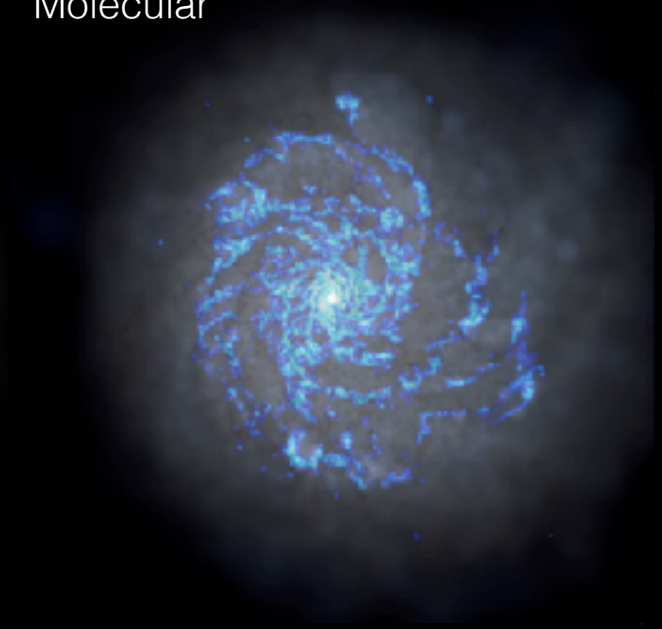
Feedback & Dark Matter: Are there actually small-scale challenges?

Observed Starlight

Molecular



Galaxy Merger

X-Rays

Star Formation

Philip F. Hopkins & the FIRE Team
www.tapir.caltech.edu/~phopkins

Caltech

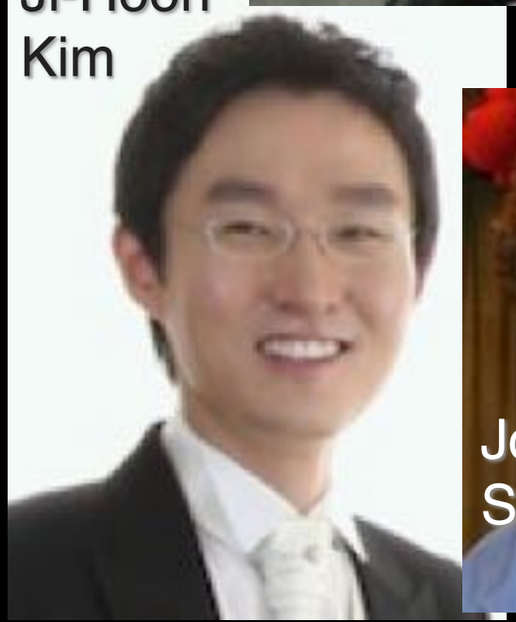
Postdocs

Andrew
Wetzel

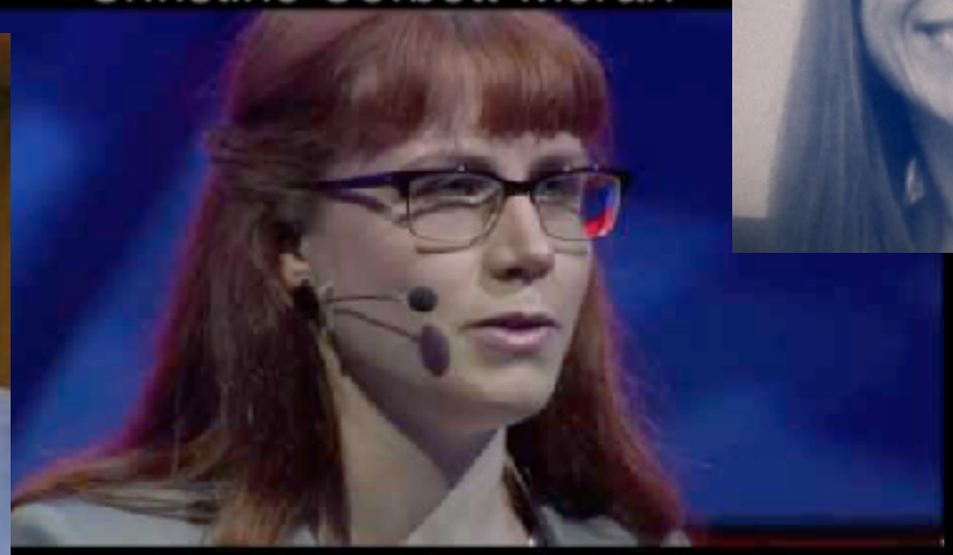
Shea Garrison-Kimmel

Robyn
Sanderson

Coral Wheeler



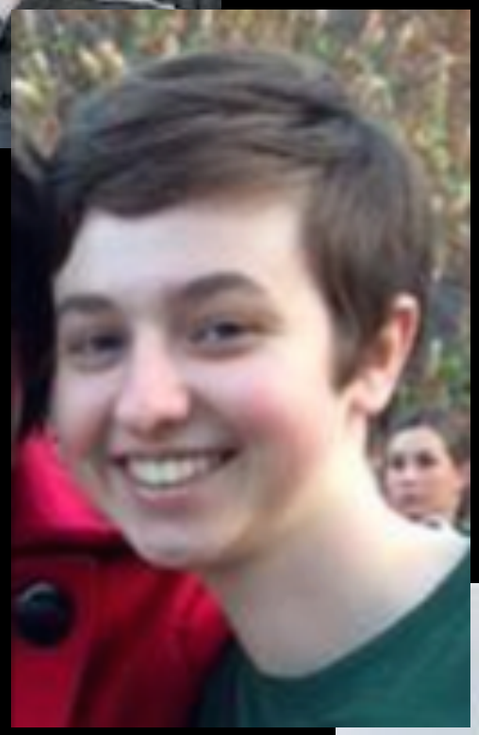
Christine Corbett-Moran



Chris Hayward

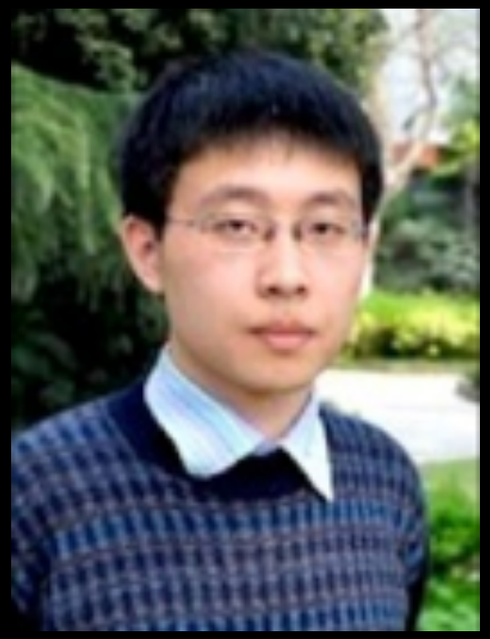
Grad Students

David Guszejnov



Denise Schmitz

Xiangcheng Ma

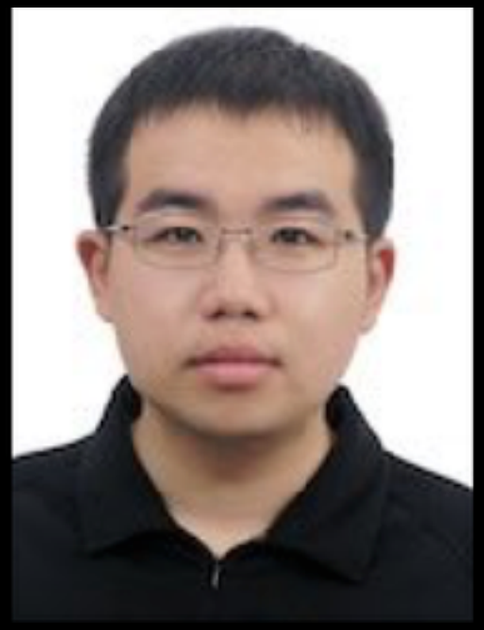


Matt Orr

Mike Grudic

Ivanna Escala

Antonija Oklopcic



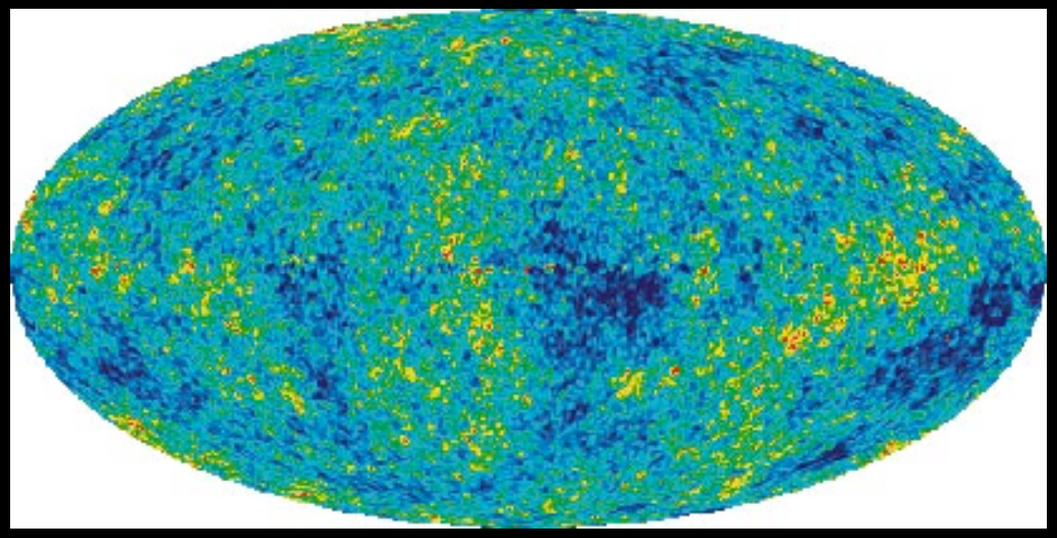
Kung-Yi Su

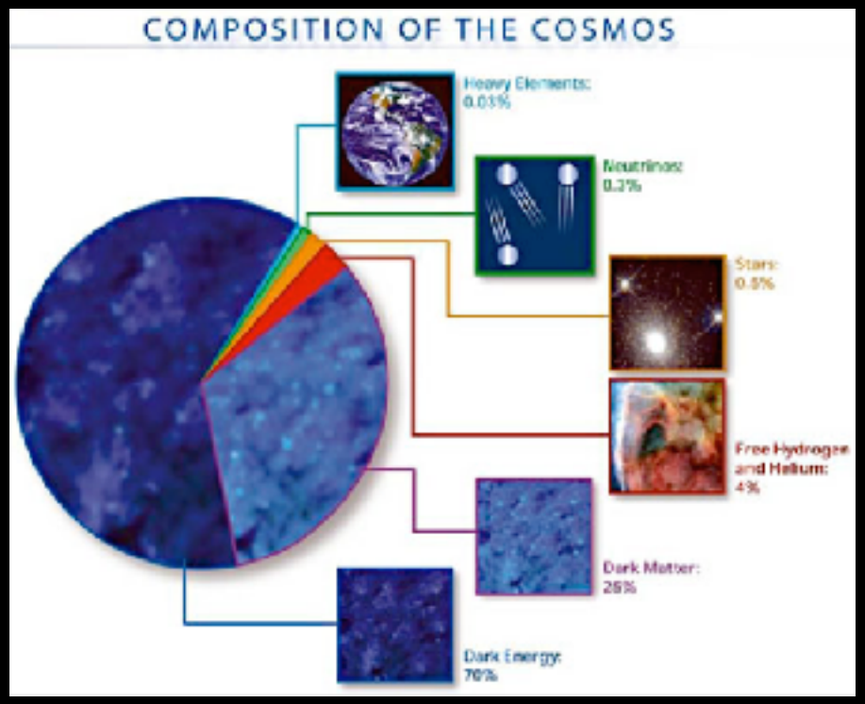
Hannalore Gerling-Dunsmore

Reminder: Big Picture

Large Scales:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?





z~1090
(t~400,000 yr)

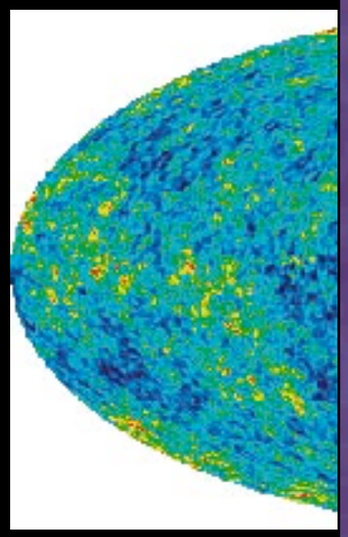
?

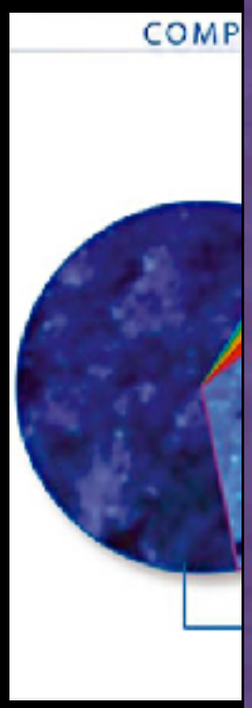
Today

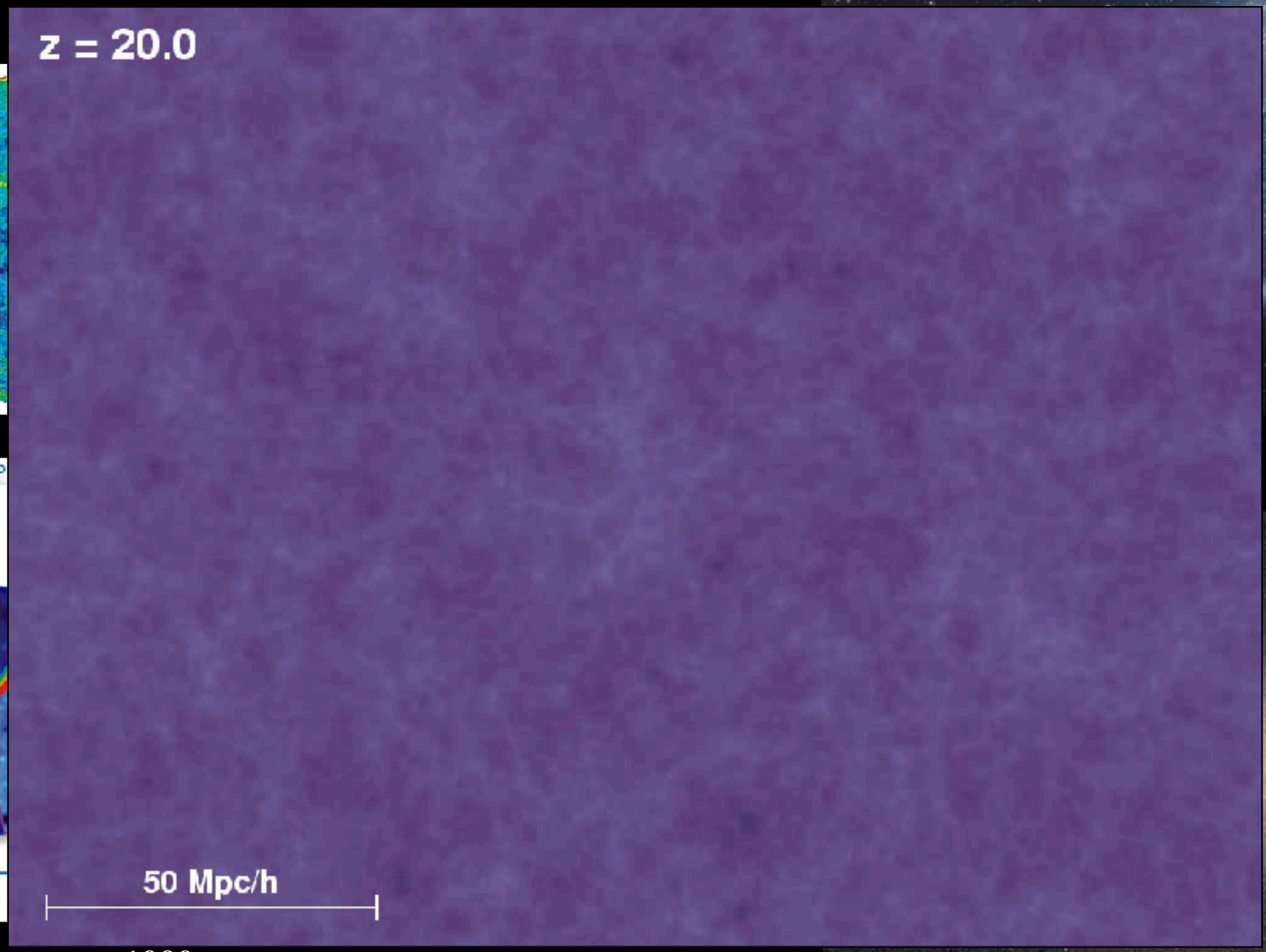
Large Scales:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?

Today





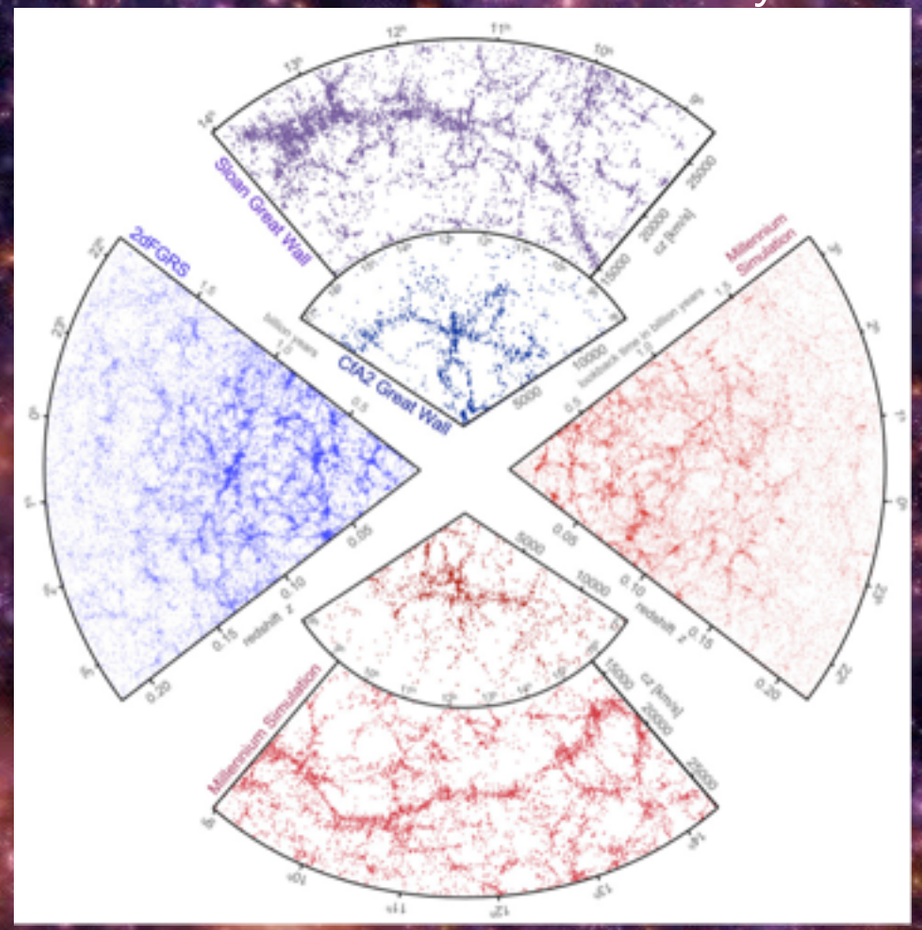


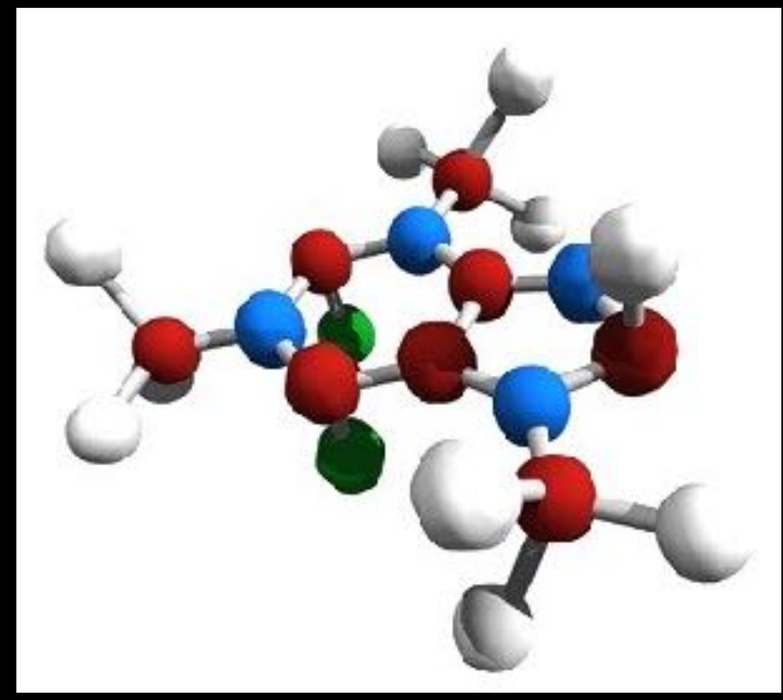
z~1090
(t~400,000 yr)

Large Scales: DM ≈

- pressure-free (relative to SM)
- non-relativistic (bulk / group)
- weakly interacting (outside GR)

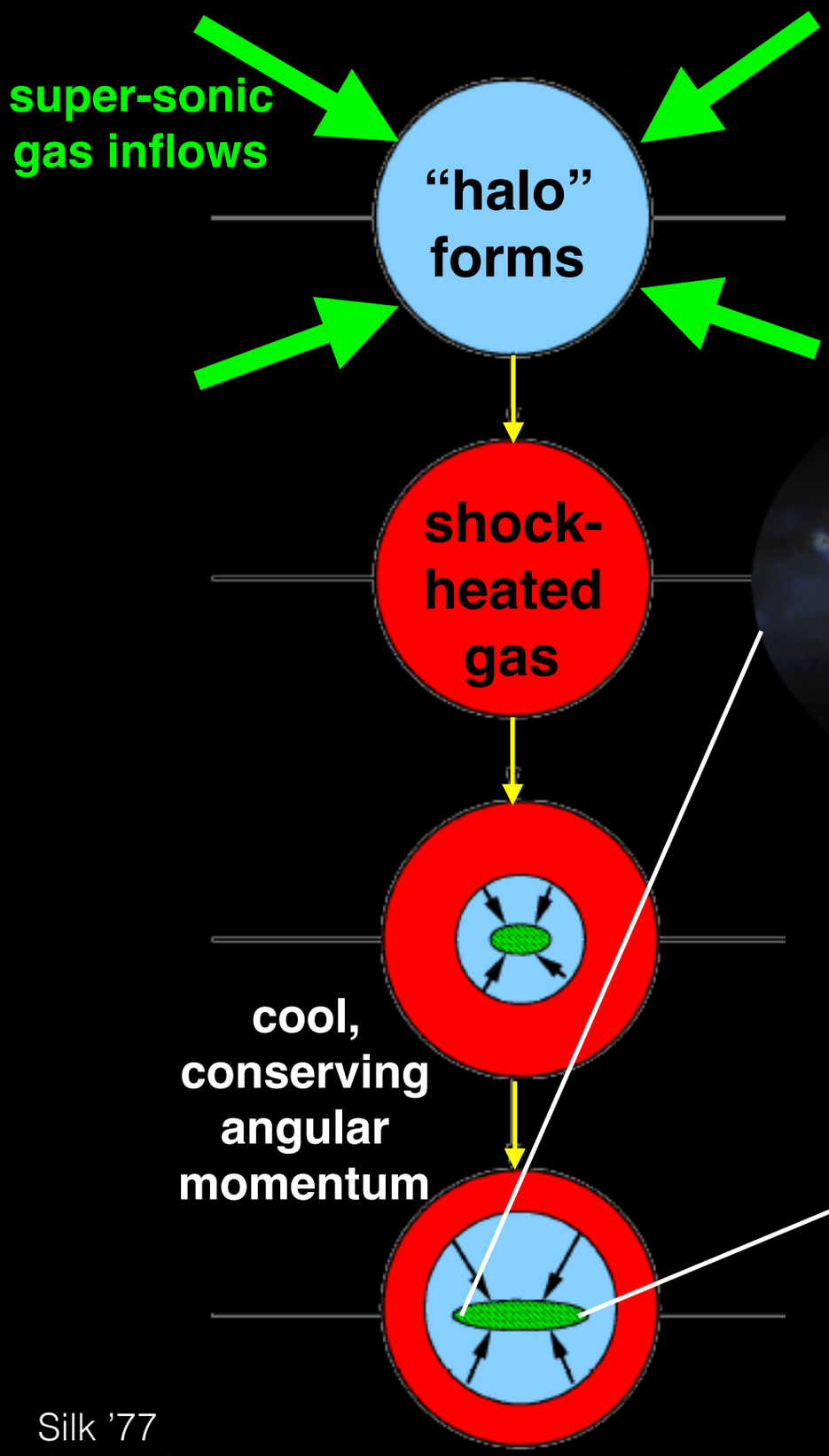
Observations vs Theory

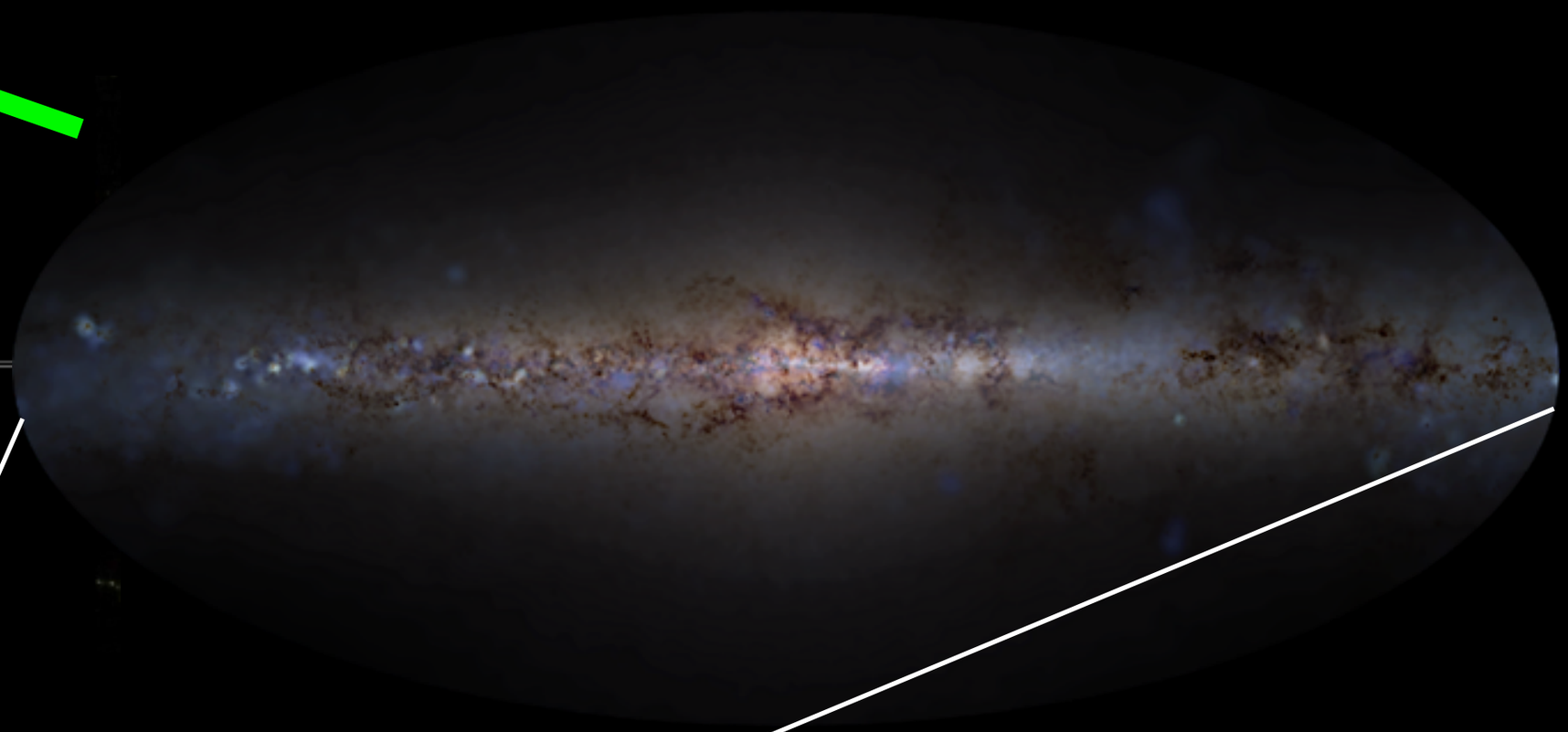




Add some fluid dynamics and chemistry, and go!

From Large Scales Down:





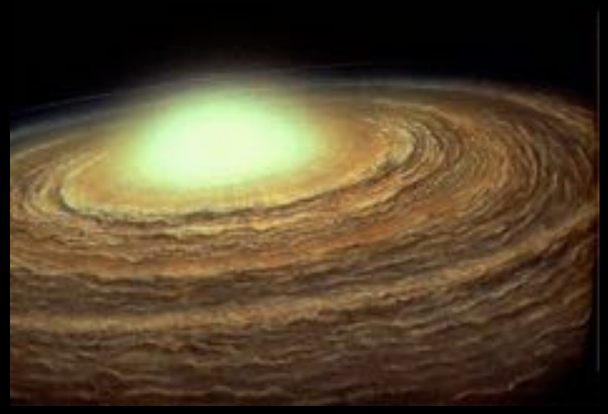
Silk ’77
Binney ’77
Rees & Ostriker ‘77

Our work:

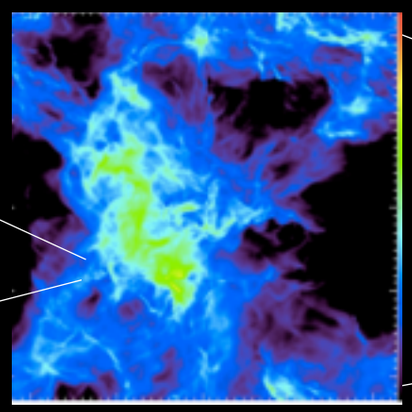
~10^{10} pc
Hubble volume

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

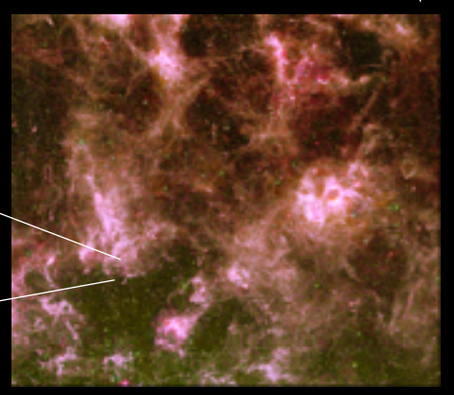
~10^{4-5} pc
Galaxy



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



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

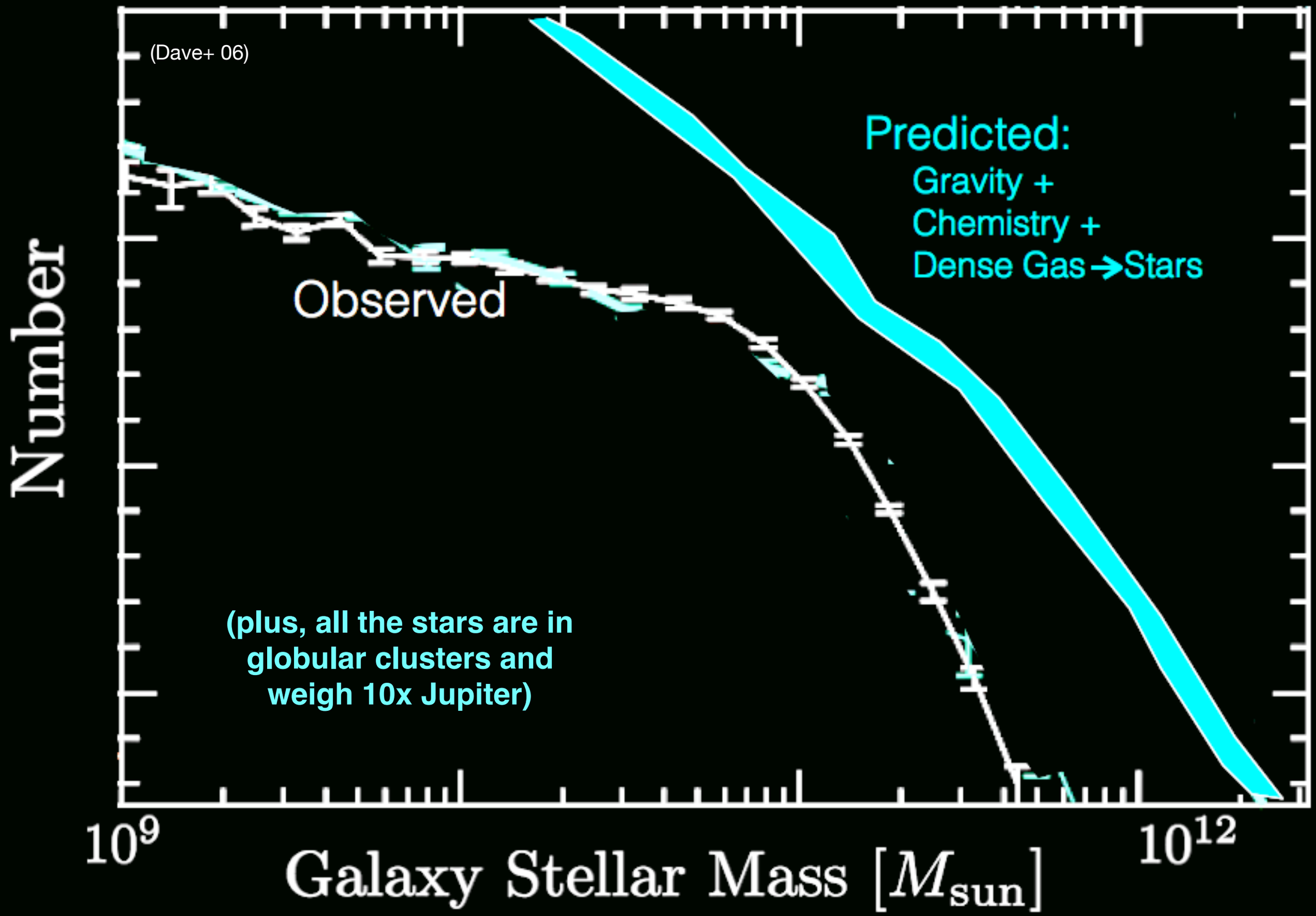


~10^{1}-10^{2} pc
Molecular clouds,
Star-Forming Regions

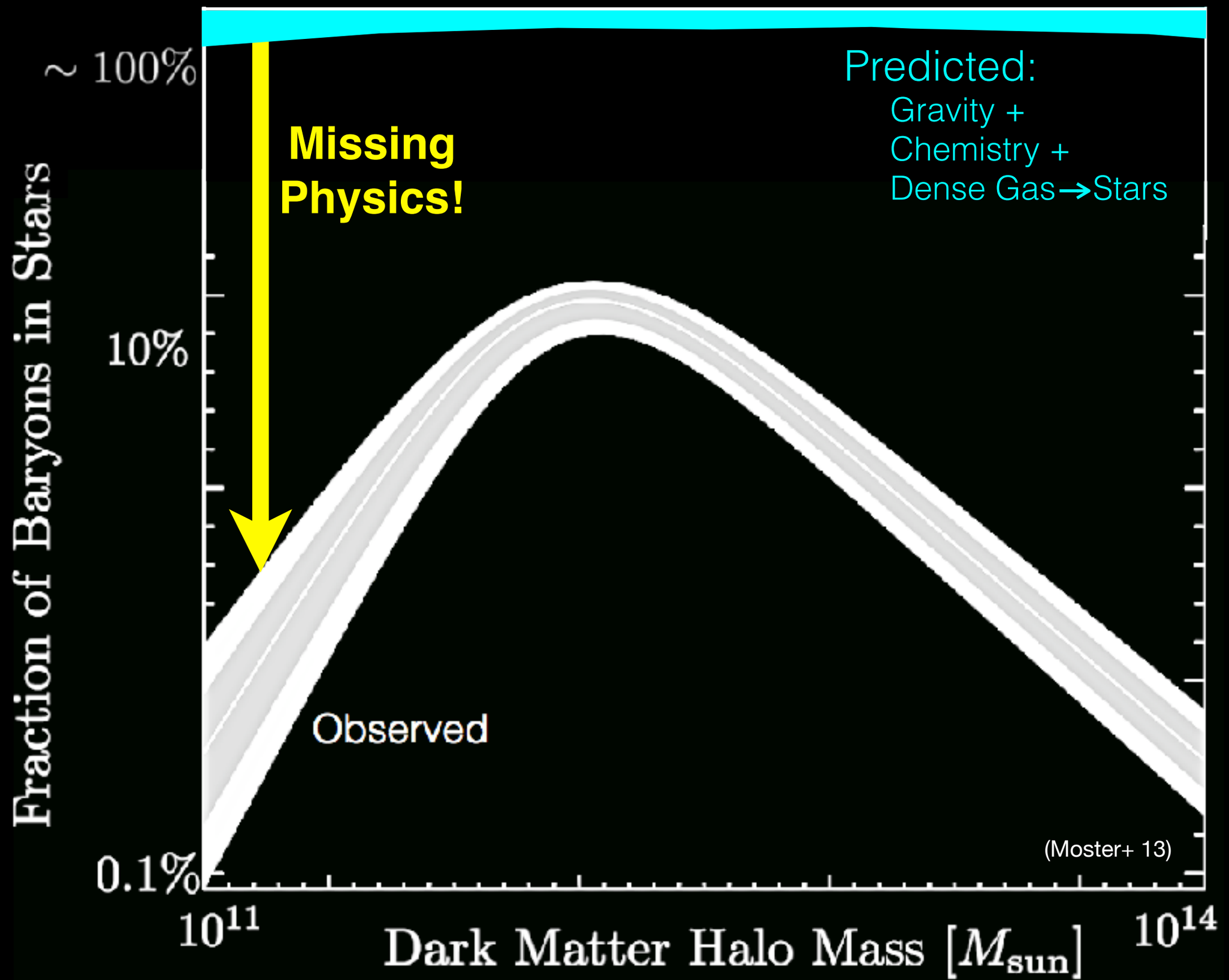
Not so fast…

Problem:

WHY SO FEW GALAXIES & STARS?



Problem:
WHY SO FEW GALAXIES & STARS?

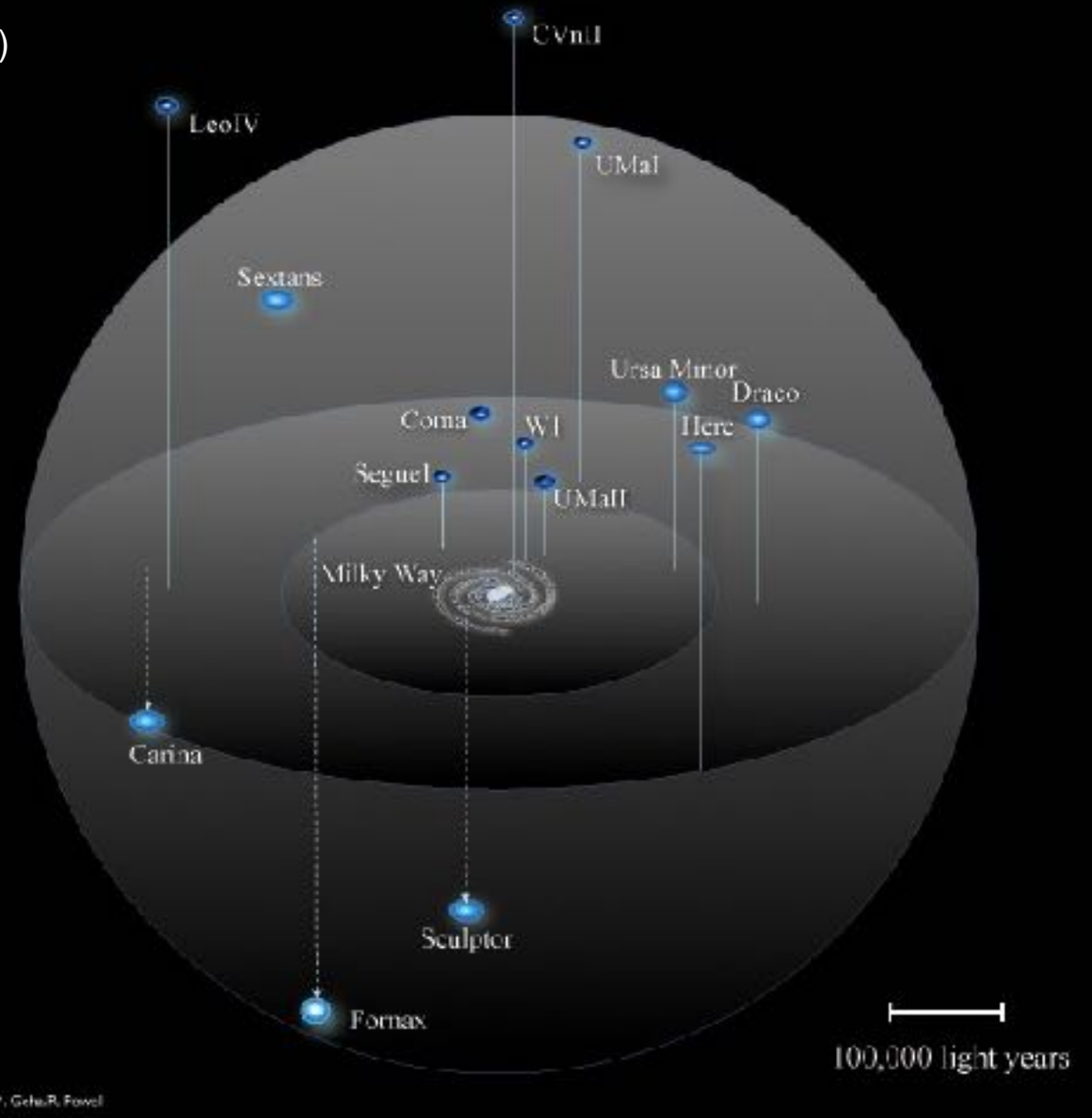


Problem:
WHERE ARE THE "MISSING SATELLITES"?

(Kravtsov+ 02)

Predicted structure
(dark matter)

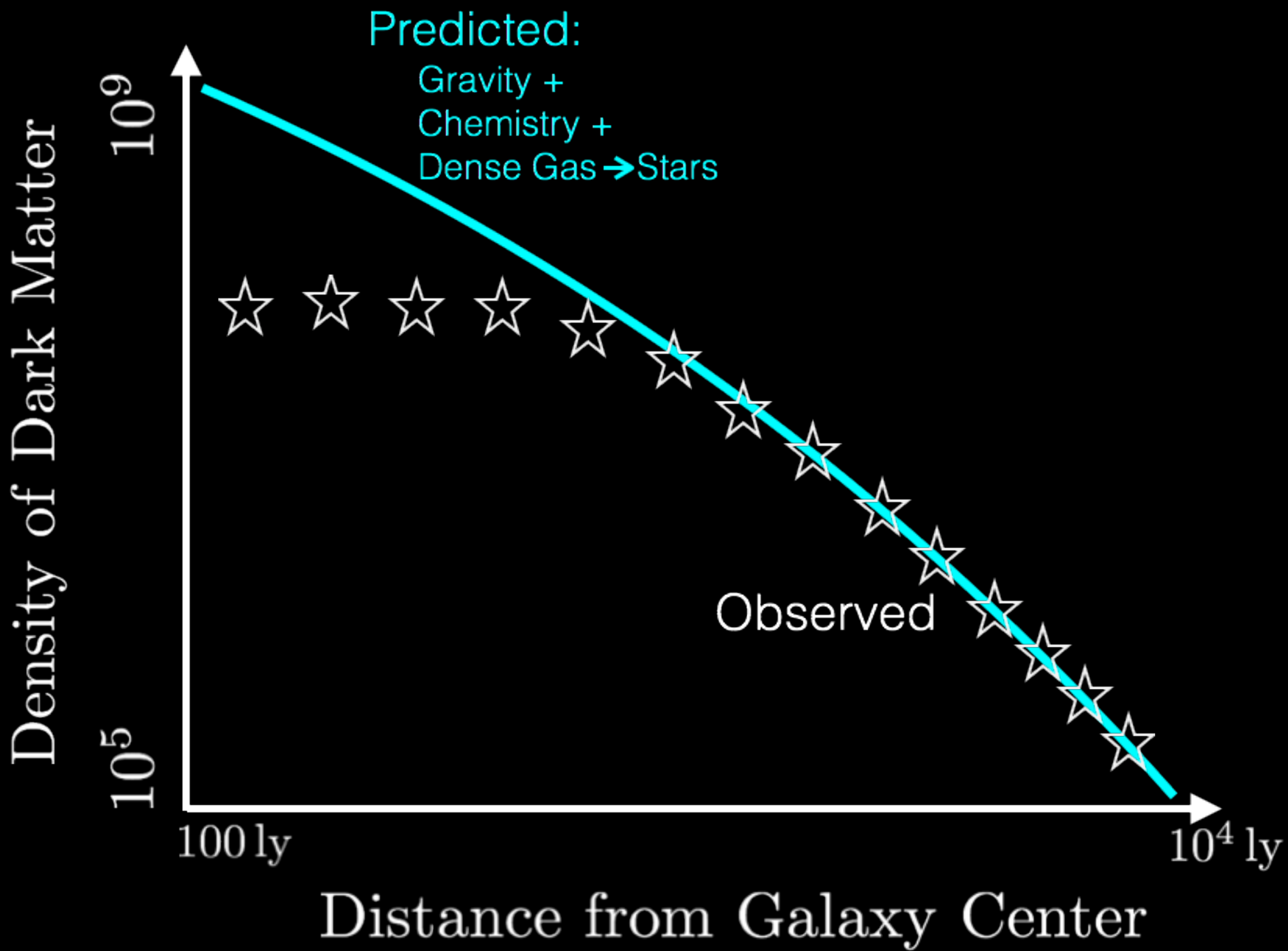
(Geha+)



Observed
around us

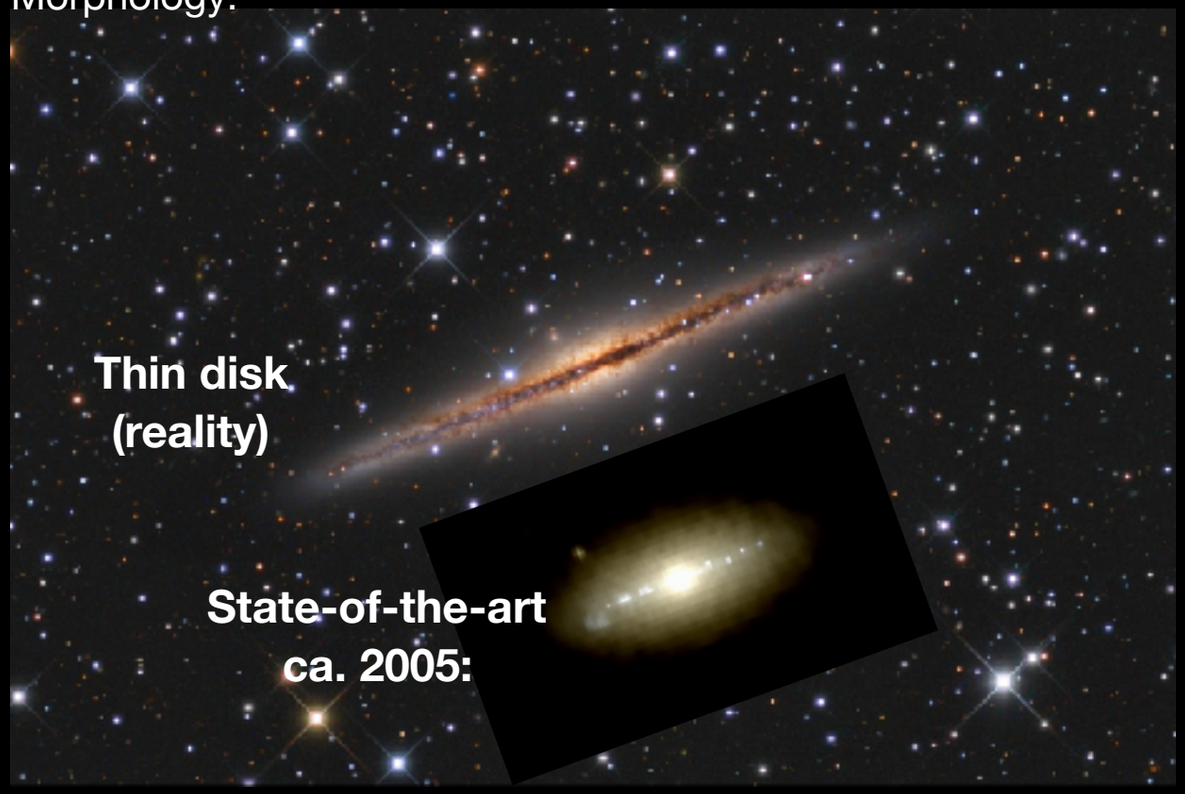
Problem:

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

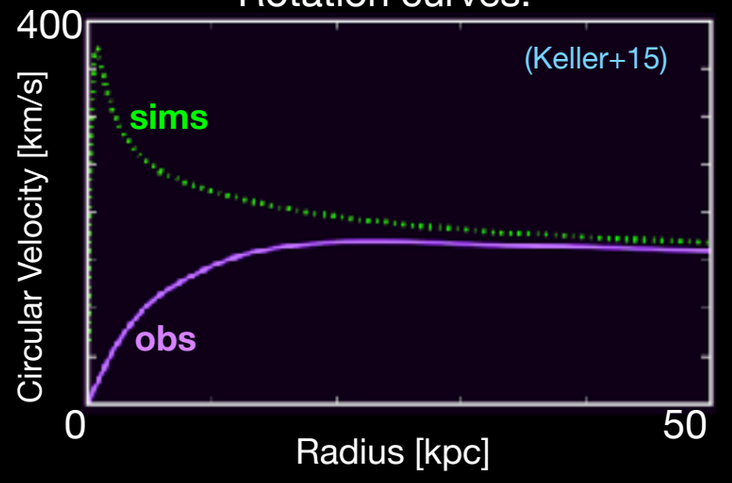


Problem:
GALAXY MORPHOLOGIES AND SCALING RELATIONS

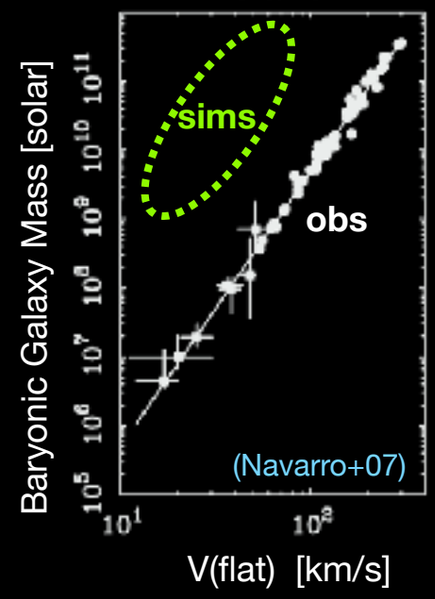
Morphology:

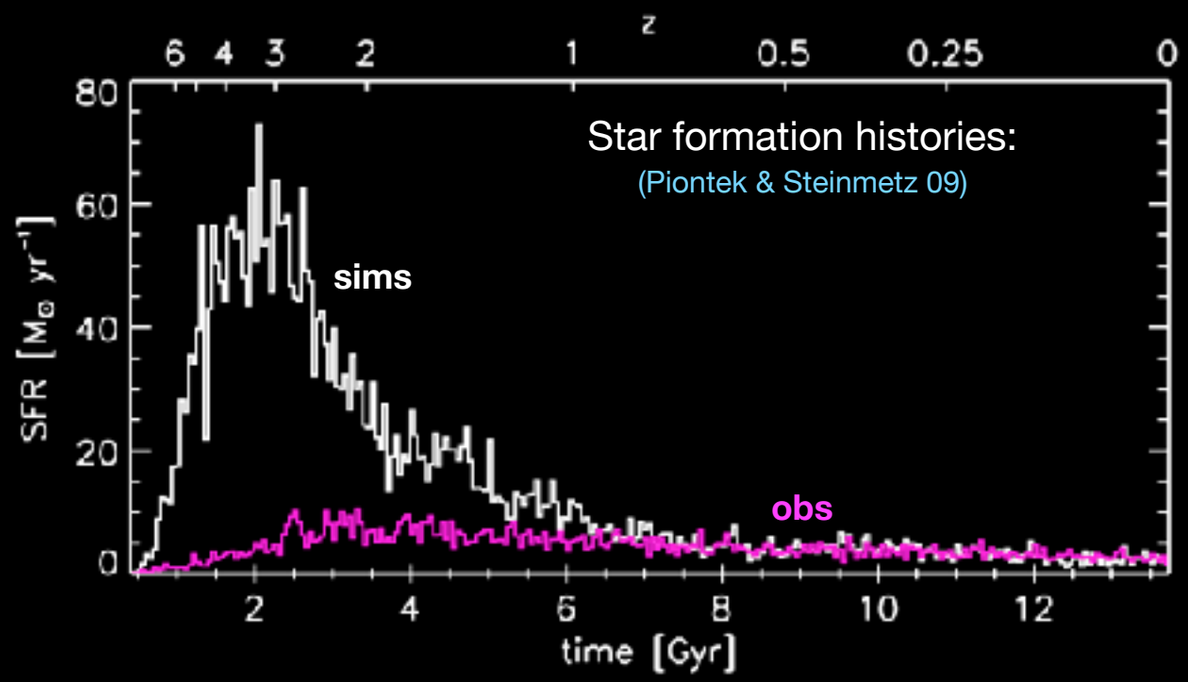


Rotation curves:



Tully-Fisher relation:





- 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)

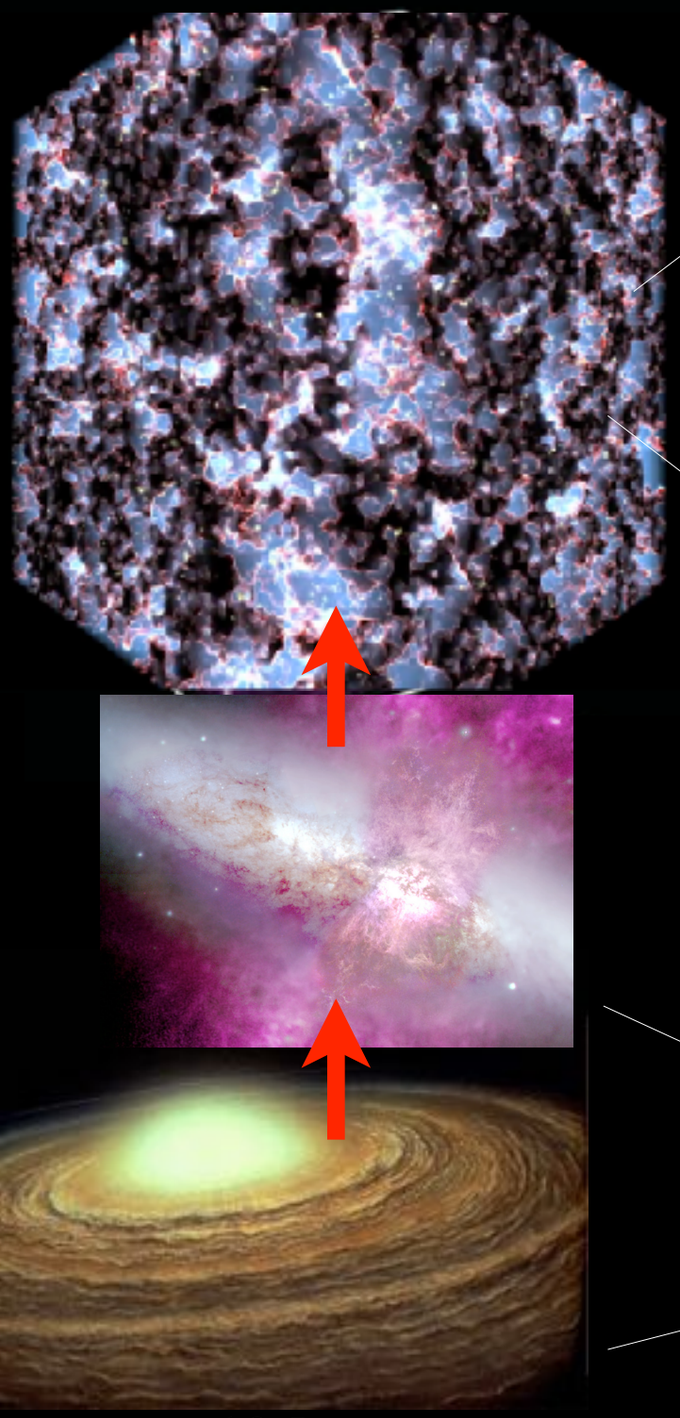
But wait…

Stars Matter

… Nature hates theorists

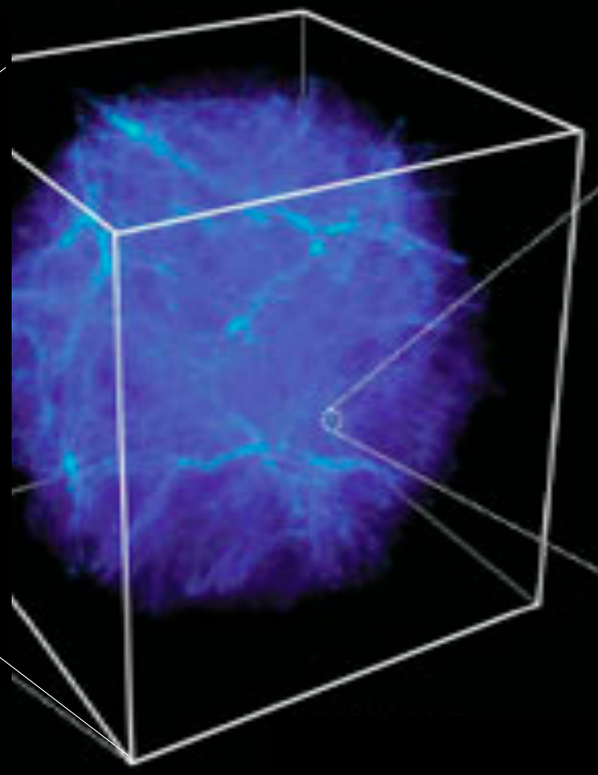
~10^{10} pc

Hubble volume



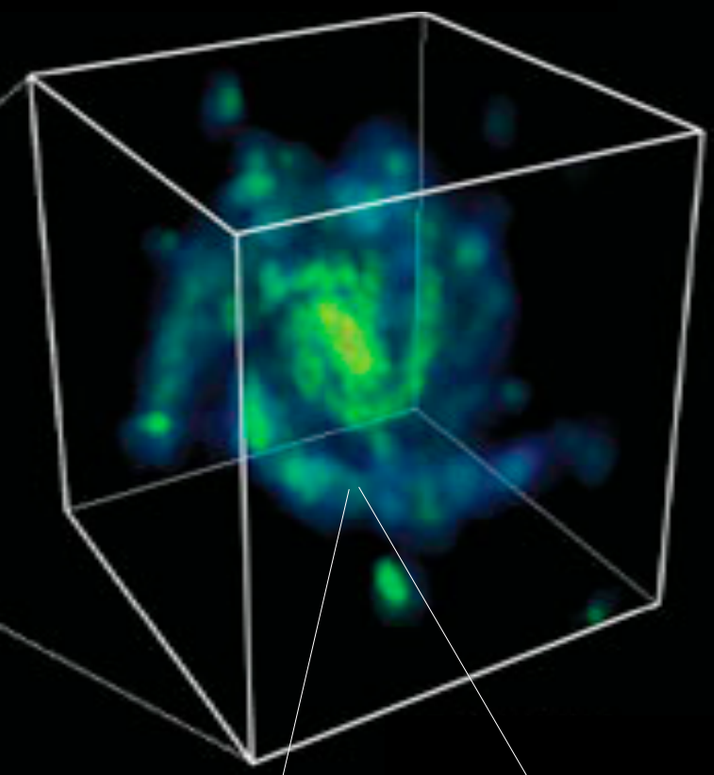
~10^{7}-10^{8} pc

Clusters, Large-scale structure



~10^{4-5} pc

Galaxy

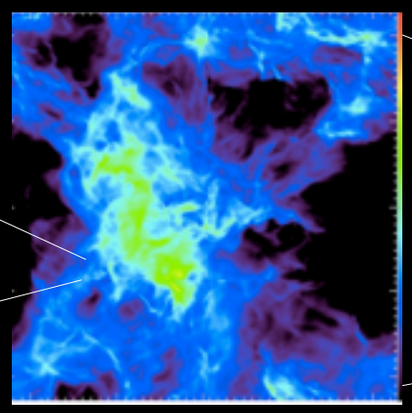


~10^{-5} pc

Stars, protostellar disks

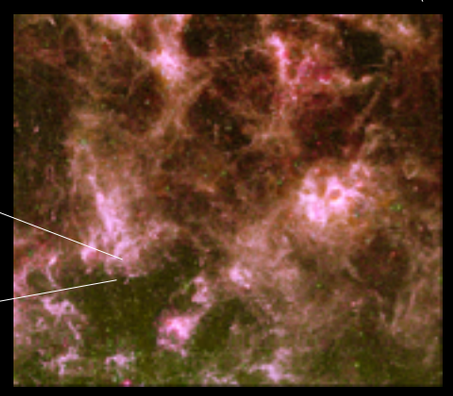
~10^{-2}-10^{0} pc

Cores, clusters,
Supernovae blastwaves



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

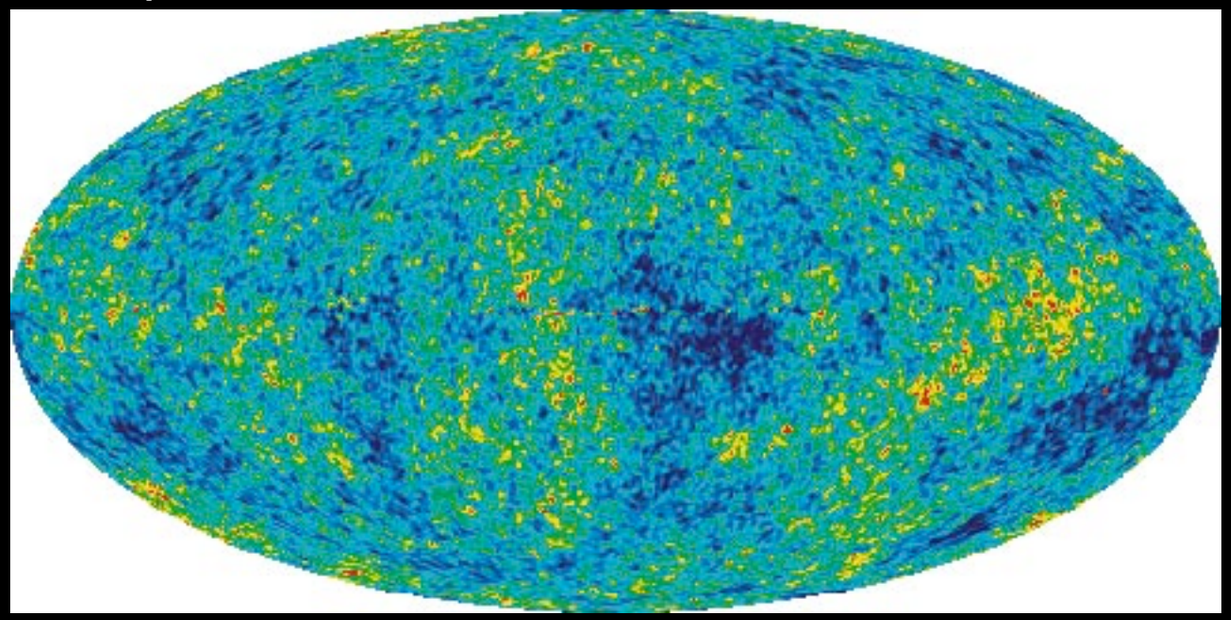
Molecular clouds,
Star-Forming Regions



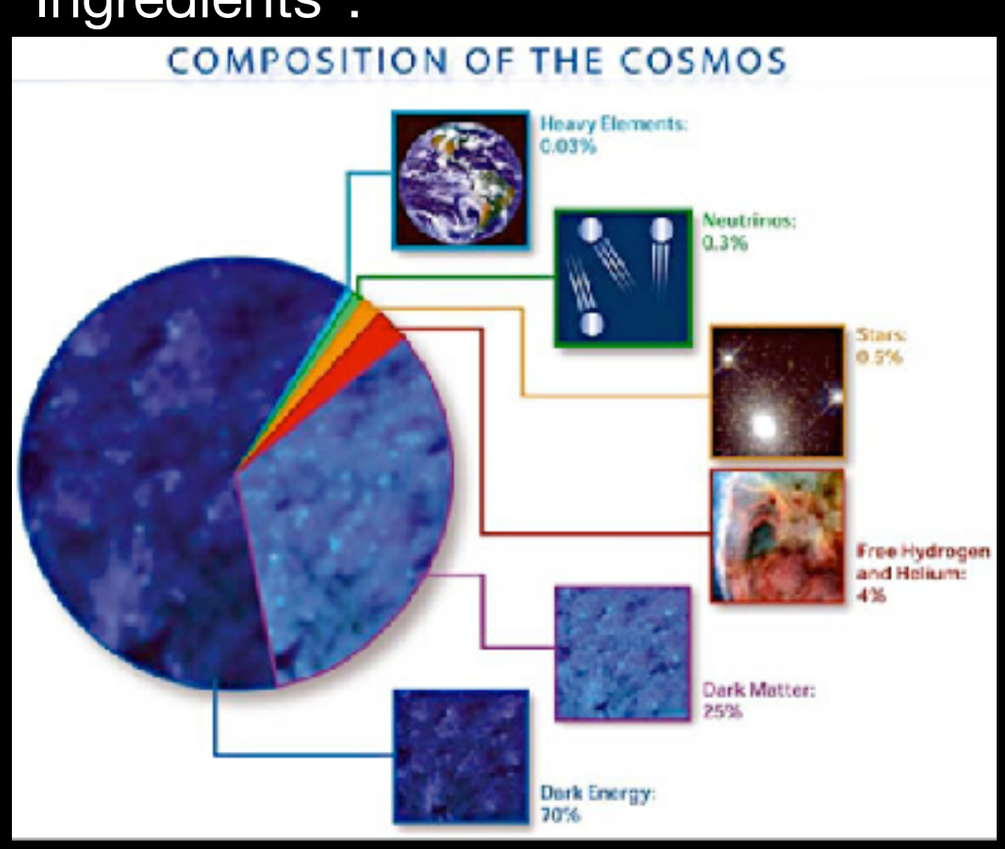
3 Breakthroughs:

1. “Concordance” cosmology

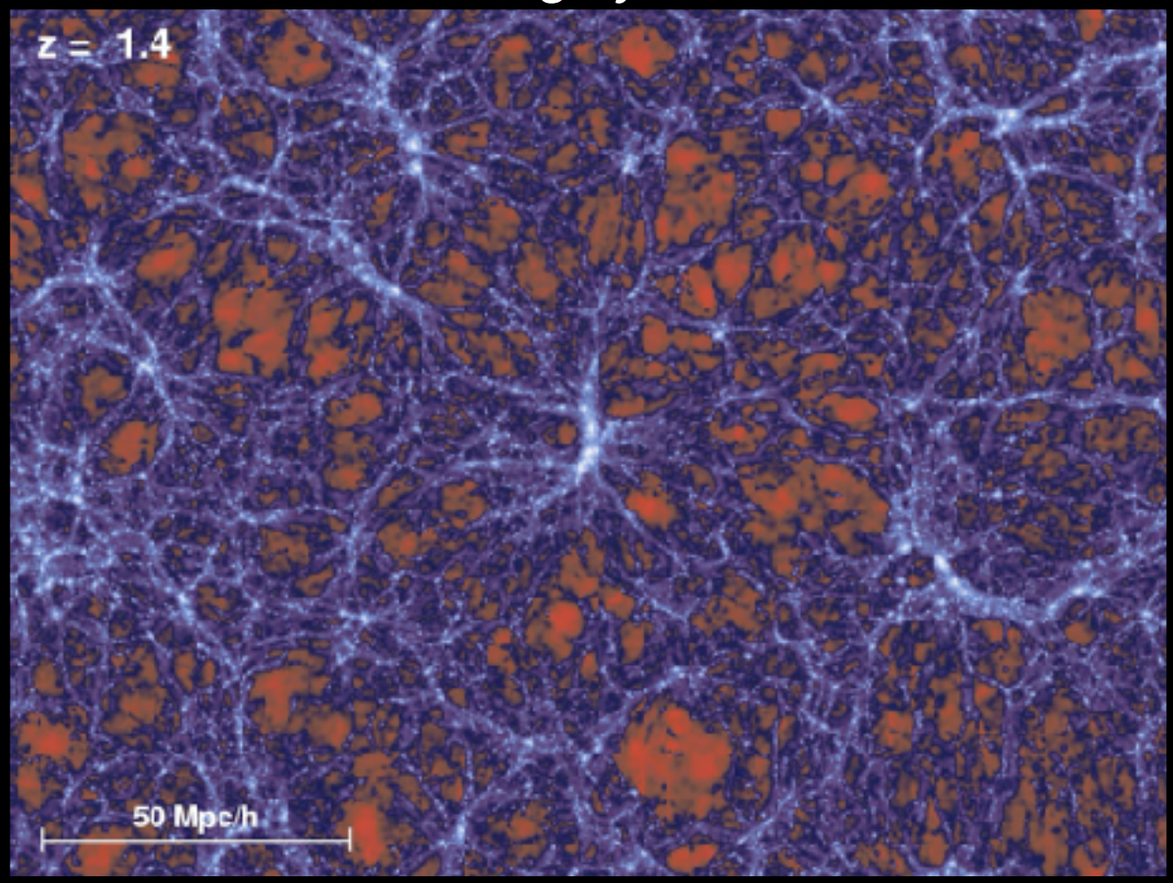
Well-posed initial conditions:



“Ingredients”:

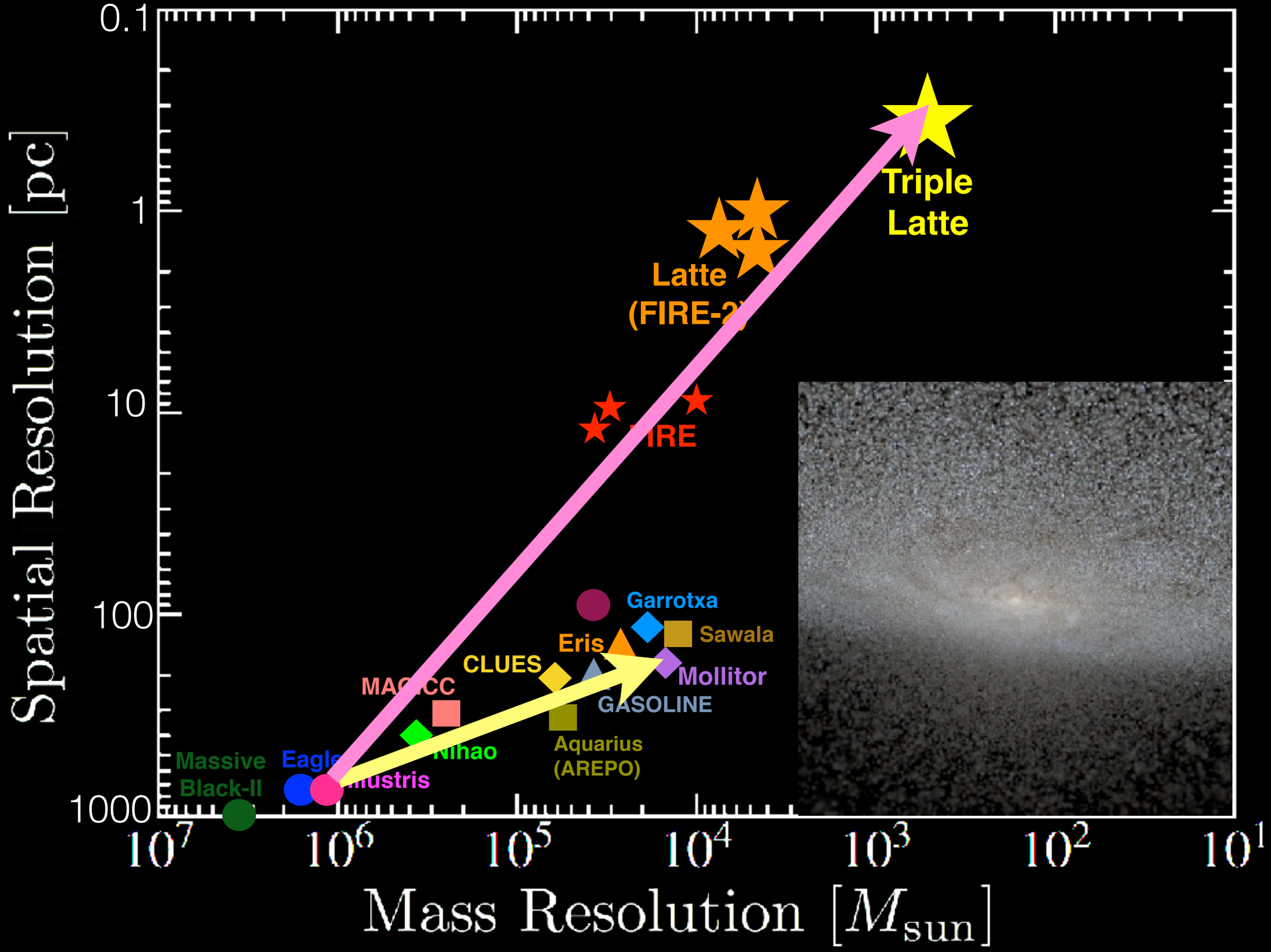


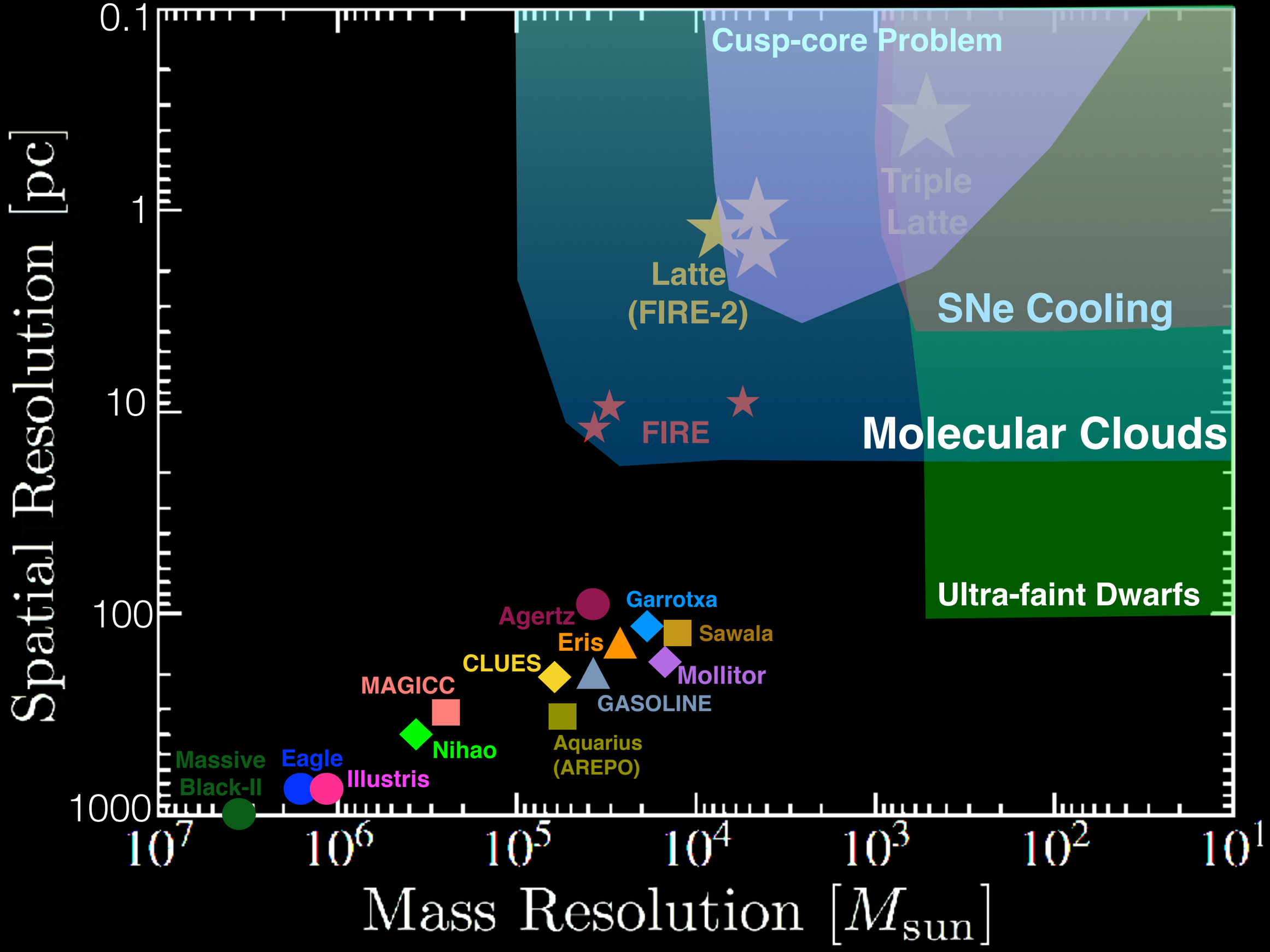
“smoothed” field
looks *roughly* like this:



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

2. Resolution (Moore's Law + Algorithms)




Spatial Resolution [pc]
0.1
1
10
100
1000
Cusp-core Problem
Triple Latte
Latte (FIRE-2)
SNe Cooling
FIRE
Molecular Clouds
Ultra-faint Dwarfs
Garrotxa
Agertz
Sawala
Eris
CLUES
Mollitor
MAGICC
GASOLINE
Nihao
Aquarius (AREPO)
Massive Black-II
Eagle
Illustris
10^7
10^6
10^5
10^4
10^3
10^2
10^1
Mass Resolution $[M_{\rm sun}]$

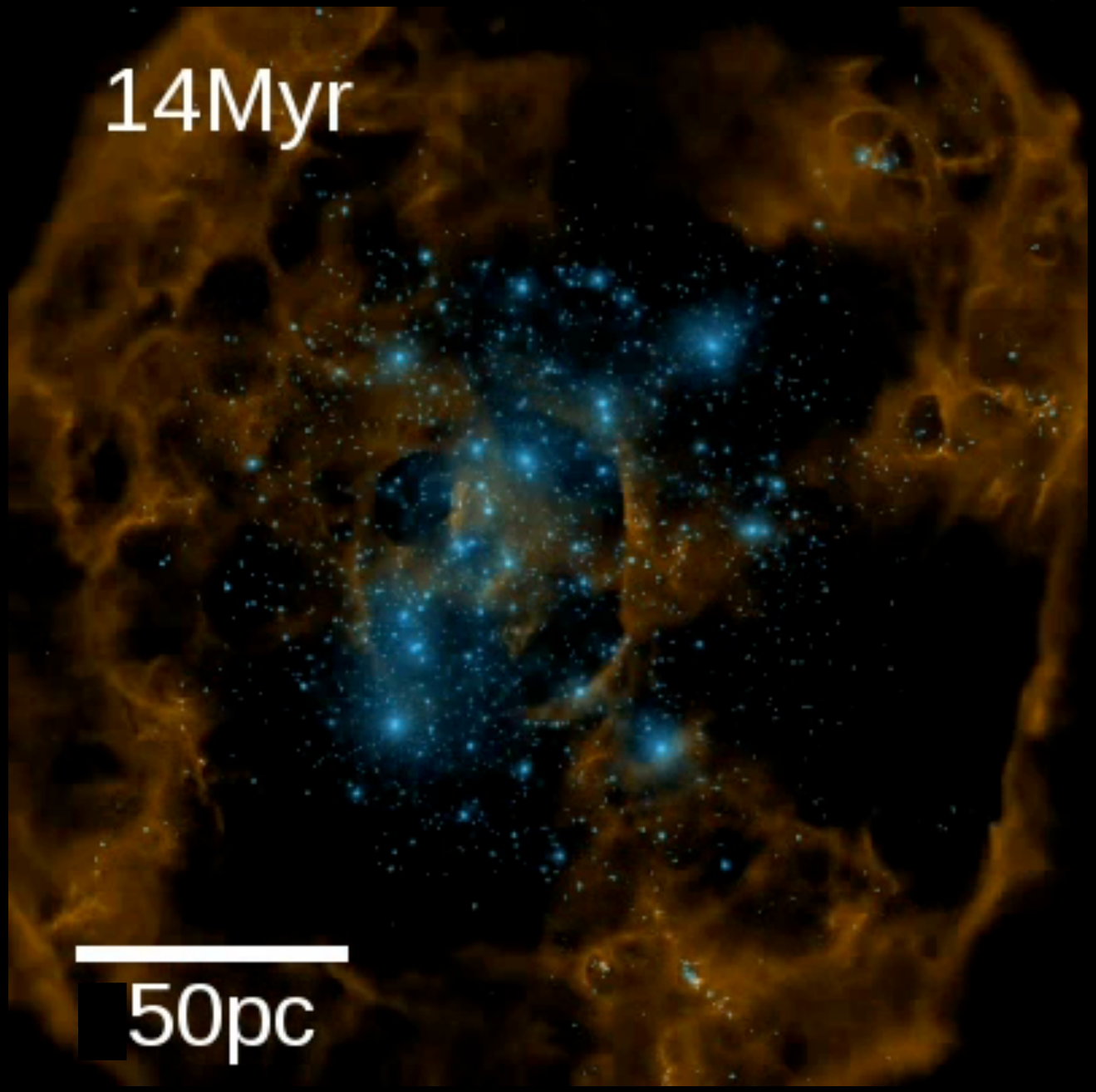
3. "New" Physics
INSIGHTS FROM STAR FORMATION

- 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})

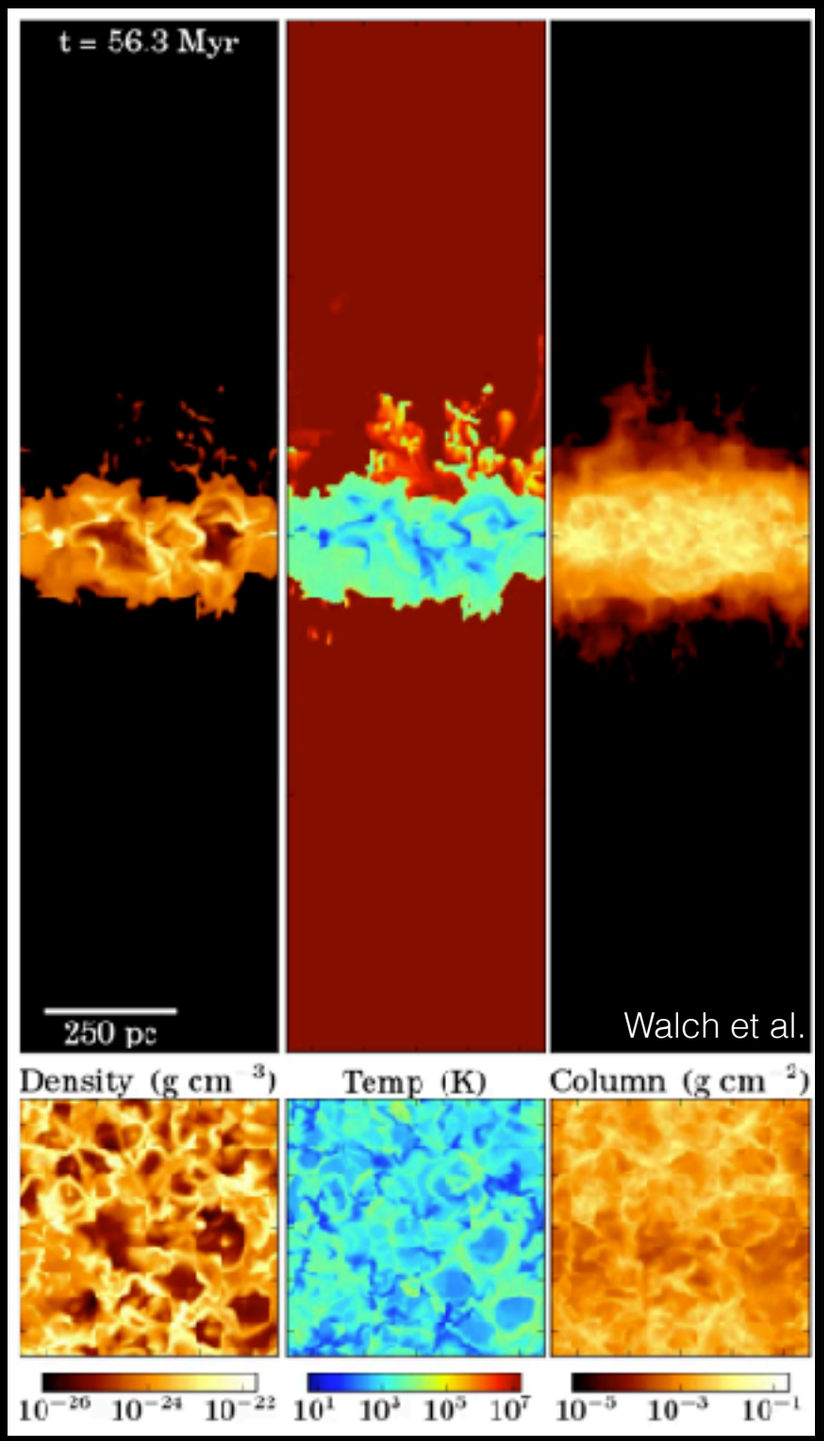


Mike Grudic
(arXiv:1612.05635)

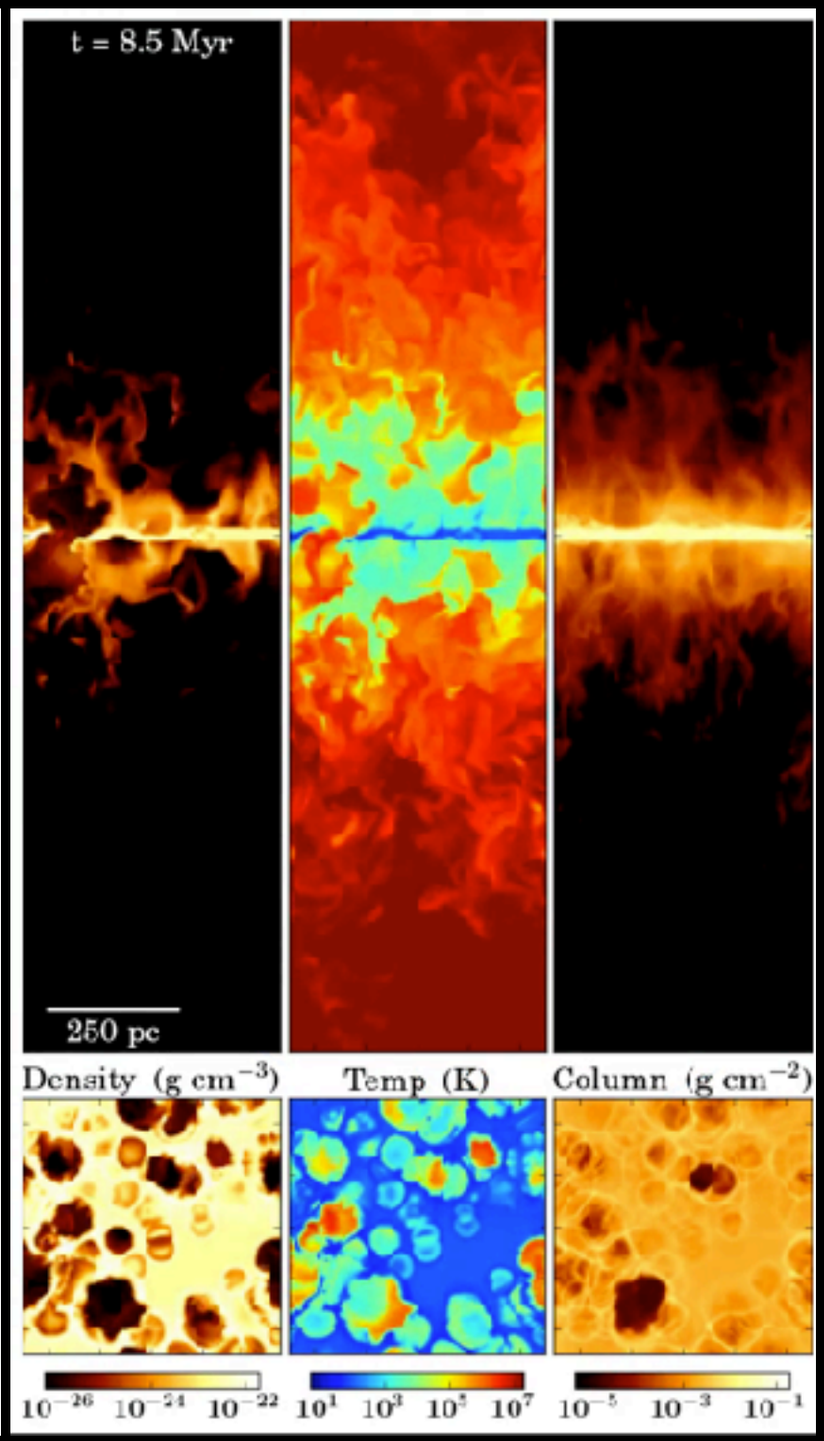
3. "New" Physics
INSIGHTS FROM STAR FORMATION

Martizzi+ '16
Walch+ '15, '17, Kimm+ '15
many others

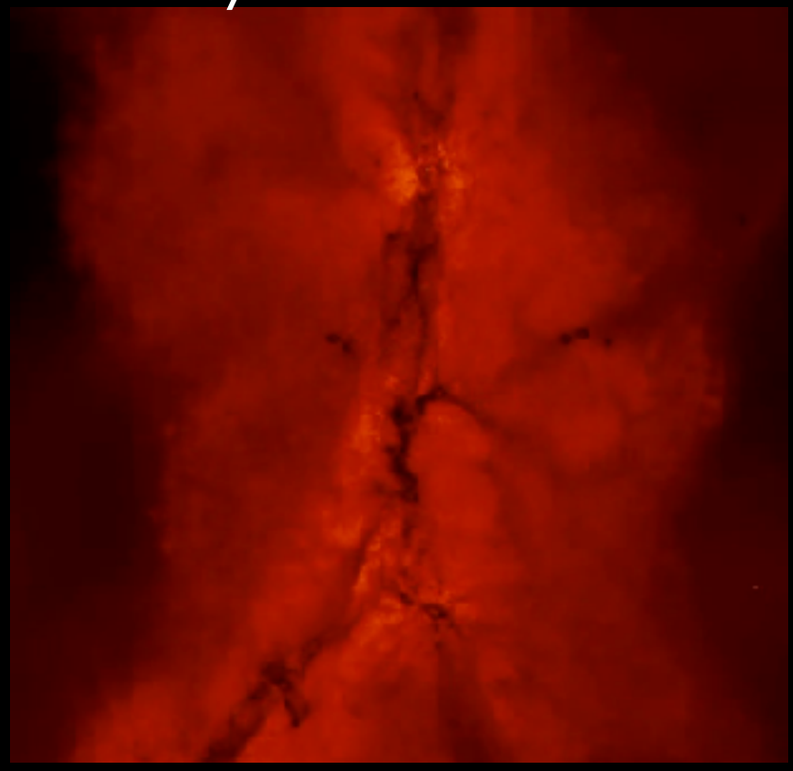
SNe Explode in Density Peaks (no radiative feedback)



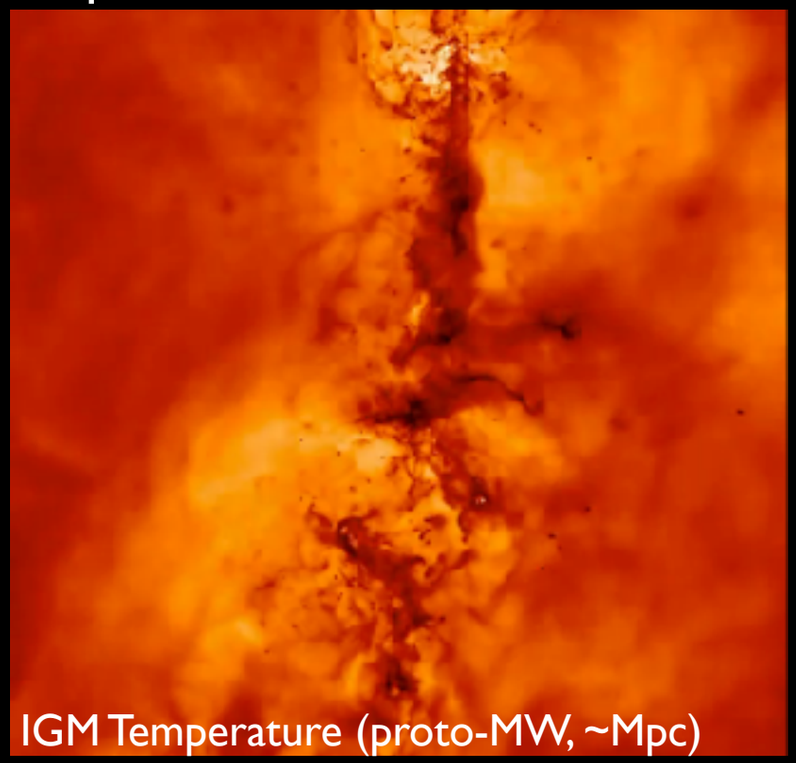
SNe Clustered & Off-Peak (radiative feedback/pre-processing)



Winds "by hand" ~SFR



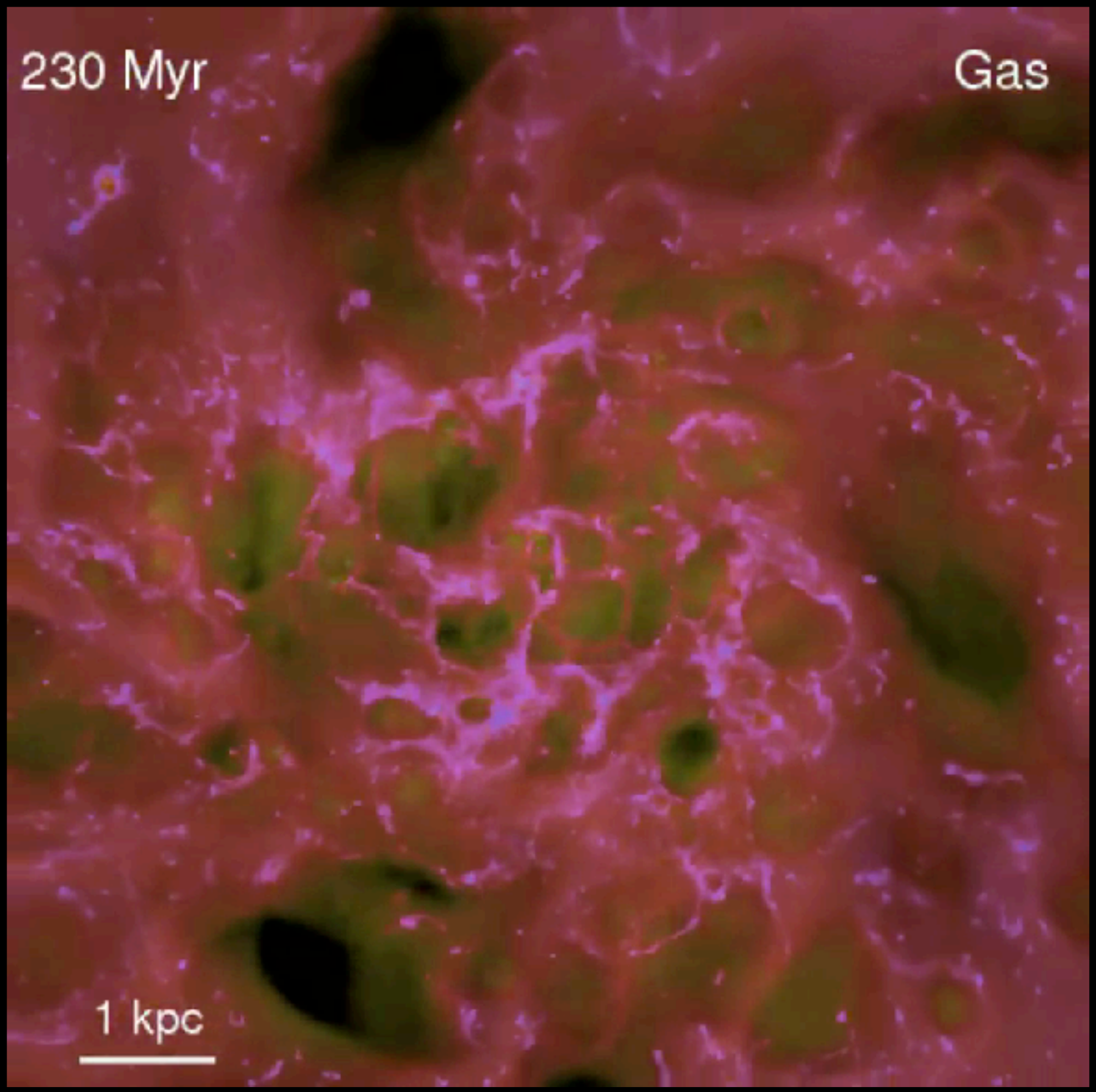
Explicit ISM/Feedback



Putting this together

Testing the "null hypothesis"

The FIRE (Feedback In Realistic Environments) Project



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

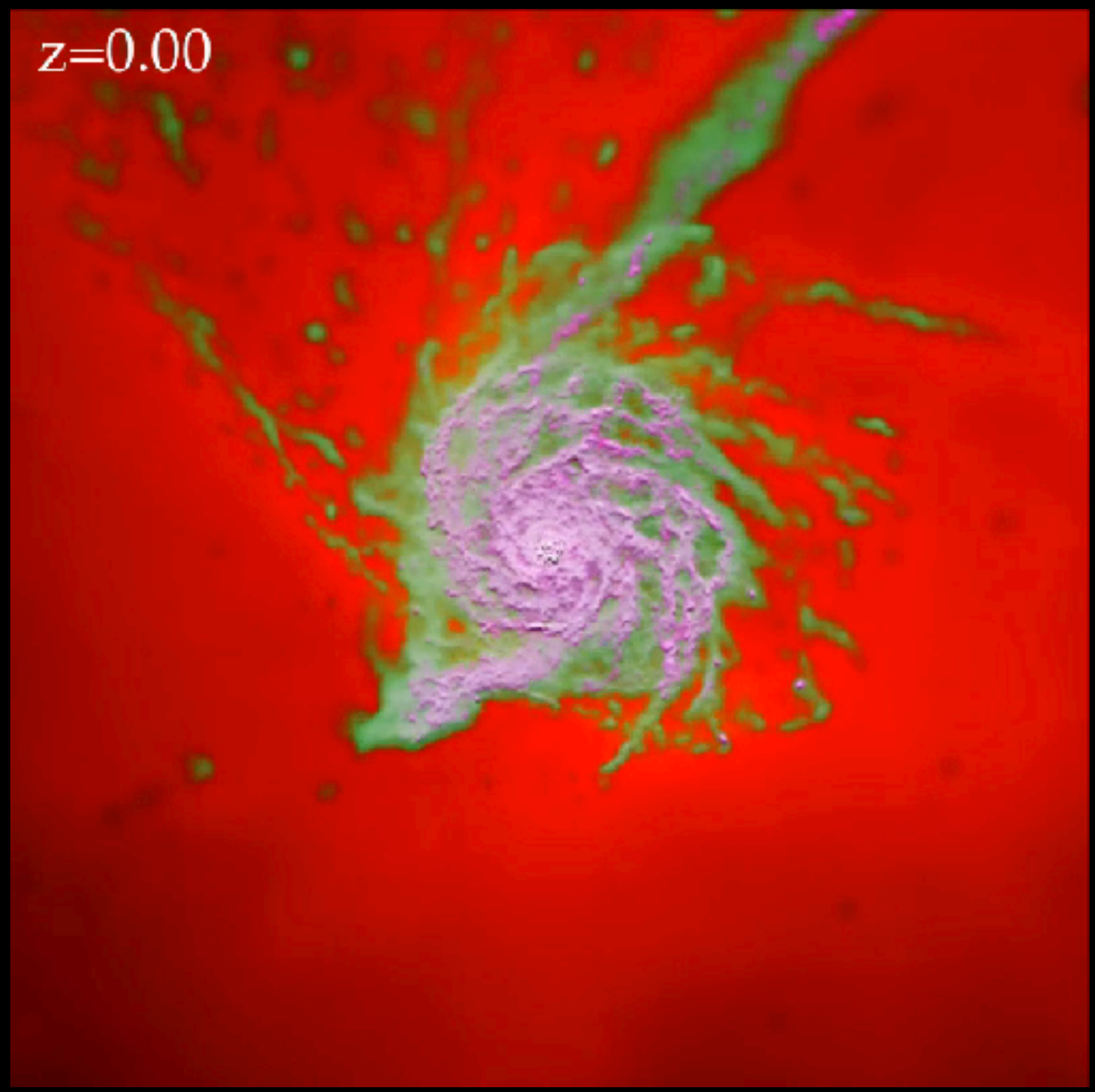
- "Vanilla" ΛCDM
- DM = collisionless, non-relativistic, gravity-only fluid

- 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

(movies at www.tapir.caltech.edu/~phopkins)



Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

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

Green: warm (ionized)

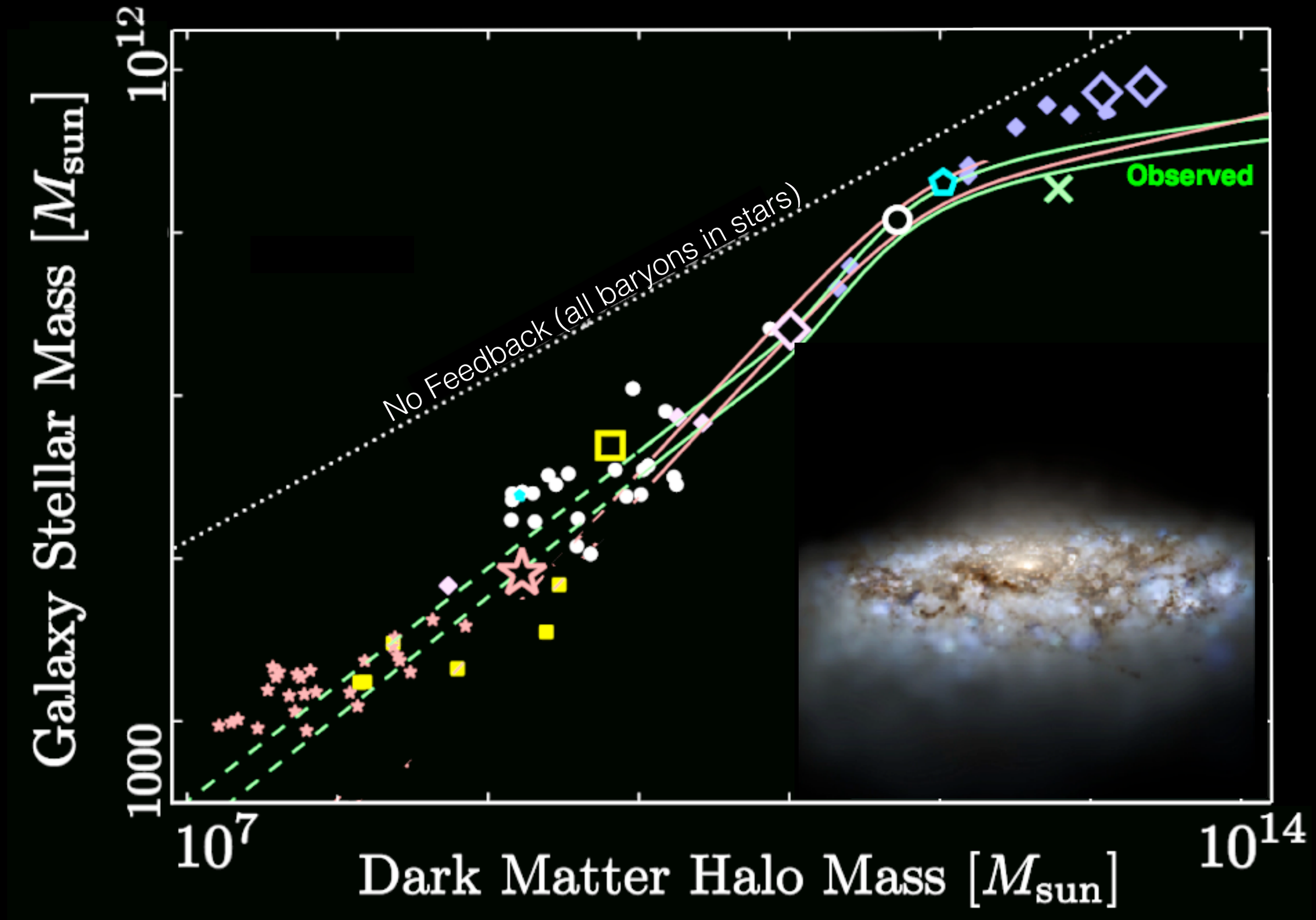
Red: hot $(> 10^6\,K)$

(A. Wetzel+1602.05957)

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)



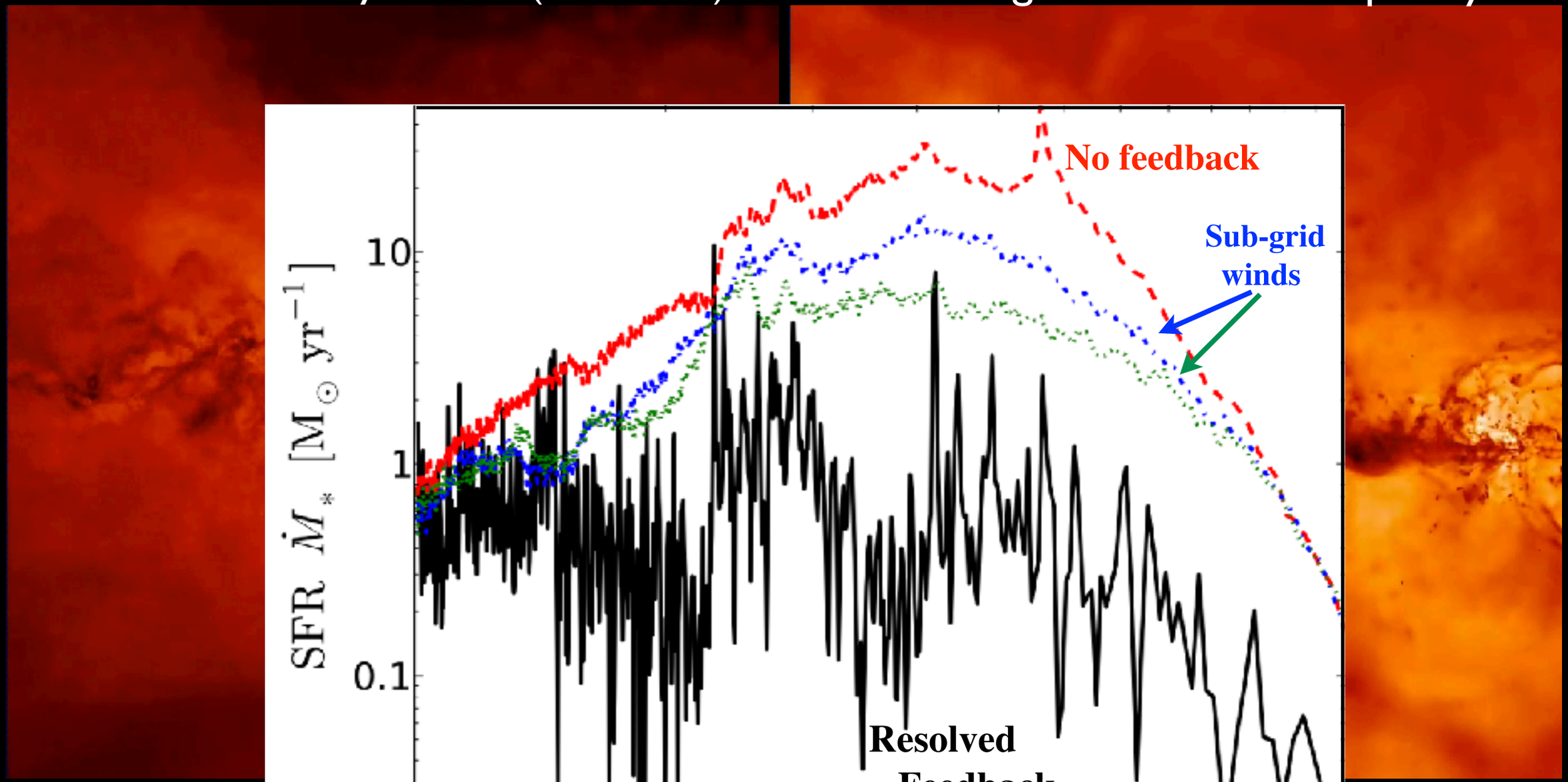
Clustering in Time & Space Matters
(NOW ON GALAXY SCALES)

PFH '14
M. Sparre (arxiv:1510.03869)
A. Fitts (arxiv:1611.02281)

Proto-Milky Way: Gas Temperature:

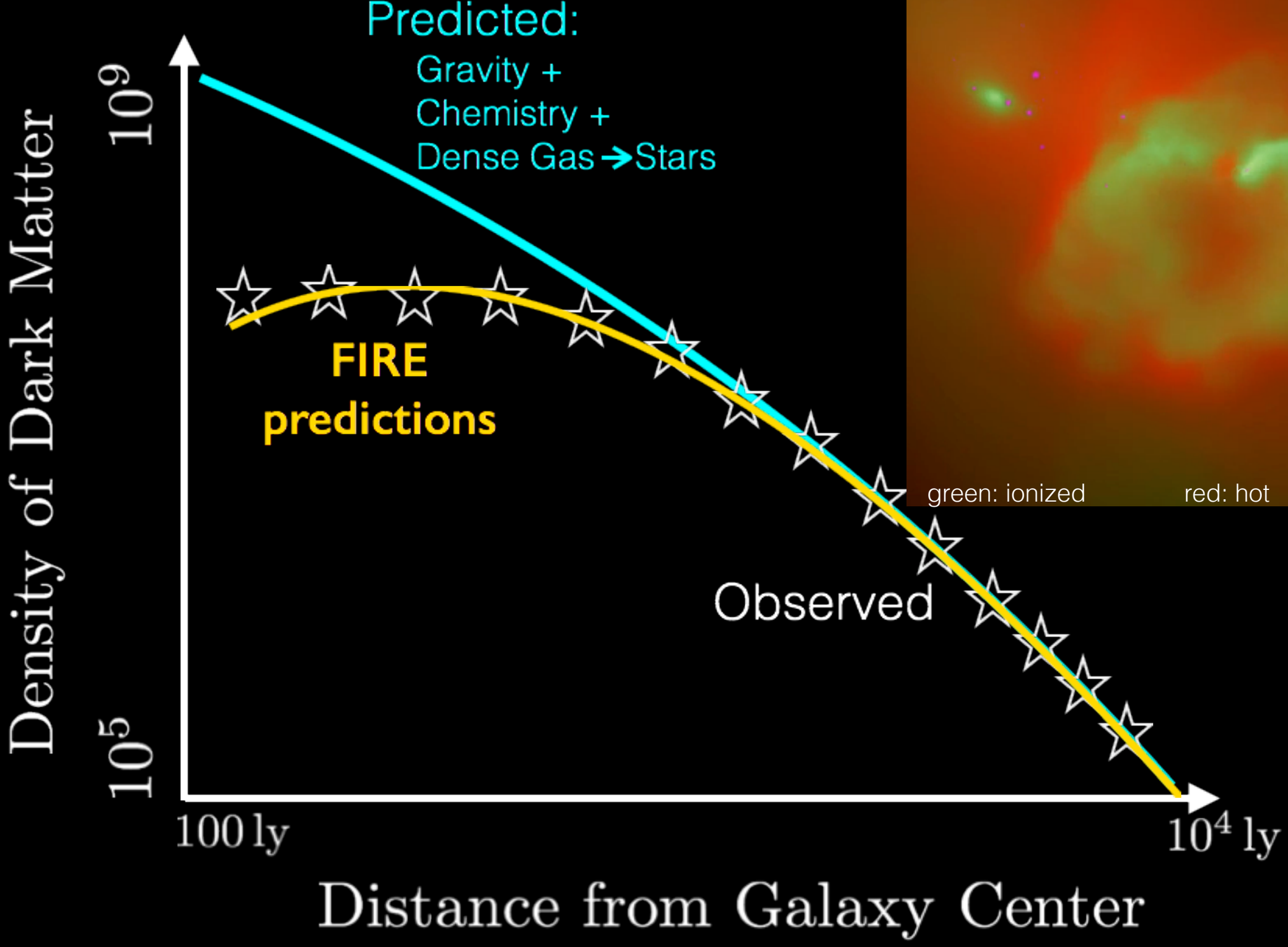
Insert Winds "By Hand" (Sub-Grid)

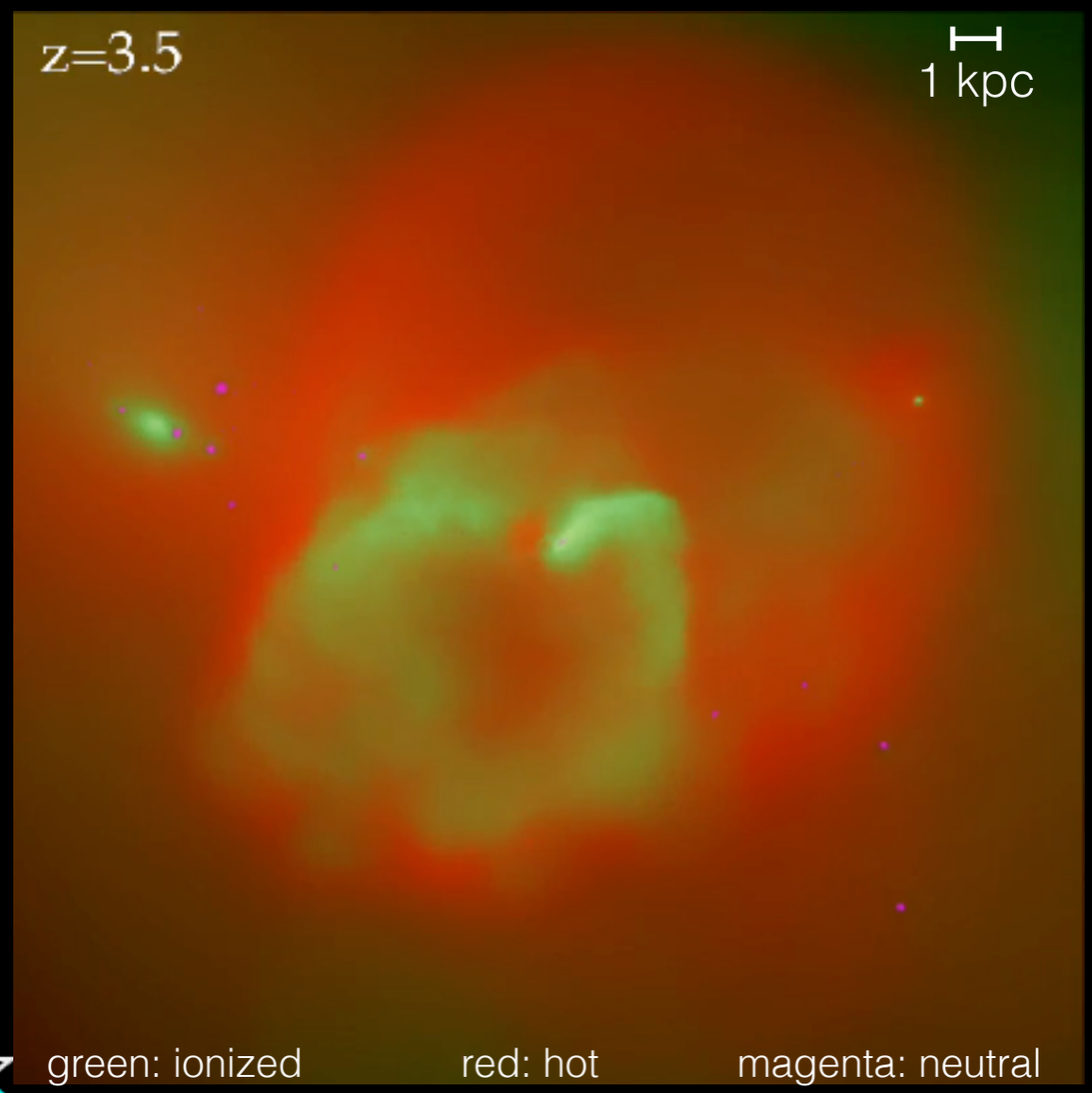
Following Feedback/ISM Explicitly



Feedback Saves Cold Dark Matter?

NO EXOTIC PHYSICS NECESSARY



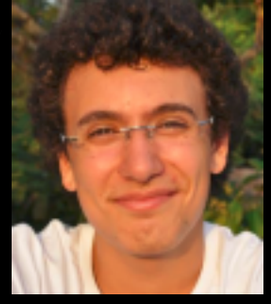


Onorbe et al. (arXiv:1502.02036)
Chan et al. (arXiv:1507.02282)
Wheeler et al. (arXiv:1504.02466)
and…
Brook +12
Pontzen+ 12
Di Cinto+ 16

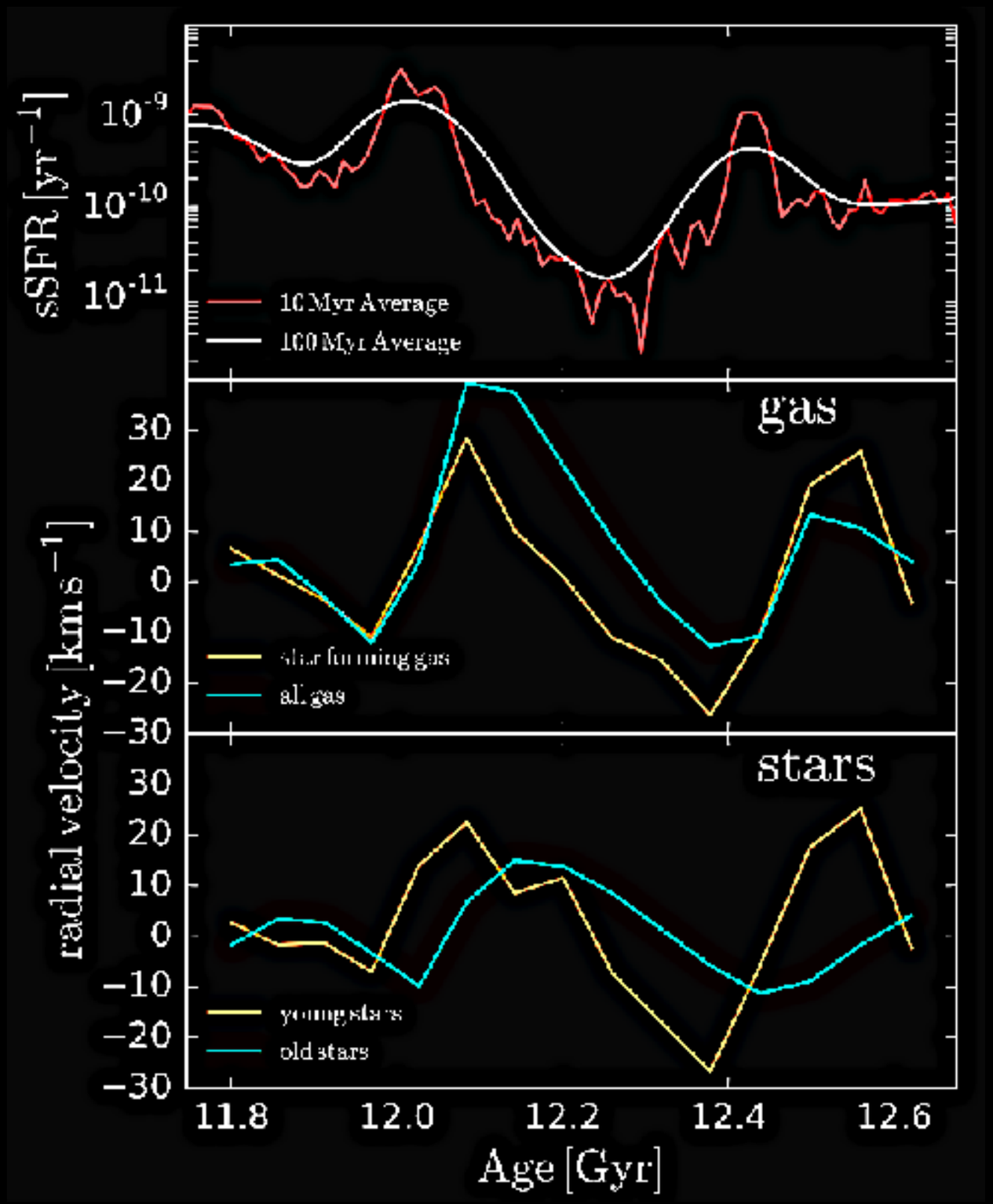
Direct Consequences for Structure

BURSTY SF = STARS MIXED, JUST LIKE DM

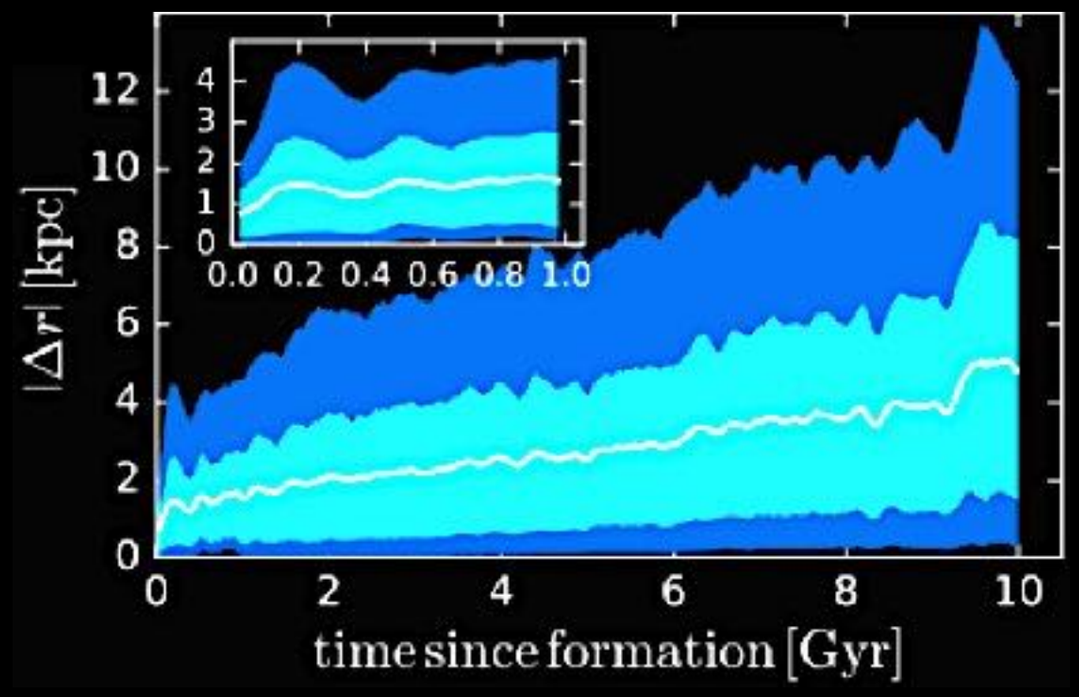
K. El-Badry
(arXiv:1512.01235)



Radial "breathing" in each burst:



Orbits "pumped up"

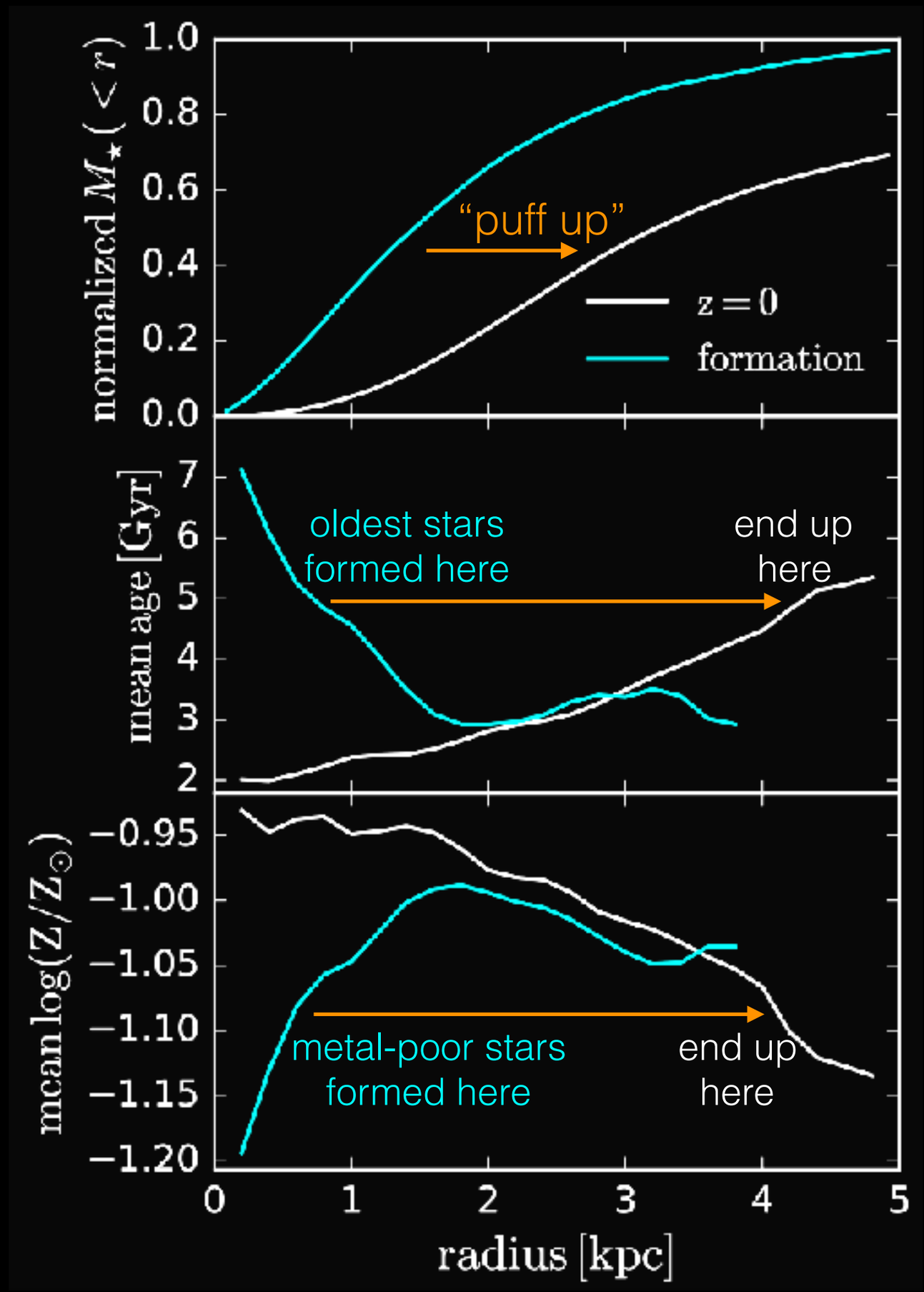


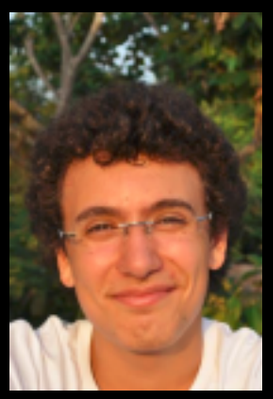
- If DM orbits perturbed, stars are too!

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*





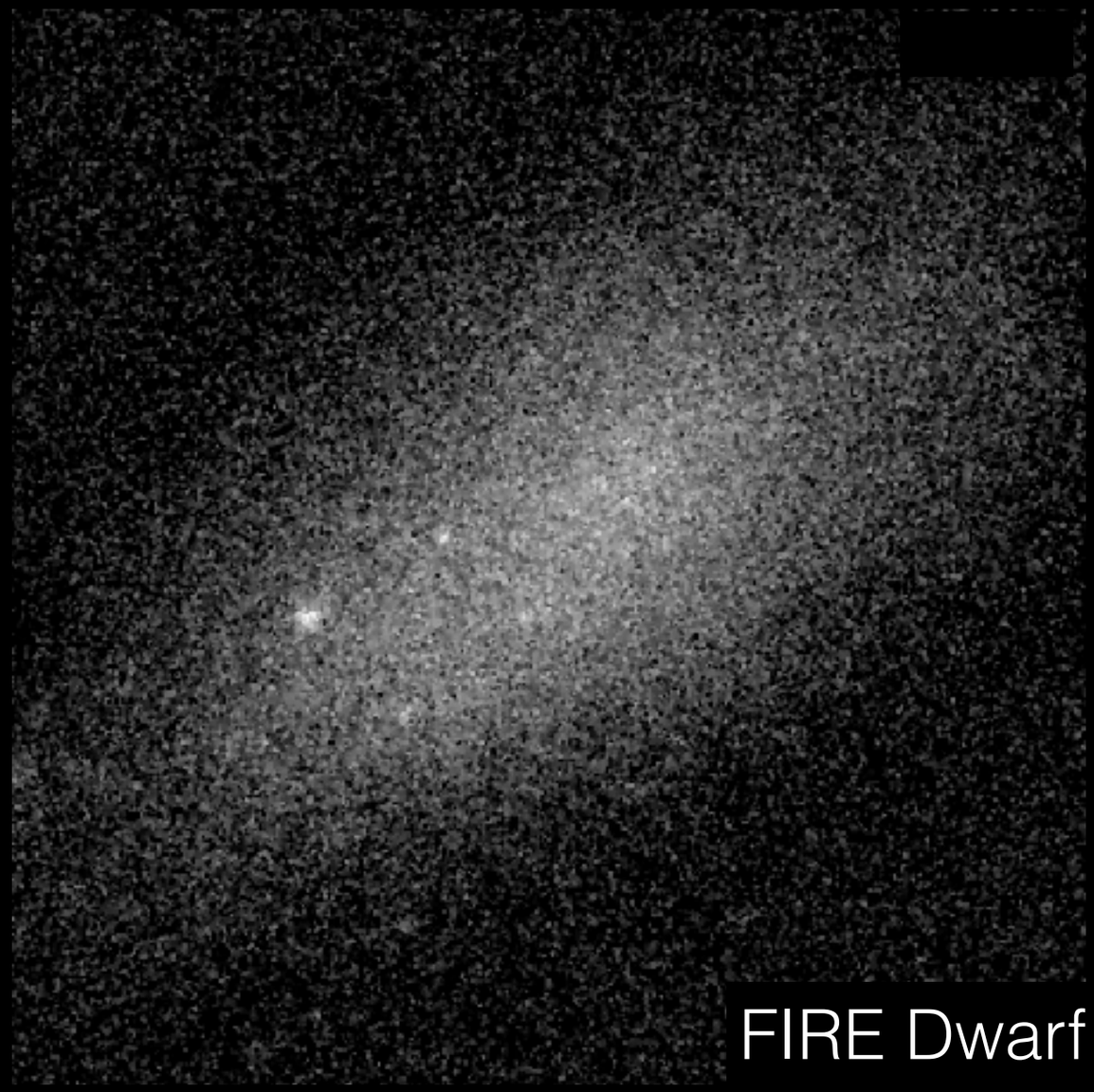
Kareem El-Badry
arXiv:1512.01235

New Classes of Galaxies

ULTRA-DIFFUSE SYSTEMS: THE NEW "NORMAL"

TK Chan
(arXiv:1711.04788)

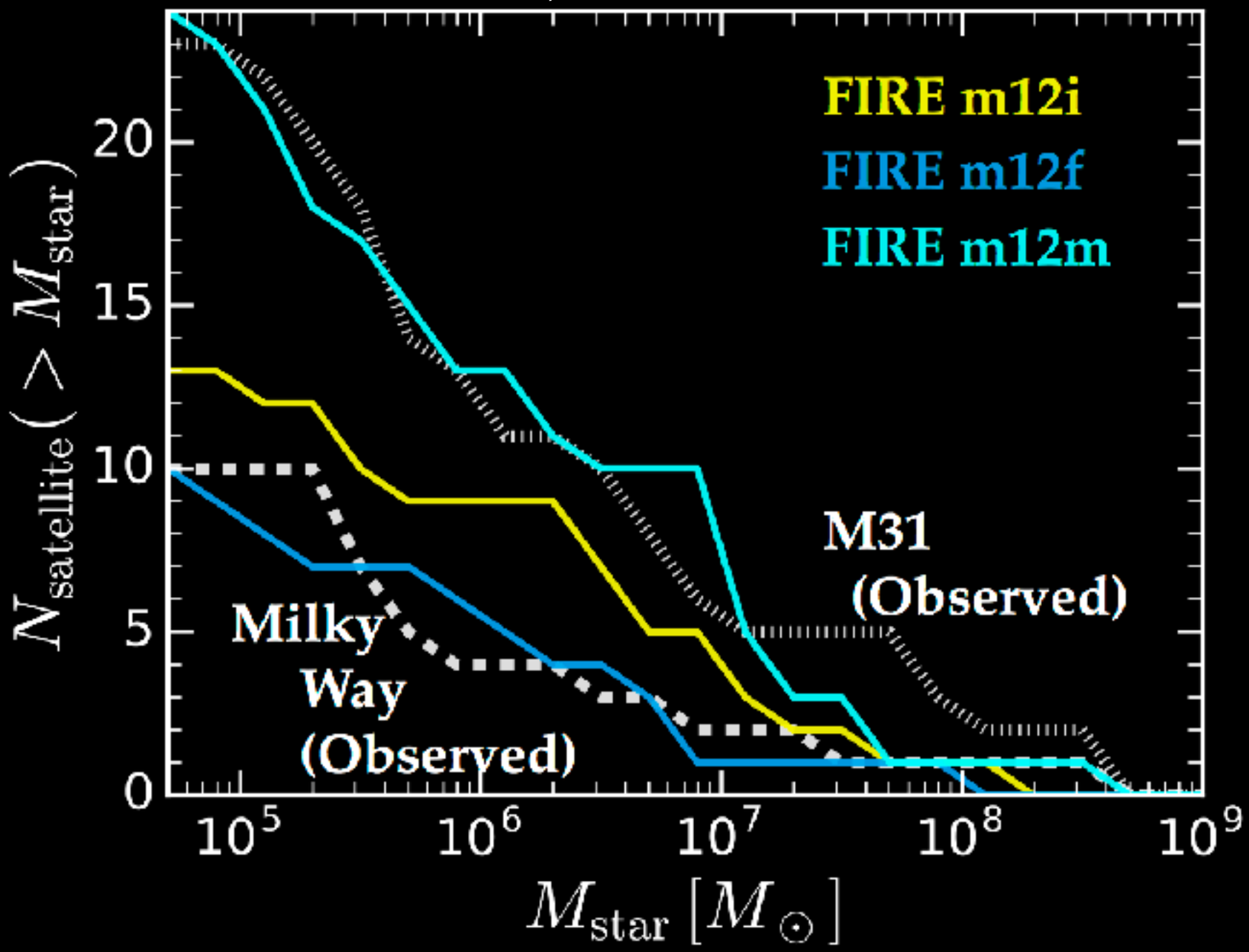
(also Santos-Santos+ 18)



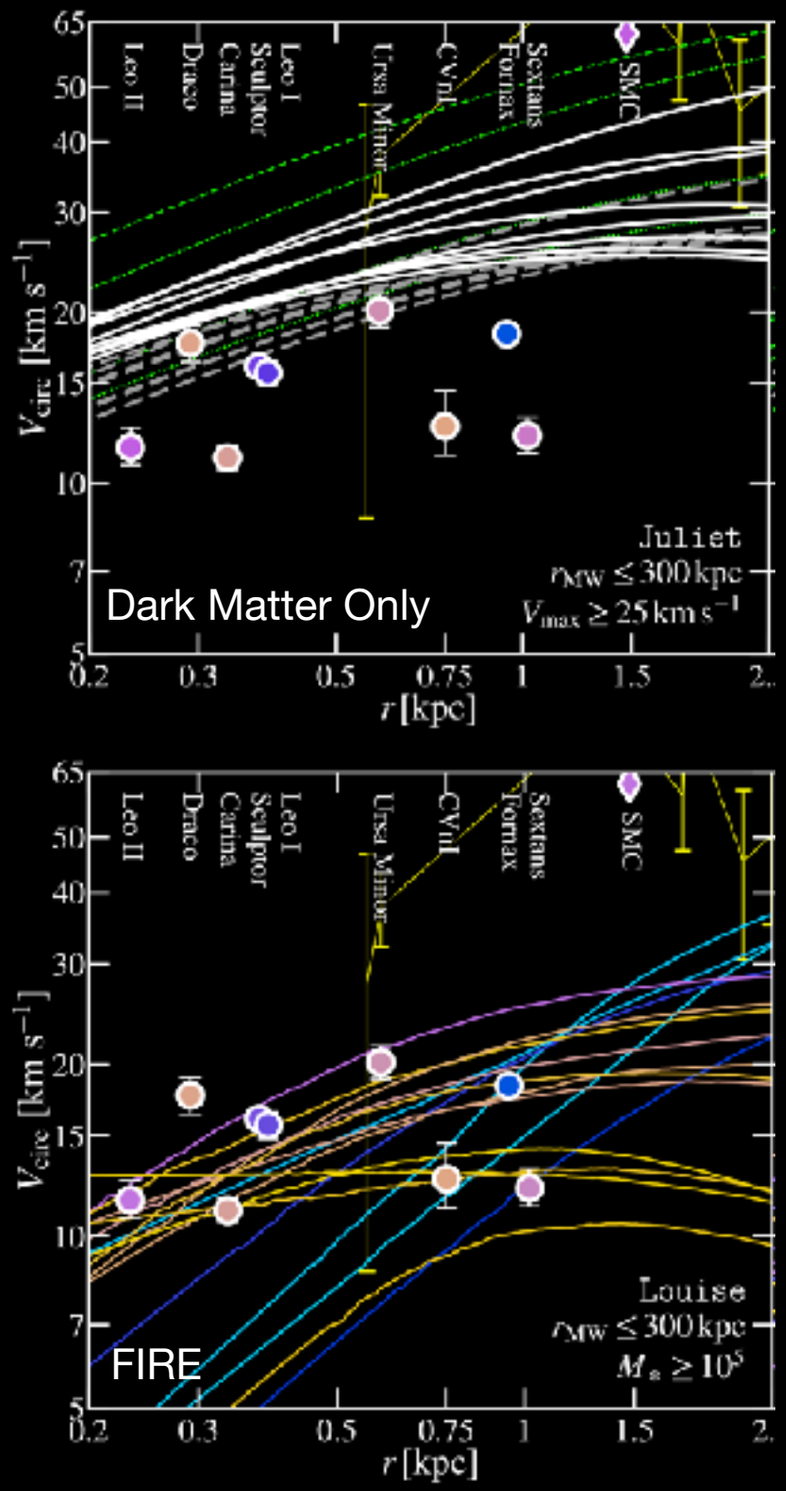
Failures No More

"MISSING SATELLITES" & "TOO BIG TO FAIL"

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



Too Big To Fail



Wetzel+ (1602.05957), Garrison-Kimmel+ (prep)

z=0.84

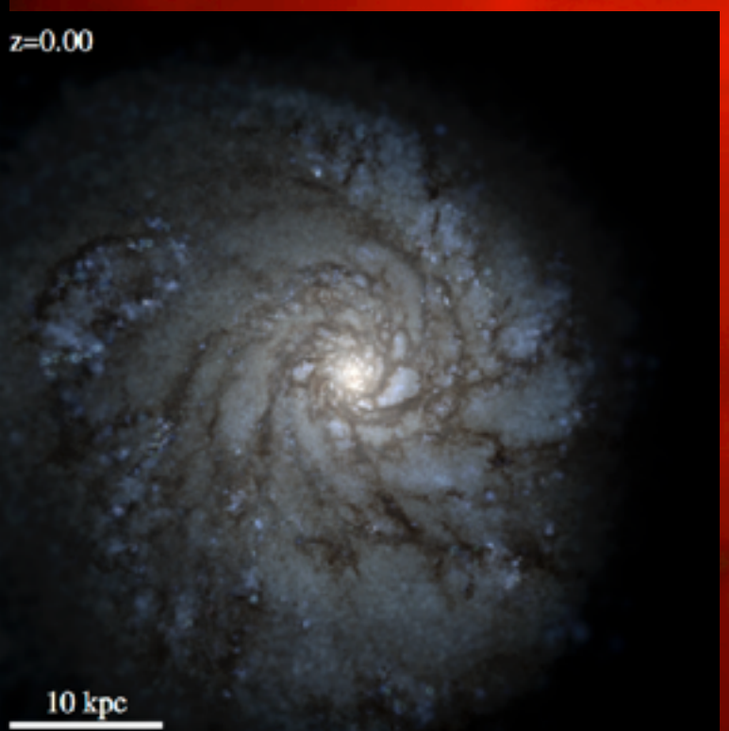
10 kpc

S. Muratov
(arXiv:1501.03155)

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

to

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



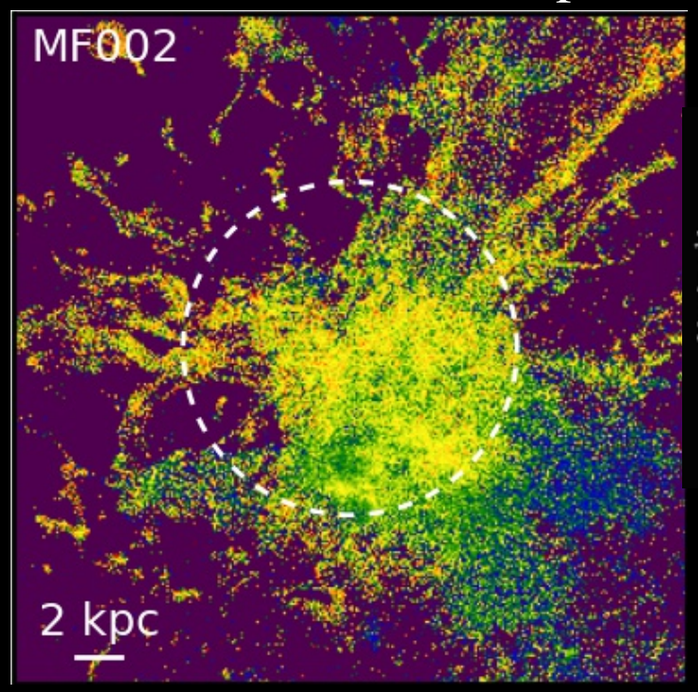
C. Hayward
(arxiv:1510.05650)

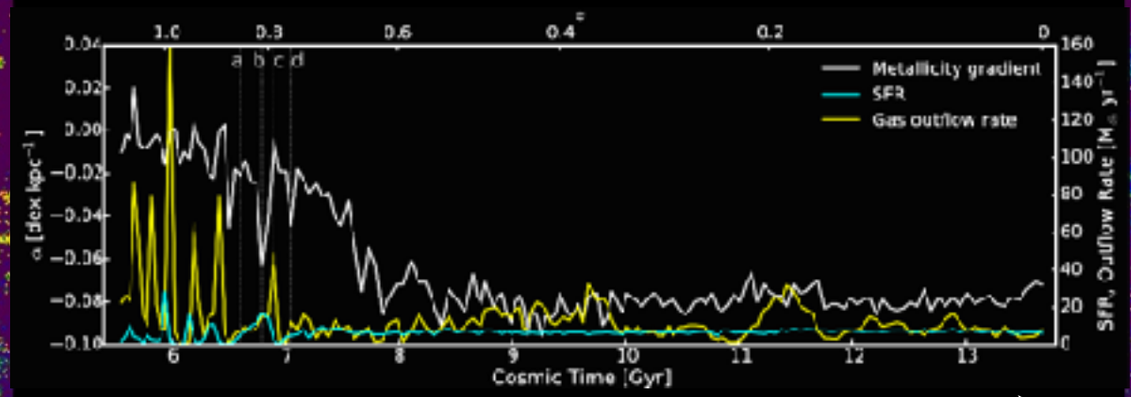
Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

BUILDUP OF METALLICITY GRADIENTS

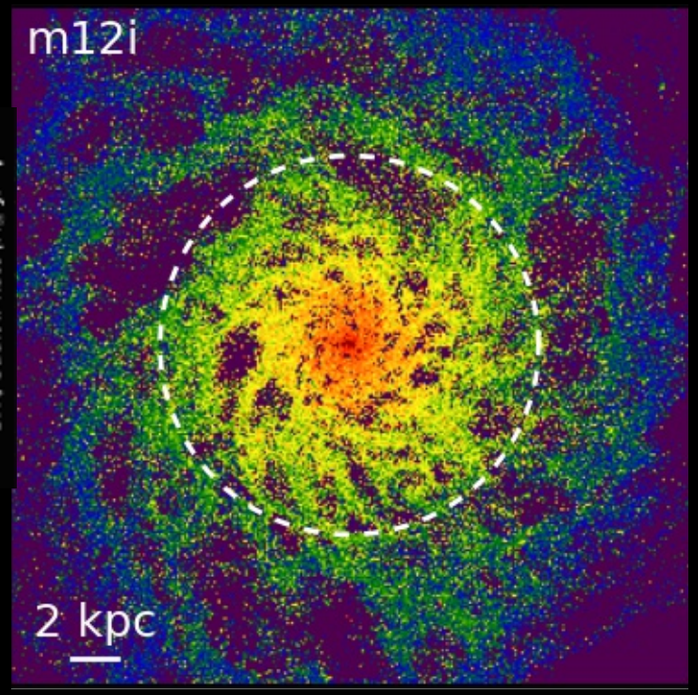
Xiangcheng Ma
(arXiv:1610.03498)

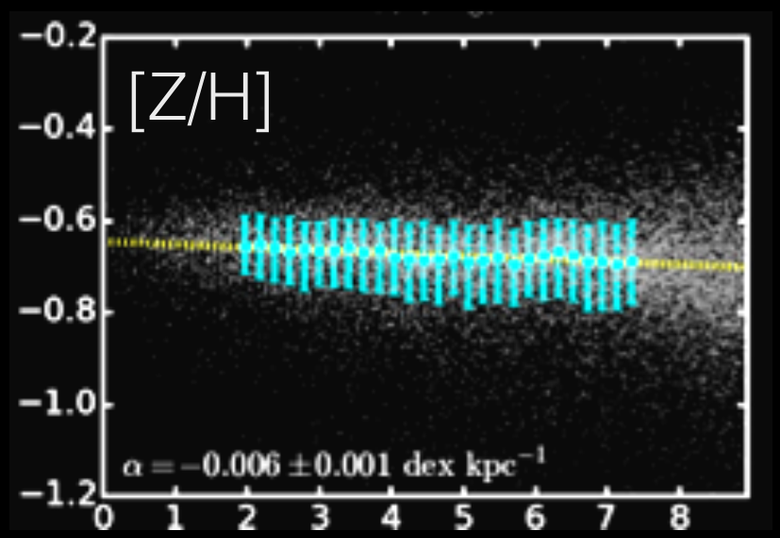
"feedback-dominated" phase

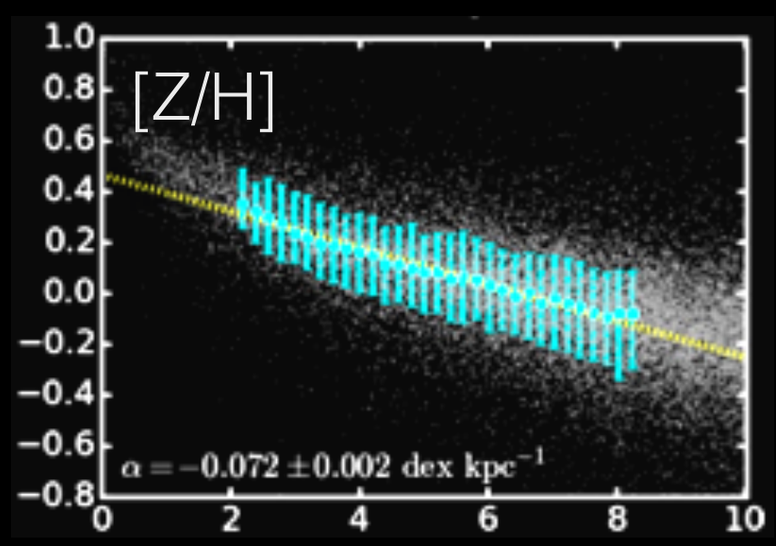




"gravity-dominated" phase



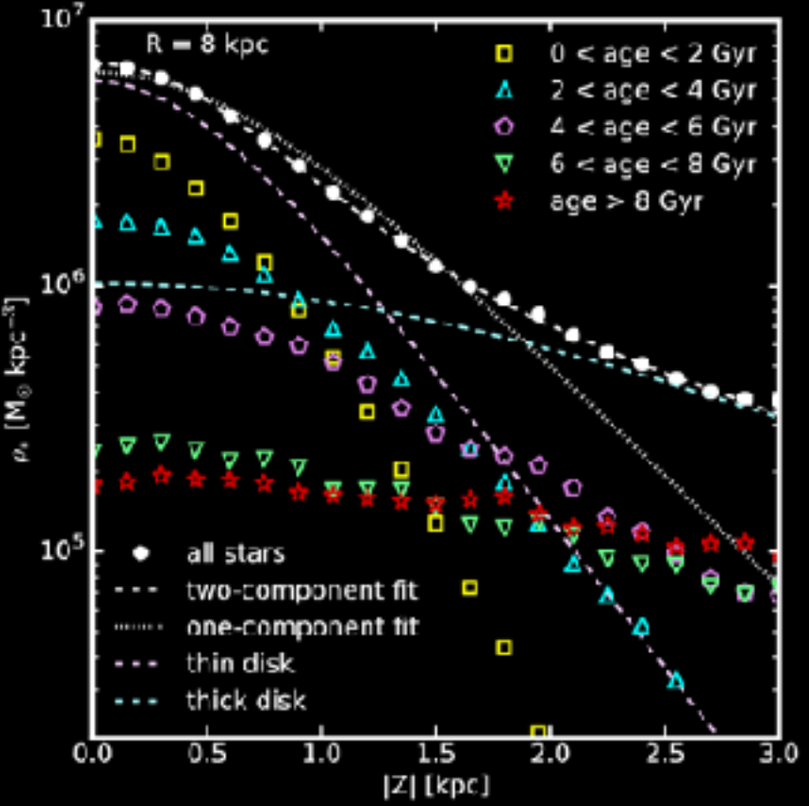


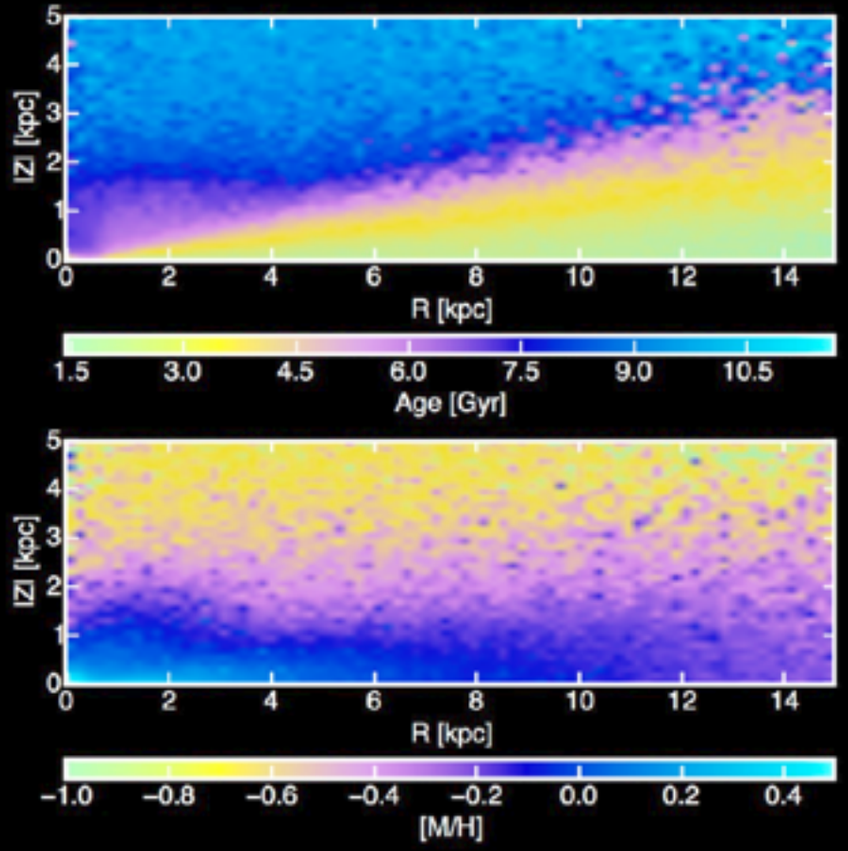


Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

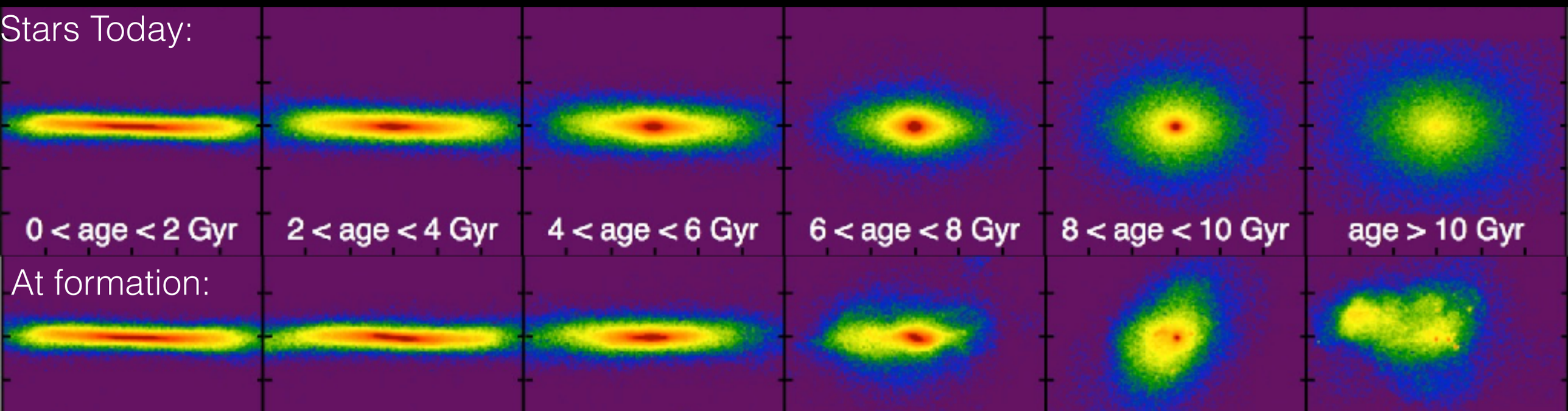
THICK -> THIN DISK

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



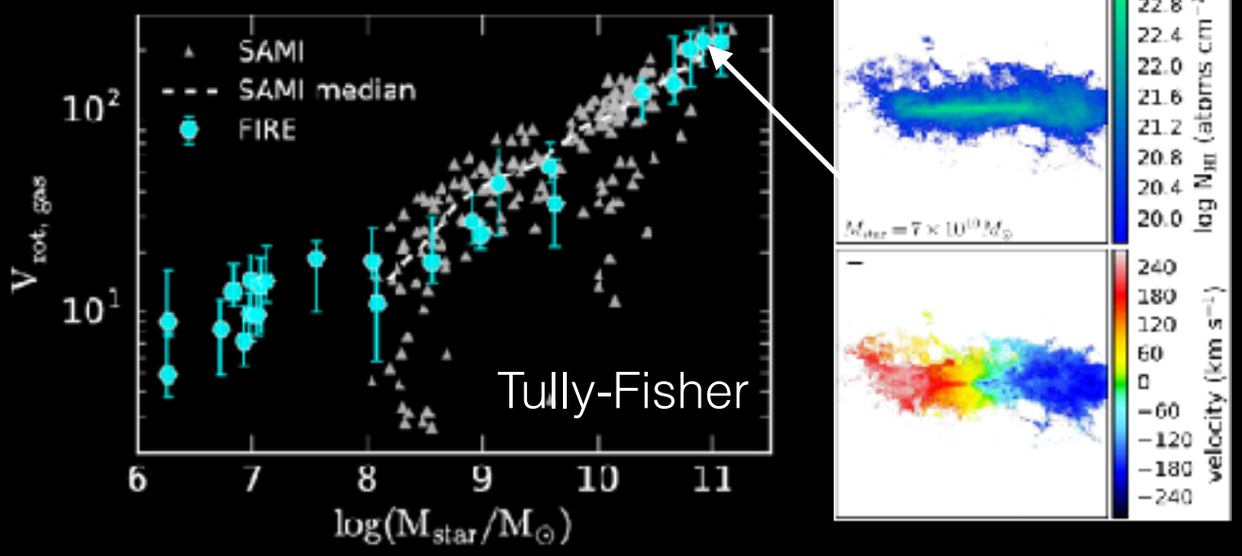


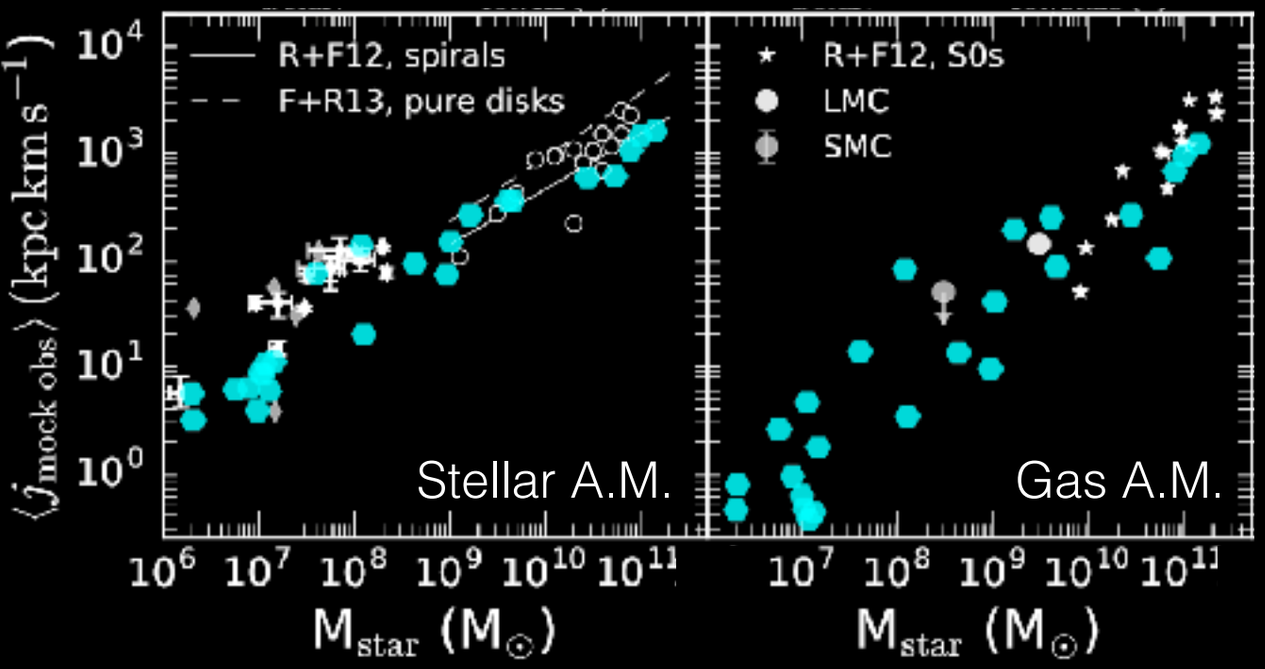
Detailed vertical+radial
abundance gradients & kinematics
of thin/thick disk populations



Angular Momentum of Gas+Stars

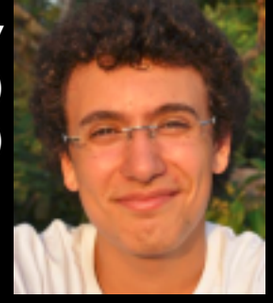
ROTATION BUILDS UP OVER TIME

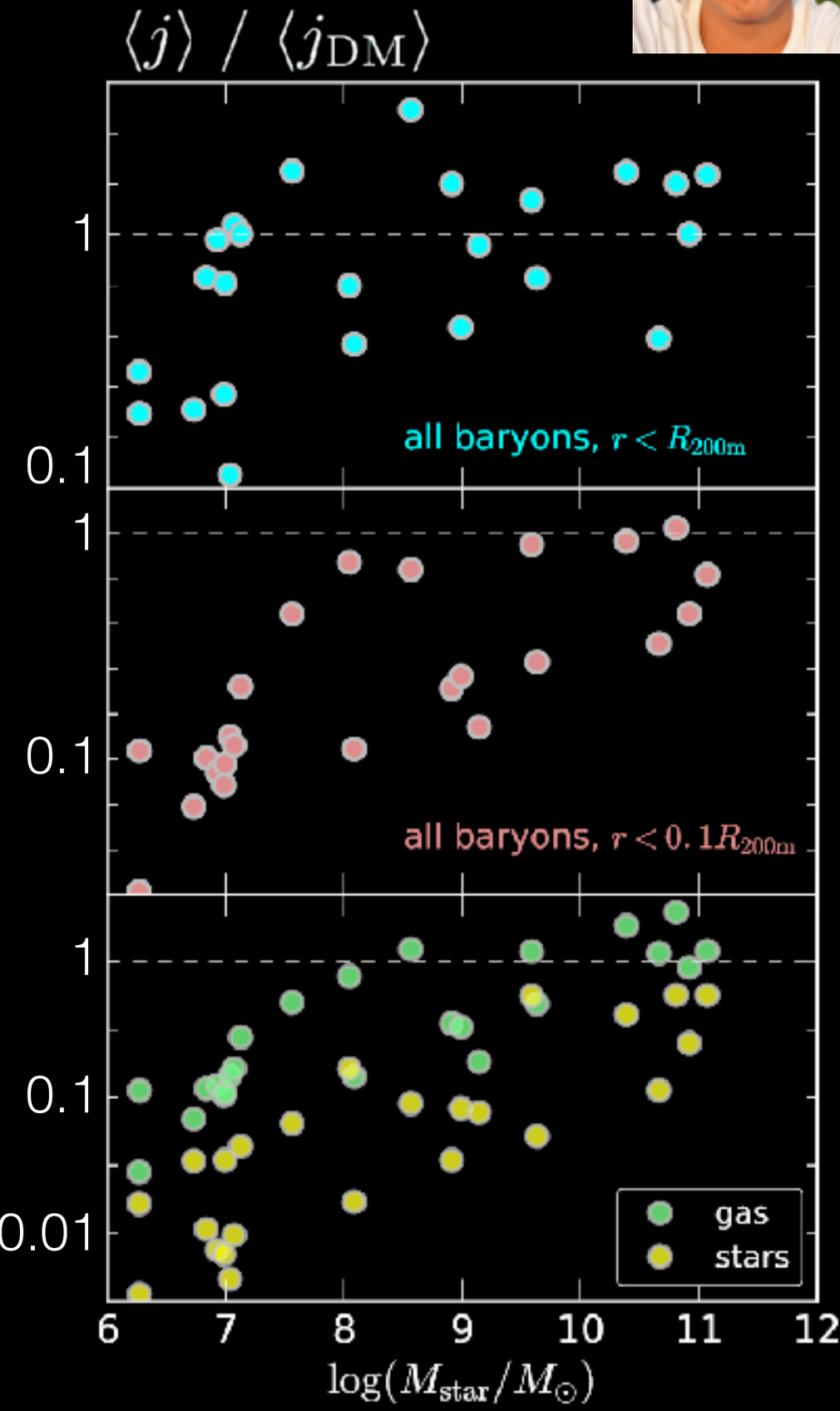




- Dwarfs: Thick/irregular [clumpy + bursty]

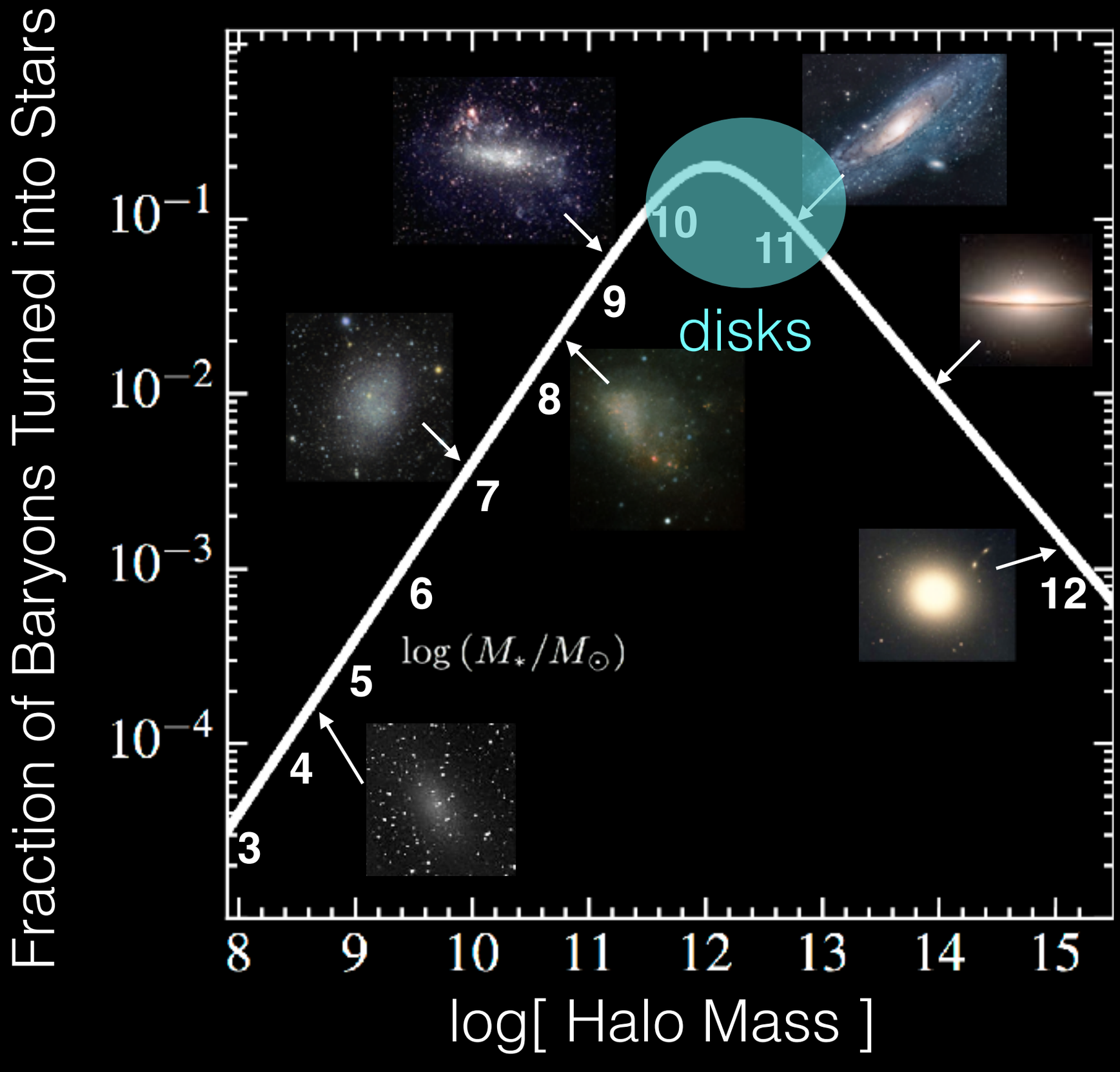
Kareem El-Badry
(arXiv:1705.10321)
(also Sales+ 16)



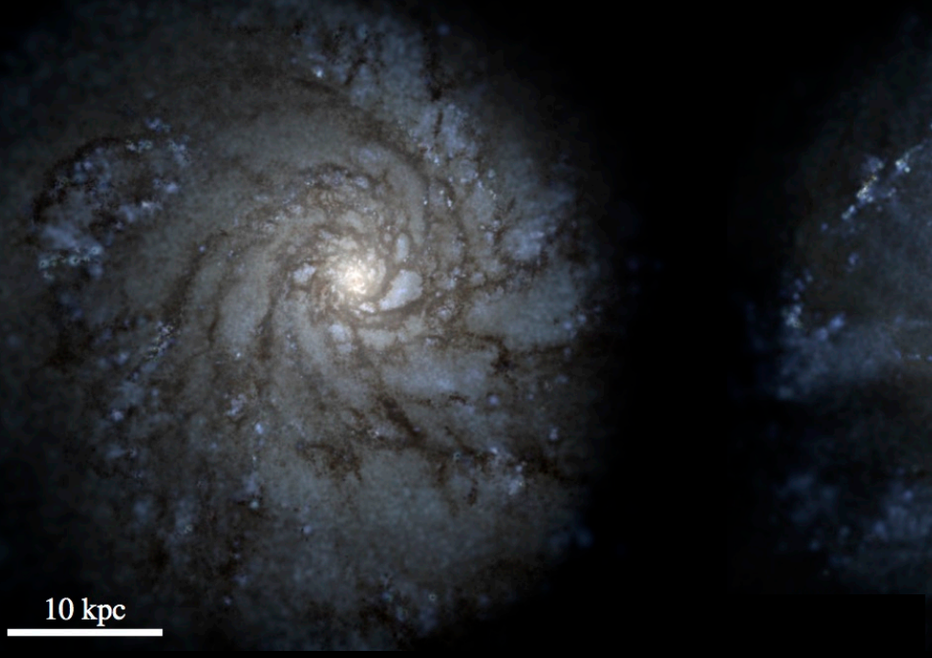


Rotation is Rare:

ONLY COMMON AT PEAK STAR FORMATION EFFICIENCY



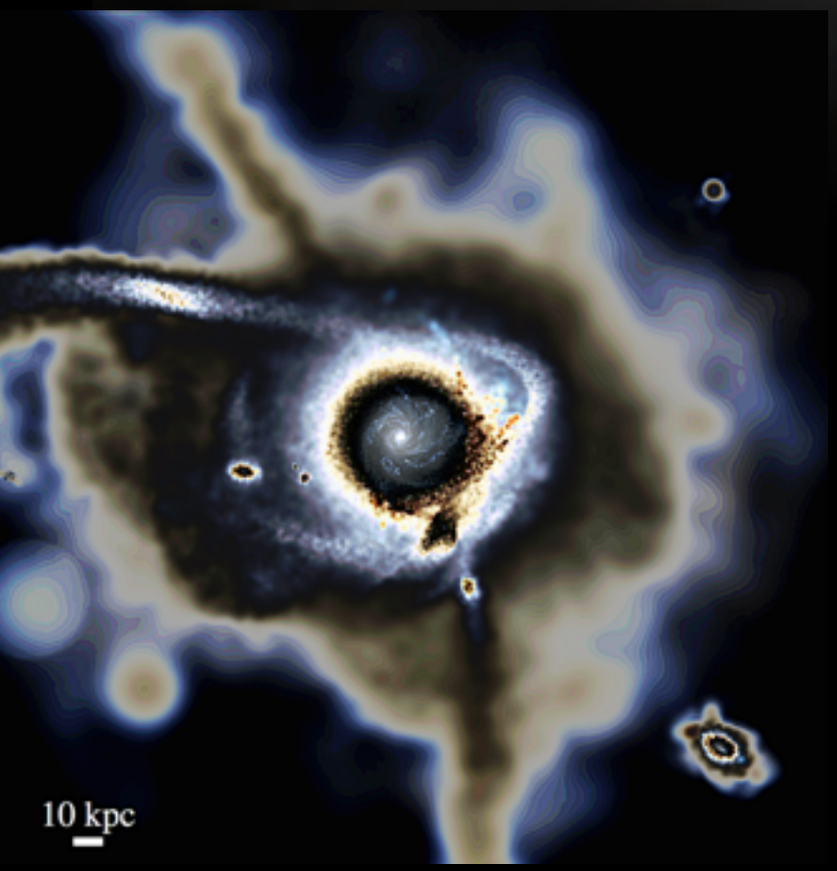
Thin Disks Emerge Naturally

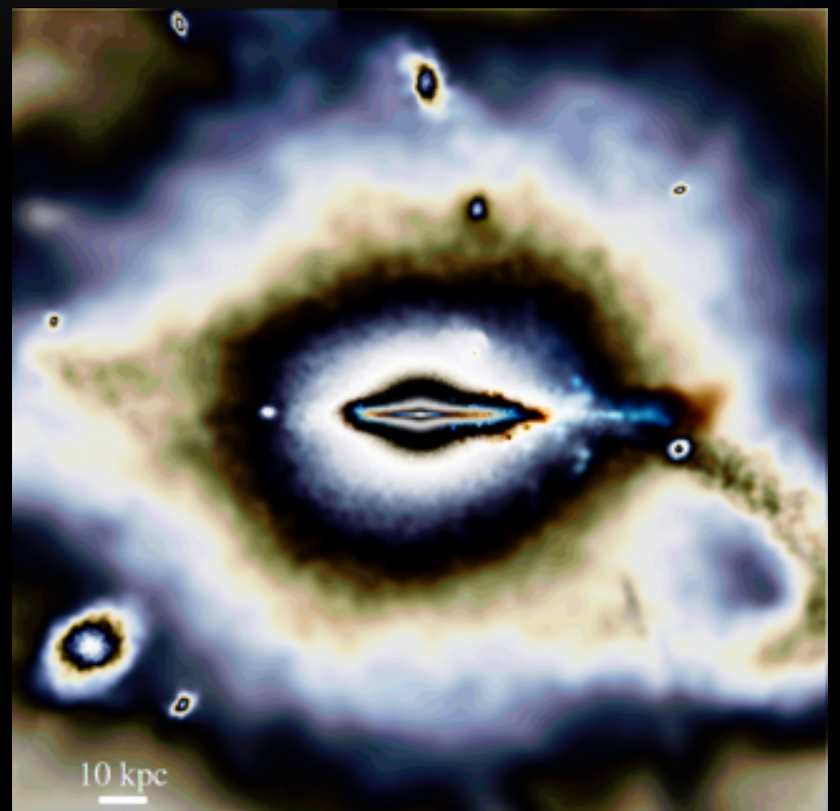


Garrison-Kimmel+
1712.03966

Halo Structure & Mass Maps in *exacting* detail

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

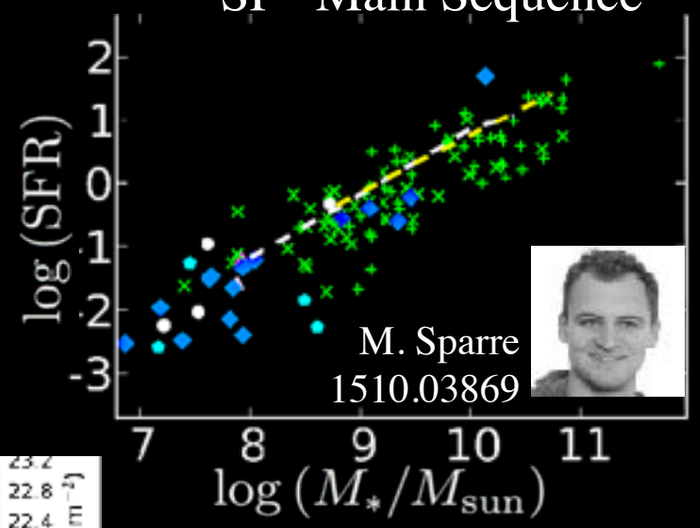




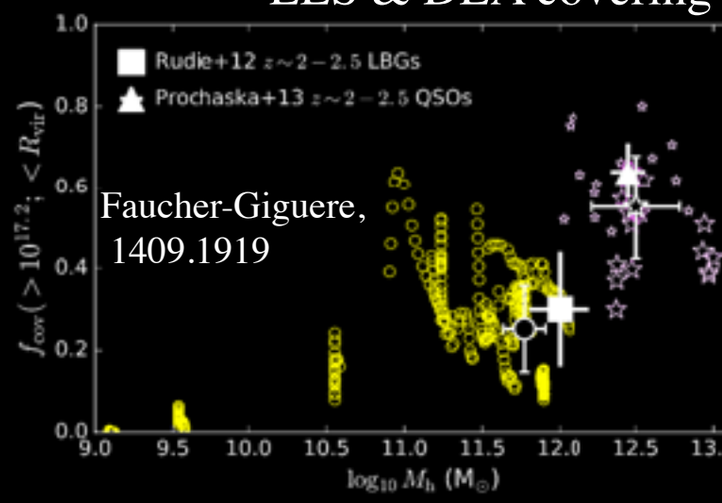
Sanderson et al.
(this month)

Galaxy Scaling Relations:

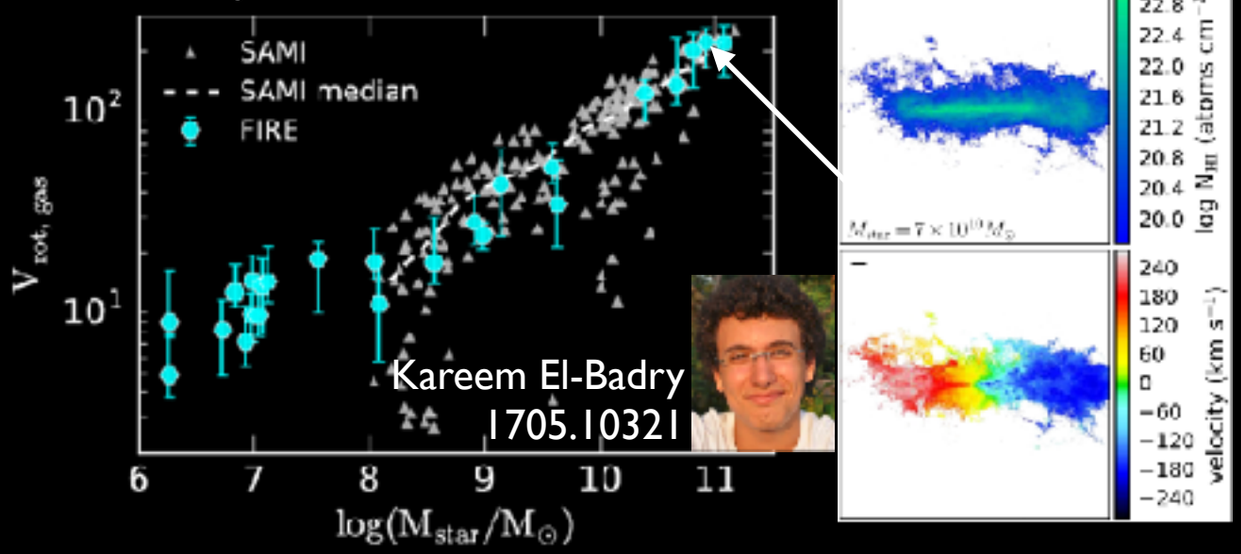
SF "Main Sequence"



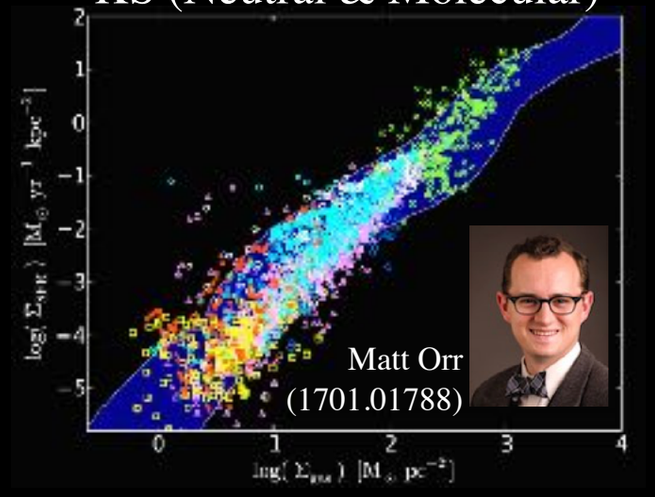
LLS & DLA covering



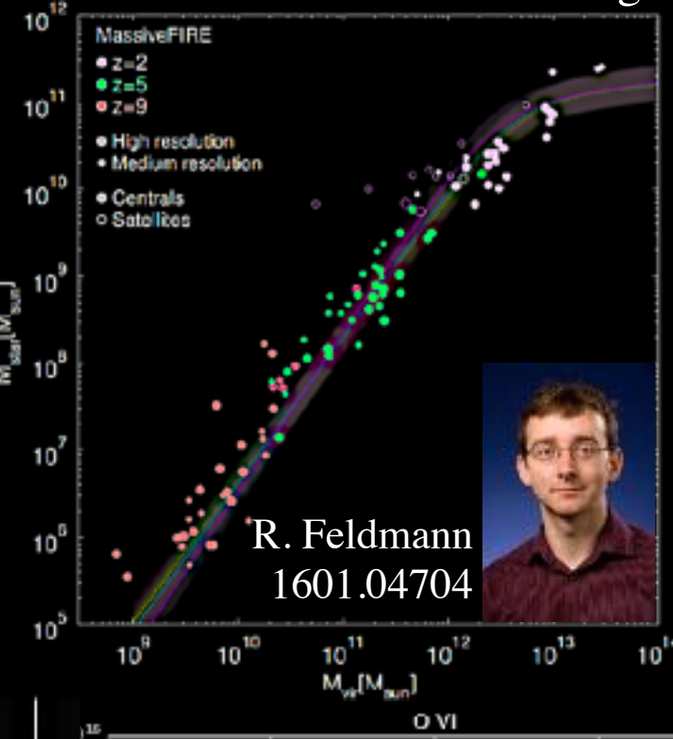
Tully-Fisher Relation



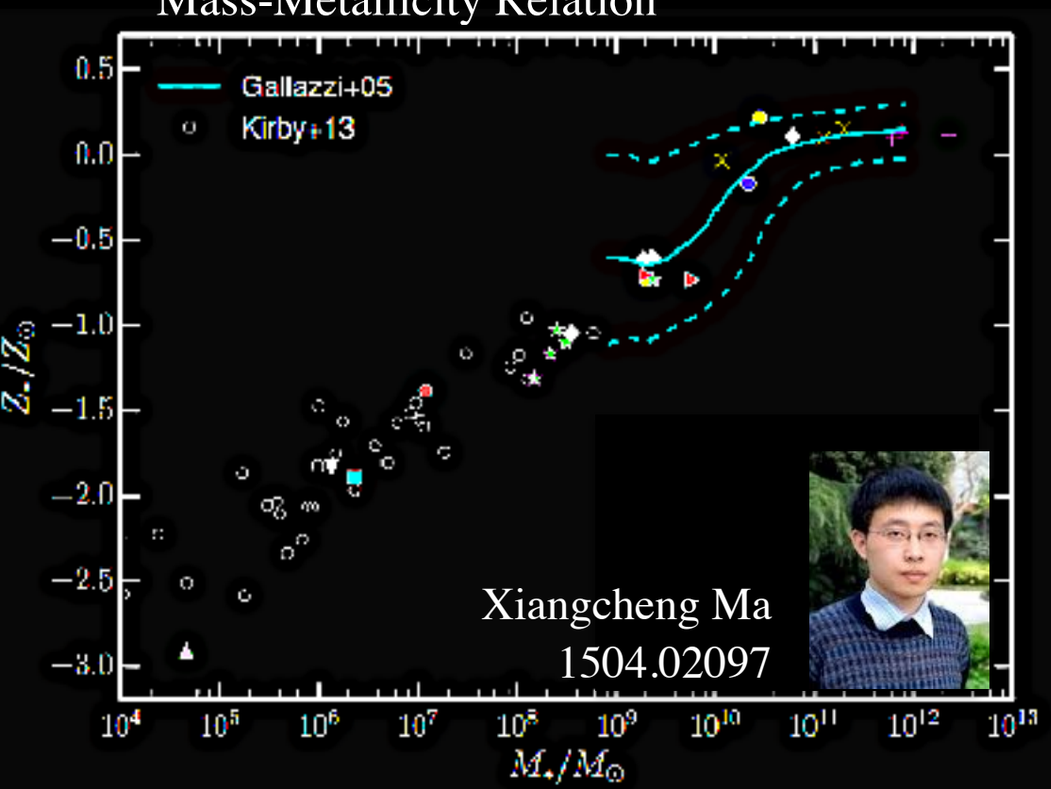
KS (Neutral & Molecular)



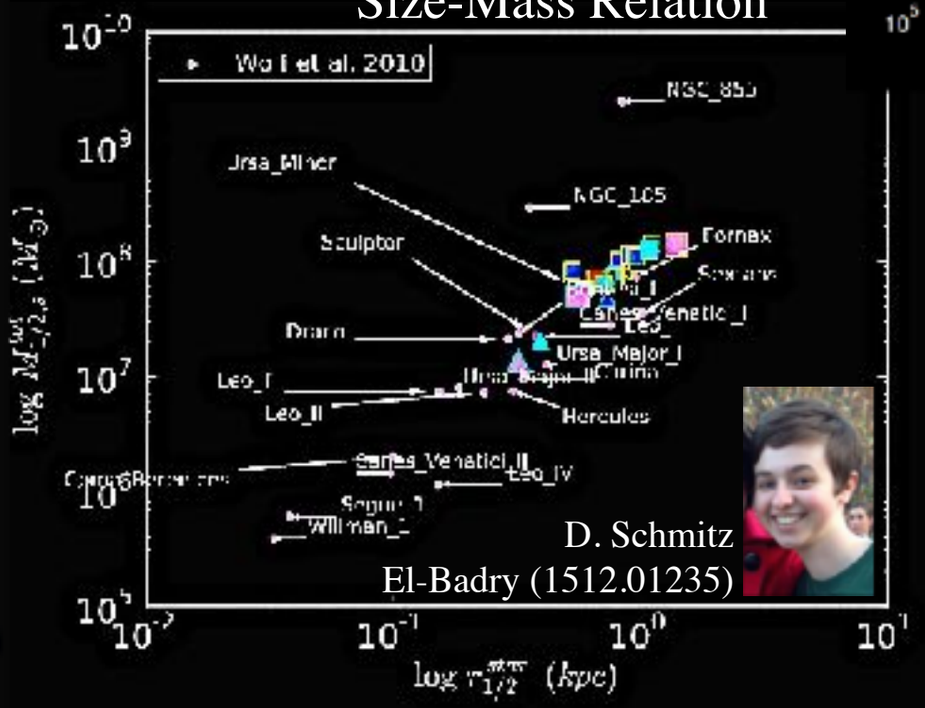
Abundance Matching



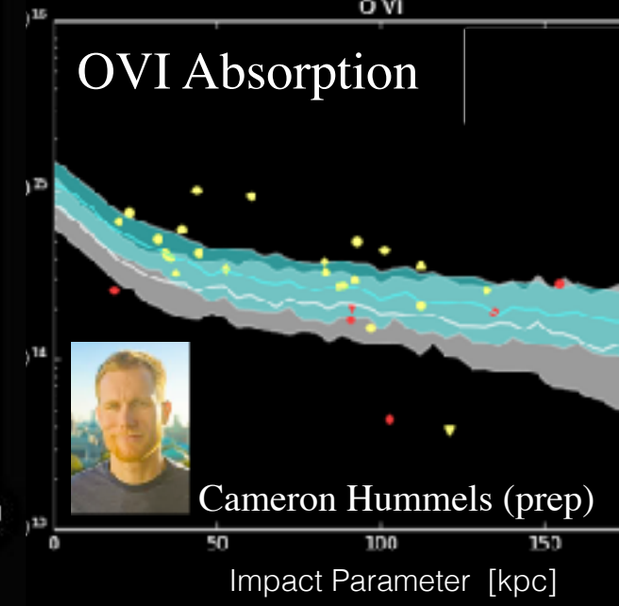
Mass-Metallicity Relation



Size-Mass Relation



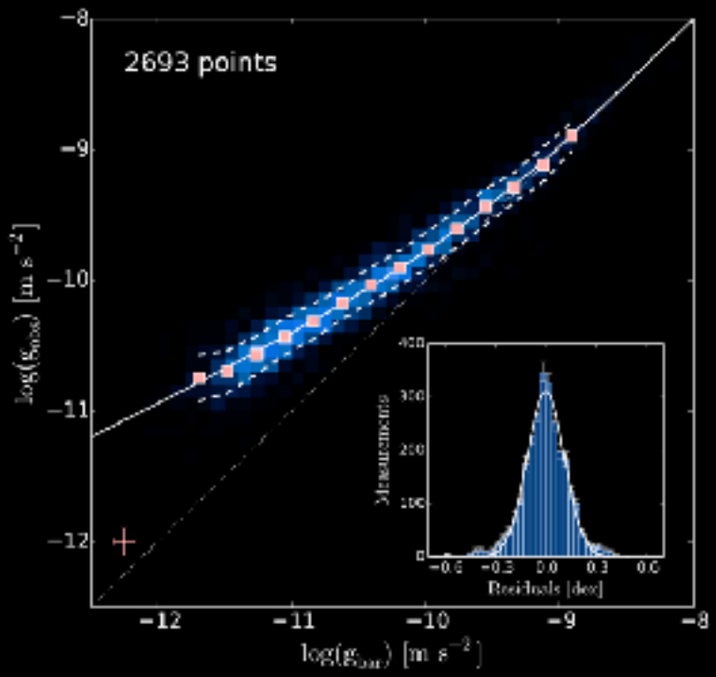
OVI Absorption



What About X?
OTHER INTERESTING TENSIONS?

- "Diversity" of rotation curves
  - Driven by baryons and core-creation! [El-Badry+ 17; Santos-Santos+ 18]

- "Radial Acceleration Relation"
  - Exactly equivalent to Baryonic Tully-Fisher relation: no new information! [Wheeler+1803.01849]



- "Planes of Satellites"
  - In simulations if "detected" same way [Skillman+17]
  - Most not real "structures" [Gillet+15, Buck+16]

- Fornax globulars "aren't sinking" (dynamical friction time too short)
  - Fornax exactly where core expected [Chan+]: slightly lower DM density inside <300 pc makes timescale >>10 Gyr [Read+15]

- Ultra-Diffuse Galaxies: "too much" or "too little" DM
  - See above! Easily reproduced in CDM

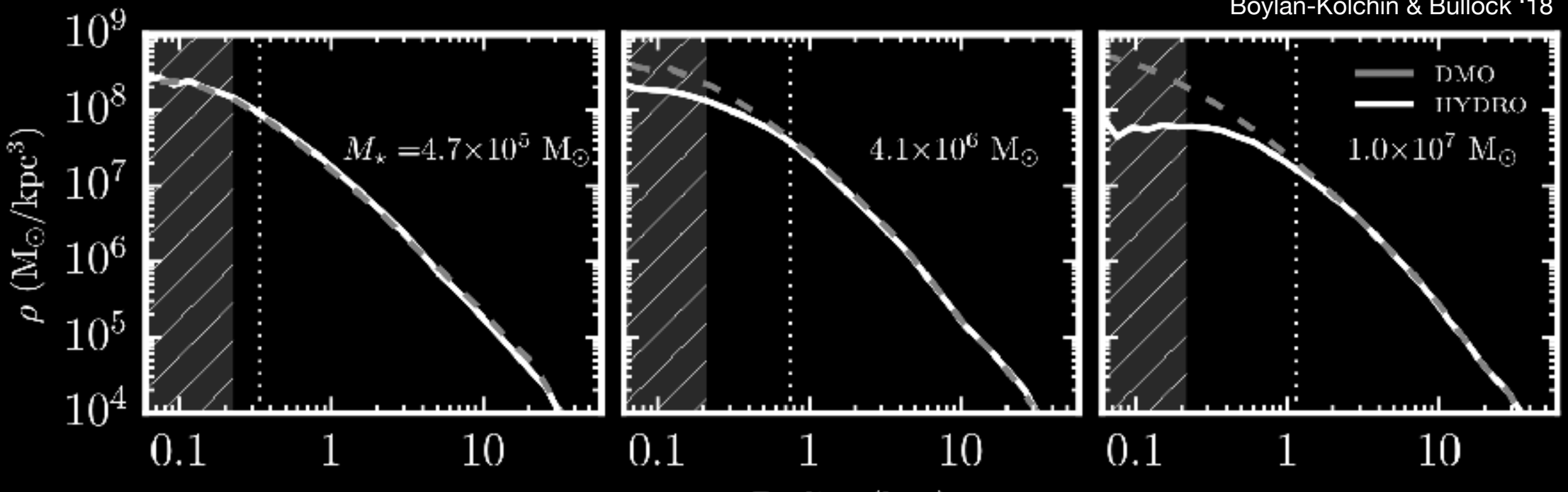
- Galaxy clusters: DM+stars follow NFW (so DM is "more shallow"?) [Newman+ 13]
  - NFW from hierarchical, collisionless merging: this is *expected* [100s of papers]

What do we do next?

Go Smaller!

ULTRA-FAINTS & BELOW: TOO FEW BARYONS TO PERTURB DM

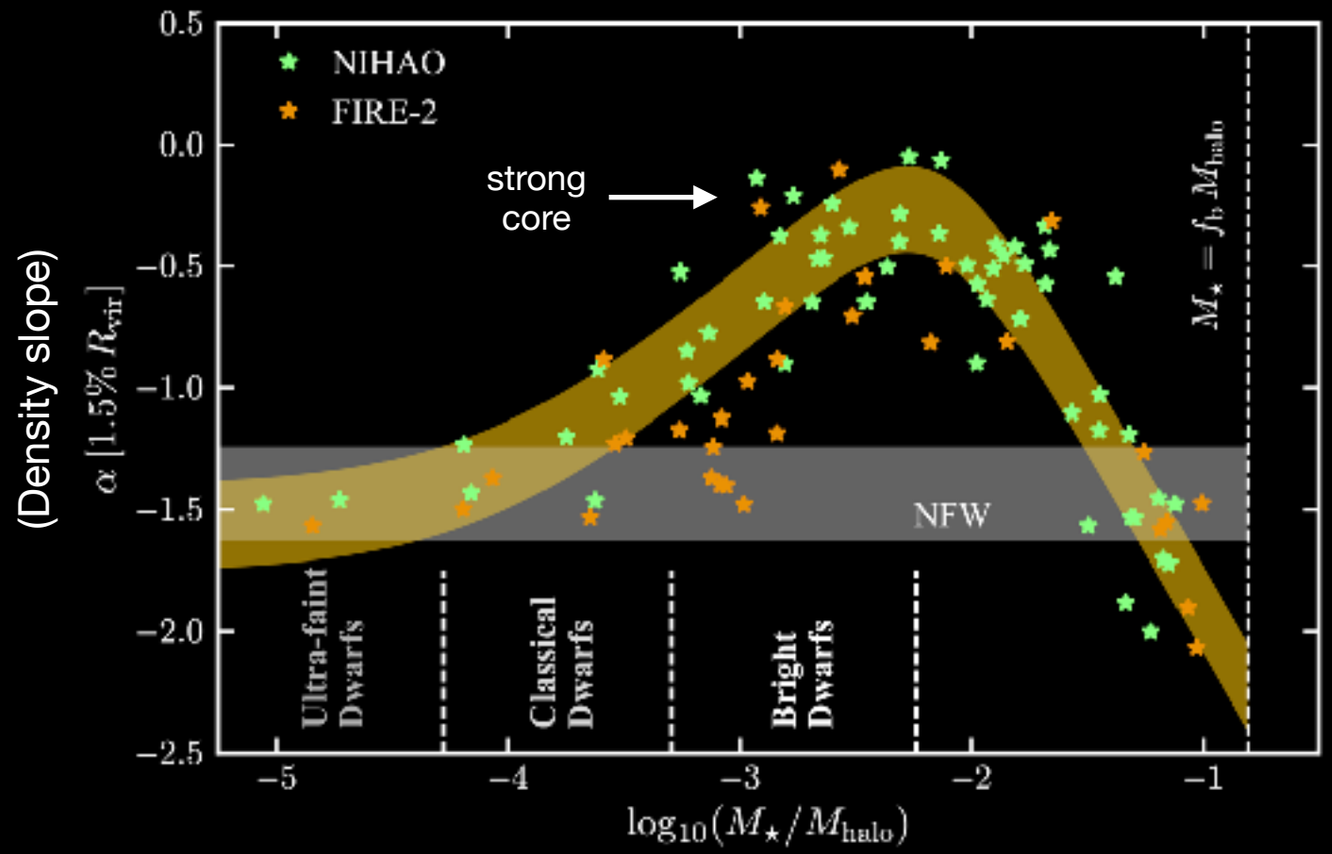
Boylan-Kolchin & Bullock ‘18



CDM Cores:

- Strength scales with stellar / halo mass

- Size scales with stellar size

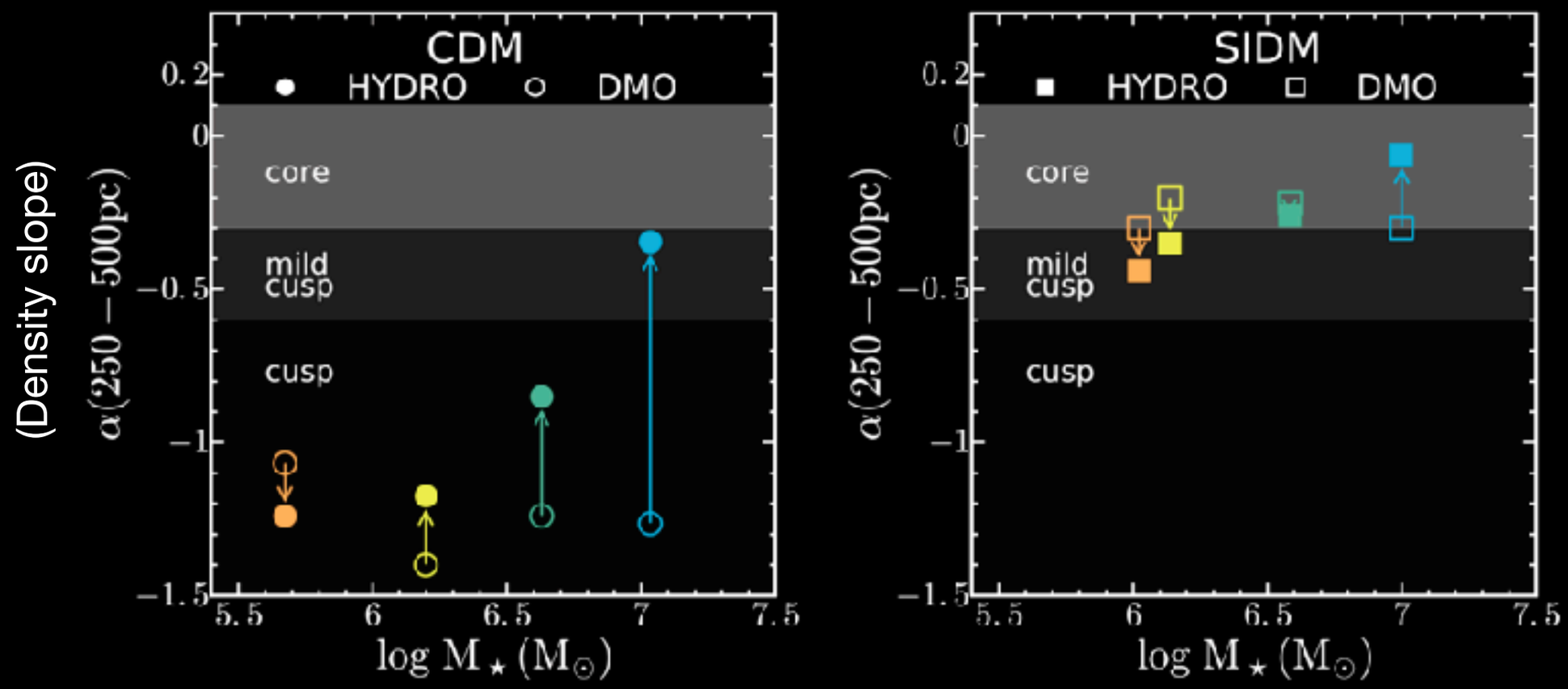


Go Smaller!

ULTRA-FAINTS & BELOW: TOO FEW BARYONS TO PERTURB DM

Compare:

SIDM: scattering: $\sigma/m \sim \mathrm{cm}^2\,\mathrm{g}^{-1}$ [Robles+1706.07514]
WDM (e.g. sterile neutrino): ~few keV [Bozek+1803.05424]
“Fuzzy” DM (ultra-light/scalar field): $10^{-(20\text{-}22)}$ eV [Robles+18]
Primordial BHs (~10-100 M_{sun}) [Zhu+18]

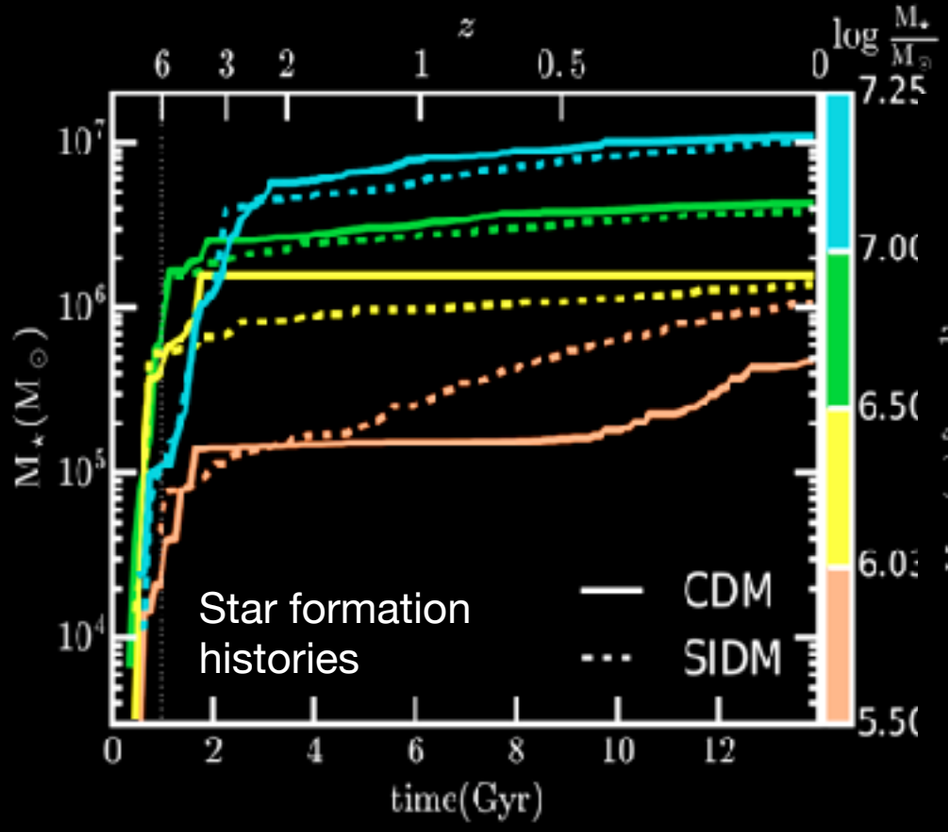


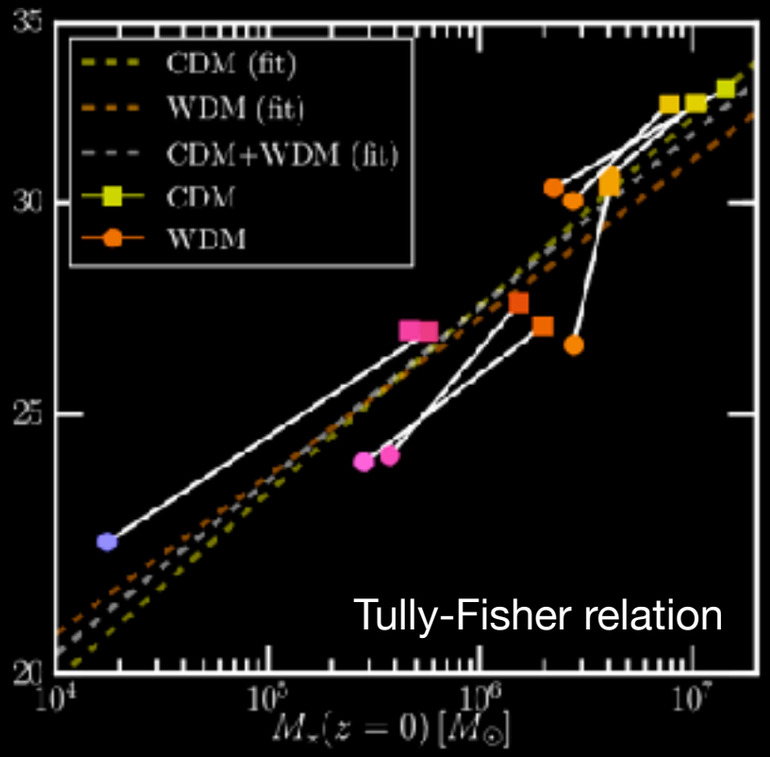
Similarly:

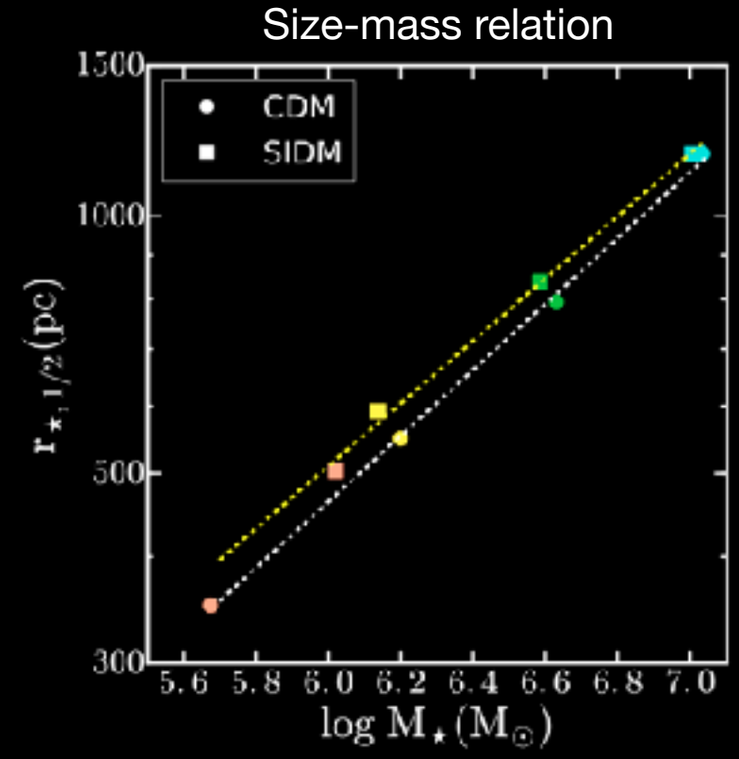
- Satellites-of-satellites (Wheeler+15)
- Halo mass function below << 1e9

But Baryons control Baryons:

MODIFIED DM (OR GRAVITY) *DOES NOT* "IMPROVE THE FIT"







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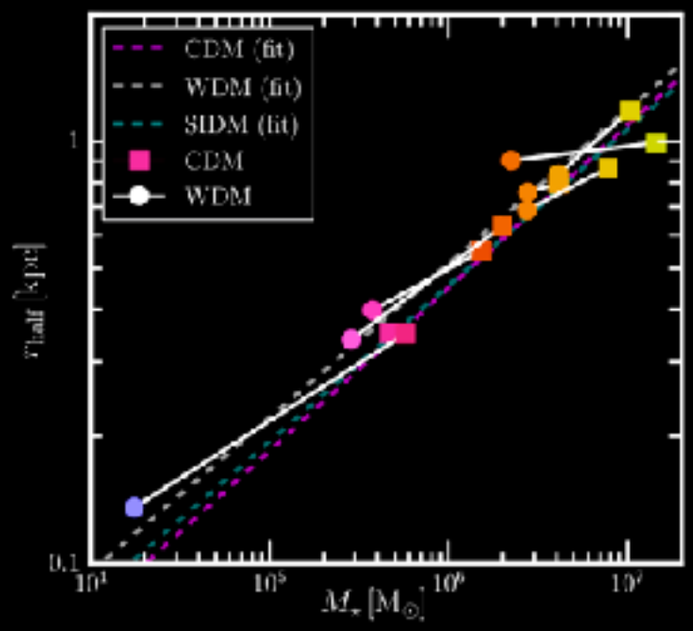
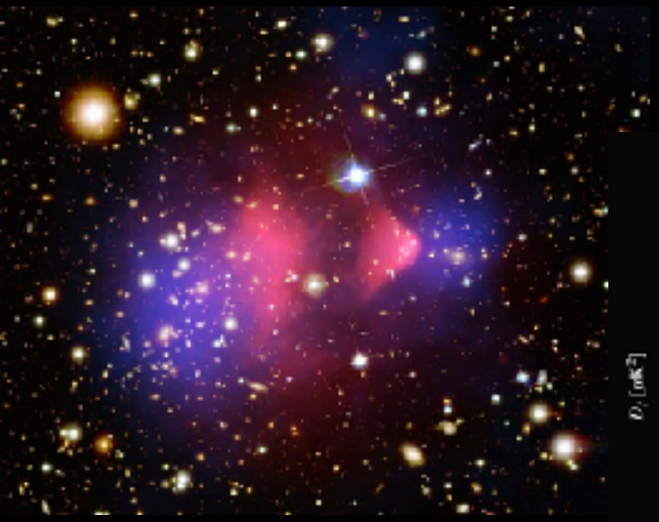
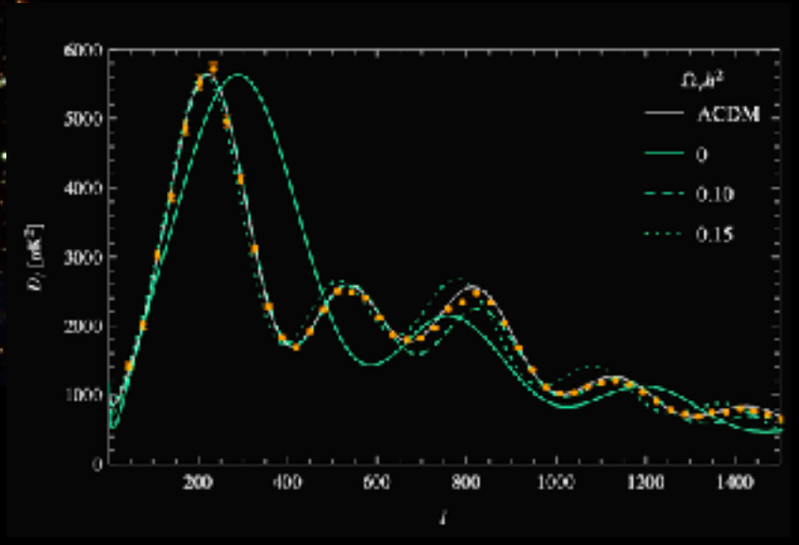


“Gravity-Only” DM Constraints

(*zero* SM cross-section)

- **Bullet-like clusters**
  - **Gravity does not follow baryons**
- **Rotation curves**
  - **Different shapes for same baryonic mass profiles**
- **Dark-matter poor galaxies**
  - **Ultra-diffuse**
  - **Tidal dwarfs**
  - **Compact ellipticals**
- **CMB (3rd peak)**
  - **Need pressure free fluid: $\Omega_M > 0.17$ even in MOND**
- **BBN + LSS**
  - **Flatness + low Ω_B**
- **Precision GR (Solar system, binary pulsar, LIGO)**
  - **Can’t modify strongly enough**
  - **GW speed ~ c**
- **Orbital stability [star clusters+satellites]**
  - **Globulars inspiral rapidly**



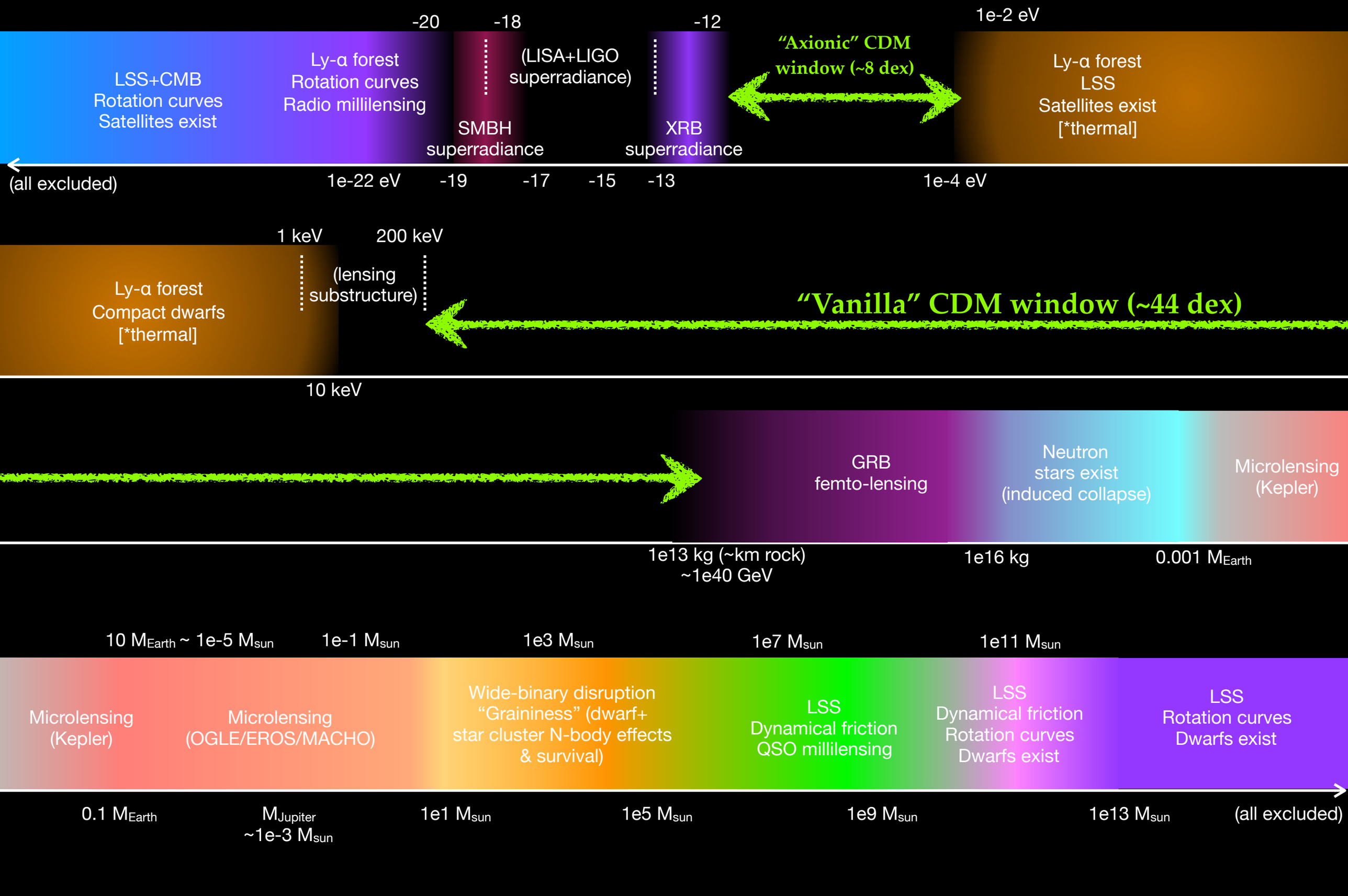


- (Beyond GR is alive & well, but *cannot* replace Dark Matter without adding degrees of freedom that mimic it!)

“Gravity-Only” DM Constraints

(*zero* SM cross-section)

~100 dex ruled out!



The State of FIRE

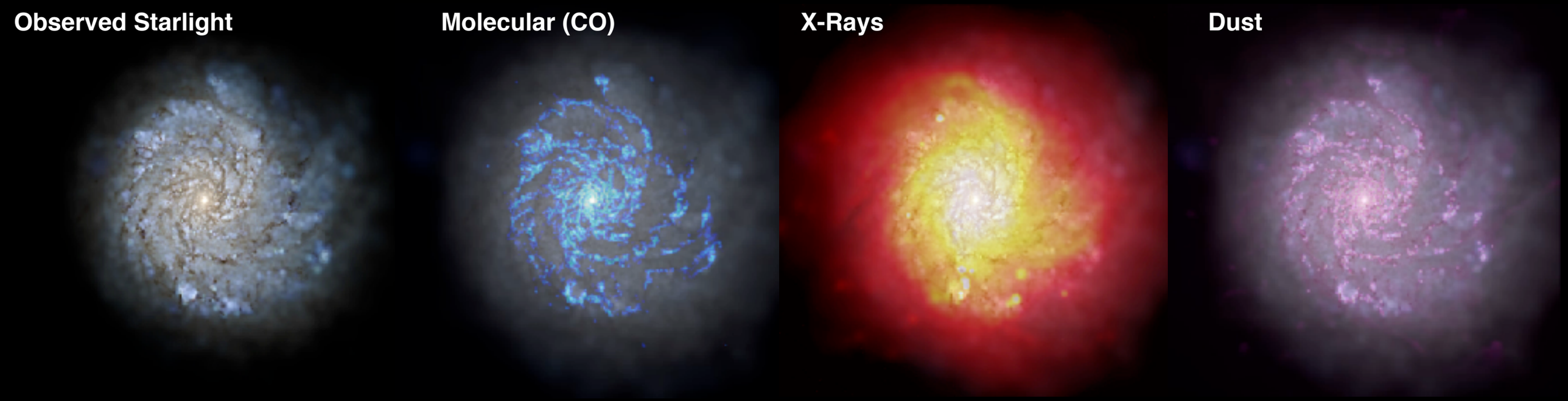
- Resolution (cosmological to z=0):
  - Mass: Dwarfs ~30 M_{sun}, MW-Mass & Local-Group ~800 M_{sun}
  - Spatial (in dense gas): ~ 0.1 - 1 pc
  - Densities (with resolved M_{Jeans}): ~ 1000 - 100,000 cm^{-3}
  - Time (dense/hot gas): ~50-100 yr
  - (Star clusters & GMCs with same physics: ~0.01 M_{sun}, 0.1 au)

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

- Black Holes:
  - Seed models: exploring (lots of small seeds, few big seeds?)
  - Accretion models: gravitational torques & gravito-turbulent & Bondi
  - Radiative: photo-ionization & photo-electric & Compton & radiation pressure
  - "Hydrodynamic" (accretion disk winds): dM/dt~BHAR, v~30,000 km/s
  - "Non-Hydrodynamic" (jets & bubbles of cosmic rays & magnetic fields)

- Plasma Physics:
  - MHD (non-ideal in GMCs)
  - Anisotropic Viscosity & Conduction
  - Cosmic Rays (injection, streaming, anisotropic diffusion, cooling)
  - Dust dynamics (drag+Lorentz forces)
  - Dust formation/evolution
  - Explicit 5-10 band RHD

- Dark Matter Physics + Baryons:
  - Self-Interacting DM (v-dep't, anisotropic)
  - "Fuzzy" DM (quantum pressure tensor)
  - Explicit Collisionless-Boltzmann (Phase-Space) Solvers (non Monte-Carlo)



- 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?

- But *the "null" DM hypothesis remains a good fit* to all *gravitational* astrophysical observations

  - "Missing satellites"/"Cusp-core"/"Too Big to Fail"/"Angular Momentum Catastrophe"/"Over-merging"/ "Diversity/Rotation Curve Shapes"/"Baryonic Tully-Fisher (or Radial Acceleration)"
    — all *predicted* by null hypothesis [no fine-tuning! just *what we know about stars*]

  - Modified DM/gravity can differ at < kpc, but *does not significantly improve agreement with current observations*

- Have we reached the limit of gravitational dynamics / galaxies as a [useful] constraint on DM physics?

  - Model space not motivated by "making things less dense at ~kpc" remains poorly-explored

  - Room for *astrophysically interesting* DM-SM interactions? Probes of *"dark sector"* structure?