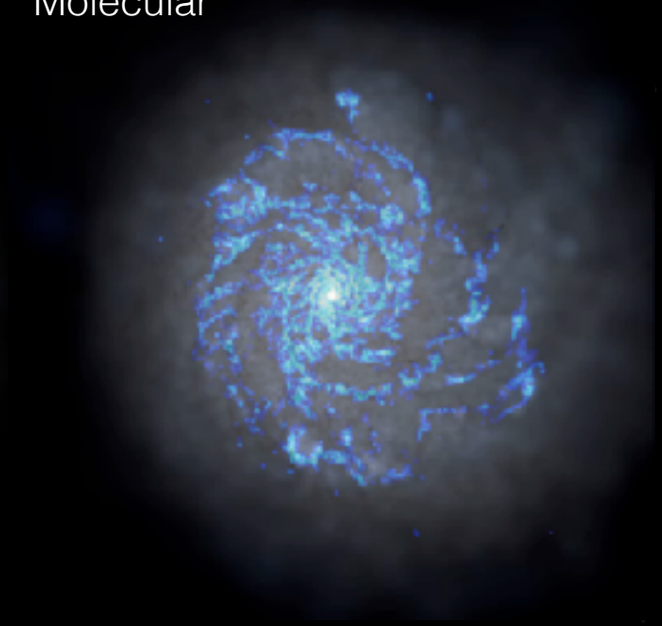
Feedback: Nature Hates Theorists

Observed Starlight

Molecular



Galaxy Merger

X-Rays

Star Formation

Philip F. Hopkins & the FIRE Team

Caltech

~10^{10} pc

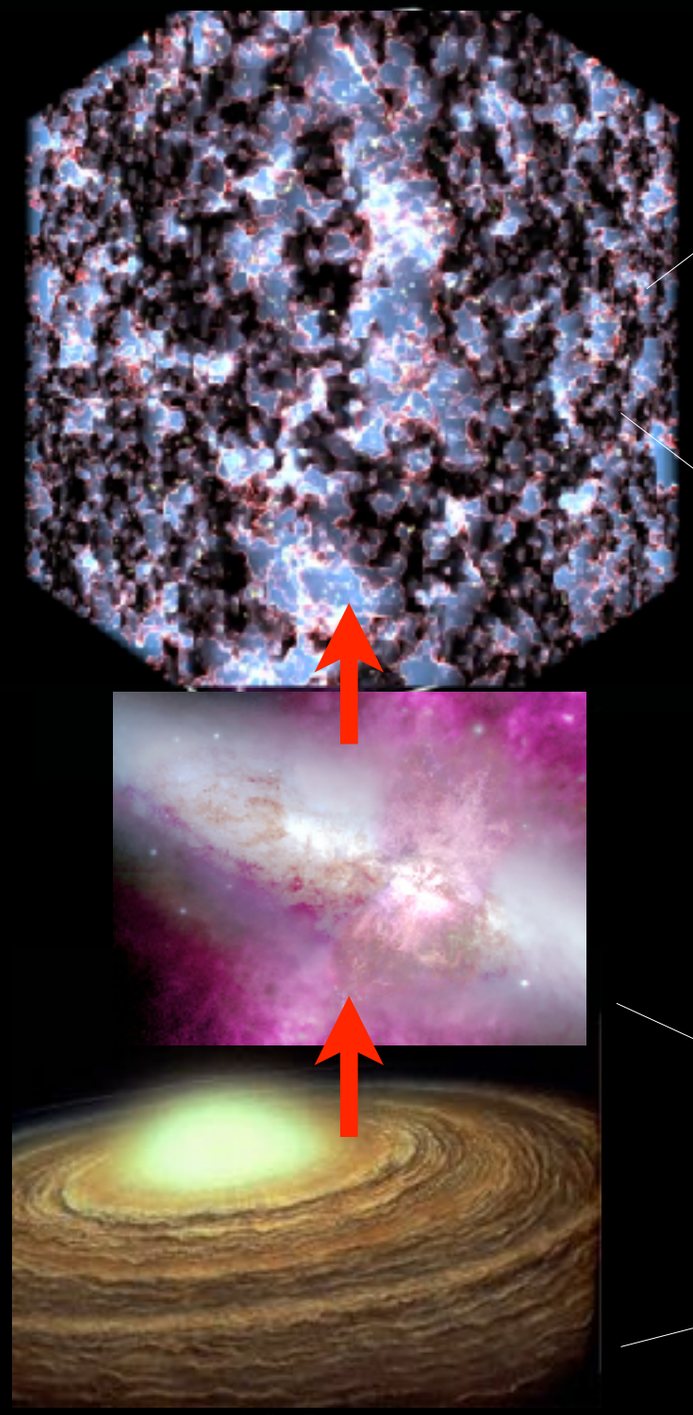
Hubble volume

~10^{7}-10^{8} pc

Clusters, Large-scale structure

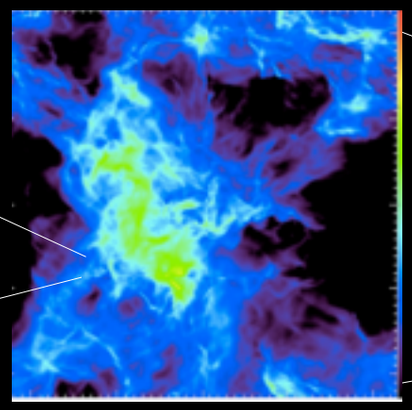
~10^{4-5} pc

Galaxy



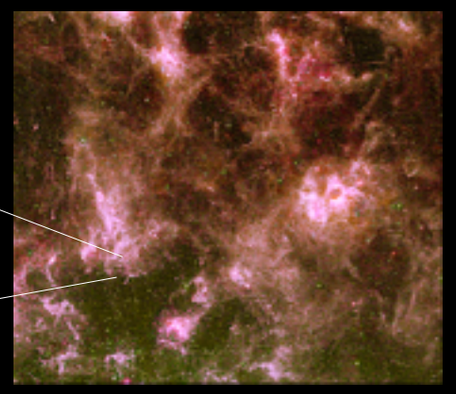
~10^{-5} pc

Stars, protostellar disks



~10^{-2}-10^{0} pc

Cores, clusters,
Supernovae blastwaves

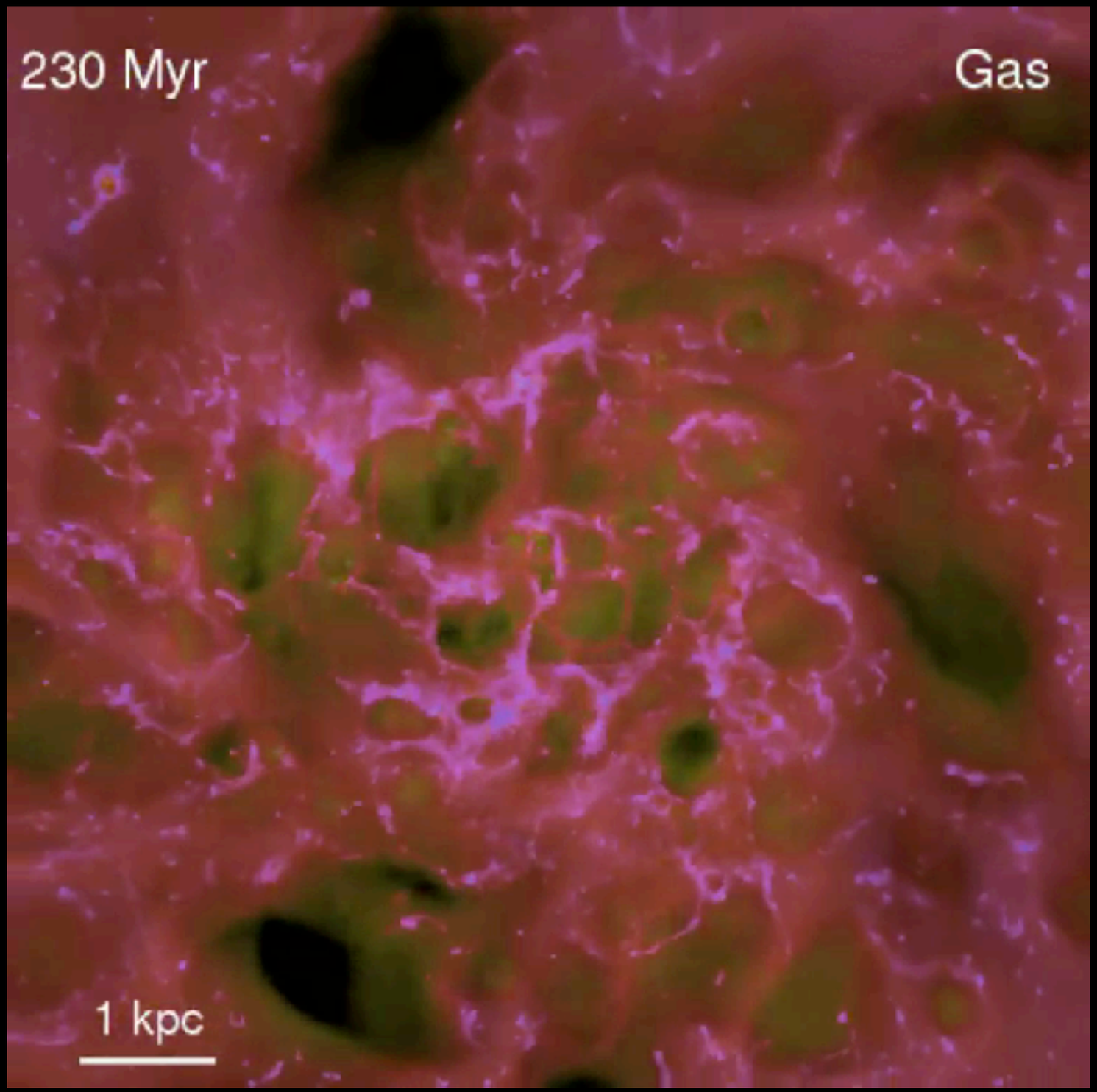


~10^{1}-10^{2} pc

Molecular clouds,
Star-Forming Regions

The FIRE Project

Feedback In Realistic Environments



Yellow: hot (>10^6 K) Pink: warm (ionized, ~10^4K) Blue: cold (neutral <10-8000 K)

- Resolution ~pc
  Cooling & Chemistry ~10 - 10^{10} K

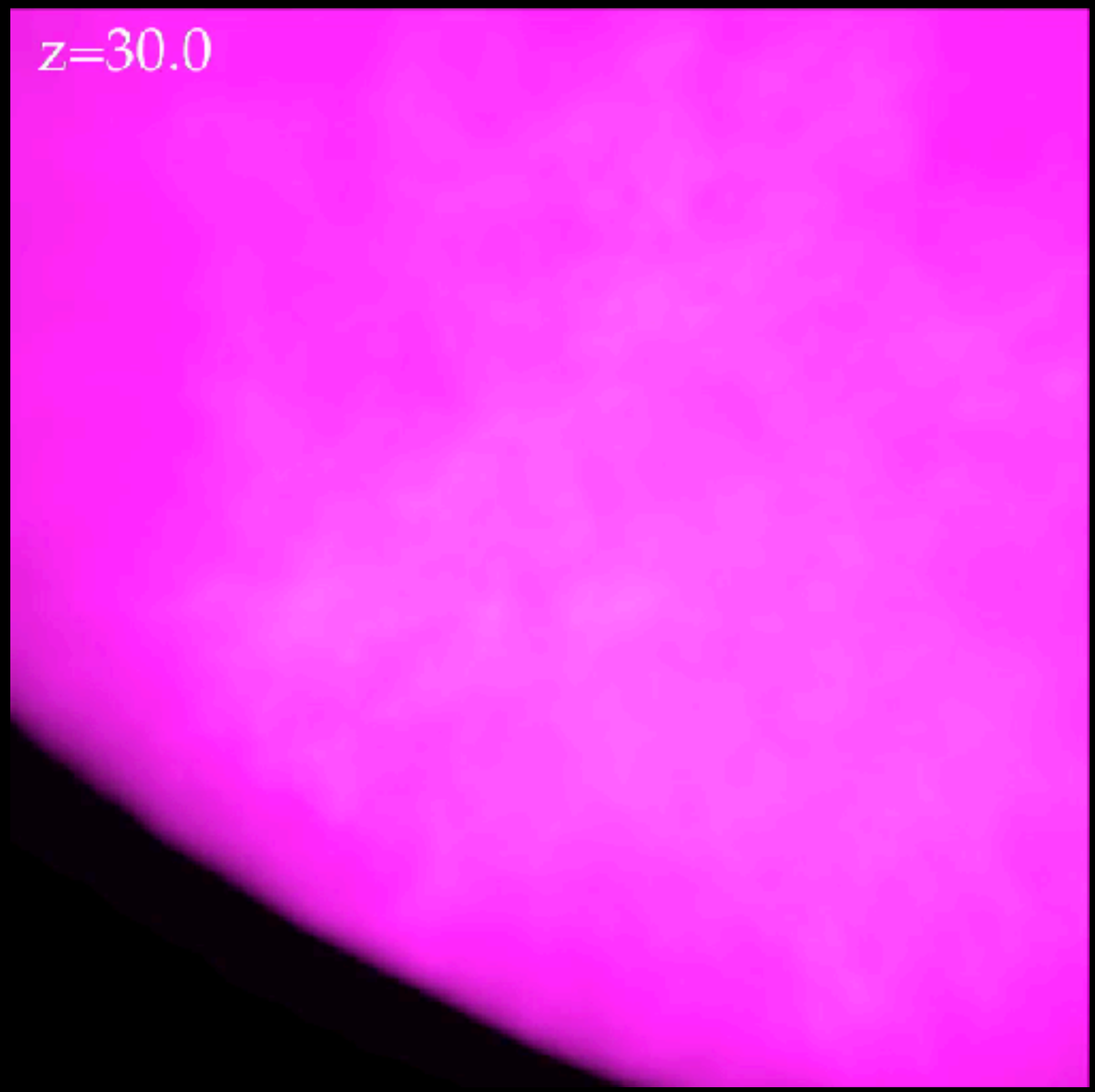
- **<u>Feedback:</u>**
  - SNe (II & Ia)
  - Stellar Winds (O/B & AGB)
  - Photoionization (HII regions)
    & Photo-electric (dust)
  - Radiation Pressure (IR & UV)

- now with…
  - Magnetic fields
  - Anisotropic
    conduction & viscosity
  - Cosmic rays

www.tapir.caltech.edu/~phopkins

z=30.0

10 kpc



Stars (Hubble image):

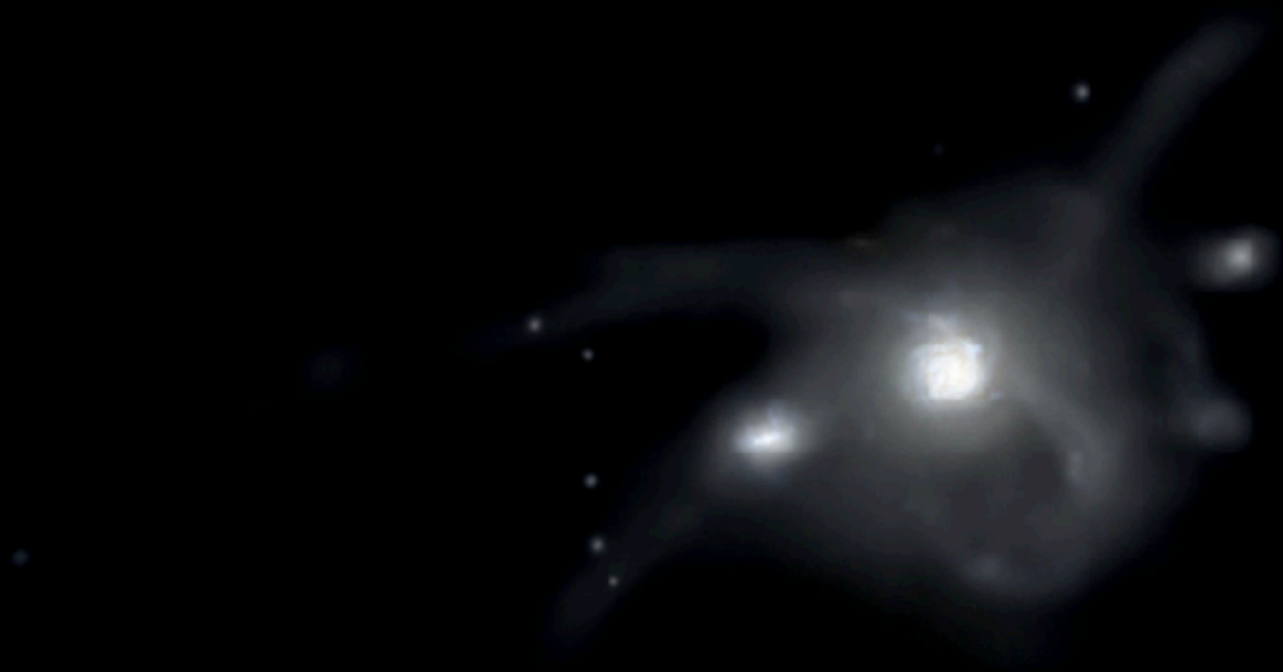
Blue: Young star clusters

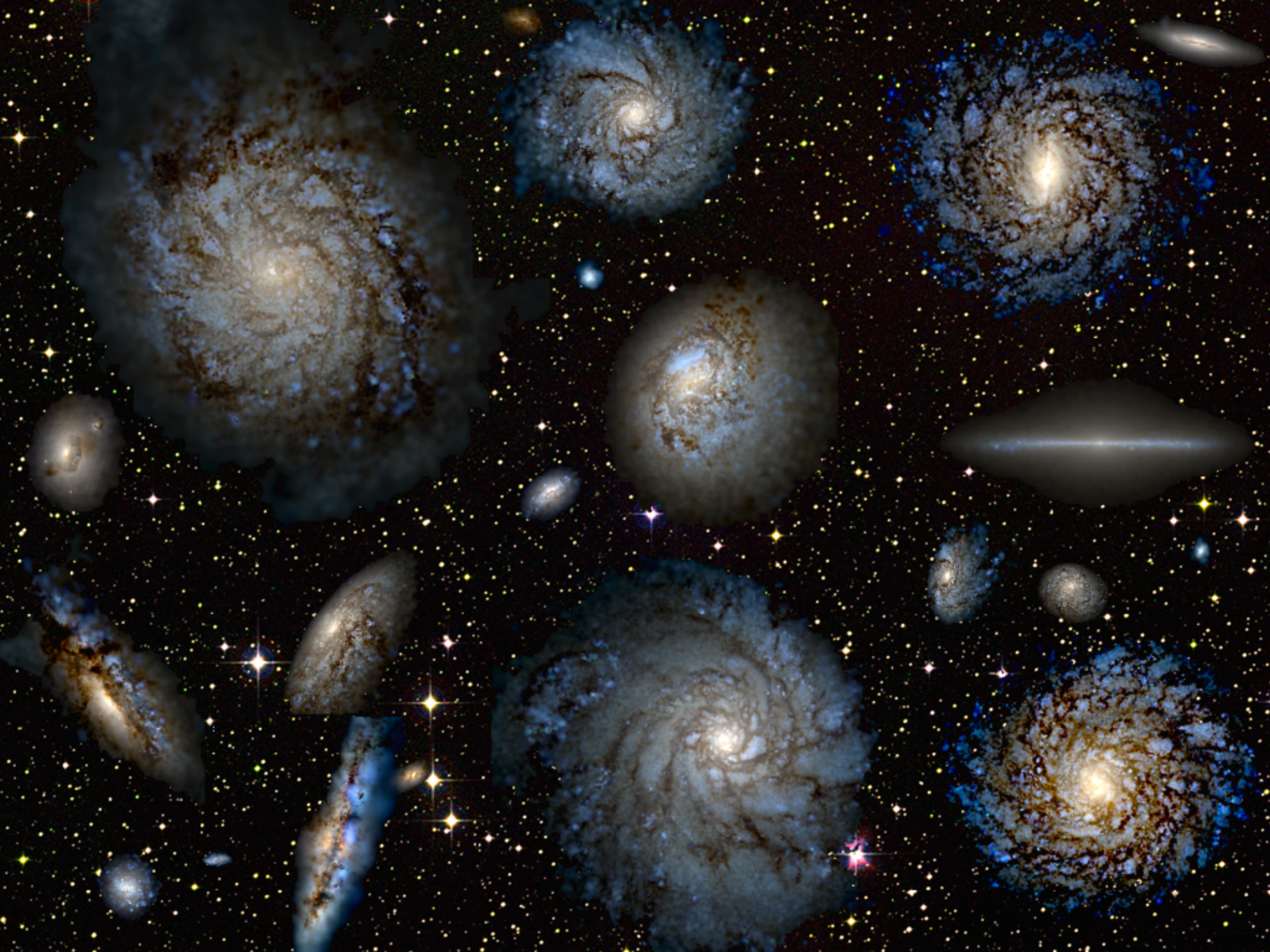
Red: Dust extinction

Gas: Magenta: cold $(< 10^4\ K)$

Green: warm (ionized)

Red: hot $(> 10^6\ K)$

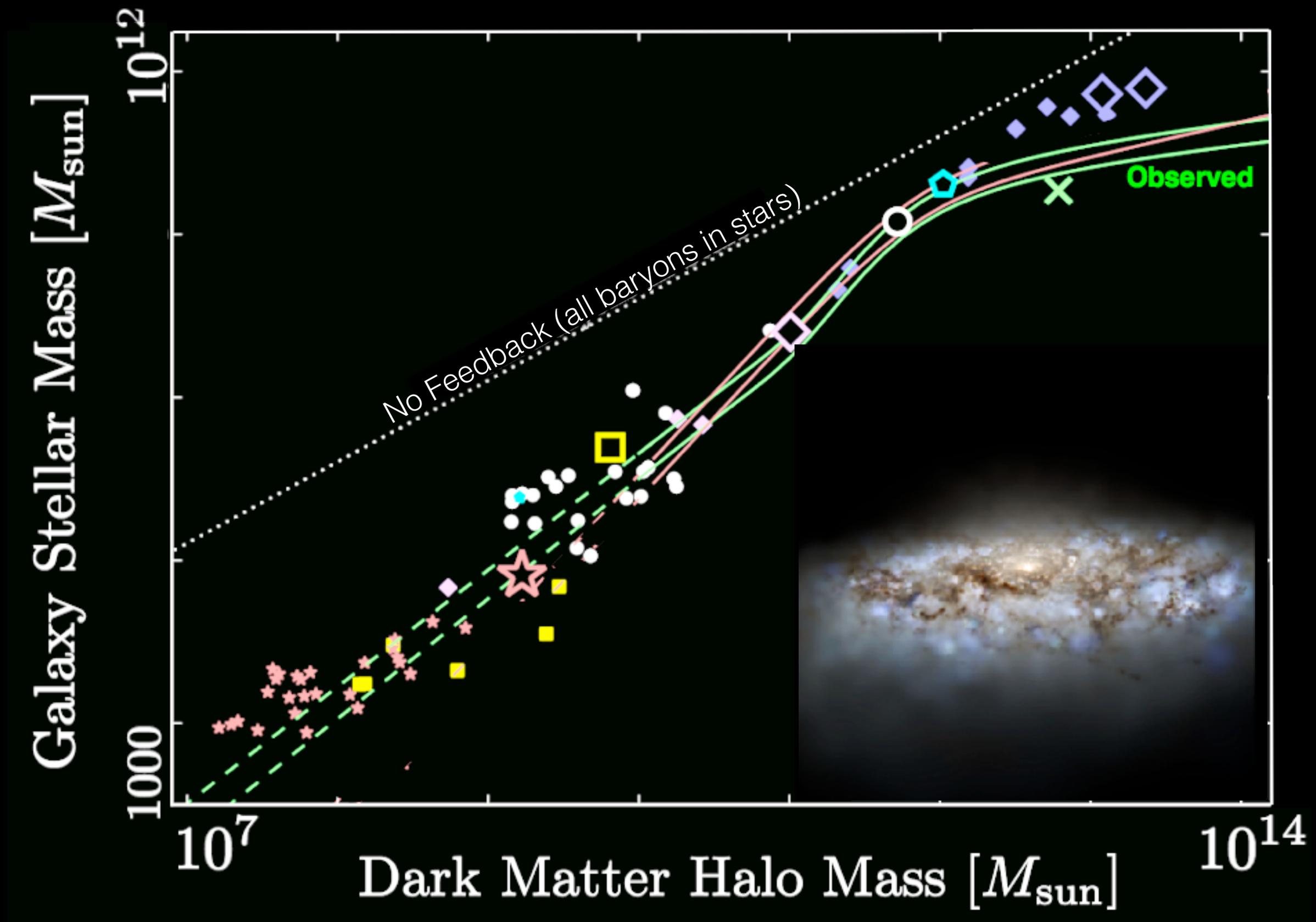




Why Are Galaxies Such Lightweights?

GAS IS BLOWN OUT, INSTEAD OF TURNING INTO STARS

PFH et al.
(arXiv:1311.2073)



Sub-Grid is not Enough

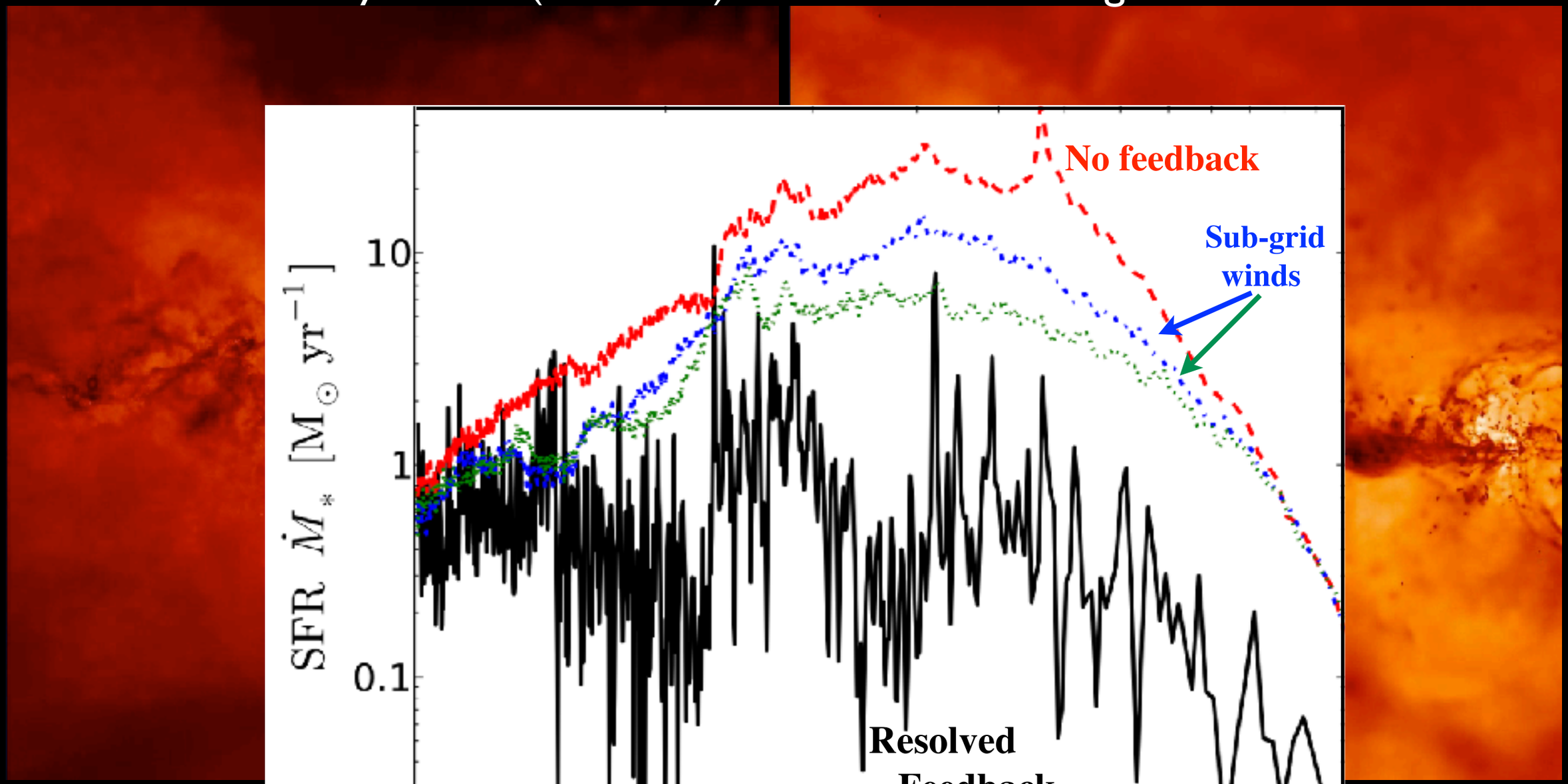
PHASE STRUCTURE & OUTFLOW DETAILS MATTER

PFH '14
M. Sparre
arxiv:1510.03869

Proto-Milky Way: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)

Following Full Feedback

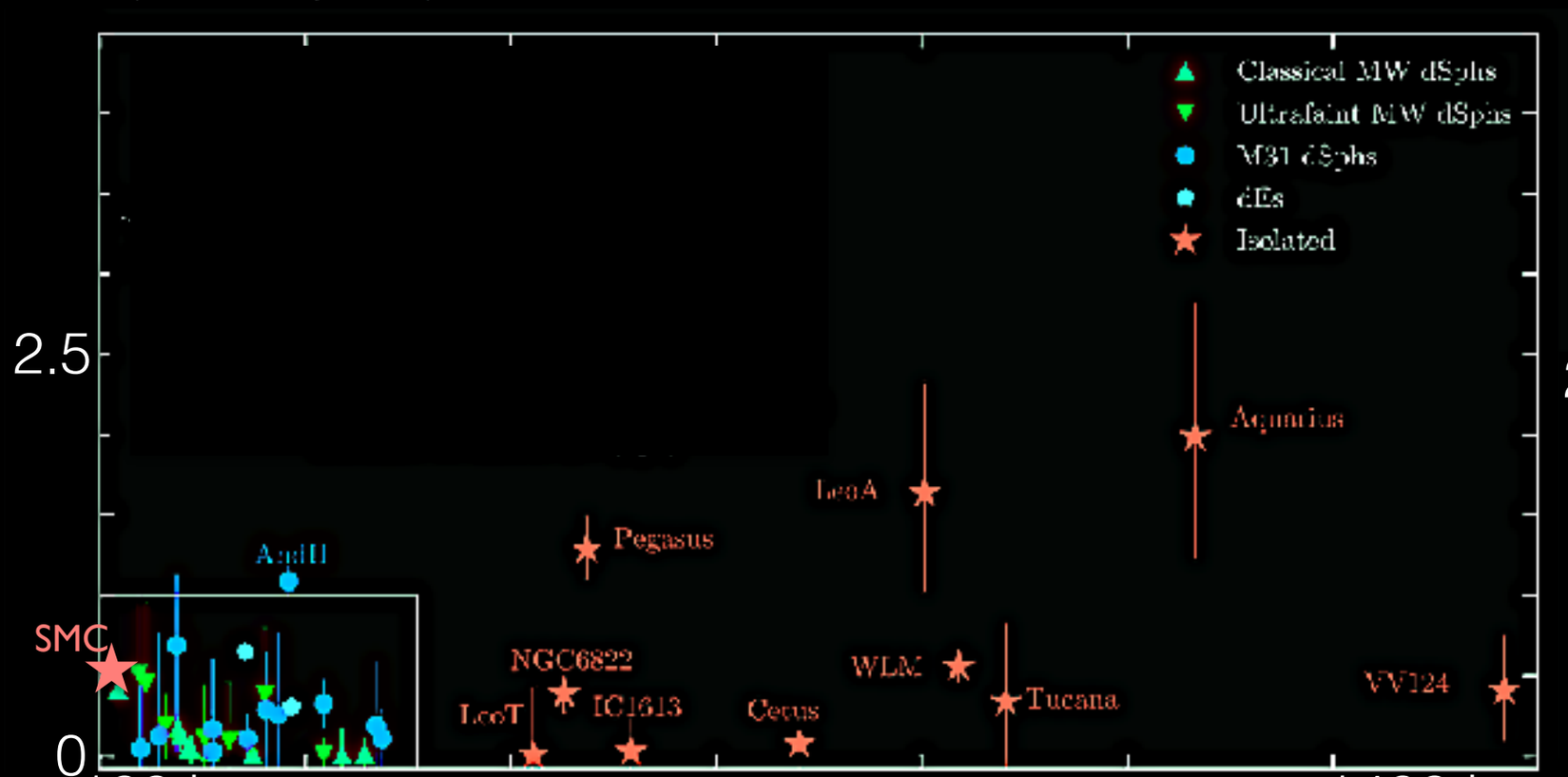


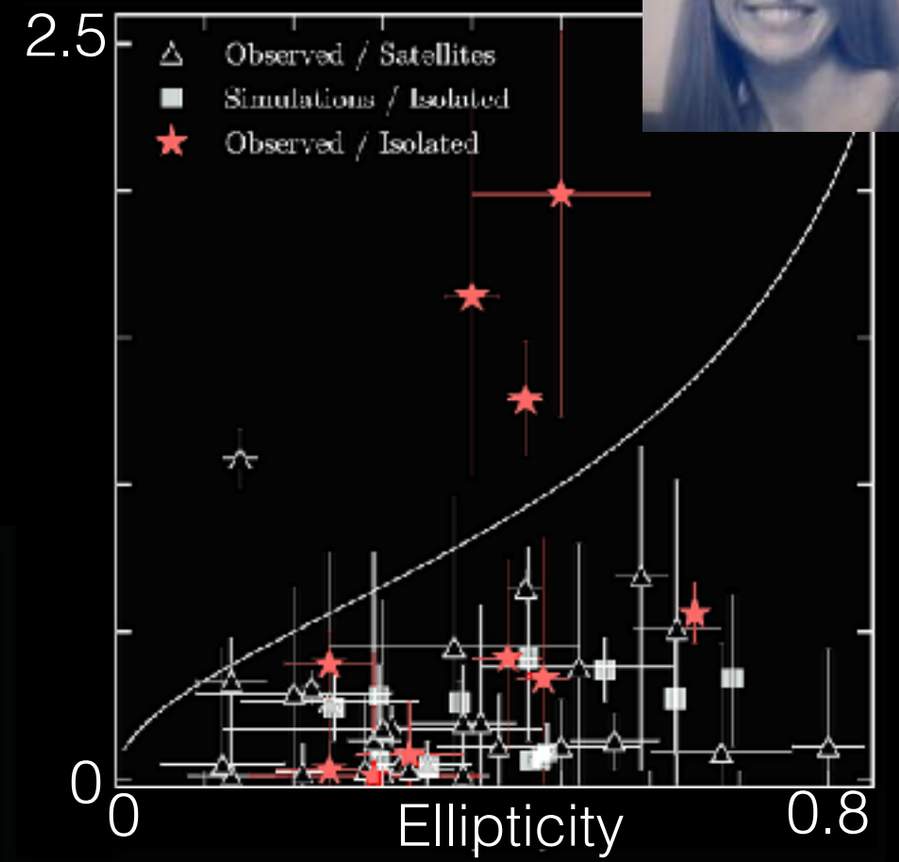
"Stirring" By Feedback = Most Dwarfs Don't Rotate

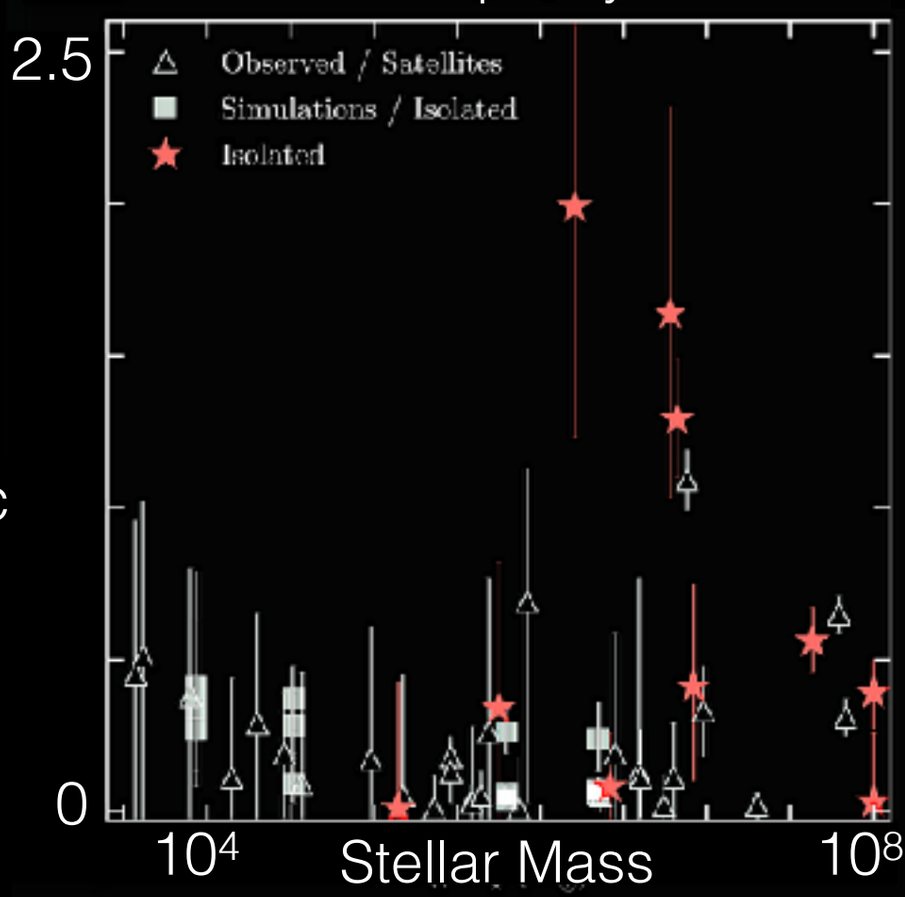
OBSERVED+SIMULATED dIrr/dSph

C. Wheeler
arXiv:1504.02466

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

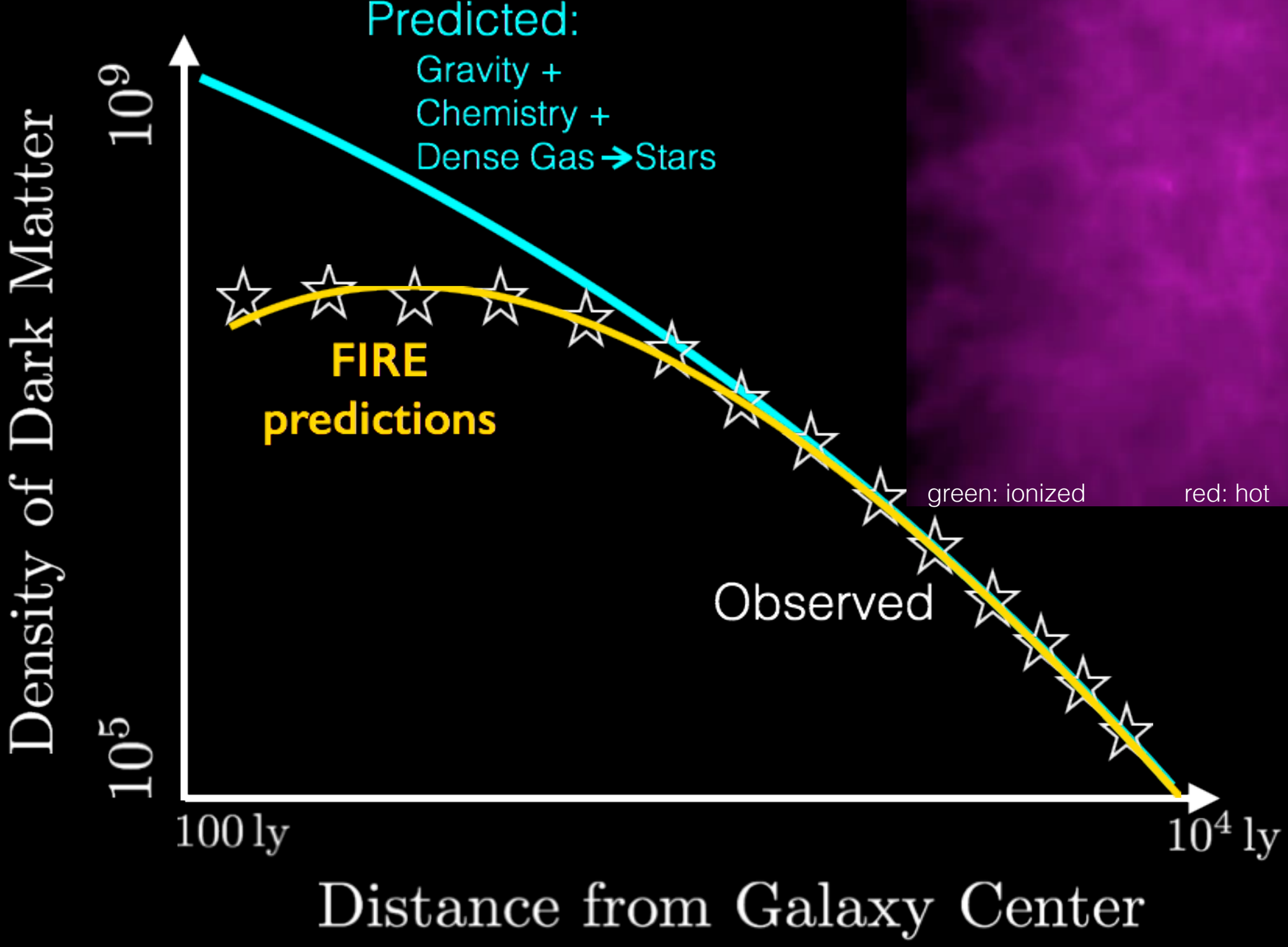


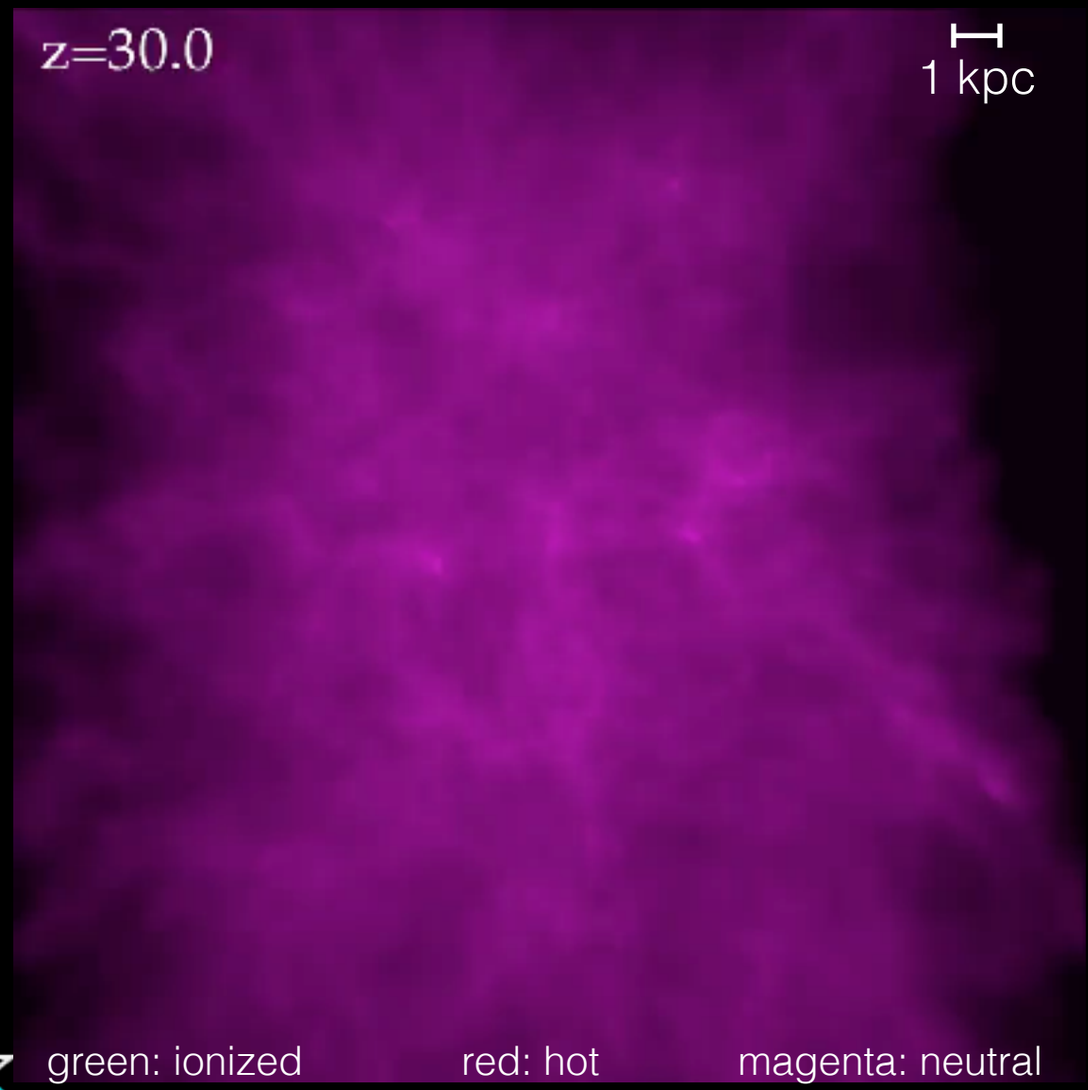




Feedback Saves Cold Dark Matter?

NO EXOTIC PHYSICS NECESSARY



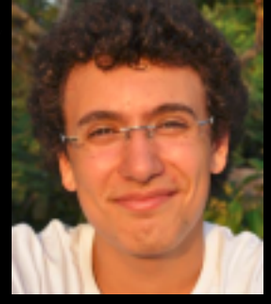


Onorbe et al.
(arXiv:1502.02036)
Chan et al.
(arXiv:1507.02282)
Wheeler et al.
(arXiv:1504.02466)

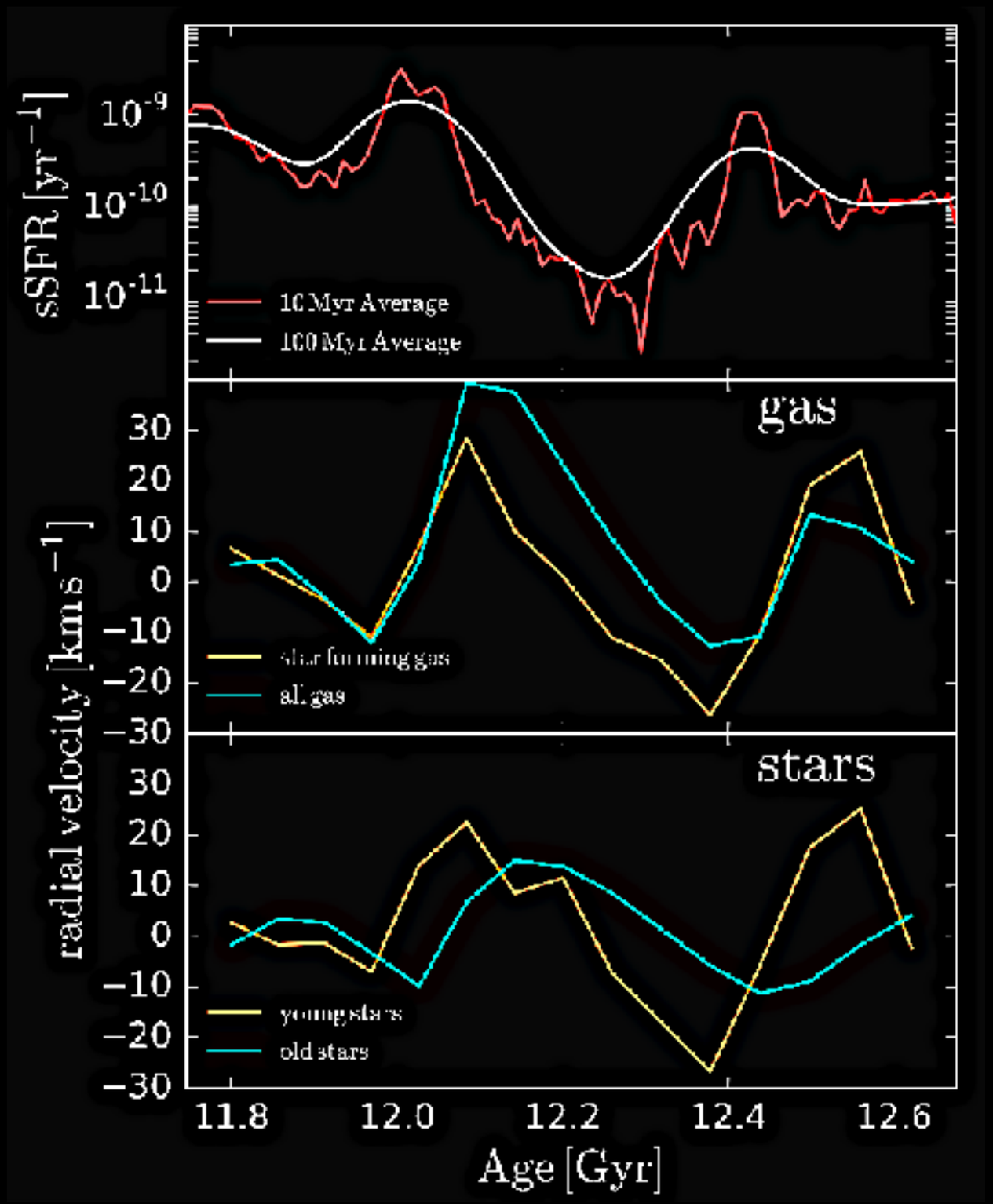
Direct Consequences for Structure

BURSTY SF = STARS MIXED, JUST LIKE DM

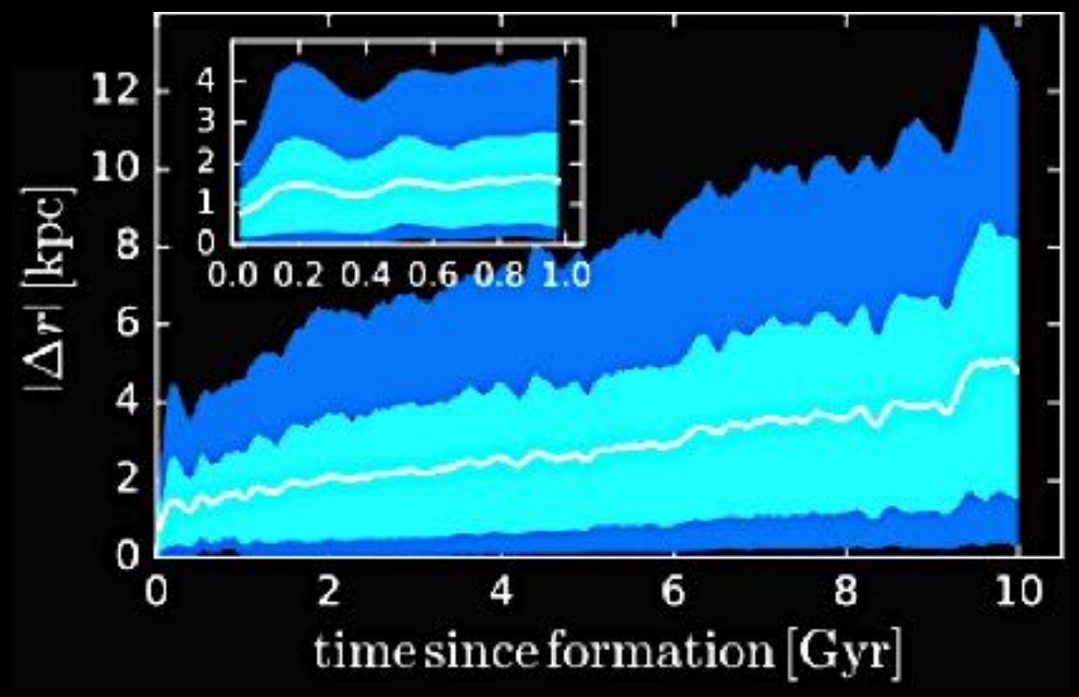
K. El-Badry
(arXiv:1512.01235)



Radial "breathing" in each burst:



Orbits "pumped up"



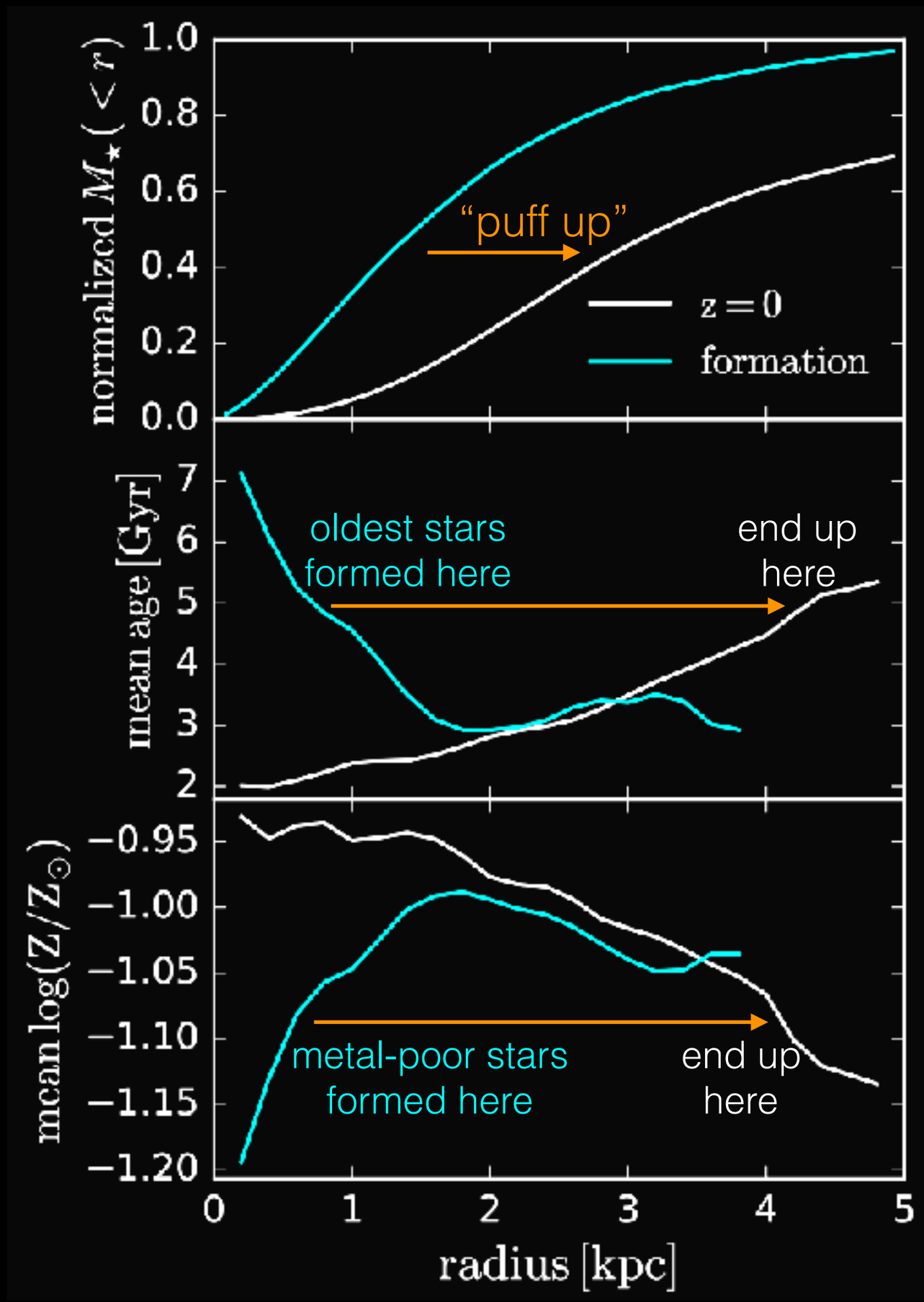
- If DM orbits perturbed, stars are too!

Direct Consequences for Structure

BURSTY SF = STARS MIXED, JUST LIKE DM

K. El-Badry, arXiv:1512.01235

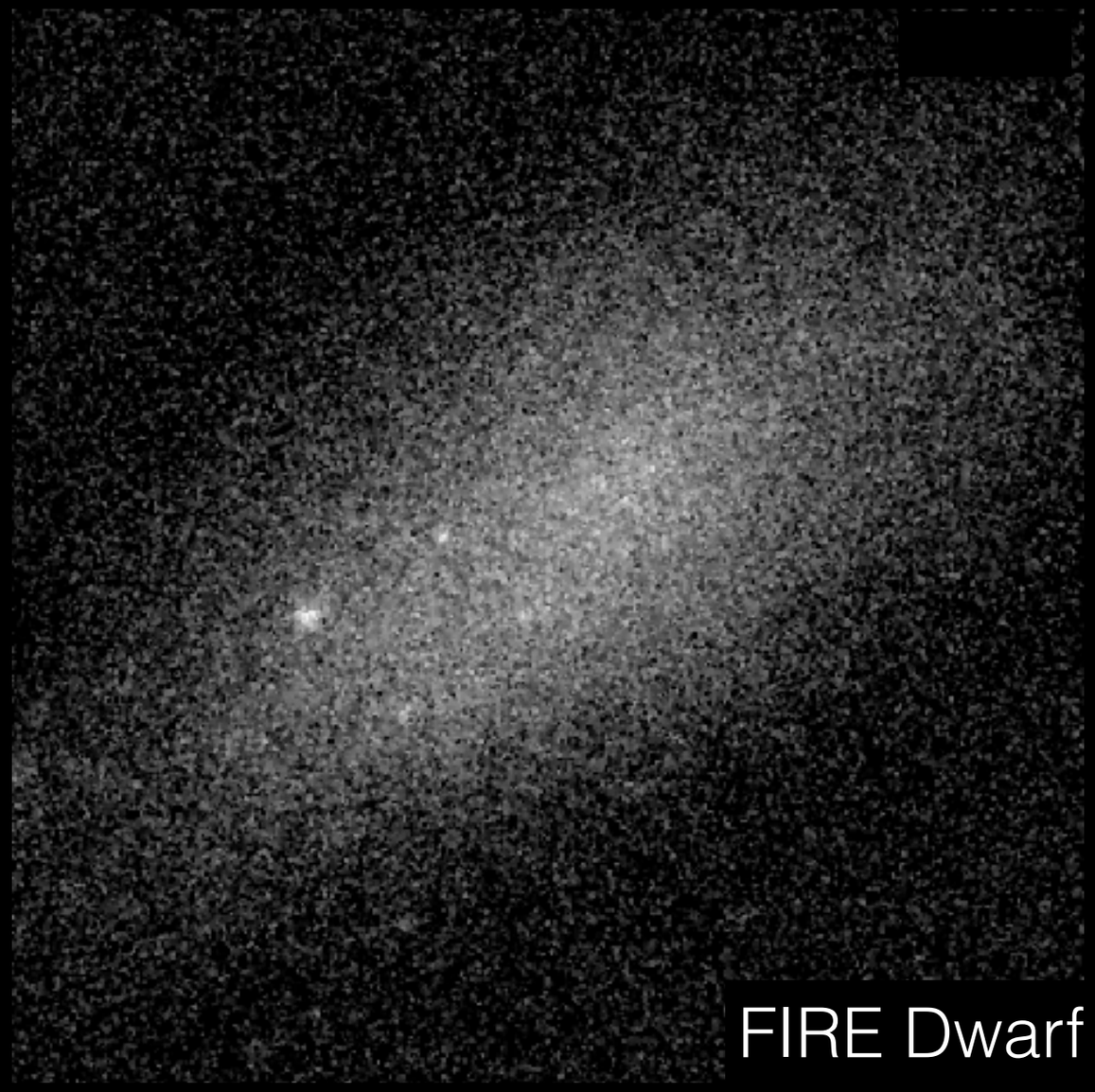
- If DM orbits perturbed, stars are too!
  - Radial anisotropy
  - Gradients "wiped out"
  - Galactic radii *oscillate*



Predicts New Classes of Galaxies

ULTRA-DIFFUSE SYSTEMS: THE NEW "NORMAL"

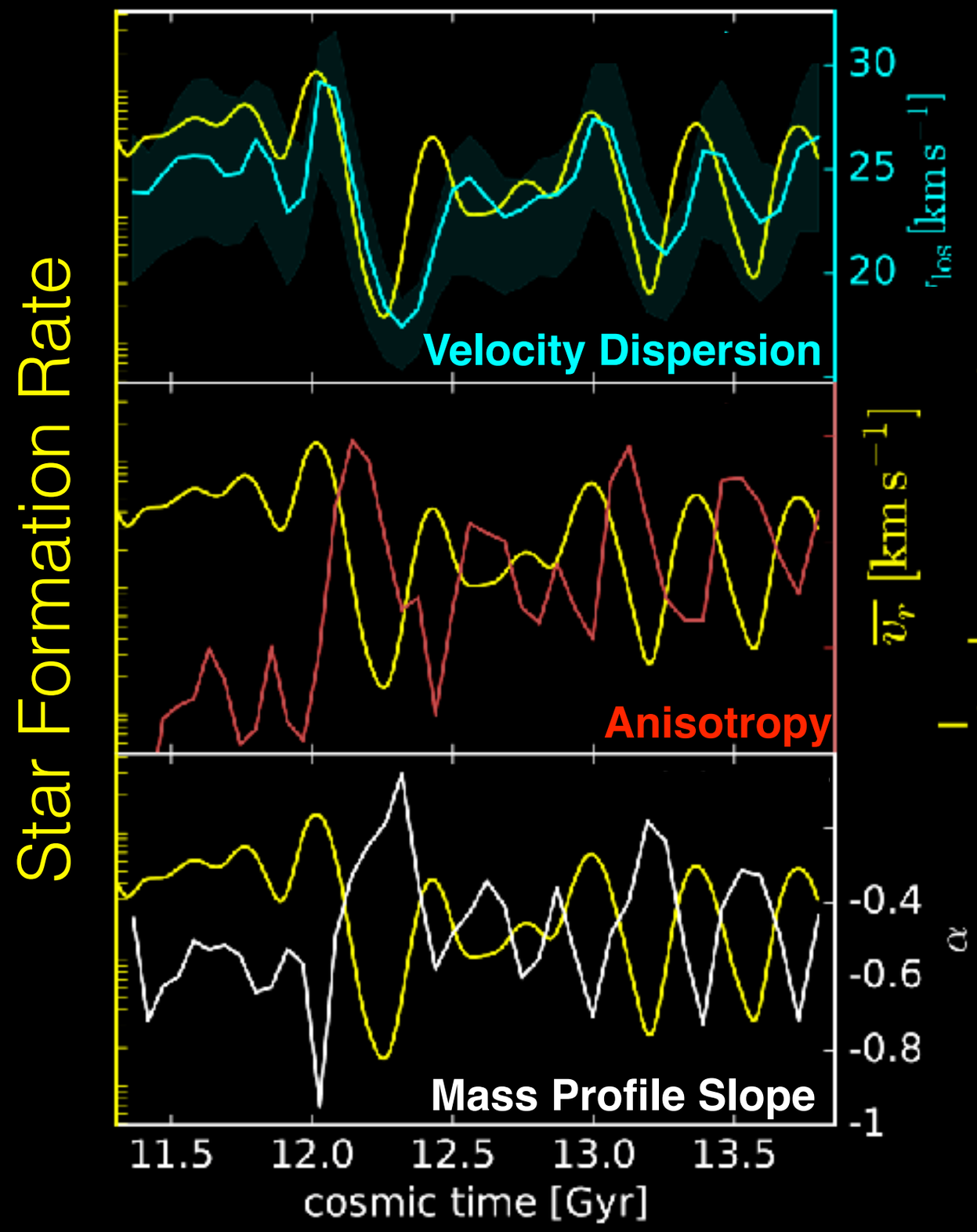
K. El-Badry
(arXiv:1512.01235)
+ TK Chan (prep)

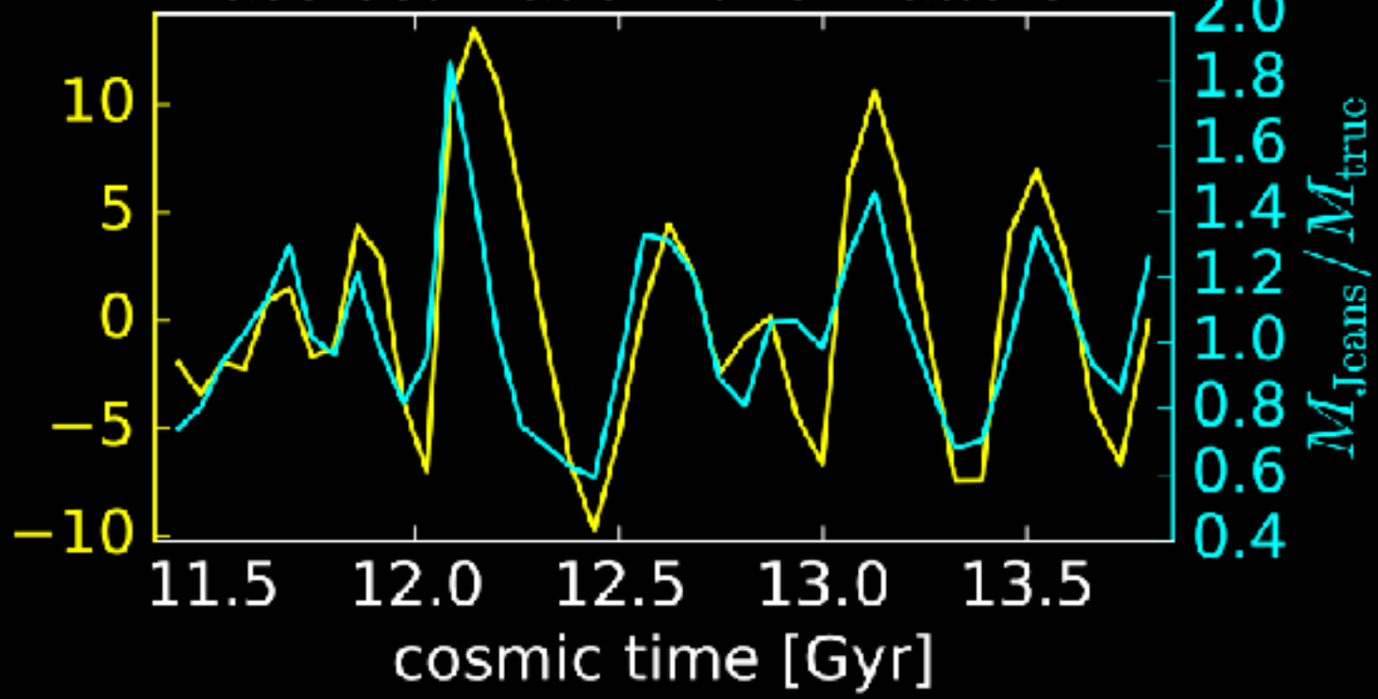


It Gets Worse!

GALAXIES ARE NOT STEADY-STATE OBJECTS!

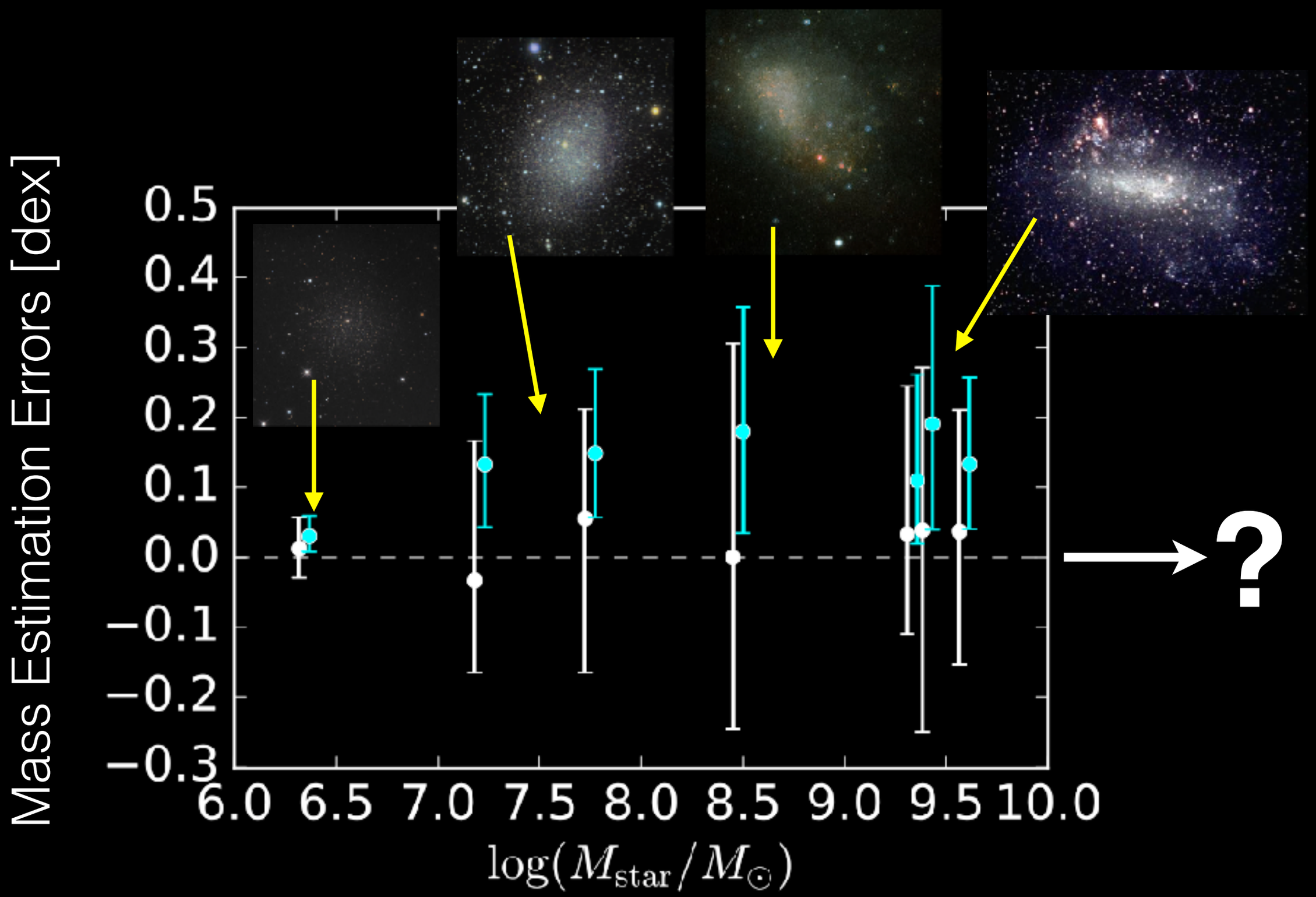
K. El-Badry
(arXiv:1610.04232)





Where Does It End?

K. El-Badry
(arXiv:1610.04232)



z=30.0

10 kpc

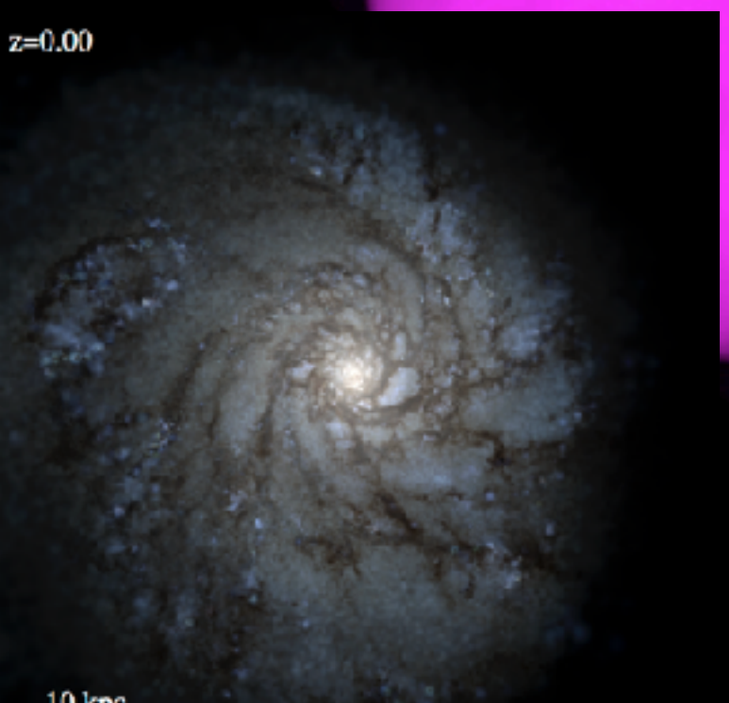
S. Muratov
(arXiv:1501.03155)

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

to

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

z=0.00



10 kpc

C. Hayward
(arxiv:1510.05650)

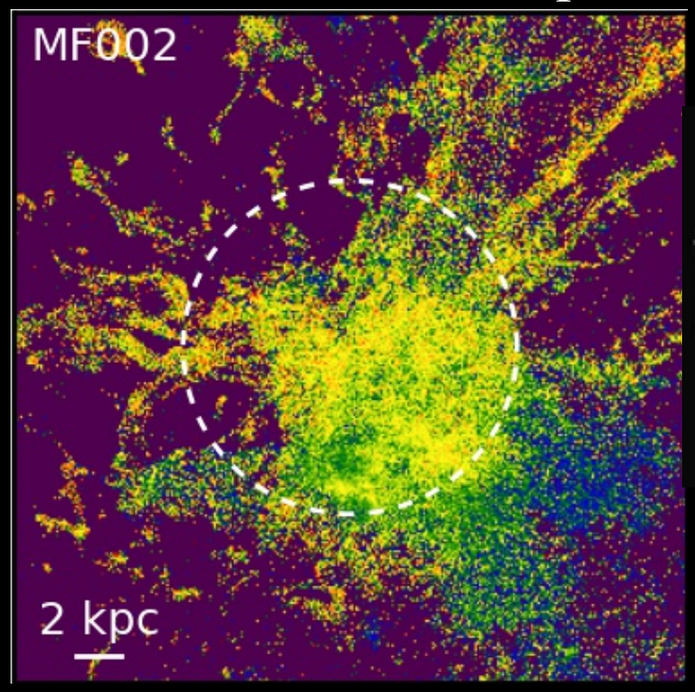
Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

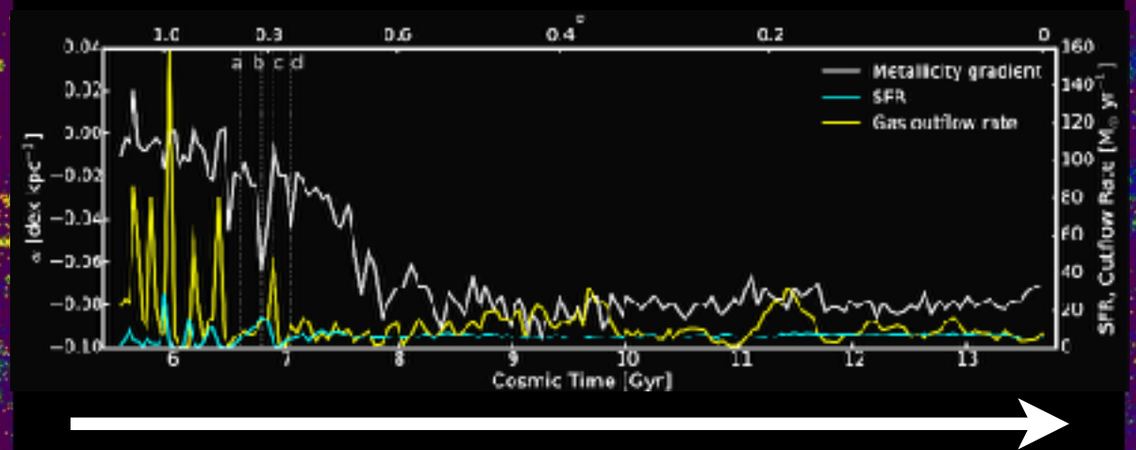
BUILDUP OF METALLICITY GRADIENTS

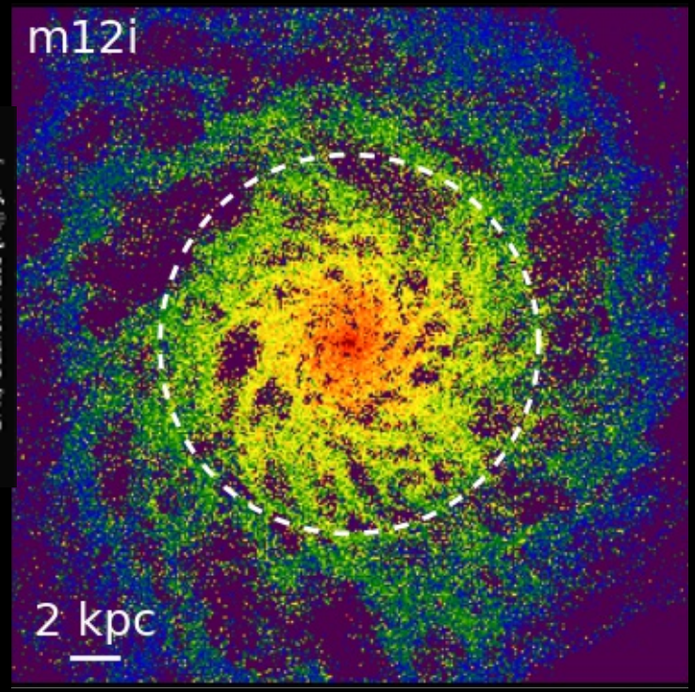
Xiangcheng Ma
(arXiv:1610.03498)

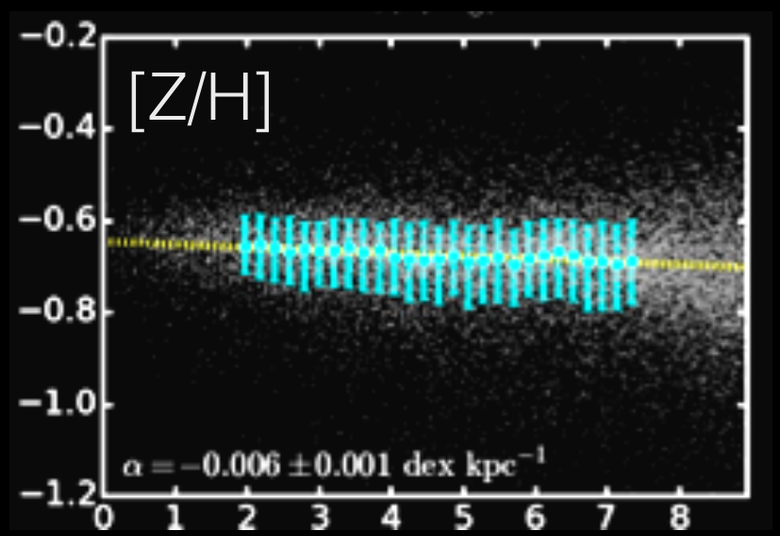
"feedback-dominated" phase

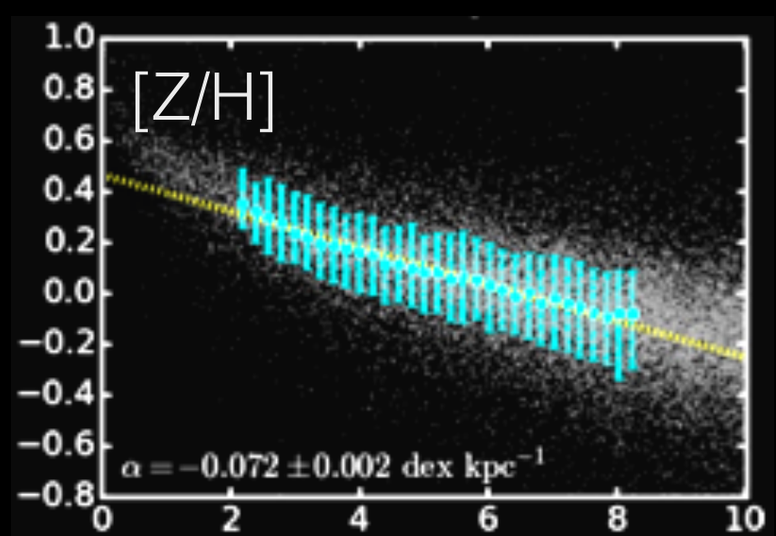
"gravity-dominated" phase







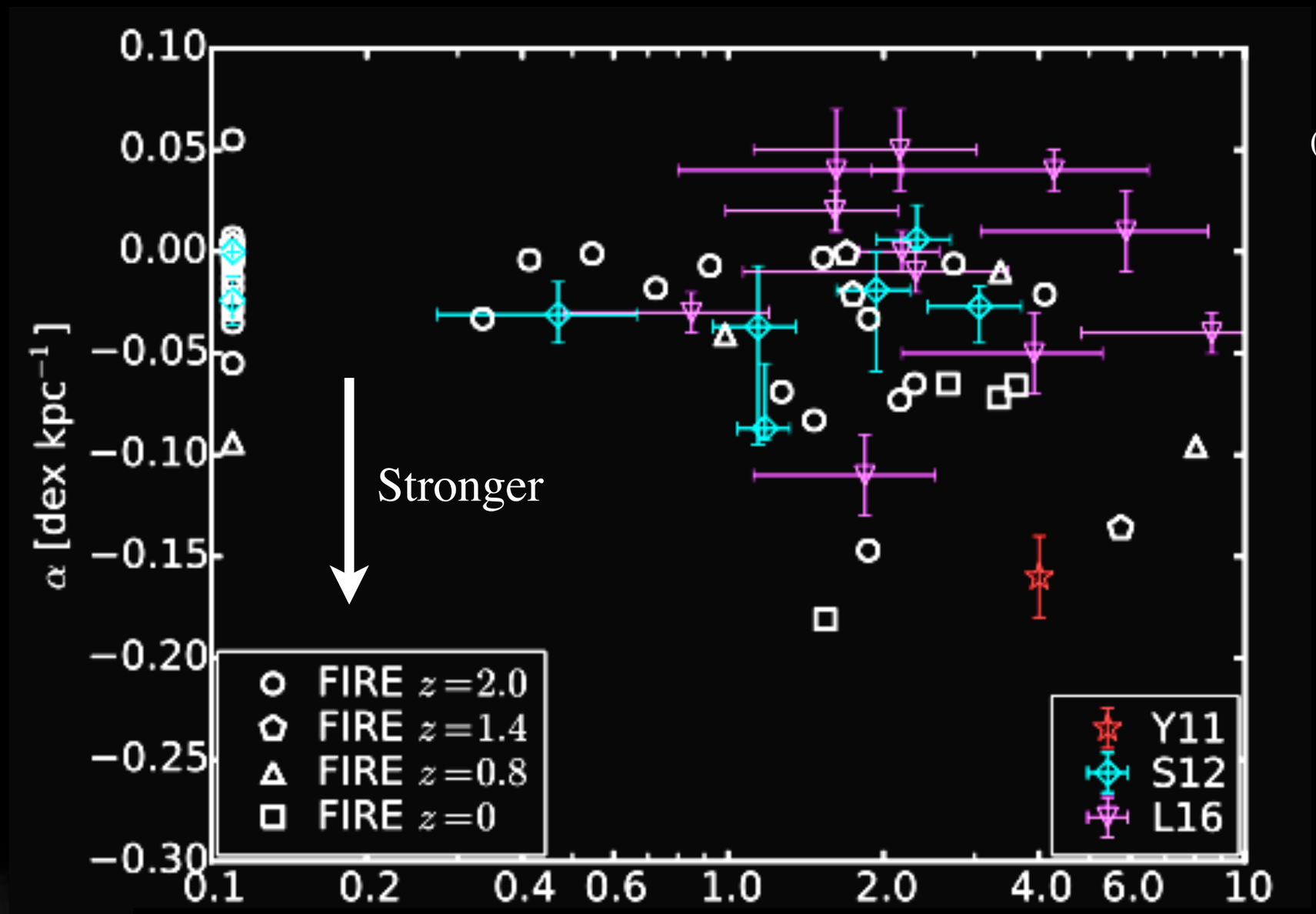


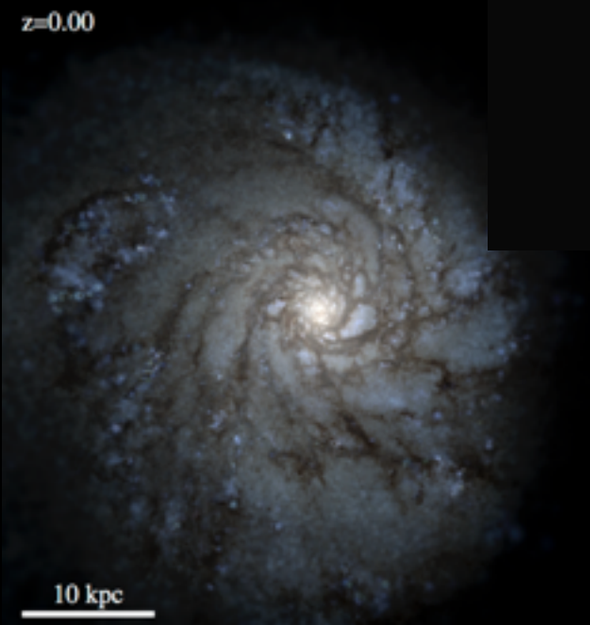


Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

BUILDUP OF METALLICITY GRADIENTS

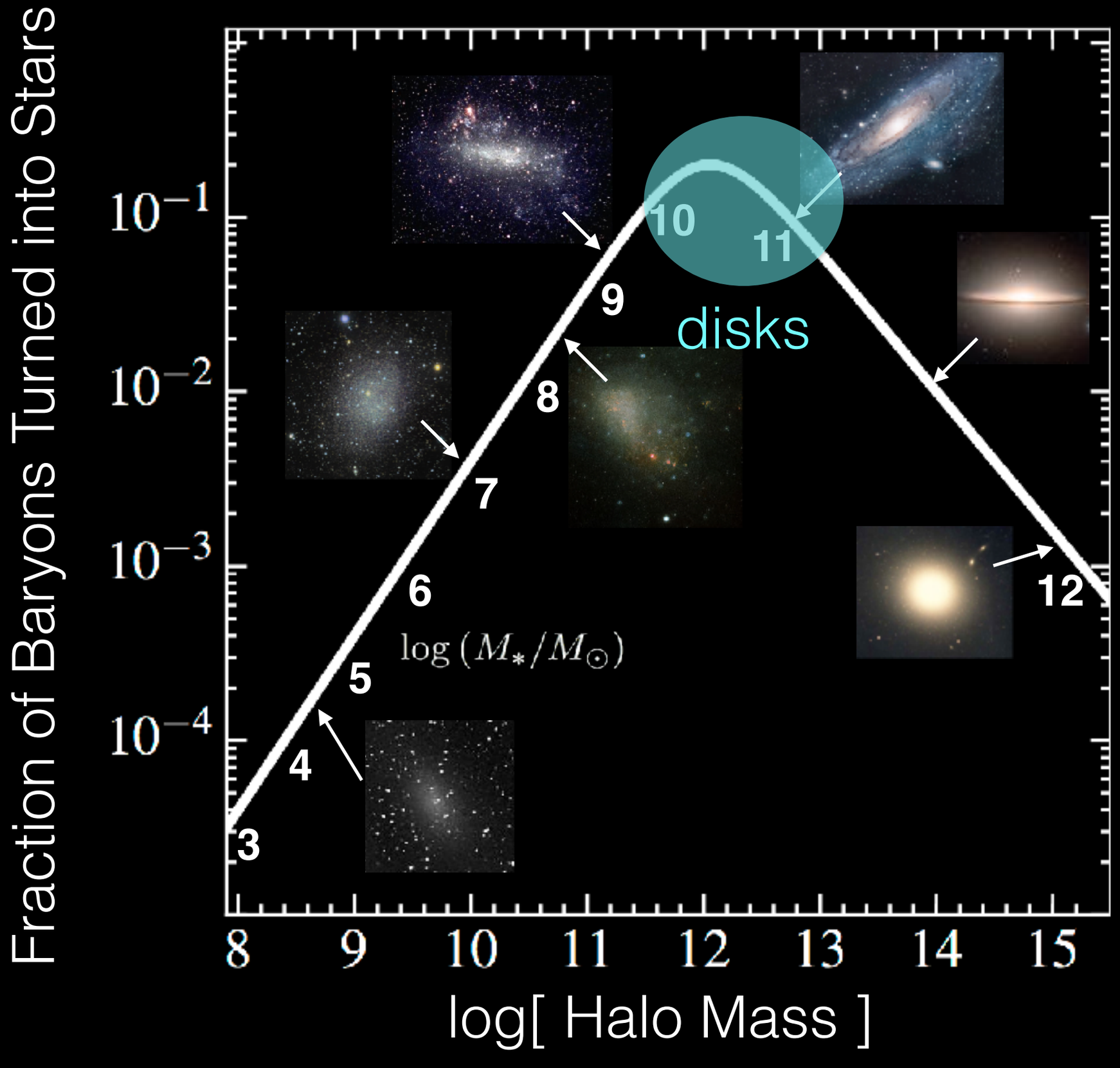
Xiangcheng Ma
(arXiv:1610.03498)





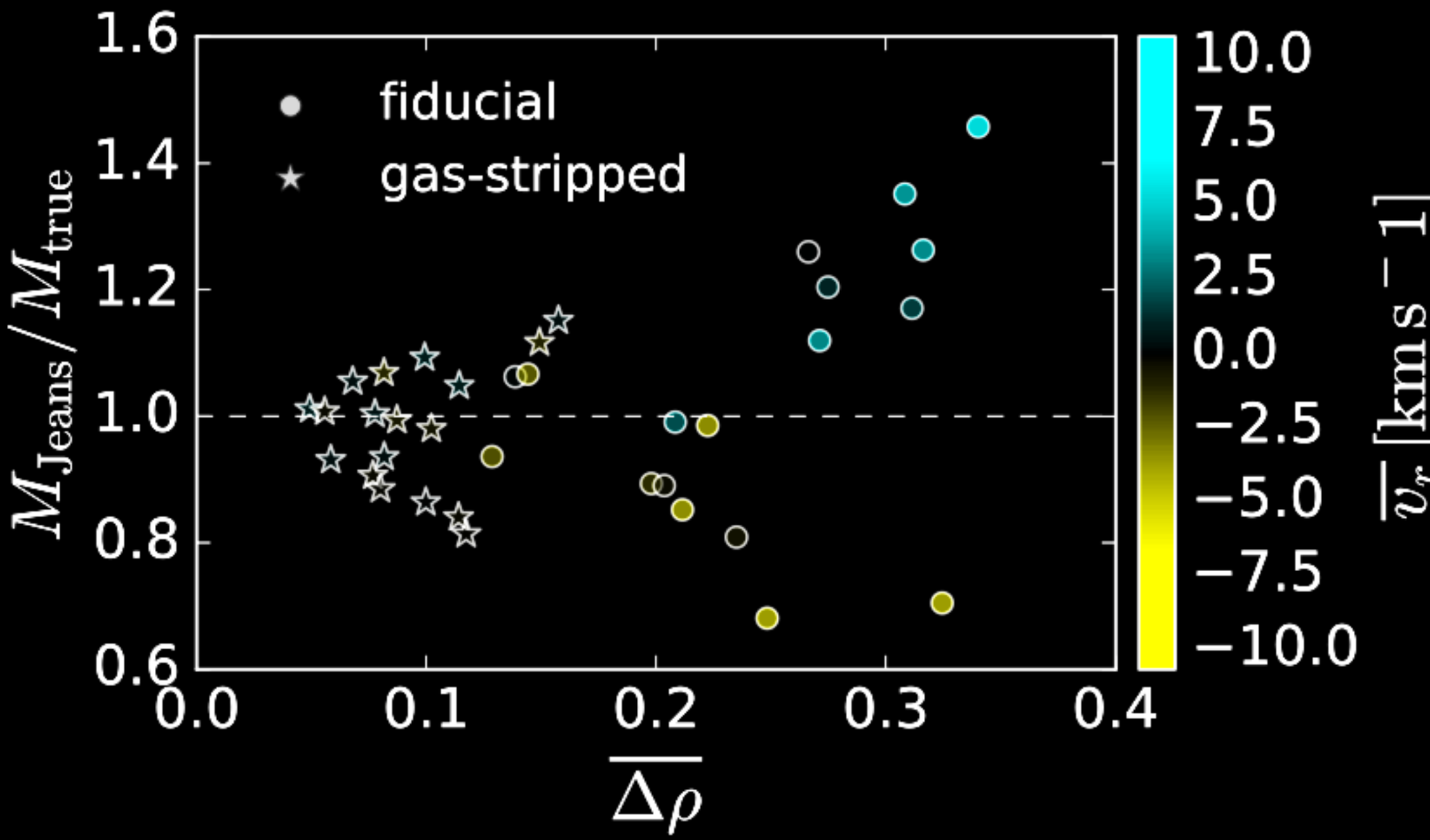
Rotation is Rare:

ONLY COMMON AT PEAK STAR FORMATION EFFICIENCY



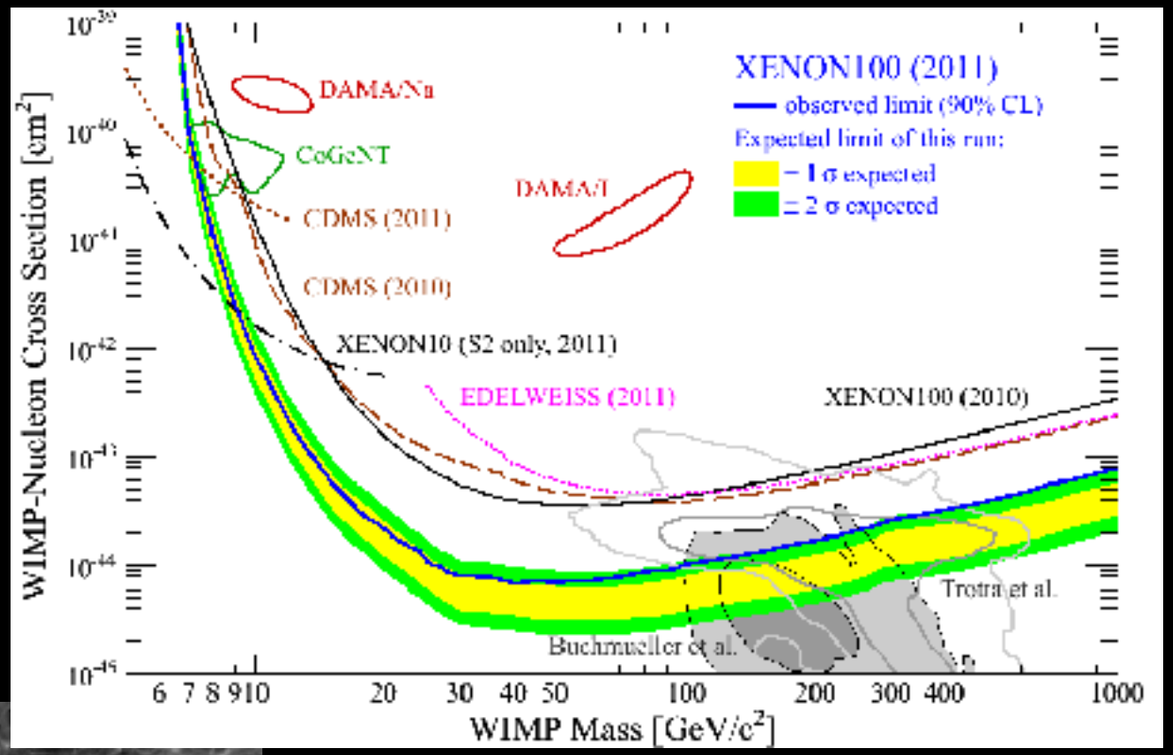
Another Way Out:
THINGS CALM DOWN ONCE SF CEASES

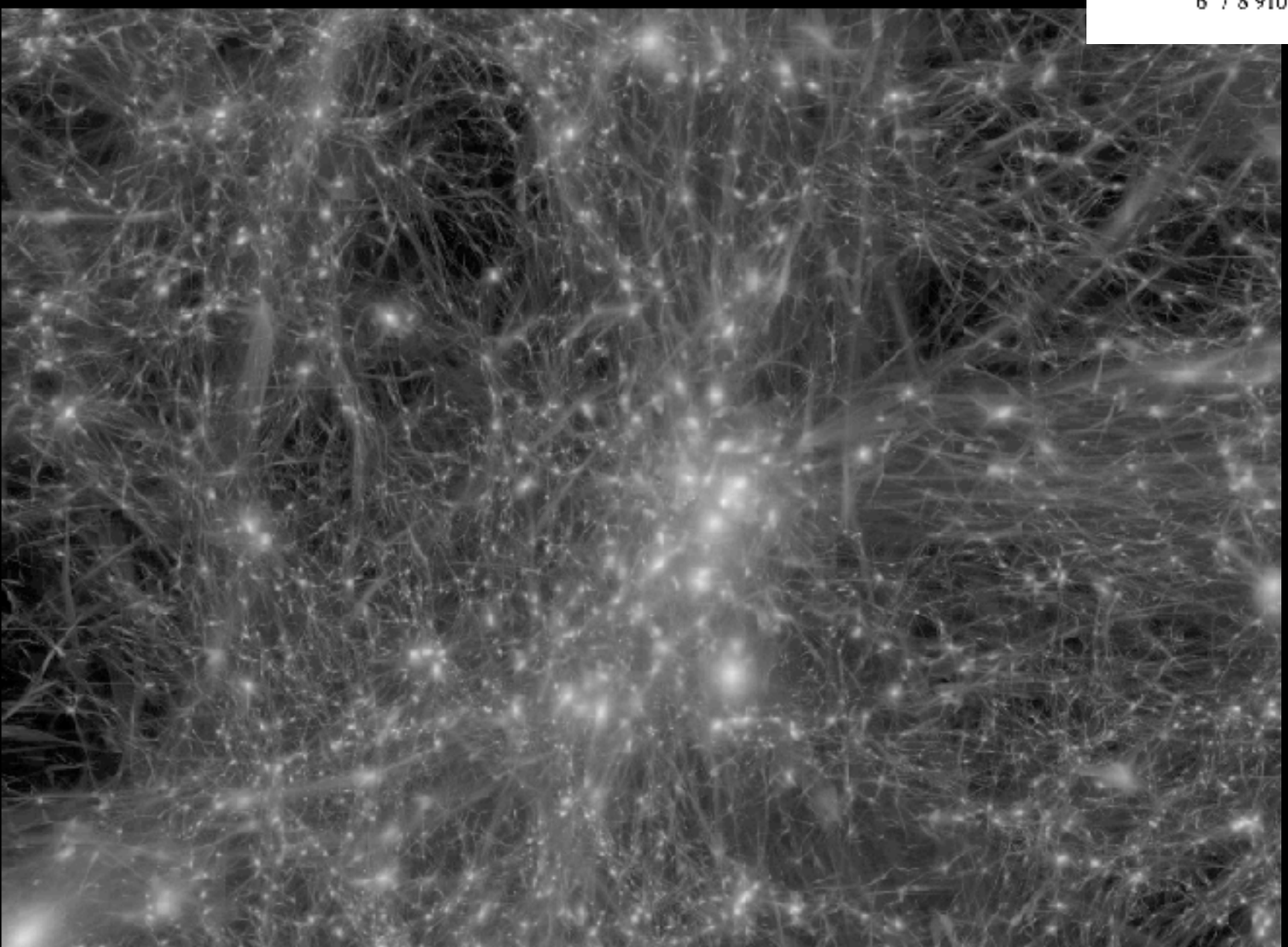
K. El-Badry
(arXiv:1610.04232)



What keeps me up at night?
(BESIDES THE TWINS)

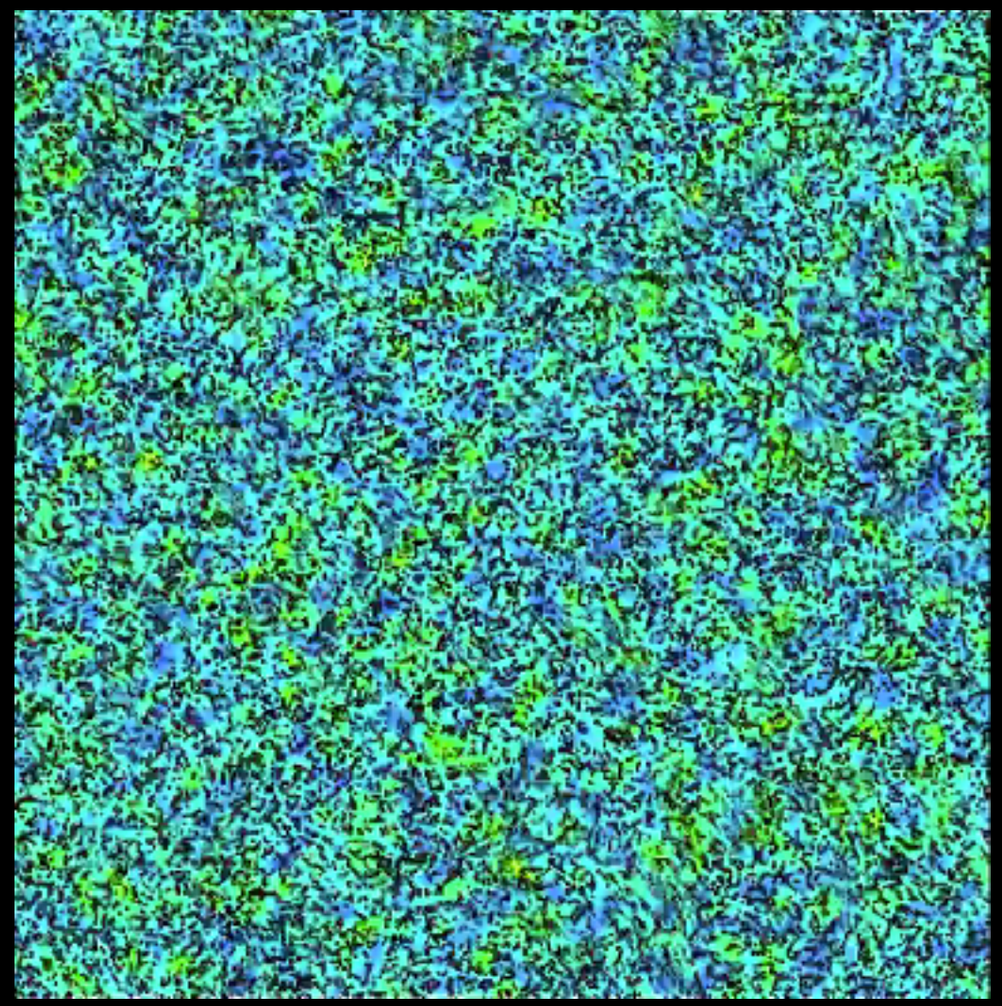
- CDM: What is it?

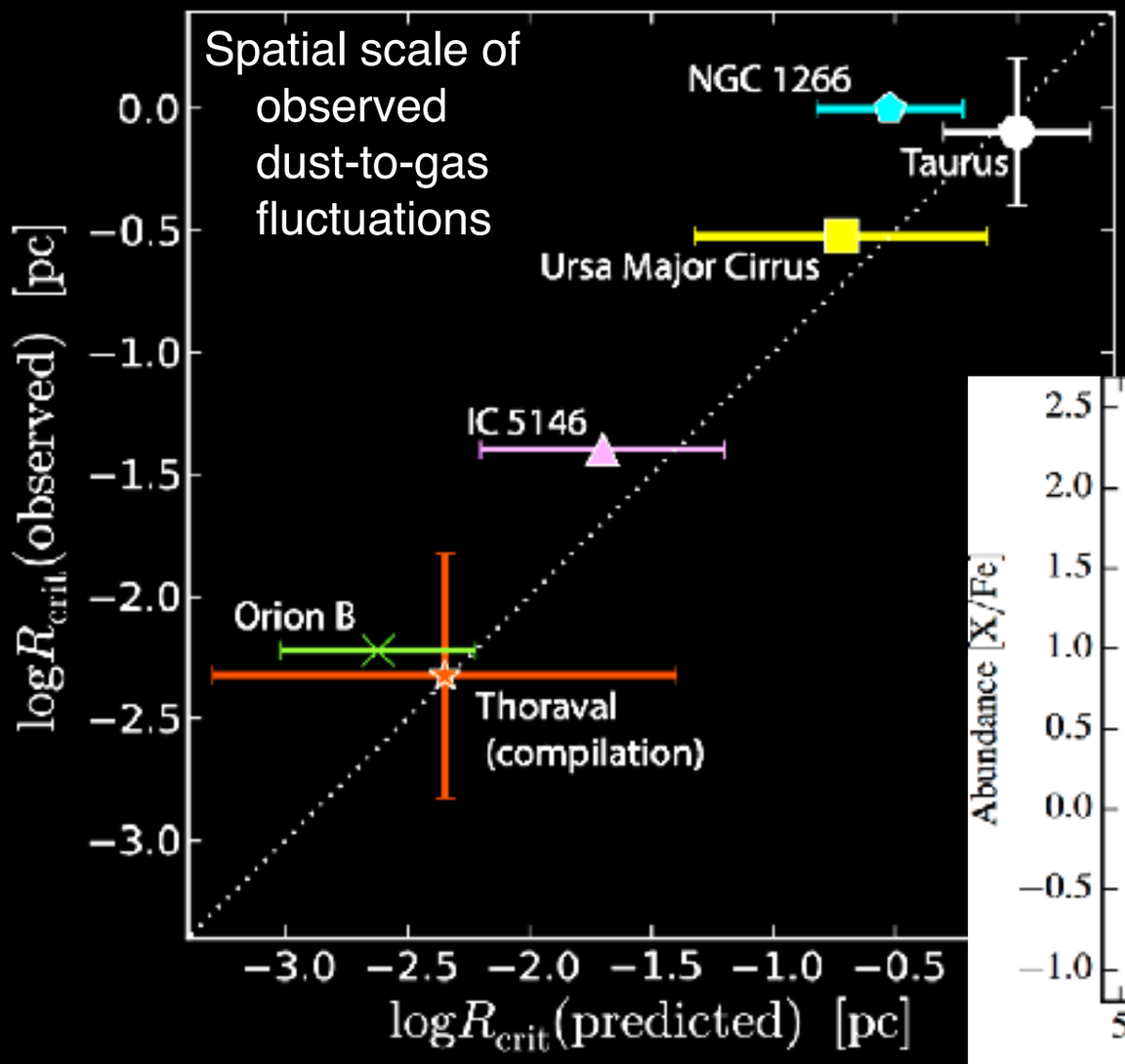


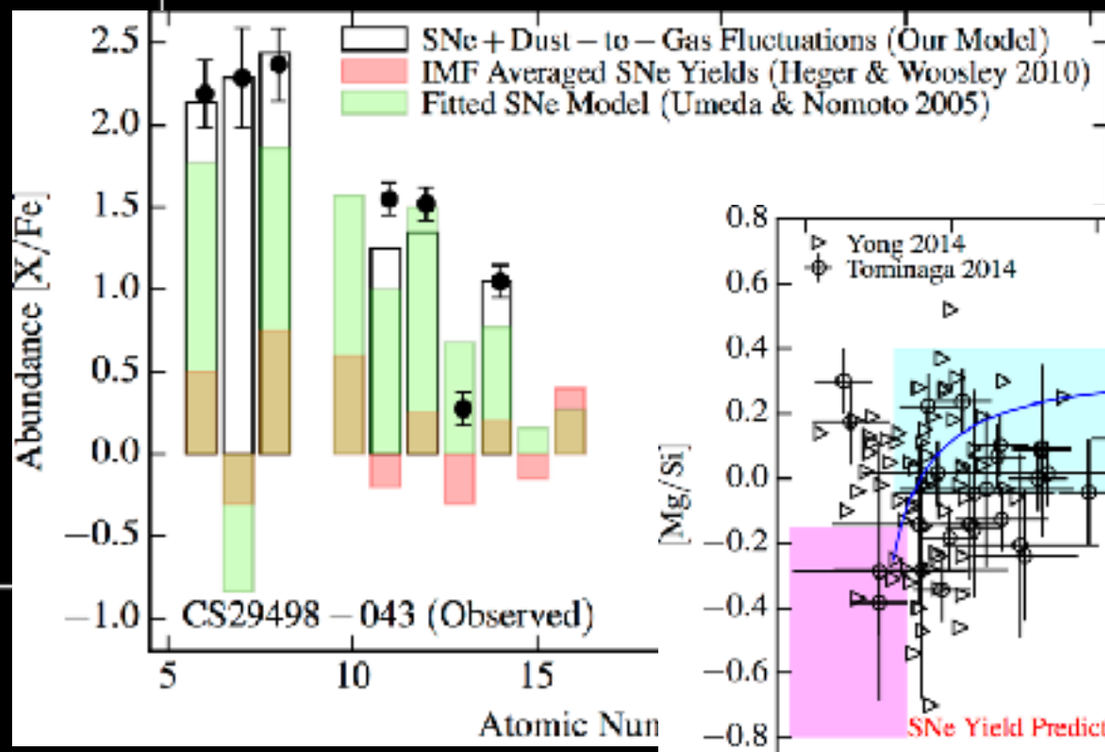


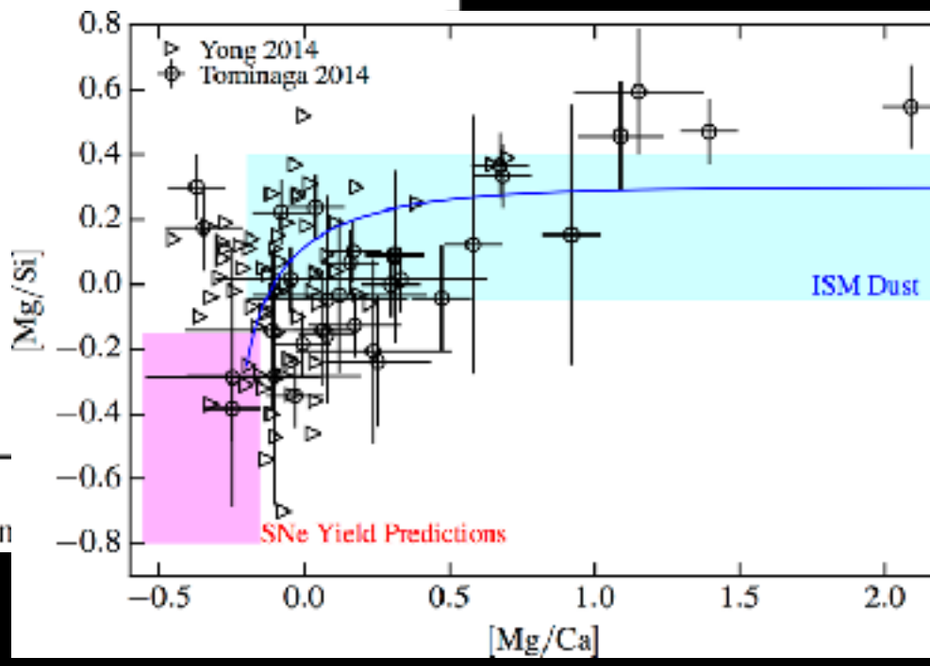
What keeps me up at night?
(BESIDES THE TWINS)

- CDM: What is it?
- Dust: What's it doing?





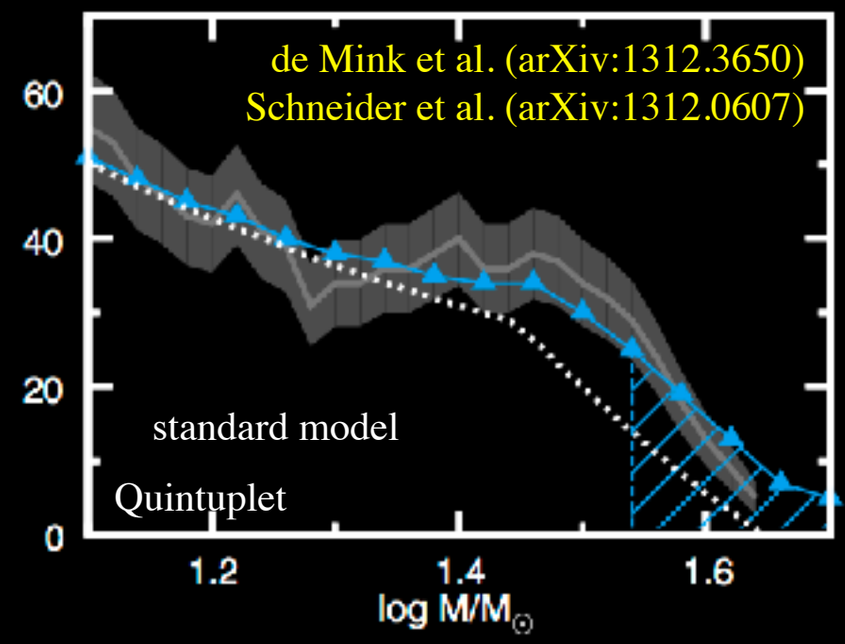


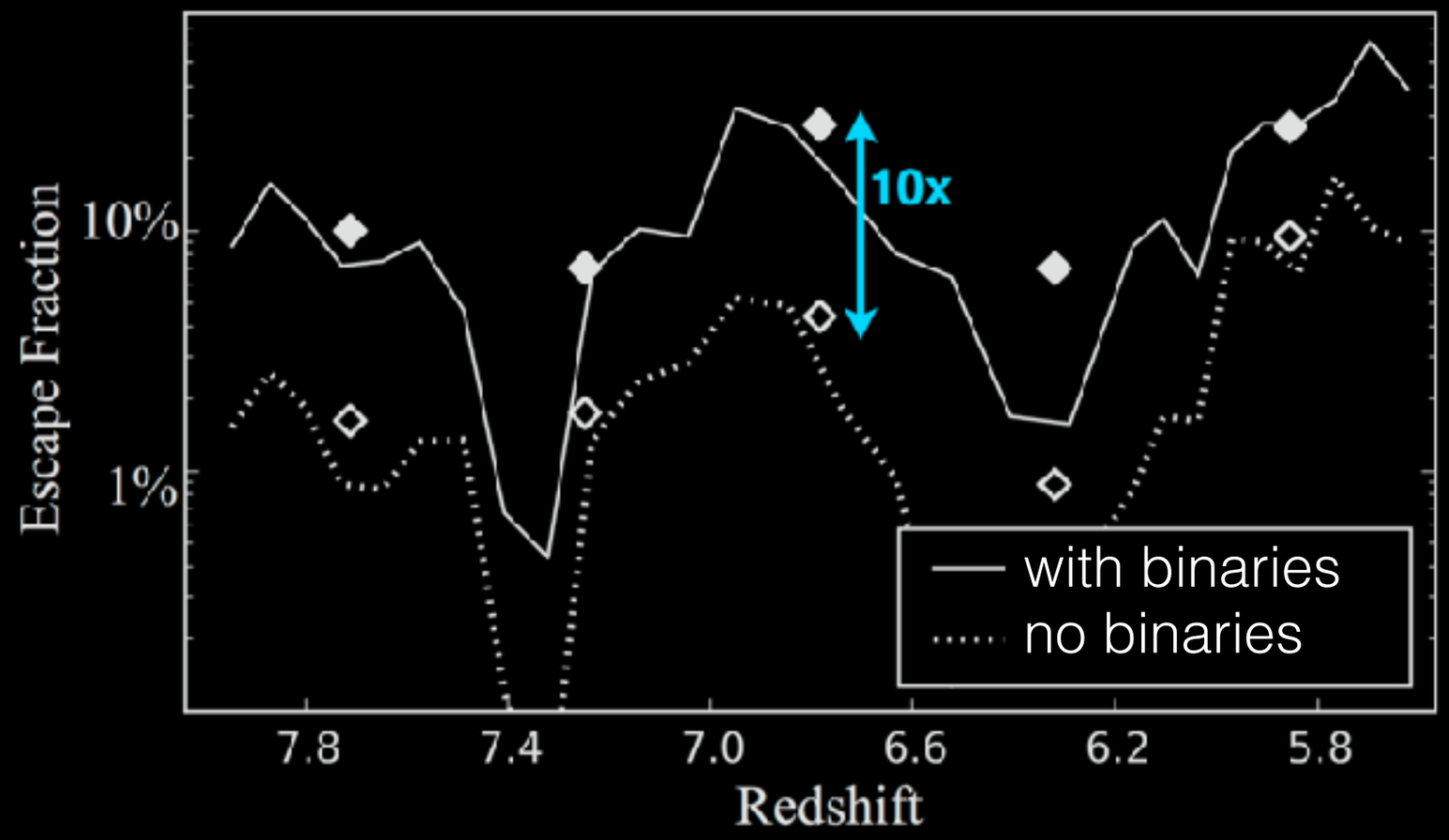


PFH & Conroy (arXiv:1512.03834)

What keeps me up at night?
(BESIDES THE TWINS)

- CDM: What is it?
- Dust: What's it doing?
- Binarity: It matters

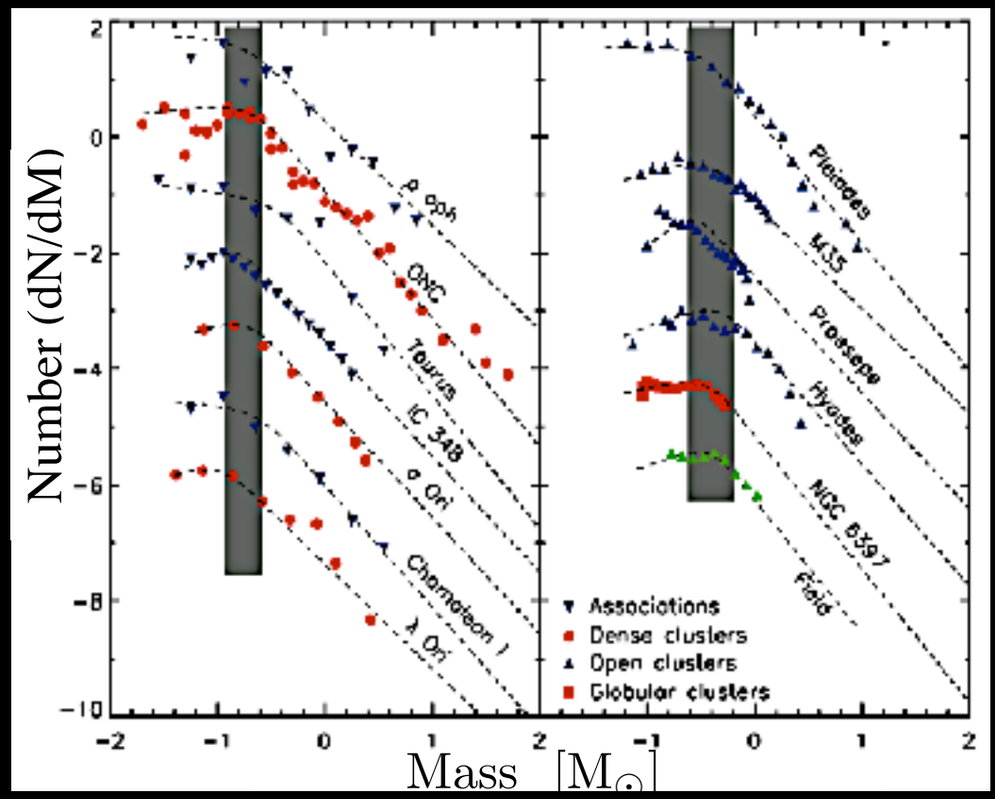


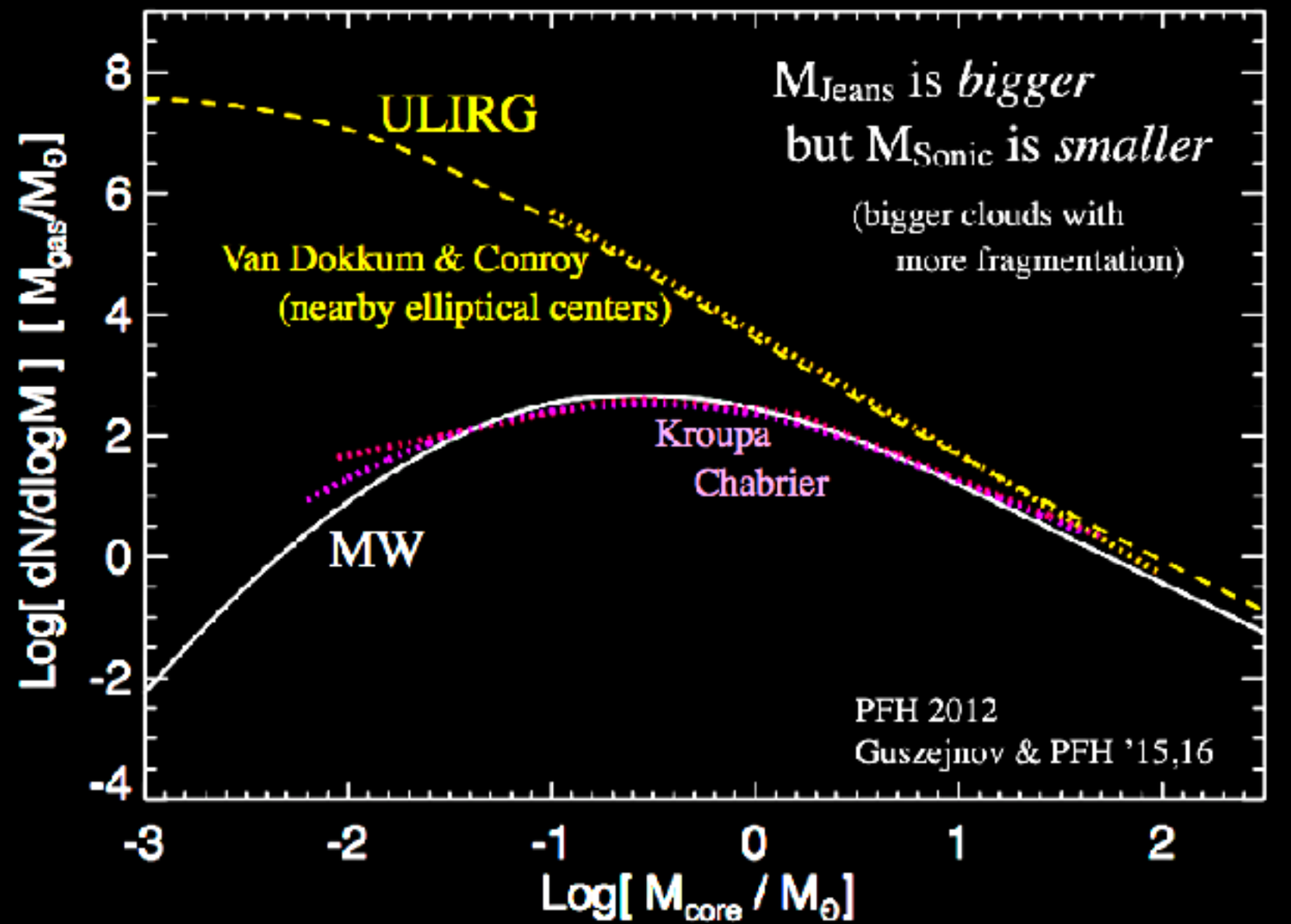


- GC abundances?
- Escape fractions
- IMF & massive stars
- Galaxy dynamics / masses
- High-z galaxy metallicities
- LIGO massive mergers
- Halpha as SFR indicator

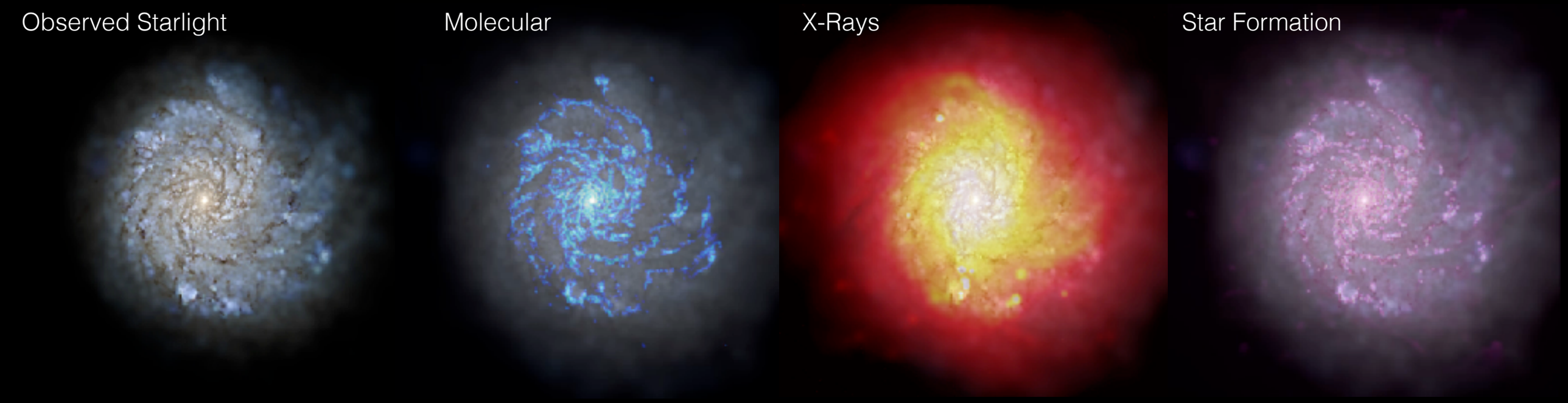
What keeps me up at night?
(BESIDES THE TWINS)

- CDM: What is it?
- Dust: What's it doing?
- Binarity: It matters
- IMF: How fixed?





Observed Starlight | Molecular | X-Rays | Star Formation



- **Dwarfs are violent, non-equilibrium places**
  - Abundances, gradients, kinematics *may not tell us what we think*

- **There are no major astrophysical challenges to ΛCDM**
  - Cusps to cores: no exotic dark matter needed!
  - Missing satellites, "too big to fail," thin disks, Tully-Fisher relation, flat rotation curves, etc — all fall out
  - Violent "burstiness" visible in abundances, SFHs, kinematics

- **Dominant uncertainties are "small scale":**
  - Dust: 1/2 the metals and could seriously mess with us!
  - Binaries: at dwarf masses? changes a *lot* on galaxy scales
  - IMF: really evidence for evolution?