# Stream-Driven Galaxy Formation at High Redshift

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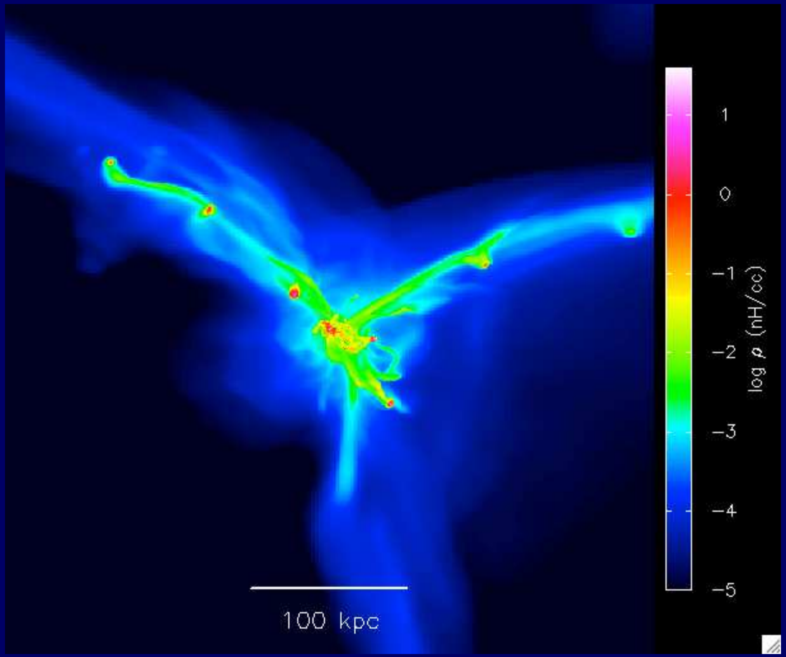
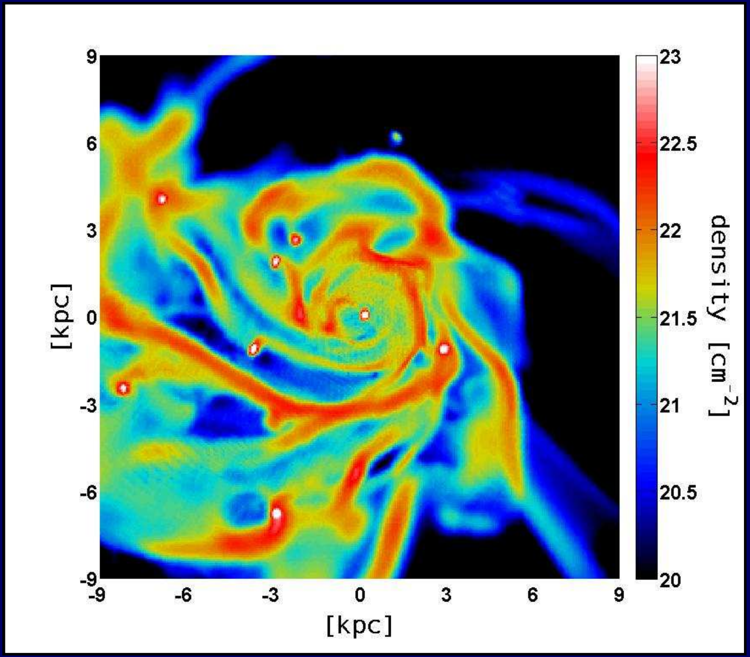
KooFest, Santa Cruz, August 2011





# Outline

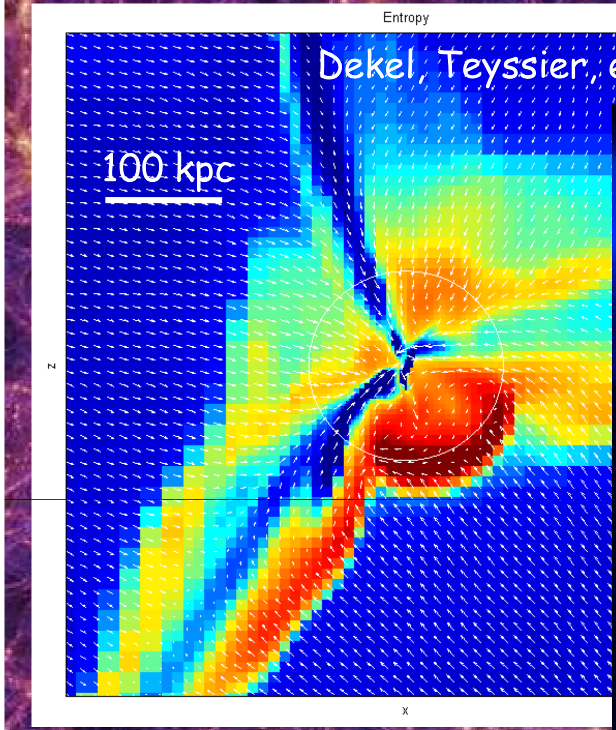
1. Streams in pancakes from the cosmic web (Hahn)
2. Is **angular momentum** conserved in disk formation?
3. Outflows and inflows
4. Observing cold streams (Fumagalli, Kasen)
5. SFR and quenching in stream-fed disks (Krumholz)
6. Violent disk instability, clumpy disks (Ceverino, Mozena, Burkert, Genzel, Newman)
7. Evolution of instability (Cacciato, Forbes)
8. Instability-driven **bulge** and **black hole**

# 1. Streams in Pancakes from the Cosmic Web

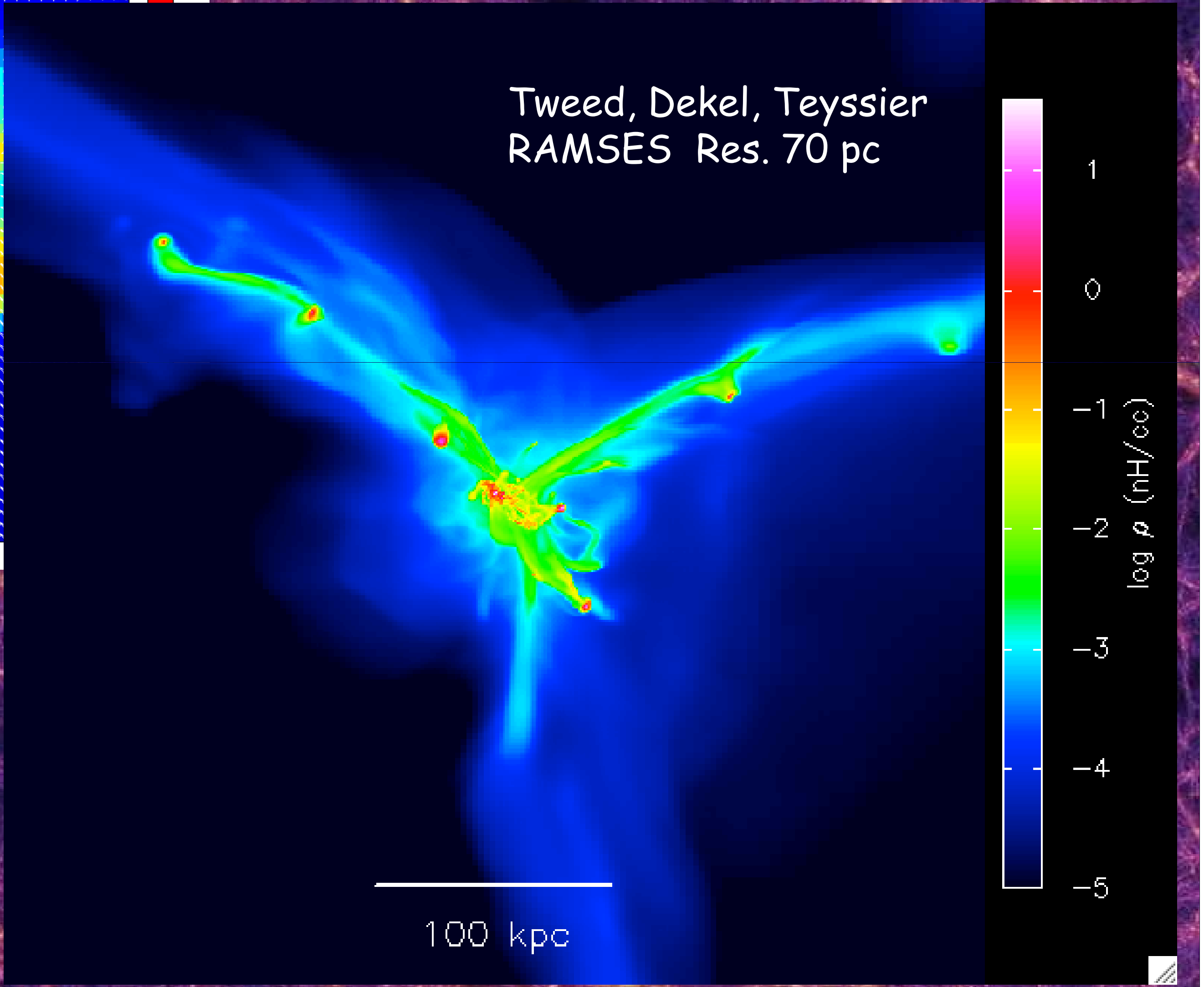
Danovich, Dekel, Hahn, Teyssier 2011; Pichon et al. 2011
AMR cosmological simulation MareNostrum
RAMSES, resolution 1 kpc, 350 galaxies, at z=2.5

Hahn, Dekel, Ceverino, Primack et al. 2011; Kimm et al. 2011
AMR cosmological zoom-in simulations
ART, resolution 35-70 pc, 7 galaxies, at z=7-1

# Streams riding DM filaments of Cosmic Web

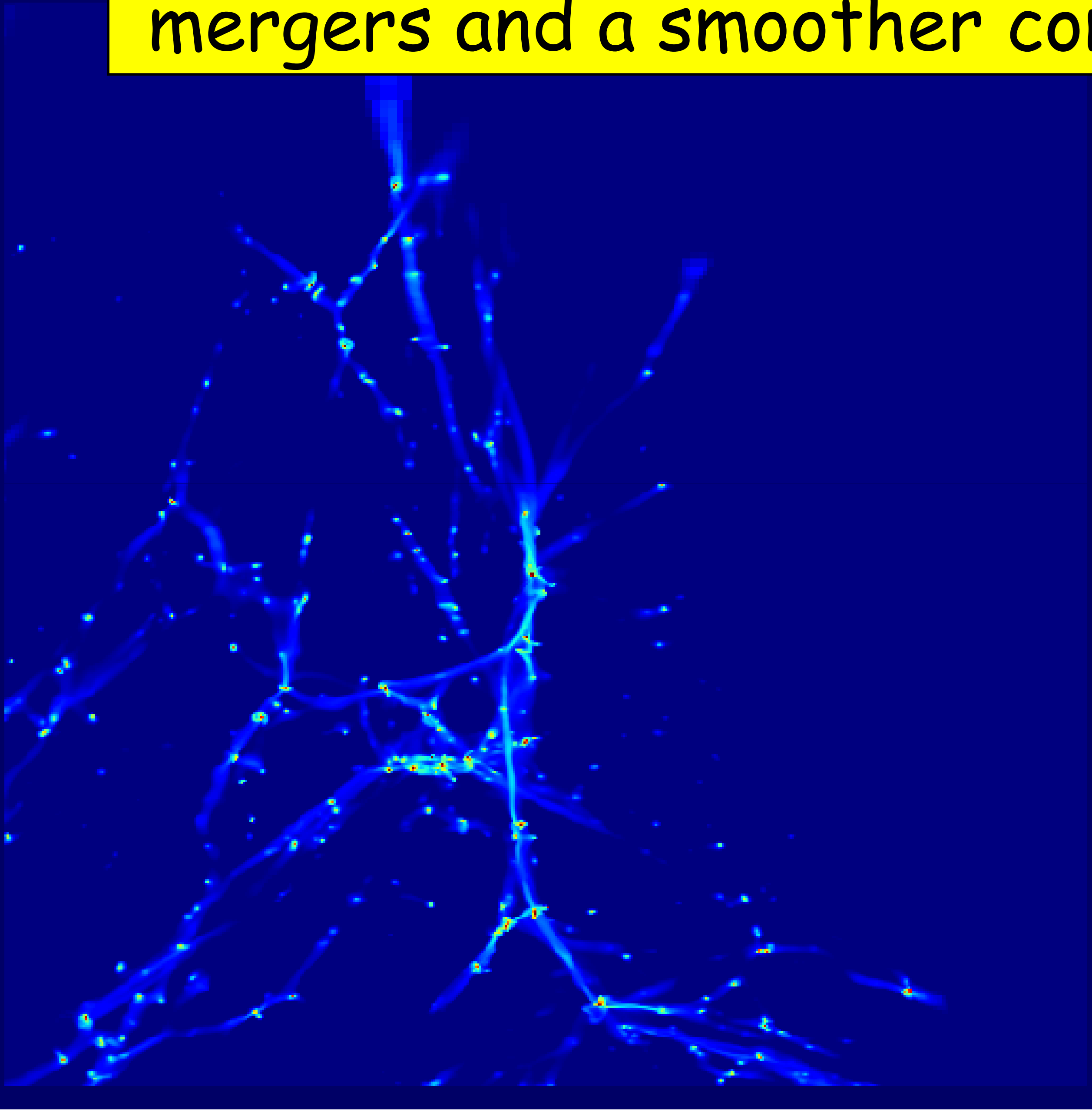


Dekel, Teyssier, et al 09



Tweed, Dekel, Teyssier
RAMSES Res. 70 pc

# Cosmic-web Streams feed galaxies: mergers and a smoother component



AMR RAMSES
Teyssier, Dekel

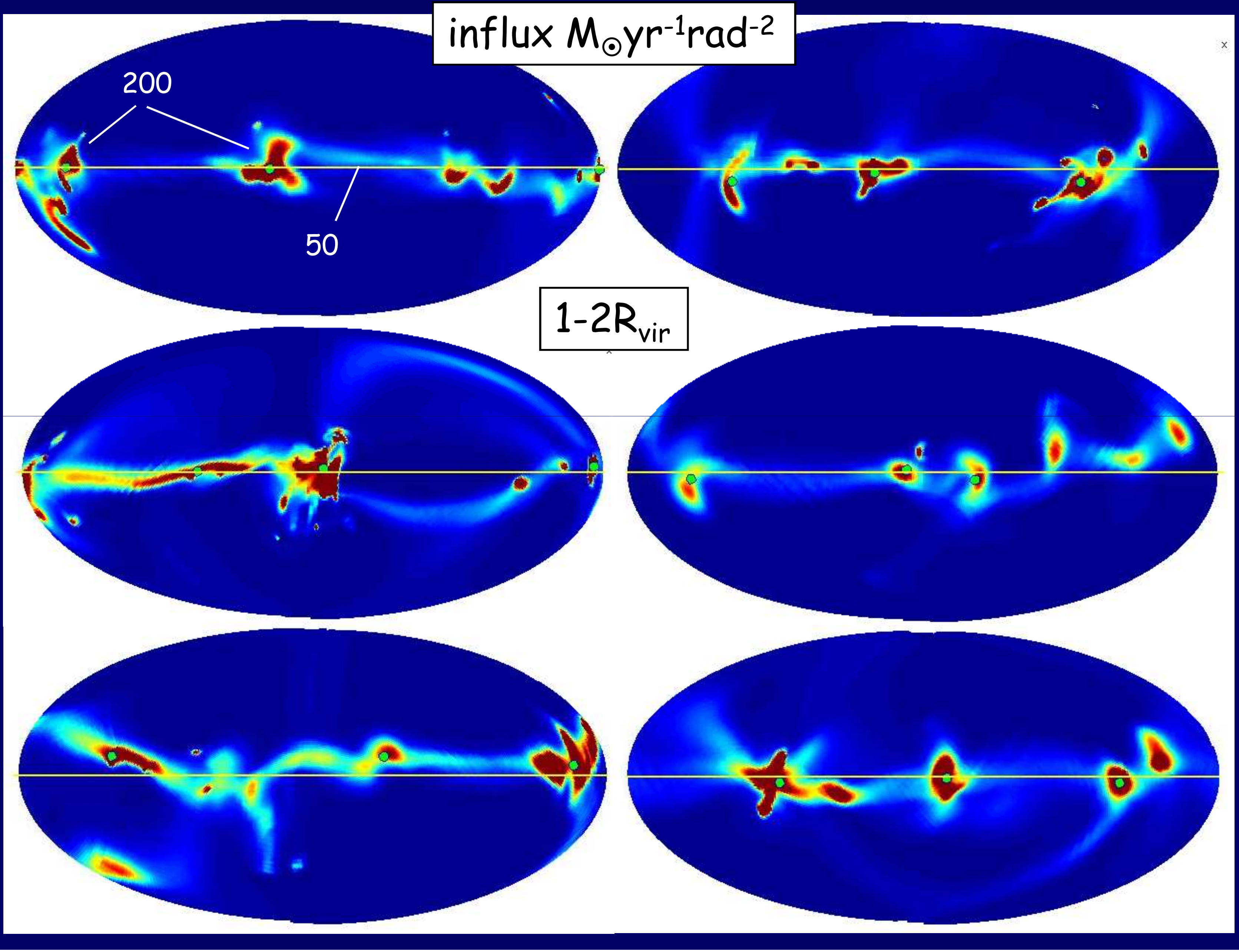
box 300 kpc

res 30 pc

$z = 5.0$ to 2.5

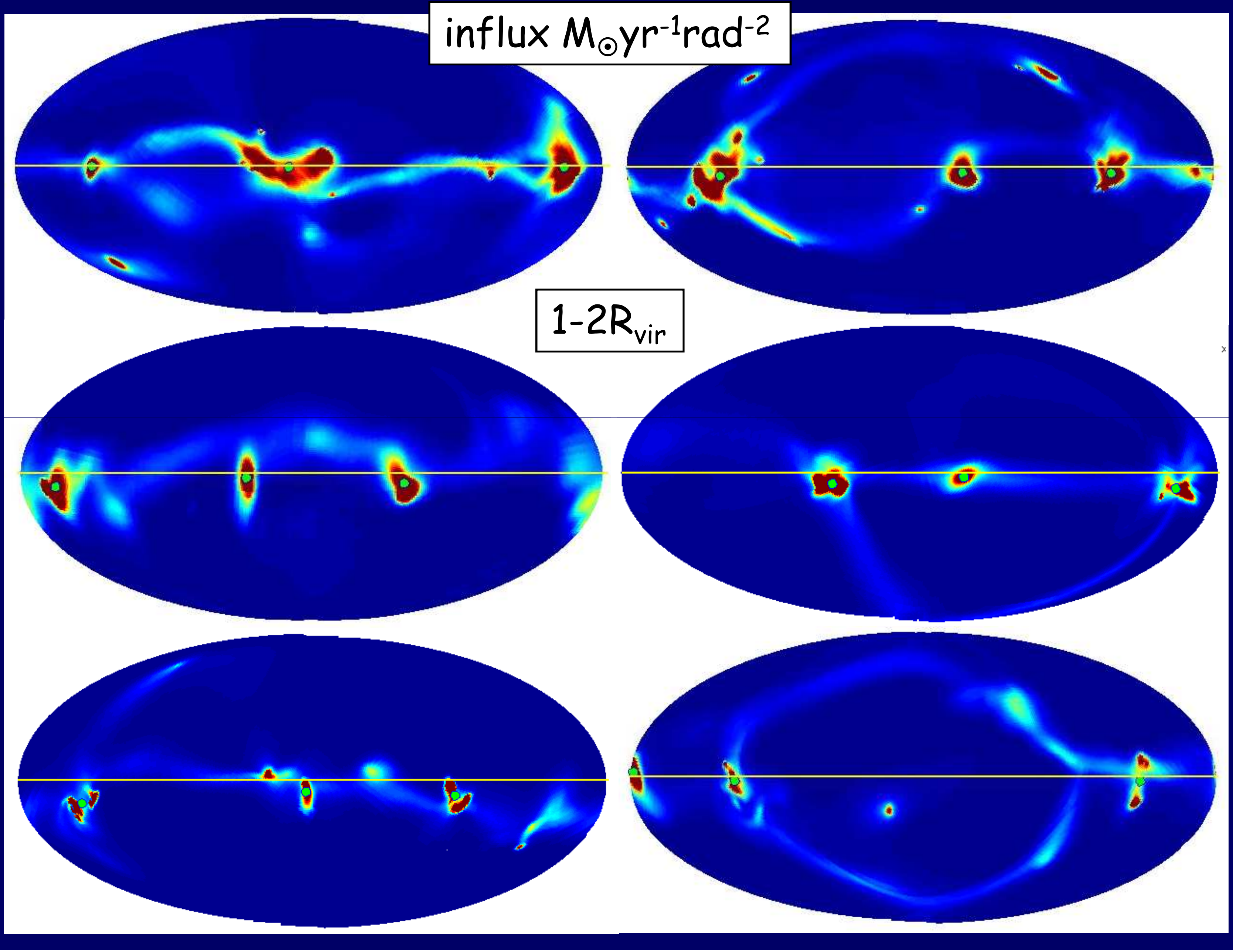
# Co-planar Streams and Pancakes

Danovich, Dekel, Teyssier



# Co-planar Streams and Pancakes

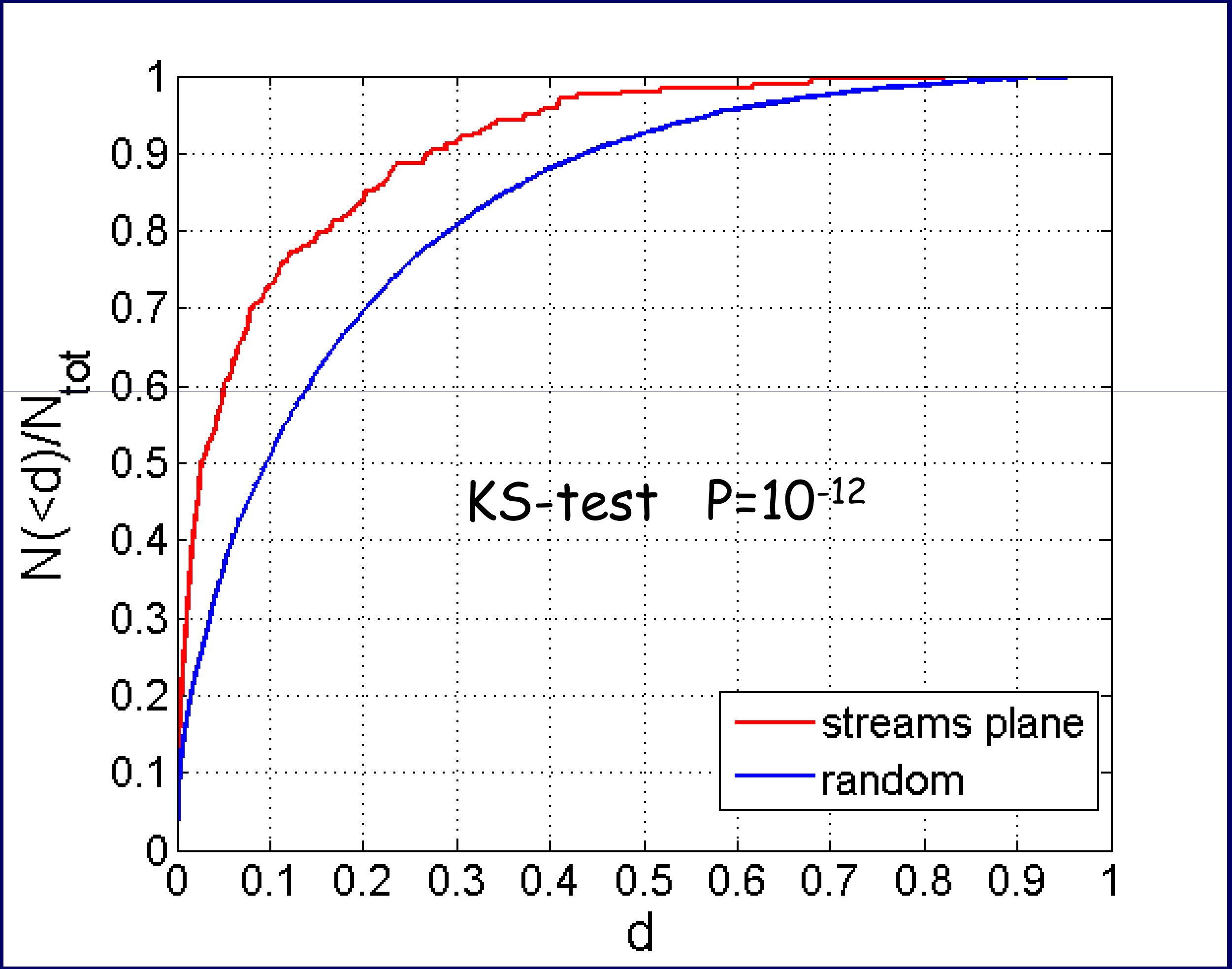
Danovich, Dekel, Teyssier



influx $M_{\odot} yr^{-1} rad^{-2}$

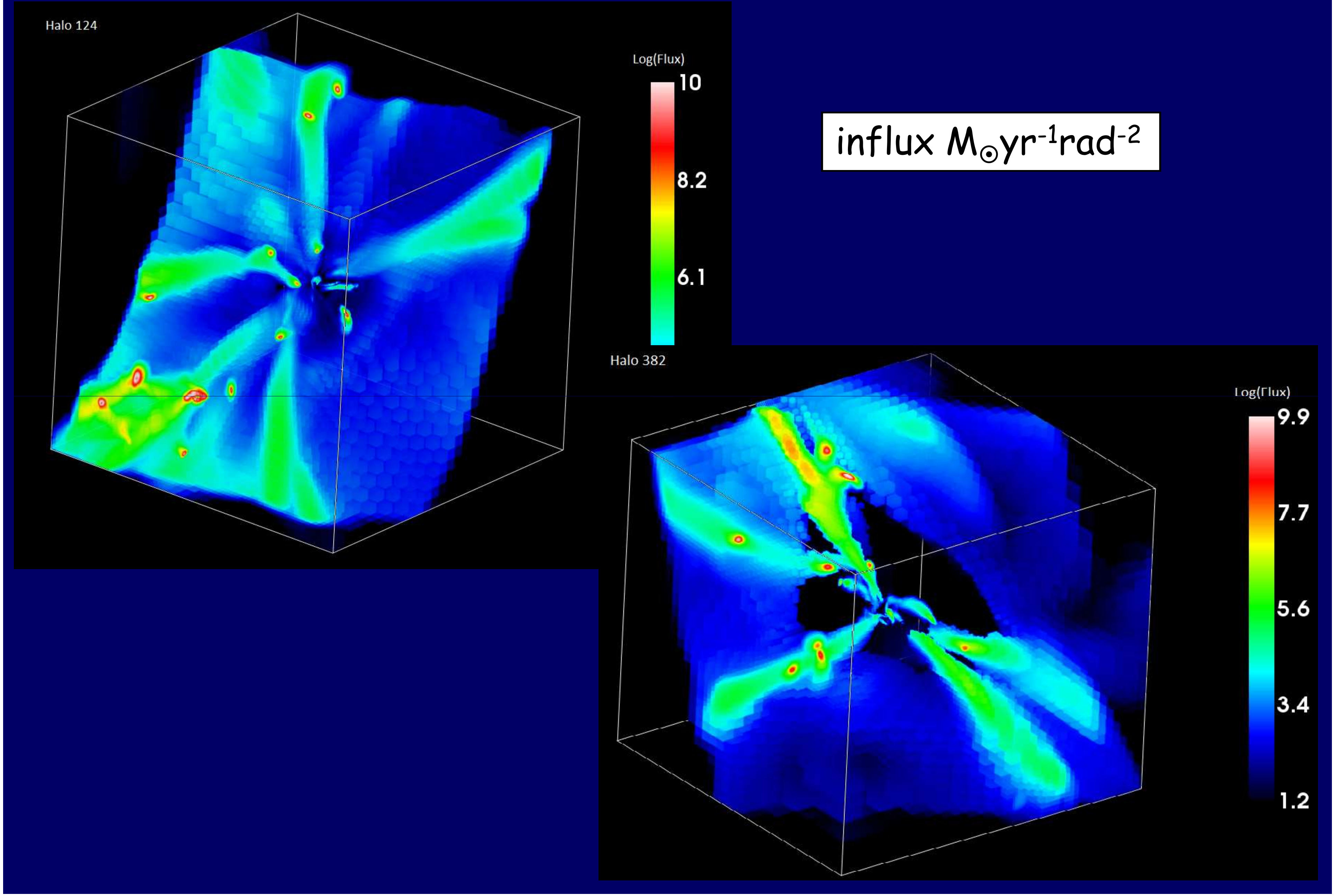
$1\text{-}2R_{vir}$

# The Streams tend to be Co-plannar



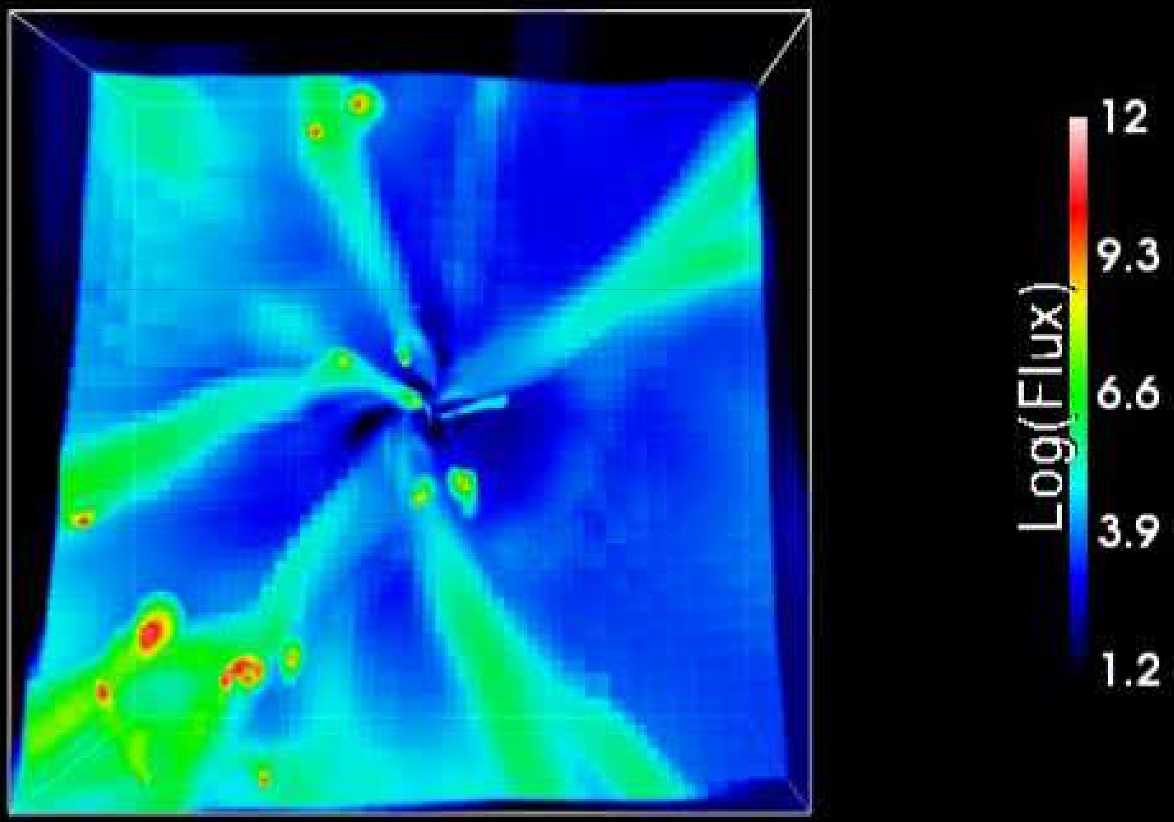
rms distance from best-fit plane

# Streams in a Pancake

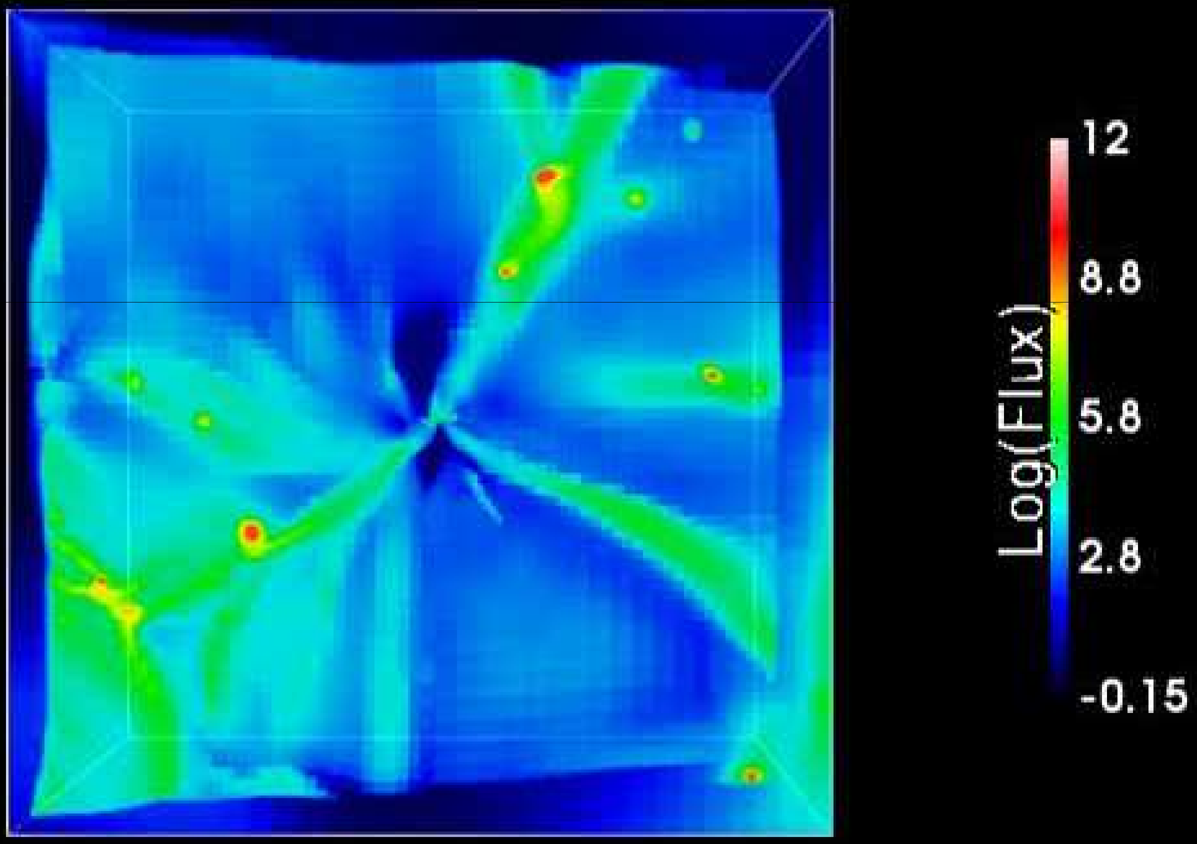


influx $M_\odot yr^{-1} rad^{-2}$

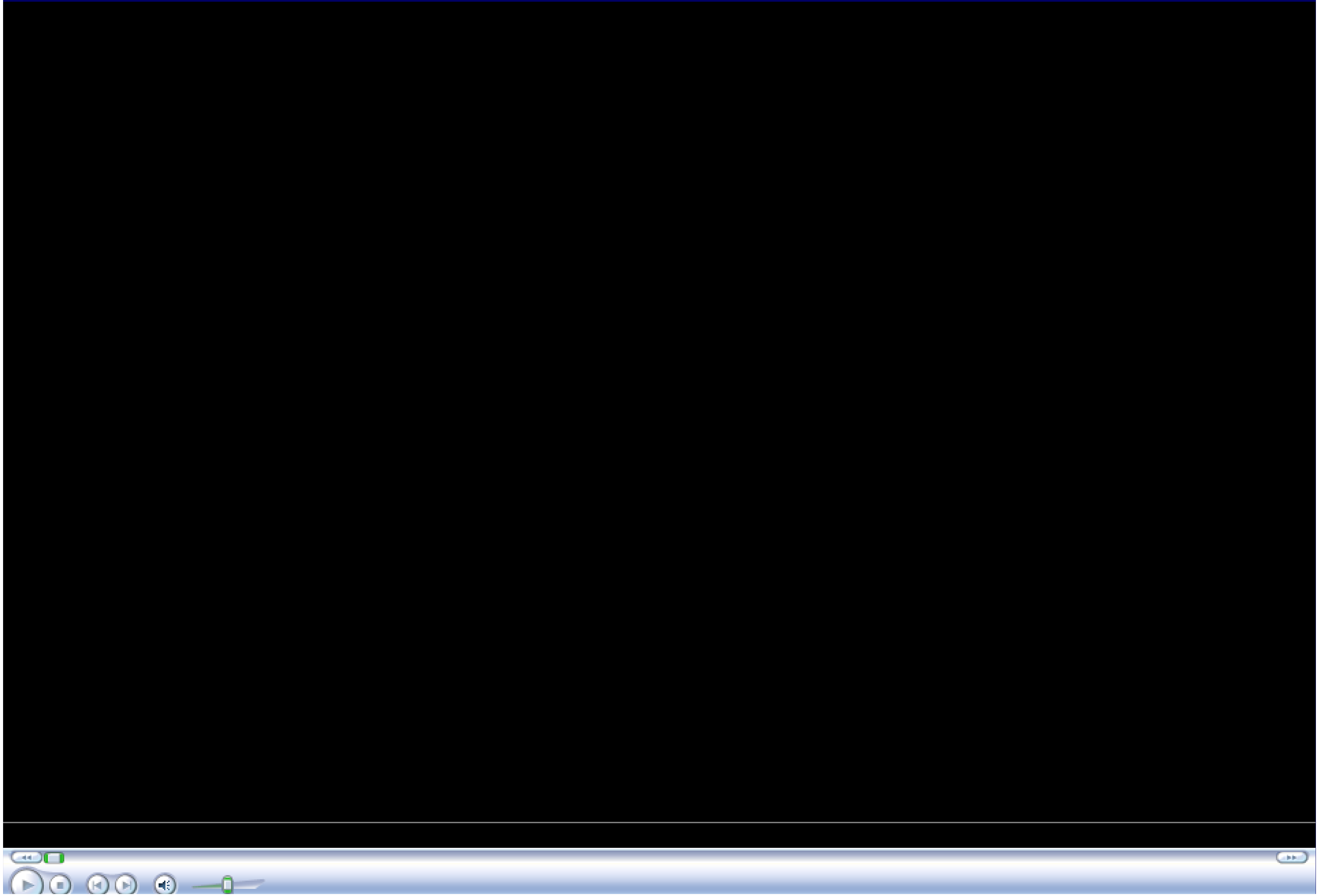
# Streams in a Pancake



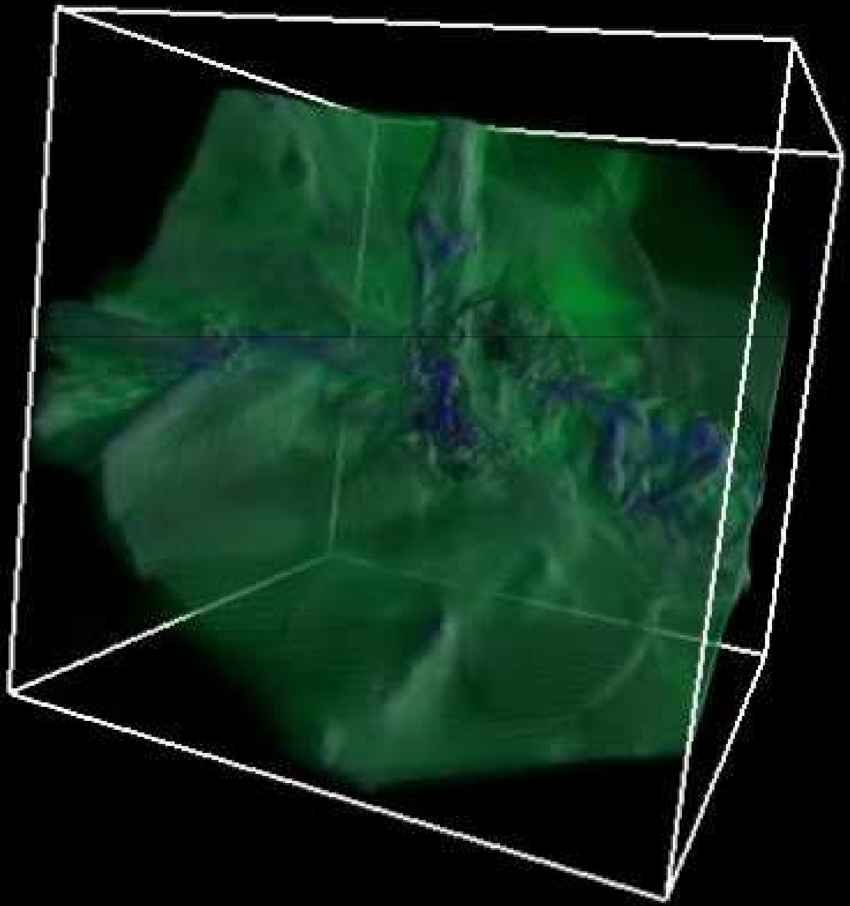
# Streams in a Pancake



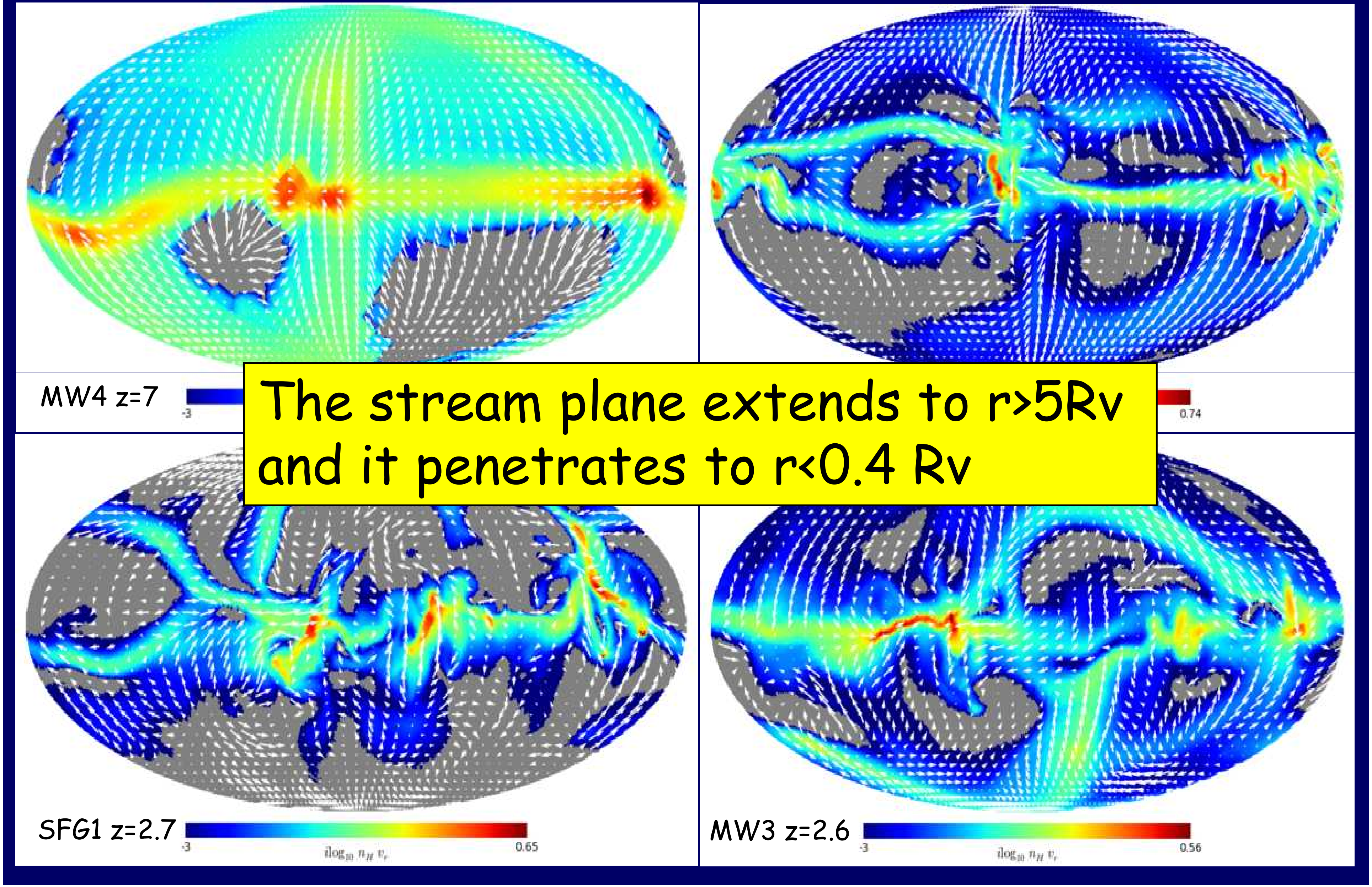
# Streams in Pancakes



# Streams in a Pancake

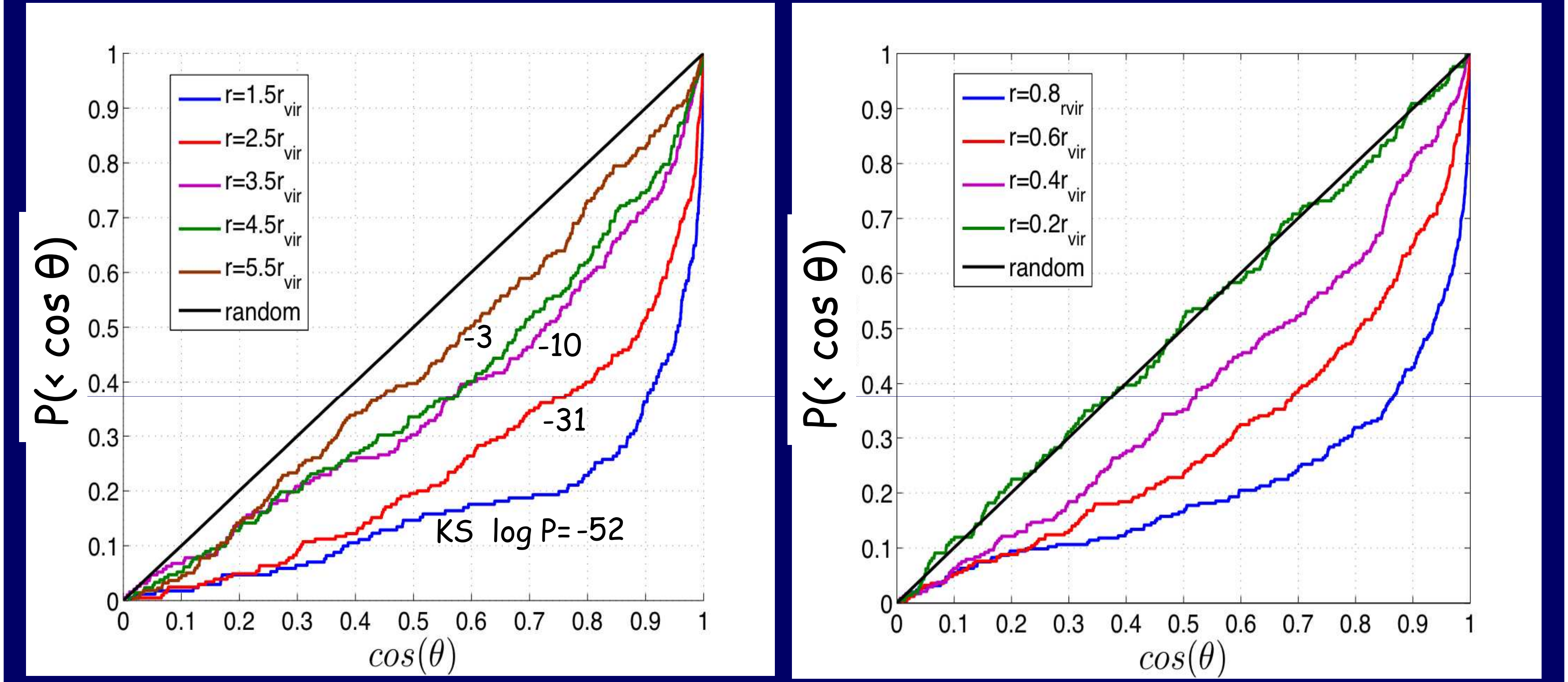


# Flows into pancakes, and along pancakes to filaments



The stream plane extends to r>5Rv
and it penetrates to r<0.4 Rv

# Extension of the Stream Plane

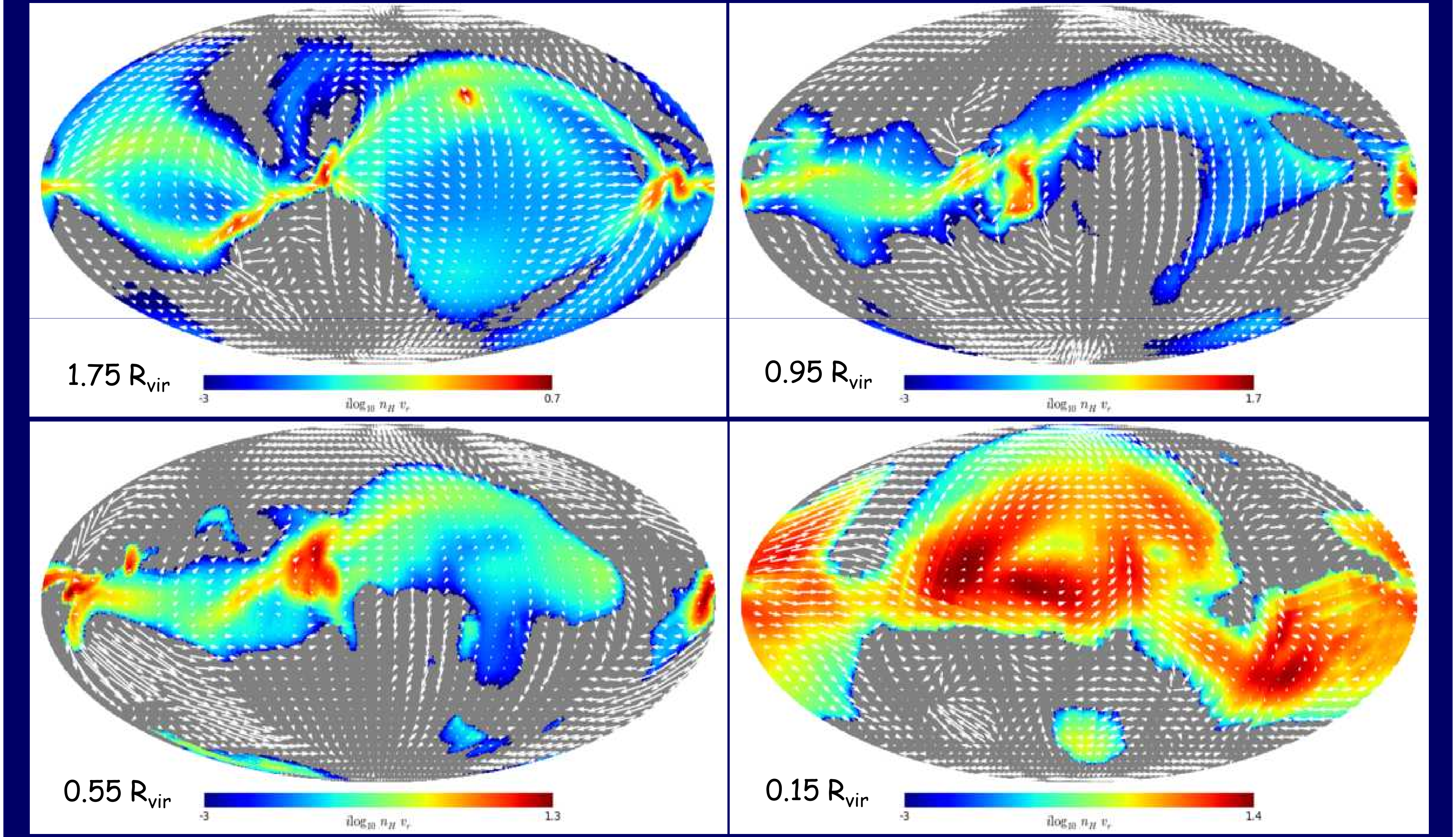


Angle between plane at $R_{vir}$ and plane at r

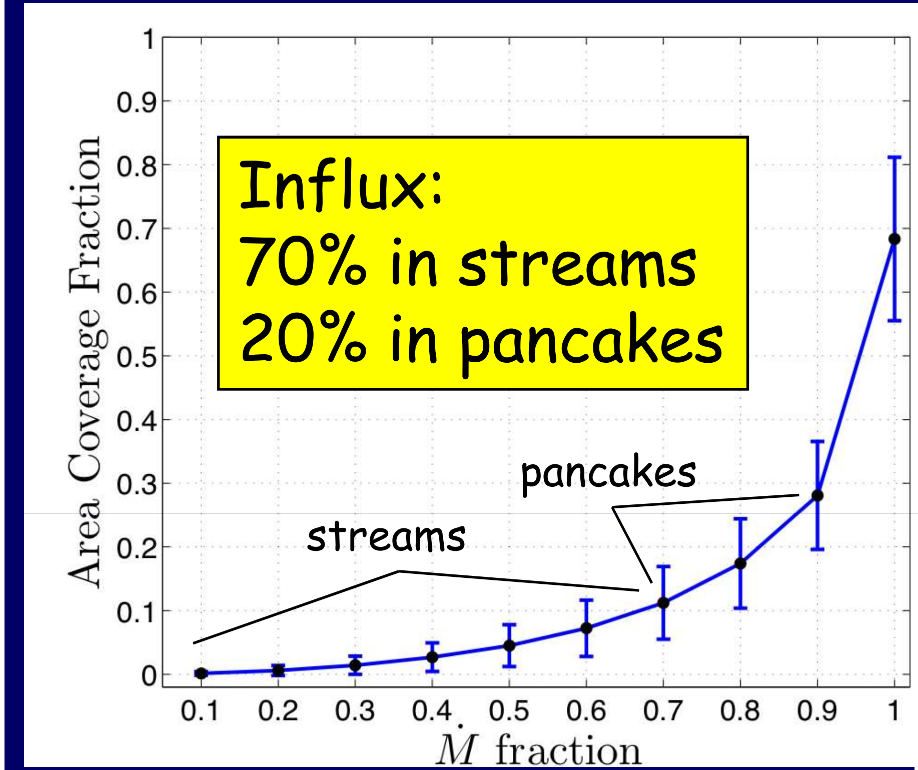
The stream plane extends to r>5Rv and it penetrates to r<0.4 Rv

# Deep Penetration of streams and pancake

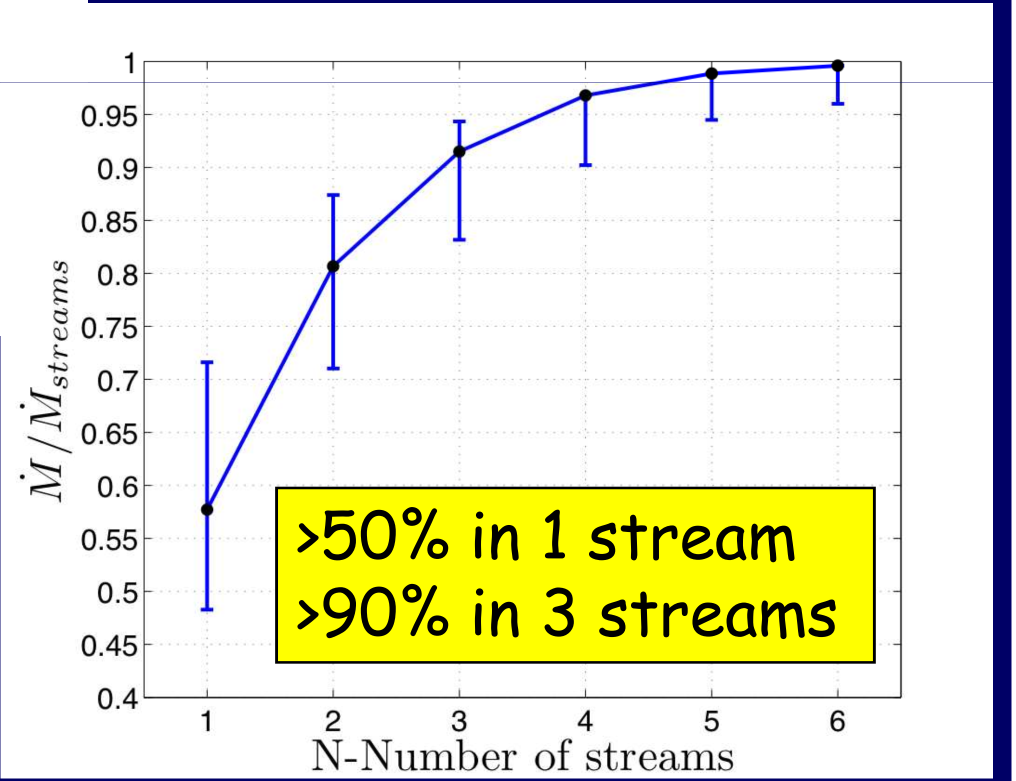
MW4 z=4



# Distribution of Influx in Streams and Pancakes



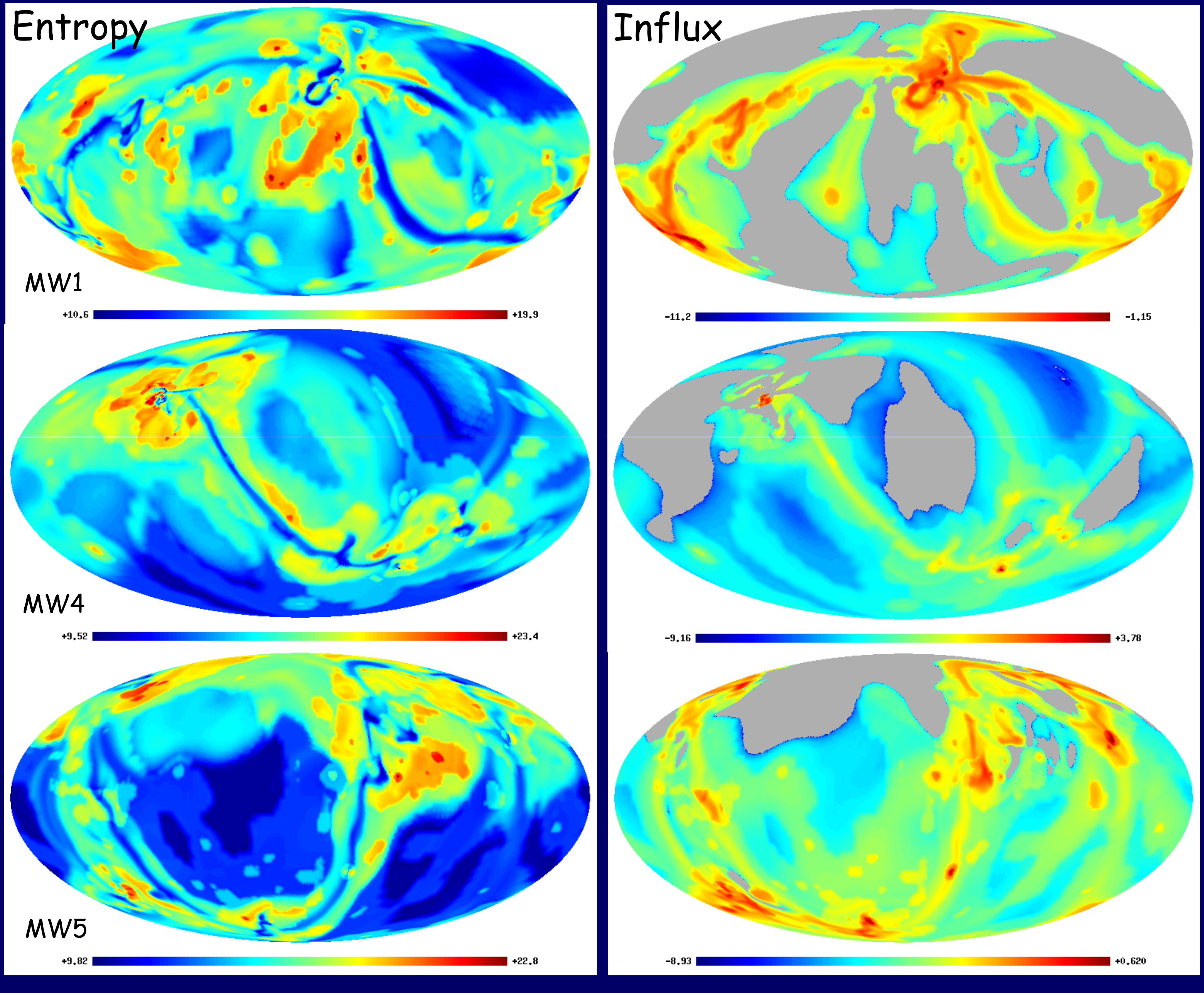
Influx:
70% in streams
20% in pancakes



>50% in 1 stream
>90% in 3 streams

# Pancakes of low Entropy

Hahn



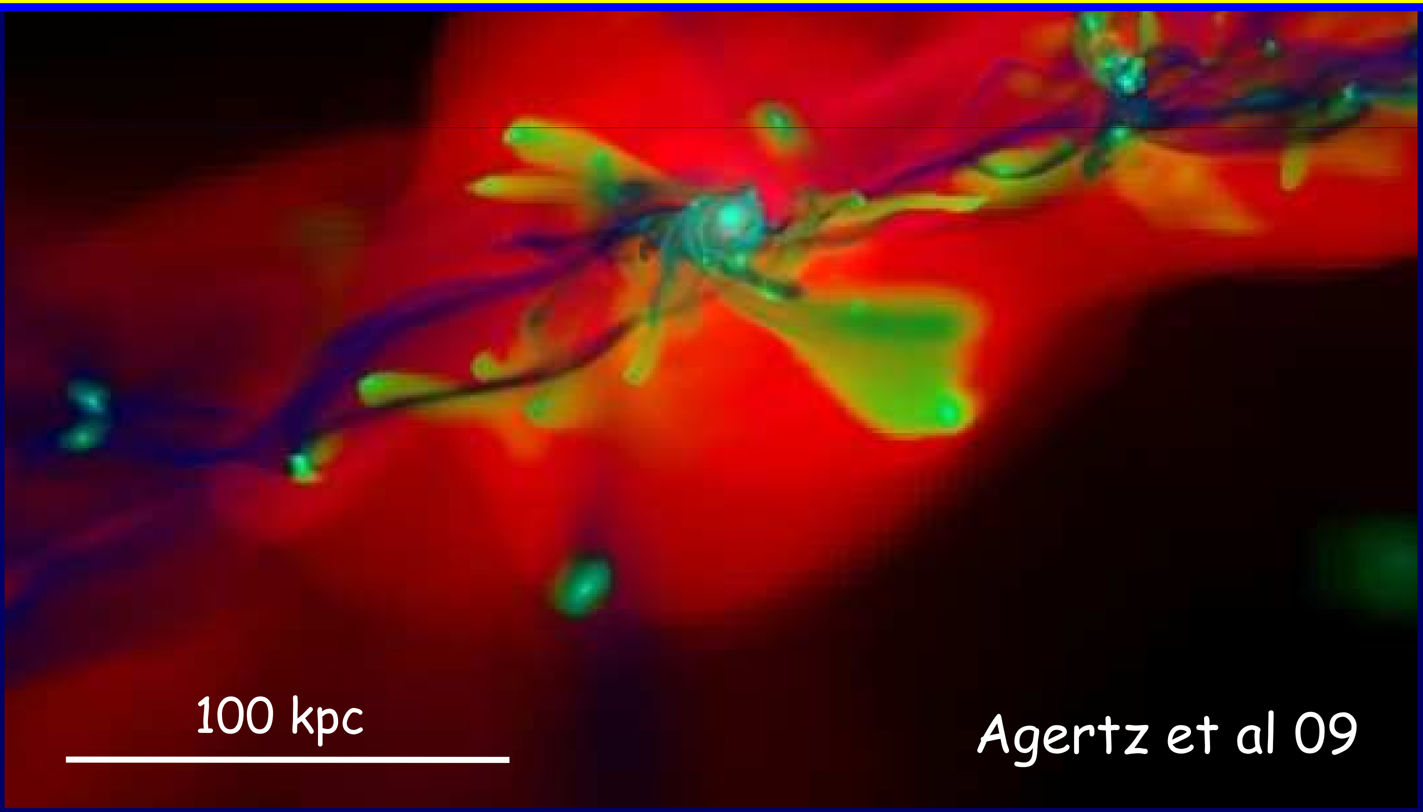
# 2. Is Angular Momentum Conserved in Disk Formation?

Danovich, Dekel, Hahn, Teyssier 2011
Hahn, Dekel, Ceverino, Primack et al. 2011

Pichon et al. 2011; Kimm et al. 2011

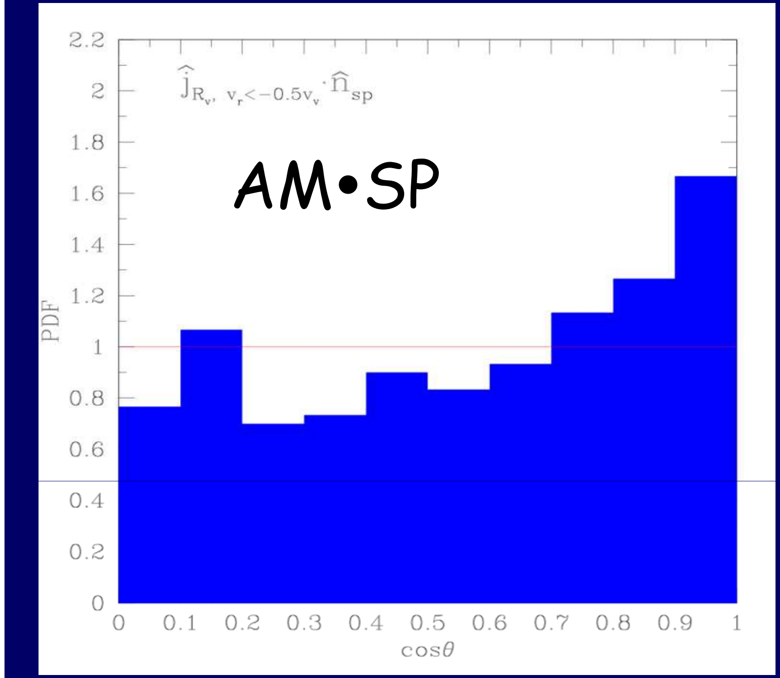
# In-streaming → Extended Rotating Disk

- AM by transverse motion of streams – impact parameter
- Streams transport AM into the inner halo
- One stream is dominant
- Higher J/M at later times → inside-out disk buildup



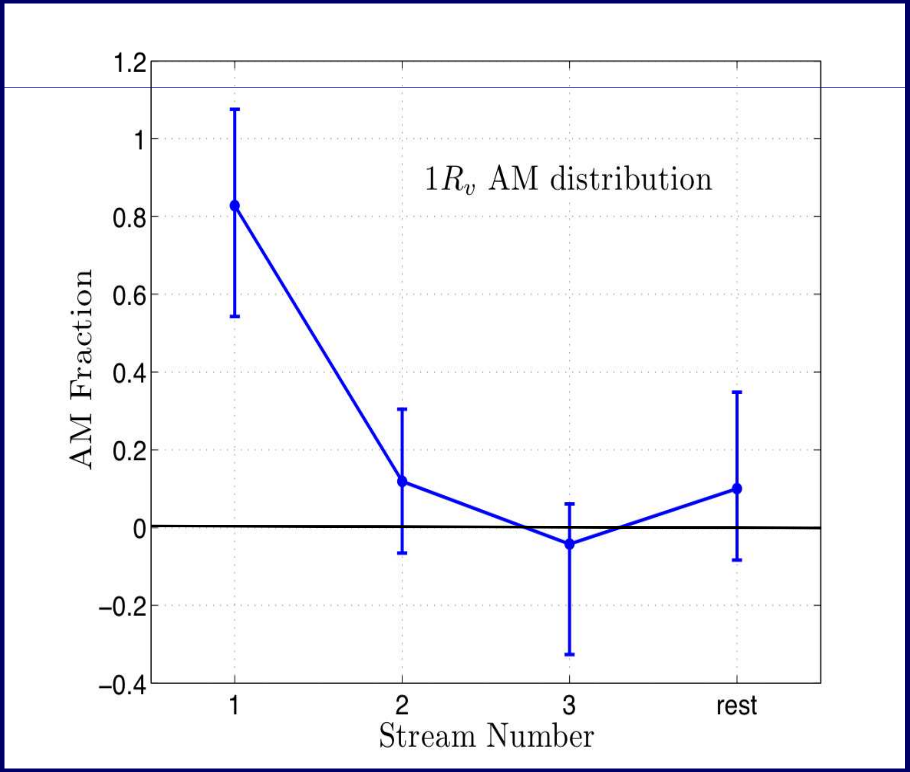
Agertz et al 09

# Angular Momentum on Halo Scale

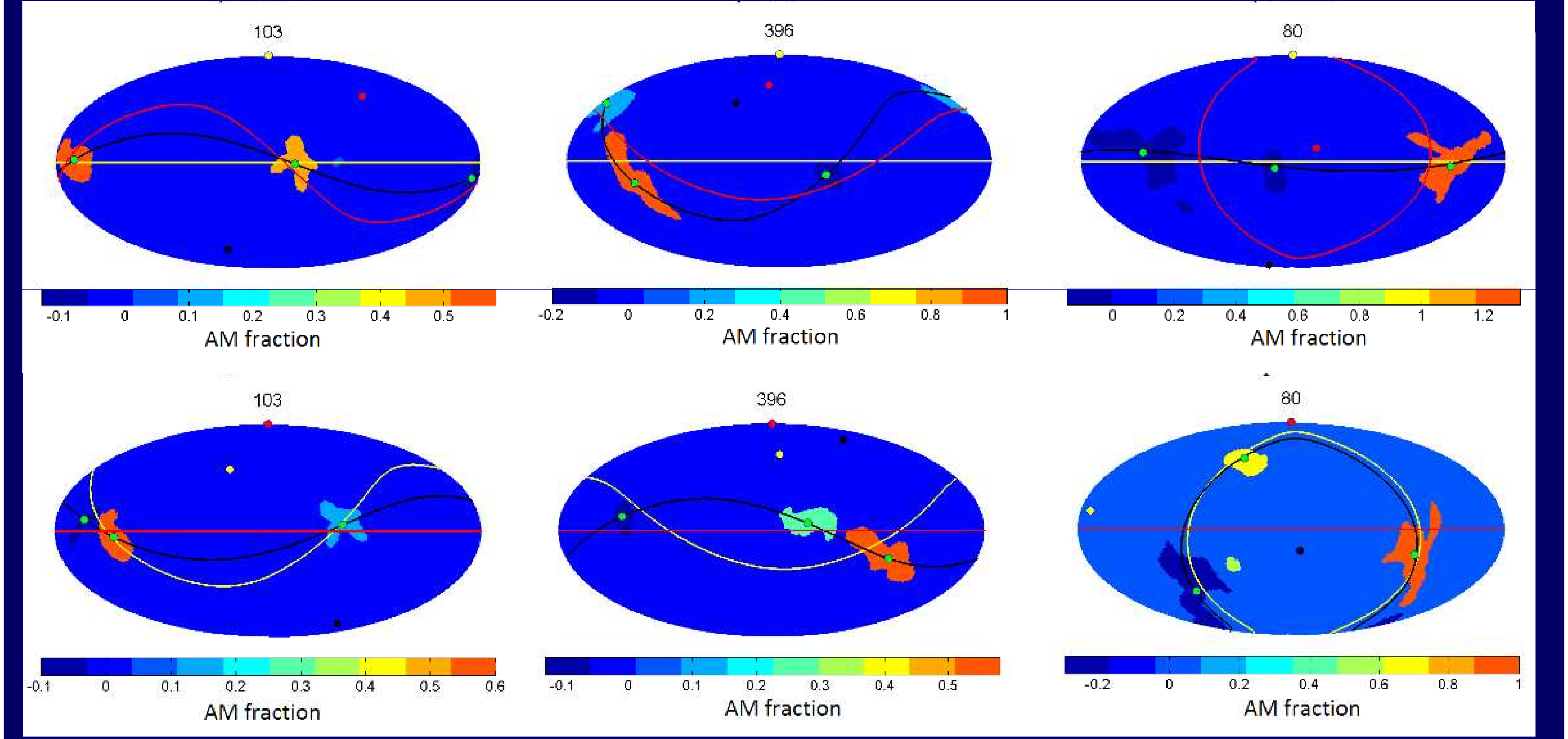


Only little correlation between stream plane and AM at $R_v$

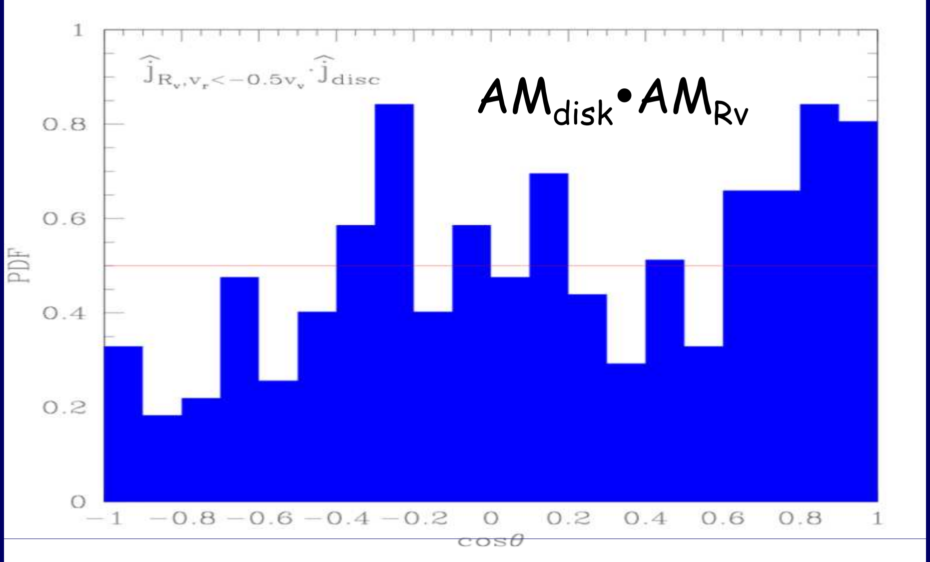
**Most of the AM in one stream**

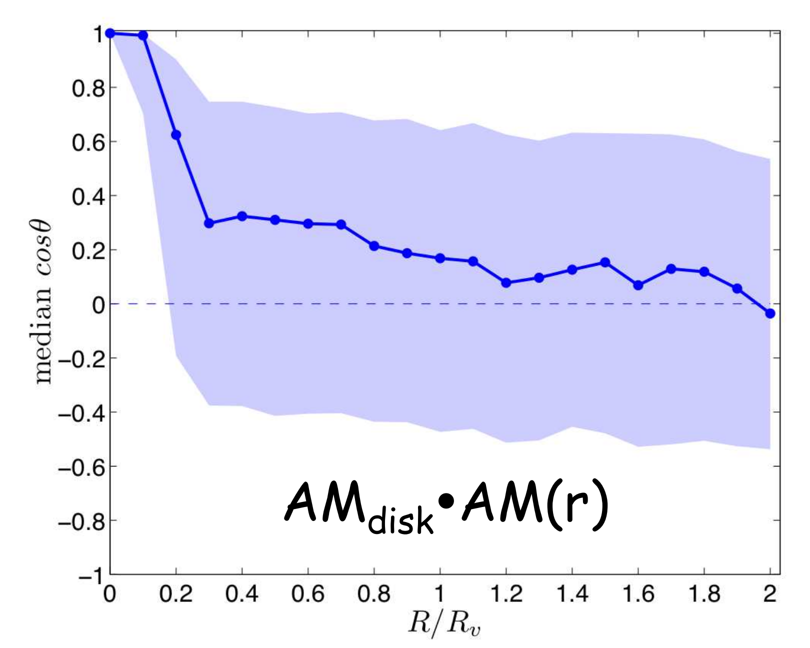


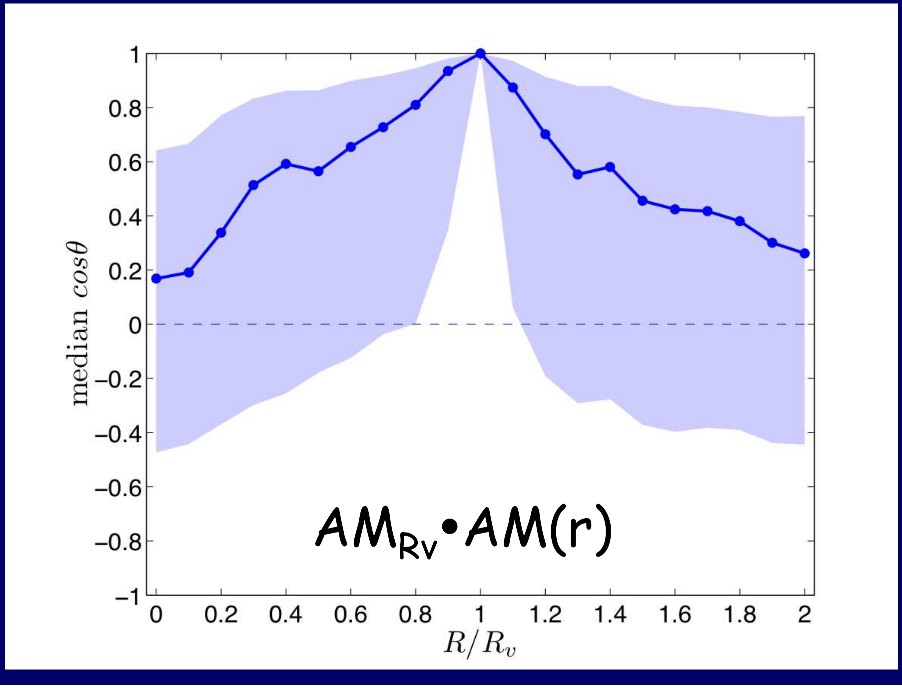
# Most of the AM in one Stream



# Disk is not aligned with AM at r>0.3$R_{vir}$

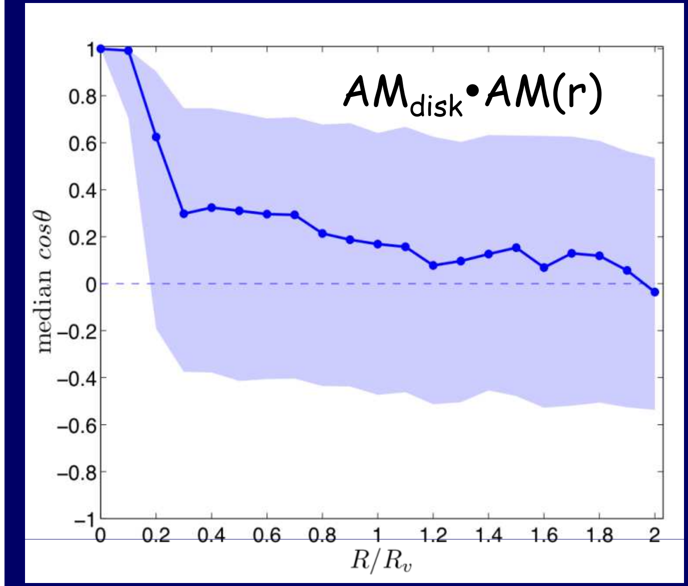




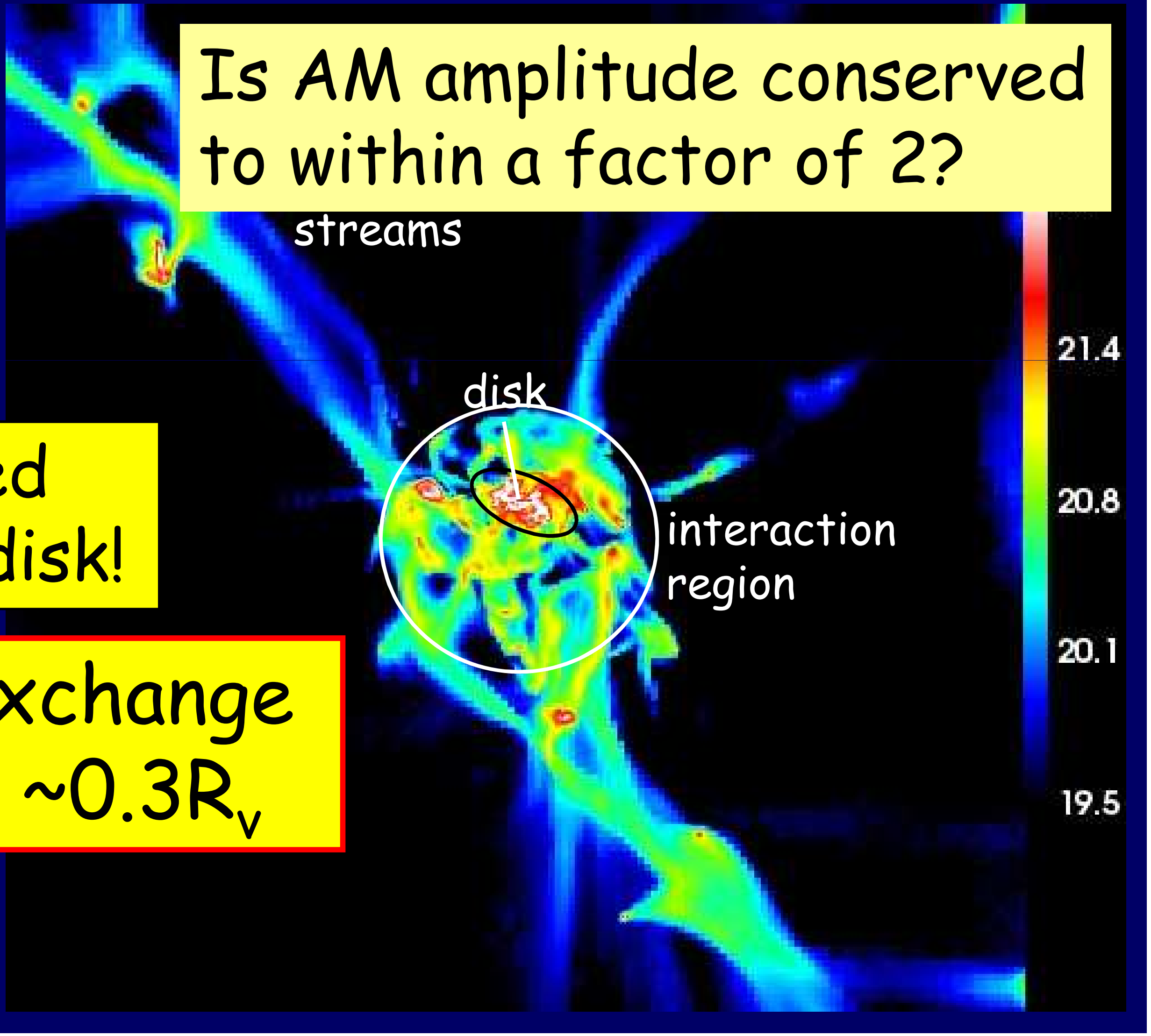


# AM Exchange in the Inner Halo

Ceverino, Dekel, Bournaud, Primack
ART 70-pc resolution



Is AM amplitude conserved to within a factor of 2?



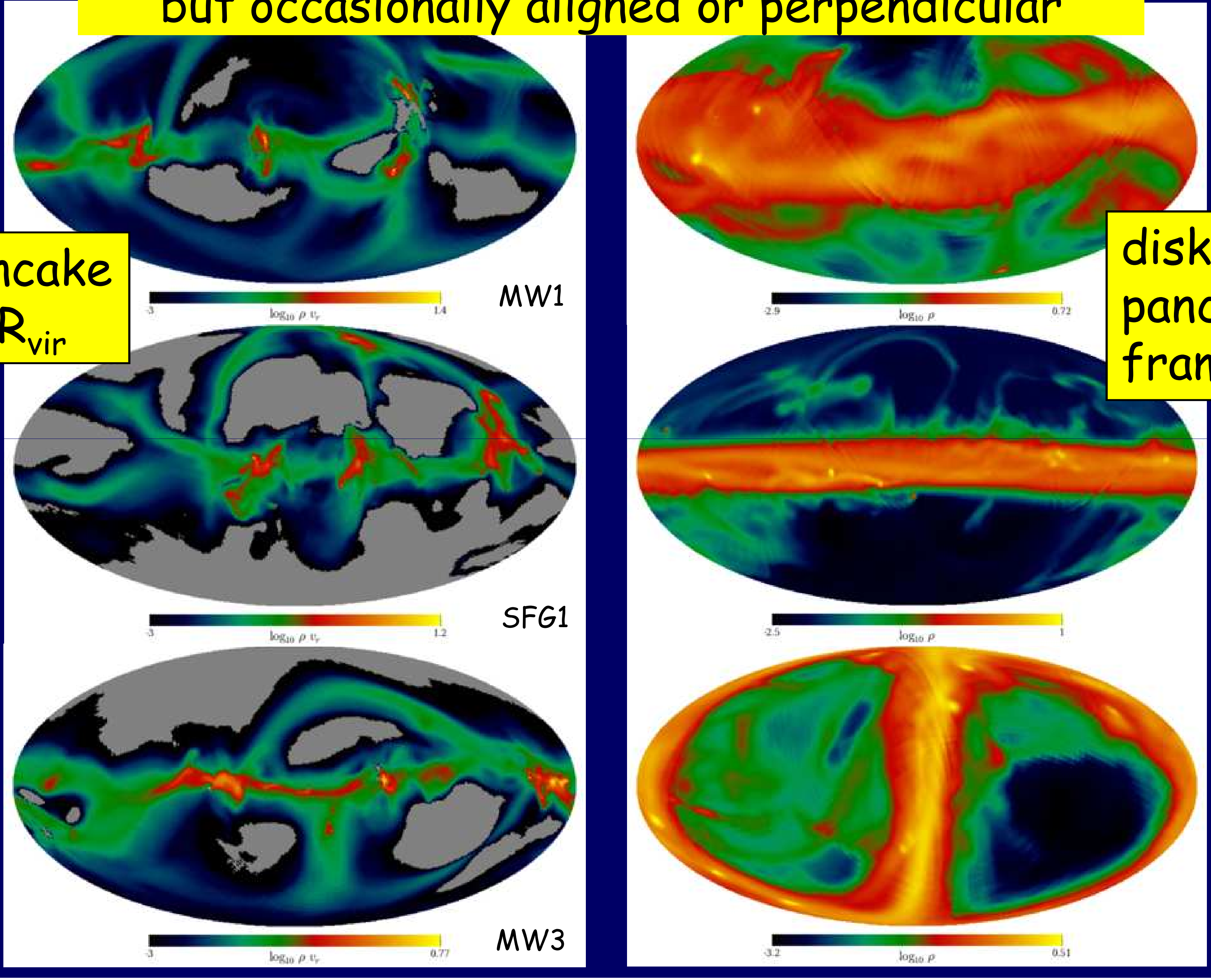
AM is not conserved all the way to the disk!

Torques & AM exchange in the inner halo ~$0.3R_v$

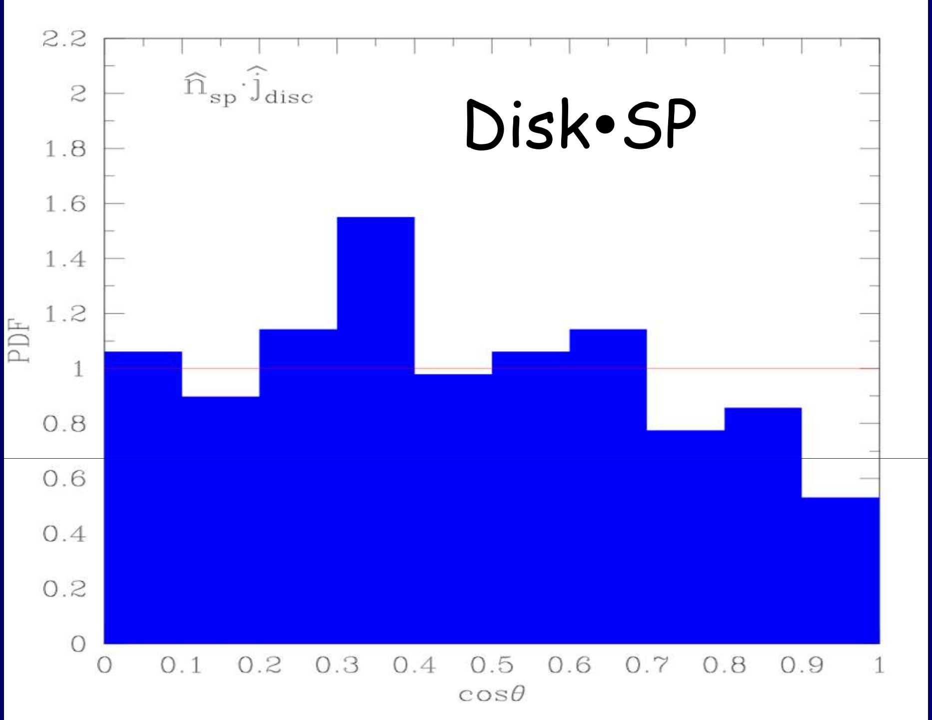
# Disk and Pancake are only weakly correlated, but occasionally aligned or perpendicular

pancake at $R_{vir}$

disk in pancake frame



# Planes: Disk versus Pancake



A weak correlation:
Disk spin tends to lie in the pancake

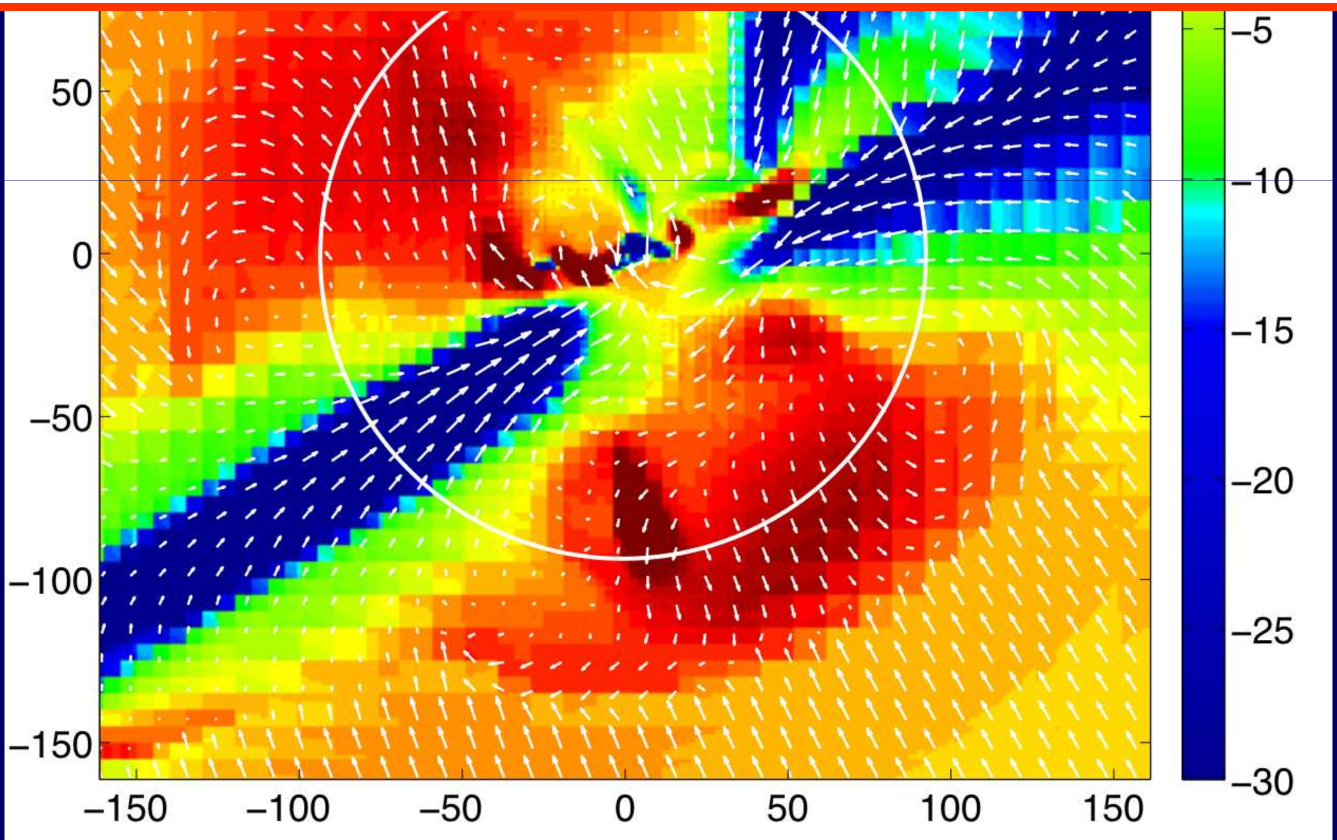
Tidal Torque Theory: the spin tends to align with the intermediate eigenvector of the tidal tensor

# 3. Outflows and Inflows

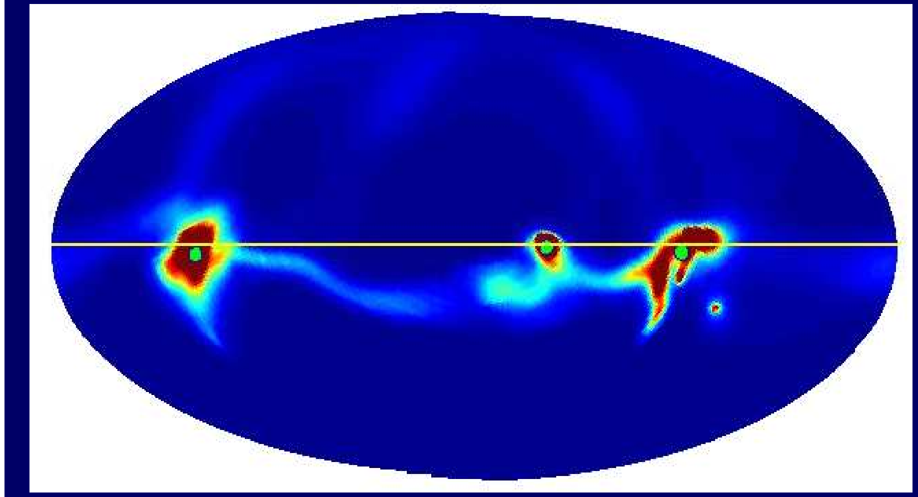
# Theory Challenge: Inflow and Outflow

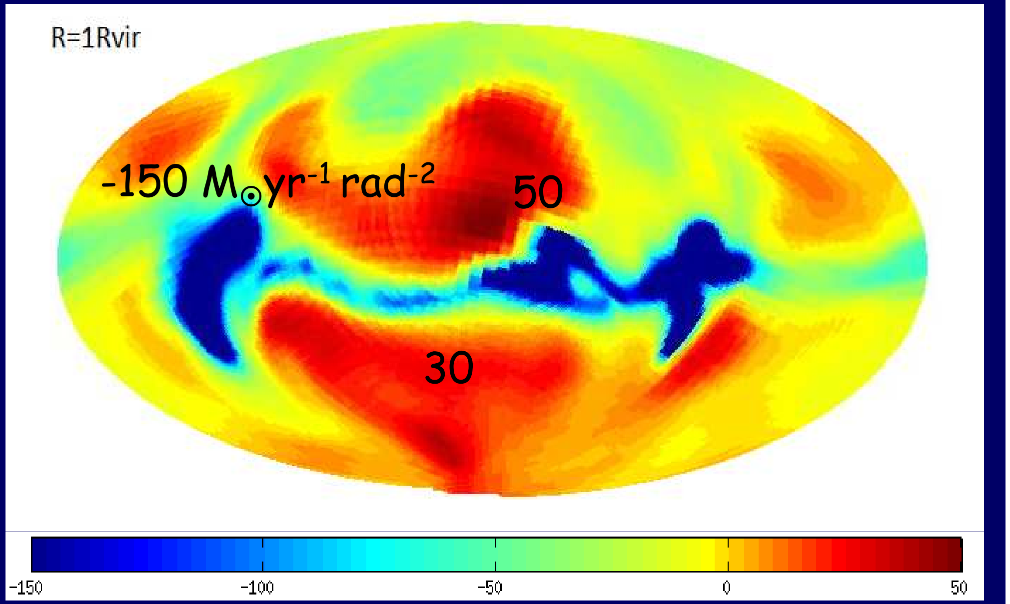
- What drives the massive outflows in massive galaxies?

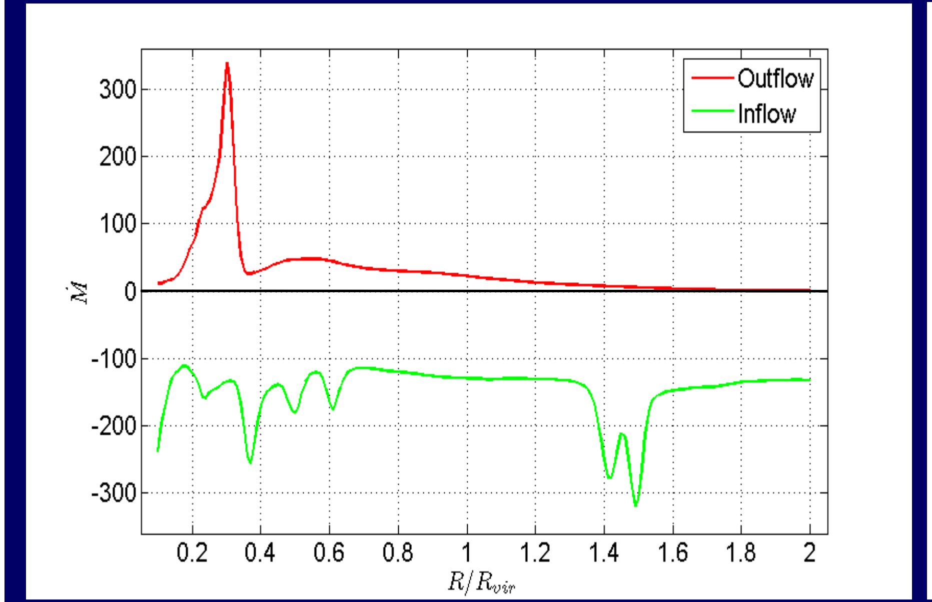
– How do the outflows affect the inflows?
Need to maintain Inflow + Reservoir = SFR + Outflow

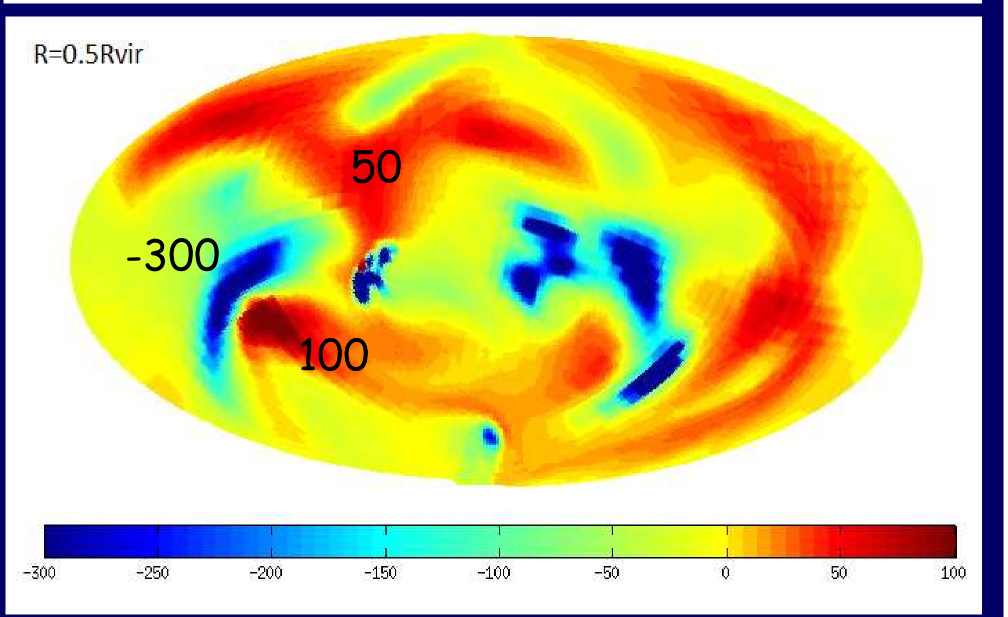


# Outflows and Inflows





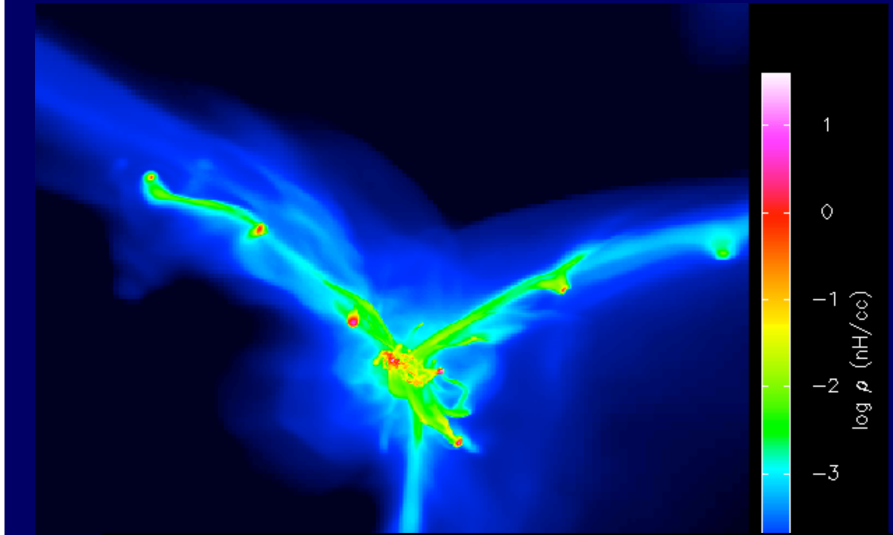




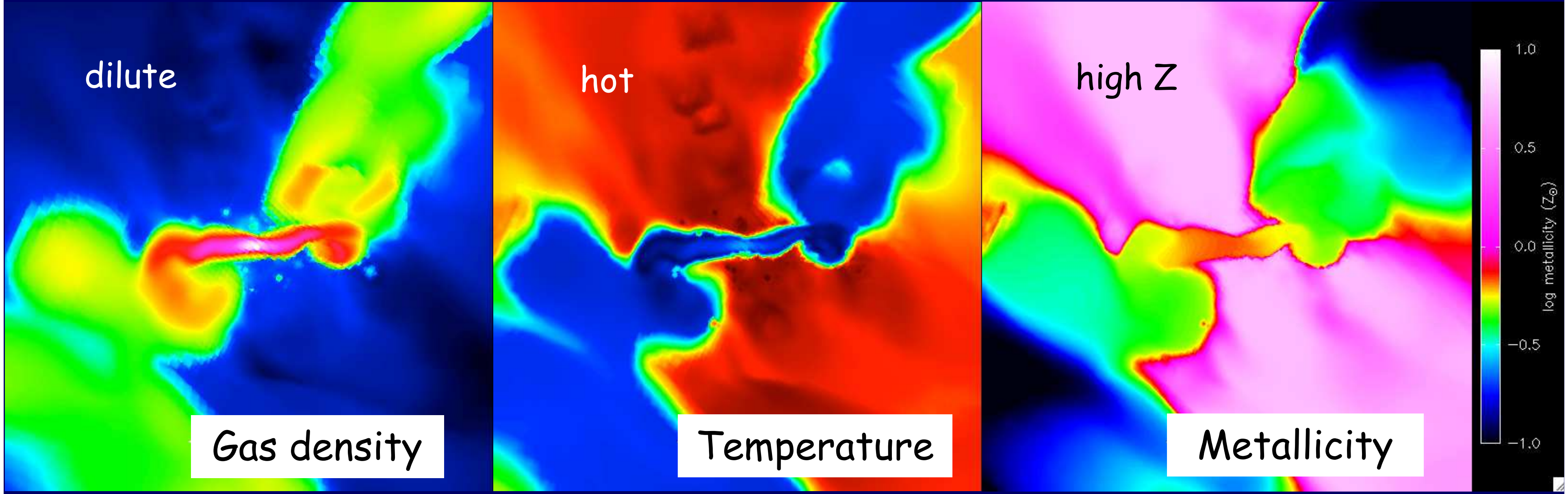
# Inflow-disk-outflow

Tweed, Dekel, Teyssier

RAMSES 70-pc resolution



Outflows find their way out through the dilute medium
no noticeable effect on the dense cold rapid inflows



Gas density

Temperature

Metallicity

# 4. Observing Cold Streams

Emission: Goerdt et al. 2010, Kasen et al. 2011
Absorption: Fumagalli et al. 2011, Goerdt et al. 2011

ART code (Klypin, Kravtsov)
Simulations: Ceverino, Dekel, Bournaud 2010

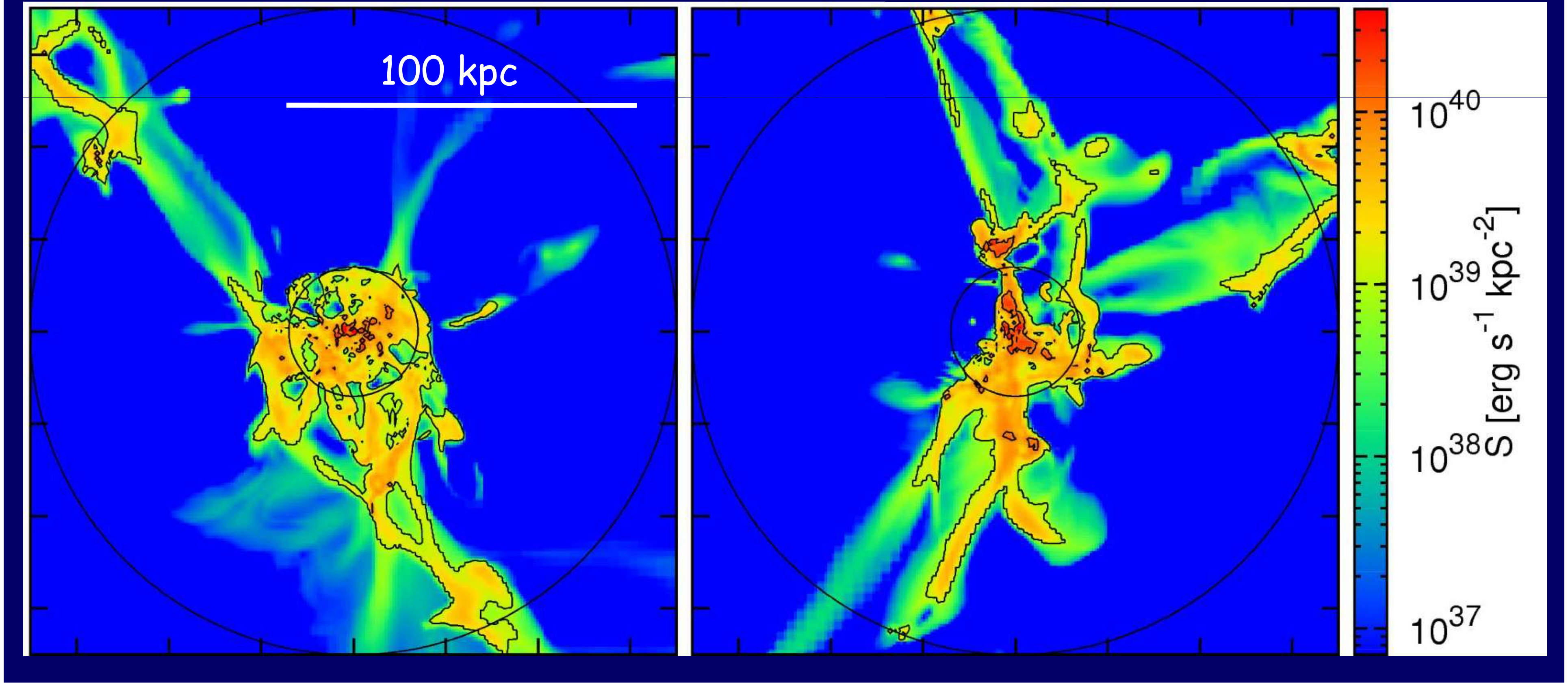
# Lyman-alpha from Cold streams

Fardal et al 01; Furlanetto et al 05; Dijkstra & Loeb 09
Goerdt, Dekel, Sternberg, Ceverino, Teyssier, Primack 09

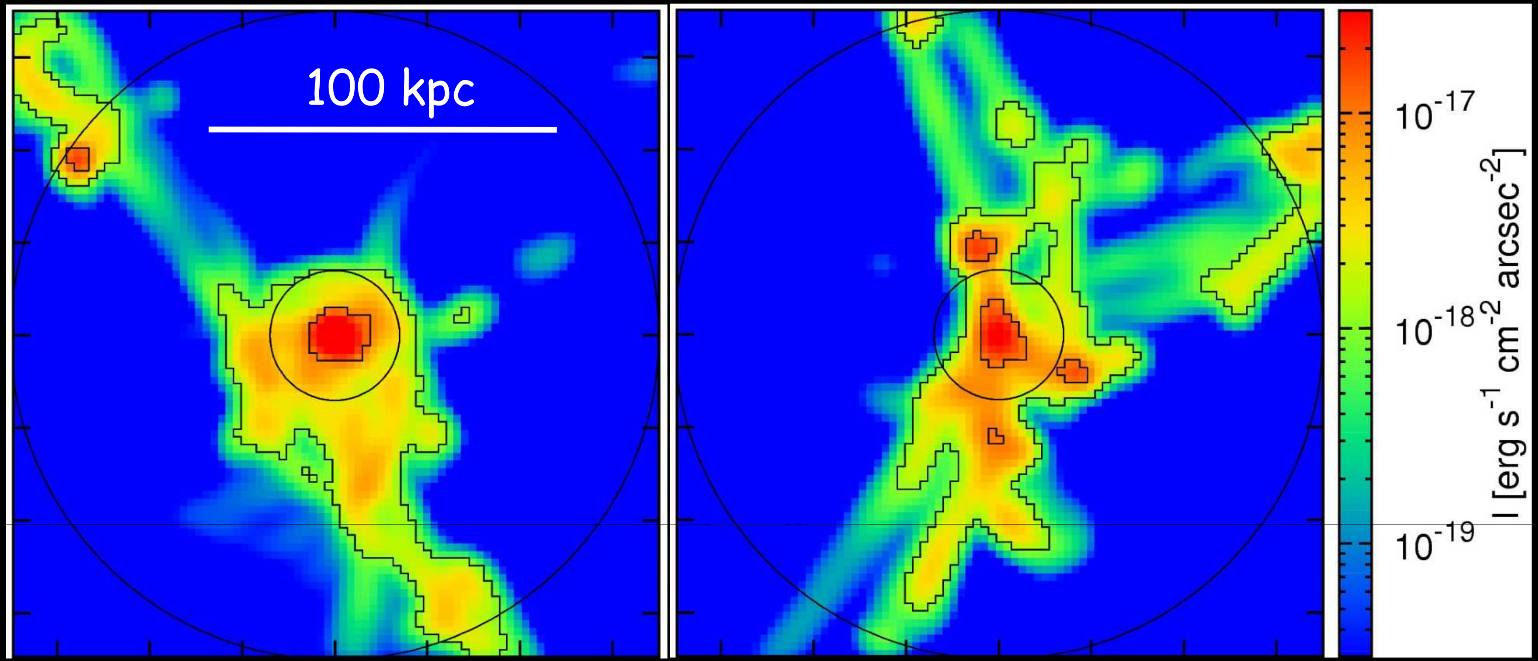
T=(1-5)x$10^4$ K    n=0.01-0.1 $cm^{-3}$    $N_{HI}$~$10^{20}$ $cm^{-2}$    pressure equilib.

L ~$10^{43-44}$ erg $s^{-1}$

Surface brightness



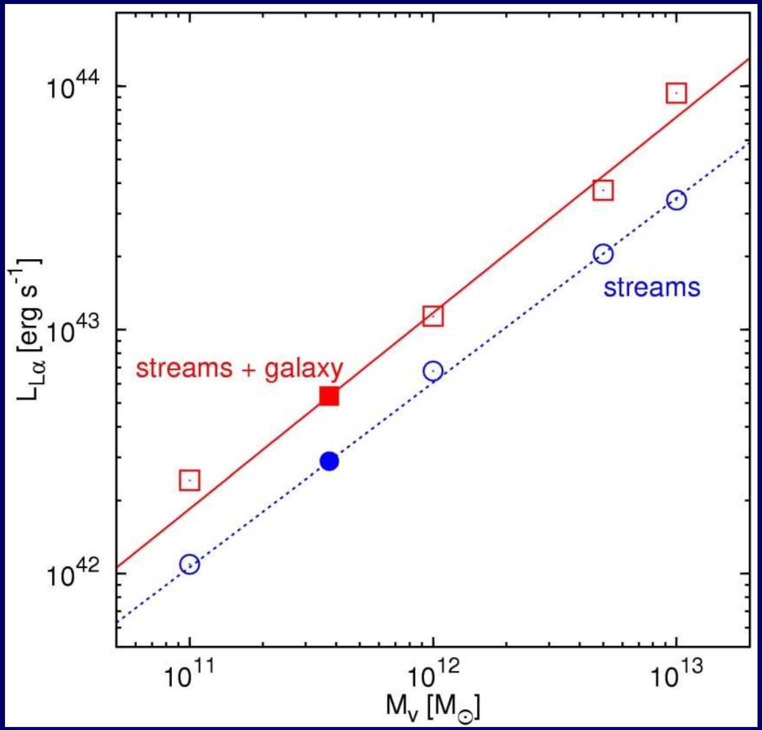
# Cold streams as Lyman-alpha Blobs

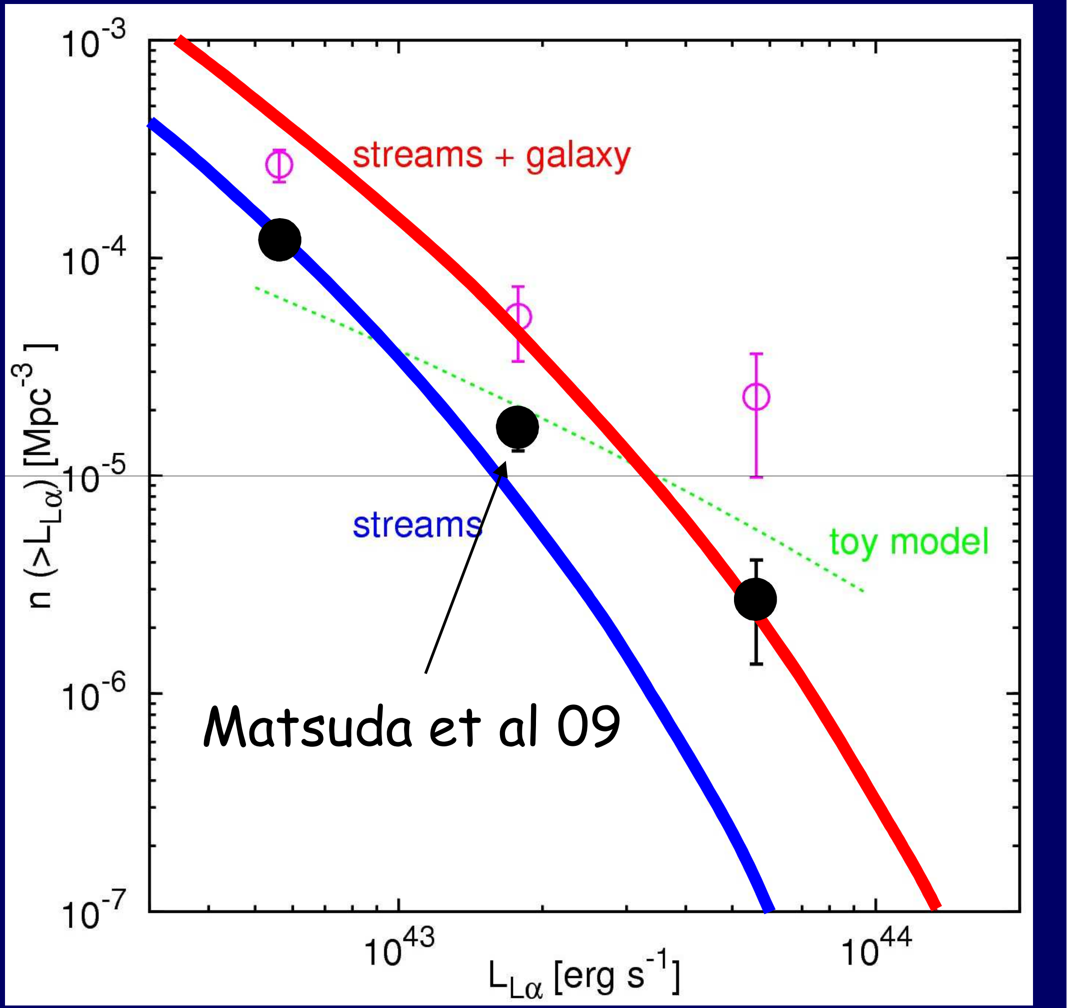


Goerdt,
Dekel,
Sternberg,
Ceverino,
Teyssier,
Primack 09

Matsuda et al 06-09

# Lyman-alpha Luminosity Function



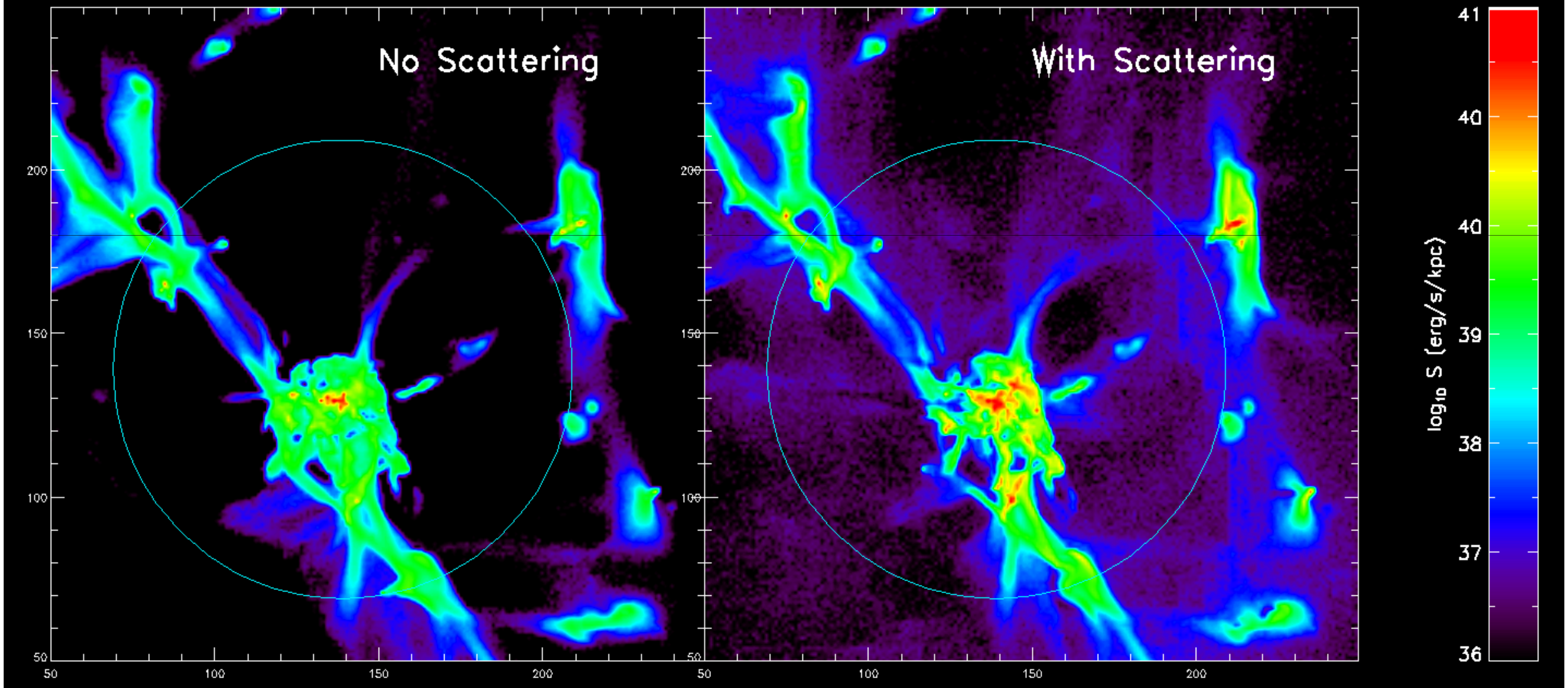


Matsuda et al 09

Isophotal area and kinematics also consistent with data

# Lya Image – radiative transfer

Kasen et al 11: including Lya multiple scattering,
UV bkgd, Fluorescence from stars



# Lyman-alpha Emission (LAB)

Kasen

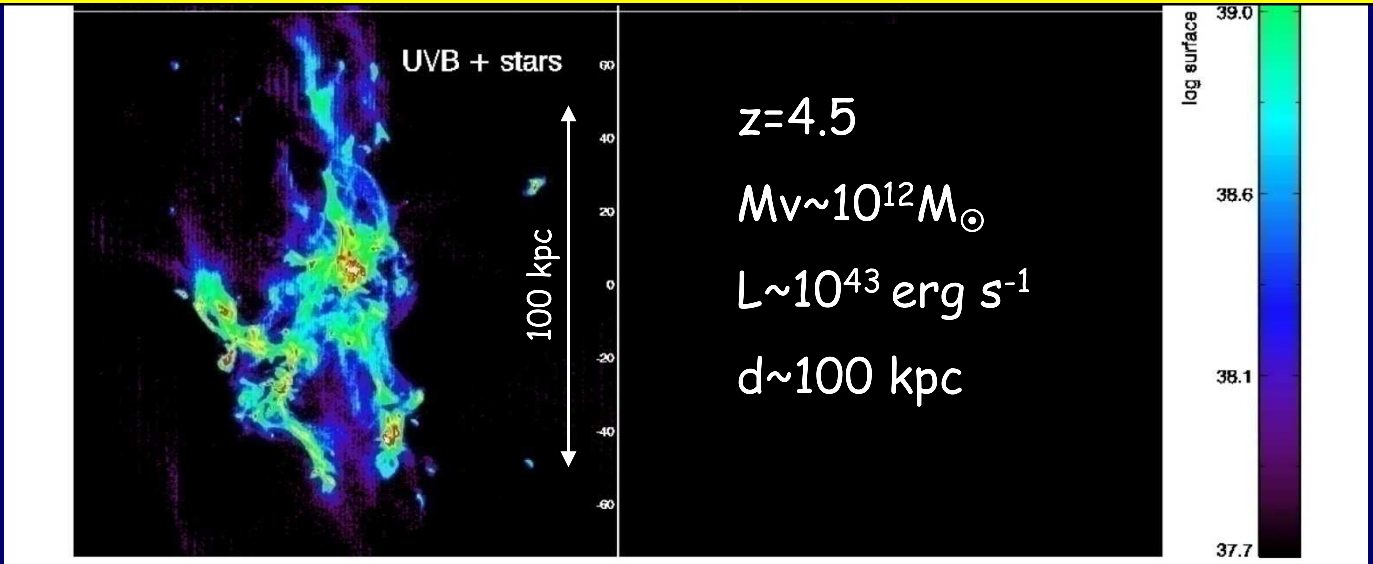
Radiative transport of UV & Lya, fluorescence from stars, dust

Kasen, Ceverino, Fumagalli, Dekel, Prochaska, Primack

Inflowing (clumpy) streams provide an extended **source** of cold hydrogen

**Energy** is provided (in comparable fractions) by:
1. inflow down the gravitational potential gradient
2. fluorescence by stars

Yet to be incorporated: AGN, enhanced outflows



z=4.5

$M_v \sim 10^{12} M_\odot$

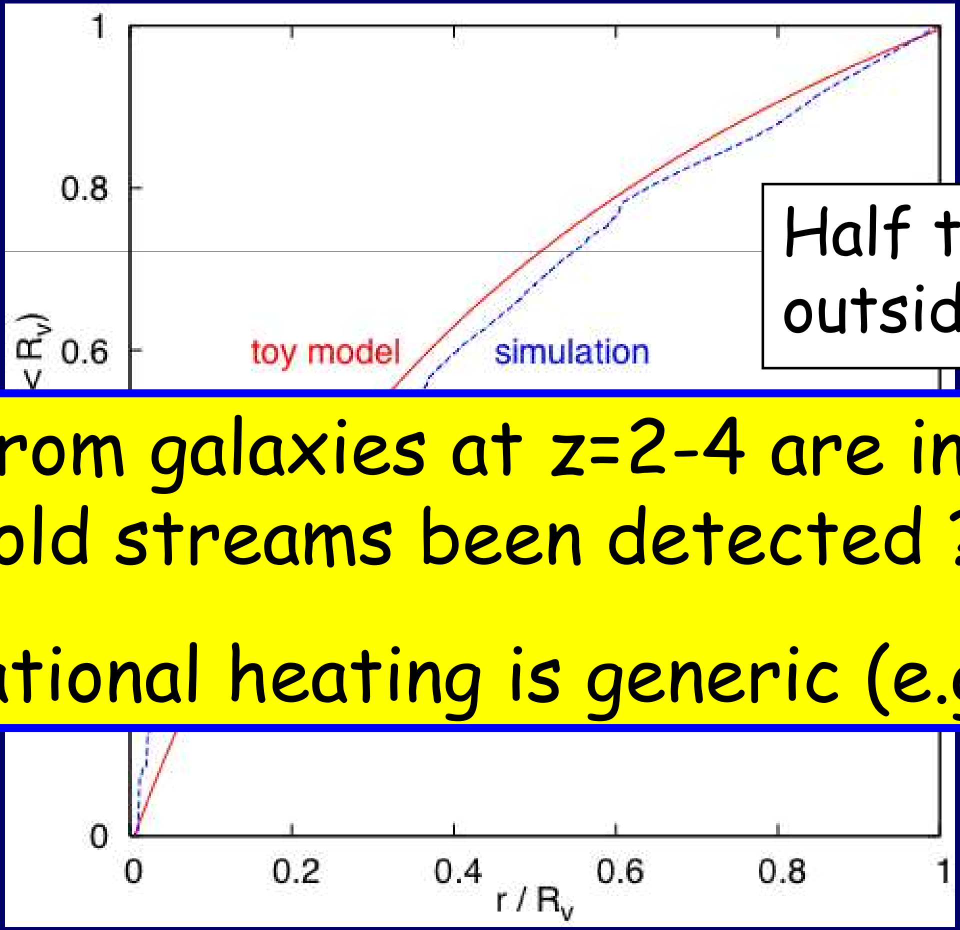
$L \sim 10^{43}$ erg $s^{-1}$

d~100 kpc

# Gravity Powers Lyman-alpha Emission

$$E_{heat}(r) = f_c\,\dot{M}_c \left|\frac{\partial \varphi}{\partial r}\right|$$

$$E_{heat} \approx 1.2\times10^{43}\,erg\,s^{-1}\,f_c\,M_{12}^{1.82}\,(1+z)_4^{3.25}$$



Half the luminosity outside $0.3R_v$

LABs from galaxies at z=2-4 are inevitable
Have cold streams been detected ?

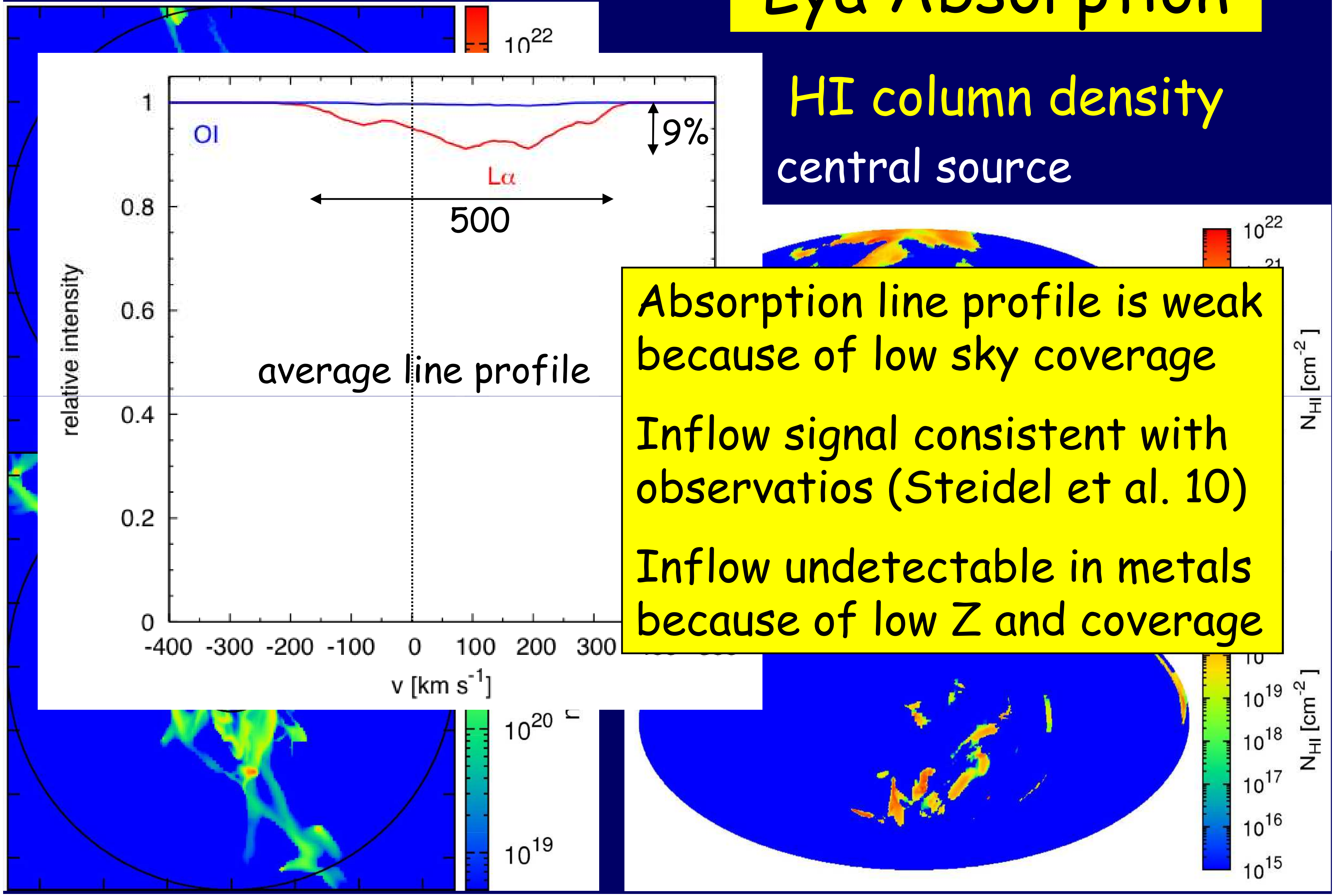
Gravitational heating is generic (e.g. clusters)

# Lya Absorption

HI column density

background source

central source



Absorption line profile is weak because of low sky coverage

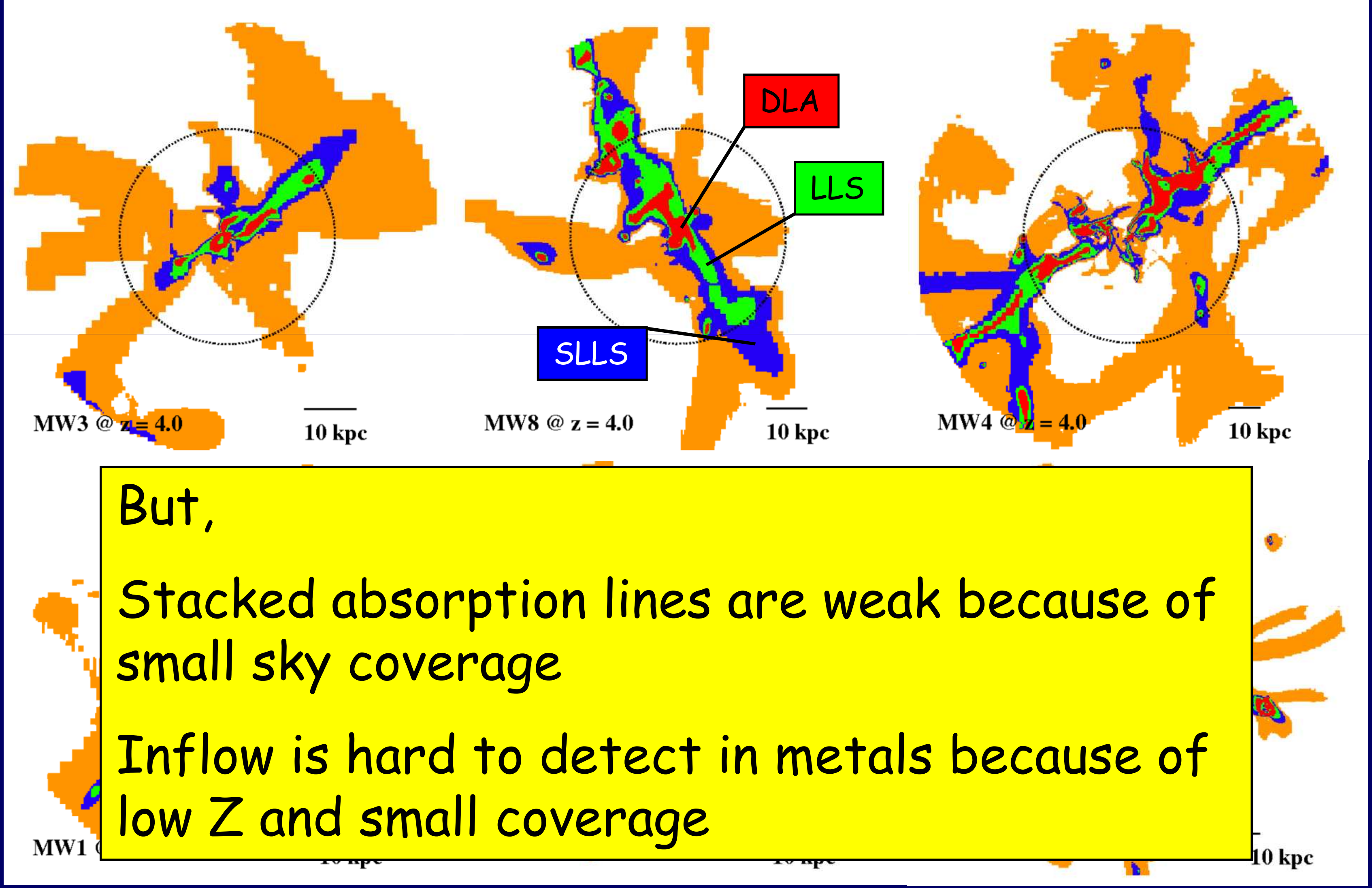
Inflow signal consistent with observatios (Steidel et al. 10)

Inflow undetectable in metals because of low Z and coverage

# Cold Streams as LLS and DLAS

Fumagalli

Fumagalli, Prochaska, Kasen, Dekel, Ceverino, Primack 11



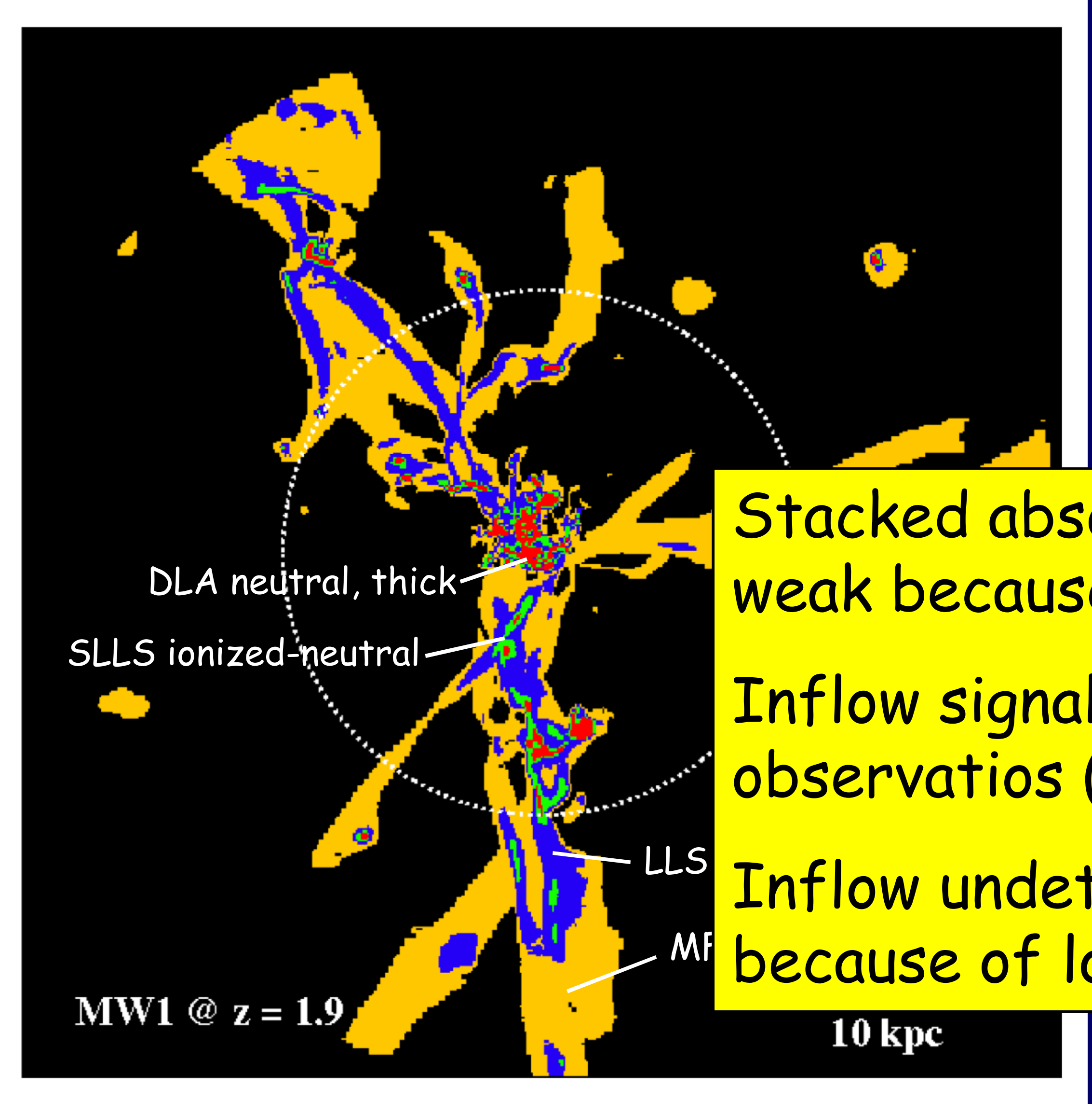
But,

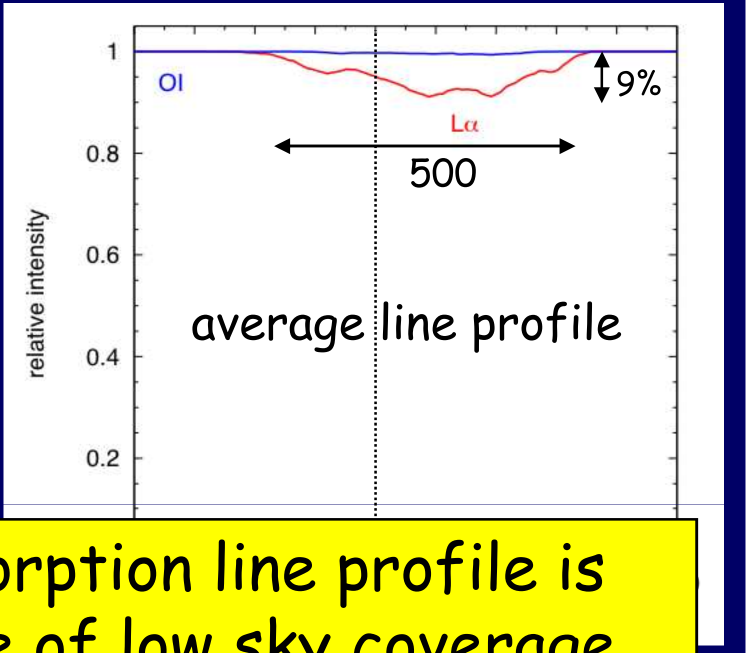
Stacked absorption lines are weak because of small sky coverage

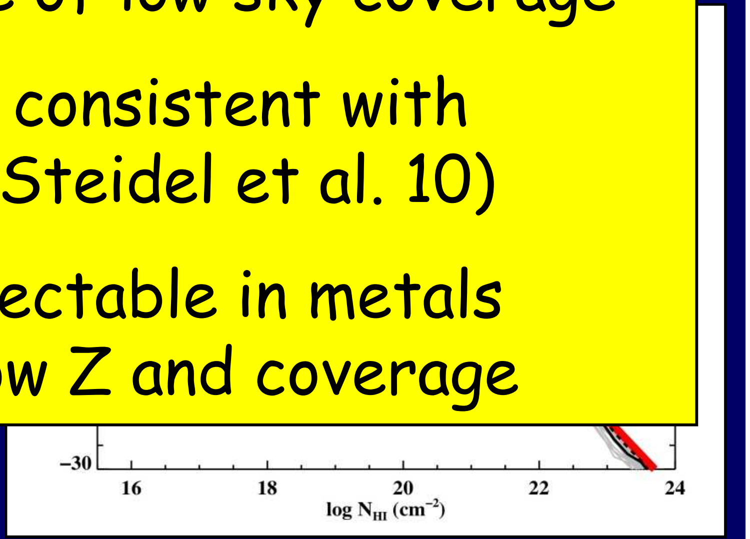
Inflow is hard to detect in metals because of low Z and small coverage

# HI Absorption Systems

Fumagalli, Prochaska, Kasen, Dekel, Ceverino, Primack 11







Stacked absorption line profile is weak because of low sky coverage

Inflow signal consistent with observatios (Steidel et al. 10)

Inflow undetectable in metals because of low Z and coverage

# 5. High SFR at $z\sim2$, Low SFR and High Gas Fraction at $z>2$

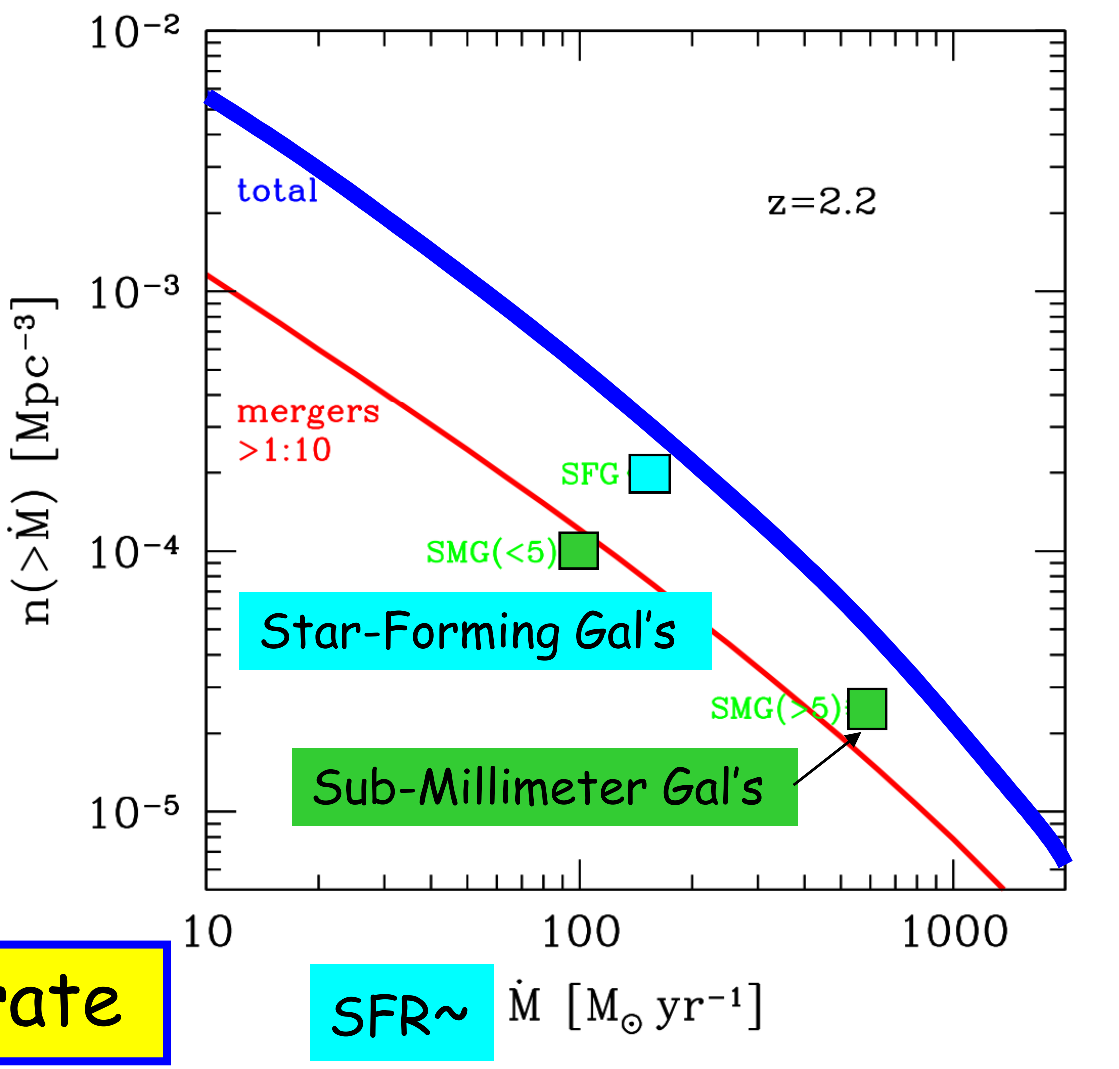
Dekel et al. 2009
Krumholz, Dekel 2011

# Cosmological inflow rate allows high SFR

Dekel et al 09, Nature

$$n(\dot{M}) = \int_0^\infty P(\dot{M}\,|\,M)\, n(M)\, dM$$

From cosmological hydro simulations (MareNostrum)



Star-Forming Gal's

Sub-Millimeter Gal's

SFR~

**SFR ~(1/2) inflow rate**

# SFR Driven by Accretion?

Mass conservation $$\dot{M}_{\rm gas} = \dot{M}_{\rm acc} - (1 + f_{out})\,\dot{M}_{*}$$

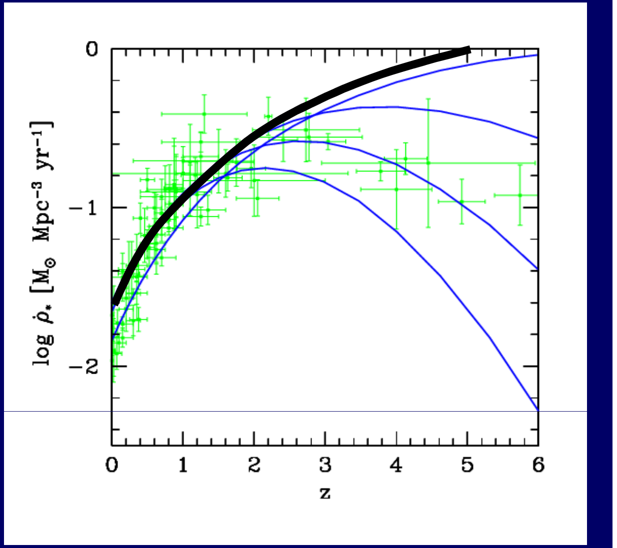
Kennicutt SFR $$\dot{M}_{*} = \varepsilon \frac{M_{\rm gas}}{t_{\rm ff}}$$

Steady state $$\dot{M}_{\rm gas} \to 0 \quad \dot{M}_{*} \to \dot{M}_{\rm acc}$$

$$\left\langle \dot{M}_{baryon} \right\rangle = 80\, M_{\otimes} yr^{-1}\; M_{12}^{1.14}\; (1+z)_{3}^{2.5}$$

Neistein, Dekel 08

Bouchet et al. 10



## But at z>>2, the SFR cannot catch up with the accretion

1. $t_{acc}$~2 Gyr $$\frac{t_{sfr}}{t_{acc}} \approx \left(\frac{1+z}{3}\right)^{1-1.8}$$ ~2.5 Gyr $(1+z)_3^{-0.7}$

$t_{sf}$ by Krumholz, McKee, Tumlinson 09

2. SFR is suppressed by the low metallicity at high z in small galaxies

Krumholz, Dekel 11

# SFR Driven by Accretion?

Mass conservation

$$\dot{M}_{\rm gas} = \dot{M}_{\rm acc} - \varepsilon \frac{M_{\rm gas}}{t_{\rm ff}}$$

SFR

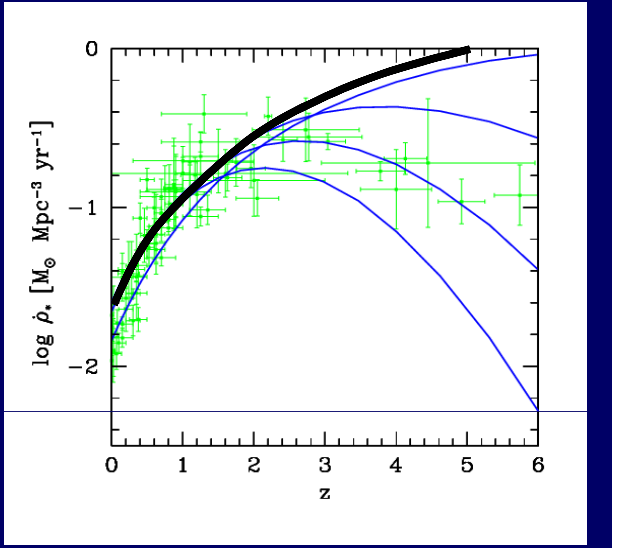
Steady state

$$\dot{M}_{\rm gas} \rightarrow 0 \quad \dot{M}_{*} \rightarrow \dot{M}_{\rm acc}$$

$$\left\langle \dot{M}_{baryon} \right\rangle = 80\, M_{\otimes} yr^{-1}\ M_{12}^{1.14}\ (1+z)_3^{2.5}$$

Neistein, Dekel 08

Bouchet et al. 10



## But at z>>2, the SFR cannot catch up with the accretion:

1. $$\frac{t_{sfr}}{t_{acc}} \approx \left(\frac{1+z}{3}\right)^{1-1.8}$$

$t_{sf}$ by Krumholz, McKee, Tumlinson 09

2. SFR is suppressed by low metallicity at high z in small galaxies

Krumholz, Dekel 11

# Z-dependent Quenching in small M at high z

Krumholz & Dekel 11

- $H_2$ is a proxy for SF conditions: cooling (CII,CO) and high density

$$\boxed{SFR \sim f_{H2}}$$

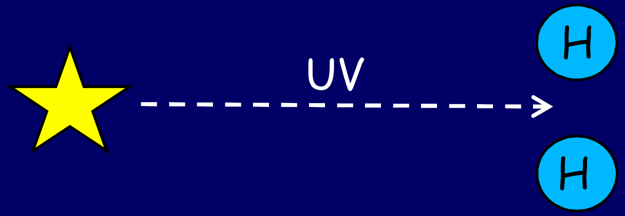
Krumholz & McKee 11

- SFR (& $H_2$): needs shielding by dust and high density against stellar UV

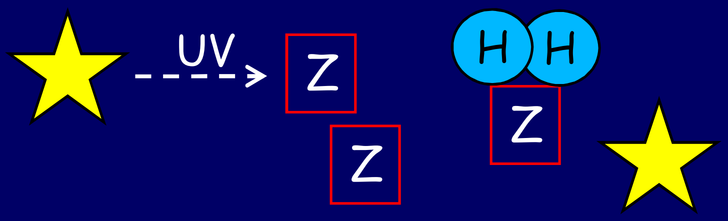
$$\boxed{f_{H2} \sim Z\,\Sigma}$$

McKee & Krumholz 09

Low Z – gas heating, $H_2$ dissociation



High Z - star formation (CII, CO) and $H_2$



- Metals are ejected by SN, and retained in massive halos

$$\boxed{f_{eject} \sim \exp(-M_{11}/3)}$$

Dekel & Silk 86
McLow & Ferrara 99

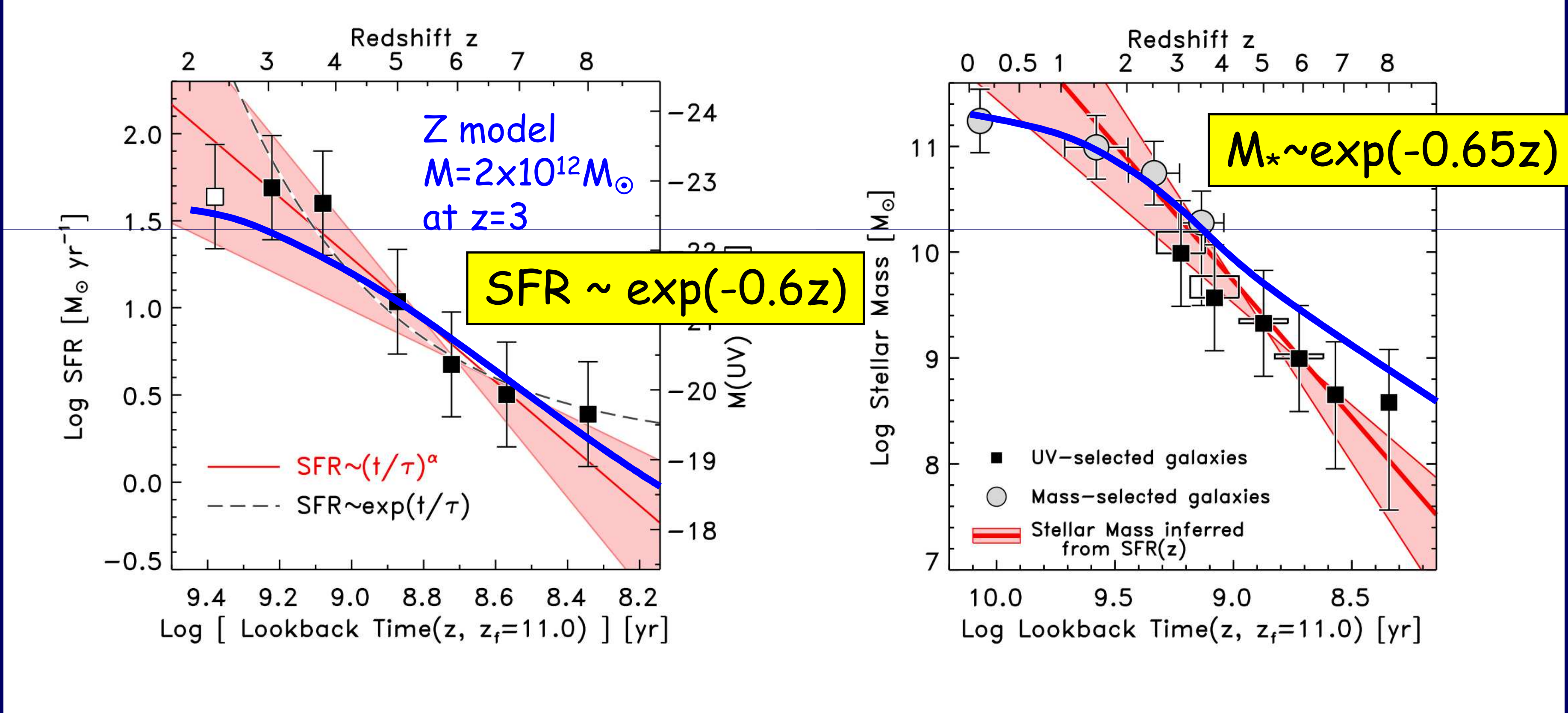
→ SFR is suppressed in $M_v < 10^{11}\,M_\odot$ at high z

# Growing Galaxy: SFR is Growing

Krumholz, dekel 11

Same comoving $n=2\times10^{-4}\mathrm{Mpc}^{-3}$ at all z

Papovich et al. 10



Z model
$M=2\times10^{12}M_\odot$
at z=3

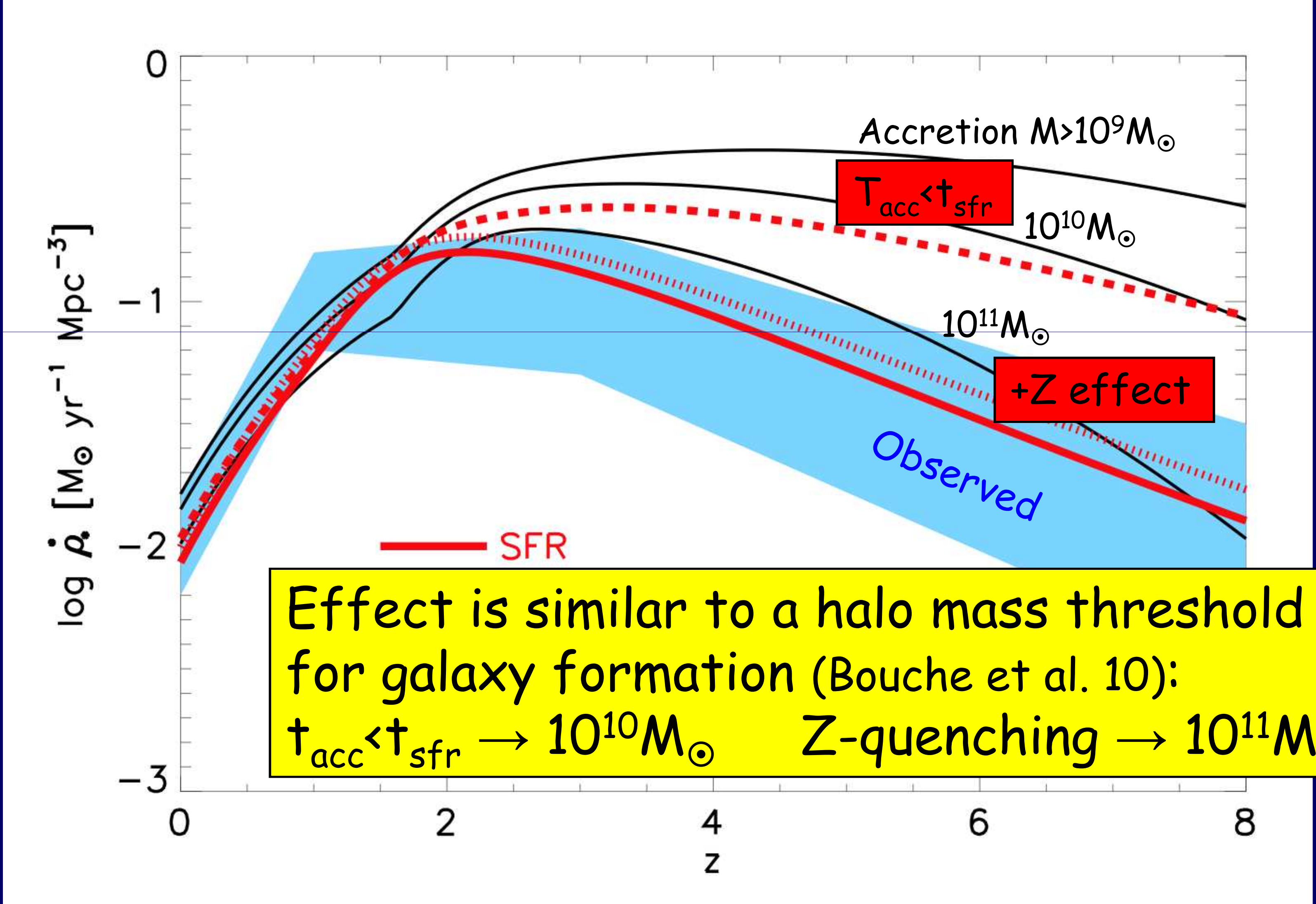
SFR ~ exp(-0.6z)

$M_*$~exp(-0.65z)

# Cosmological SFR Density

Integrated over all halos

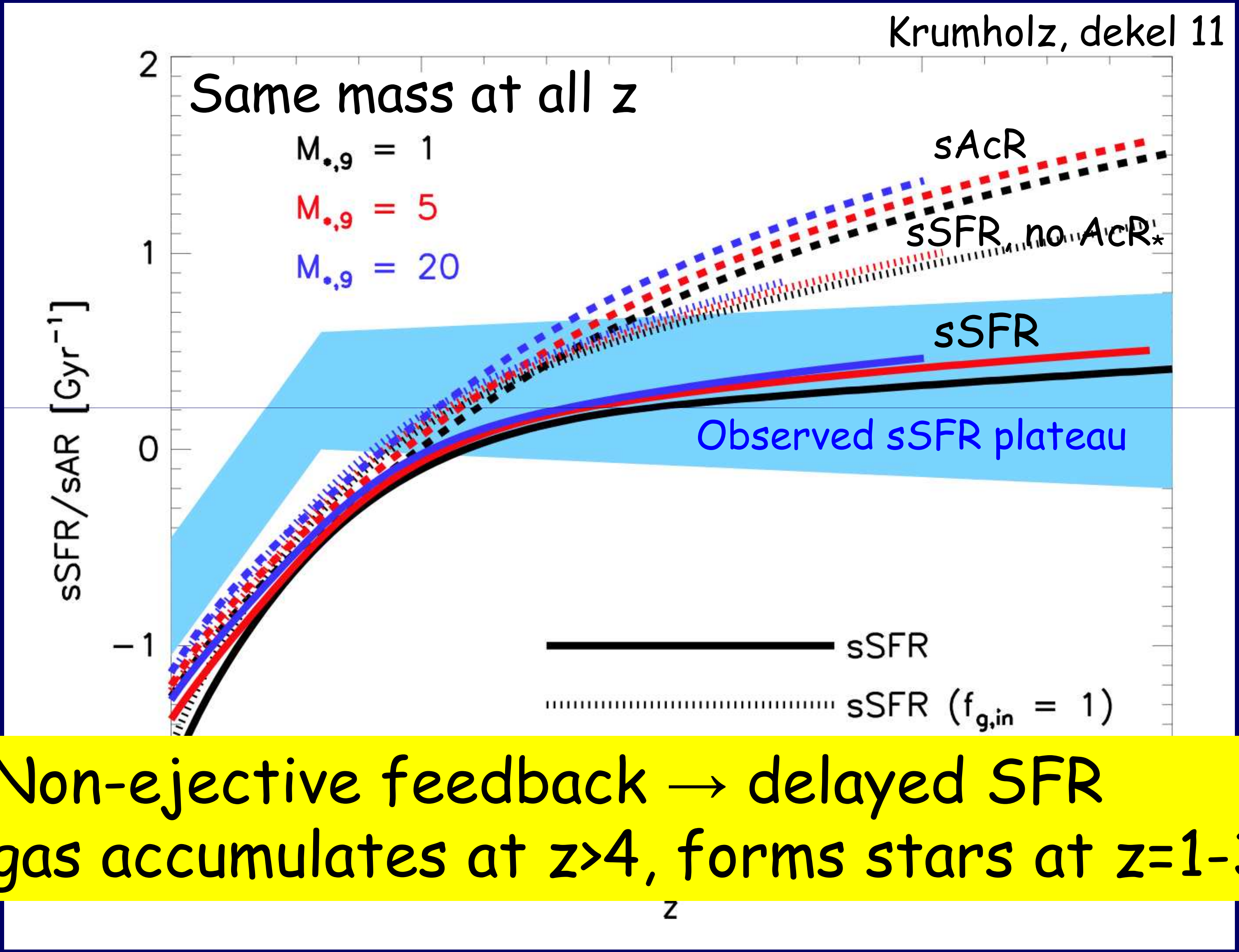
Krumholz, dekel 11



Effect is similar to a halo mass threshold for galaxy formation (Bouche et al. 10):

$t_{acc}<t_{sfr} \rightarrow 10^{10} M_\odot$ Z-quenching $\rightarrow 10^{11} M_\odot$

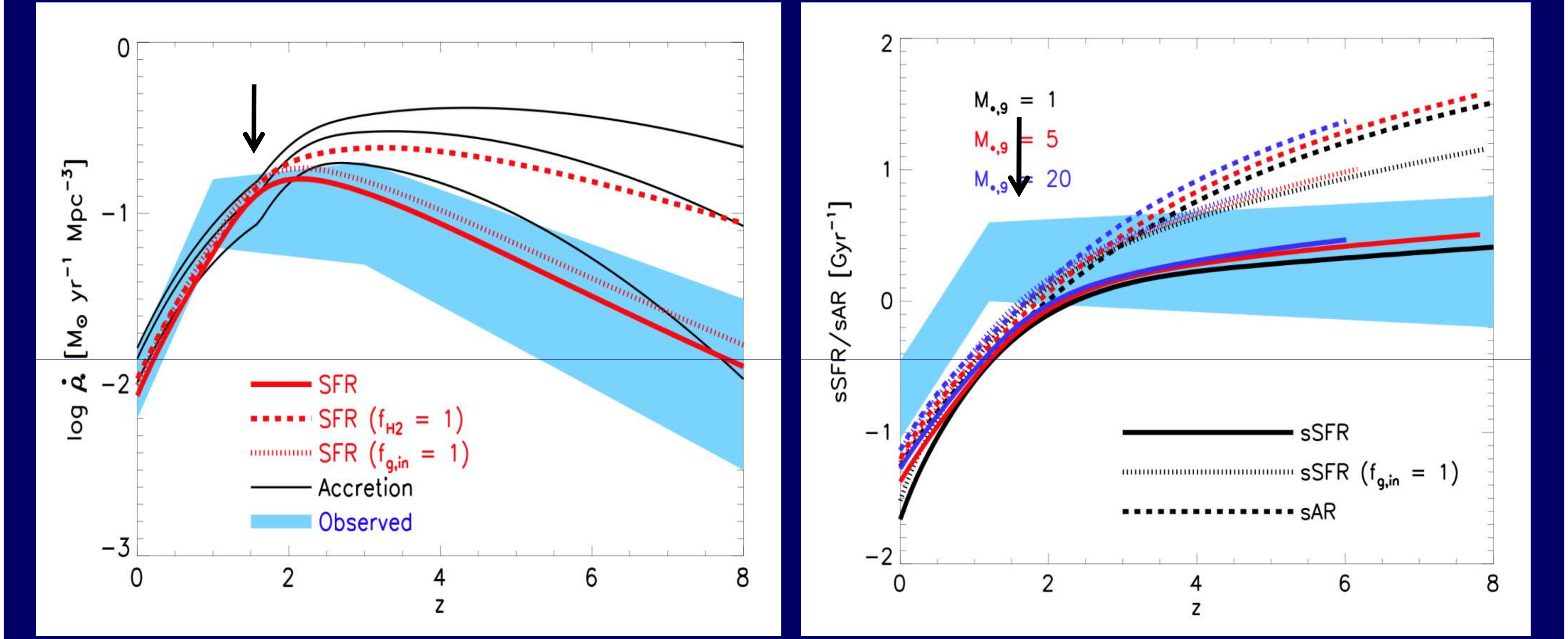
# sSFR for galaxies of fixed mass: Plateau at z=2-8



Krumholz, dekel 11

Non-ejective feedback → delayed SFR
gas accumulates at z>4, forms stars at z=1-3

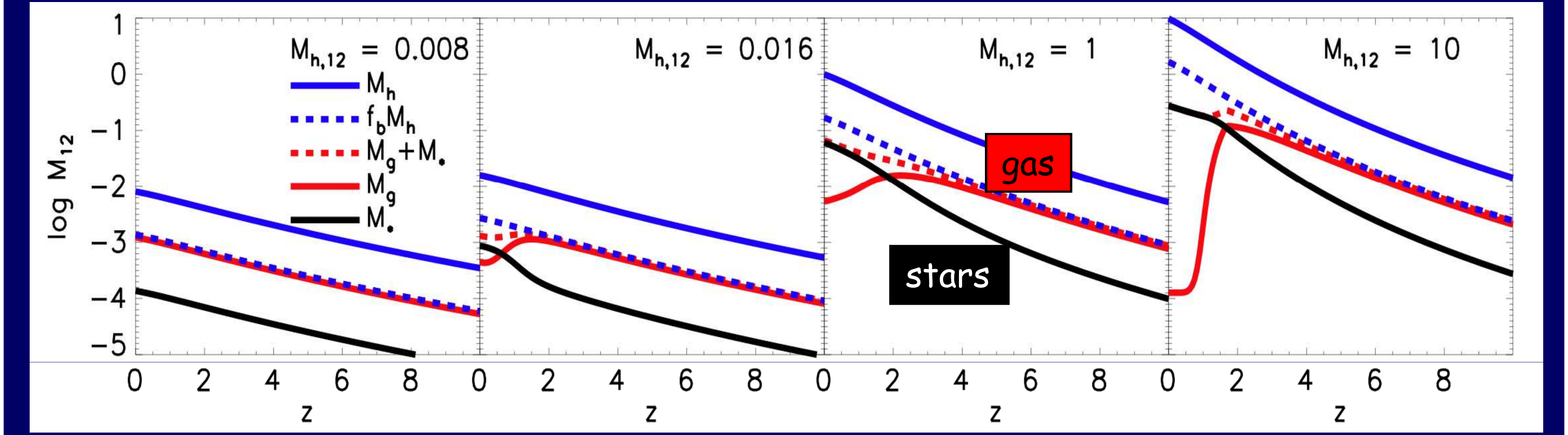
# SFR > Accretion Rate at z=1-2



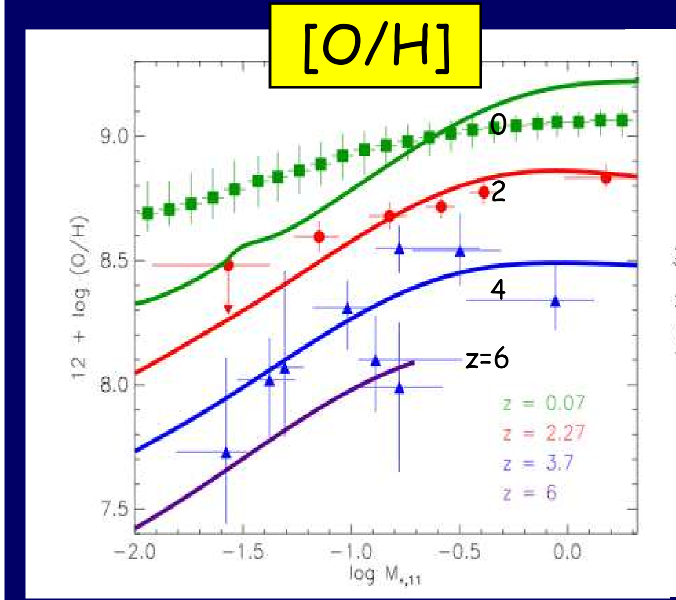
Non-ejective feedback → delayed SFR
gas accumulates at z>4, forms stars at z=1-3

# Very High Gas Fraction at High z

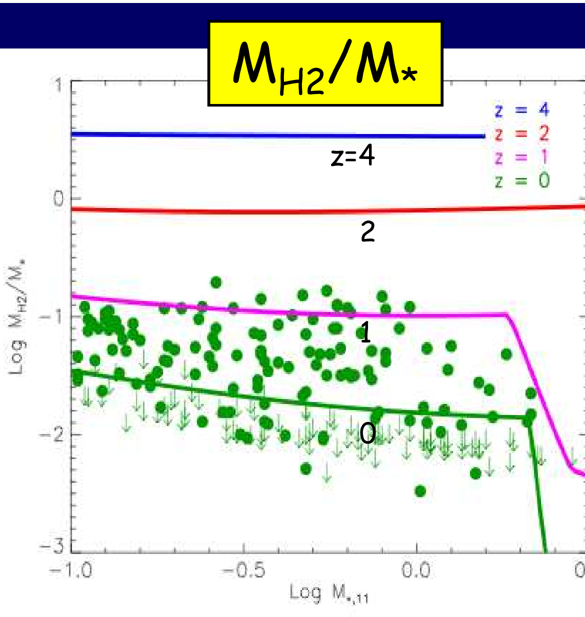
Krumholz, dekel 11



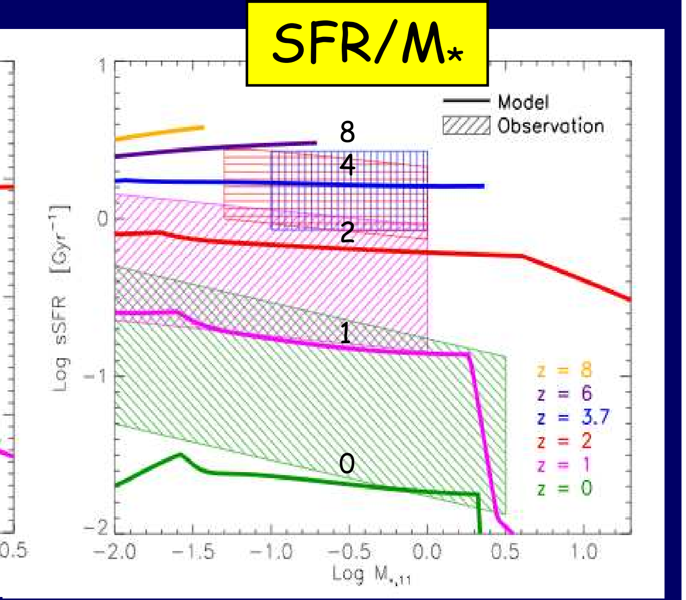
[O/H]



$M_{H2}/M_*$



$SFR/M_*$



# 6. Violent Disk Instability: Clumpy Disks at High Redshift

Isolated galaxy simulations:

Noguchi 99; Immeli et al. 04ab; Bournaud, Elmegreen, Elmegreen 06, 08

now reaching 1-pc resolution for 1-Gyr

Zoom-in cosmological simulations:

Dekel, Sari, Ceverino 09; Agertz et al. 09; Ceverino, Dekel, Bournaud 10; Genel et al 11

ART, RAMSES, GADGET with 50-pc resolution to z=1

# Violent Disk Instability

High gas density → disk unstable

$$Q \propto \frac{\sigma \Omega}{G\Sigma} \leq 1$$

Giant clumps and transient features: processes on dynamical timescales

$$R_{\text{clump}} \propto \frac{G\Sigma}{\Omega^2}$$

Noguchi 99

Immeli et al. 04

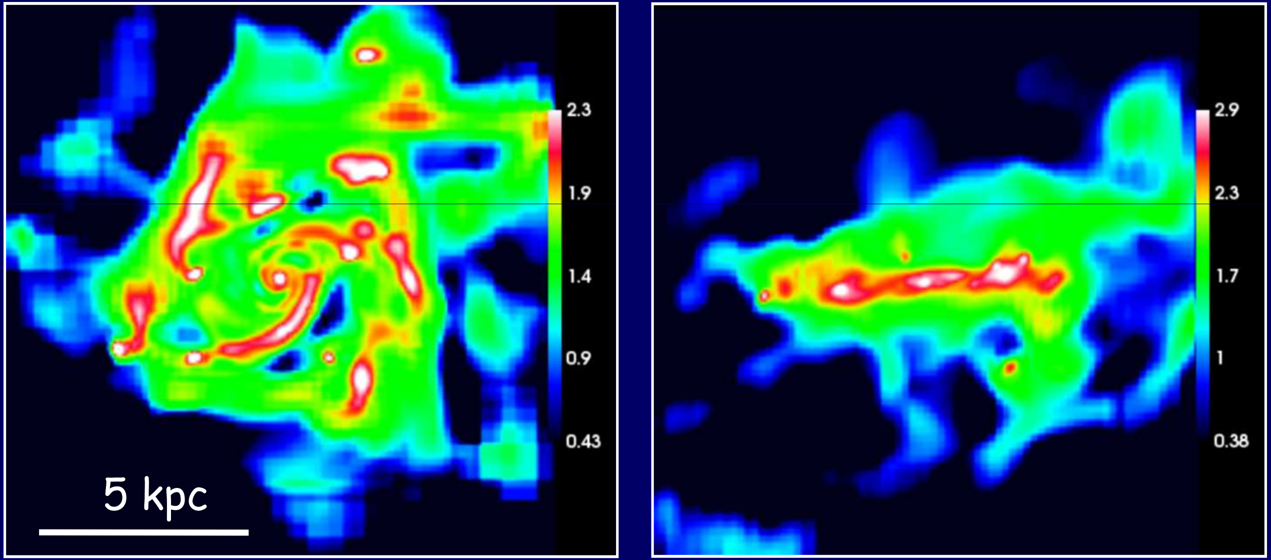
Bournaud, Elmegreen, Elmegreen 06, 08

In cosmology:

Dekel, Sari, Ceverino 09

Agertz et al. 09

Ceverino, Dekel, Bournaud 10



Self-regulated at Q~1 by torques and encounters → high σ/V~1/4

Torques induce inflow, e.g. rapid clump migration → bulge formation

Cosmological steady state: migration and replenishment, bulge ~ disk

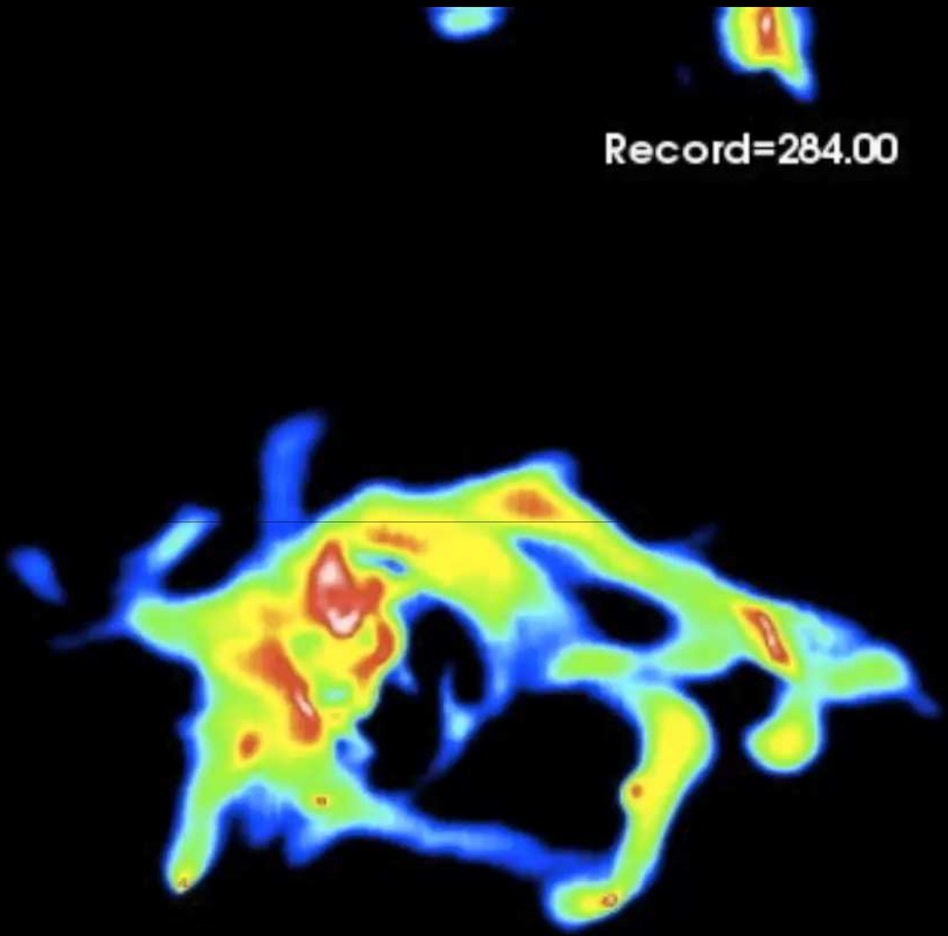
Star formation and feedback in clumps (to be understood)

# Clumpy Disk

Ceverino, Dekel et al.

10 kpc

z=4-2.1

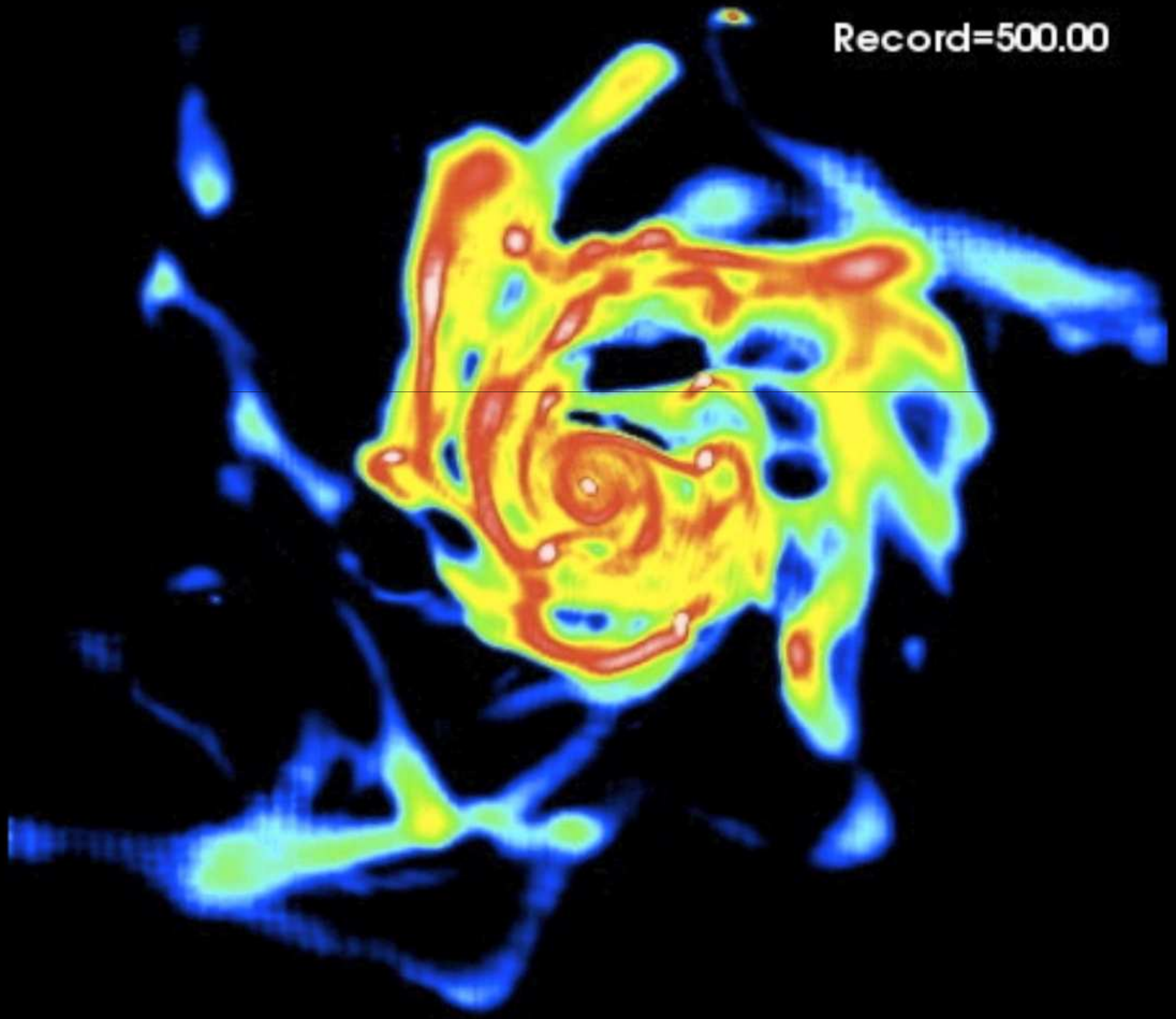


# Clumpy Disk

Ceverino, Dekel et al.

10 kpc

z=2.4-2.1

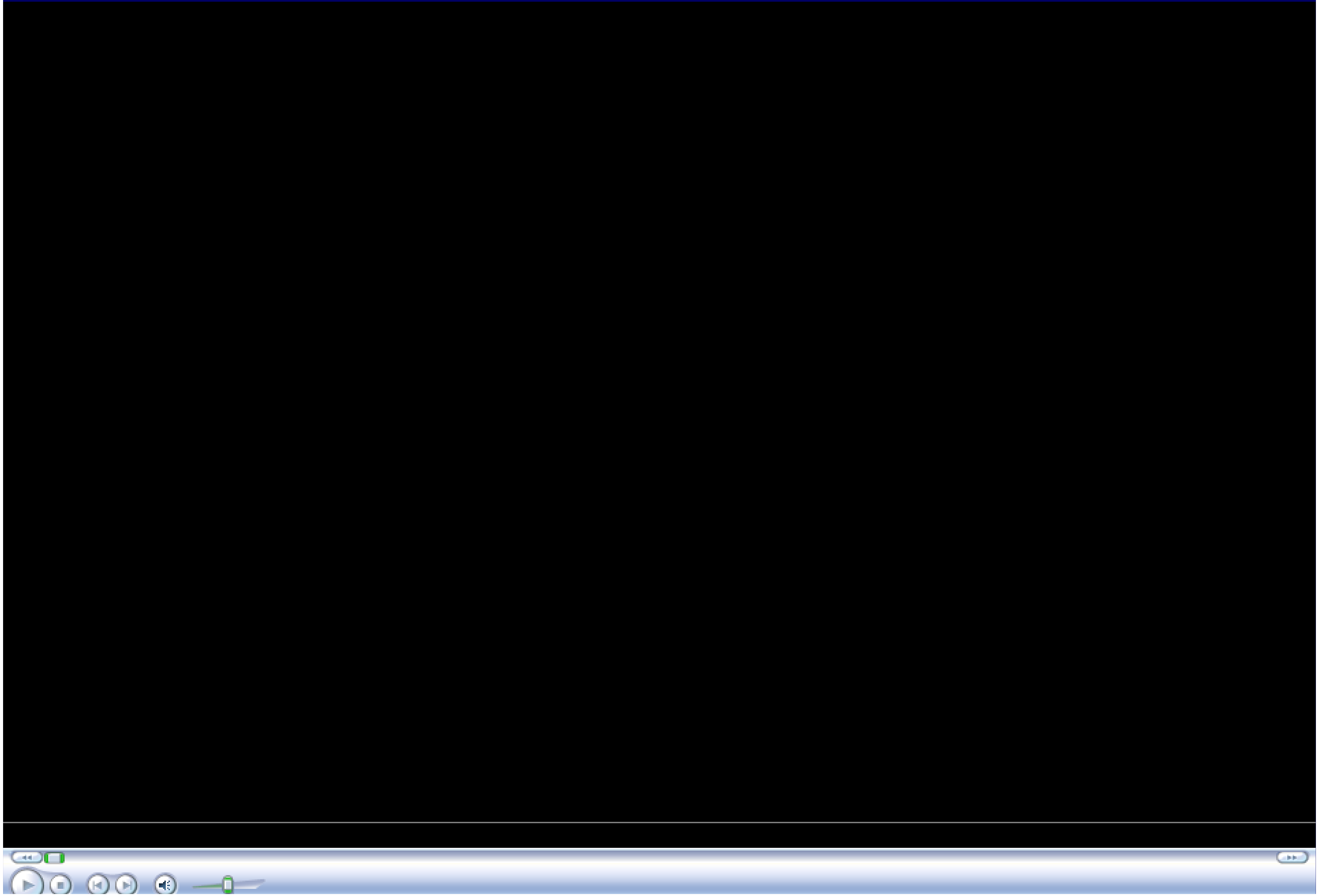


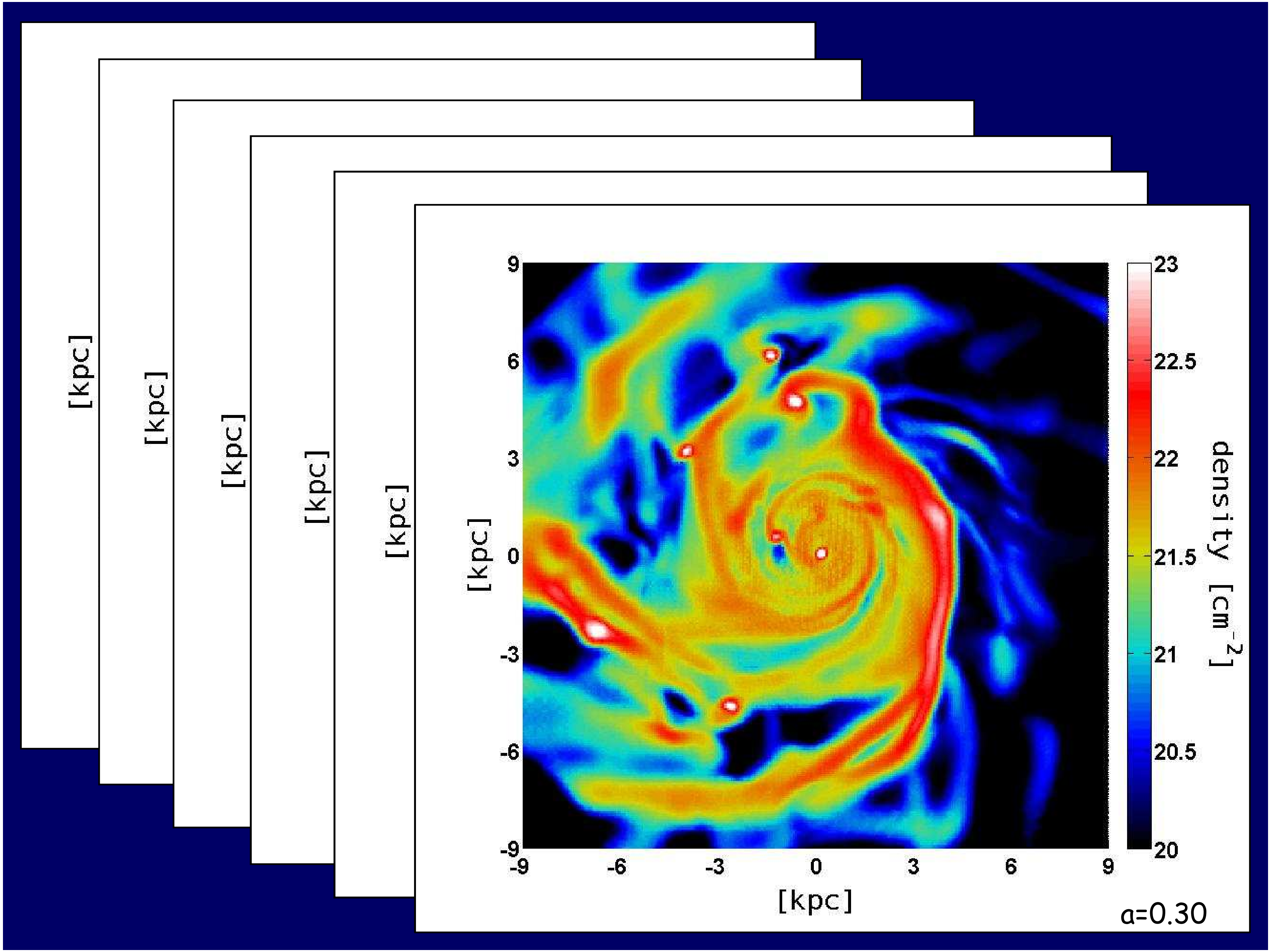
# Clumpy Disk

Ceverino, Dekel et al.

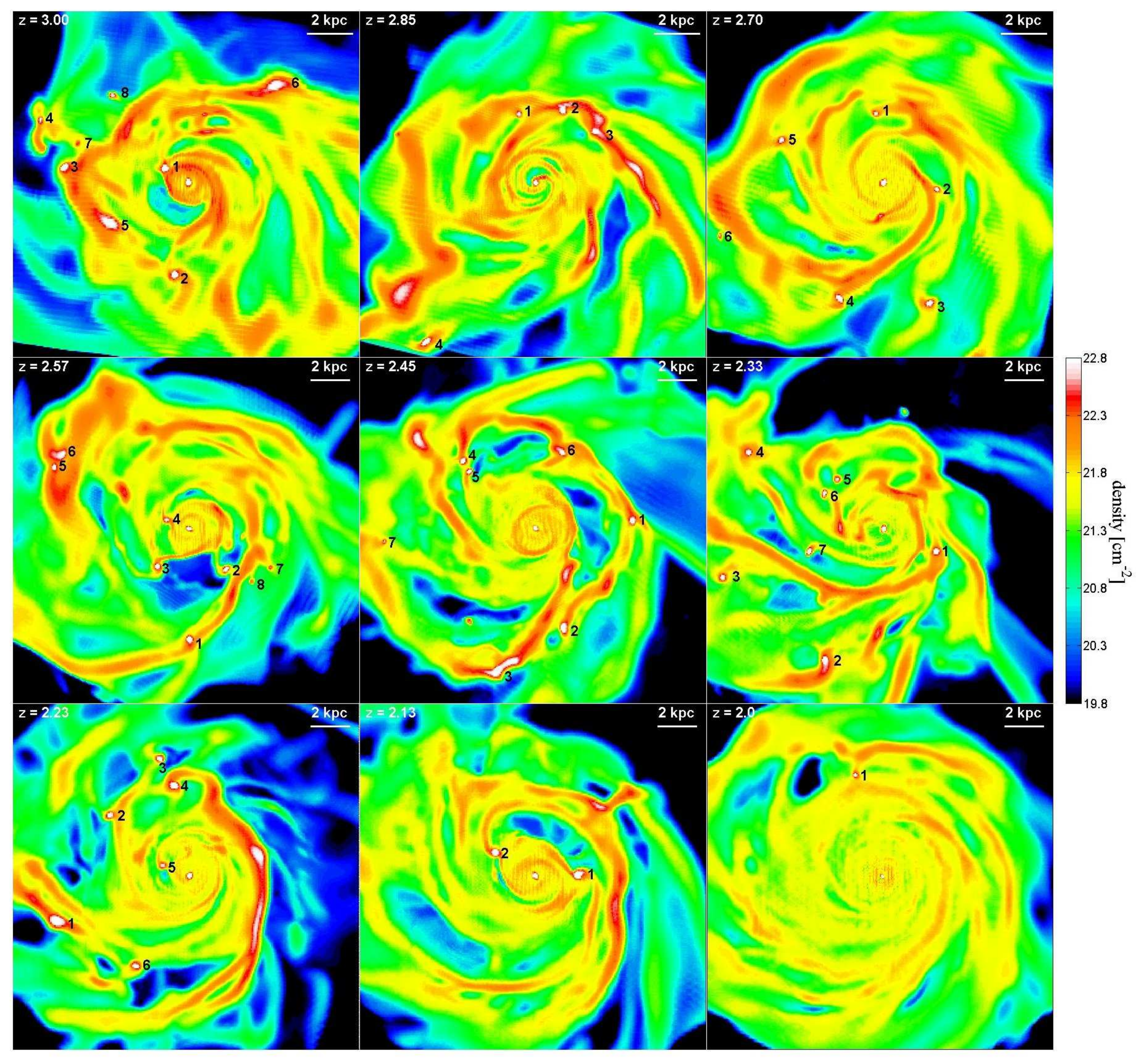
10 kpc

$z=2.4-2.1$




[kpc]
[kpc]
[kpc]
[kpc]
[kpc]
9
6
3
0
-3
-6
-9
[kpc]
-9
-6
-3
0
3
6
9
[kpc]
23
22.5
22
21.5
21
20.5
20
density [cm$^{-2}$]
a=0.30

# Clumpy Disk in a cosmological steady state

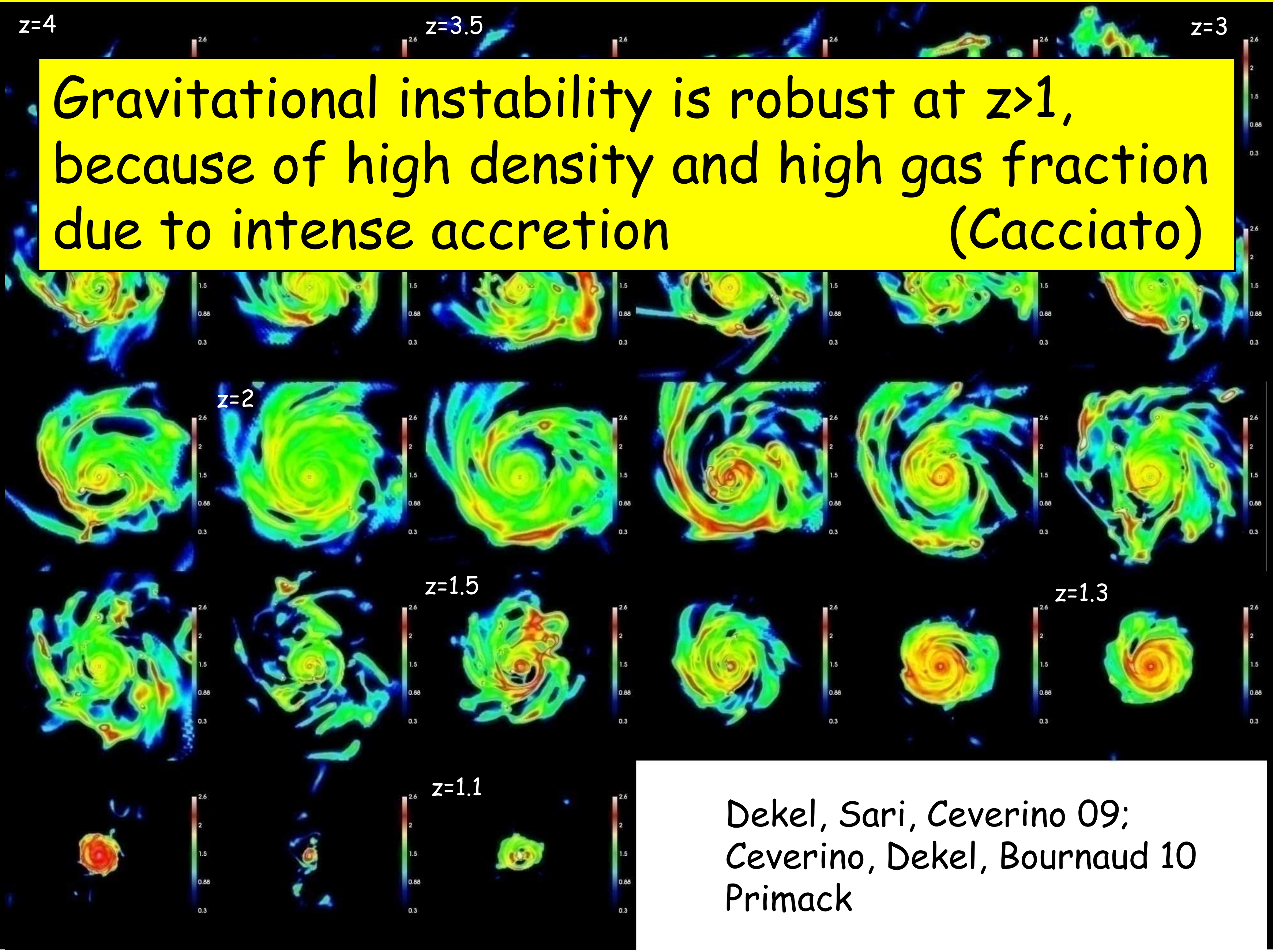


Dekel, Sari, Ceverino 09;

Ceverino, Dekel, Bournaud 10

From z>3 to z=1.4

# Clumpy Disk in a cosmological steady state



Gravitational instability is robust at z>1, because of high density and high gas fraction due to intense accretion (Cacciato)

Dekel, Sari, Ceverino 09;
Ceverino, Dekel, Bournaud 10
Primack

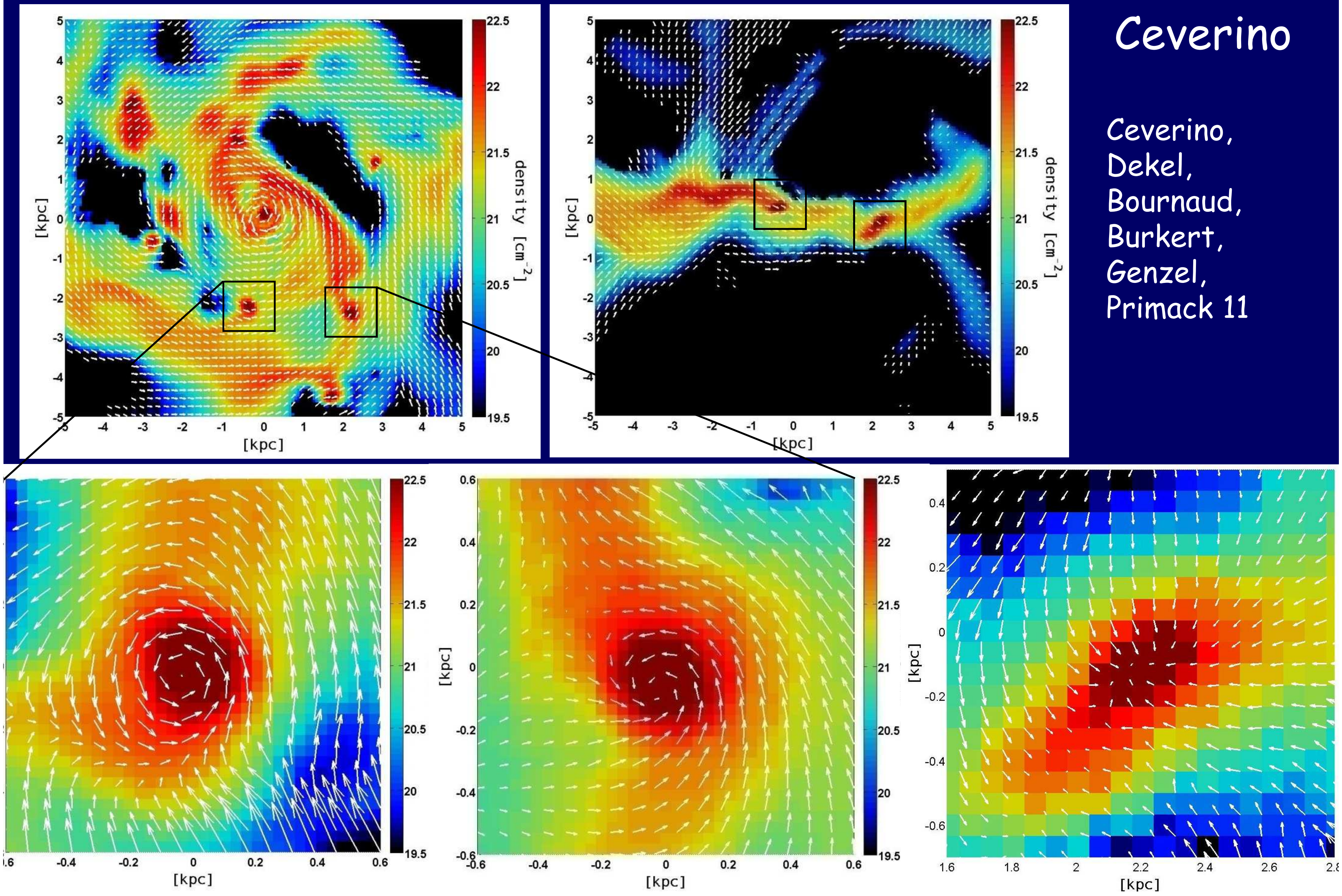
# Dependence on M and z

$f_{gas}$ is higher for small M and high z (e.g. Z-dependent SFR)
downsizing of star formation

If galaxies are unstable disks with Q~1,
galaxies of lower M and higher z:

- are more dispersion dominated $\frac{\sigma}{V} \approx 0.4 f_{\text{gas}}$
- have relatively more massive clumps $\frac{M_{\text{clump}}}{M_{\text{baryon}}} \approx 0.2 f_{\text{gas}}^{3}$
- migrate faster to a bulge and BH $\frac{\dot{M}}{M_{\text{baryon}} / t_{\text{dis}}} \approx 0.2 f_{\text{gas}}^{3}$
- maintain the instability longer (instability downsizing)

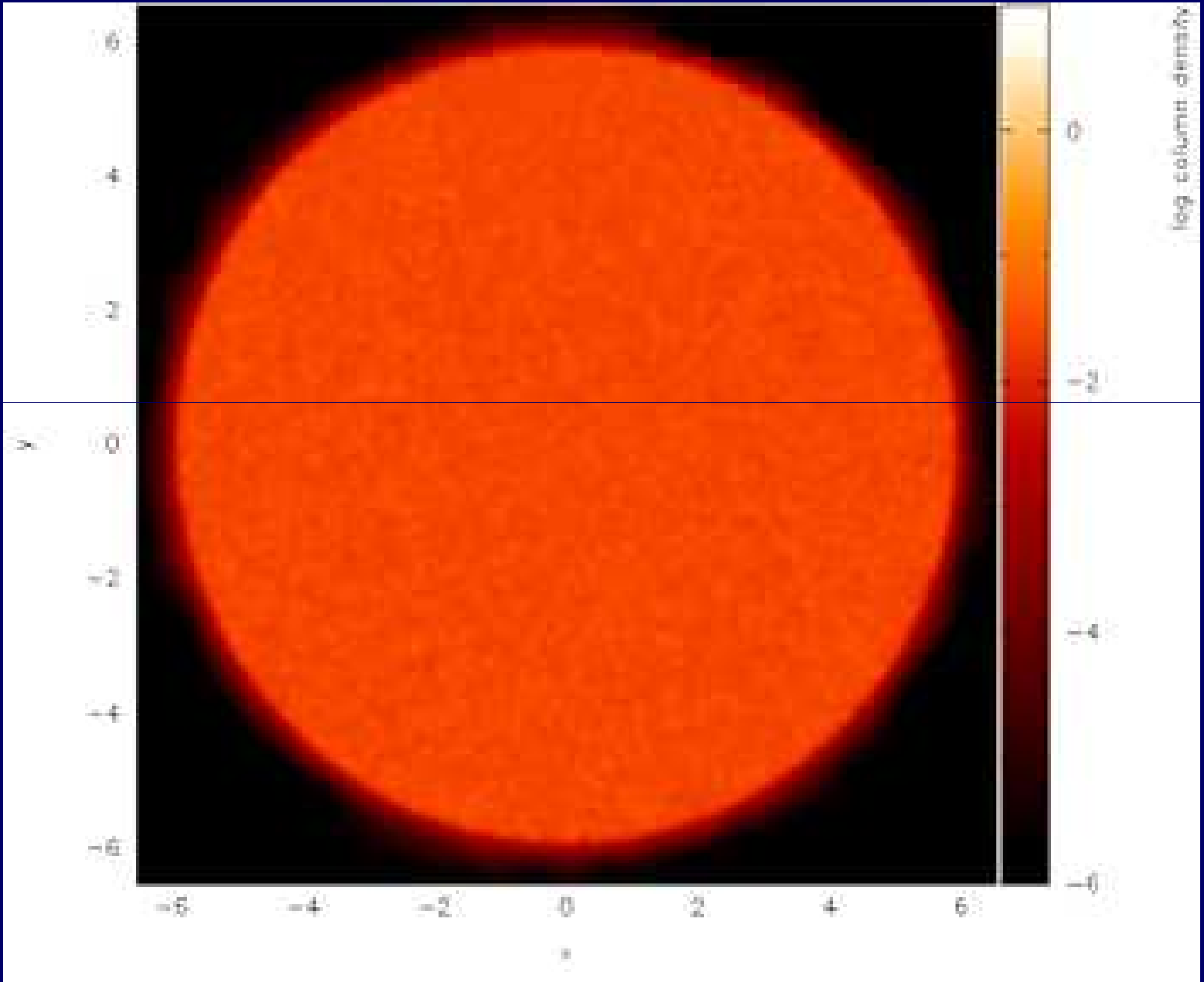
# Clump Support: The Clumps are Spinning



## Ceverino

Ceverino,
Dekel,
Bournaud,
Burkert,
Genzel,
Primack 11

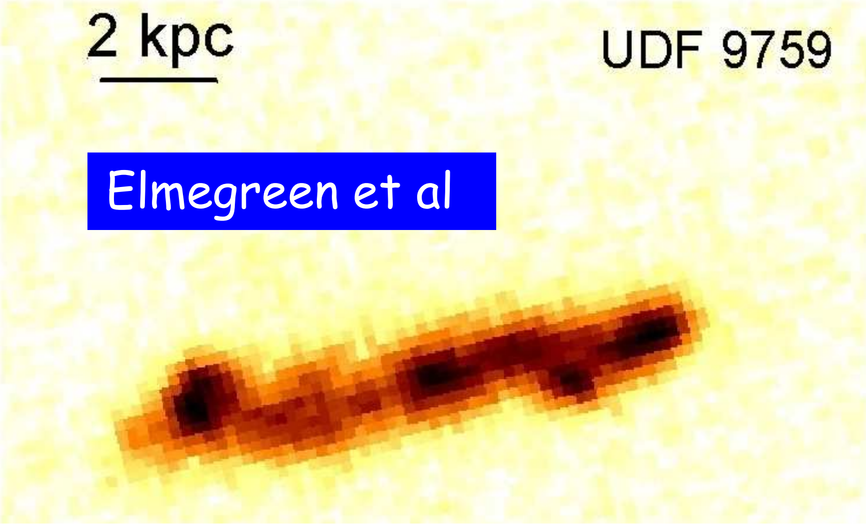
# Rotating Clumps in a Wildly Unstable Disk



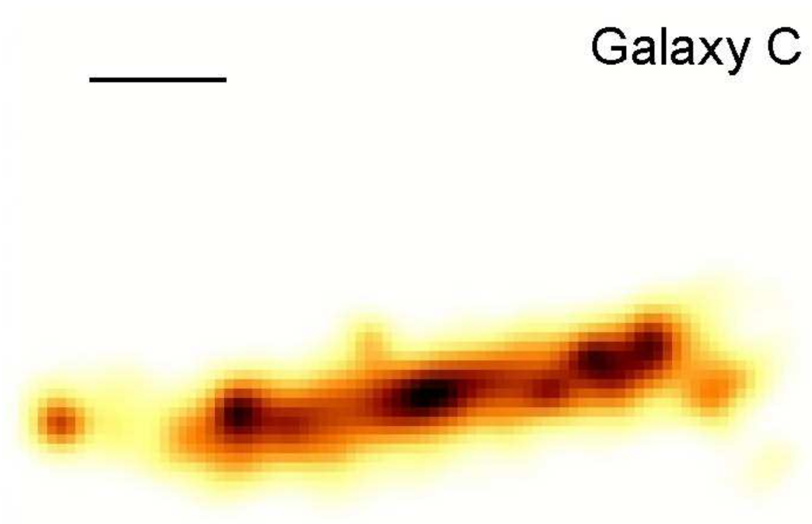
Naab

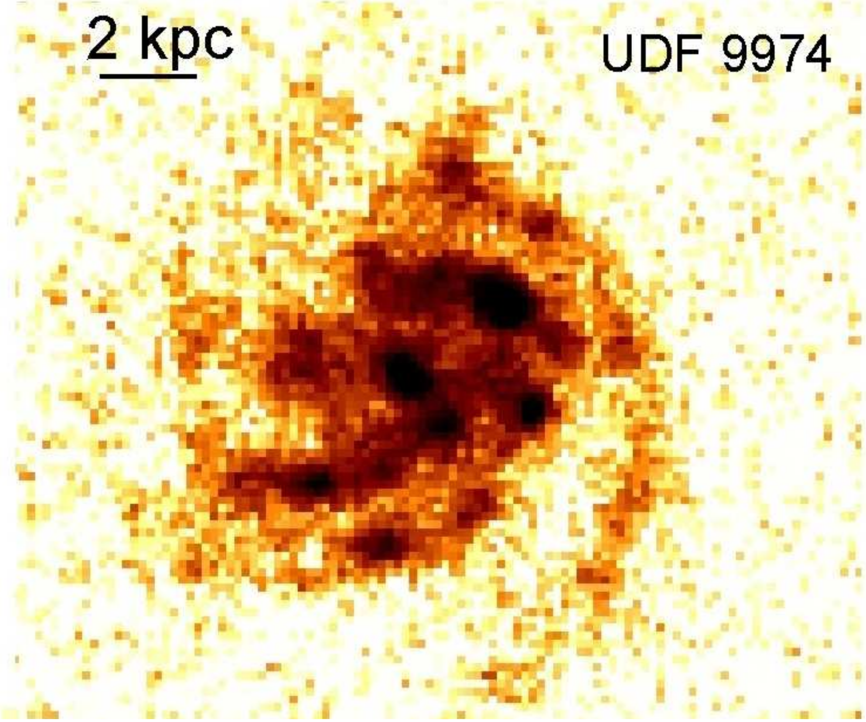
# Observations vs. Simulations

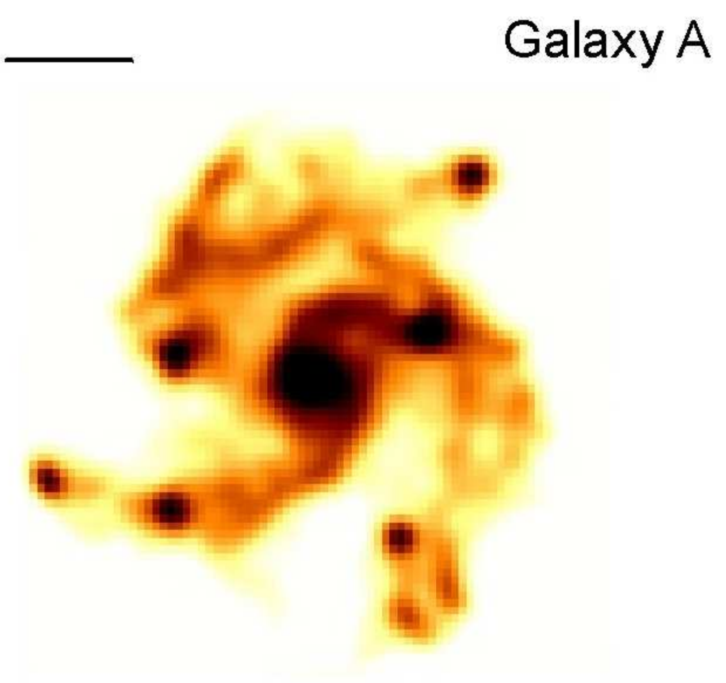
Mozena



Elmegreen et al



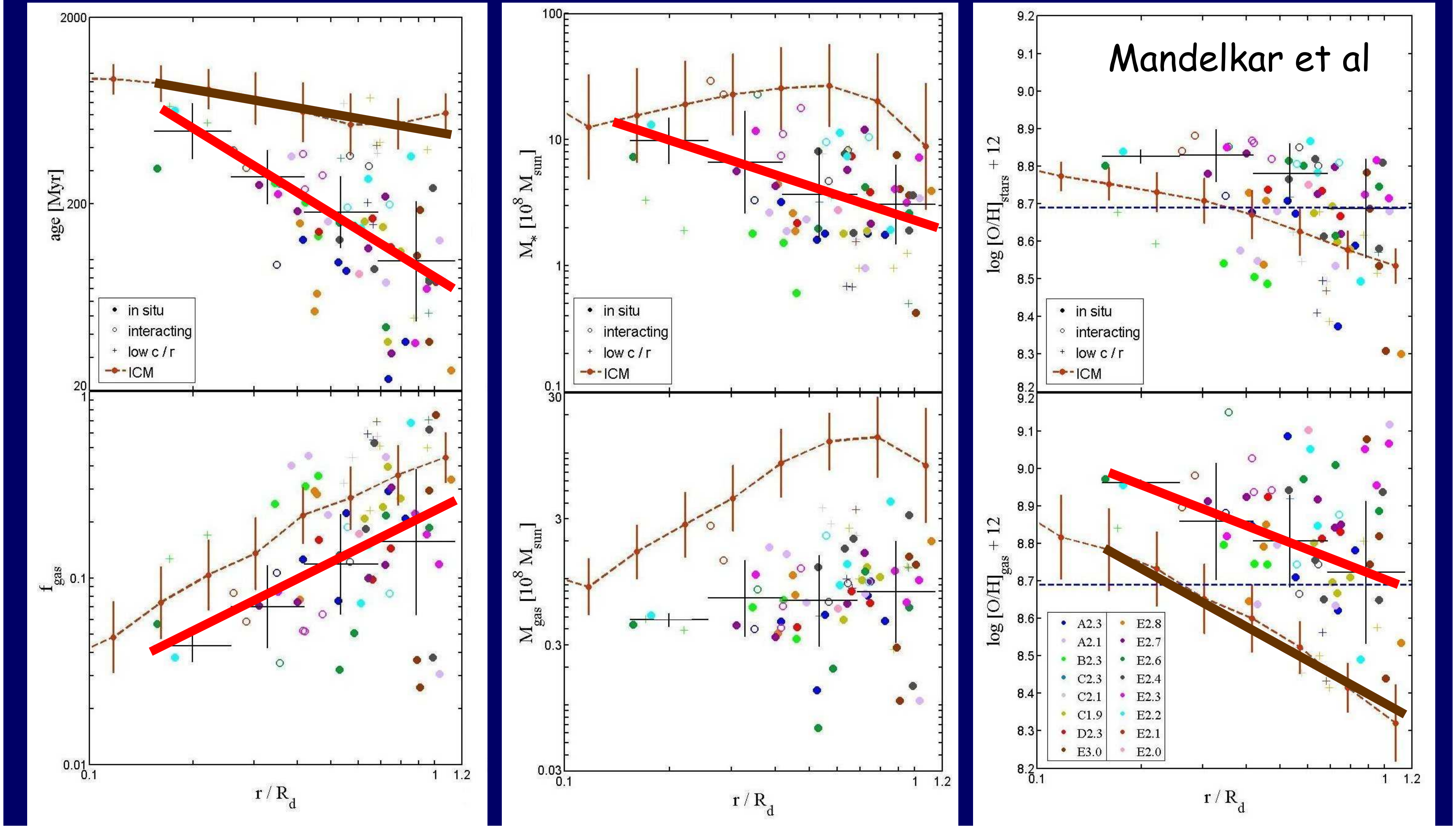




# Gradients in Disk Clumps -- clump disruption?

Low r clumps = massive, old, low gas, hi Z, low SSFR, ~SFR

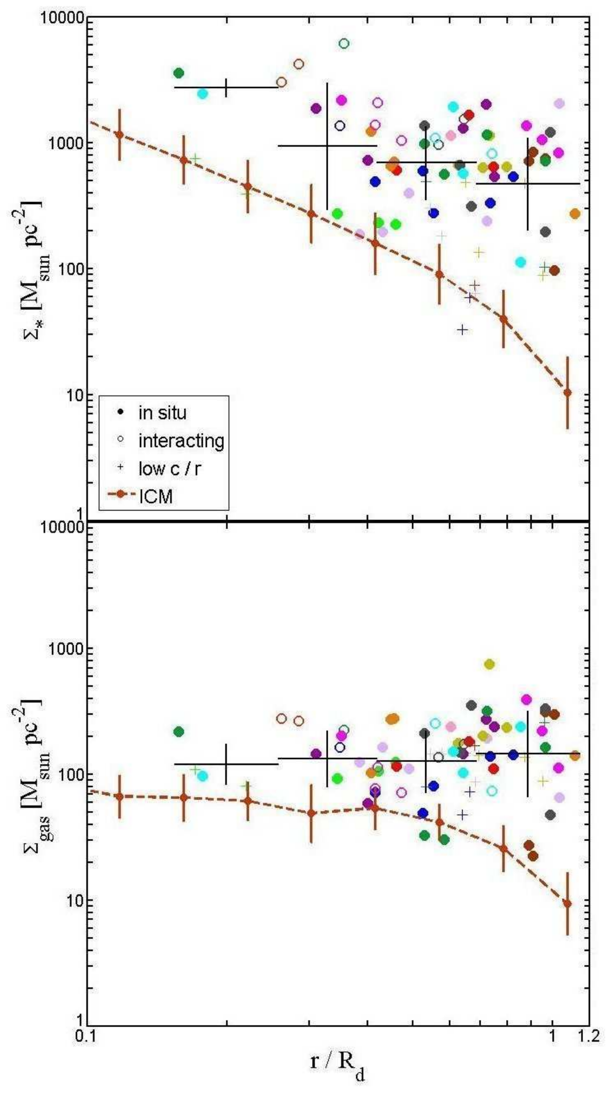
Gradients in disk are different from clumps

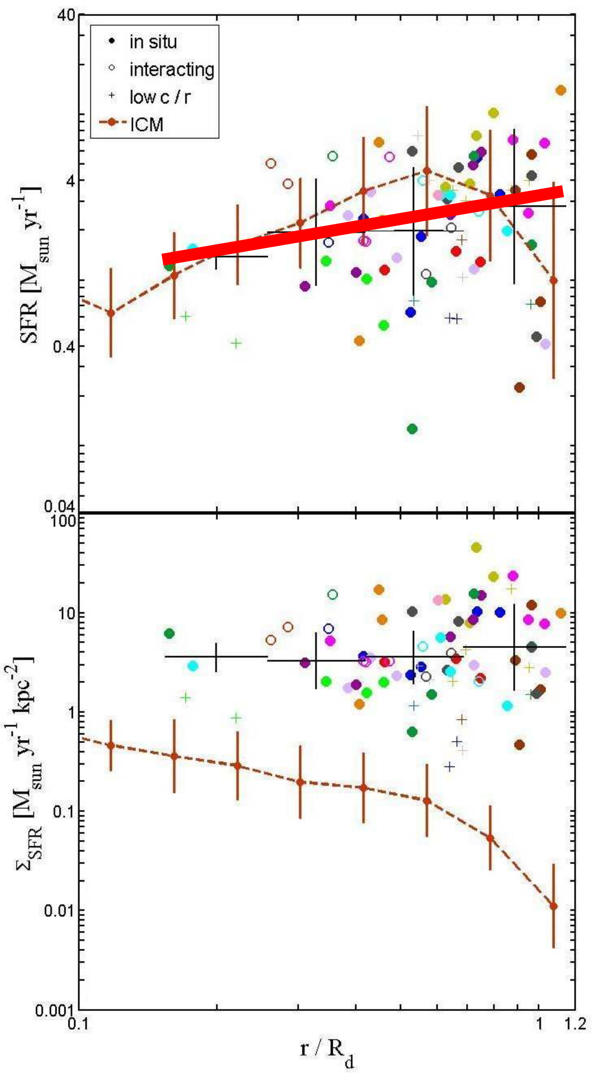


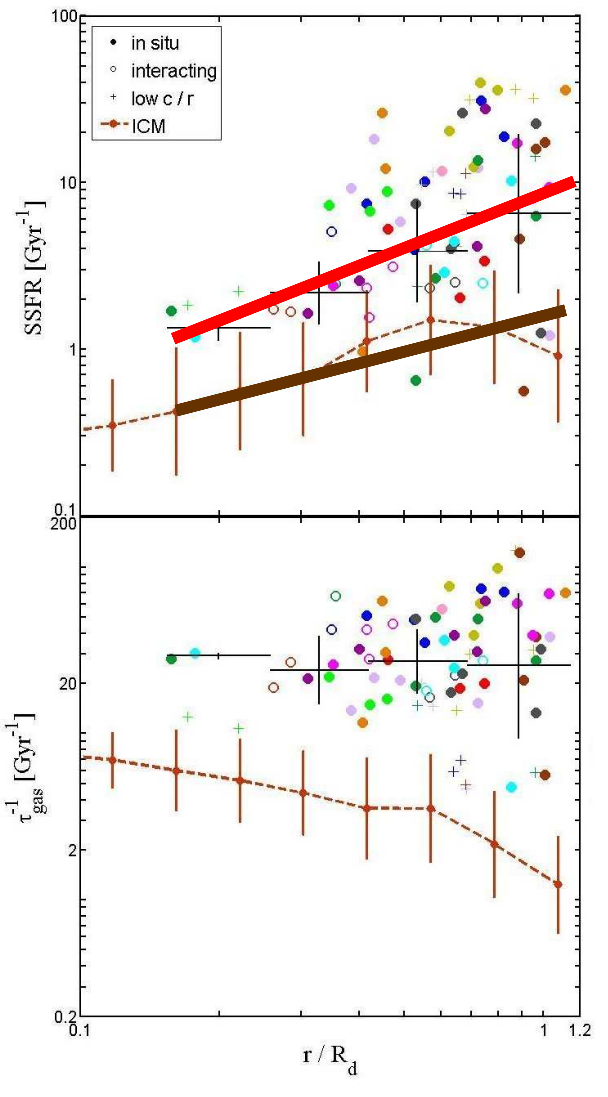
# Gradients in Disk Clumps -- clump disruption?

Low r clumps = massive, old, hi Z, low gas, low SSFR, ~SFR

Gradients in disk are different from clumps

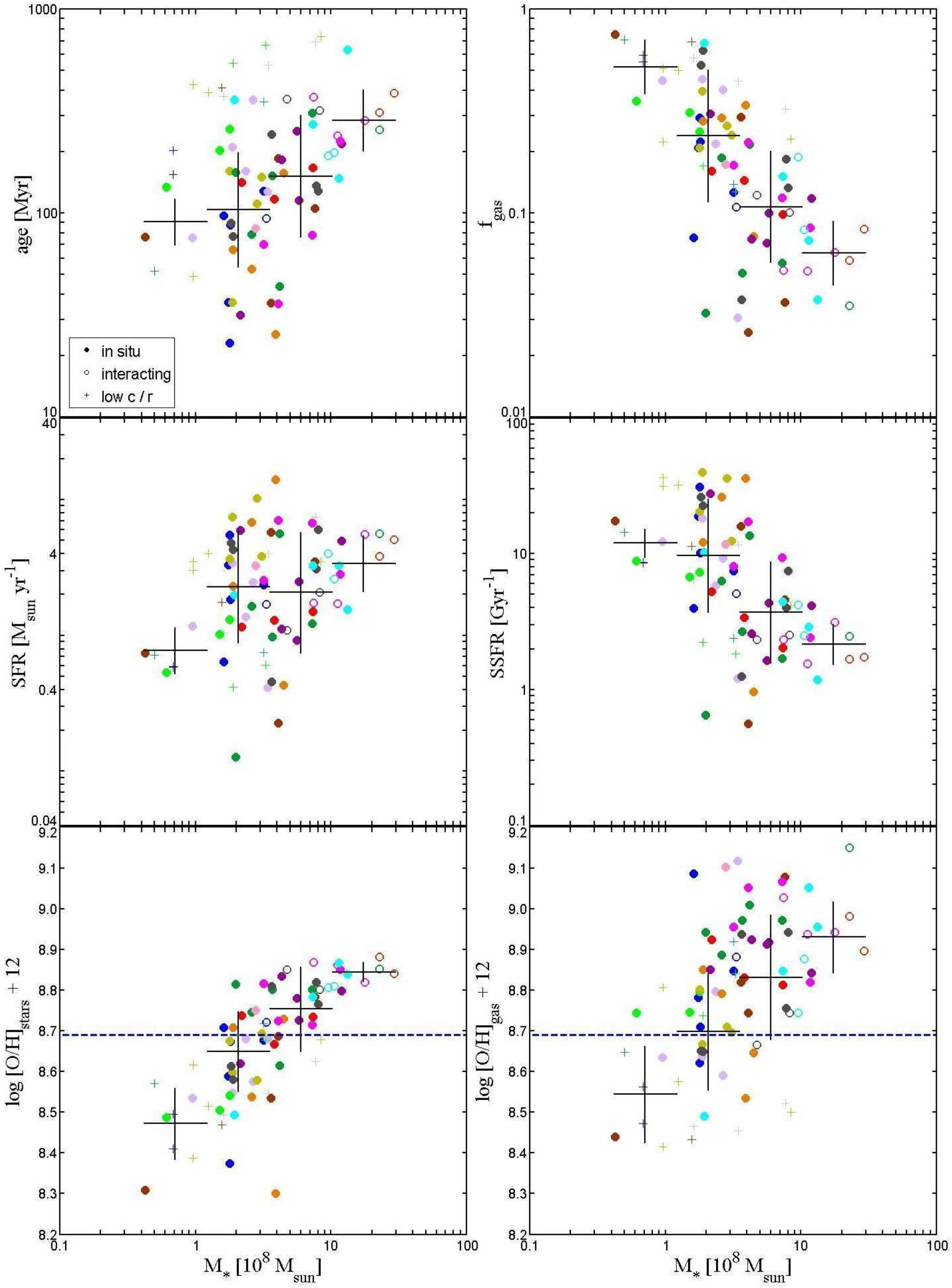




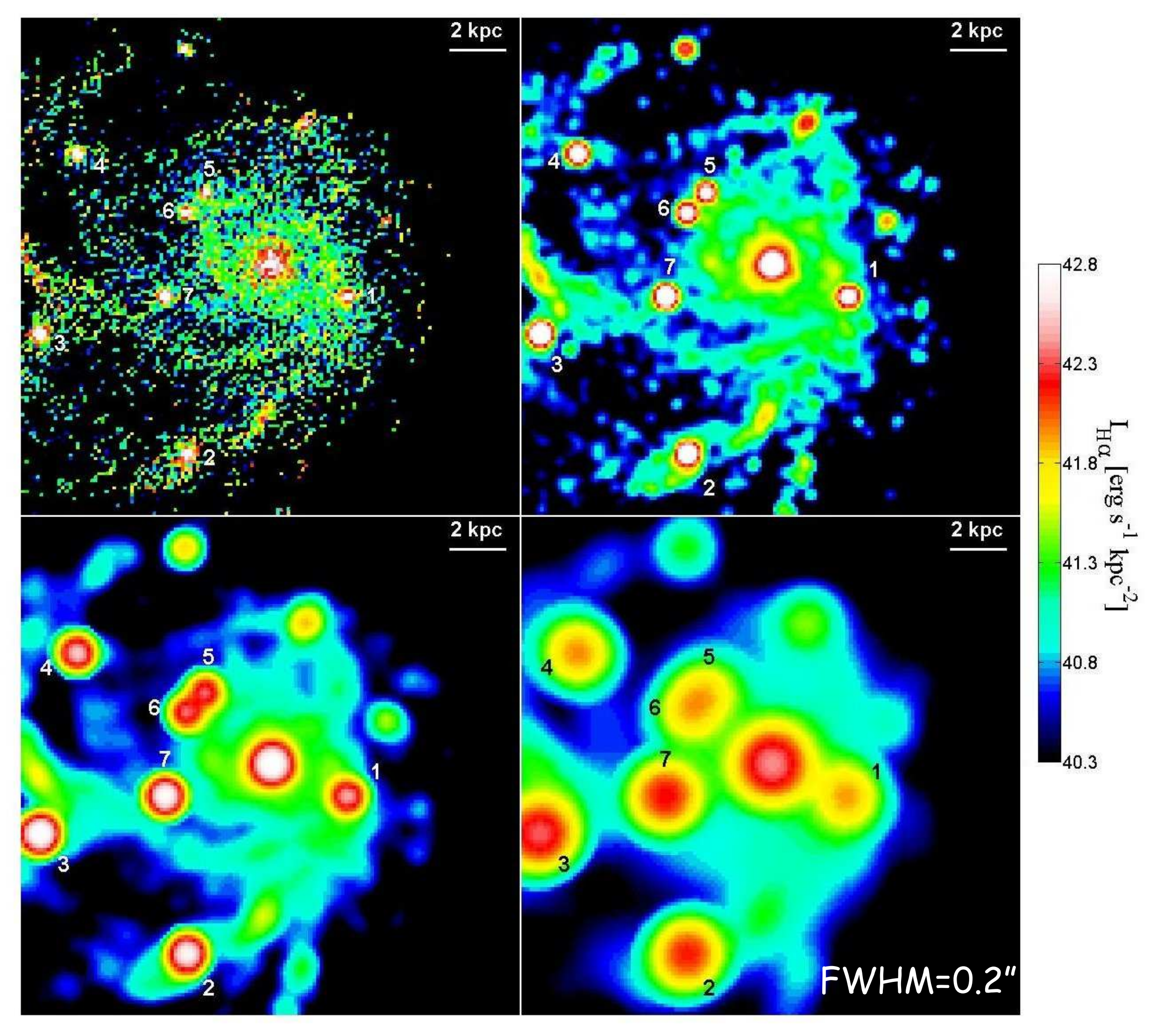


# Clump properties vs clump mass

Massive =
old stars
metal rich
low gas fraction
low SSFR
but high SFR

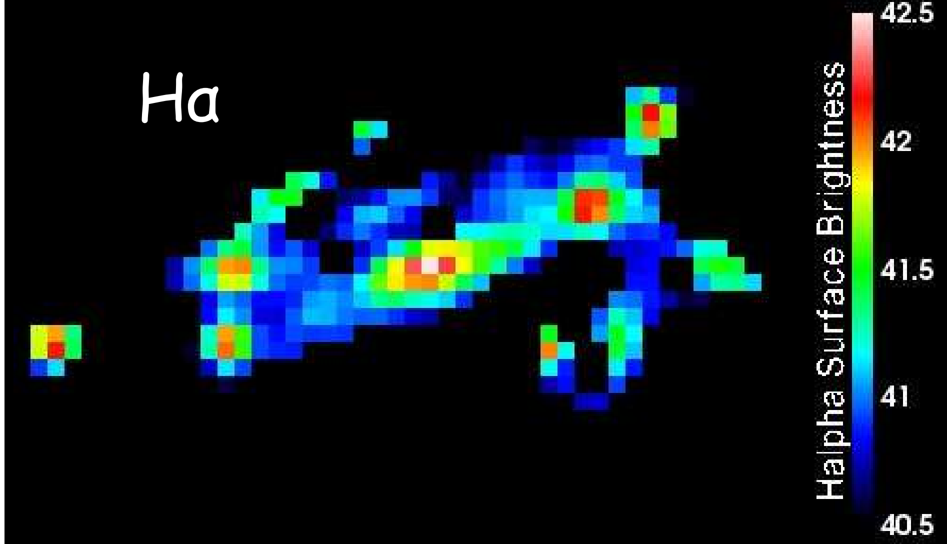


# Beam Smearing of Ha Images

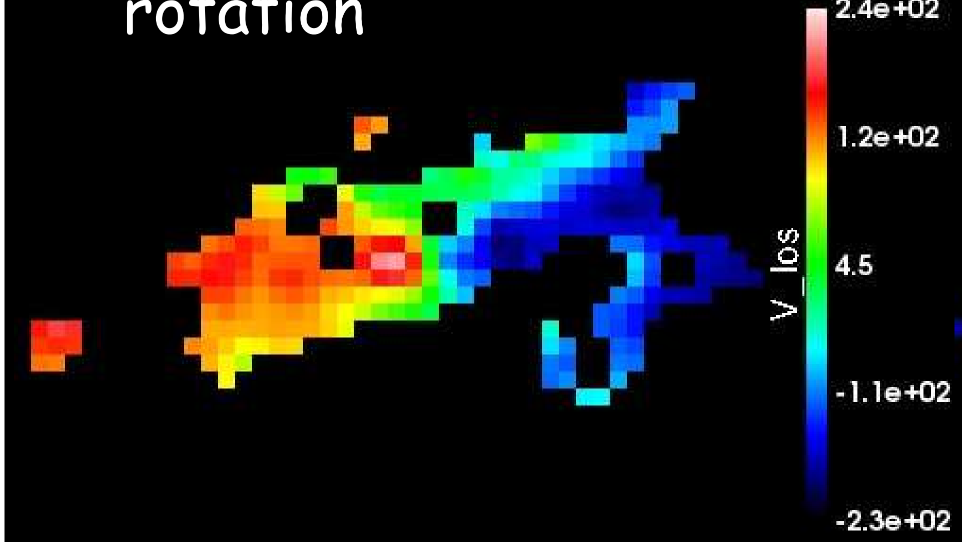


# Kinematics of Simulated Clumpy Disk

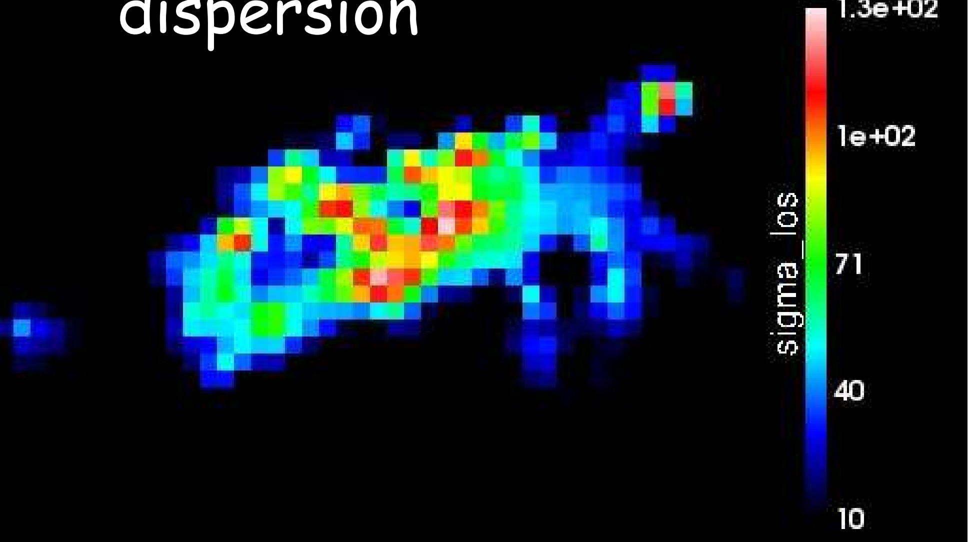
Hα



rotation

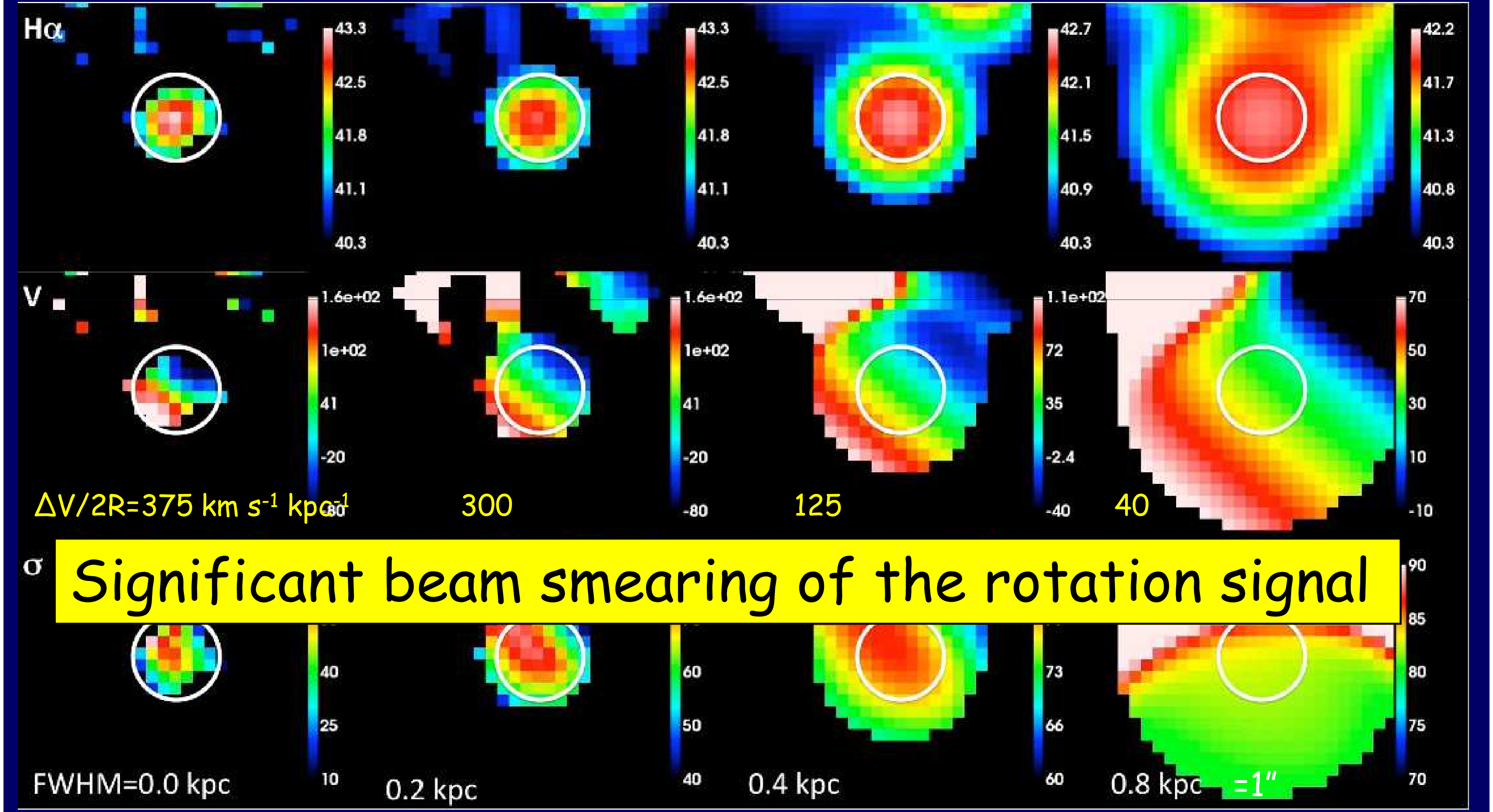


dispersion



# Clump Kinematics Under Beam Smearing

$M_c=2\times10^9 M_\odot$, $R_c=0.4$ kpc, $V_{circ}=125$ km s$^{-1}$, $V_{rot}=114$ km s$^{-1}$



Significant beam smearing of the rotation signal

# 8. Violent Disk Instability: Growing a Bulge and a Black Hole

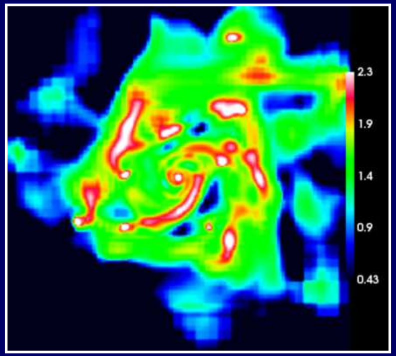
Bournaud, Dekel et al. 2011

# Violent Disk Instability ↔ Inflow to Center

Self-regulated Toomre instability at $Q \sim \sigma\Omega/\Sigma \sim 1$

$$\frac{M_{\text{disk}}}{M_{\text{tot}}} \approx \sqrt{2}\,\frac{\sigma}{V} \qquad \frac{M_{\text{clump}}}{M_{\text{disk}}} \approx \frac{1}{2}\left(\frac{\sigma}{V}\right)^2$$

$$\dot{M}_{\text{inflow}} \approx 0.2\,\frac{M_{\text{disk}}}{t_{\text{dyn}}}\left(\frac{\sigma}{V}\right)^2$$



1. Torques between perturbations drive AM out and mass in (e.g. clump migration)

Gammie 01; Dekel, Sari, Ceverino 09

2. Inflow down the potential gradient provides the energy for driving σ to Q~1 and it compensates for dissipative losses Krumholz, Burkert 10; Cacciato, Dekel 11

$$\dot{M}_{\text{inflow}} \approx 25\,M_{\Theta}\,yr^{-1}\,M_{\text{disk},11}\,(1+z)_3^{3/2}\,(\sigma/V)_{0.2}^2\,f_{\text{dis},4}^{-1}$$

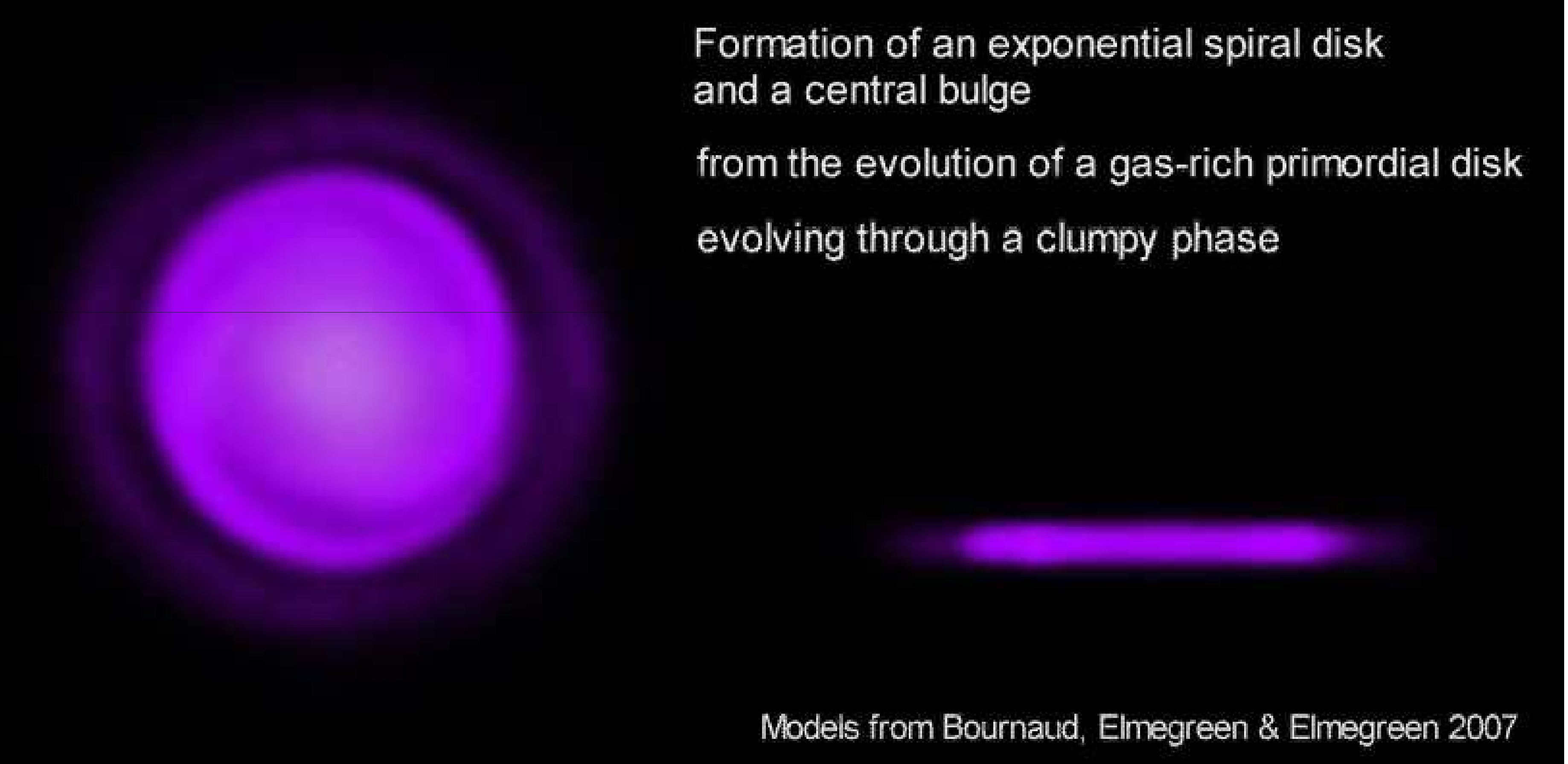
into the inner 100 pc

3. $$\dot{M}_{\text{gas}} \approx \dot{M}_{\text{cos-acc}} - \frac{M_{\text{gas}}}{t_{\text{dyn}}}\left(\varepsilon_{\text{inflow}} + \varepsilon_{\text{sfr}} + \varepsilon_{\text{out}}\right)$$

At z~2 $\dot{M}_{\text{inflow}} \approx \dot{M}_{\text{sfr}} \approx \dot{M}_{\text{out}} \approx \frac{1}{3}\dot{M}_{\text{cos-acc}}$

Bouche et al 10; Krumholz, Dekel 11; Dave et al 11

# Isolated, gas-rich, turbulent disk - giant clumps - migration - bulge



Formation of an exponential spiral disk
and a central bulge

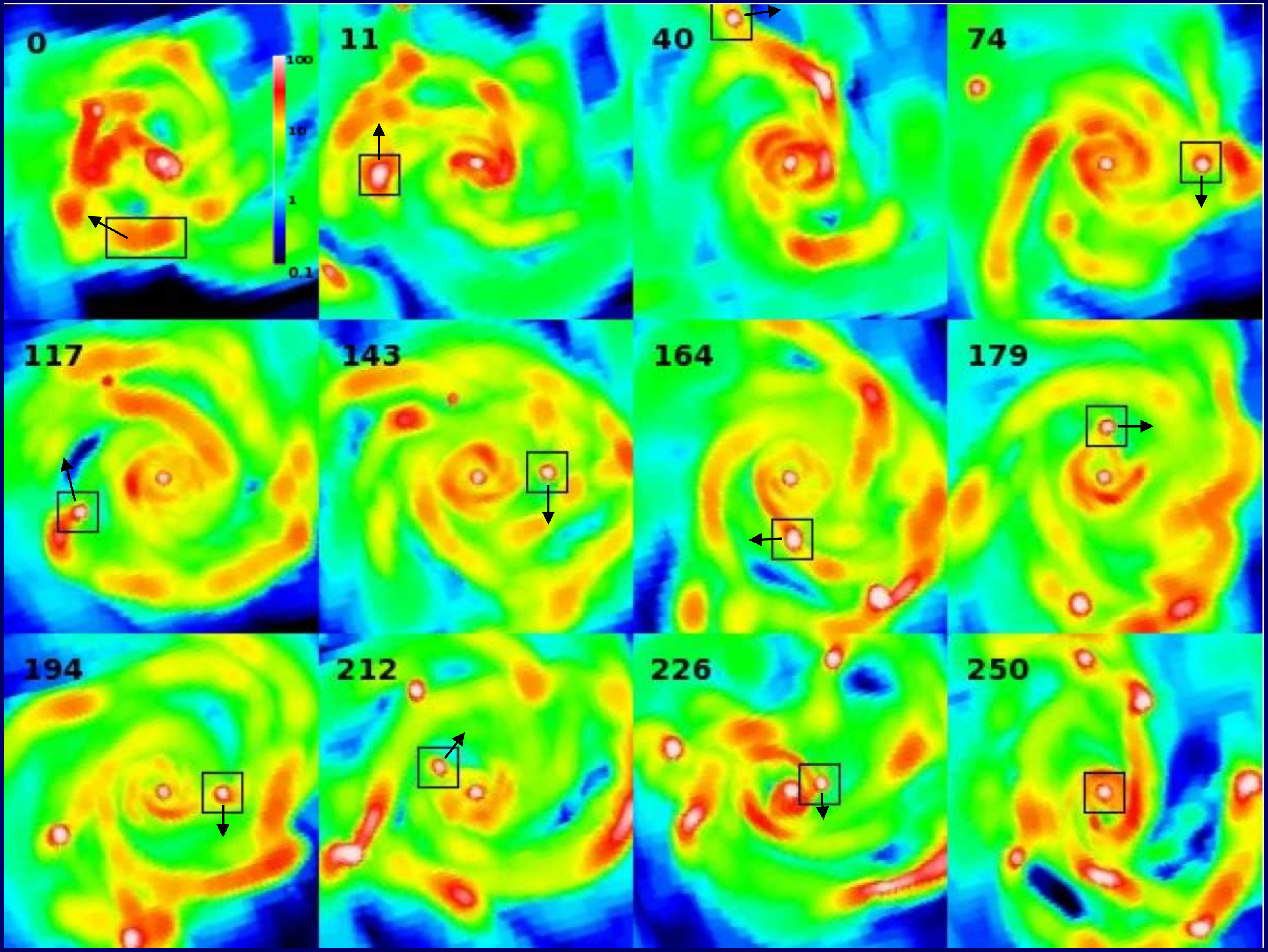
from the evolution of a gas-rich primordial disk

evolving through a clumpy phase

Models from Bournaud, Elmegreen & Elmegreen 2007

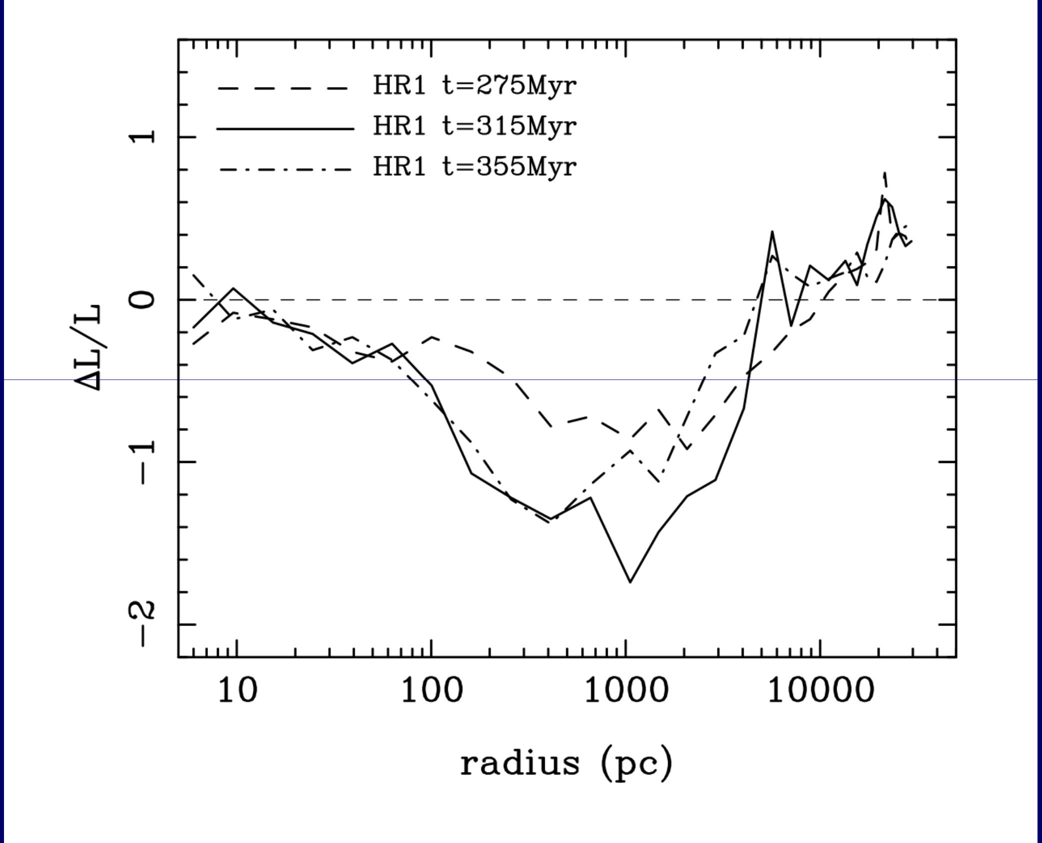
Noguchi 99; Immeli et al. 04; Bournaud, Elmegreen, Elmegreen 06, 08

# Clump Formation & Migration



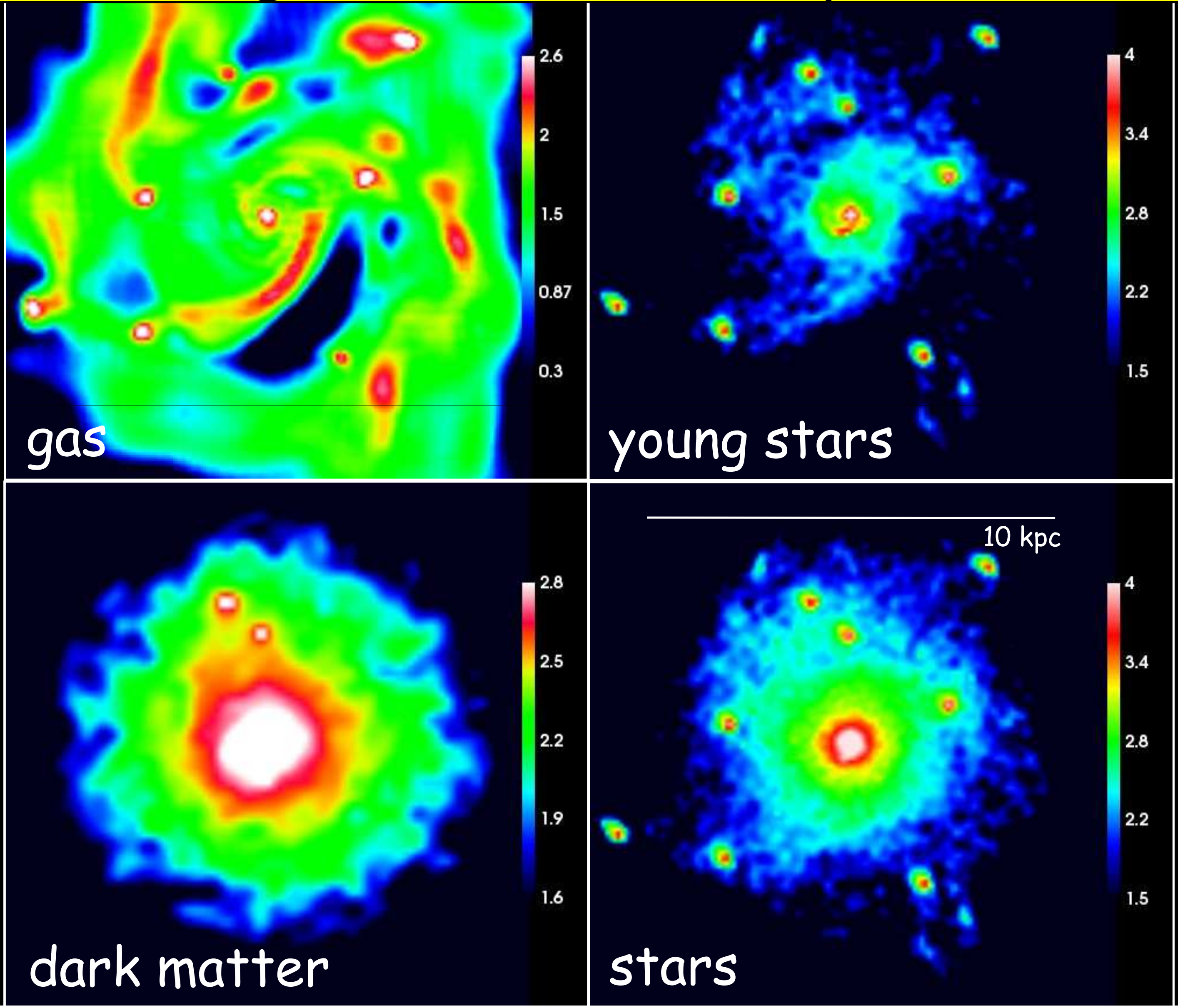
# Torques in Simulated Disks

Bournaud, Dekel et al. 2011 Isolated disk at 1-pc res



Inflow in an unstable disk is not limited to clump migration, and it occurs even if clumps are disrupted, and involves stars

# Formation of Spheroid by Disk Instability
# Bulge~Disk in Steady State



# Bulge – Black Hole - AGN

Bournaud, Dekel et al. (+simulations)

At z~2, $M_{bar}$~$10^{11}M_{\odot}$
inflow ~20 $M_{\odot}yr^{-1}$ into the inner disk

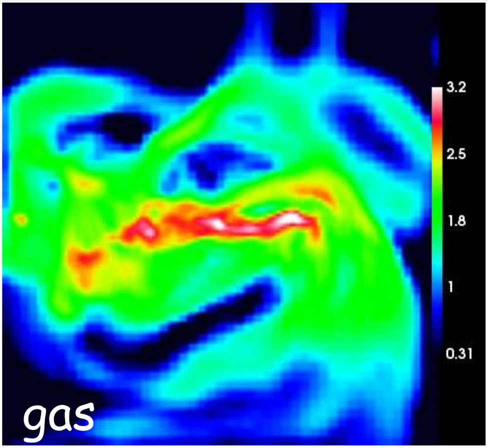
$M_{BH}$-σ relation → 0.003xInflow accretes onto BH

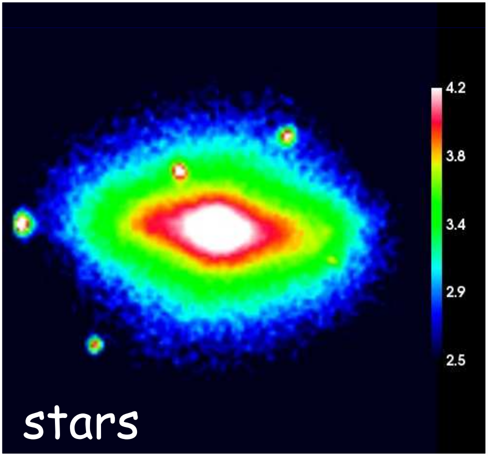
$M_{bulge}$~$M_{disk}$~$5x10^{10}$ $M_{\odot}$   $M_{BH}$ ~$10^{8}$ $M_{\odot}$
Classical bulge, n~3, compact

<accretion> ~2% Eddington,   $\langle L_x \rangle$ ~ $10^{42-43}$ erg $s^{-1}$
Short brighter episodes due to clump coalescence

Gas column density ~$10^{23-24}$ $cm^{-2}$ can obscure AGN

Similar to major mergers, but more abundant





At z>6: inflow in the disk allows Eddington accretion onto the BH
By z~6 grow $M_{BH}$~$10^{9}M_{\odot}$ from a seed ~$5x10^{4}M_{\odot}$ at z~10

# Conclusions

High-z galaxies are fed by cold streams from the cosmic web, including mergers. The streams are co-planar to >5$R_{vir}$, embedded in a pancake, and penetrate into the inner halo. Inflow is 70% in streams (92% in 3), 20% in pancakes

Streams transport AM, mostly through one dominant stream. The disk orientation is only weakly correlated with AM at $R_{vir}$: AM is exchanged in the disk vicinity

Wide-angle outflows are in harmony with the dense inflowing streams

The cold streams are observable in emission (LAB) and in absorption (LLS, DLAS), but low sky coverage and low metallicity.

SFR ~ instreaming rate at z<2 → high SFR at z~2.
SFR is suppressed at z>>2, e.g. by low metallicity in small galaxies
→ very high gas fraction

Intense gas input → gas-rich disks → violent instability → giant clumps and transient features → self-regulated inflow ~10 $M_\odot yr^{-1}$ to the disk center → compact classical bulge, BH, AGN, obscuration

# Rotating Clumps

Ceverino, Dekel, Bournaud, Burkert, Genzel, Primack 2011

ART, resolution 35-70 pc, 5 galaxies, $z=3-2$, 77 clumps

# Non-rotating Extreme Clumps?

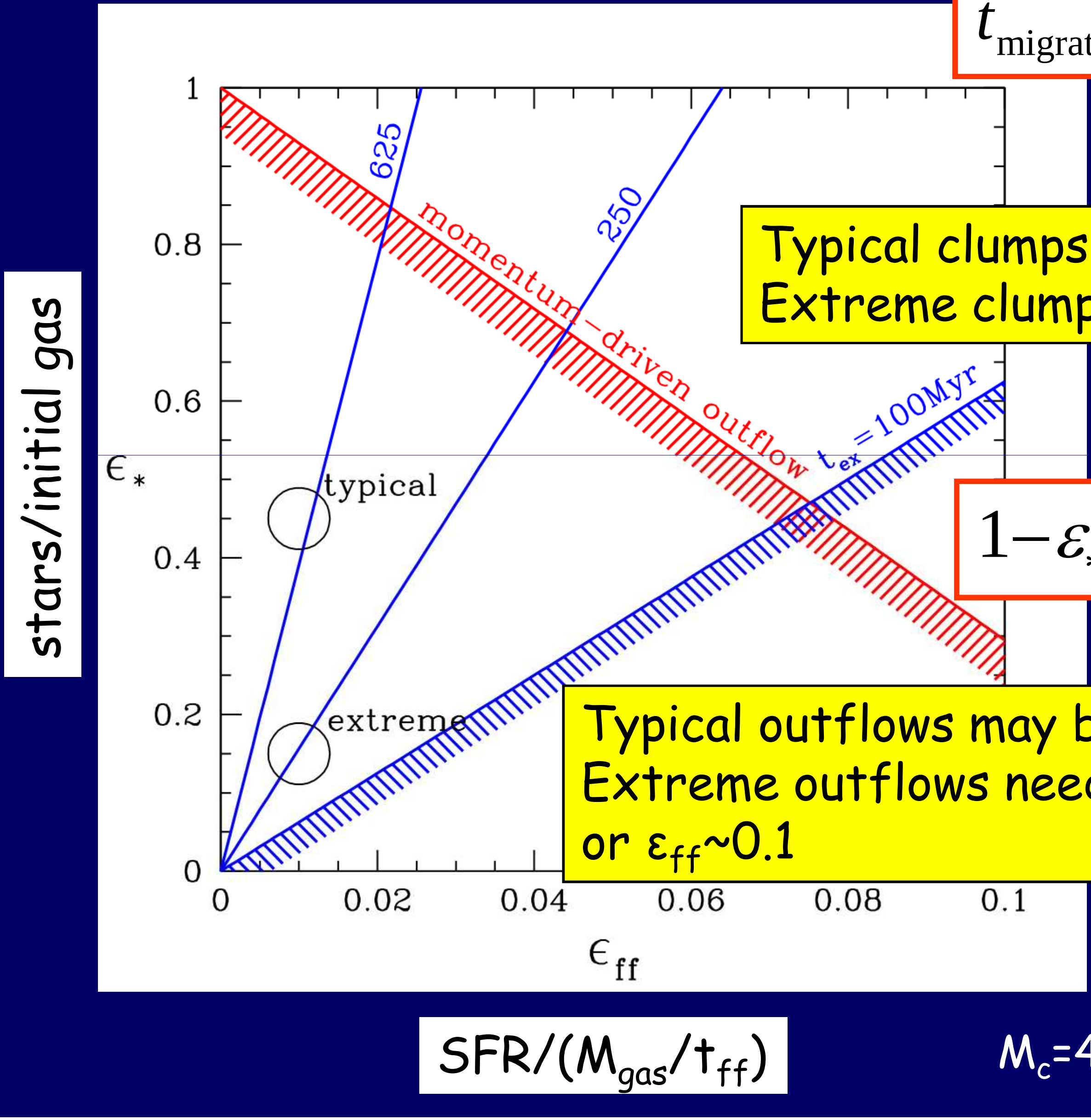
Observed (0.2″): $M_c \sim 10^{10} M_\odot \sim 0.25 M_d$, $R_c \sim$kpc,
no rotation signal, outflows

Origin?

- Toomre in-situ clumps: $M_c/M_d \sim 0.03$
- In-situ merged clumps? $M_c/M_d \sim 0.06$, 1/3 half-rotating
- Ex-situ merged galaxies? $M_c/M_d \sim 0.1$, can be non-rotating

- Disrupting clumps? If $\Sigma > 5\text{x}10^3 M_\odot \text{pc}^{-2}$ then rad force >> L/c
- Tilted clumps?
- Rotation unresolved?

# Clump Survival, Momentum-driven Outflows



$$t_{\rm migration} \approx 250\,{\rm Gyr} \approx 1.3\,t_{\rm orbit}$$

Dekel, Sari, Ceverino 09
Ceverino, Dekel, Bournaud 10

Typical clumps complete their migration,
Extreme clumps disrupt

Krumholz & Dekel 10

$$1-\varepsilon_* \approx 0.07\, f_{\rm trap,3}\,\varepsilon_{\rm ff,0.01}\,V_{\rm c,135}^{-1}$$

force = $f_{trap}$ L/c

Typical outflows may be momentum driven.
Extreme outflows need $f_{trap}$>>1 ($\Sigma$>5000 $M_{\odot}pc^{-2}$)
or $\varepsilon_{ff}$~0.1

$M_c$=4x$10^9 M_{\odot}$, $R_c$=1 kpc, $t_{ff}$=8Myr

# Conclusion I

Metallicity has a major role in galaxy formation

$f_{H2} \sim Z\Sigma$,   Z is increasing with time and mass
→ quenching of SFR at $z>2$ in $M<10^{11}M_\odot$

At $z>2$, SFR cannot catch up with the accretion + Z is low
→ in a growing galaxy SFR is rising faster than the AcR
SFR ~ exp(-0.6z),    $M_* \sim \exp(-0.65z)$

Cosmic SFR density rise ($z>2$) and fall ($z<1$)
Effective SFR in a narrow mass band $10^{11}$-$2\times10^{12}M_\odot$ (not sharp cutoffs)

At $z>4$, Z quenching → ex-situ > in-situ stars + $M_g \gg M_*$
→ sSFR plateau at z=2-8

At $z>4$, non-ejective Z quenching → gas accumulates
→ high SFR at z=1-2, SFR>AcR

Many other implications: extended disks, less bulge, Low SFR in DLAS, etc.

# Conclusion II

The streams feeding high-z galaxies tend to be co-planar

The plane extends to ~5$R_{vir}$ , and penetrates into the haho

The streams are embedded in a pancake of low entropy

Inflow: 70% in streams (95% in 3), 20% in pancakes

The stream plane and AM at $R_{vir}$ are uncorrelated with the disk:
AM is transferred in the larger disk vicinity

Wide-angle outflows seem to be in harmony with the dense inflowing streams

# Conclusion III

Simulated clumps are in Jeans equilibrium, supported by rotation with some dispersion, consistent with simple theory & AM conservation.

Many clumps are highly tilted with respect to the disk

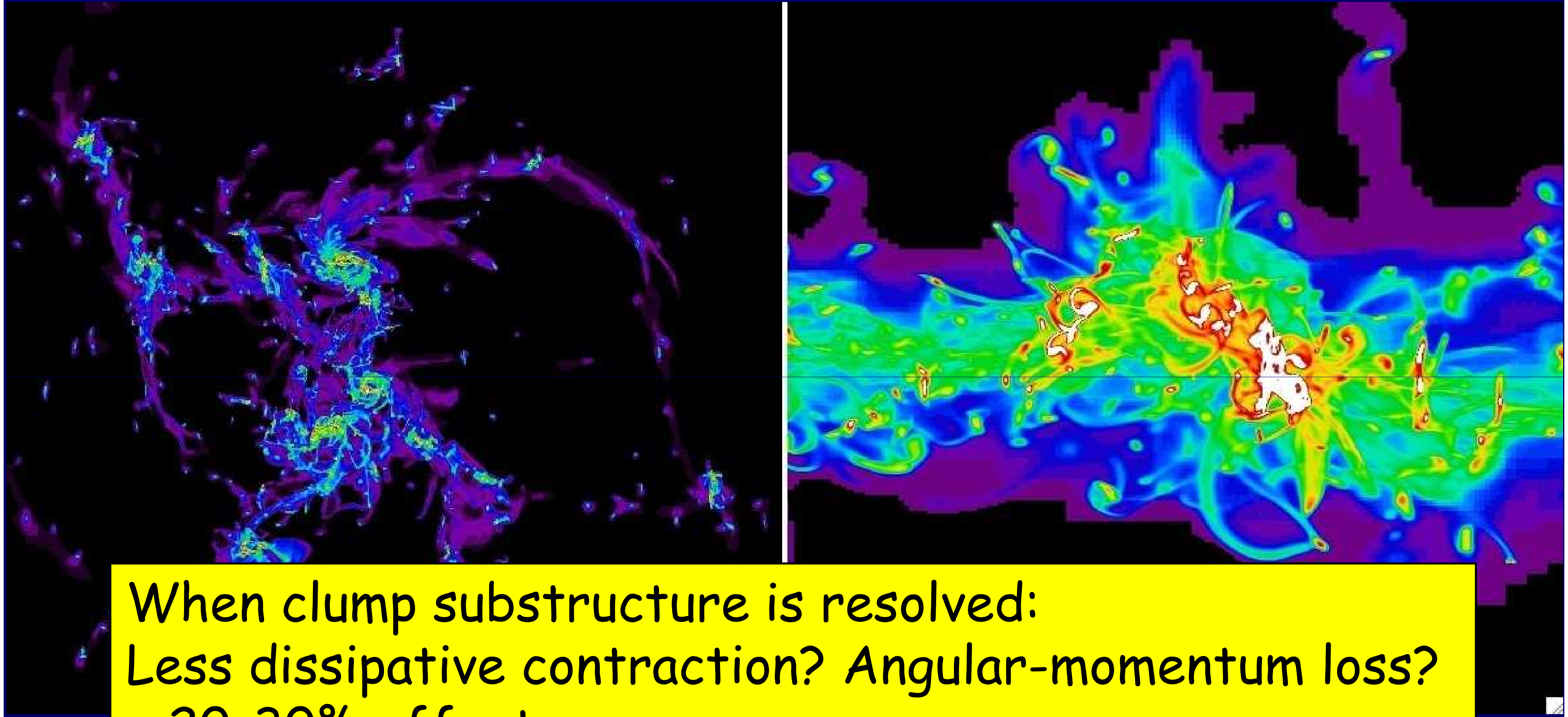
Beam smearing >0.1″ reduces the rotation signal to small values, consistent with typical observed clumps

Retrograde merging galaxies can be seen as disk giant clumps with no rotation signal

Typical observed clumps will complete their migration before exhaustion by outflows, while extreme clumps are disrupted.

Extreme outflows can be generated by momentum-driven feedback if $\Sigma > 5000\ M_{\odot} pc^{-2}$ allowing multiple scattering, or if the SFR efficiency is higher than Kennicutt

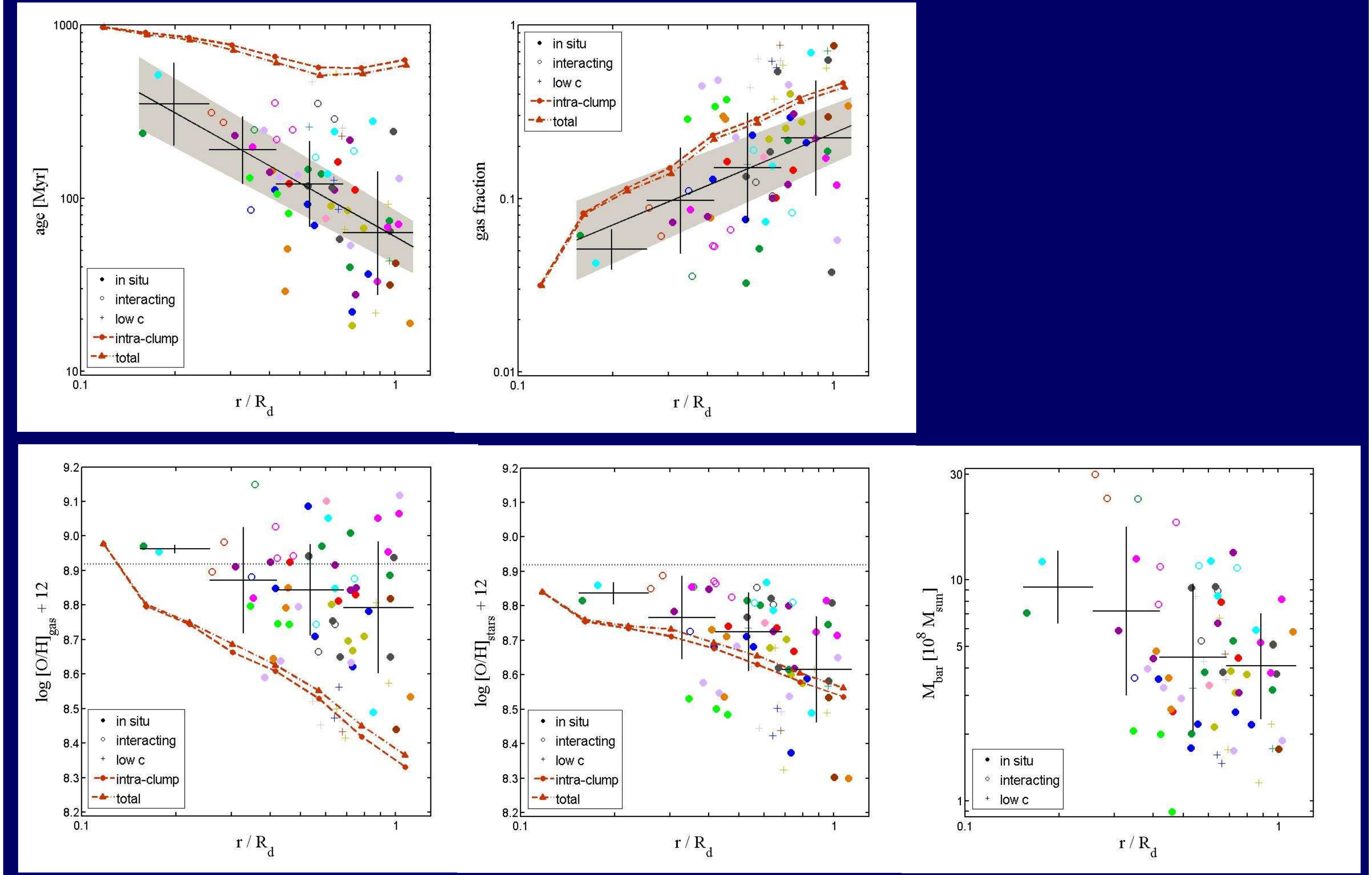
# Sub-structure in the disk giant clumps

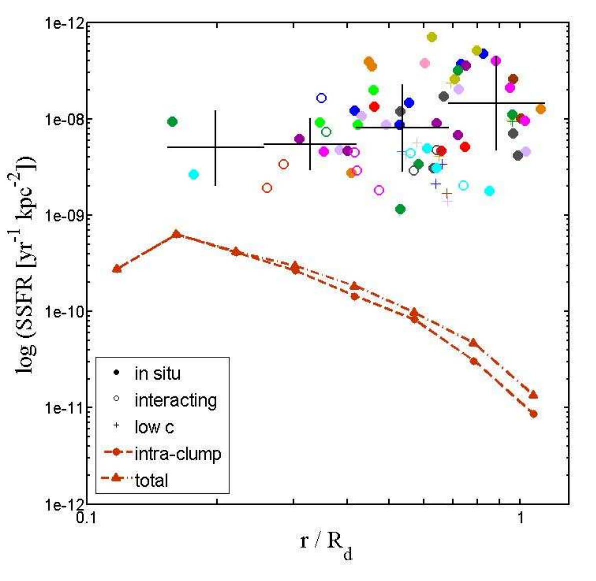


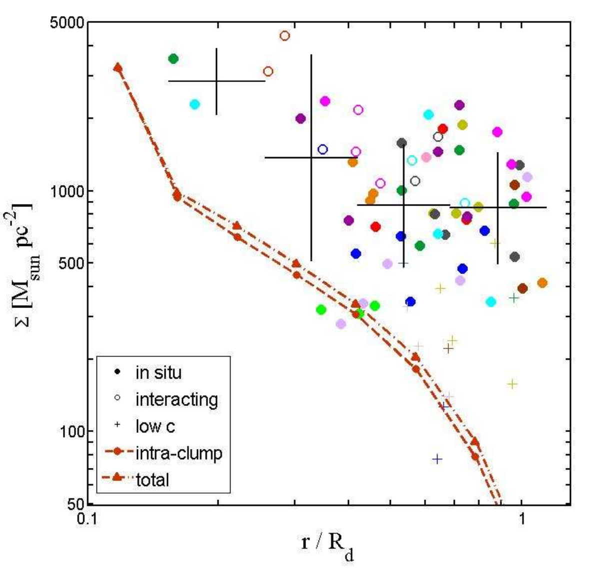
When clump substructure is resolved:
Less dissipative contraction? Angular-momentum loss?
a 20-30% effect

Caution: MW molecular clouds are not spin-supported

Bournaud, Teyssier AMR 2 pc resolution


age [Myr]
1000
100
10
0.1
1
r / R_d
in situ
interacting
low c
intra-clump
total
gas fraction
1
0.1
0.01
0.1
1
r / R_d
in situ
interacting
low c
intra-clump
total
log [O/H]_gas + 12
9.2
9.1
9.0
8.9
8.8
8.7
8.6
8.5
8.4
8.3
8.2
0.1
1
r / R_d
in situ
interacting
low c
intra-clump
total
log [O/H]_stars + 12
9.2
9.1
9.0
8.9
8.8
8.7
8.6
8.5
8.4
8.3
8.2
0.1
1
r / R_d
in situ
interacting
low c
intra-clump
total
M_bar [10^8 M_sun]
30
10
5
1
0.1
1
r / R_d
in situ
interacting
low c


log (SSFR [yr$^{-1}$ kpc$^{-2}$])
1e-12
1e-08
1e-09
1e-10
1e-11
1e-12
0.1
1
r / R$_d$
in situ
interacting
low c
intra-clump
total


Σ [M$_{sun}$ pc$^{-2}$]
5000
1000
500
100
50
0.1
1
r / R$_d$
in situ
interacting
low c
intra-clump
total