Deciphering the ubiquitous ***bursty*** phase of galaxy formation at early times

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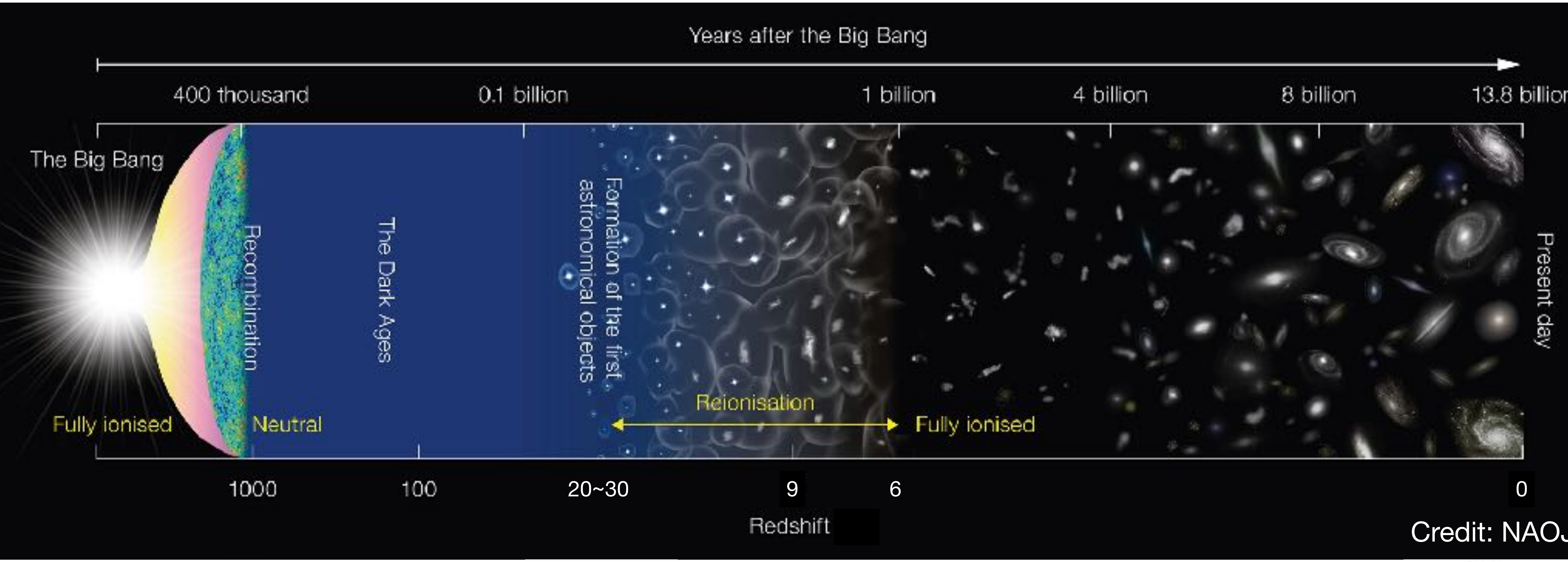
Astronomy @ Tsinghua

12/22/2020

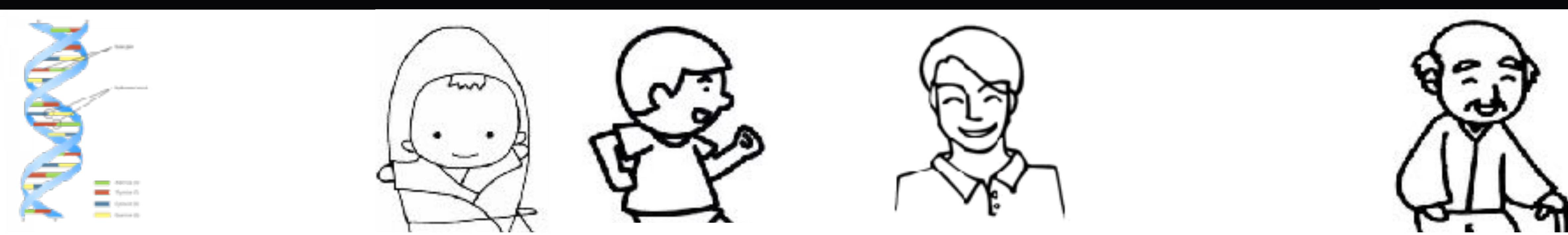
Galaxy formation: what do we do?

Cosmic dawn
z>6

Cosmic noon
z~2–3

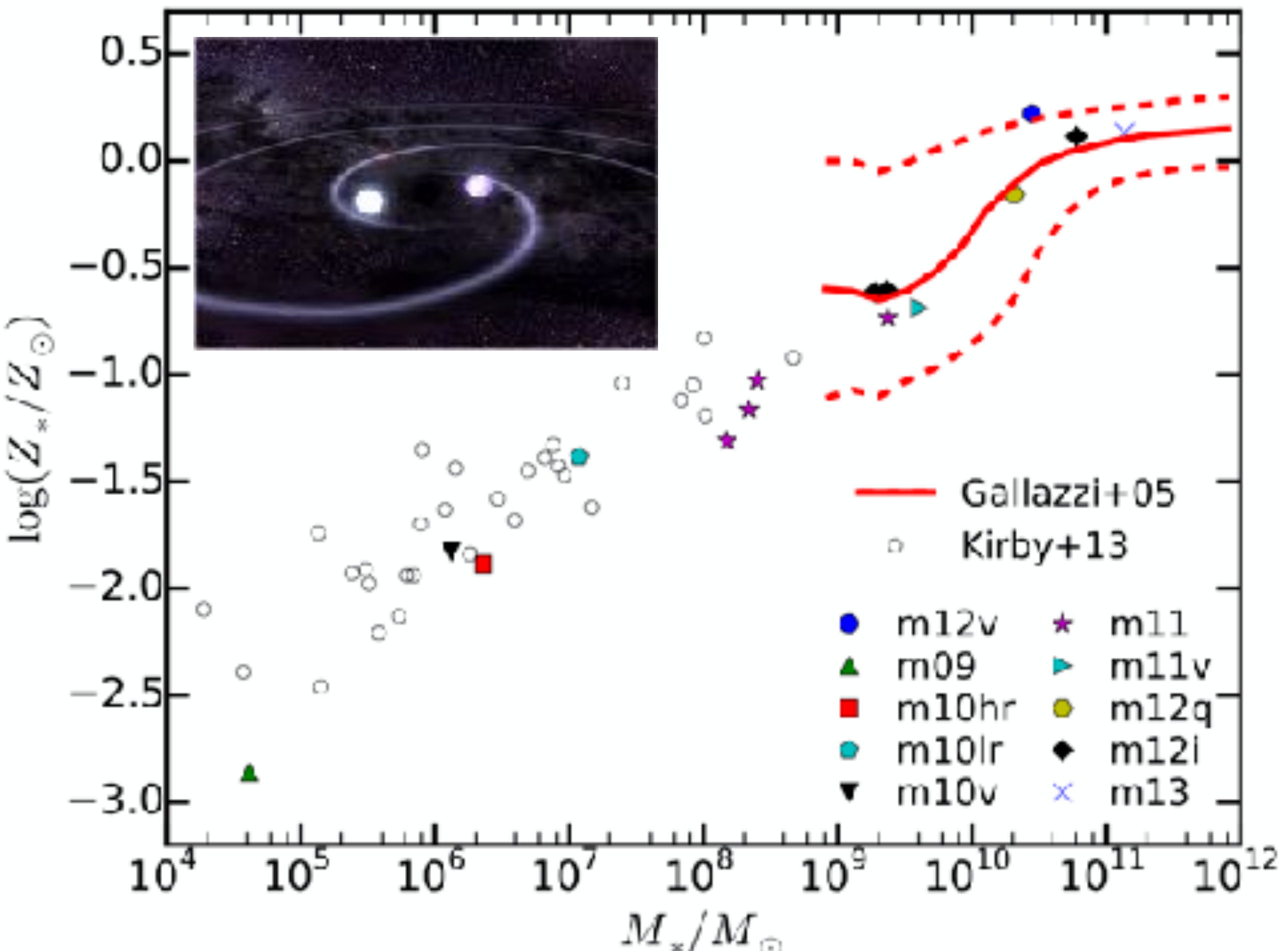


Analogy from
S. Furlanetto
(UCLA)



The ultimate question: How galaxies of ***all types*** form and evolve at ***all stages*** of their lives?

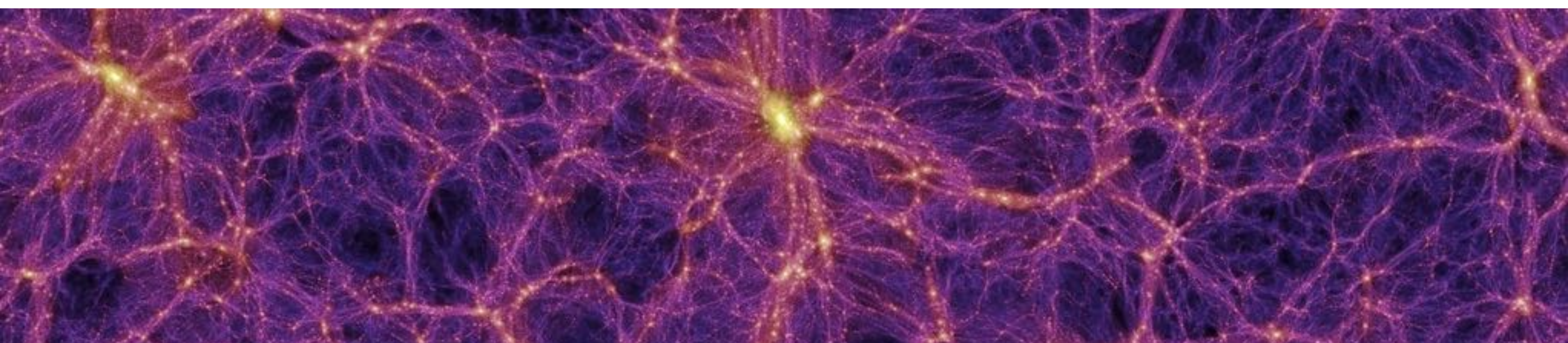
Galaxy formation: essential to other astrophysical areas



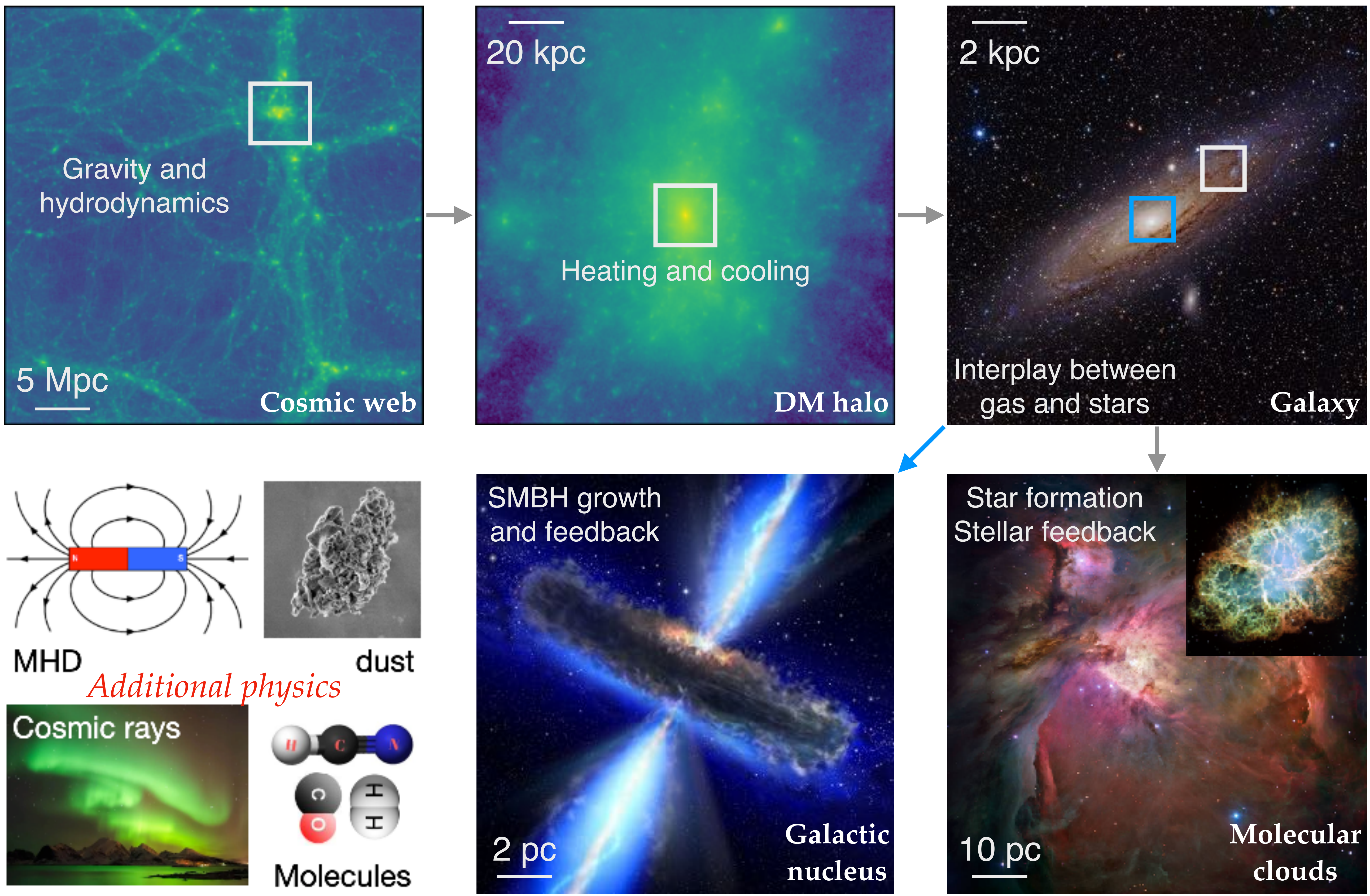
Ma+2016a

- Probing the large-scale structure and dark matter halos
- Galactic chemical evolution → BH binary populations (GW)
  (Rodriguez+19; Tsukada+19; Cusin+20; …)
- Using Fast Radio Bursts (FRBs) to probe reionization history
  (Beniamini, Kumar, Ma, Quataert, in press)

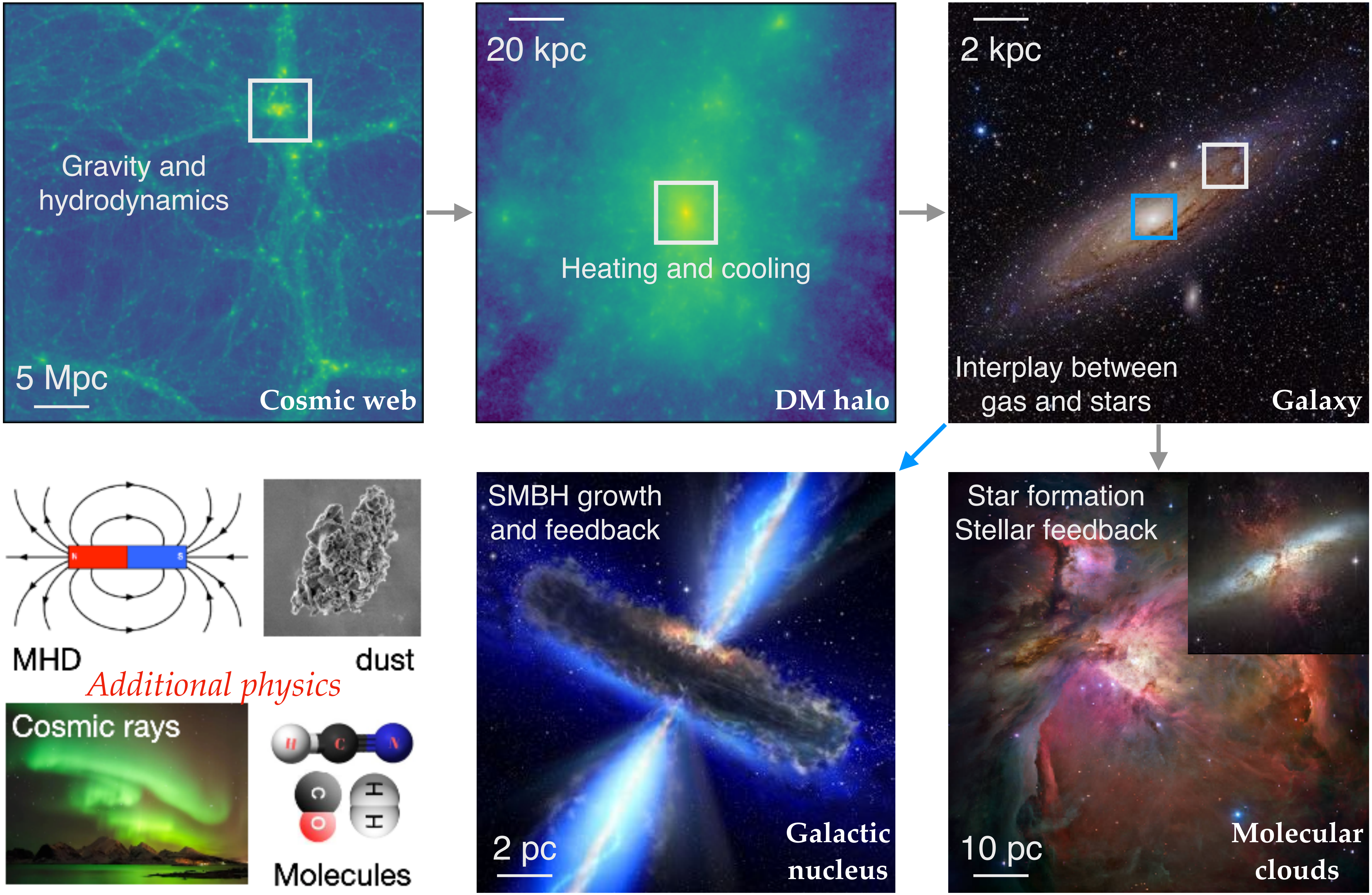
LSS & DM halos



Galaxy formation: the messiest problem

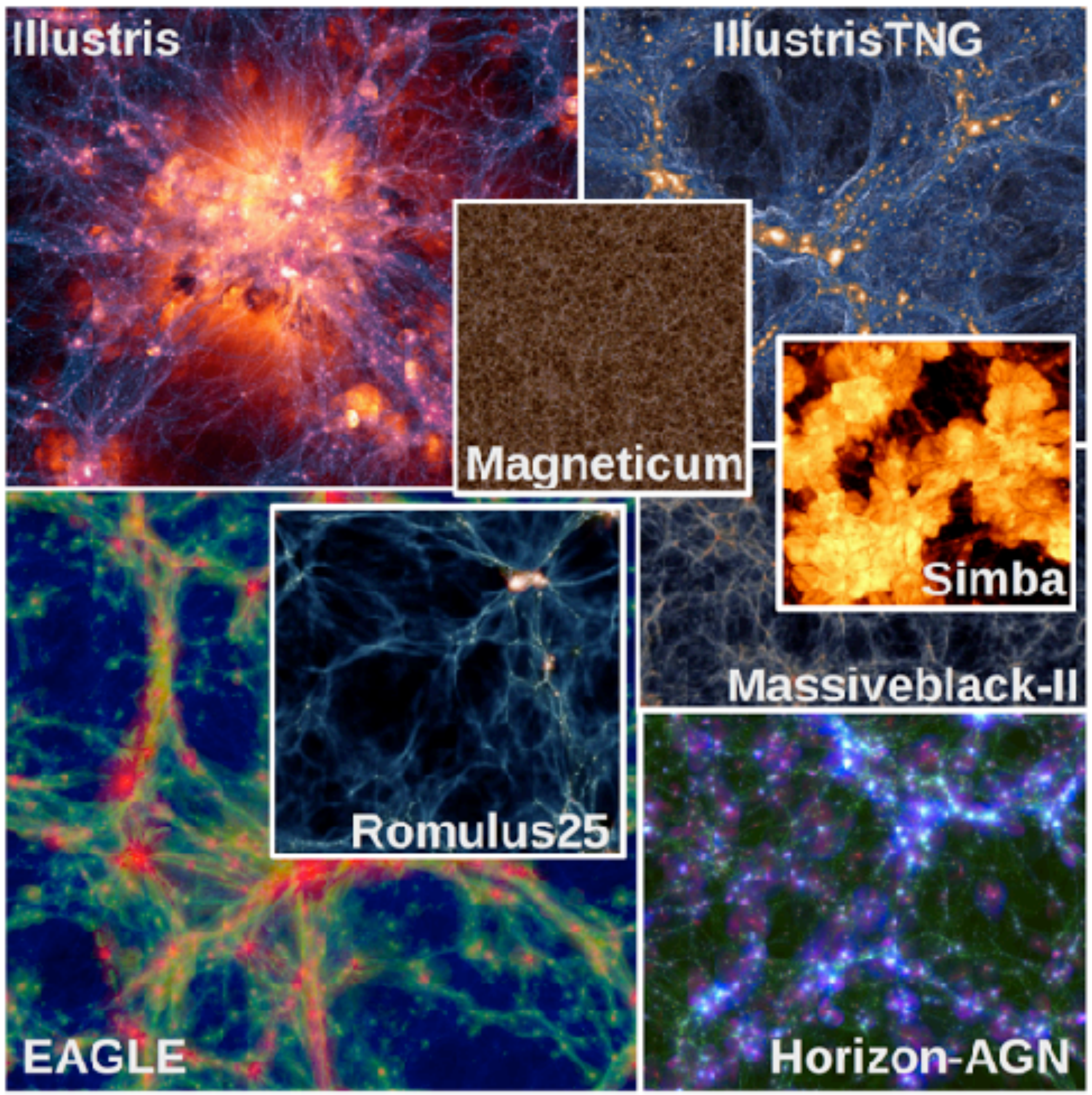


Galaxy formation: the messiest problem

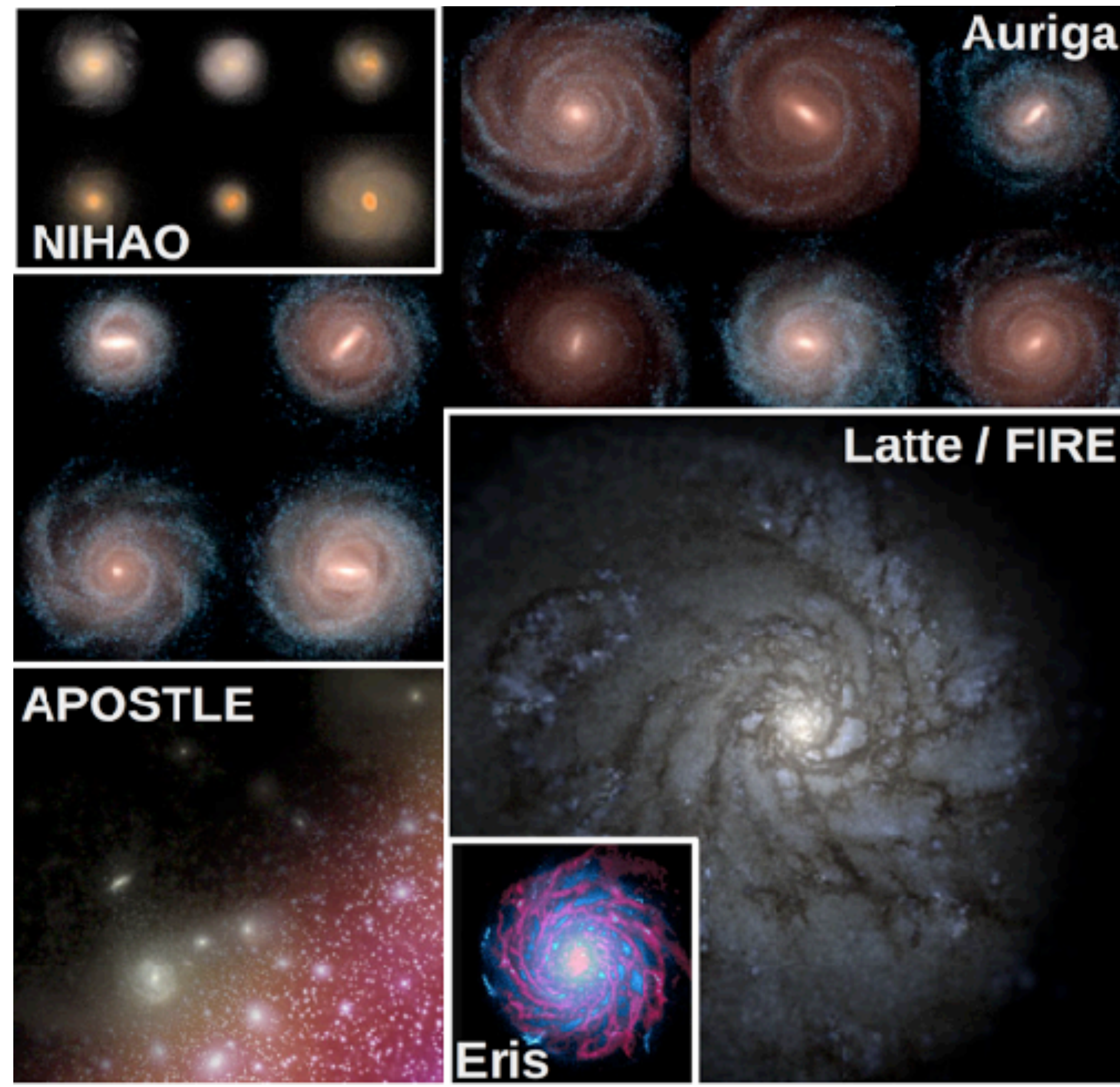


Cosmological simulations: a powerful tool

Large-volume (statistics)



Zoom-in (more physics & details)



Vogelsberger+2019

Box size ~(100 Mpc/h)^3
~10^5–10^6 $M_\odot$, ~1 kpc

One halo at a time
~10–10^4 $M_\odot$, ~0.1–1 pc

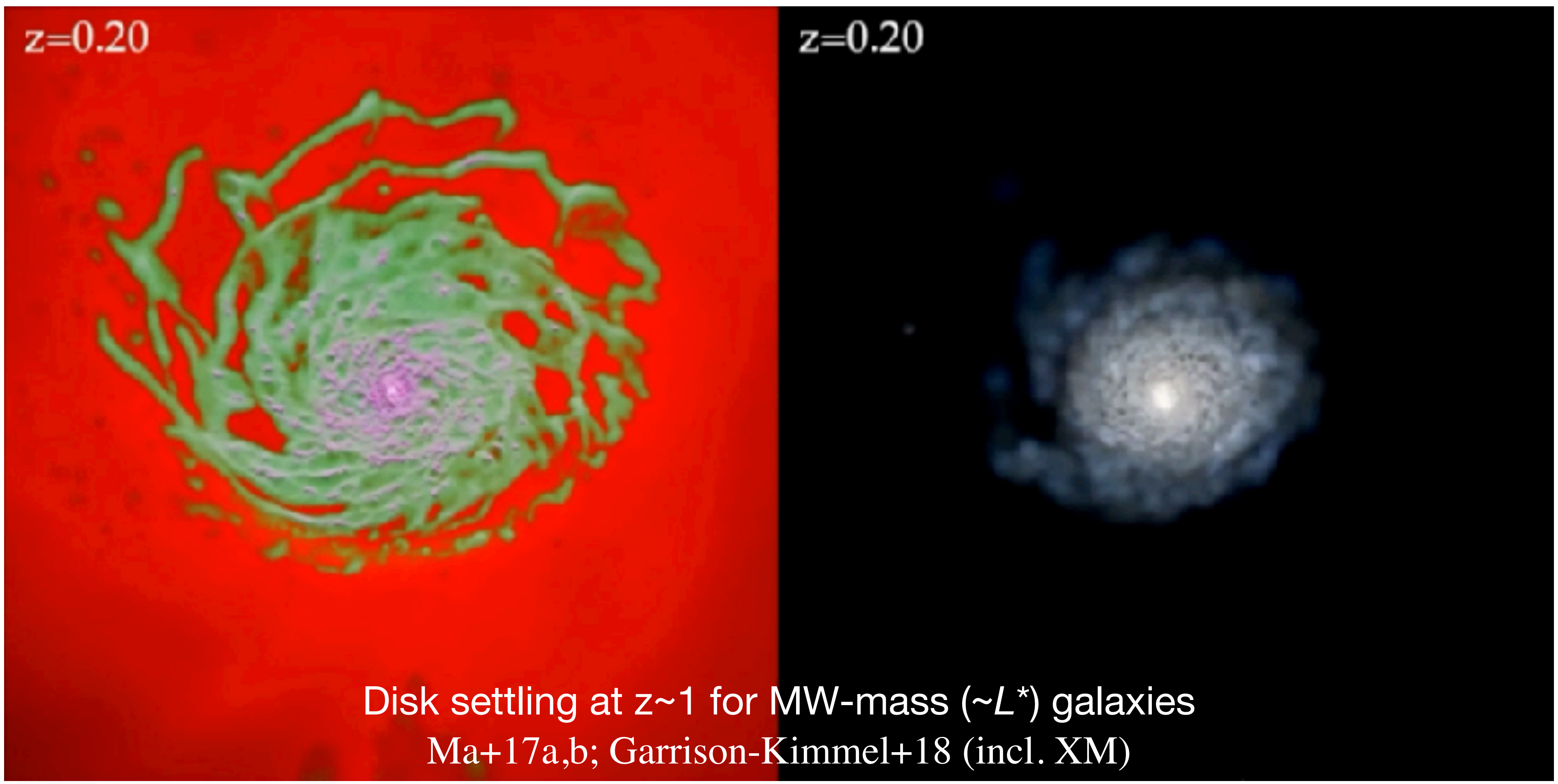
FIRE — Feedback In Realistic Environments

Hopkins+14,18

Explicitly resolved multi-phase ISM & feedback

in cosmological zoom-in simulations

- Demanded by detailed observations (JWST, ALMA & 30-m telescopes)
- Maximally possible *ab initio* models to gain physical insights
- Many problems cannot be addressed in low-resolution simulations



Hot
Warm
Cold

Disk settling at z~1 for MW-mass (~L^*) galaxies
Ma+17a,b; Garrison-Kimmel+18 (incl. XM)

The multi-phase ISM: *cooling down to 10 K* ◦ ***Star formation:*** *dense, molecular, self-gravitating gas at 100% per local* t_{ff} ◦ ***Stellar feedback:*** *photoionization, radiation pressure, stellar winds, supernovae (exact solution for single SN in uniform medium)* ◦ ***Other physics:*** *non-ideal MHD, CRs, etc.*

FIRE
Feedback In Realistic Environments
Hopkins+14,18

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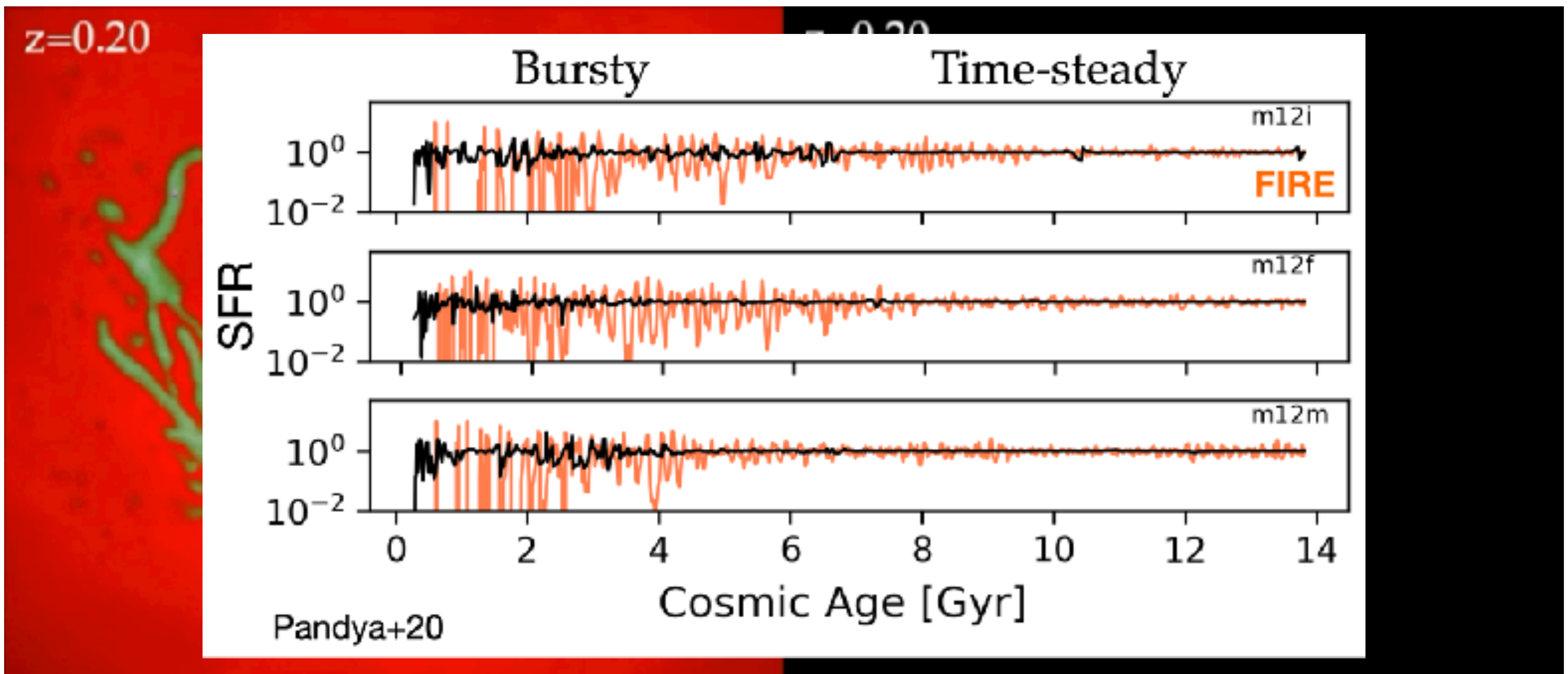

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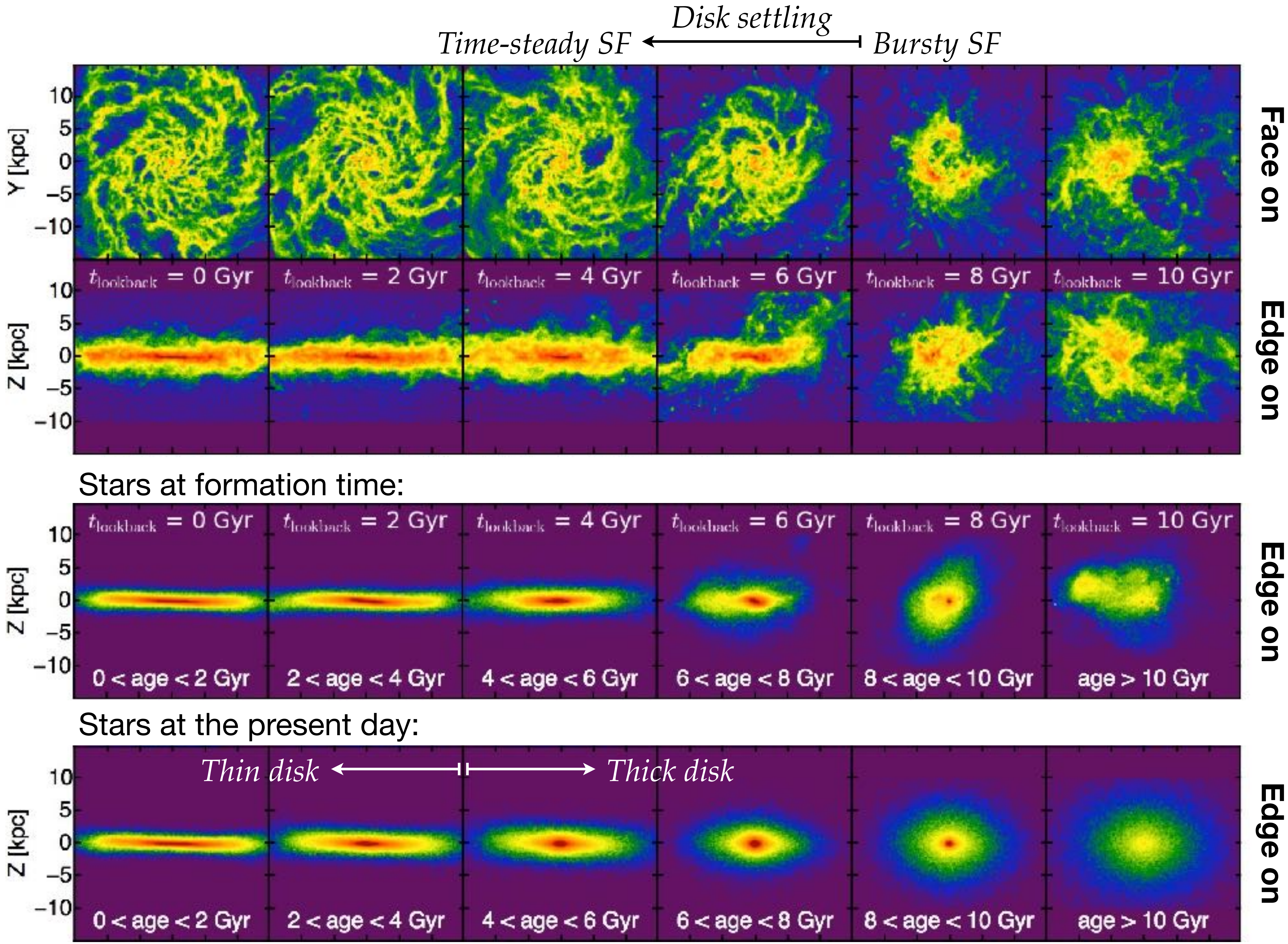


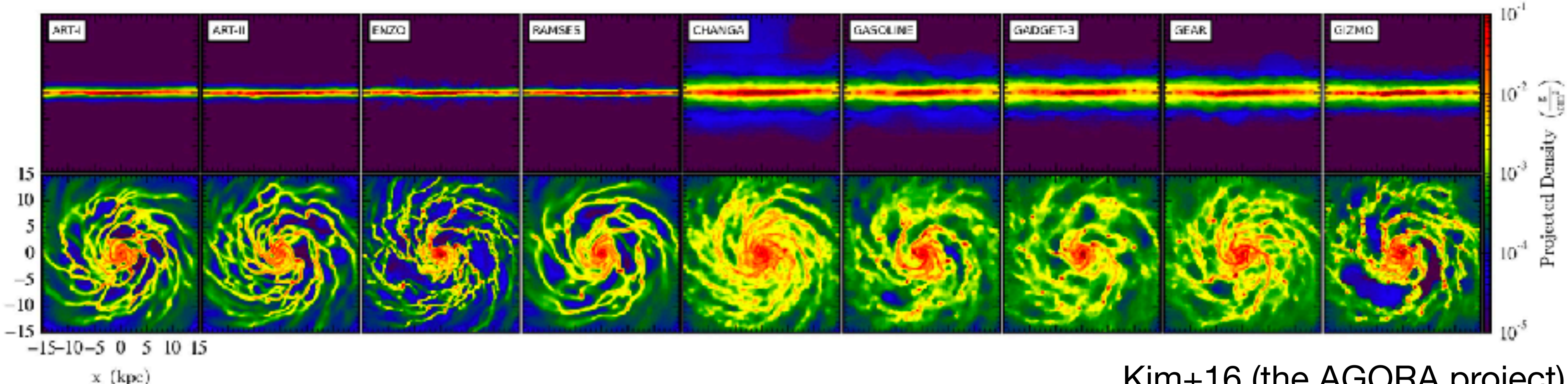
Ma+17a, MNRAS, 467, 2430

Cosmic dawn
z>6

Self-regulated SF in quasi-equilibrium disks

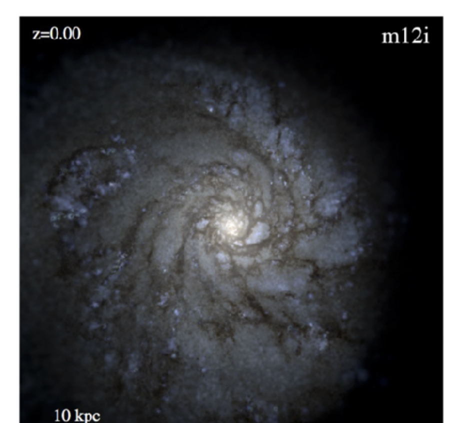
(Silk 1991; Krumholz & McKee 2005; Thompson+2005; Krumholz+2009; Ostriker & Shetty 2011; Forbes+2014; Semonov+2017; Orr+2018; …)

Cosmic noon
z~2–3



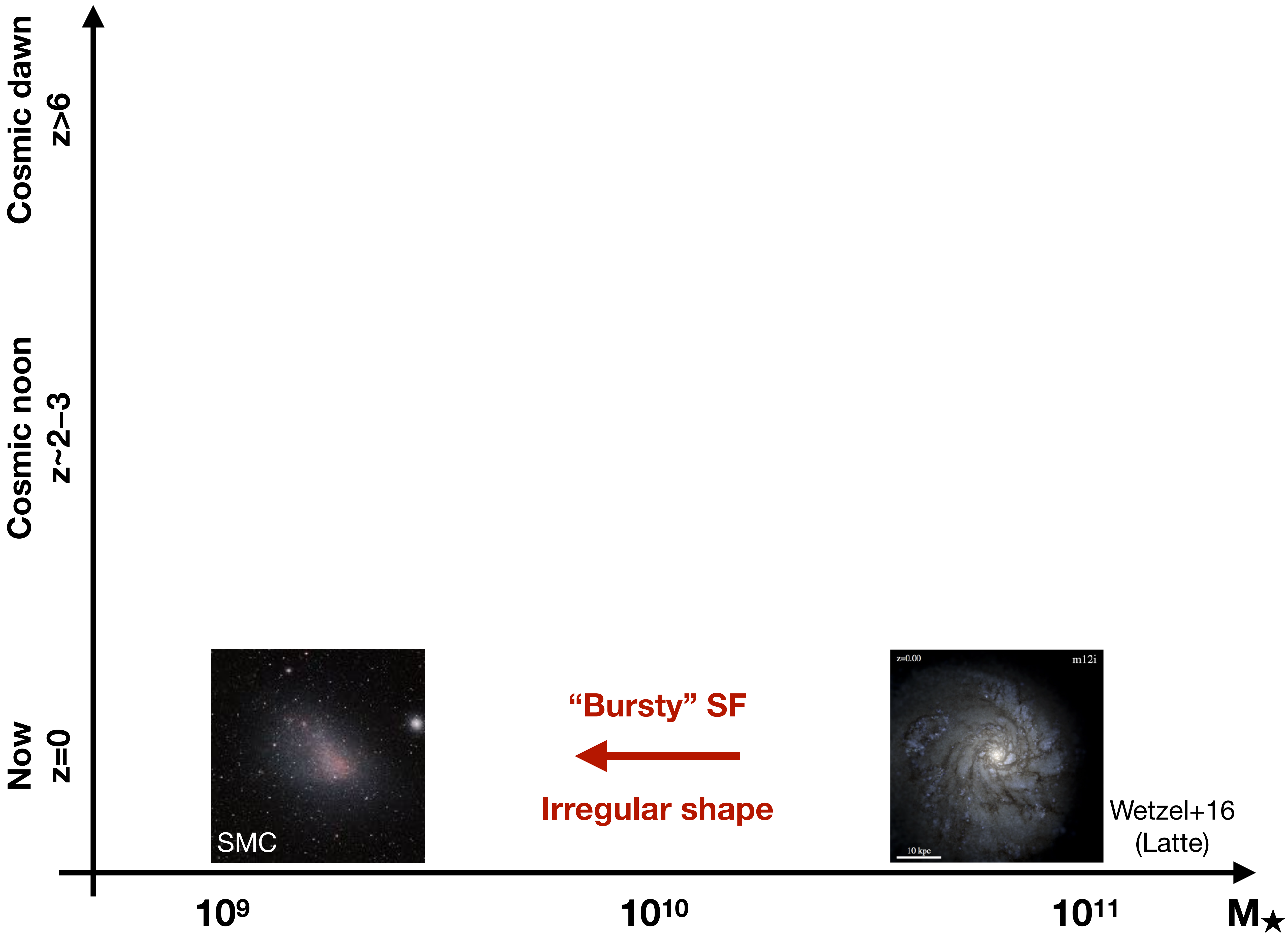
Kim+16 (the AGORA project)

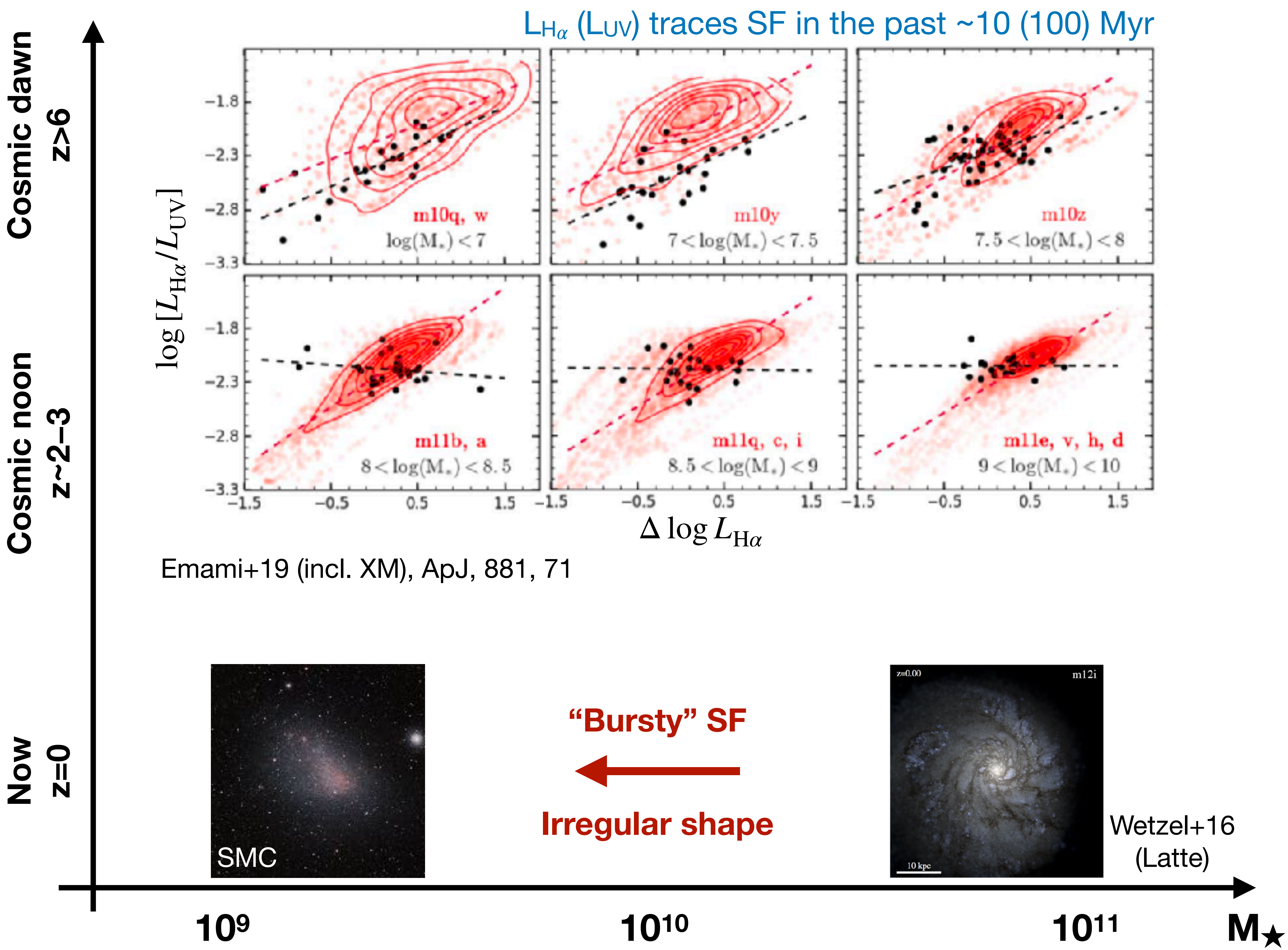
Now
z=0



Wetzel+16
(Latte)

10^9 10^{10} 10^{11} $M_\star$


Cosmic dawn
z>6
Cosmic noon
z~2–3
Now
z=0
SMC
"Bursty" SF
Irregular shape
z=0.00
m12i
10 kpc
Wetzel+16
(Latte)
10^9
10^{10}
10^{11}
$M_\star$



$L_{H\alpha}$ (L_{UV}) traces SF in the past ~10 (100) Myr
Cosmic dawn
z>6
Cosmic noon
z~2–3
Now
z=0
$\log[L_{H\alpha}/L_{UV}]$
$\Delta \log L_{H\alpha}$
m10q, w
$\log(M_*) < 7$
m10y
$7 < \log(M_*) < 7.5$
m10z
$7.5 < \log(M_*) < 8$
m11b, a
$8 < \log(M_*) < 8.5$
m11q, c, i
$8.5 < \log(M_*) < 9$
m11e, v, h, d
$9 < \log(M_*) < 10$
−1.8
−2.3
−2.8
−3.3
−1.5
−0.5
0.5
1.5
Emami+19 (incl. XM), ApJ, 881, 71
SMC
"Bursty" SF
Irregular shape
z=0.00
m12i
10 kpc
Wetzel+16
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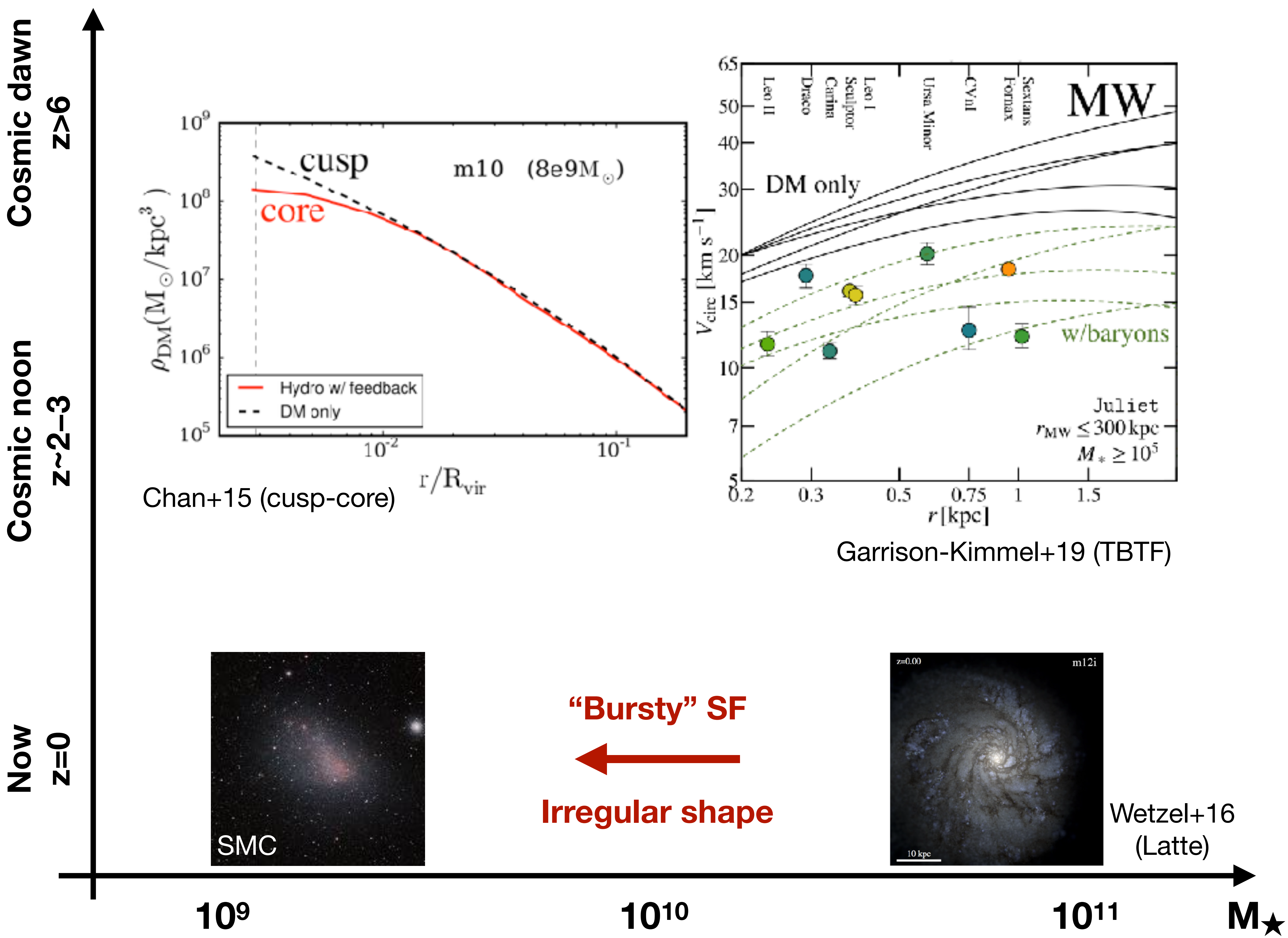
10^9
10^{10}
10^{11}
$M_\star$

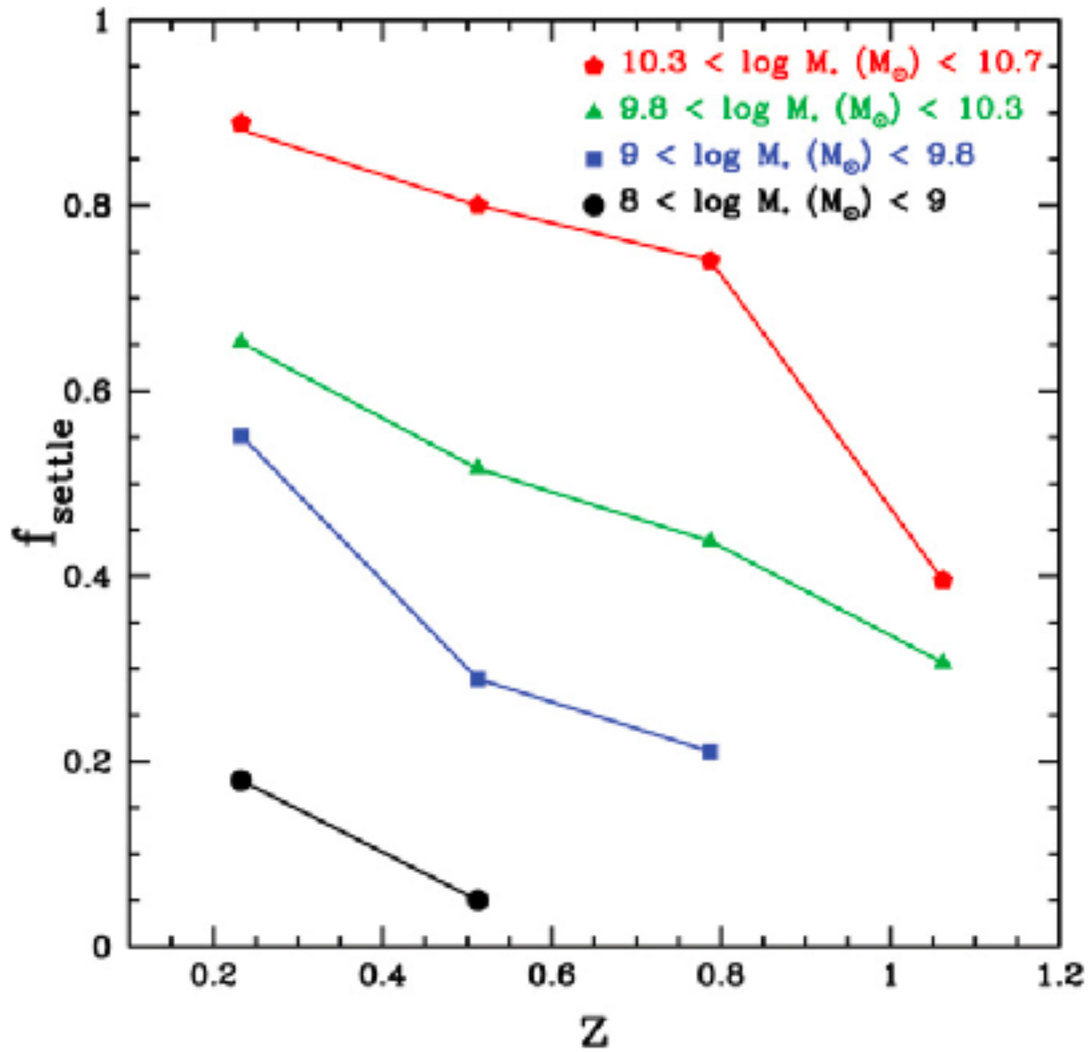


Cosmic dawn
z>6
Cosmic noon
z~2–3
Now
z=0
cusp
m10 (8e9M⊙)
core
$\rho_{DM}(M_\odot/kpc^3)$
Hydro w/ feedback
DM only
r/R_{vir}
Chan+15 (cusp-core)
MW
Leo II
Draco
Carina
Sculptor
Leo I
Ursa Minor
CVnI
Fornax
Sextans
DM only
w/baryons
Juliet
$r_{MW} \leq 300$ kpc
$M_* \geq 10^5$
V_{circ} [km s^{-1}]
r [kpc]
Garrison-Kimmel+19 (TBTF)
SMC
"Bursty" SF
Irregular shape
z=0.00
m12i
10 kpc
Wetzel+16
(Latte)
10^9
10^{10}
10^{11}
$M_\star$

Cosmic dawn
z>6

Cosmic noon
z~2–3

Now
z=0



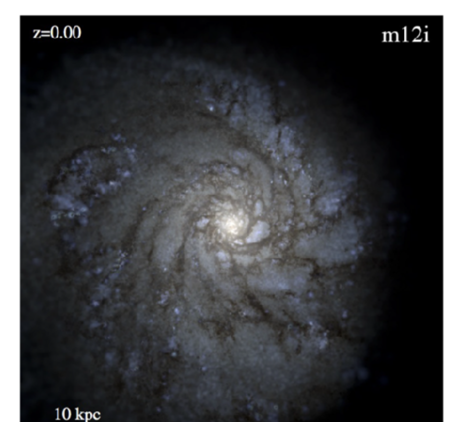
Kassin+2012

Disk formation is more difficult at higher redshift

Observations: Kassin+2012; Wisnioski+2015,2019
Theories: Hayward & Hopkins 2017; Faucher-Giguere+2018; Dekel+2020; Stern+2020, …

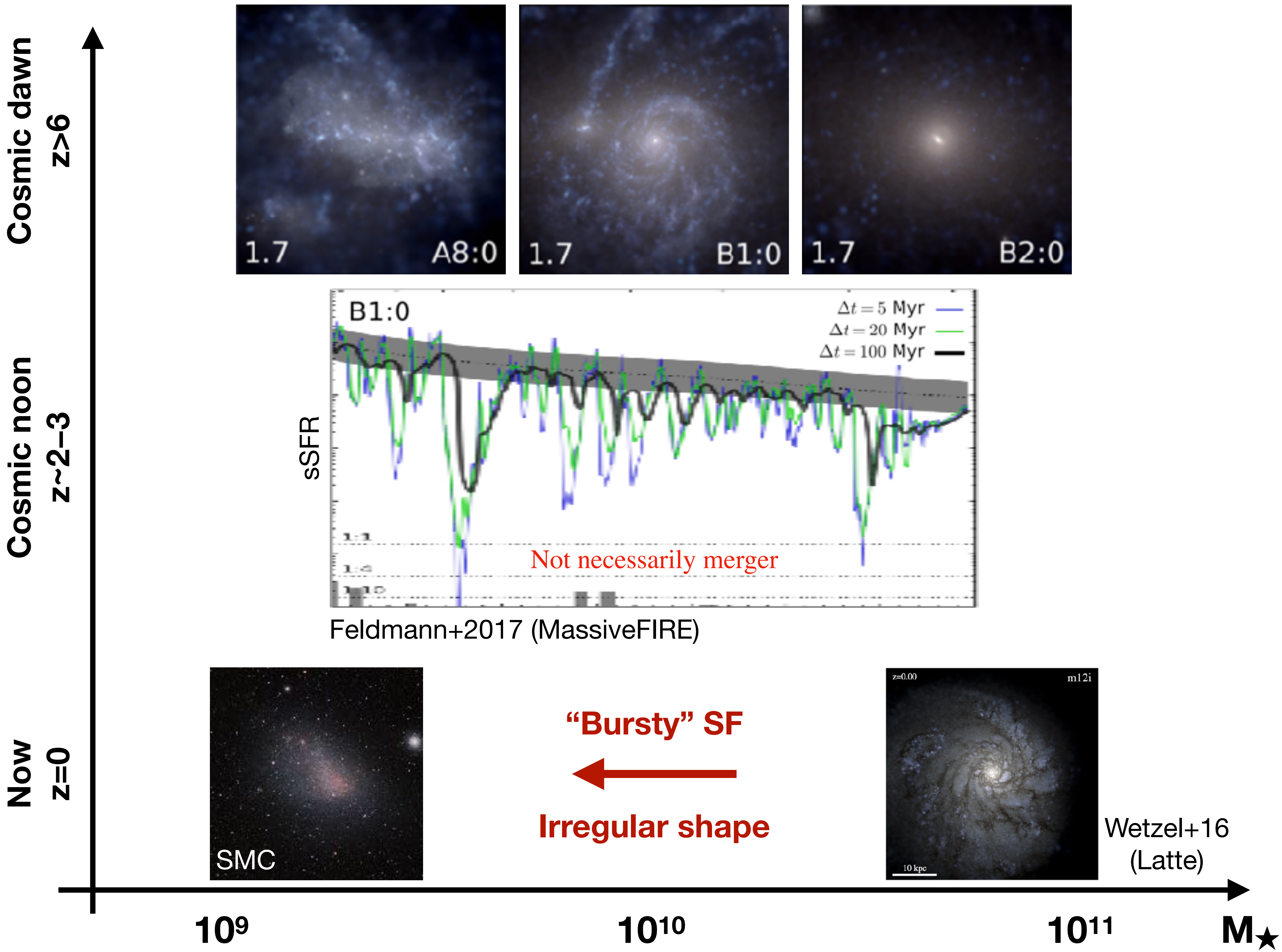
"Bursty" SF

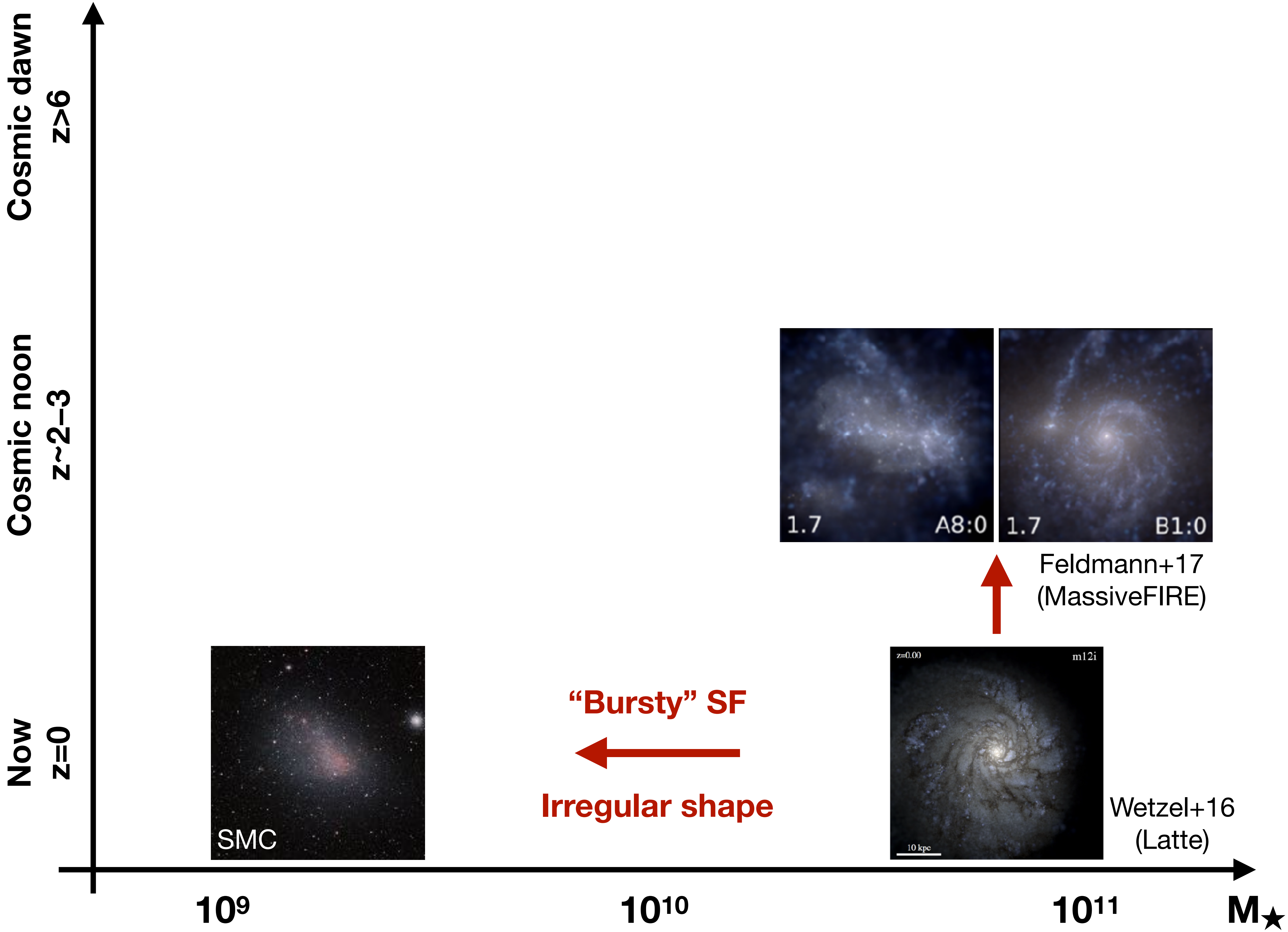
Irregular shape



Wetzel+16
(Latte)

10^9 10^{10} 10^{11} $M_\star$


Cosmic dawn
z>6
Cosmic noon
z~2–3
Now
z=0
1.7
A8:0
1.7
B1:0
1.7
B2:0
B1:0
Δt = 5 Myr
Δt = 20 Myr
Δt = 100 Myr
sSFR
Not necessarily merger
Feldmann+2017 (MassiveFIRE)
z=0.00
m12i
10 kpc
SMC
"Bursty" SF
Irregular shape
Wetzel+16
(Latte)
10^9
10^10
10^11
M★



Cosmic dawn
z>6
Cosmic noon
z~2–3
Now
z=0
1.7
A8:0
1.7
B1:0
Feldmann+17
(MassiveFIRE)
"Bursty" SF
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10 kpc
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10^9
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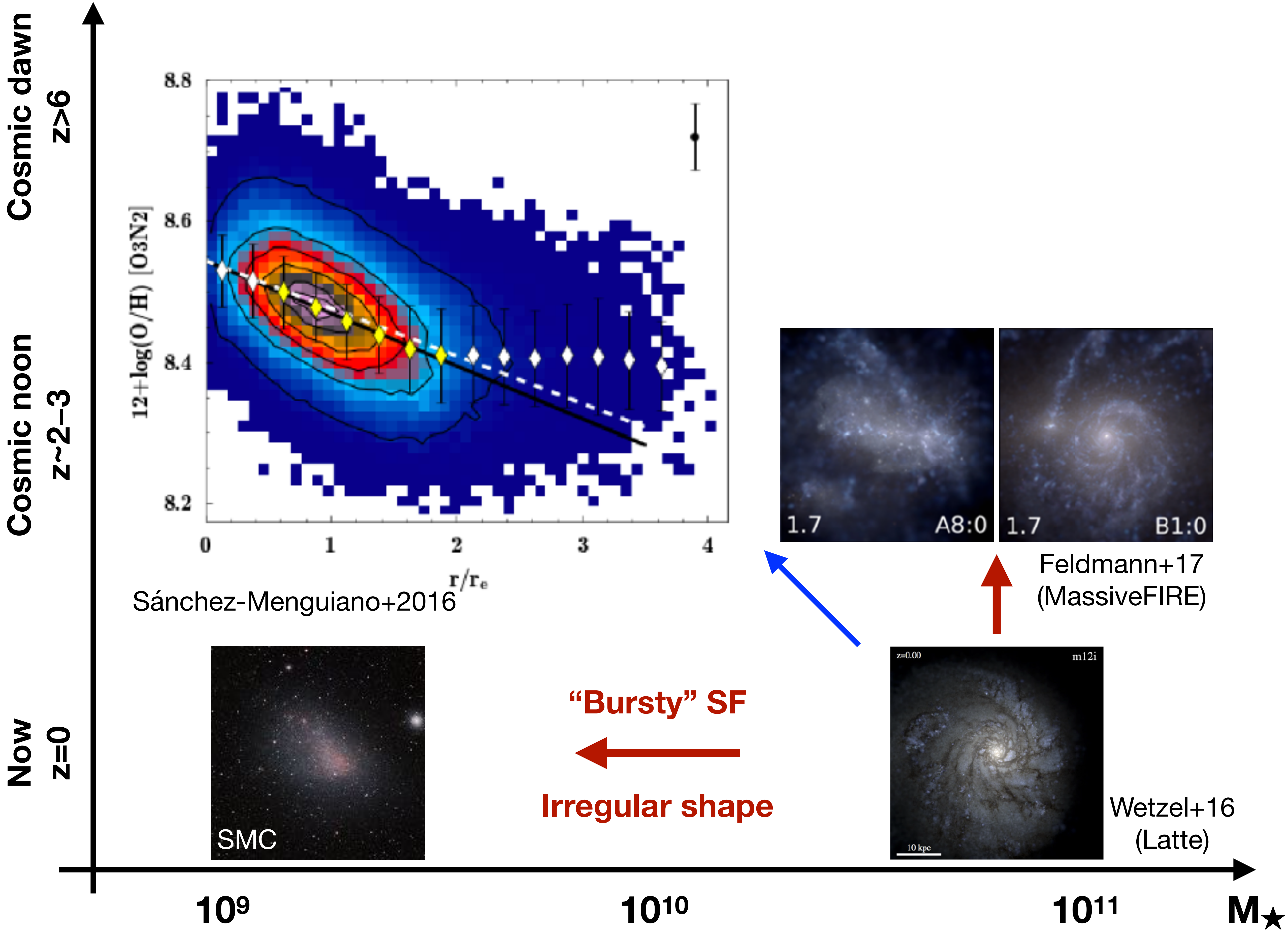
M★



Cosmic dawn
z>6
Cosmic noon
z~2–3
Now
z=0
8.8
8.6
8.4
8.2
12+log(O/H) [O3N2]
0
1
2
3
4
r/r$_e$
Sánchez-Menguiano+2016
1.7
A8:0
1.7
B1:0
Feldmann+17
(MassiveFIRE)
SMC
"Bursty" SF
Irregular shape
z=0.00
m12i
10 kpc
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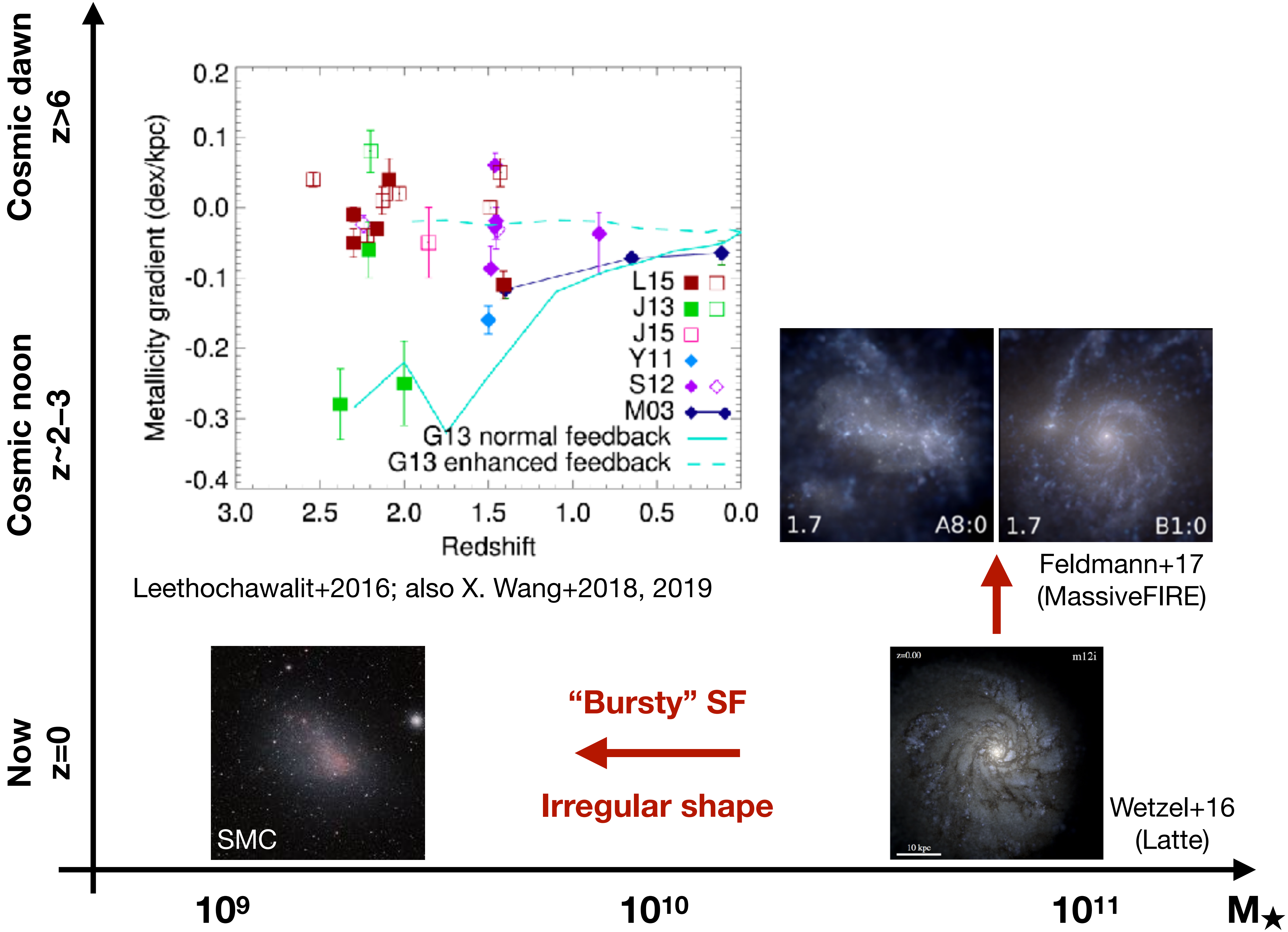
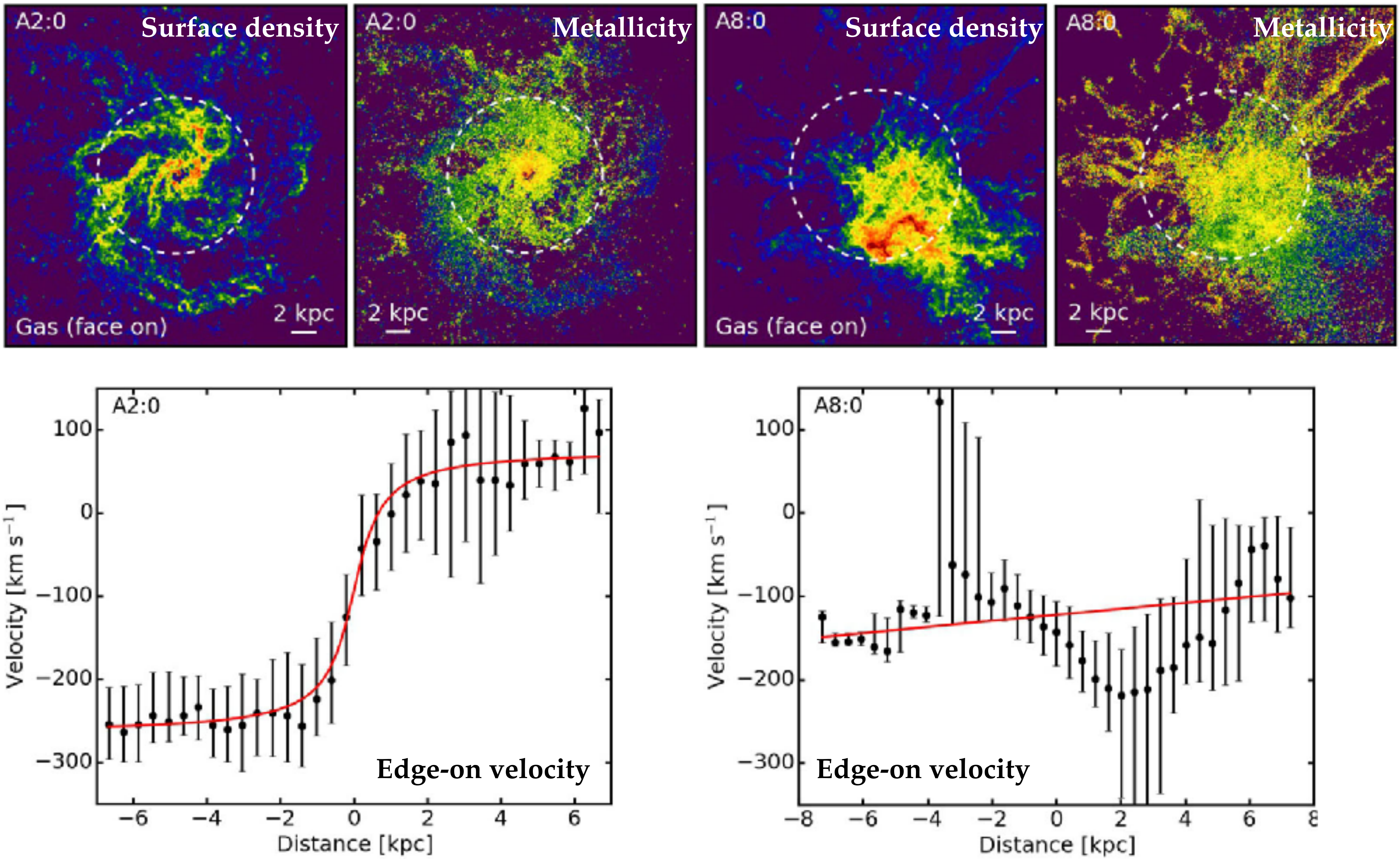
(Latte)
10^9
10^{10}
10^{11}
M$_\star$


Cosmic dawn
z>6
Cosmic noon
z~2–3
Now
z=0
Metallicity gradient (dex/kpc)
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Redshift
L15
J13
J15
Y11
S12
M03
G13 normal feedback
G13 enhanced feedback
Leethochawalit+2016; also X. Wang+2018, 2019
1.7
A8:0
1.7
B1:0
Feldmann+17
(MassiveFIRE)
z=0.00
m12i
10 kpc
Wetzel+16
(Latte)
SMC
"Bursty" SF
Irregular shape
10^9
10^10
10^11
M★

Diverse kinematics + metallicity gradient at z~2

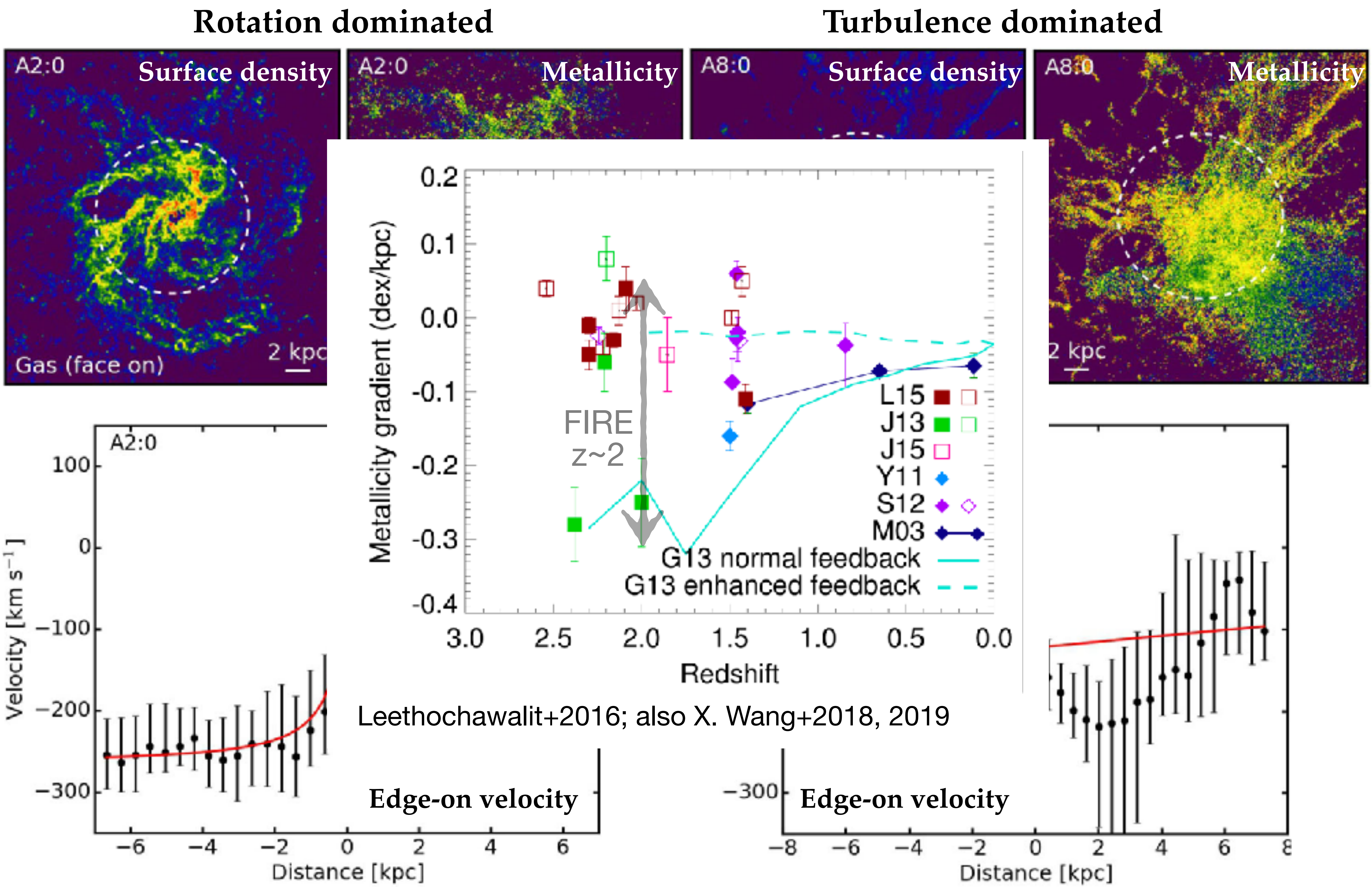
Rotation dominated **Turbulence dominated**



cf. IllustrisTNG only has steep negative gradients (Hemler+20, incl. XM)

Ma+2017b, MNRAS, 466, 4780

Diverse kinematics + metallicity gradient at z~2



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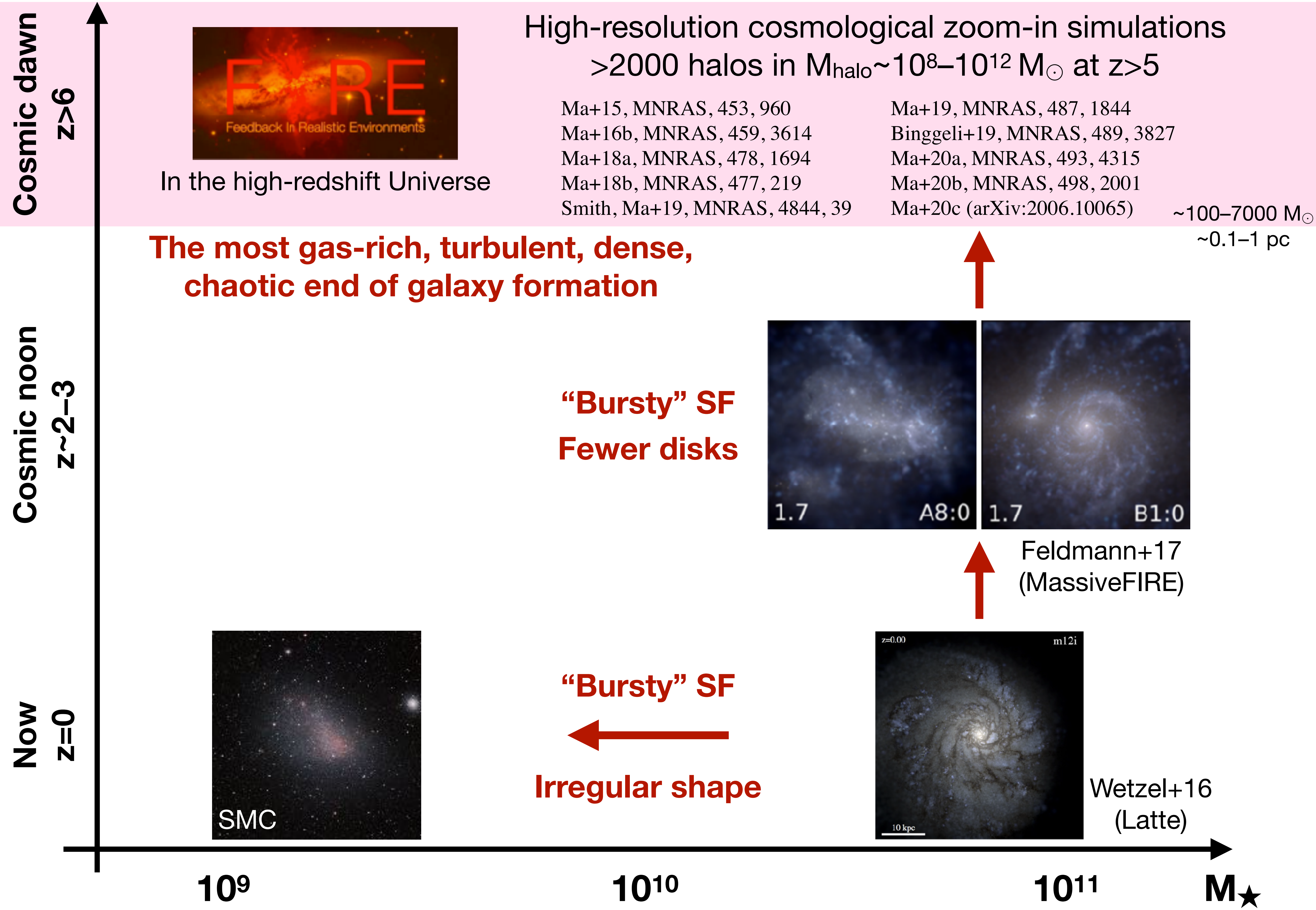
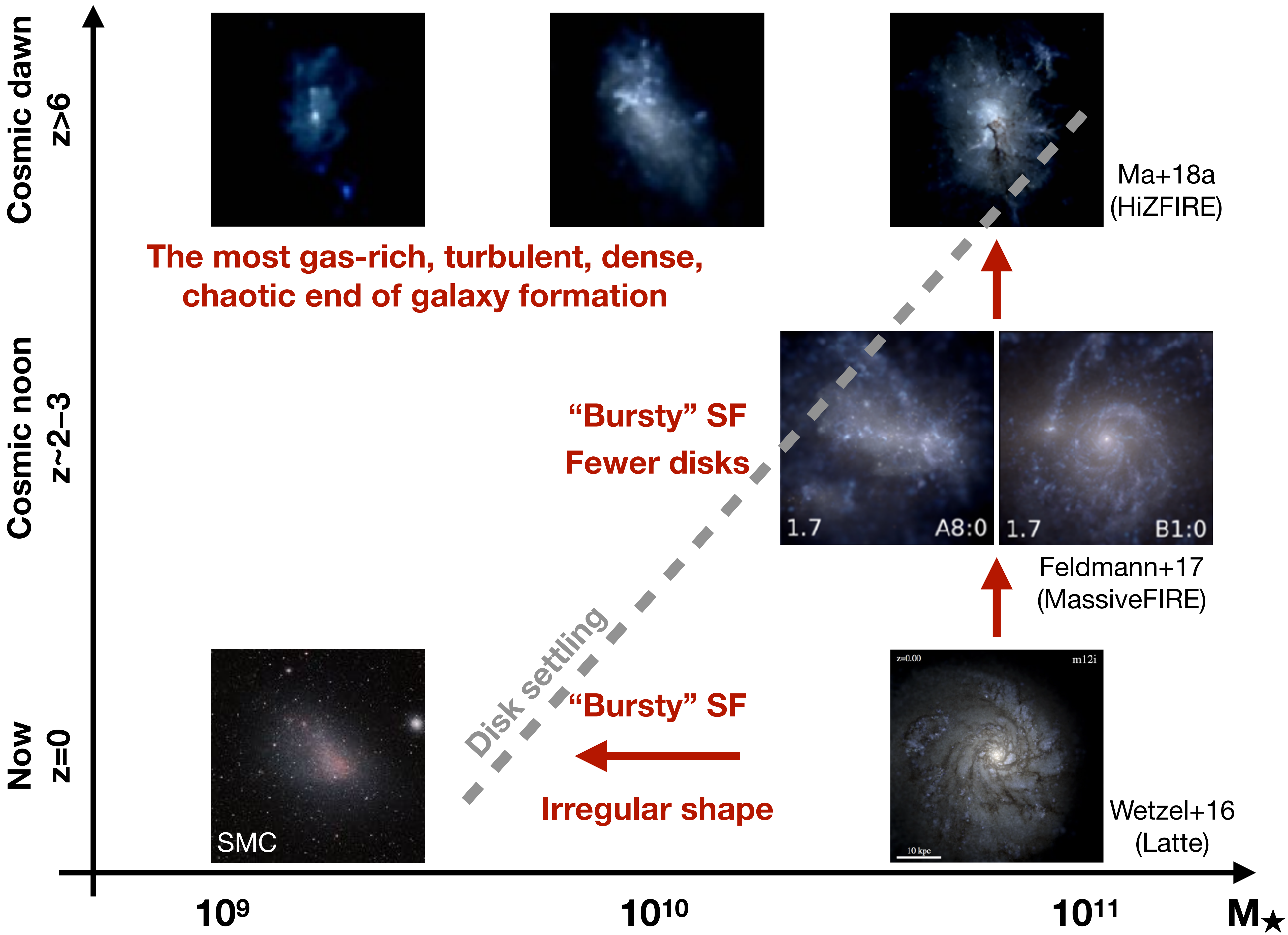
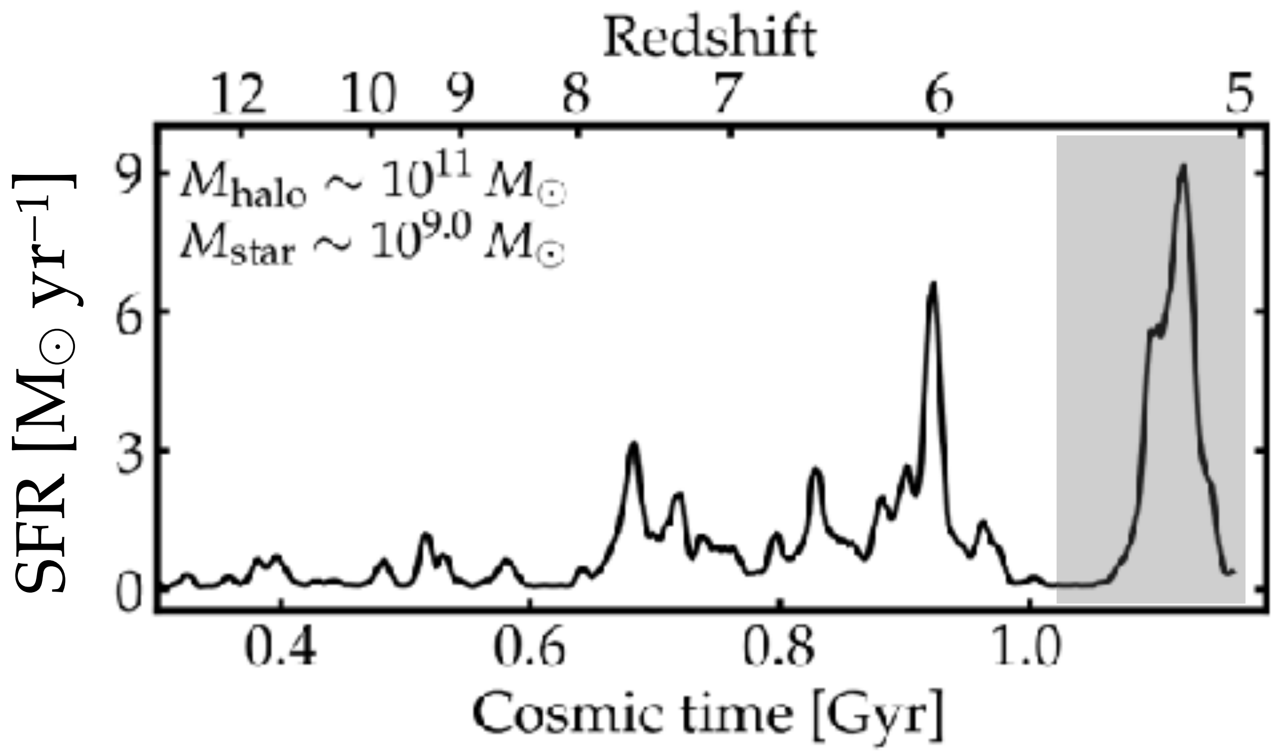
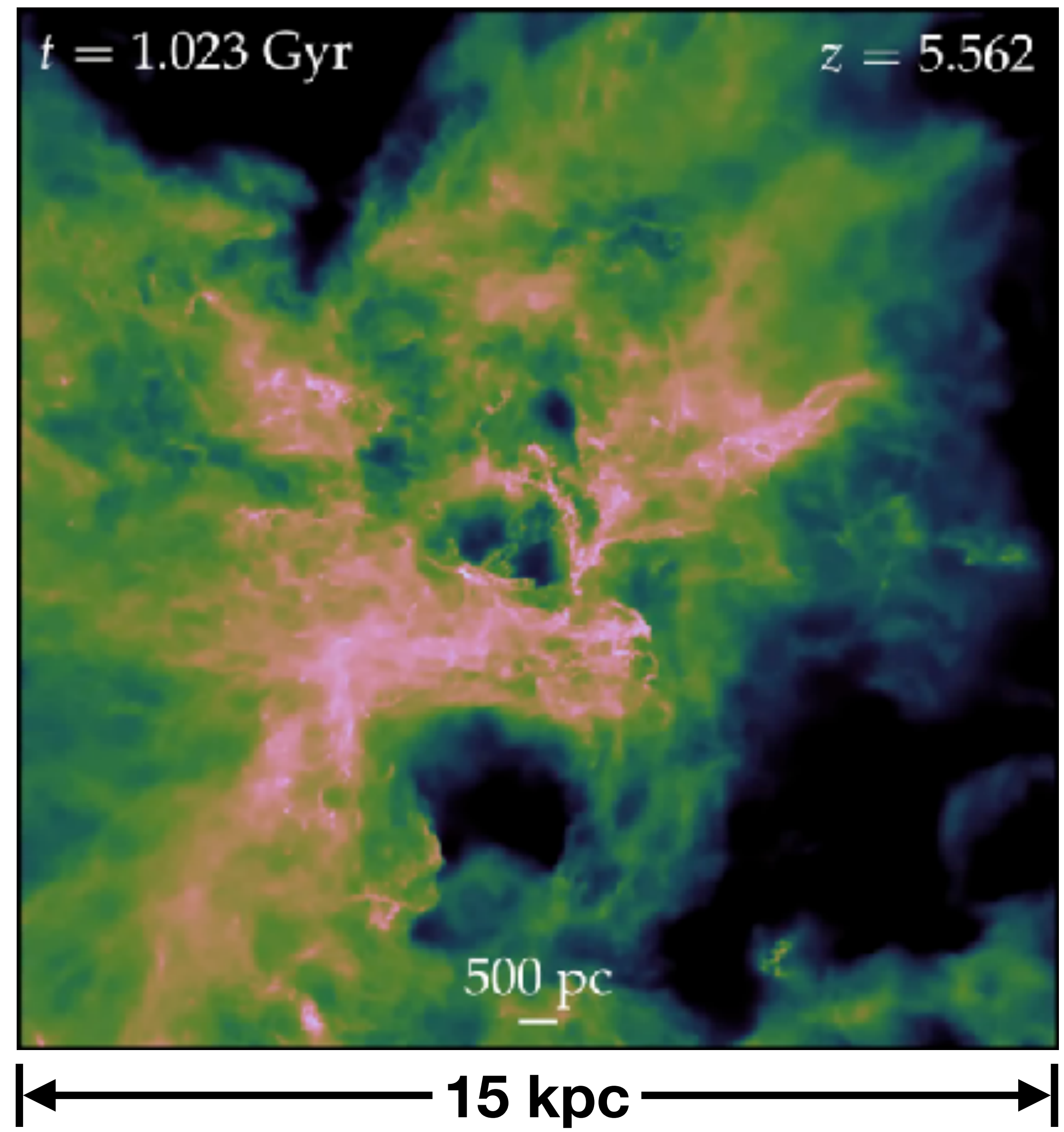

Cosmic dawn
z>6
Cosmic noon
z~2–3
Now
z=0
FIRE
Feedback In Realistic Environments
In the high-redshift Universe
High-resolution cosmological zoom-in simulations
>2000 halos in Mhalo~10^8–10^12 M⊙ at z>5
Ma+15, MNRAS, 453, 960
Ma+16b, MNRAS, 459, 3614
Ma+18a, MNRAS, 478, 1694
Ma+18b, MNRAS, 477, 219
Smith, Ma+19, MNRAS, 4844, 39
Ma+19, MNRAS, 487, 1844
Binggeli+19, MNRAS, 489, 3827
Ma+20a, MNRAS, 493, 4315
Ma+20b, MNRAS, 498, 2001
Ma+20c (arXiv:2006.10065)
~100–7000 M⊙
~0.1–1 pc
The most gas-rich, turbulent, dense,
chaotic end of galaxy formation
“Bursty” SF
Fewer disks
1.7
A8:0
1.7
B1:0
Feldmann+17
(MassiveFIRE)
SMC
“Bursty” SF
Irregular shape
z=0.00
m12i
10 kpc
Wetzel+16
(Latte)
10^9
10^10
10^11
M★



Cosmic dawn
z>6
Cosmic noon
z~2–3
Now
z=0
Ma+18a
(HiZFIRE)
The most gas-rich, turbulent, dense,
chaotic end of galaxy formation
"Bursty" SF
Fewer disks
1.7
A8:0
1.7
B1:0
Feldmann+17
(MassiveFIRE)
Disk settling
"Bursty" SF
Irregular shape
z=0.00
m12i
10 kpc
SMC
Wetzel+16
(Latte)
10^9
10^10
10^11
M★

The bursty phase: what drives the burst?



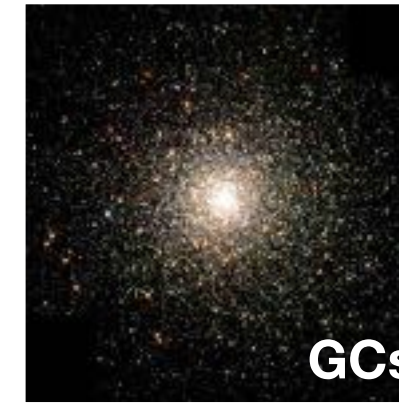


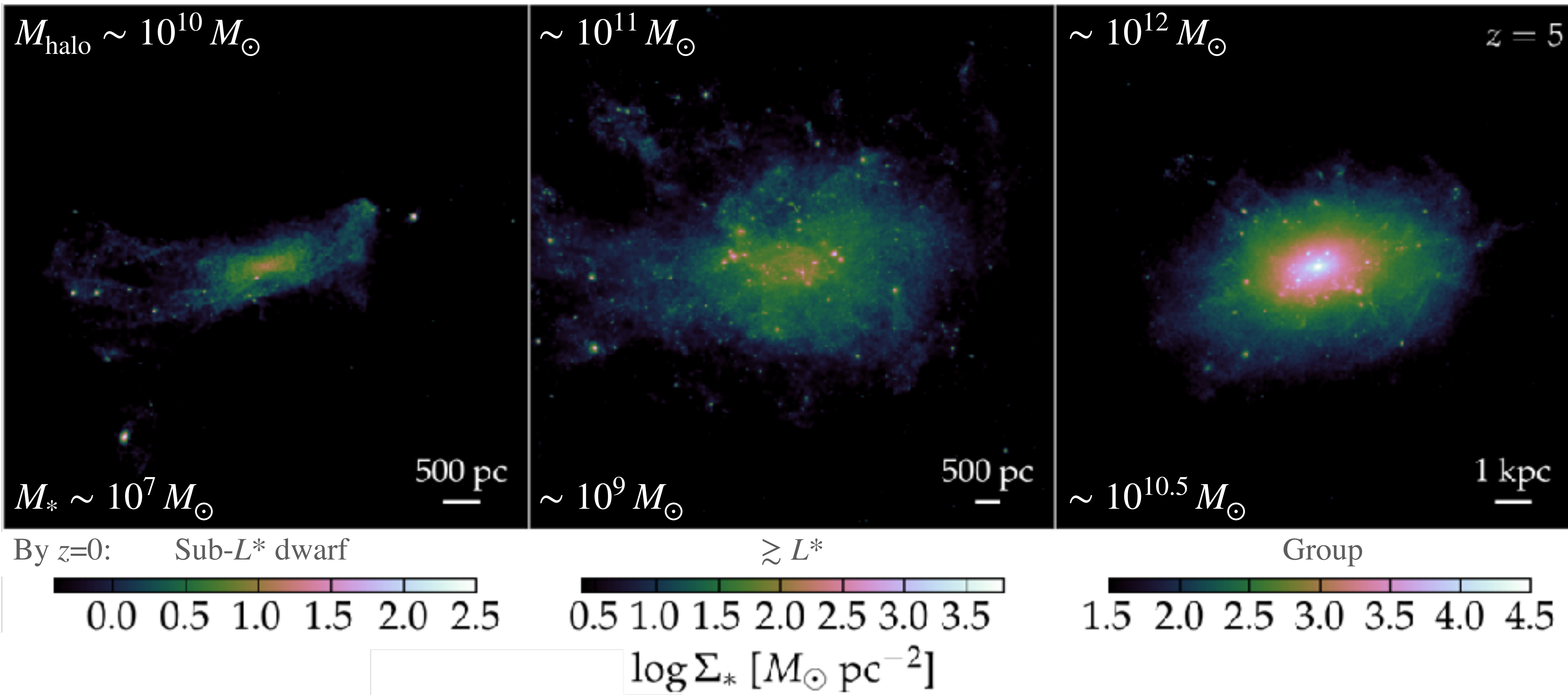
Four stages of a starburst:

1. Gas falls back, SF begins
2. SN bubble triggers SF nearby
3. This propagates in the galaxy
4. All gas is blown out

Ma+18a, MNRAS, 478, 1694

Prediction 1:
Efficient GC formation in the bursty phase





The first **cosmological** simulations with explicitly resolved GC formation

cf. Lahen+20 (non-cosmological); Kim, Ma+18, Mandelker+18 (one cluster); Li+17,18,19: ("sub-grid" cluster model)

Ma+20a, MNRAS, 493, 4315
Ma+20c, arXiv:2006.10065

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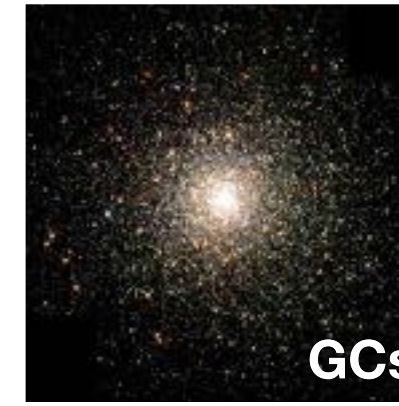

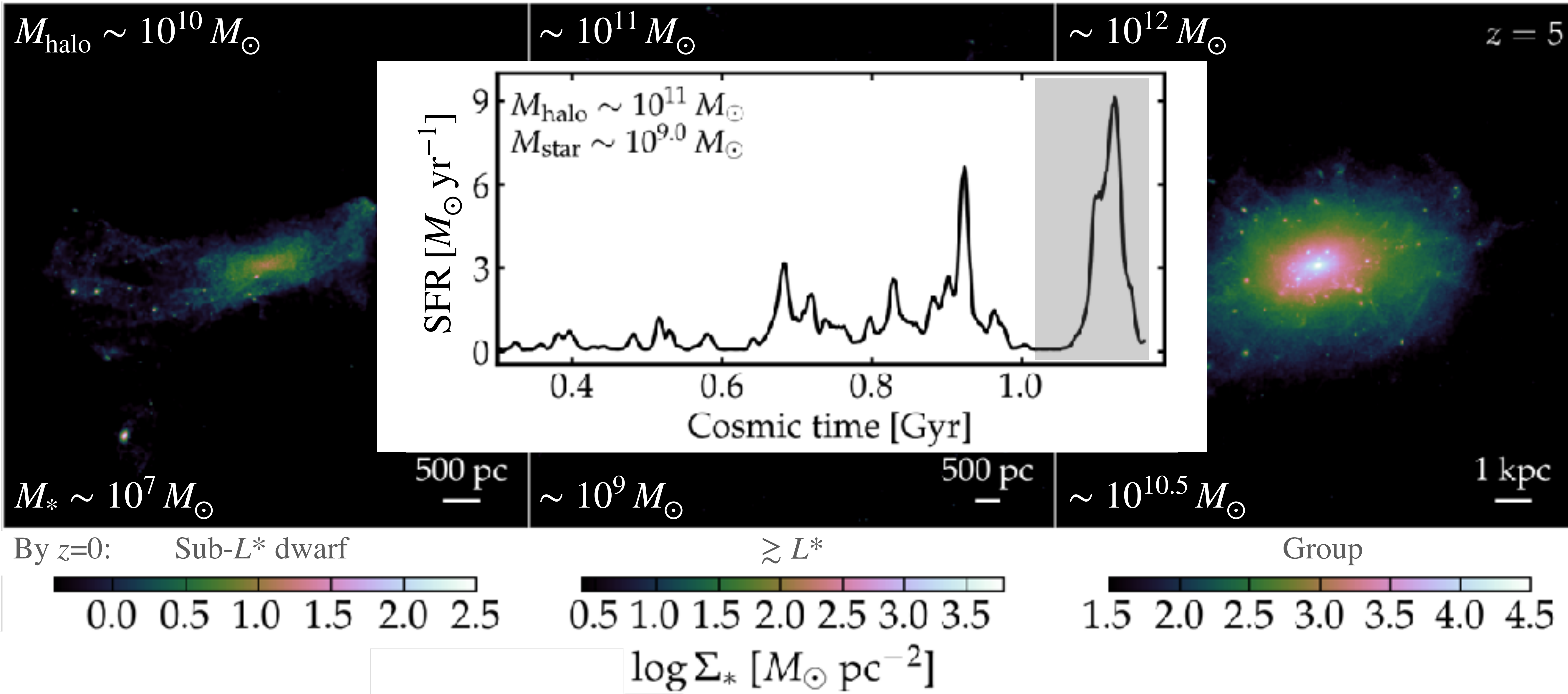

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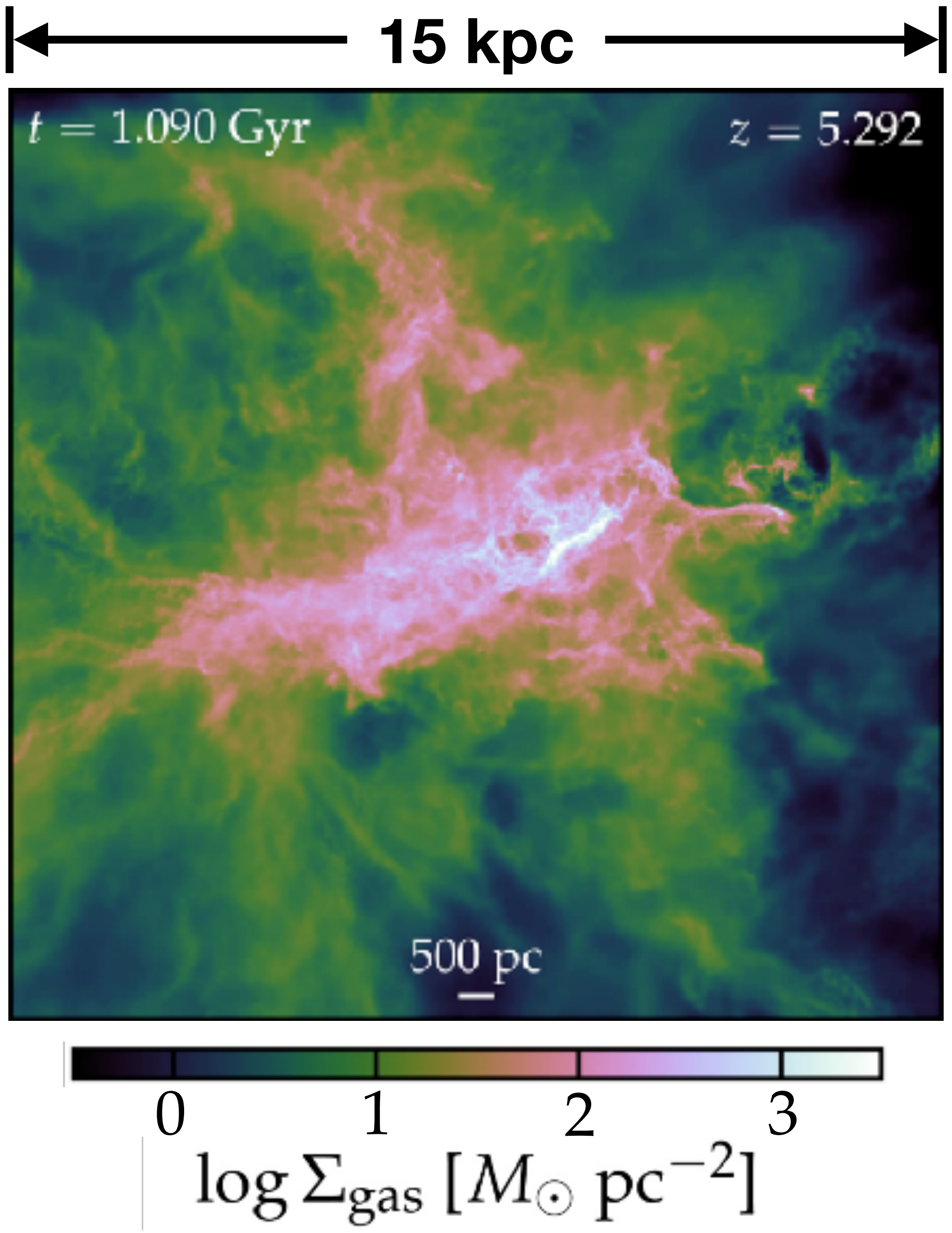
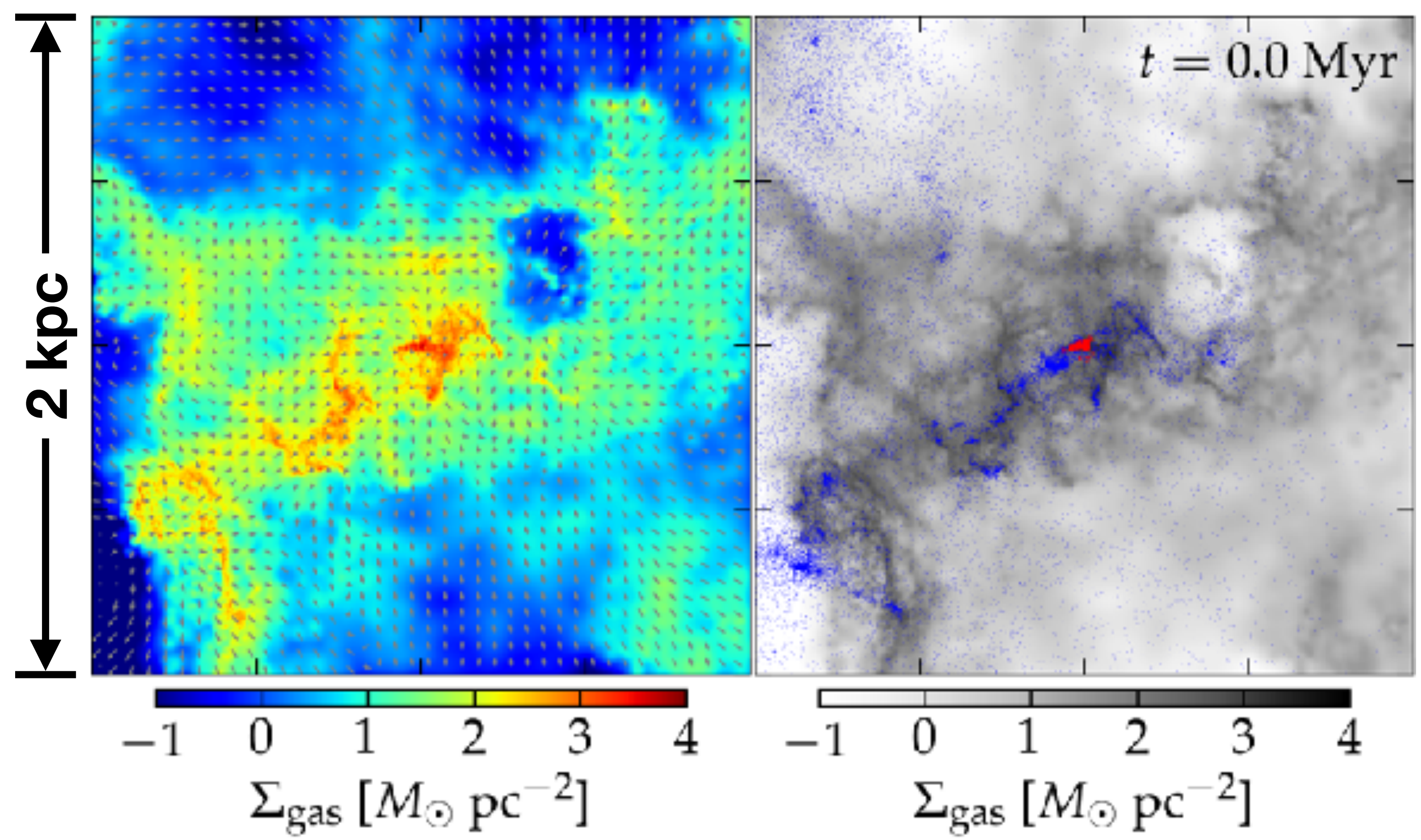
Clusters form efficiently in gas-rich, turbulent ISM



Cloud-cloud collision



Ma+20a, MNRAS, 493, 4315

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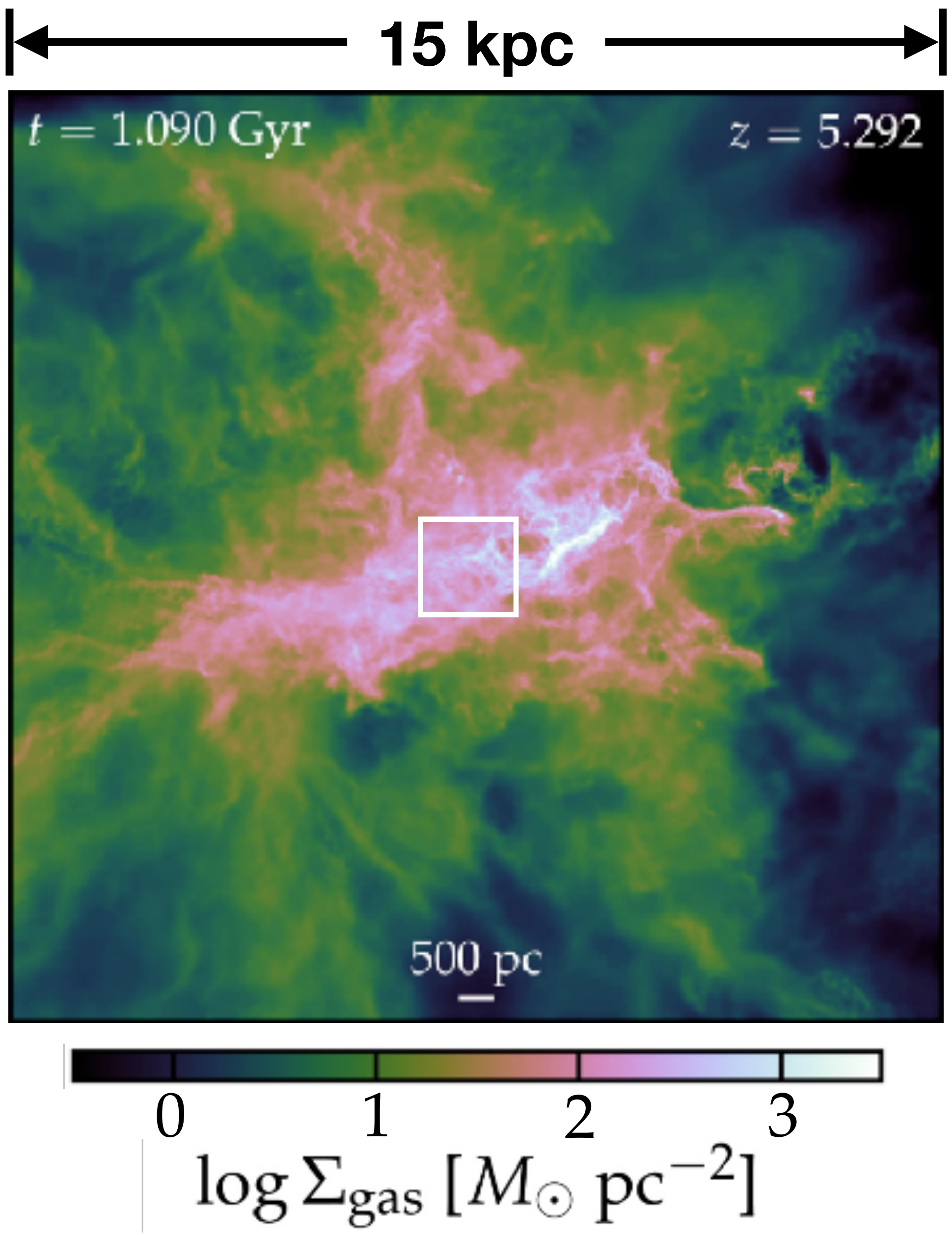
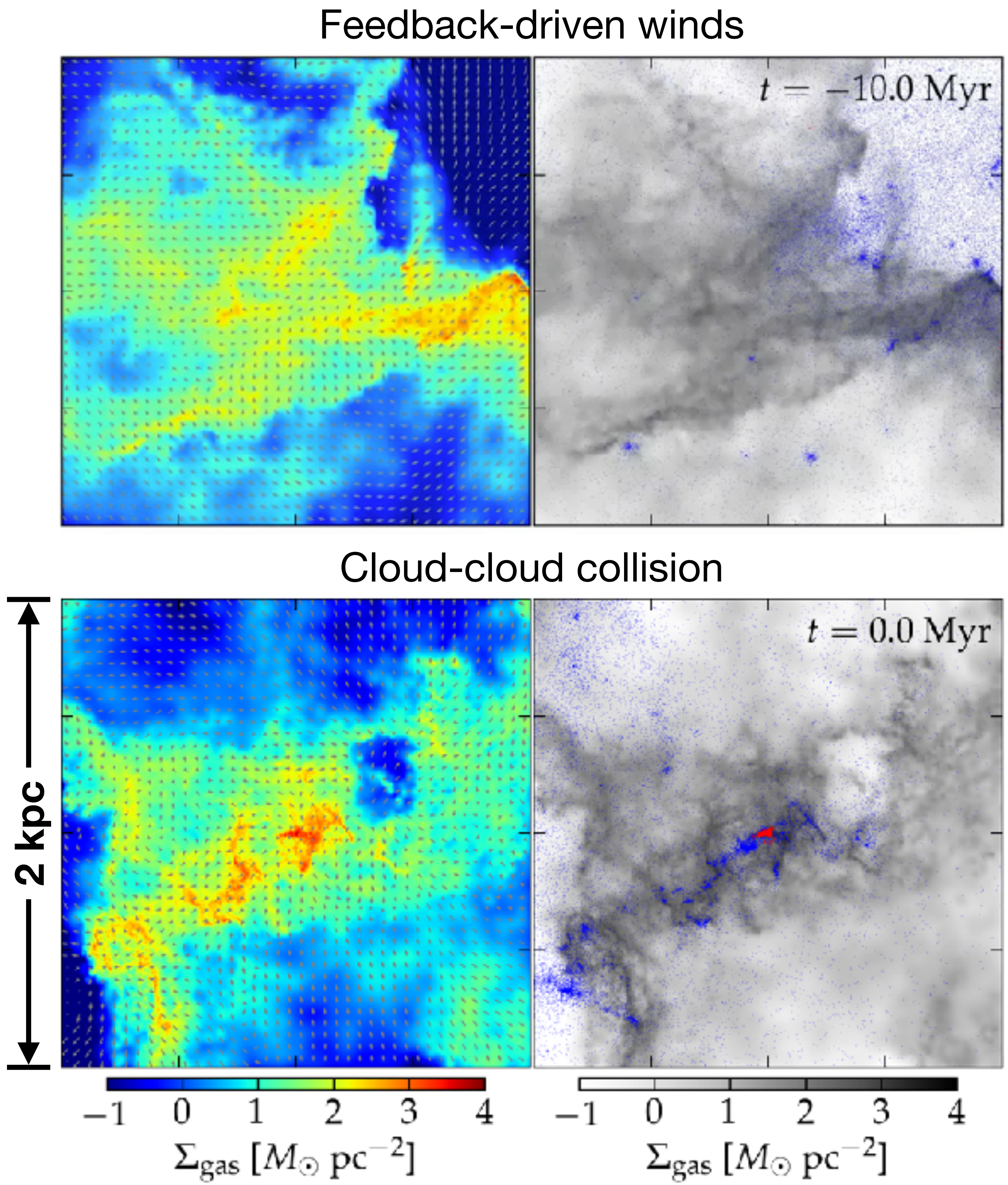


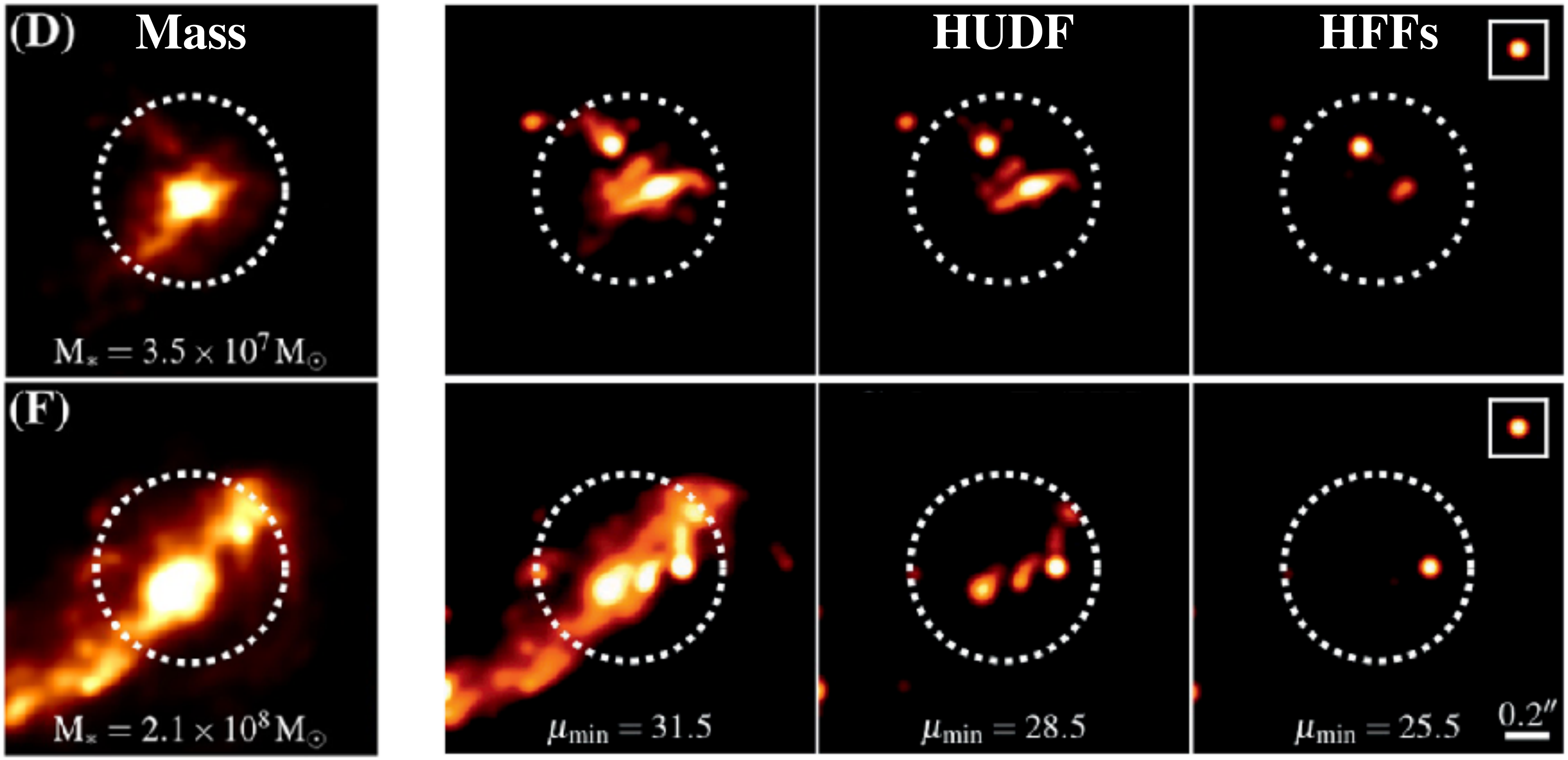
High-pressure regions created by **external** forces

(Elmegreen & Efremov 97; Kruijssen 12)



Ma+20a, MNRAS, 493, 4315

Star clusters "stand out" in deep surveys



Ma+18b, MNRAS, 477, 219

Possibly a severe bias for probing faint galaxies at high redshift

(e.g. Bouwens+2017a,c; Vanzella+2017a,b,2019)

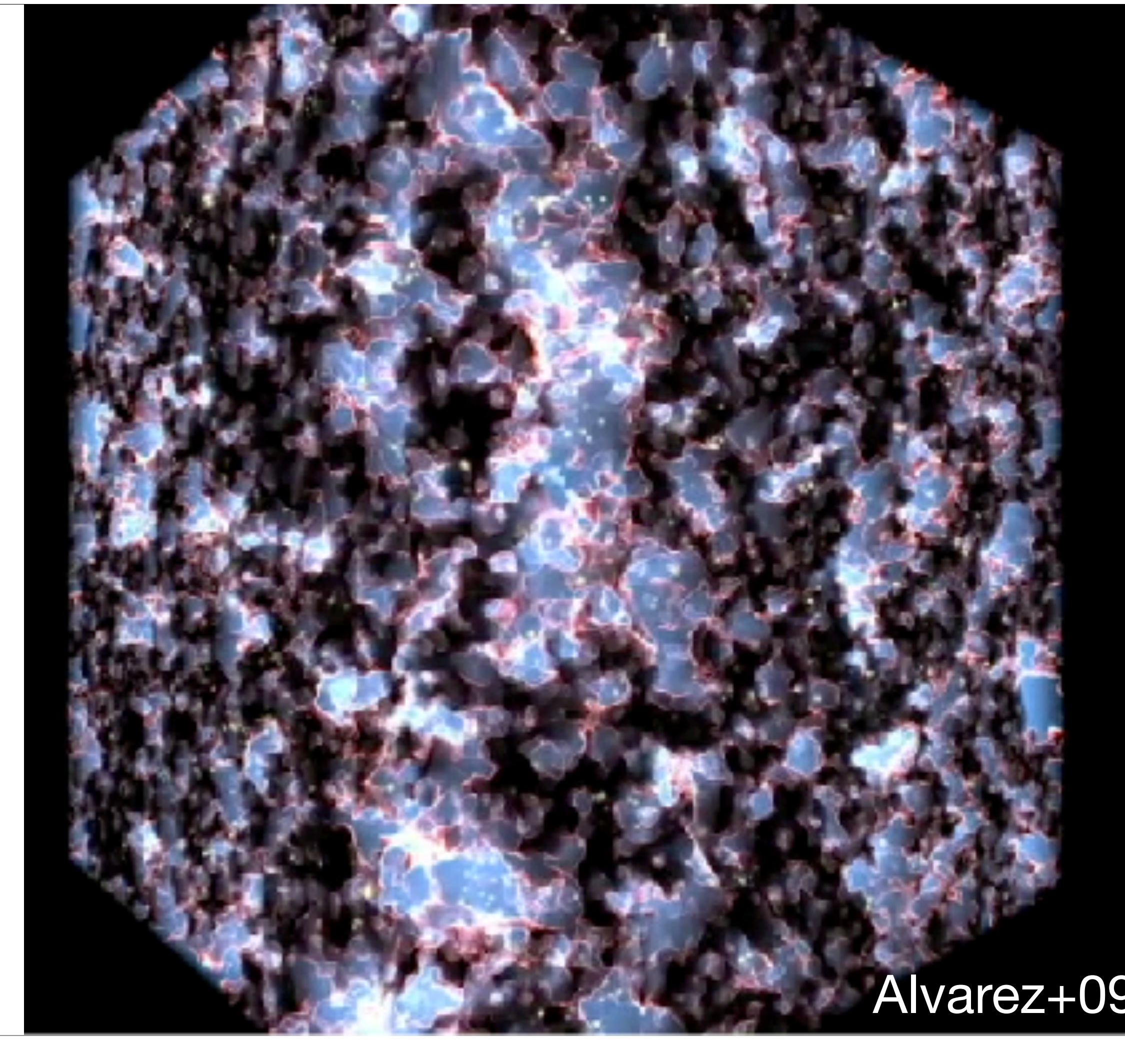
Prediction 2: Efficient Lyman-continuum (LyC) leakage for reionization

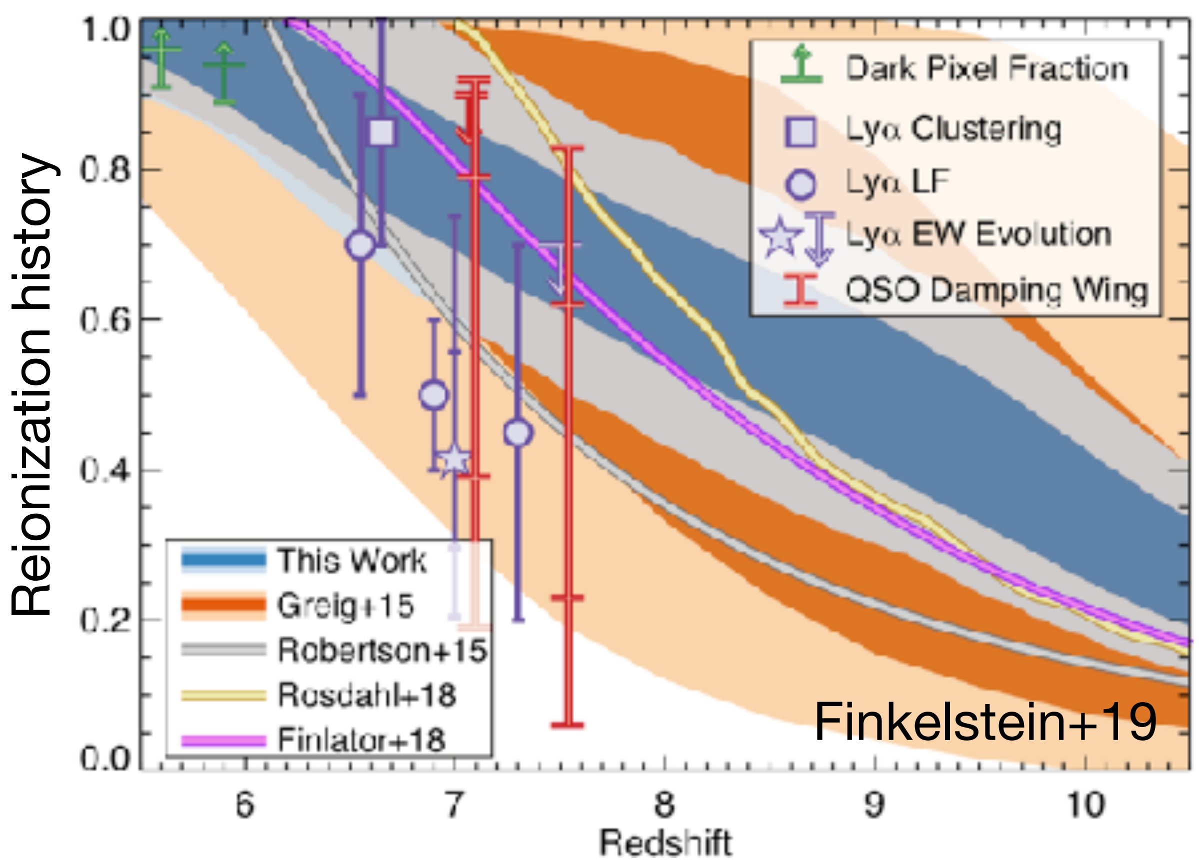
$$\dot{n}_{\rm ion} = f_{\rm esc}\, \xi_{\rm ion}\, \rho_{\rm SFR}$$

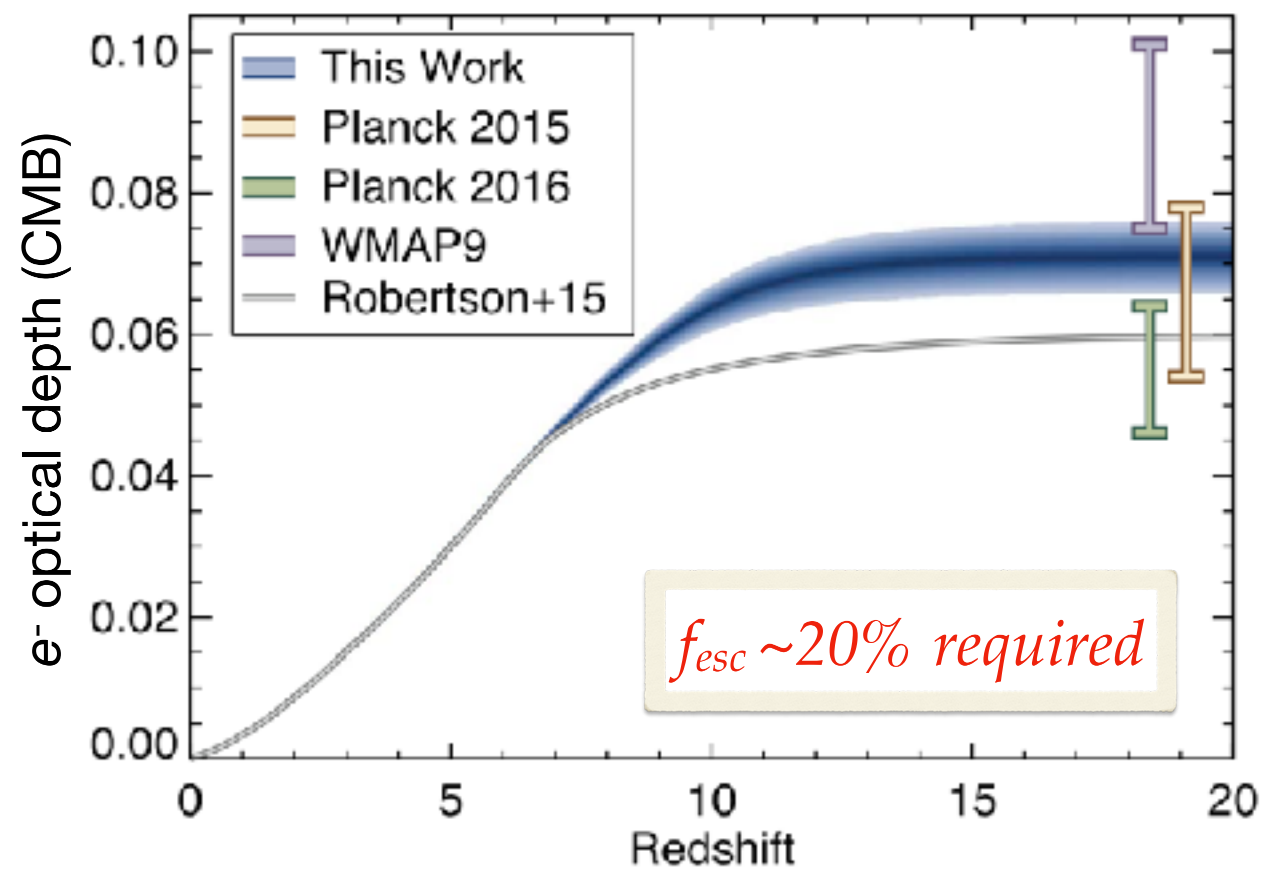
escape fraction ($f_{\rm esc}$) — Stellar population ($\xi_{\rm ion}$)

$$\dot{Q}_{\rm H\,II} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm H\,II}}{t_{\rm rec}}$$

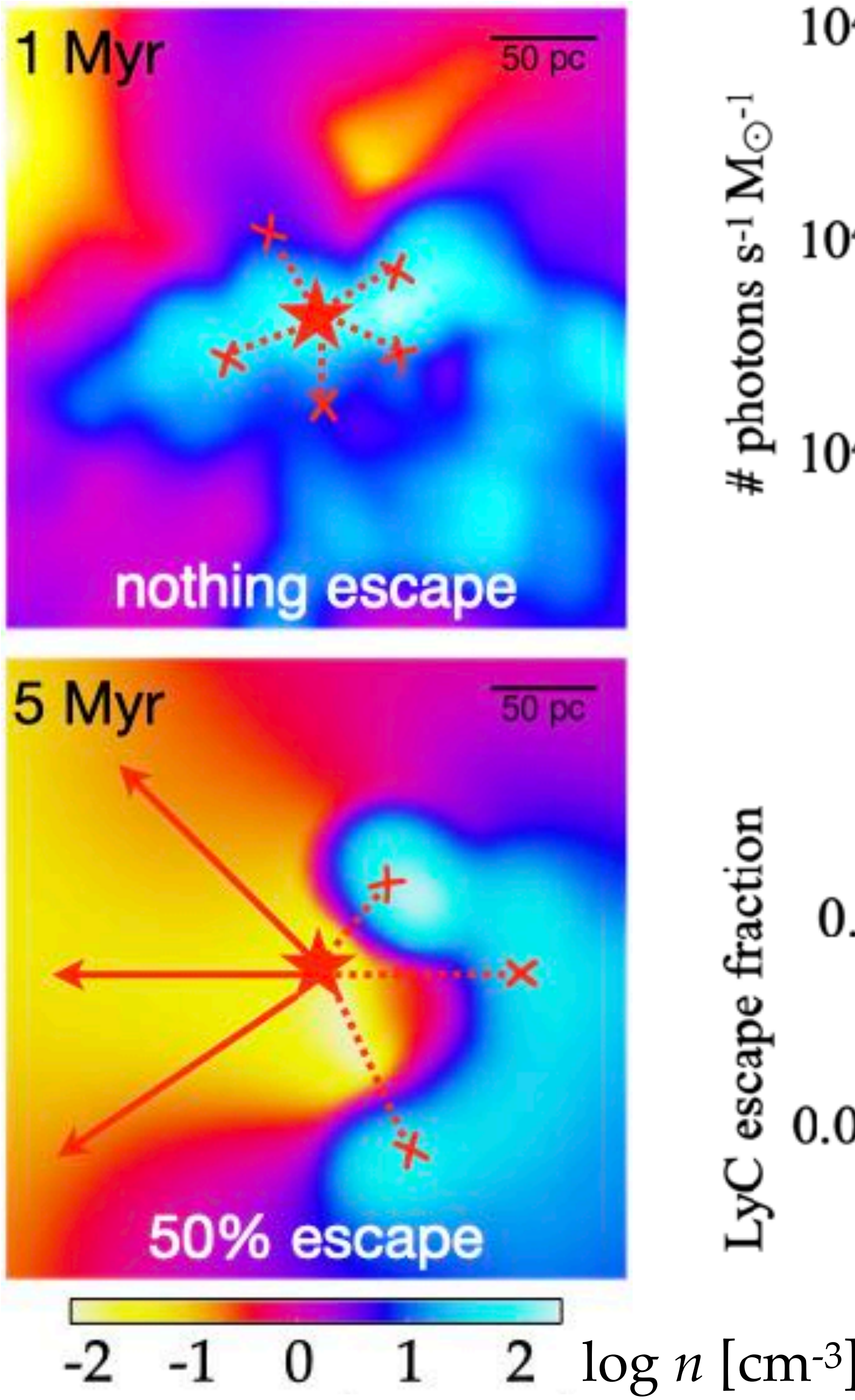
Photoionization — Recombination



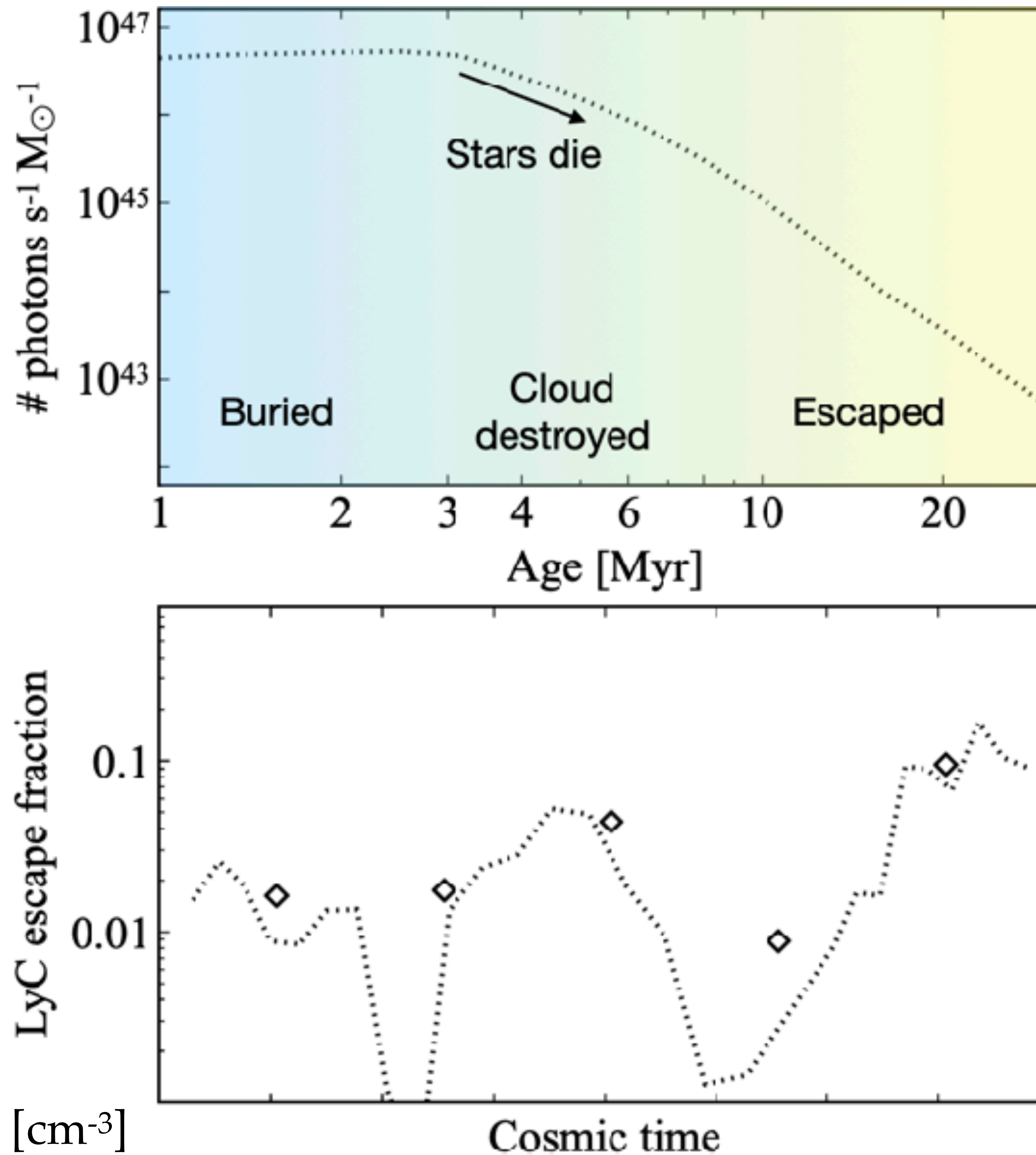




High $f_{\rm esc}$ is hard in “normal” clouds,

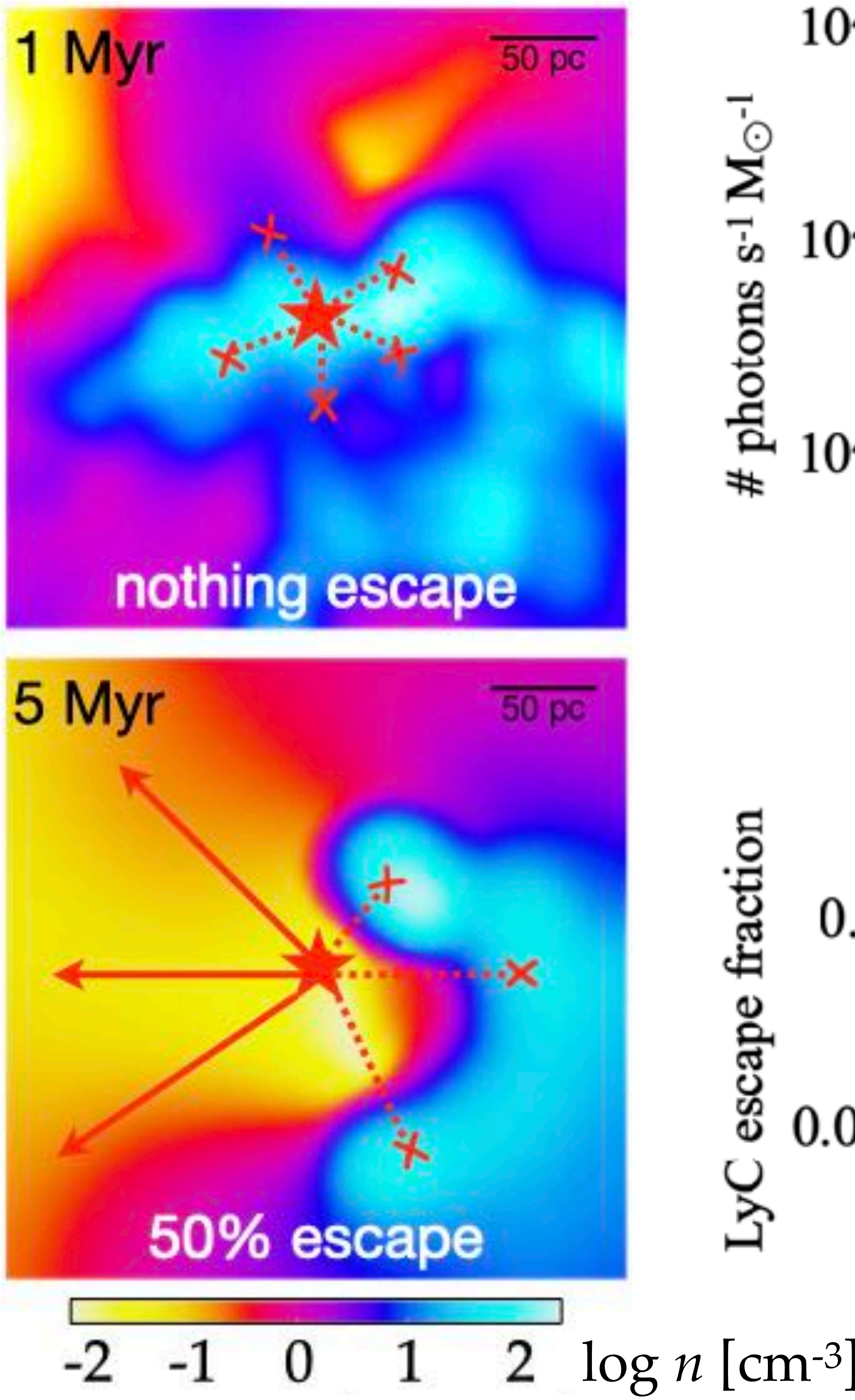


Ma+15, MNRAS, 453, 960

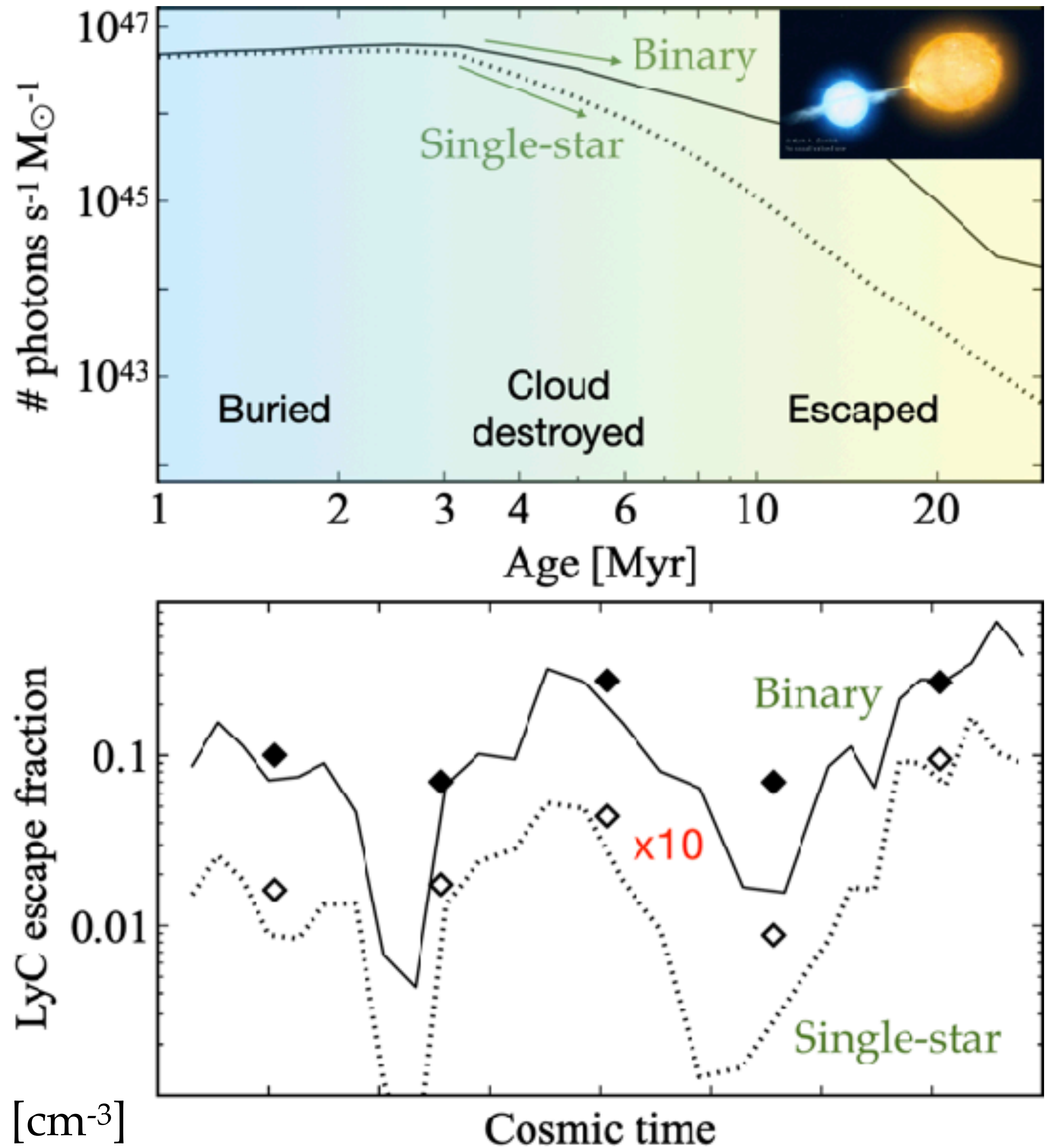


Ma+16b, MNRAS, 459, 3614

High $f_{\rm esc}$ is hard in "normal" clouds, unless including binaries



Ma+15, MNRAS, 453, 960

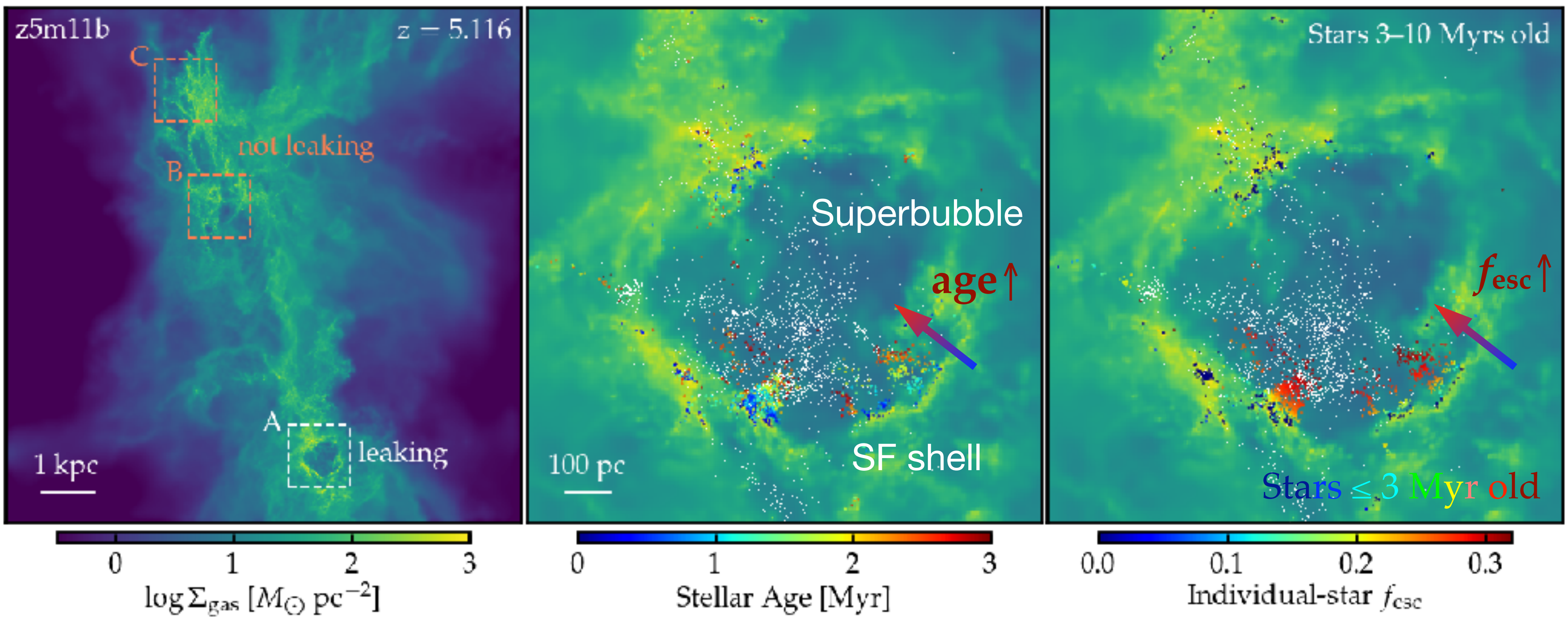


Ma+16b, MNRAS, 459, 3614

Alternative: "burstiness" drives up f_{esc}

- Characteristic geometry of LyC-leaking regions:
  kpc-scale superbubble driven by SNe + accelerated star-forming shell
- Key physics: SN + photoionization feedback

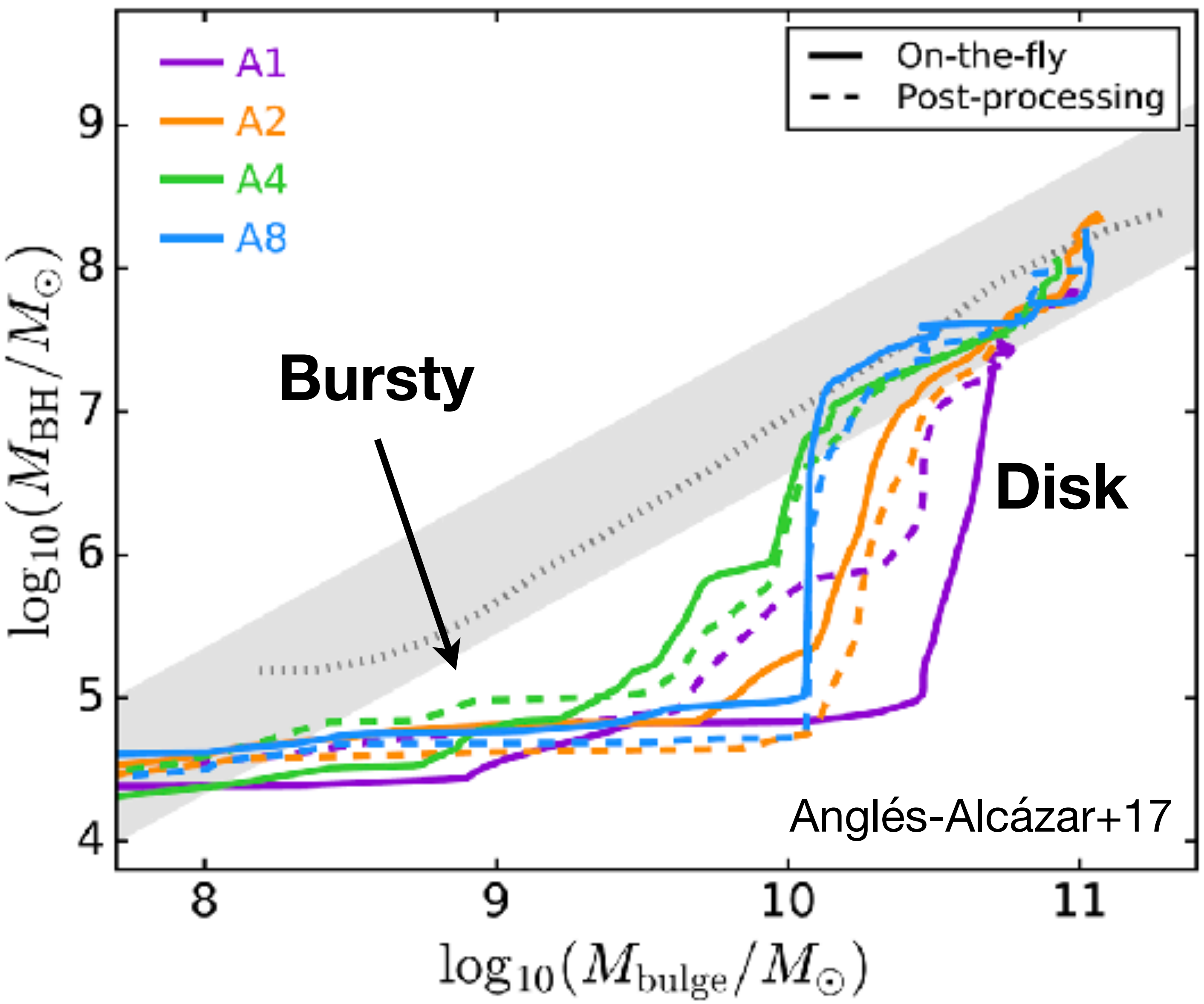
Ma+20b, MNRAS, 498, 2001 (f_{esc}~20%)

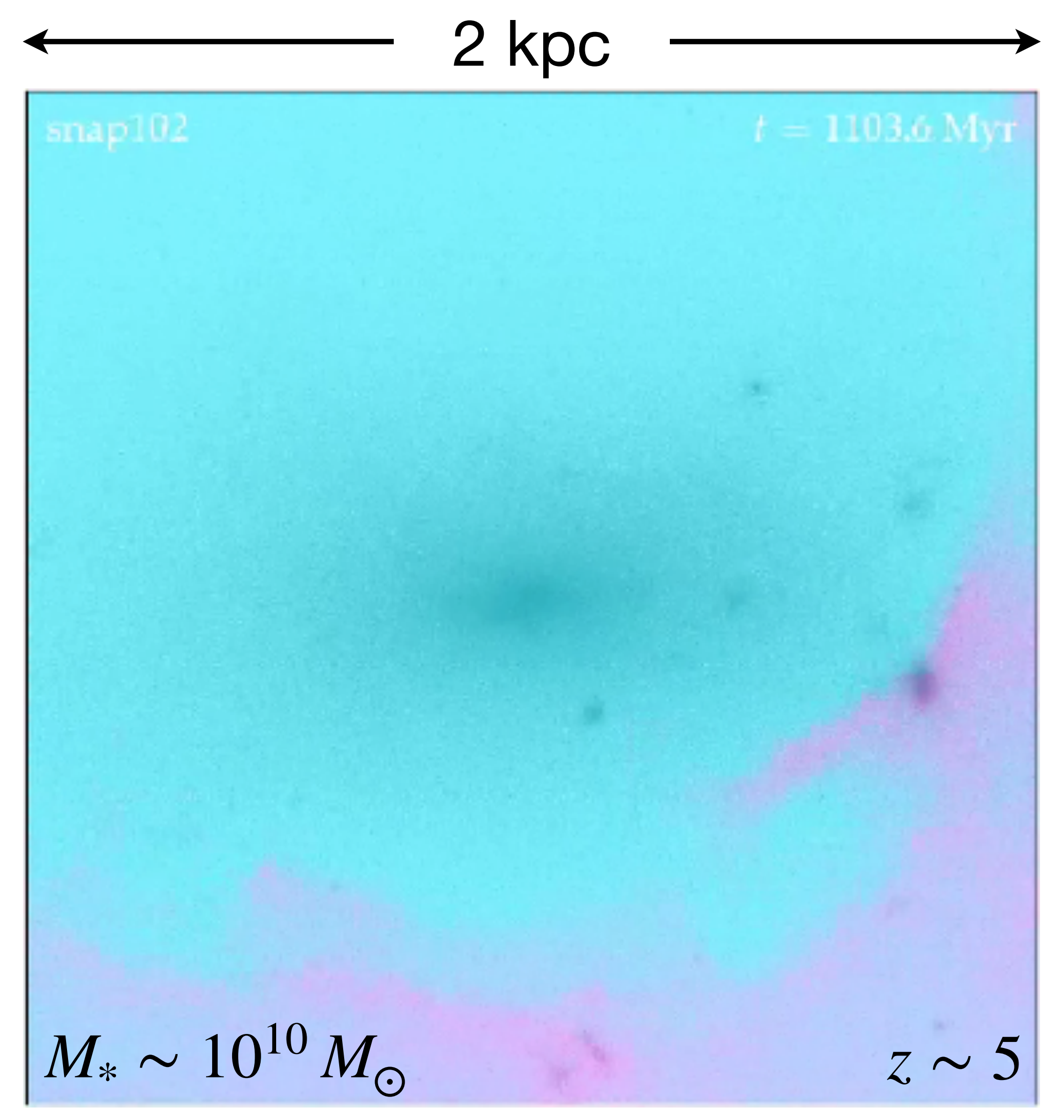


Prediction 3: bursty SF suppresses SMBH growth

- SMBHs remain undermassive w.r.t. $M_{\rm bulge}$, until disk settling occurs
  (Anglés-Alcázar+2017; see also Dubois+15; Habouzit+18; Lapiner+19; Çatmabacak+20)

- But… how does the bulge grow while the central BH doesn't?

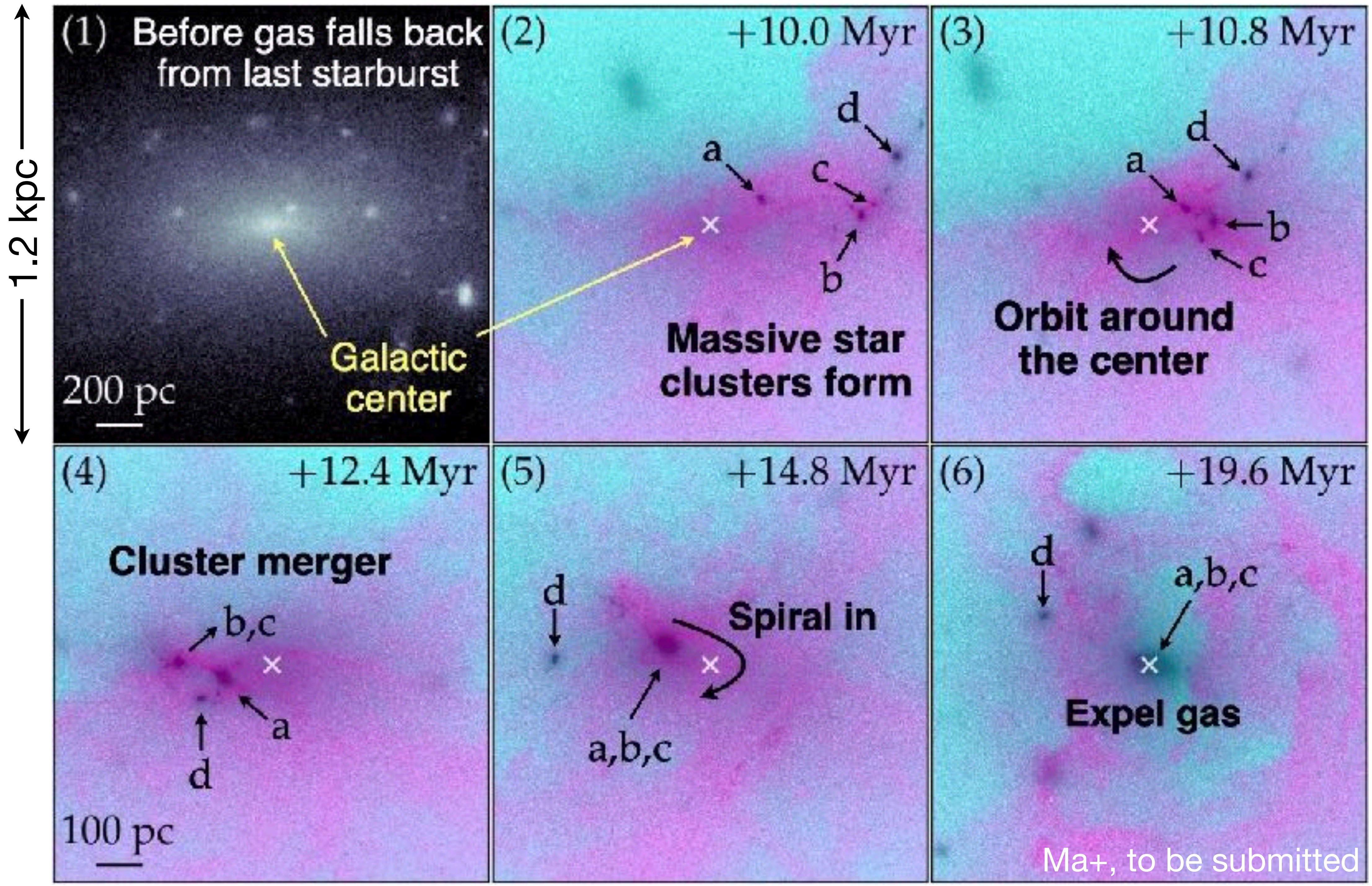




Ma+, to be submitted

Stellar nuclei grow by merging star clusters rather than *in situ* SF:

*not enough gas for BHs to growth **proportionally***

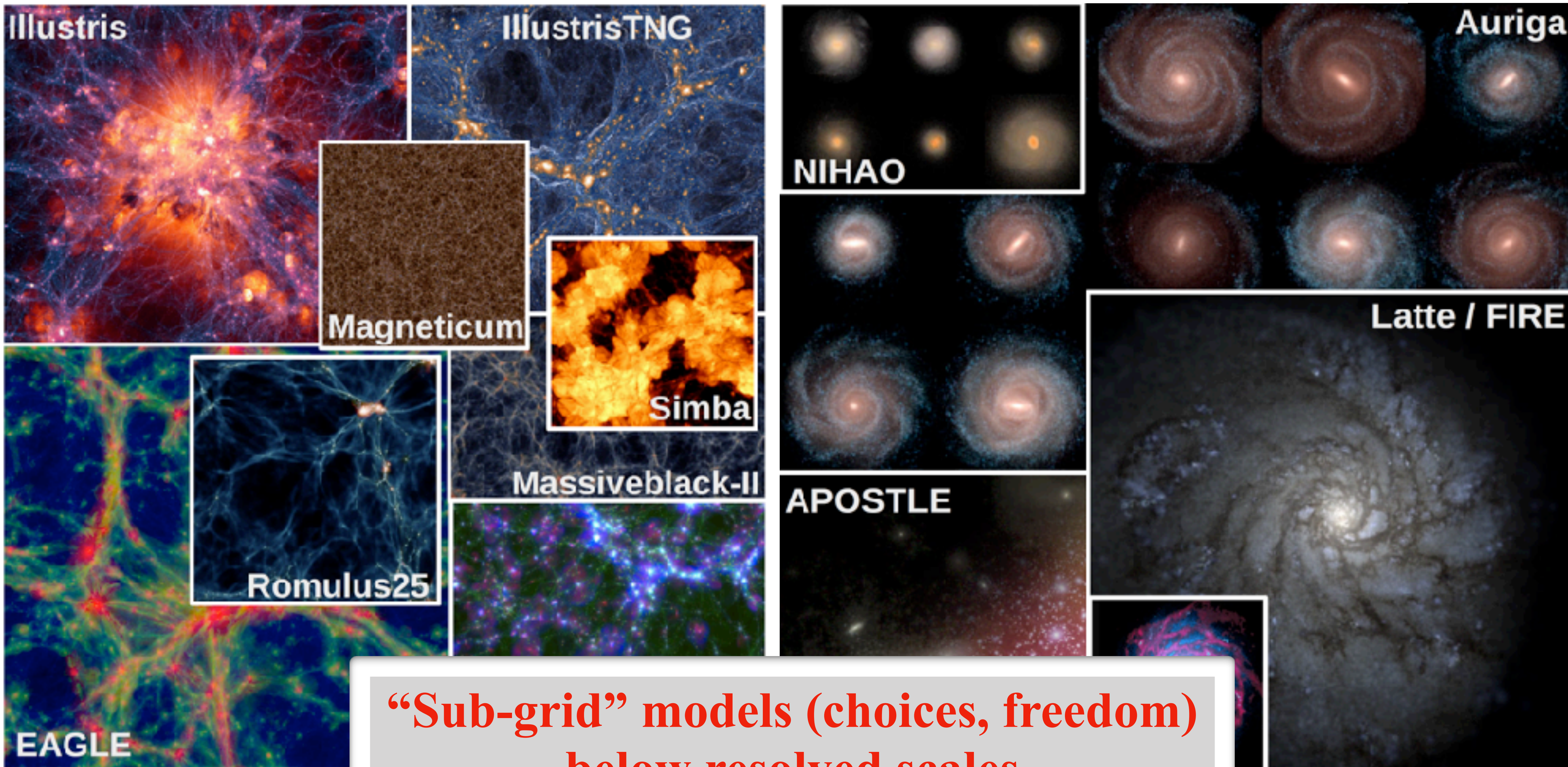


Not the same as Violent Disk Instability & clump migration (Dekel+09; Bournaud+14)

A few 100 pc, ~10 Myr *vs.* A few kpc, ~300 Myr (VDI)

Cosmological simulations: a powerful tool

Large-volume (statistics) | **Zoom-in** (more physics & details)



"Sub-grid" models (choices, freedom) below resolved scales

Vogelsberger+2019

Box size $\sim(100\ \mathrm{Mpc}/h)^3$
$\sim10^5$–$10^6\ M_\odot$, ~1 kpc

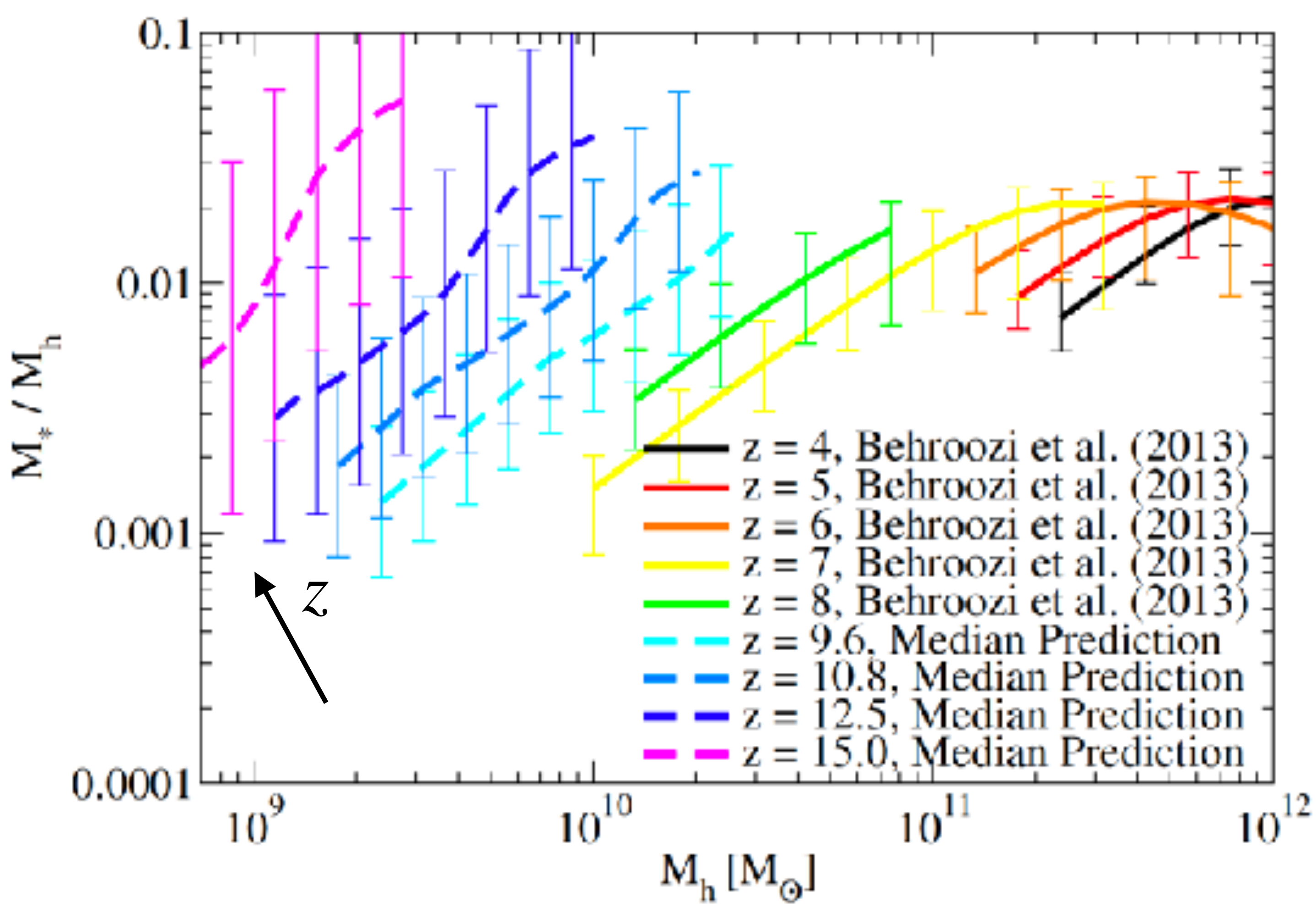
One halo at a time
~10–$10^4\ M_\odot$, ~0.1–1 pc

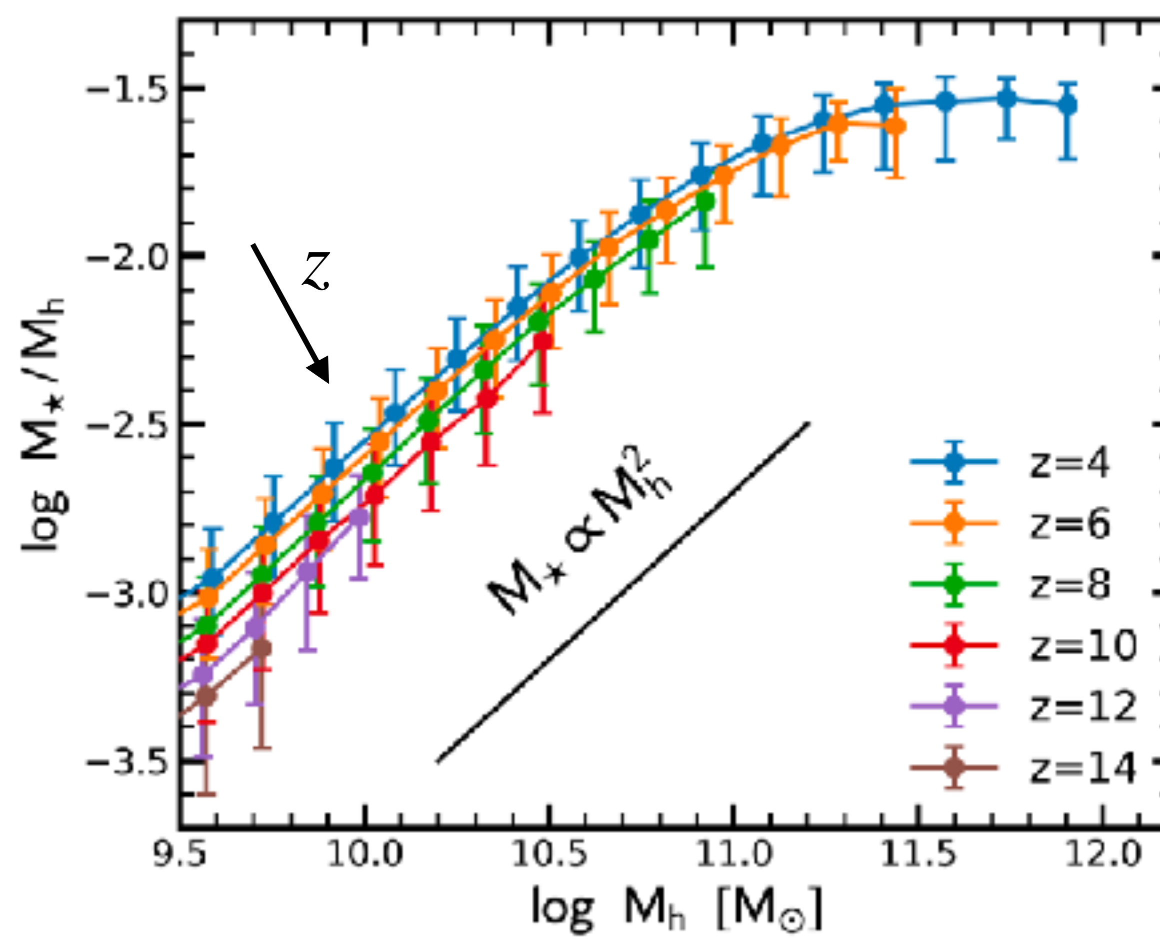
The bursty regime: A challenge for galaxy formation

Or an opportunity?

- Models and simulations disagree on the **0th**-order predictions at high z.
  (see e.g. Finkelstein+15; Stefanon+17; O'Shea+15; Behroozi+13,15,19,20; Ceverino+17; Rodriguez-Puebla+17; Wilkins+17; Ma+18a; Tacchella+18; …)

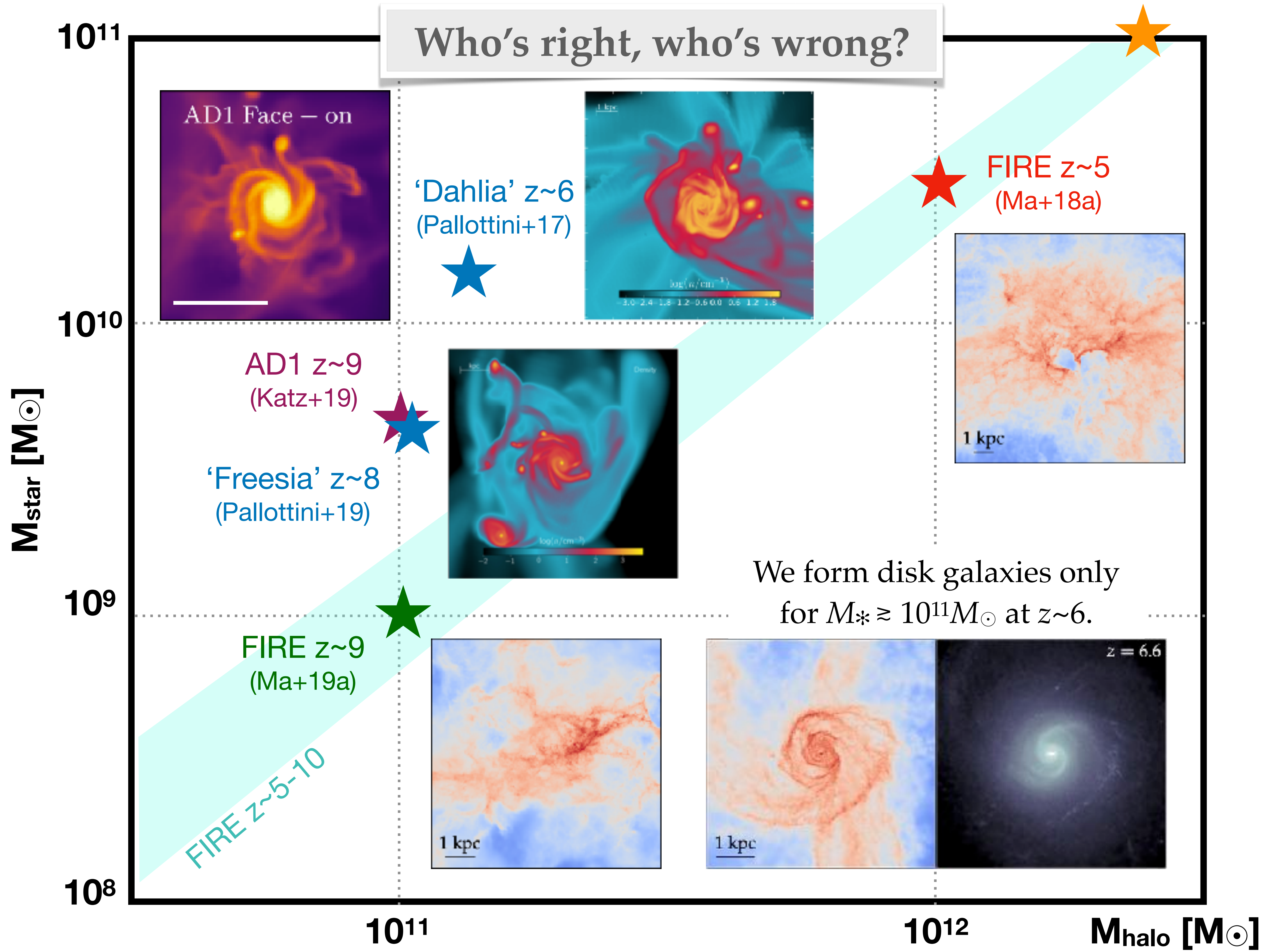
- Different groups produce diverging morphology, kinematics, sizes, etc.





Behroozi+13,15,18

Tacchella+18



Who's right, who's wrong?
AD1 Face – on
'Dahlia' z~6
(Pallottini+17)
FIRE z~5
(Ma+18a)
AD1 z~9
(Katz+19)
'Freesia' z~8
(Pallottini+19)
FIRE z~9
(Ma+19a)
FIRE z~5-10
We form disk galaxies only
for $M_* \gtrsim 10^{11} M_\odot$ at z~6.
1 kpc
1 kpc
1 kpc
z = 6.6
10^{11}
10^{10}
10^{9}
10^{8}
M_{star} [$M_\odot$]
10^{11}
10^{12}
M_{halo} [$M_\odot$]

Great opportunity to constrain galaxy formation physics in the next 5-10 years

pace missions

Ground-based teles

Future 30 m-class telescope

21-cm cosmology

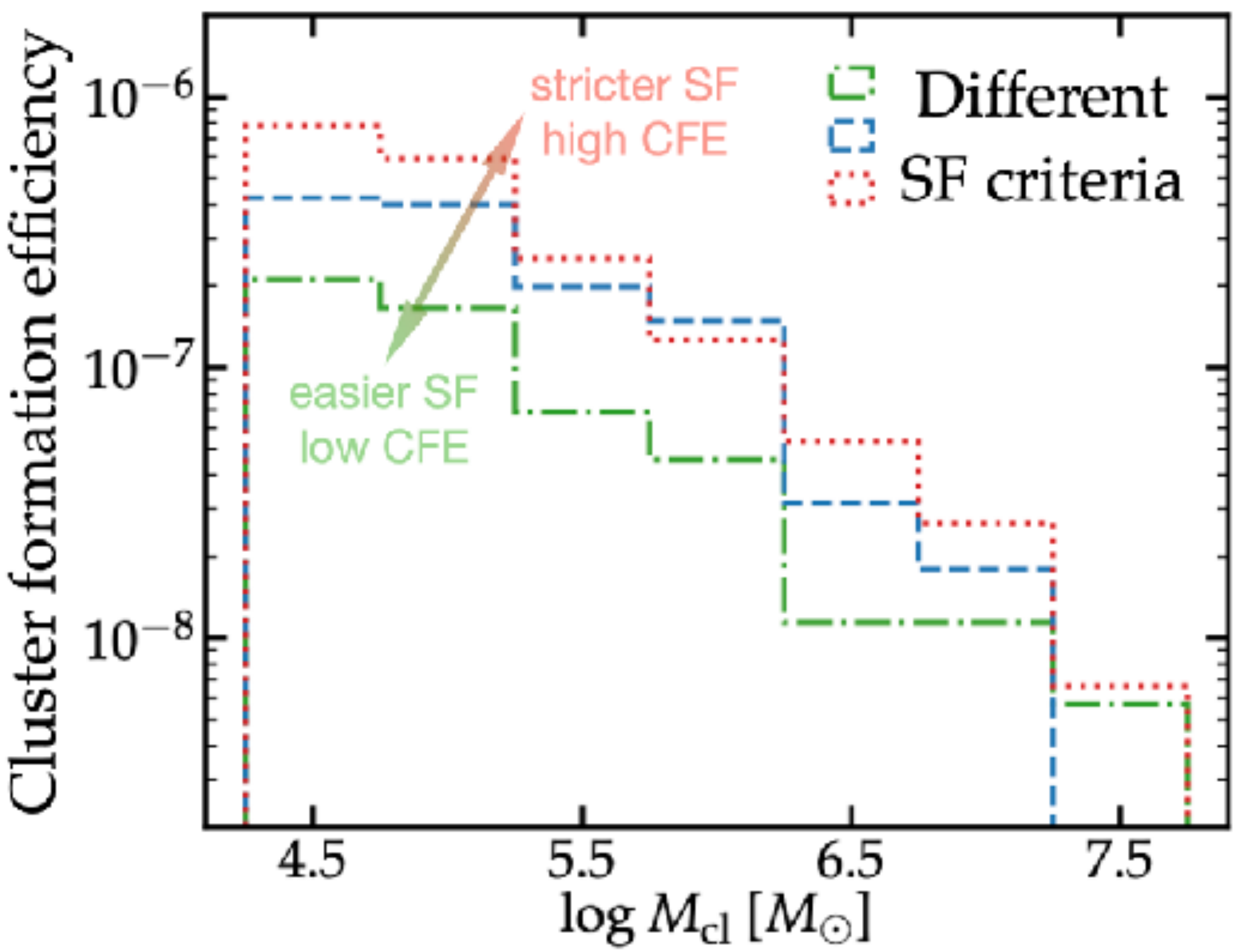
Dust continuum, [C II], CO, molecular lines

Star clusters to constrain SF & feedback physics

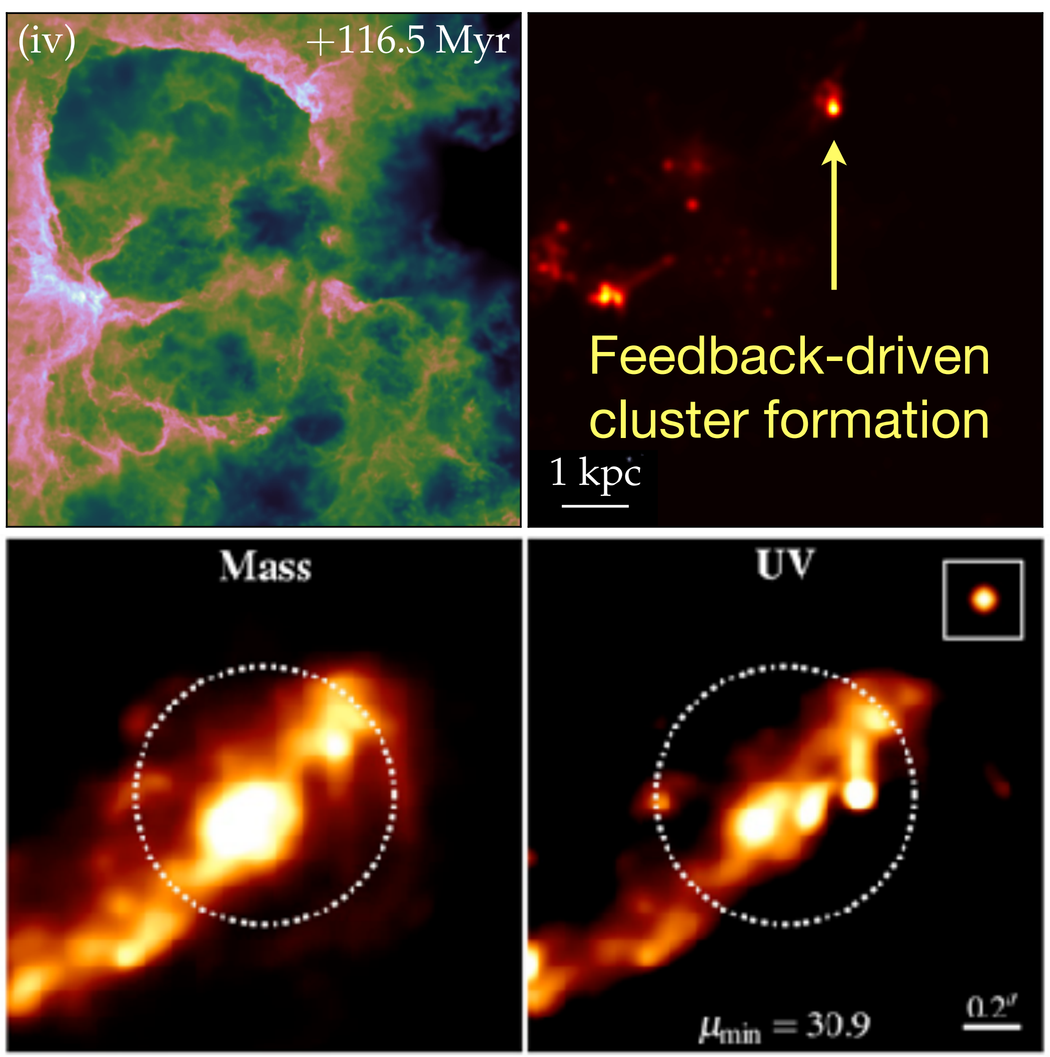
- Young star clusters and complexes appear as UV bright clumps (Ma+18b, Meng+20), detectable up to z~8 with HST (with lensing; Bouwens+17; Vanzella+17,19; Hashimoto+18)

  Predictions required: number counts, LFs & 2PCFs of bright clumps for JWST, CSST, WFIRST, and 30 m-class telescopes (GMT, TMT, ELT)

- Understanding the completeness at the faint-end for UVLFs, SMFs, CSFRD, …



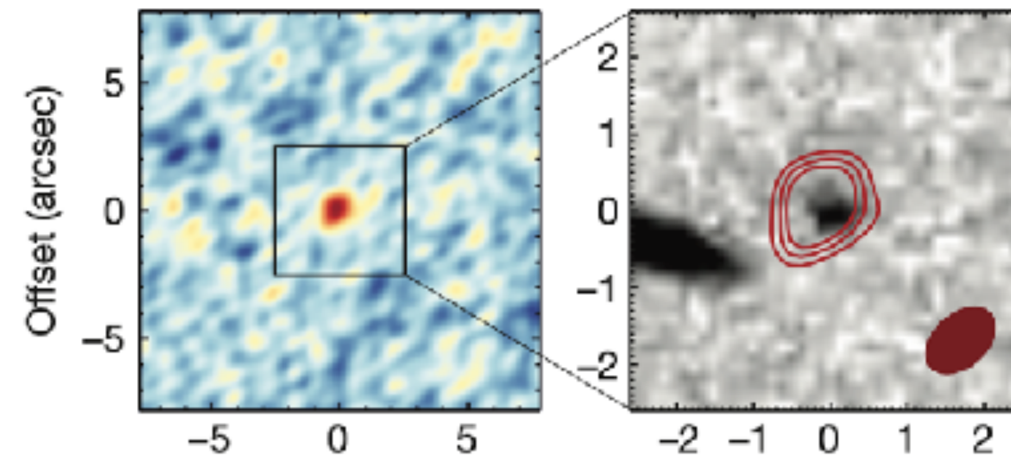
Ma+20a, MNRAS, 493, 4315



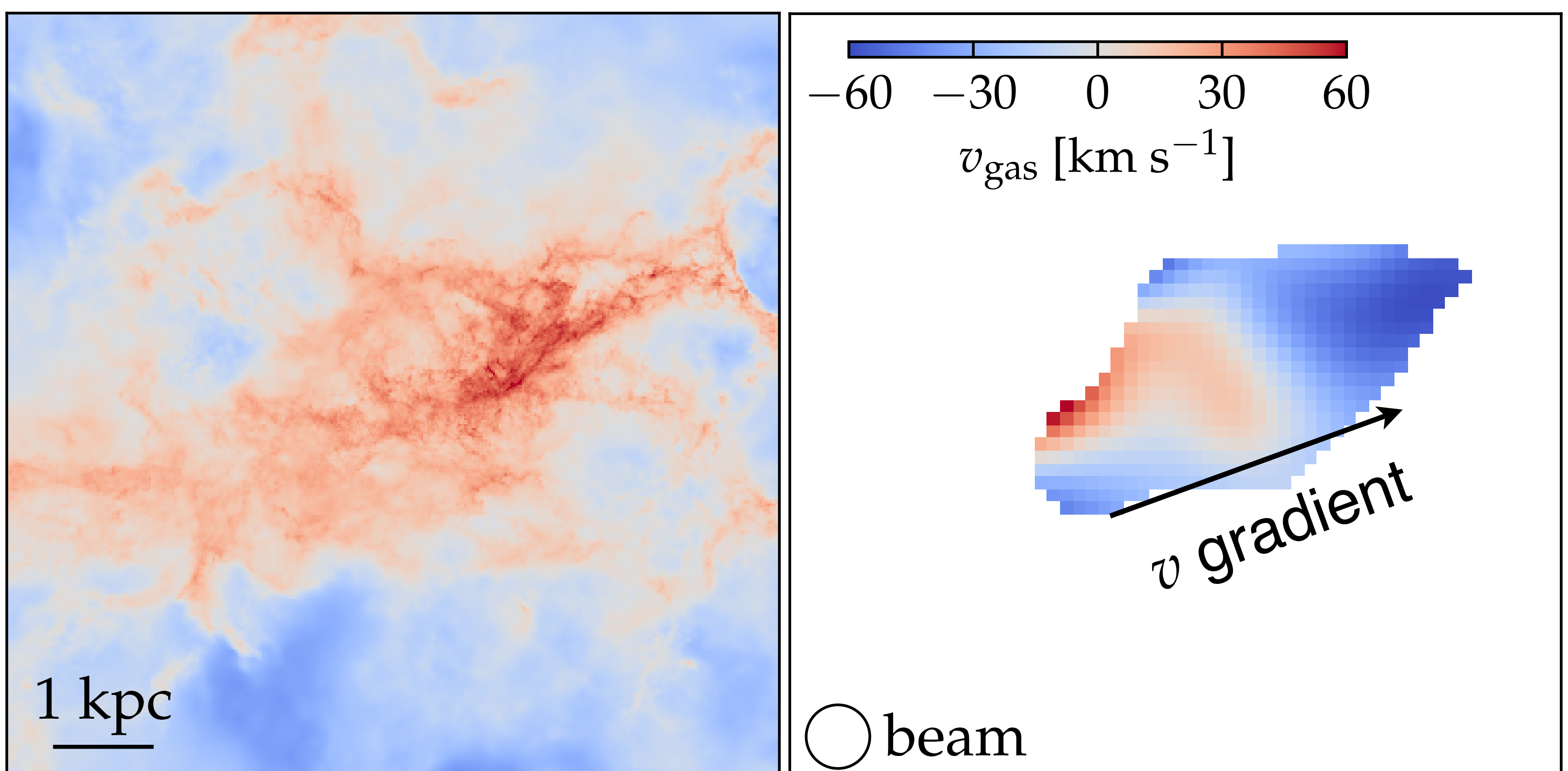
Ma+18b, MNRAS, 477, 219

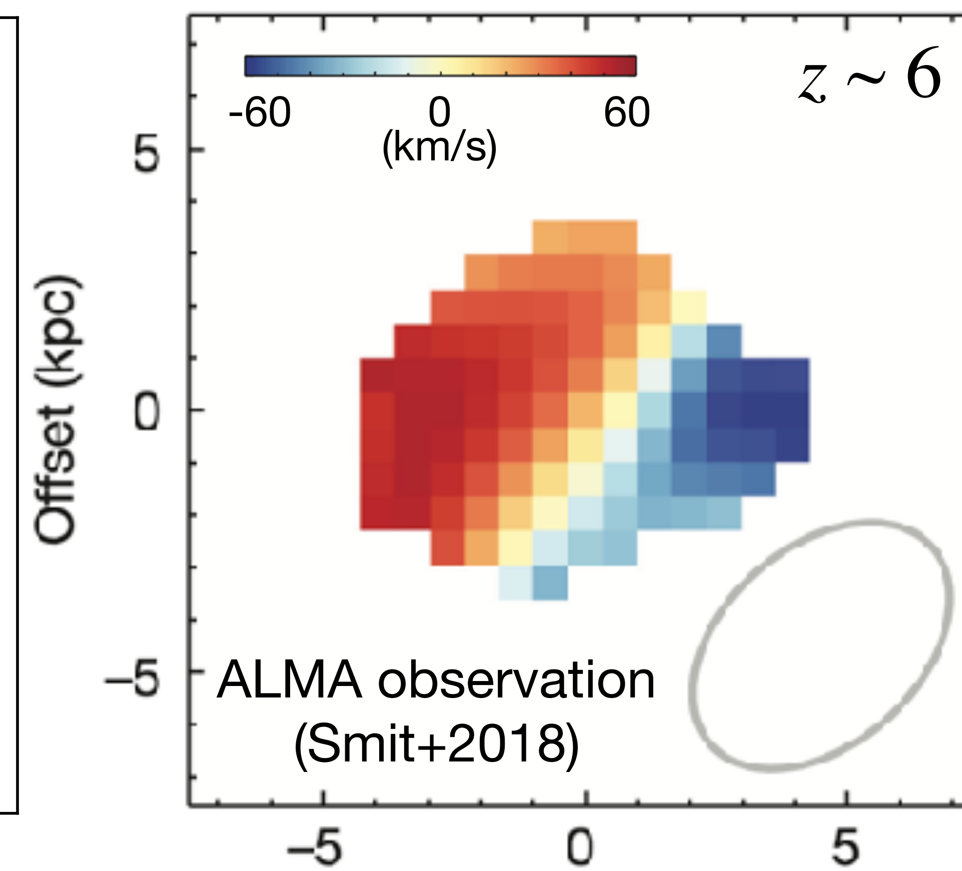
Kinematics: a test of simulation outcomes

- Are high-redshift galaxies dominated by turbulence or rotation?
- Do we misinterpret velocity differences from ALMA/JWST as rotation?
- When and why do the first disks form?
  - Stern+20 (incl. XM): forming a hot inner halo
  - Alternative: less effective feedback?



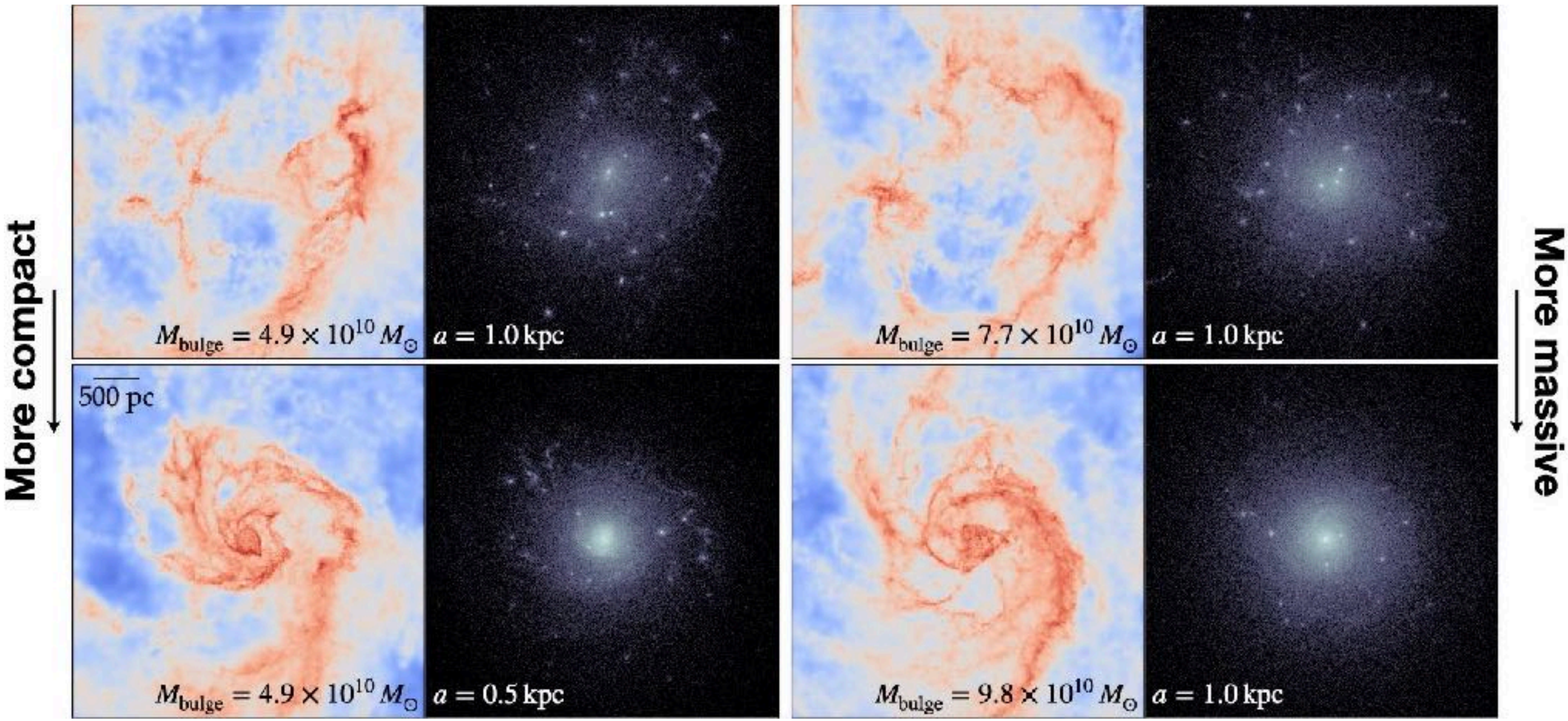
FIRE simulation





A massive, compact bulge → disk formation at early times

deep potential prevents feedback from disrupting disk settling

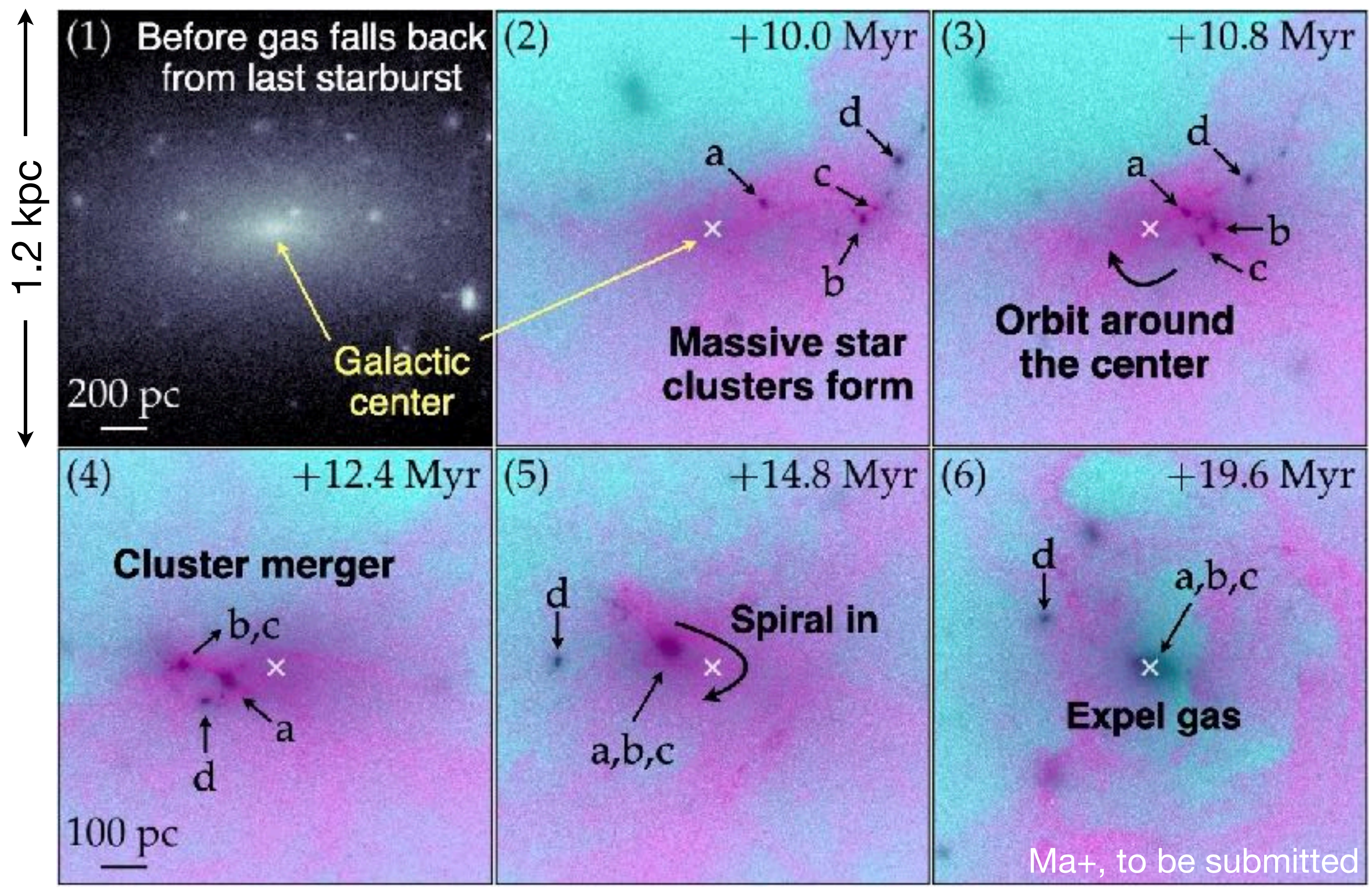


An isolated $M_{\rm halo} \sim 10^{12}\, M_\odot$ halo at $z \sim 8$

Preliminary

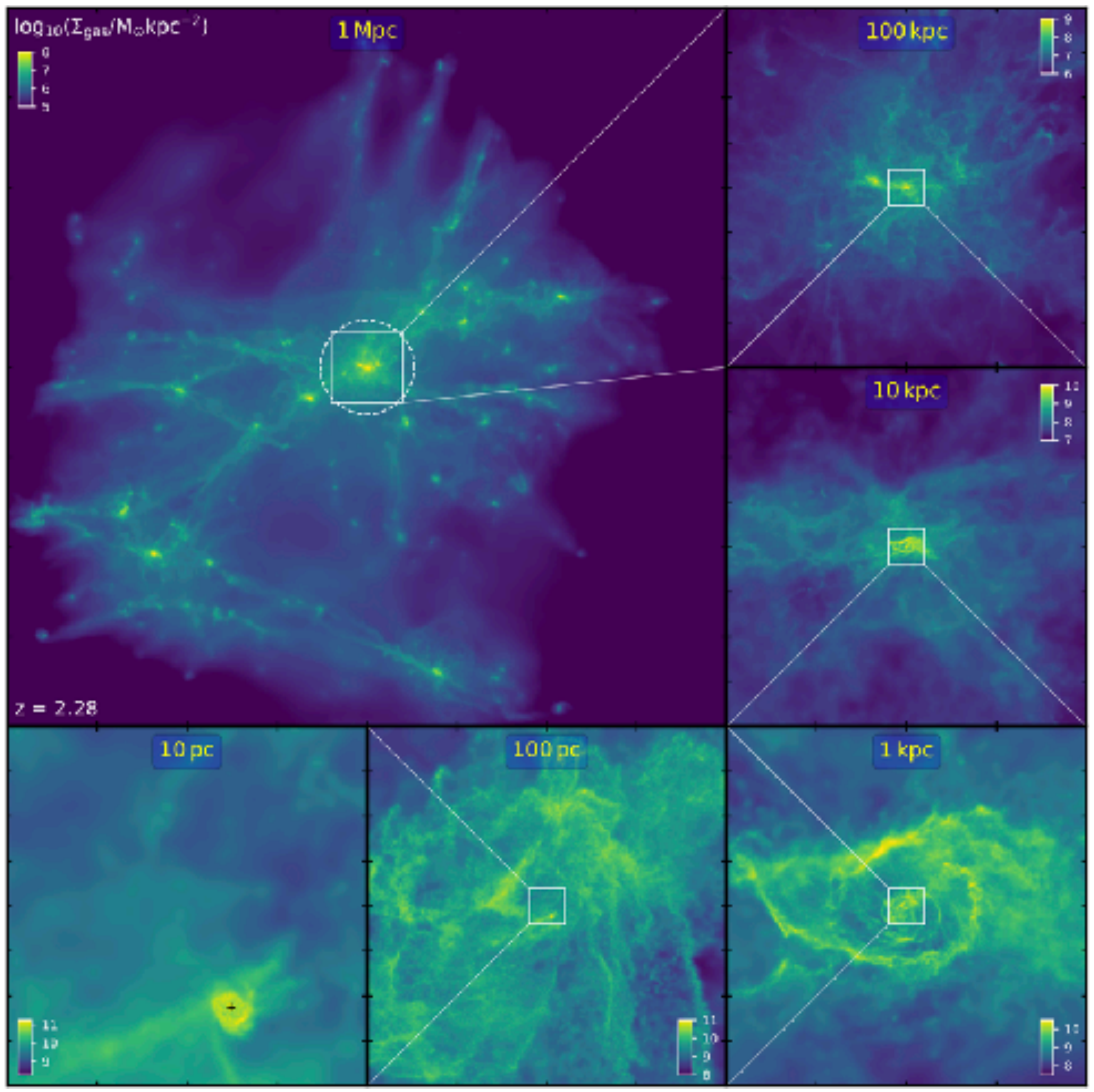
How can SMBHs $\gtrsim 10^9 M_\odot$ exist at z>6?

- Can the central BH be captured by a forming star cluster and accrete?
- Can these clusters seed IMBHs that coalesce at the galactic center?



How can SMBHs $\gtrsim 10^9 M_\odot$ exist at z>6?

- What about BH feedback? Can heating prevent fragmentation and SF?
- What is the predicted SMBH population at high redshift? How to test?



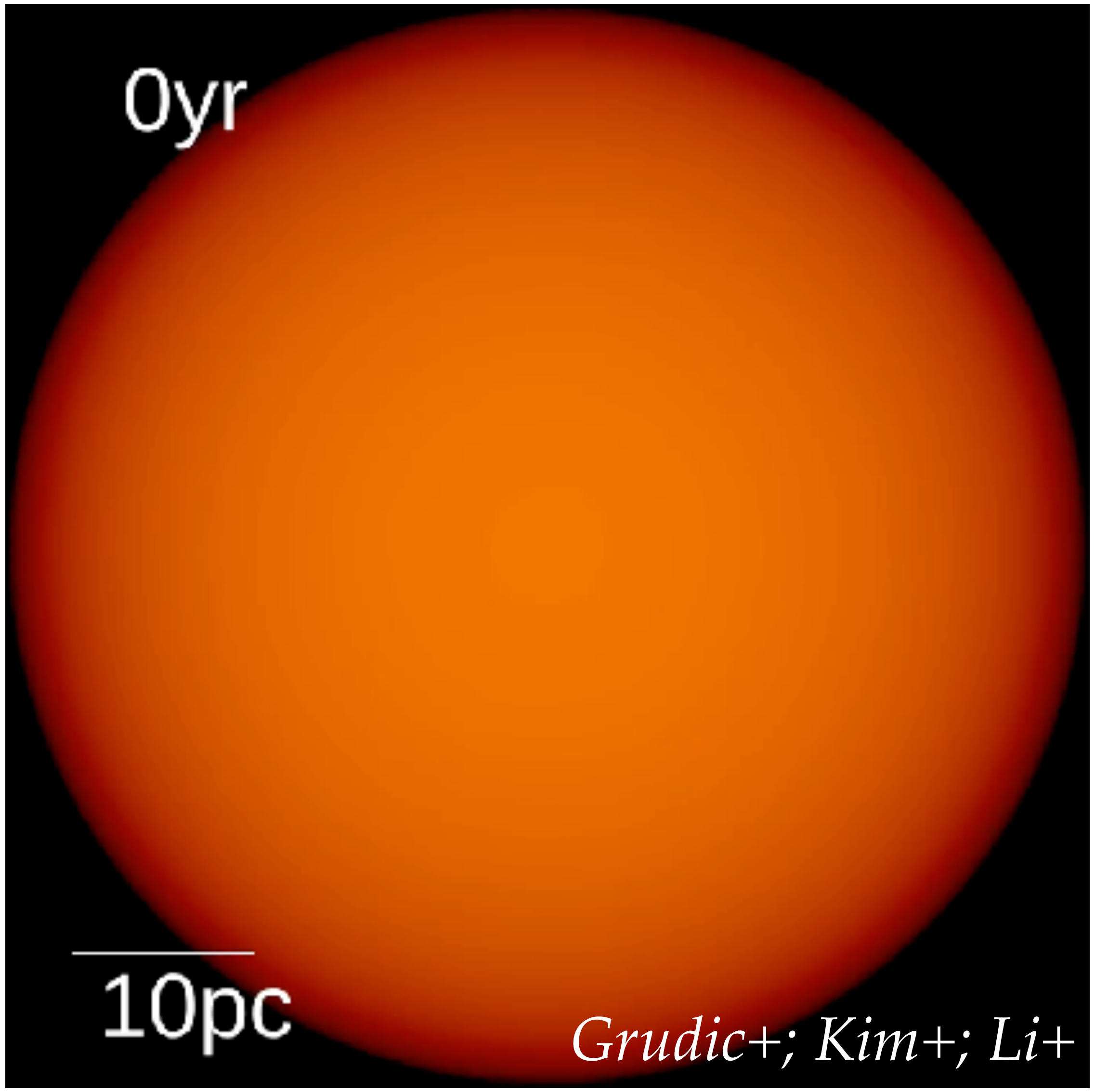
New methods:

- Multi-scale zoom-in technique (Anglés-Alcázar+20)
- Radiation-hydrodynamics (Hopkins+20, incl. XM)
- Accretion-disk winds (Torrey+20, incl. XM)
- Radio jests (Su+20, incl. XM)
- SAMs and post-processing

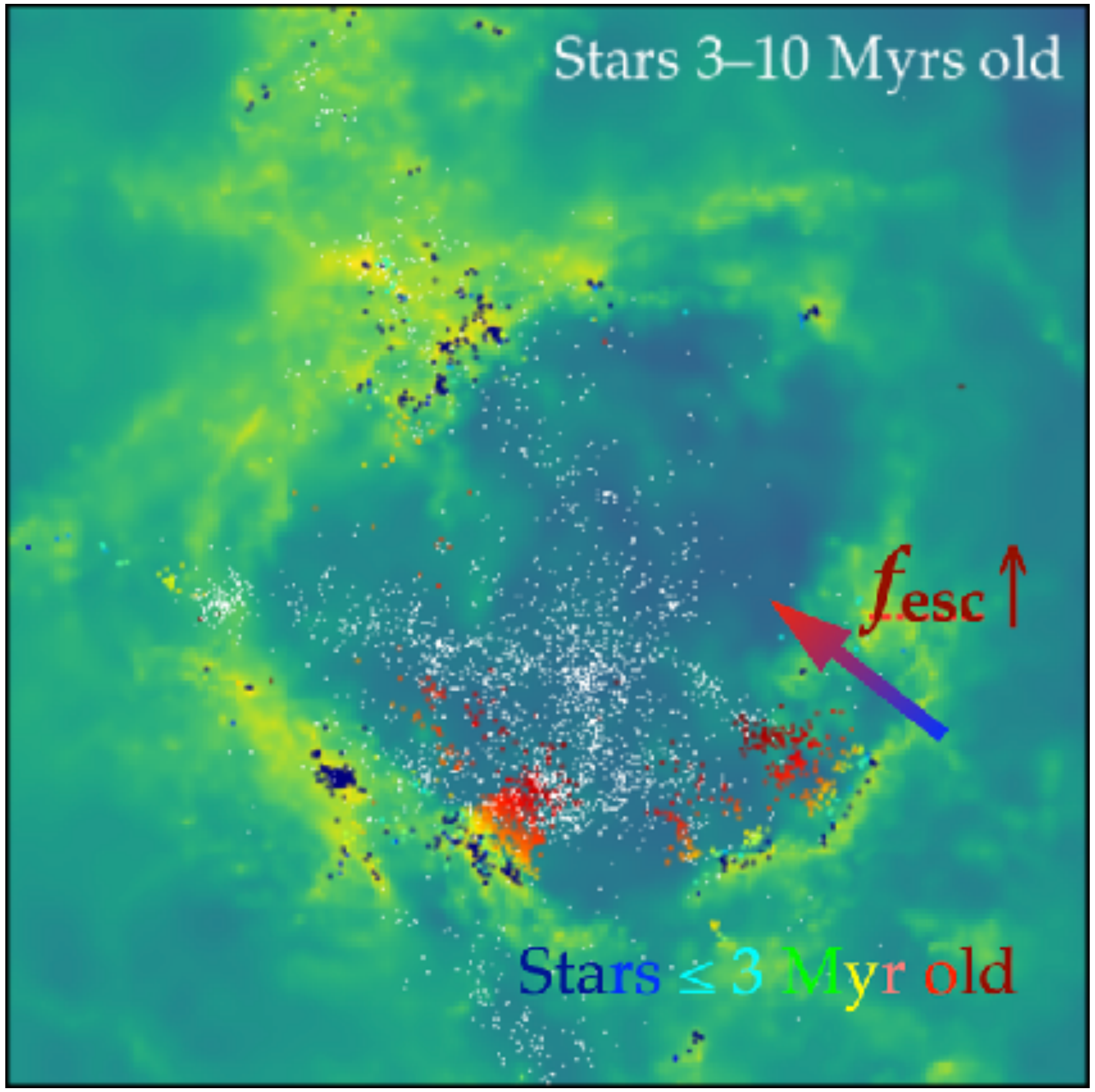
Self-consistent, first-principle simulations of galactic nuclei: the future of SMBHs studies

Overlooked physics: triggered SF in supergiant shells

- The vast majority of current studies focus on SF in isolated GMCs



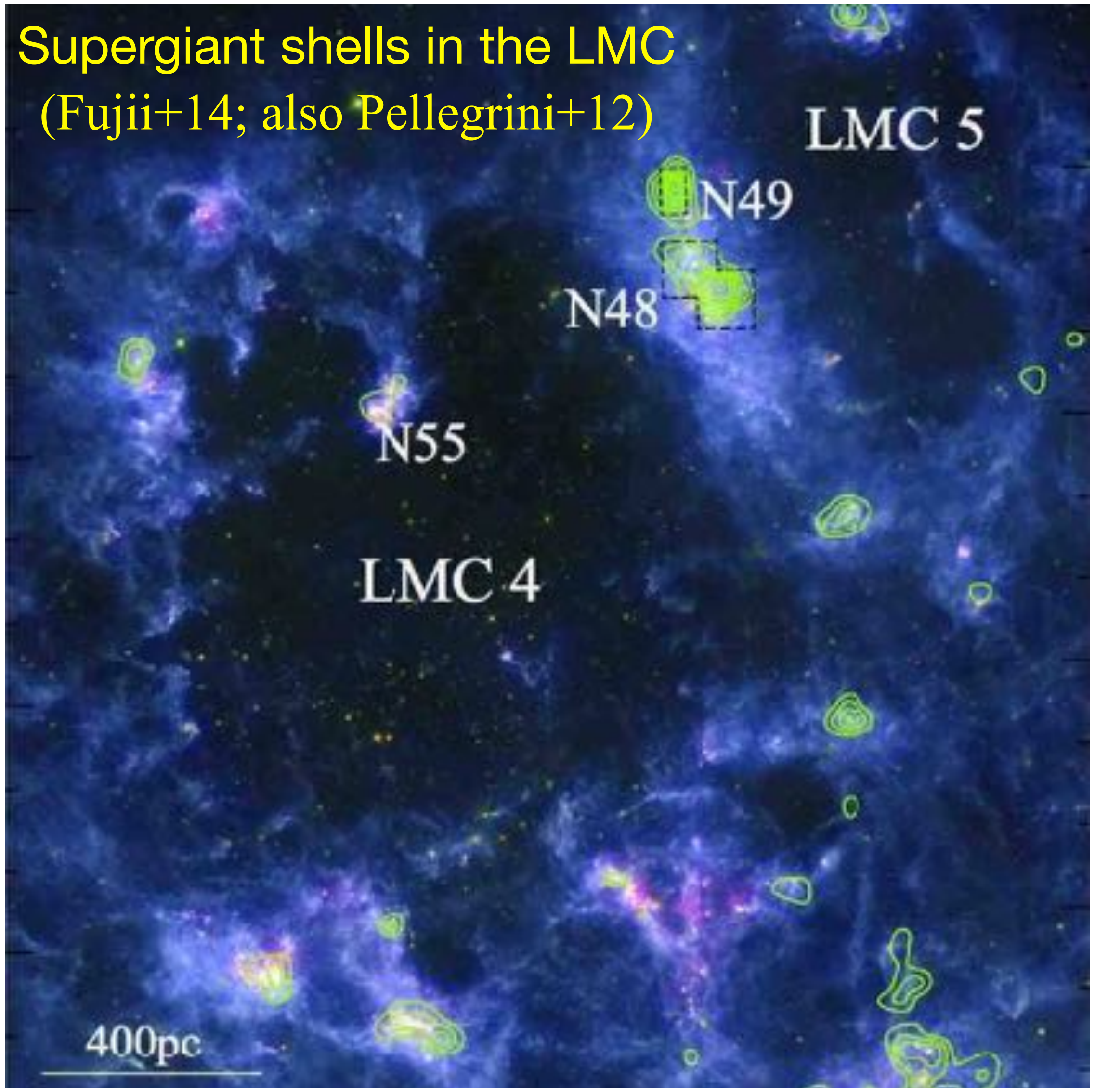
Typical in the local Universe



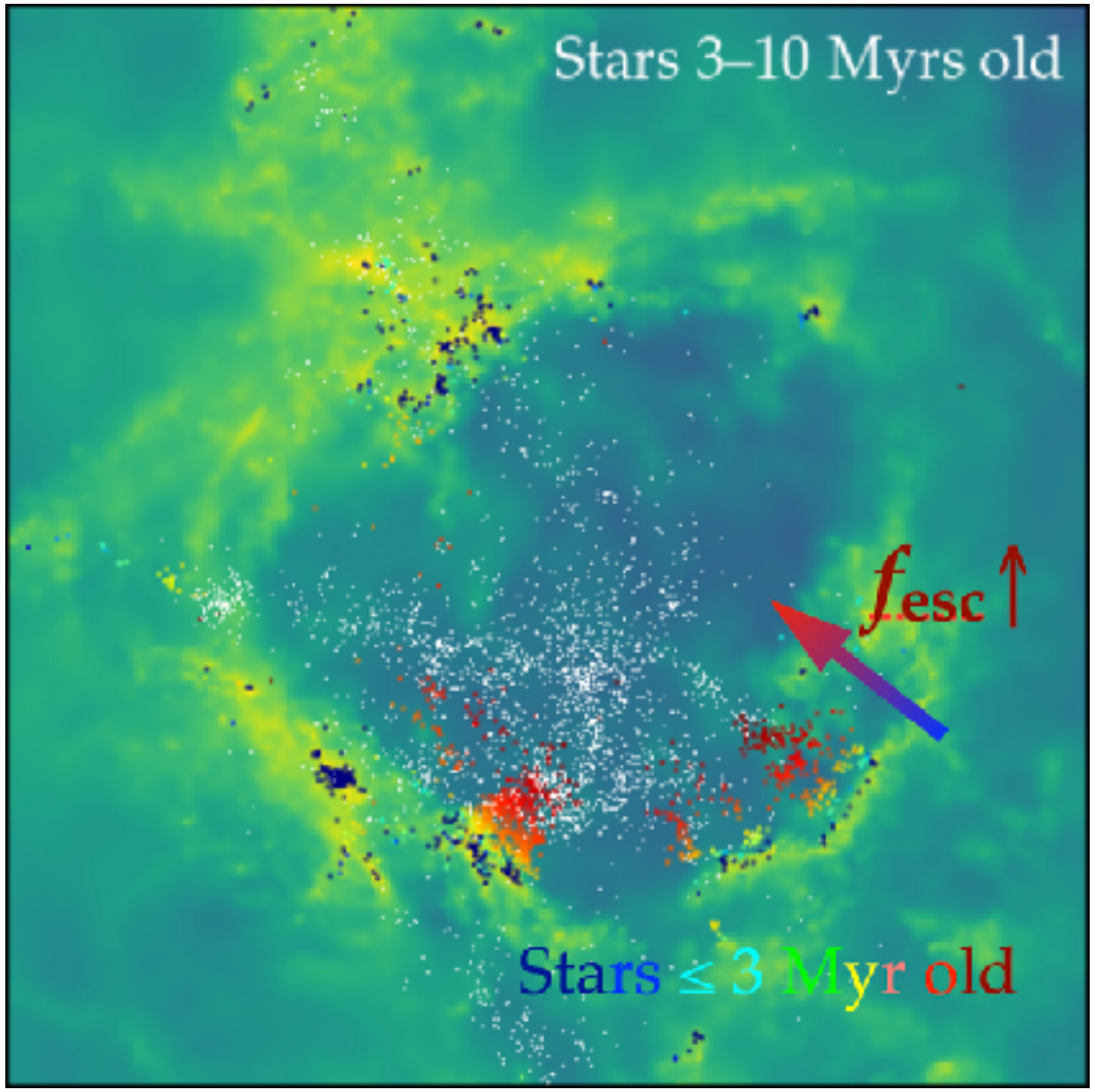
Typical in the early Universe?

Overlooked physics: triggered SF in supergiant shells

- The vast majority of current studies focus on SF in isolated GMCs
- Radiative shocks, dust & molecular chemistry in shell not well captured
  - Ultra-high-resolution simulations of ISM patches: proper set-up needed
  - Useful for understanding LyC & Lyα escape, emission line diagnostics



Rare in the local Universe



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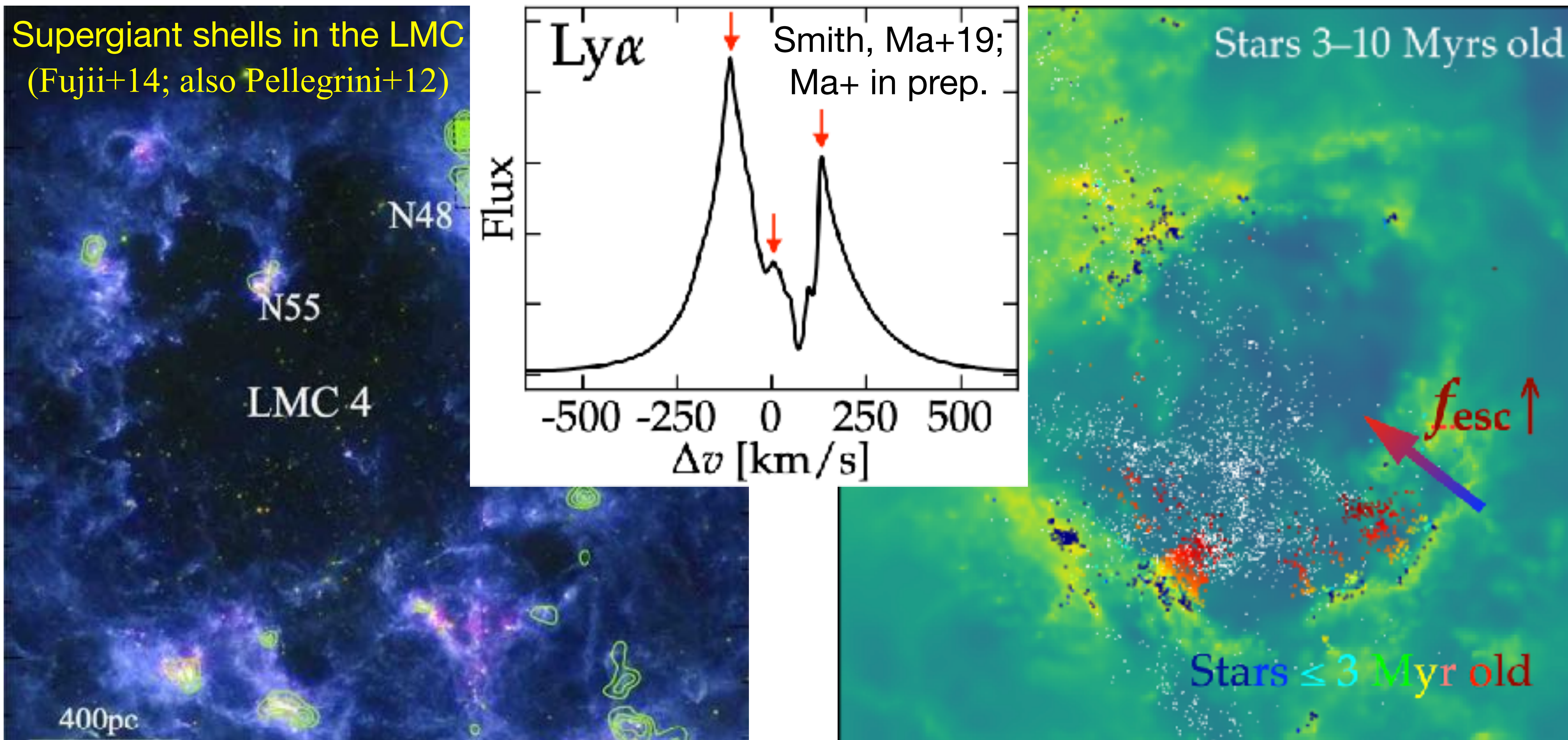

Rare in the local Universe

Typical in the early Universe?

Key progress for the next ~5 years

- Next-generation cosmological simulations
  - *FIRE-3: Adaptive SF, more accurate SN coupling, full radiation-hydrodynamics, magnetic fields, non-ideal MHD, cosmic rays, dust & molecules, …*
  - *FIRE box: Full FIRE explicitly resolved physics in a "large" volume*
- State-of-the-art tools for synthetic observations (JWST-ALMA era)
  - *Nebular emission lines* (Lya, [O III], He II, C III]): *Indicators of f_{esc} ◦ Probing reionization with LAEs ◦ Mysterious emission lines: shocks, geometry, or stellar populations? …*
  - *Cool/cold gas tracers* ([C II], CO): *Kinematic measurements ◦ Intensity mapping …*
- Idealized, controlled experiments of ISM, SF, and feedback
  - *Crucial physics to understand: Disk formation ◦ triggered SF in supergiant shells …*
  - *To calibrate SF & feedback models for even newer-generation cosmological simulations*
- Ultra-high-resolution simulations of galactic nuclei–SMBHs
  - *BH seeding and early growth: Nuclear star clusters ◦ first SMBHs ◦ BH populations …*
  - *Resolving BH fueling and feedback down to the BH self-consistently*
  - *To develop "sub-grid" BH models to implement in future cosmological simulations*

Summary

Bursty star formation is *typical* in dwarf and high-redshift galaxies

- In highly gas-rich, turbulent ISM: SN-driven bubble + SF in compressed shell
- Many astrophysical implications:

  Diverse kinematics & metallicity gradients ▫ Efficient GC formation ▫ High $f_{\rm esc}$ of Lyman-continuum and Lyman-alpha ▫ Suppressed SMBH growth

The bursty regime at early times is poorly understood

- Great opportunity to constrain galaxy formation physics in the next ~5-10 yrs
- Too much theoretical work needs to be done
- Number counts & correlation functions of star clusters ▫ Kinematics of high-z galaxies ▫ Disk formation physics ▫ ISM physics of triggered SF in super shell ▫ Modeling observables ▫ SMBH growth & feedback ▫ and many more…

Long-term goal: to converge on the ultimate galaxy formation models

- Working with leading extragalactic observers – to test theory directly with data
- Comparing outcomes between independent simulation groups