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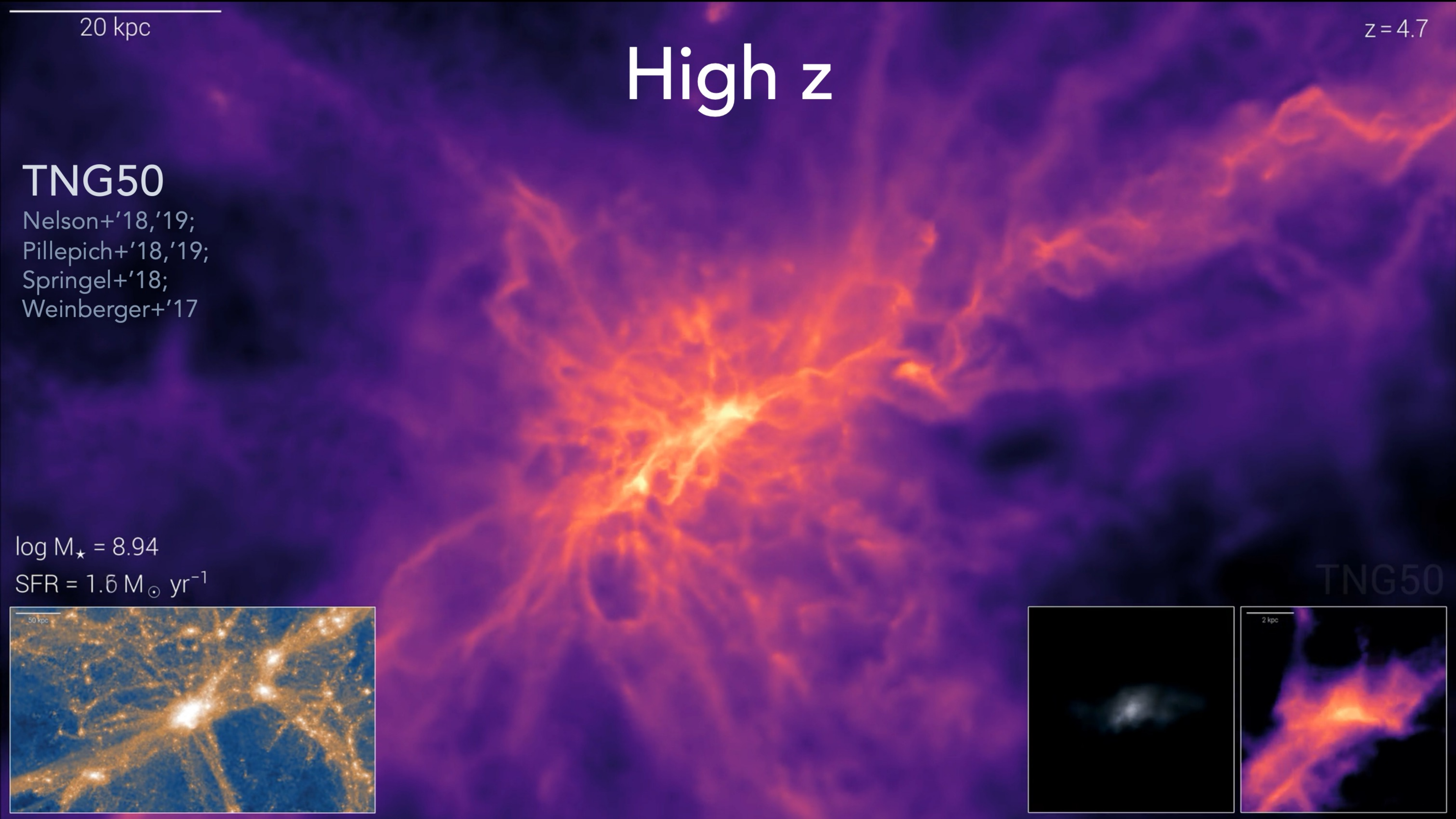
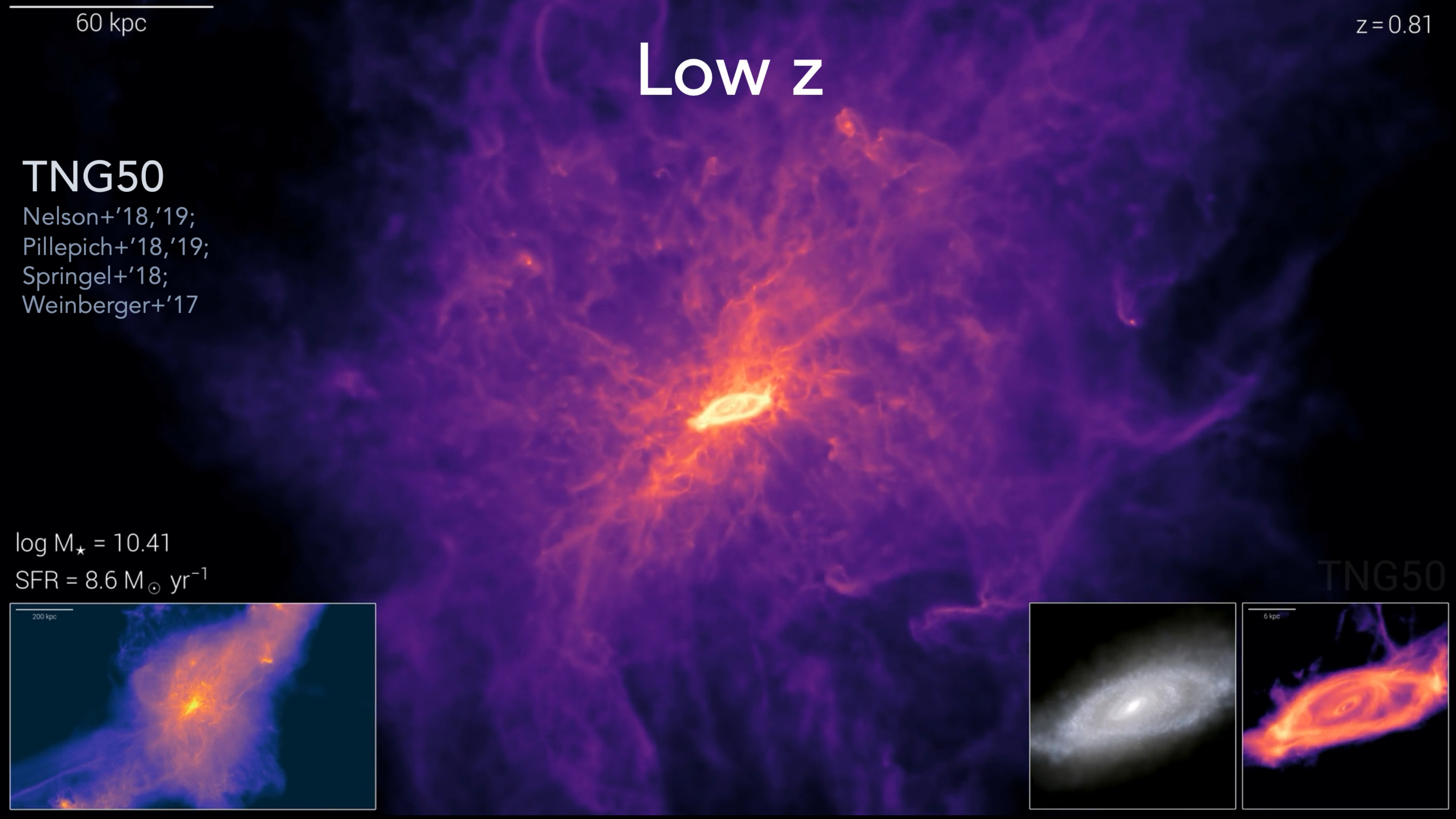
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Feedback at “low” z: the Role in Shaping Galactic Disks

Vadim Semenov
Harvard University



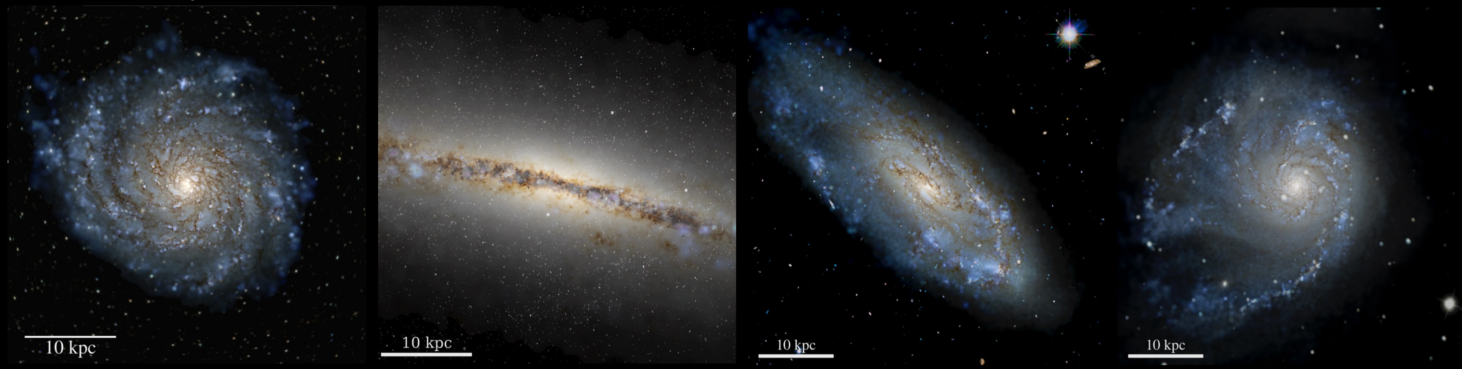
High z
20 kpc
z = 4.7
TNG50
Nelson+'18,'19;
Pillepich+'18,'19;
Springel+'18;
Weinberger+'17
log $M_\star$ = 8.94
SFR = 1.6 $M_\odot$ yr^{-1}
50 kpc
2 kpc
TNG50



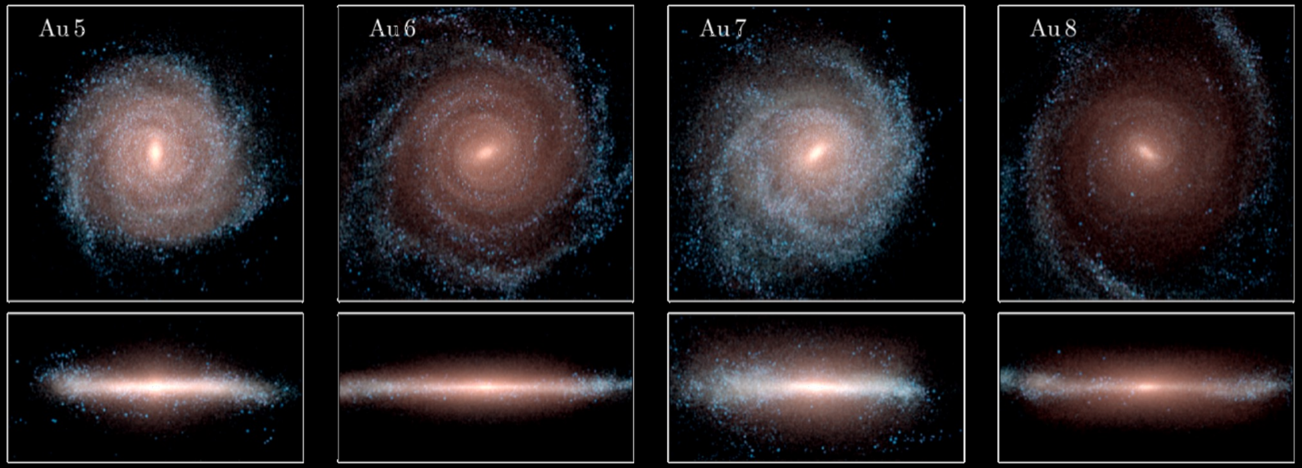
Low z
60 kpc
z = 0.81
TNG50
Nelson+'18,'19;
Pillepich+'18,'19;
Springel+'18;
Weinberger+'17
log $M_\star$ = 10.41
SFR = 8.6 $M_\odot$ yr^{-1}
200 kpc
6 kpc
TNG50

State-of-the-art galaxy simulations produce reasonably realistic disks

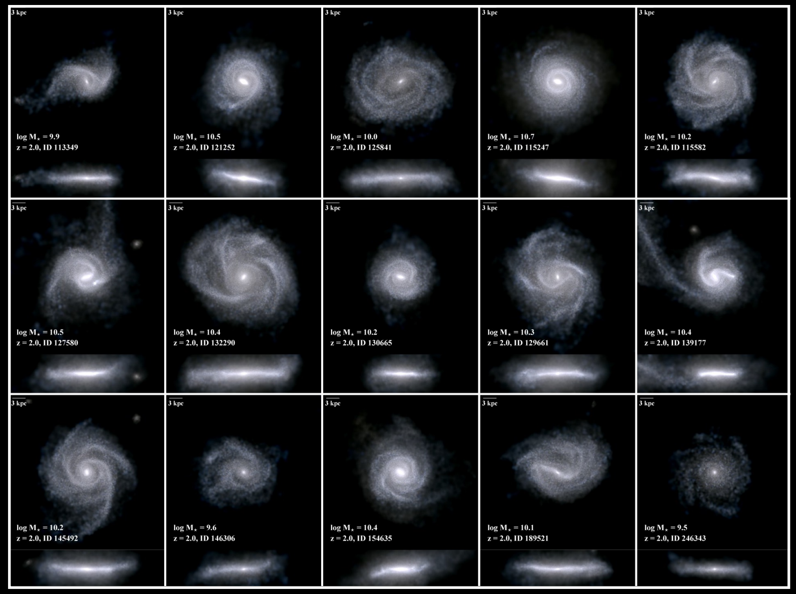
FIRE Hopkins+ '18



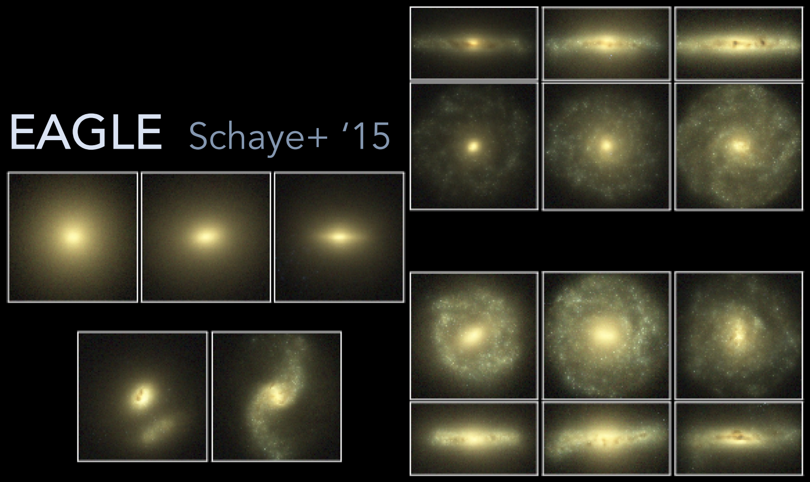
Auriga Grand+ '17, '18



TNG50 Pillepich+ '19



EAGLE Schaye+ '15



Also, e.g., Brook+'12; Bird+'13,'21; Ubler+'14; Agertz & Kravtsov '15,'16; Genel+ '15; Christensen+'16; Kretschmer+'20a,b,'22; Agertz+'21; Renaud+'21a,b; Khoperskov+'22a,b,c

State-of-the-art galaxy simulations produce reasonably realistic disks

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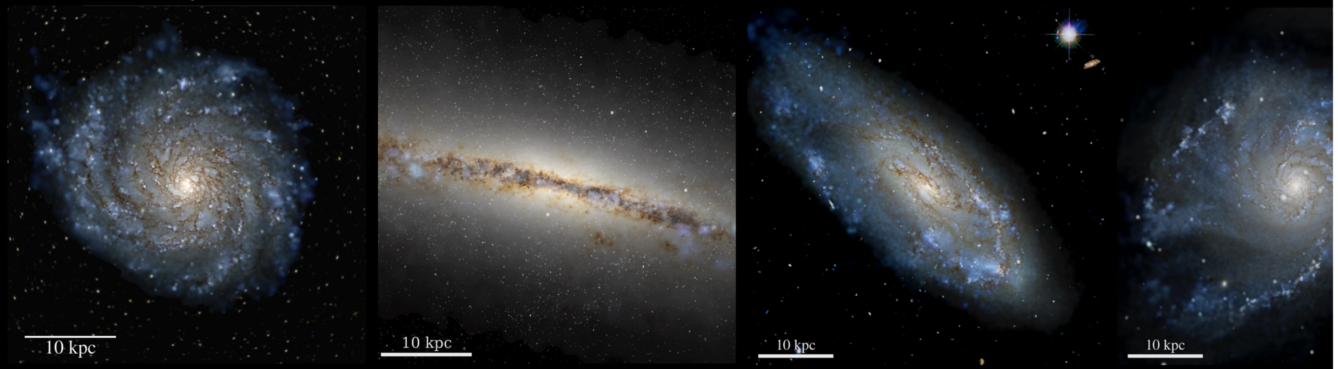
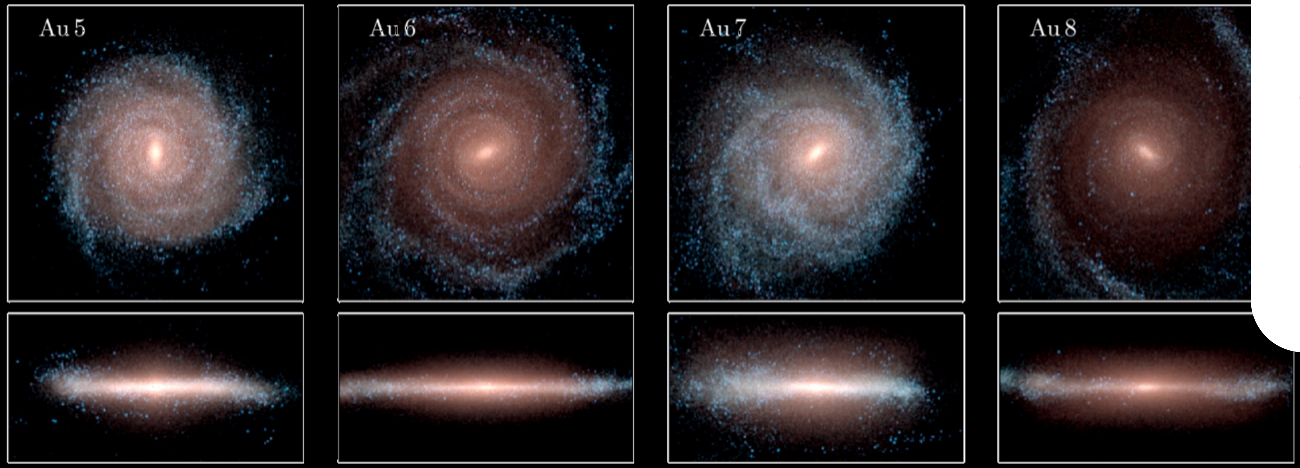
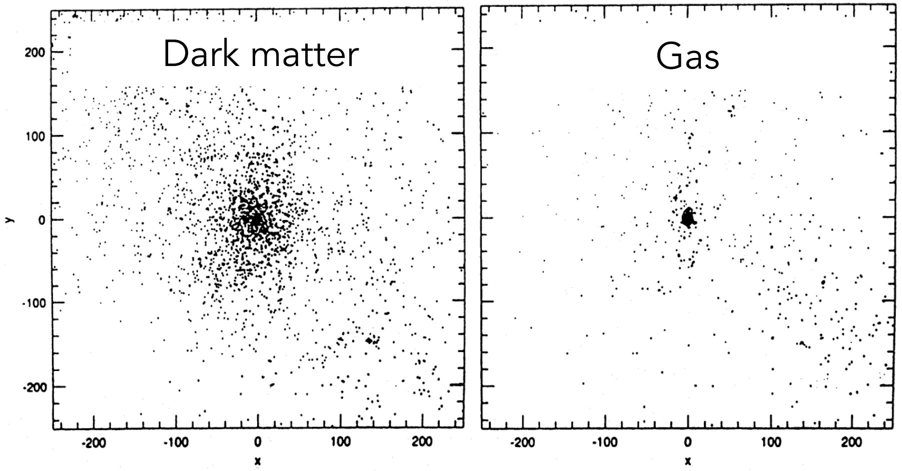


Auriga Grand+ '17, '18



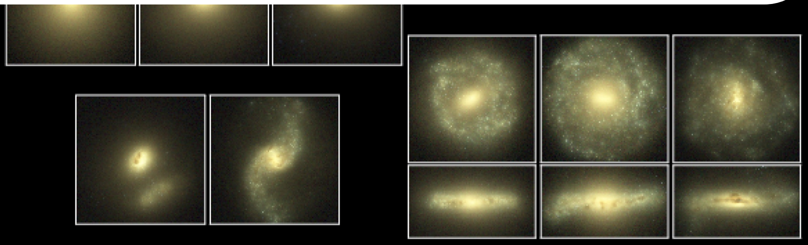
"Angular momentum catastrophe"
in early galaxy simulations



Navarro & White '94

Galactic disks were too massive, compact, and centrally-concentrated

e.g., Navarro & White '94, Navarro+ '95; Navarro & Steinmetz '00



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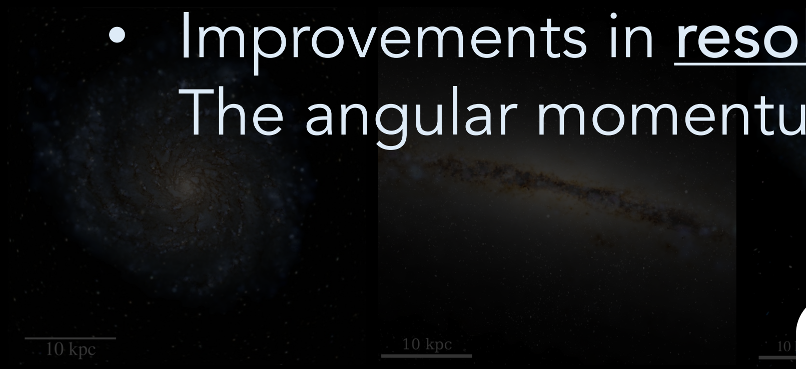
Solutions to the "angular momentum catastrophe"

FIRE Hopkins+ '18

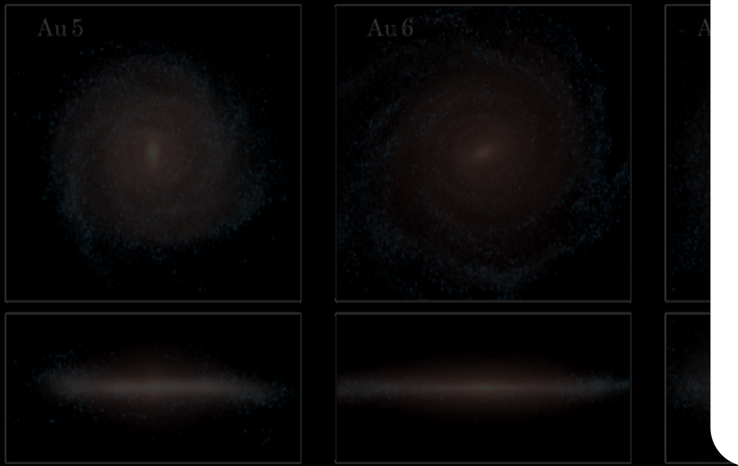


TNG50 Pillepich+ '19

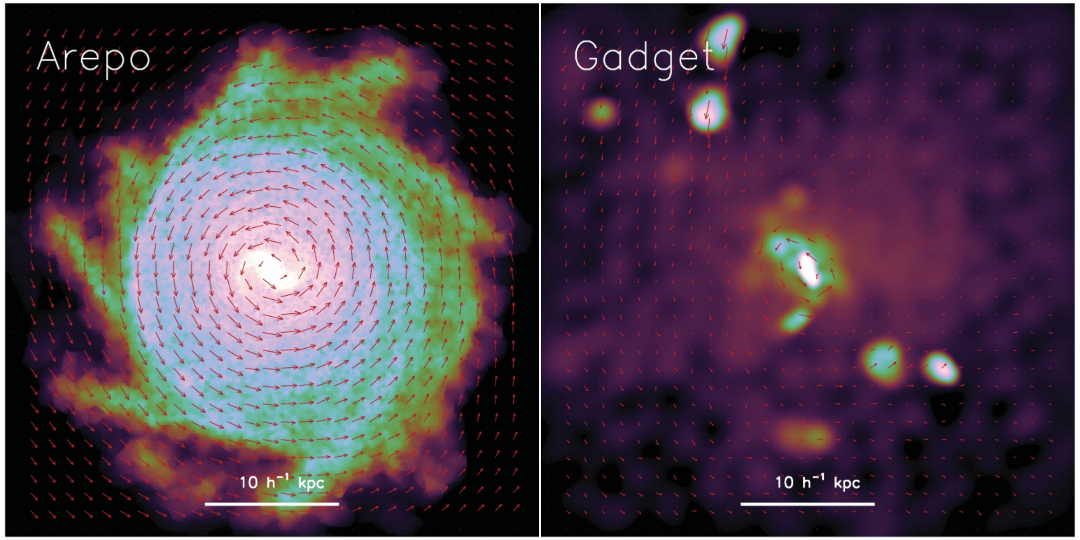
- Improvements in <u>resolution and hydrodynamical methods</u>.
  The angular momentum loss was partially numerical

e.g., Governato+ '04,'07; Torrey+'12; Vogelsberger+'12

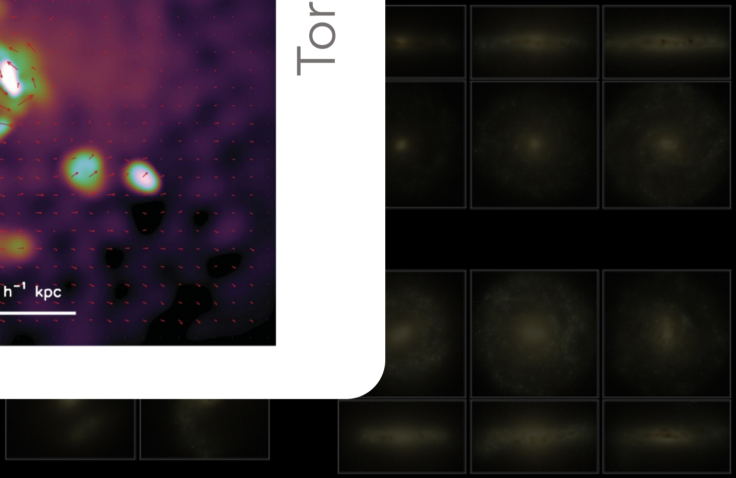
Auriga Grand+ '17, '18



New moving-mesh   Old flavor SPH



Torrey+'12



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Solutions to the "angular momentum catastrophe"

FIRE Hopkins+ '18

TNG50 Pillepich+ '19

- Improvements in <u>resolution and hydrodynamical methods</u>. The angular momentum loss was partially numerical

  e.g., Governato+ '04,'07; Torrey+'12; Vogelsberger+'12

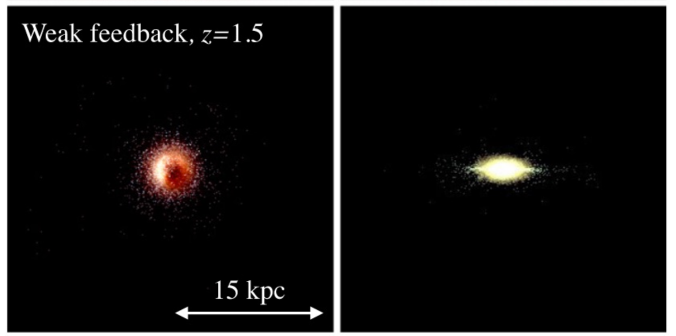
- <u>Efficient star formation feedback</u> is required to form realistic disks

  e.g., Okamoto+'05; Scannapieco+'08; Zavala+'08; Brook+'12; Sales+'12; Ubler+'14; Agertz & Kravtsov '15,'16; Genel+'15; Christensen+'16; DeFelippis+'17

Auriga Grand+ '17, '18

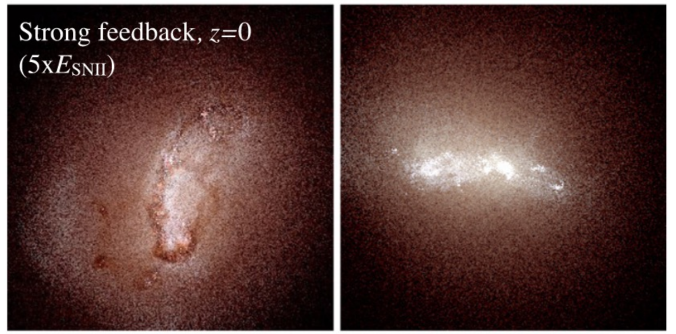
EAGLE Schaye+ '15

When feedback is too weak



When feedback is optimal

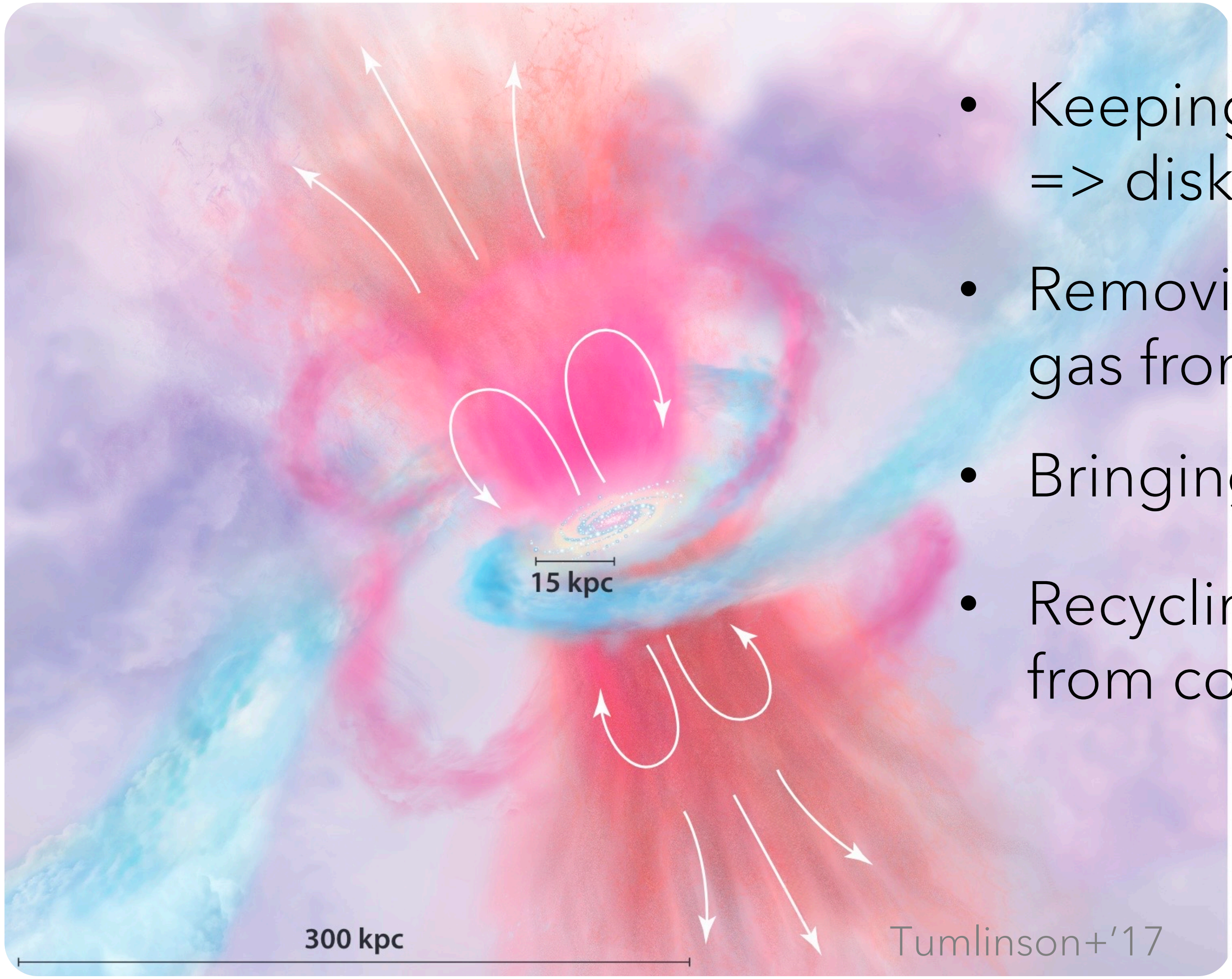
When feedback is too strong



Agertz & Kravtsov '16

Also, e.g., Brook+'12; Bird+'13,'21; Ubler+'14; Agertz & Kravtsov '15,'16; Genel+ '15; Christensen+'16; Kretschmer+'20a,b,'22; Agertz+'21; Renaud+'21a,b; Khoperskov+'22a,b,c

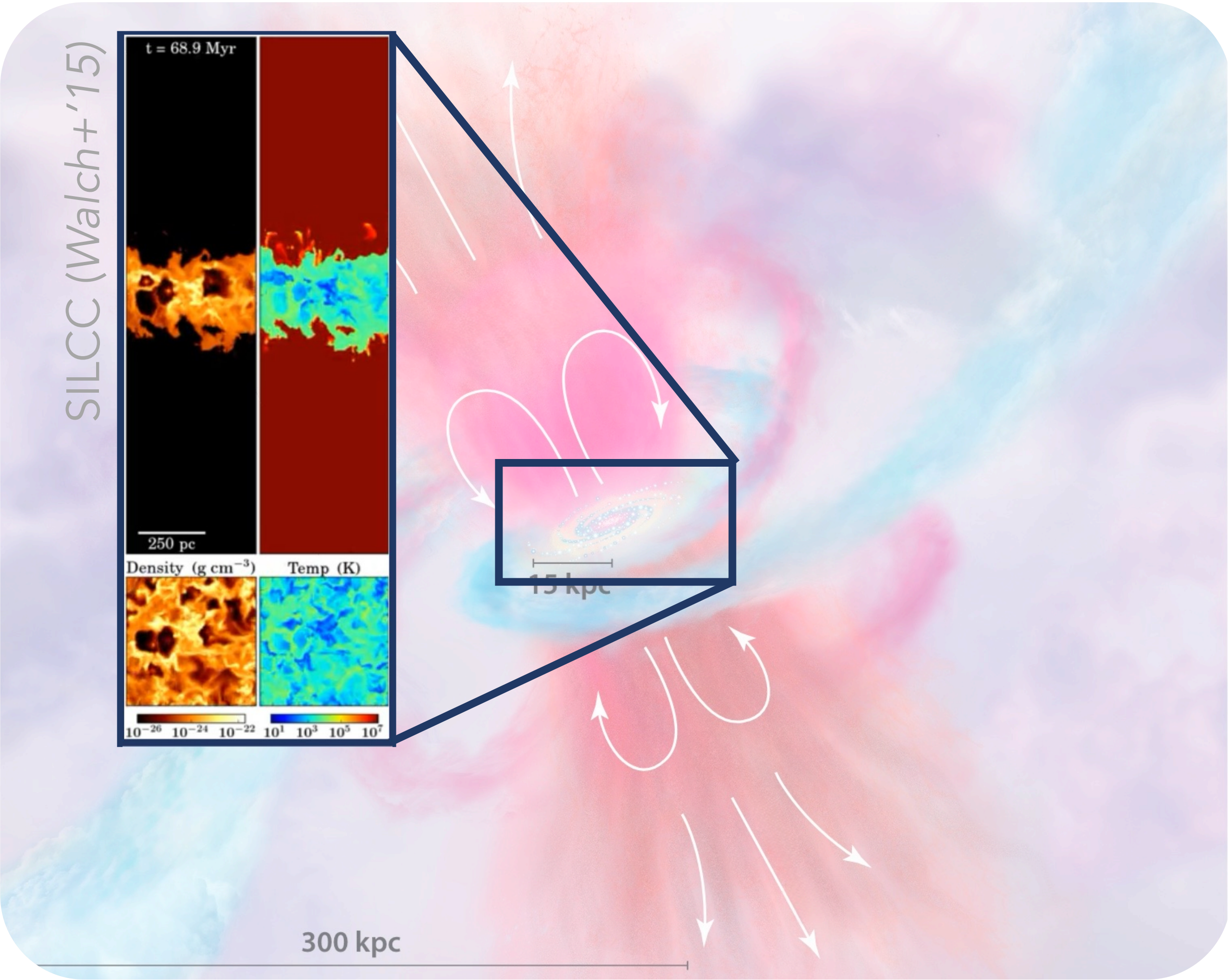
The multifaceted role of feedback in disk evolution



- Keeping gas in the halo => disk fraction low => disk stability
- Removing low-angular-momentum (AM) gas from the center
- Bringing-in high-AM gas from the halo outskirts
- Recycling of pre-aligned AM from co-rotating outflows

Efstathiou+'82; Mo+'98; Okamoto+'05; Zavala+'08; Brook+'12; Sales+'12; Ubler+'14; Agertz & Kravtsov '15, '16; Genel+ '15; Christensen+'16; DeFelippis+'17; Fraternali '17; Semenov+'24b

The multifaceted role of feedback in disk evolution



- Providing vertical support (ISM turbulence; cosmic rays)

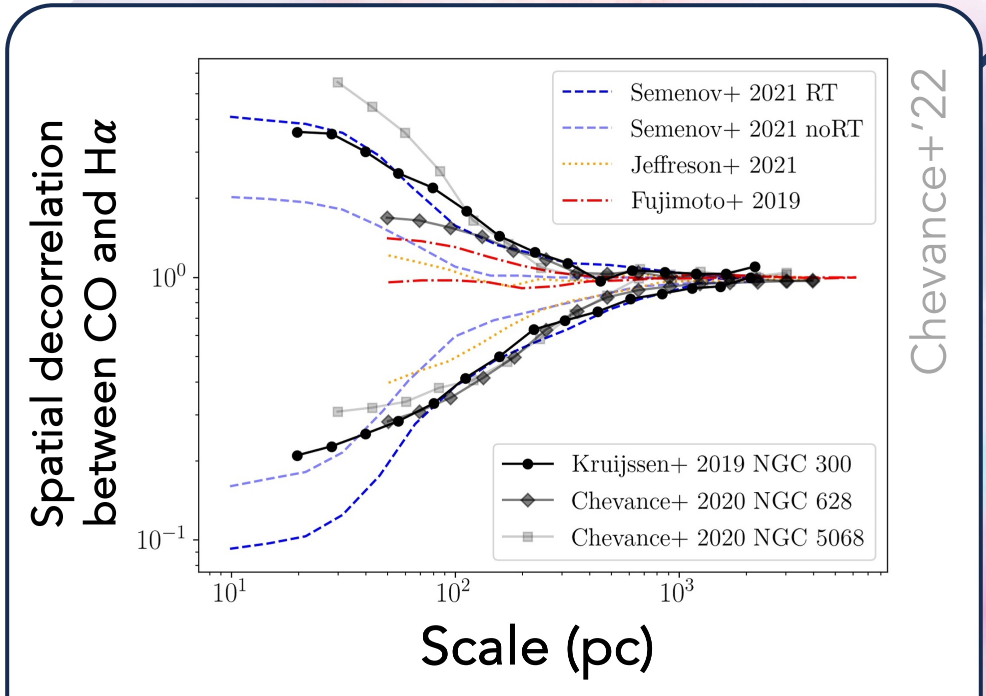
Dynamical equilibrium in marginally stable disks (Toomre Q ~ 1)

SFR ↑ ⇒ FB drives more turbulence ⇒ disk puffs up ⇒ gas density ↓ ⇒ SFR ↓

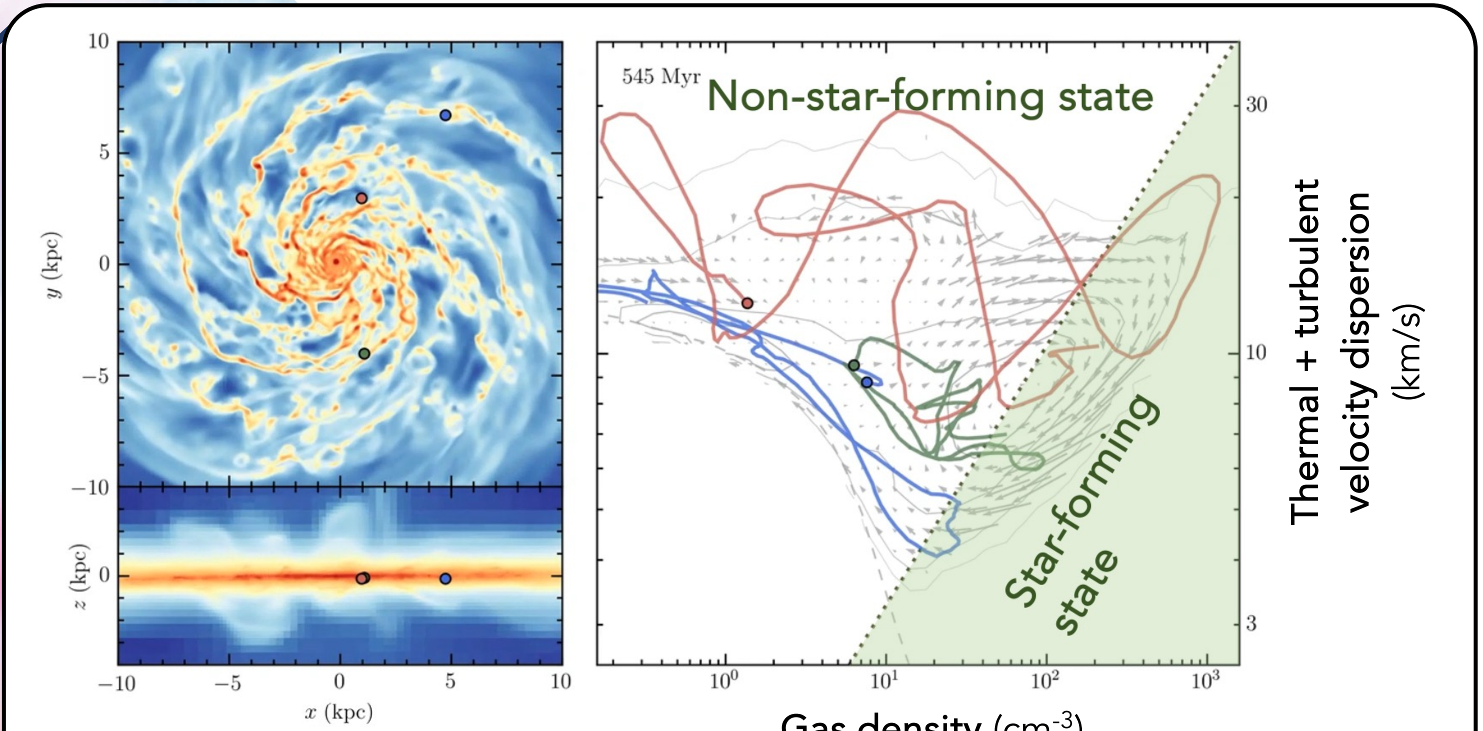
Vertical weight ~ $P_{turb} \propto \Sigma_{SFR}$

e.g., Ostriker & Shetty'11; Faucher-Giguère+'13; Benincasa+'16; Hayward & Hopkins '17; Ostriker & Kim '22

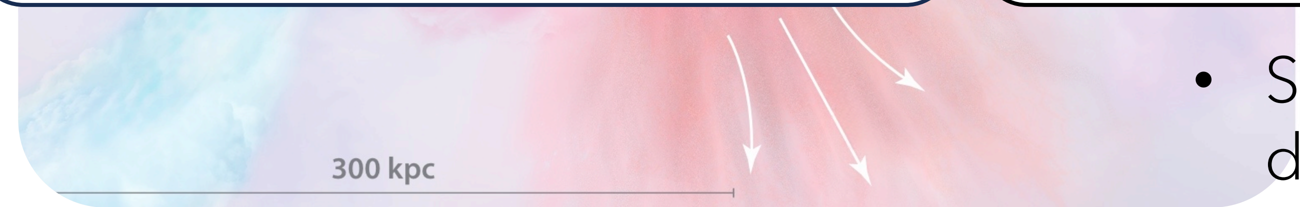
The multifaceted role of feedback in disk evolution



See also Schruba+'10; Kruijssen+'14,'18,'19; Chevance+'20; Kim+'22; Ramambason+'25



Semenov+'17,'18



- Setting SFR and depletion times via dispersal of SF gas on small scales

e.g., Madore'10; Schruba+'10; Kruijssen+'14,'18,'19; Elmegreen'15,'18; Semenov+'17,'18,'21; Chevance+'20, Kim+'22; Jeffreson+'24; Ramambason+'25

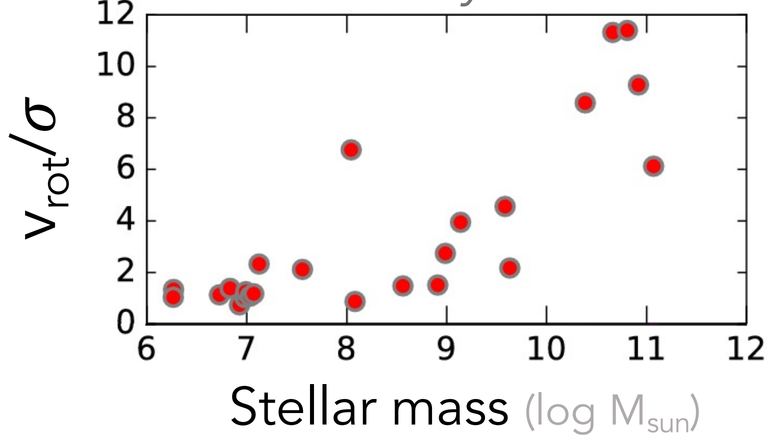
The multifaceted role of feedback in disk evolution

Disk evolution

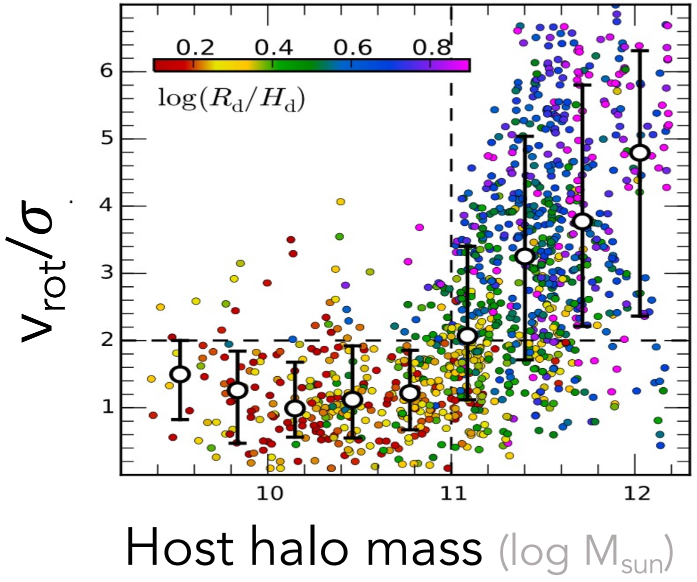
- Keeping disk fraction low
- Removing low-AM gas
- Bringing-in high-AM gas
- Recycling of co-rotating outflows
- Providing vertical support
- Setting SFR and depletion times via dispersal of SF gas on small scales

When do disks form?

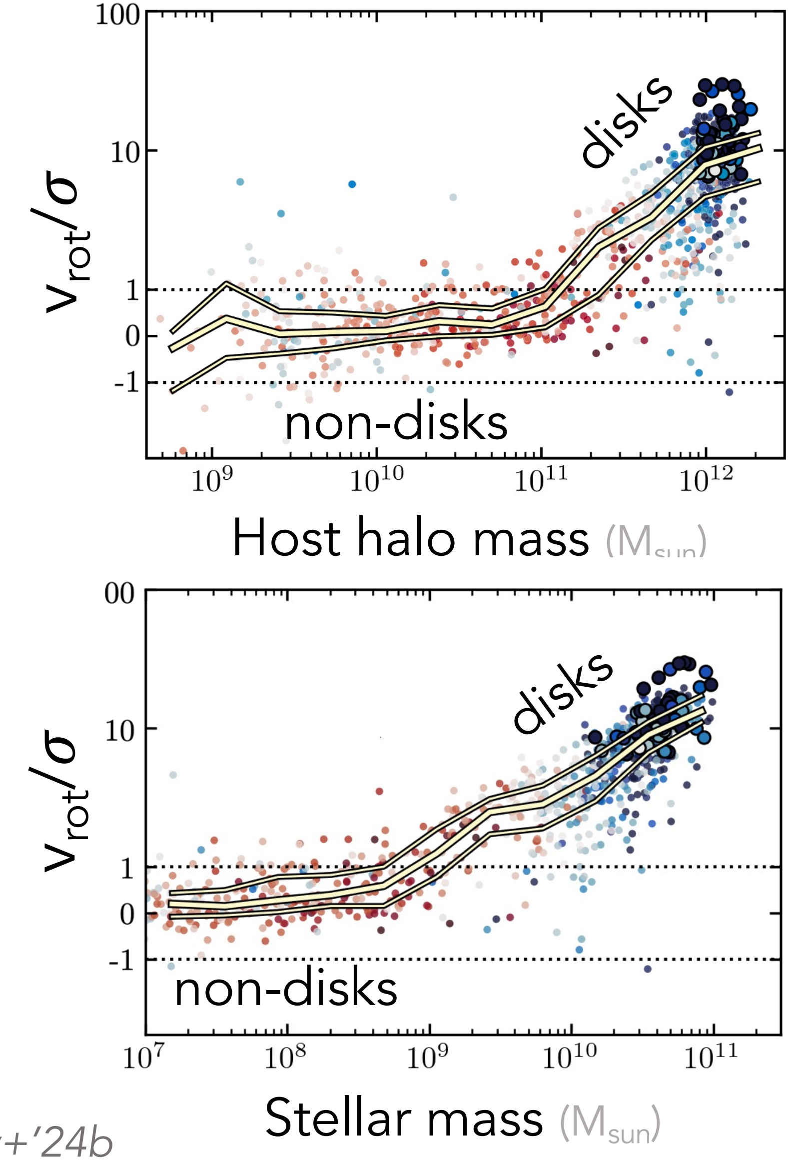
FIRE *El-Badry+'18*



VELA *Dekel+'20*



TNG50 *Semenov+'24b*



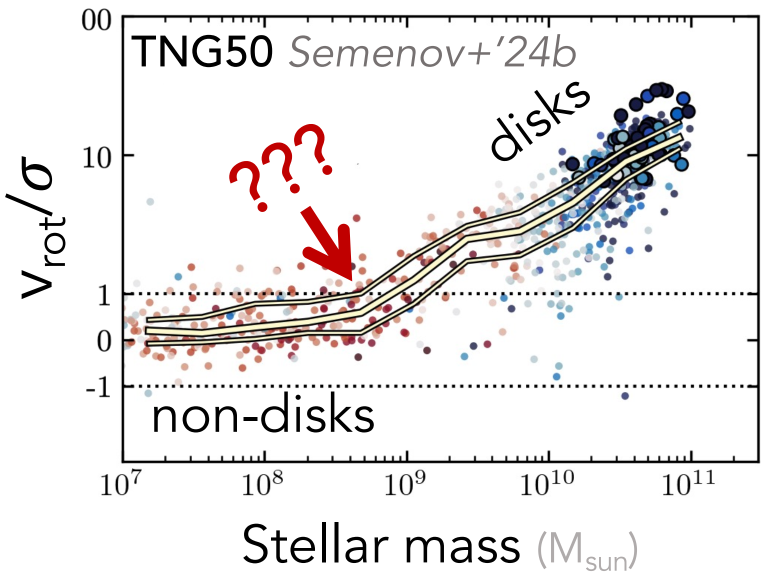
Mass threshold for disk formation:

$M_* \sim 10^9\ M_{sun}$ or $M_{vir} \sim 10^{11}\ M_{sun}$

Feng+'15; El-Badry+'18; Pillepich+'19; Trayford+'19; Dekel+'20; Dubois+'21; Semenov+'24b

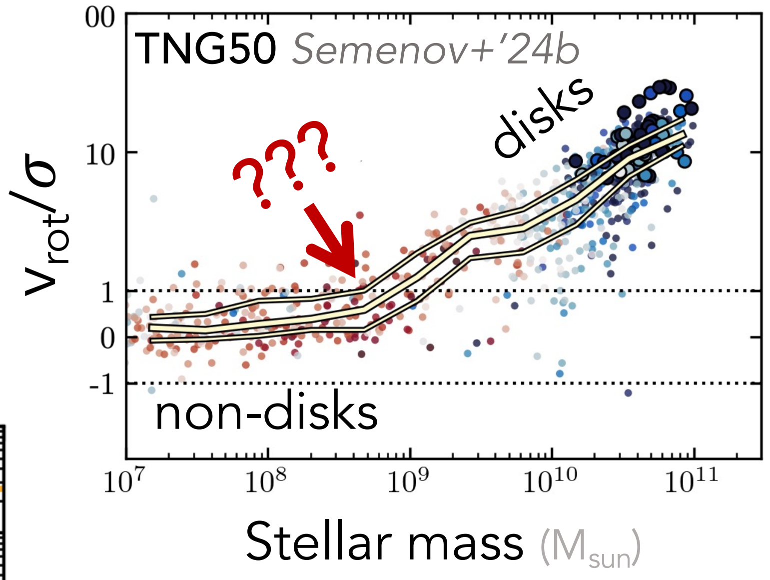
The role of feedback in disk formation

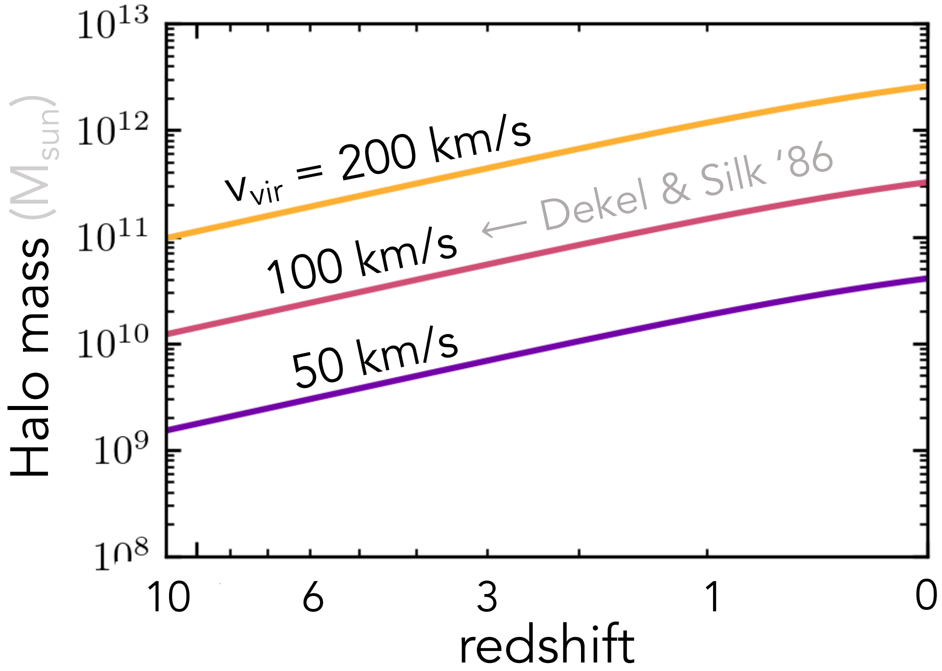
- Limiting the early galaxy growth =>
  setting the time when M_* reaches $\sim 10^9\ M_{sun}$



The role of feedback in disk formation

- Limiting the early galaxy growth => setting the time when M_* reaches $\sim 10^9$ M_{sun}
- Stirring up and expelling gas before it settles





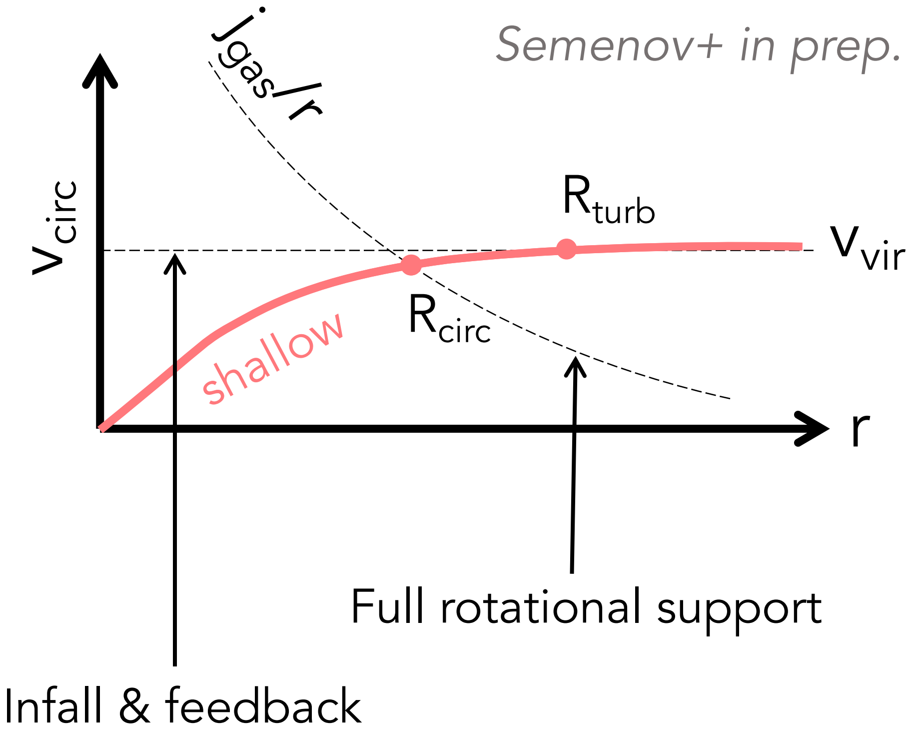
e.g., Dekel & Silk '86; Read+'06; Kaufmann+'07; Dalcanton & Stilp '10

FIRE simulations: http://www.tapir.caltech.edu/~sheagk/firemovies.html

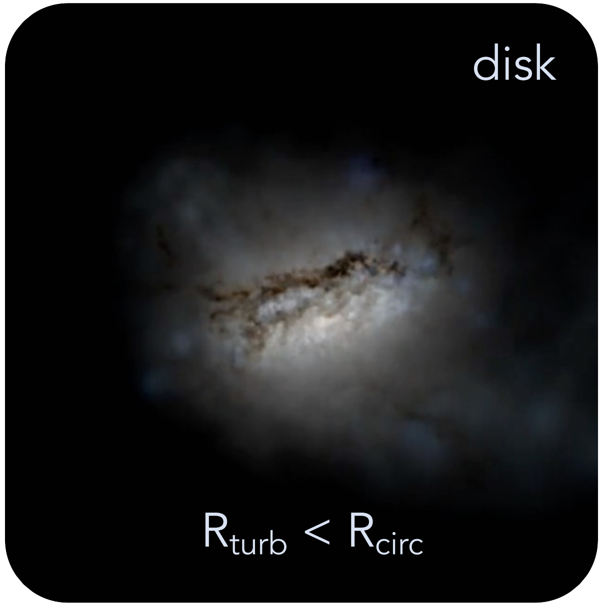
The role of feedback in disk formation

- Limiting the early galaxy growth => setting the time when M_* reaches $\sim 10^9\ M_{sun}$
- Stirring up and expelling gas before it settles

Semenov+ in prep.



R_{turb}

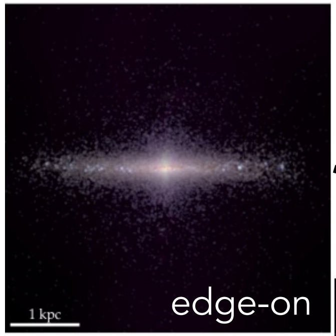


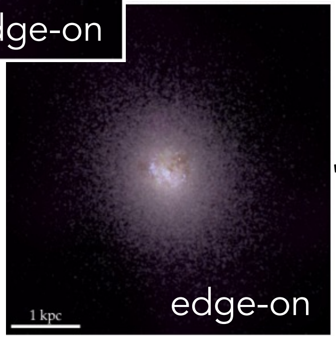
R_{circ}

FIRE simulations: http://www.tapir.caltech.edu/~sheagk/firemovies.html

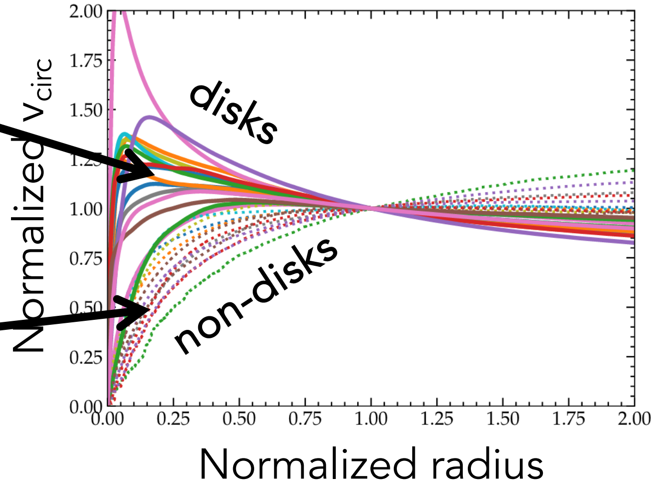
The role of feedback in disk formation

- Limiting the early galaxy growth =>
  setting the time when M_* reaches ~10^9 M_{sun}
- Stirring up and expelling gas before it settles
- Shaping the inner gravitational potential





Hopkins+'23



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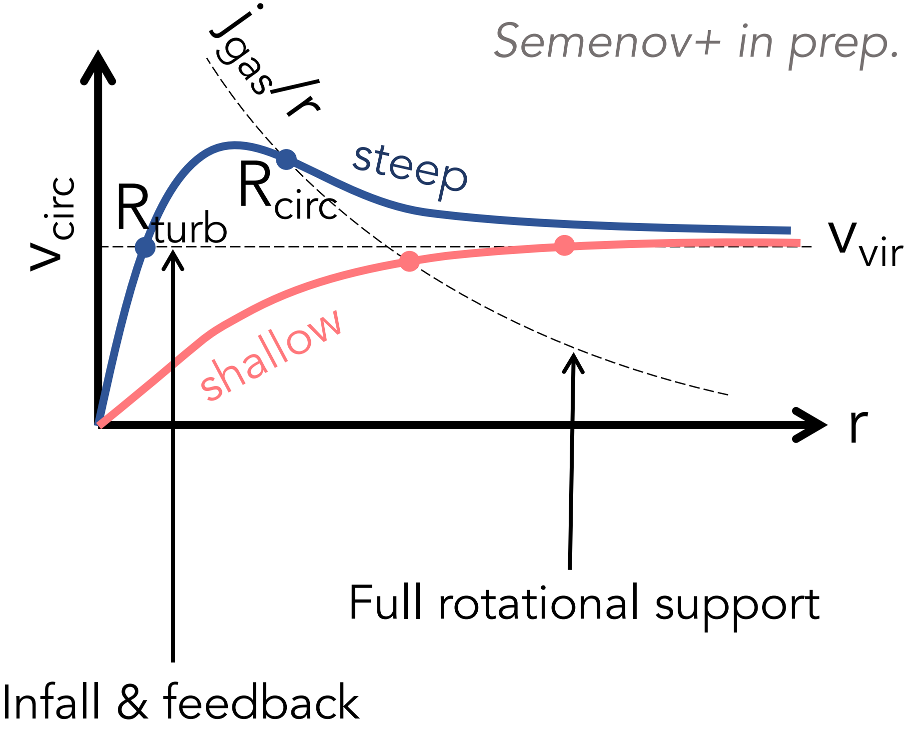
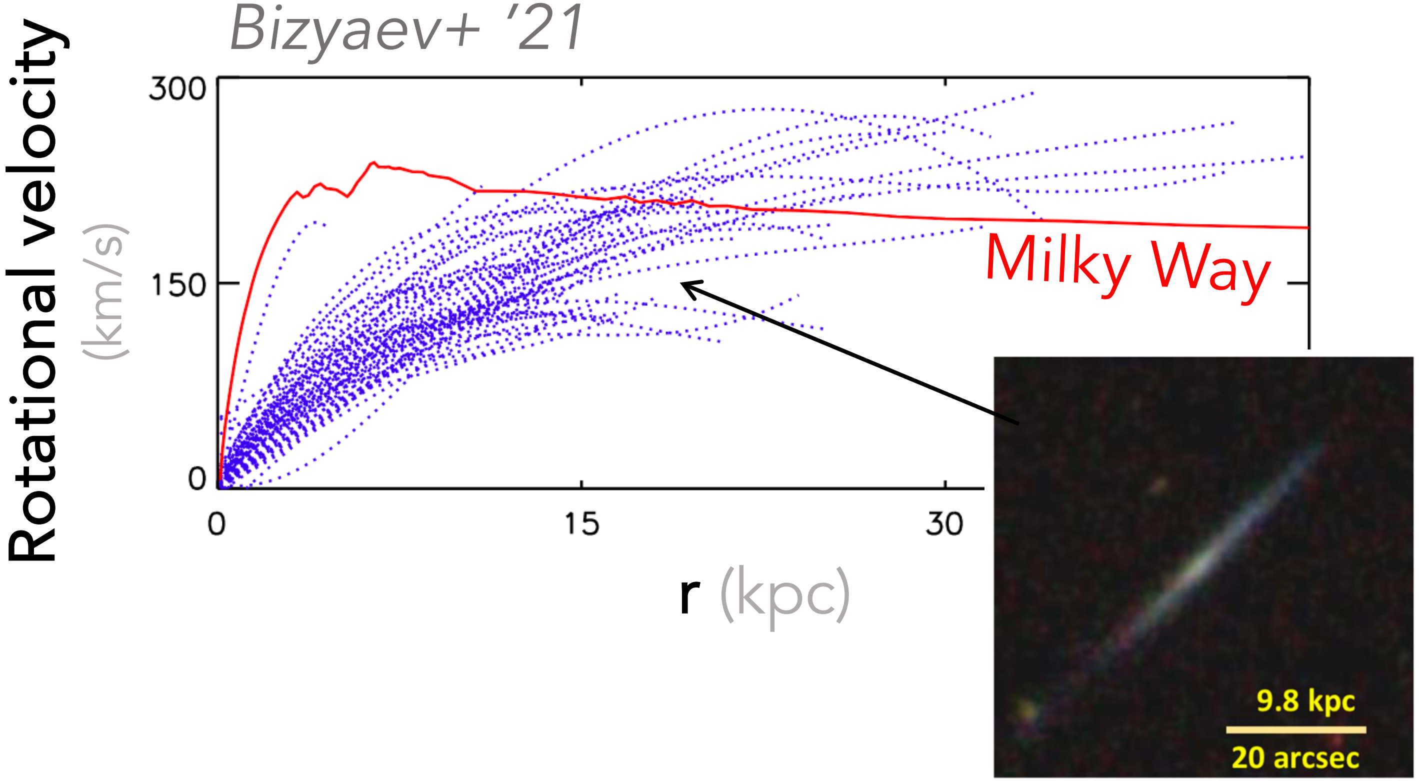


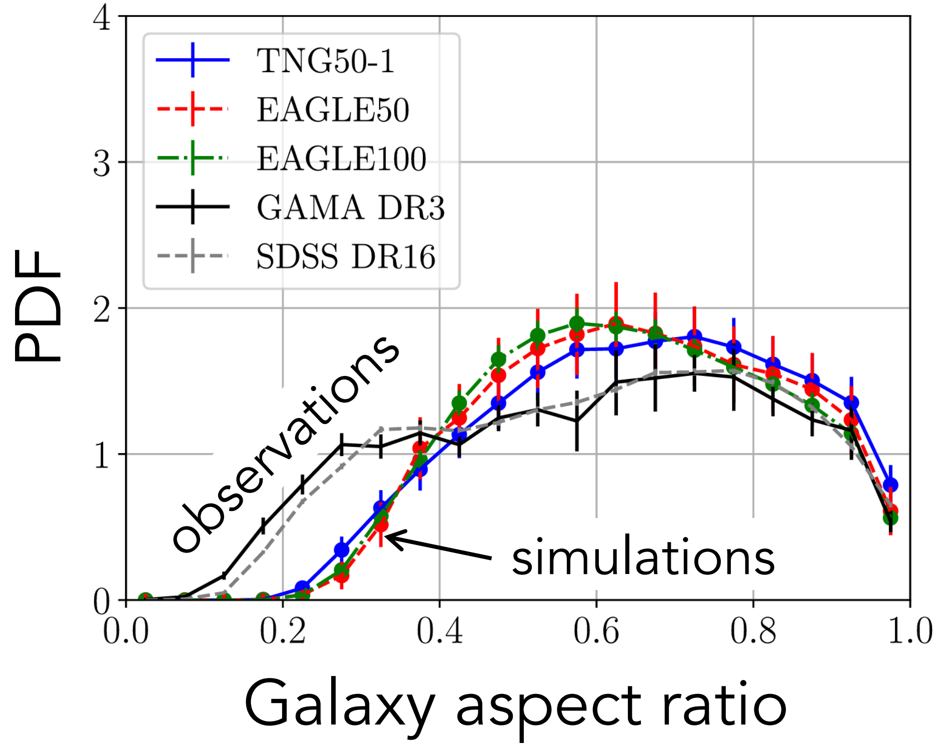
Thin bulgeless disk galaxies contradict this scenario?

- Gradually rising rotation curves suggest potentials without central concentration
- Current simulations underproduce the abundance of very thin galaxies

Bizyaev+ '21



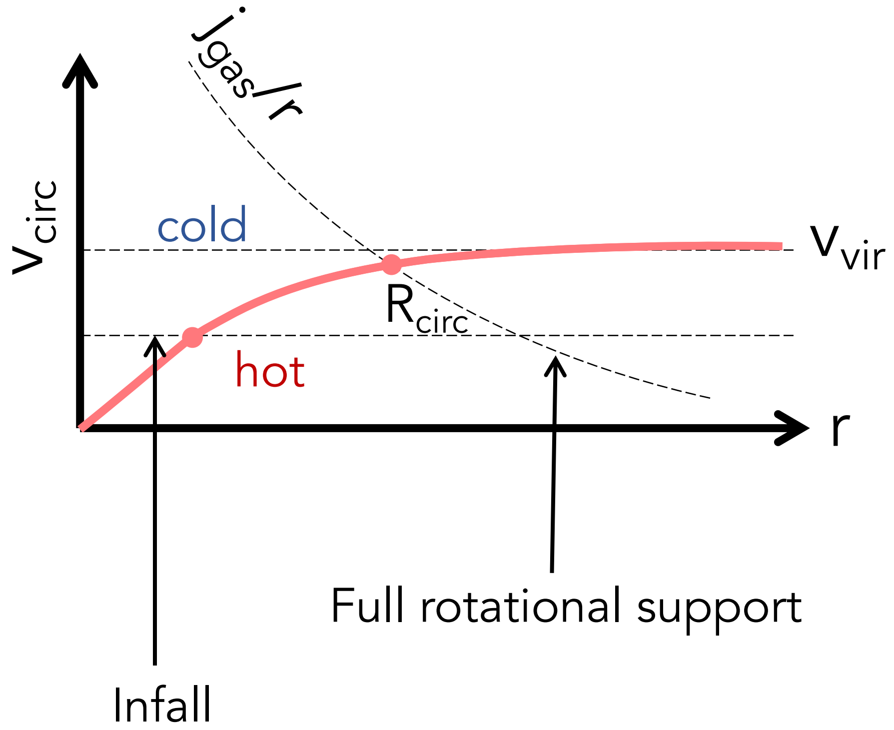
Haslbauer+'22

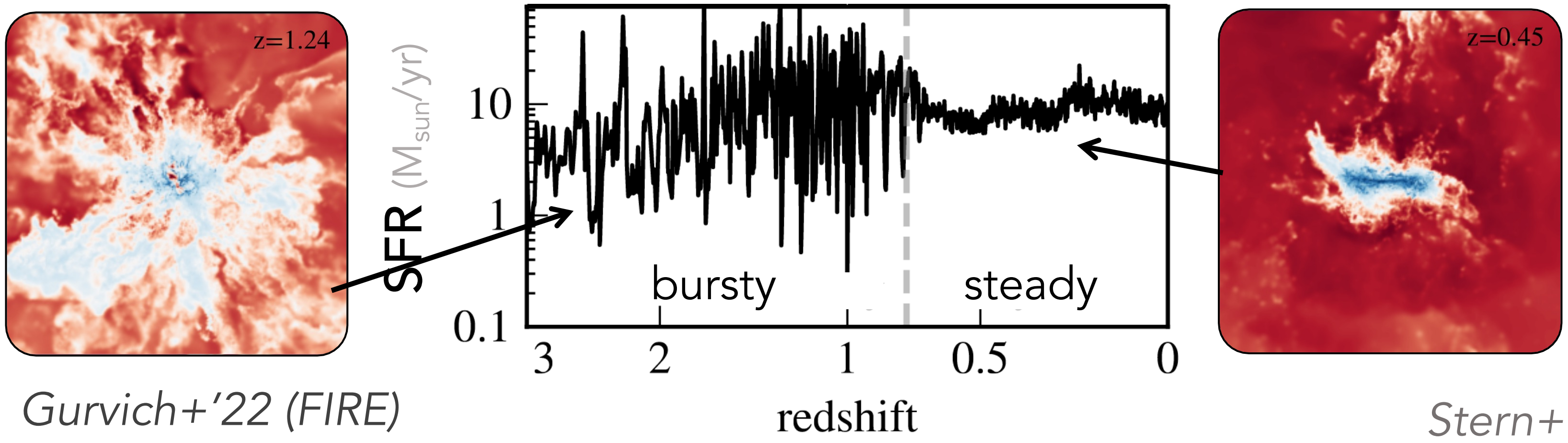


See also Kormendy+'10; Fisher & Drory '11; Kormendy & Bender '12; Simmon+'13; Rodríguez+'25

The role of feedback in disk formation

- Limiting the early galaxy growth =>
  setting the time when M_* reaches ~10^9 M_{sun}
- Stirring up and expelling gas before it settles
- Shaping the inner gravitational potential
- Facilitating cold-to-hot mode inflow transition
  (heating of halo gas; cosmic ray-dominated halo)



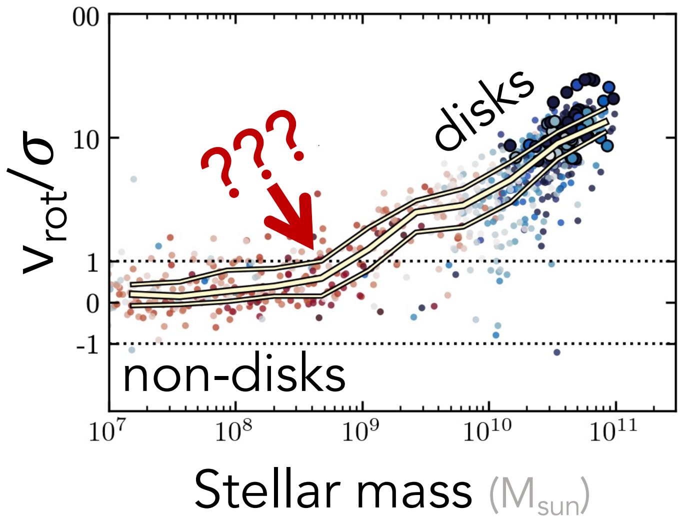


Gurvich+'22 (FIRE)

Stern+'19,'20,'21,'23; Gurvich+'22; Hafen+'22

The role of feedback in disk formation

- Limiting the early galaxy growth => setting the time when M_* reaches $\sim 10^9\ M_{sun}$



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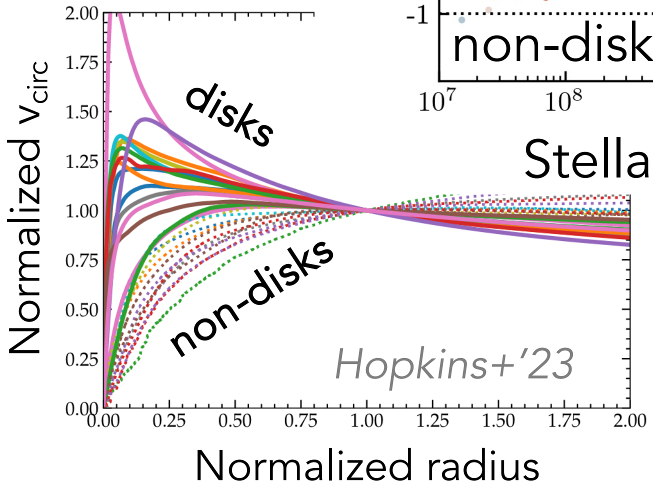

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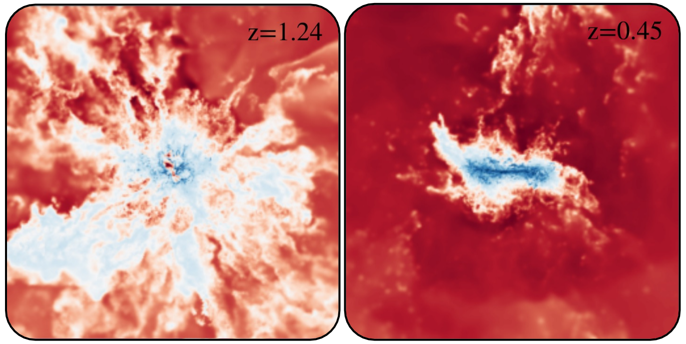
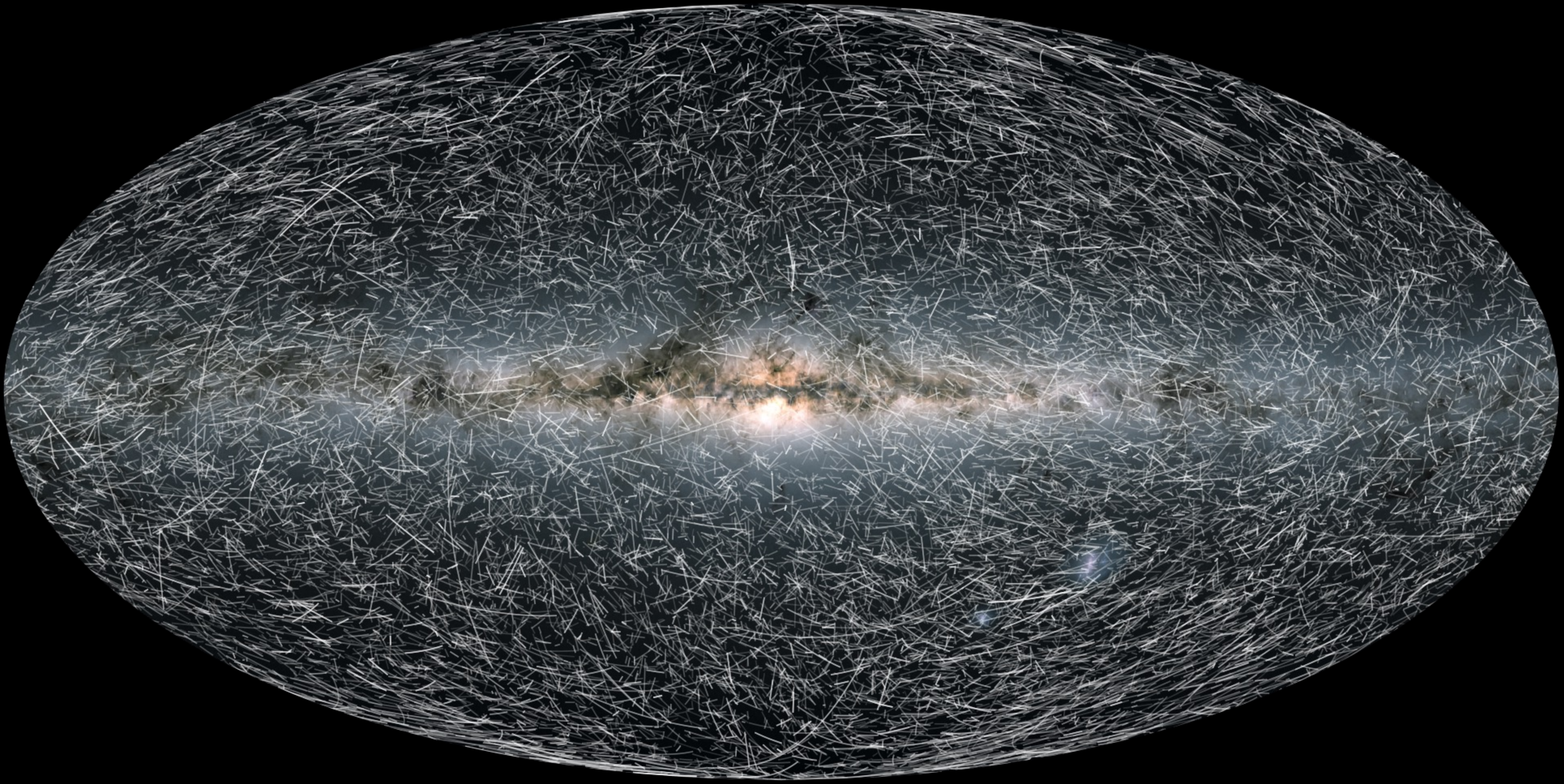
- Facilitating cold-to-hot mode inflow transition (heating of halo gas; cosmic ray-dominated halo)

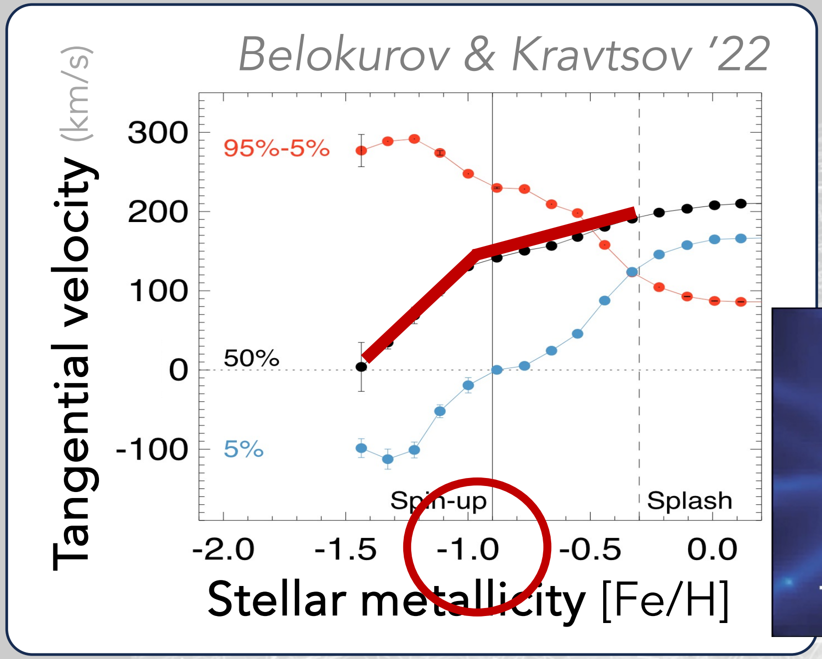


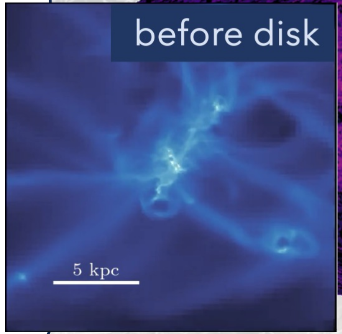
Stern+'19,'20,'21,'23

Gaia DR3

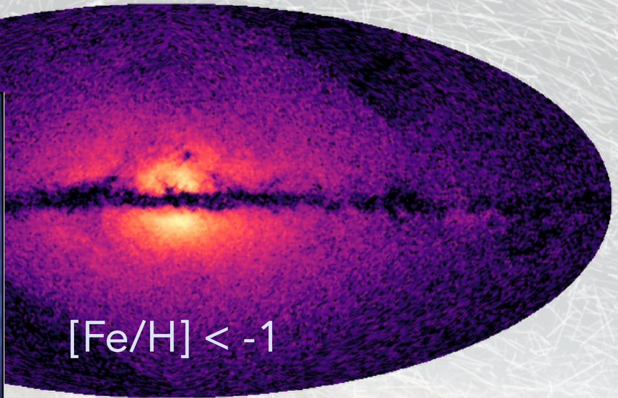


Formation of the Milky Way's disk

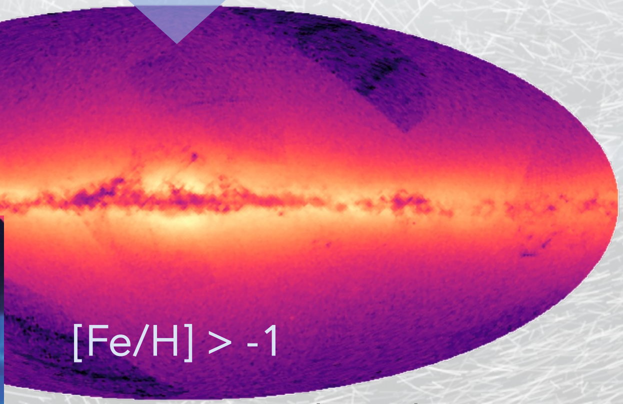


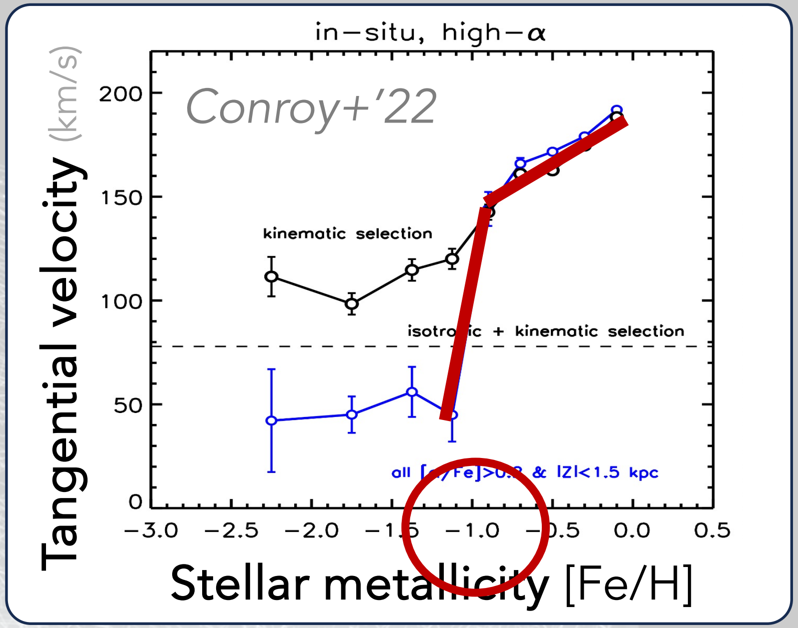


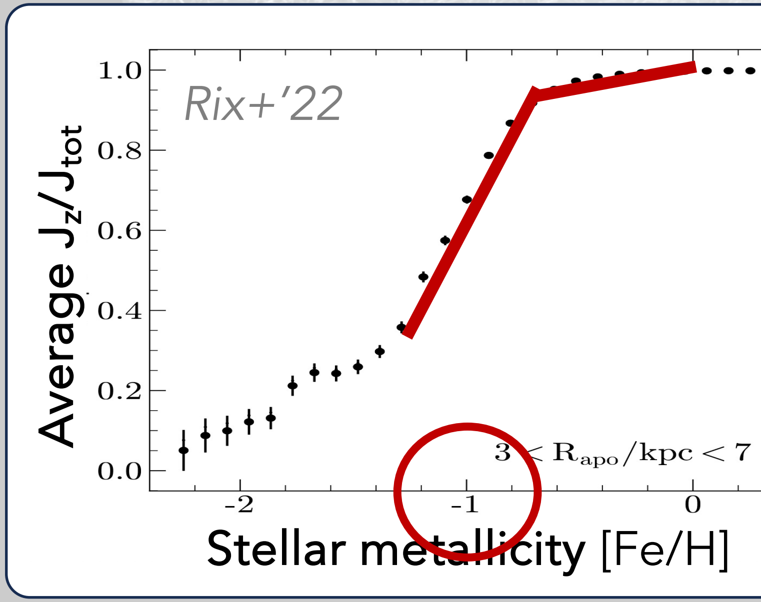
The remnant of pre-disk evolution

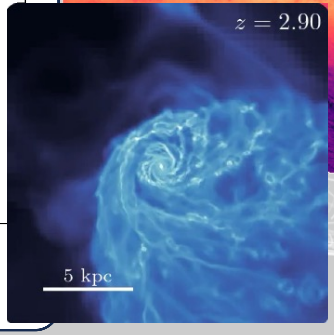


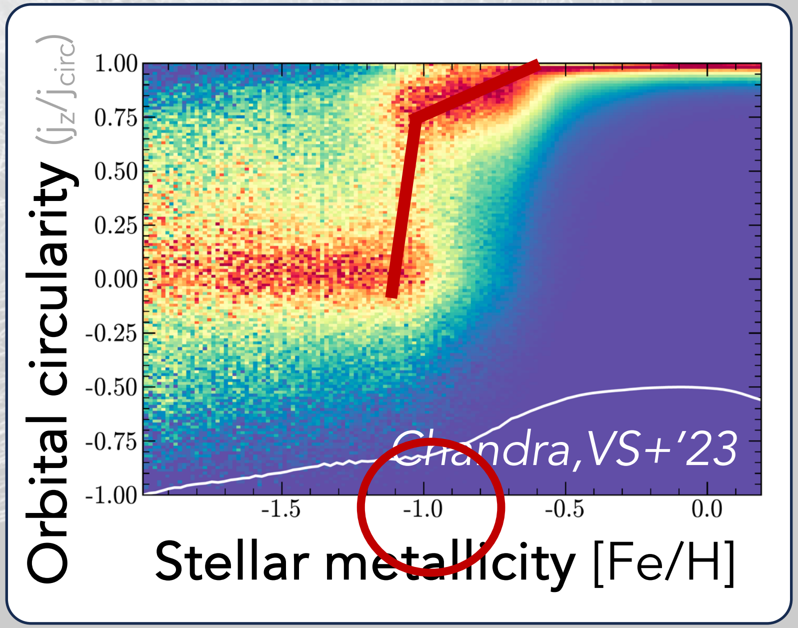
Disk spin-up





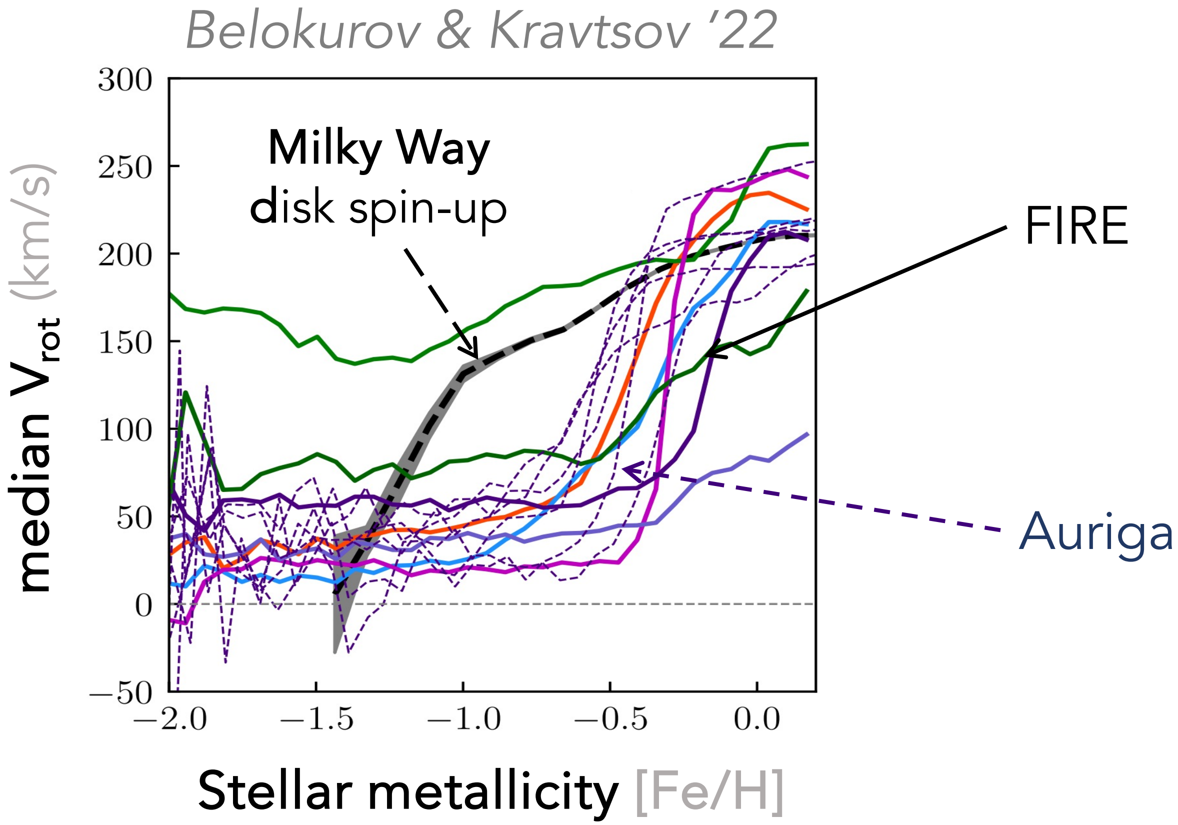






Do state-of-the-art simulations form disks too late?

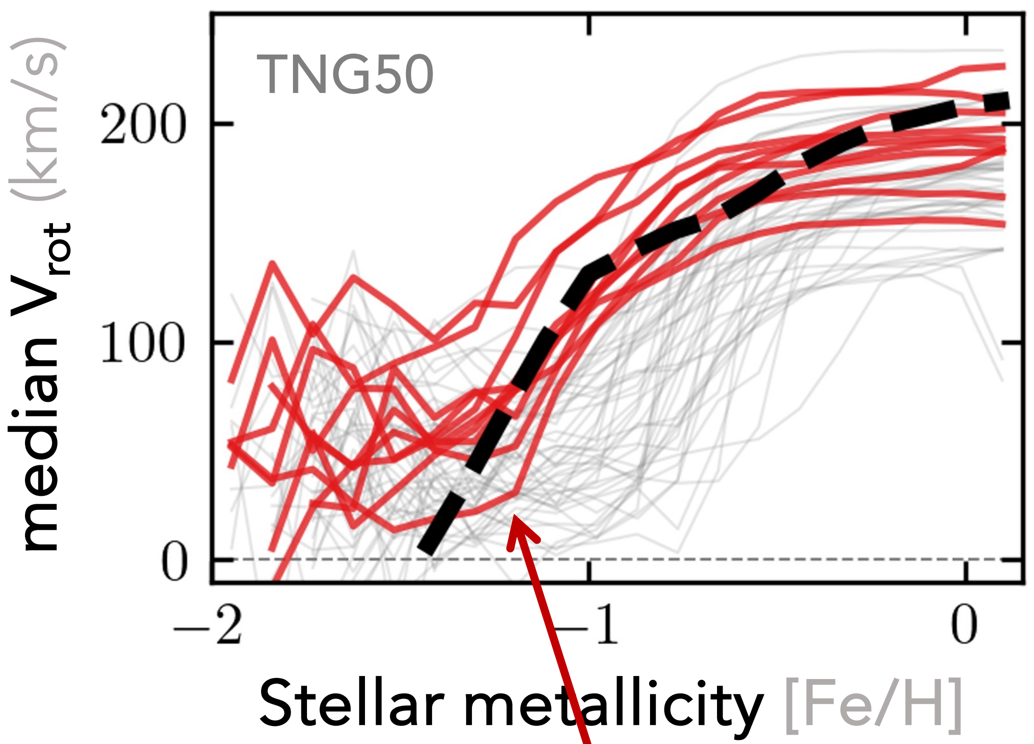
Does early bursty star formation delay disk formation?



MW disk spin-up: *Belokurov & Kravtsov '22,'23; Conroy+'22; Rix+'22; Xiang & Rix '22; Chandra,VS+'23*

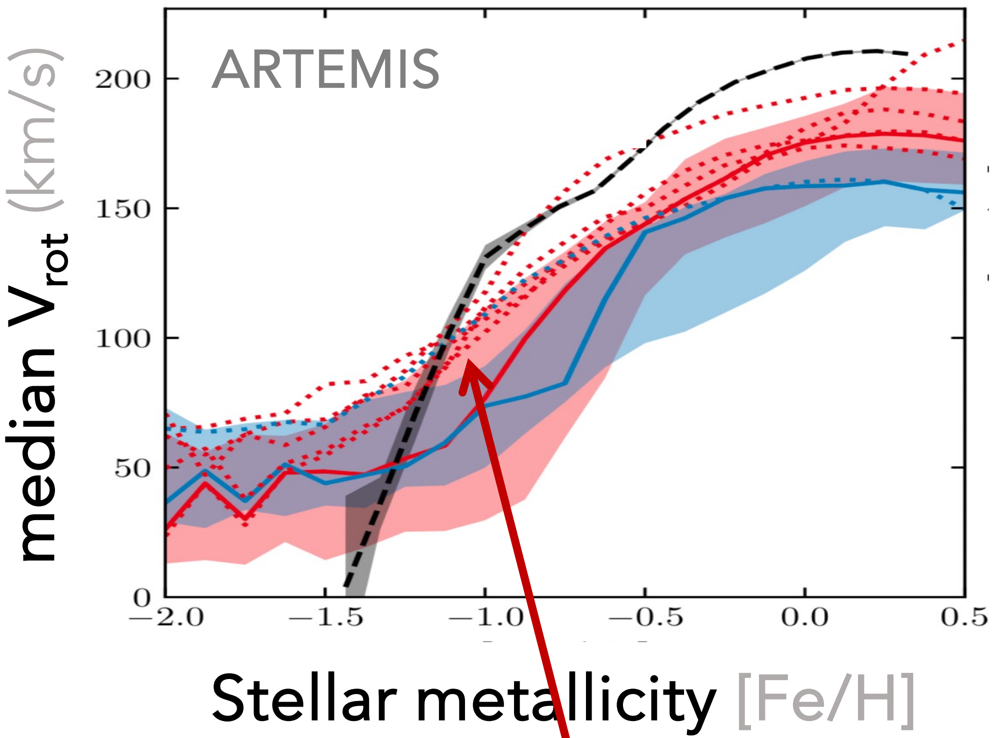
…or is the Milky Way just unusual?

Semenov+'24a,b



~10% of MW-mass galaxies form disks early (early-forming dark matter halos)

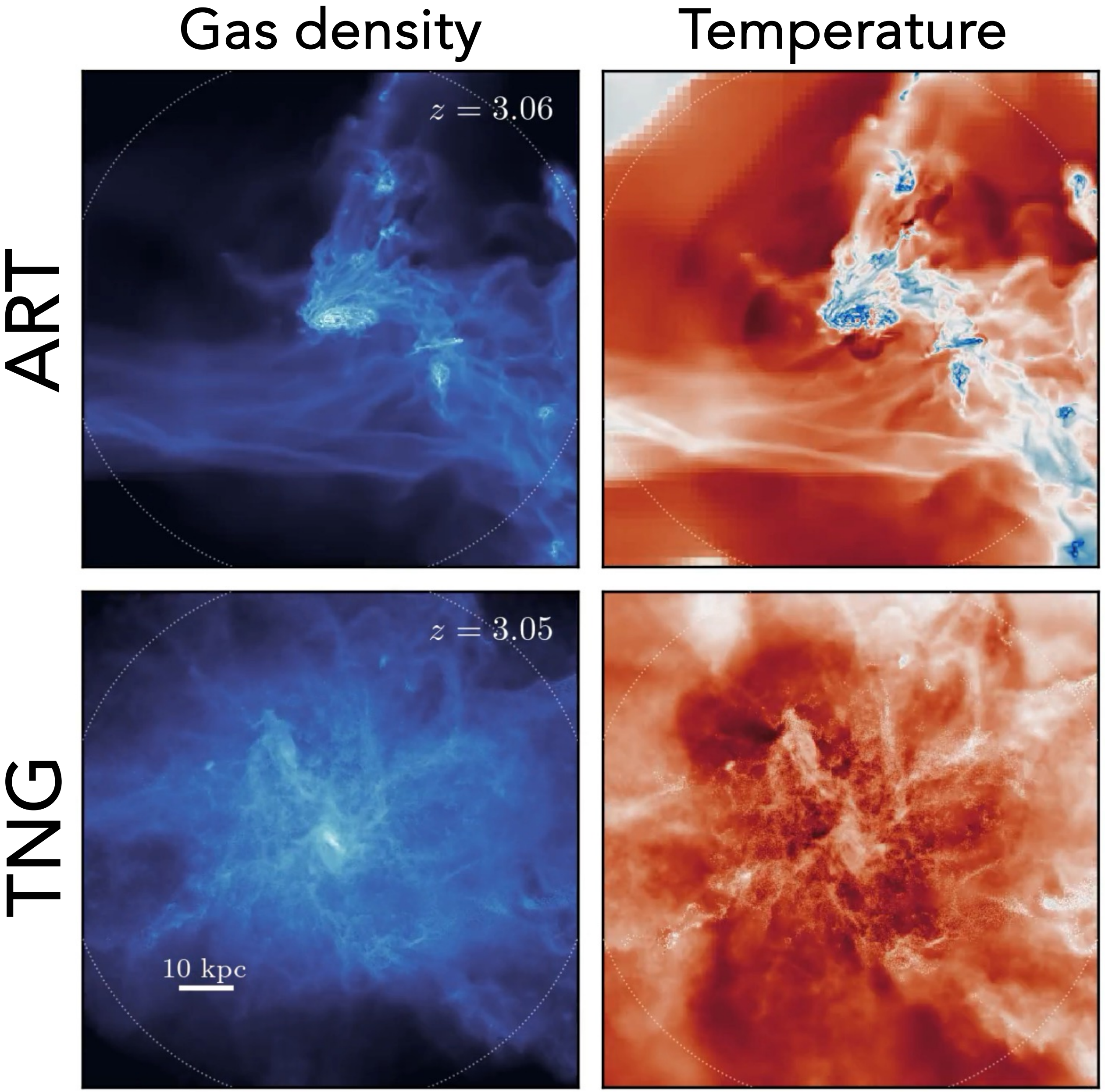
Dillamore+'24



Galaxies with a GSE-like last major merger (also preferentially early-forming halos)

see also Khoperskov+'22

Simulations of an early-forming Milky Way analog



Same initial conditions:

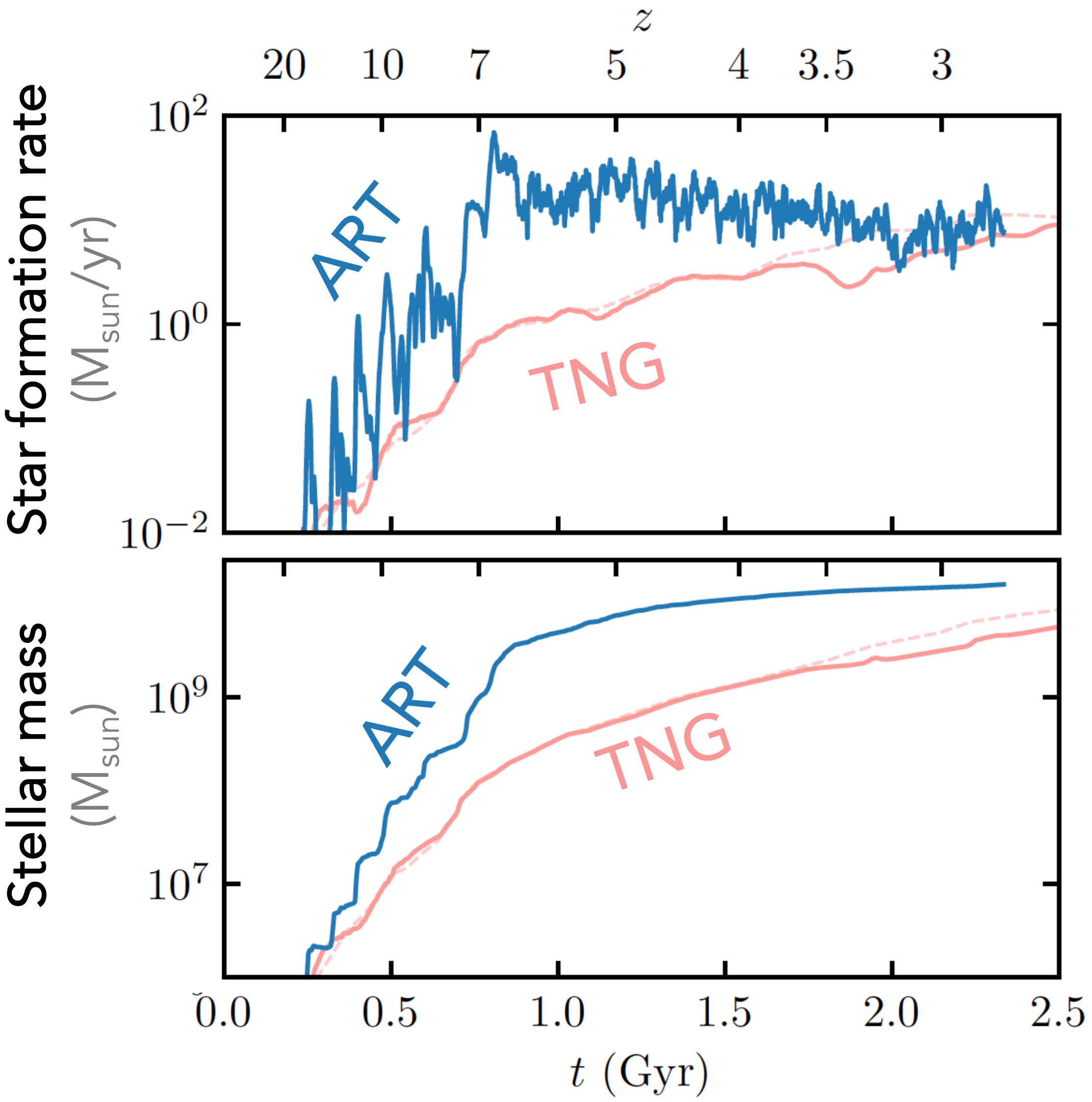
an early-forming MW analog extracted from TNG50 and re-simulated with the ART code

Key improvements in ART vs TNG:

- Higher resolution (x10 in mass; dx_{min}~20 pc)
- Explicit cooling to few K (Z and UV dependent)
- On-the-fly transfer of UV radiation
- Explicit subgrid turbulence
- Locally variable star formation efficiency
- Mechanical feedback from SNe + early FB
- Non-equilibrium molecular chemistry

Semenov+'24c,d

Early bursty evolution…

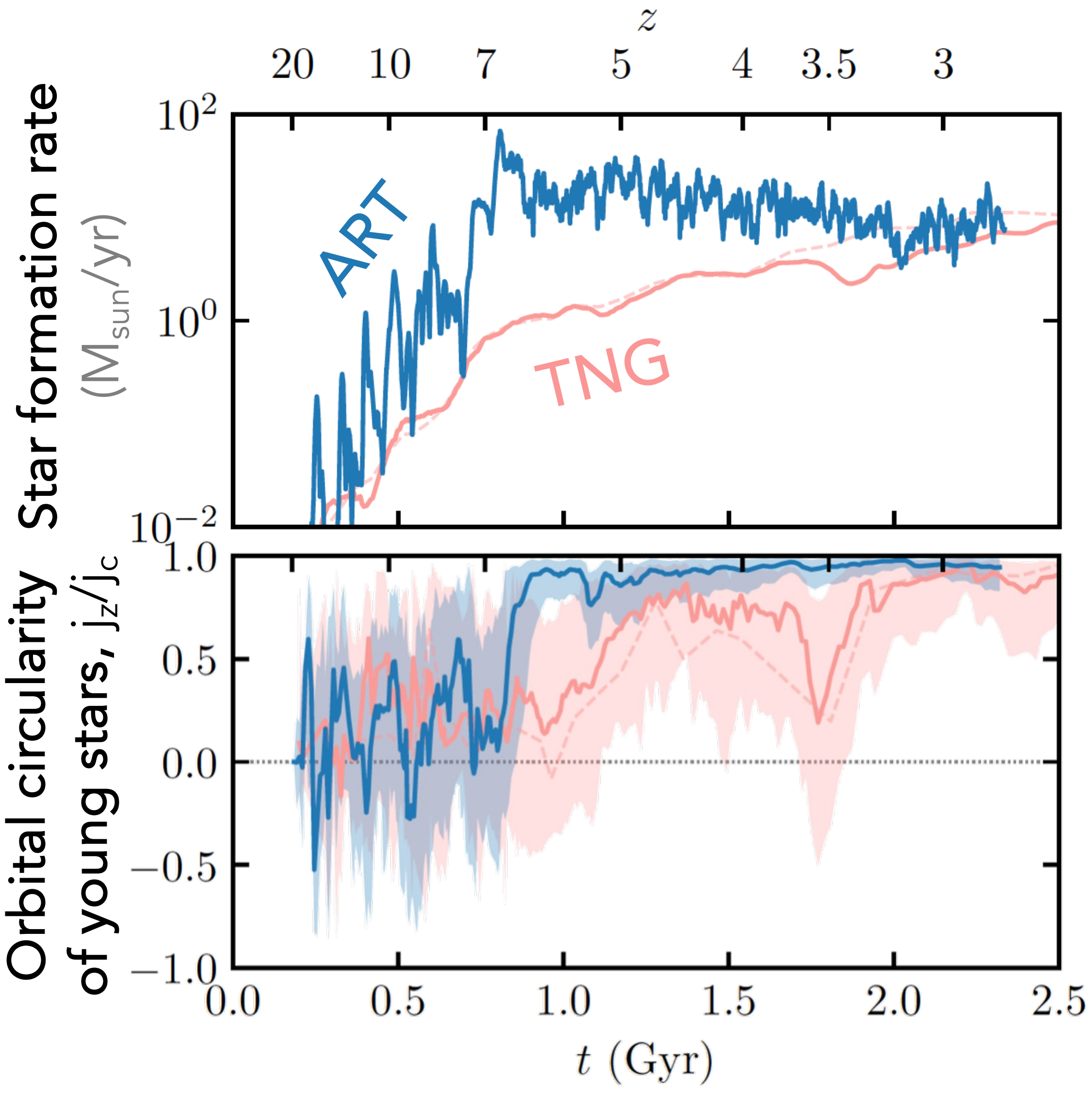


Modeling of turbulent cold ISM leads to:

- Efficient, early, and bursty star formation

Semenov+'24c,d

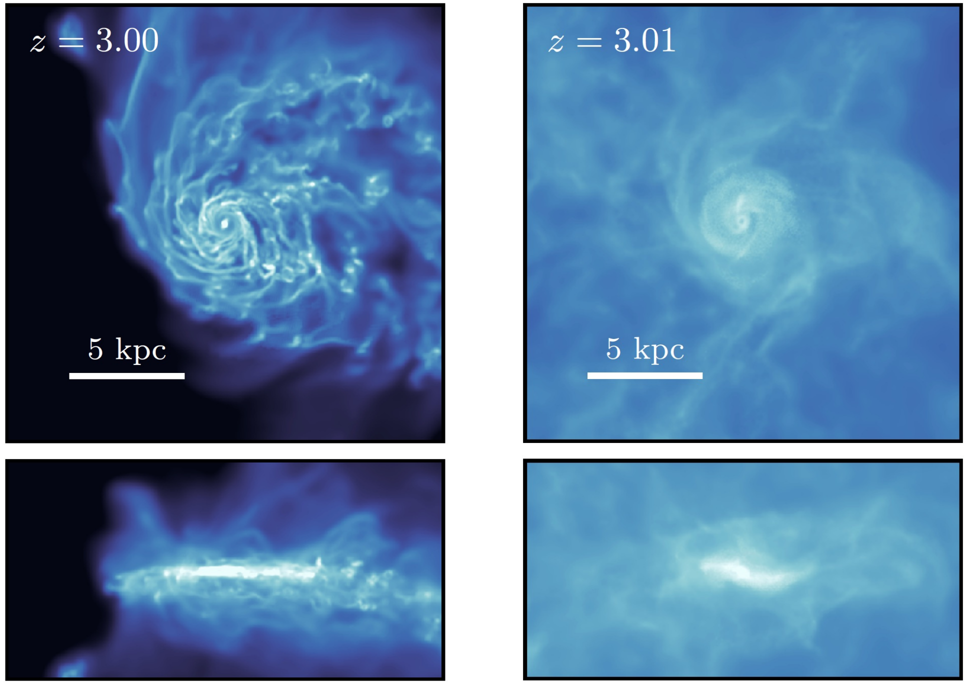
Early bursty evolution and early disk formation



Modeling of turbulent cold ISM leads to:

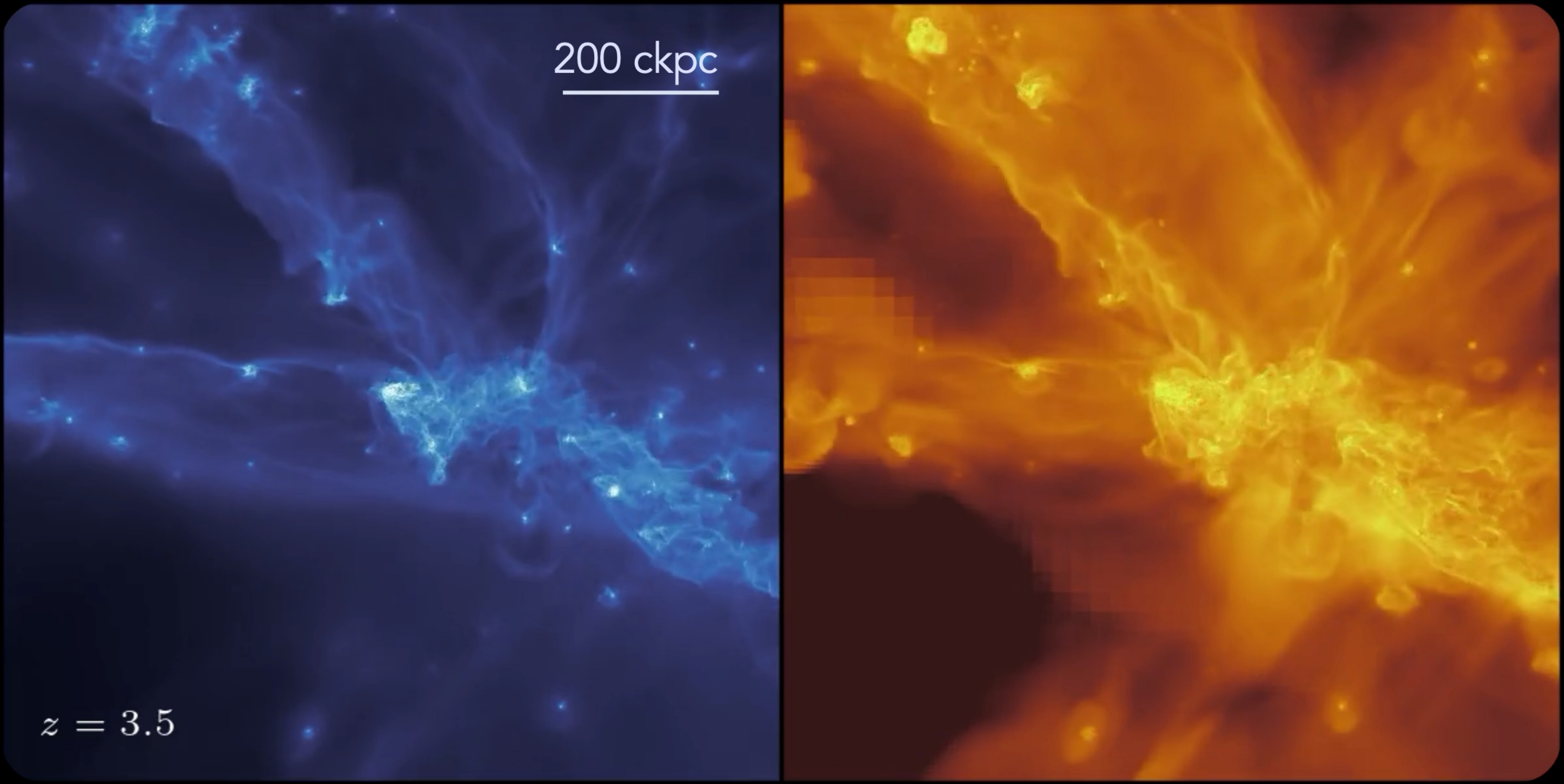
- <u>Efficient,</u> <u>early,</u> and <u>bursty</u> star formation
- Extremely early MW disk formation (z~6)

see also Conroy+'22; Belokurov & Kravtsov '23



Semenov+'24c,d

Accounting for small-scale turbulence in star formation and feedback



Gas density

Turbulent velocity on unresolved scales

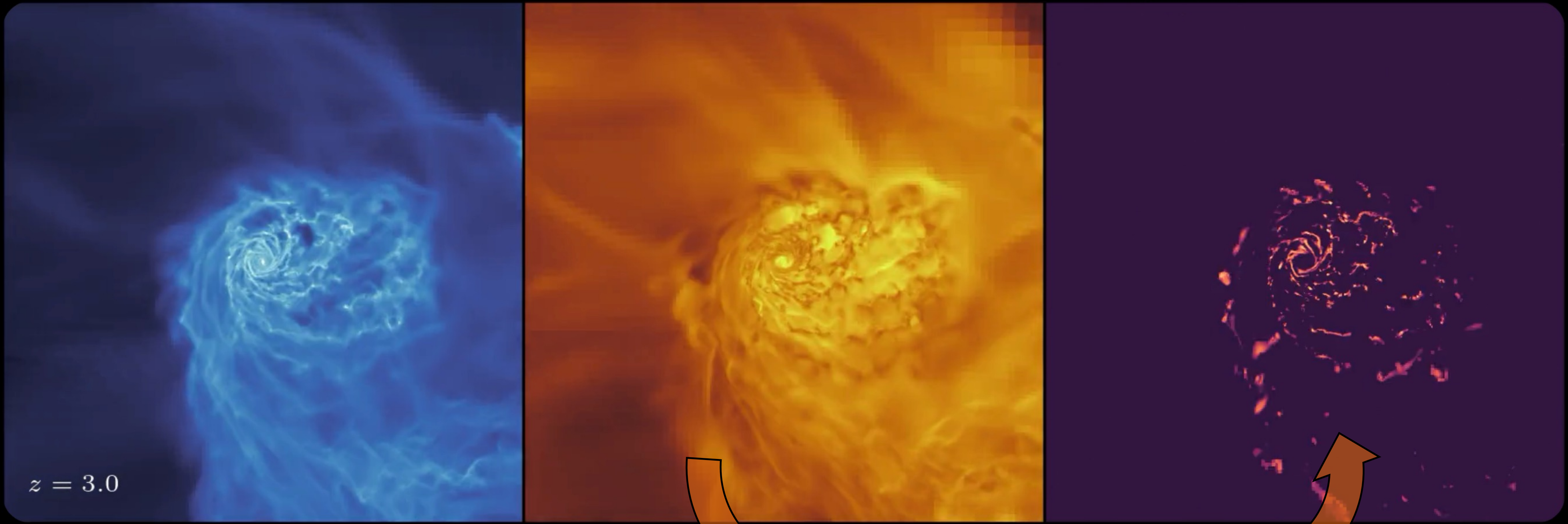
Semenov+ '24c,d

Accounting for small-scale turbulence in star formation and feedback

Gas density

Turbulent velocity on unresolved scales

Star formation efficiency per free-fall time



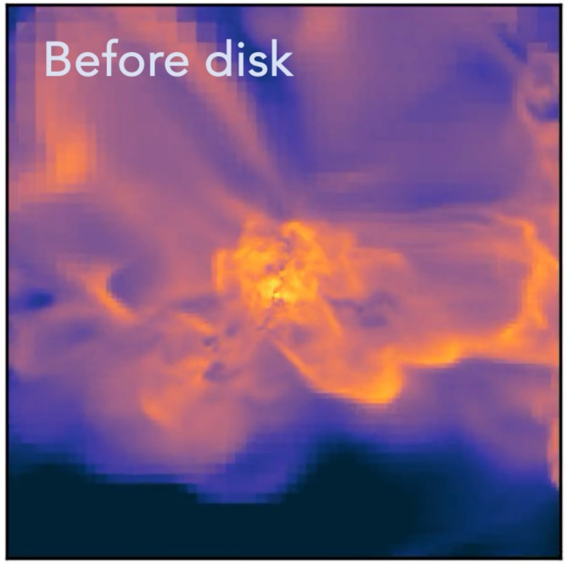
$$\epsilon_{\rm ff} \propto \exp(-\sqrt{\alpha_{\rm vir}/0.53})$$

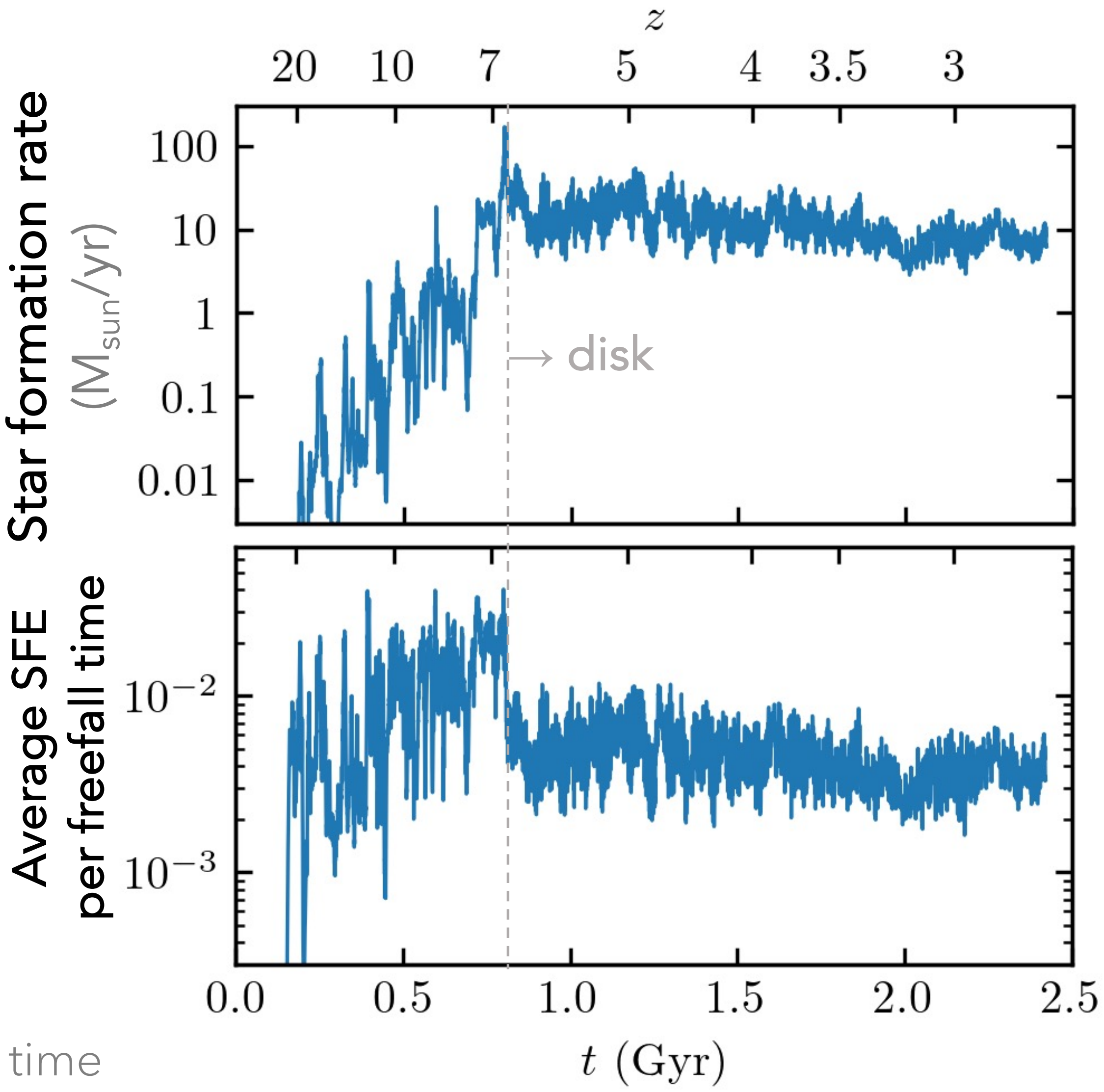
$\alpha_{\rm vir} \propto \sigma^2/\rho L^2$ - subgrid virial parameter

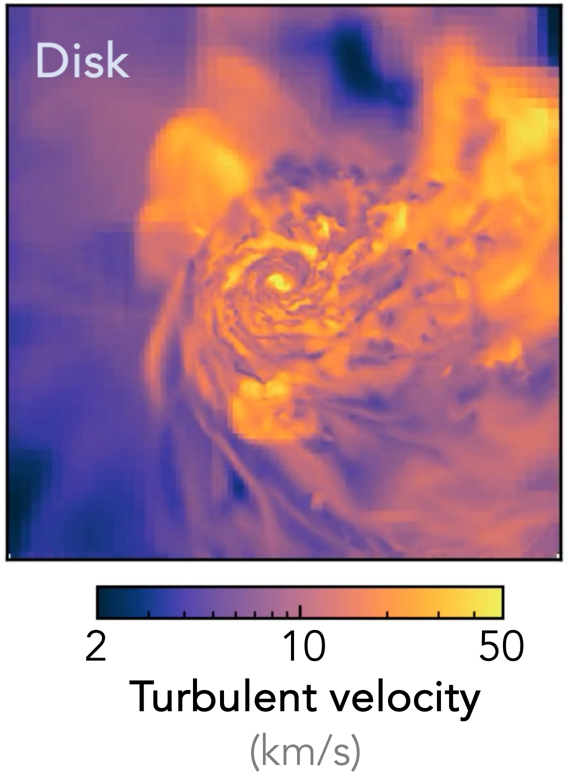
Padoan+'12; see also Krumholz & McKee '05; Padoan & Nordlund '11; Federrath & Klessen '12

Semenov+ '24c,d

Turbulent star formation in early galaxies







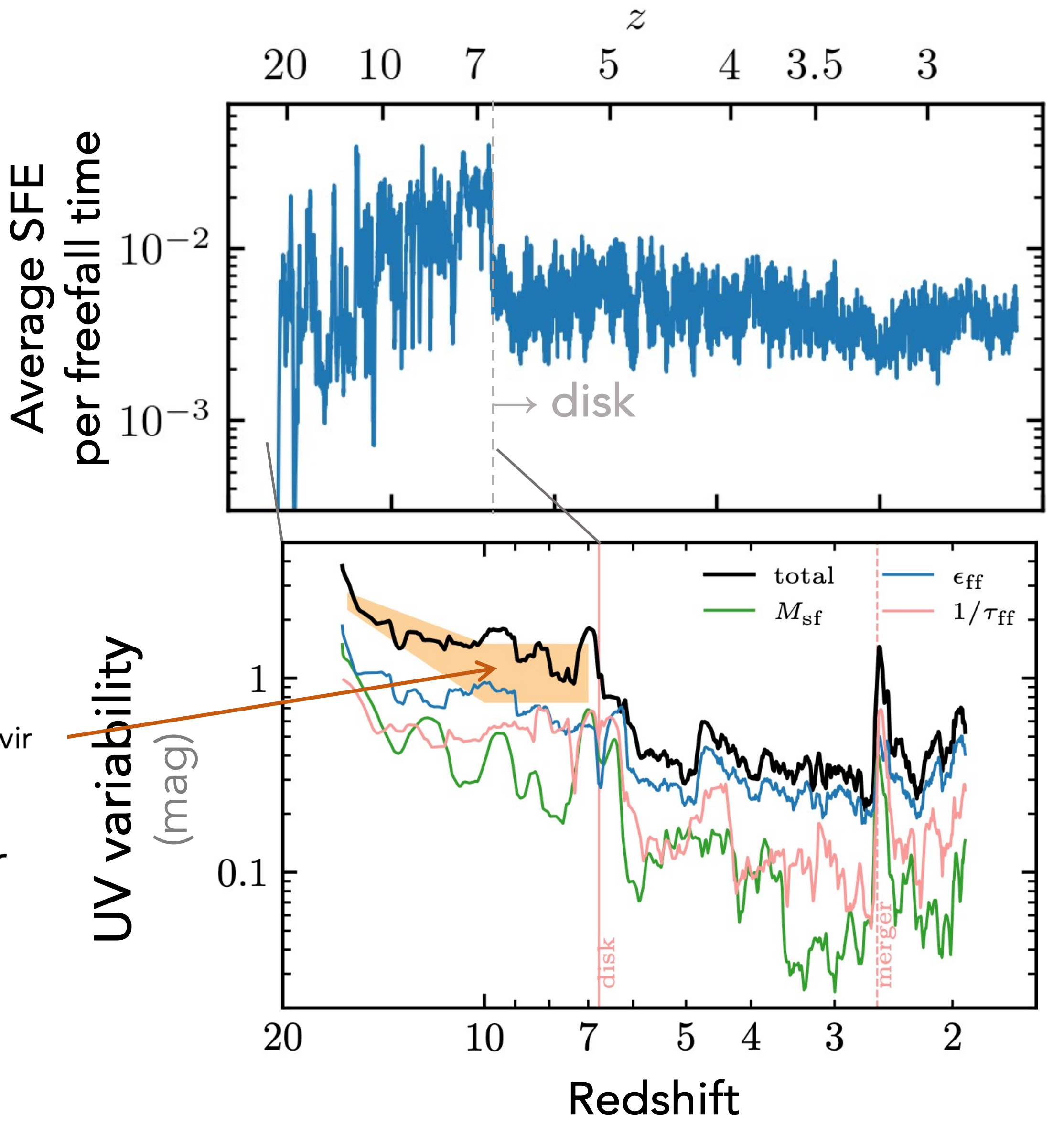
$\mathrm{SFR} = \langle \epsilon_{\rm ff} \rangle \, M_{\rm sf} \, / \, \tau_{\rm ff}$

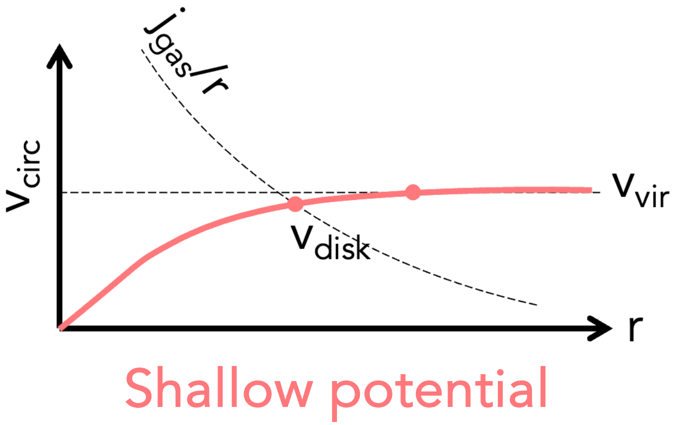
Mass and freefall time
of star-forming gas

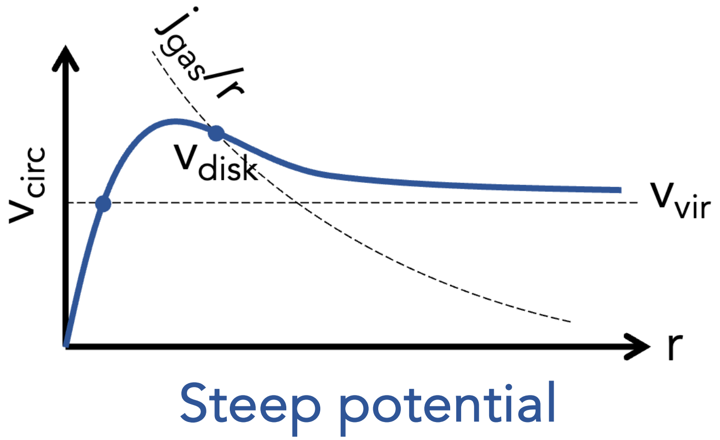
Typical $\langle \epsilon_{\rm ff} \rangle$ ~ 1%
just like in nearby SF regions!

Semenov+'24d

Turbulent star formation in early galaxies







Semenov+'24d

Takeaways

The role of feedback in disk formation:

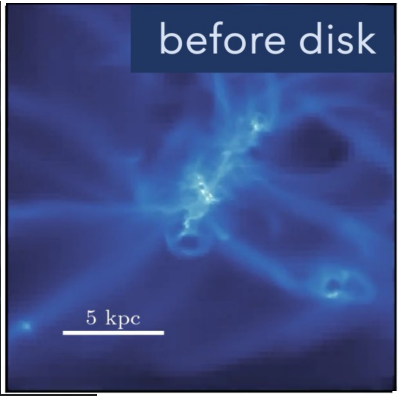
- Limiting early growth ($M_* \sim 10^9\ M_{sun}$ threshold)
- Removing gas and preventing it from settling
- Shaping the inner gravitational potential
- Cold-to-hot mode transition (hot or CR halo)

…and in disk growth and survival:

- Lowering disk fraction => disk stability
- Redistributing angular momentum btw disk and halo
- Providing vertical support (ISM turbulence, CRs)
- Powering gas cycle => SFRs and depletion times

Early formation of the MW disk is a test for FB models but it's only one data point

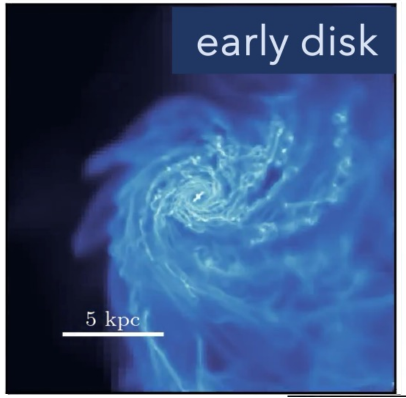
Early bursty galaxies

Turbulence driving on ~halo scale =>
Large variations of SF efficiency =>
Bursty galaxies

Disk spin-up

Early disks



Turbulence driving on ~disk height scale =>
Mild variations of SF efficiency =>
Survival of early disks