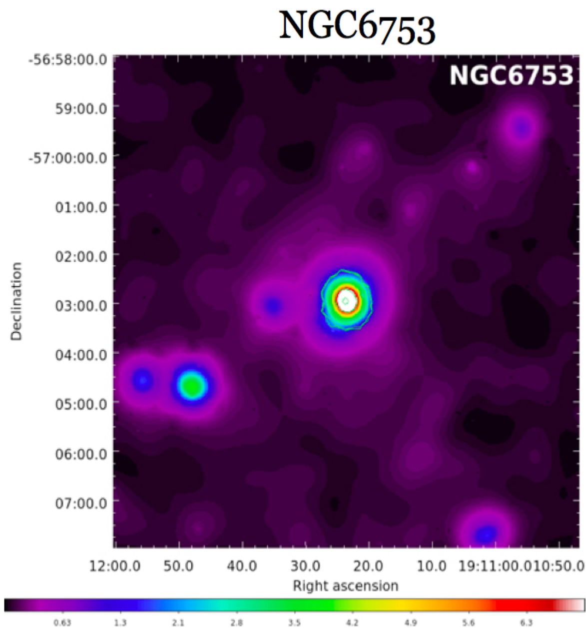


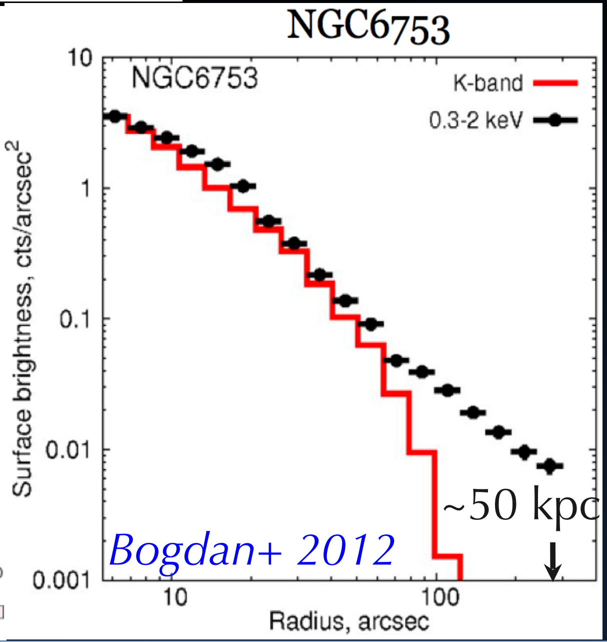
Emission OVII

~600 spectra around the MW



Miller & Bregman 2015, ApJ





Bogdan+ 2012

T_{cor} >~ few x 10^6 K

Z ~ 0.1-0.3 Solar (*Hodges-Kluck & Bregman 2012, ApJ; Bogdan at al. 2013, ApJ*)

If $R \sim R_{vir}$ ->

$M_{hot} \sim 2\text{-}6 \times 10^{10}\ M_\odot$

(10-50% of missing)

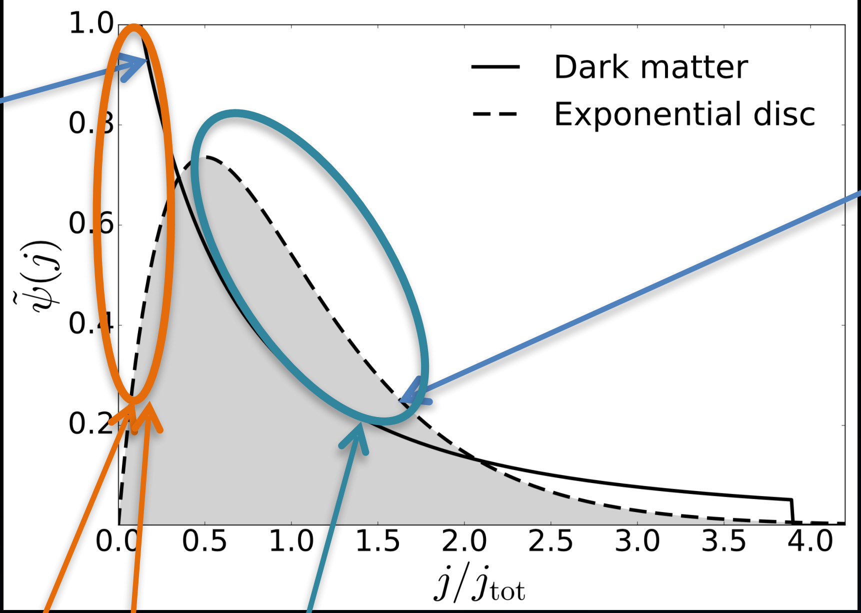
$M_{cool} \sim 0.2\ M_\odot/yr$

Local angular momentum problem

Angular momentum distributions

Pre-galactic gas

Beginning of formation



Exponential disc

End production of formation

Cimatti, Fraternali & Nipoti 2019, CUP

Strong feedback

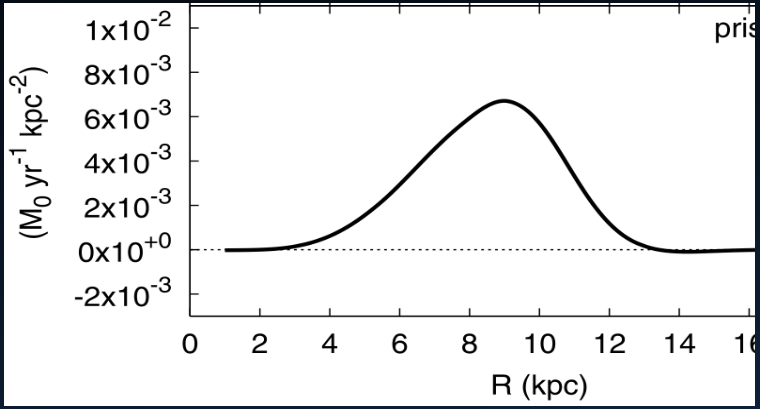
-> selective removal of low-j gas

Fountain + condensation

1) Mixes gas producing intermediate ang mom gas
2) Accretion at large radii -> large j = R v

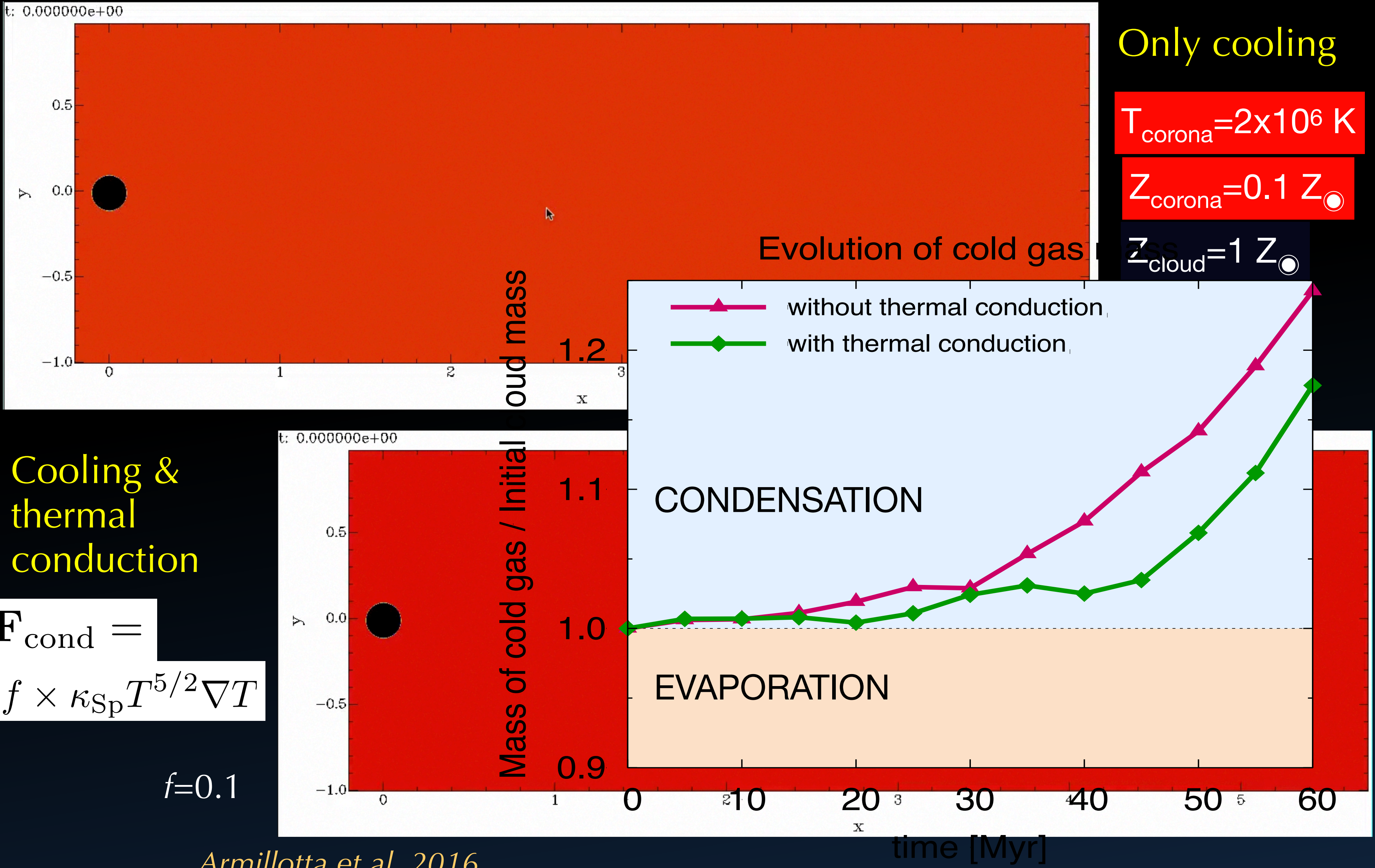
-> selective accretion

Accretion profile of the Milky Way



Marasco, Fraternali & Binney 2012

The effect of thermal conduction



Only cooling

$T_{corona}=2\times10^6$ K

$Z_{corona}=0.1\ Z_\odot$

$Z_{cloud}=1\ Z_\odot$

Cooling & thermal conduction

$$\mathbf{F}_{\rm cond} = f \times \kappa_{\rm Sp} T^{5/2} \nabla T$$

f=0.1

Armillotta et al. 2016

Modified corona

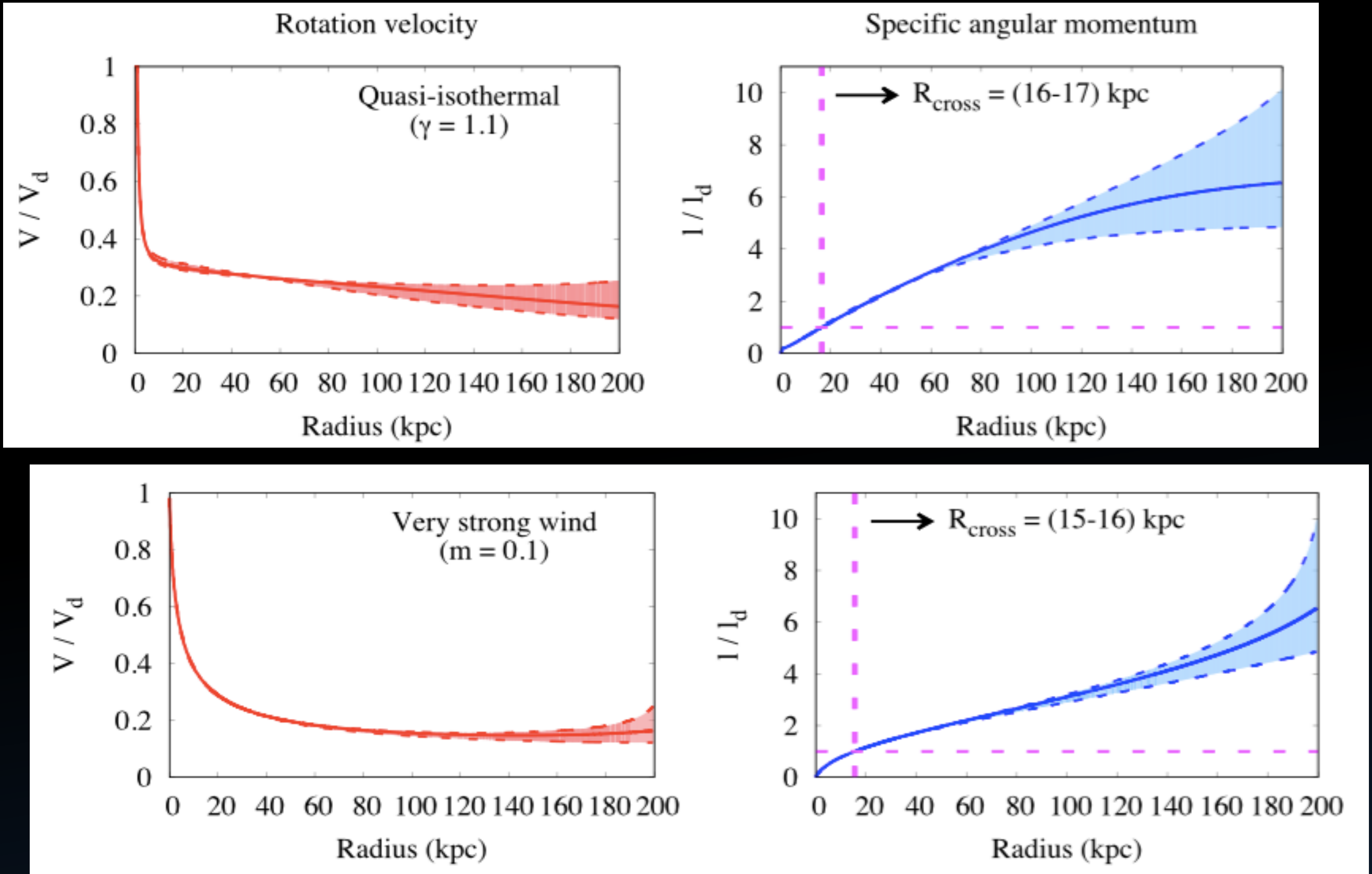
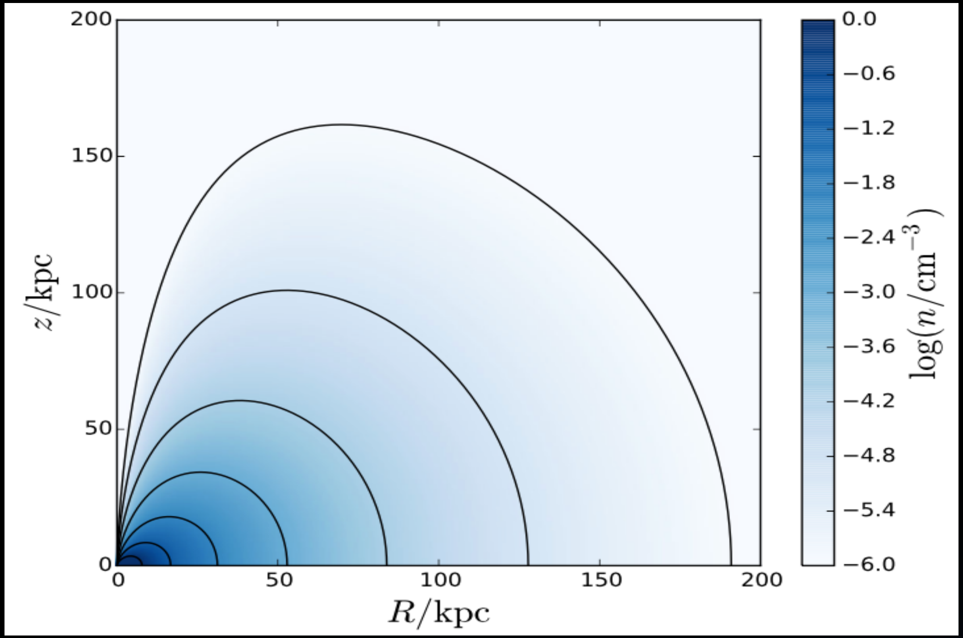
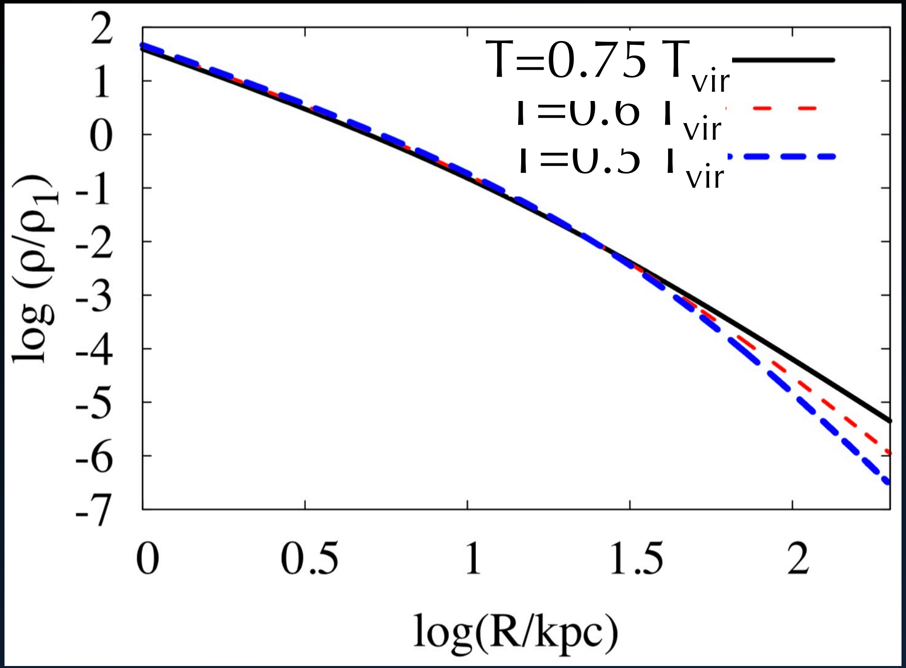


Figure 5. Similar to Fig. 4, but assuming that a Galactic wind expelled the low angular momentum material from the halo, leaving a *surviving* mass equal to a fraction $m = 0.4$ (upper panels) or $m = 0.1$ (lower panels) of the initial value. Note that in these models the average specific angular momentum of the corona is larger than l_1 (see text). The rotation velocity is high in the centre, but declines very steeply with radius. The angular momentum rises relatively slowly and even the model with the most extreme feedback ($m = 0.1$) is only marginally compatible with driving inside-out growth, since l becomes larger than l_d only at the edge of the Galactic disc.

Pezzulli, Fraternali & Binney 2017, MNRAS

A cosmologically motivated corona



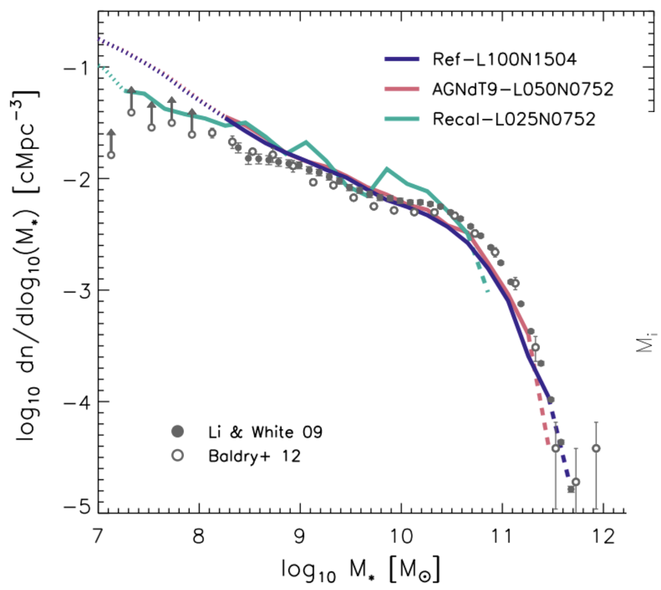


Strong Feedback

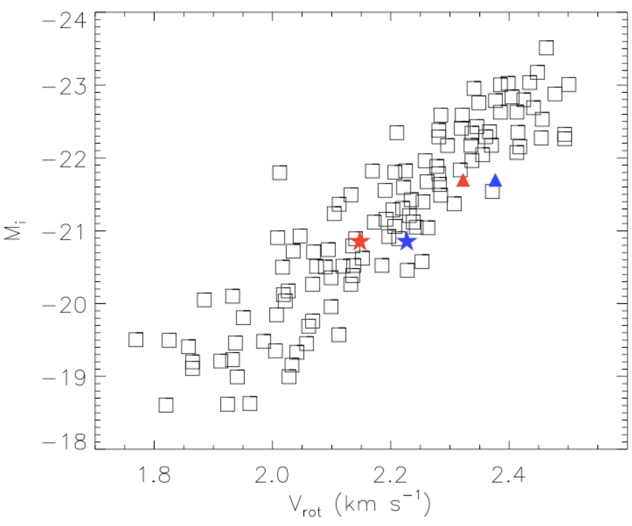
Classical problems in galaxy formation:

- Halo mass function vs stellar mass function
- Angular momentum of discs -> scaling relations
- Missing satellites, cusps, too big to fail etc.

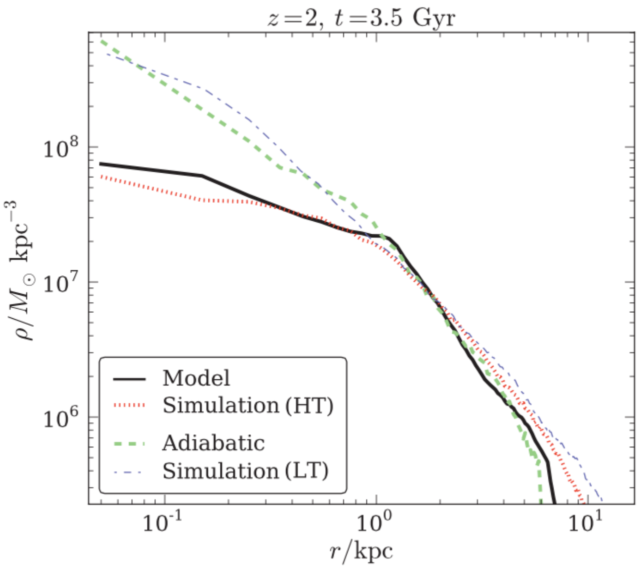
-> Solved by: Very strong feedback



Schaye et al. 2015



Brook et al. 2012

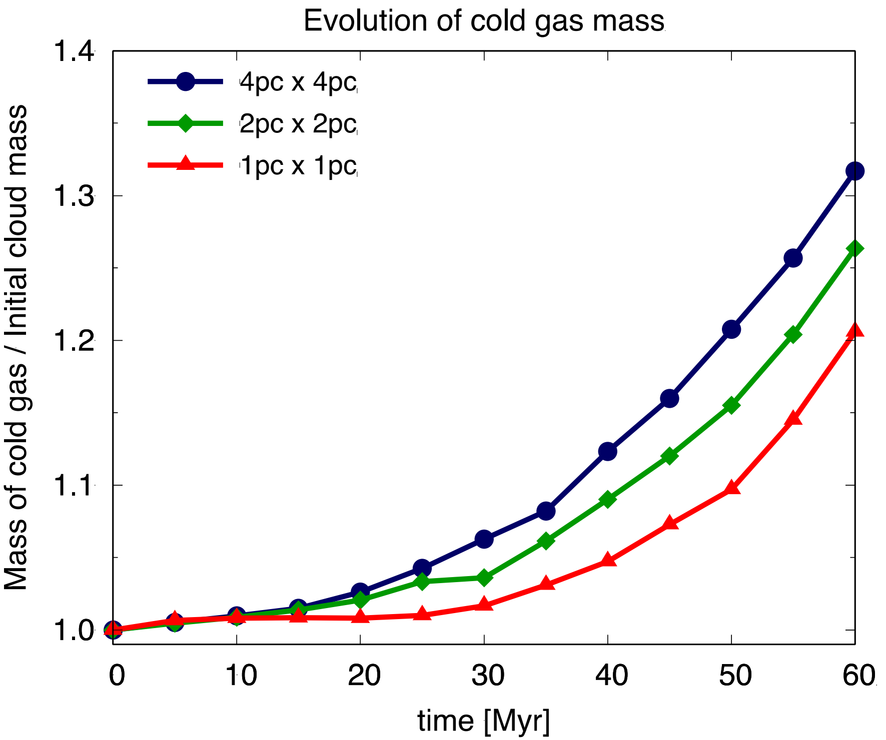


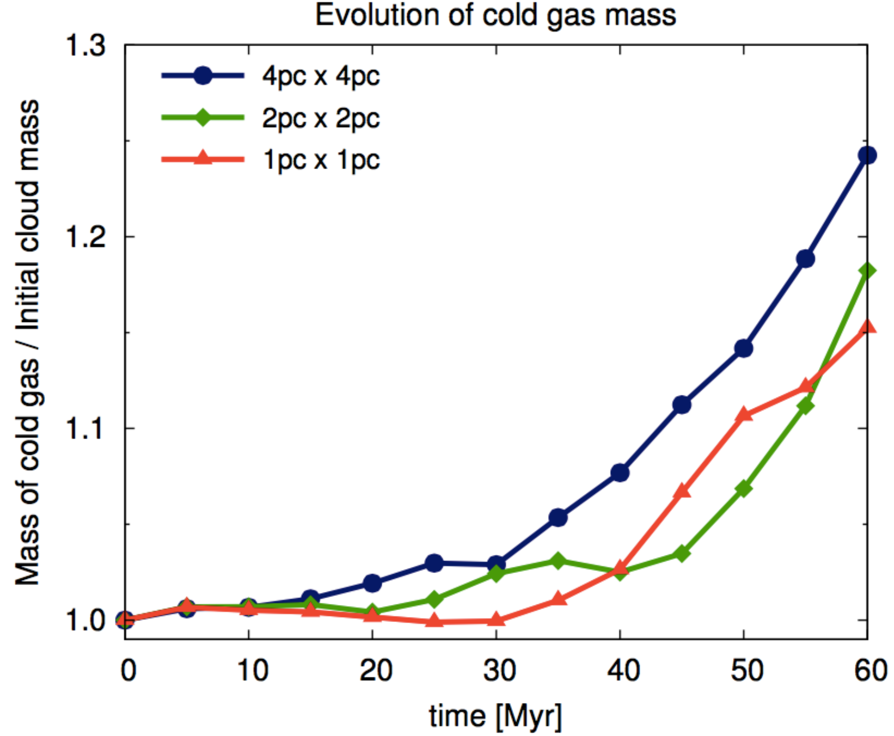
Pontzen & Governato 2012

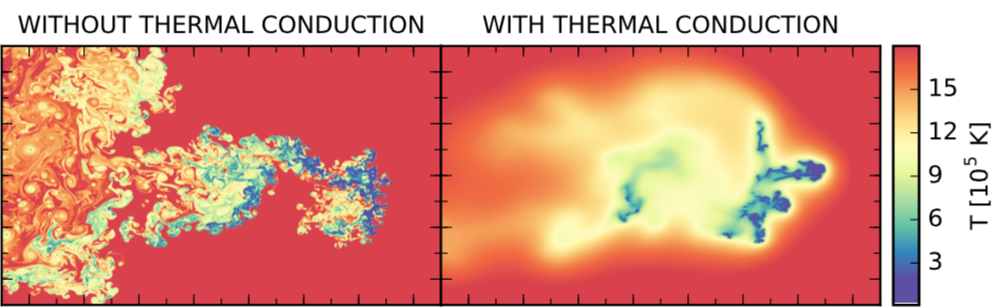
Resolution Convergence

NO thermal conduction

WITH thermal conduction







Armillotta et al. 2016, 2017

There is a physical scale!

$$\lambda_{\rm Field} \equiv \sqrt{\frac{\kappa_{\rm Sp} T_{\rm hot}}{n^2_{\rm cold}\Lambda(T_{\rm cold})}}$$

~ 10-20 pc

Gas accretion needed to feed star formation

Chemical evolution models
G-dwarf problem
Larson 1972; Tynsley 80; Tosi 1988; Chiappini et al. 1997, 2001; Boissier & Prantzos 1999; Schoenrich & Binney 2009

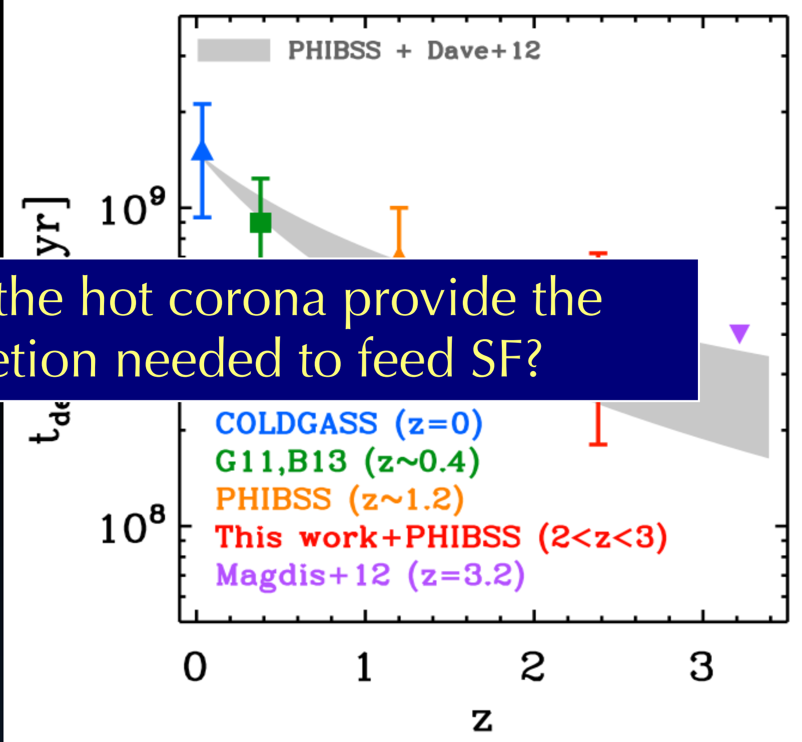
Deuterium in local ISM appears to be re-supplied *Linsky et al. 2006*

~ constant SFR in the MW (thin) disk
Aumer & Binney 2009; Fraternali & Tomassetti 2012; Haywood et al. 2016

Need for metal-poor gas accretion
At ~ 1 $M_\odot$/yr

Gas depletion time ~ 1 Gyr

$t_{depl} = M_{gas} / SFR$



Can the hot corona provide the accretion needed to feed SF?

Saintonge et al. 2015; Kennicutt et al. 1983; Bigiel et al. 2011, Genzel et al. 2015

Summary so far

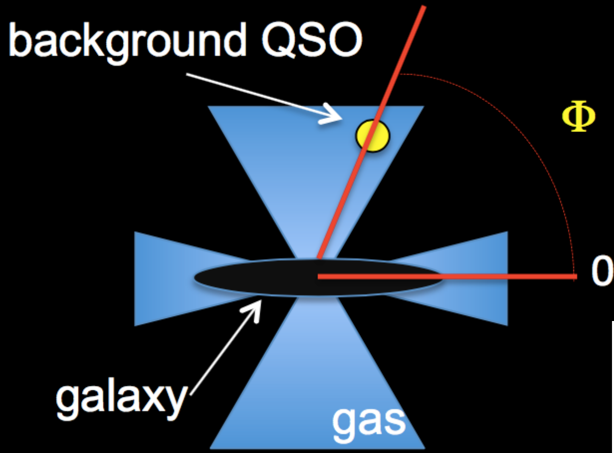
1. Condensation of the lower corona at rate ~1 Mo/yr
   -> feeds star formation

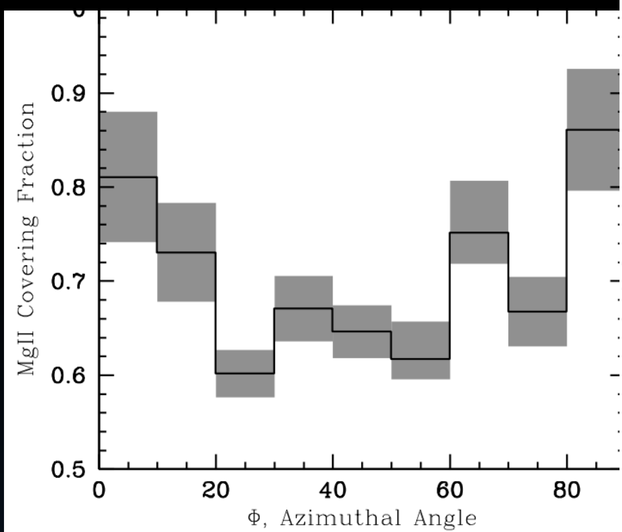
2. Explains MW extraplanar gas kinematics (HI and ionised)

3. Explains formation of high-velocity clouds

4. Predicted the rotation of the corona (lag 70-100 km/s)

Detection of accretion? (absorption III)

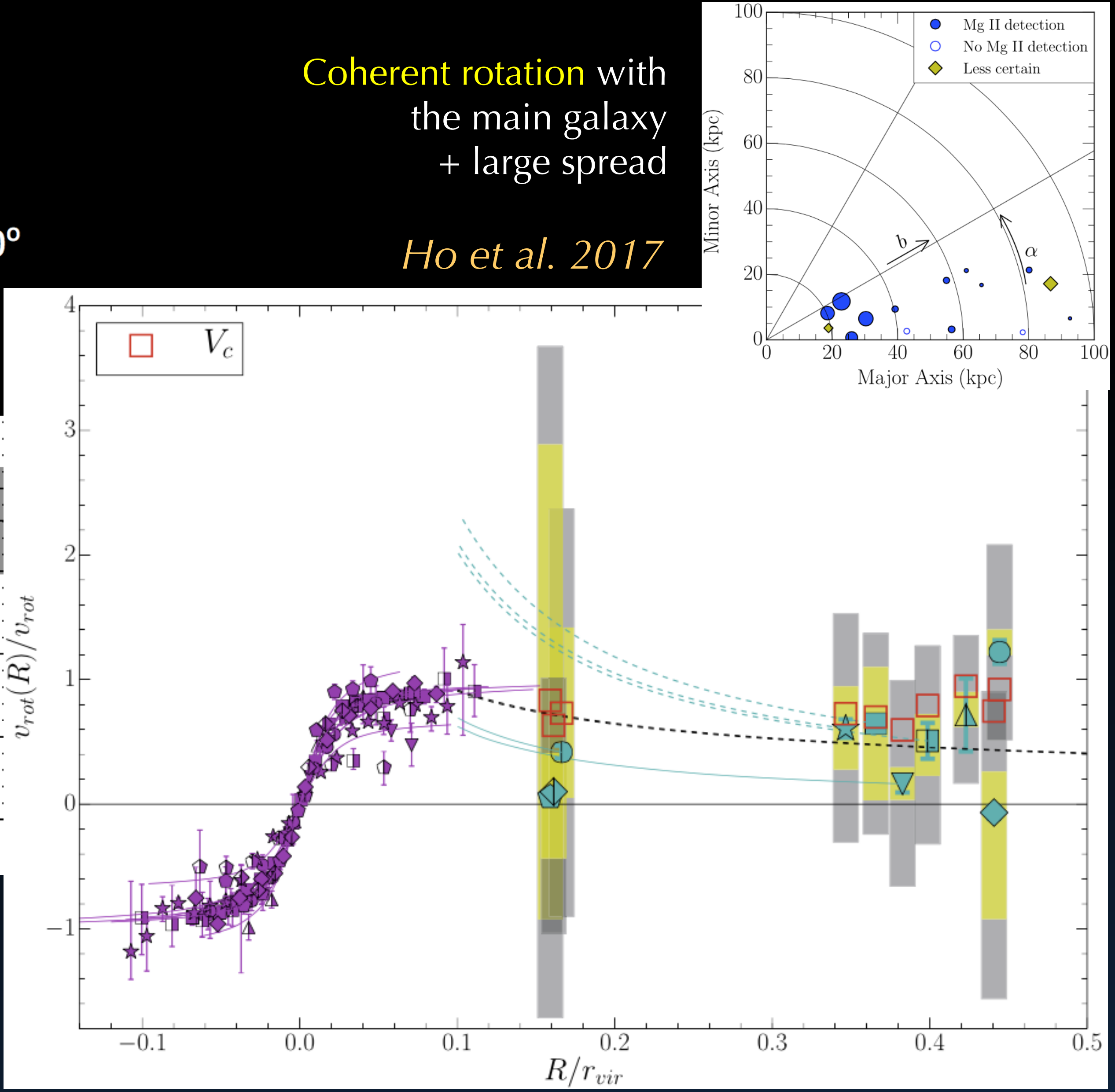




Kacprzak et al. 2012

Coherent rotation with the main galaxy + large spread

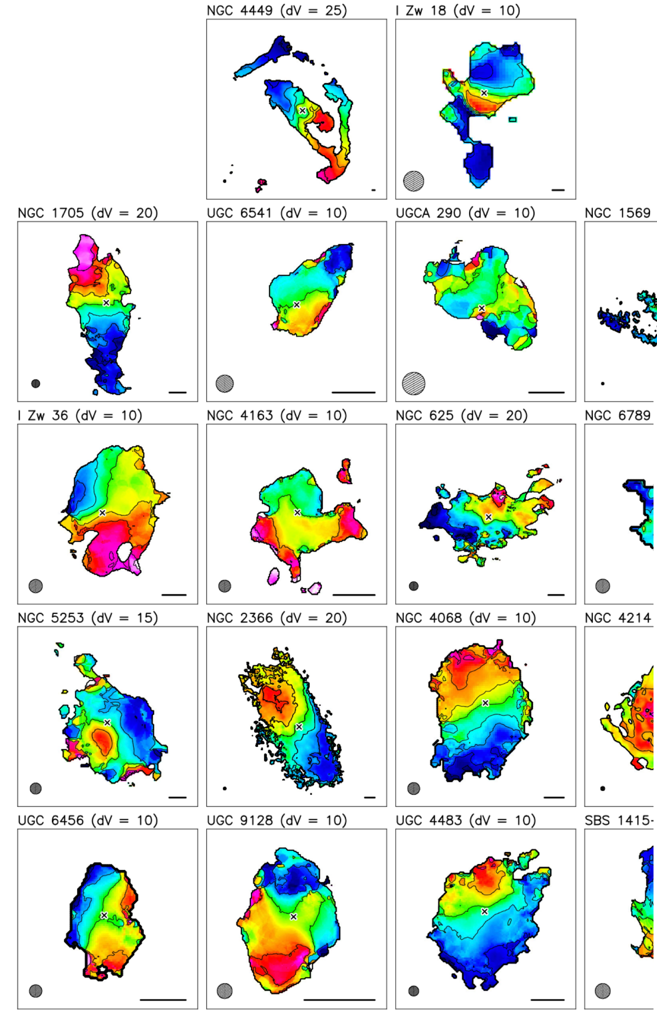
Ho et al. 2017



3) Do real galaxies explode? (III)

Blue compact dwarfs

HI velocity fields



Lelli, Verheijen & Fraternali 2016

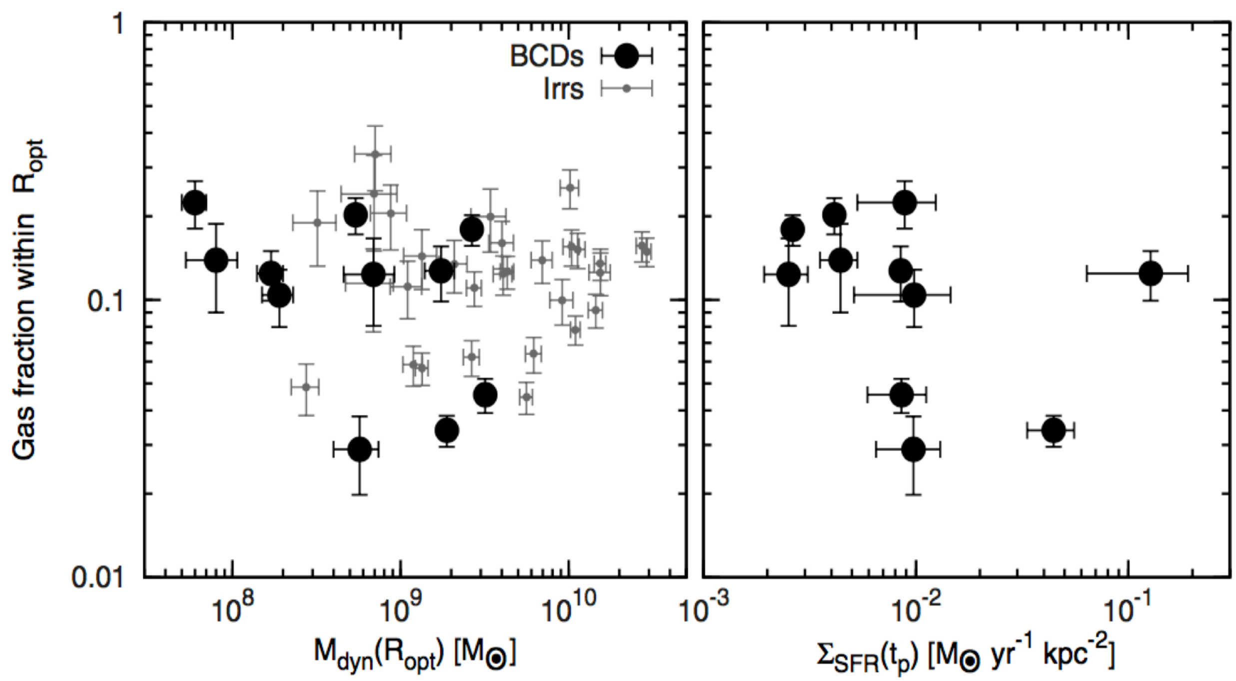
They are tiny super starburst

Very rare: ~ 1% of the irregulars

HI observations

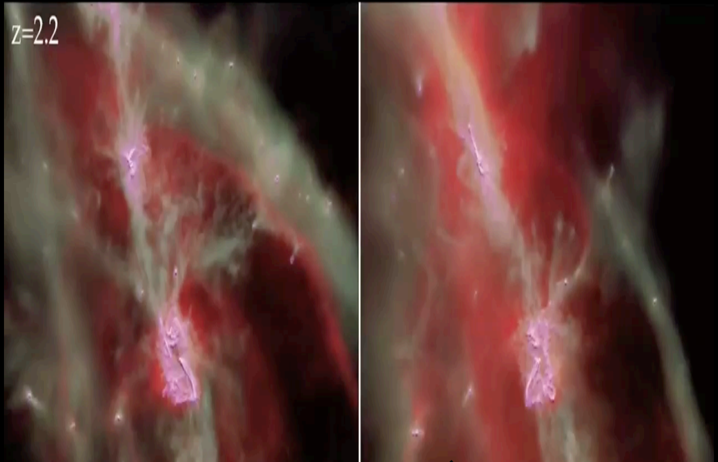
~ Half of them regular rotation, most have some rotation

Similar gas fraction than *quiescent* irregulars



Lelli, Verheijen & Fraternali 2014

3) Do real galaxies explode? (I)



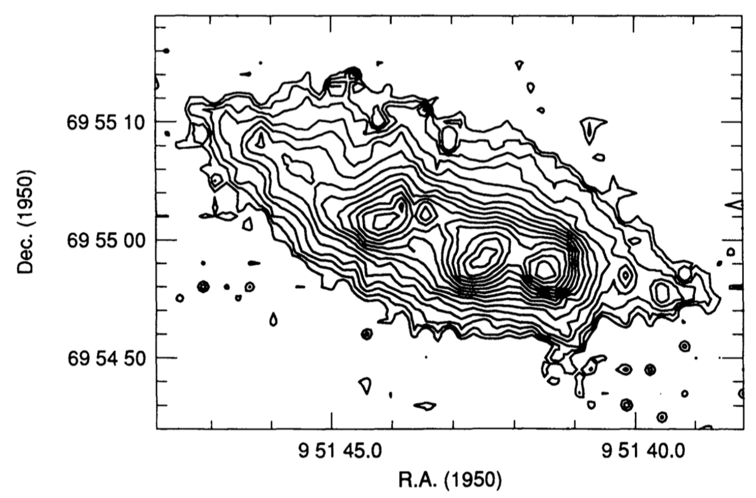
FIRE simulation

Formation of a Milky Way galaxy

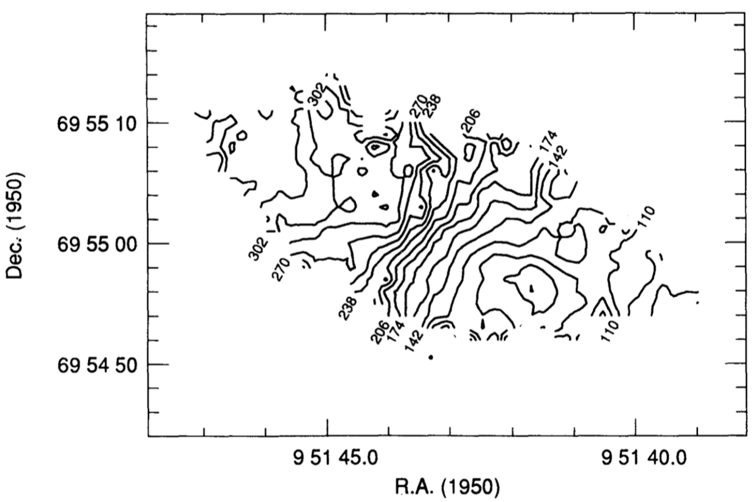
Movie credit: P. Hopkins

M82: a special galaxy

M82 inner disk – [Ne II] 12.8 μm



Velocity field – regular rotation



Achtermann & Lacy 1995

Things we may be missing

Feedback is used to get rid of cold gas: why is there so much cold gas?

Numerical effects really under control?

1. Maybe explore more preheating/preventive feedback? (e.g. *Lu+ 2015*)

2. Do we understand cooling?
    - are equilibrium functions good enough? (*Gnat 2017*)
    - should we include turbulence? (*Gray, Scannapieco & Kasen 2015*)

3. Do we understand heating?
    - large uncertainties in the EUVB
    - photons from local sources? (*Cantalupo 2010*)
    - about X-ray binaries/ULXs? (*Prestwich et al. 2015*)
    - and *small* black holes (*Su et al. 2015*)?
    - do we believe CLOUDY too much?

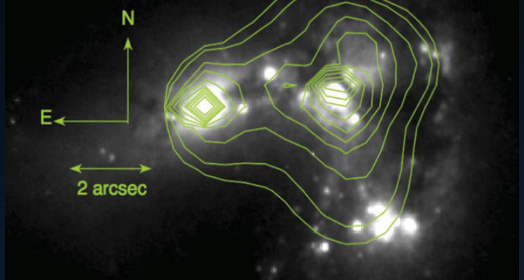
4. Magnetic fields, CRs and thermal conduction?

5. Different dark matter? Would affect SF feedback?

Ultra-luminous X-ray sources

Insane luminosity

$L_X \sim 10^{40}$-10^{41} erg s^{-1}



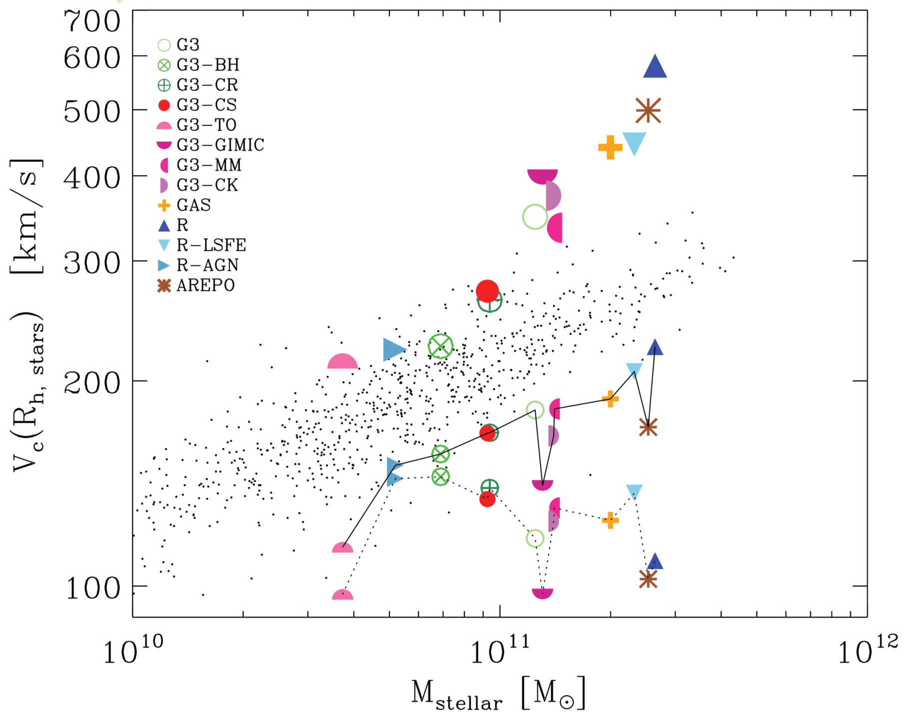
This is L_X of M87 BH!

Prestwich et al. 2015

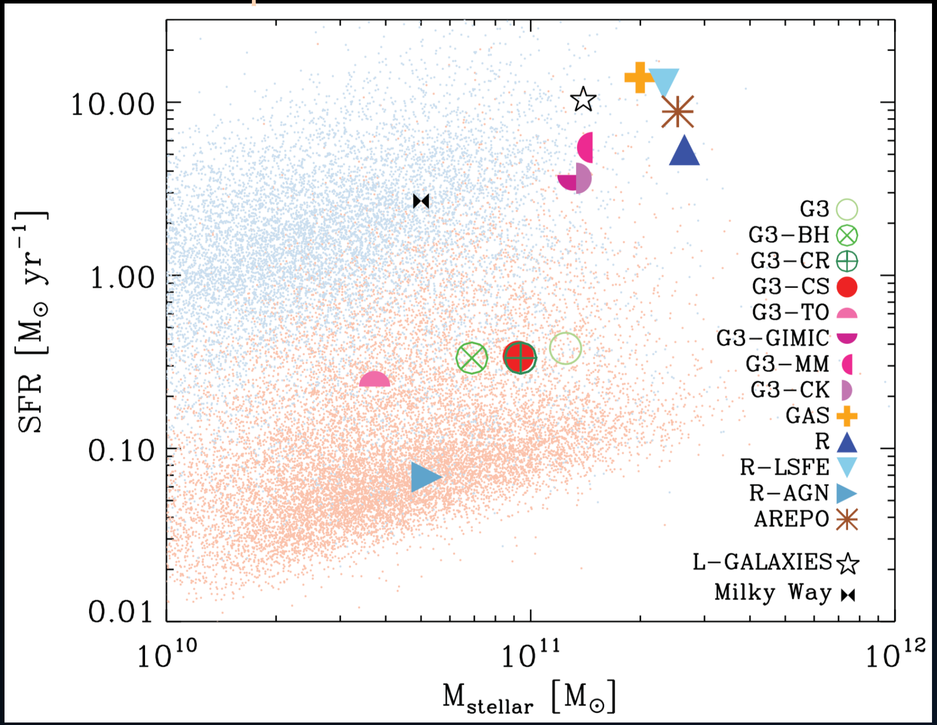
2) Different simulations use different recipes

Galaxy formation in cosmological simulations with different codes

Tully Fisher relations



Main sequence



Scannapieco et al. 2012

“Despite the common halo assembly history, we find large code-to-code variations in the stellar mass, size, morphology and gas content of the galaxy at $z = 0$, due mainly to the different implementations of star formation and feedback.”

1) Energy requirement

$\dot{E}_{\rm K} = \eta \, {\rm SNR} \, E_{\rm SN}$ Energy available from supernovae

$\dot{E}_{\rm K} = 3 \times 10^{40} \left(\frac{\eta}{0.1}\right) \left(\frac{\rm SFR}{1\,M_\odot/yr}\right) \,{\rm erg\,s^{-1}}$ → IF this all goes into outflow → $\dot{E}_{\rm K} = \frac{1}{2} \dot{M}_{\rm out} \, v_{\rm out}^2$

$$\dot{M}_{\rm out} \simeq 1 \left(\frac{\eta}{0.1}\right) \left(\frac{\rm SFR}{1\,M_\odot\,{\rm yr}^{-1}}\right) \left(\frac{v_{\rm out}}{300\,{\rm km\,s^{-1}}}\right)^{-2} M_\odot\,{\rm yr}^{-1}$$

Dwarf galaxies can eject potentially to $r_{\rm vir}$

See *Murray+ 05*

Milky Way $v_{\rm esc}$ ~ 800 km/s -> and this is only gravity…

Strong feedback in cosmological simulations means η ~ 1

usually justified because there may be other sources: radiation pressure, winds, CRs…

Should we care about these differences?

Tension with small-scale studies?

classic calculations: η~0.0few-0.2 (*e.g. Chevalier 1975, Weaver et al. 1977*)

superbubbles: only 5-10% of the accelerated mass in outflow (*Mac Low+1989*)

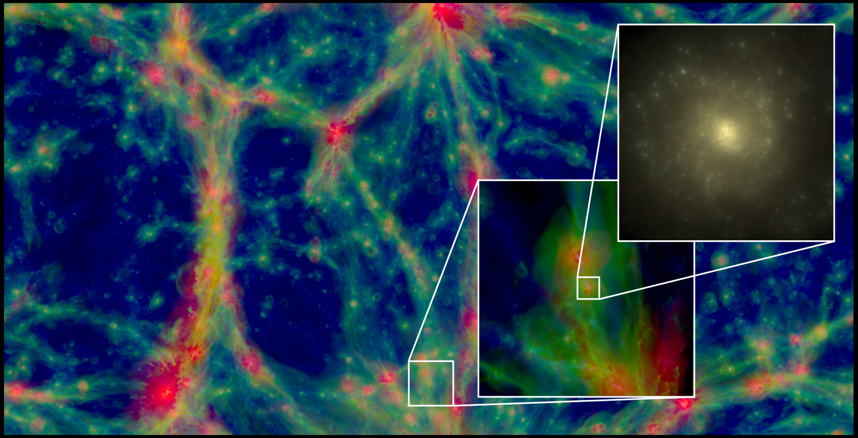
η = 0.05-0.1 (*Yadav+2016*)

galaxies: losses due to K-H instabilities (*MacLow & Ferrara 1999, Krumholz & Thomson 2012*)

high-res simulations of disc: at >4kpc $M_{\rm out}$/SFR < 0.1 (*Kim & Ostriker 2018*)

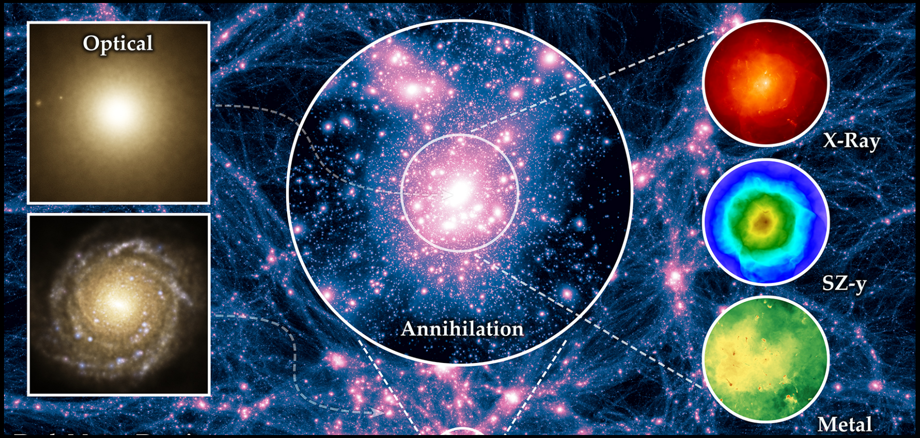
2) Different recipes and calibrations

EAGLE



Schaye et al. 2015

Illustris(TNG)



Vogelsberger et al. 2013, Pillepich et al. 2017

Thermal feedback

- Gas heated to log(T/K)=7.5 stochastically
- Efficiency function of Z and ρ can be up to 300%

AGN reaches higher temperatures

Star formation

- Threshold depending on Z
- SFR function of pressure

Kinetic feedback

- Hydro OFF until particles leave the ISM
- Mass loading set by SFR
- Velocity set by DM

AGN is a mixture

Star formation

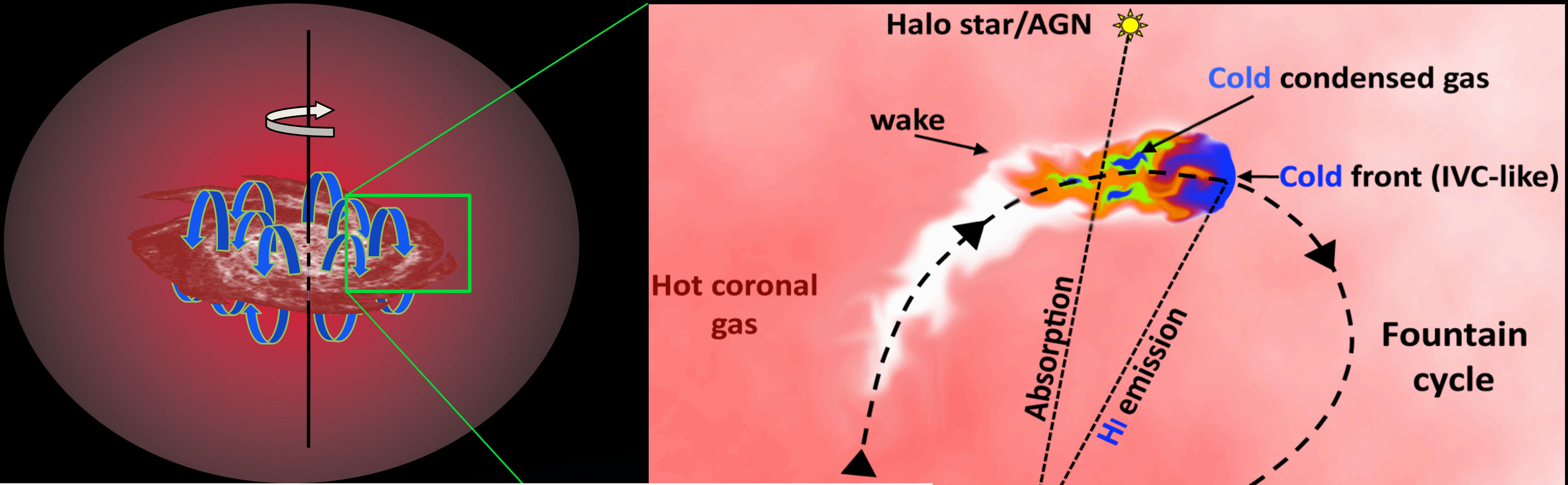
- Threshold in density
- SFR depending on t_{ff}^{-1}

<u>And more ways</u>

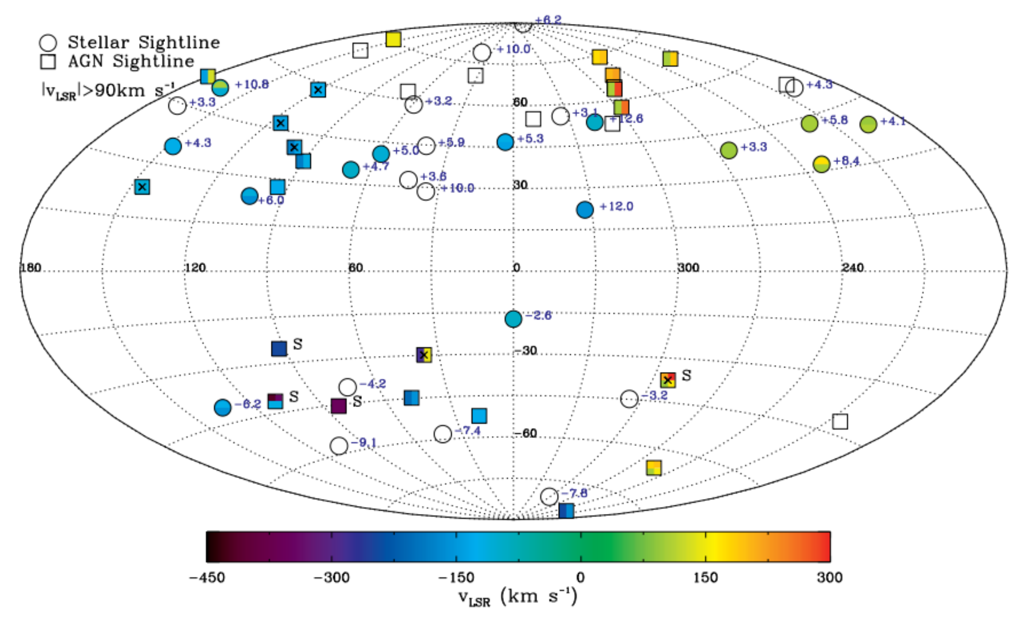
Switching off cooling (*Stinson et al. 2006*)
Strong thermal conduction (*Keller et al. 2014*)
Radiation pressure + momentum injection (*Hopkins et al. 2012, 2014*)

What does this mean?
What are we learning?

Cooling in the wake



Fraternali et al. 2013, ApJL



Shull+ 2009, ApJ

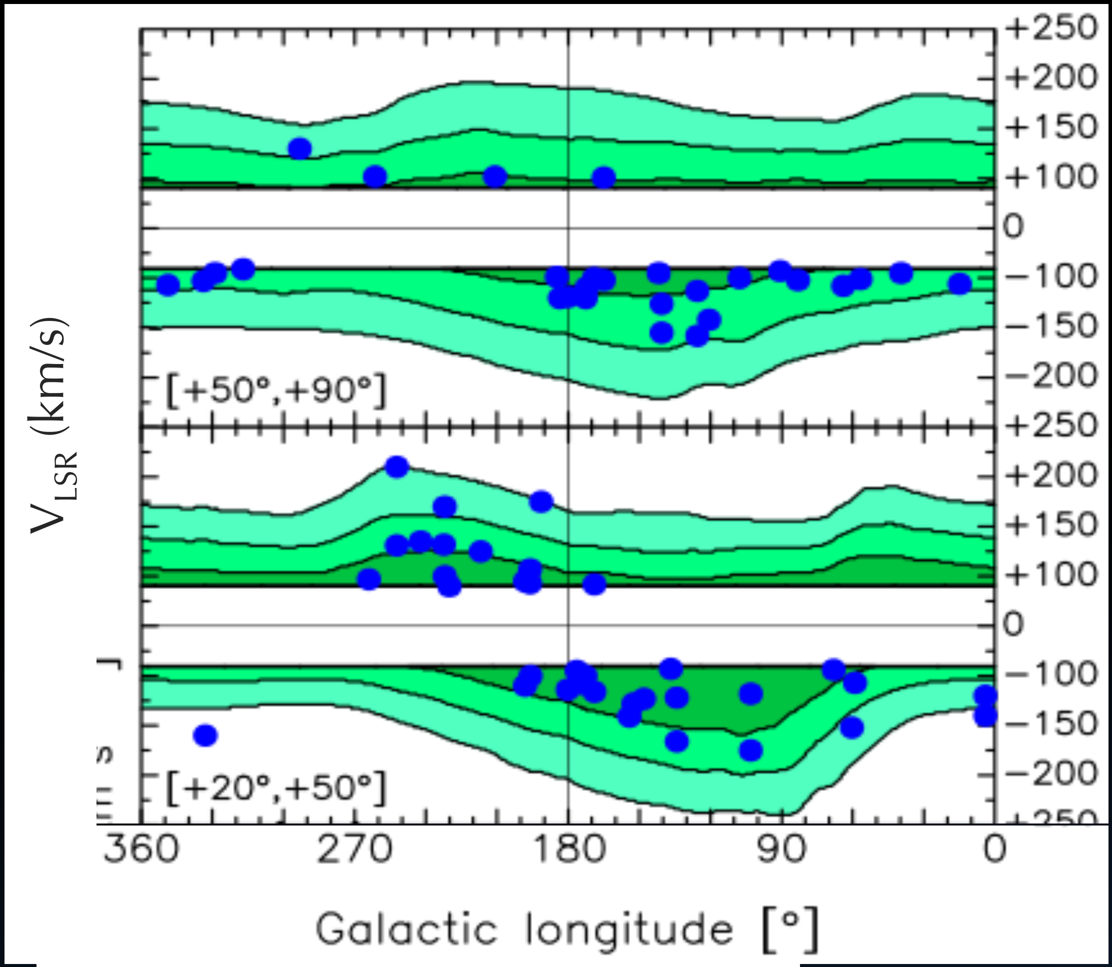
Lehner & Howk 2011, Science

Lehner et al. 2012, MNRAS

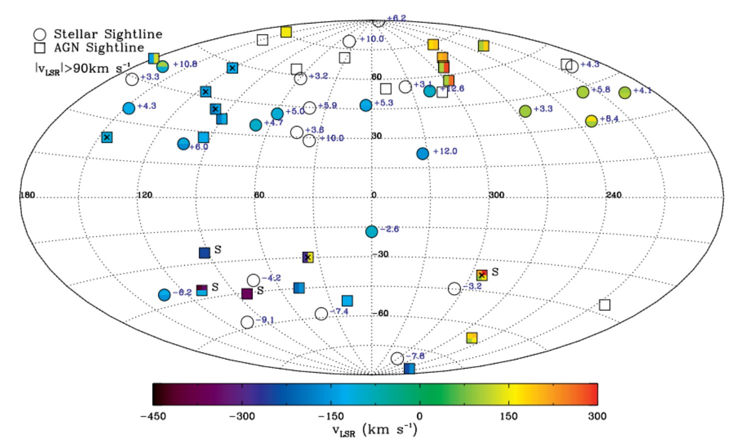
C II, Si II, Si III, … $4.3<\log T<5.3$ K

Ionized gas in the MW

Marasco, Marinacci & Fraternali 2013, MNRAS



● Data from Lehner et al. 2012, MNRAS



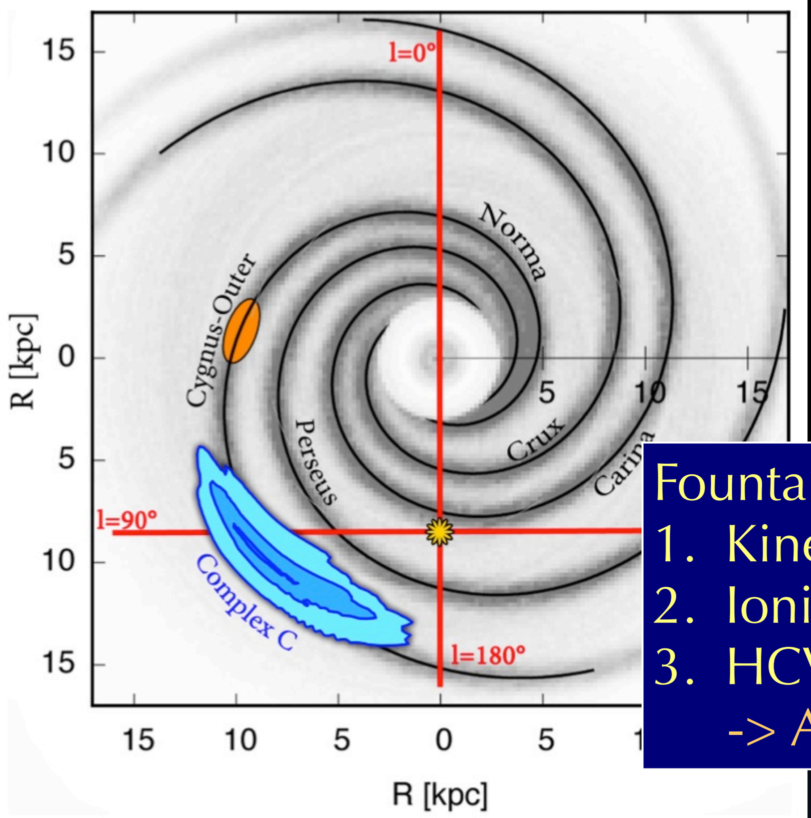
This model reproduces:

- Positions & velocities of 95% absorbers
- Average column density
- Number of absorbers along the l.o.s.
- High velocity dispersions of absorbers

'Warm' accretion: ~1 $M_{\odot}$/yr

High-velocity clouds

Complex C

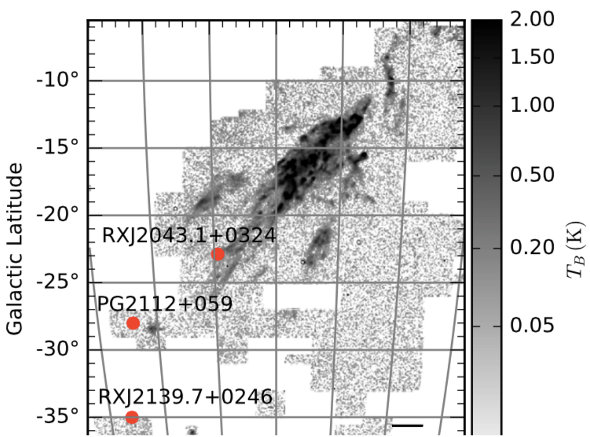


Fraternali et al. 2015, MNRAS Letters

Reproduce: emission, distance and Z

Half gas from the disc,
half from the corona

Smith cloud



Metallicity
> 0.53 Solar

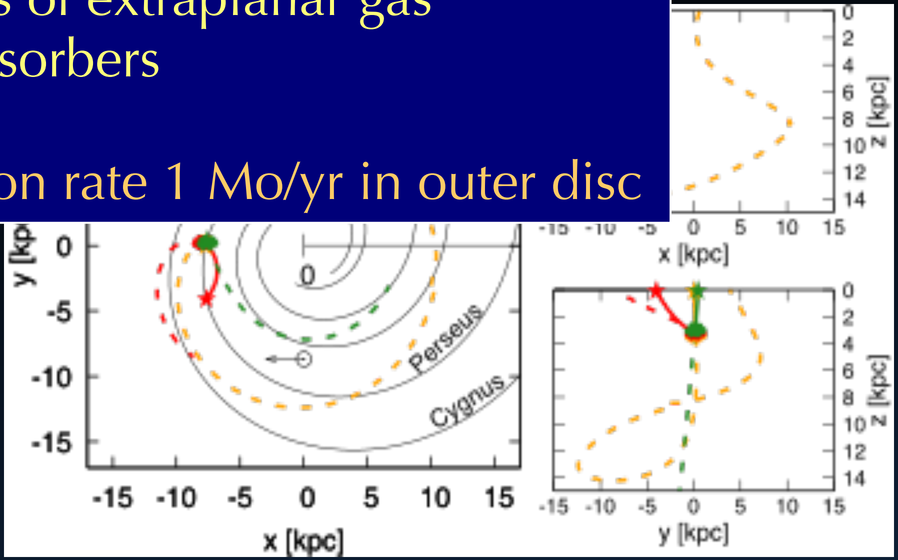
Mixture of fountain and external material

Fox et al. 2016, ApJL

Fountain accretion reproduces:

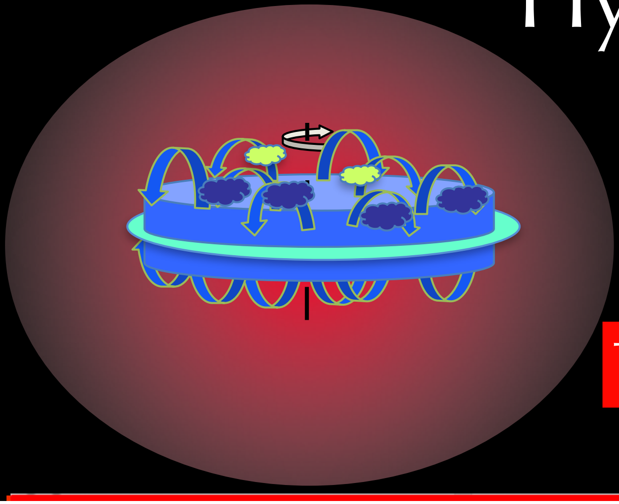
1. Kinematics of extraplanar gas
2. Ionised absorbers
3. HCVs

-> Accretion rate 1 Mo/yr in outer disc



Marasco & Fraternali 2017, MNRAS Letters

Hydrodynamic simulations



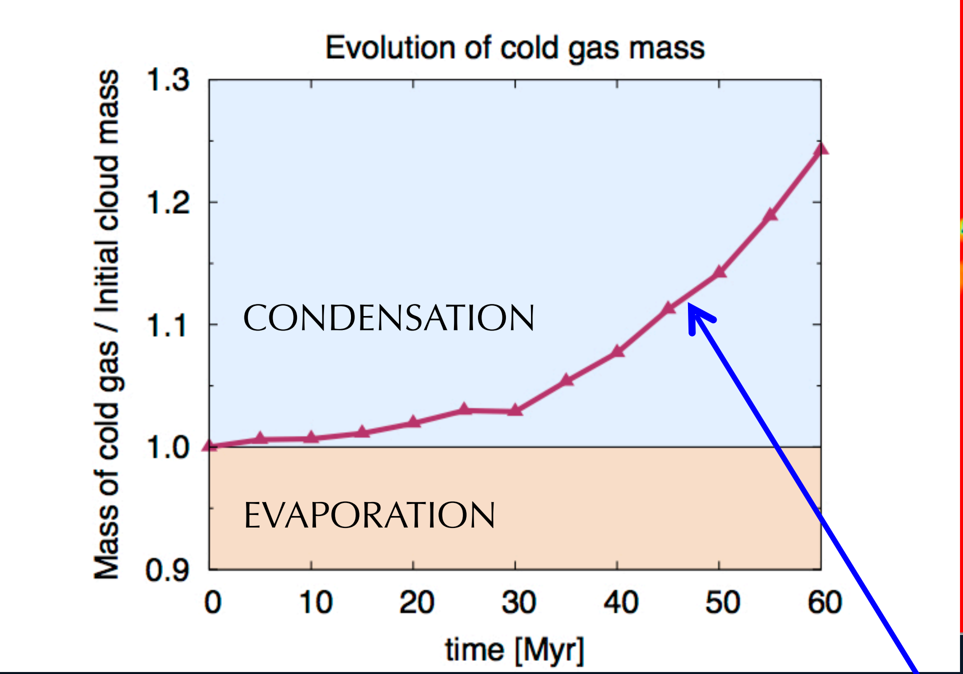
Marinacci+ 2010; Armillotta, Fraternali+ 2016, MNRAS

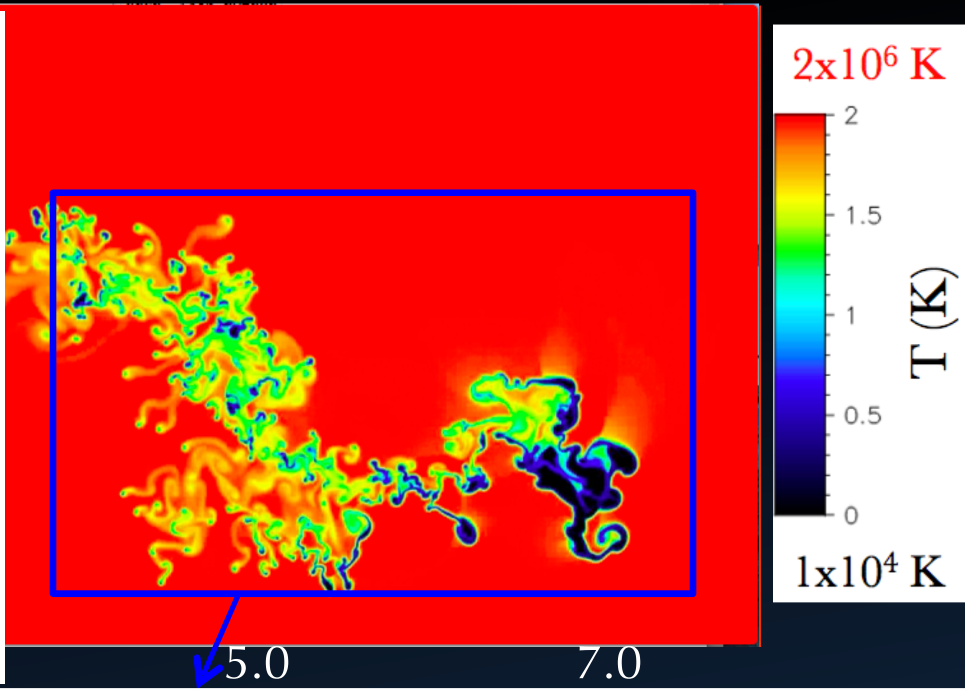
Corona is rotating more slowly than the disc

$T_{corona}=2x10^6$ K

$Z_{corona}=0.1\ Z_\odot$

$Z_{cloud}=1\ Z_\odot$



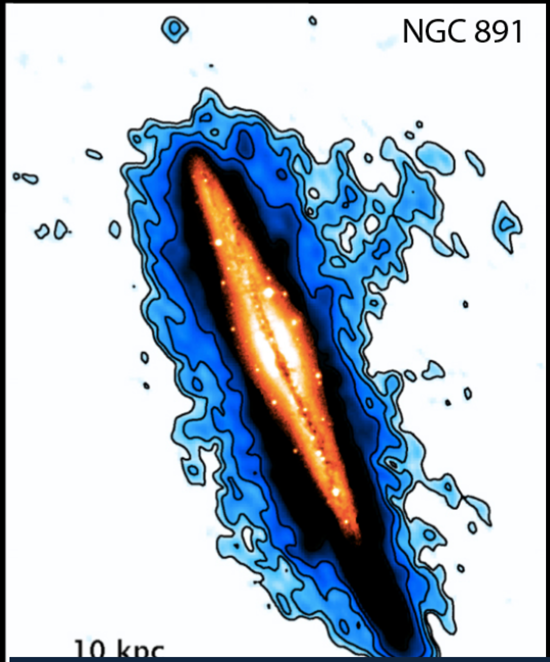


2D fixed grid, 2 pc x 2 pc!

X (kpc)

Mass of cold gas increased by ~20%!

Extraplanar HI

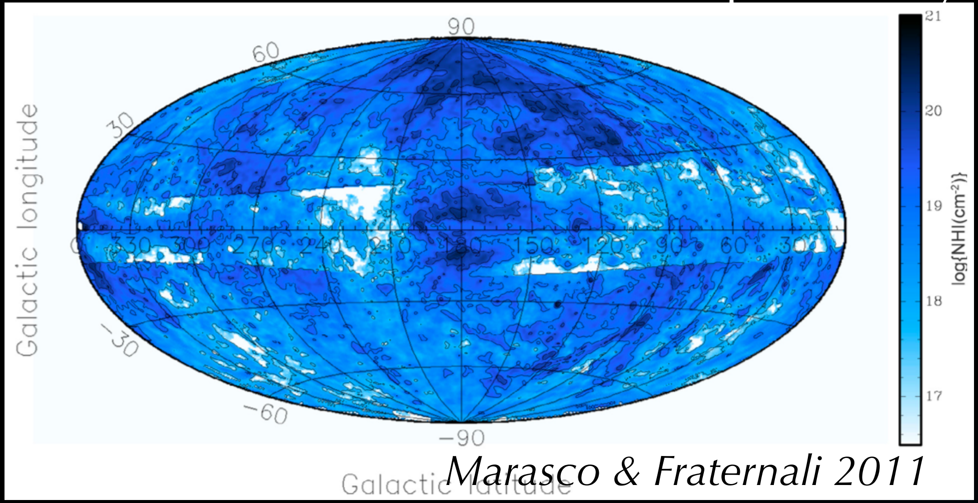


Oosterloo, Fraternali & Sancisi 2007

10-25% of the total HI mass

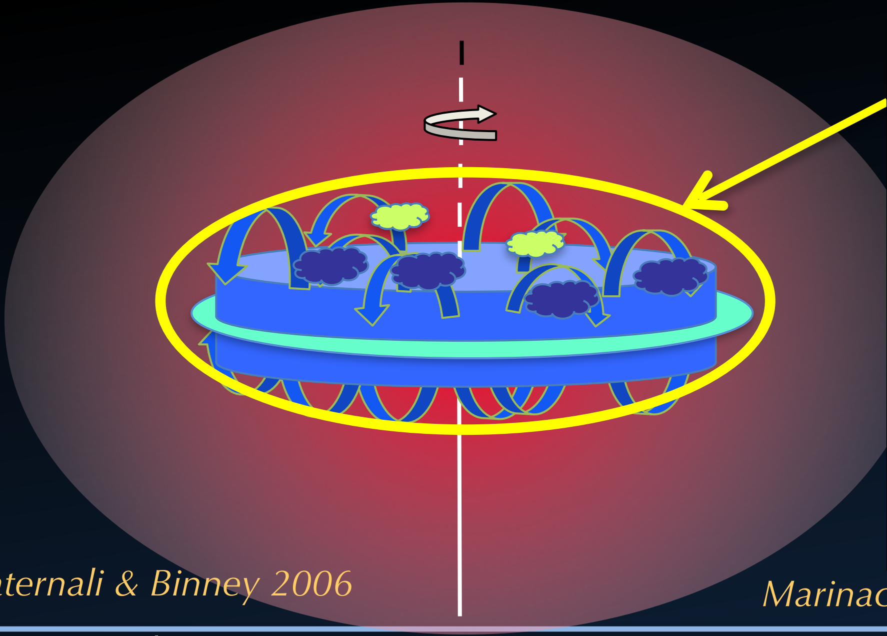
h ~ 1-2 kpc

MW extraplanar only

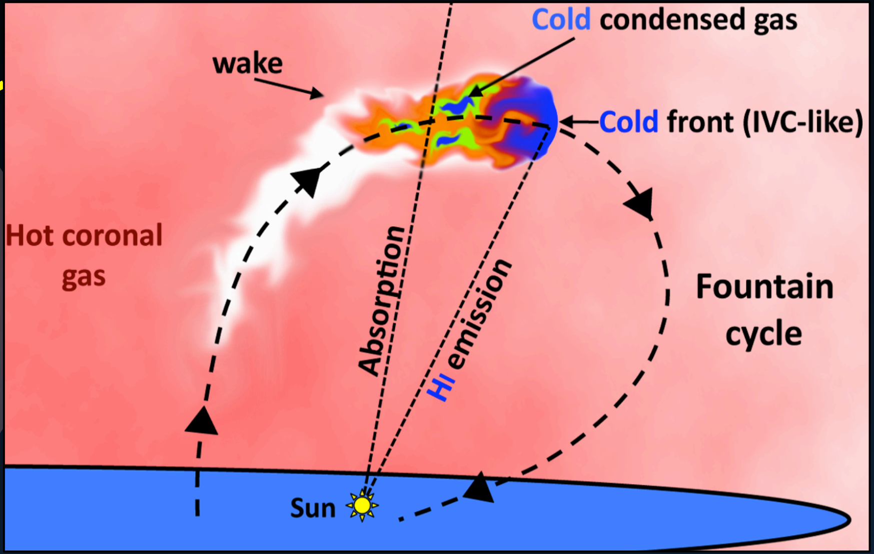


Marasco & Fraternali 2011

Not in hydro simulations (Marasco, Debattista, Fraternali+ 2015)



Fraternali & Binney 2006



Marinacci, et al. 2010, 2011, Fraternali et al. 2013

Indirect evidence very clear

Chemical evolution models
G-dwarf problem
Larson 1972; Tynsley 80; Tosi 1988; Chiappini et al. 1997, 2001; Boissier & Prantzos 1999; Schoenrich & Binney 2009, Pezzulli & Fraternali 2016

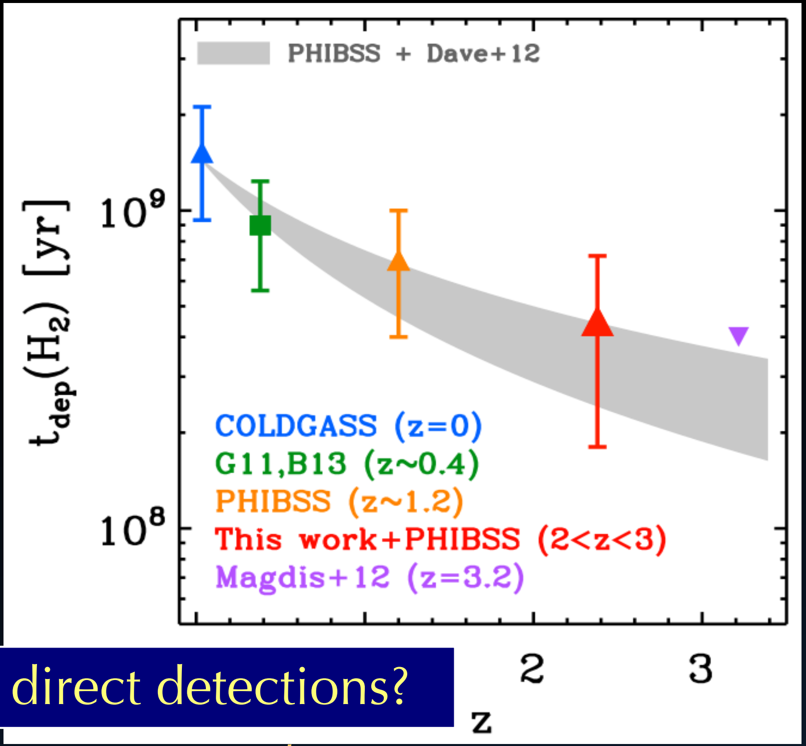
Deuterium in local ISM appears to be re-supplied *Linsky et al. 2006*

~ constant SFR in the MW (thin) disk
Aumer & Binney 2009; Fraternali & Tomassetti 2012; Haywood et al. 2016

Need for metal-poor gas accretion
At ~ 1 $M_\odot$/yr

Gas depletion time ~ 1 Gyr

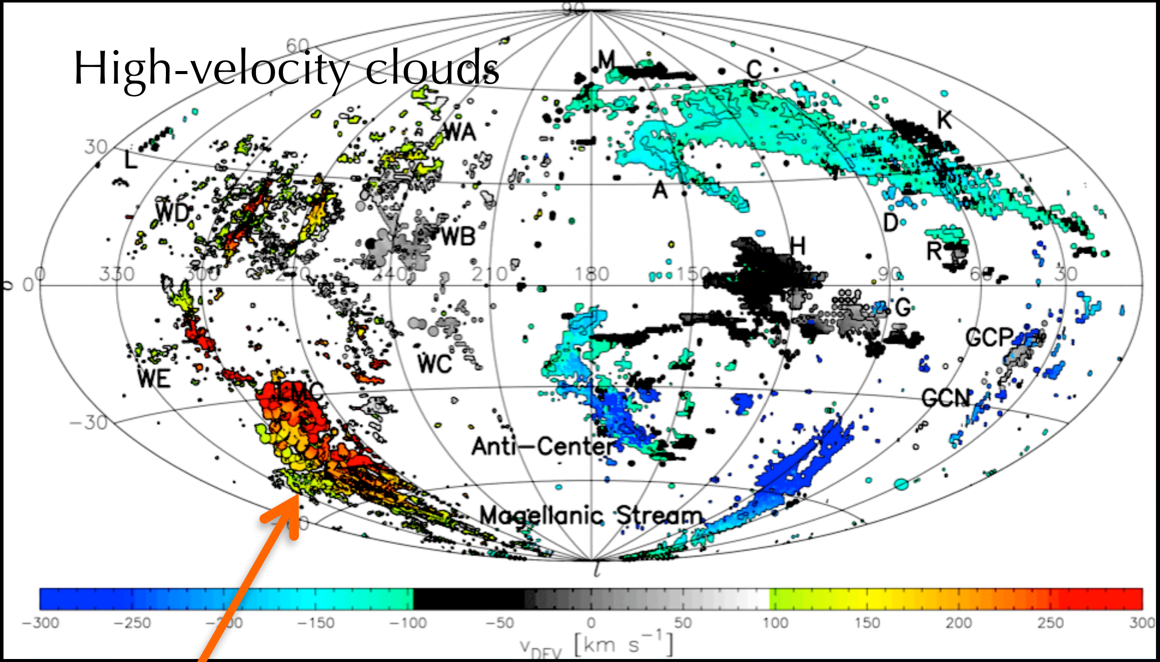
$$t_{depl} = M_{gas} / SFR$$

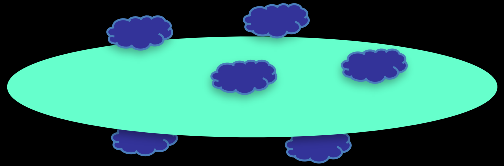


What about direct detections?

*Saintonge et al. 2015;
Kennicutt et al. 1983; Bigiel et al. 2011, Genzel et al. 2015*

Detection of accretion? (HI emission)





Masses < few x 10^6 $M_\odot$

Accretion from HVCs
~ 0.08 $M_\odot$/yr

Includes He and factor 2 of ionised gas!

Putman, Peek, Joung 2012, ARA&A

Accretion of Magellanic Stream: M_{HI}~2×10^8 $M_\odot$,

much more ionised (*Bland-Hawthorn et al. 2007, Fox et al. 2014*)
Will it happen? How often does it happen?

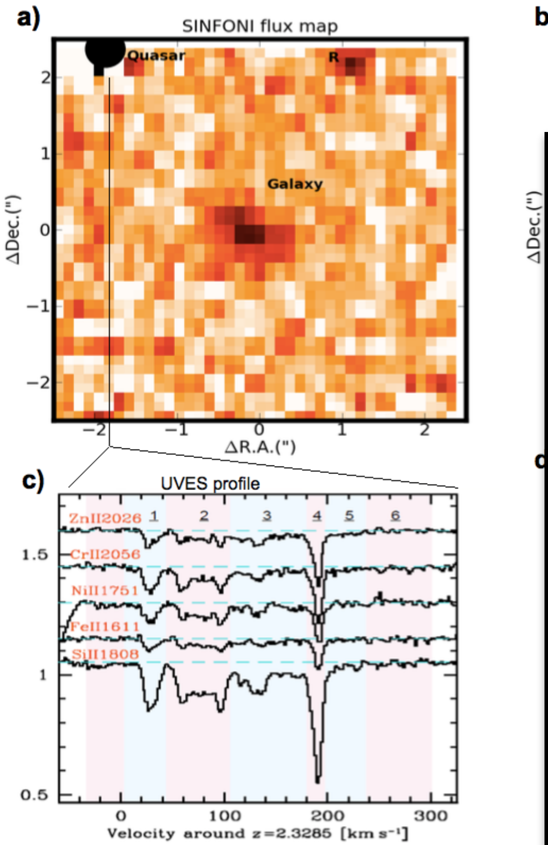
Origin not clear: probably mixing between disc and ambient material (e.g. *Fraternali et al. 2015*)

External nearby galaxies: several studies using GBT, Parkes, Arecibo
-> NO significant population of floating HI clouds (N

Pisano et al. 2004, Zwaan et al. 2005, Kovac et al. 2009, Chynoweth et al. 2009, Haynes et al. 2011, Westmeier+ 2017

Hopefully this will improve with SKA and precursors

Detection of accretion? (absorption II)

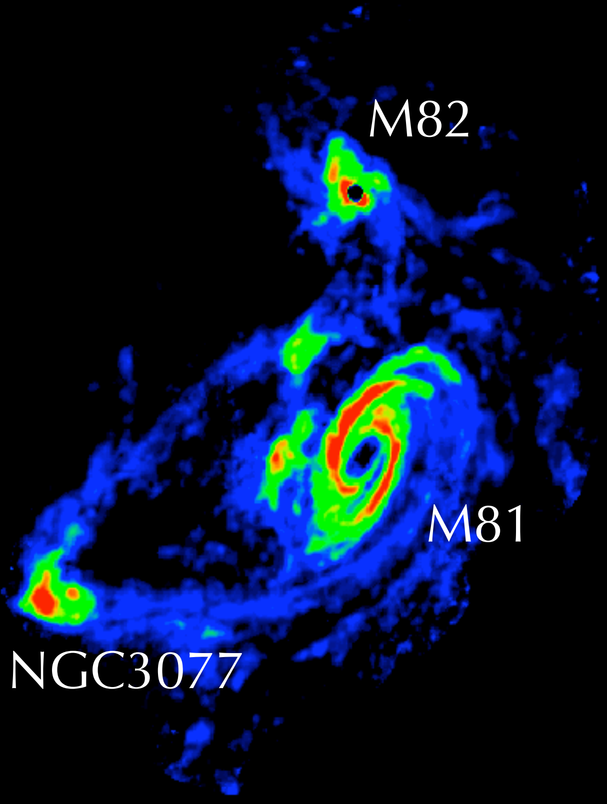


Bouché et al. 2013

Interpreted as an accretion
Mass inflow: 30-60 Mo/yr

SDSS

HI - VLA



Yun et al. 1997

This is above $N_{HI} \sim 10^{20}$ cm^{-2} (very high column density)

Below there will much more

e.g. the Magellanic Stream covers 25% of the sky (e.g. *D'Onghia & Fox 2016*)

1) High energy requirement

$\dot{E}_{\rm K} = \eta\, {\rm SNR}\, E_{\rm SN}$ Energy available from supernovae

$$\dot{E}_{\rm K} = 3 \times 10^{40} \left(\frac{\eta}{0.1}\right) \left(\frac{\rm SFR}{1\, M_\odot/yr}\right) {\rm erg\, s^{-1}}$$

IF this all goes into outflow →

$$\dot{E}_{\rm K} = \frac{1}{2} \dot{M}_{\rm out}\, v_{\rm out}^2$$

$$\dot{M}_{\rm out} \simeq 1 \left(\frac{\eta}{0.1}\right) \left(\frac{\rm SFR}{1\, M_\odot\, {\rm yr}^{-1}}\right) \left(\frac{v_{\rm out}}{300\, {\rm km\, s^{-1}}}\right)^{-2} M_\odot\, {\rm yr}^{-1}$$

Dwarf galaxies can eject potentially to $r_{\rm vir}$

Milky Way $v_{\rm esc}$ ~ 800 km/s -> and this is only gravity…

See *Murray+ 05*

Strong feedback in cosmo simulations essentially means η ~ 1

usually justified because there may be other sources: winds, CRs…

Limited resolution of simulations -> to achieve high efficiencies

recipes are needed

Kinetic energy + switching off hydrodynamics (*Springel & Hernquist 2003*)

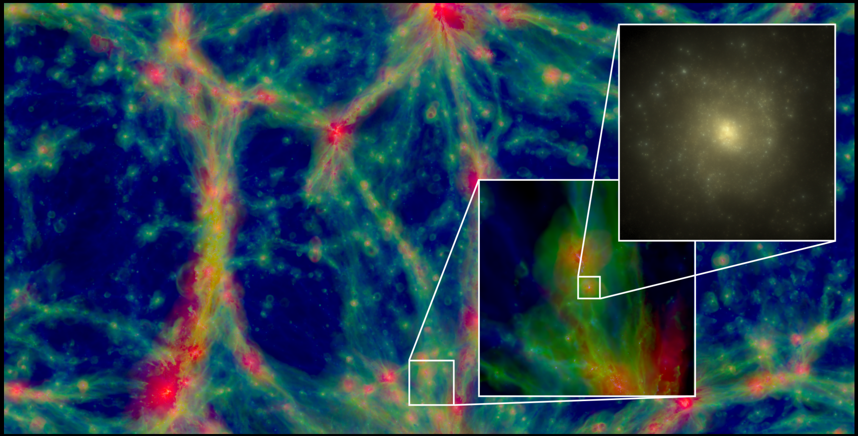
+ switching off cooling (*Stinson et al. 2006*)

Thermal feedback: very high T -> no cooling (*Dalla Vecchia & Schaye 2012)*

Strong thermal conduction *(Keller et al. 2014*)

2) Different simulations use different recipes

EAGLE



Schaye et al. 2015

Thermal feedback

- Gas heated to log(T/K)=7.5 stochastically
- Efficiency function of Z and ρ can be up to 300%

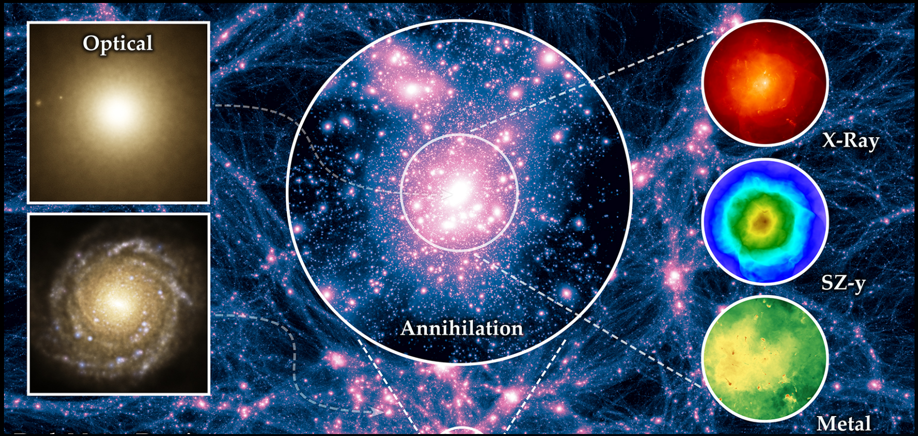
AGN reaches higher temperatures

Star formation

- Threshold de
- SFR function of pressure

What is this? Two ways to form galaxies? How many other ways are there?

Illustris(TNG)



Vogelsberger et al. 2013, Pillepich et al. 2017

Kinetic feedback

- Hydro OFF until particles leave the ISM
- Mass
- Veloc

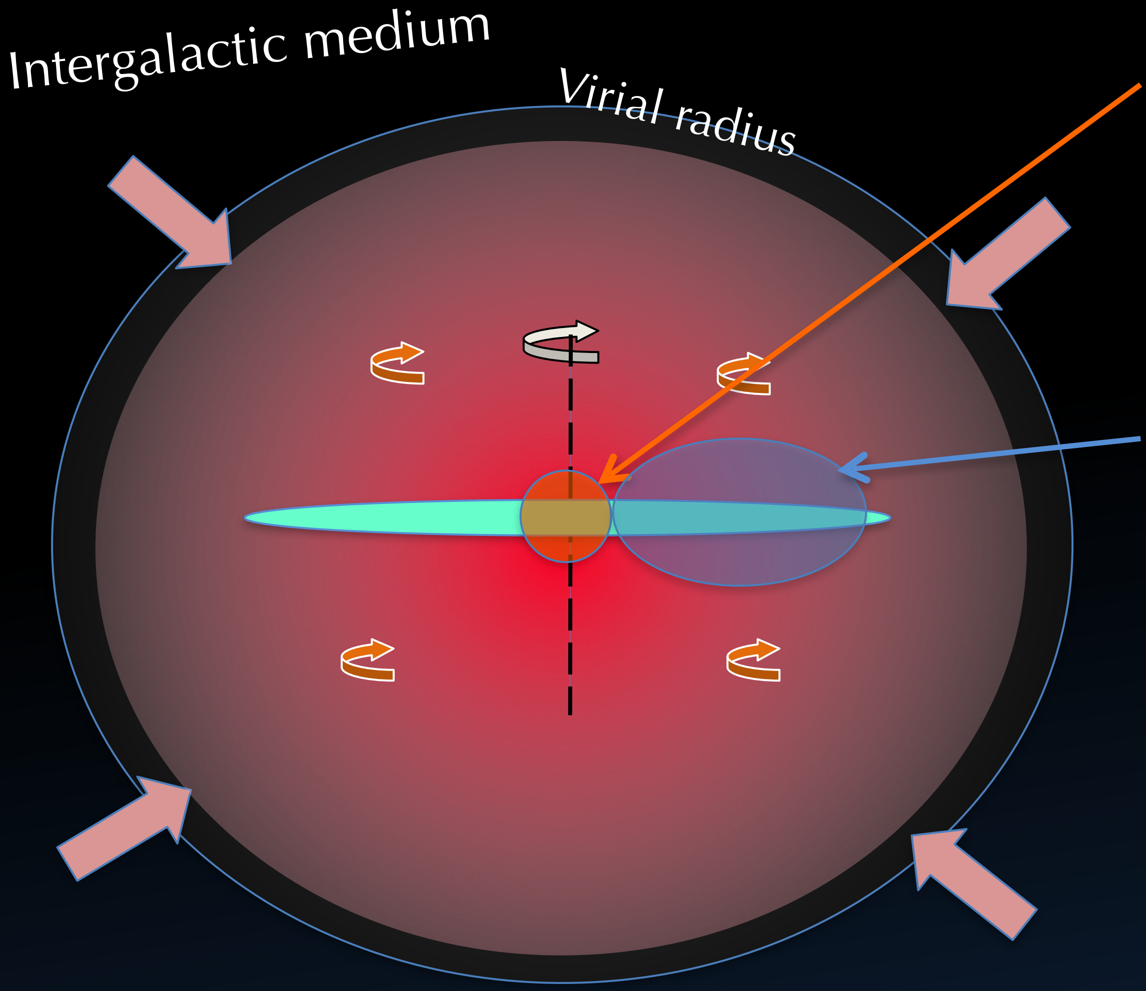
AGN is a

Are we learning something or compensating for numerical limitations?

Star formation

- Threshold in density
- SFR depending on t_{ff}^{-1}

Gas accretion from corona



Should cool here

Heating mechanisms:
e.g. Stellar/AGN feedback

Cools here

Condensation driven by galactic fountains, i.e. mix with disc material

Disc acquires high angular momentum gas
$j = R\, v_\varphi$

-> inside–out growth

Condensation efficiency & galaxy evolution

Armillotta, Fraternali, Marinacci 2016, MNRAS

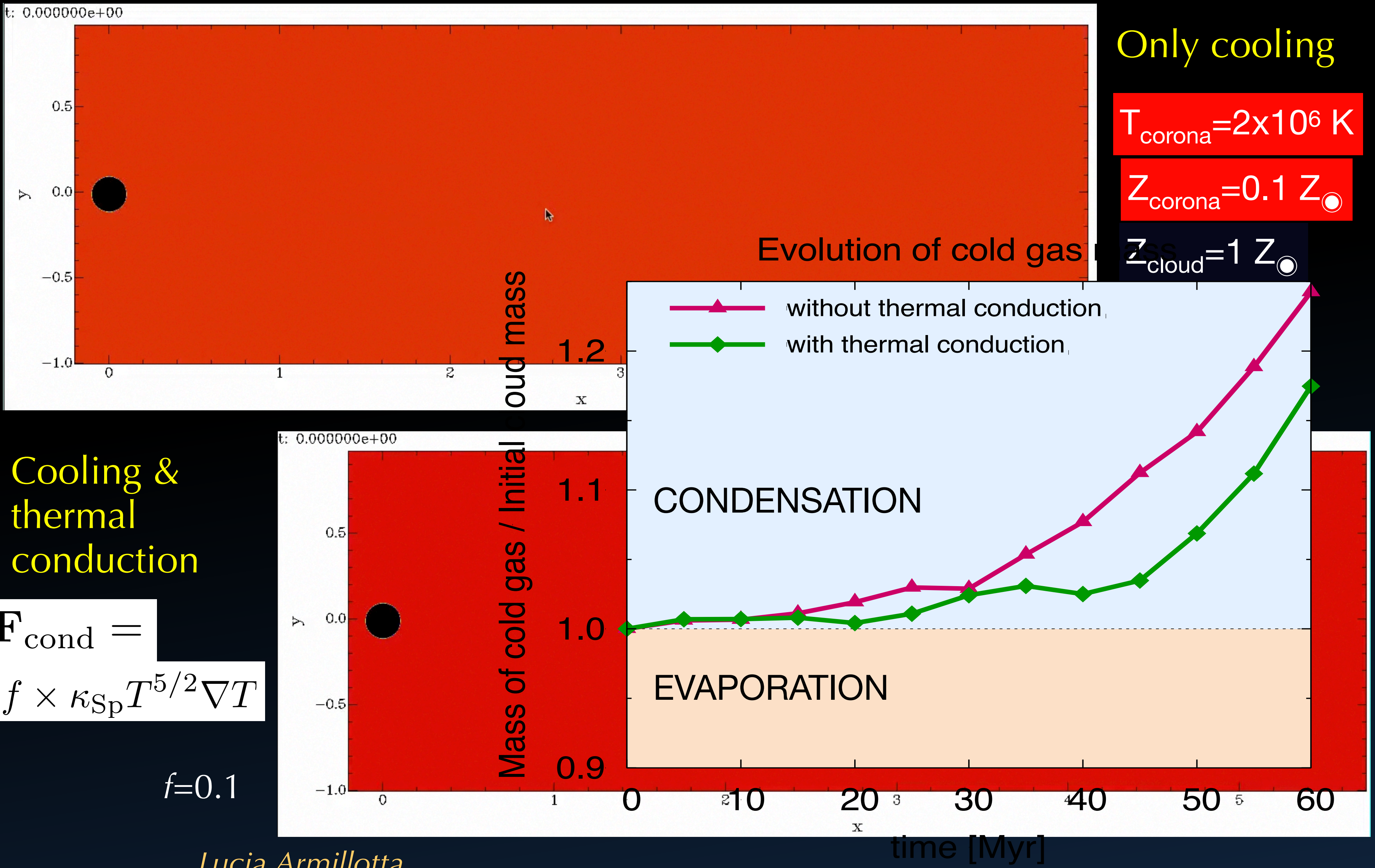
The effect of thermal conduction

Only cooling

T_{corona}=2x10^6 K

Z_{corona}=0.1 $Z_{\odot}$

Z_{cloud}=1 $Z_{\odot}$



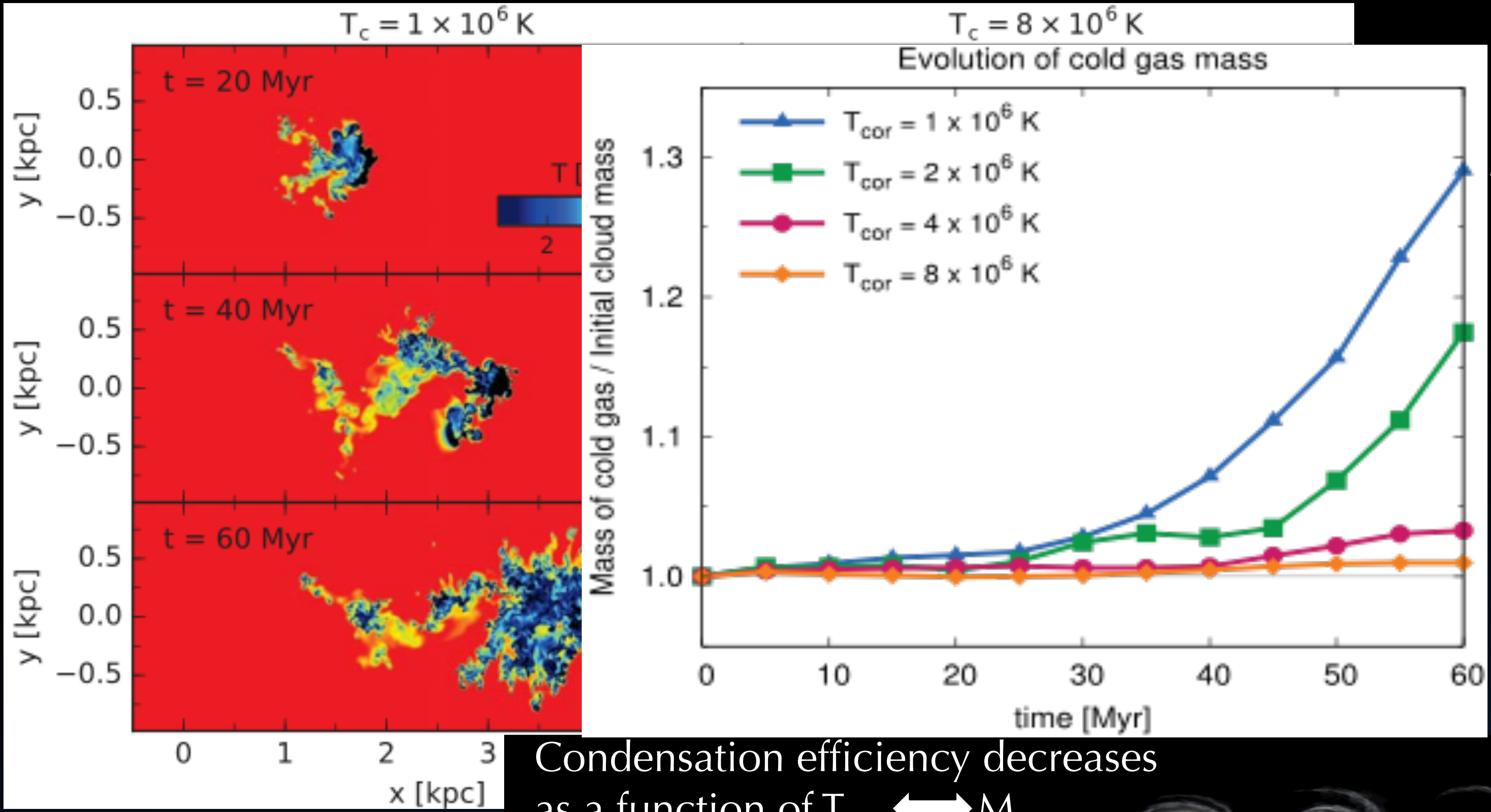
Cooling & thermal conduction

$$\mathbf{F}_{\rm cond} = f \times \kappa_{\rm Sp} T^{5/2} \nabla T$$

f=0.1

Lucia Armillotta

Condensation: different temperatures



Smaller halos

↑

MW

↓

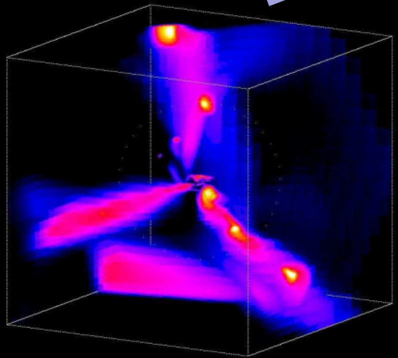
Larger halos

Lucia Armillotta, Fraternali Marinacci 2016, MNRAS

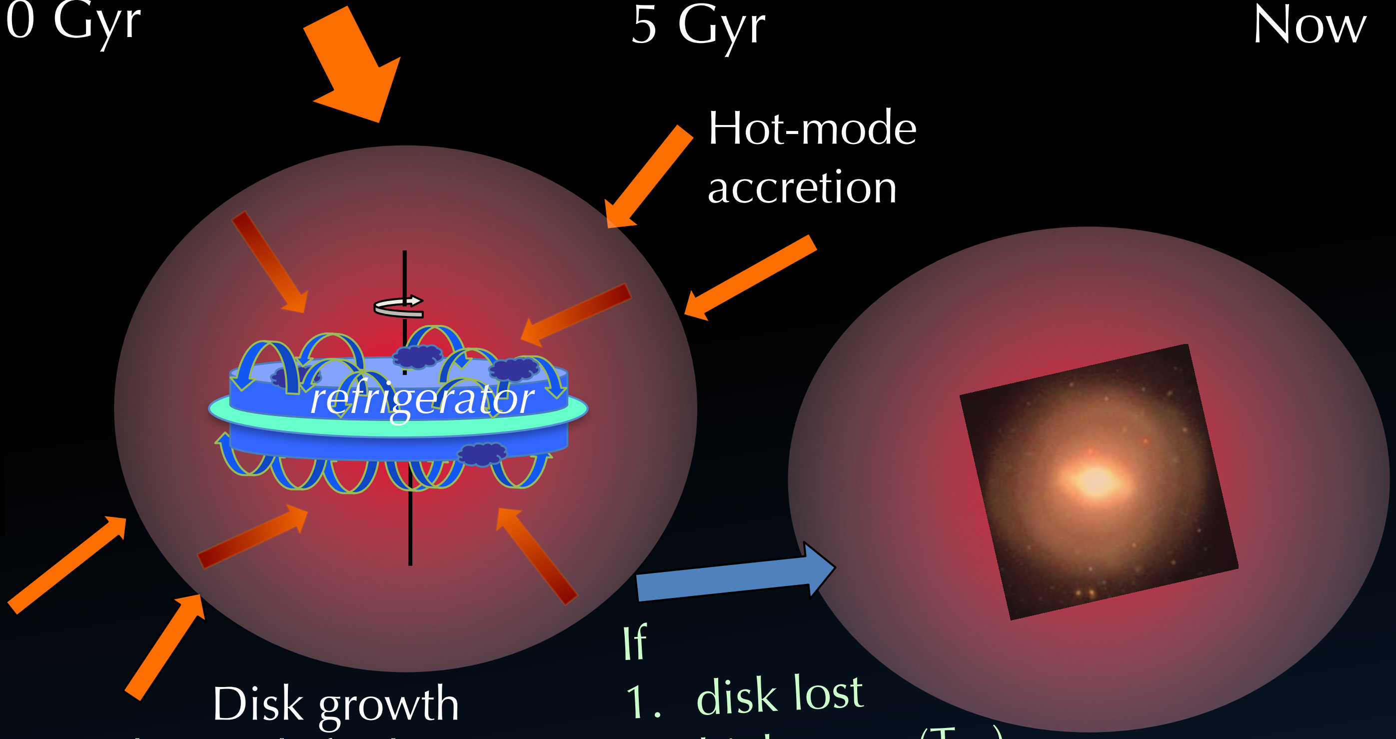
Condensation efficiency decreases as a function of $T_{vir} \longleftrightarrow M_{vir}$

← T_{vir}

Possible Evolution



Dekel et al. 2009



Hot-mode
accretion

Disk growth
(hot mode feeds corona
fountain feeds the disc)

If
1. disk lost
2. high mass (T_{vir})
3. dense ambient (high T)

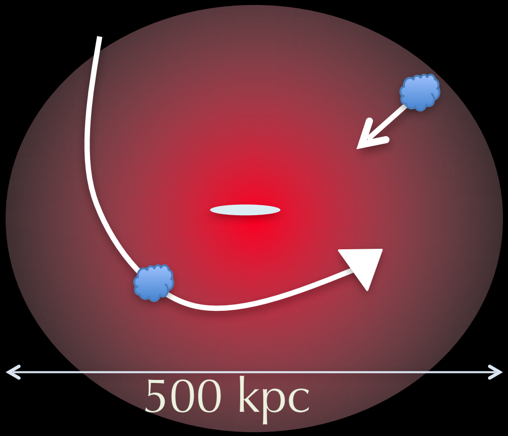
Galaxies lose ability
to cool their corona:
red & dead

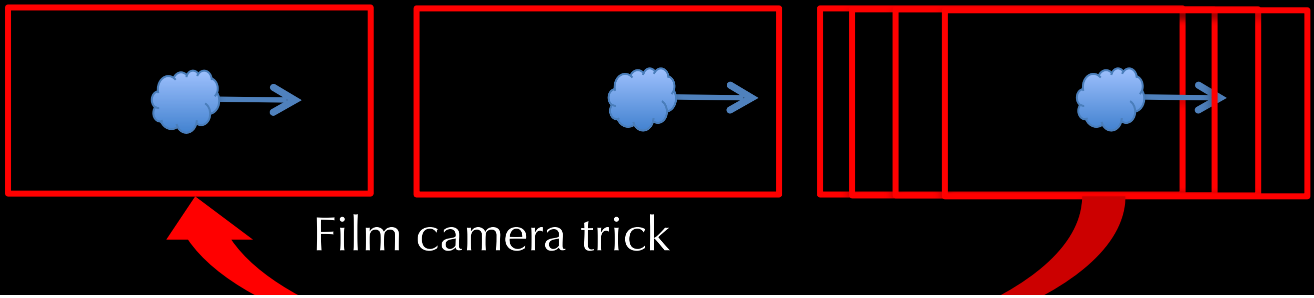
Survival of clouds

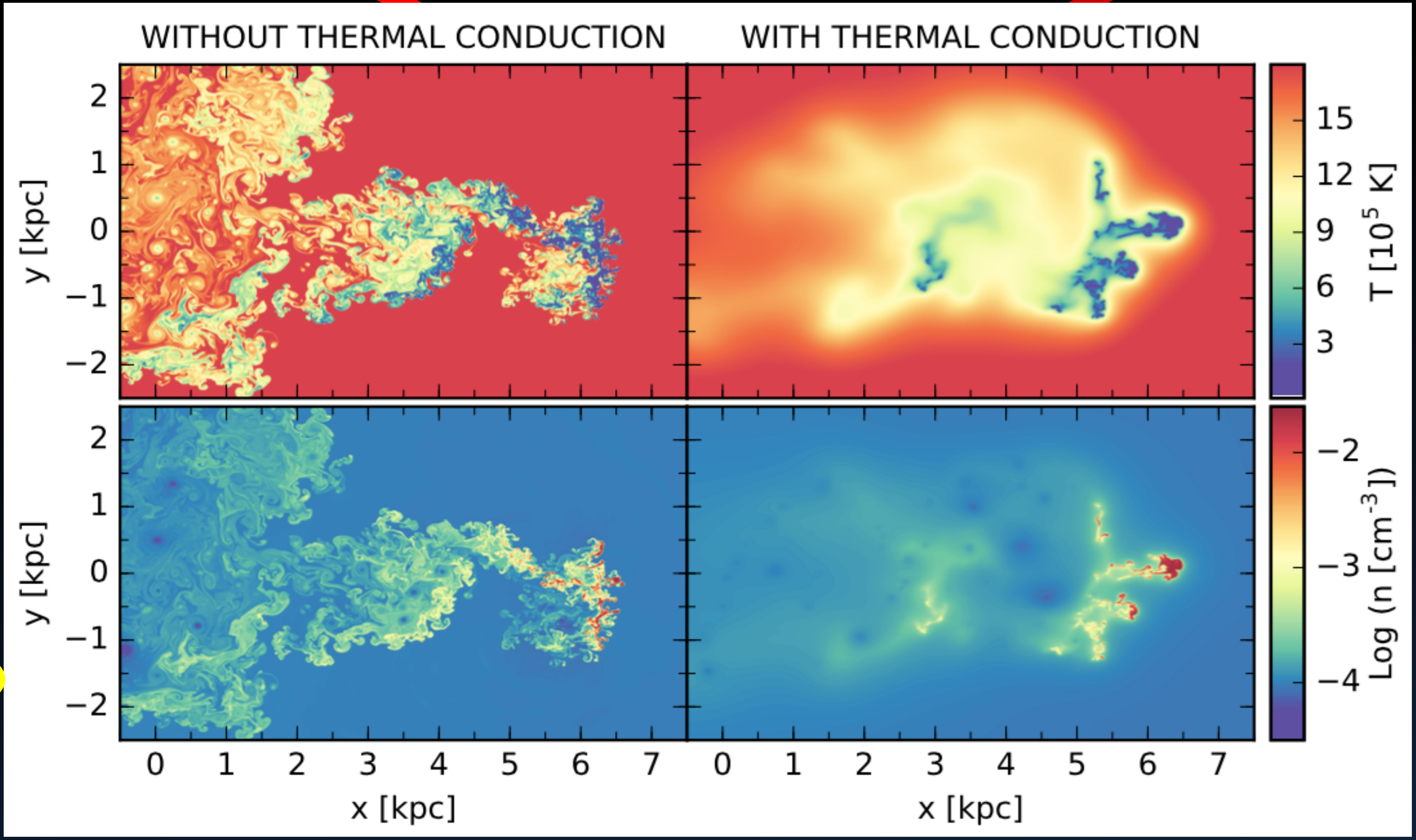
Armillotta, Fraternali, Werk, Prochaska & Marinacci 2017, MNRAS

Cloud survival

Armillotta+ 2017




Film camera trick

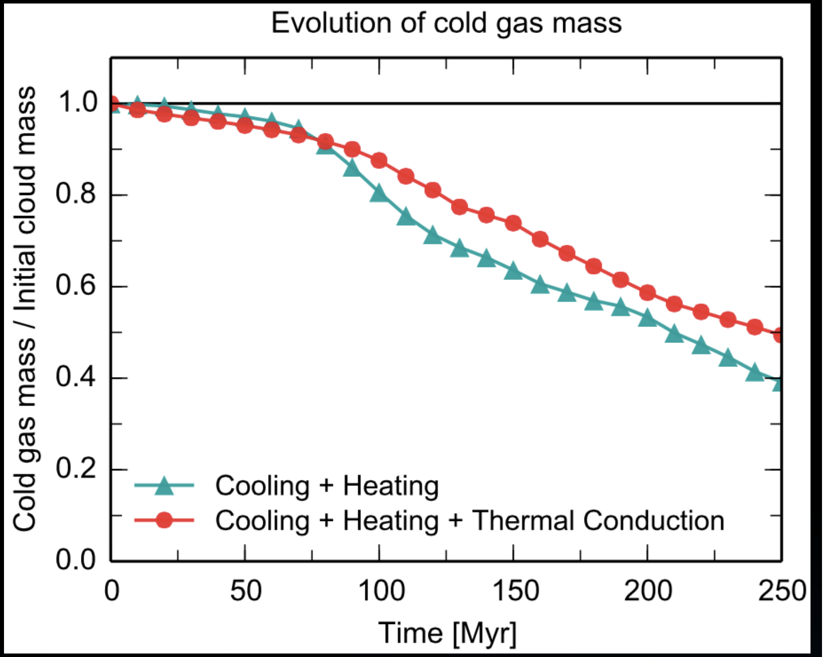


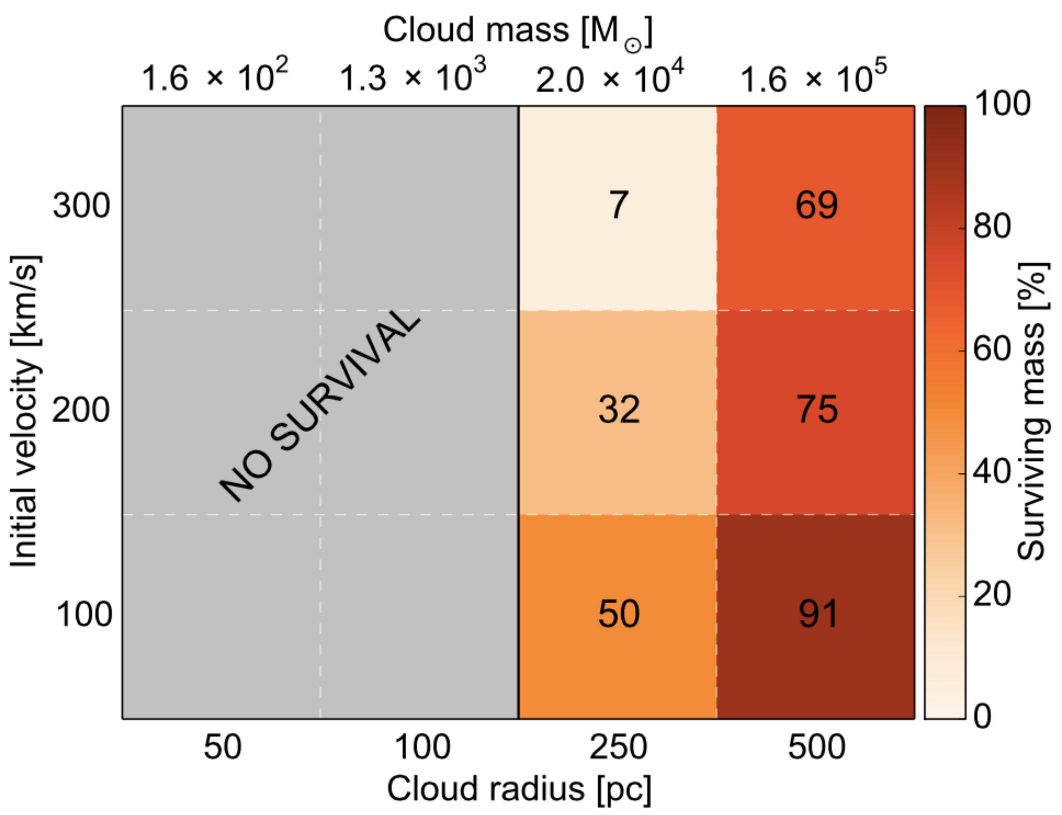
Temperature
&
Density
After 200 Myr

T_{cold} = 1x 10^4 K
Z_{cold} = 0.3 Z_{sun}

T_{hot} = 2x 10^6 K
n_{hot}=1x10^{-4} cm^{-2}
Z_{hot} = 0.1 Z_{sun}

How long do these clouds survive?





Armillotta, Fraternali+ 2017, MNRAS

Cold gas can survive for hundreds of Myr -> tens of kpc

Properties are shaped by turbulent mixing and thermal conduction

Away from galaxies cold clouds tend to evaporate in the corona

Things we may be missing

Feedback is used to get rid of cold gas: why is there so much cold gas?

Numerical effects really under control?

1. Maybe explore more preheating/preventive feedback? (e.g. *Lu+ 2015*)

2. Do we understand cooling?
    - are equilibrium functions good enough? (*Gnat 2017*)
    - should we include turbulence? (*Gray, Scannapieco & Kasen 2015*)

3. Do we understand heating?
    - large uncertainties in the EUVB
    - what about heating from local sources? (*Cantalupo 2010*)
    - what about X-ray binaries/ULXs? (*Prestwich et al. 2015*)
    - and *small* black holes (*Su et al. 2015)*?
    - do we believe CLOUDY too much?

4. Magnetic fields, CRs and thermal conduction?

5. Different dark matter? Would affect SF feedback?