Gas accretion and removal: theoretical perspective

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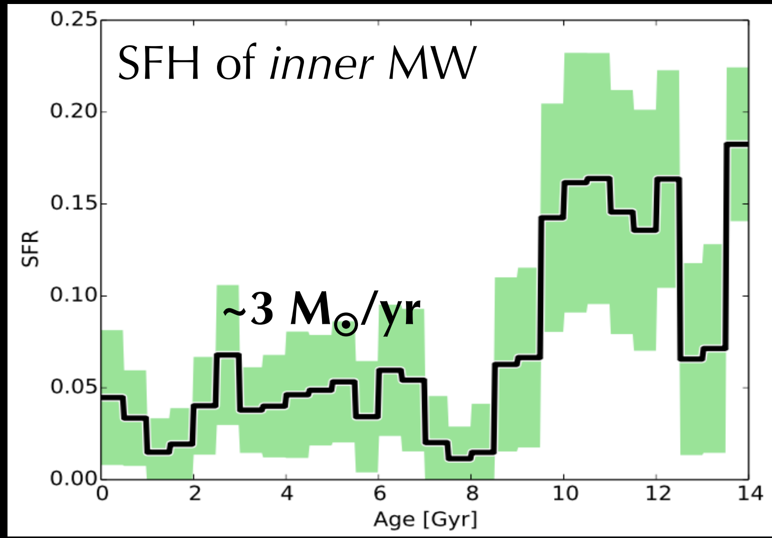
Cosmological gas accretion

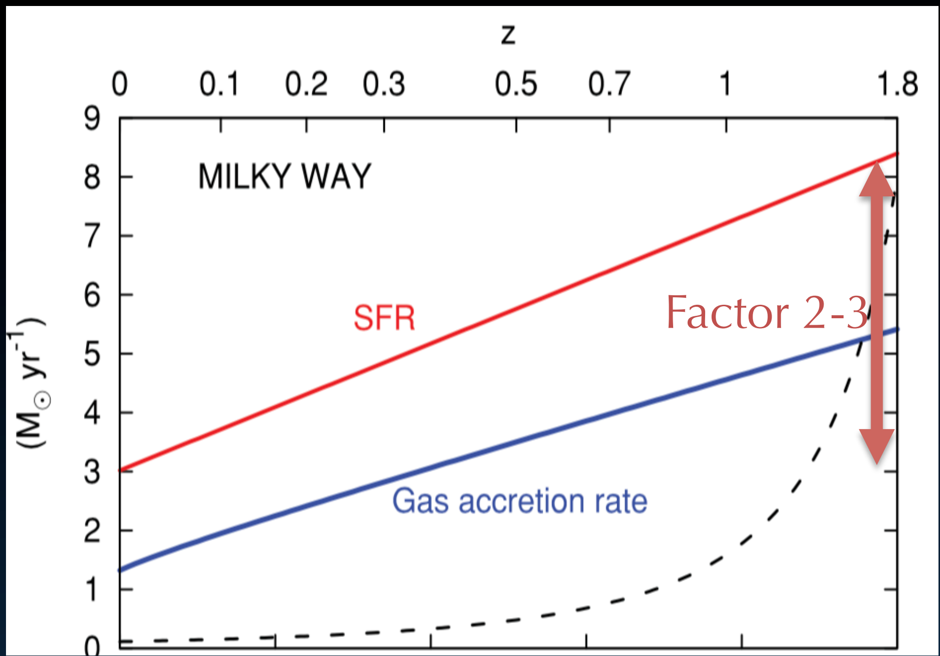
Milky Way's growth reconstructed backward

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

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



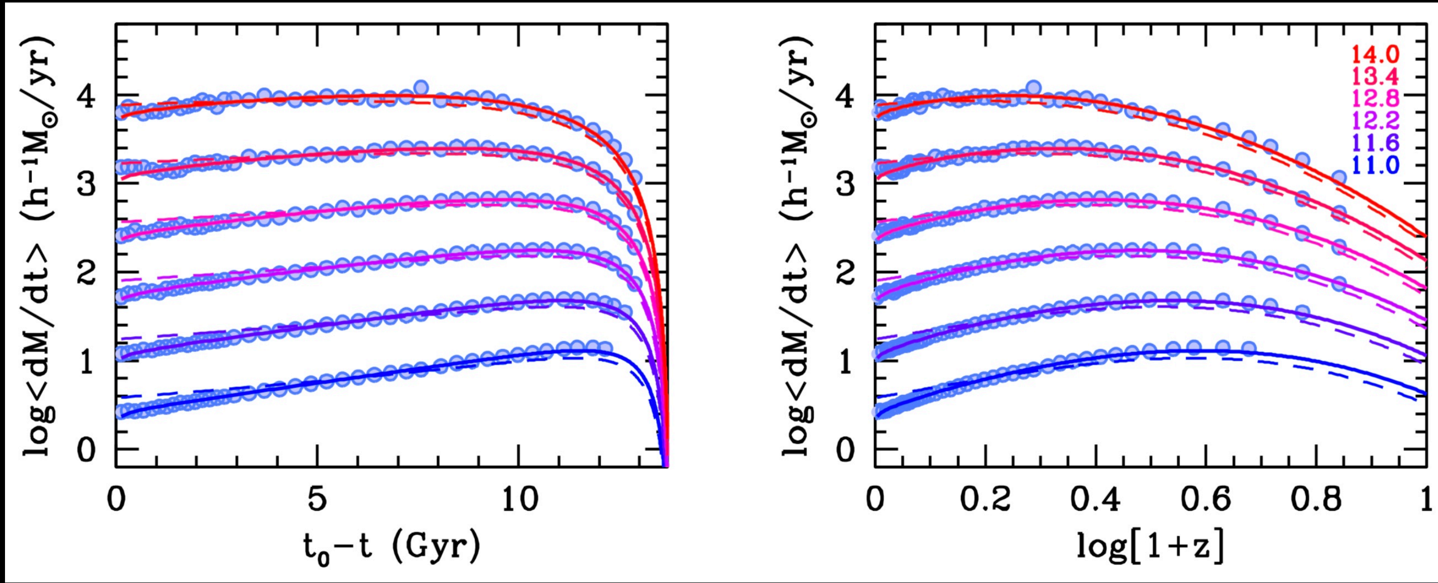
Snaith et al. 2015



Fraternali & Tomassetti 2012

Cosmological accretion

Press & Schechter 1974



Van den Bosch et al. 2014

Dark matter accretion in the Bolshoi DM-only simulation

Klypin et al. 2011

For halos that have certain masses at z=0

Dark matter mean accretion rate onto halos *Fakhouri et al. 2010*

$$\langle \dot{M} \rangle_{\rm mean} = 46.1\ {\rm M_\odot\ yr^{-1}} \left(\frac{M}{10^{12}\ {\rm M_\odot}} \right)^{1.1} \times (1 + 1.11z) \sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda}$$

Is it really so simple?

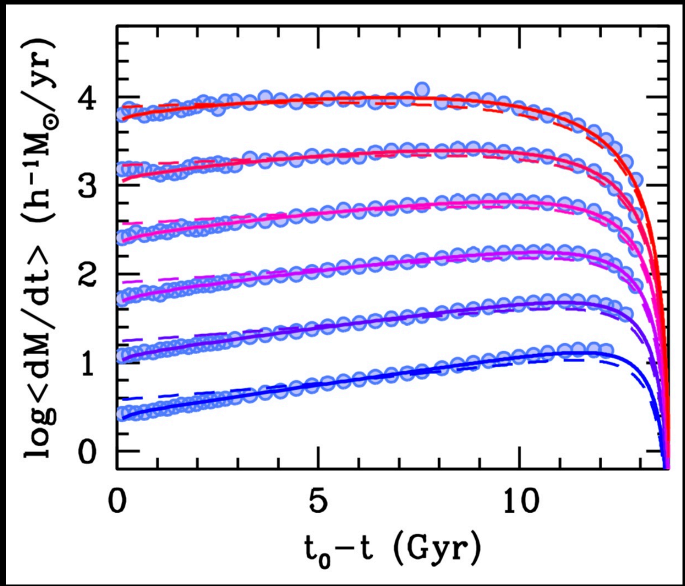
For a MW-galaxy

at z=2: M_{DM} ~ 3.5e11
Accretion: DM ~ 143 Mo/yr
baryons ~ 27 Mo/yr

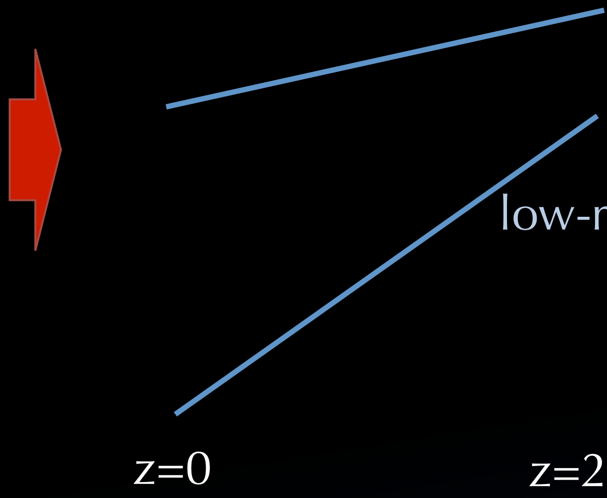
at z=0: M_{DM} ~ 1.2e12
Accretion: DM ~ 56 Mo/yr
baryons ~ 11 Mo/yr

Factor 2-3

Accretion of DM and gas



Van den Bosch et al. 2014



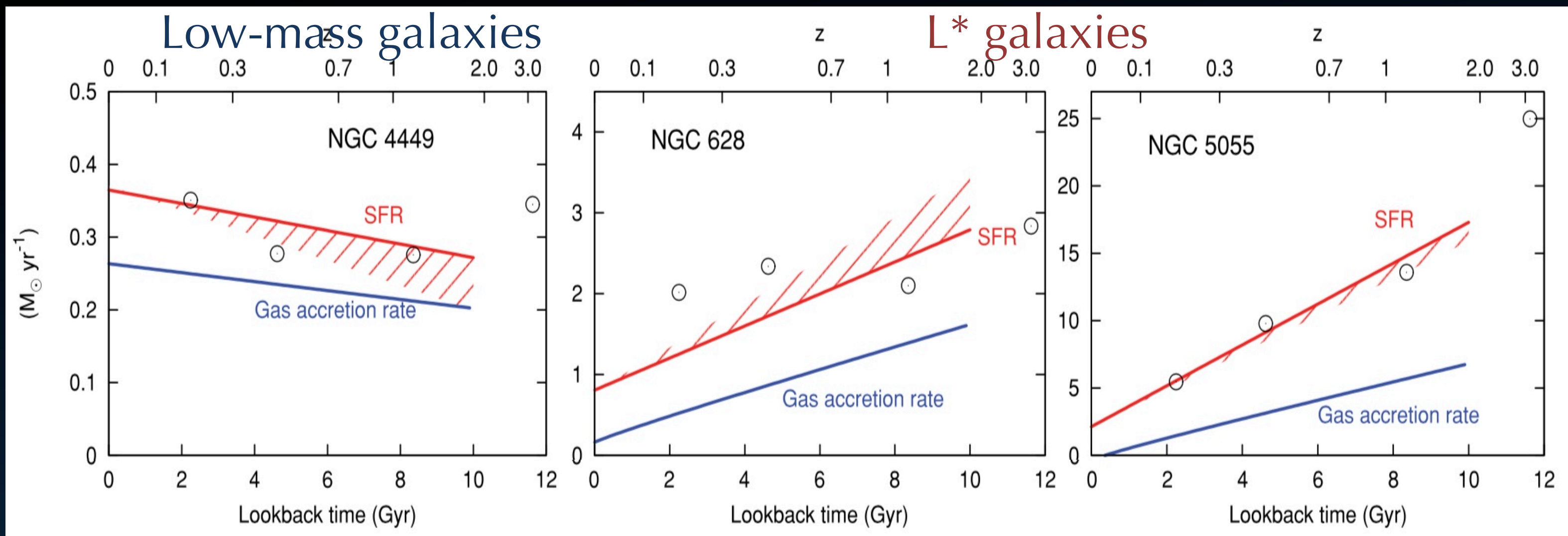
L* galaxies Factor 2-3

low-mass galaxies Factor 10

Growth driven by cosmological accretion but not trivially!

Low-mass galaxies

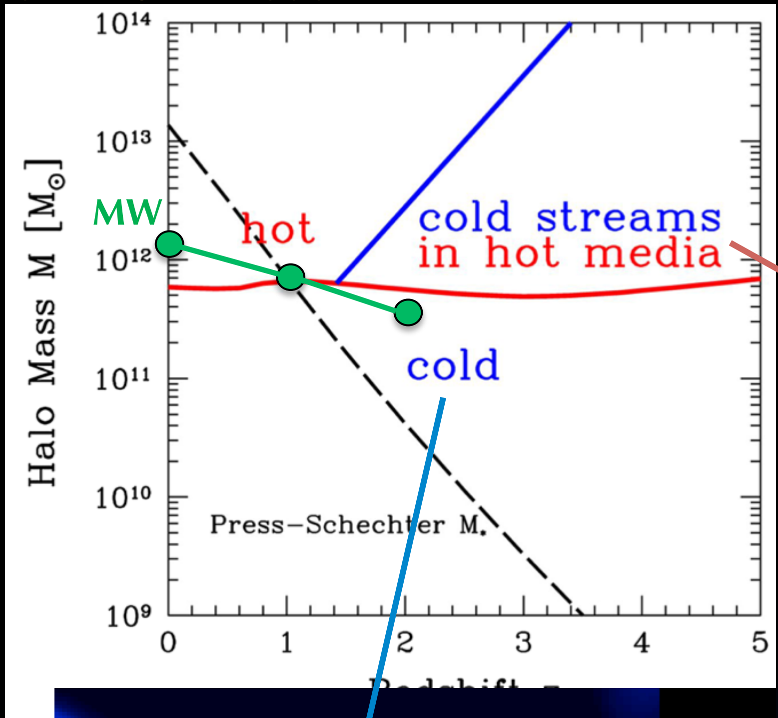
L* galaxies



Fraternali & Tomassetti 2012

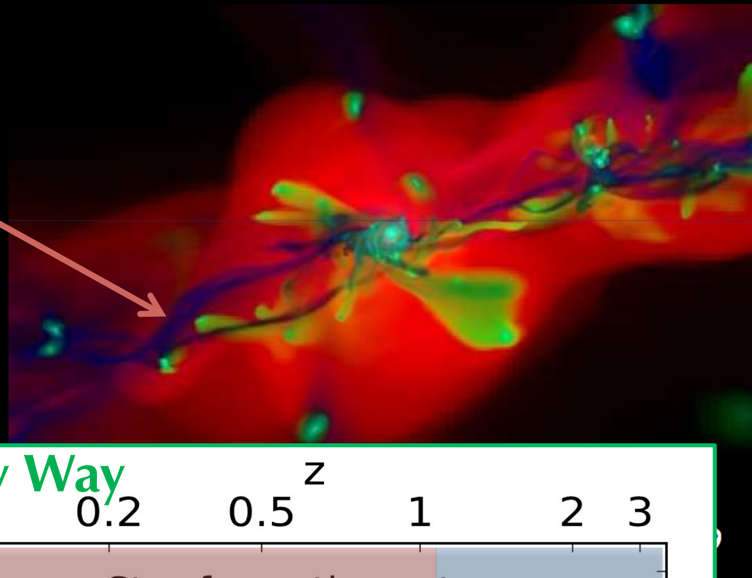
Cold versus hot mode

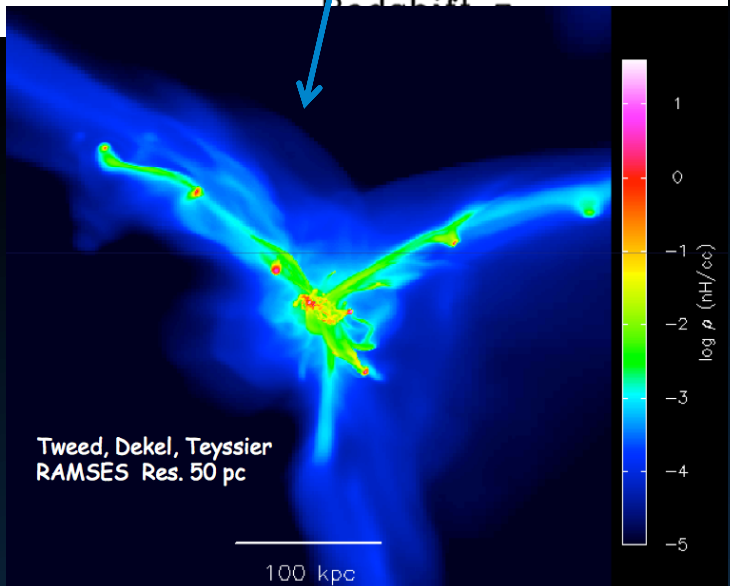
Dekel & Birnboim 2006

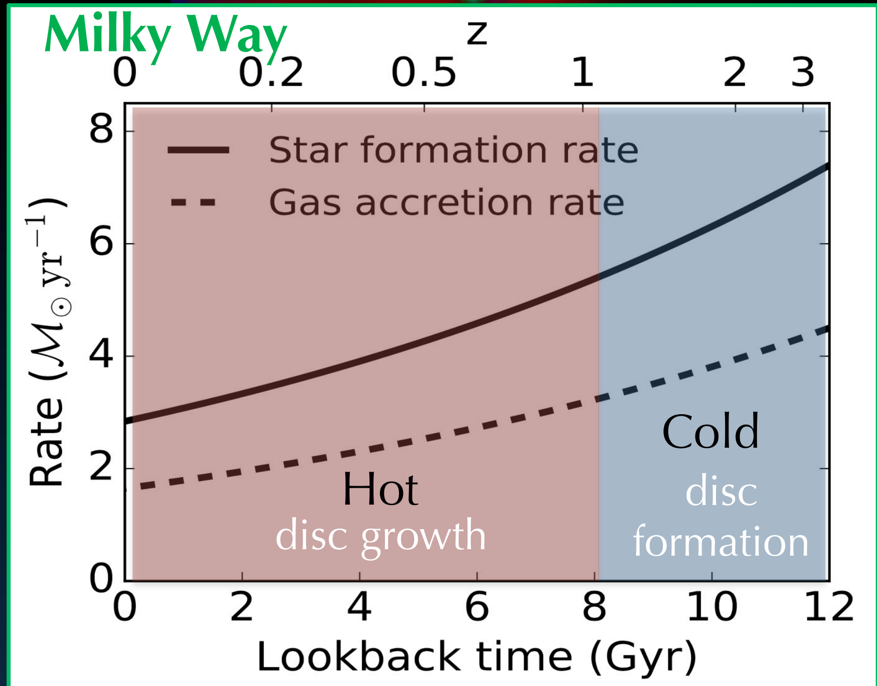


Galaxy formation via dissipation & collapse

Binney 1977; Silk 1977; Rees & Ostriker 1977; White & Rees 1978



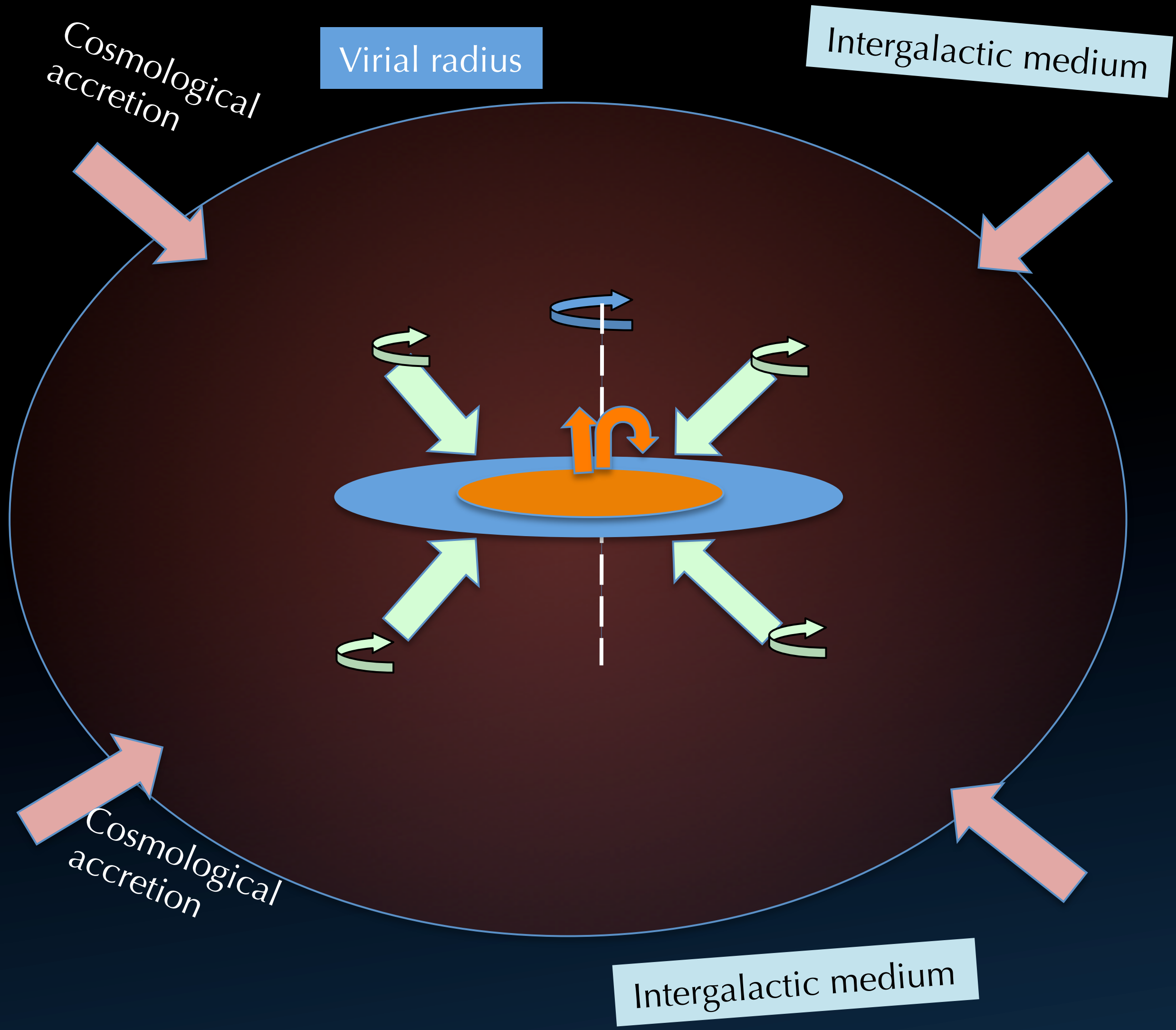




The angular momentum of the accreting gas

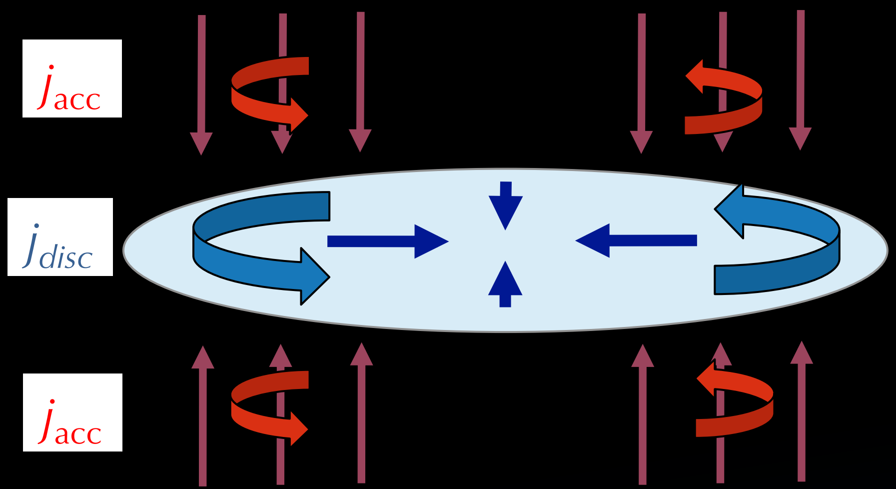
Disc growth

Dissipative collapse & ang mom conservation
Fall & Efstathiou 1980



Local Angular Momentum Mismatch

Pezzulli & Fraternali 2016, MNRAS



$j = R\, v_{rot}$

Pitts & Tyler 1989

$$\dot{\Sigma}_{\rm eff} = \dot{\Sigma}_{\rm acc} - \frac{1}{2\pi R}\frac{\partial \mu}{\partial R}$$

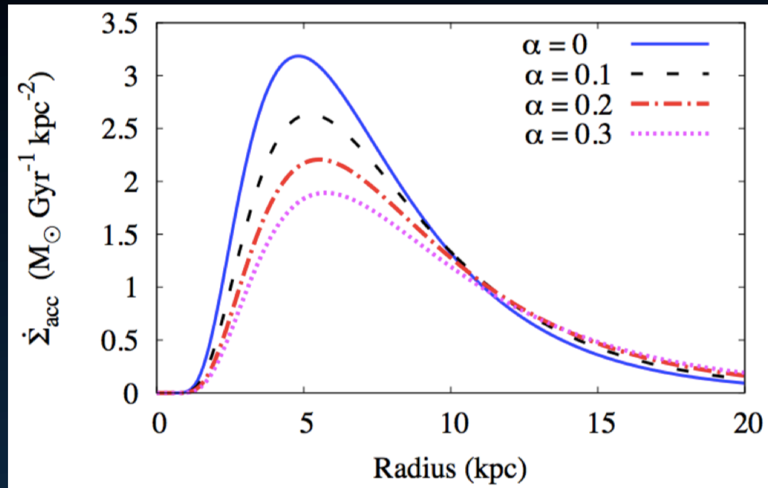
Radial mass flux

$$\mu = -2\pi \alpha R^2 \dot{\Sigma}_{\rm acc}$$

Angular momentum mismatch

$$\alpha = 1 - \frac{V_{\rm acc}}{V_{\rm disc}}$$

$j_{acc} < j_{disc}$ → Radial inflow



→ Influence on metallicity gradients: measurable!

Mayor & Vigroux (1981); Lacey & Fall (1985)

Metallicity gradients vs mismatch

Structural+chemical evolution model

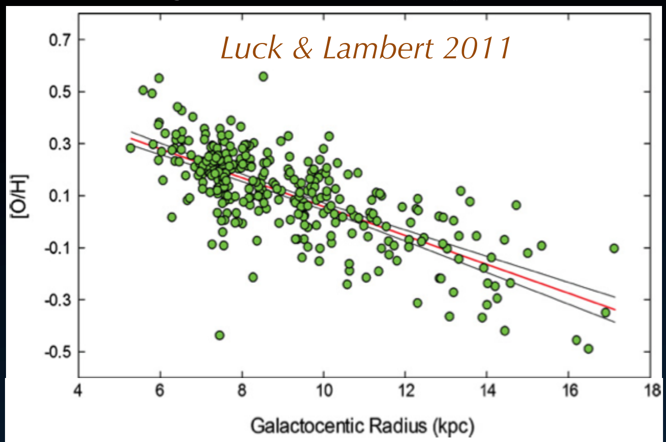
1. Exponential disc
2. Kennicutt-Schmidt law
3. Exponential SFH
4. Conservation of angular momentum
5. Instantaneous recycling approximation

Analytical solution → Abundance vs mismatch parameter

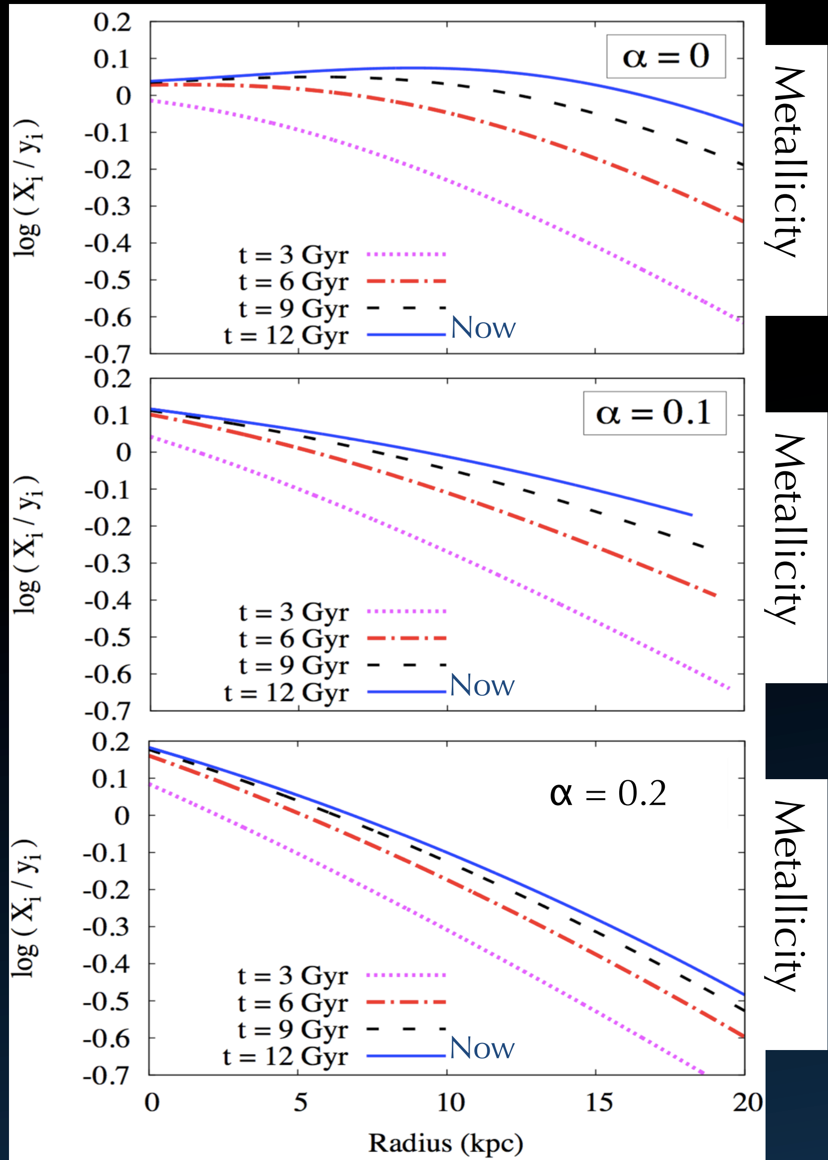
$$\alpha = 1 - \frac{V_{acc}}{V_{disc}}$$

$\alpha = 0$ no mismatch
$\alpha > 0$ $j_{acc} < j_{disc}$

Observed gradients from Cepheids



See also Bilitewski & Schoenrich 2012, MNRAS

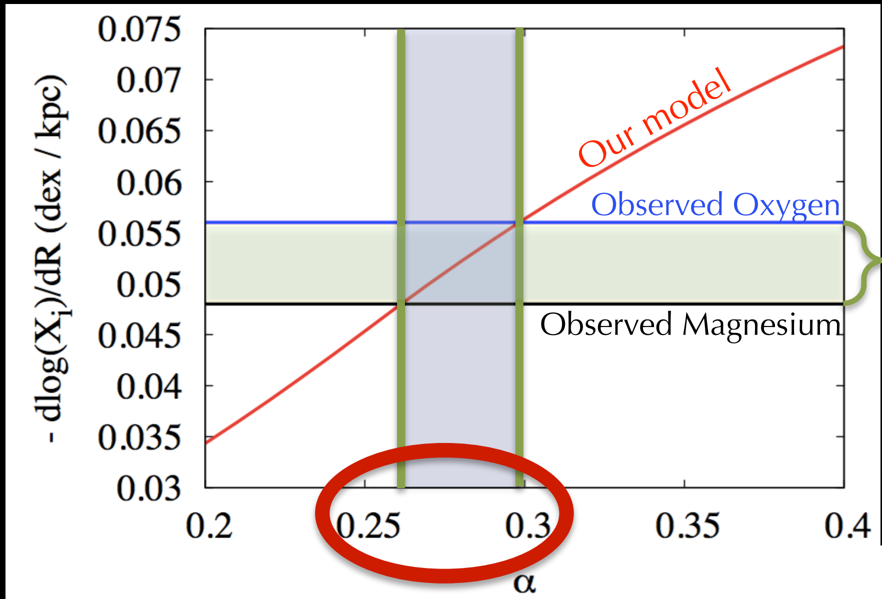


Pezzulli & Fraternali 2016, MNRAS

Angular momentum of the accreting gas

Pezzulli & Fraternali 2016, MNRAS

Metallicity gradients



Angular momentum mismatch

$$\alpha = 1 - \frac{V_{\rm acc}}{V_{\rm disc}}$$

Range allowed by observations in the Milky Way

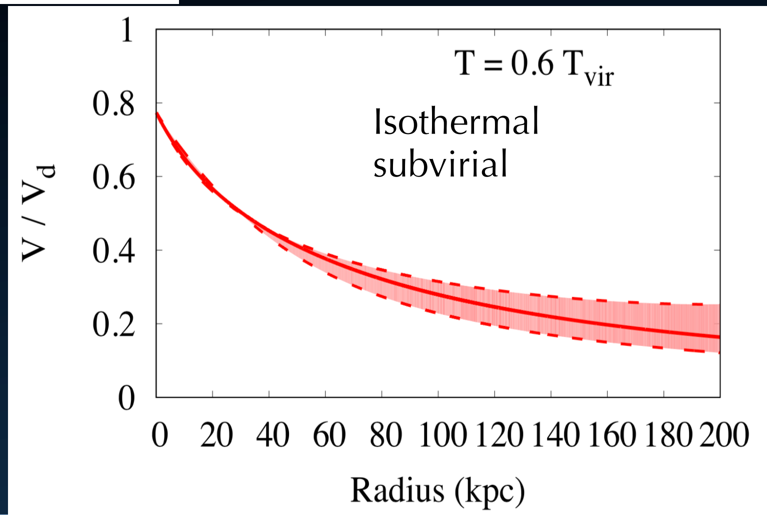
Accreting gas rotates 70-80% more slowly than the disc

$v_{\rm rot,\,acc}$ ~170-190 km/s in the MW

Few months later the rotation of the corona was observed!
$V_{\rm rot} = 183 \pm 41$

Hodges-Kluck et al. 2016, ApJ

Observed O: *Luck & Lambert 2011*
Observed Mg: *Genovali et al. 2015*

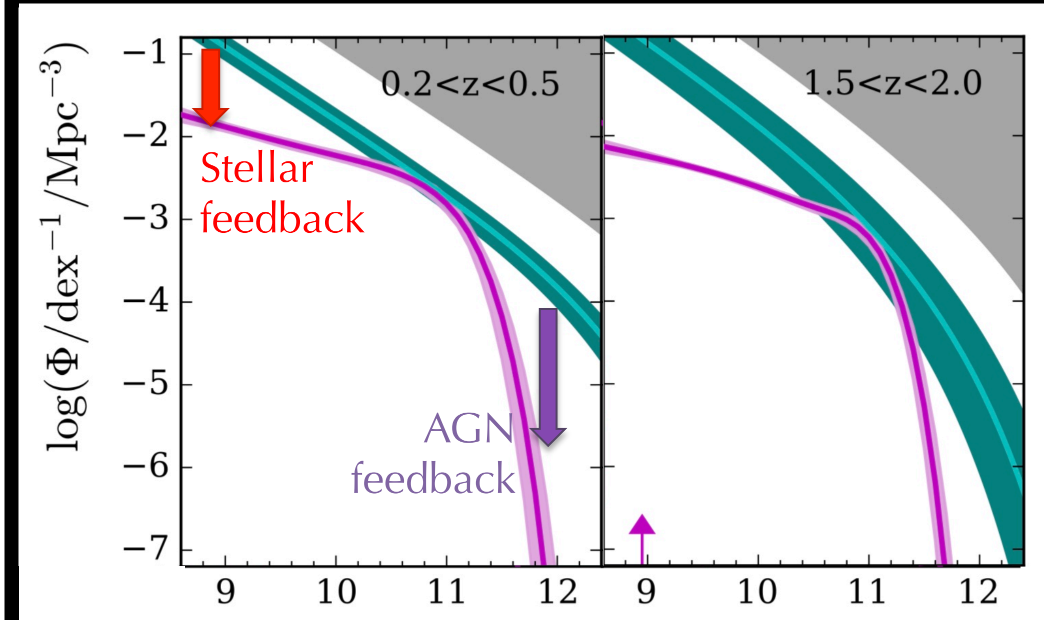


Pezzulli, Fraternali & Binney 2017, MNRAS

Feedback

Need for strong feedback

Davidzon et al. 2017



Strong gas losses in dwarfs, v_{vir}<100 km/s

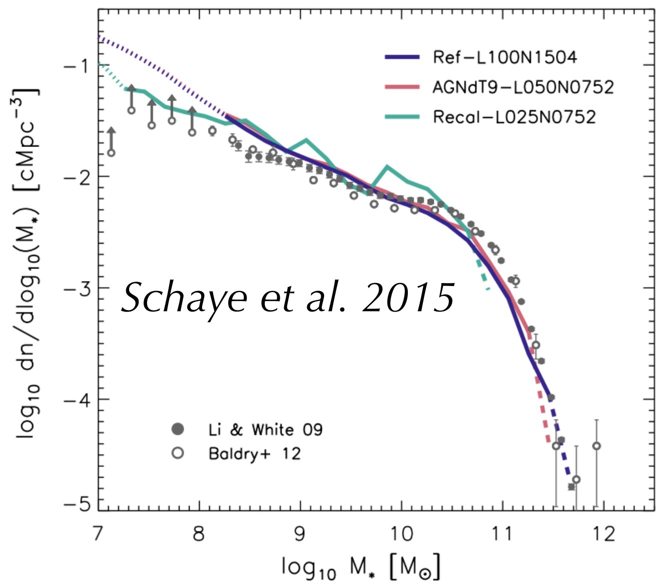
Dekel & Silk 1986

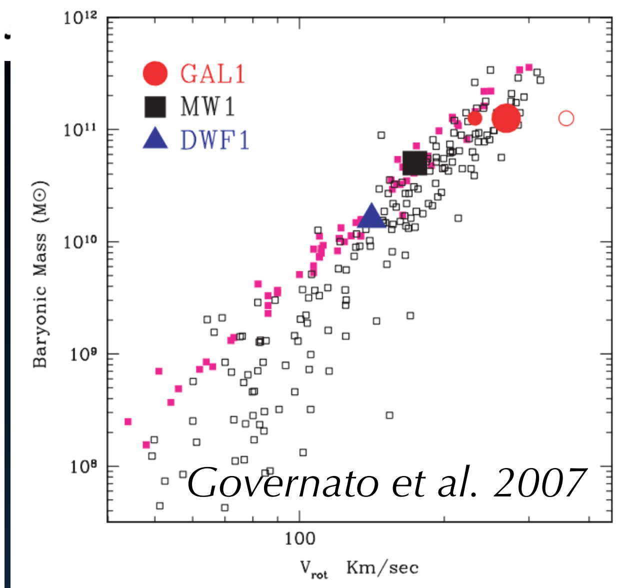
Classical problems in galaxy formation:

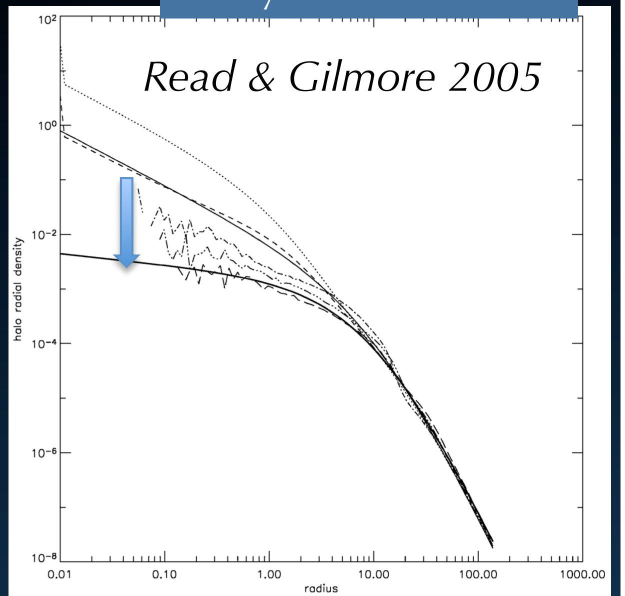
- Halo mass function vs stellar mass function
- Angular momentum of discs -> scaling relations
- Missing satellites, cusps, too big to fail

-> Possibly solved by

But are these issues really solved?



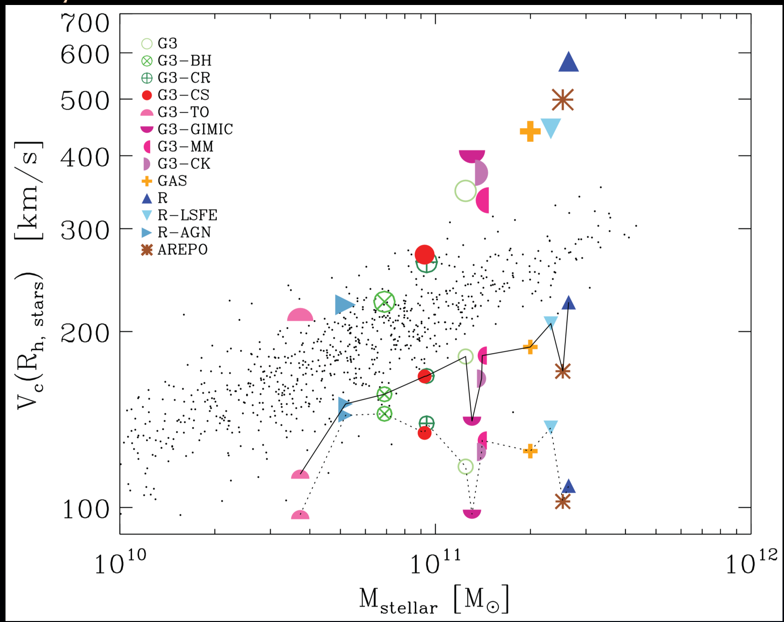




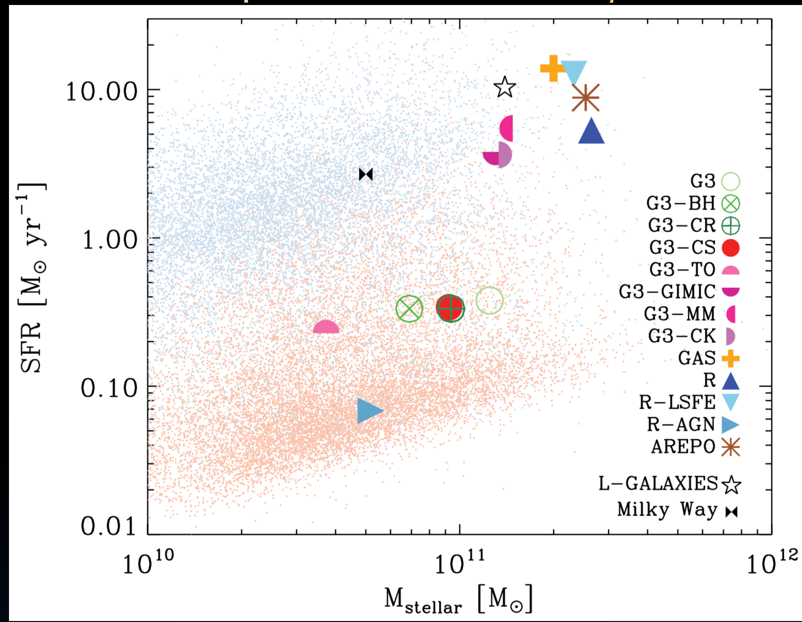
Different recipes and calibrations

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."

EAGLE *Schaye et al. 2015*

Thermal feedback

Gas heated to log(T/K)=7.5 stochastically

GASOLINE/NIHAO

Switching off cooling (*Stinson et al. 2006*)

High T conduction (*Keller et al. 2014*)

Illustris(TNG) *Vogelsberger et al. 2013, Pillepich et al. 2017*

AREPO / Kinetic feedback

Hydro OFF until particles

What does this mean?
What are we learning?

FIRE *Hopkins et*

Radiation pressure + momentum injection

Do real galaxies explode?

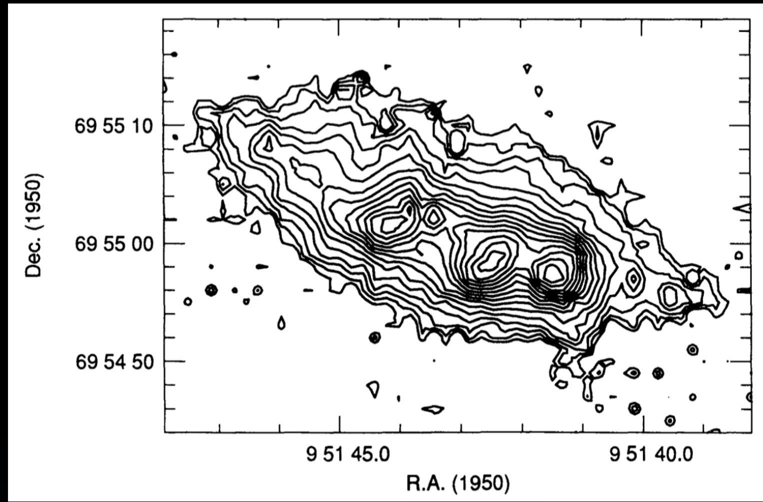
FIRE
simulation

Formation of
a Milky Way
galaxy

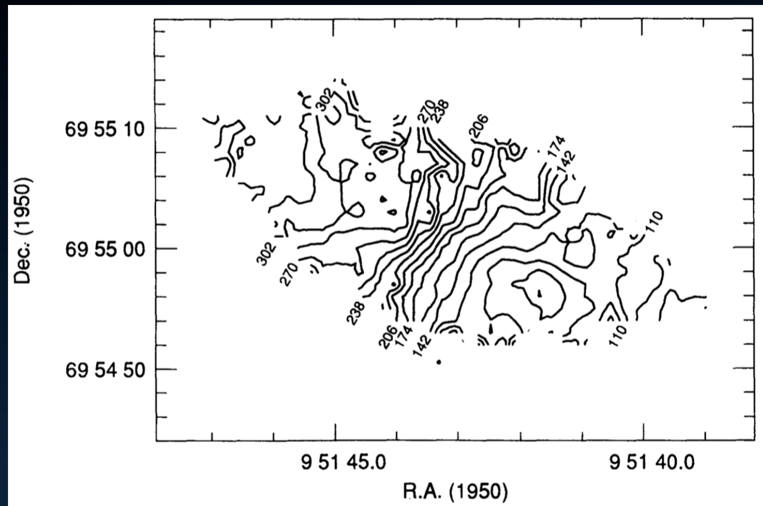
Movie credit:
P. Hopkins

M82: a starburst
that we know well

M82 inner disk – [Ne II] 12.8 μm



Velocity field – regular rotation



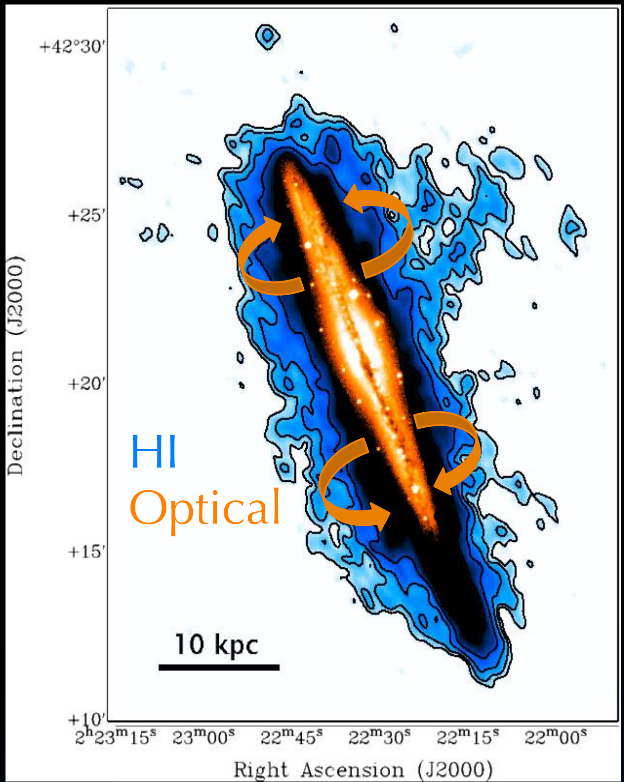
Achtermann & Lacy 1995

Galactic fountain and corona condensation

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

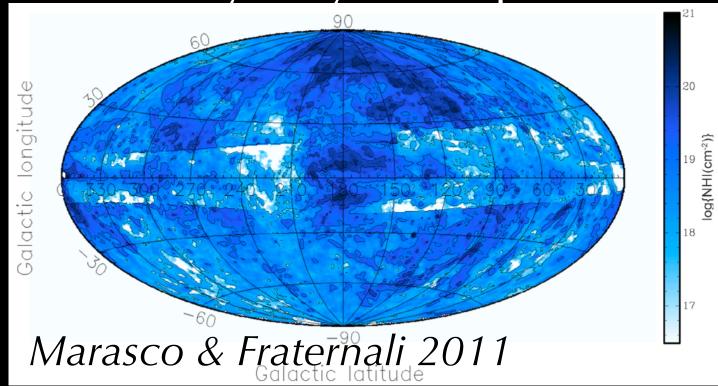
Massive local circulation

NGC 891



Oosterloo, Fraternali, Sancisi 2007, AJ
Marasco et al. 2011

Milky Way's extraplanar HI

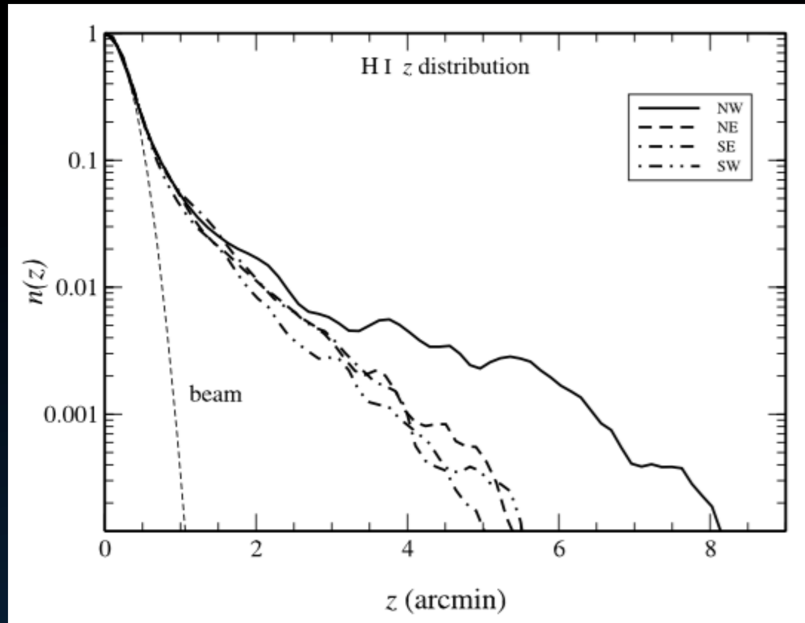


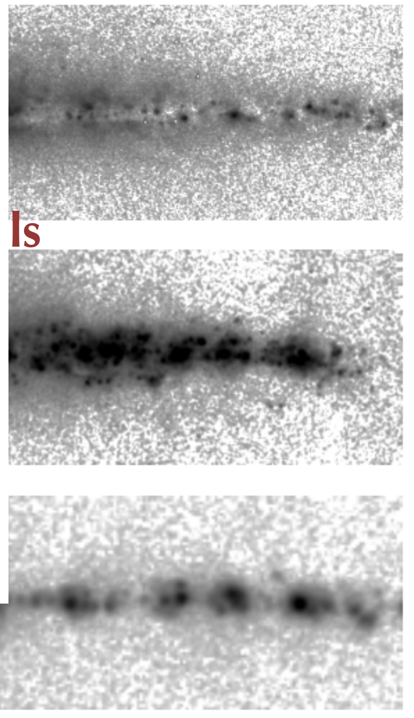
Marasco & Fraternali 2011

Extraplanar HI
h ~ 1-2 kpc, M~4x10^8 M$_\odot$

Falls in few x 10^7 yr
-> galactic fountain circulates ~ 10 M$_\odot$/yr

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

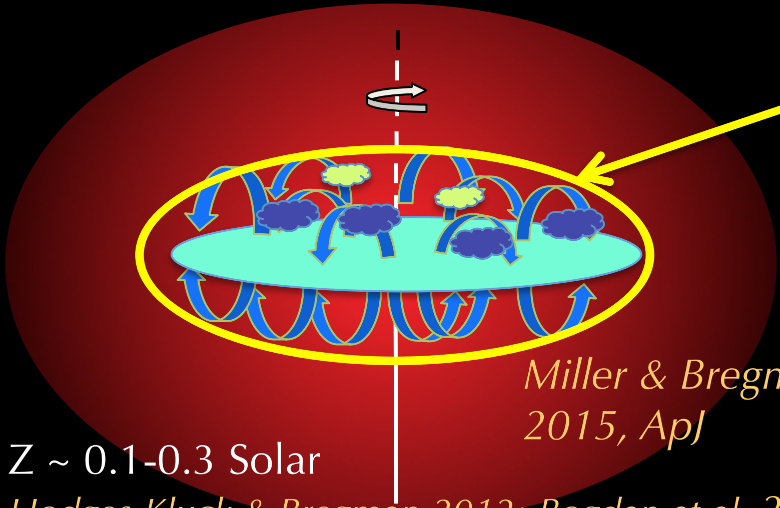




Hoopes et al. 1999
Rossa & Dettmar 2003

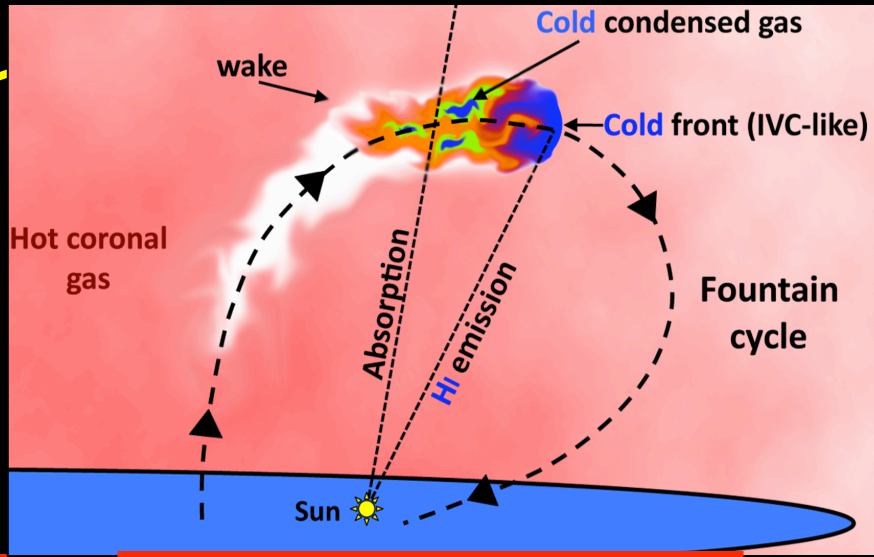
Low-velocity fountain produces a massive circulation

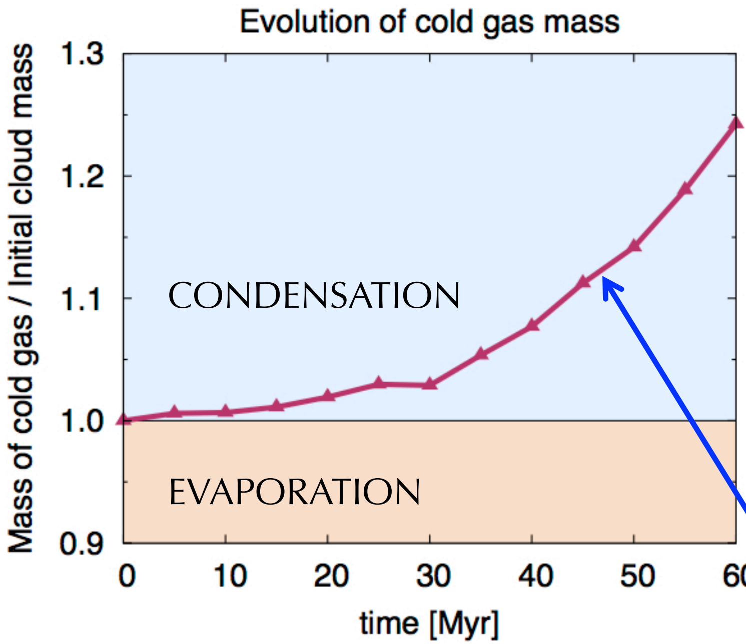
Mixing promotes corona condensation/accretion

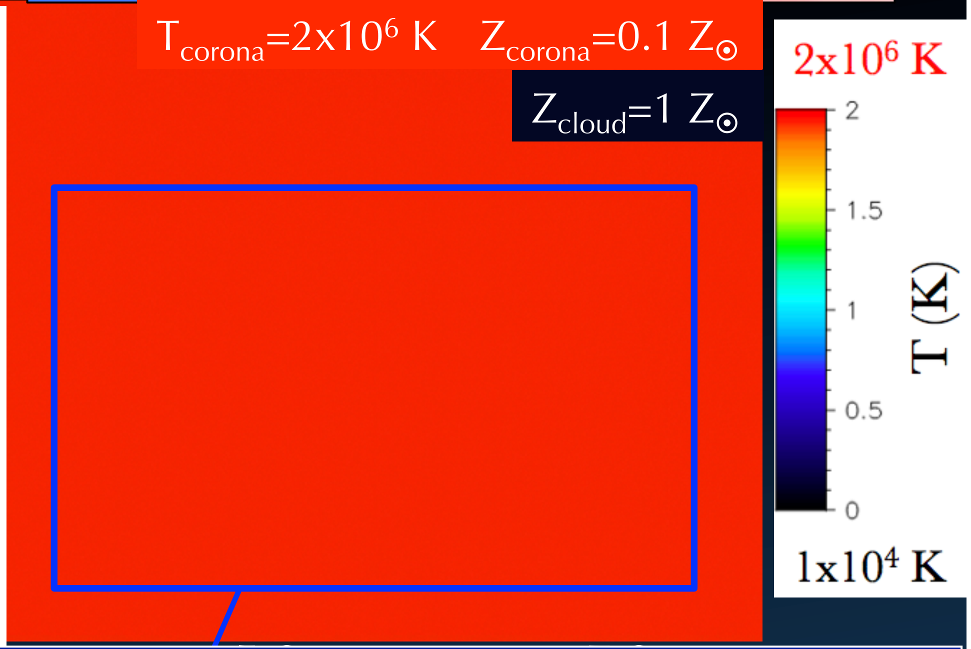


Z ~ 0.1-0.3 Solar

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







T_{corona}=2x10^6 K Z_{corona}=0.1 $Z_\odot$

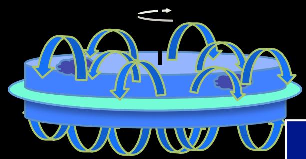
Z_{cloud}=1 $Z_\odot$

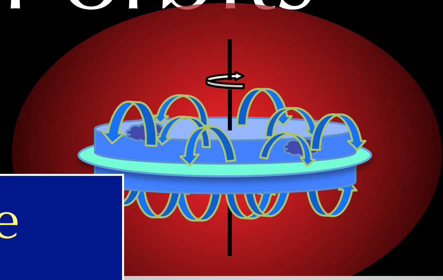
2D fixed grid, 2 pc x 2 pc!

X (k

Mass of cold gas increased by ~20%!

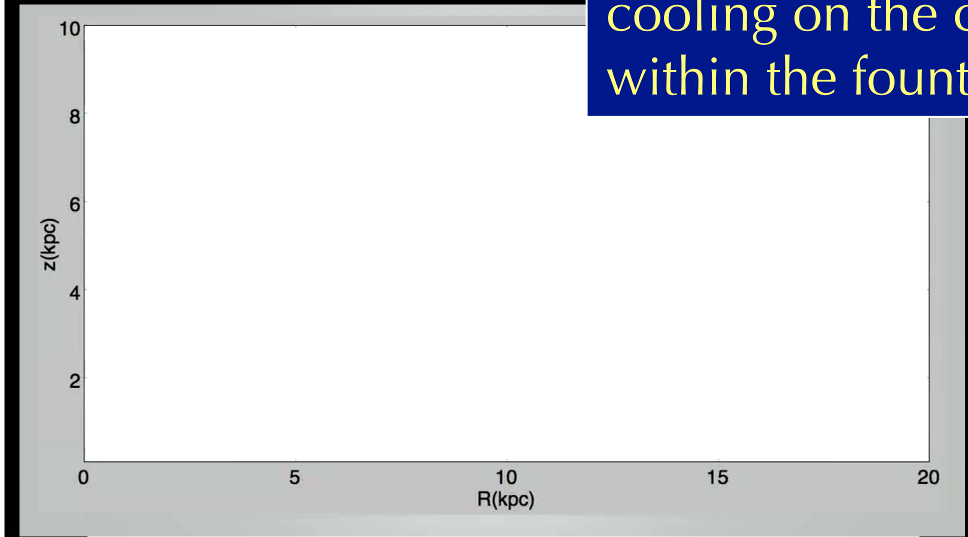
Modification of orbits

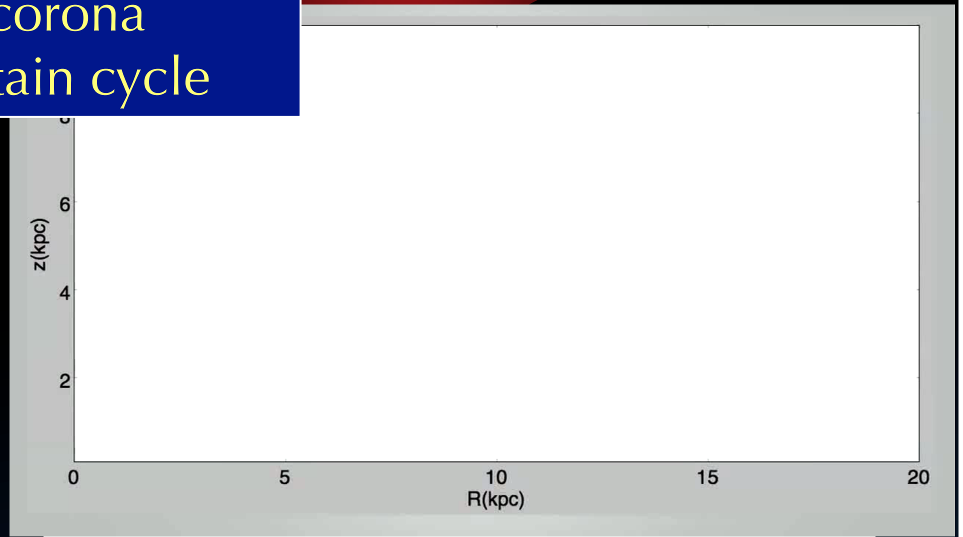


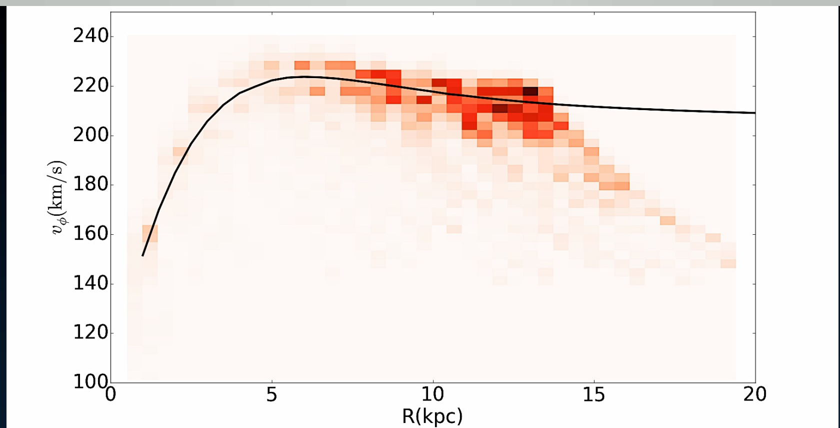


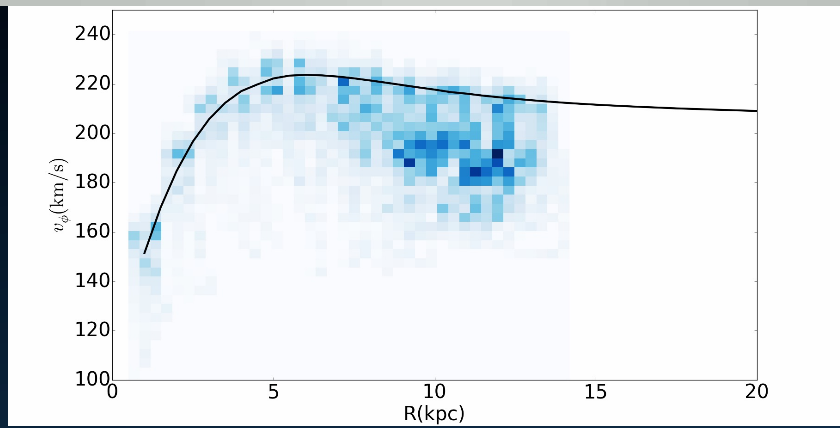
Corona rotates with a lag of ~ 75 km/s

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



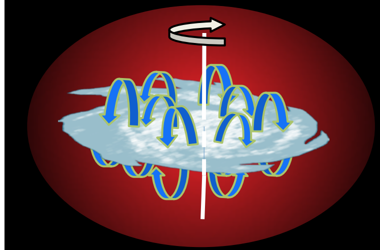




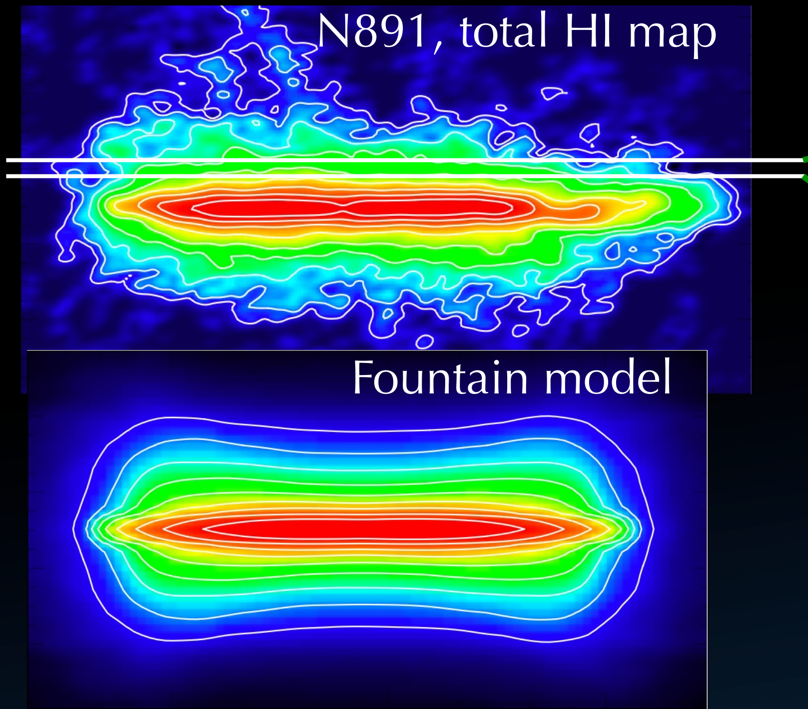


Rotation of the corona from (*Marinacci, Fraternali et al. 2011, MNRAS*)

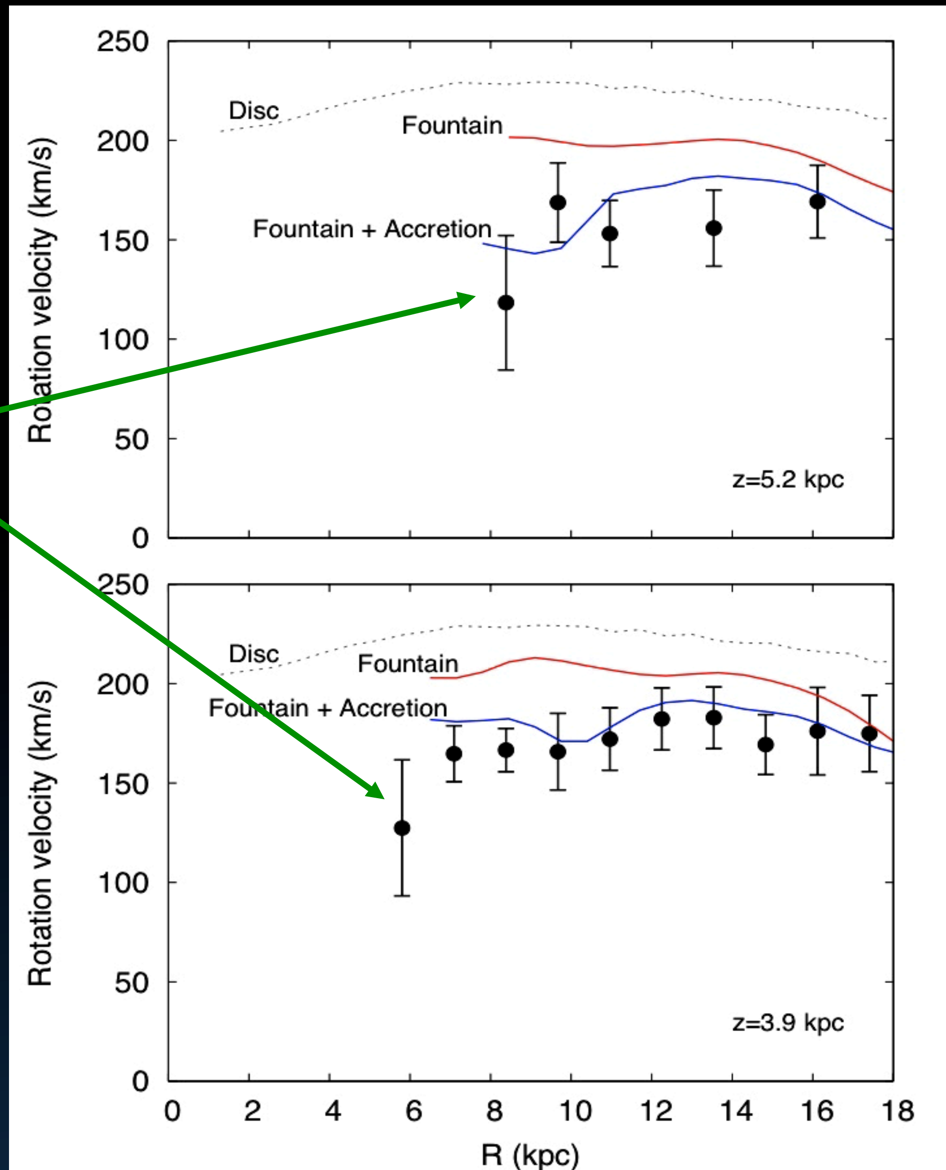
Data require fountain accretion



Kick velocities (v_k)
Accretion rate (dM/dt)



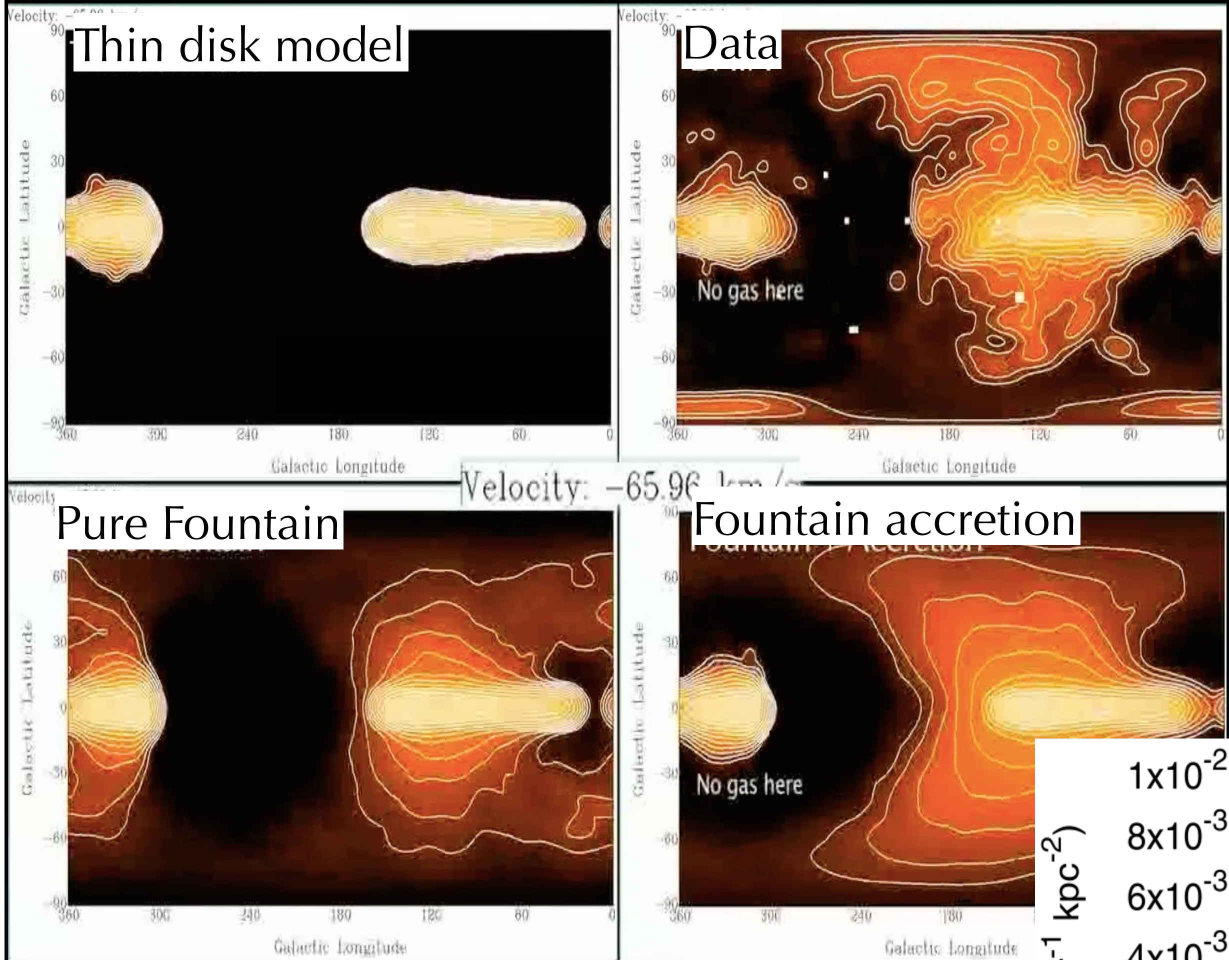
Best-fit v_k = 70-80 km/s
Best-fit Accretion Rate ~ 3 $M_\odot yr^{-1}$
Compare to SFR ~ 4 $M_\odot yr^{-1}$



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

Fraternali & Binney, 2008

HI emission in the Milky Way



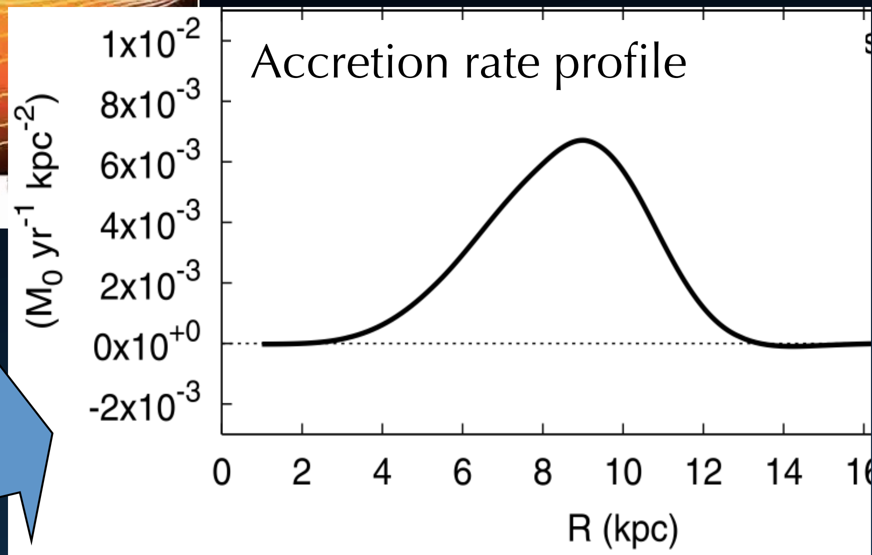
Marasco, Fraternali & Binney 2012, MNRAS

Movie in www.filippofraternali.com

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

Compatible with inside-out growth ($j_{acc} > j_{disc}$)

$j = R\, v_{rot}$

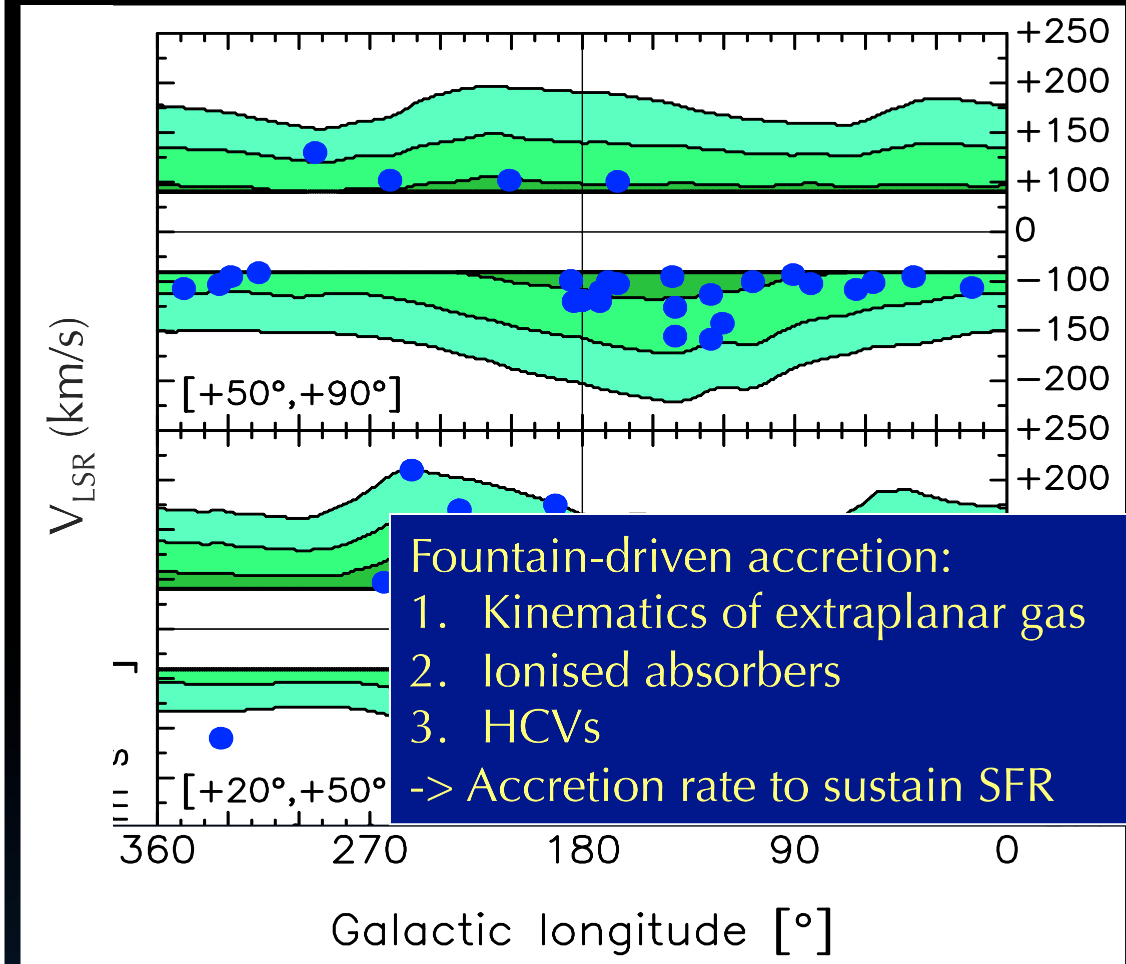


Best-fit Accretion Rate ~ 2 $M_{\odot} yr^{-1}$

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

Ionized gas around the MW

Marasco, Marinacci & Fraternali 2013, MNRAS

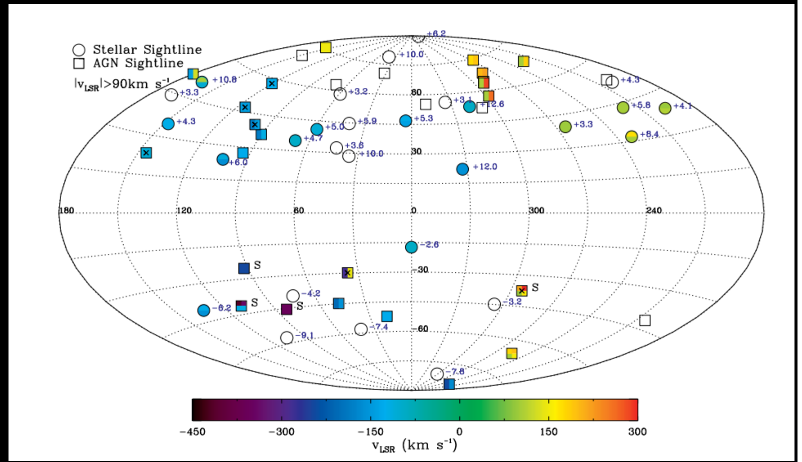


Fountain-driven accretion:

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

-> Accretion rate to sustain SFR

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



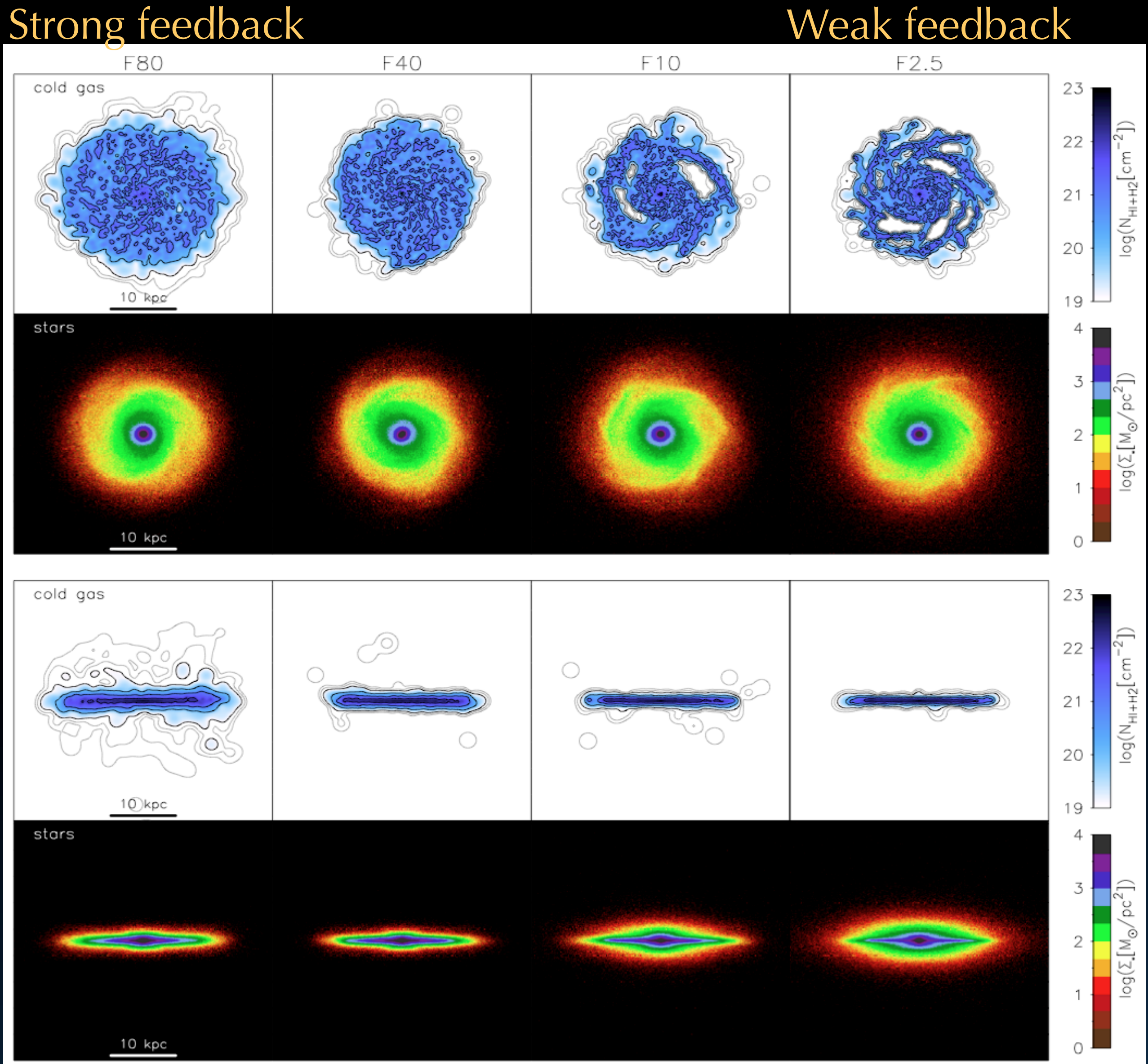
This model reproduces:

- 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

Cold (HI) fountain in simulations

Extraplanar HI in controlled simulations



Code GASOLINE

Milky Way-like

$M_{vir}=10^{12}\ M_{\odot}$

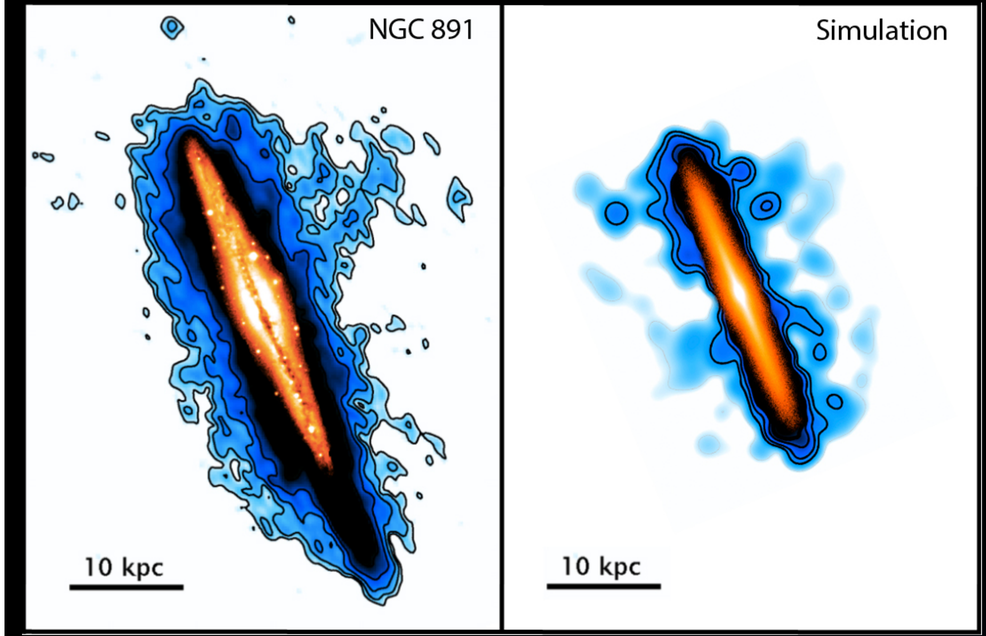
Lifetime = 10 Gyr

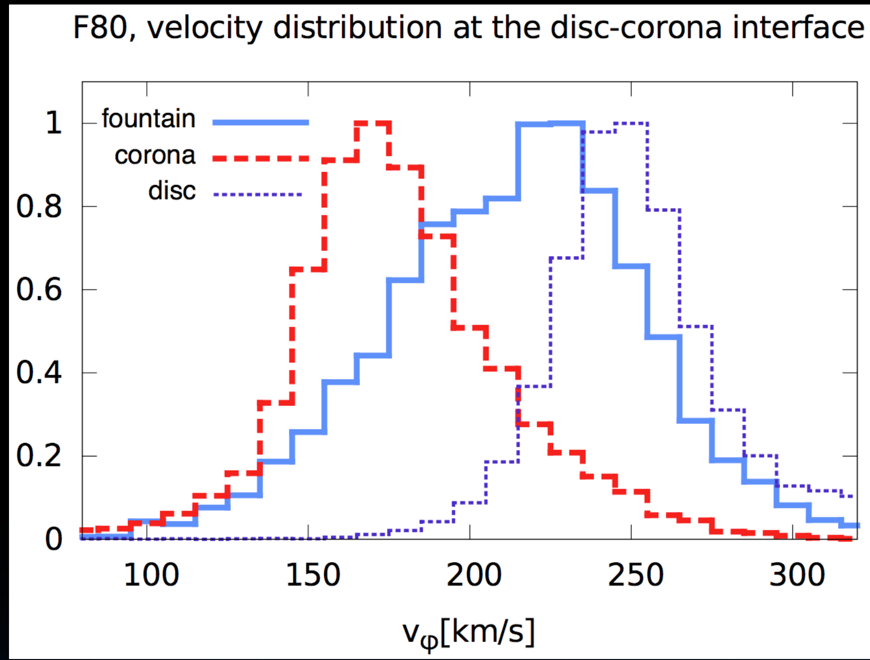
Different Feedback (*Stinson+ 06*) strength:

From 2.5 to 80 % of the total SN energy

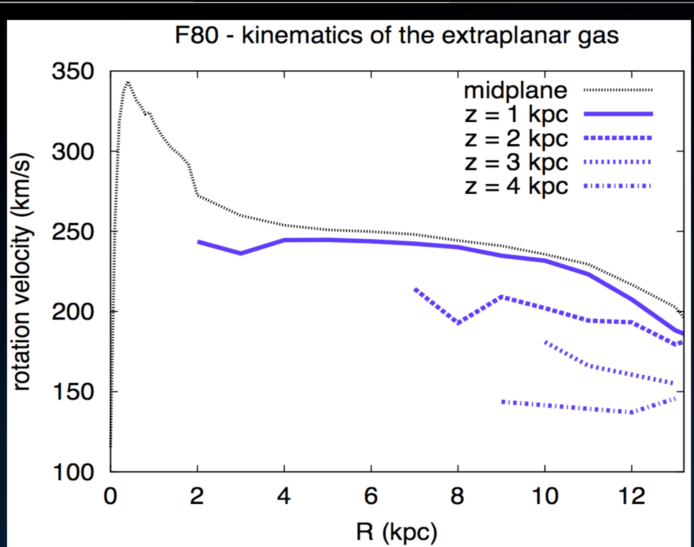
Marasco, Debattista, Fraternali, van der Hulst+ 2015, MNRAS

Extraplanar HI in controlled simulations

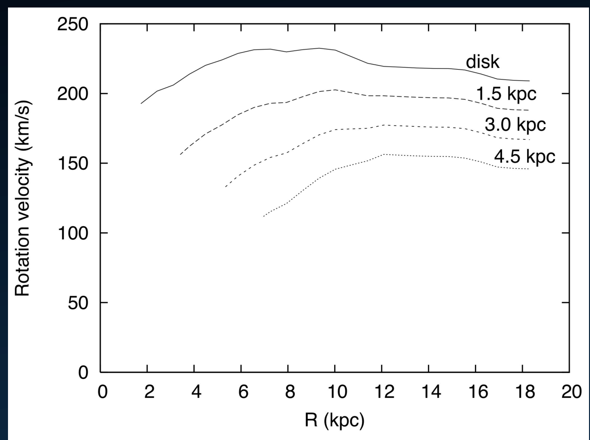




Gas at $1<|z|<4$ kpc



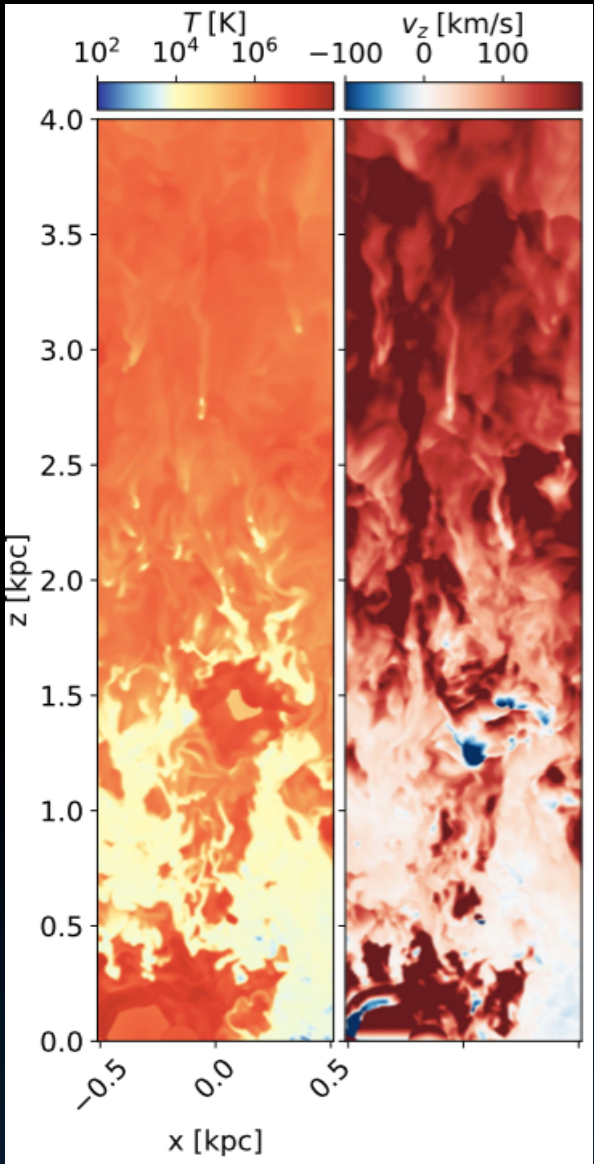
Marasco et al. 2015, MNRAS



Observed: N891

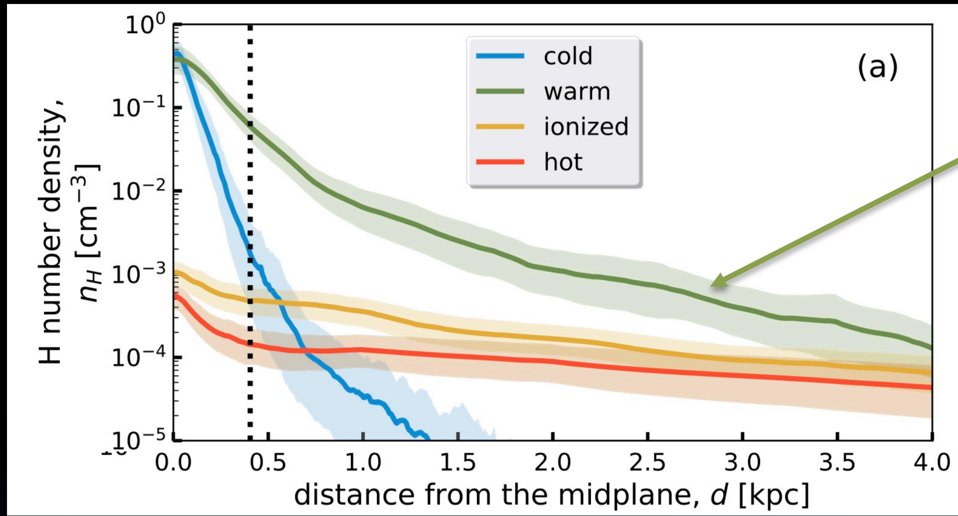
Oosterloo+ 2007

Simulations of portions of discs

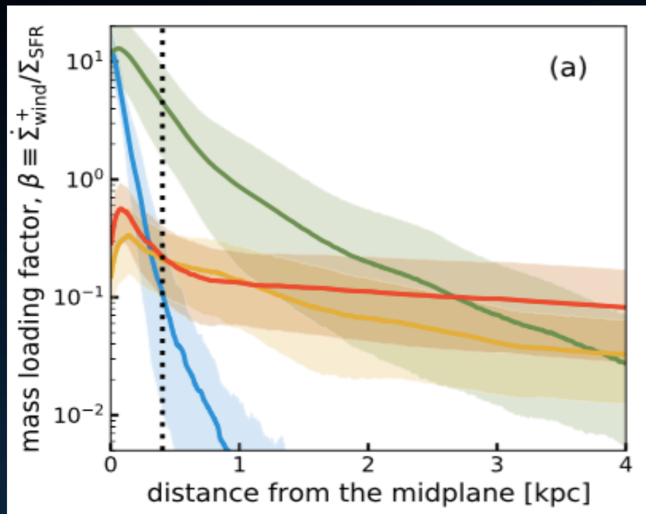


Kim & Ostriker 2018

Milky Way around Solar circle
TIGRESS very high resolution simulations
Athena code, fixed grid



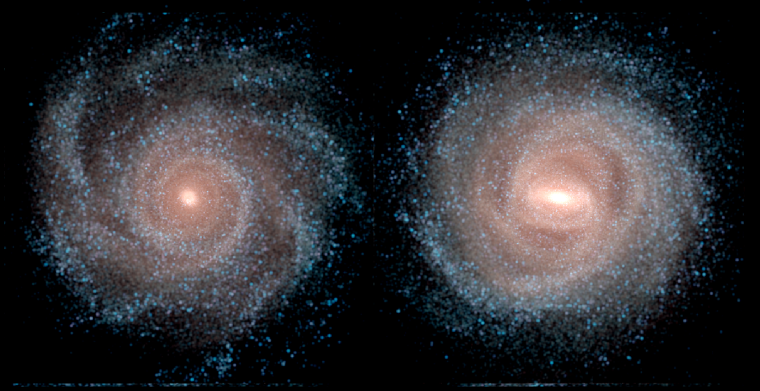
Warm gas dominated the density

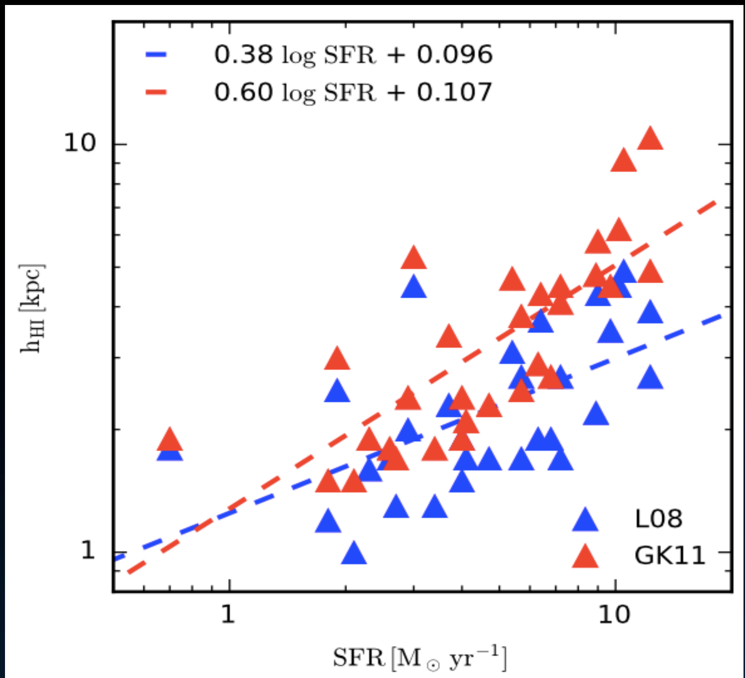


Most of the gas circulates at T~10^4 K (HI / Hα)

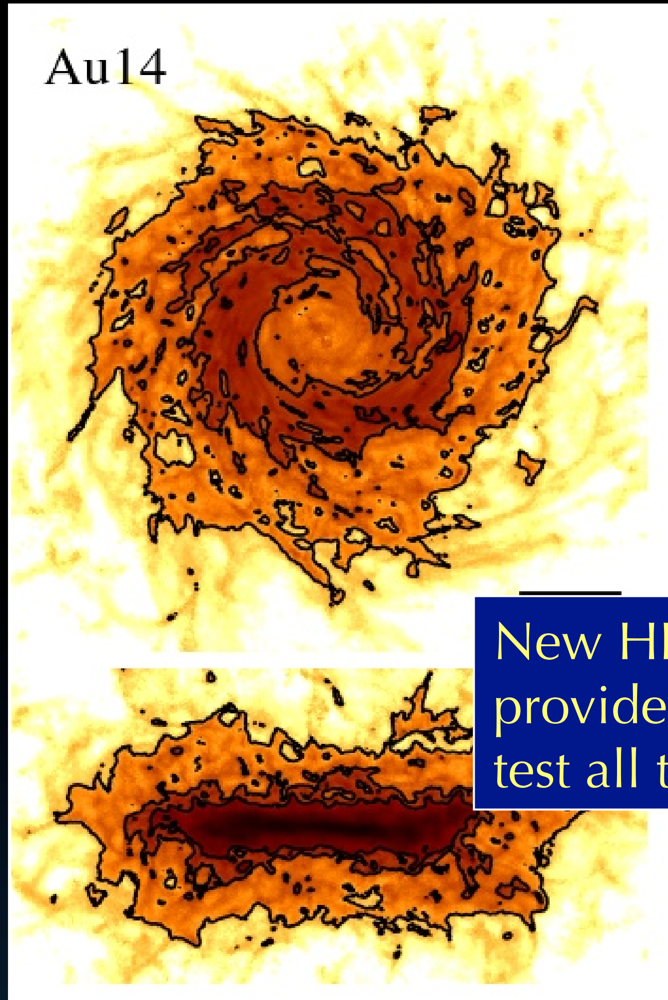
Hot gas reaches high velocities but at very low mass outflows

Extraplanar HI in Auriga simulations





Marinacci, Grand et al. 2017



Zoom-in cosmological simulations with AREPO

Significant mass of extraplanar HI

New HI surveys will provide new data to test all these models!

Influence of the galactic fountain on accretion and angular momentum
Grand et al., in prep

Summary

1) Gas accretion
   Cosmological gas accretion and accretion in the disc not trivially linked
   High angular momentum of the accreting gas

2) Stellar Feedback
   Needed: strong for dwarfs and at high-z
   Very different implementations but similar results

3) Galactic fountain
   Circulates a large mass & triggers the condensation of lower corona
   First indication of HI fountain in simulations