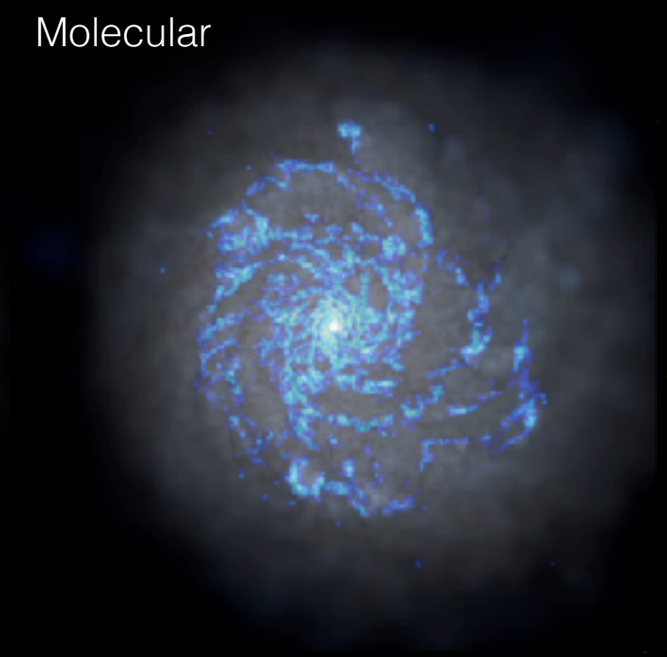
Universal Star Formation Laws

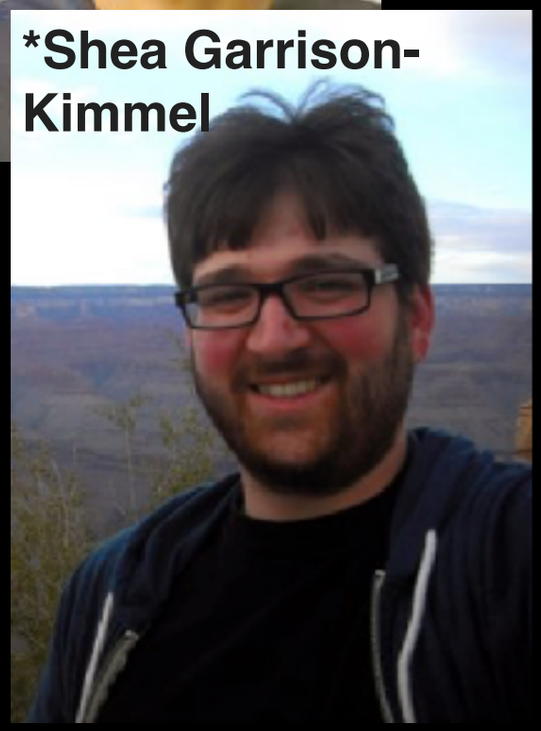


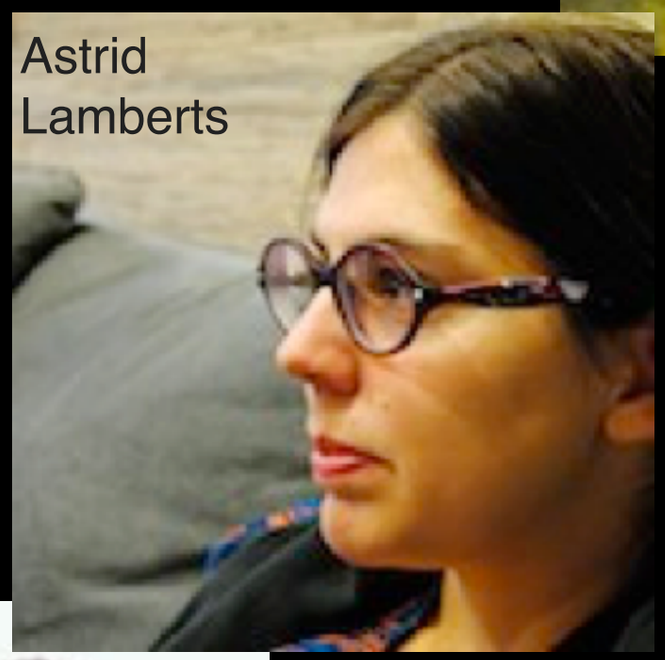
Philip F. Hopkins with
Xiangcheng Ma, David Guszejnov, Matt Orr, Mike Grudic,
Shea Garrison-Kimmel, Robyn Sanderson, Coral Wheeler, & the FIRE Team

Caltech

Postdocs

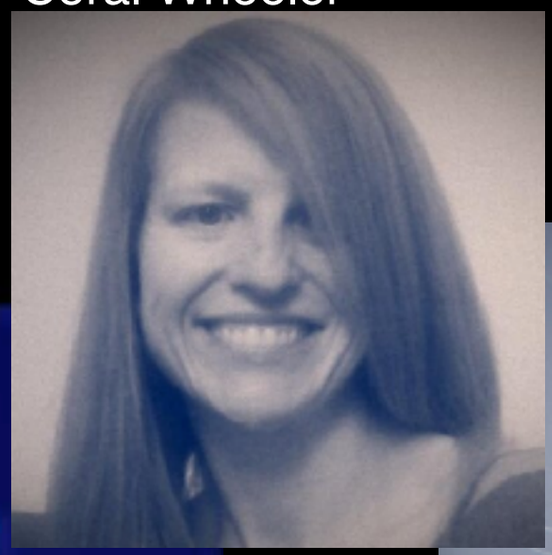
Anne
Medling





*Robyn
Sanderson

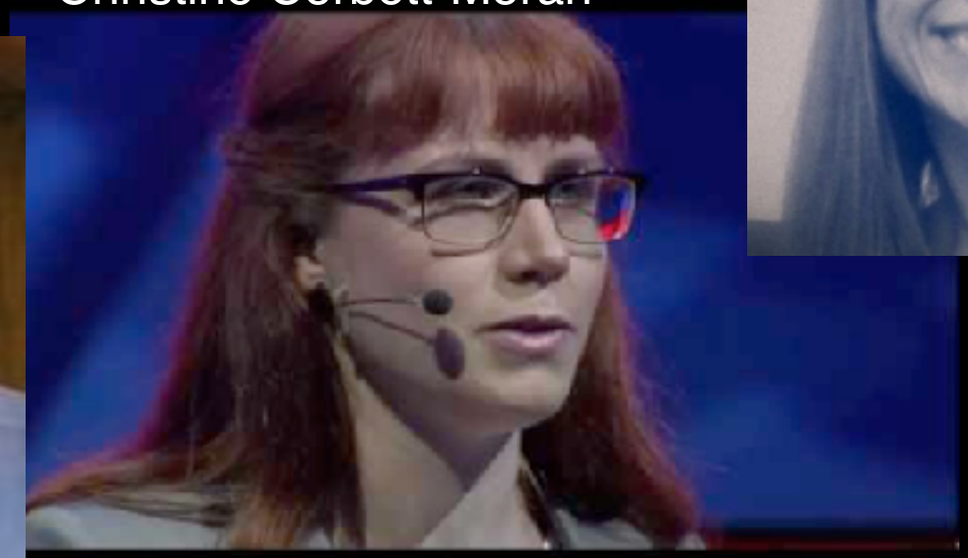
Coral Wheeler



Lina
Necib

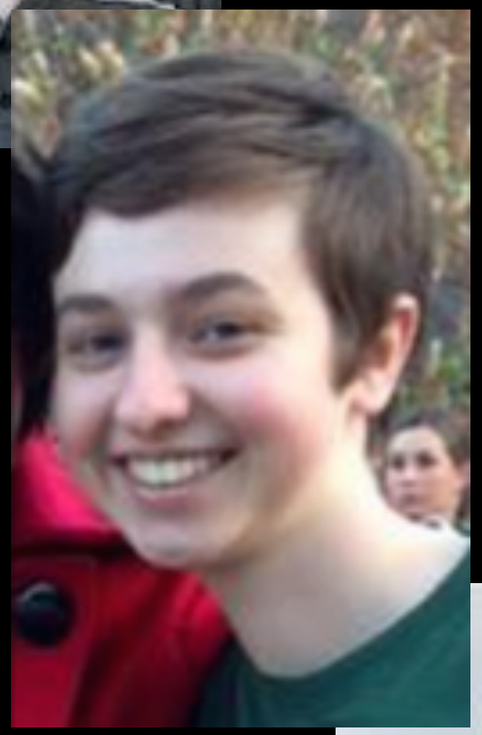
Ji-Hoon
Kim

Christine Corbett-Moran

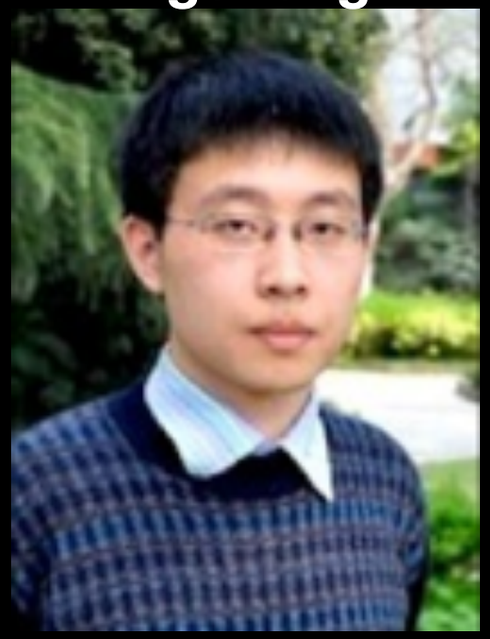


Grad Students

*David Guszejnov



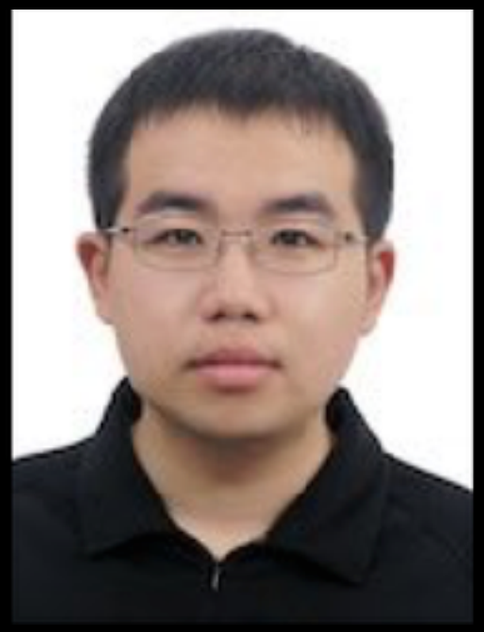
Denise Schmitz



*Xiangcheng Ma

Antonija Oklopcic

Matt Orr



Kung-Yi Su

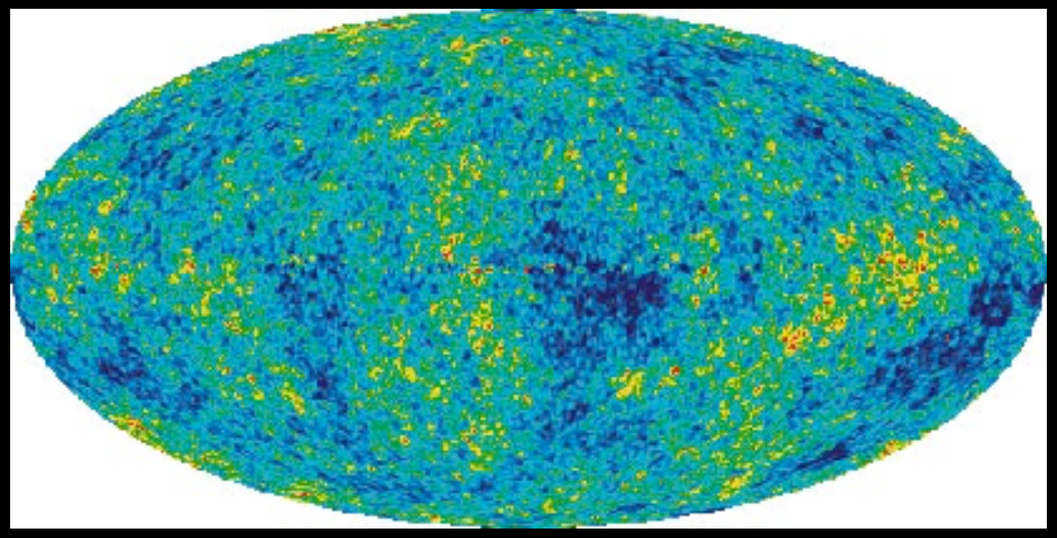
Mike Grudic

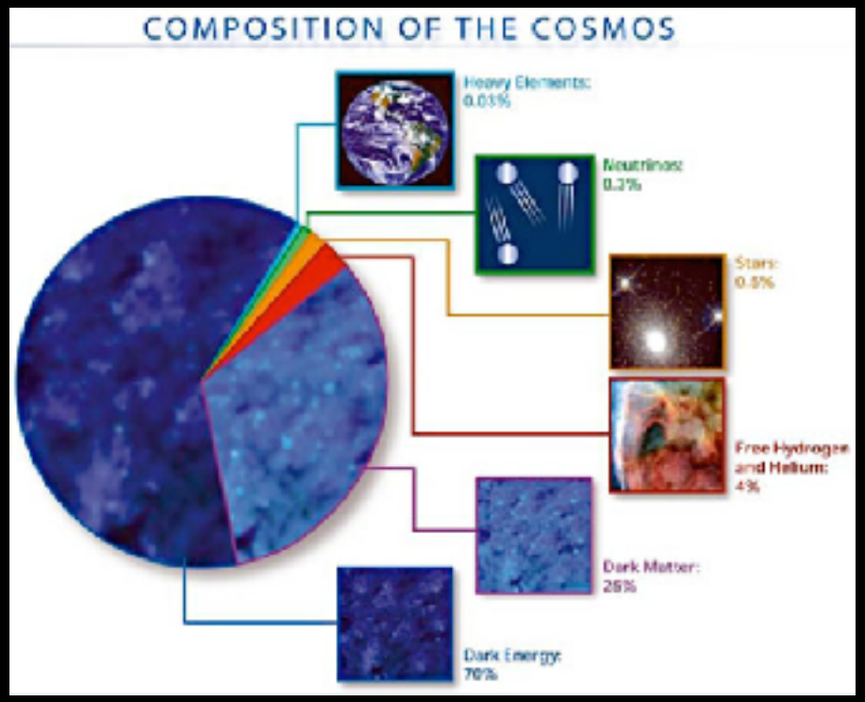
Ivanna Escala

Hannalore Gerling-Dunsmore

The Big Question:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?





z~1090
(t~400,000 yr)

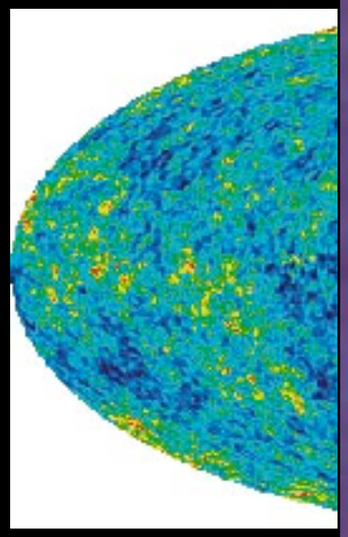
?

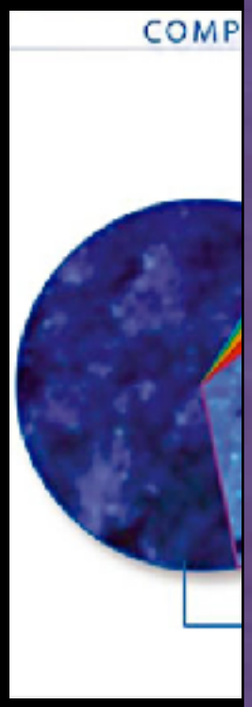
Today

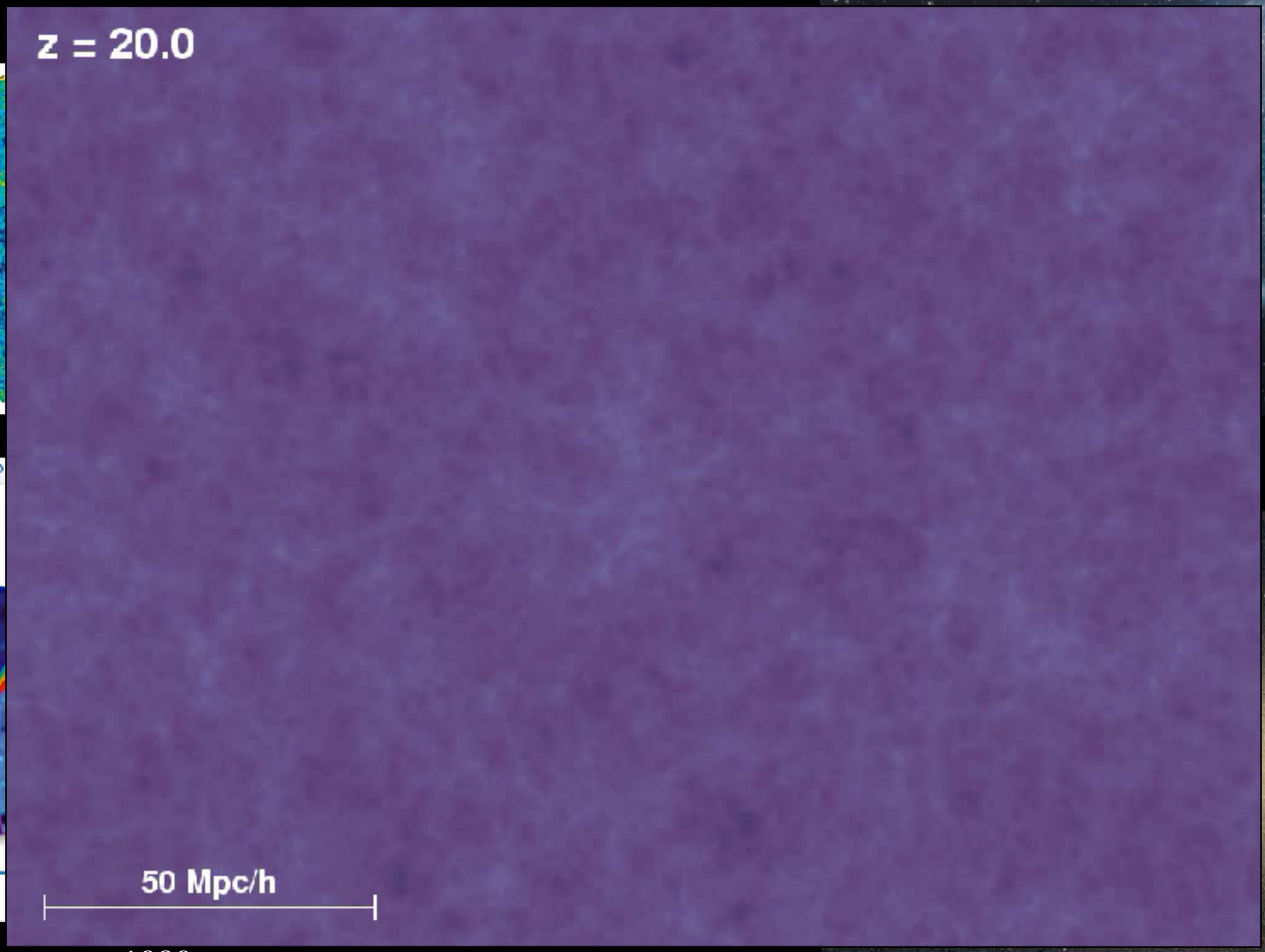
The Big Question:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?

Today







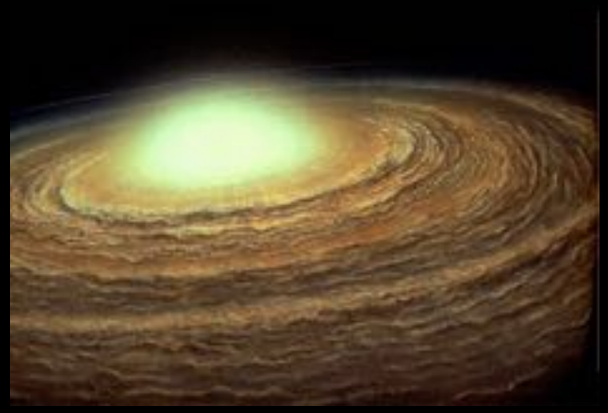
z~1090
(t~400,000 yr)

Our work:

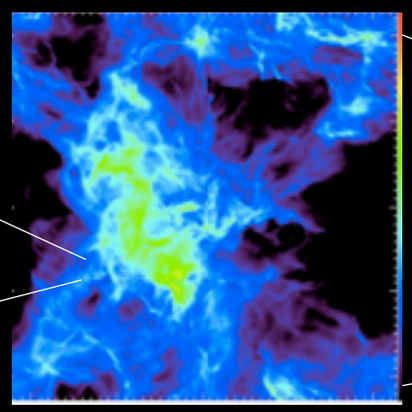
~10^{10} pc
Hubble volume

~10^{7}-10^{8} pc
Clusters, Large-scale structure

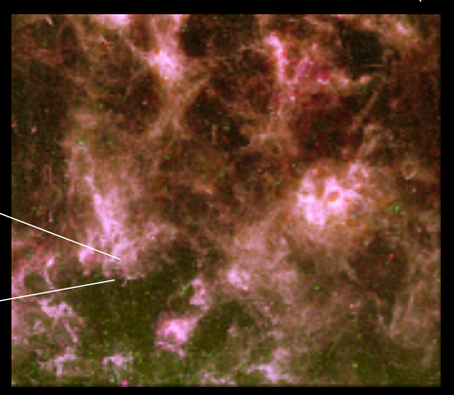
~10^{4-5} pc
Galaxy



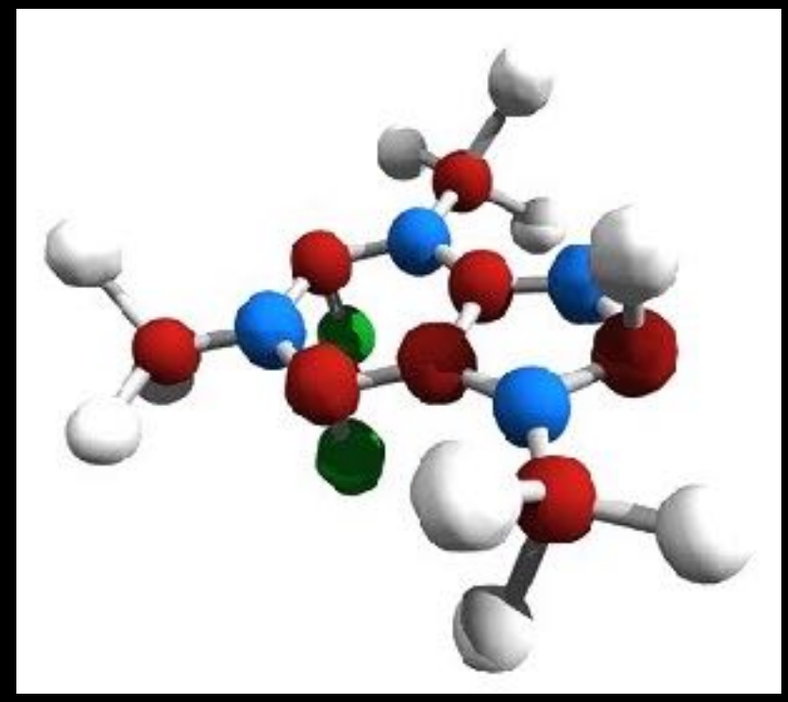
~10^{-5} pc
Stars, protostellar disks



~10^{-2}-10^{0} pc
Cores, clusters,
Supernovae blastwaves



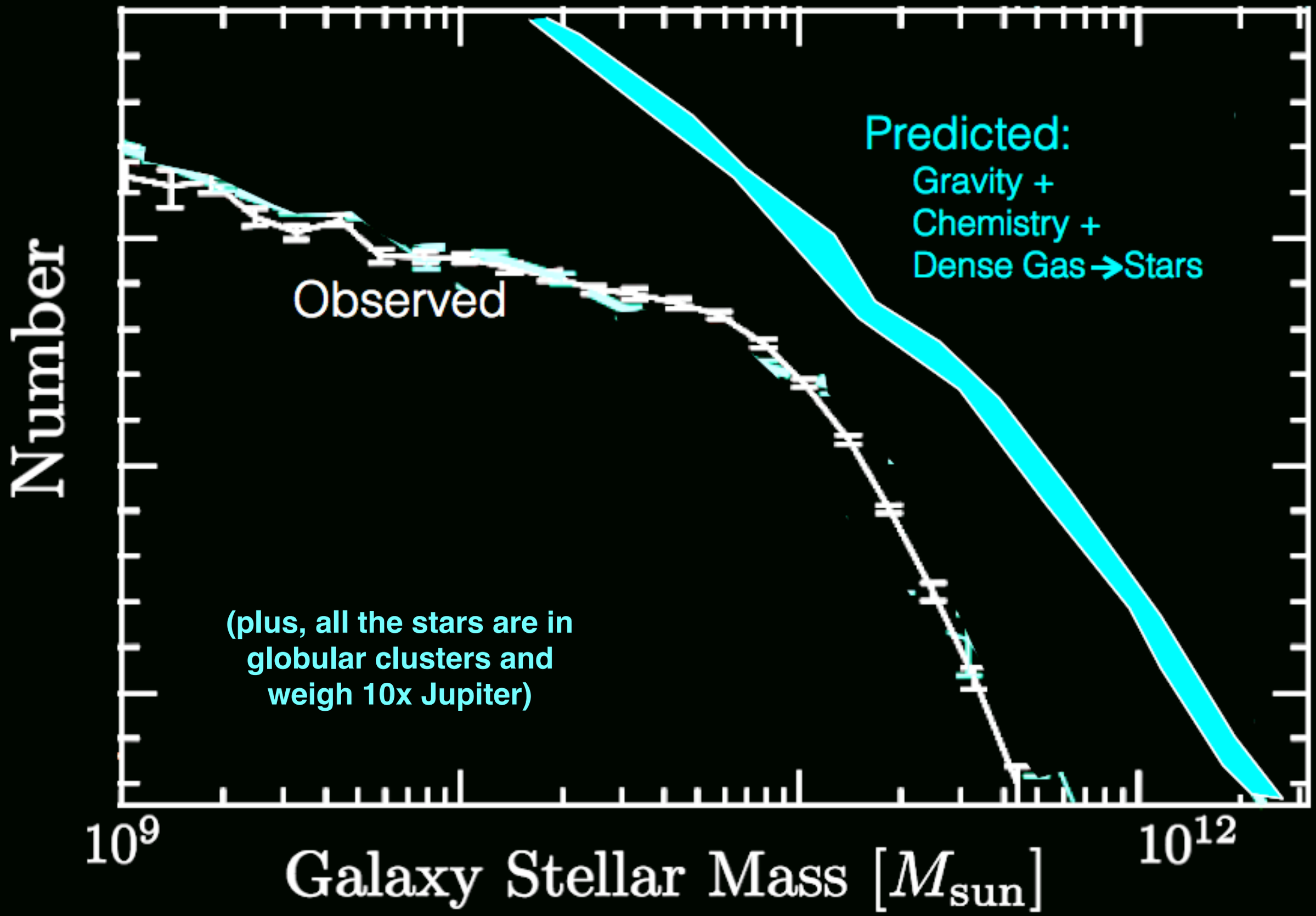
~10^{1}-10^{2} pc
Molecular clouds,
Star-Forming Regions



Add some fluid dynamics and chemistry, and go!

Problem:

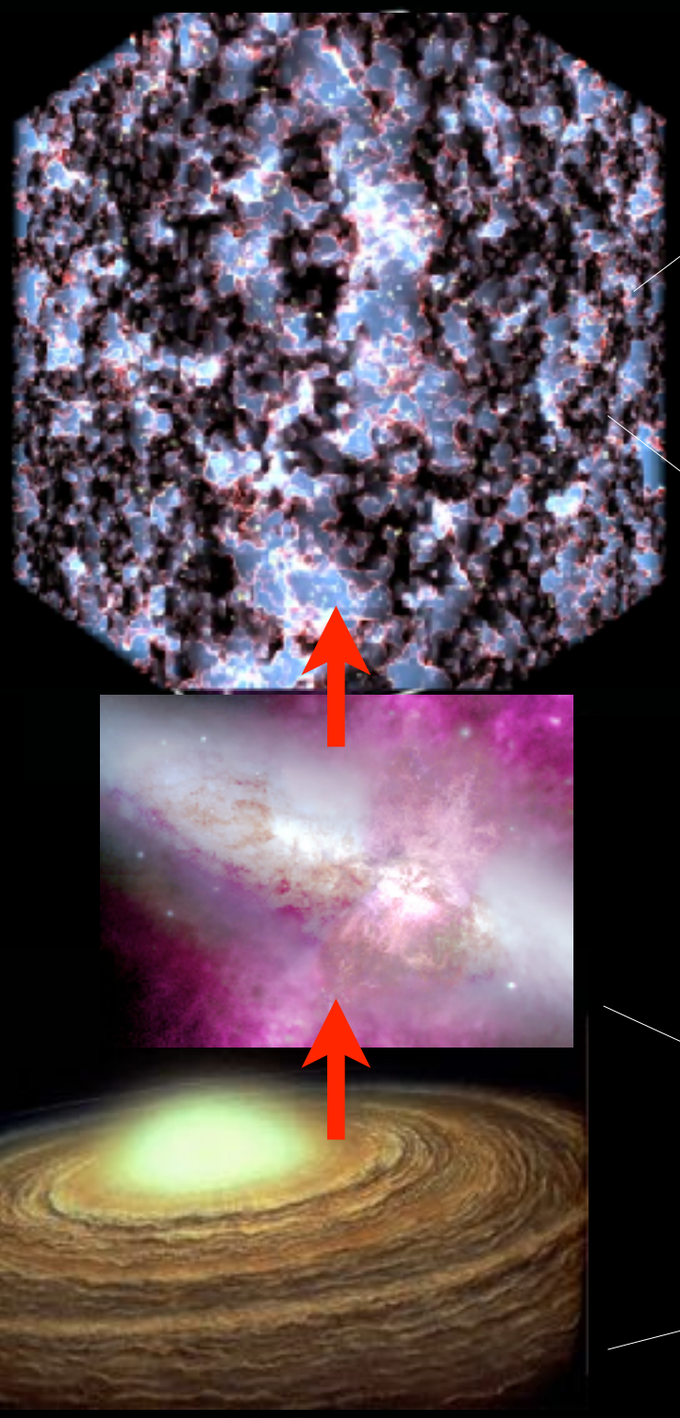
WHY SO FEW GALAXIES & STARS?



… Nature hates theorists

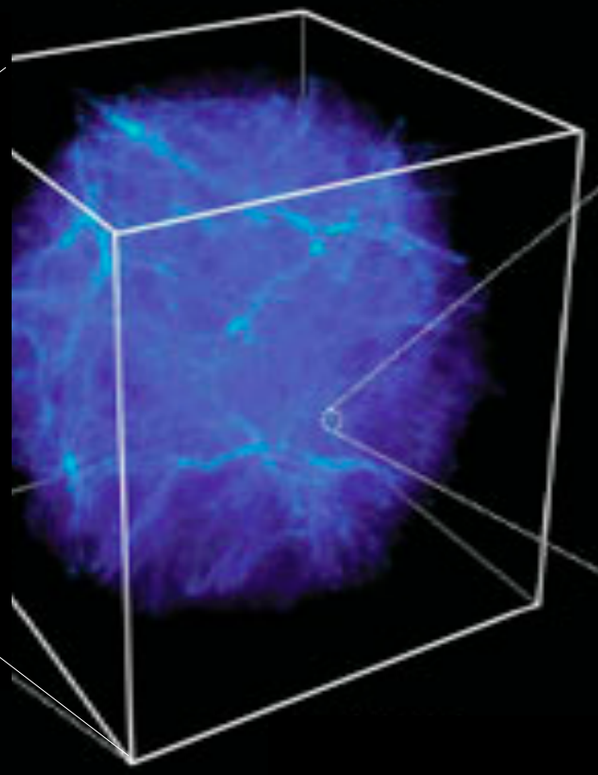
~10^{10} pc

Hubble volume



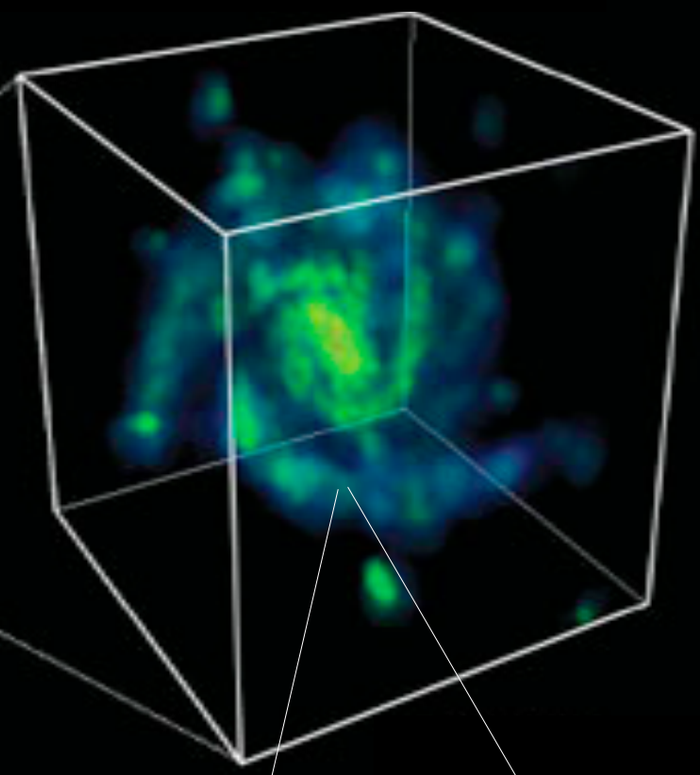
~10^{7}-10^{8} pc

Clusters, Large-scale structure



~10^{4-5} pc

Galaxy

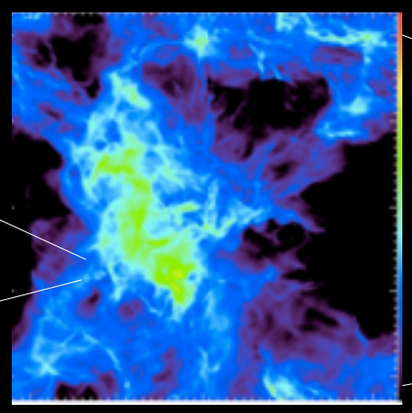


~10^{-5} pc

Stars, protostellar disks

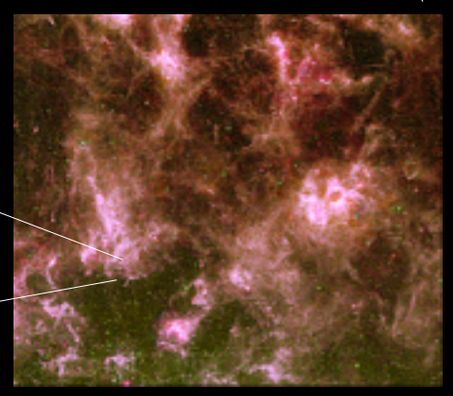
~10^{-2}-10^{0} pc

Cores, clusters,
Supernovae blastwaves



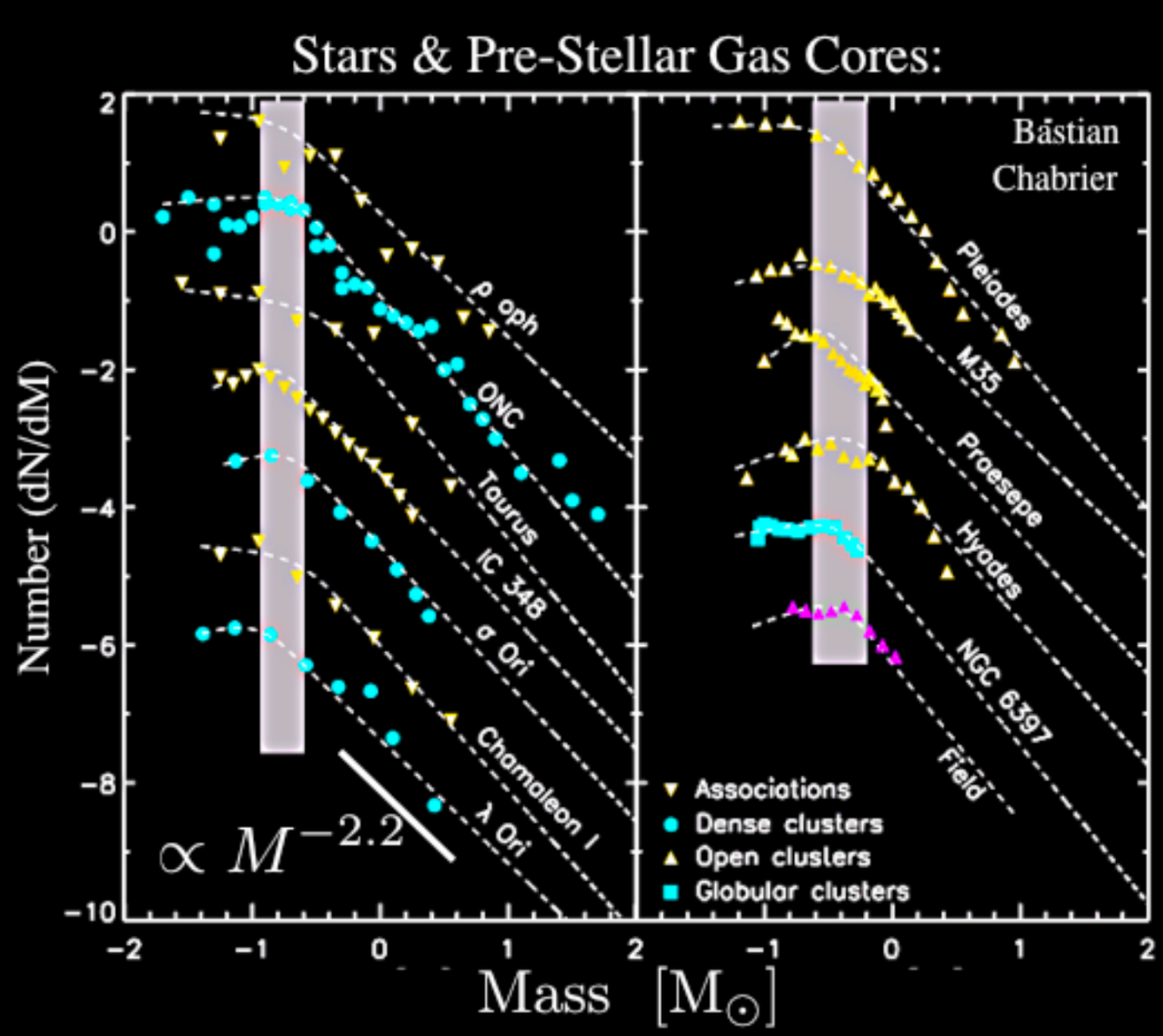
~10^{1}-10^{2} pc

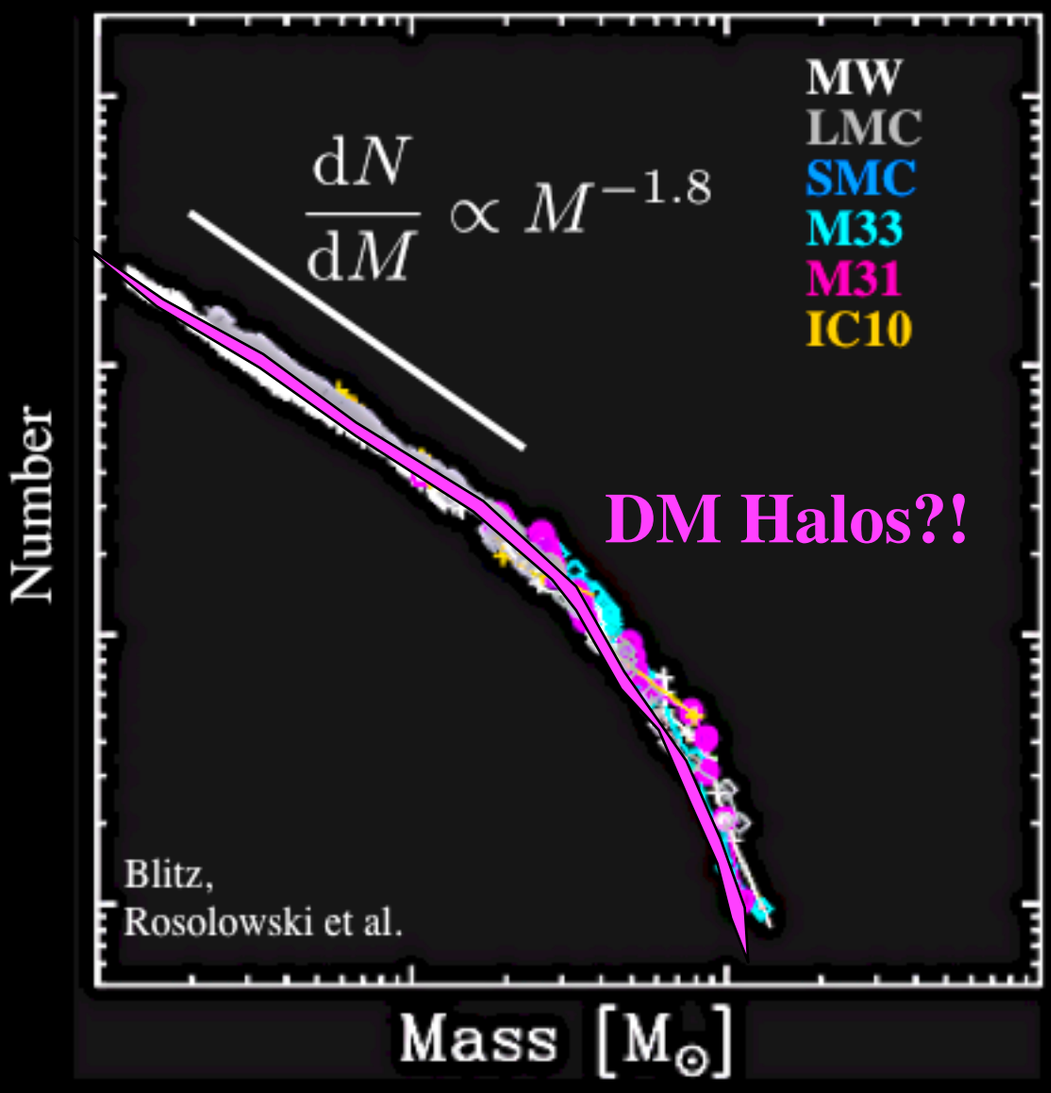
Molecular clouds,
Star-Forming Regions



Feedback is *Hard*, the ISM Is *Messy*….

YET THERE IS SHOCKING REGULARITY

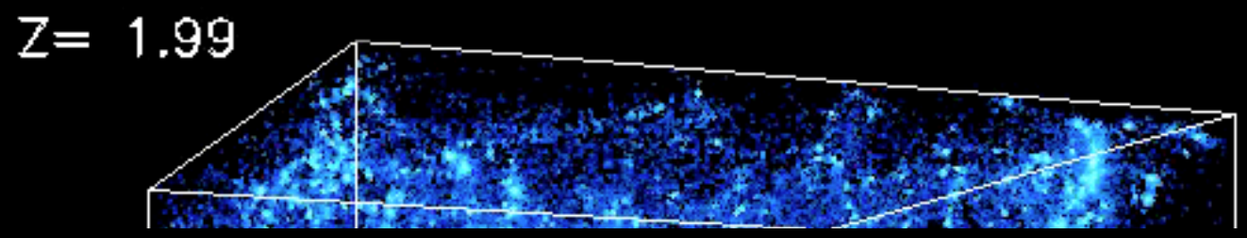




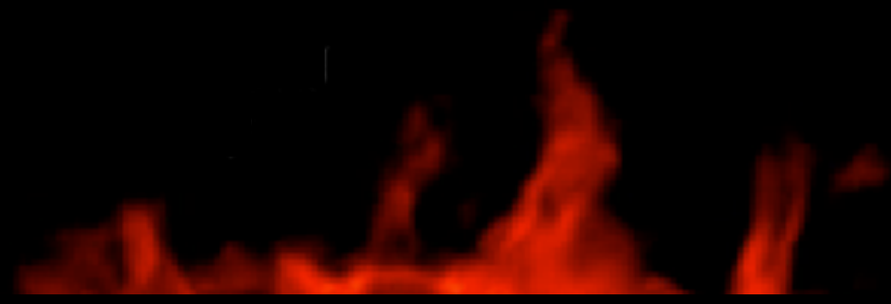
Correlation functions, SFRs (Kennicutt-Schmidt),
Scaling laws (Tully-Fisher)

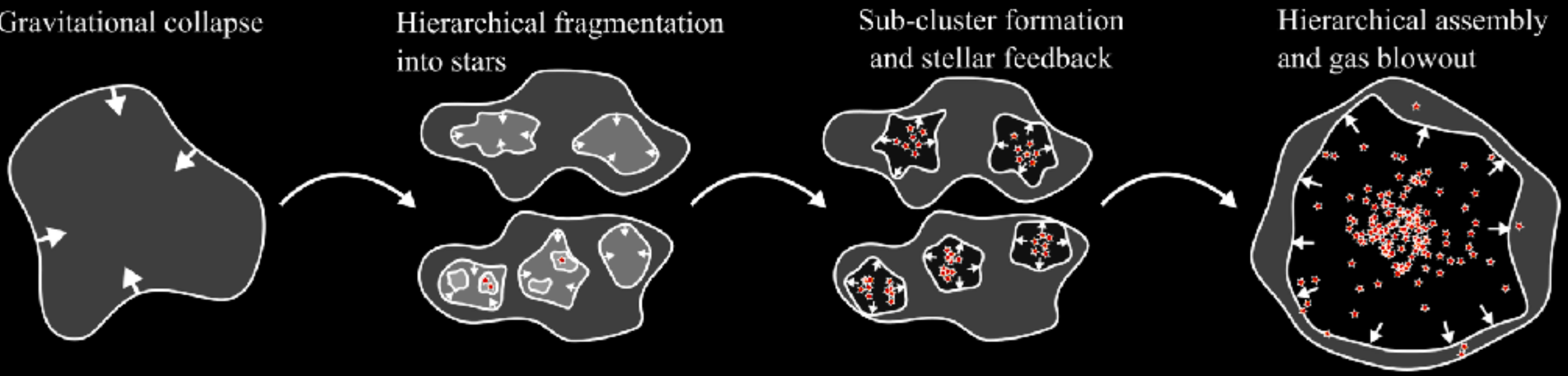
Is this an accident?

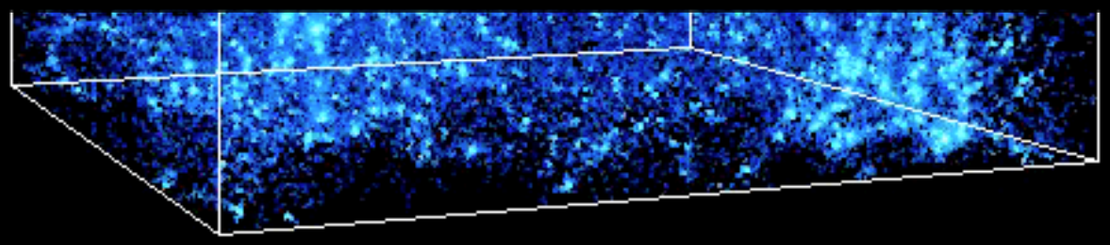
STRUCTURE FORMATION

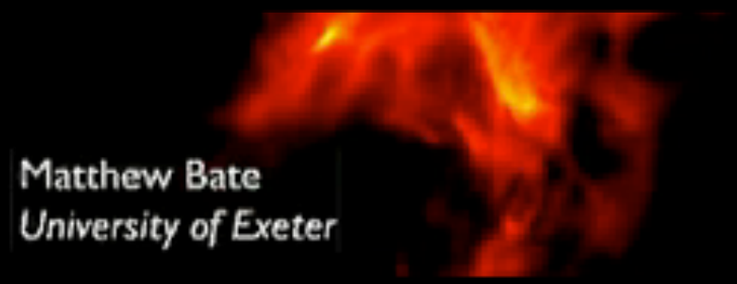


STAR FORMATION





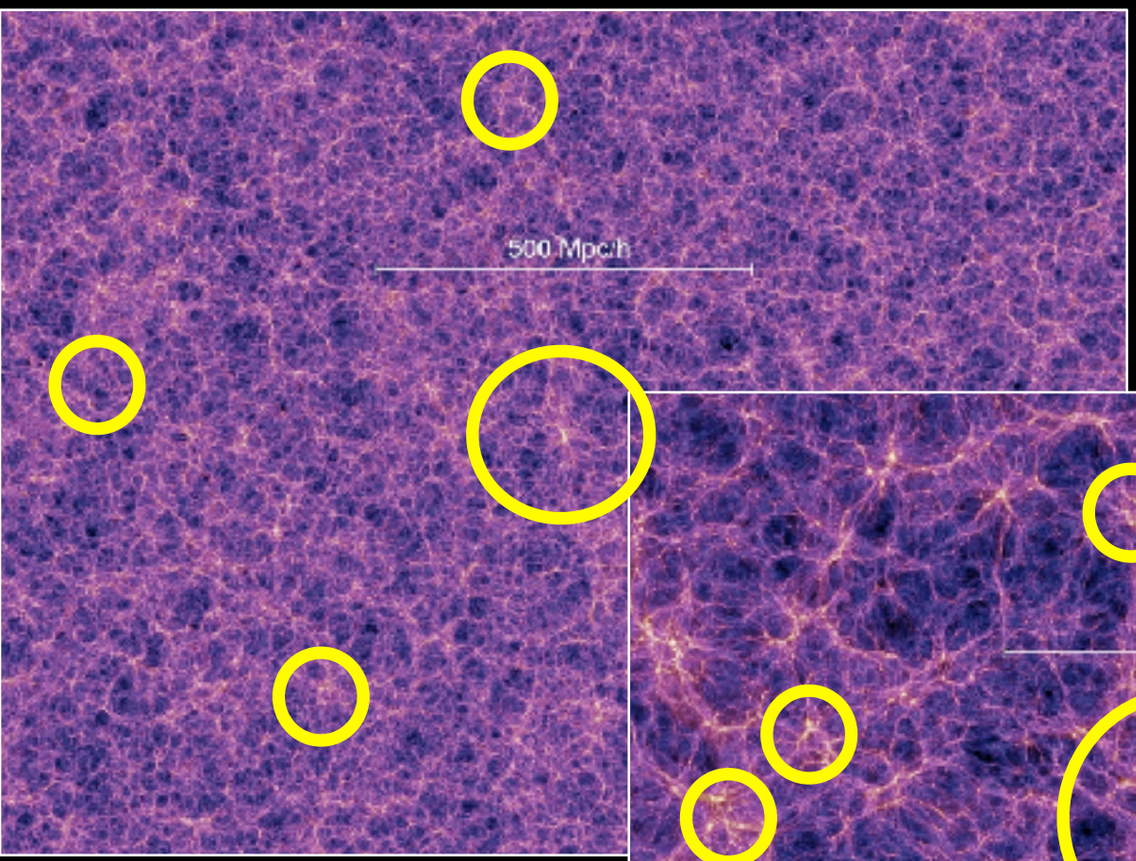


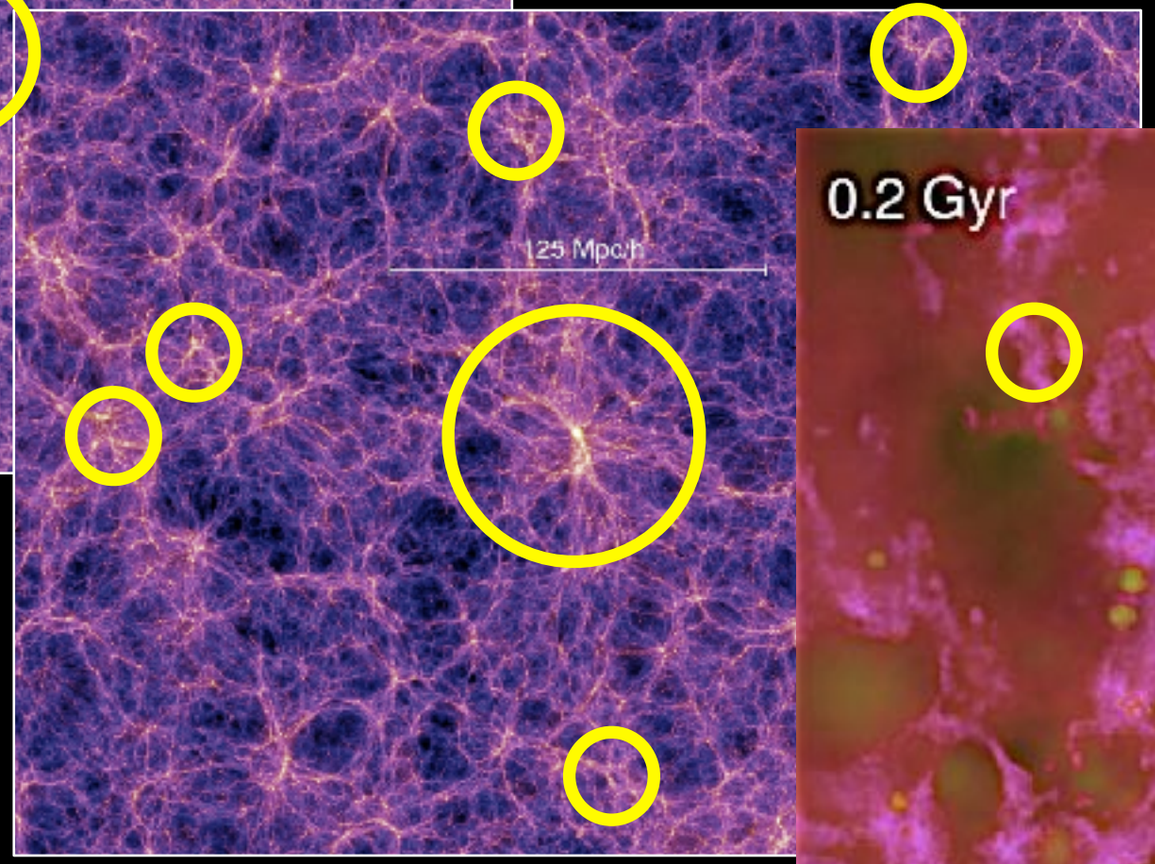


Guszejnov 15,16, 17
Grudic 16, 17

The IMF & Sub-Cloud Scales

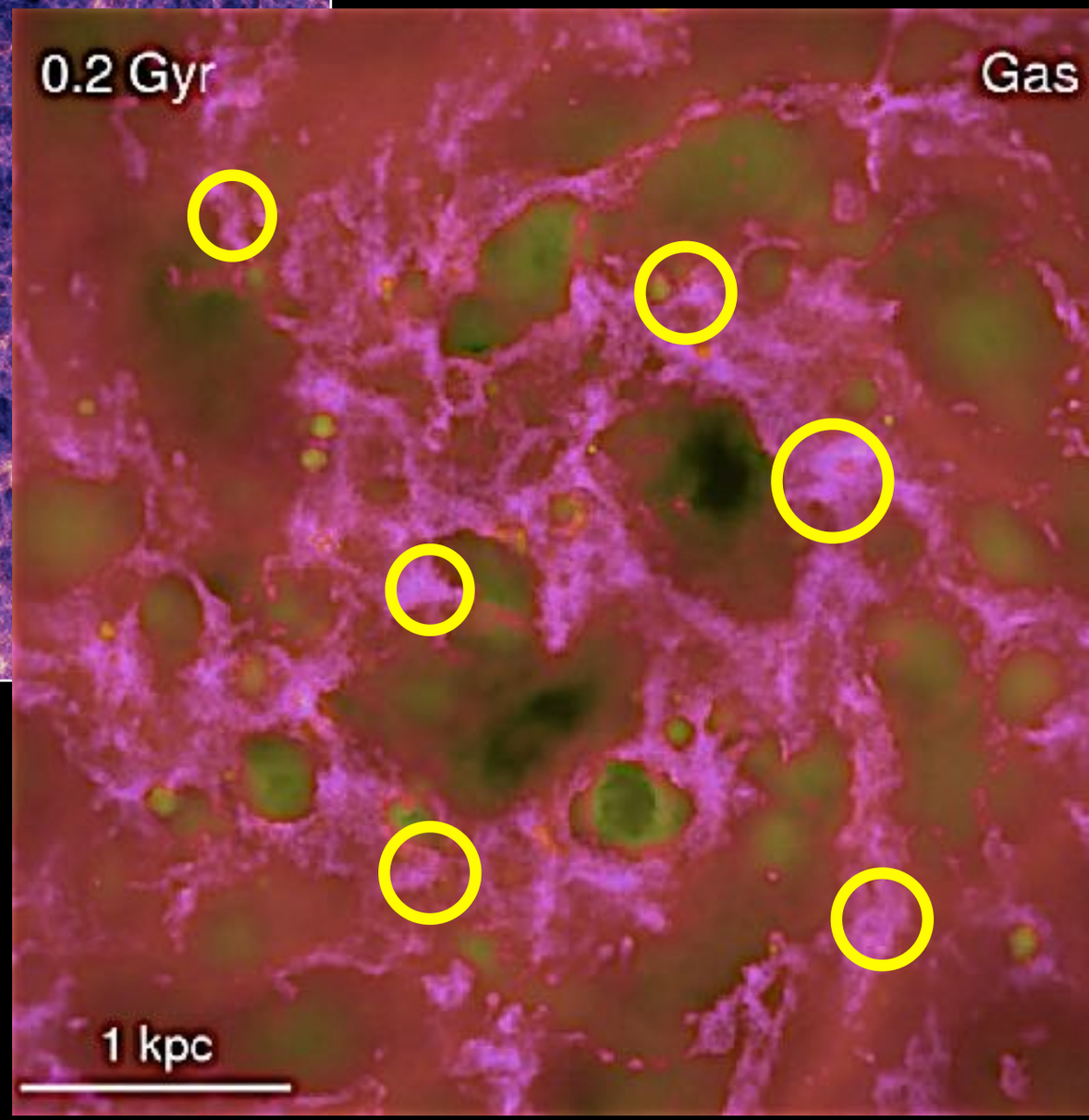
An idea from cosmology?





- Press & Schechter ‘74:
  - Something generates “random” density fluctuations

- Gravity is our “filter”
  - Picks out regions to collapse



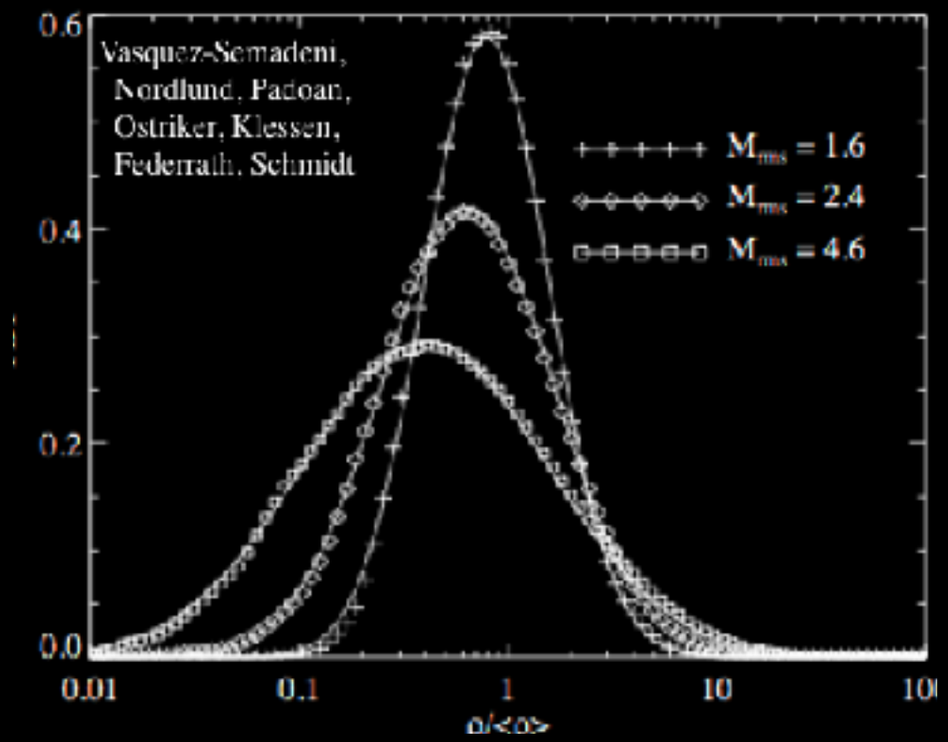
Fluctuations + Gravity = Hierarchical Structure

"FRAGMENTATION" = "STRUCTURE FORMATION"

Chandrasekhar '51
Zeldovich '70
Toomre '77

Turbulence: Velocity: $v_{\rm turb}(R) \propto R^{1/2}$

Density:



Lognormal
(broader at higher Mach number)

Gravity: $$\omega^2 = \kappa^2 + c_s^2\, k^2 + u_t(k)^2\, k^2 - \frac{4\pi\, G\, \rho\, |k| h}{1 + |k| h}$$

Angular Momentum: $\kappa \sim \dfrac{V_{\rm disk}}{R_{\rm disk}}$

Thermal Pressure: $\propto r^{-2}$

Turbulence: $\propto r^{p-3} \sim r^{-1}$

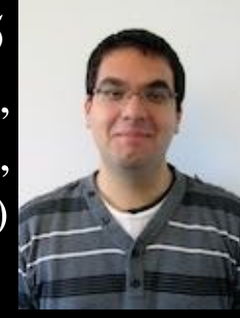
$r > r_{\rm sonic}: \quad u_t^2 > c_s^2$

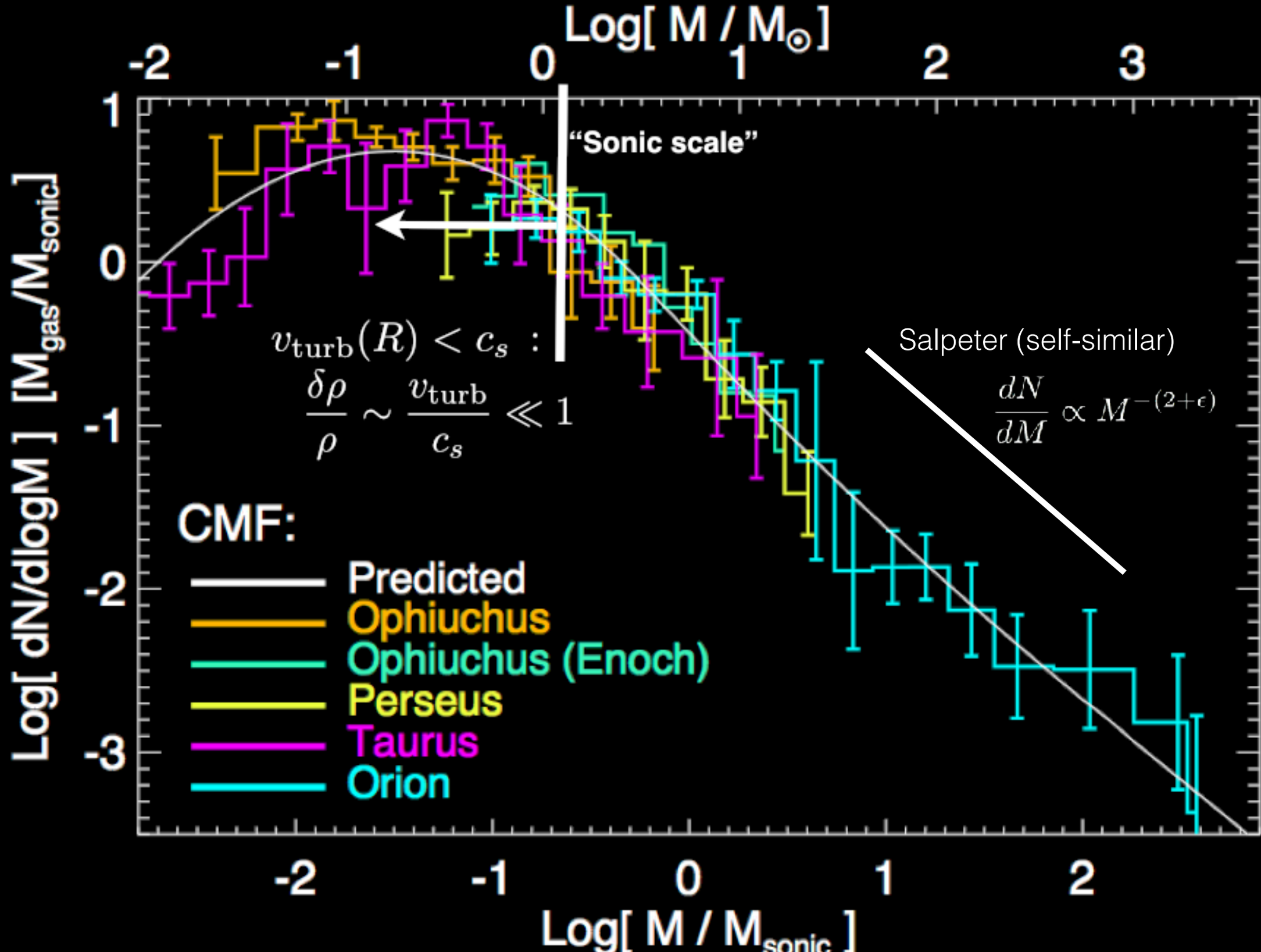
Gravity

Cores: "Smallest Structures" (Before IMF)

SALPETER SLOPE UNTIL NON-SCALE-FREE

Guszejnov '15
(Hennebelle & Chabrier,
Padoan & Nordlund,
PFH)

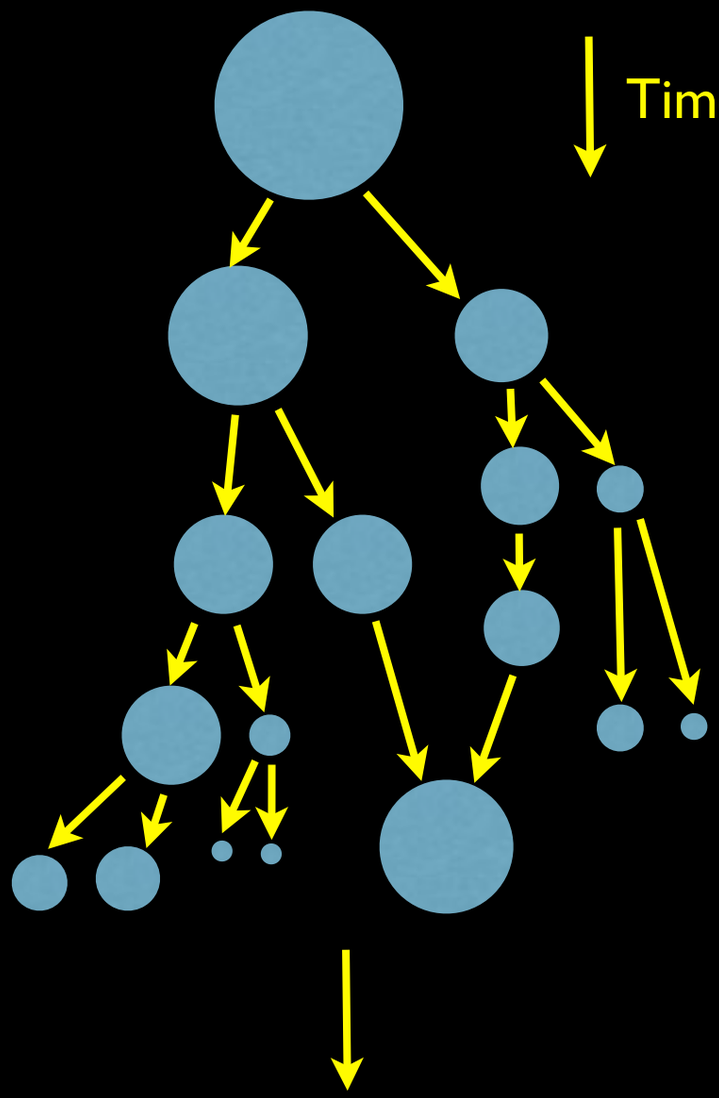




Cores to Stars
HOW TO STOP FRAGMENTATION?

Guszejnov+ '16, 17

"Fragmentation Cascade":



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

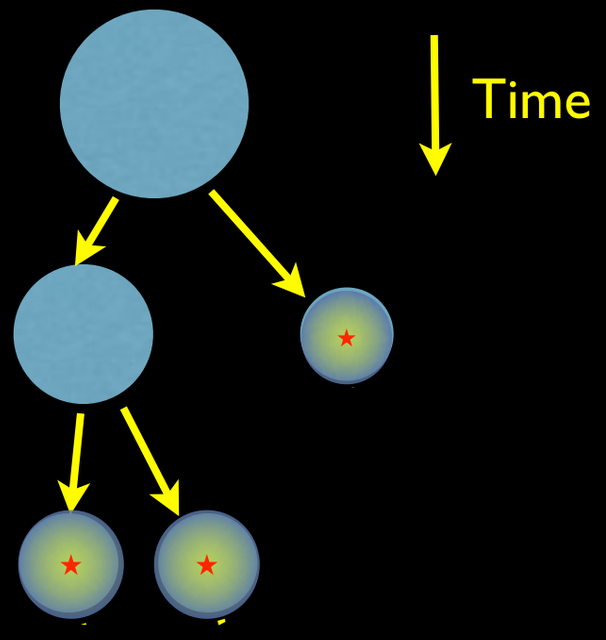
Isothermal fragmentation:

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

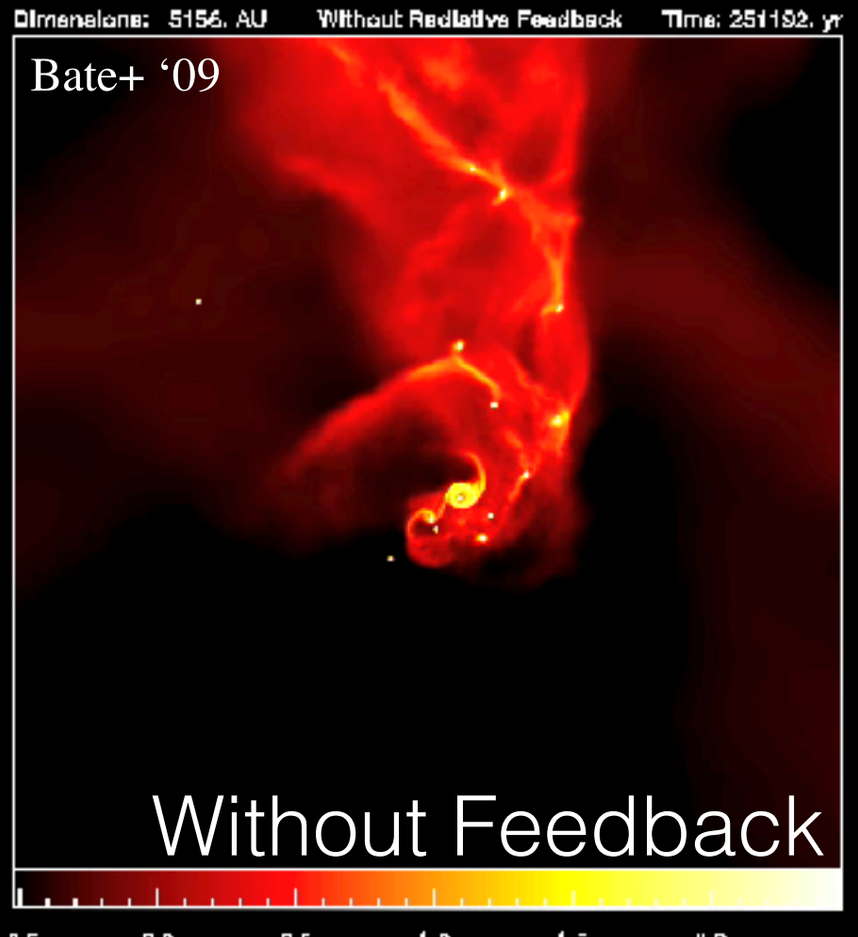
$$M_{\rm sonic} \sim \frac{c_s^2 R_{\rm sonic}}{G} \sim L_{\rm core}\frac{c_s^2}{v_{\rm shocks}^2} \propto L_{\rm core}^2$$

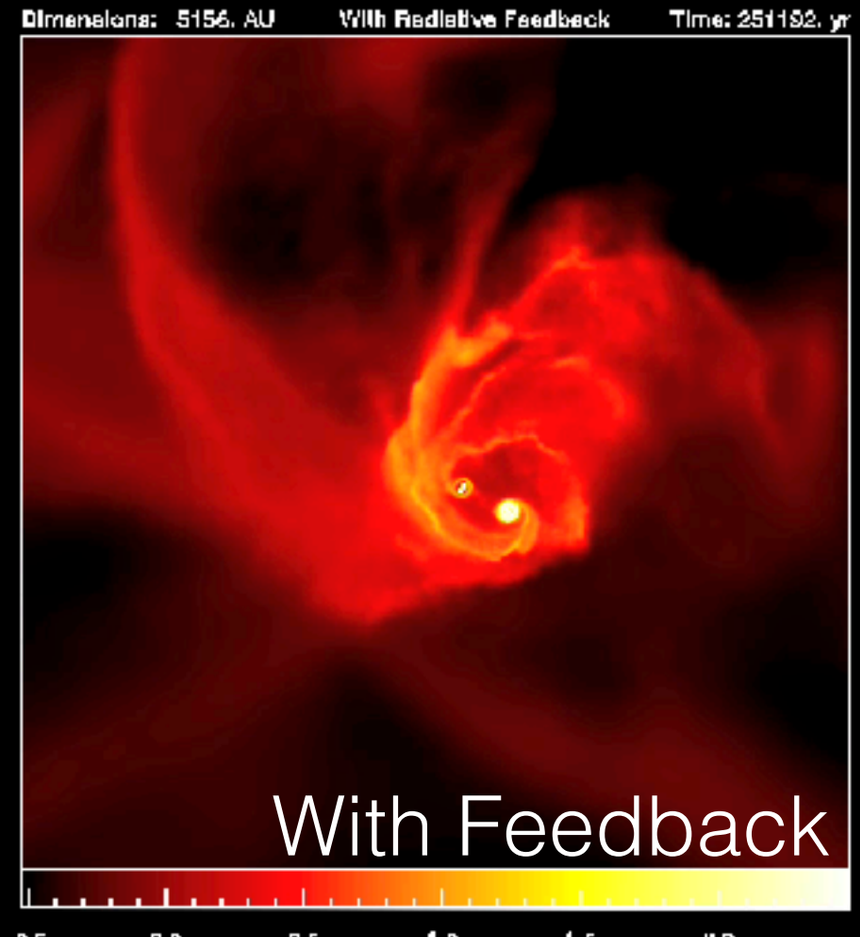
Feedback vs. Gravity

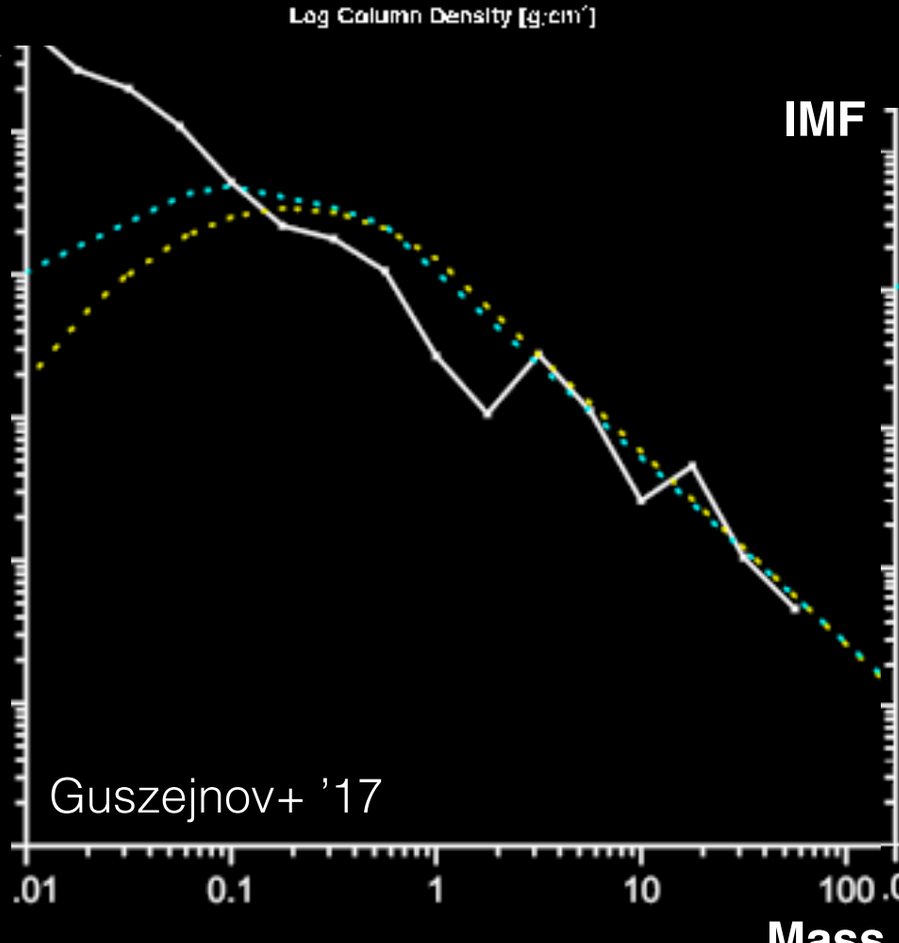
Guszejnov, Hopkins, & Krumholz 2015

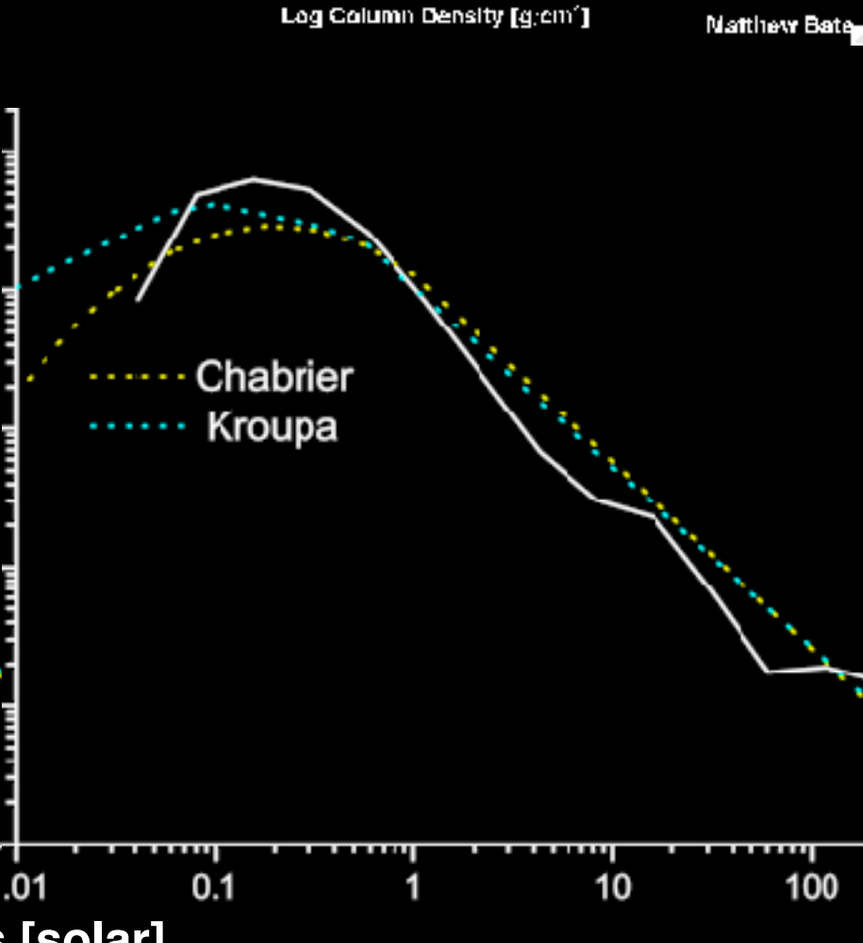


$$M_{\rm crit} \sim 0.1\,M_\odot \left(\frac{\psi}{\psi_0}\right)^{0.4} \left(\frac{R_{\rm core}}{0.1\,{\rm pc}}\right)^{0.1}$$







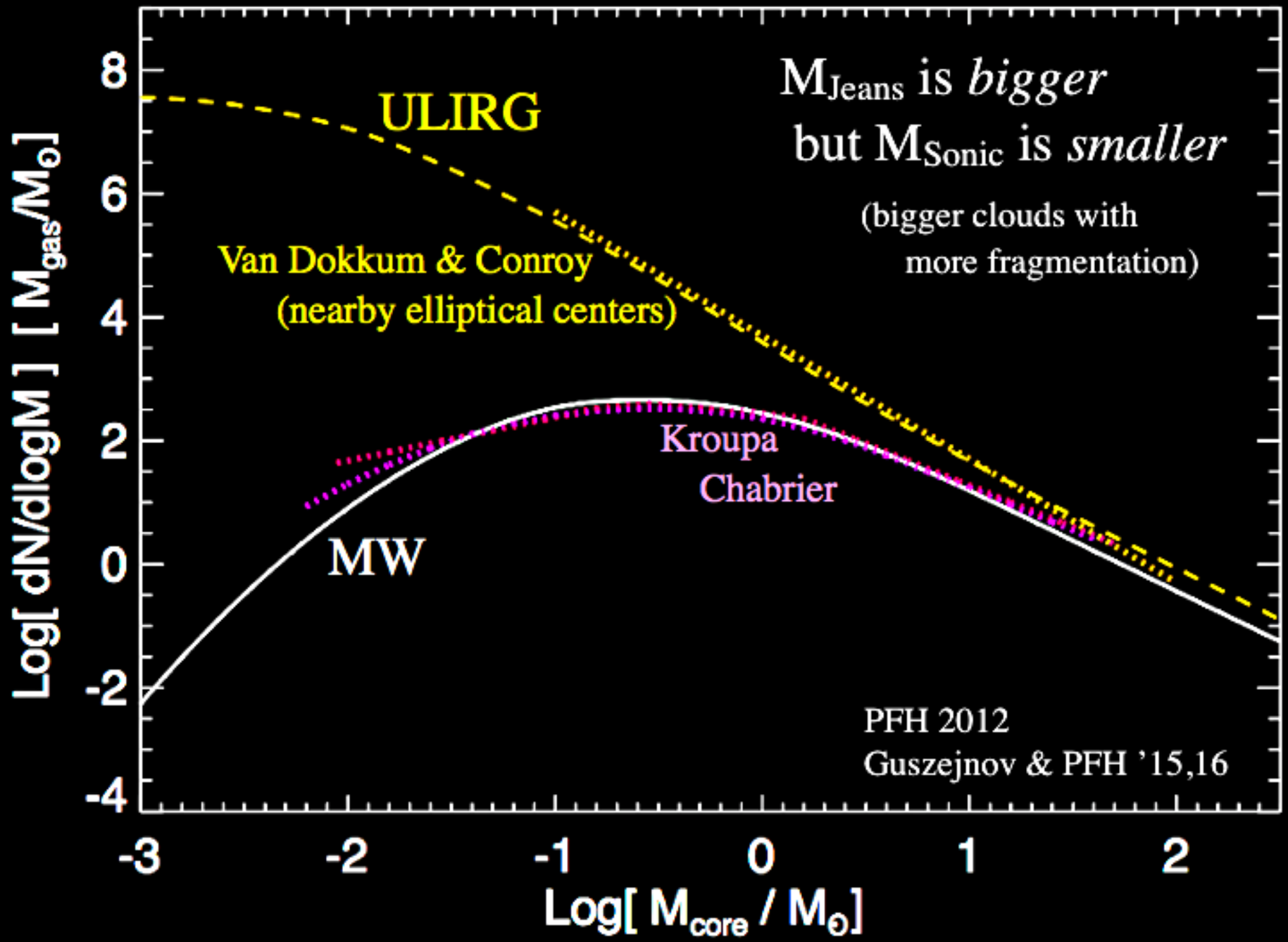


See also:
- Bate+ '09, '12
- Offner+ '09, '14
- Krumholz+ '12
- Guszejnov+ '16, 17

- (Multiplicity [same refs])

IMF Evolution?

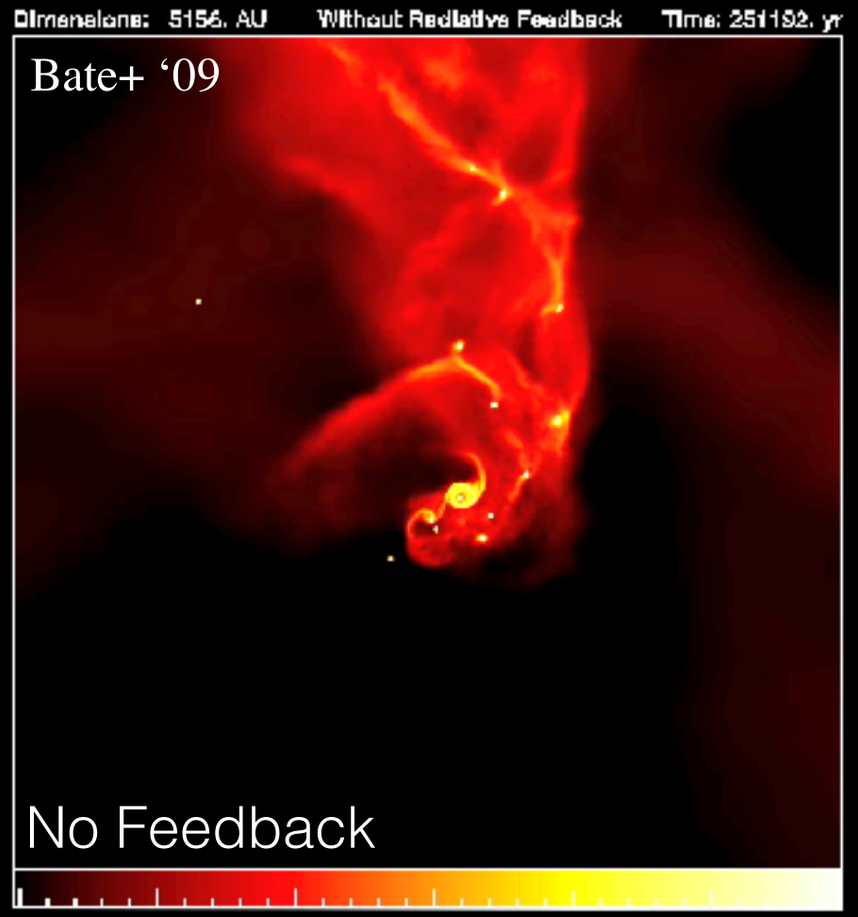
WEAK, OR VERY WEAK?

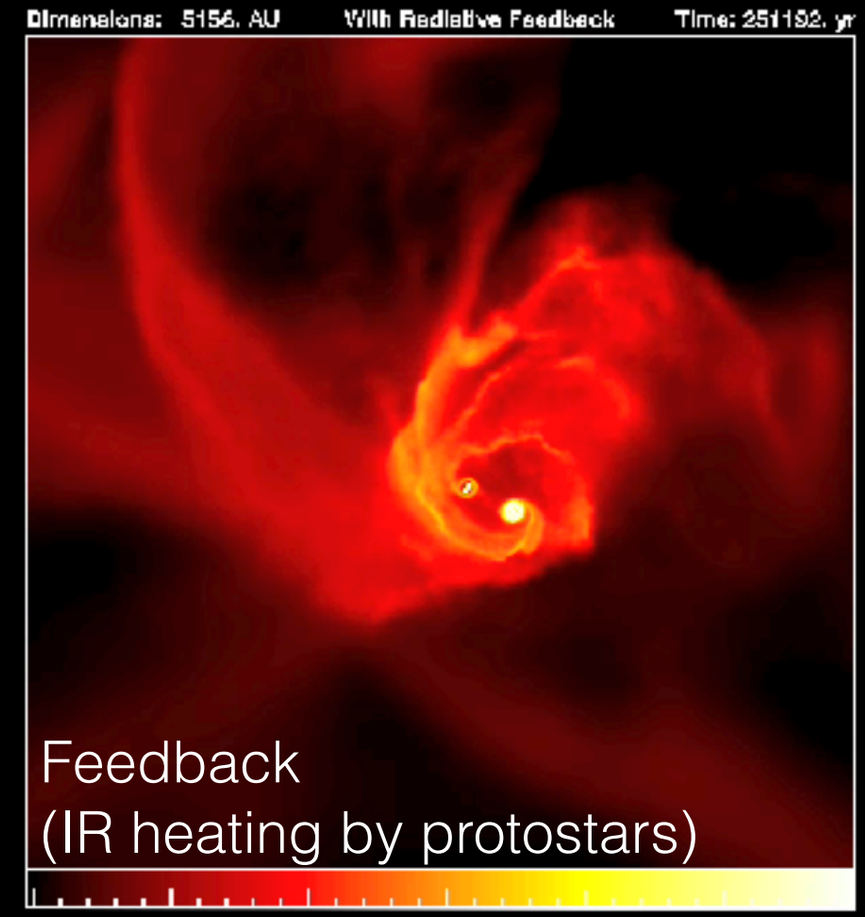


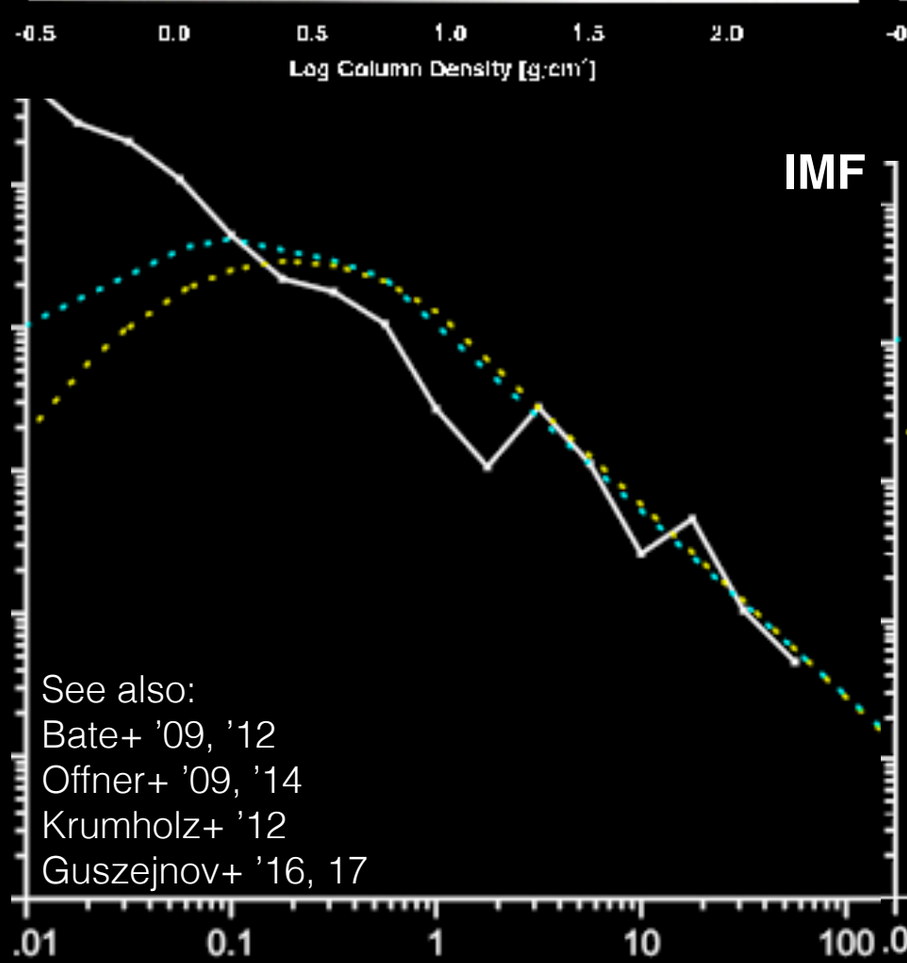
BUT, can't ignore FB

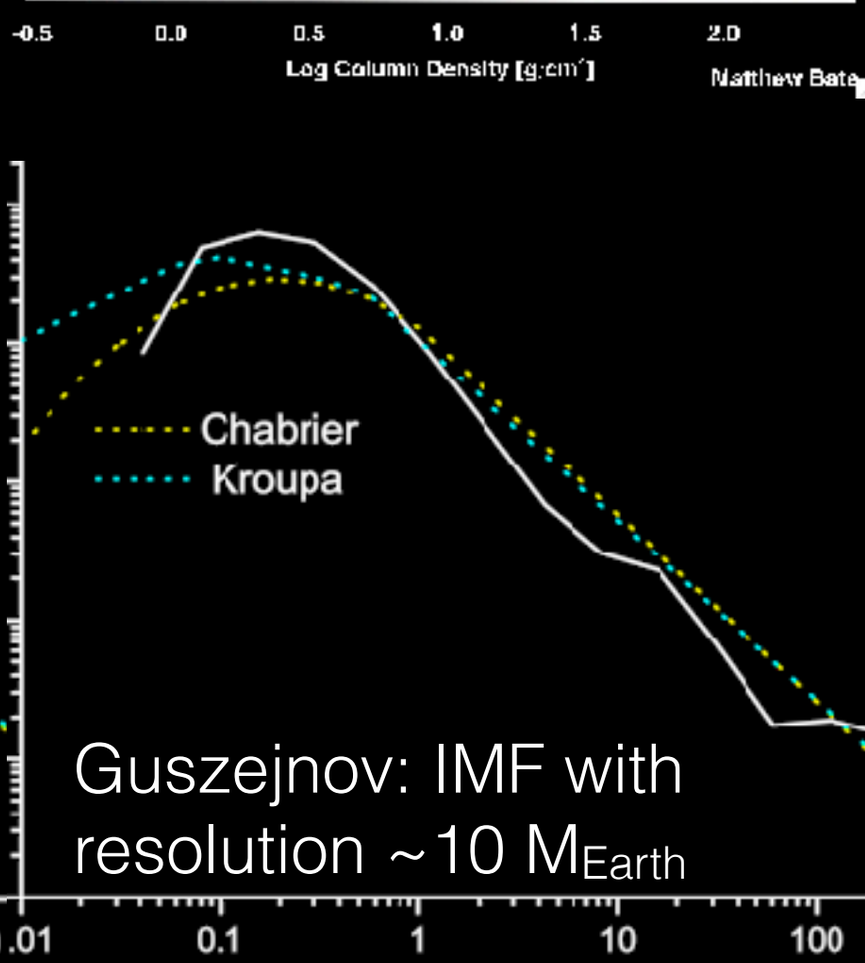
Guszejnov, Hopkins, & Krumholz
2015, 2016, 2017

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



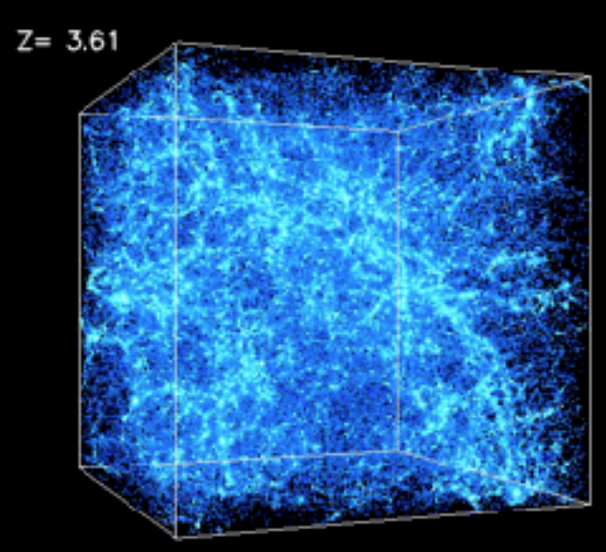




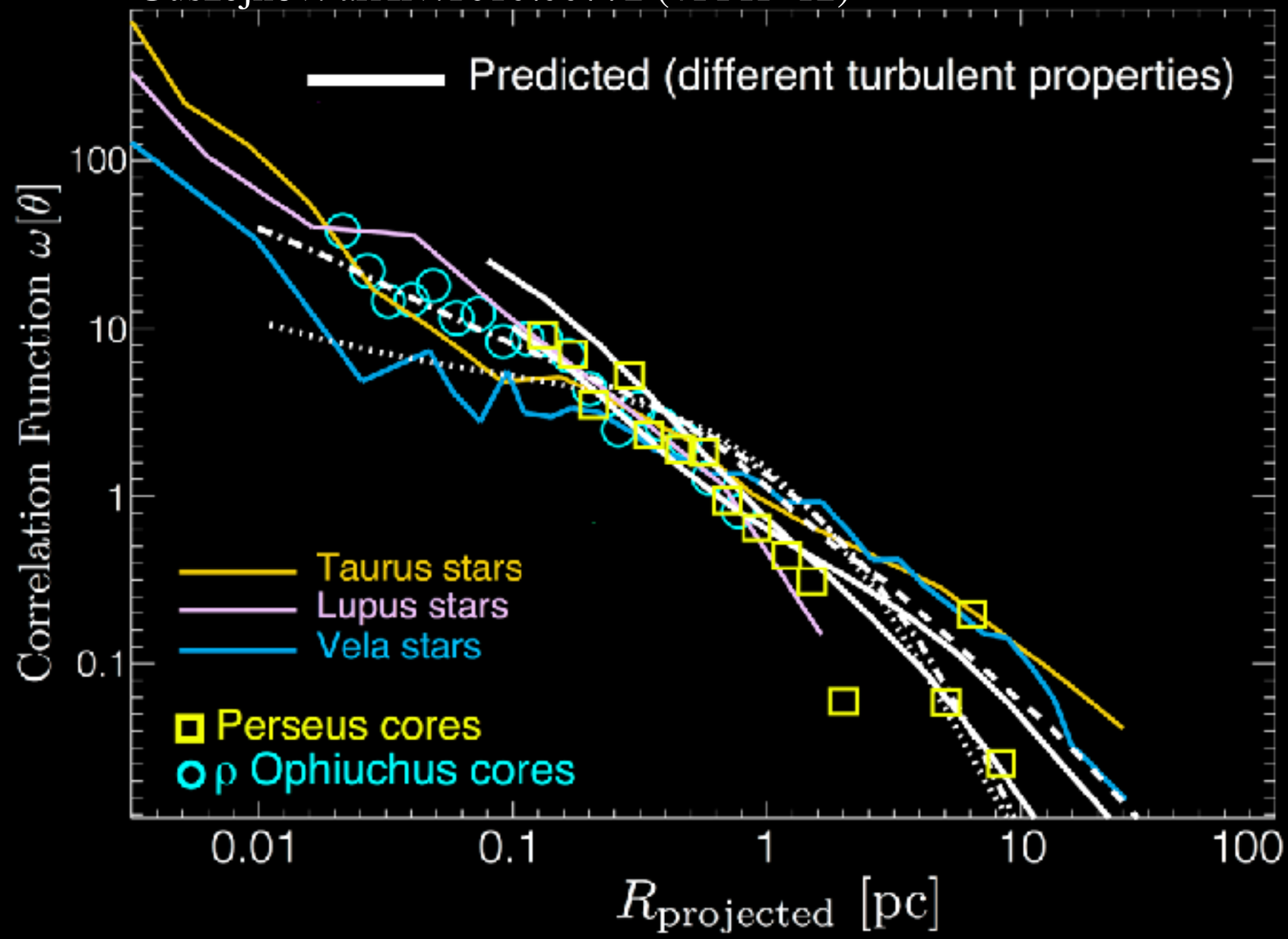


Why Is Star Formation Clustered?

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

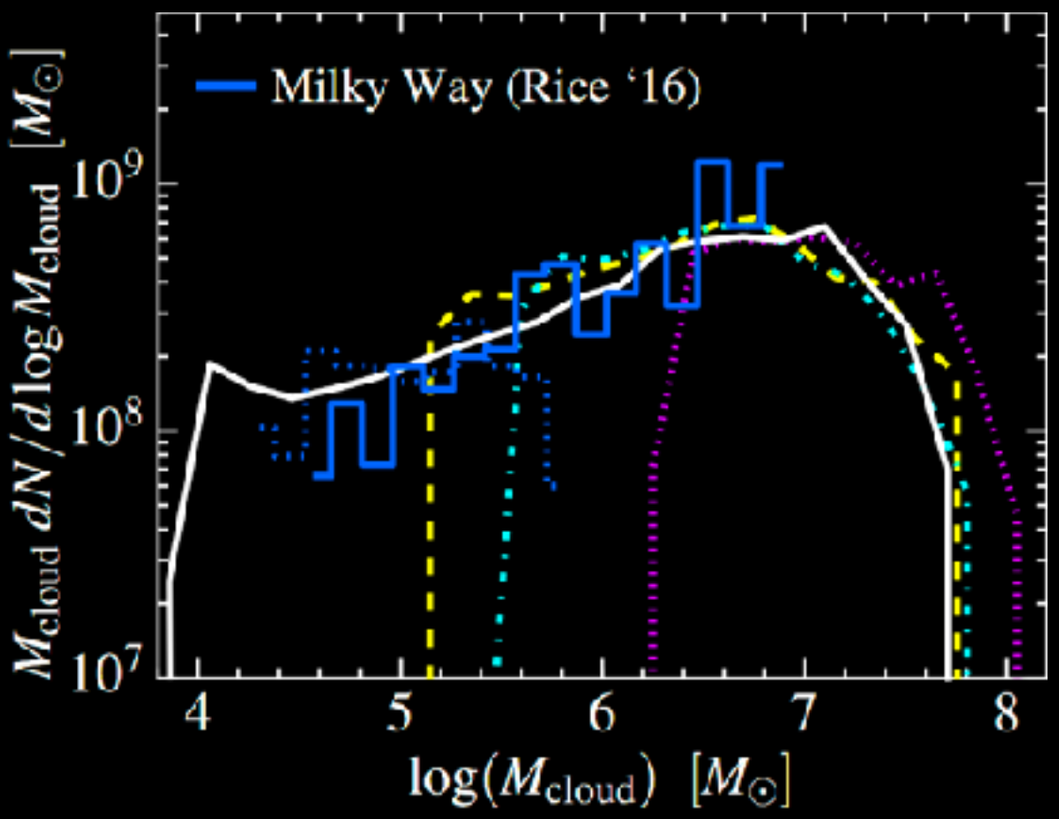
$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto M^{-\alpha}\, e^{-(M/M_J)^{\beta}}$$

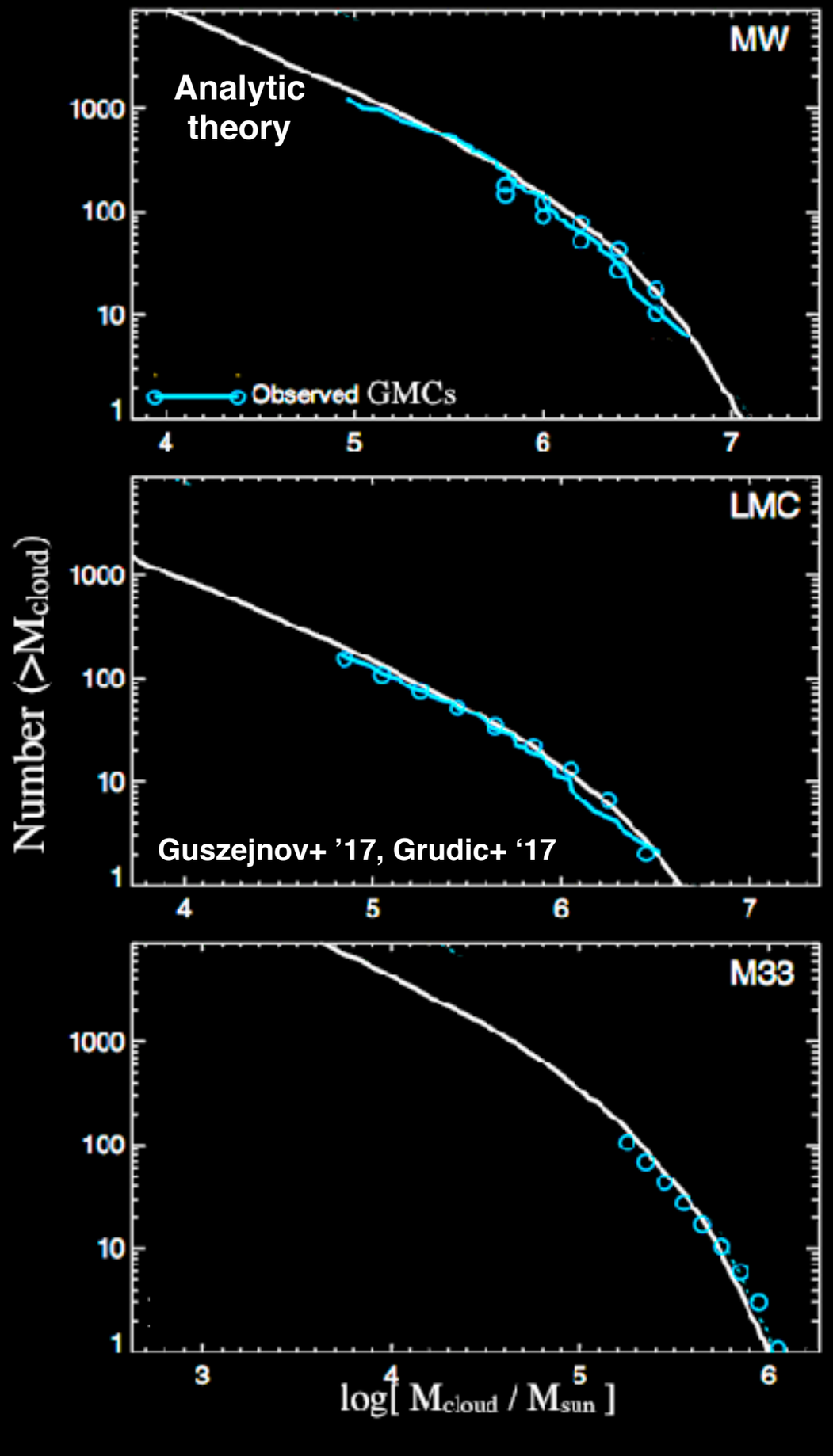
(Toomre mass)

$$\alpha \approx 2 - \epsilon(M)$$

(scale-free)

Cosmological simulations: Guszejnov (arXiv:1702.04431)





What Determines Cloud Star Formation Efficiencies?

FEEDBACK VS. GRAVITY

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

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

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

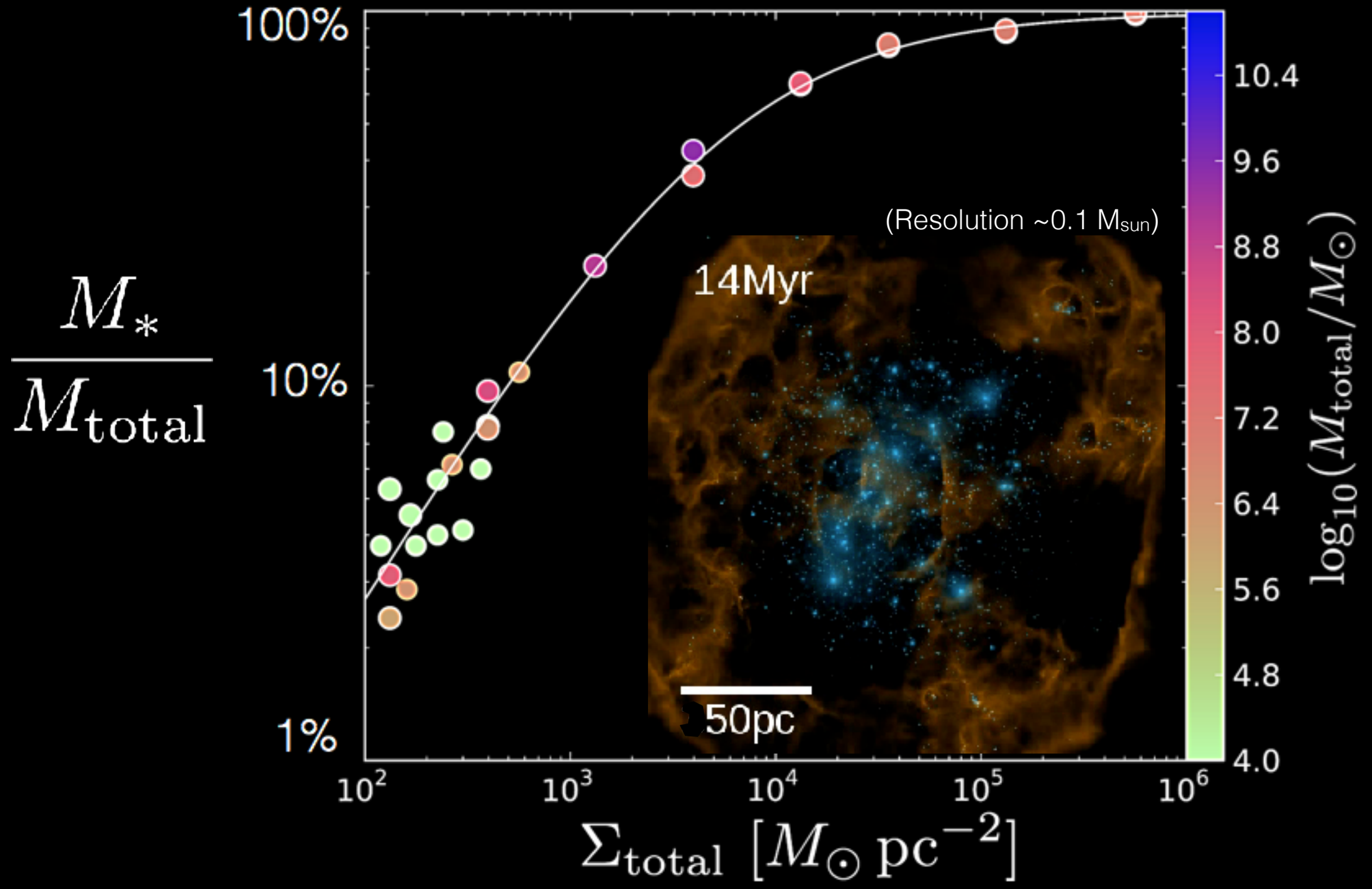
$$\rightarrow \frac{M_*}{M_{\rm tot}} \sim \frac{\Sigma}{(\text{few})\, 10^4\, M_\odot\, \text{pc}^{-2}}$$

see Matzner ’08,10

What Determines Cloud Star Formation Efficiencies?

FEEDBACK VS. GRAVITY

Mike Grudic
(arXiv:
1612.05635)

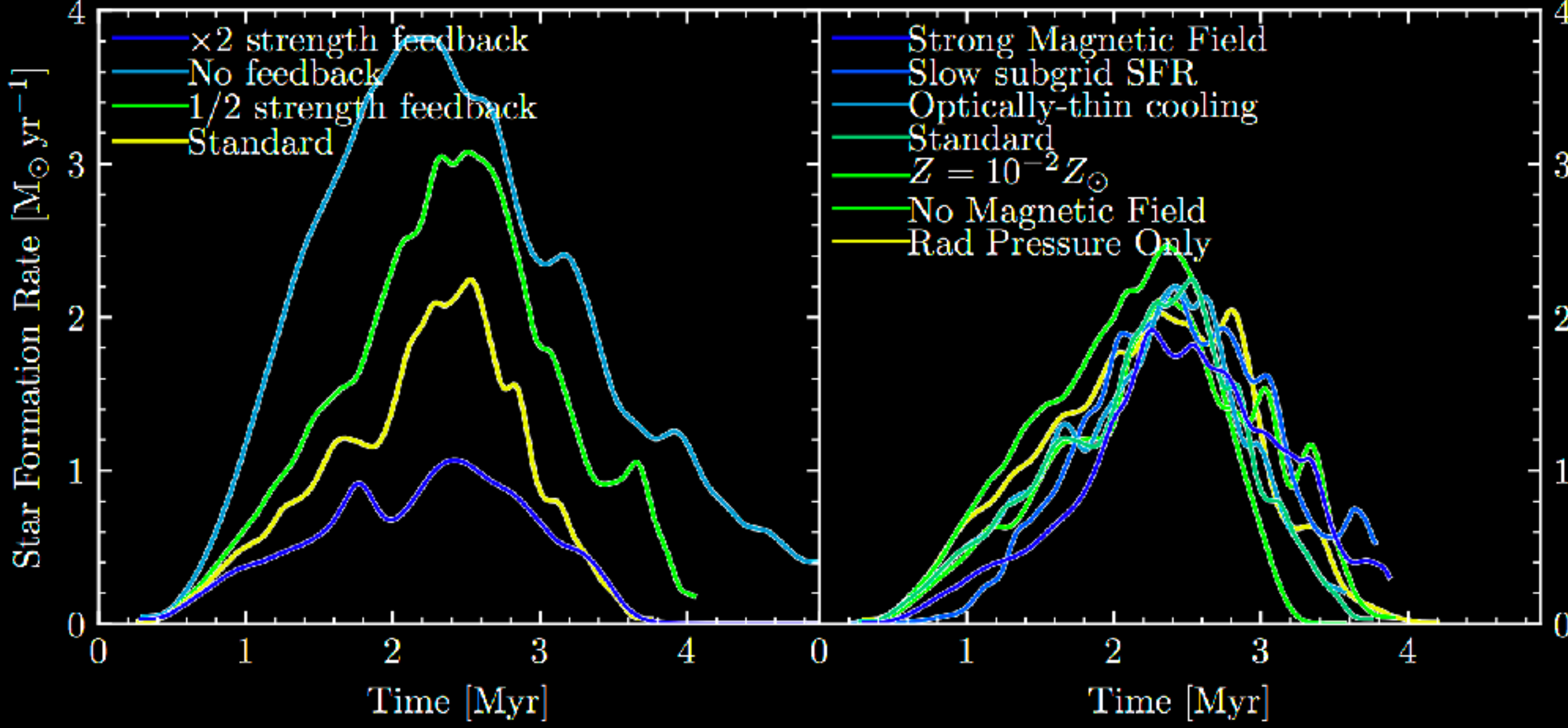


$$\text{Gravity} \sim \frac{G\,M_{\rm tot}\,M_{\rm gas}}{R^2} \propto M_{\rm tot}\,\Sigma_{\rm gas} \qquad \text{vs.} \qquad \text{Feedback} \sim \frac{\text{Momentum}}{\text{Time}} \propto (...)\,M_*$$

What Determines Cloud Star Formation Efficiencies?

FEEDBACK VS. GRAVITY

Mike Grudic
(arXiv:
1612.05635)

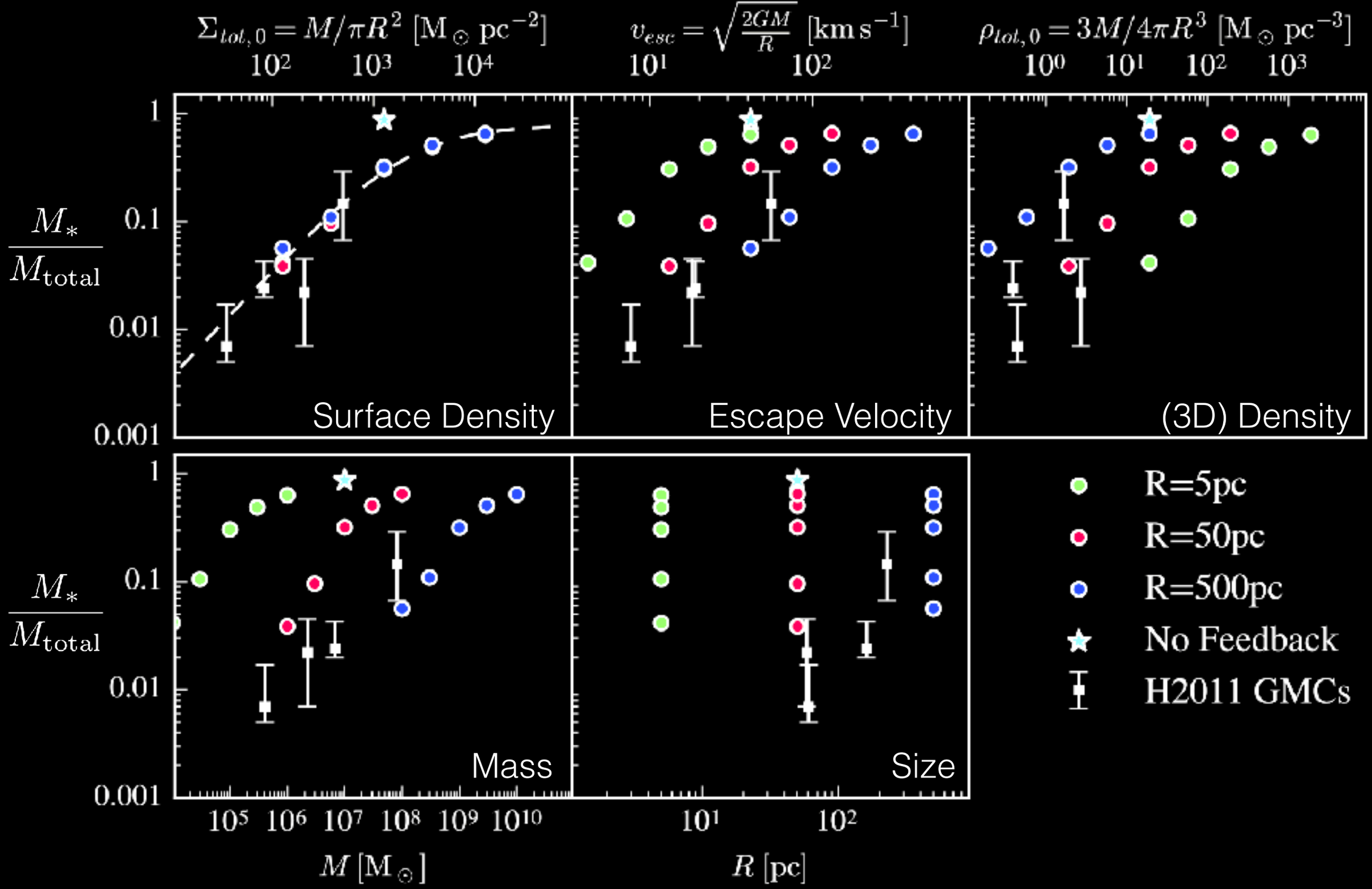


(also RT method: LEBRON, M1, FLD;
non-ideal MHD; conduction+viscosity)

What Determines Cloud Star Formation Efficiencies?

FEEDBACK VS. GRAVITY = SURFACE DENSITY

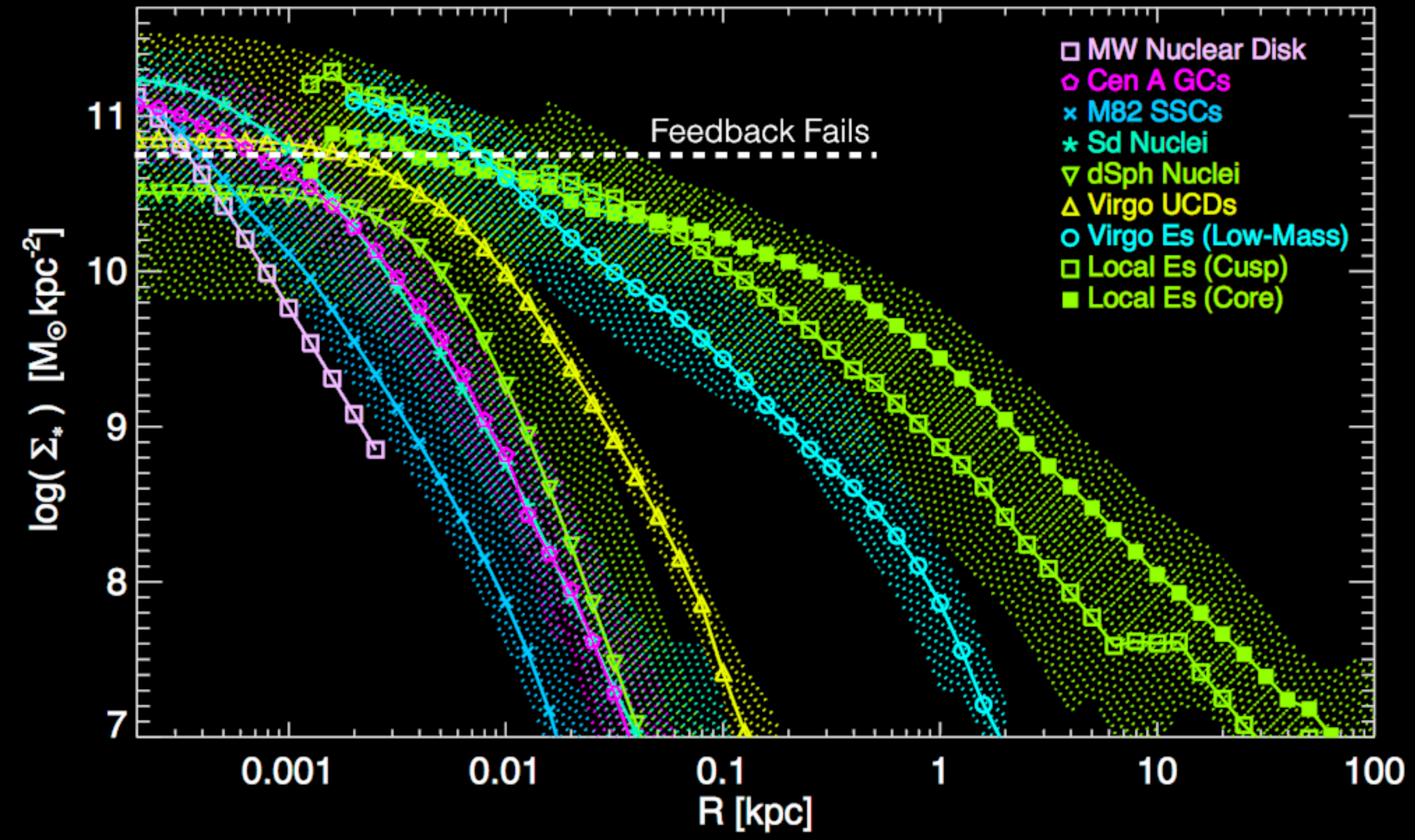
Mike Grudic
(arXiv:
1612.05635)



Where Does Feedback Fail?

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

Hopkins, Murray, Quataert, & Thompson 2010



Where Does Feedback Fail?

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

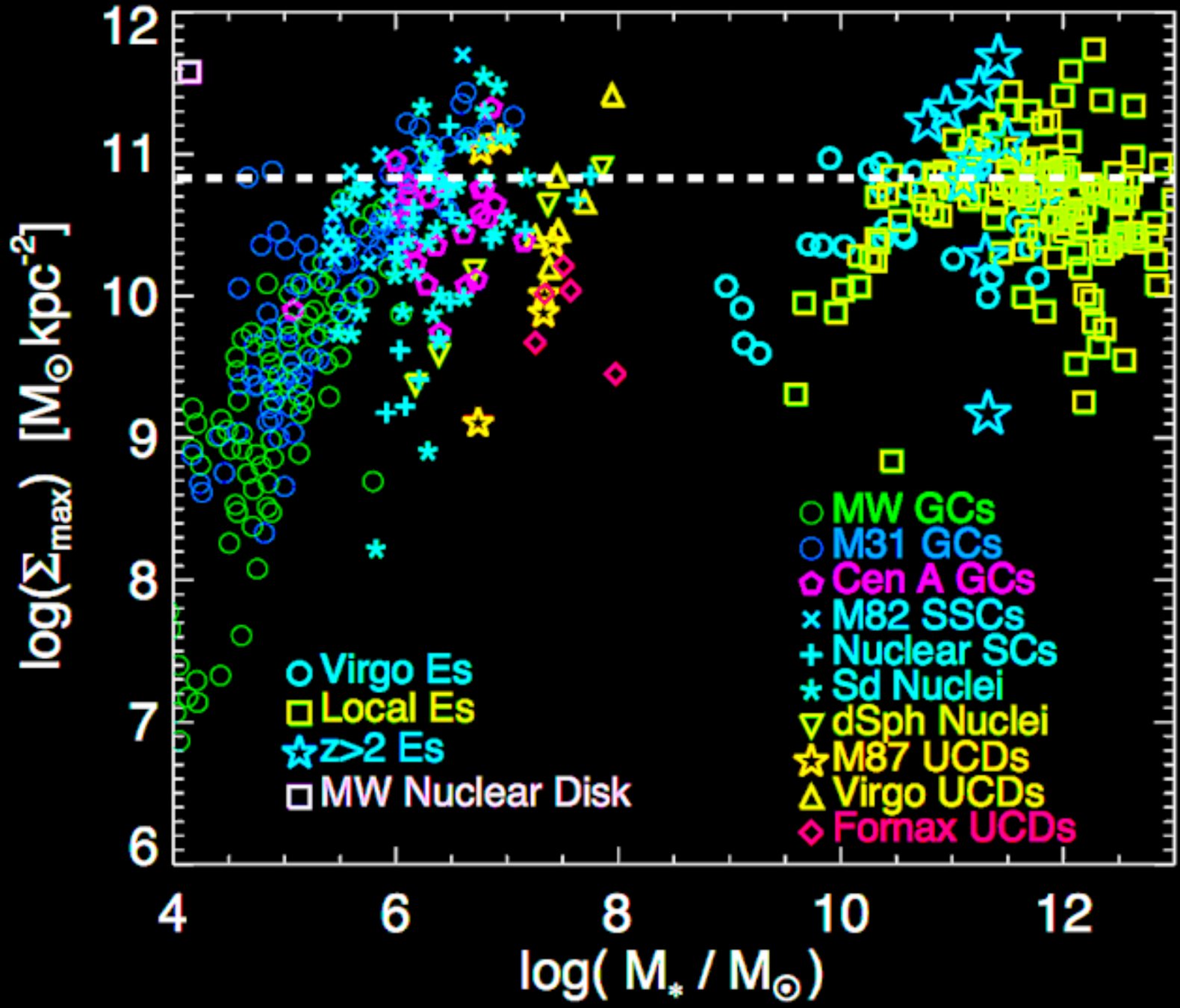
$$R_{\rm eff} \sim 0.1 - 10^4\,{\rm pc}$$

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

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

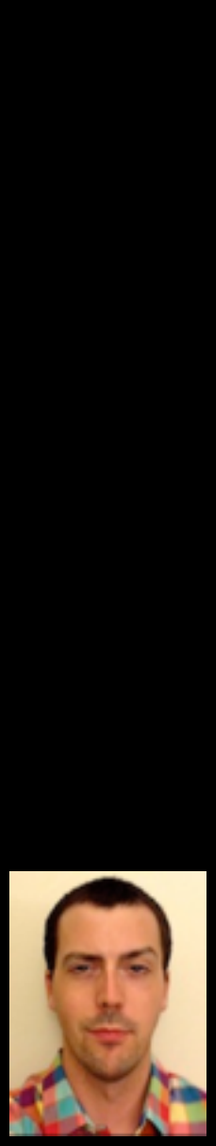
$$Z \sim 0.01 - 5\,Z_\odot$$

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



Hopkins, Murray, Quataert, & Thompson 2010

Resolving Globulars in Cosmological Simulations

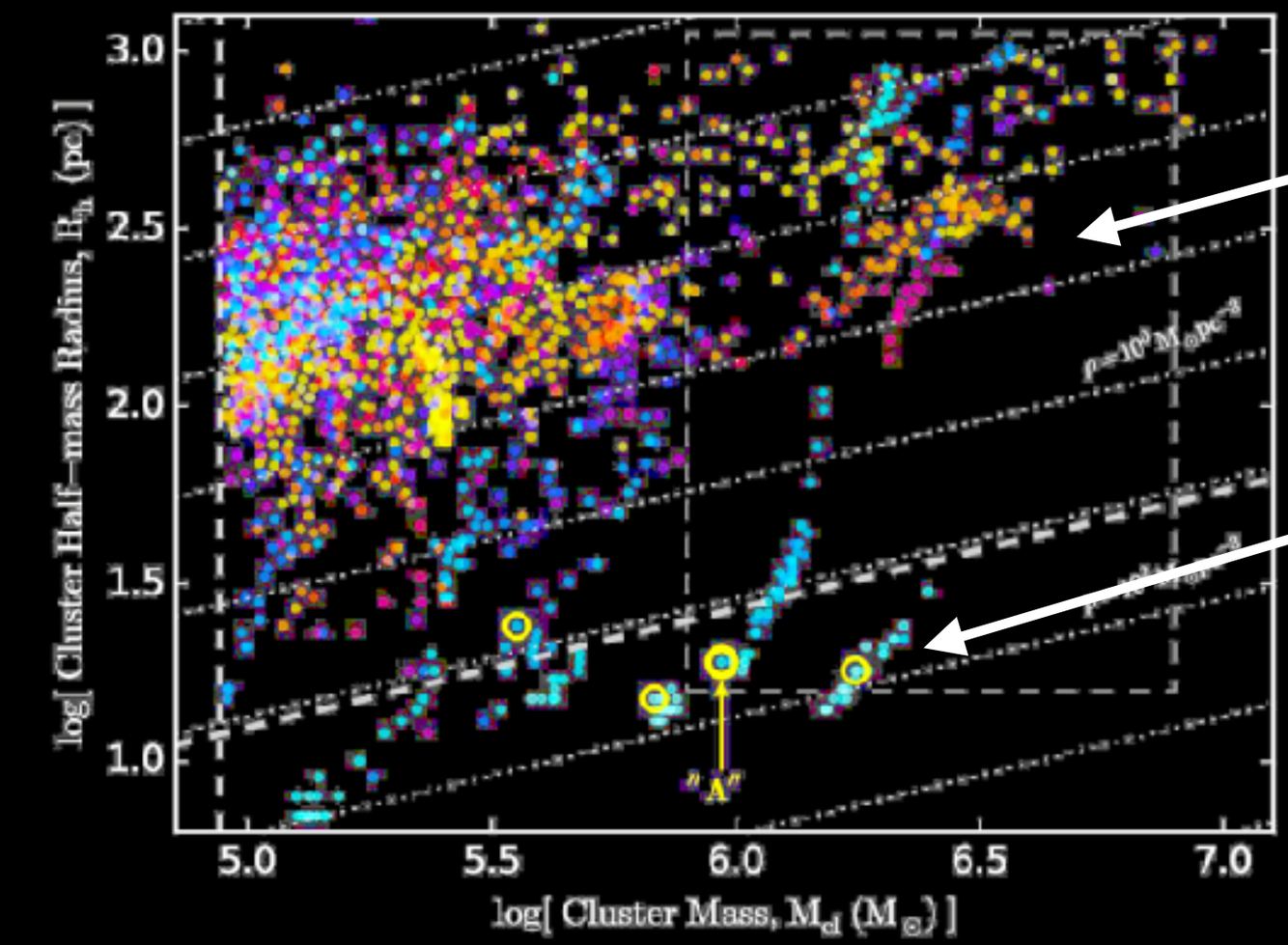


Andrew Wetzel
(arXiv:1602.05957)

"Triple Latte" (A. Wetzel): Cosmological MW with ~800 M_{sun} , sub-pc resolution

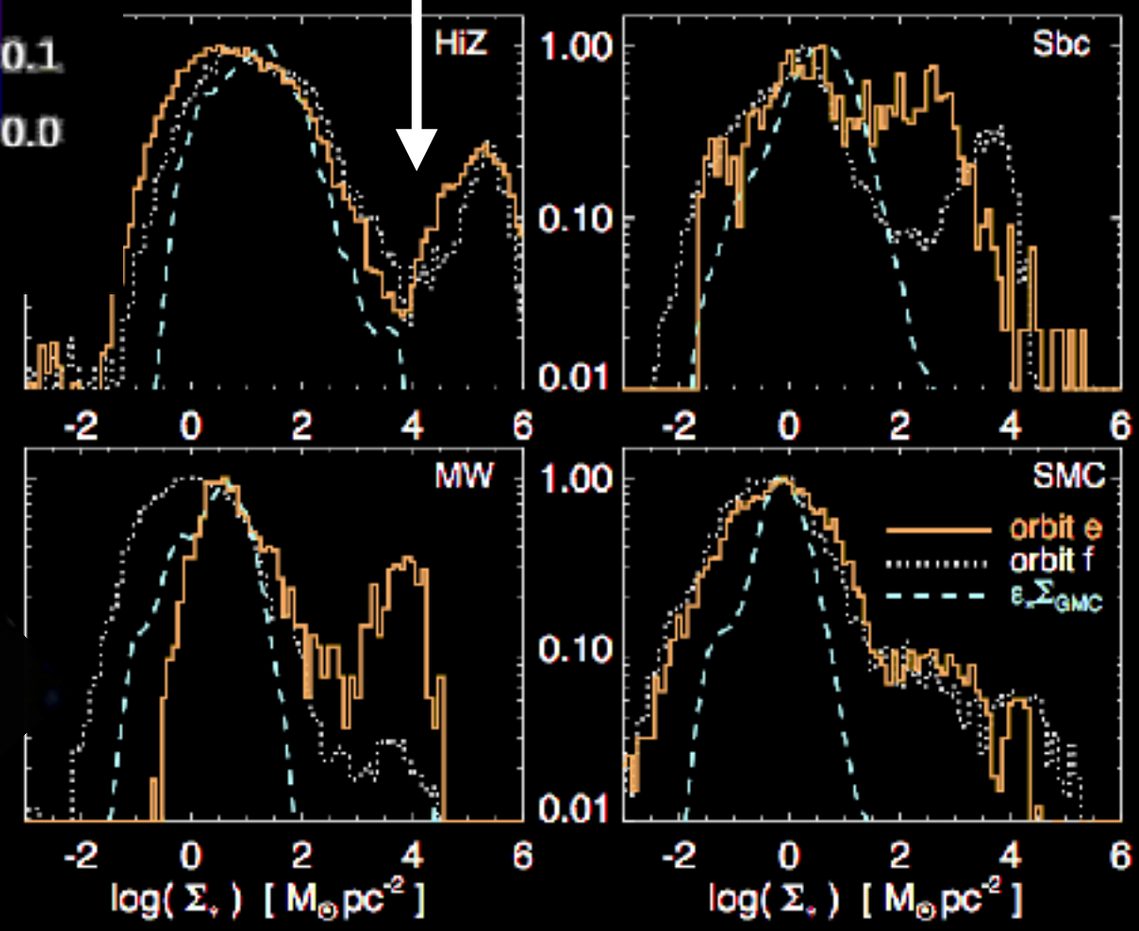
Resolving Globulars in Cosmological Simulations

(KIM '17 + GRUDIC '17)



Most form open clusters

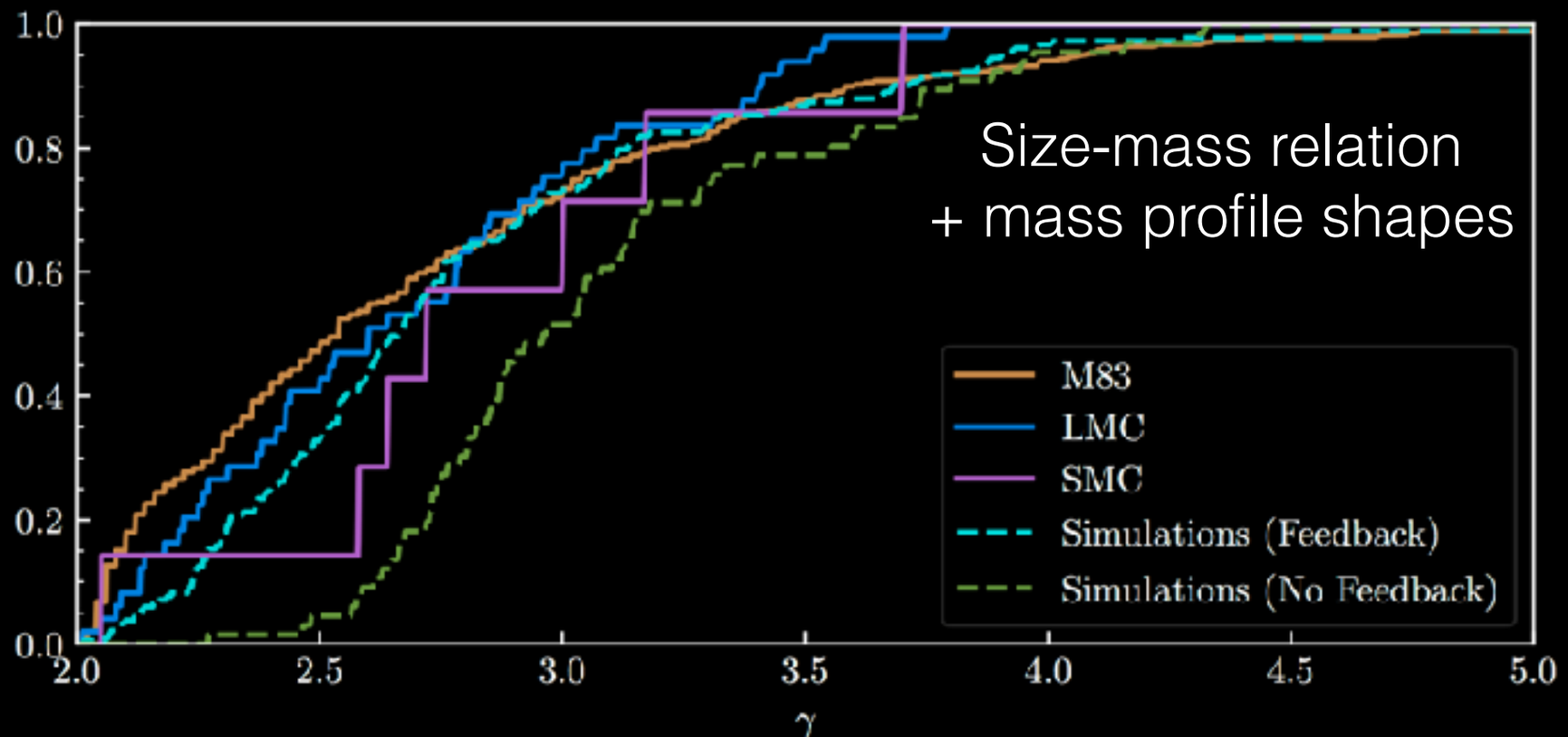
Except long-lived population, around critical Σ_{cloud}



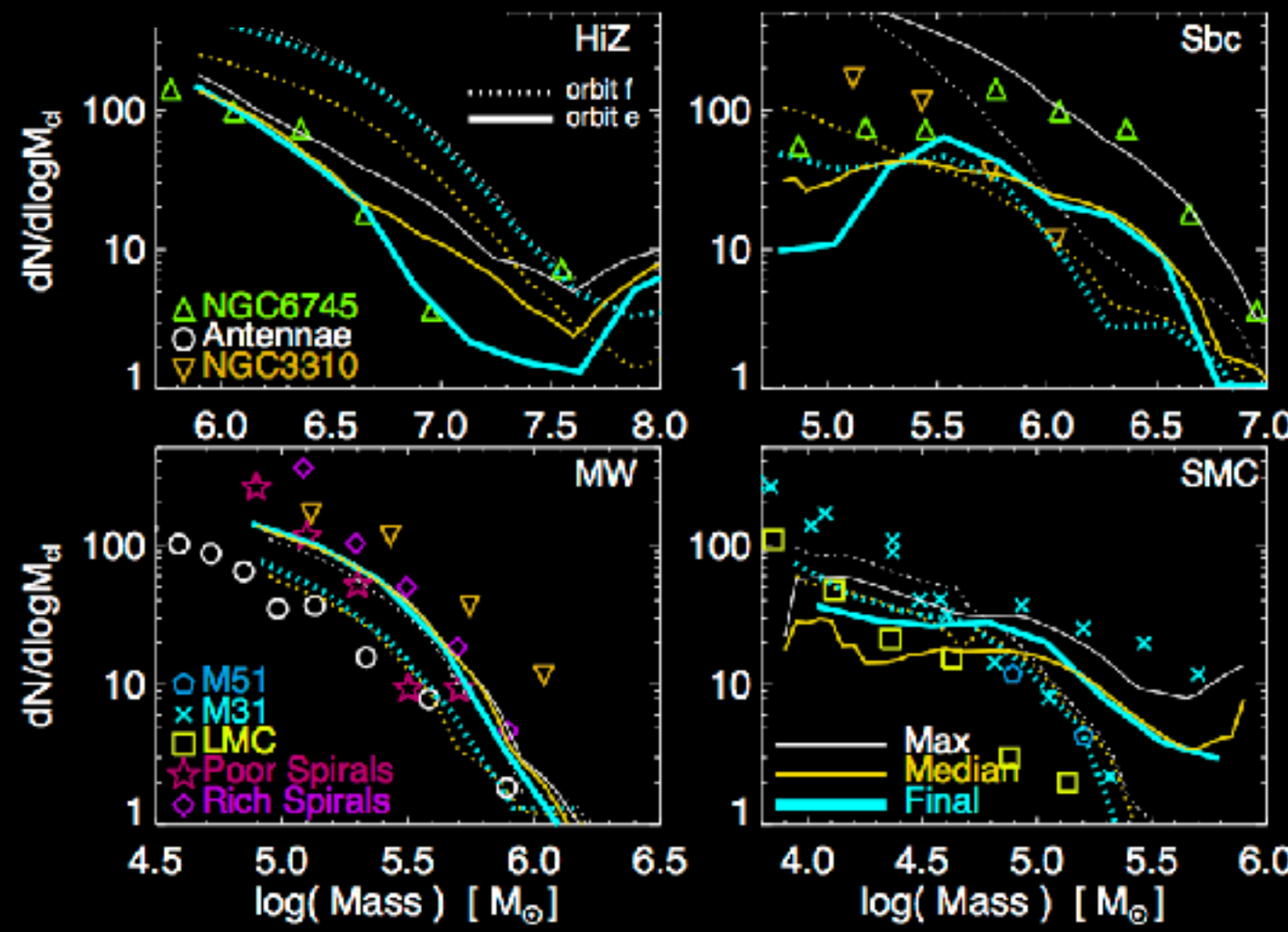
Ji-Hoon Kim (arXiv: 1704.02988)

Mike Grudic
(in prep)

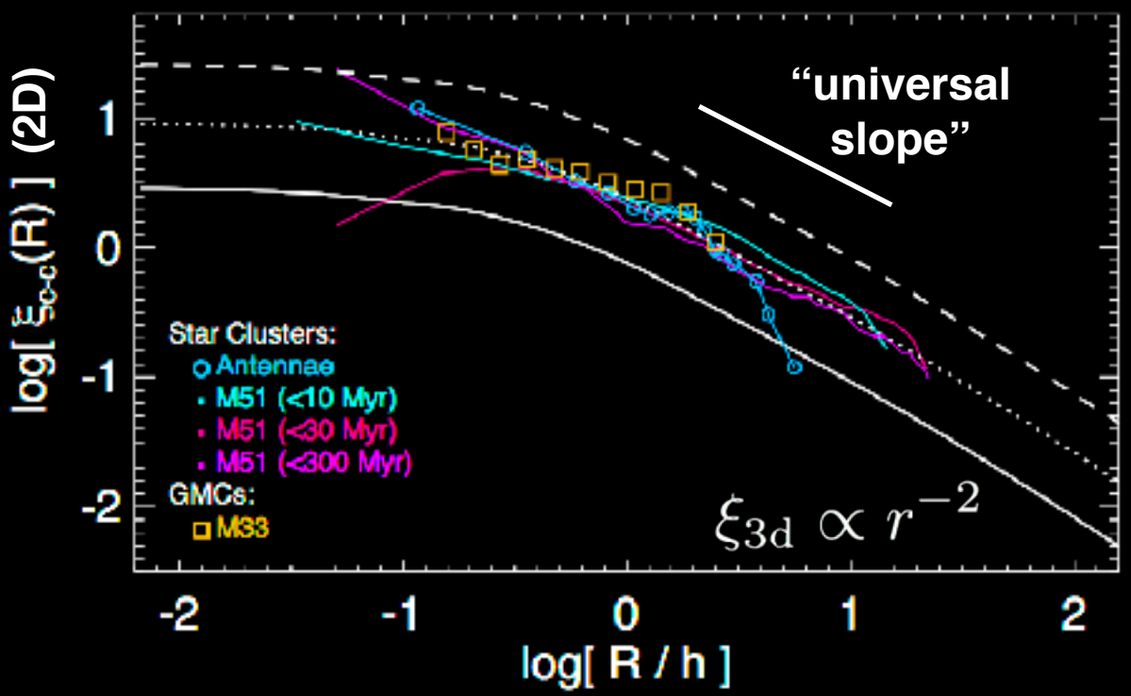
Size-mass relation
+ mass profile shapes



Mass functions (~M^{-2})
vs. environment



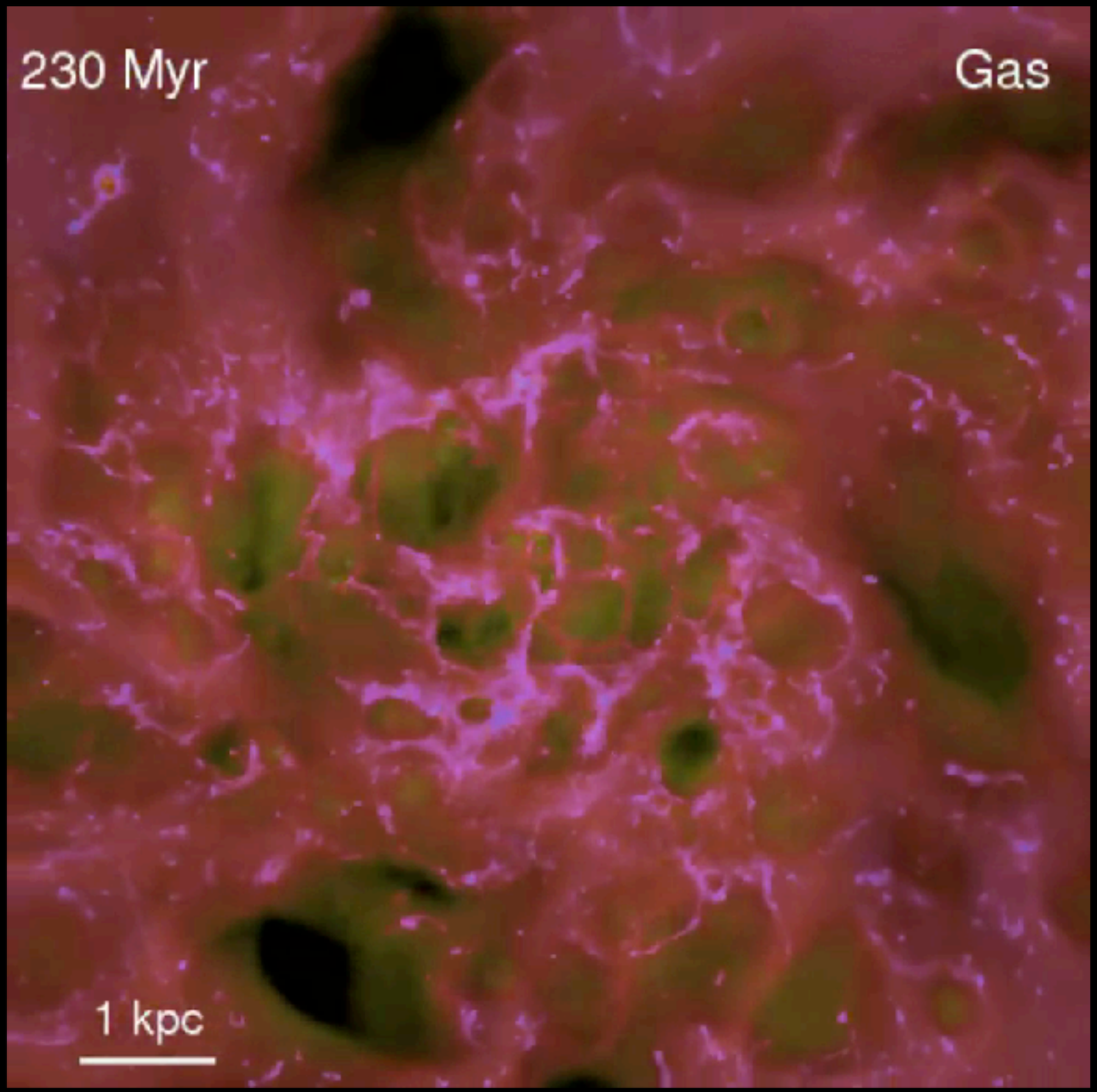
Correlation functions



~kpc Scales: Kennicutt-Schmidt

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

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

No Feedback

Observed

$$\frac{\text{Feedback}}{\text{Area}} \propto (...)\,\dot{\Sigma}_*$$

$$\frac{\text{Gravity}}{\text{Area}} \propto G\,\Sigma_{\rm tot}\,\Sigma_{\rm gas} \propto \Sigma_{\rm gas}^{1-2}$$

$\log(\,\Sigma_{\rm SFR}\,)$ $[\mathrm{M_\odot\ yr^{-1}\ kpc^{-2}}]$

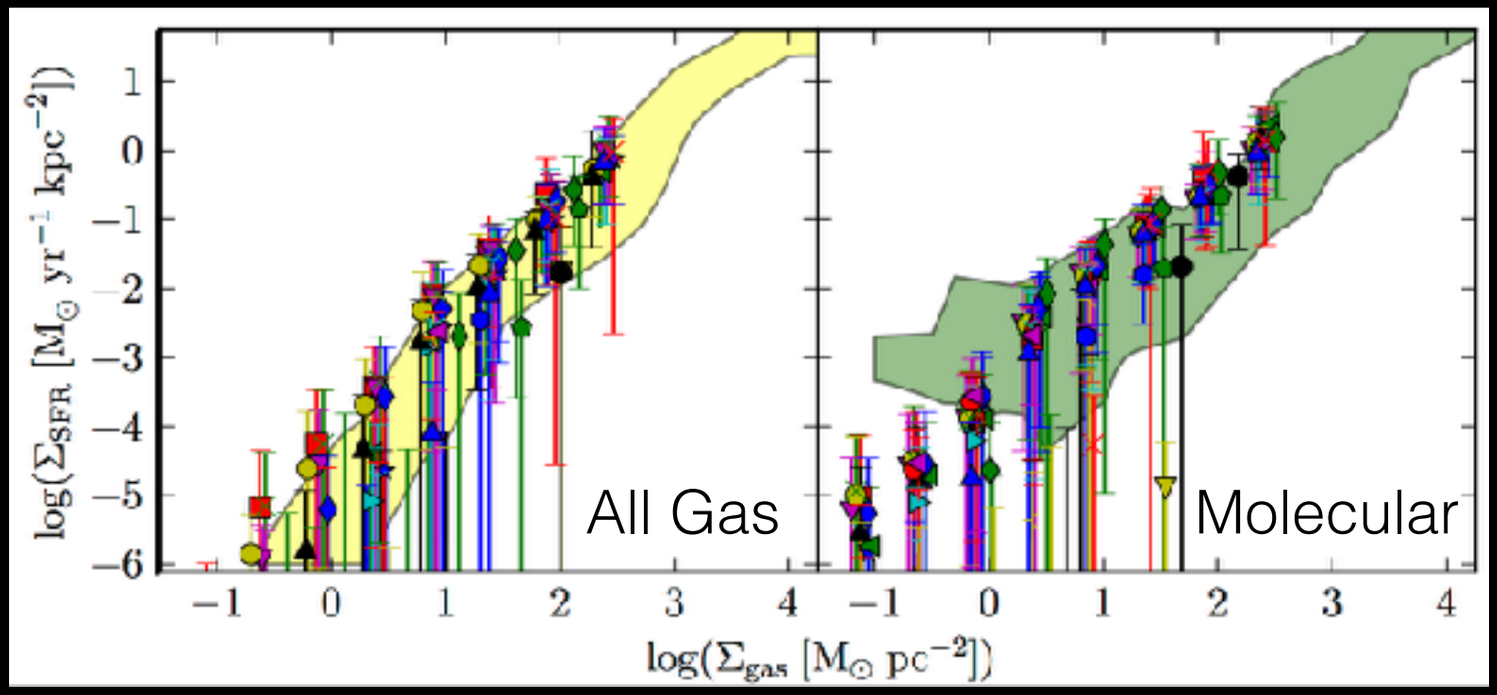
$\log(\,\Sigma_{\rm gas}\,)$ $[\mathrm{M_\odot\ pc^{-2}}]$

2 1 0 −1 −2 −3 −4 −5

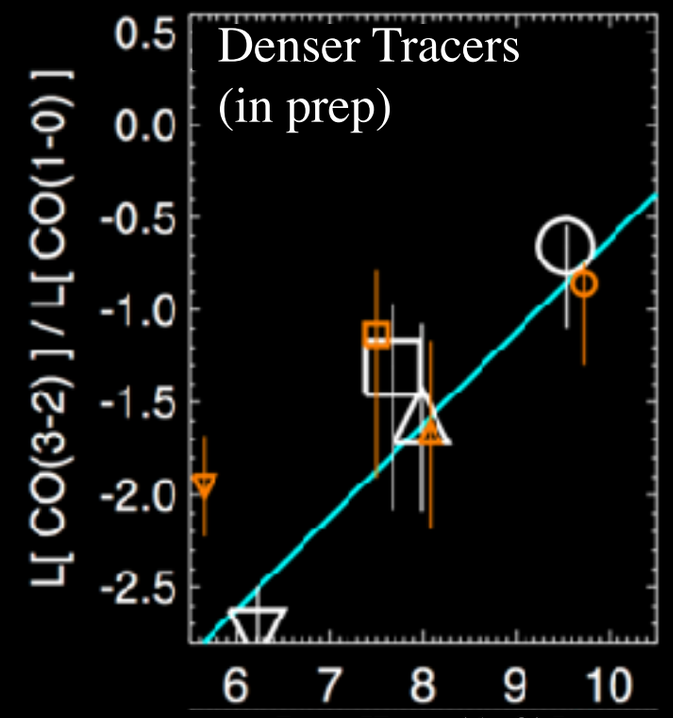
0 1 2 3 4

The KS Law: Different Information on Different Scales

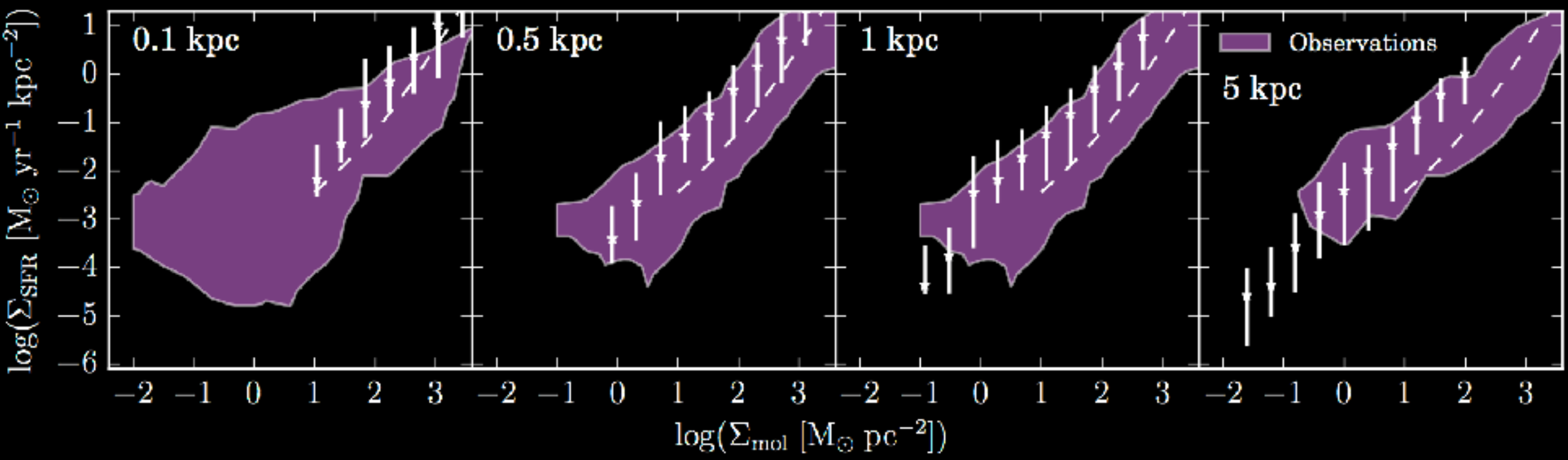
Matt Orr (1701.01788)
+ '17 (in prep)



Redshift-independent, weakly metallicity-dependent

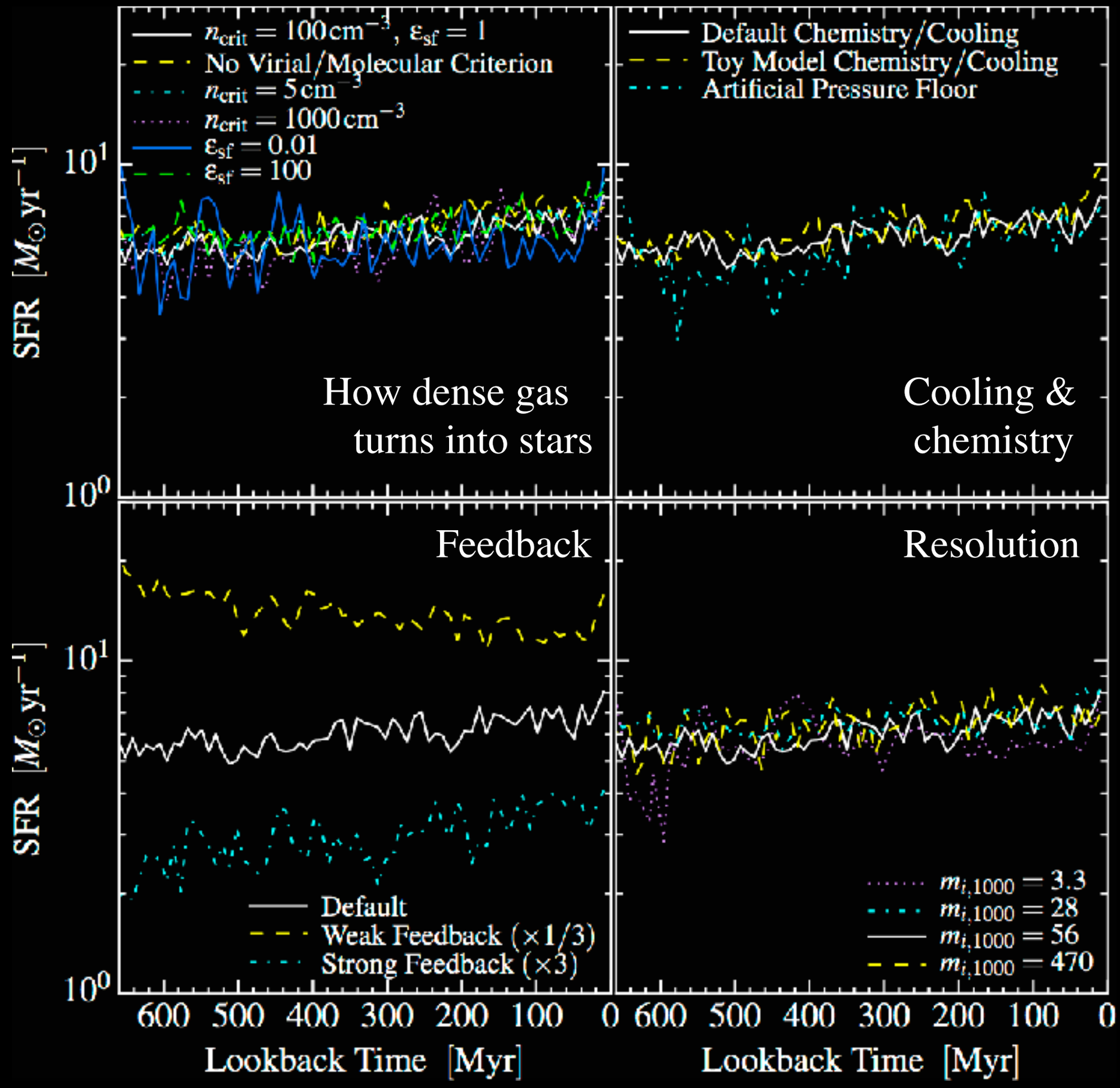


Different "resolved" laws: **no dependence on "numerical" SF law!!!**



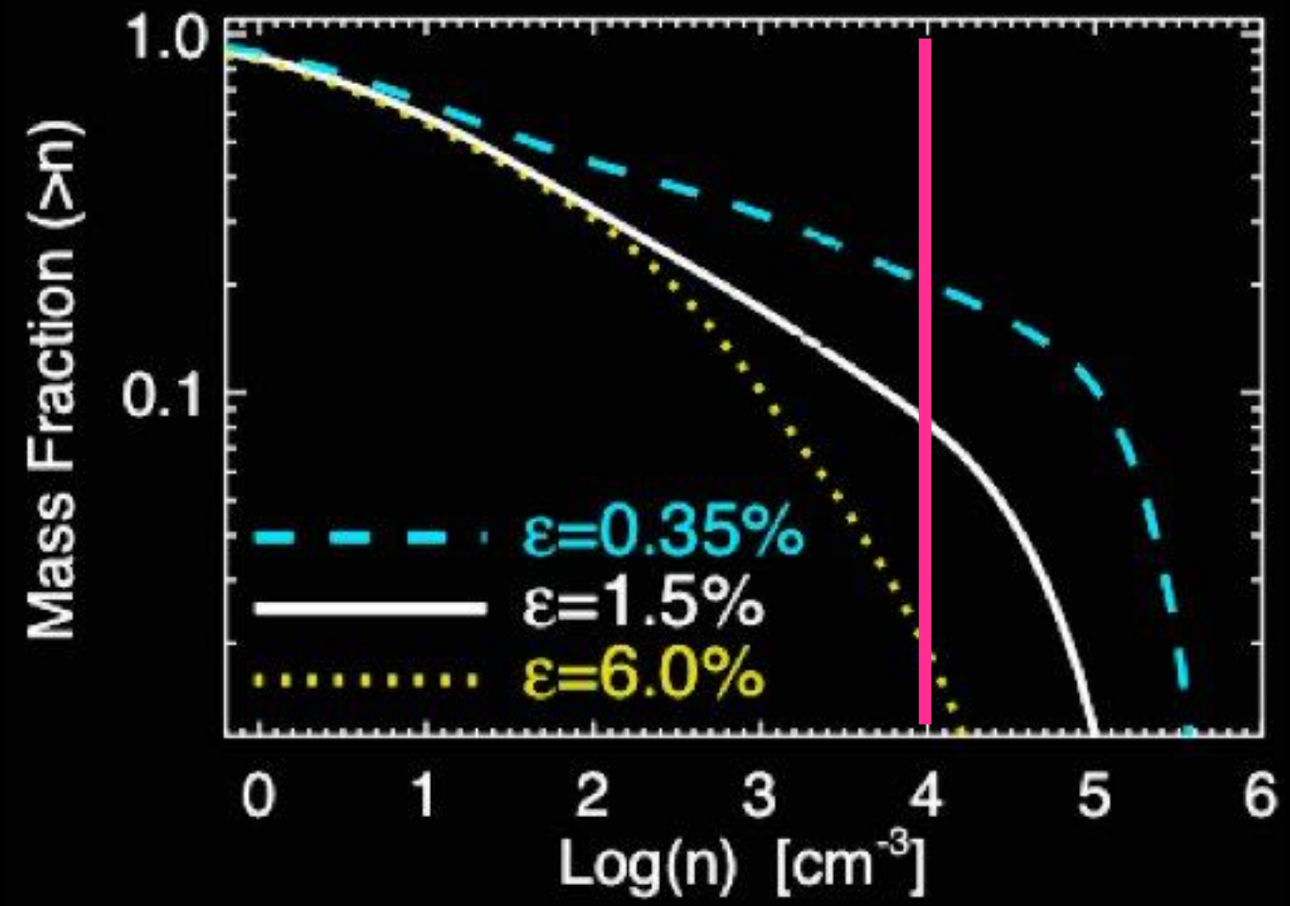
(Galactic) Star Formation Rates are *INDEPENDENT* of how stars form!

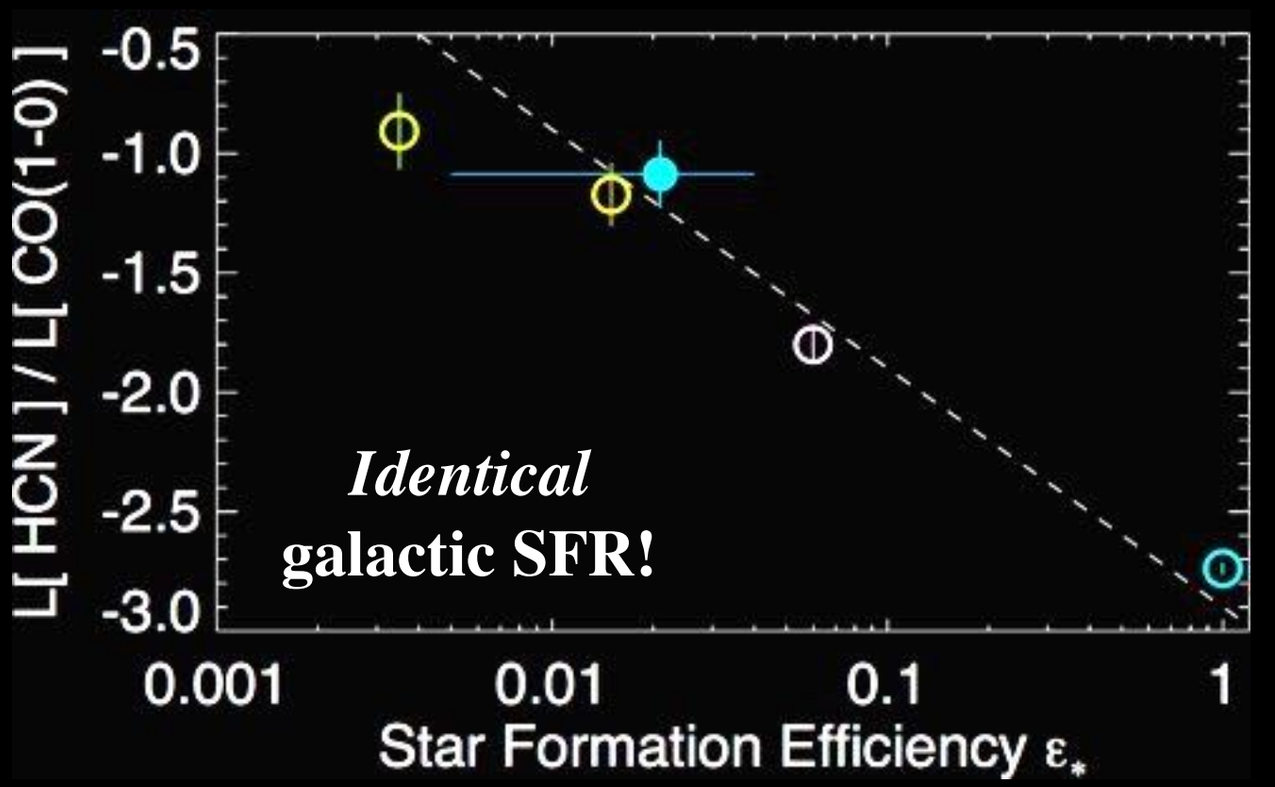
Orr (1701.01788)
Saitoh+ 11
Hopkins+ 11,12,14
Agertz+14



Dense Gas *Does* Change
SELF-REGULATES TO "NEEDED" SFR LEVEL

Efficiency (SF per t_{dyn}) in *dense* gas





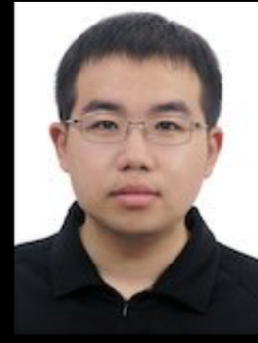
(molecular gas)

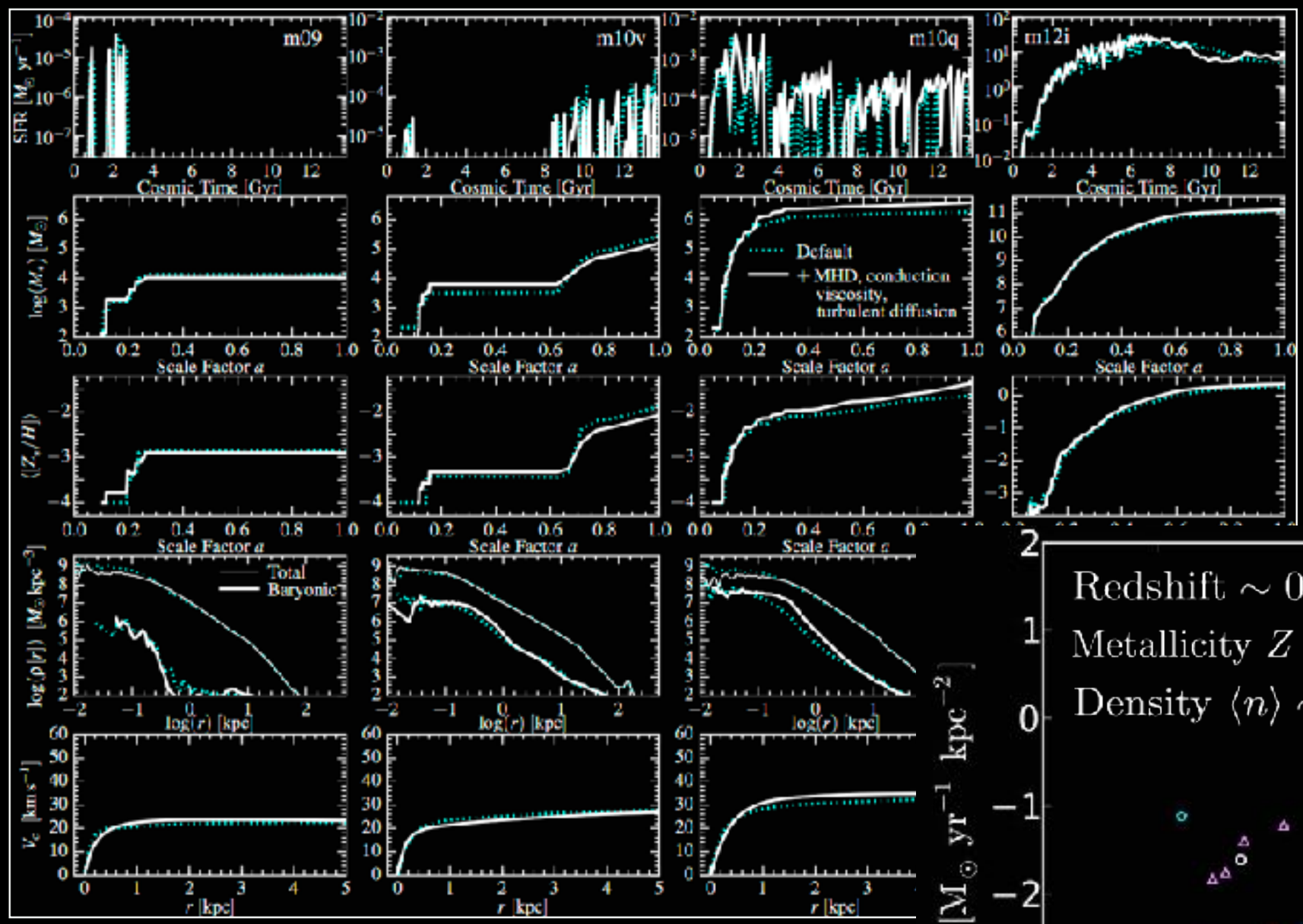
Matt Orr (1701.01788)
Hopkins+ 11,12,14
Shetty+ 14
Narayanan+ 13

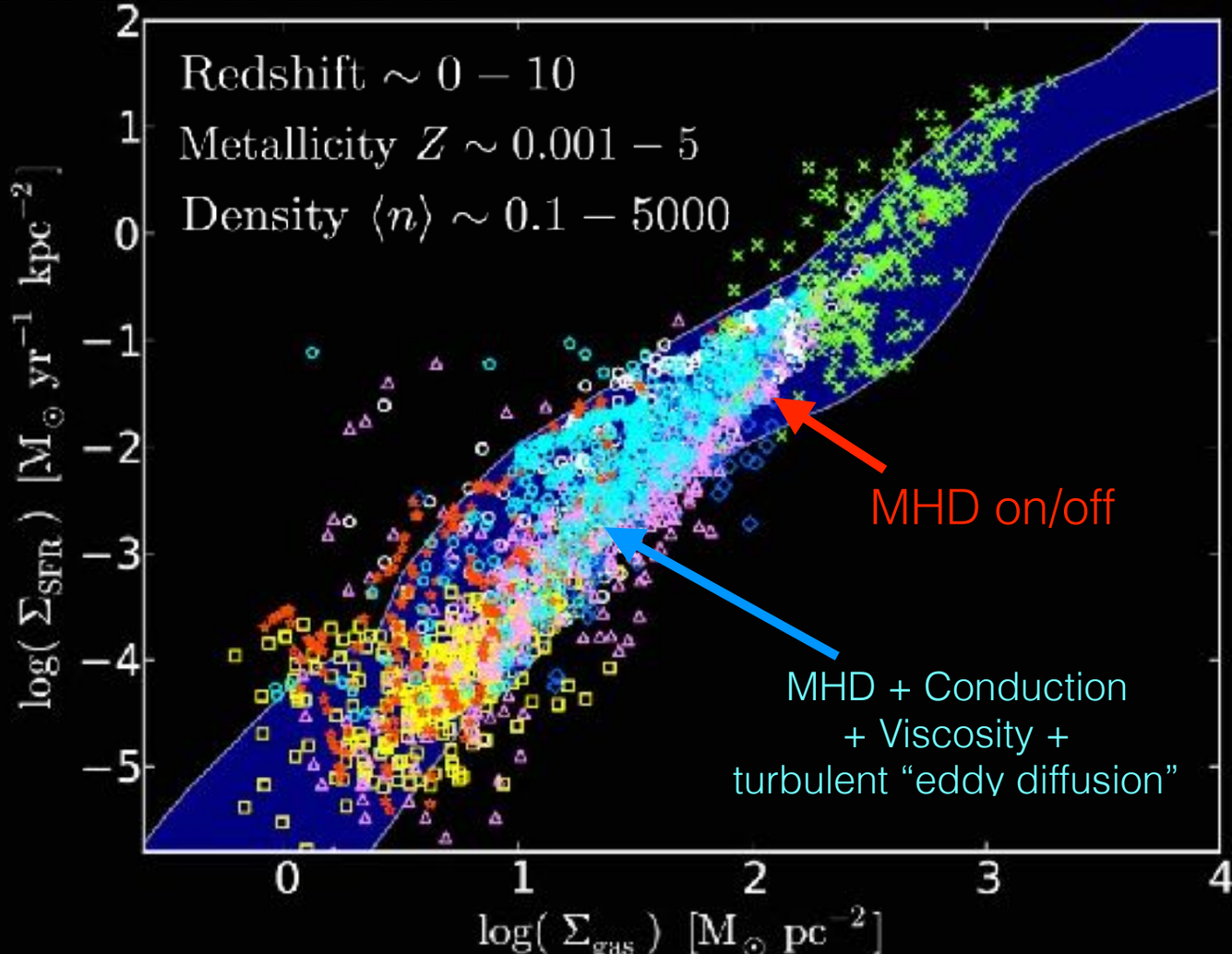
No dependence on MHD, conduction, viscosity, etc.

ONLY SEE IF FEEDBACK IS ARTIFICIALLY WEAK

Kung-Yi Su
(arXiv:
1607.05274)







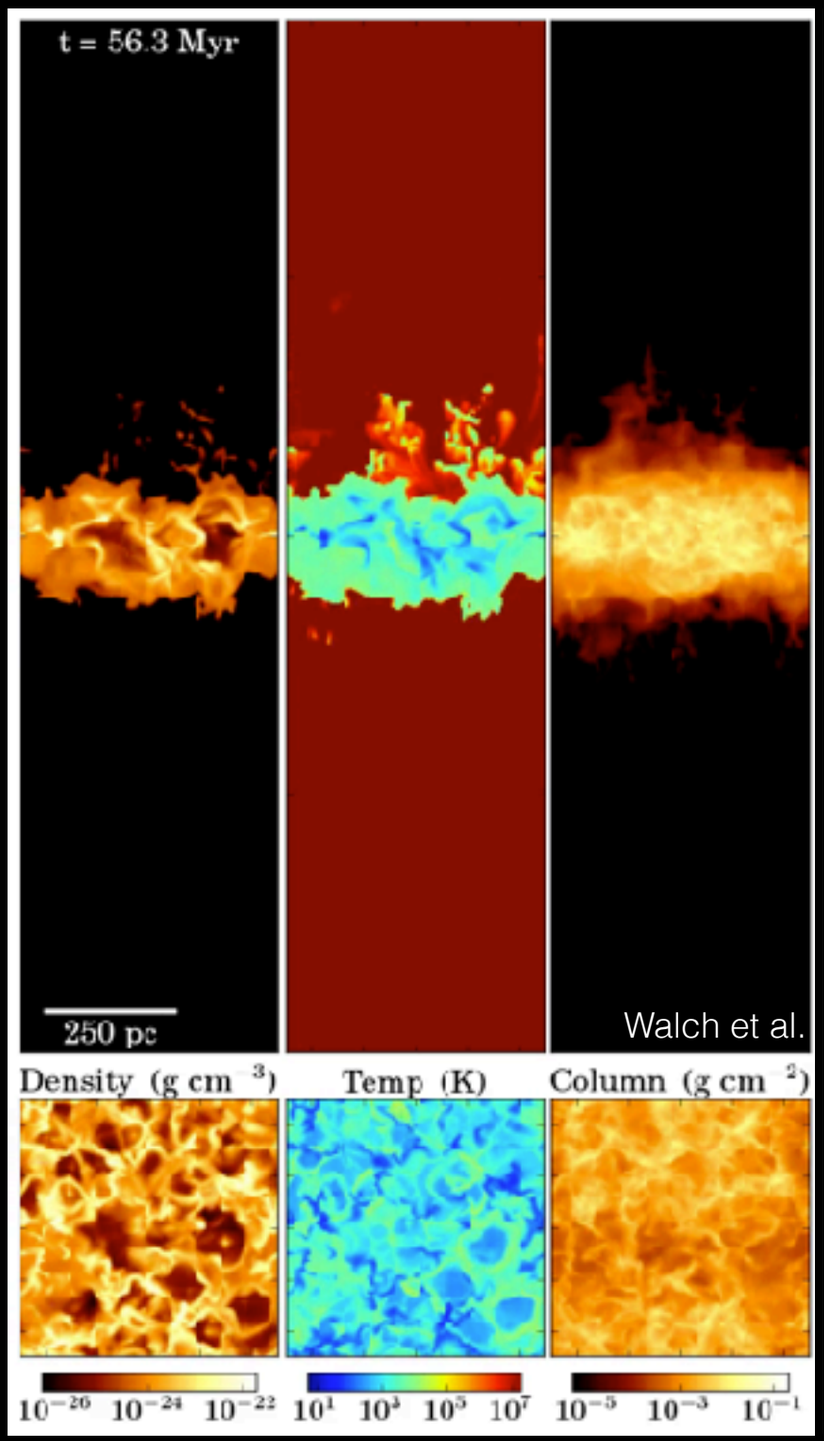
Galactic/Cosmological SFRs:
Driving Winds

Remember Stellar Clustering?

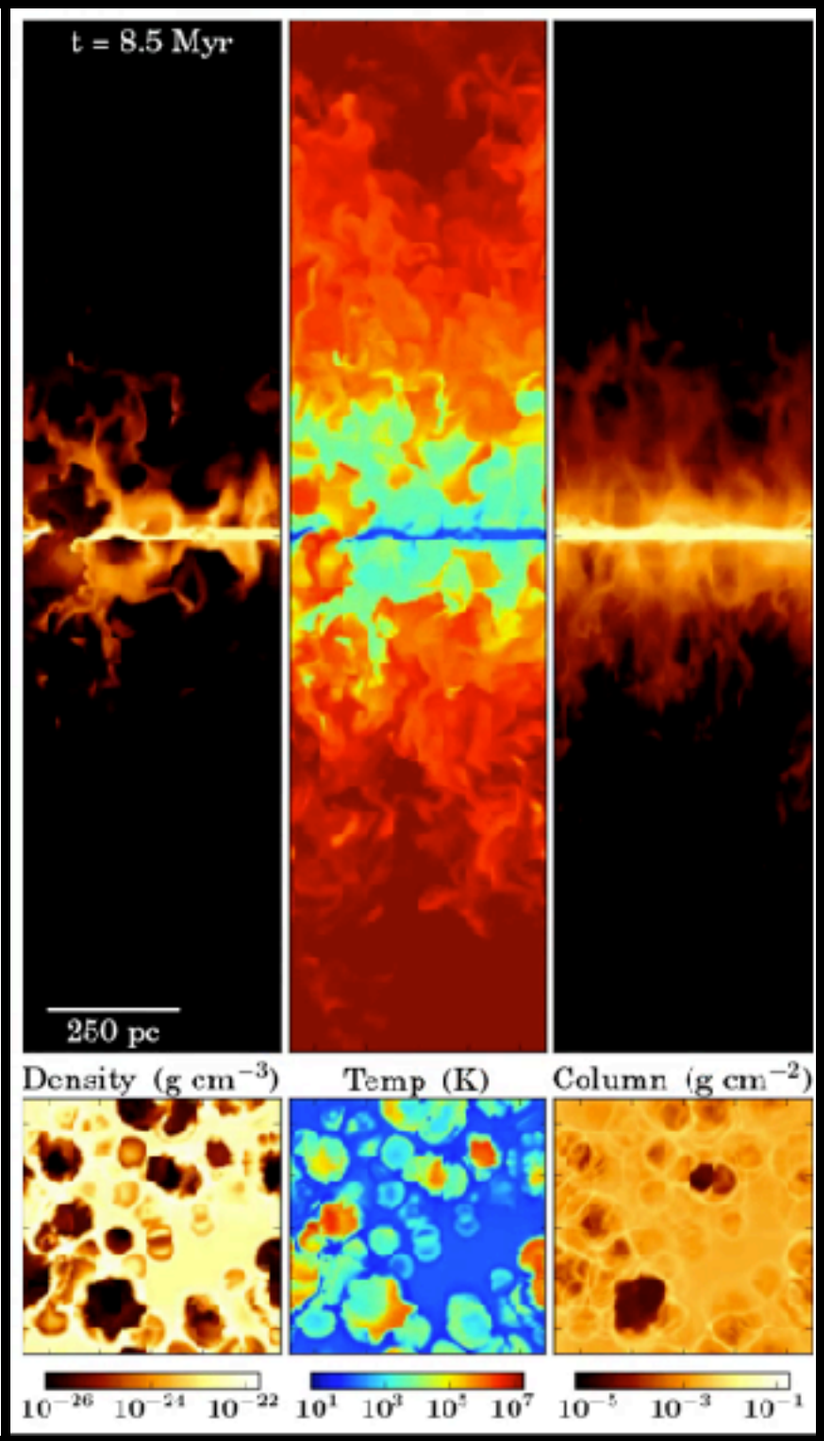
THIS MATTERS, A LOT!

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

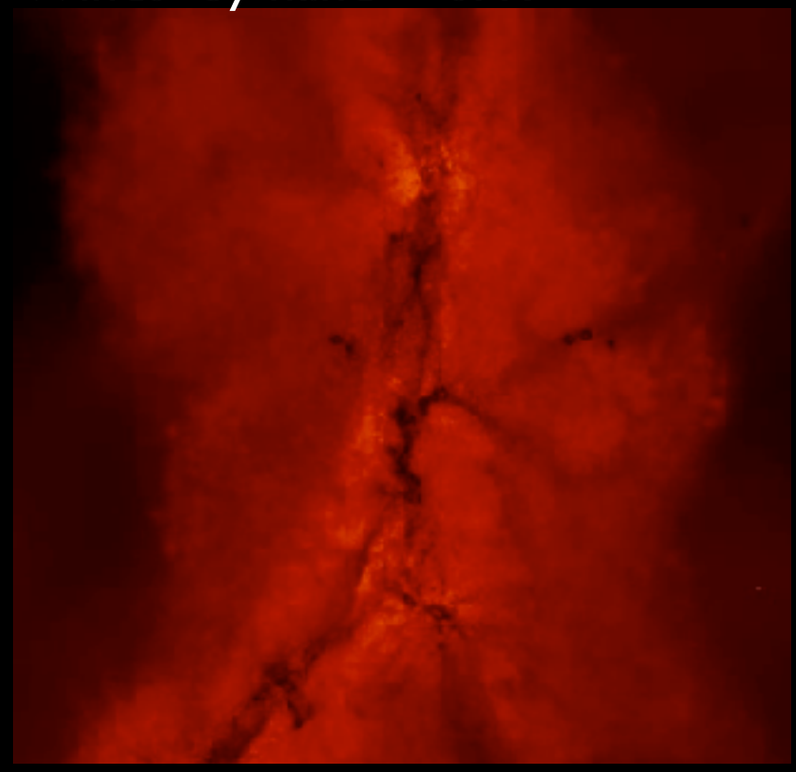
SNe Explode in Density Peaks
(no radiative feedback)



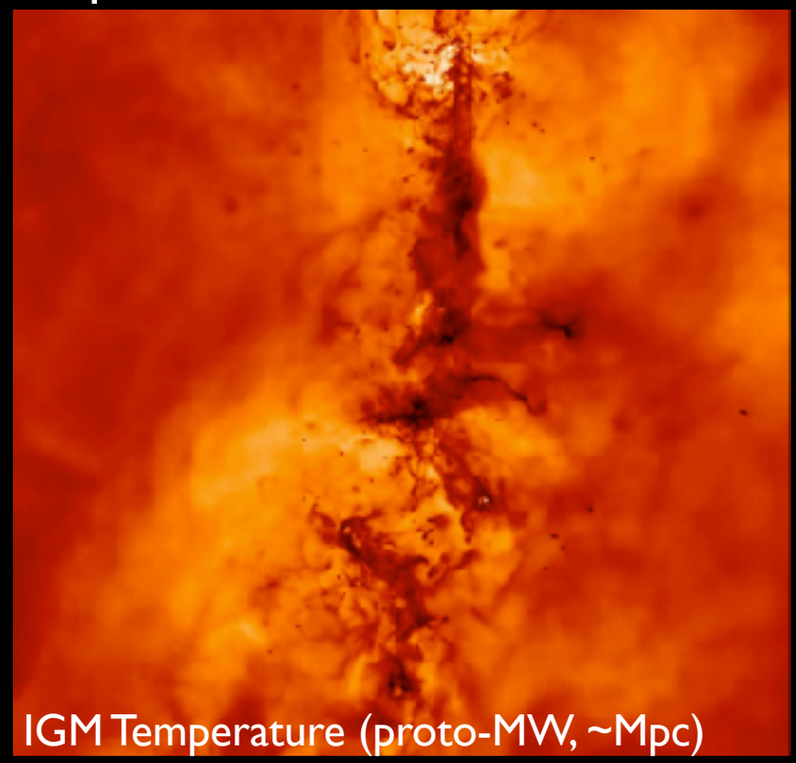
SNe Clustered & Off-Peak
(radiative feedback/pre-processing)



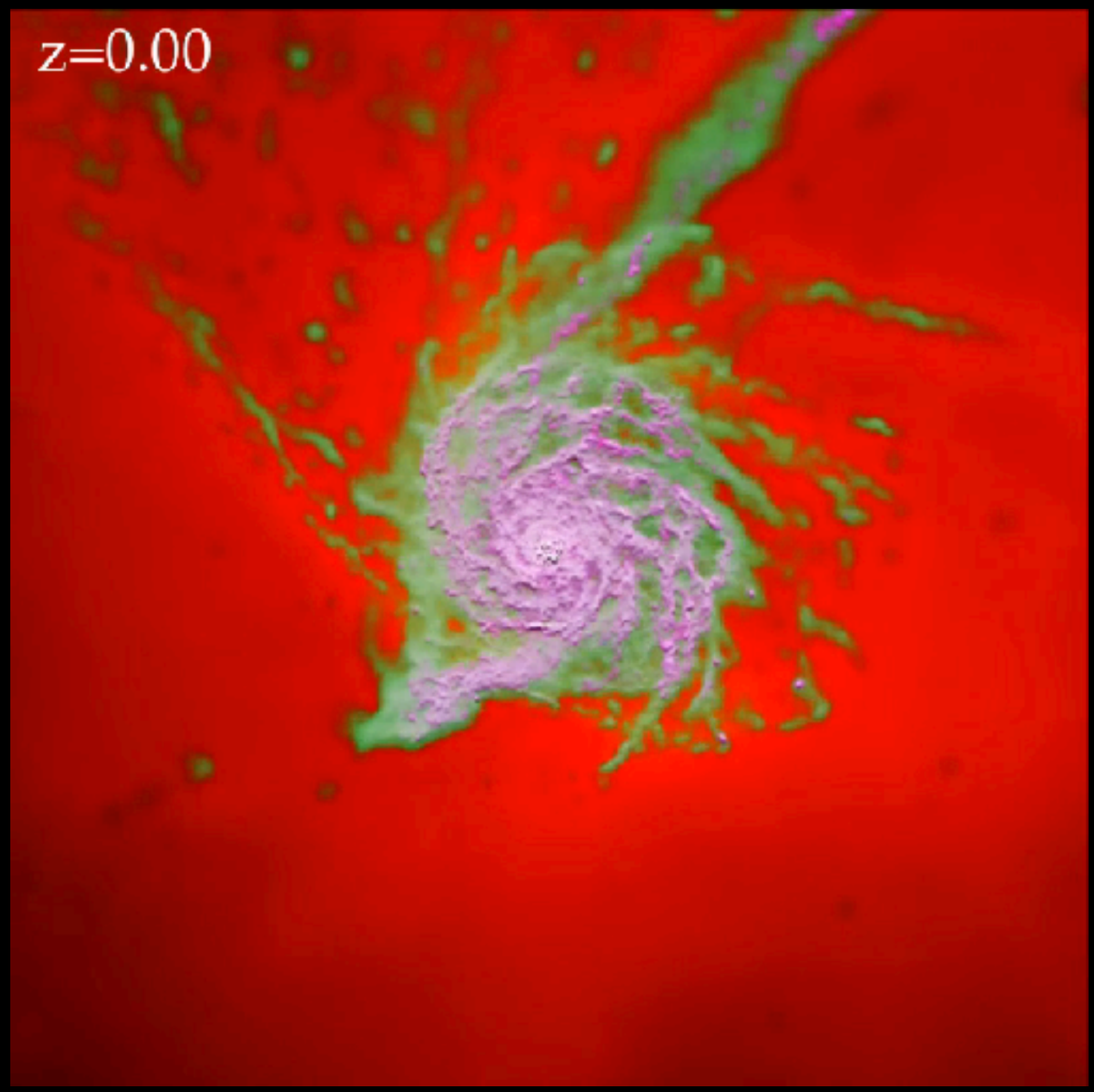
Winds “by hand” ~SFR



Explicit ISM/Feedback



(movies at fire.northwestern.edu)



Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

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

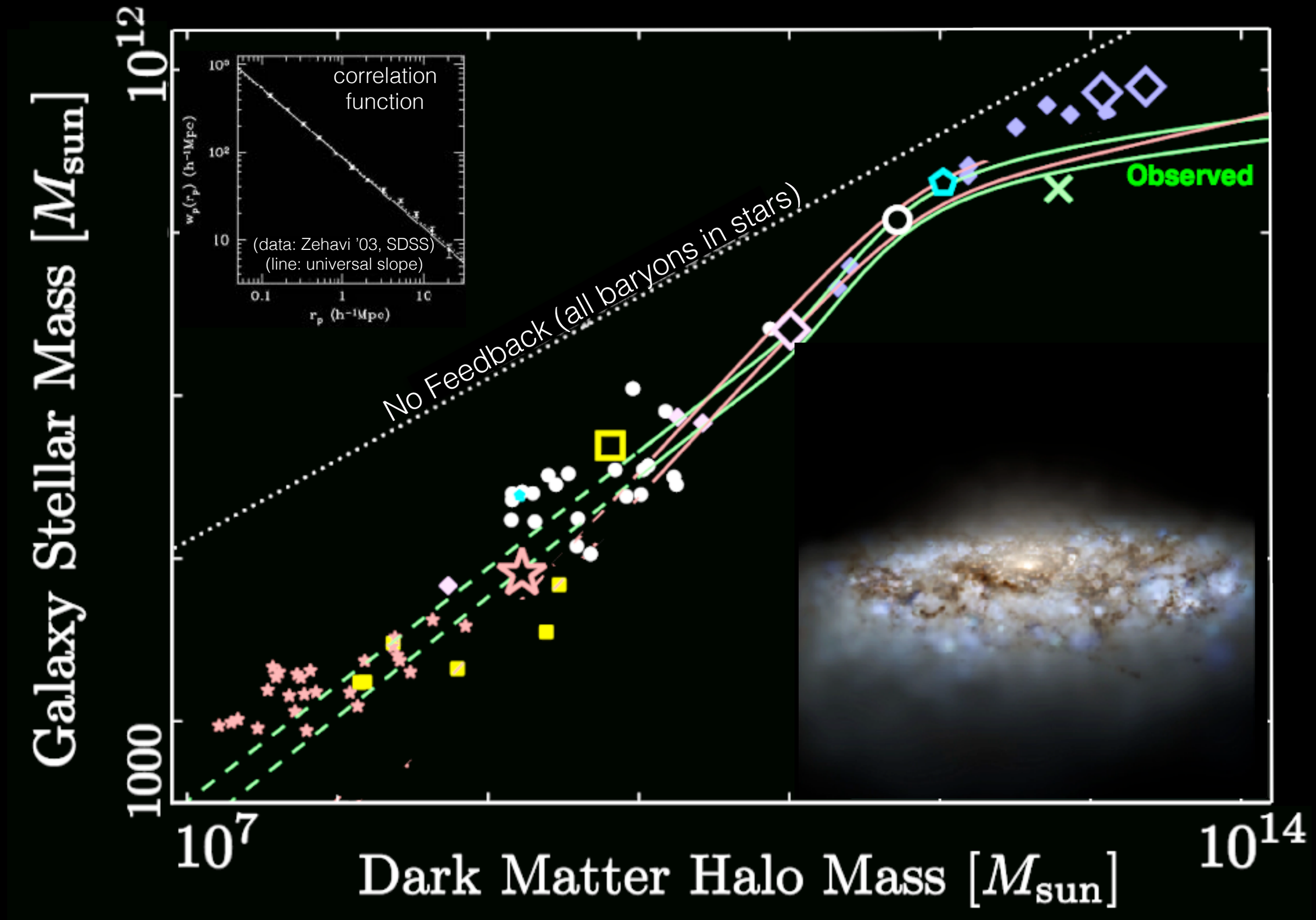
Green: warm (ionized)

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

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

GAS IS BLOWN OUT, INSTEAD OF TURNING INTO STARS

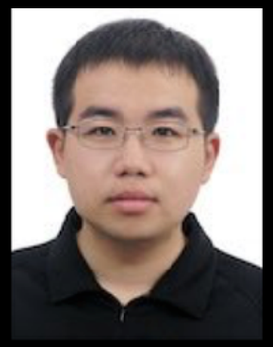
PFH et al.
(arXiv:1311.2073)

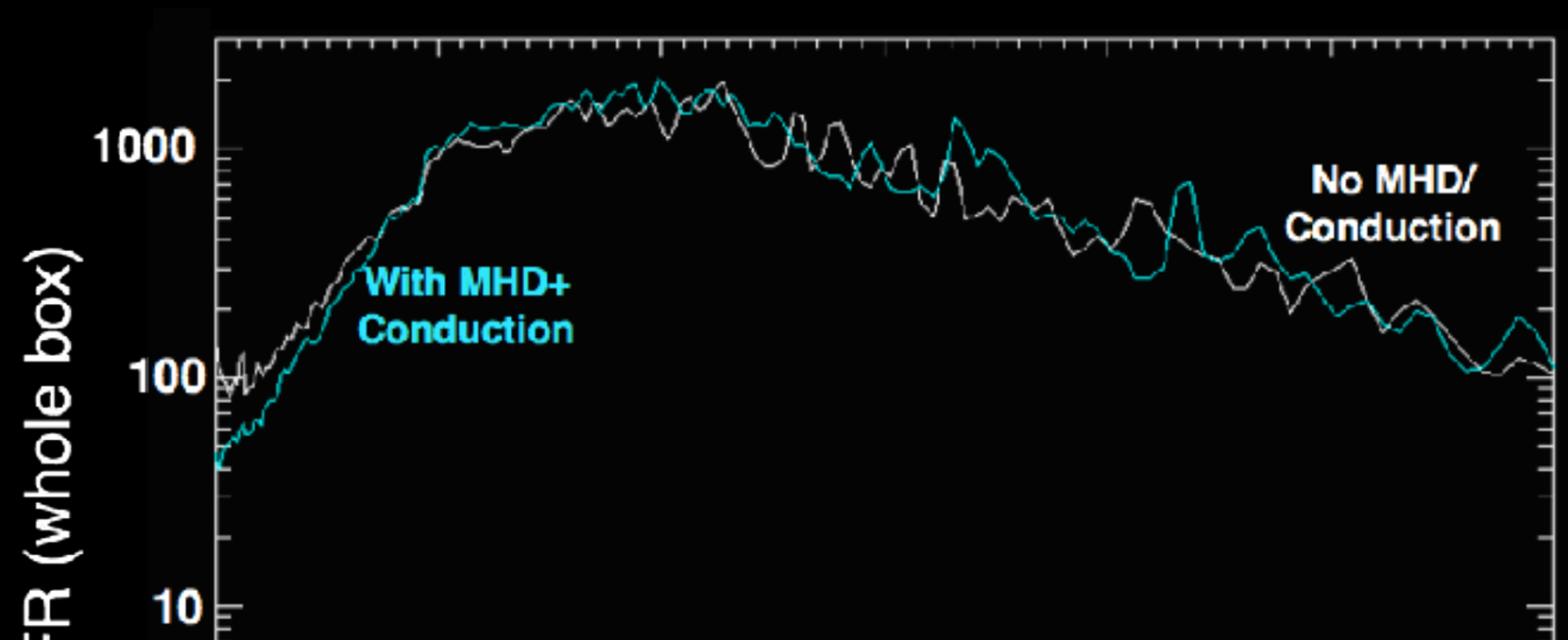


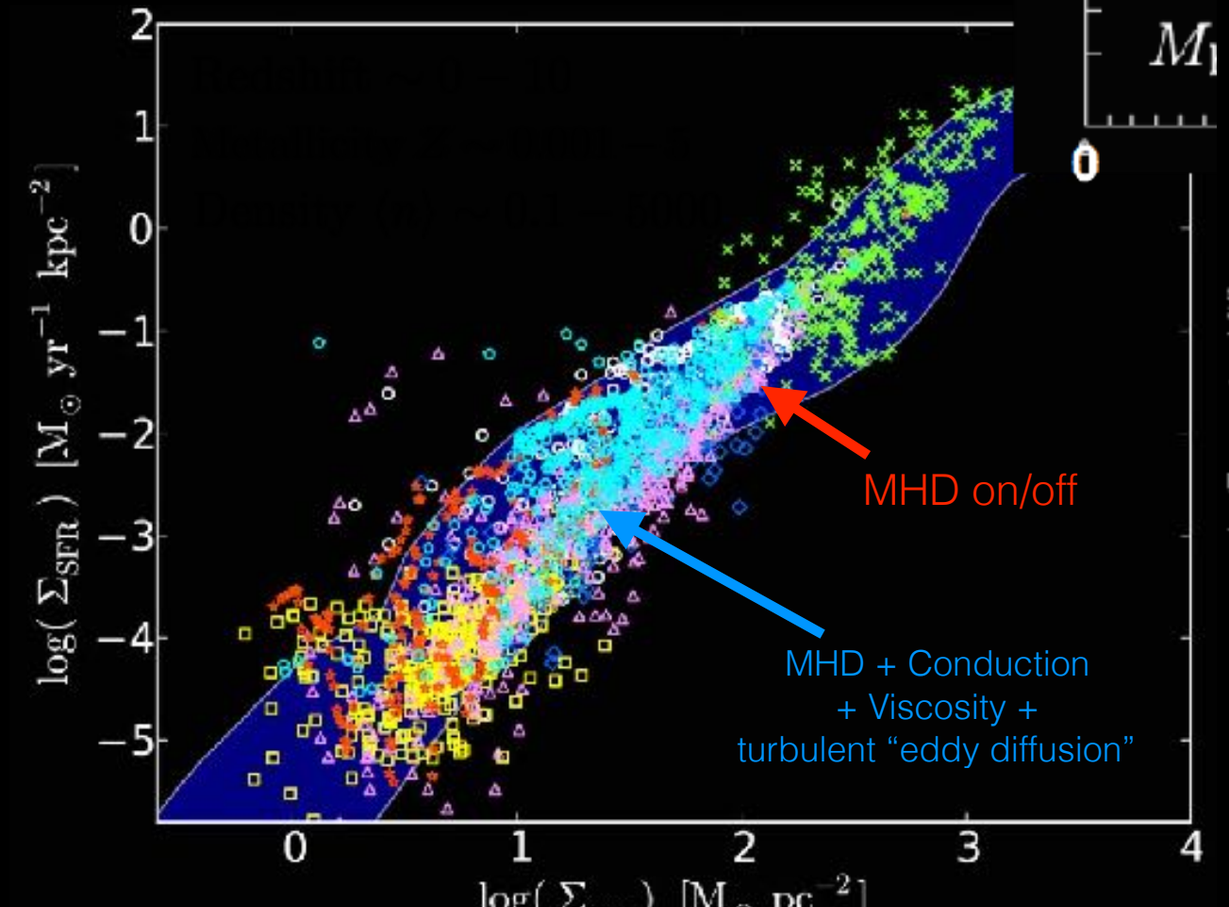
Fluid Microphysics… Don't Do Much

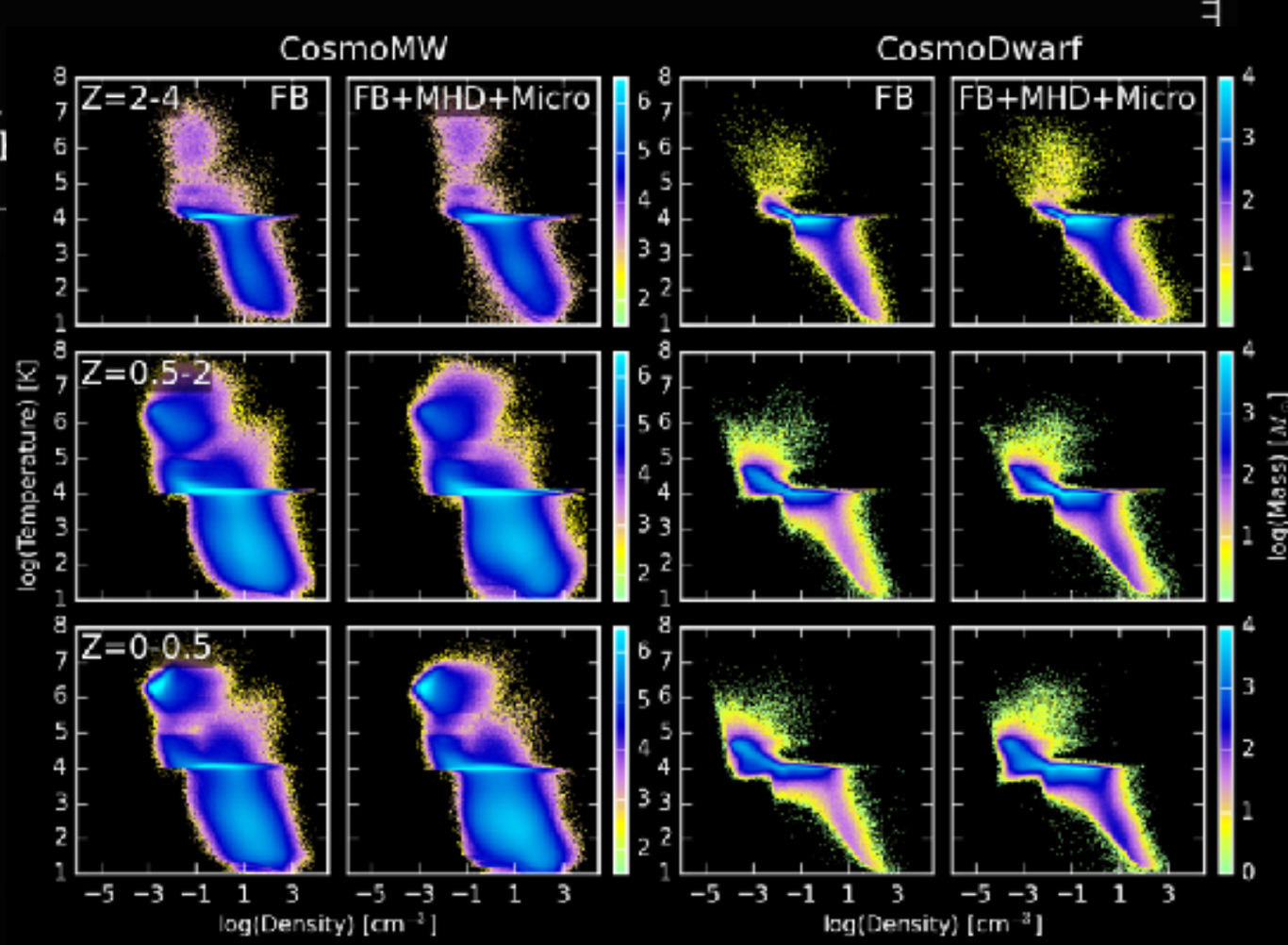
MHD, Spitzer-Braginskii conduction & viscosity, micro-eddy diffusion …

Kung-Yi Su (arXiv: 1607.05274)



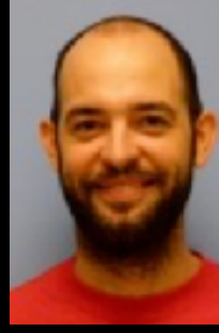






Clustering in Time & Space Matters
(NOW ON GALAXY SCALES)

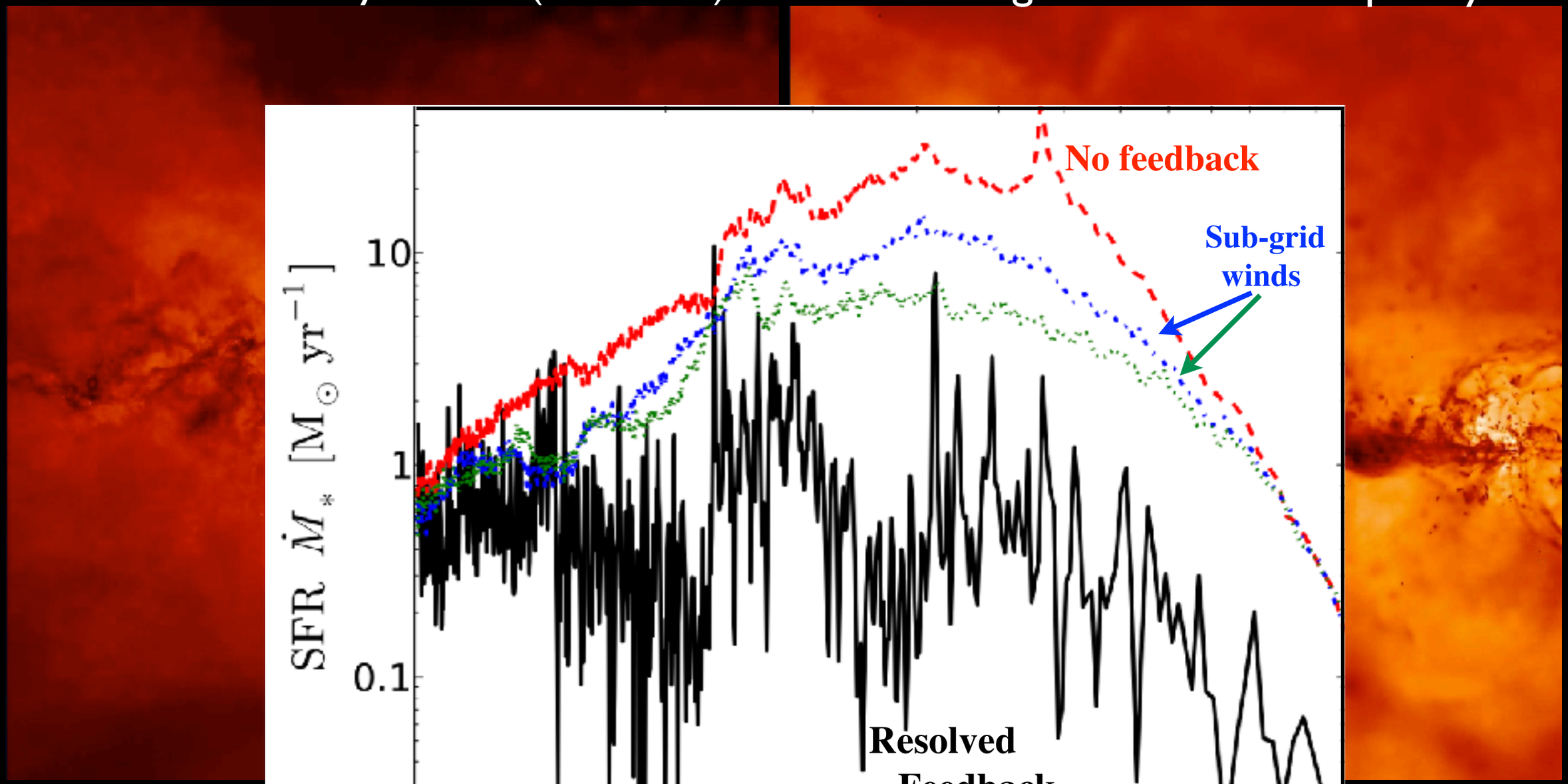
Recycling: D. Anglés-Alcázar+17
Burstiness: M. Sparre '15



Proto-Milky Way: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)

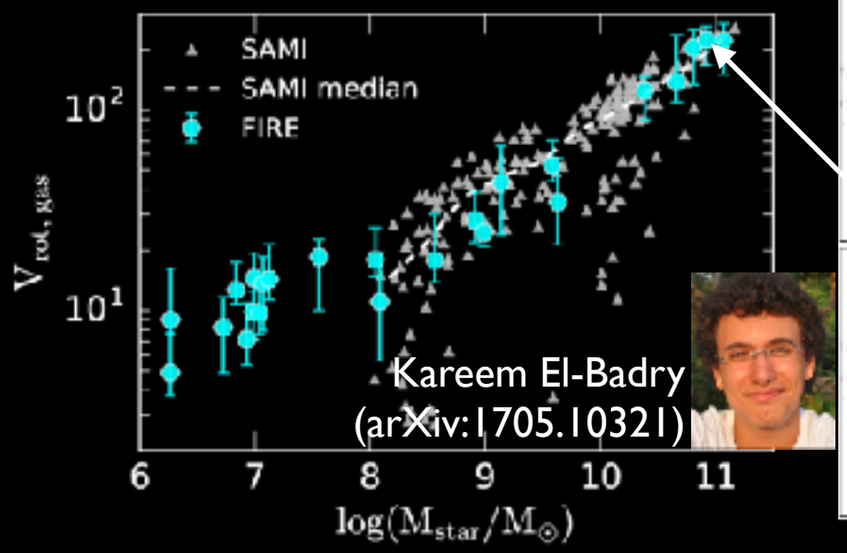
Following Feedback/ISM Explicitly



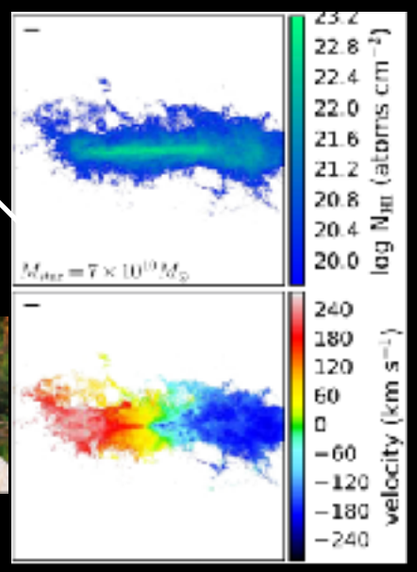
Galaxy Scaling Relations

FEEDBACK VS. GRAVITY (WHEN STARS FORM)

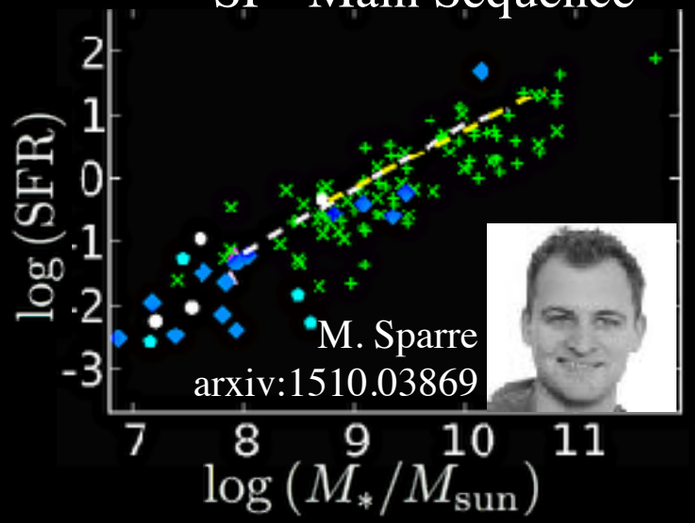
Tully-Fisher Relation



Kareem El-Badry
(arXiv:1705.10321)

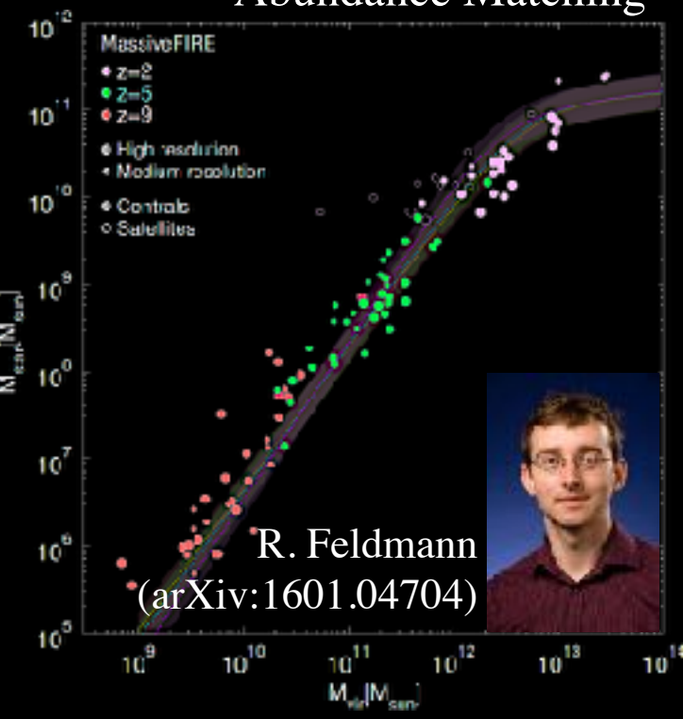


SF "Main Sequence"



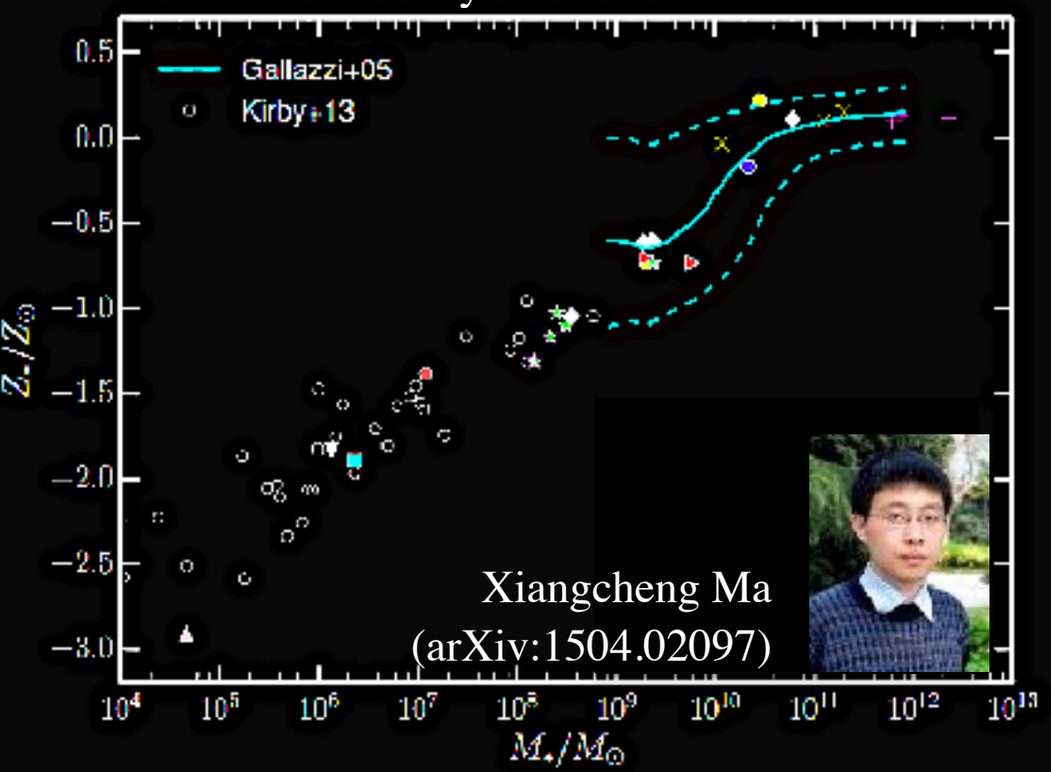
M. Sparre
arxiv:1510.03869

Abundance Matching

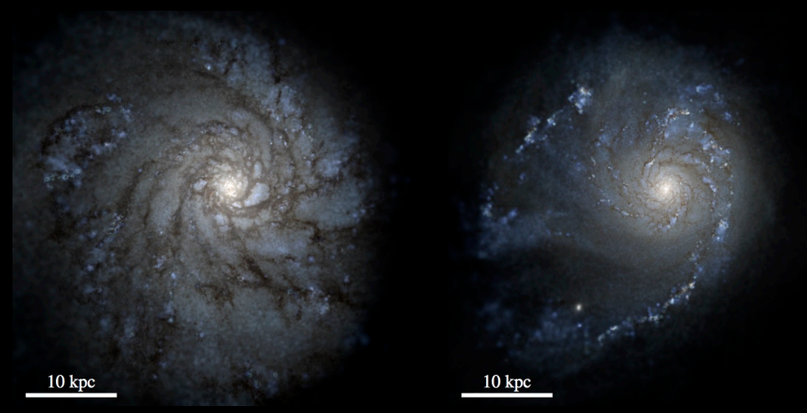


R. Feldmann
(arXiv:1601.04704)

Mass-Metallicity Relation

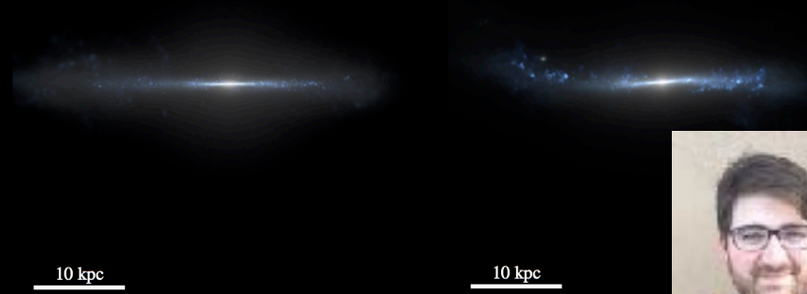


Xiangcheng Ma
(arXiv:1504.02097)



Thin Disks

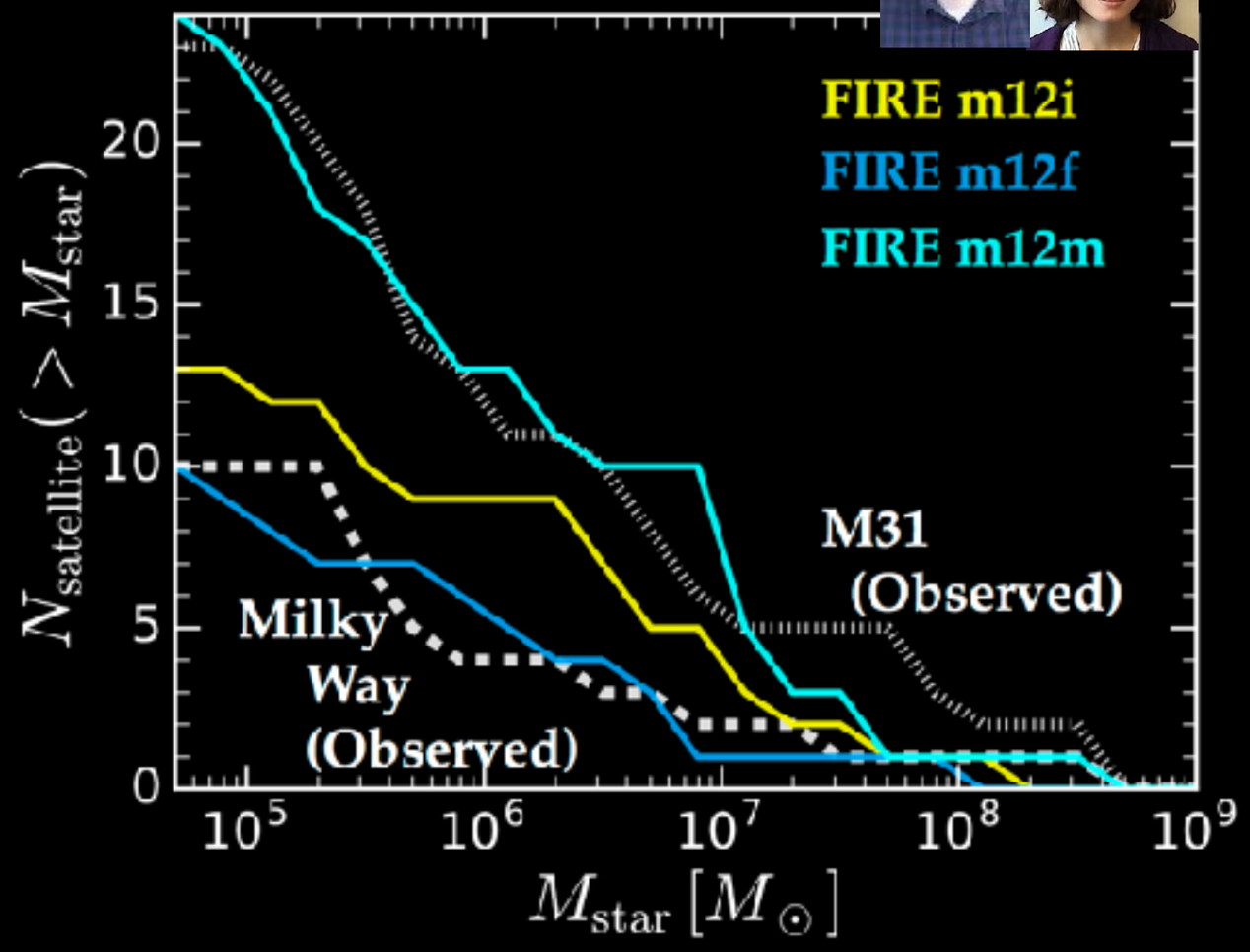
Shea Garrison-Kimmel (prep)



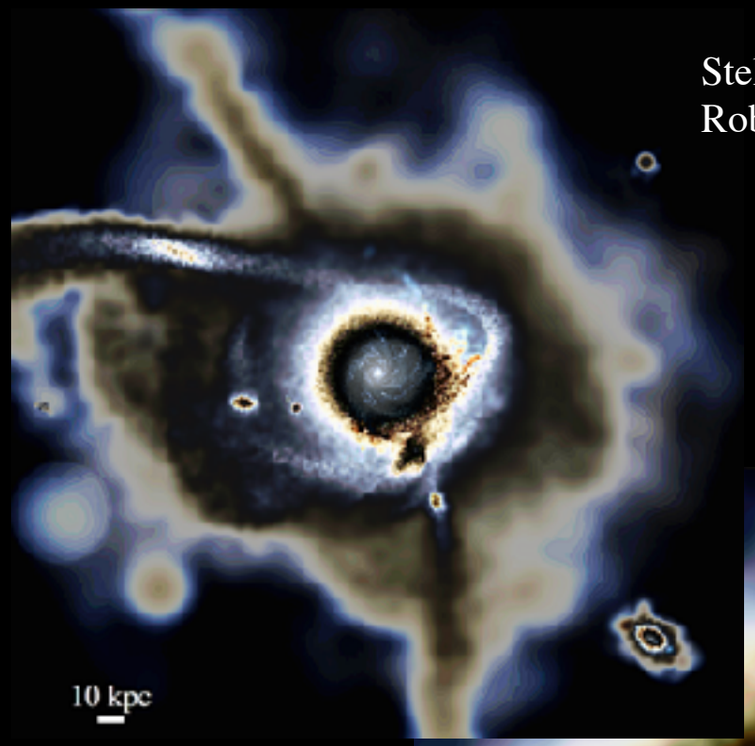
Failures No More

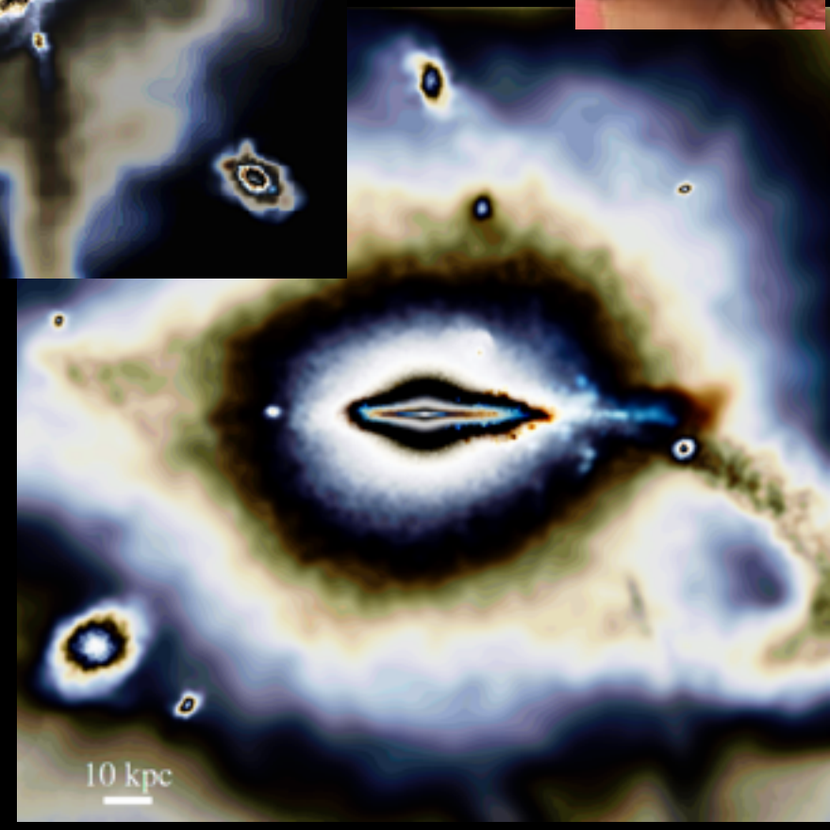
FEEDBACK SUPPRESSES STAR FORMATION AND DENSITIES

"Missing Satellites"
Garrison-Kimmel & Wetzel & Escala, in prep



Stellar Halos
Robyn Sanderson (prep)

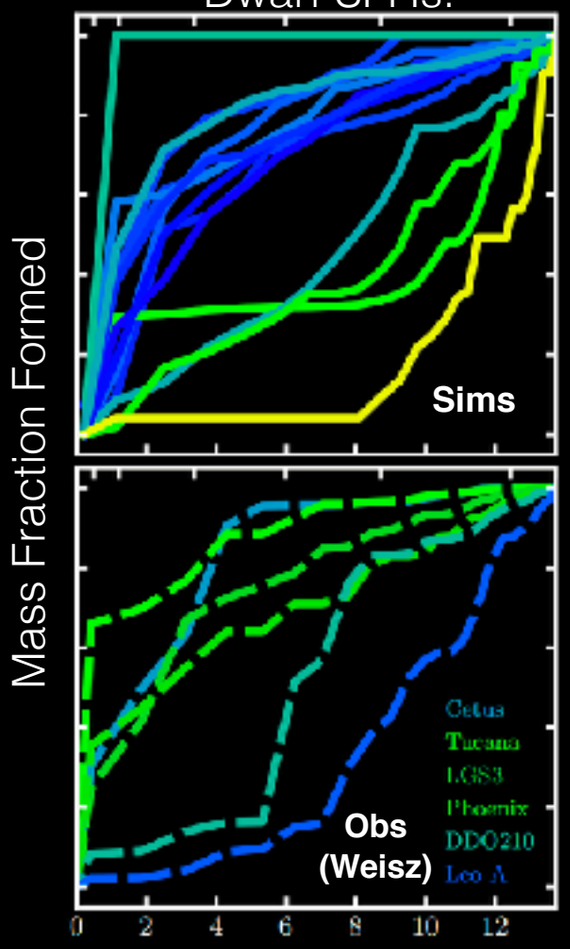




Bursty vs. Calm SF is Important

MORESO THAN MOST "EXOTIC DM"

Dwarf SFHs:

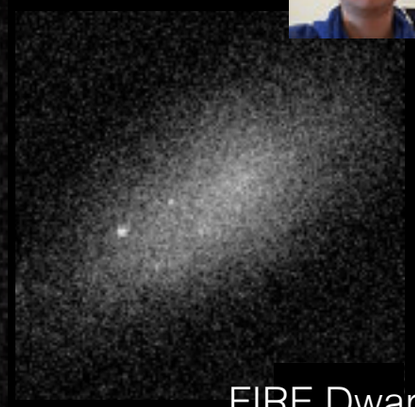


Fitts et al.
(arXiv:1611.02281)

Kareem El-Badry
(arXiv:1512.01235)

Ultra-Diffuse Galaxies

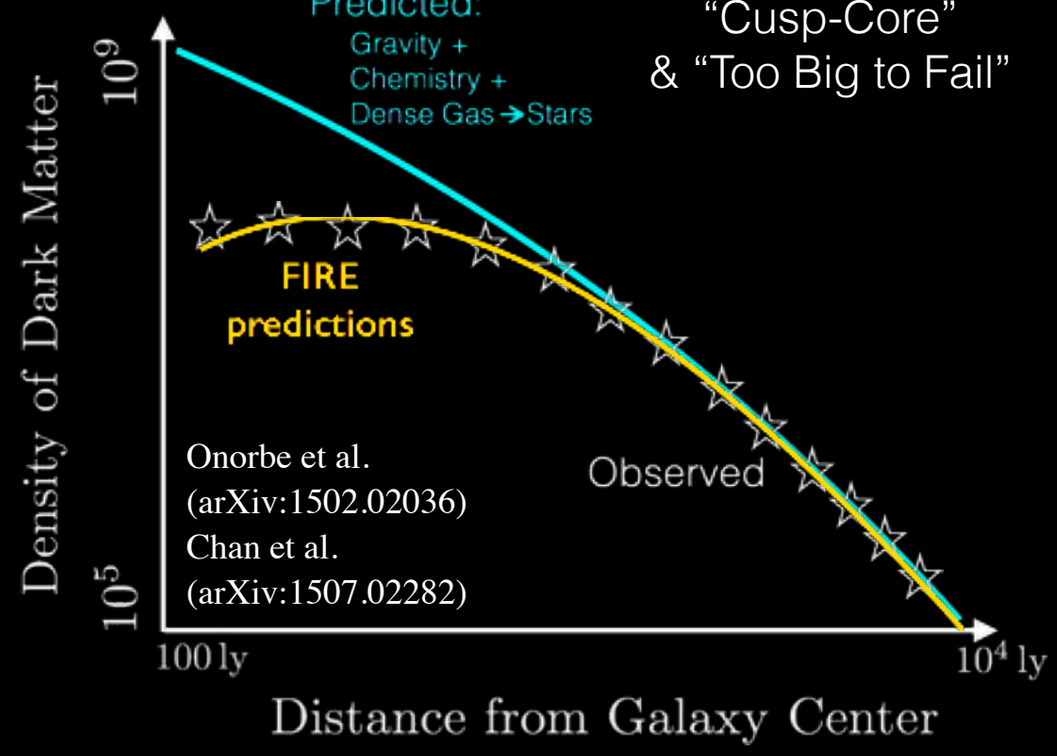
TK Chan
(prep)



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

What Makes dSph?

Coral Wheeler
(arXiv:1504.02466)



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

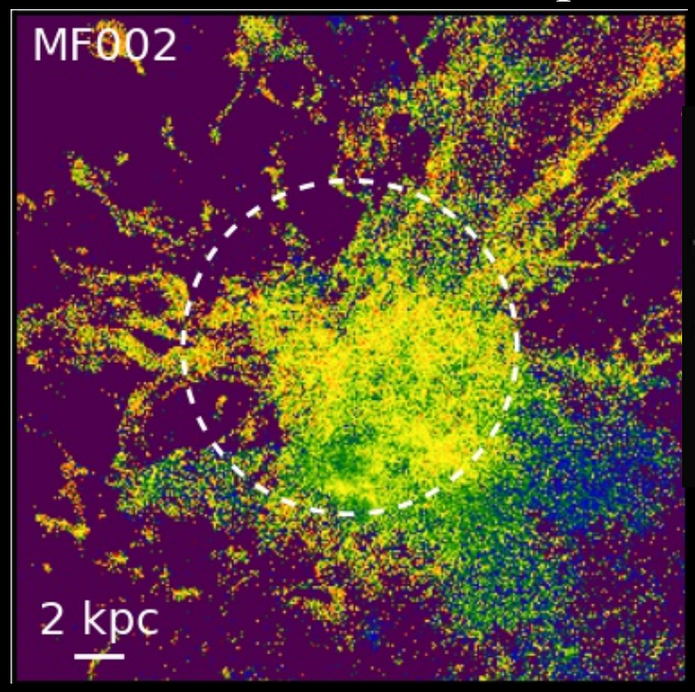
Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

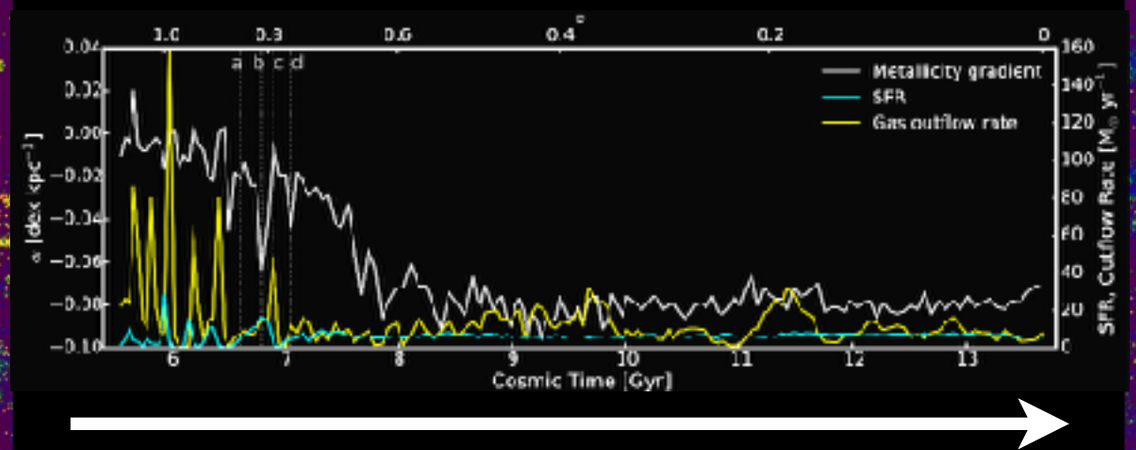
BUILDUP OF METALLICITY GRADIENTS

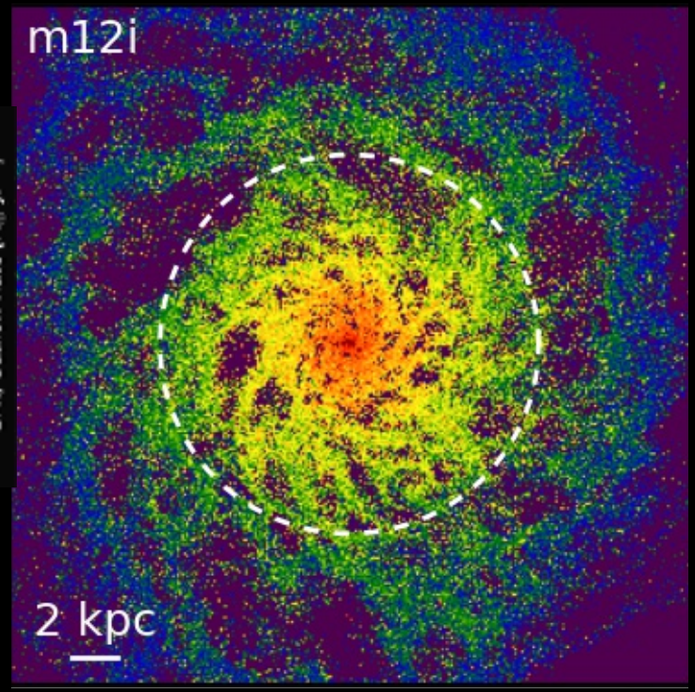
Xiangcheng Ma
(arXiv:1610.03498)

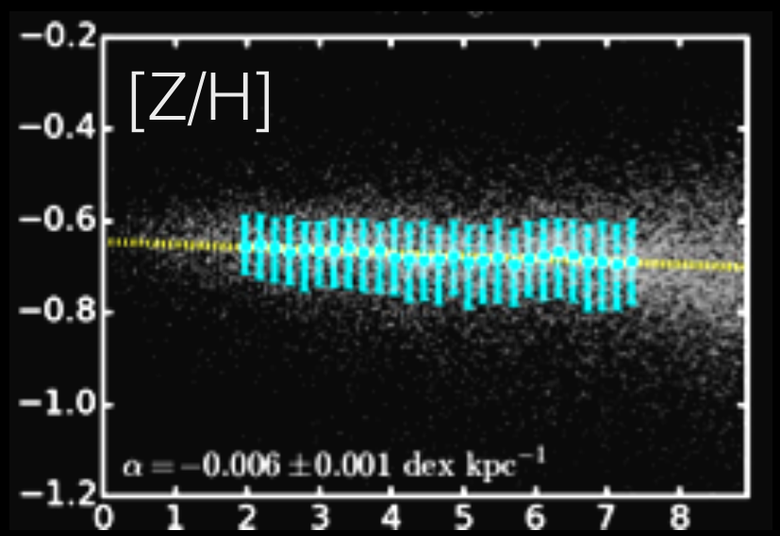
"feedback-dominated" phase

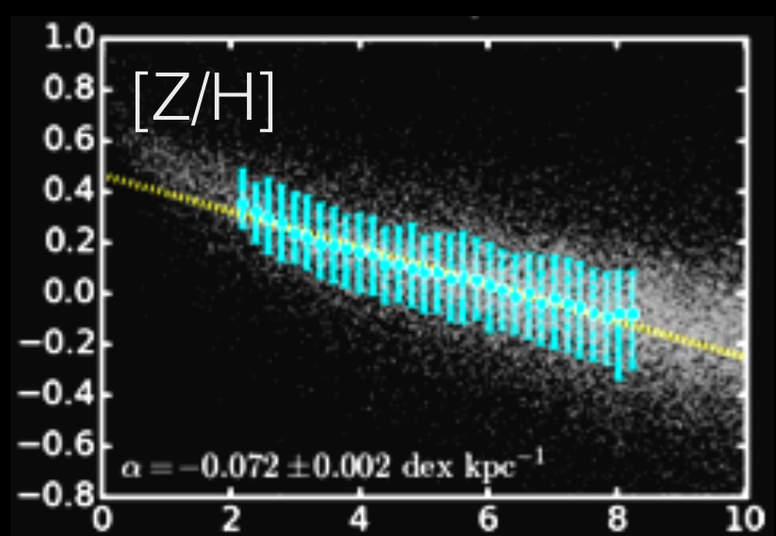
"gravity-dominated" phase







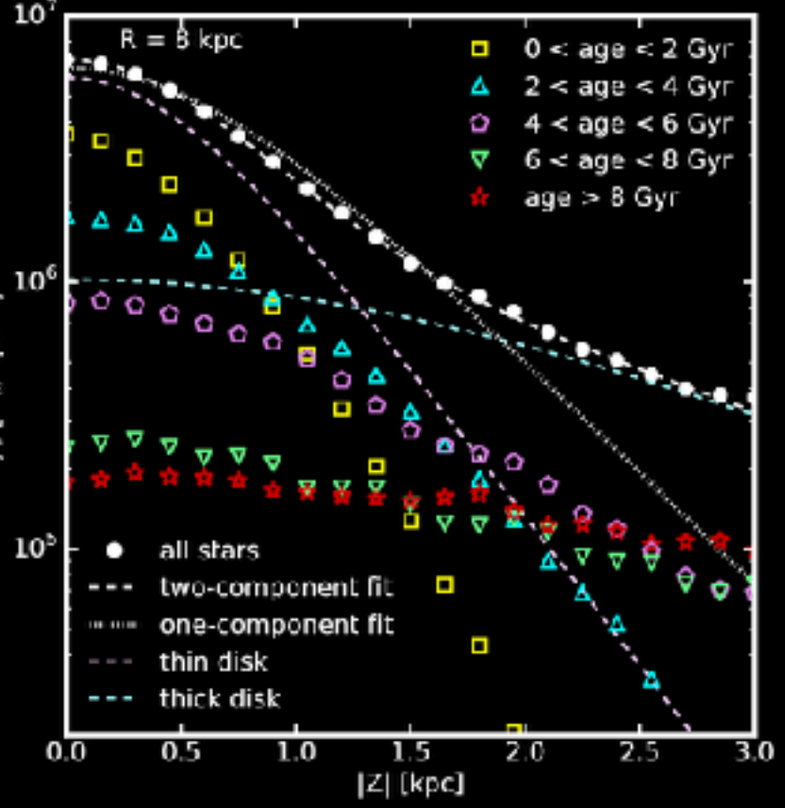


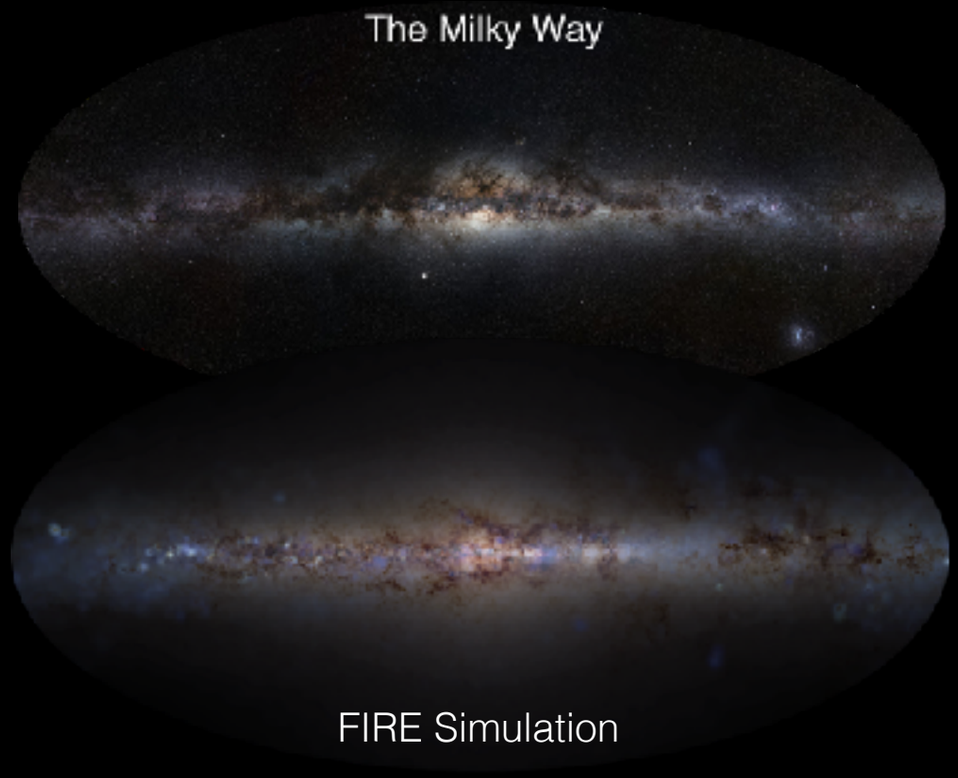


Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

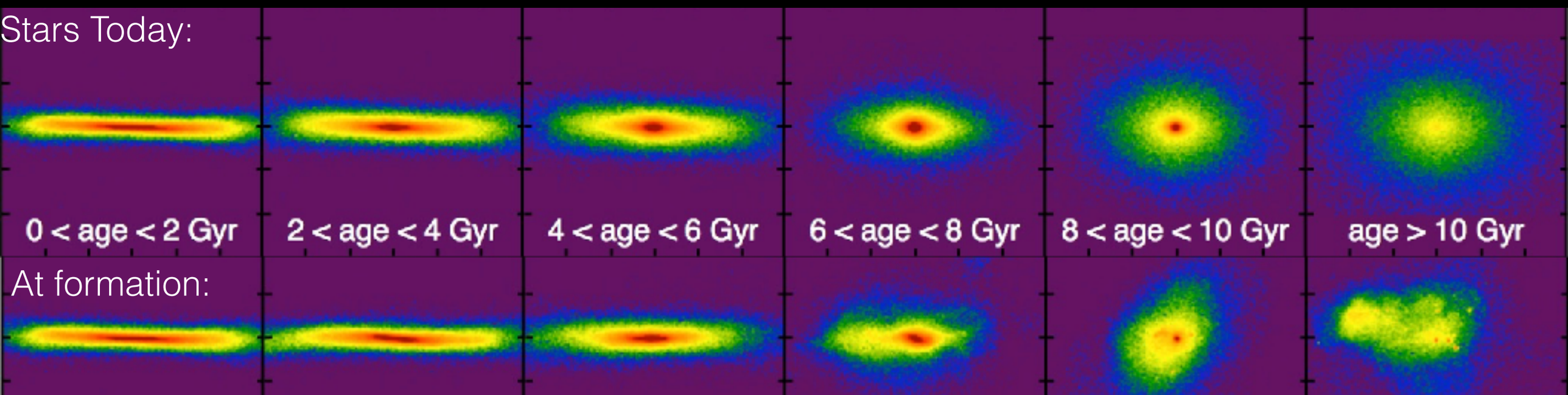
THICK -> THIN DISK

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



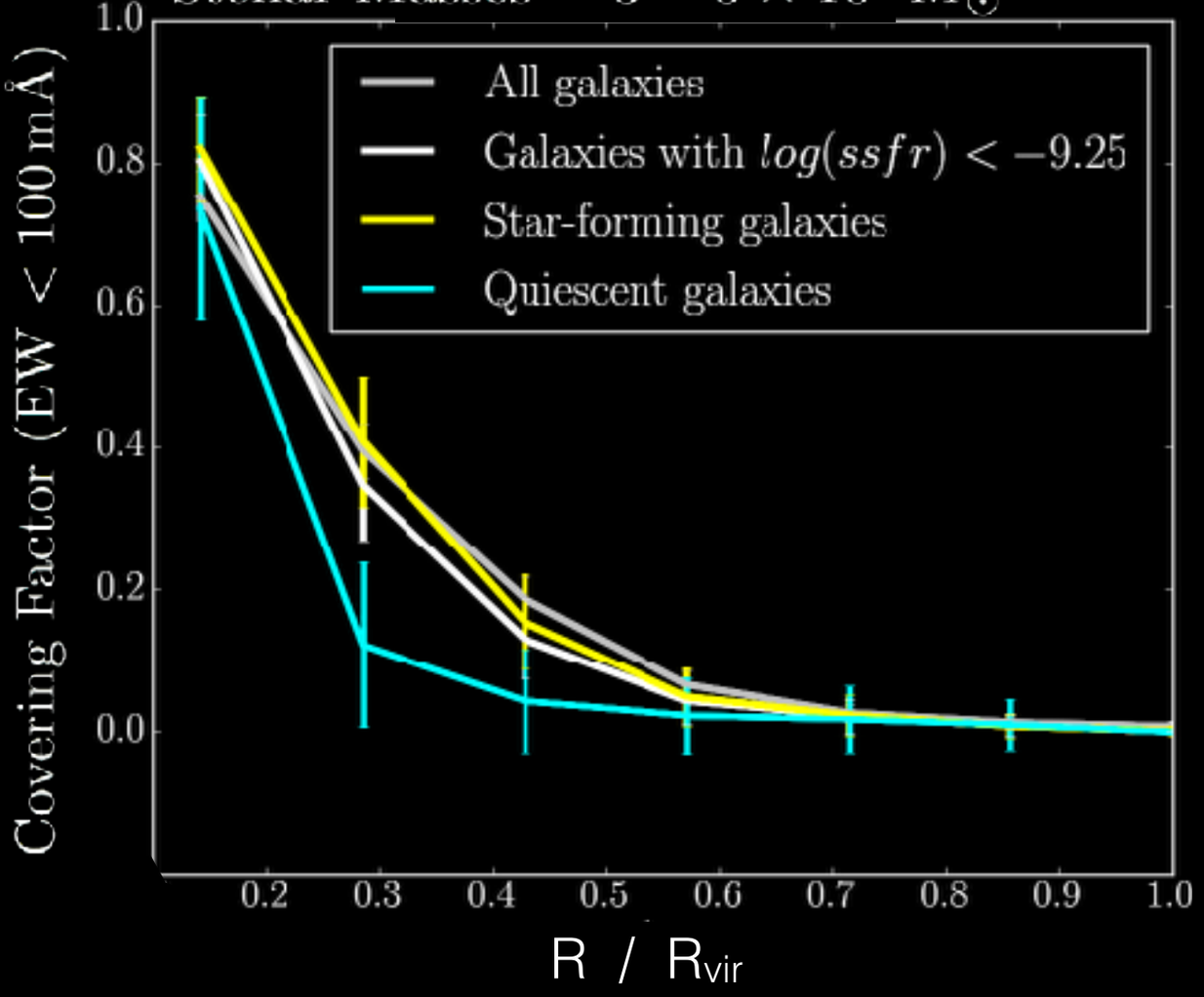


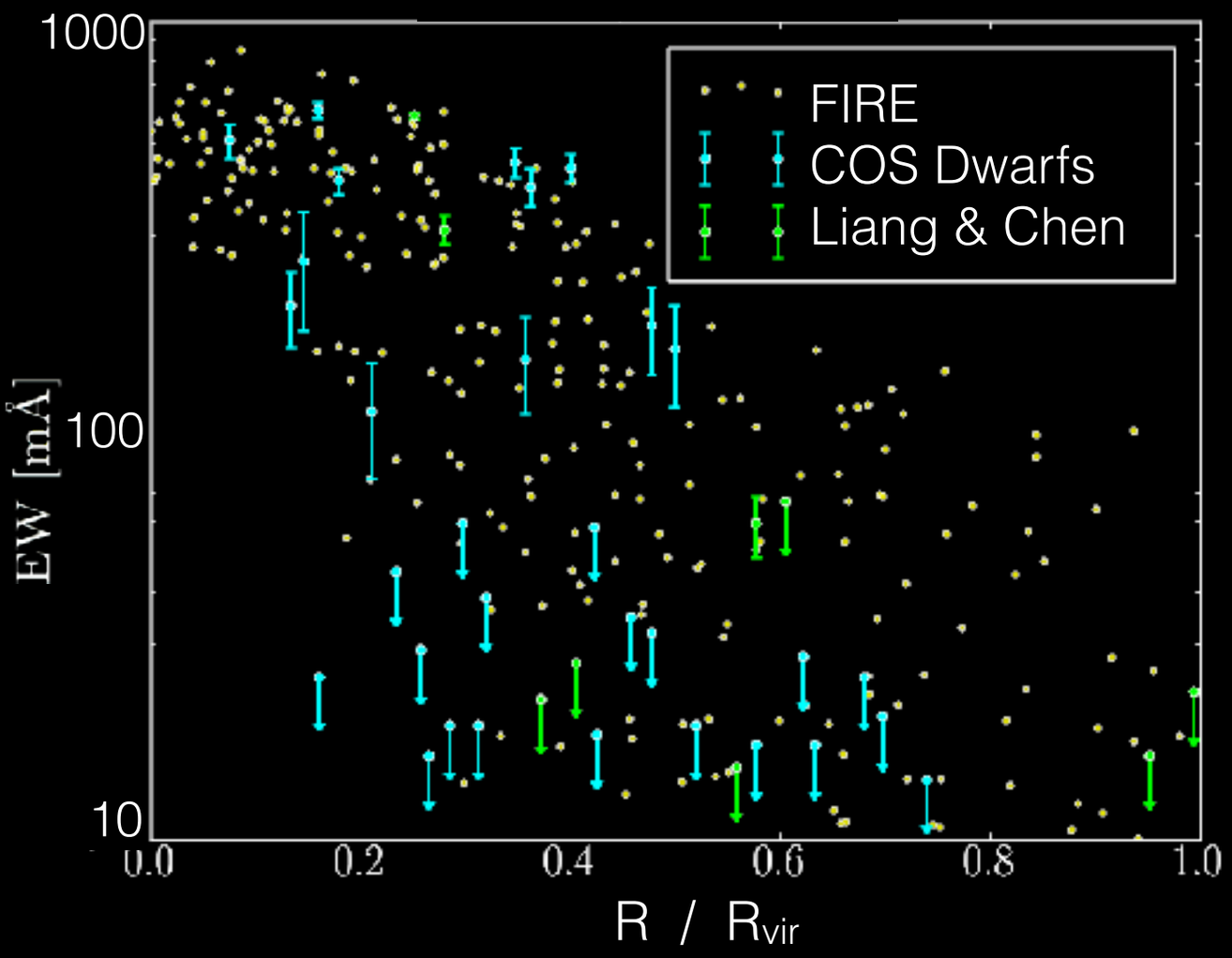
Vertical + Radial
Abundance & Kinematics
of thin/thick populations



Metals in the CGM at Dwarf Masses

RELATED TO BURSTY STAR FORMATION





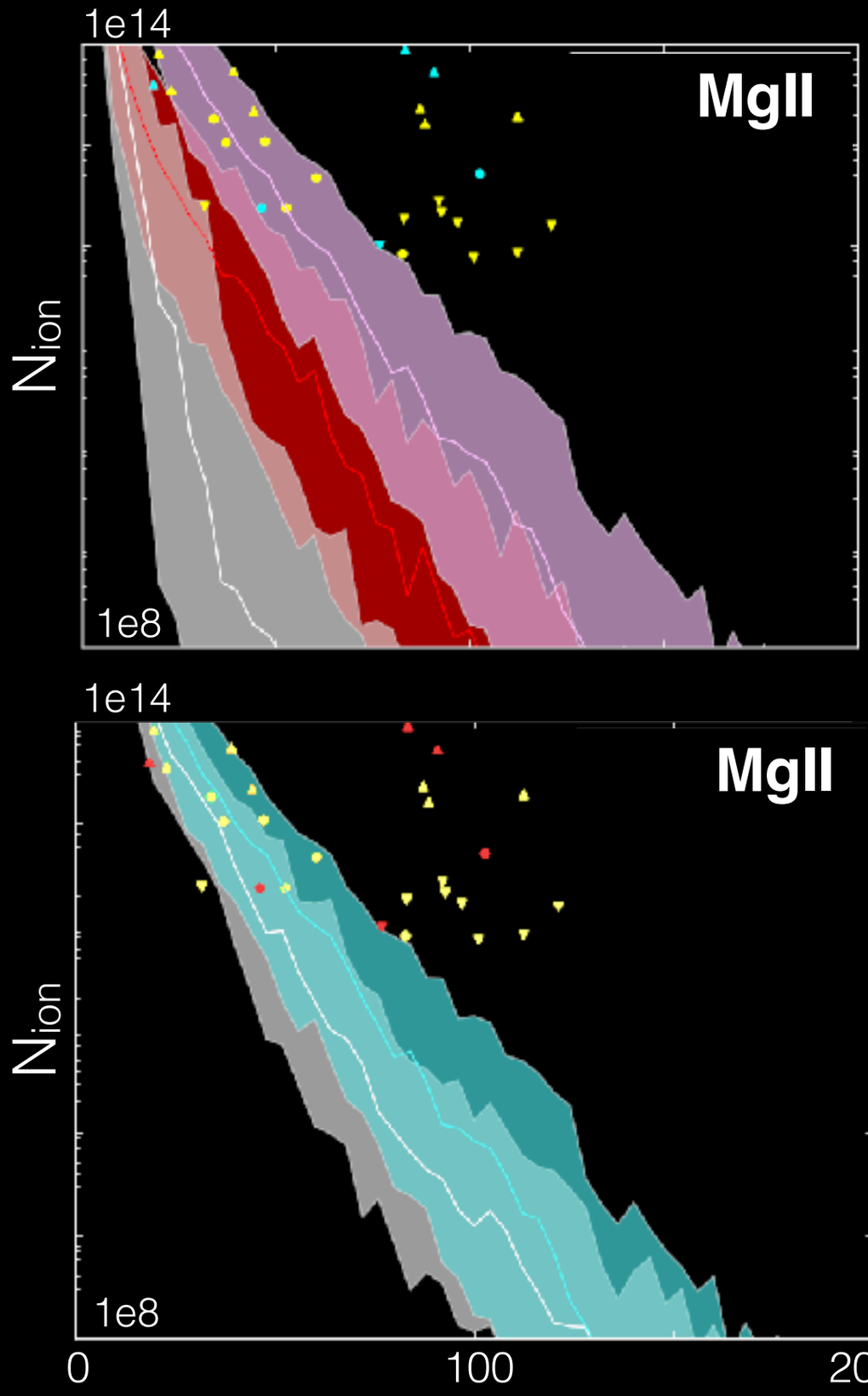
- Resolutions are good (~30 - 7000 M_{sun}): appears converged

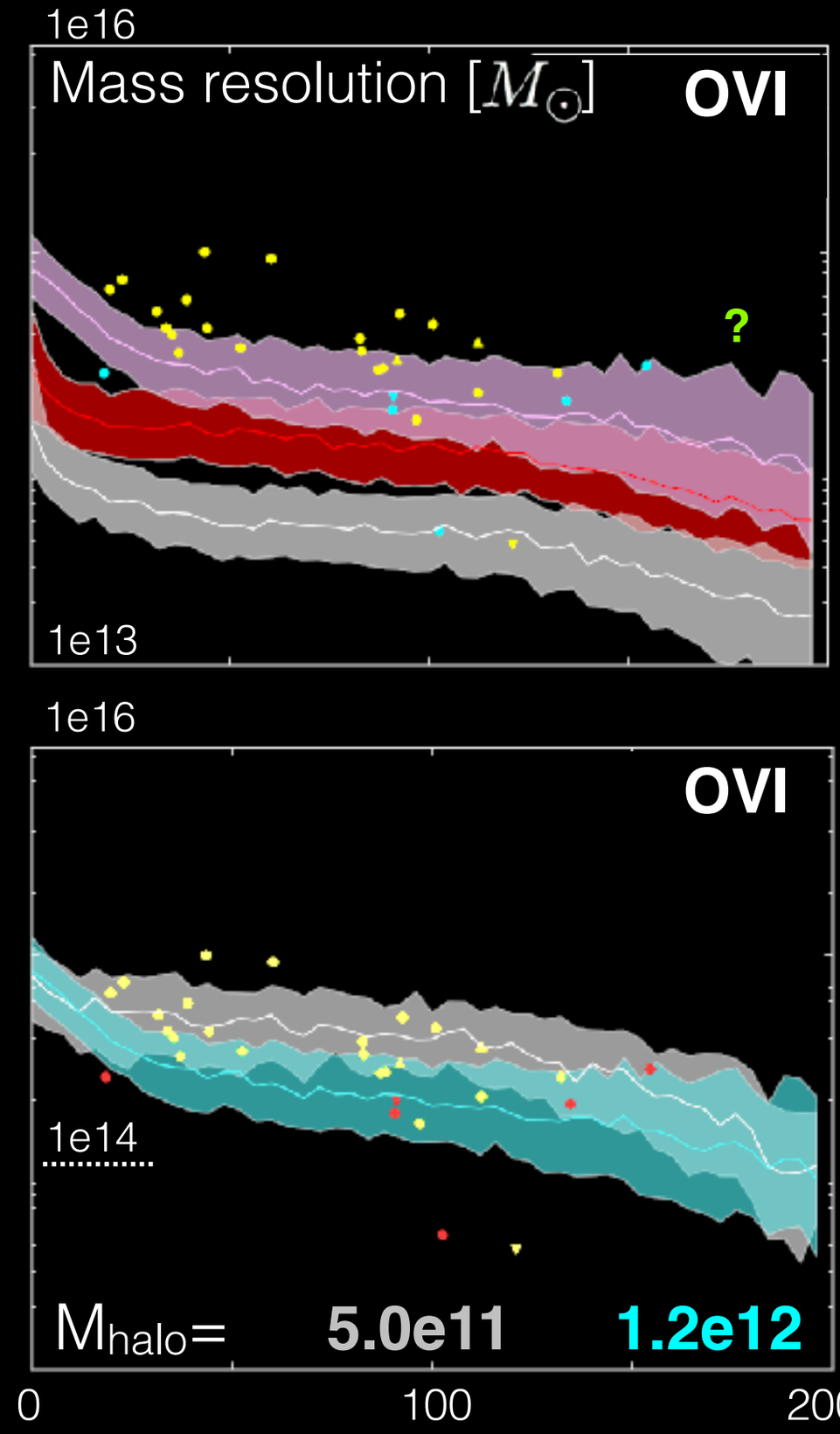
Li, Murray, CAFG, PFH+ (in prep)

Metals in the CGM at L*: Resolution Matters

MASS DOES TOO

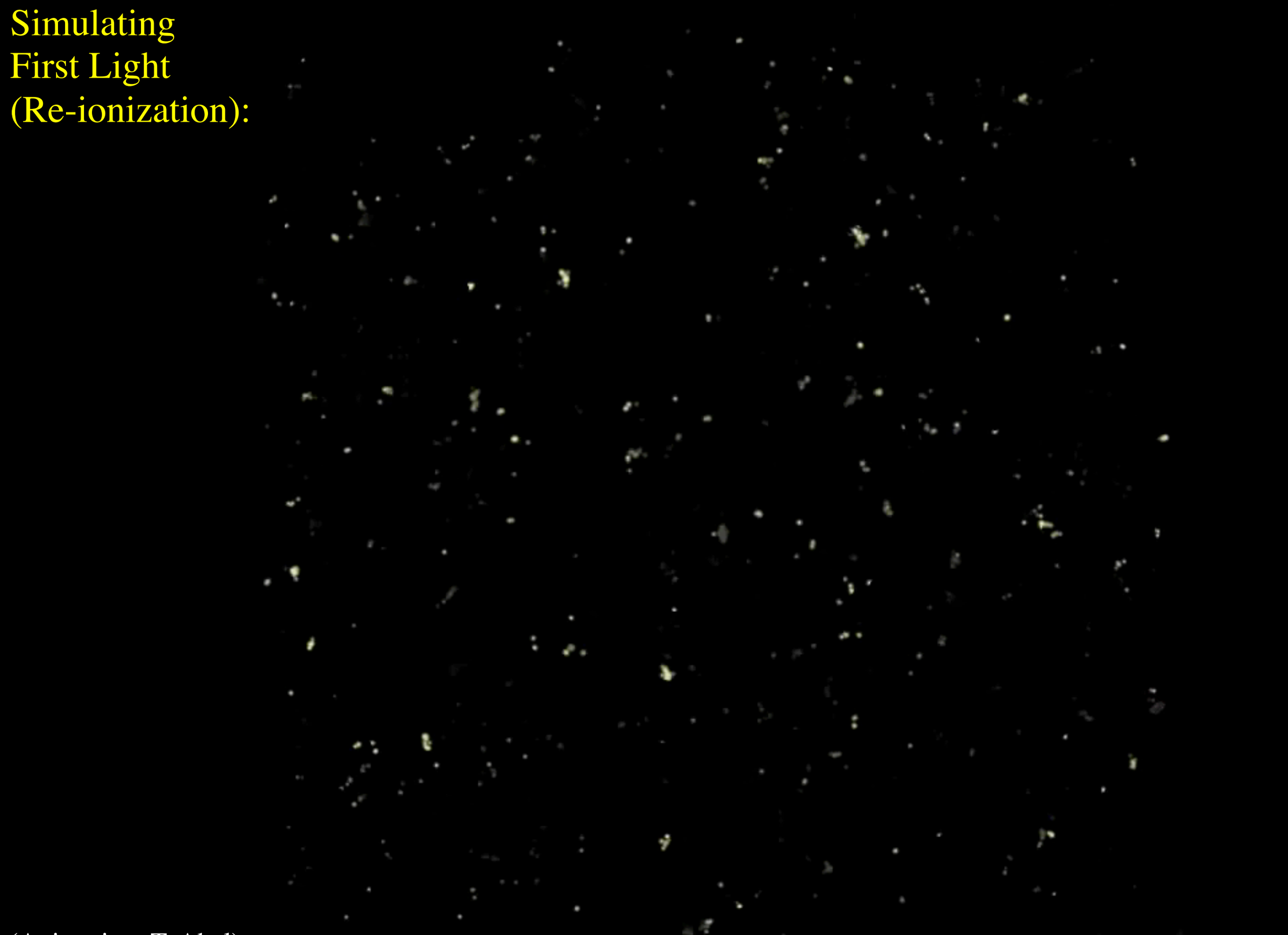
Cameron Hummels (in prep)





Bottom To Top: Example

Simulating
First Light
(Re-ionization):



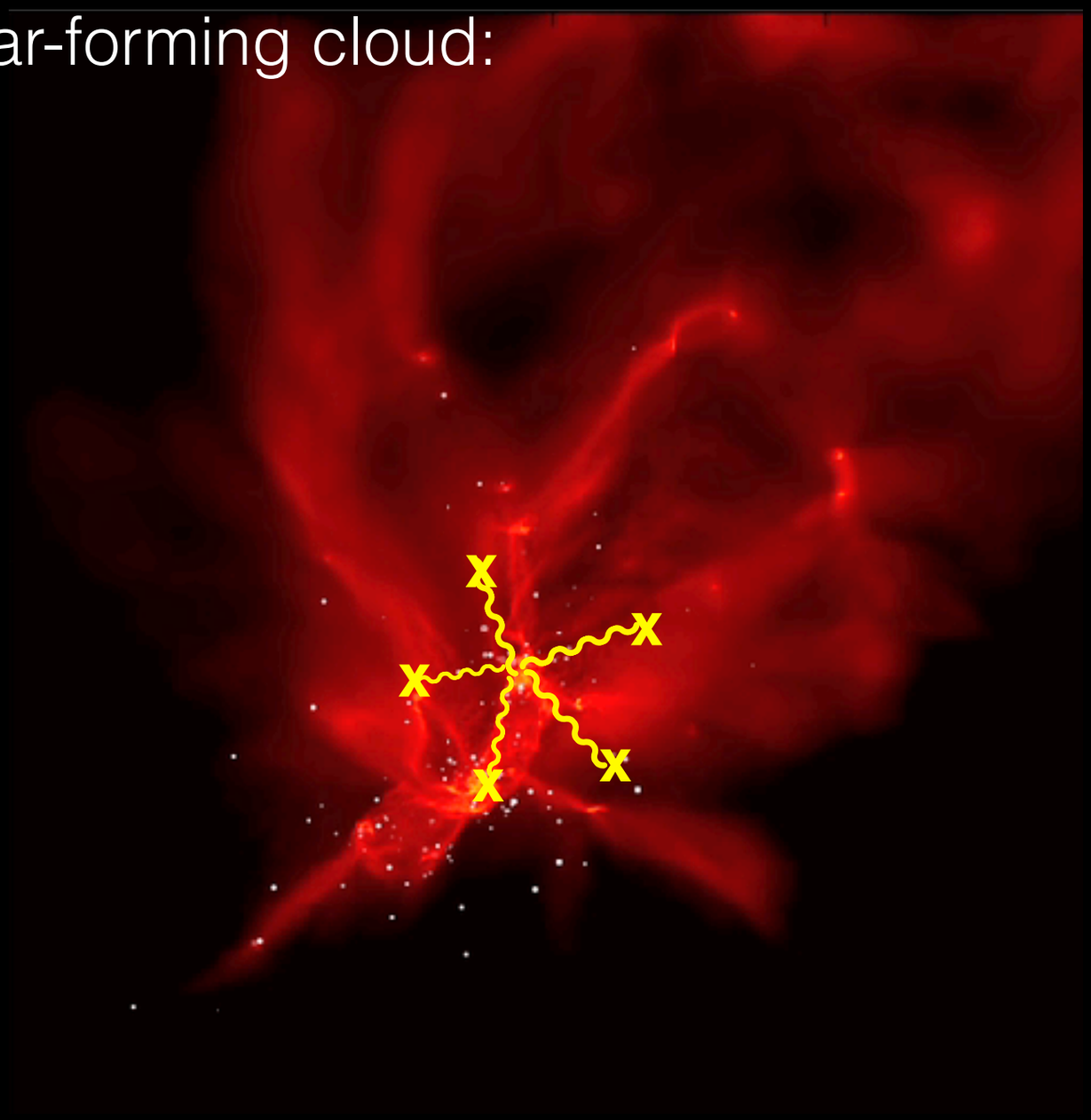
(Animation: T. Abel)

Problem:
STARS FORM IN DENSE, COLD CLOUDS

Xiangcheng Ma
(arXiv:1503.07880)

- Naively: form the stars, calculate where the light goes

Star-forming cloud:



- Nothing escapes!

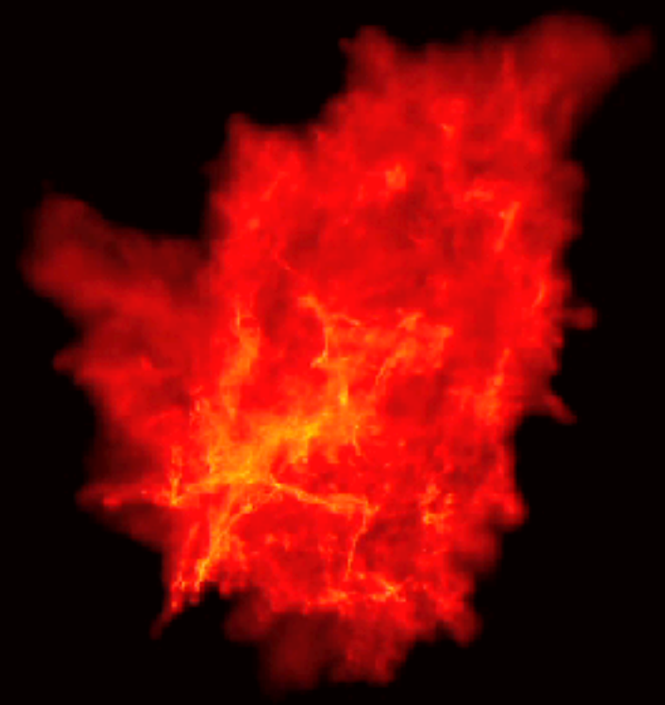
$$f_{\rm escape} \ll 0.1\%$$

Problem:
STARS FORM IN DENSE, COLD CLOUDS

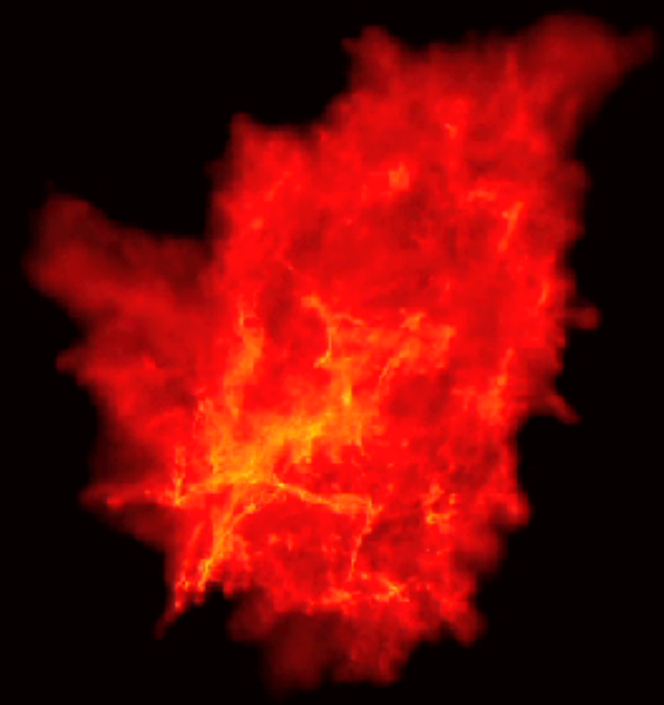
- Actually:
  - Stars destroy the cloud
  - Stars get “flung around” (“runaway stars”)

Xiangcheng Ma
(arXiv:1503.07880)

Star-forming
cloud:



If stars were passive
(“no feedback”)



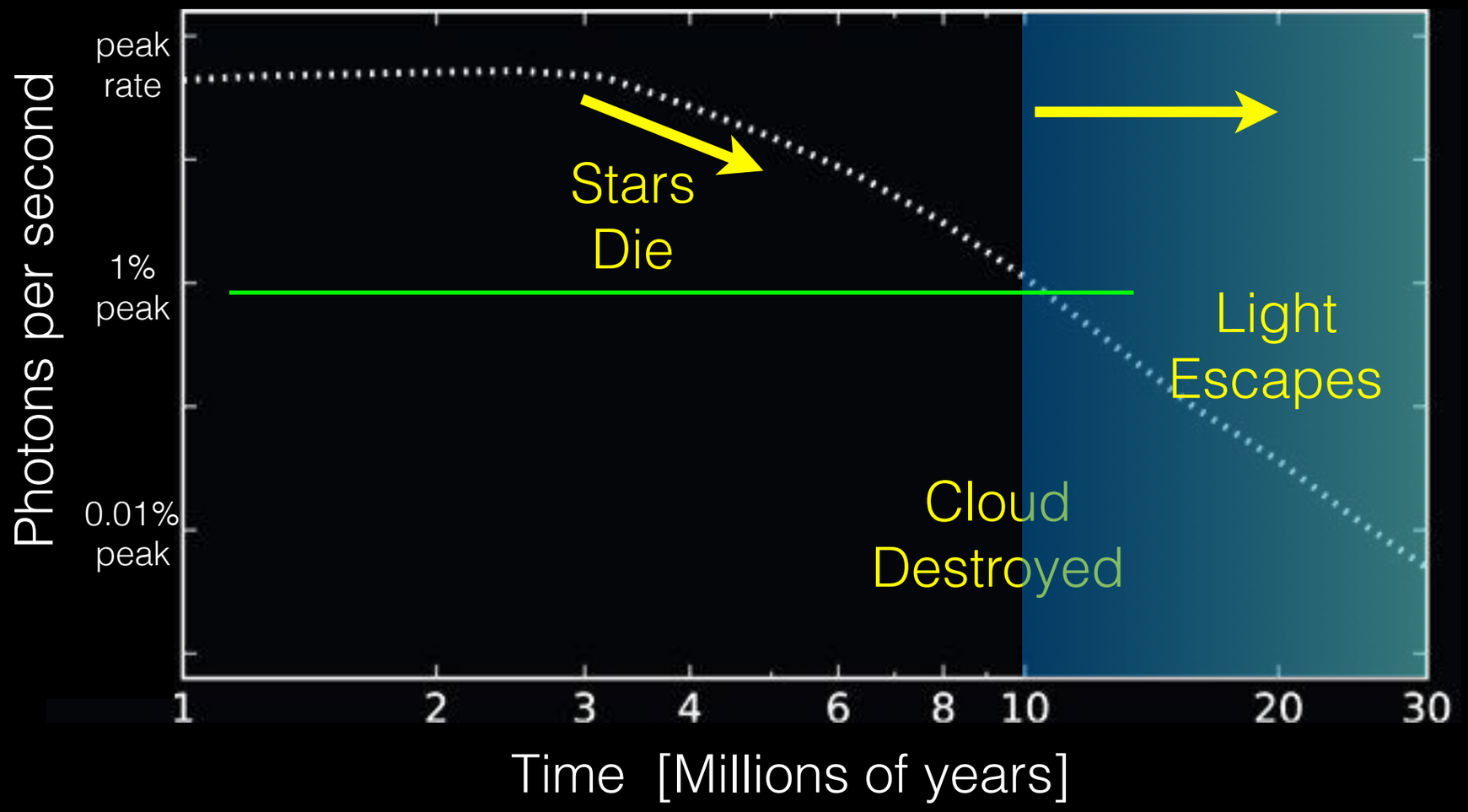
Realistic
(stellar winds & radiation included)

It's Not Enough!

TAKES TOO LONG TO DESTROY THE CLOUDS

Xiangcheng Ma
(arXiv:1503.07880)

Ionizing photon production rate:
(from a stellar population)



- Invariant to:
  - Resolution
  - Strength of feedback
  - Numerical methods
  - Star formation rates
  - IMF shape/sampling
  - Runaway stars

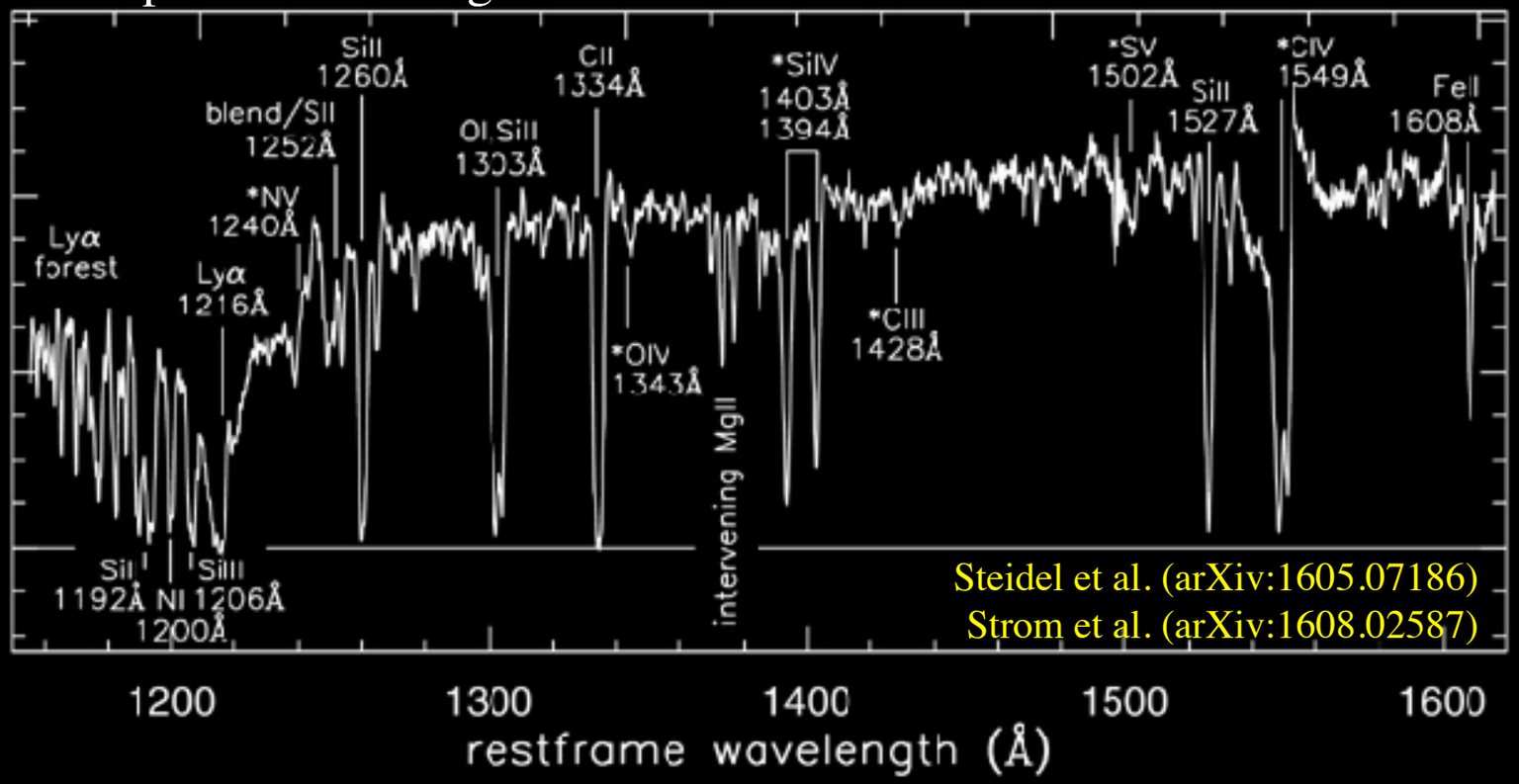
Simulation: only ~1% escape!

(also Wise et al., Kimm & Cen 2015)

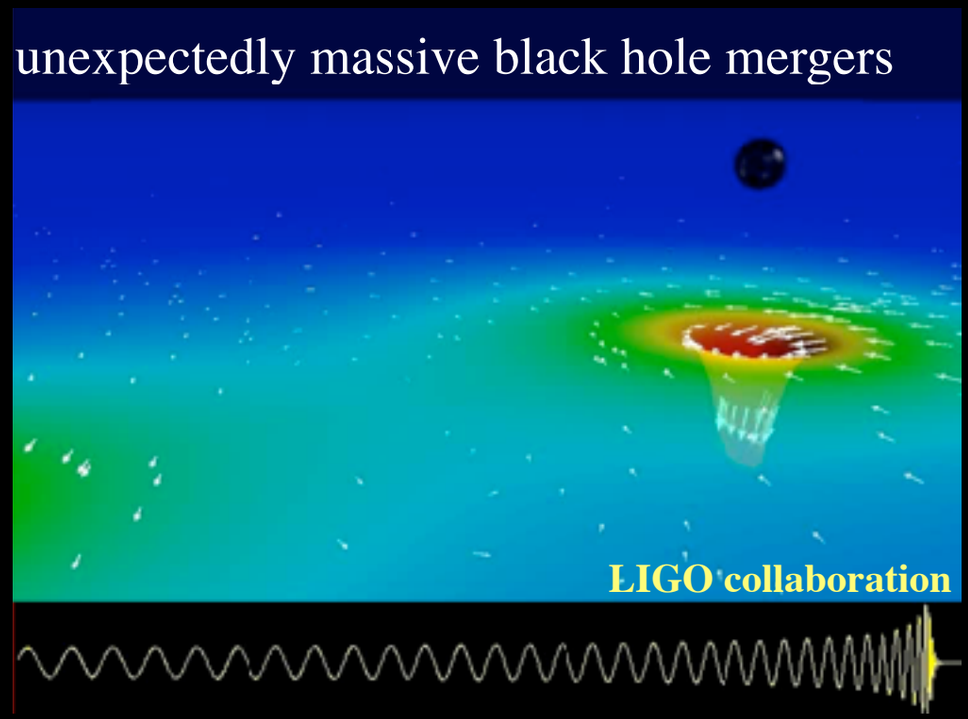
Other Mysteries?

SOME PHYSICS IS MISSING HERE

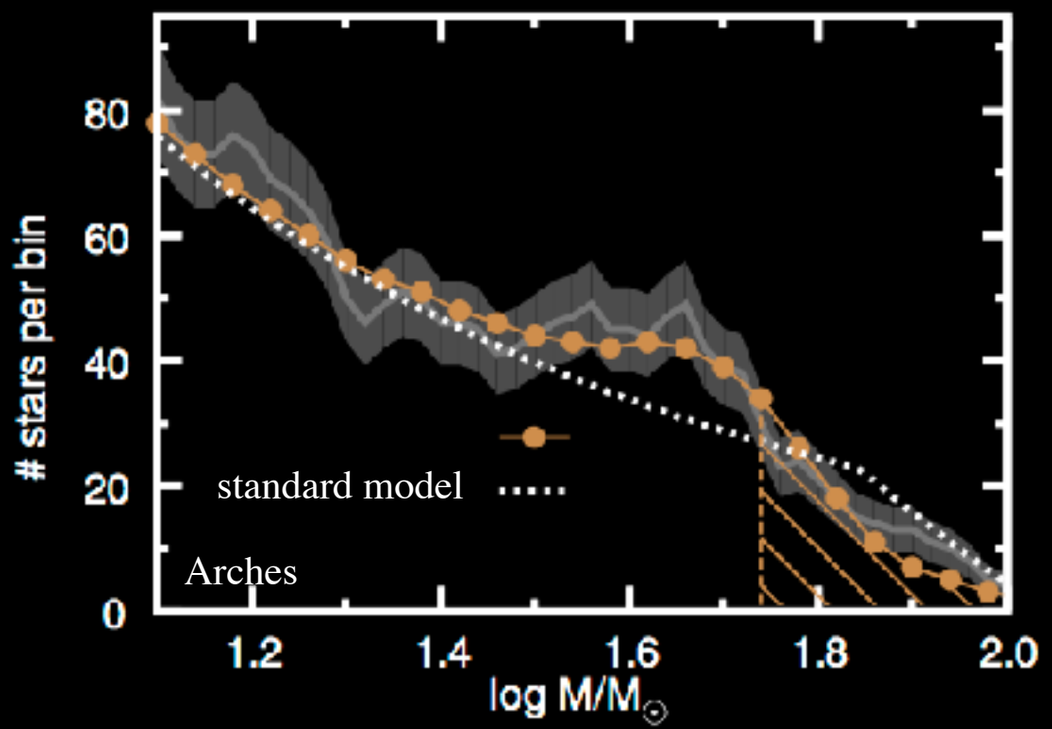
the spectra are wrong…

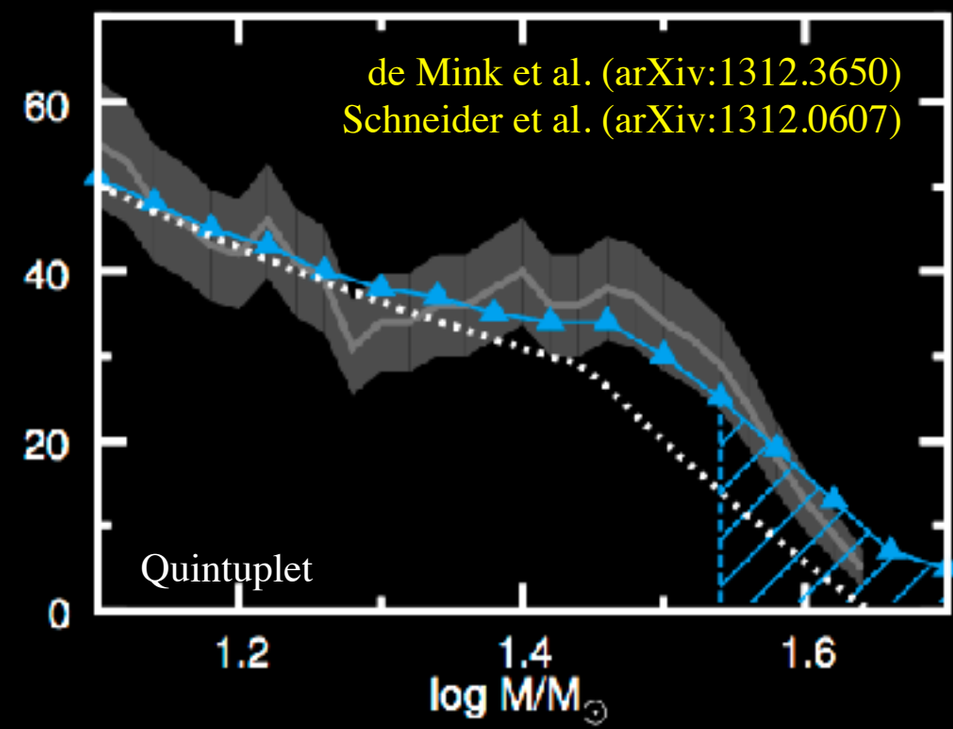


Steidel et al. (arXiv:1605.07186)
Strom et al. (arXiv:1608.02587)

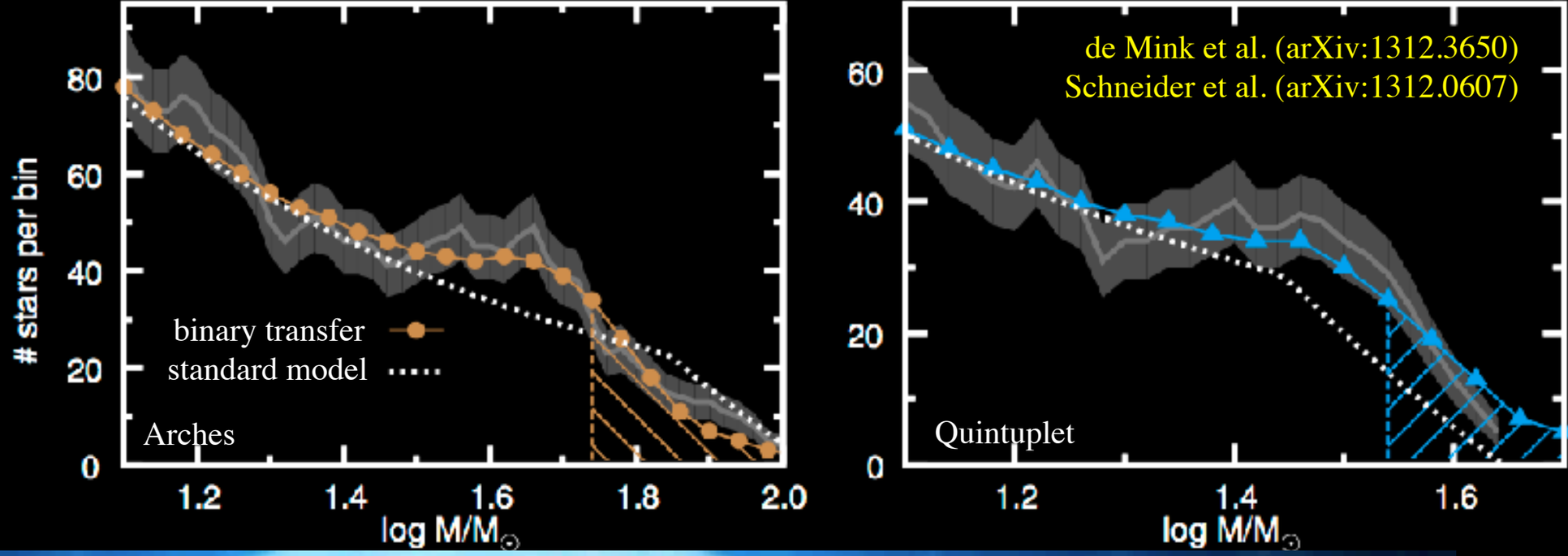


"mass-gainers": (stars more massive & longer-lived than they should be)



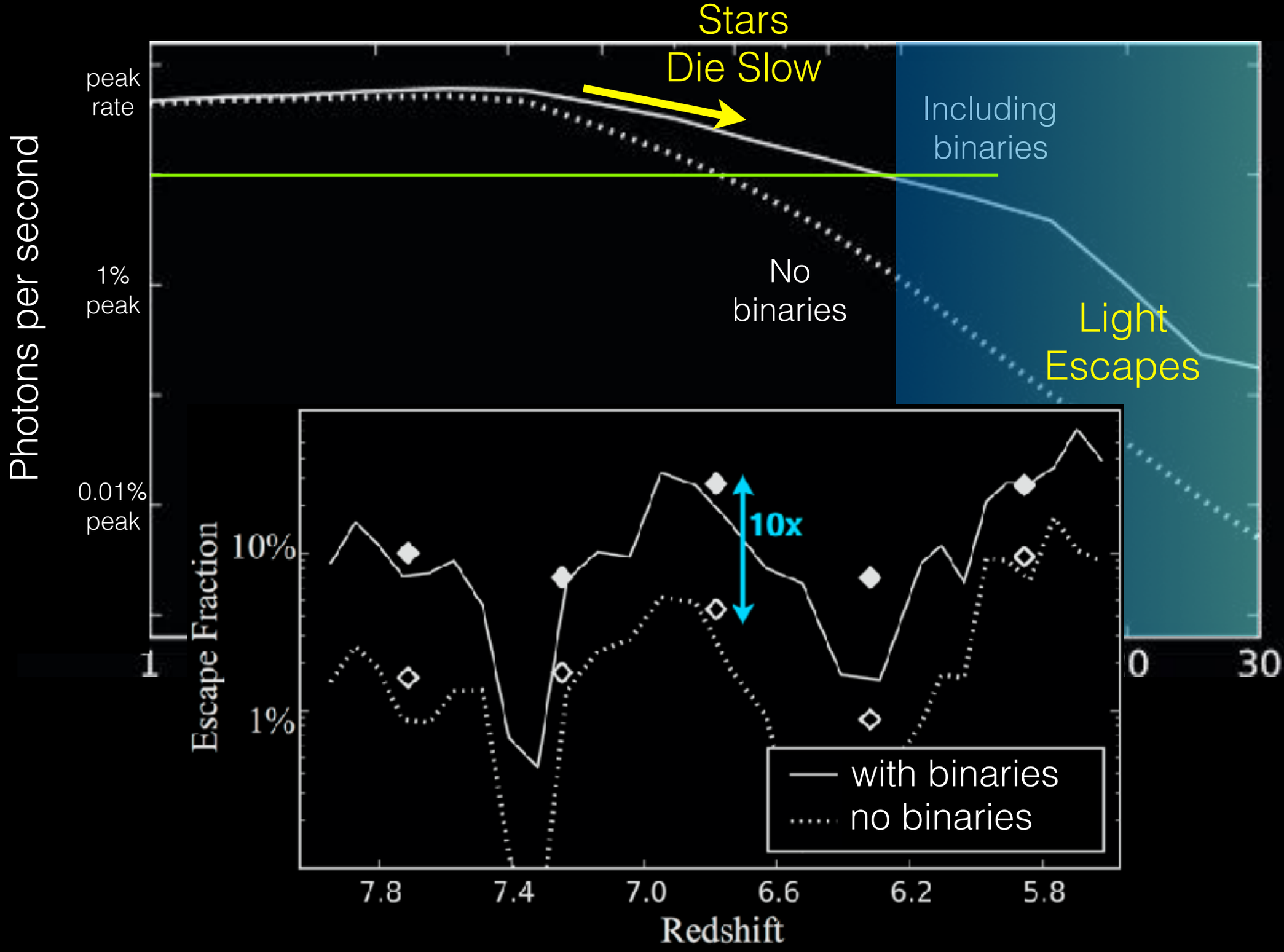


Binary Stars:
"FEEDING" MASSIVE STARS



Binary Stars:
THE ORIGIN OF THE "MISSING PHOTONS"

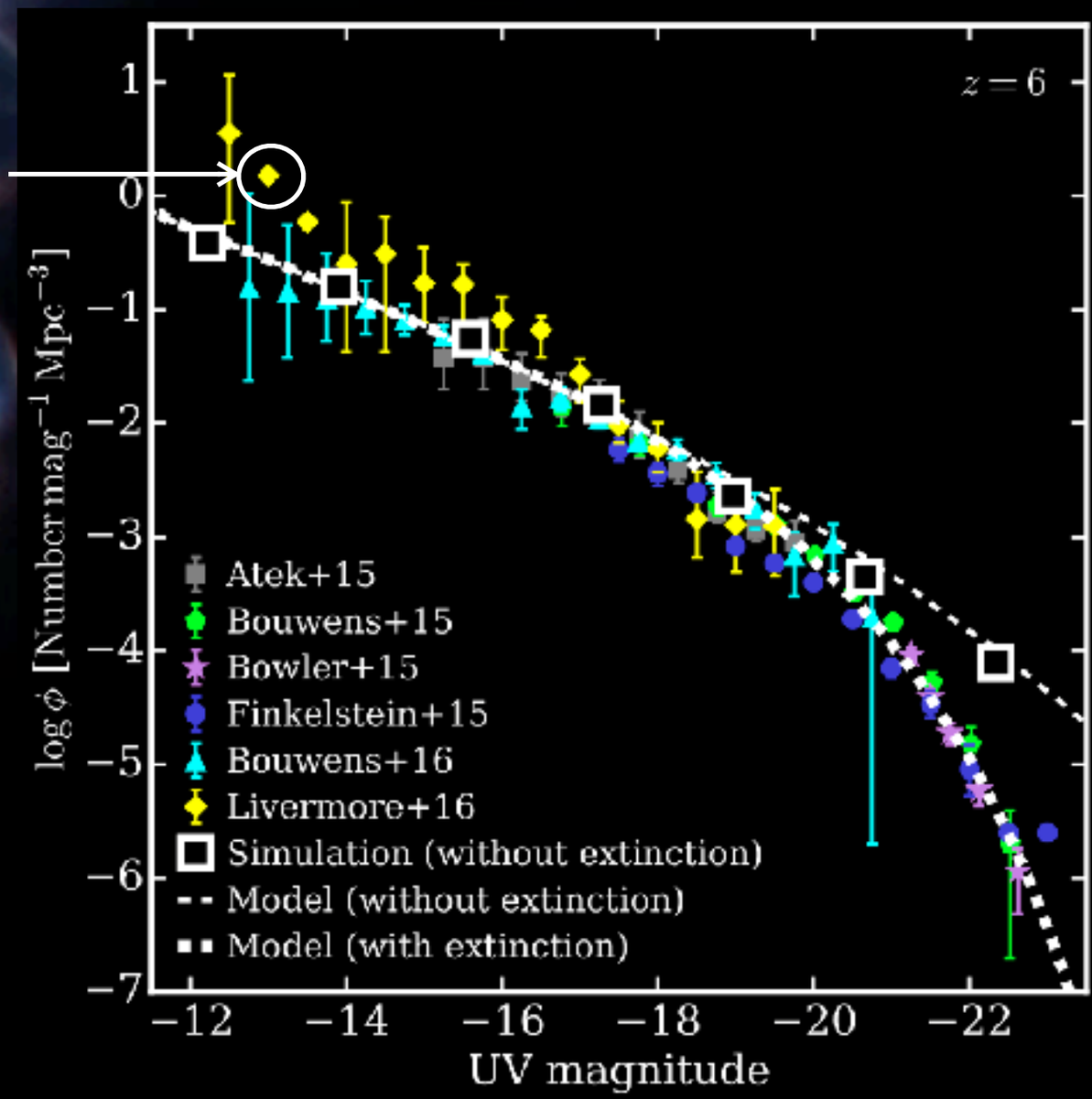
Xiangcheng Ma
(arXiv:1601.07559)

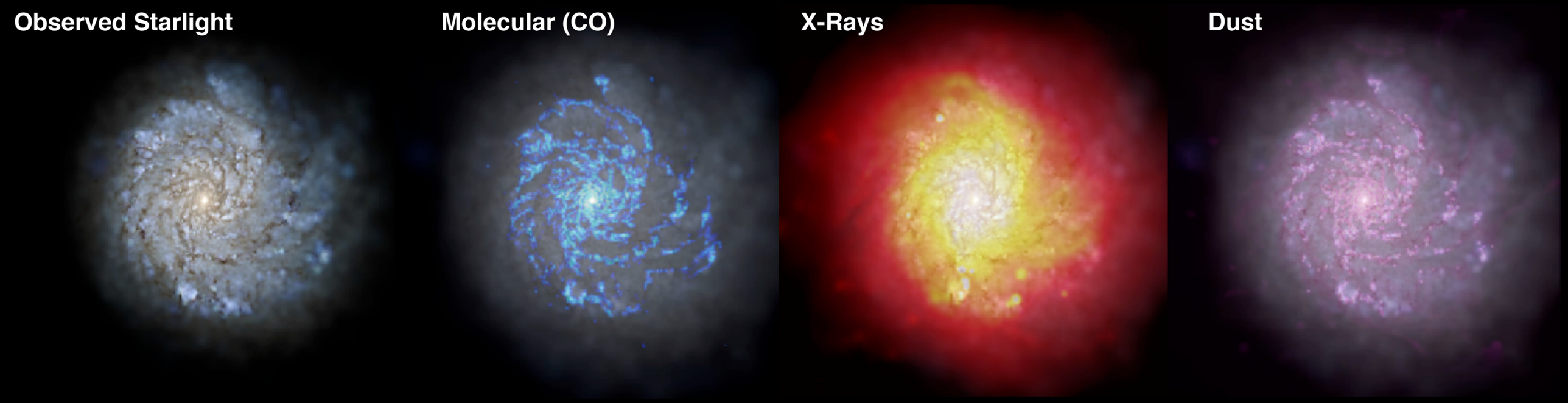


EoR & JWST Predictions:
PUTTING IT ALL TOGETHER

Xiangcheng Ma
(arXiv:1706.06605)

(Animation: J. Wise)





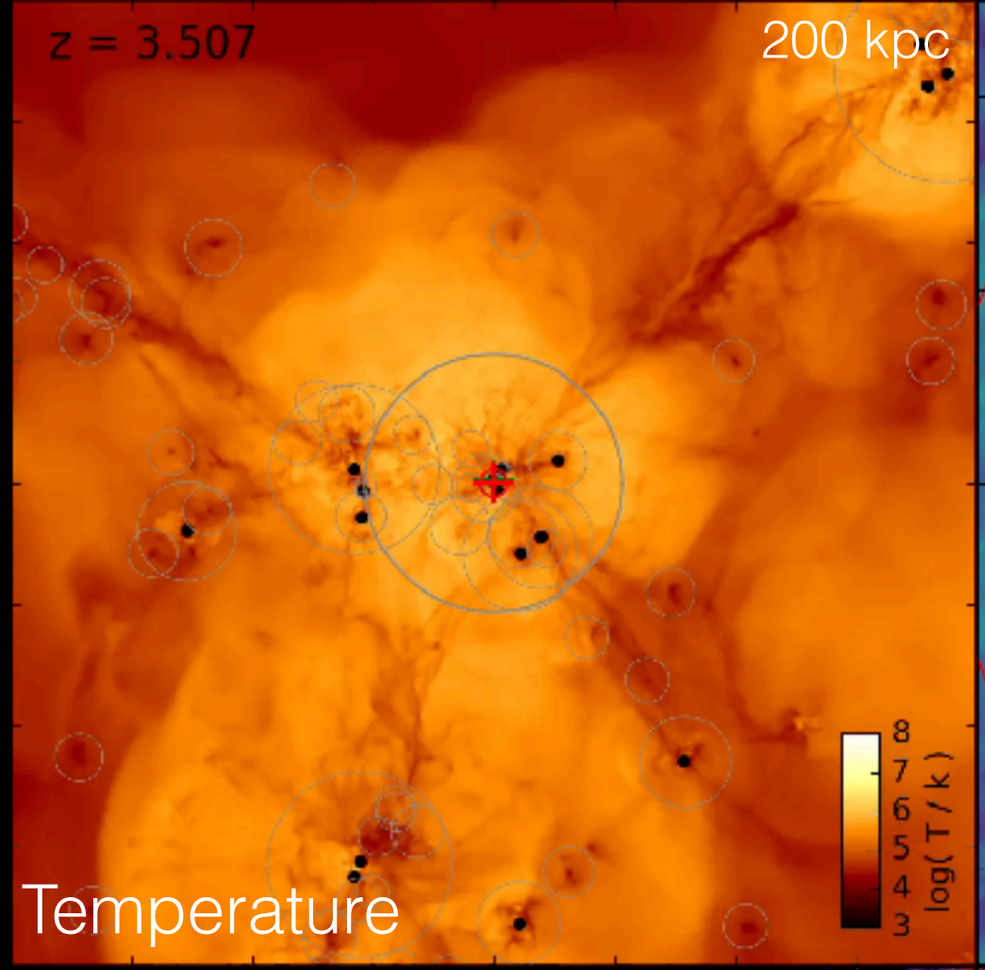
- IMF: Feedback or Galaxy-Scale Models are Wrong (Guszejnov+ 17)
- Stellar clustering is Universal (Guszejnov+ 17)
- Clusters: Cloud surface density determines properties (Grudic+ 17)
- Globulars resolved(?) (Kim+ 17)
- KS=feedback: dense laws different from galaxy-scale (Orr+17)
- Weak dependence on MHD, etc (Su+ 17)
- Bursty SF important to galaxy structure (El-Badry+ 16, Ma+16)

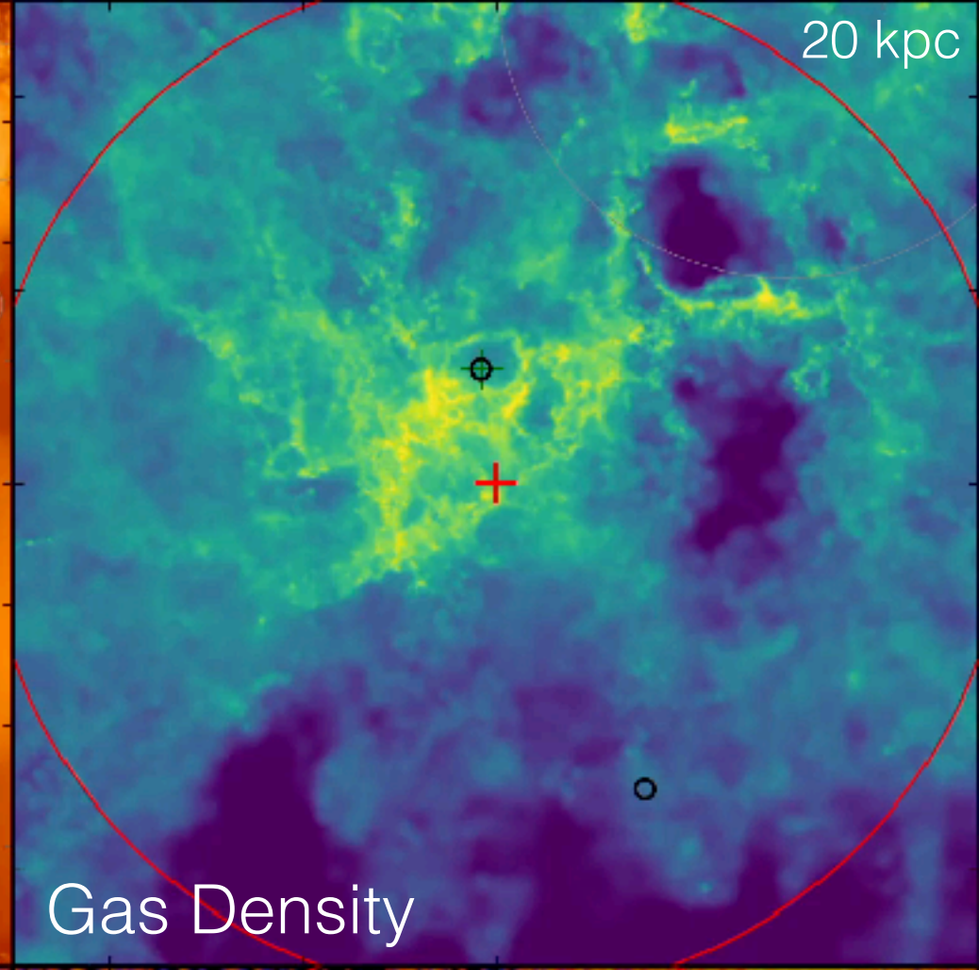
Ask me about:

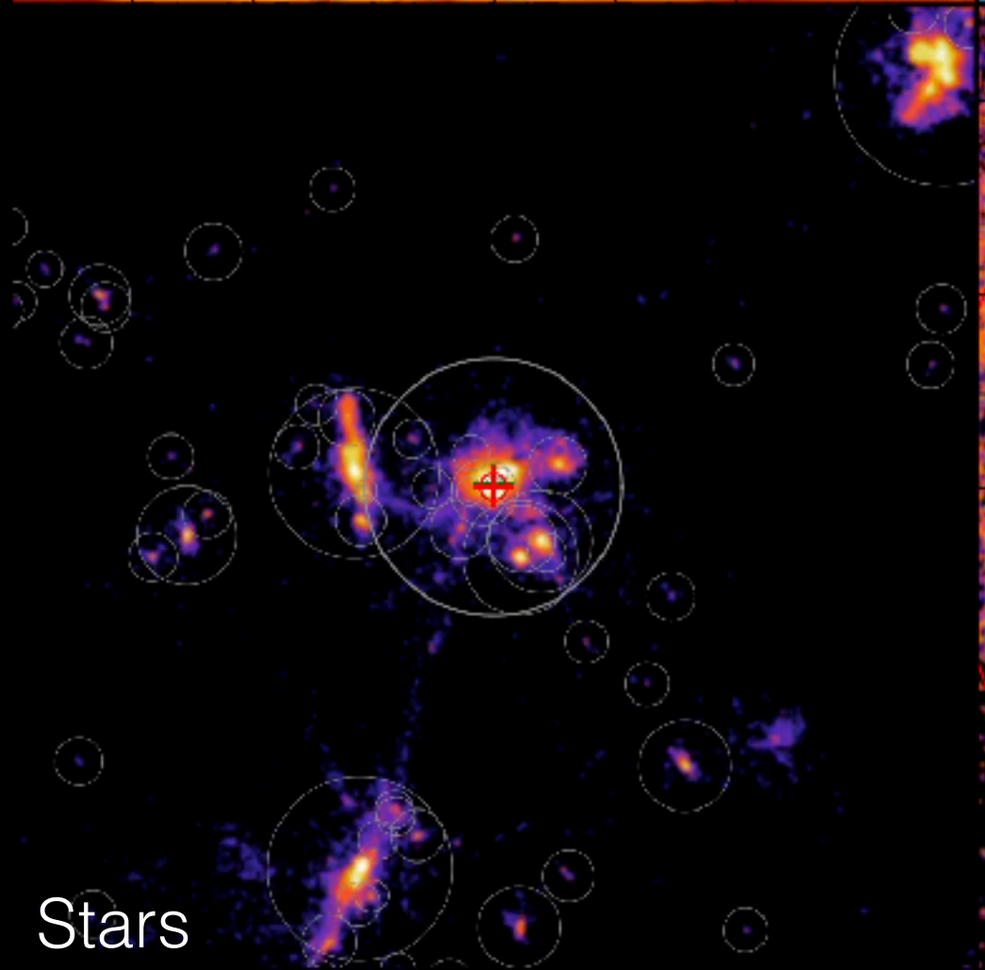
- Dust (instabilities)
- AGN (+feedback)
- Galaxy structure/ morphologies
- Alternative DM
- Radiation pressure
- Numerical methods (DM & Hydro & FB)
- SMBH formation
- GW populations

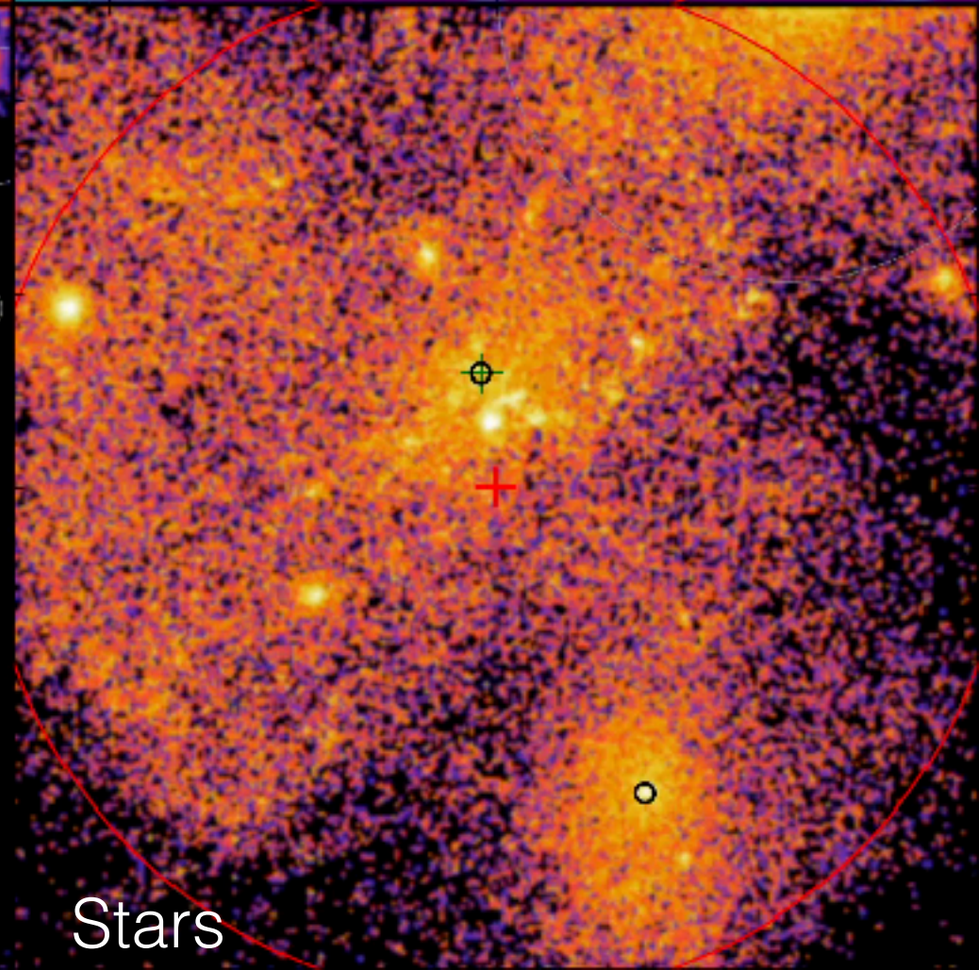
What About AGN?

Lumpiness + SNe
Need big seeds
or “anchors”





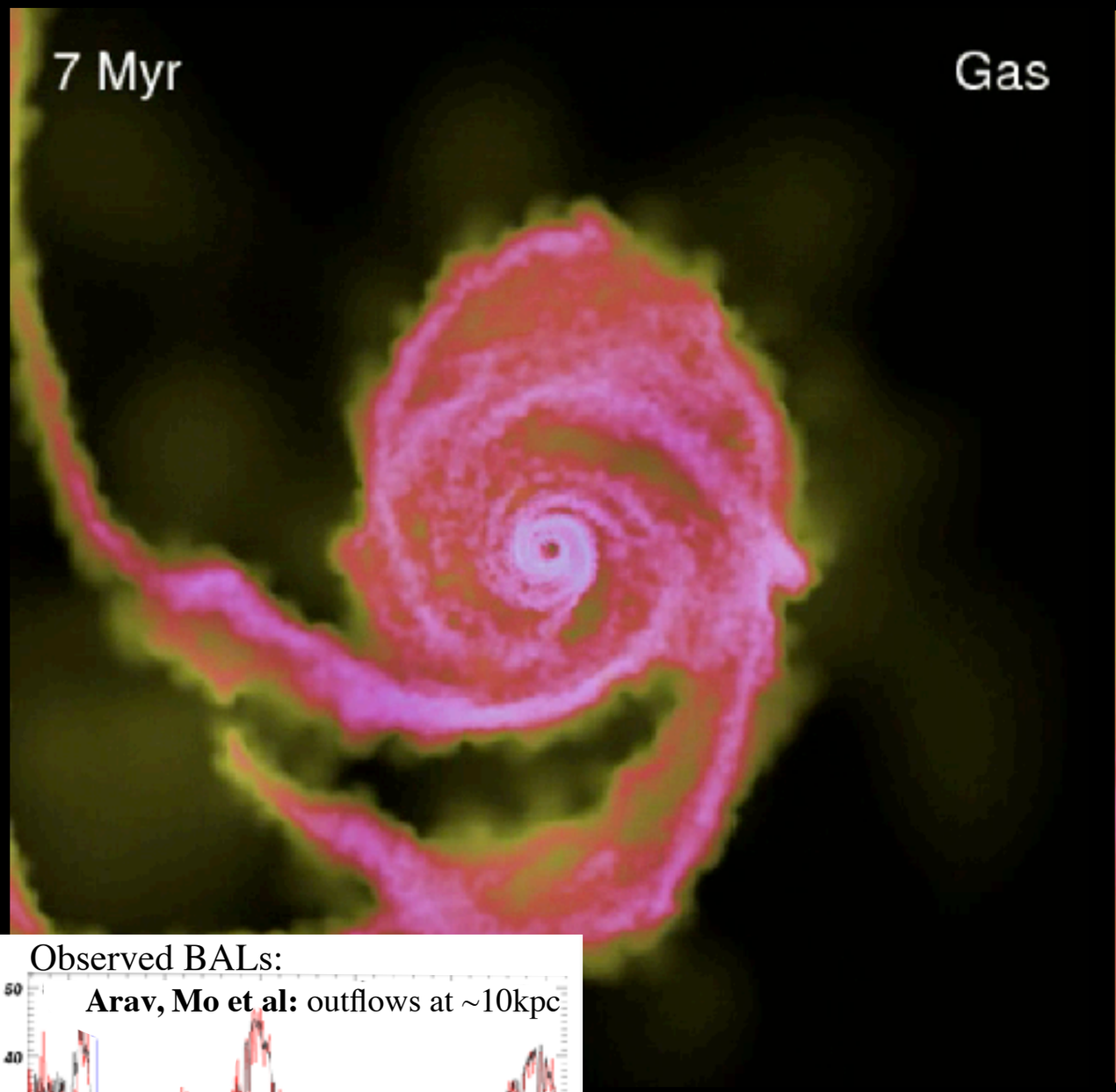




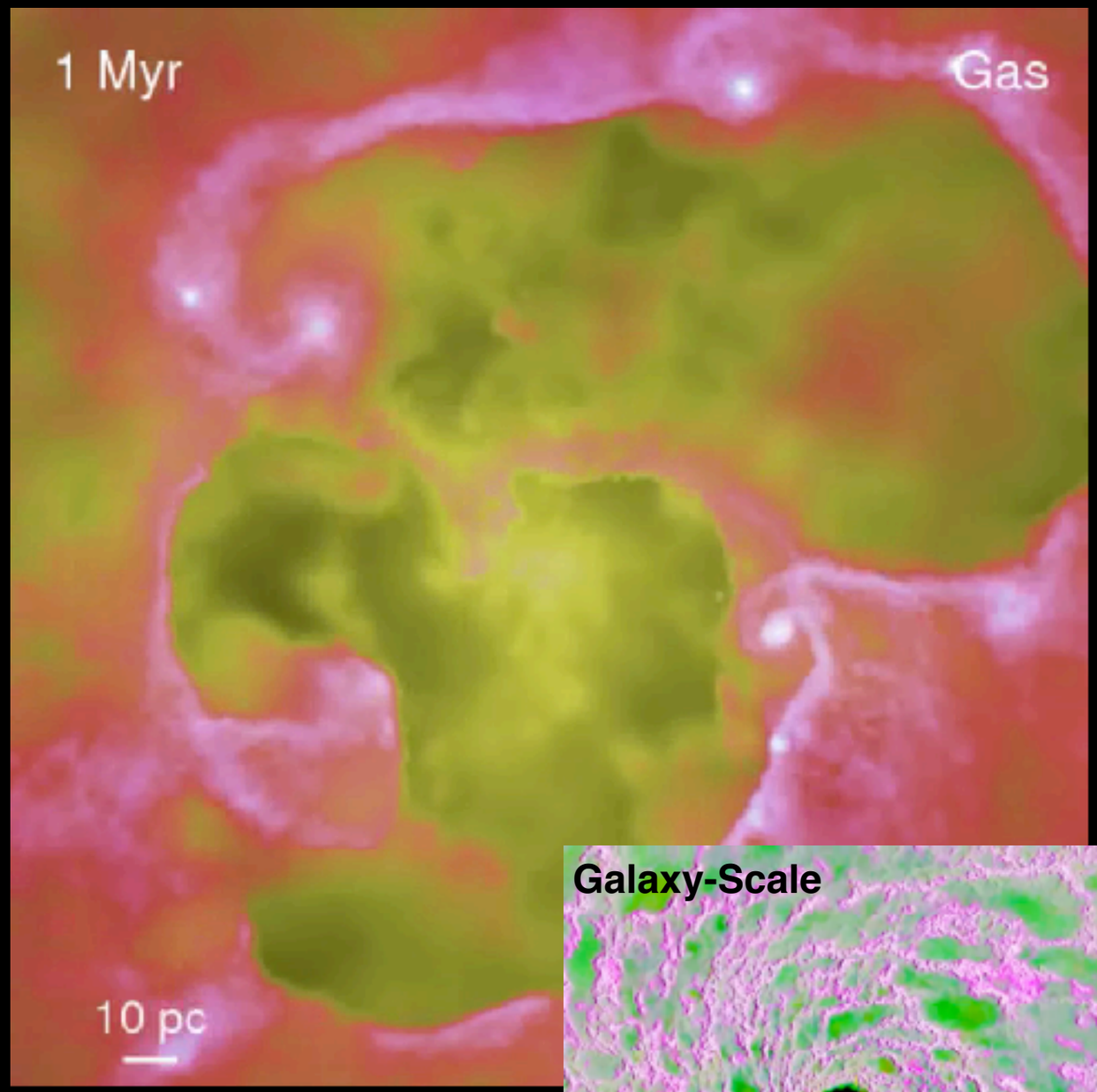
D. Angles-Alcazar
arXiv:1707.03832

Accretion Disk Winds: 0.01-10,000 pc

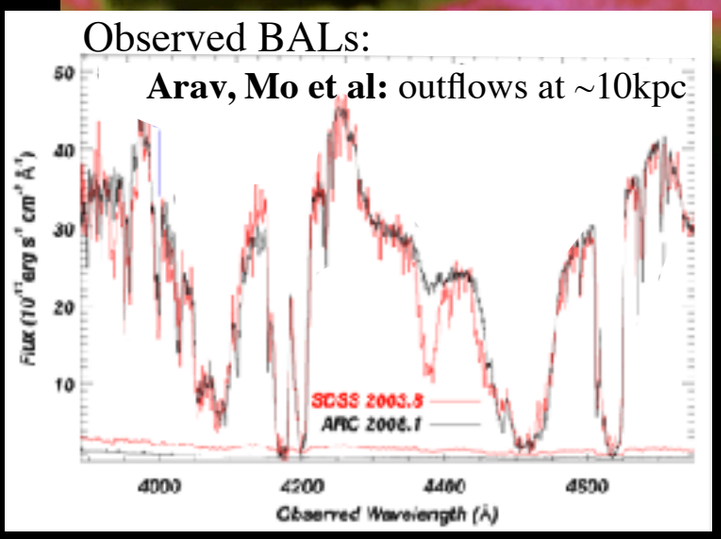
No BAL Winds



With BAL Winds

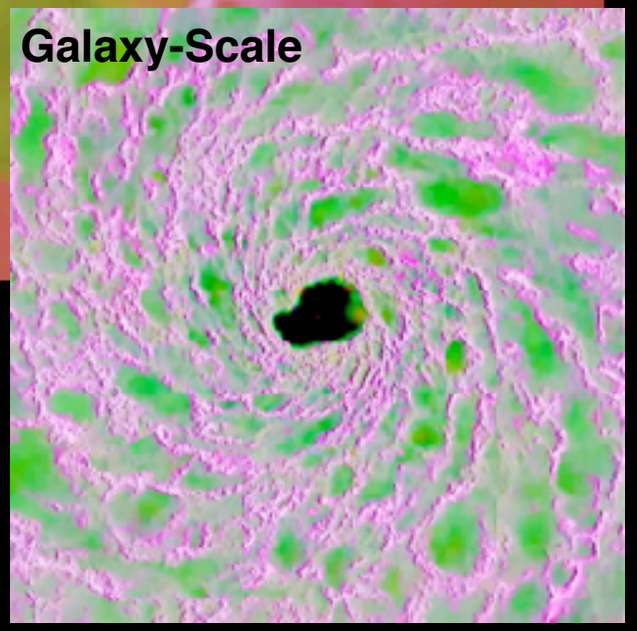


Observed BALs:



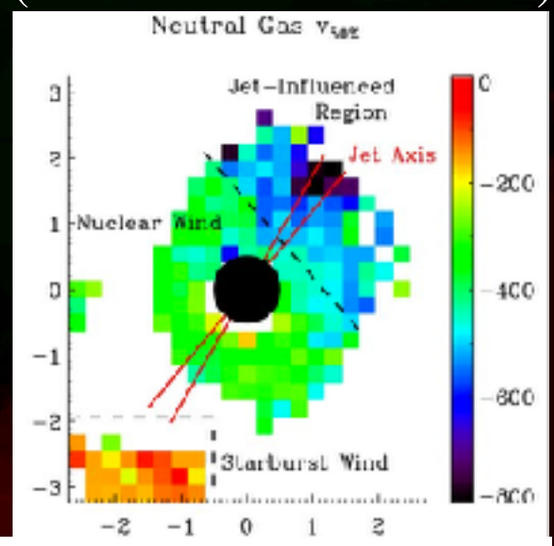
$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

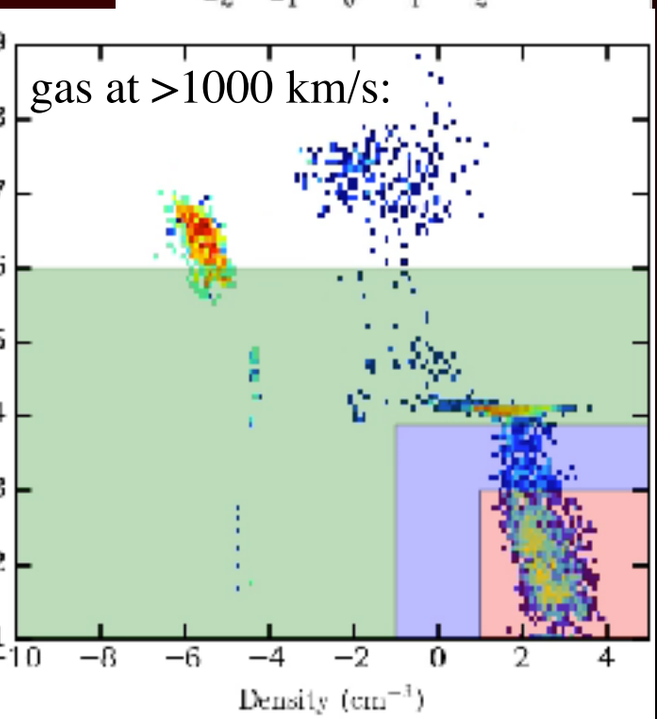
$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$



Accretion Disk Winds: 0.01-10,000 pc

Mrk 231
(+all other warm ULIRGs)





Torrey et al.
in prep