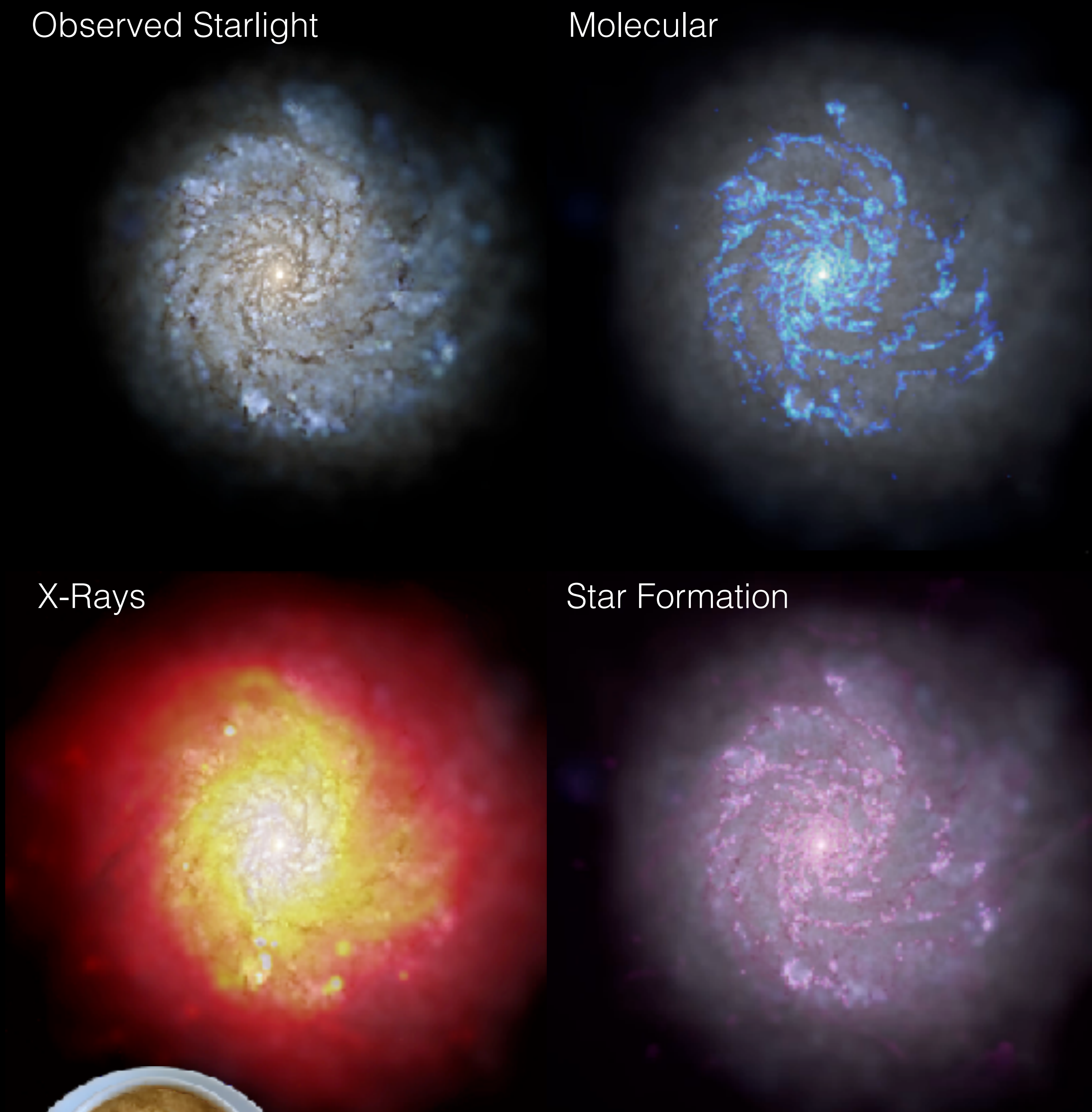
Stars Re-Shaping Galaxies

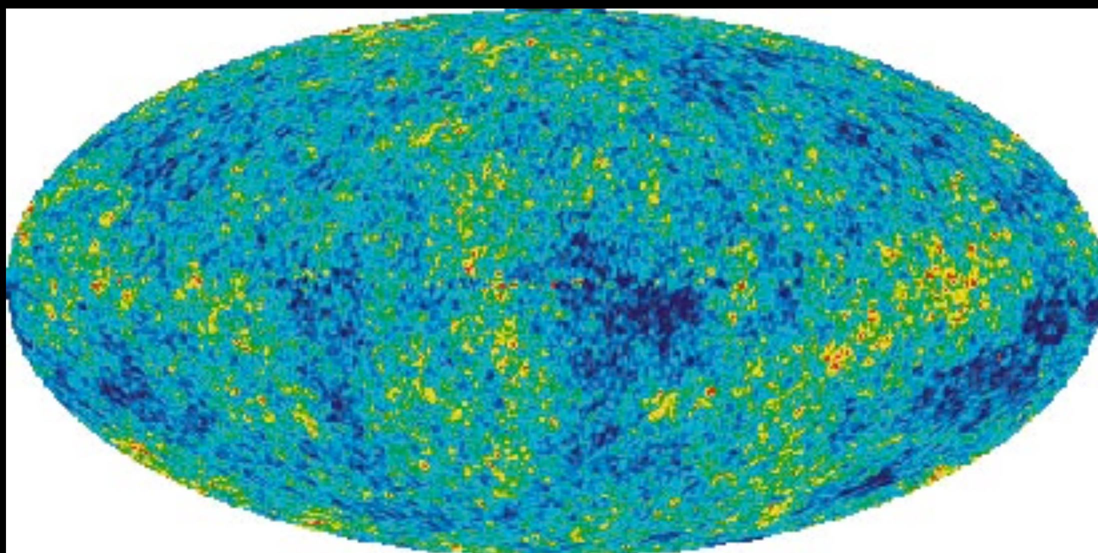


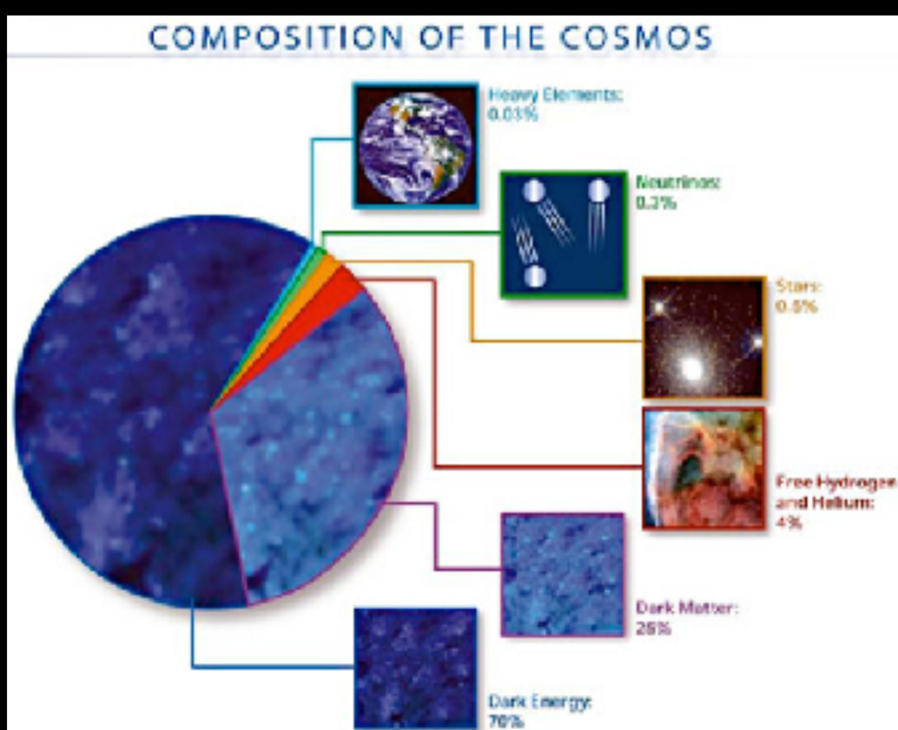
FIRE
Feedback In Realistic Environments

Philip F. Hopkins with
Xiangcheng Ma, David Guszejnov, Matt Orr, Mike Grudic,
Shea Garrison-Kimmel, Robyn Sanderson, Coral Wheeler, & the FIRE Team
Caltech

The Big Question:
HOW DO WE GO FROM BIG BANG TO MILKY WAY?

Today





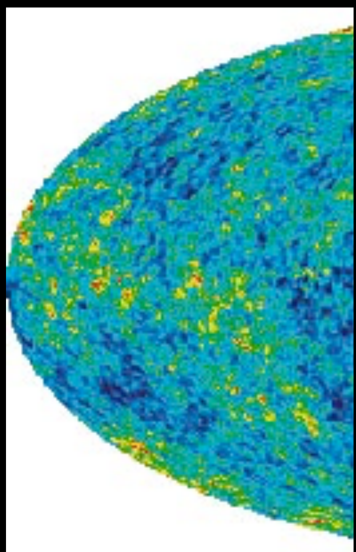
z~1090
(t~400,000 yr)

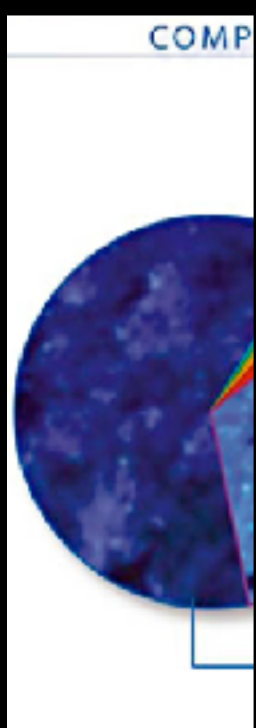
?

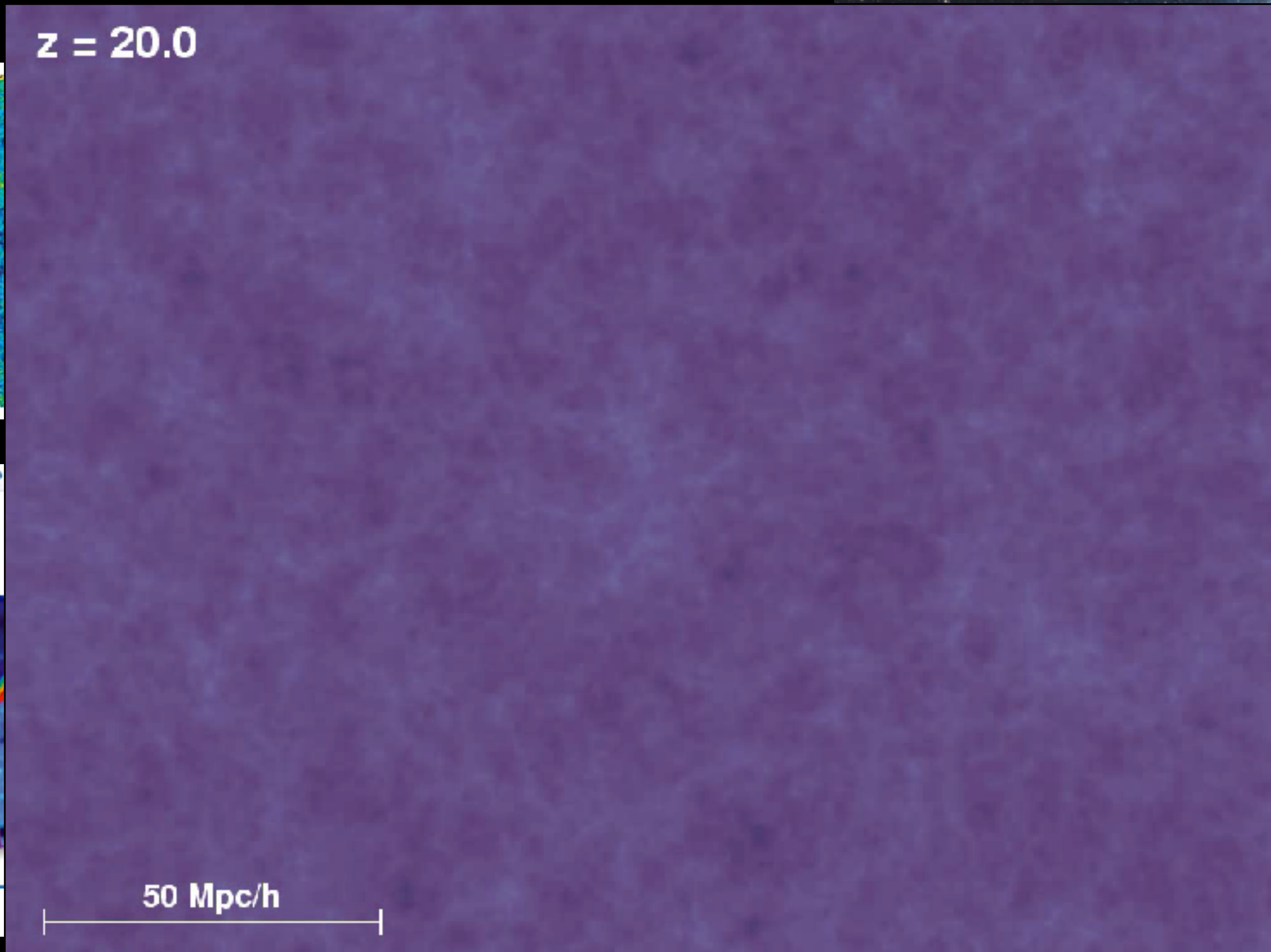
The Big Question:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?

Today



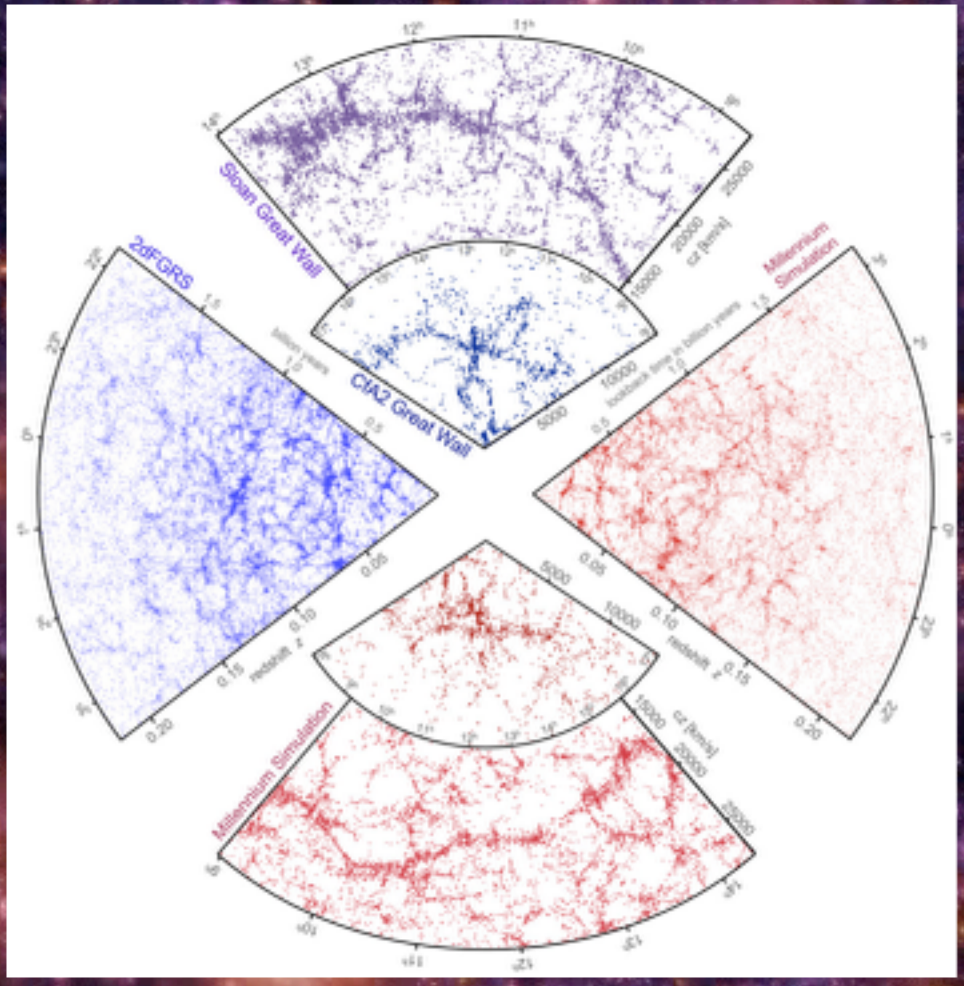




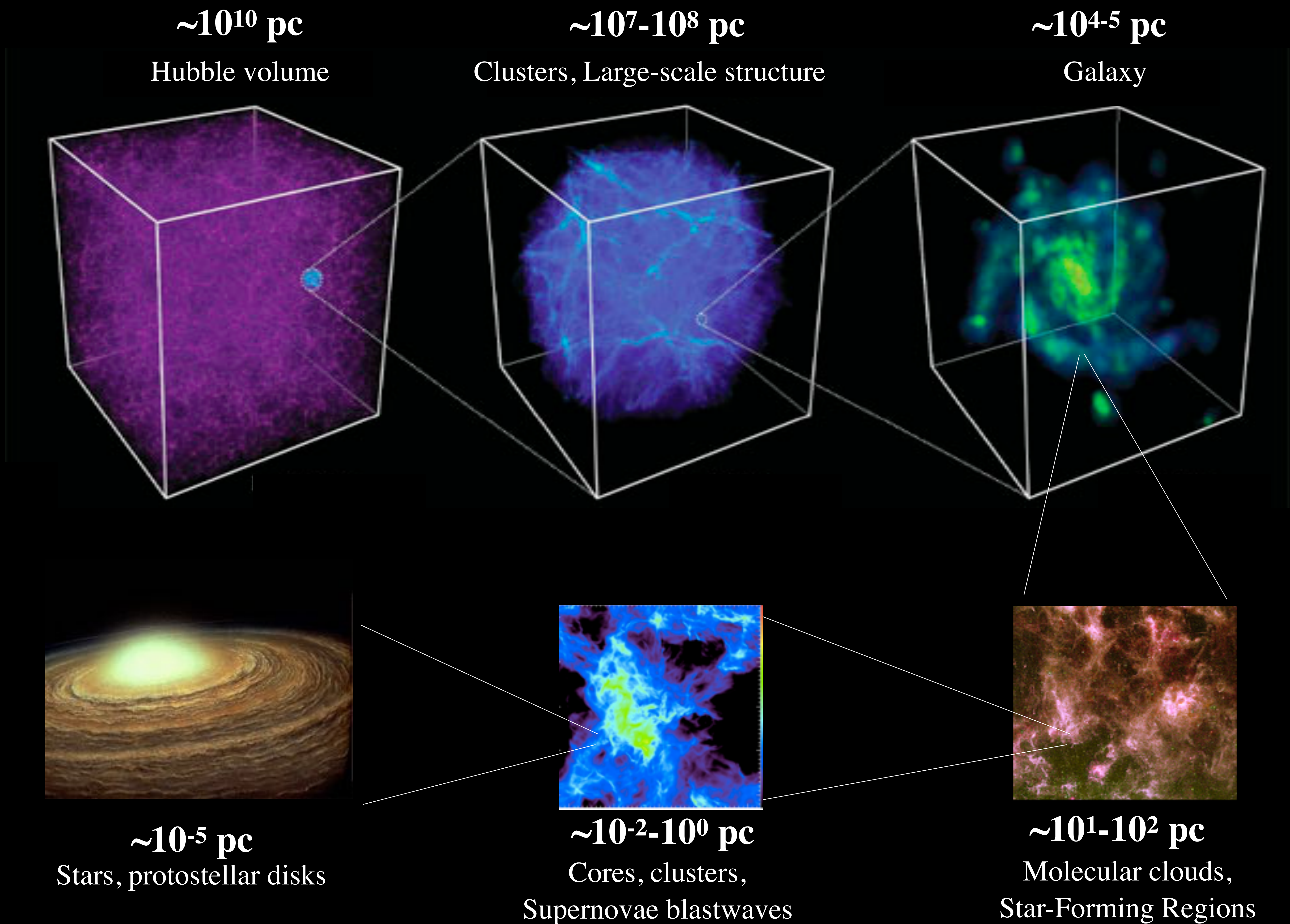
z~1090
(t~400,000 yr)

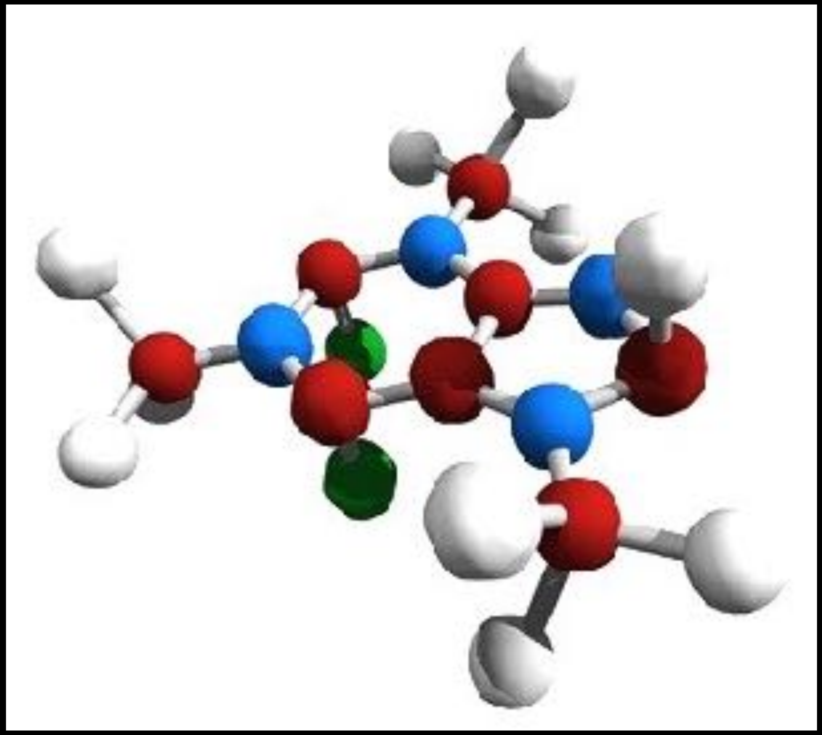
Large scales: Gravity + Dark Matter/Energy Works!

Observations vs Theory
(SDSS vs Millennium Simulation)



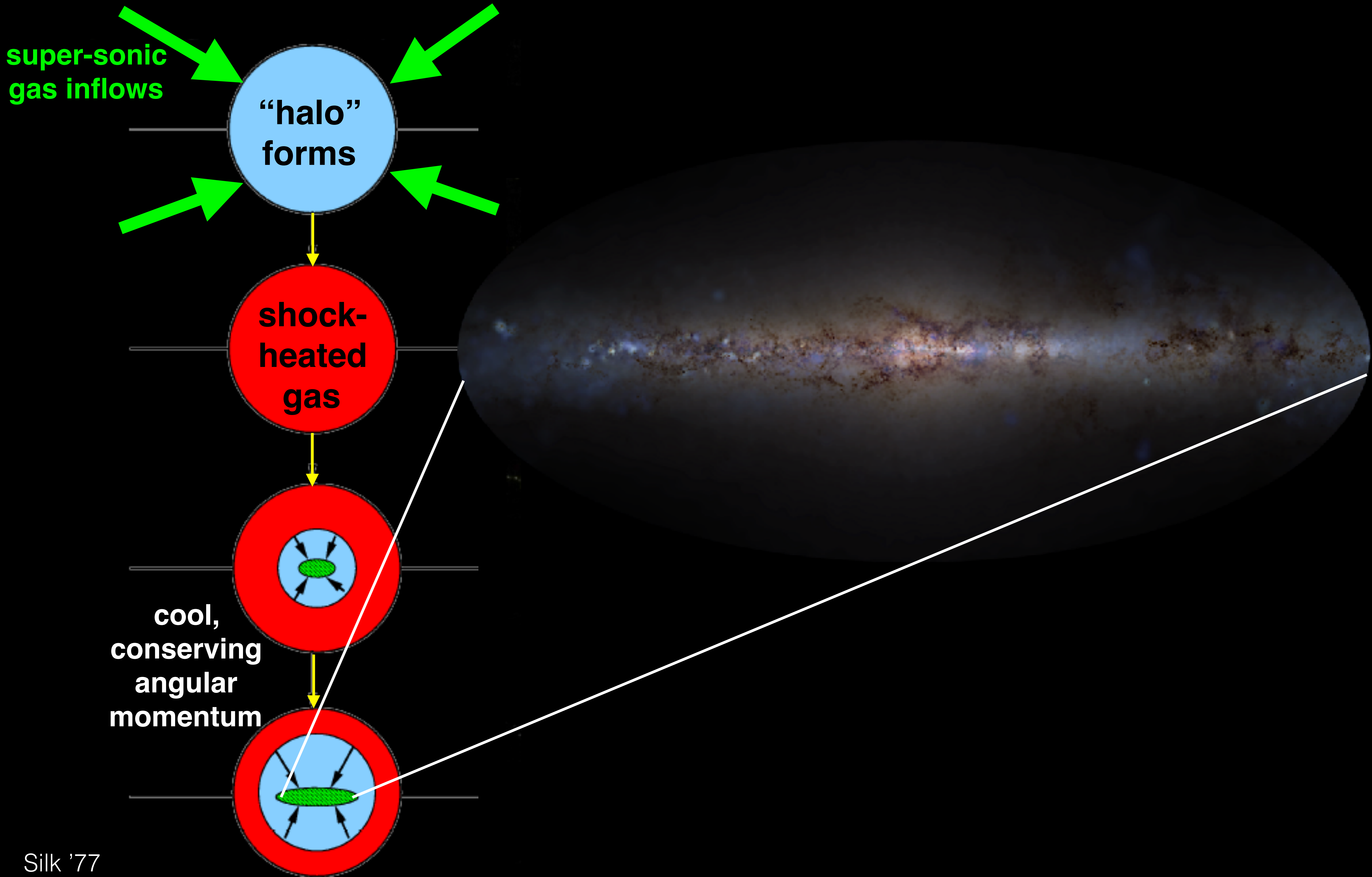
Our work:


~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



Add some fluid dynamics
and chemistry, and go!

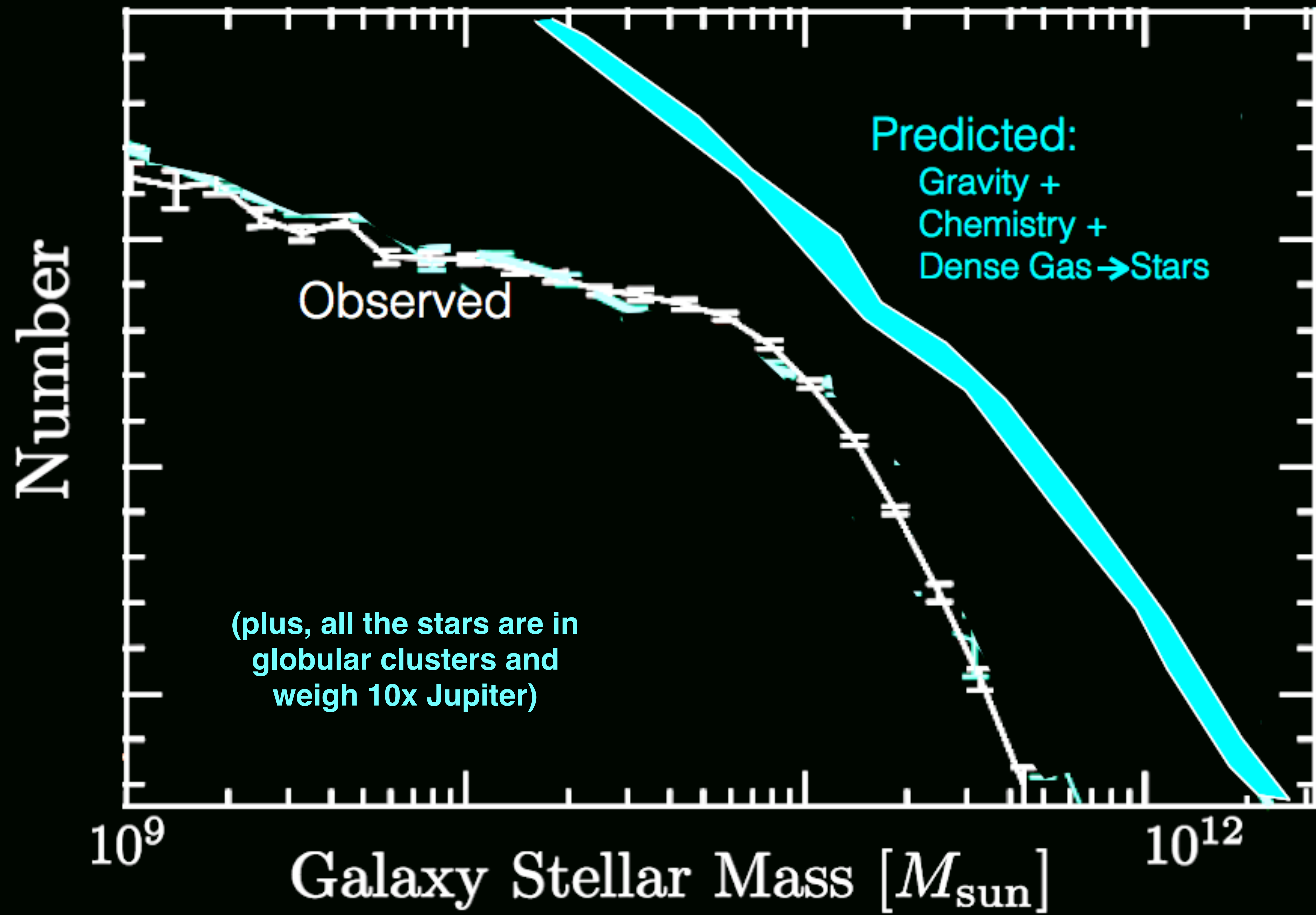
The Basic Picture:



Silk ’77
Binney ’77
Rees & Ostriker ‘77

Problem:

WHY SO FEW GALAXIES & STARS?



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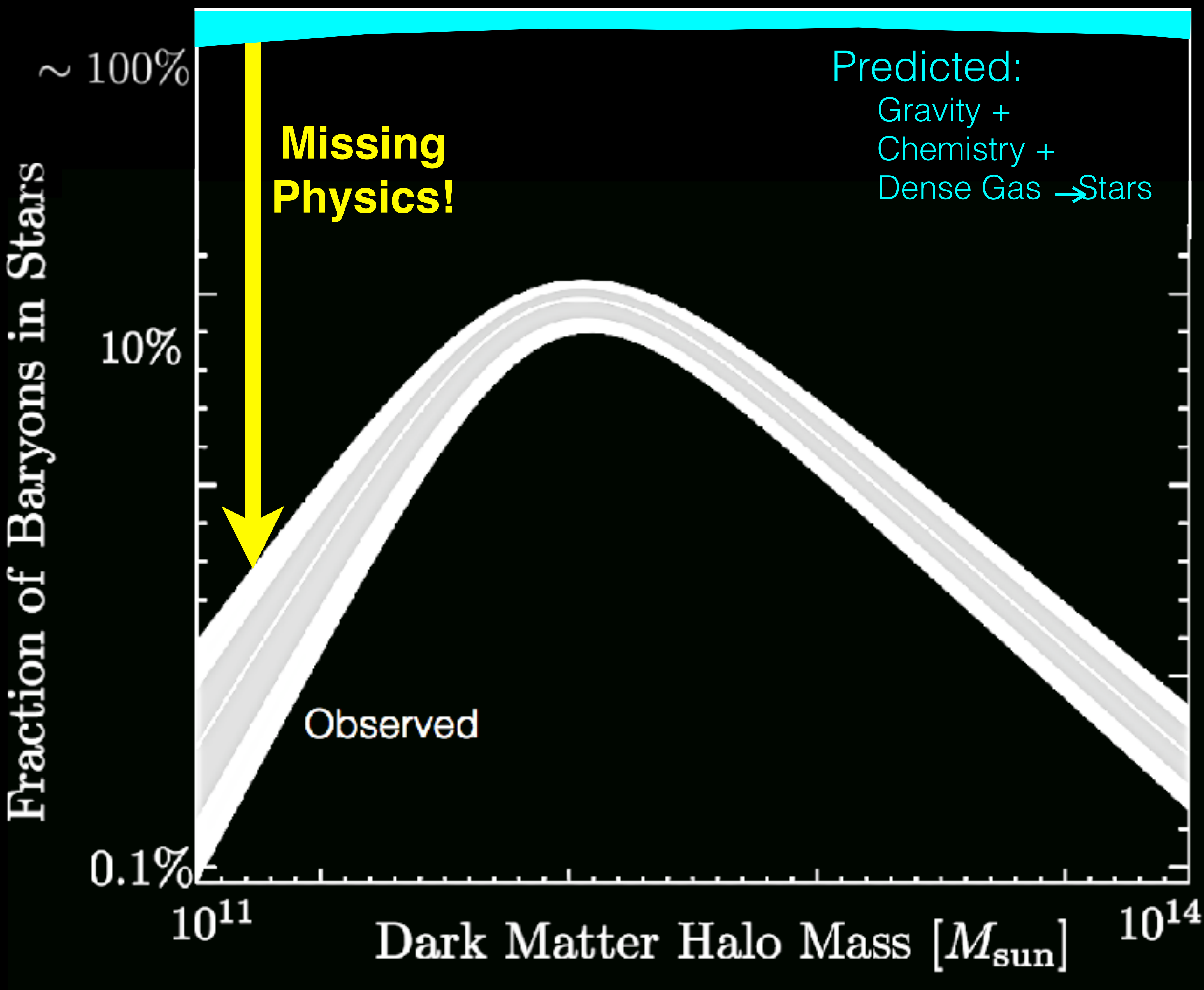
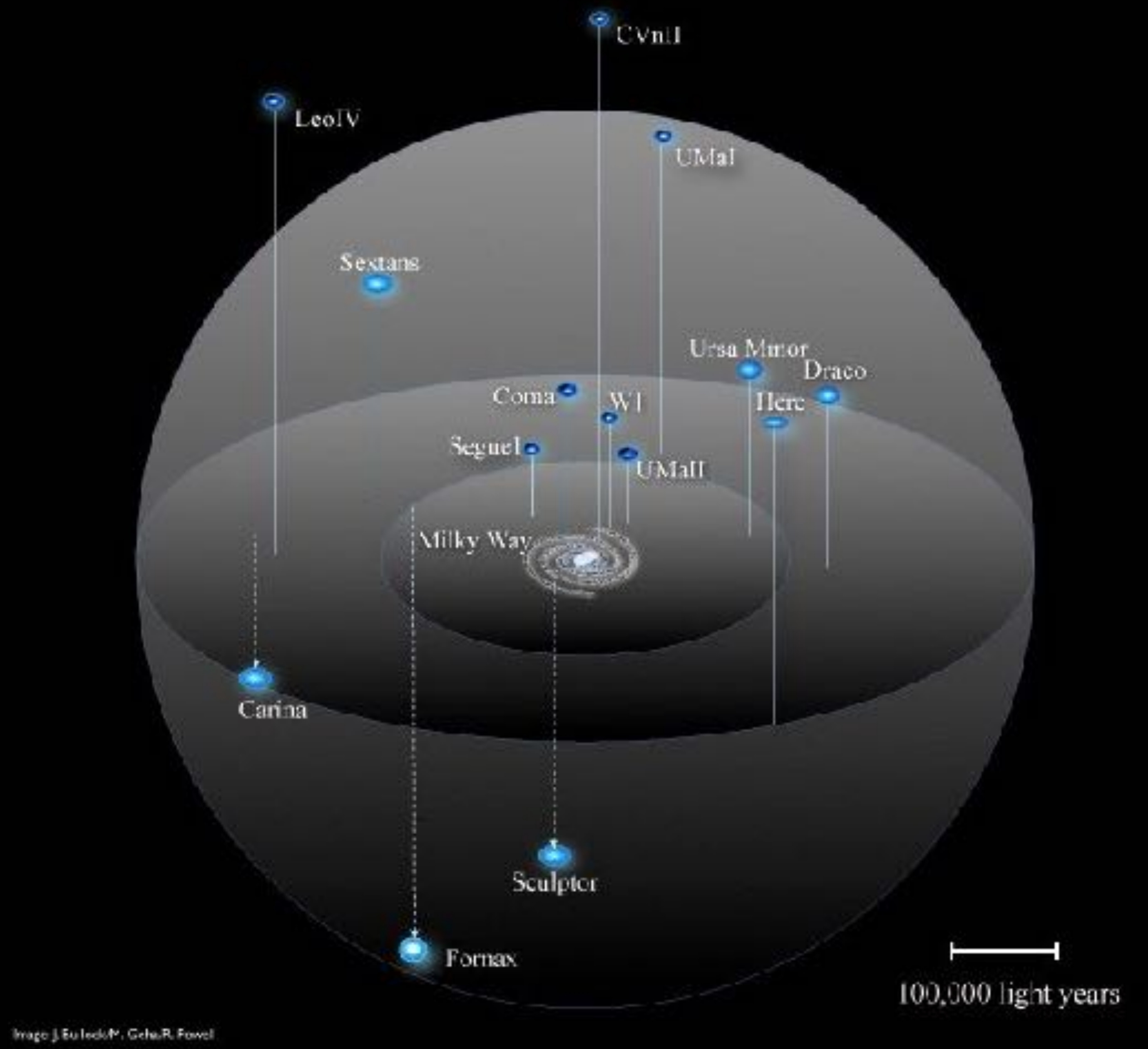


Problem:
WHERE ARE THE “MISSING SATELLITES”?

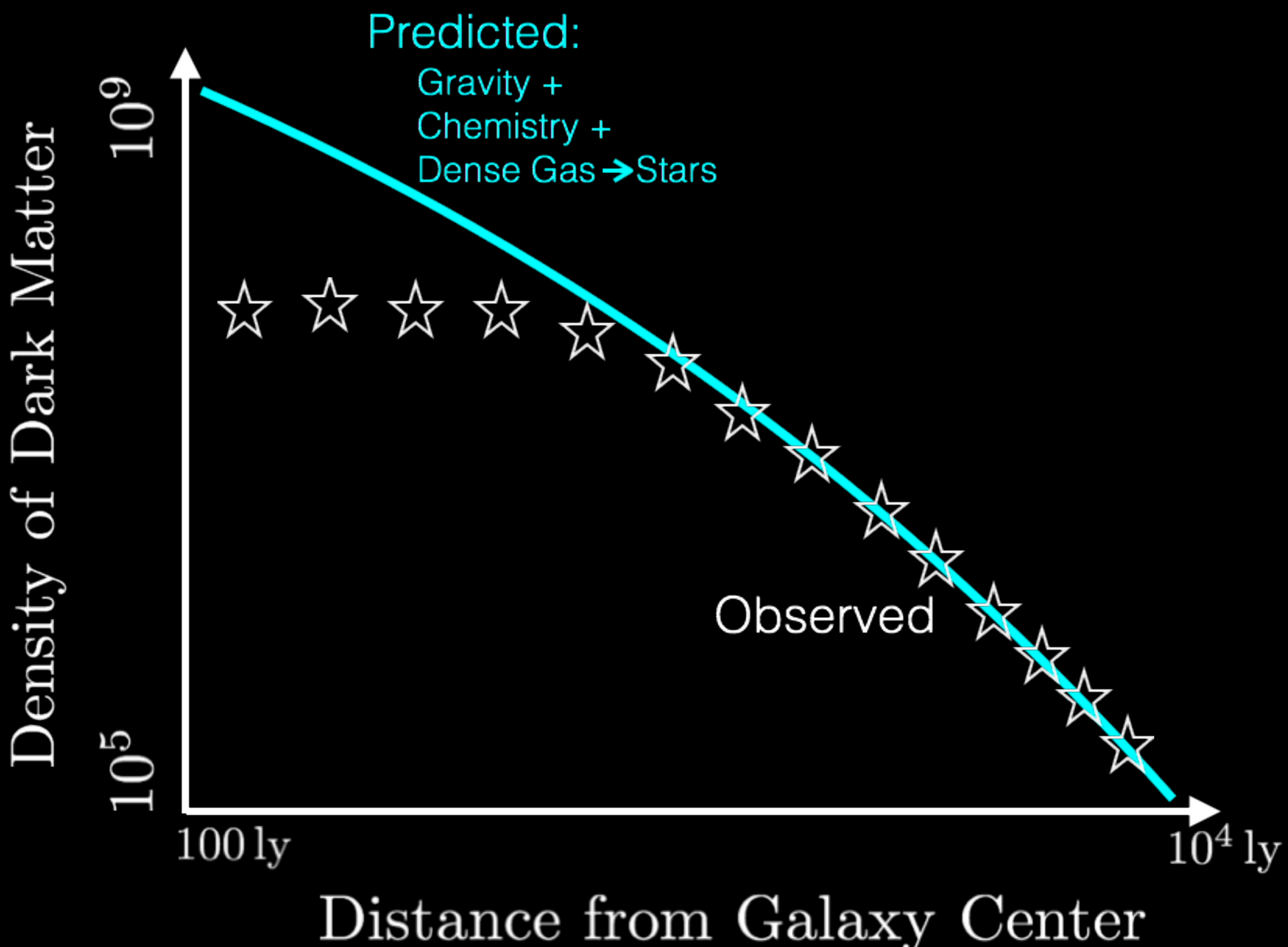
Predicted structure
(dark matter)



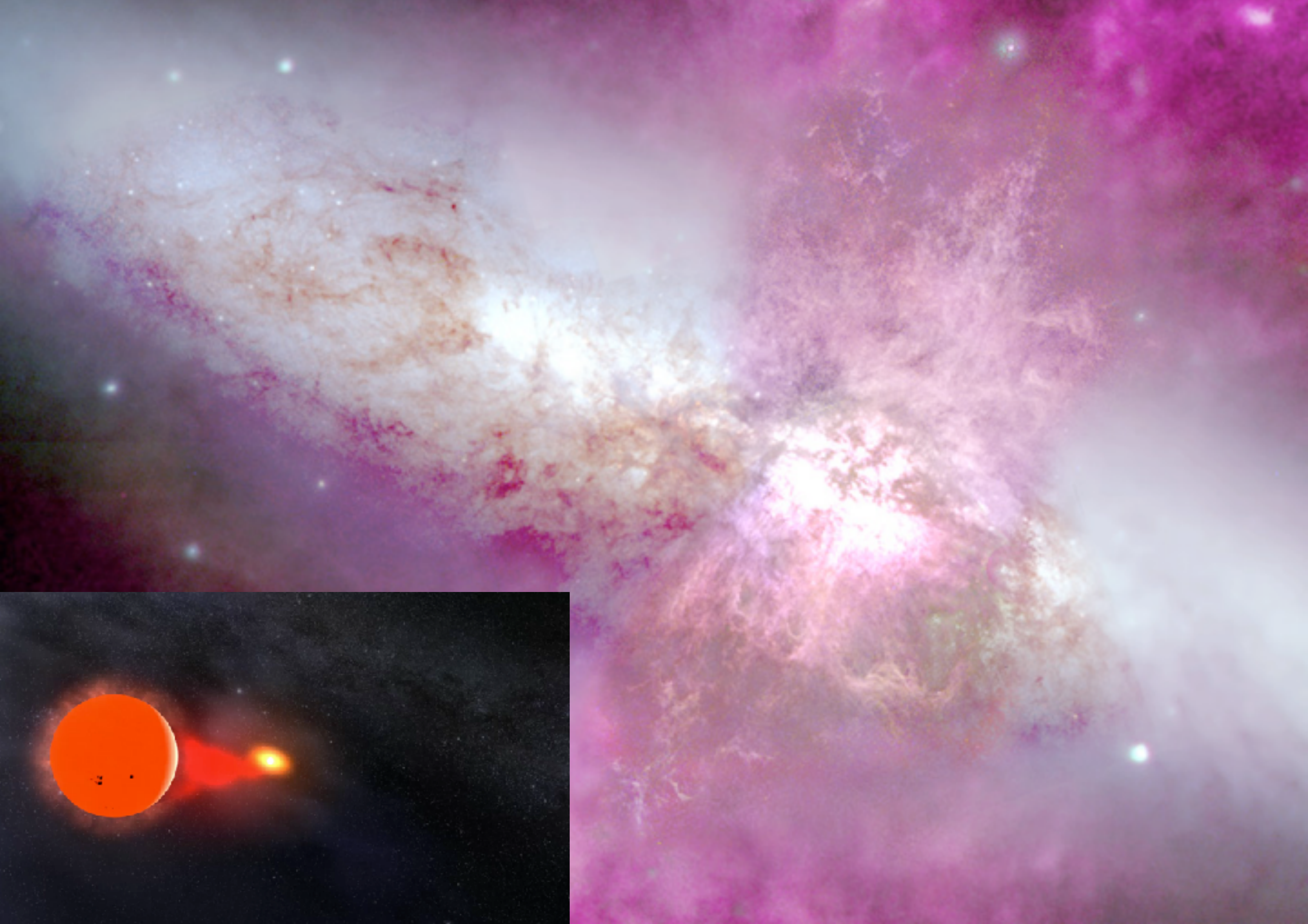
Observed
around us

Problem:

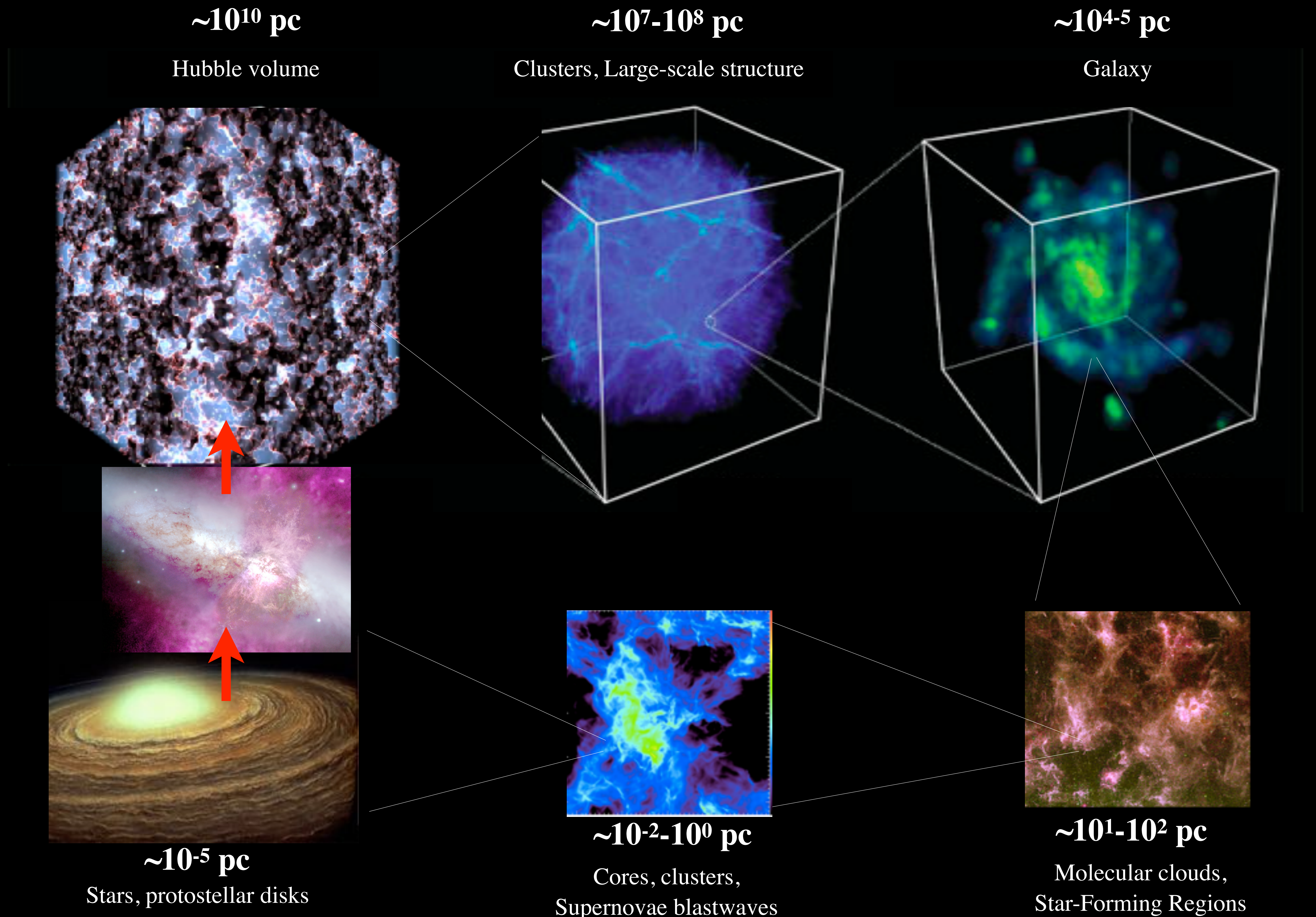
WHY ISN'T THERE MORE DARK MATTER?
("CUSP-CORE" or "TOO BIG TO FAIL")



Stars Matter



… Nature hates theorists



But we know what stars do!
(…well enough…)

Previous "State of the Art"

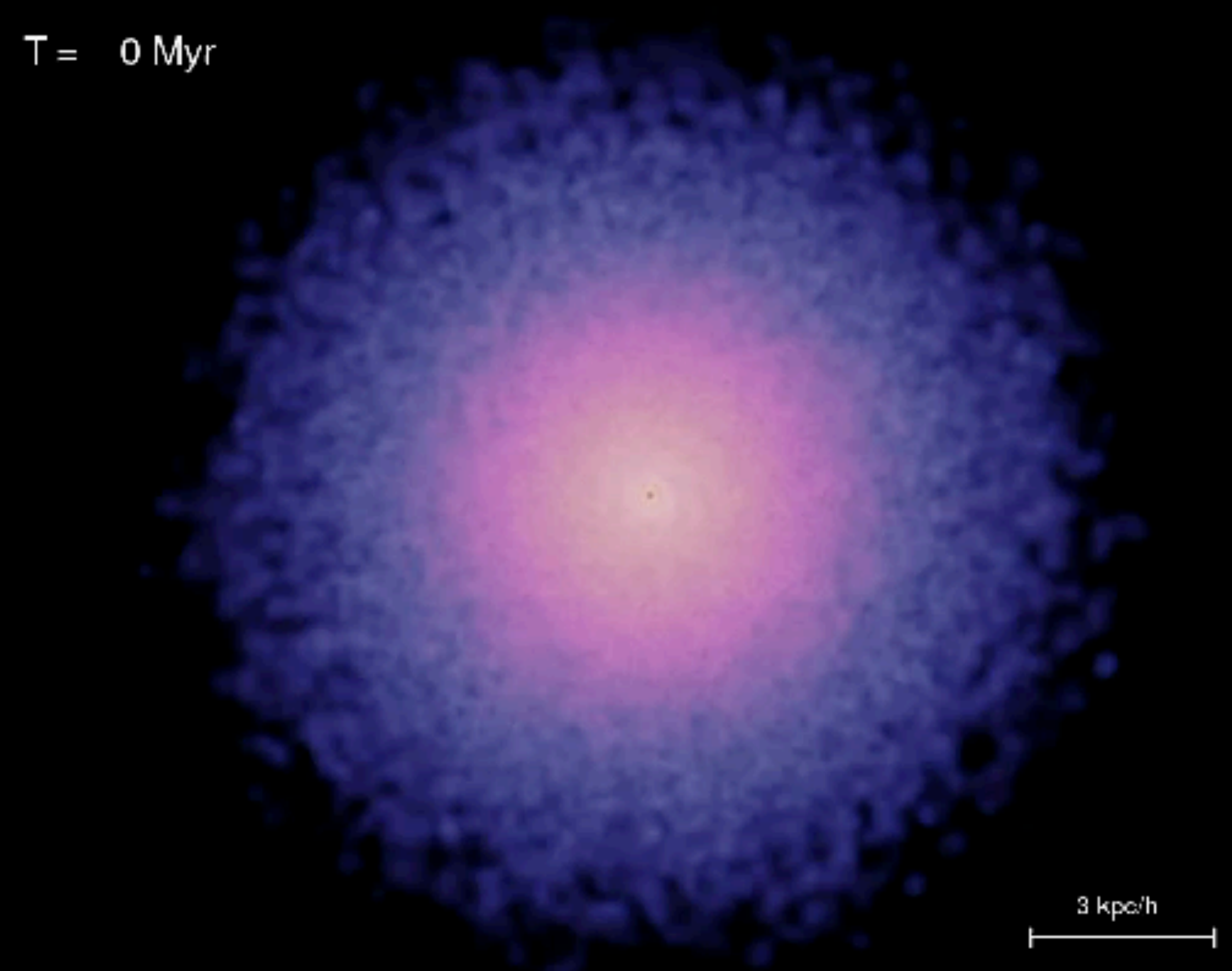
Resolution:
~kpc
~10^6 M_{sun}

Interstellar Medium:
single, ideal fluid

Winds?
"sub-grid" (cheat a bit)

- turn off cooling
- throw out mass "by hand"

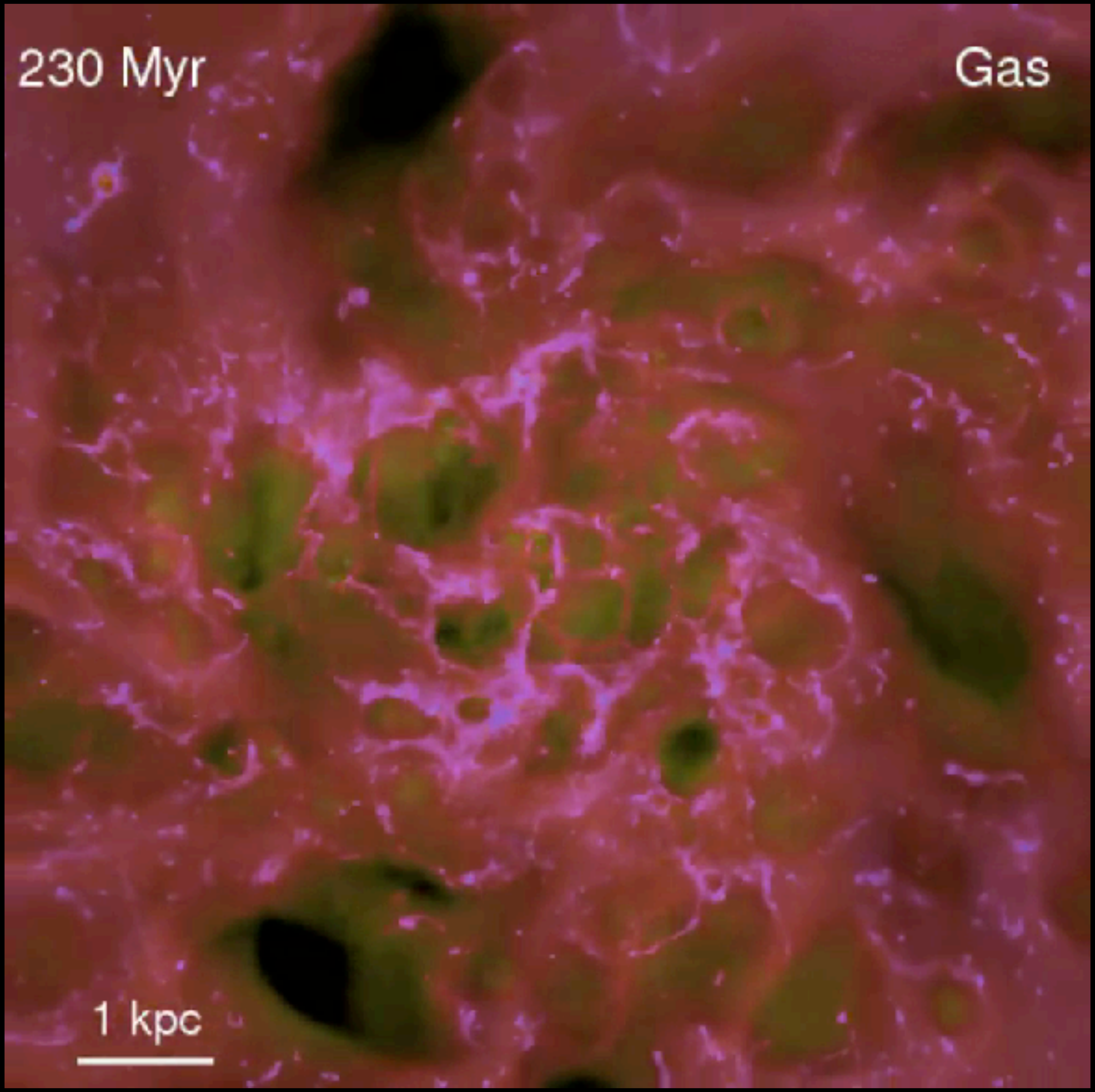
$$M_{\rm wind} = ({\rm fudge}) \times M_{\rm stars}$$



e.g. "Illustris", "OWLS," "EAGLE,"
…anything I wrote before 2012…

The FIRE Project

Feedback In Realistic Environments



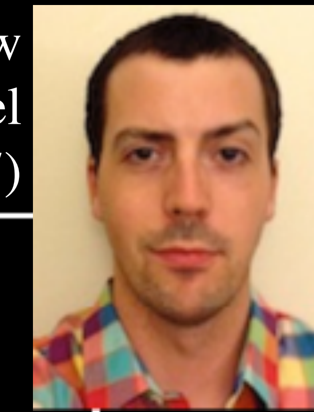
Yellow: hot (>10^6 K) Pink: warm (ionized, ~10^4K) Blue: cold (neutral <10-8000 K)

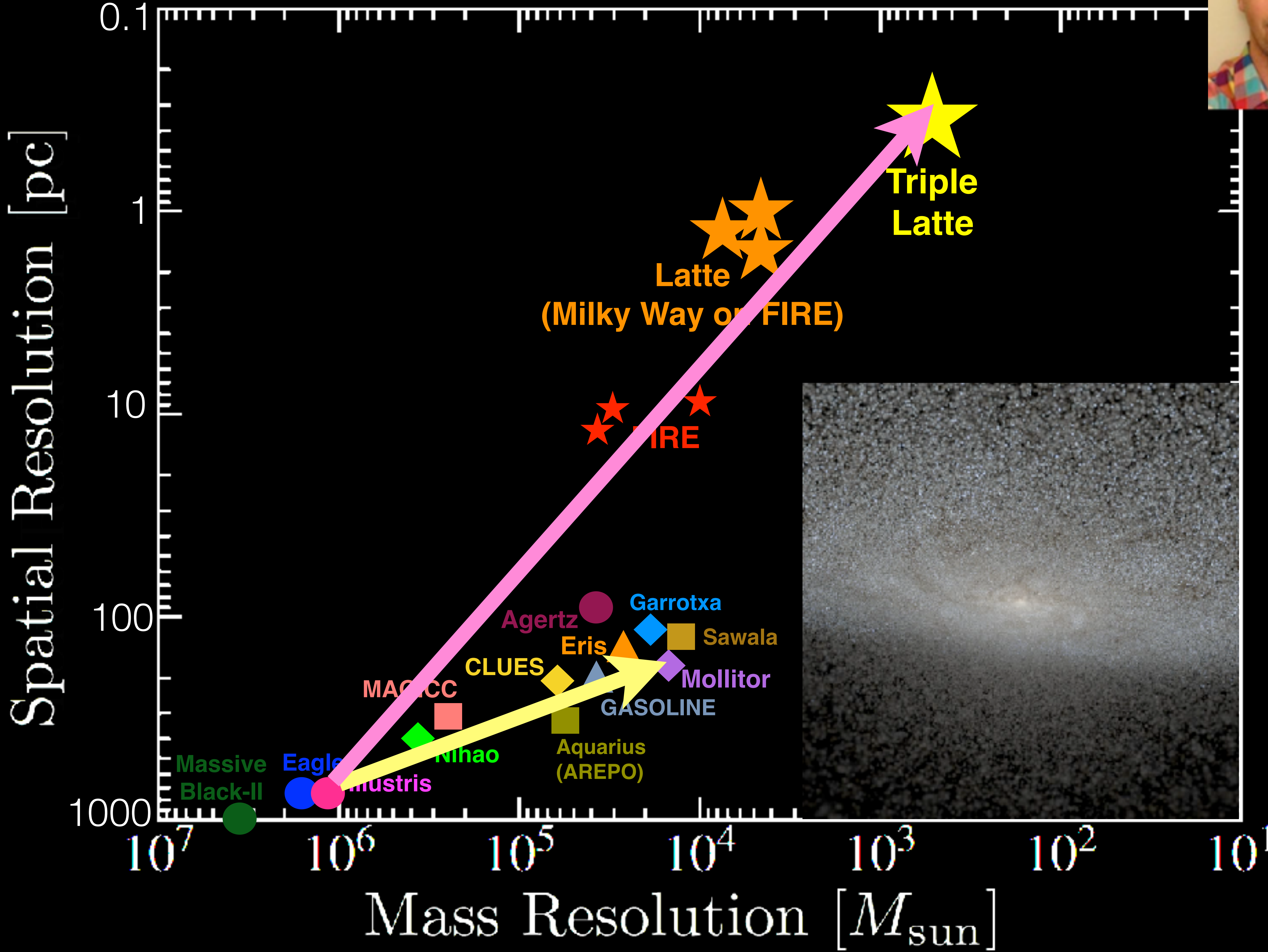
- Resolution ~pc
  Cooling & Chemistry ~10 - 10^{10} K
- **Feedback:**
  - SNe (II & Ia)
  - Stellar Winds (O/B & AGB)
  - Photoionization (HII regions)
    & Photo-electric (dust)
  - Radiation Pressure (IR & UV)
  - now with…
    - Magnetic fields
    - Anisotropic
      conduction & viscosity
    - Cosmic rays

The Future is Now

ALGORITHMIC BREAKTHROUGHS ENABLE NEW PHYSICS

Andrew Wetzel (arXiv:1602.05957)

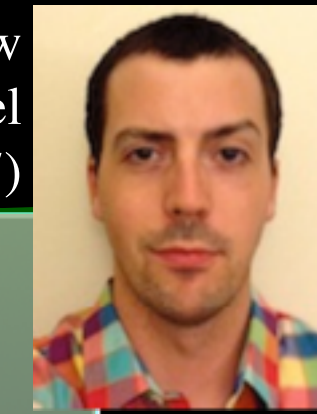


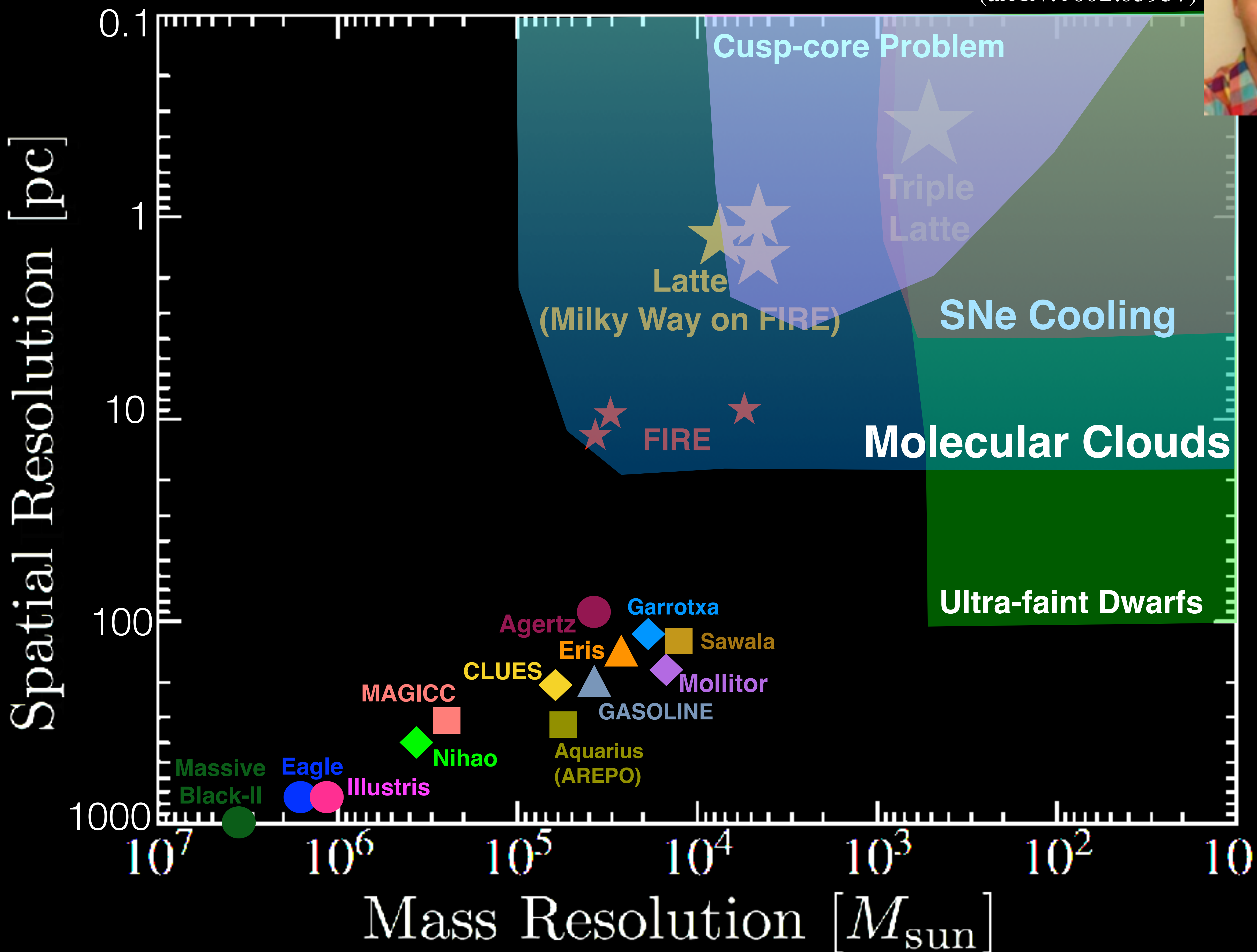


The Future is Now

NEW PHYSICS AT NEW SCALES

Andrew
Wetzel
(arXiv:1602.05957)





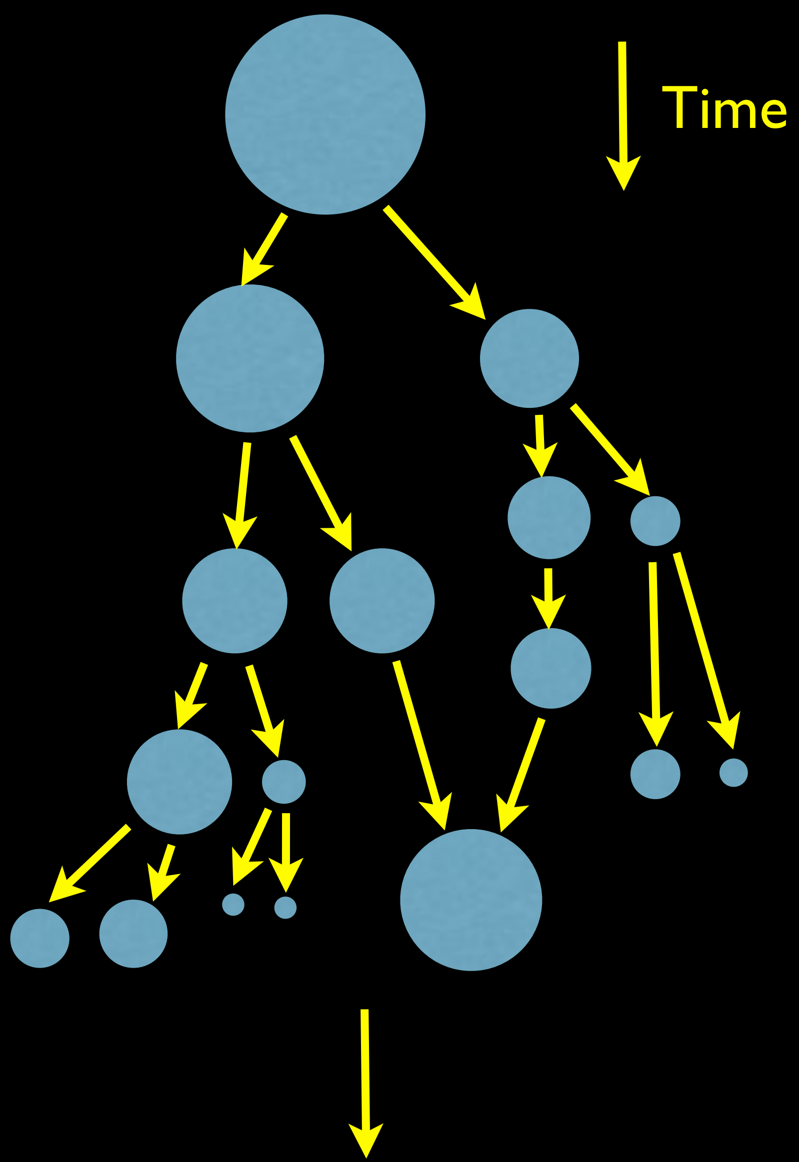
Feedback On All Scales
(From the Bottom-Up)

The IMF & Sub-Cloud Scales

Cores to Stars

HOW TO STOP FRAGMENTATION?

"Fragmentation Cascade":



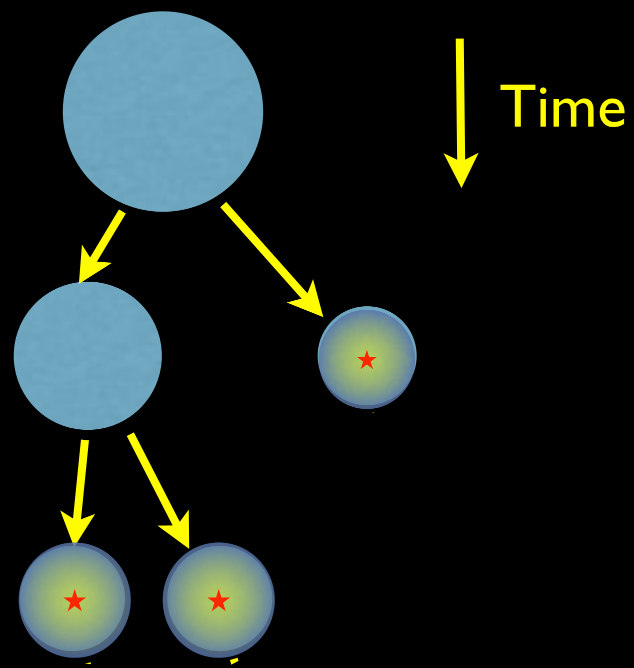
To opacity limit!
(all stars ~10 $M_{Jupiter}$)

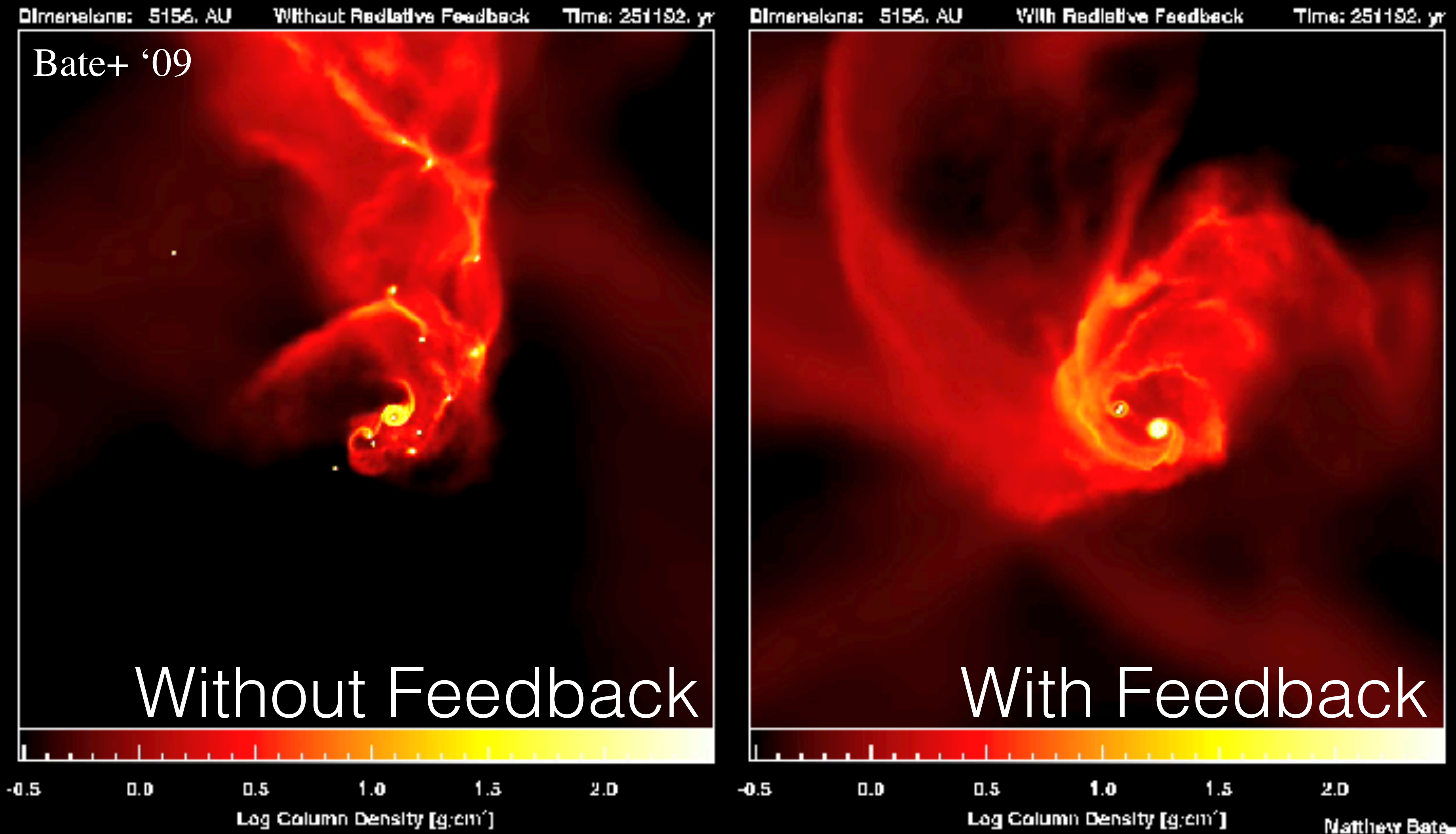
Isothermal fragmentation:

$$M_{\rm Jeans} \sim \frac{c_s^3}{G^{3/2}\rho^{1/2}} \longleftarrow \propto L_{\rm core}^{3/2}$$

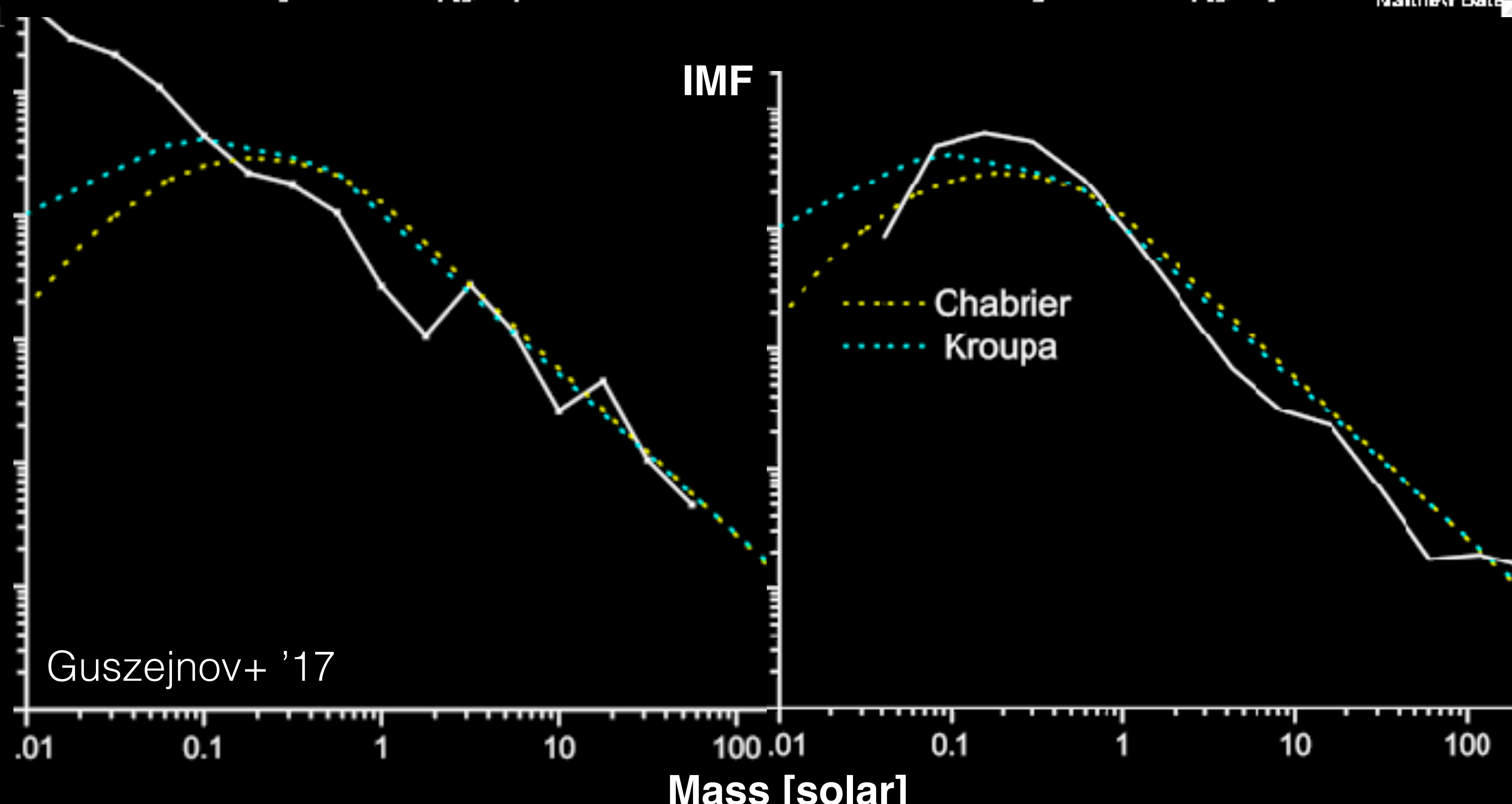
Feedback vs. Gravity

Guszejnov, Hopkins, & Krumholz 2015





$$M_{\rm crit} \sim 0.1\, M_{\odot} \left(\frac{\psi}{\psi_0}\right)^{0.4} \left(\frac{R_{\rm core}}{0.1\,{\rm pc}}\right)^{0.1}$$



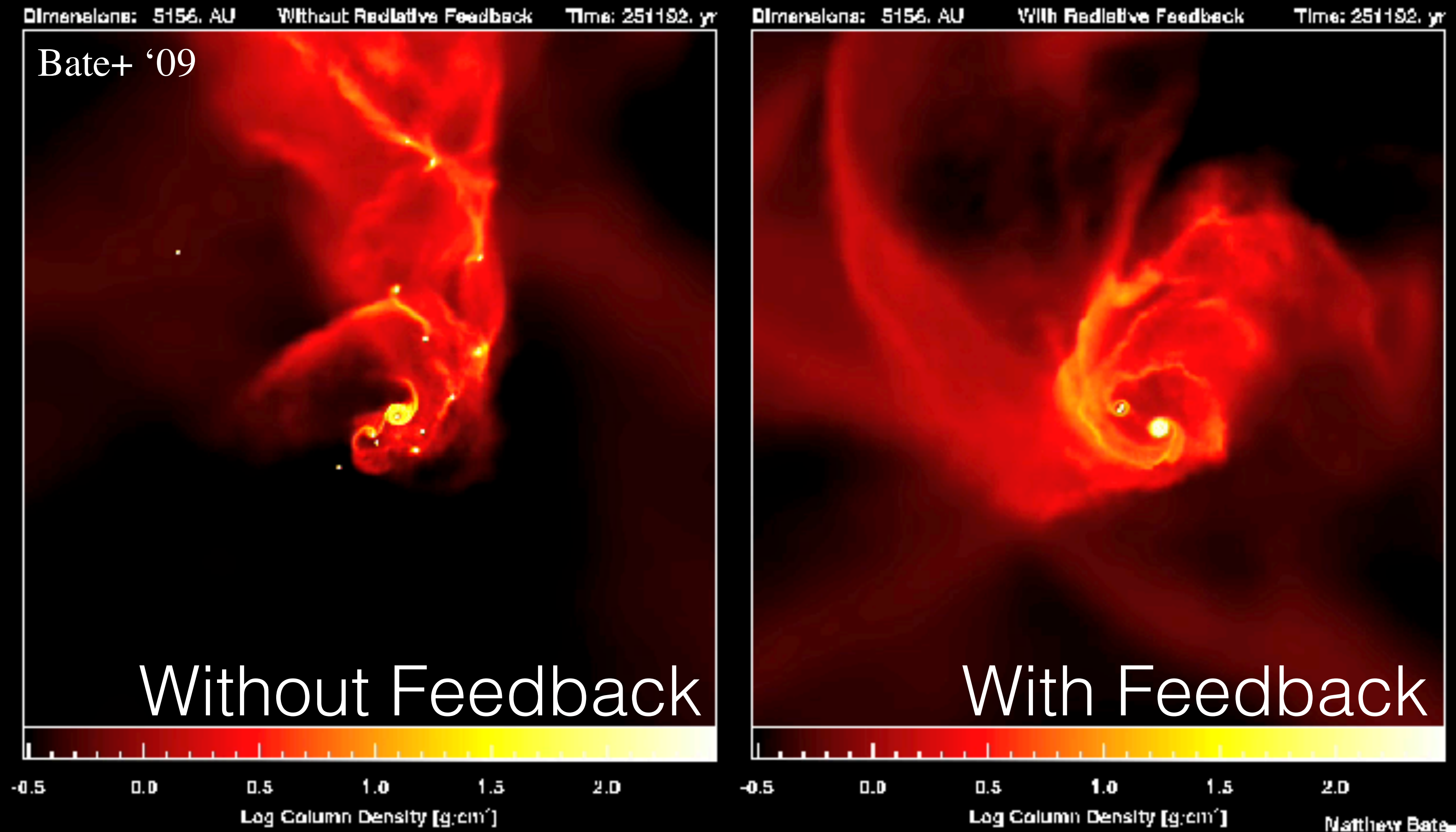
See also:
- Bate+ '09, '12
- Offner+ '09, '14
- Krumholz+ '12
- Guszejnov+ '16, 17

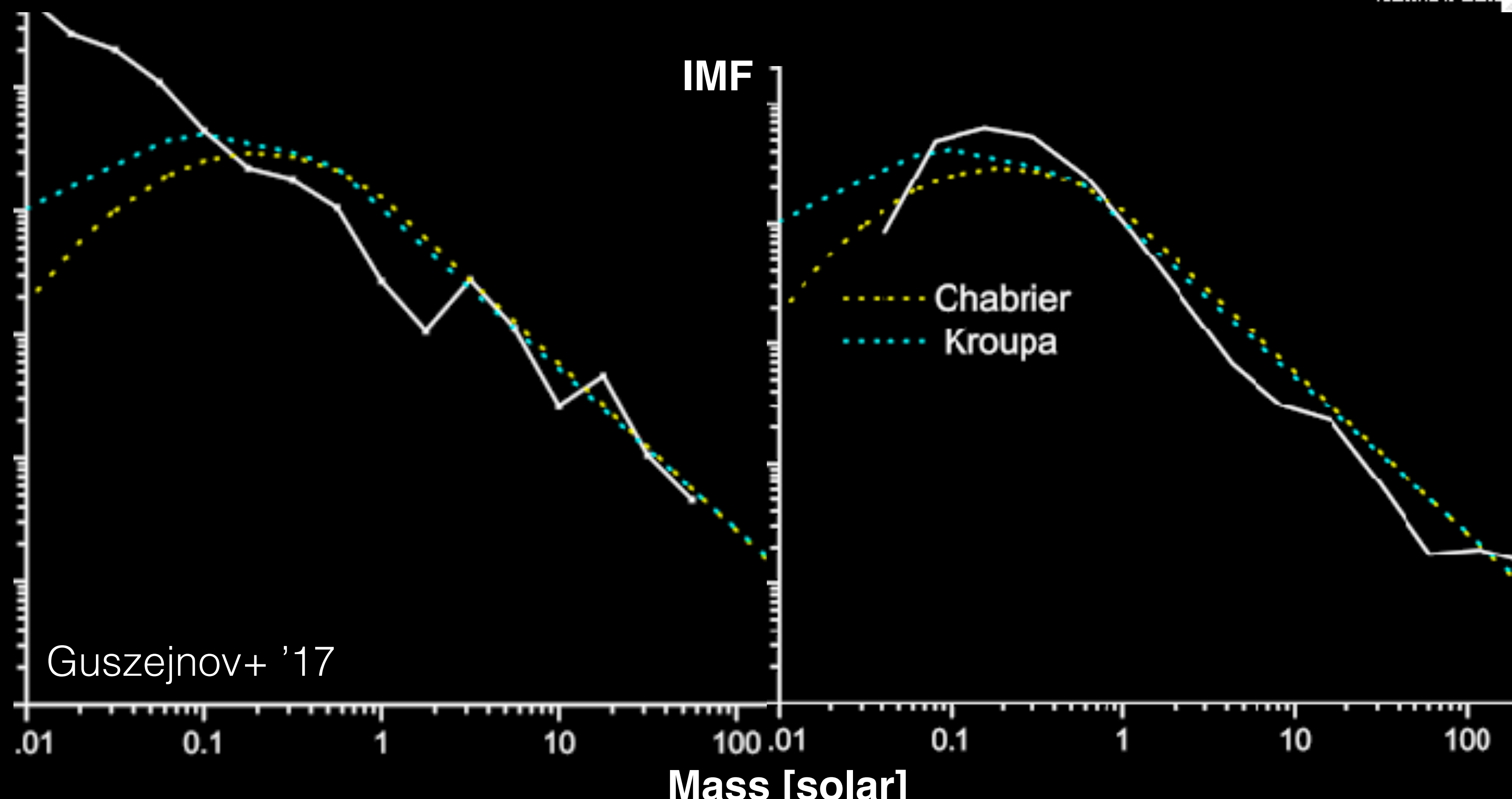
- (Multiplicity [same refs])

Feedback vs. Gravity

Guszejnov, Hopkins, & Krumholz 2015

EVERY VARIABLE-IMF MODEL USED EXTRA-GALACTICALLY IS WRONG (arXiv:1702.04431)



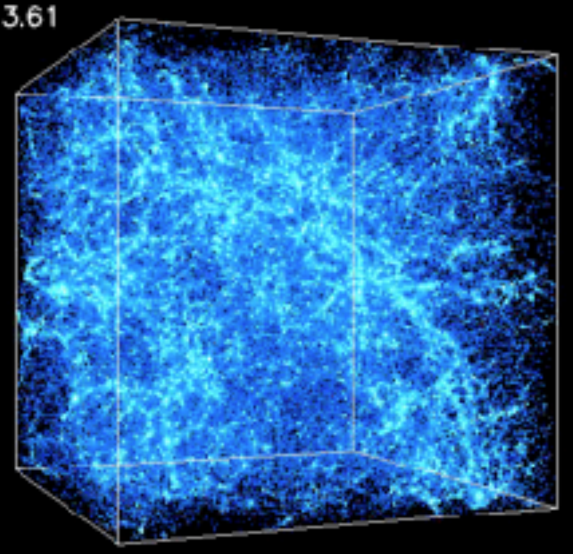


See also:
- Bate+ '09, '12
- Offner+ '09, '14
- Krumholz+ '12
- Guszejnov+ '16, 17

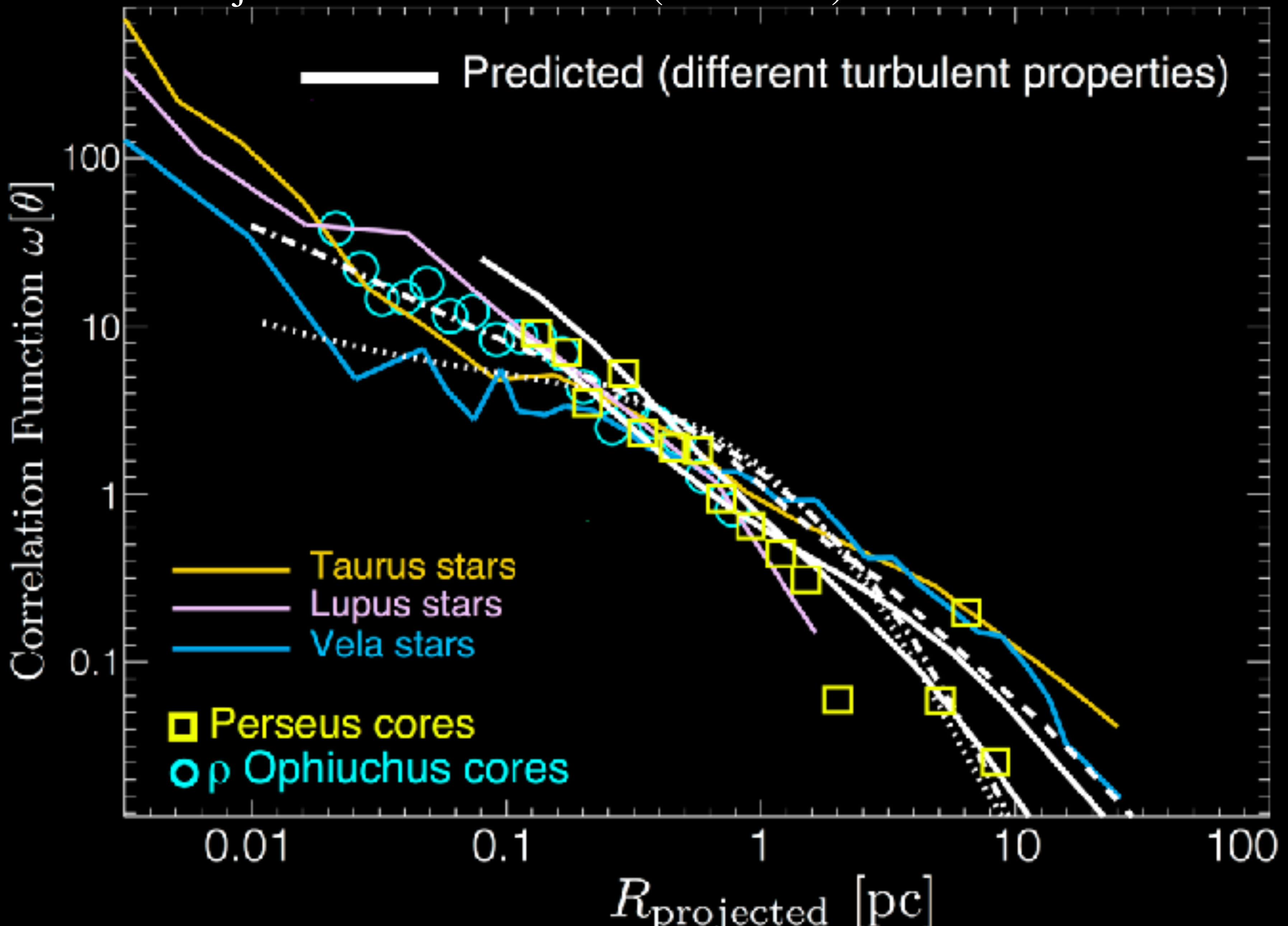
- (Multiplicity [same refs])

Why Is Star Formation Clustered?

INEVITABLE IN GRAVITATIONAL COLLAPSE



Guszejnov: arXiv:1610.00772 (+PFH '12)



Universal
(Guszejnov: 1707.05799):

Stars
Cores
Clumps
GMCs
Star clusters
Galaxies

$$\xi_{\rm 3d} \propto r^{-2}$$

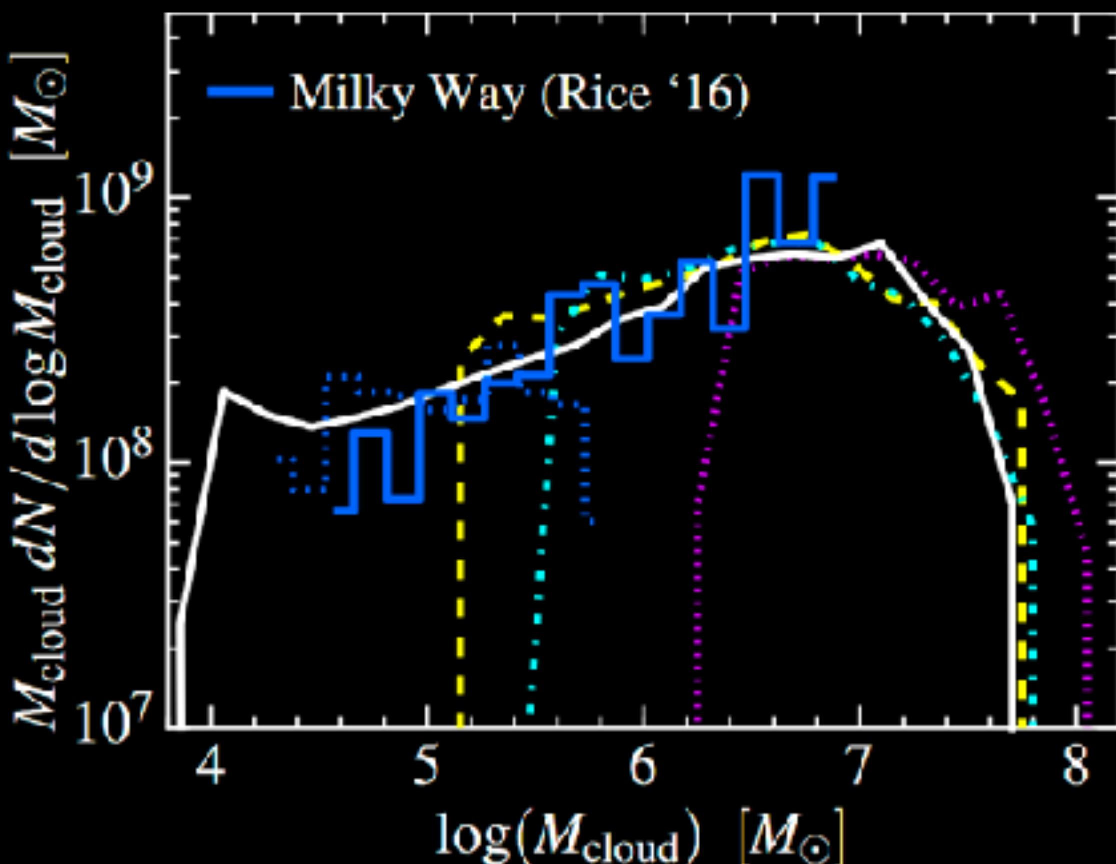
$$(\omega(\theta) \propto \theta^{-1})$$

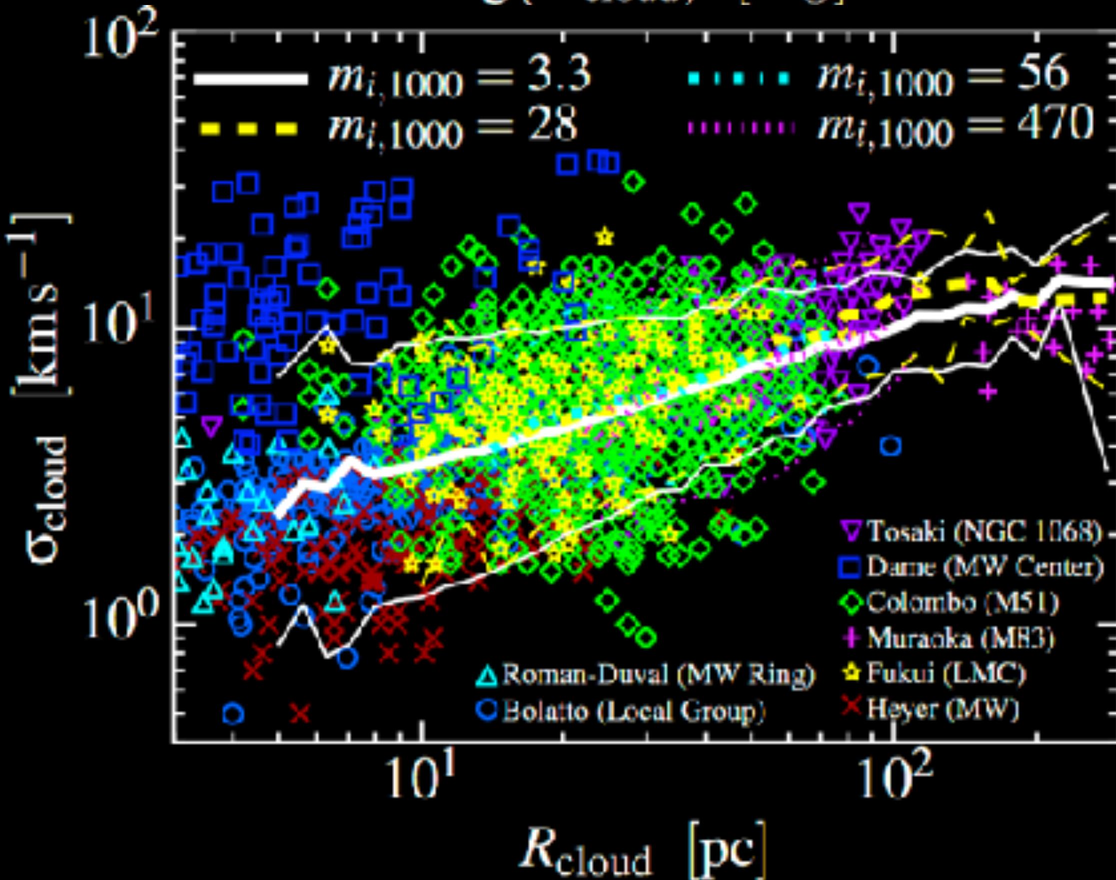
GMC & Star Cluster Scales

GMCs: Turbulence+Gravity

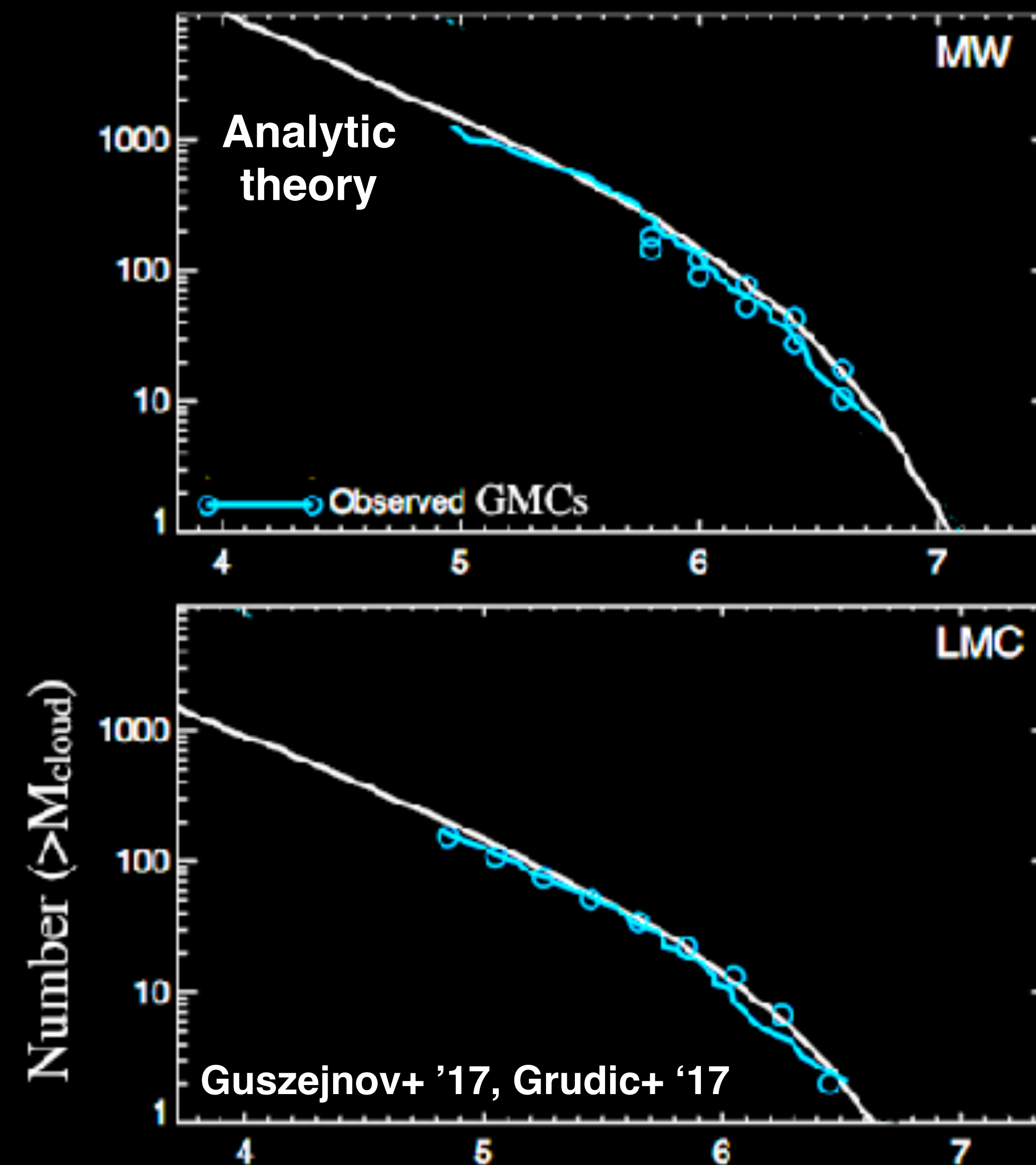
RESOLVING "TOP SCALE" OF FRAGMENTATION

FIRE simulations: Guszejnov (arXiv:1702.04431)

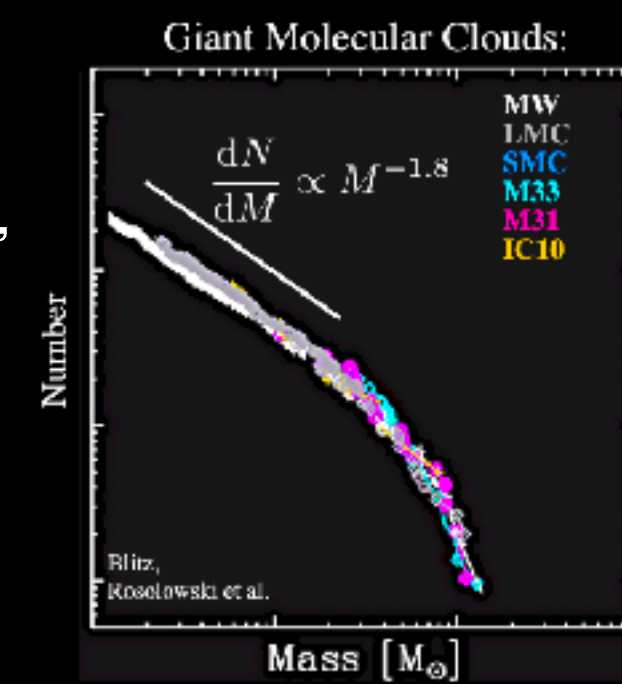




(+cloud sizes, virial parameters)



"Universal" Mass Function (GMCs, star clusters, and more!)



What Determines Cloud Star Formation Efficiencies?

FEEDBACK VS. GRAVITY

$$\text{Feedback} \sim \frac{\text{Momentum}}{\text{Time}} \propto (\ldots)\, M_*$$

Supernovae
+ Winds
+ Radiation Pressure
(+ Jets + Photo-heating
+ Cosmic-rays)

$$\text{Gravity} \sim \frac{G\, M_{\rm tot}\, M_{\rm gas}}{R^2} \propto M_{\rm tot}\, \Sigma_{\rm gas}$$

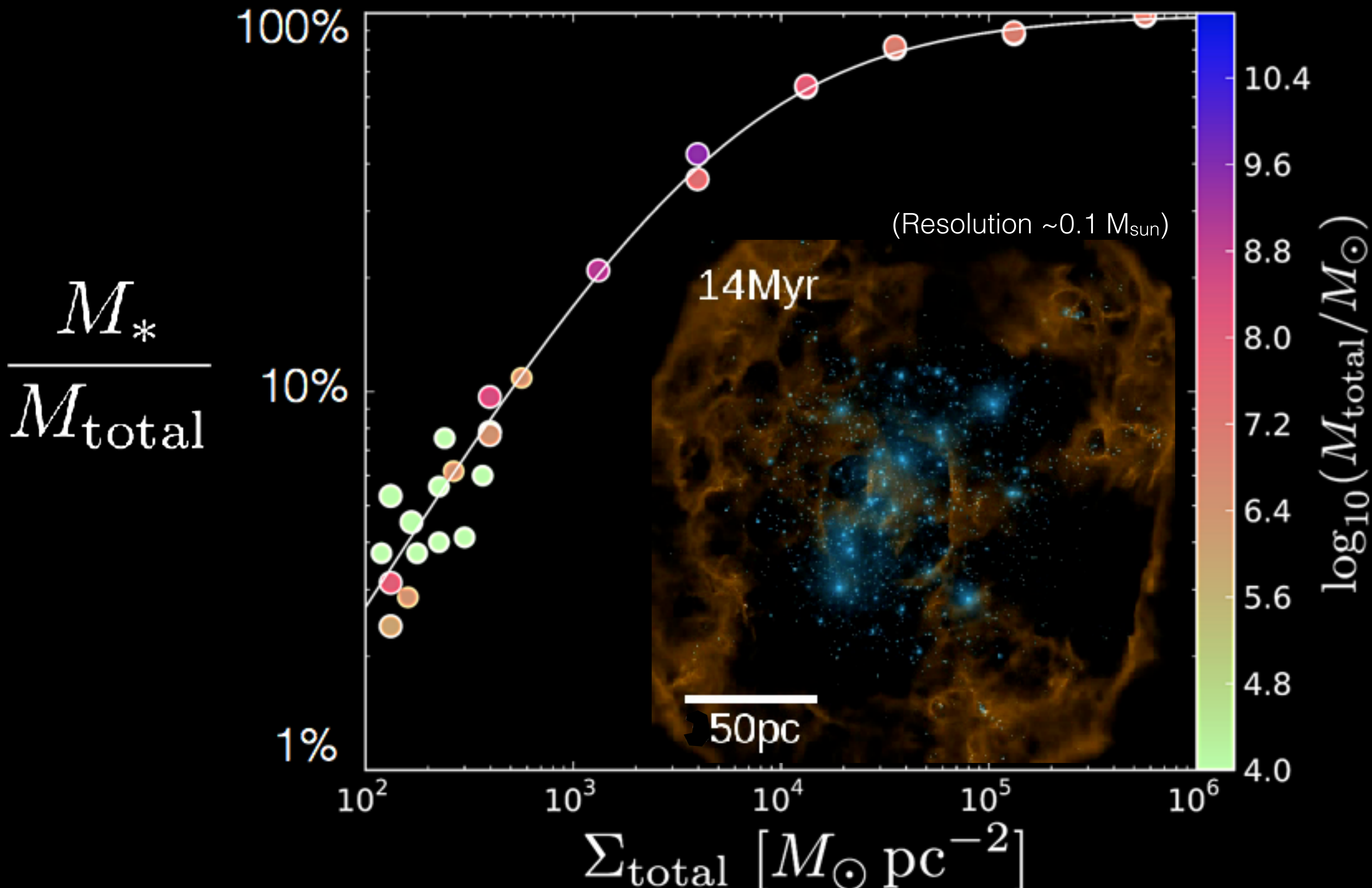
$$\rightarrow \frac{M_*}{M_{\rm tot}} \sim \frac{\Sigma}{(\text{few})\; 10^4\, M_\odot\, {\rm pc}^{-2}}$$

see Matzner '08,10

What Determines Cloud Star Formation Efficiencies?

FEEDBACK VS. GRAVITY

Mike Grudic (arXiv: 1612.05635)

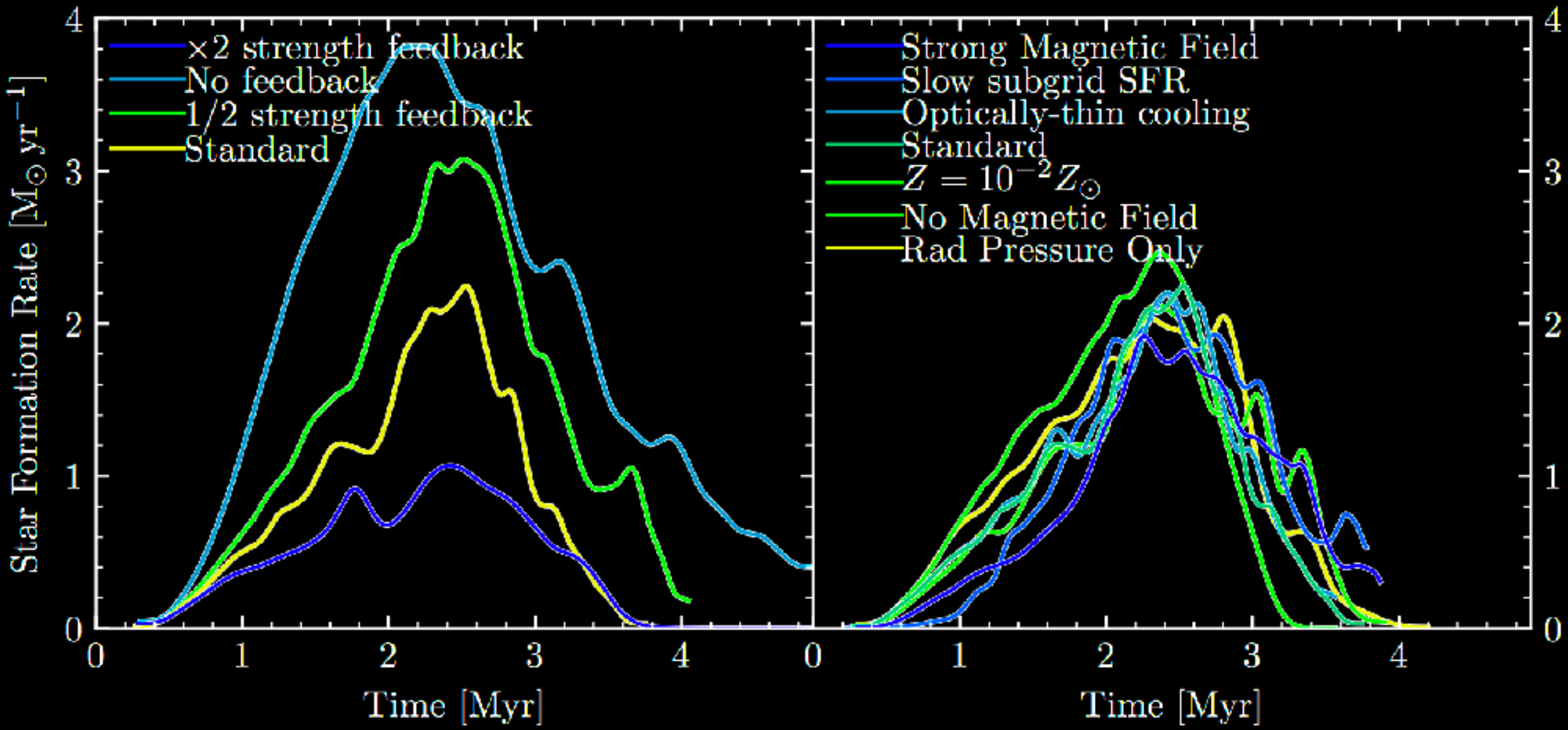


$$\text{Gravity} \sim \frac{G\,M_{\rm tot}\,M_{\rm gas}}{R^2} \propto M_{\rm tot}\,\Sigma_{\rm gas} \qquad \text{vs.} \qquad \text{Feedback} \sim \frac{\text{Momentum}}{\text{Time}} \propto (\ldots)\,M_*$$

What Determines Cloud Star Formation Efficiencies?

FEEDBACK VS. GRAVITY

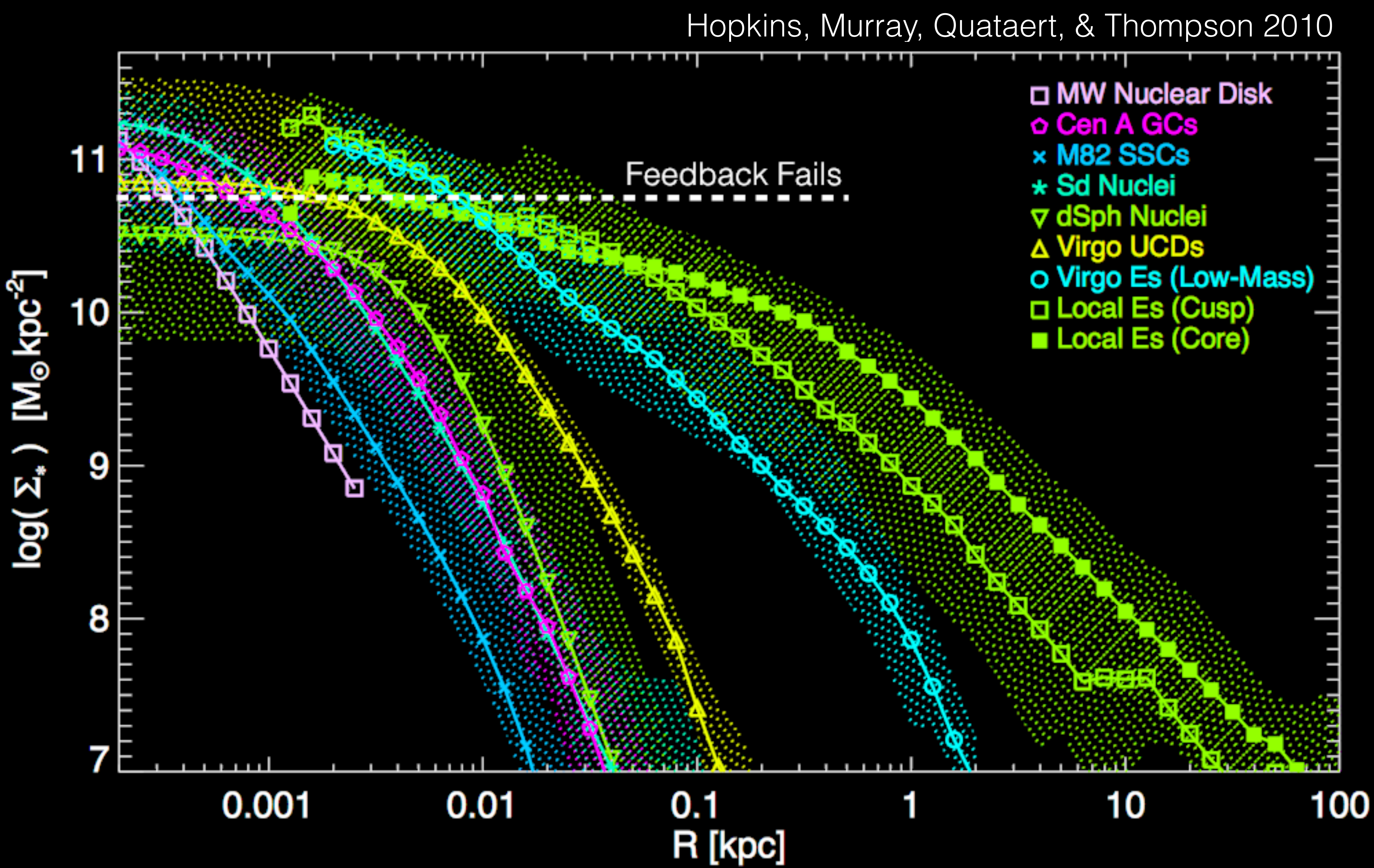
Mike Grudic (arXiv: 1612.05635)



(also RT method: LEBRON, M1, FLD; non-ideal MHD; conduction+viscosity)

Where Does Feedback Fail?

GRUDIC ’17 (prep): PREDICT AN “UPPER LIMIT”



Where Does Feedback Fail?

GRUDIC ’17 (prep): PREDICT AN “UPPER LIMIT”

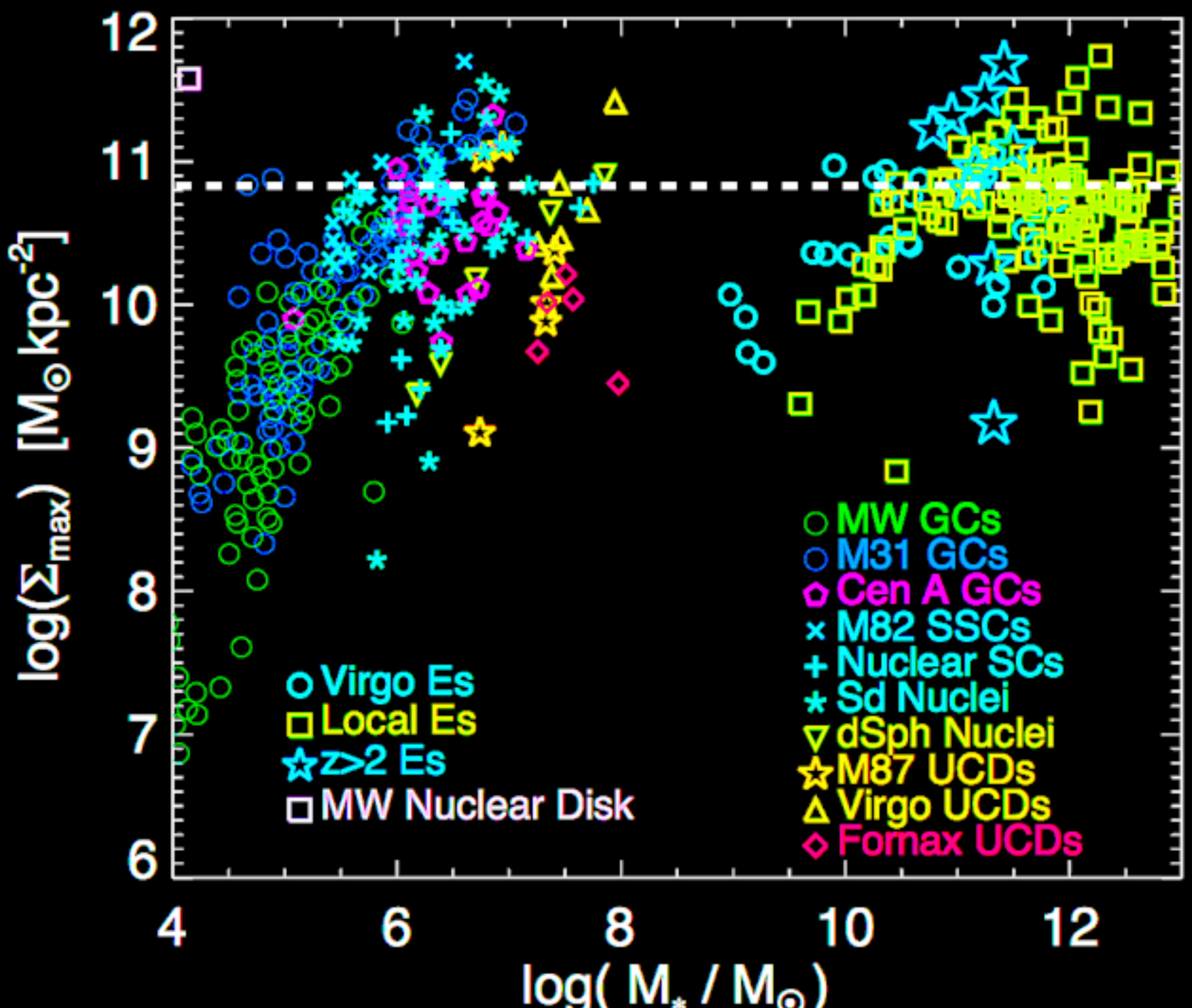
$$R_{\rm eff} \sim 0.1 - 10^4\,{\rm pc}$$

$$M_* \sim 10^4 - 10^{12}\,M_\odot$$

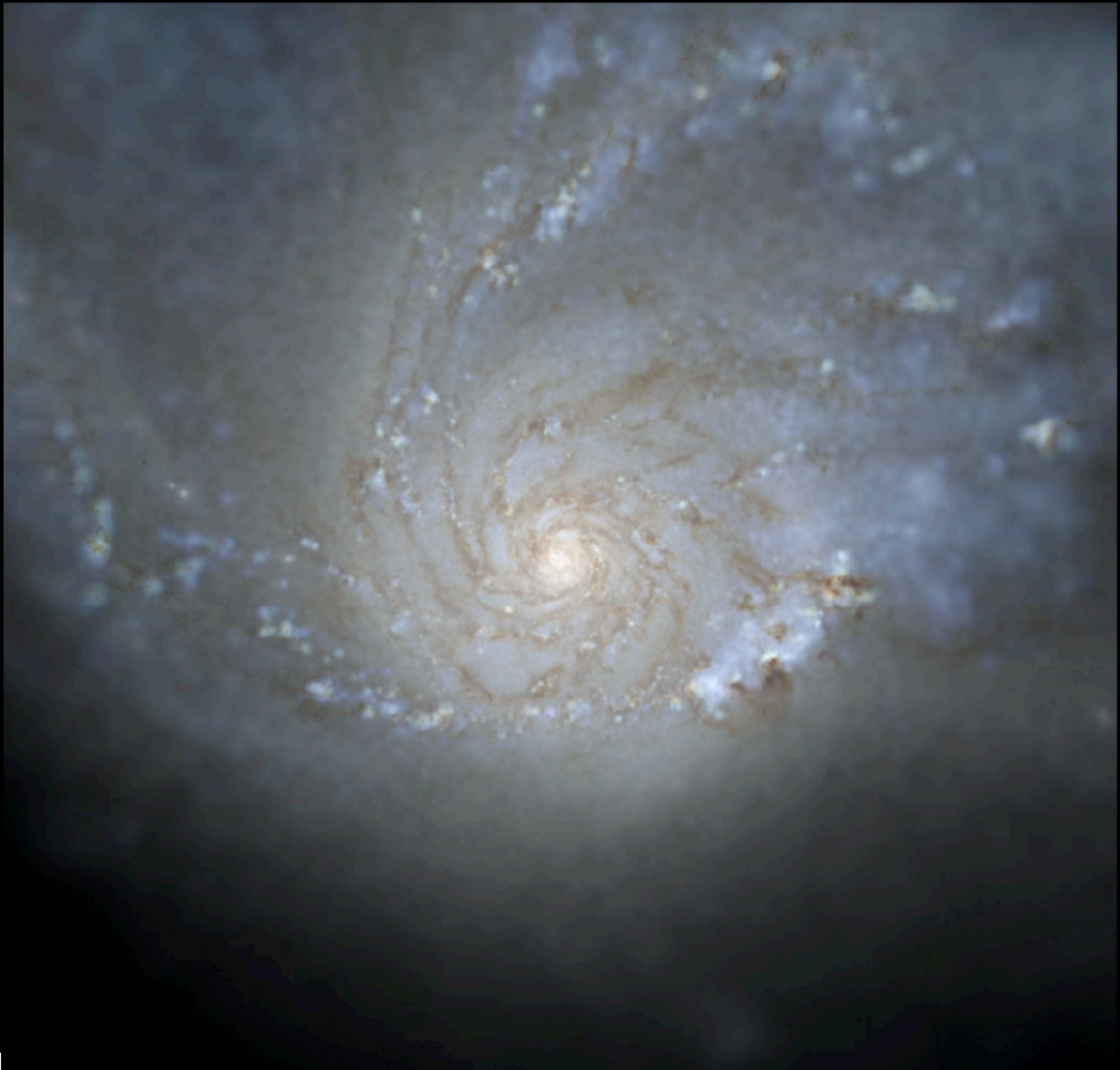
$$\rho \sim 1 - 10^5\,\frac{M_\odot}{{\rm pc}^3}$$

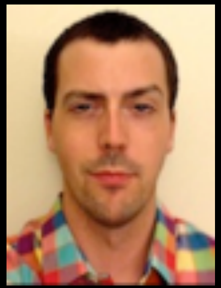
$$Z \sim 0.01 - 5\,Z_\odot$$

$$\text{Redshift}_{\rm form} \sim 0 - 6$$



Hopkins, Murray, Quataert, & Thompson 2010



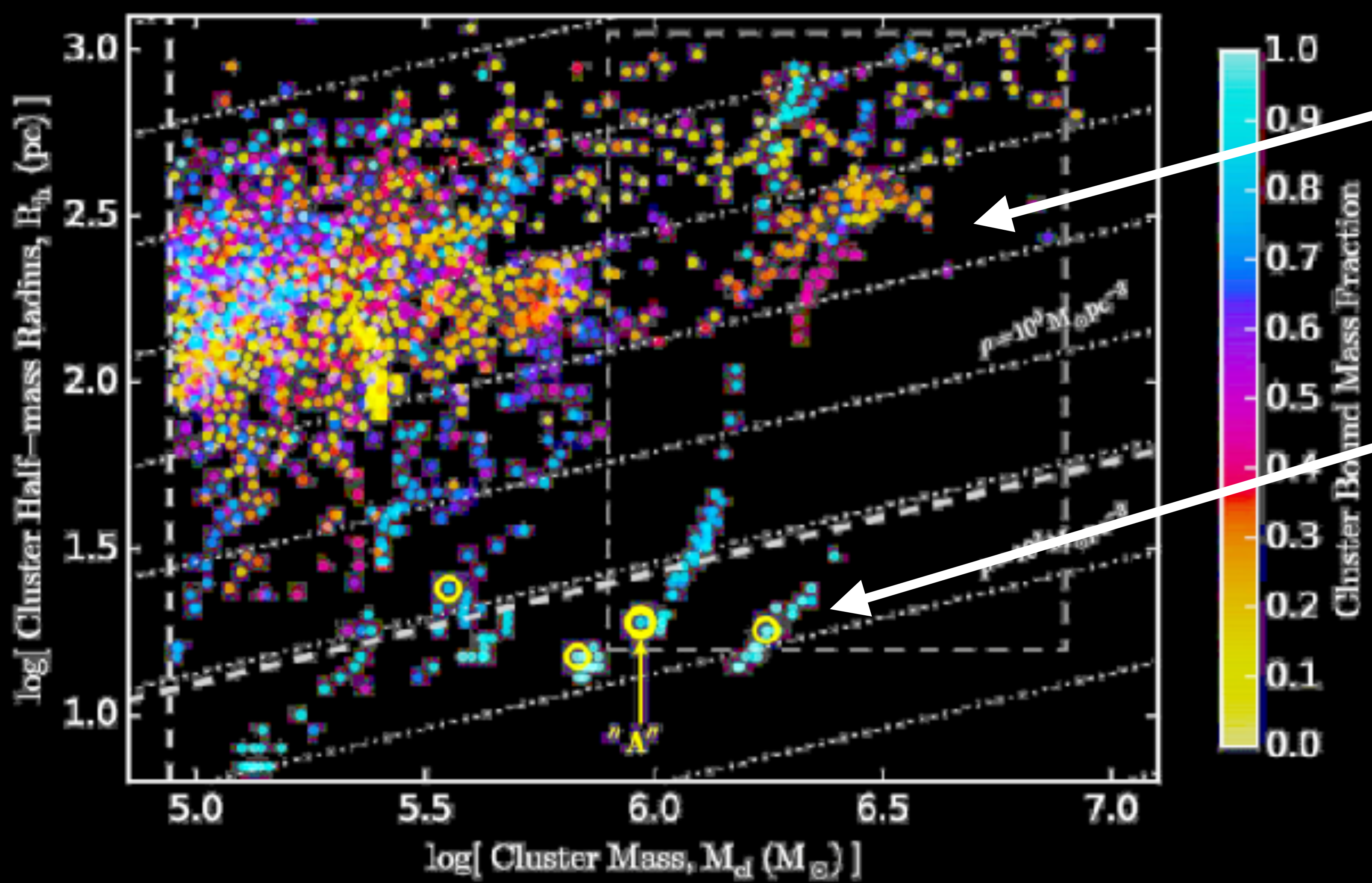


Andrew Wetzel
(arXiv:1602.05957)

"Latte" (A. Wetzel): Cosmological MW with ~7000 M_{sun} , pc-scale resolution

Resolving Globulars in Cosmological Simulations

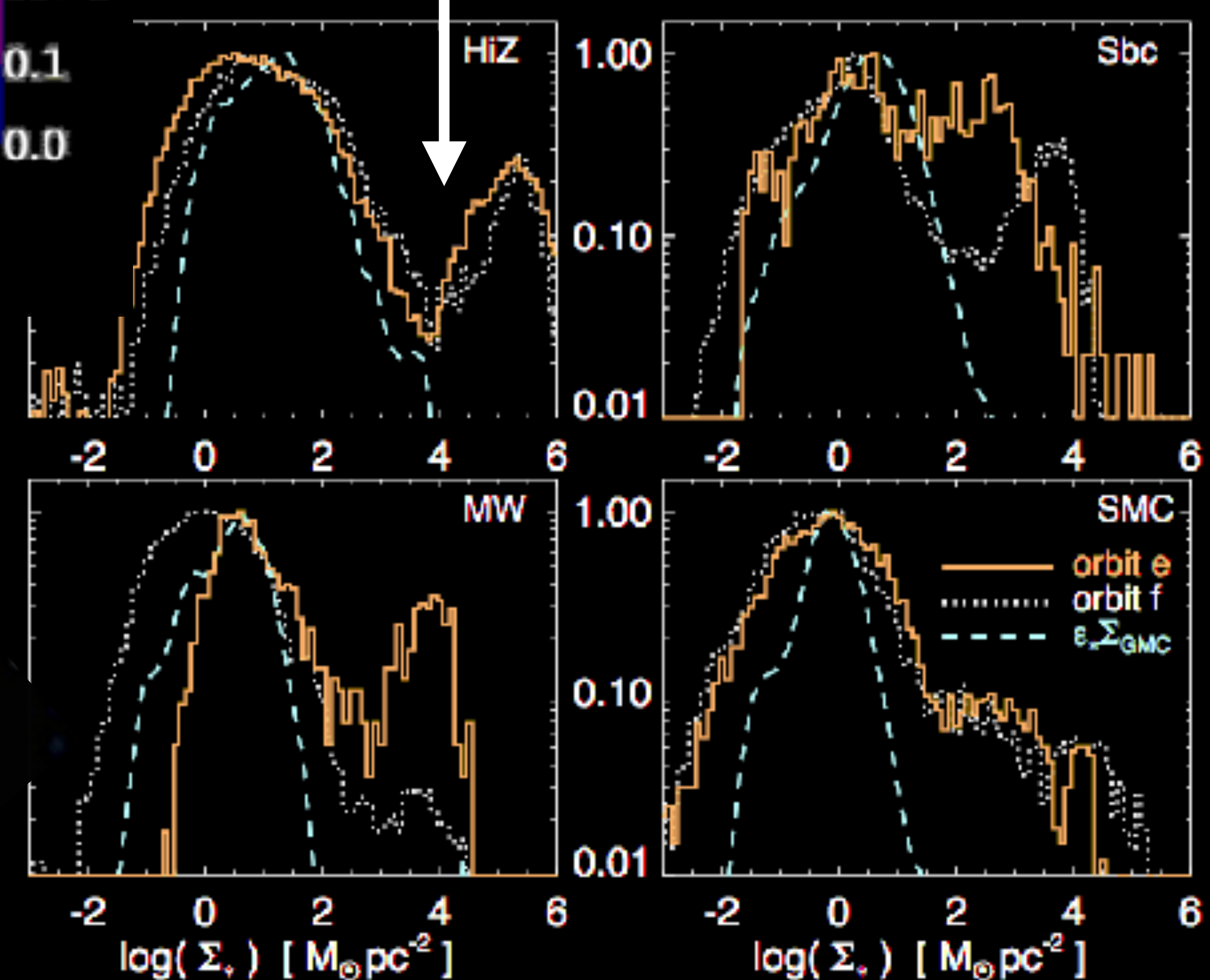
(KIM '17 + GRUDIC '17)



Most form open clusters

Except long-lived population, around critical Σ_{cloud}

Ji-Hoon Kim (arXiv: 1704.02988)

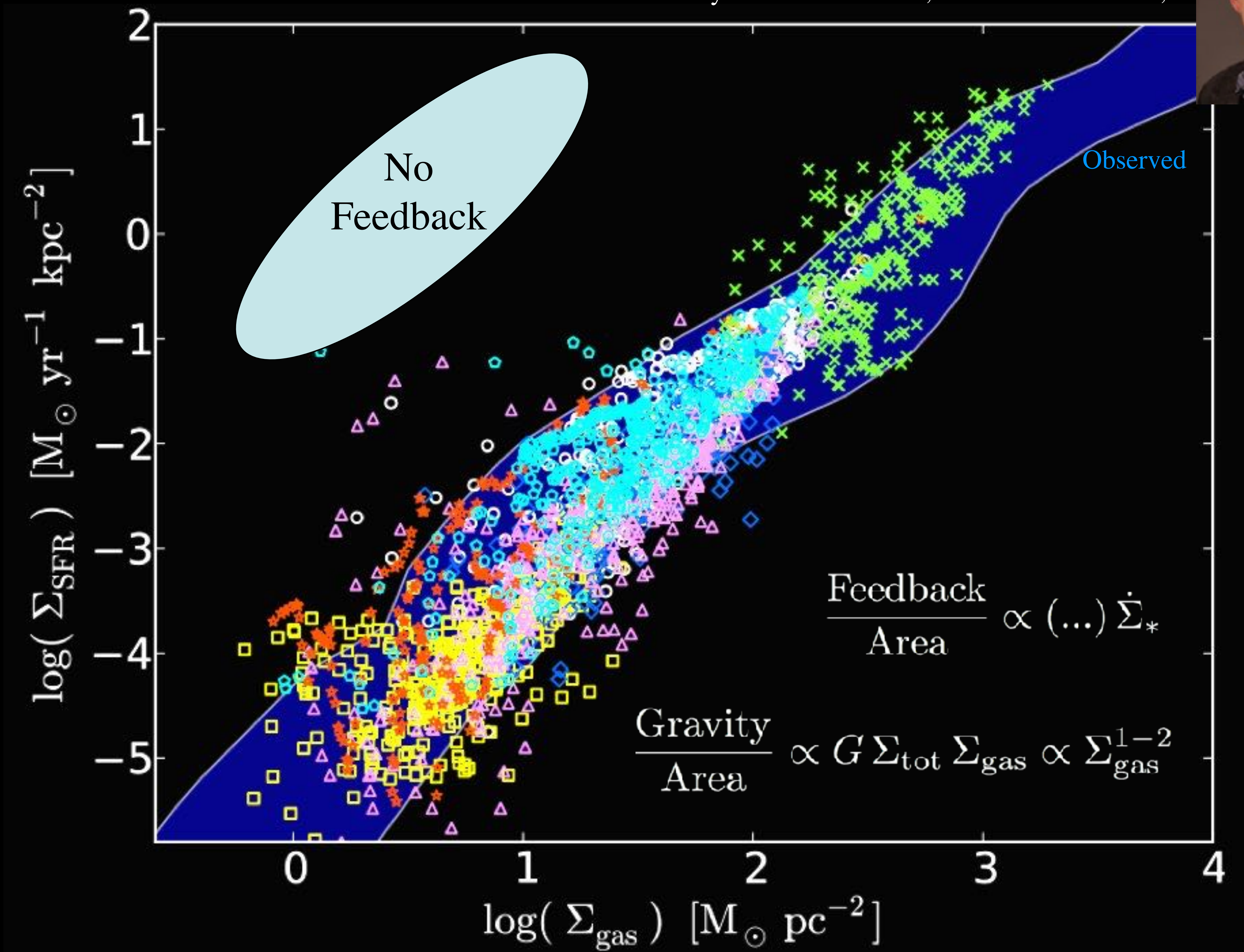


~kpc Scales: Kennicutt-Schmidt

KS Law Emerges Naturally

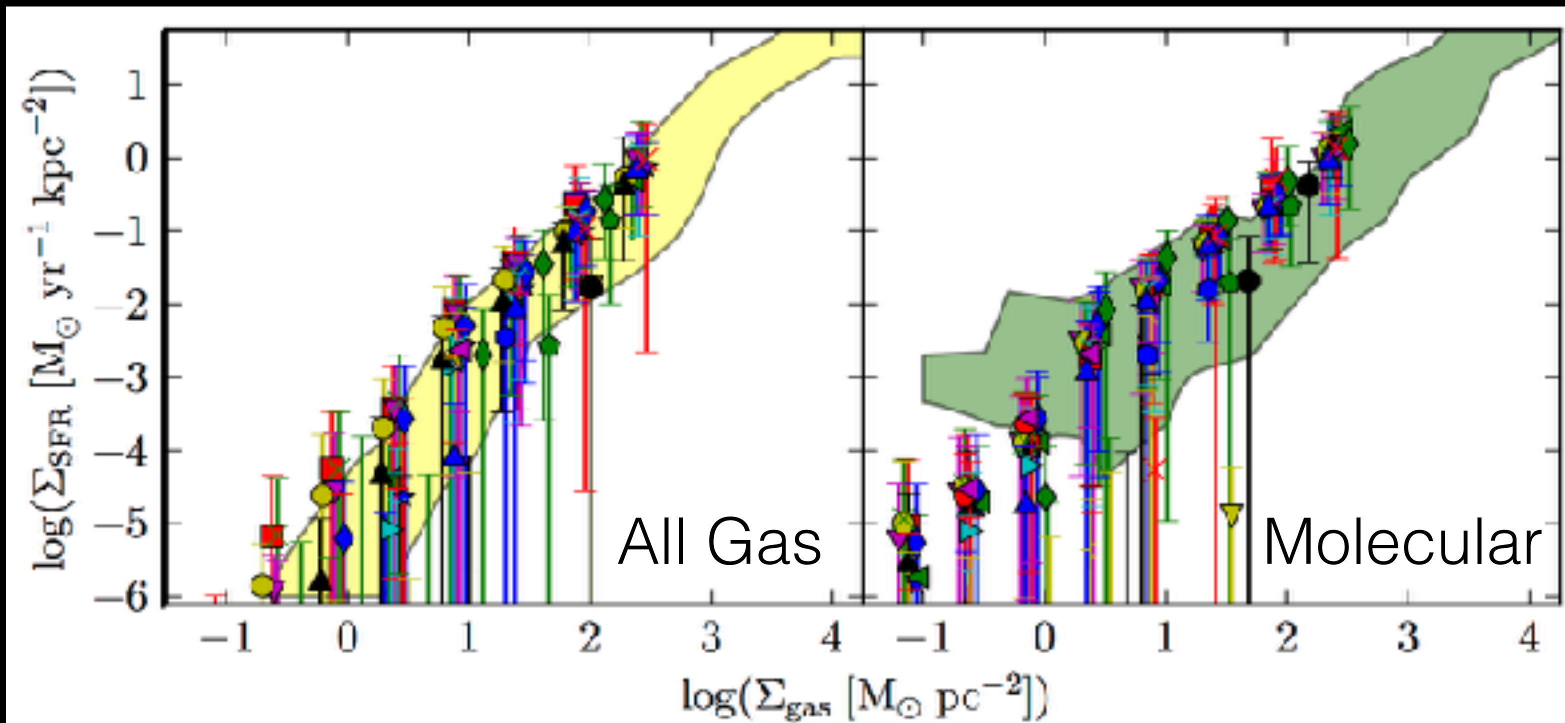
FEEDBACK VS. GRAVITY

Matt Orr (1701.01788)
Agertz+14 , PFH+ 11,12,14
Shetty & Ostriker '08.11, Kim & Ostriker '11,13

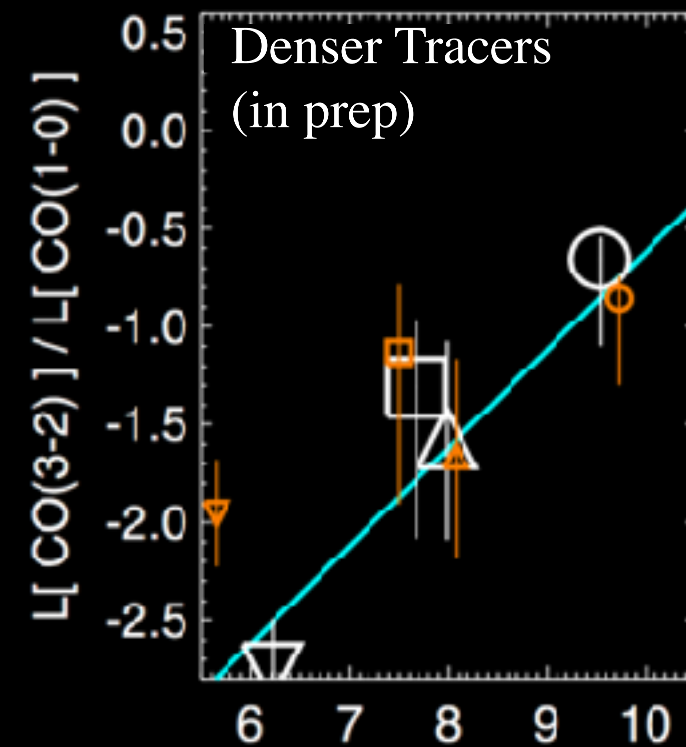


The KS Law: Different Information on Different Scales

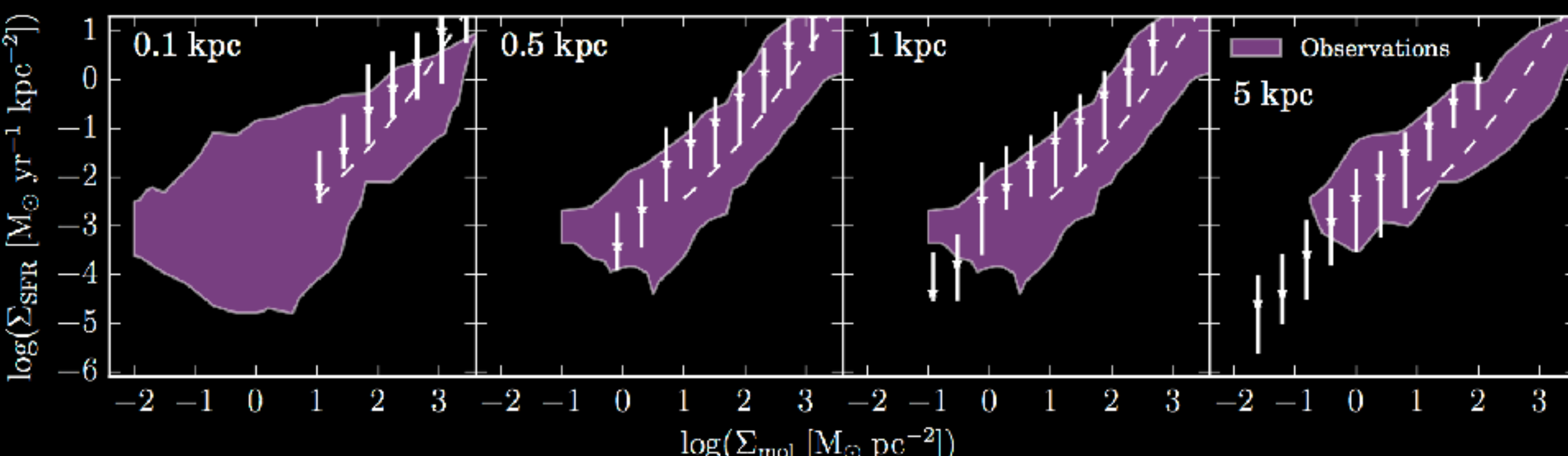
Matt Orr (1701.01788)
+ ’17 (in prep)



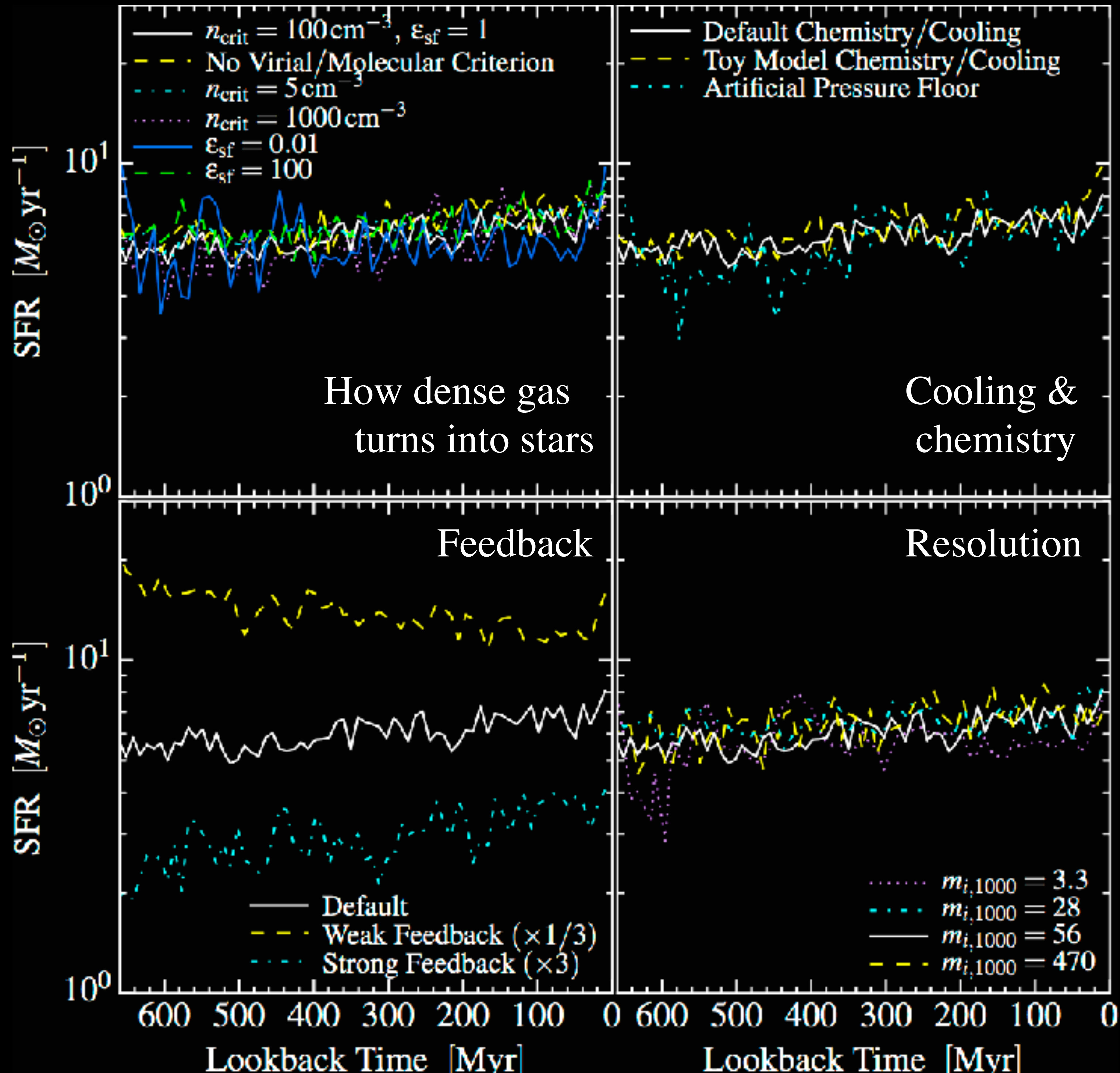
Redshift-independent, weakly metallicity-dependent



Different “resolved” laws:



(Galactic) Star Formation Rates are *INDEPENDENT* of how stars form!



Orr (1701.01788)
Saitoh+ 11
Hopkins+ 11,12,14
Agertz+14

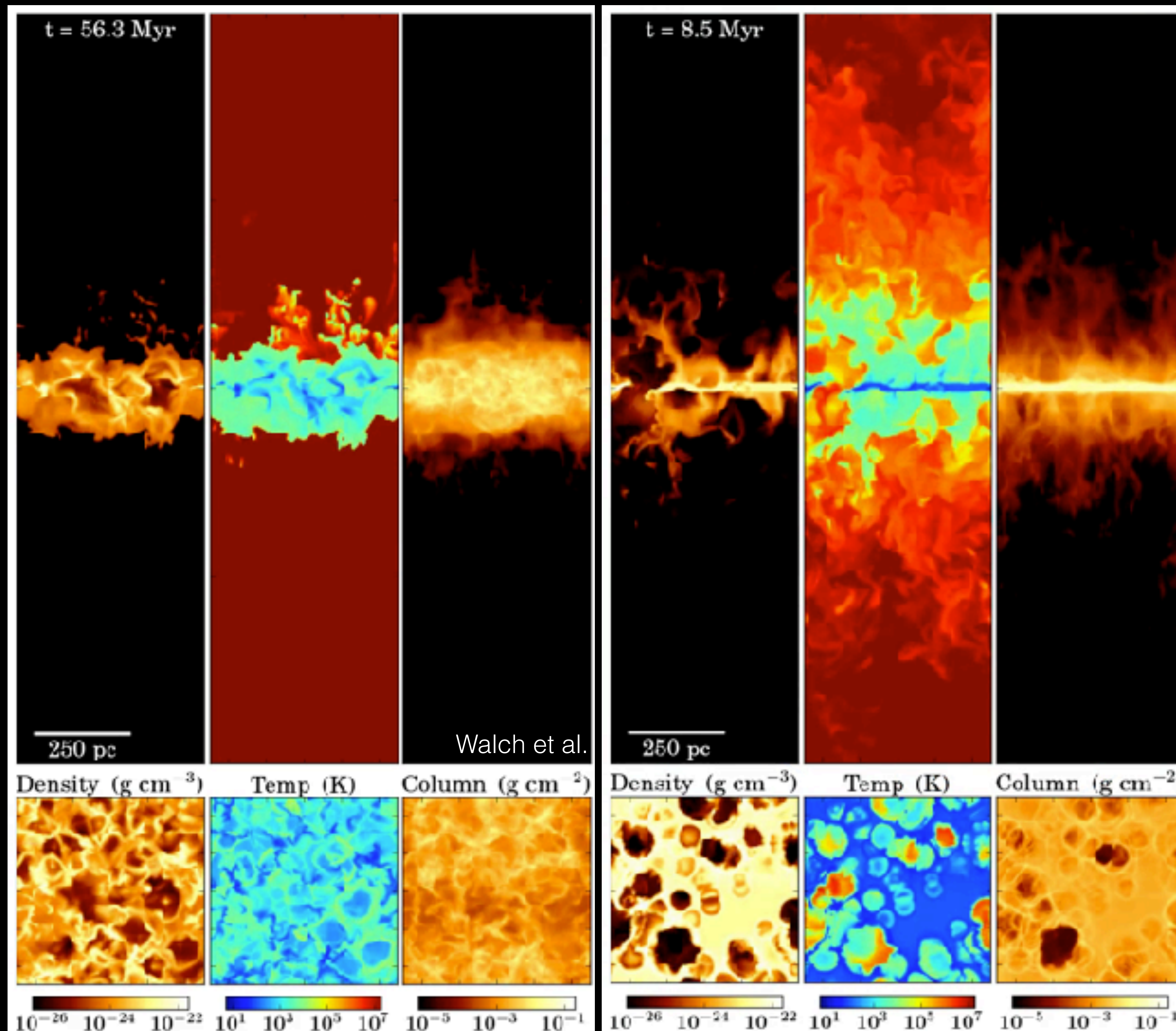
Galactic/Cosmological SFRs: Driving Winds

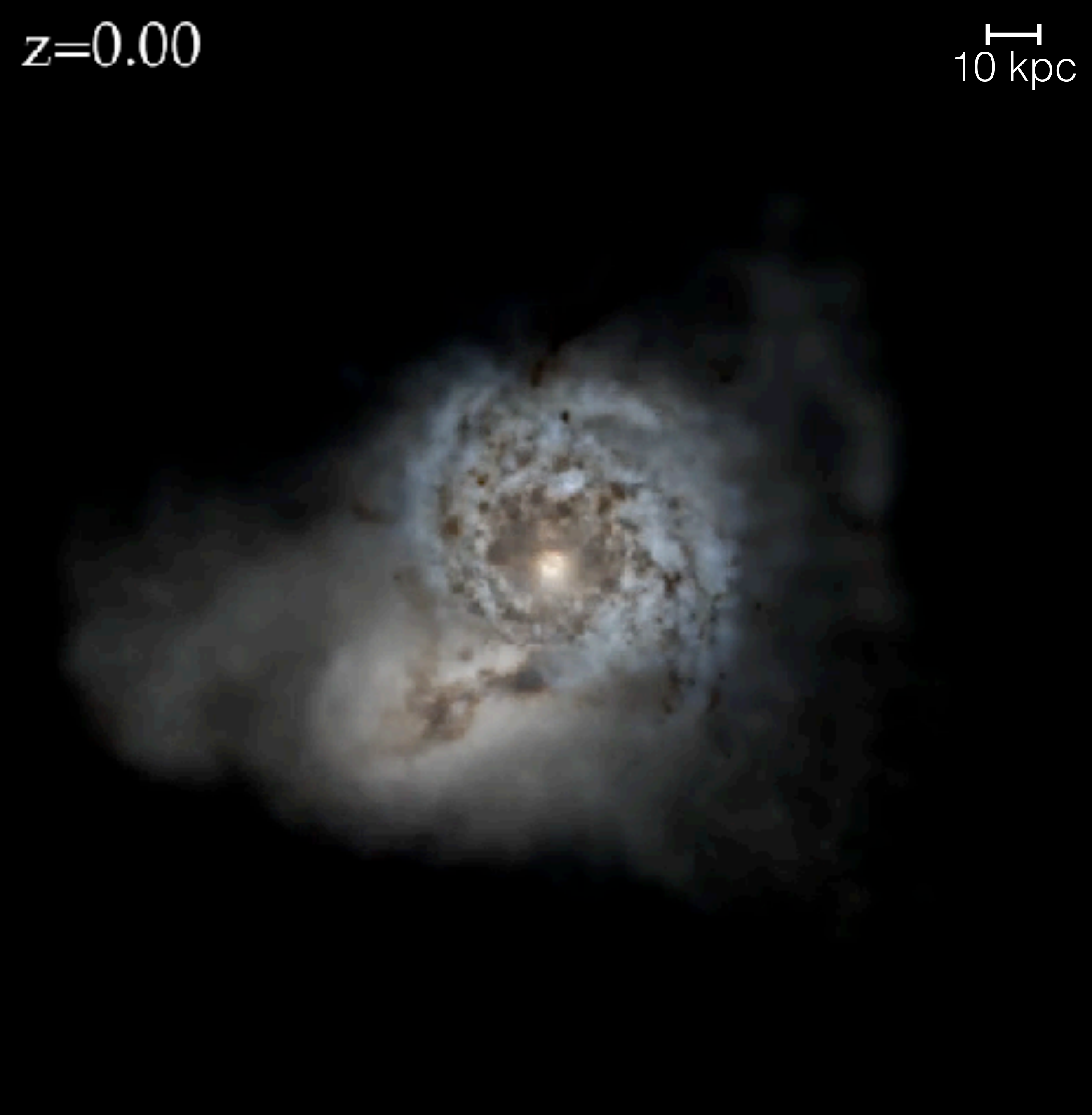
Remember Stellar Clustering?
THIS MATTERS, A LOT!

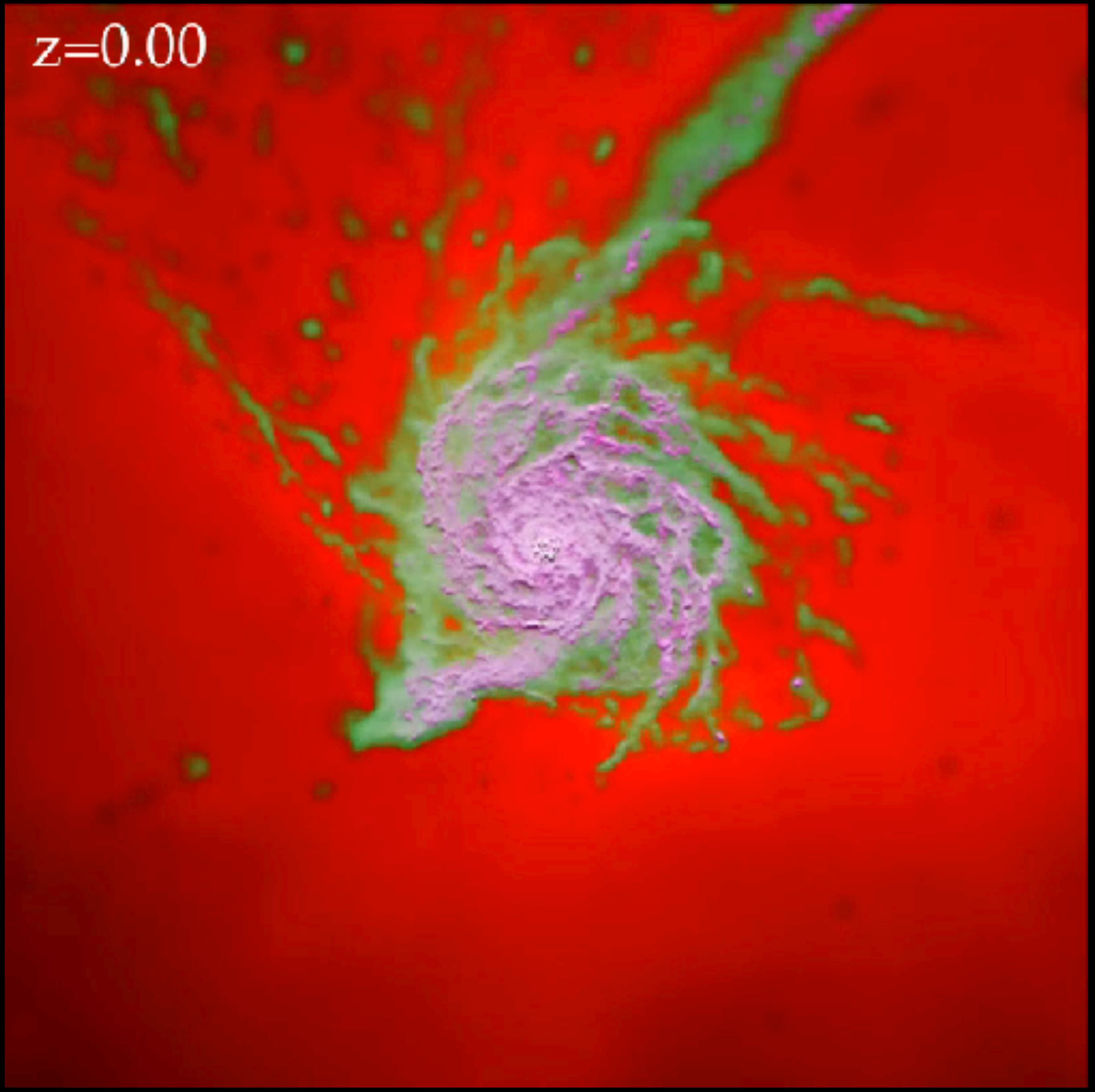
Martizzi+ '16
Walch+, Kimm+, many others

SNe Explode in Density Peaks (no radiative feedback)

SNe Clustered & Off-Peak (radiative feedback/pre-processing)







Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

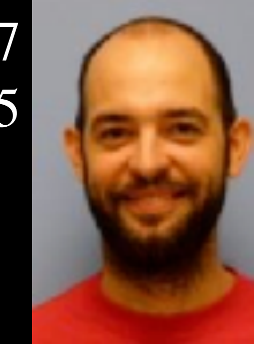
Gas: Magenta: cold $(< 10^4\ K)$

Green: warm (ionized)

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

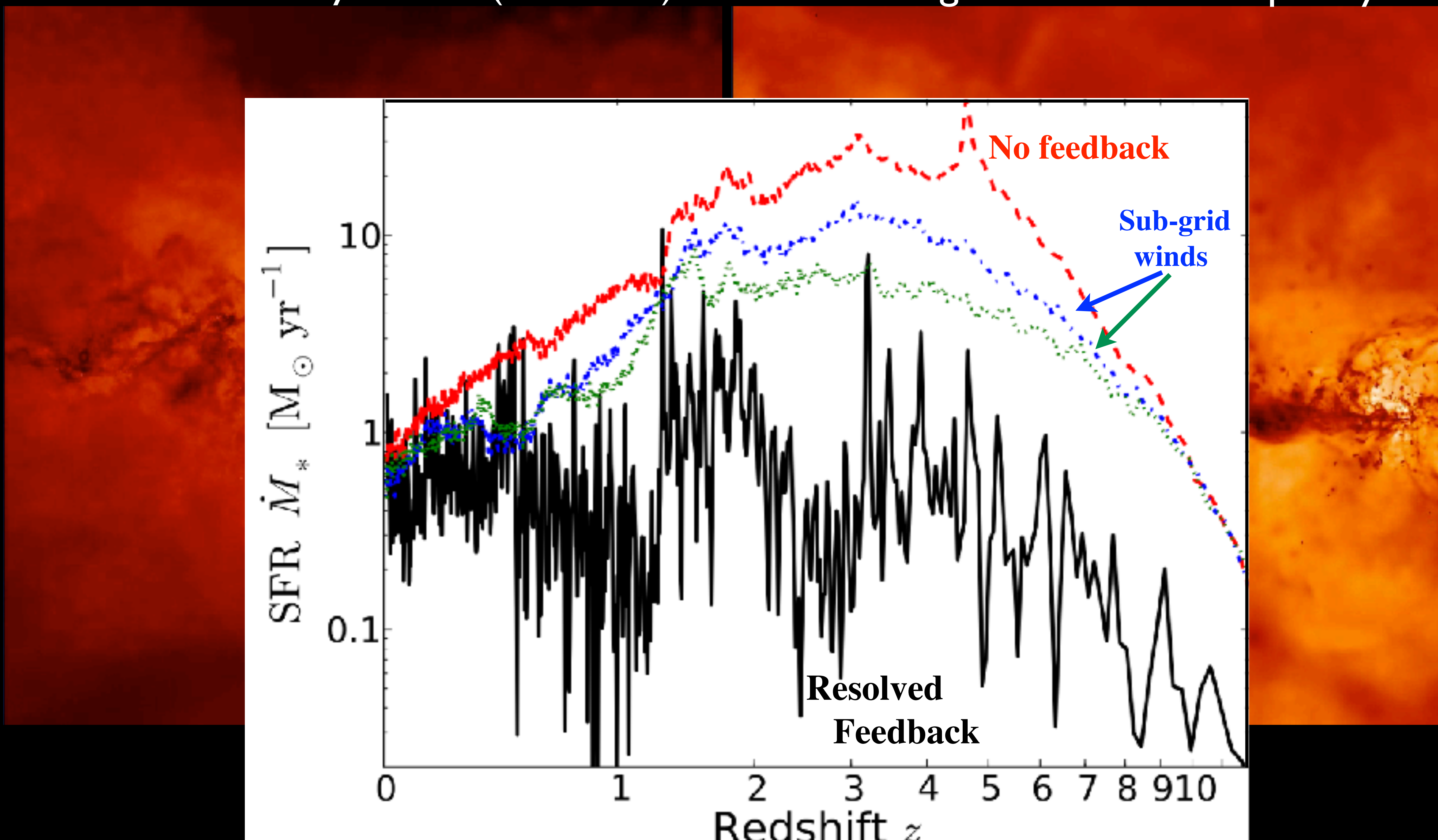
Clustering in Time & Space Matters
(NOW ON GALAXY SCALES)

Recycling: D. Anglés-Alcázar+17
Burstiness: M. Sparre '15



Proto-Milky Way: Gas Temperature:

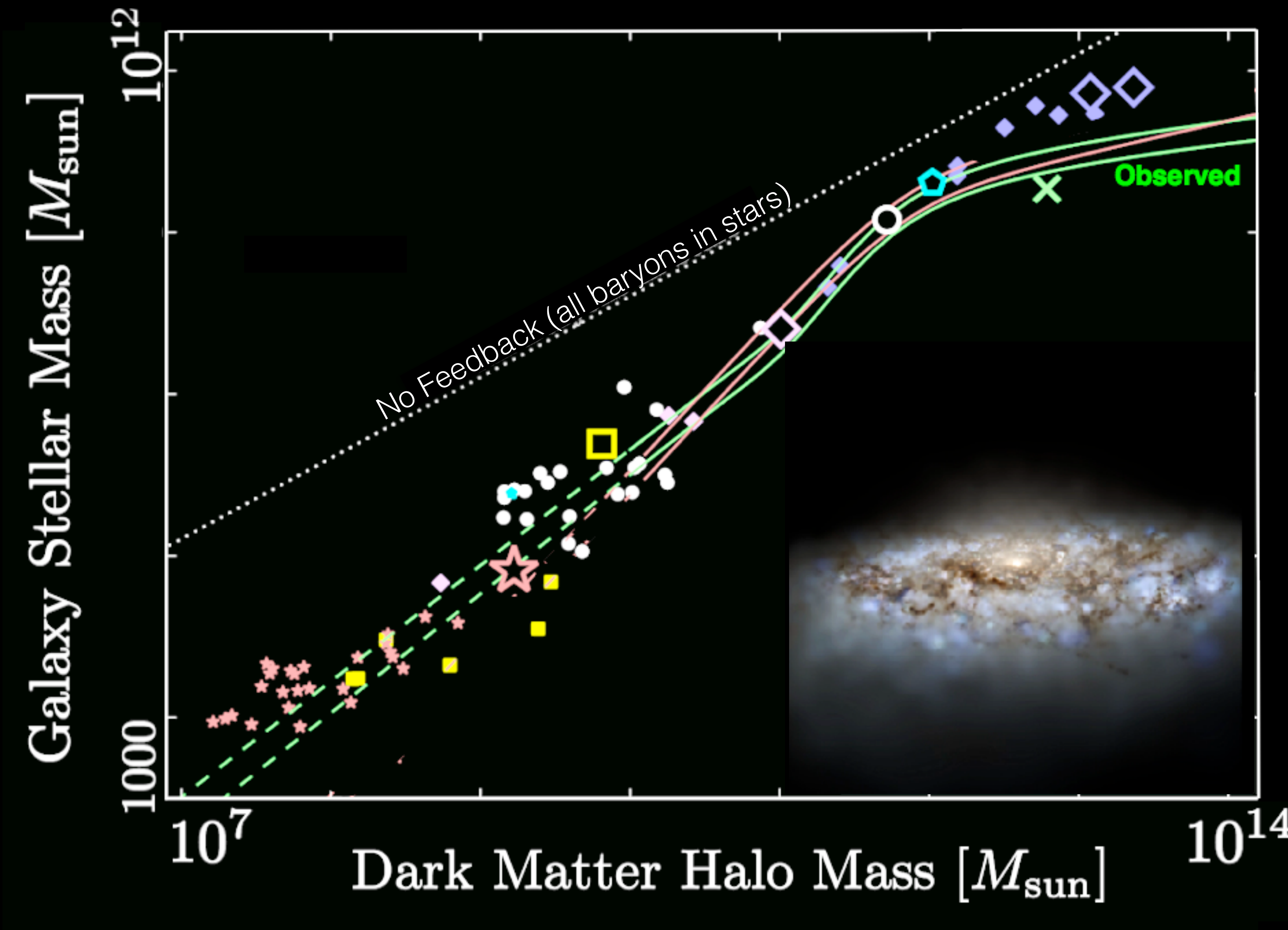
Insert Winds "By Hand" (Sub-Grid) | Following Feedback/ISM Explicitly



This Works (More or Less) if You Resolve Key Scales

GAS IS BLOWN OUT, INSTEAD OF TURNING INTO STARS

PFH et al.
(arXiv:1311.2073)

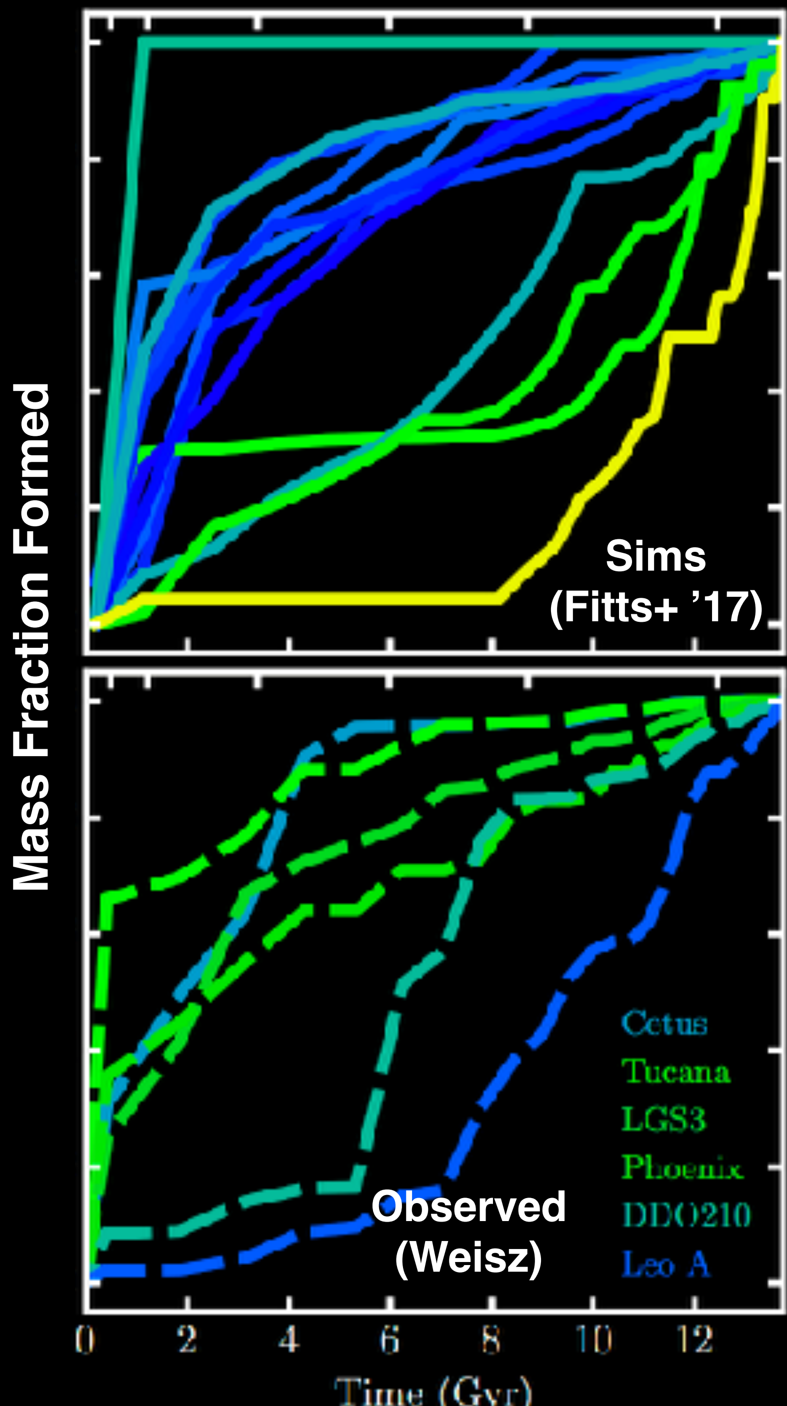


Bursty/Calm Star Formation & Galactic Structure

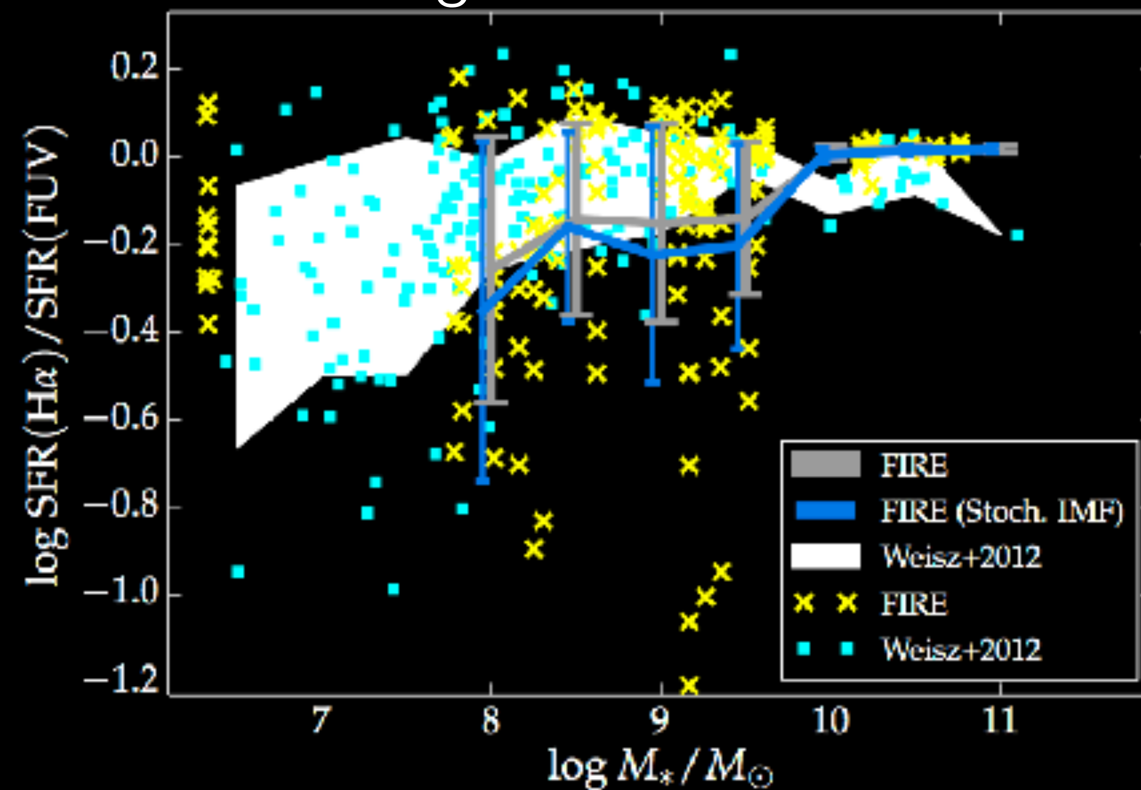
Burstiness & SFR-M_{stars} Relation

M. Sparre
arxiv:1510.03869

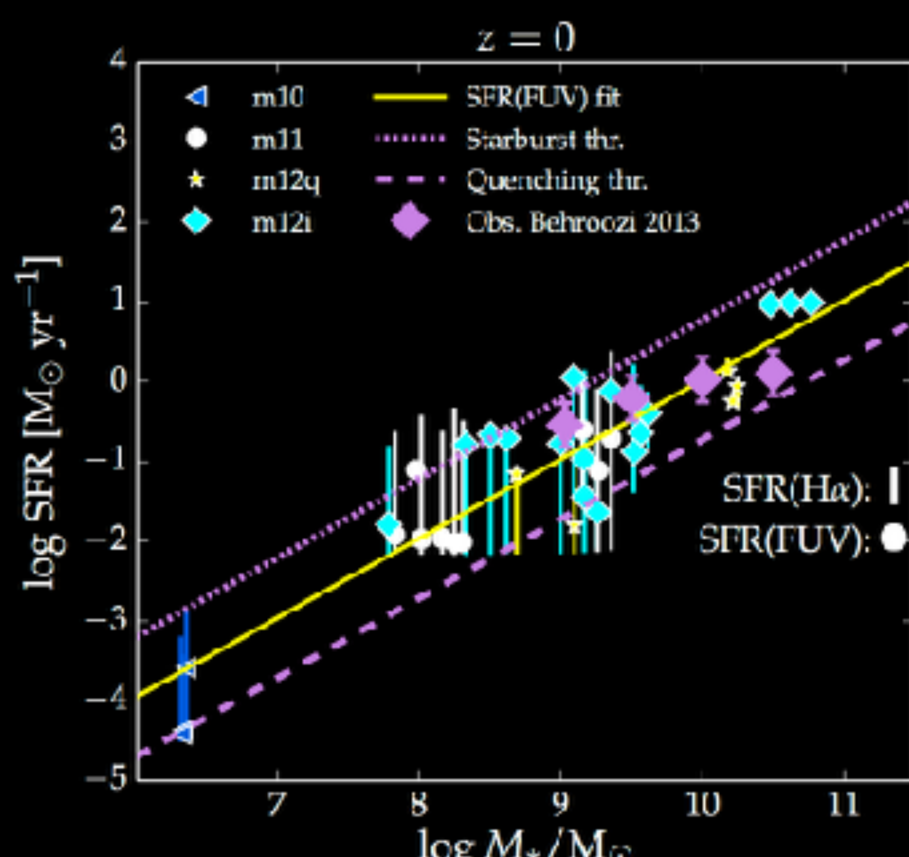
dwarfs:

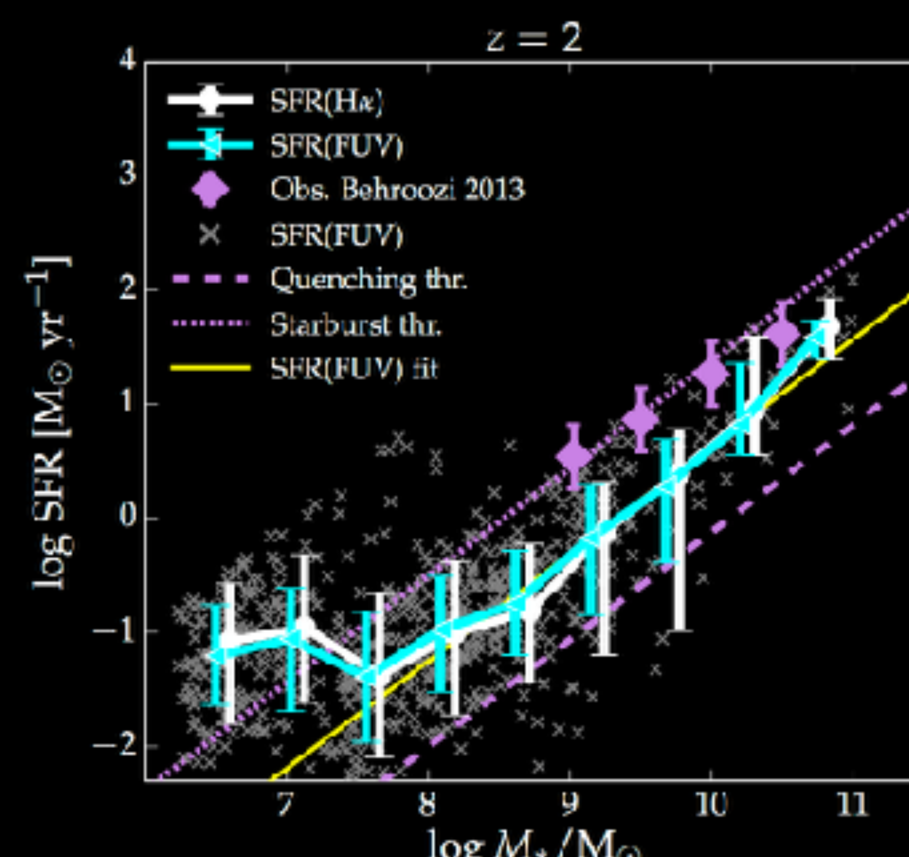


massive galaxies:



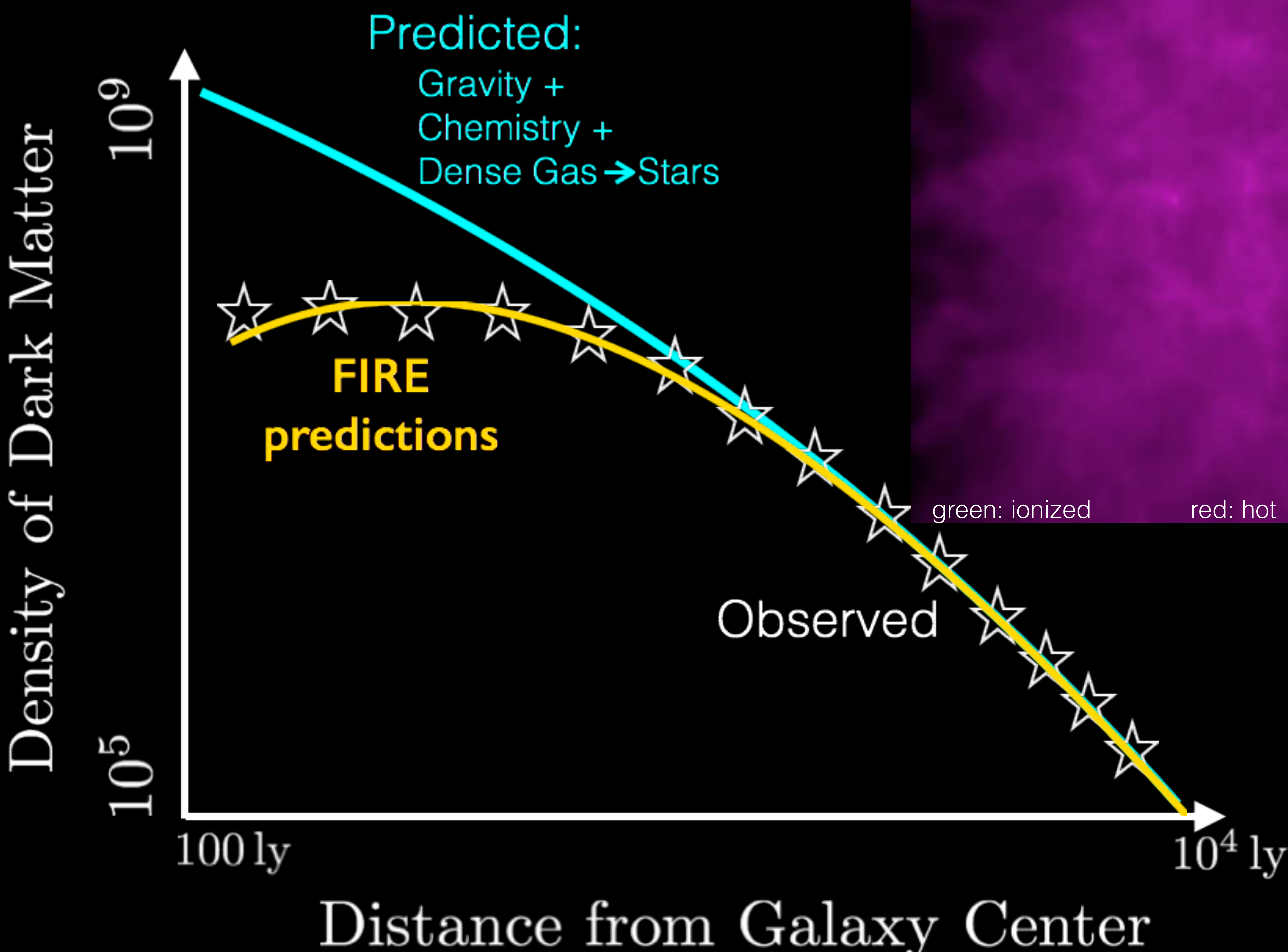
Low-mass scatter is *not* a "hidden variable"

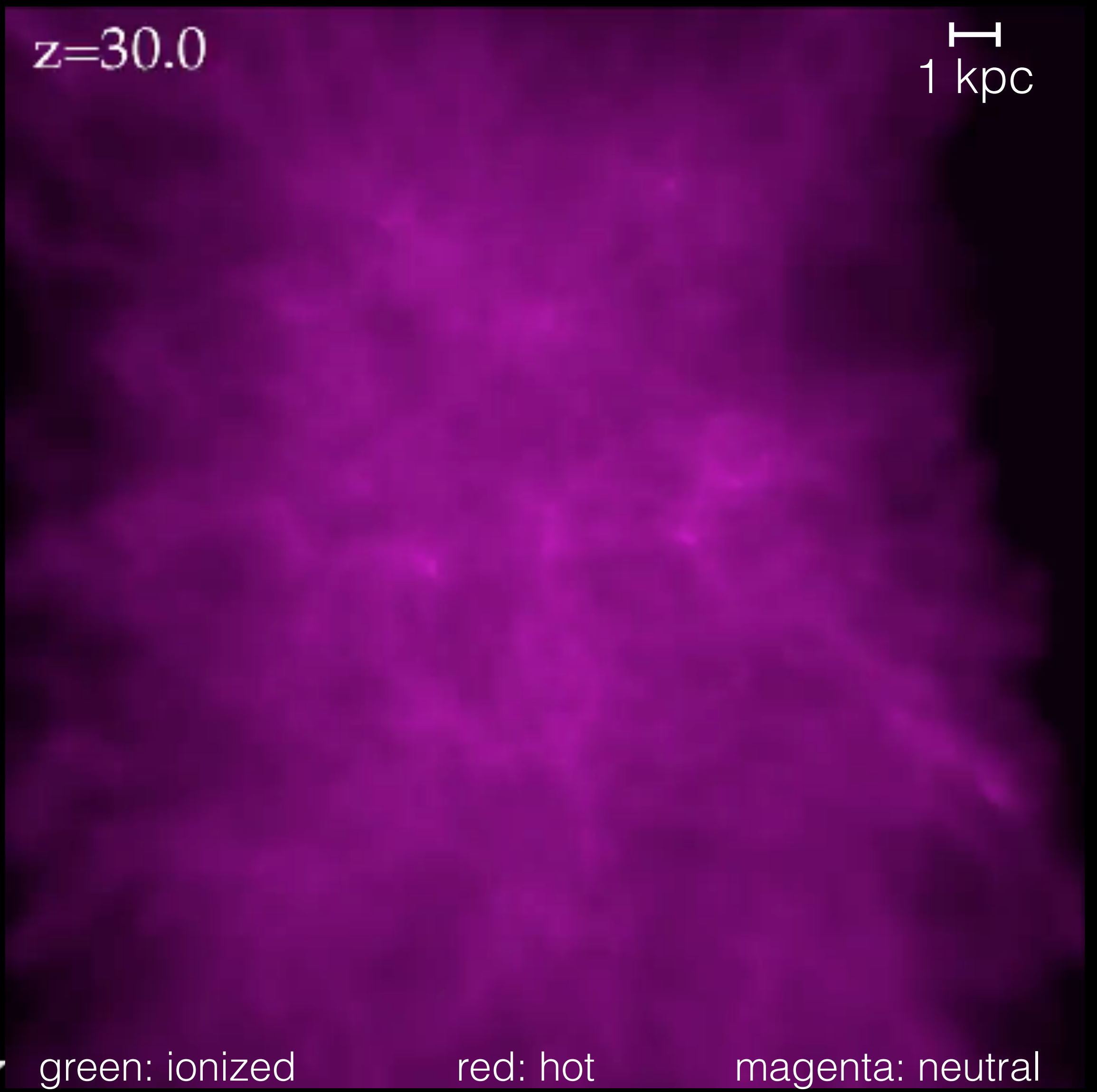




Feedback Saves Cold Dark Matter?

NO EXOTIC PHYSICS NECESSARY





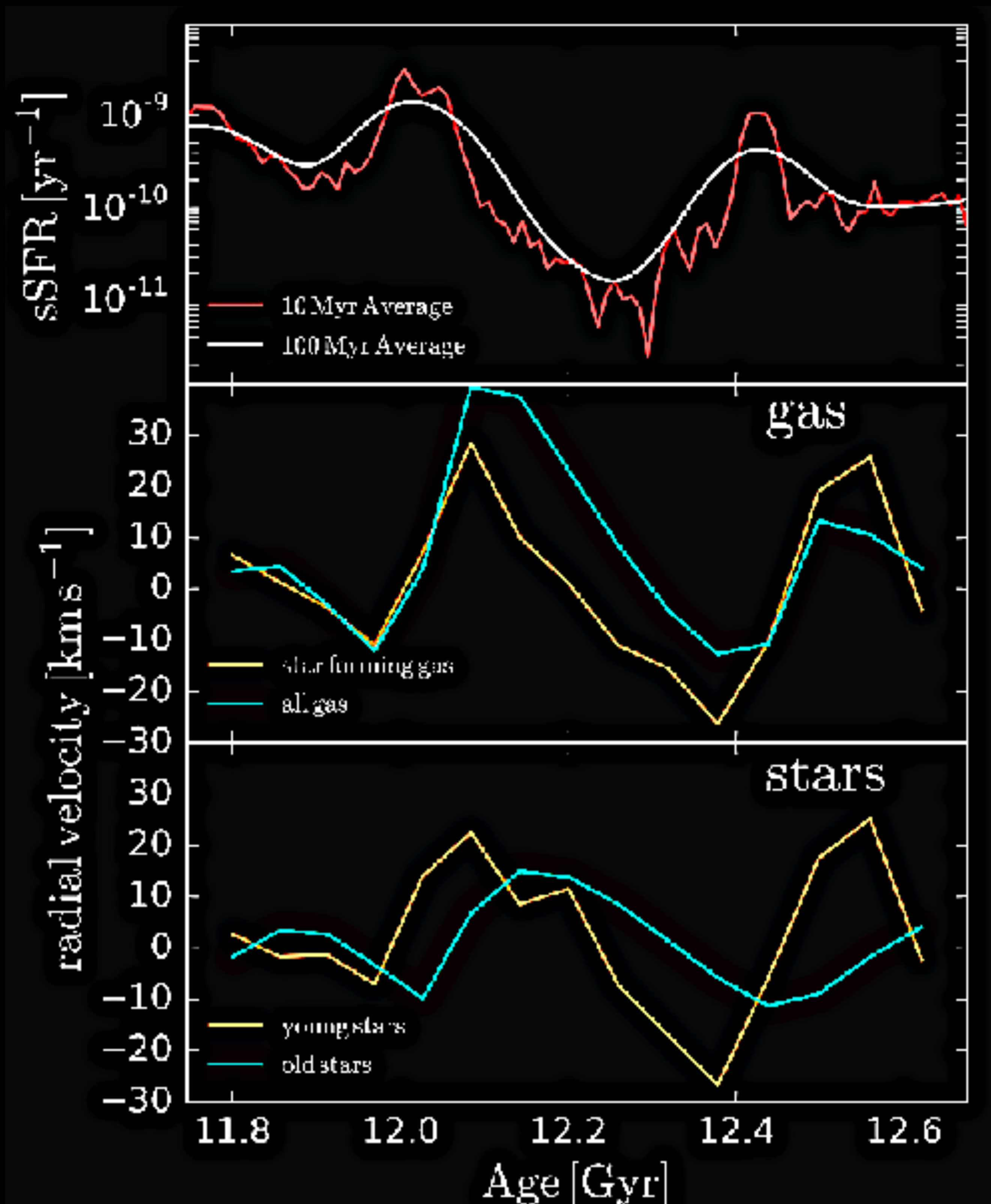
Onorbe et al.
(arXiv:1502.02036)
Chan et al.
(arXiv:1507.02282)
Wheeler et al.
(arXiv:1504.02466)

Direct Consequences for Structure

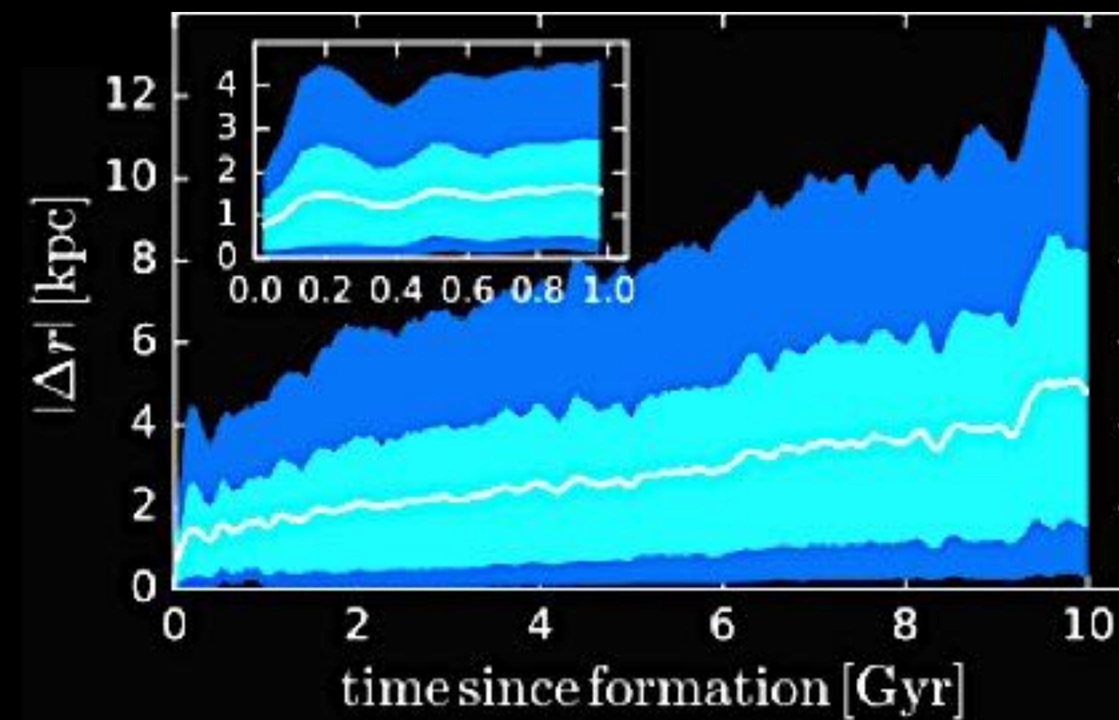
BURSTY SF = STARS MIXED, JUST LIKE DM

K. El-Badry
(arXiv:1512.01235)

Radial "breathing" in each burst:



Orbits "pumped up"



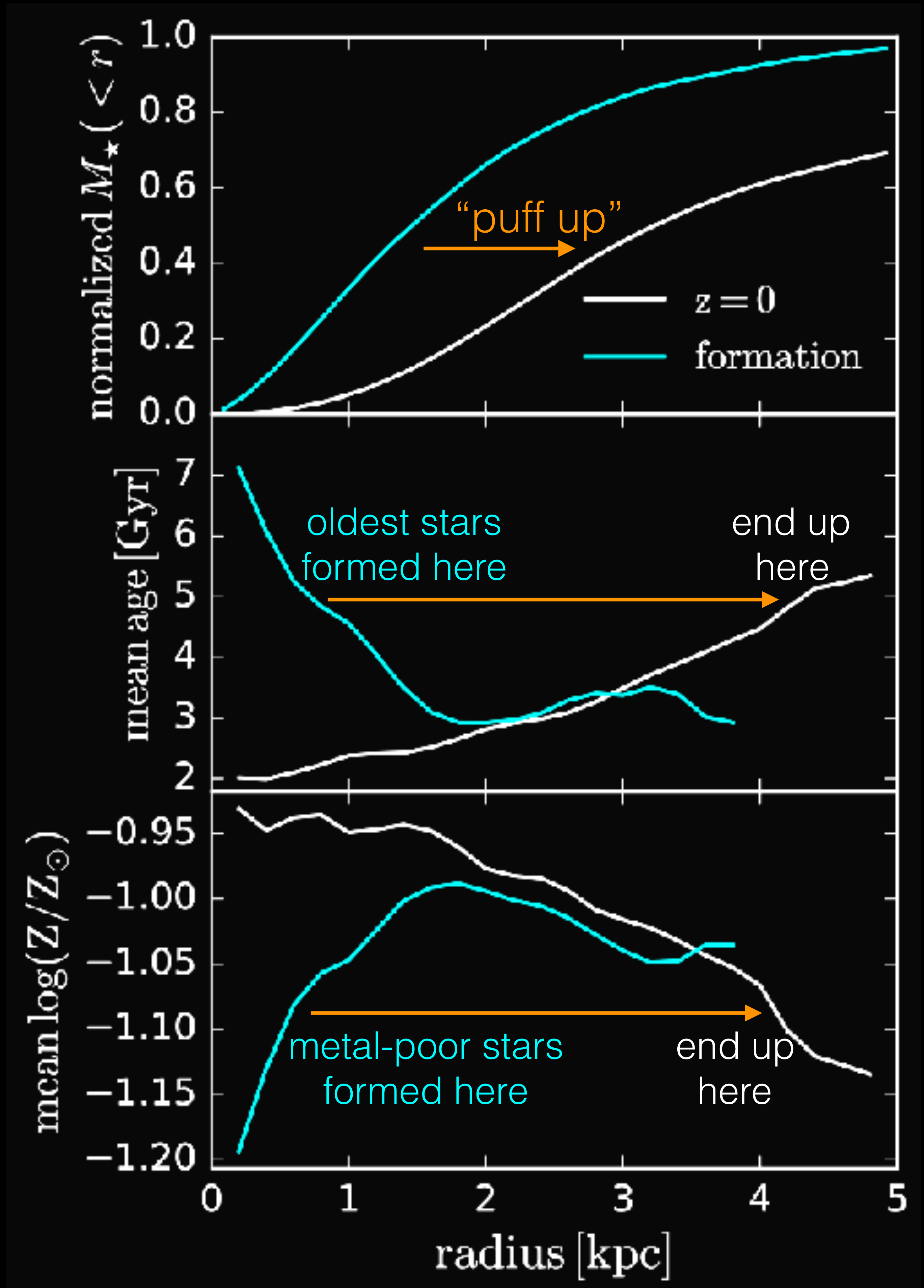
- If DM orbits perturbed, stars are too!

Direct Consequences for Structure

BURSTY SF = STARS MIXED, JUST LIKE DM

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

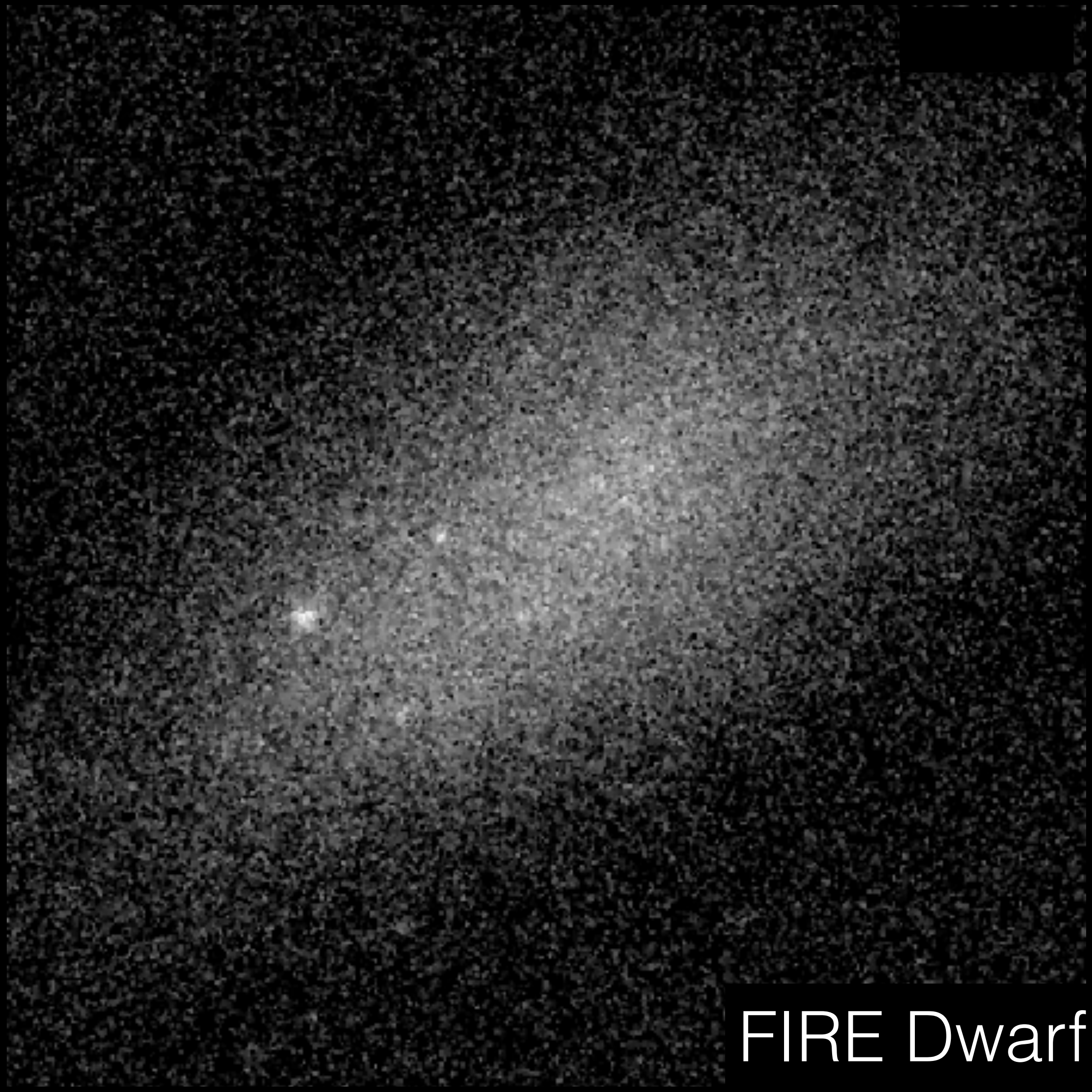
Kareem El-Badry
arXiv:1512.01235



New Classes of Galaxies

ULTRA-DIFFUSE SYSTEMS: THE NEW "NORMAL"

TK Chan (prep)

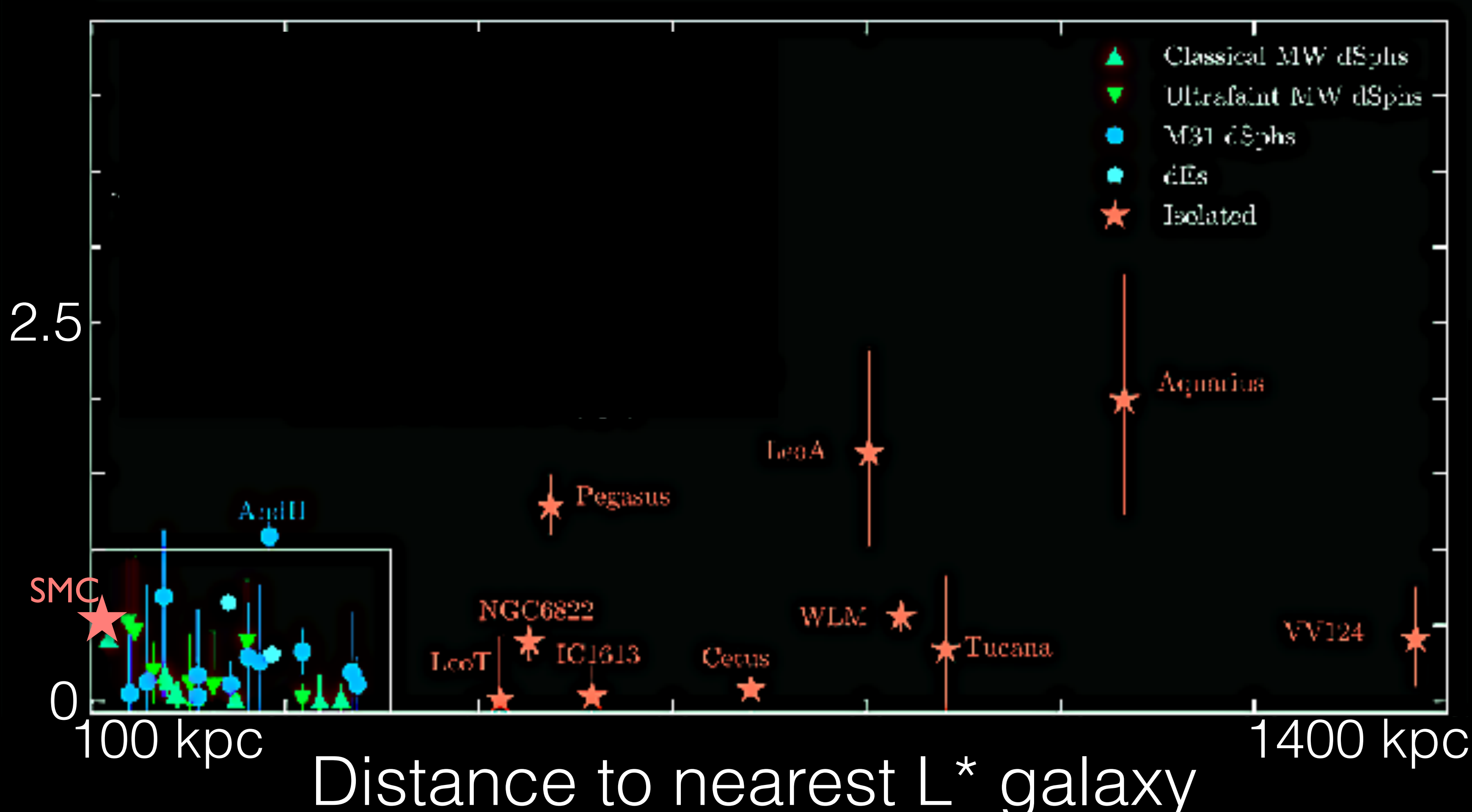


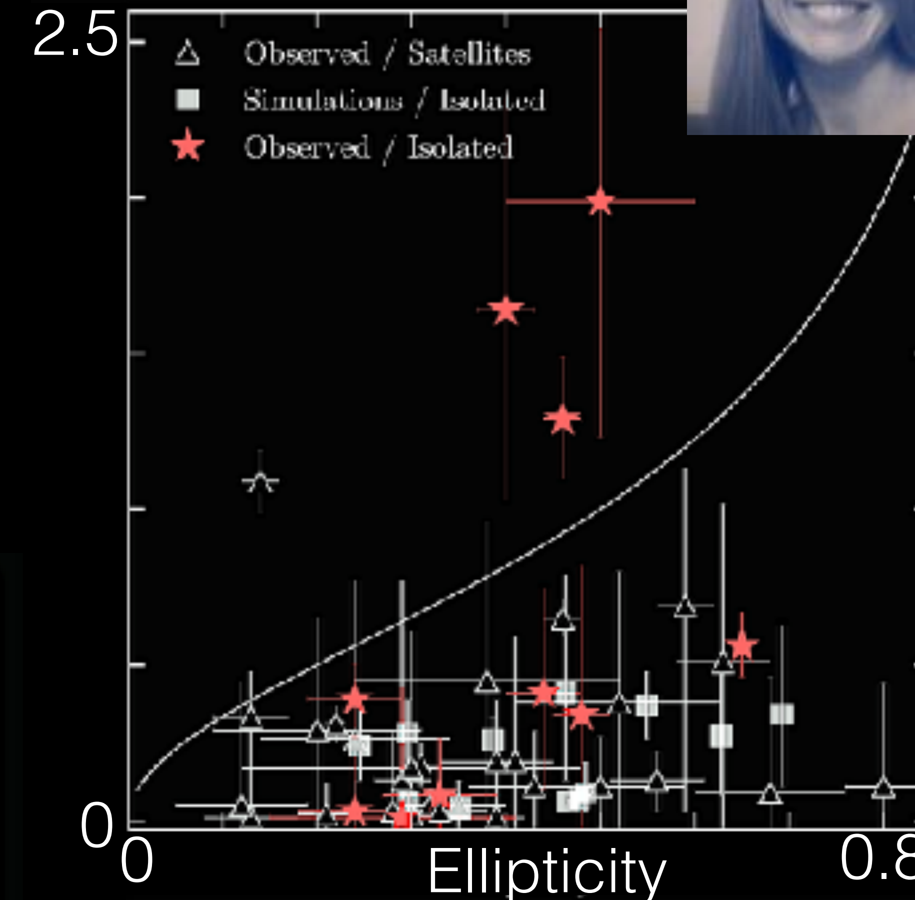
“Stirring” By Feedback = Most Dwarfs Don’t Rotate

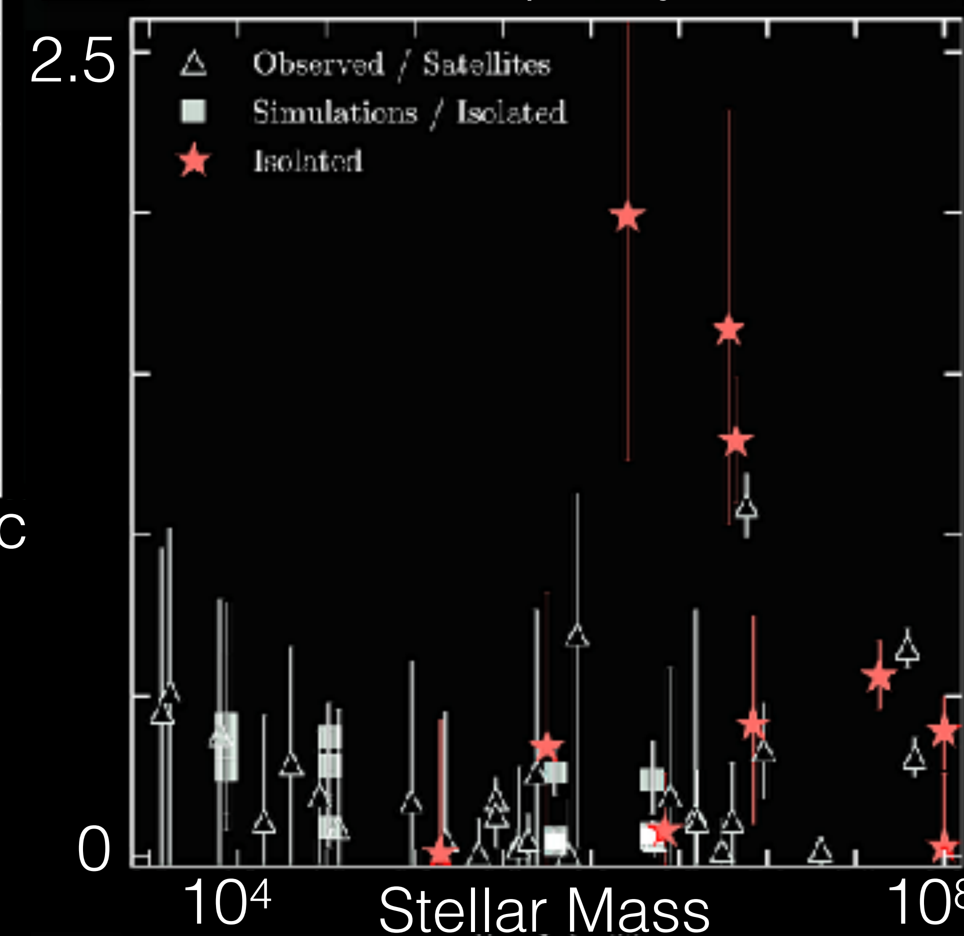
OBSERVED+SIMULATED dIrr/dSph

C.Wheeler
arXiv:1504.02466

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





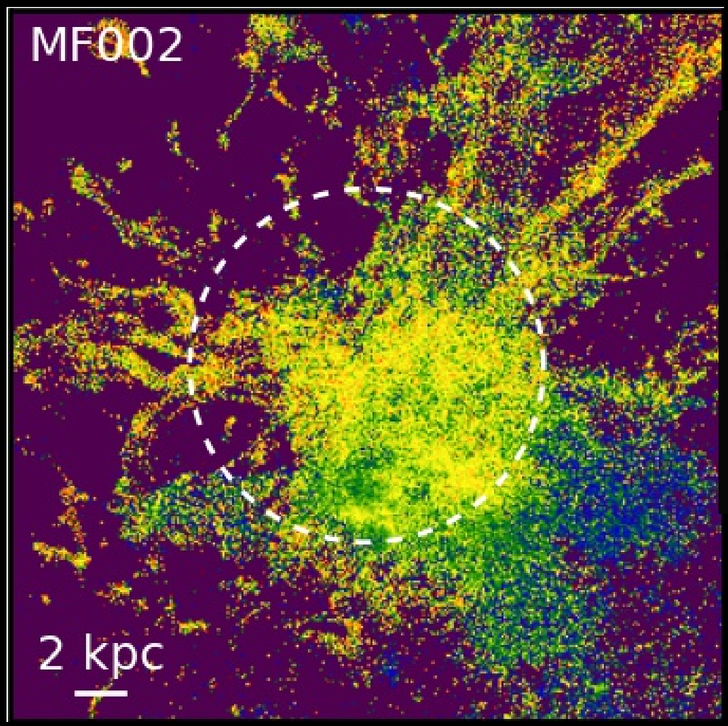


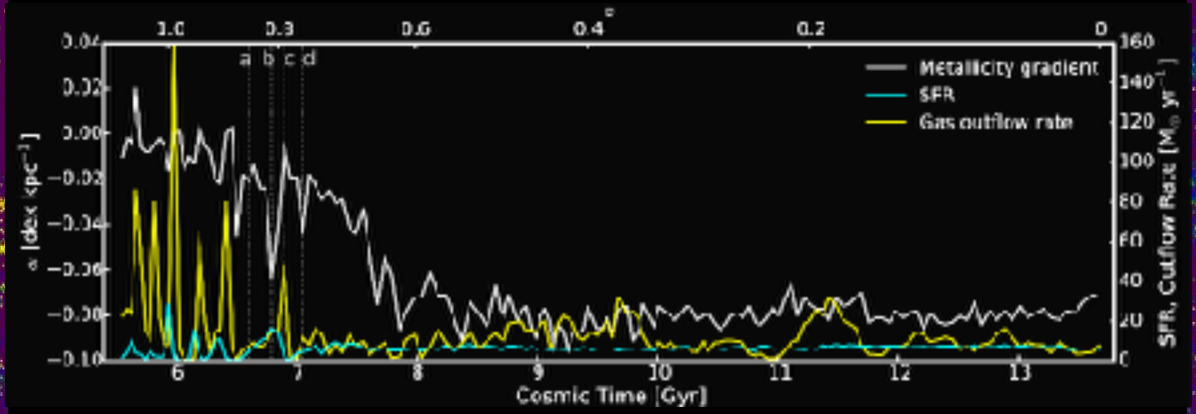
Transition from Feedback-Dominated to “Calm” (Gravity-Dominated)

BUILDUP OF METALLICITY GRADIENTS

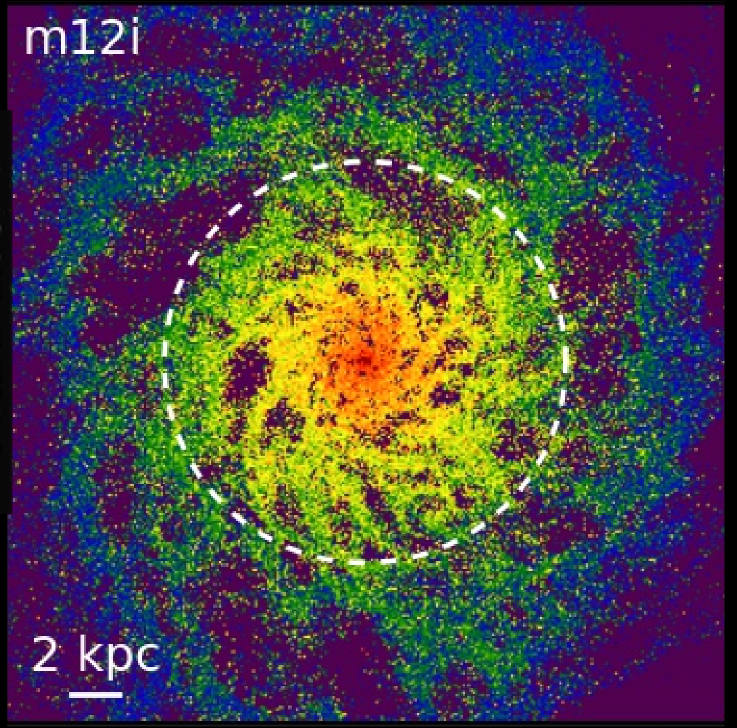
Xiangcheng Ma
(arXiv:1610.03498)

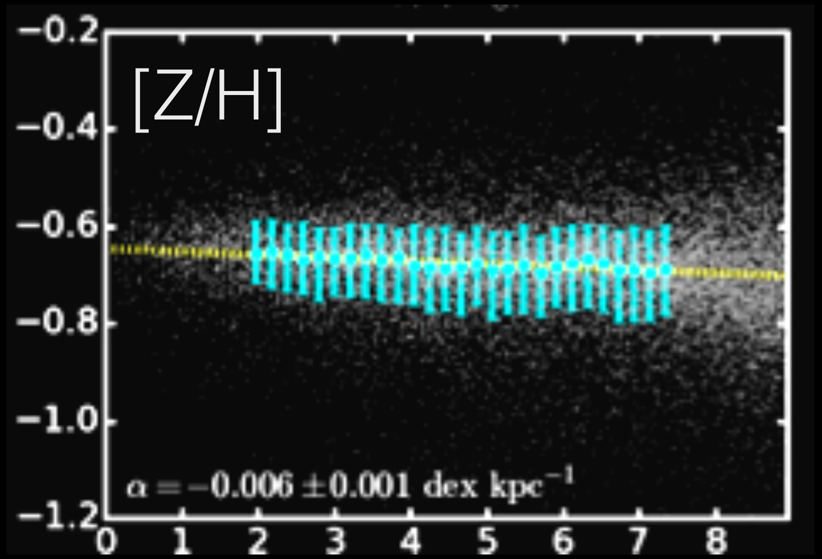
“feedback-dominated” phase



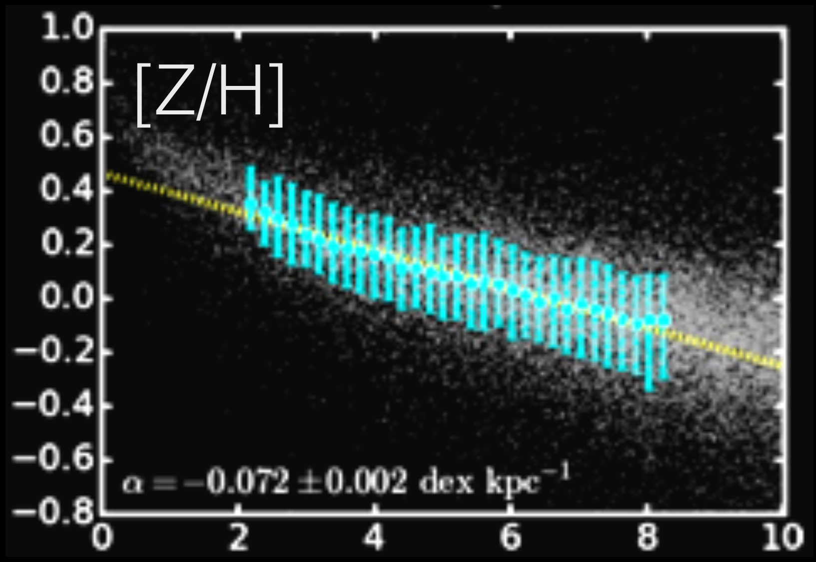


“gravity-dominated” phase





R [kpc]

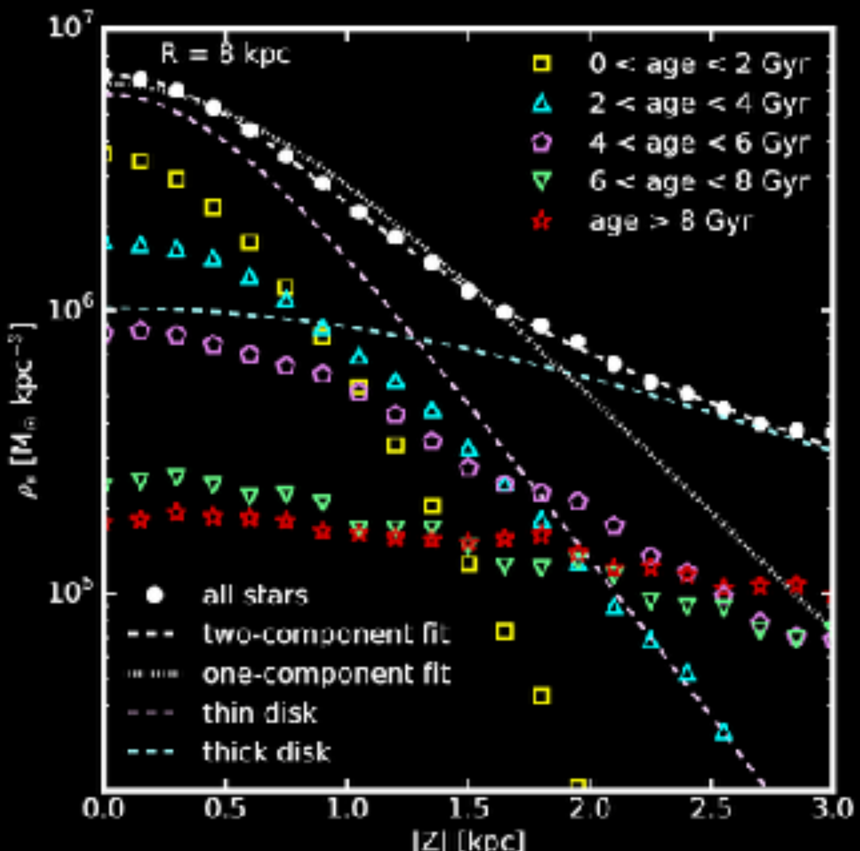


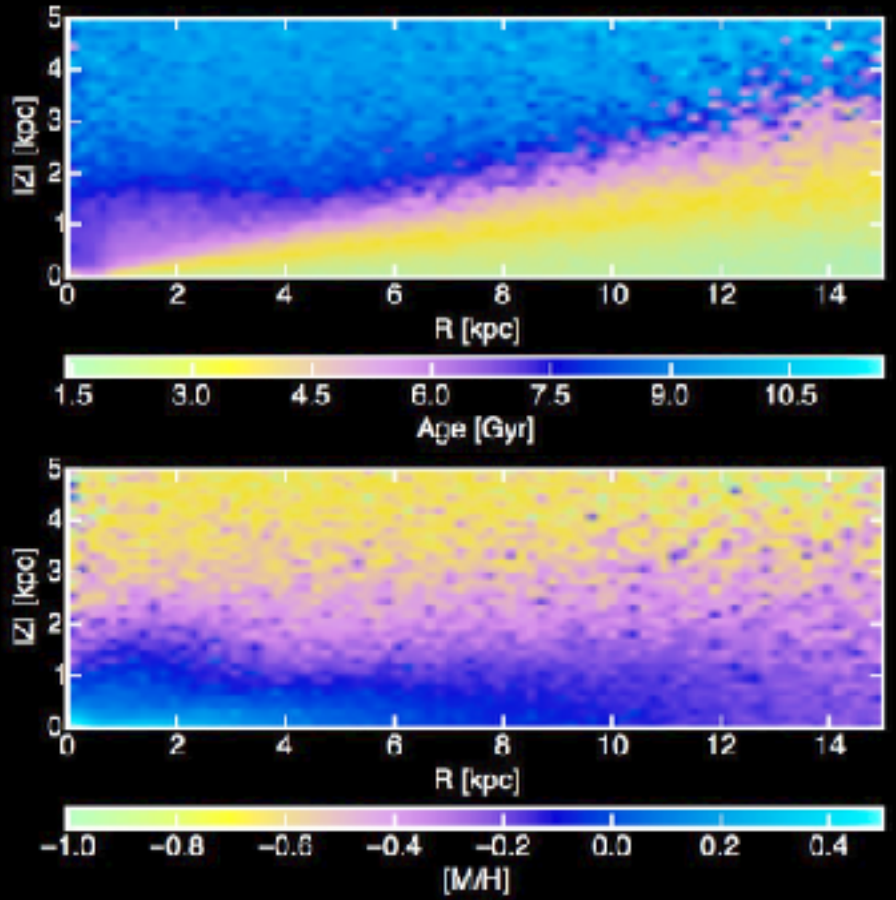
R [kpc]

Transition from Feedback-Dominated to “Calm” (Gravity-Dominated)

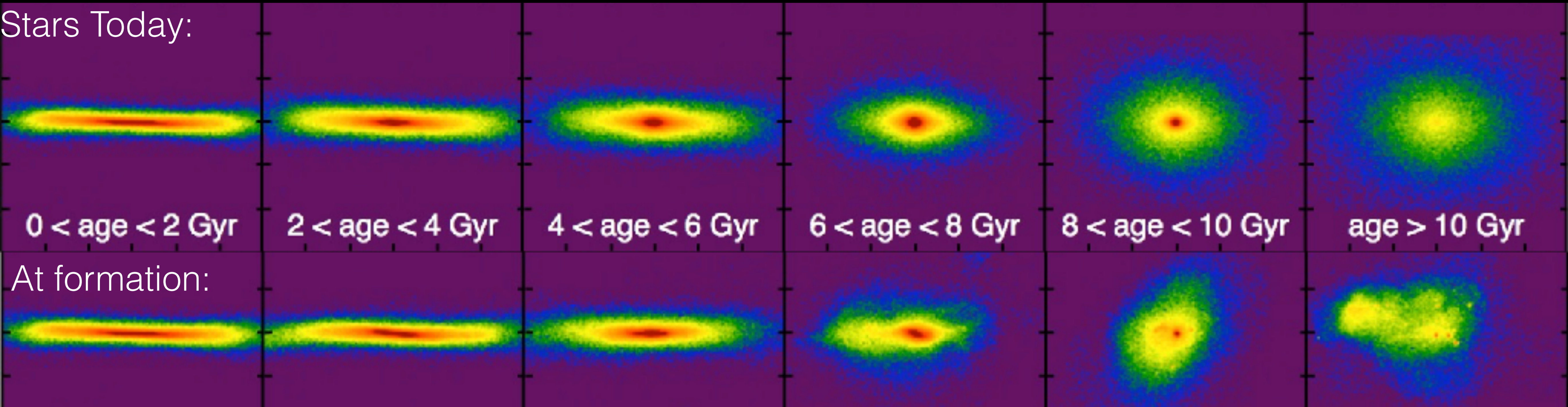
THICK -> THIN DISK

Xiangcheng Ma
(arXiv:1608.04133)
Ana Bonaca
(arXiv:1704.05463)

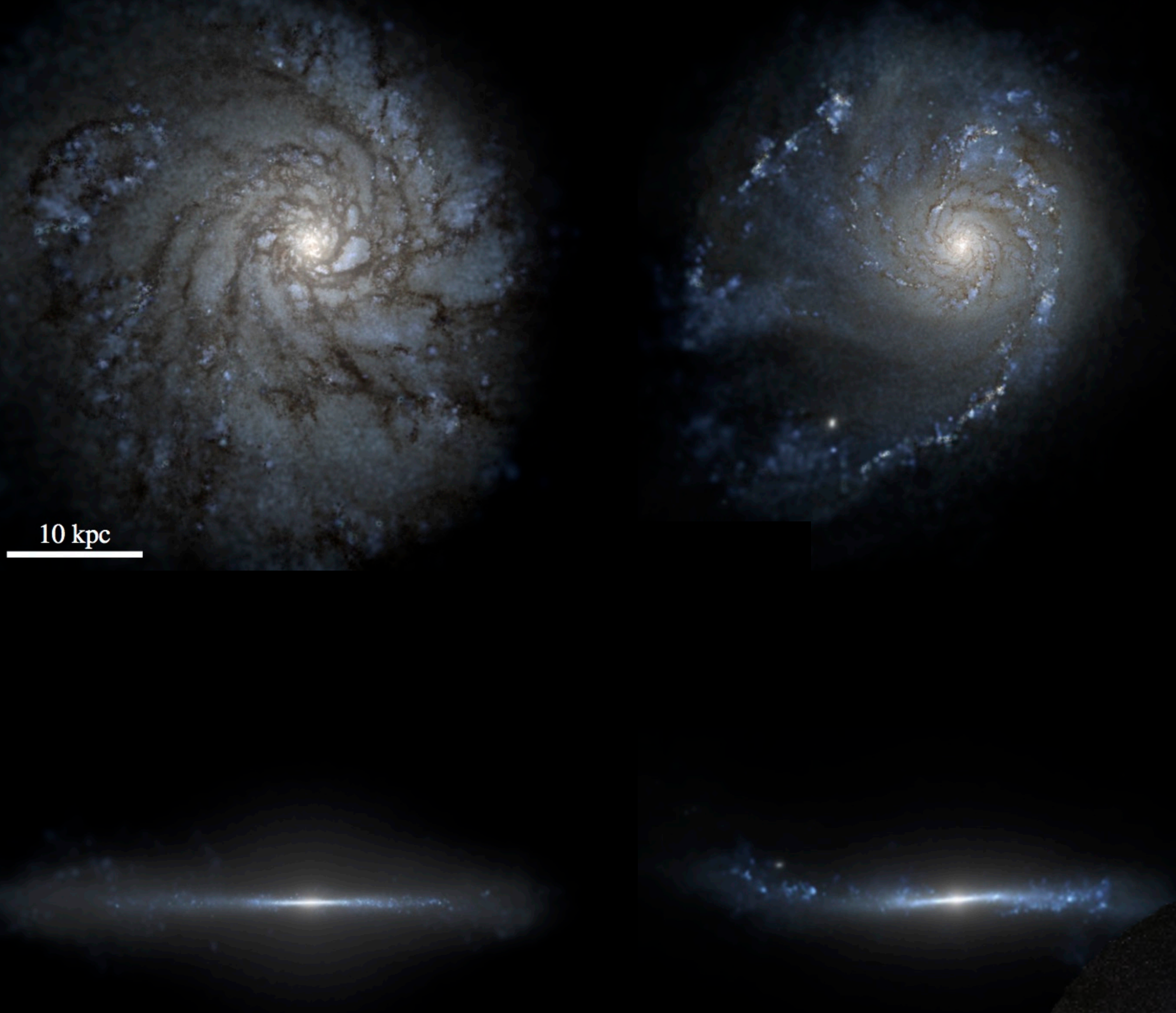




Detailed vertical+radial abundance gradients & kinematics of thin/thick disk populations



Thin Disks Emerge Naturally… but when/where?

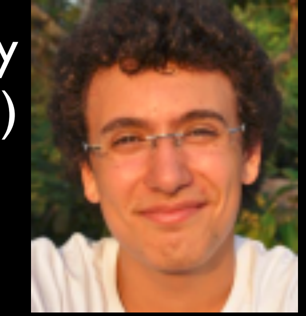


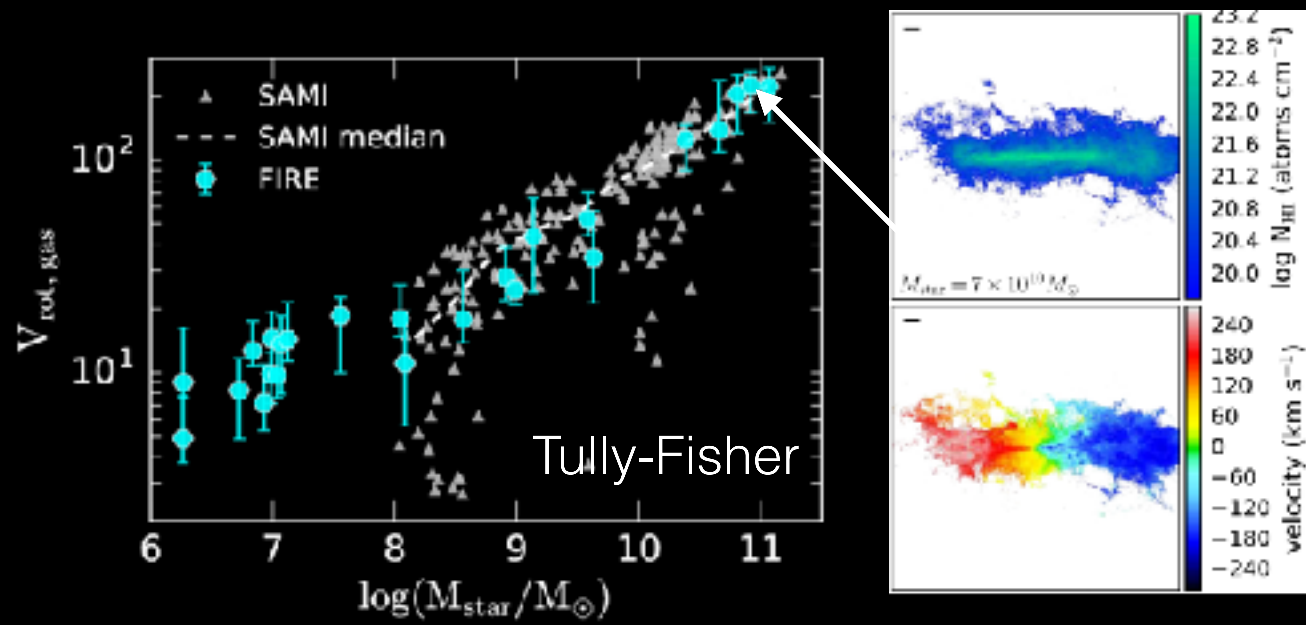
Garrison-Kimmel et al., in prep

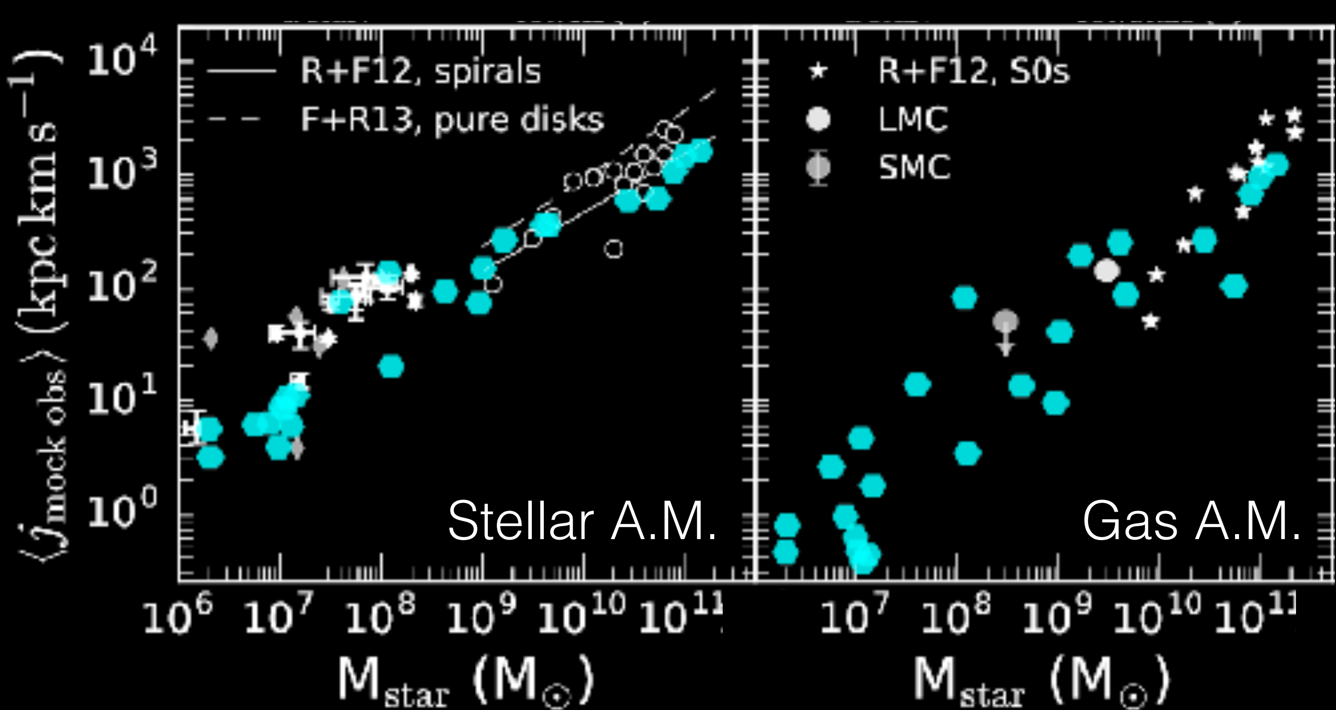
Angular Momentum of Gas+Stars

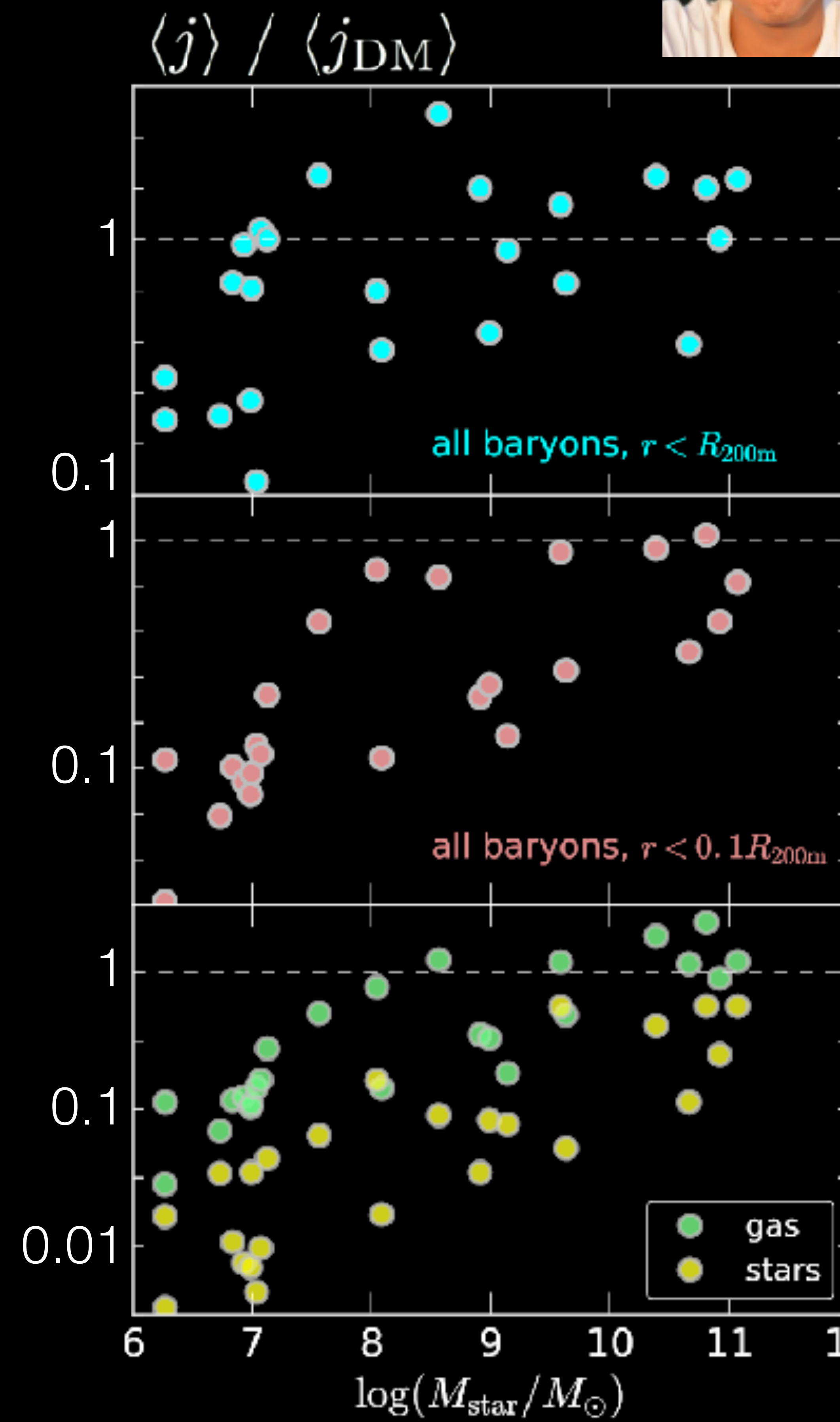
THINNER DISKS IN MORE MASSIVE SYSTEMS

Kareem El-Badry
(arXiv:1705.10321)





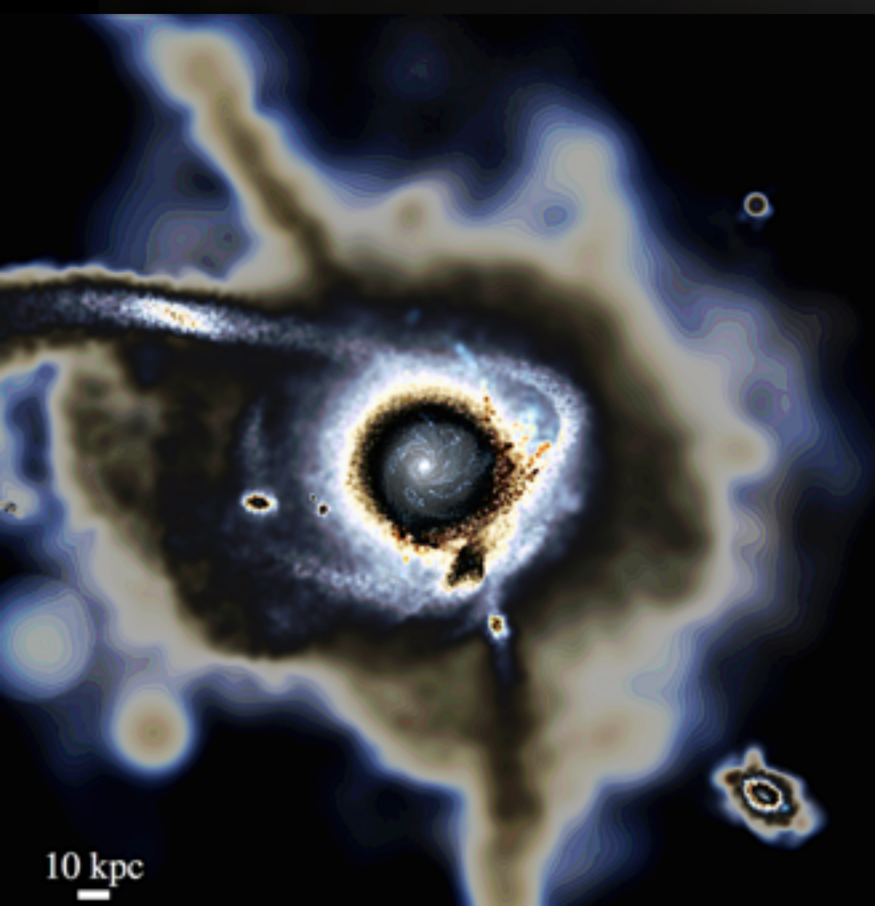


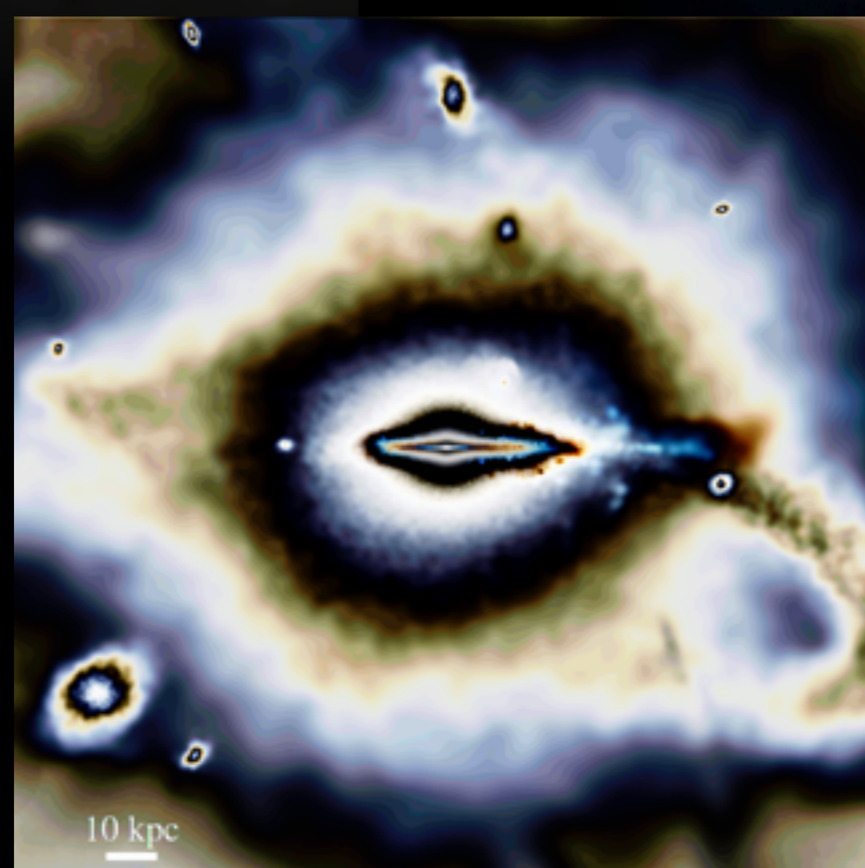


- Thick/irregular [clumpy+bursts+pressure]
- Suppressed late-time accretion [UVB+FB]

Halo Structure

Mock GAIA Catalogues with ~100,000,000 Stars in the (Simulated) Galaxy



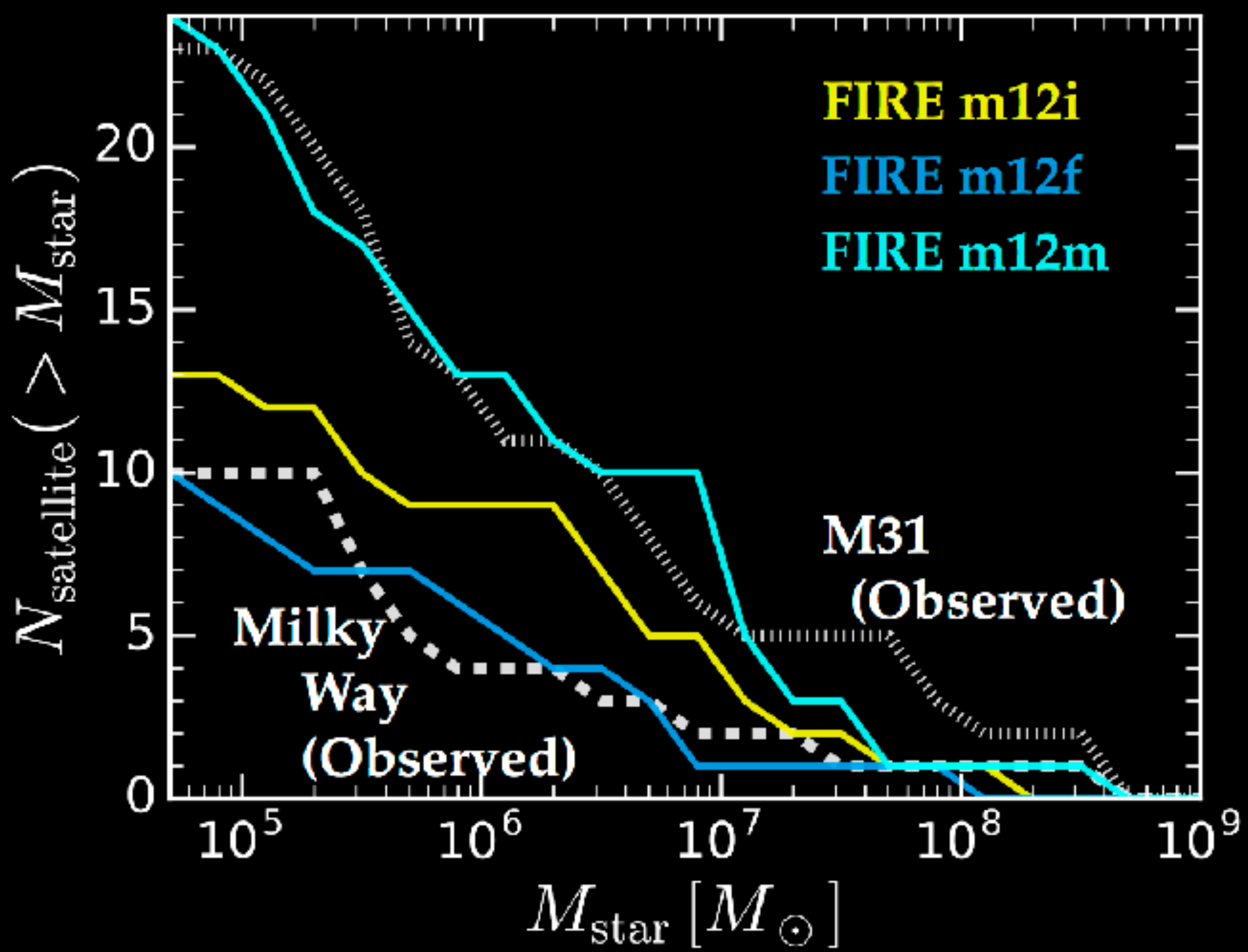


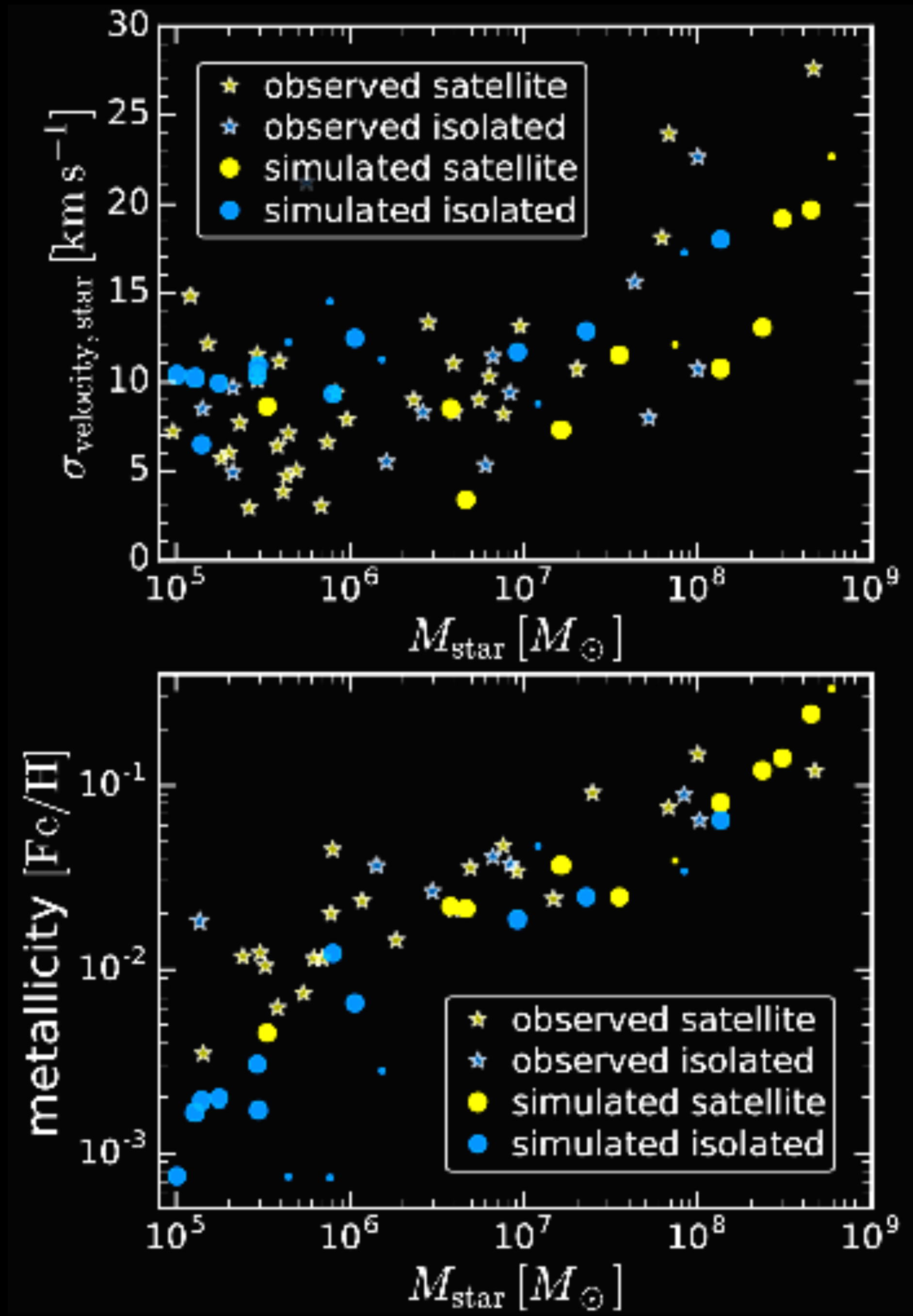
Sanderson et al. (in prep)

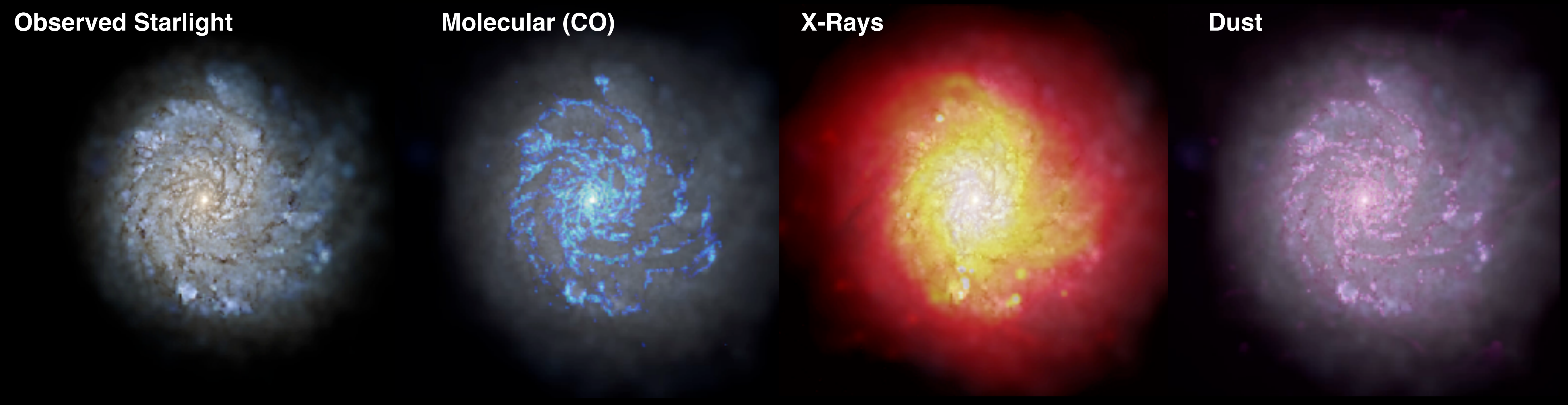
Failures No More

FEEDBACK SUPPRESSES STAR FORMATION AND DENSITIES

Wetzel + I. Escala (prep)



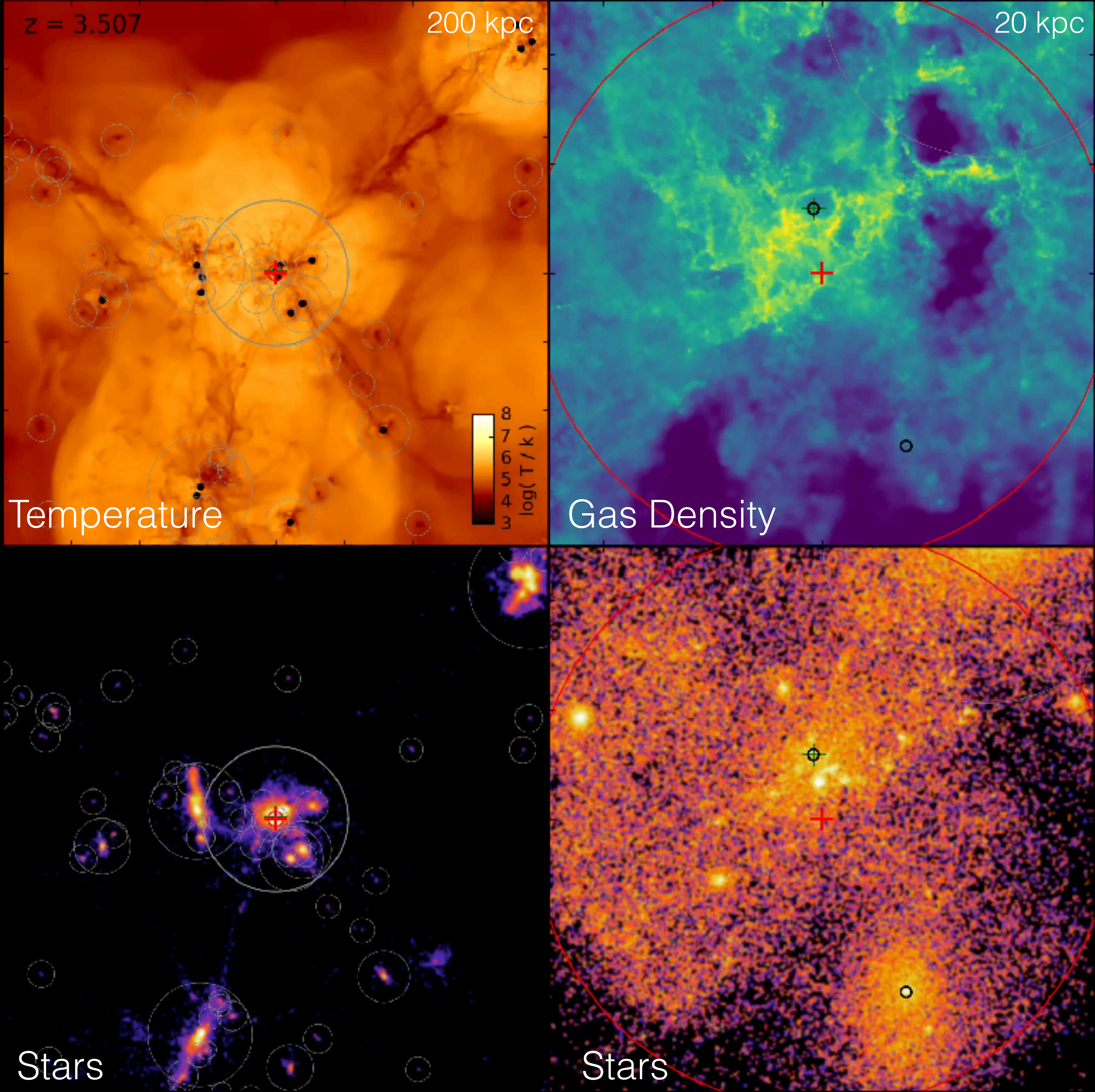




- IMF: Feedback [protostars] vs. gravity = stellar masses (Guszejnov+ 17)
- Clusters: Feedback [radiative] vs. gravity = SF efficiency/lifetime & bound vs. open (Grudic+ 17)
  - Globulars resolved(?) (Kim+ 17)
- KS Law: Feedback [SNe “stirring”] vs. gravity = low SF per free-fall time (Orr+17)
- Galaxy Masses: Feedback [SNe launching winds] vs. gravity = low masses, missing satellites (Wetzel+15)
  - *Clustering* of SF & *destruction* of GMCs is *critical*
- Bursty SF important to galaxy structure
  - Changes dwarf DM profiles (Chan+16): “cusps” only below ~1e6 solar
  - Changes kinematics/sizes/gradients (El-Badry+ 16, Wheeler+ 16)
  - Thick disk formed as a thick disk (Ma+16)
  - “Calm down” to form thin, rotating component later (Ma+16, El-Badry+17, Garrison-Kimmel+ 17)

AGN?

Lumpiness + SNe
Need big seeds or "anchors"

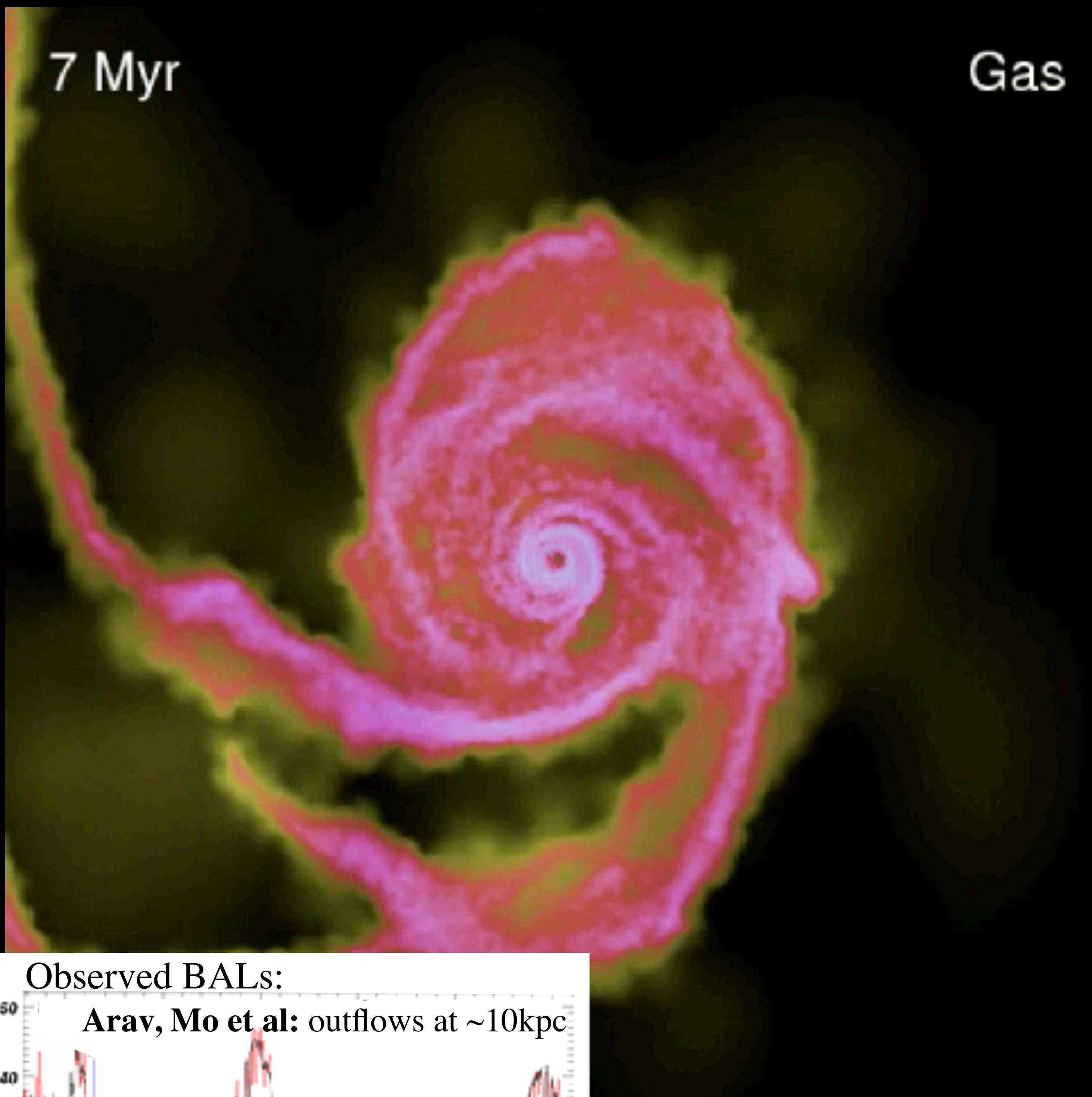


D. Angles-Alcazar
arXiv:1707.03832

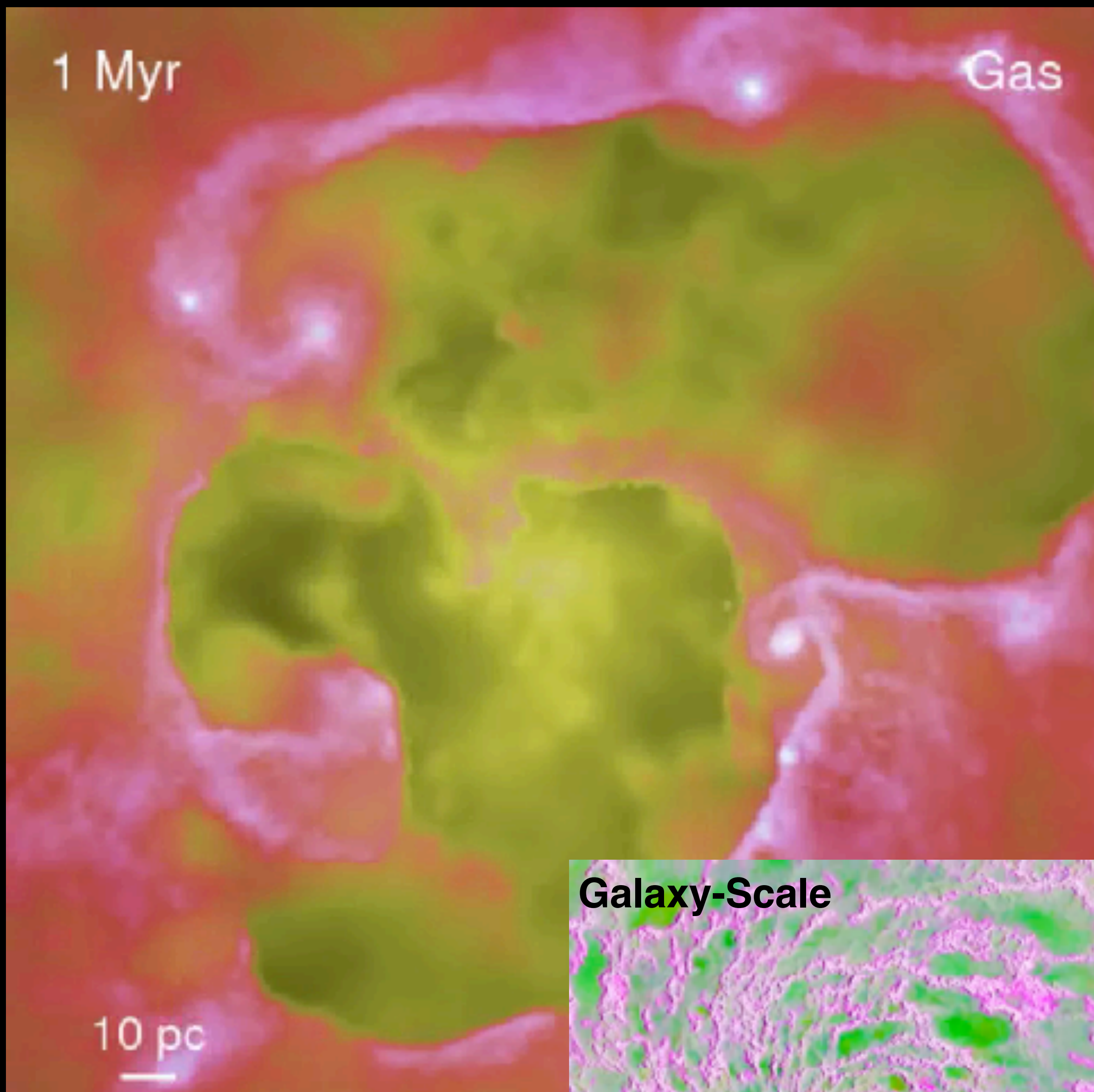
Accretion Disk Winds: 0.01-10,000 pc

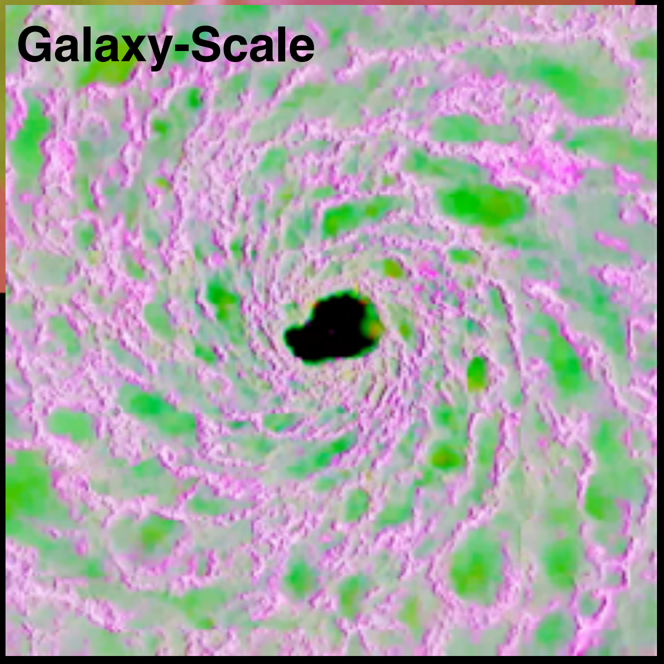
Torrey et al.
in prep

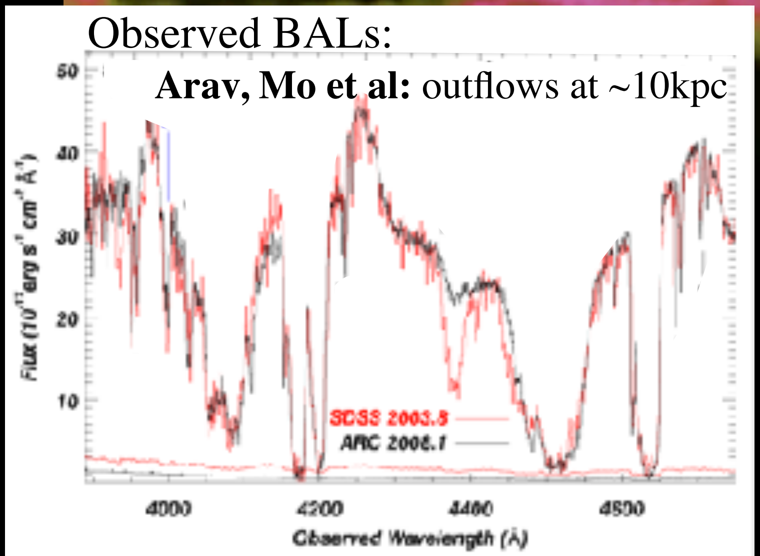
No BAL Winds



With BAL Winds



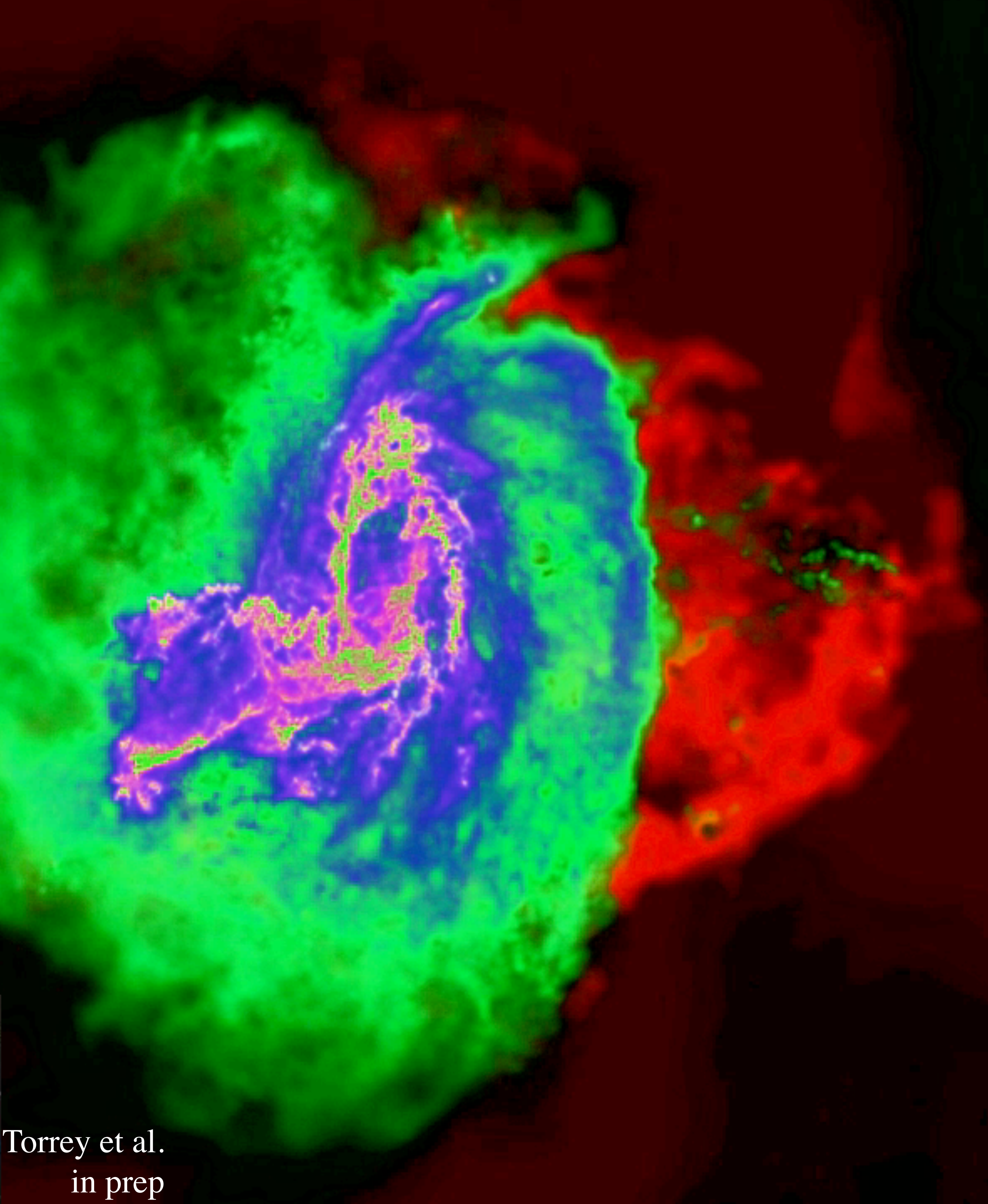




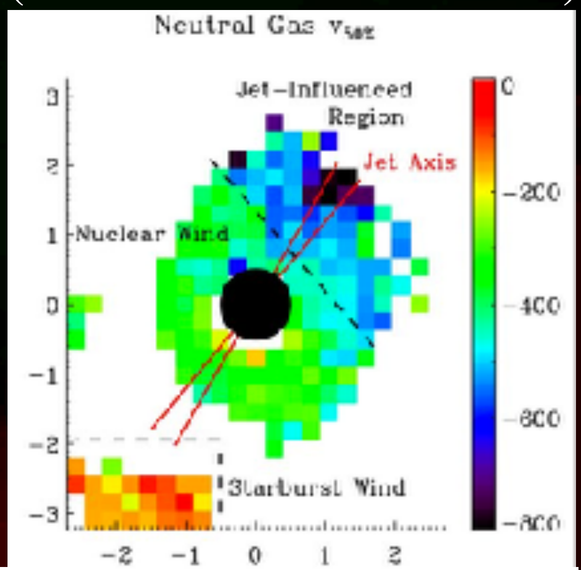
$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

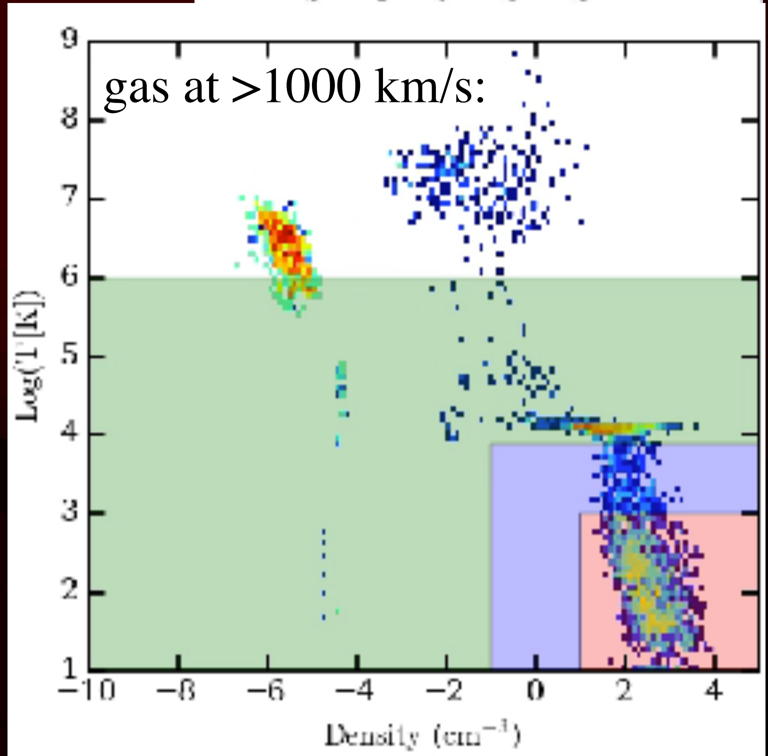
$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$

Accretion Disk Winds: 0.01-10,000 pc



Mrk 231
(+all other warm ULIRGs)





Torrey et al.
in prep