Title: Review Talk: Galactic to intergalactic scales

Speakers: Nir Mandelker

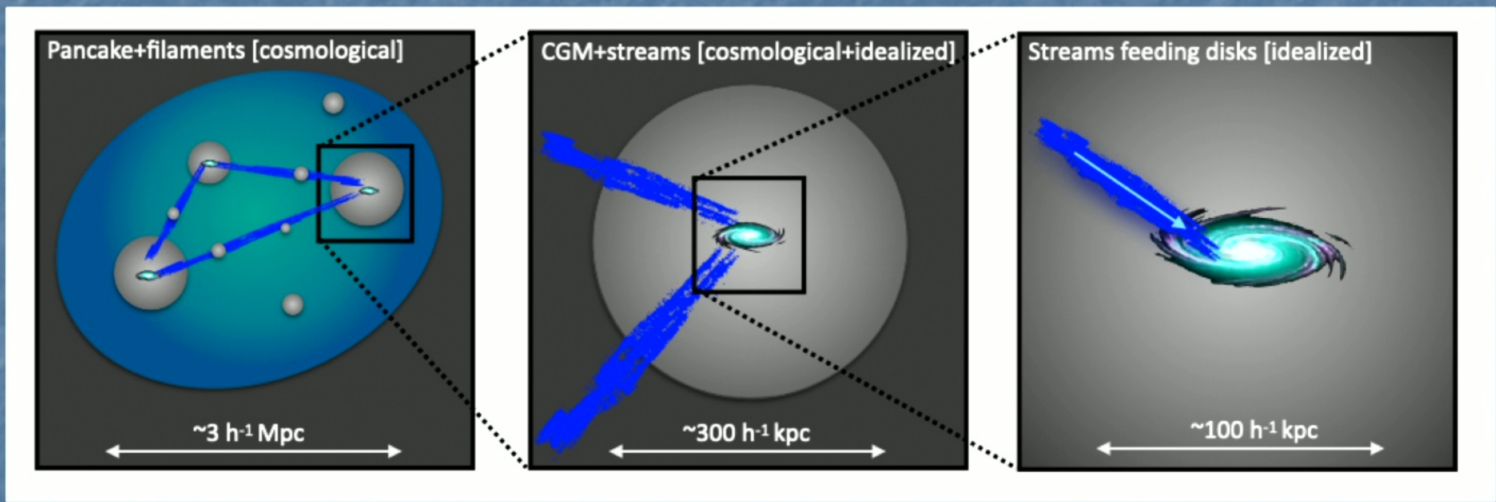
Collection/Series: Cosmic Ecosystems

Subject: Cosmology

Date: July 30, 2025 - 9:00 AM

URL: https://pirsa.org/25070036

Galactic to Intergalactic Scales: How Cosmic Web Accretion Drives Galaxy Evolution

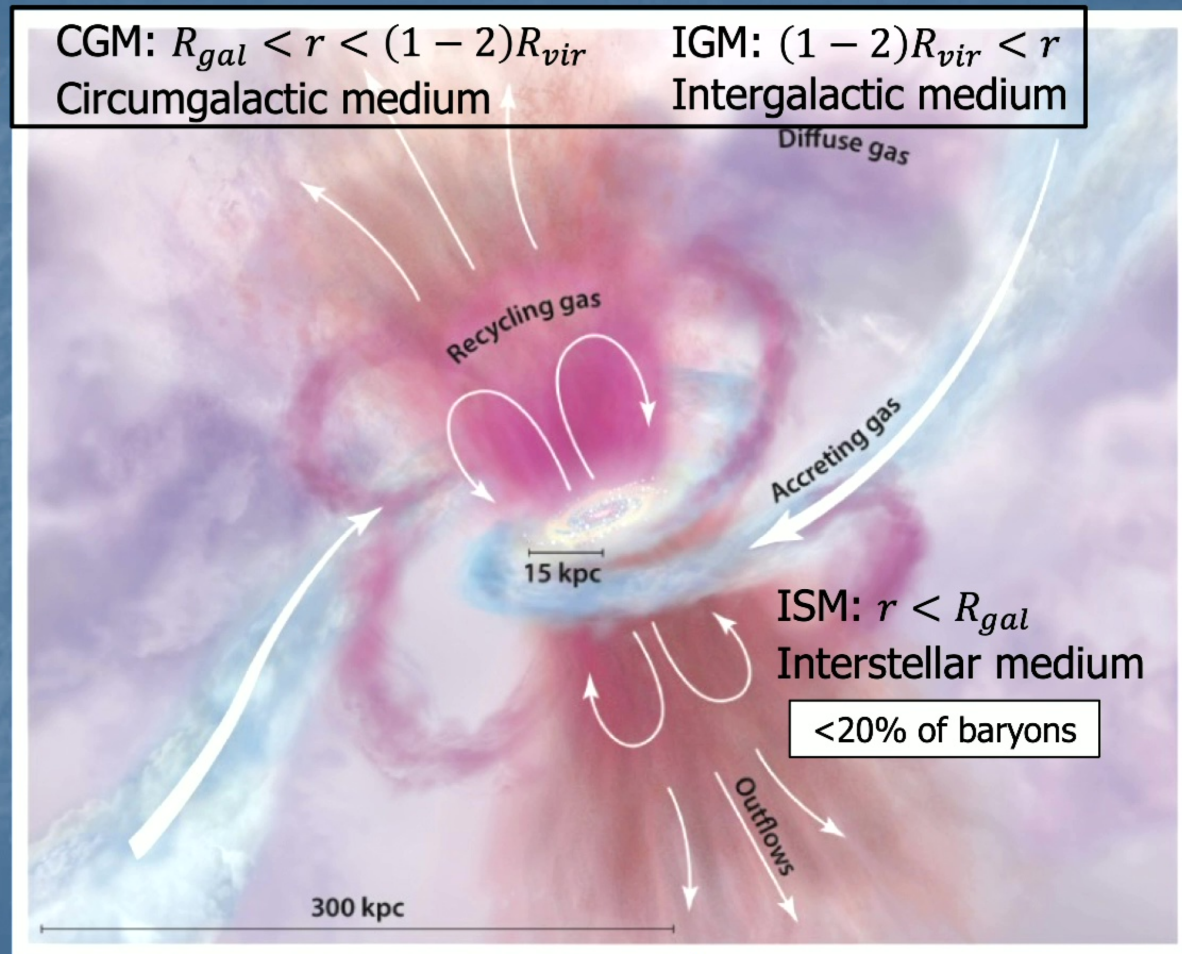


Nir Mandelker, Hebrew University of Jerusalem

Cosmic Ecosystems, Perimeter Institute, July 30 2025

The CGM/IGM – The Baryon Cycle

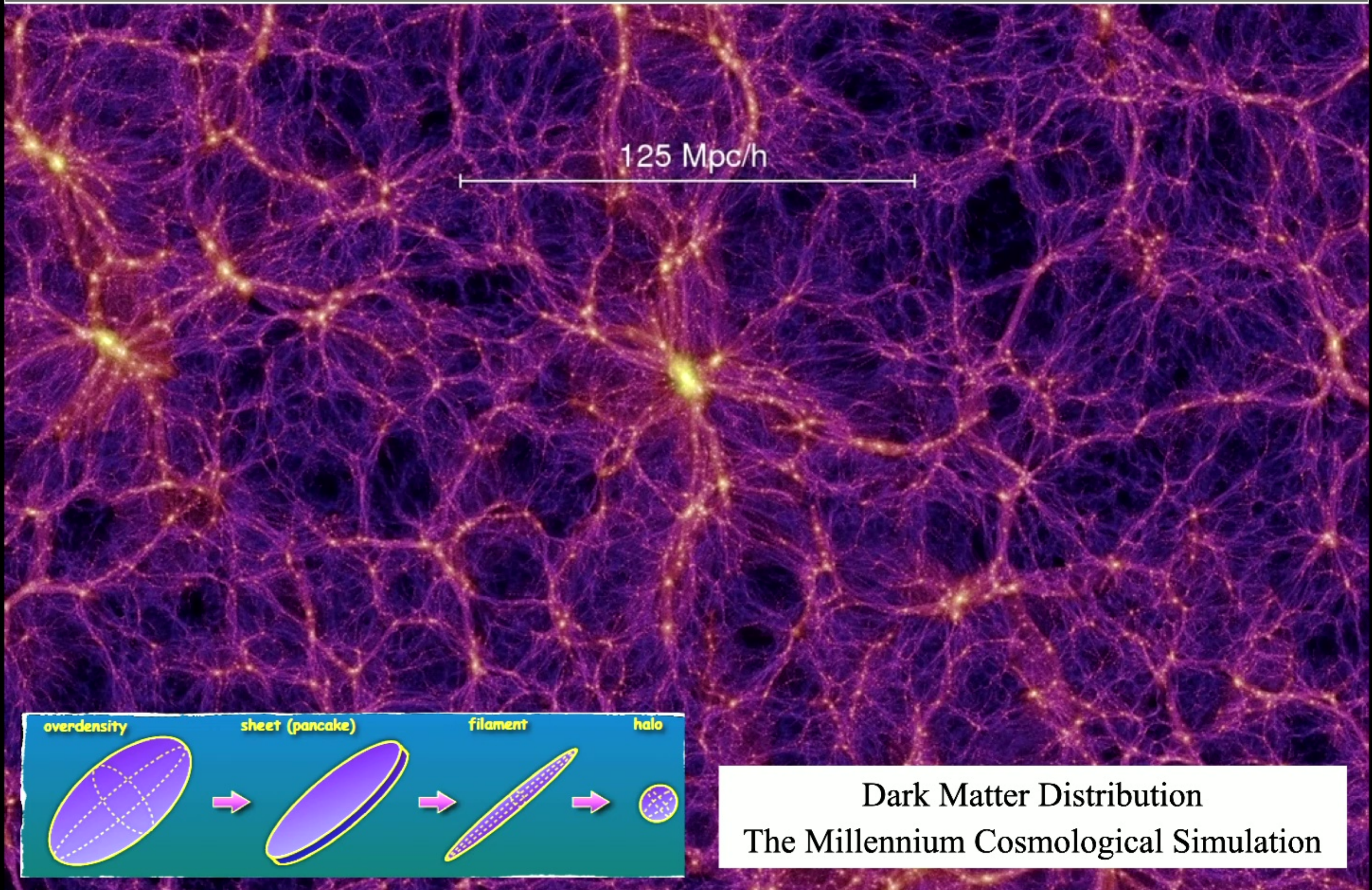
>80% of baryons



Tumlinson, Peeples and Werk 2017

Galaxy Formation in the Cosmic Web

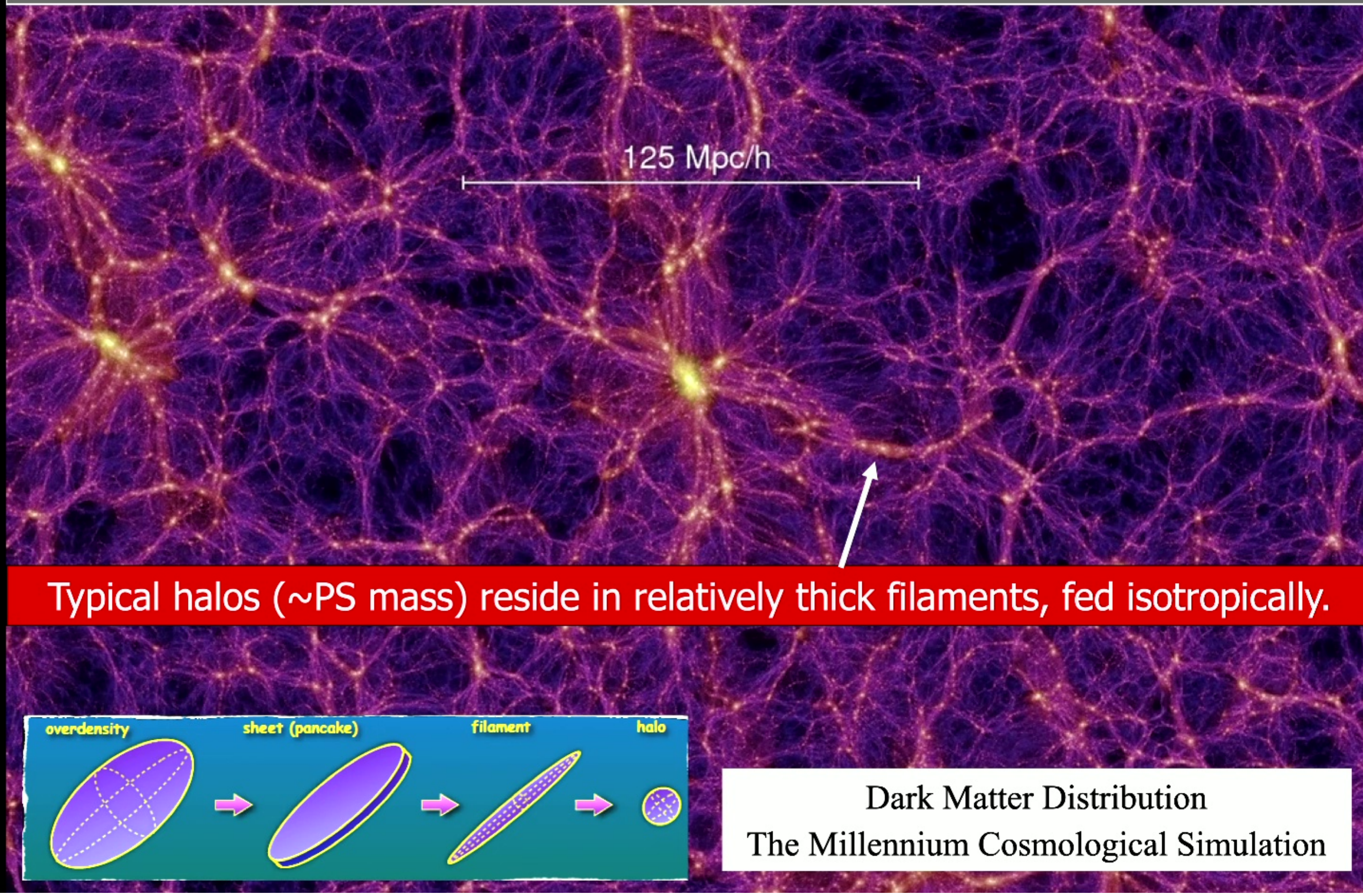
Web of Voids, Sheets, Filaments, Nodes due to anisotropic collapse (Zel'dovich 1970)



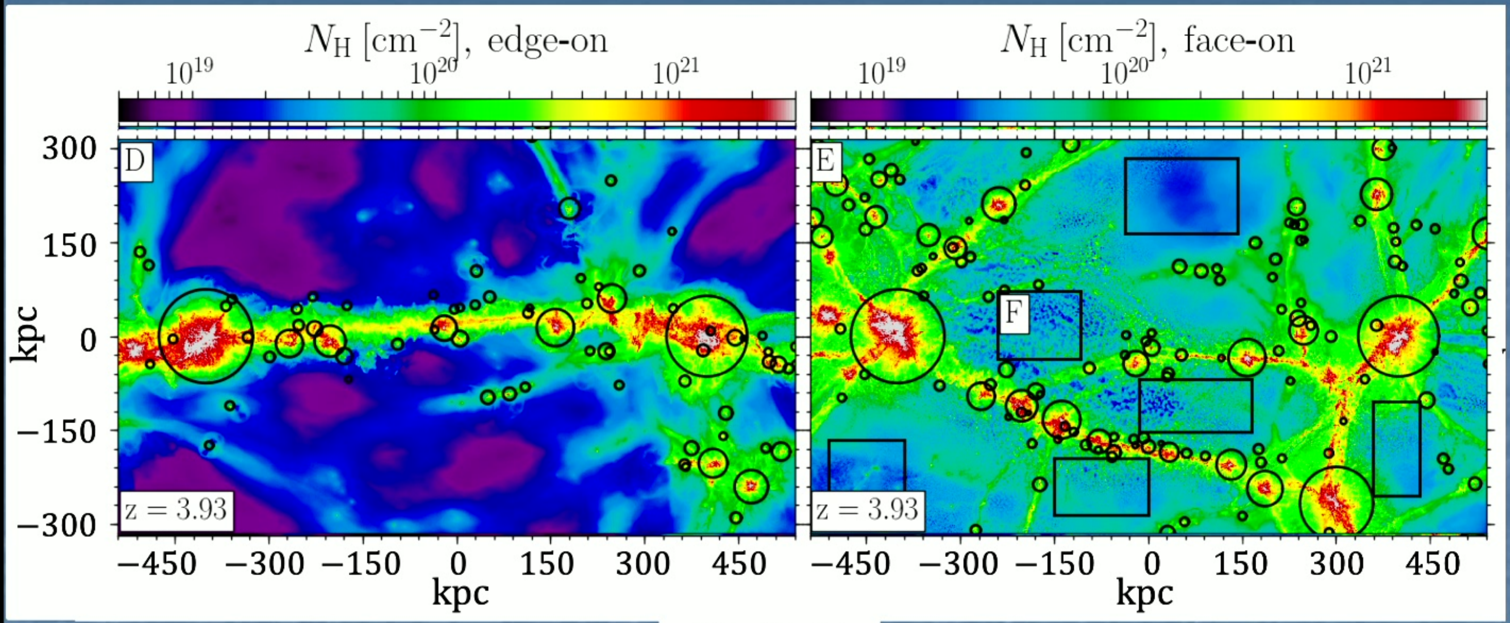
Dark Matter Distribution
The Millennium Cosmological Simulation

Galaxy Formation in the Cosmic Web

Web of Voids, Sheets, Filaments, Nodes due to anisotropic collapse (Zel'dovich 1970)



Galaxy Formation in the Cosmic Web

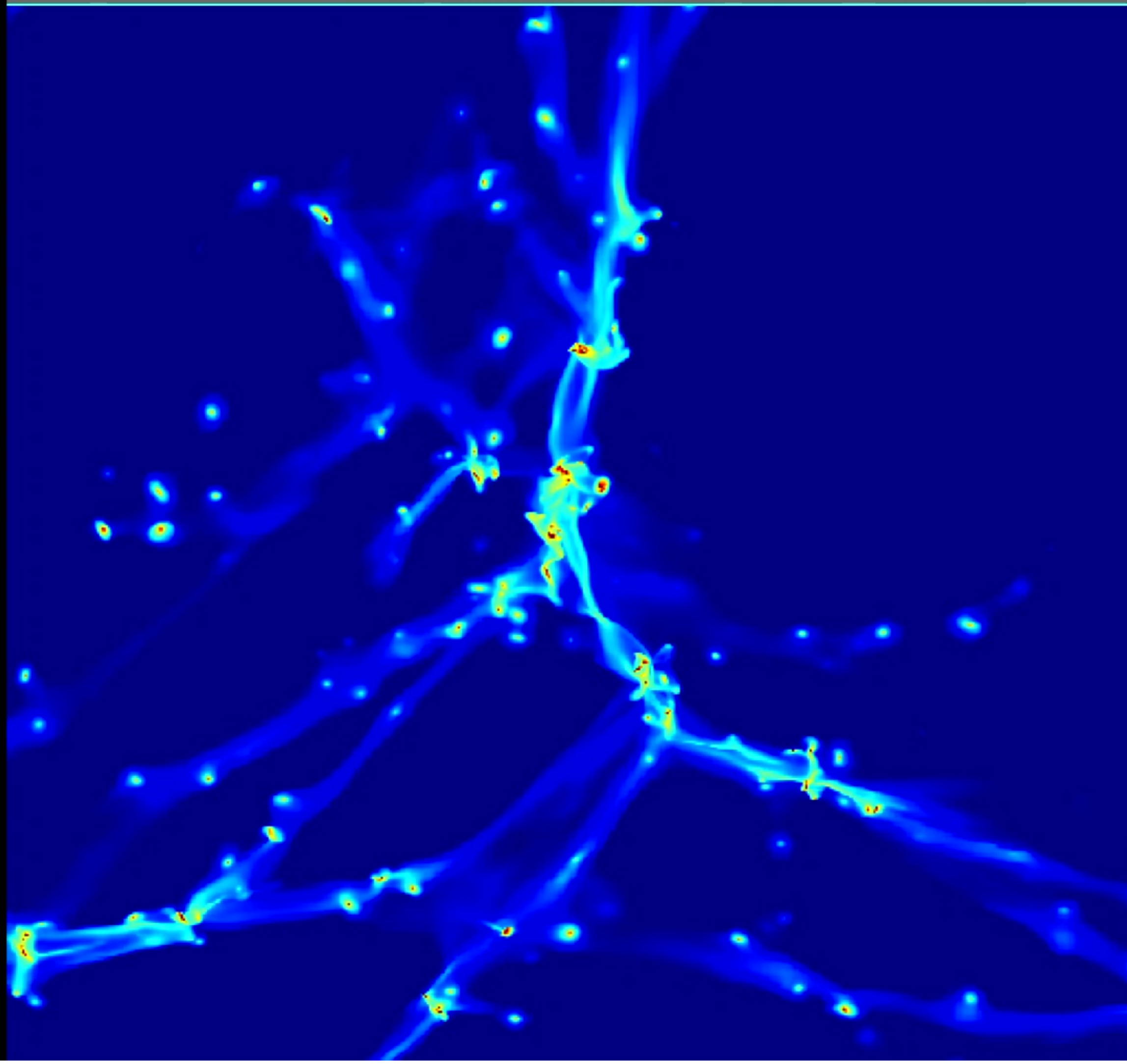


NM+19b,21

AREPO cosmological simulations
Zoom-in on cosmic web between two $\sim 5{\times}10^{12} M_\odot$ halos at $z \sim 2$

Typical haloes reside in filaments
Massive haloes fed by narrow streams

Gas Flows in the Cosmic Web



Cosmic-web streams feed galaxies: Mergers and a smoother component

AMR RAMSES
Teyssier, Dekel

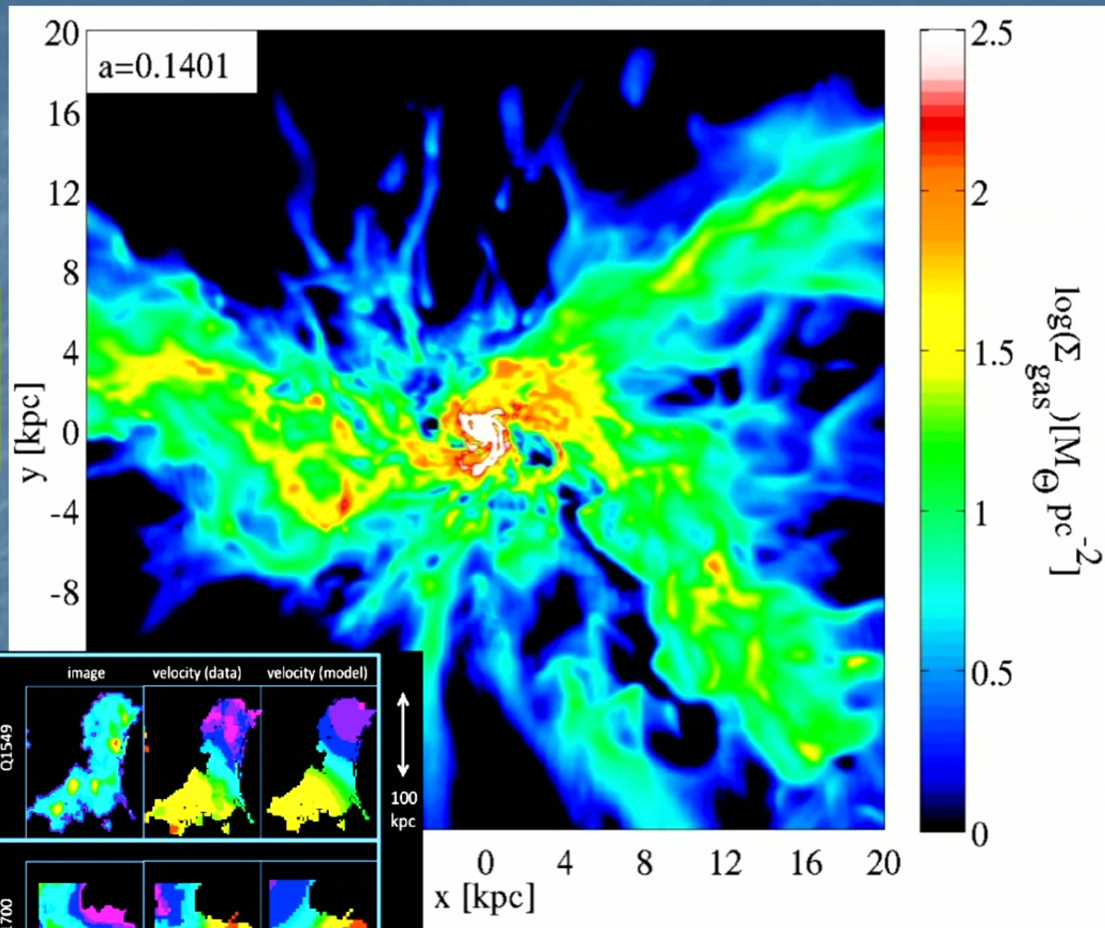
Box Size 300 kpc
Resolution 30 pc
z ~ 5.0 – 2.5

Cold Streams → Disk Growth and Clump Formation

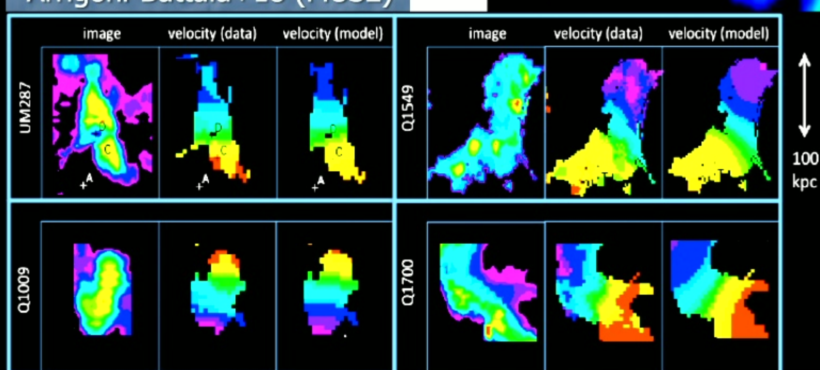
Pichon+11; Stewart+11,13; Danovich+12,15; Codis+12,15; Laigle+15; Tillson+15; Martin+15,16,19; Ginzburg, Dekel, NM, + 22

VELA Simulations
Ceverino+14; Zolotov+16; NM+17; …

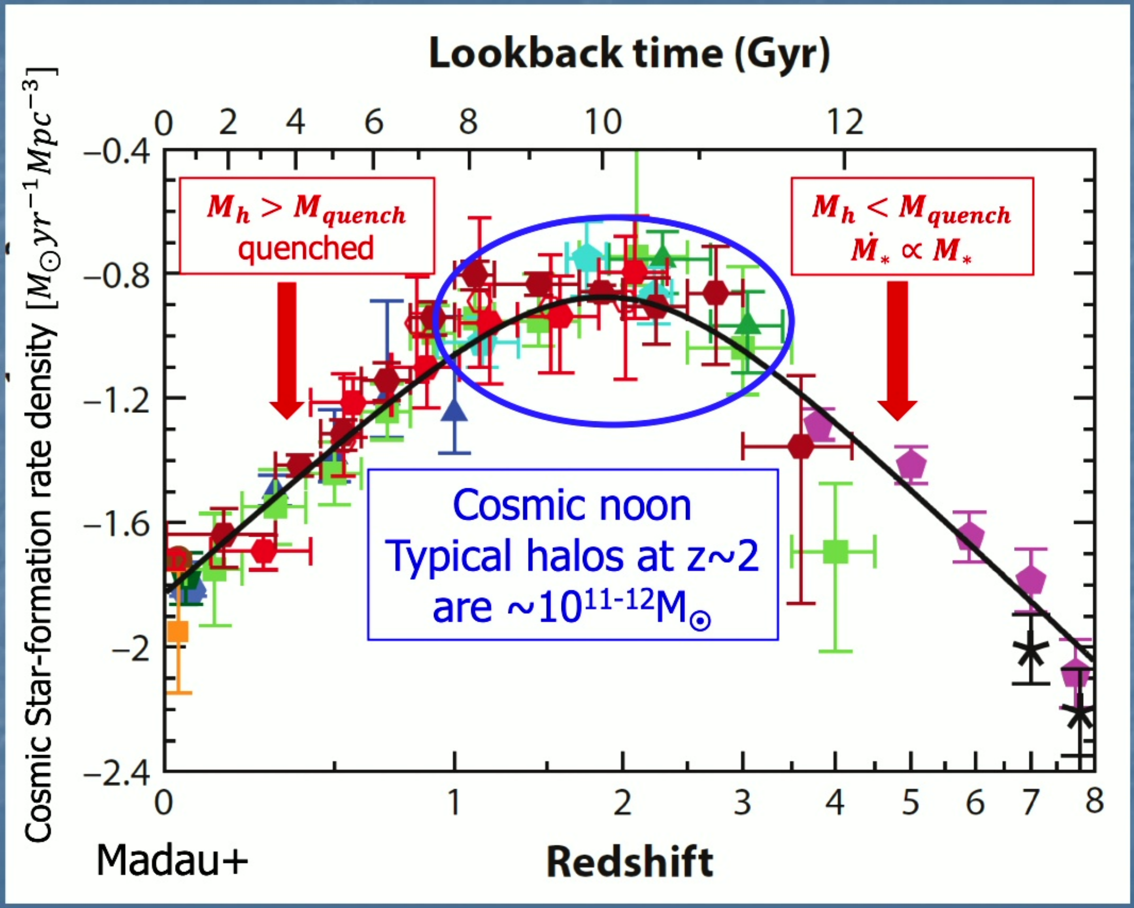
Streams supply disks with mass, angular momentum, and turbulence



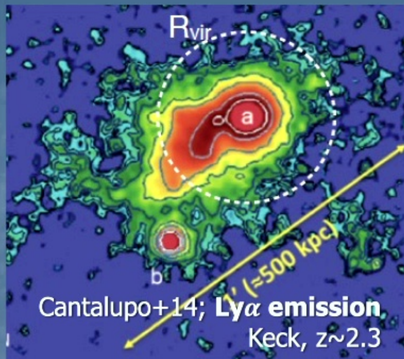
Martin+14,15,16,19 (KCWI)
Arrigoni-Battaia+18 (MUSE)



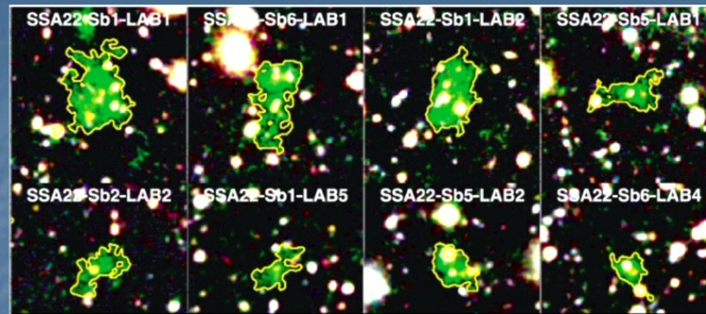
Cosmic Noon - A Golden Epoch for Galaxy Formation



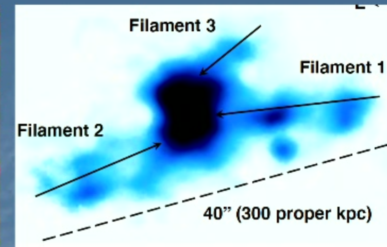
High-z CGM in emission – Lots of Cold Gas



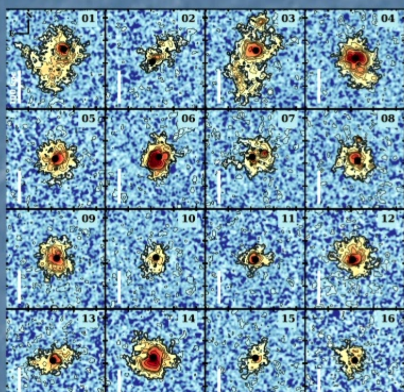
Cantalupo+14; **Lyα emission**
Keck, z~2.3



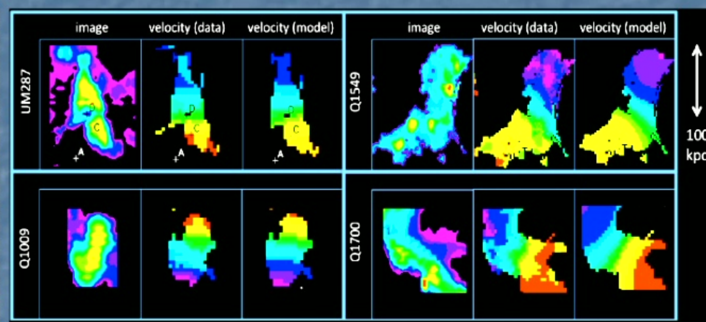
Matsuda+11; **Lyα emission**; Subaru, z~3 (No QSO)



Daddi+20; **Lyα emission**
KCWI, z~3 (No QSO)



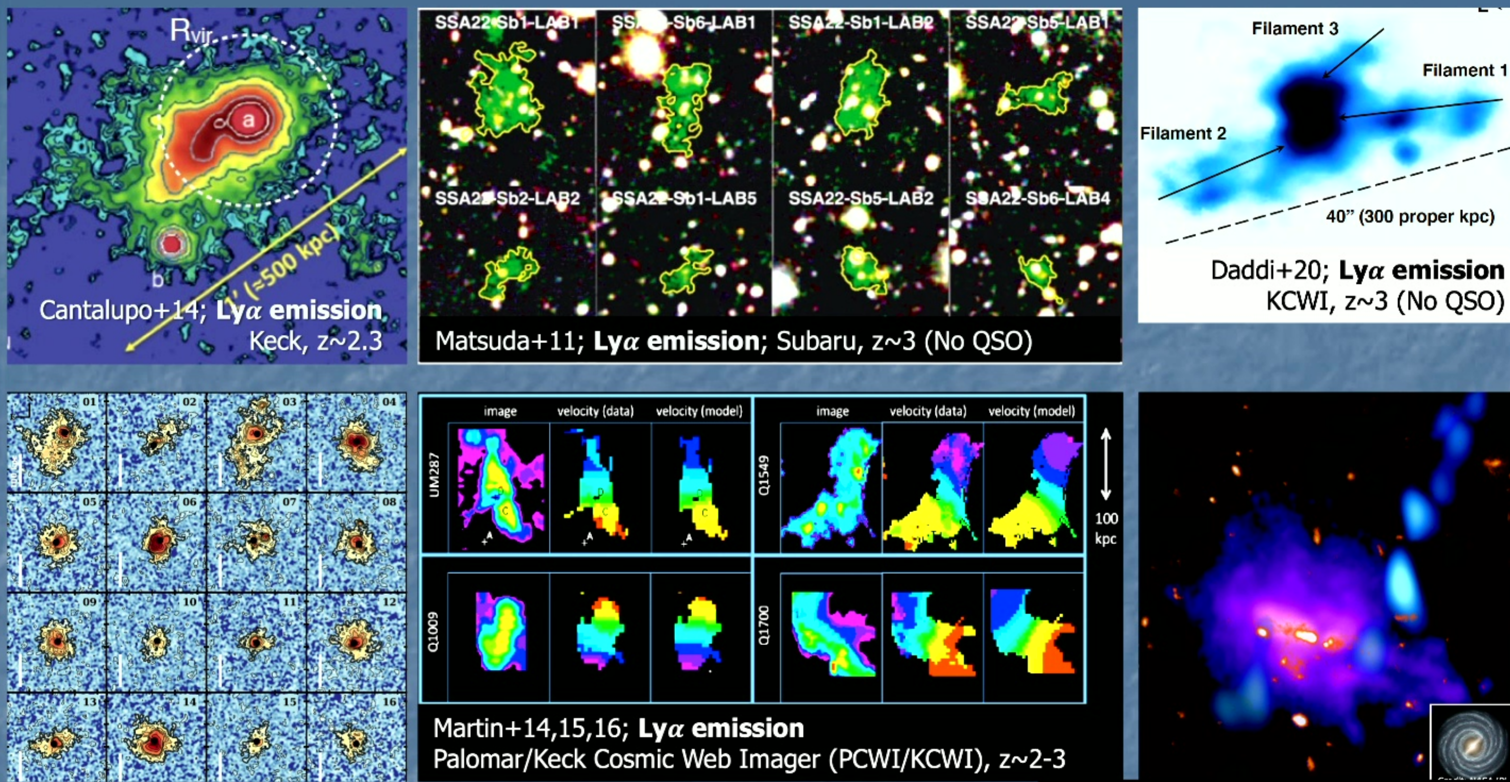
Borisova+16; **Lyα emission**
MUSE, z~3-4



Martin+14,15,16; **Lyα emission**
Palomar/Keck Cosmic Web Imager (PCWI/KCWI), z~2-3

Lyα nebulae ubiquitous around massive galaxies at z>2 → **Cold streams / cosmic filaments?**
What powers emission? (Hennawi+09; Dijkstra & Loeb 2009; Goerdt+2010; Fauchere-Giguere+10; Daddi+20)

High-z CGM in emission – Lots of Cold Gas



Cantalupo+14; **Lyα emission** Keck, z~2.3

Matsuda+11; **Lyα emission**; Subaru, z~3 (No QSO)

Daddi+20; **Lyα emission** KCWI, z~3 (No QSO)

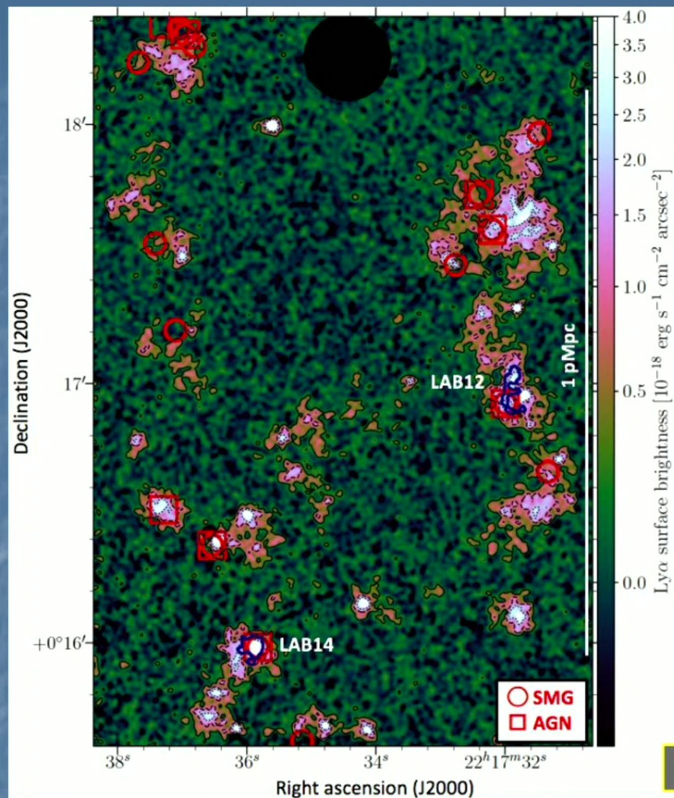
Borisova+16; **Lyα emission** MUSE, z~3-4

Martin+14,15,16; **Lyα emission**
Palomar/Keck Cosmic Web Imager (PCWI/KCWI), z~2-3

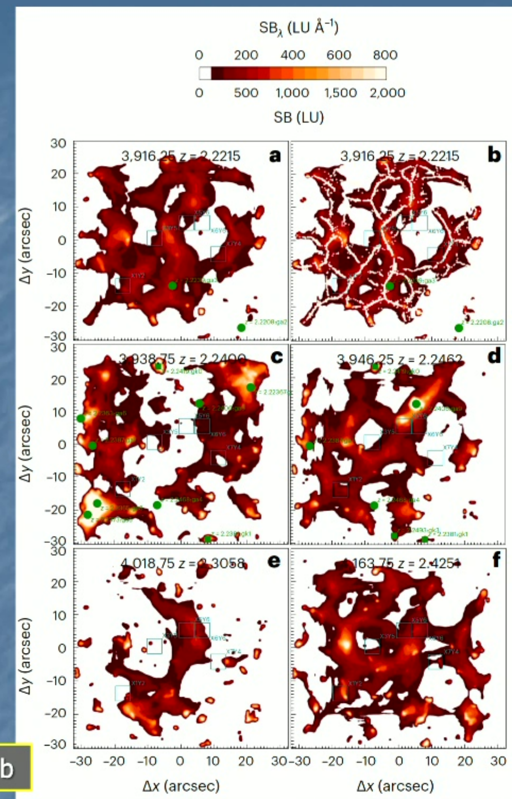
Emonts, Lehnert, Yoon, NM, et al 2023
ALMA, z~4, **CI emission**
100K gas, metal enriched

Lyα nebulae ubiquitous around massive galaxies at z>2 → **Cold streams / cosmic filaments?**
What powers emission? (Hennawi+09; Dijkstra & Loeb 2009; Goerdt+2010; Fauchere-Giguere+10; Daddi+20)

Lyα Emission from the Cosmic Web



See also Tornotti+ 2025a,b

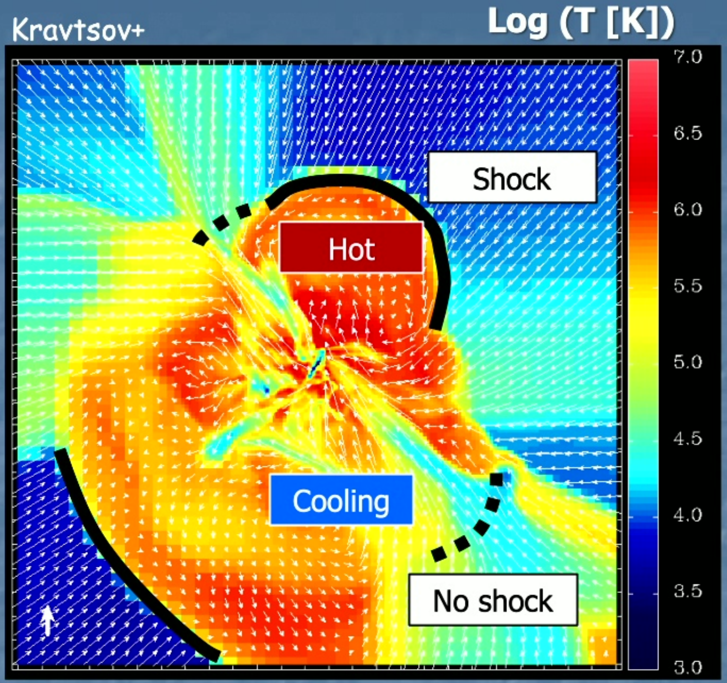


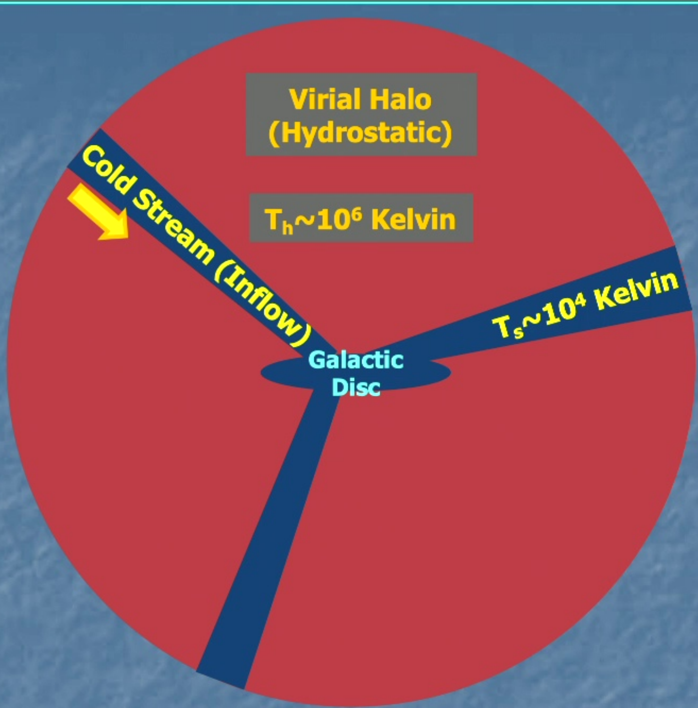
Umehata+ 2019, MUSE (IFU on the VLT)
Lyα emission on ~Mpc scales around active galaxies in a protocluster at z~3.1

Martin+ 2024, KCWI
"Emission Lyα forest" at z~2.3, ~Mpc scale filaments

Cosmic web reconstruction from Euclid, DESI, MOONS combined with Lyα from KCWI, BlueMUSE, GMT
Unbiased sample of cosmic web filaments in different environments during cosmic noon

Cold Streams in Hot Halos





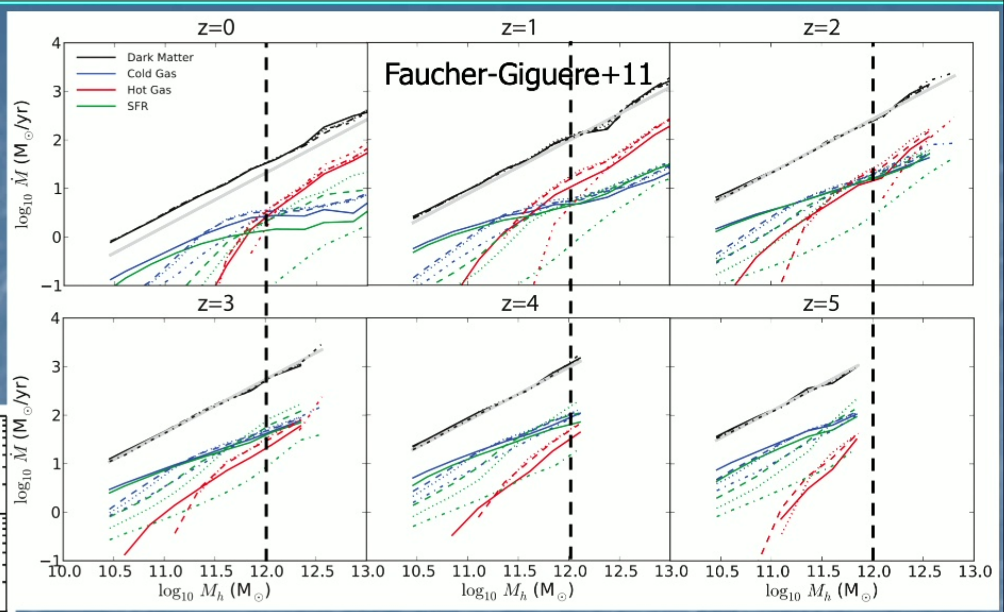
Birnboim & Dekel 03; Keres+ 05; Dekel & Birnboim 06; van de Voort+11; Fielding+ 17; Stern+20

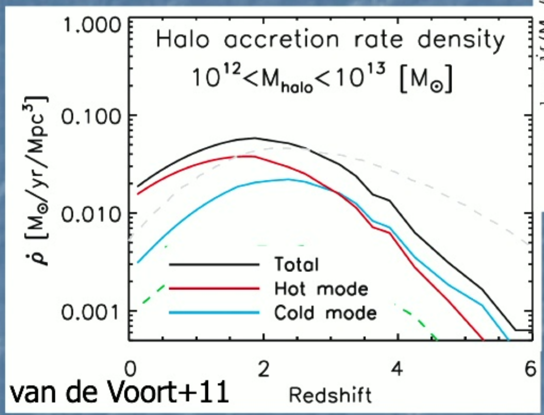
At $z > 2$ in $M_{vir} > 10^{12} M_\odot$:

Cold streams ($T \sim 10^4$ K) penetrate shock heated CGM ($T \sim T_{vir} \geq 10^6$ K, hydrostatic equilibrium)

Supplies disk with mass ($\dot{M}_* \sim 100 M_\odot yr^{-1}$) and angular momentum, drives turbulence and disk instabilities (Dekel+09b; Danovich+15; Ginzburg+22; NM+24)

Transition in Accretion Mode - Simulations





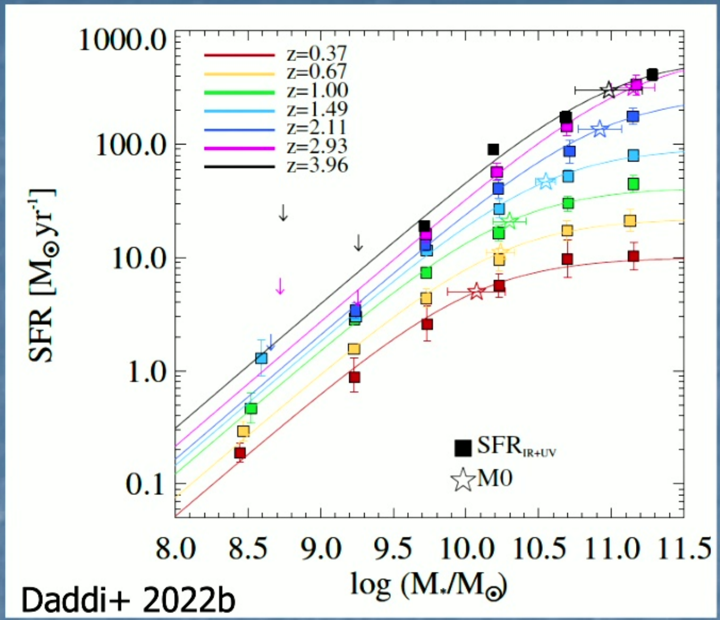
See also: Keres+05; Dekel & Birnboim 06; Dekel+09a; Stern+21

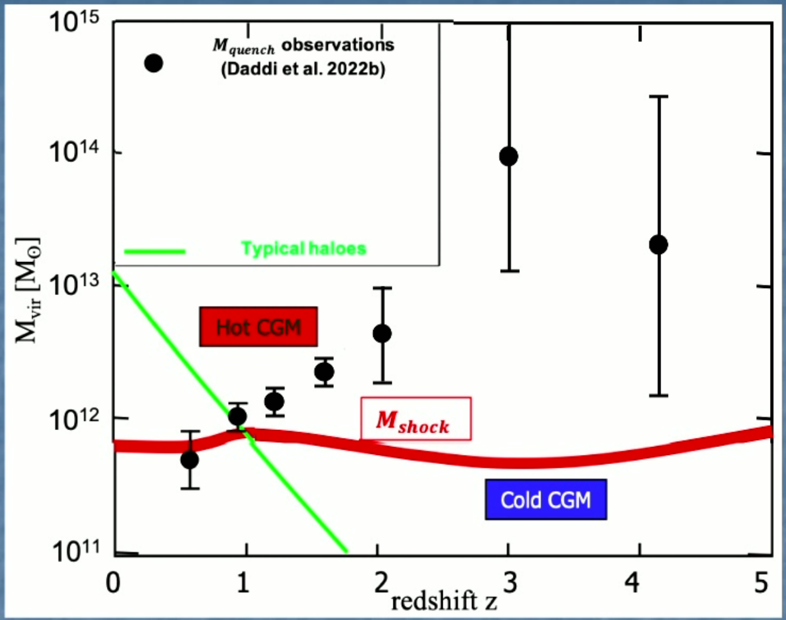
For $10^{12} M_\odot$ halos:

Cold mode accretion dominates at $z > 2$

Hot mode accretion dominates at $z < 2$

Transition in Accretion Mode - Observations

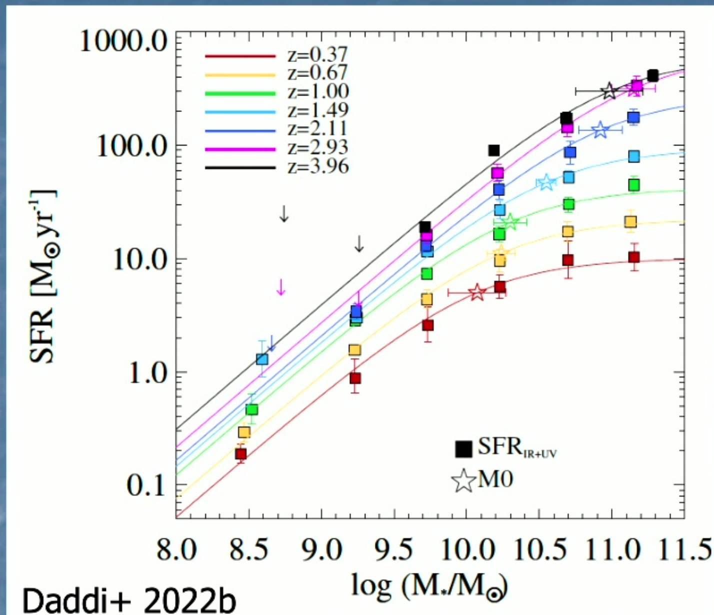


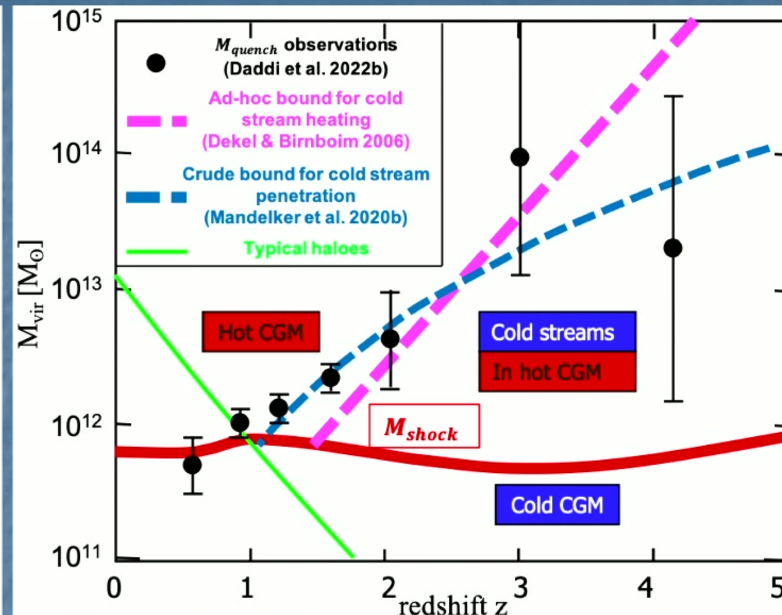


See also: Behroozi+19; Popesso+23

- Quenching mass: Turnover in galaxy SFR-M* relation
- At earlier times, more massive halos host star-forming galaxies
- High-mass quenching driven by something other than internal feedback

Transition in Accretion Mode - Observations

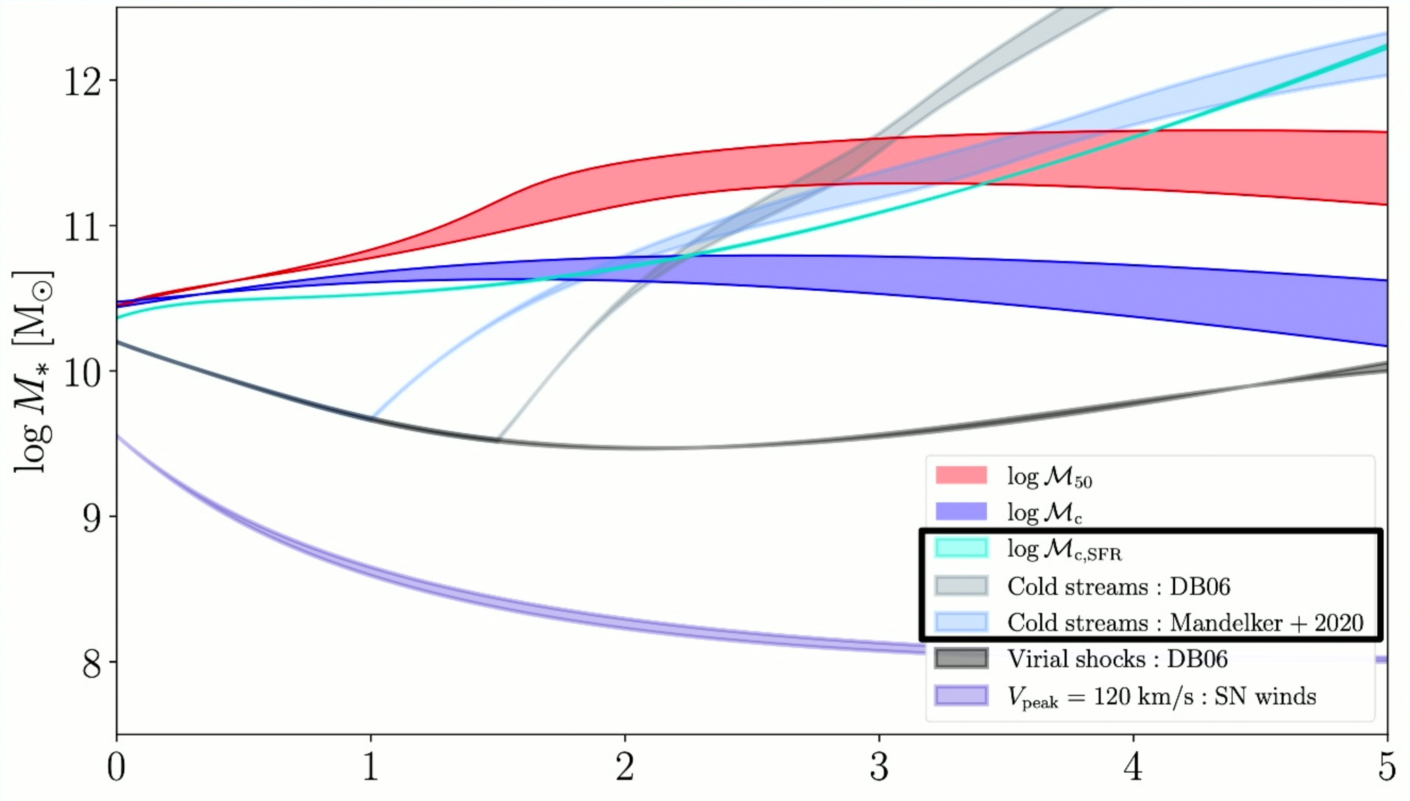




See also: Behroozi+19; Popesso+23

- Quenching mass: Turnover in galaxy SFR-M* relation
- At earlier times, more massive halos host star-forming galaxies
- High-mass quenching driven by something other than internal feedback
- **Suggested link between cosmic web accretion and the decline of the quenching mass during cosmic noon**

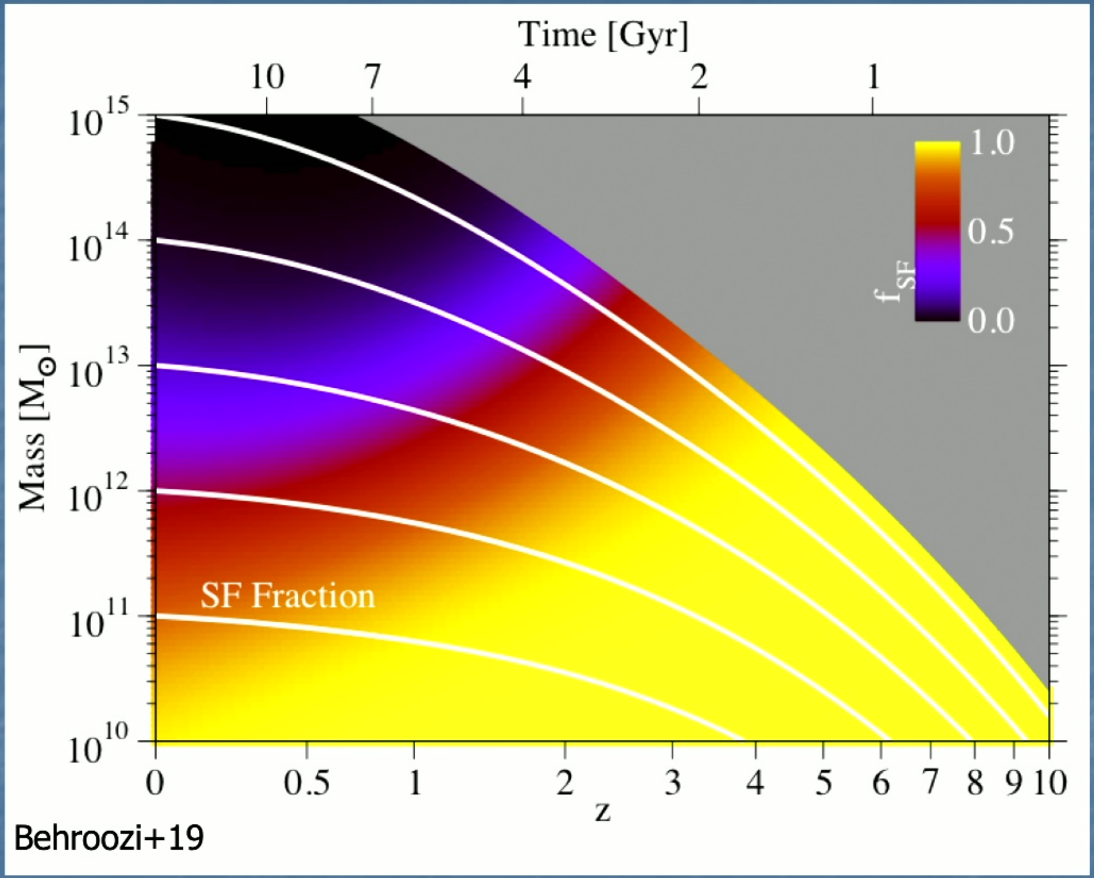
Empirical Model From Observations



Rodriguez-Puebla et al (in prep)

Link between stream disruption and the bend of the star-forming main sequence

Empirical Model From Observations



Fraction of star-forming massive galaxies seems related to cosmic web accretion

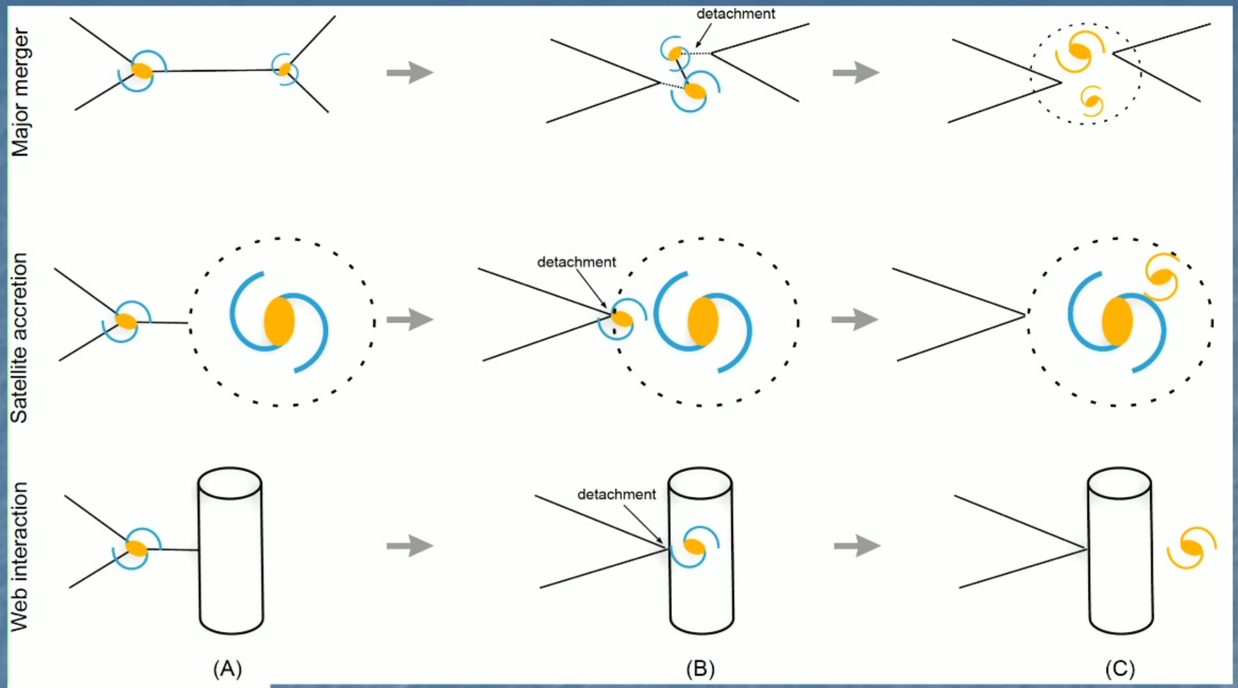
Fundamental Question

Does a transition in the accretion mode drive the decline of the main-sequence turnover mass during cosmic noon, and thus the evolution of the cosmic SFR density?

What drives the transition in accretion mode?

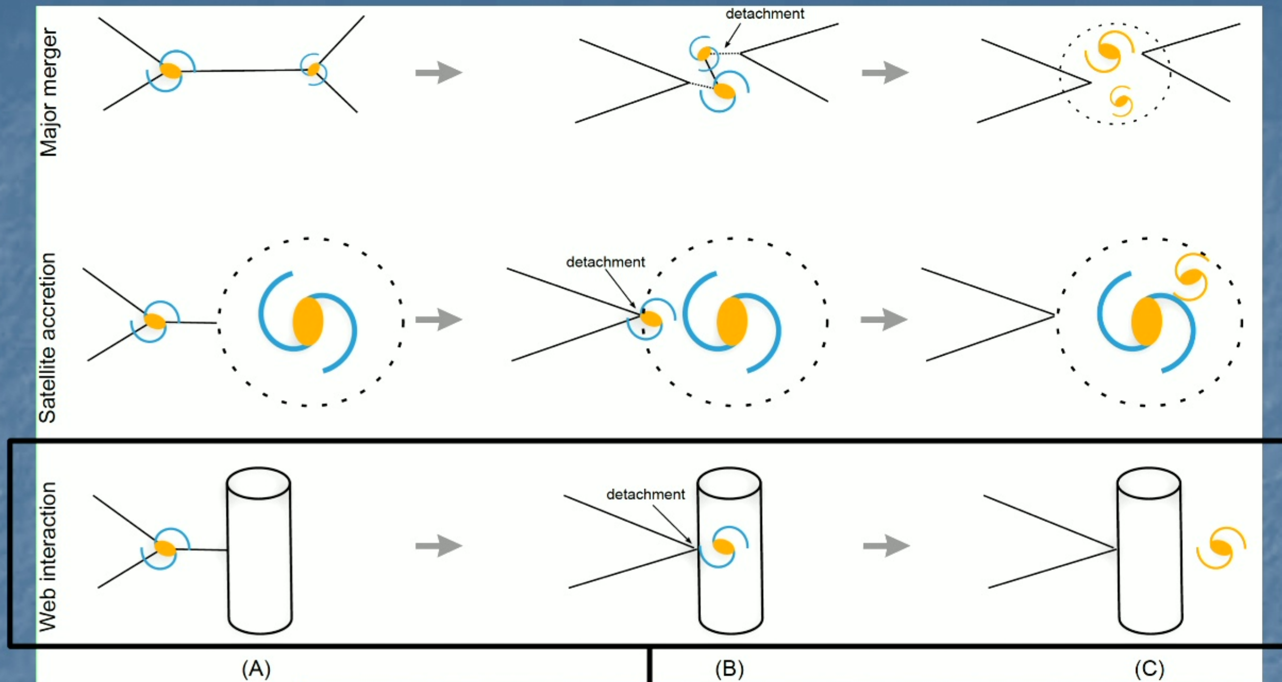
- Change in how dark matter halos connect to the cosmic web? (e.g. Aragon-Calvo 2019)

Cosmic Web Detachment



Aragon-Calvo+19

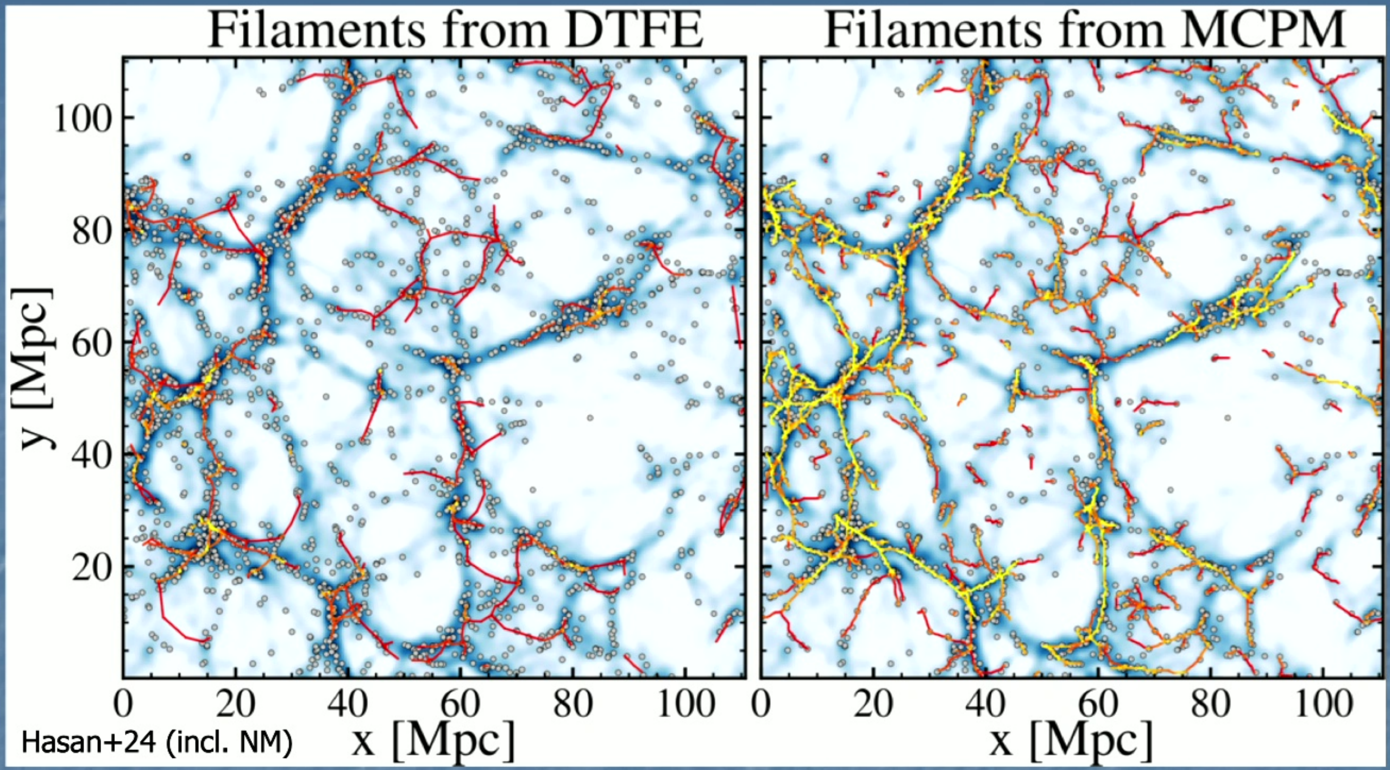
Cosmic Web Detachment



Aragon-Calvo+19

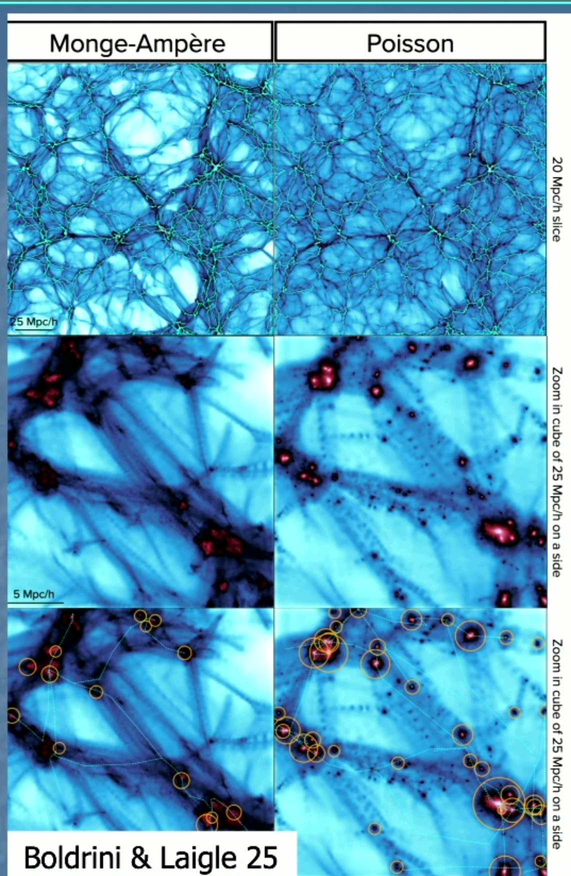
See also "Cosmic web quenching" (Benitez-Llambay+13; Pasha, NM+23; Herzog+23)

Measuring Connectivity in Galaxy Surveys

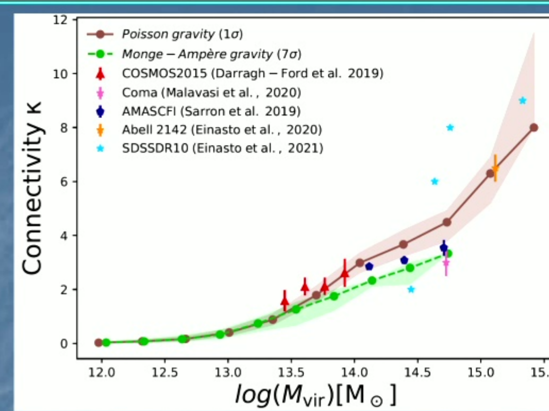


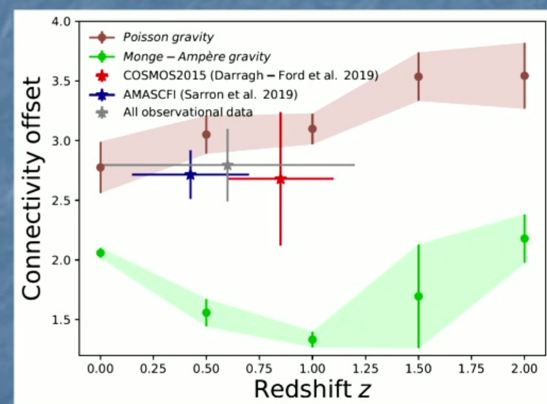
DISPERSE (Sousbie+11) plus Monte-Carlo Physarum Machine (MCPM, aka Slime-Mold – Burchett+20, Hasan+24)
Currently being applied to SDSS (Hassan+ in prep)

Halo Connectivity as Probe of Cosmology



Boldrini & Laigle 25



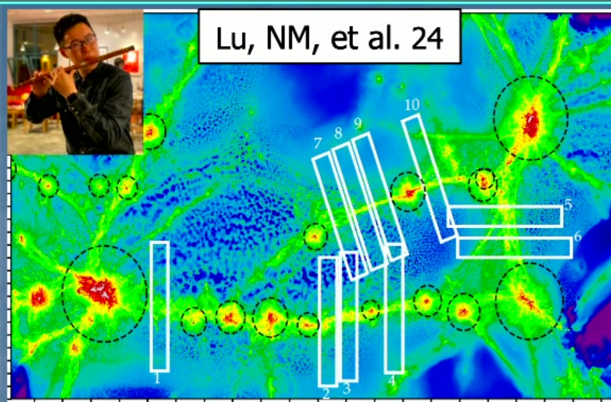


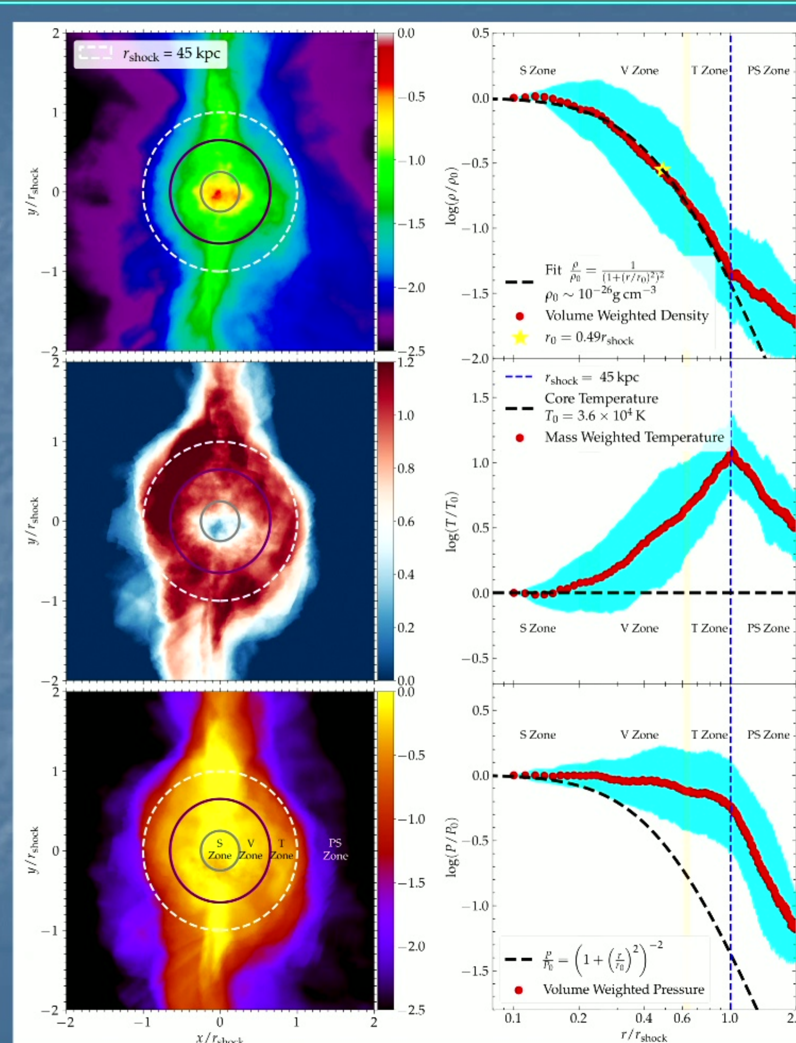
See also Codis+18; Gouin+21

Complications: Cosmic web filament catalogs are not yet very robust, can depend on method (e.g. Libeskind+18) and on tracer used (e.g. Zakharova+23)

Structure and Dynamics of Intergalactic Filaments

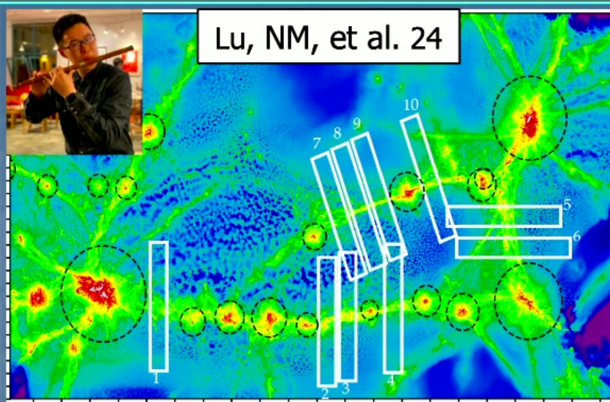
Lu, NM, et al. 24

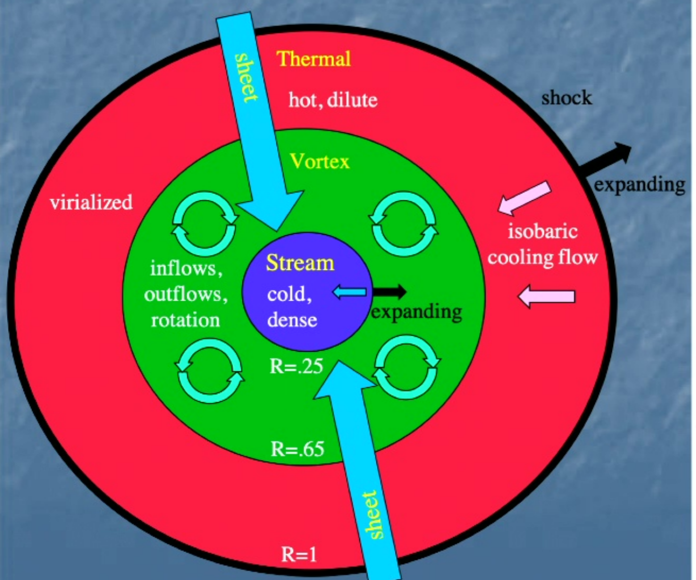




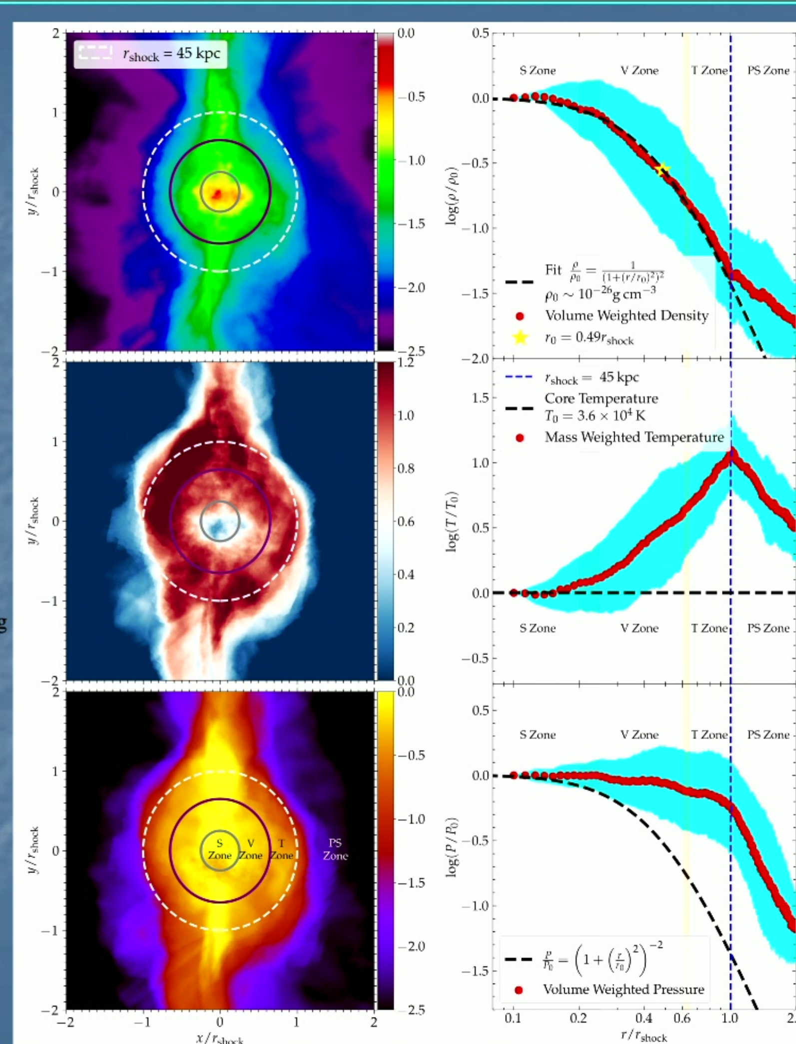
See also Ramsoy+21

Structure and Dynamics of Intergalactic Filaments

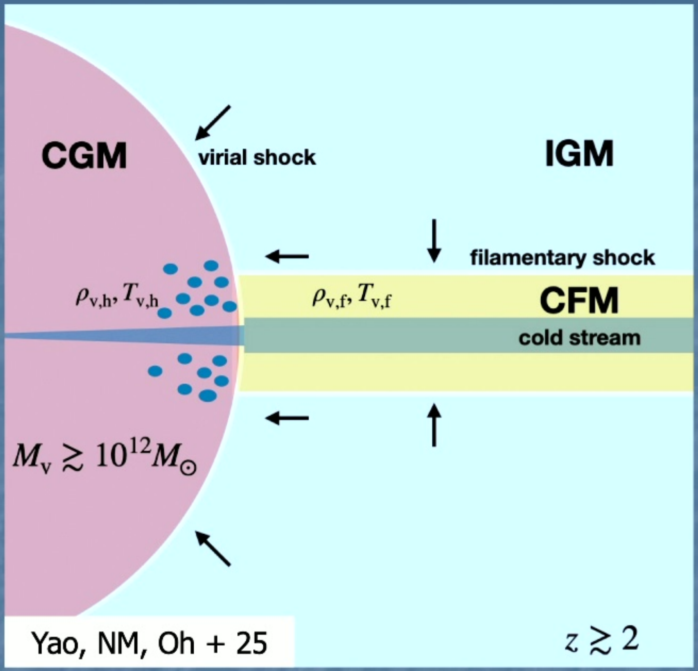


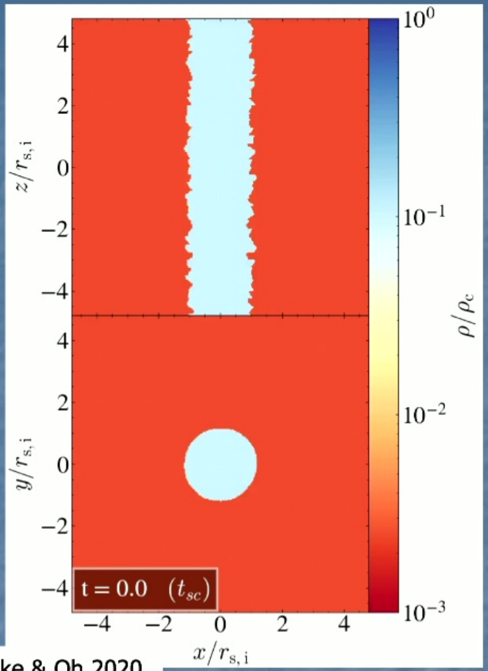


See also Ramsoy+21



How do Filaments/Streams Penetrate Halos?





See also Gronke & Oh 2020

Rapidly under-pressurized streams may **shatter**, down to cloudlets of size $l_{cool} \sim c_s t_{cool}$

This may explain observations of very large-covering fractions with very small volume-filling factor (Cantalupo+2019; Pezzulli & Cantalupo 2019), and prevent stream accretion onto galaxies

$$\frac{P_{CGM}}{P_{CFM}} \sim \frac{P_{vir,halo}}{P_{vir,Fil}} \simeq 10 \left(\frac{M_{vir}}{10^{12} M_\odot}\right)^{-0.1} \left(\frac{1+z}{3}\right)^{-1} \left(\frac{\Delta_{v,h}}{10\Delta_{v,f}}\right)\left(\frac{f_s}{1/3}\right)\left(\frac{V_{vir}}{V_s}\right)$$

Fundamental Questions

Does a transition in the accretion mode drive the decline of the quenching mass during cosmic noon, and thus the evolution of the cosmic SFR density?

What drives the transition in accretion mode?

- Change in how dark matter halos connect to the cosmic web? (Aragon-Calvo 2019)
- Do cosmic web filaments no longer harbor cold streams? (Lu, NM, Oh+2024; Aung, NM+2024)
- Do cold streams shatter when they penetrate the CGM of massive halos? (Yao, NM, Oh+2024)
- Are cold streams disrupted by instabilities in the CGM?

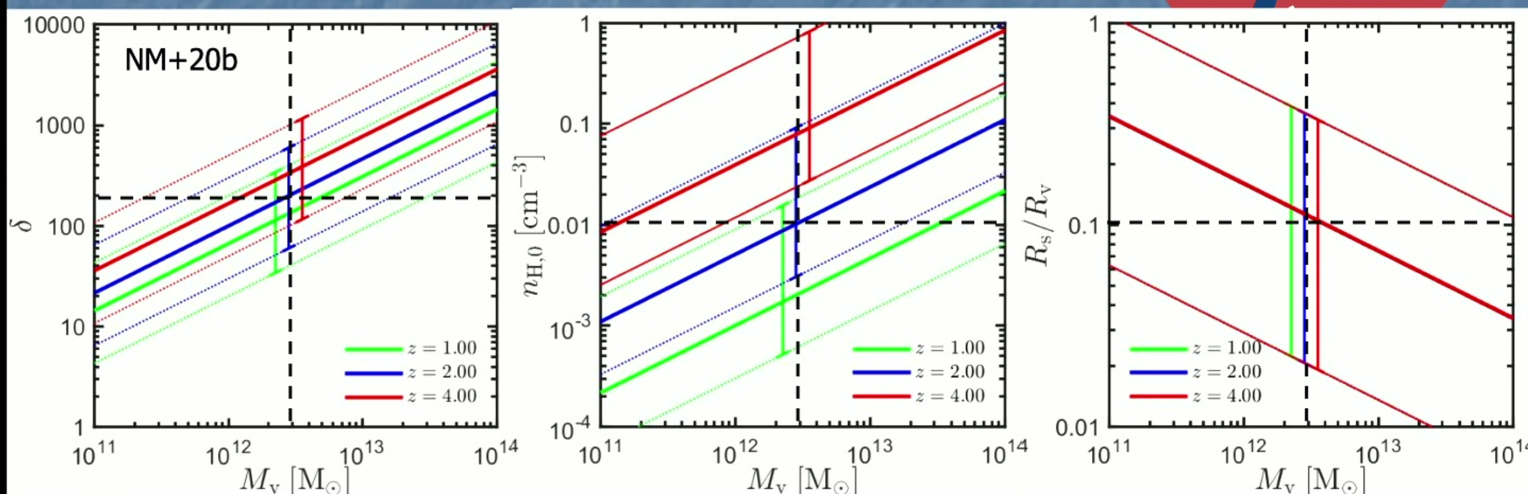
Stream Properties: A Toy Model

* $V_{vir}^2 = GM_{vir}/R_{vir}$, $c_{hot}^2 \sim k_B T_{vir}/\mu m_p$

DN1 $= M_b \sim \frac{V_{vir}}{c_{hot}} \sim 0.5 - 2$

DN2 $= \delta = \frac{\rho_s}{\rho_b}$

DN3 $= \frac{R_s}{R_V} \sim \frac{t_{sc}}{t_V}$



$T_h \sim T_{vir}$ $T_s \sim 10^4$ Pressure equilibrium	δ Halo density at R_{vir} Hot gas mass fraction	n_s $V_s \sim V_{vir}$ $\dot{M}_{vir} \propto M_{vir}(1+z)^{2.5}$ (cosmology) Fraction of accretion along stream

$M_V = 10^{12.5}$ @ $z = 2$ | $\delta \sim 200$ | $n_s \sim 0.01$ cm^{-3} | $R_s/R_V \sim 0.1$

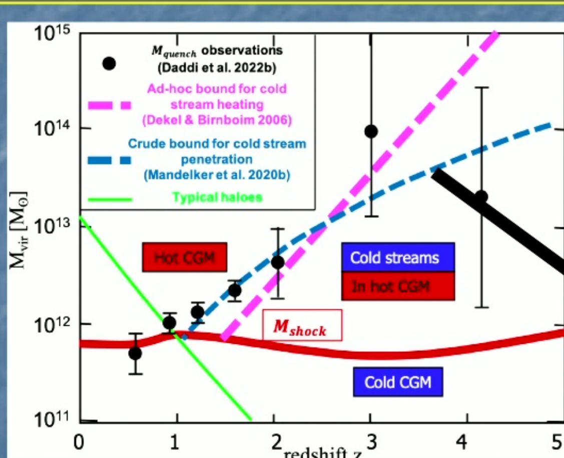
Kelvin Helmholtz Instability with Cooling

Importance of cooling in non linear evolution depends on ratio of cooling time in mixing region, $t_{cool,mix}$, to non-radiative shear layer growth time, t_{shear}

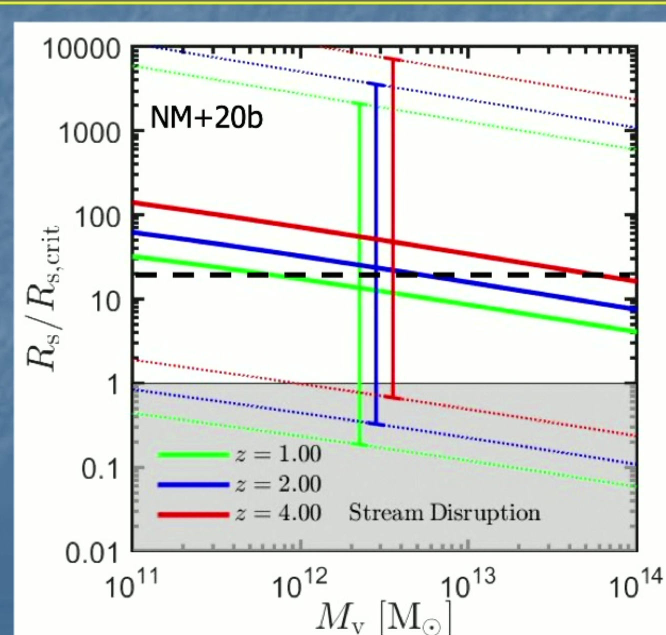
See also: Gronke & Oh 2018,2020; Ji+ 2019; Fielding+ 2020; Sparre+ 2020; Kanjilal+ 2020; …

<u>Additional dimensionless number:</u> **DN4** $= \tau \equiv \frac{t_{shear}}{t_{cool,mix}} = \frac{R_s}{R_{s,crit}}$

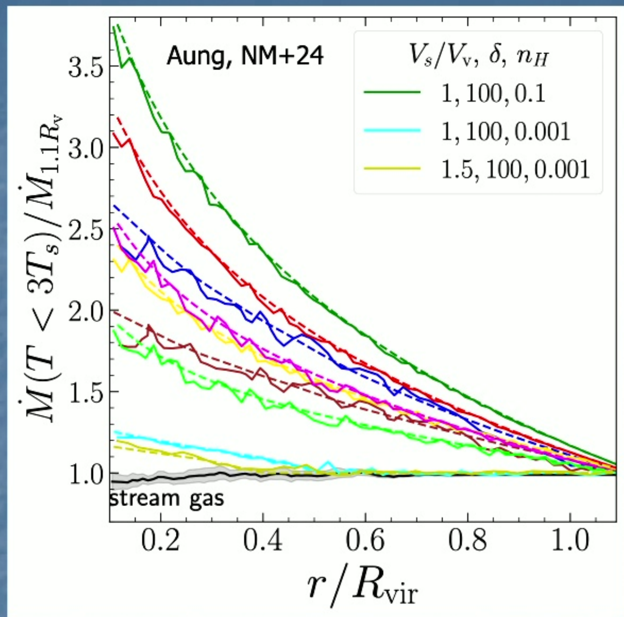
Cooling important for $R_s > R_{s,crit} \simeq 0.3\text{kpc}\, \alpha_{0.1} \delta_{100}^{1.5} M_b \frac{T_{s,4}}{n_{s,0.01} \Lambda_{\text{mix},-22.5}}$

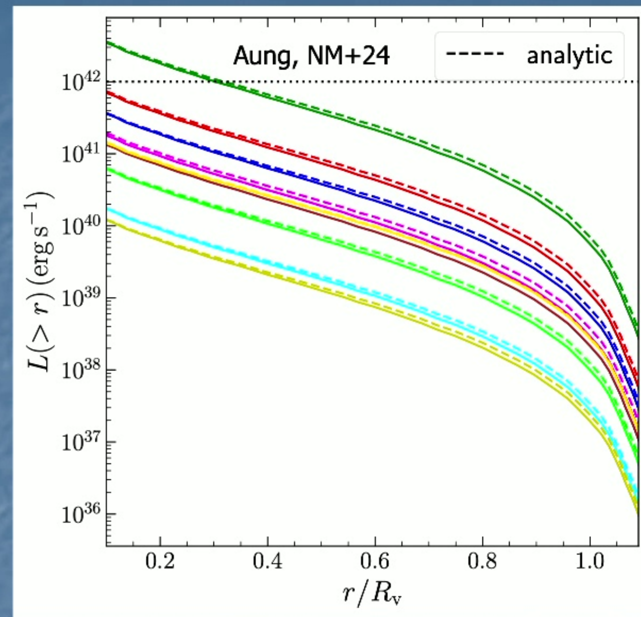


$\frac{R_s}{R_{s,crit}} \leq 20$



Streams in Halo Potential



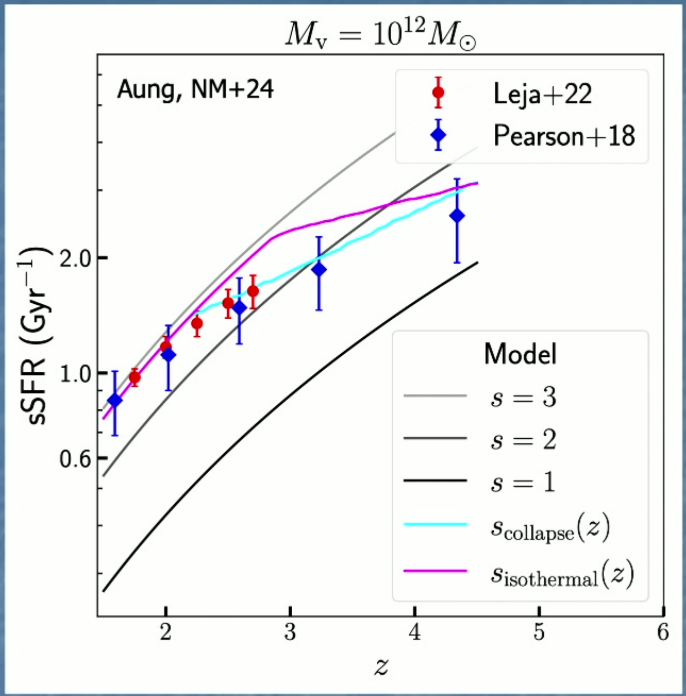


Solid lines – simulations (w/ different stream parameters)
Dashed lines – analytic model

Simulations of streams in NFW halo, $M_{vir} = 10^{12} M_{\odot}$, $z = 2$

- Cold gas inflow rates onto galaxies increase by a factor of ~ 3 due to entrainment (Implications for galaxy star-formation rates)
- Dissipation leads to total $Ly\alpha$ emission of $L_{Ly\alpha} \sim (0.3 - 3)\times 10^{42} \mathrm{erg\,s^{-1}}$

Mass Entrainment and Galaxy sSFR (SFR/M_*)

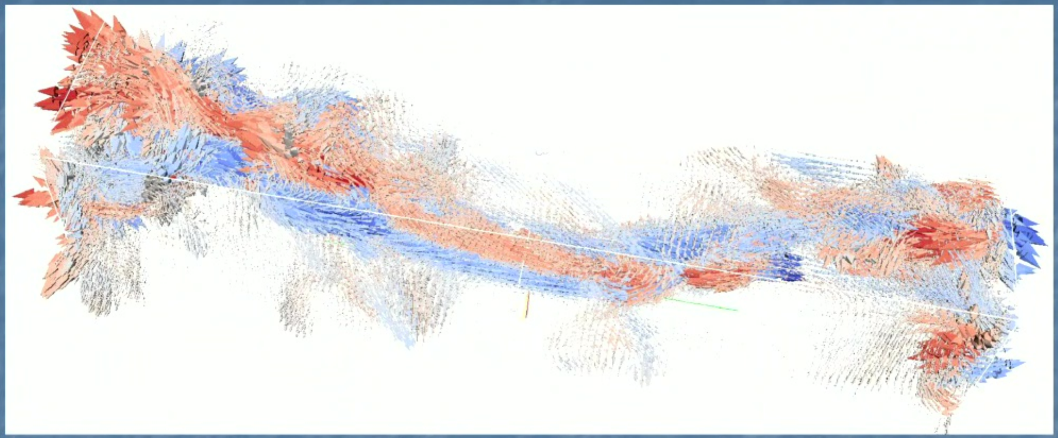


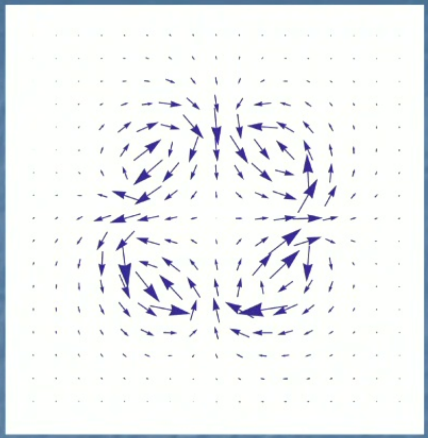
Bathtub model following Dekel & NM 2014 (SFR follows accretion to 1st order)

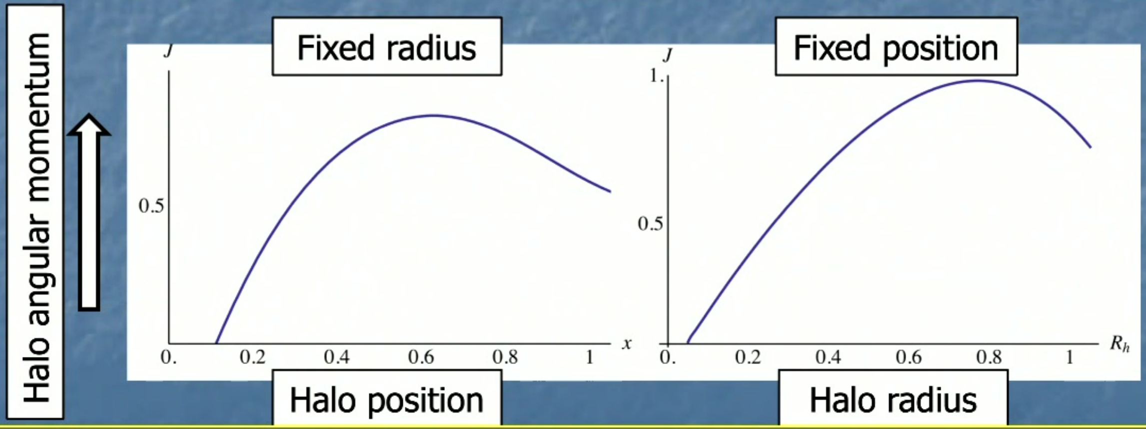
- Without entrainment ($s = 1$), sSFR under-predicted by $\sim$ x3
- Entrainment model $s(z)$ matches observations well (hot/cold fractions in streams/halos)
- Accounts for hot gas fraction in CGM and cold gas fraction in cosmic web filament

Angular Momentum Buildup by Filament Vorticity

Pichon+ 11; Codis+ 12, 15; Laigle+ 15; Stewart+ 11, 13; Song+21; Lu, NM+24; Wang+25



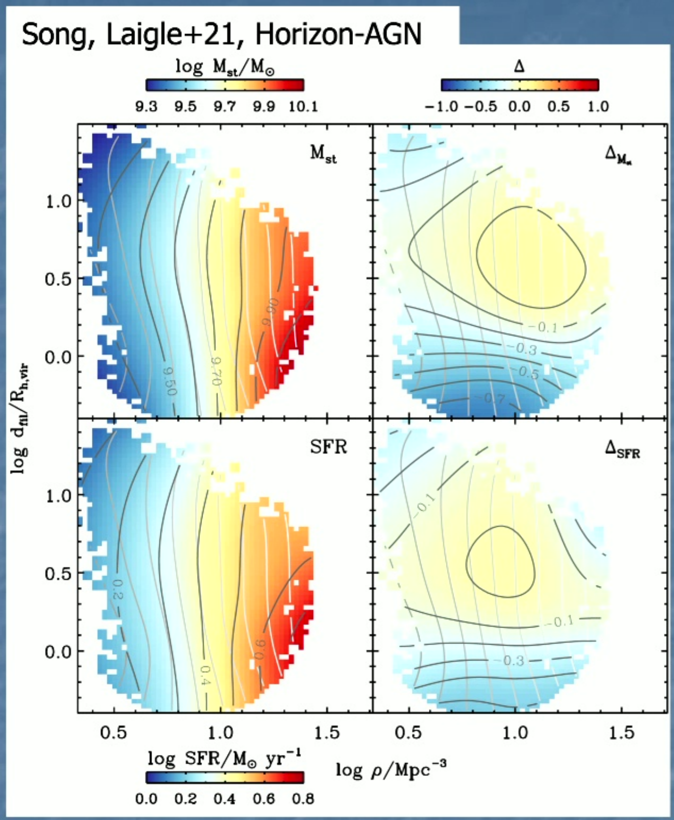


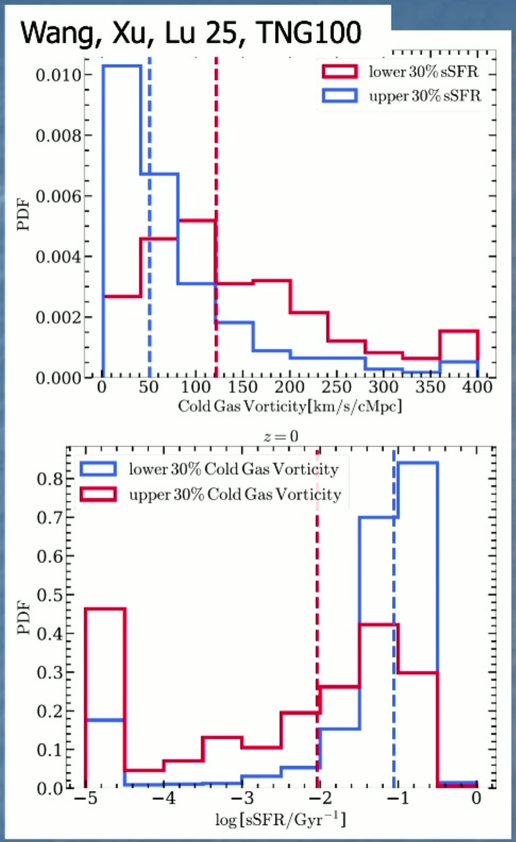


Single quadrant → High halo spin

Multiple quadrants → Low halo spin

Quenching by High Filament Vorticity





Galaxies near filament outskirts live in high vorticity environment → Gas has high specific angular momentum → Less accretion onto galaxy → Lower SFR

Turbulence driving in High-z Disks

Ginzburg, Dekel, NM, Krumholz 2022

High-z disks are highly turbulent, $V/\sigma \sim (1-3)$

What are potential drivers of turbulence?

Build an analytic model for turbulence driving by three sources simultaneously

What is the dominant driver as a function of mass and redshift?

SN Feedback

Radial transport by disk instabilities

Assume the disk self-regulates to Toomre Q parameter $Q \sim \frac{\sigma\Omega}{G\Sigma} \sim 1$

Transport: Dekel+ 2009b; Krumholz & Burkert 2010; Cacciato+ 2012

SN feedback: Faucher-Giguere+ 2013; Hayward & Hopkins 2017

Transport+SN feedback: Krumholz+ 2018

General Conclusions: Transport dominates at high mass and high-z, Feedback dominates at low mass and low-z

Cosmological accretion

Dekel+ 2009b; Elmegreen & Burkert 2010; Genel+ 2012; Hopkins+ 2013

Studies do not agree on efficiency of accretion in driving turbulence!

Main Takeaway

Cosmic web filaments and cold streams supply galaxy disks with:

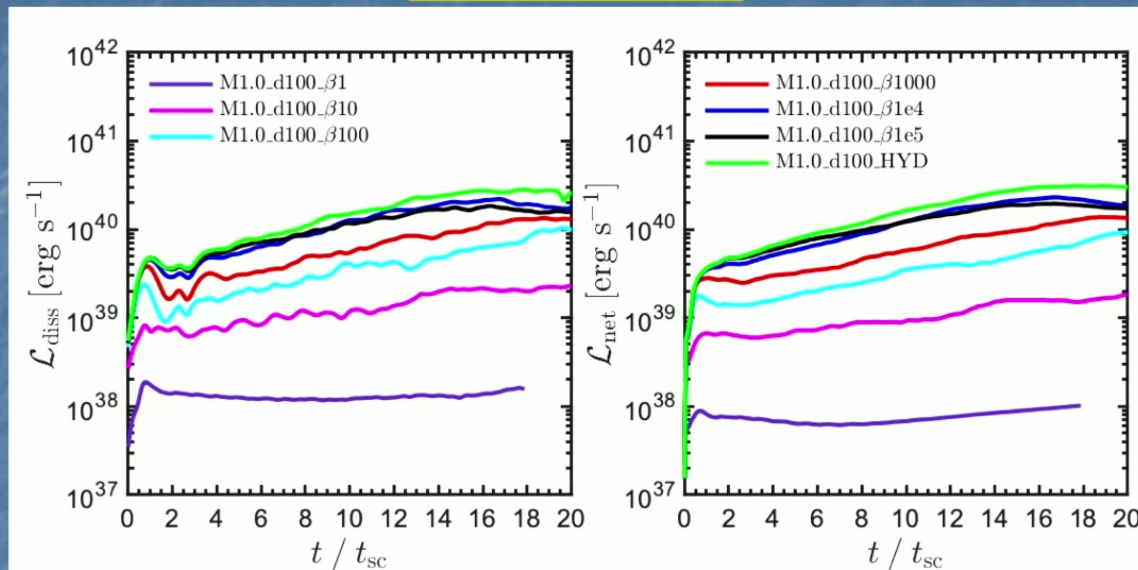
1. Mass → fuel for star-formation
2. Angular momentum → Disk growth, planes of satellites, quenching
3. Turbulence

The details depend sensitively on the thermal, kinematic, and morphological properties of streams as they reach the disk

These are still open issues of ongoing study

$Ly\alpha$ Emission

$M_b = 1.0, \delta = 100$



- MHD suppresses emitted luminosity – magnetic energy amplified
- What about $Ly\alpha$ blobs?
- Very similar to hydro result for initial $\beta > 1000$
- Even better convergence for $M_b = 2.0$