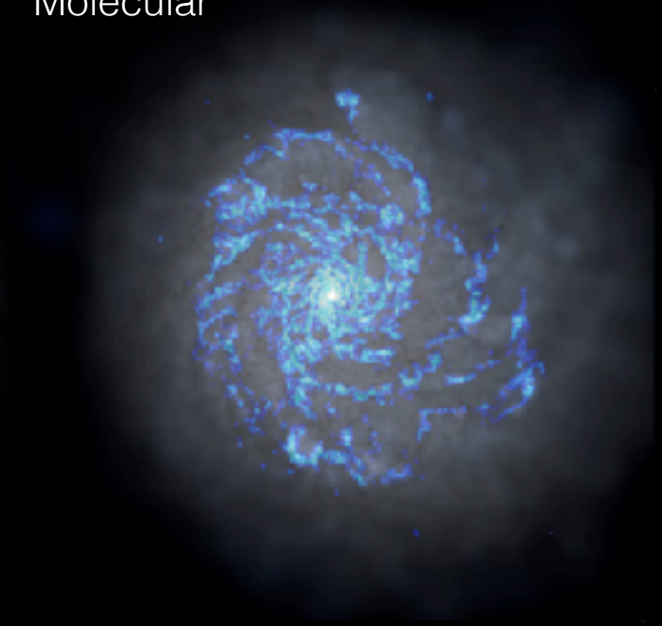
Feedback: Now With Physics

Observed Starlight

Molecular



Galaxy Merger

X-Rays

Star Formation

Philip Fajardo Hopkins & the FIRE Team

Caltech

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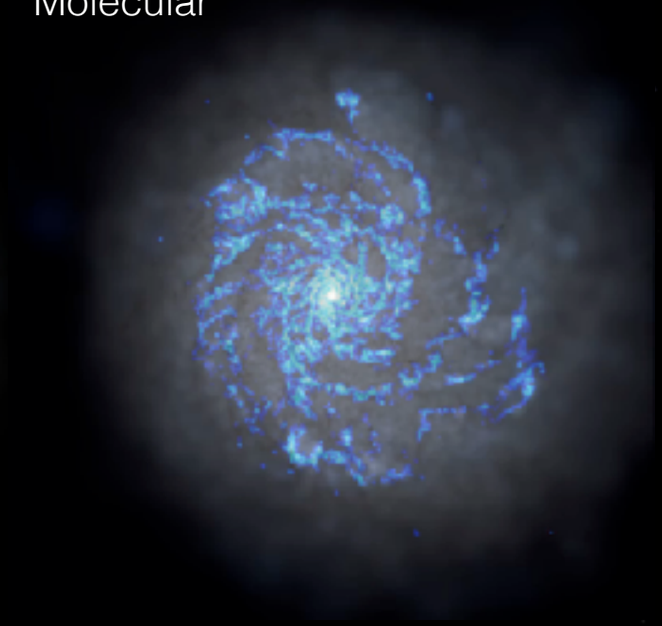

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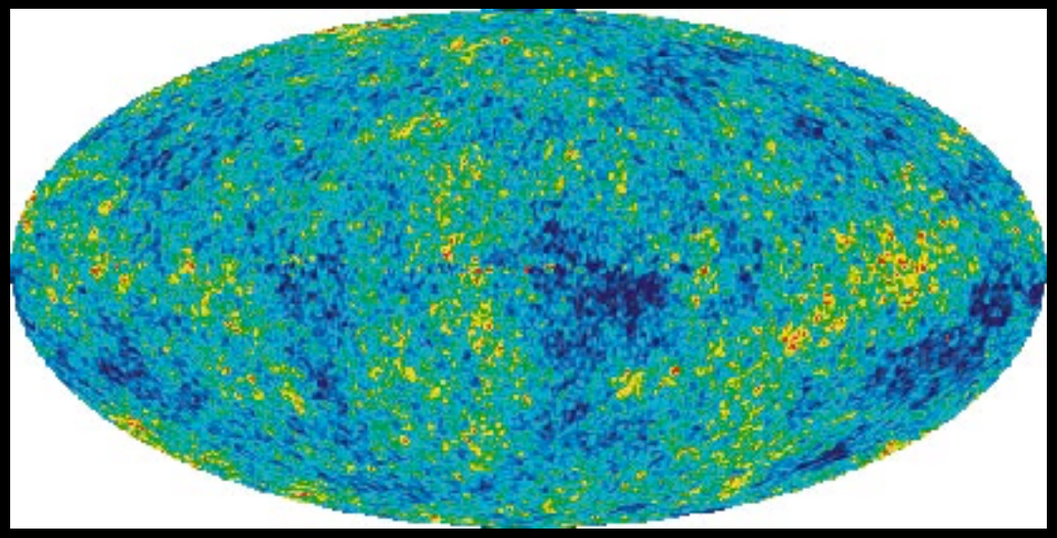
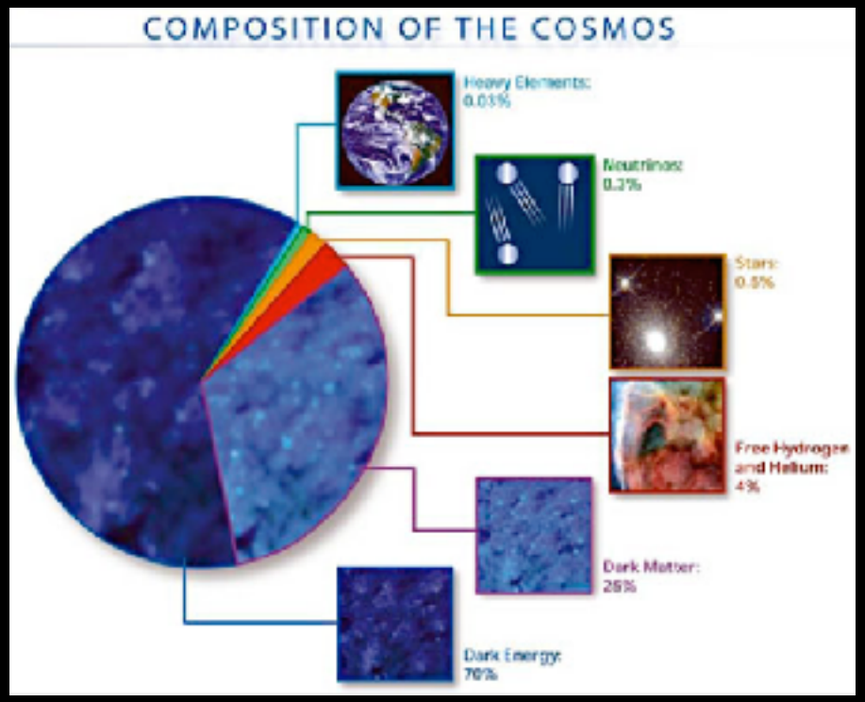
What's the Big Picture?

The Big Question:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?





z~1090
(t~400,000 yr)

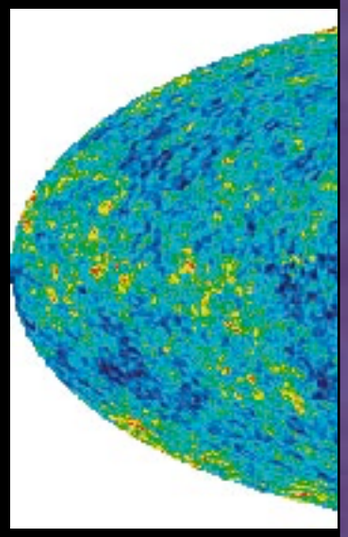
?

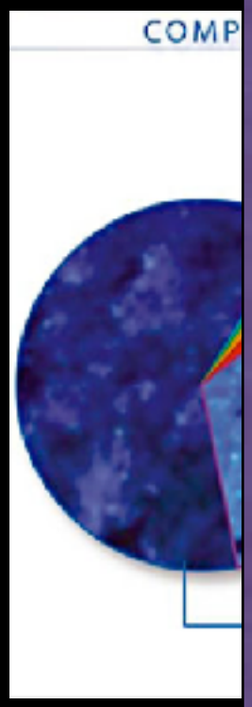
Today

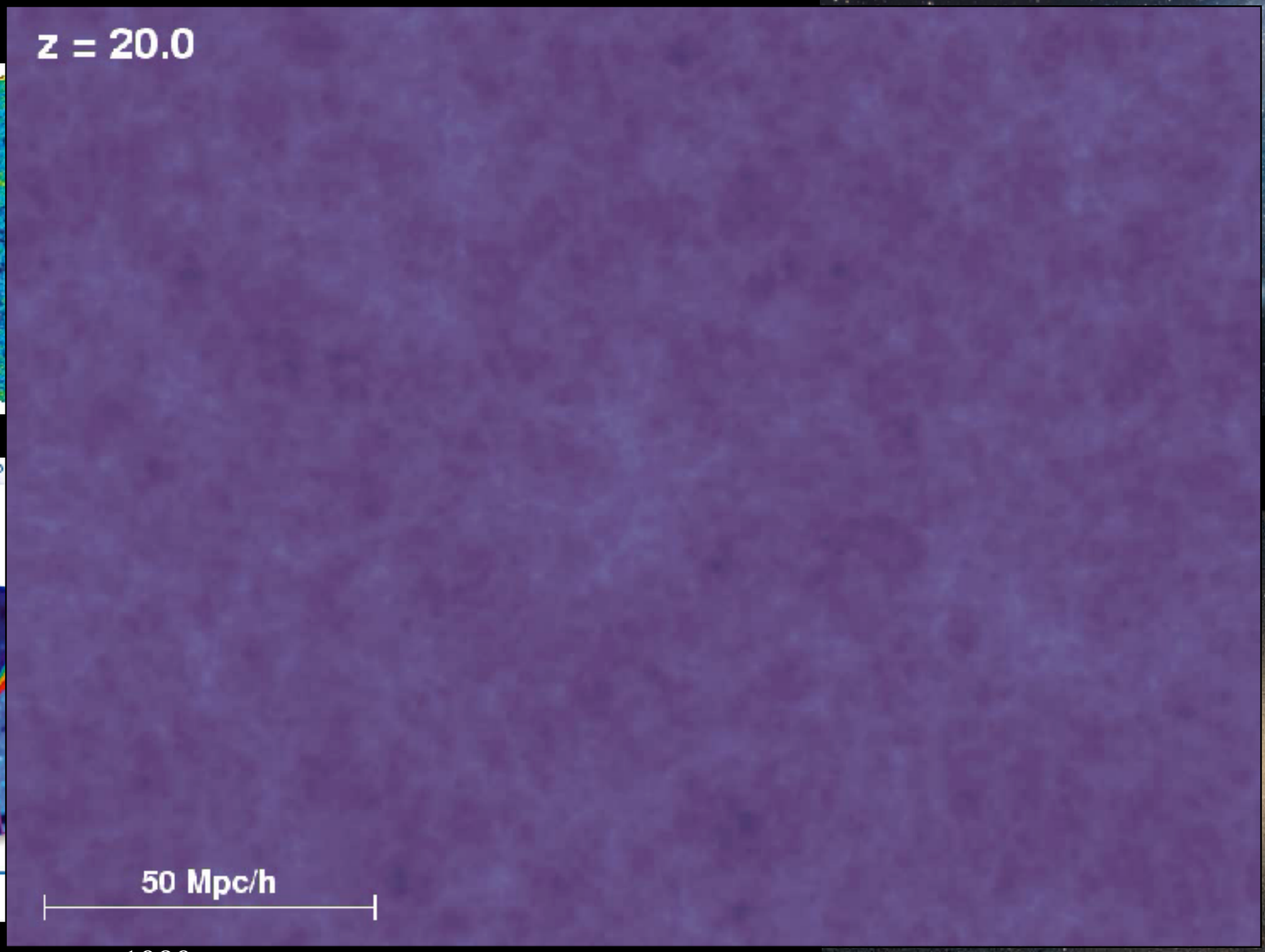
The Big Question:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?

Today







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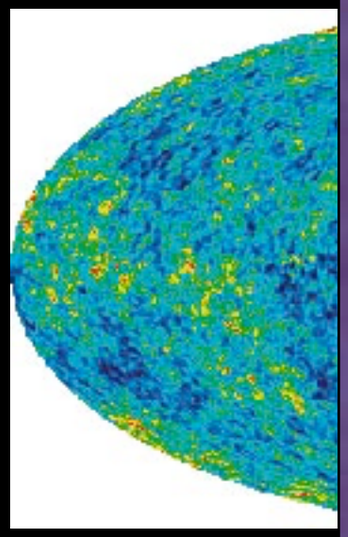
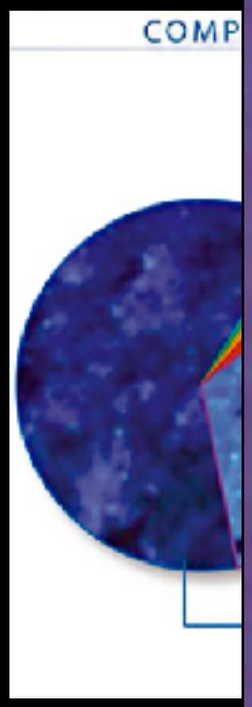
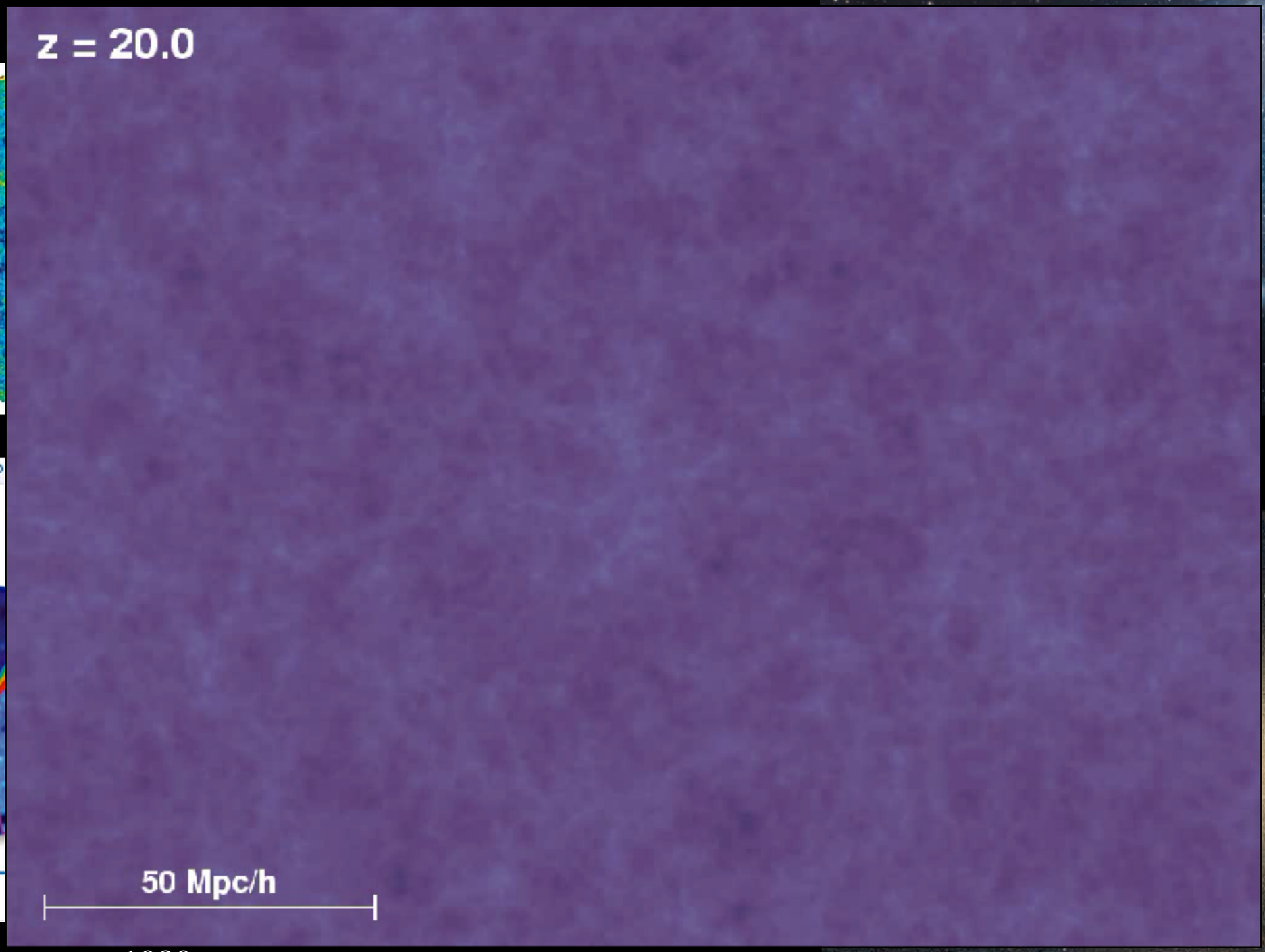


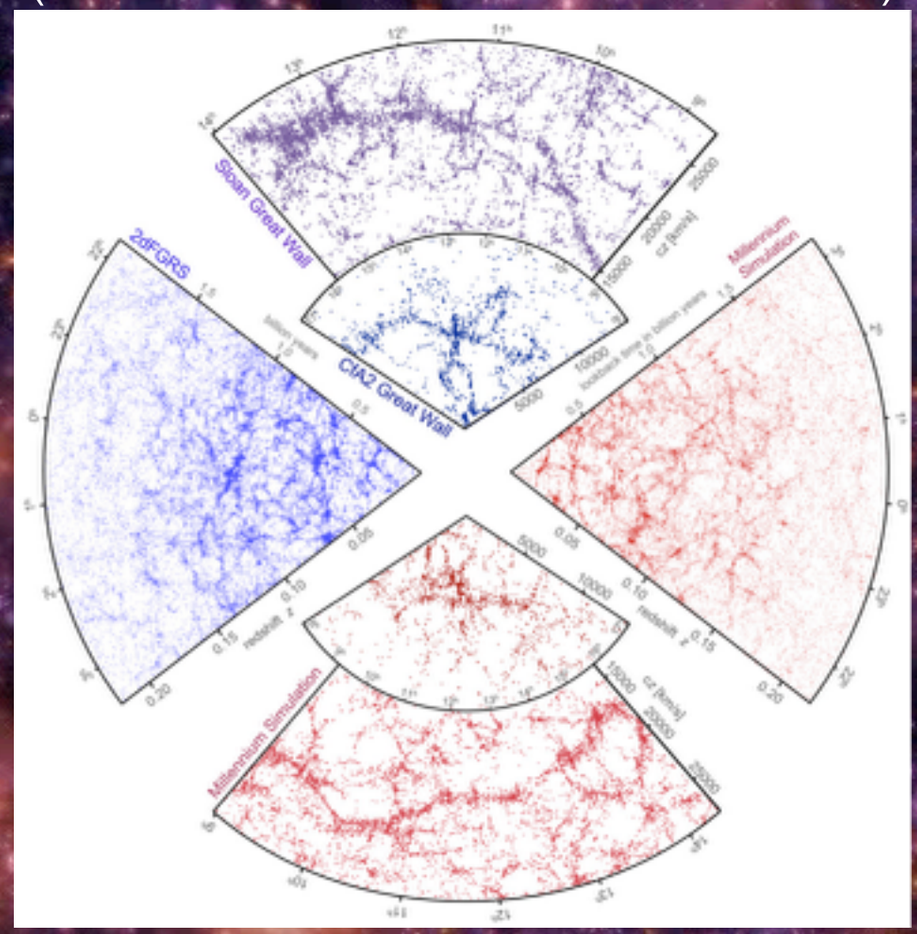




z~1090
(t~400,000 yr)

Large scales: Gravity +
Dark Matter / Energy Works!

Observations vs Theory
(SDSS vs Millennium Simulation)



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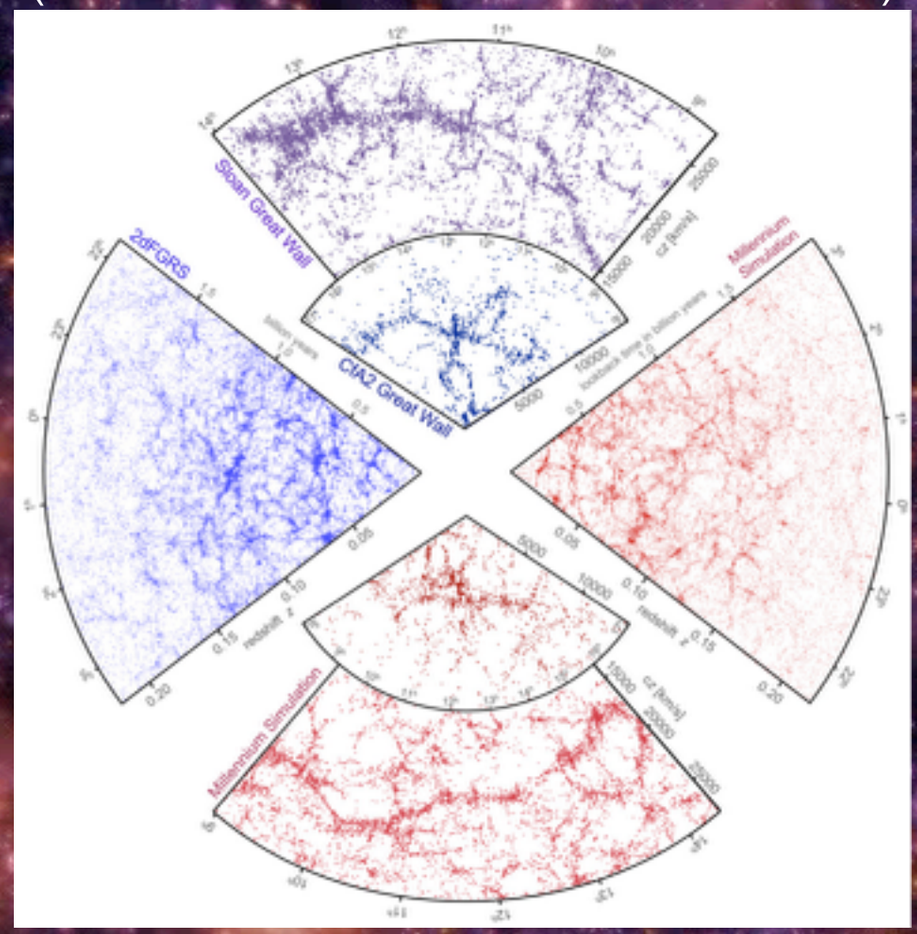
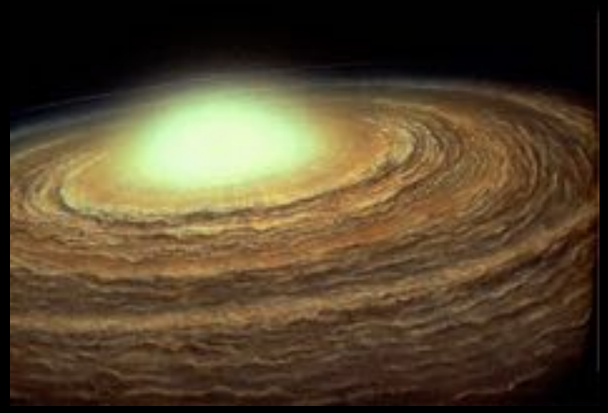


Our work:

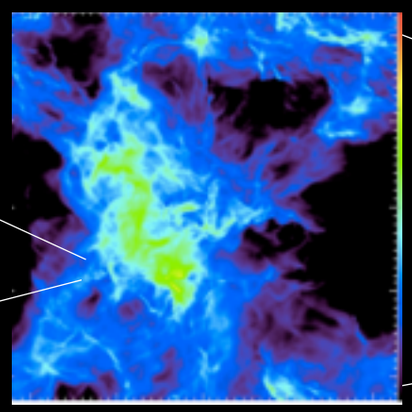
~10^{10} pc
Hubble volume

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

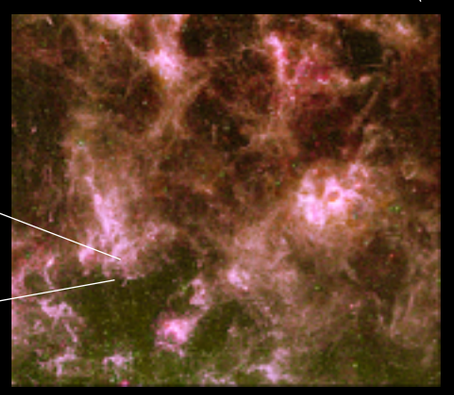
~10^{4-5} pc
Galaxy



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



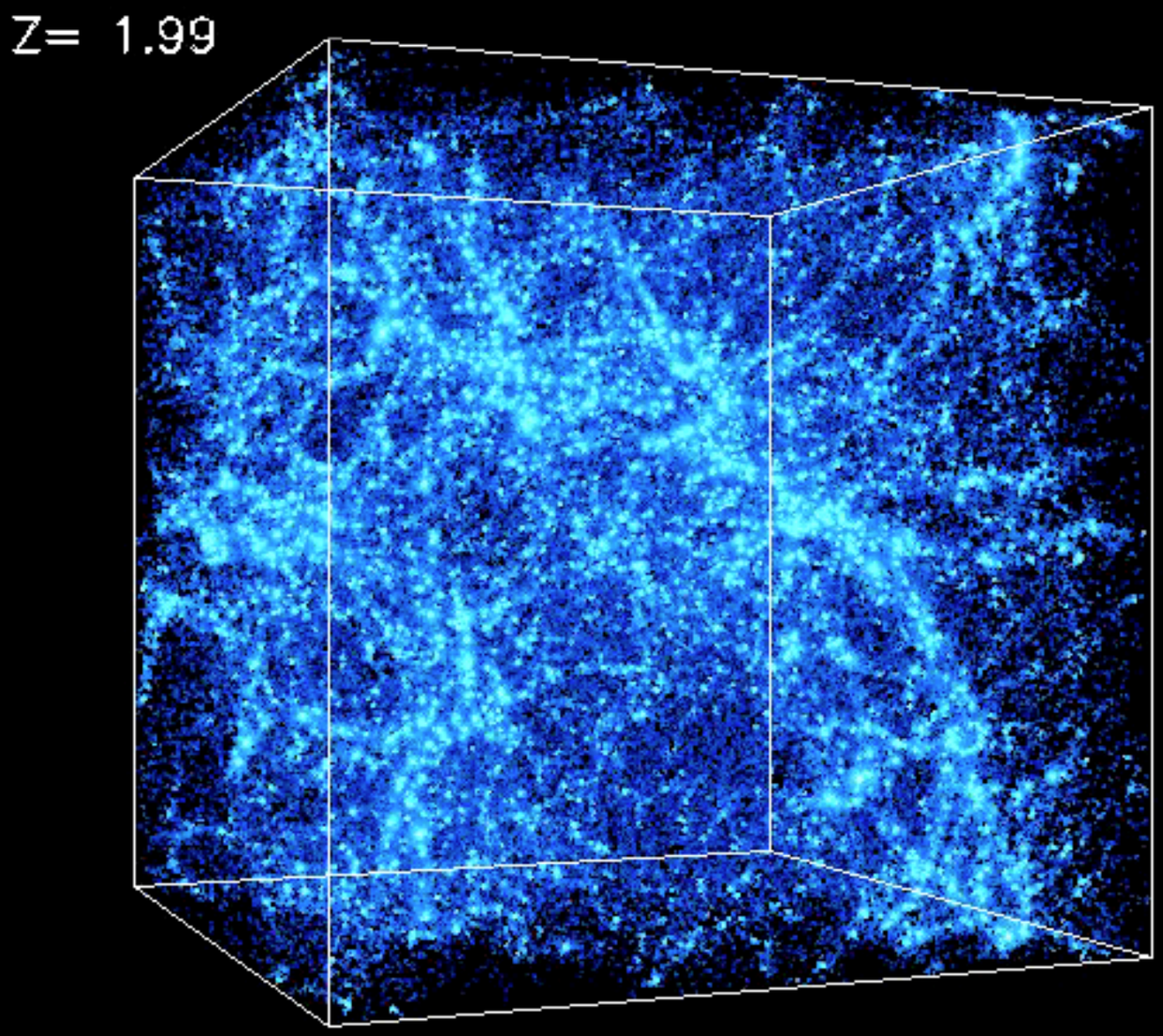
~10^{-2}-10^{0} pc
Cores, clusters,
Supernovae blastwaves



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

Our work:

STRUCTURE FORMATION



STAR FORMATION

Guszejnov 15,16
PFH 10,12

→ Planet formation (PFH & Christiansen)

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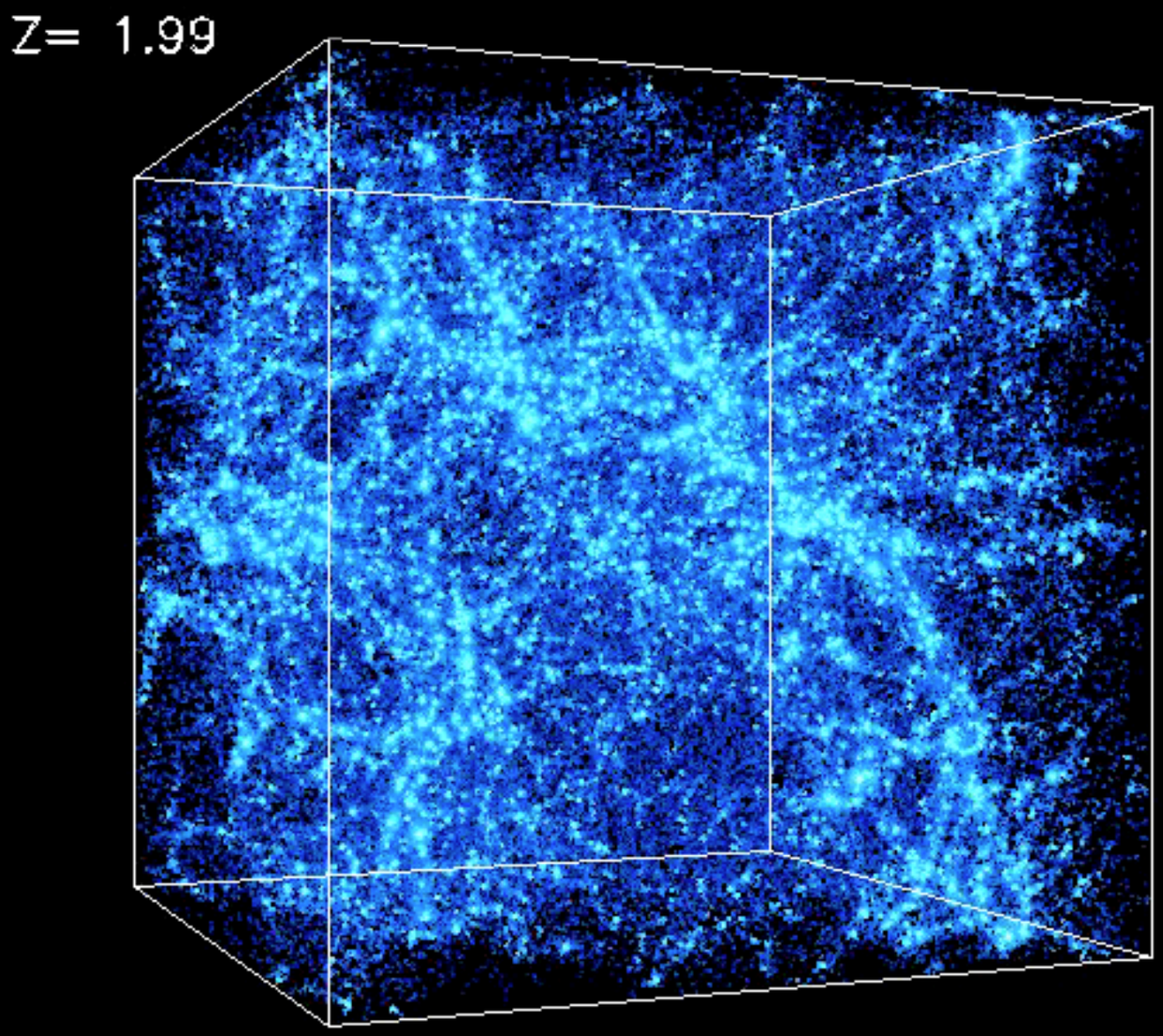
STRUCTURE FORMATION



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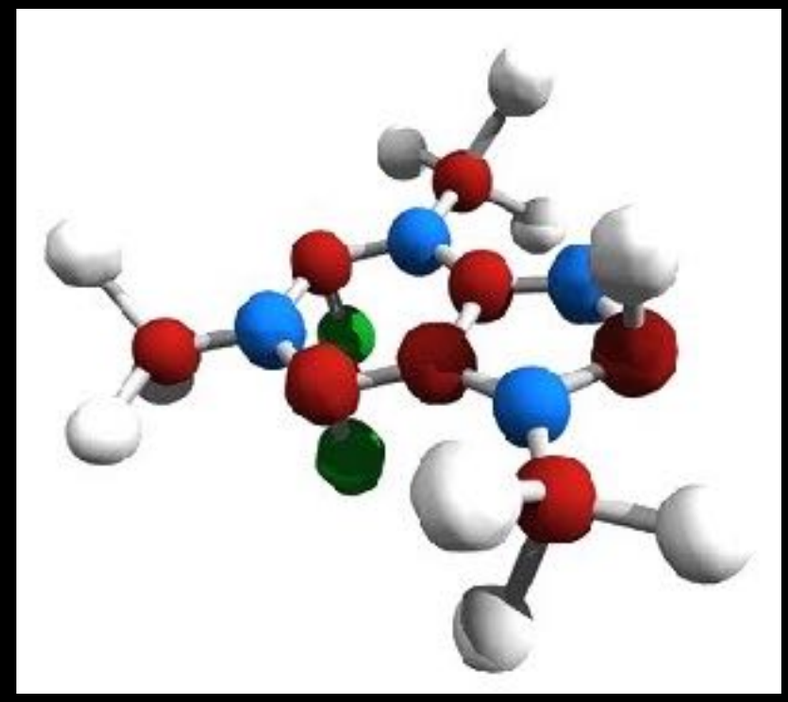
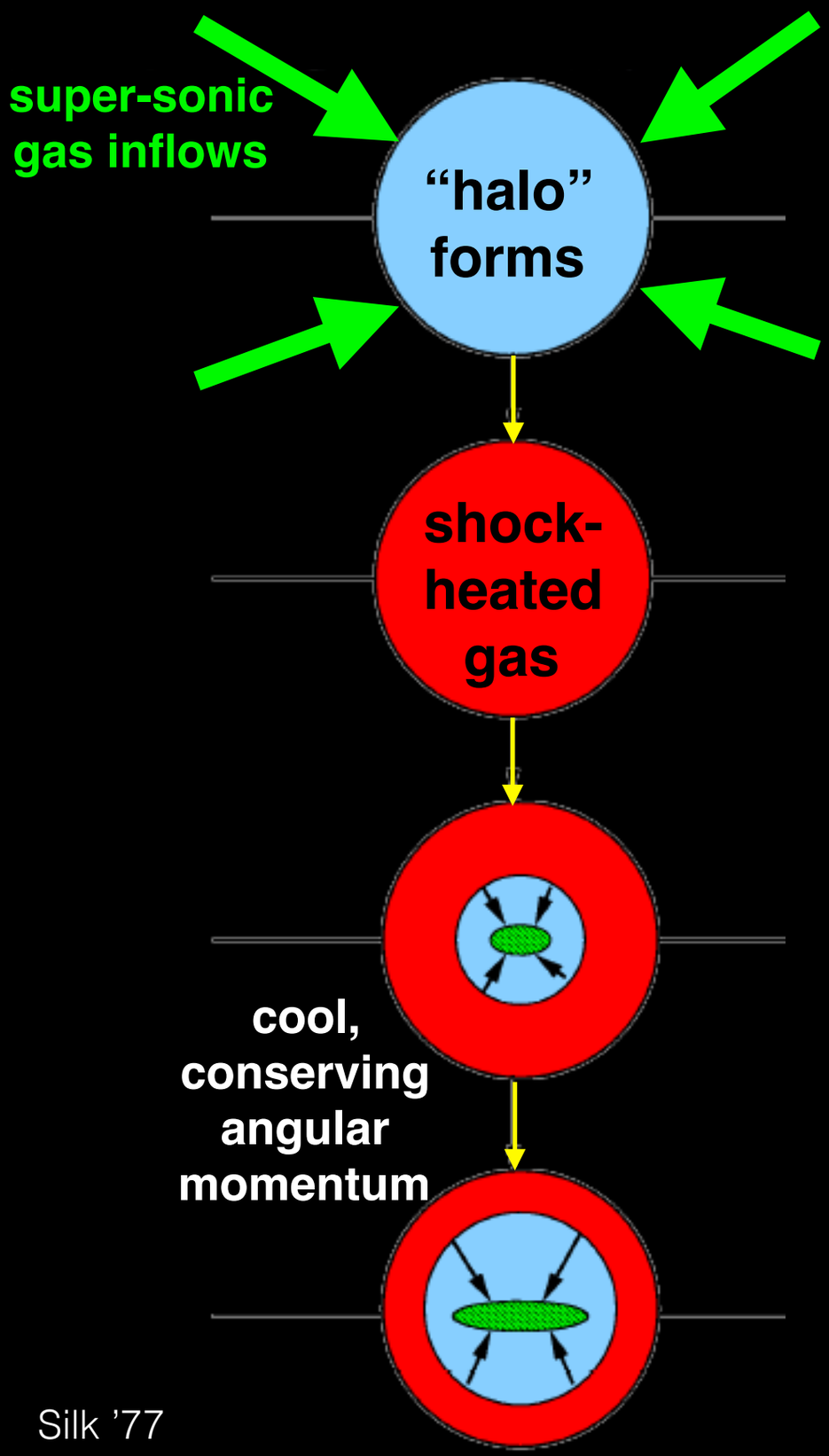


Add some fluid dynamics and chemistry, and go!

The Basic Picture:



Silk ’77
Binney ’77
Rees & Ostriker ‘77

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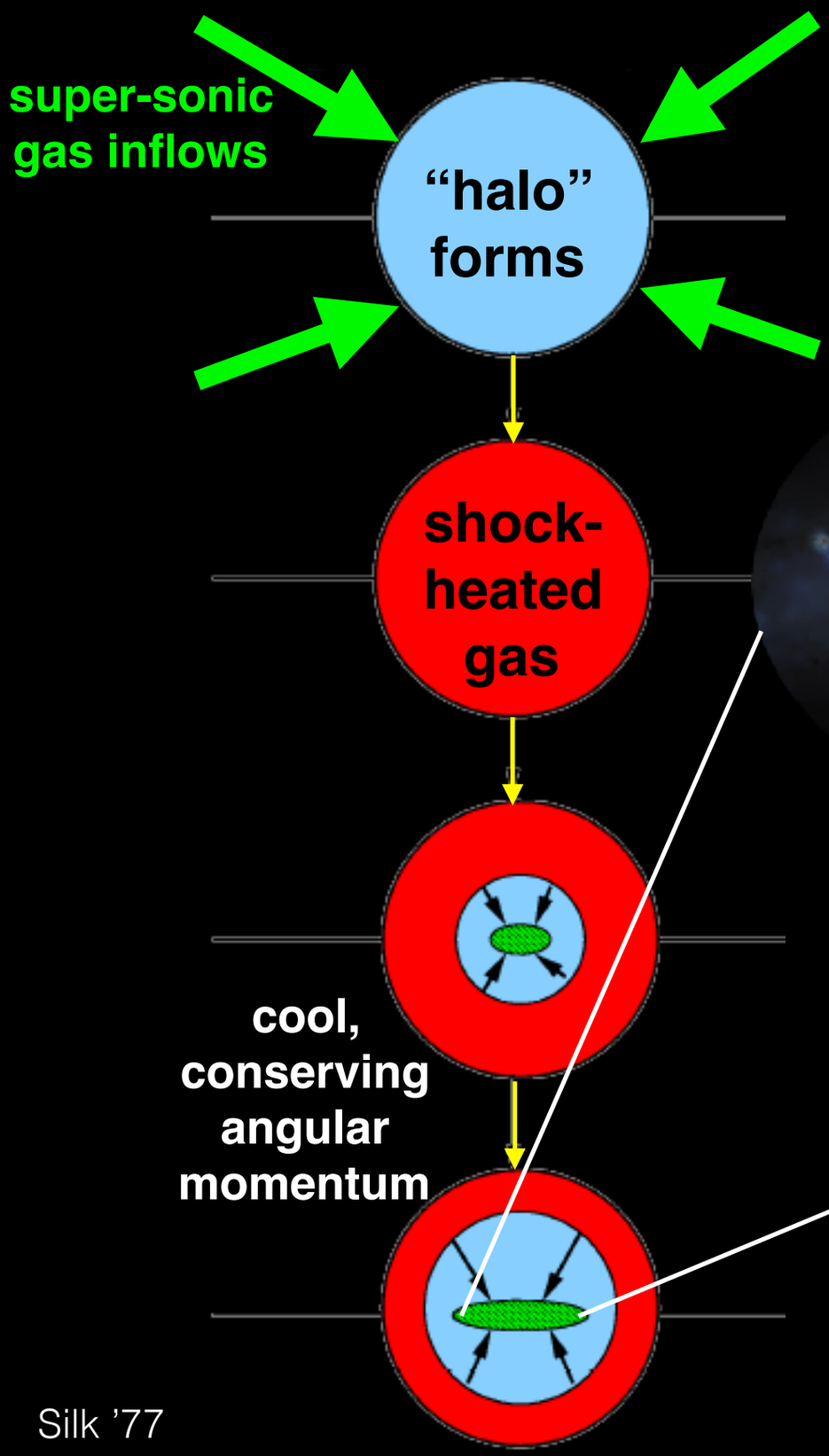
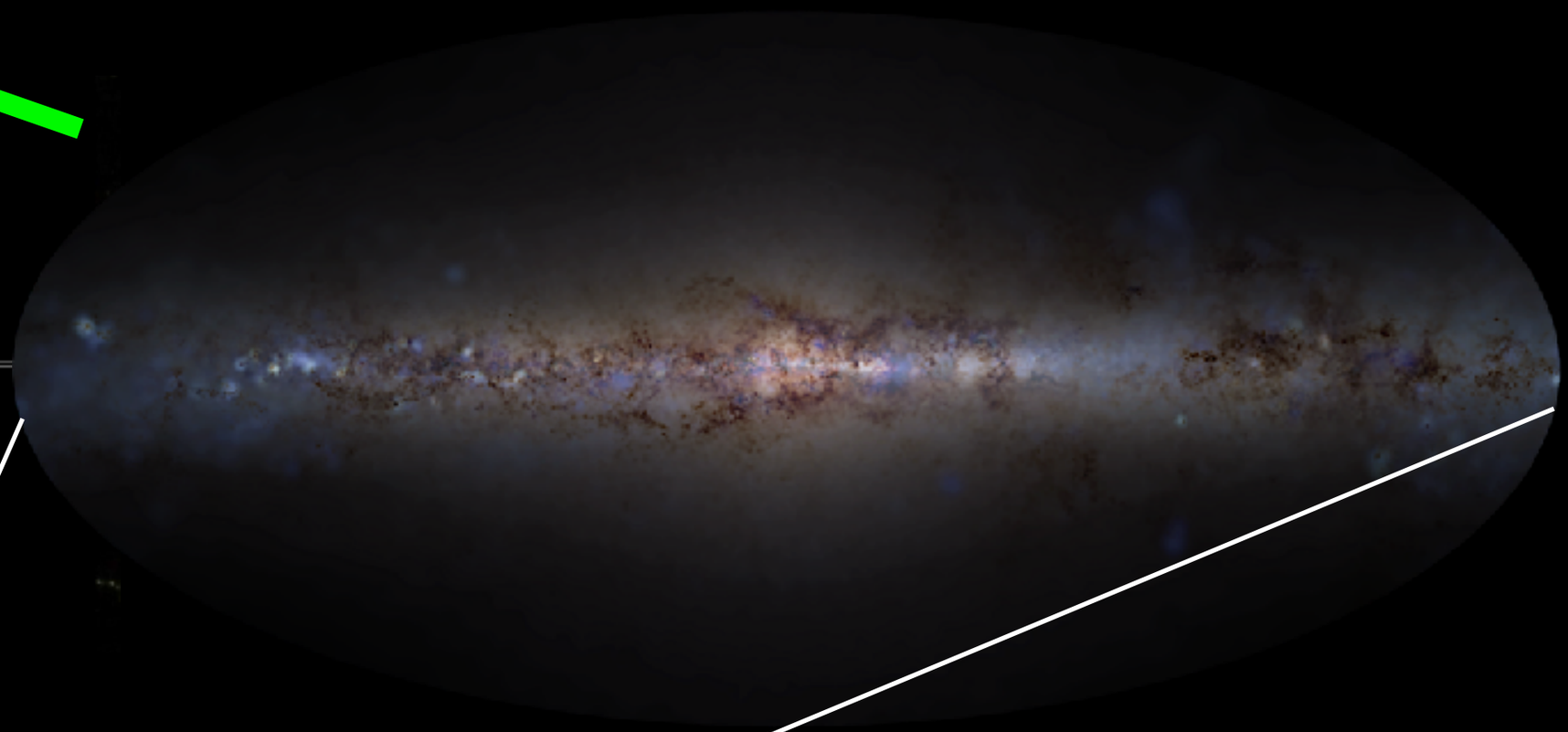




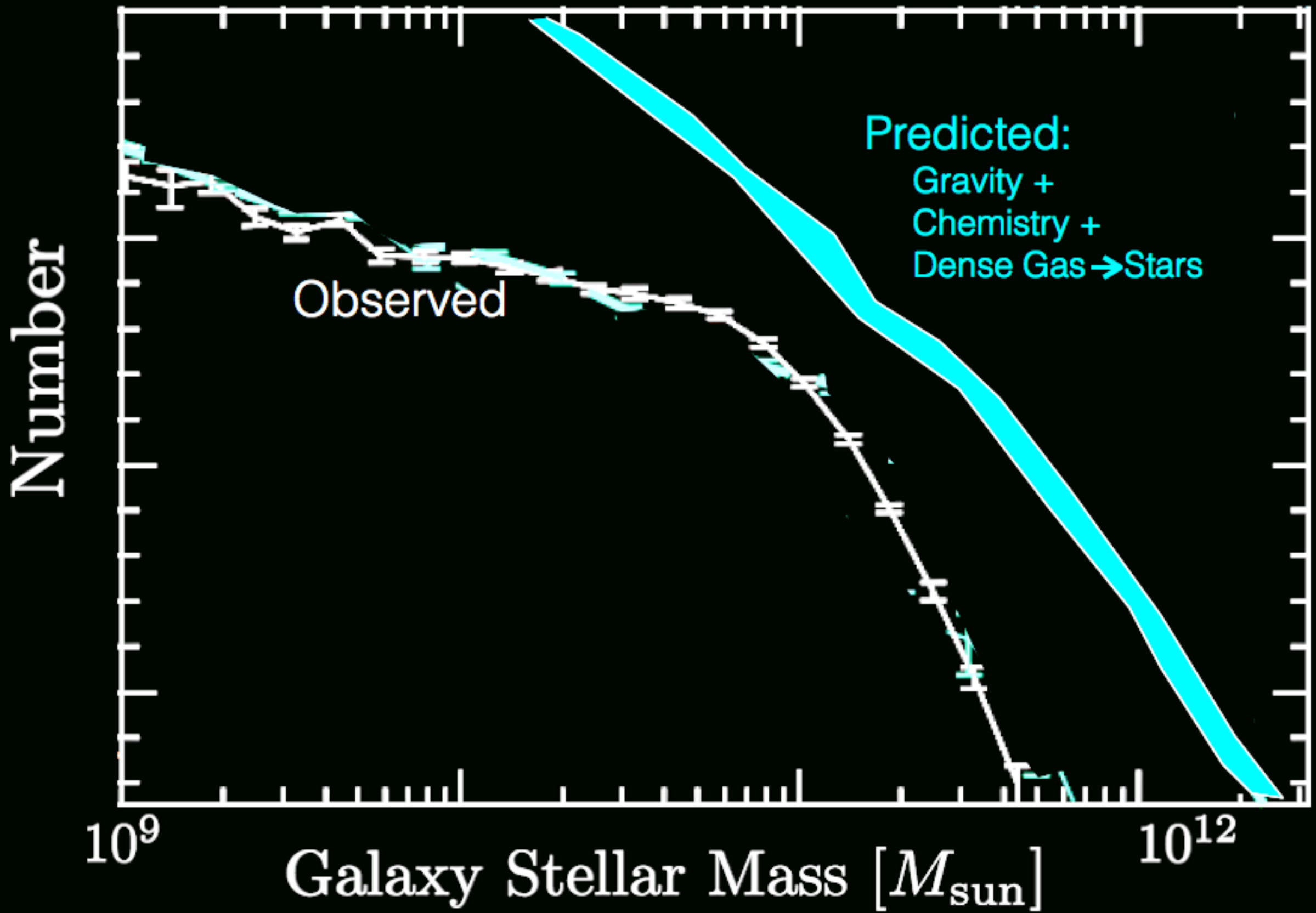
Silk ’77
Binney ’77
Rees & Ostriker ‘77

Done!

Not so fast…

Problem:

WHY SO FEW GALAXIES & STARS?



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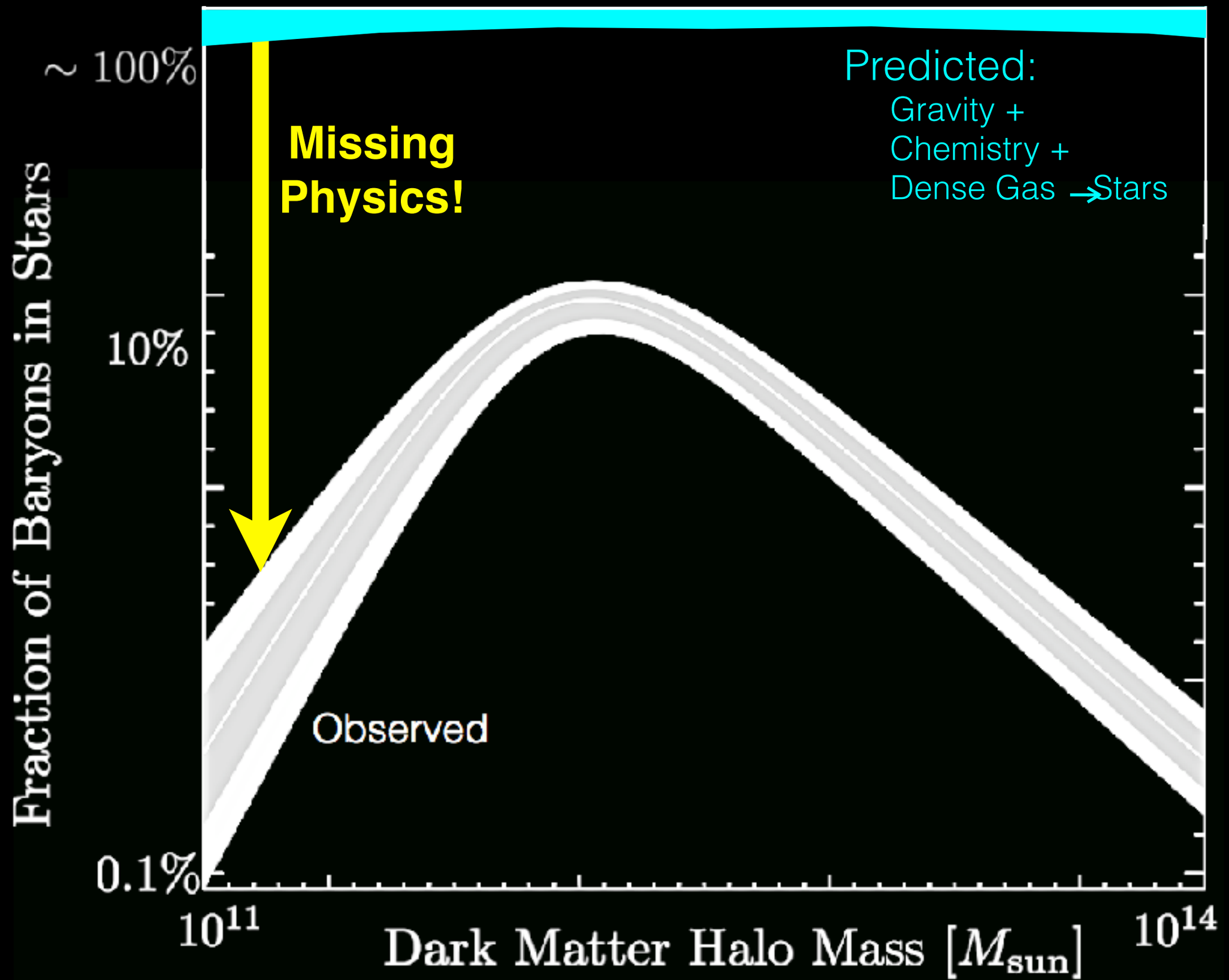
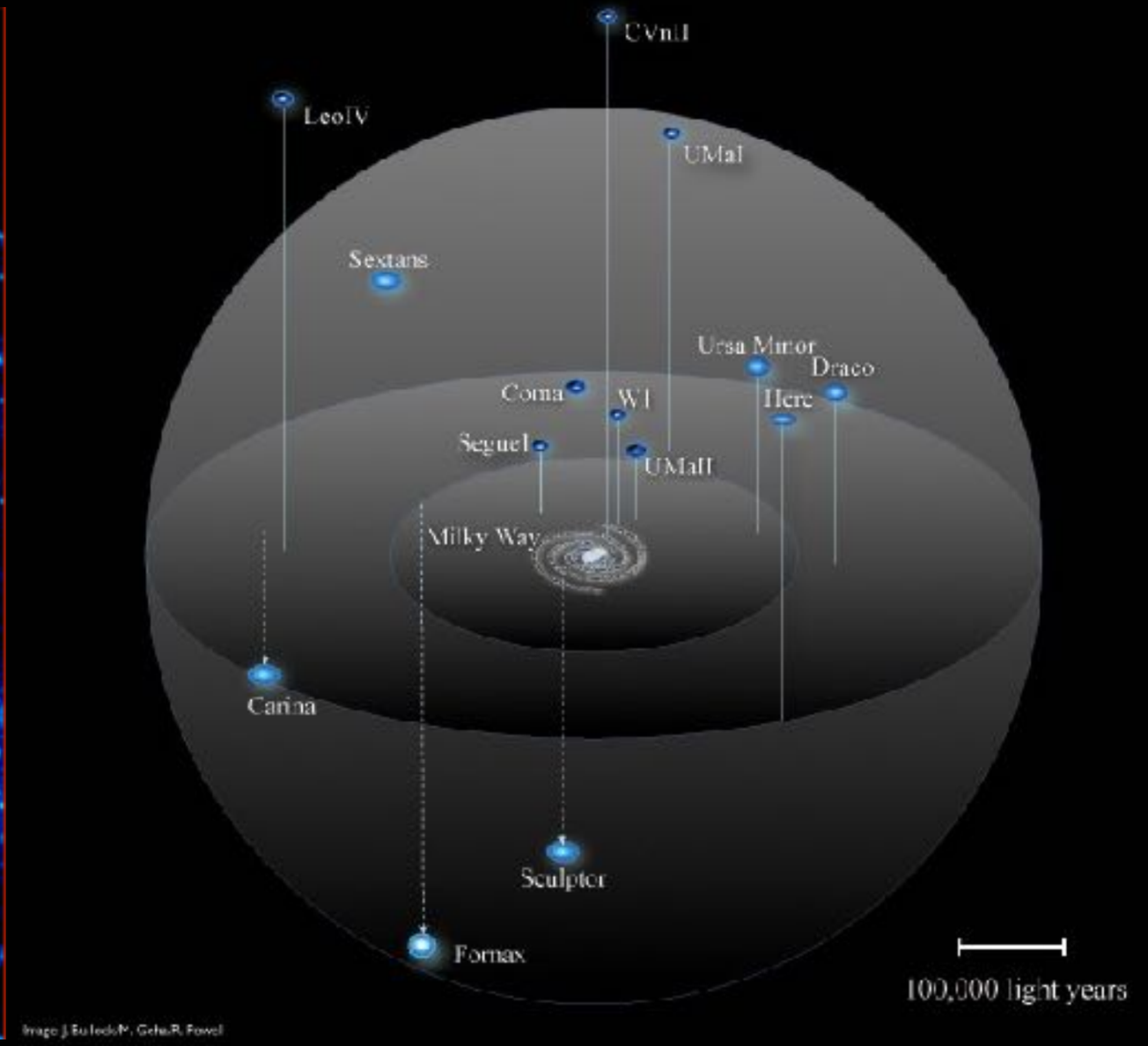


Problem:
WHERE ARE THE "MISSING SATELLITES"?

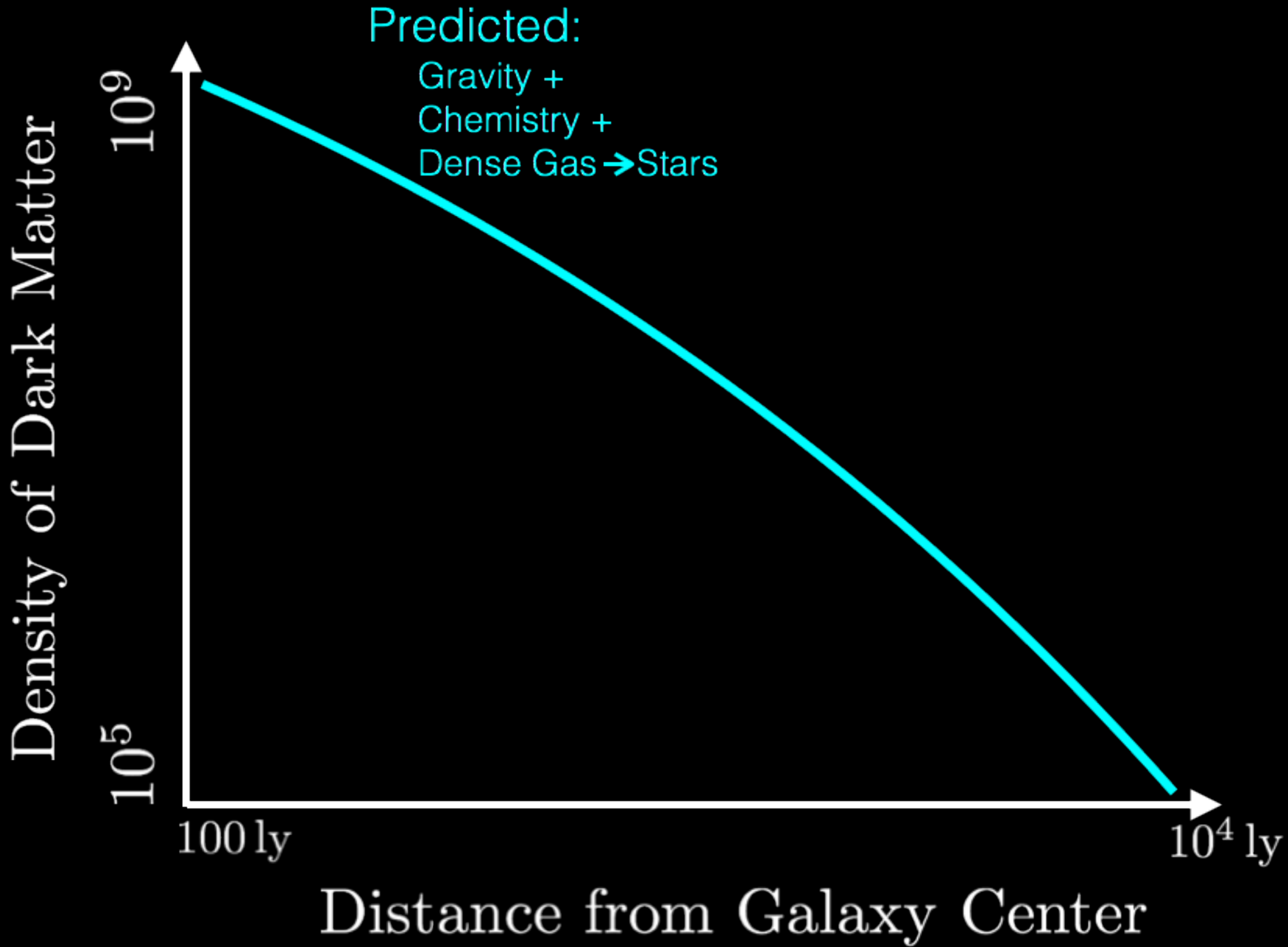
Predicted structure
(dark matter)



Observed
around us

Problem:

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



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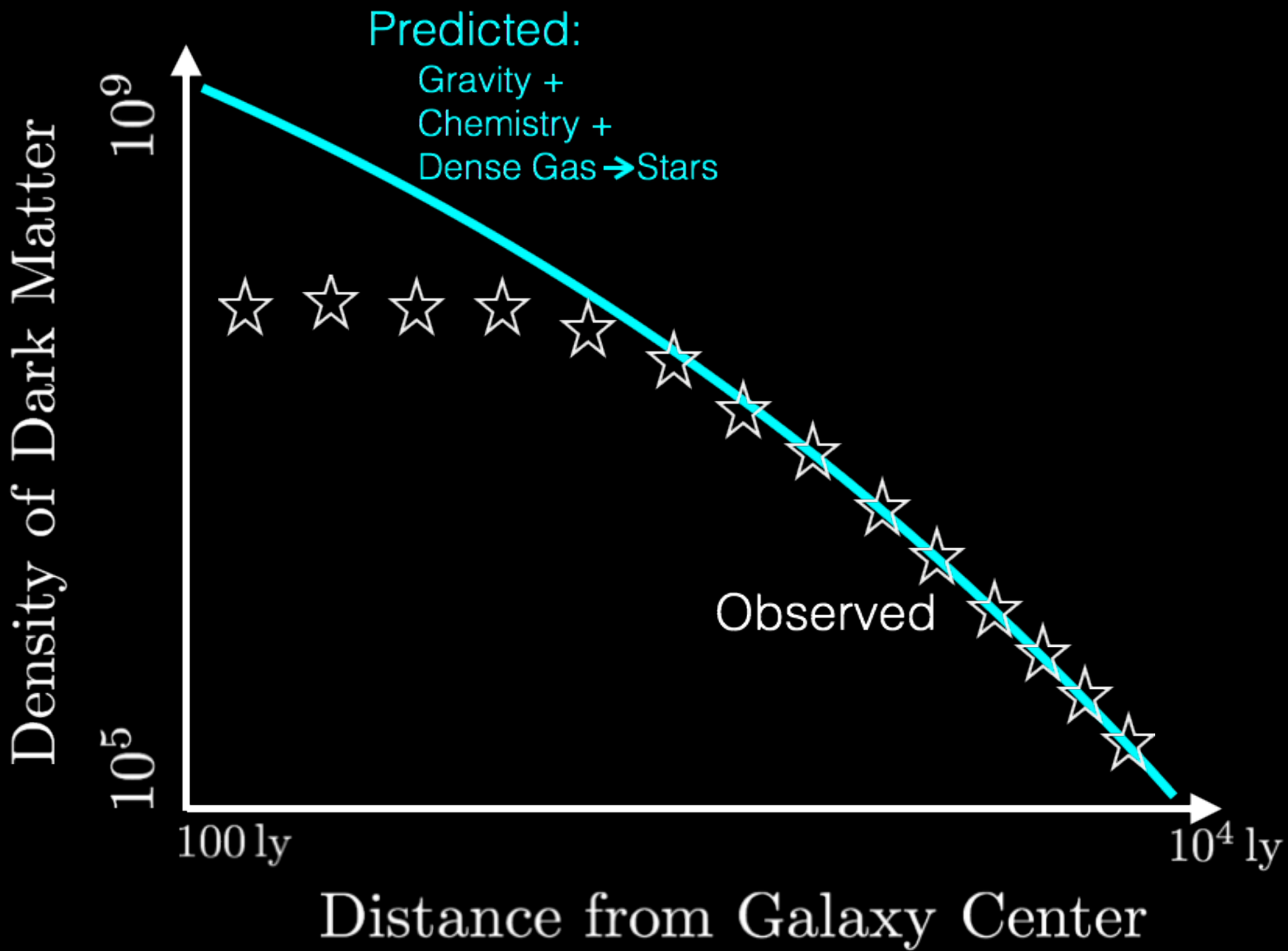


Stars Matter

Stars Matter

… Nature hates theorists

~10^{10} pc

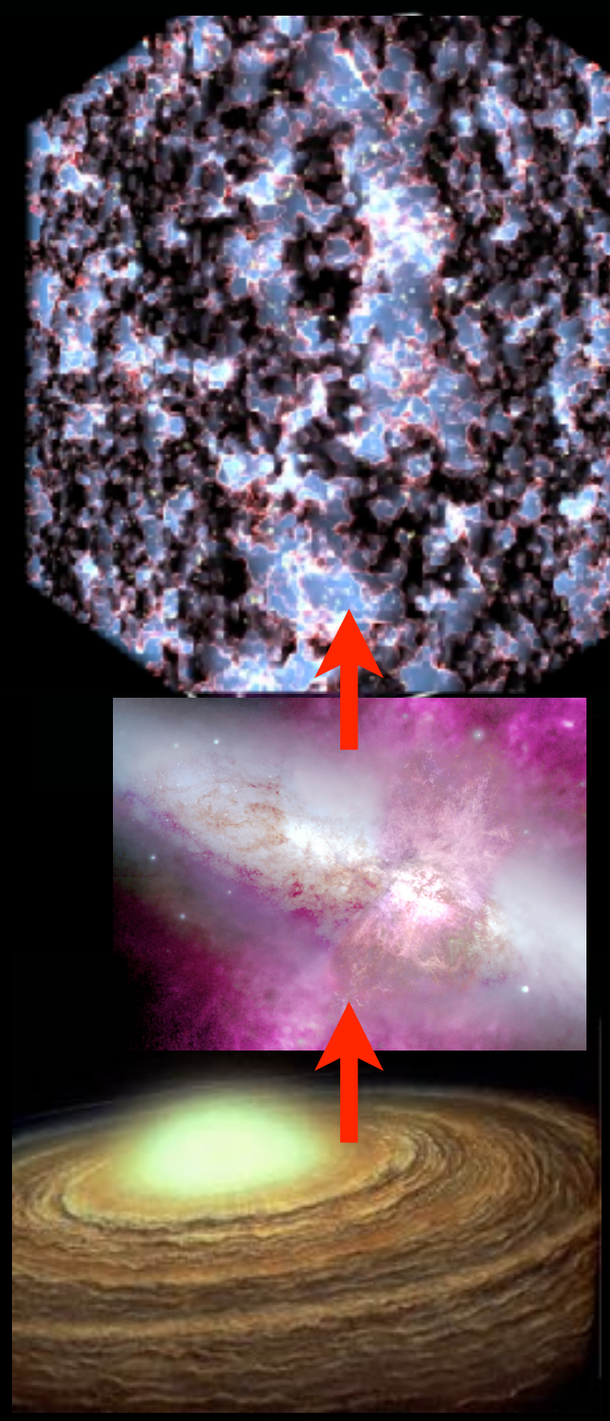
Hubble volume

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

Clusters, Large-scale structure

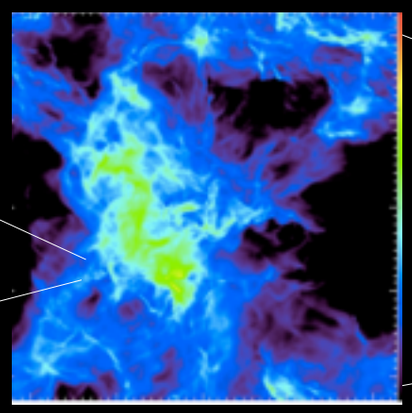
~10^{4-5} pc

Galaxy



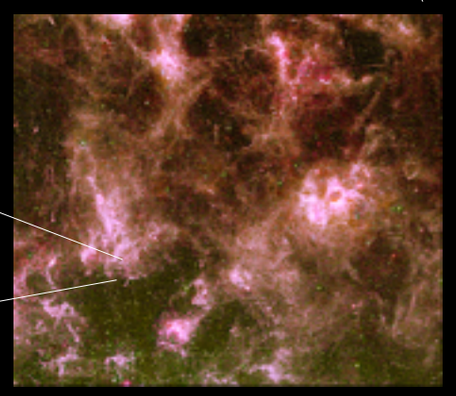
~10^{-5} pc

Stars, protostellar disks



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

Cores, clusters,
Supernovae blastwaves



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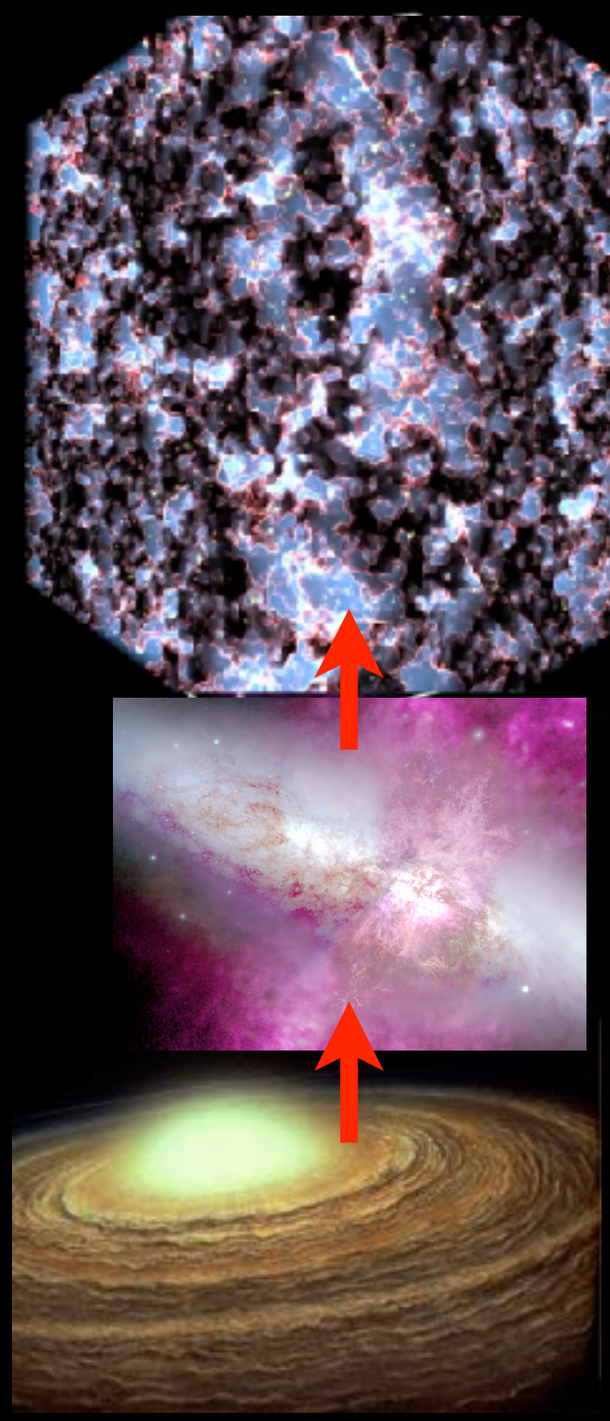

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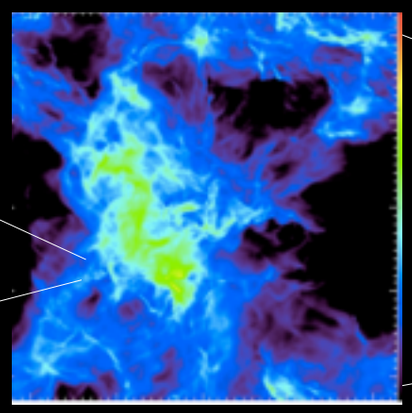

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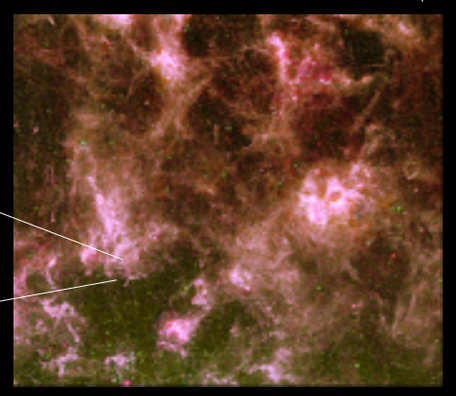


~10^{1}-10^{2} pc

Molecular clouds,
Star-Forming Regions

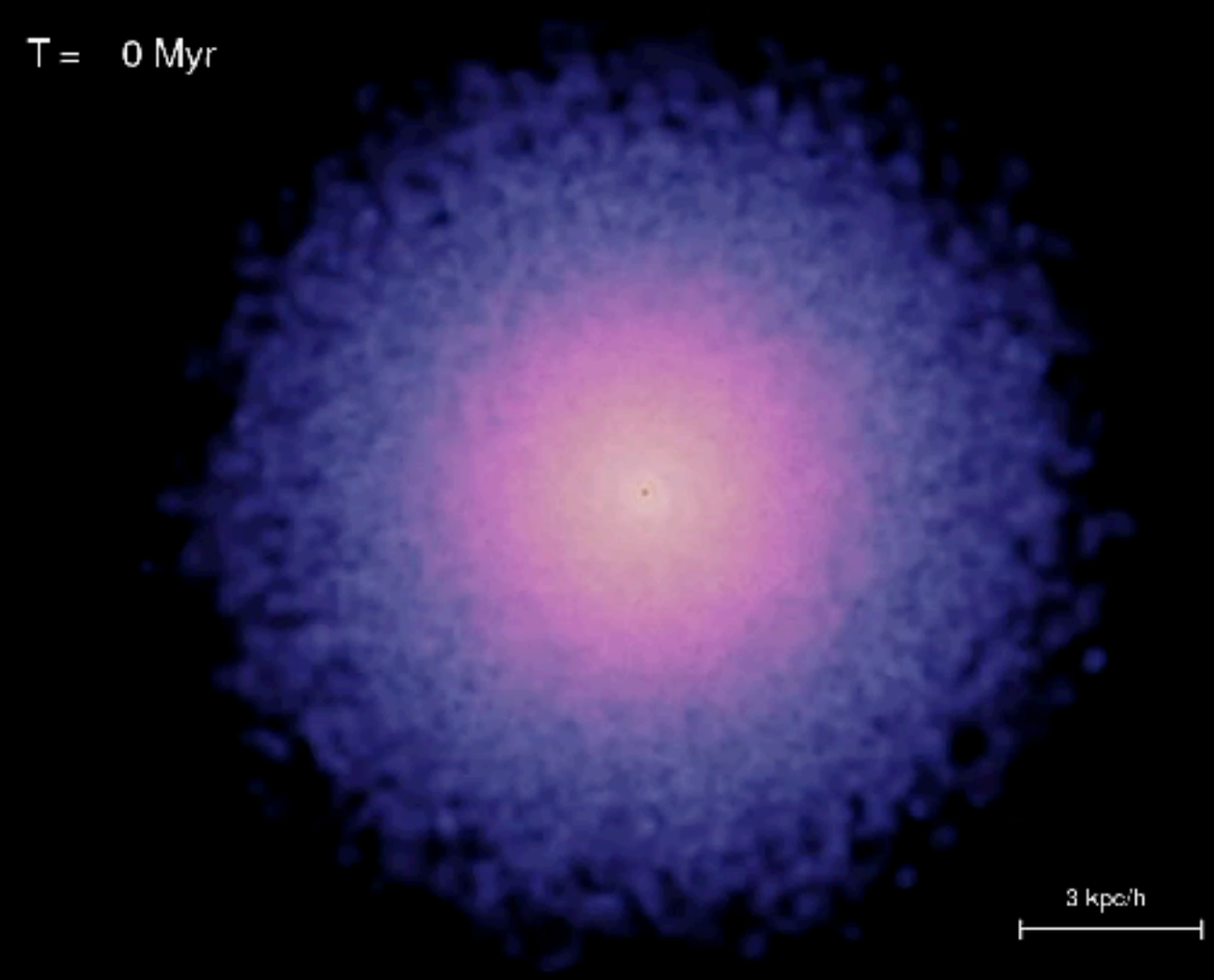
But we know what stars do!

(…well enough…)

Previous “State of the Art”

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

Interstellar Medium:
single, ideal fluid



Winds?
“sub-grid” (cheat a bit)

- turn off cooling
- throw out mass “by hand”

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

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

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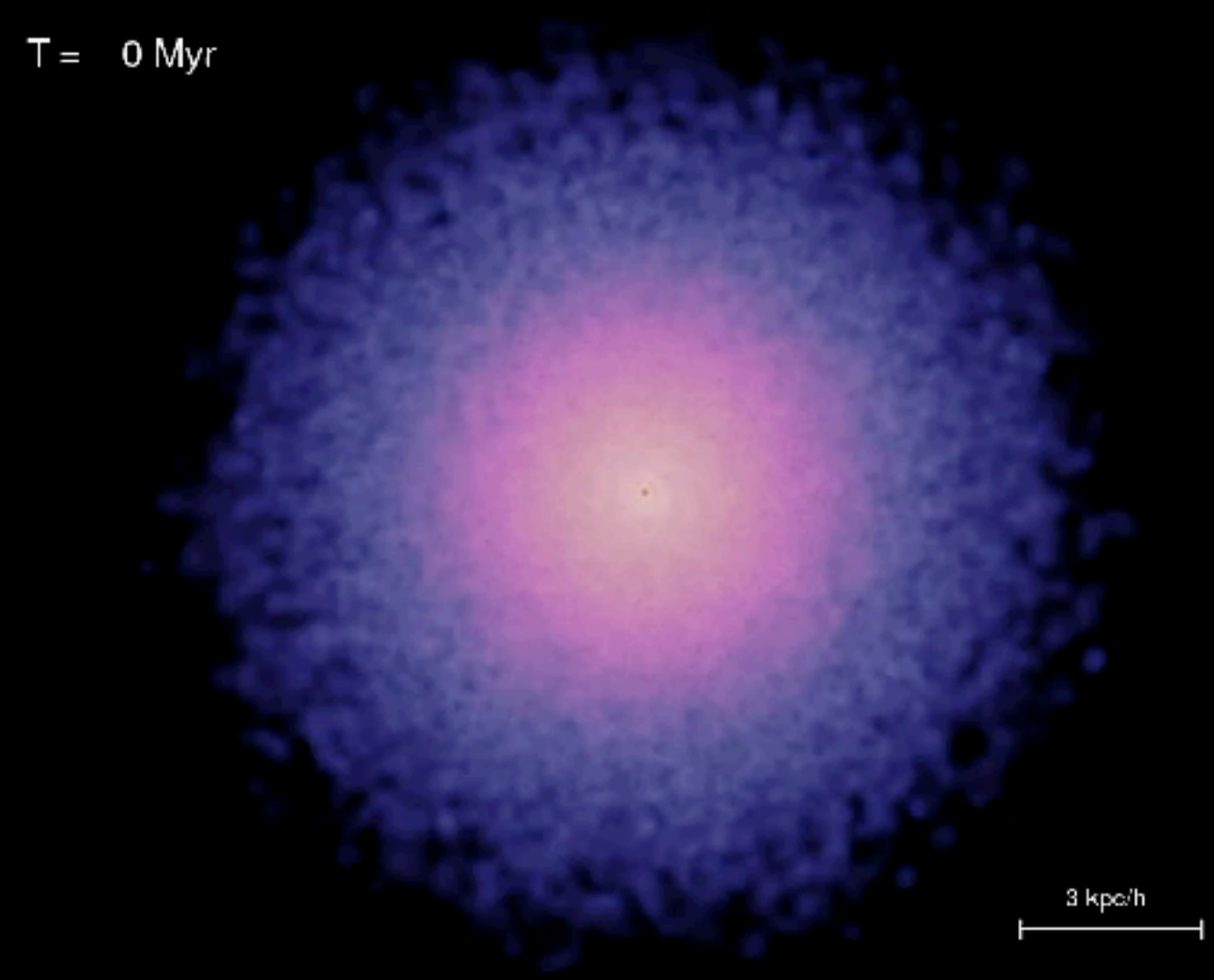

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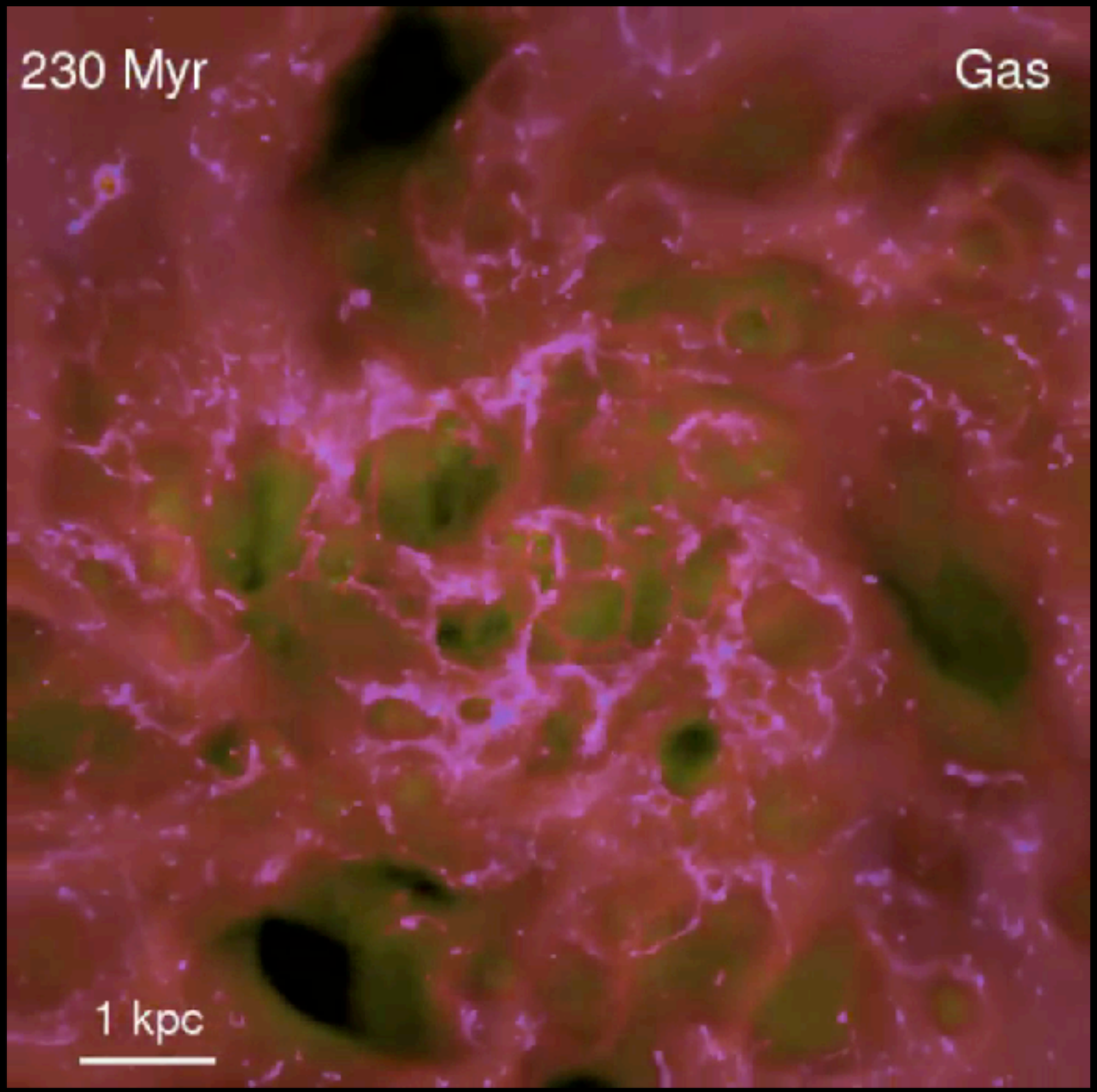
The FIRE Project

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…
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  - Anisotropic
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  - Cosmic rays

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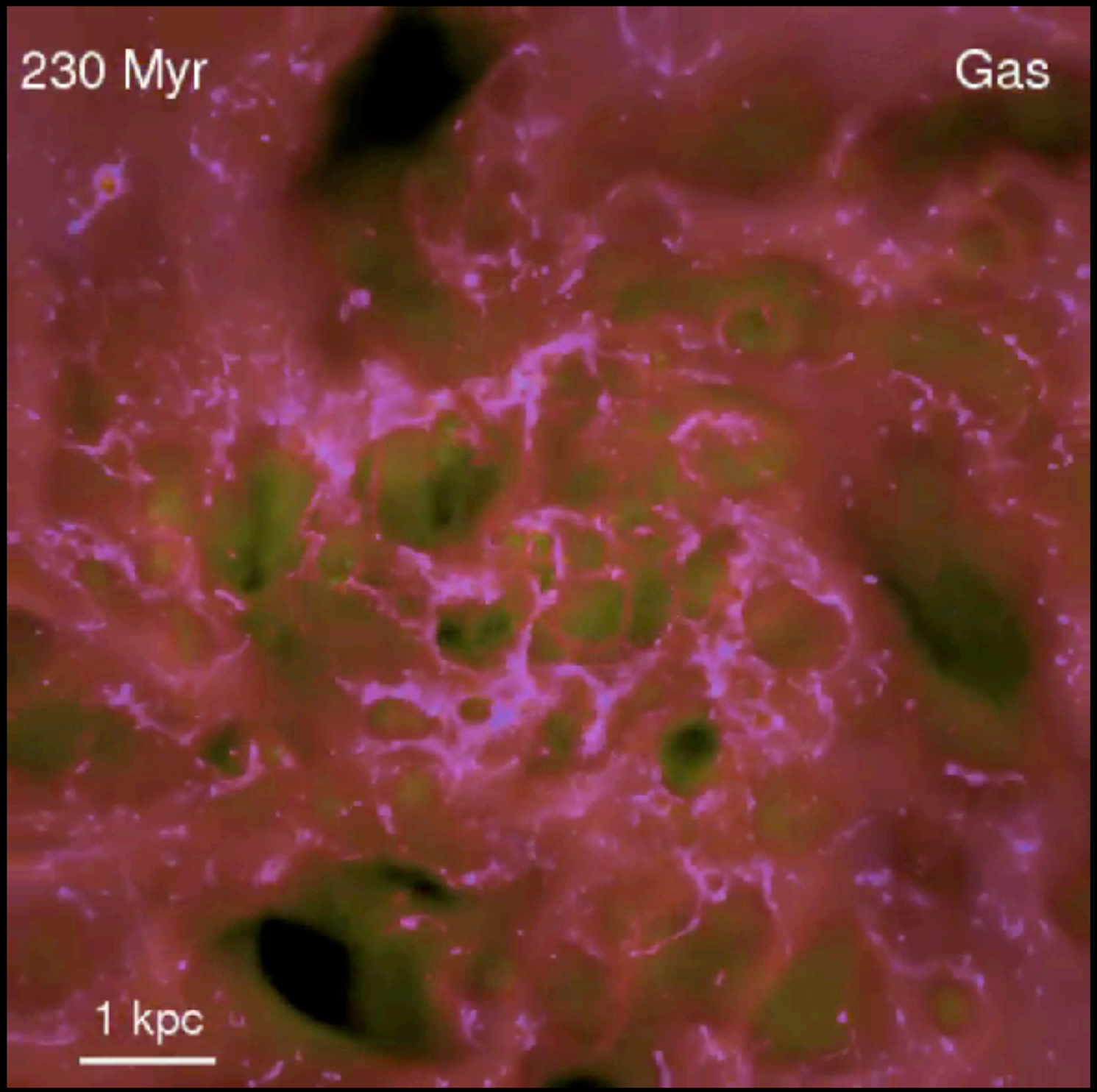

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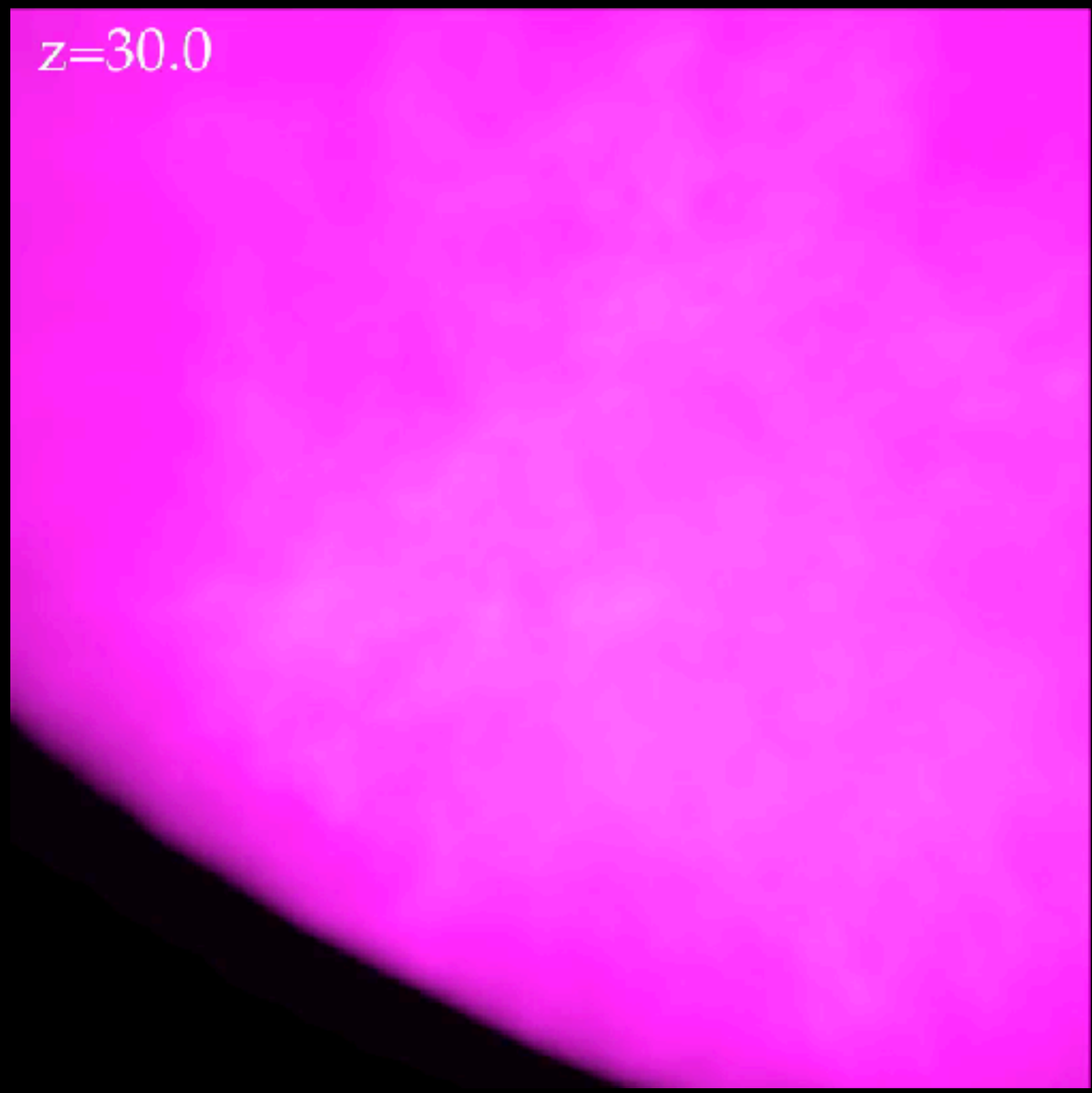
(movies at fire.northwestern.edu)

z=30.0

10 kpc



Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

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

Green: warm (ionized)

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

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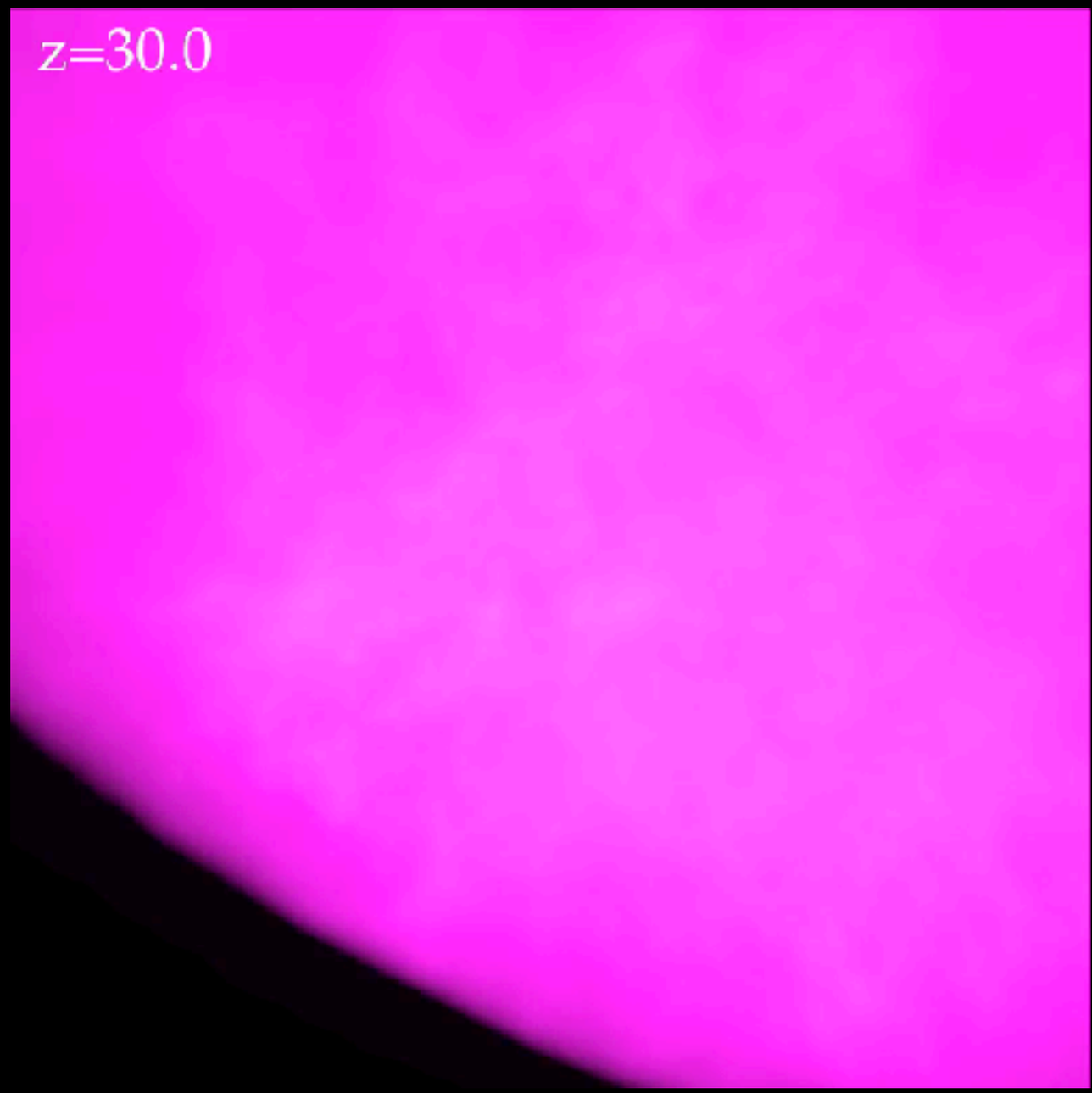

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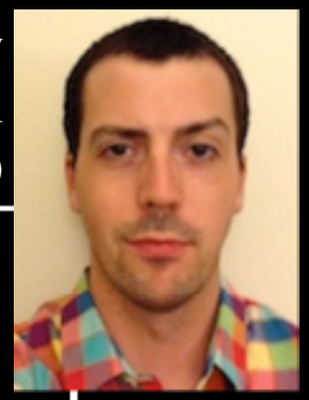
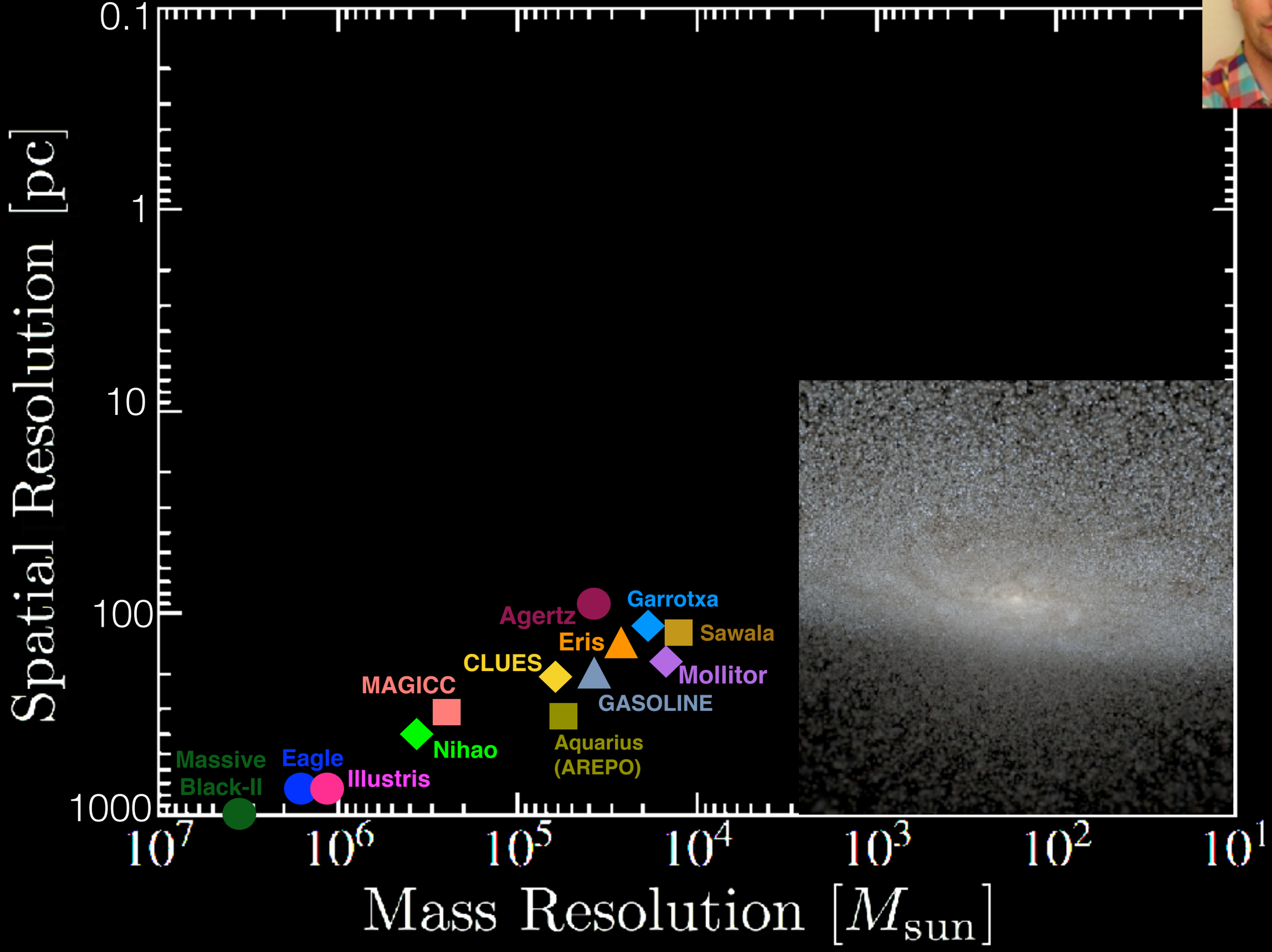
The Future is Now

ALGORITHMIC BREAKTHROUGHS ENABLE NEW PHYSICS

Andrew Wetzel (arXiv:1602.05957)





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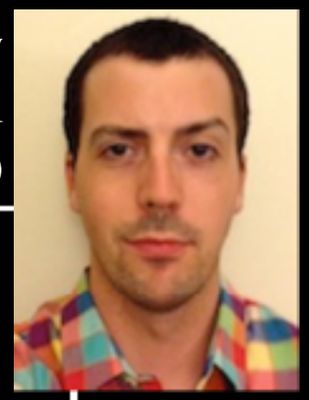

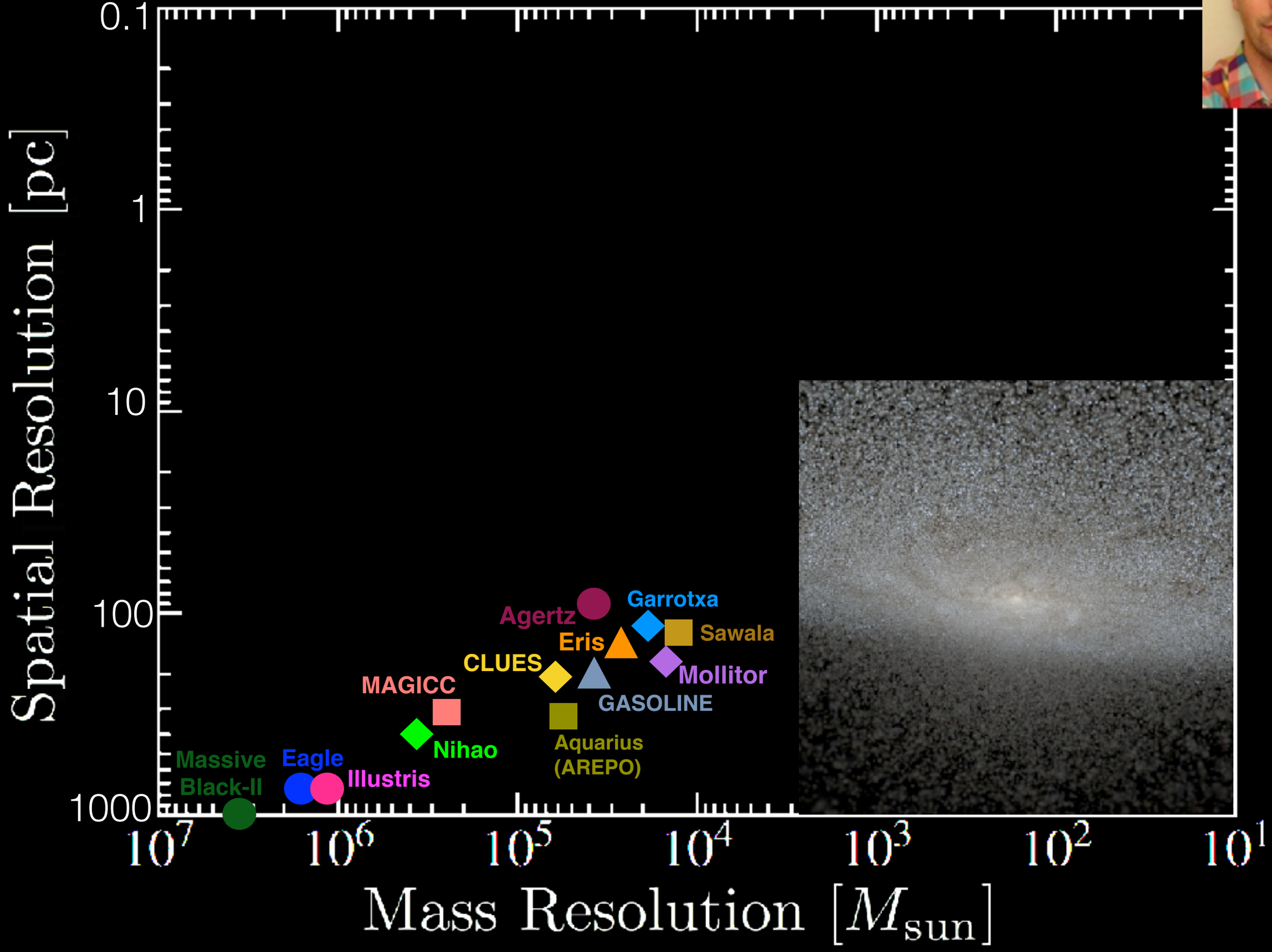

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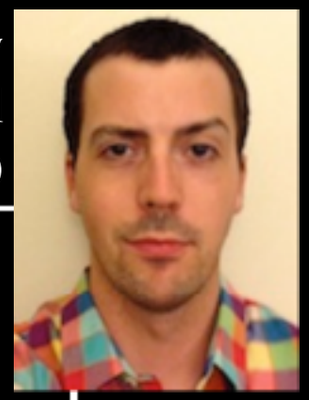

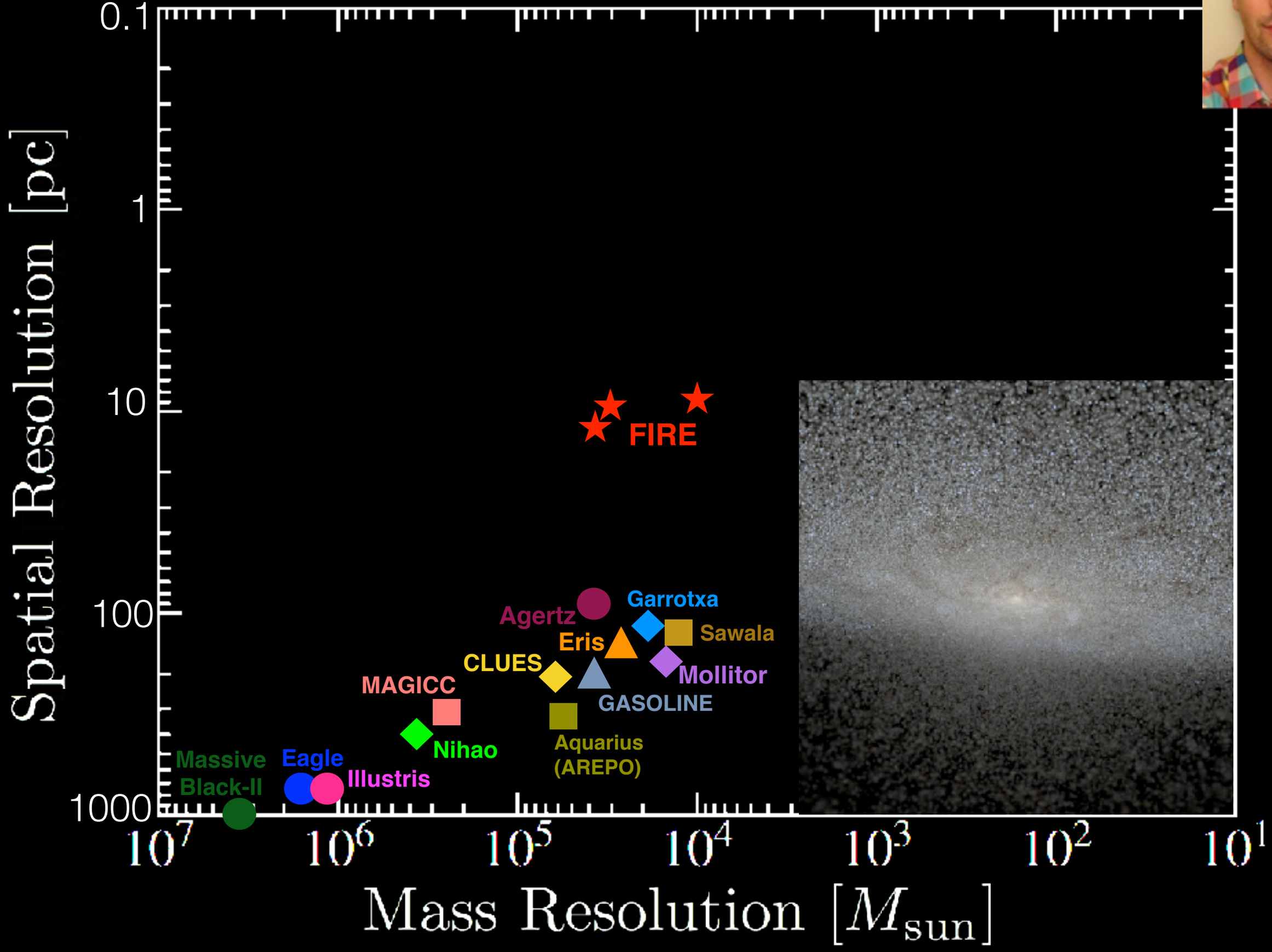

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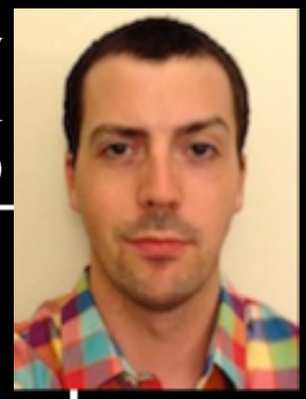

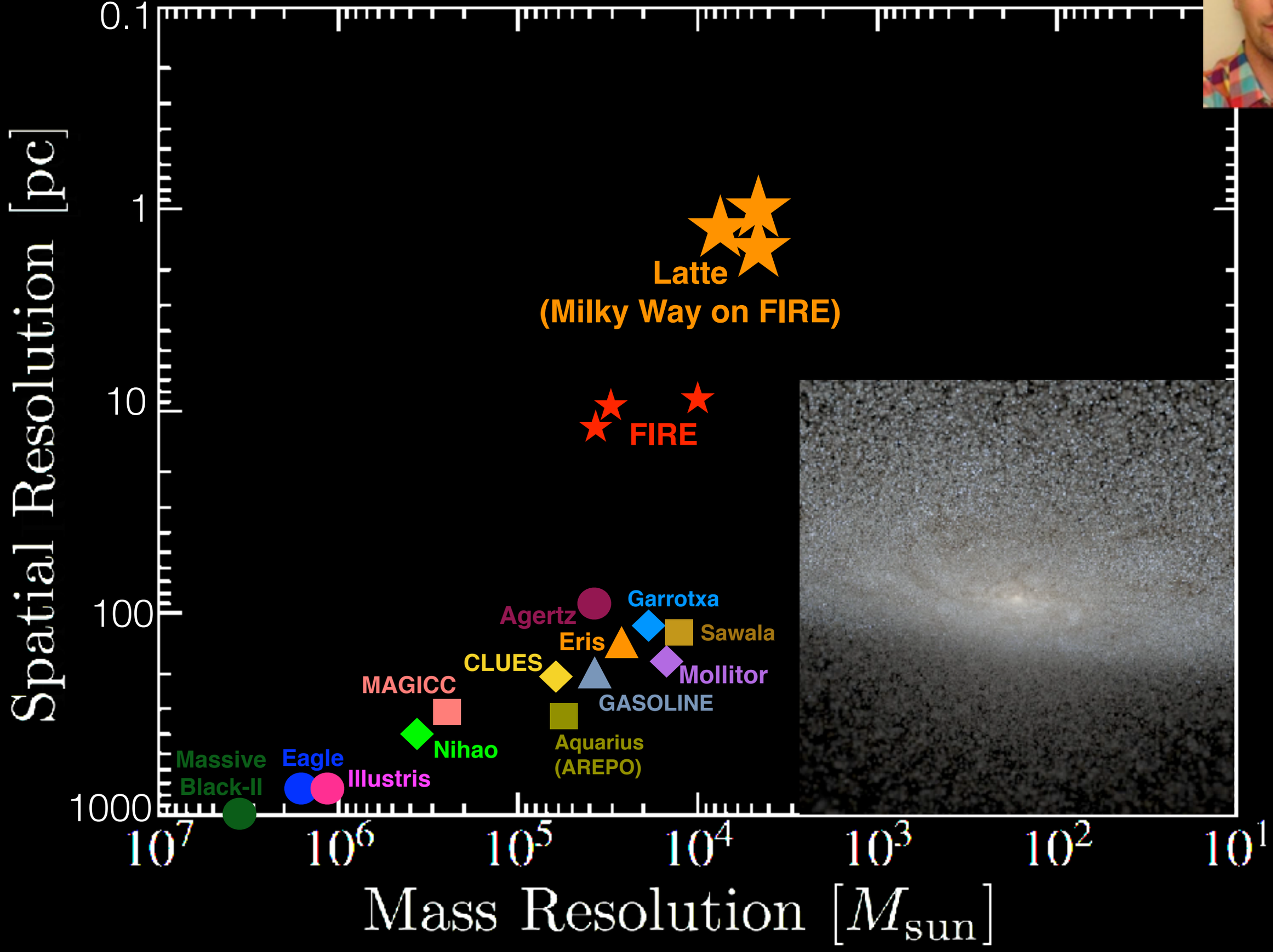

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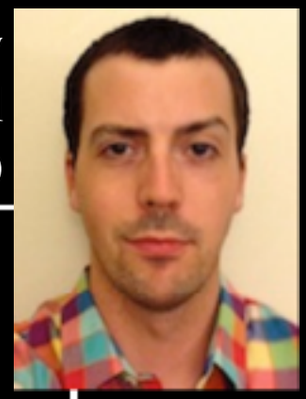

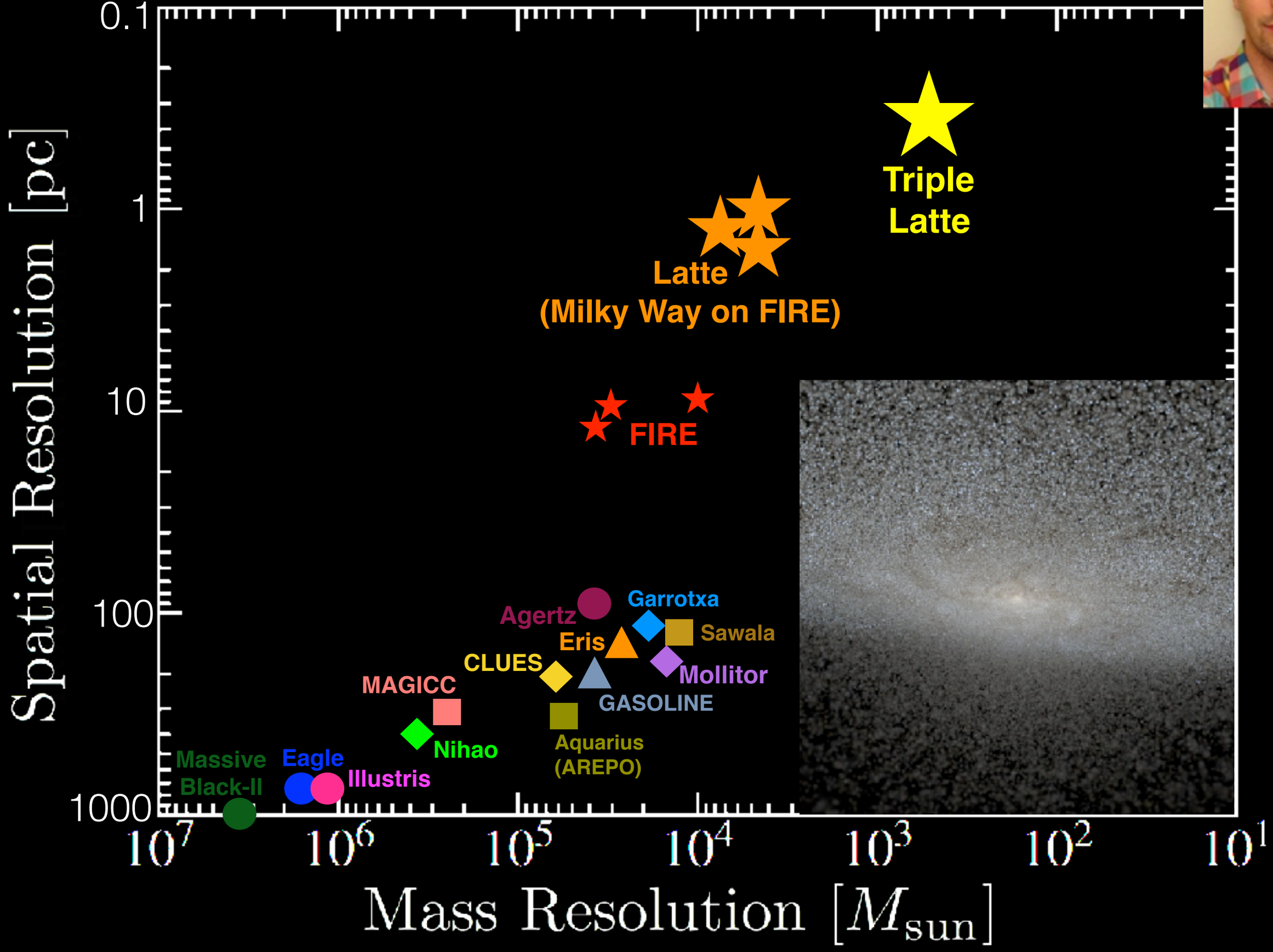

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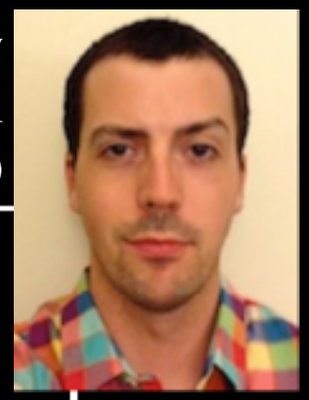
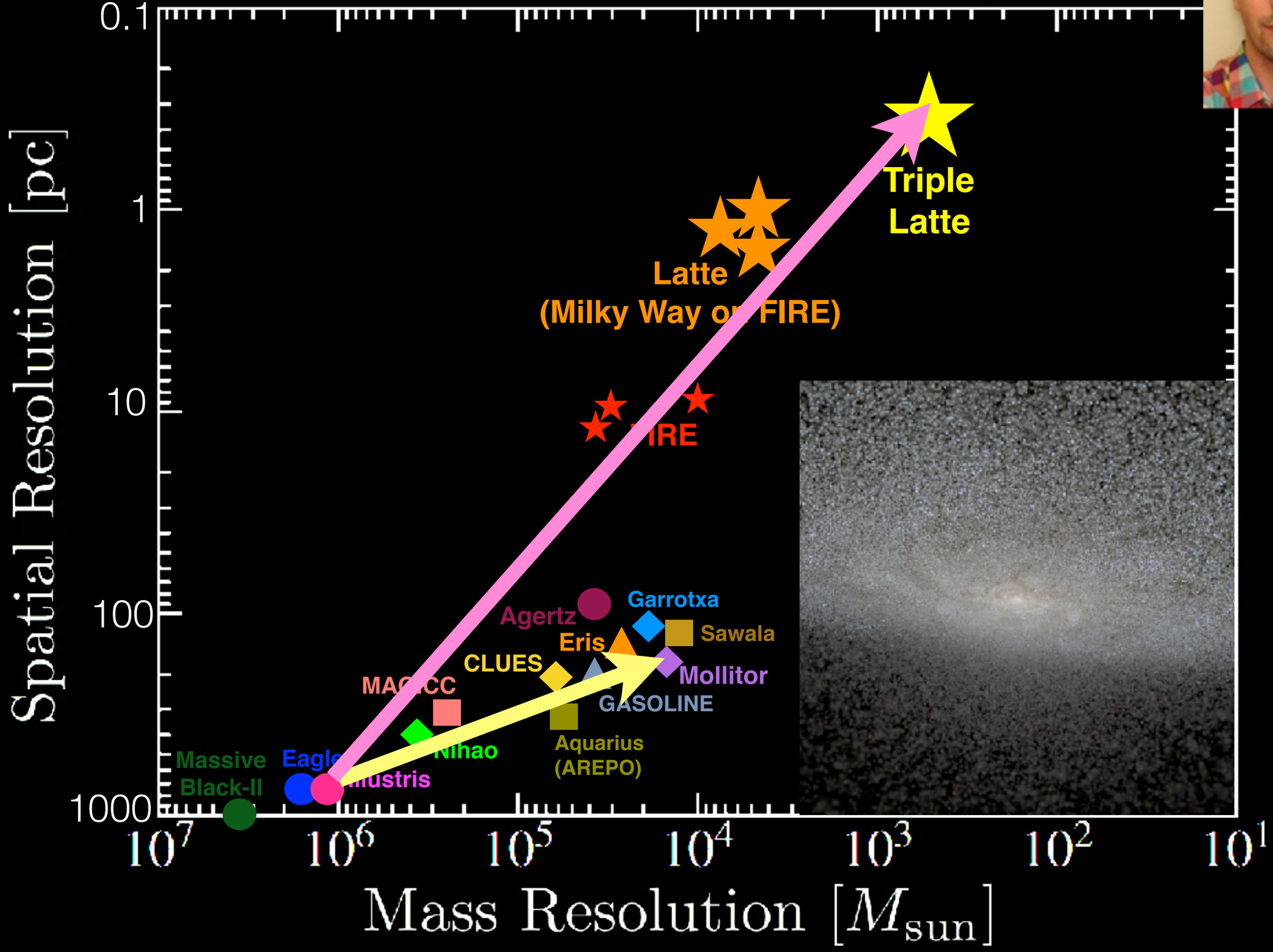
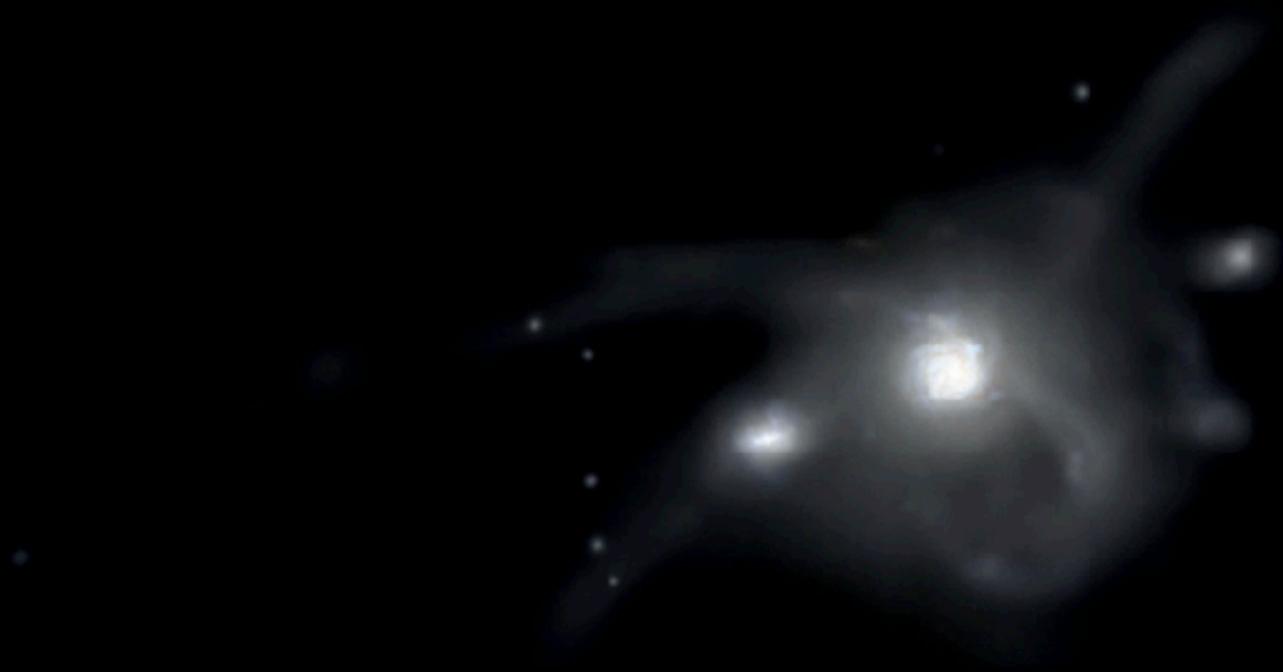
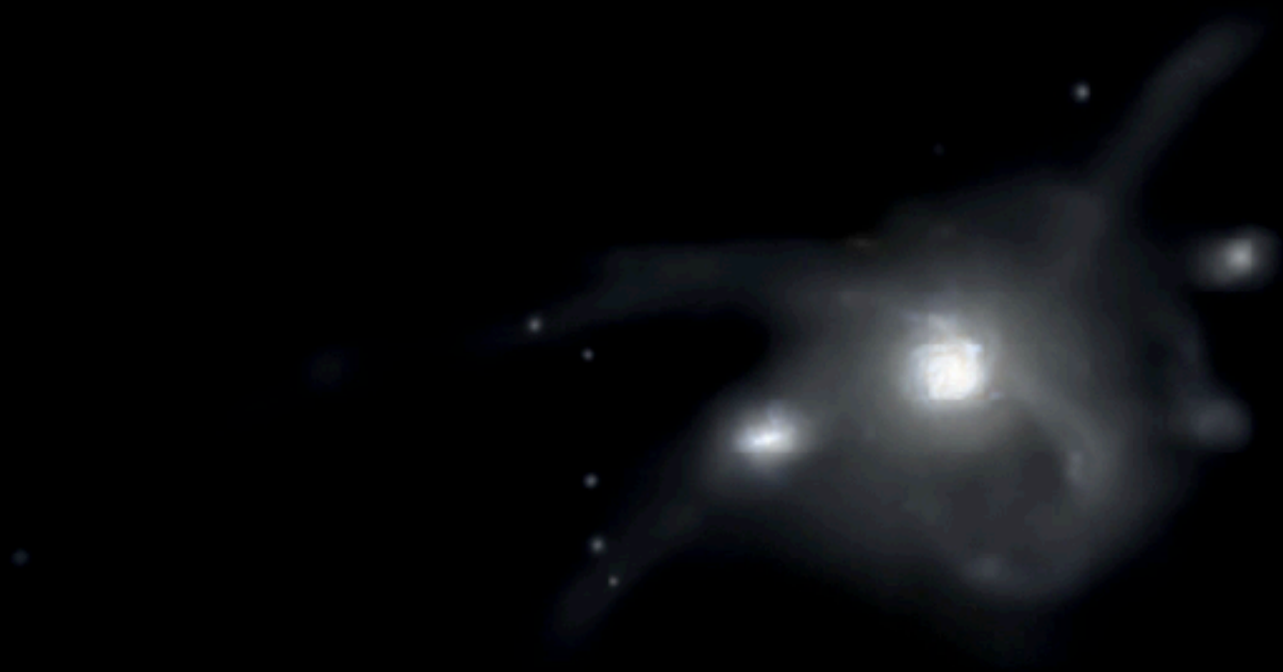
ALGORITHMIC BREAKTHROUGHS ENABLE NEW PHYSICS

Andrew Wetzel (arXiv:1602.05957)







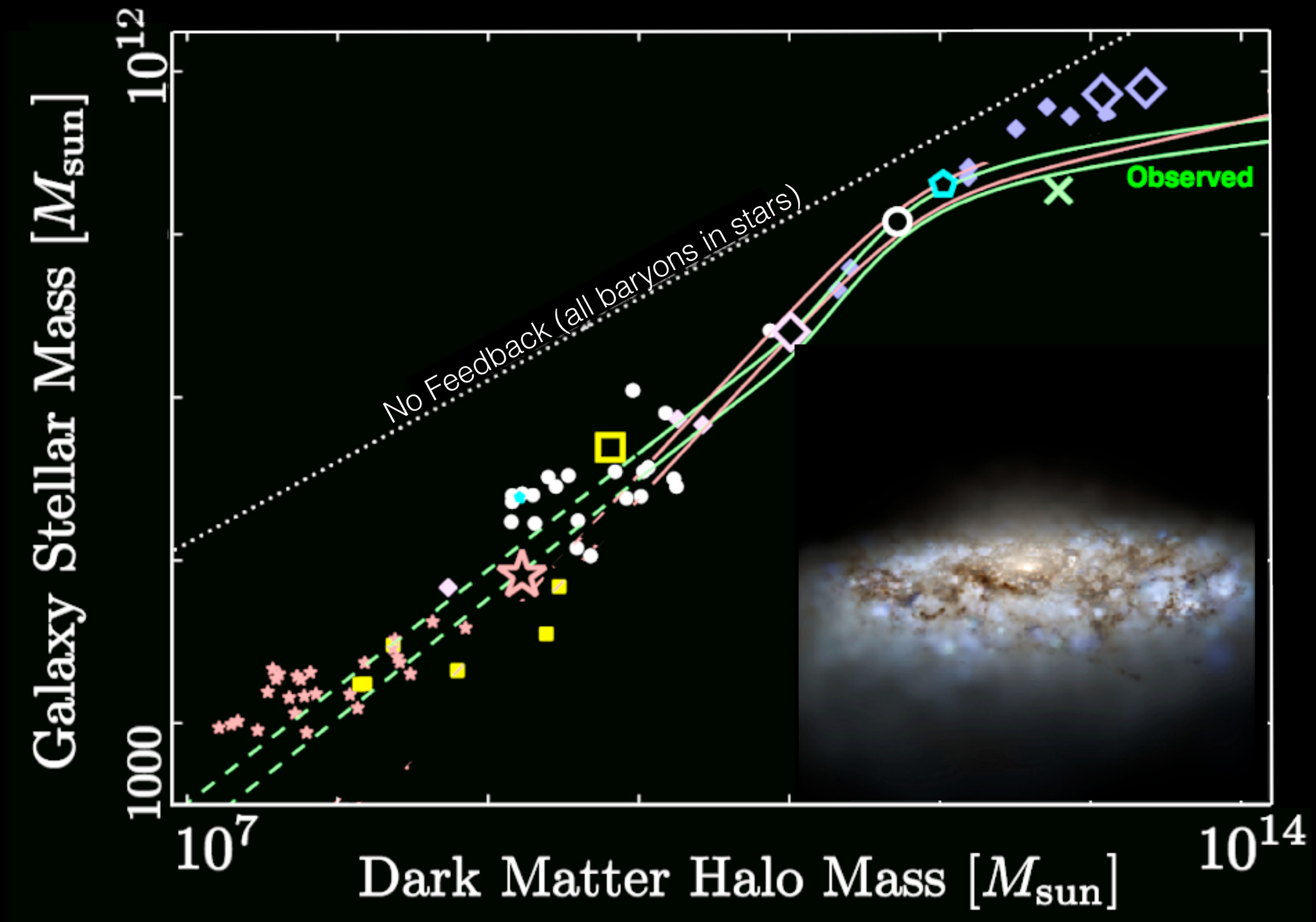


It Works!

Why Are Galaxies Such Lightweights?

GAS IS BLOWN OUT, INSTEAD OF TURNING INTO STARS

PFH et al.
(arXiv:1311.2073)



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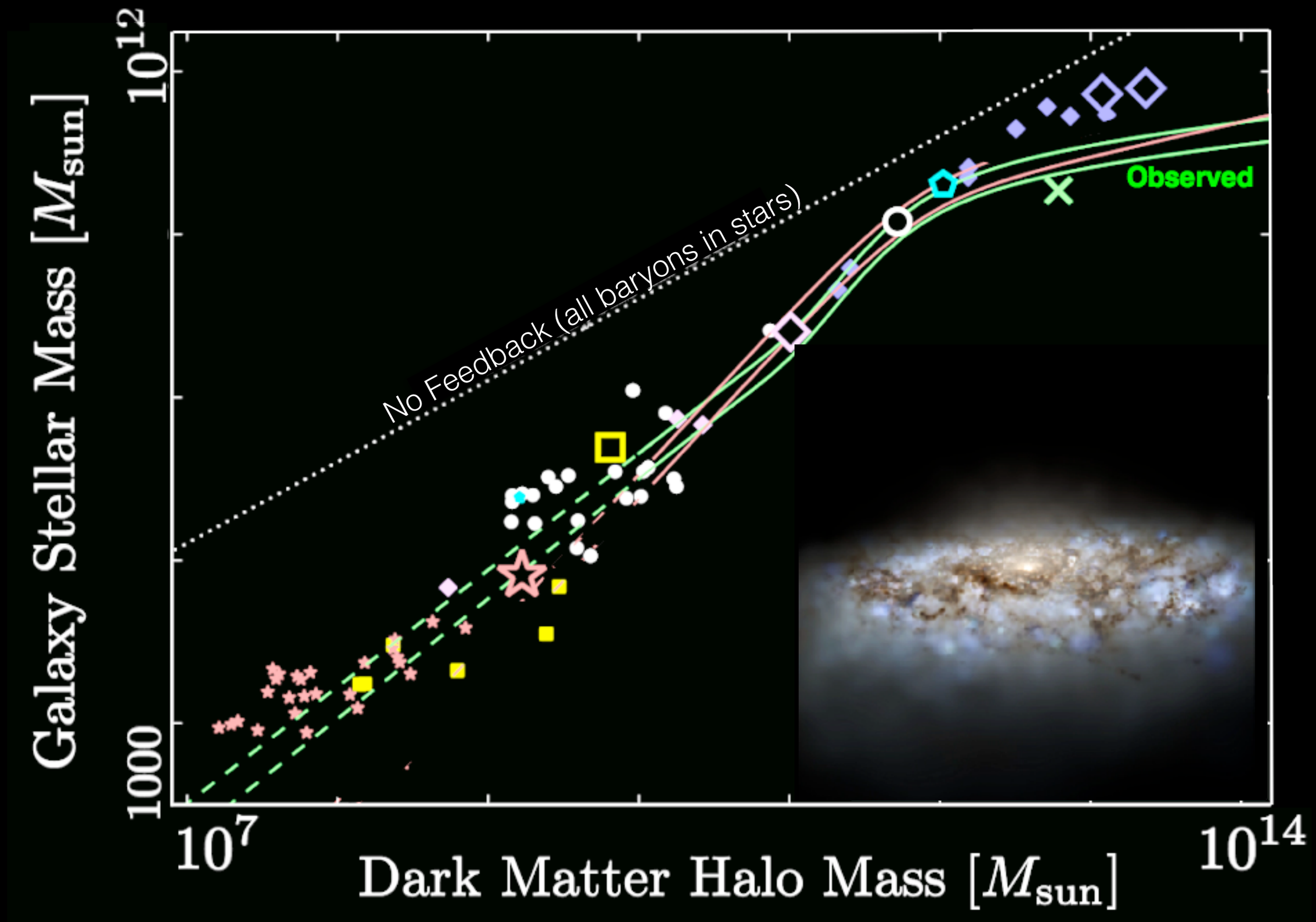


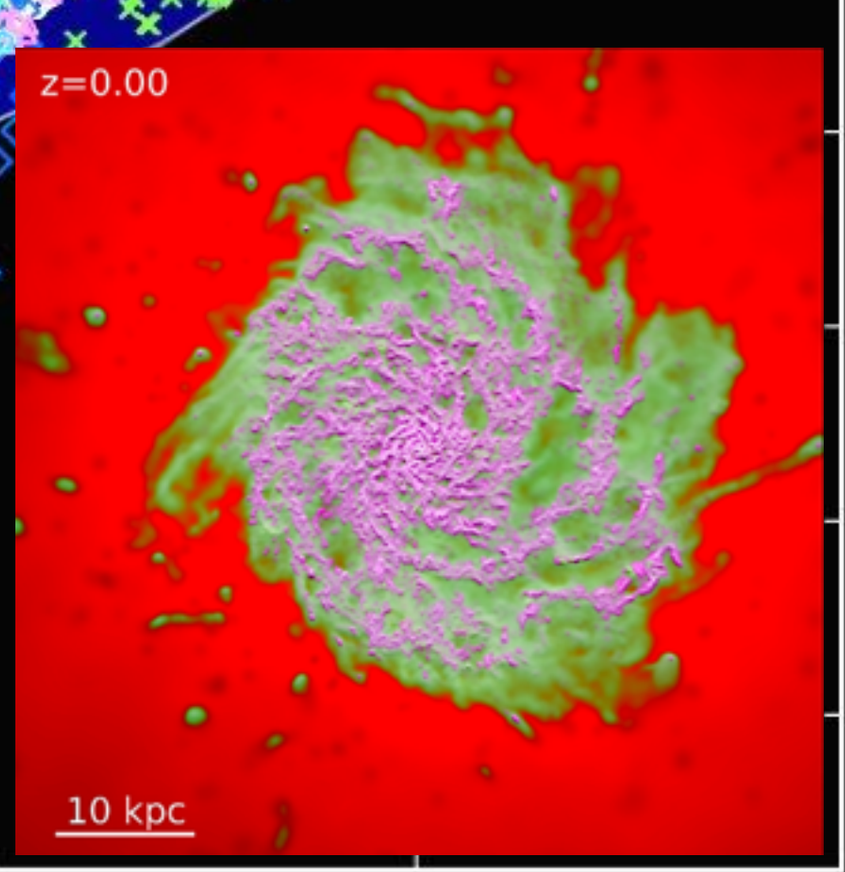
The KS Law is *Predicted*, Naturally, by Feedback

TOTALLY INDEPENDENT OF "SUB-GRID" SF MODEL

Matt Orr (in prep)
Hopkins+ 11,12,14
Agertz+14

No Feedback

Observed



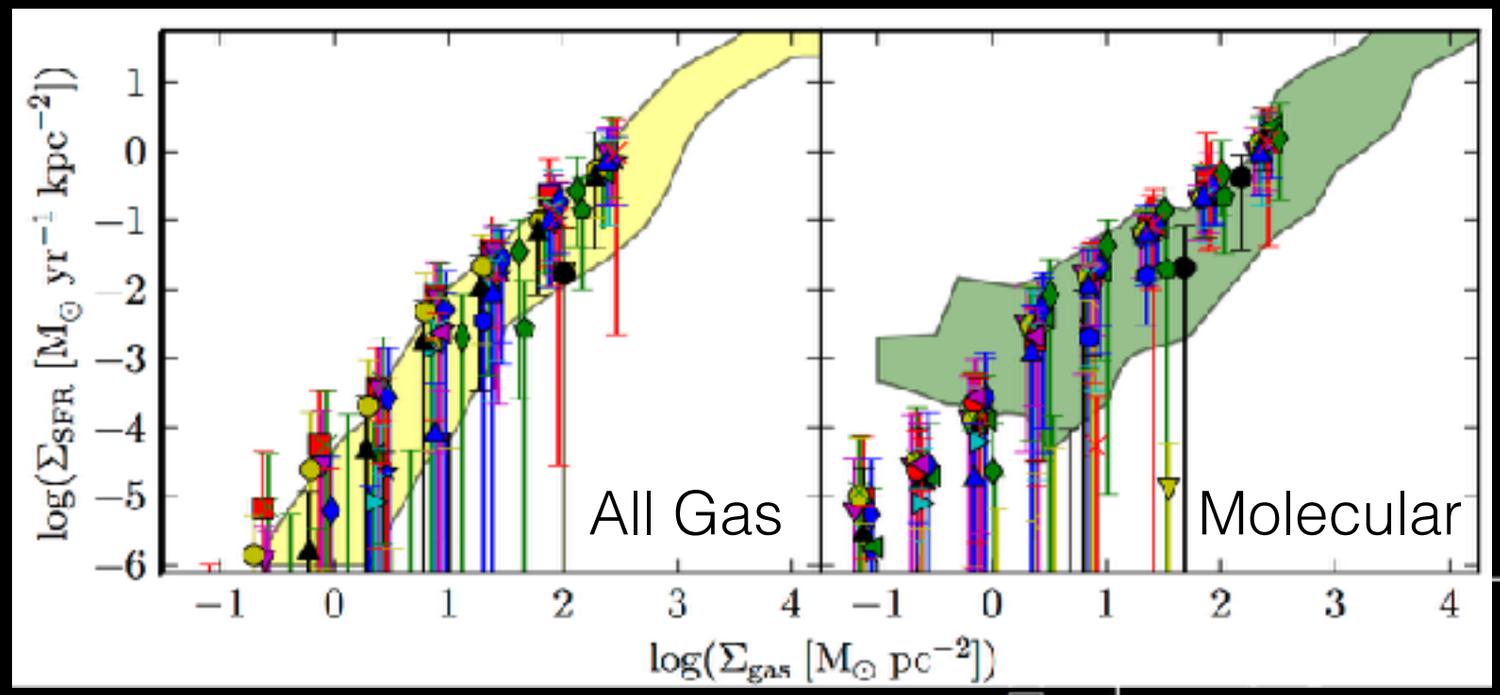
$\log(\Sigma_{\rm SFR})$ [$M_\odot$ yr^{-1} kpc^{-2}]

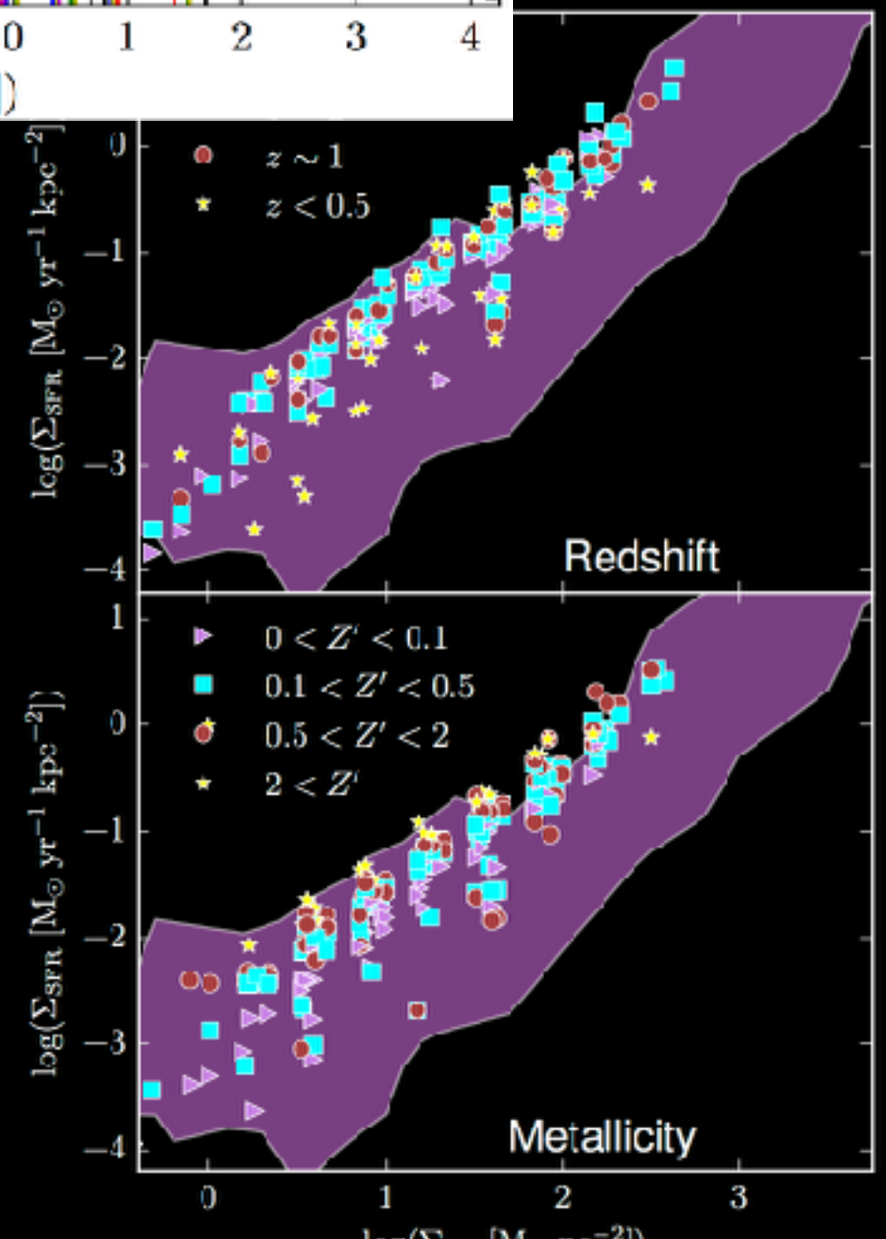
$\log(\Sigma_{\rm gas})$ [$M_\odot$ pc^{-2}]

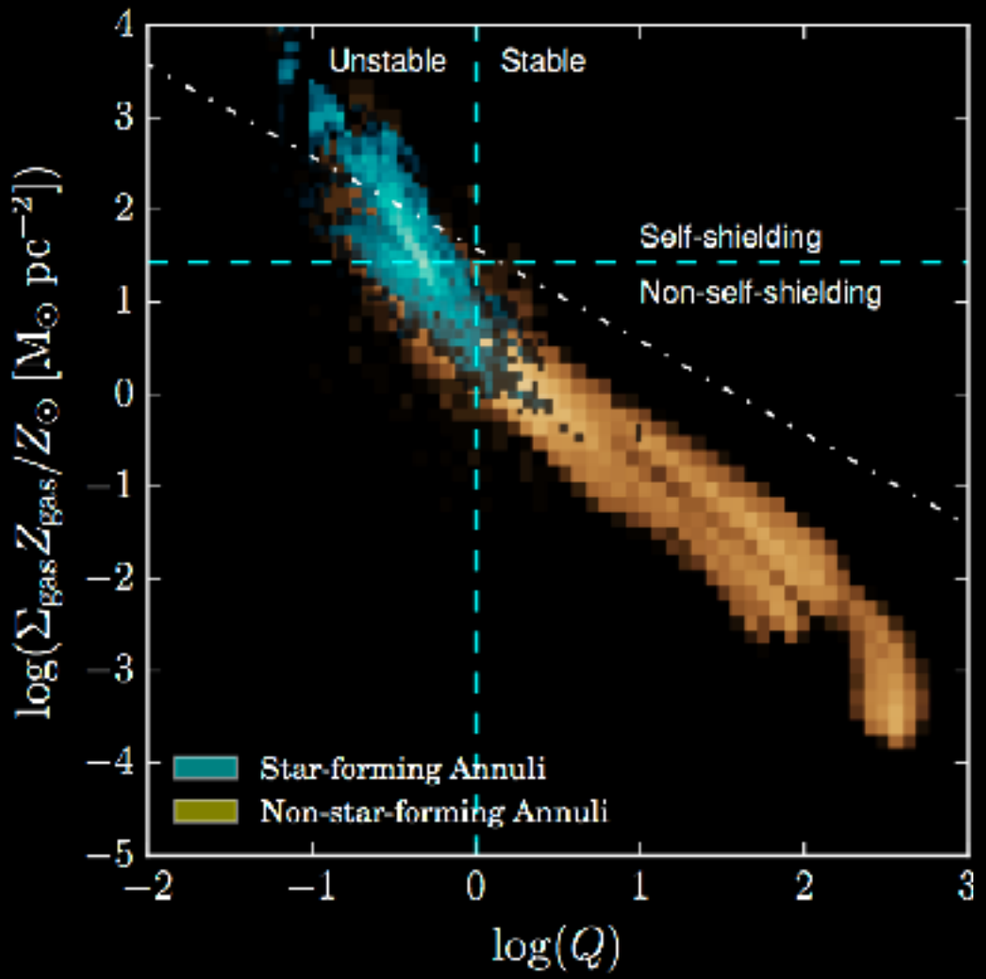
2
1
0
−1
−2
−3
−4
−5
0
1
2
3
4

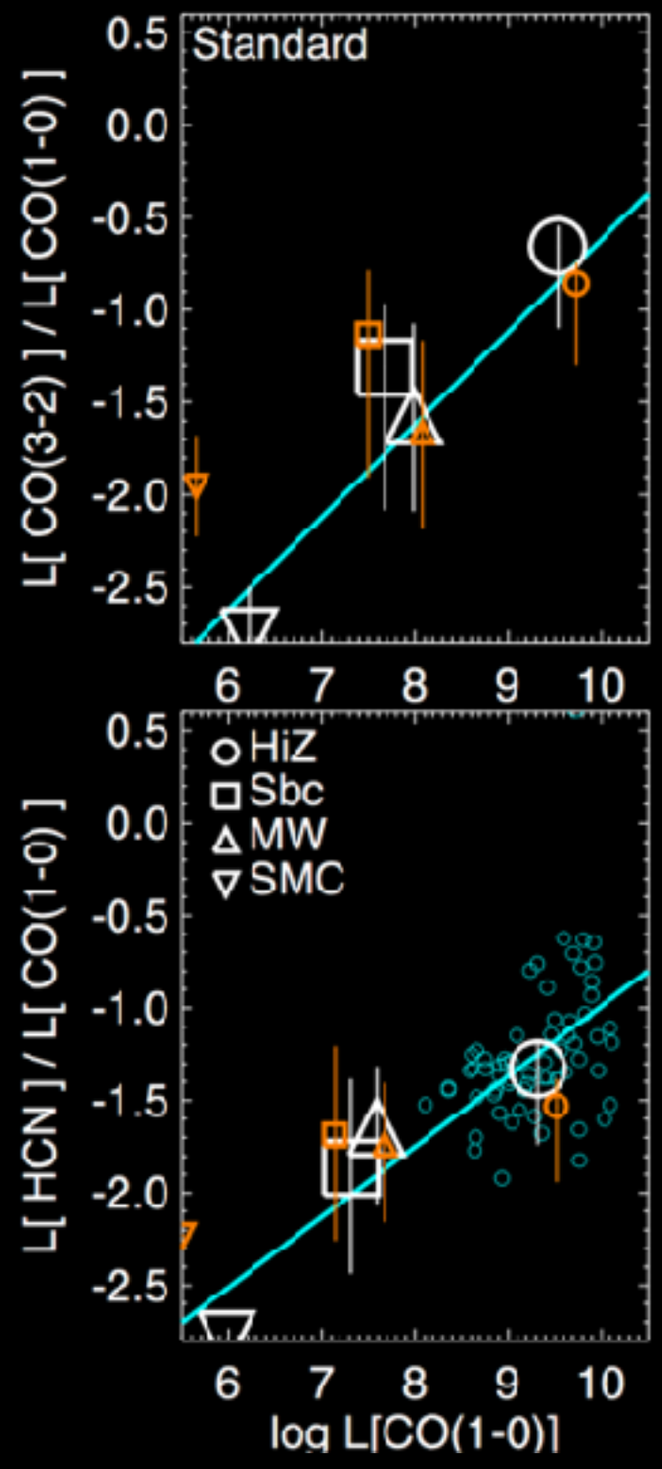
The KS Law: It's Feedback.

Matt Orr (in prep)
Hopkins+ 11,12,14



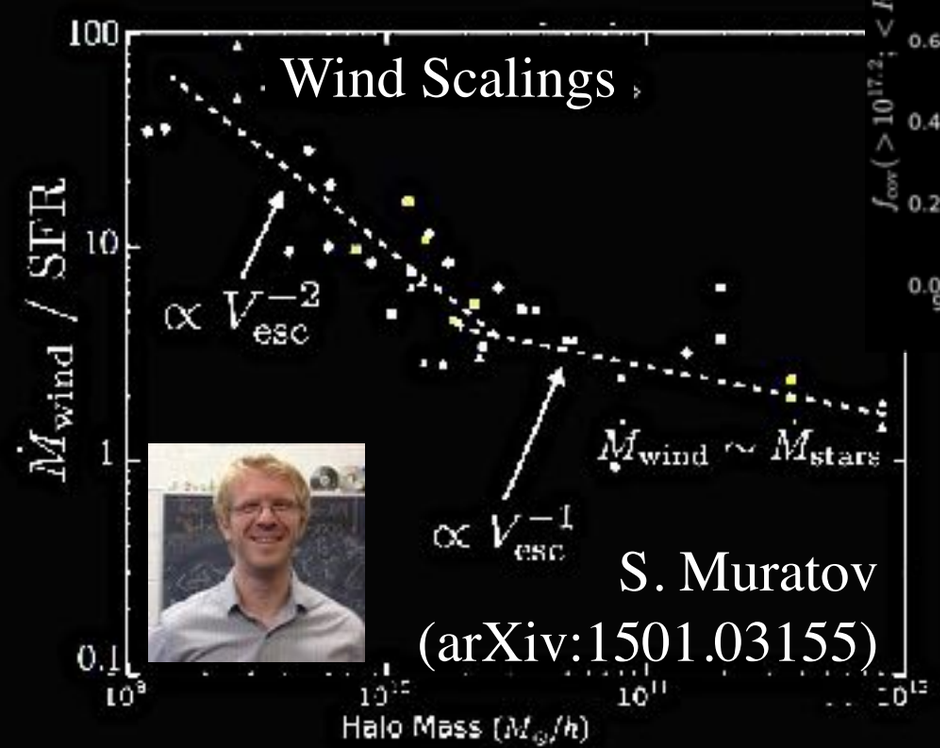






Galaxy Scaling Relations:

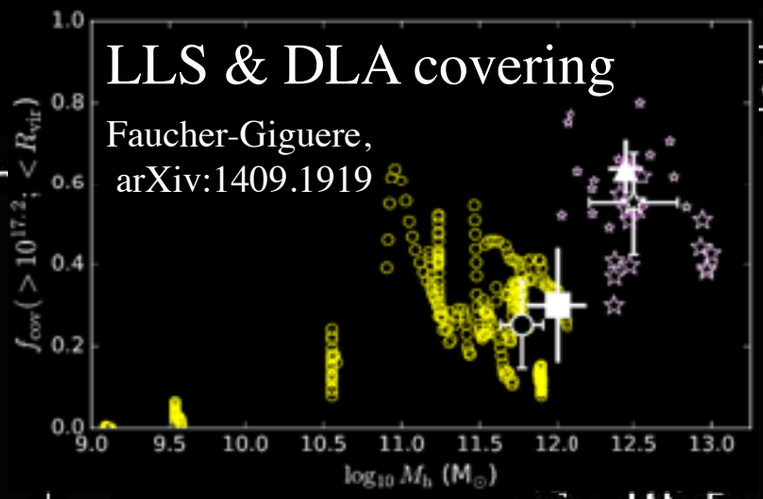
Wind Scalings



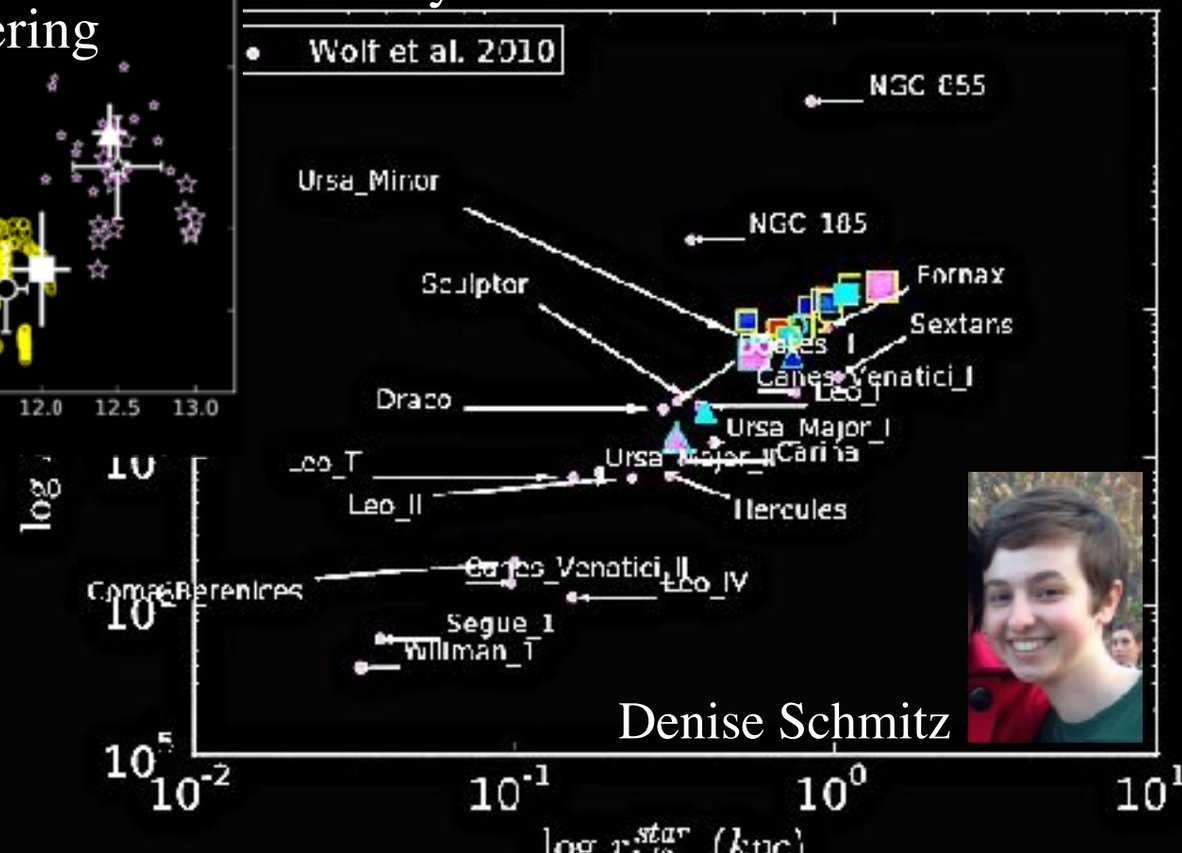
S. Muratov
(arXiv:1501.03155)

LLS & DLA covering

Faucher-Giguere,
arXiv:1409.1919

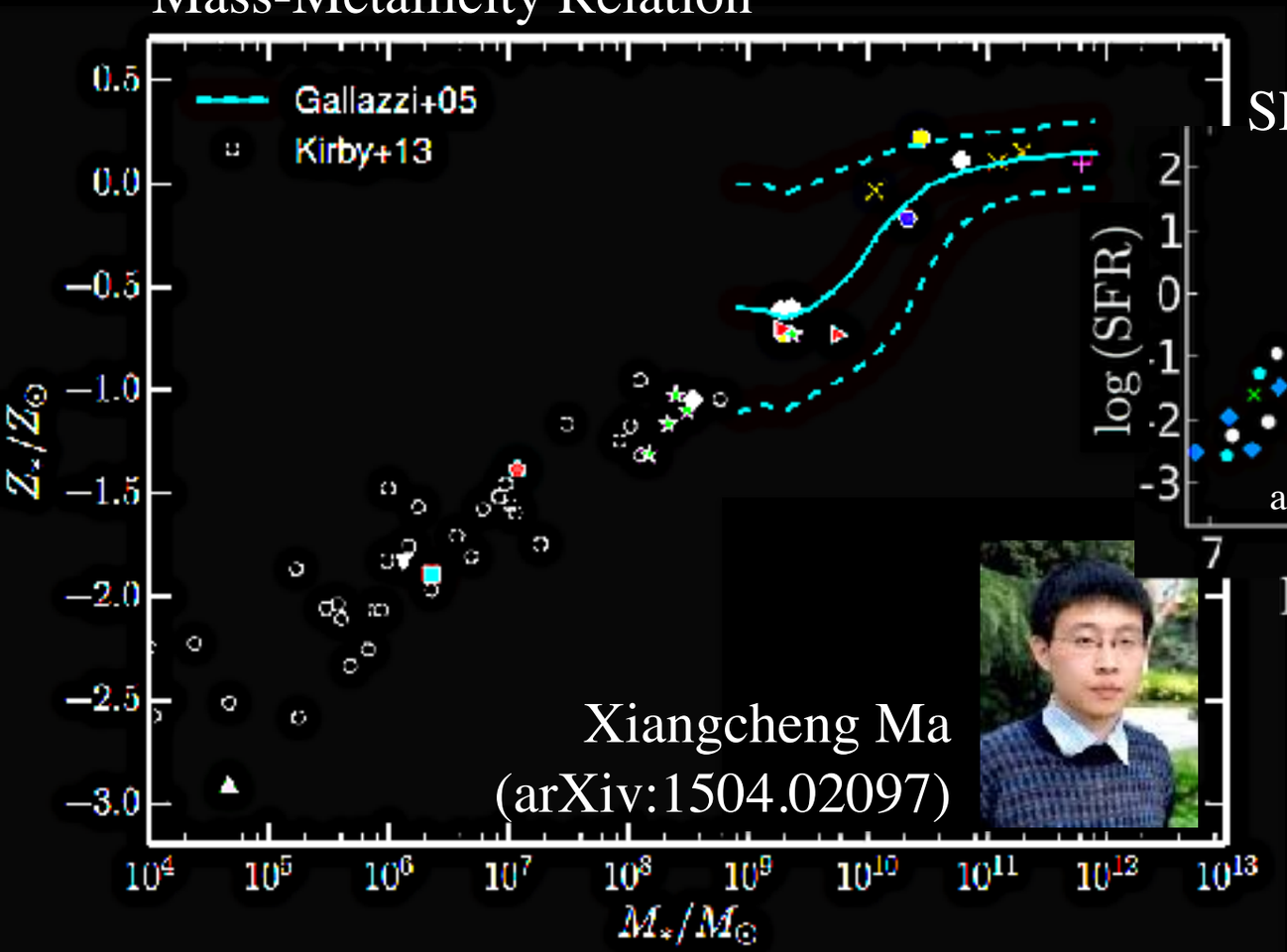


Tully-Fisher & Size-Mass Relation



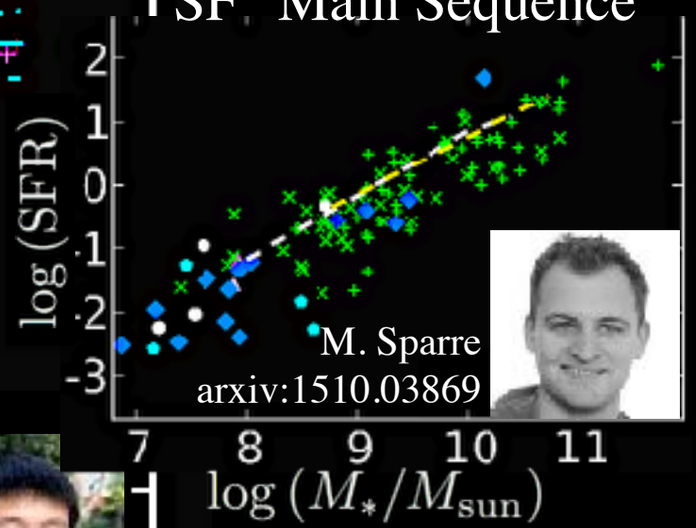
Denise Schmitz

Mass-Metallicity Relation



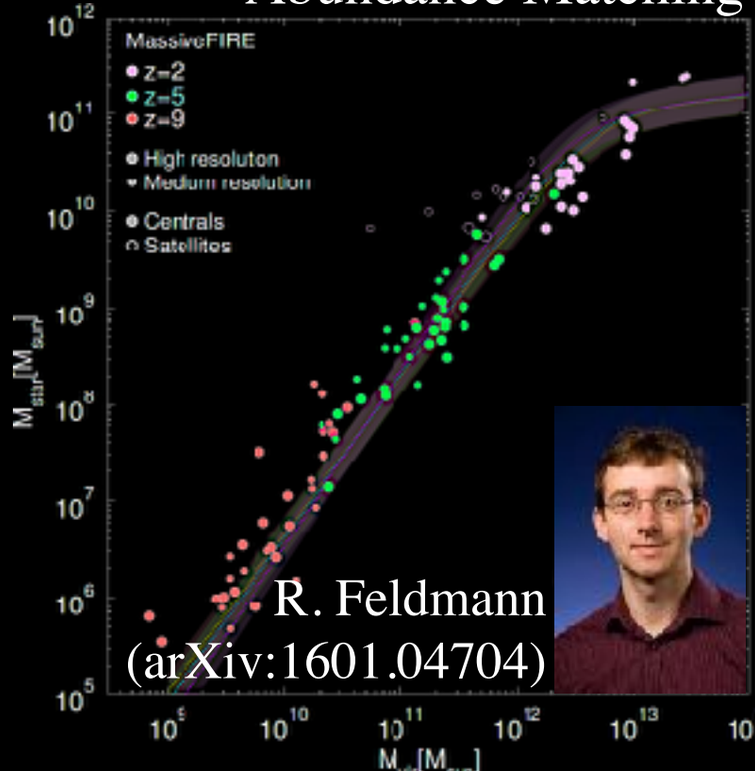
Xiangcheng Ma
(arXiv:1504.02097)

SF "Main Sequence"



M. Sparre
arxiv:1510.03869

Abundance Matching



R. Feldmann
(arXiv:1601.04704)

Sub-Grid is not Enough

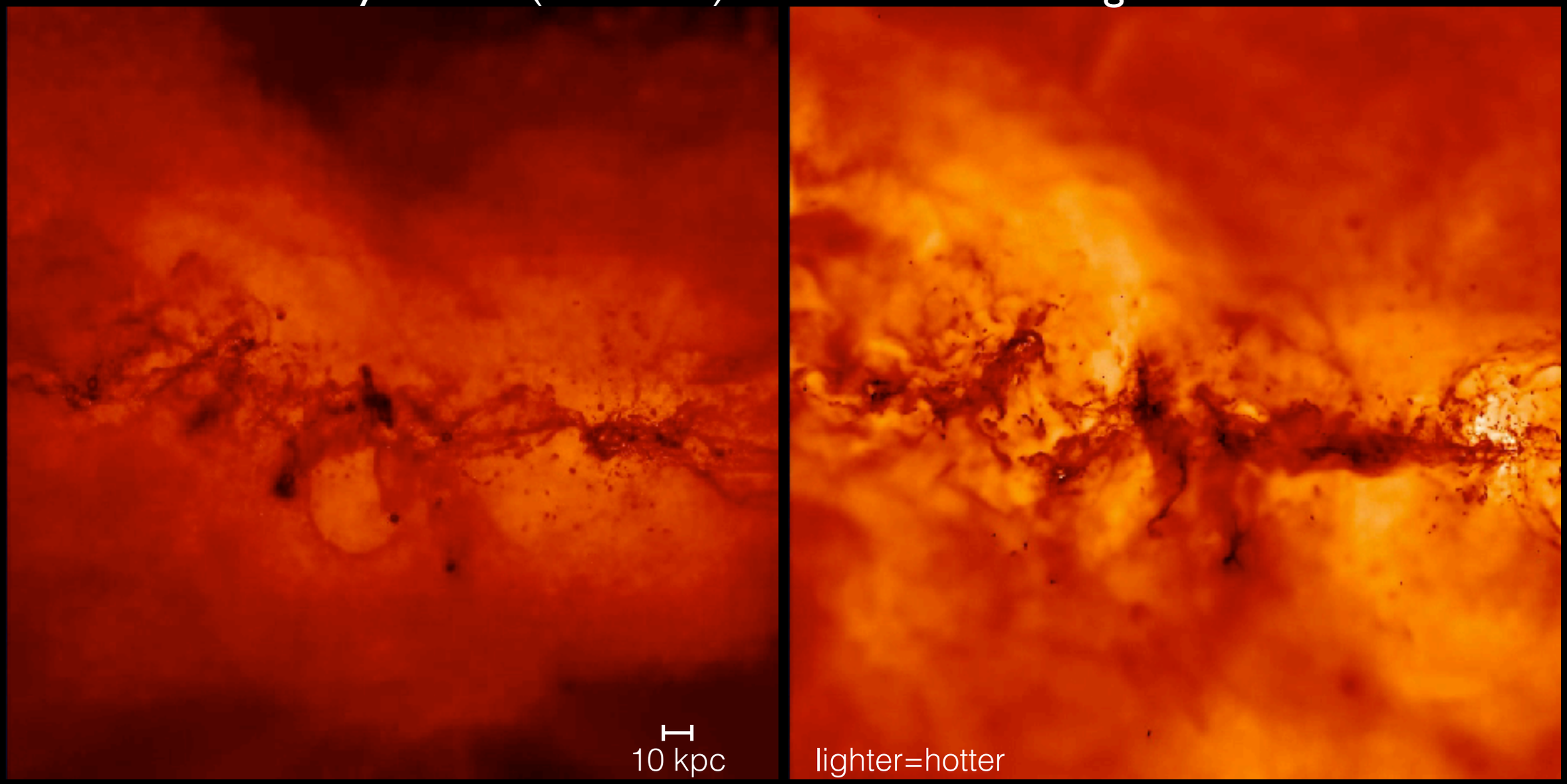
PHASE STRUCTURE & OUTFLOW DETAILS MATTER

PFH '14
M. Sparre
arxiv:1510.03869

Proto-Milky Way: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)

Following Full Feedback



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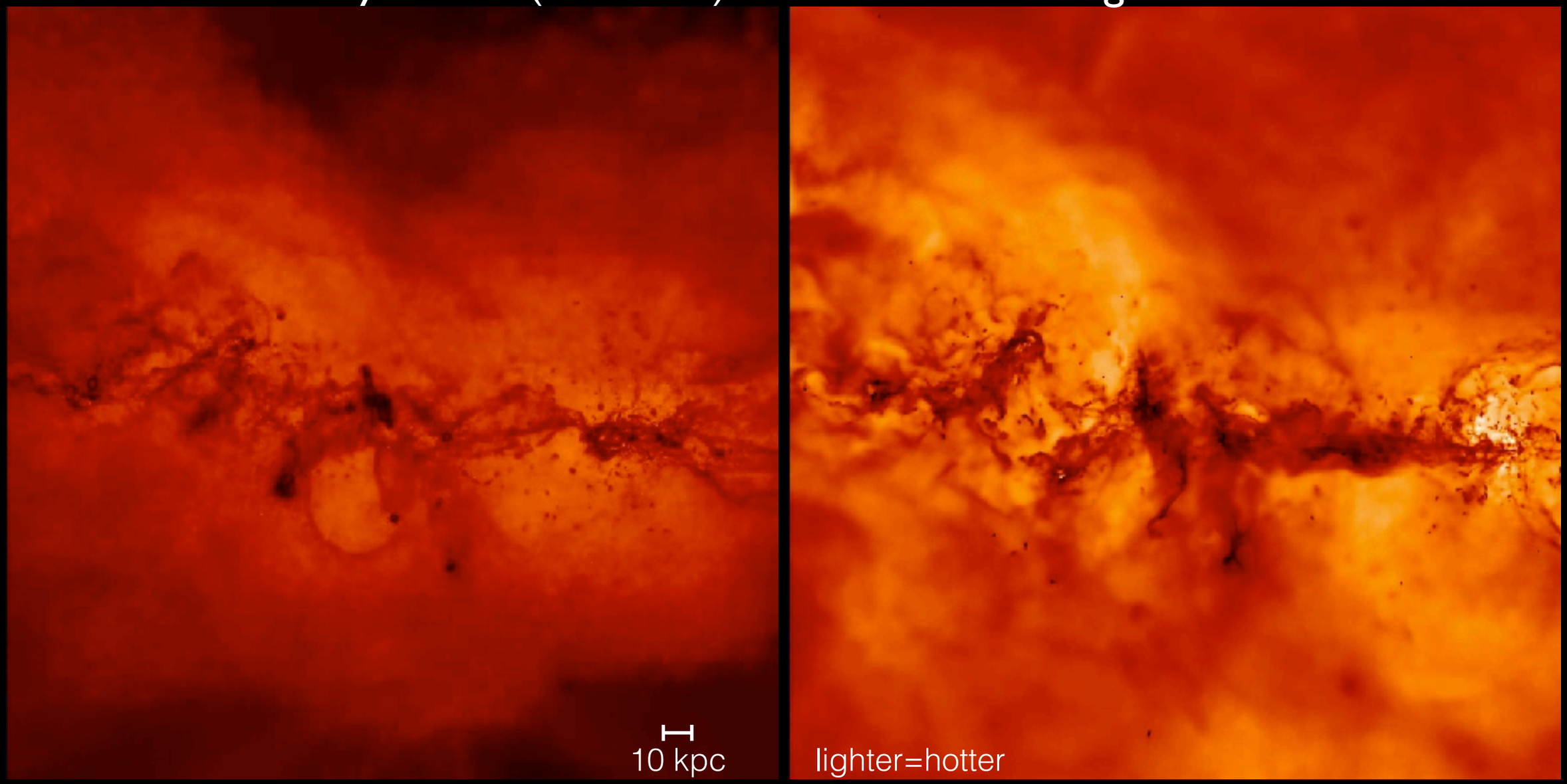

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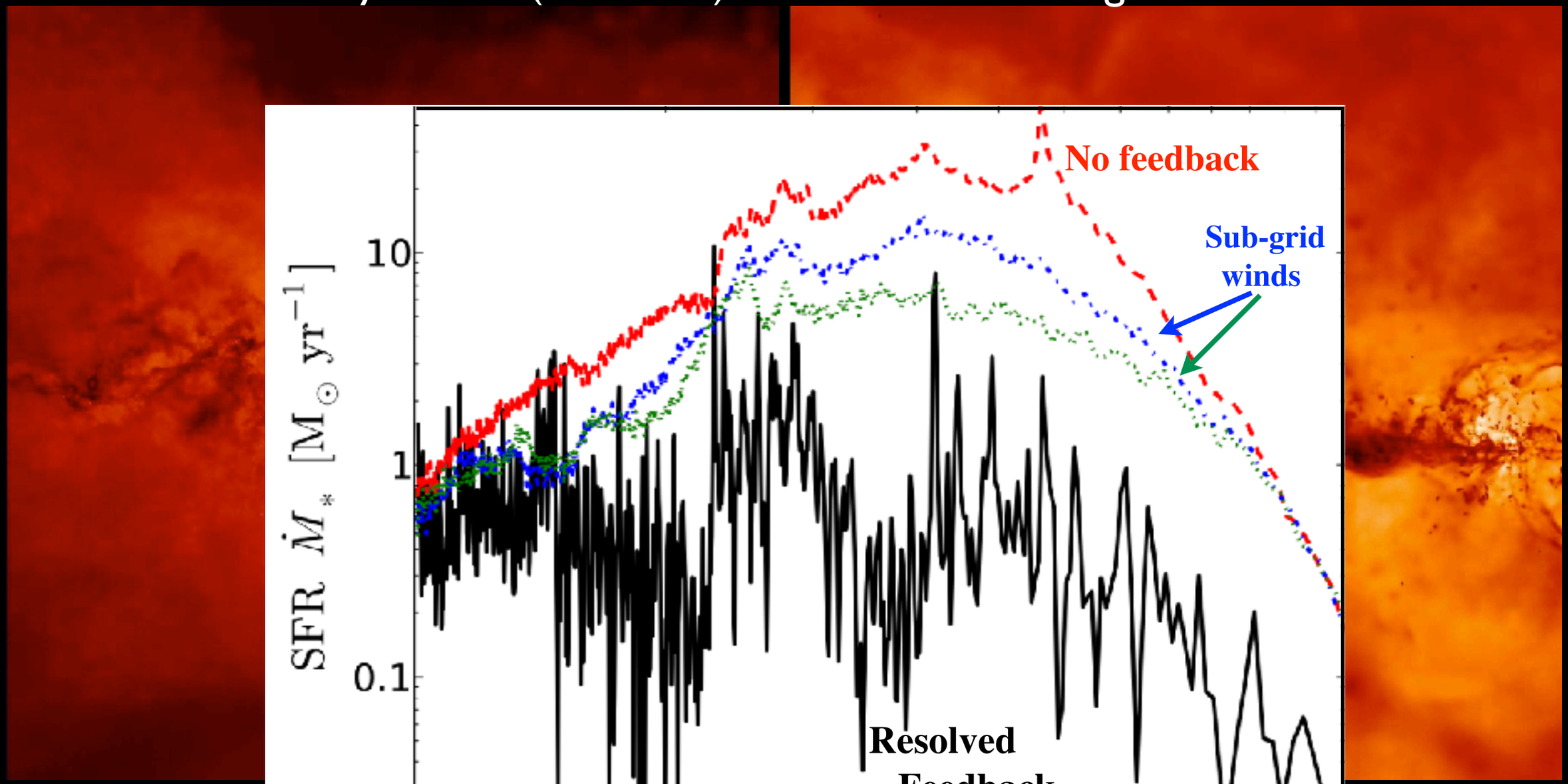
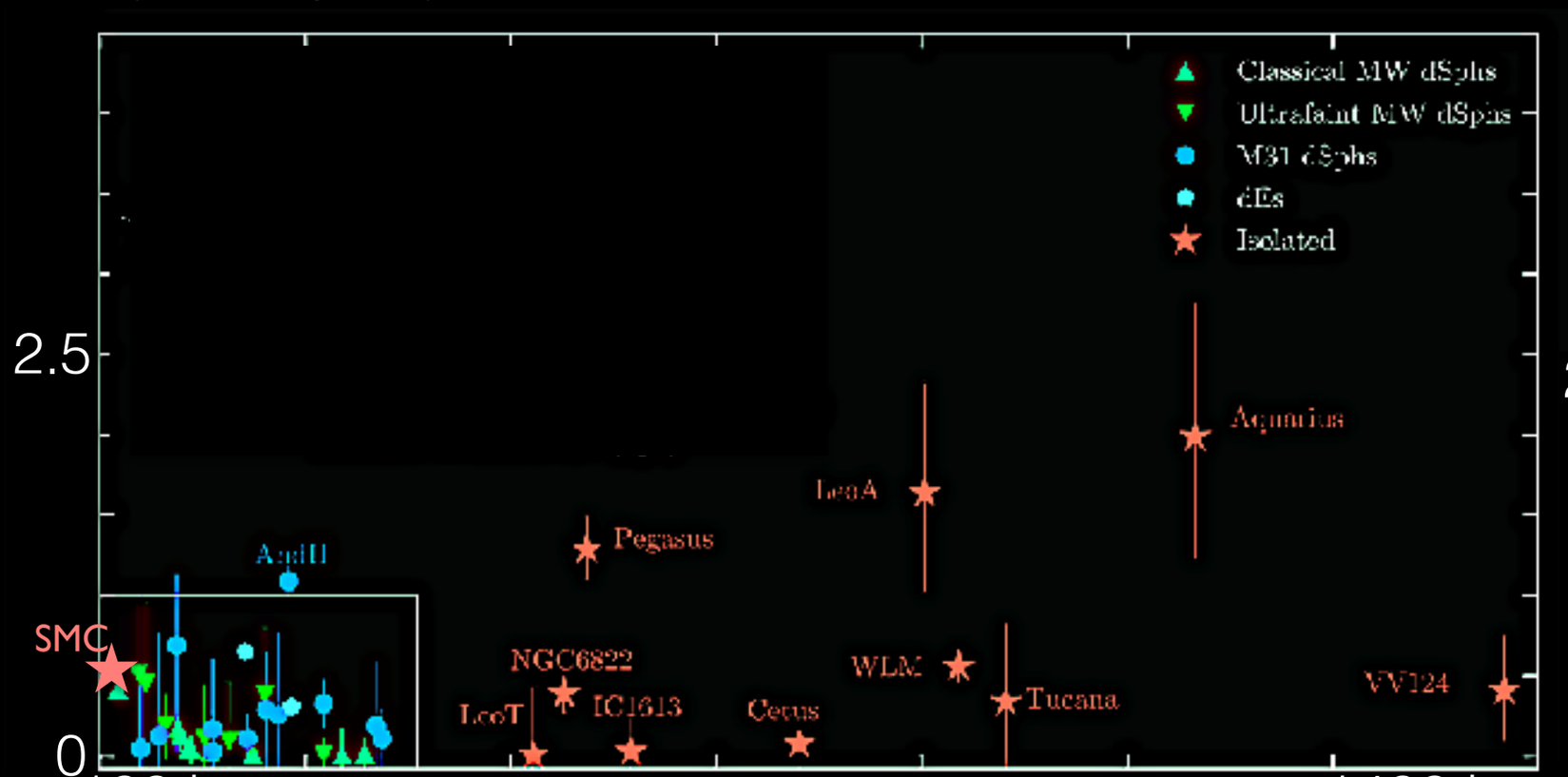


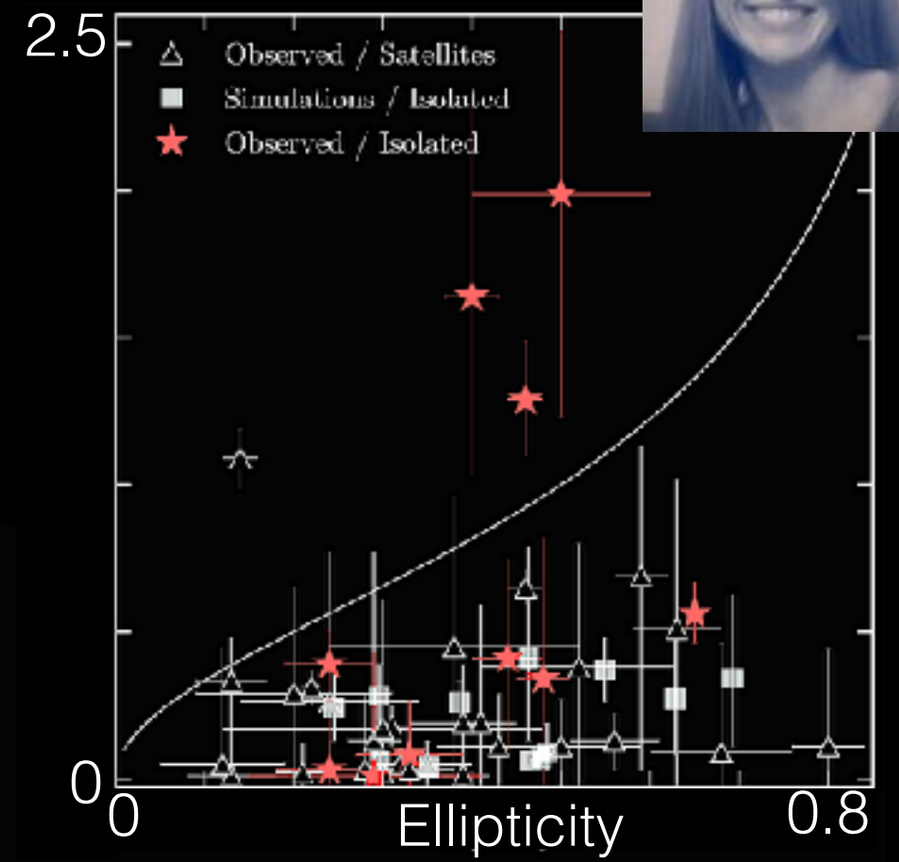
"Stirring" By Feedback = Most Dwarfs Don't Rotate

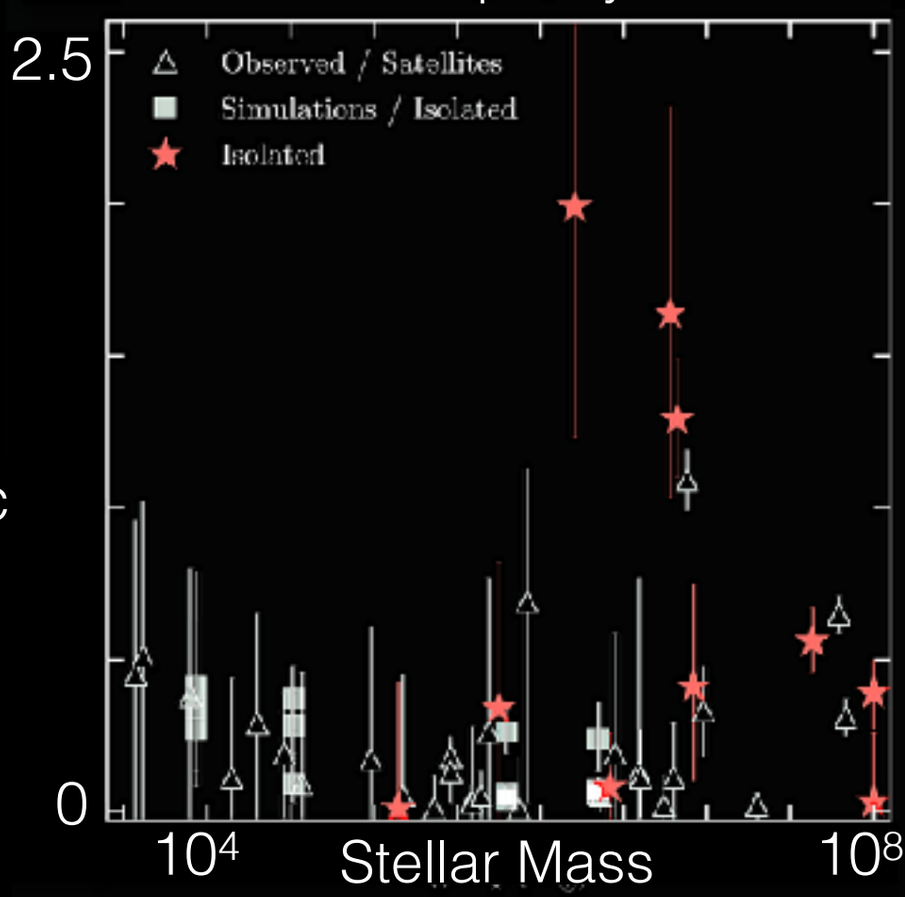
OBSERVED+SIMULATED dIrr/dSph

C. Wheeler
arXiv:1504.02466

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

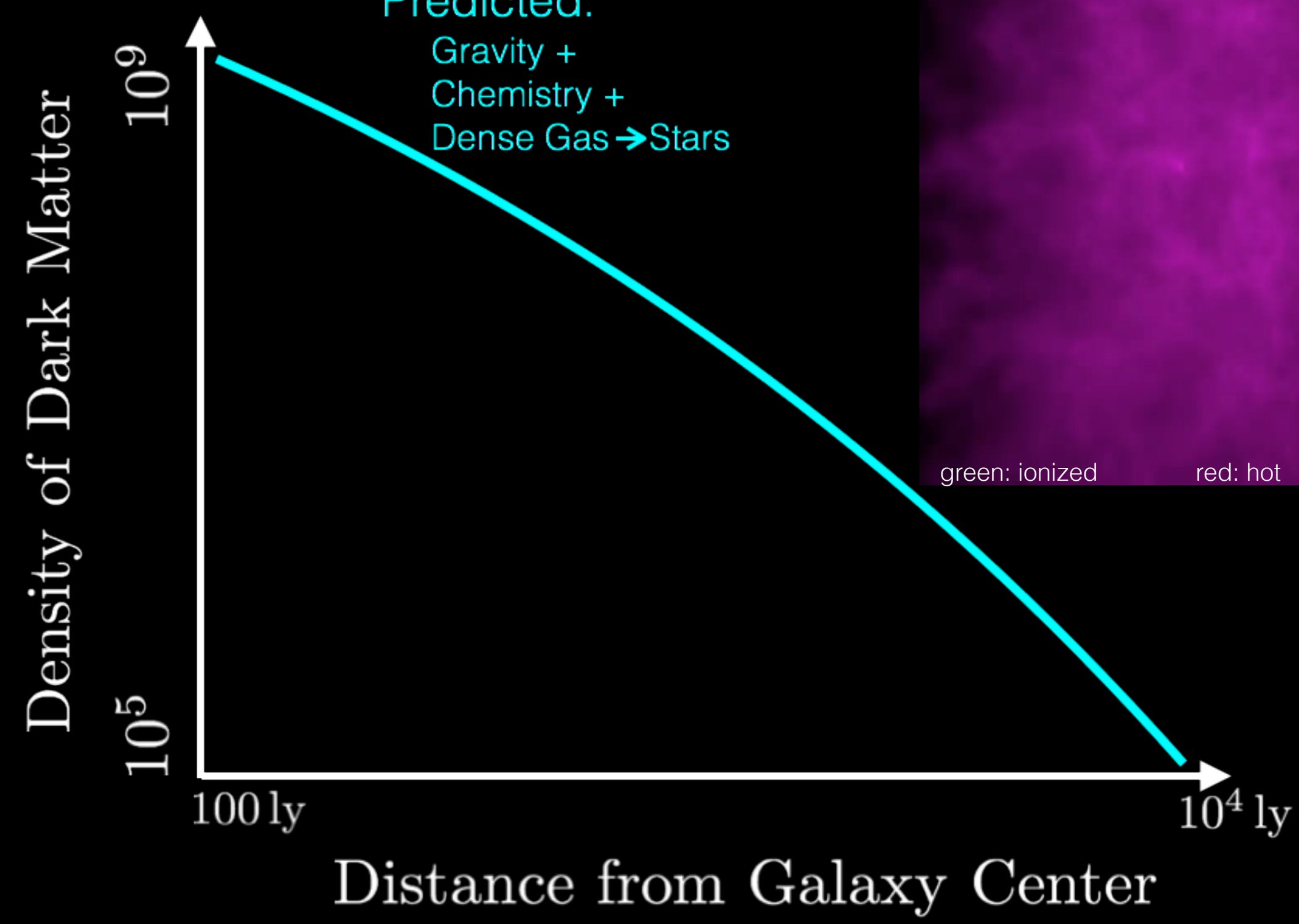


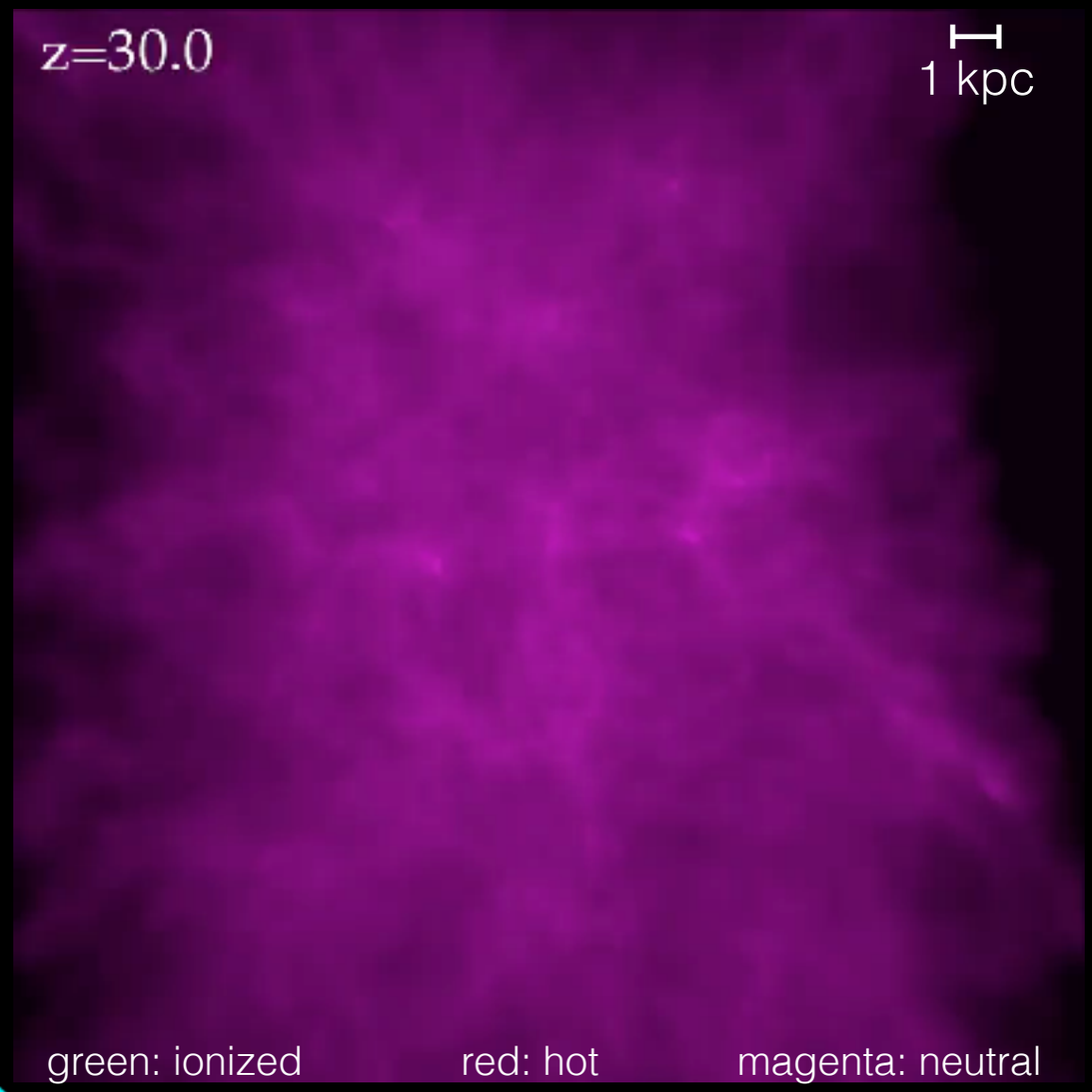




Feedback Saves Cold Dark Matter?

NO EXOTIC PHYSICS NECESSARY





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

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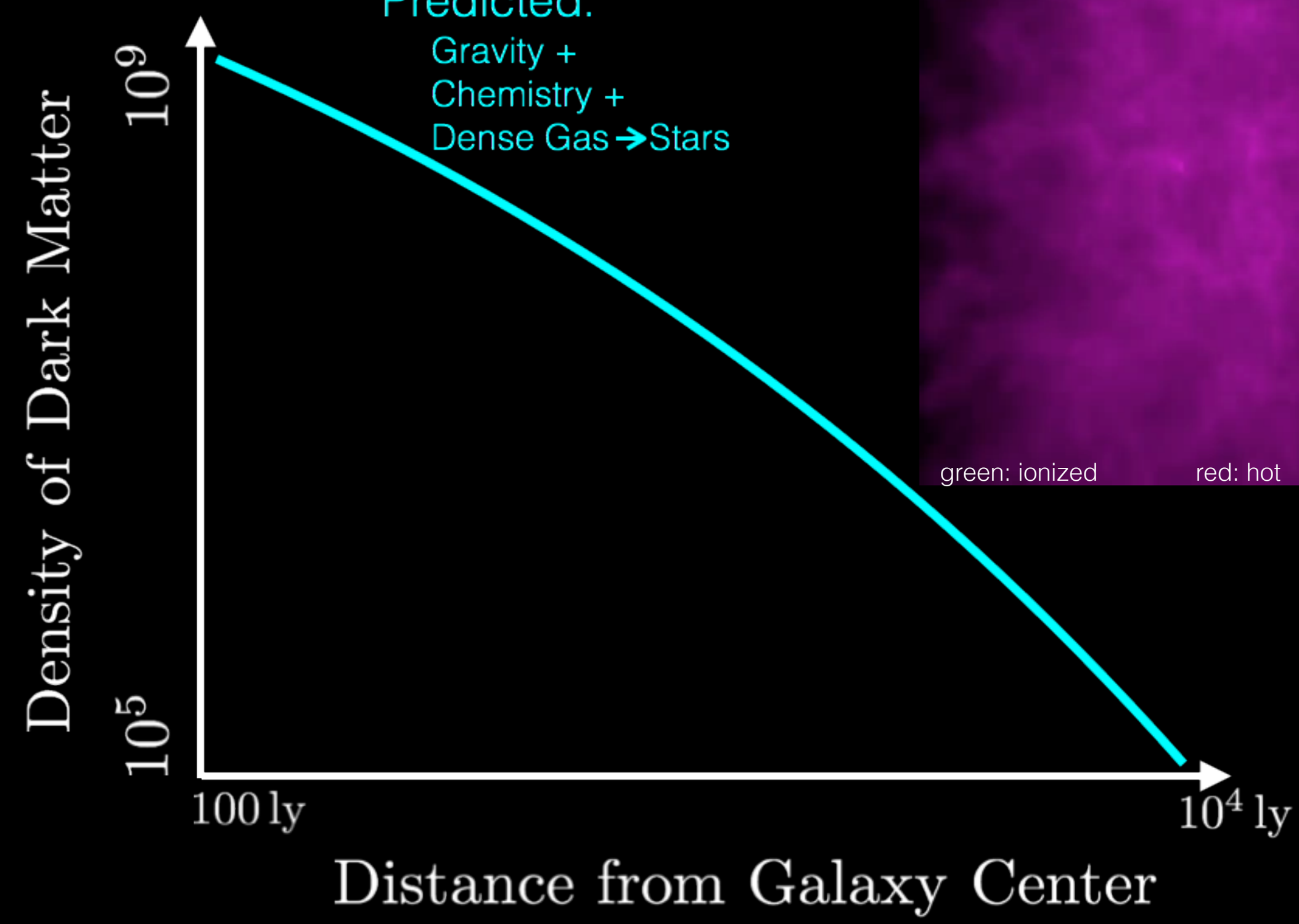

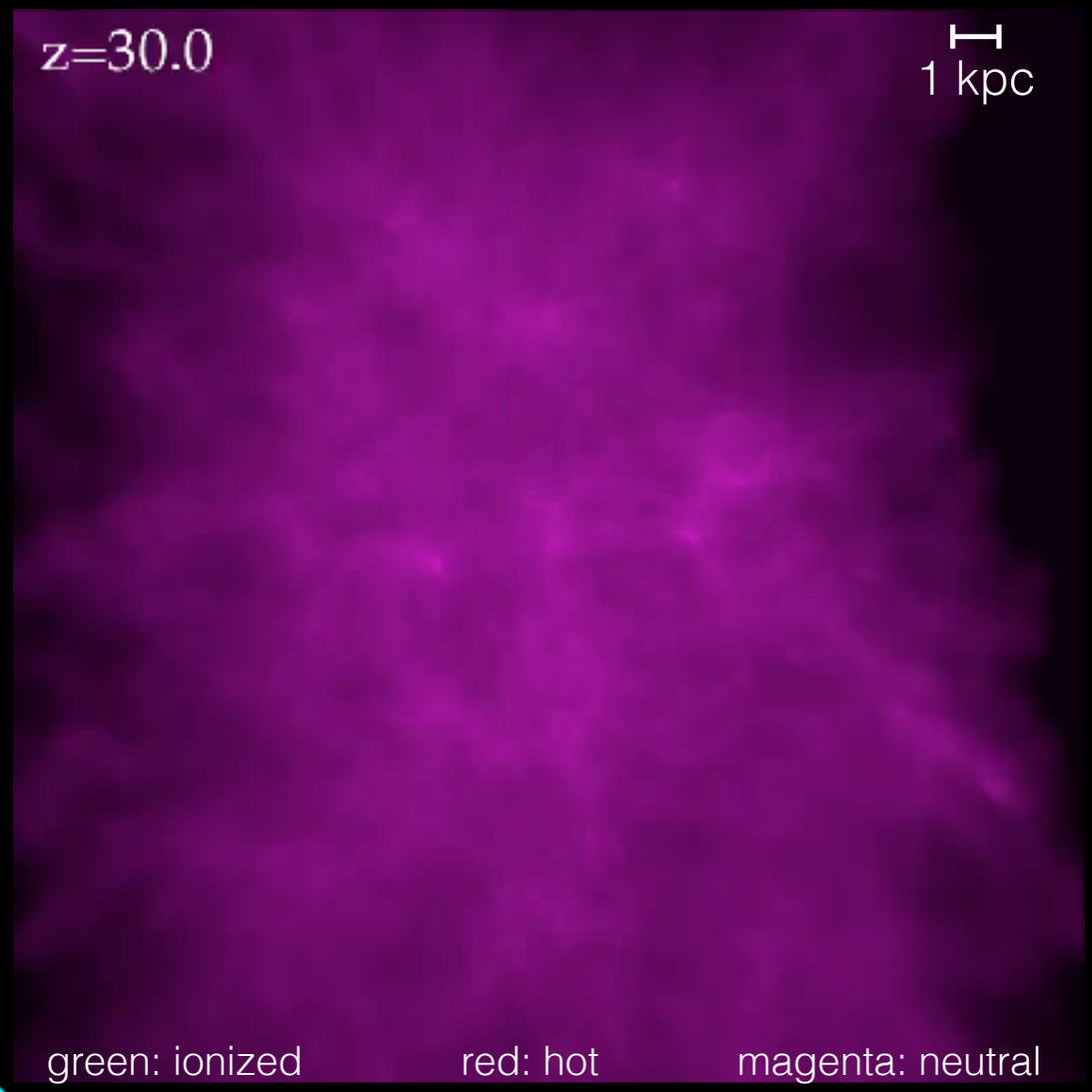

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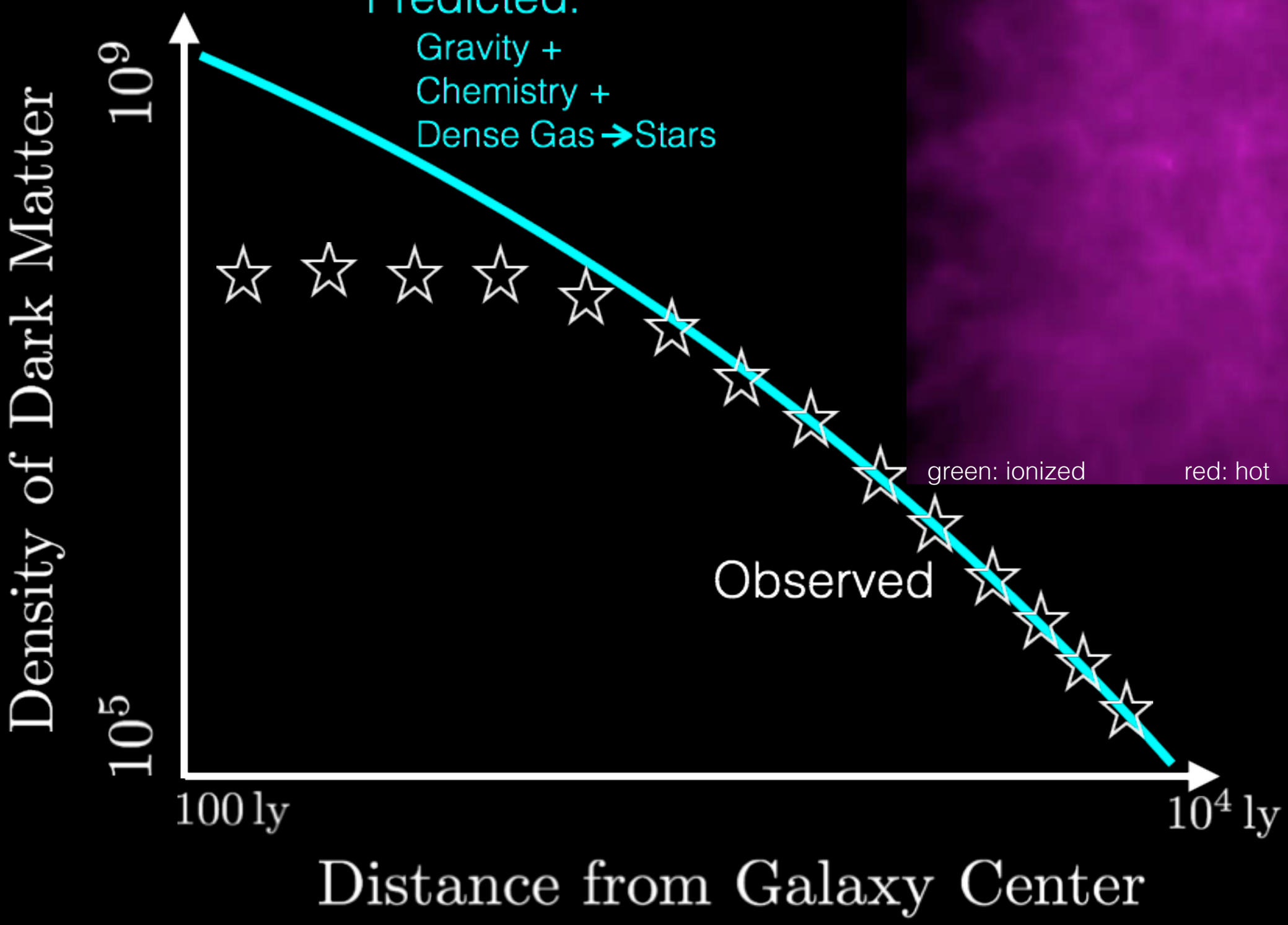

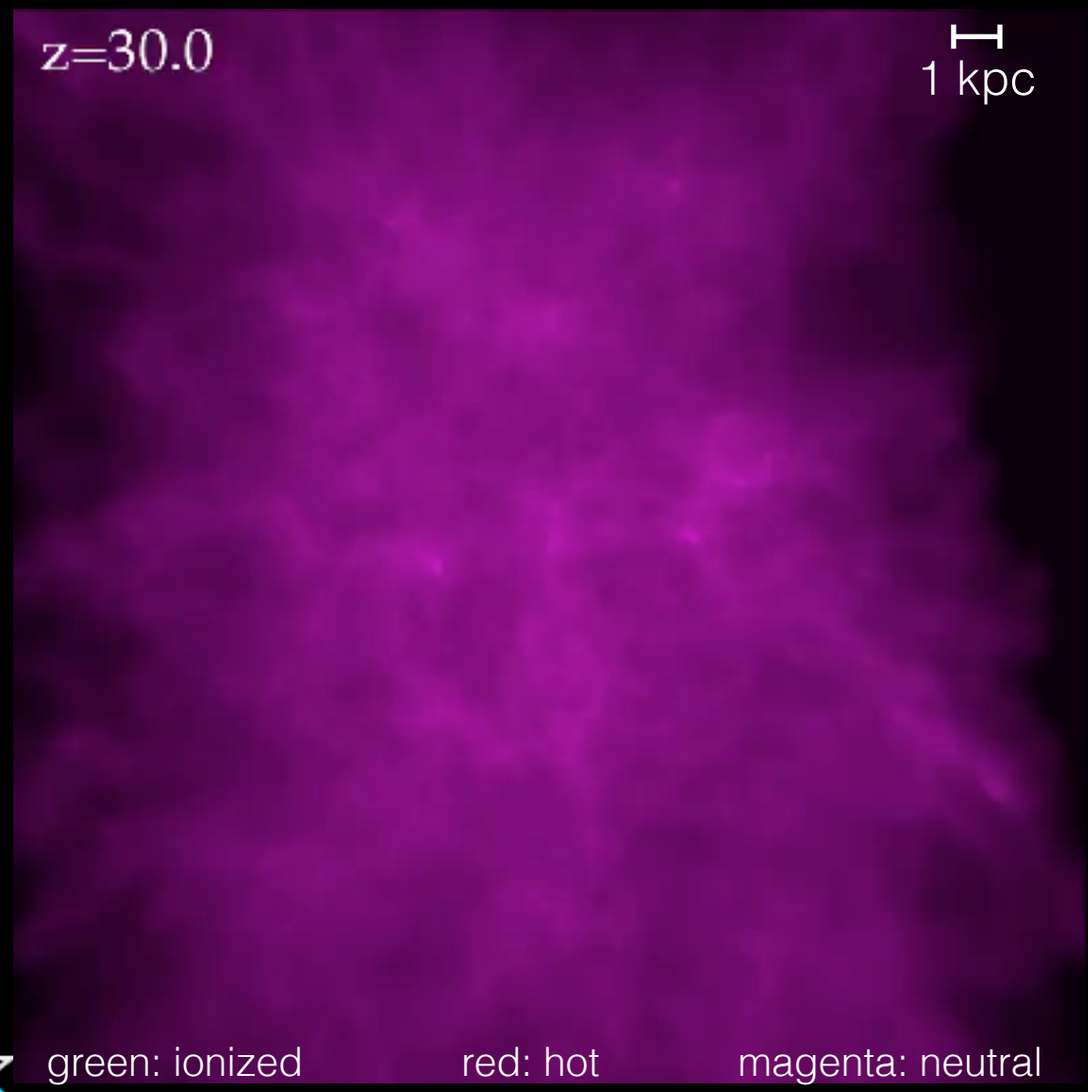

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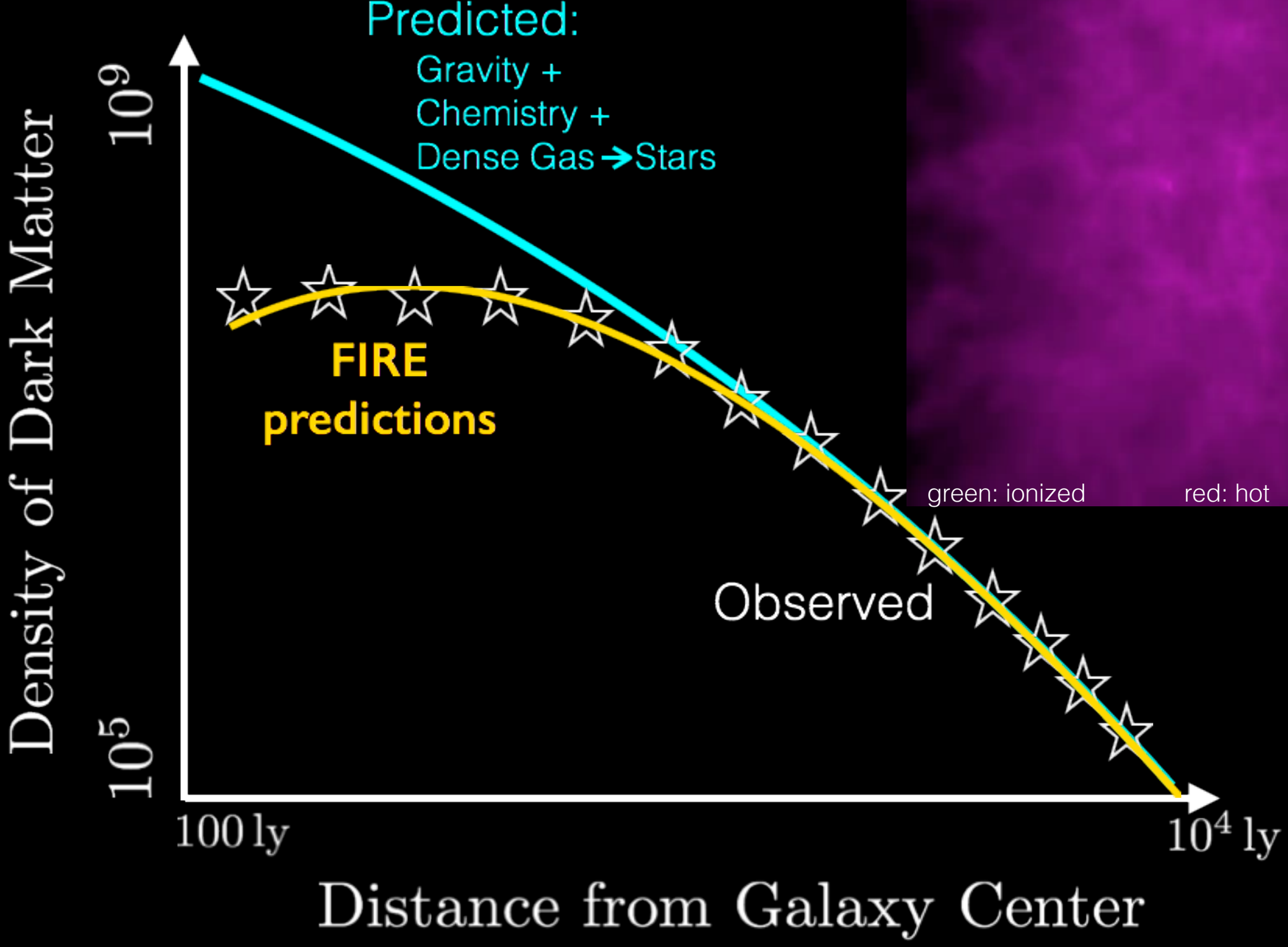

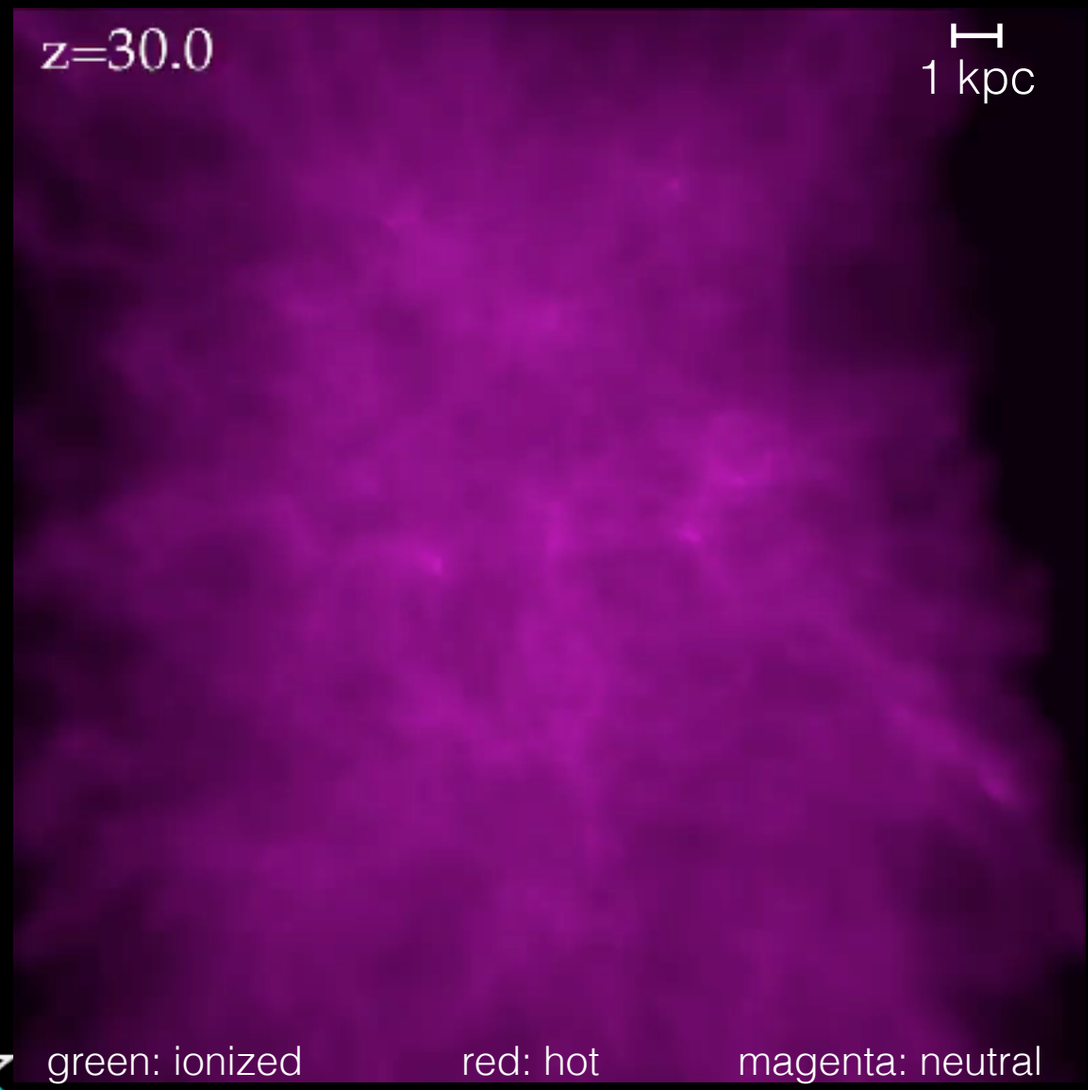

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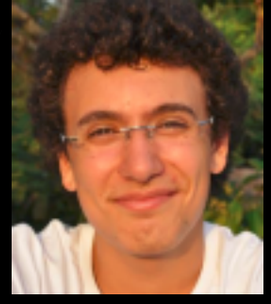
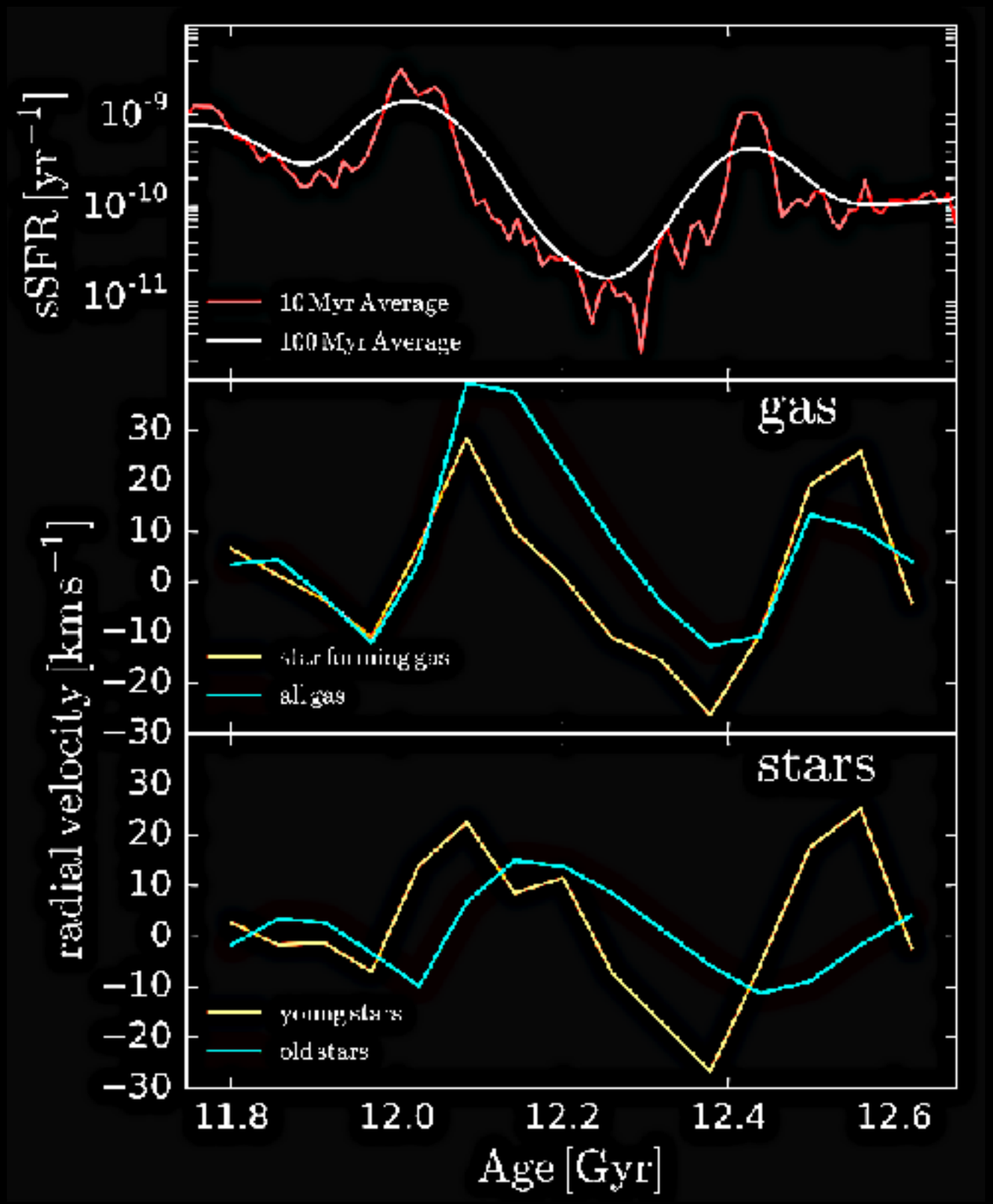
Direct Consequences for Structure

BURSTY SF = STARS MIXED, JUST LIKE DM

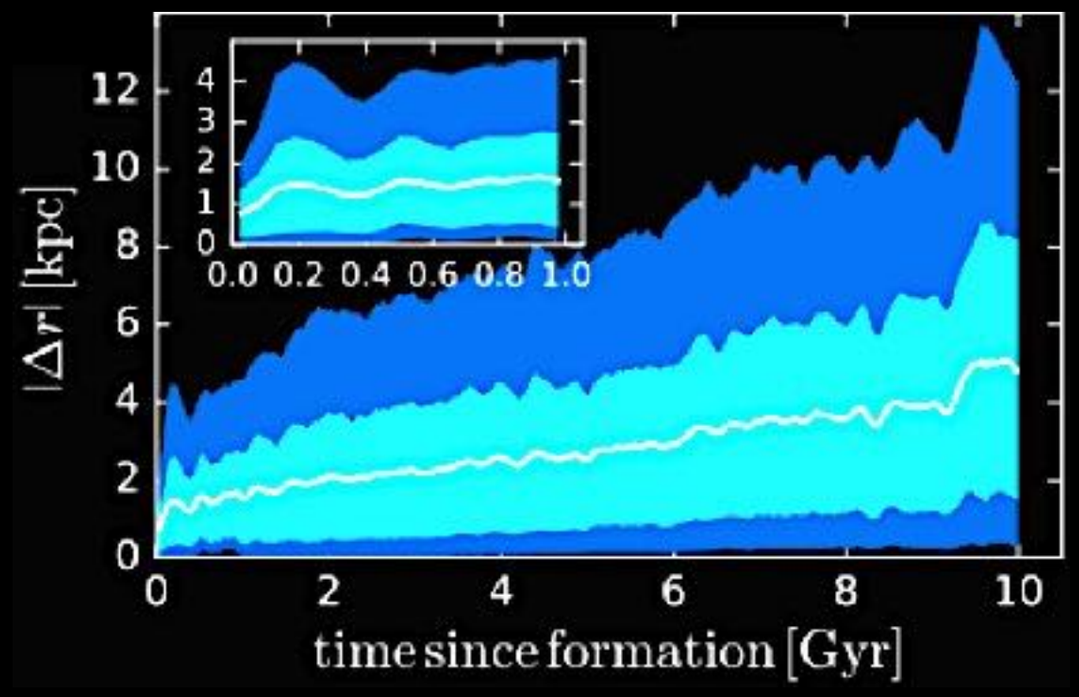
K. El-Badry
(arXiv:1512.01235)



Radial "breathing" in each burst:



Orbits "pumped up"



- If DM orbits perturbed, stars are too!

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K. El-Badry, arXiv:1512.01235

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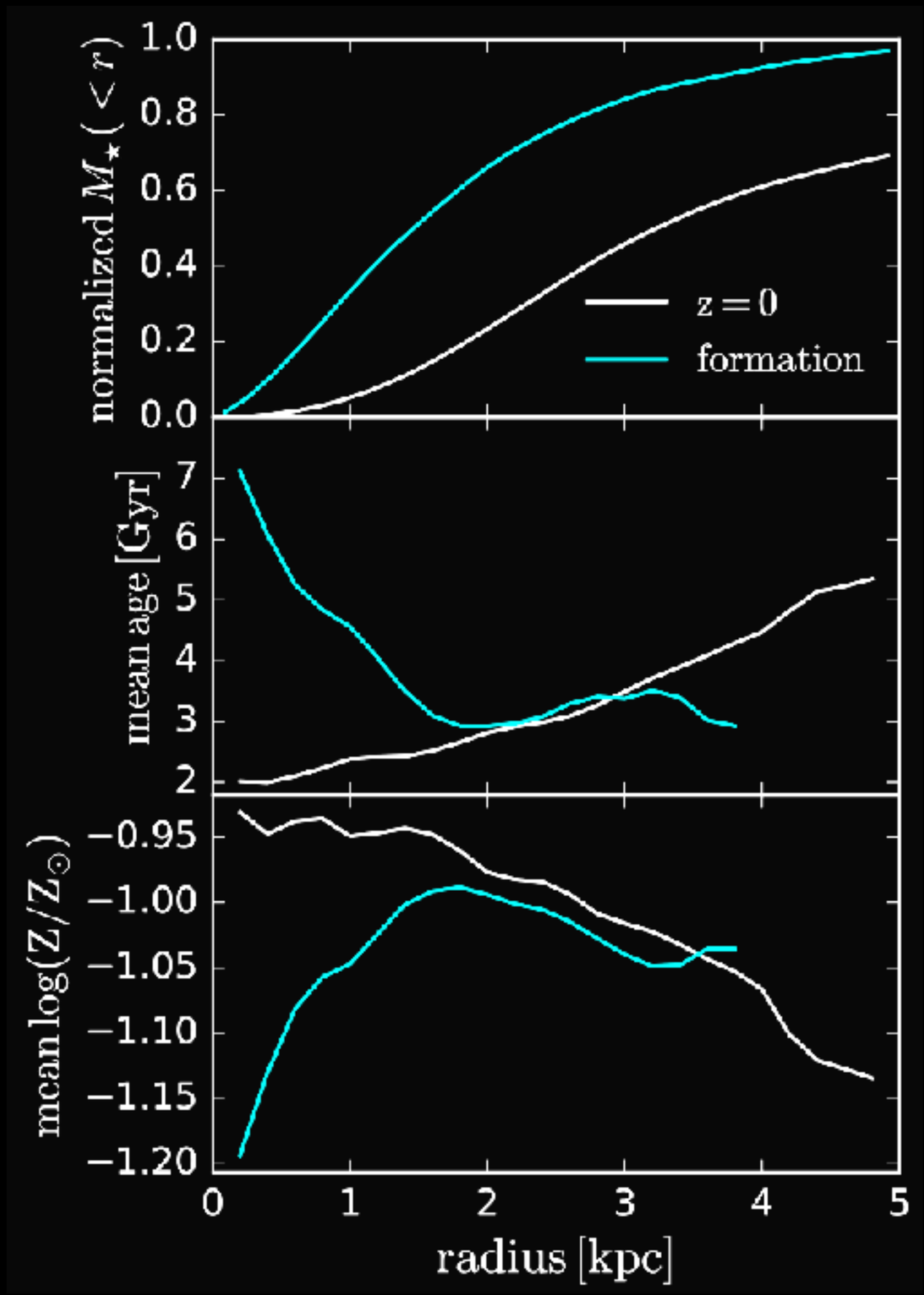
  - Gradients "wiped out"
  - Galactic radii *oscillate*



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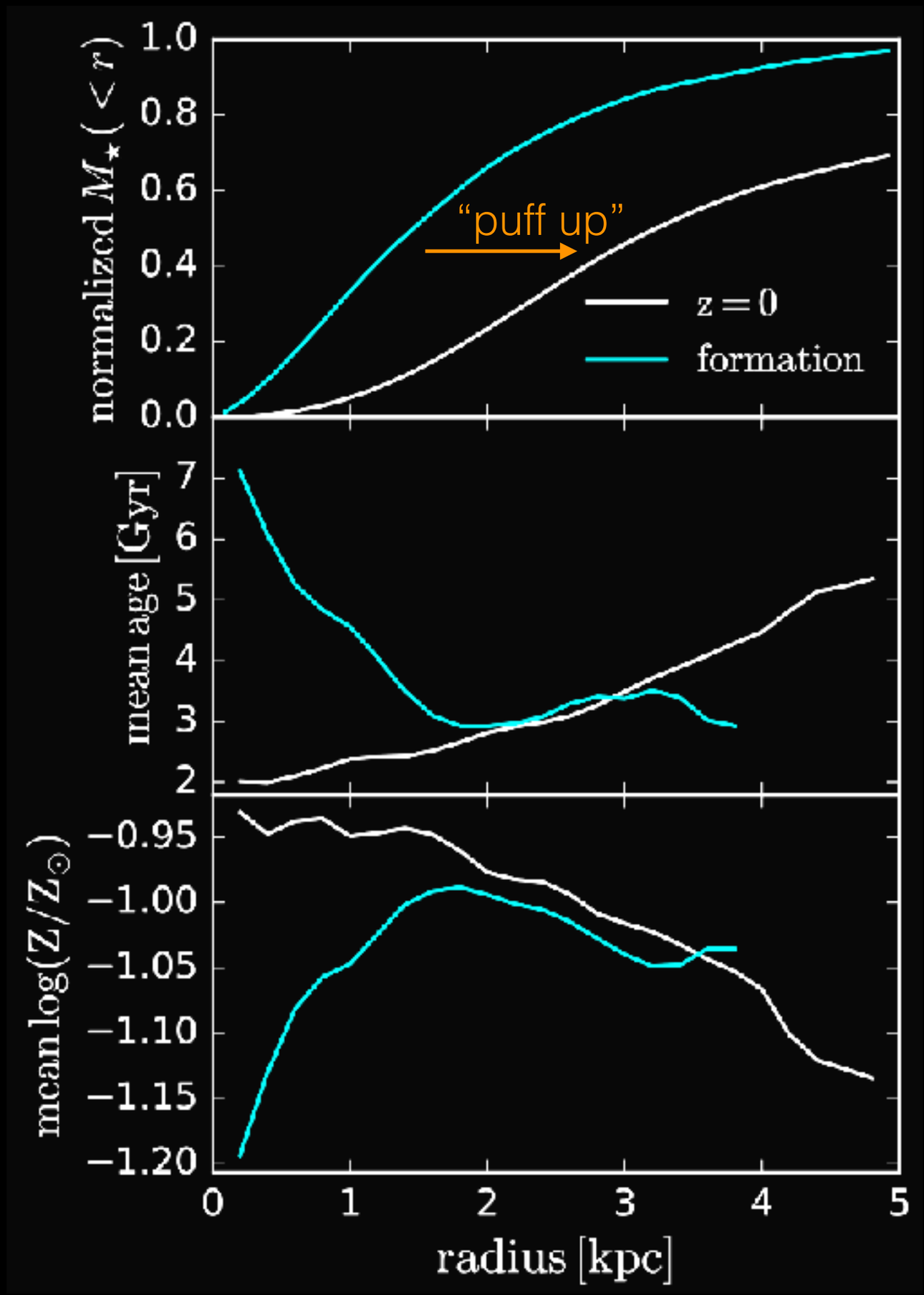

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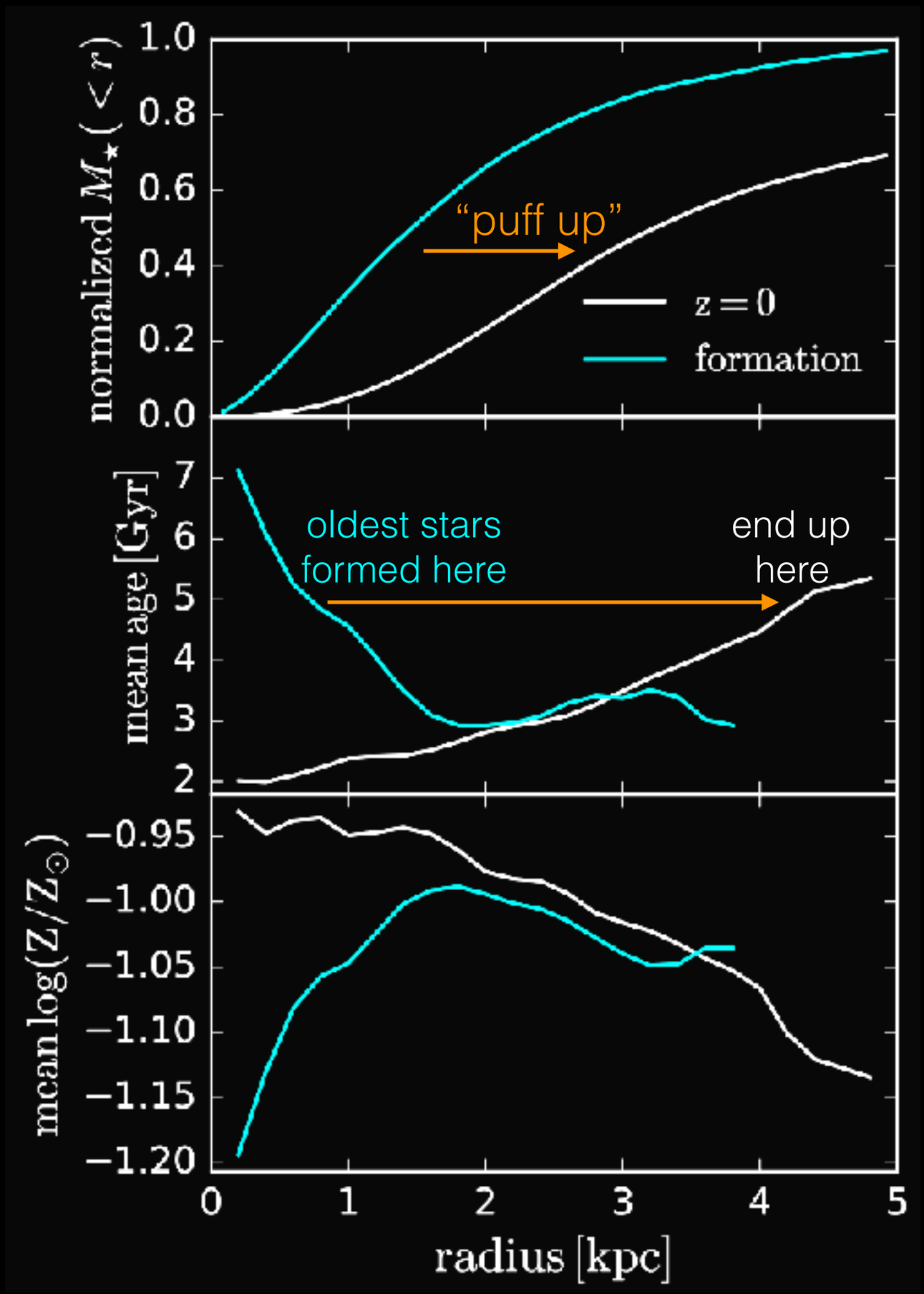

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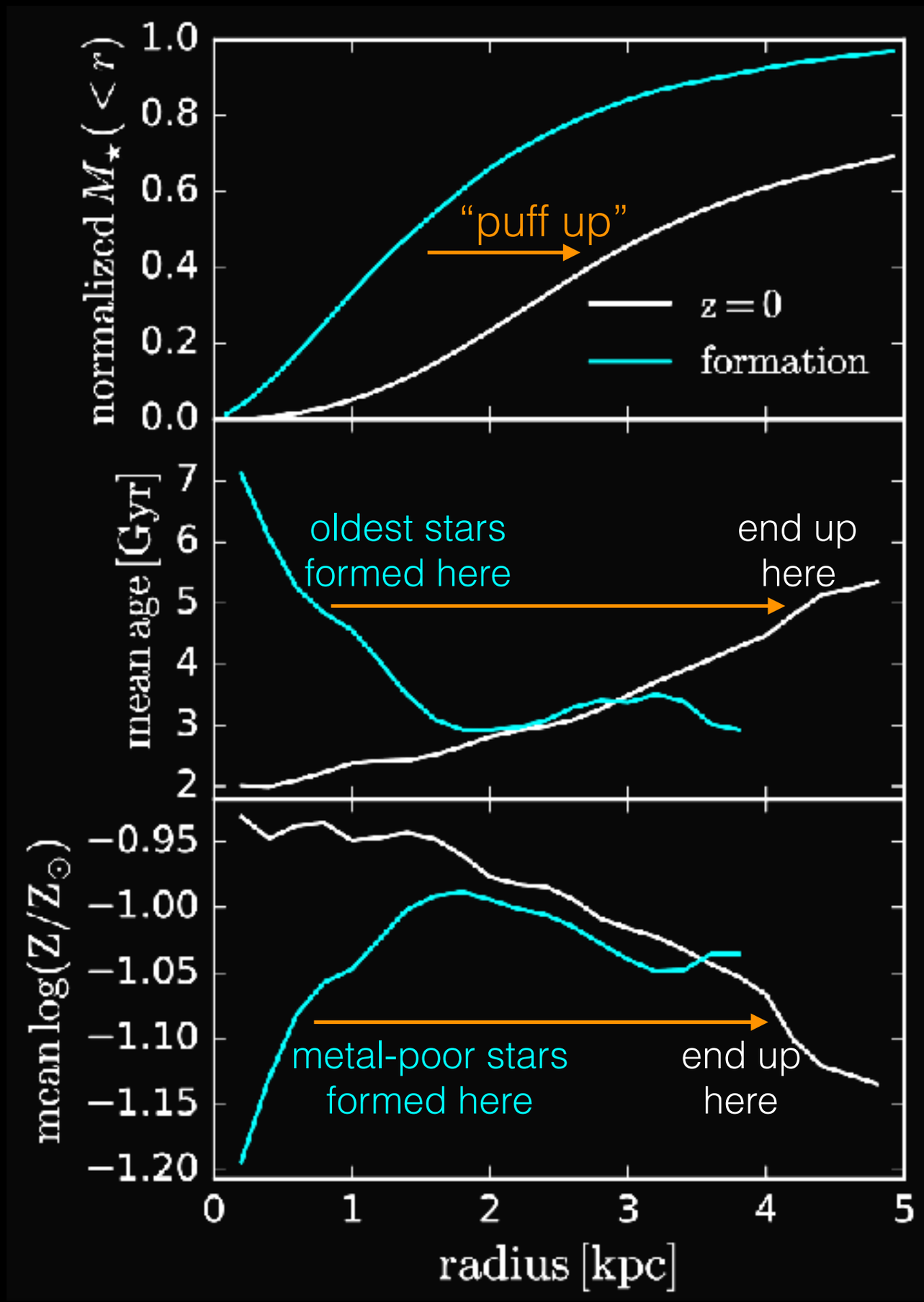
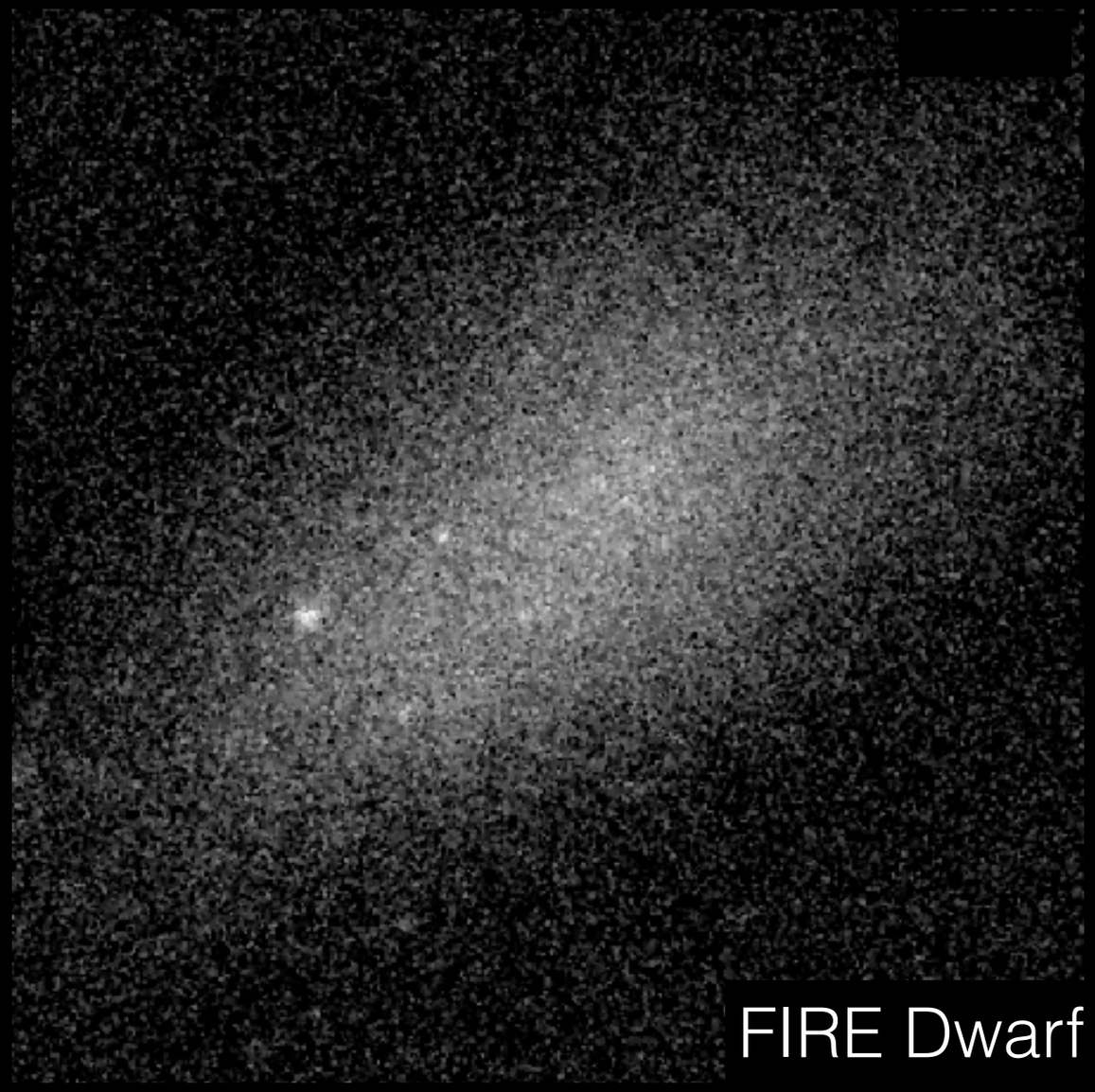


Predicts New Classes of Galaxies

ULTRA-DIFFUSE SYSTEMS: THE NEW "NORMAL"

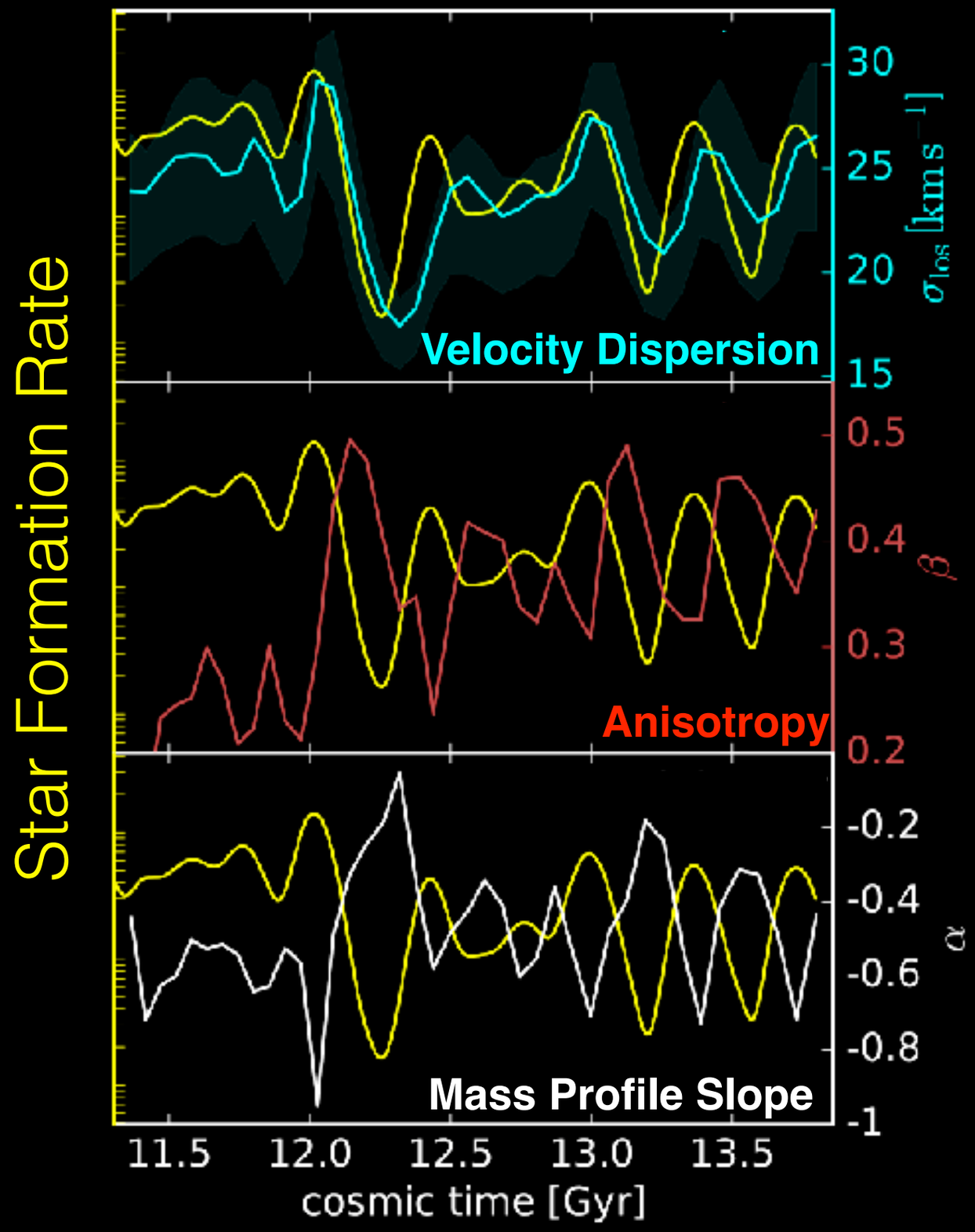
K. El-Badry
(arXiv:1512.01235)
+ TK Chan (prep)



It Gets Worse!

GALAXIES ARE NOT STEADY-STATE OBJECTS!

K. El-Badry
(arXiv:1610.04232)



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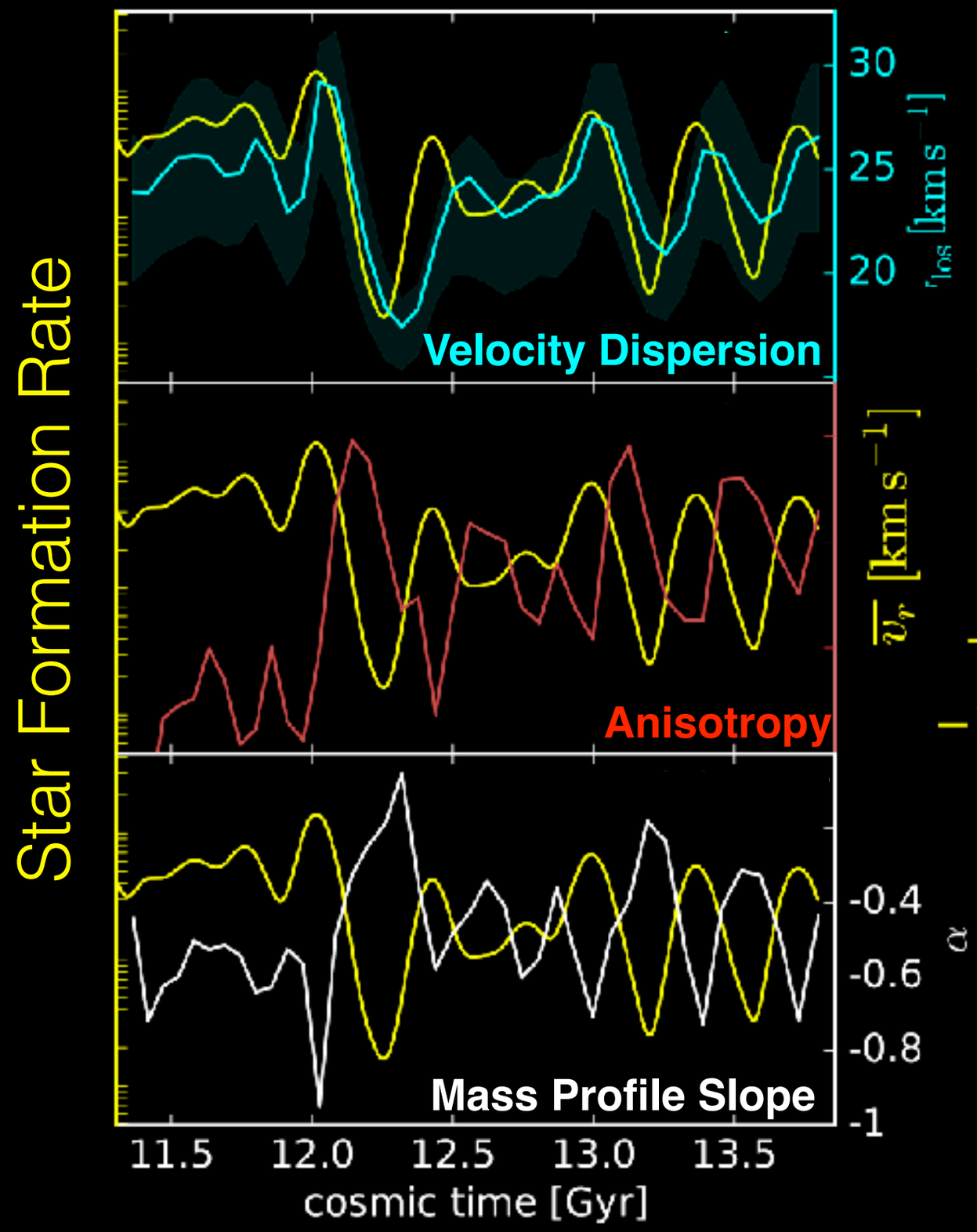
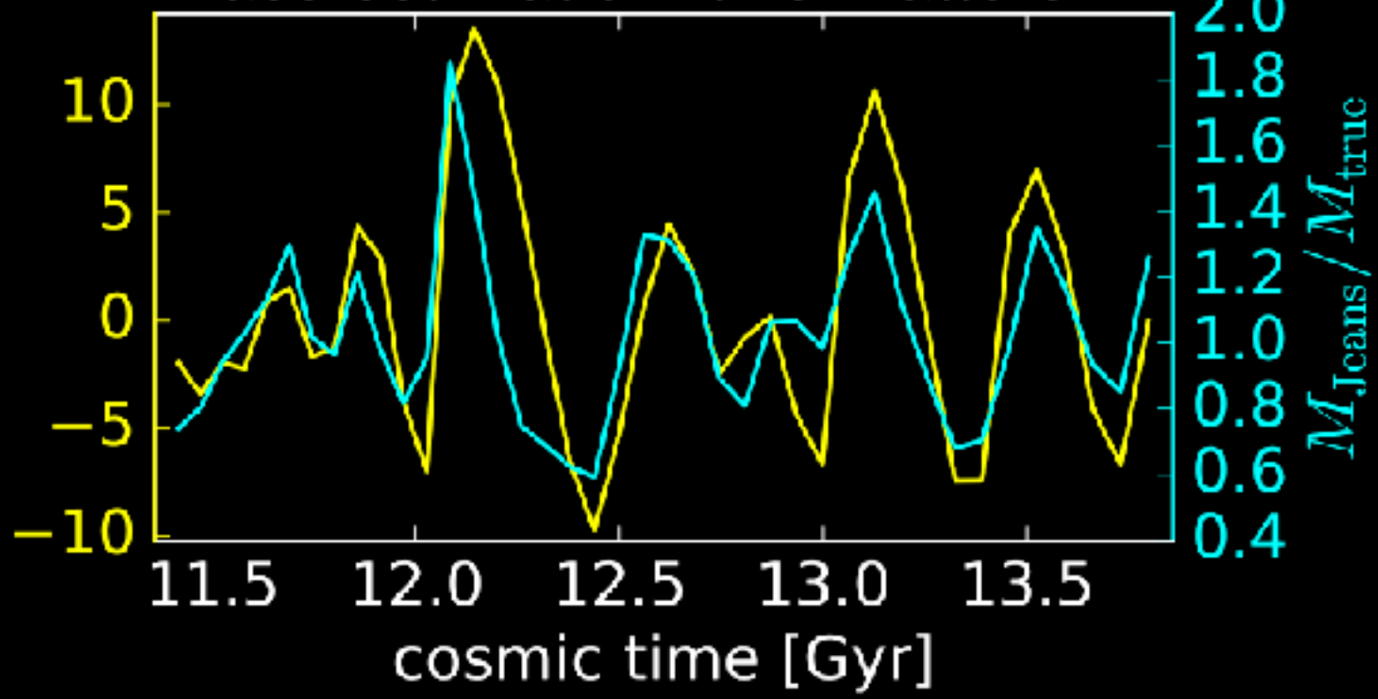
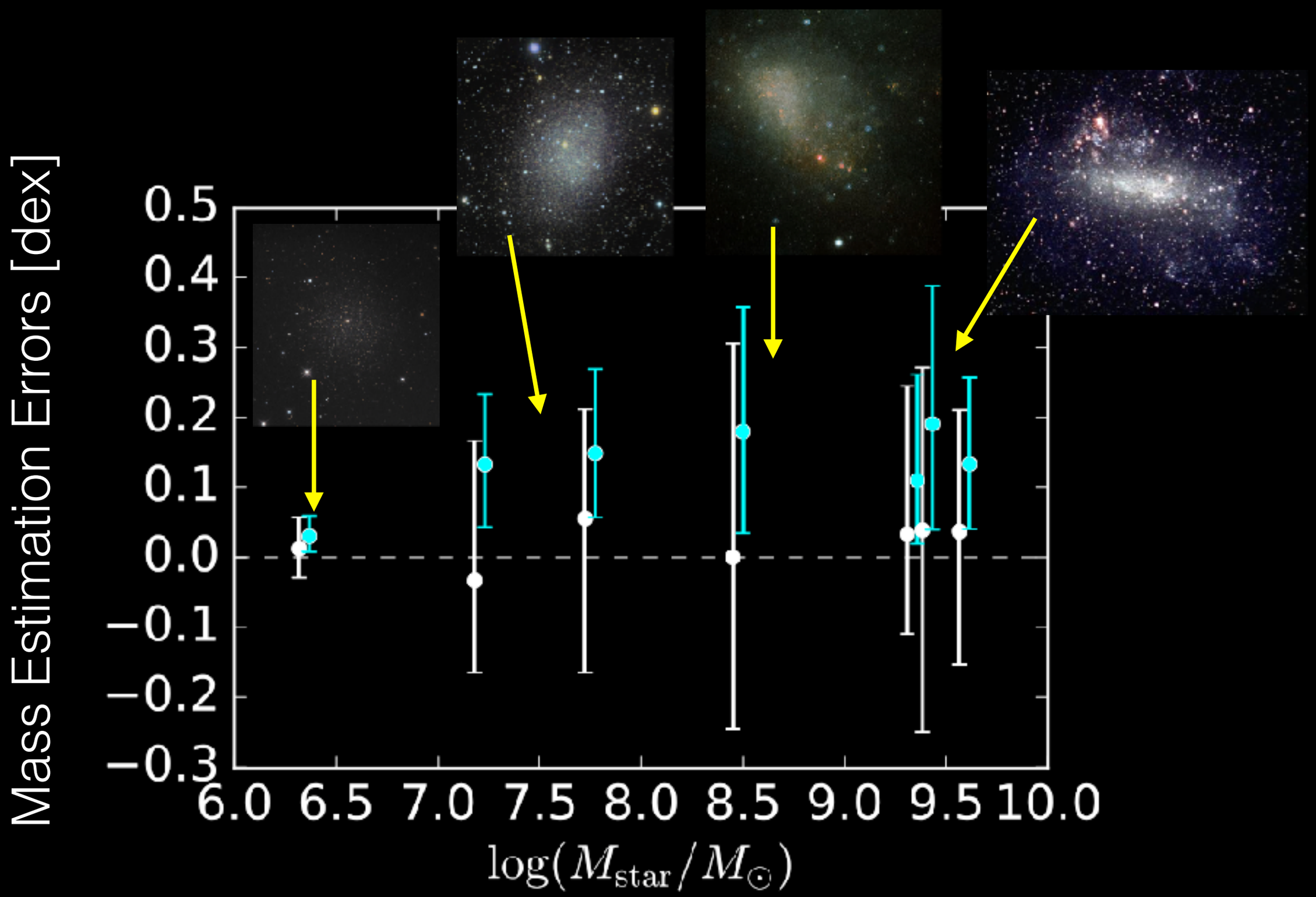




Where Does It End?

K. El-Badry
(arXiv:1610.04232)



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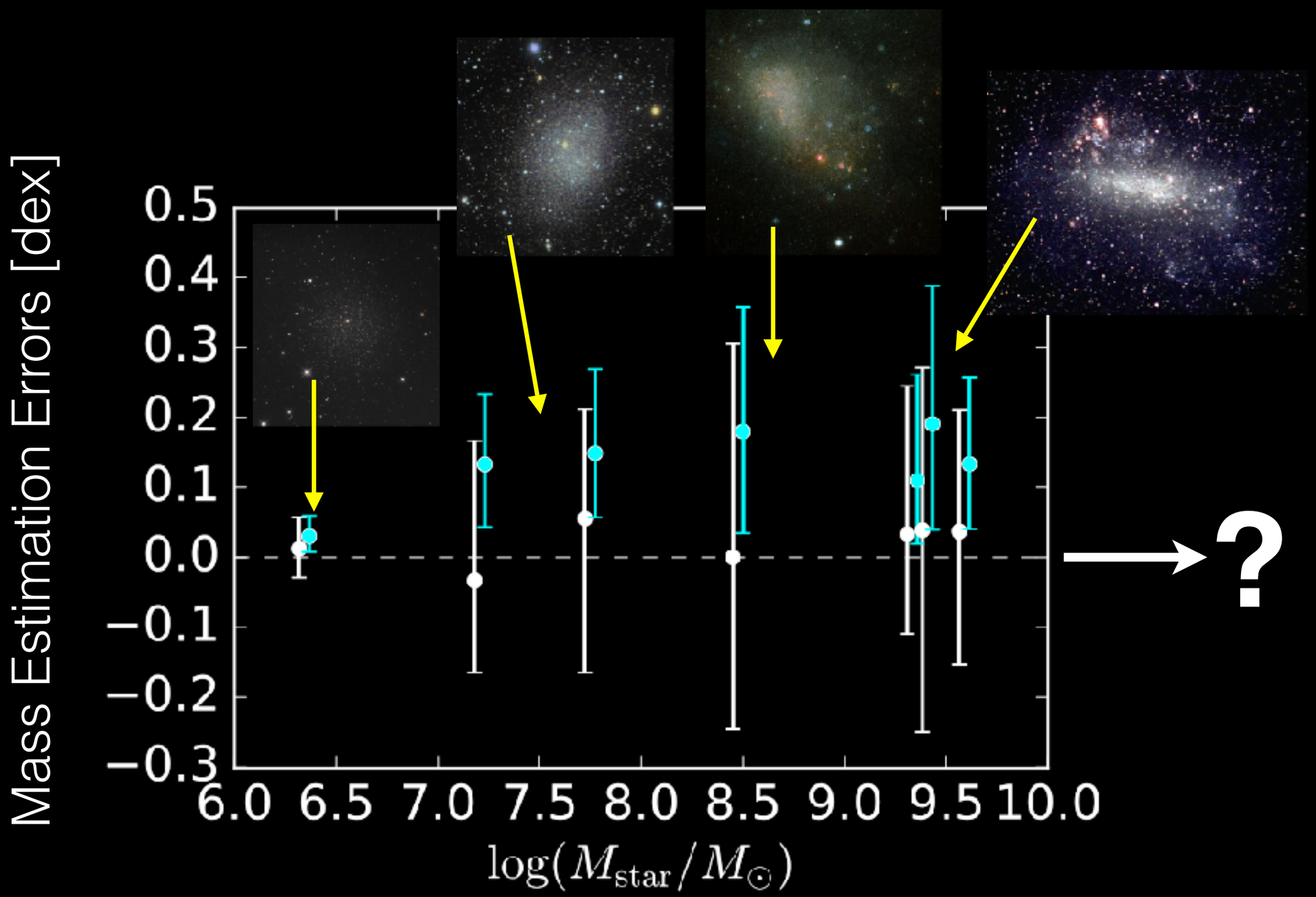


z=30.0

10 kpc

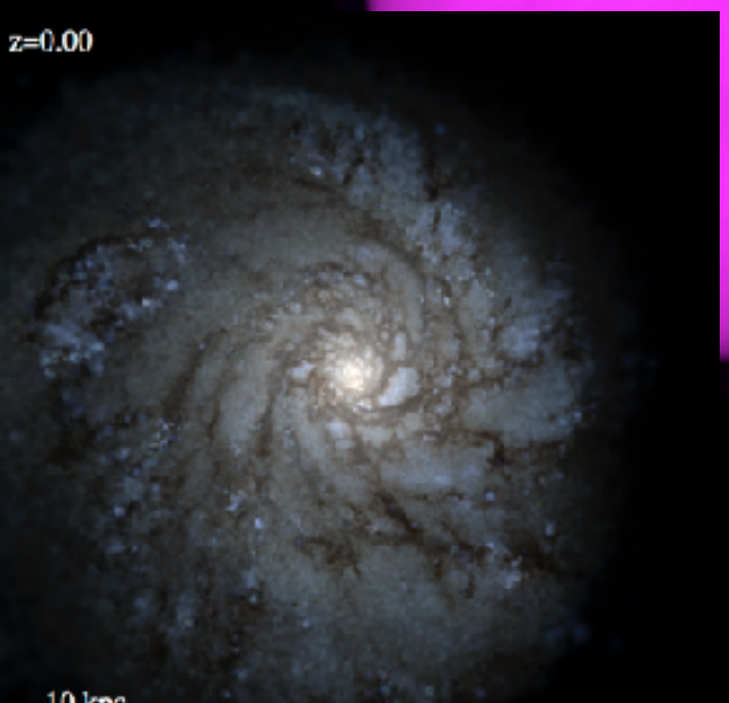
S. Muratov
(arXiv:1501.03155)

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

to

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

z=0.00



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C. Hayward
(arxiv:1510.05650)

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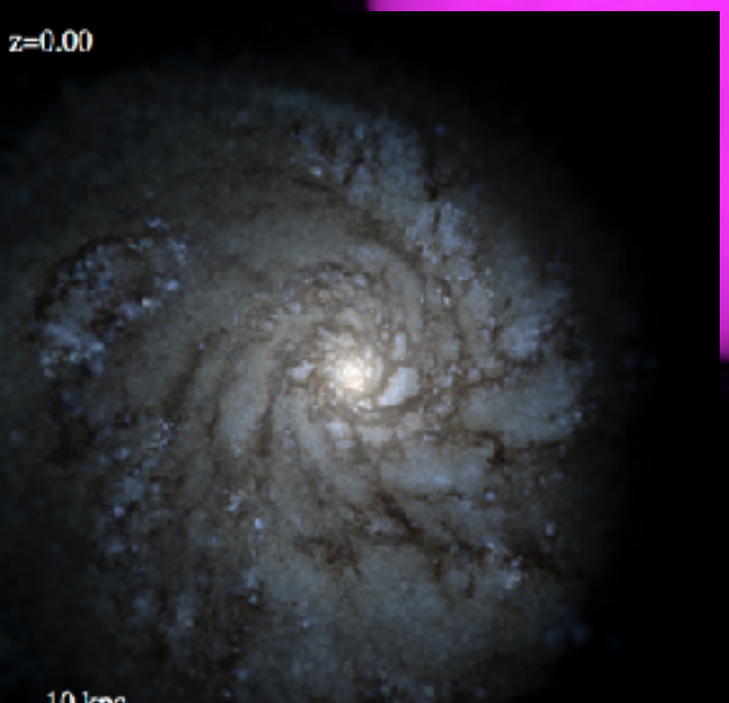


10 kpc

C. Hayward
(arxiv:1510.05650)

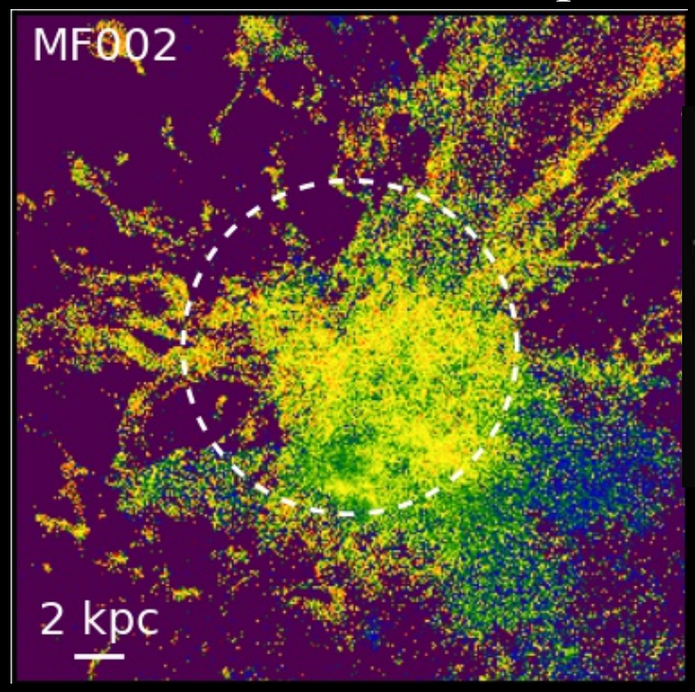
Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

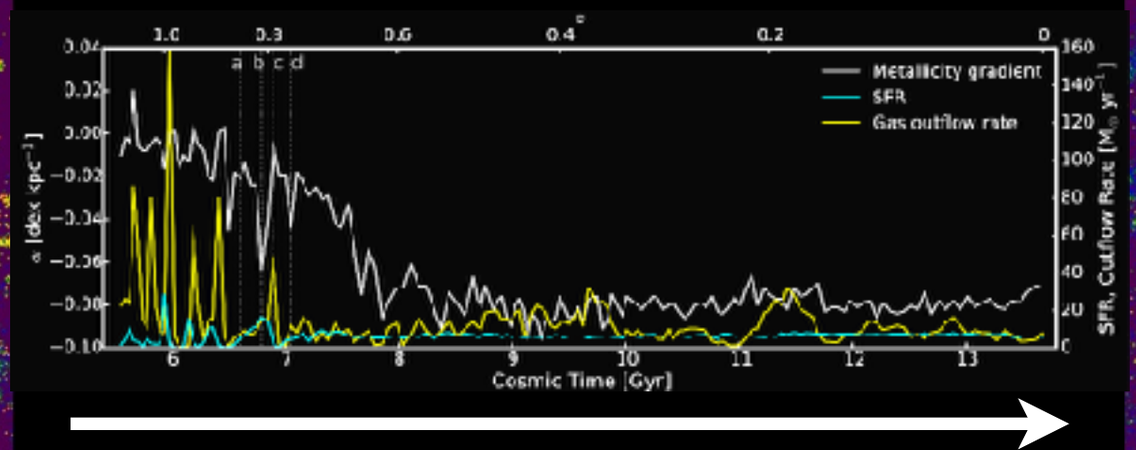
BUILDUP OF METALLICITY GRADIENTS

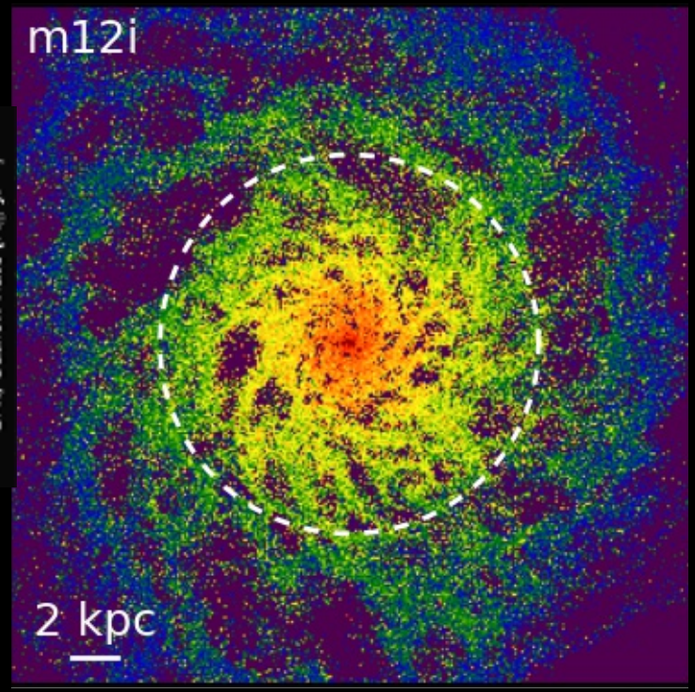
Xiangcheng Ma
(arXiv:1610.03498)

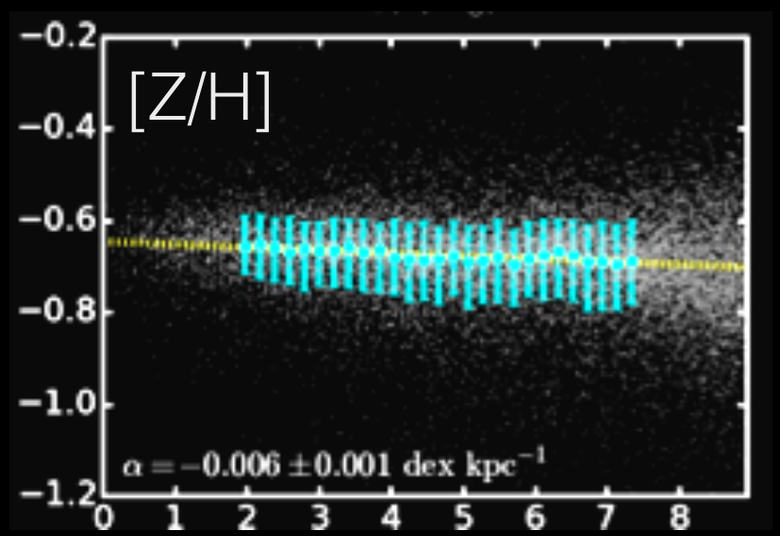
"feedback-dominated" phase

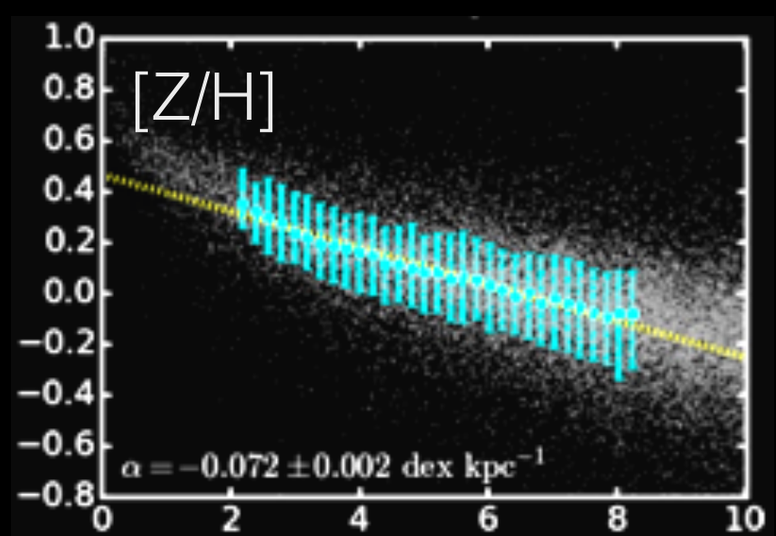
"gravity-dominated" phase







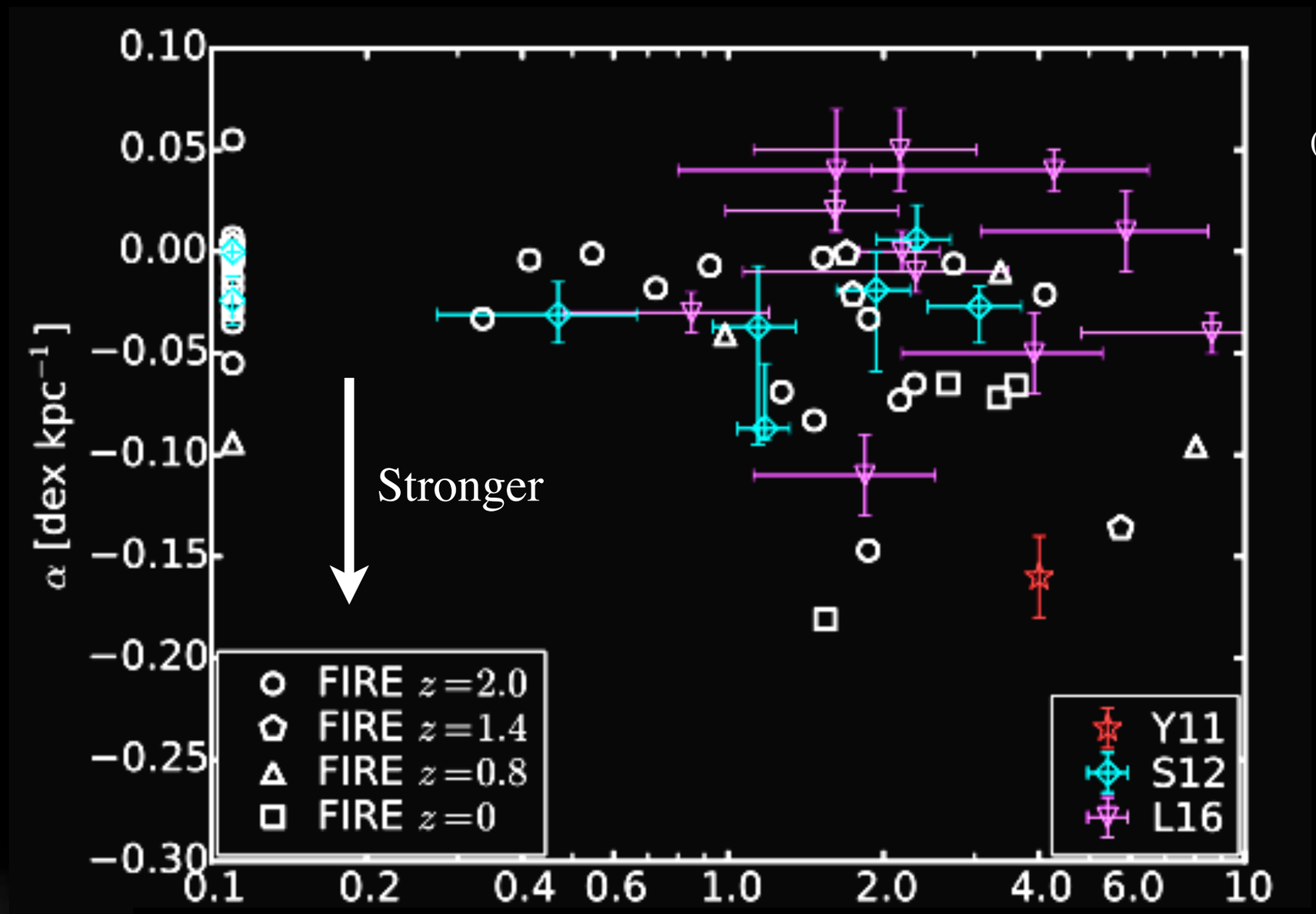


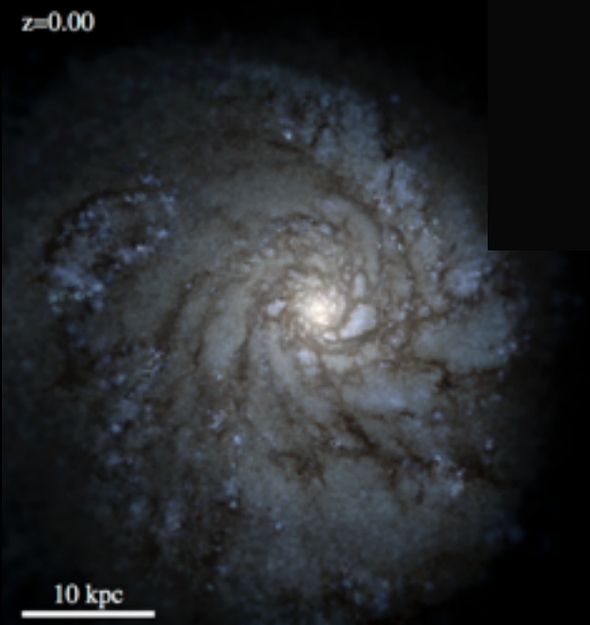


Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

BUILDUP OF METALLICITY GRADIENTS

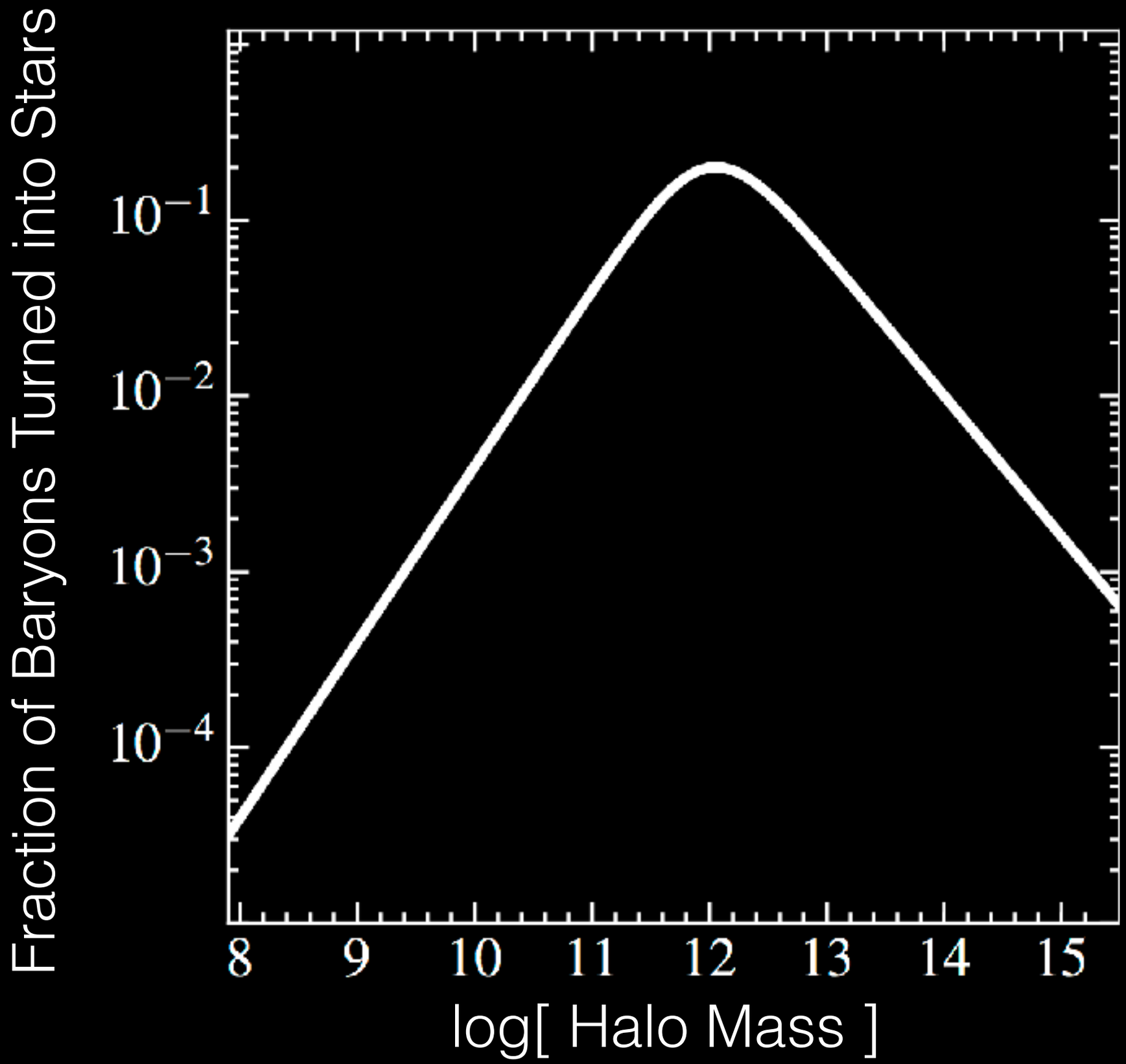
Xiangcheng Ma
(arXiv:1610.03498)





Rotation is Rare:

ONLY COMMON AT PEAK STAR FORMATION EFFICIENCY



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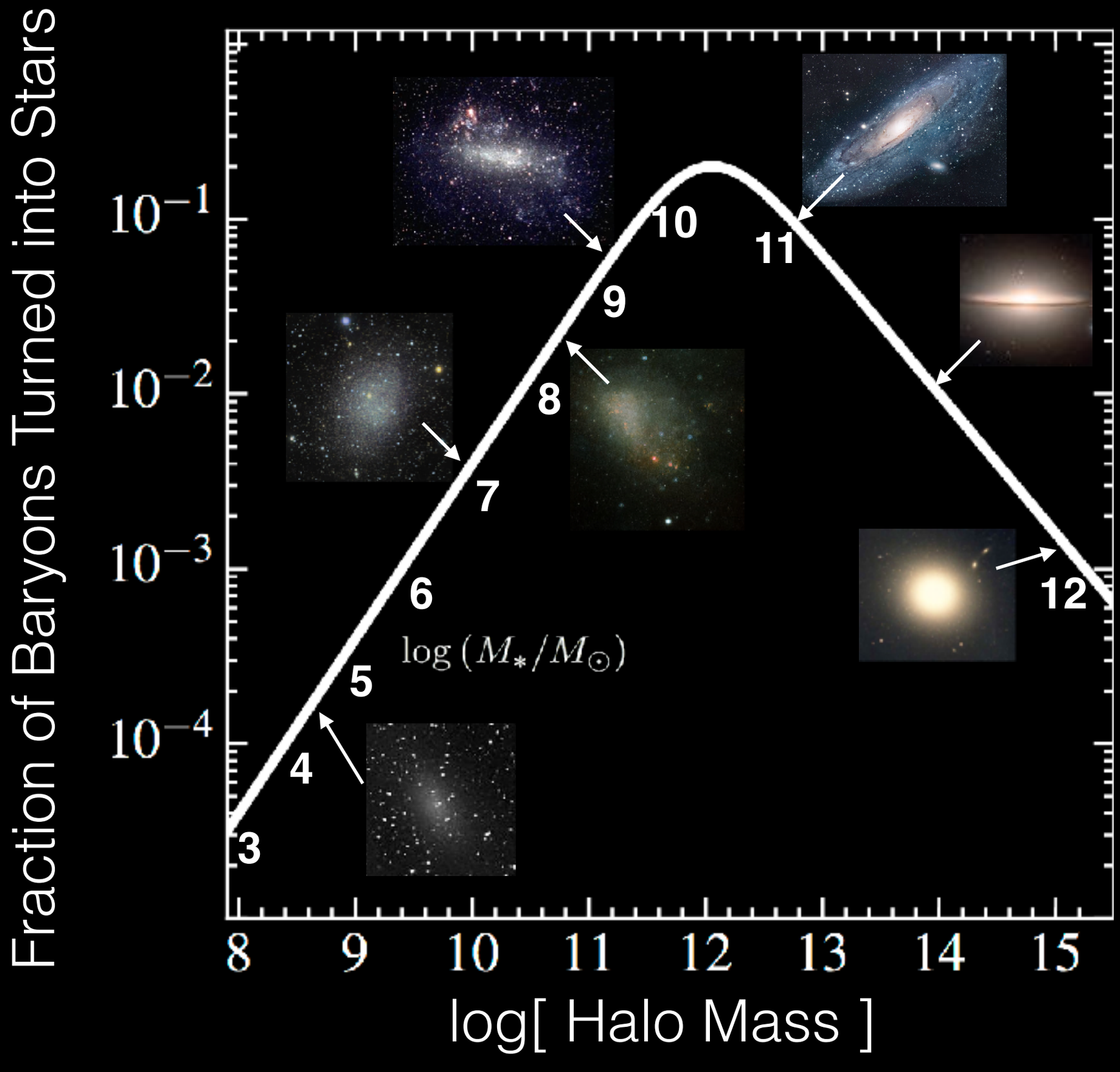

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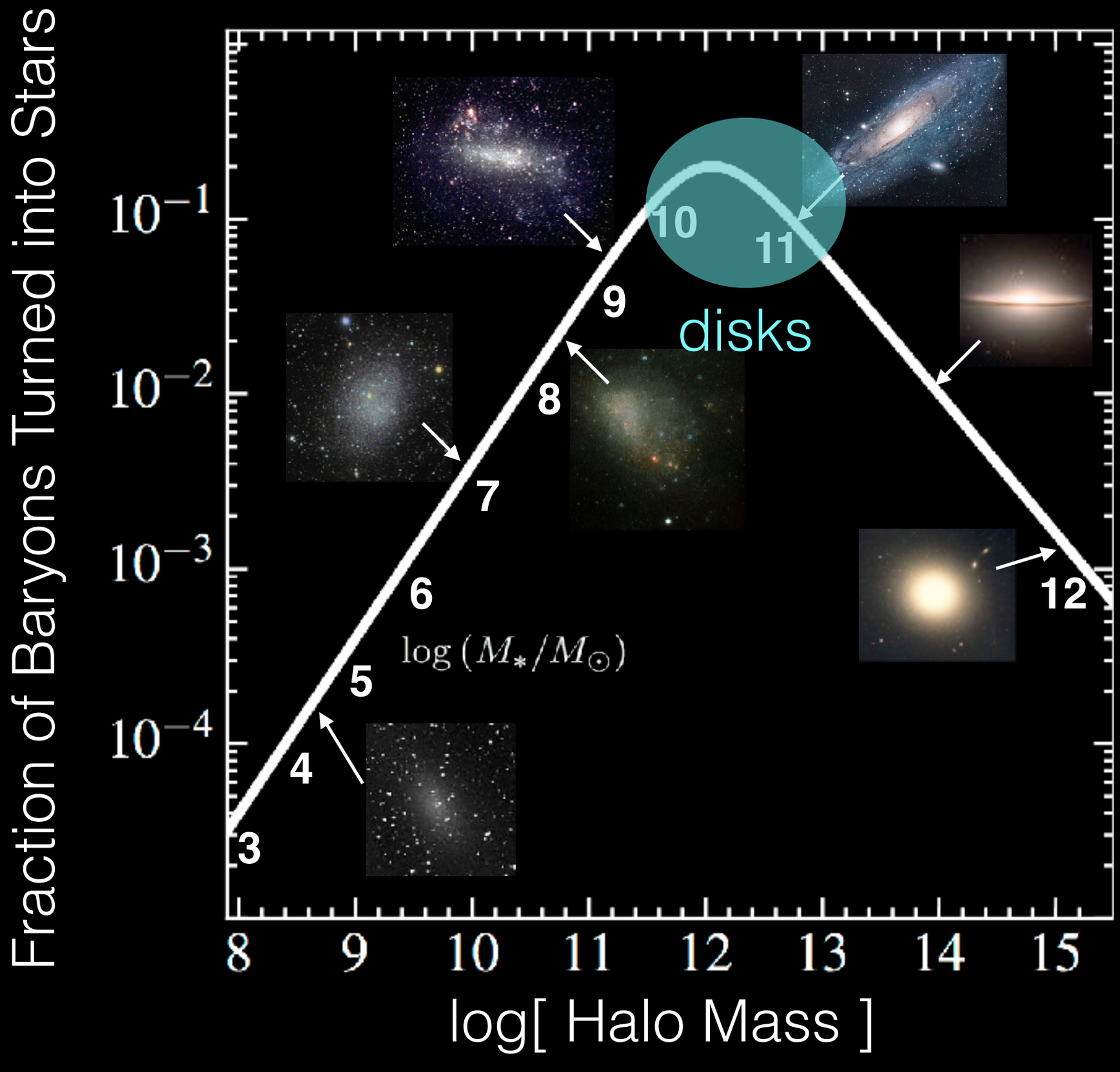
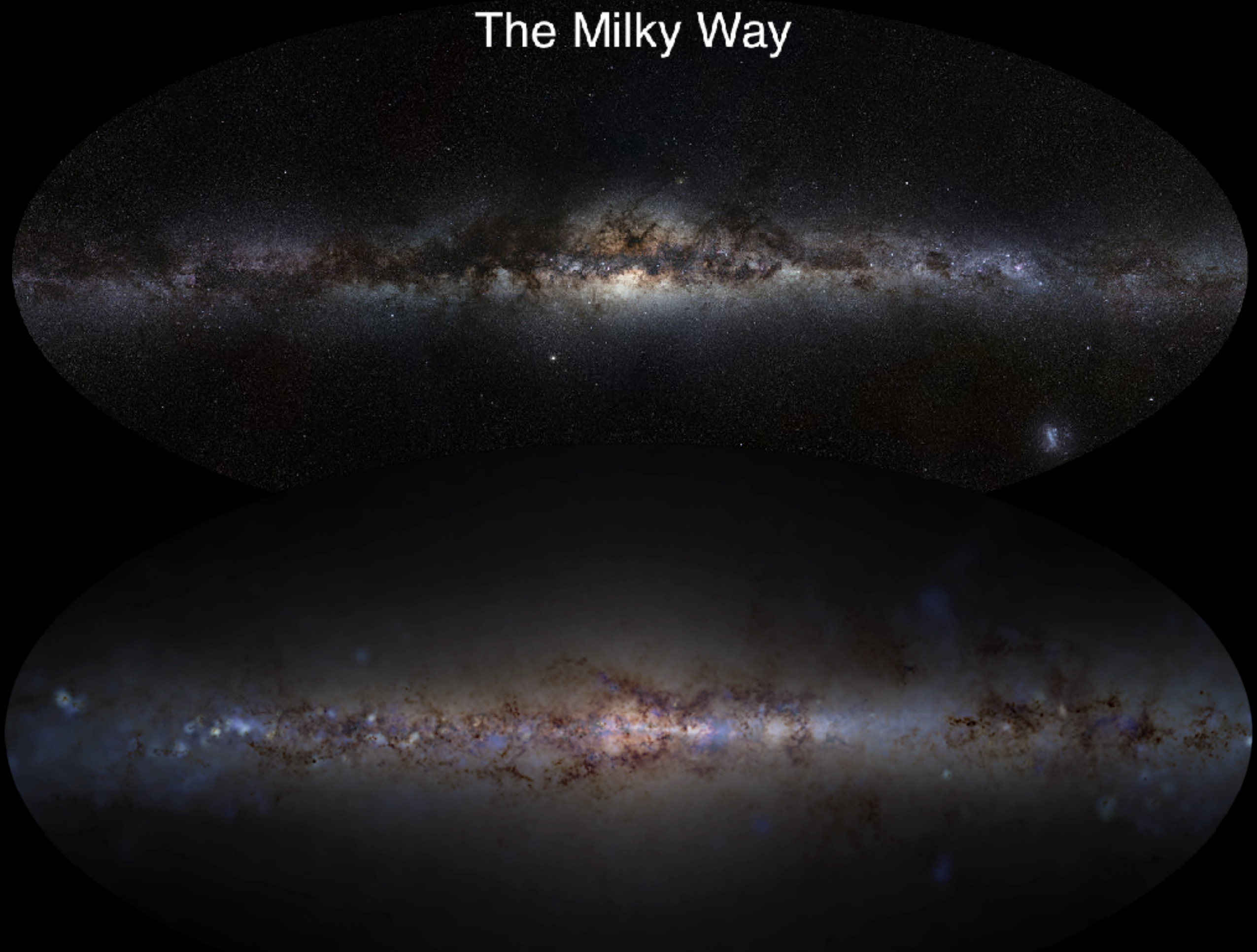


Have we gone “Big Bang to Milky Way”?

The Milky Way



Failures No More

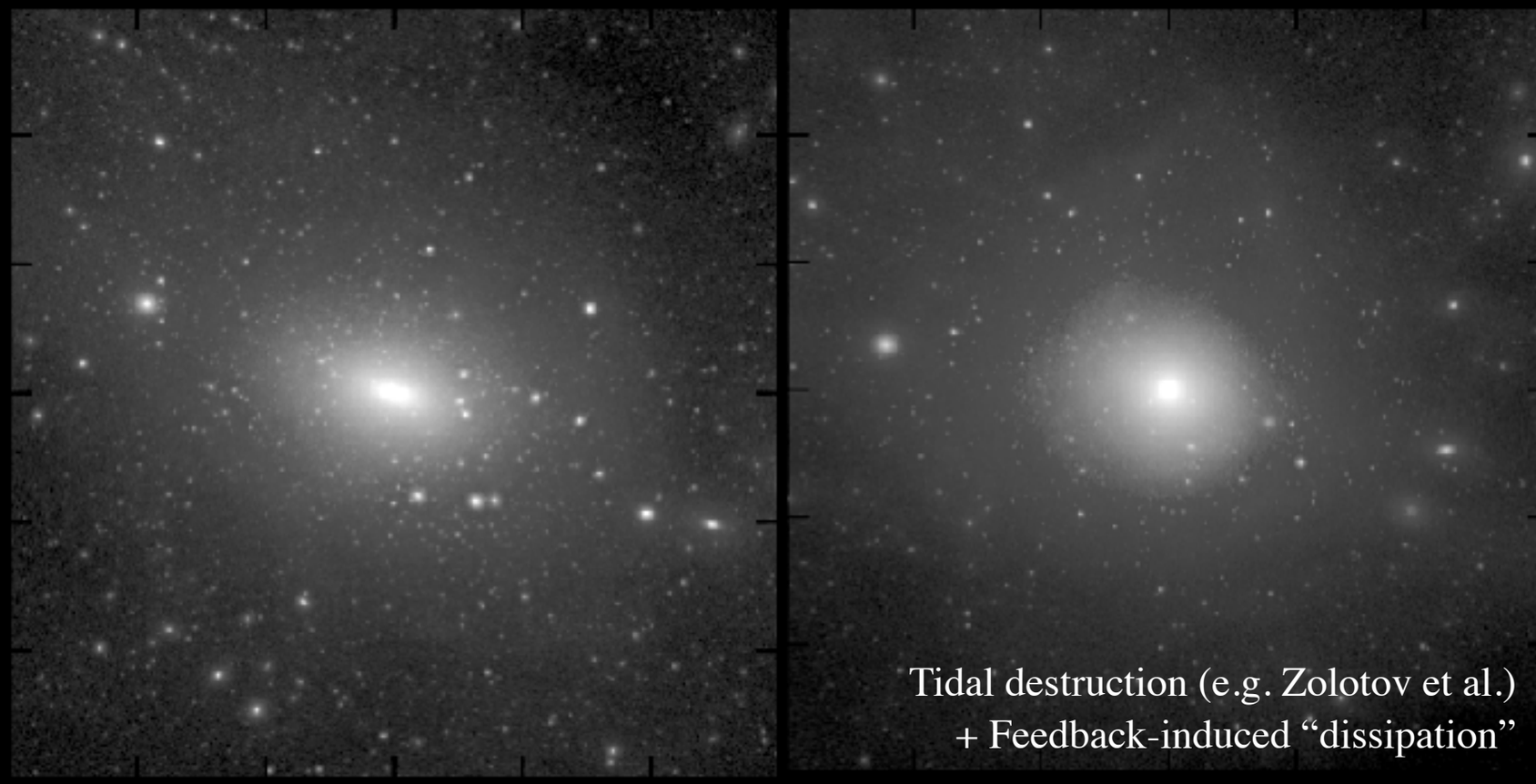
FEEDBACK EXPLAINS WHY SATELLITES ARE "MISSING"

Andrew Wetzel
(arXiv:1602.05957)

Dark matter only simulation
(dark matter)

+ baryons & feedback
(dark matter)

+ baryons & feedback
(stars)



Tidal destruction (e.g. Zolotov et al.)
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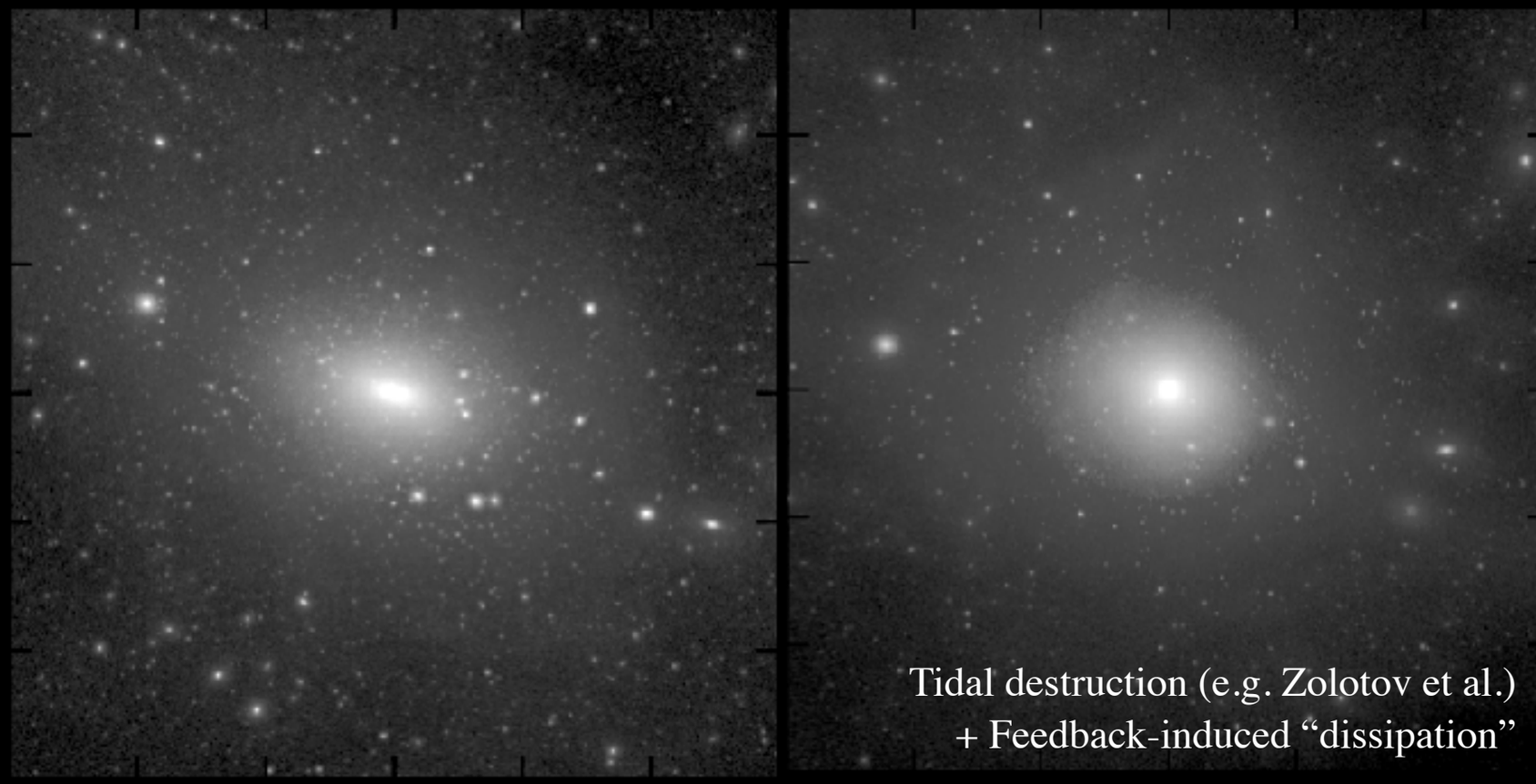

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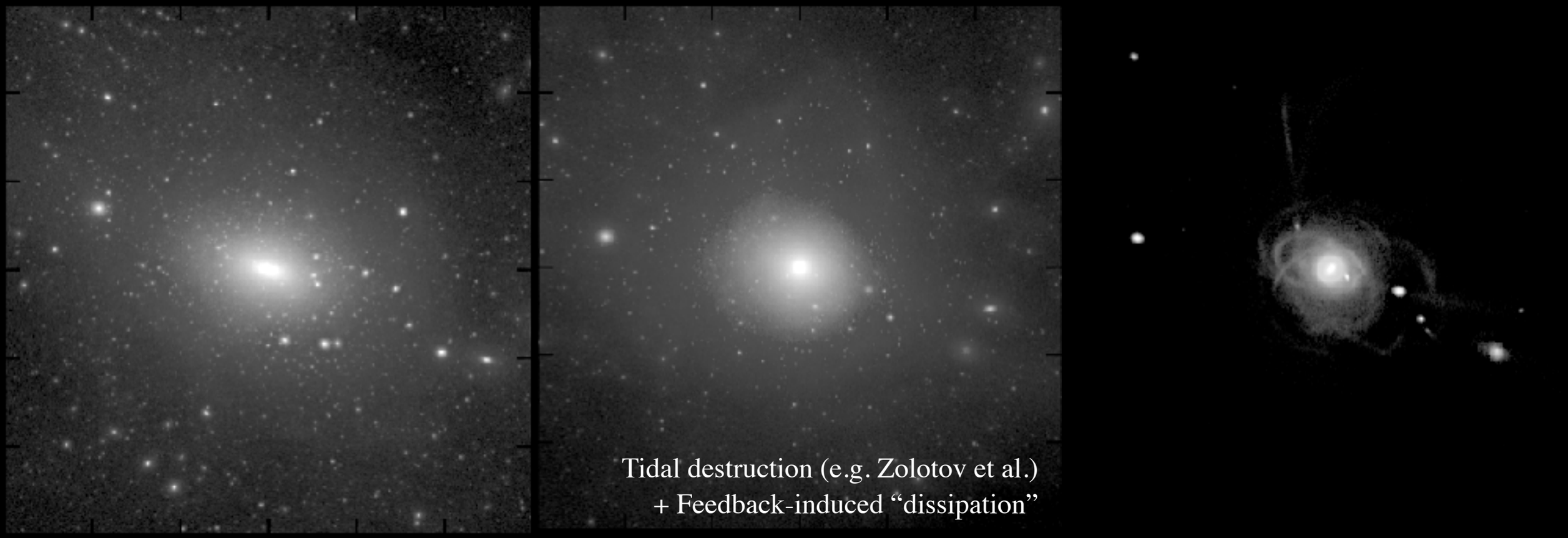

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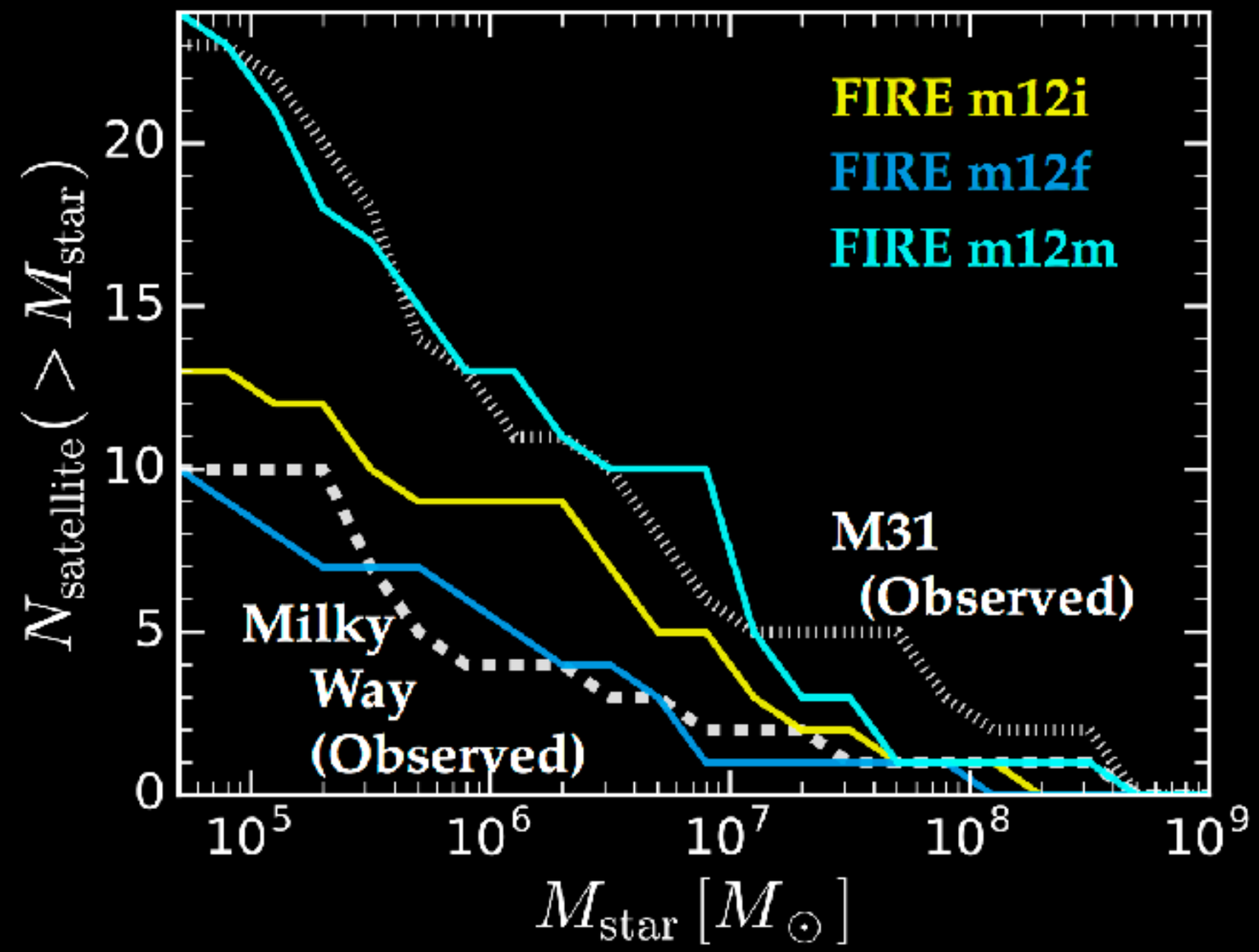
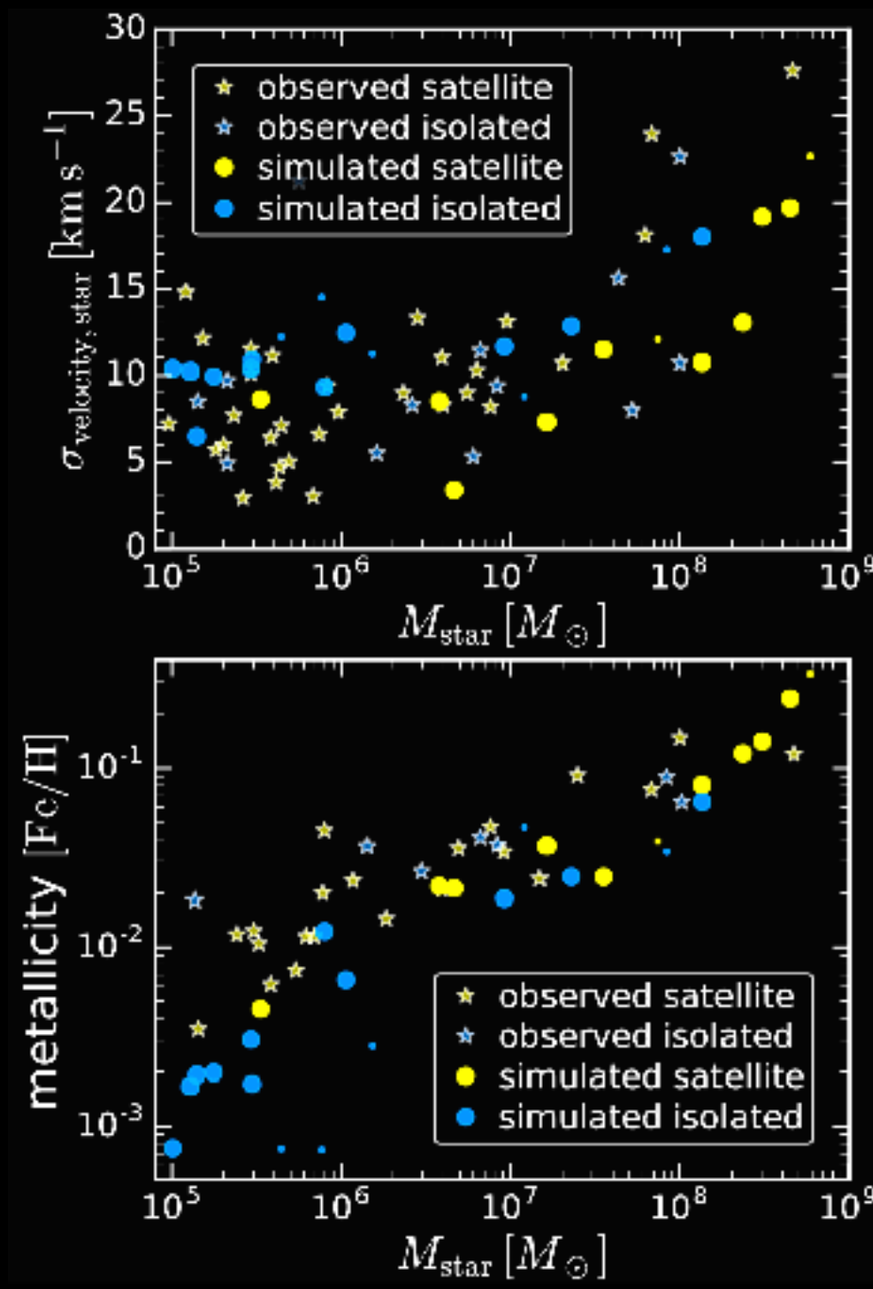
Failures No More

FEEDBACK SUPPRESSES STAR FORMATION AND DENSITIES

Wetzel + I. Escala (prep)

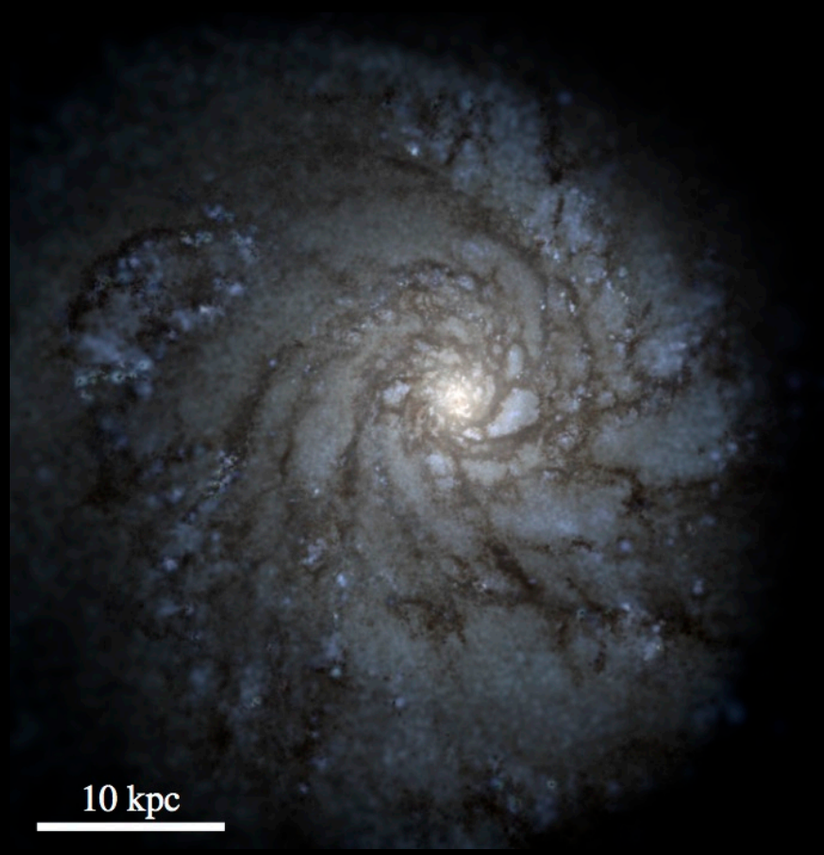


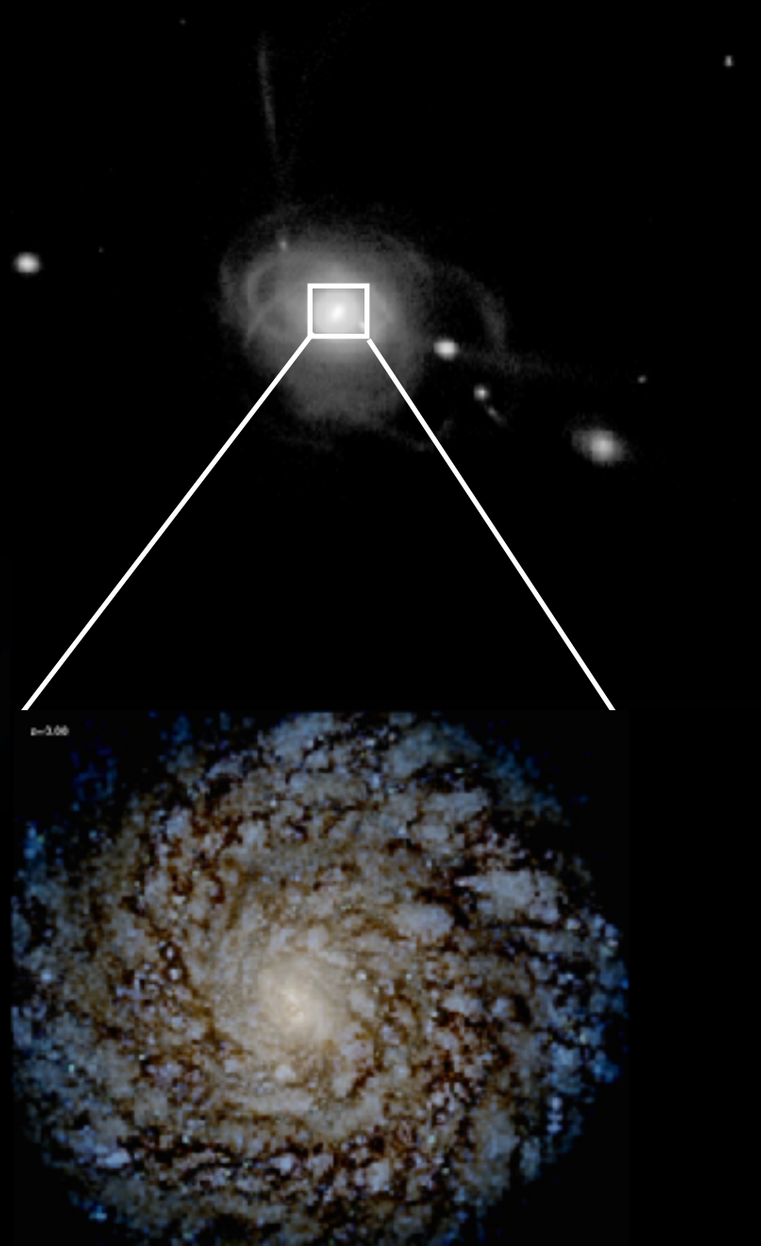


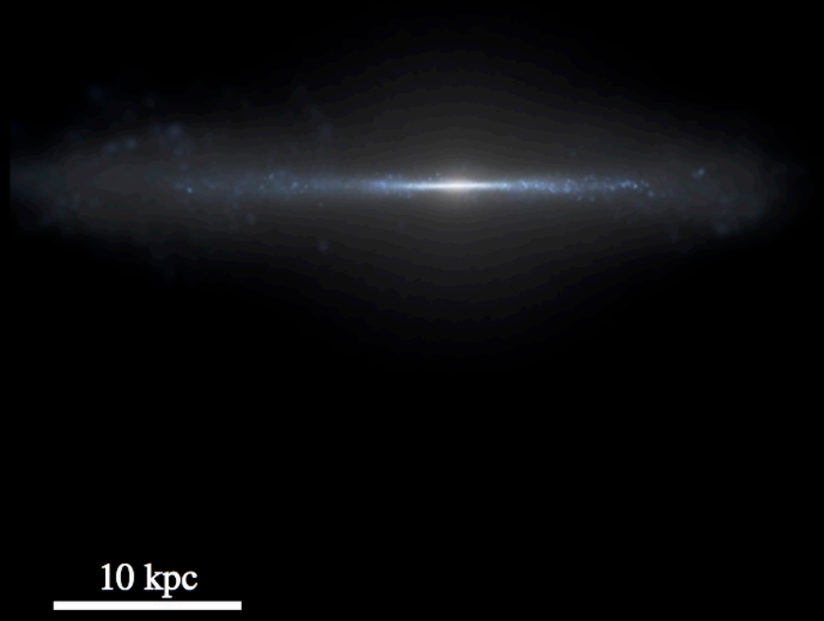
Thin Disks Emerge Naturally

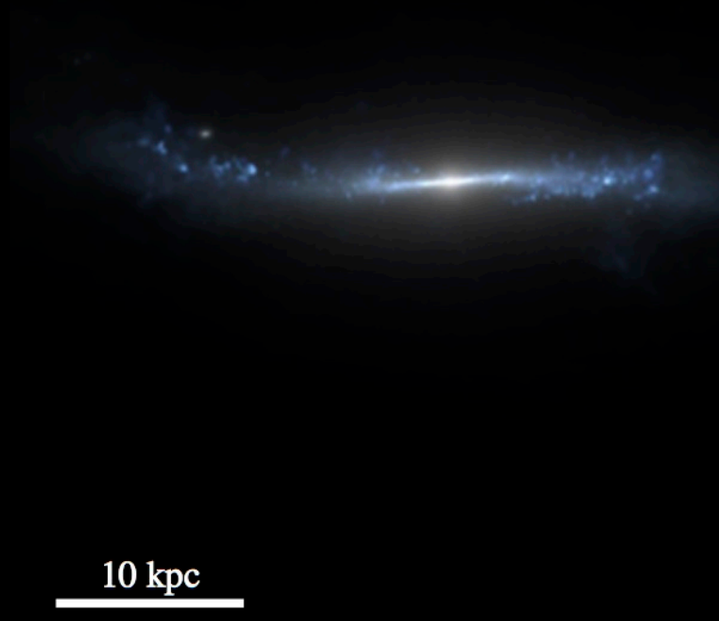
Garrison-Kimmel et al., in prep

+ baryons & feedback (stars)









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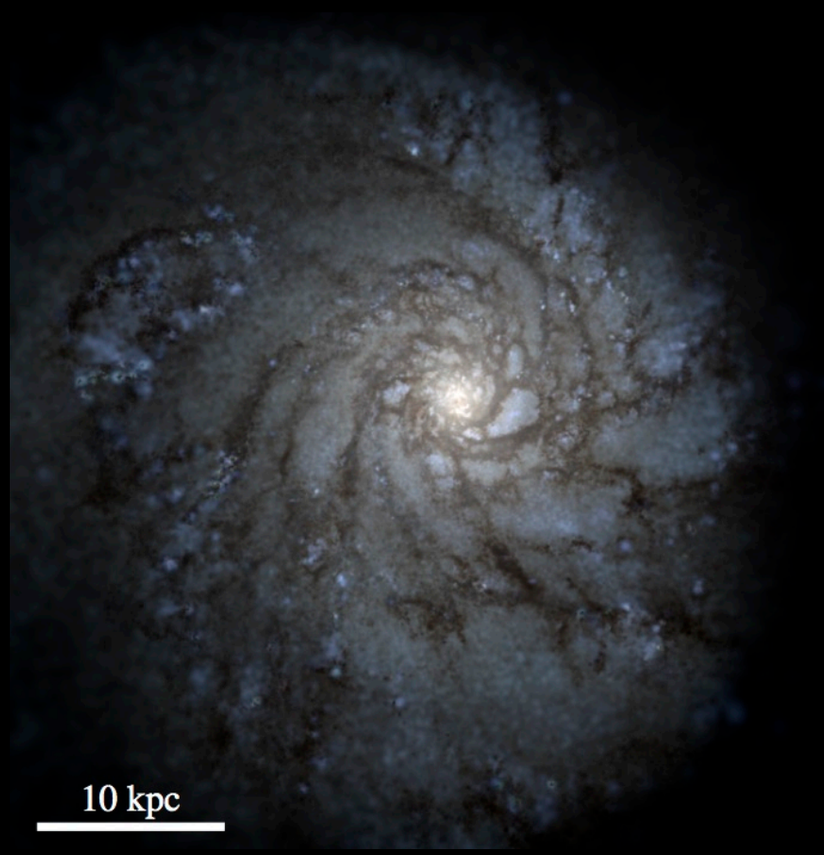
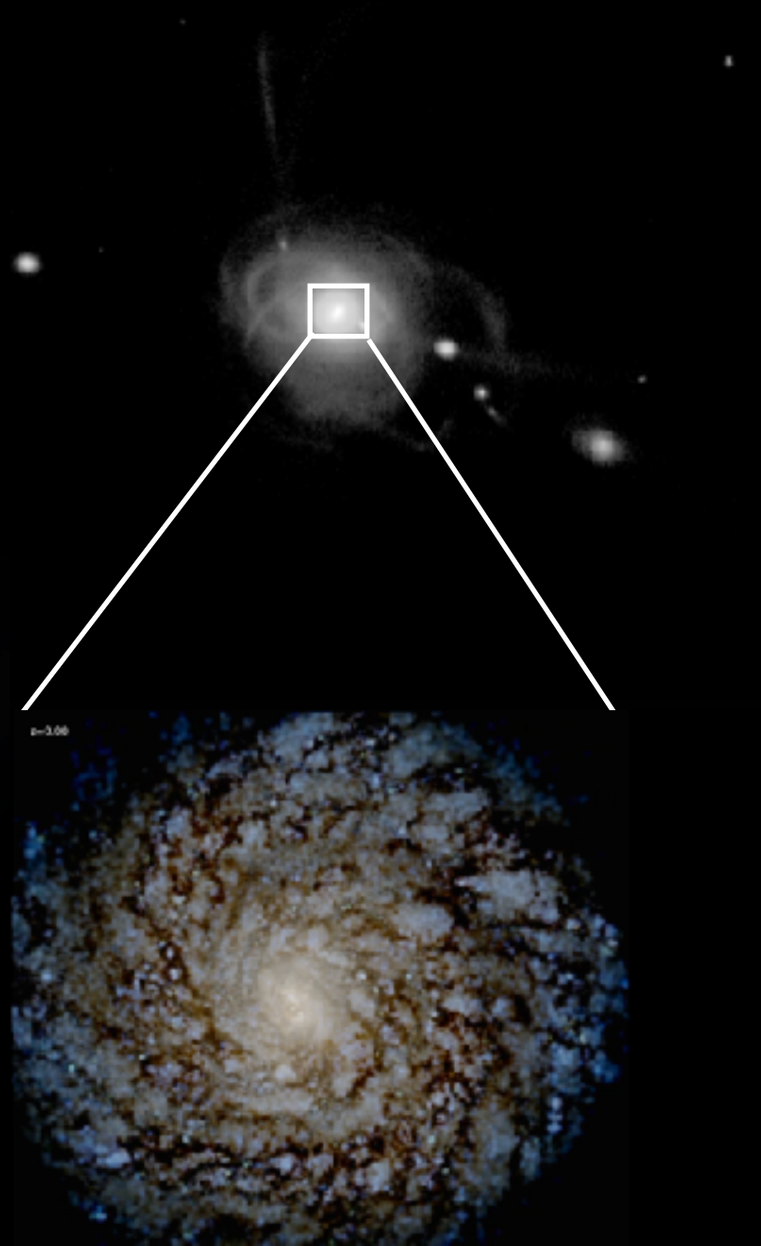
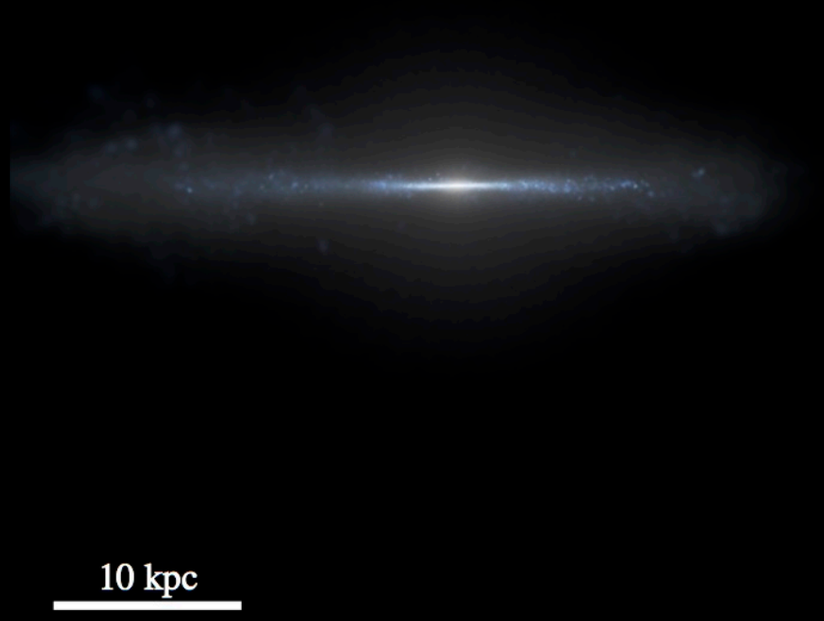
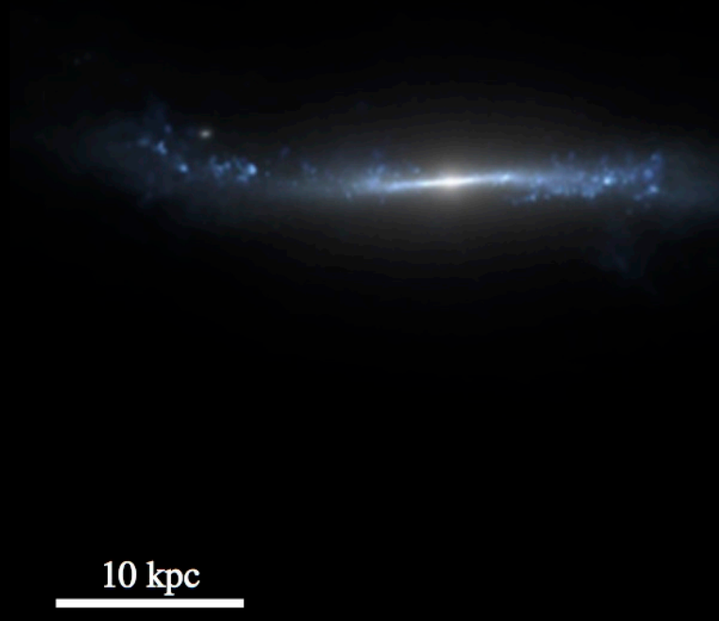


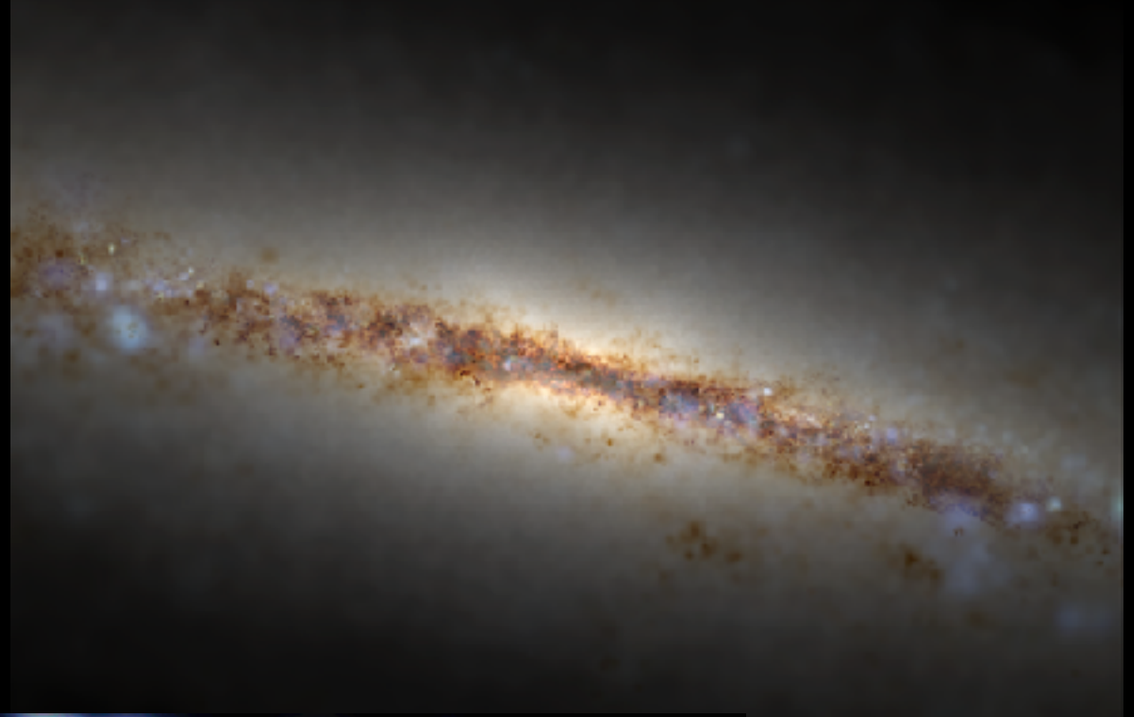


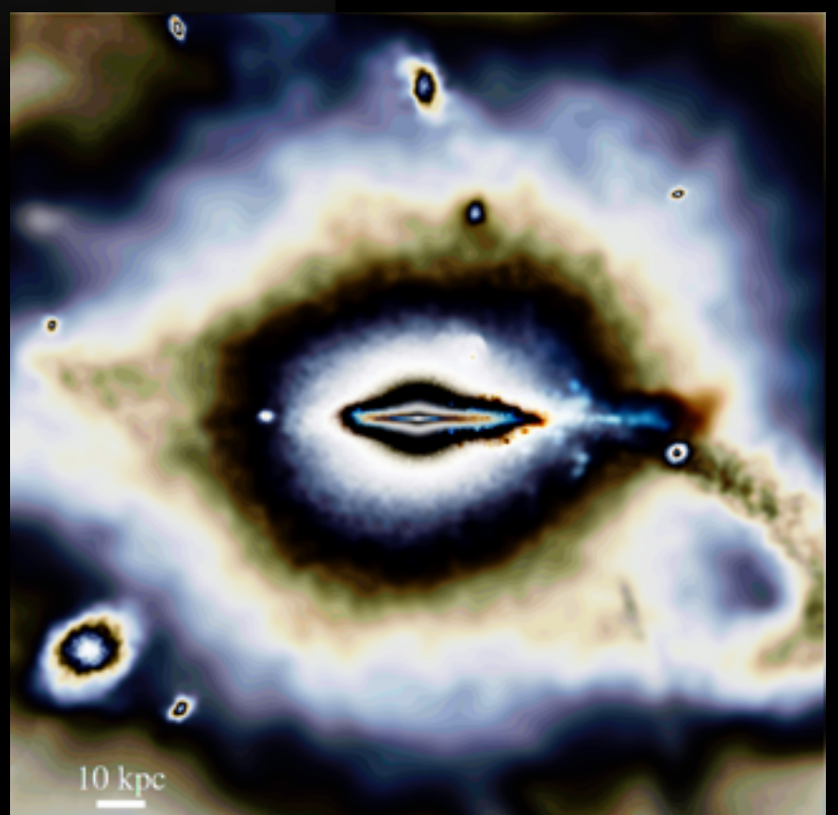




Halo Structure

A NEW GENERATION OF MODELS FOR STELLAR STRUCTURE SURVEYS





Sanderson et al. (in prep)

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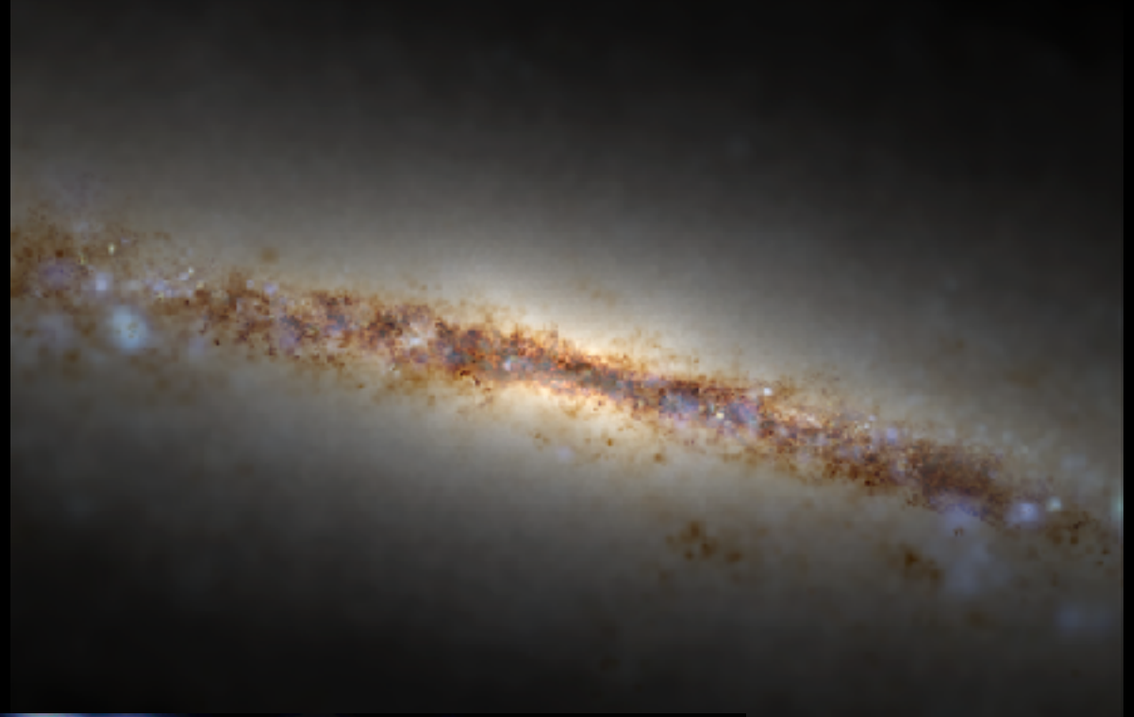

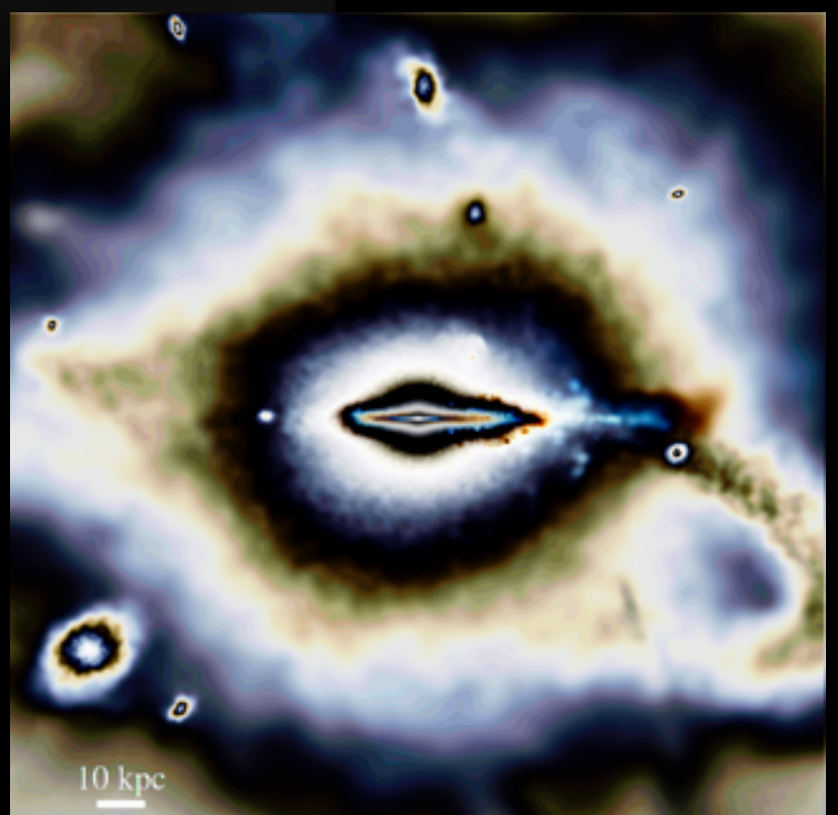

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Where Does Feedback Fail?

Big Bang to Us:

STARS “LIGHT UP” THE UNIVERSE

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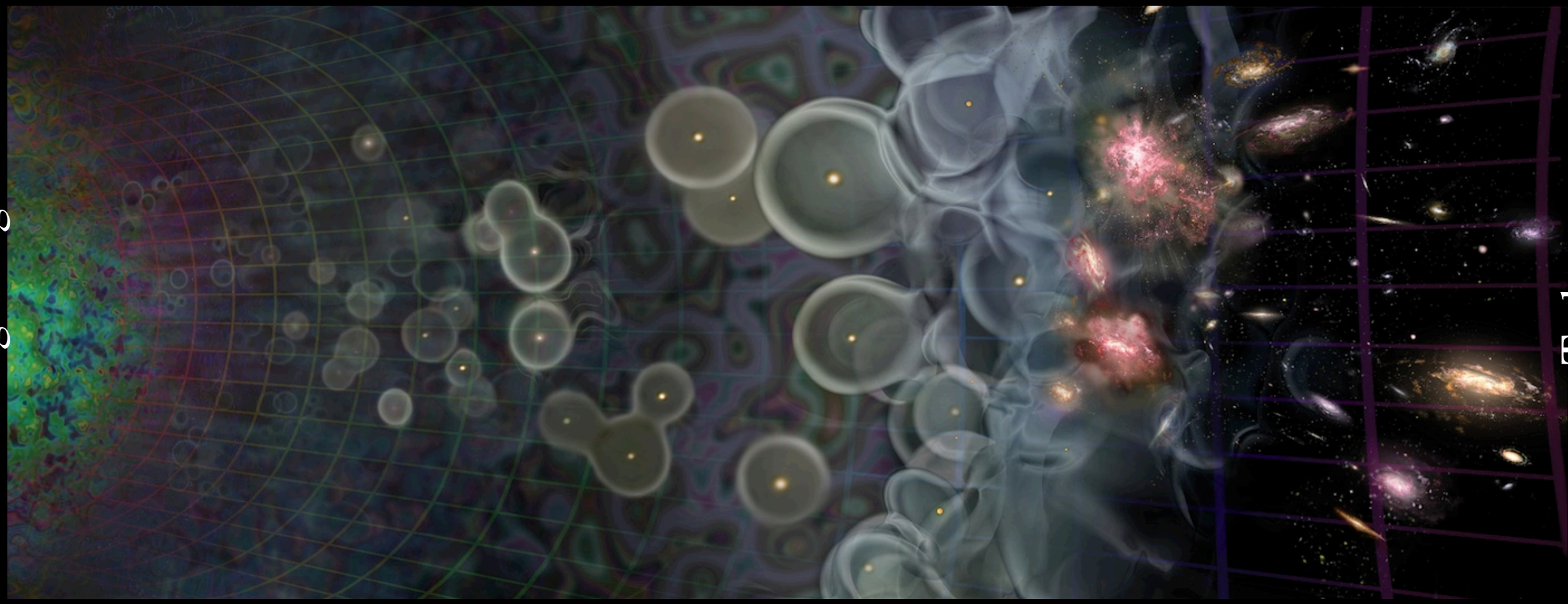

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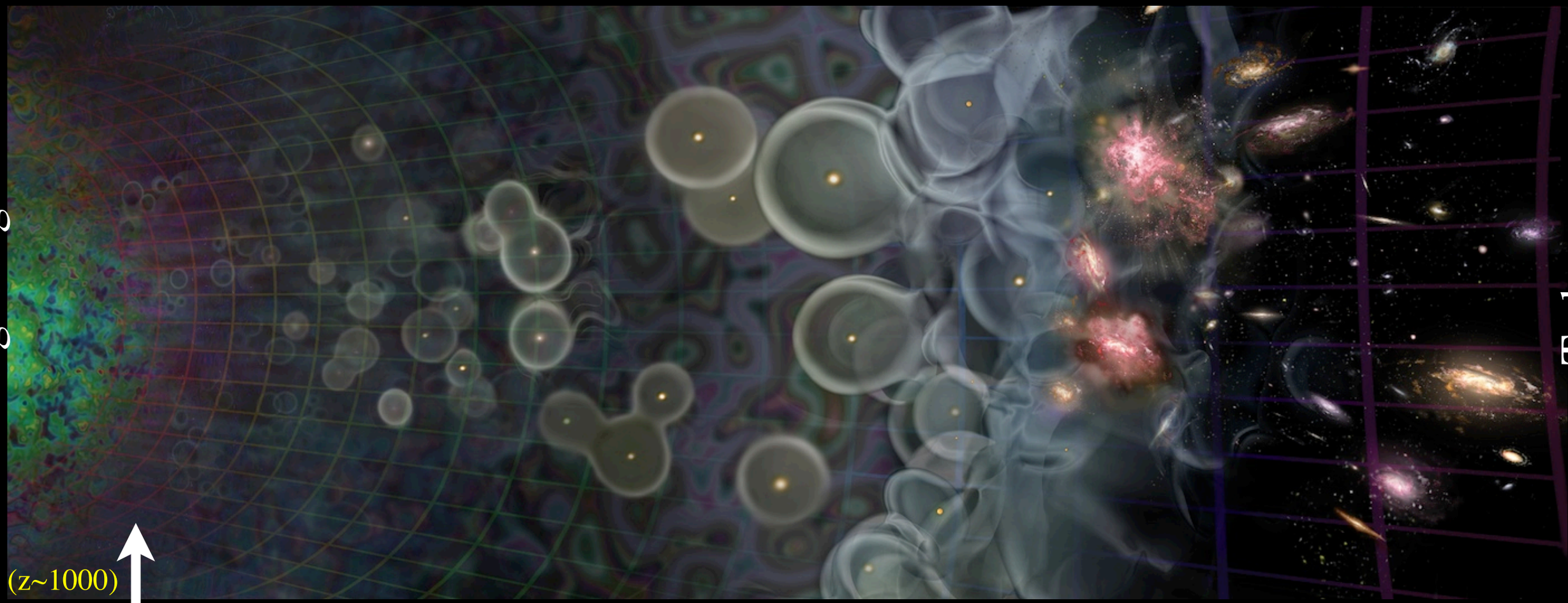

electrons & protons combine:
Cosmic Microwave Background
released

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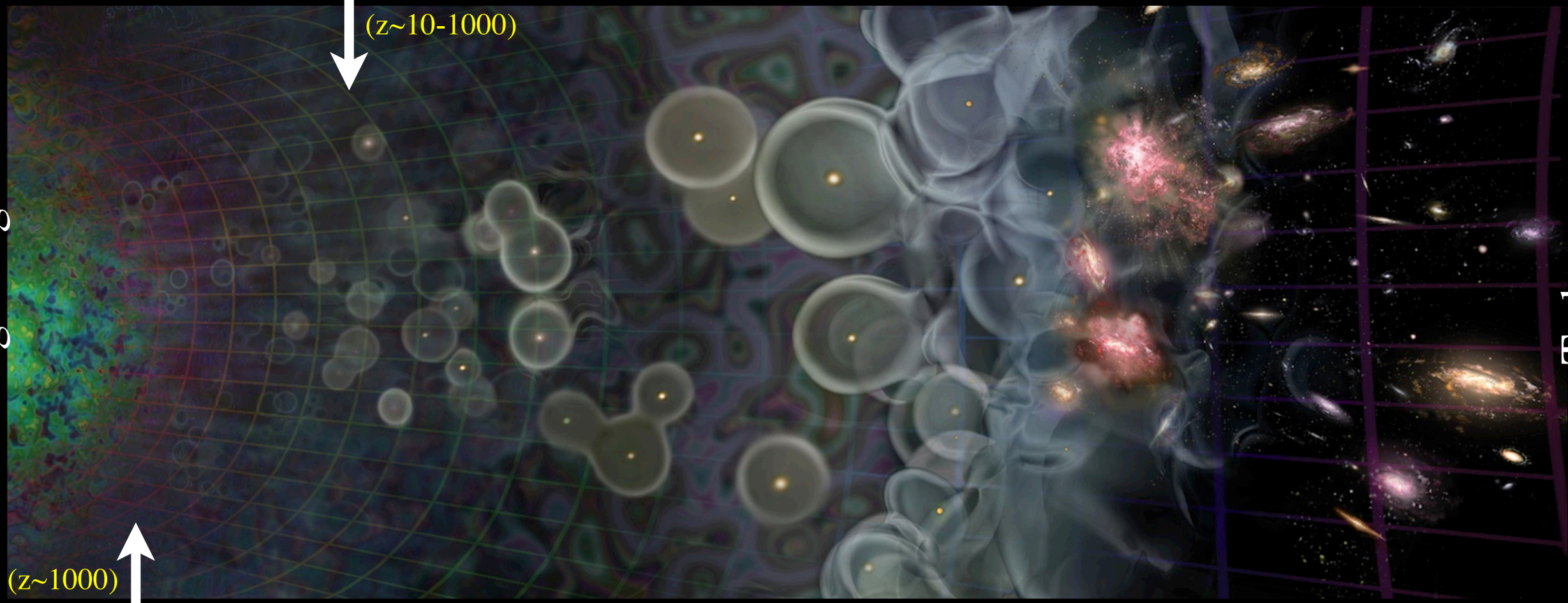
Dark Ages:
first stars form

(z~10-1000)



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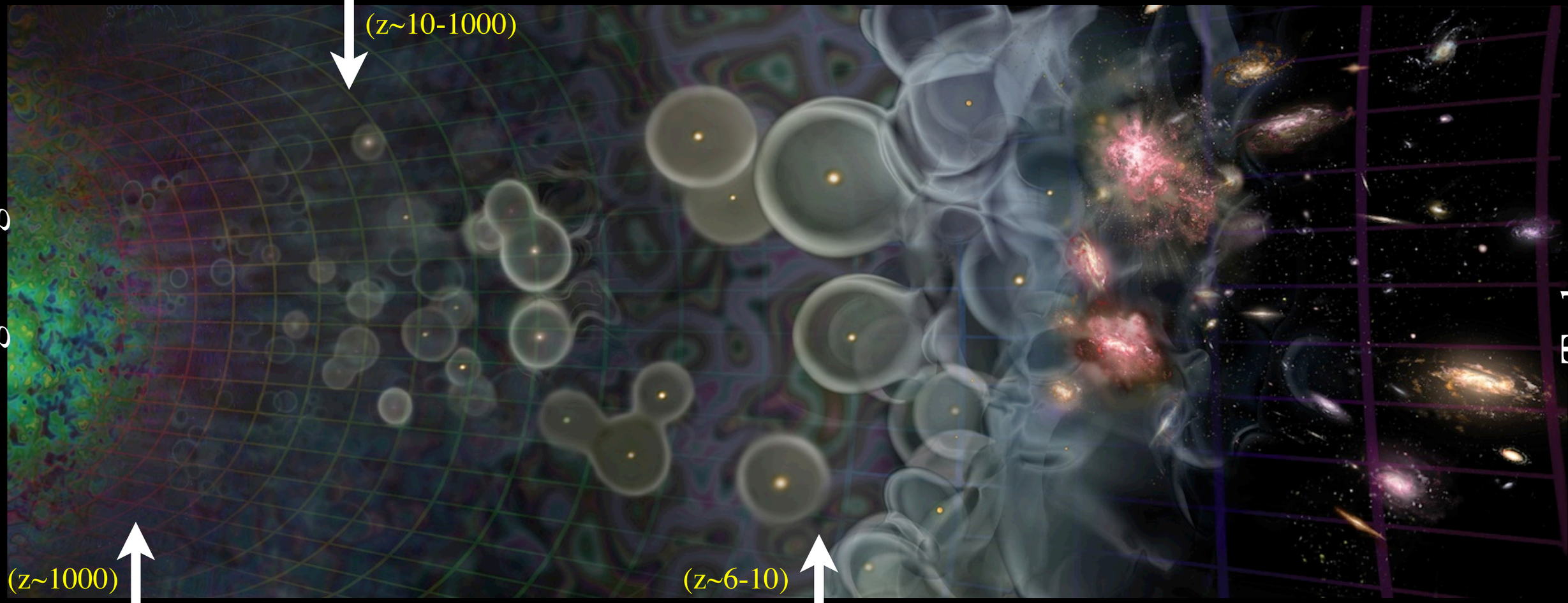

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(z~6-10)

Re-ionization:
starlight fills the Universe,
can reach us

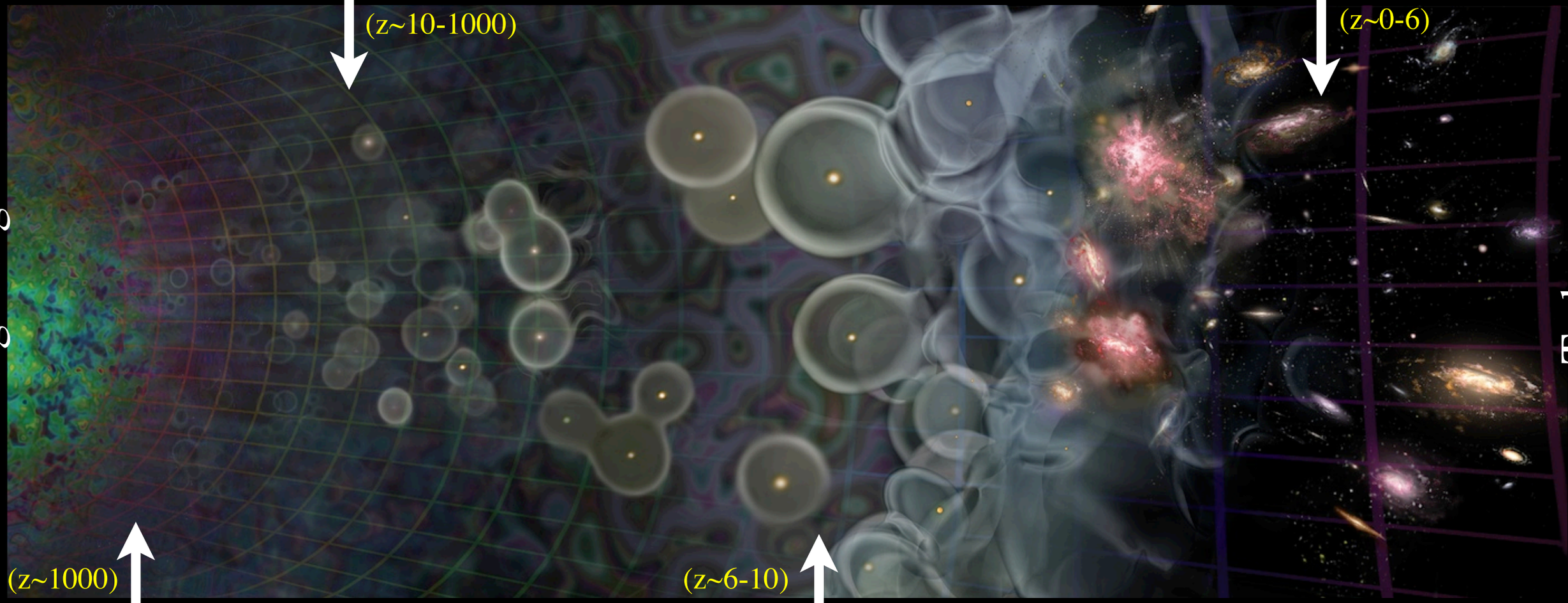
Big Bang to Us:
STARS "LIGHT UP" THE UNIVERSE

Dark Ages:
first stars form

(z~10-1000)

"epoch of galaxies"
begins

(z~0-6)



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Simulating
First Light
(Re-ionization):

(Animation: T. Abel)

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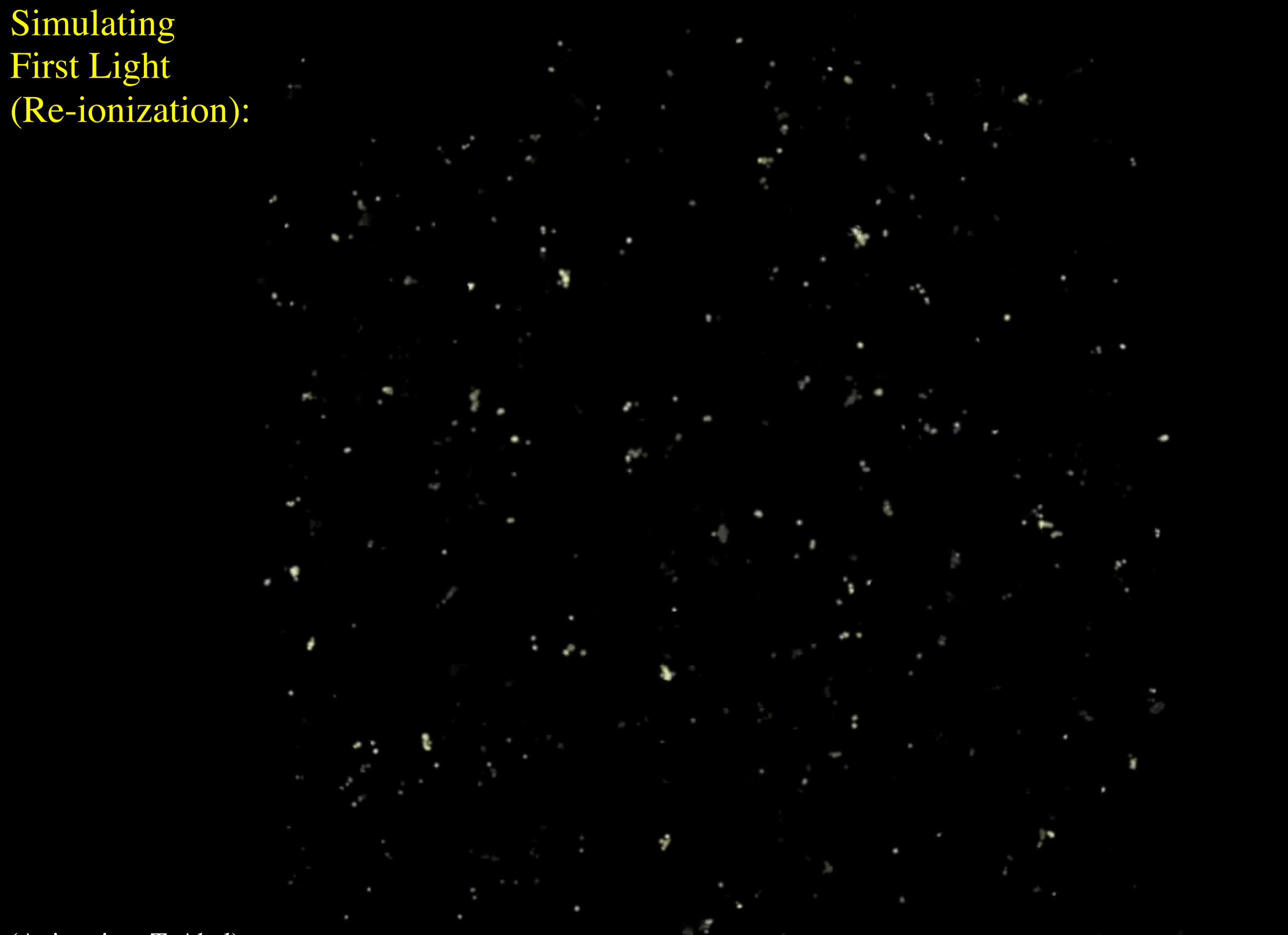

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Re-ionization:

IONIZING PHOTONS FROM STARS MUST “ESCAPE” GALAXIES

(e.g. Robertson et al. 2015, 2016)

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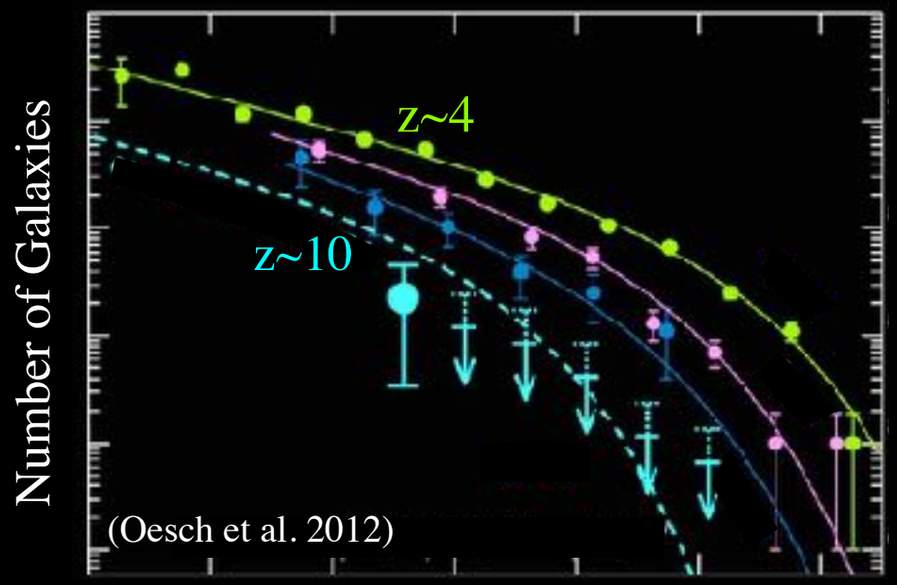
of photons *emitted* (how many stars)
(galaxy counts, re-emitted/absorbed H-alpha light)



Luminosity (Mass in Young Stars)

(e.g. Robertson et al. 2015, 2016)

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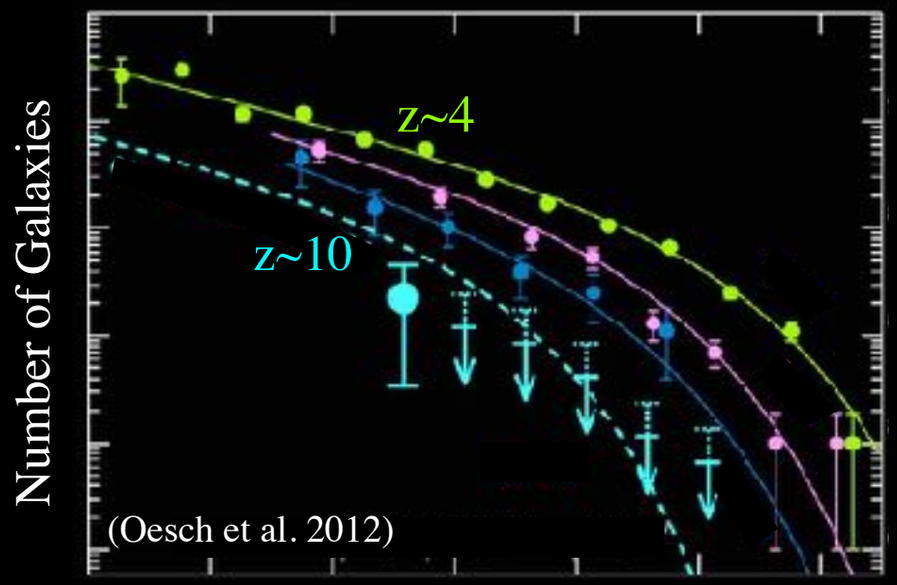

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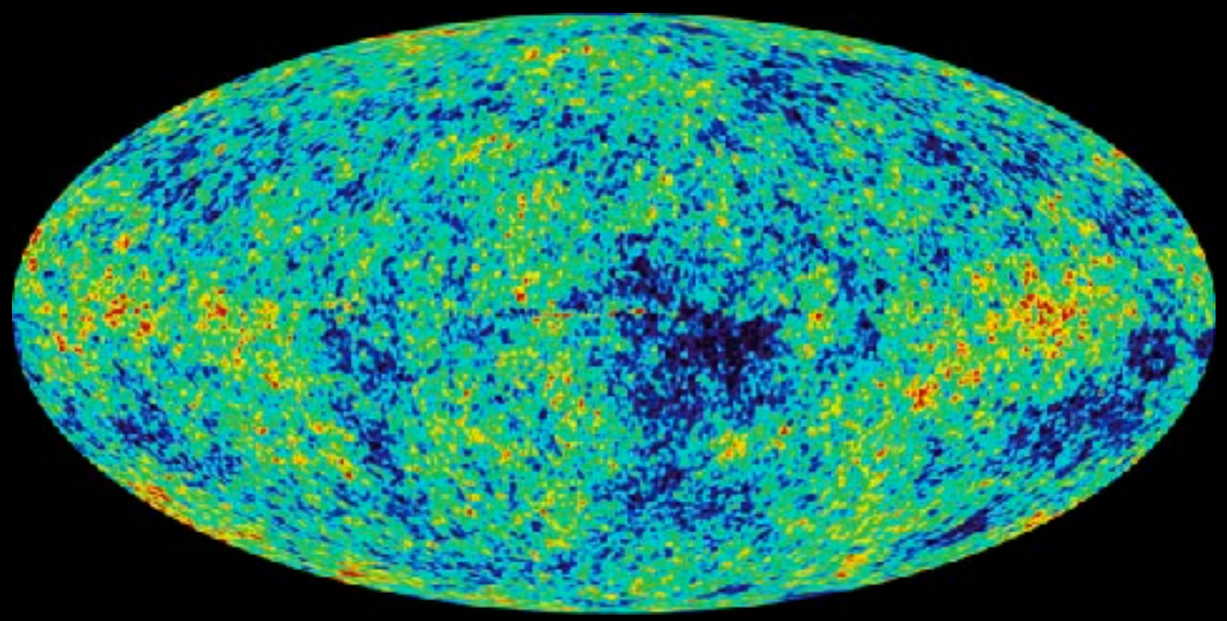

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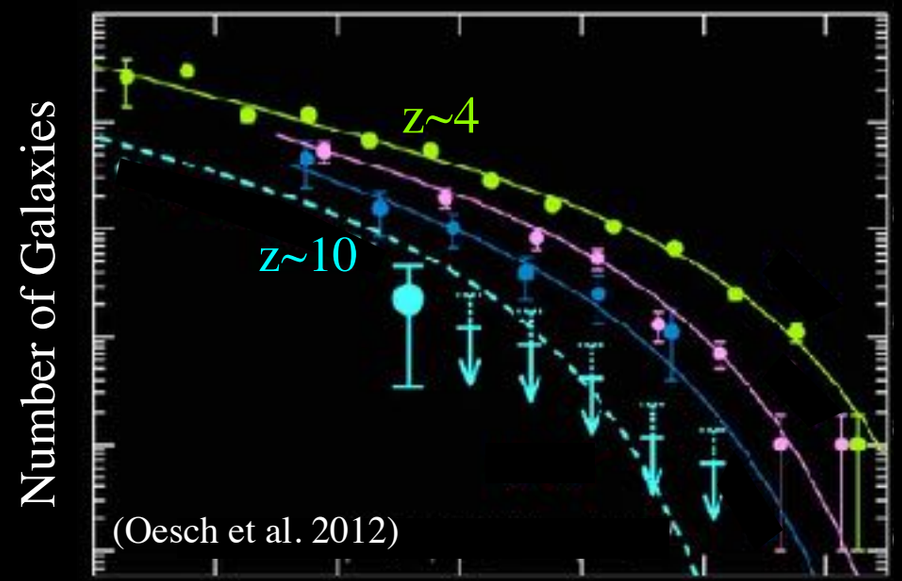

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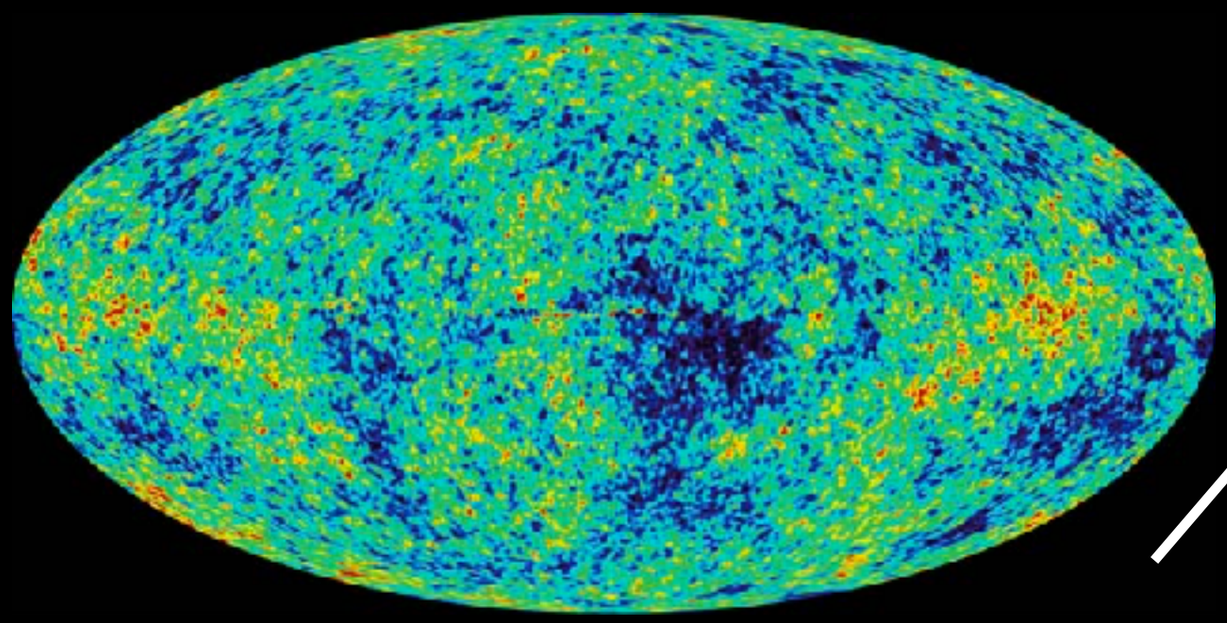


~20% must *escape* their galaxies

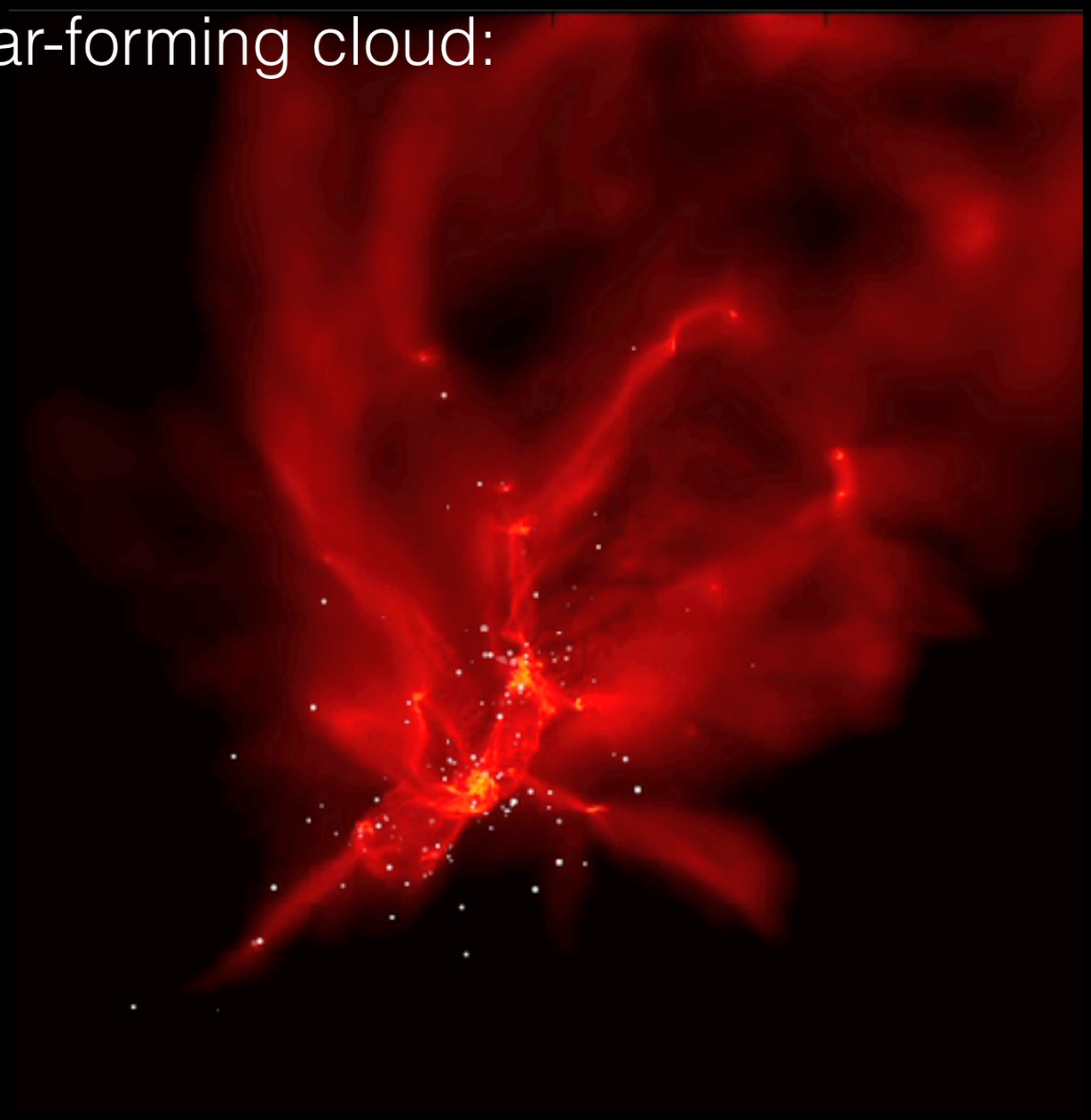
(e.g. Robertson et al. 2015, 2016)

Problem:
STARS FORM IN DENSE, COLD CLOUDS

Xiangcheng Ma
(arXiv:1503.07880)

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

Star-forming cloud:



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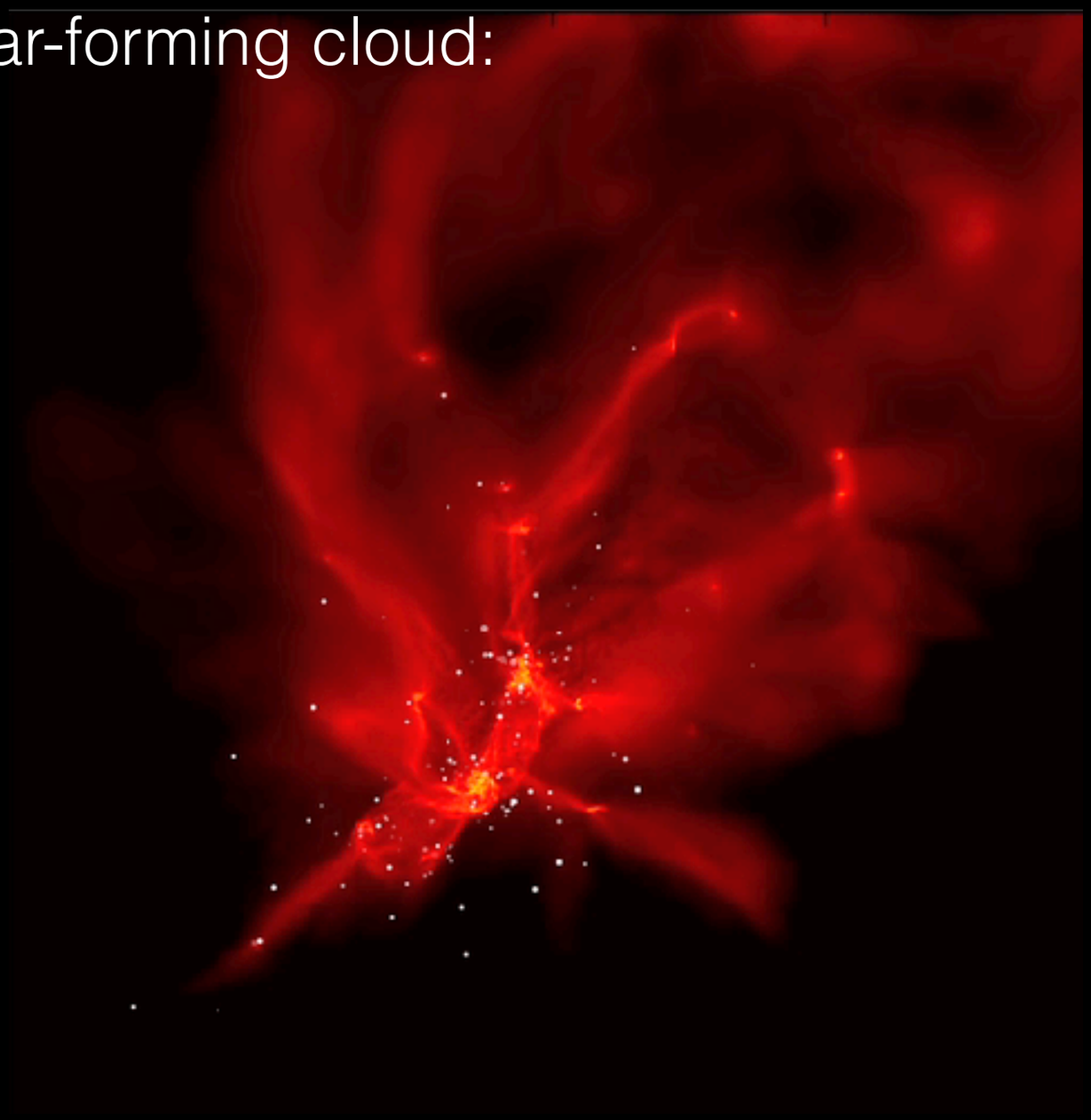

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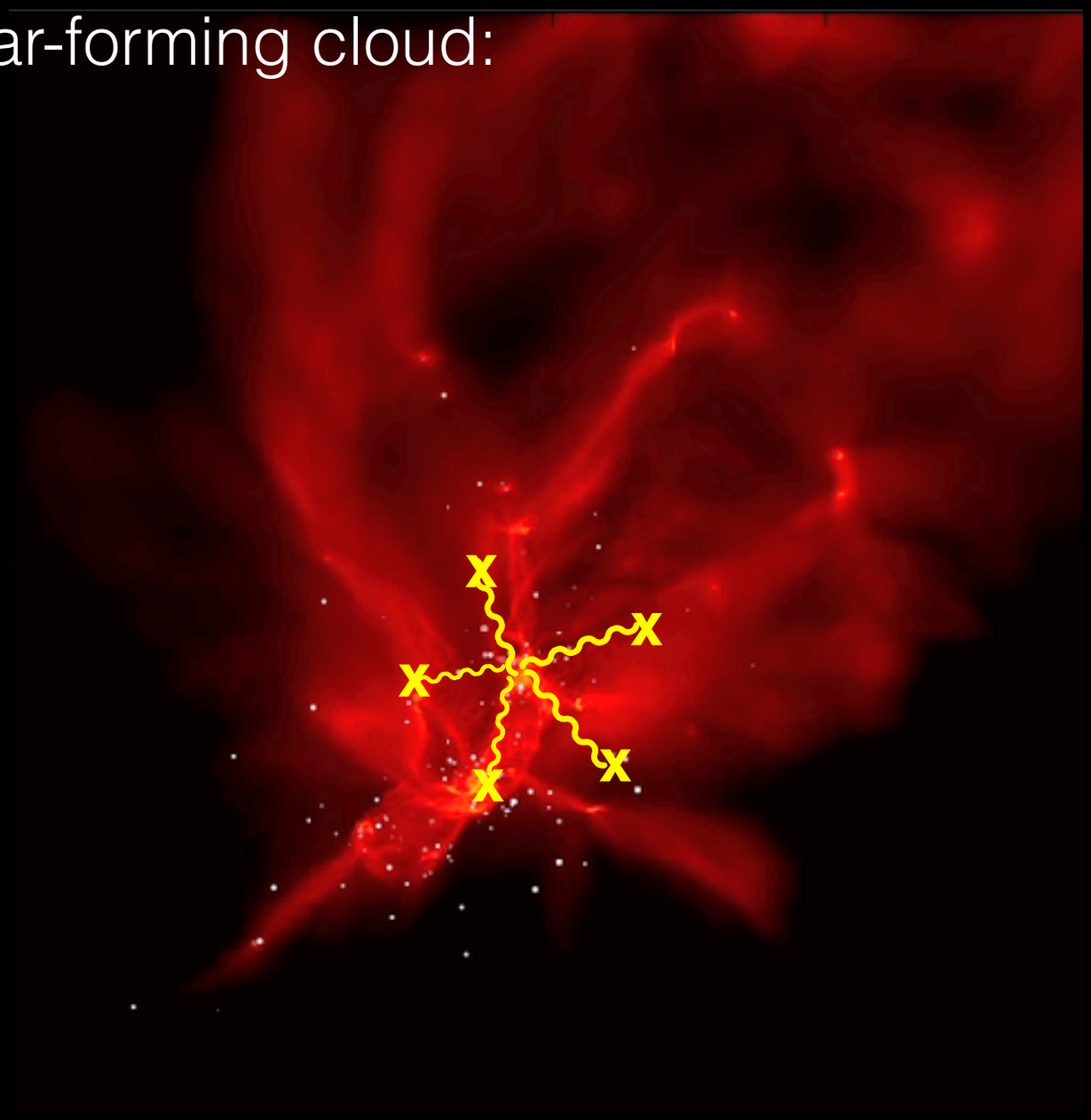

- Nothing escapes!

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

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STARS FORM IN DENSE, COLD CLOUDS

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

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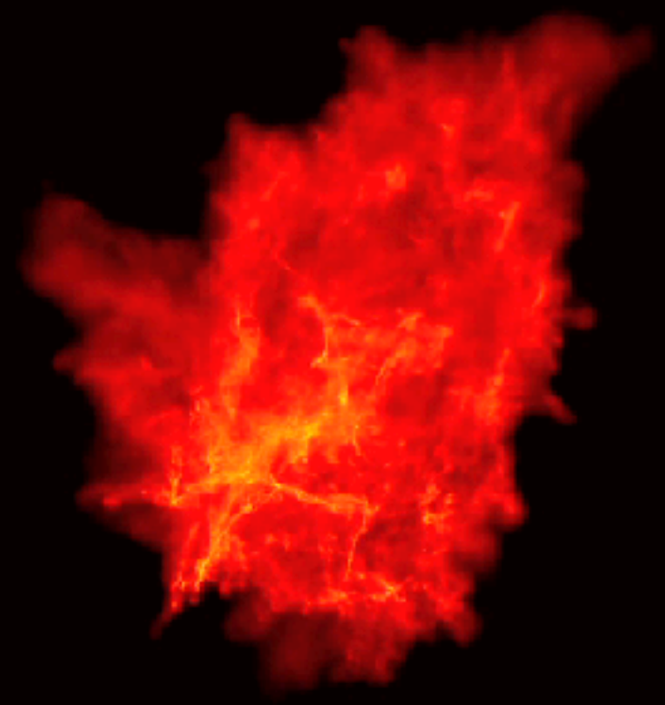

If stars were passive
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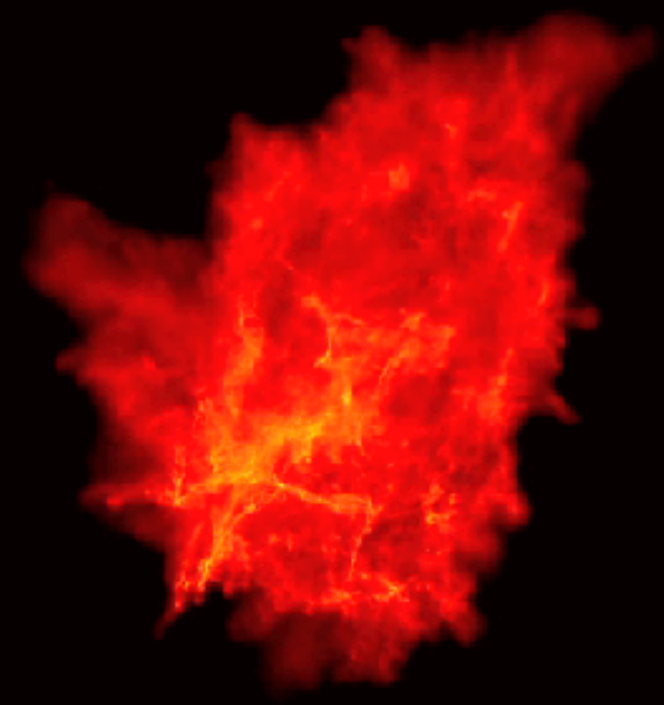

Realistic
(stellar winds & radiation included)

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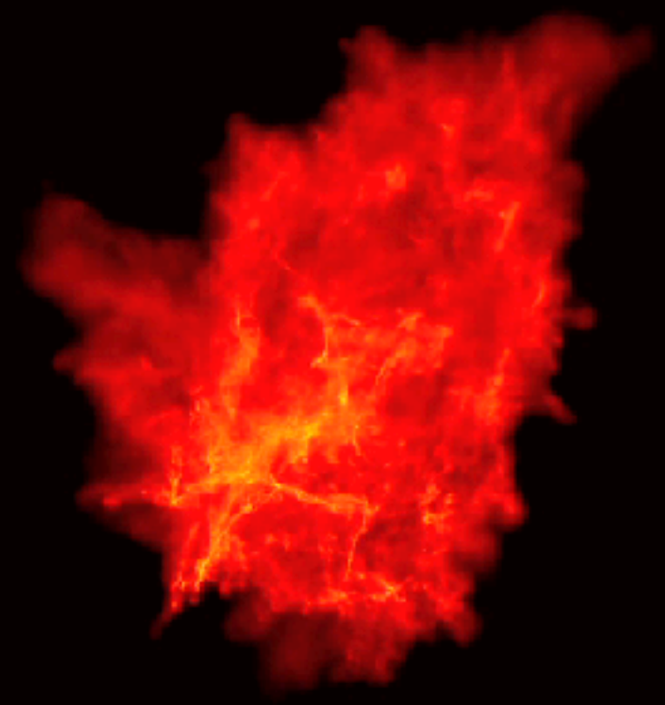

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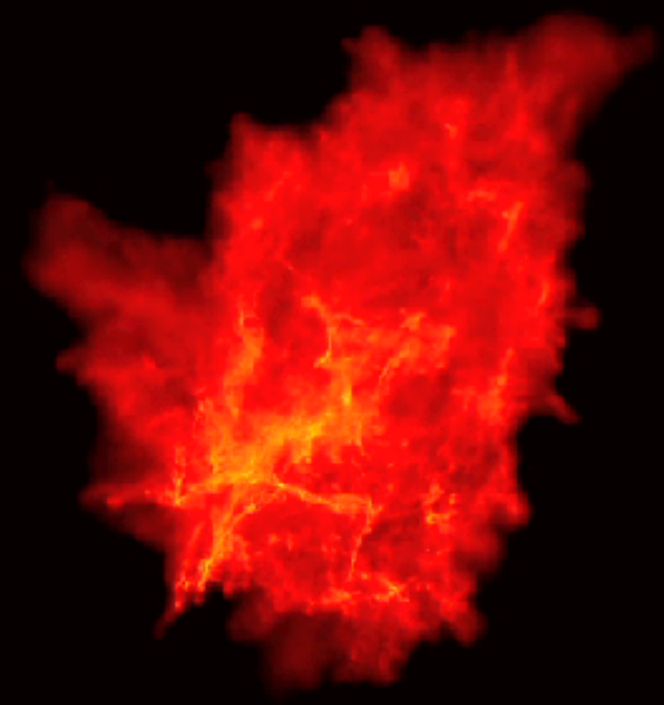

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It's Not Enough!

TAKES TOO LONG TO DESTROY THE CLOUDS

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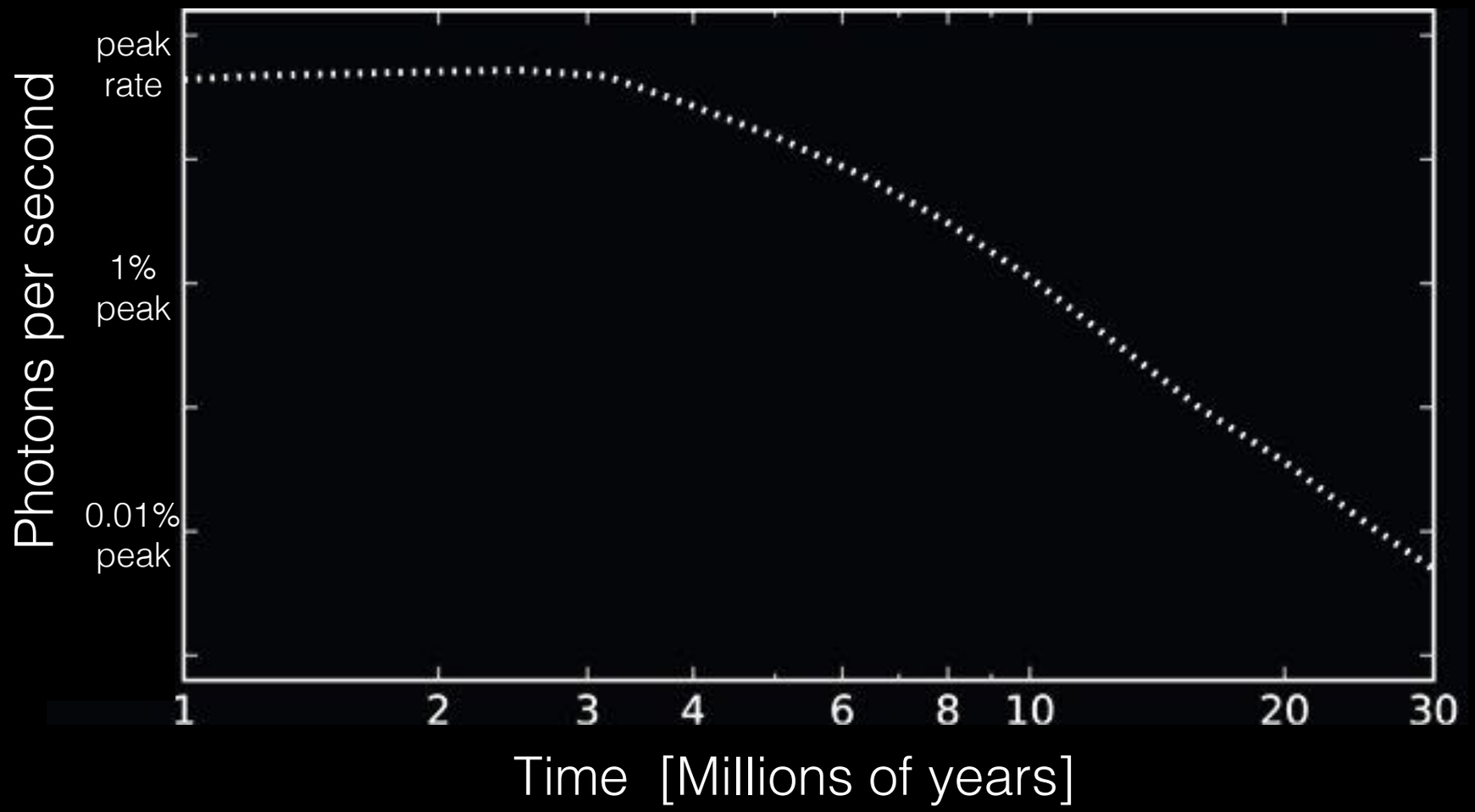
(from a stellar population)



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

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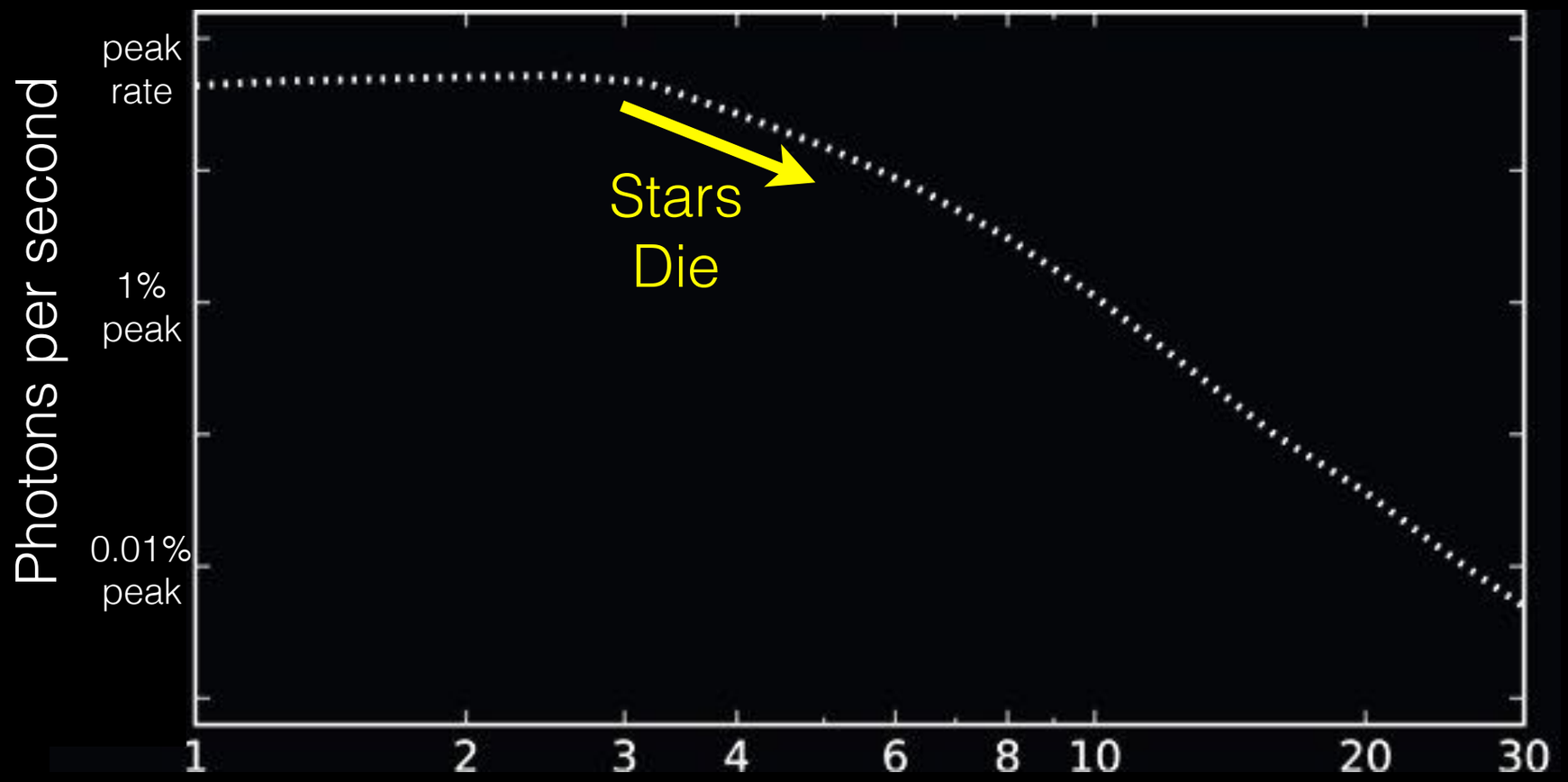

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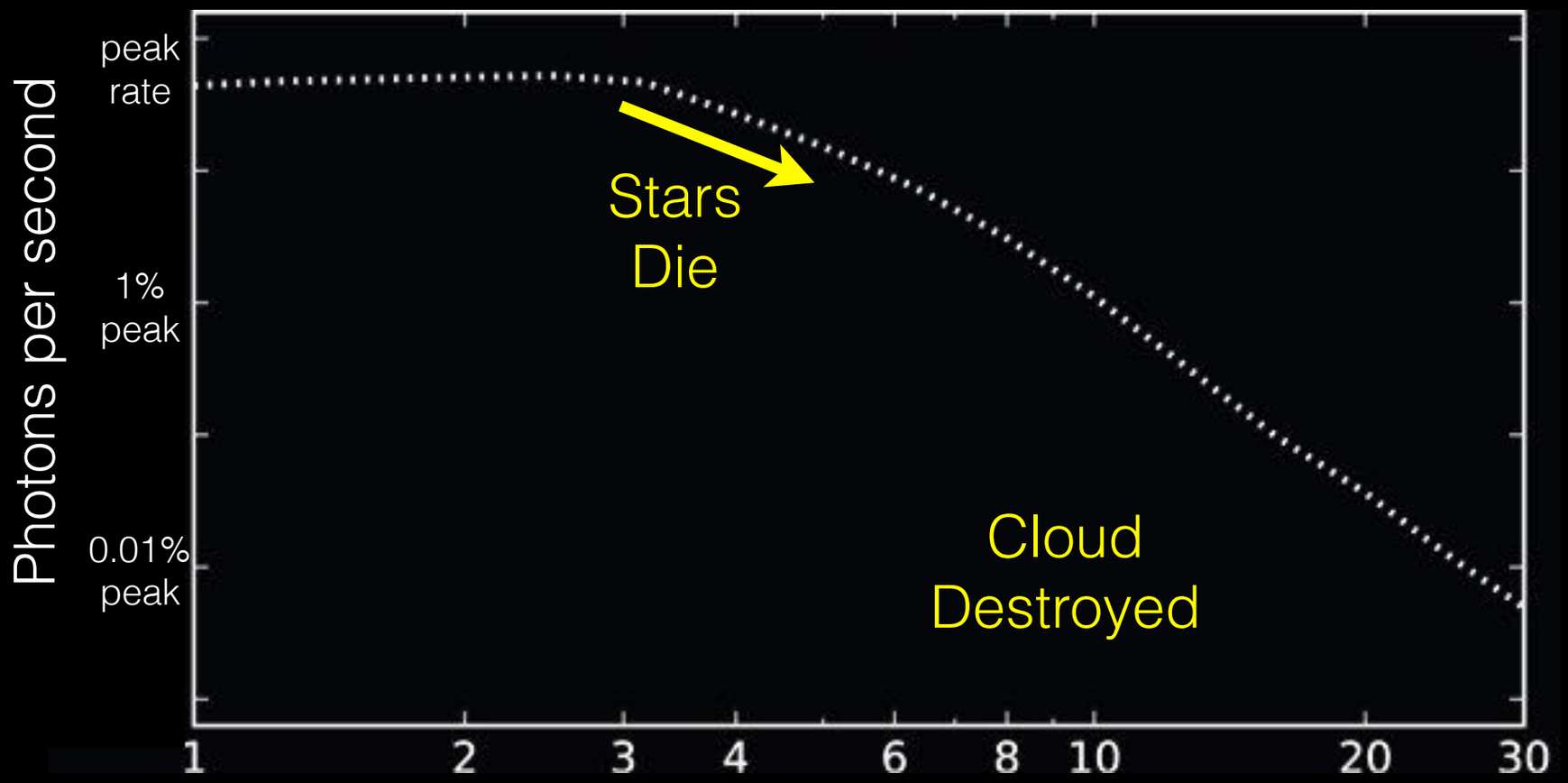

(also Wise et al., Kimm & Cen 2015)

It's Not Enough!

TAKES TOO LONG TO DESTROY THE CLOUDS

Xiangcheng Ma
(arXiv:1503.07880)

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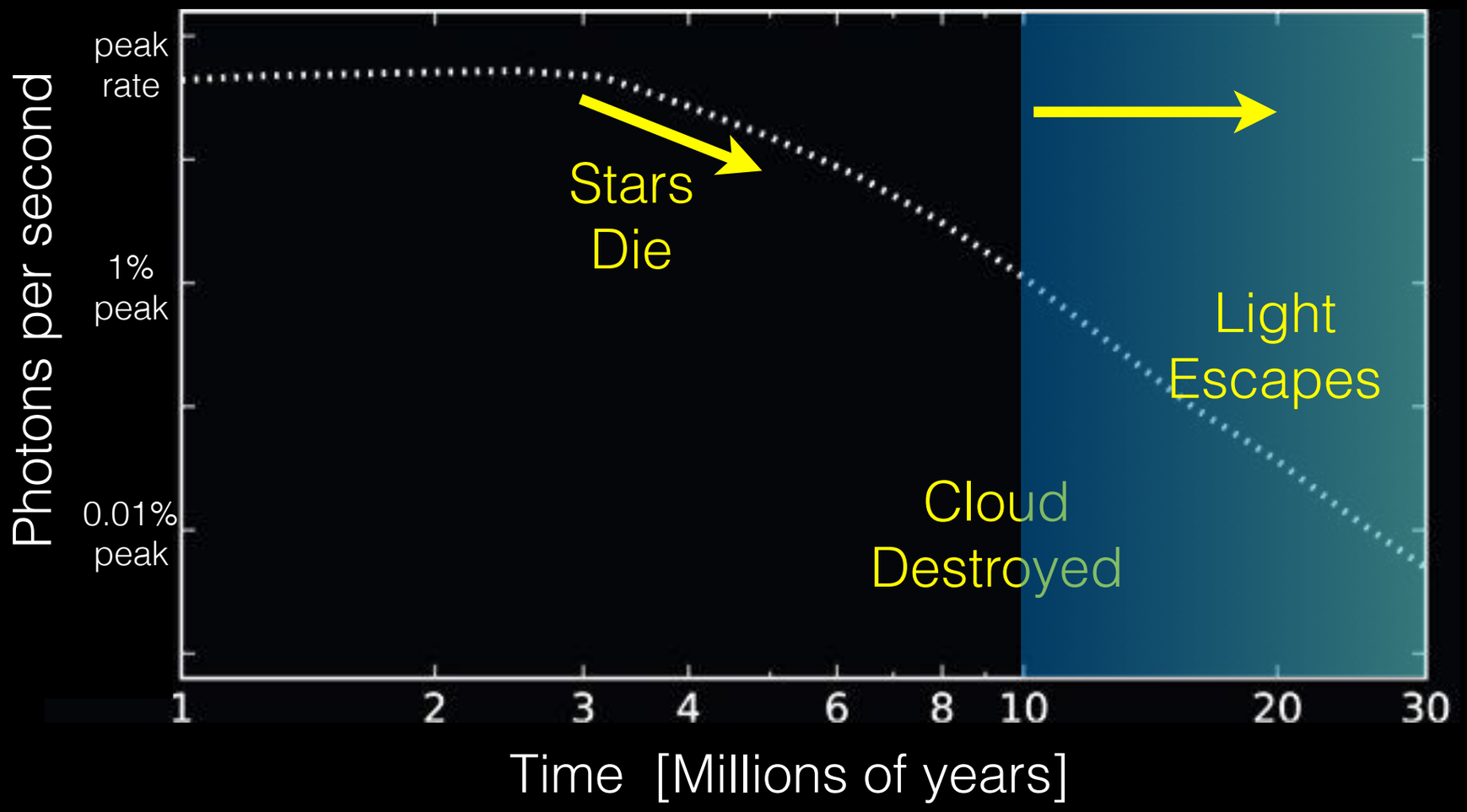

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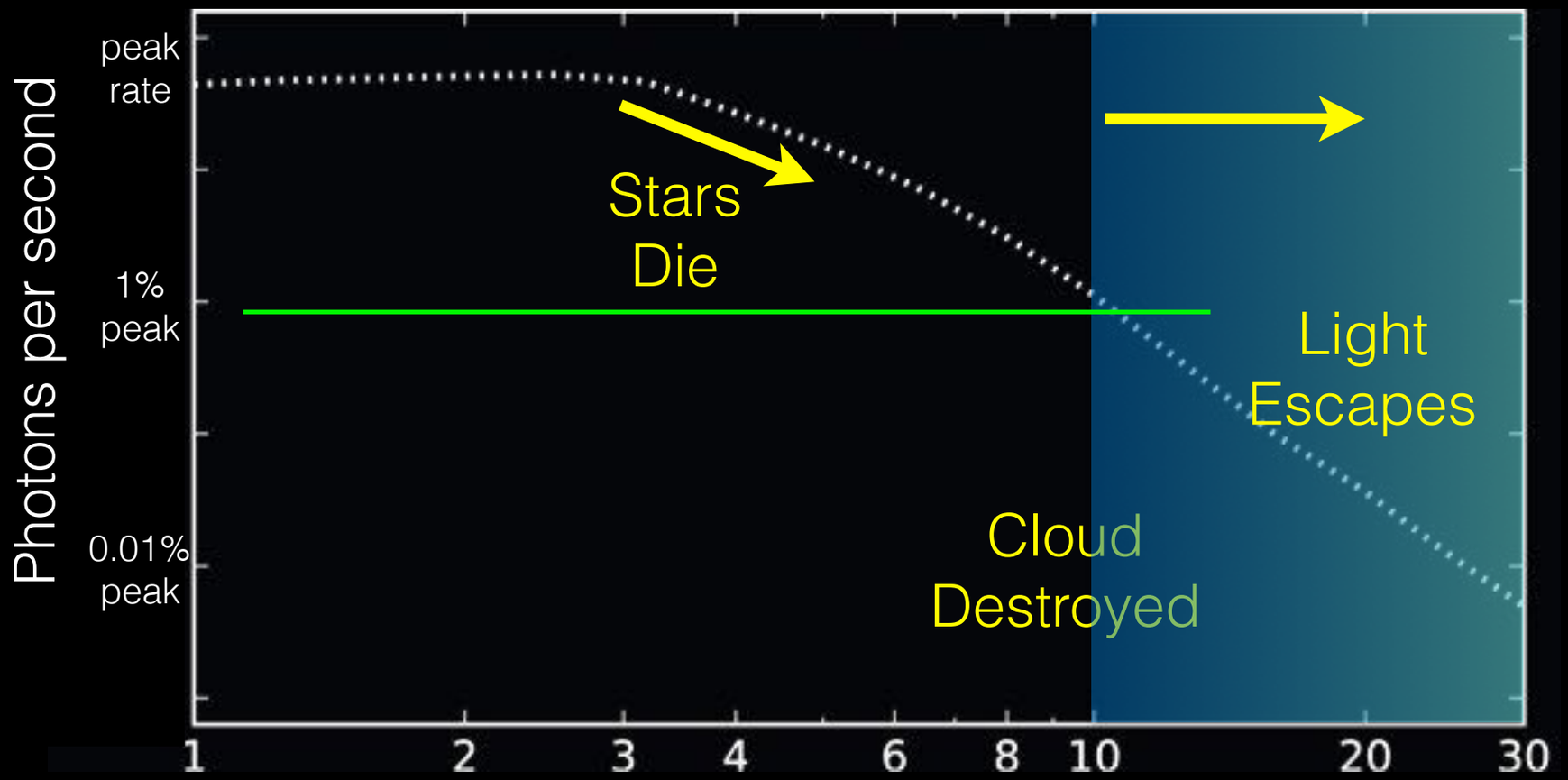

Simulation: only ~1% escape!

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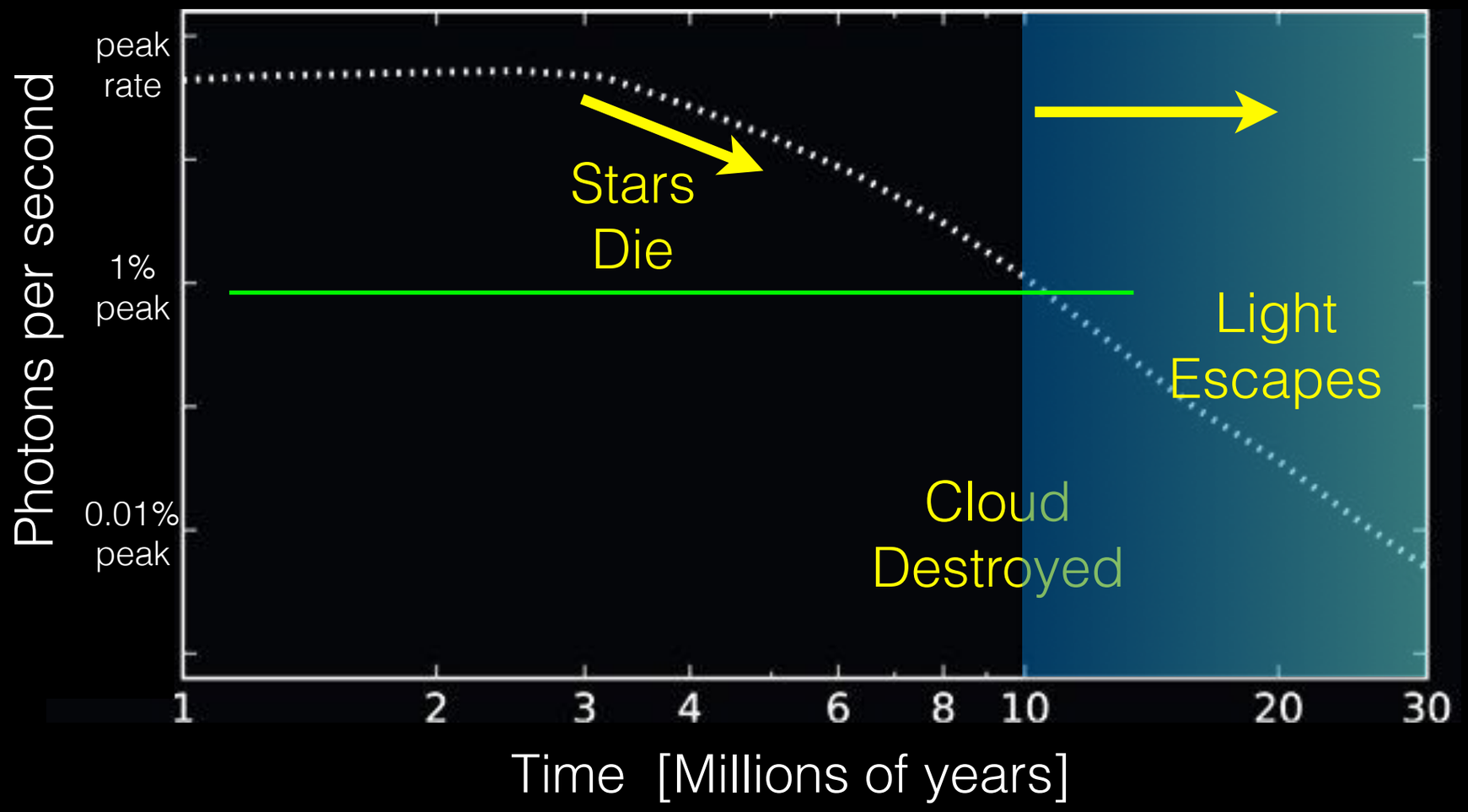

- Invariant to:
  - Resolution
  - Strength of feedback
  - Numerical methods
  - Star formation rates
  - IMF shape/sampling
  - Runaway stars

Simulation: only ~1% escape!

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

Other Mysteries?

SOME PHYSICS IS MISSING HERE

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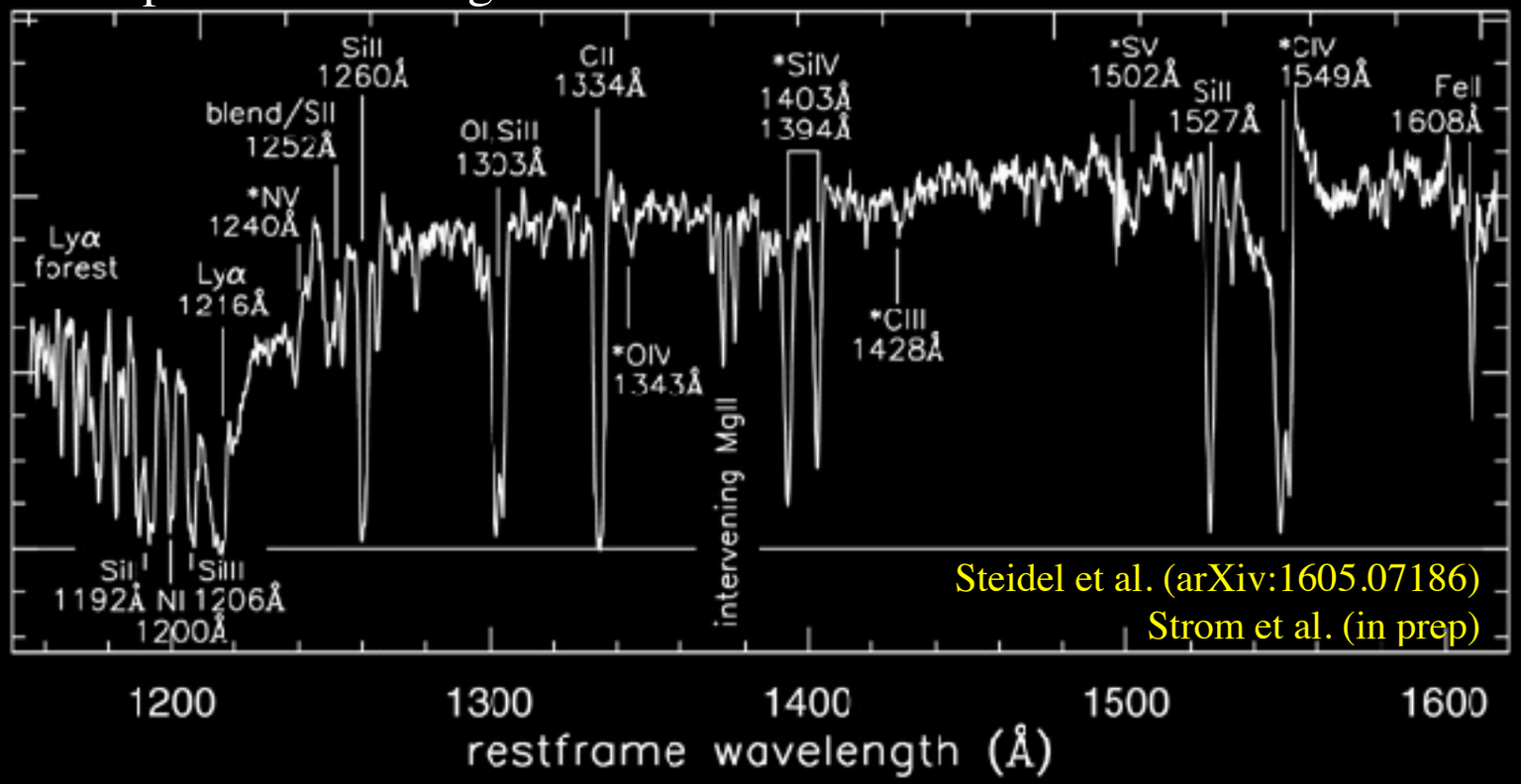
the spectra are wrong…



Steidel et al. (arXiv:1605.07186)
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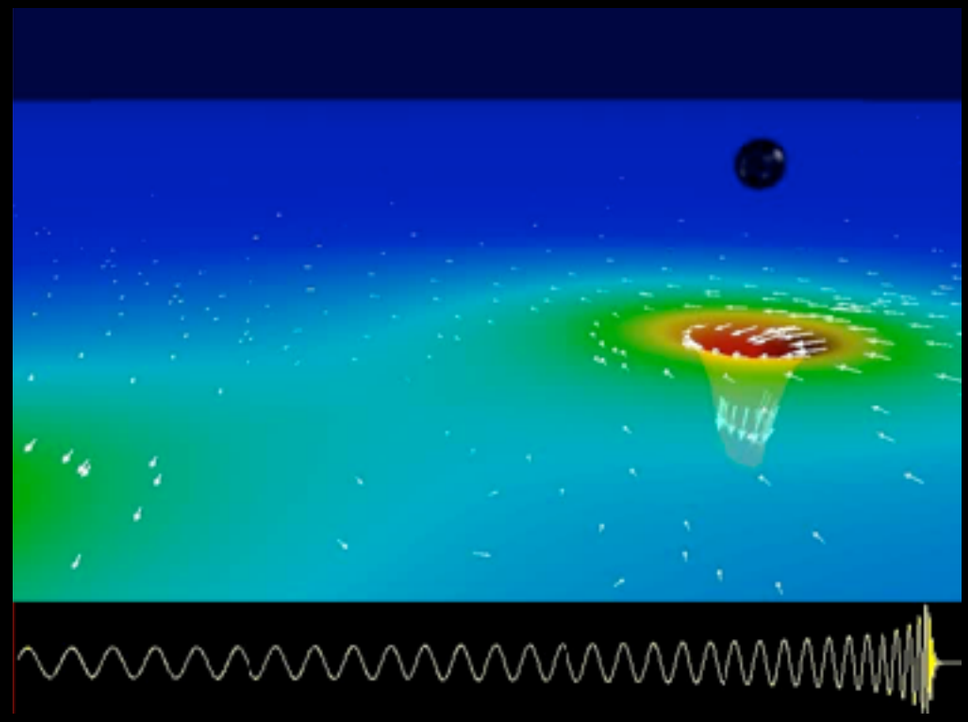

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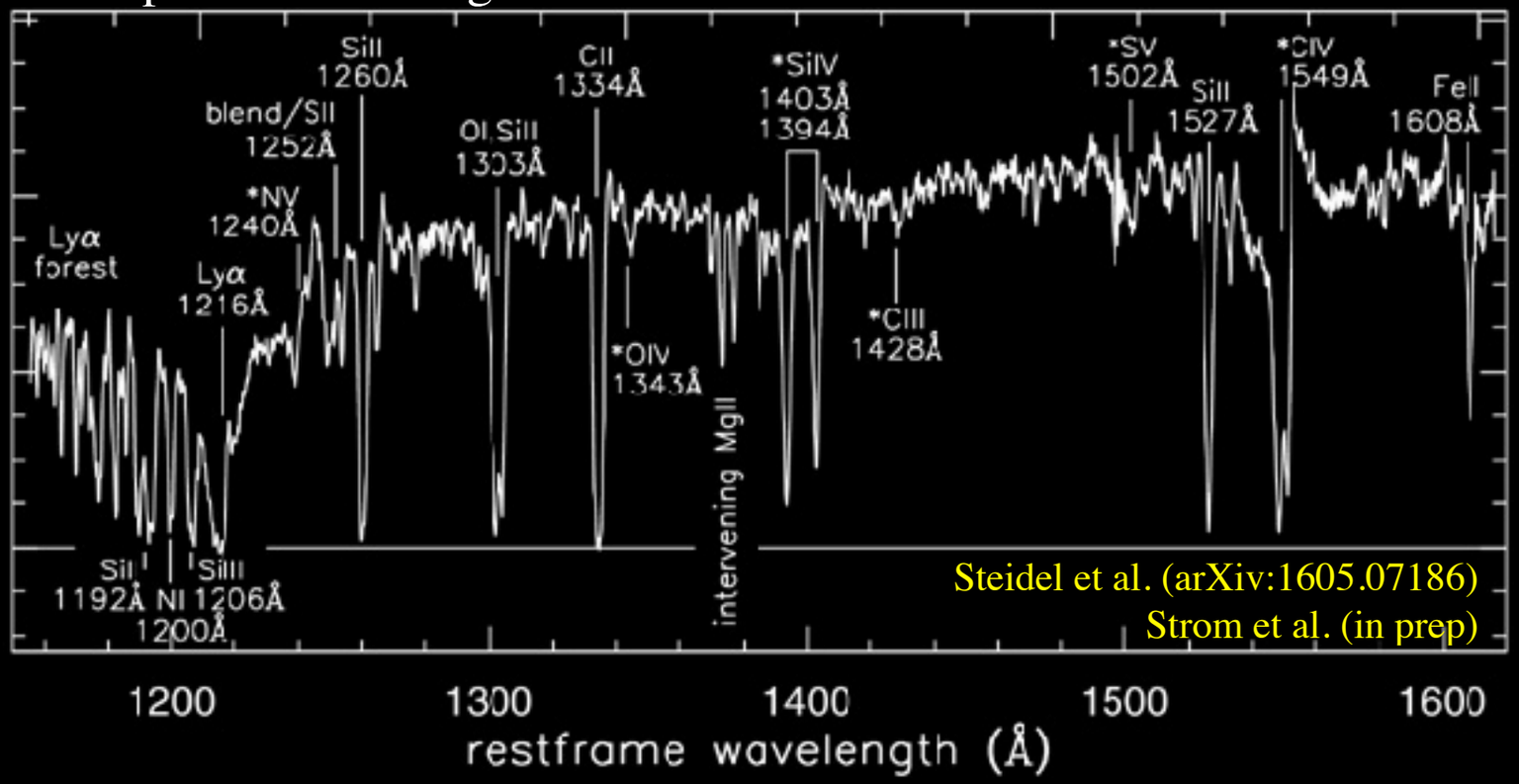

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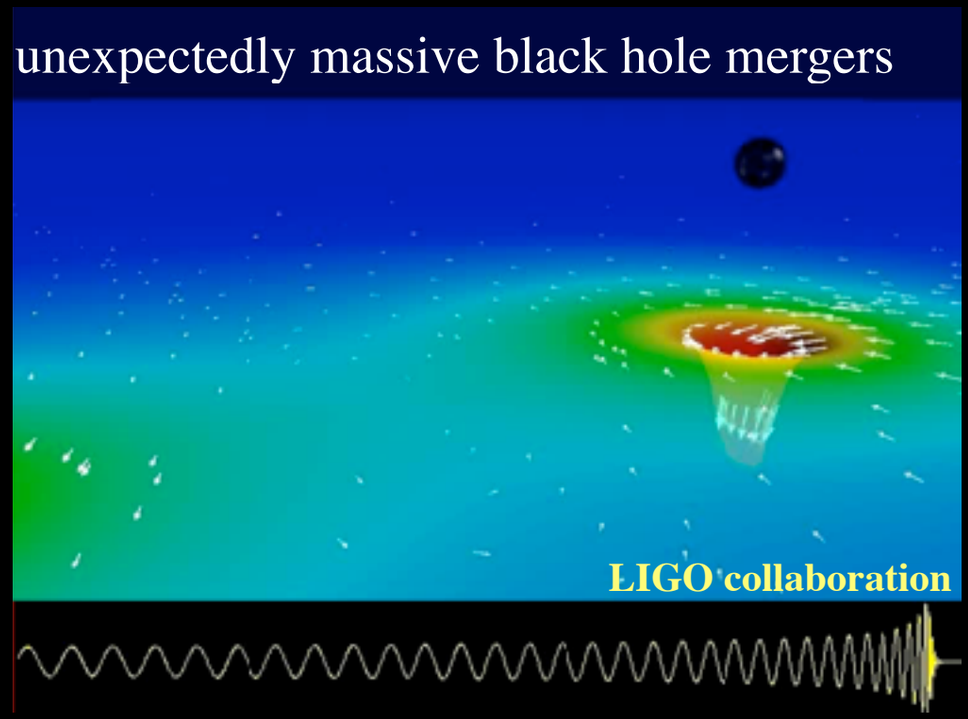
unexpectedly massive black hole mergers



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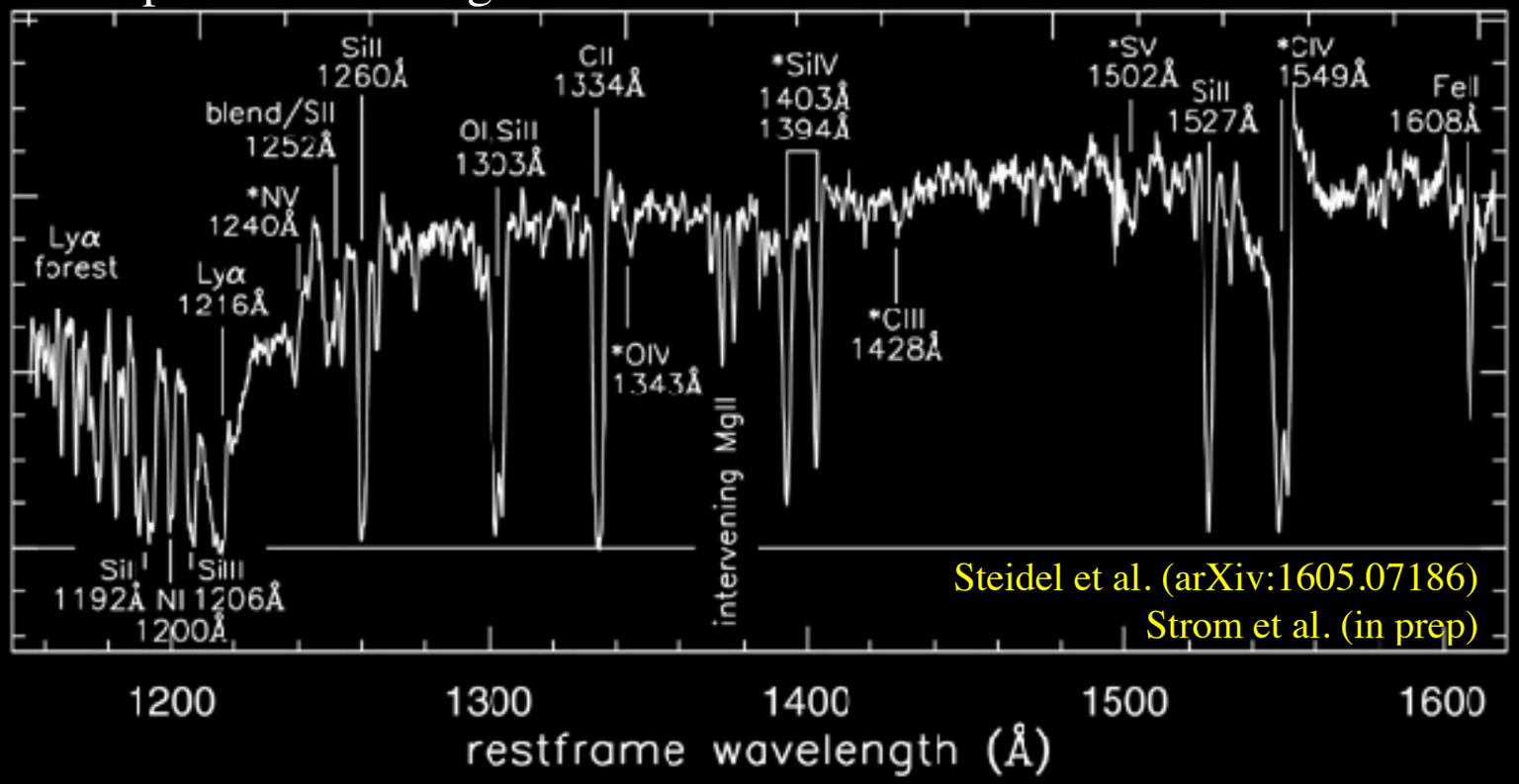

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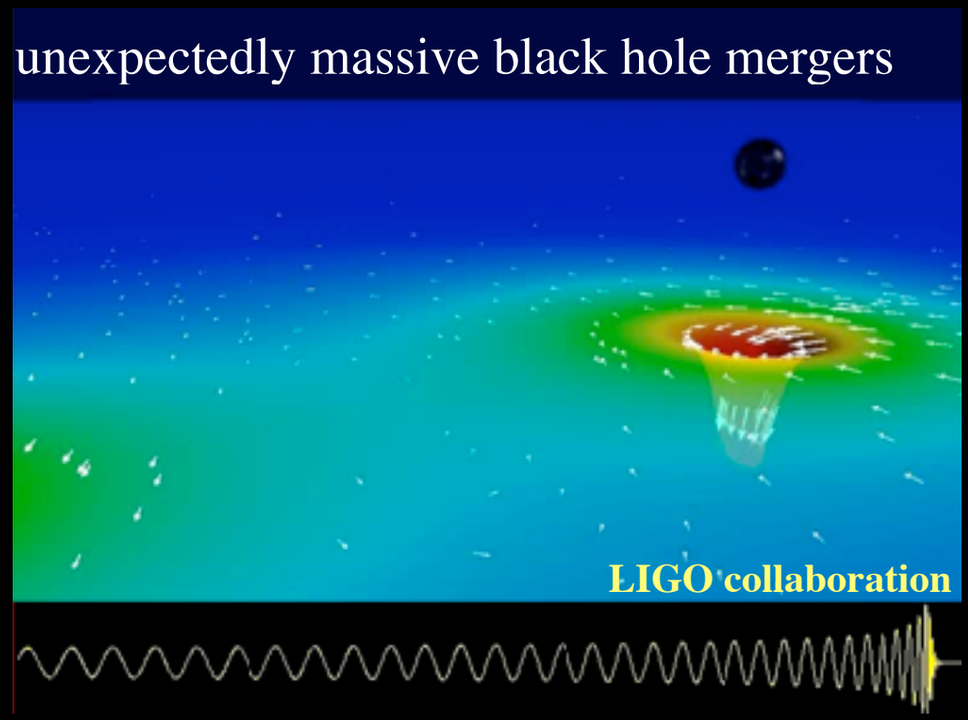
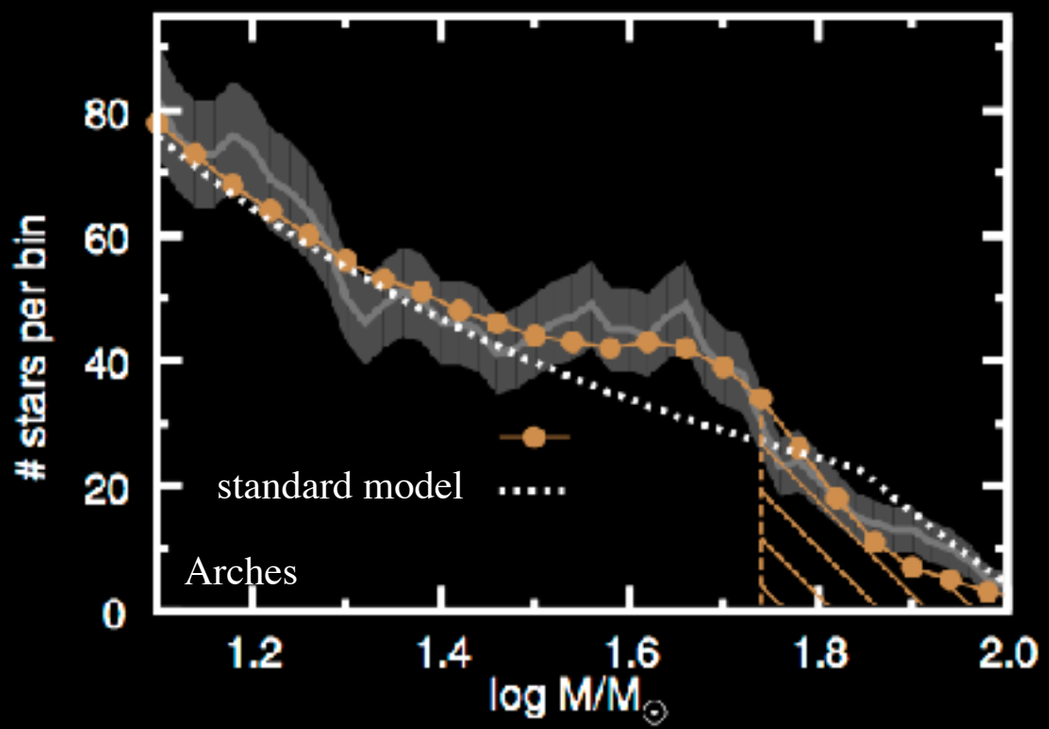
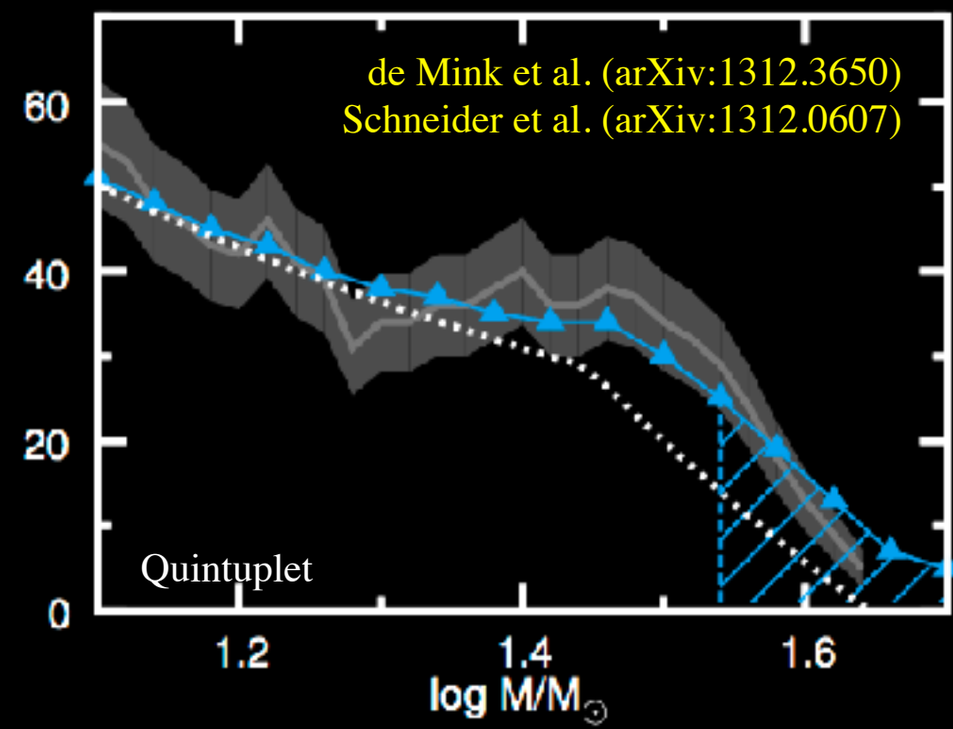
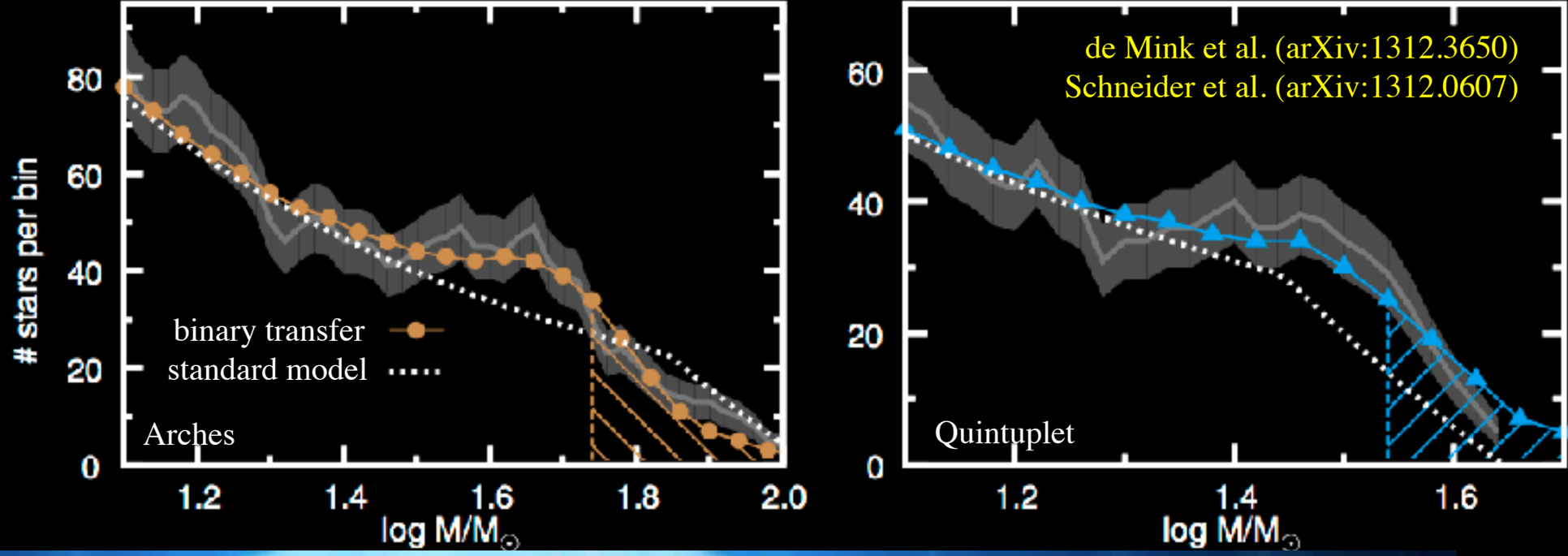


"mass-gainers": (stars more massive & longer-lived than they should be)





Binary Stars:
"FEEDING" MASSIVE STARS



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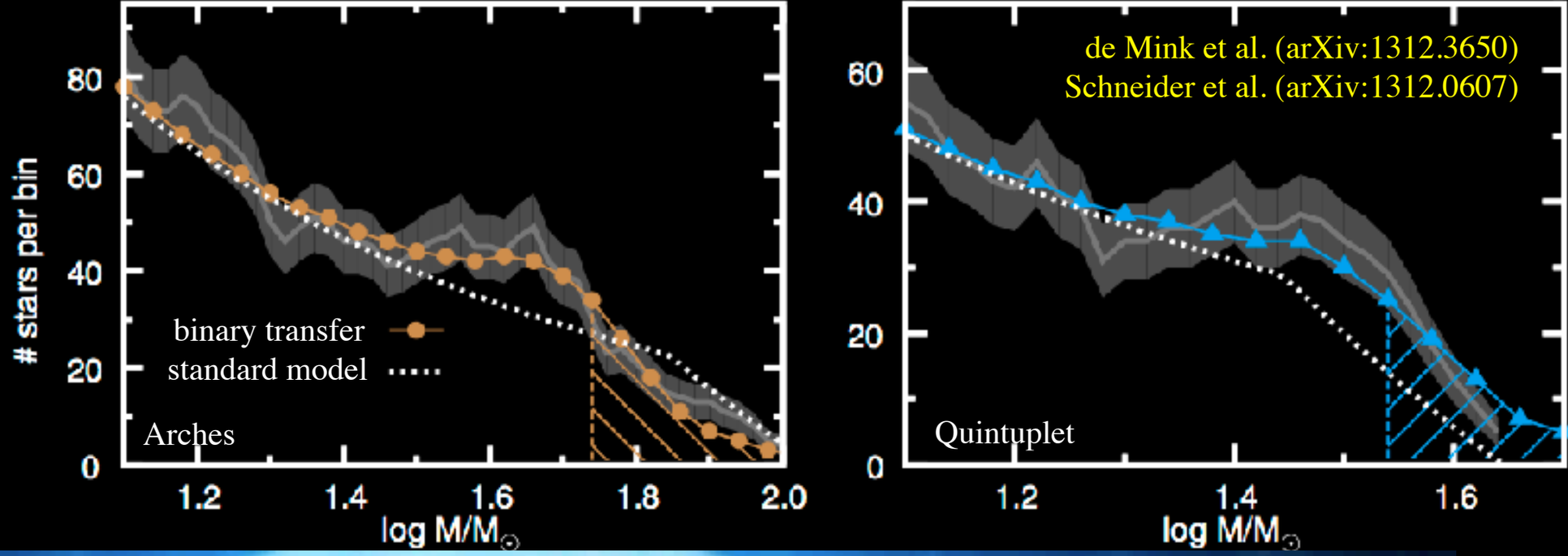
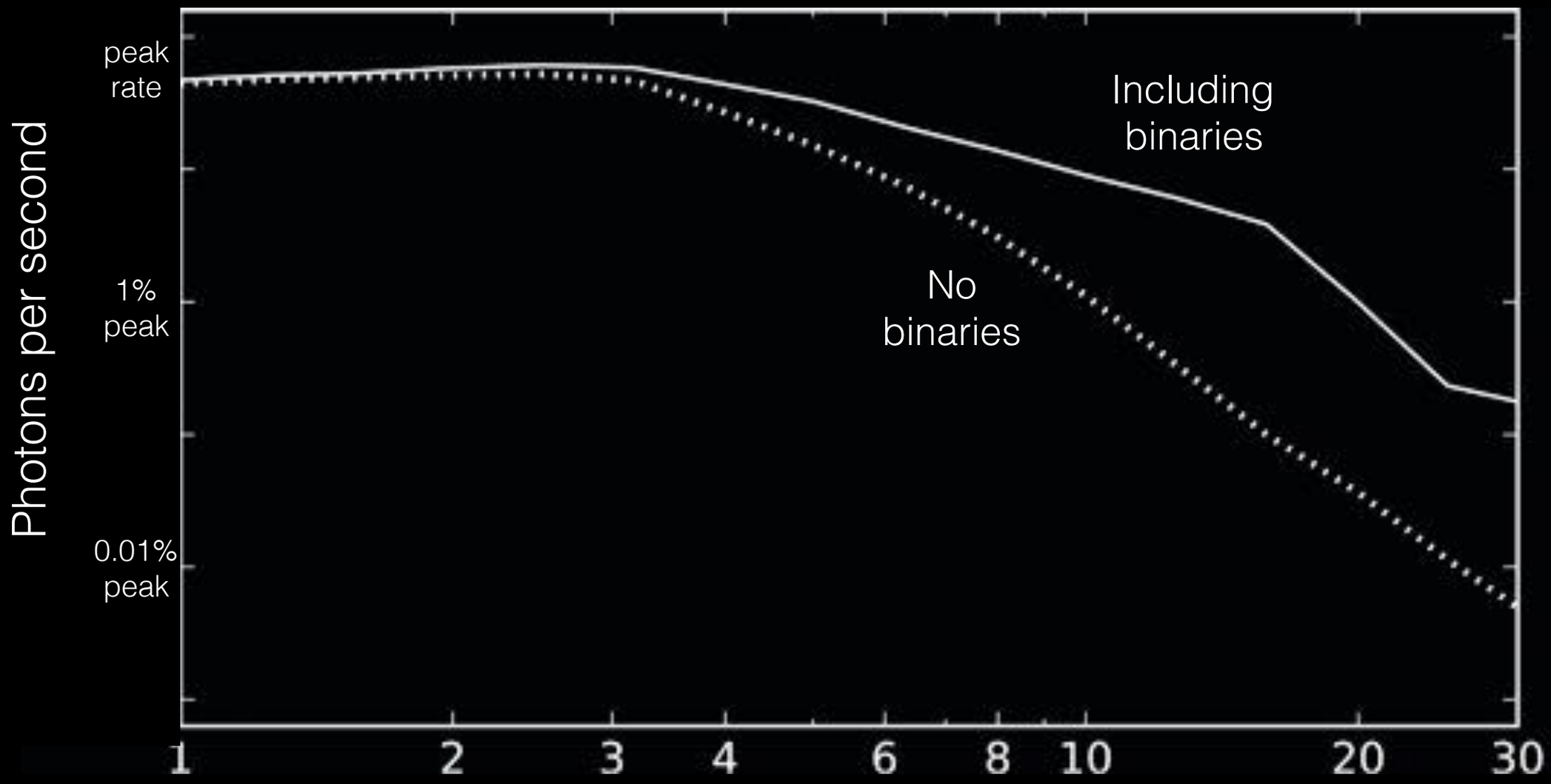


Binary Stars:
THE ORIGIN OF THE "MISSING PHOTONS"

Xiangcheng Ma
(arXiv:1601.07559)



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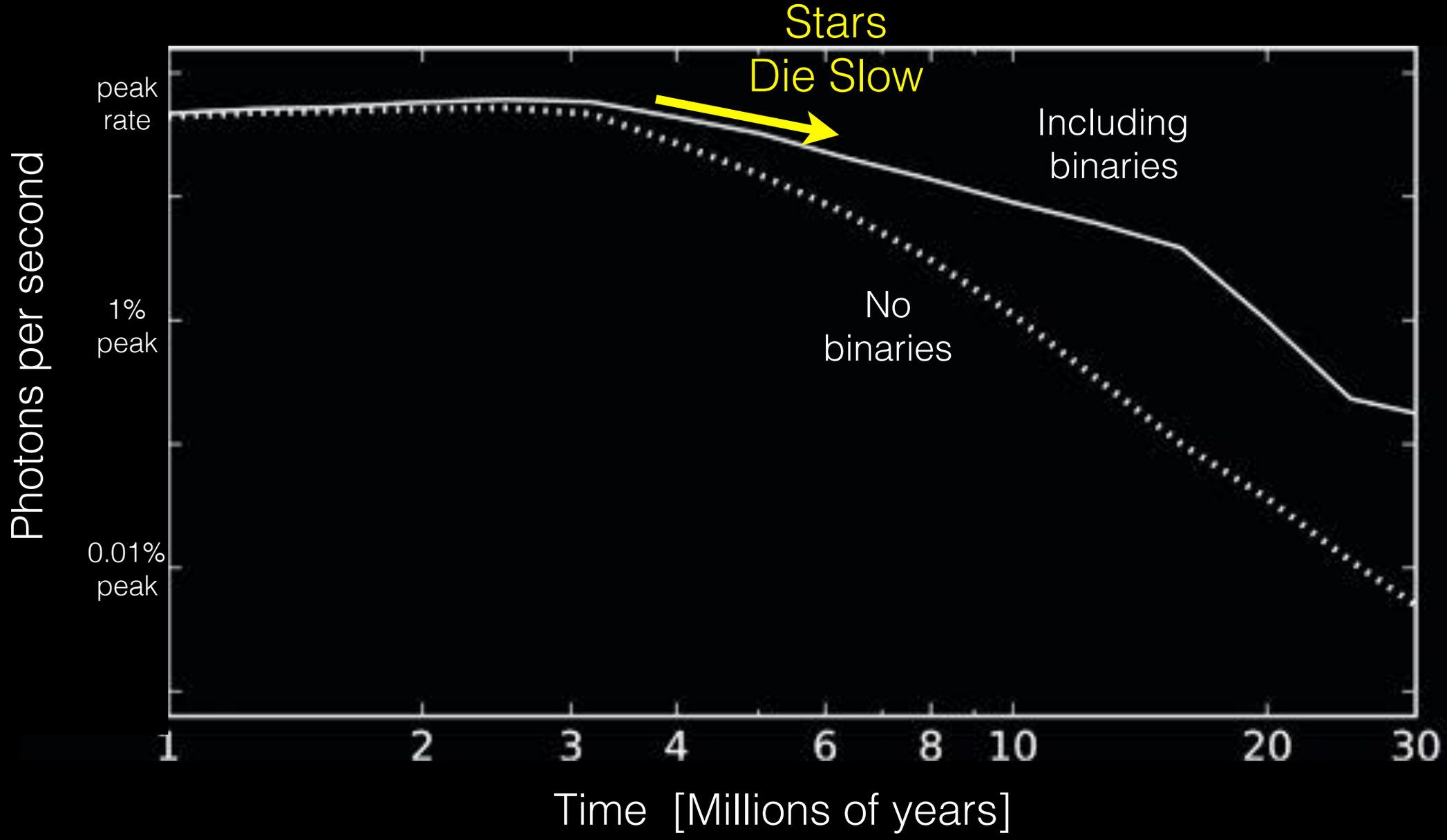

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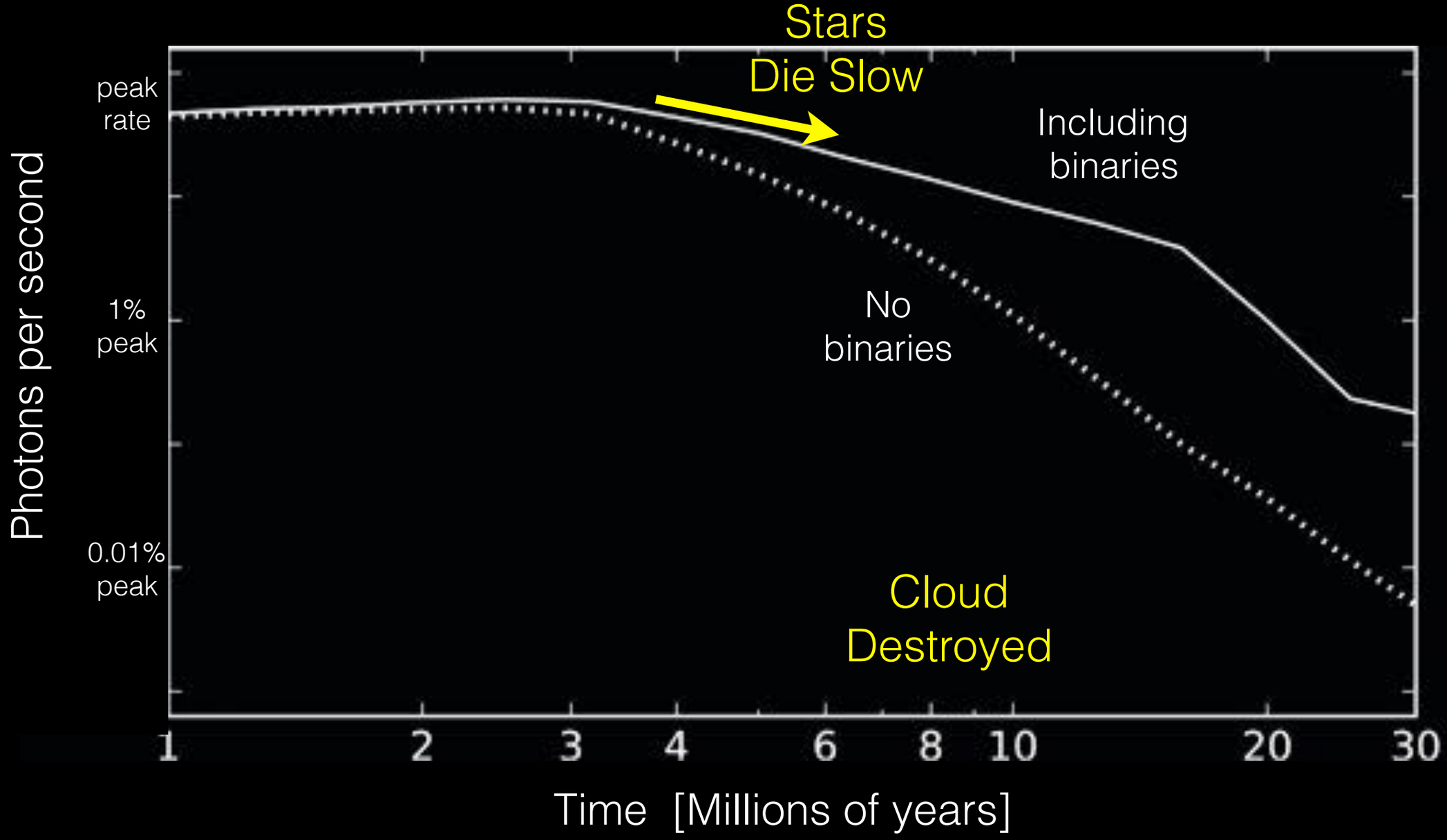

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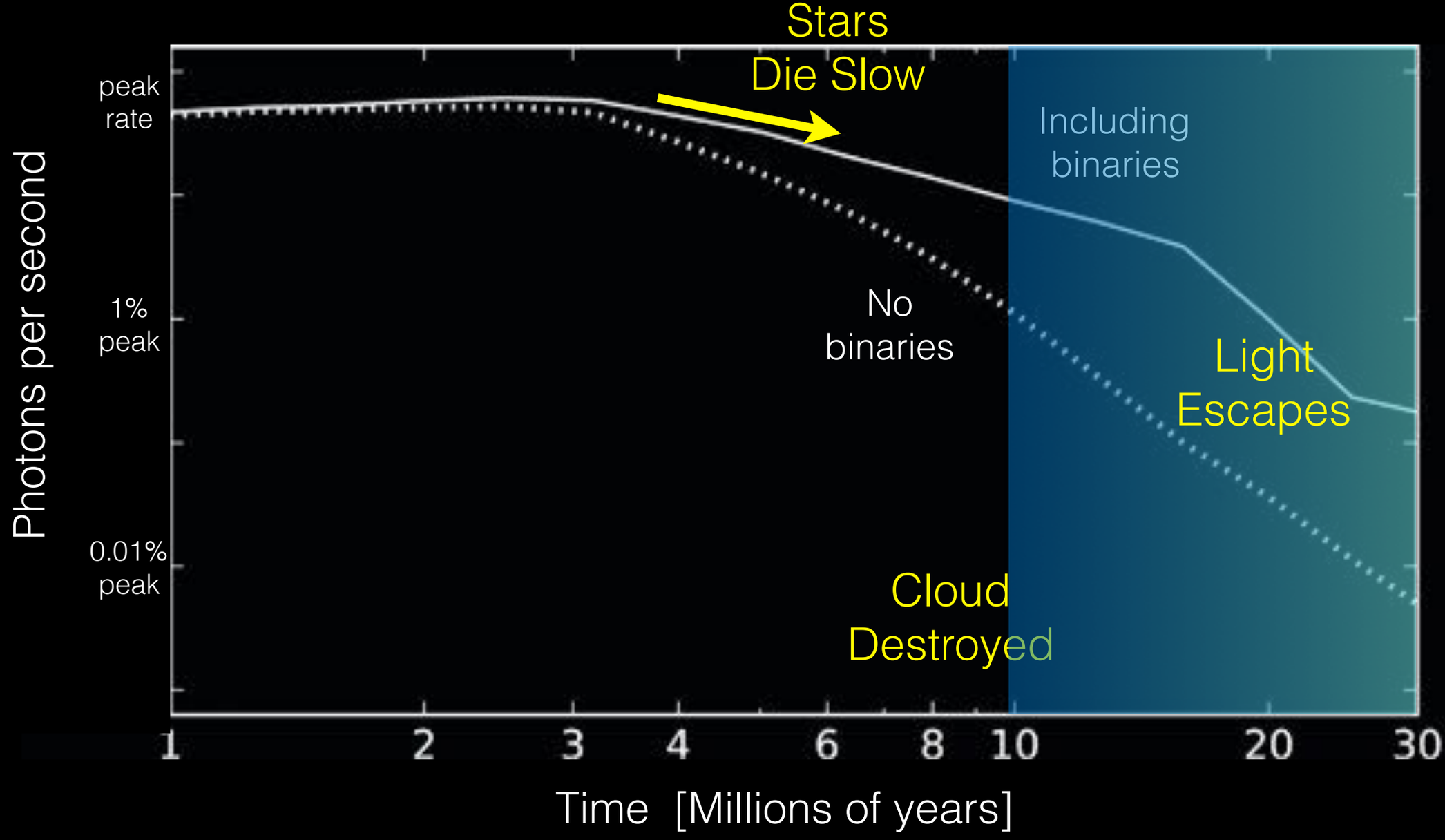

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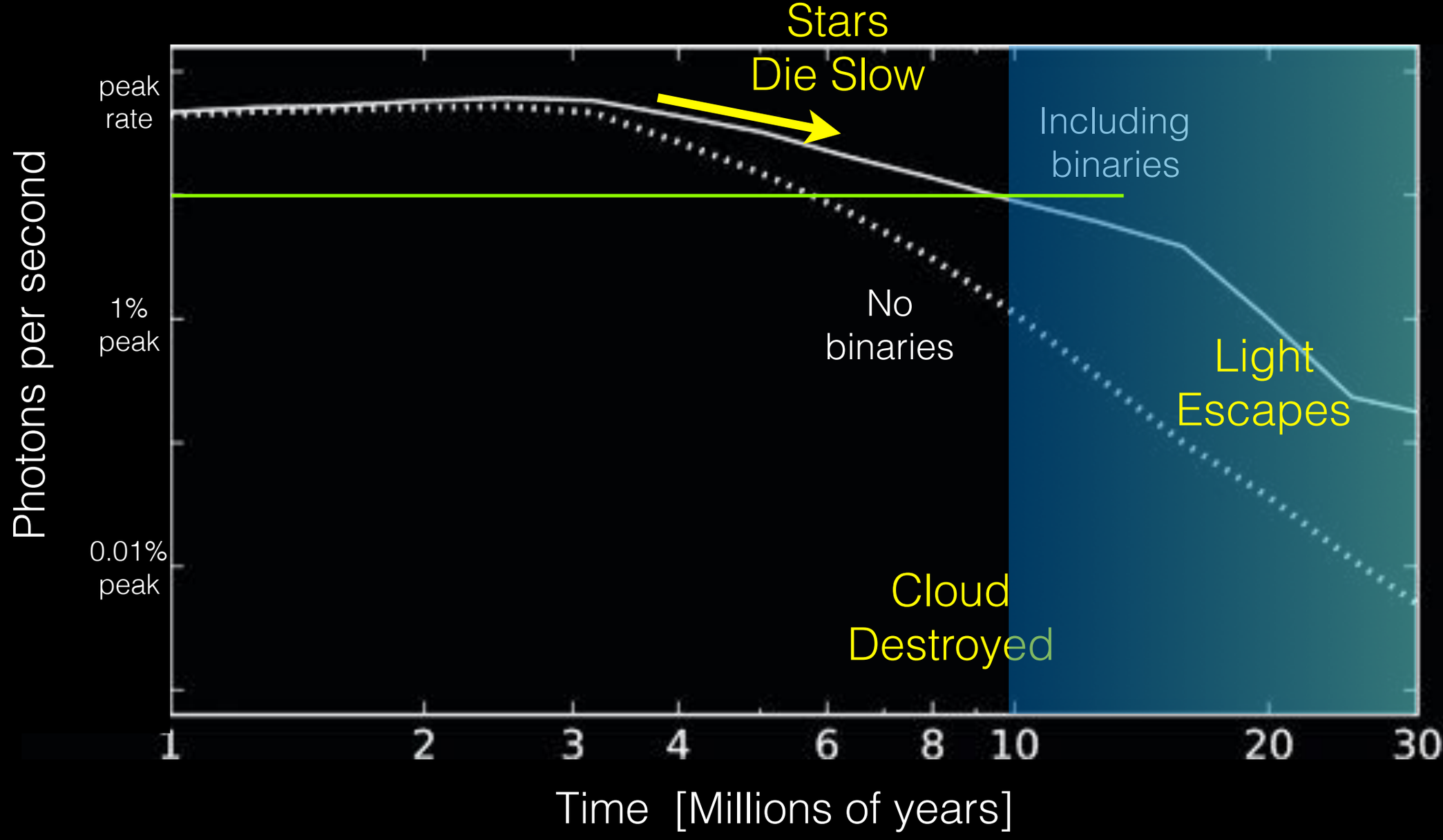
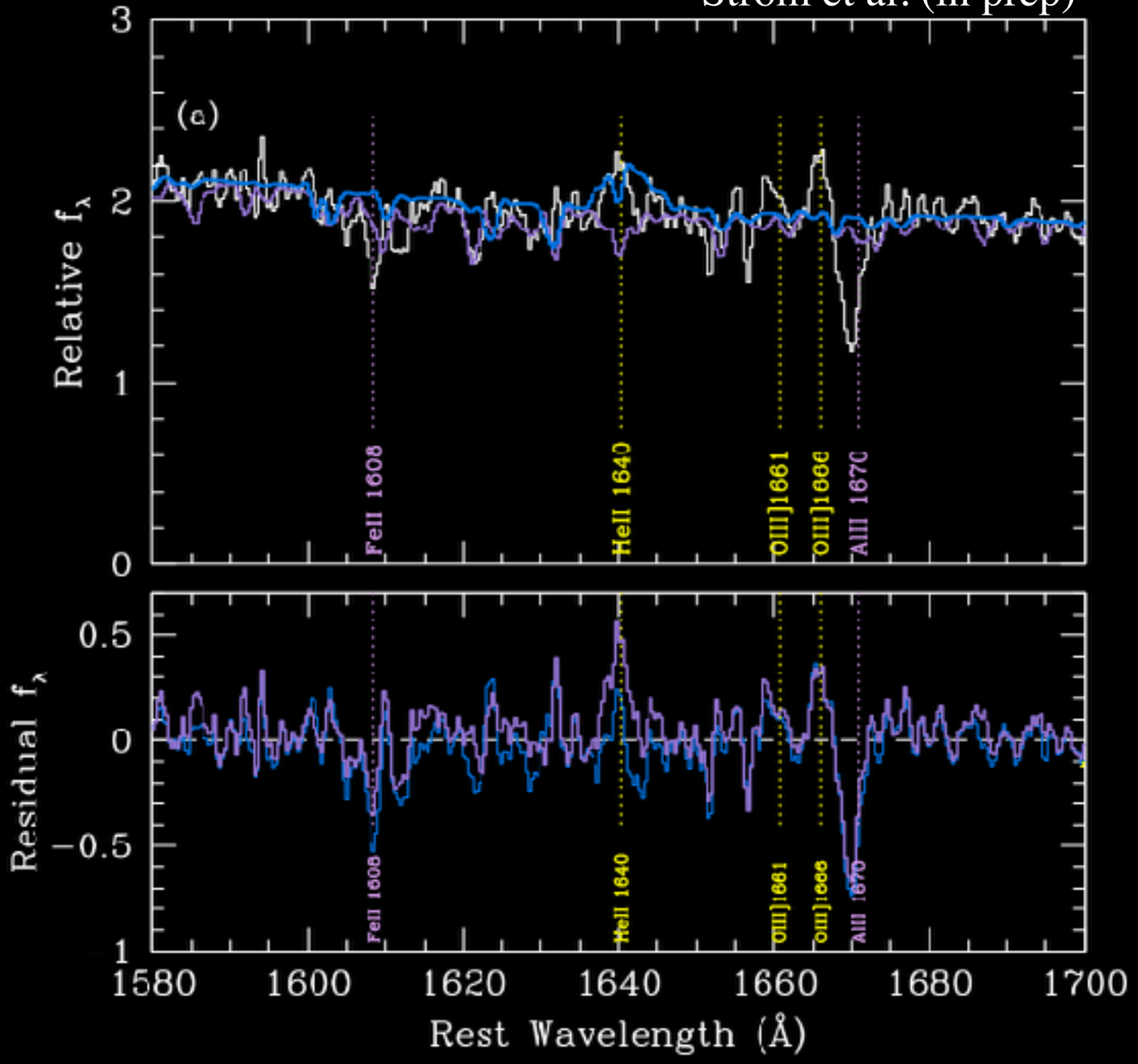


Simulation: ~20% escape!

Binaries Work

EXPLAIN THE MYSTERIES OF HIGH-REDSHIFT GALAXIES

Steidel et al. (arXiv:1605.07186 & 1405.5473),
Strom et al. (in prep)



Ma, Hopkins et al.
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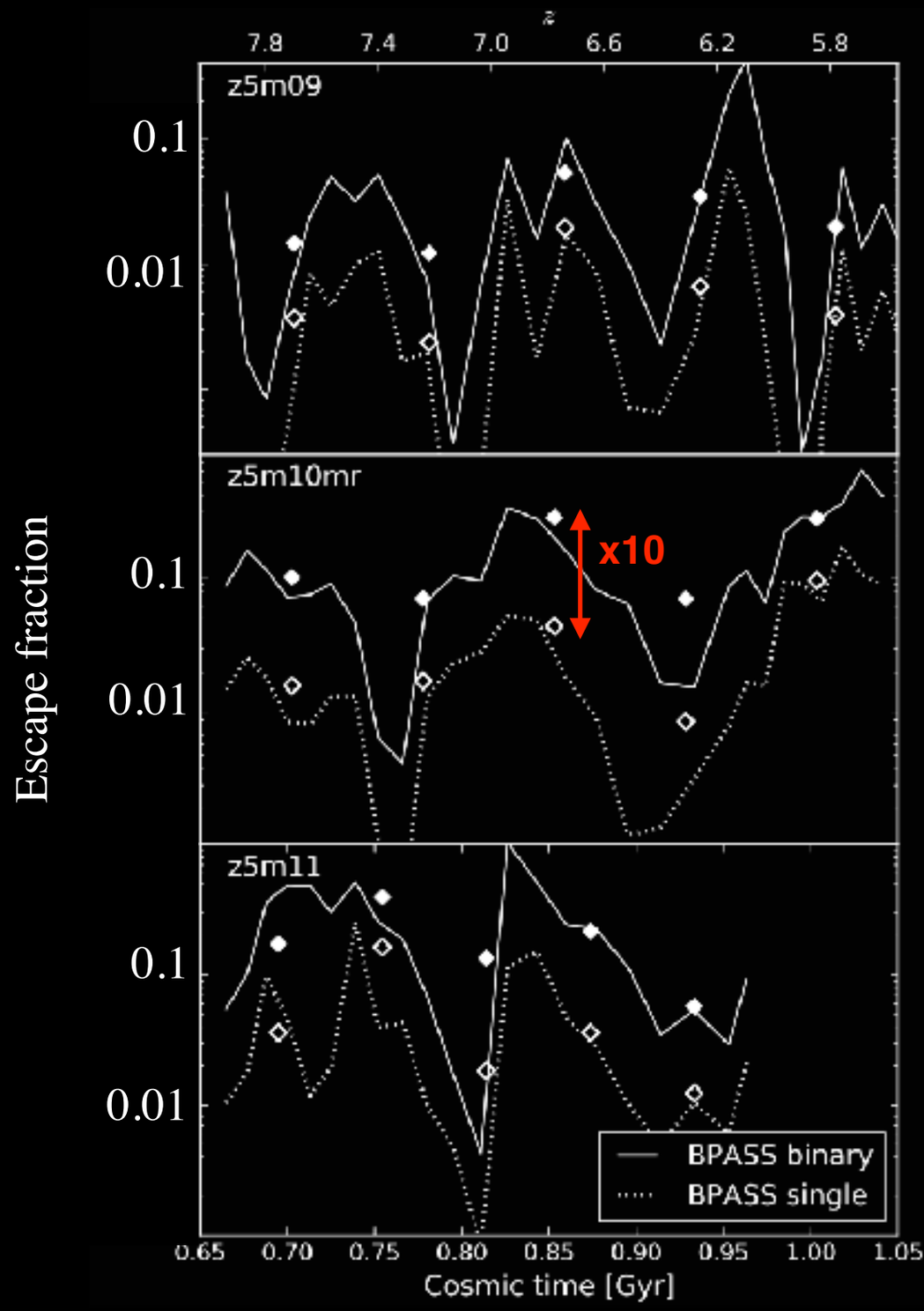

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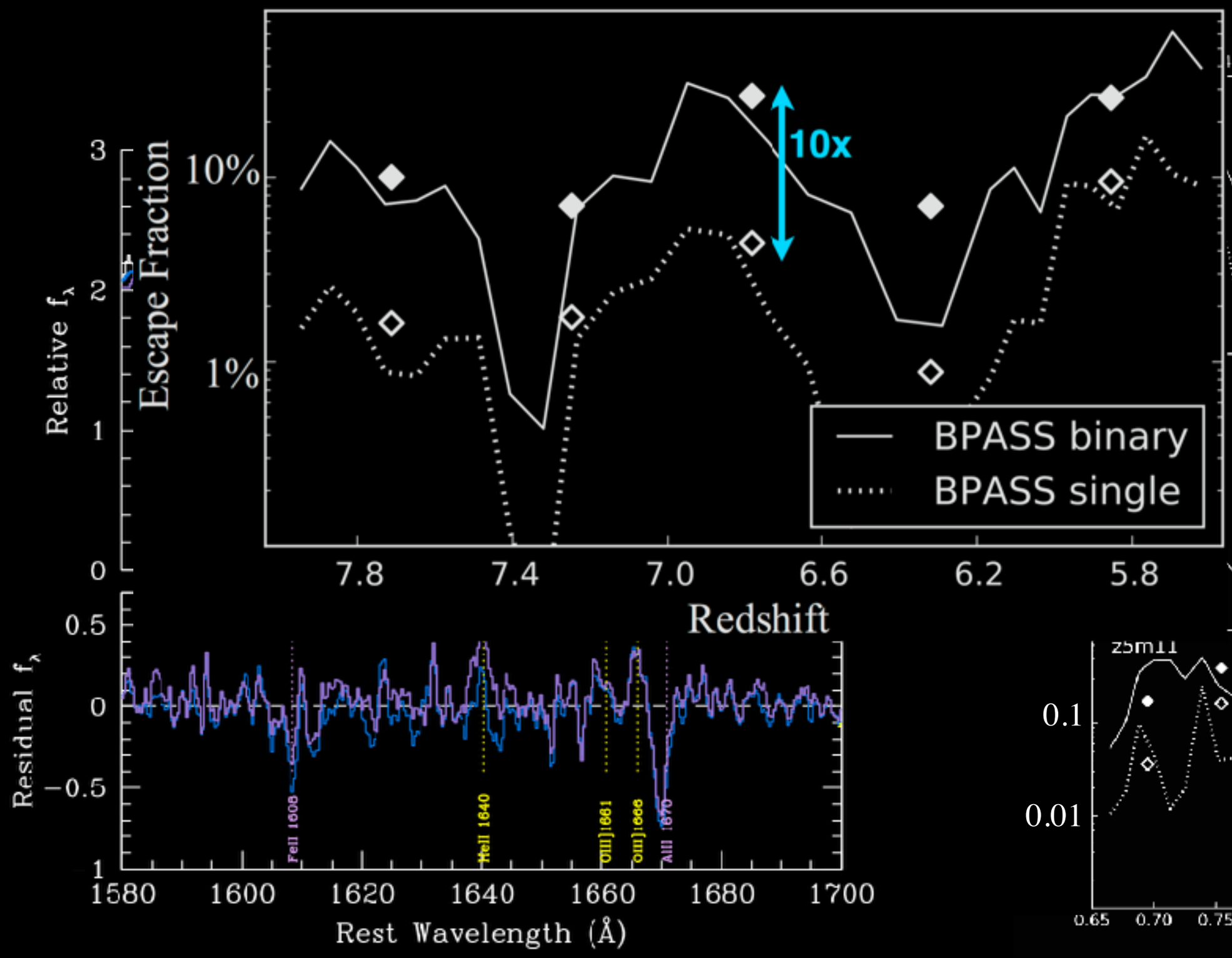

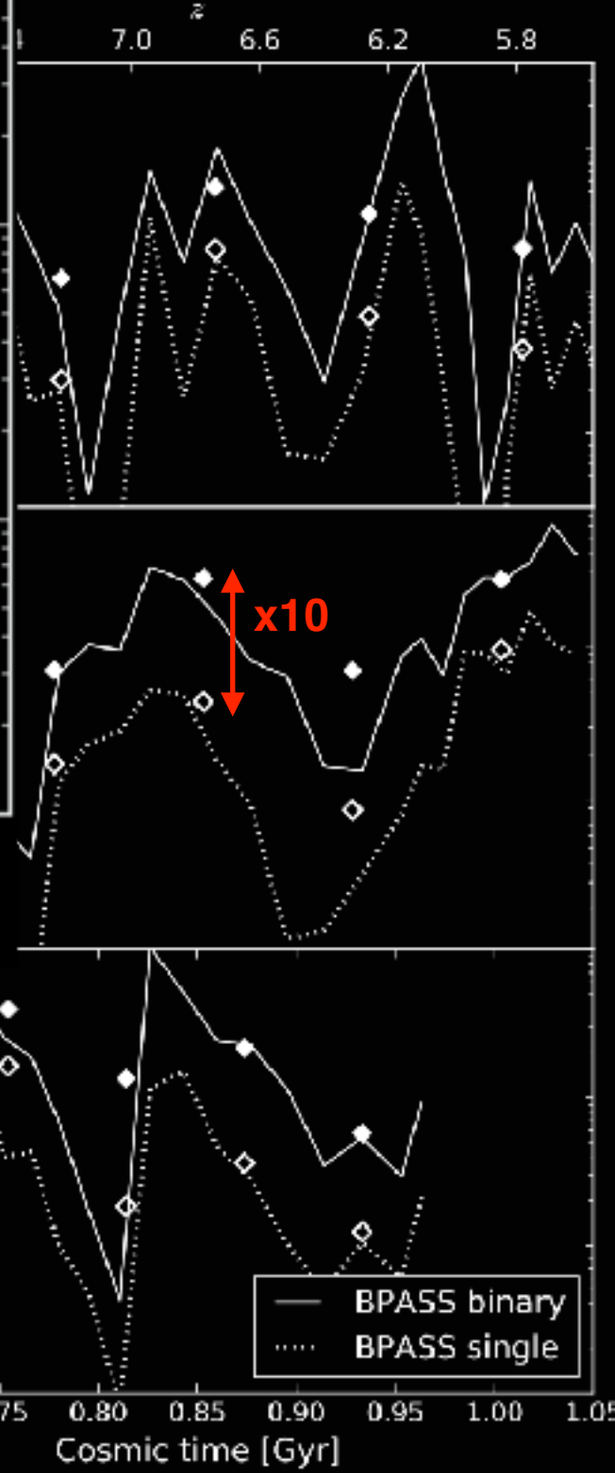

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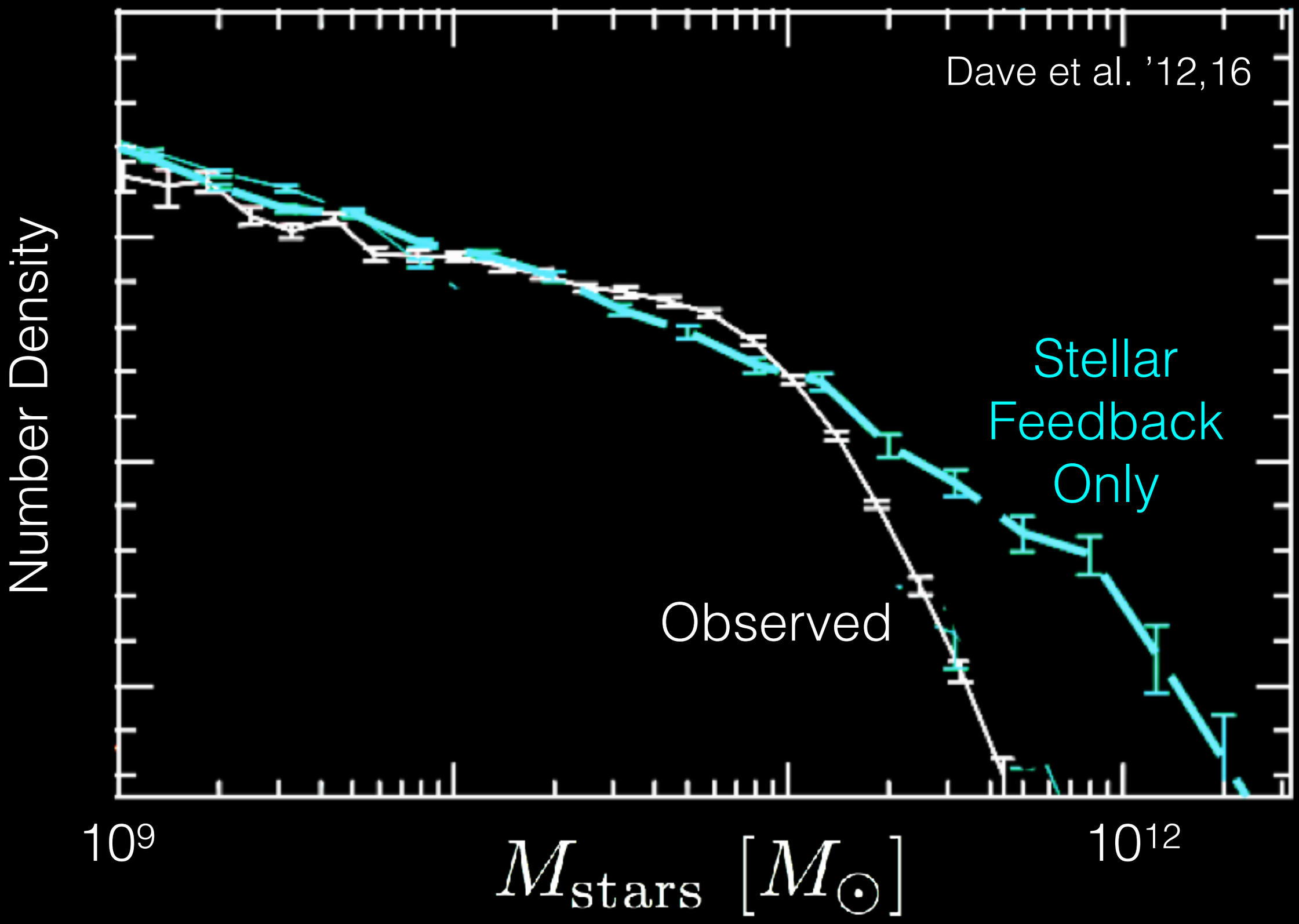
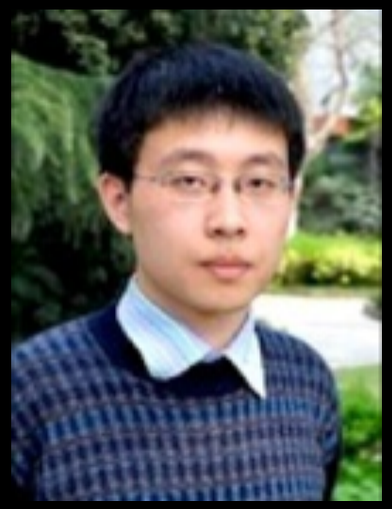
Need Additional Physics To *Turn Off* Star Formation

STELLAR FEEDBACK + COOLING = COOLING FLOW PROBLEM

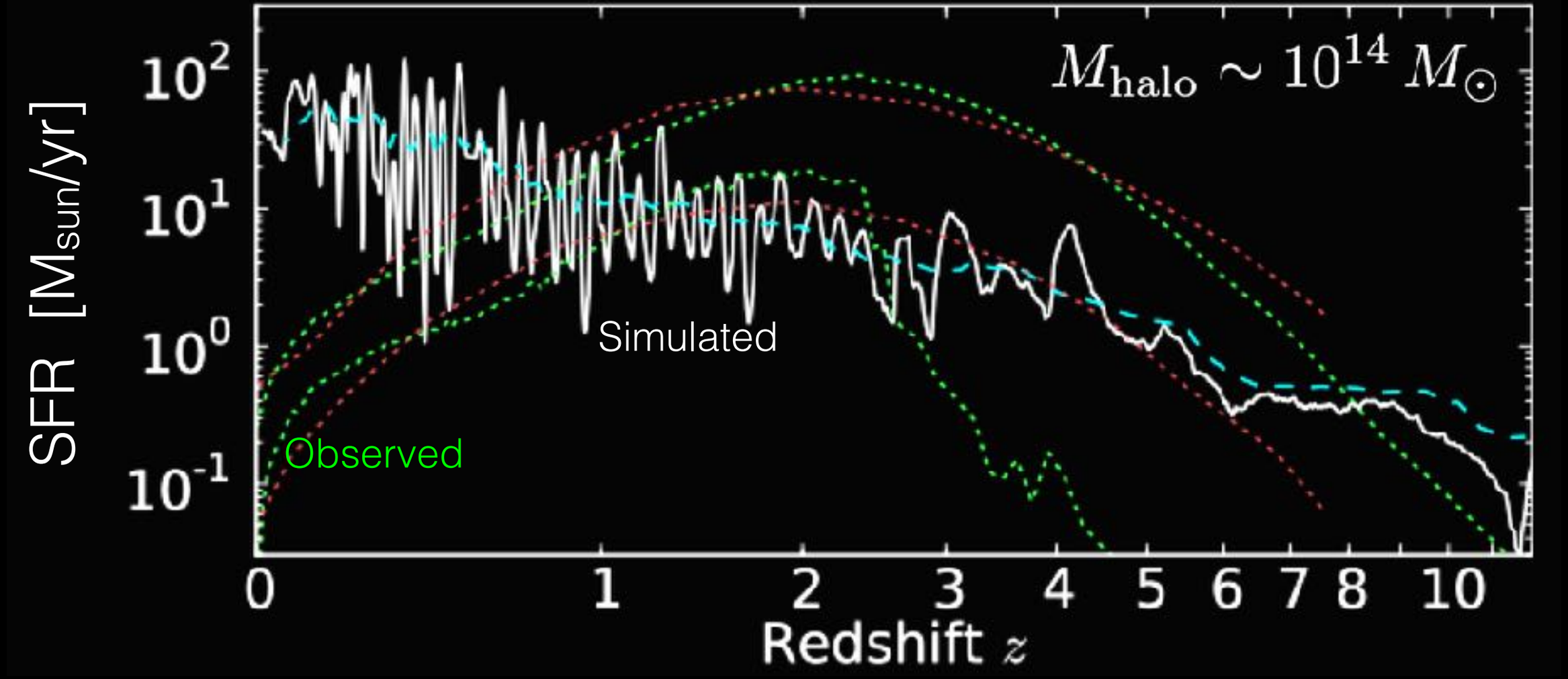


Quenching: Need Additional Physics

STELLAR FEEDBACK + COOLING = COOLING FLOW PROBLEM



Xiangcheng Ma
Robert Feldmann



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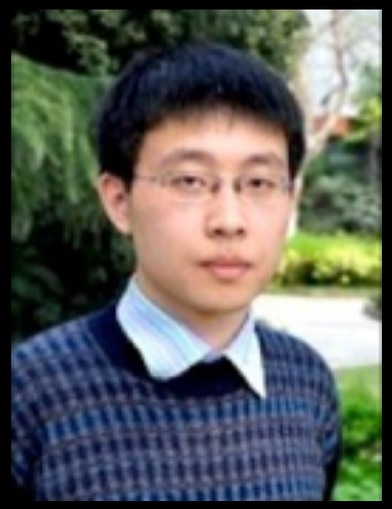
- Virial shocks



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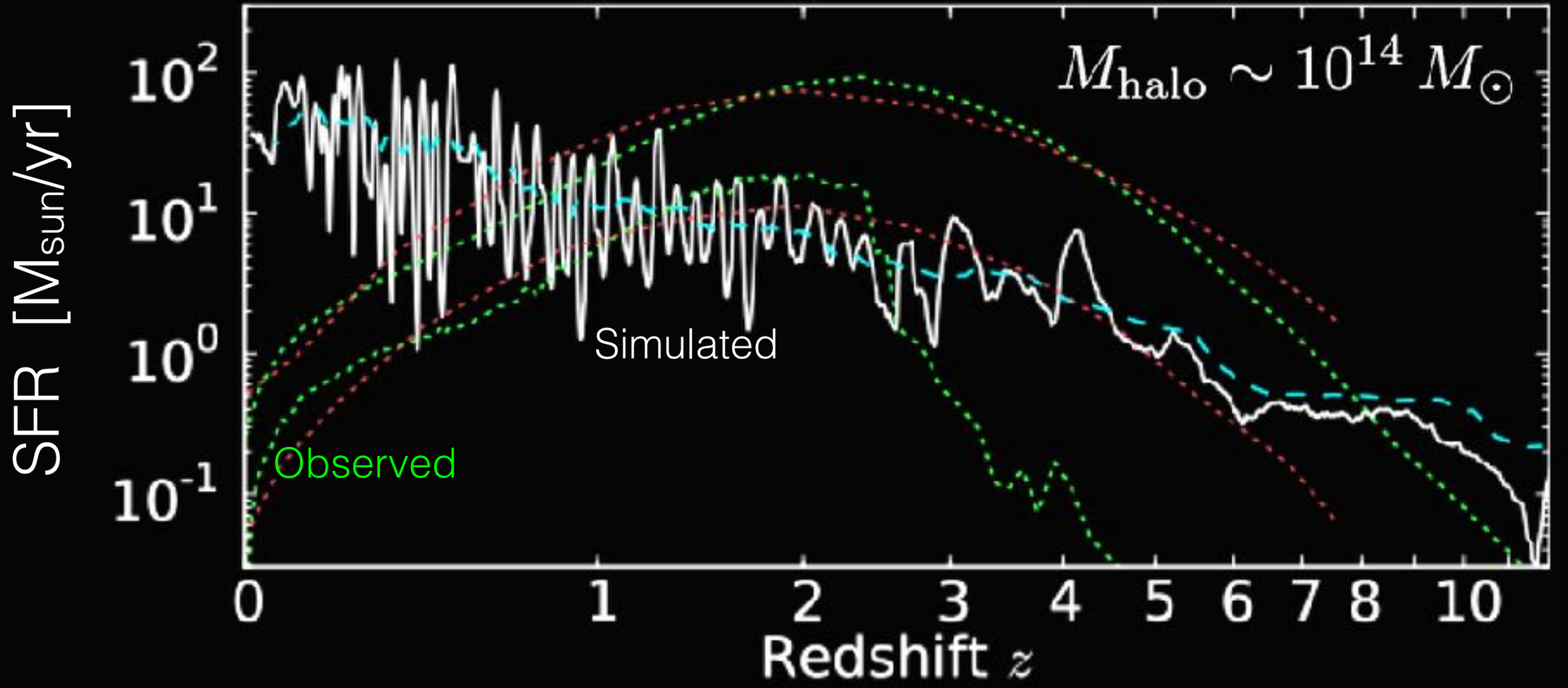

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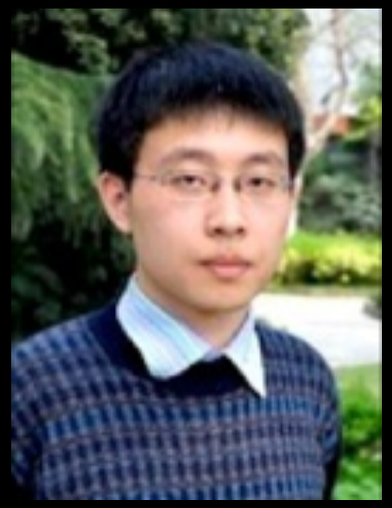
- "Morphological Quenching"



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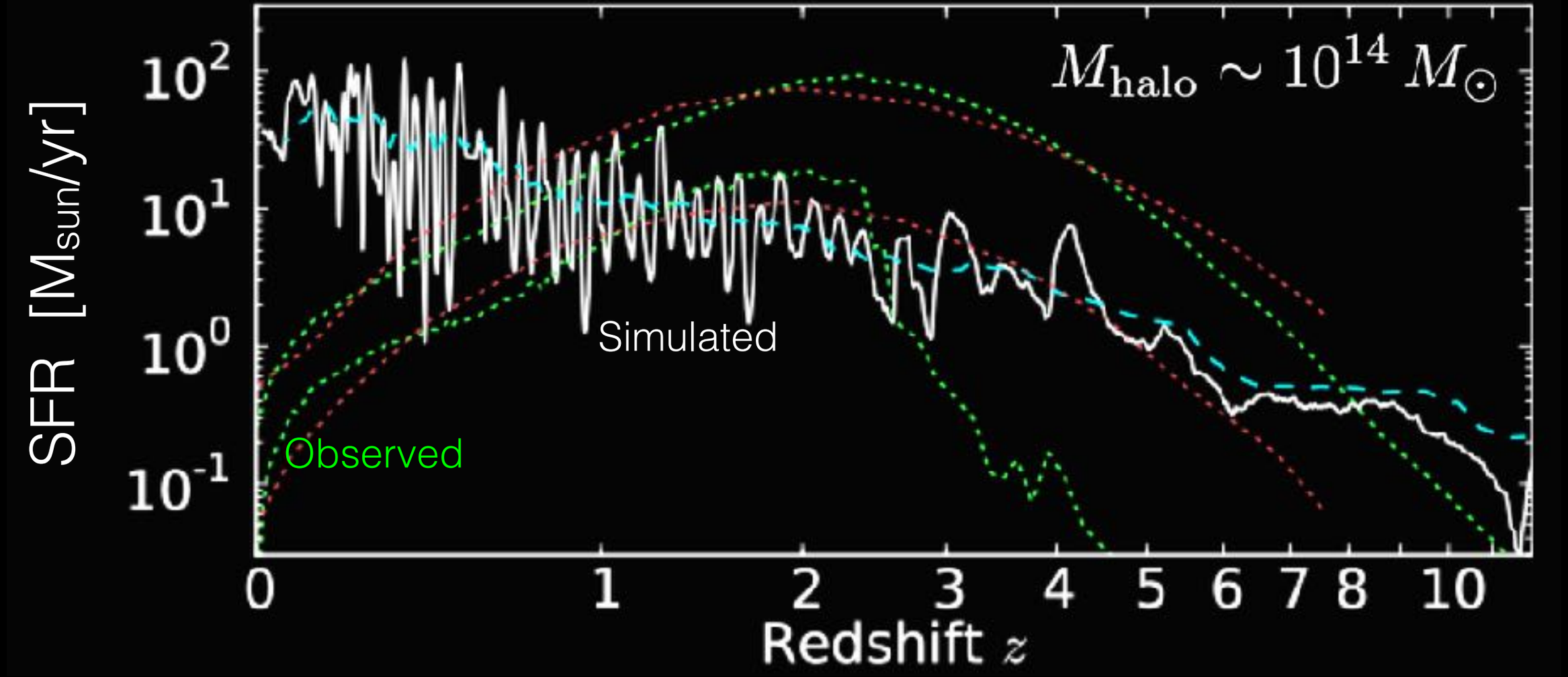

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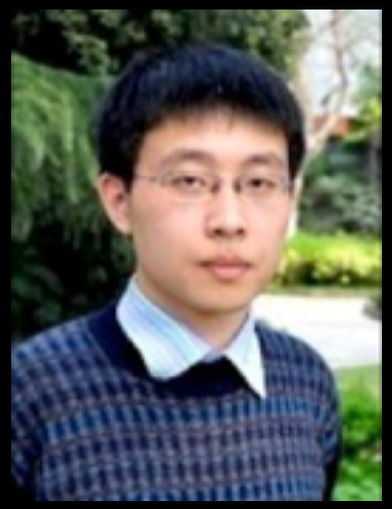

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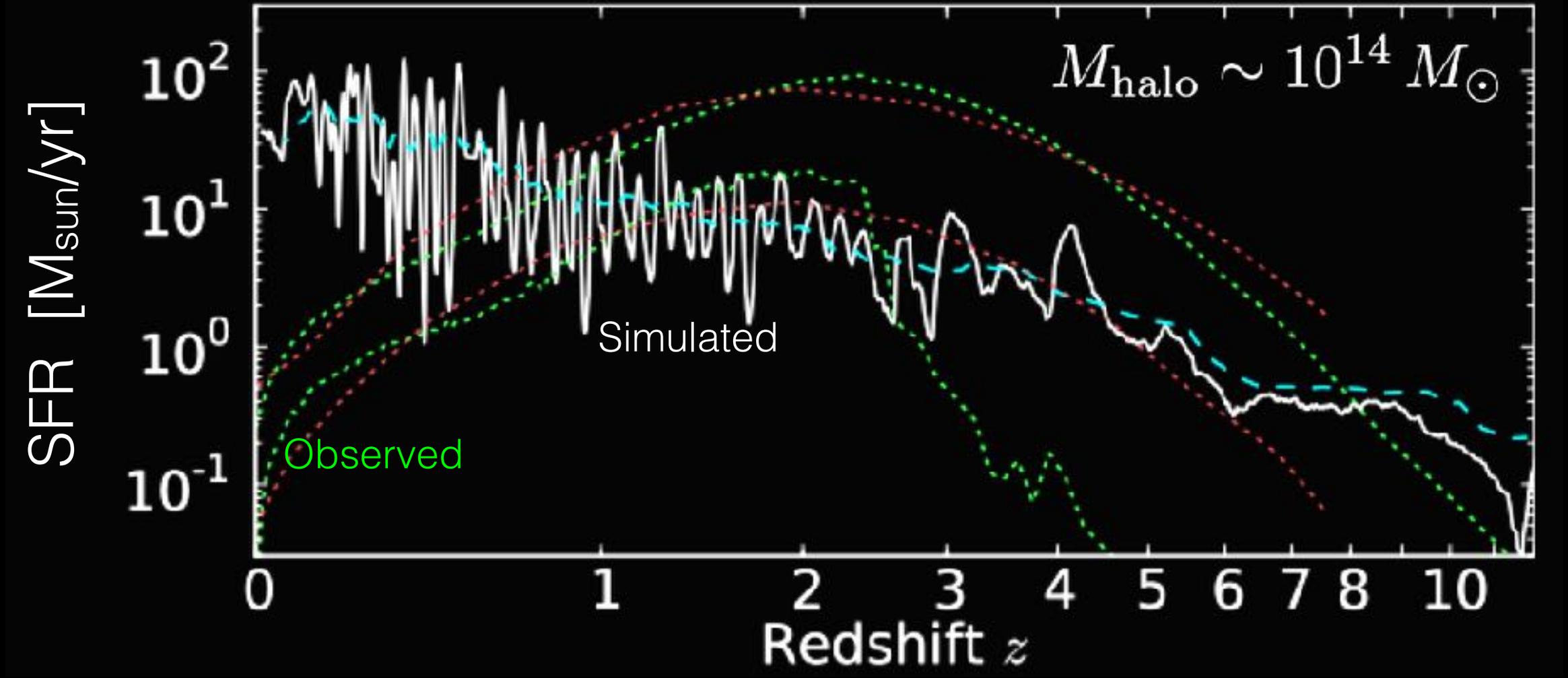

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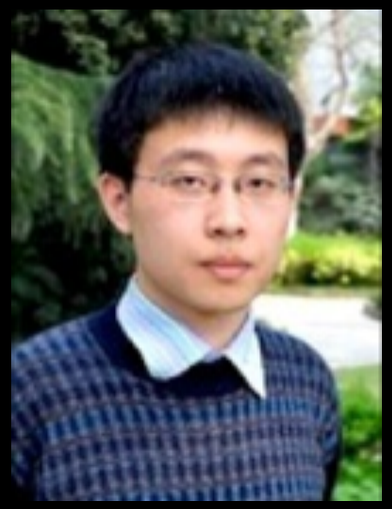

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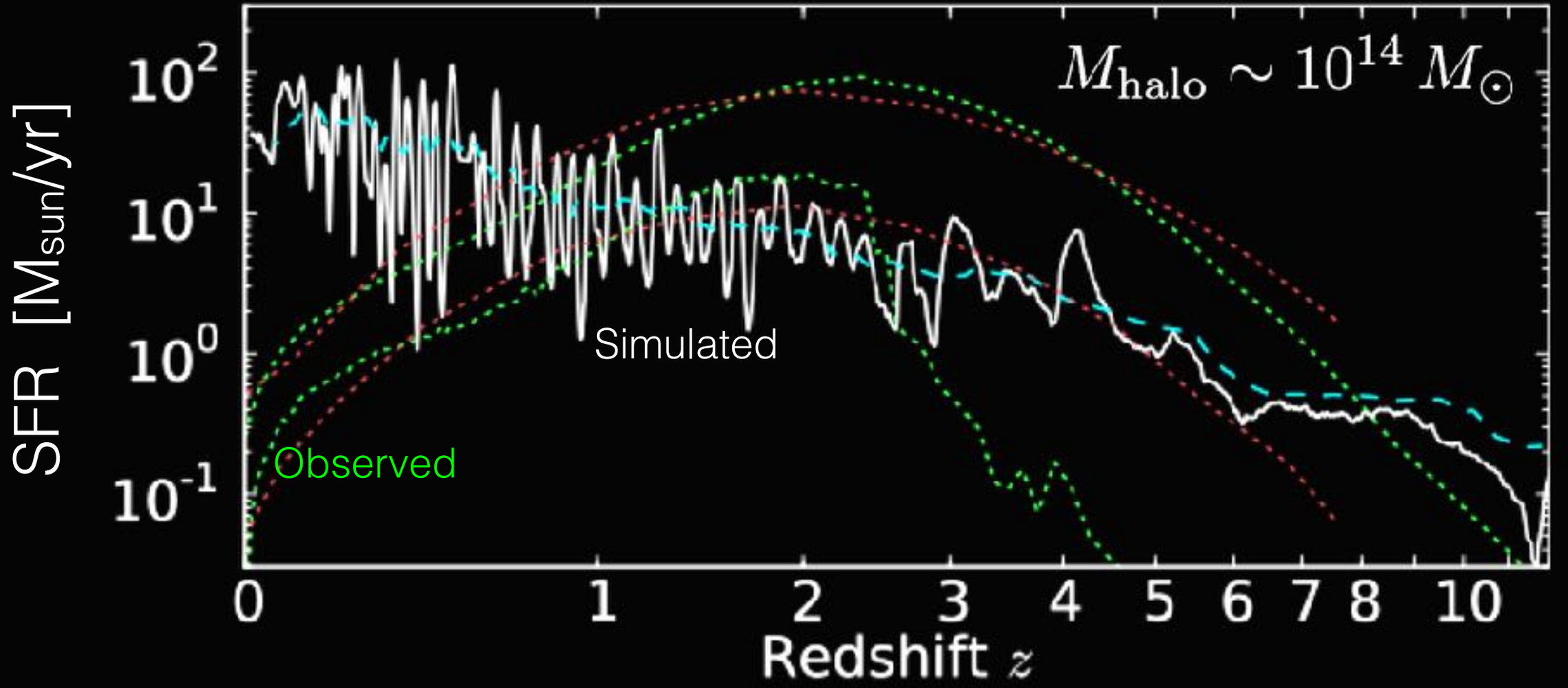

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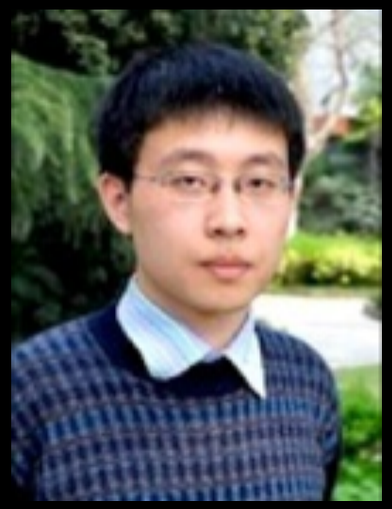

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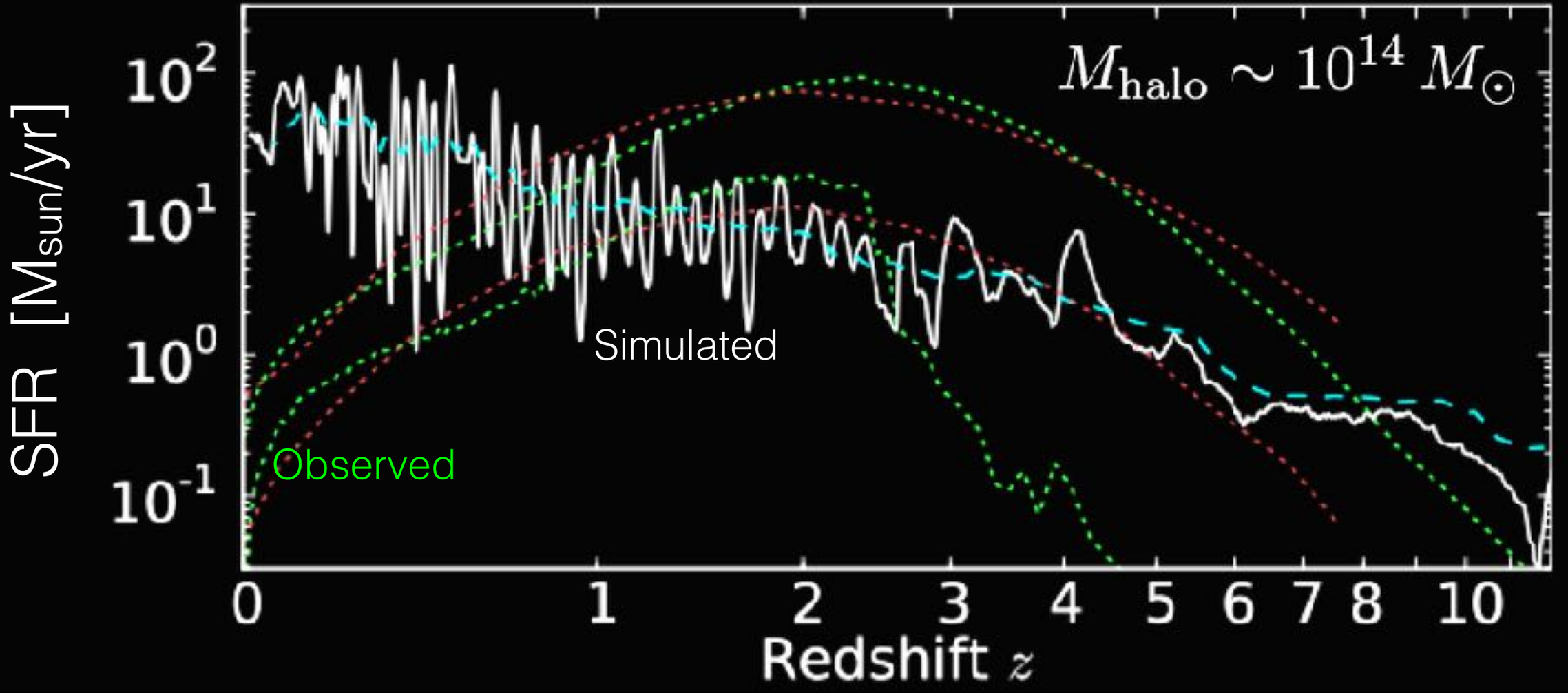
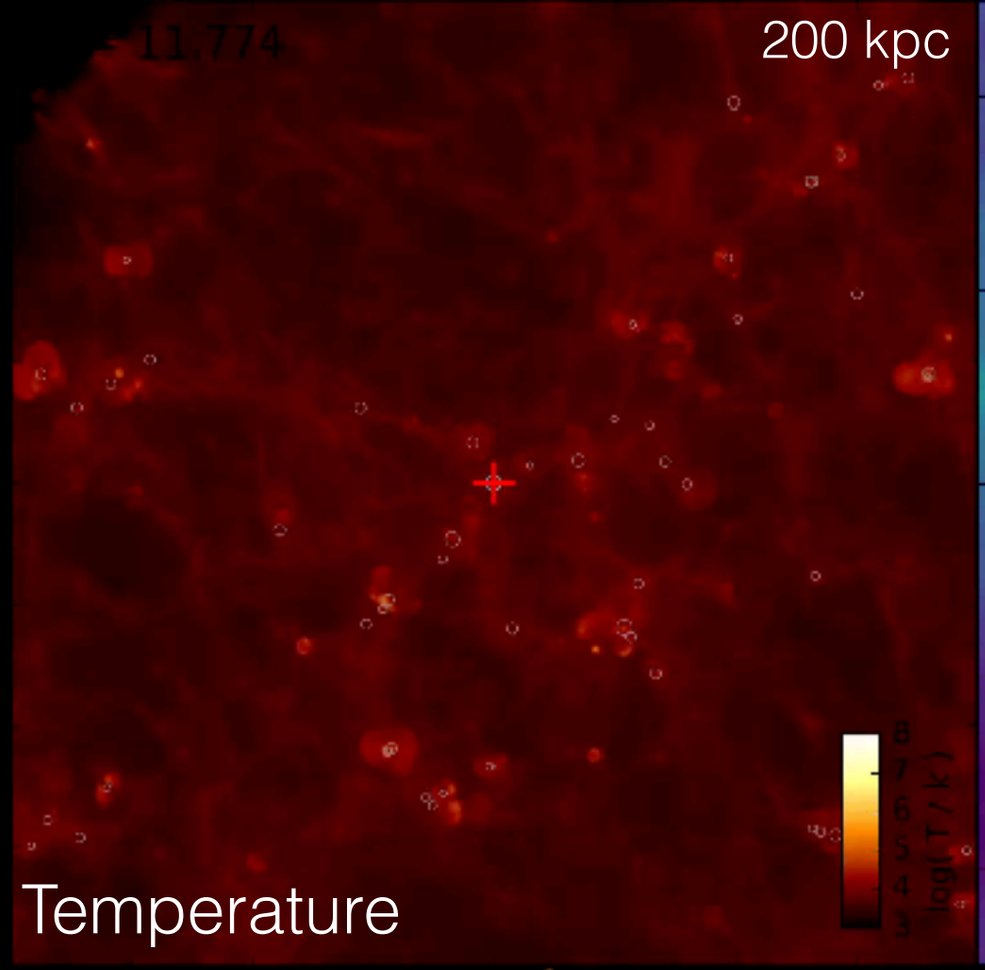
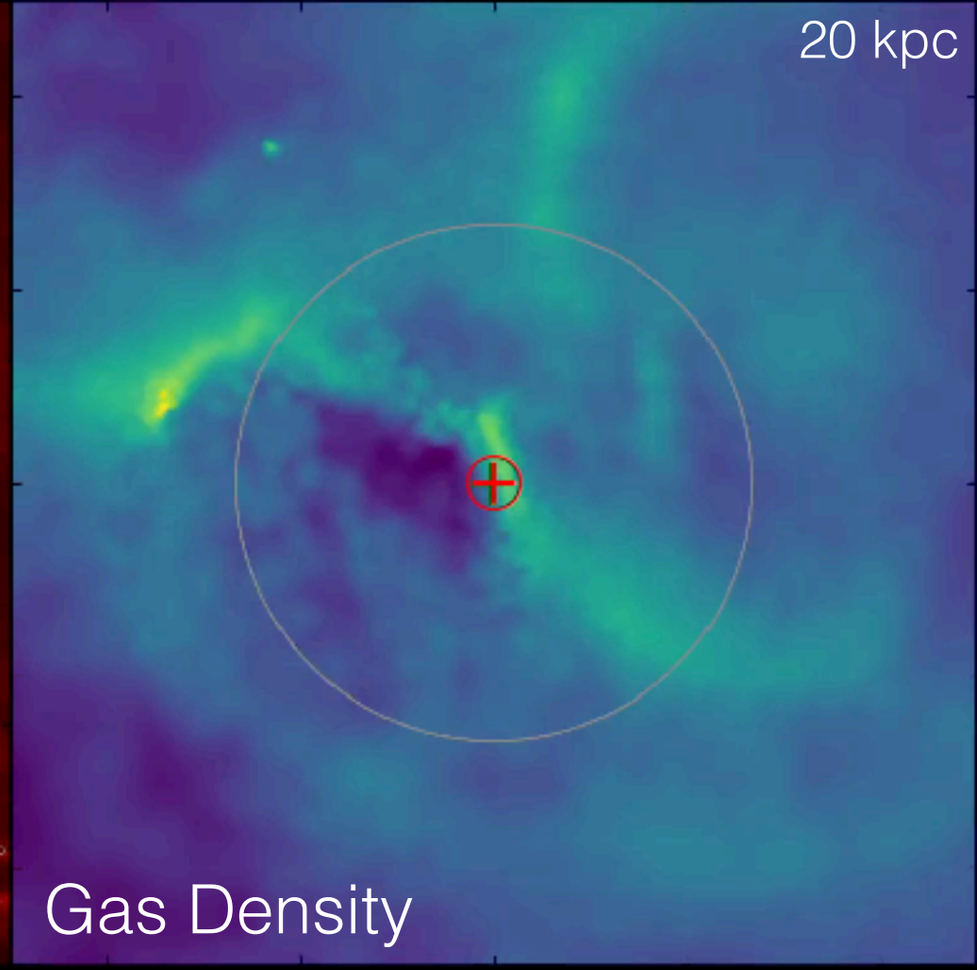
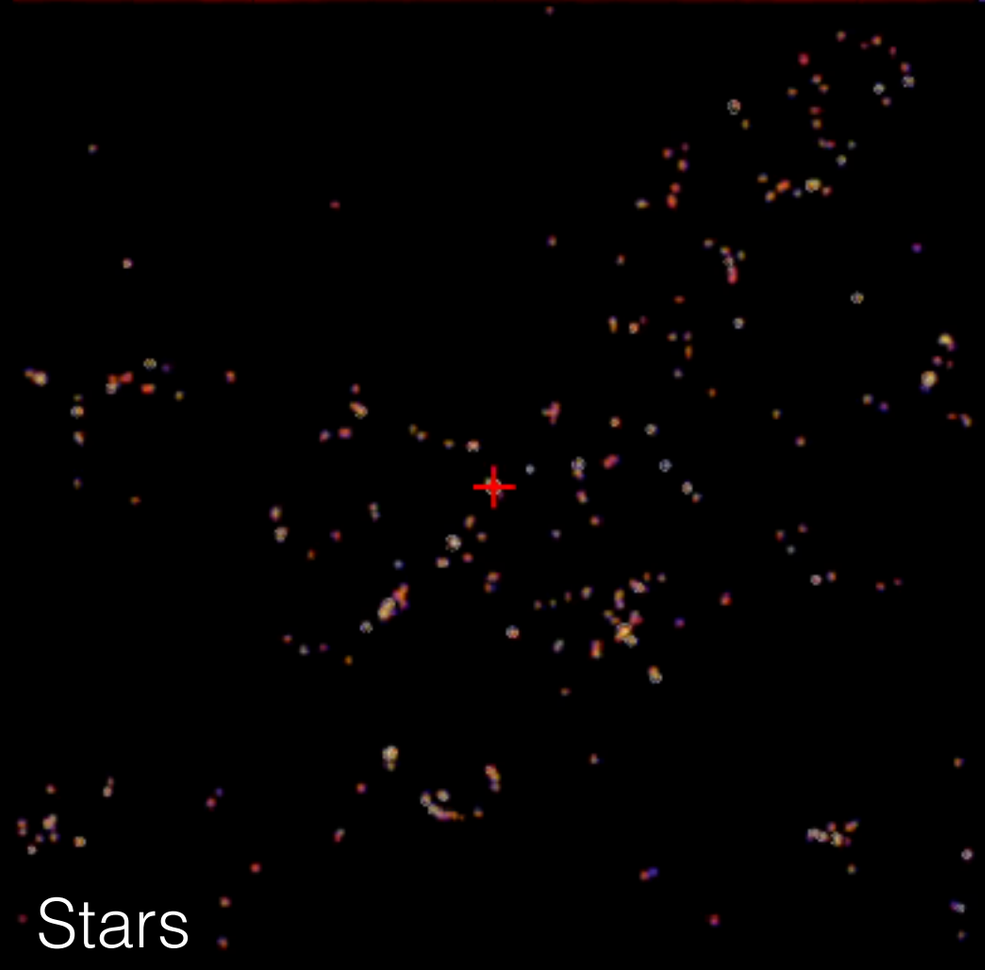
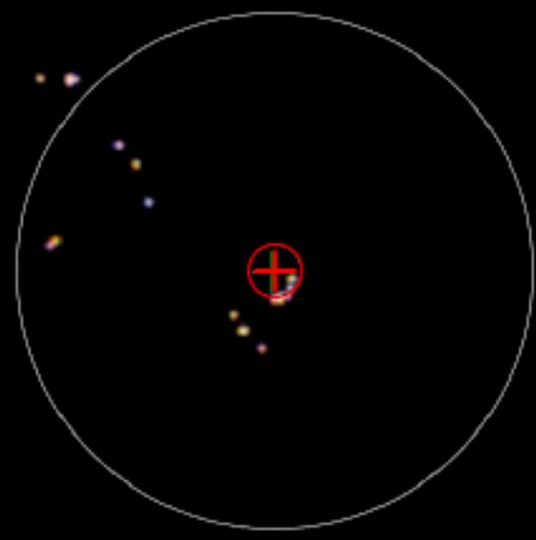


Lumpiness Changes the Story









D. Angles-Alcazar
in prep

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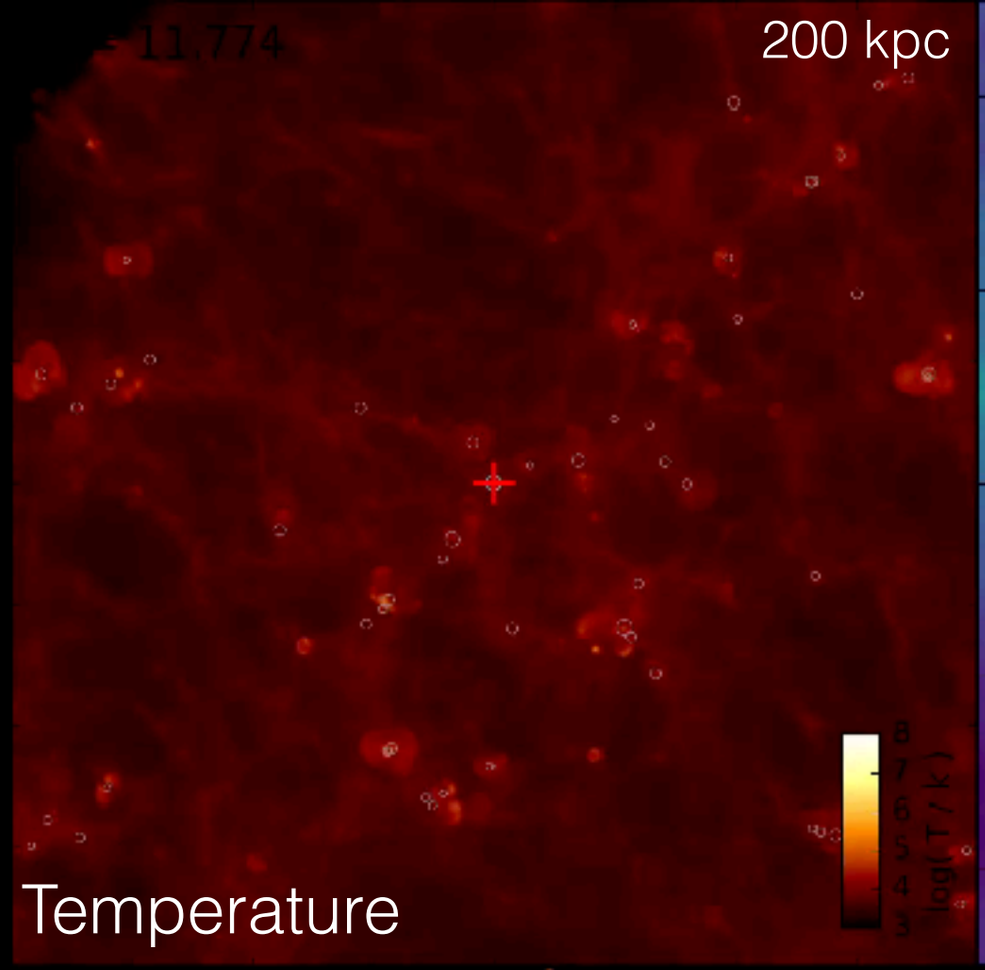

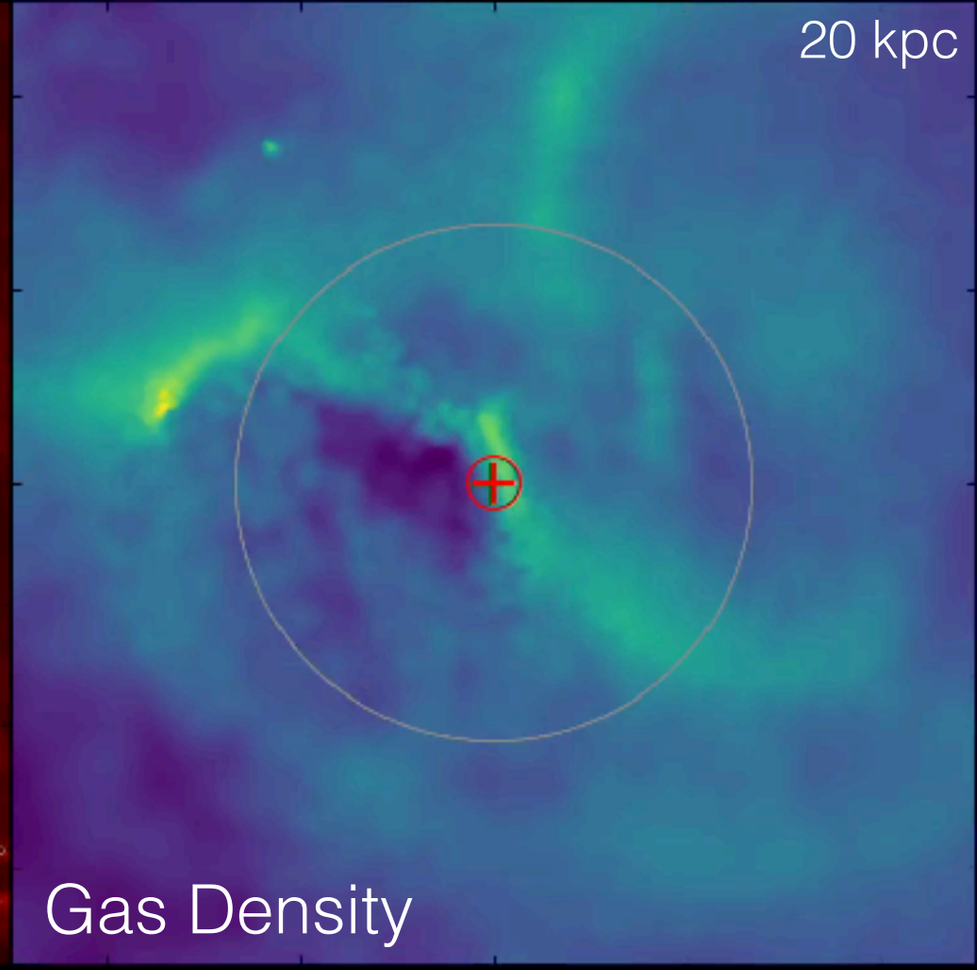

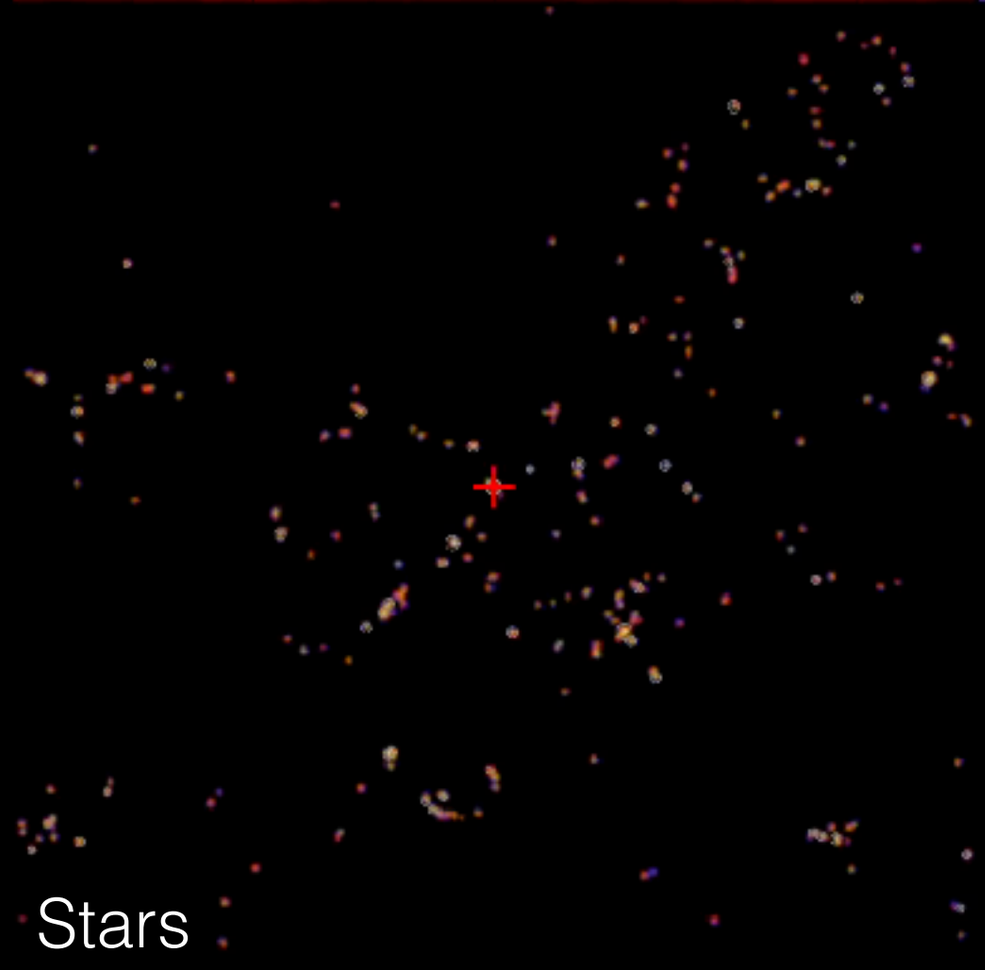

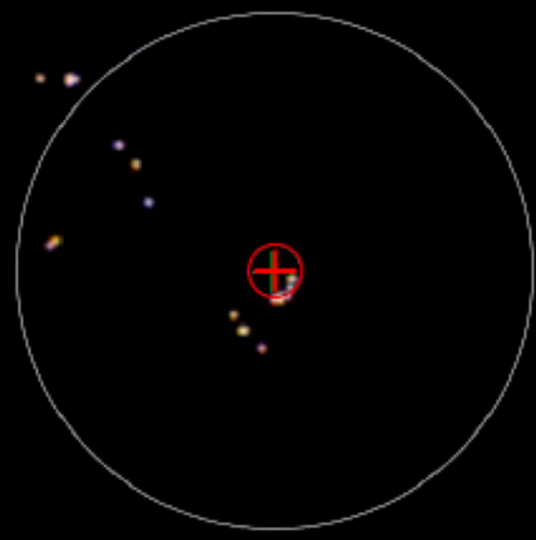

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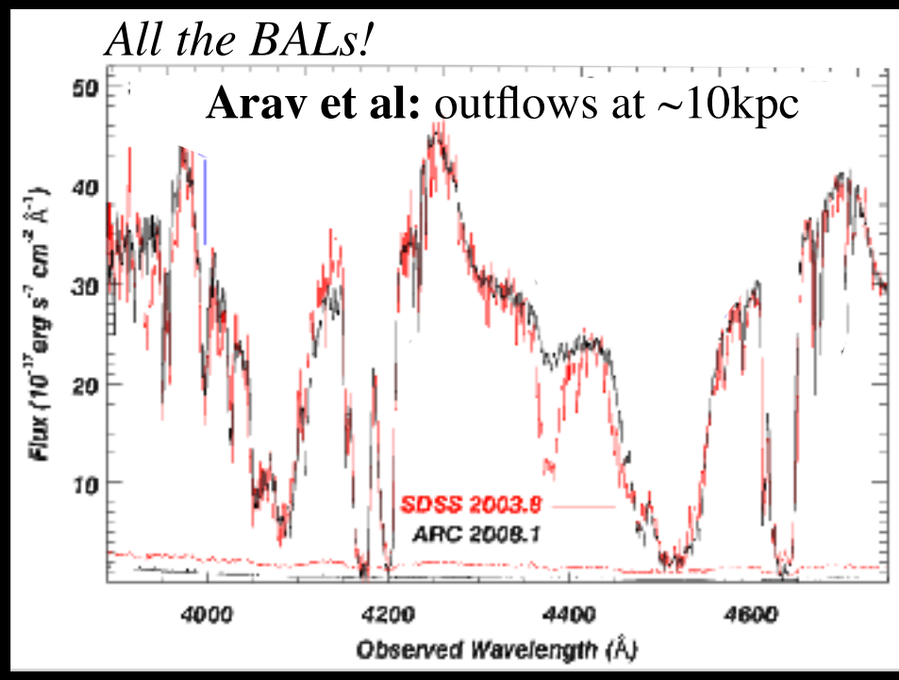
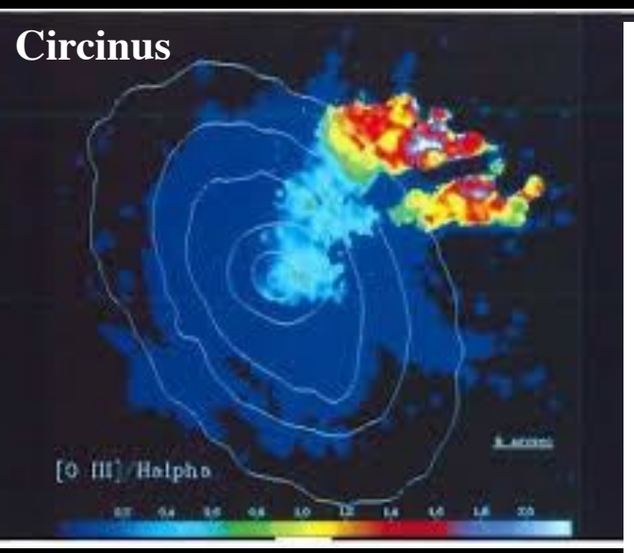
in prep

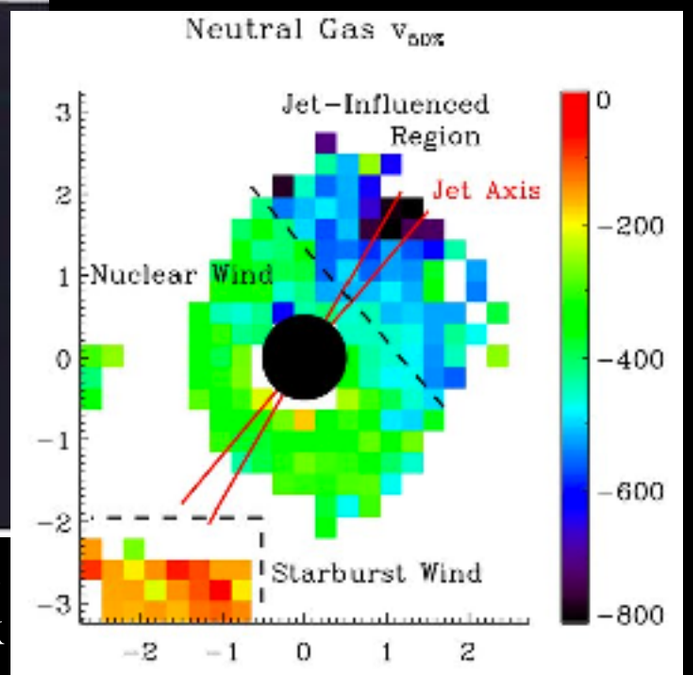
Accretion Disk Winds & Radiation Pressure

THEY MATTER

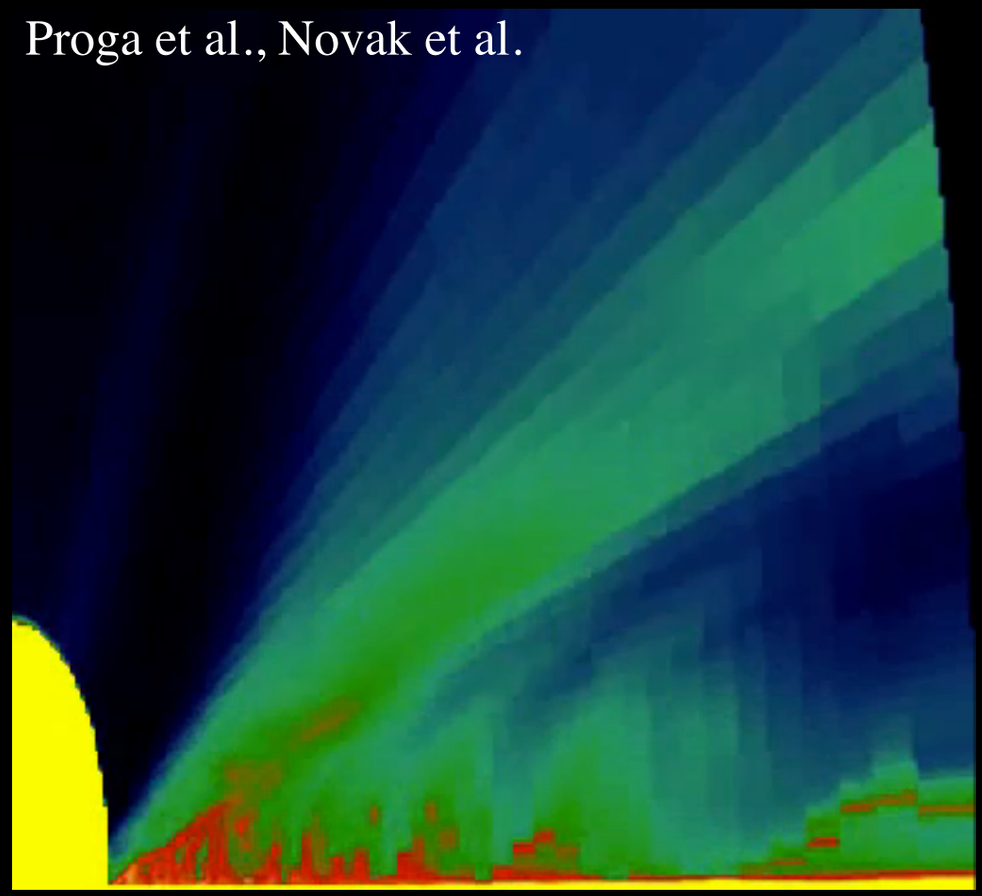




Mrk 231
Rupke & Veilleux



Proga et al., Novak et al.



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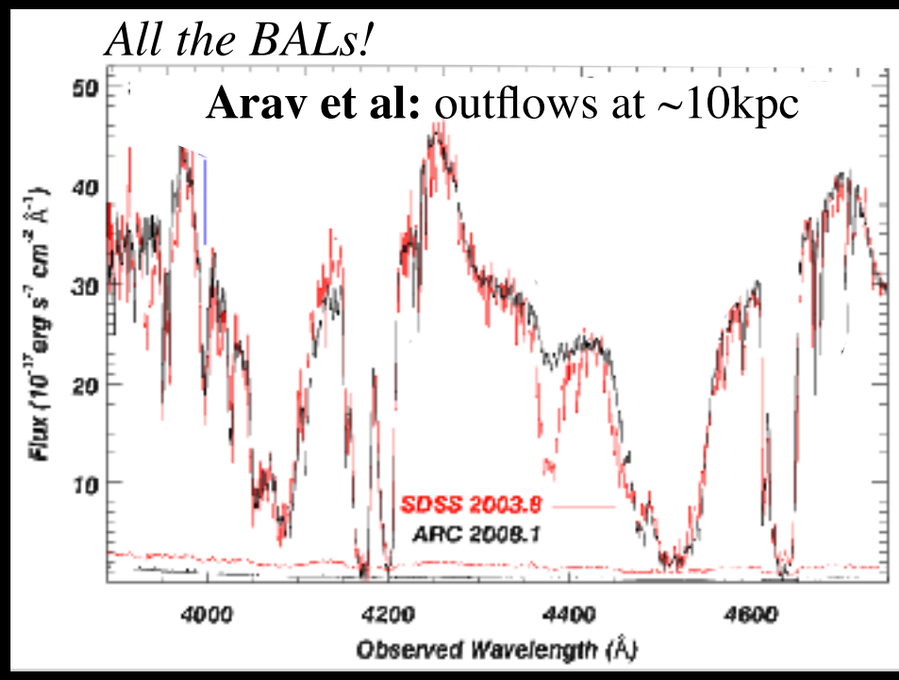

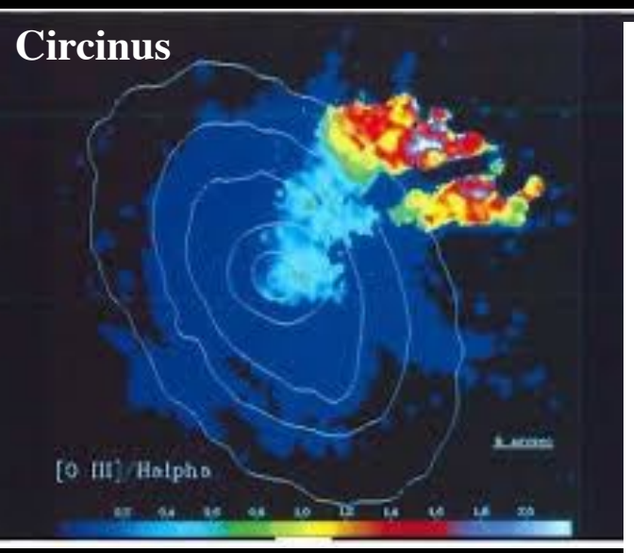

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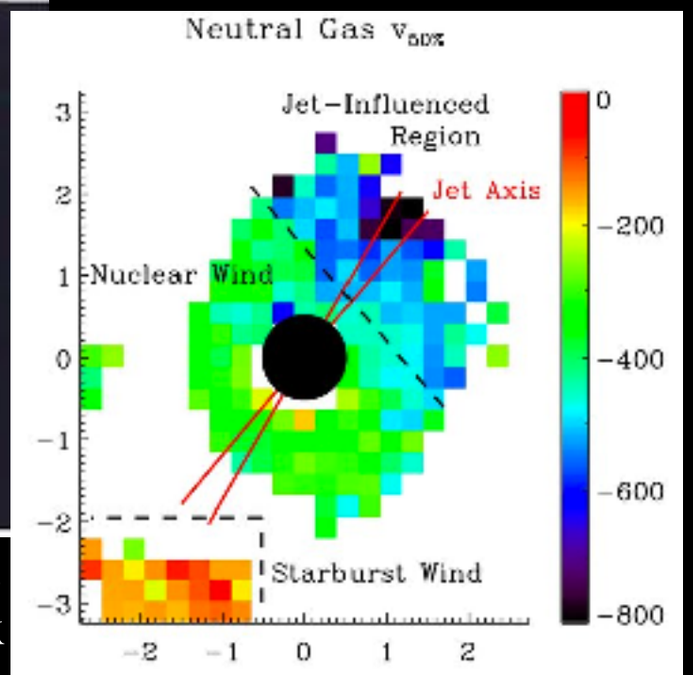
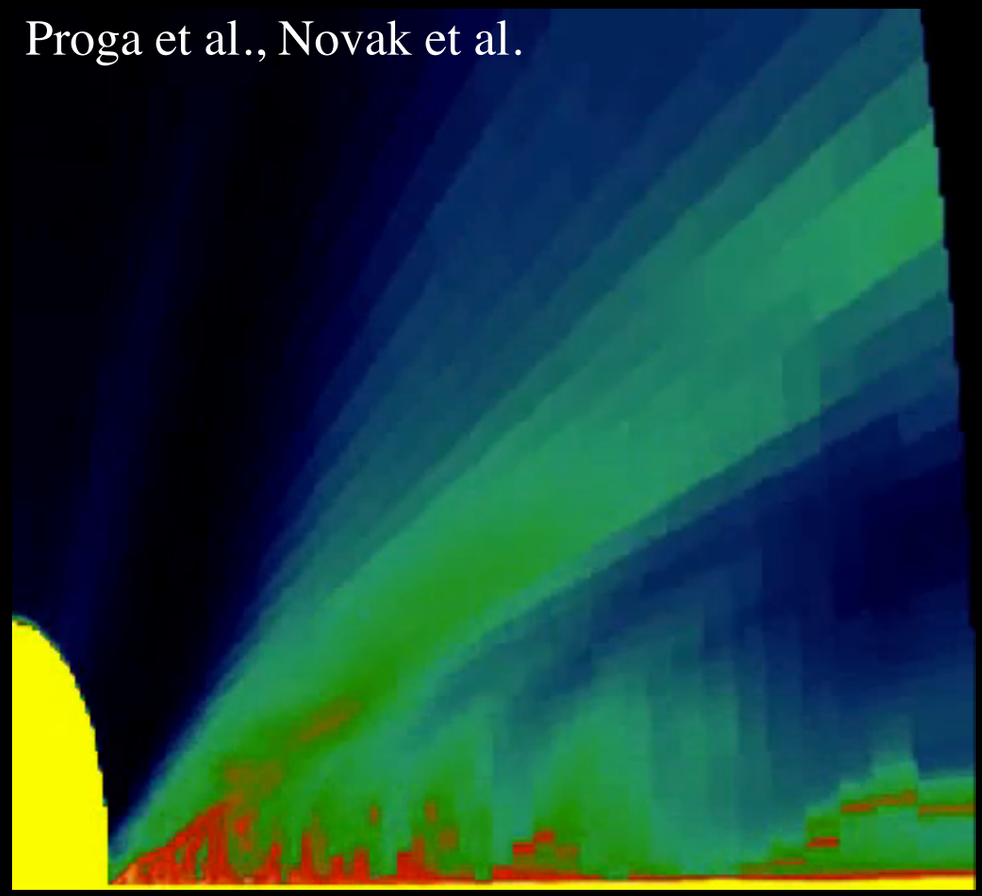


Proga et al., Novak et al.



Accretion Disk Winds & Radiation Pressure

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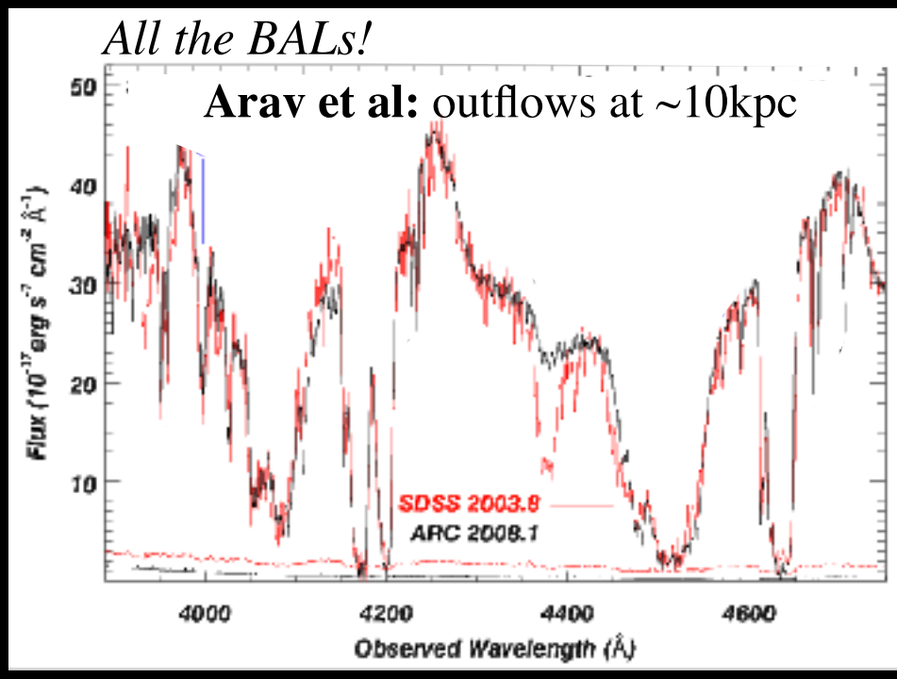
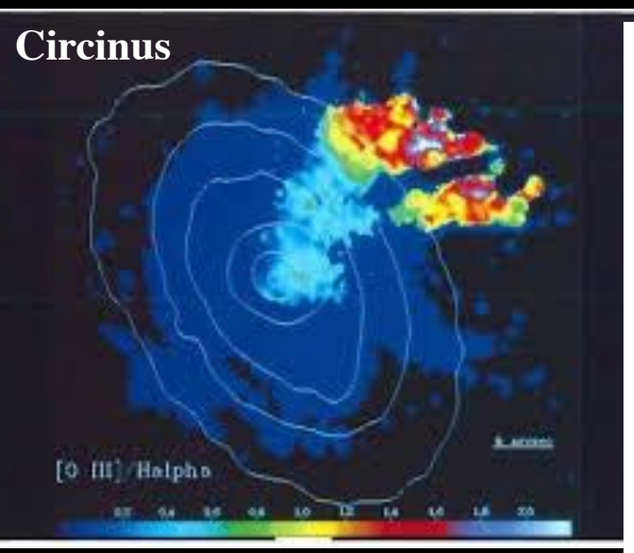
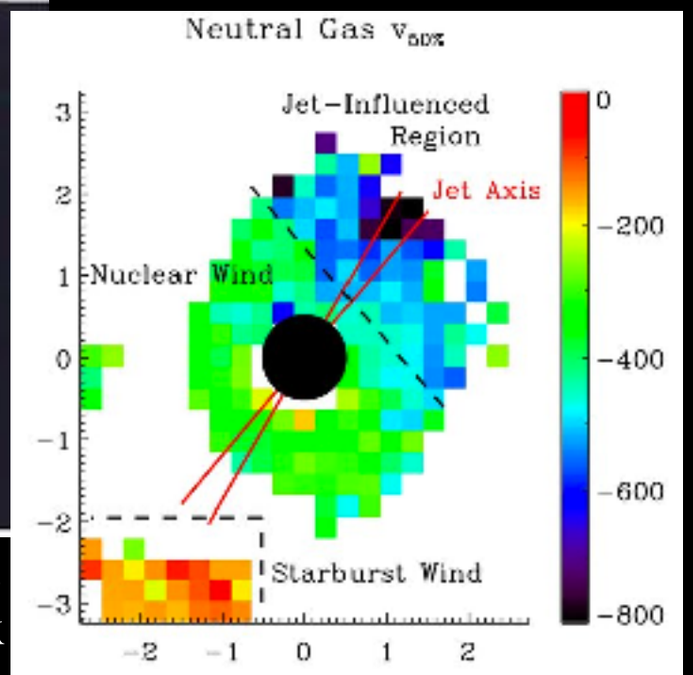




Mrk 231
Rupke & Veilleux



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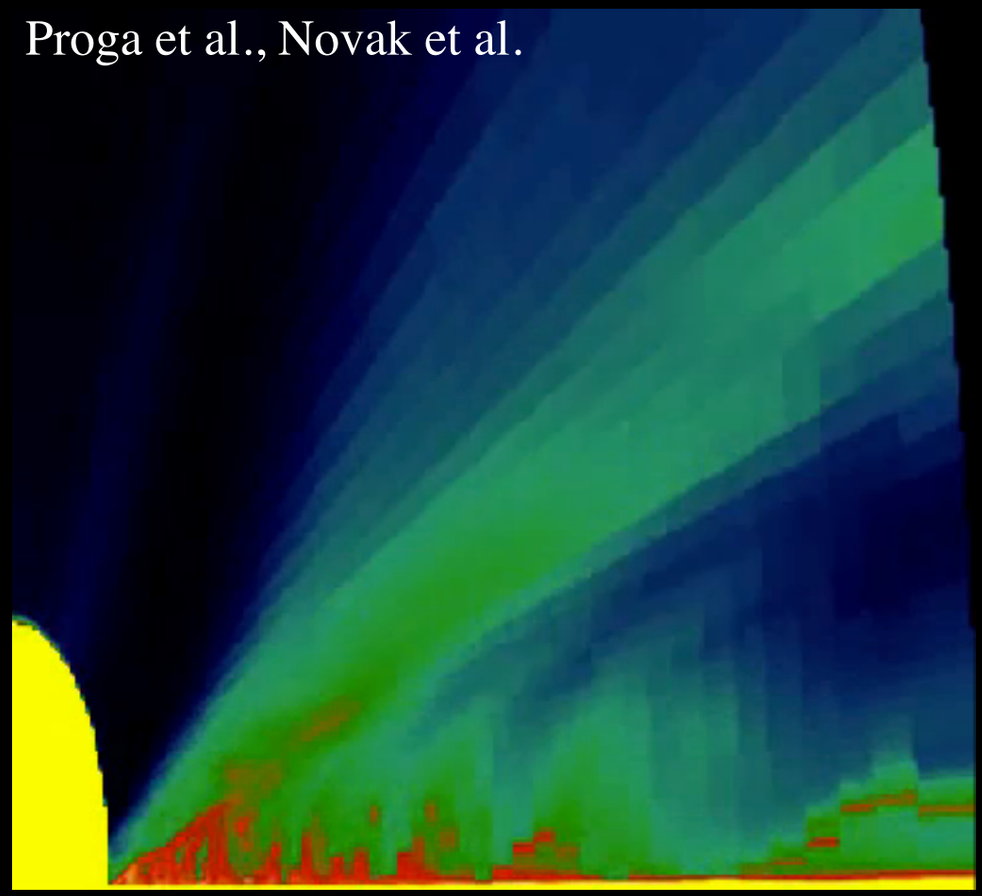

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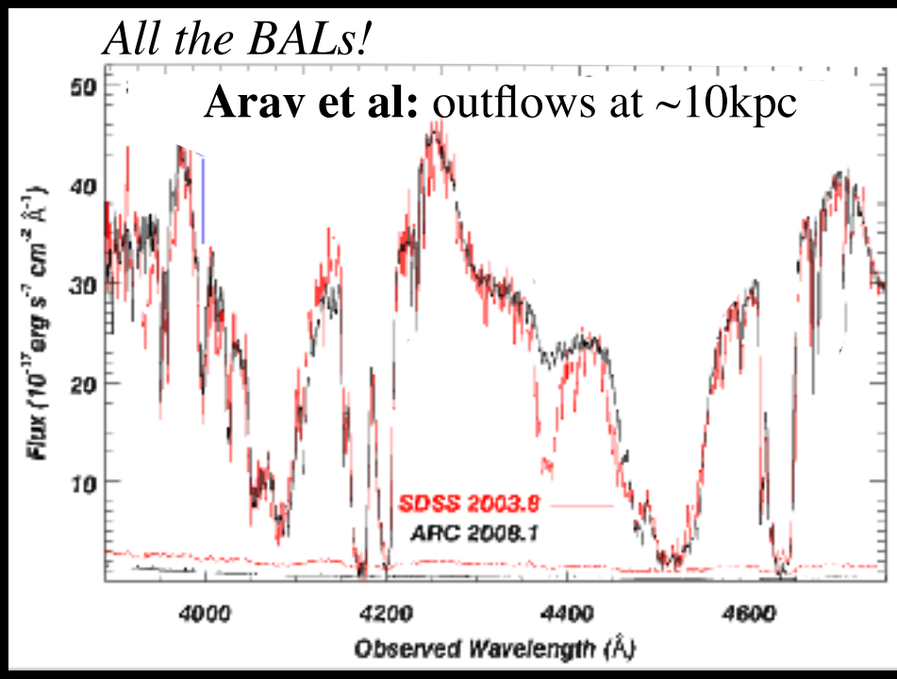

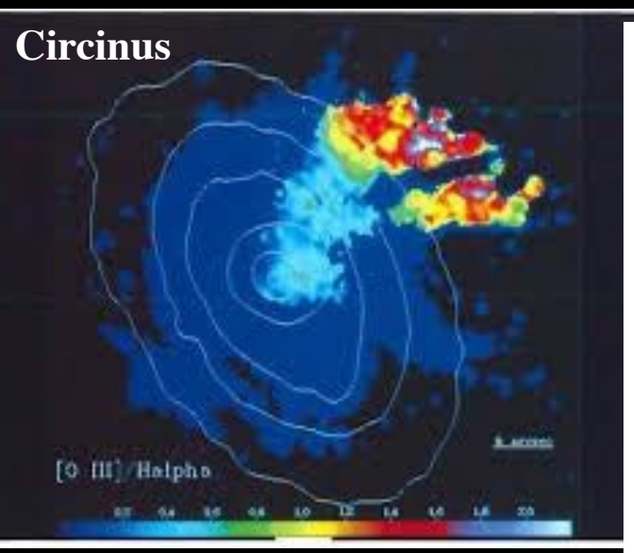

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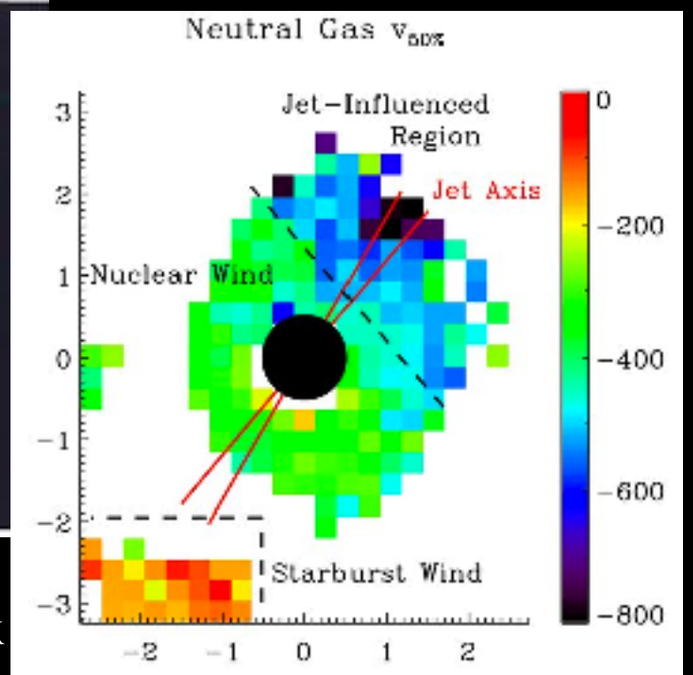

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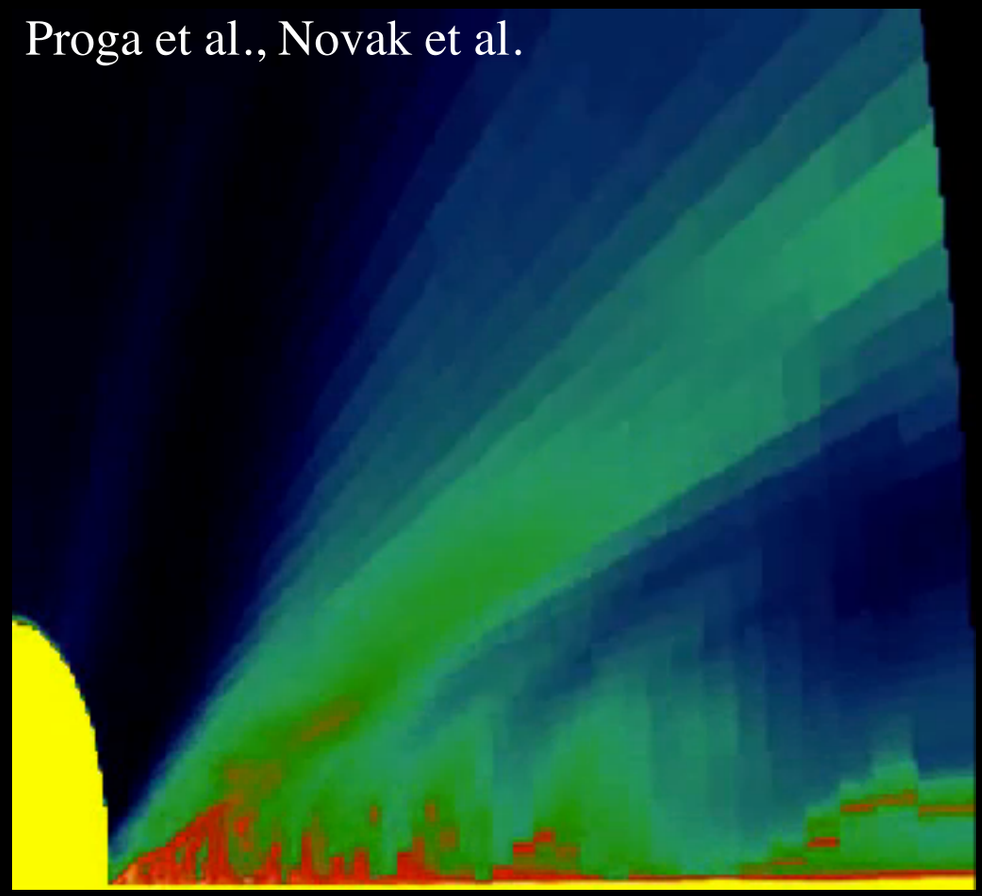

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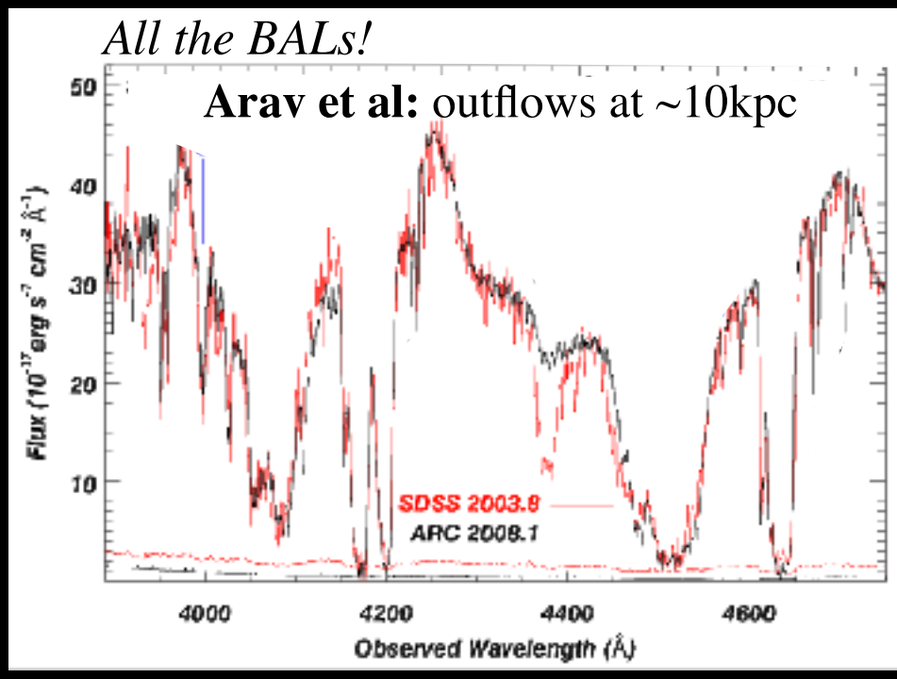

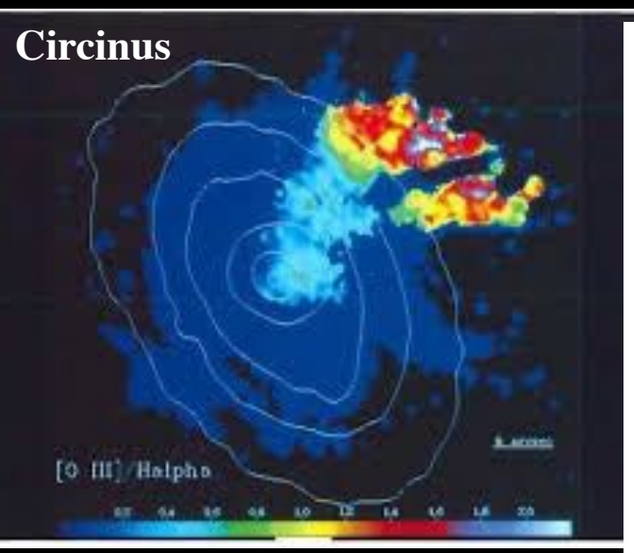

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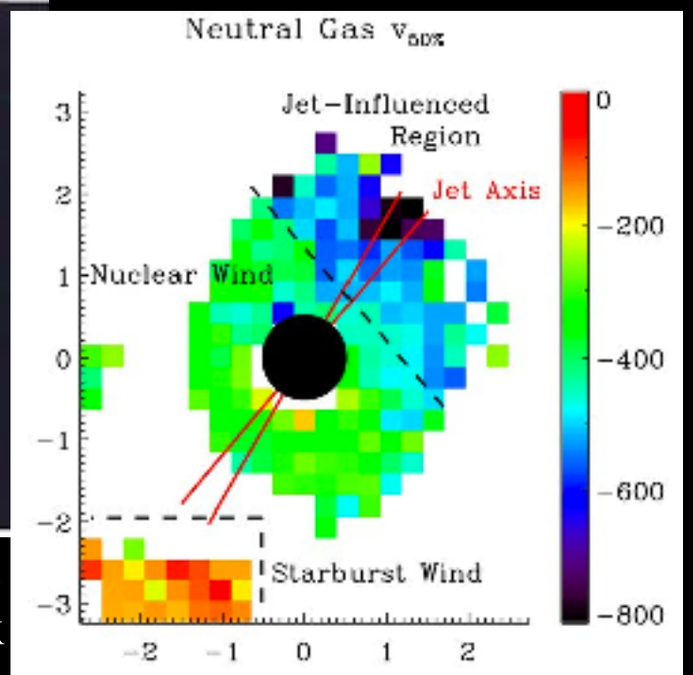

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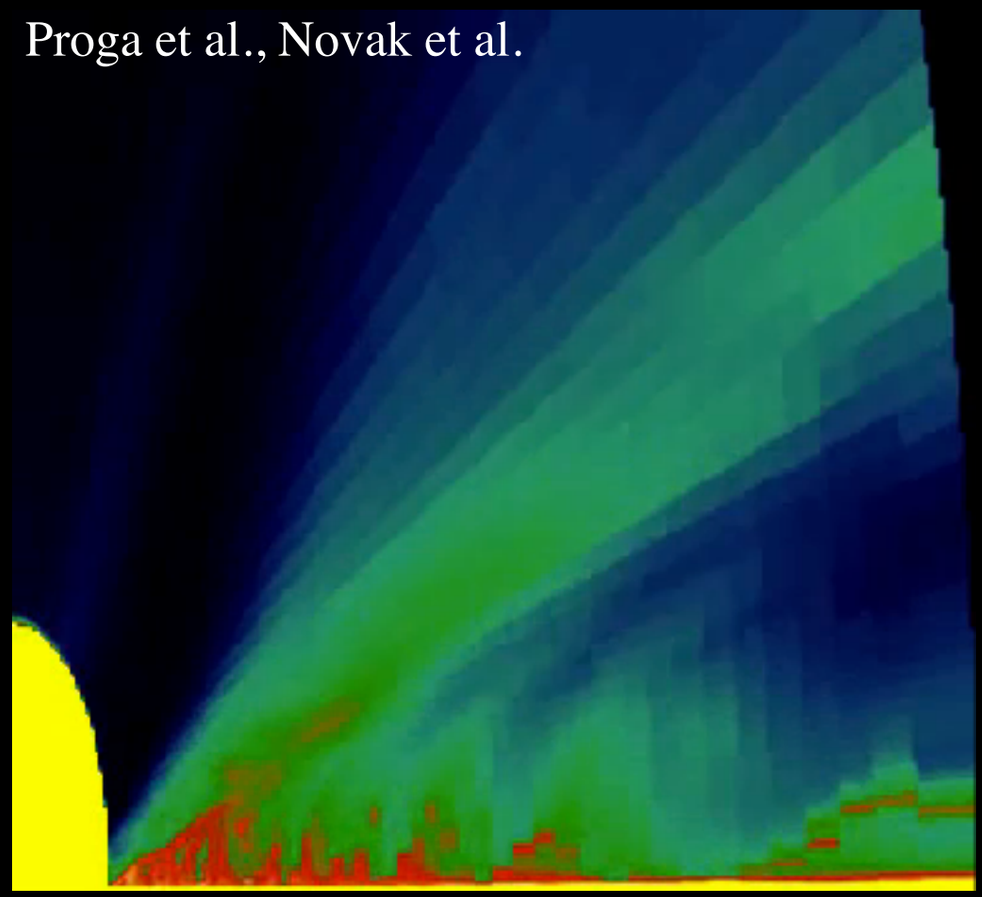

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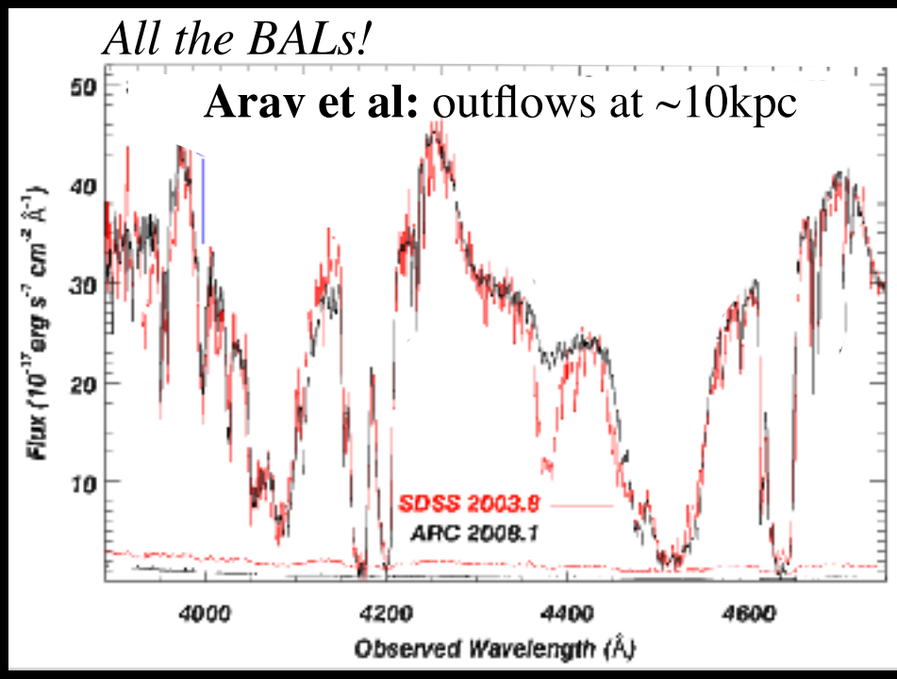

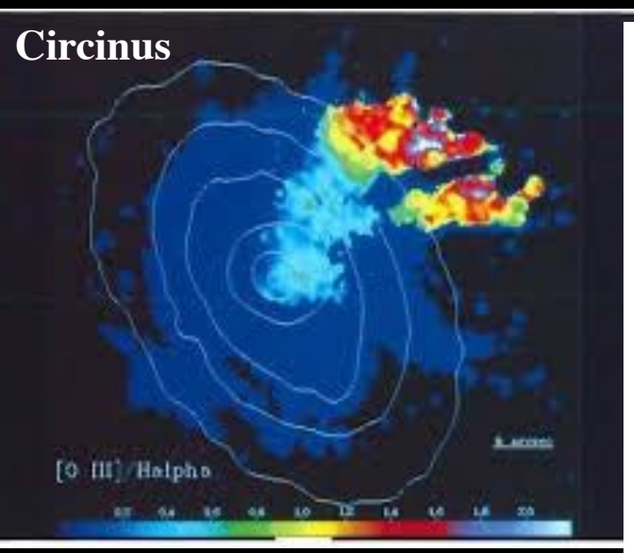

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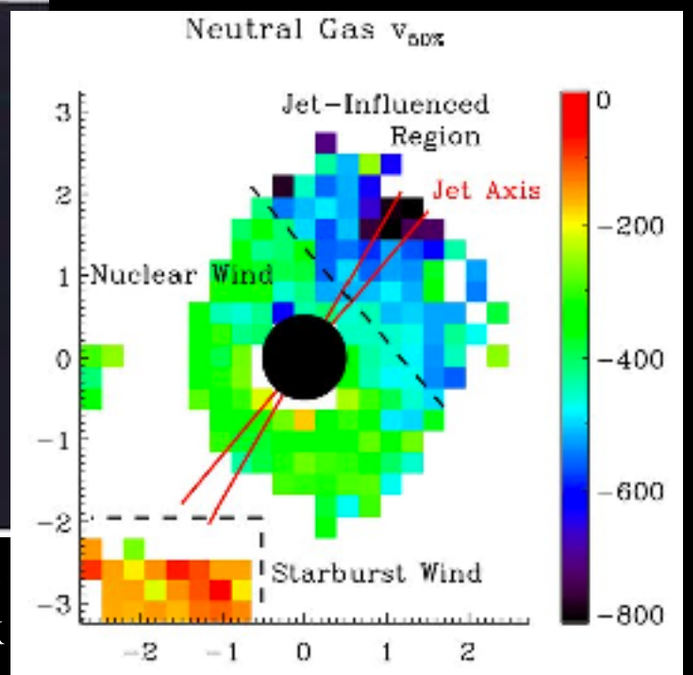

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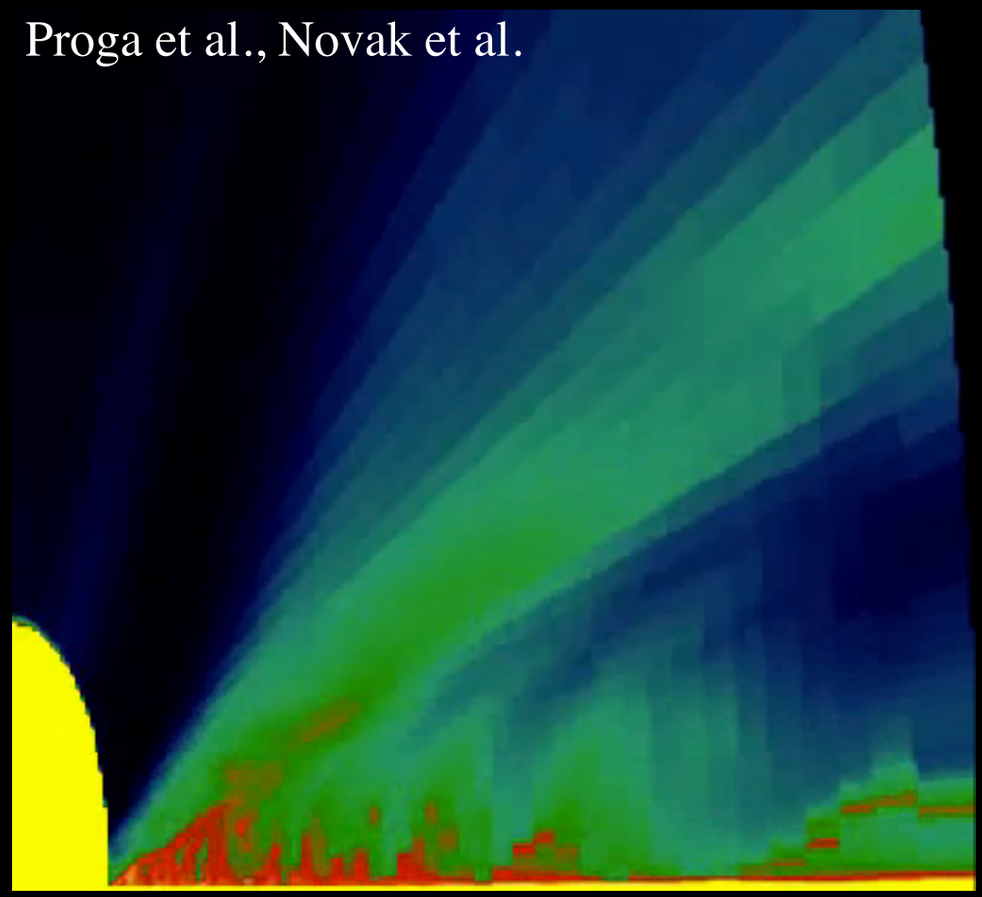


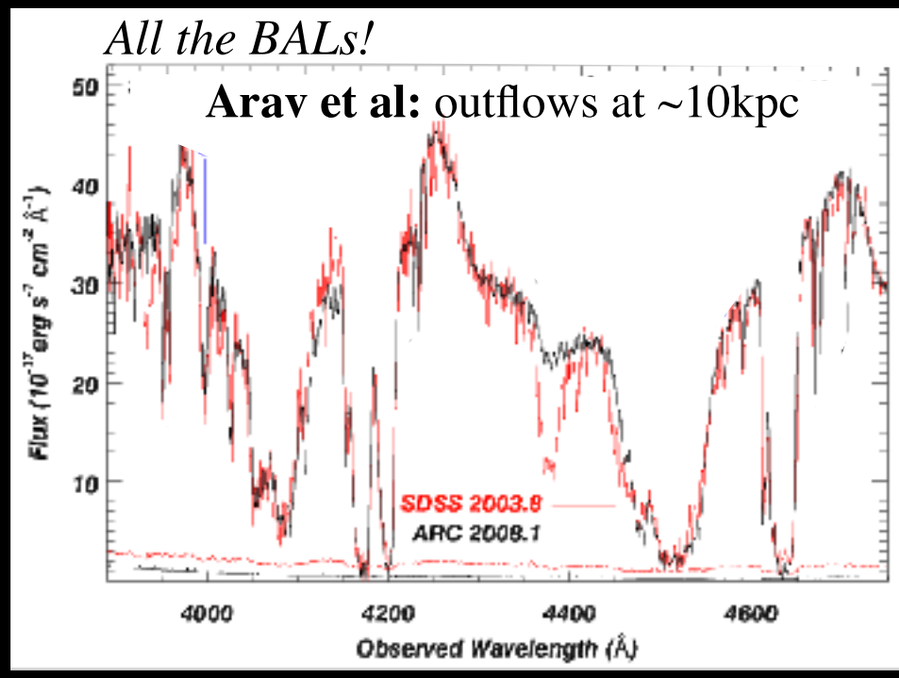
Accretion Disk Winds & Radiation Pressure

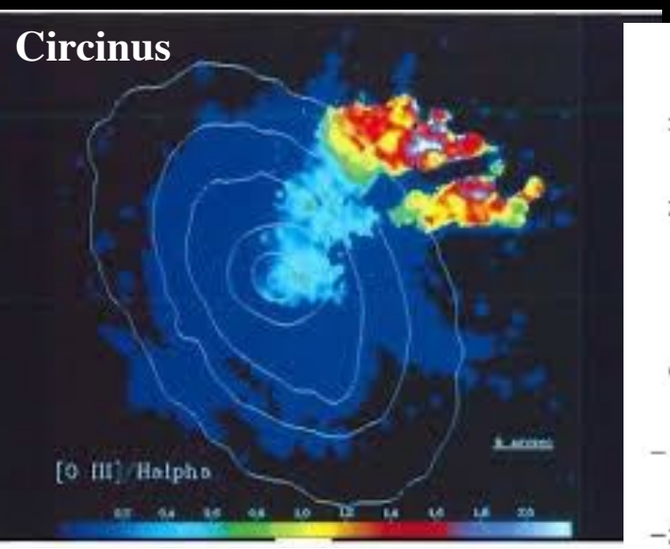
THEY MATTER

- "sweep up ISM" (molecular outflows), shock
- coupling? multi-phase winds & ISM, radiation cooling?
  launch: disk? torus? NLR?
- rare! (luminous QSOs, duty cycle ~1%)
  phases: molecular gas

timescale: ~10 Myr to ~few kpc

HAPPENS BEFORE QUENCHING!!!!





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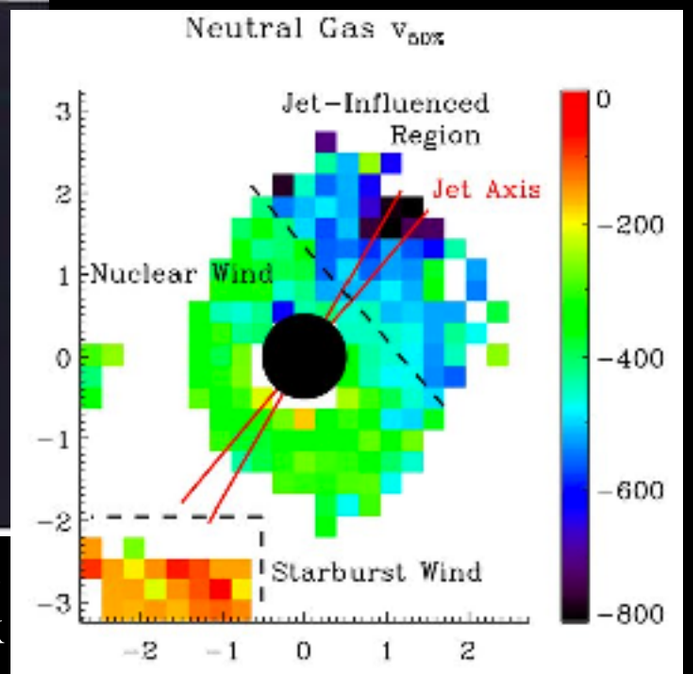

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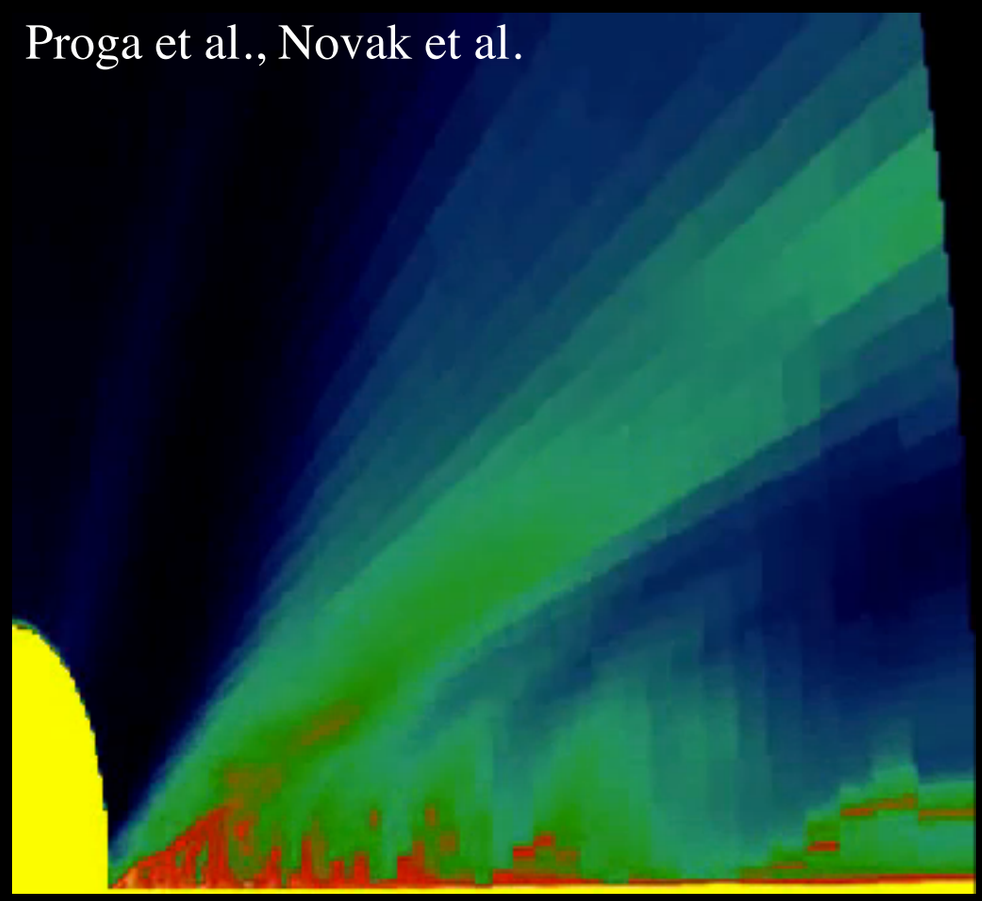
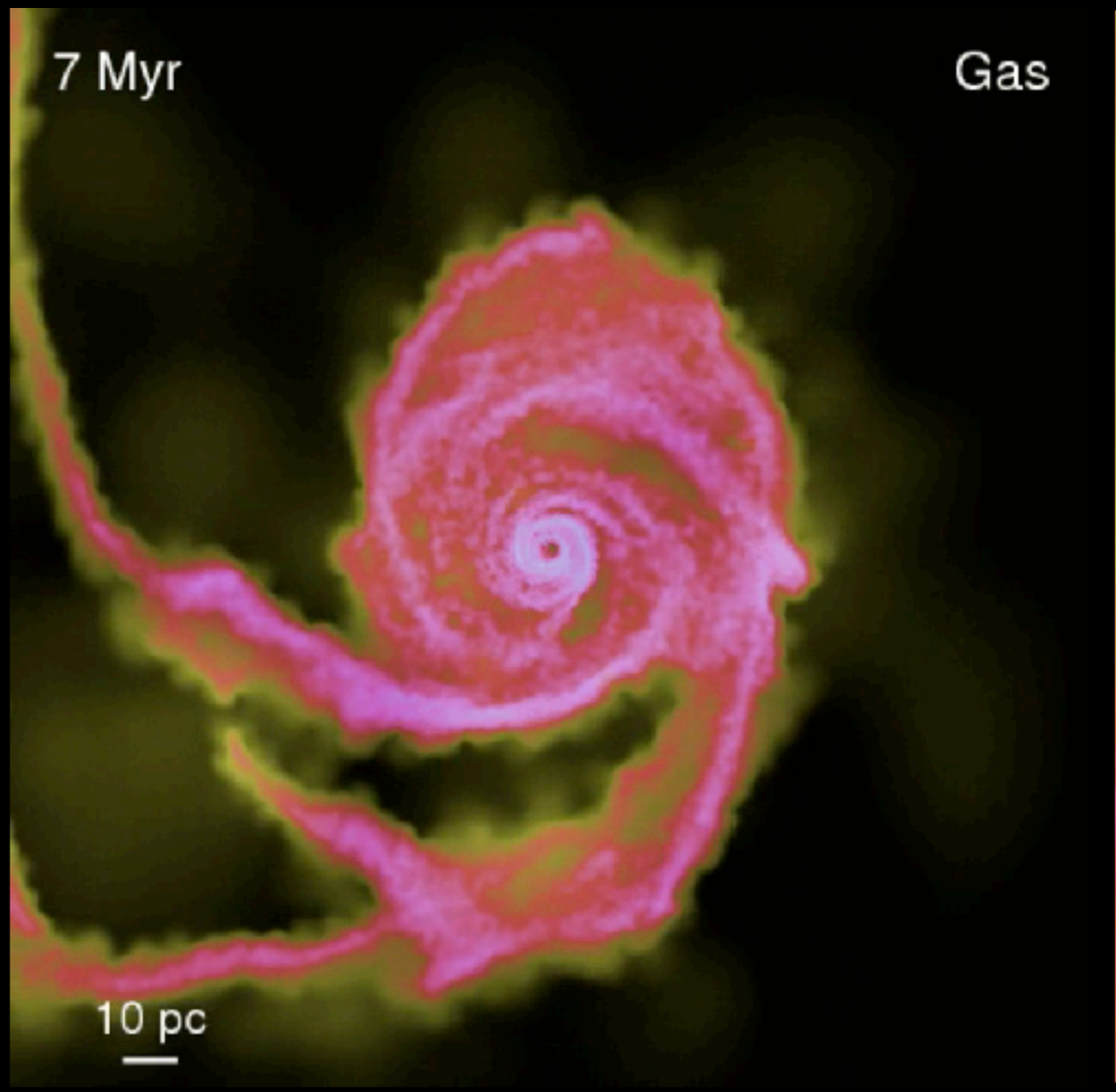
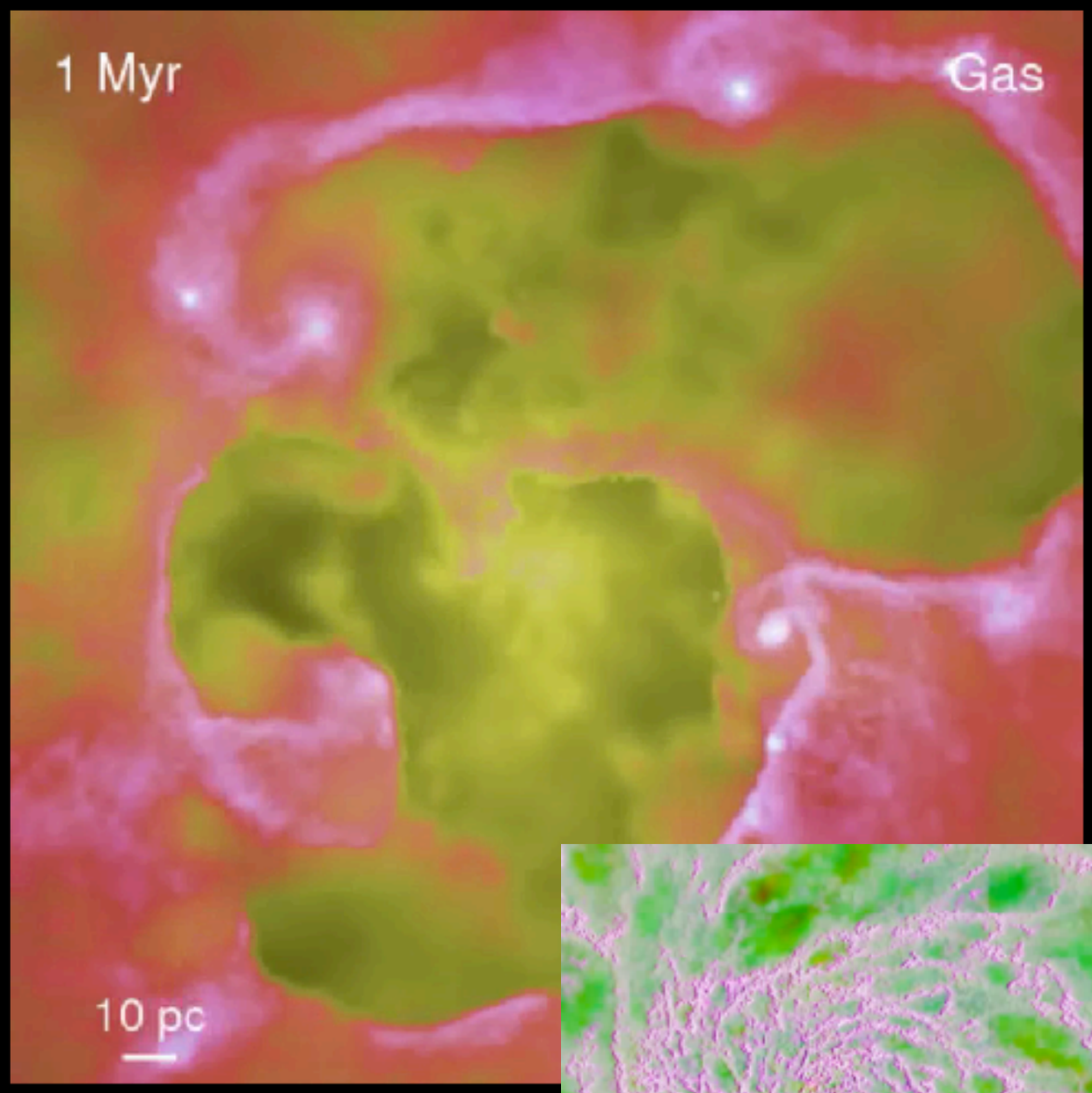


Accretion Disk Winds: 0.01-10,000 pc

No BAL Winds



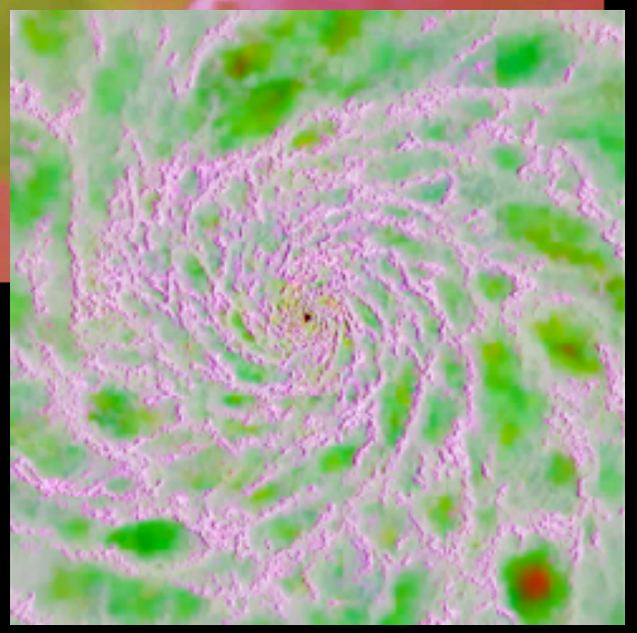
With BAL Winds



Torrey et al.
in prep

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

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



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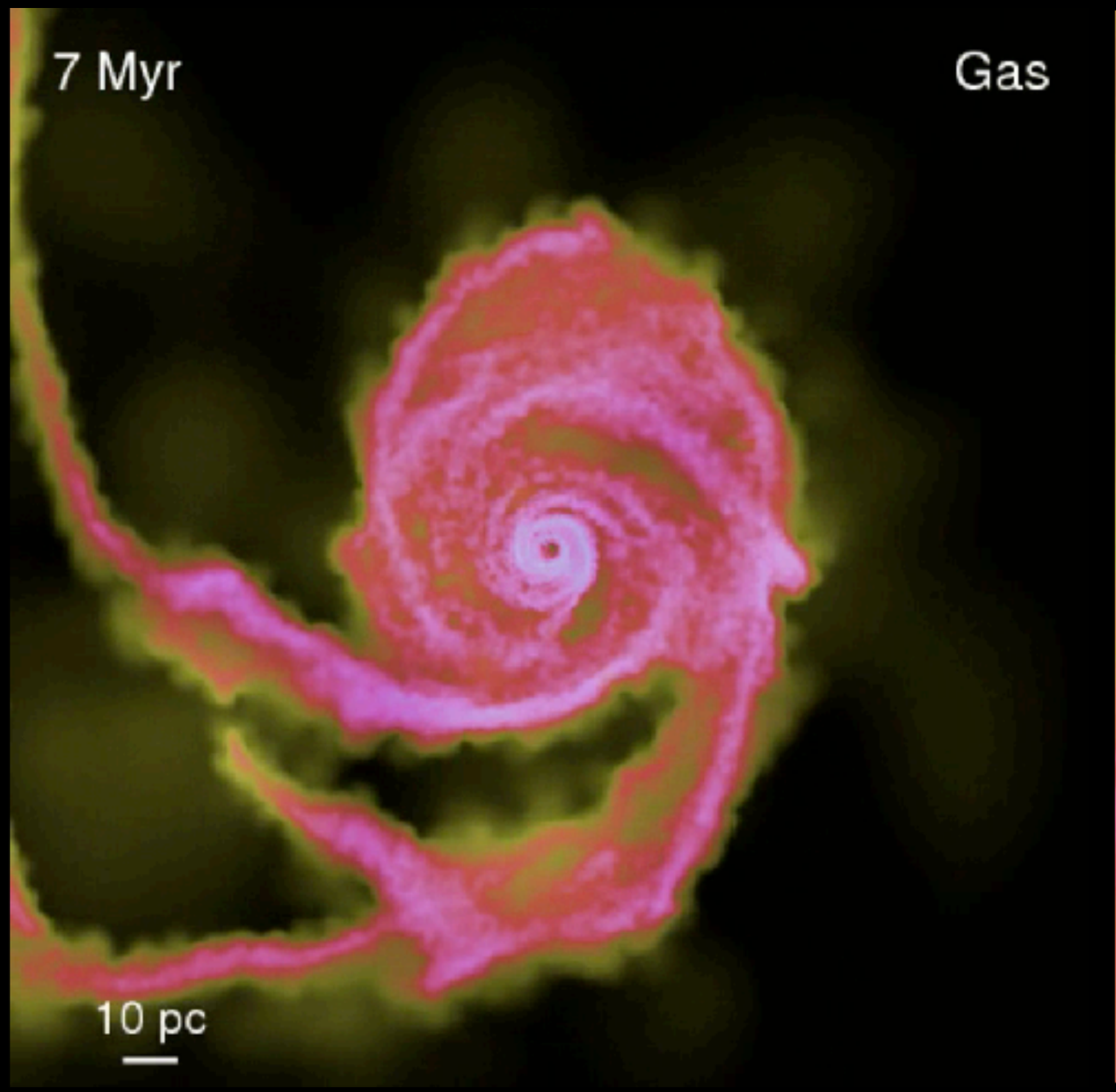

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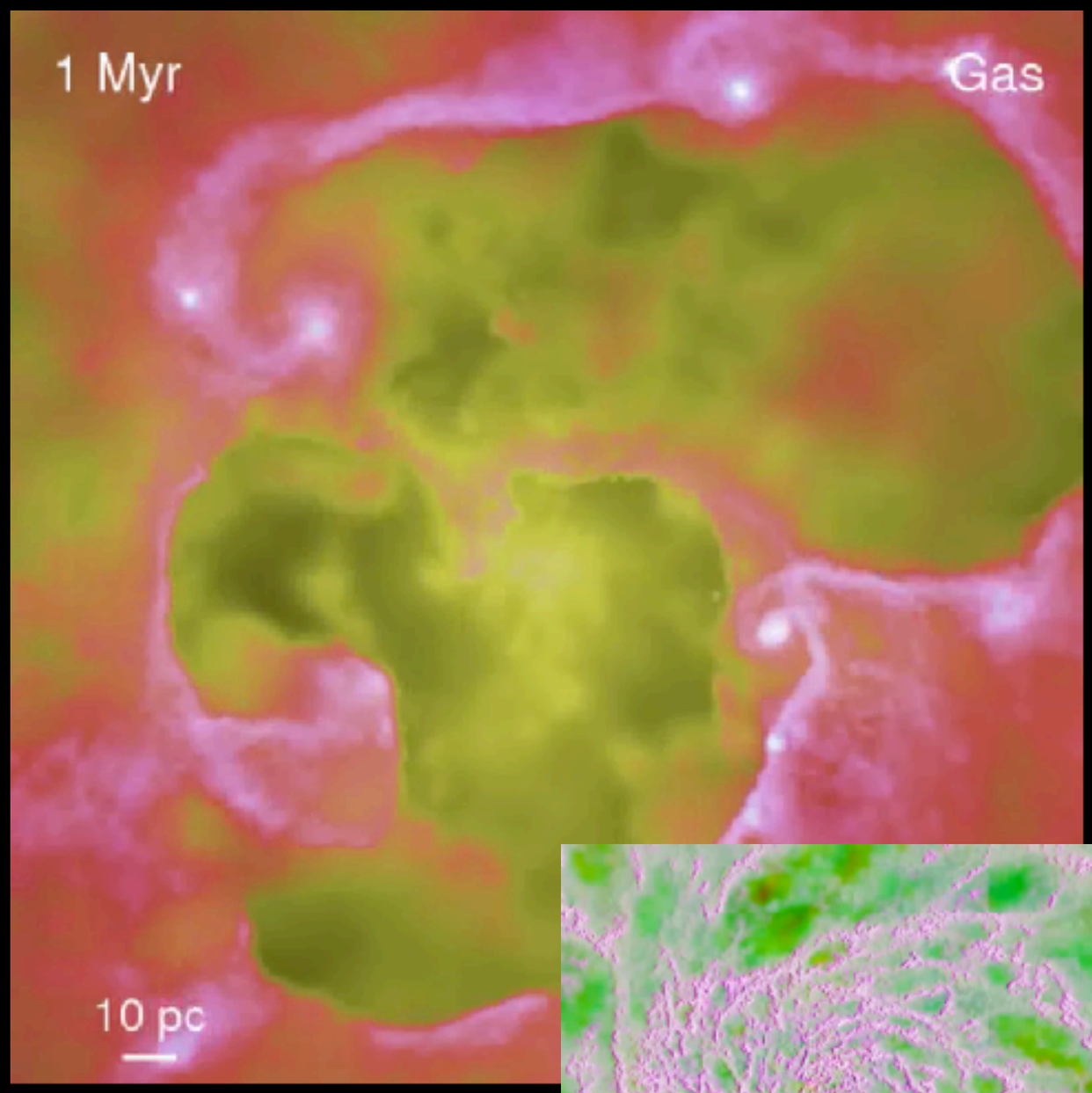

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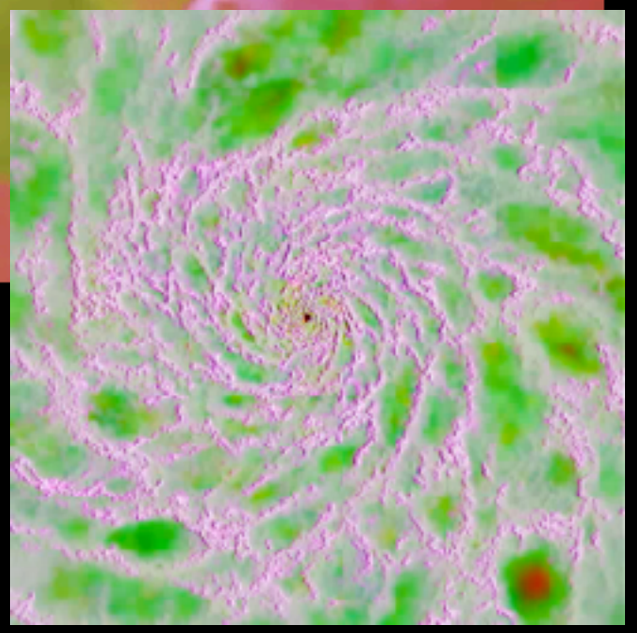

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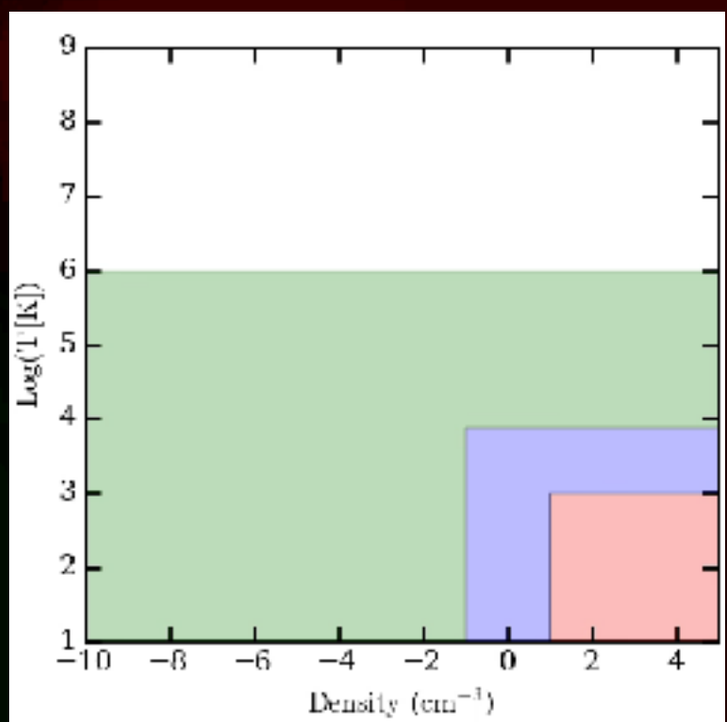

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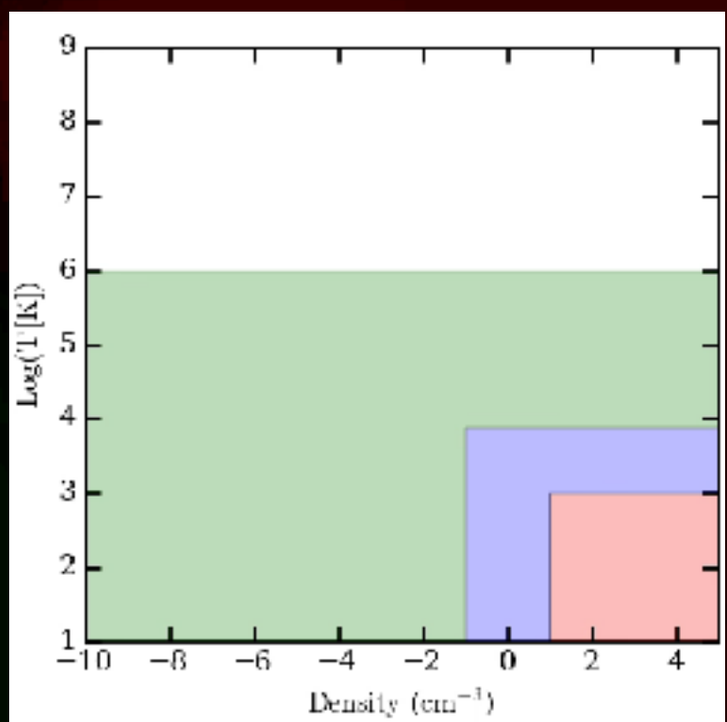
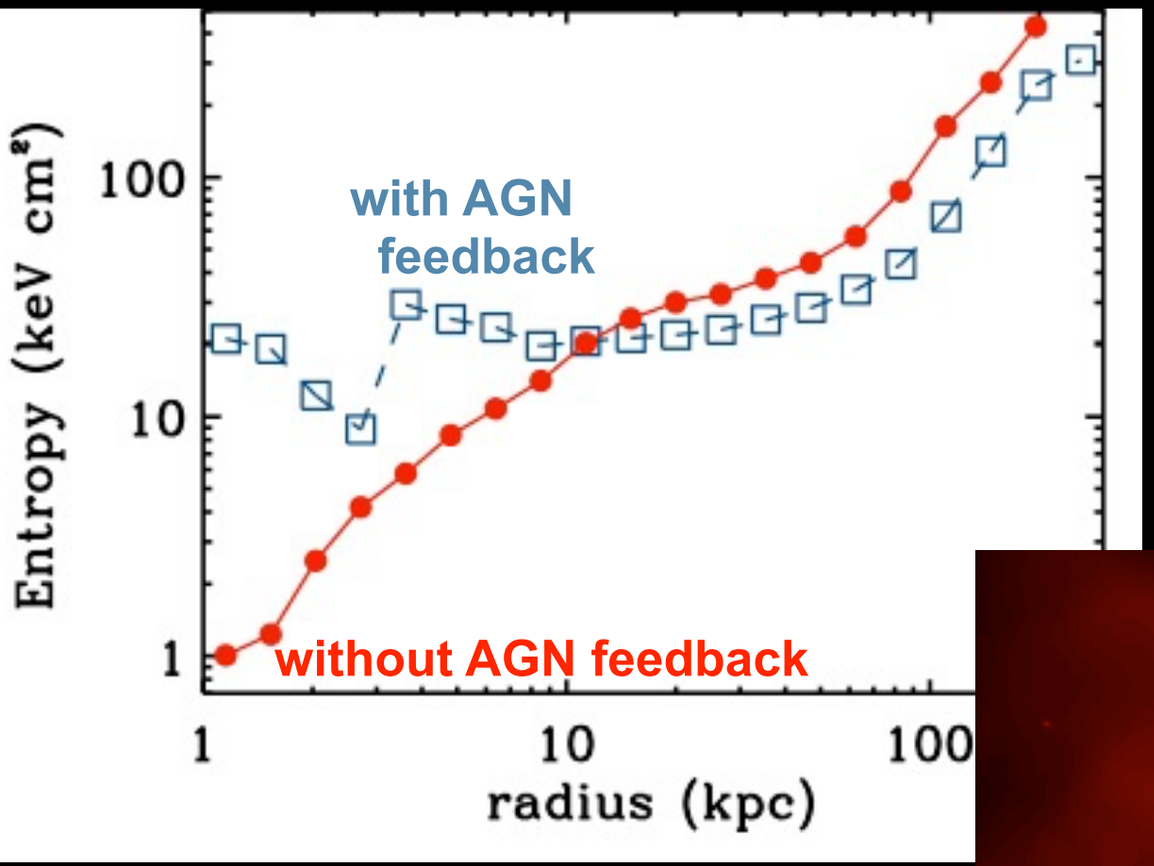


Need to Link "Radio Mode" to Cosmological Evolution

CAN YOU HEAT "GENTLY"?

Illustris & Eagle simulation papers



Angles-Alcazar (in prep)

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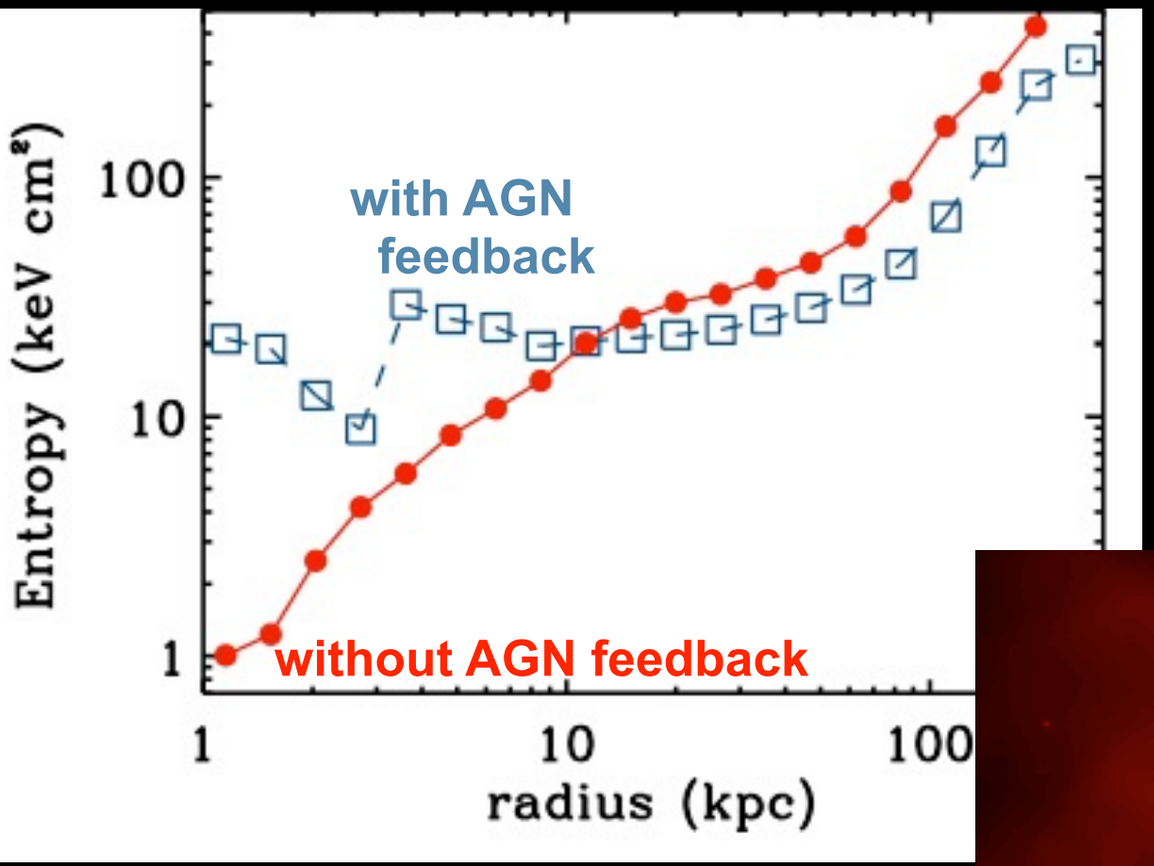
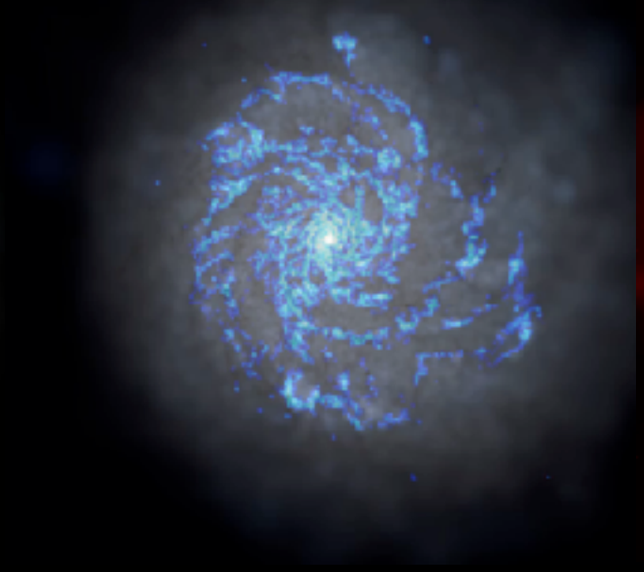


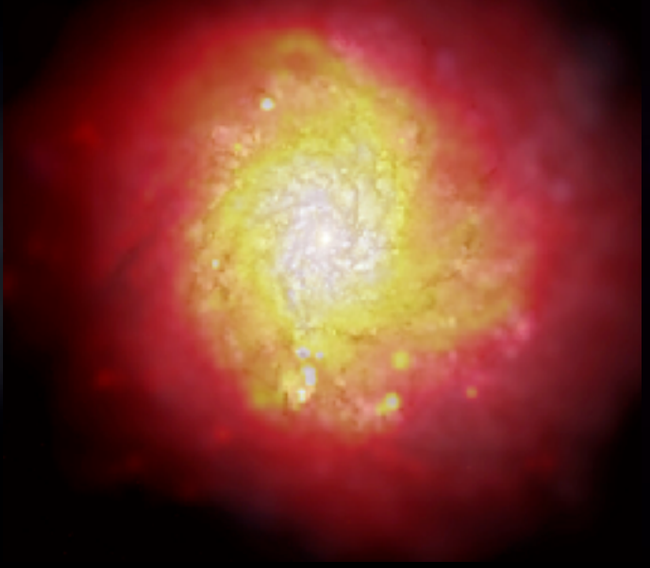
Angles-Alcazar (in prep)

Observed Starlight

Molecular



X-Rays



Star Formation

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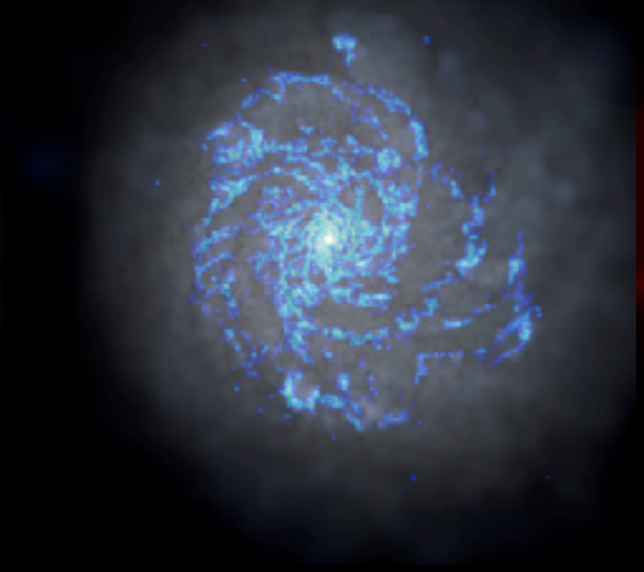

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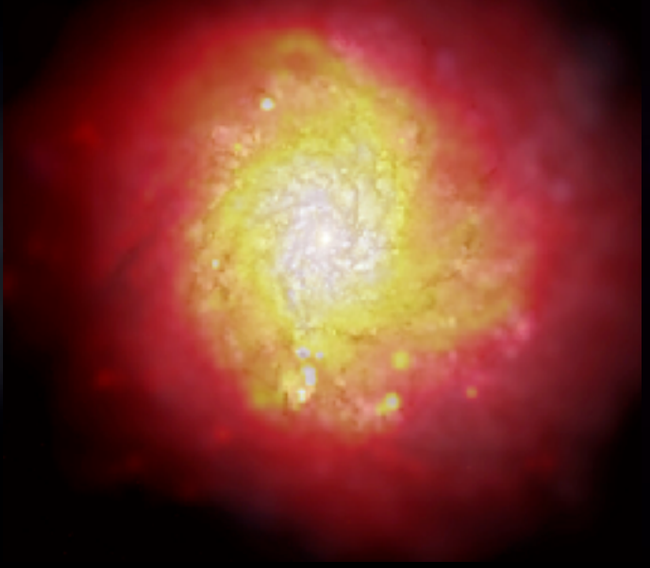

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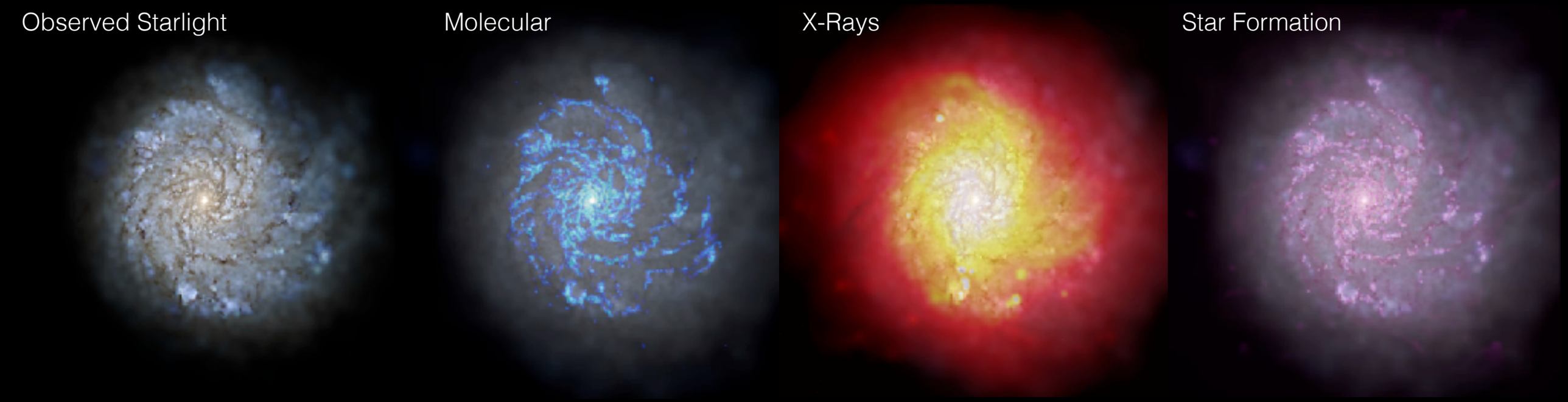

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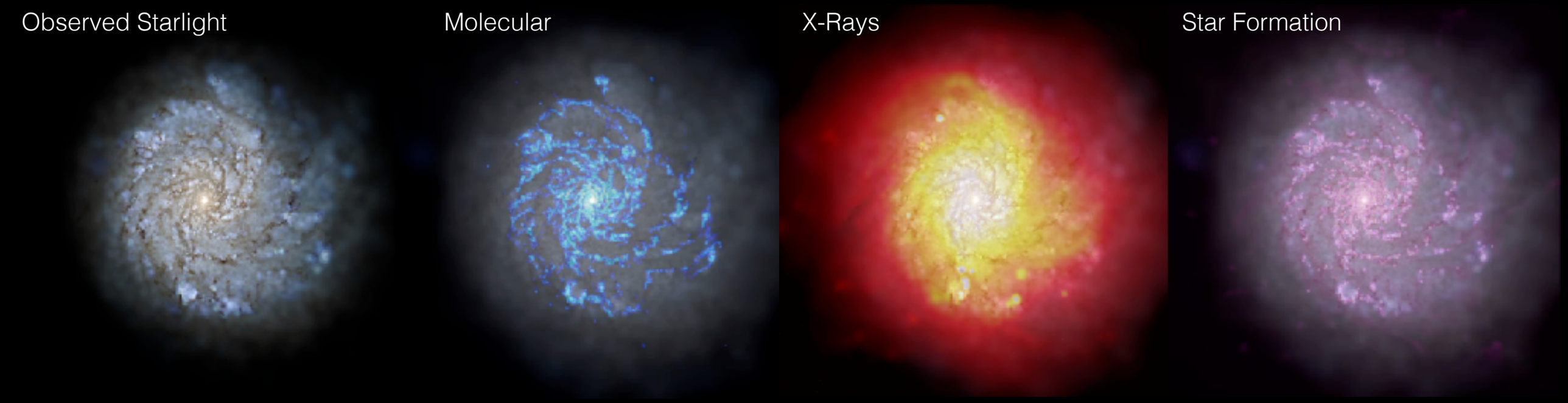
  - Feedback naturally predicts masses, KS law, scaling relations *without fine-tuning*



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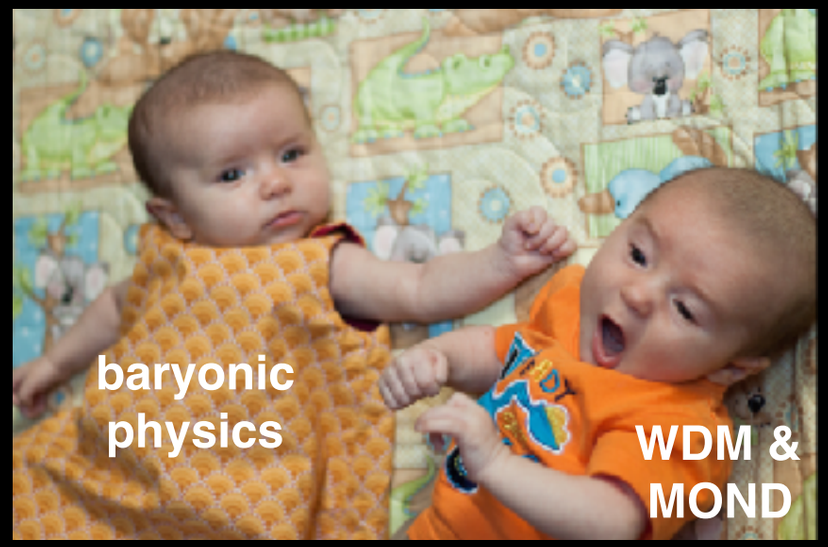
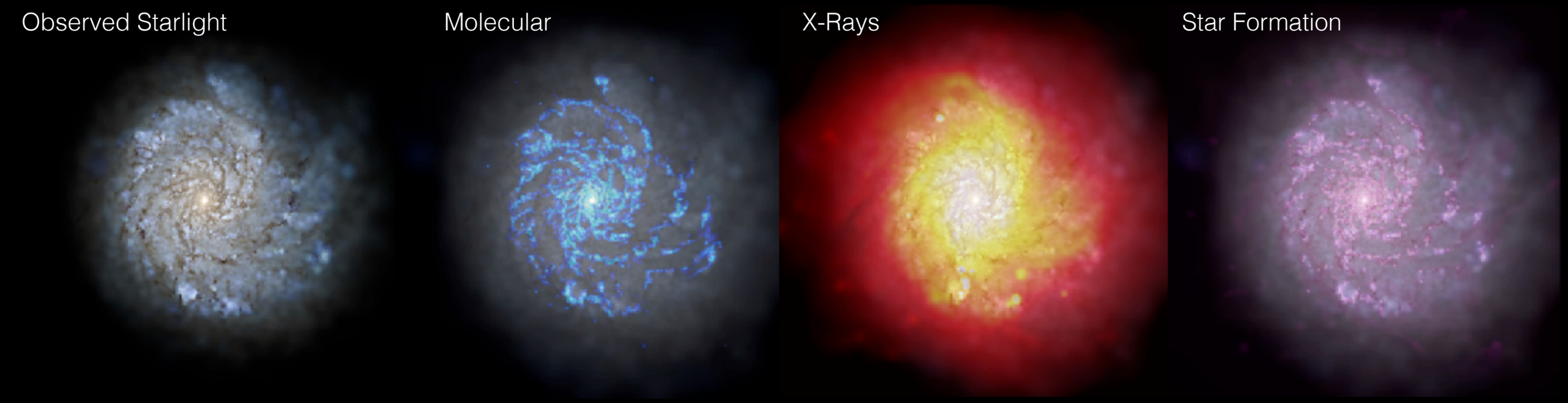


Observed Starlight | Molecular | X-Rays | Star Formation



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- **AGN feedback is real and here to stay**
  - Fueling: gravitational instabilities, *not Bondi* (factor 100,000,000 wrong)
  - Accretion disk winds & radiative feedback: *probably* the "quasar mode"
  - Jets & cosmic ray bubbles: *probably* the "radio mode"