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## The impact of galactic fountains on the global evolution of galaxy disks

Fraternali, F.; Binney, J.; Marasco, A.; Marinacci, F.

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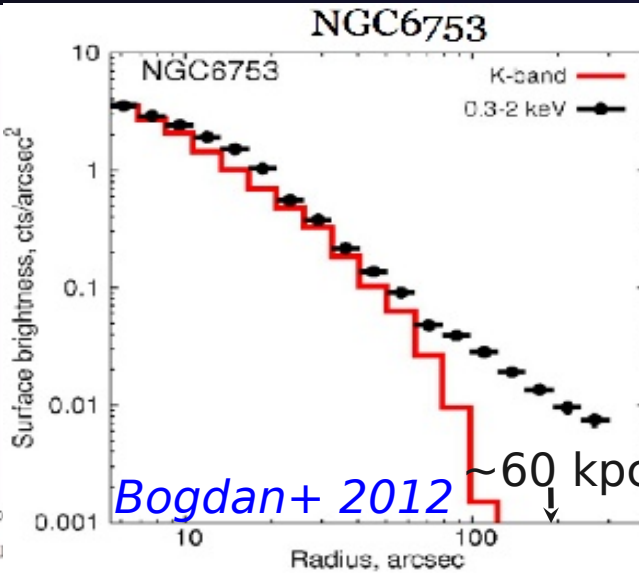
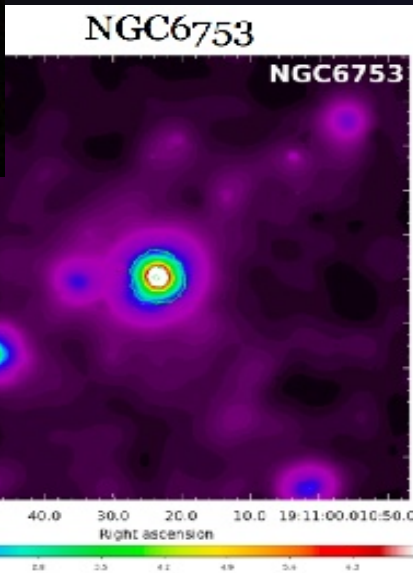
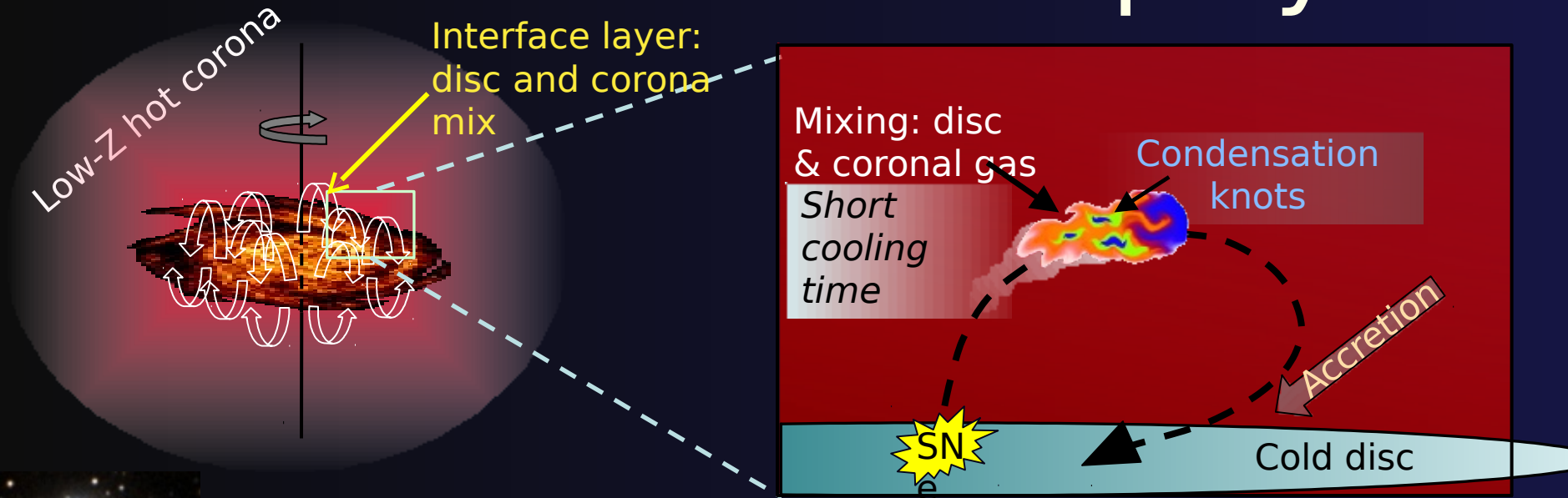
# The impact of galactic fountain on disc evolution

Filippo Fraternali

Department of Physics and Astronomy, University of Bologna, I  
Kapteyn Astronomical Institute, University of Groningen, NL

L. Armillotta (Bologna), J. Binney (Oxford), A. Marasco (Groningen), F.  
Marinacci (MIT)

# Disc-corona interplay



Anderson & Bregman

2012

Dai+ 2012, Anderson+

2013

MW Miller & Bregman+

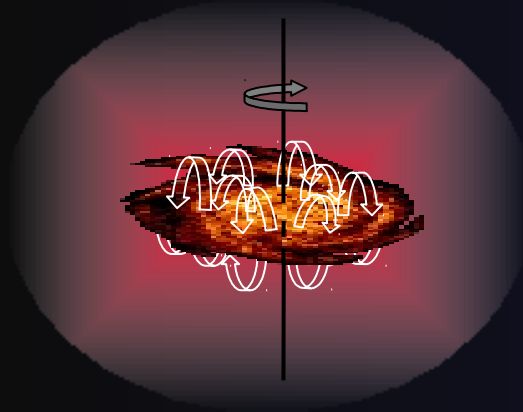
2013, 2015; Gatto+13

Mass corona  
~ 10-50% missing  
baryons

Cooling rate ~ 0.1 Mo/yr

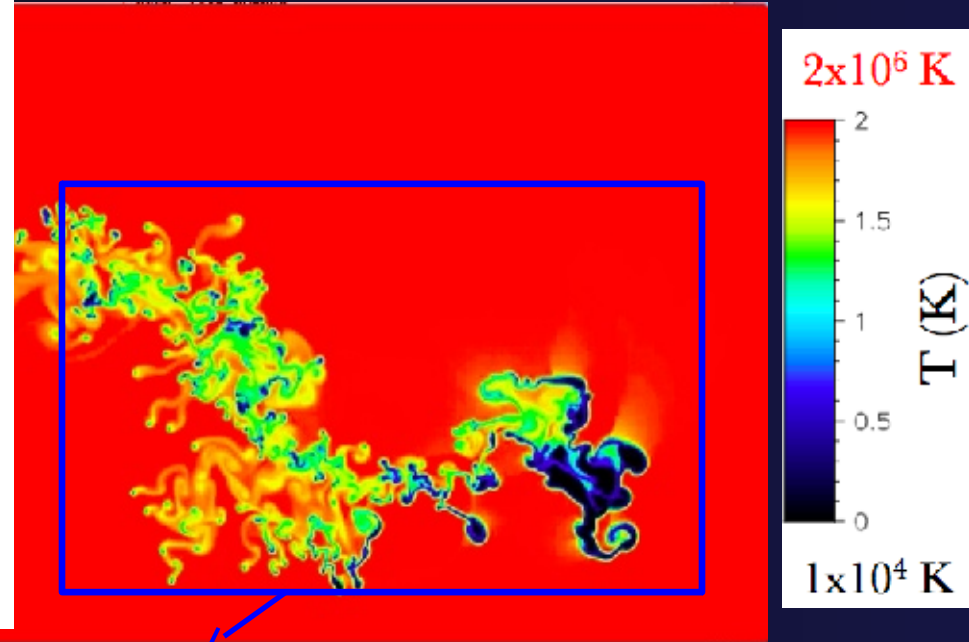
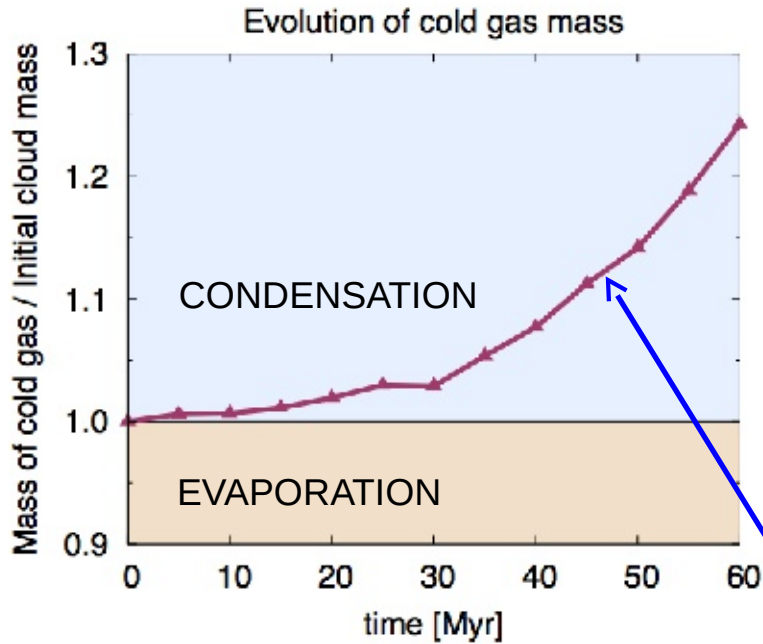
# Global process: Fountain-driven gas accretion

# Disc-cloud corona interaction



$T_{\text{corona}} = 2 \times 10^6 \text{ K}$   $Z_{\text{corona}} = 0.1 Z_{\odot}$

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

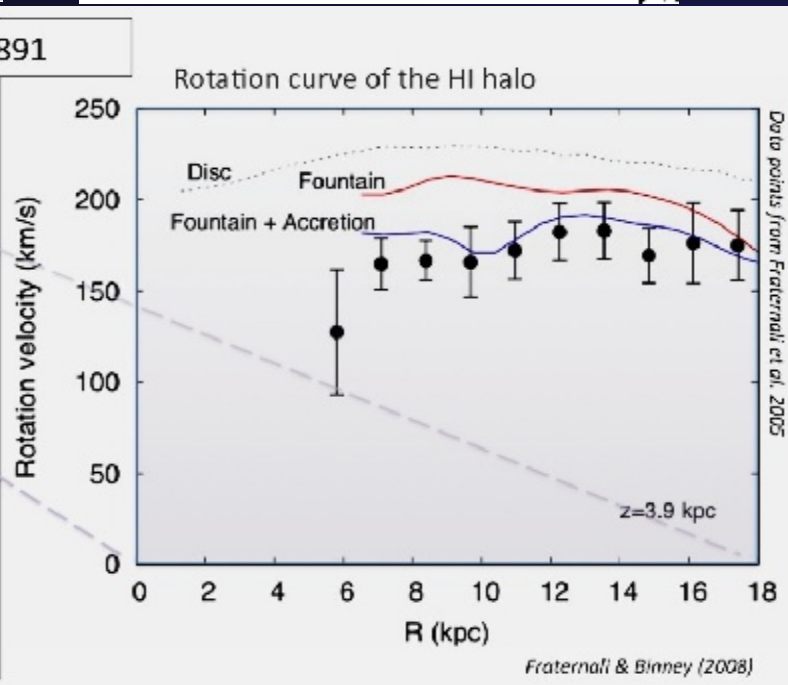
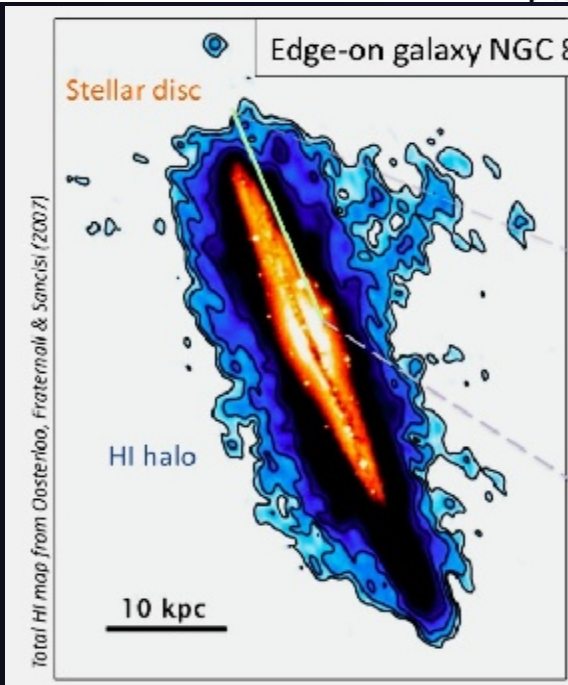
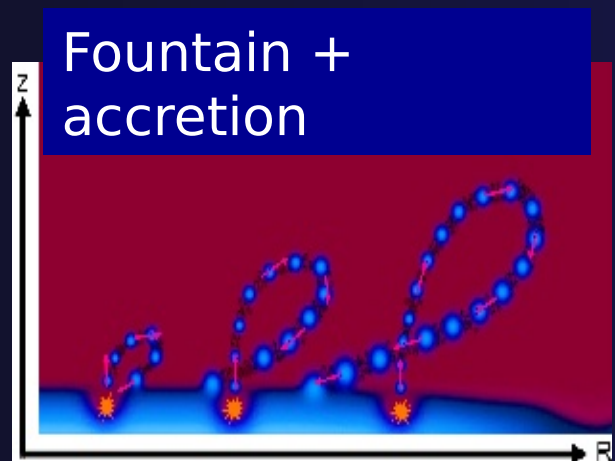
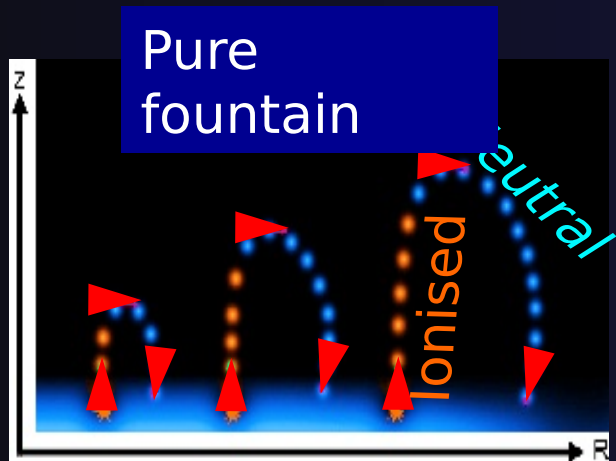
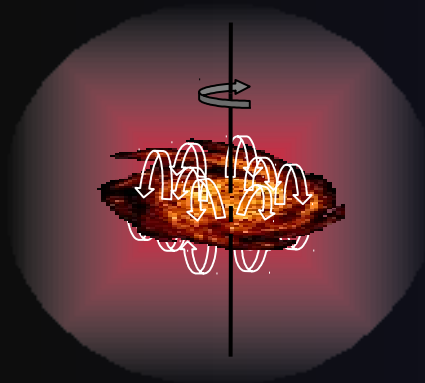


Mass of cold gas increased by ~20%!

1.0                      3.0  
X (kpc)

Marinacci, et al. 2010, 2011, MNRAS Lucia Armillotta

# Global fountain

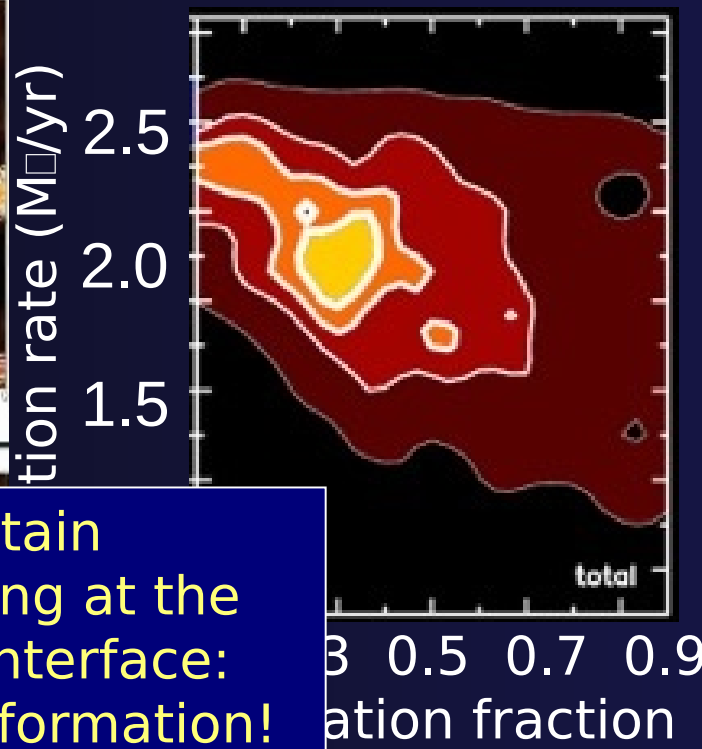
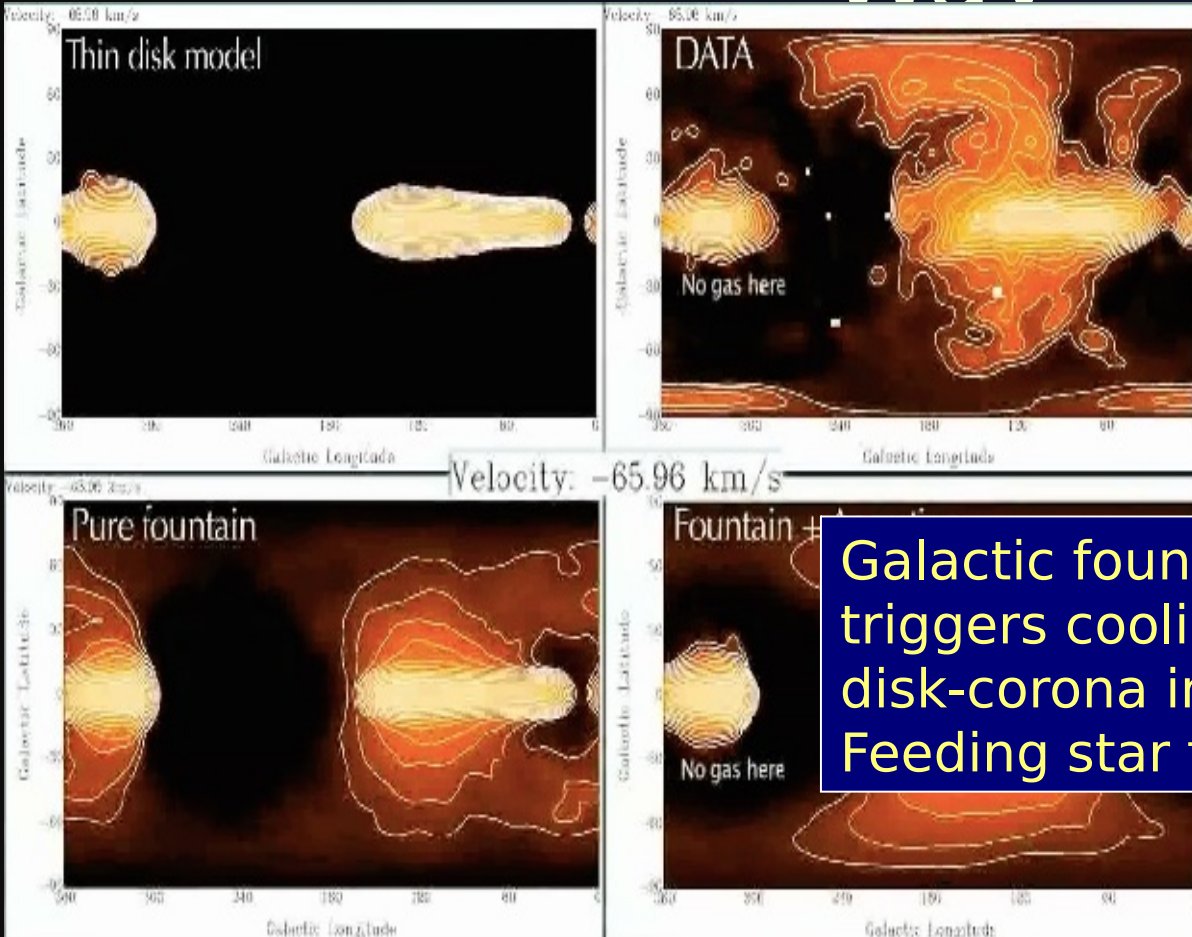


Best-fit Accretion Rate  $\sim 3 M_{\odot} \text{yr}^{-1}$

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

*Fraternali & Binney 2008, MNRAS; Marinacci, Fraternali+ 2011, MNRAS*

# Extrapolation in the Milky Way



Galactic fountain triggers cooling at the disk-corona interface: Feeding star formation!

Marasco, Fraternali & Binney 2012, MNRAS Best-fit Accretion Rate  $\sim 2 M_{\odot} \text{yr}^{-1}$   
 Compare to SFR  $\sim 1-3 M_{\odot} \text{yr}^{-1}$

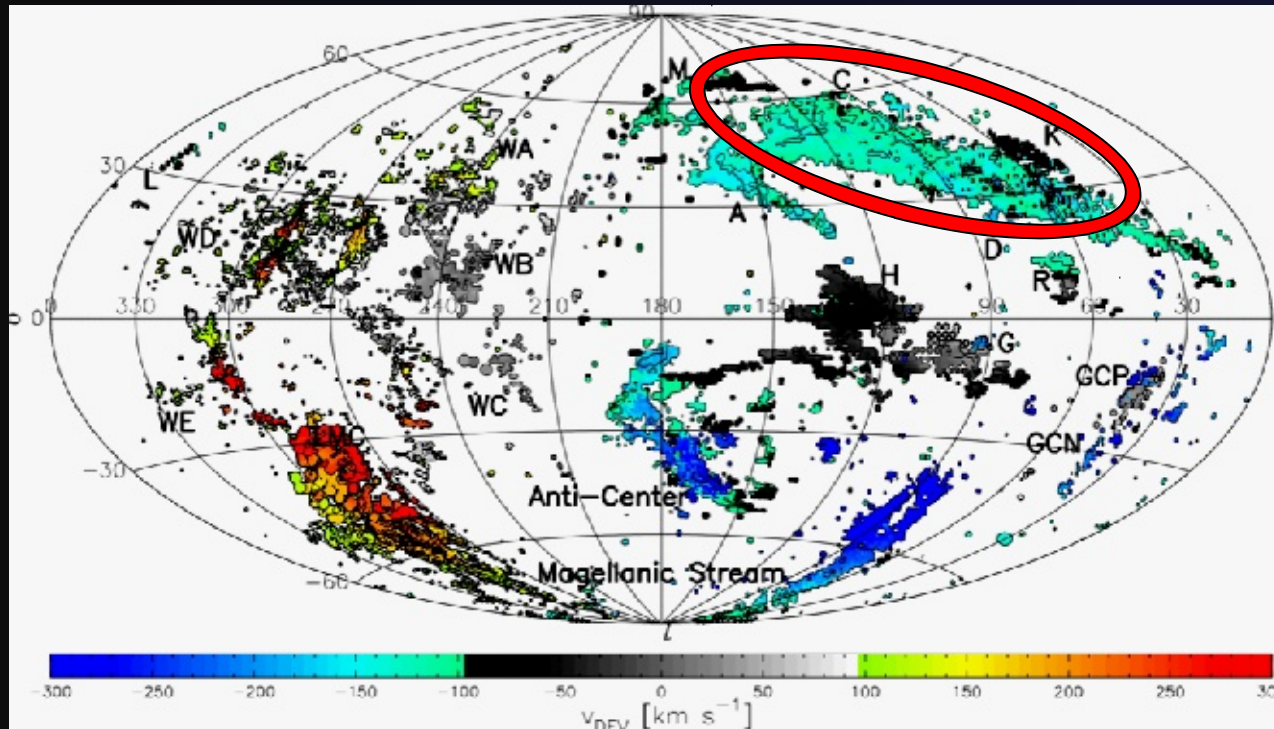
Local process:

Galactic hail: origin of the  
High Velocity Cloud  
complex C





# Origin of HVCs



**Oort 70** leftover of galaxy formation  
**Bregman 80** Galactic fountain  
 + satellites (*Olano 2001*), thermal instabilities  
 (*Kaufmann+ 06*), no thermal instabilities (*Binney+ 09*),  
 filaments (*Fernandez+ 12*)

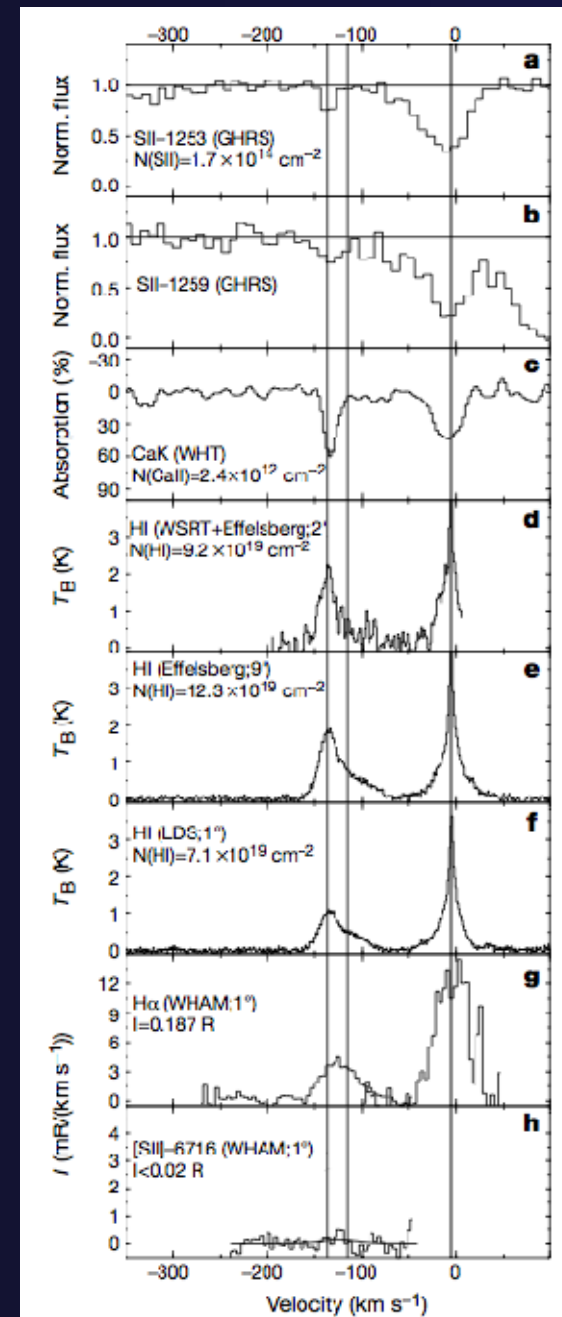
**Wakker+ 1999, Nat**  $Z \sim 0.1$  Solar  $\rightarrow$  Accretion!

**Gibson+ 2001**  $Z \sim 0.3$  Accretion?

**Collins+ 2007** overabundance  $\alpha$  elements

(SN II?)

Filippo Fraternali (Bologna/Groningen)

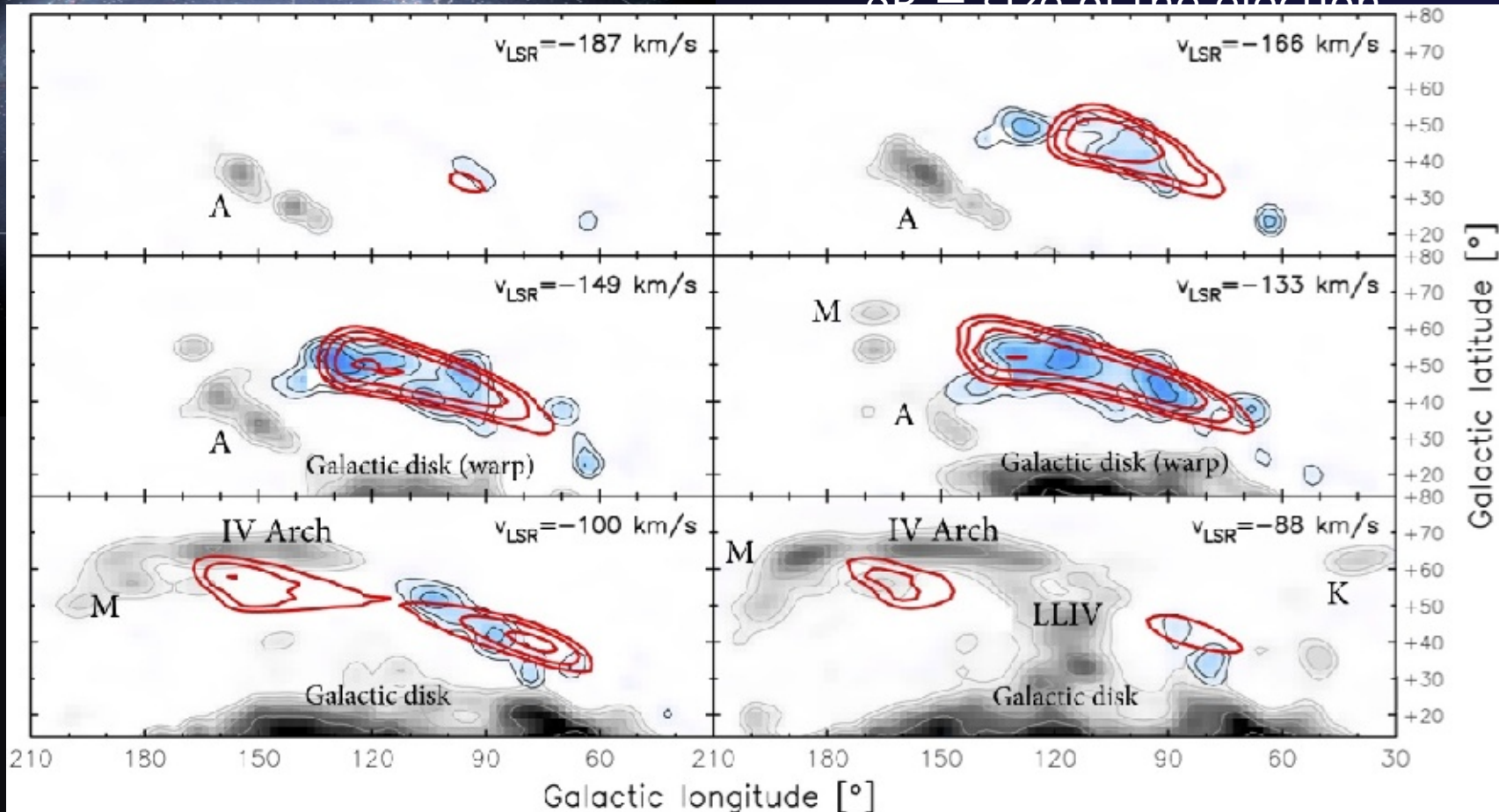


Interplay local & global processes in galaxies - Cozumel, Mexico - 14/4/16

# Formation of complex C

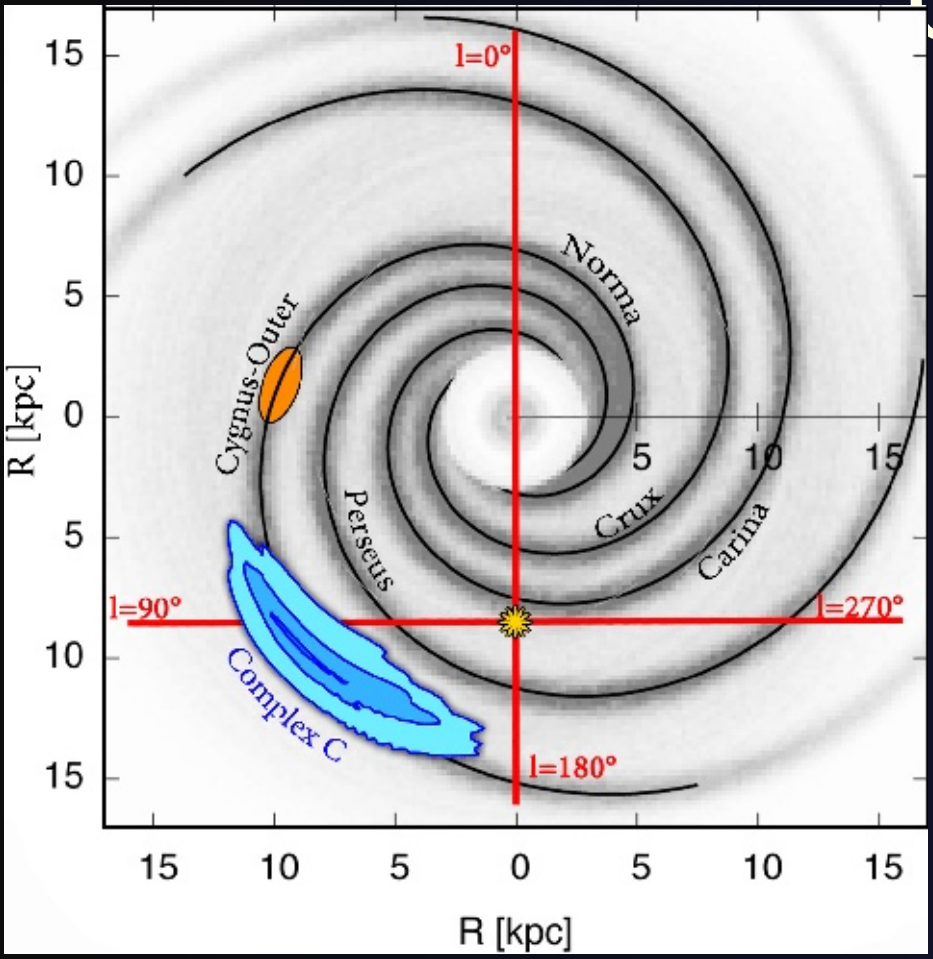


Six free parameters:  
 $V_0$  = ejection velocity  
 $R_0$  = ejection location  
 $\delta R$  = size of the ejection

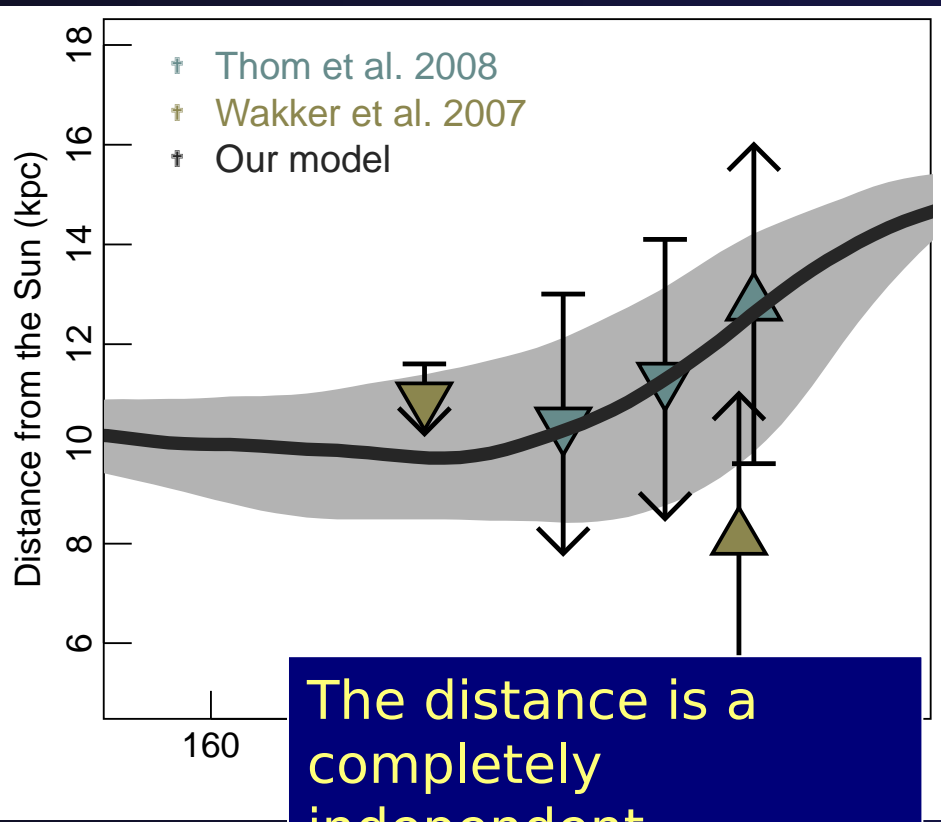


Fraternali, Marasco, Armillotta, & Marinacci 2015, MNRAS Letter, 447, 70

# Origin & Location of Complex



## Distance from the Sun

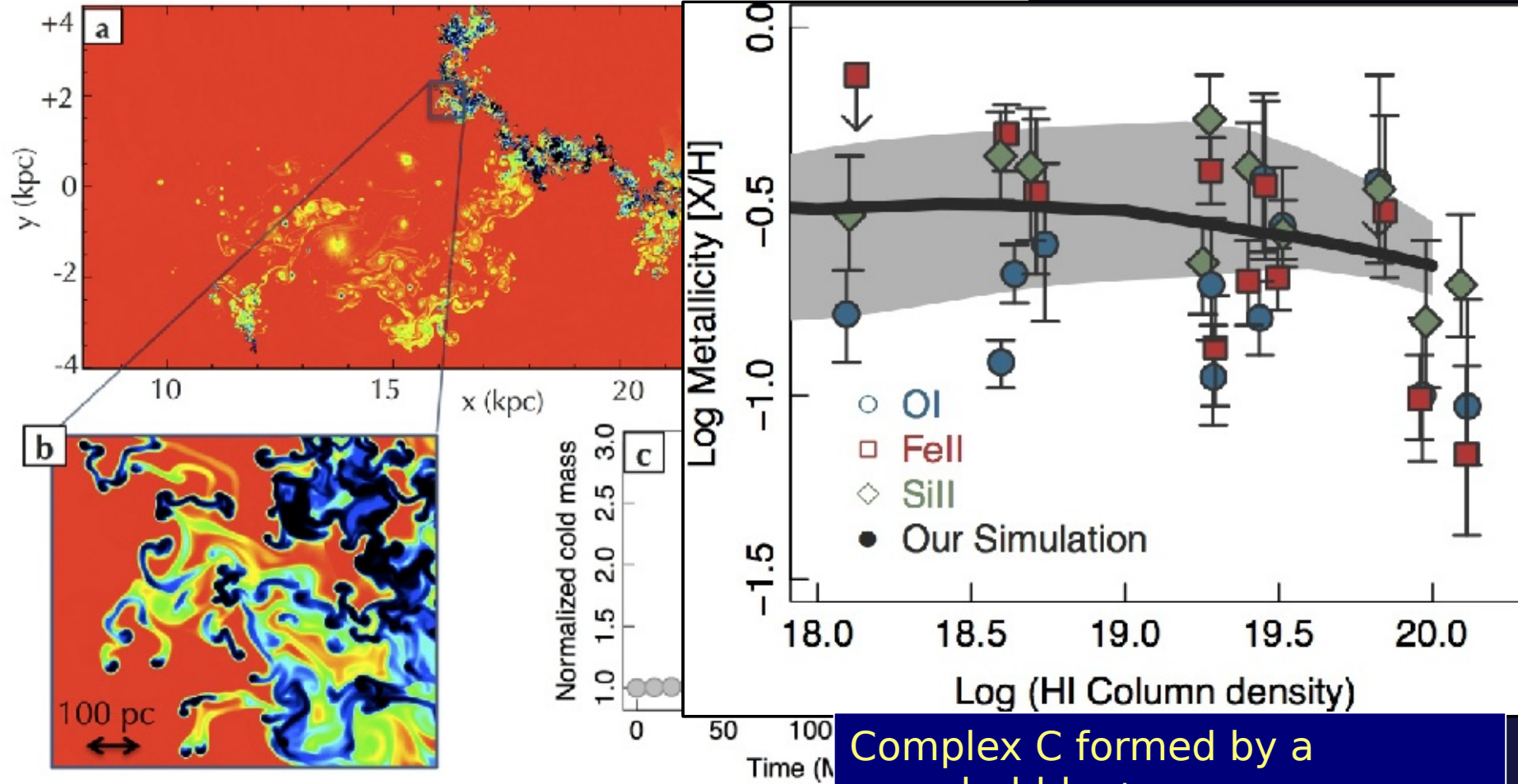


The distance is a completely independent confirmation

	$v_0$	$R_0$	$\delta_{\text{arm}}$	$t_0$	$\Delta t$	$t_{\text{dc}}$	(seed)	(final)
	[ $\text{km s}^{-1}$ ]	[kpc]	[kpc]	[Myr]	[Myr]	[Myr]	[ $10^6 M_\odot$ ]	[ $10^5 M_\odot$ ]
Best-fit	211	9.5	2.9	150	53	46	3.4	6.8

$E_{\text{kin}} \sim 2 \times 10^{54} \text{ erg}$

# Hydrodynamical simulations



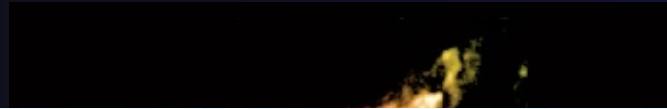
Average metallicity at the end: **0.27 Solar**  
 Compared to complex C: **0.1-0.3 Solar**

Complex C formed by a superbubble + corona condensation

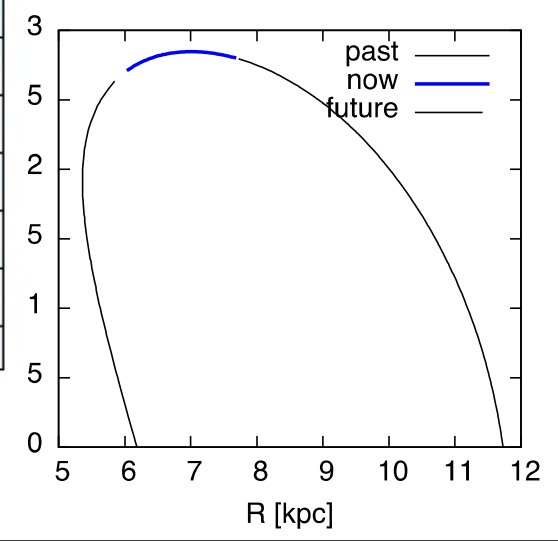
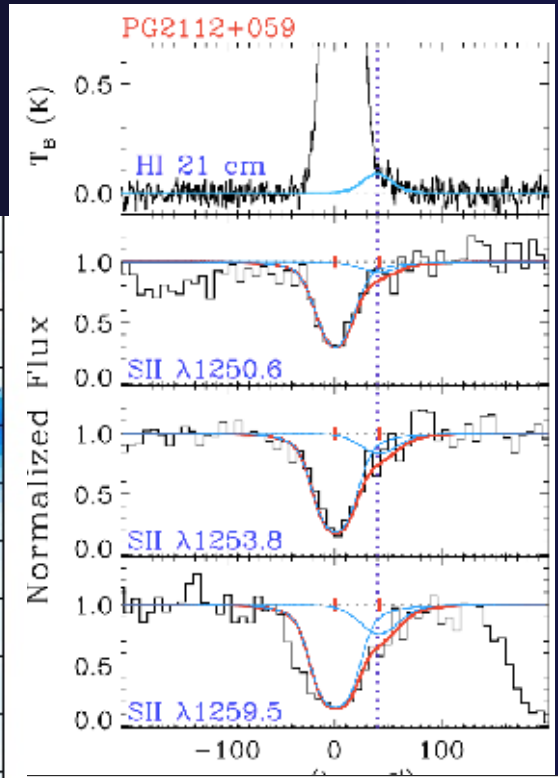
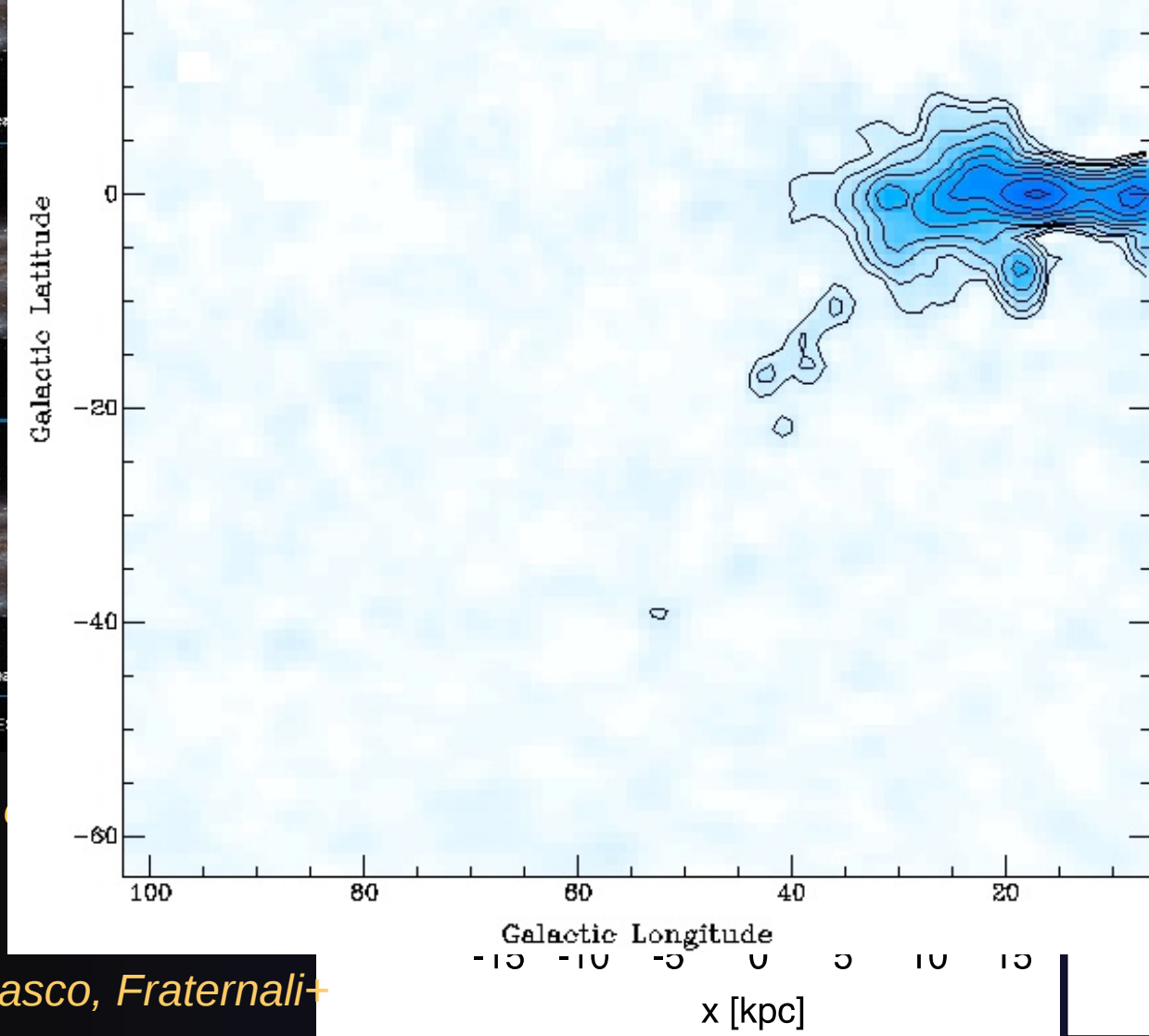
*Local* manifestation of fountain-driven accretion

# Trajectory of Smith Cloud

# Smith cloud



70 Million Year  
Today  
30 Million Year  
NASA and ESO

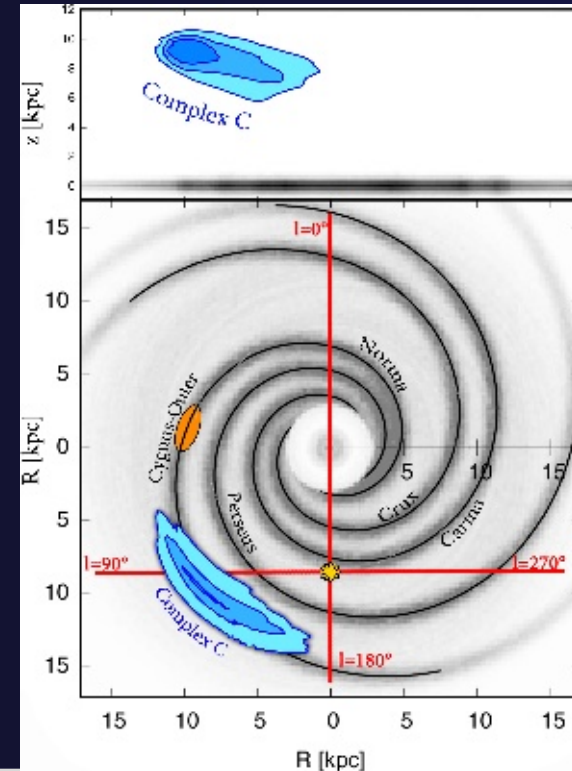
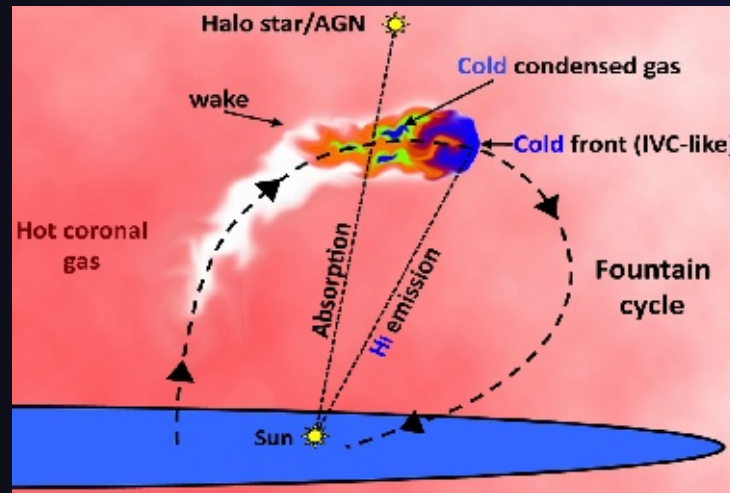
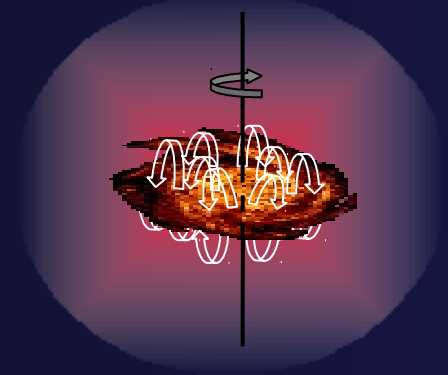


Fox

Marasco, Fraternali+

# Conclusions

- Galactic fountain can cool the corona and feed the star formation in disc galaxies like the MW
- Local features like HVCs can form (condense) out of this non-linear perturbation of the corona
- Very good fit for the prototypical complex C, promising results for Smith cloud



# CROSSING THE RUBICON

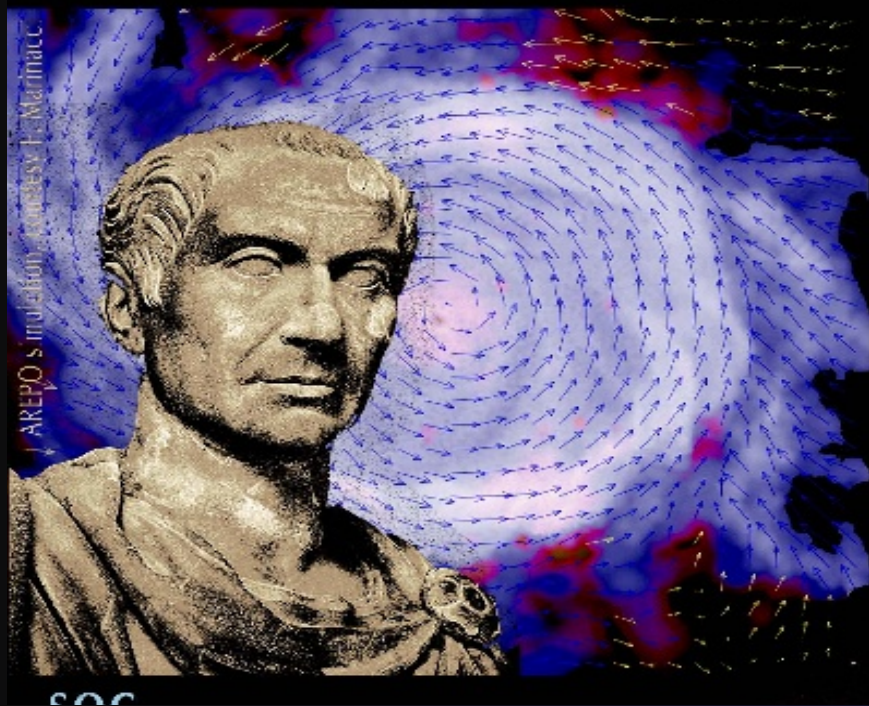
The fate of gas flows in galaxies



<https://sites.google.com/site/rubiconf2016>

Santarcangelo di Romagna, Italy

5-9 September, 2016



## INVITED SPEAKERS

Manda Banerji (IoA, UK)

Joel Bregman (Michigan Univ., USA)

Natascha Förster-Schreiber (MPE, Germany)

Joe Hennawi (MPIA, Germany)

Andrew King (Leicester Univ., UK)

Simon Lilly (ETH, CH)

Federico Marinacci (MIT, USA)

Raffaella Morganti (ASTRON, NL)

Kate Rubin (CfA, USA)

Jorge Sanchez-Almeida (IAC, Spain)

Joop Schaye (Leiden Obser., NL)

Francesco Tombesi (Goddard SFC, USA)

Sylvain Veilleux (Maryland Univ., USA)

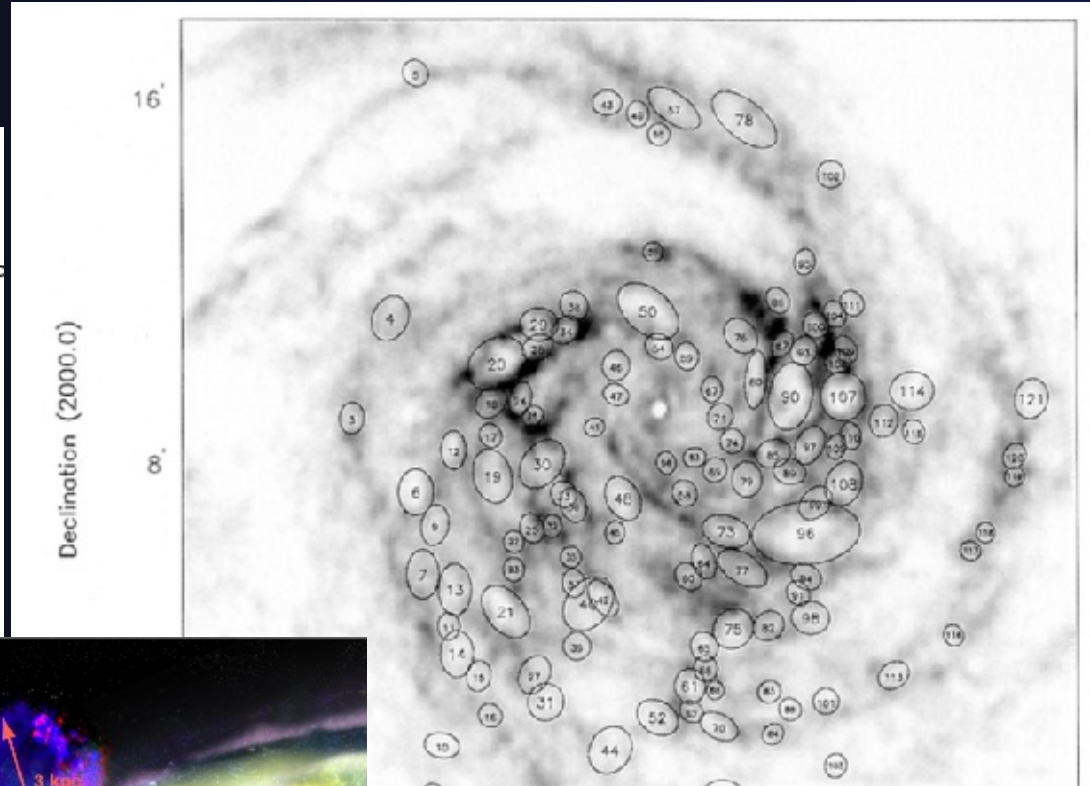
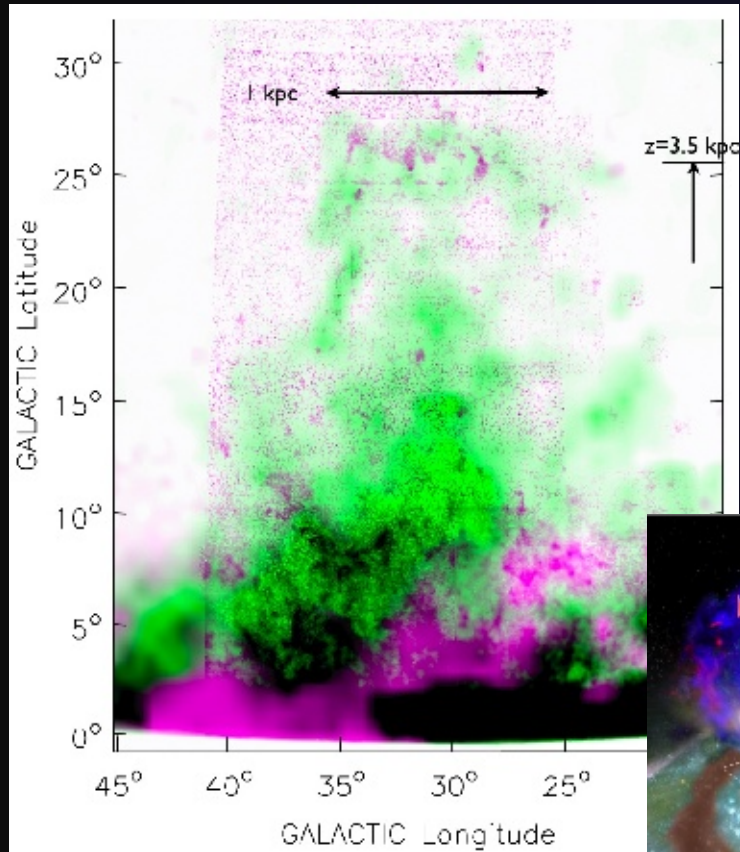
Jessica Werk (UC S. Cruz, USA)

# Thanks



# Ophiucus superbubble

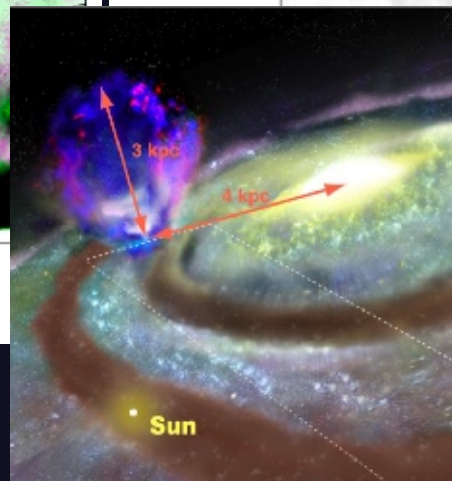
Purple HI  
Green H $\alpha$



Energy to produce the holes:  
 $E \sim 1 \times 10^{53} - 1 \times 10^{55}$  erg

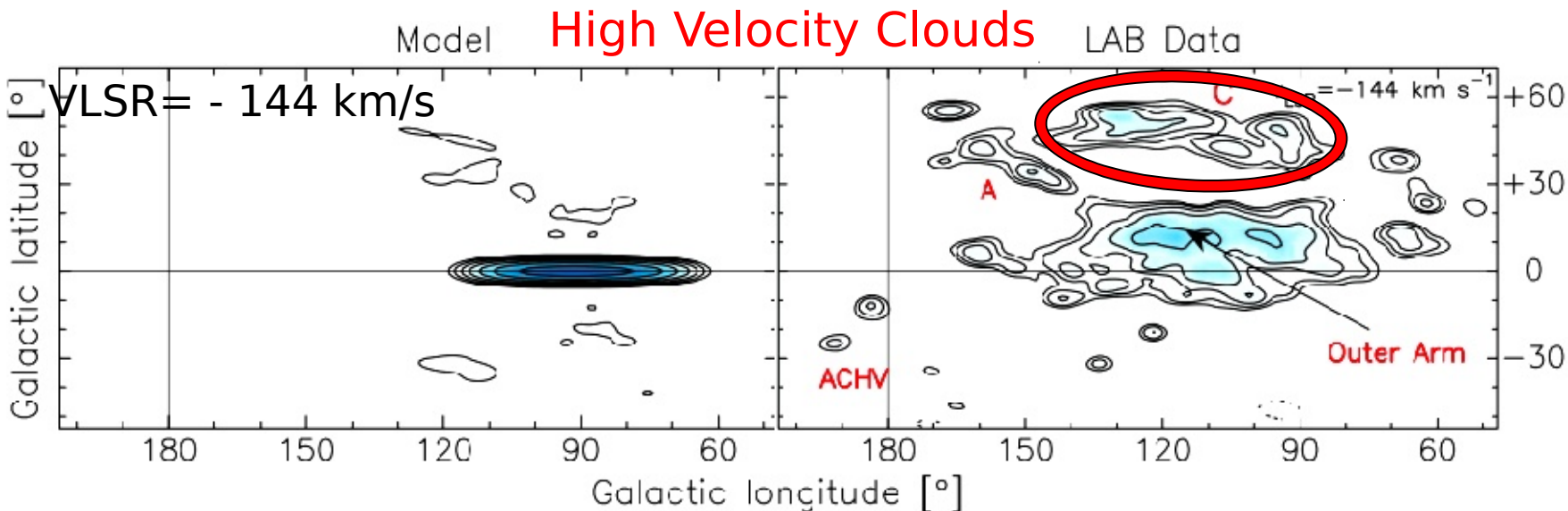
35<sup>m</sup> 20<sup>h</sup>34<sup>m</sup>10<sup>s</sup>  
Right Ascension (2000.0)

Boomsma et al. 2008,  
A&A

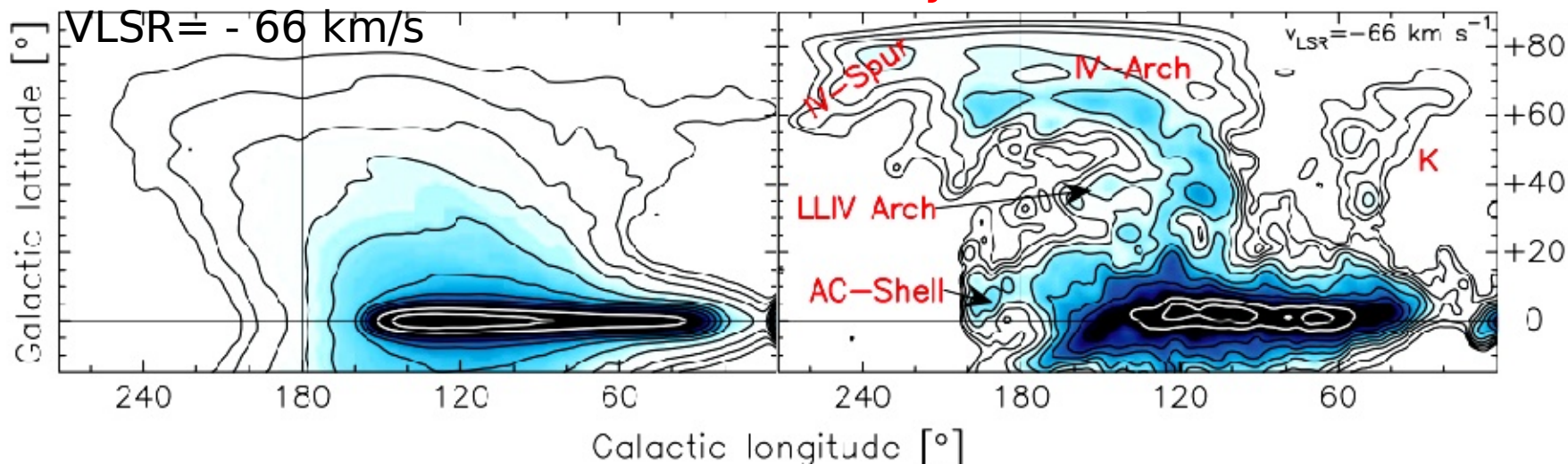


Pidopryhora et al. 2007,  
Apj

# Our galactic fountain model



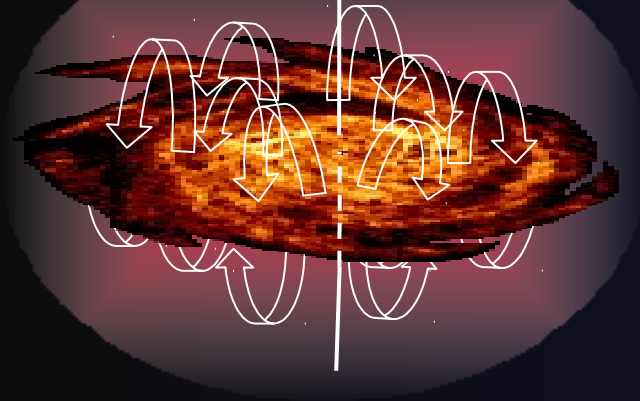
## Intermediate Velocity Clouds



Marasco, Fraternali & Binney 2012,

MNRAS

# Effect of spiral arms



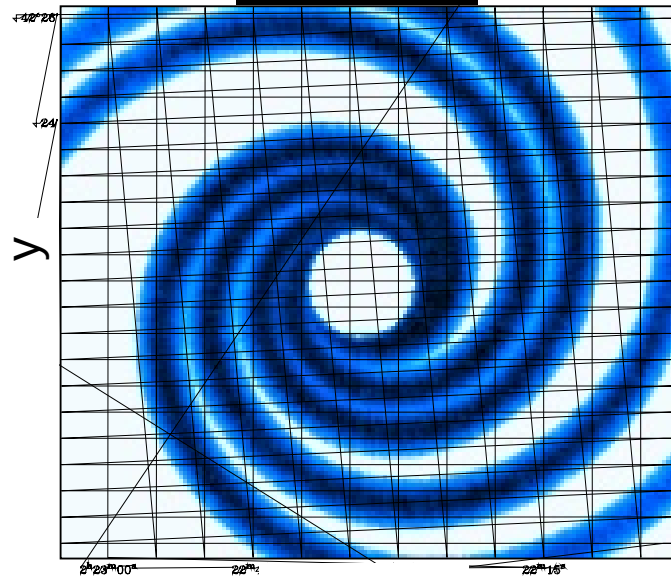
Two limitations of our model:

1. *Axisimmetry*
2. *Average ejection velocities*

→ We introduced spiral arms

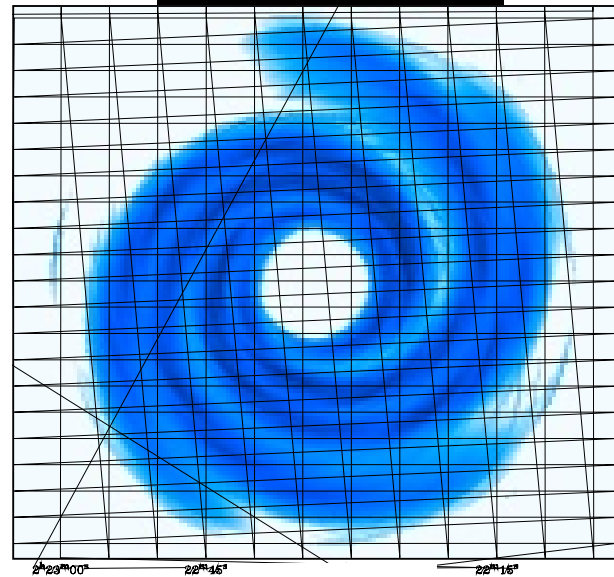


Disk gas



X

Fountain gas

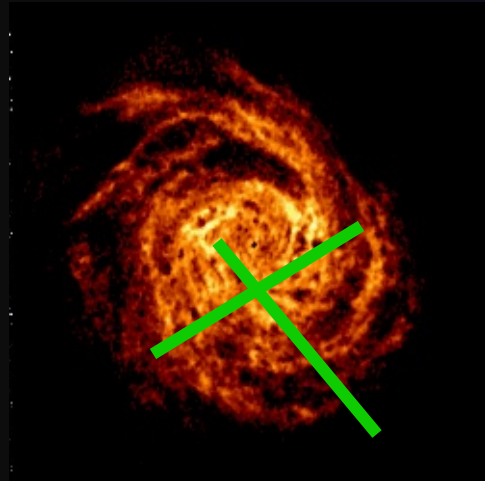


X

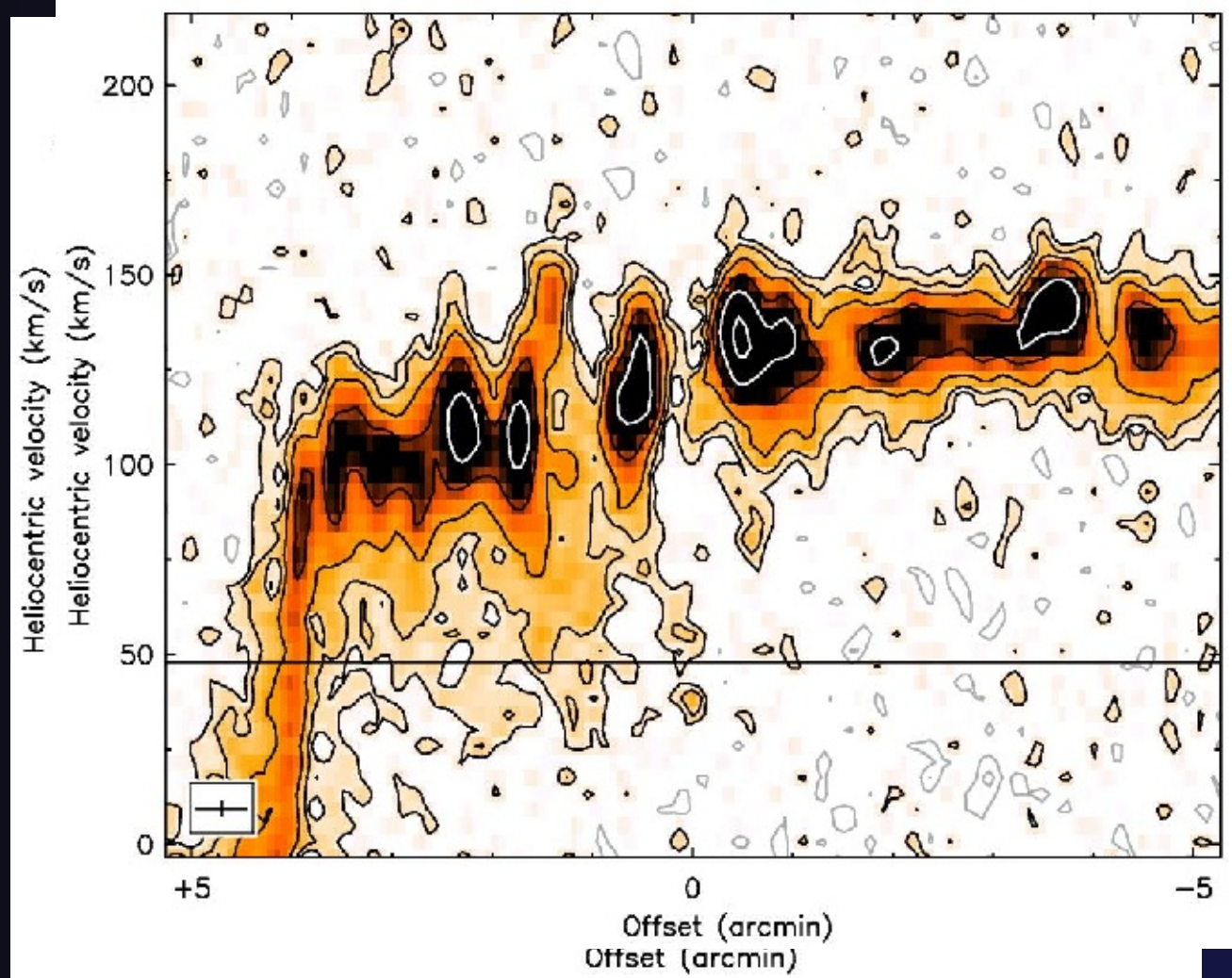
Global model unchanged!

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

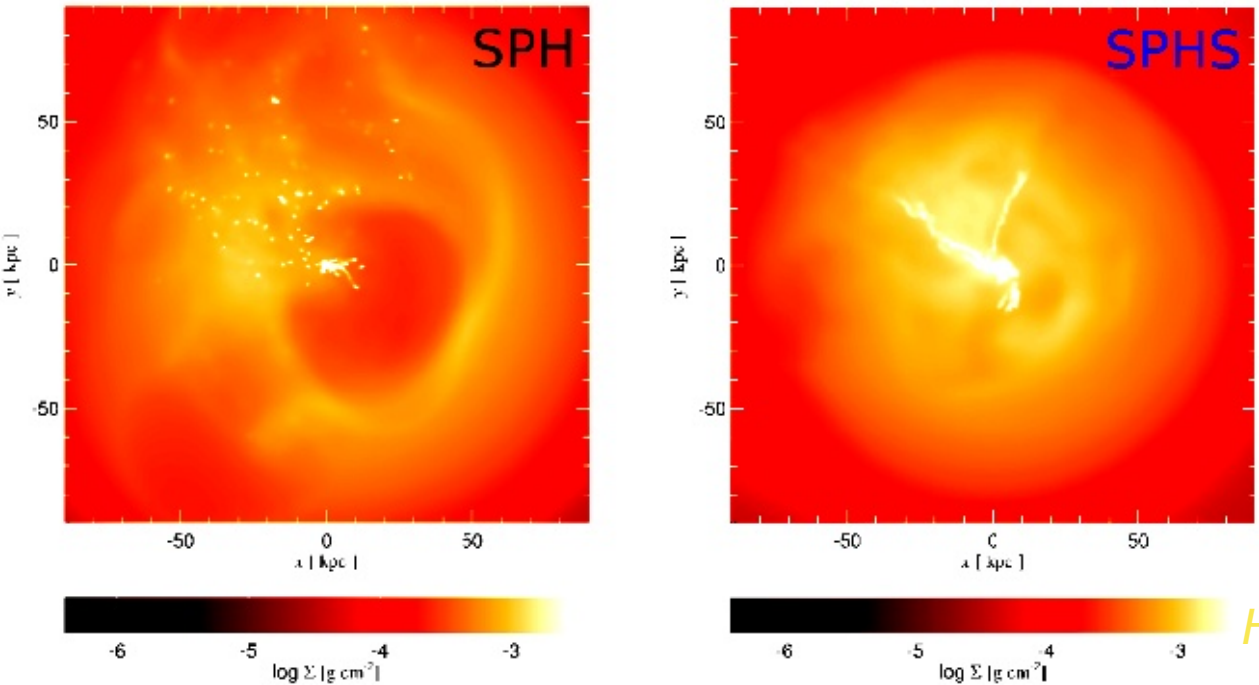
# NGC 6946



*Boomsma et al. 2007*



# SN-driven accretion in other sims



Modified SPH

No formation of clumps

*“Cold gas condenses from the halo at the intersection of supernovae-driven bubbles. This positive feedback feeds cold gas to the galactic disc*

*Hobbs et al. 2013, MNRAS*

MaGICC - GASOLINE

Halos enriched by galactic fountain

Gas in the fountain cycle comes back to the disk **more metal poor!**

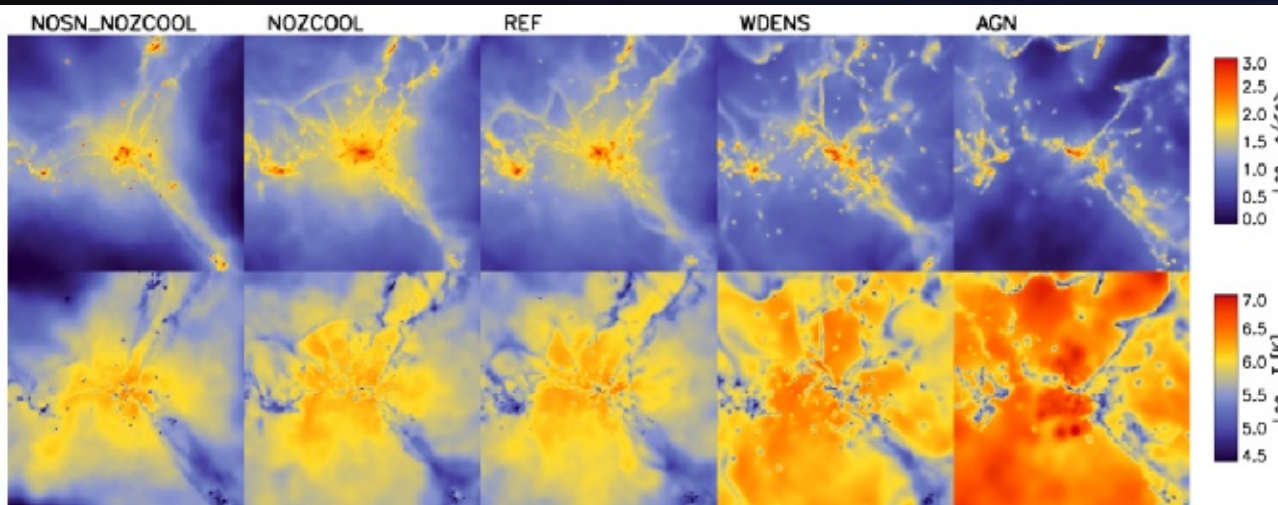
*Brook+12, Brook+13*



# Impact of galactic fountain on disc evolution

1. Corona-disc interface
2. **Global process**: supernova-driven accretion
3. **Local process**: formation of condensed clouds
  - Origin of the high-velocity cloud complex C

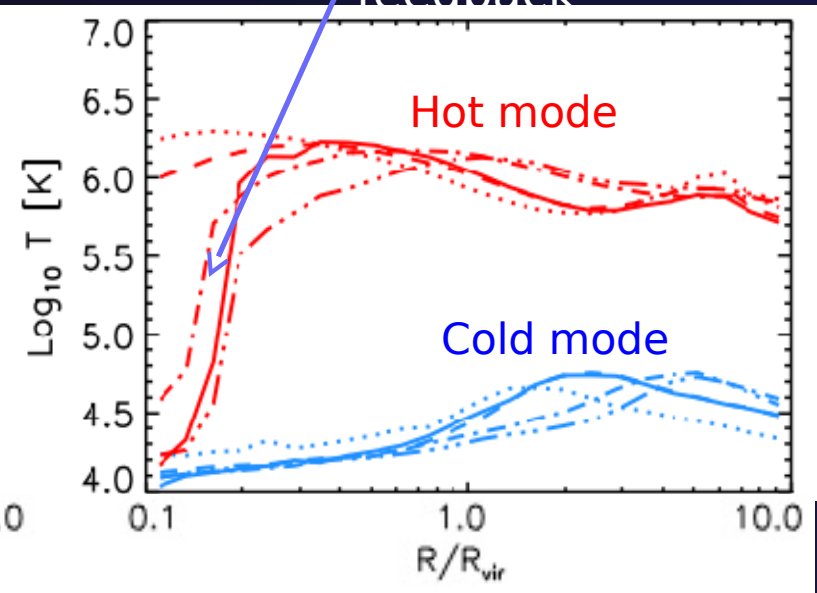
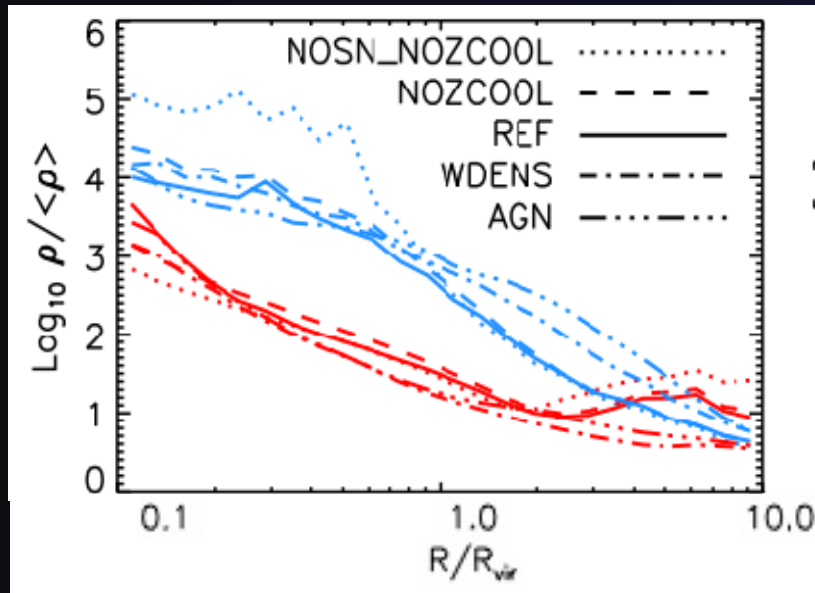
# Positive feedback is there



$z=2$

Cooling induced close to galaxies by metals ejected by feedback

OWLS  
GADGET-3

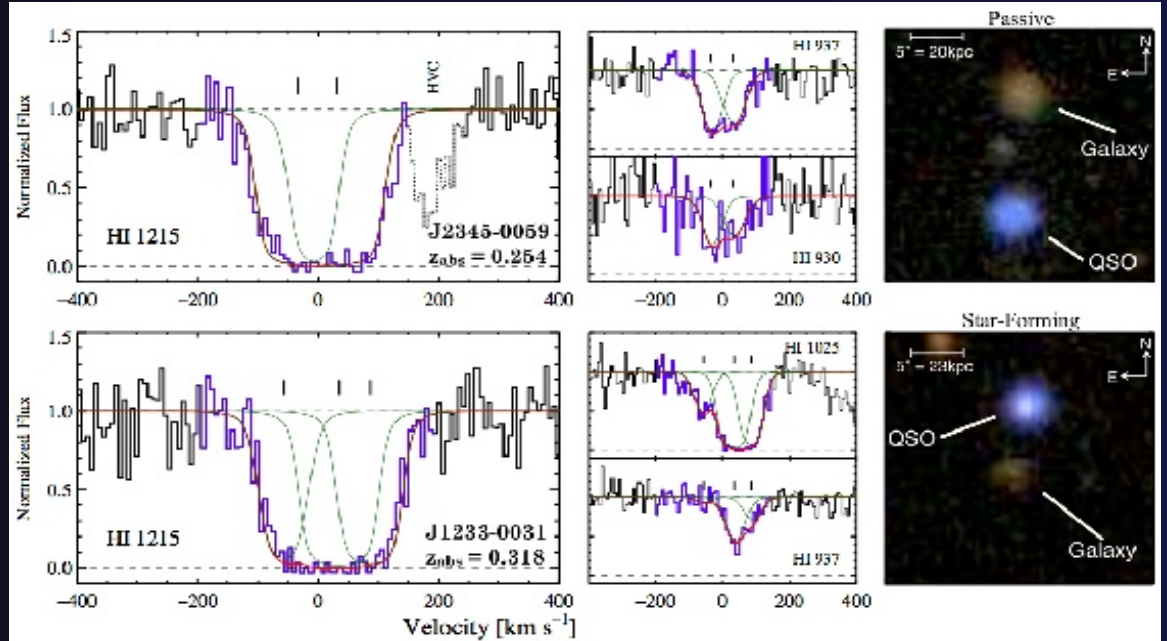


*van de Voort & Schaye 2012*

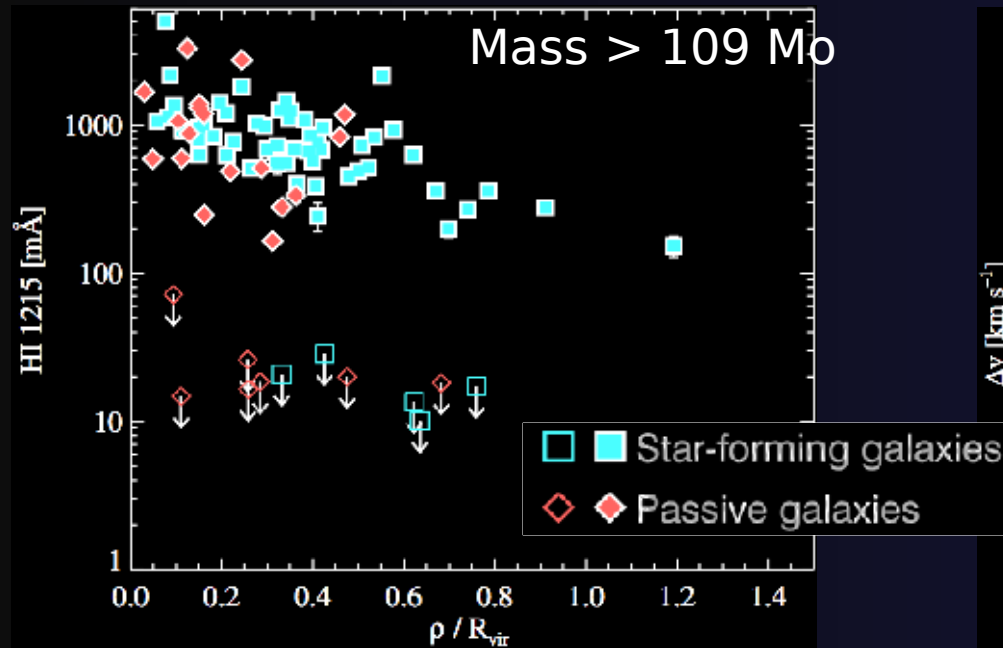
# Ly $\alpha$ absorbers

HST/COS data

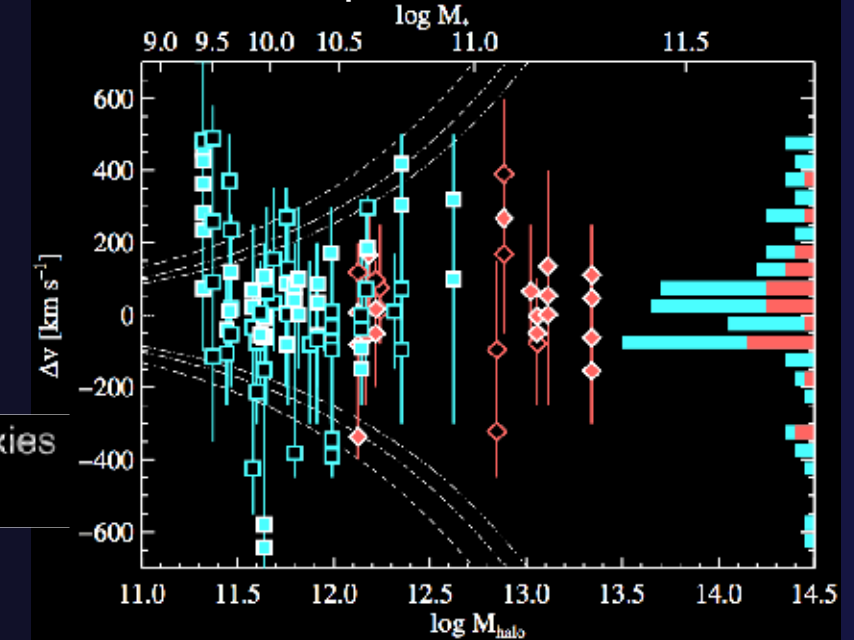
*Thom+ 2012, ApJL*



Impact parameters



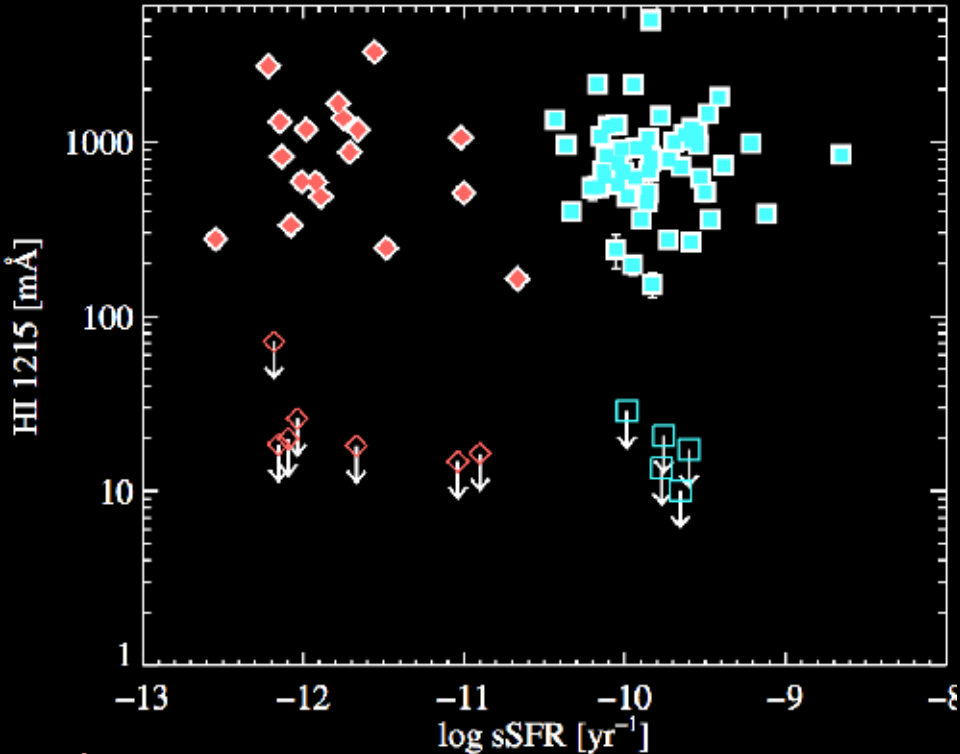
Bound to the potential wells





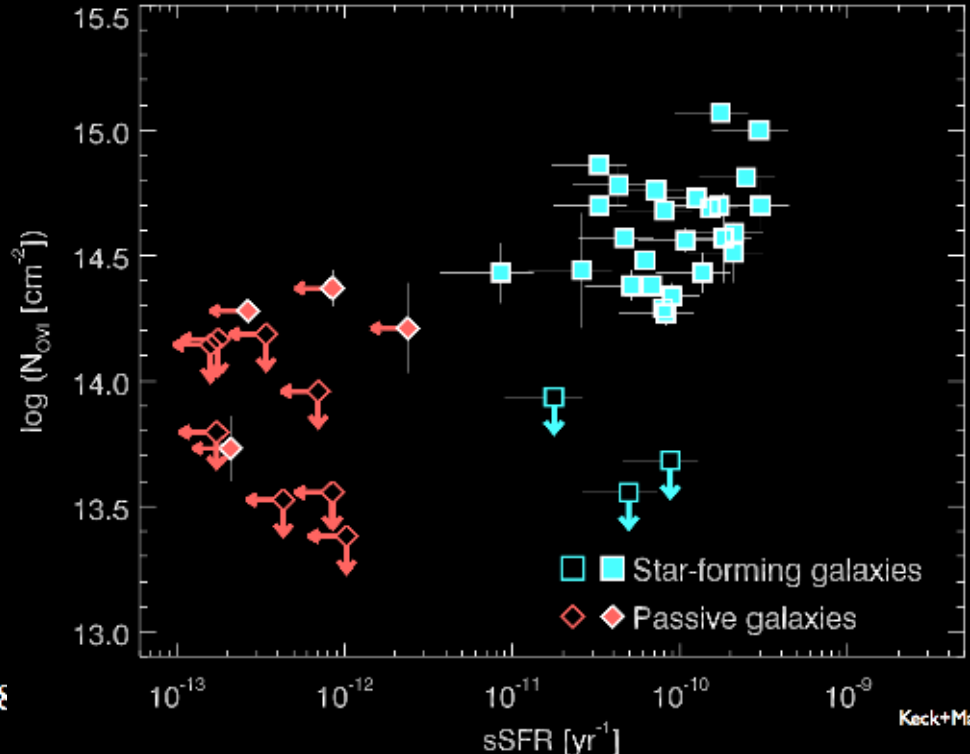
# Early types vs star-forming

Cold gas ( $\log(T) < 5$ )



Thom+ 2012, *ApJL*

Hot gas ( $\log(T) \sim 5.5$ )

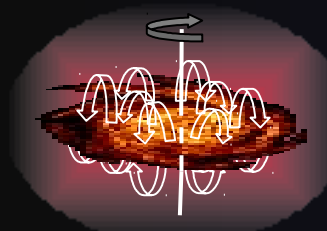


Tumlinson+ 2013

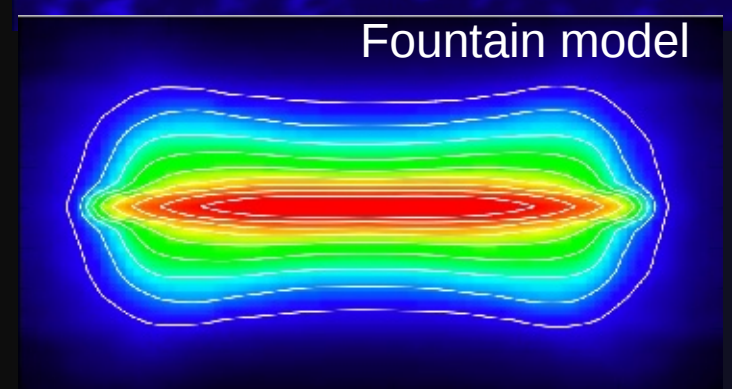
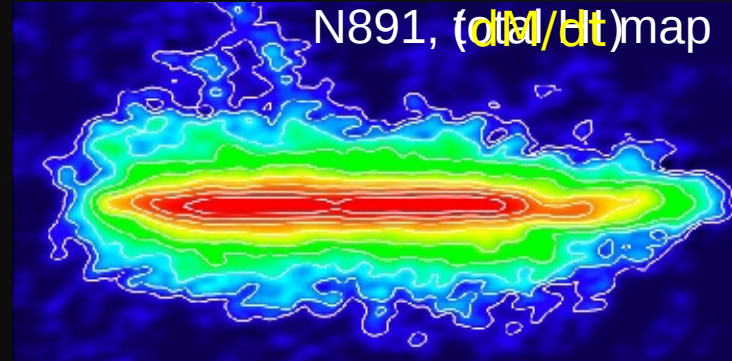
Werk+ 2013

Is this *cold* gas used for star formation?

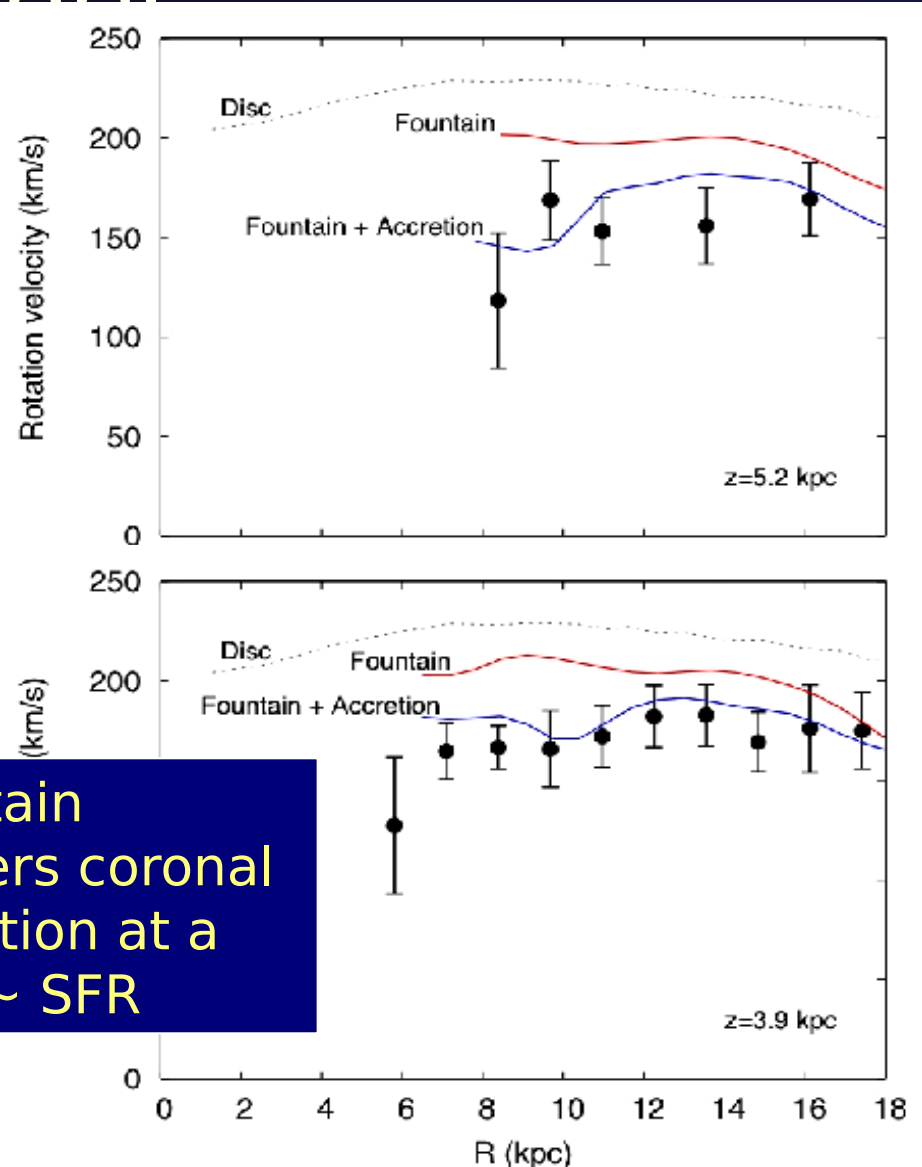
# Fountain-driven accretion model



1. kick velocities ( $v_k$ )
2. Ionised fraction ( $f_{ion}$ )
3. Accretion rate



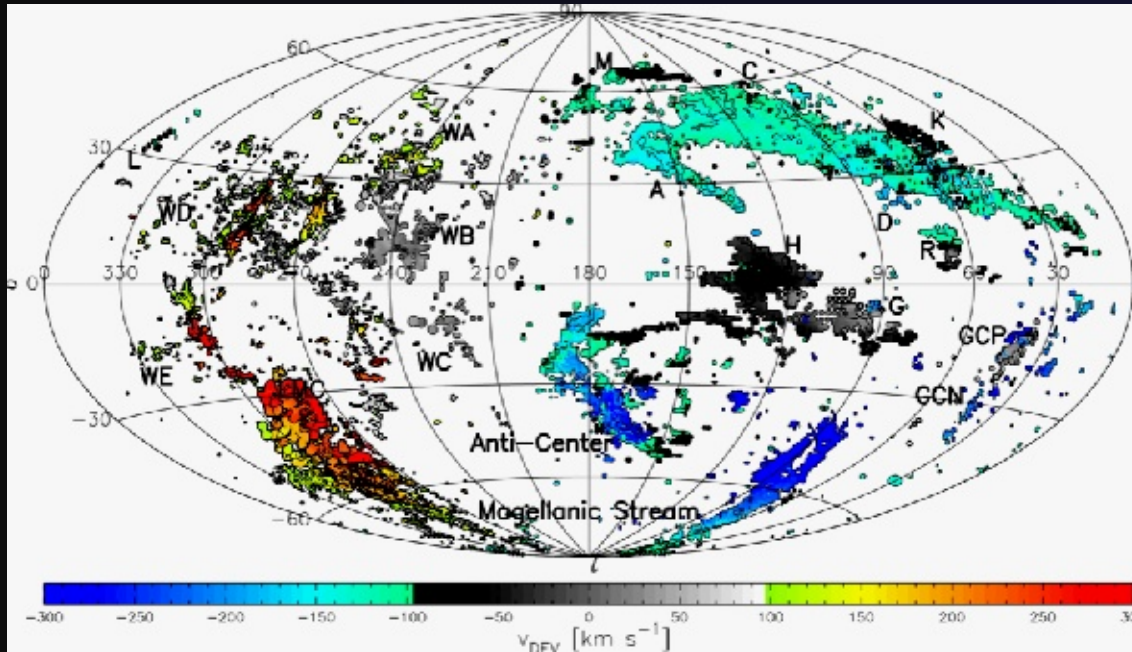
Fountain triggers coronal accretion at a rate  $\sim$  SFR



Best-fit Accretion Rate  $\sim 3 M_{\odot} \text{yr}^{-1}$   
 Compare to SFR  $\sim 4 M_{\odot} \text{yr}^{-1}$

Fraternali & Binney, 2008

# HI High Velocity Clouds



Typical Distances:  
 $\sim 10$  kpc

$h \sim \text{few}-10$  kpc

$Z \sim 0.1-0.4 Z_{\odot}$

$M < 10^7 M_{\odot}$

*Wakker et al. 2007, 2008; Tripp et al. 2003*

Accretion from High Velocity Clouds



$\sim 0.08 M_{\odot}/\text{yr}$

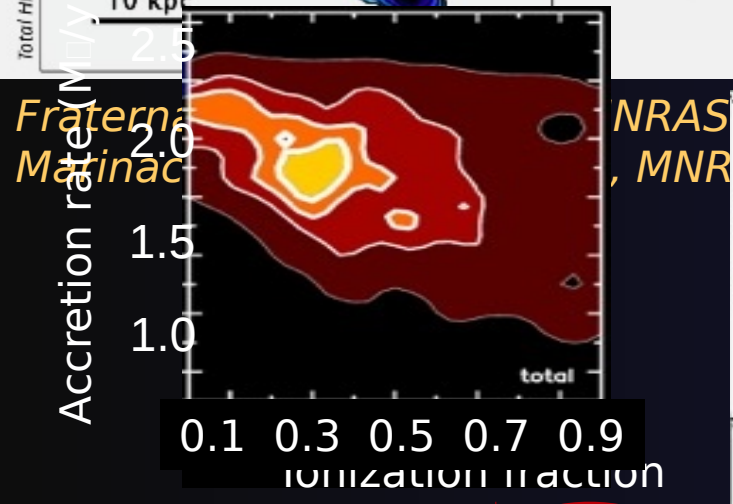
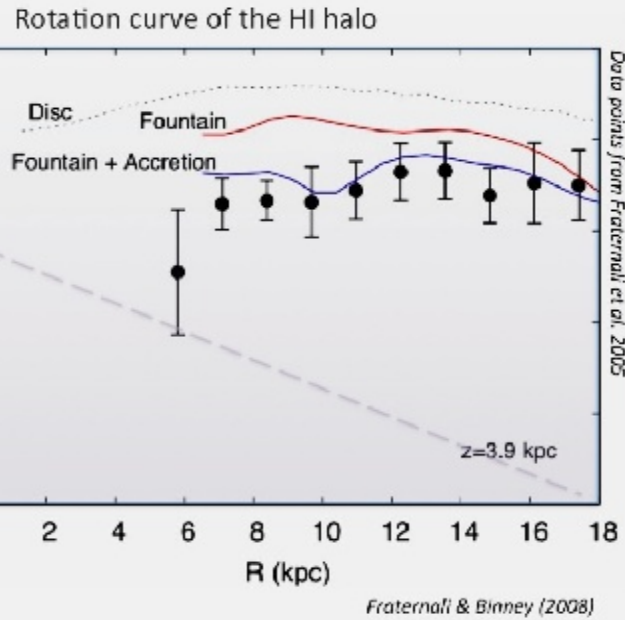
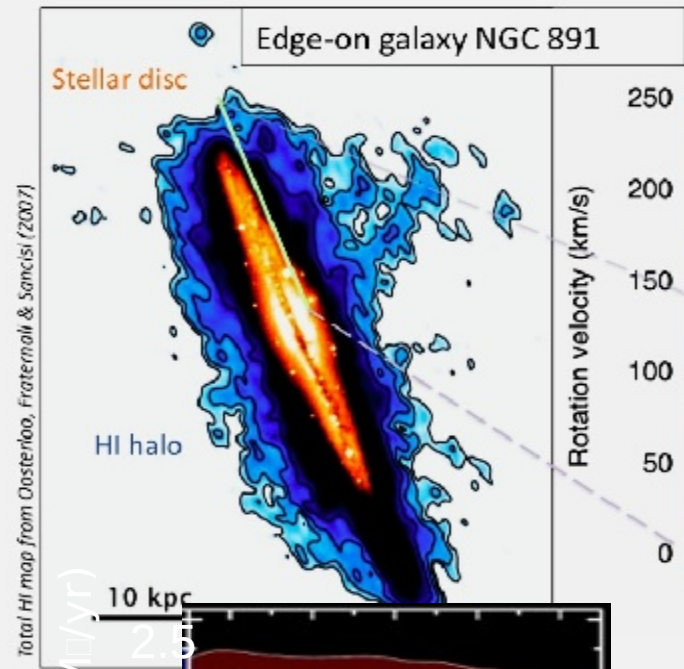
Includes He and factor 2 of ionised gas!

HI HVCs cannot feed SF

*Putman, Peek, Joungh 2012, ARA&A*

# Implications for galaxy evolution

# Global fountain

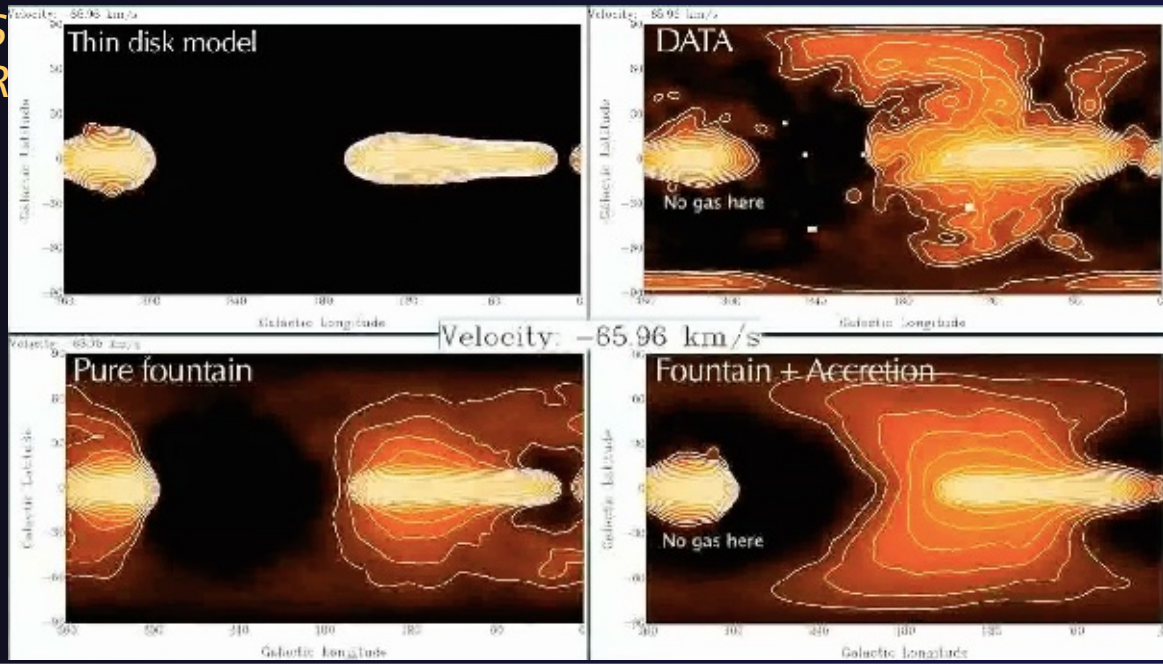


Best-fit Accretion Rate  $\sim 2 M_{\odot}\text{yr}^{-1}$

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

Marasco, Fraternali+ 2012, MNRAS

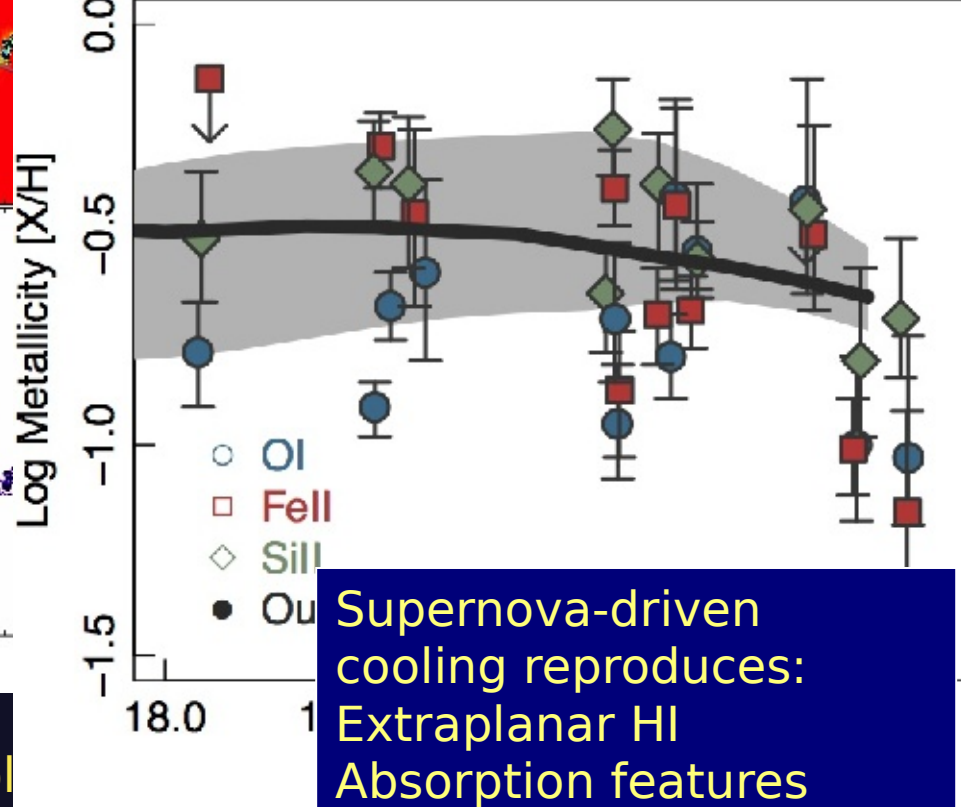
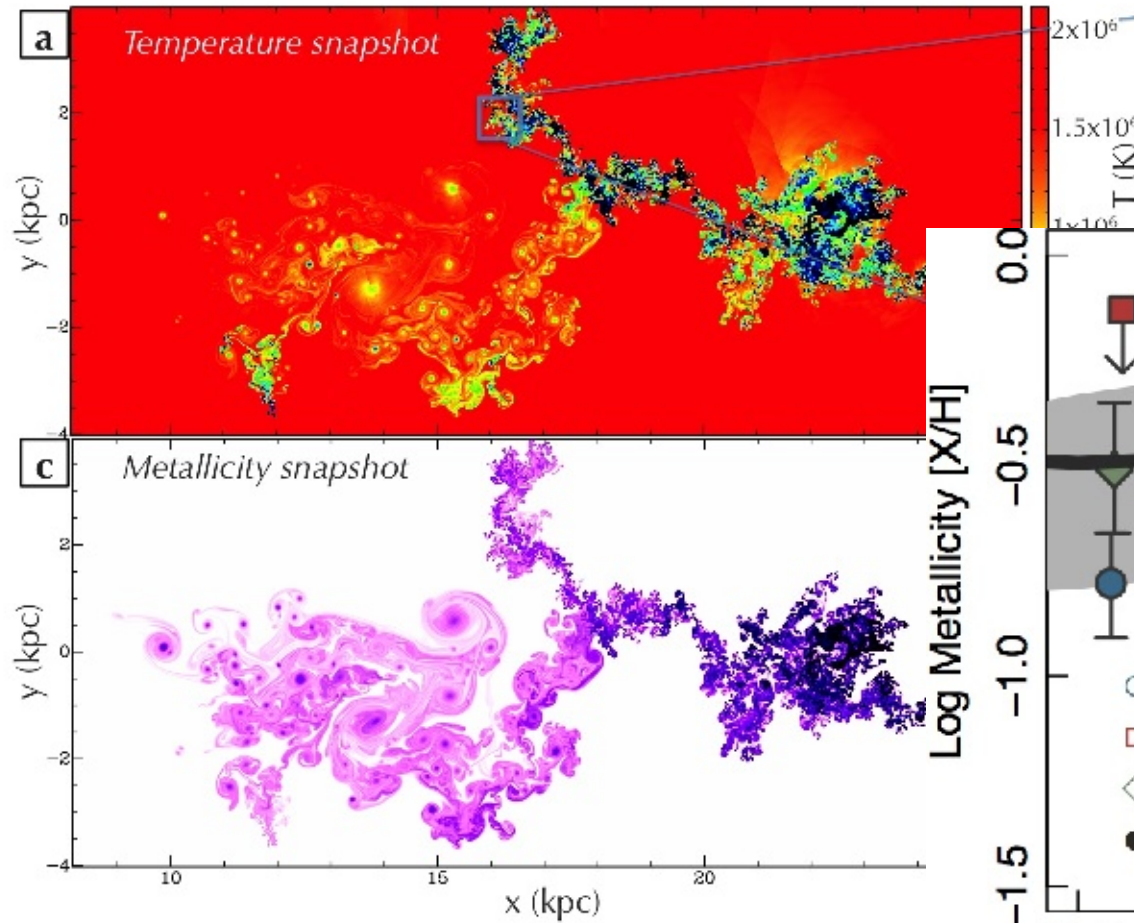
Filippo Fraternali (Bologna/Groningen)



Interplay local & global processes in galaxies - Cozumel, Mexico - 11/1/16

# Metallicity

## Condensation of the corona



Supernova-driven cooling reproduces:  
 Extraplanar HI  
 Absorption features  
 And even HVCs

Average metallicity at the end: **0.27 Solar**  
 Compared to complex C: **0.1-0.3 Solar**

# Galactic fountain model

Building of several model cubes -> minimization residuals with LAB



We fit:

1. kick velocities ( $v_k$ )



scaleheight

2. Ionised fraction ( $f_{ion}$ )



vertical motions

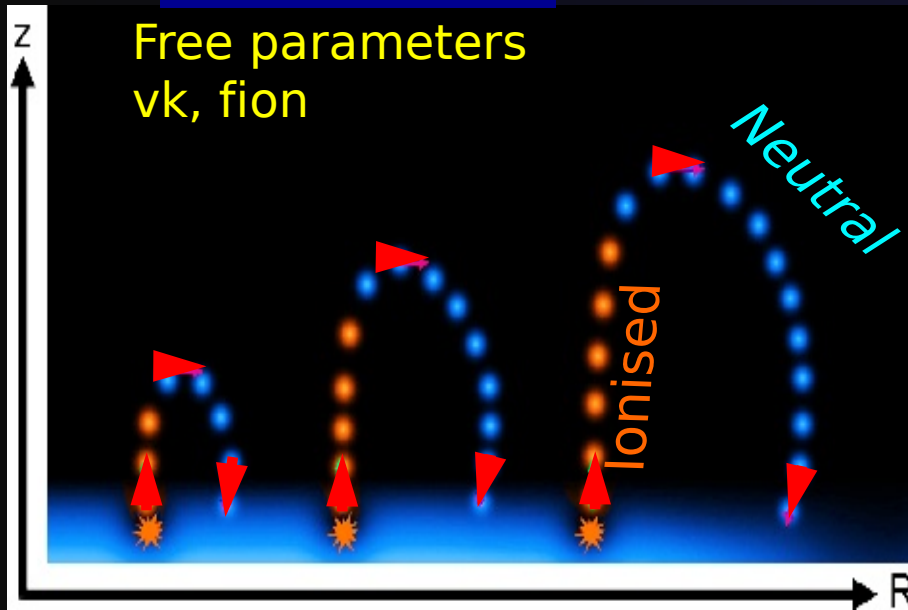
3. Accretion coefficient ( $\alpha$ )



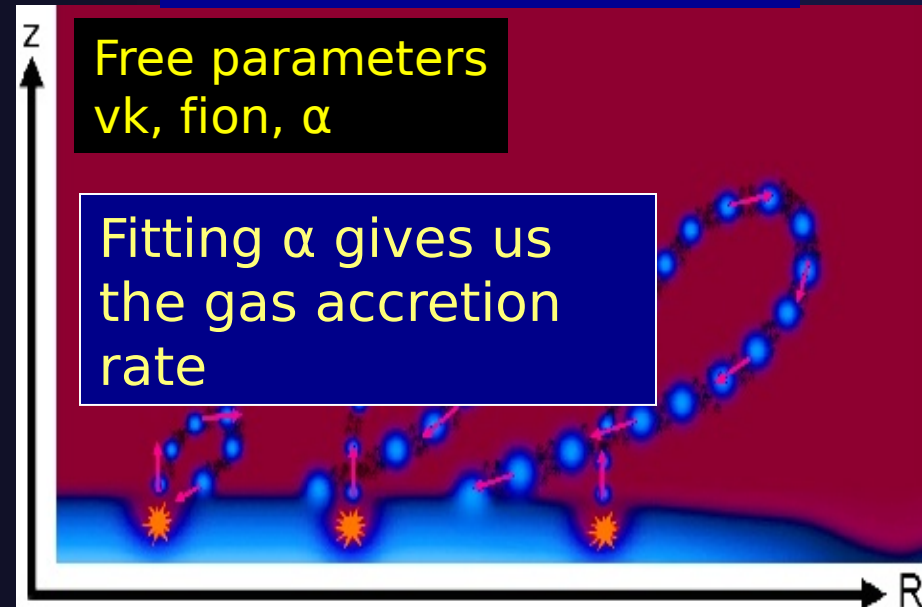
radial motions

$$\dot{m} = \alpha \dot{m}$$

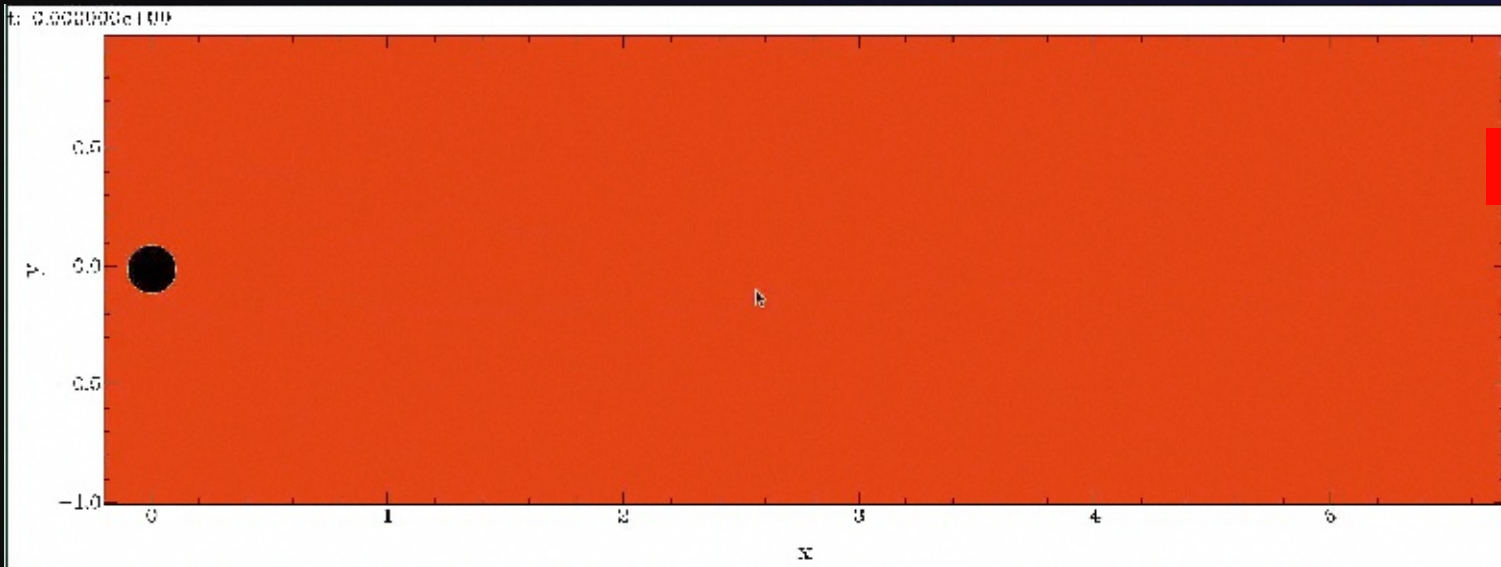
## Pure fountain



## Fountain + accretion



# The effect of thermal conduction



Only cooling

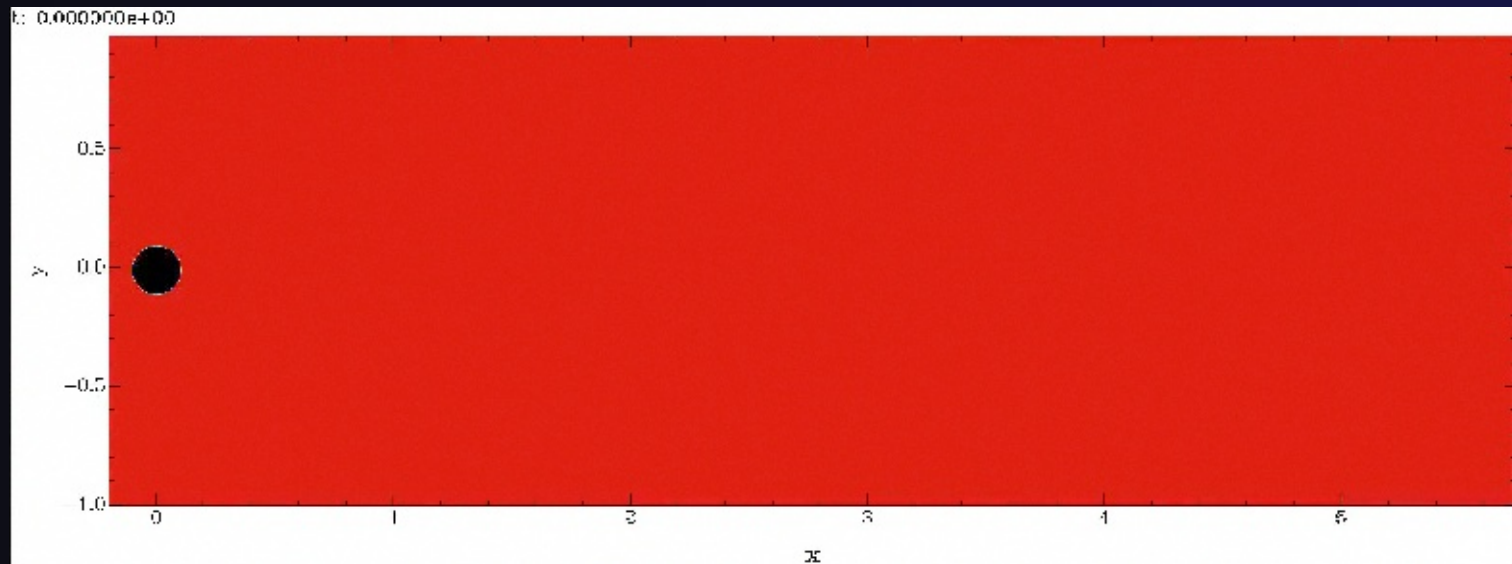
$T_{\text{corona}} = 2 \times 10^6$

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

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

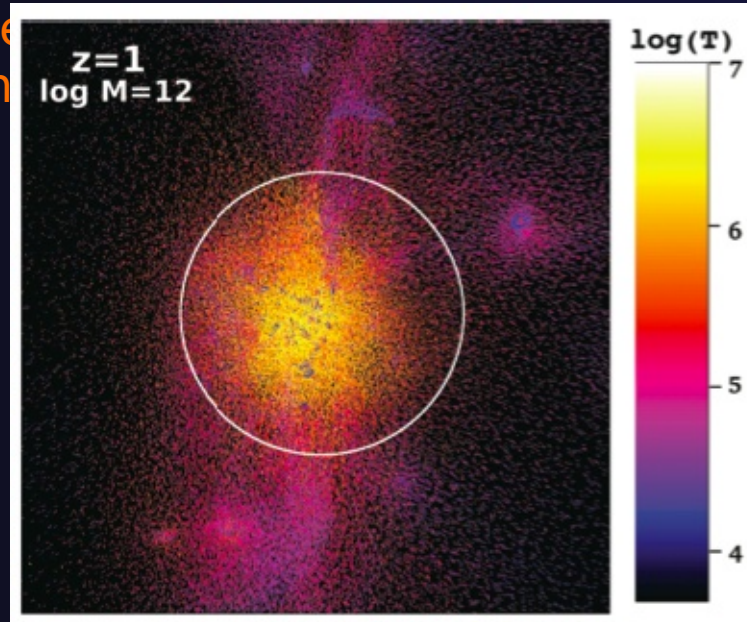
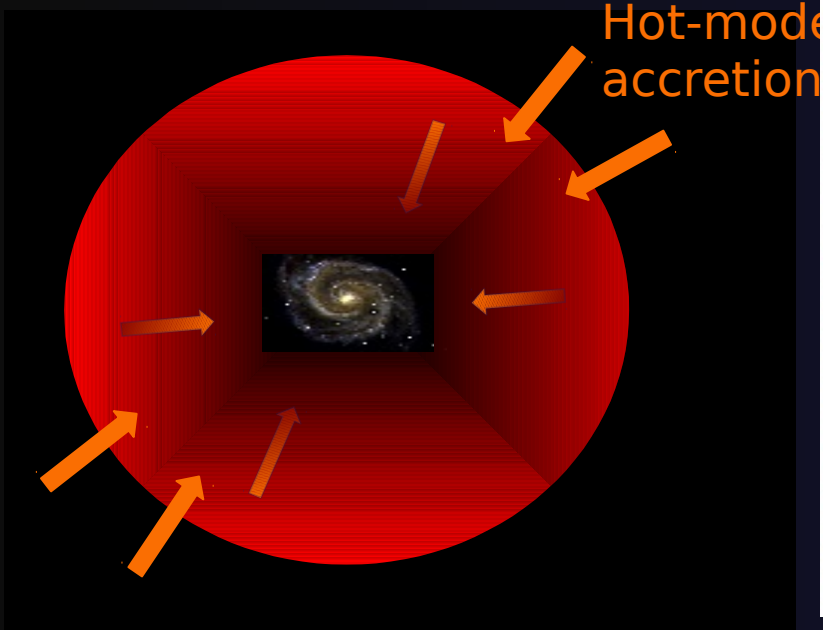
Cooling & thermal conduction

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

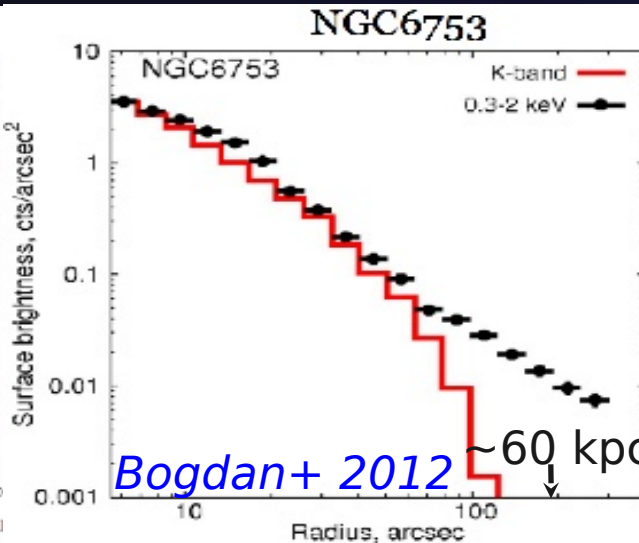
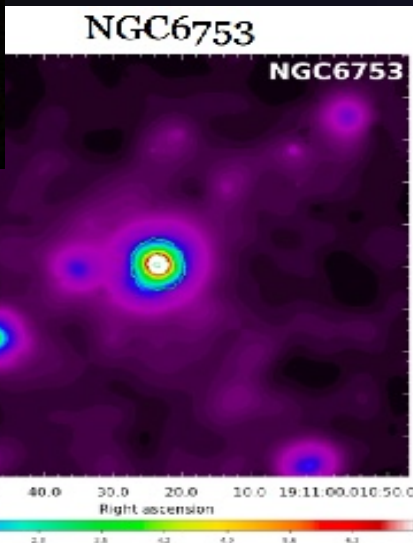




# Galactic coronae



*Keres+ 2009*  
Hot-mode accretion. Similar to classical theory (e.g. *White & Rees 1978*)  
*Bregman*

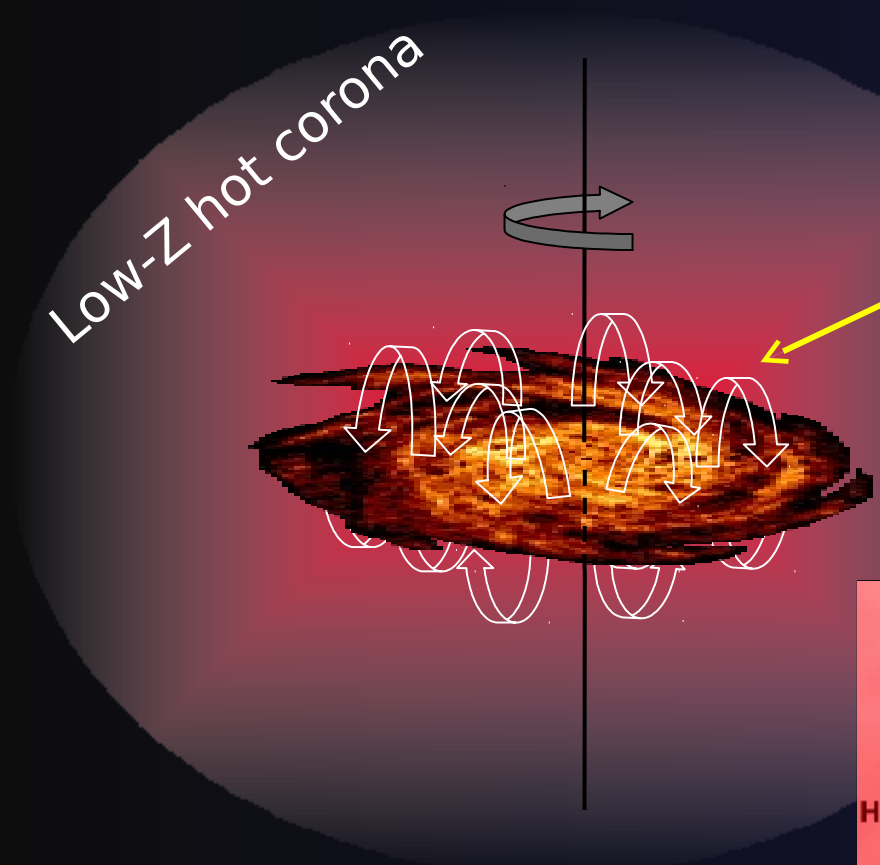


*2012*  
*Dai+ 2012, Anderson+ 2013*

MW *Miller & Bregman+ 2013, 2015; Gatto+13*  
Mass corona  
~ 10-50% missing baryons

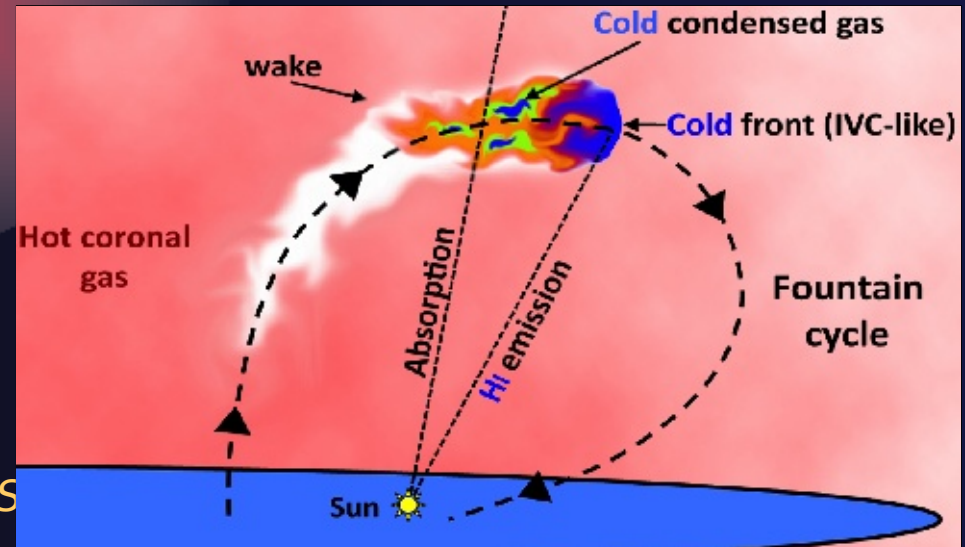
Cooling rate ~ 0.1 Mo/yr

# Disc-corona interplay



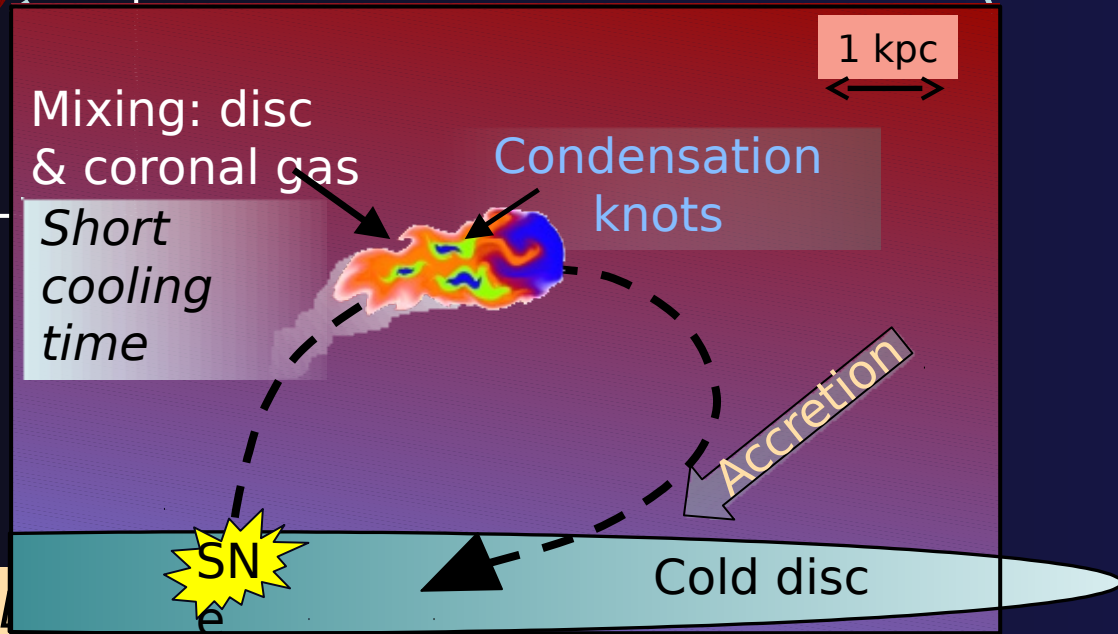
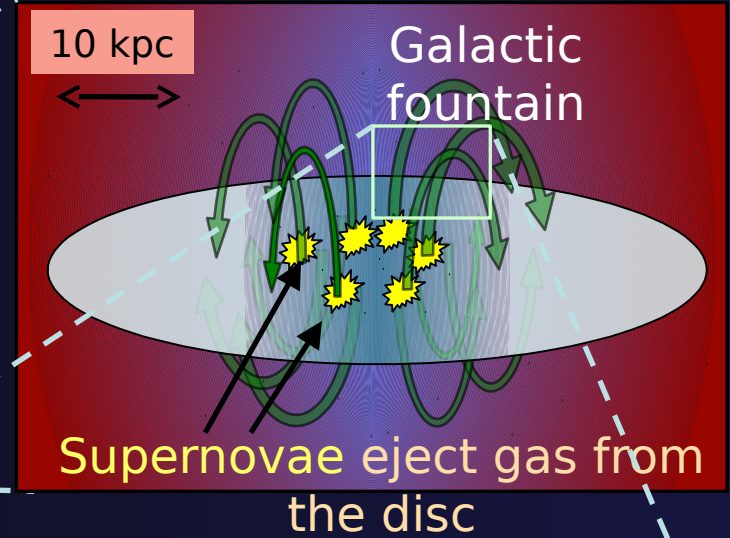
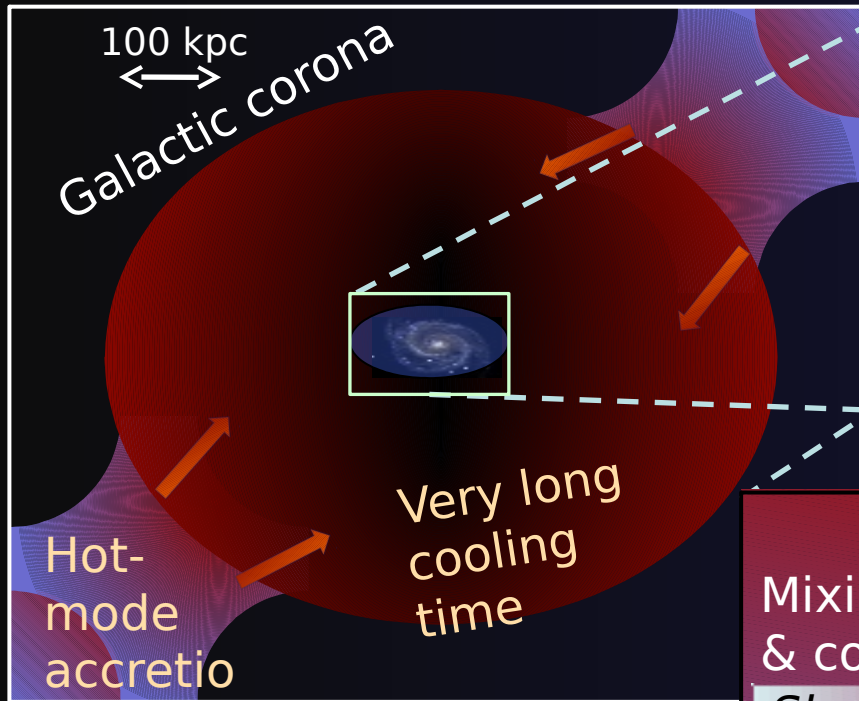
Interface layer where disc and coronal materials mix

High metallicity "cold" gas (from the disc) mixes with low metallicity hot gas



*Fraternali & Binney 2008, MNRAS*  
*Marinacci, et al. 2010, 2011, MNRAS*  
*Marasco, Fraternali & Binney 2012, MNRAS*

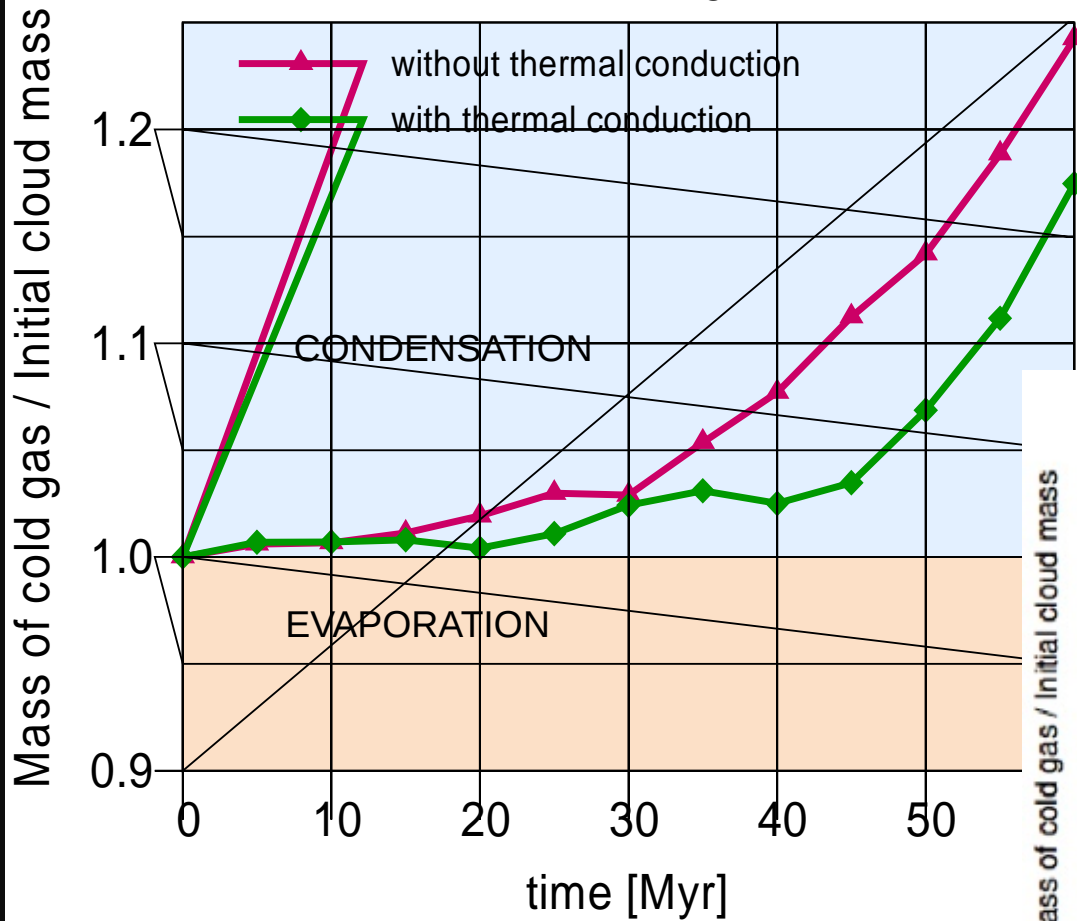
# Supernova-driven accretion



Fraternali et al. 2013, *ApJ*

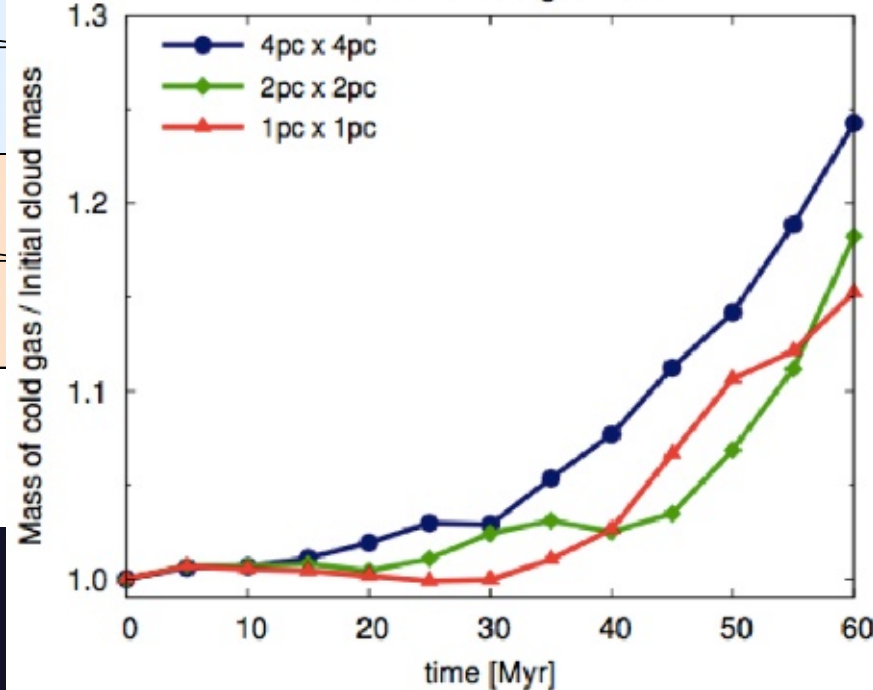
# Efficiency of fountain-driven cooling

## Evolution of cold gas mass



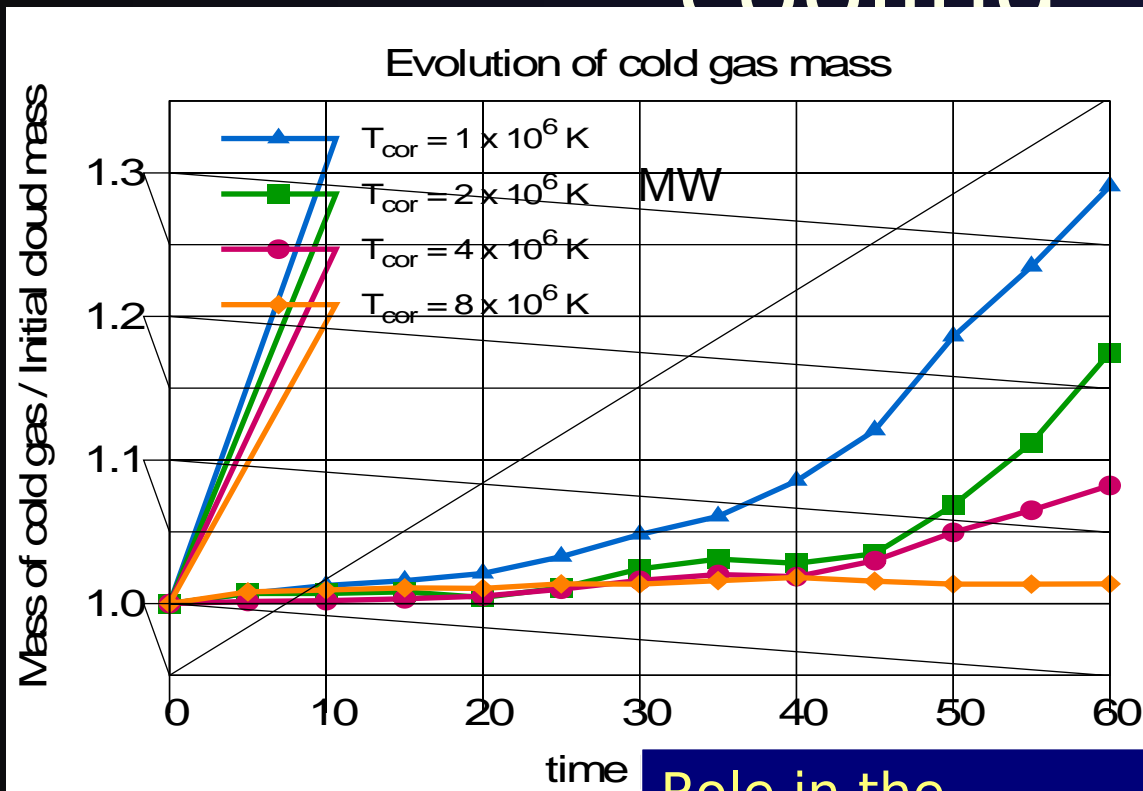
Convergence at  $\sim 2$  parsec

## Evolution of cold gas mass



Armillotta, Fraternali & Marinacci, in prep

# Efficiency of fountain-driven cooling



Condensation strongly depends on coronal temperature

At  $T_{cor} > 4 \times 10^6$  K clouds evaporate

*Armillotta, Fraternali & Marinacci, in prep*

Role in the quenching of star formation?

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



$T_{vir}$

# Milky Way evidence

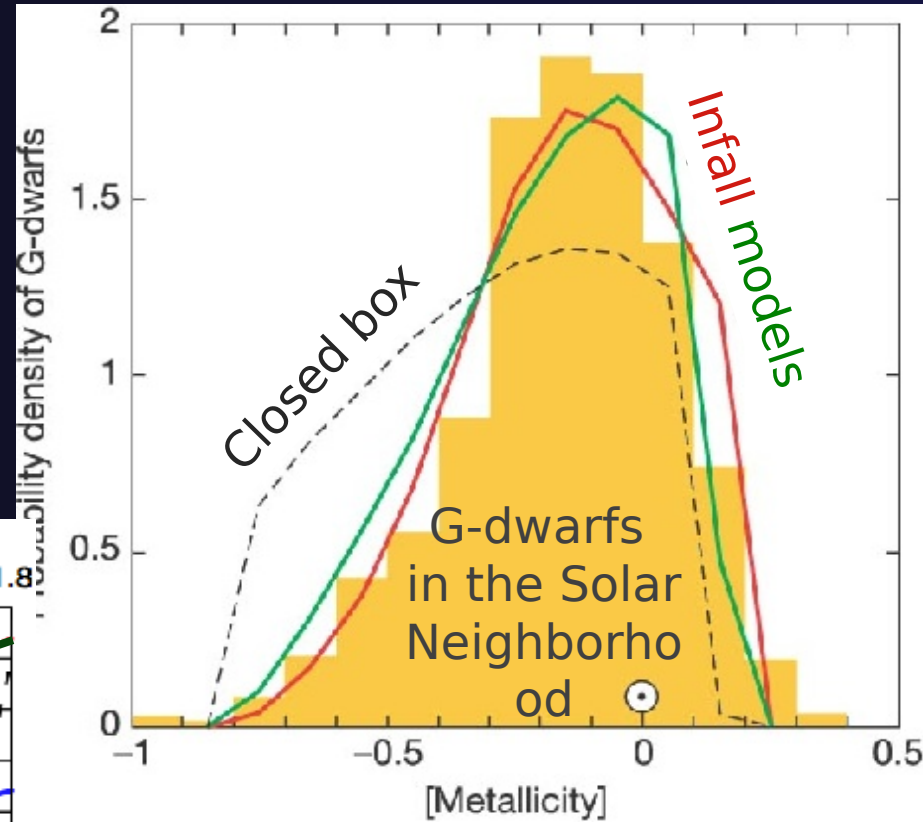
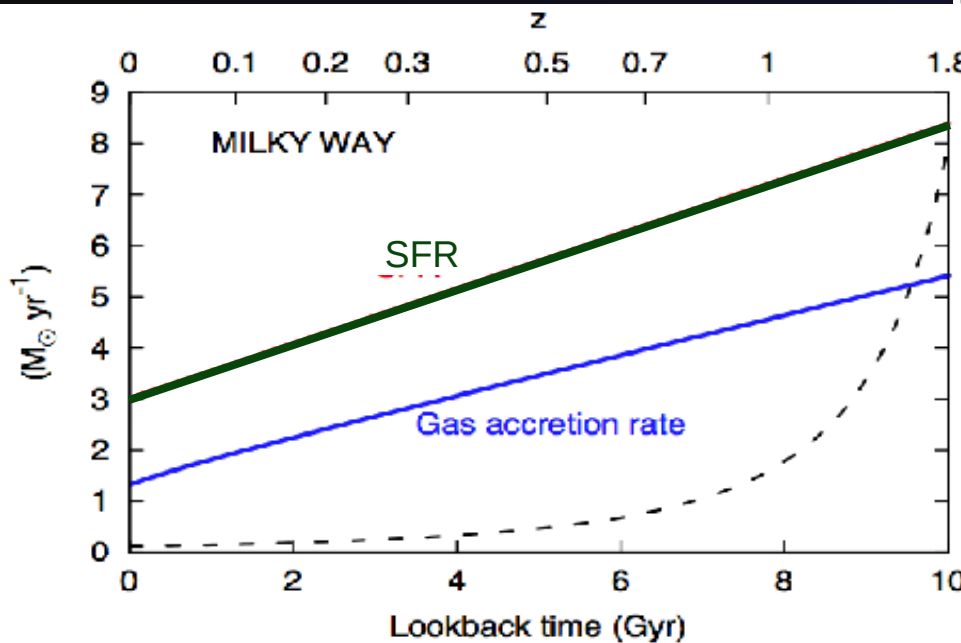
Chemical evolution models

G-dwarf problem

Larson 1972, Tinsley 80,  
Chiappini+ 97, 01; Schoenrich &  
Binney 09

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

Need for gas  
accretion at  $Z < \sim 0.1$



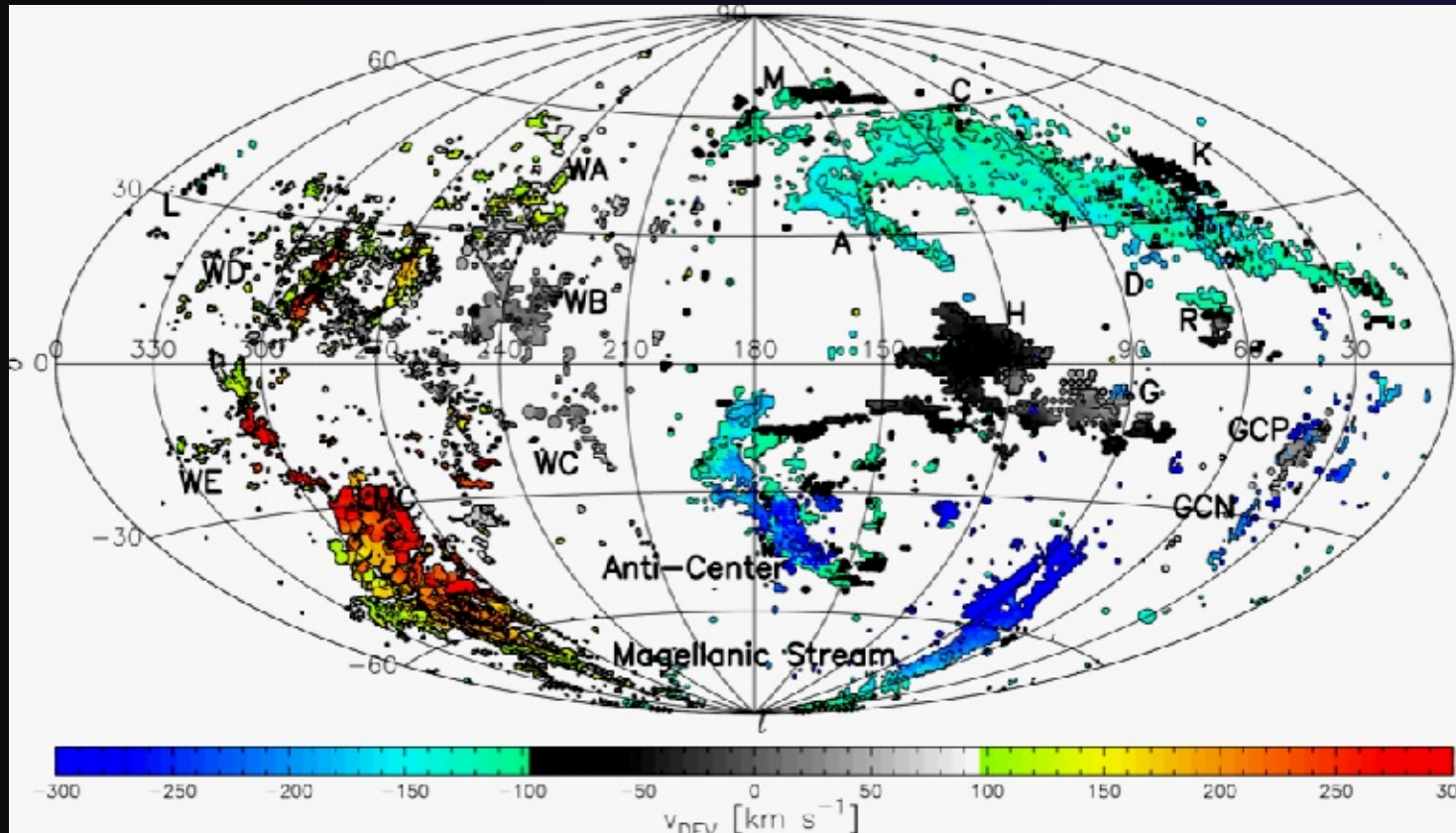
*Dauphas et al. 2005, Nature*

$$\text{SFR} \propto \dot{M}_{\text{acc}}$$

$\sim 1 M_{\odot}/\text{yr}$

*Fraternali & Tomassetti 2012, MNRAS*

# HI High Velocity Clouds



*Wakker et al. 2007, 2008; Tripp et al. 2003*

Typical Distances:  
 $\sim 10$  kpc

$h \sim \text{few}-10$  kpc

$Z \sim 0.1-0.4 Z_{\odot}$

$M < 10^7 M_{\odot}$

Accretion from High Velocity Clouds



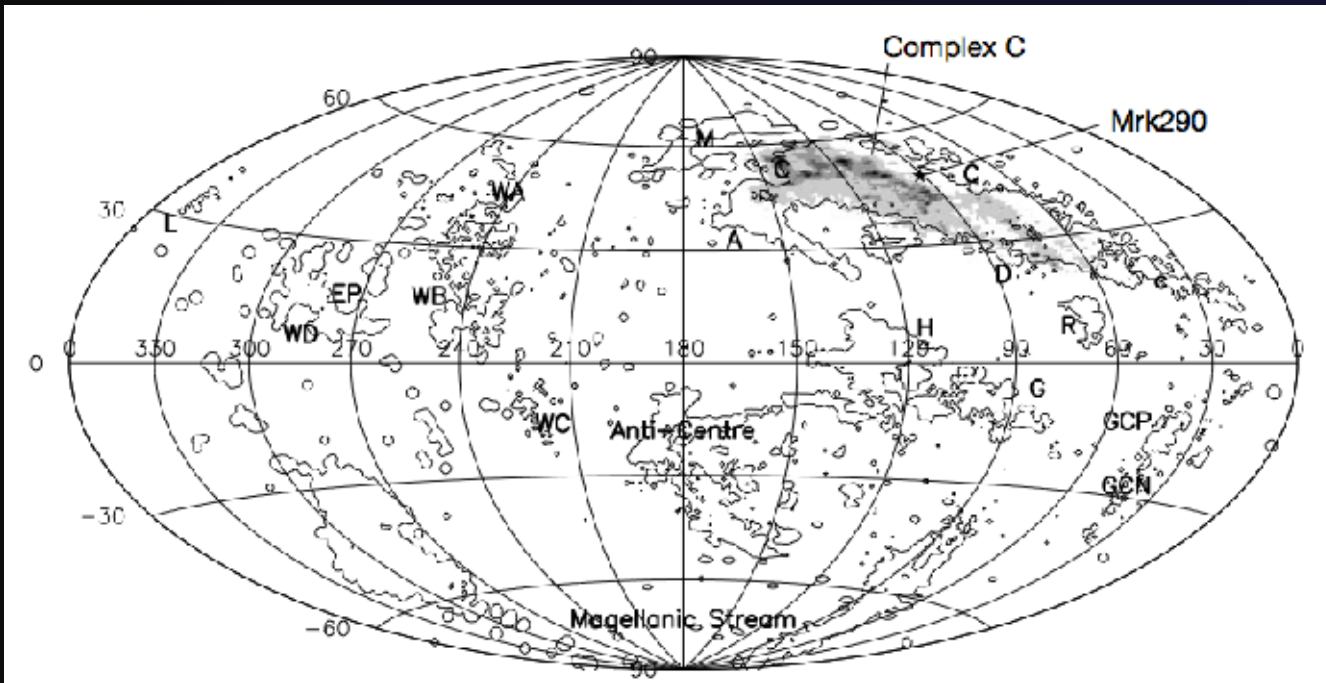
$\sim 0.08 M_{\odot}/\text{yr}$

Includes He and factor 2 of ionised gas!

HI HVCs cannot feed SF

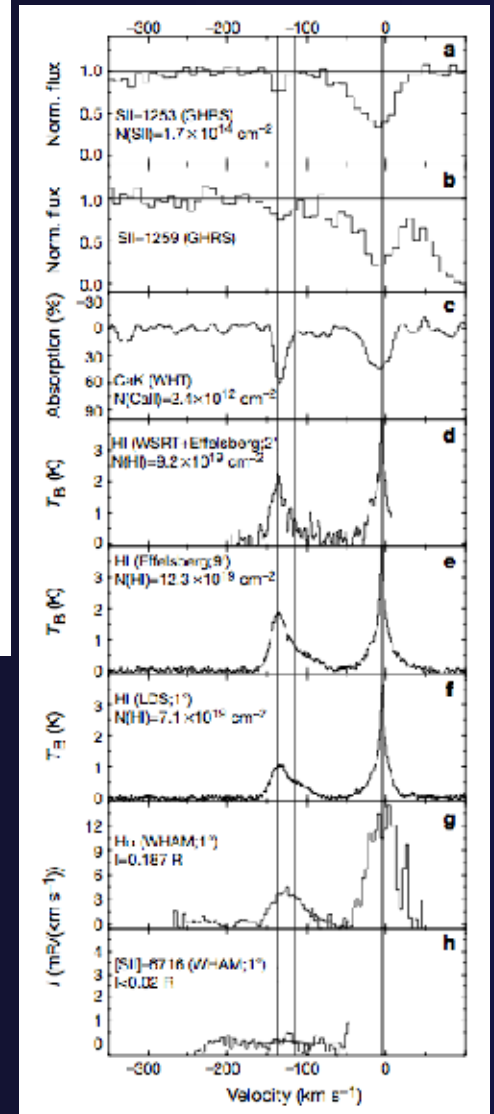
*Putman, Peek, Joungh 2012, ARA&A*

# Origin of HVCs



**Oort 70** leftover of galaxy formation  
**Bregman 80** Galactic fountain  
 + satellites (*Olano 2001*), thermal instabilities (*Kaufmann+06*), no thermal instabilities (*Binney+09*), filaments (*Fernandez+12*)

**Wakker+ 1999, Nature**  $Z \sim 0.1$  Solar  $\rightarrow$  Accretion!  
**Gibson+01**  $Z \sim 0.3$  Accretion?  
**Collins+07** overabundance  $\alpha$  elements (SN II?)

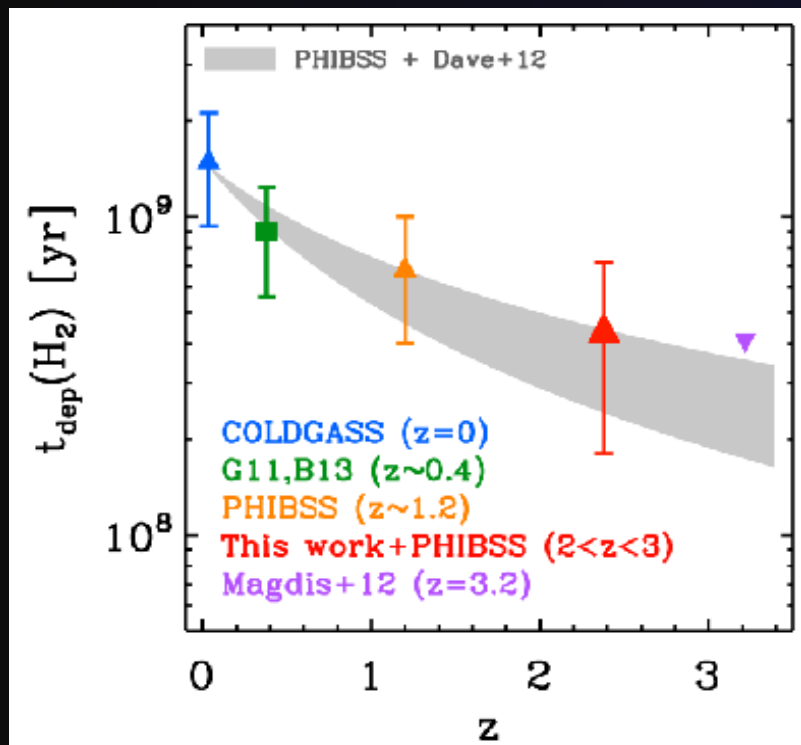




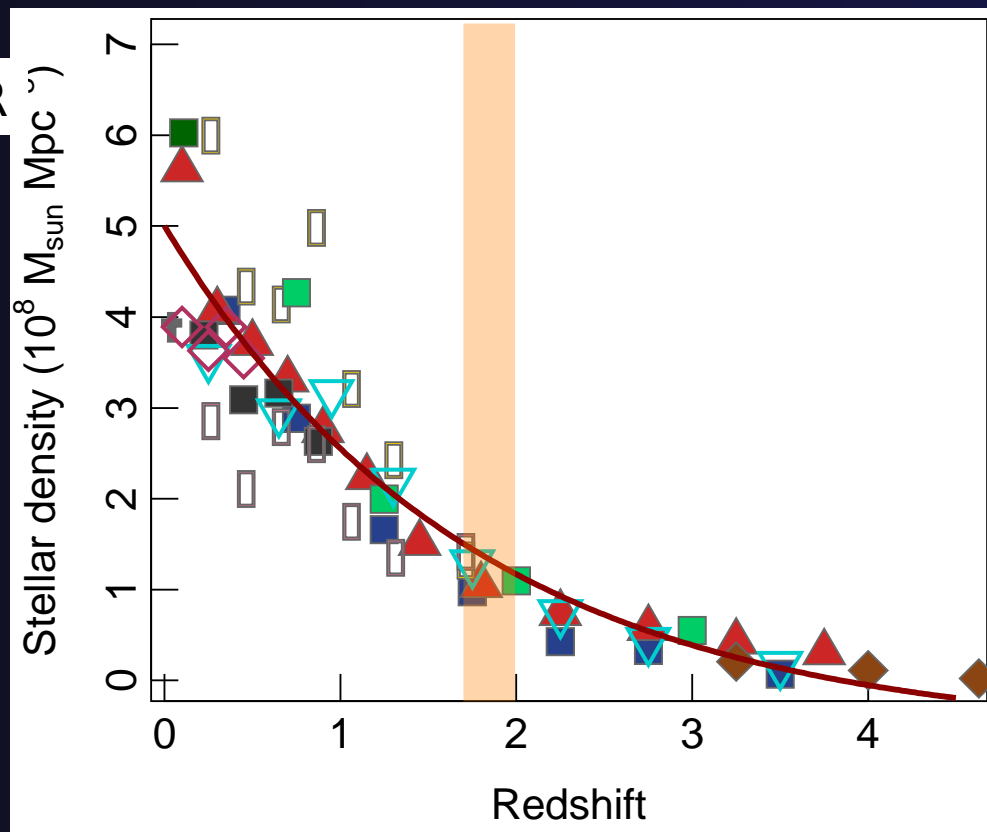
# Cosmology evidence

Gas depletion time  $\sim 1$  Gyr Assembly of stellar mass in the Universe

Gas depletion time  $t_{\text{depl}} = M_{\text{gas}} / \text{SFR}$



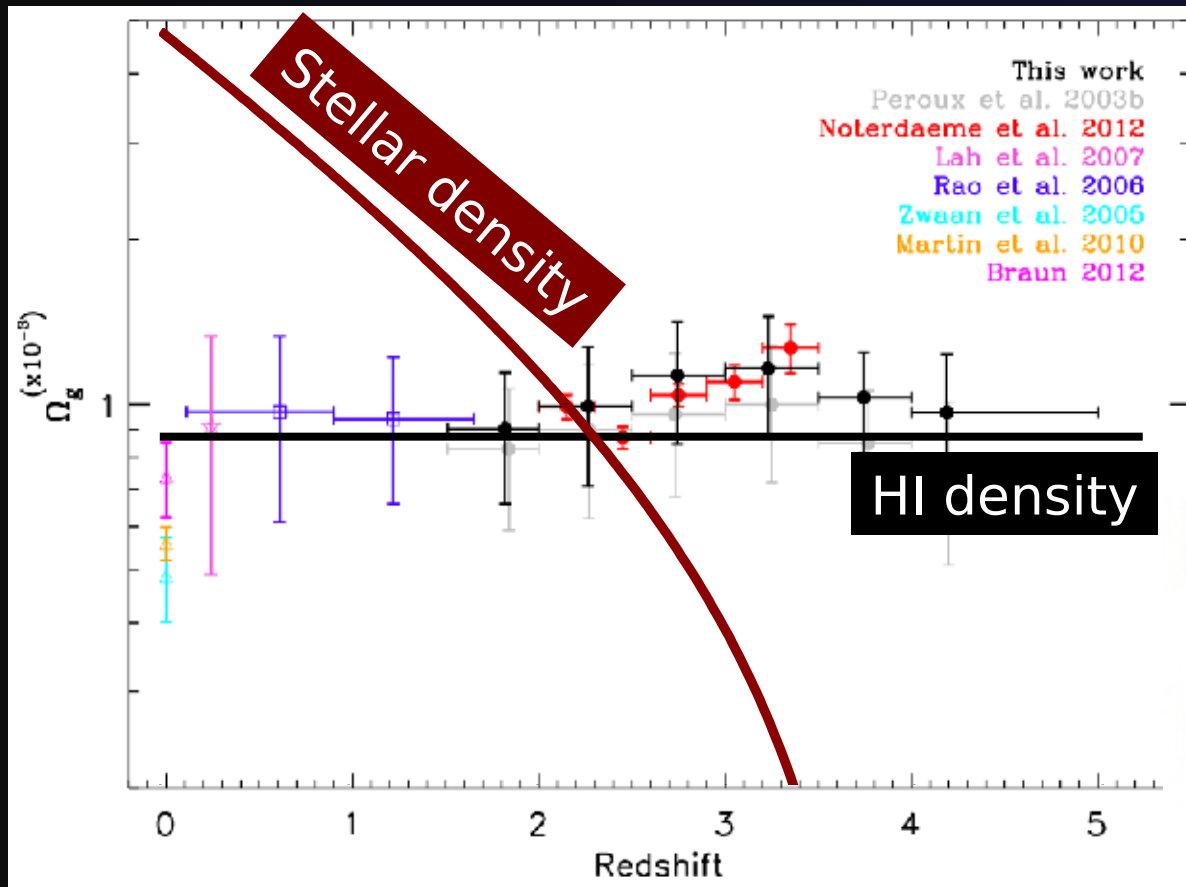
Saintonge+ 15  
 Kennicutt+83, Genzel+ 10,  
 Bigiel+11, Genzel+15



Compilation from *Madau & Dickinson 2014*

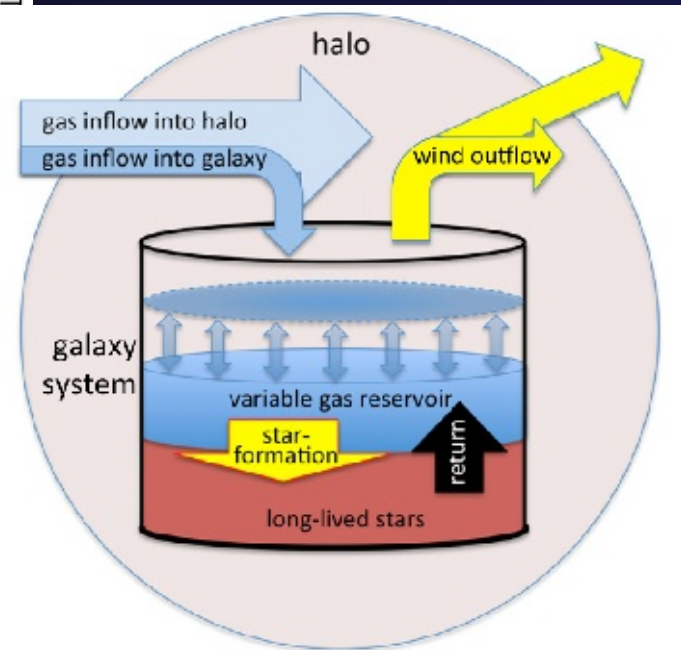
# Cosmology evidence

Constant HI in galaxies



Accretion needed to keep forming stars at level of  $\sim$  SFR

Bathtub model



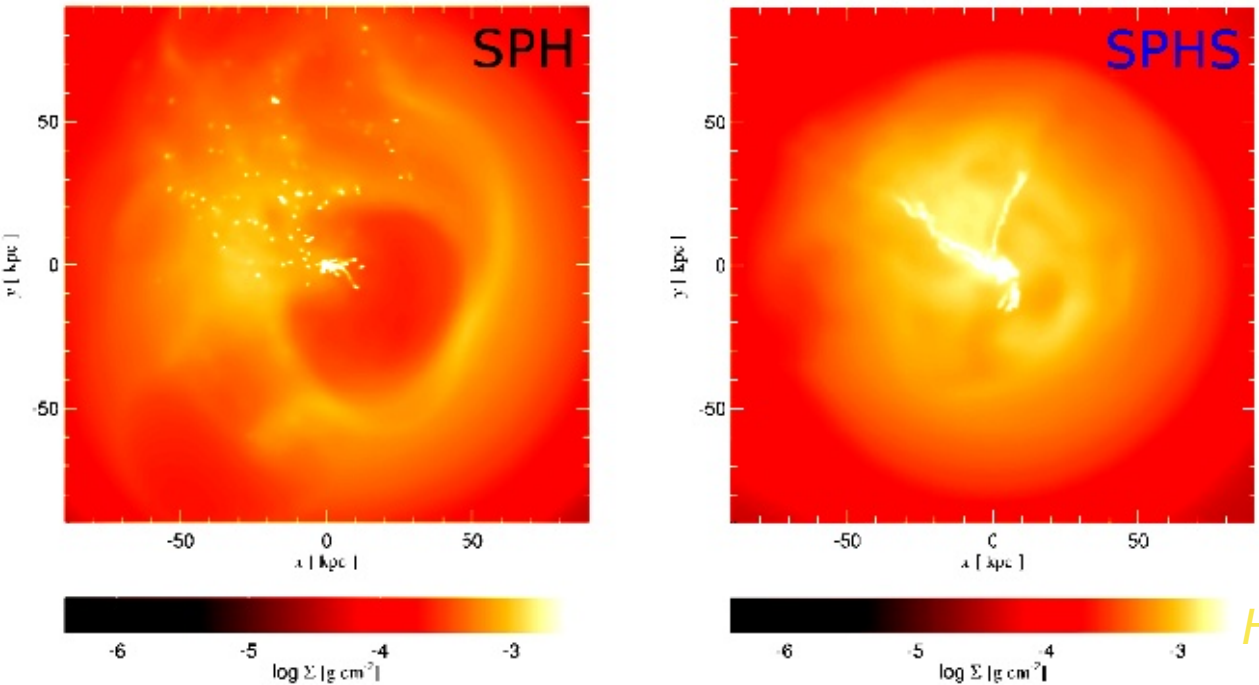
Zafar+ 13

$$\text{SFR} \sim \dot{M}_{\text{acc}} - \dot{M}_{\text{outflow}} + \mathcal{R}\text{SFR}$$

Bouché+2010, Davé+ 2012, Lilly+1

# Supernova-driven accretion in other sims

# SN-driven accretion in other sims



Modified SPH

No formation of clumps

*“Cold gas condenses from the halo at the intersection of supernovae-driven bubbles. This positive feedback feeds cold gas to the galactic disc*

*Hobbs et al. 2013, MNRAS*

MaGICC - GASOLINE

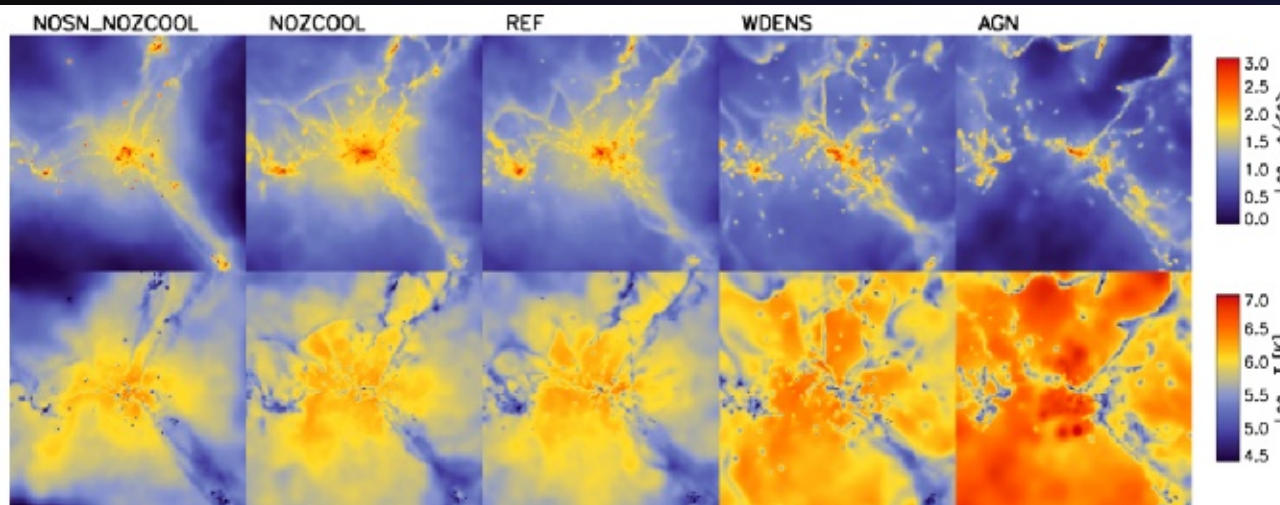
Halos enriched by galactic fountain

Gas in the fountain cycle comes back to the disk **more metal poor!**

*Brook+12, Brook+13*



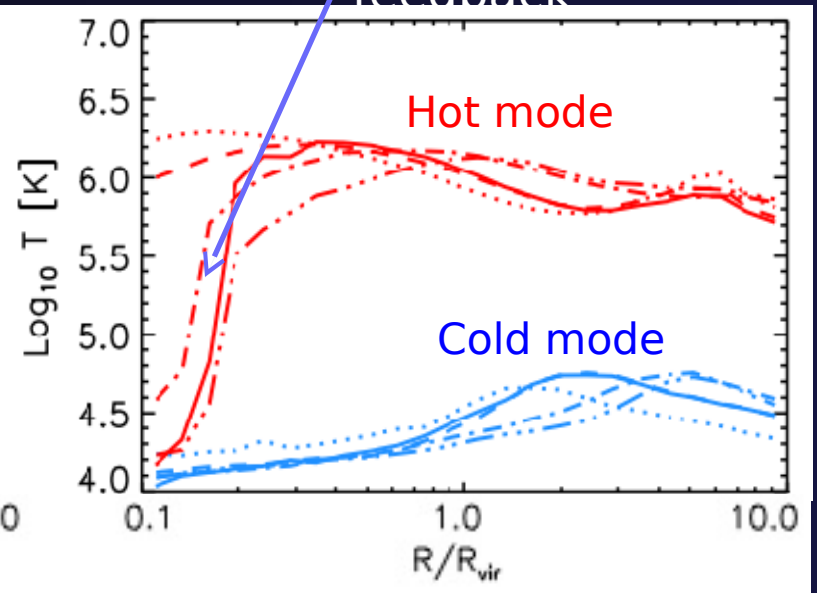
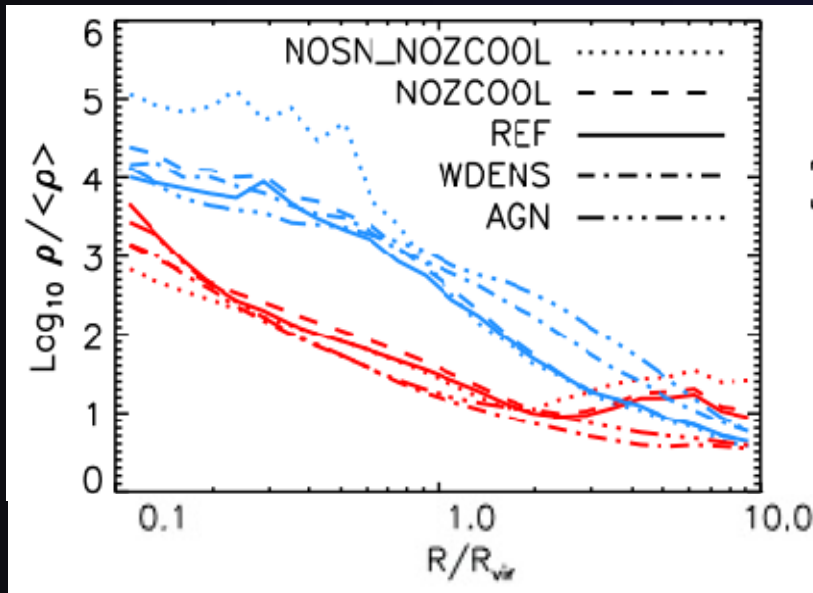
# Positive feedback is there



$z=2$

Cooling induced close to galaxies by metals ejected by feedback

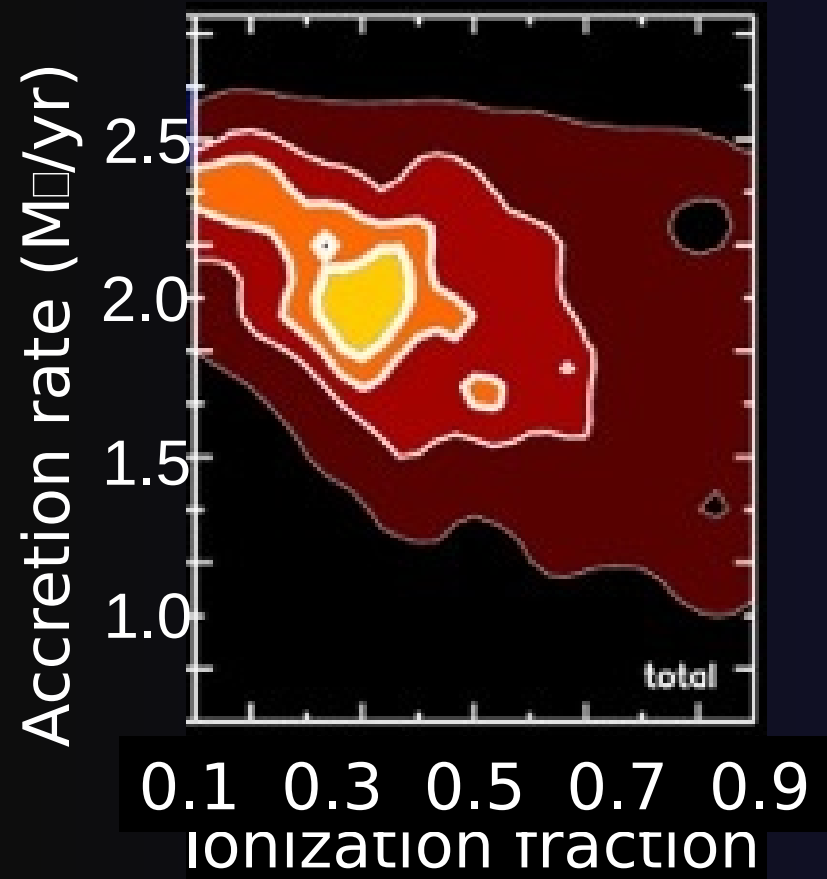
OWLS  
GADGET-3



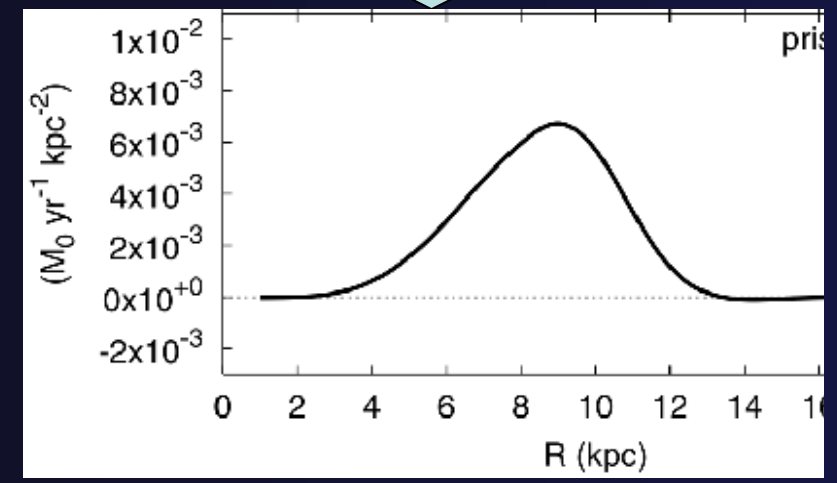
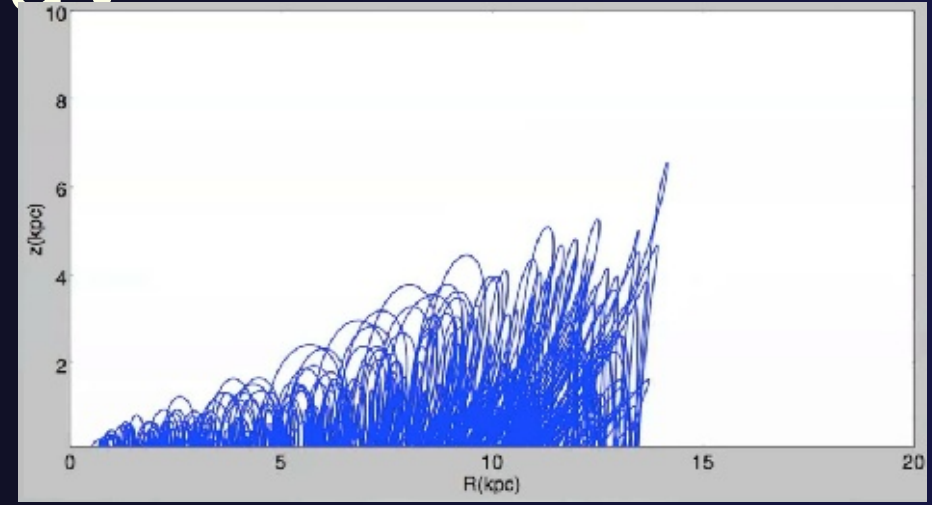
*van de Voort & Schaye 2012*

# Extrapolation in the Milky Way

## Way

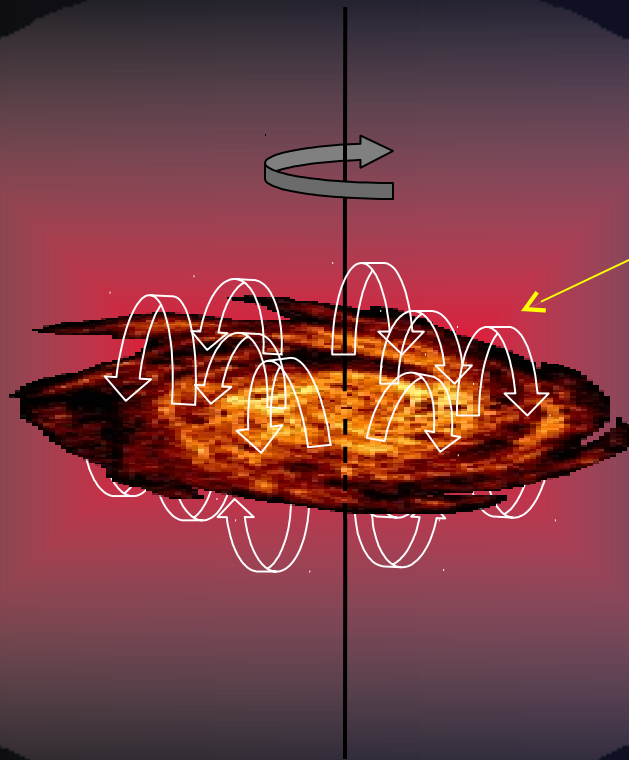


Best-fit Accretion Rate  $\sim 2 \text{ M}_{\odot}\text{yr}^{-1}$   
 Compare to SFR  $\sim 1\text{-}3 \text{ M}_{\odot}\text{yr}^{-1}$



*Marasco, Fraternali & Binney 2012, MNRAS* Accretion in the outer disc

# Disc-corona interplay



Interface layer where  
disc and coronal  
material mix

Cooling time of the  
corona (typically very  
long) decreases  
dramatically because  
it is mixed with:

1. *cold* gas
2. High Z gas

*Fraternali & Binney 2008, MNRAS*

*Marinacci, et al. 2010, 2011, MNRAS*

*Marasco, Fraternali & Binney 2012, MNRAS*

# Implications for galaxy evolution



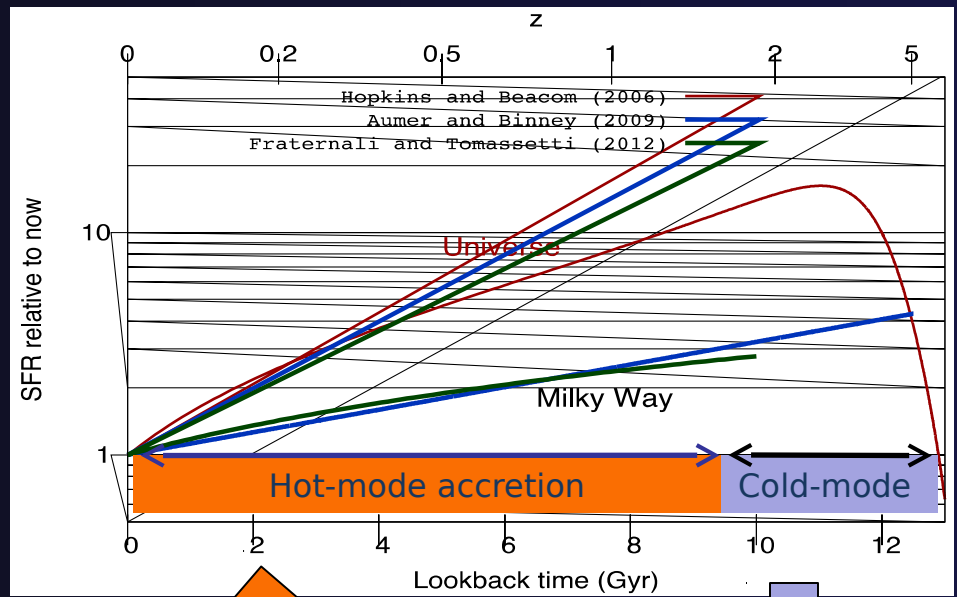
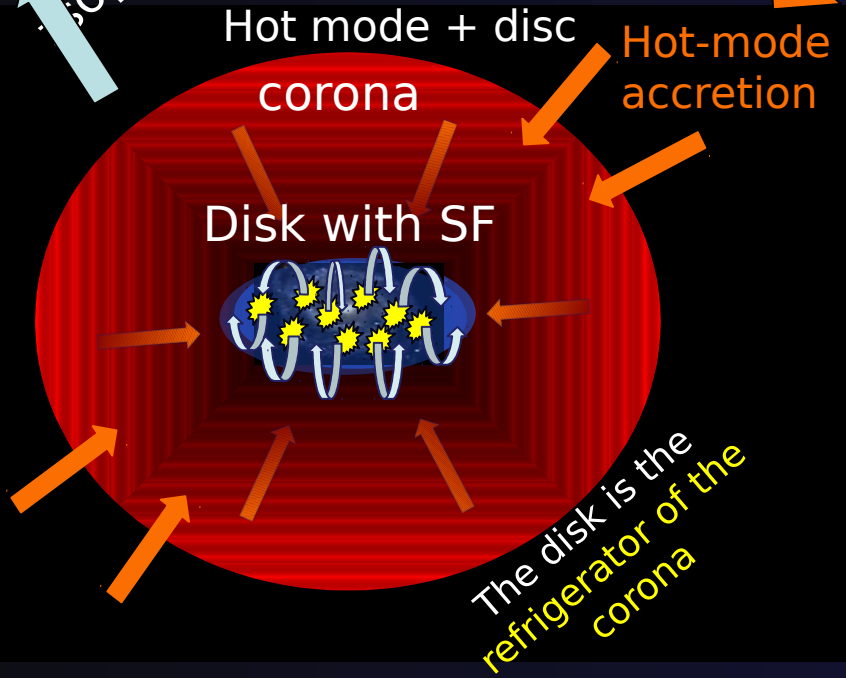
# Evolution of discs

Red and dead

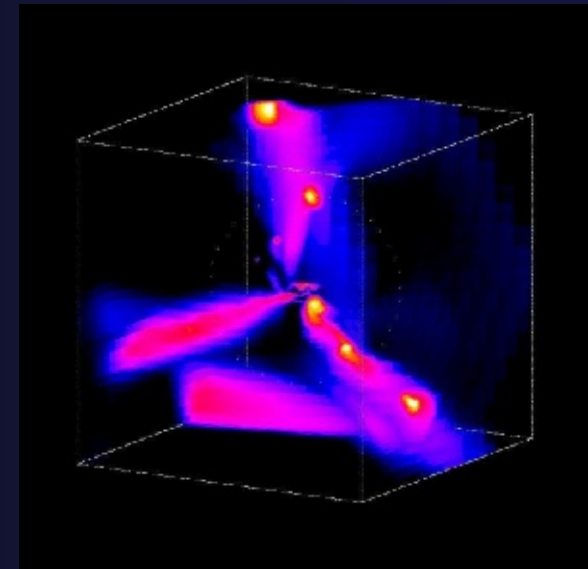


And the corona does not cool further

If gaseous disc is hot

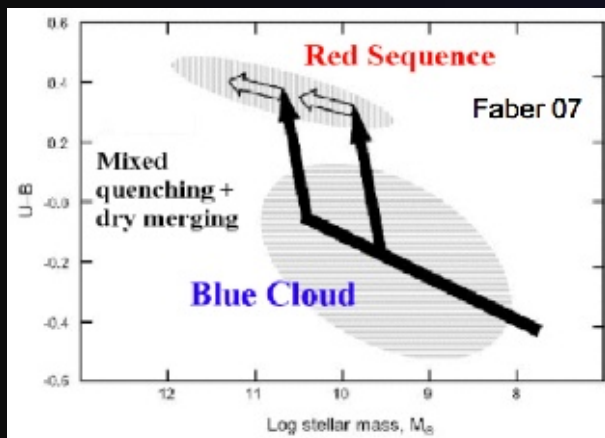
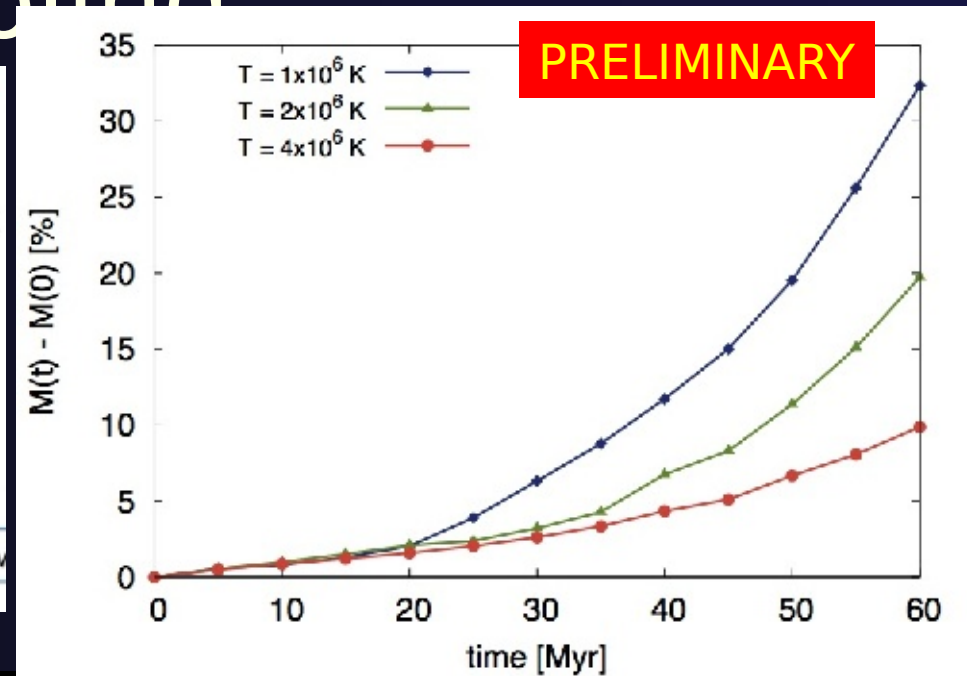
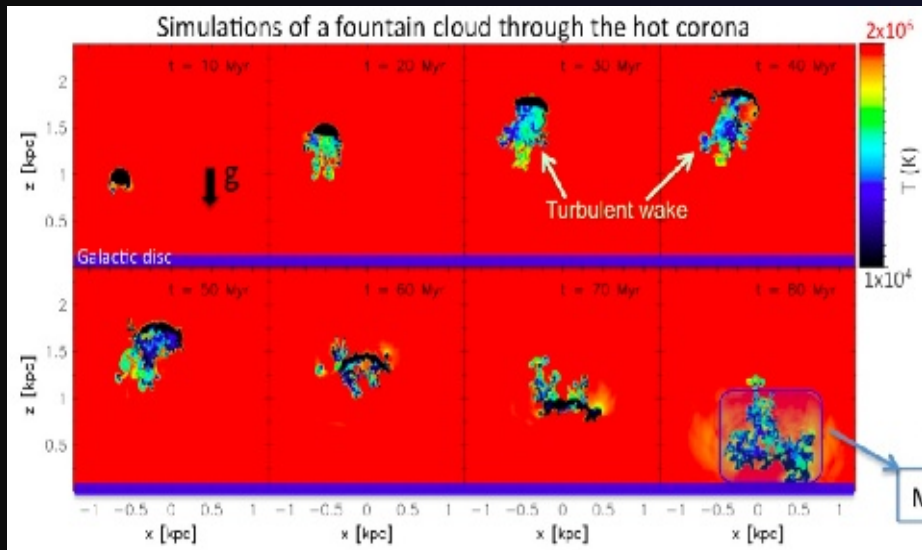


Cold mode



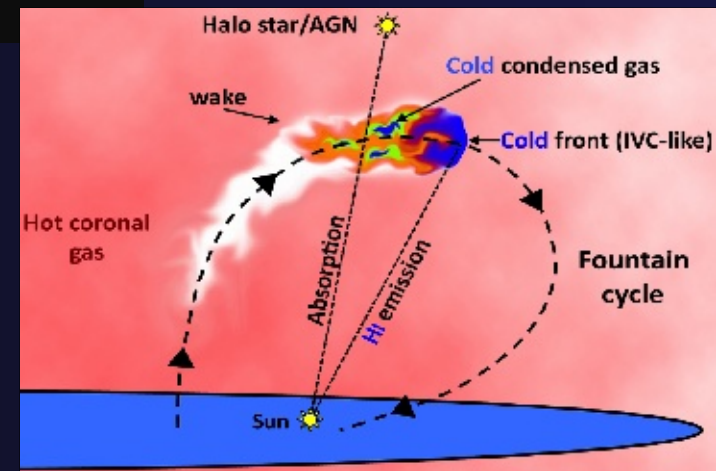
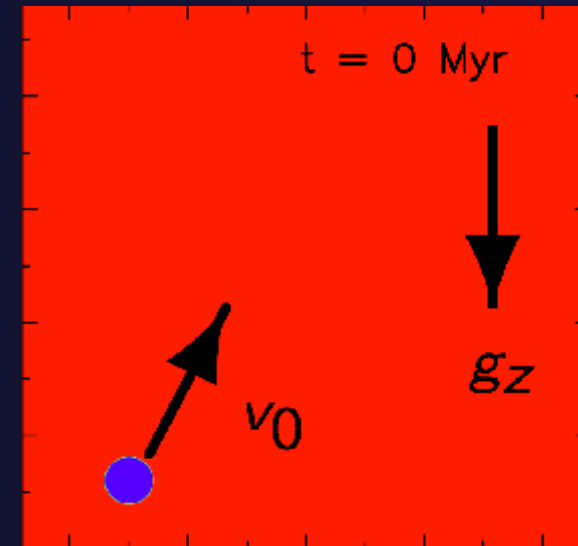
Dekel et al. 2009

# Efficiency of SN-driven cooling



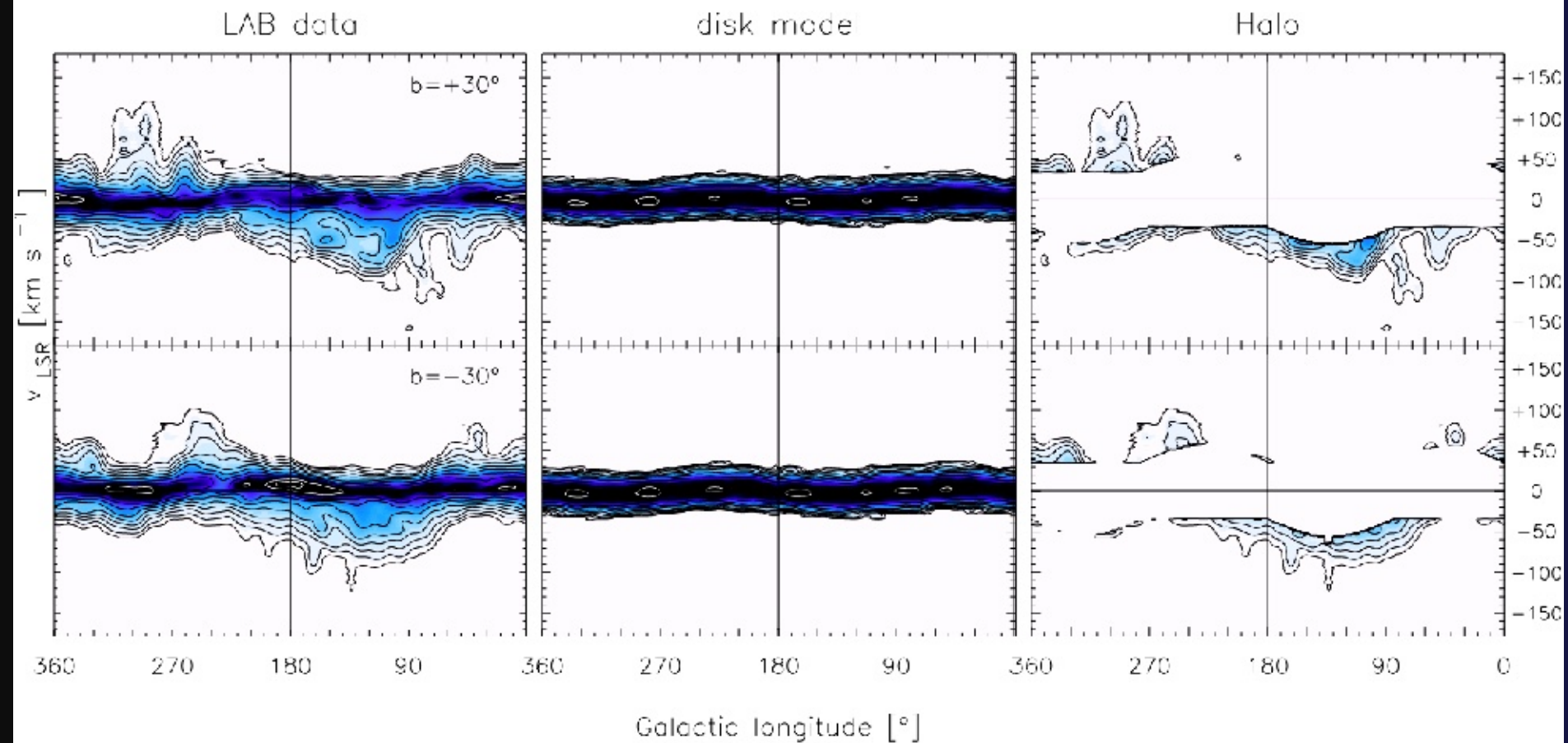
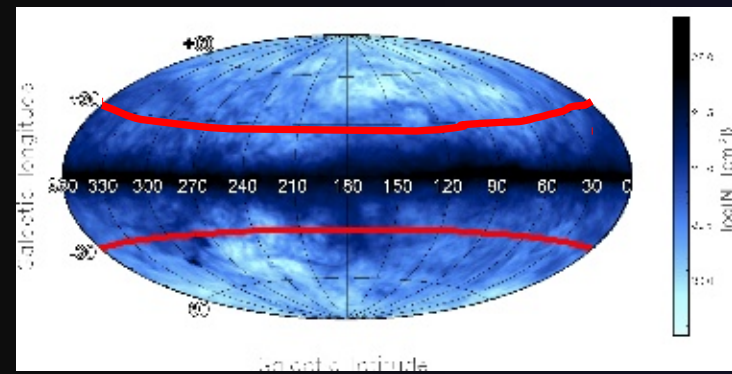
# Conclusions

- Supernova feedback cools the corona in star-forming galaxies like the MW
- **Very good fits:**
  - HI in the MW and external galaxies,
  - ionized absorbers in the MW
- This can be the way hot-mode accretion feeds star formation in disc galaxies

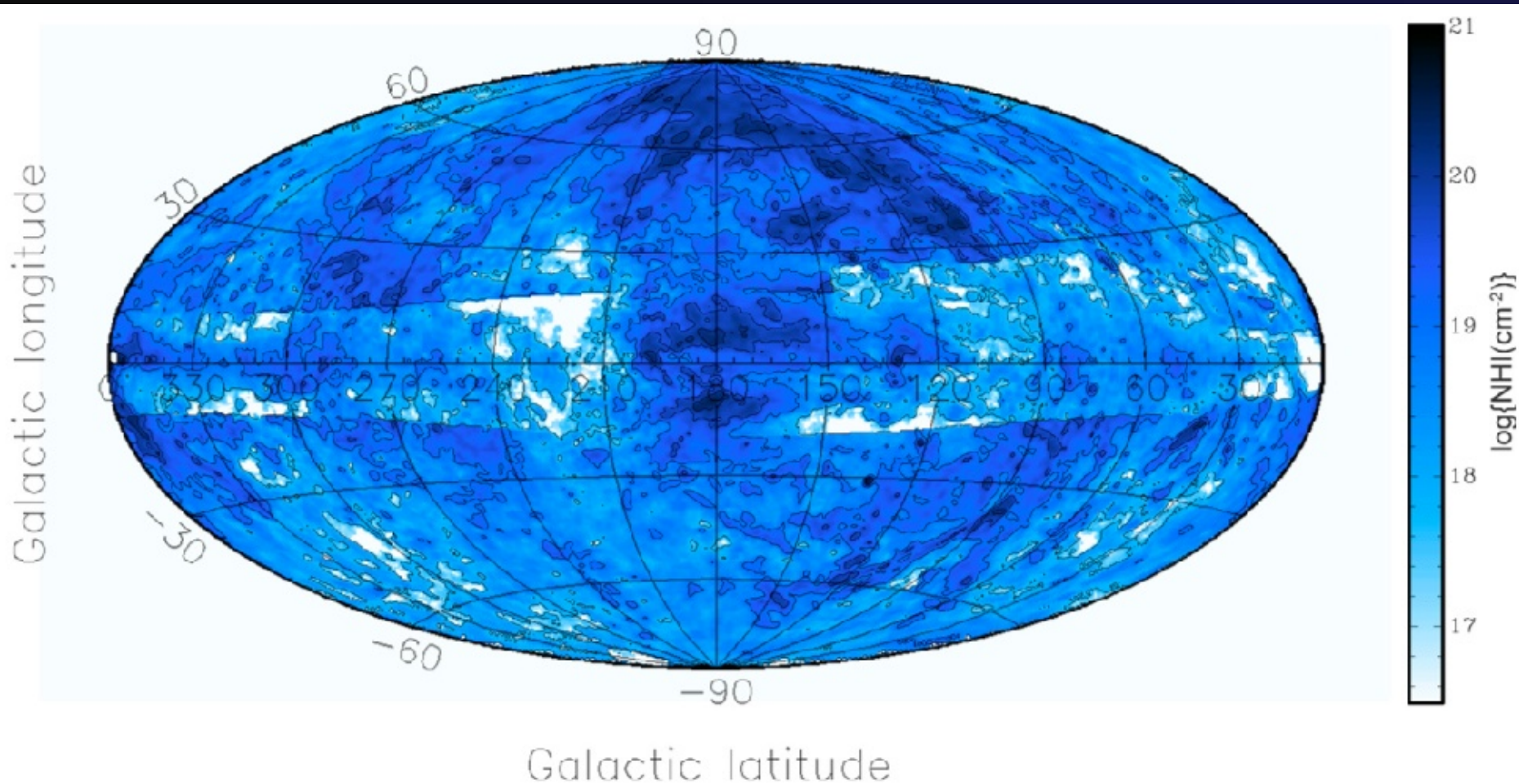


# 1. Extraplanar HI in the Milky Way

# HI disk and halo in the Milky Way



# HI halo - all-sky



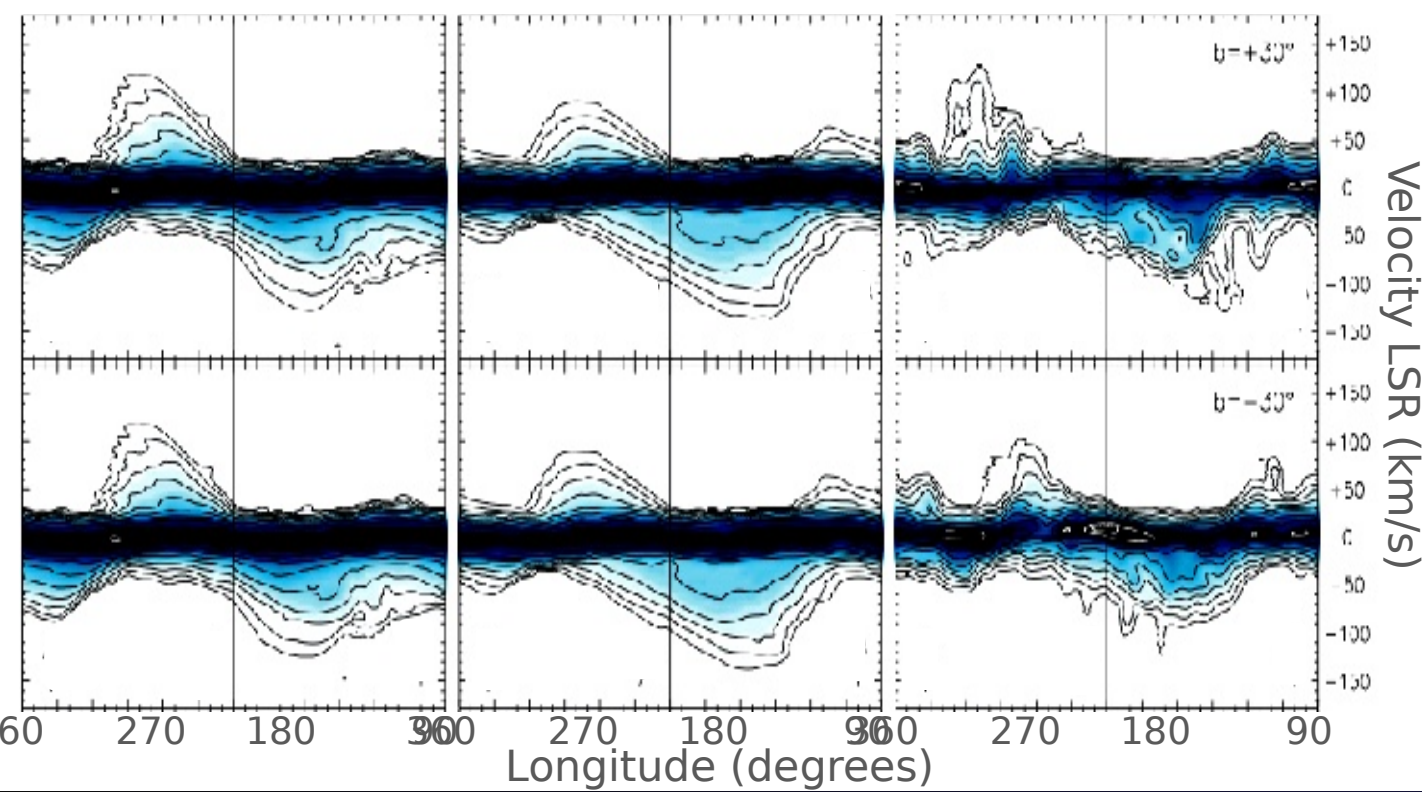
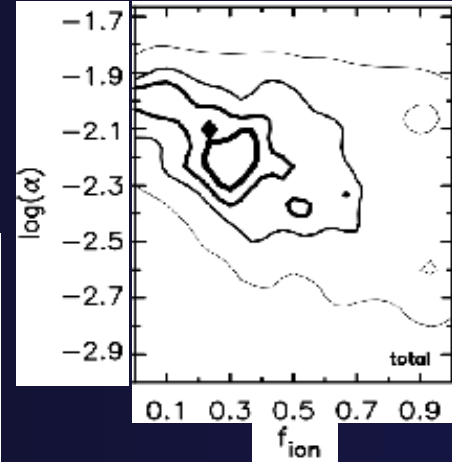
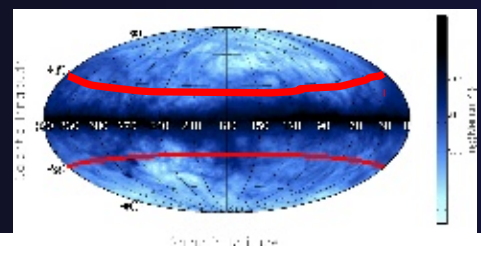
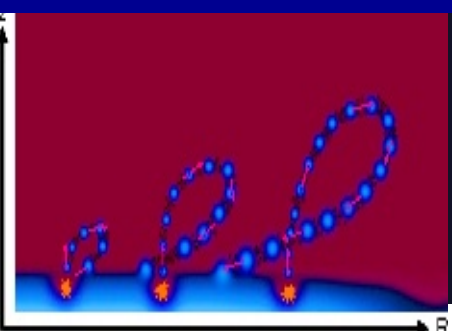
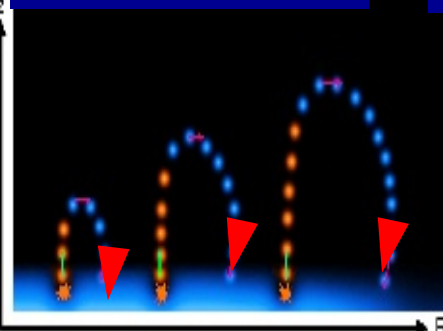
*Marasco & Fraternali 2011, A&A*

Pure fountain

Fountain + accretion

HI data

Best fit



$v_k = 75 \text{ km/s}$   
 $f_{\text{ion}} = 0.3$

$M_{\text{cor}} \sim 2 M_{\odot}/\text{yr}$

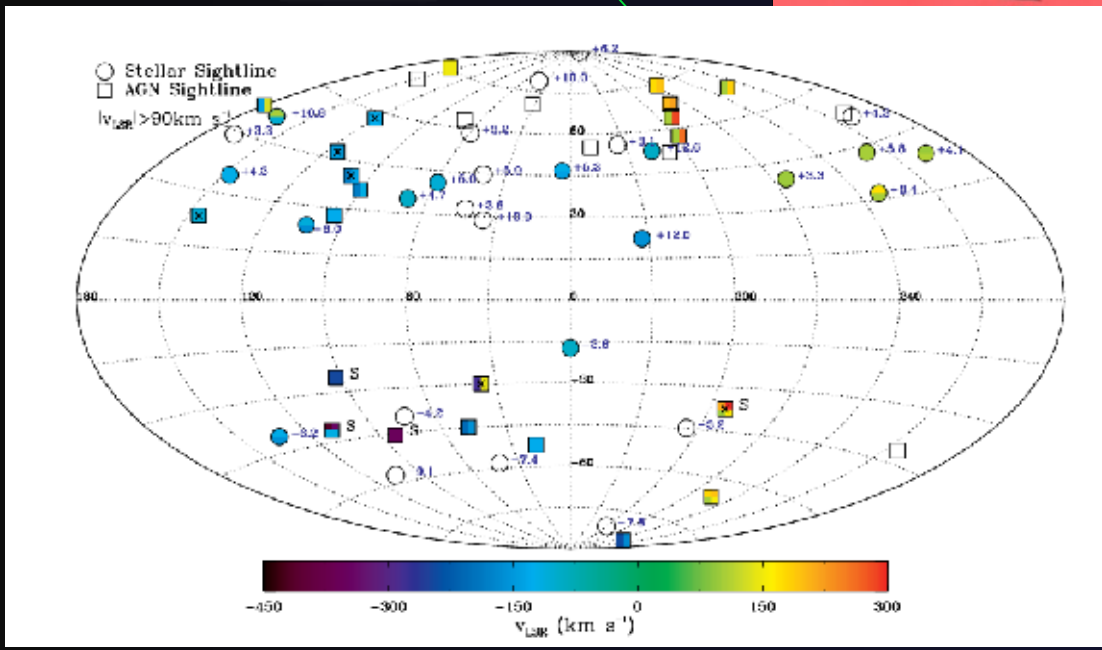
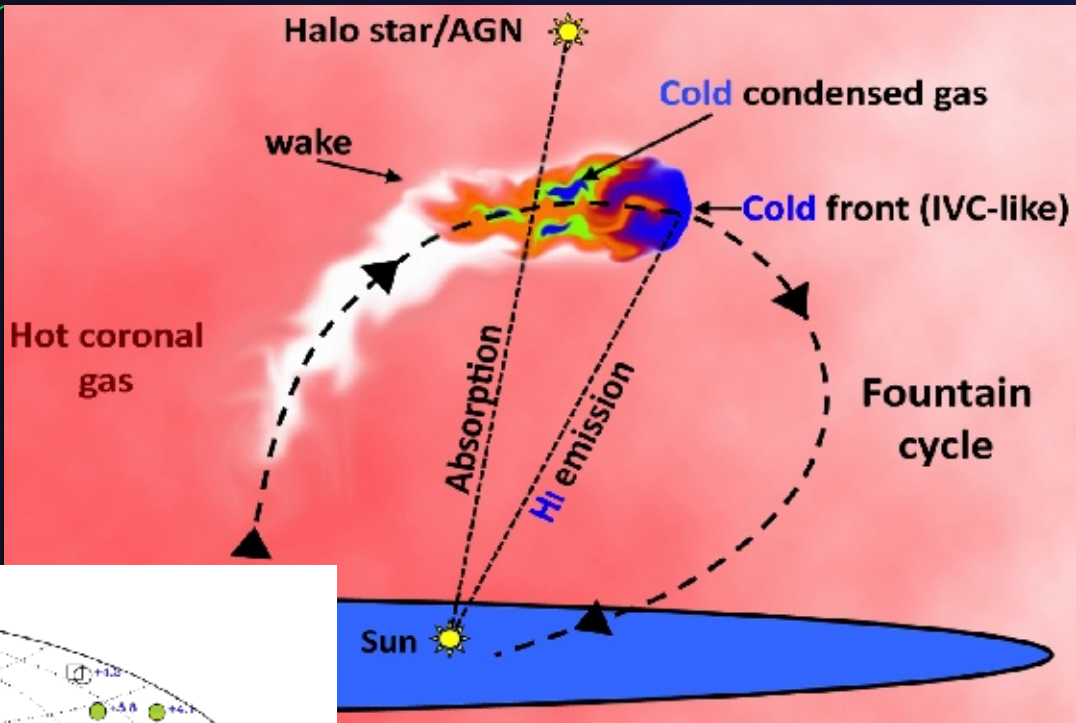
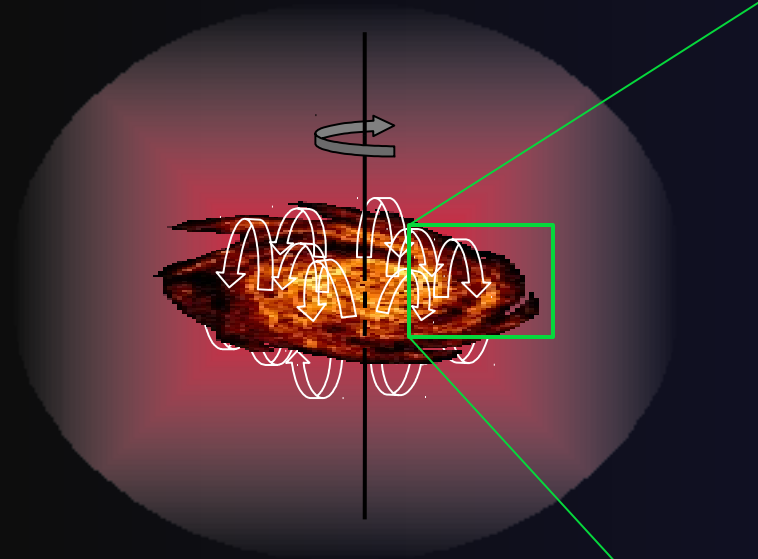
Halo gas:  
 ~80% from fountain  
 ~20% from corona

*Marasco, Fraternali & Binney 2012*

# 2. Absorption features



# Cooling in the wake



*Fraternali et al. 2013, ApJL*

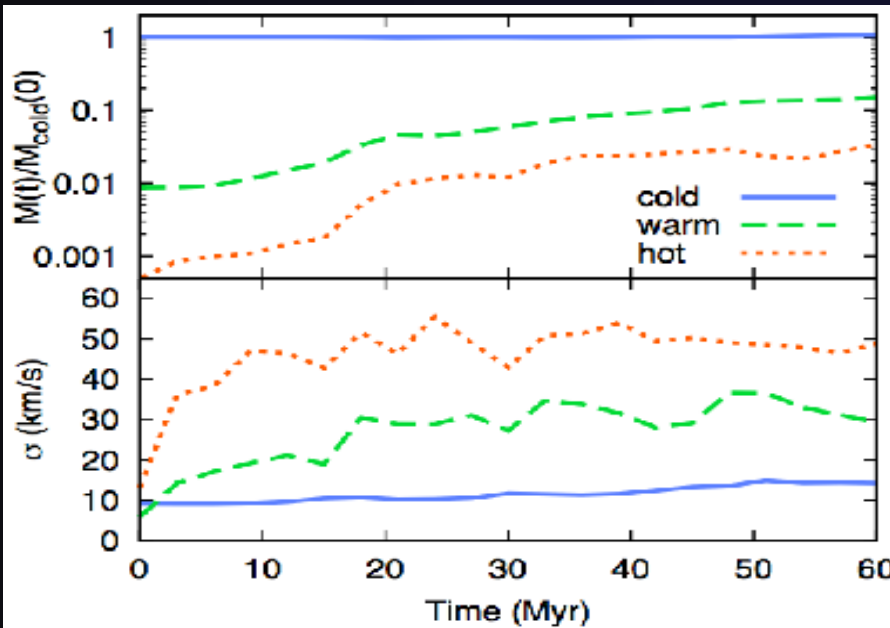
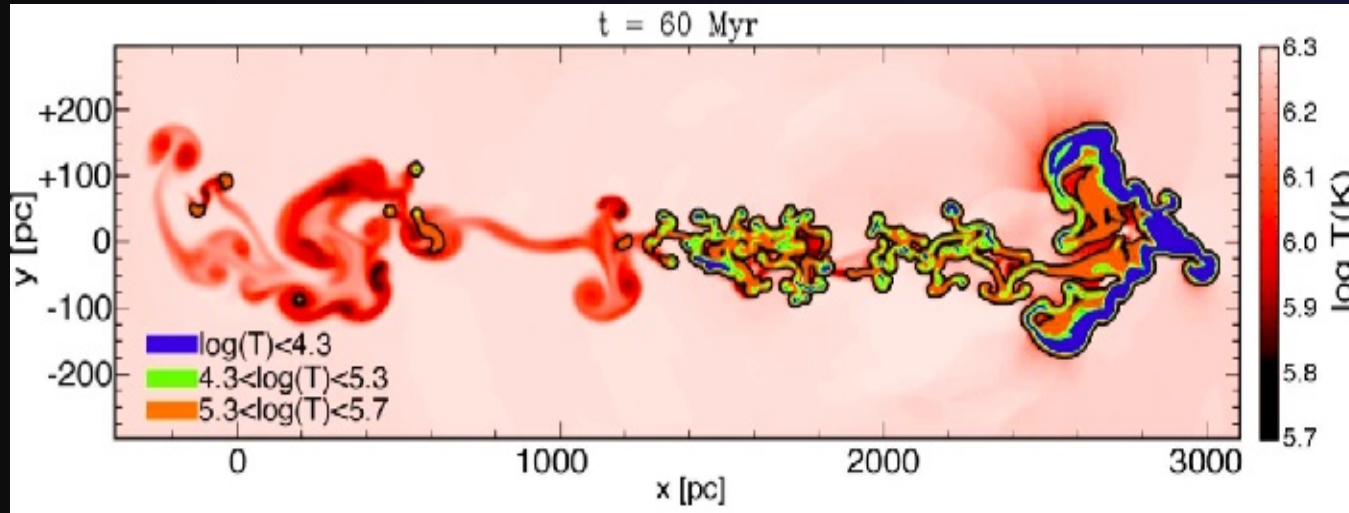
*Shull+ 2009, ApJ*

*Lehner & Howk 2011, Science*

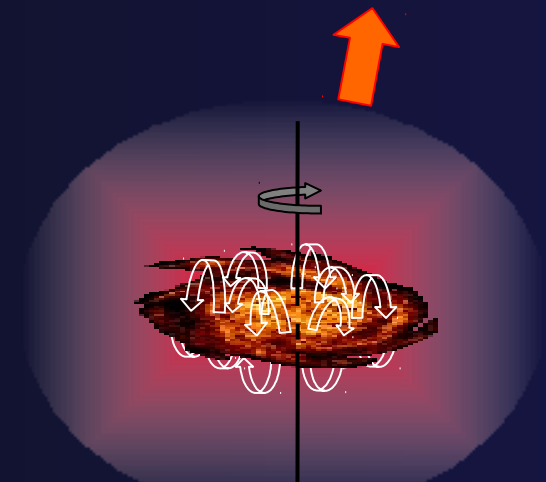
*Lehner et al. 2012, MNRAS*

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

# Evolution of the wake



DYNAMICAL MODEL  
for the IONISED GAS  
(no free parameters)



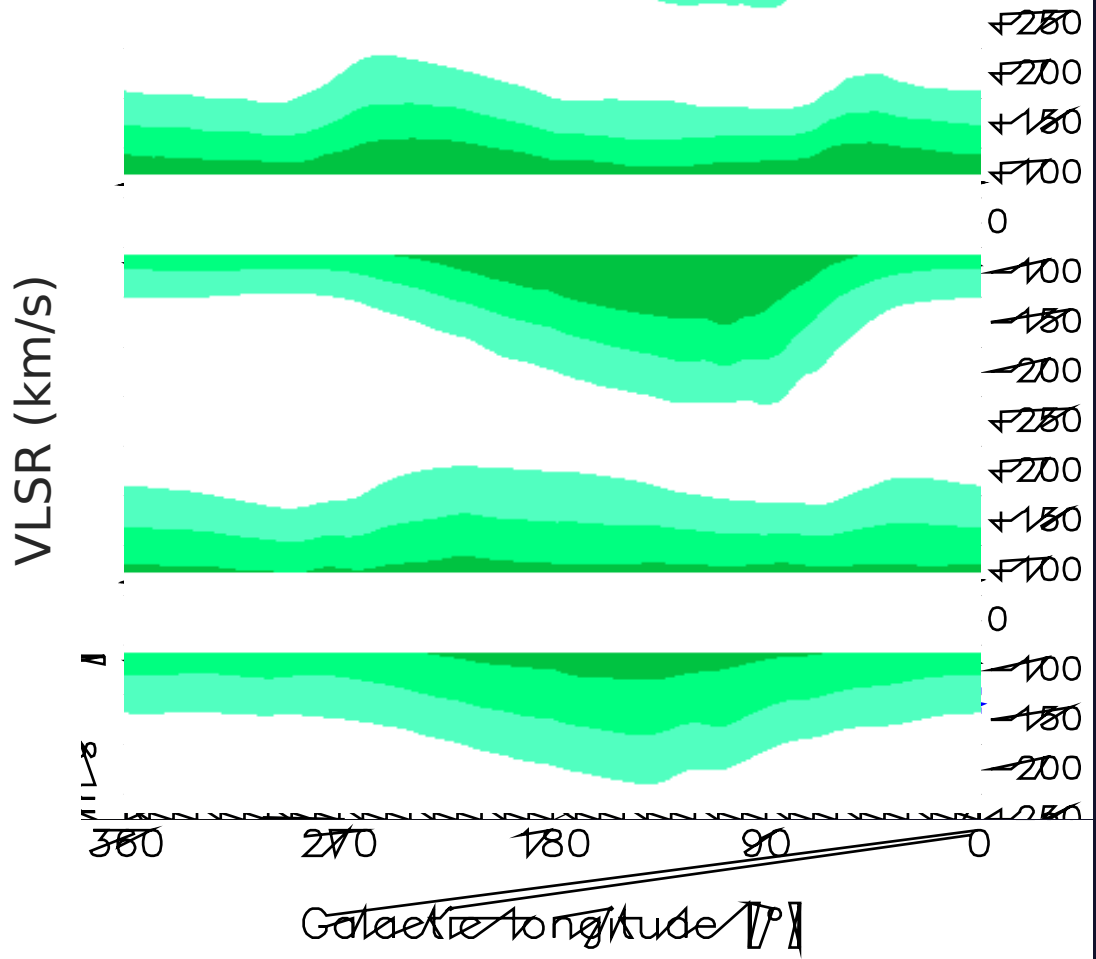
Marasco, Marinacci & Fraternali 2013, MNRAS

Filippo Fraternali (Bologna/Groningen)

Interplay local & global processes in galaxies - Cozumel, Mexico - 14/4/16

# in the MW

Marasco



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:  $\sim 1 M_{\odot}/\text{yr}$

Filippo