Exploring the extremes of galaxy formation using Blue Waters

Forrest Glines (Blue Waters graduate fellow @ MSU),
on behalf of Brian O'Shea (MSU; **PI**) and:

David Collins (FSU)
Lauren Corlies (U. Arizona/LSST)
Cameron Hummels (CalTech)
Michael Norman (UCSD)
Molly Peeples (STScI)
John Regan (Dublin)
Devin Silvia (MSU)
Britton Smith (U. Edinburgh)
Jason Tumlinson (STScI)
John Wise (Georgia Tech)
Hao Xu (IBM)

Blue Waters allocations:
PRAC OCI-0832662
PRAC ACI-1514589
GLCPC 2015
PRAC OAC-1810584

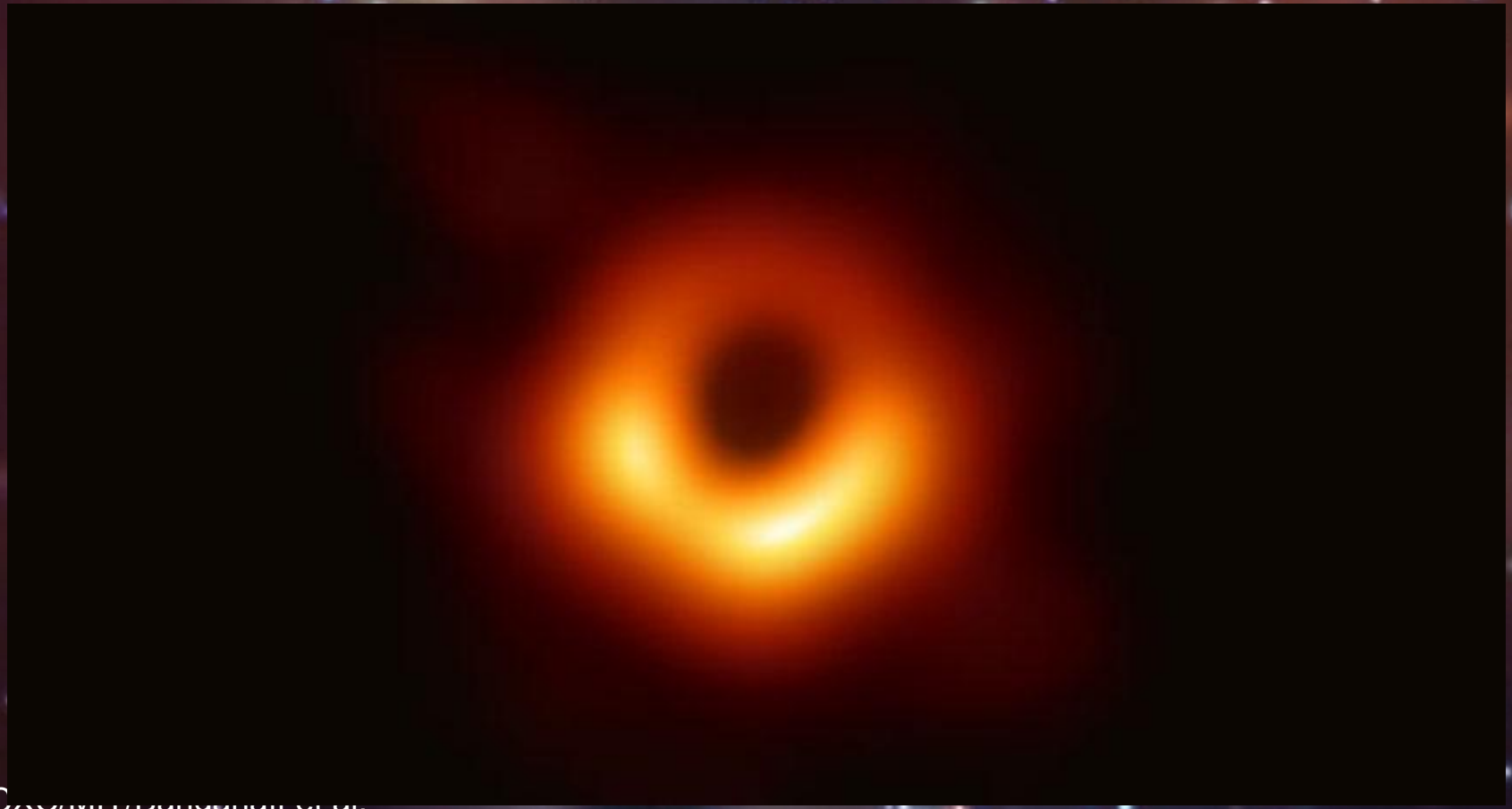
What has Blue Waters done for our research?

1. Provided a stable, capability-class computational platform for several years with large memory per core, a fast interconnect, and an excellent I/O subsystem.
2. Provided excellent, friendly, and highly capable technical staff throughout our time working with the project.
3. Provided strong support for students, including excellent training and opportunities to present their work to a national audience!

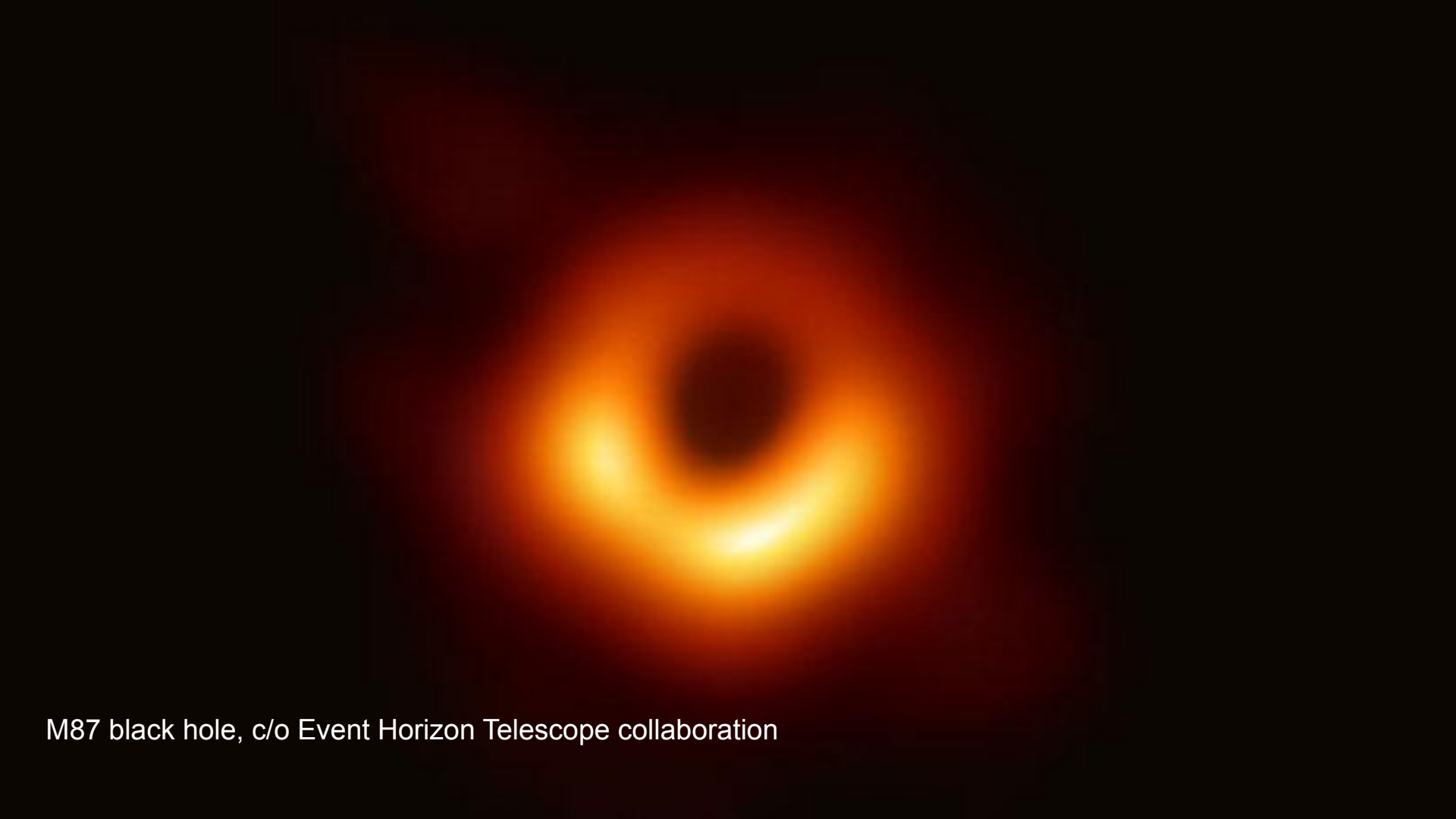
Two key results from our Blue Waters simulation campaigns

A new mechanism for forming supermassive black holes in the early universe

Wise et al. 2019, Nature, 566:85-88



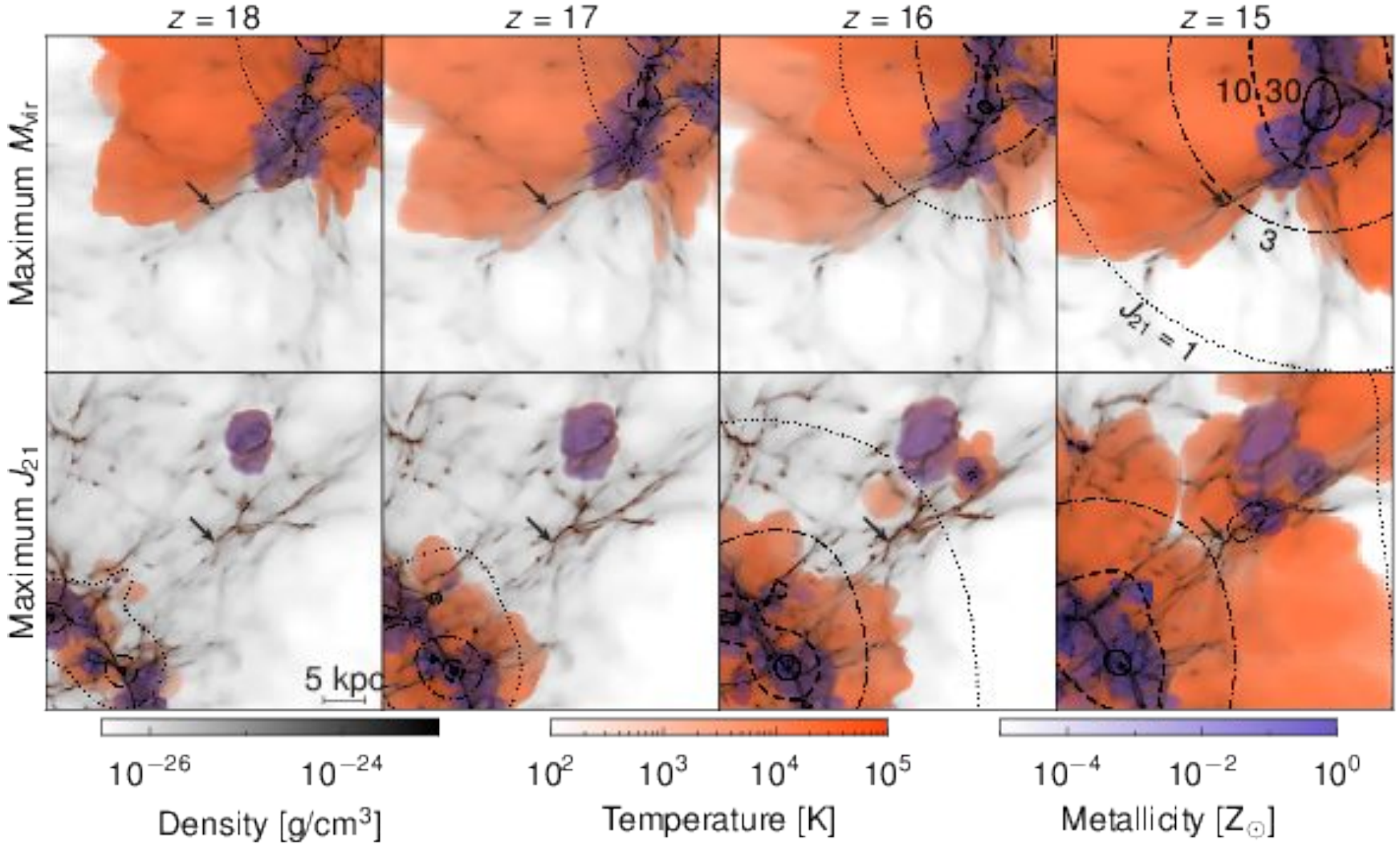
NASA/CXC/MIT/Bañgañan et al.

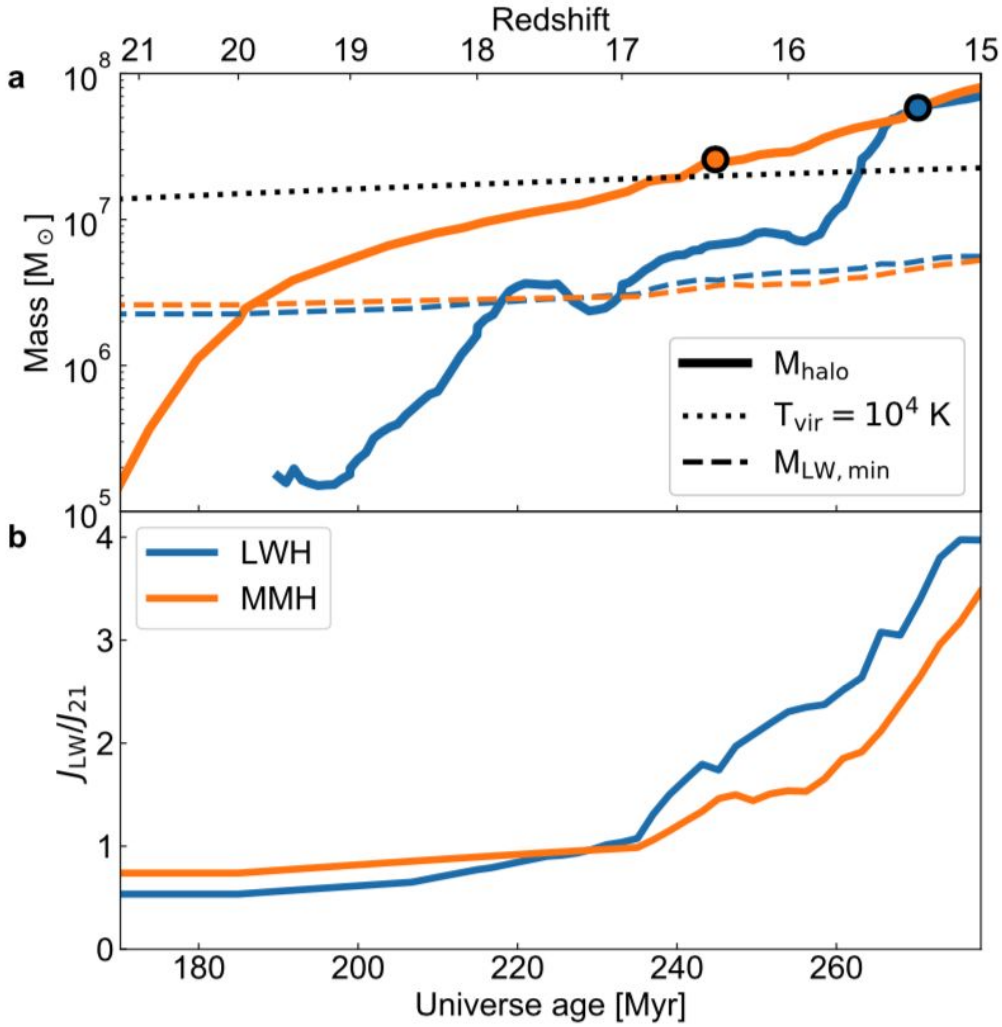


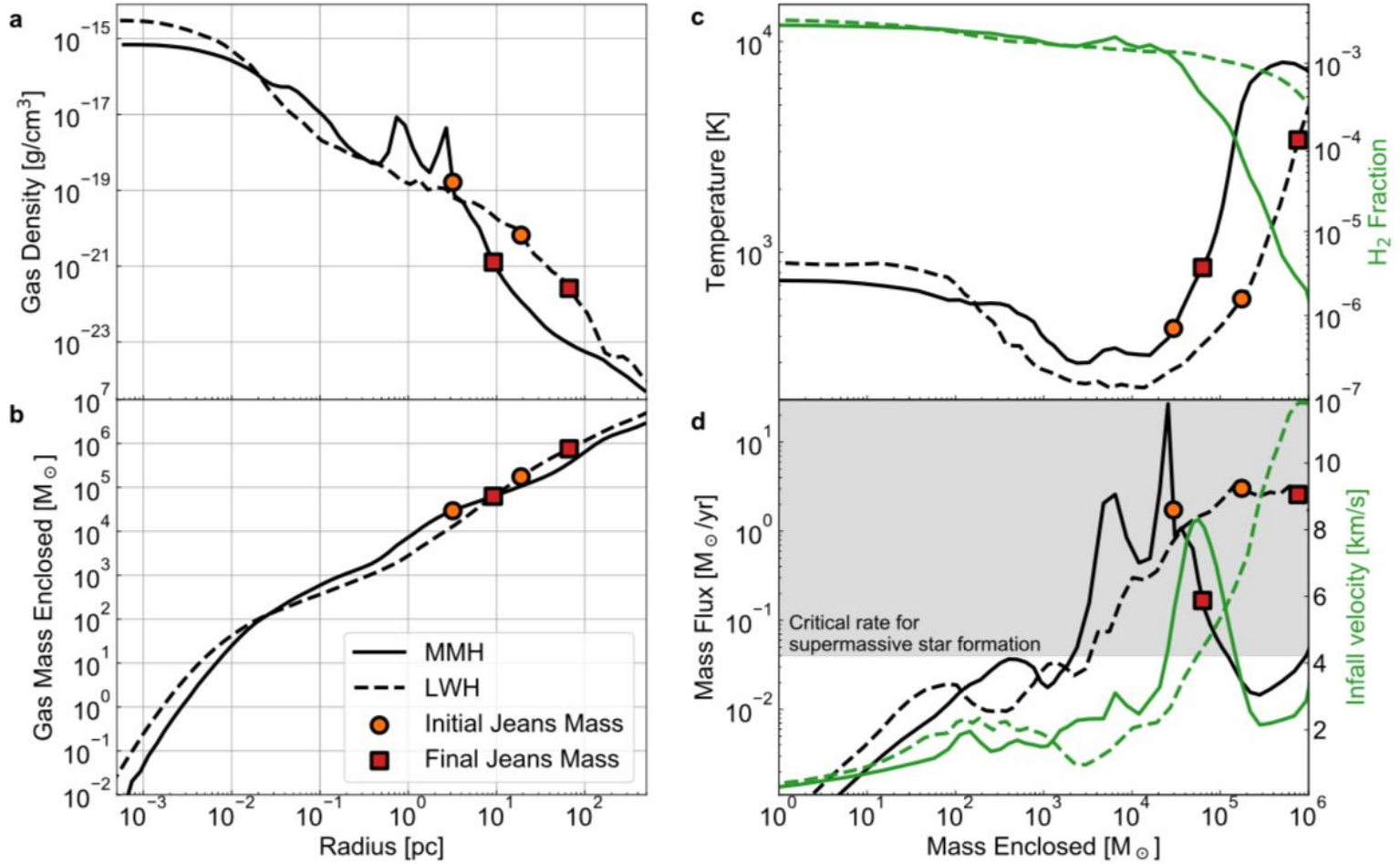
M87 black hole, c/o Event Horizon Telescope collaboration

The Renaissance Simulations (O’Shea et al. 2015)

Movie c/o Donna Cox, Bob Patterson, NCSA Advanced Visualization Laboratory

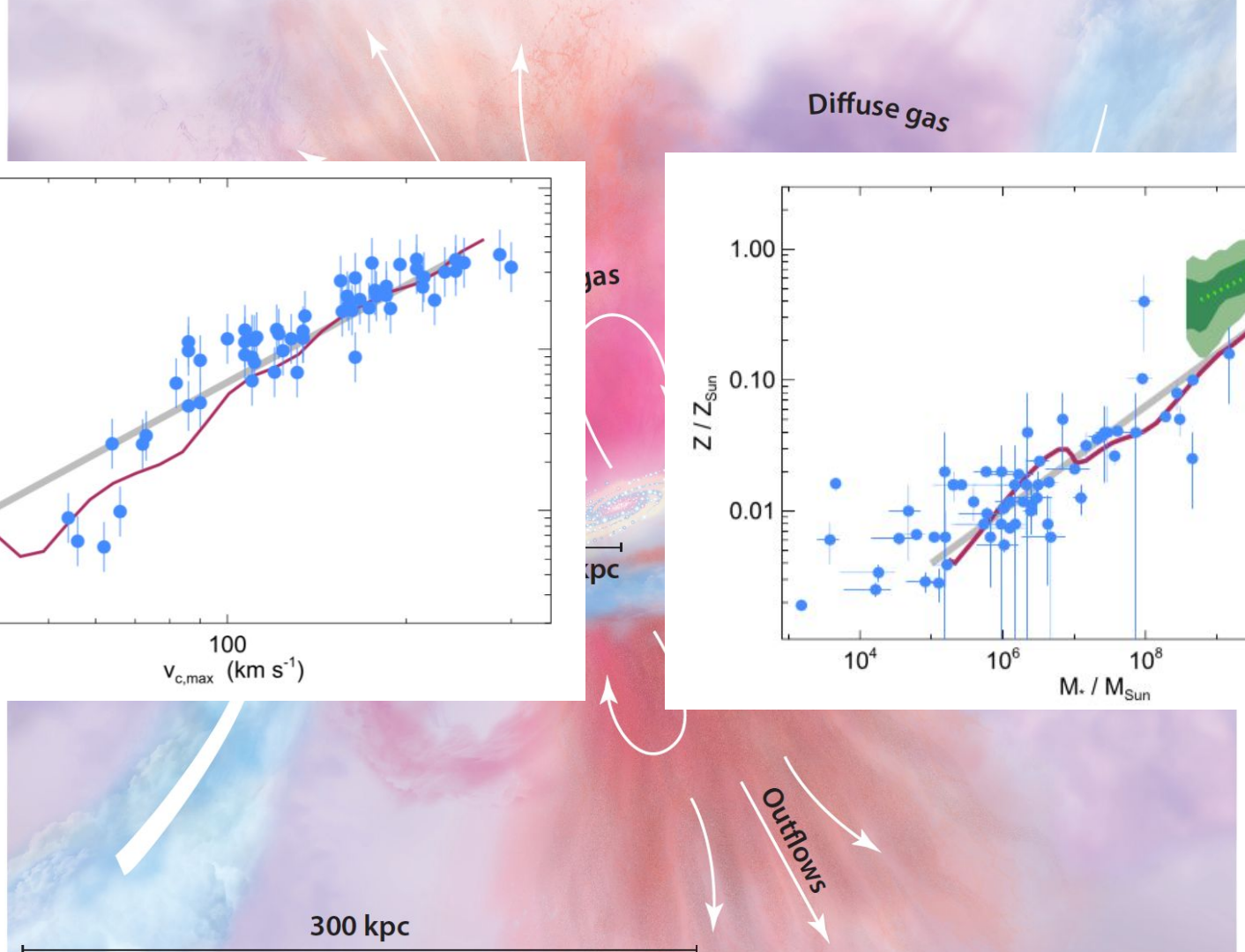

z = 18
z = 17
z = 16
z = 15
Maximum $M_{\rm vir}$
Maximum J_{21}
$10^{3.0}$
3
$J_{21} = 1$
5 kpc
10^{-26}
10^{-24}
Density [g/cm^3]
10^2
10^3
10^4
10^5
Temperature [K]
10^{-4}
10^{-2}
10^0
Metallicity [$Z_\odot$]


Redshift
21
20
19
18
17
16
15
a
10^8
10^7
10^6
10^5
Mass [$M_\odot$]
M_{halo}
$T_{vir} = 10^4$ K
$M_{LW,\,min}$
b
4
3
2
1
0
LWH
MMH
J_{LW}/J_{21}
180
200
220
240
260
Universe age [Myr]

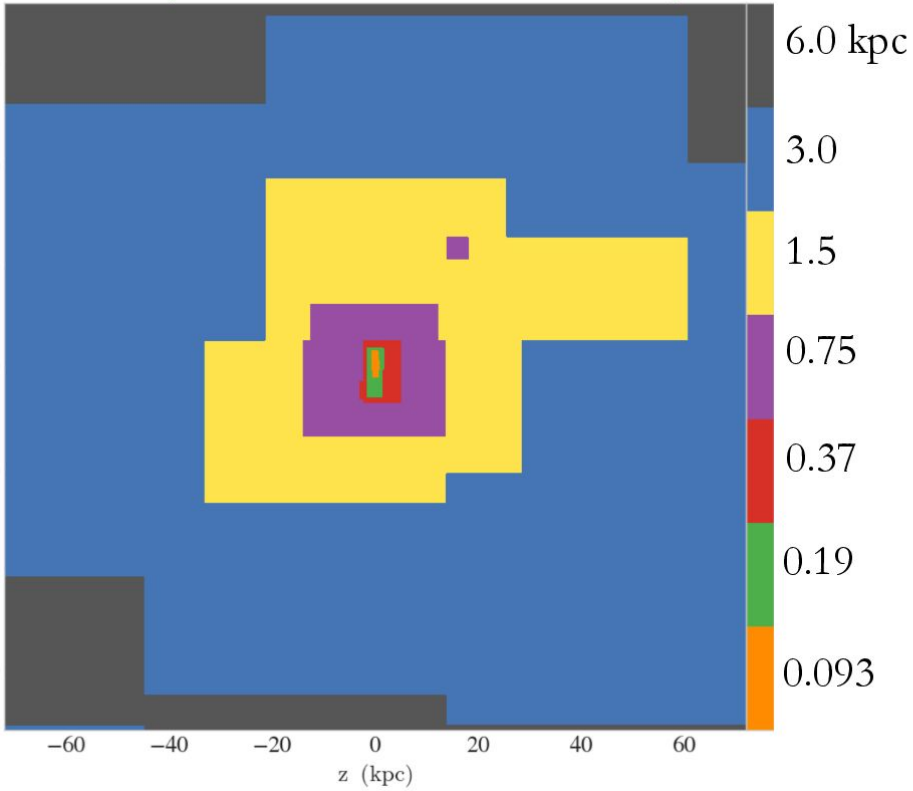

a
b
c
d
Gas Density [g/cm^3]
Gas Mass Enclosed [M$_\odot$]
Radius [pc]
MMH
LWH
Initial Jeans Mass
Final Jeans Mass
Temperature [K]
H$_2$ Fraction
Mass Flux [M$_\odot$/yr]
Infall velocity [km/s]
Critical rate for
supermassive star formation
Mass Enclosed [M$_\odot$]

The high-resolution circumgalactic medium

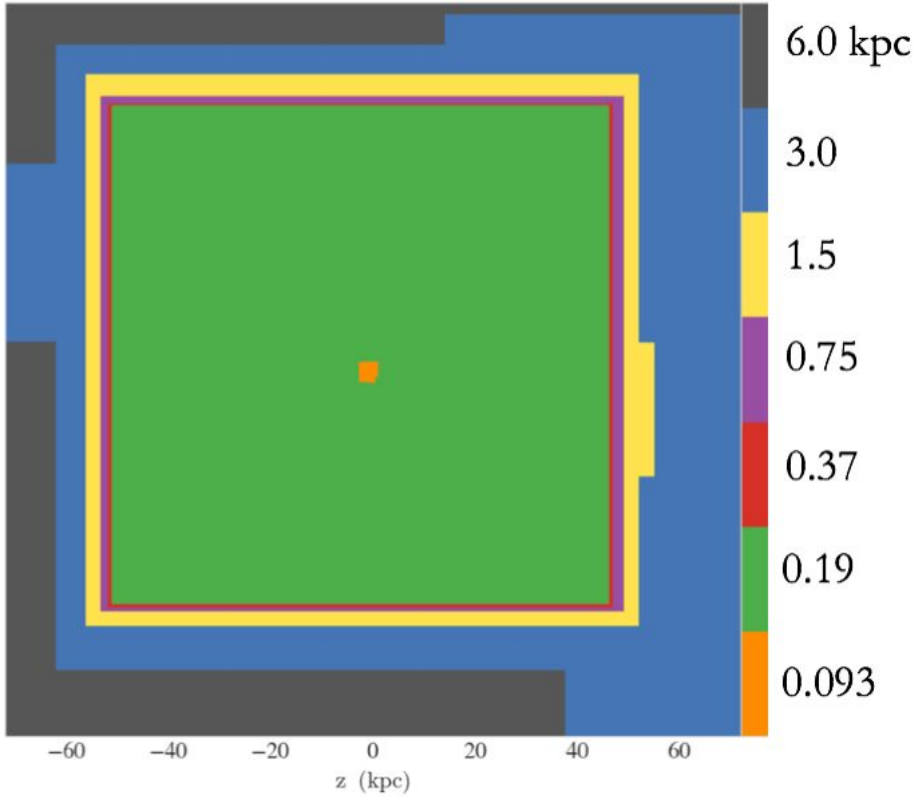
Peeples et al. 2019 (ApJ, 873, 129; arXiv:1810.06566)
Corlies et al. 2019 (ApJ, submitted; arXiv:1811.05060)
Hummels et al. 2019 (ApJ, submitted; 1811.12410)


Diffuse gas
gas
pc
Outflows
300 kpc
1.00
0.10
0.01
f* = M* / fb M500
100
vc,max (km s-1)
1.00
0.10
0.01
Z / ZSun
10^4
10^6
10^8
10^10
M* / MSun

Spatial size of "cells" (resolution elements):

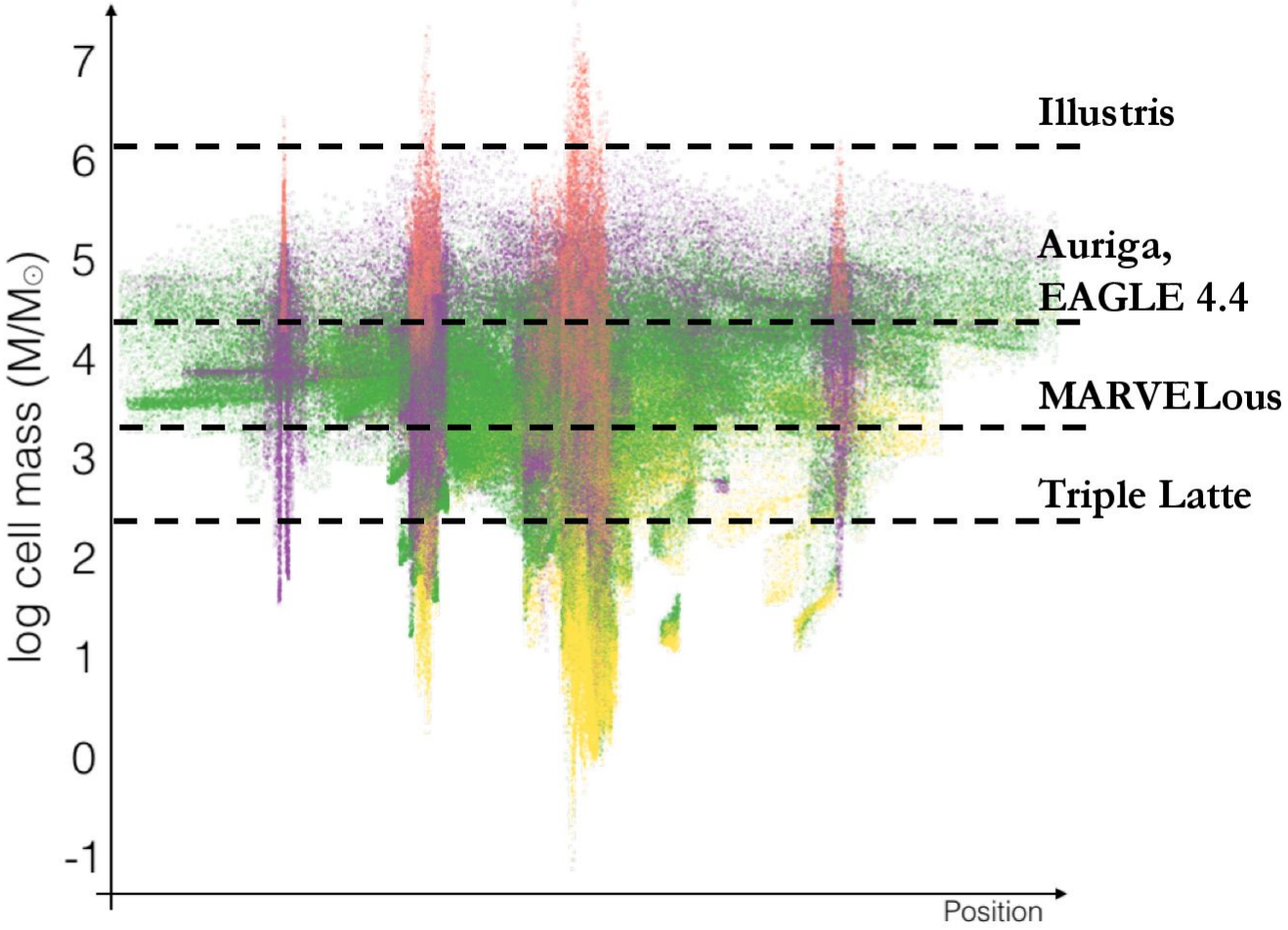


Slice of gas metallicity:



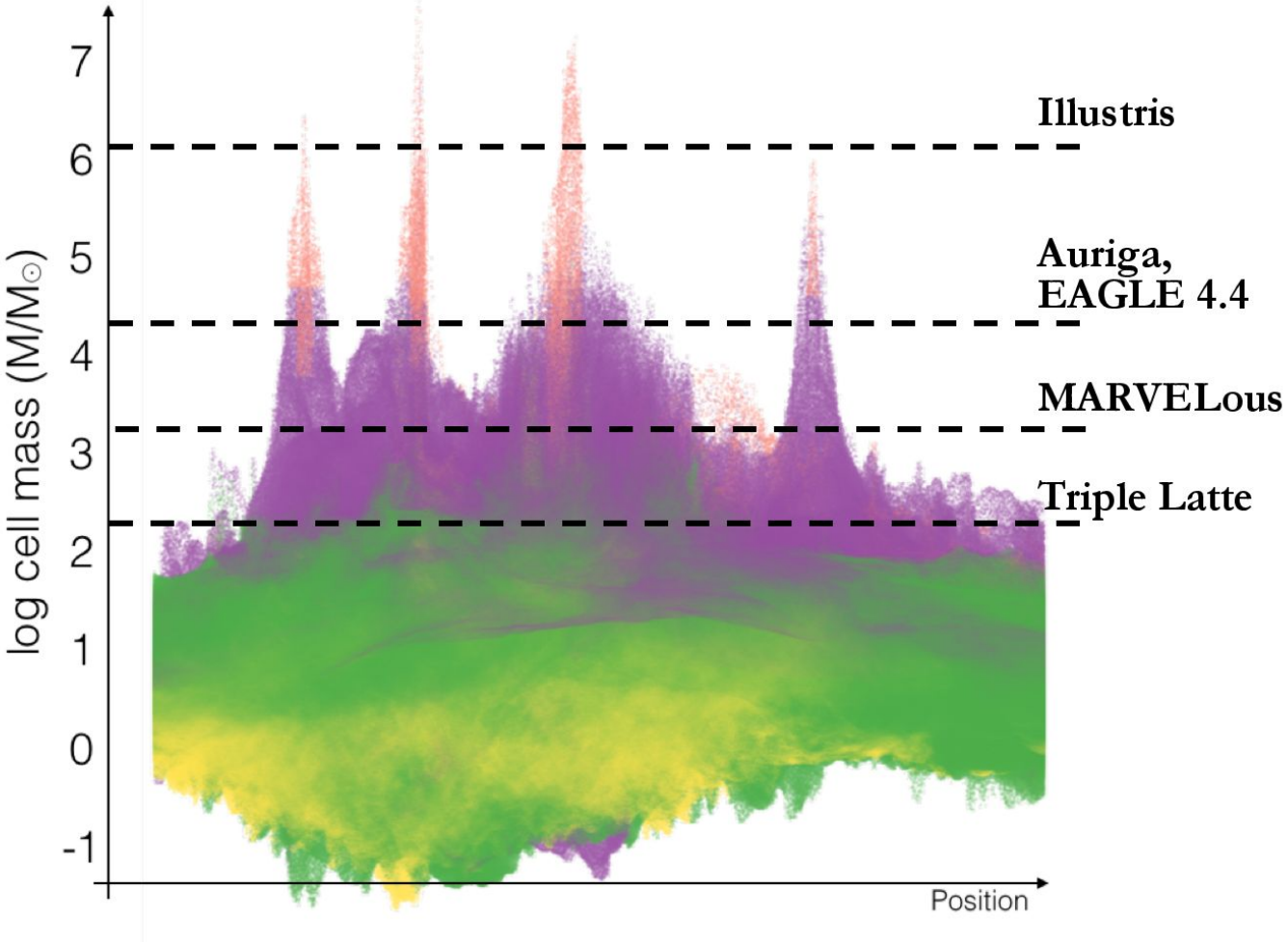
Standard simulation

Cold, $T < 10^4$
Cool, $10^4 < T < 10^5$
Warm, $10^5 < T < 10^6$
Hot, $T > 10^6$



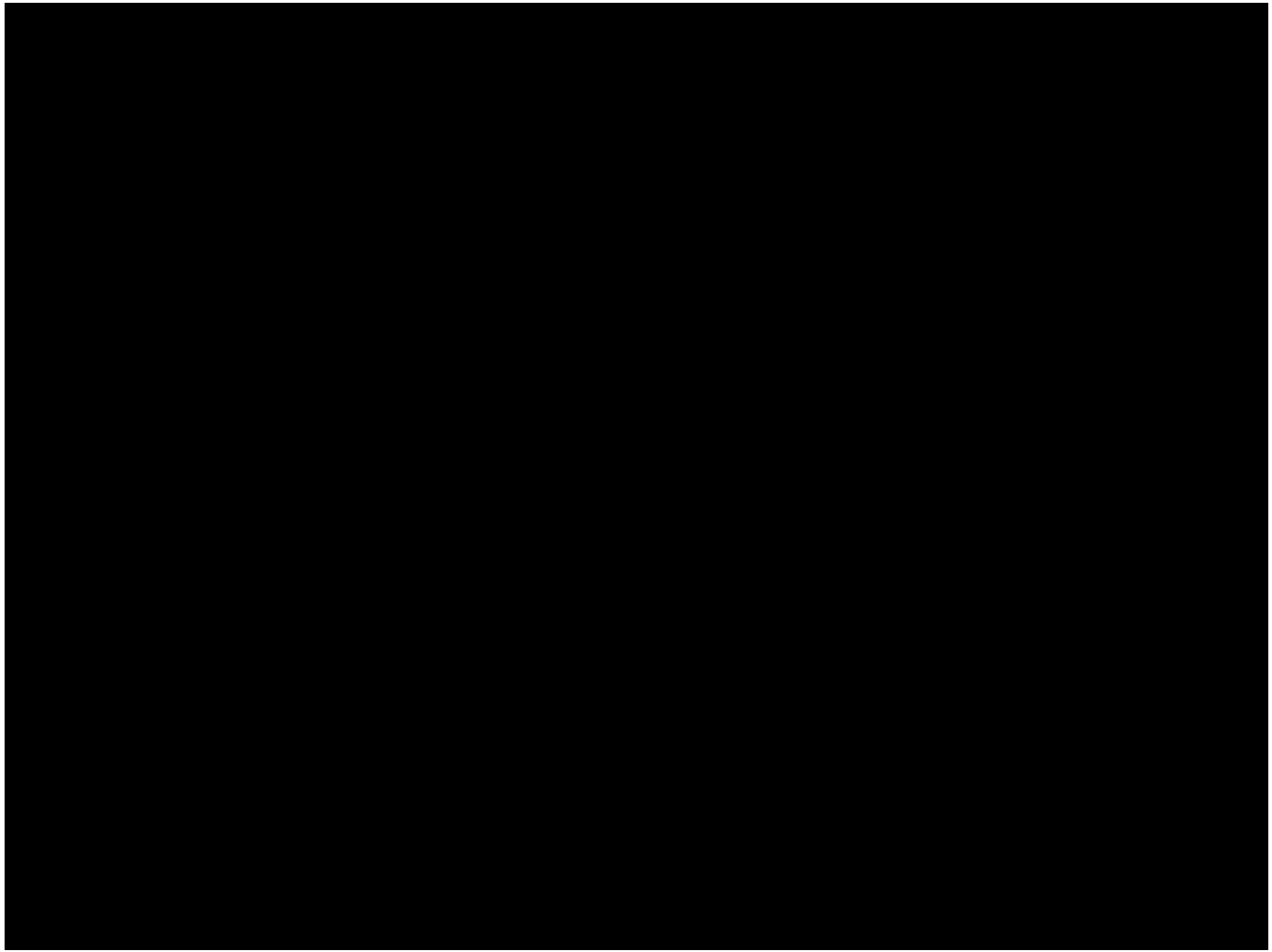
Forced refinement simulation

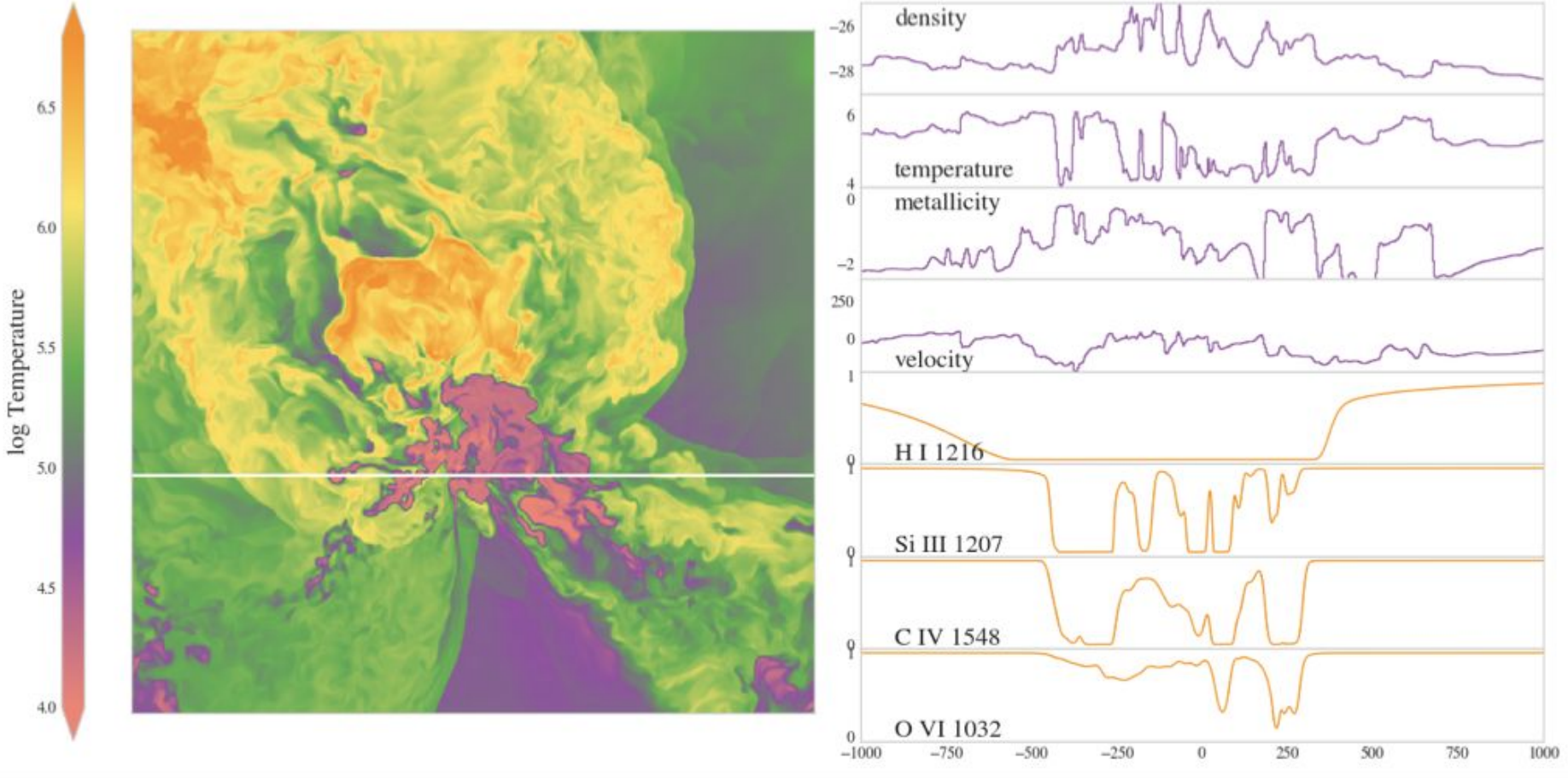
Cold, $T < 10^4$
Cool, $10^4 < T < 10^5$
Warm, $10^5 < T < 10^6$
Hot, $T > 10^6$



Enhanced CGM resolution

Standard CGM resolution

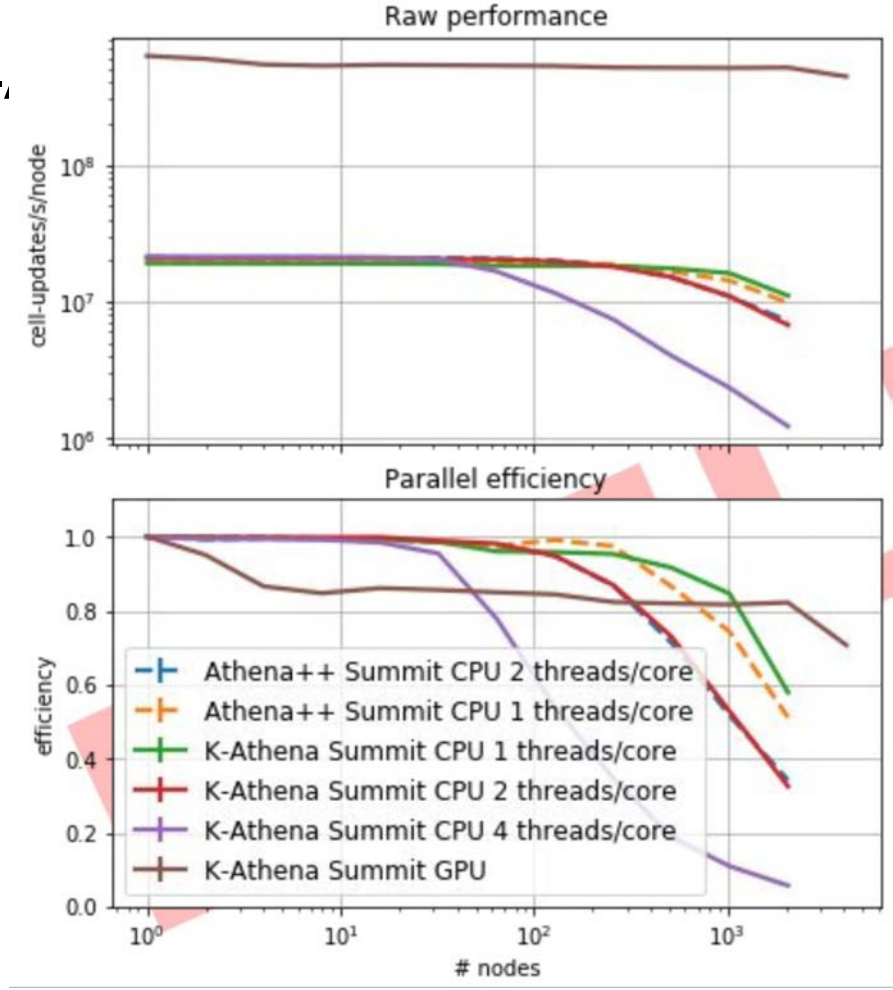


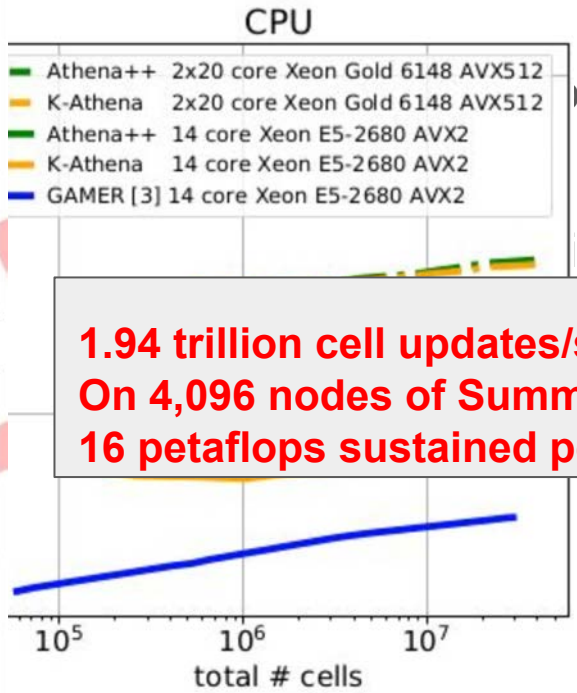

log Temperature
6.5
6.0
5.5
5.0
4.5
4.0
density
−26
−28
temperature
6
4
metallicity
0
−2
velocity
250
0
H I 1216
1
0
Si III 1207
1
0
C IV 1548
1
0
O VI 1032
1
0
−1000
−750
−500
−250
0
250
500
750
1000

Preparing for exascale architectures

K-A…plementation of Athena++

- …rmance
- …gh level of
-



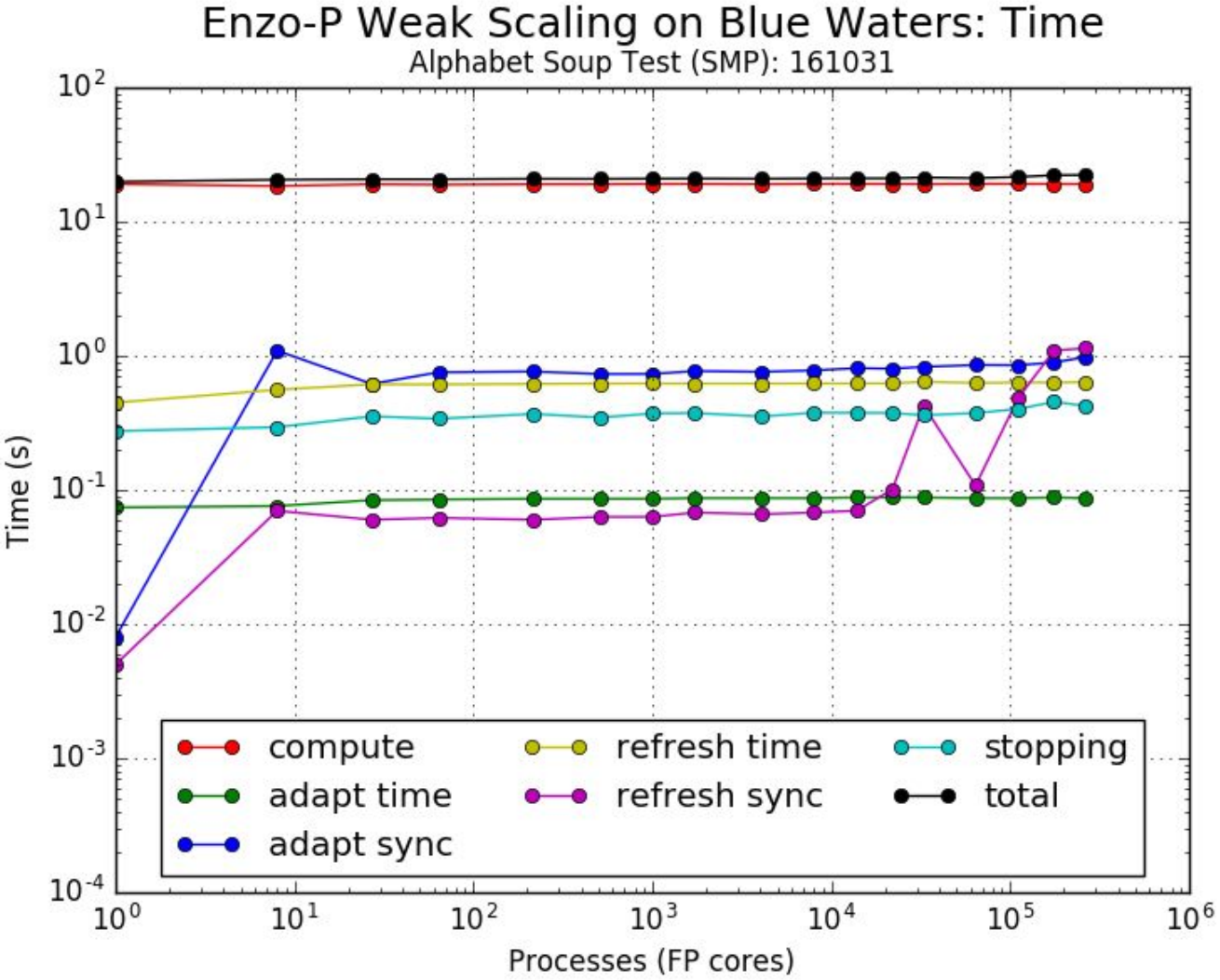


1.94 trillion cell updates/s
On 4,096 nodes of Summit:
16 petaflops sustained performance!

1905.04341; code publicly available)

Enzo

- Us
  rec
- “Fo
- Sc
  sol
- De
  -
  -
  -
  -



Summary

- Blue Waters has provided a powerful platform for exploring some of the most extreme physical phenomena in the universe.
- We have discovered a new mechanism for forming supermassive black holes, in primordial galaxies that grow quickly in radiation-rich environments.
- We have discovered that highly resolving the circumgalactic medium is critical to forming observationally-plausible structures and interpreting observations.
- Our experiences on Blue Waters have given us crucial insights to preparing for exascale supercomputers.