Stellar Clustering in 4D

Observed Starlight

Molecular

Galaxy Merger

X-Rays

Star Formation

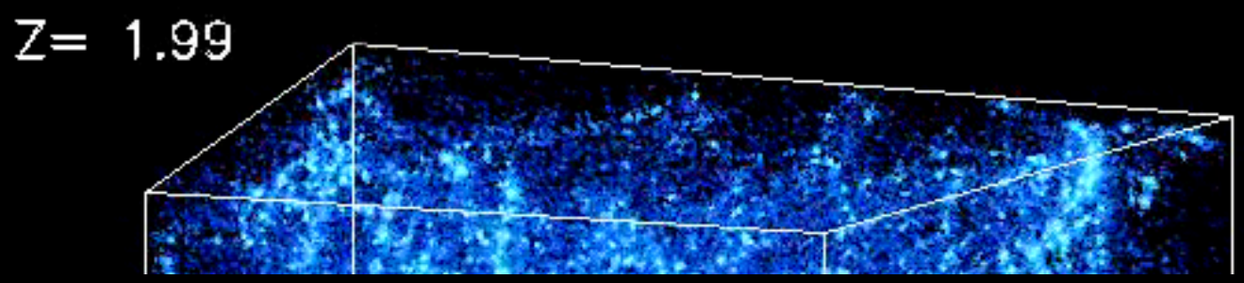
Philip F. Hopkins, the FIRE & STARFORGE collaborations

www.tapir.caltech.edu/~phopkins

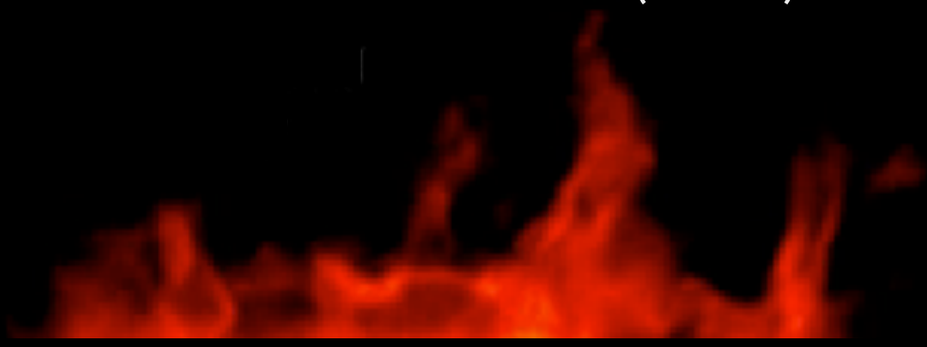
Mike Grudic, David Guszejnov, Matt Orr, Sarah Loebman, Samantha Benincasa, Alex Gurvitch, Stella Offner, Anna Rosen, Eliot Quataert, Drummond Fielding, Sam Ponnada, Gina Panopoulou, Iryna Butsky, and many more

Massive Stars are (Statistically) *Clustered* on All Scales

COSMOLOGY (DARK MATTER)



STAR FORMATION (GMC)

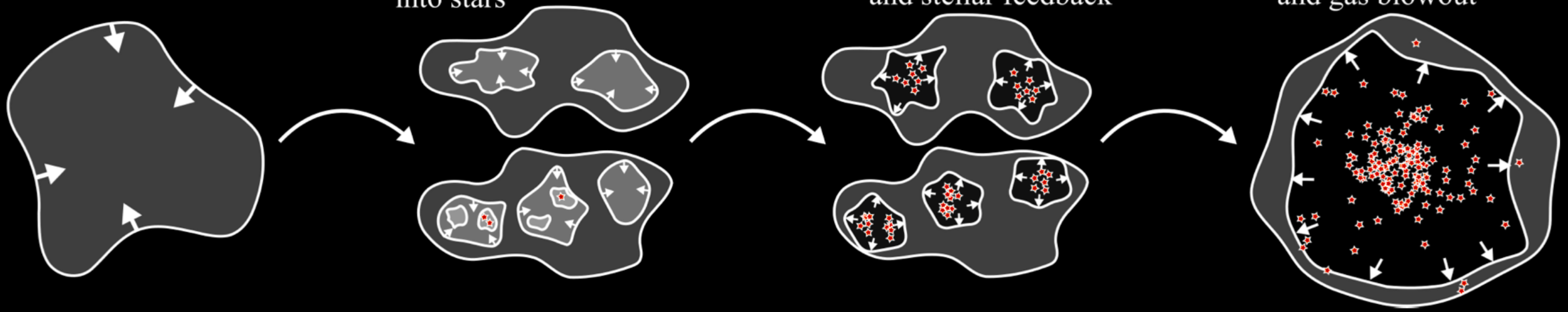


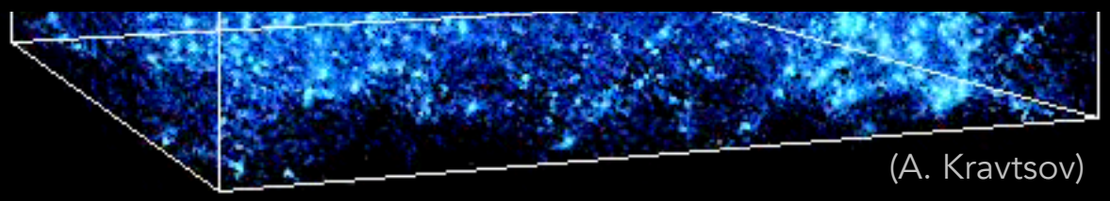
Gravitational collapse

Hierarchical fragmentation into stars

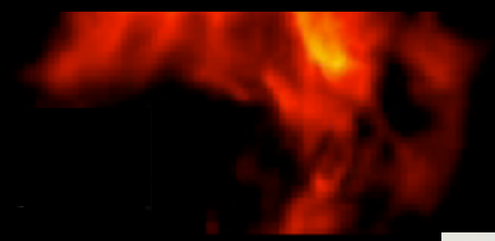
Sub-cluster formation and stellar feedback

Hierarchical assembly and gas blowout



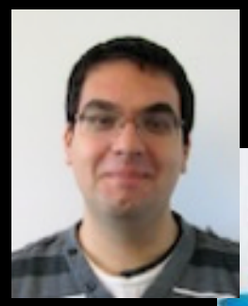


(A. Kravtsov)



(M. Bate)

- Correlation functions / clustering in ***space*** & ***time***
- "Fractal" & "Filamentary" morphologies & "Bursty-ness" in time
- Galaxies & ISM are ***dynamic systems***

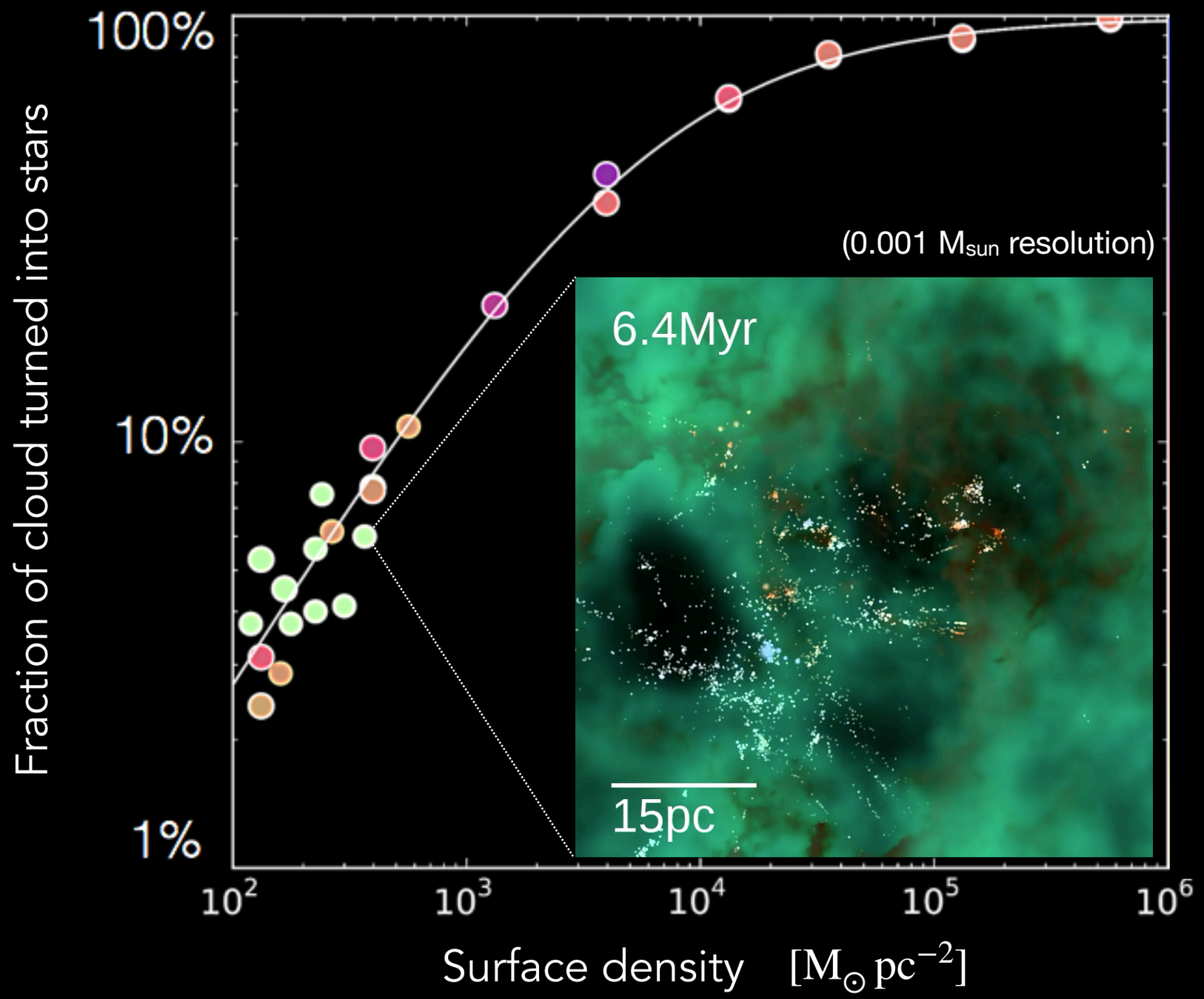


Guszejnov+ 15,16, 17

Grudic+ 16, 17

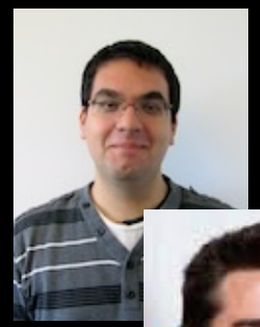
Clustering (in space AND time) Matters

STAR FORMATION (~au-pc) scales



- Multiplicity (disk & core)
- "Cluster" formation
- Sub-cluster dynamics/ merging/supermassive stars/IMBHs/LIGO sources
- IMF: turbulent fragmentation & competitive accretion
- GMC destruction & lifetimes

IMF: arXiv:2205.10413
Jets are crucial: arXiv: 2010.11249
Global dynamics: arXiv:2201.00882
Cluster formation: arXiv:2201.01781

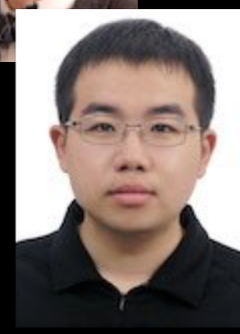


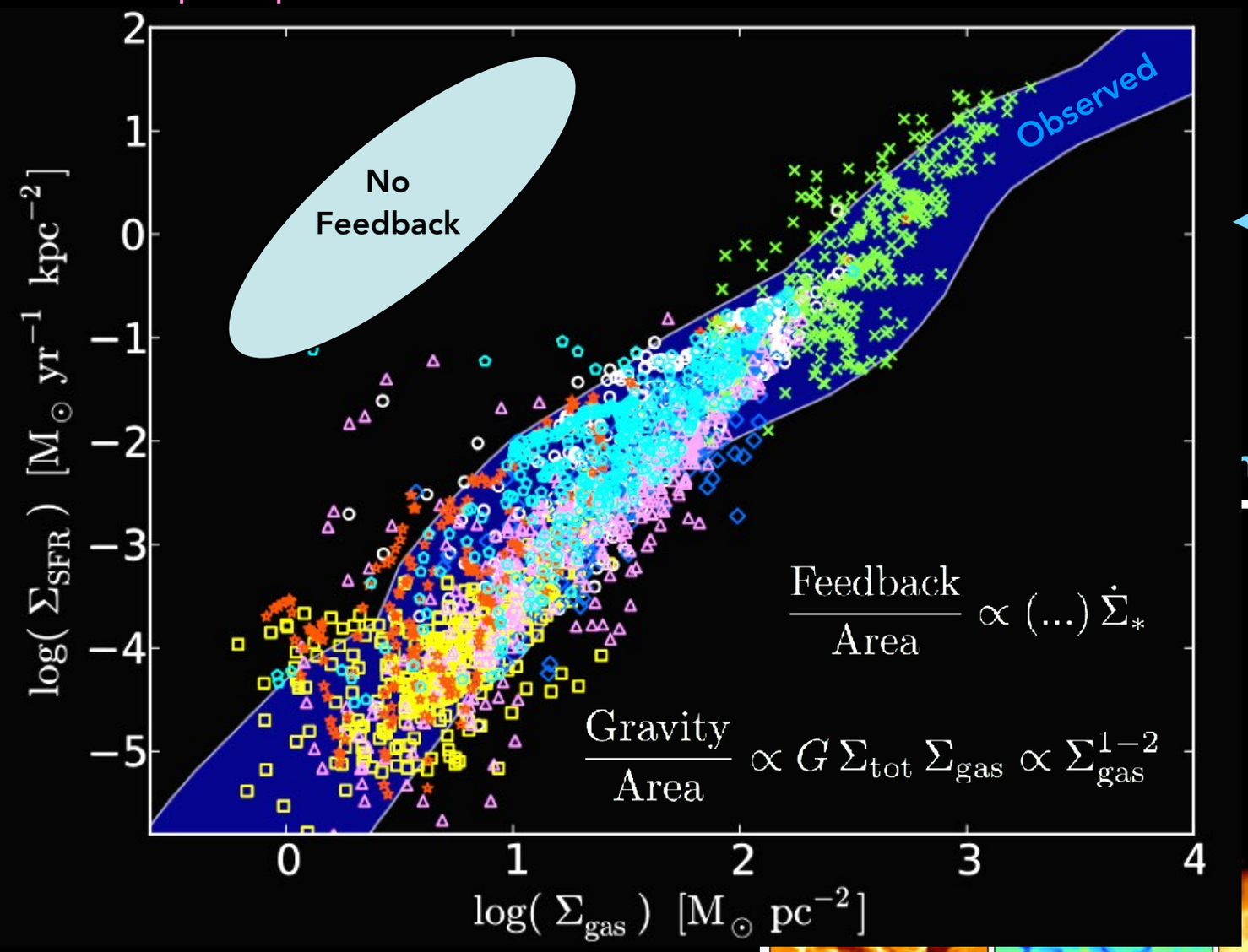
STARFORGE:
David Guszejnov & Mike Grudic
+ Anna Rosen & Stella Offner

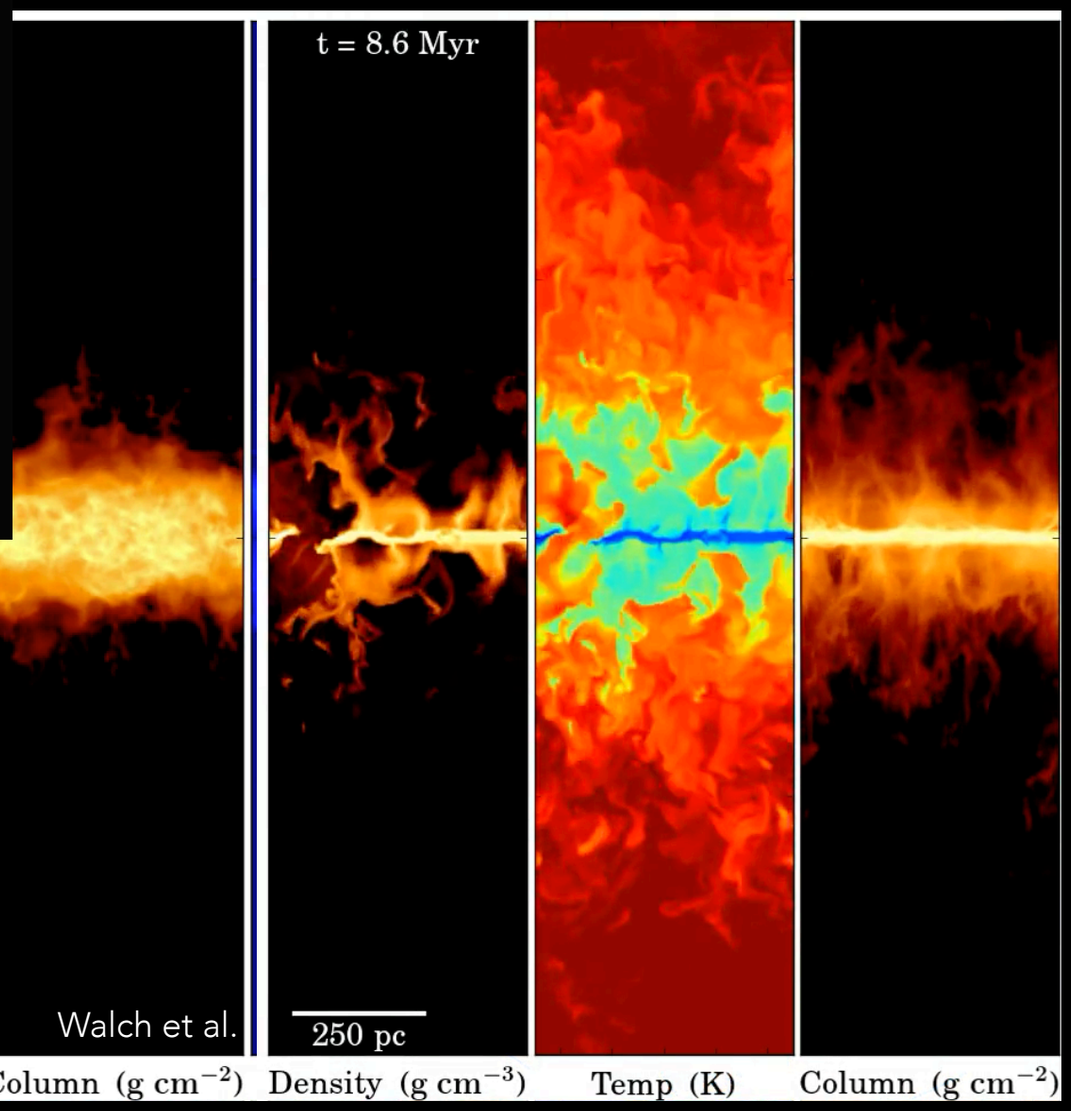
Clustering Matters

ISM (~pc-kpc) scales

Orr+ 17,18,19, 20, 22, 23 (1701.01788)
Su+17,18, 23 (1607.05274)
(also Torrey+17, Martizzi+16, Walch+17, Kimm+18)





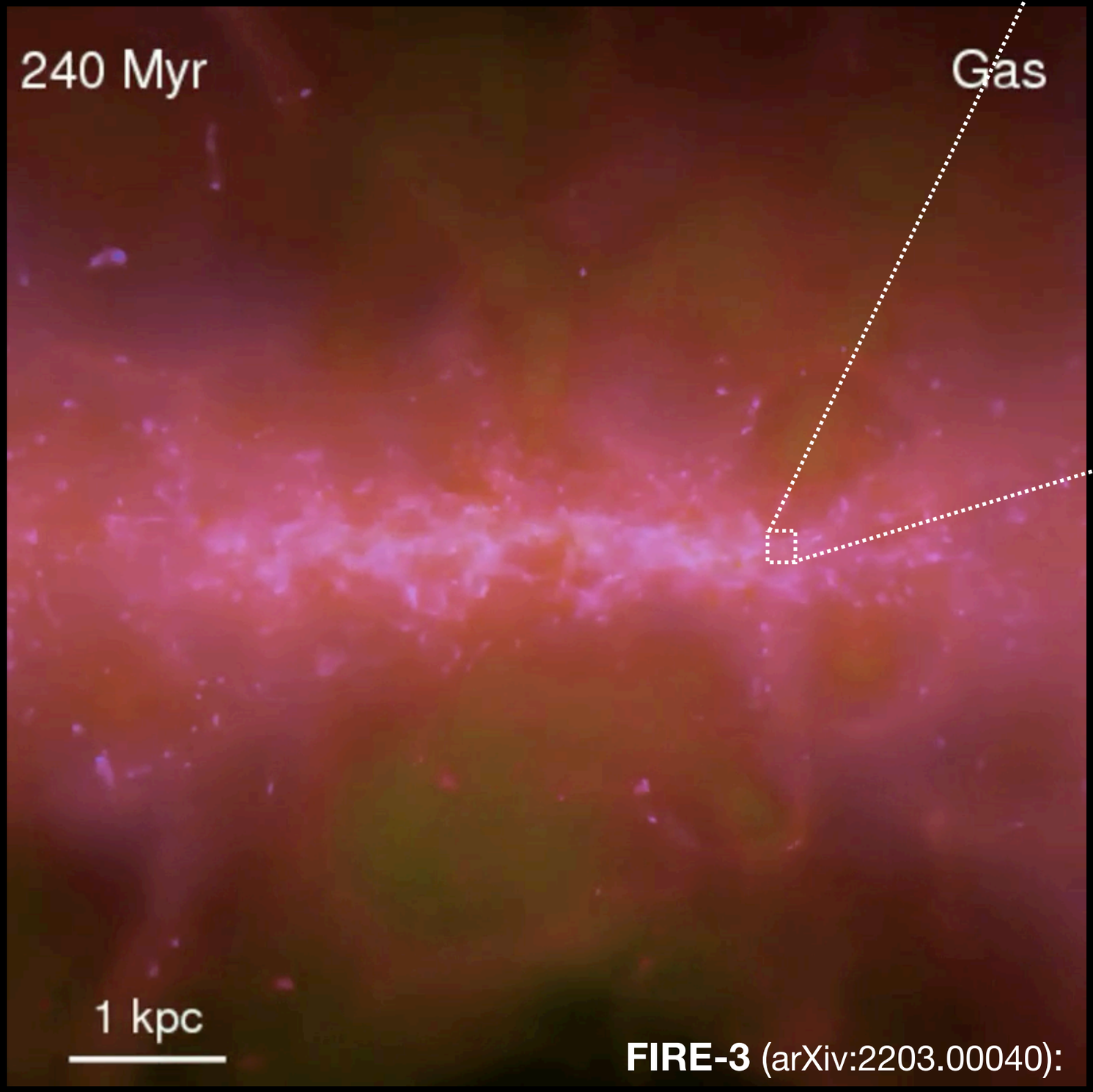


- "Burstiness" vs. scale
- Non-equilibrium SF
- GMCs/Star clusters
- ISM Turbulence

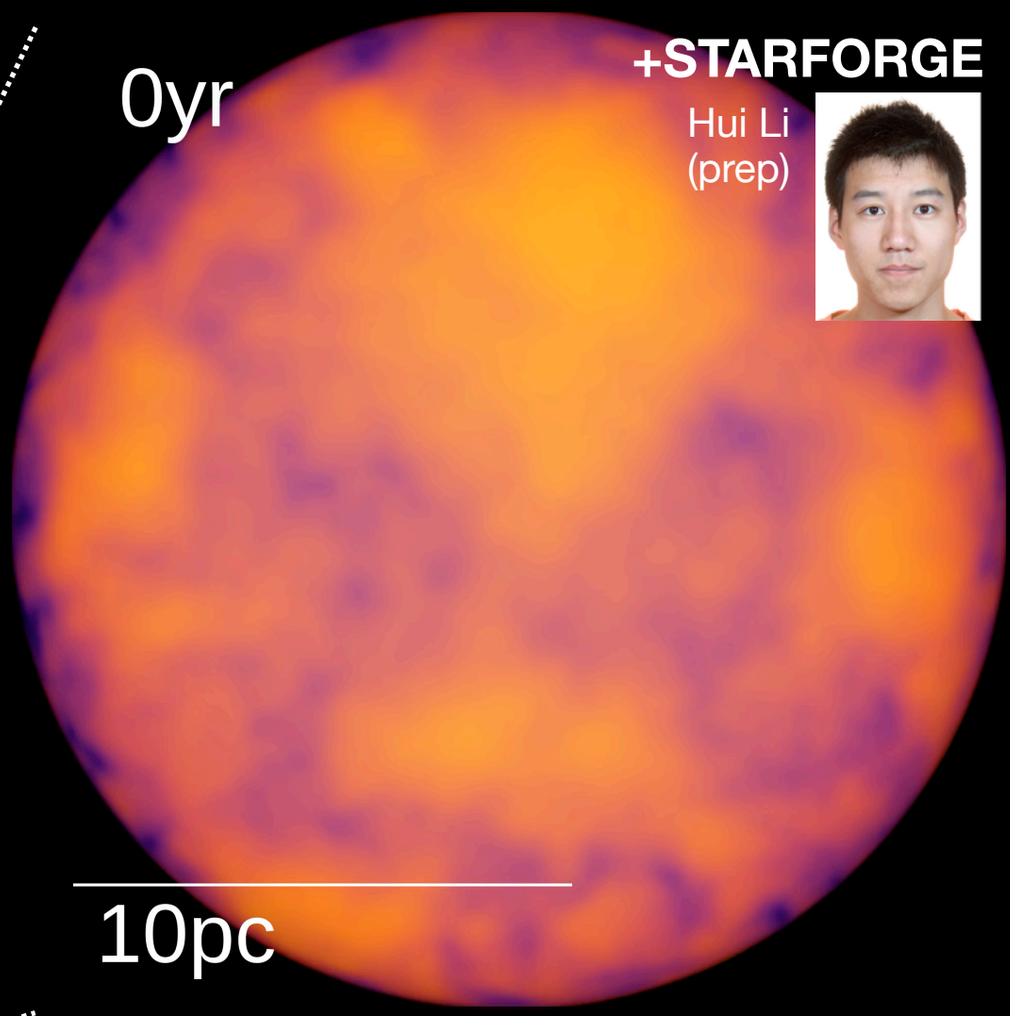
FIRE-3 + STARFORGE

From Cosmological scales to to $\ll M_\odot$ resolution
in GMCs, ultra-faints, & galactic nuclei

Yellow: hot (>million K) Pink: warm (~10,000 K) Blue: cold (~100 K)



FIRE-3 (arXiv:2203.00040):



+STARFORGE

Hui Li
(prep)

- Galactic Outflows & Chimneys
- Super-Bubbles & ISM Structure
- GMCs/Star cluster IMFs
- Dark Matter Profiles
- Stellar & Gas Kinematics
- Re-ionization (FUV Escape Fractions)
- Outflow Duty Cycles/Observability
- Abundances/Enrichment

Clustering Matters

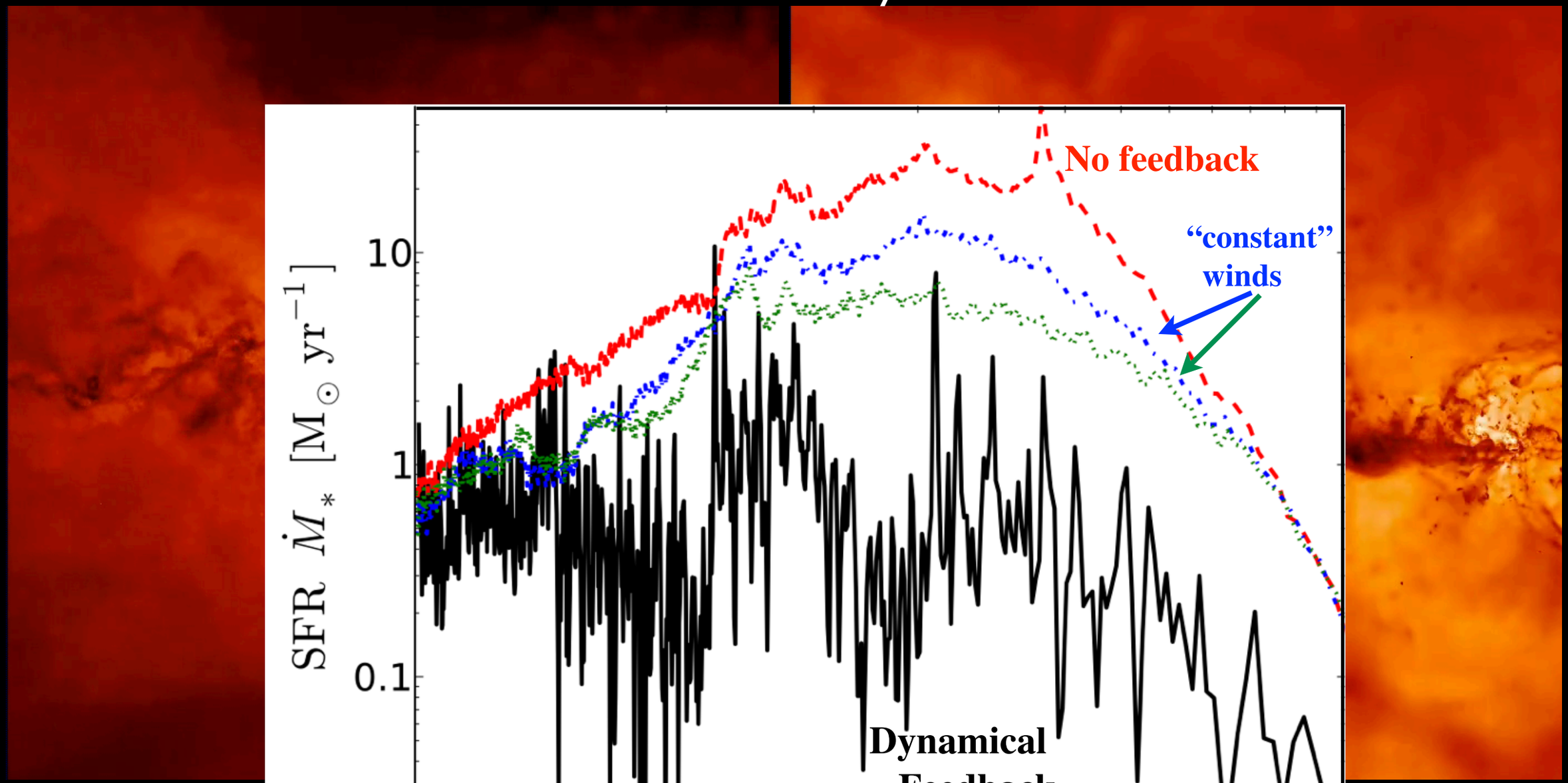
GALACTIC (kpc-Mpc) scales

PFH ‘14
M. Sparre
arxiv:1510.03869

Proto-Milky Way: Gas Temperature:

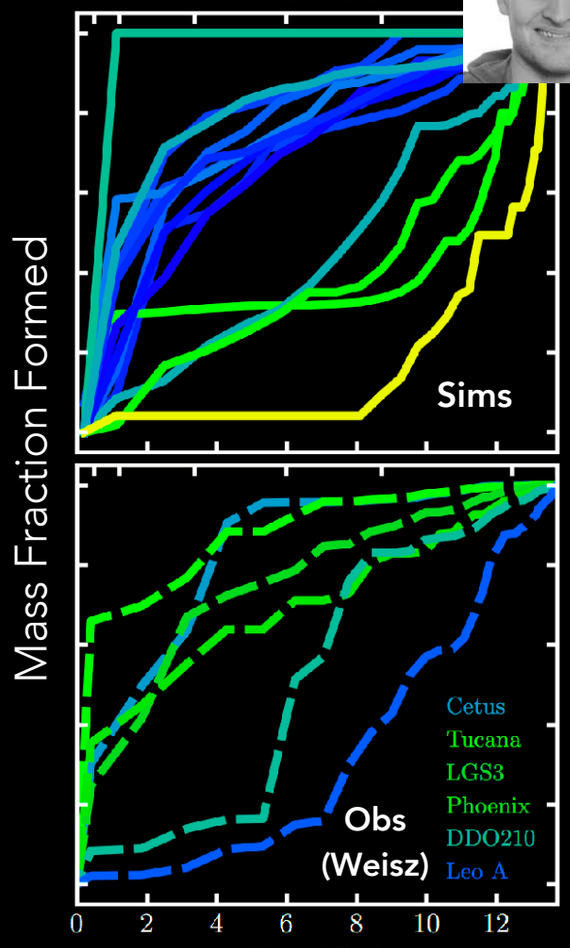
“Constant” Star Formation & Feedback

“Dynamical” Star Formation & Feedback



Imprints of Clustering in Dwarfs

Star Formation Histories

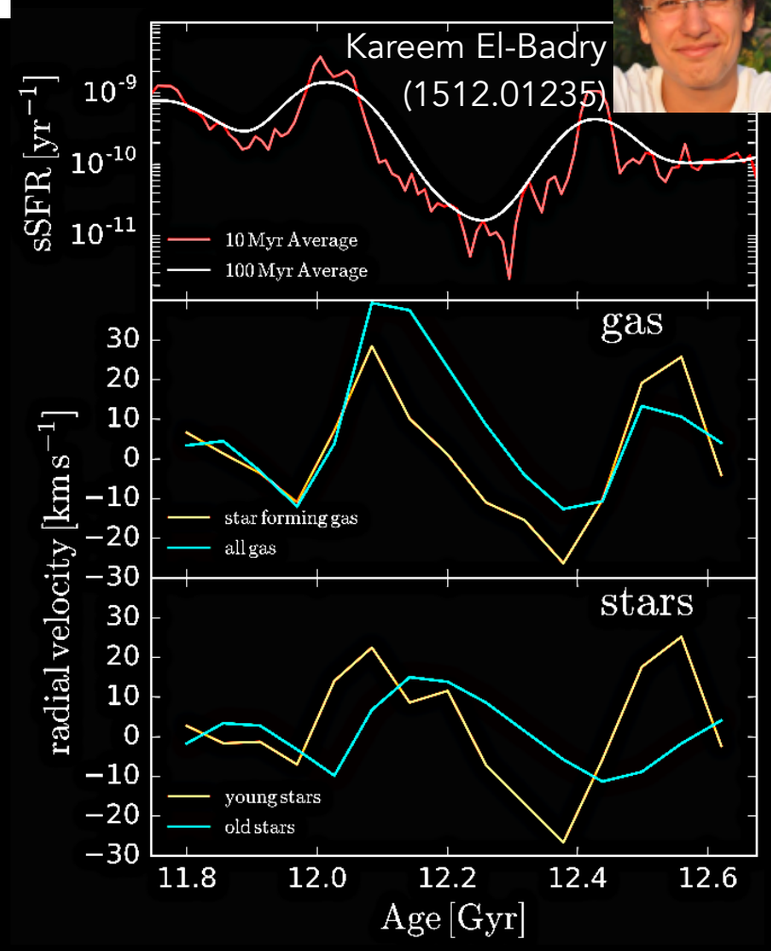


(Dwarfs) Fitts+1611.02281

(SFR-M*) Sparre +1510.03869

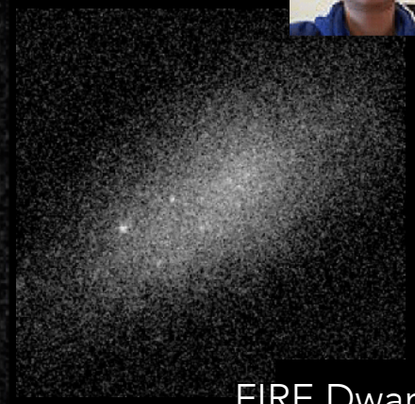
Dynamics & Profiles

Kareem El-Badry (1512.01235)



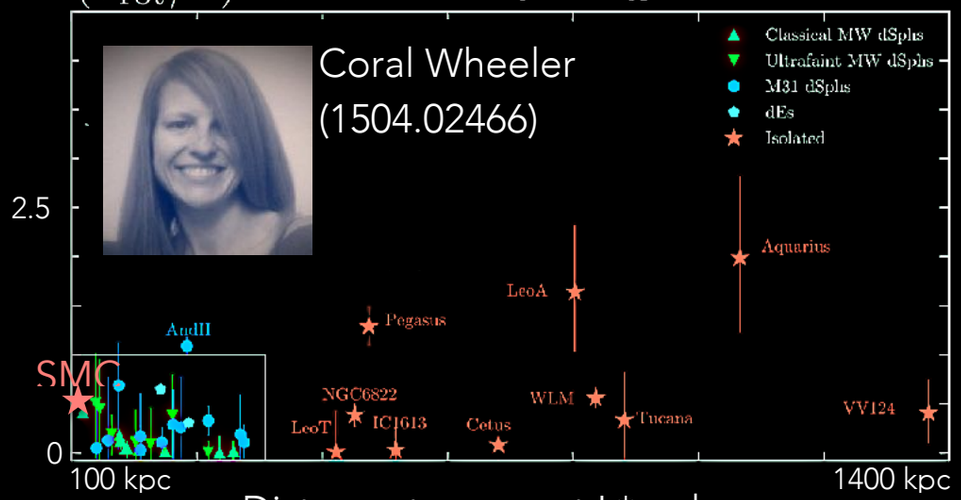
Cored DM profiles & Ultra-Diffuse Galaxies

TK Chan (1711.04788)



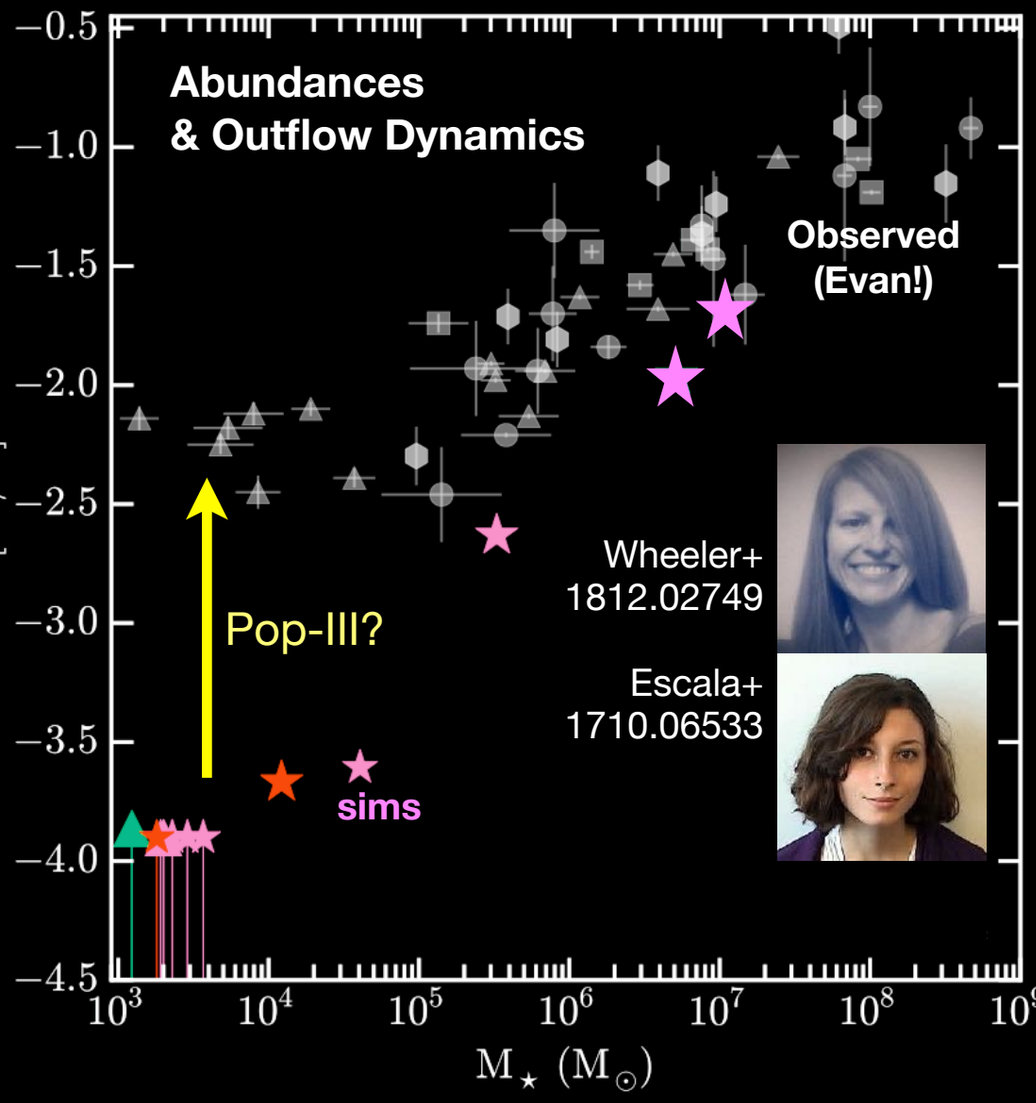
Morphologies & Kinematics

$(V_{\rm rot}/\sigma)$ vs :



Coral Wheeler (1504.02466)

Abundances & Outflow Dynamics

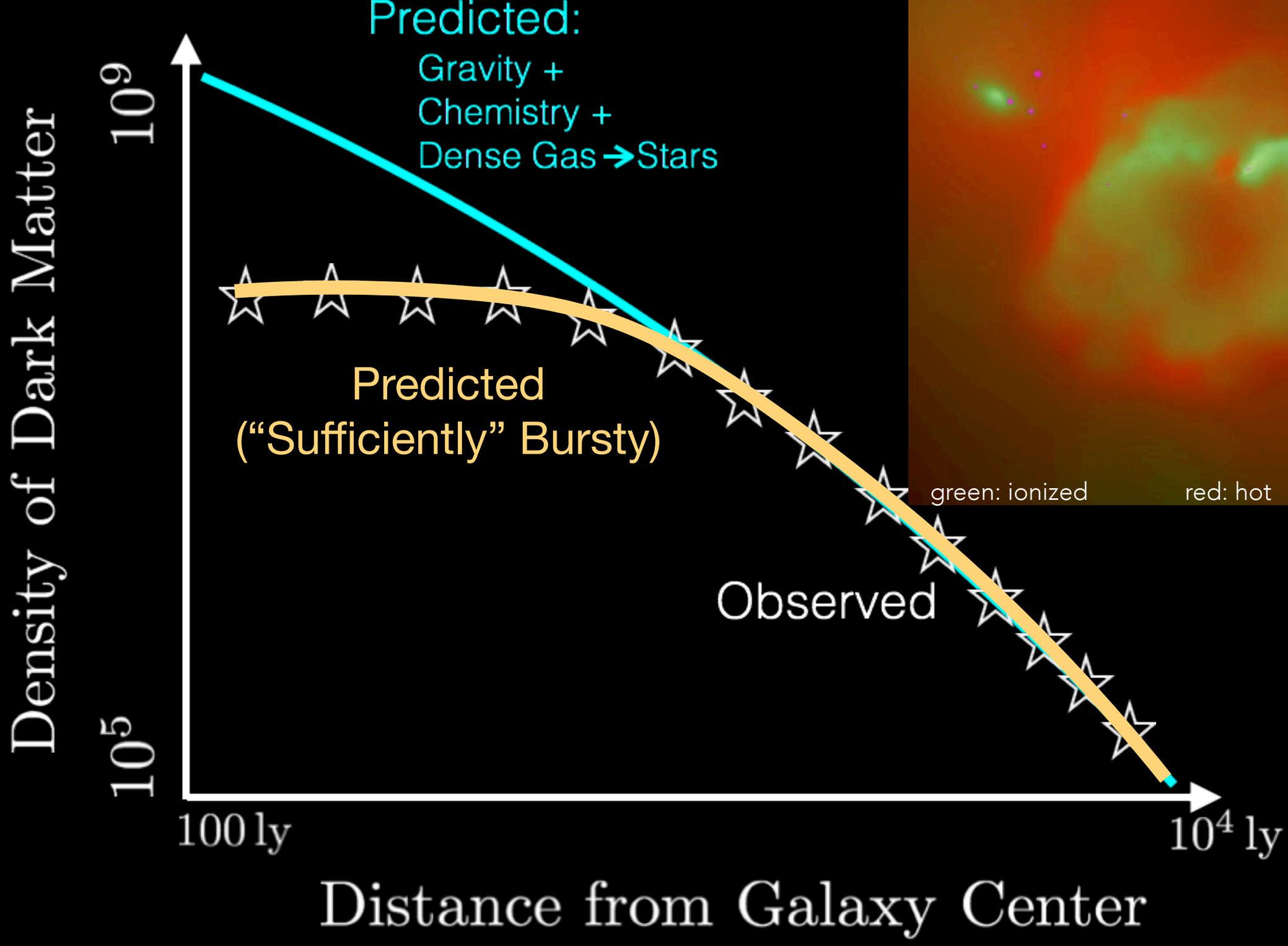


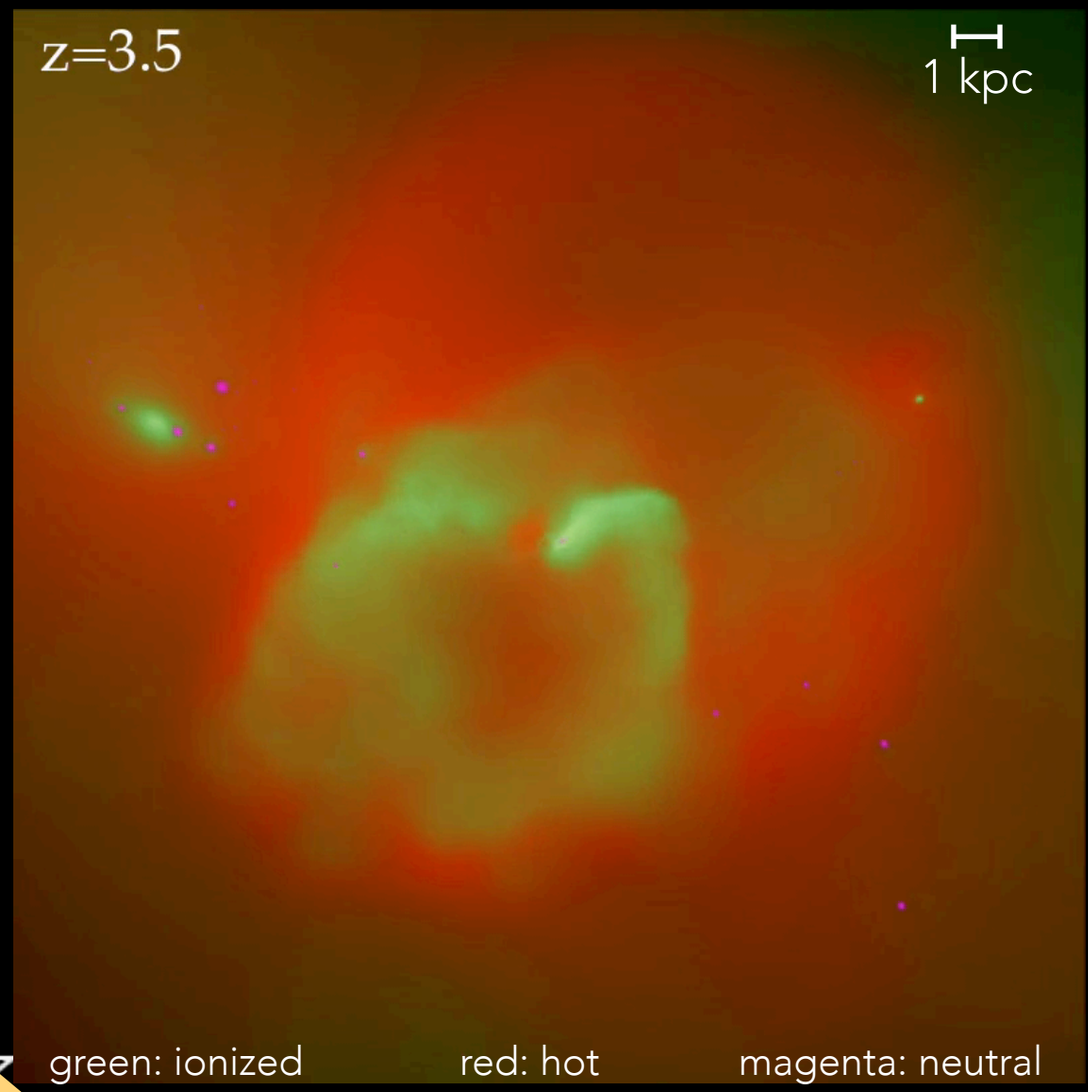
Wheeler+ 1812.02749

Escala+ 1710.06533

Feedback Saves Cold Dark Matter?

NO EXOTIC PHYSICS?





Onorbe et al.
(arXiv:1502.02036)
Chan et al.
(arXiv:1507.02282)
Wheeler et al.
(arXiv:1504.02466)
and…
Brook +12
Pontzen+ 12
Di Cinto+ 16

z=0.84

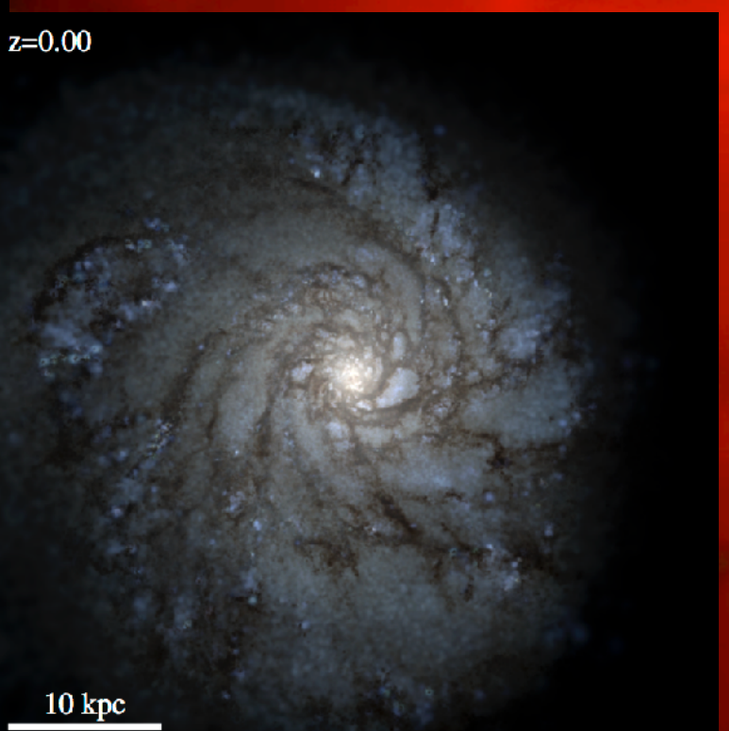
10 kpc

S. Muratov
(arXiv:1501.03155)

"feedback-dominated"
low mass
gas rich
cold, violent outflows

to

"gravity-dominated"
high mass
gas poor
gentle hot gas "venting"

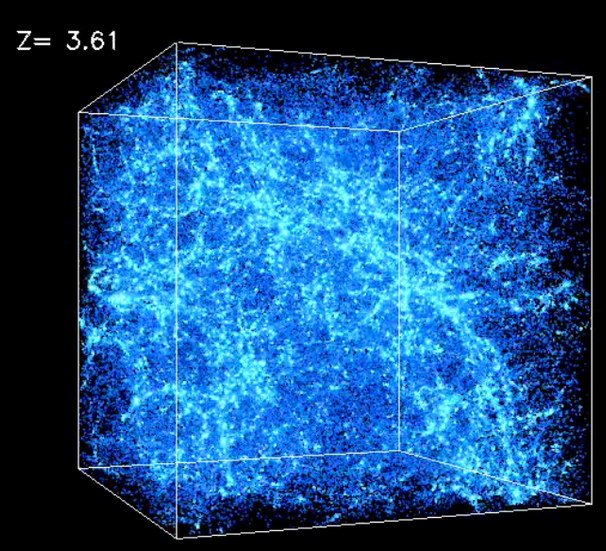


C. Hayward
(arxiv:1510.05650)

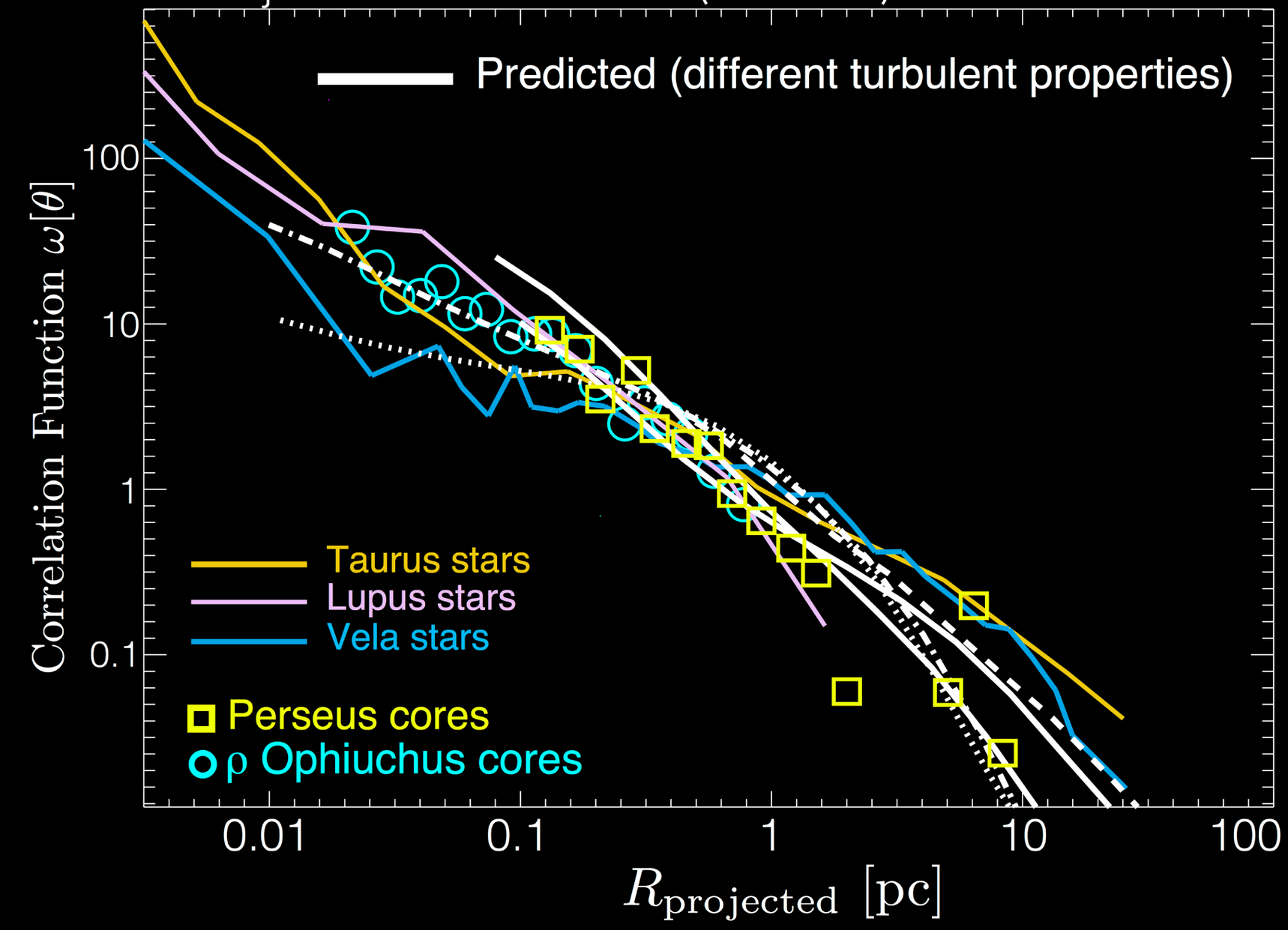
Transitions Key to Disk Formation

What is “Bursty-ness”?
Do We Understand Any of This?

Clustering is *inevitable* in gravitational structure



Guszejnov: arXiv:1610.00772 (+PFH '12)



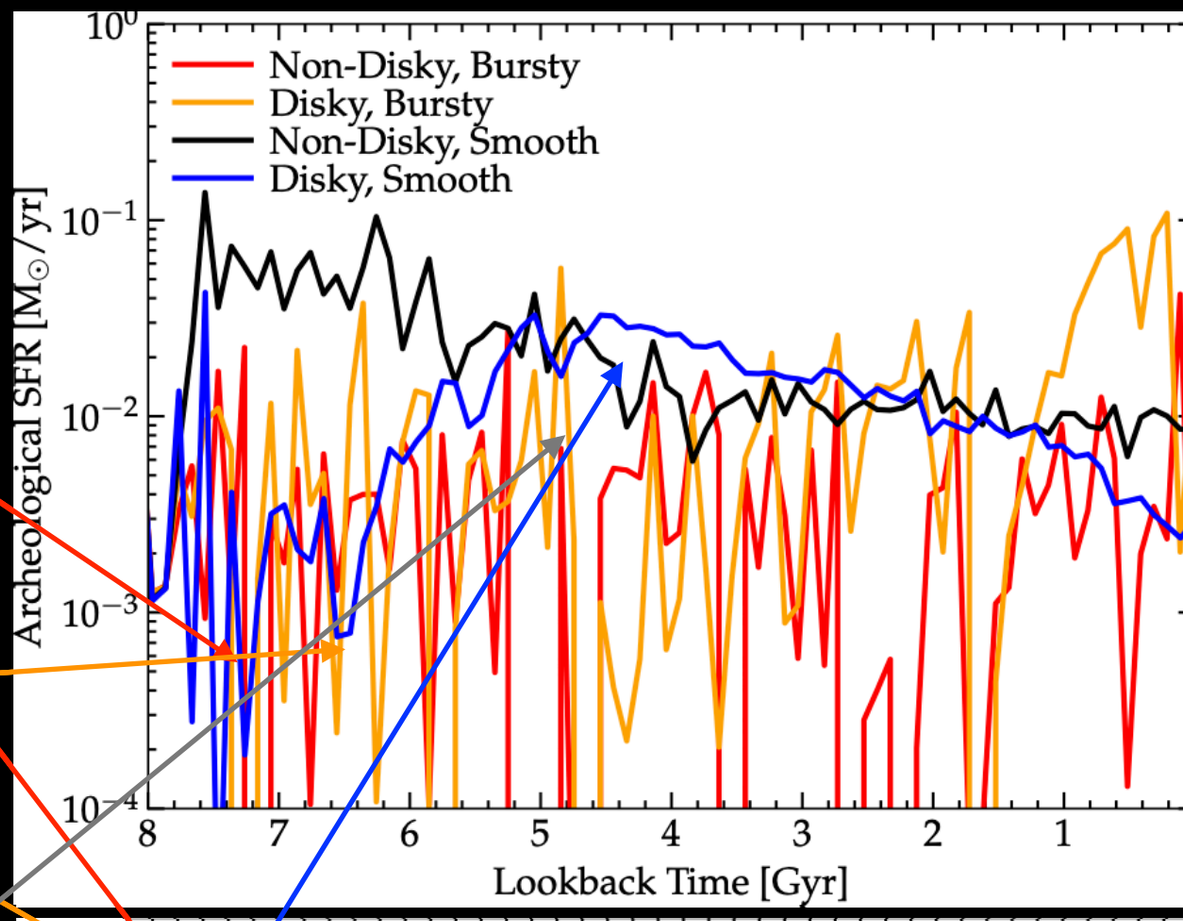
Universal
(Guszejnov+Grudic: 1707.05799):

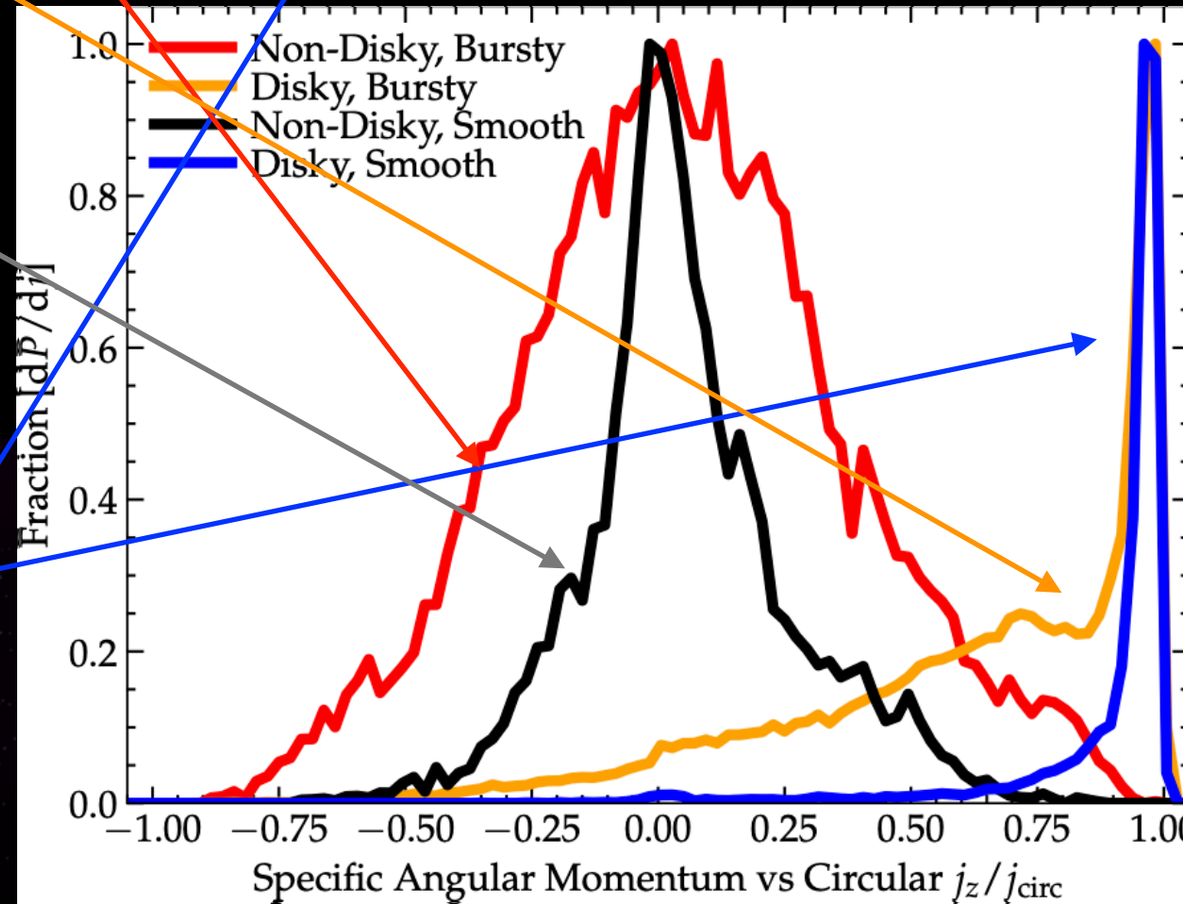
Stars
Cores
Clumps
GMCs
Star clusters
Galaxies

$$\xi_{\rm 3d} \propto r^{-2}$$
$$(\omega(\theta) \propto \theta^{-1})$$

BUT... Wide Range of Behaviors

PFH, Gurvich, Shen, Hafen+: arXiv:2301.08263



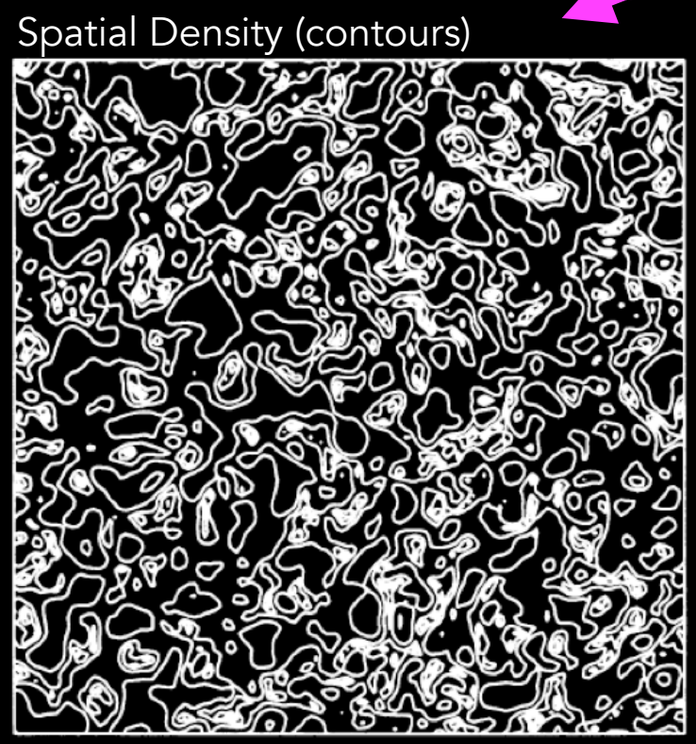


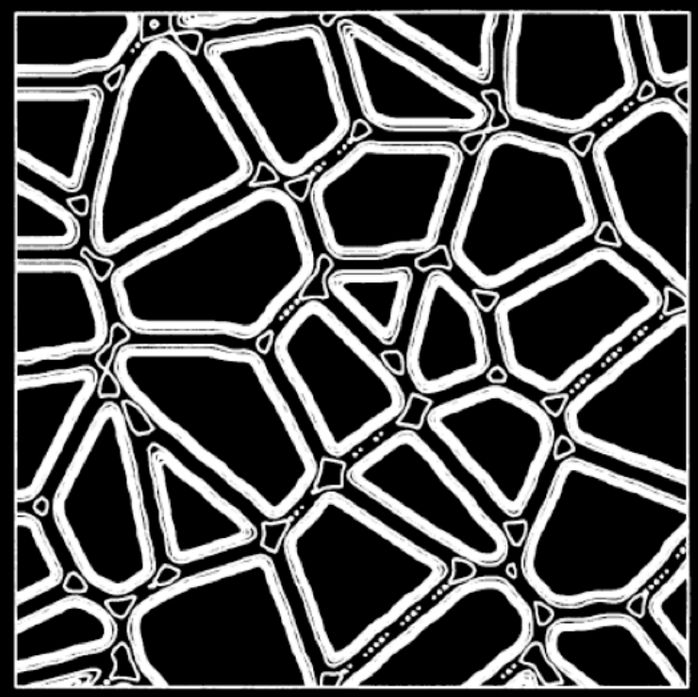
AND… Correlation functions aren't everything

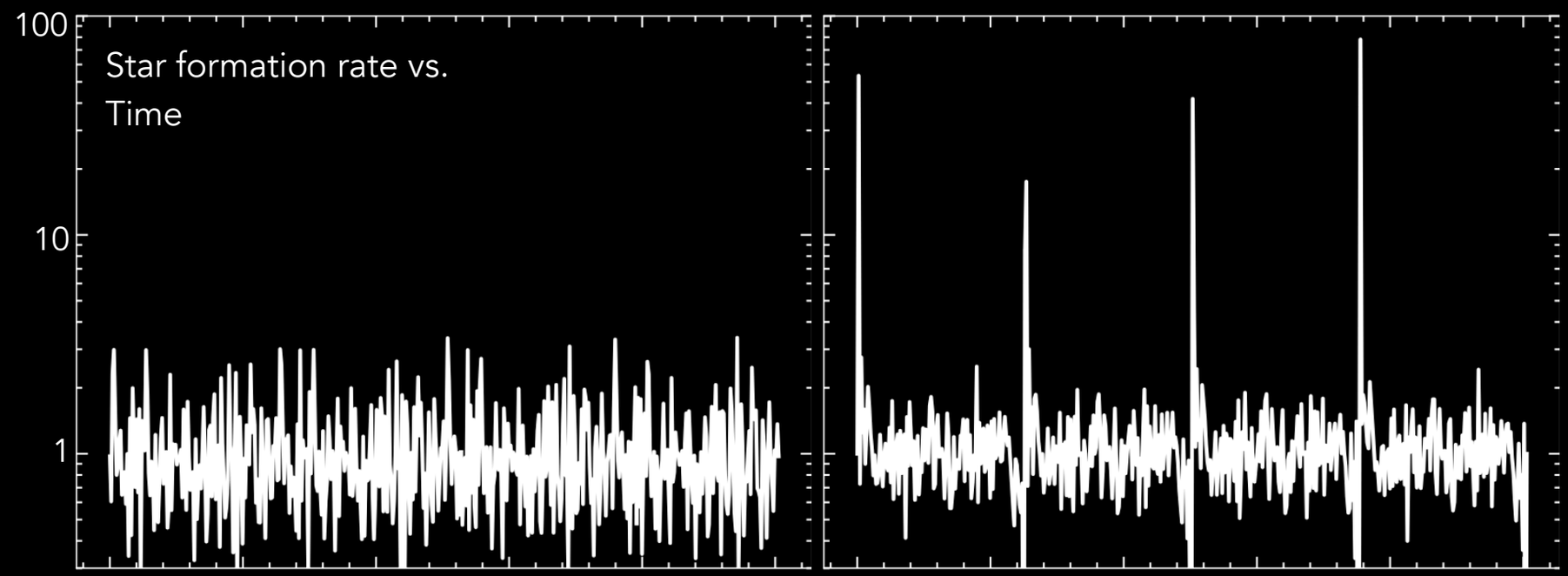
identical
power spectra

- **Theory**:
  - *Correlations important*
  - *Highly non-linear*
  - *How to compare? What's the metric?*

- **Observations**:
  - *Need additional diagnostics*
  - *Kinematics of the young stars key*
  - *Compare to gas*
  - *Large samples with different ages, to infer bursty-ness!*







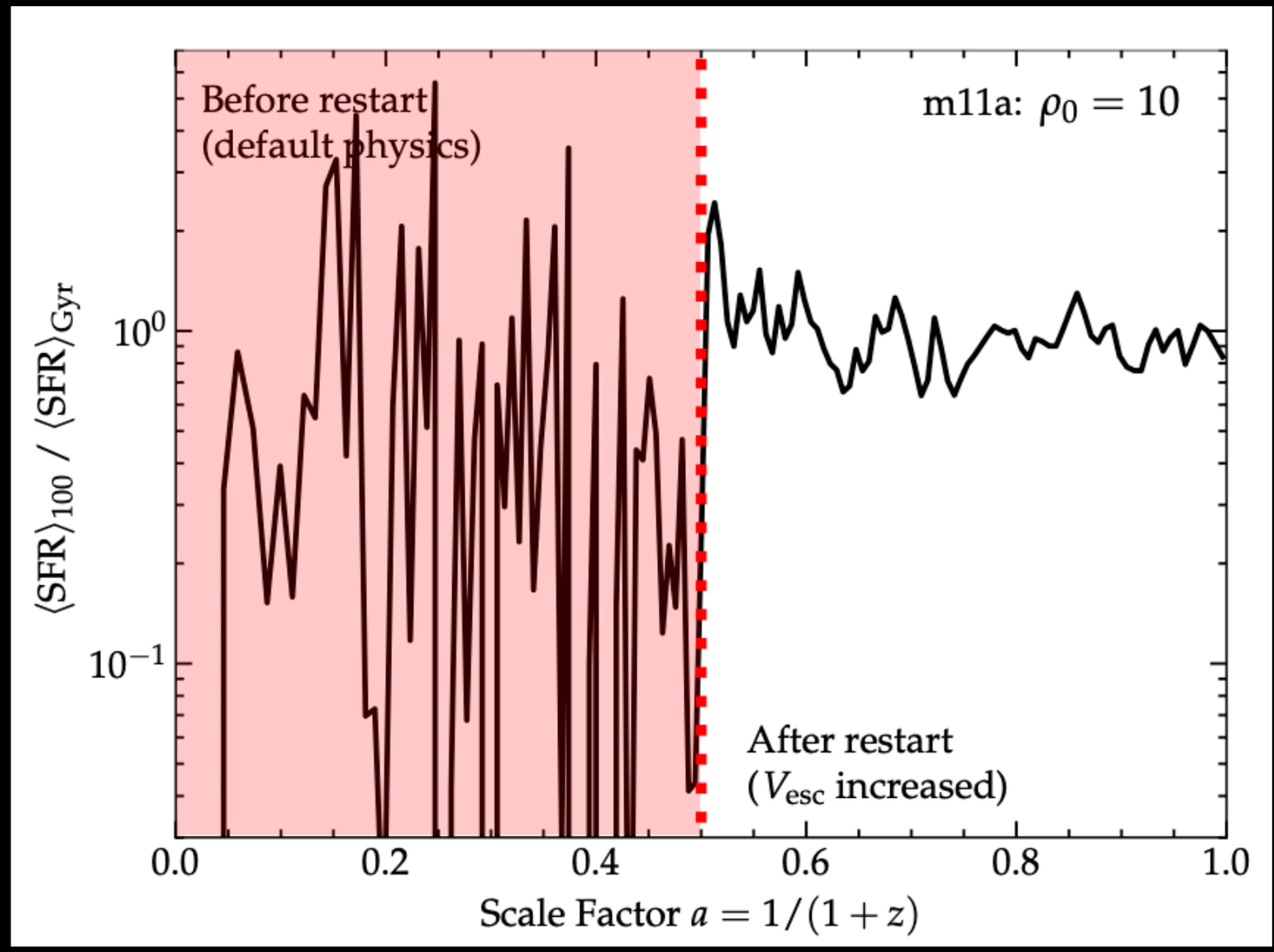
What *Physically* Influences Burstiness on "Global" Scales?

Many ideas:
All mutually correlated….

- Mass (halo or stellar or gas)
- Potential *shape*
- Gas fraction
- Feedback rates/strengths/physics/forms
- SF criteria/rates
- Formation times
- Spin (gas or halo)
- Toomre Q
- Cooling/dynamical times/rates
- Numerical methods
- Metallicities
- Accretion rates
- CGM vs ISM vs IGM temperature/pressure

Most *directly* sensitive to:

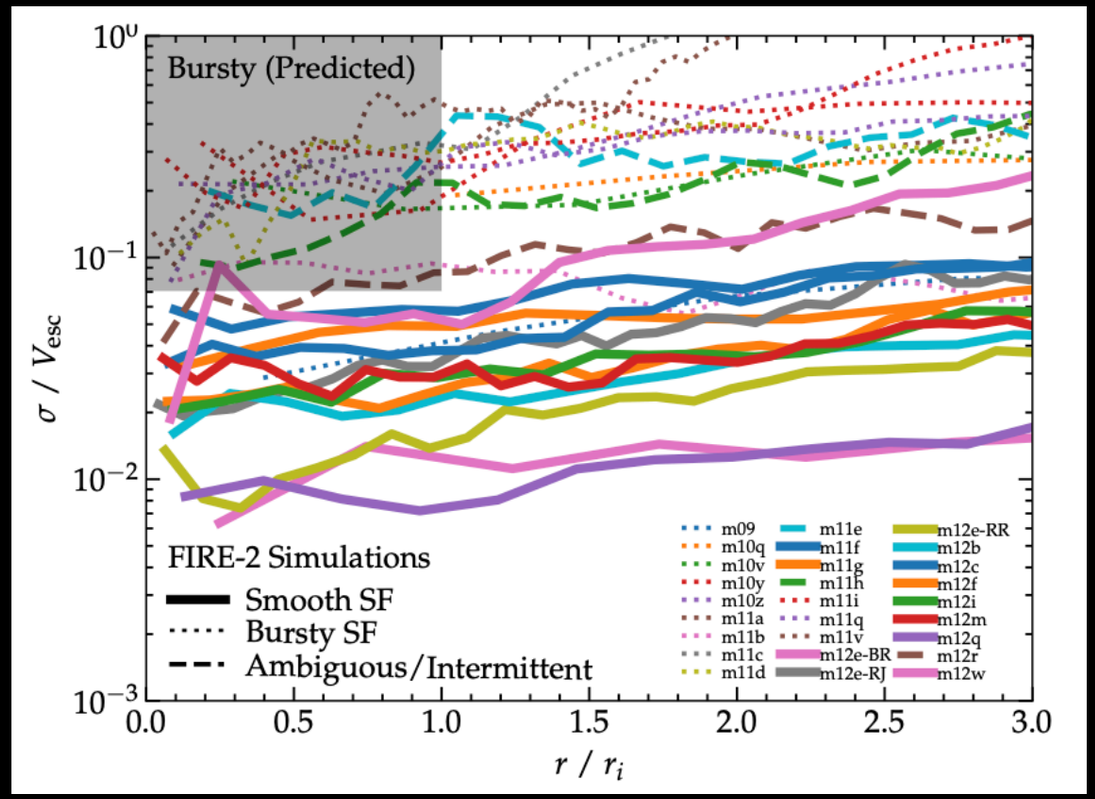
- *Depth* of the potential



PFH, Gurvich, Shen, Hafen+: arXiv:2301.08263

Why?

“Overshoot” and ejection of the ISM is minimized

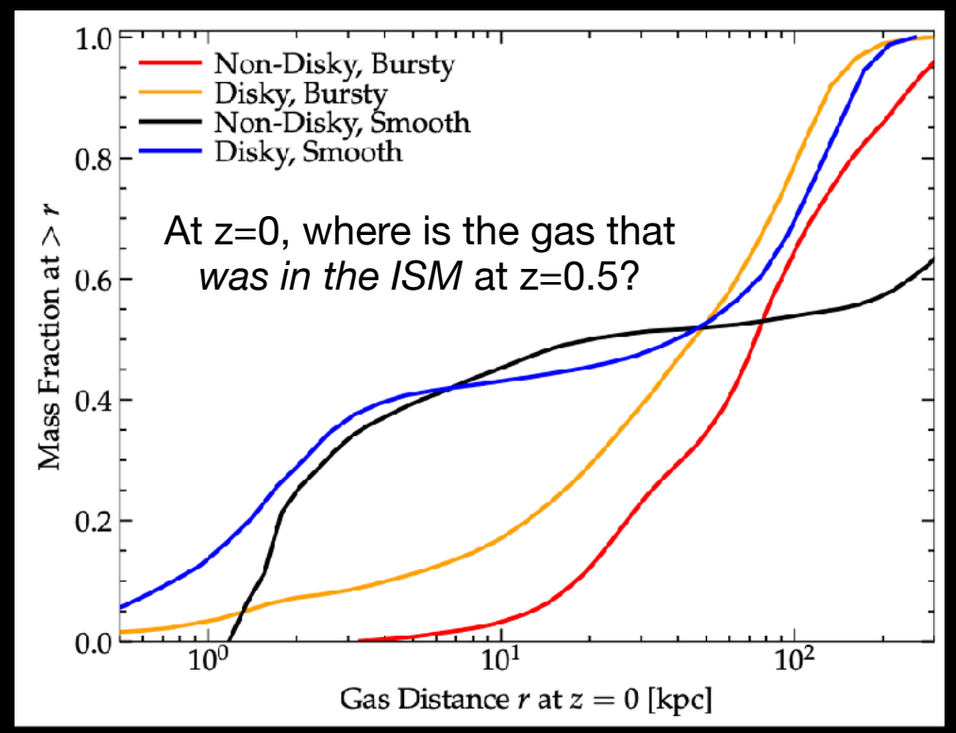


Chris Hayward (HH17):
Predicted “overshoot zone”

1. Deeper potential = harder to eject the ISM?
   - given SF in ISM from *local* self-regulation, ability to eject scales $\sim \sigma/V_{\rm esc}$? amplitude?

2. Ejected gas travels less far, stays in/near disk?
   - SF always *locally* bursty (~kpc or galaxy center), but “ejected” gas stays in disk? coherence?

3. Recycling time reduced: outflows → fountains?



Lots to do!

- **SF is “coherent” (*clustered* in space & time) on *all scales***
- **“How Clustered?” matters, & *deeply uncertain***
  - **“How strong?” (amplitude)**
  - **“How coherent?” (phases)**
  - **“What scales?” (spatial/time coherence)**
  - **“Is it stable?” (self-reinforcing/non-linear)**

“Zoom in” on AGN accretion disks

Sarah Wellons (2203.06201)

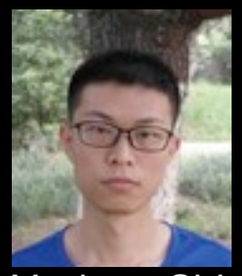
Daniel Angles-Alcazar

Axion & dissipative & EMD dark matter tests

X. Jacob Shen (2206.05327)

Isabelle Sands

Stellar mergers & hyper-Eddington accretion -> IMBH



Yanlong Shi (2008.12290)

Kyle Kremer

B-field diagnostics: Zeeman, RM/DM, dust polarization

Gina Panopoulou

Sam Ponnada (2206.04764)