Gastrophysics: Peeking Under the Hood

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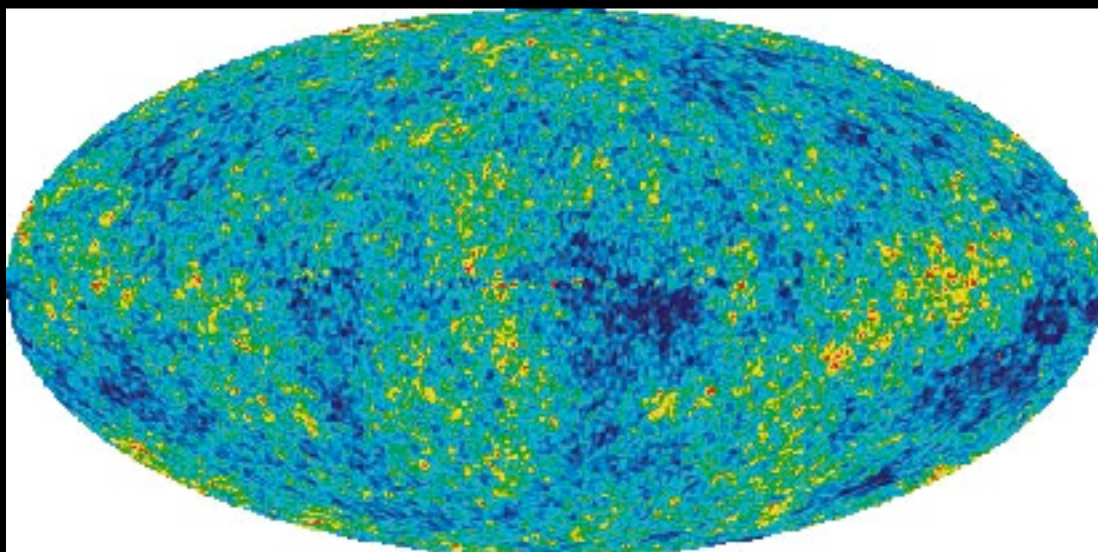
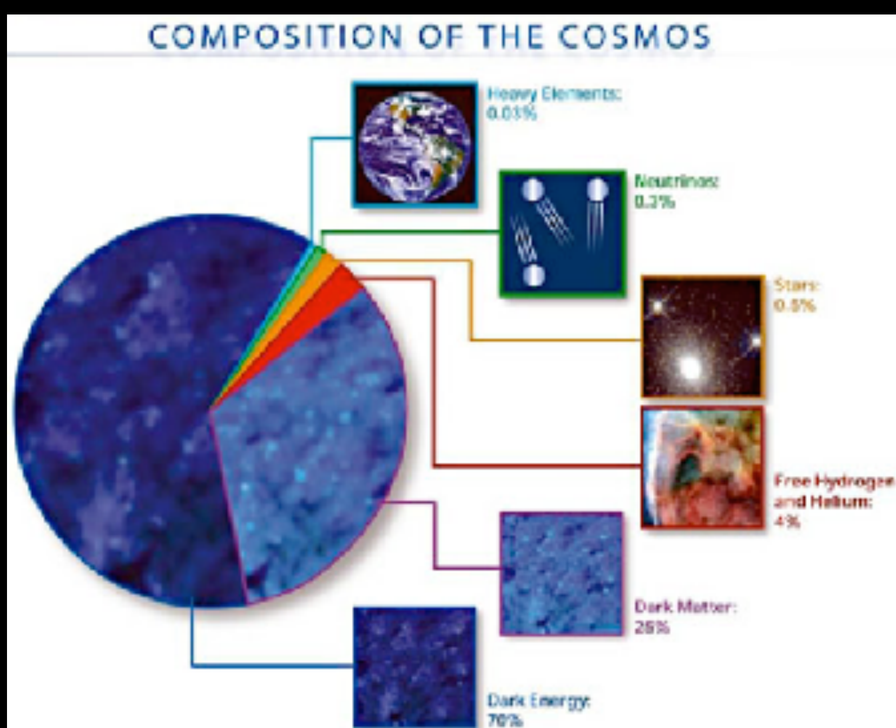
Denise Schmitz, Xiangcheng Ma, David Guszejnov, Robyn Sanderson, Anne Medling, Christine Moran

Large Scales:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?

Today





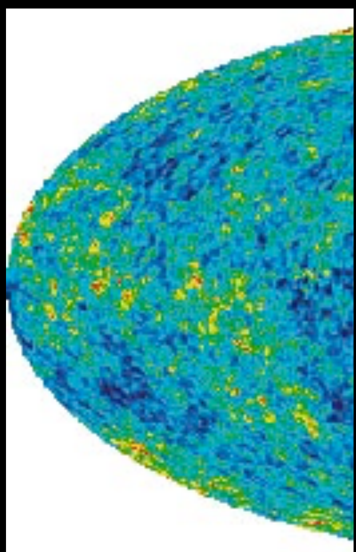
z~1090
(t~400,000 yr)

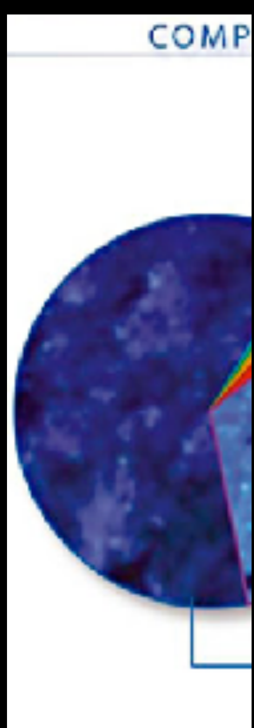
?

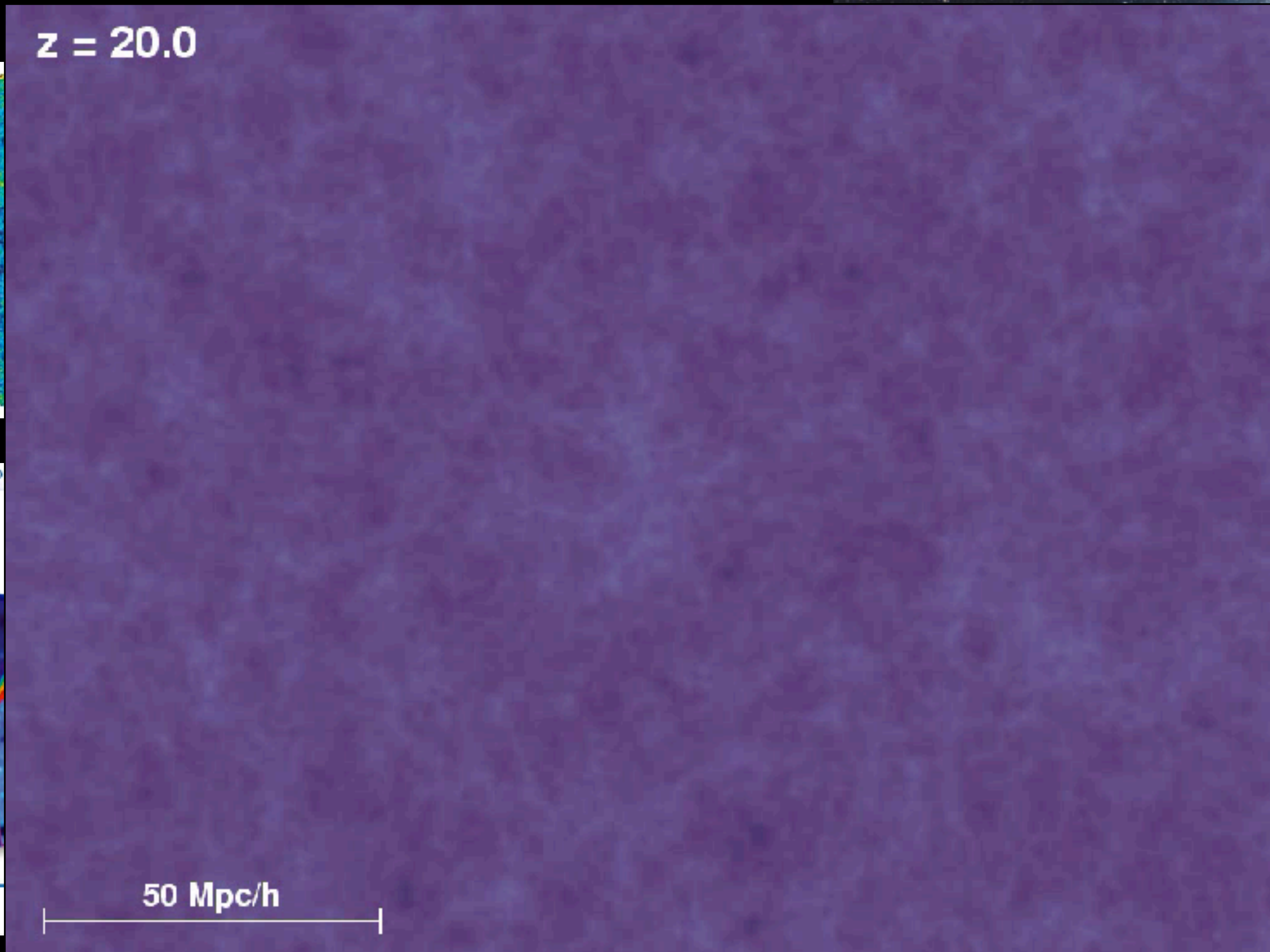
Large Scales:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?

Today

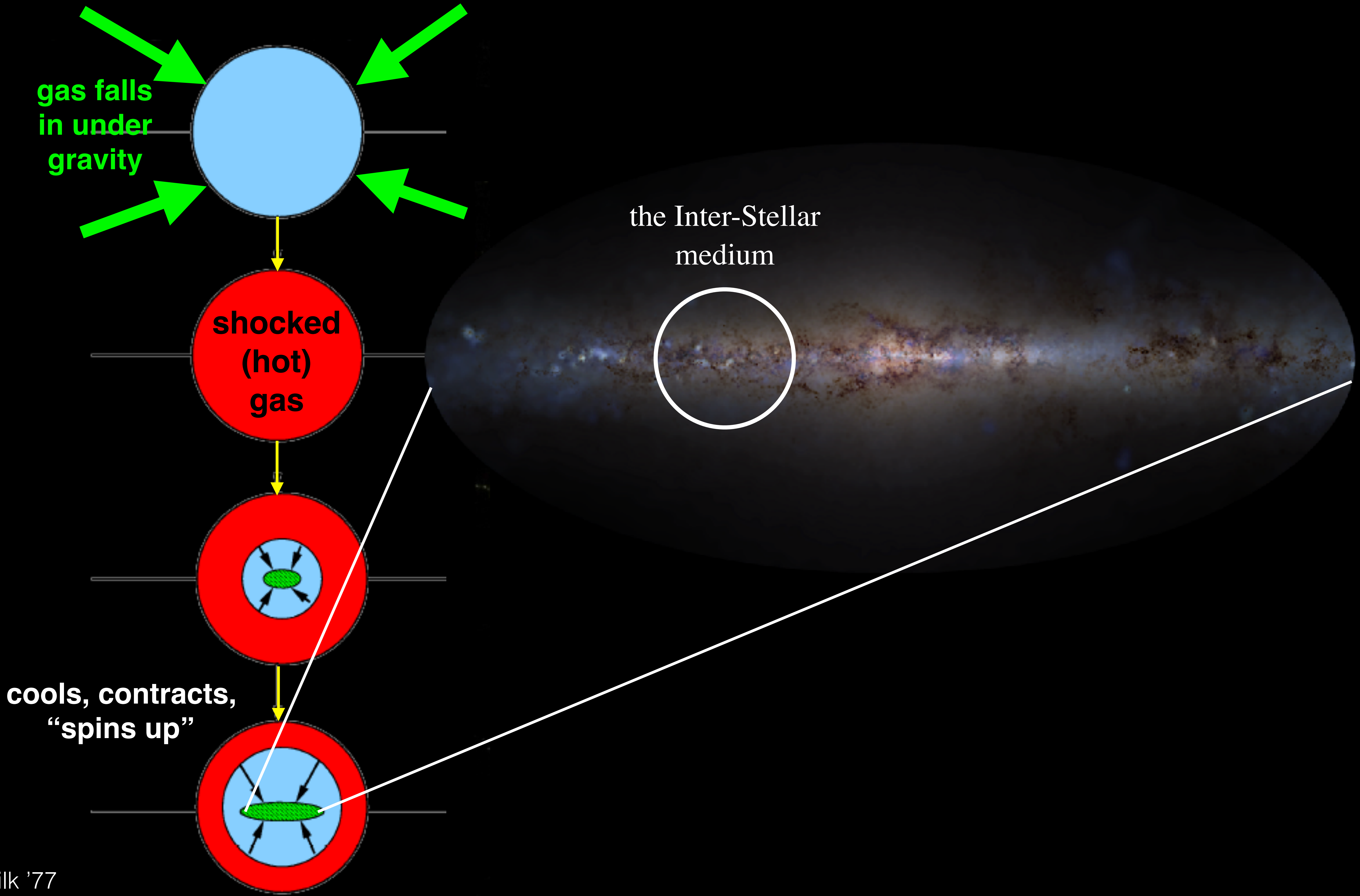






z~1090
(t~400,000 yr)

The Basic Picture

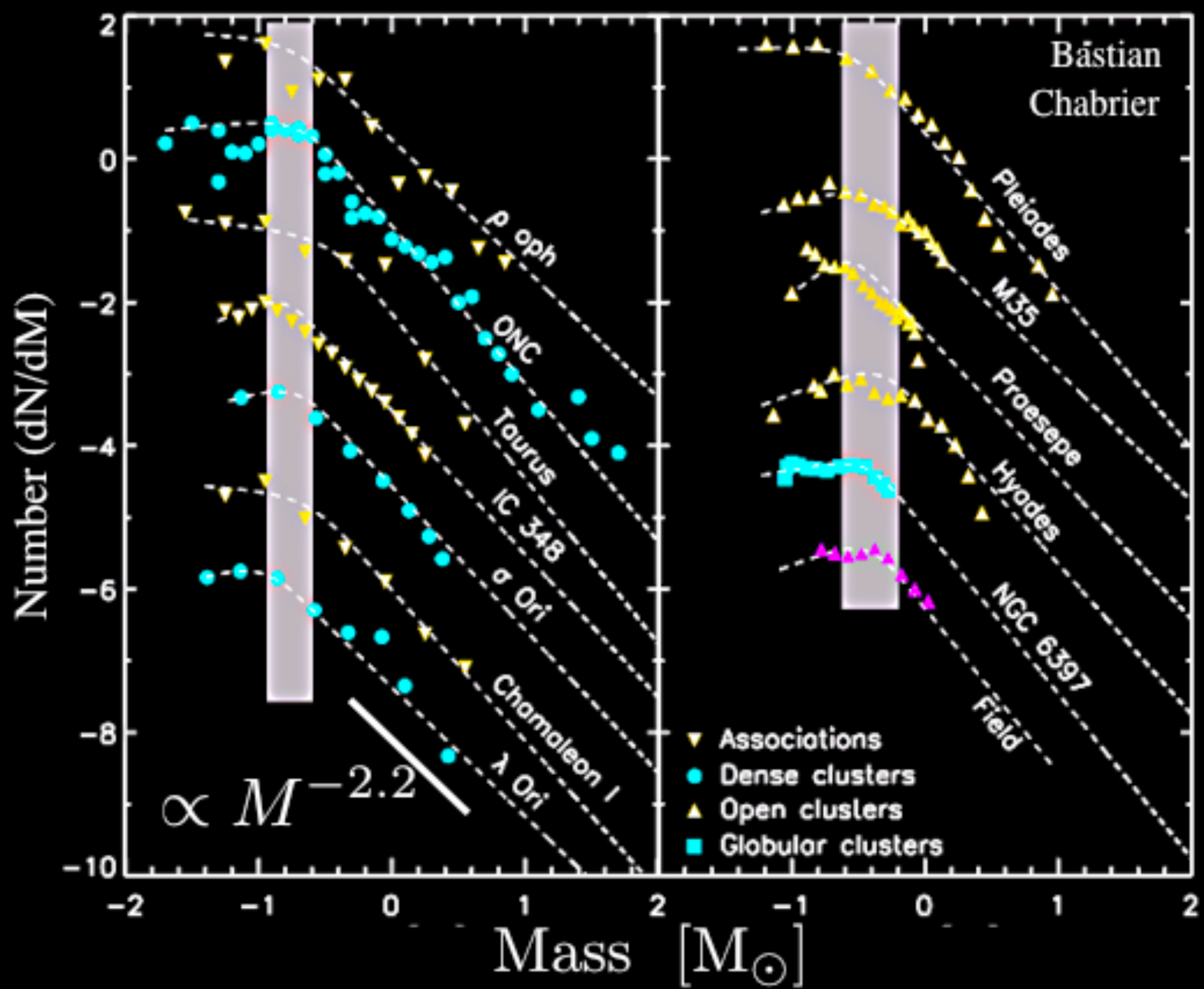


Silk ’77
Binney ’77
Rees & Ostriker ‘77

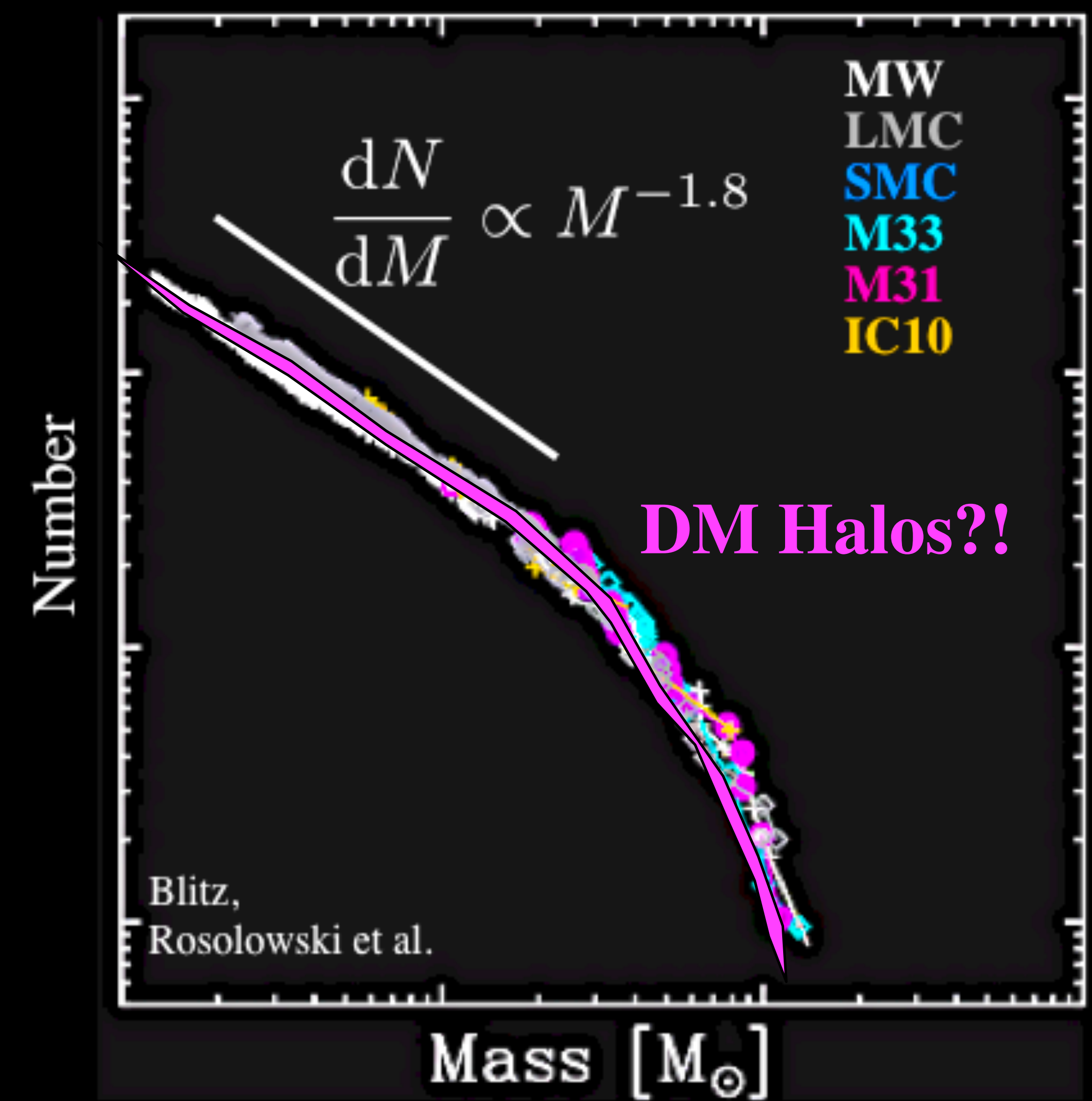
The ISM Is *Messy*….

YET THERE IS SHOCKING REGULARITY

Stars & Pre-Stellar Gas Cores:



Giant Molecular Clouds:

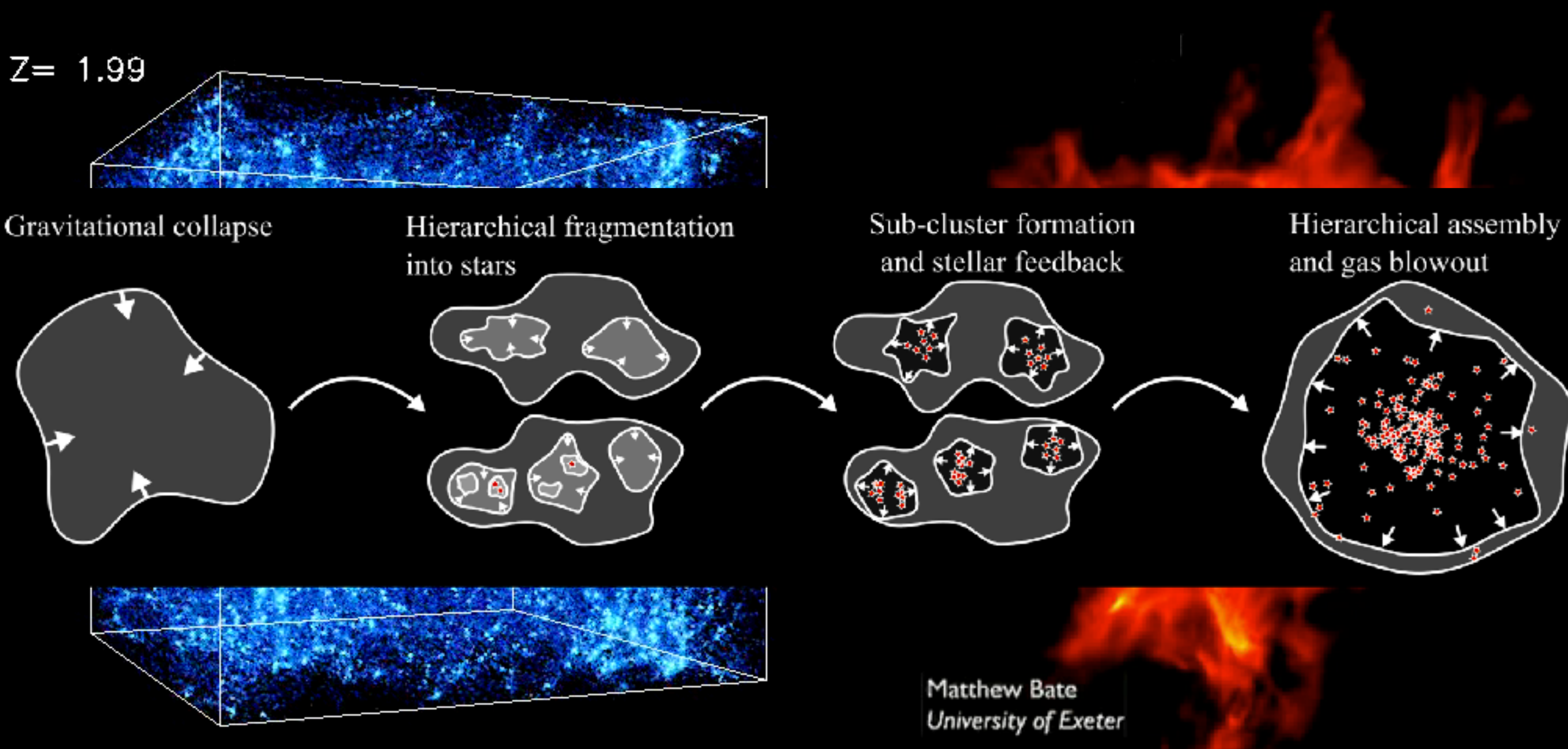


Correlation functions, SFRs (Kennicutt-Schmidt),
Scaling laws (Tully-Fisher)

Is this an accident?

STRUCTURE FORMATION

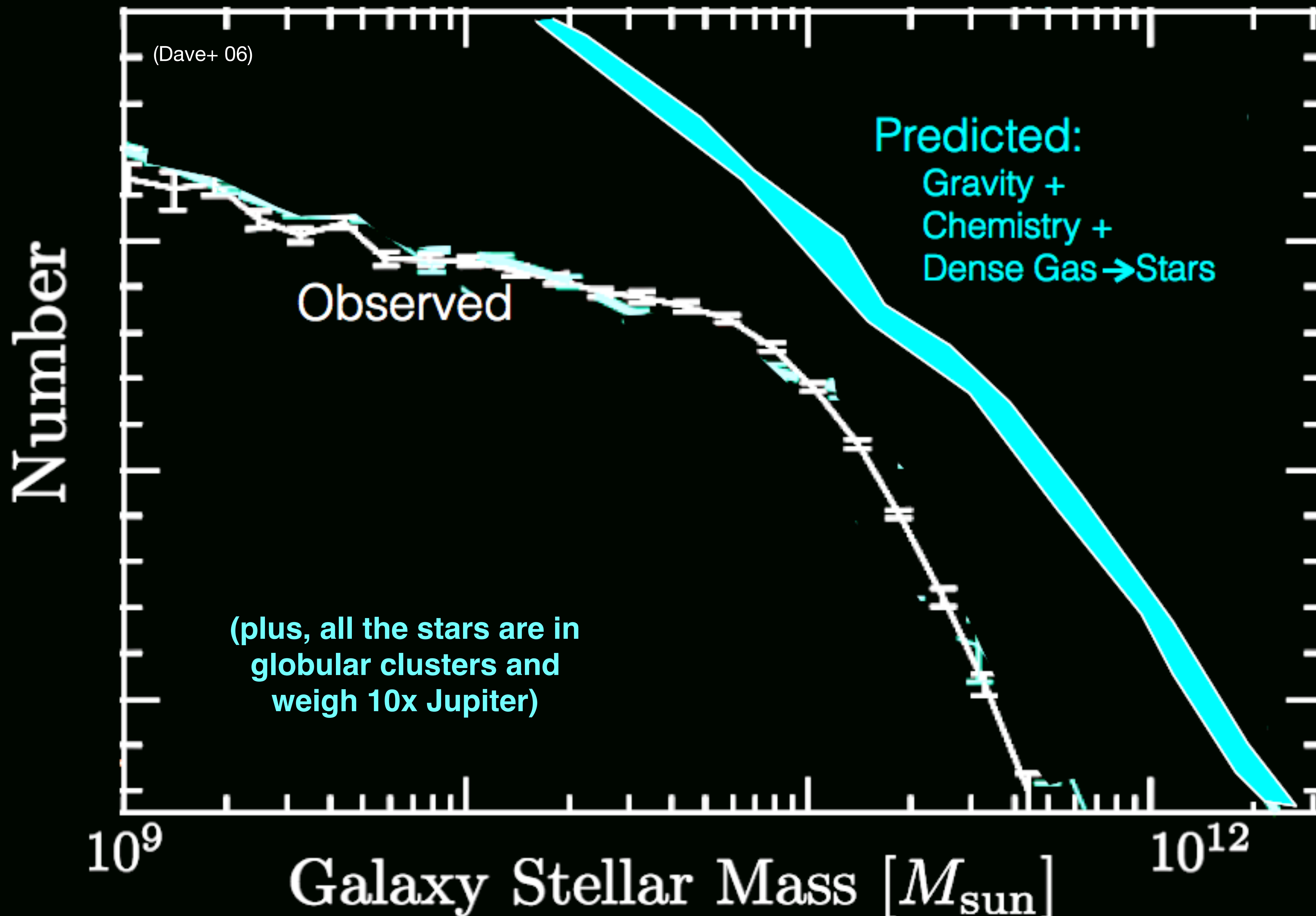
STAR FORMATION



Guszejnov 15,16, 17
Grudic 16, 17

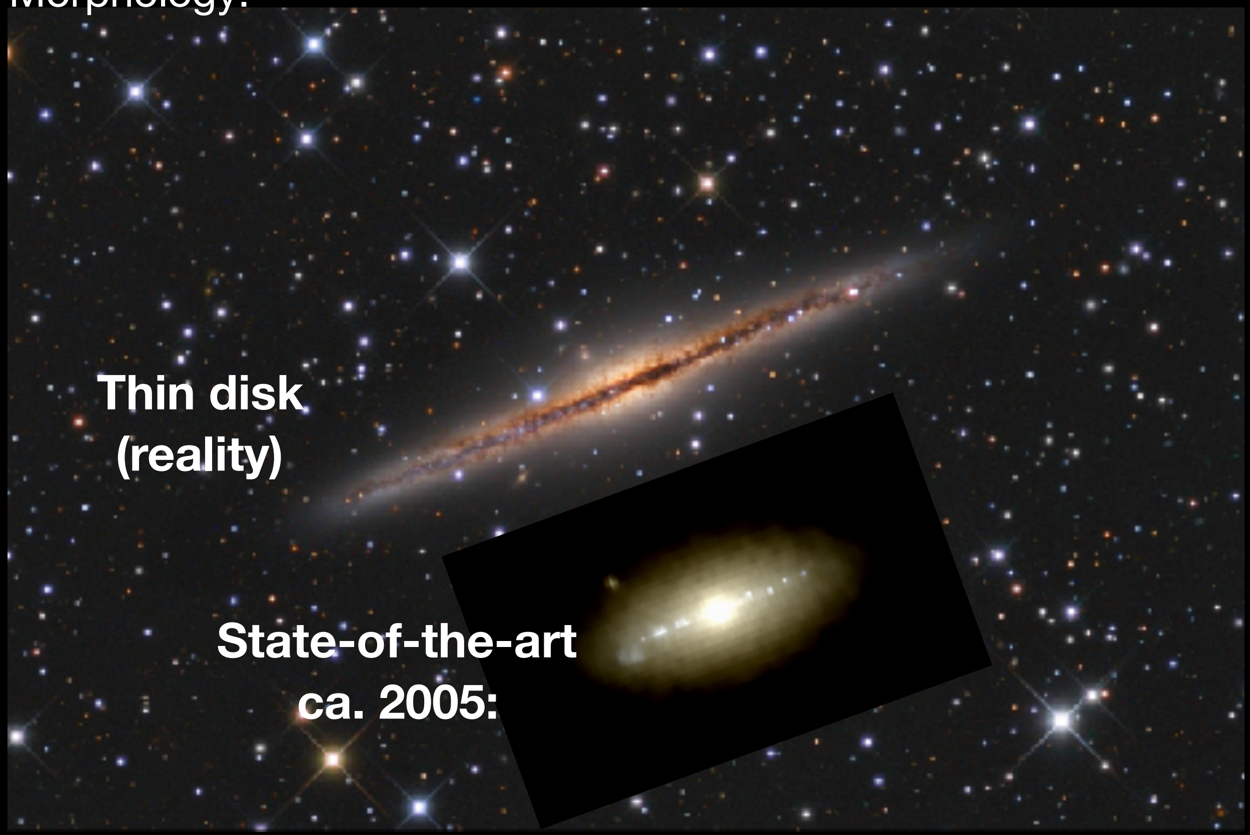
Problem:

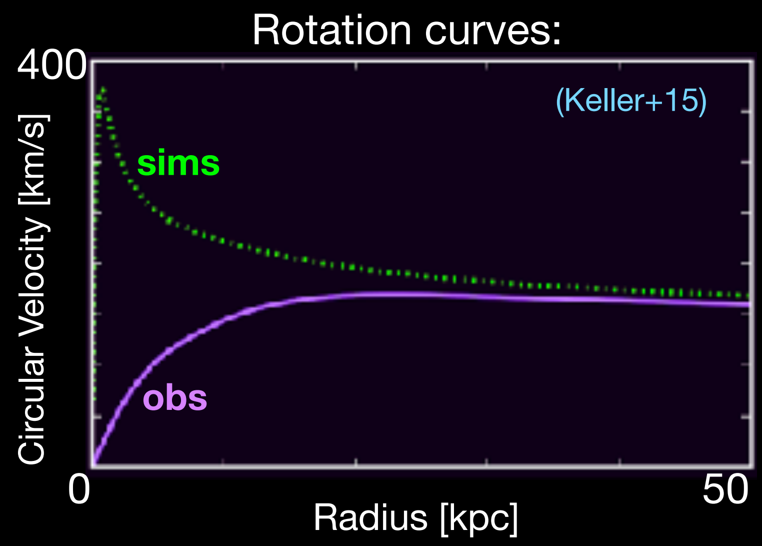
WHY SO FEW GALAXIES & STARS?

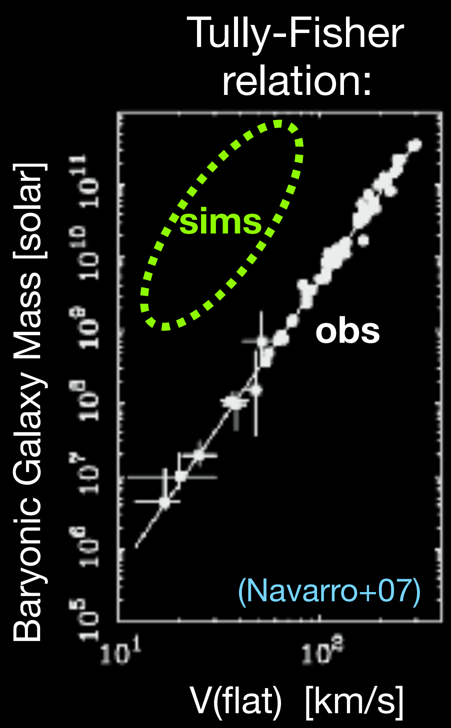


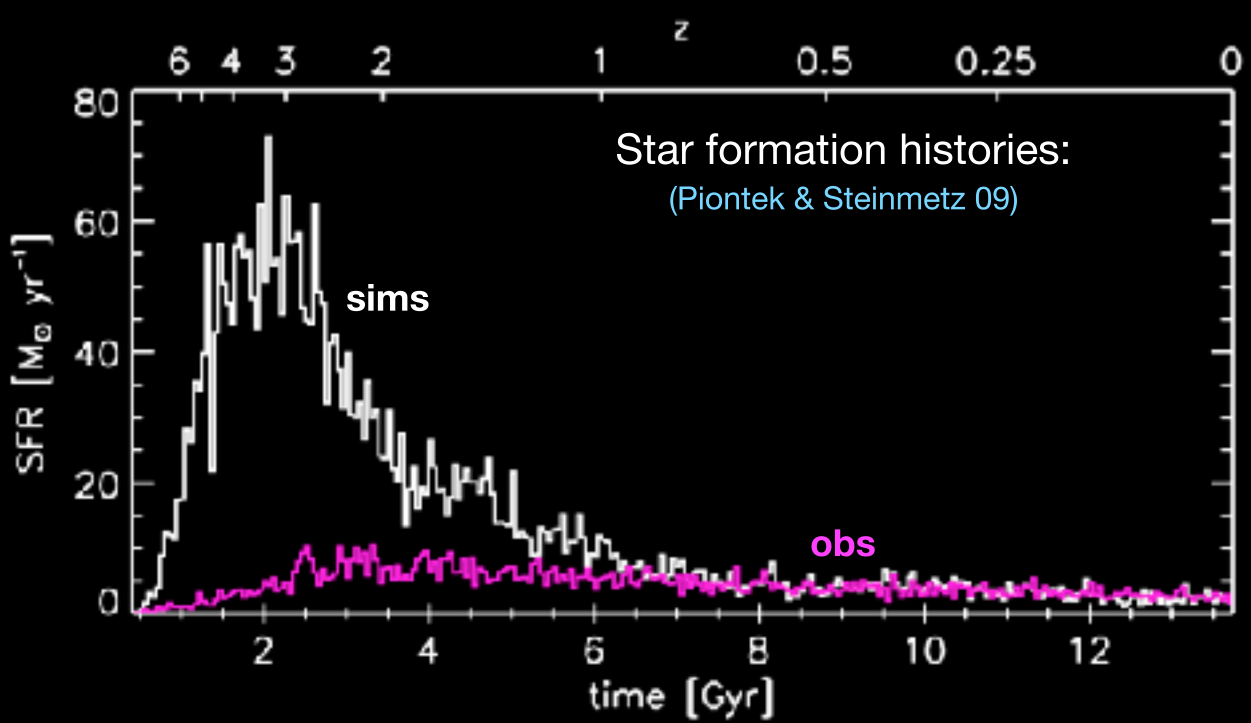
Problem:
GALAXY MORPHOLOGIES AND SCALING RELATIONS

Morphology:







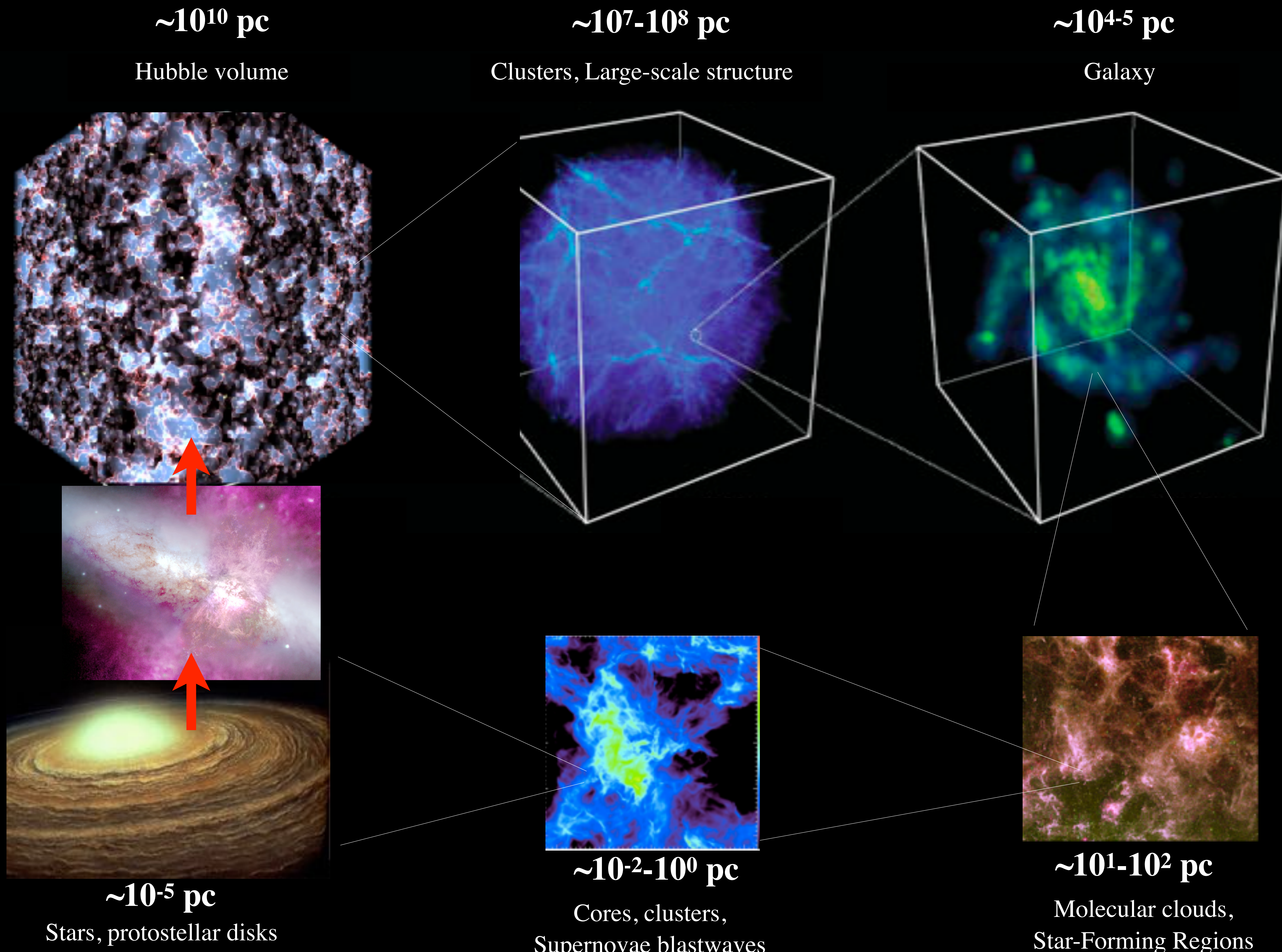


- Stars form too early
- Too many metals trapped
  ("G-dwarf problem")
- Sizes too small
  ("angular momentum catastrophe")
- Vc too large
  ("Tully-Fisher" problem)
- Stars in spheroid, not thin disk
  ("Over-merging" problem)

But wait…

Stars Matter

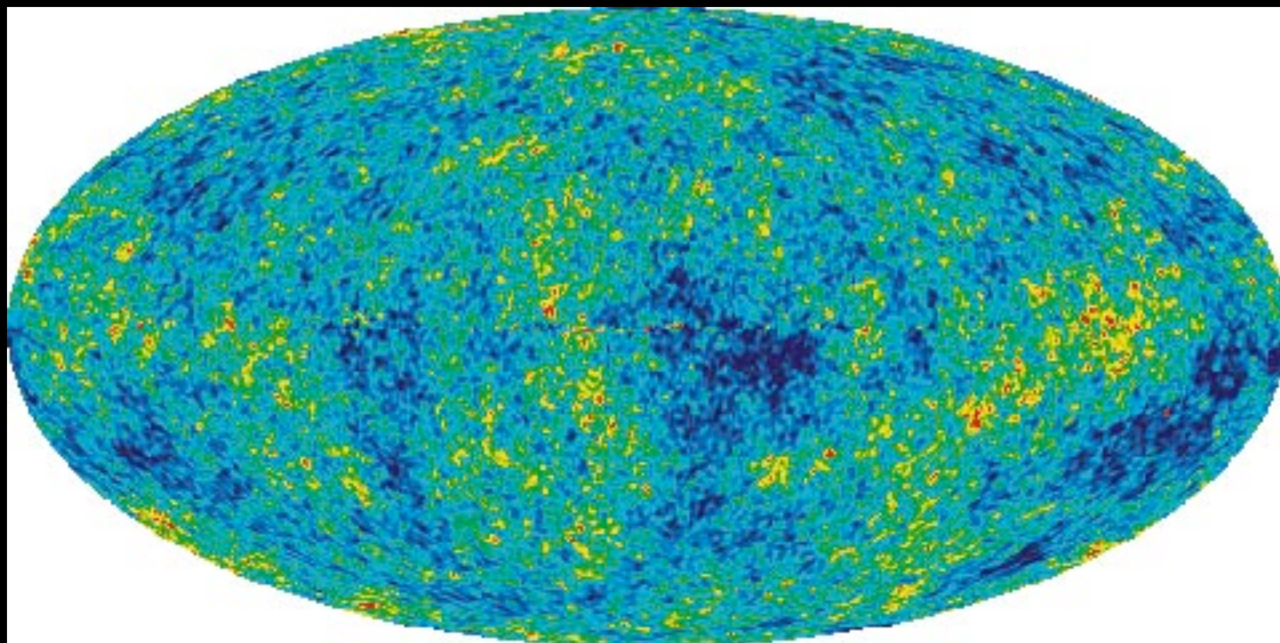
… Nature hates theorists



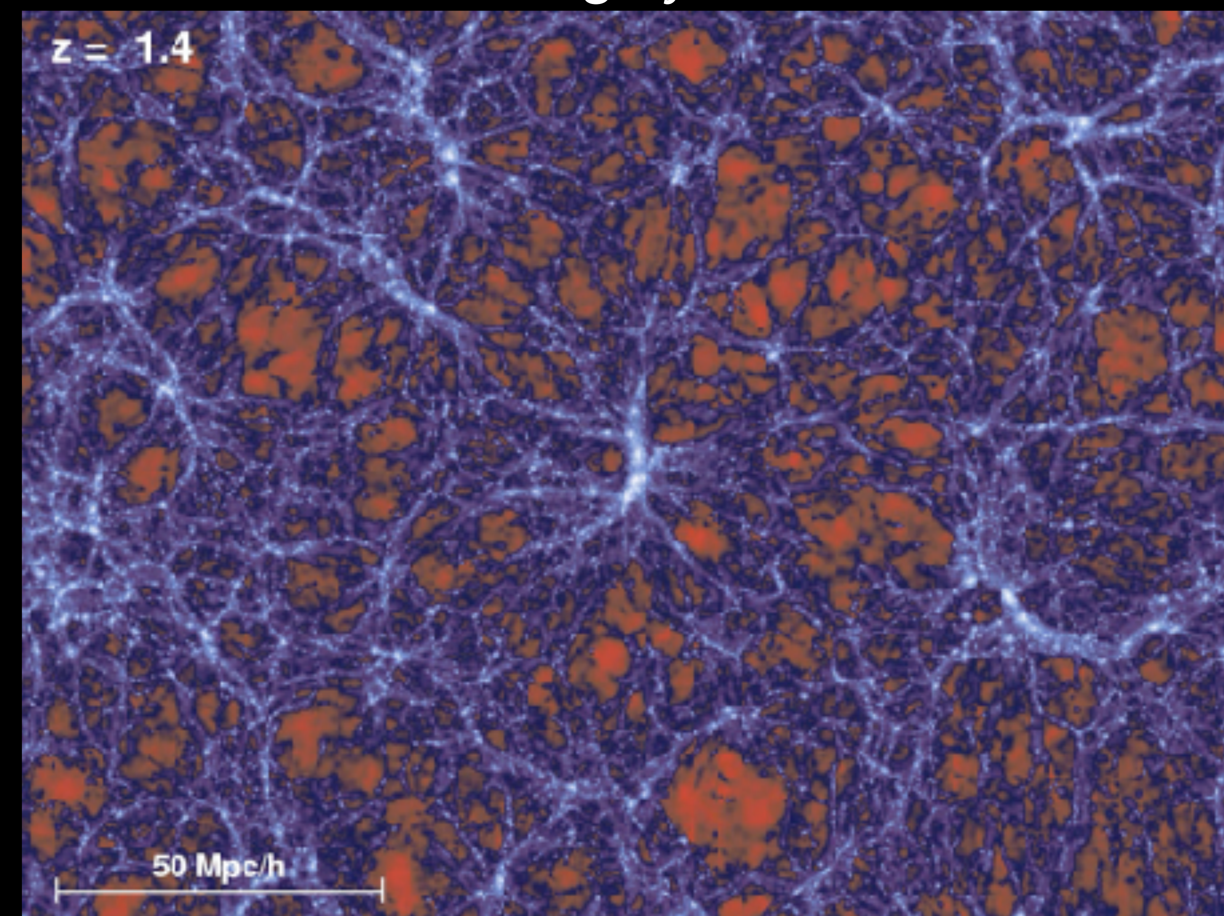
3 Breakthroughs:

1. “Concordance” cosmology

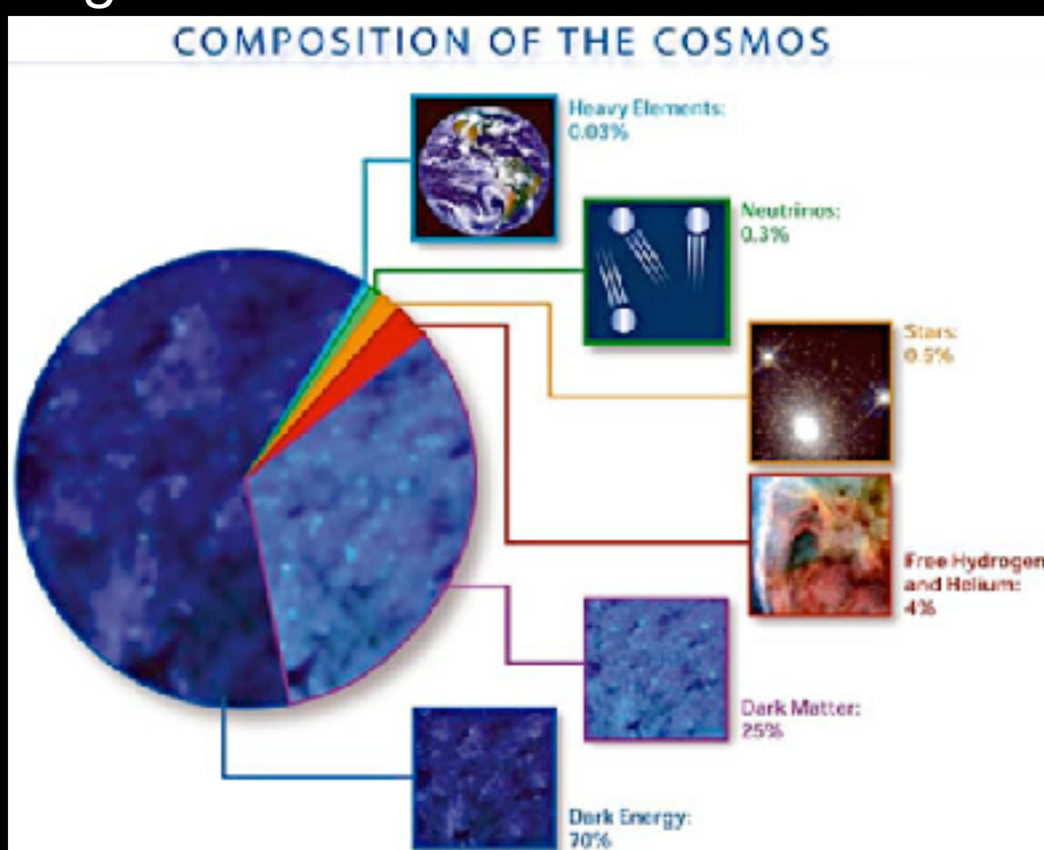
Well-posed initial conditions:



“smoothed” field
looks *roughly* like this:

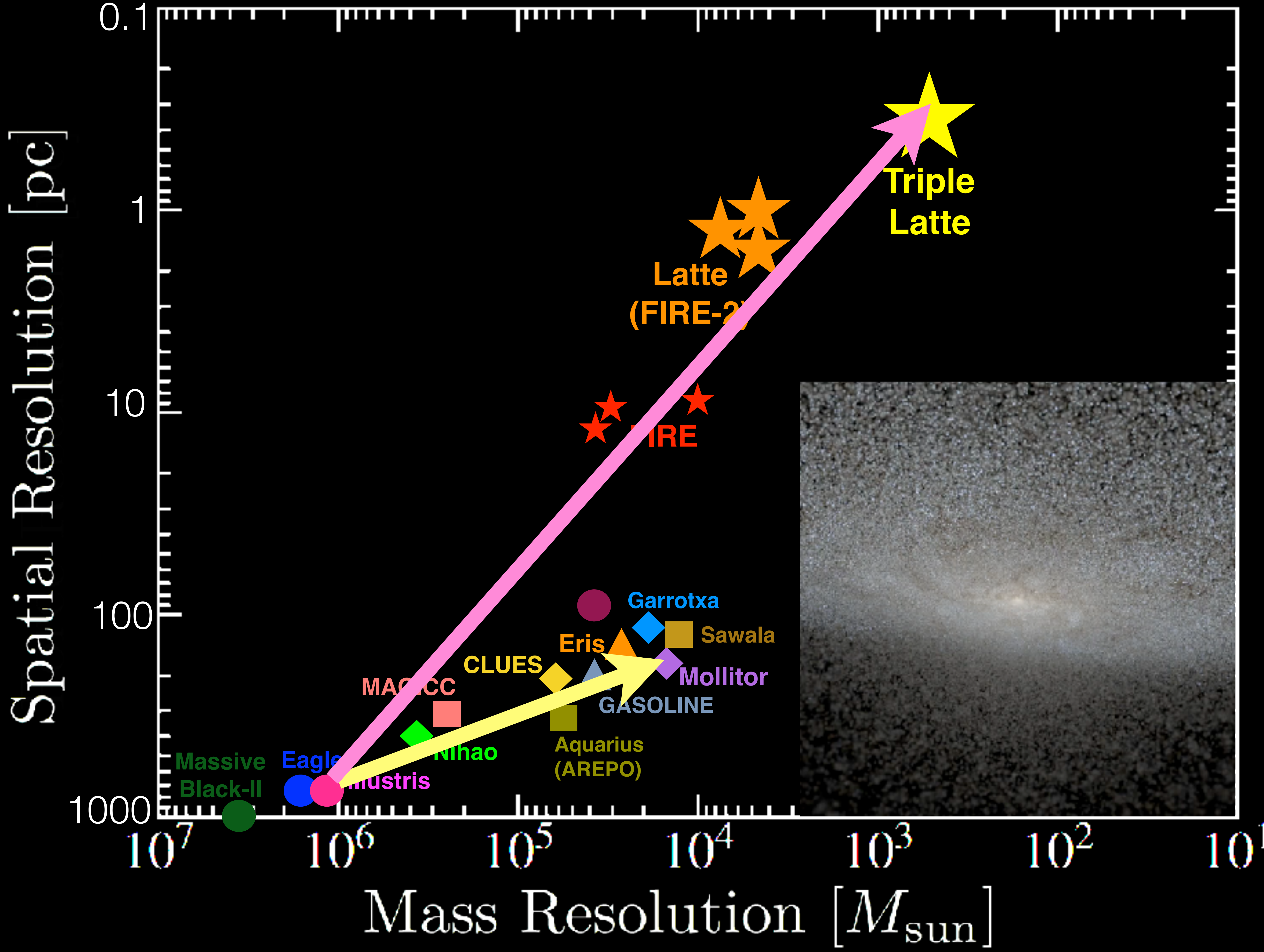


“Ingredients”:



- Large-scale structure / age of the universe are not “free parameters”!

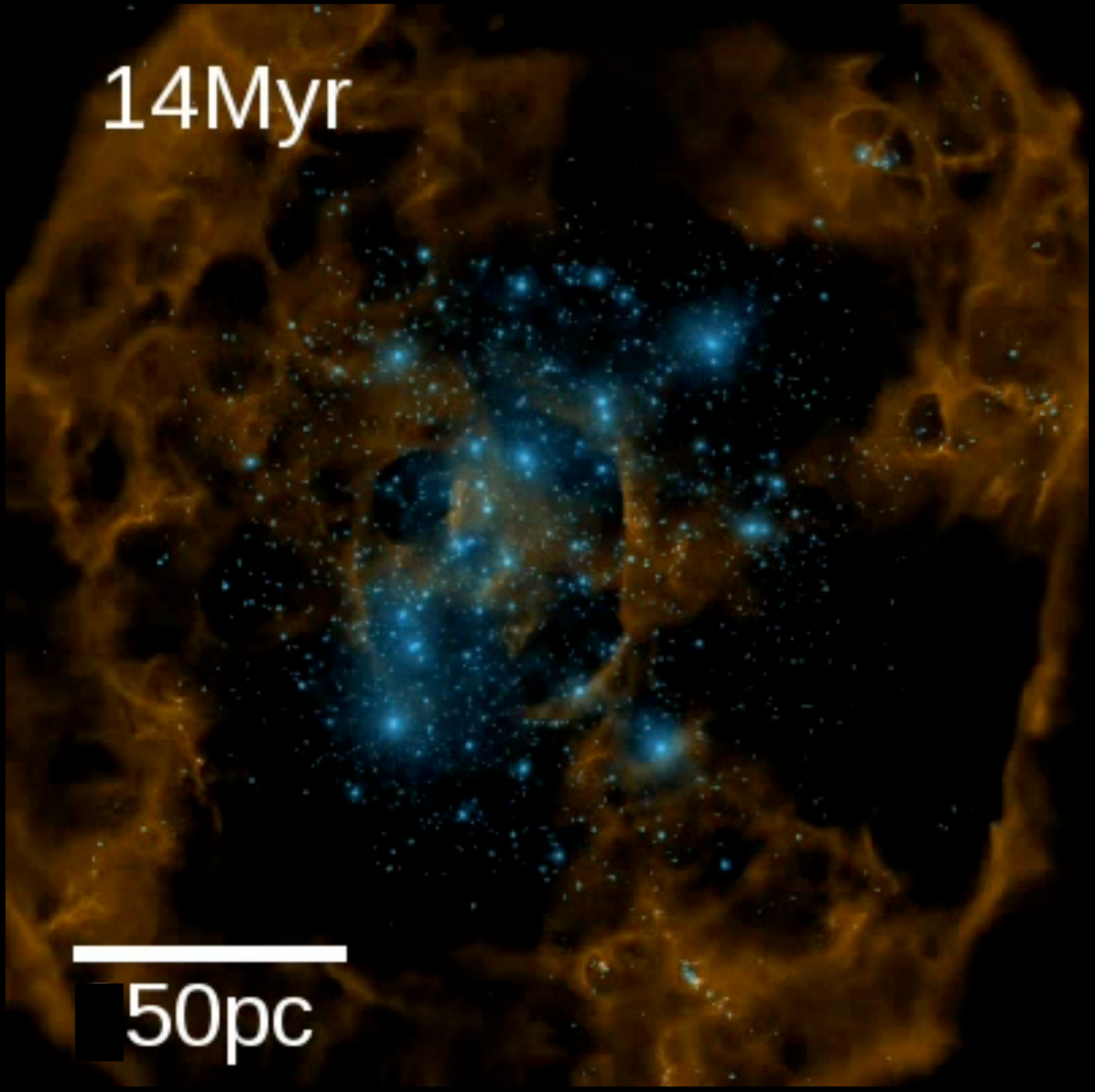
2. Resolution (Moore's Law + Algorithms)



3. “New” Physics
INSIGHTS FROM STAR FORMATION

- Star formation is ***strongly clustered*** (in space & time). So are SNe!
- GMCs are destroyed (by radiation & stellar winds) ***before*** SNe explode
- ISM is strongly ***super-sonically turbulent:*** structure is transient (short-lived)

(Resolution ~0.1 M_{sun})



Mike Grudic
(arXiv:1612.05635)

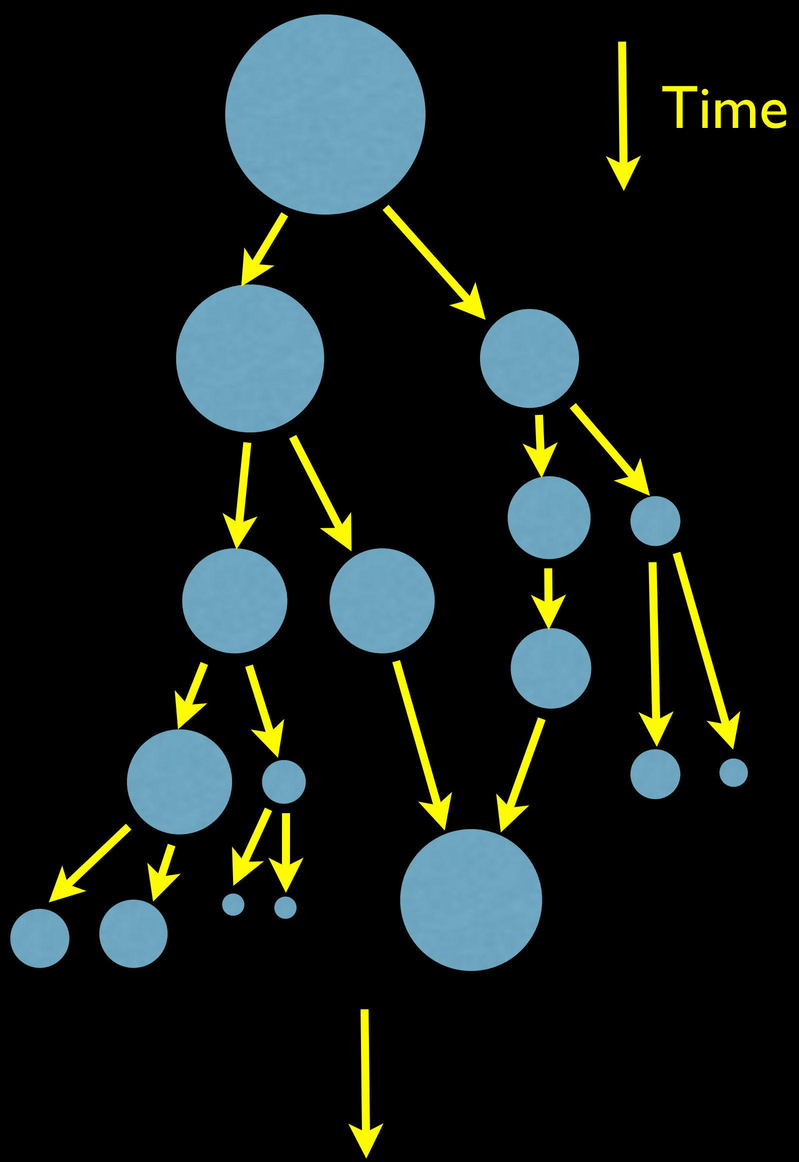
Let’s Build Back Up

Cores to Stars

HOW TO STOP FRAGMENTATION?

Guszejnov+ '16, 17

"Fragmentation Cascade":



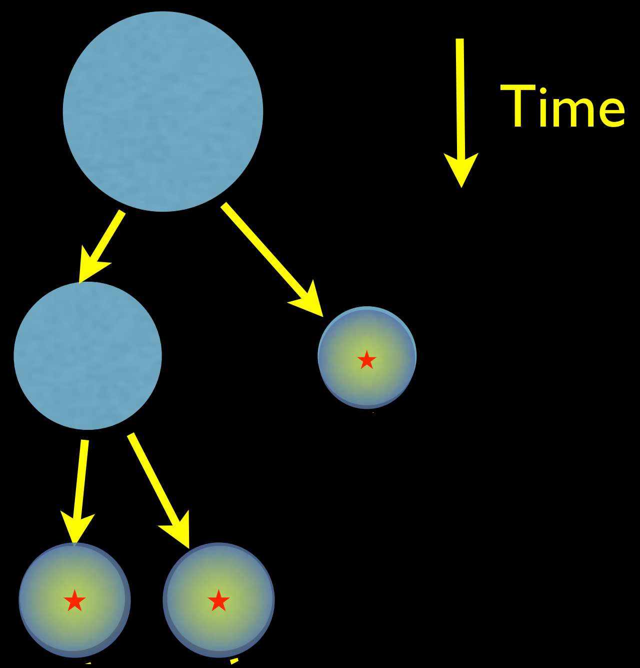
To opacity limit!
(all stars ~10 $M_{\rm Jupiter}$)

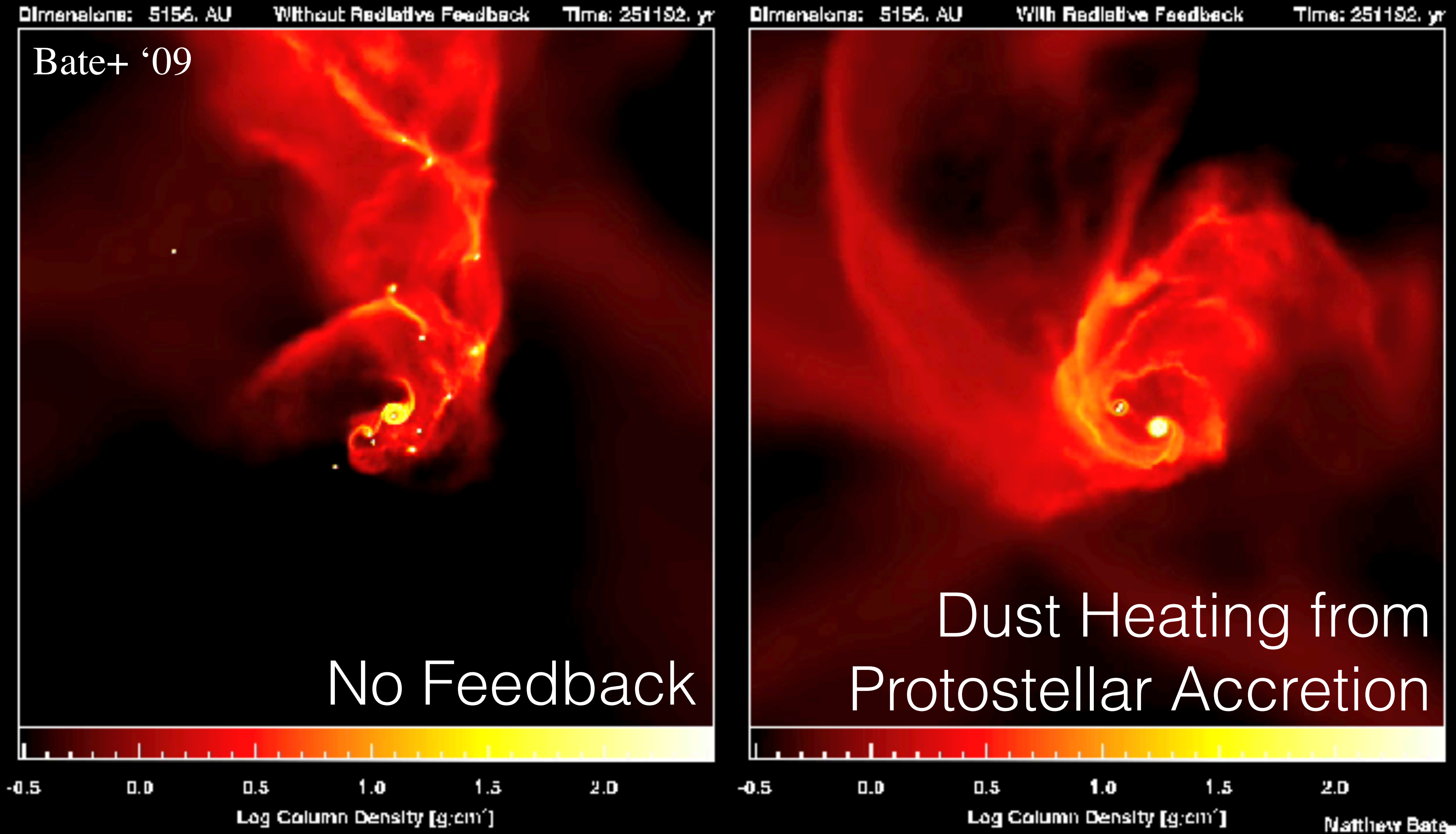
Isothermal fragmentation:

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

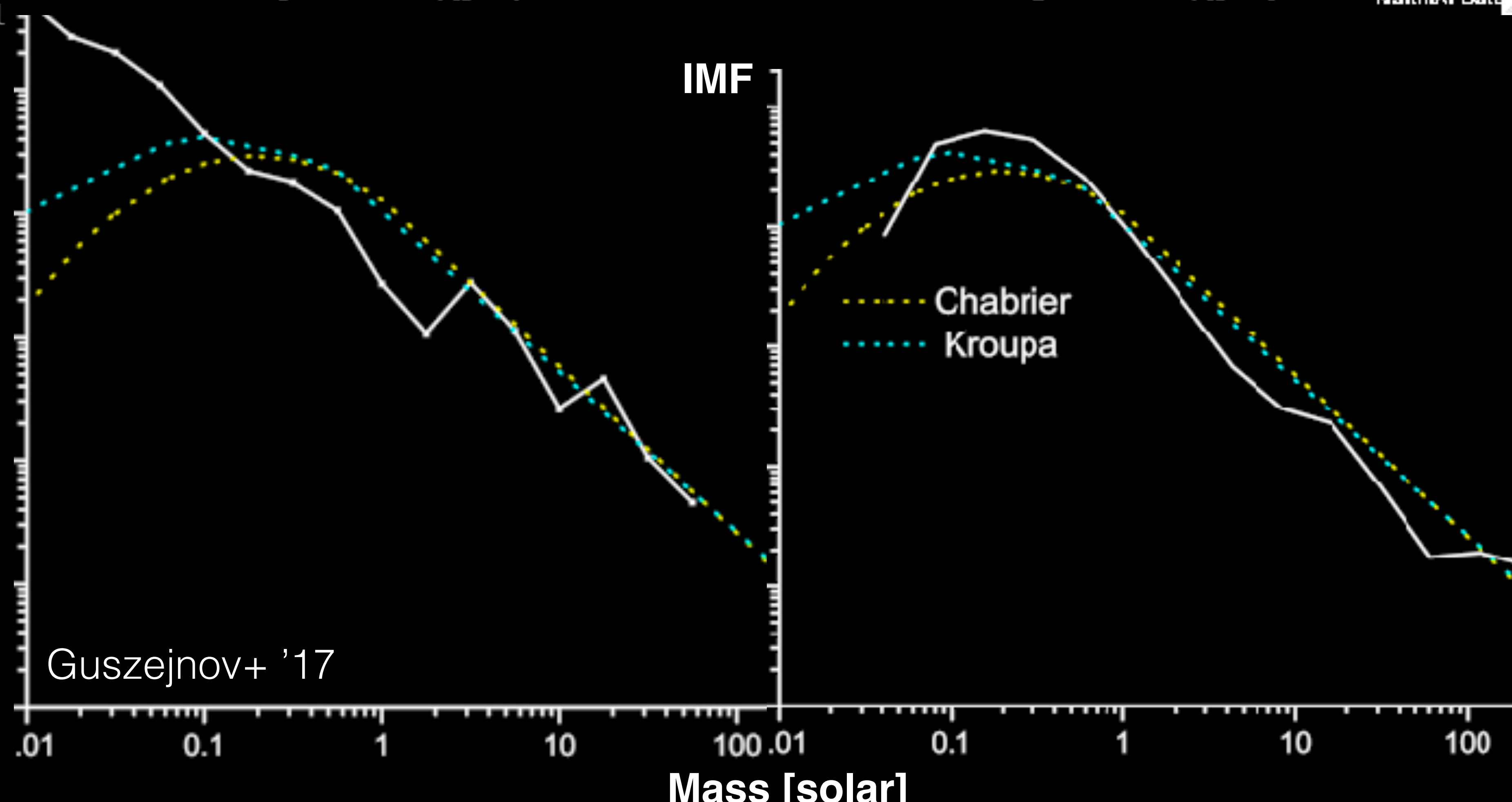
Feedback vs. Gravity

Guszejnov, Hopkins, & Krumholz 2015





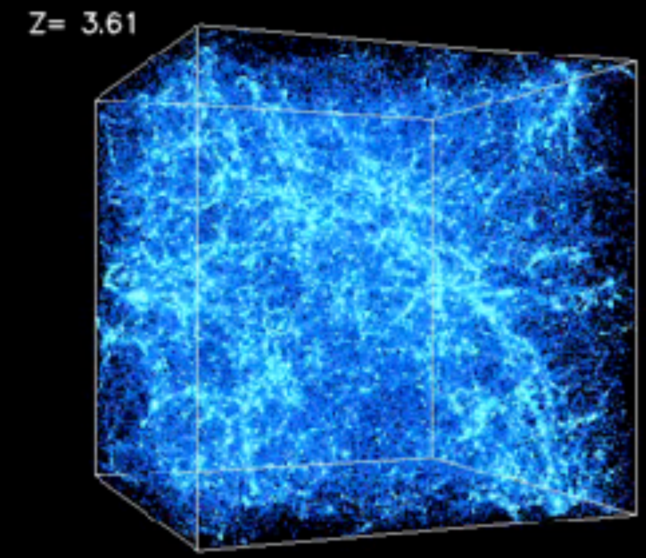
$$M_{\rm crit} \sim 0.1\, M_{\odot} \left(\frac{\psi}{\psi_0}\right)^{0.4} \left(\frac{R_{\rm core}}{0.1\,{\rm pc}}\right)^{0.1}$$

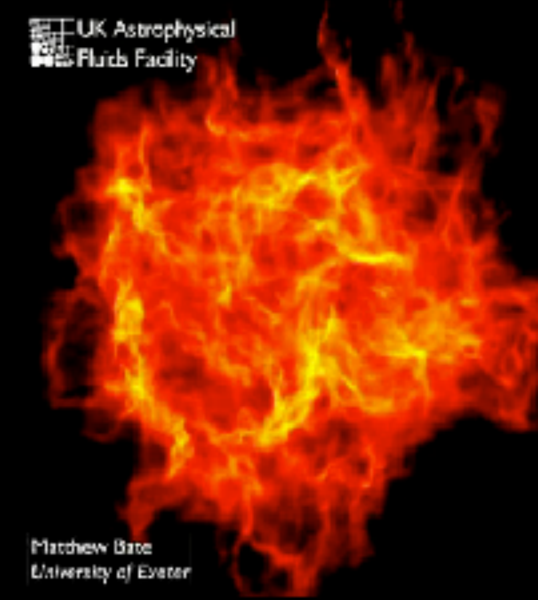


See also:
- Bate+ '09, '12
- Offner+ '09, '14
- Krumholz+ '12
- Guszejnov+ '16, 17

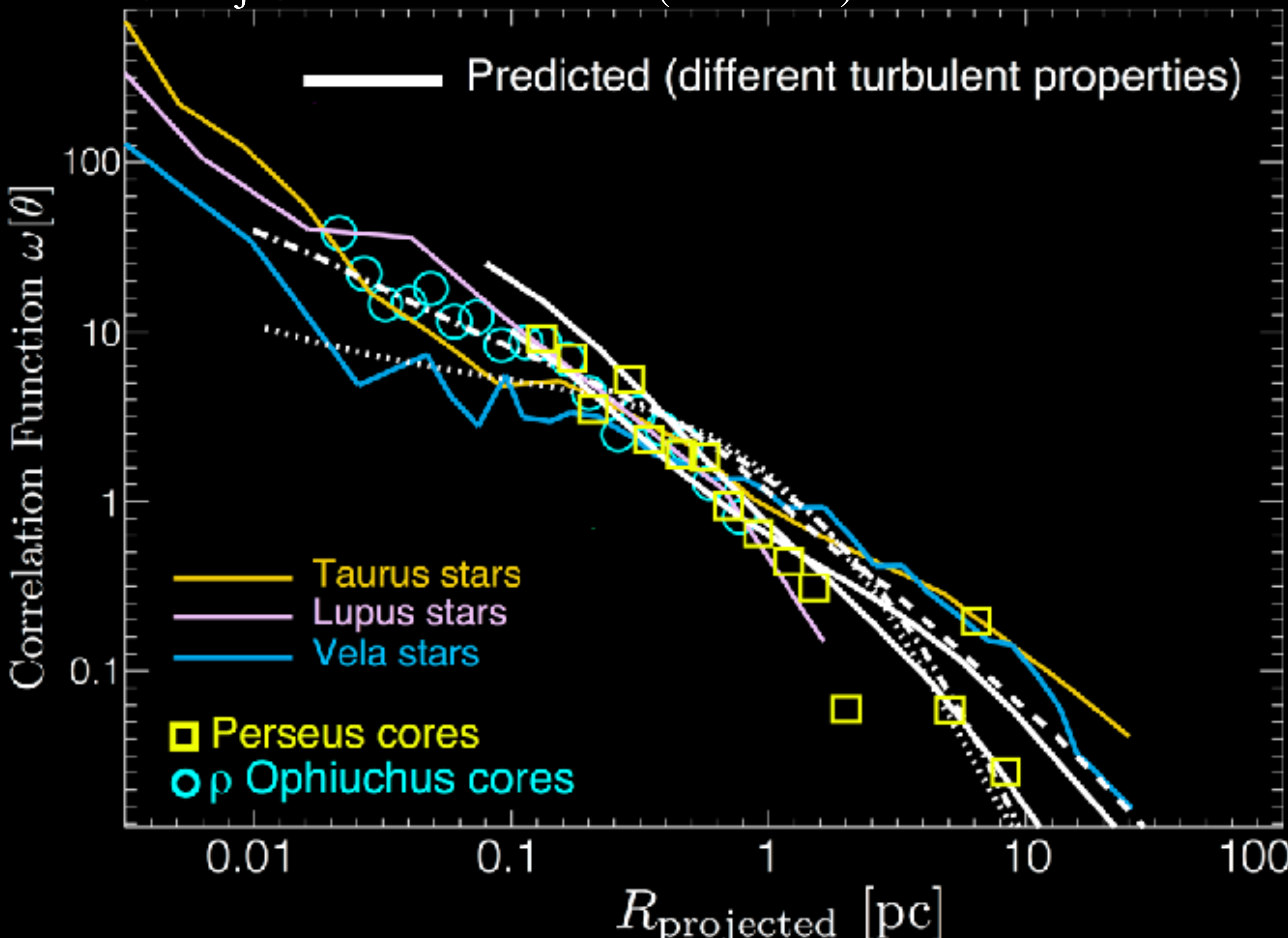
- (+Multiplicity, Periods)

Why Is Star Formation Clustered?
INEVITABLE IN GRAVITATIONAL COLLAPSE





Guszejnov: arXiv:1610.00772 (+PFH ’12)



Universal
(Guszejnov+Grudic: 1707.05799):

Stars
Cores
Clumps
GMCs
Star clusters
Galaxies

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

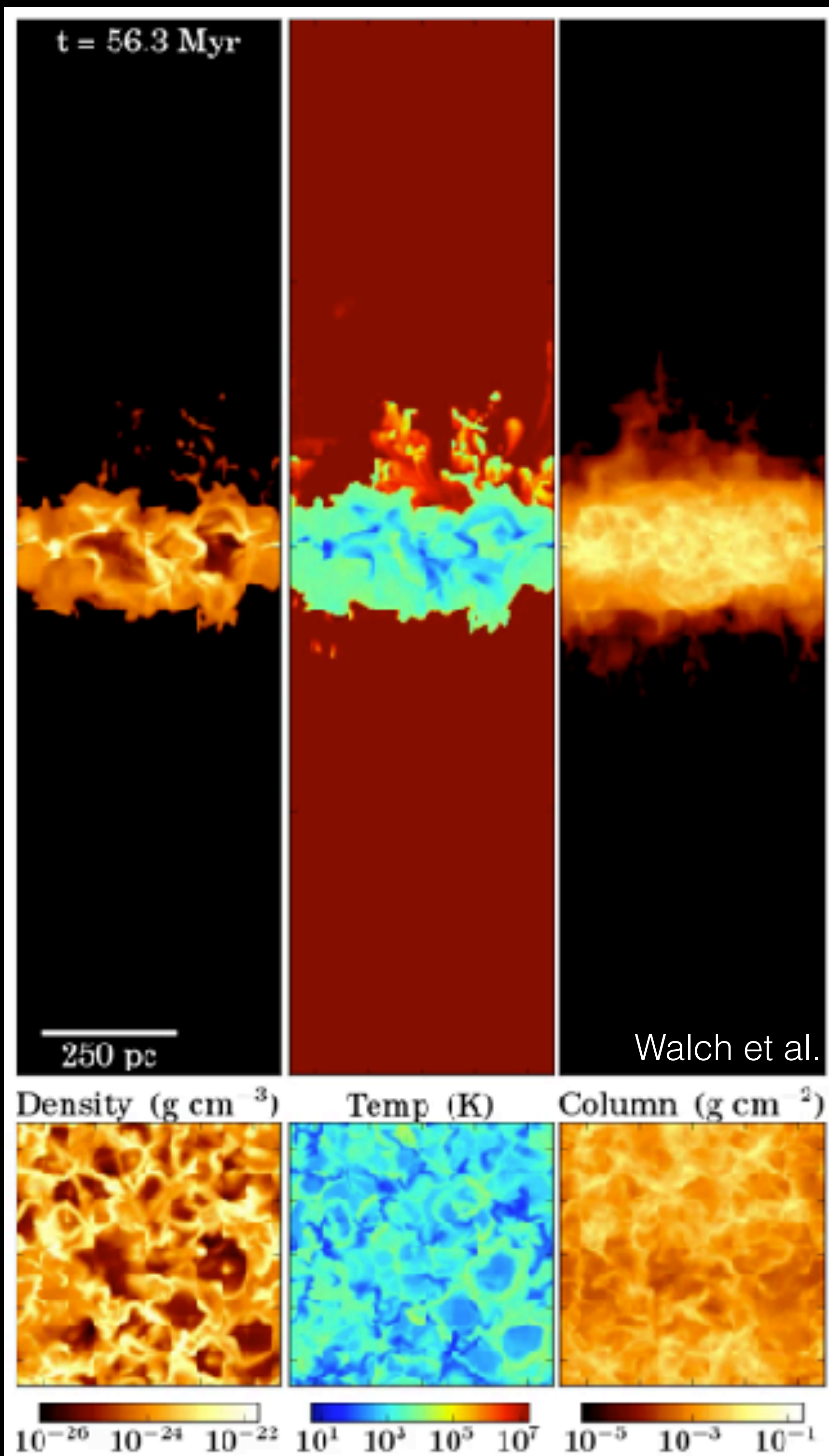
$$(\omega(\theta) \propto \theta^{-1})$$

Clustering Matters

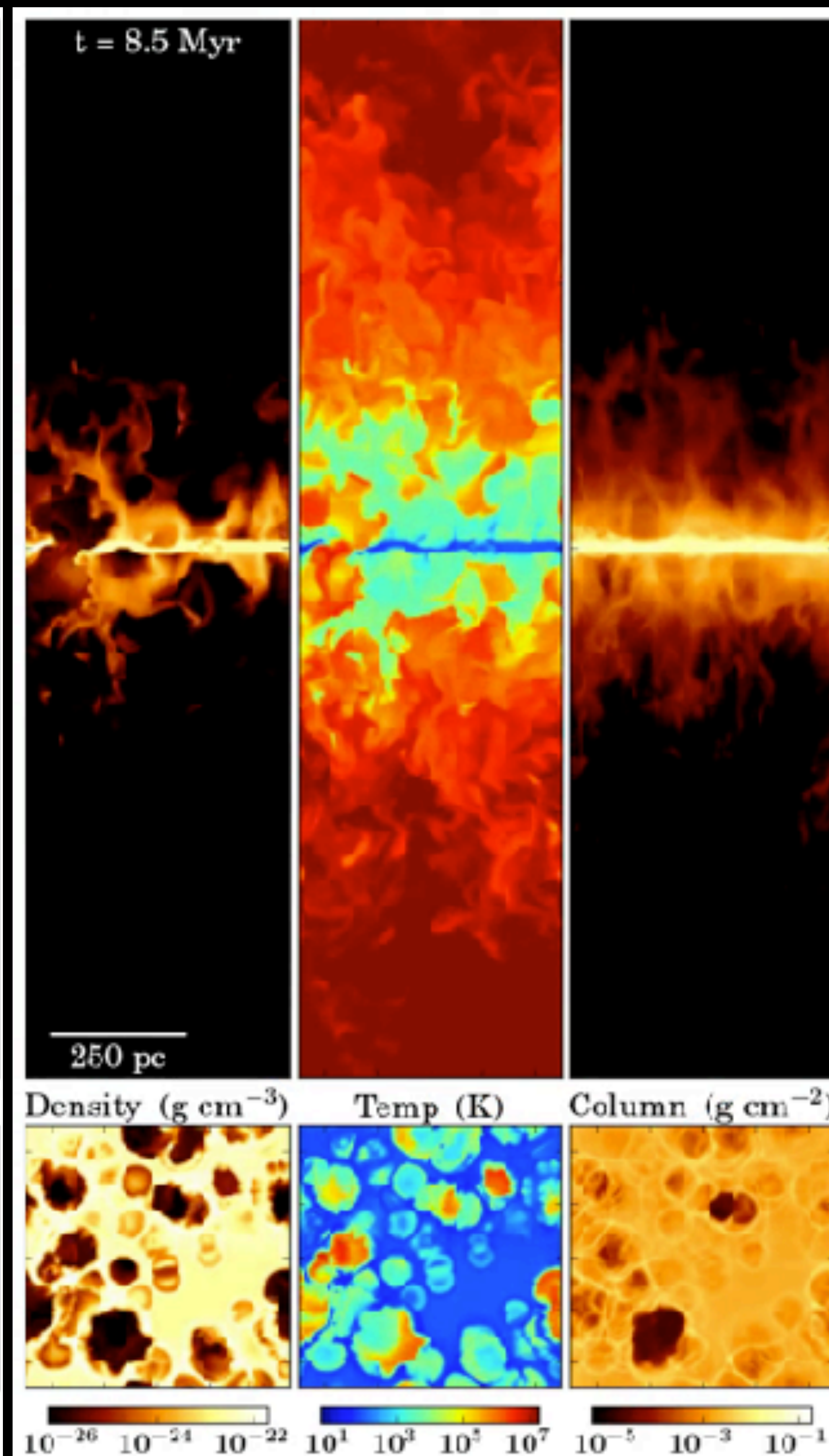
INSIGHTS FROM STAR FORMATION

Kung-Yi Su+ 17, 18
(also Martizzi+ '16
Walch+ '15, '17, Kimm+ '15)

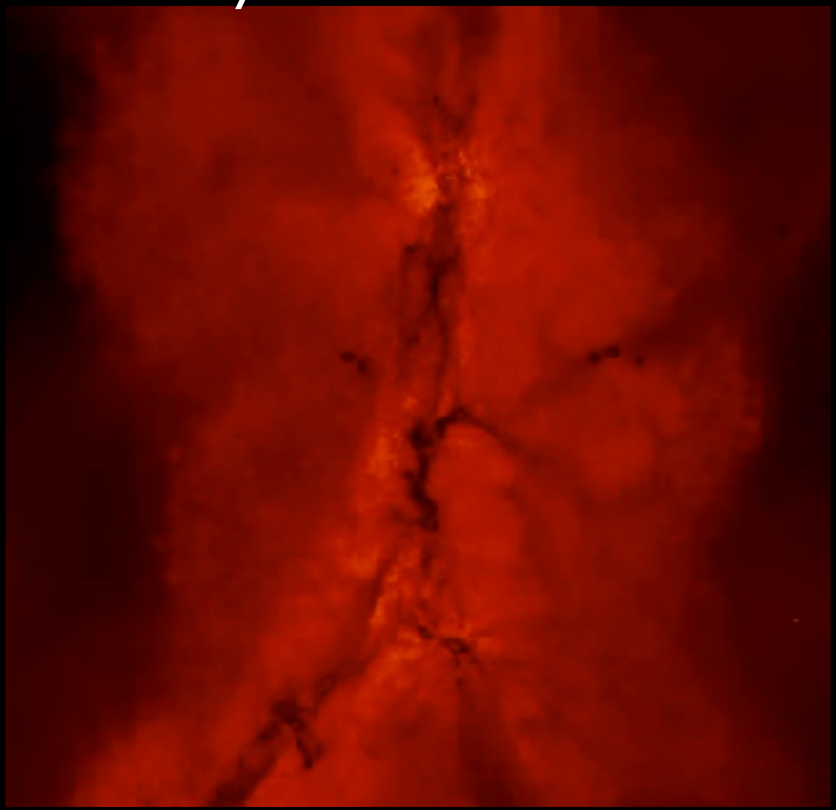
SNe Explode in Density Peaks
(no radiative feedback)



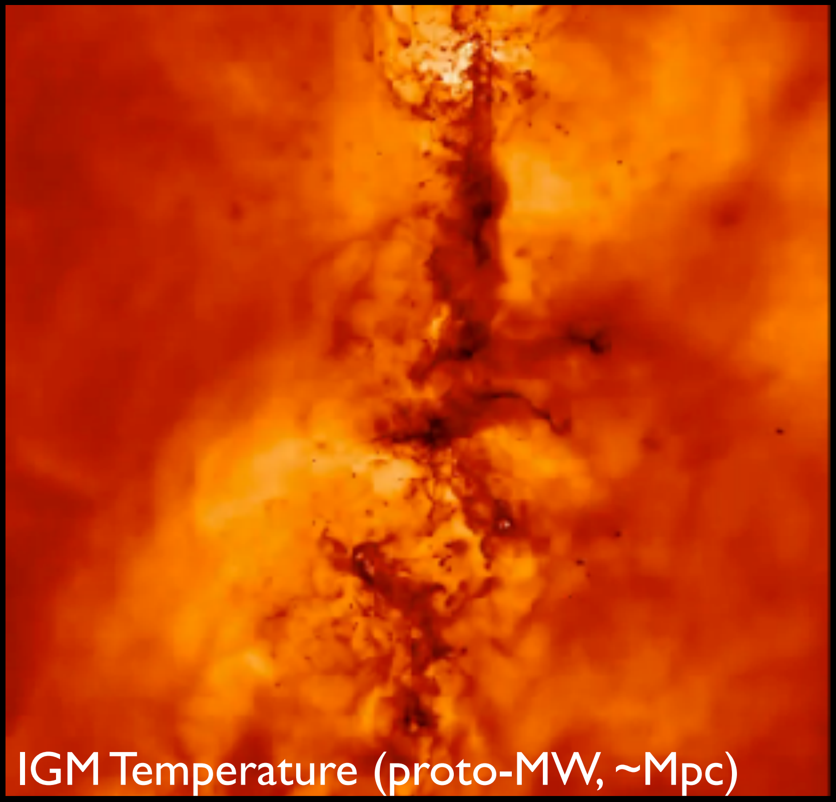
SNe Clustered & Off-Peak
(radiative feedback/pre-processing)



Winds "by hand" ~SFR



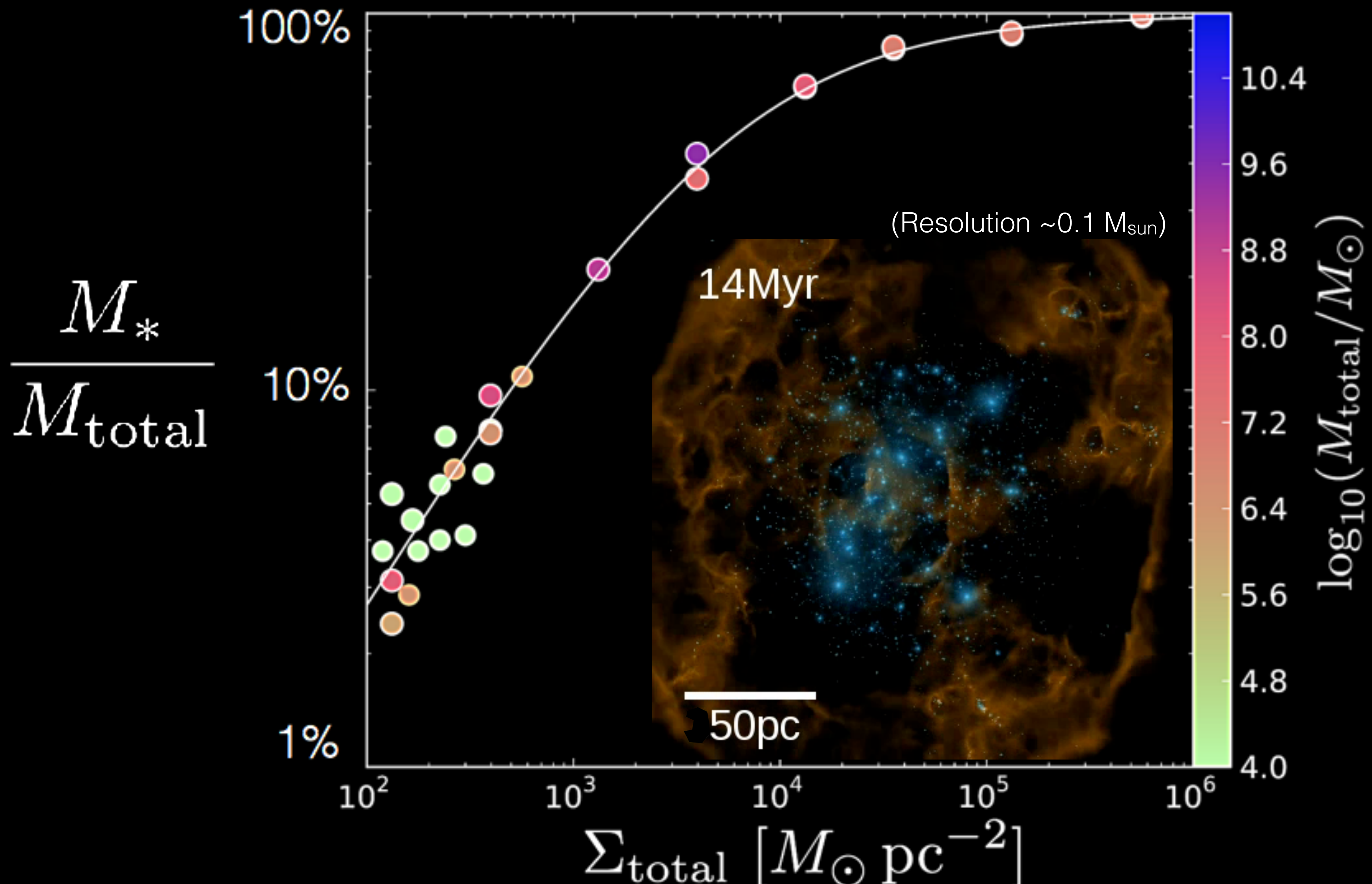
Explicit ISM/Feedback



Star Clusters & GMCs: Radiation+O/B Winds Destroy Clouds

FEEDBACK VS. GRAVITY

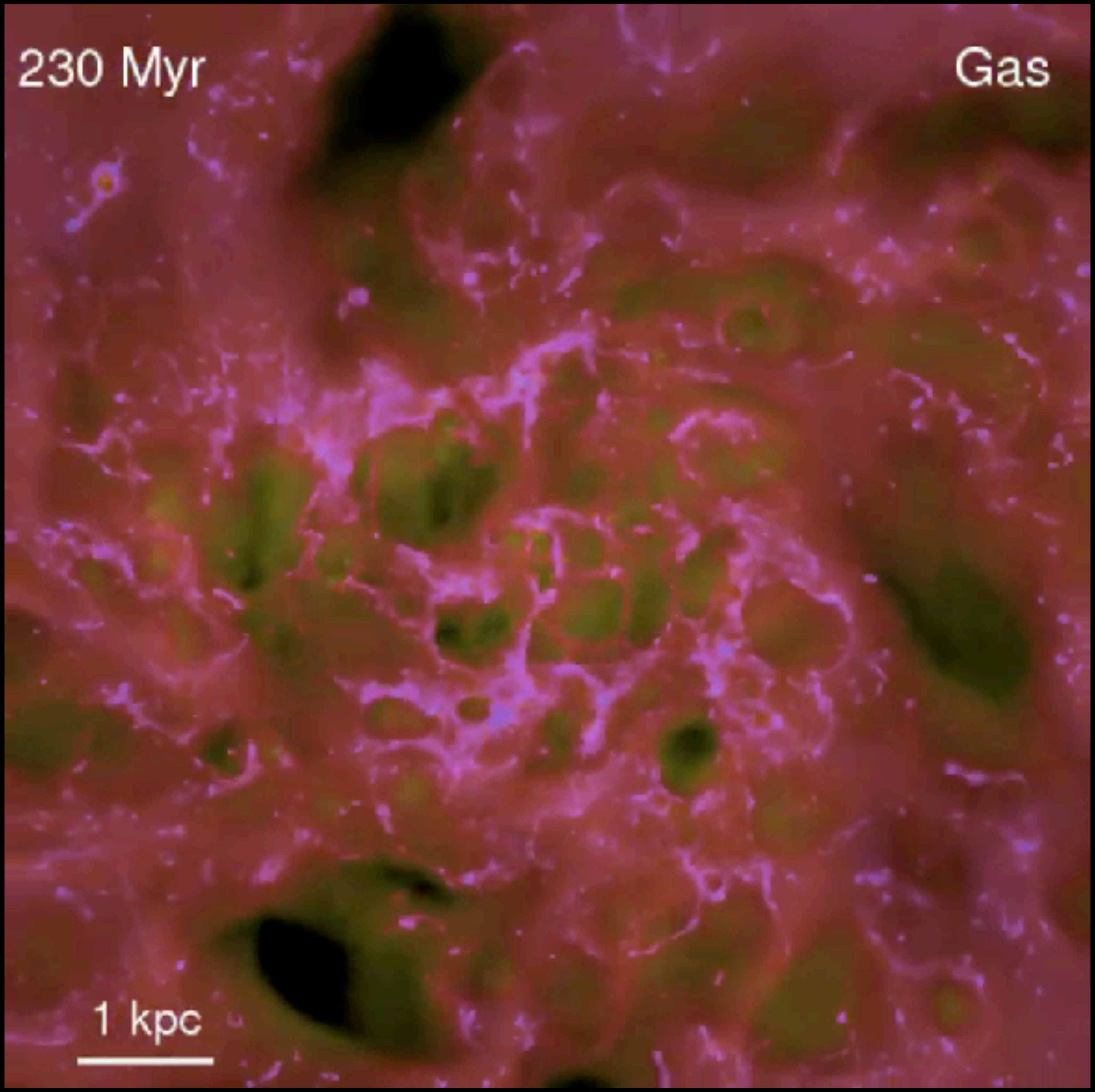
Mike Grudic (arXiv: 1612.05635)



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

Building Up to Galaxy Scales

The FIRE (Feedback In Realistic Environments) Project



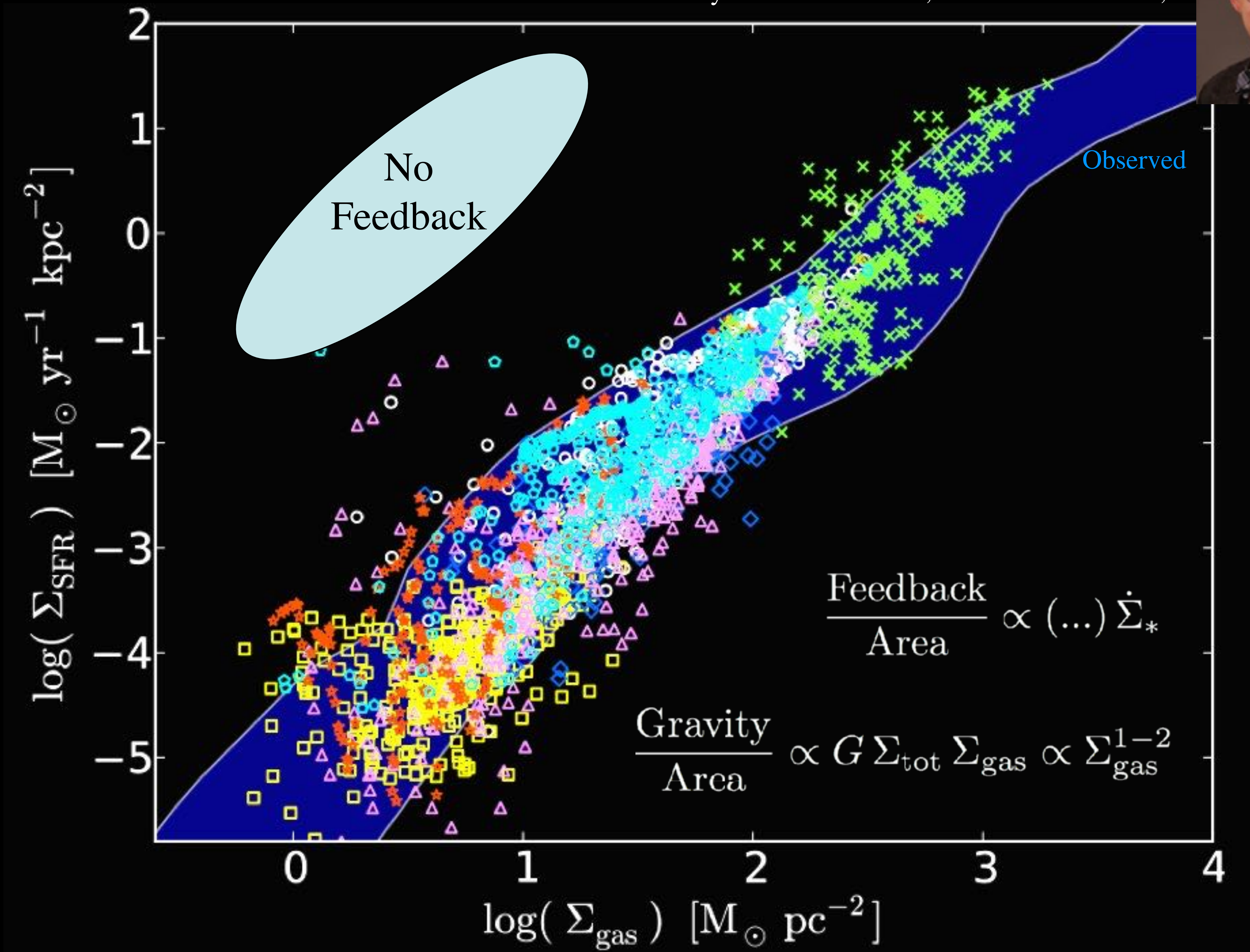
- DM = collisionless, non-relativistic, gravity-only fluid (or your preferred idea…)
- Resolution ~pc
  Cooling & Chemistry ~10 - 10^{10} K
- **<u>Feedback:</u>**
  - SNe (II & Ia)
  - Stellar Winds (O/B & AGB)
  - Photoionization (HII regions) & Photo-electric (dust)
  - Radiation Pressure (IR & UV)
  - now with… (Su+ 18)
    - Magnetic fields
    - Anisotropic conduction & viscosity
    - Cosmic rays

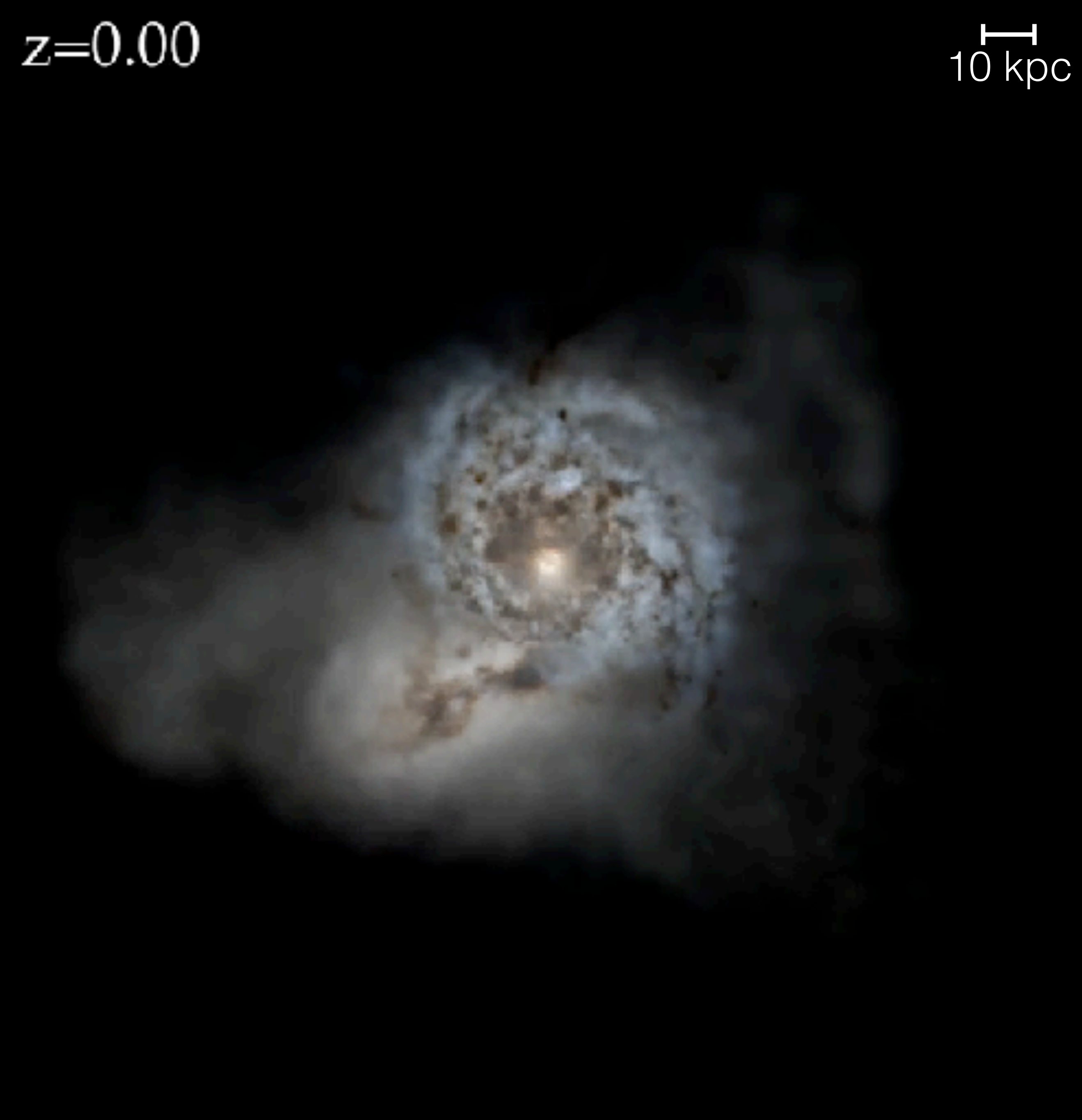
Yellow: hot (>10^6 K) Pink: warm (ionized, ~10^4K) Blue: cold (neutral <10-8000 K)

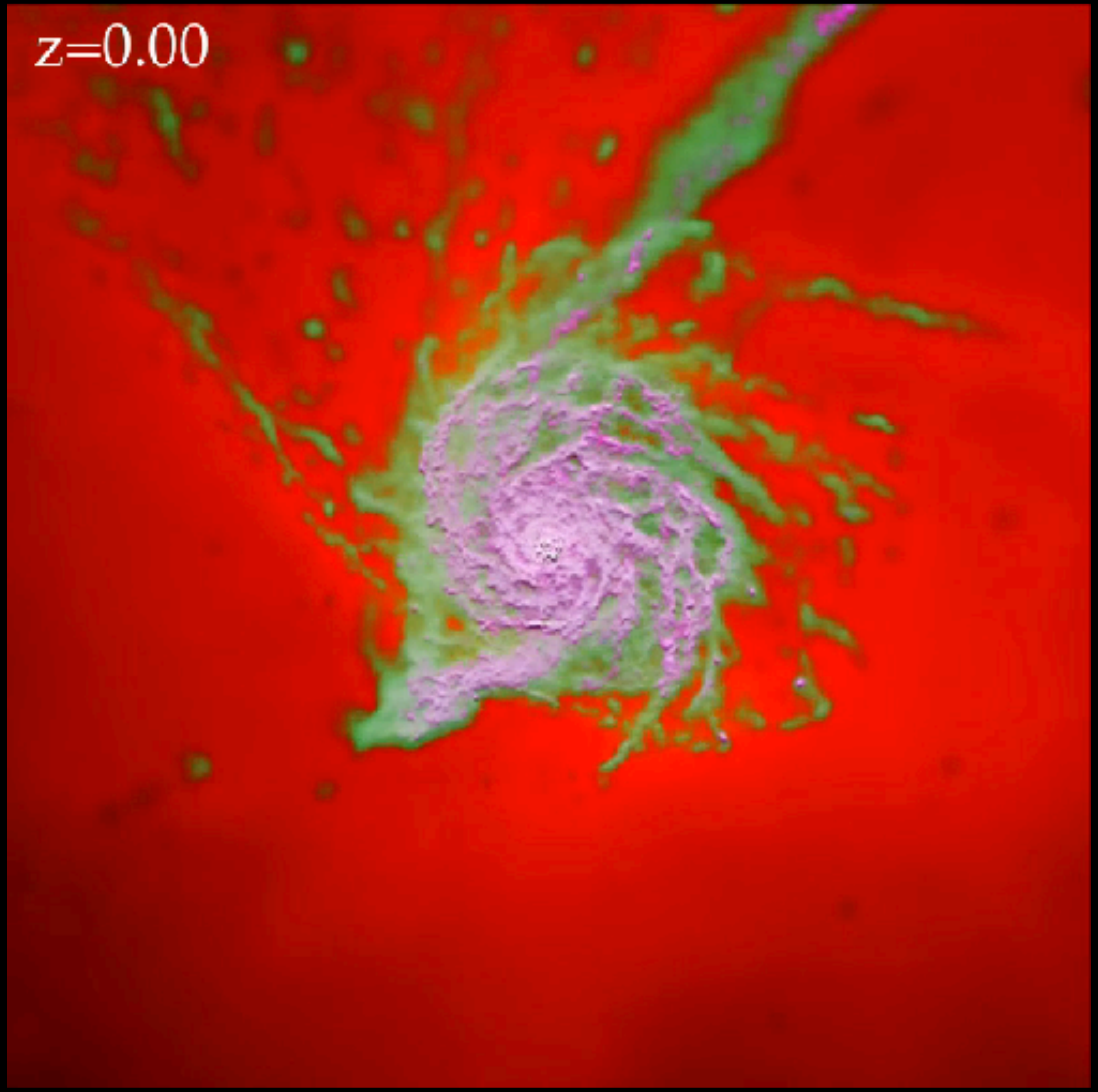
KS Law Emerges Naturally

FEEDBACK VS. GRAVITY

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







Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

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

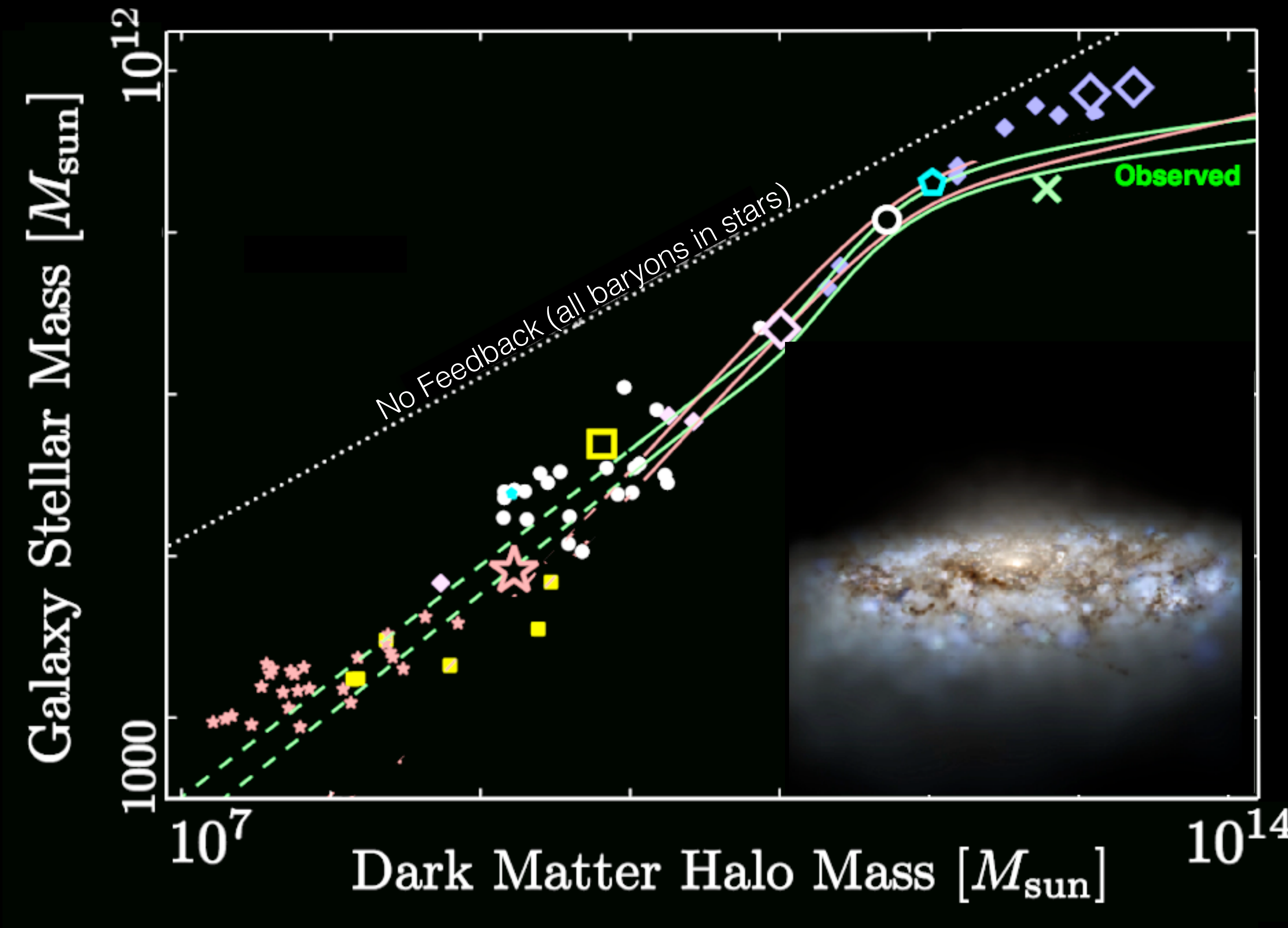
Green: warm (ionized)

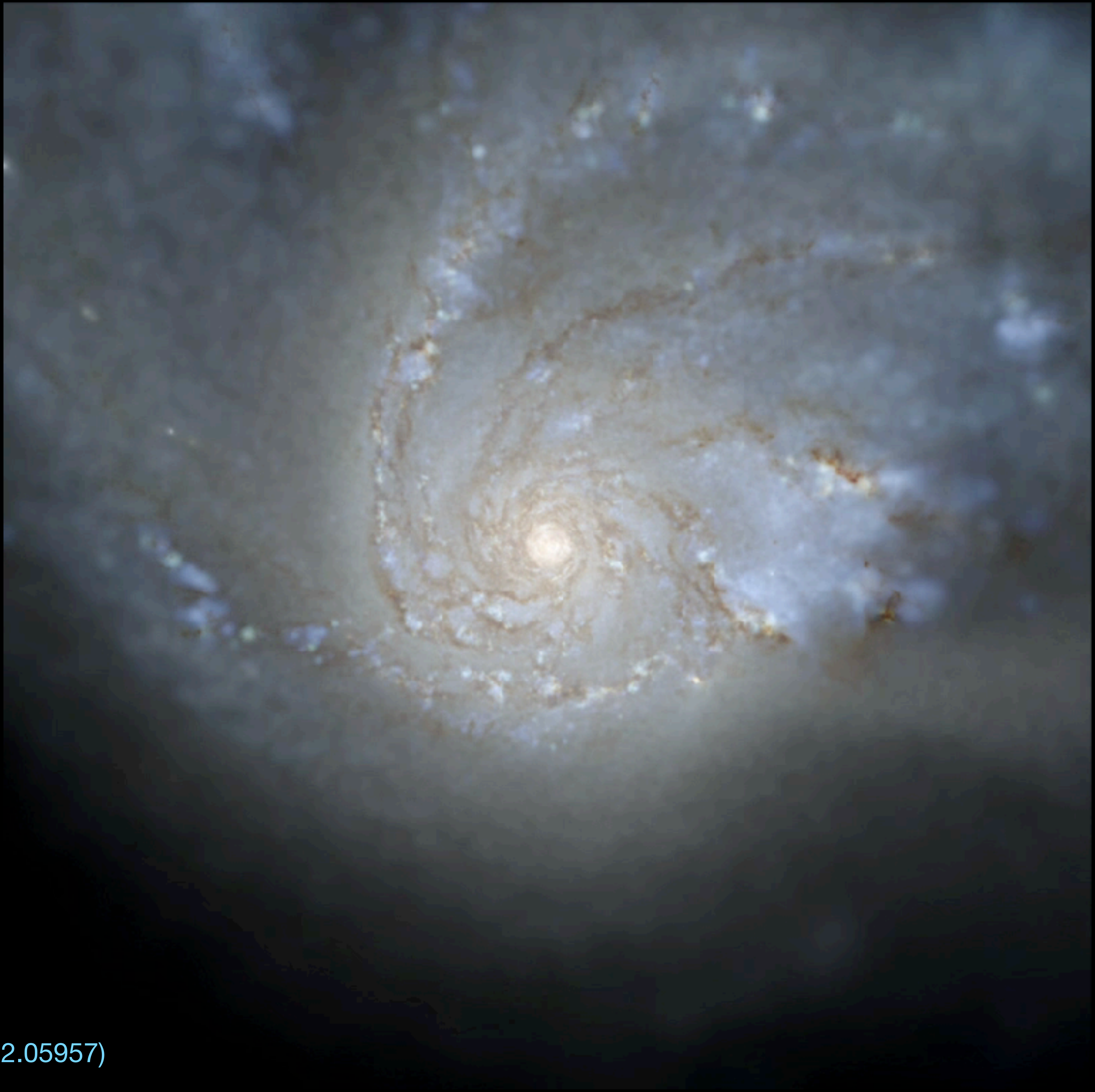
Red: hot $(> 10^6\ K)$

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,
arXiv:1702.06148)



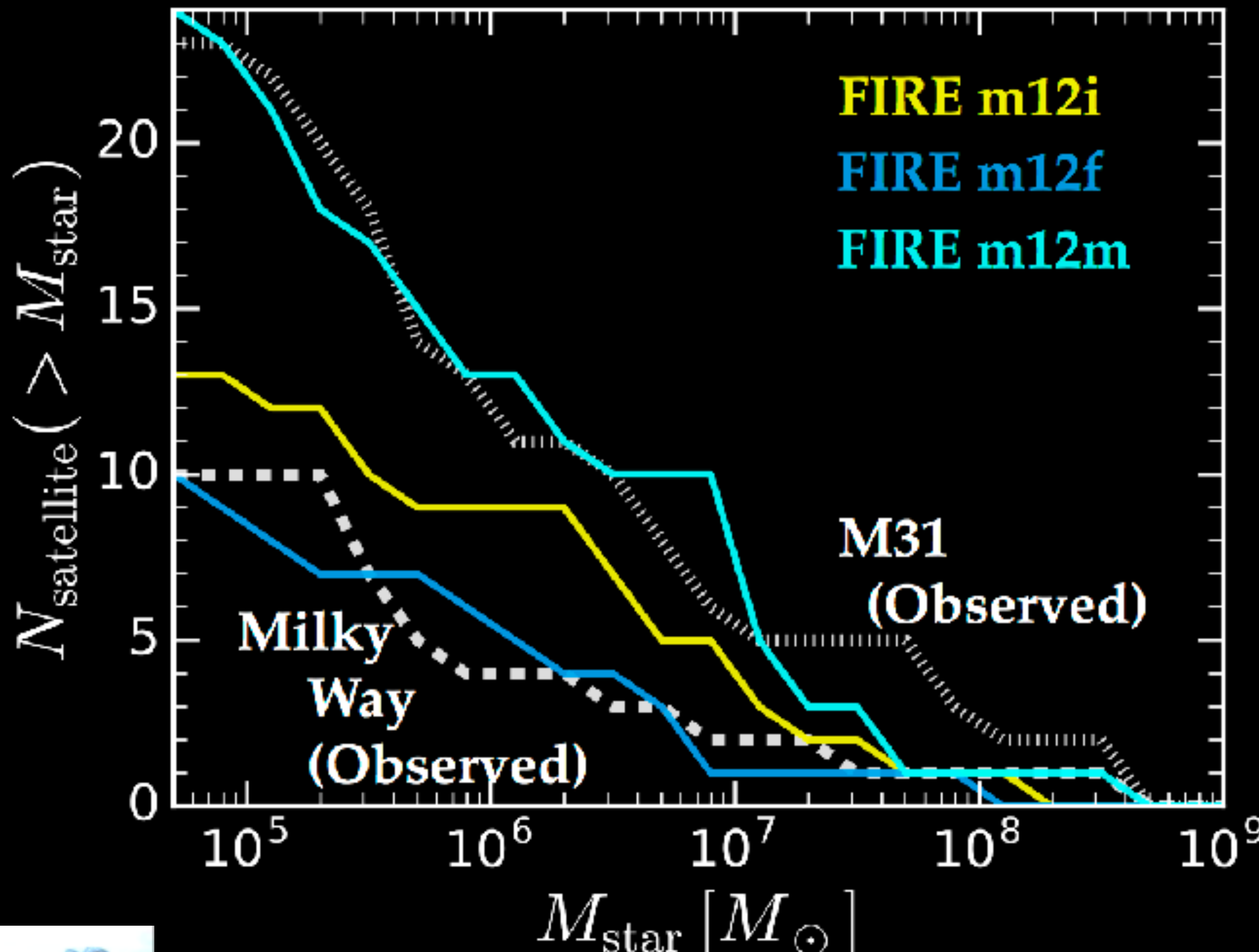


(A. Wetzel+1602.05957)

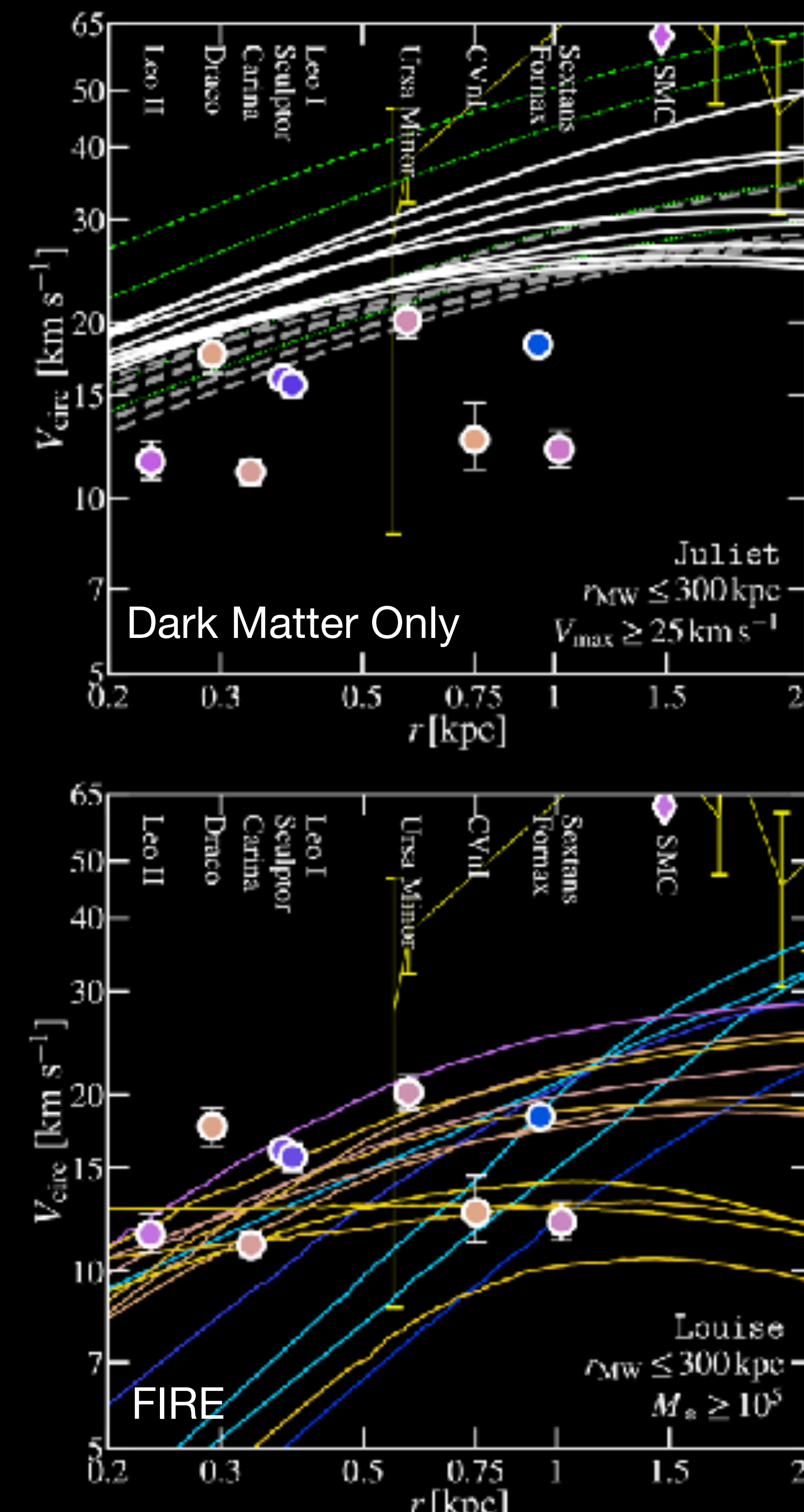
Failures No More

“MISSING SATELLITES” & “TOO BIG TO FAIL”

(now with ~14 halos
with resolution ~1000 M_{sun})

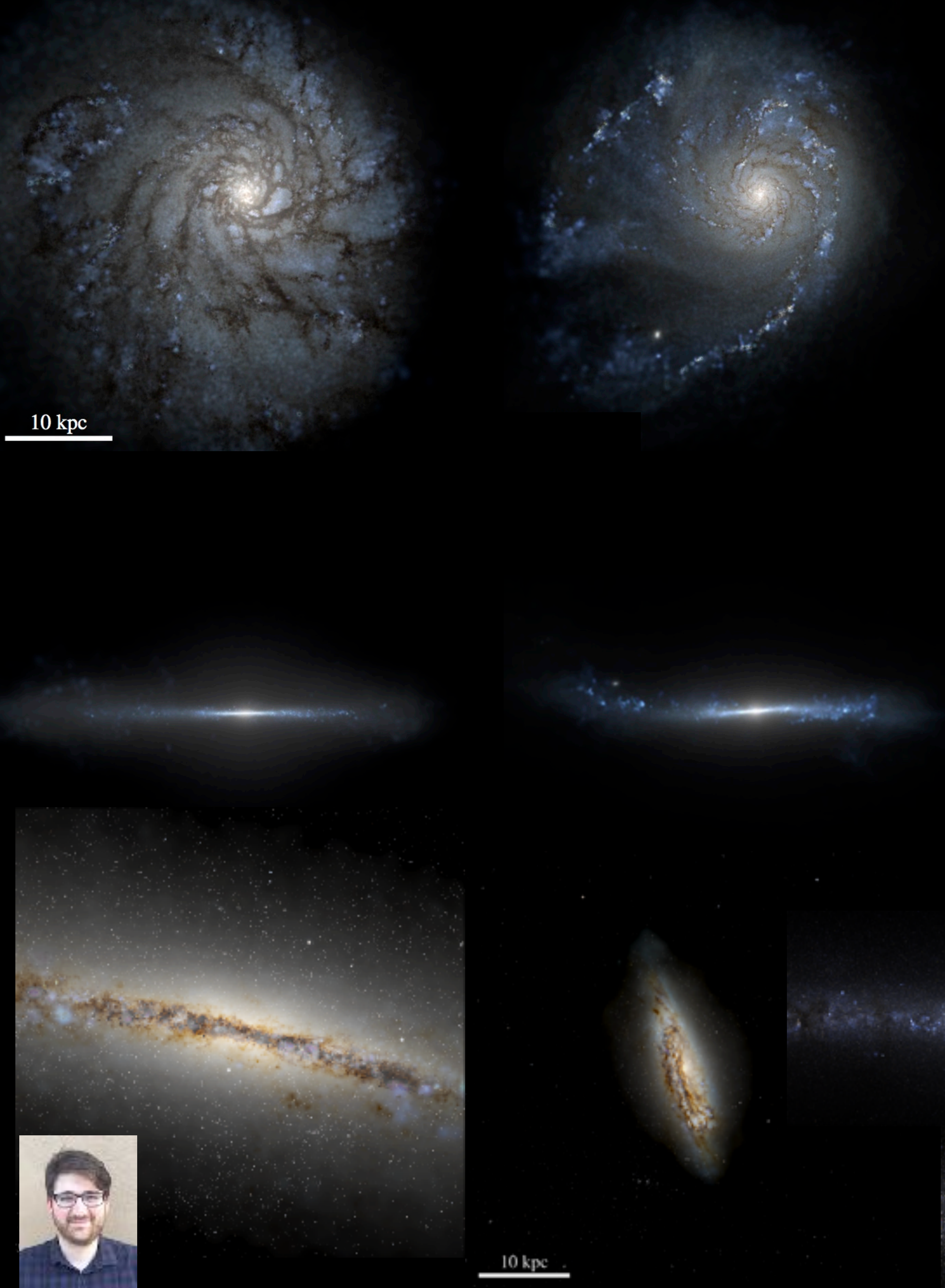


Too Big To Fail




Shea Garrison-Kimmel+ (arXiv:1806.04143)
(also Escala+ in prep)

Thin Disks Emerge Naturally

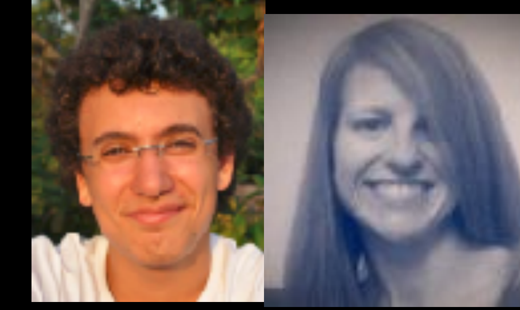


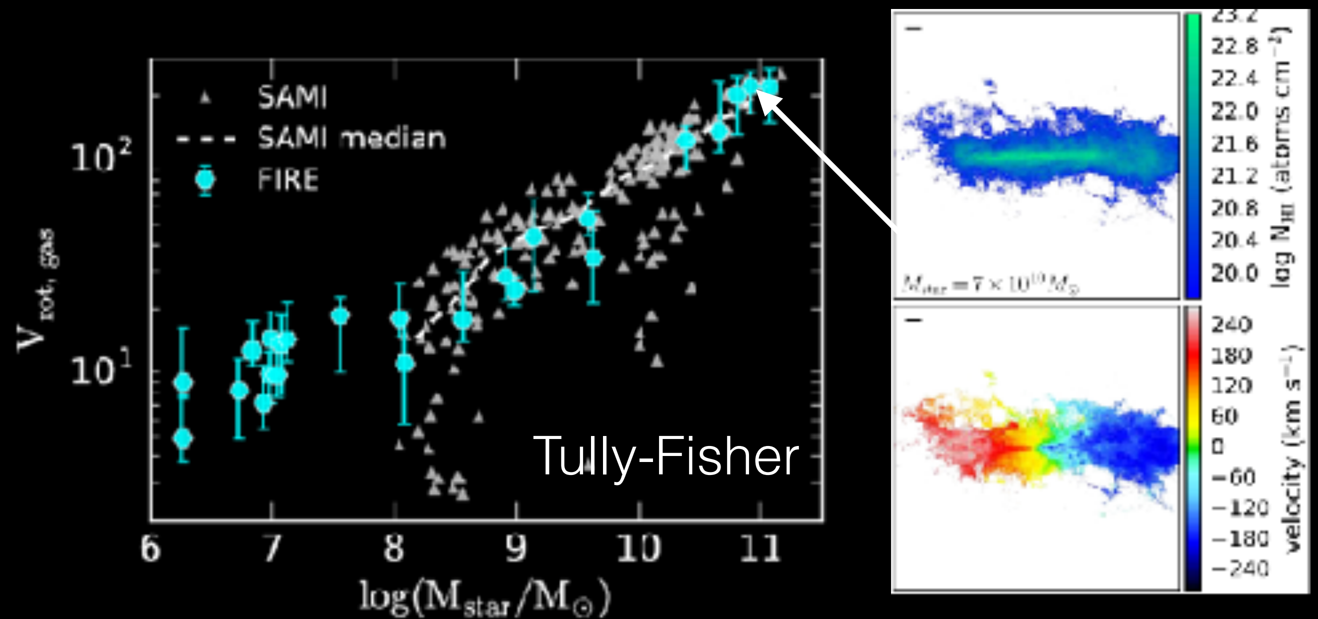
Garrison-Kimmel+ 1712.03966

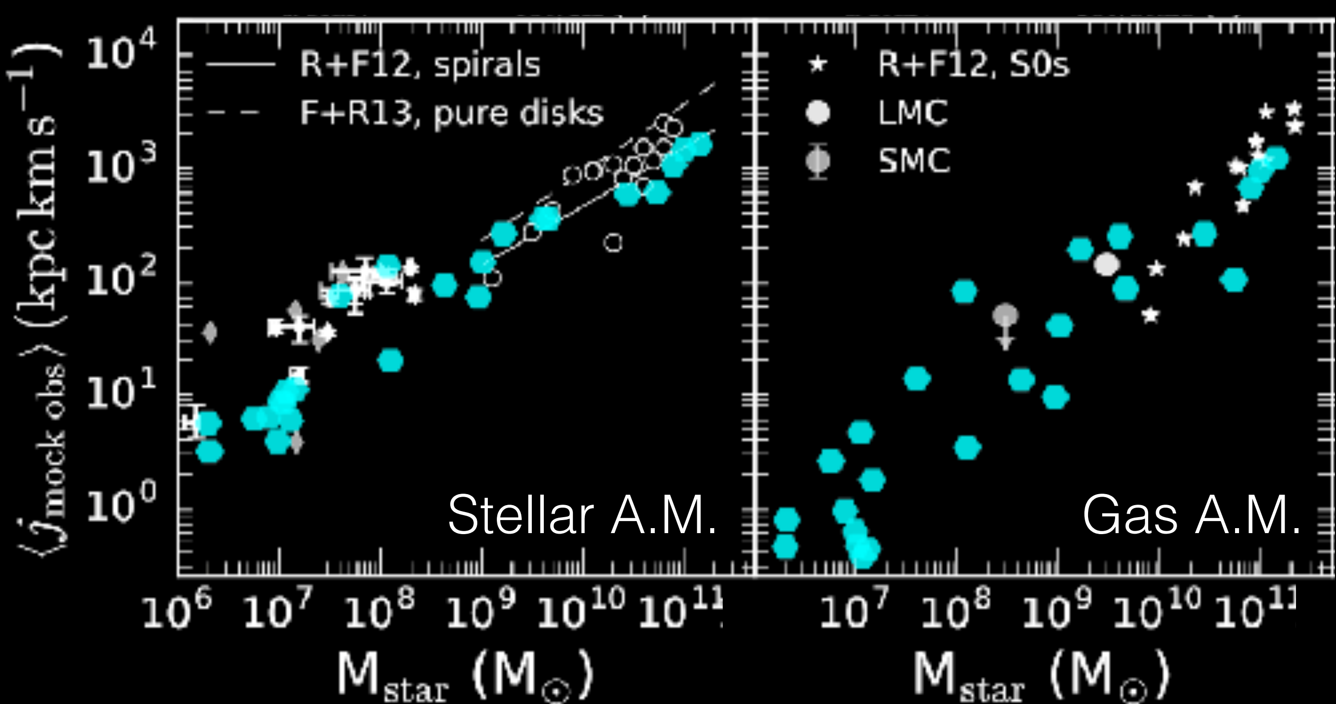
Angular Momentum of Gas+Stars

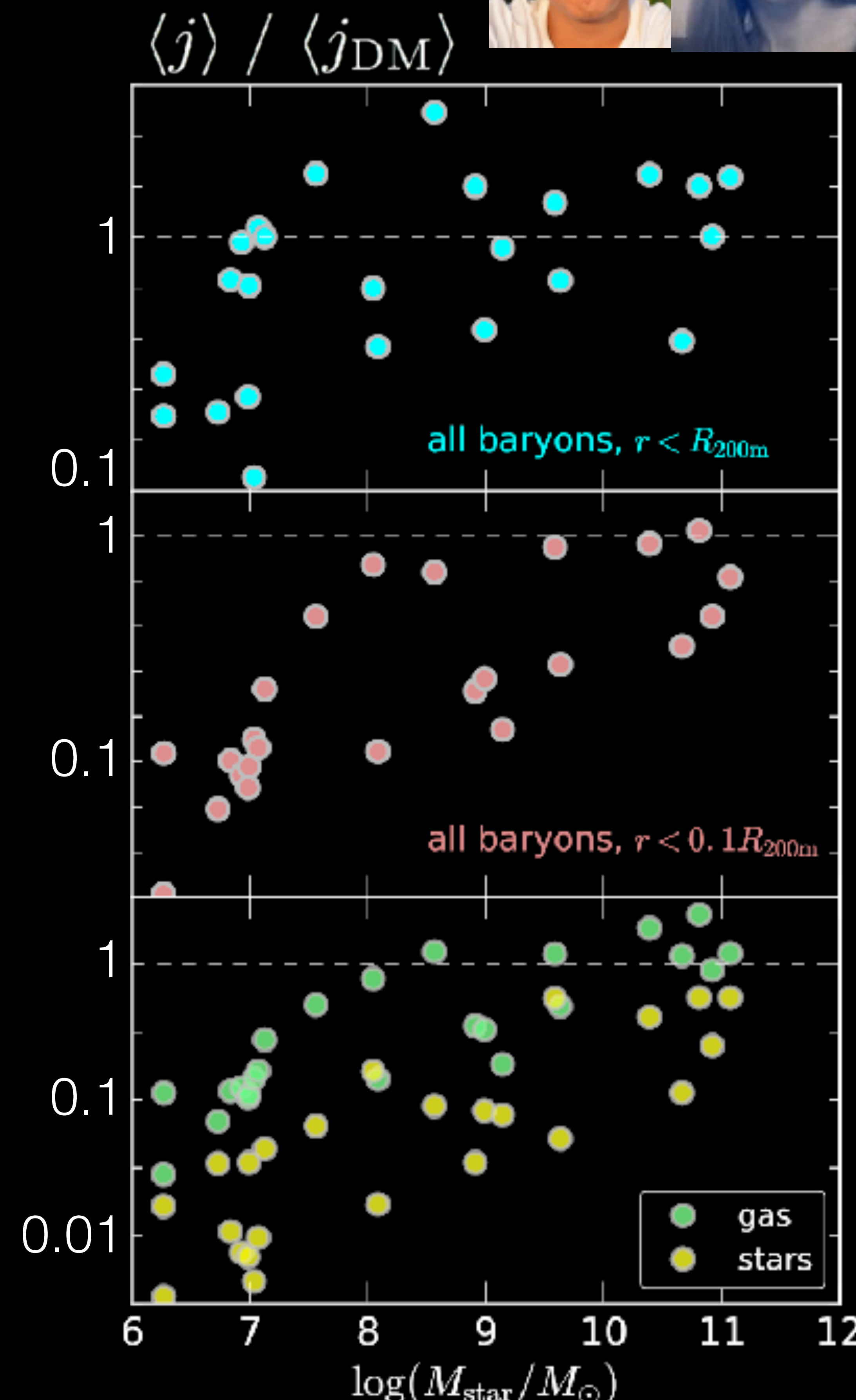
ROTATION BUILDS UP OVER TIME

Kareem El-Badry
(arXiv:1705.10321)
(also Weeler+ 17)





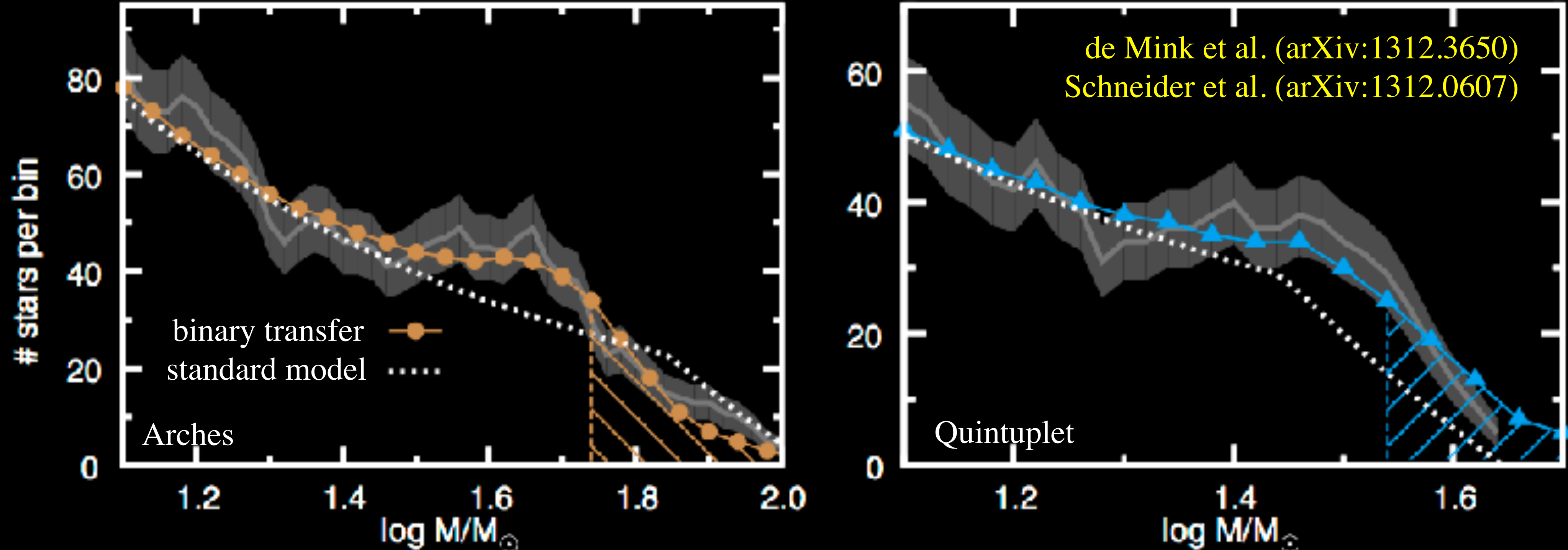




- Dwarfs: Thick/irregular [clumpy + bursty]

Some Remaining Uncertainties

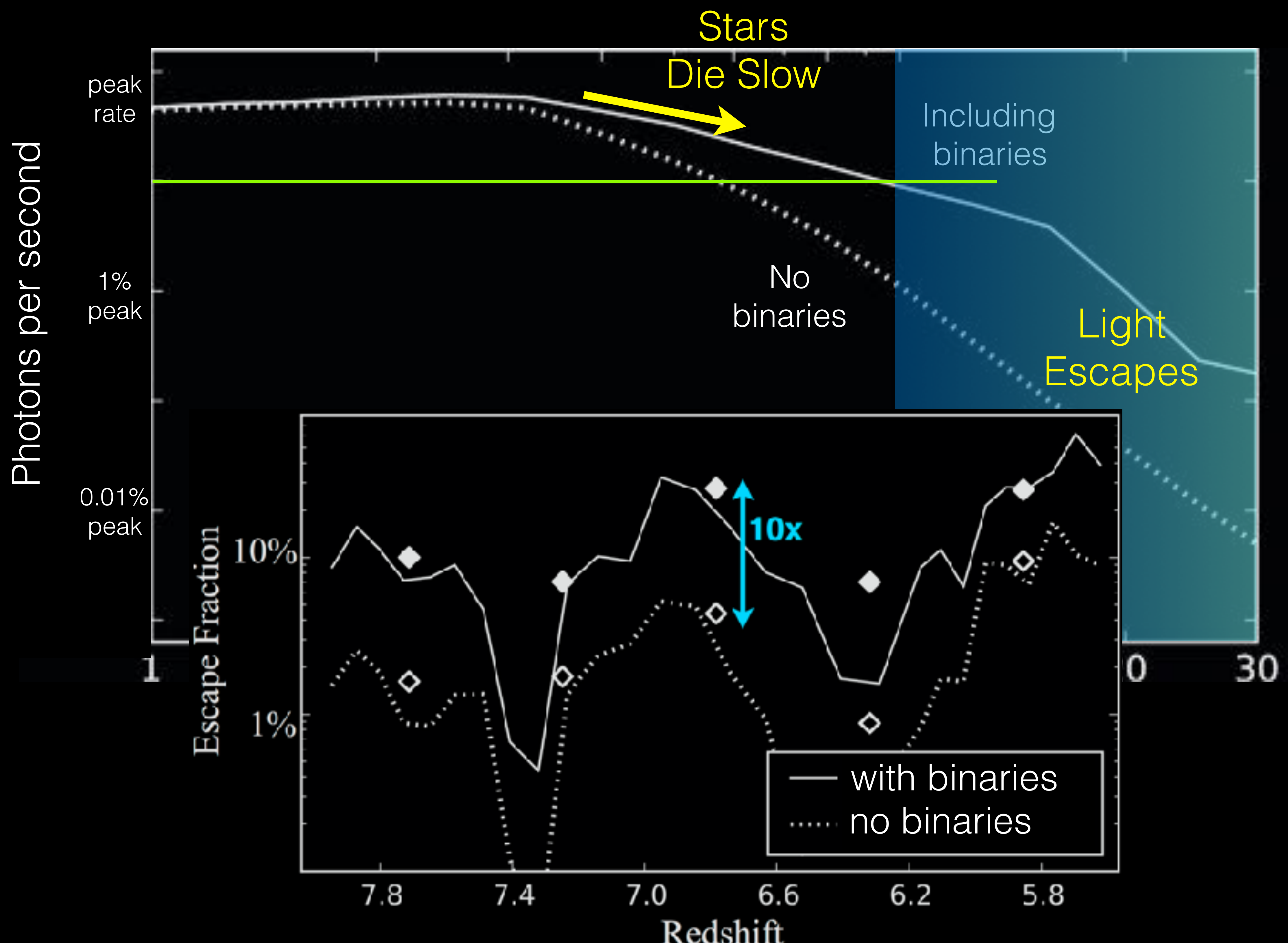
Binary Stars:
"FEEDING"
MASSIVE STARS



Binarity & Rotation:

VERY IMPORTANT FOR THINGS THAT DEPEND ON MOST MASSIVE STARS

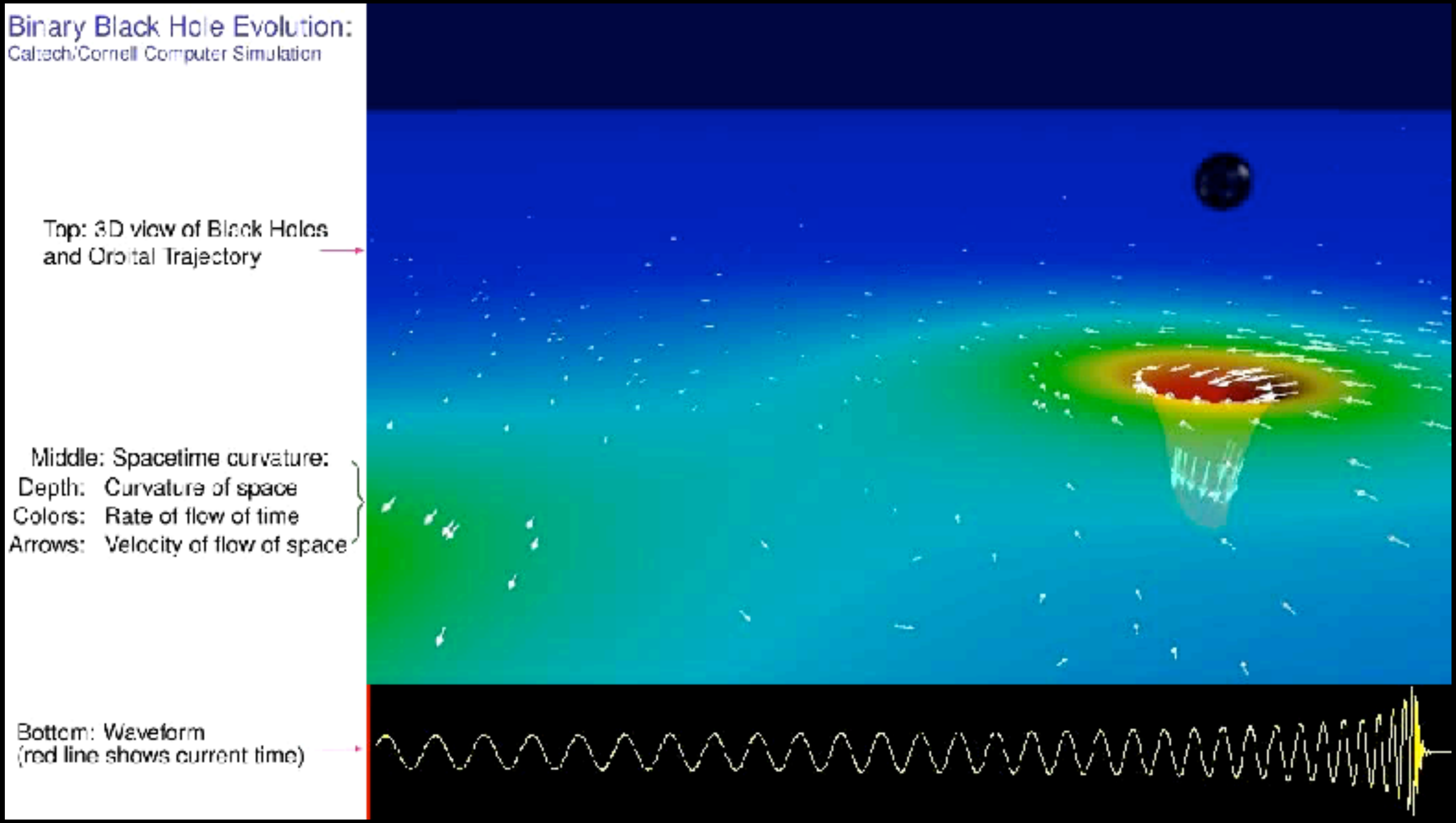
Xiangcheng Ma
(arXiv:1601.07559)



Binarity & Rotation:

VERY IMPORTANT FOR THINGS THAT DEPEND ON MOST MASSIVE STARS

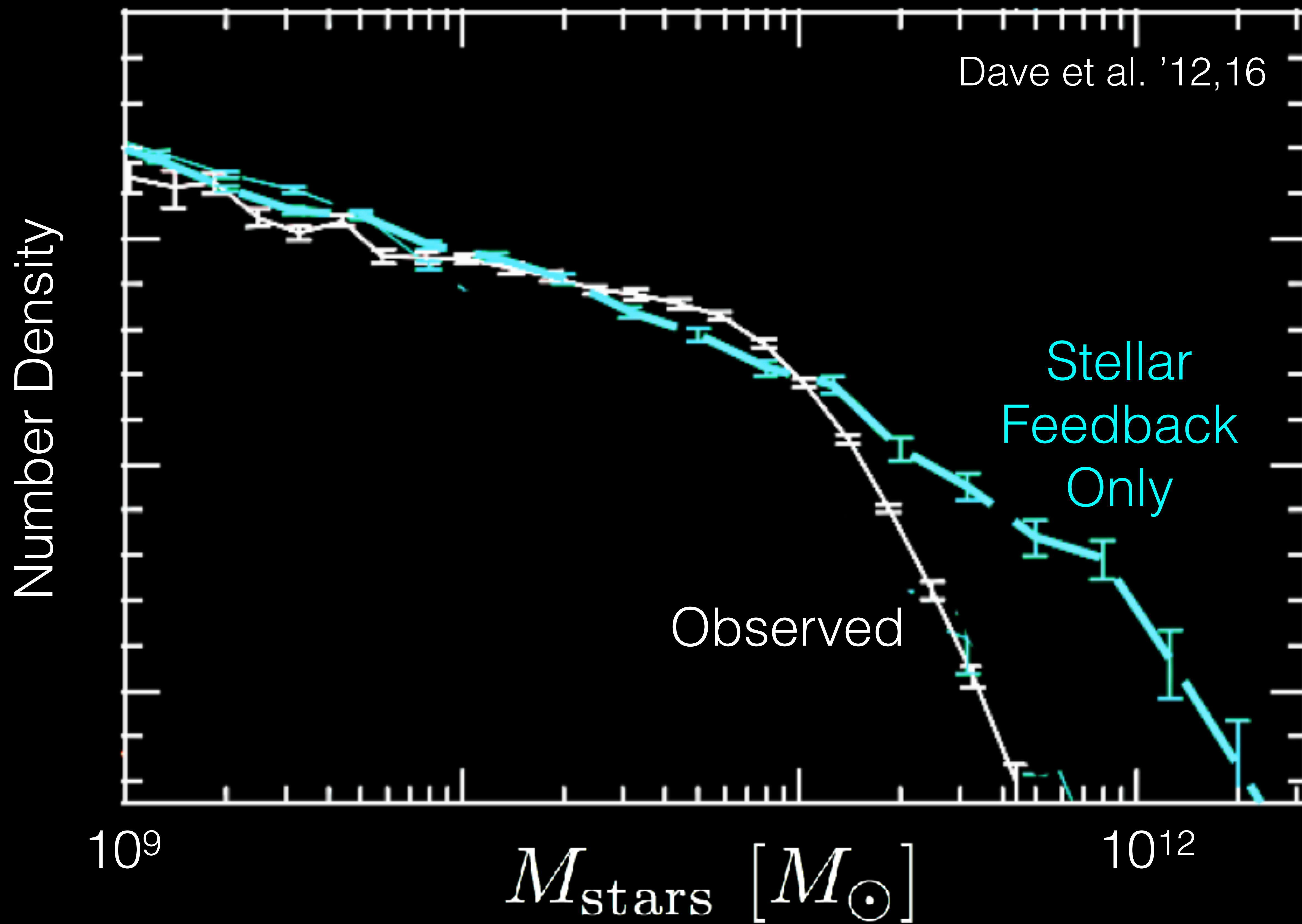
Astrid Lamberts
(1605.08783, 1801.03099)



SXS Collaboration

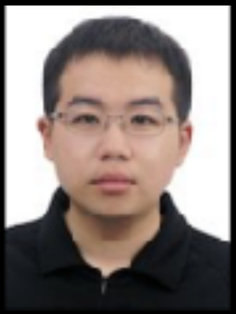
Need Additional Physics To *Turn Off* Star Formation

STELLAR FEEDBACK + COOLING + HYDRO = COOLING FLOW PROBLEM



Progress: Physics Beyond Those Above Clearly Needed

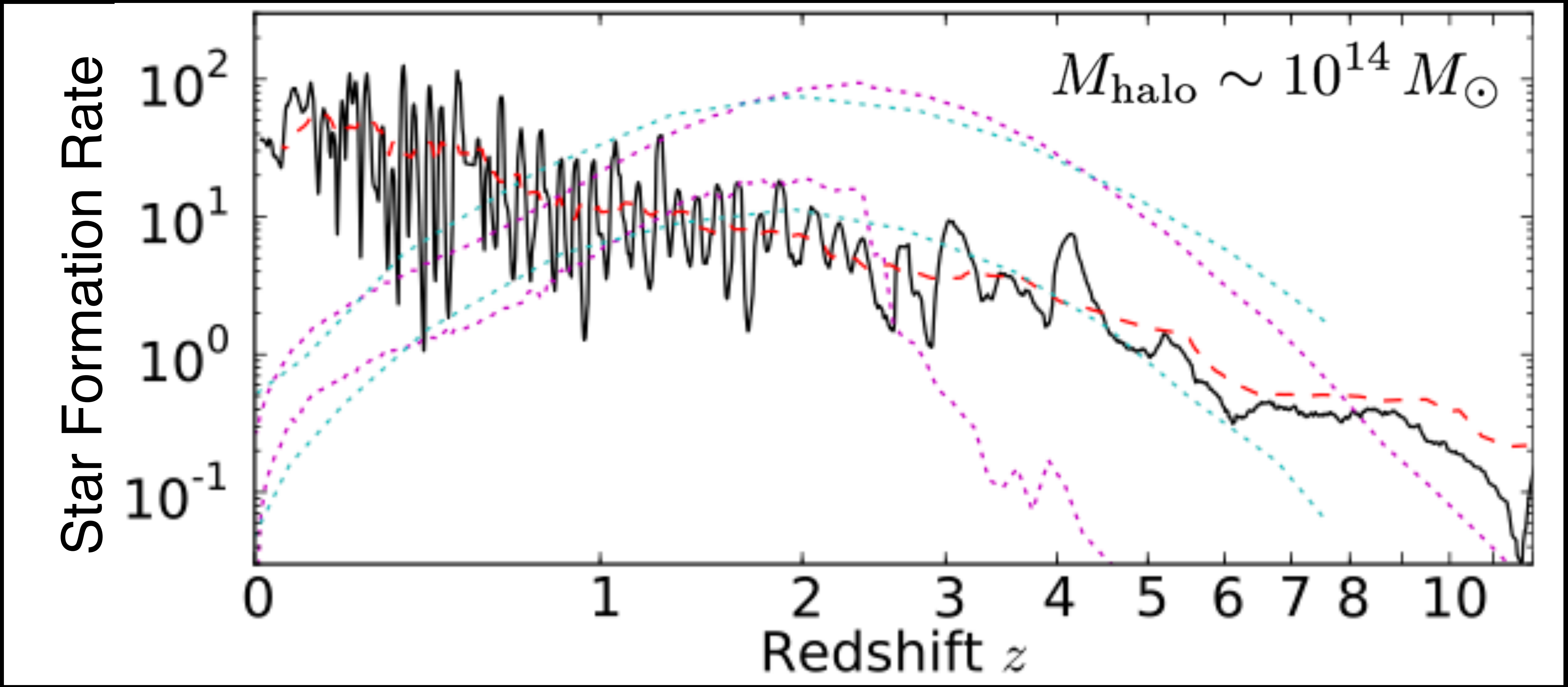
STELLAR FEEDBACK + COOLING + HYDRO = COOLING FLOW PROBLEM



Kung-Yi Su (prep)
+ many others

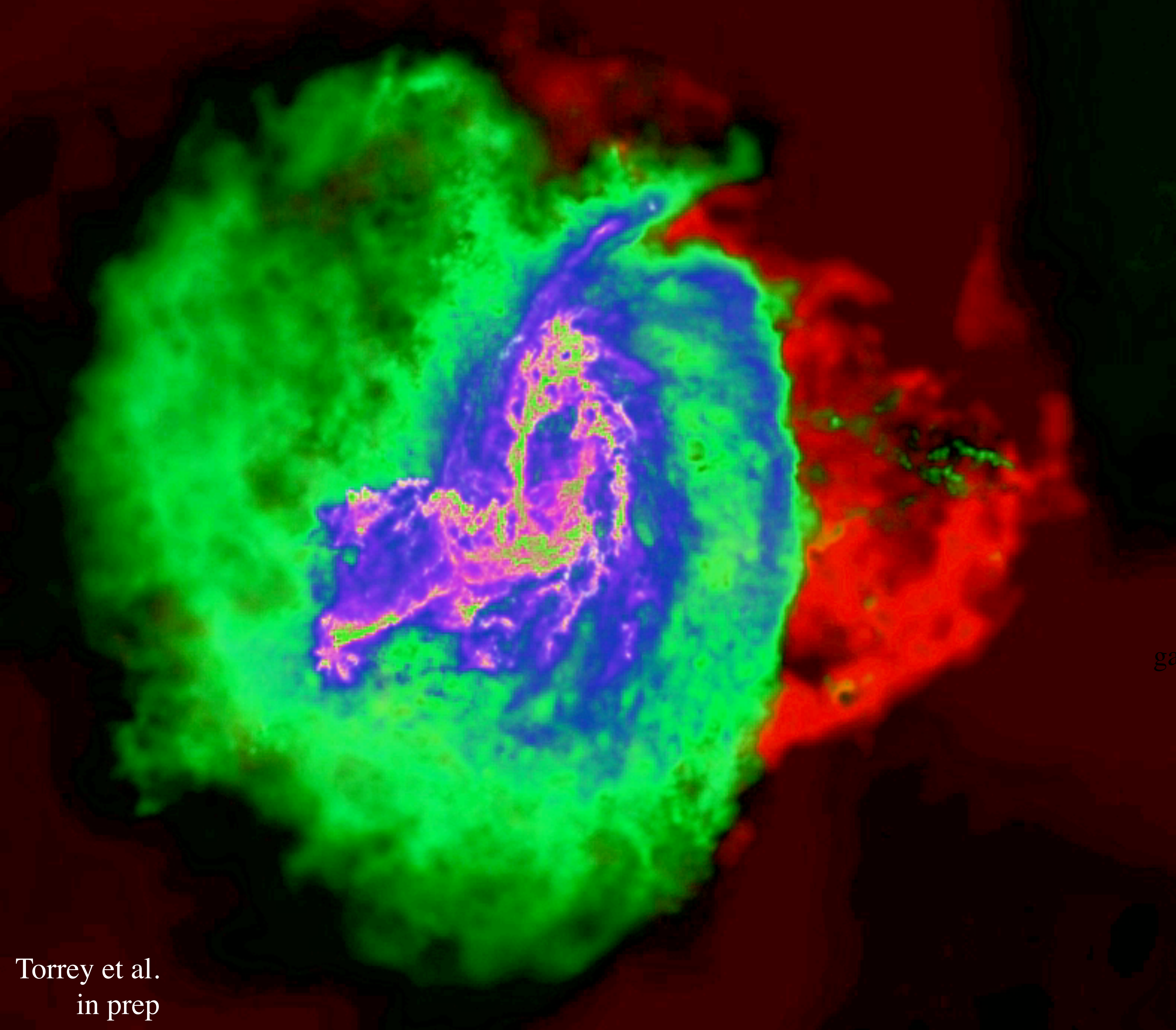
- Virial shocks
- "Morphological Quenching"
- AGB Winds & SNe Ia
- Magnetic Fields, Conduction

Not Enough



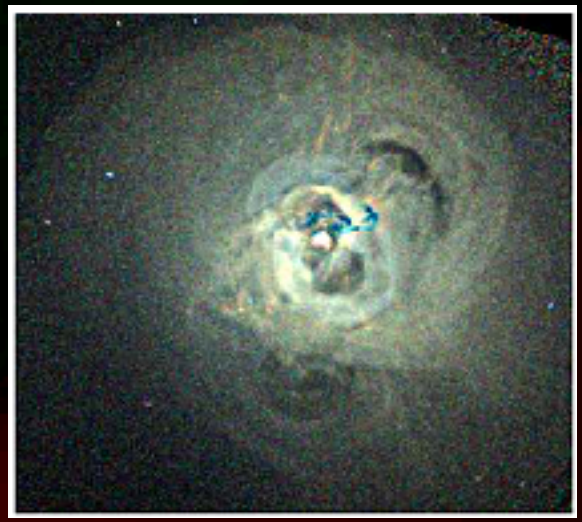
AGN *can* do it: “Maintenance” (Jets) + (?) “Transition” (Winds)

ALSO RULING *OUT* SOME CHANNELS (CAN’T OVERHEAT/BLOW OUT CGM)



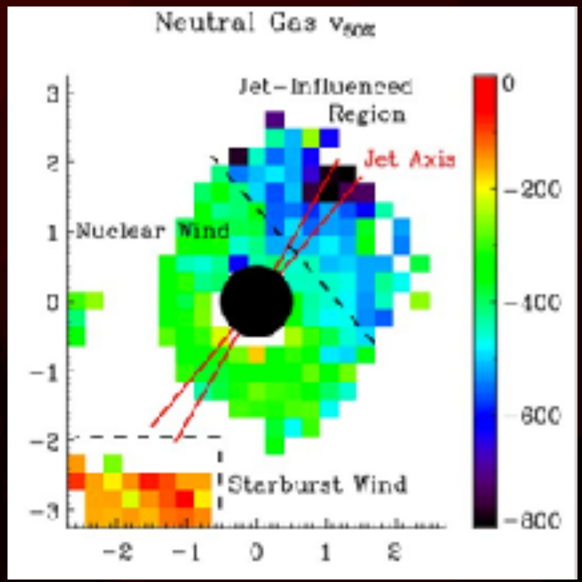
Torrey et al.
in prep

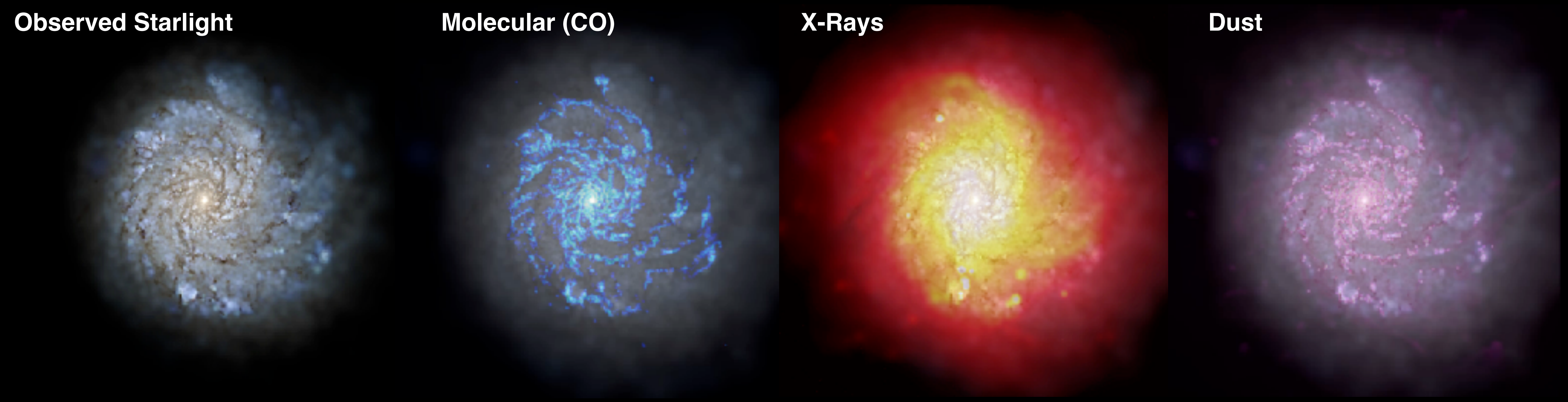
Perseus
(+other massive clusters)



gas at >1000 km/s:

Mrk 231
(+other warm ULIRGs)





- In the last decade: *galaxy & star formation* have seen tremendous progress
  - How does "feedback" work? Where is the evidence? What does it do? Why is star formation inefficient? Where do thin disks come from? What drives scaling relations? Where are the baryons? What's universal?

- *"Null hypothesis"* (CDM + *known* stellar processes) resolves most of the classic "CDM problems"
  - "Missing satellites"/"Cusp-core"/"Too Big to Fail"/"Angular Momentum Catastrophe"/"Over-merging"/ "Diversity/Rotation Curve Shapes"/"Baryonic Tully-Fisher (or Radial Acceleration)" *predicted* [no fine-tuning!]

  - Changing e.g. DM model, or stellar evolution, doesn't really improve match *Without violating stellar evolution constraints*, hard to differ at factor >~ 2

- Open: (1) "Over-cooling/quenching," (2) subtleties of massive stars on short spatial/time-scales
  - (1) Probably AGN, inputs/coupling physics remain uncertain (certainly *can* do it).
  - (2) Matters for ionizing photons, LIGO source pops, globular internal abundances, NS-NS + Ia prompt rates

- Ad: Mock Gaia Catalogues + Galaxy Snapshots, public *this week* (Robyn Sanderson+)
  - Multiple galaxies with ~100M resolved stars