Where galaxies keep their cool in the heat: *tracing the remains of gas filaments in massive halos*

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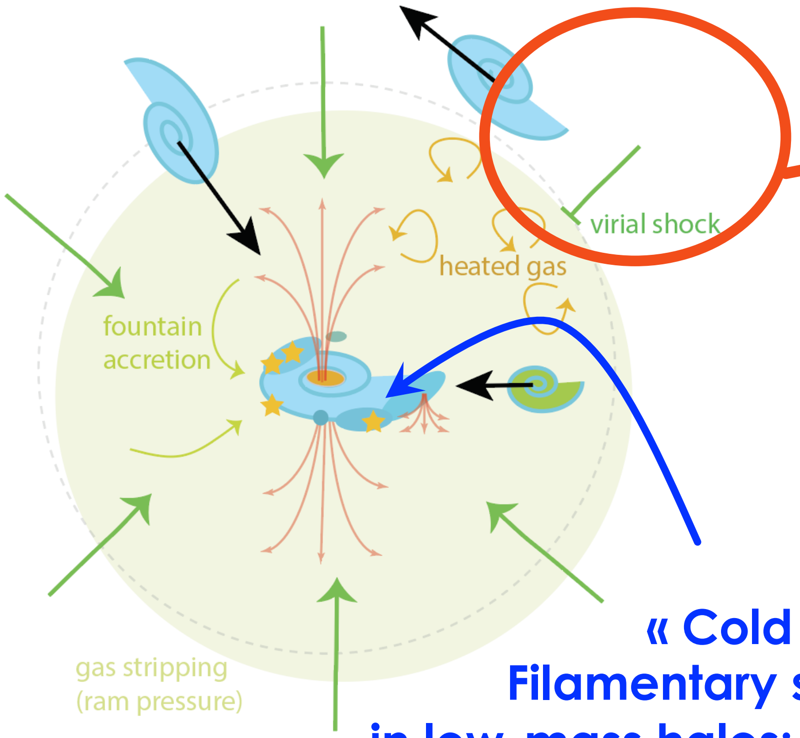
KITP
01/19/2023

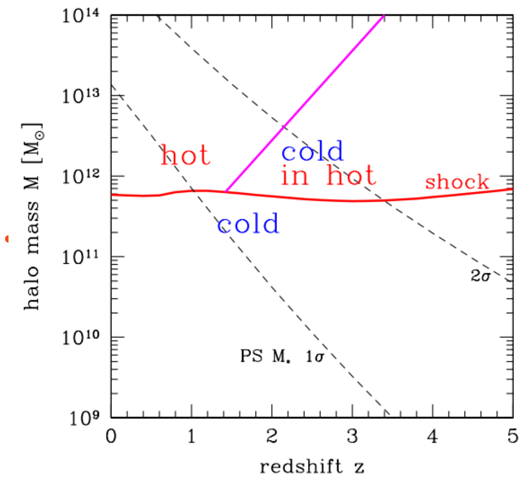
Where does the cosmic web end when the CGM starts?

Do galaxies in massive haloes disconnect from the cosmic web

A standard view of cold gas accretion into galaxies?



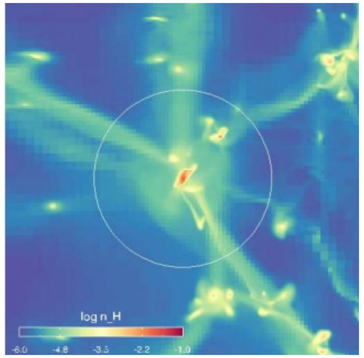
$$M_{\rm halo} > 10^{12}\ M_{\rm sun}$$



At z<2 cold flows from filaments shock at the virial sphere before entering the halo. (Birnboim+03, Dekel+06, Danovich+15)…

« Cold flows »:
Filamentary streams
in low-mass halos: T~10^4 K

But is the end of cold flows really the end of the connection to the cosmic web?

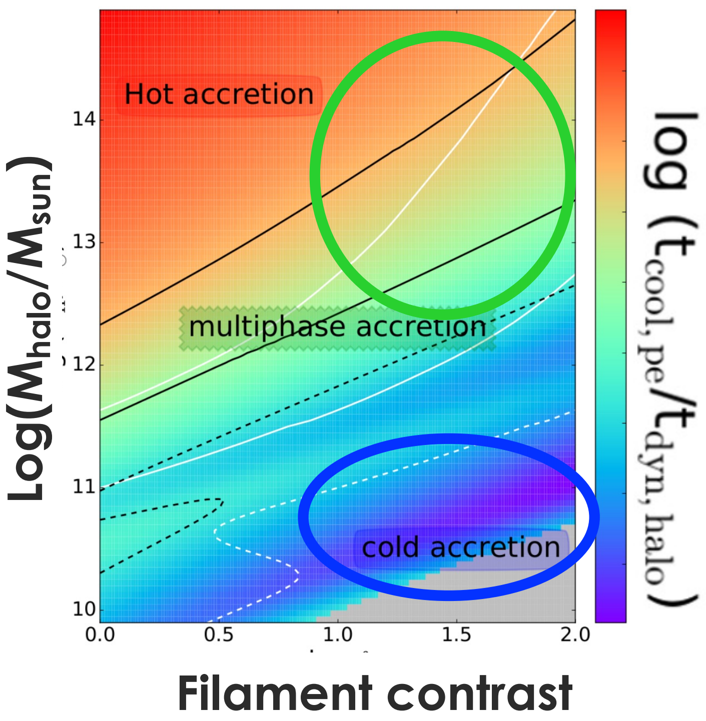


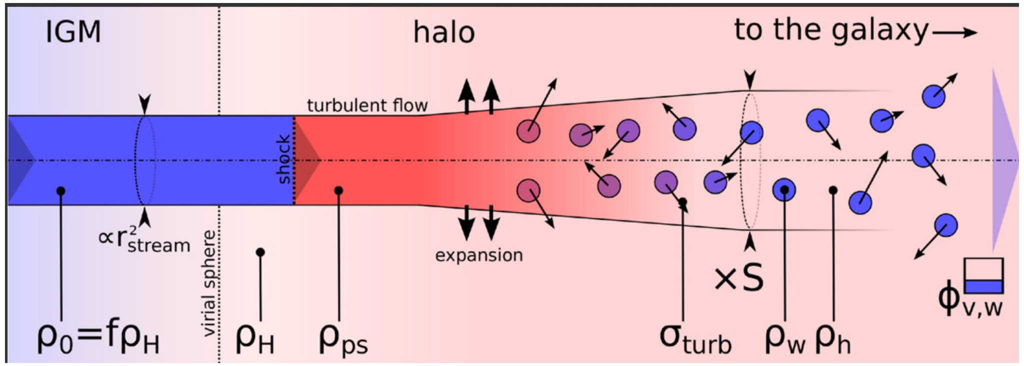
Pichon+2011

Post-shock accretion can be multiphase

Warm/cool pockets of gas may reform in the turbulent flow due to post-shock expansion.
If turbulence is high, the stream decollimates

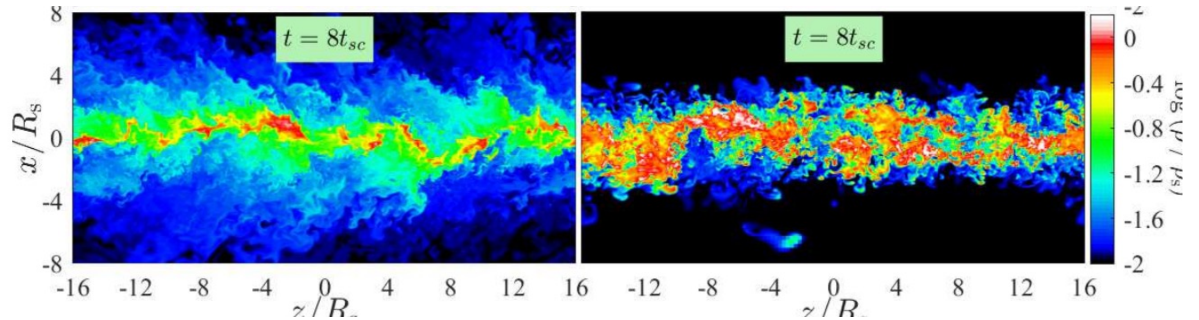
Cornuault+2018





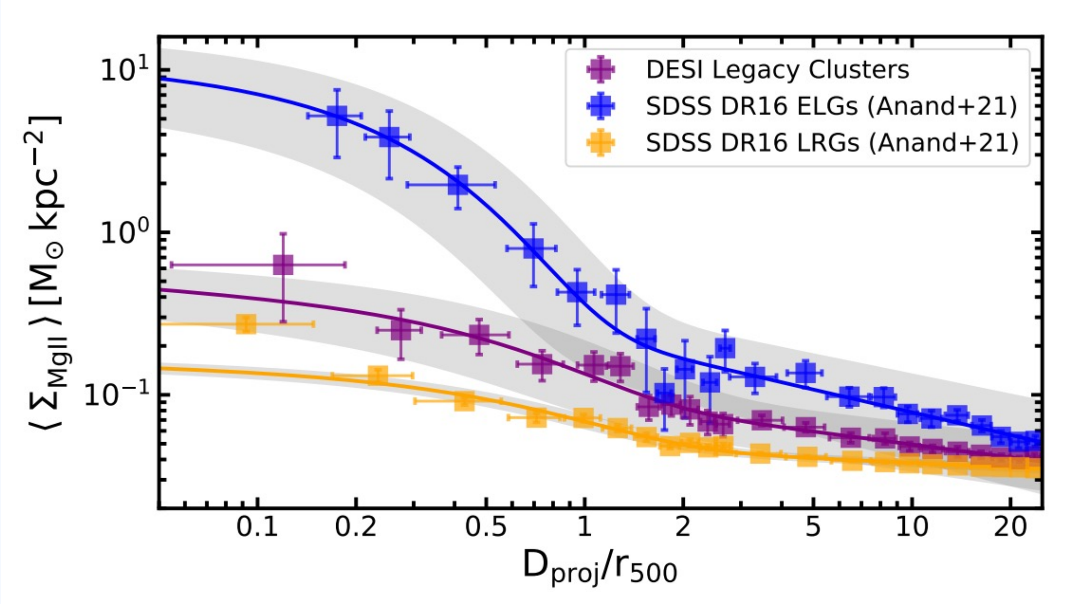
Mandelker+2019

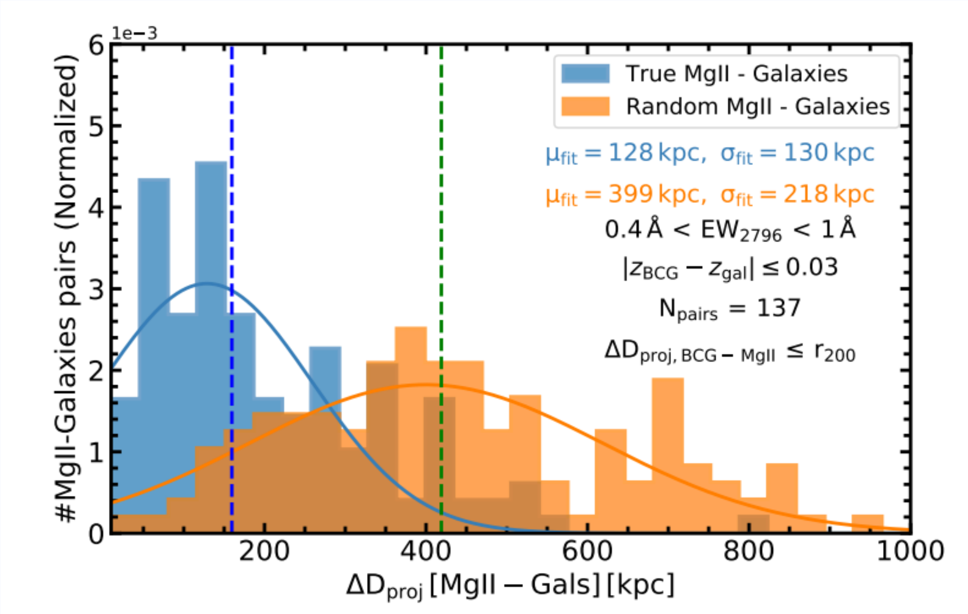
The decollimation of a cool stream depends on the cooling time in the mixing layer.



Cold clouds of MgII absorbers detected in DESI clusters

0.4<z<1 Anhand+2022

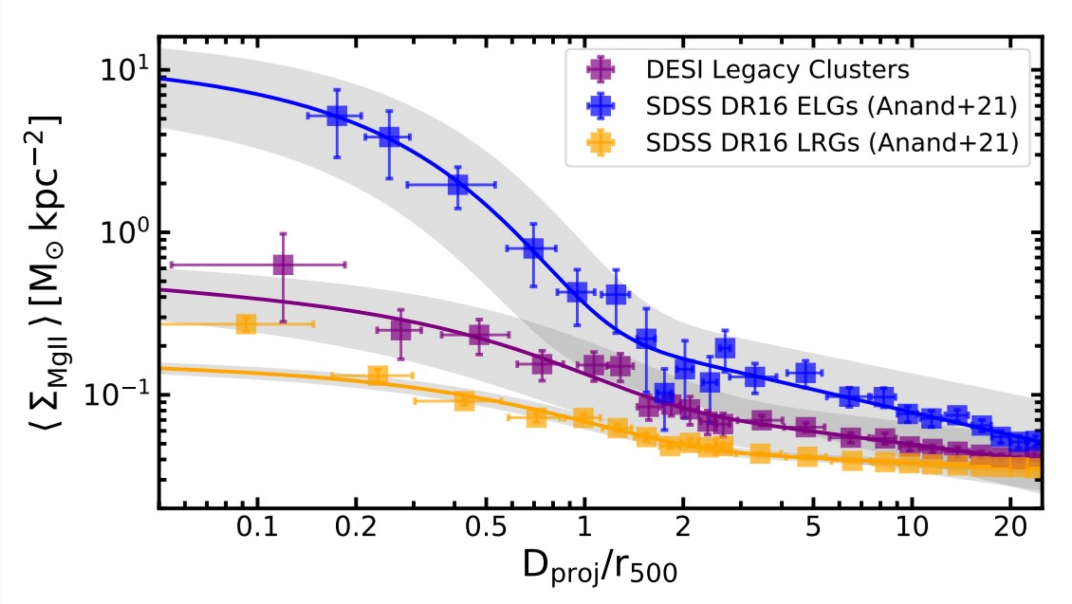


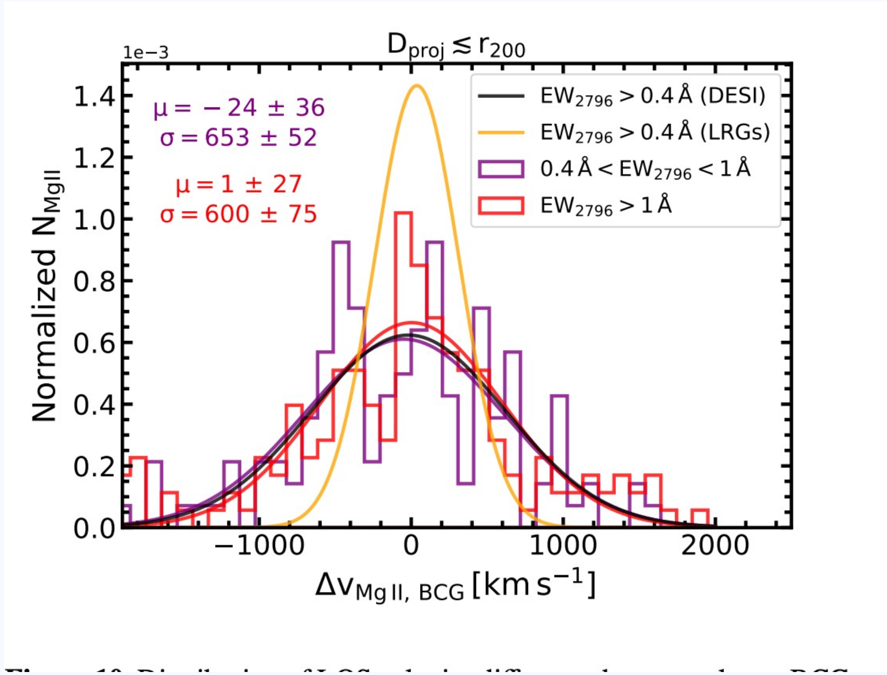


- **Significantly more Mg II absorbers in clusters than around non-cluster massive galaxies**
- **Most absorbers detected far away from the central galaxy (>200 kpc)**
- **Mg II cloud location correlated to the position of cluster satellites.**

Cold gas associated to satellites

0.4<z<1 Anhand+2022





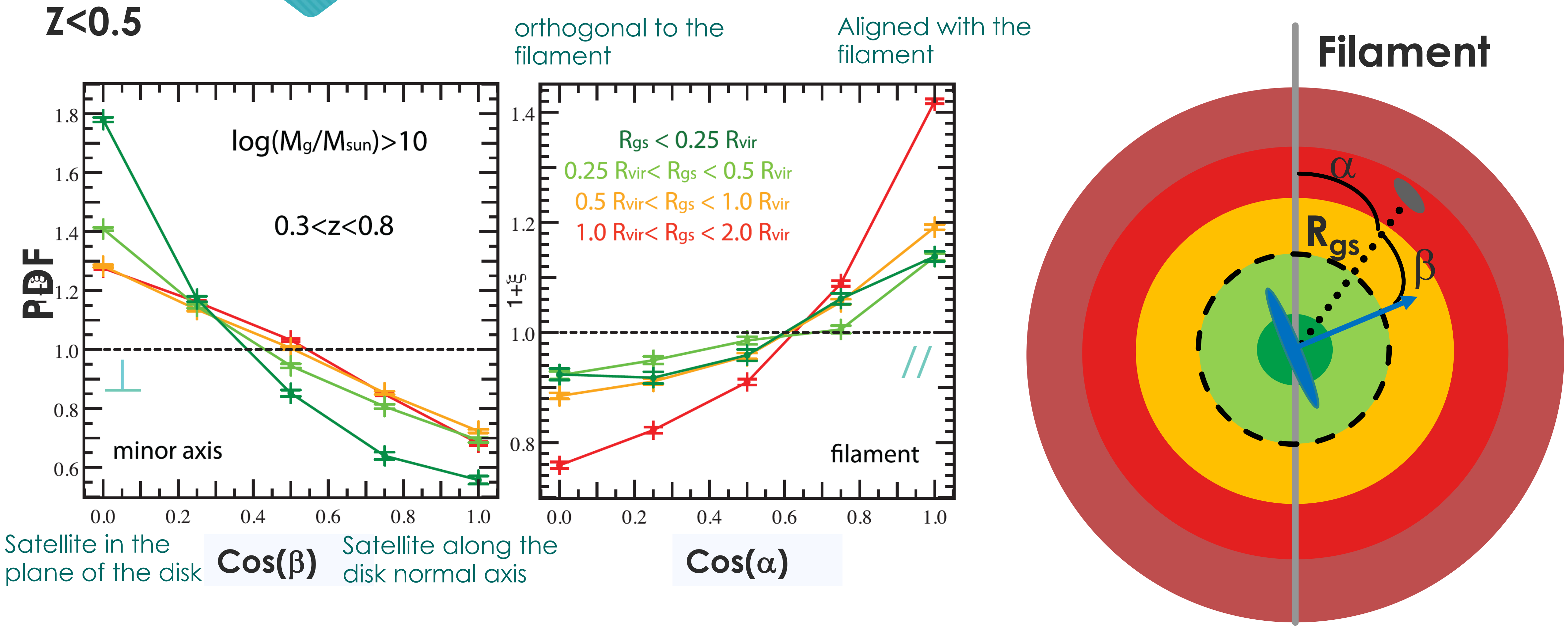
- **Significantly more Mg II absorbers in clusters than around non-cluster massive galaxies**
- **Most absorbers detected far away from the central galaxy (>200 kpc)**

- **Weak evidence of a secondary peak with negative velocity (inflow?)**
- **Or stripped from infalling satellites?**

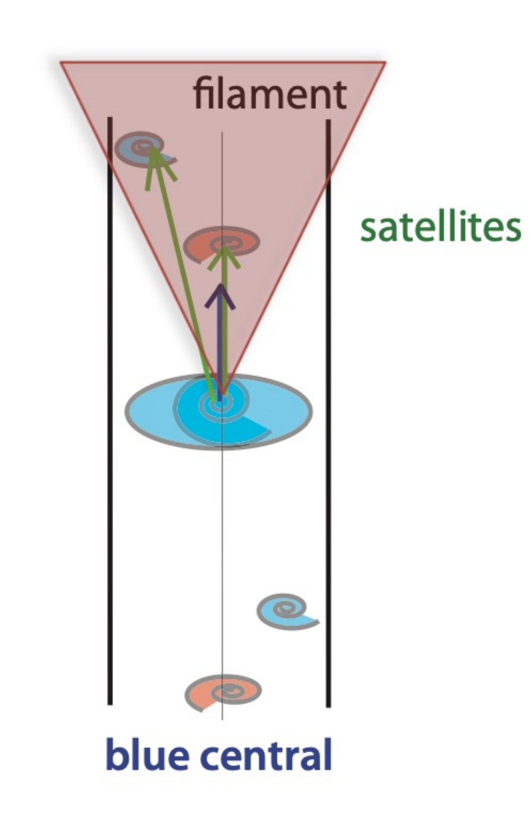
The distribution of satellites at z<0.5 recapitulates the helicoidal structure of cold flows

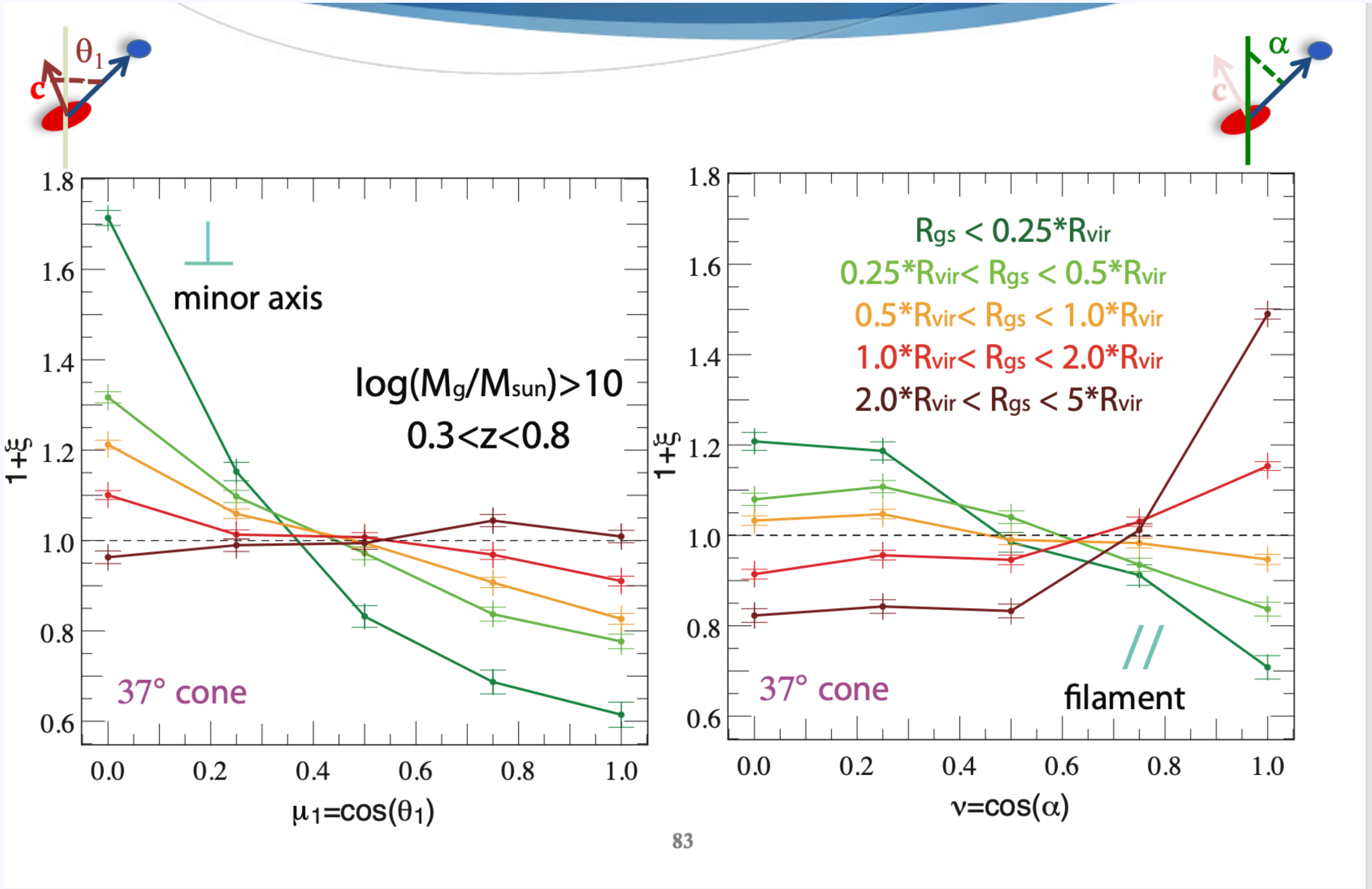
But visible in the distribution of satellites

Welker+2018



The extreme case of massive galaxies with spin aligned to the filament



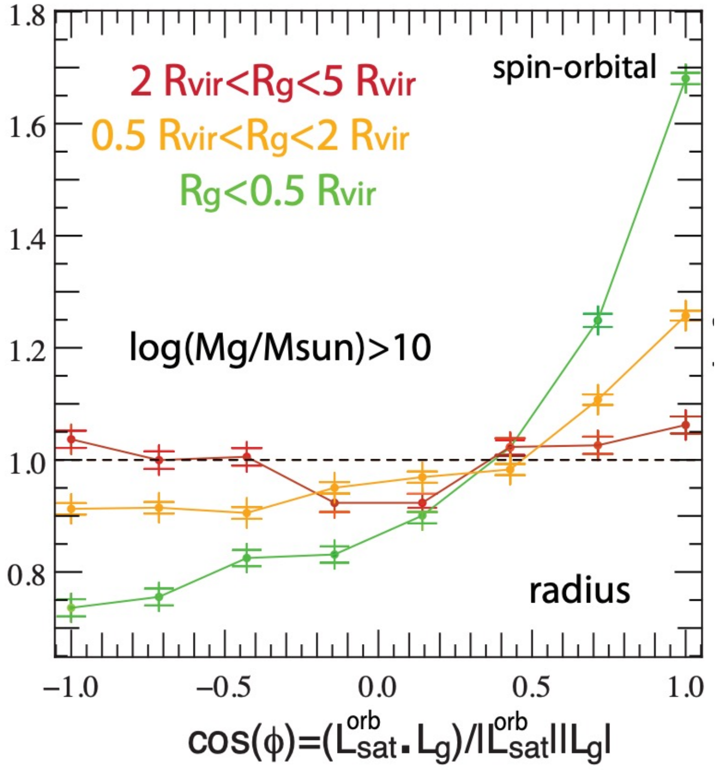


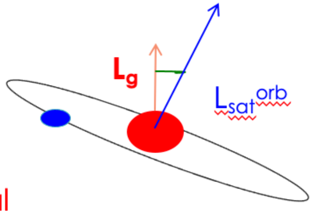
Inner satellites align their orbital momentum with the central galaxy's spin

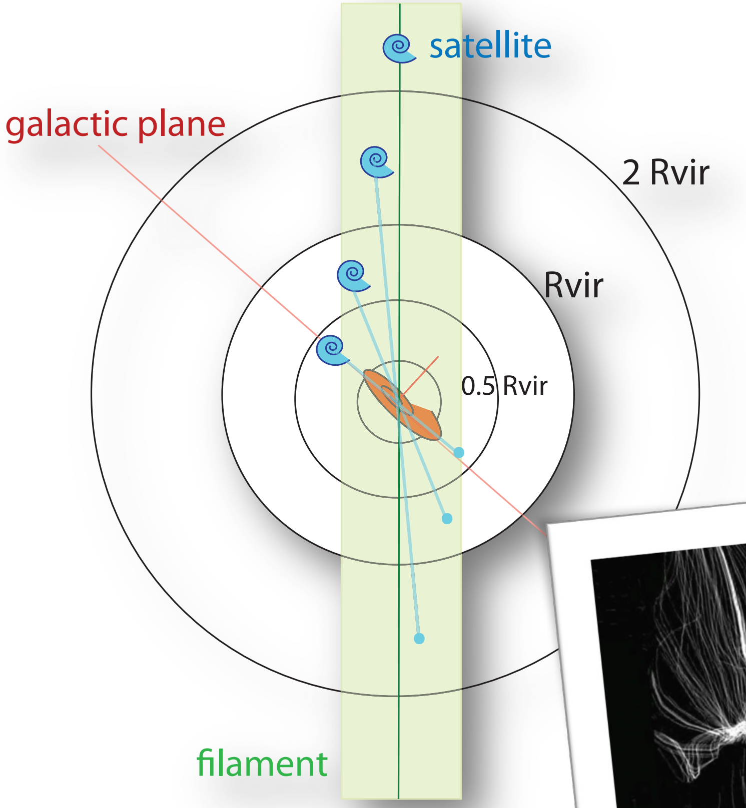
Welker+2018

Orbital momentum orthogonal to central spin

Orbital momentum aligned with central spin



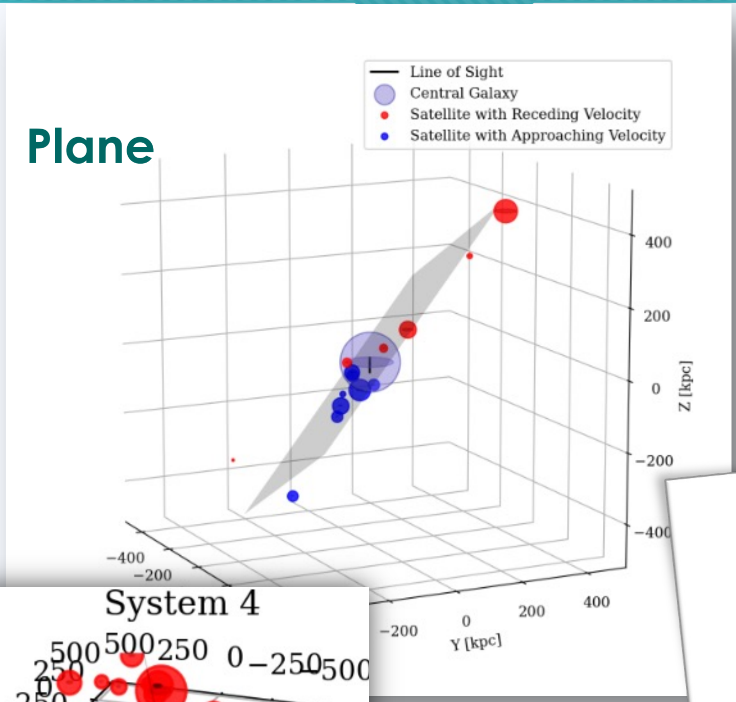


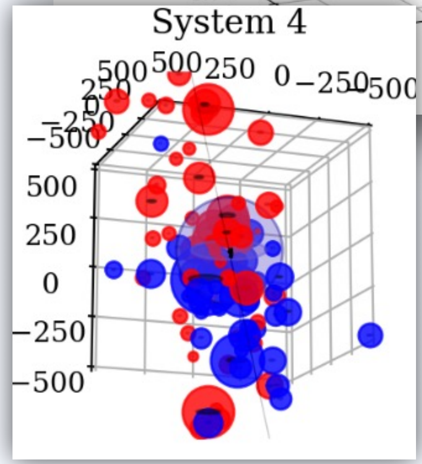


Planes of dwarfs in MW mass halos: ubiquitous in New-Horizon… among other elongated coherent structures!

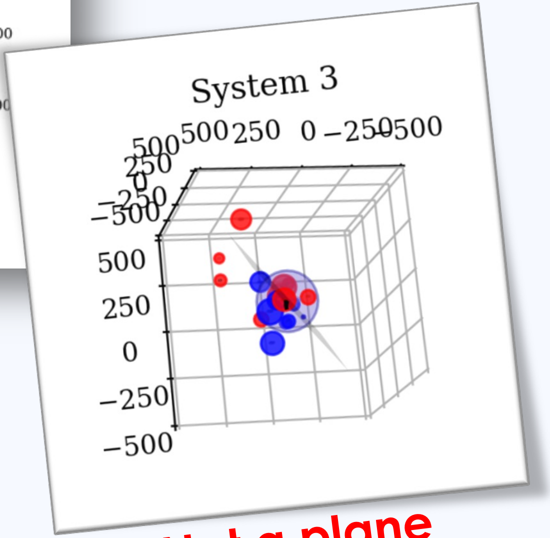
Madhani,Welker+ ,in prep

Plane



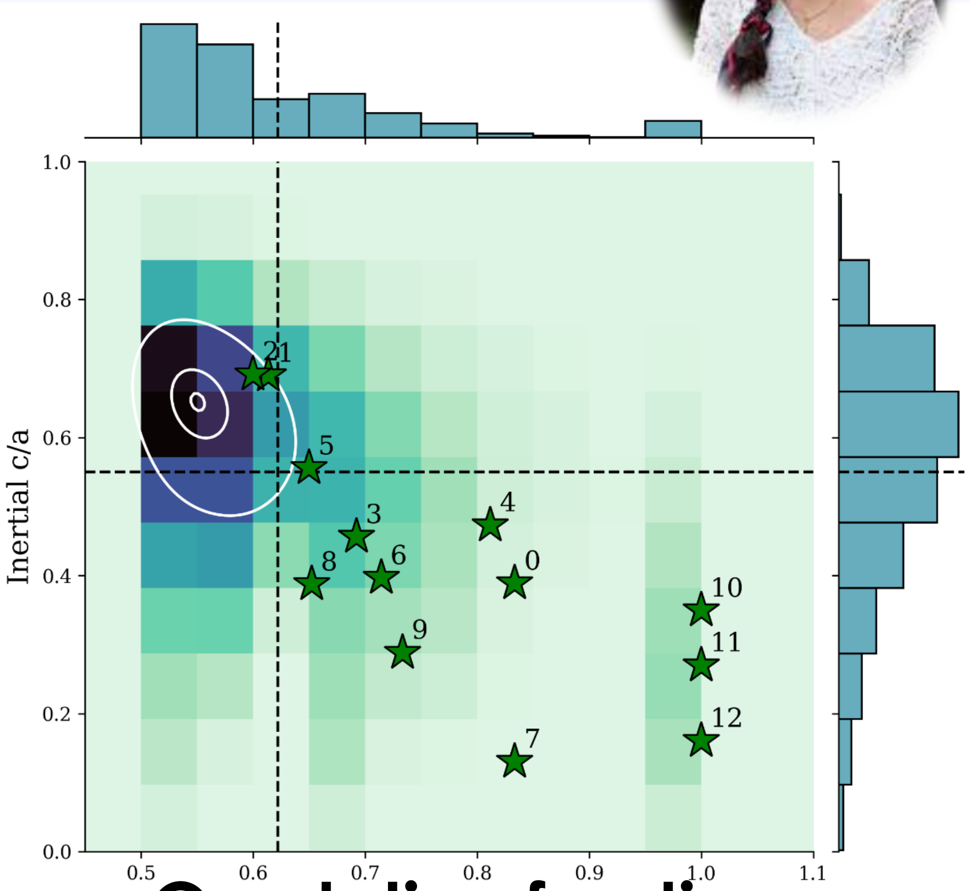


Borderline

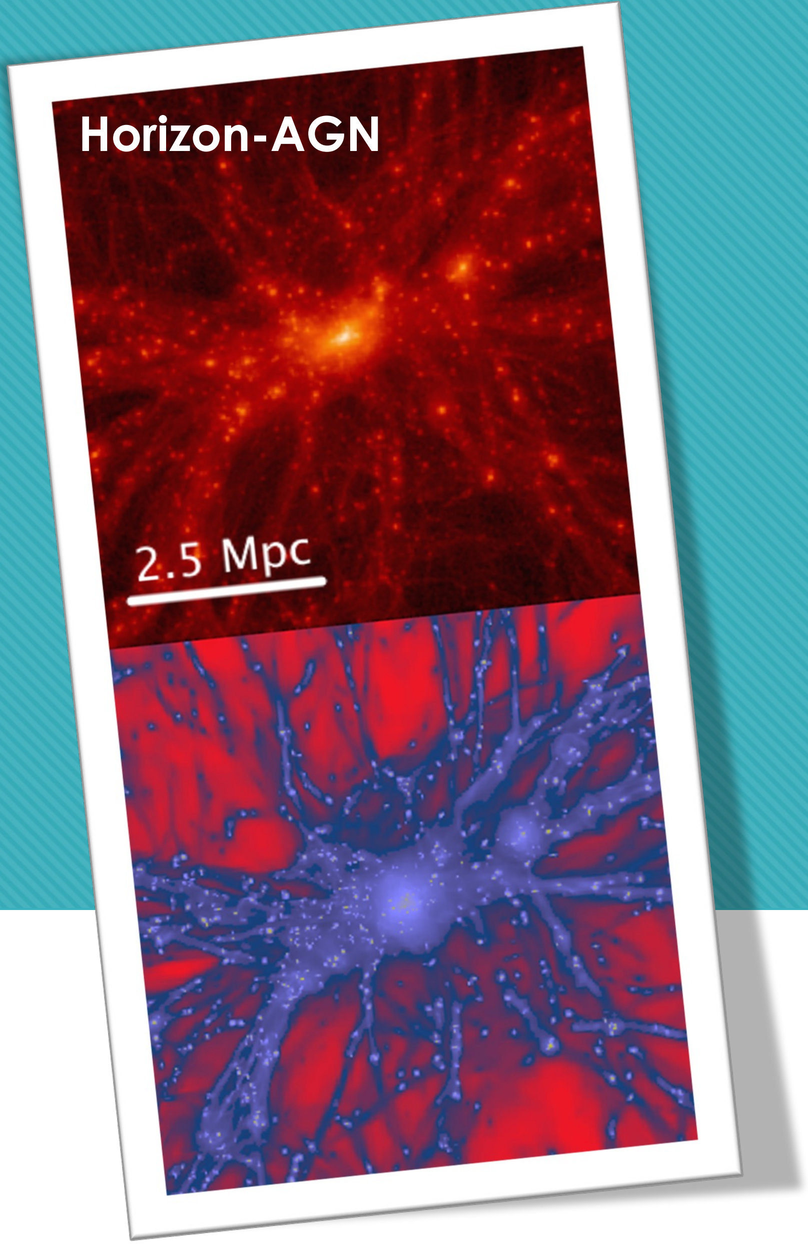


Not a plane

shape



Corotating fraction

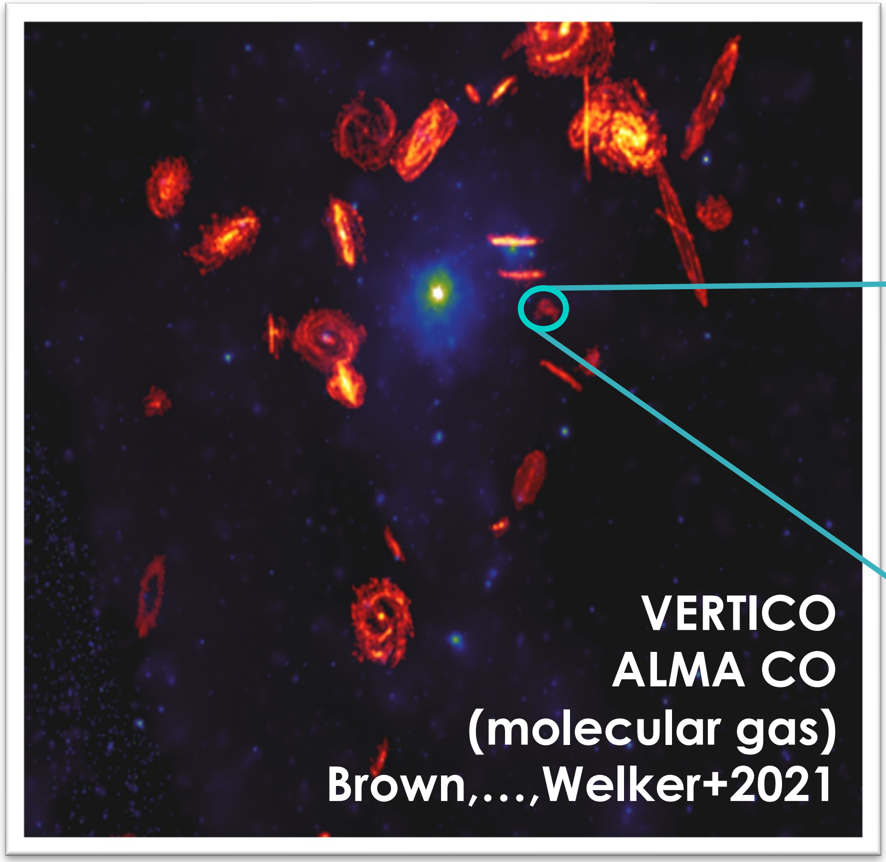


Life in inter/intra-cluster filaments

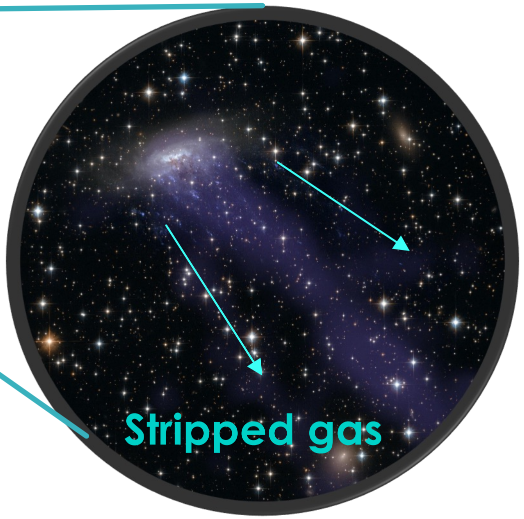
The most detectable of gas filaments!

The fate of galaxies in clusters

Virgo cluster



- Several 100s to 1000 galaxies
- M_{halo} ~ 10^{14} to 10^{15} M_{sun}



Starvation:
Hot, turbulent medium prevents cooling of gas into stars

Ram pressure stripping:
dynamic pressure from dense cluster strips galaxy of its gas as it is ploughing through

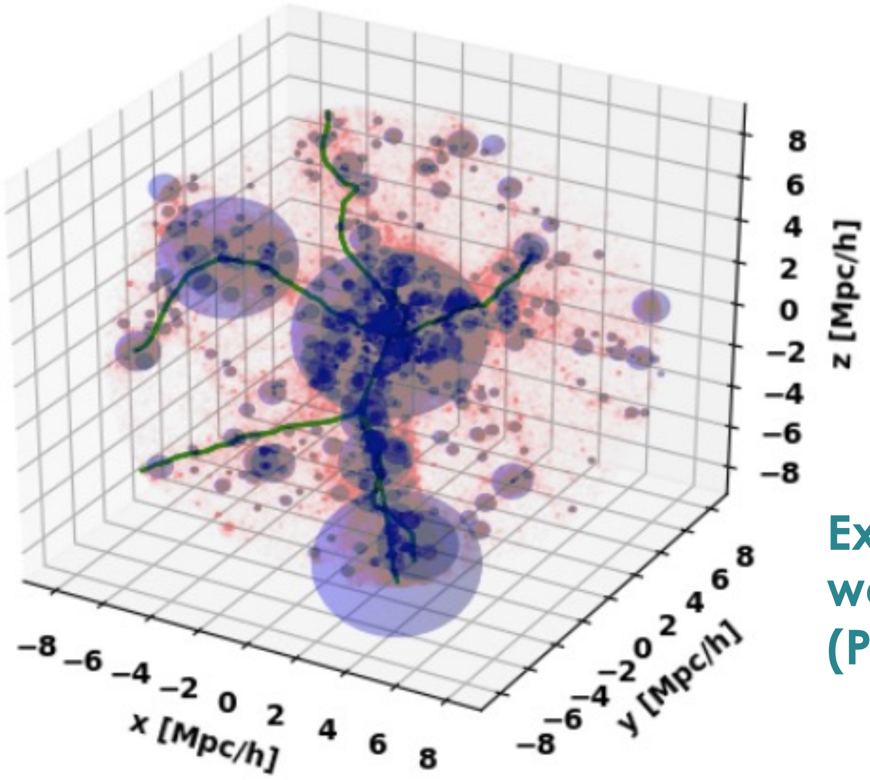
$$P_{\rm ram} \approx \rho_{\rm ICM} V_{\rm gal}^2 > 2\pi {\rm G} \Sigma_* \Sigma_{\rm ISM}$$

Gunn & Gott (1972)

Galaxies stop forming stars: they quench!

Identification of intra-cluster filaments in The Three Hundred simulated suite

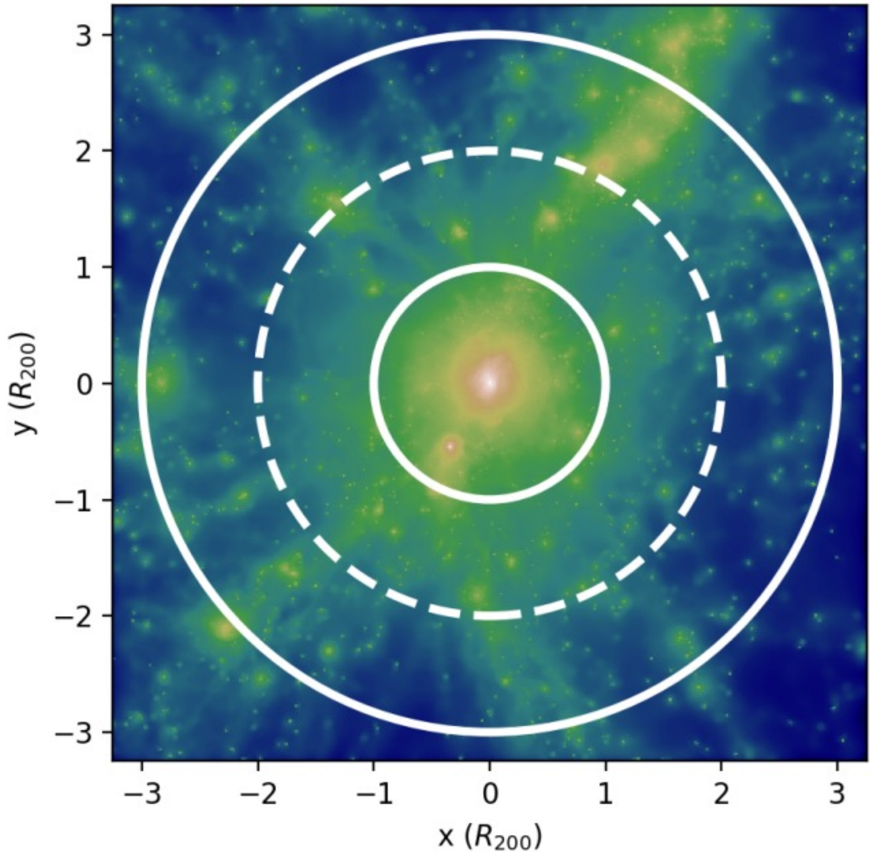
TheThreeHundred :
324 simulated clusters at intermediate resolution (~ few kpc)
Cui,(…),Welker+2018



>1 million galaxies above 10^9 Msun

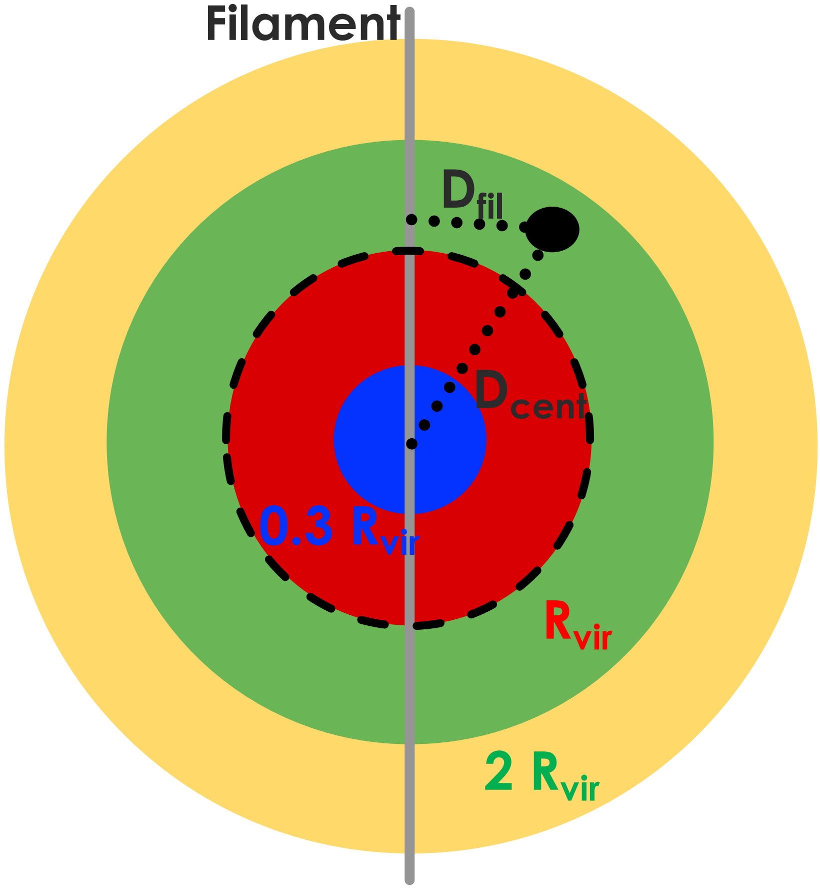
Extraction of the cosmic web for TheThreeHundred (PI:Welker)

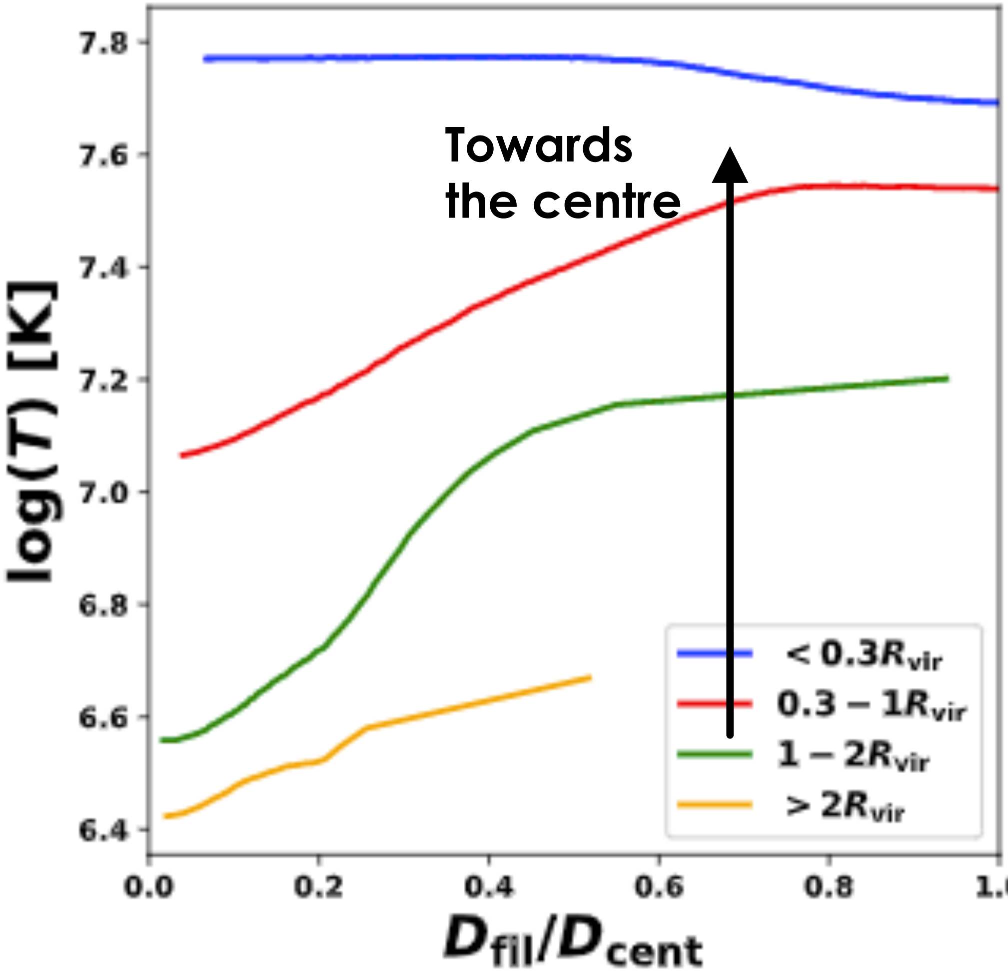
At z=0



Intra-cluster filaments are regions of reduced gas temperature

Kotecha&Welker+2022



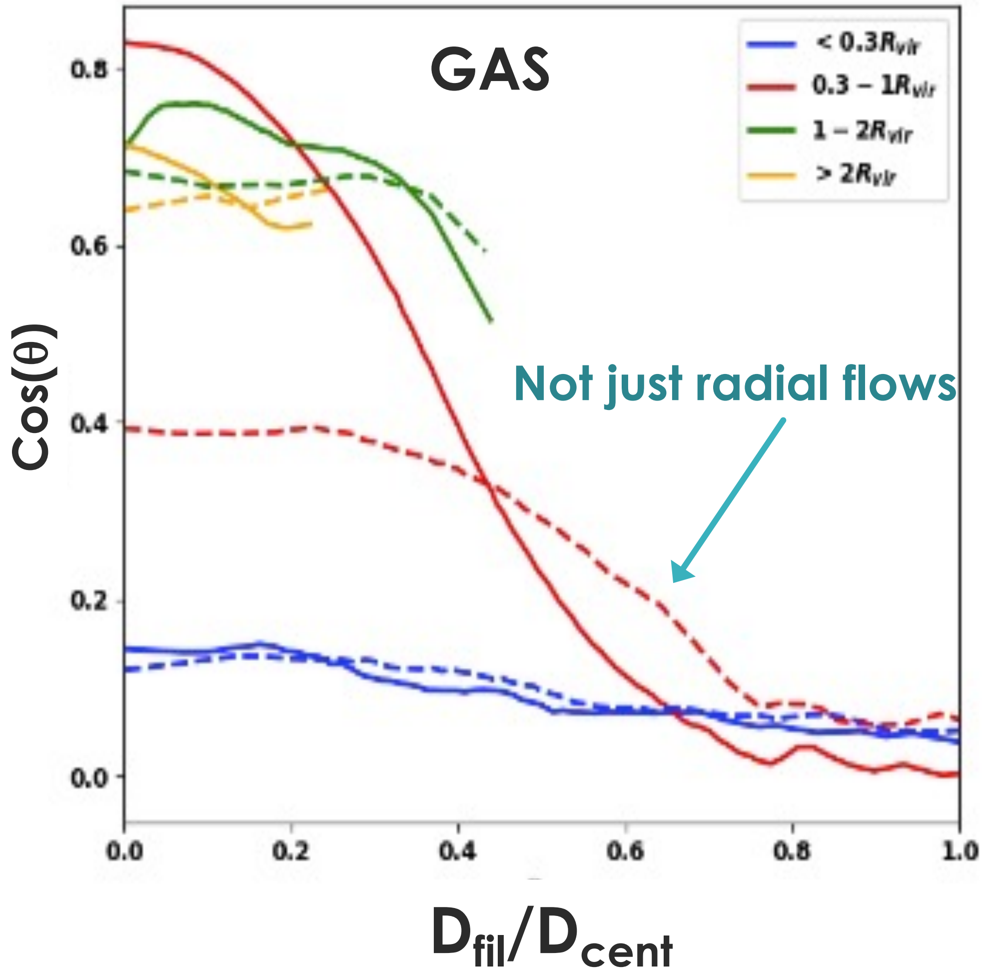


Sachin Kotecha

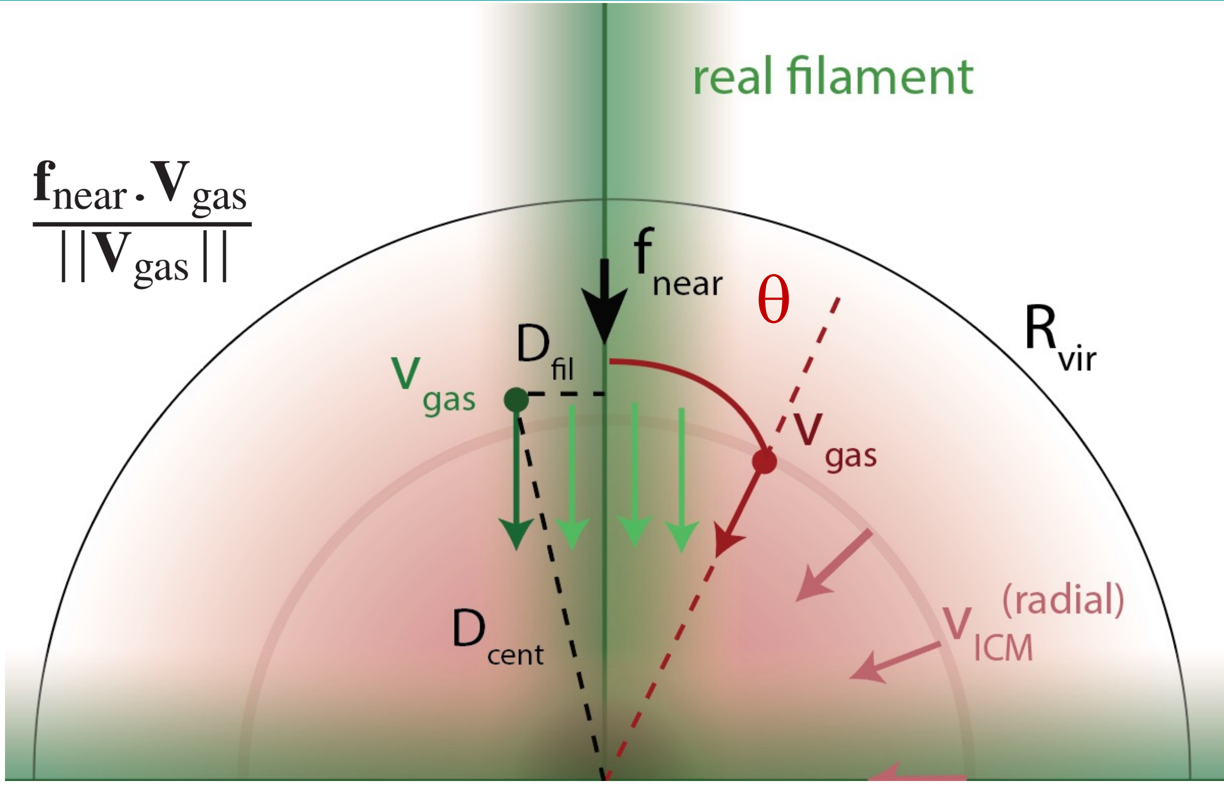
Zihan Zhou

Intra-cluster filaments are regions of coherent streams

Kotecha&Welker+2022



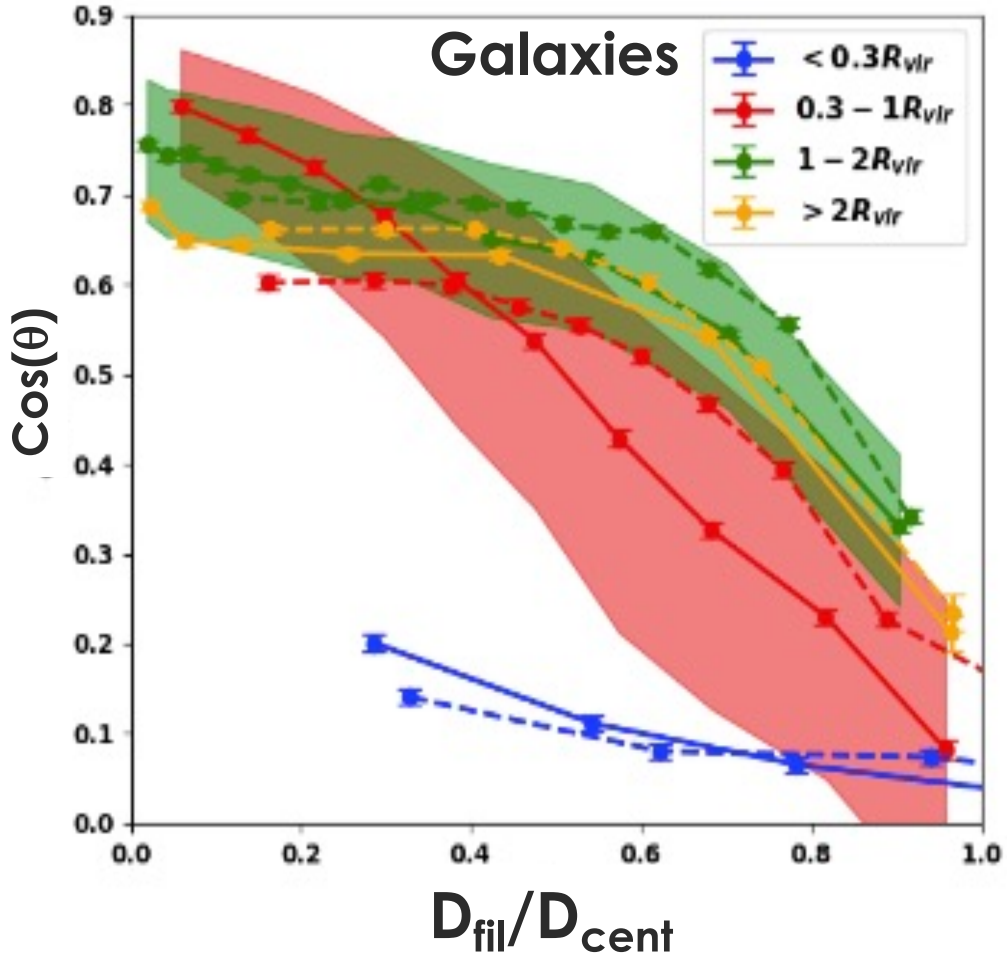
$$\cos\theta = \frac{\mathbf{f}_{\mathrm{near}} . \mathbf{V}_{\mathrm{gas}}}{||\mathbf{V}_{\mathrm{gas}}||}$$



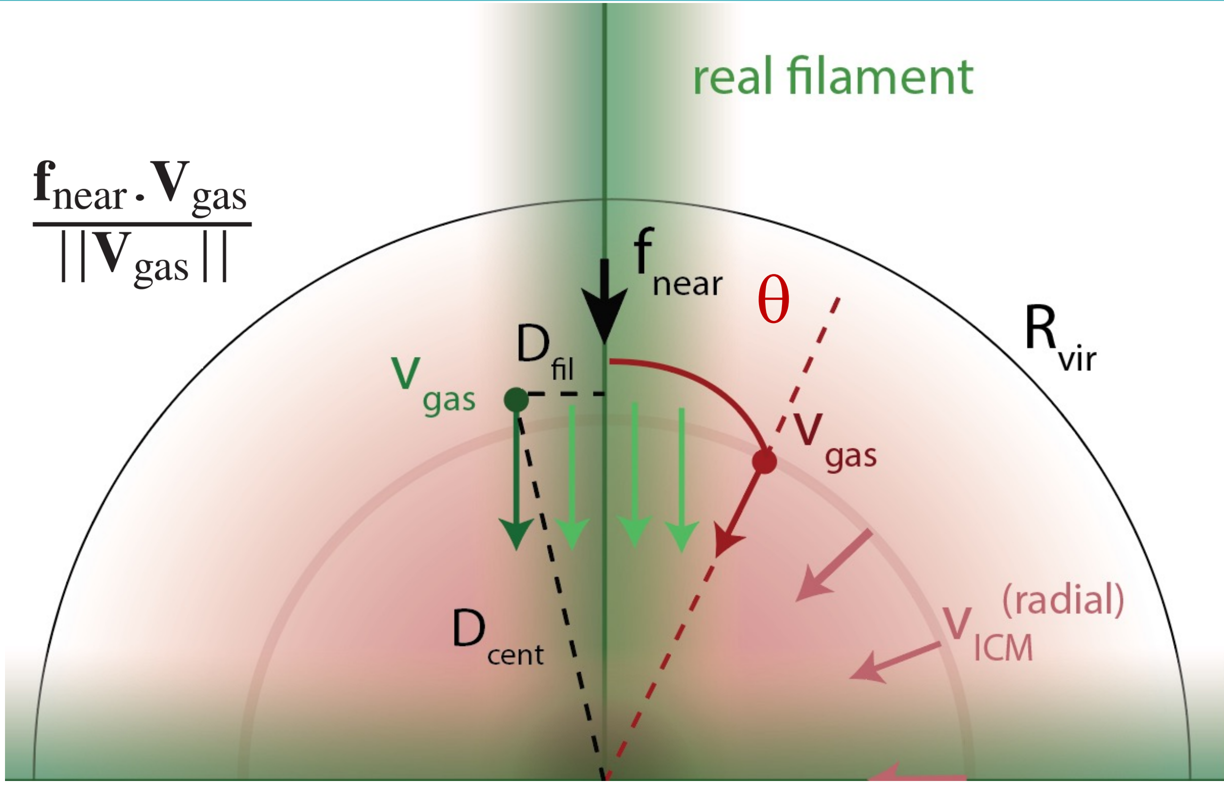
Diffuse gas markedly flows along the filaments, inwards!

Intra-cluster filaments are regions of coherent streams… of galaxies

Kotecha&Welker+2022



$$\cos\theta = \frac{\mathbf{f}_{near} \cdot \mathbf{V}_{gas}}{||\mathbf{V}_{gas}||}$$



Galaxies markedly flow along the filaments, inwards!

Could they impact quenching?

Coherent flows of cool gas and haloes could locally:

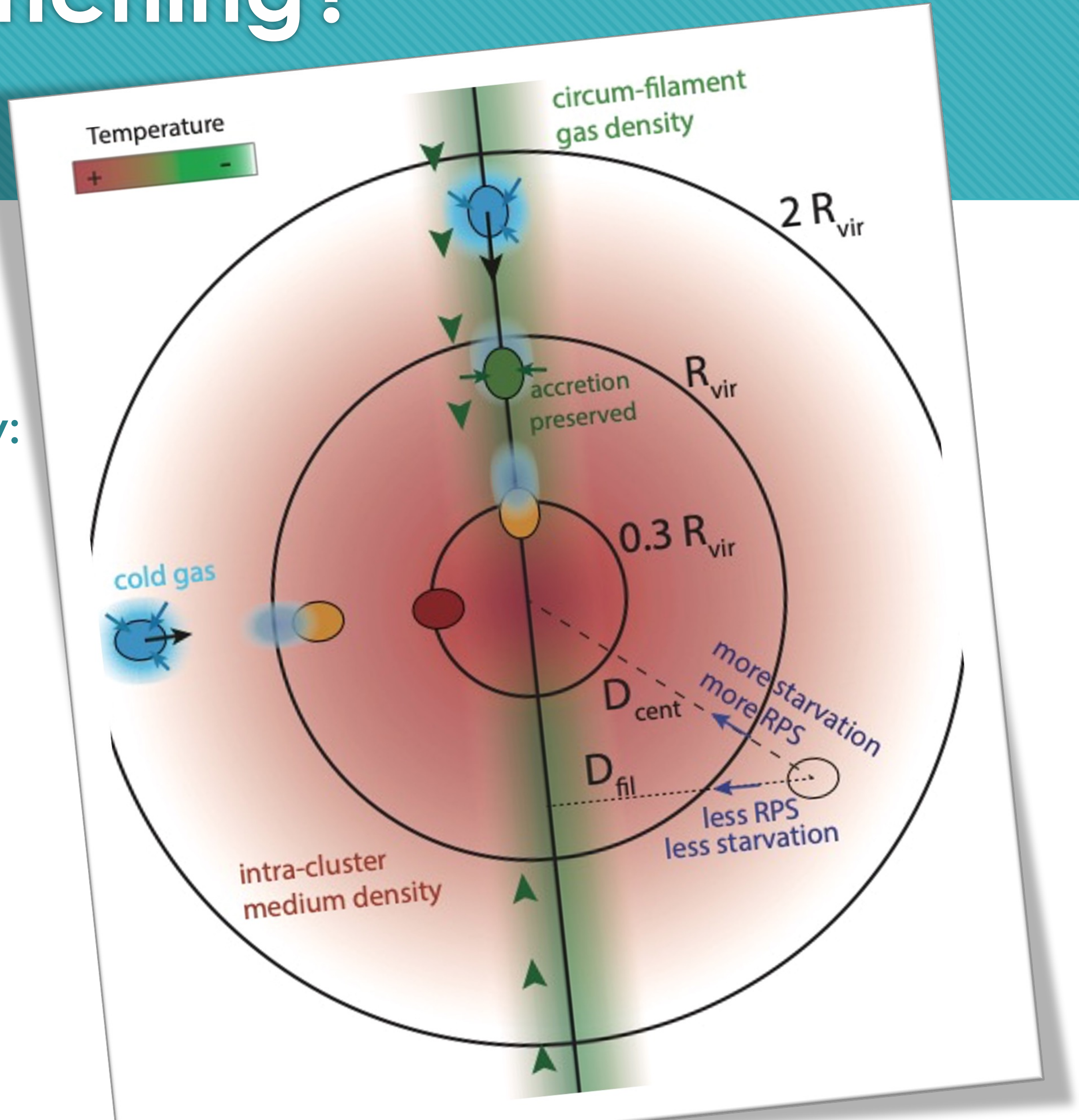
a. help preserve cold gas accretion

b. reduce ram-pressure stripping

c. Preserve gas fraction and star formation

That would be in stark contrast with filaments *outside clusters* where we expect *pre-processing*!

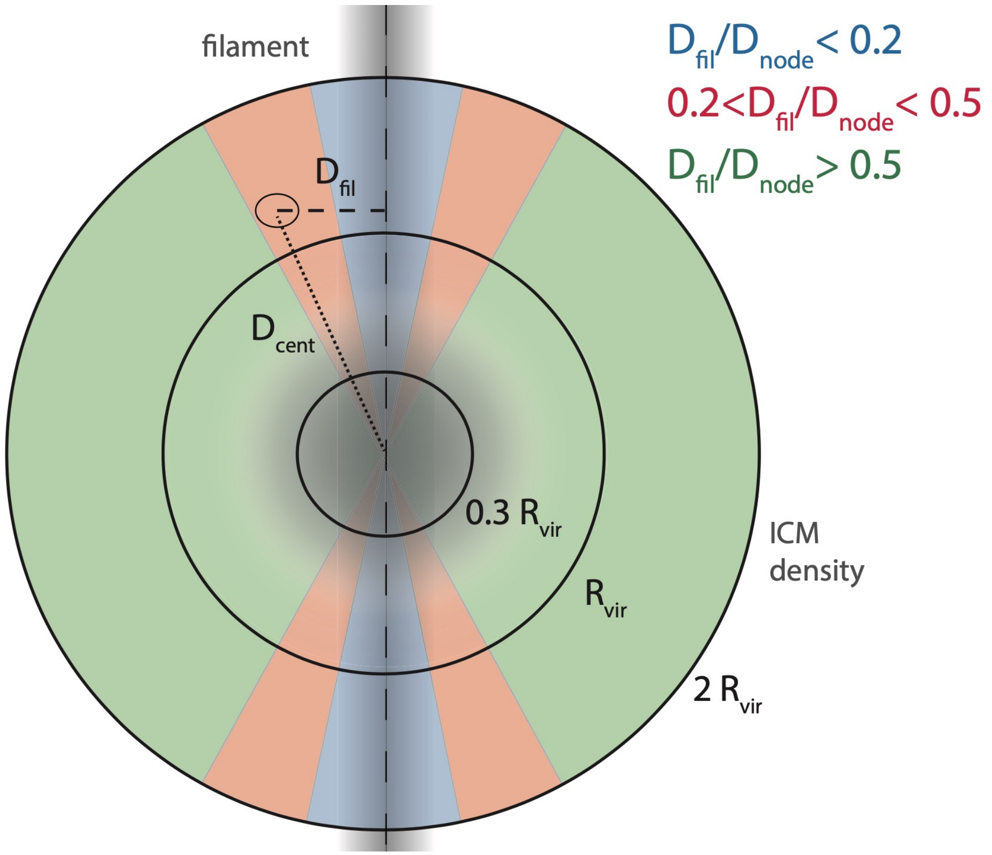
Let’s check!



Cold gas fraction preserved near intra-cluster filaments

Kotecha&Welker+2022
Welker+2022

$$f_{\rm gas}^{\rm cold} = \frac{M_{\rm gas}(\mathrm{T} \leq 10^5\ \mathrm{K})}{M_{\rm gas}(\mathrm{T} \leq 10^5\ \mathrm{K}) + M_{\rm star}}$$



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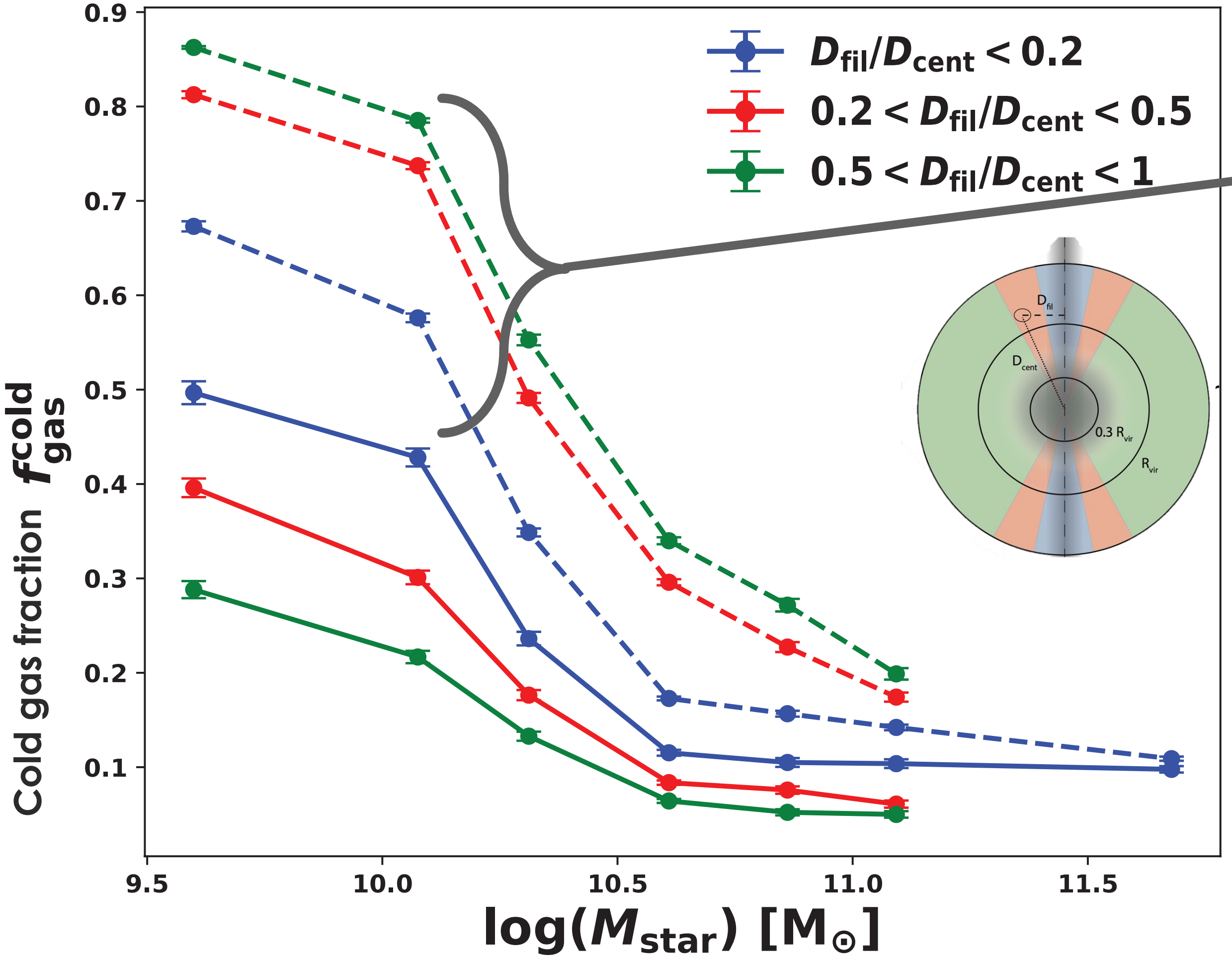
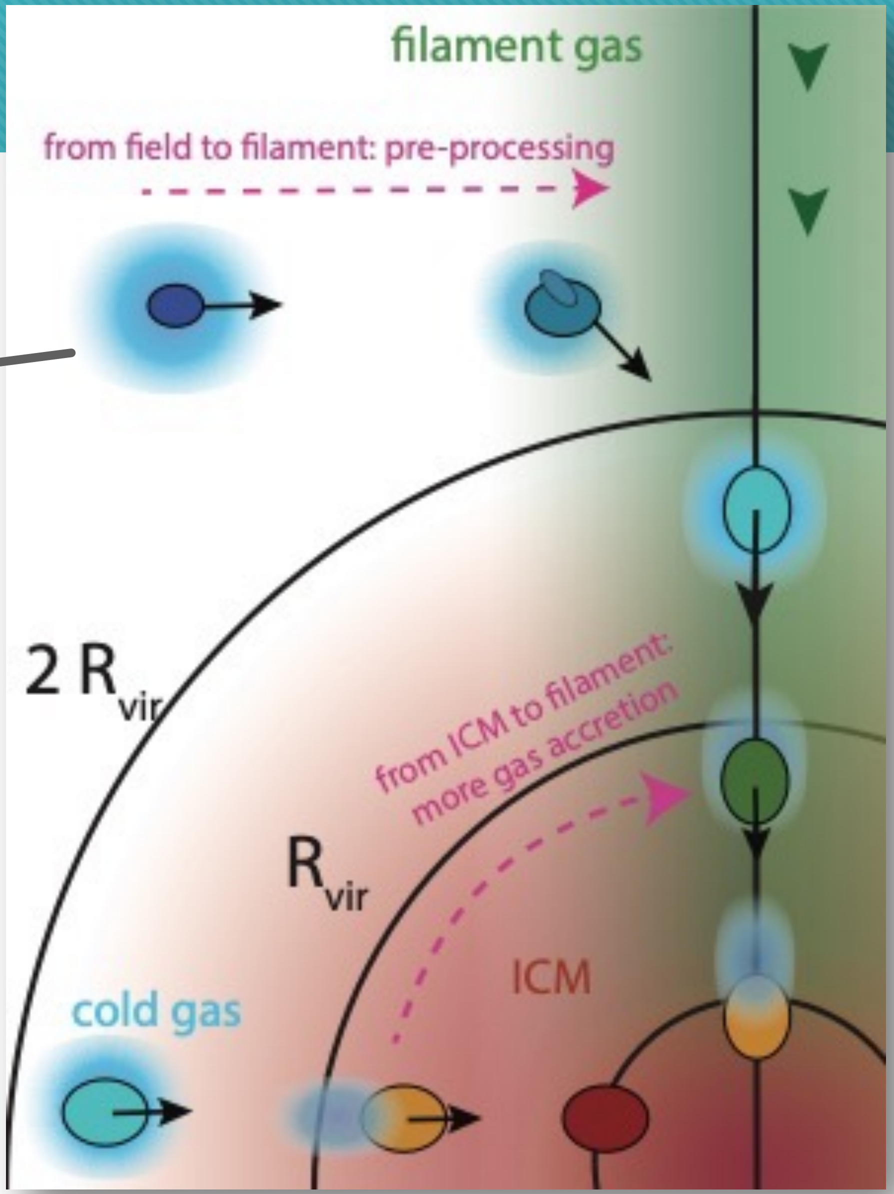
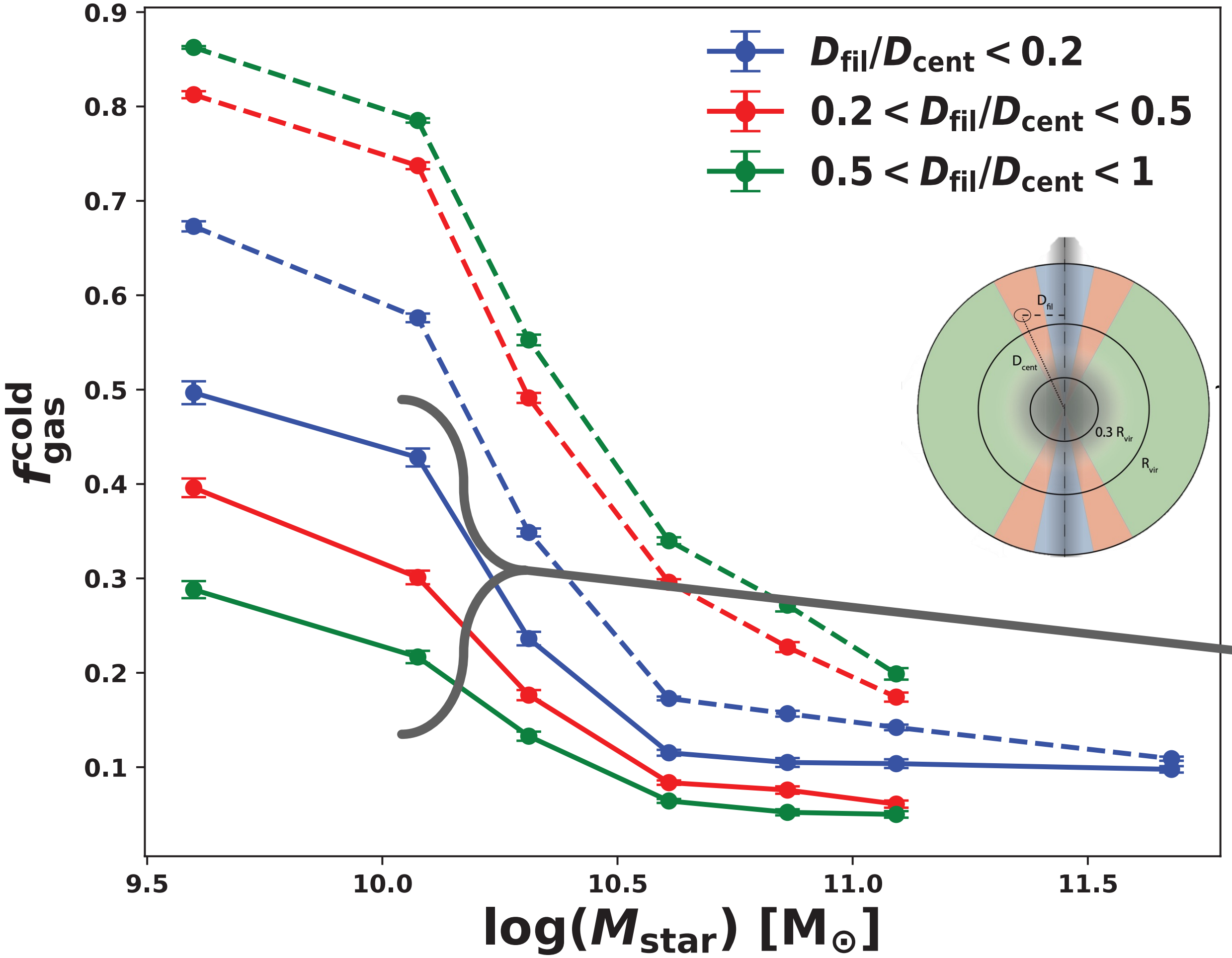
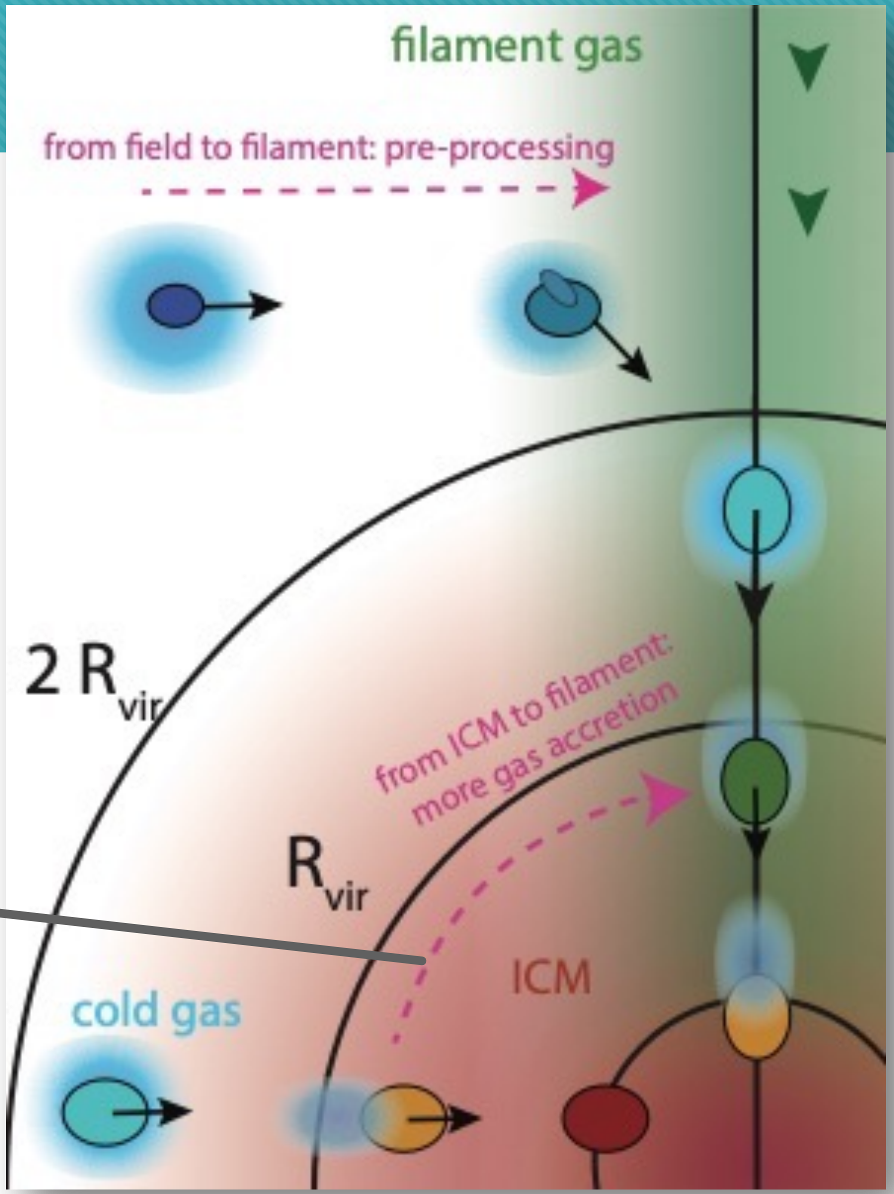


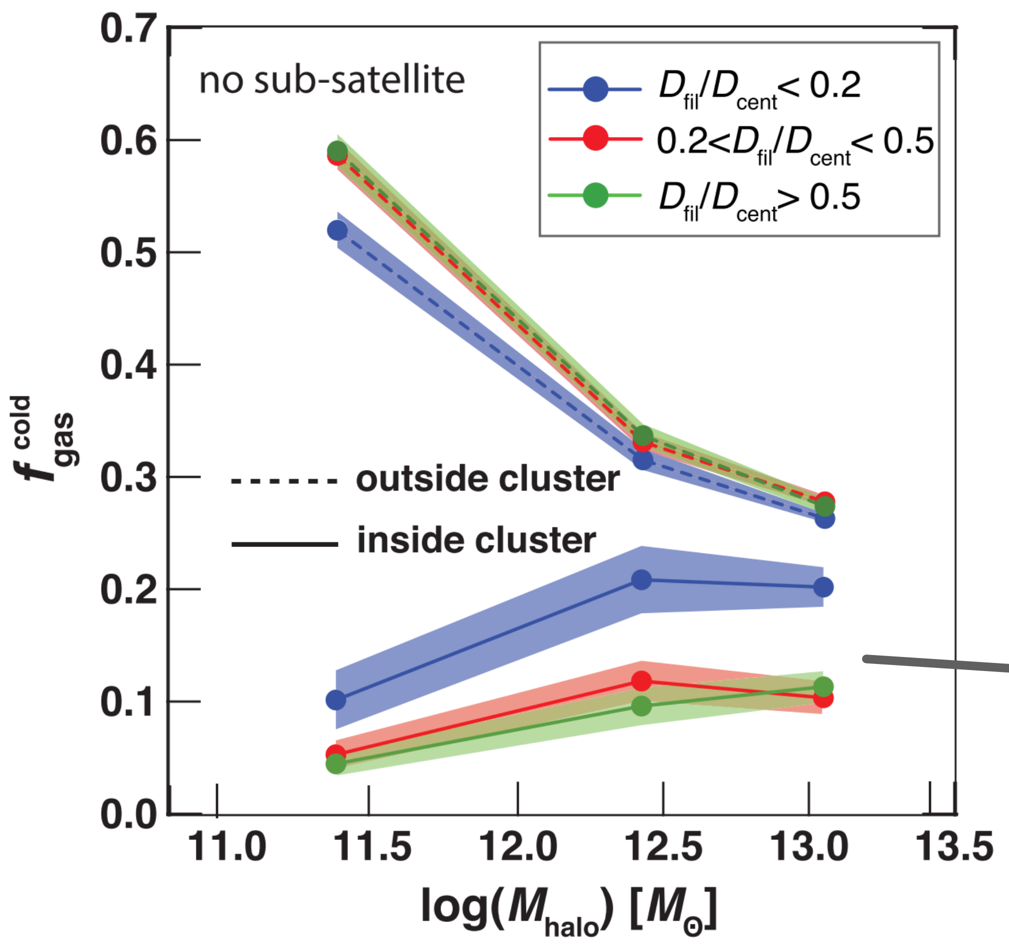


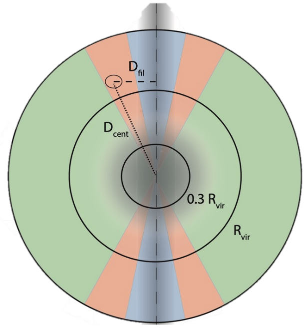
Cold gas fraction preserved near intra-cluster filaments

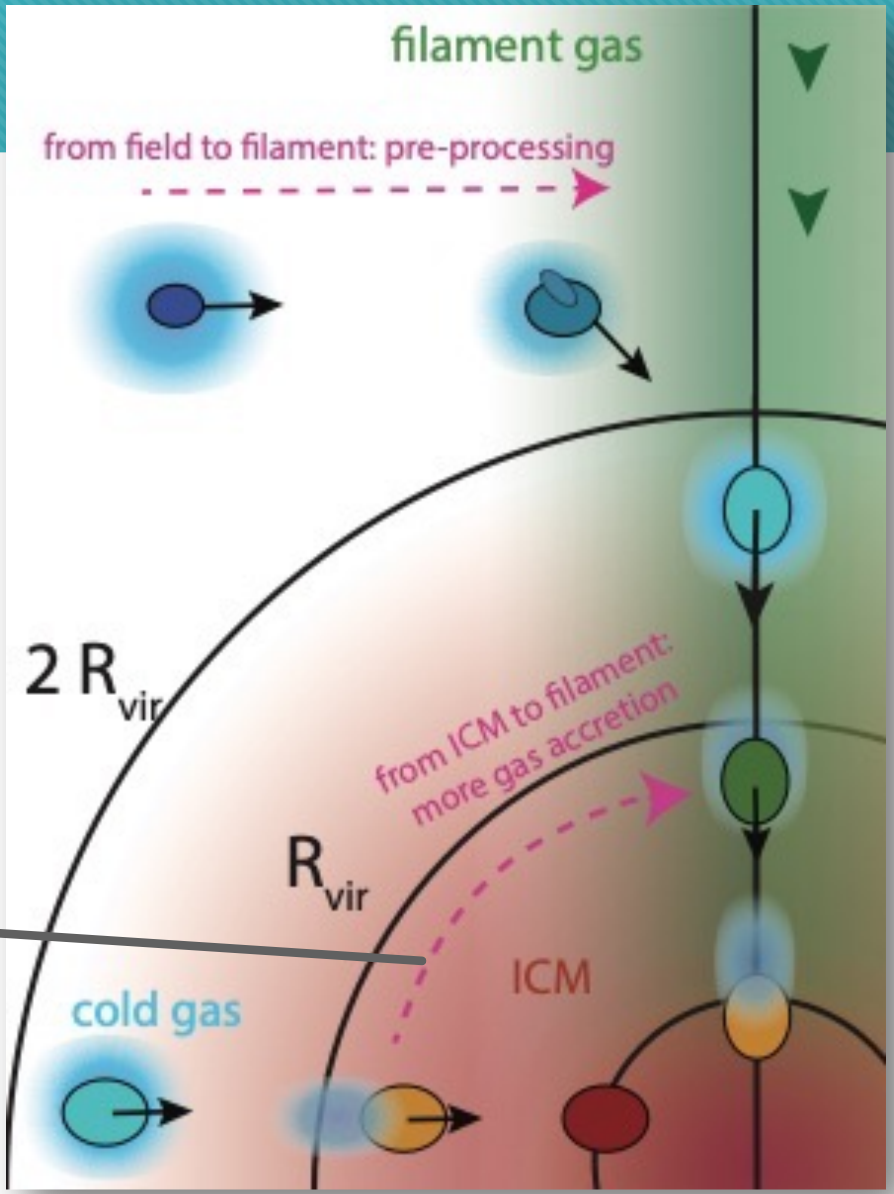




This effect is seen at all stellar and halo masses

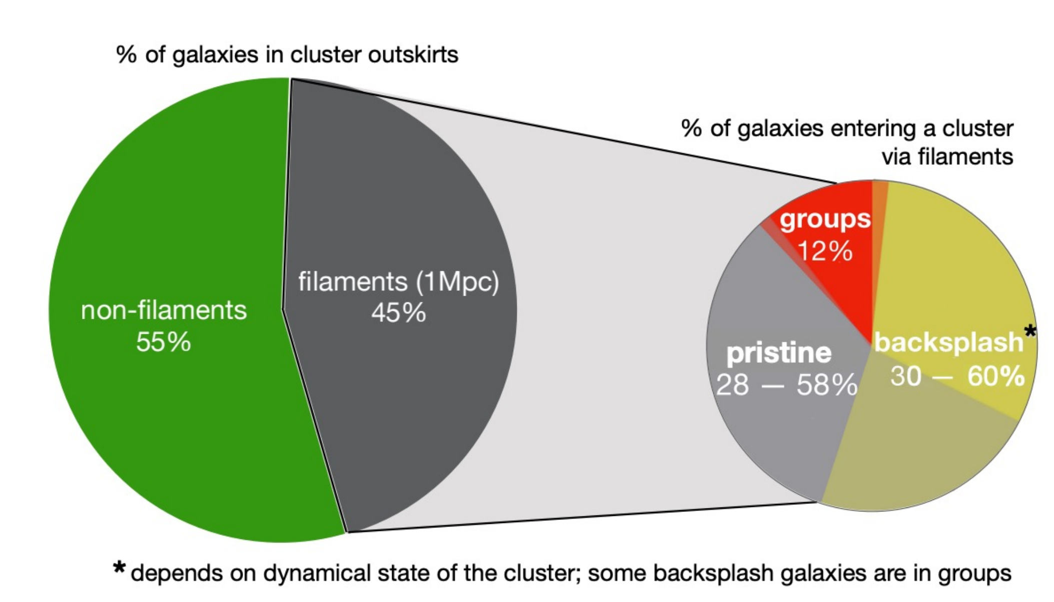


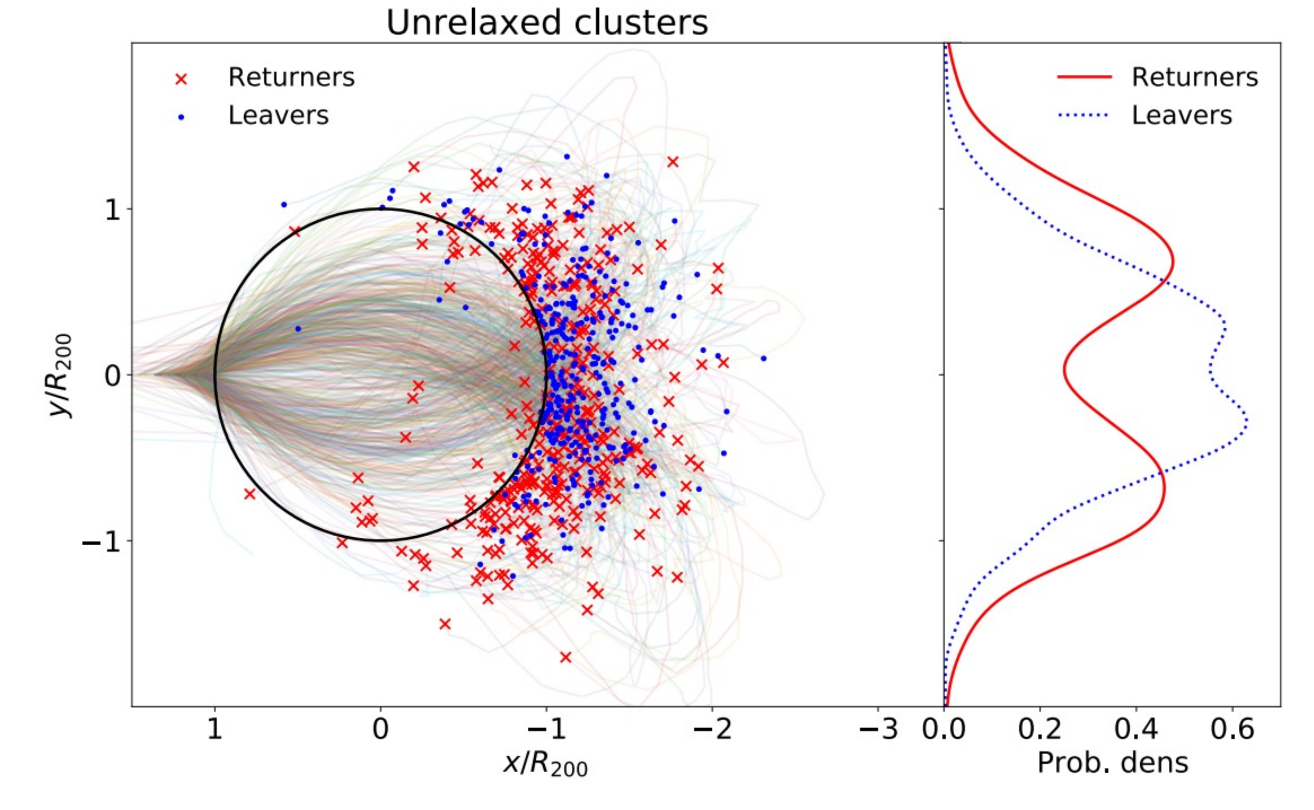




A comment on backsplash galaxies

Kuchner+2022 in TheThreeHundred

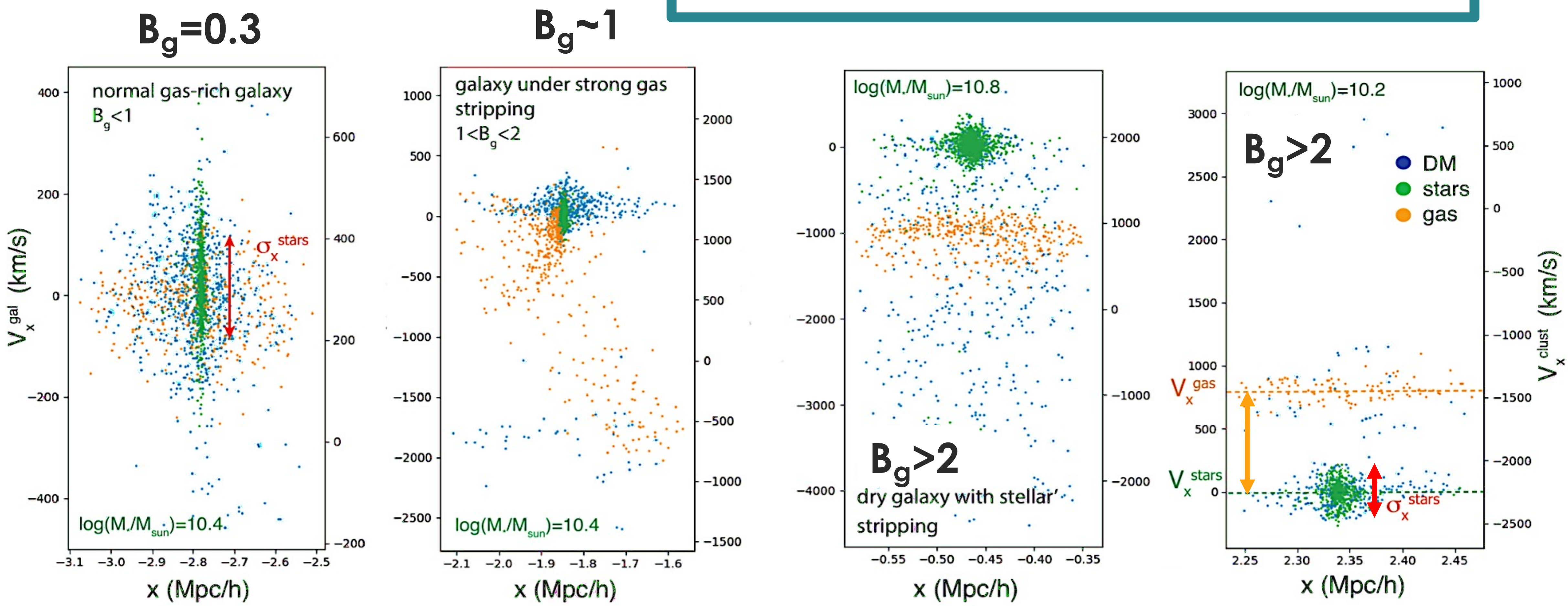




- **Over-estimated! <20% in cones within Rvir**
- **similar fraction of backspash galaxies inside and outside filaments**

Gas binds more tightly near intra-cluster filaments

$$B_g = \frac{\sqrt{(v_{x,g} - v_{x,sdm})^2 + (v_{y,g} - v_{y,sdm})^2 + (v_{z,g} - v_{z,sdm})^2}}{\sqrt{\sigma^2_{v_x,s} + \sigma^2_{v_y,s} + \sigma^2_{v_z,s}}}$$



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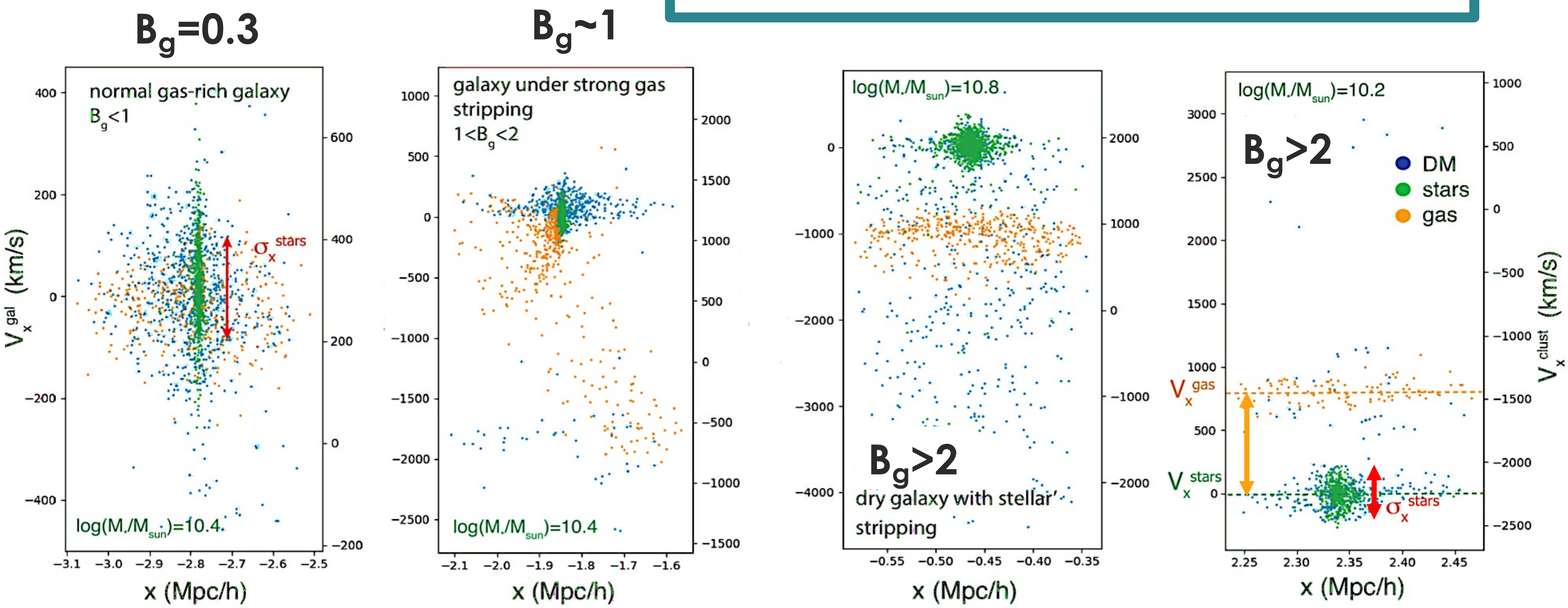

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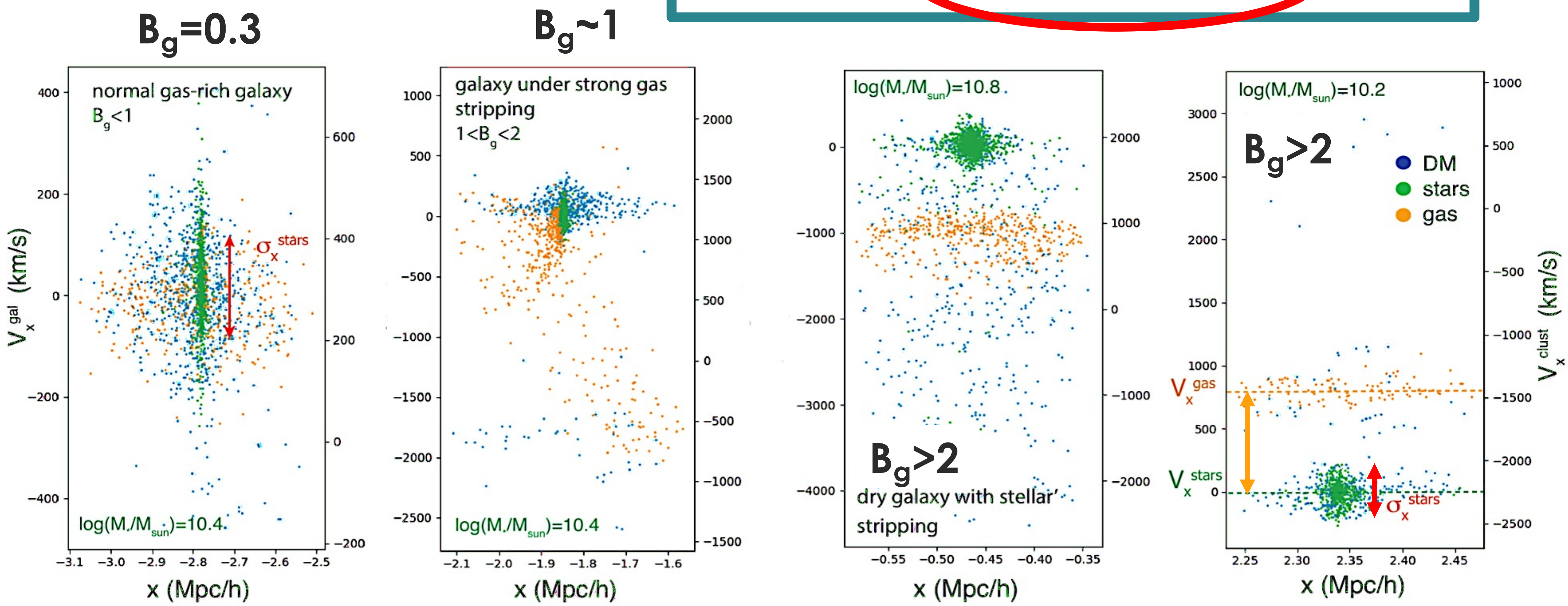

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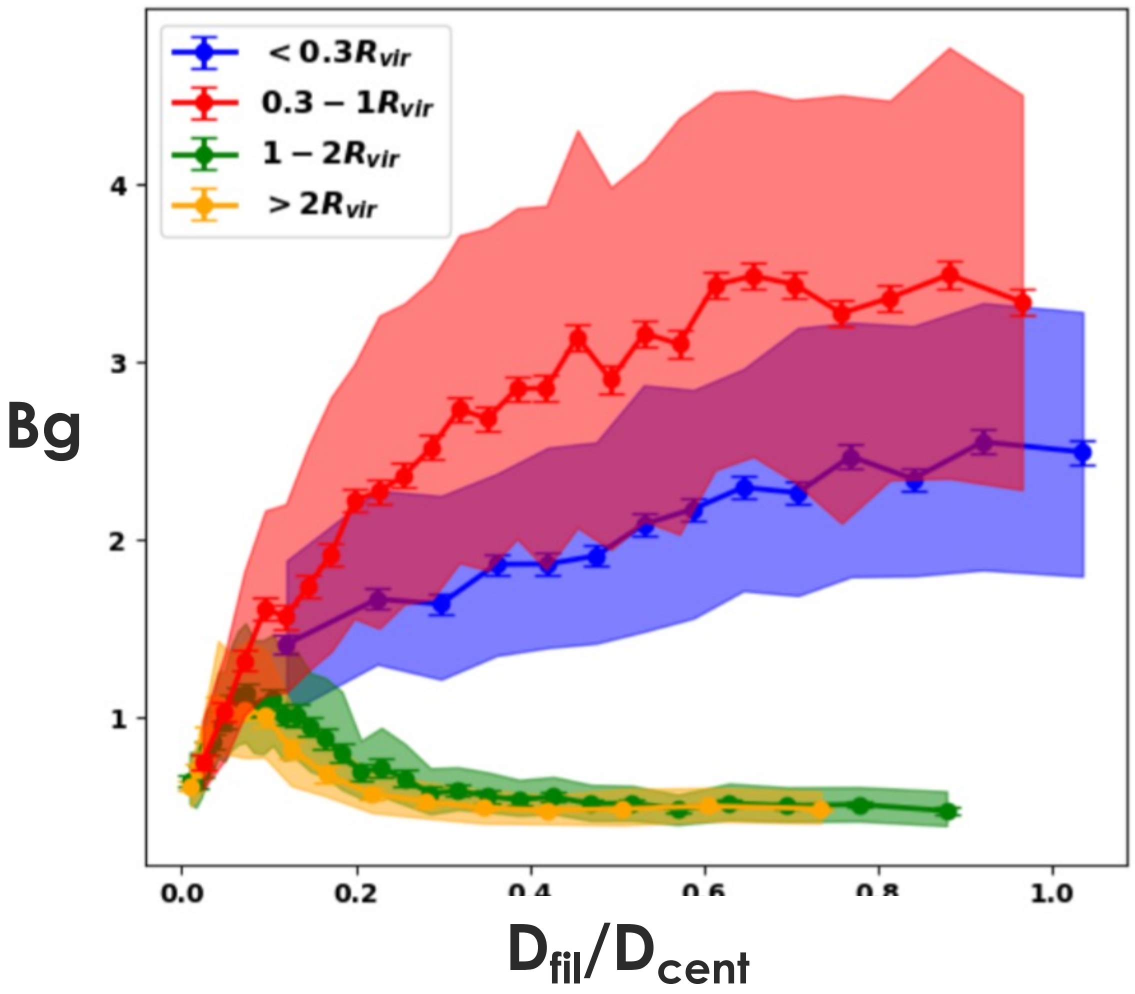
- **Outside Clusters:**

Gas mostly bound to haloes,
but more disturbances closer to filaments

- **Inside Clusters:**

Gas mostly unbound and/or being stripped, but less so near filaments.



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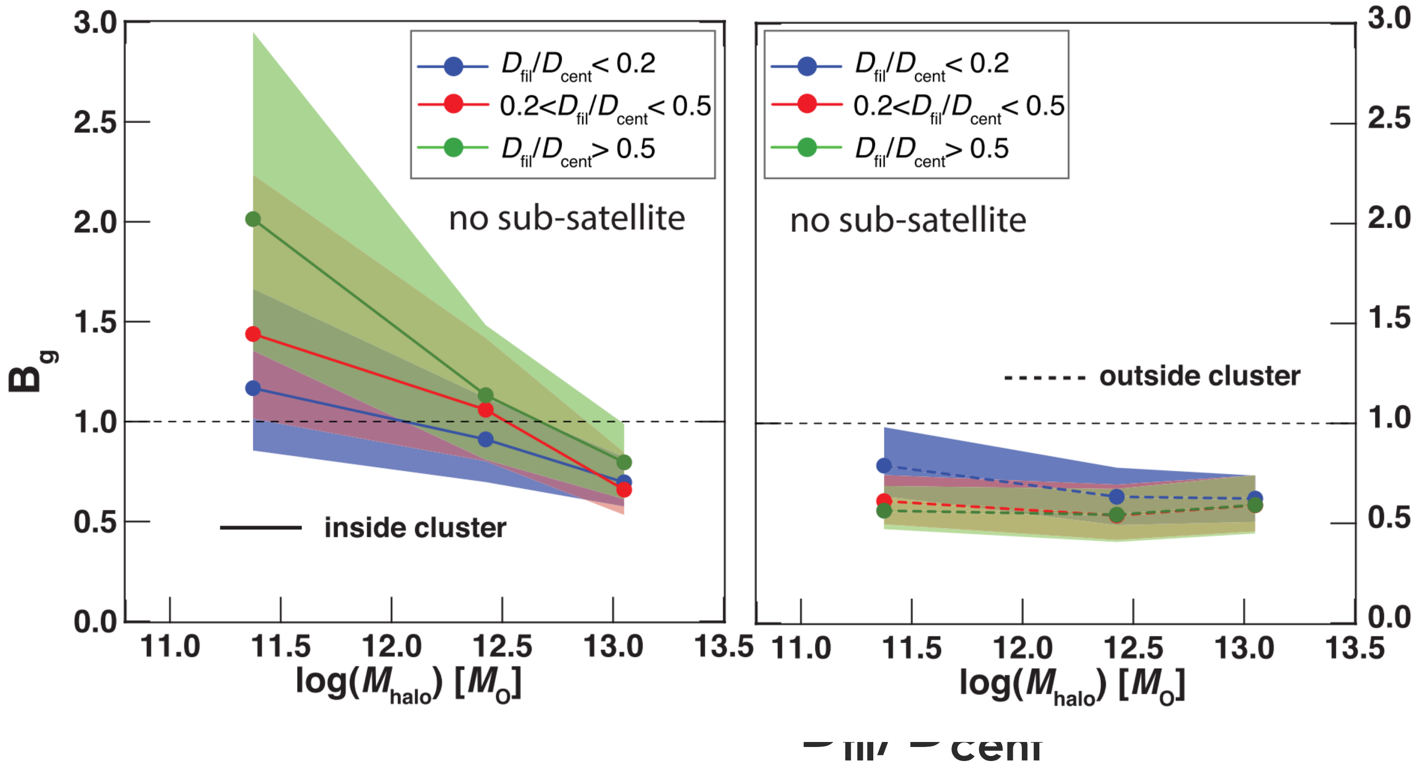
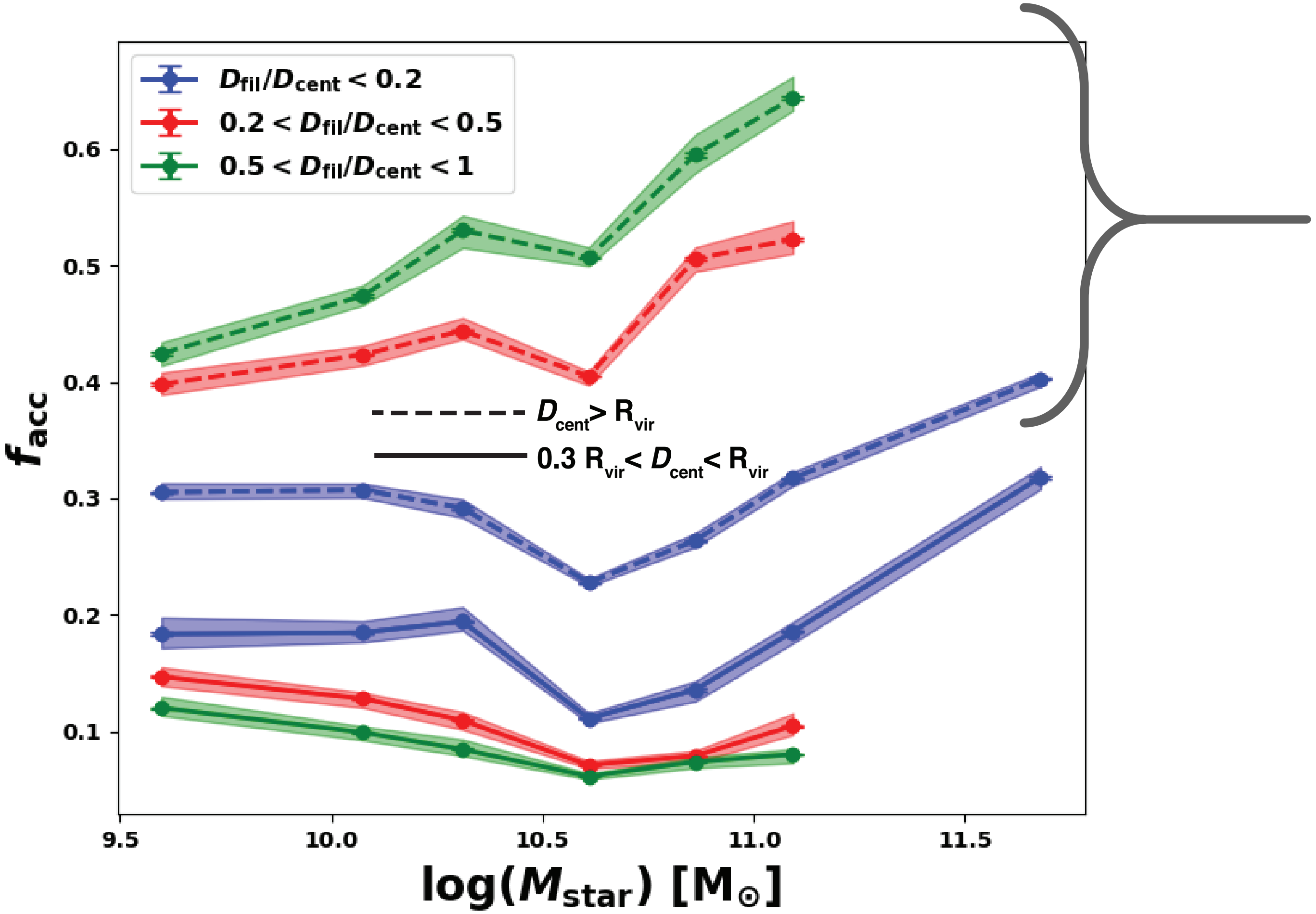


Cold accretion preserved in intra-cluster filaments!

Kotecha&Welker+2022



- **Outside Clusters:**

Less cold accretion near filaments

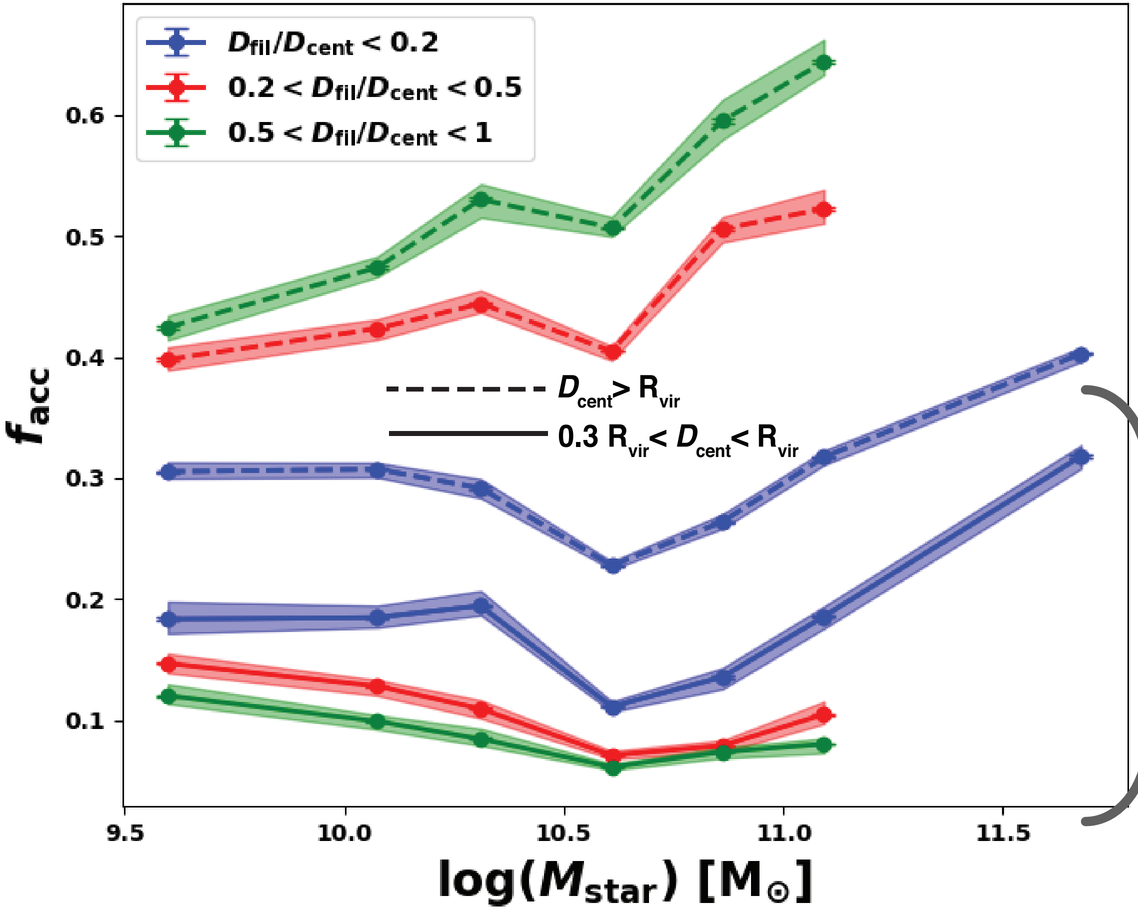
- **Inside Clusters:**

More cold accretion near filaments!

Fraction of accreting galaxies:

$$f_{acc} = \frac{n(\dot{M}^{cold}_{gas} < 0)}{N}$$

Cold accretion preserved in intra-cluster filaments!



- **Outside Clusters:**

Less cold accretion near filaments

- **Inside Clusters:**

More cold accretion near filaments!

Intra-cluster filaments impact quenching

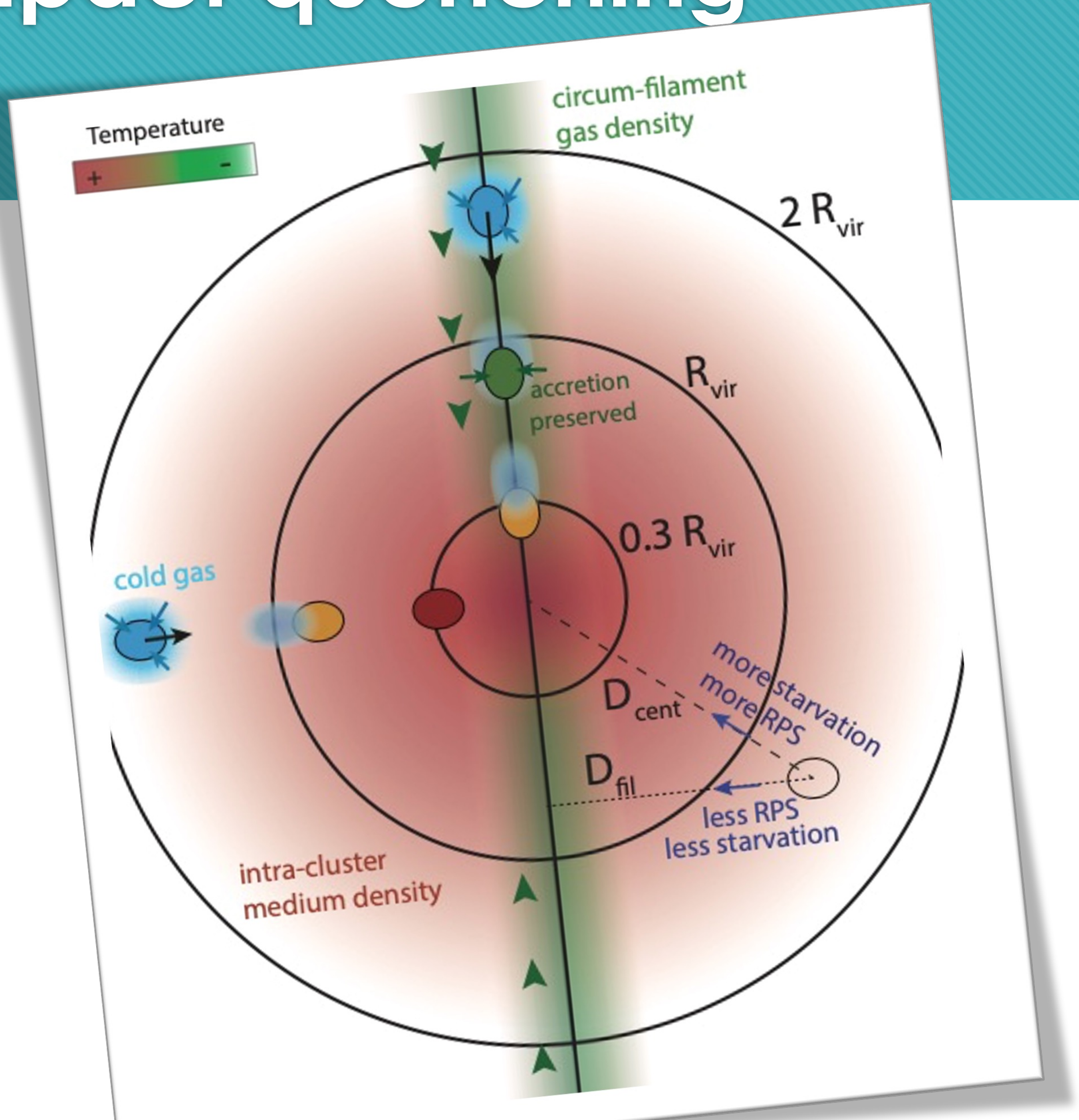
Coherent flows of cool gas and haloes locally:

a. help preserve cold gas accretion

b. reduce ram-pressure stripping

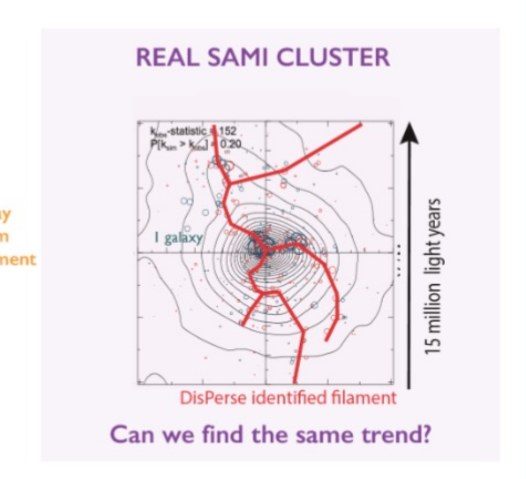
c. Preserve gas fraction and star formation

in stark contrast with filaments
outside clusters where we see *pre-processing*!



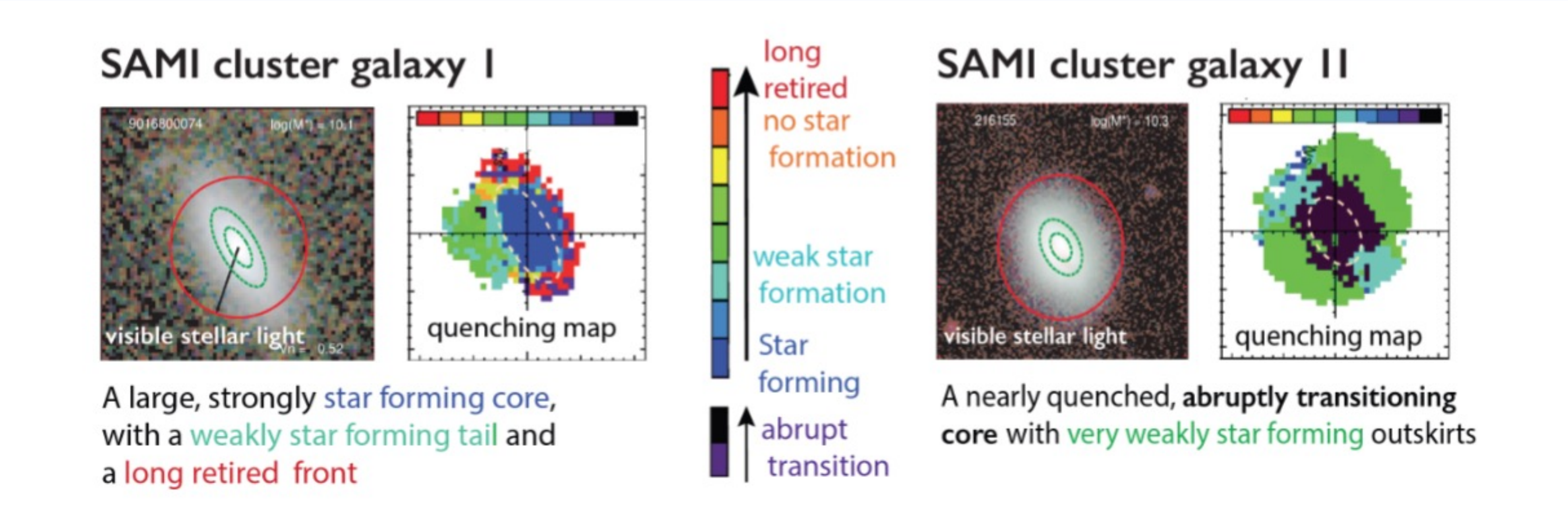
Next step: detection of cool filaments remains with integral-field spectroscopy

Identification of filaments from overlapping large spectroscopic surveys (SDSS, GAMA, 2dF)

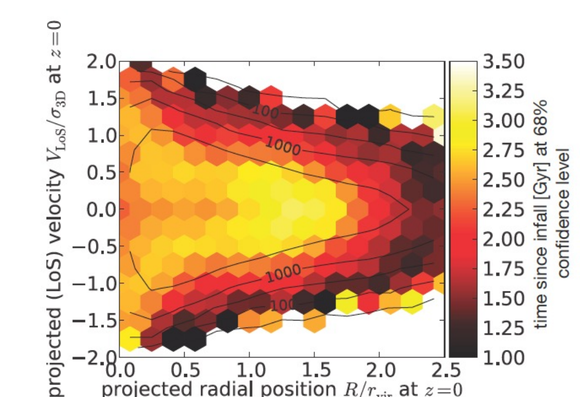


Refined quenching tracers

Owers+2018



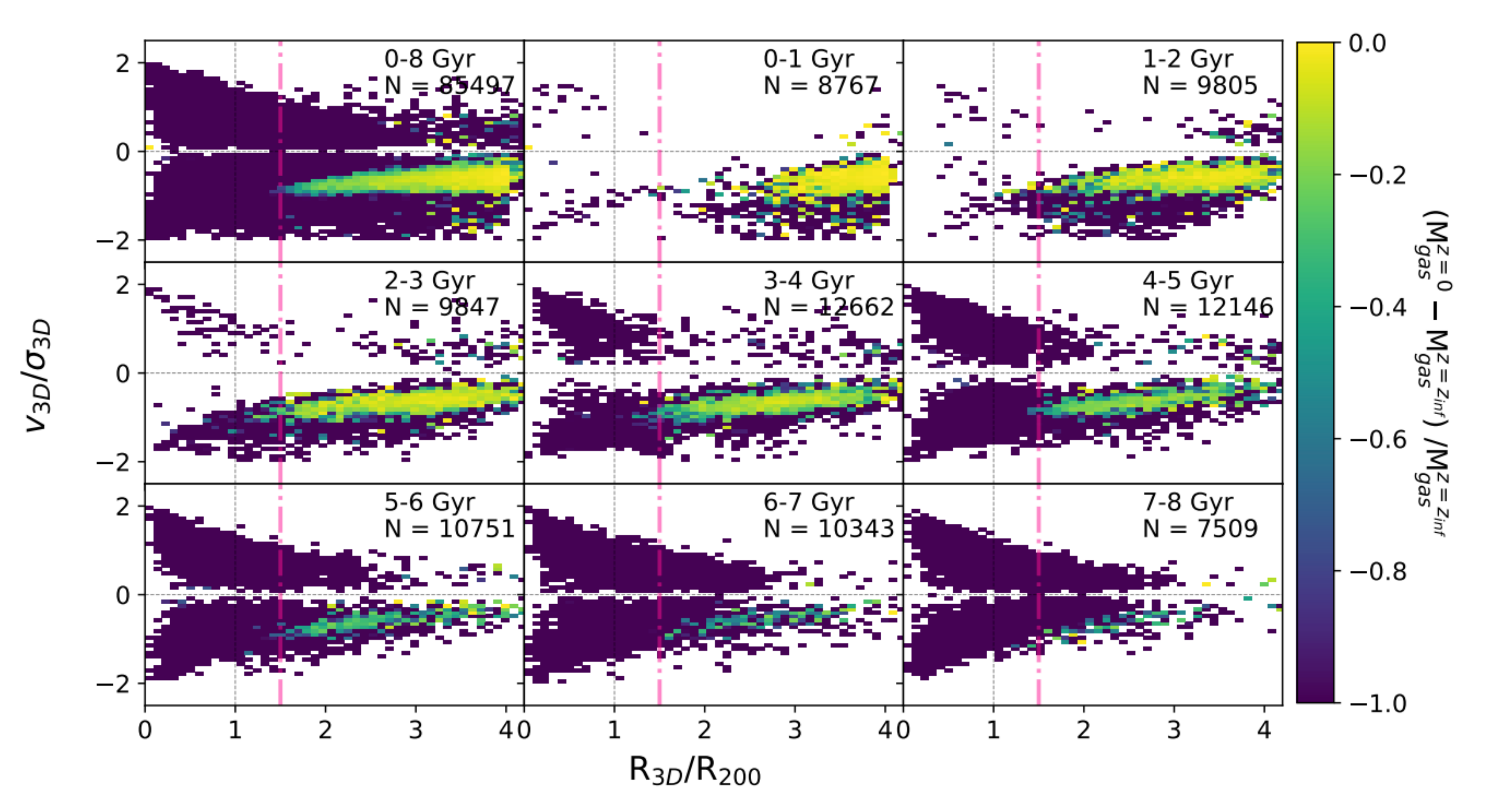
May help us better constrain backsplash galaxies?



Conclusions

- The connection between massive galaxies and the CGM can be preserved without the need for cold flows. Any anisotropic accretion of gas and satellites will do!
- The distribution of satellites in massive galaxies at $z<0.5$ recapitulates the helicoidal structure of cold flows.
- Kinematic coherence and cooler gas temperatures inherited from cosmic filaments persist in the intra-cluster medium at $z=0$
- These remains of cosmic filaments may shield galaxies from quenching

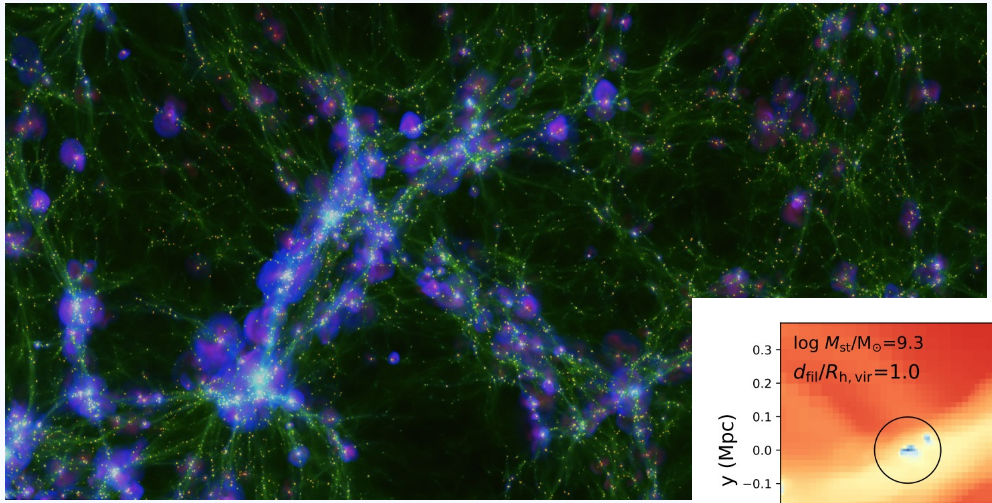
Backsplashes and quenching timescales

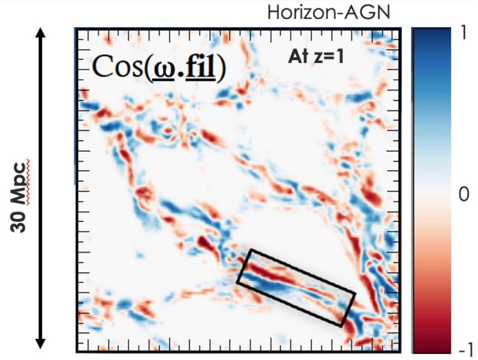


Using galaxies as tracers of gas cosmic flows

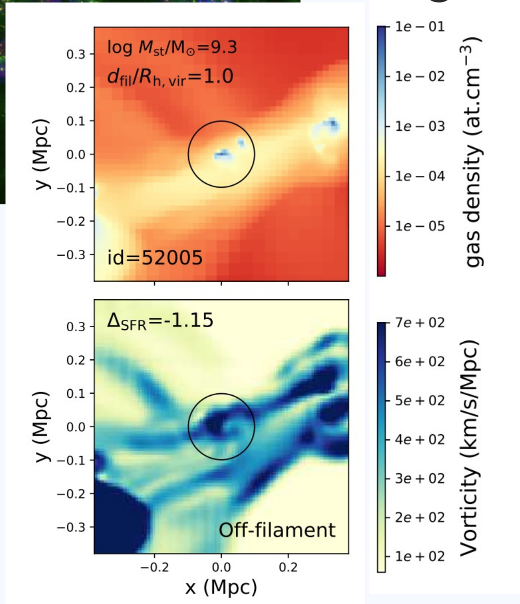
SIMULATIONS

Horizon-AGN



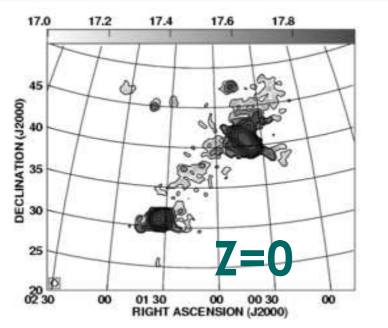


Song+2021

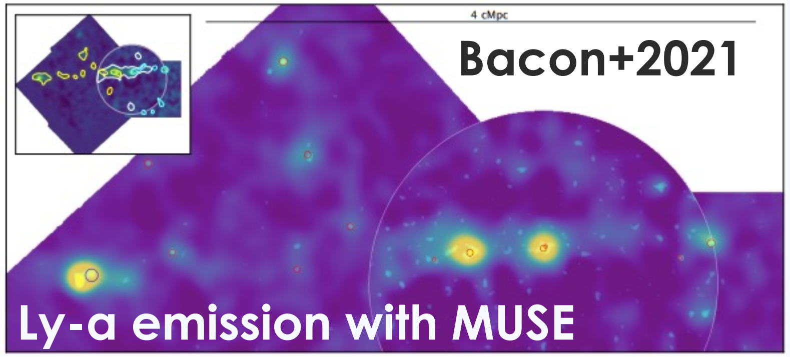


OBSERVATIONS

HI emission



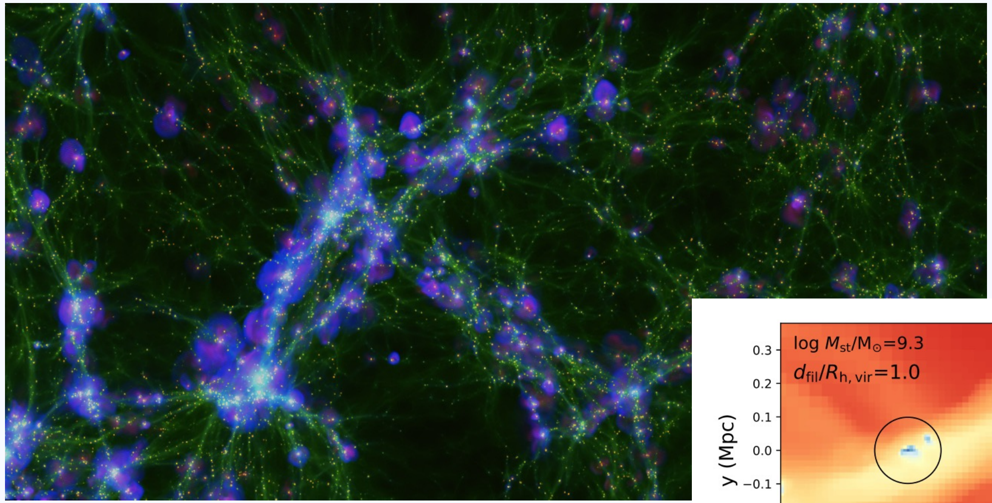
z~3

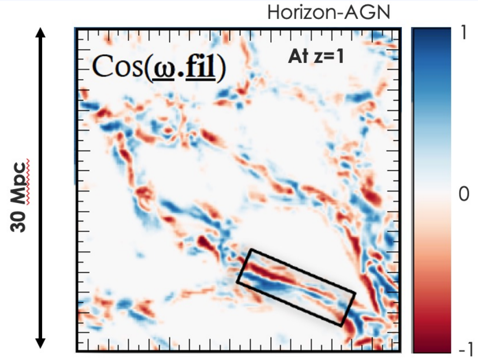


Using galaxies as tracers of gas cosmic flows

SIMULATIONS

Horizon-AGN





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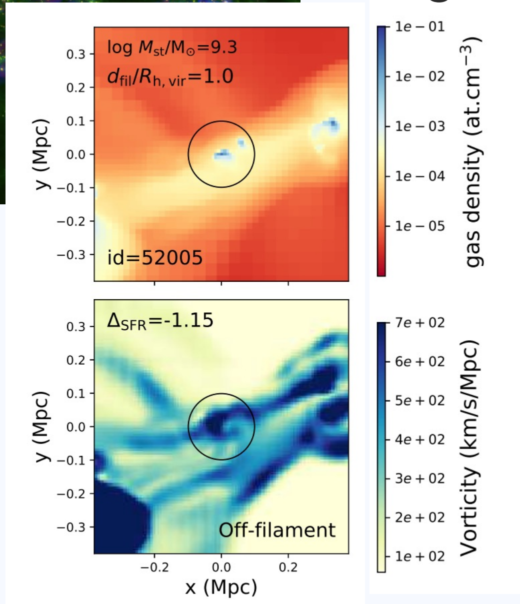
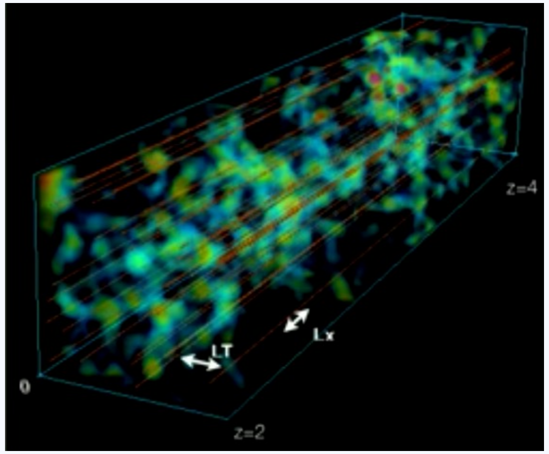


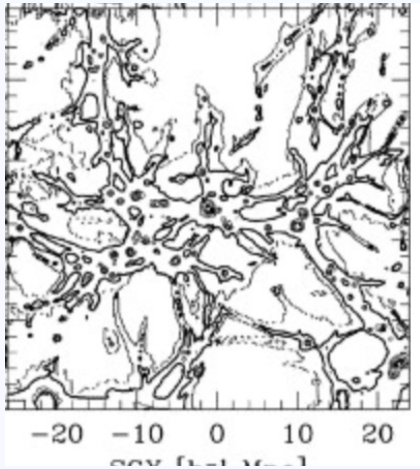
FUTURE OBSERVATIONS

z>1.5



Inversion of the Ly-α forest

Z~0



Diffuse synchrotron emission (SKA)