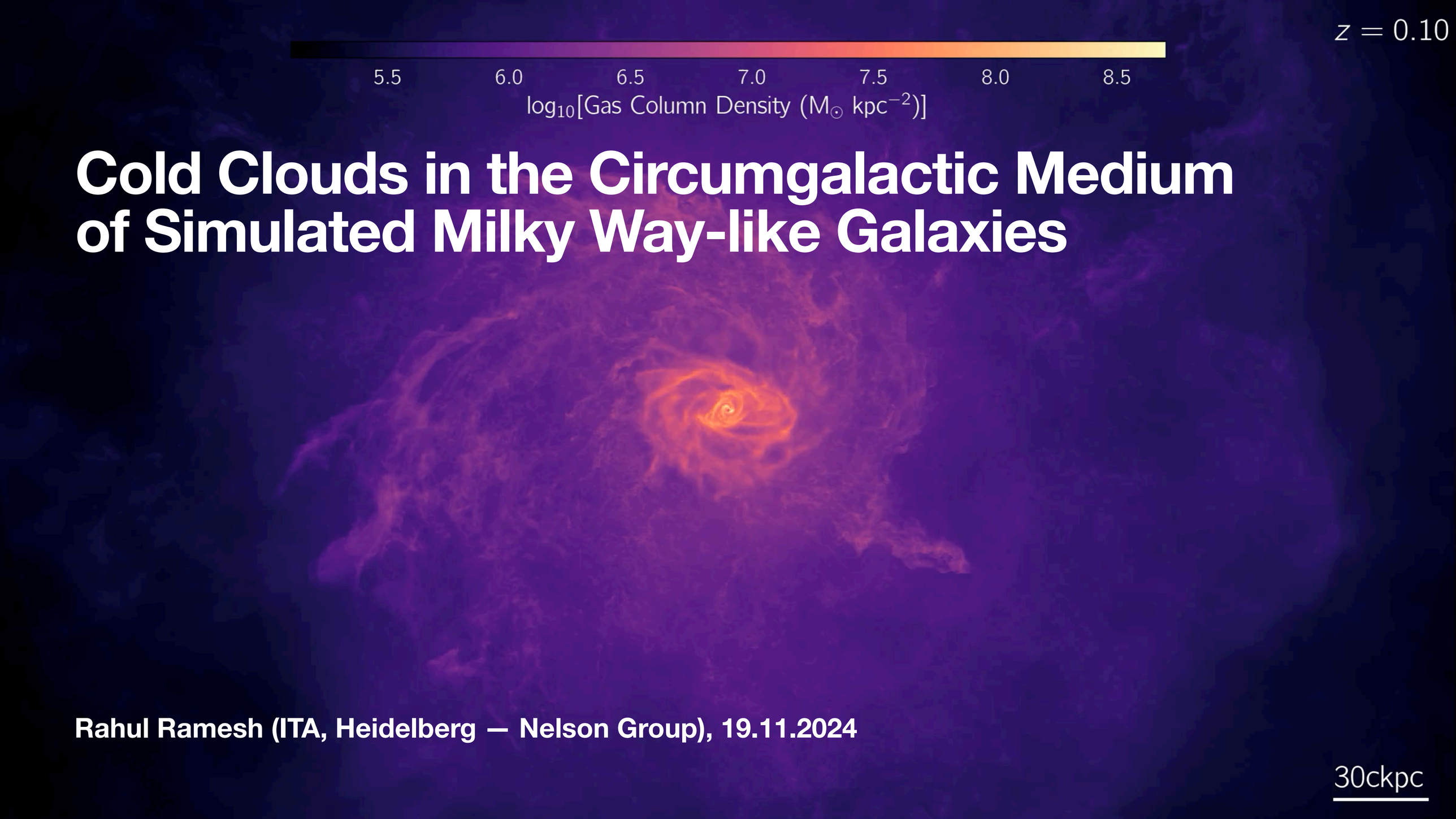
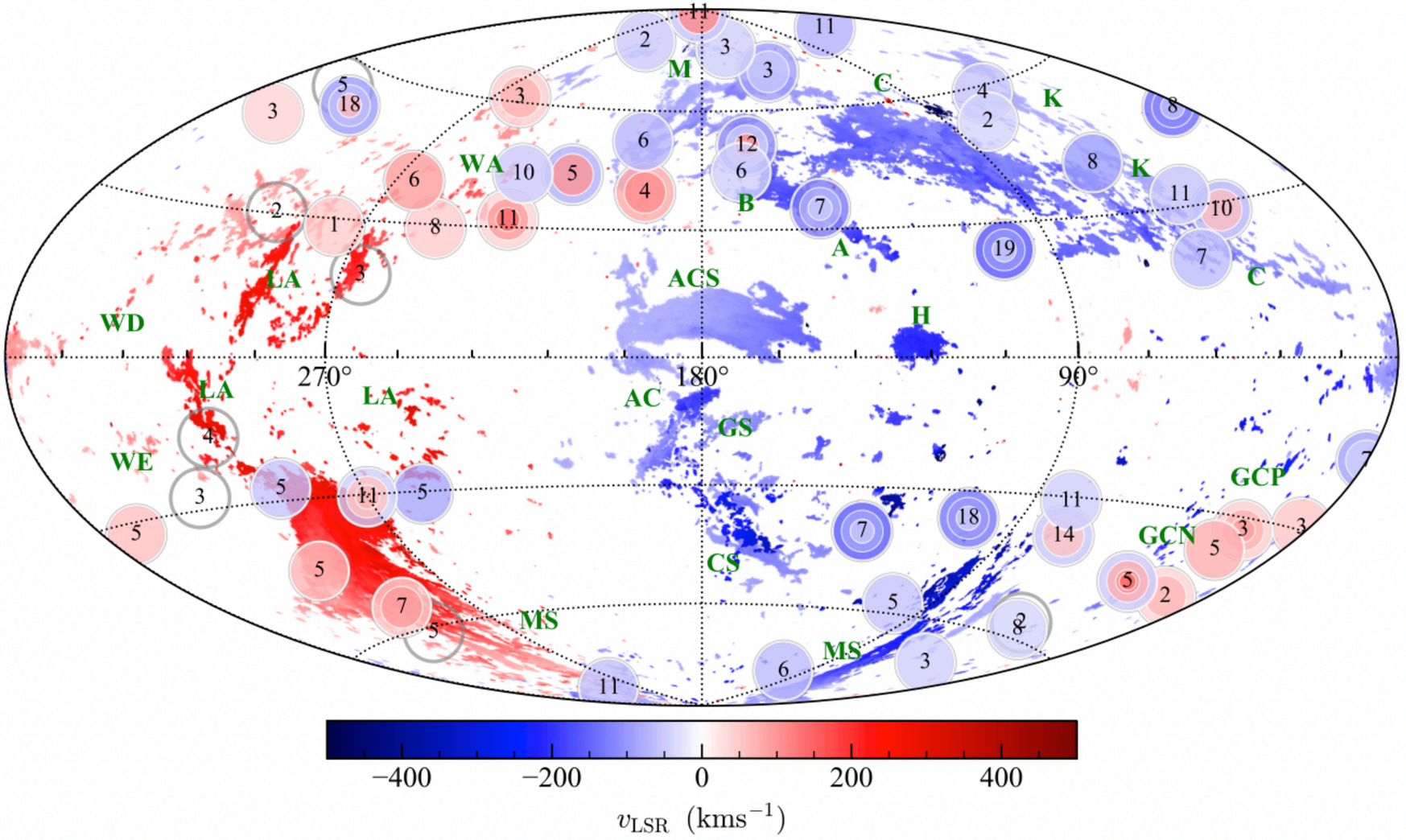


Cold Clouds in the Circumgalactic Medium of Simulated Milky Way-like Galaxies

Rahul Ramesh (ITA, Heidelberg — Nelson Group), 19.11.2024

(High Velocity) Cold, Dense Clouds



Lehner+(2022)

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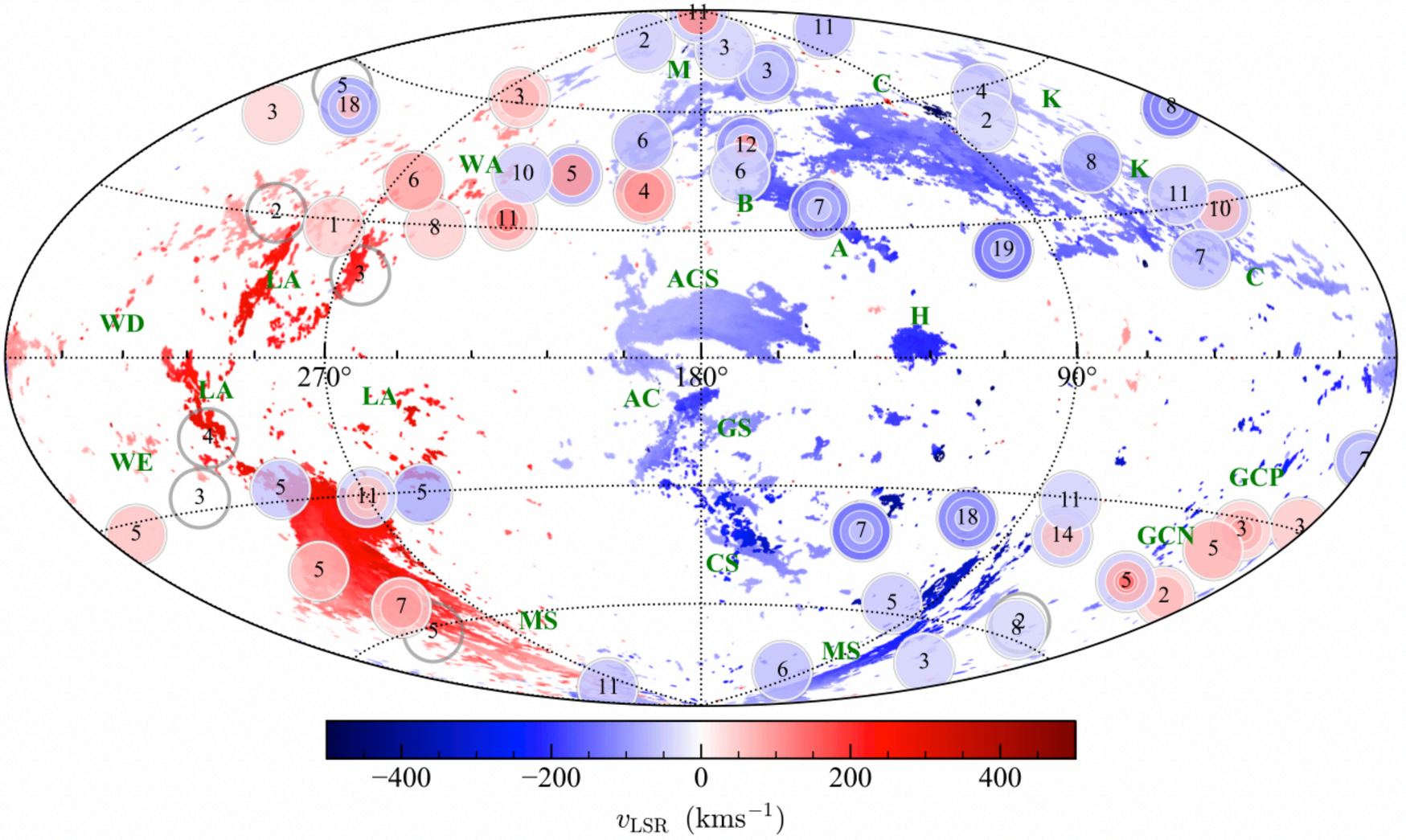


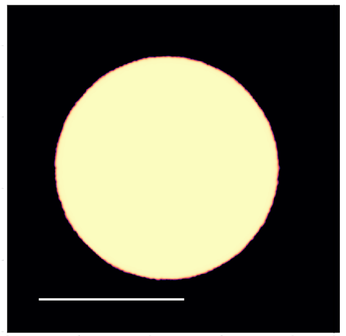
Lehner+(2022)

- **Composition**:
  Metal-rich/poor?
- **Formation**:
  Condensation out of hot halo?
  Stripped from satellites?
  Cold gas ejected from galaxies?
- **Lifetimes**:
  Short/Long-lived clouds?

Simulated Cold, Dense Gas Clouds

Idealised “Wind Tunnel” Simulations

- Lifetimes of clouds
- Interaction with ambient medium
- Impact of magnetic fields



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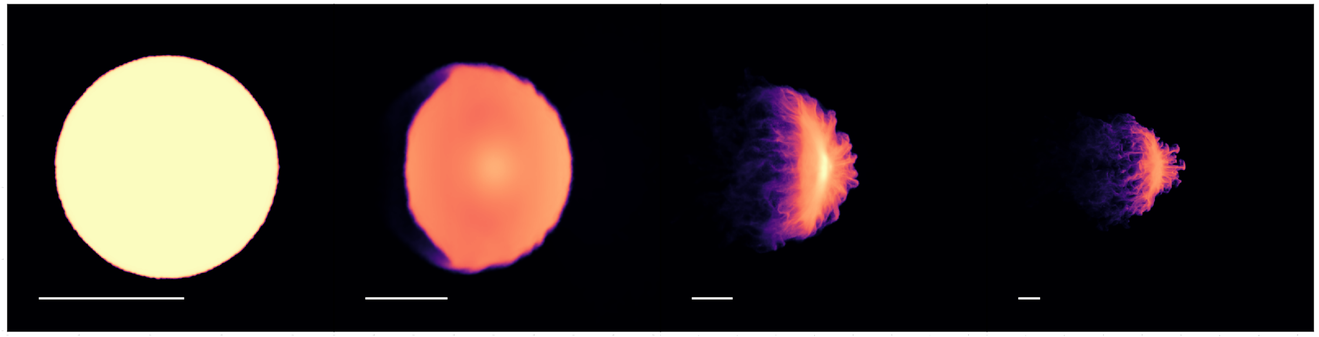

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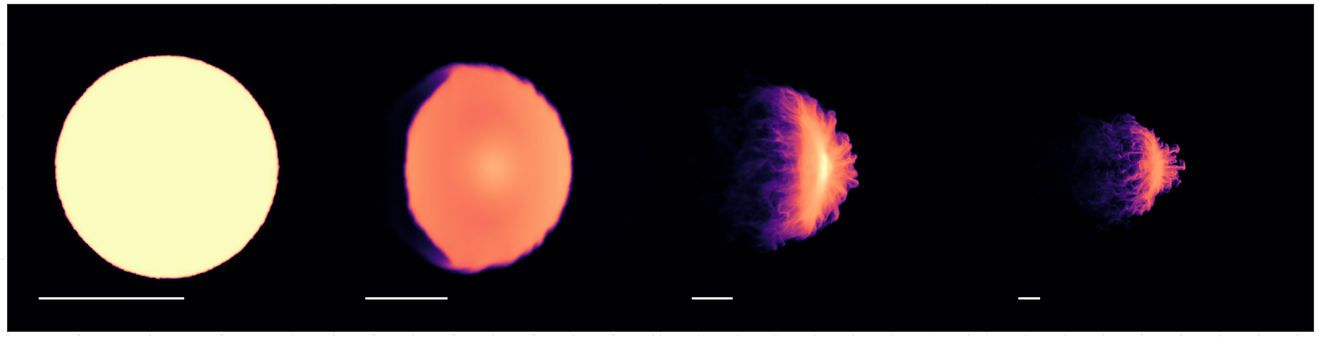
- Cannot answer questions that are input parameters: cloud metallicity, temperature, mass, size…
- Lack the complexity of a realistic CGM



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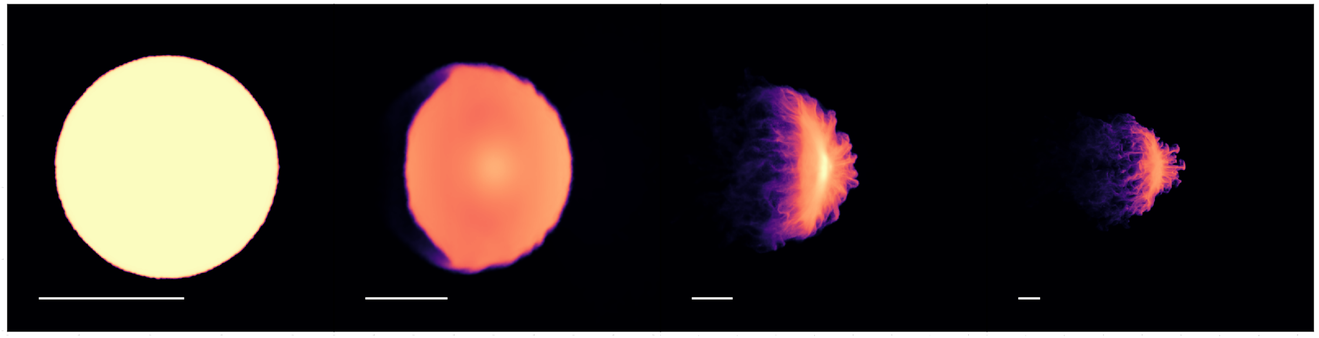
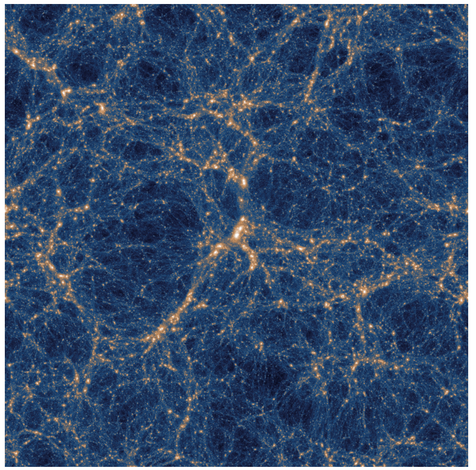


Cosmological Simulations

- Captures the evolution of halo gas over cosmic epochs and scales
- Can thus naturally account for the complexity of the CGM



Nelson+ (2018)

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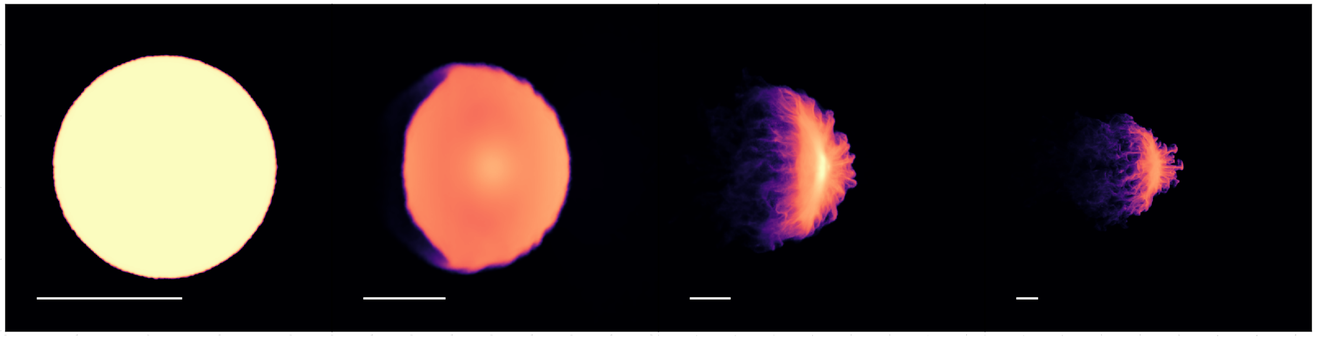

Cosmological Simulations

- Captures the evolution of halo gas over cosmic epochs and scales
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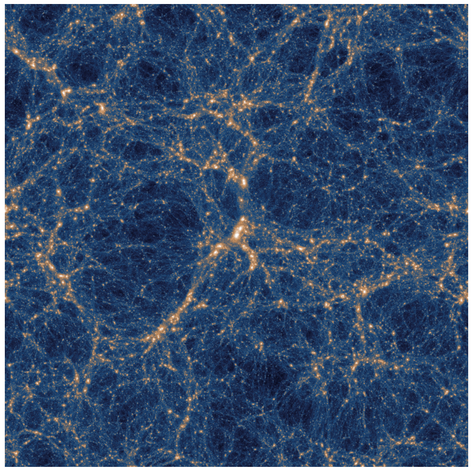
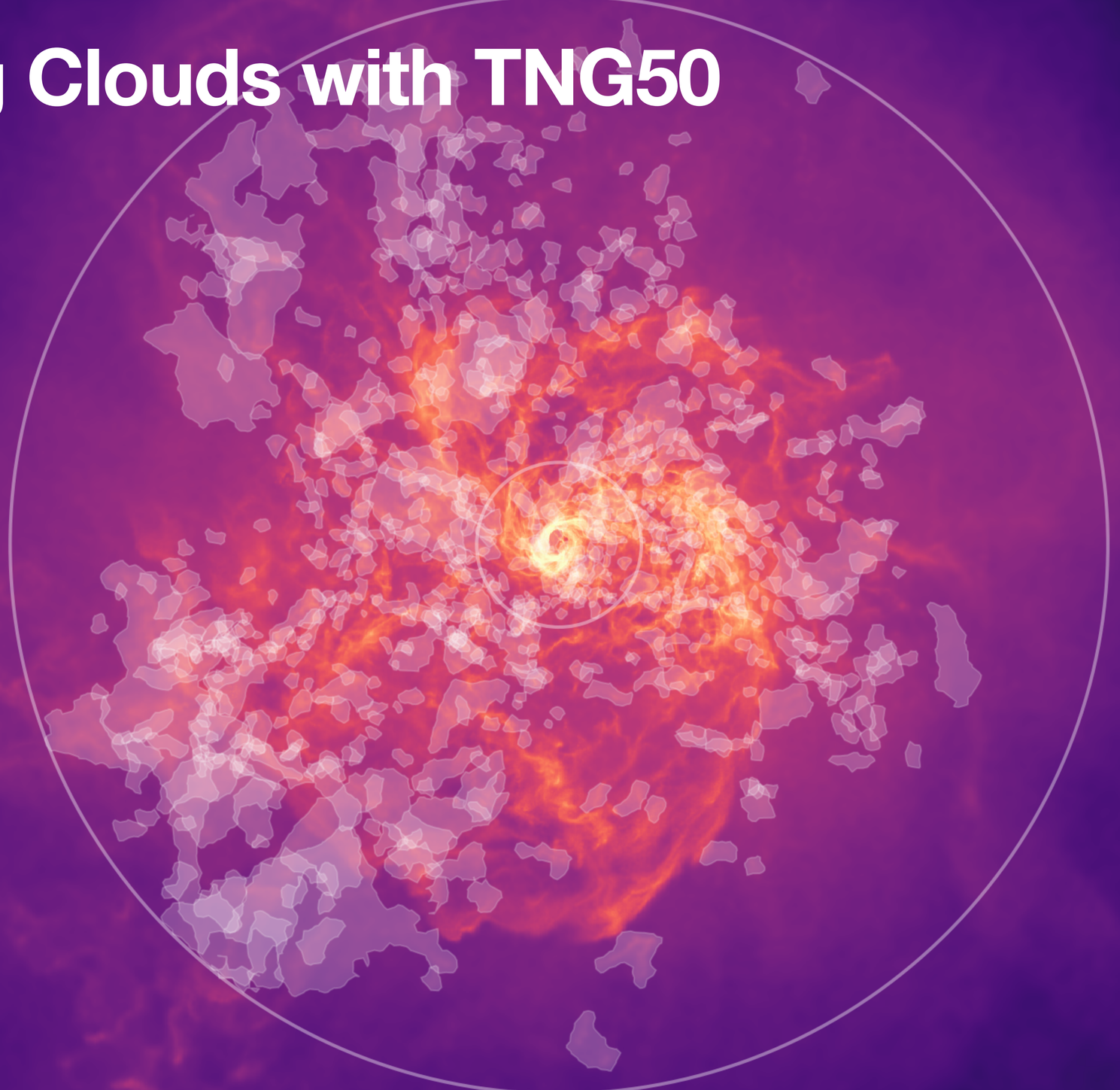
- While large-scale features are well resolved, sub-kpc objects are typically not.

Volume $\times = O(10^{12})$



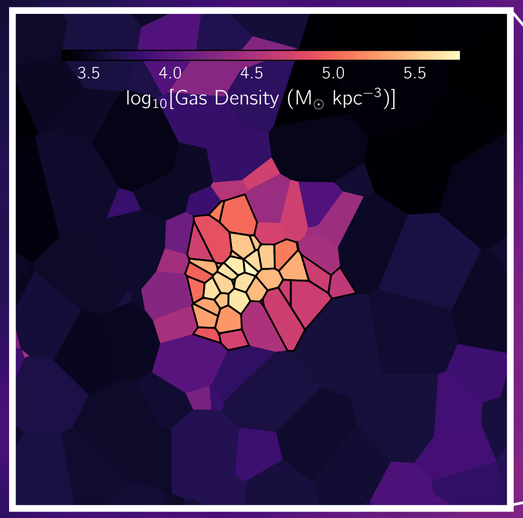
Nelson+ (2018)

Studying Clouds with TNG50



Ramesh+(2023b)

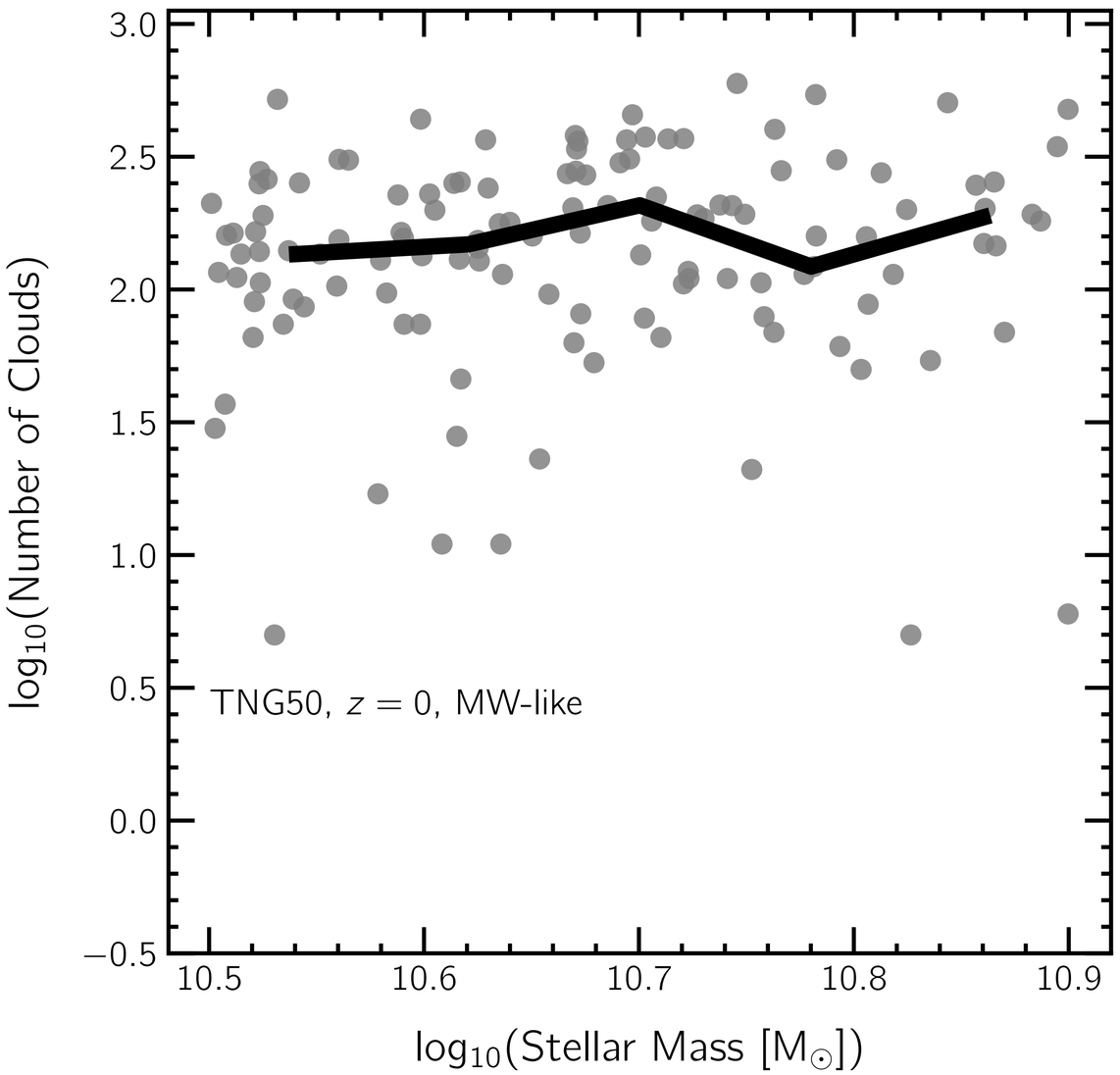
Studying Clouds with TNG50



Contingous set of cold ($T \lesssim 10^{4.5}$ K) gas cells.

Ramesh+(2023b)

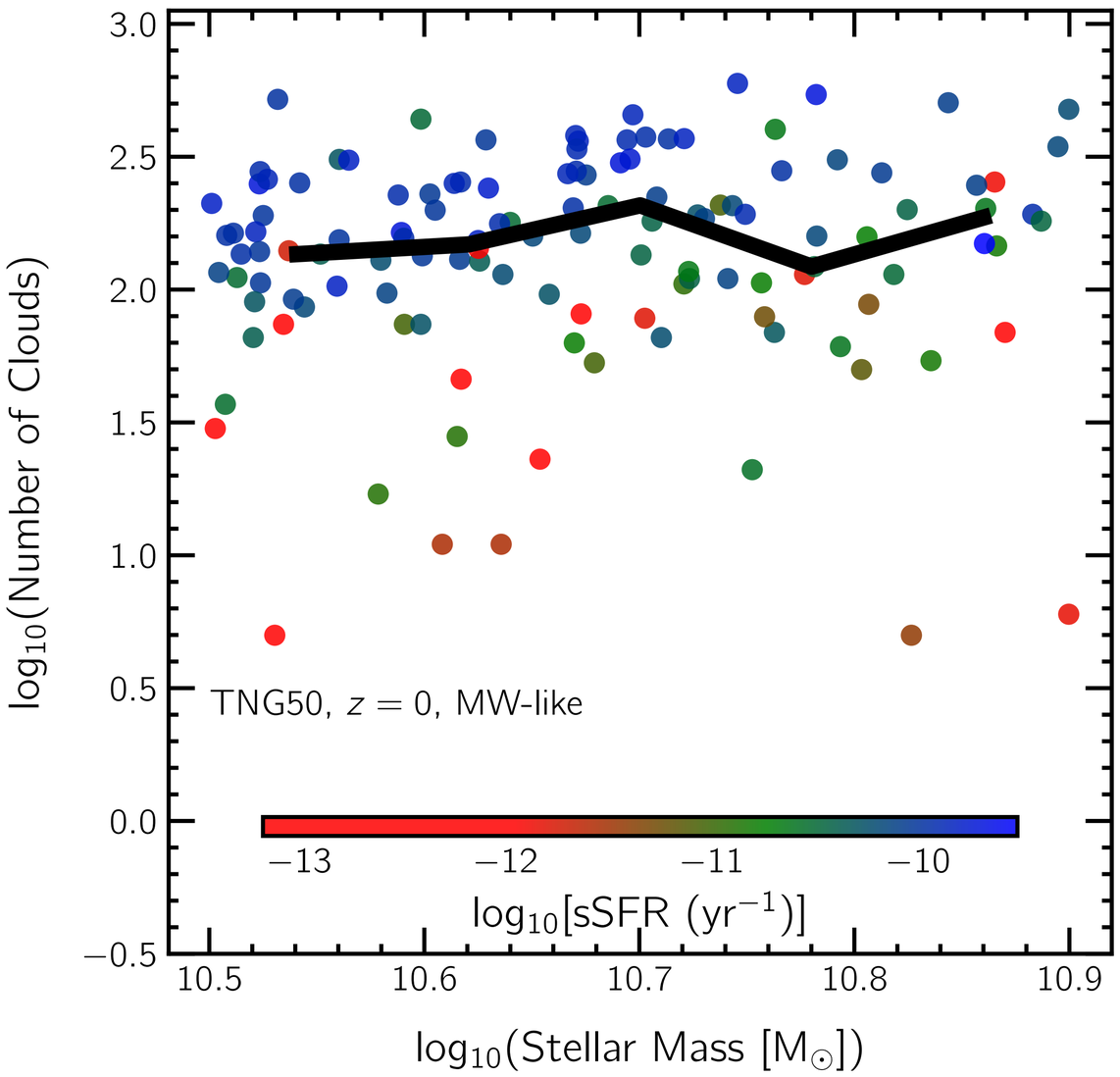
Studying Clouds with TNG50



Ramesh+(2023b)

On average, TNG50 MW-like galaxies have 100s of discrete cold, dense clouds (>= 10 cells) in their CGM.

Studying Clouds with TNG50



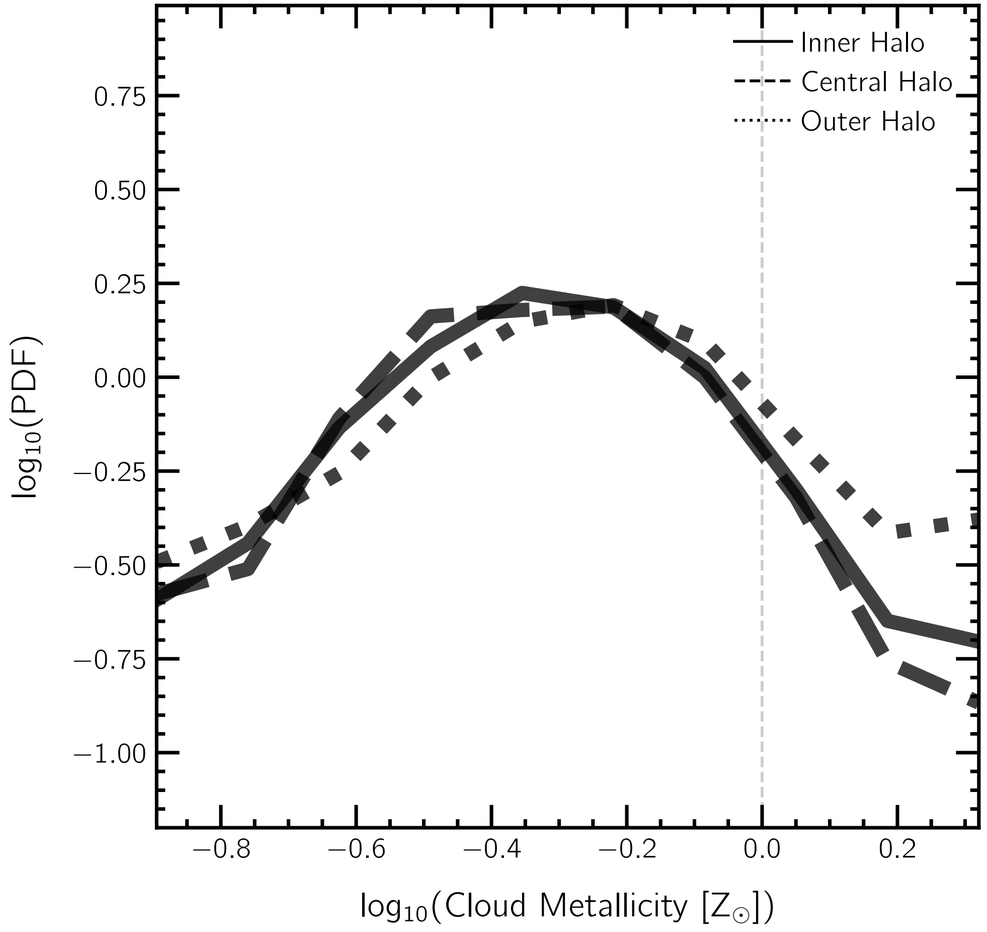
Ramesh+(2023b)

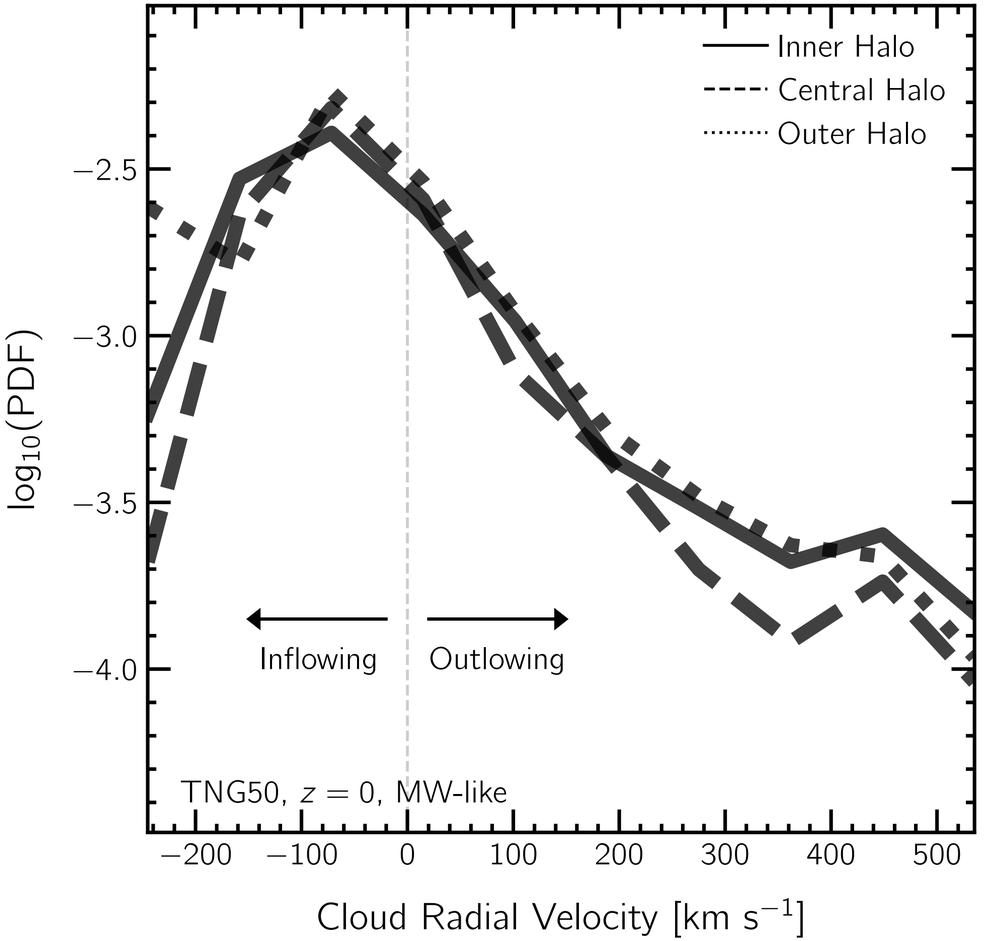
On average, TNG50 MW-like galaxies have 100s of discrete cold, dense clouds (>= 10 cells) in their CGM.

While the number of clouds correlates weakly with stellar mass, the connection with the star formation status of the central galaxy is strong.

Studying Clouds with TNG50

Properties of clouds are diverse.





Ramesh+(2023b)

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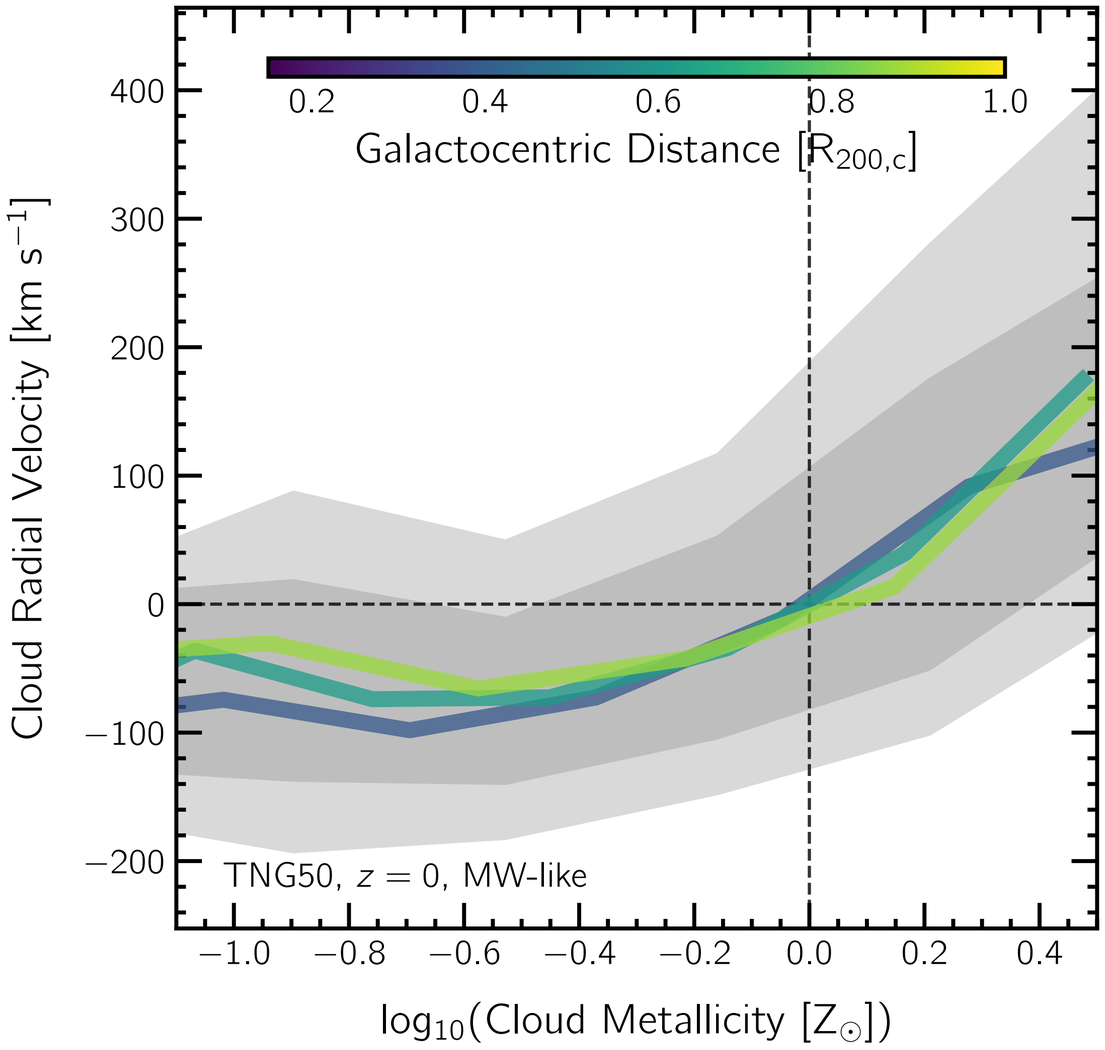
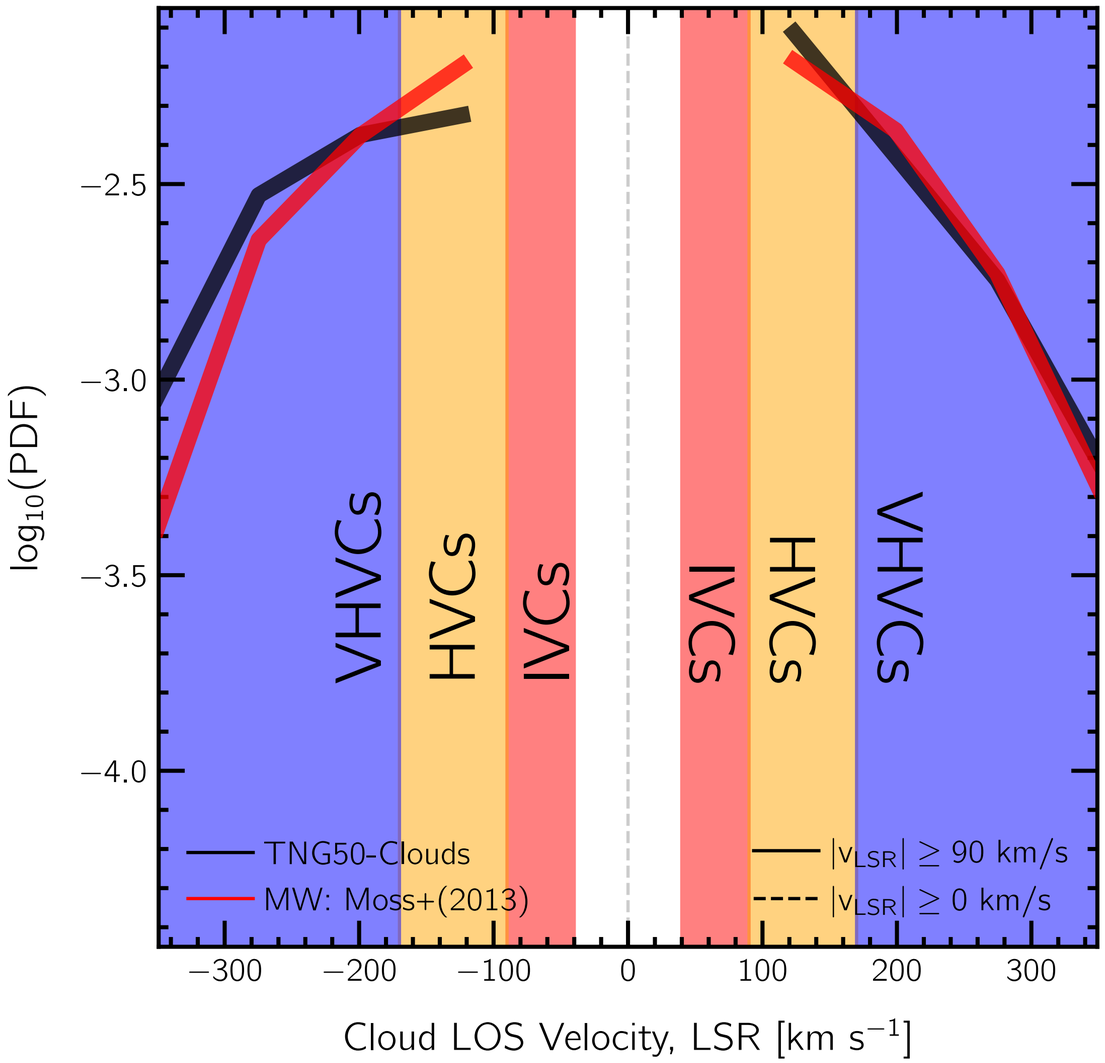


Ramesh+(2023b)

Studying Clouds with TNG50



Ramesh+(2023b)

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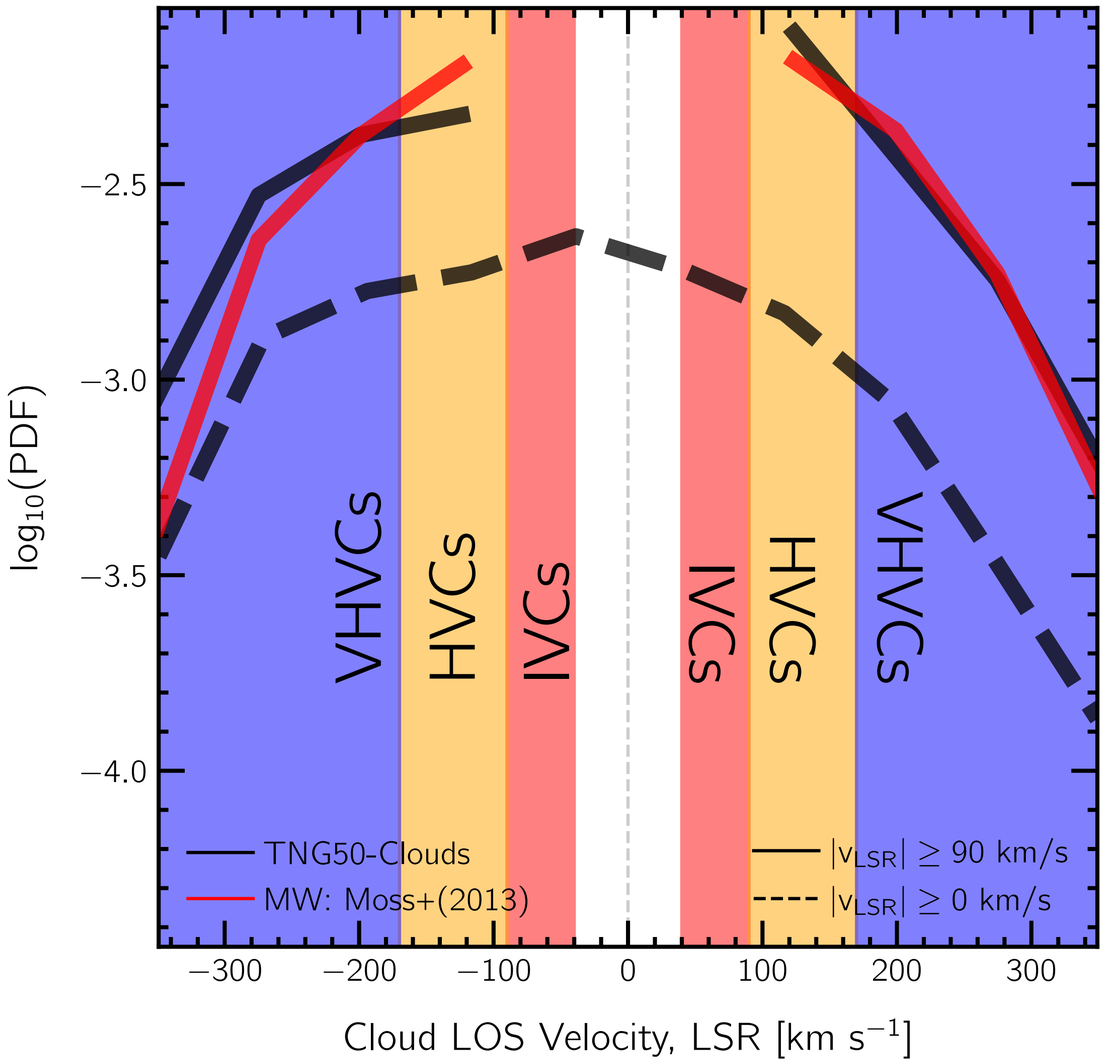
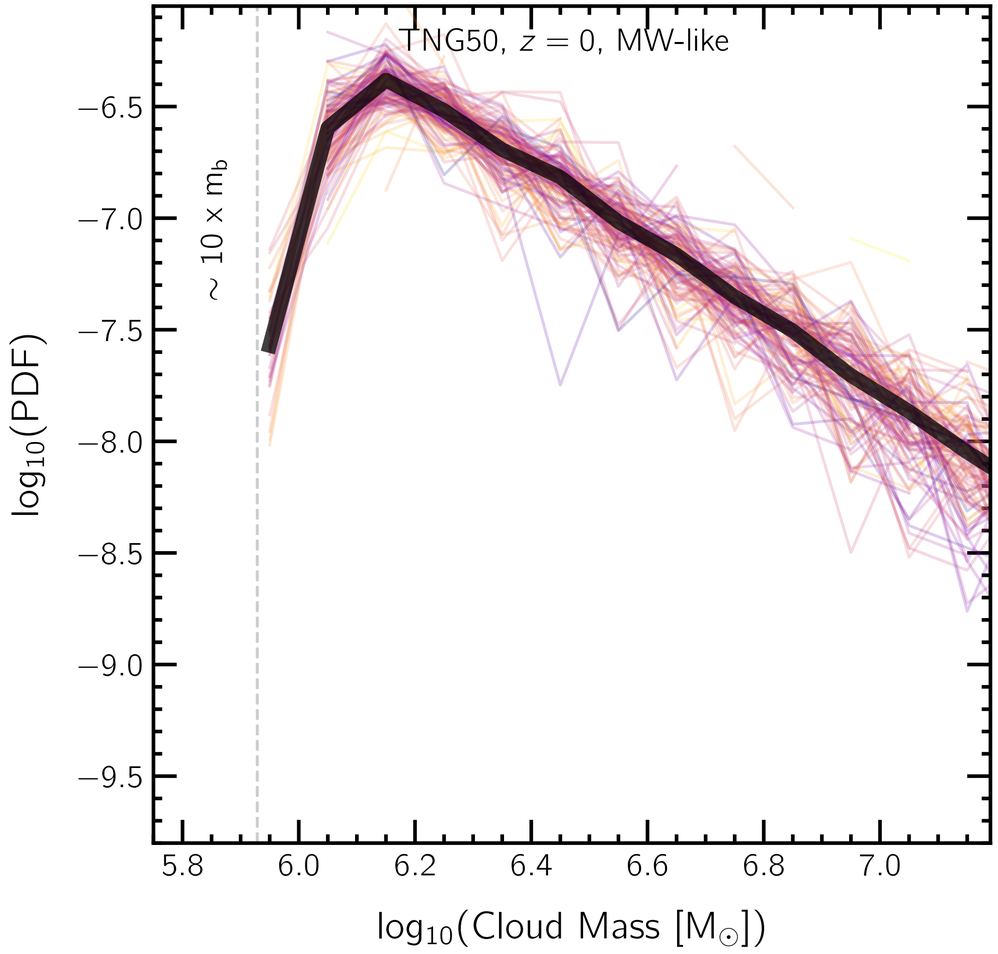


Ramesh+(2023b)

The Resolution Problem



Ramesh+(2023b)

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Why not run these simulations at higher resolutions?

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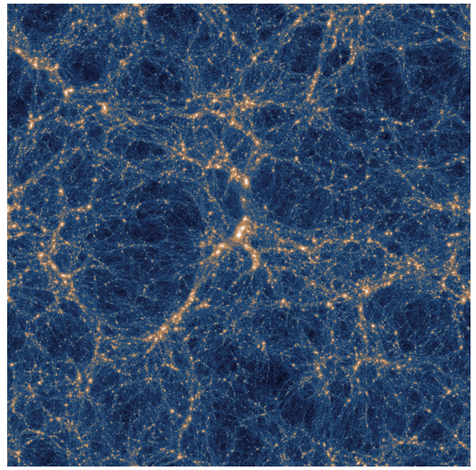
TNG50 (Large Volume Cos. Sim.)

$L_{\rm box} \sim 50$ Mpc; $m_b \sim 10^5$ $\rm M_\odot$; ~ 130 Mh



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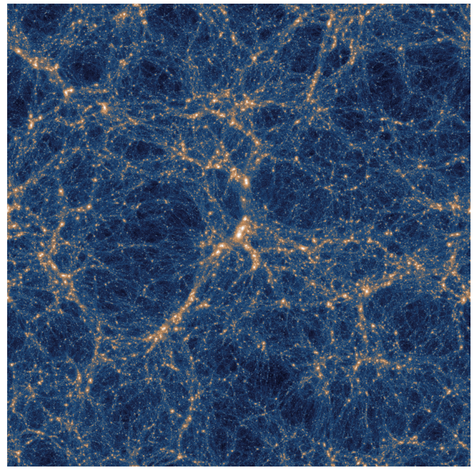

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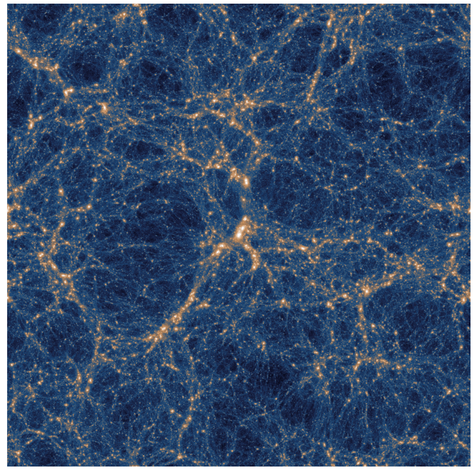
$m_b \sim 10^3$ $M_\odot$ ~ 50000 Mhr



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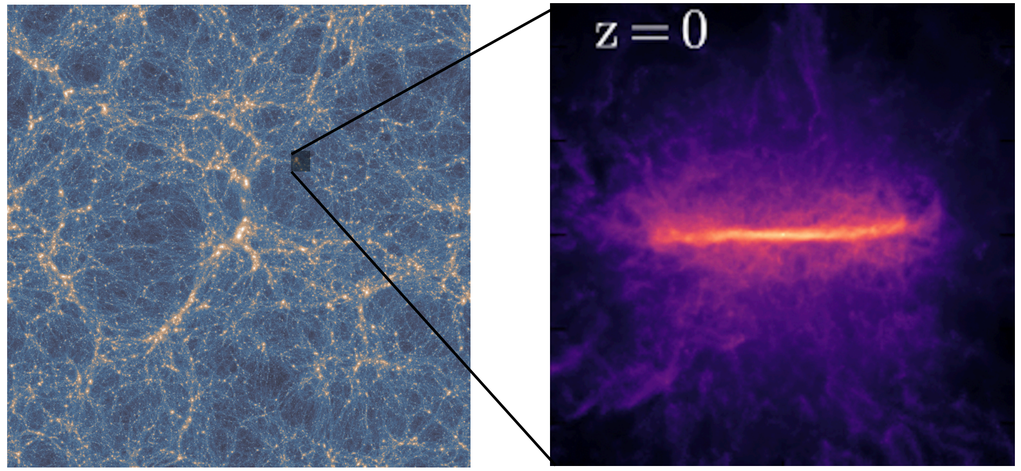
Cosmological Zoom-in Simulations



Auriga Level-2
(Grand+2021)

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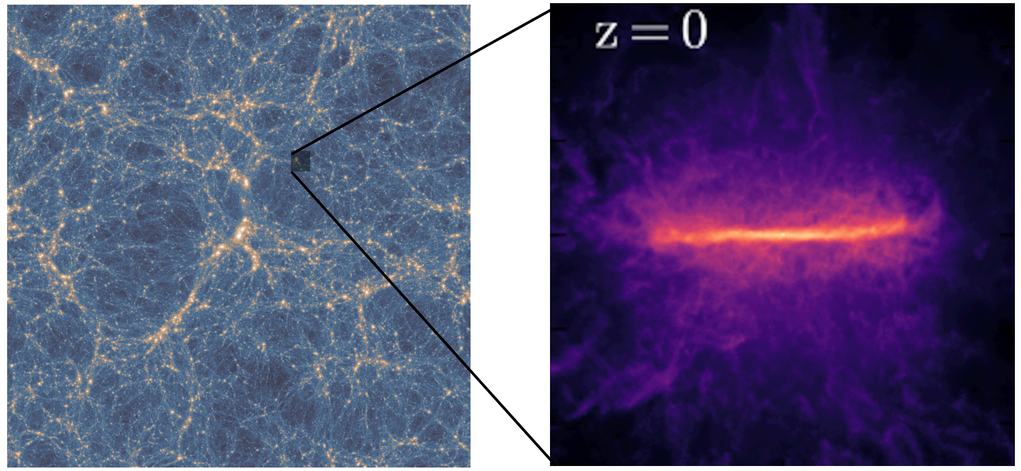

Auriga Level-2
(Grand+2021)

$m_b \sim 10^3\ {\rm M}_\odot$ ~ 15 Mhr

CGM Refinement

Run a zoom-in simulation with super-refined gas within a refinement region.

CGM Refinement

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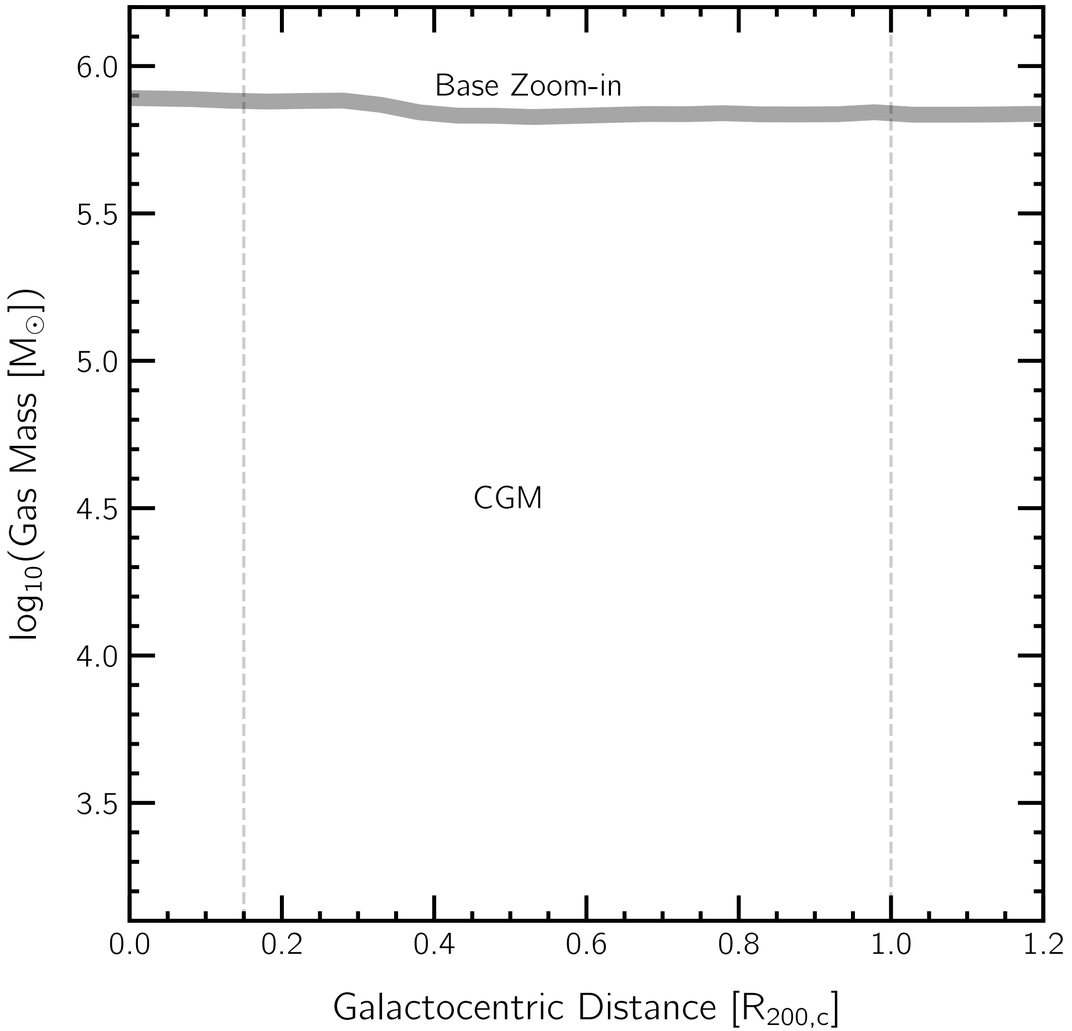

Ramesh+(2024a)

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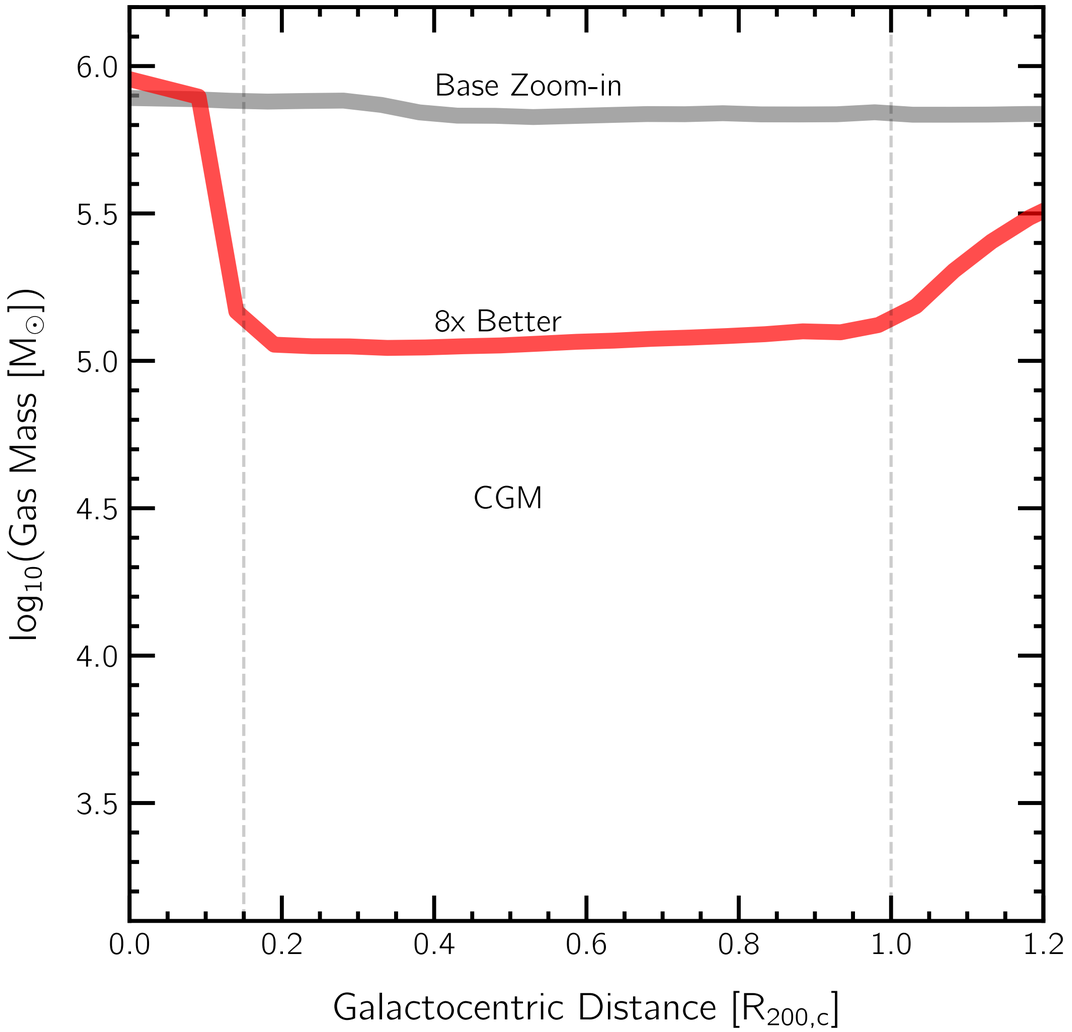

Ramesh+(2024a)

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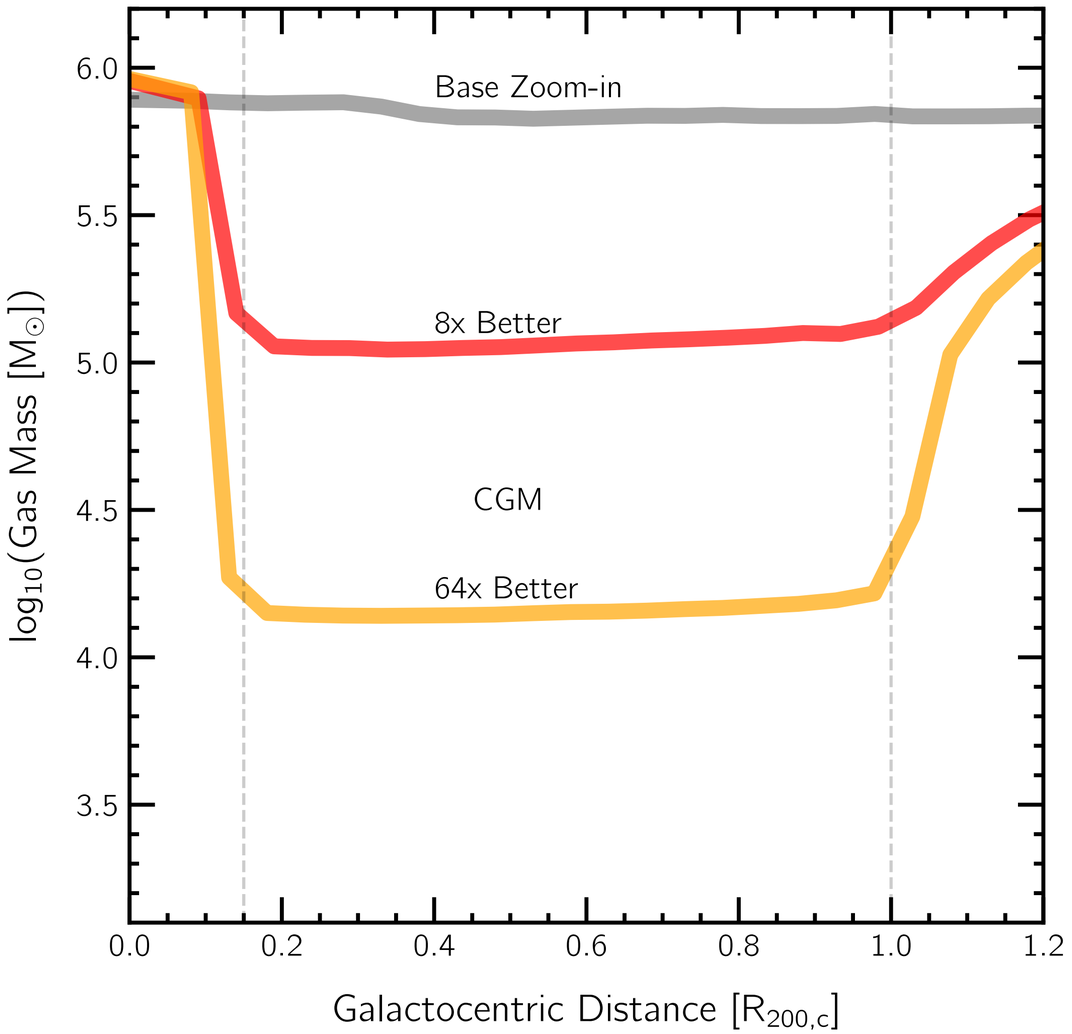

Ramesh+(2024a)

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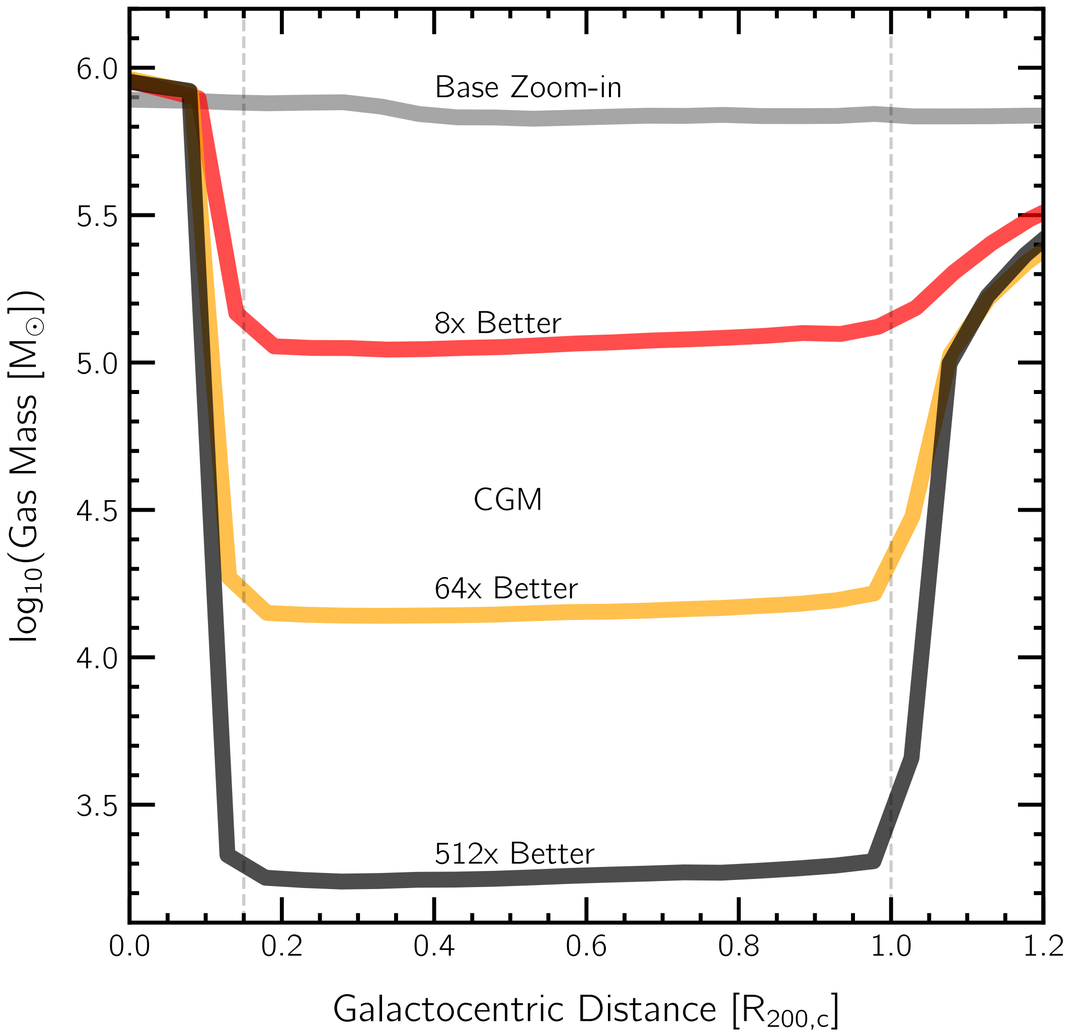
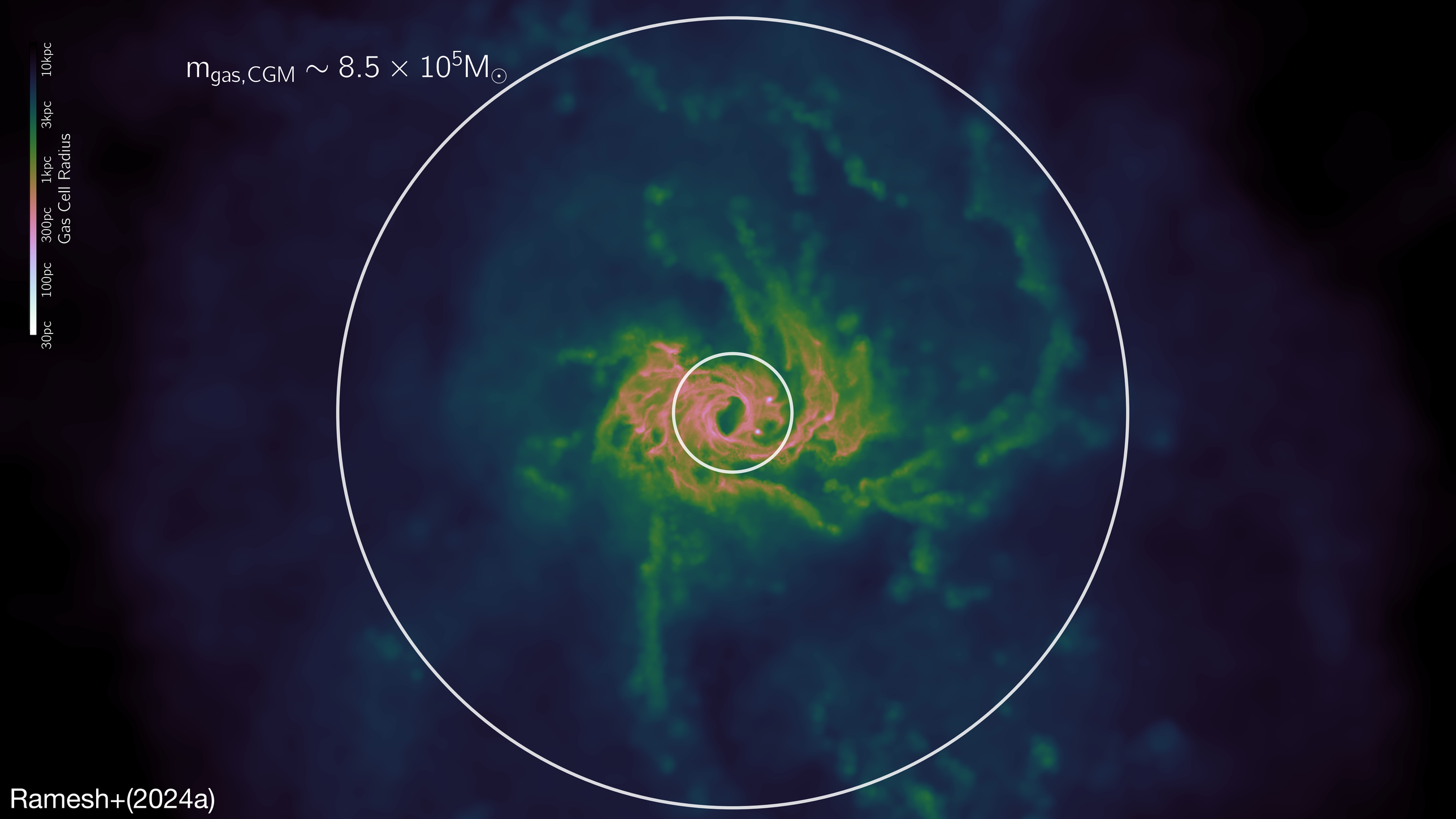
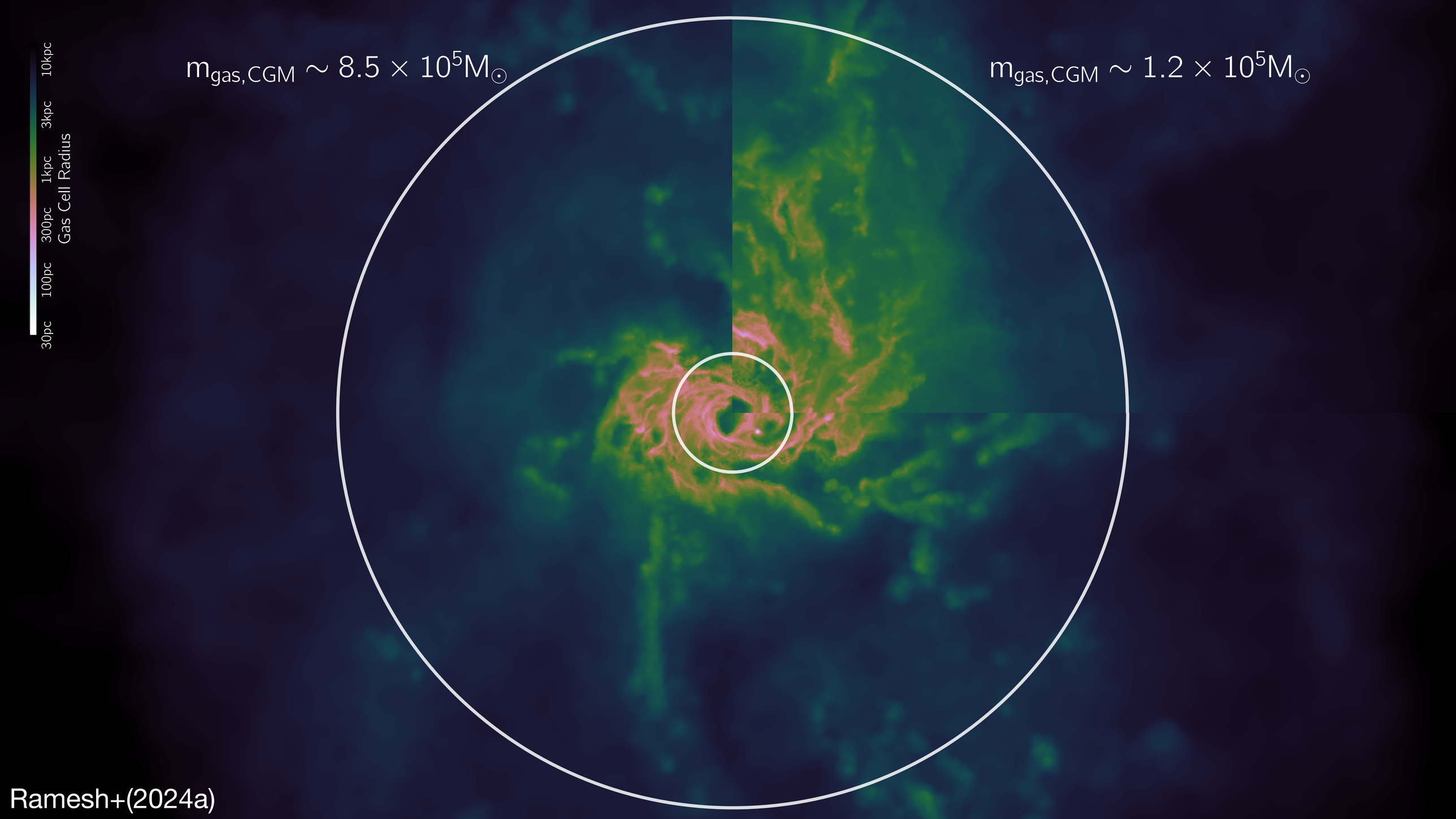
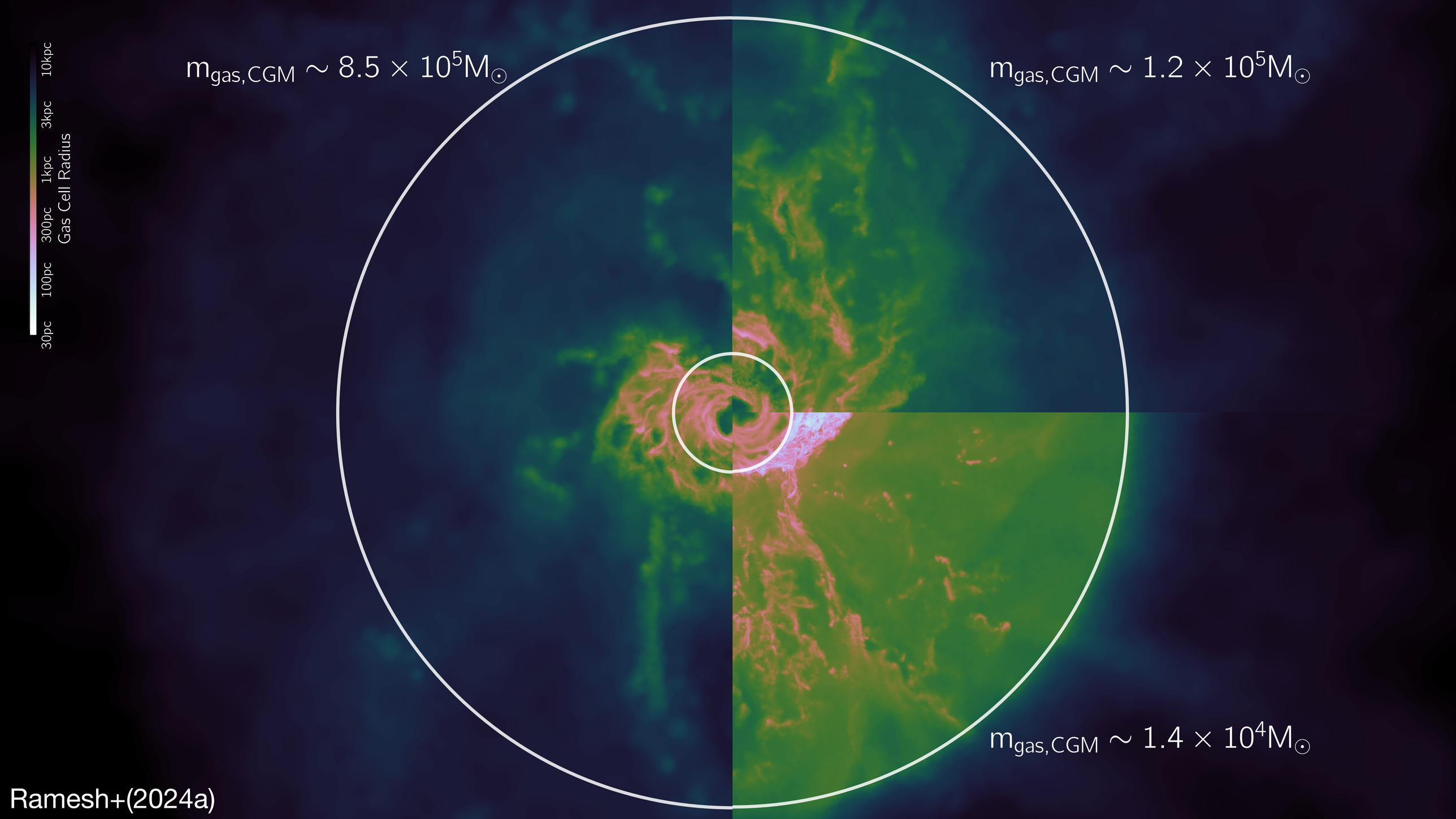


Ramesh+(2024a)



Ramesh+(2024a)


$m_{gas,CGM} \sim 8.5 \times 10^5 M_\odot$
$m_{gas,CGM} \sim 1.2 \times 10^5 M_\odot$
Gas Cell Radius
10kpc
3kpc
1kpc
300pc
100pc
30pc
Ramesh+(2024a)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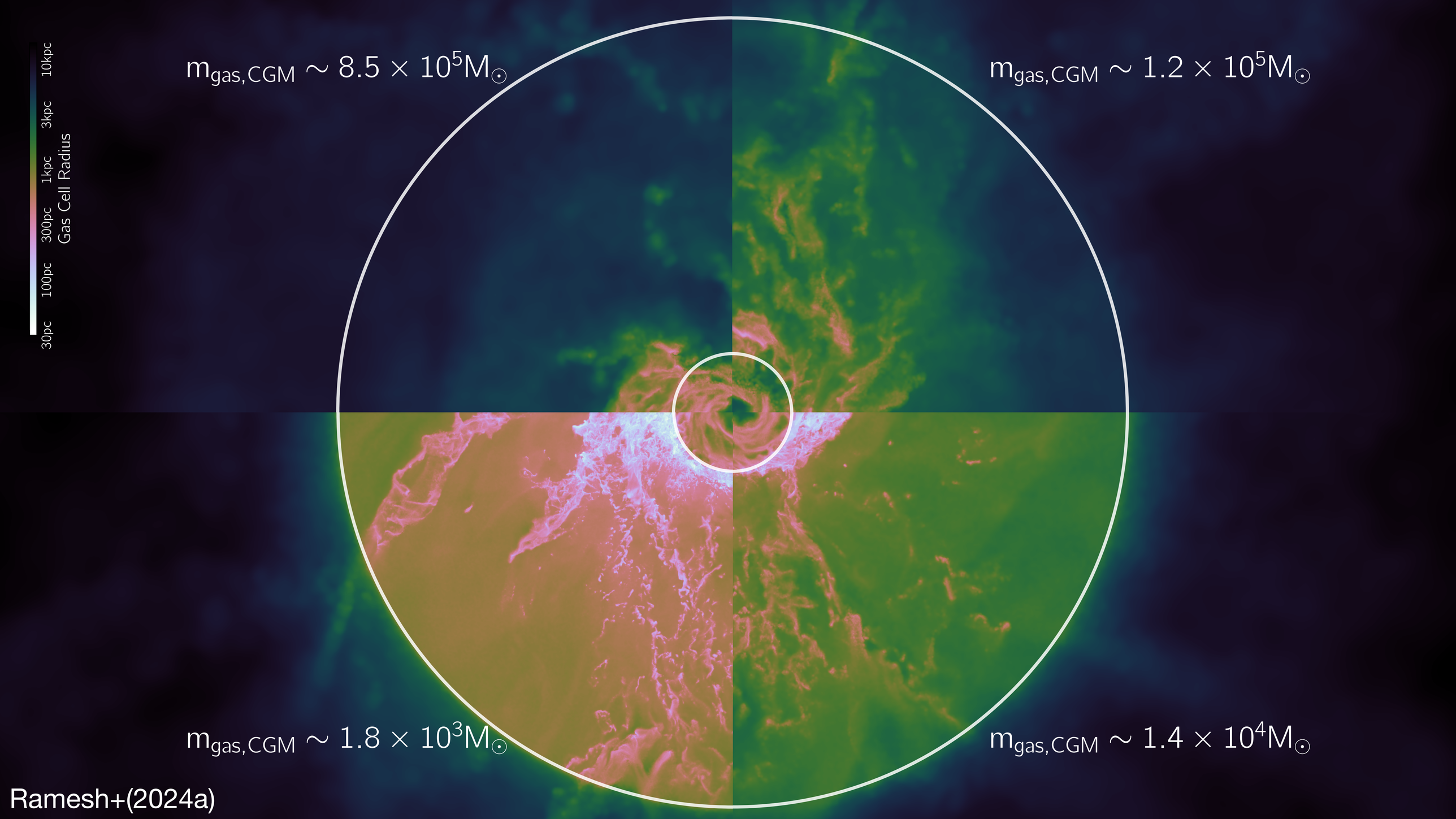
$m_{gas,CGM} \sim 1.2 \times 10^5 M_\odot$
$m_{gas,CGM} \sim 1.4 \times 10^4 M_\odot$
Gas Cell Radius
30pc
100pc
300pc
1kpc
3kpc
10kpc
Ramesh+(2024a)


$m_{gas,CGM} \sim 8.5 \times 10^5 M_\odot$
$m_{gas,CGM} \sim 1.2 \times 10^5 M_\odot$
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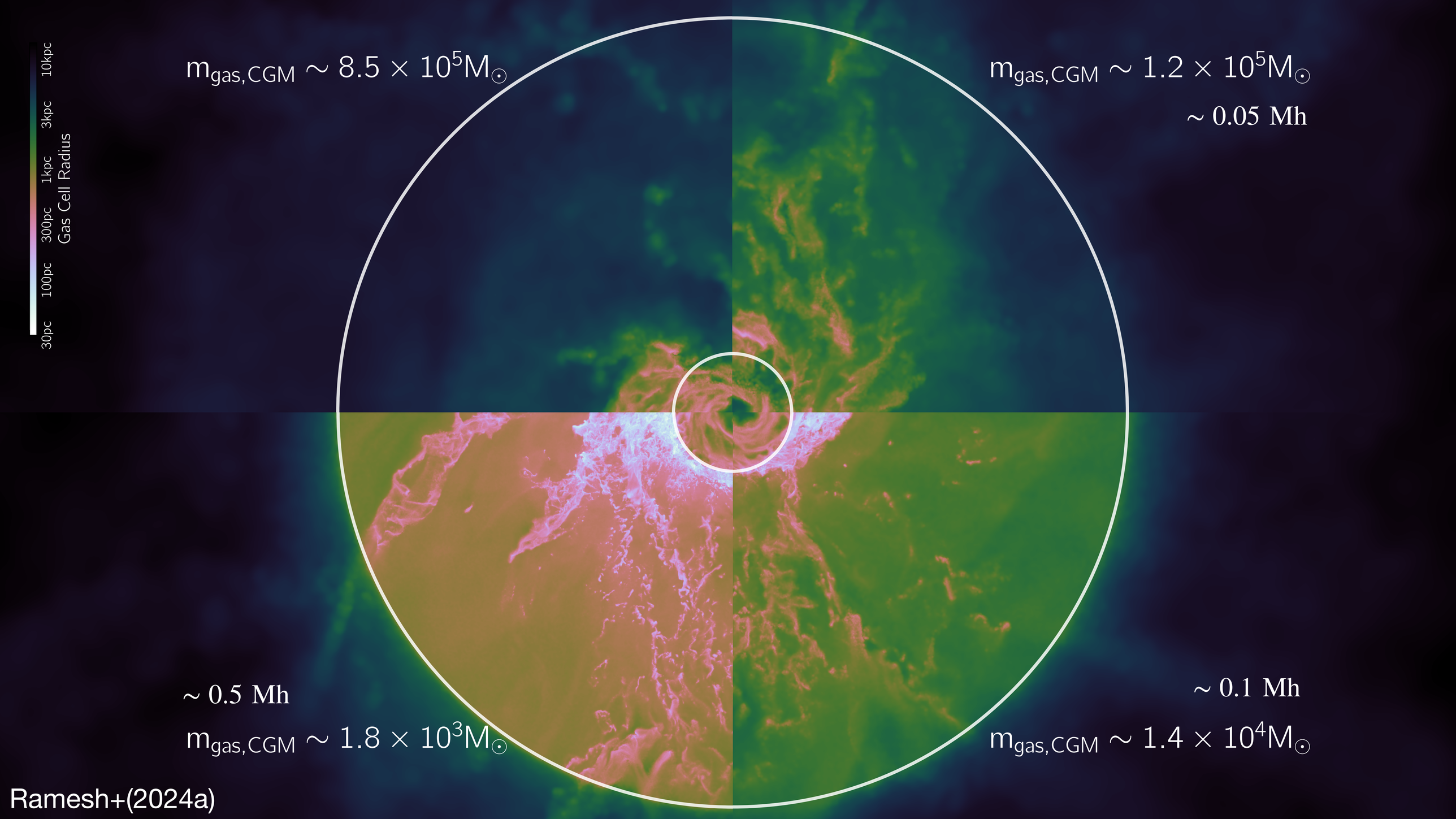
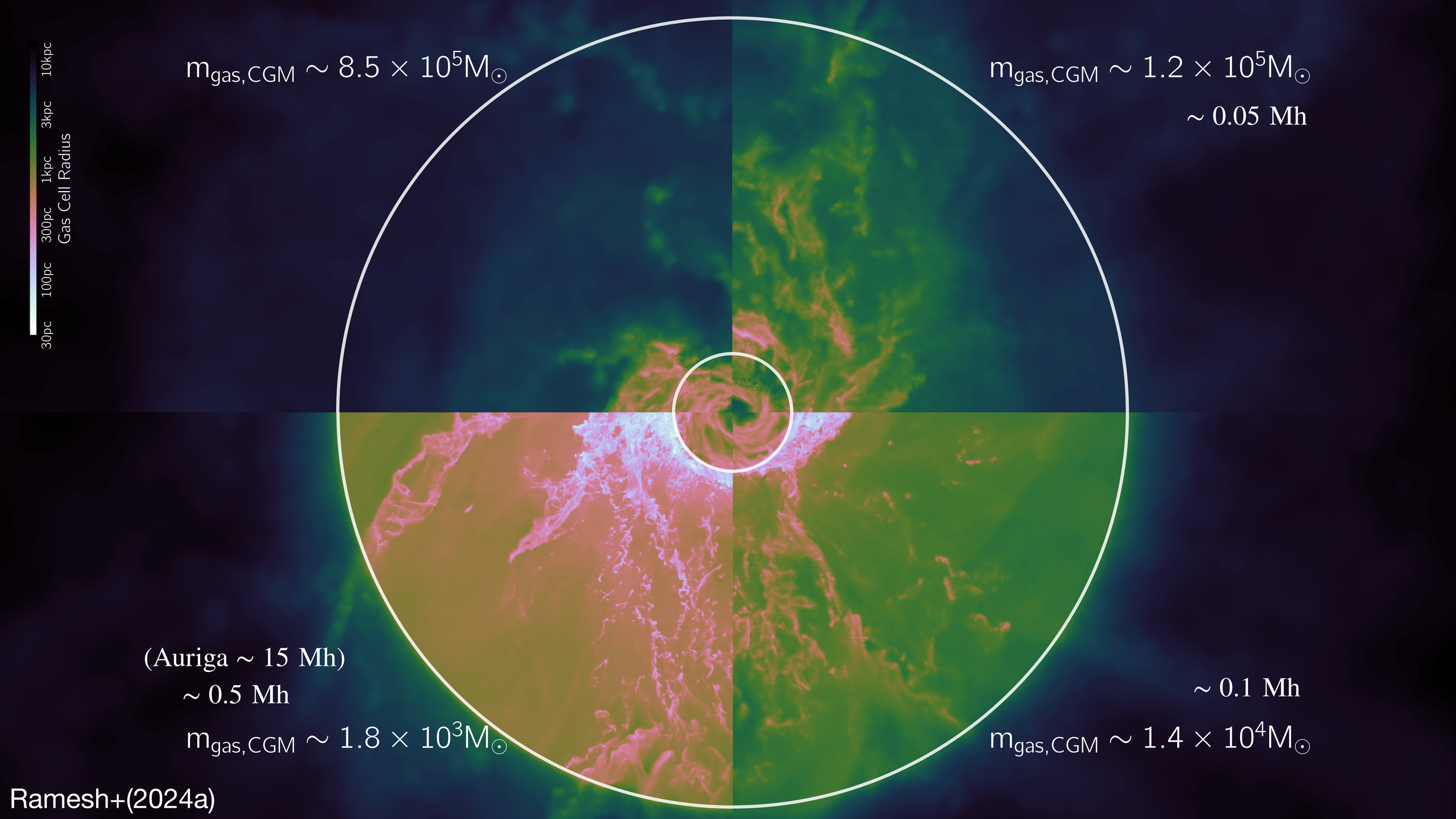
$m_{gas,CGM} \sim 1.4 \times 10^4 M_\odot$
Gas Cell Radius
30pc
100pc
300pc
1kpc
3kpc
10kpc
Ramesh+(2024a)


$m_{gas,CGM} \sim 8.5 \times 10^5 M_\odot$
$m_{gas,CGM} \sim 1.2 \times 10^5 M_\odot$
~ 0.05 Mh
~ 0.5 Mh
$m_{gas,CGM} \sim 1.8 \times 10^3 M_\odot$
~ 0.1 Mh
$m_{gas,CGM} \sim 1.4 \times 10^4 M_\odot$
Gas Cell Radius
10kpc
3kpc
1kpc
300pc
100pc
30pc
Ramesh+(2024a)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~ 0.05 Mh
(Auriga ~ 15 Mh)
~ 0.5 Mh
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Gas Cell Radius
10kpc
3kpc
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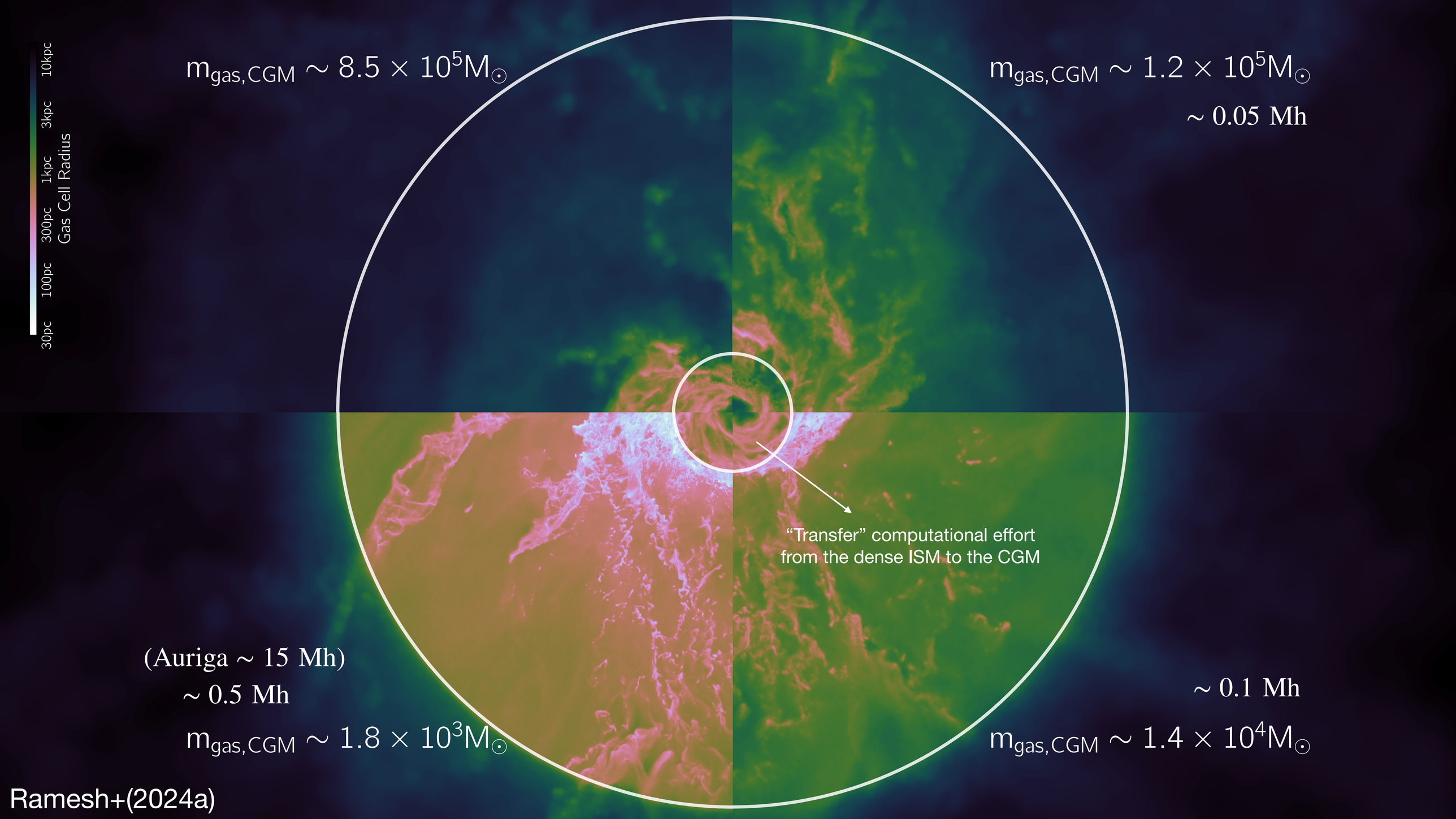
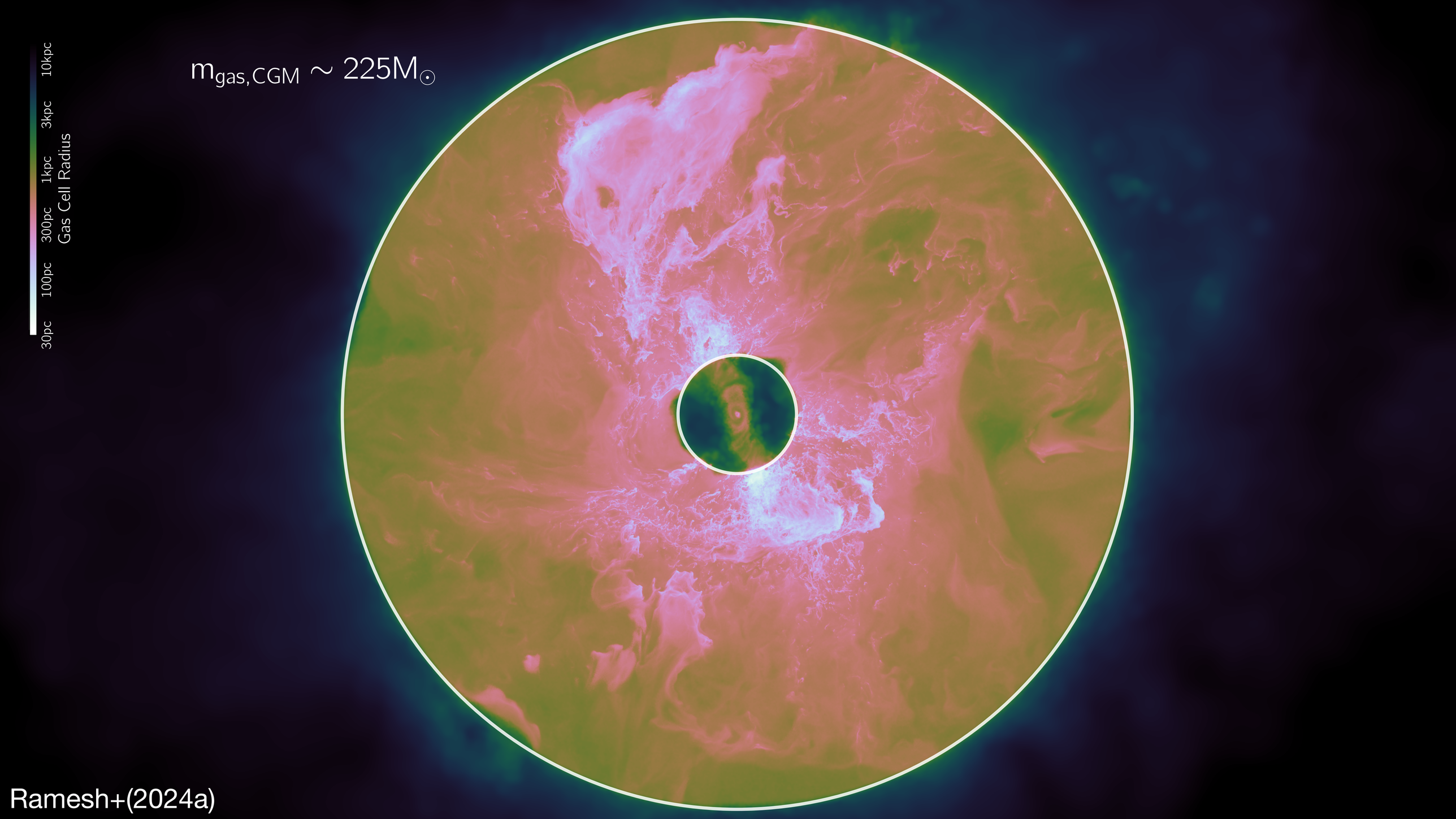
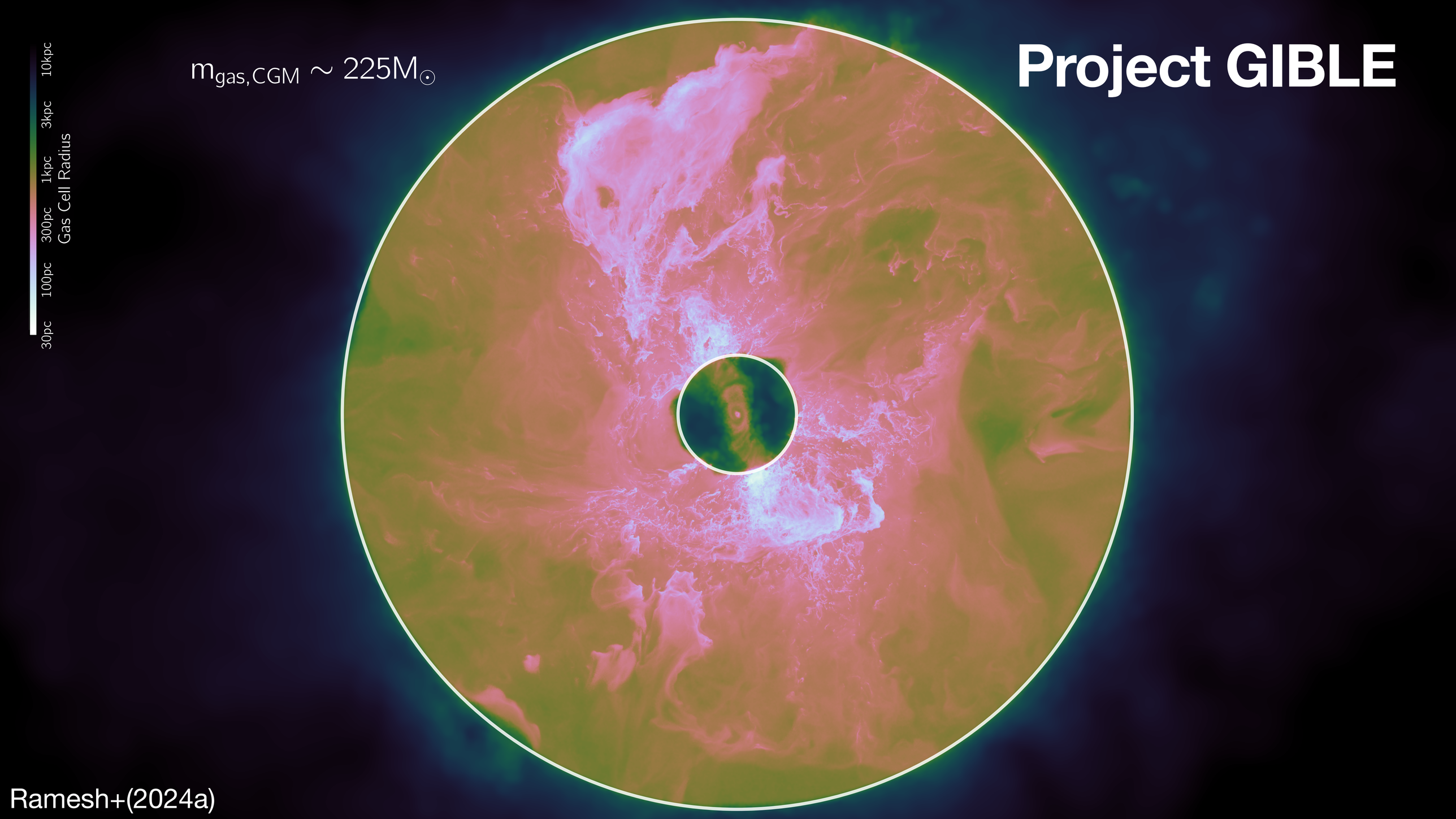
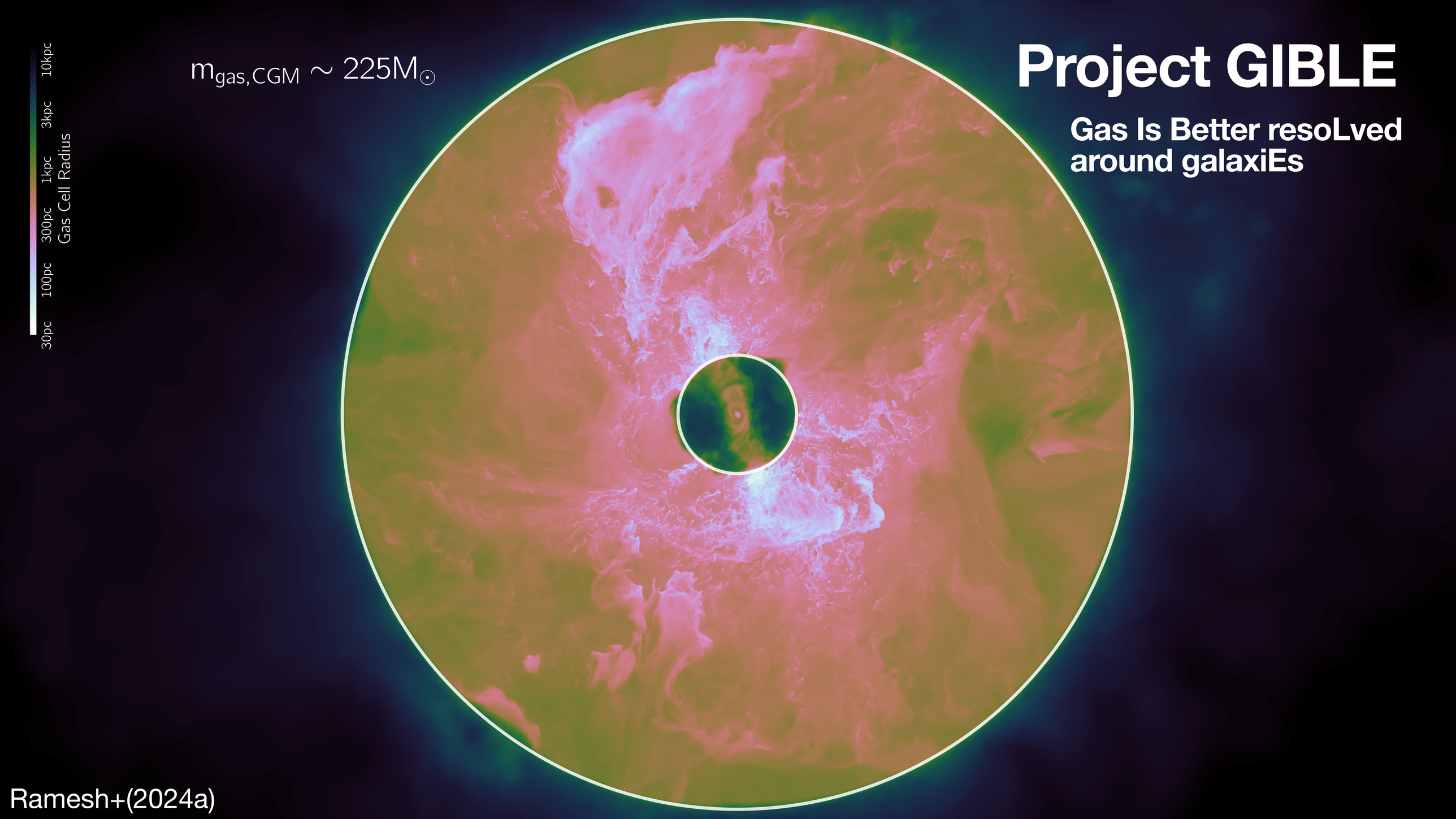
300pc
100pc
30pc
Ramesh+(2024a)

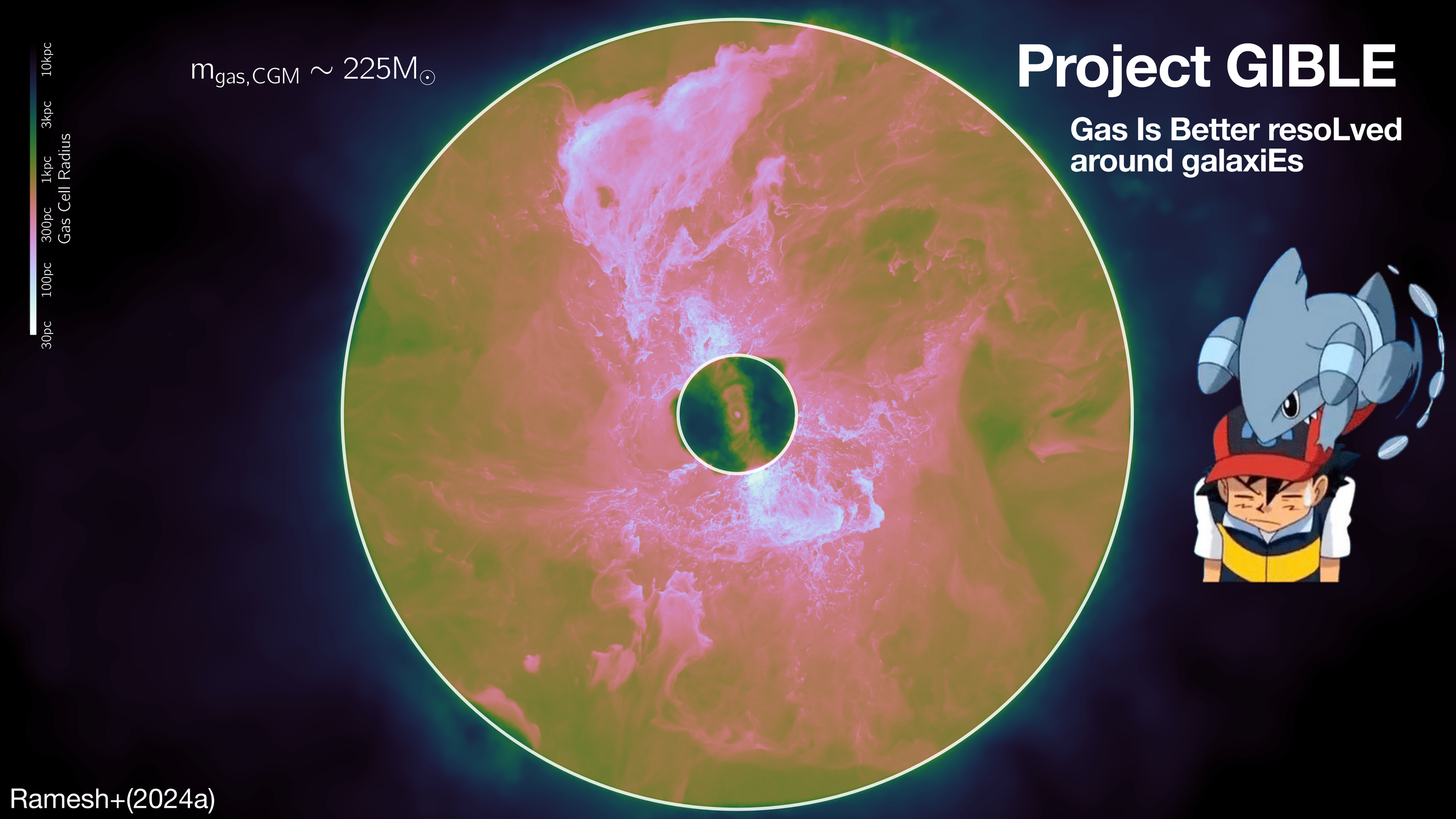


Ramesh+(2024a)


$m_{gas,CGM} \sim 225 M_\odot$
Gas Cell Radius
30pc
100pc
300pc
1kpc
3kpc
10kpc
Ramesh+(2024a)


$m_{gas,CGM} \sim 225 M_\odot$
Project GIBLE
Gas Cell Radius
30pc
100pc
300pc
1kpc
3kpc
10kpc
Ramesh+(2024a)


$m_{gas,CGM} \sim 225 M_\odot$
Gas Cell Radius
30pc
100pc
300pc
1kpc
3kpc
10kpc
Project GIBLE
Gas Is Better resoLved around galaxiEs
Ramesh+(2024a)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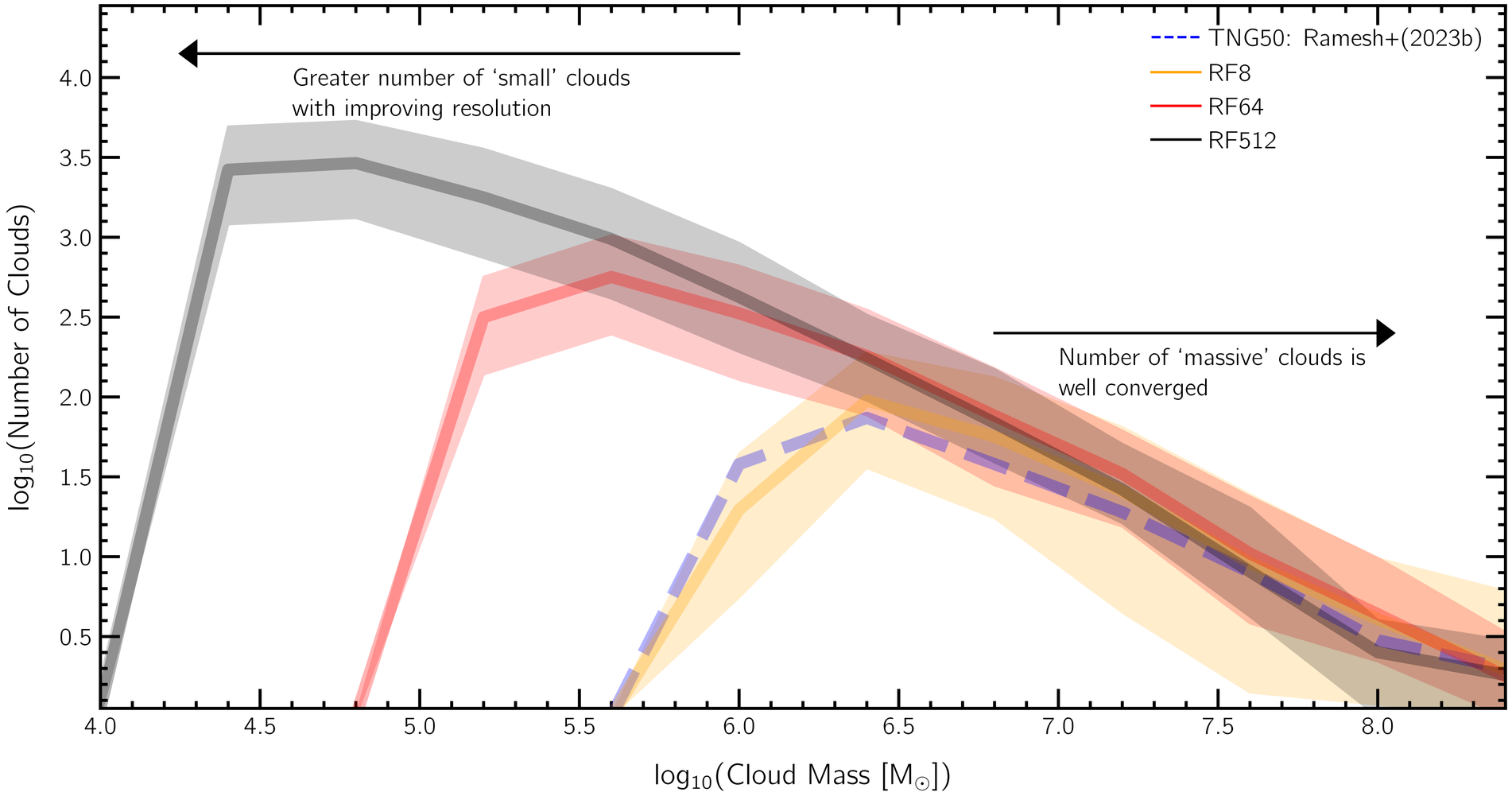
Project GIBLE
Gas Is Better resoLved around galaxiEs
Ramesh+(2024a)

Studying Clouds with GIBLE



Ramesh+(2024a)

Origin of Cold Clouds

How do these clouds originate: outflows from the central galaxy, precipitation of the hot CGM, or from satellites?

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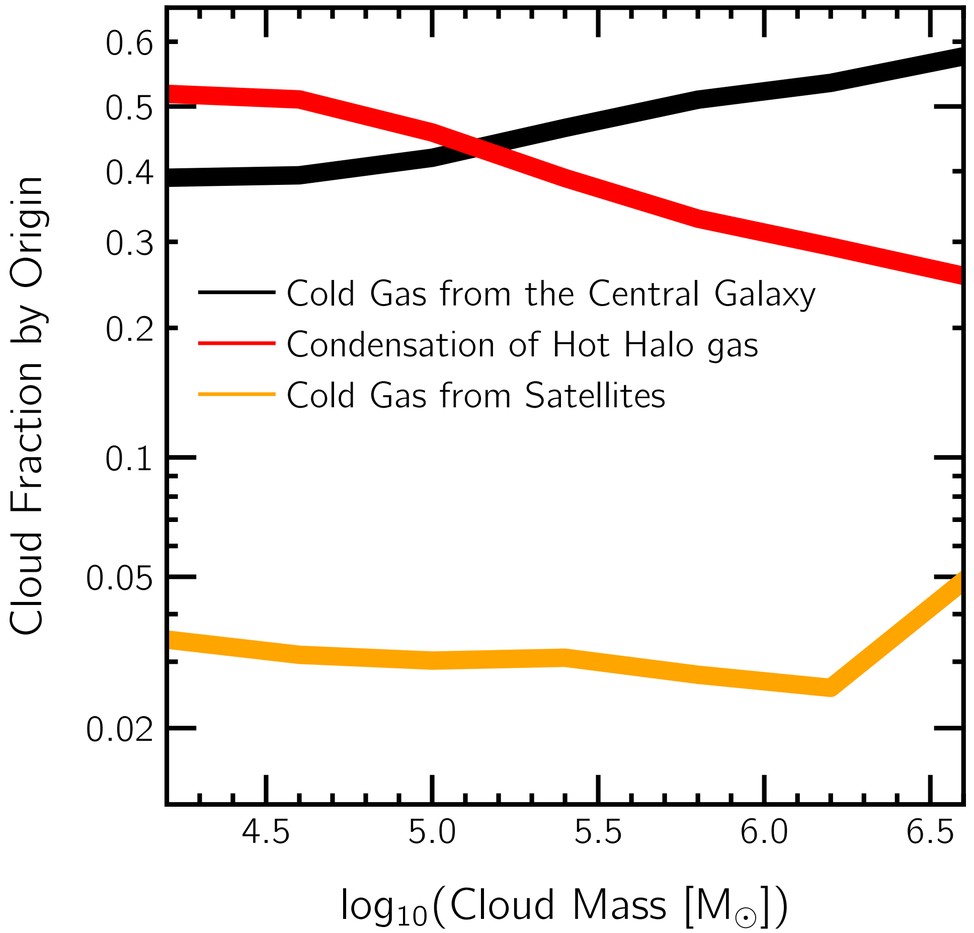
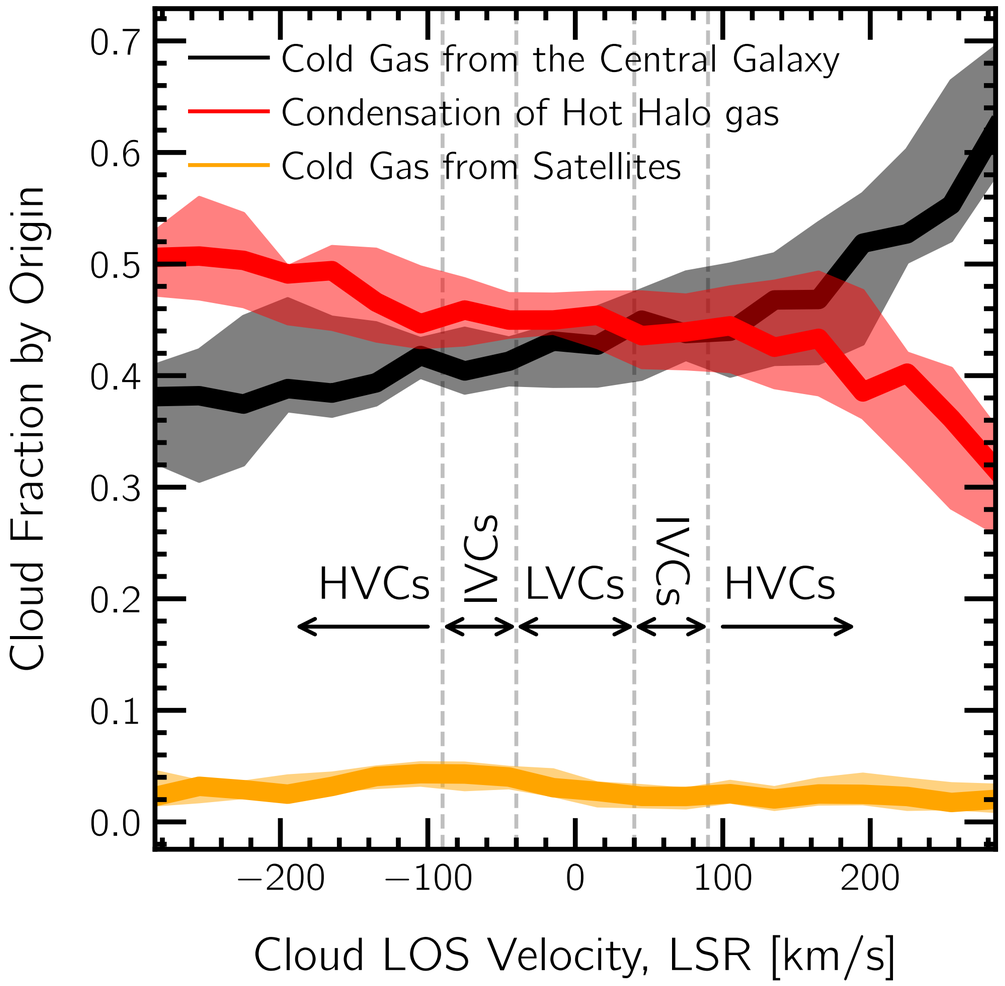


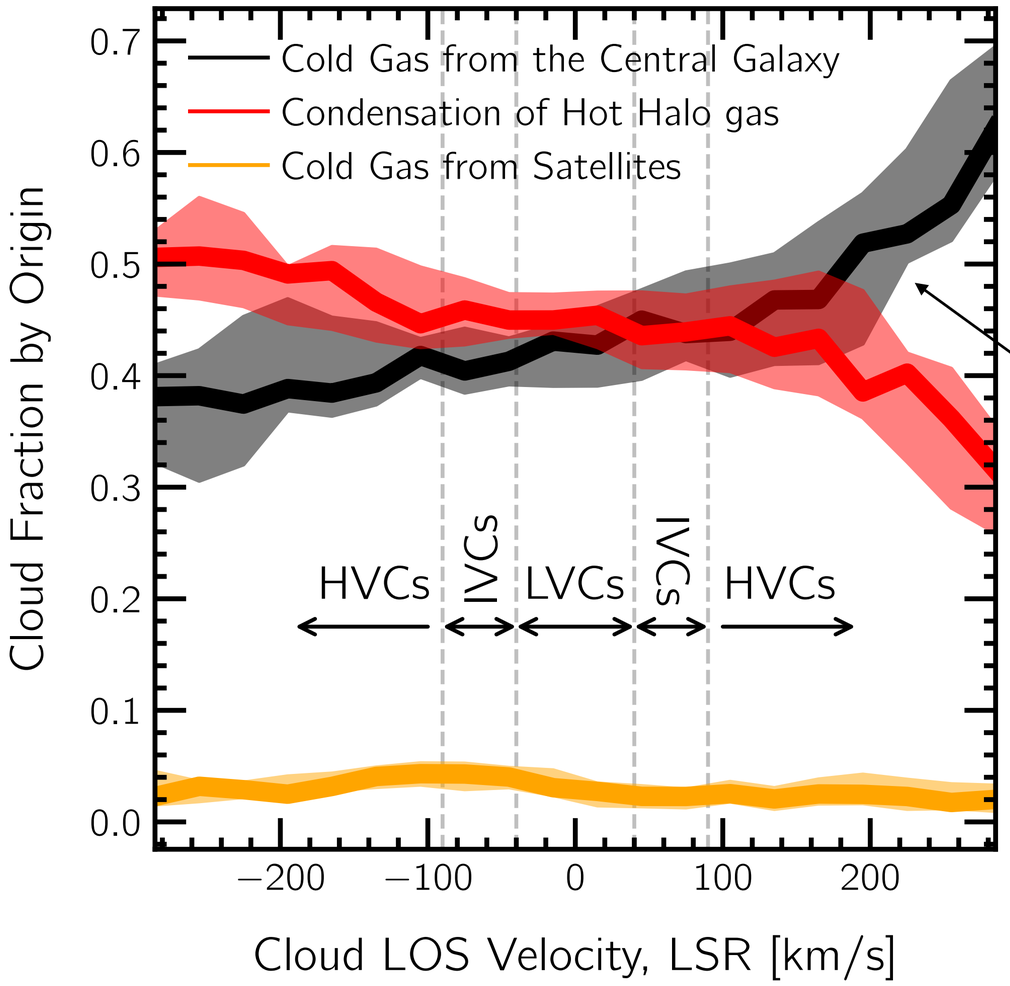
Ramesh+ (2024c)

Origin of Cold Clouds



Ramesh+ (2024c)

Origin of Cold Clouds

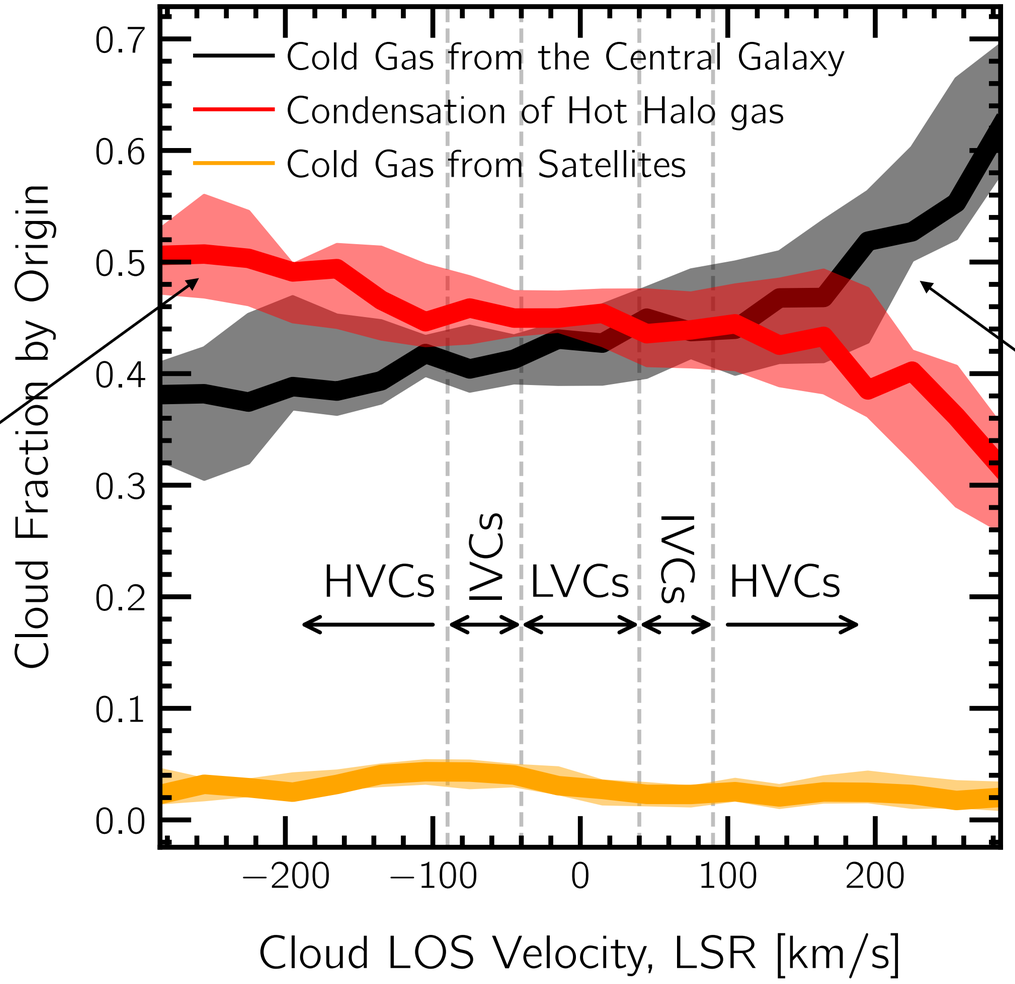


Most, but not all, outflowing HVCs are linked to outflows from the central galaxy

Ramesh+ (2024c)

Origin of Cold Clouds

Most, but not all, inflowing HVCs condense out of the hot halo



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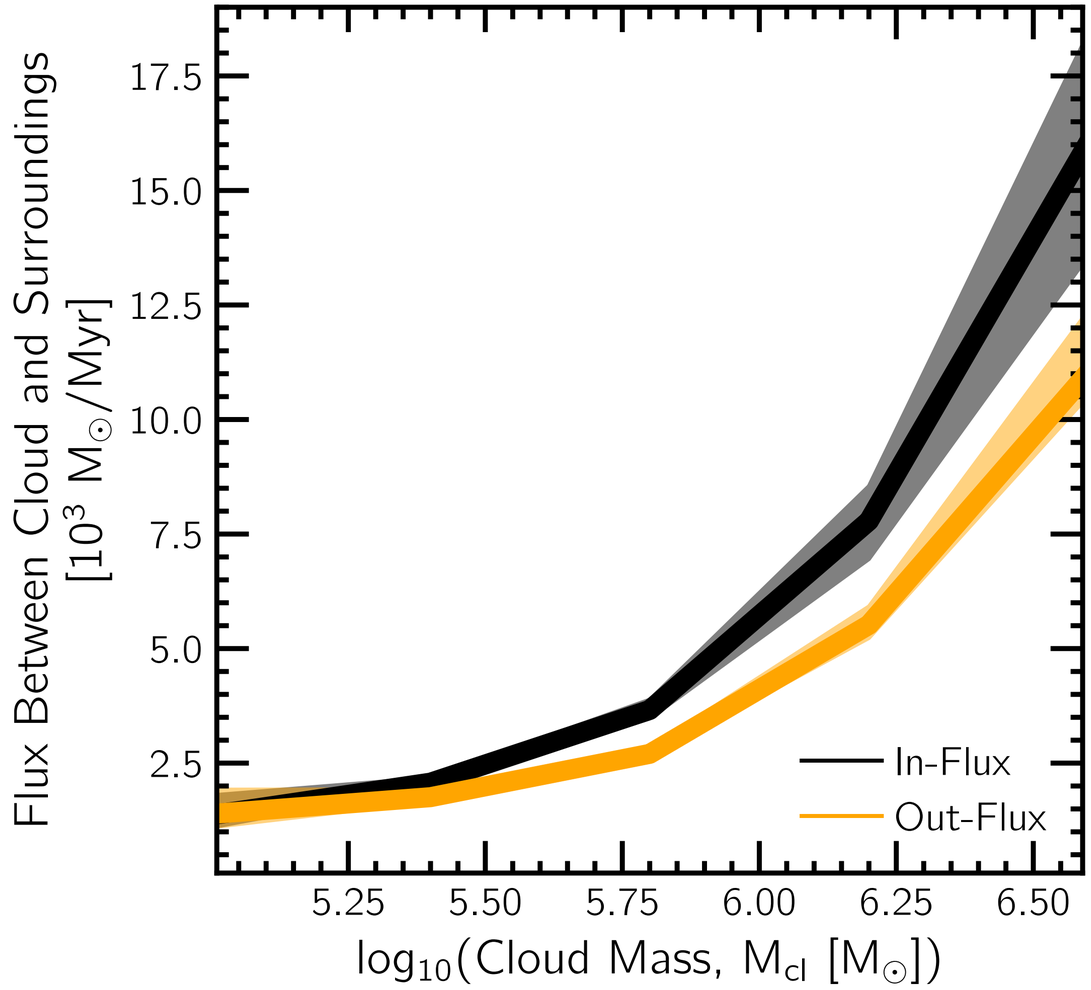
Ramesh+ (2024c)

Evolution of Cold Clouds

Evolution of Cold Clouds

1. Exchange of matter between clouds and their surroundings



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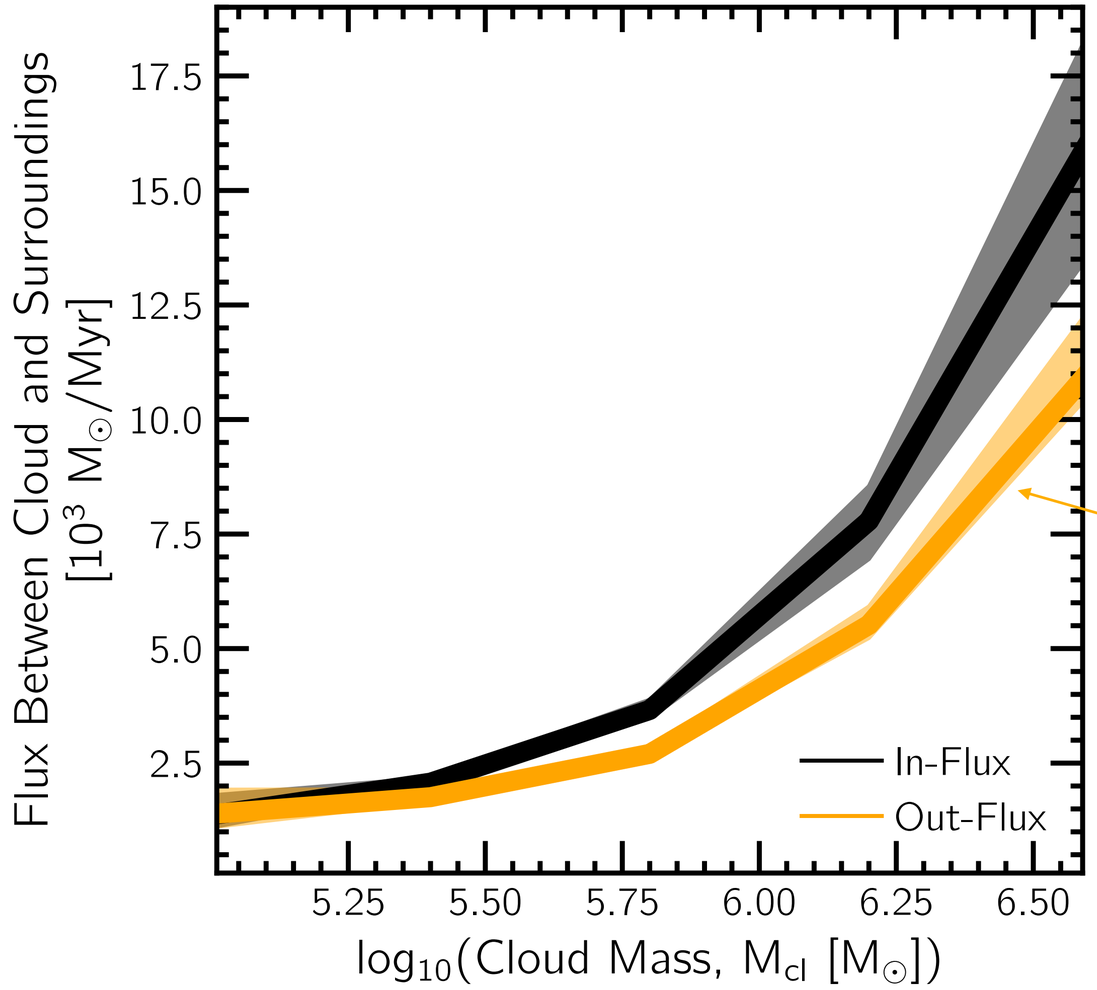

Fluid instabilities (e.g. KH) lead to mixing of cold gas with the background, resulting in an outflow of matter

Ramesh+ (2024c)

Evolution of Cold Clouds

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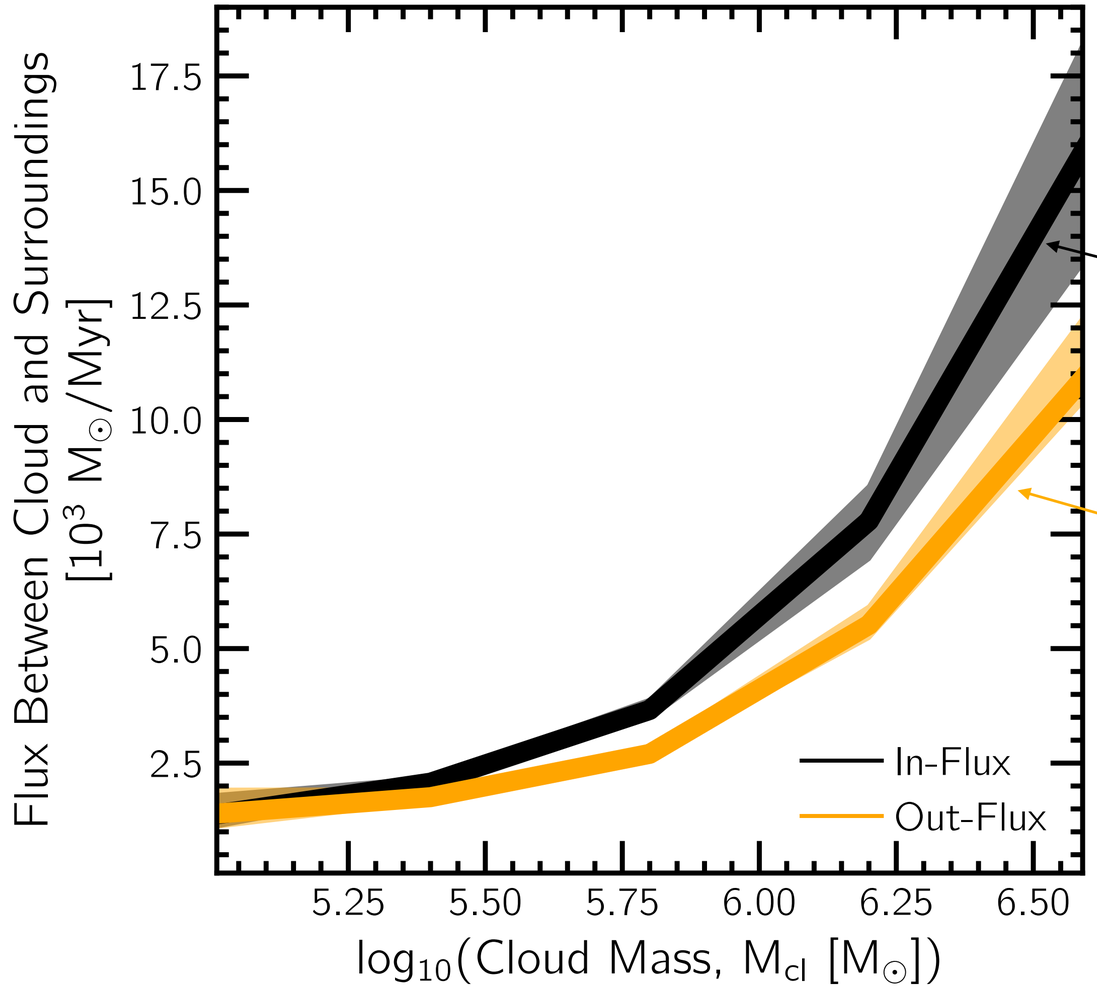

Cooling of gas in the interface layer drives an influx of cold material into the cloud

Fluid instabilities (e.g. KH) lead to mixing of cold gas with the background, resulting in an outflow of matter

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Evolution of Cold Clouds

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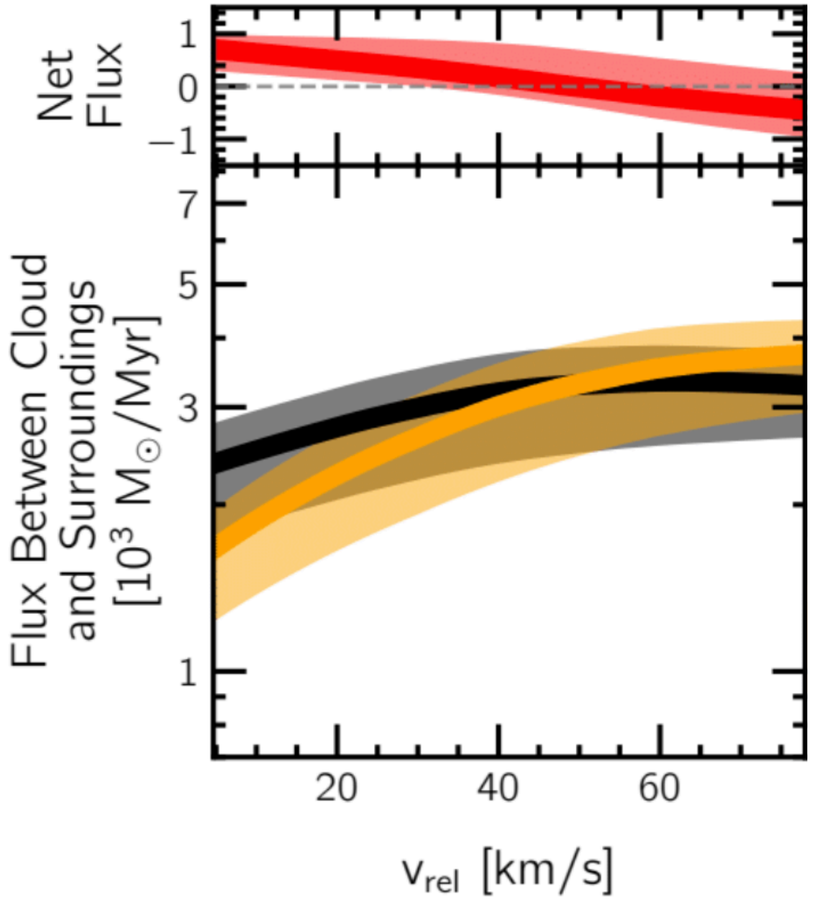

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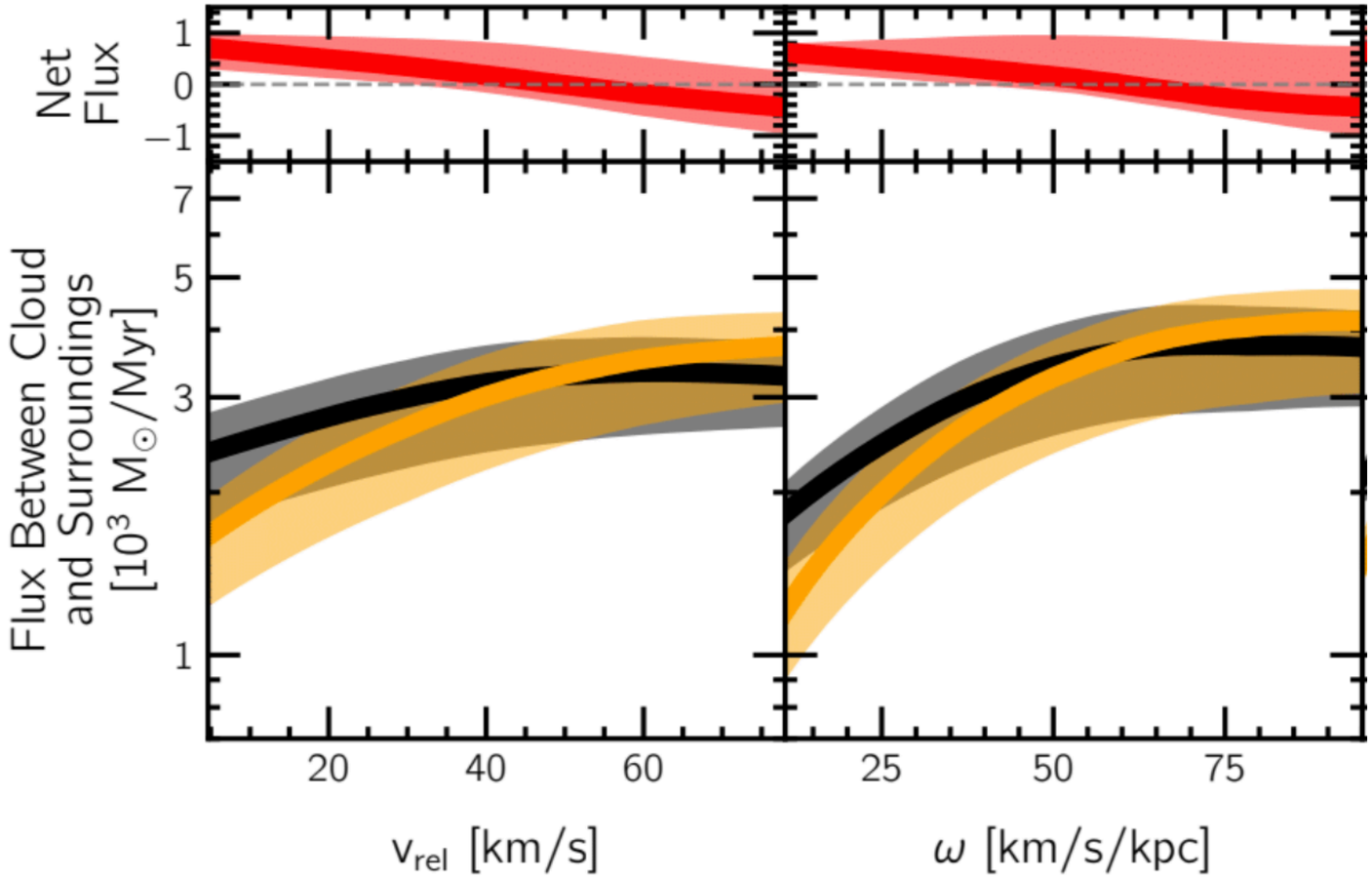

Ramesh+ (2024c)

Evolution of Cold Clouds

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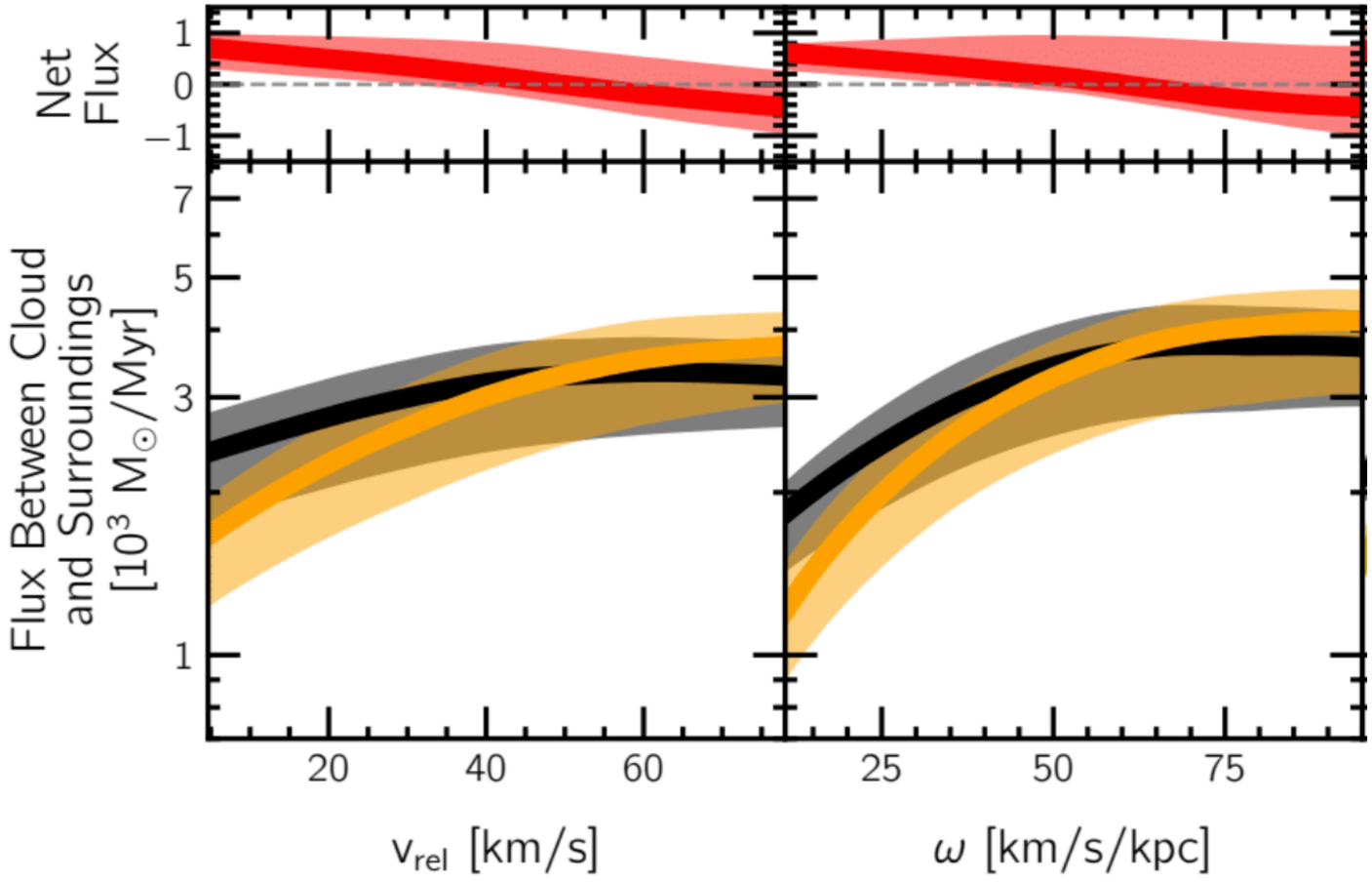

Broadly consistent with existing theoretical models (e.g. Gronke+2018):

$$\dot{m}_{\rm in} \sim A_{\rm cl}\,\rho_{\rm int}\,v_{\rm in}$$

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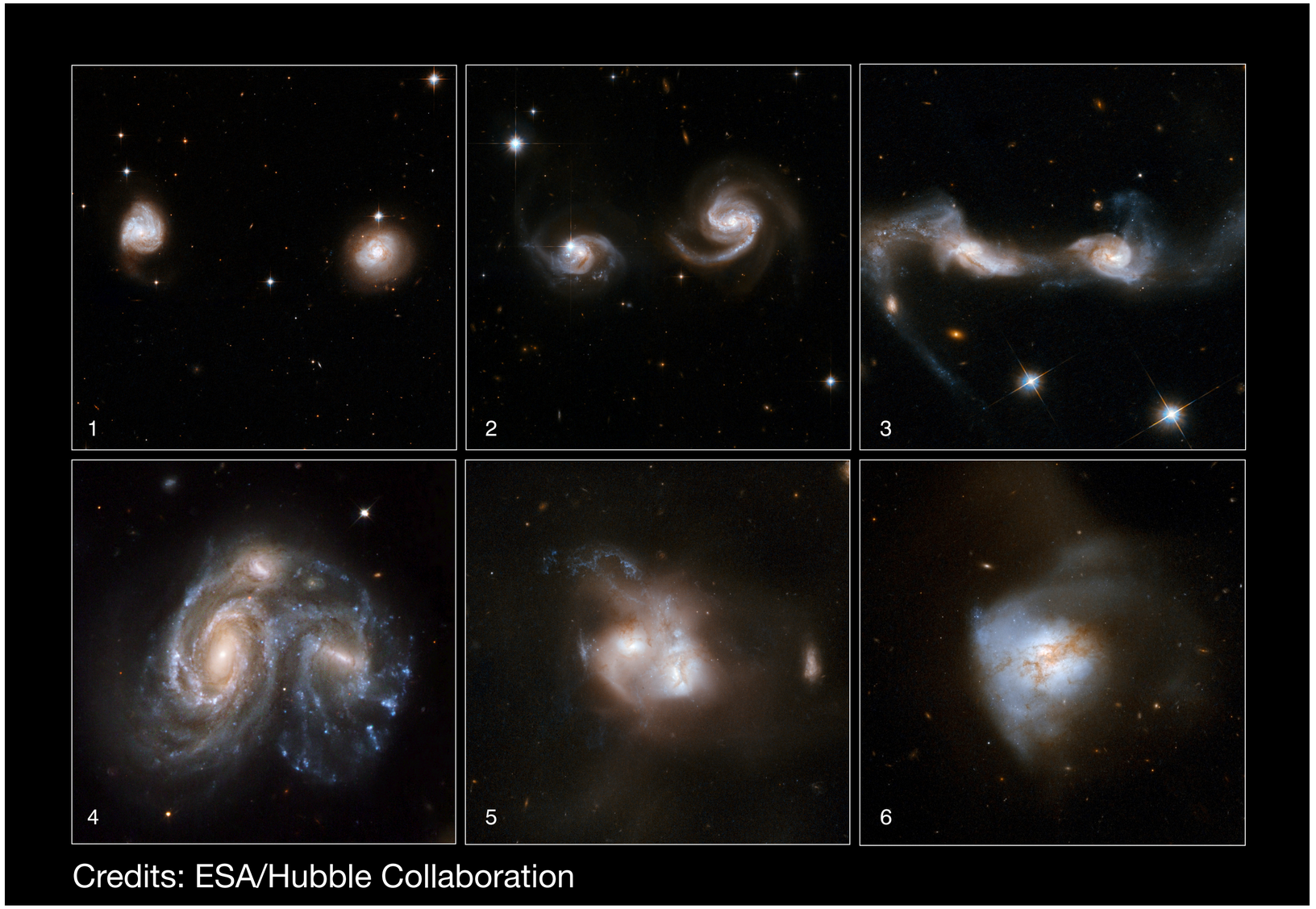
Evolution of Cold Clouds

2. Cloud-Cloud Interactions



Evolution of Cold Clouds

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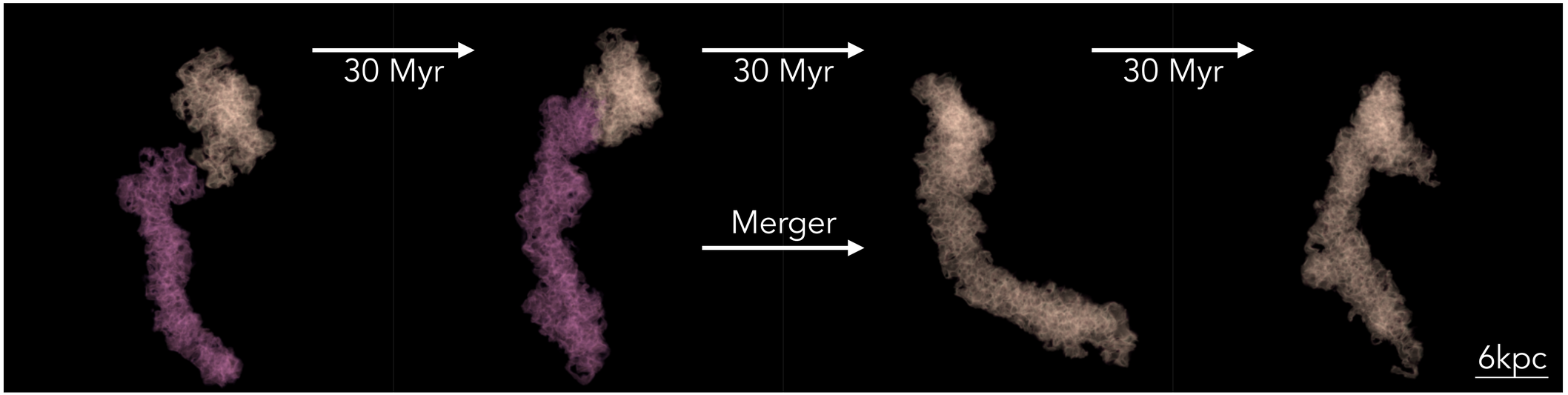

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Evolution of Cold Clouds

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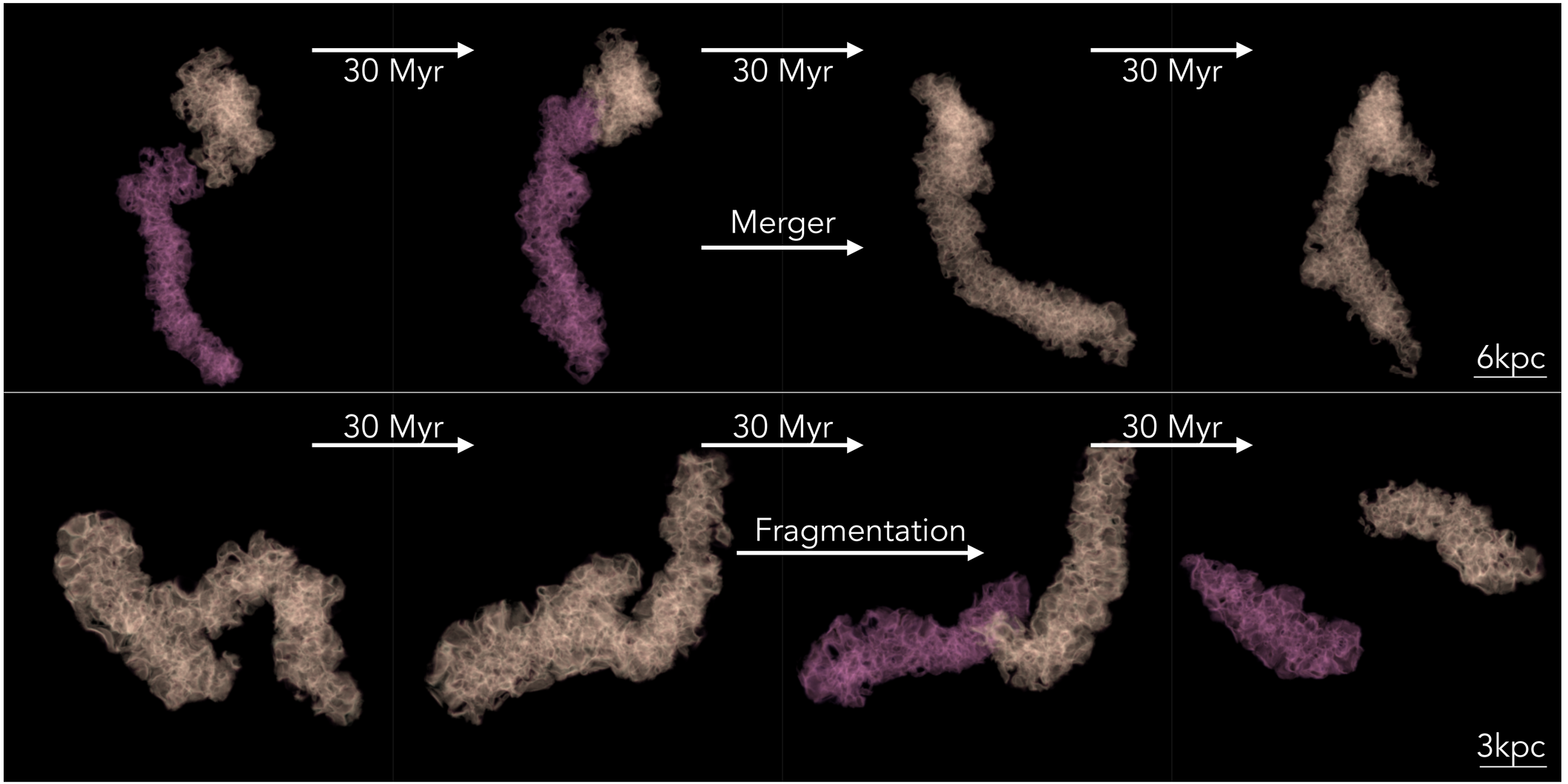

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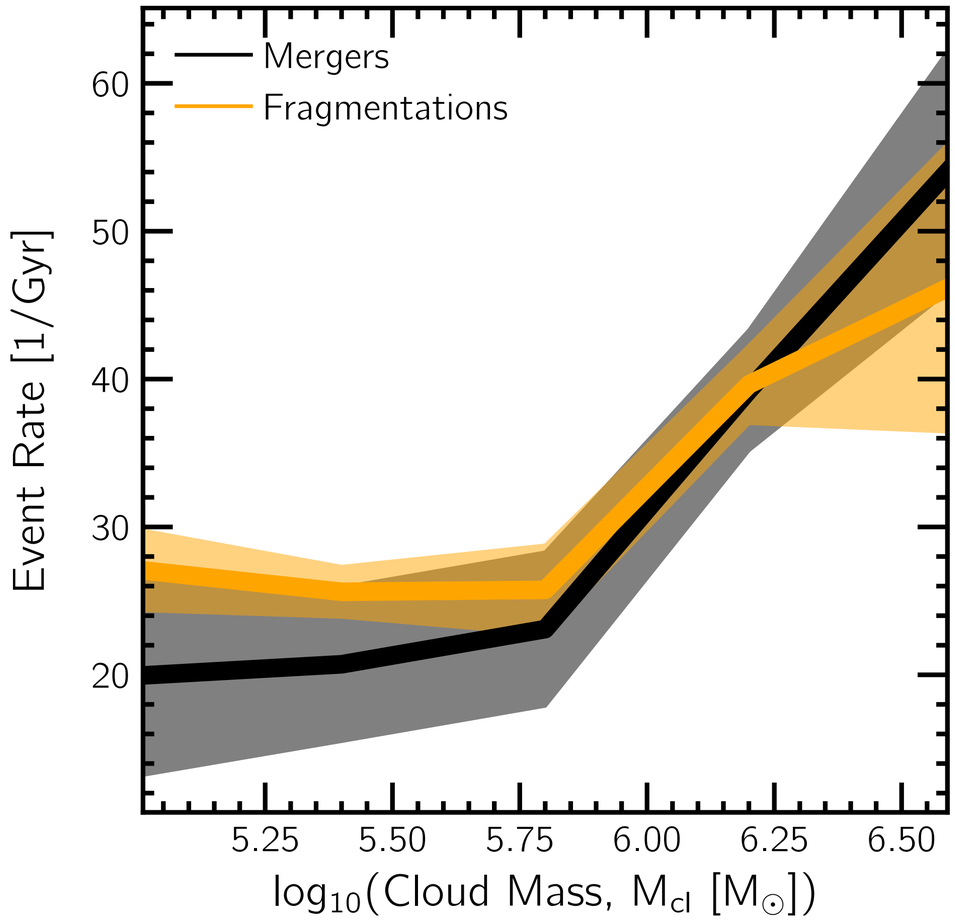

Ramesh+ (2024c)

Towards sub-pc scale resolution

How much further can we increase the mass resolution?

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$$(\text{Cloud Mass} \sim 10^5\ \text{M}_\odot)$$

$$\text{Mass Resolution} \sim 200\ \text{M}_\odot \text{ -> } 8 \text{ cells per cloud radius}$$

Towards sub-pc scale resolution

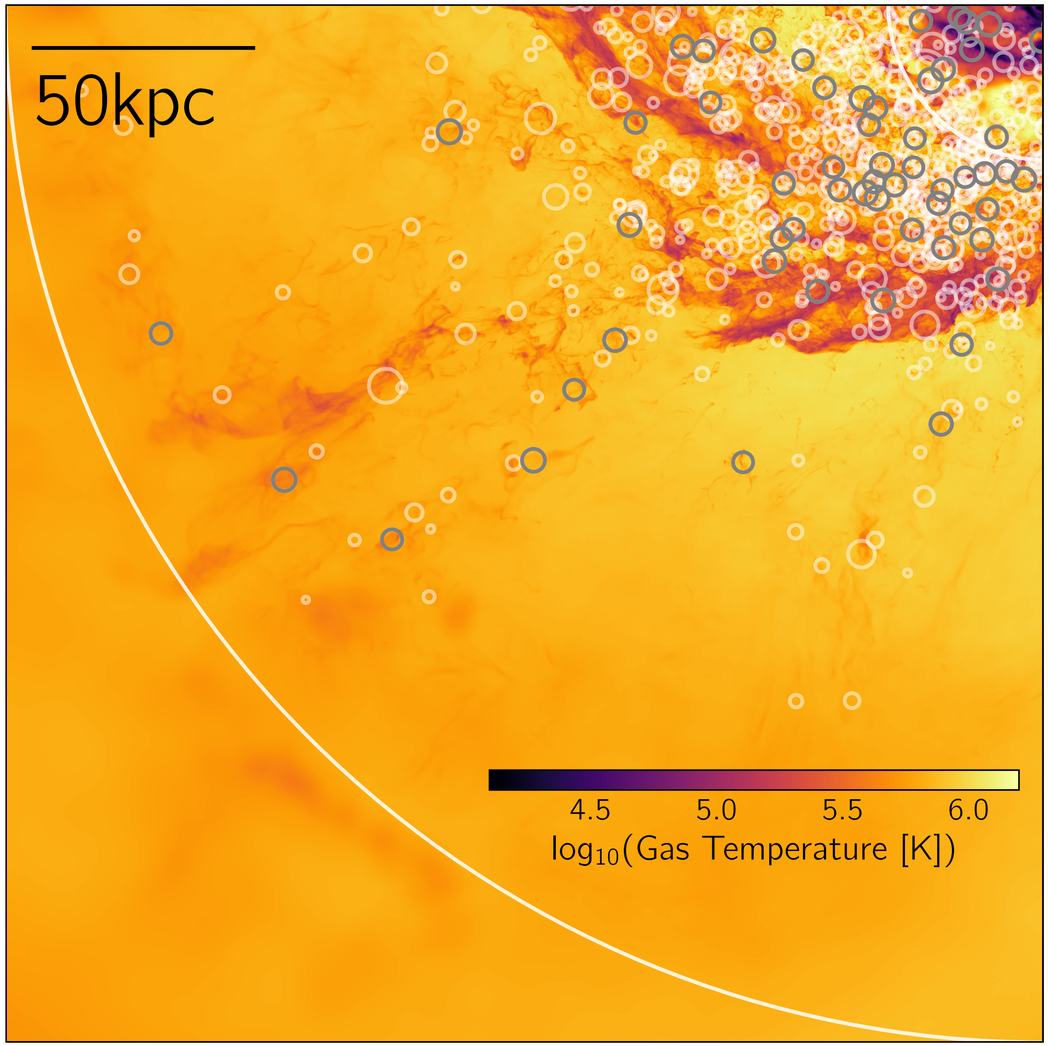
How much further can we increase the mass resolution?

$$(\text{Cloud Mass} \sim 10^5\ M_\odot)$$

$$\text{Mass Resolution} \sim 200\ M_\odot \text{ -> 8 cells per cloud radius}$$

$$\text{Mass Resolution} \sim 0.2\ M_\odot \text{ -> 64 cells per cloud radius}$$

Towards sub-pc scale resolution



Ramesh+ (in prep.)

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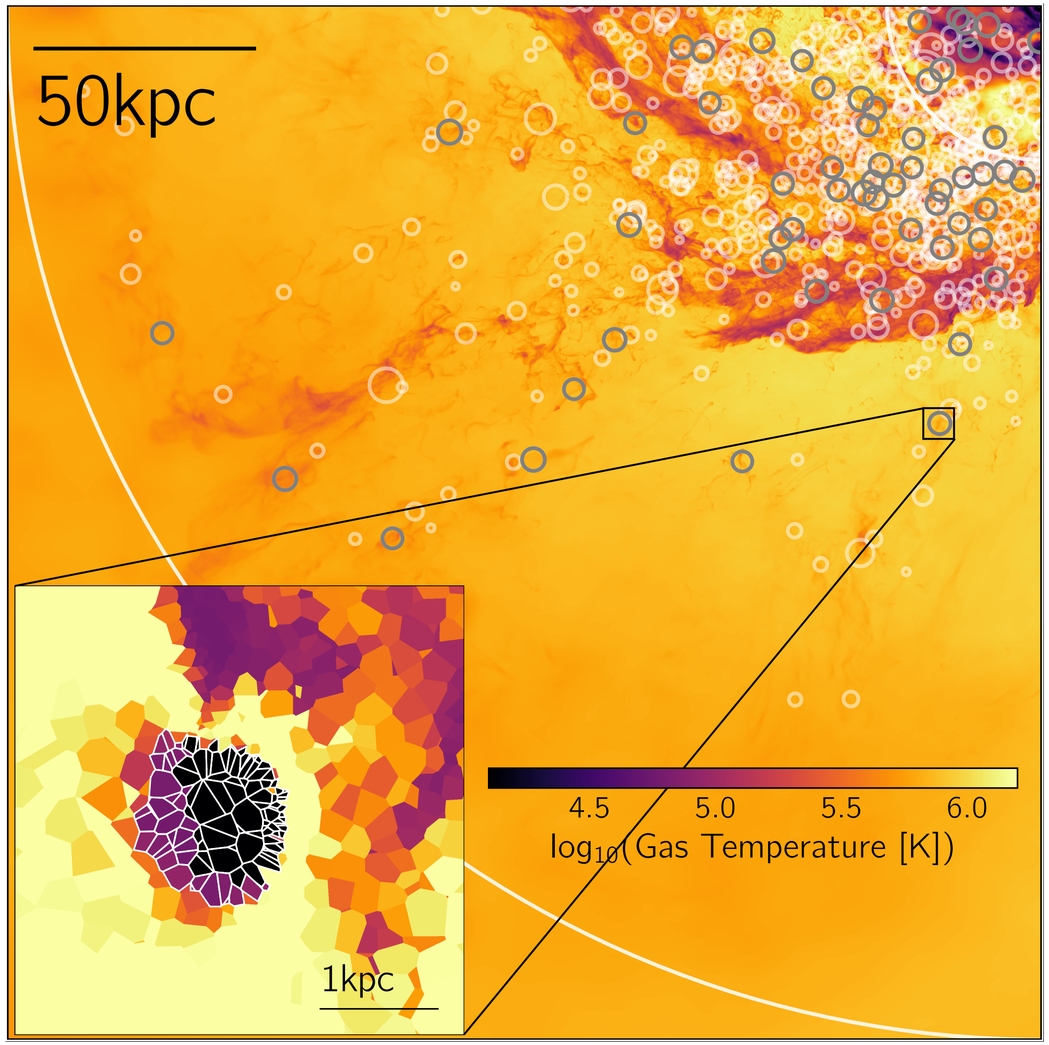

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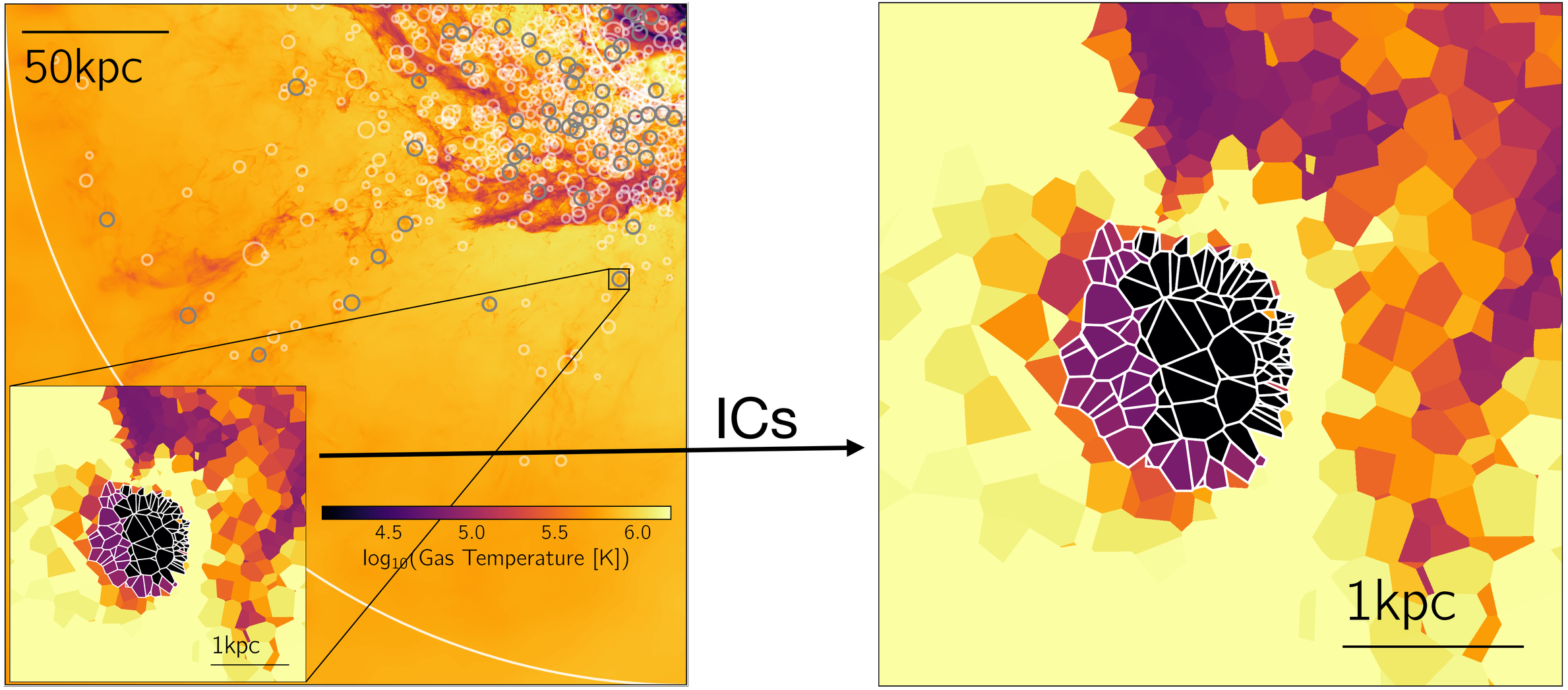
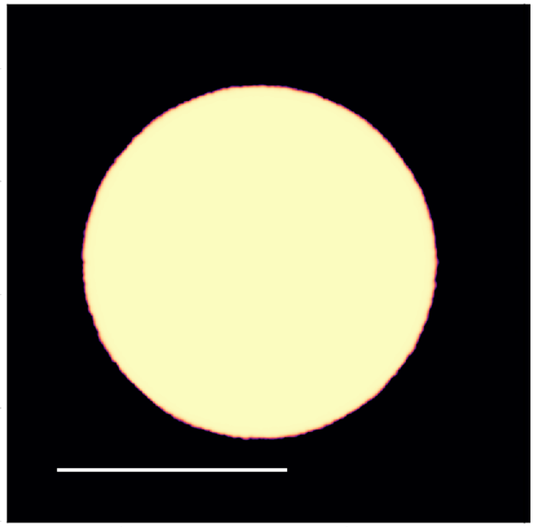


Ramesh+ (in prep.)

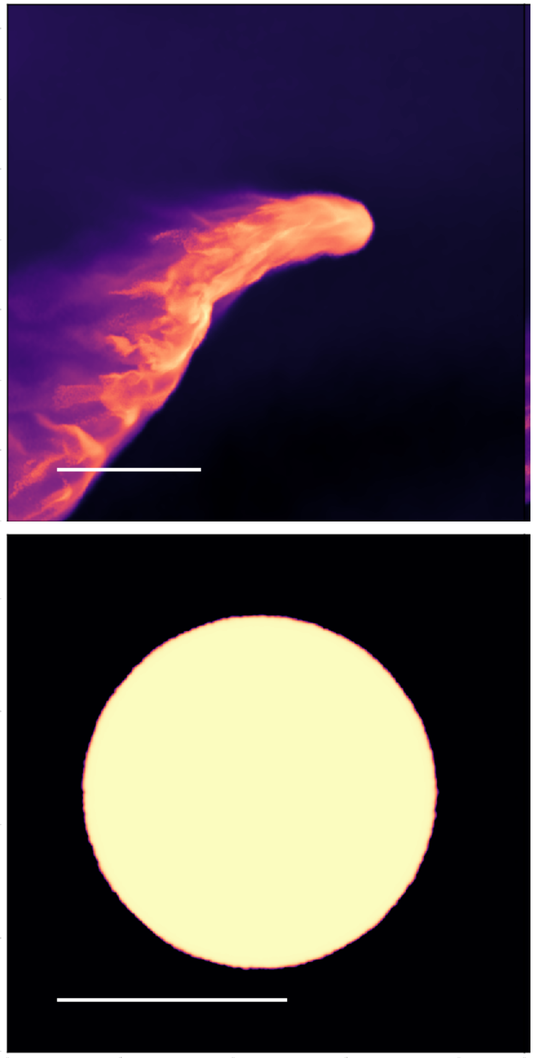
Cosmological Wind Tunnel

Standard Wind-Tunnel



Ramesh+ (in prep.)

Cosmological Wind Tunnel



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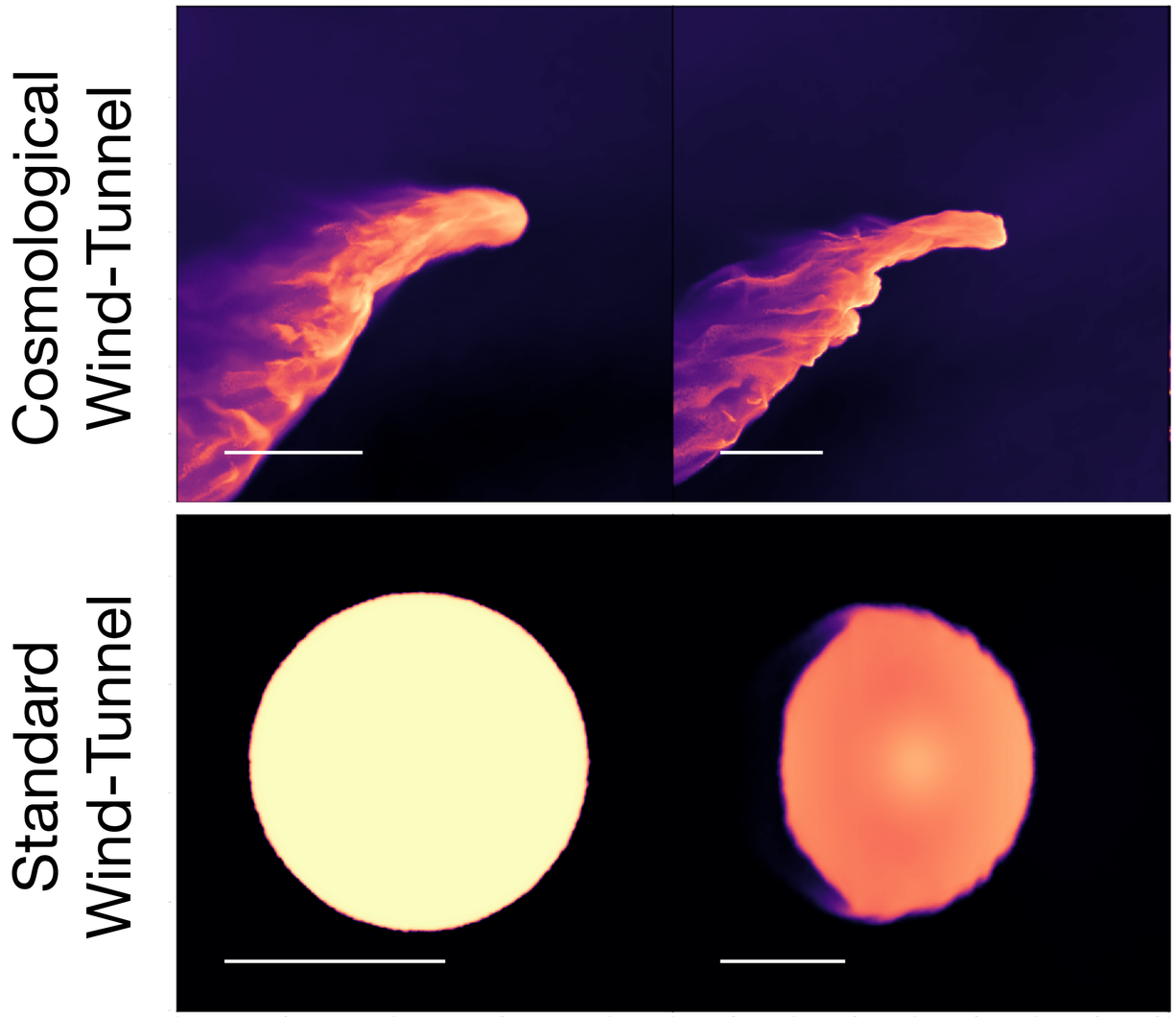

Ramesh+ (in prep.)

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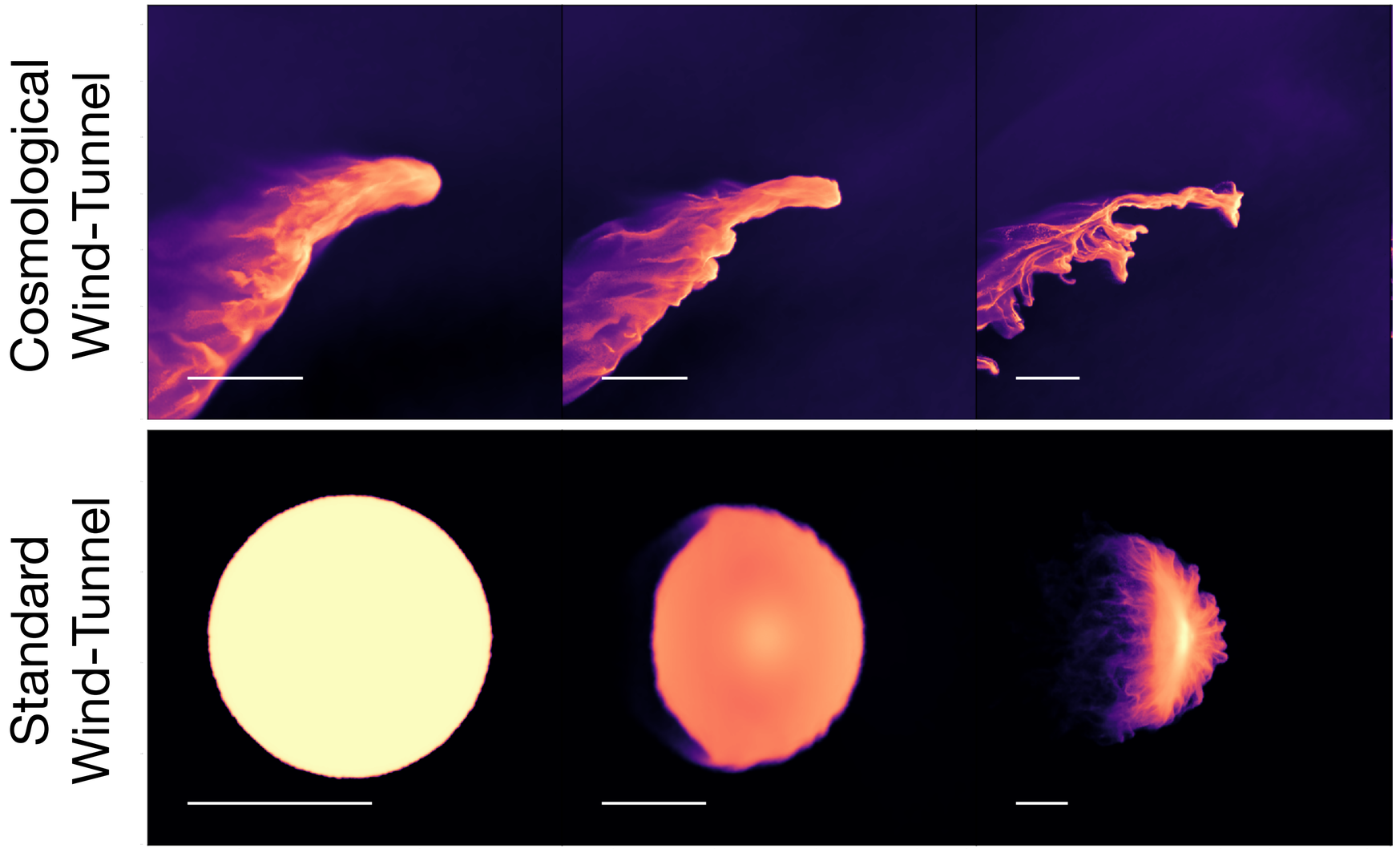

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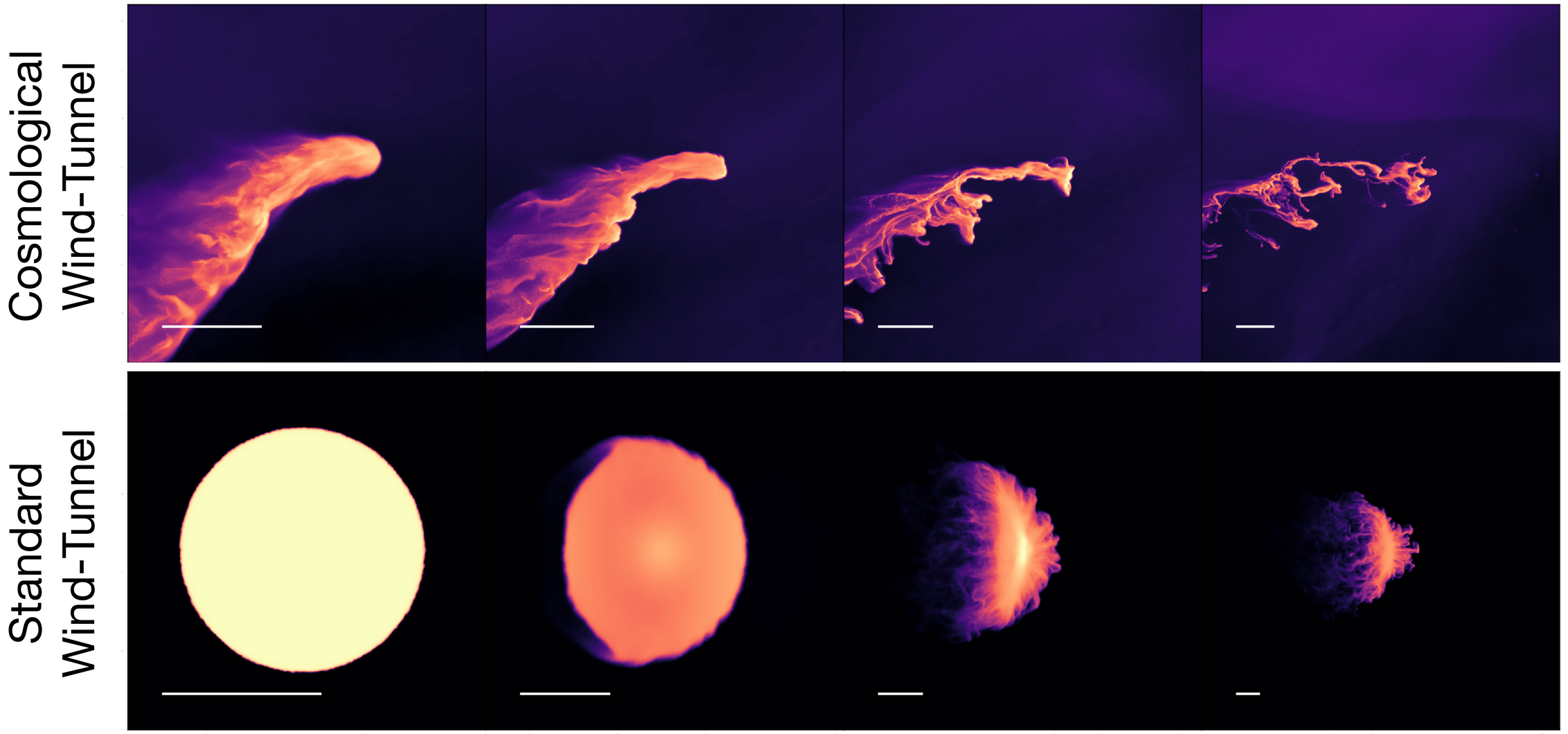

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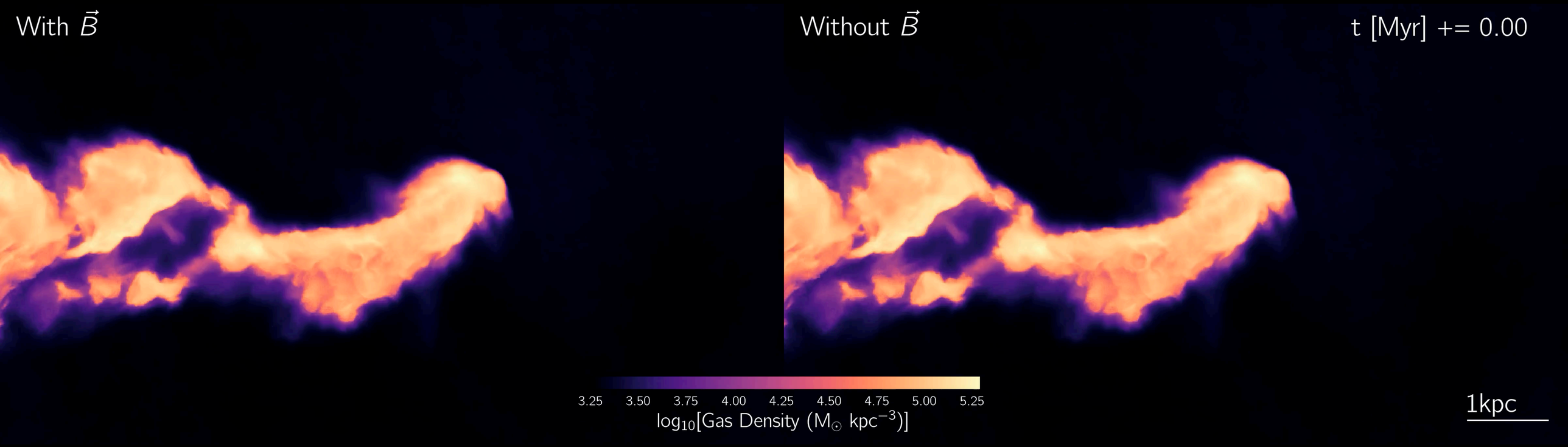

Ramesh+ (in prep.)

Summary

- Milky Way-like galaxies typically contain $\gtrsim$100s-1000s of discrete, cold clouds in their CGMs.

- Although the number of clouds is largely independent of galaxy stellar mass, it correlates strongly with the star formation status, hinting that these clouds may play in important role in refuelling the central cold gas supply.

- Most clouds originate through cold gas outflows from the central galaxy and/or condensation of the hot CGM. Our simulations predict that most, but not all, outflowing (inflowing) HVCs originate from the galaxy (hot CGM).

- Clouds evolve through a combination of flux exchanges with their surroundings, and interactions with their counterparts.

- ‘Cosmological Wind-Tunnels’ offer a promising pathway to study evolution of clouds to an even better extent, in terms of both resolution and variation of physics.