Positive feedback in galaxy formation: connecting small to large scales

Alexander Hobbs
ETH Zürich

w. Justin Read (Uni. Surrey), Chris Power (UWA), Andrina Nicola (ETH Zürich)

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Positive feedback in galaxy formation: connecting small to large scales

with SPHS

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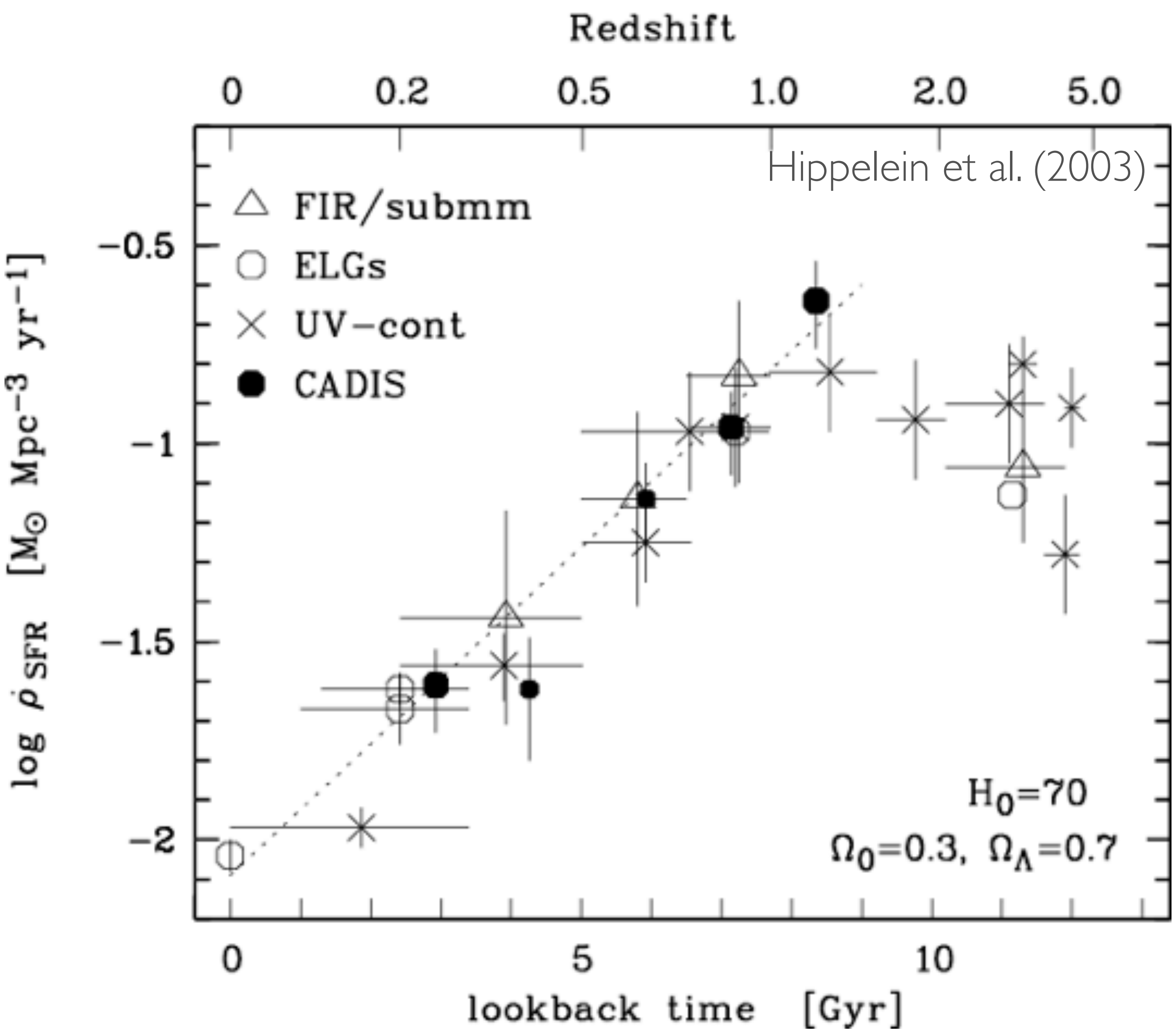
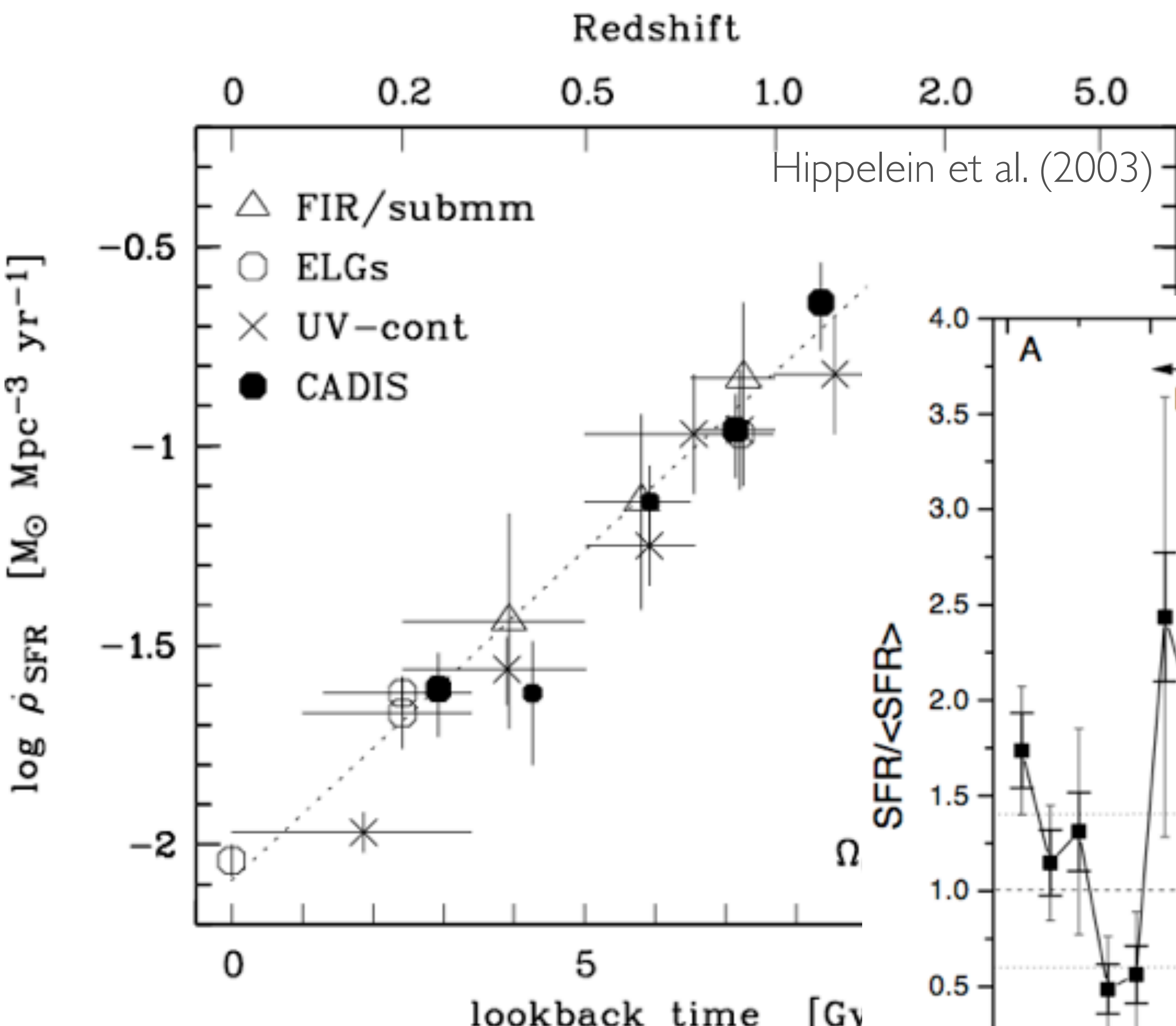
Motivation



Redshift
0
0.2
0.5
1.0
2.0
5.0
Hippelein et al. (2003)
FIR/submm
ELGs
UV−cont
CADIS
log $\dot{\rho}_{SFR}$ [$M_\odot$ Mpc^{-3} yr^{-1}]
−0.5
−1
−1.5
−2
H_0=70
Ω_0=0.3, Ω_Λ=0.7
0
5
10
lookback time [Gyr]

Motivation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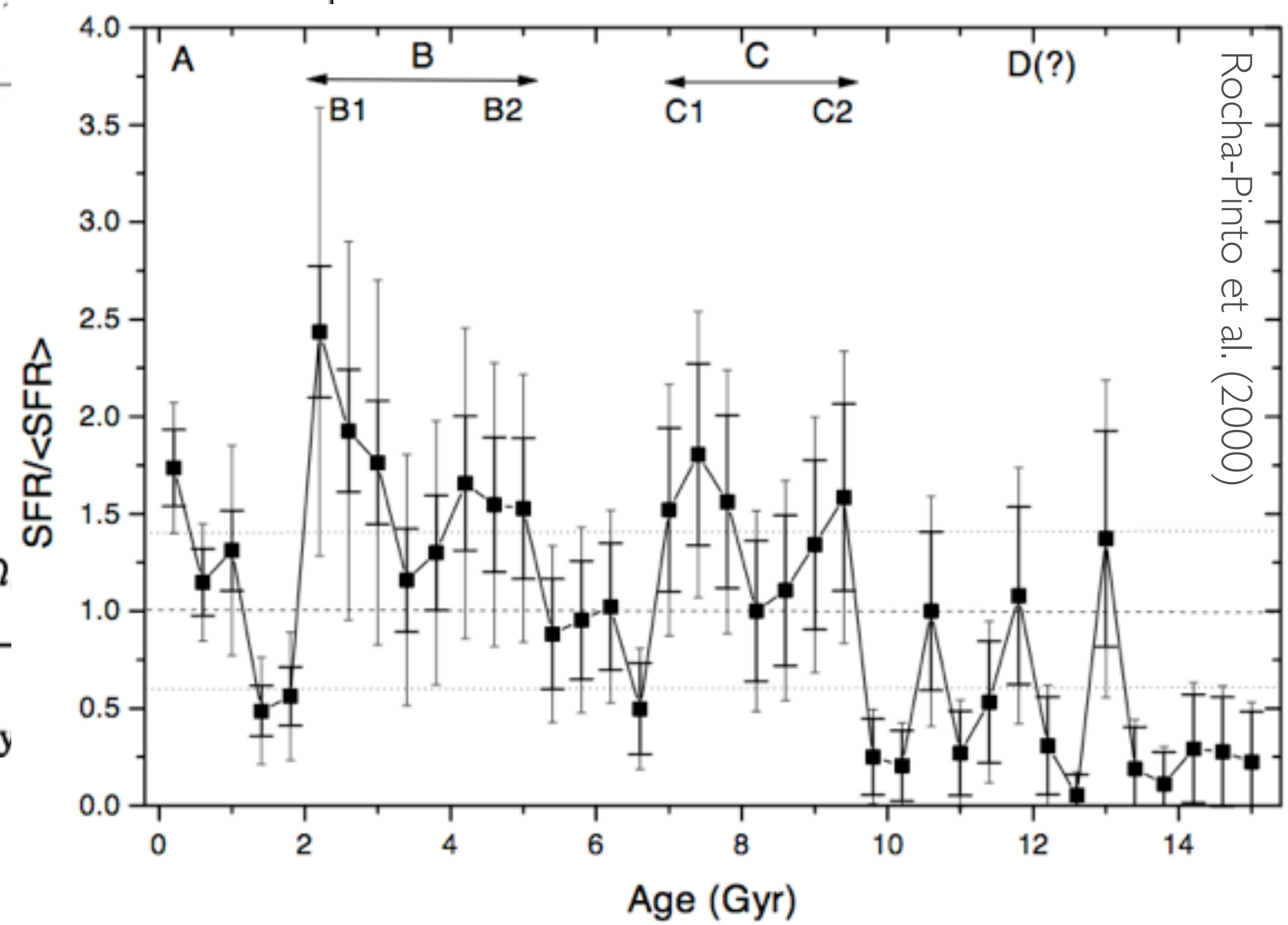
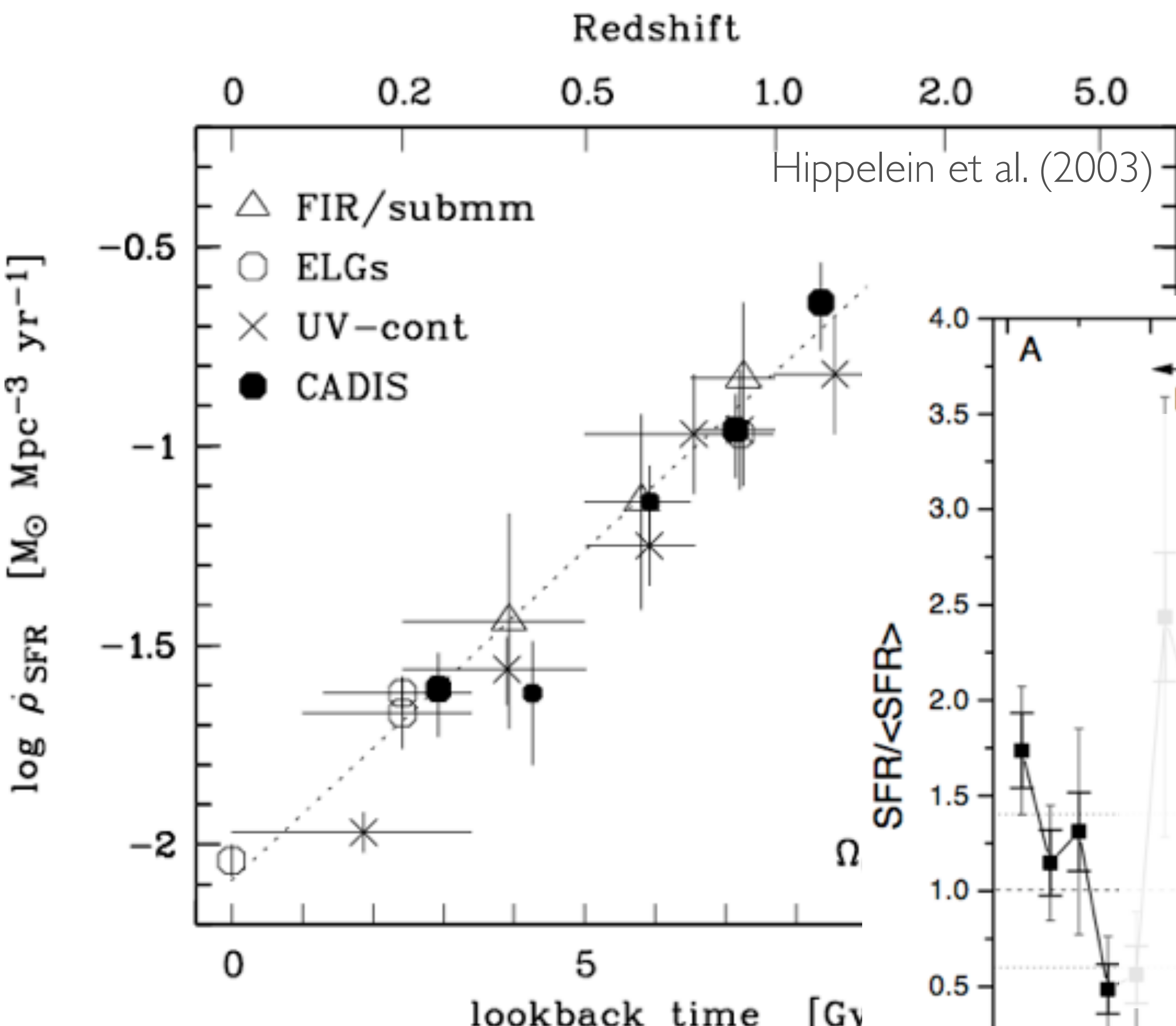
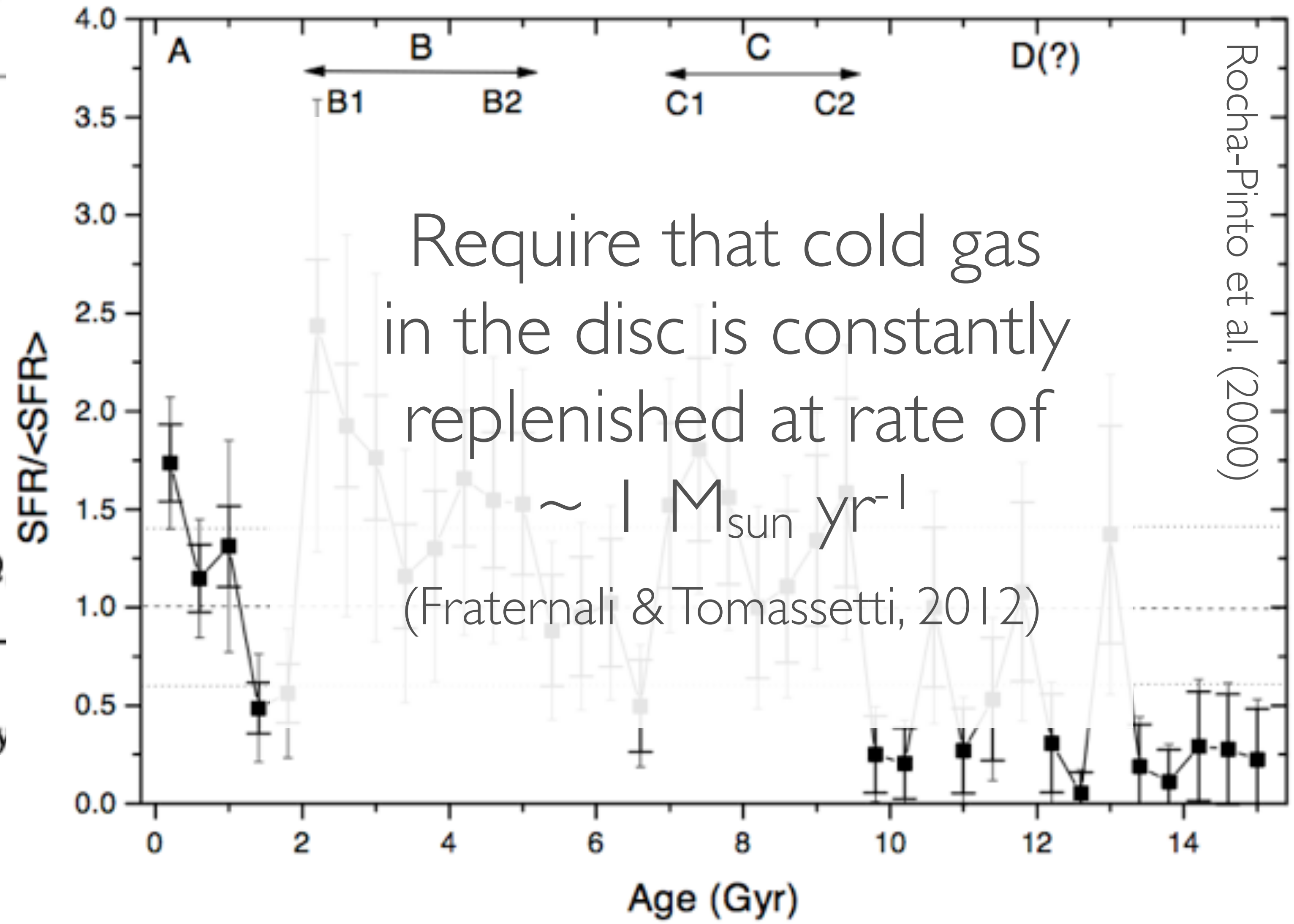

A
B
C
D(?)
B1
B2
C1
C2
Rocha-Pinto et al. (2000)
SFR/<SFR>
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
14
Age (Gyr)

Motivation



Hippelein et al. (2003)



Rocha-Pinto et al. (2000)

Require that cold gas in the disc is constantly replenished at rate of ~ 1 M_{sun} yr^{-1}

(Fraternali & Tomassetti, 2012)

Motivation

- Majority of MW baryons in extra-Galactic diffuse medium (e.g. Gupta et al. 2012)

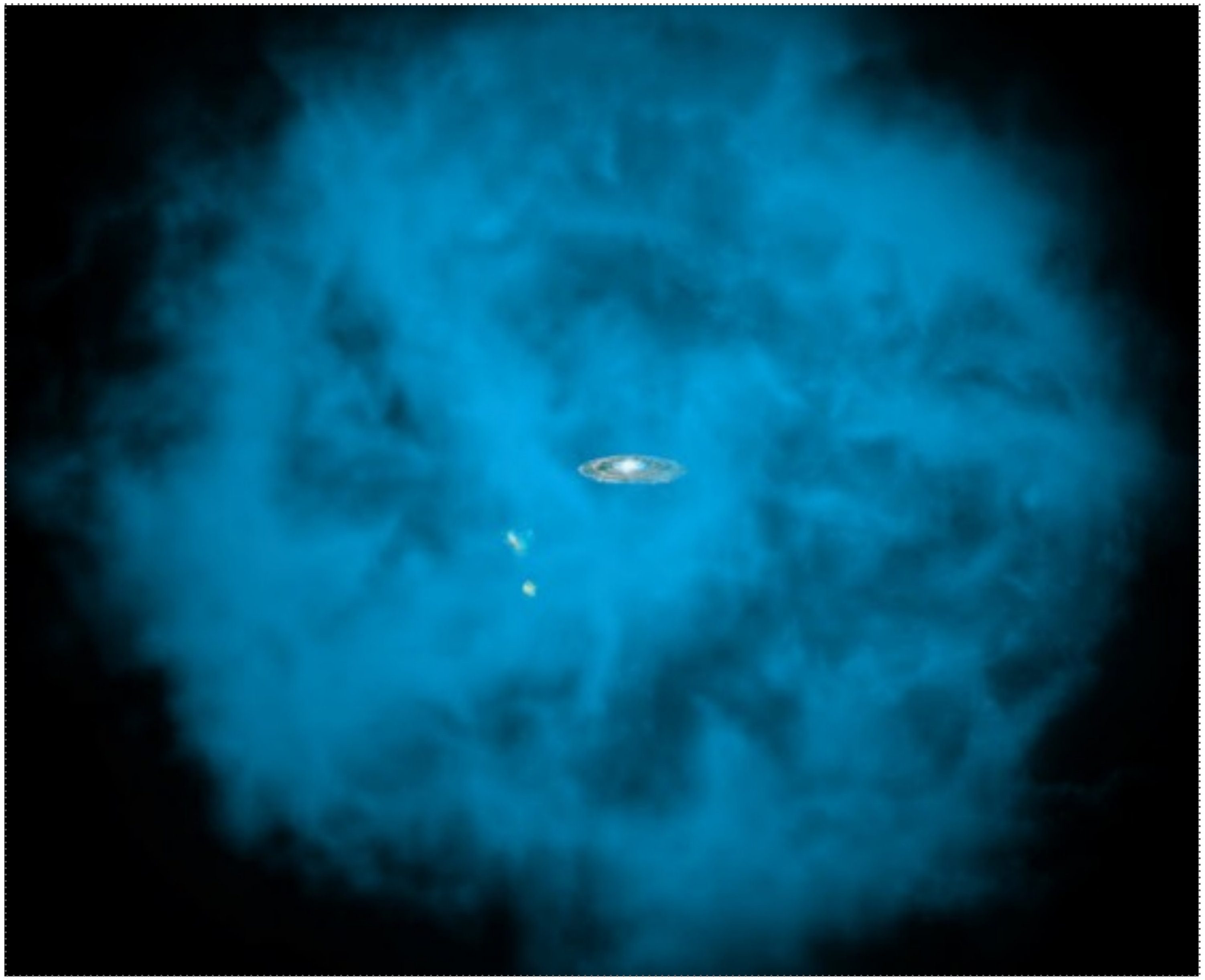
- Extends beyond ~ 100 kpc

- T ~ 10^6 K

- Mass ~ 10^{10} M_{sun}

- Detected via:
    - (i) X-ray emitting gas
    - (ii) quasar absorption lines
    - (iii) pulsar dispersion measures
    - (iv) Galactic baryon deficiency
    - (v) ram pressure stripping of Magellanic stream + dwarfs

Figure credit: NASA/CXC/M.Weiss; NASA/CXC/Ohio State/A. Gupta et al.



Motivation

- General models of galaxy formation require self-regulation of gas e.g., the 'bathtub' model (Lilly et al. 2013, and see also Bouché et al. 2010)

- Try to answer the specifics of how this occurs with simulations

- Galaxy formation simulations in full require a great deal of physics + huge range of scales + large amounts of analysis

- Can often learn more from smaller, dedicated simulations
    - Although very important to include the relevant physics + sub-grid models

Galaxy formation with SPHS

SPHS - Smoothed Particle Hydrodynamics
with a higher order dissipation Switch
(Read & Hayfield 2012)

Other flavours:
Ritchie & Thomas 2001
Price 2008
Wadsley et al. 2008
Cullen & Dehnen 2010
Hopkins 2012
Kawata et al. 2013a
"Anarchy"

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'Classic' SPH
cf. Springel (2005)

Galaxy formation with SPHS

- Cooling hot gaseous halo (e.g., Kaufmann et al. 2006, 07, 09) forming MW

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  - Late (smooth) accretion mode corresponding to main disk formation phase
    (Abadi et al. 2003, Sommer-Larsen et al. 2003, Governato et al. 2004)

Galaxy formation with SPHS

- Cooling hot gaseous halo (e.g., Kaufmann et al. 2006, 07, 09) forming MW
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$$\rho(r) = \frac{A\,\mathrm{sech}\,(r/r_t)}{(r/r_s)^{7/9}\left[1+(r/r_s)^{4/9}\right]^6}$$

Dehnen & McLaughlin (2005)

$r_t = 200$ kpc

$r_s = 40$ kpc

$M_{halo} \approx 1.9 \times 10^{12}\, M_{sun}$

$M_{gas} \approx 1.9 \times 10^{11}\, M_{sun}$

$$T(r) = \frac{\mu}{k_\mathrm{B}} \frac{1}{\rho_\mathrm{gas}(r)} \int_r^\infty \rho_\mathrm{gas}(r) \frac{GM(r)}{r^2}\, dr$$

Mastropietro et al. (2005), Kaufmann et al. (2007)

$$\lambda_\mathrm{gas} = \frac{j_\mathrm{gas}|E_\mathrm{halo}|^{1/2}}{GM_\mathrm{halo}^{3/2}}$$

Peebles 1969, Bullock et al. 2001b

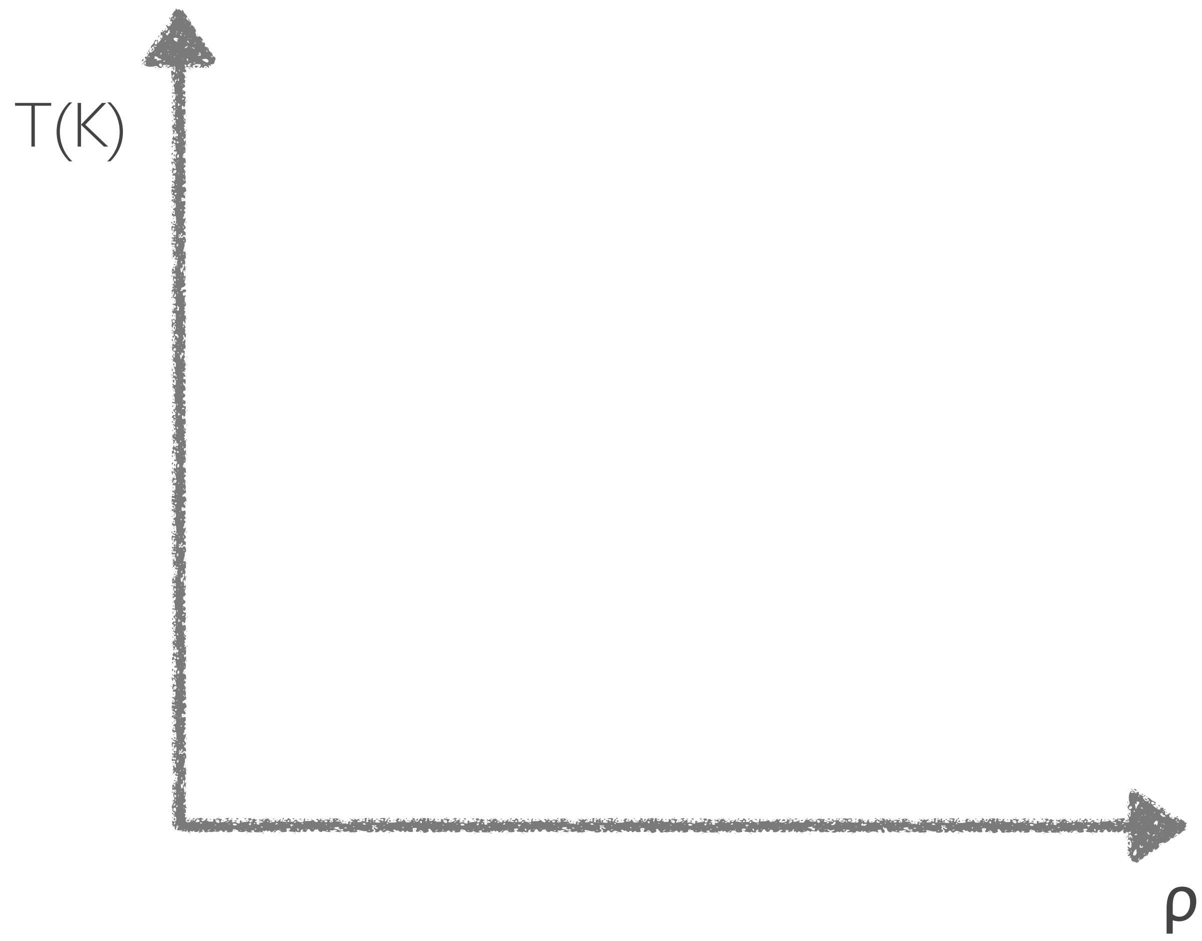
$j_{gas} \propto r^{1.0}$

$\lambda = 0.038$

Simulation

ICs relaxed with adiabatic EQS to eliminate Poisson noise

- Using HOCT442 kernel (reduces particle noise)



Simulation

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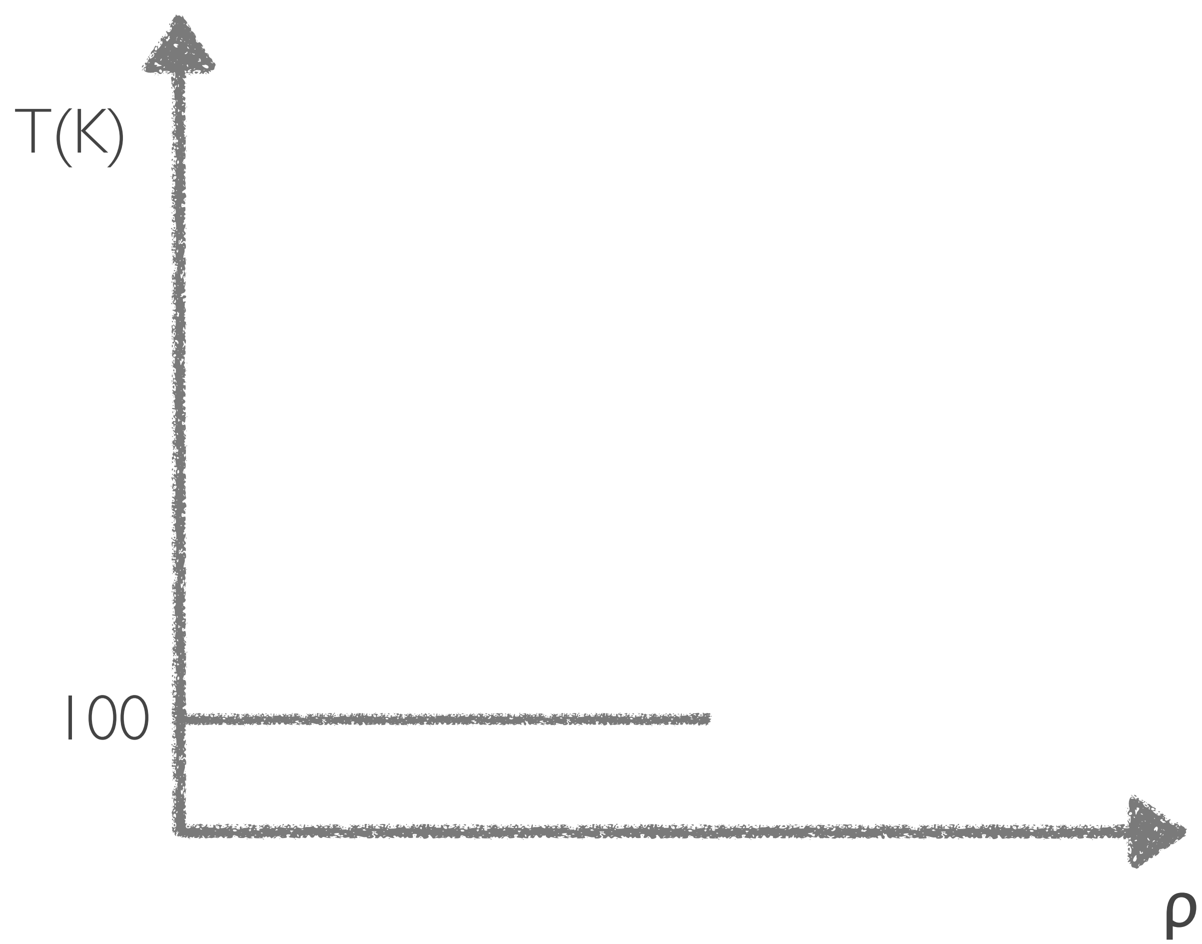
Radiative cooling

- T_{floor} = 100 K



Simulation

ICs relaxed with adiabatic EQS to eliminate Poisson noise

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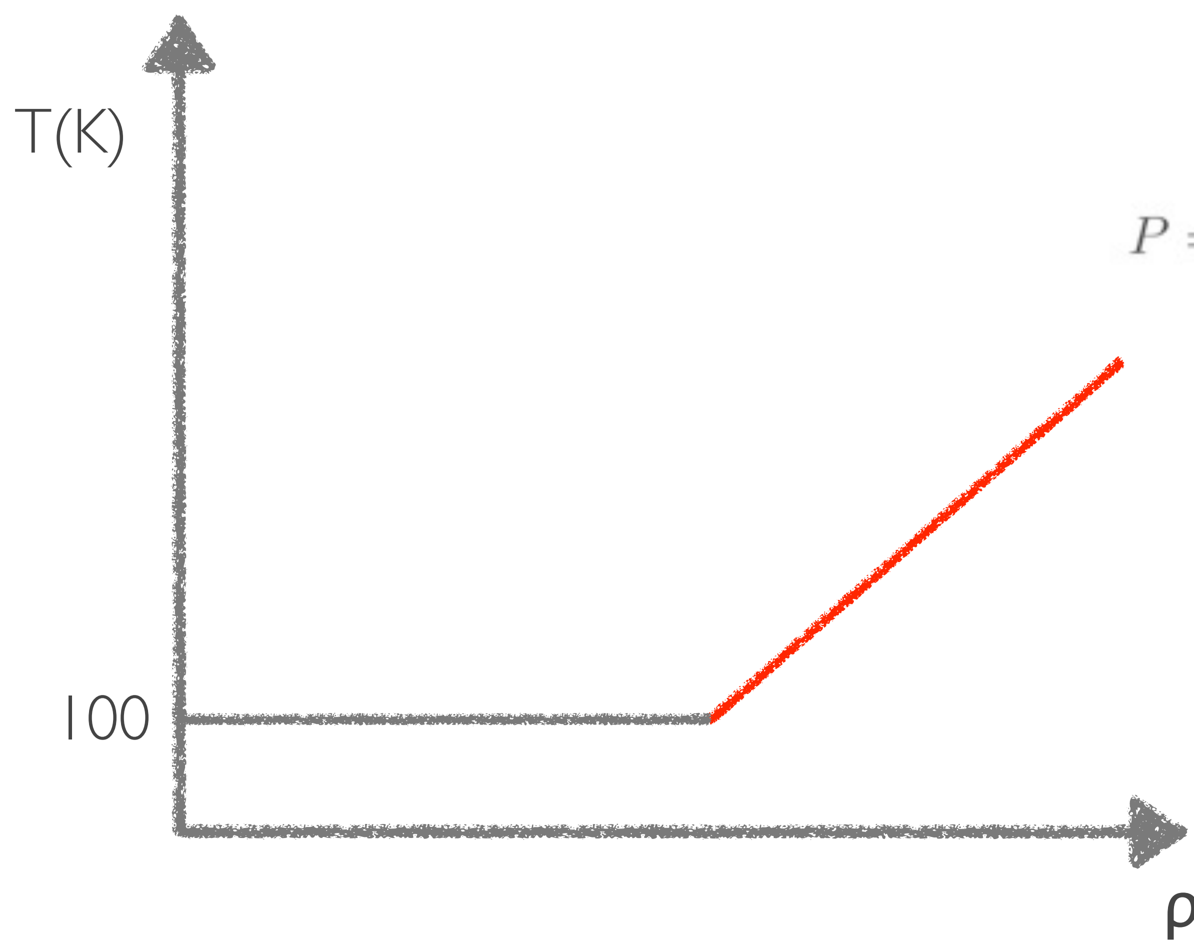
Radiative cooling

- T_{floor} = 100 K
- Ensure Jeans mass resolved with $M_{res} = N_{res}\, m_{sph}$

$$\rho_{\rm J} = \left(\frac{\pi k T}{\mu m_p G}\right)^3 \left(\frac{1}{M_{\rm res}}\right)^2$$



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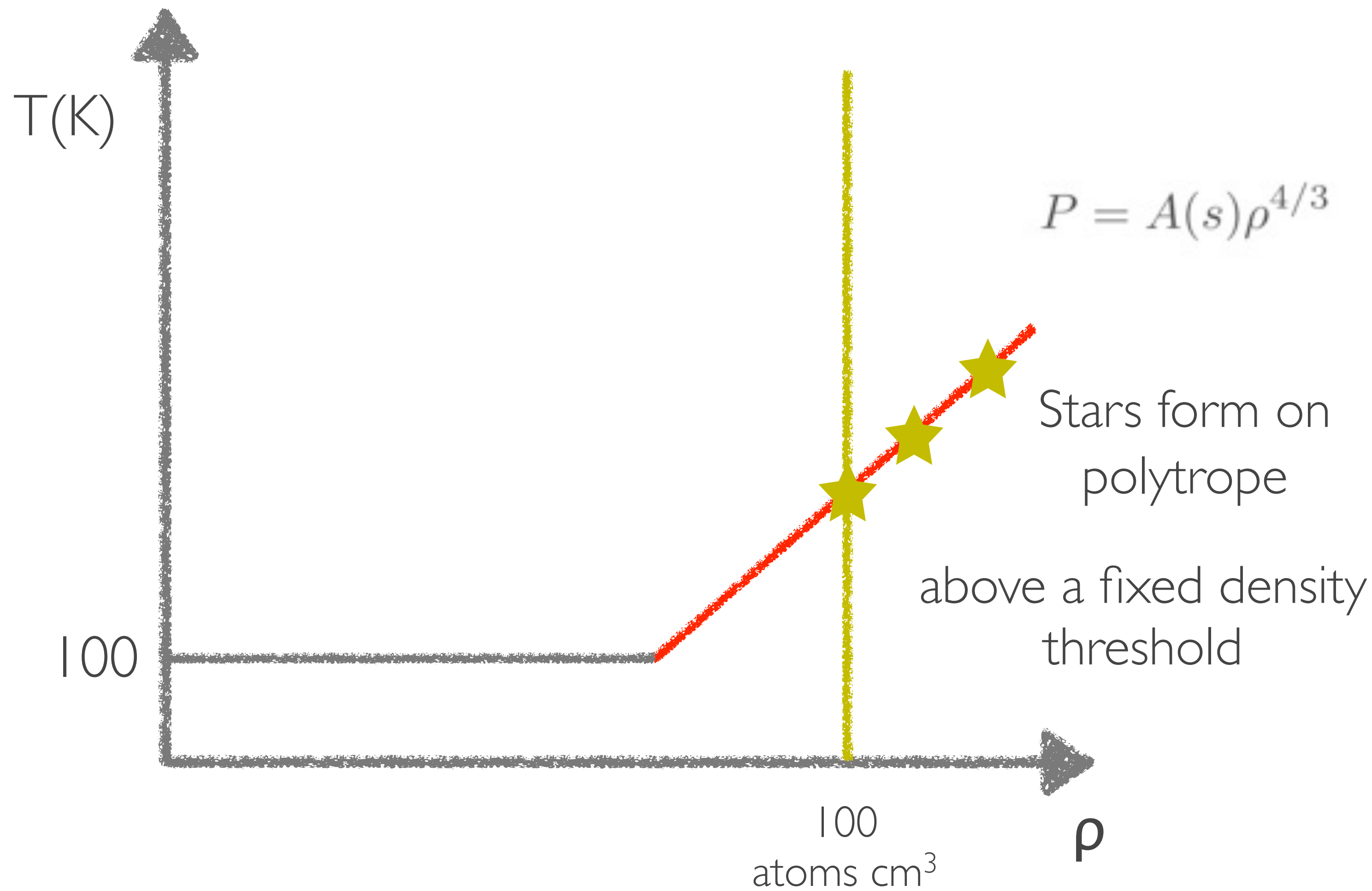
$$\rho_J = \left(\frac{\pi k T}{\mu m_p G}\right)^3 \left(\frac{1}{M_{res}}\right)^2$$



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- T_{floor} = 100 K
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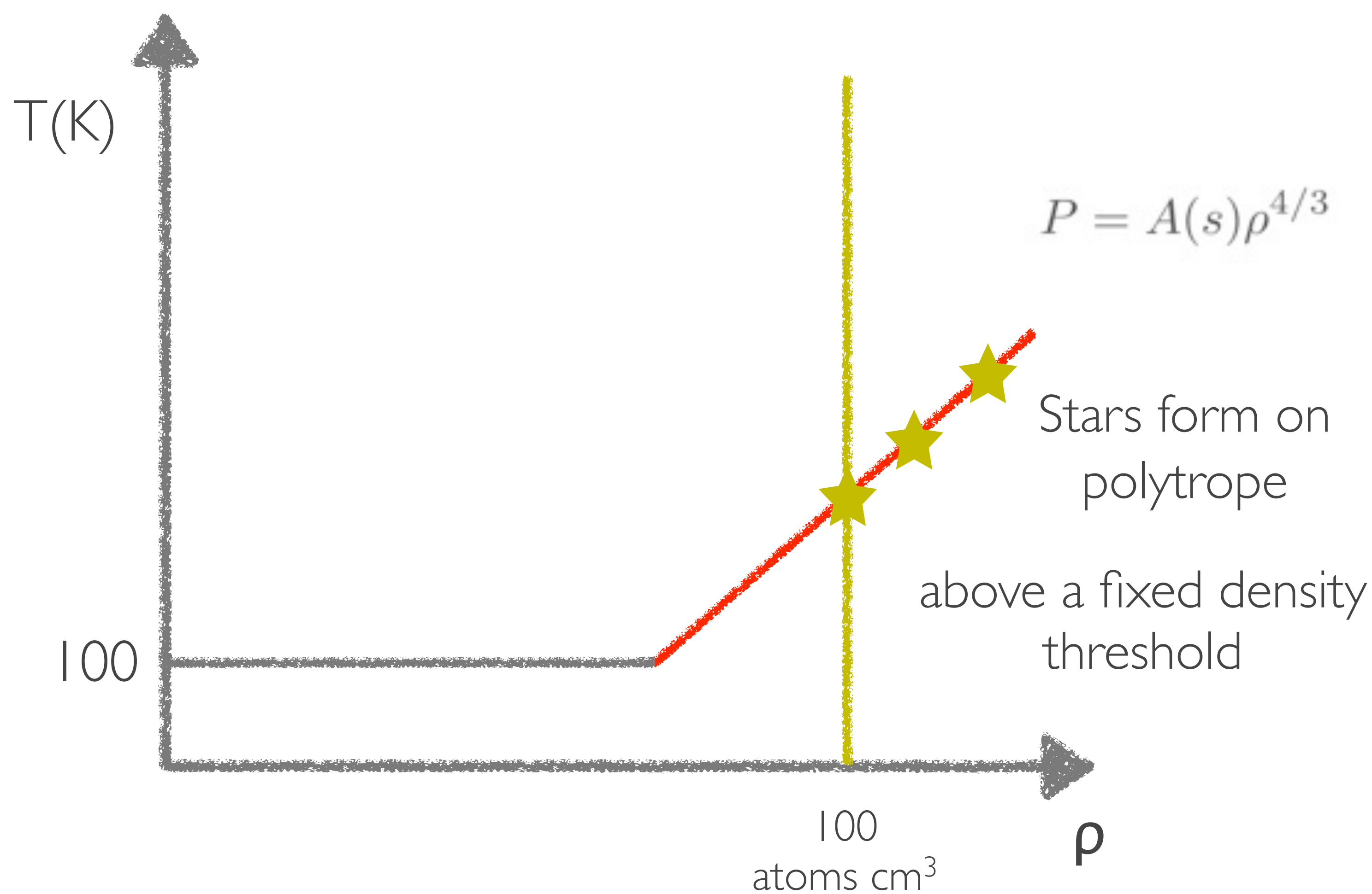
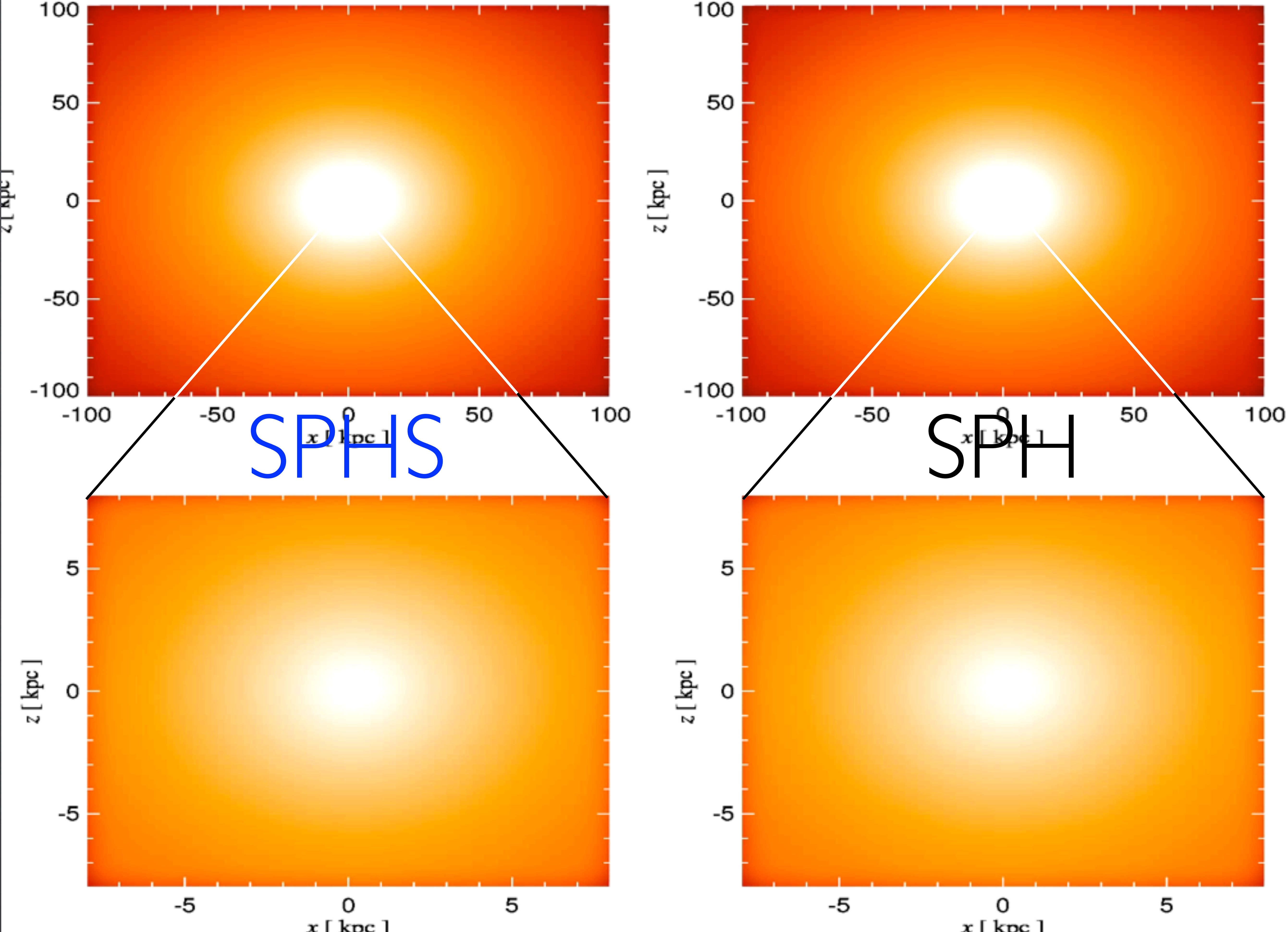
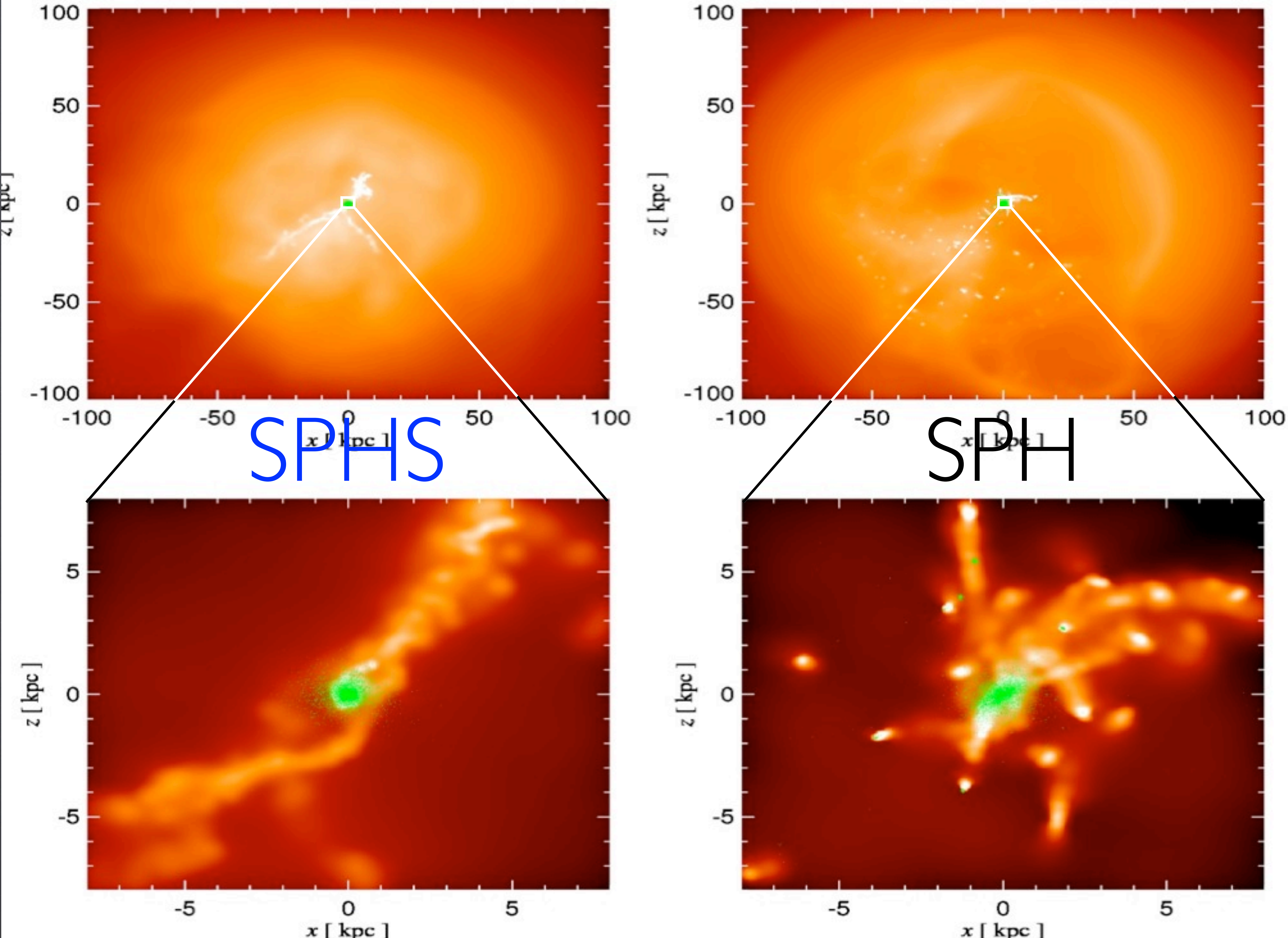
$$\rho_J = \left(\frac{\pi k T}{\mu m_p G}\right)^3 \left(\frac{1}{M_{res}}\right)^2$$

- $M_{gas} \approx 4 \times 10^4\, M_{sun}$
- $M_{res} \approx 5 \times 10^6\, M_{sun}$





Hobbs, Read, Power & Cole 2013; http://arxiv.org/abs/1207.3814



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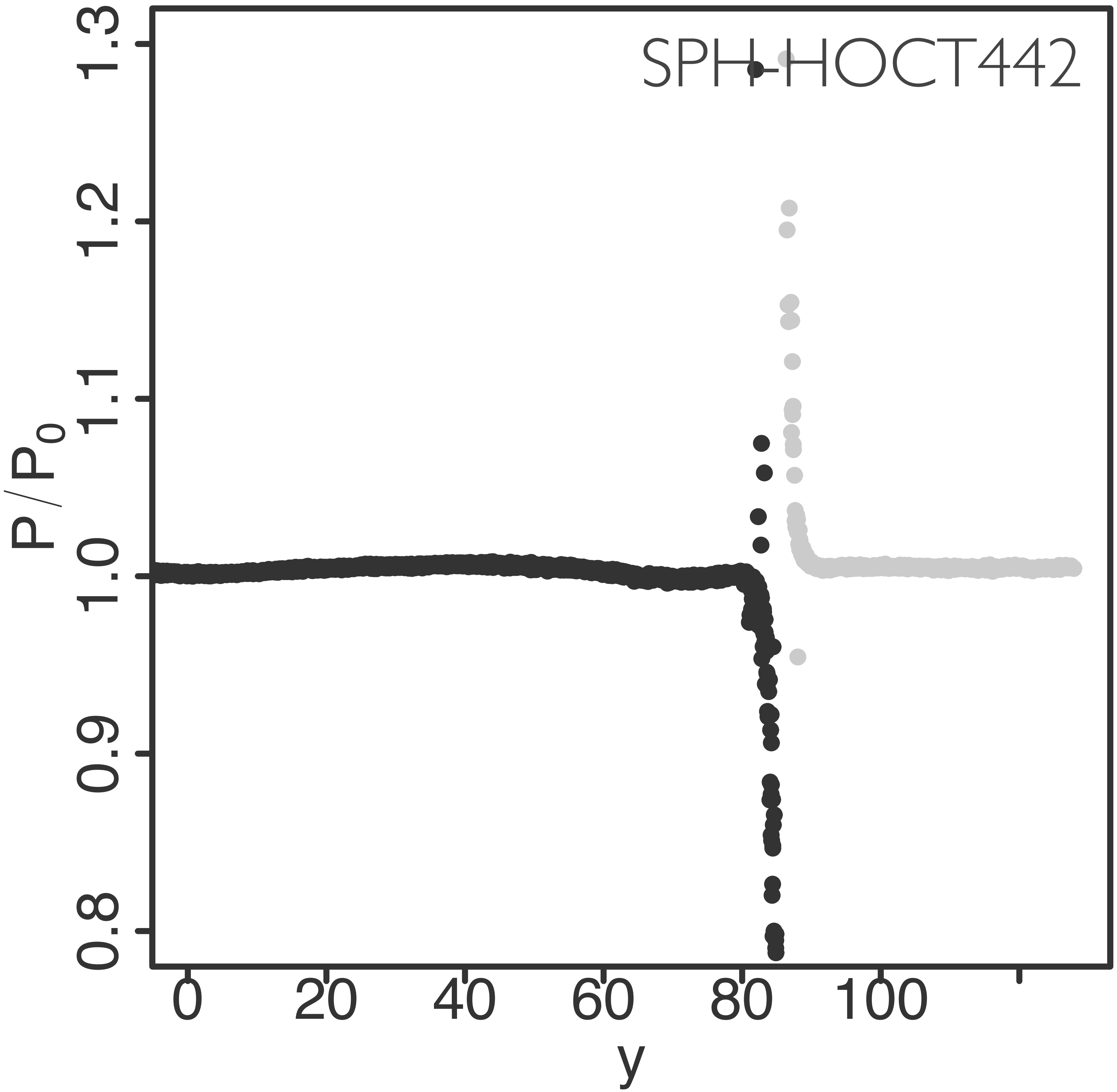
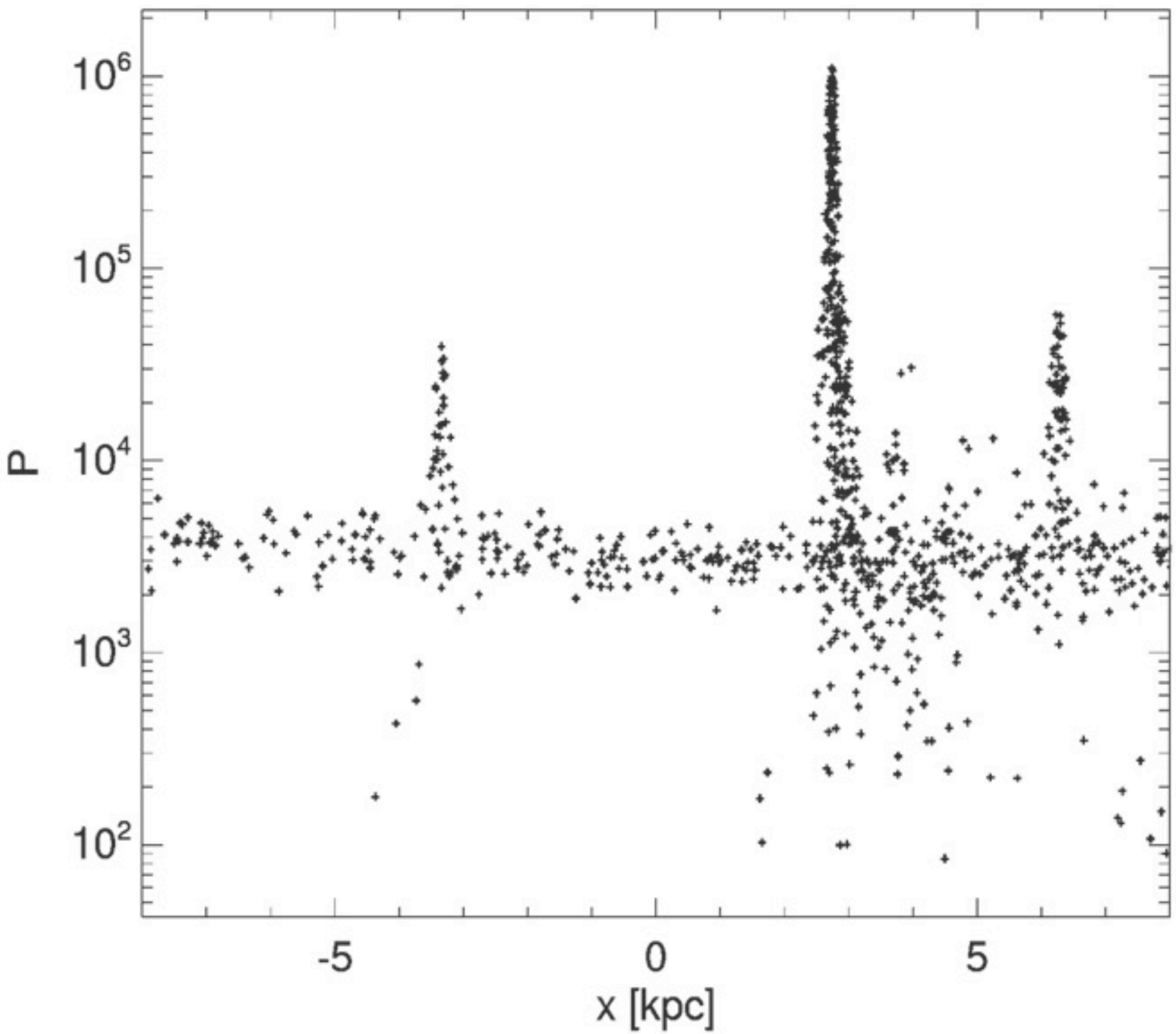
Multivalued pressures - the problem

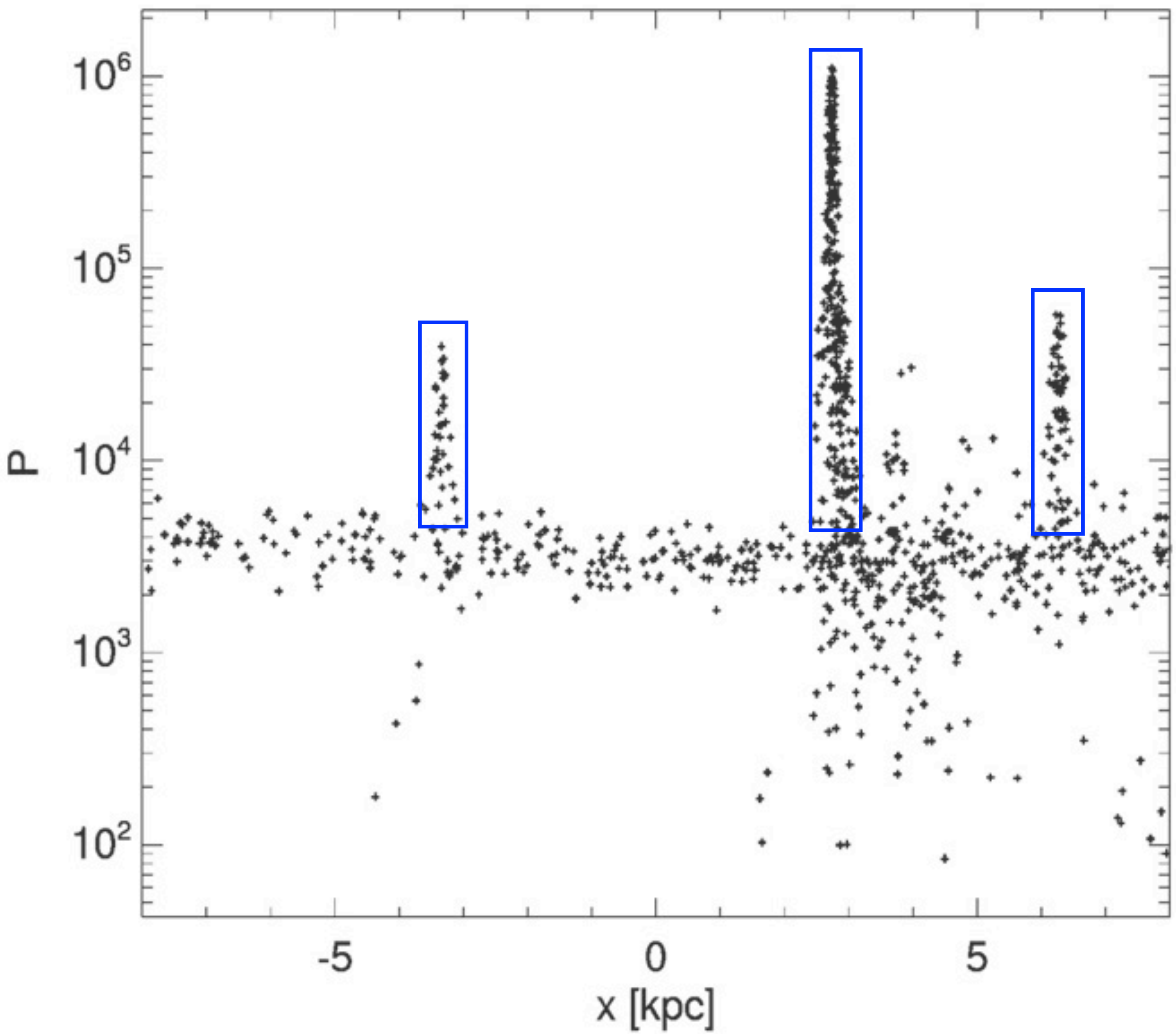


Read, Hayfield & Agertz 2010 (RHA10); Read & Hayfield 2012

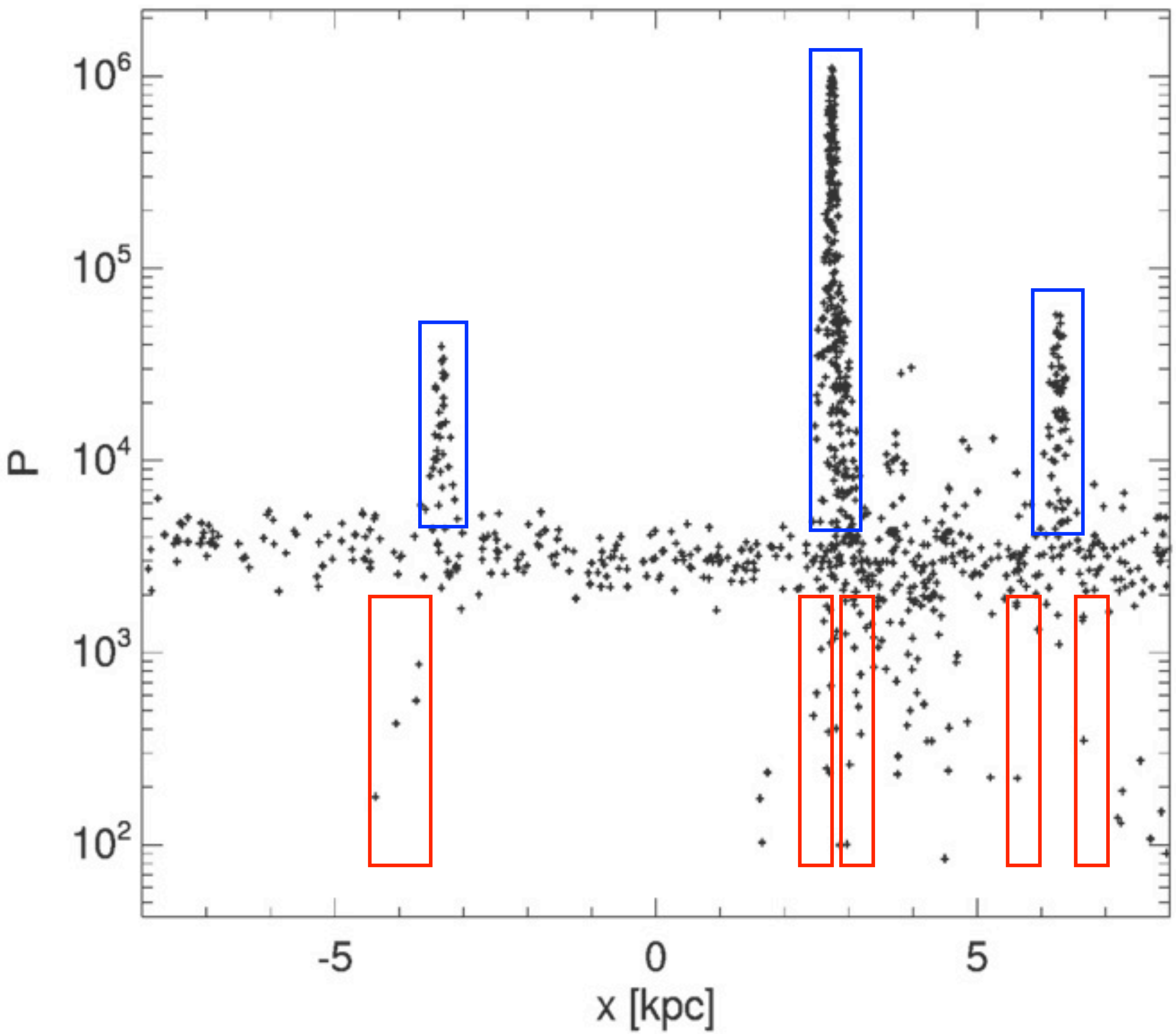
Multivalued pressures - in galaxy formation simulations



Multivalued pressures - in galaxy formation simulations



Multivalued pressures - in galaxy formation simulations



SPHS

SPH

P

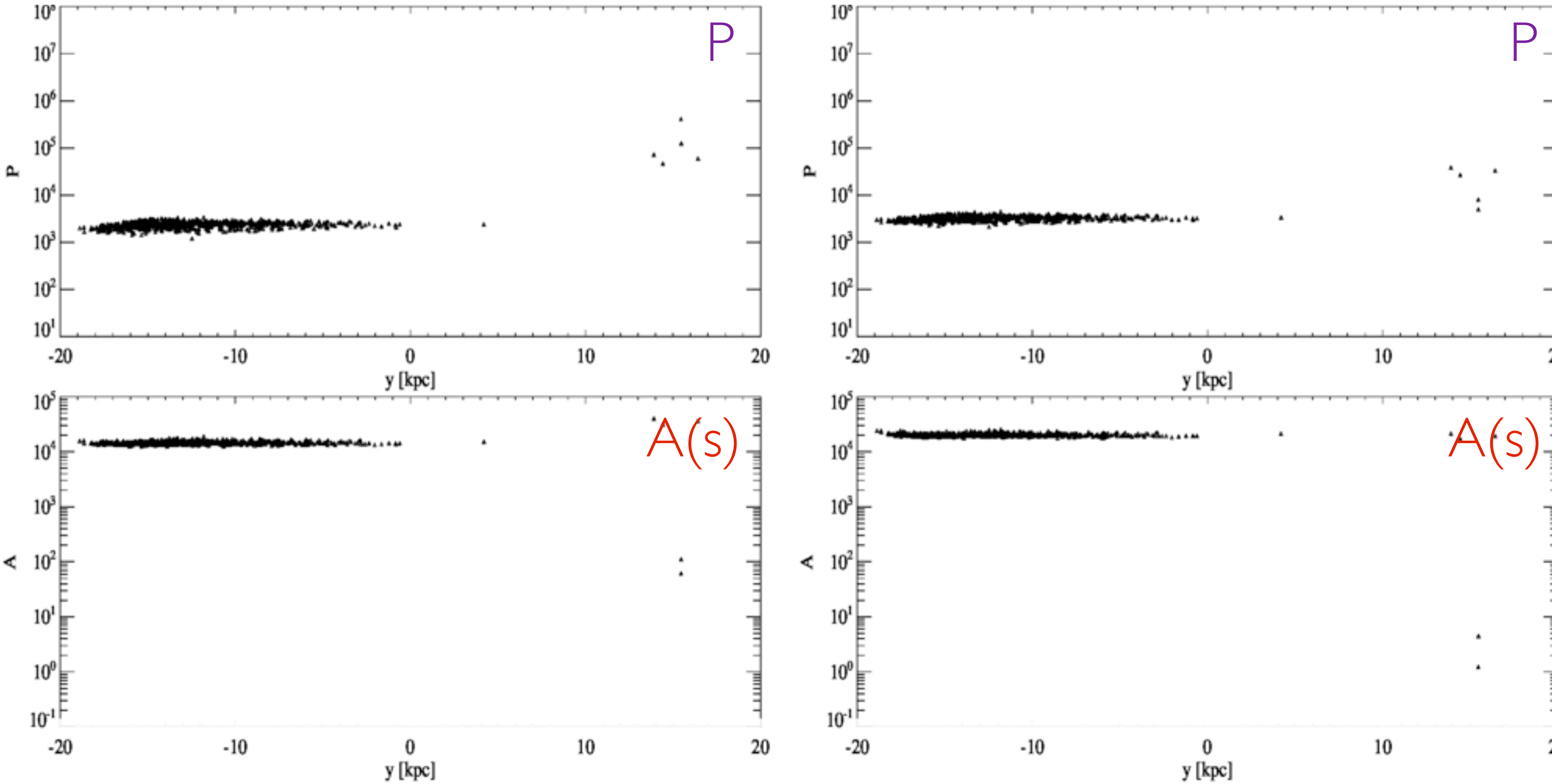
P

A(s)

A(s)

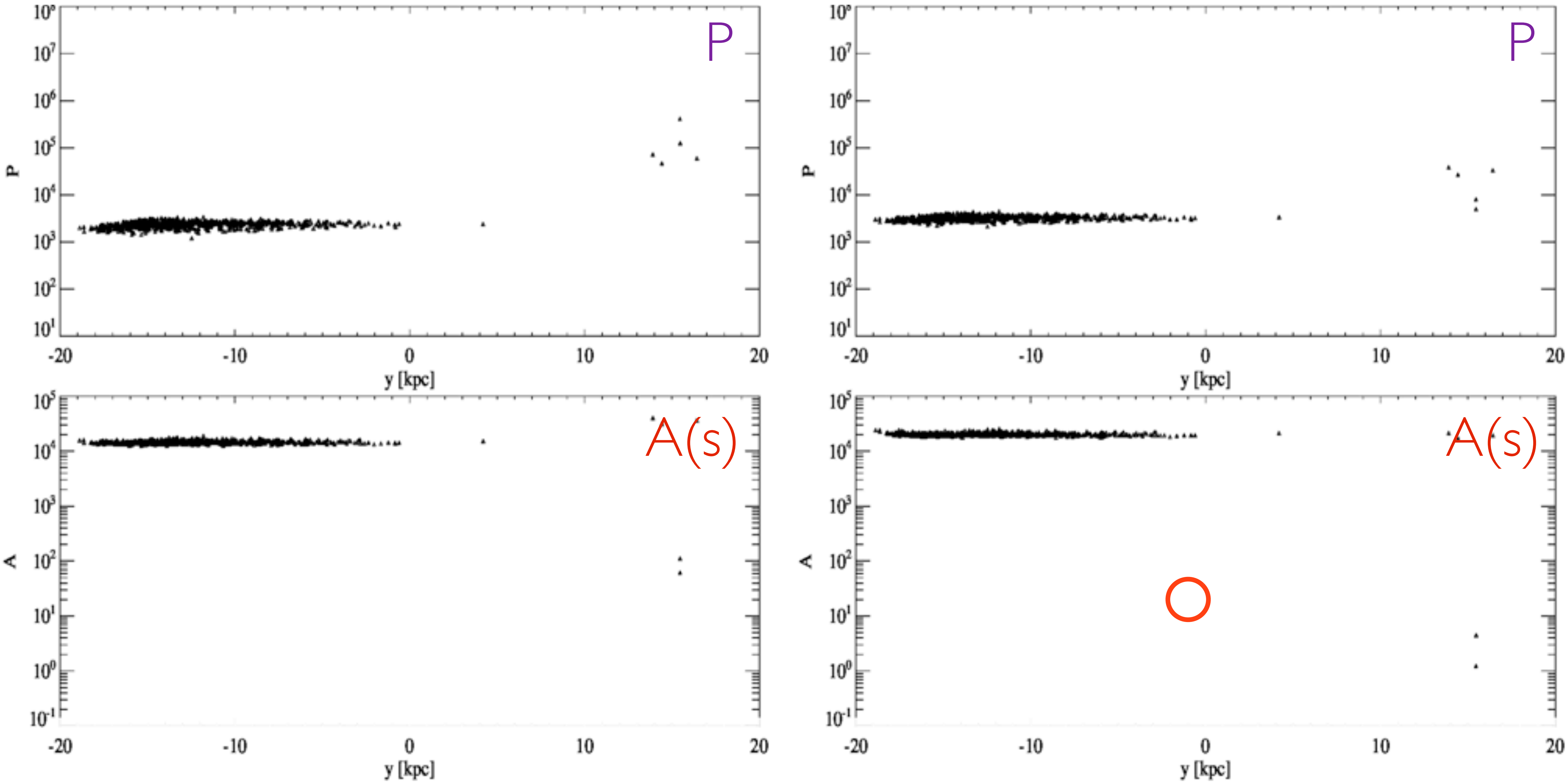
SPHS

SPH



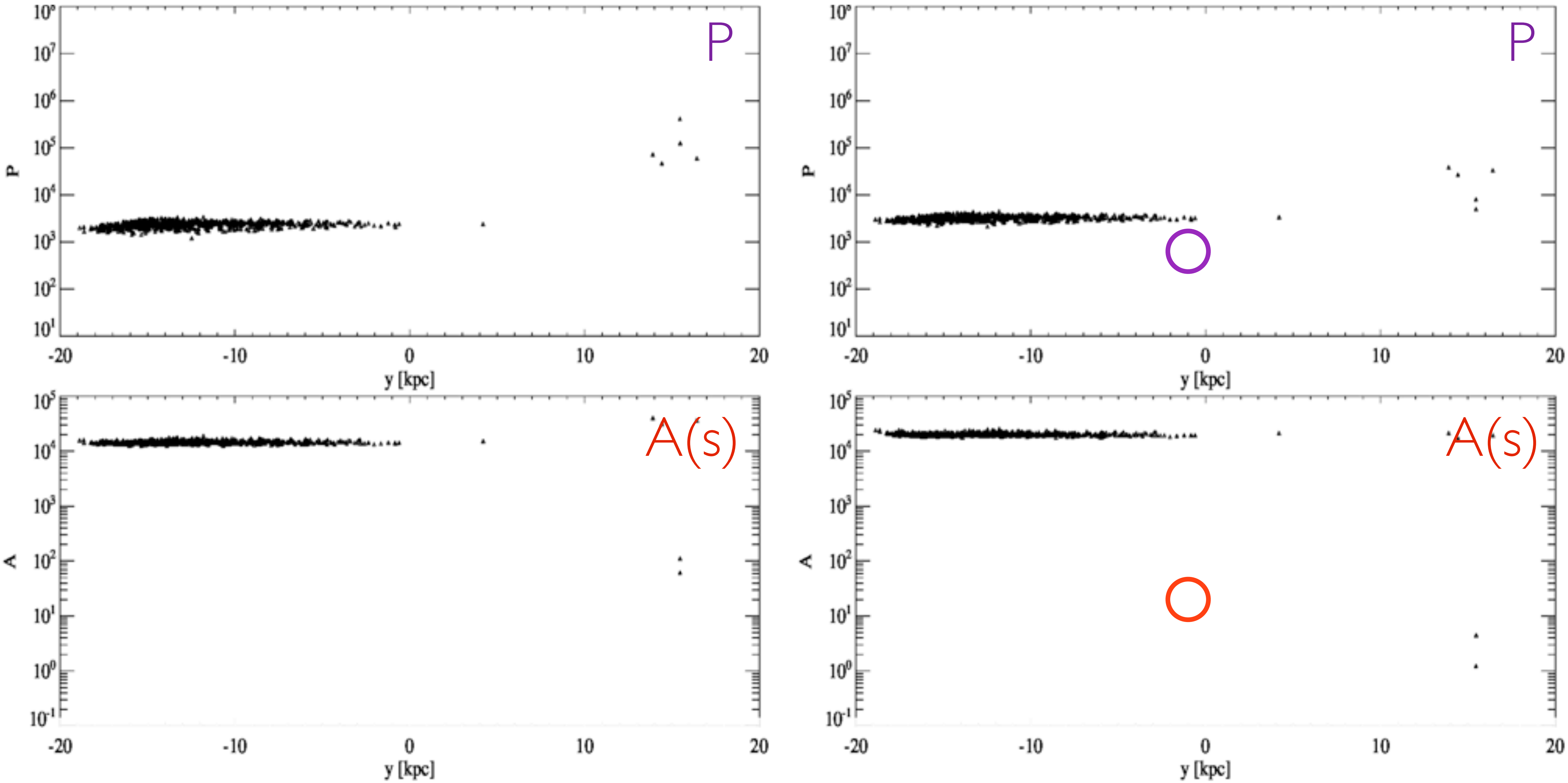
SPHS

SPH

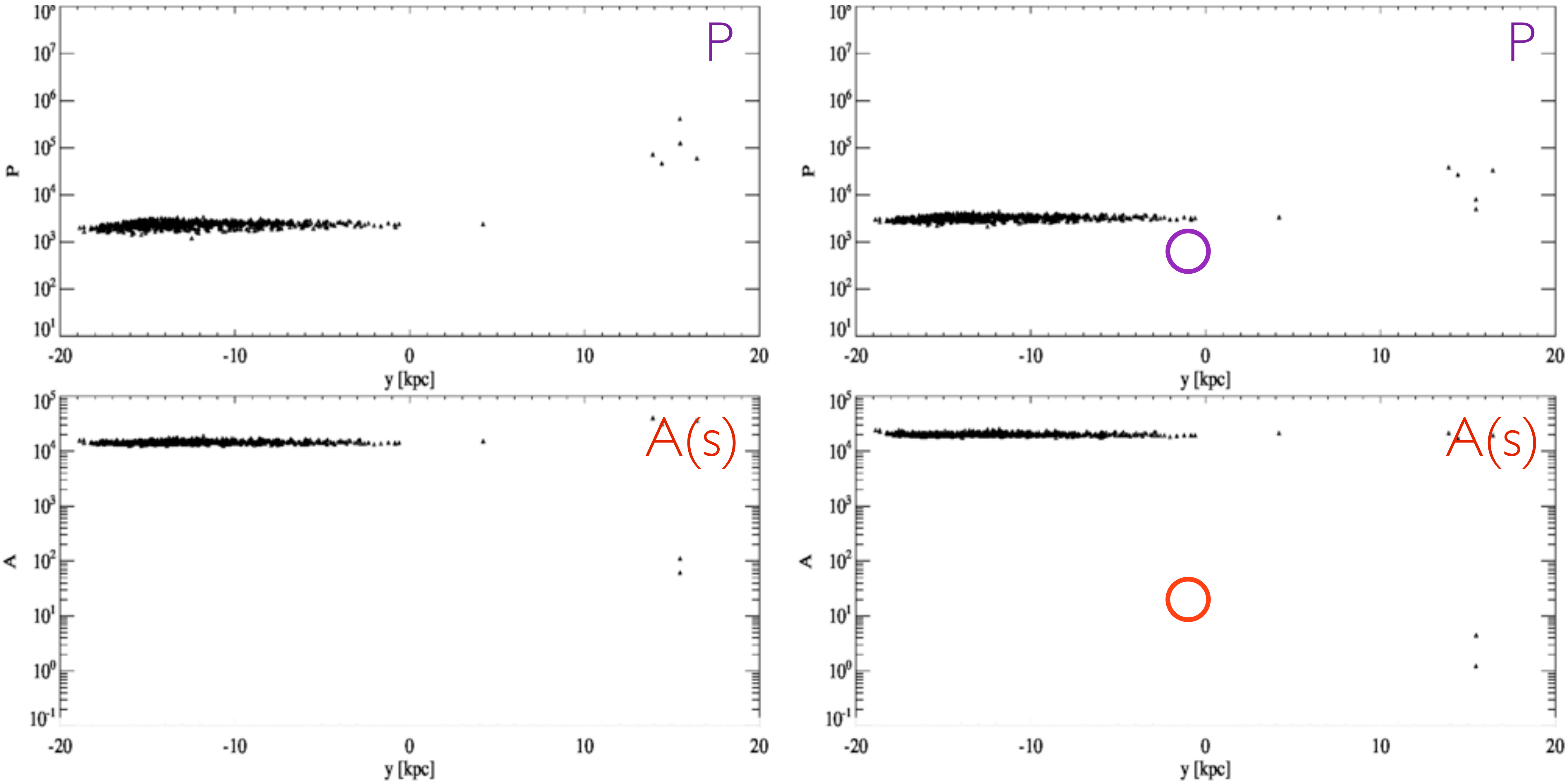


SPHS

SPH

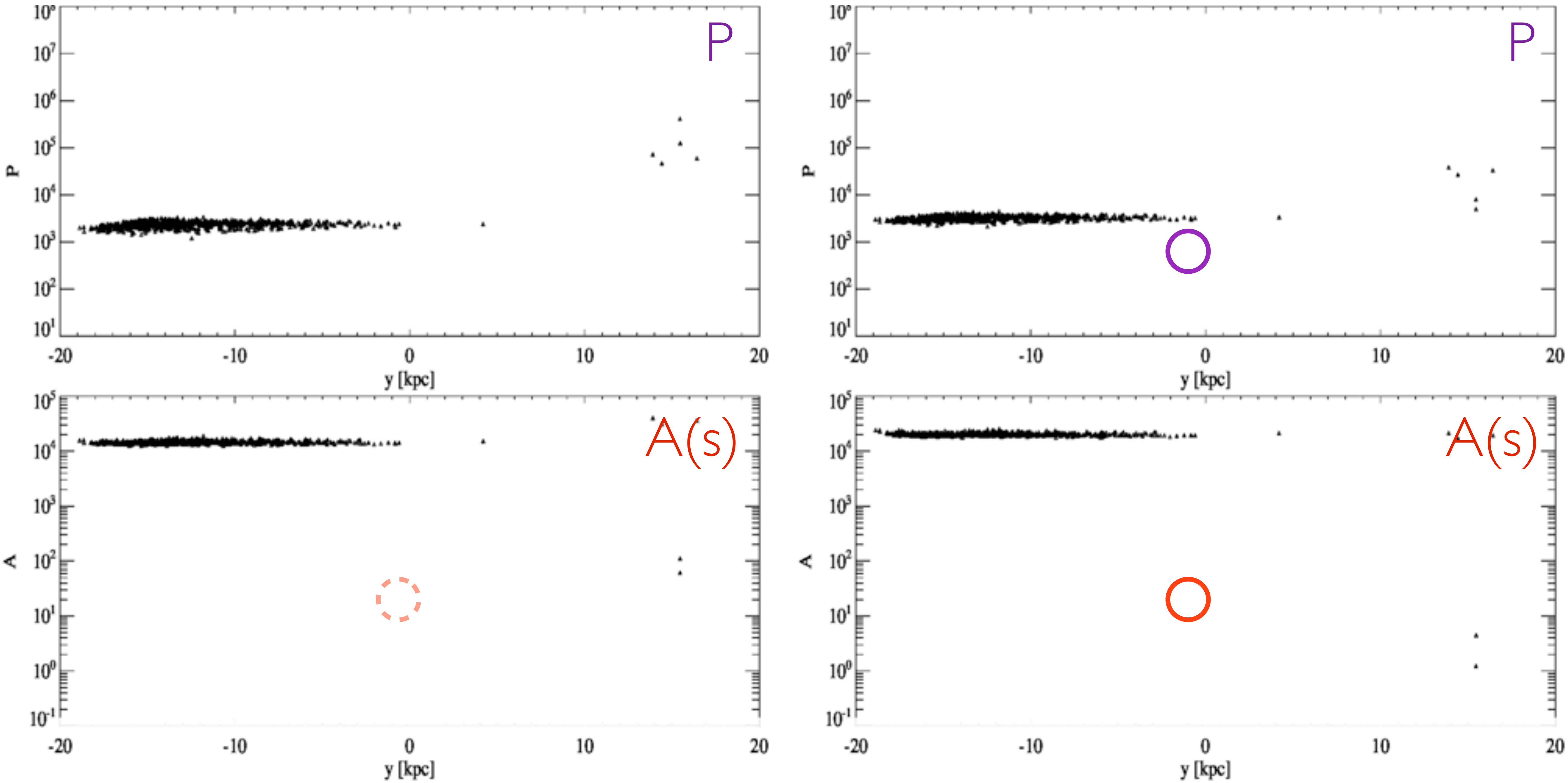


SPHS   SPH



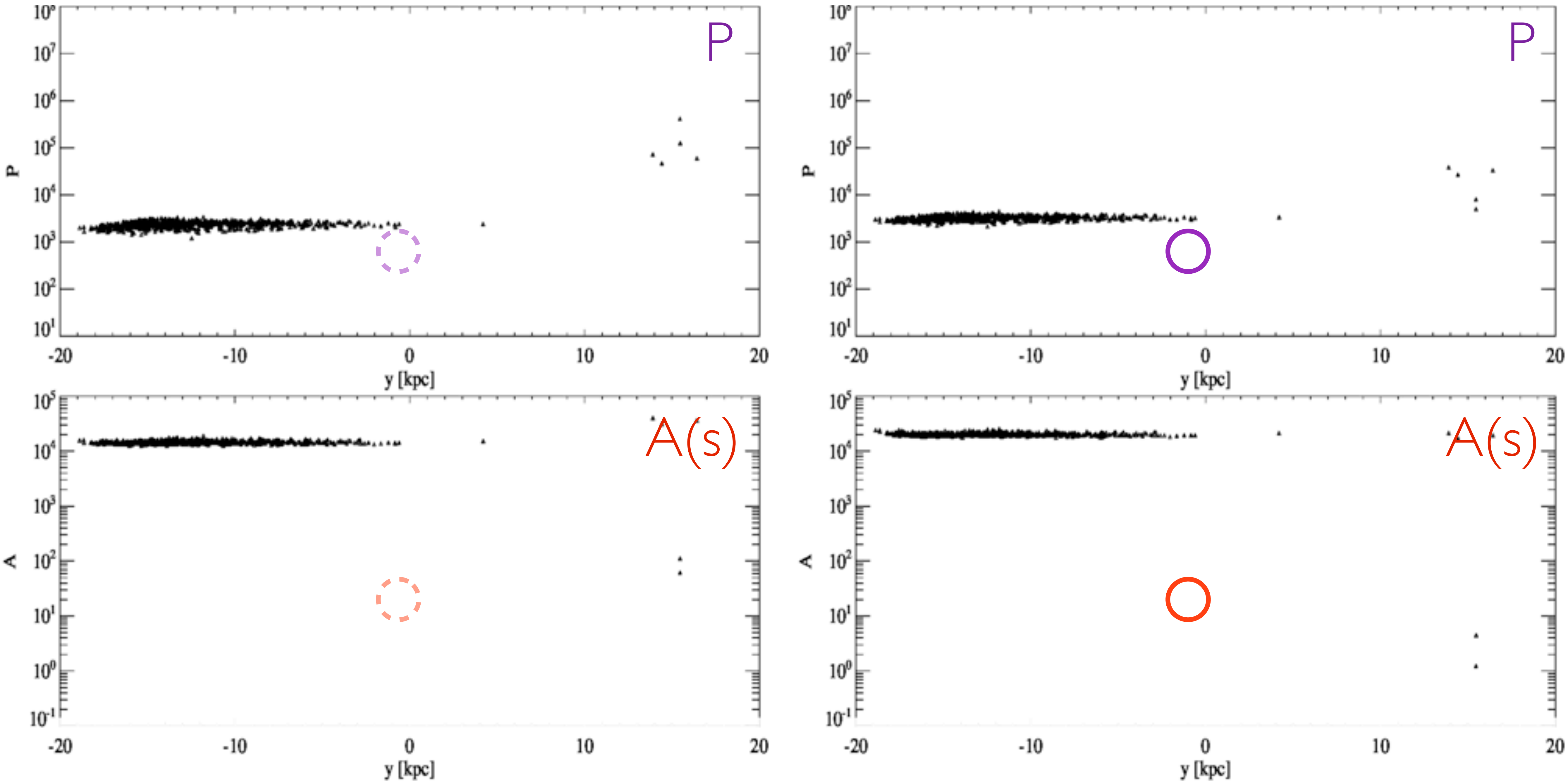
SPHS

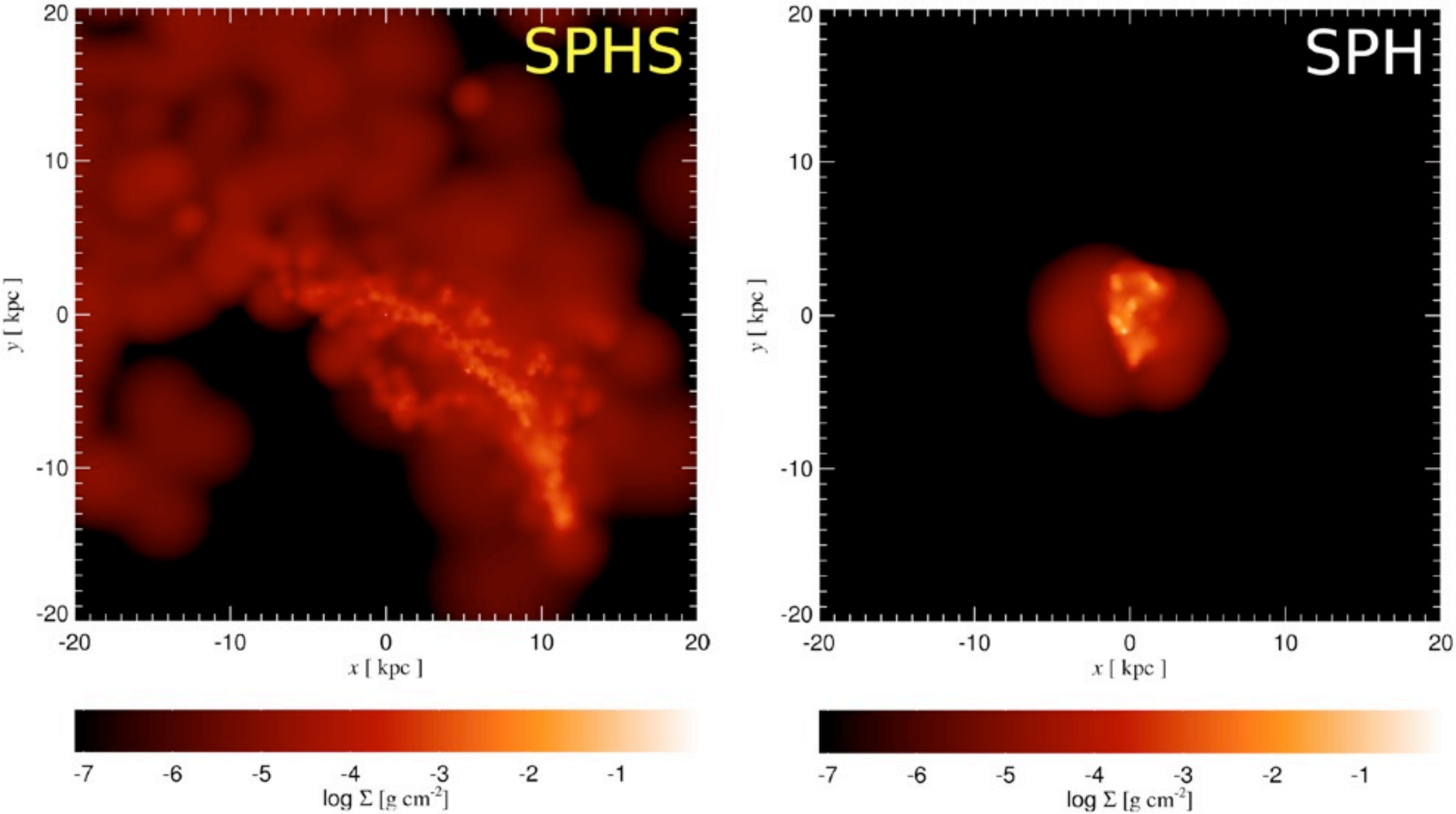
SPH

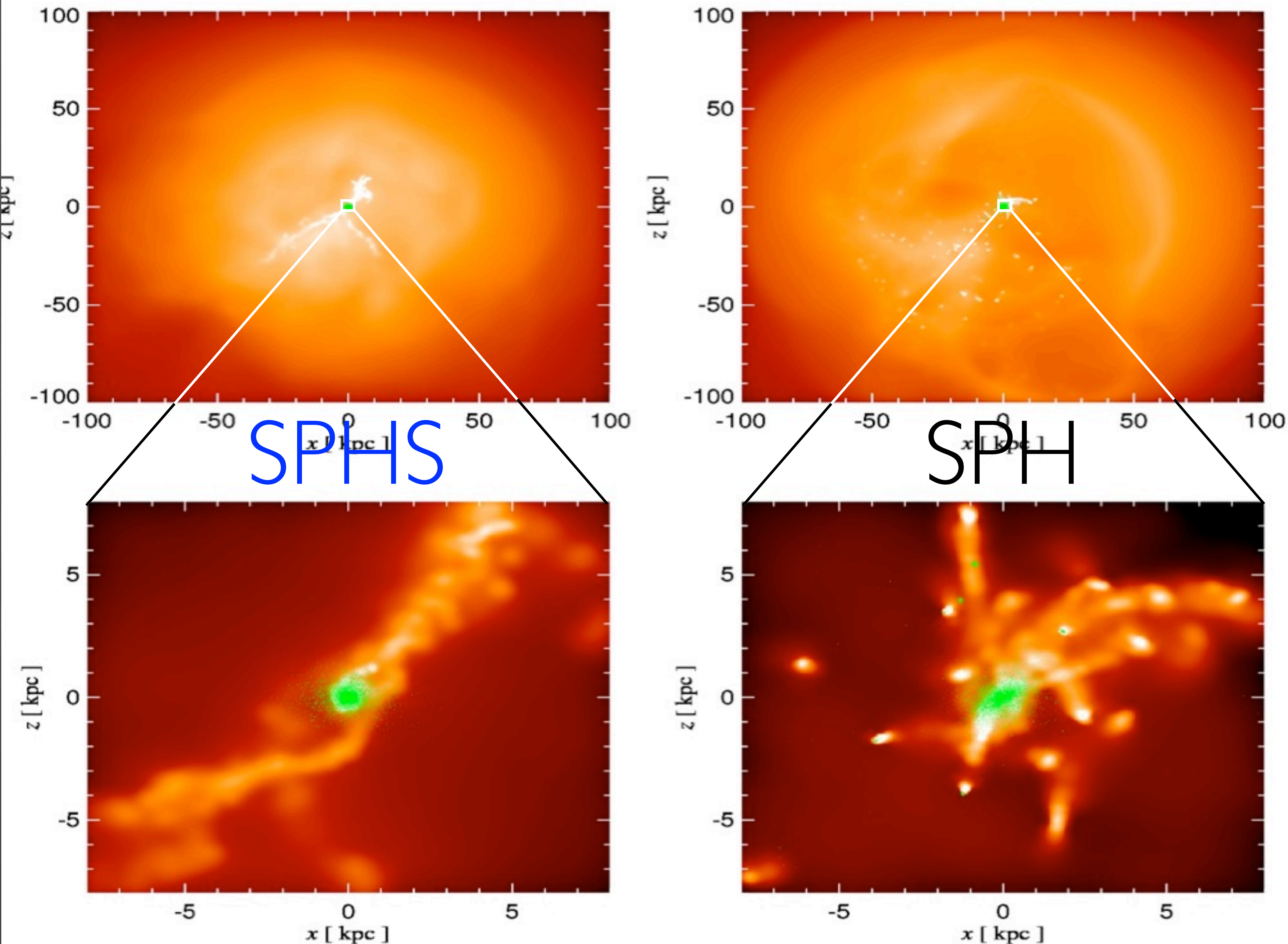


SPHS

SPH




SPHS
SPH
y [kpc]
x [kpc]
log Σ [g cm^{-2}]
log Σ [g cm^{-2}]



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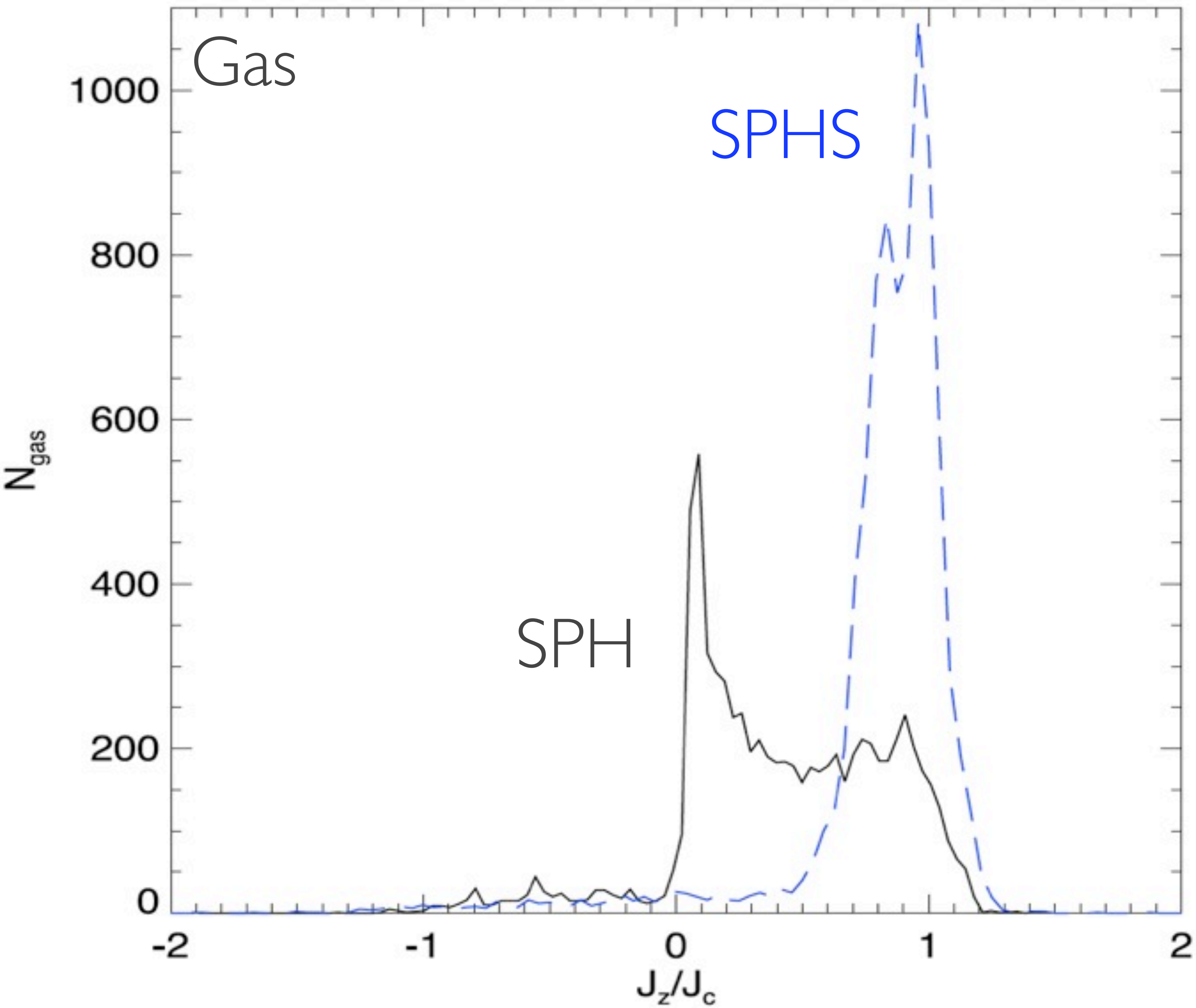

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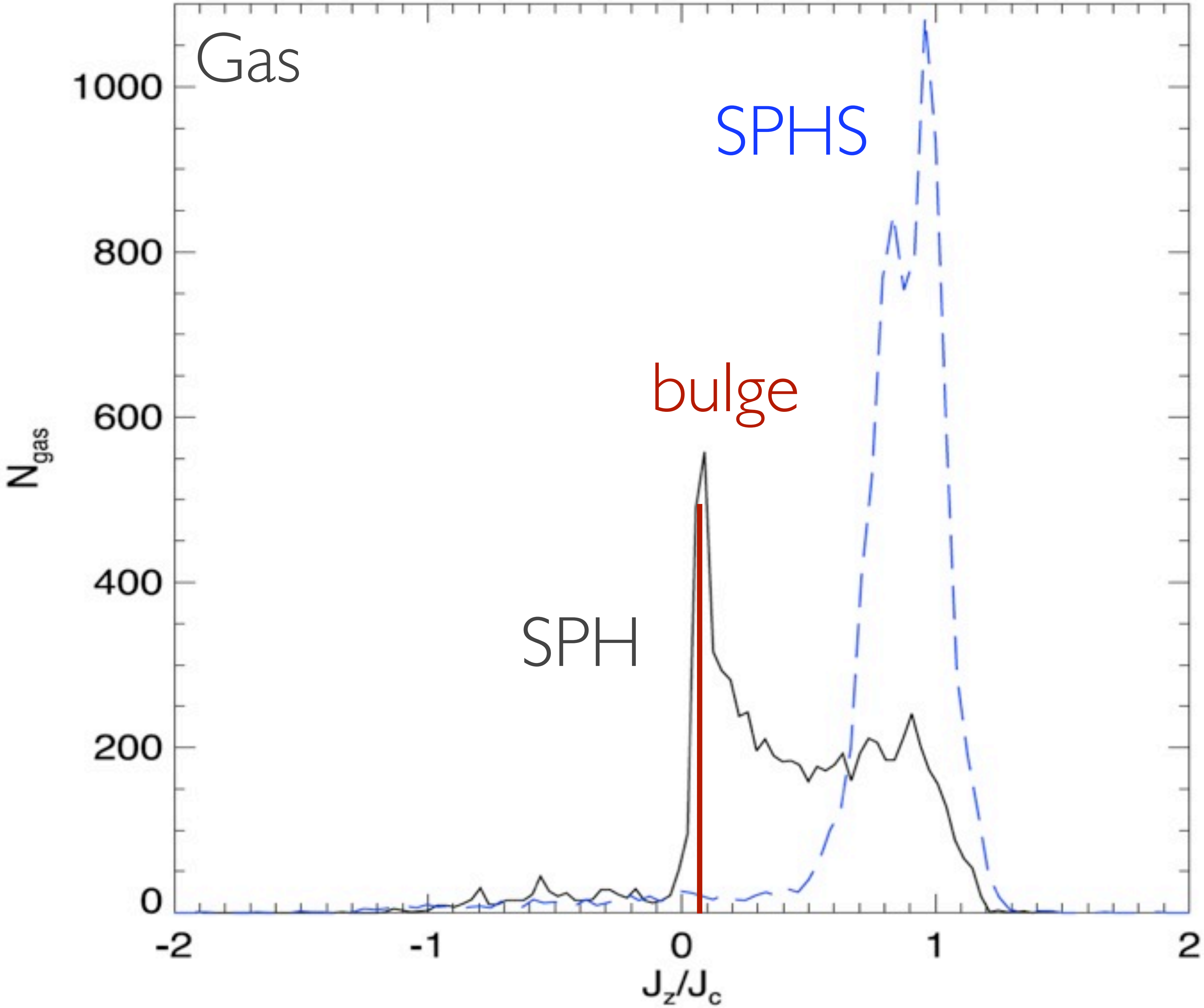

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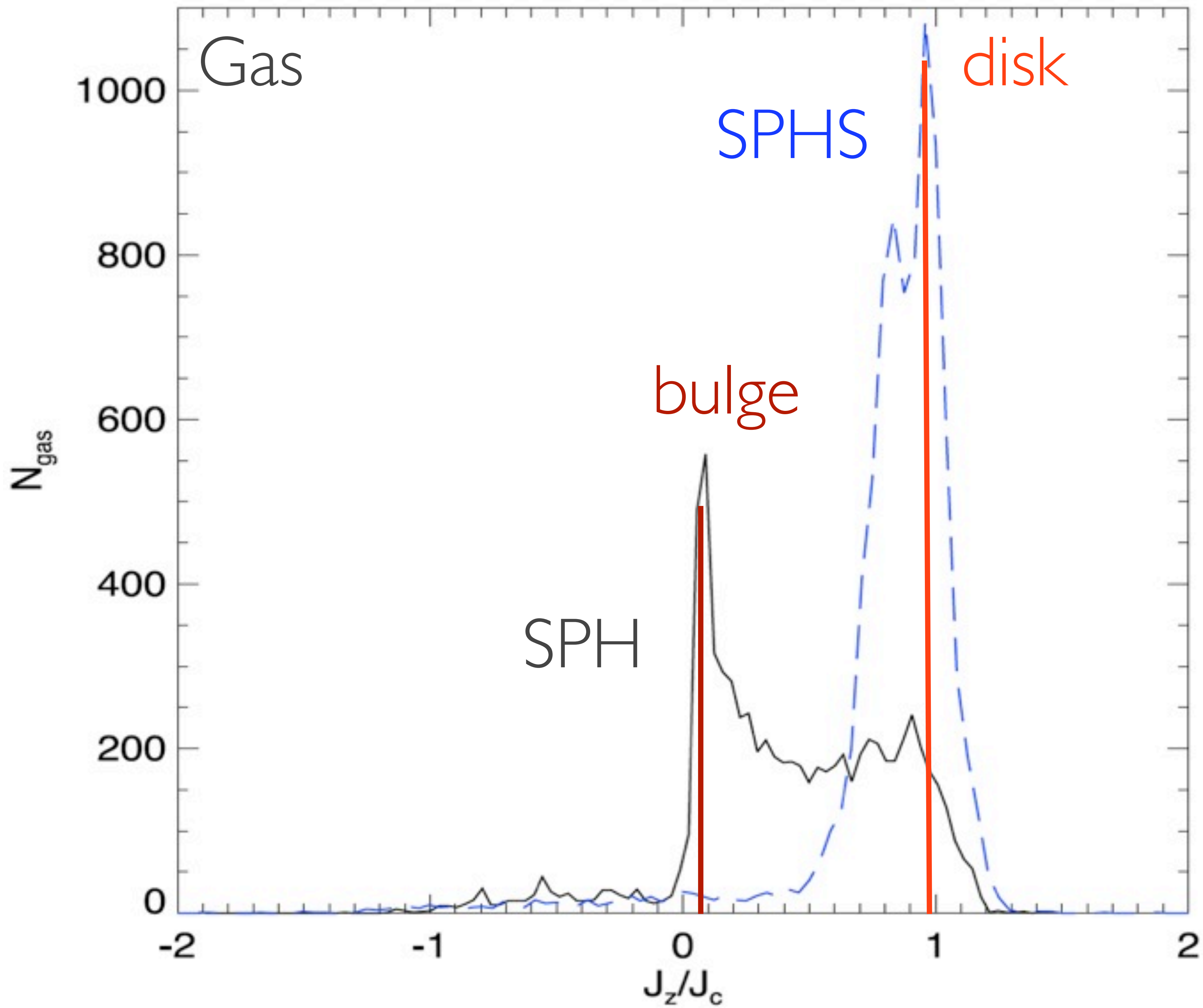

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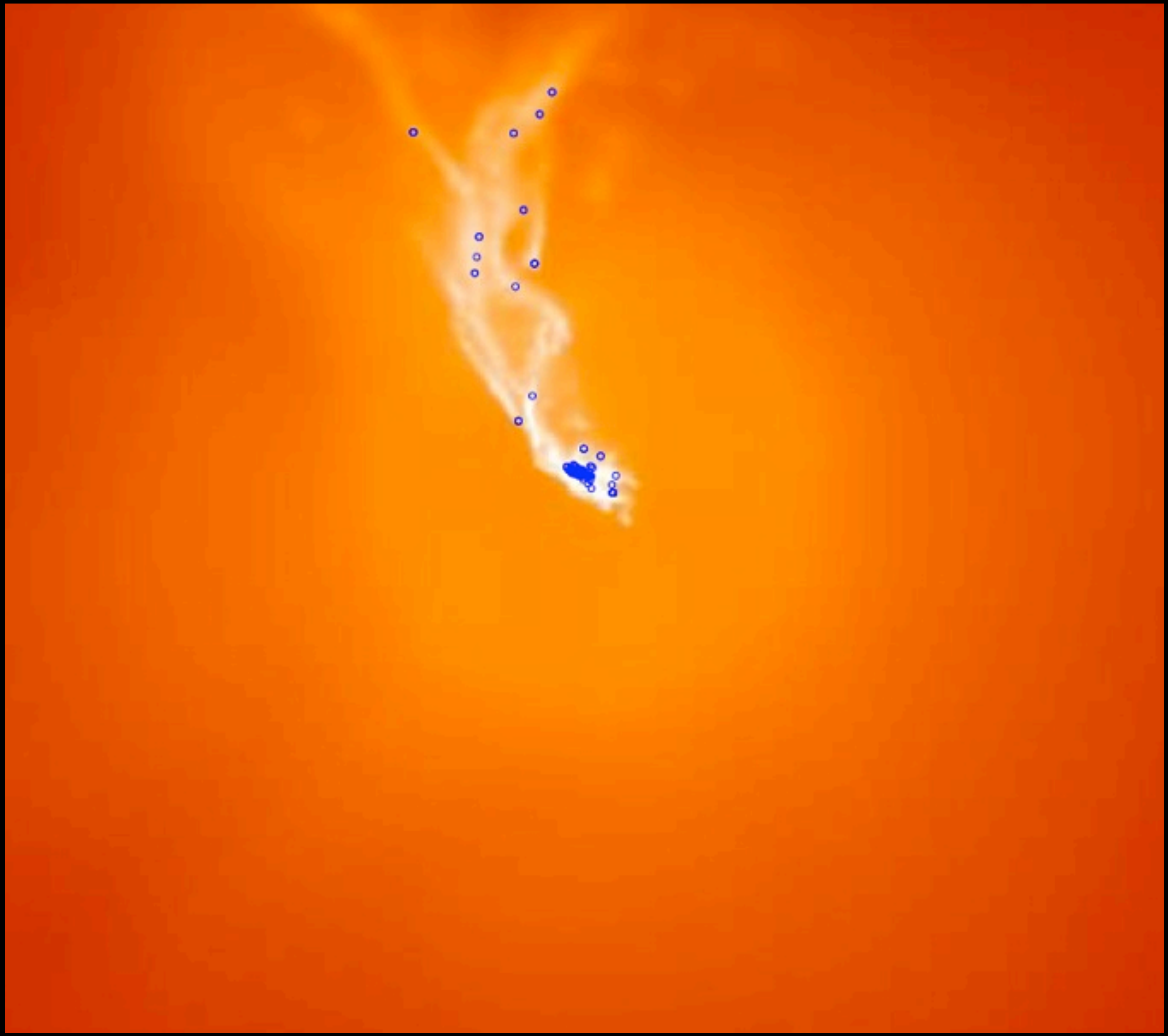
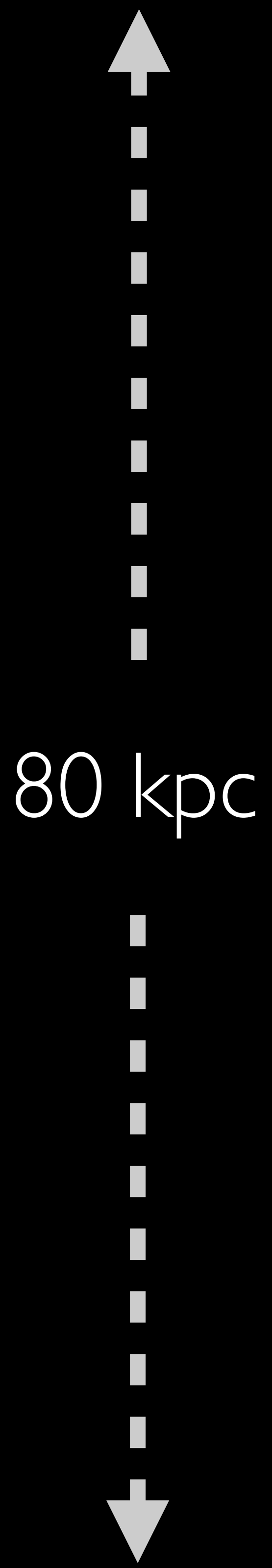
SPHS-442 | 5M





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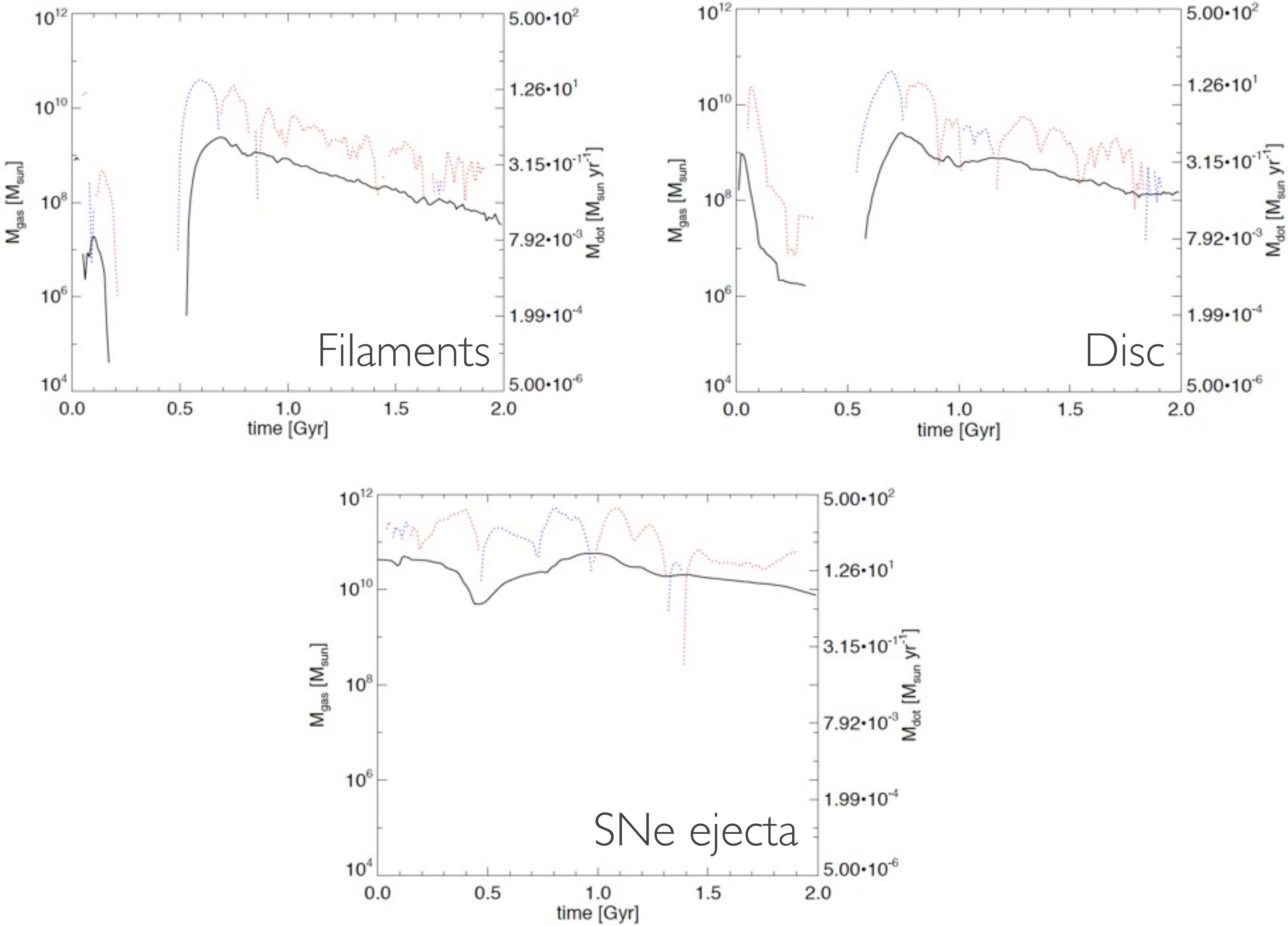

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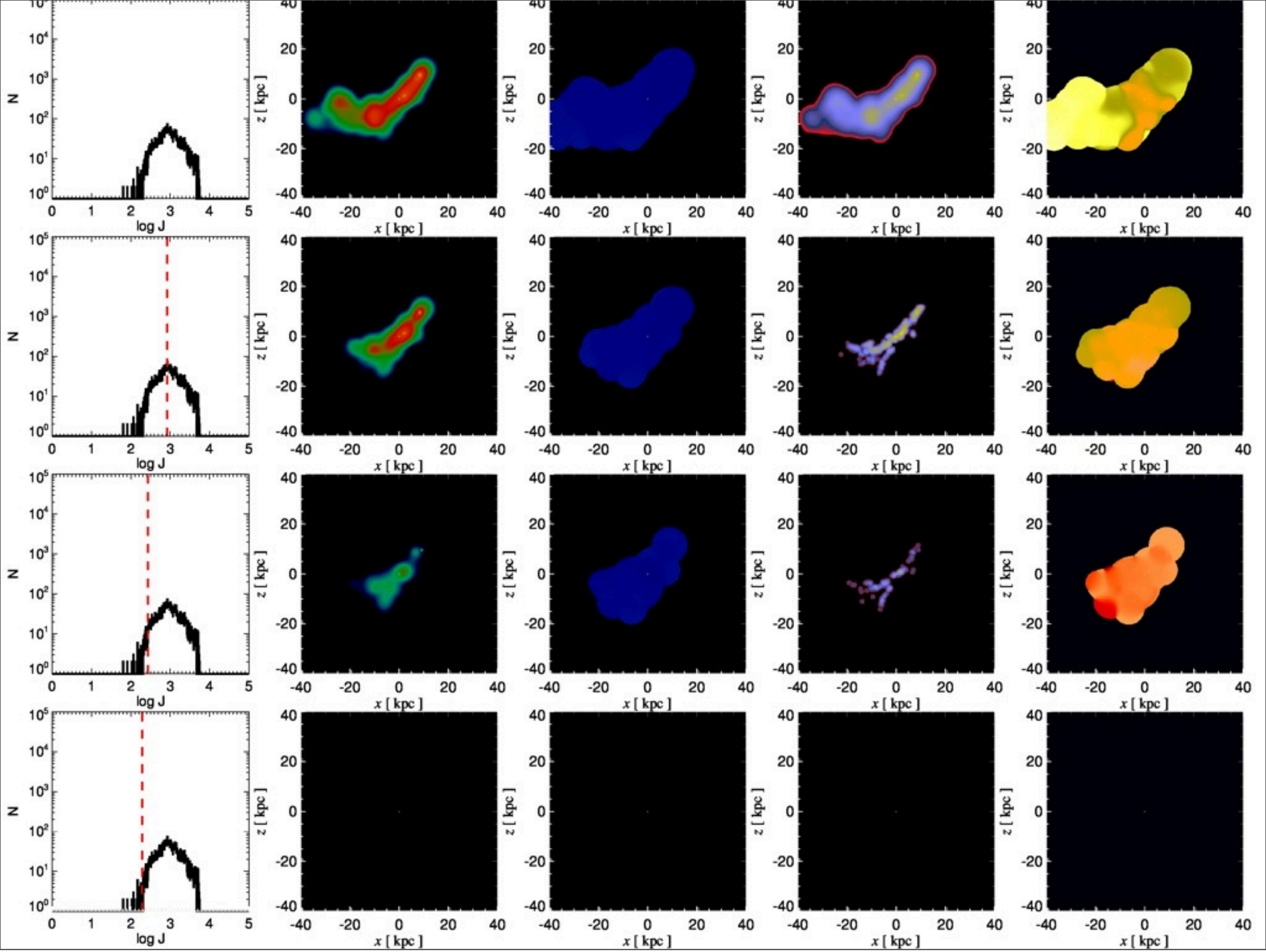
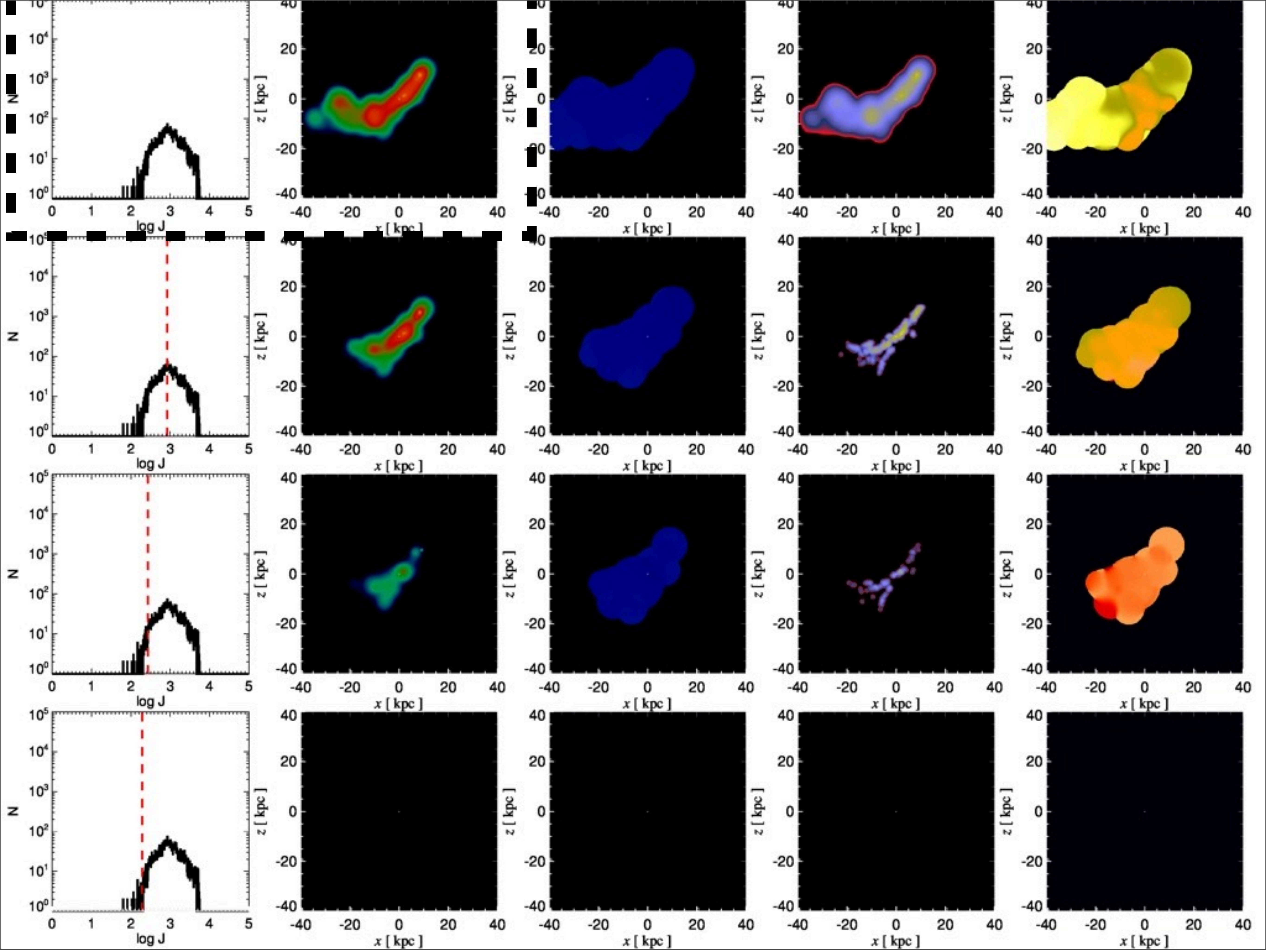
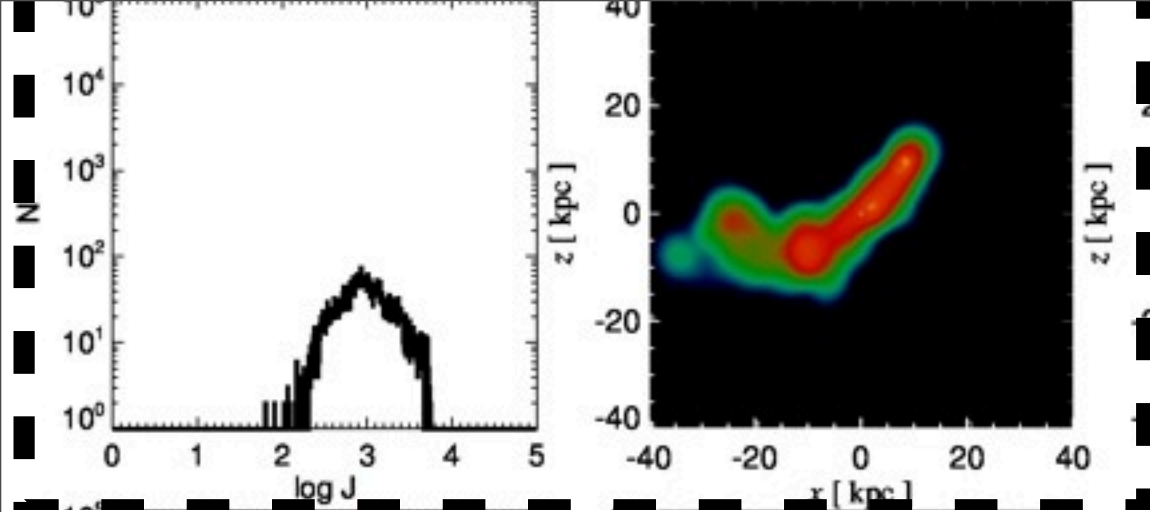
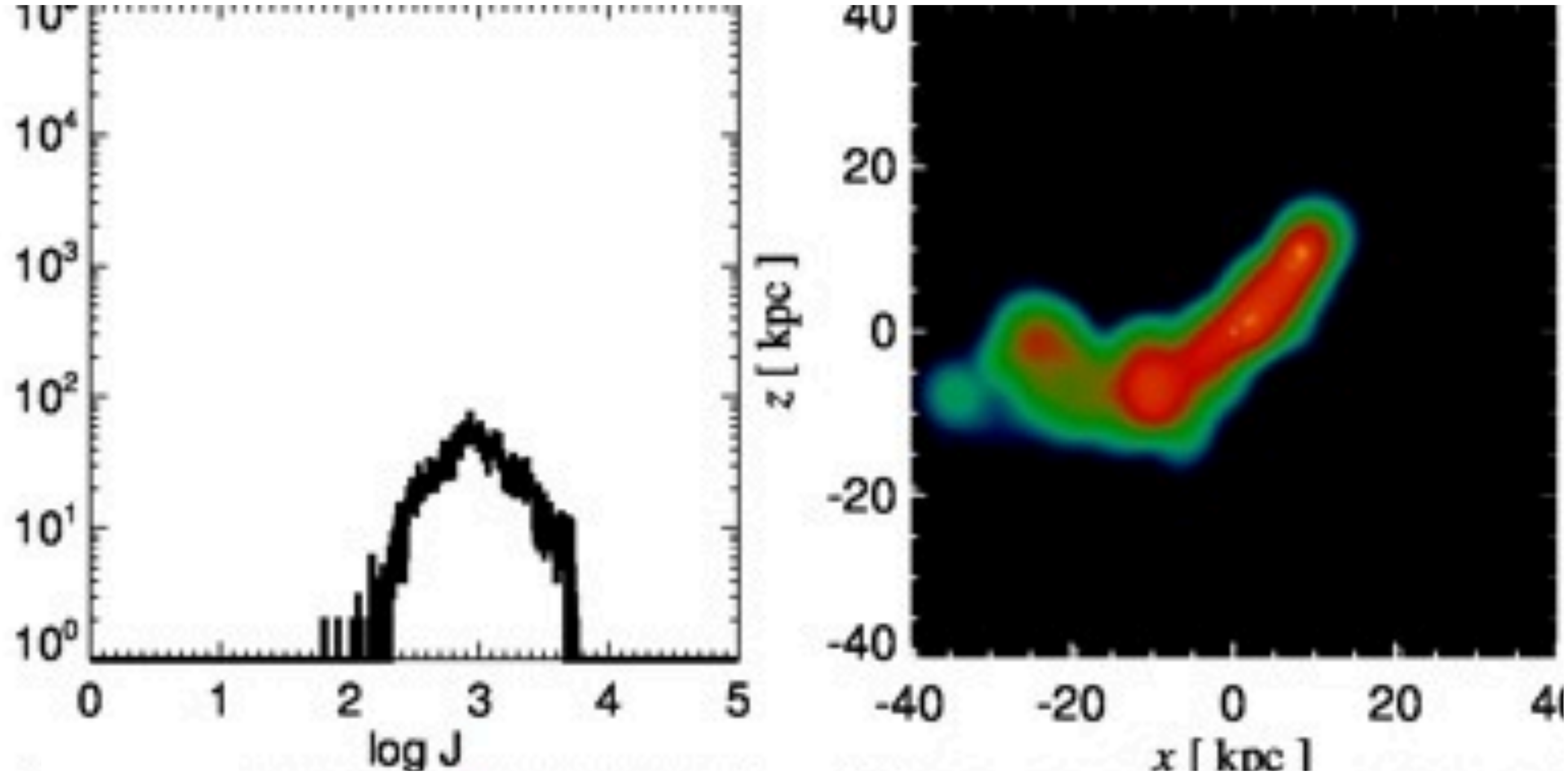


N
log J
z [kpc]
x [kpc]

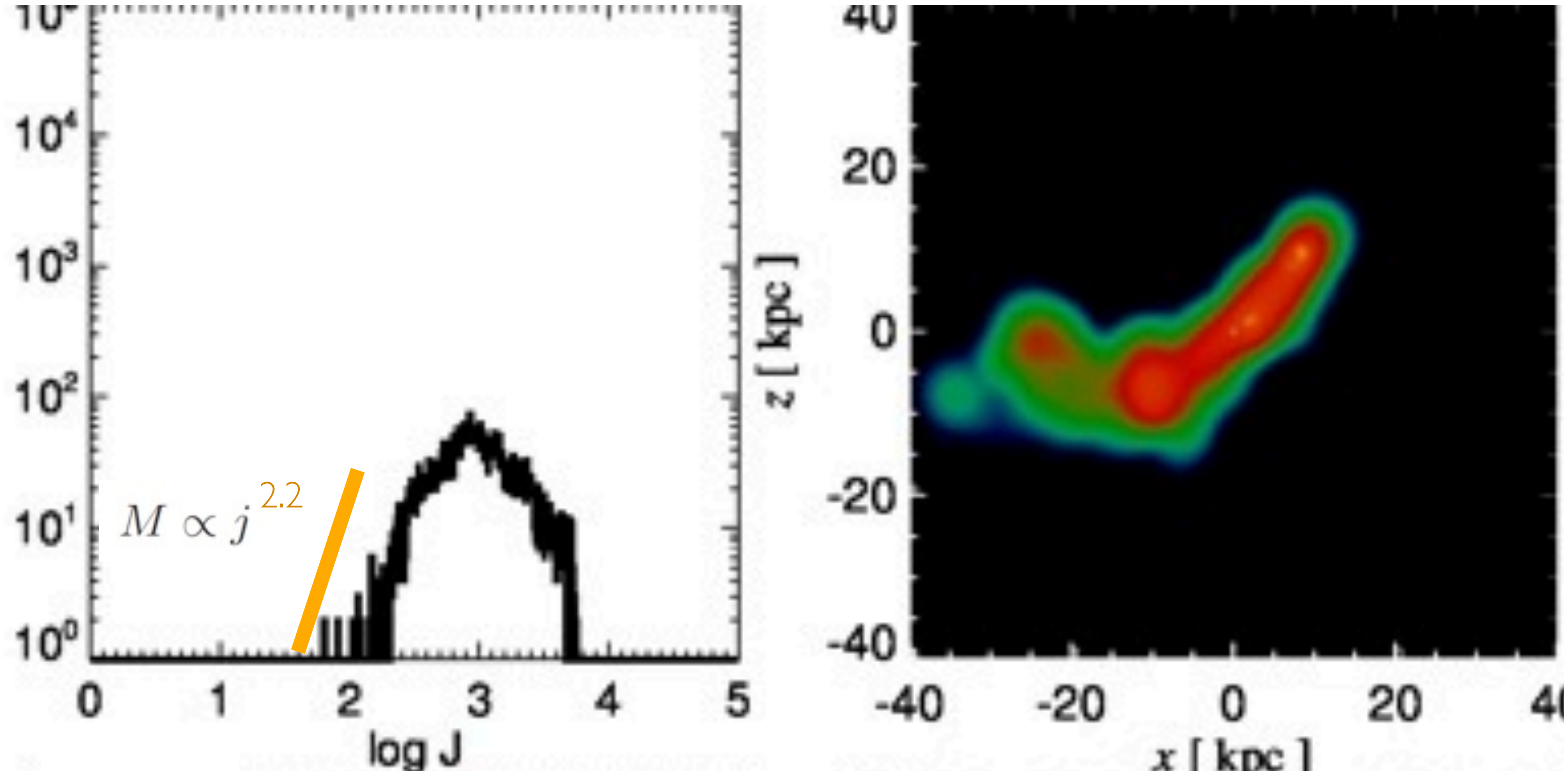

N
log J
z [kpc]
x [kpc]

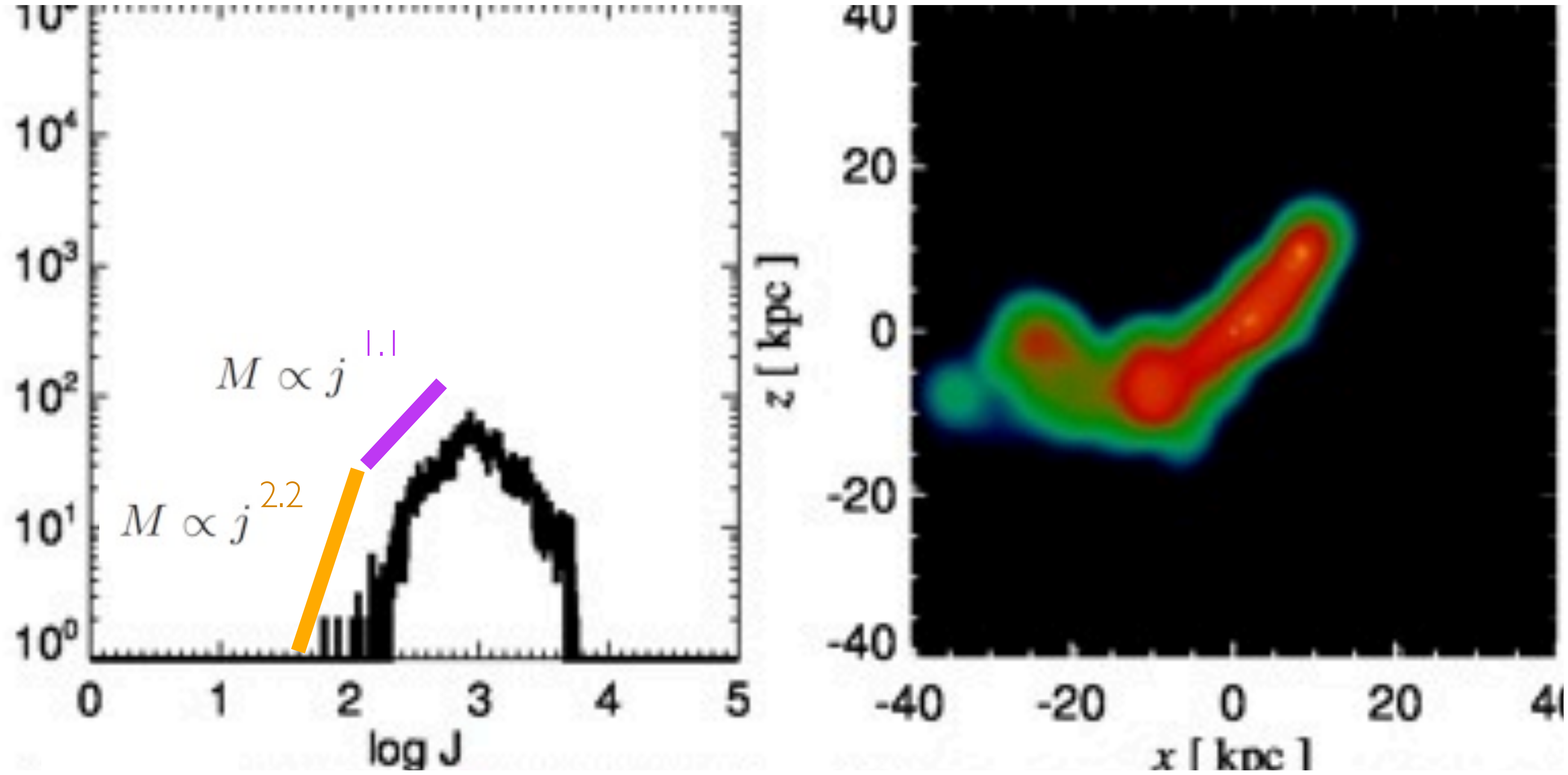


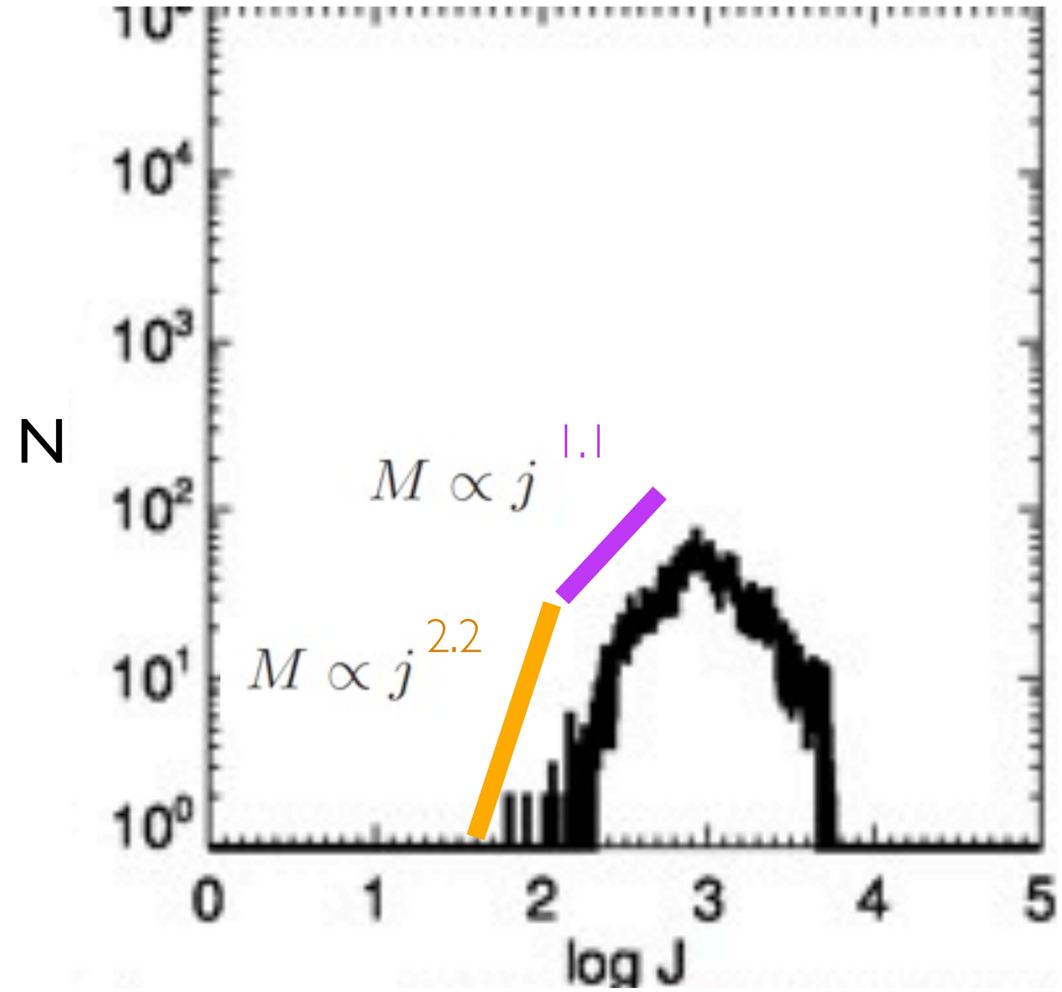
N
log J
z [kpc]
x [kpc]
z [kpc]

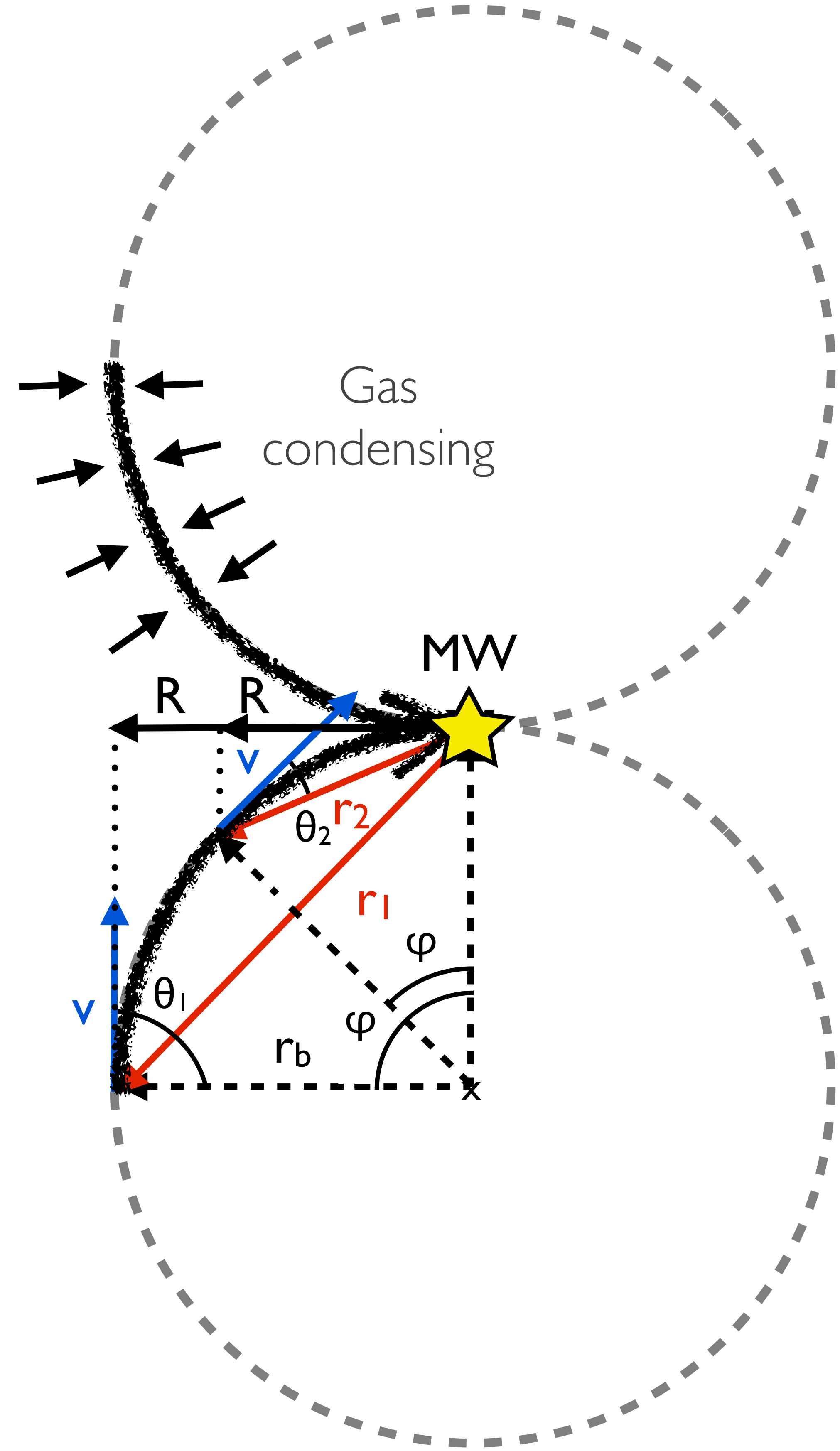


10^5
10^4
10^3
10^2
10^1
10^0
0 1 2 3 4 5
log J
40
20
0
-20
-40
z [kpc]
-40 -20 0 20 40
x [kpc]


$M \propto j^{2.2}$
log J
z [kpc]
x [kpc]


$M \propto j^{1.1}$
$M \propto j^{2.2}$
log J
z [kpc]
x [kpc]





$$j = rv \sin\left[\sin^{-1}\left(\frac{r}{2r_b}\right)\right] \qquad \theta = \sin^{-1}\left(\frac{r}{2r_b}\right)$$

$$j = rv\frac{r}{2r_b} \qquad j = r\left(\frac{2GM(r)}{r}\right)^{1/2}\frac{r}{2r_b}$$

$$M(r) = Ar$$

$$j = r(2G)^{1/2}A^{1/2}\frac{r}{2r_b} \qquad \therefore \quad j \propto r^2$$

$$M \propto \left[\left(\frac{j^{1/2}}{r_s}\right)^{4/9}\right]^5 \qquad \therefore \quad M \propto j^{1.1}$$

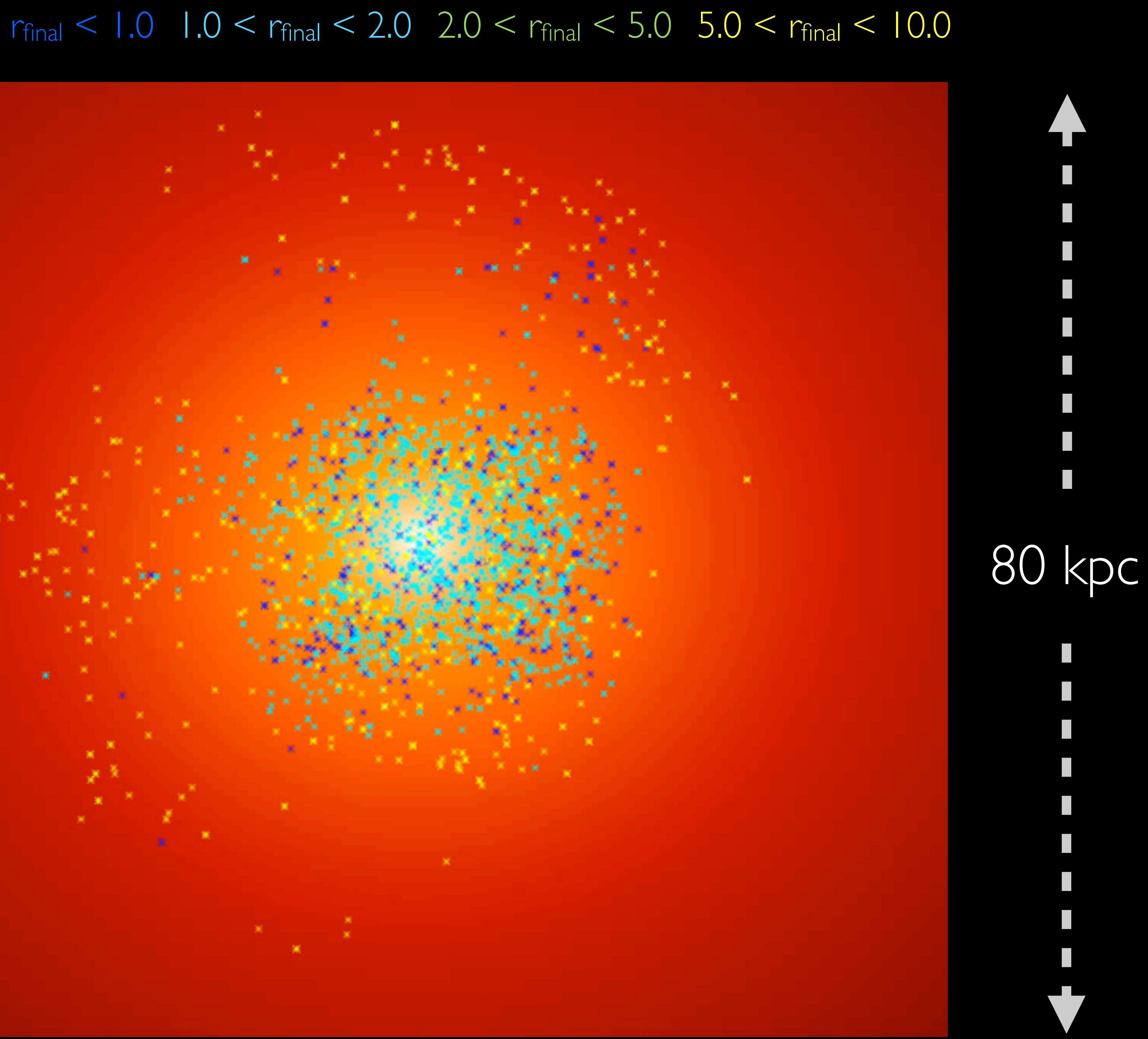
SPHS-96 | 1M

$r_{final} < 1.0$ $1.0 < r_{final} < 2.0$ $2.0 < r_{final} < 5.0$ $5.0 < r_{final} < 10.0$

80 kpc

Hobbs, Read & Nicola, in prep.

SPHS-96 | 1M



Hobbs, Read & Nicola, in prep.

SNe-driven accretion flow

- Fragmenting filament similar to break-up of 'cold-mode' cosmological streams (Keres et al. 2009, Keres & Hernquist 2009)
    - Overdensity allows for non-linear mode of collapse
    - Different progenitors (SNe vs. large-scale cosmological flows)
    - Different scales (50 kpc --> galaxy vs. > 200 kpc --> 40 kpc)
    - Different temperatures (10^4 K vs 10^5 K)

- Form of positive feedback whereby SNe give rise to cold gas flows that feed the disc and fuel further star formation

- Filaments can have preferentially low angular momentum and are efficient at bringing gas from 50 kpc → 1 kpc in t_{ff}

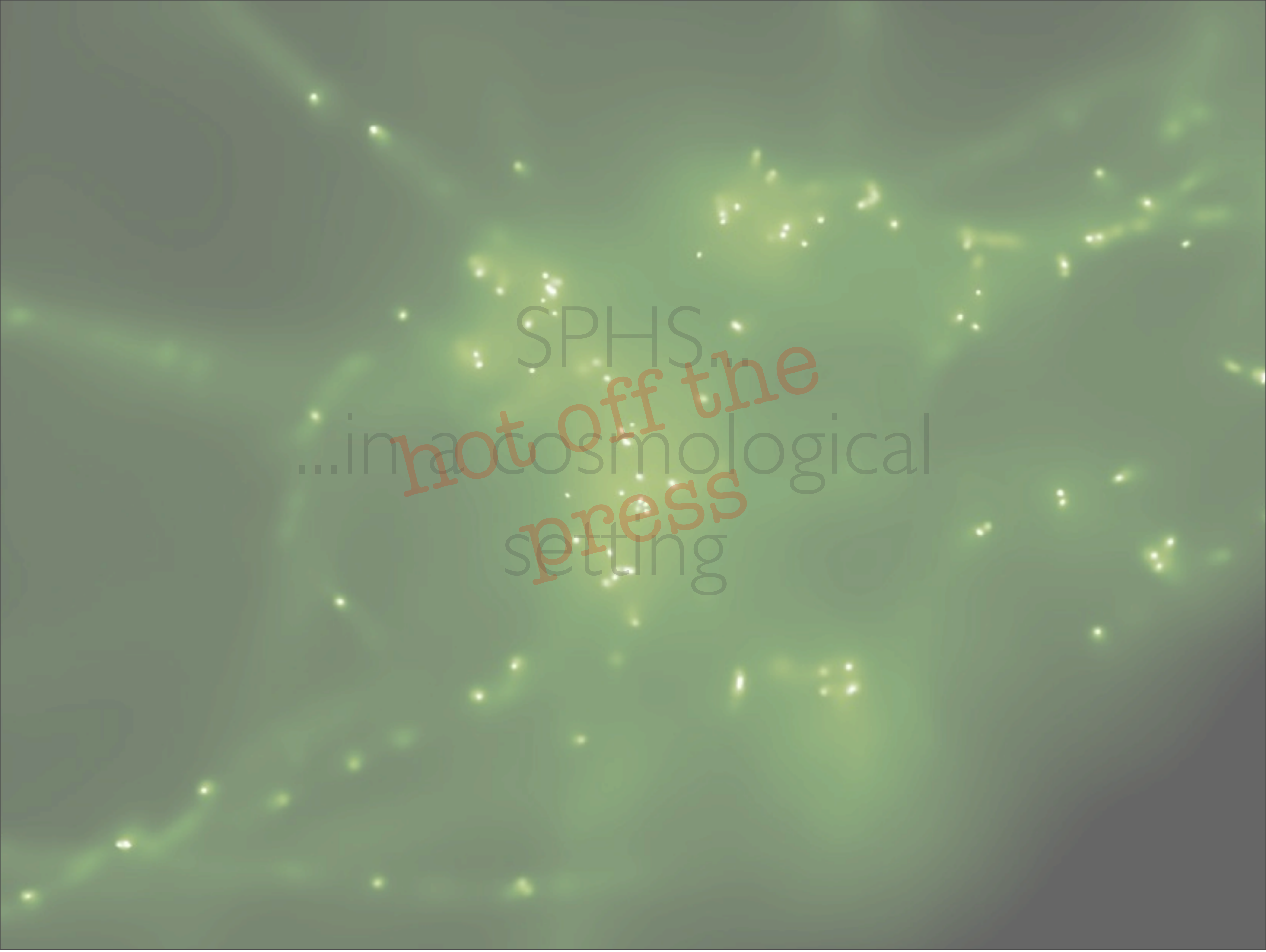

SPHS...

SPHS…

…in a cosmological setting


SPHS...
...in a cosmological setting

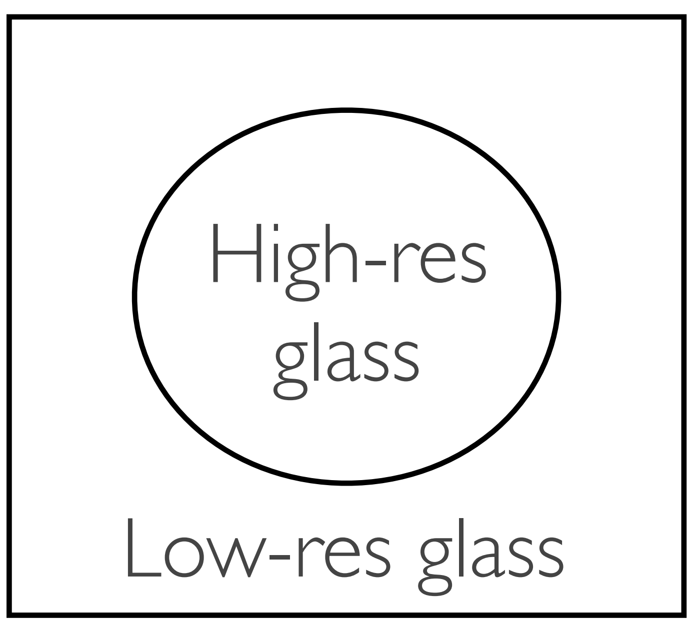

SPHS...
...in a cosmological setting
hot off the press


SPHS...
...in a cosmological setting
hot off the press


SPHS
...in a cosmological setting
not off the press
preliminary

SPHS: Cosmological setting

- Parent volume: 50 Mpc/h N-body run, WMAP-7 cosmology
- Most massive halo at $z = 4$ identified with friends-of-friends
- Re-simulation with DM + gas using zoom-in technique (Power et al. 2003)



Tidal particles

	DM-tidal	DM-LR	DM-HR	Stars	Gas
ε_{soft} (Mpc/h)	0.5	0.2	0.005	0.005	variable
mass (M_{sun}/h)	3.8×10^{10}	1.4×10^{8}	6.2×10^{7}	1.0×10^{7}	1.3×10^{7}

Halo at $z = 4$: $M_{vir} = 85.2 \times 10^{10}\ M_{sun}/h$

$R_{vir} = 0.15$ Mpc/h

SPHS: Cosmological setting

Sub-grid physics:

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Sub-grid physics:

(i) Radiative cooling down to 10K (Mashchenko et al. 2003)

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$T < 3 \times 10^4$ K

SPHS: Cosmological setting

Sub-grid physics:

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$T < 3\times10^4$ K

(iii) Feedback from SNII (lifetimes w. Chabrier IMF)

SN1a (delay times as per Maoz et al. 2012)

SPHS: Cosmological setting

Sub-grid physics:

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$T < 3\times10^4$ K

(iii) Feedback from SNII (lifetimes w. Chabrier IMF)

SN1a (delay times as per Maoz et al. 2012)

(iv) Injection of thermal energy

metals (m_{Fe} & m_O as per AGORA)

mass (AGORA)

SPHS: Cosmological setting

Sub-grid physics:

(i) Radiative cooling down to 10K (Mashchenko et al. 2003)

(ii) Star formation thresholds: $\rho > 5$ atoms cm^{-3}

$T < 3\times10^{4}$ K

(iii) Feedback from SNII (lifetimes w. Chabrier IMF)

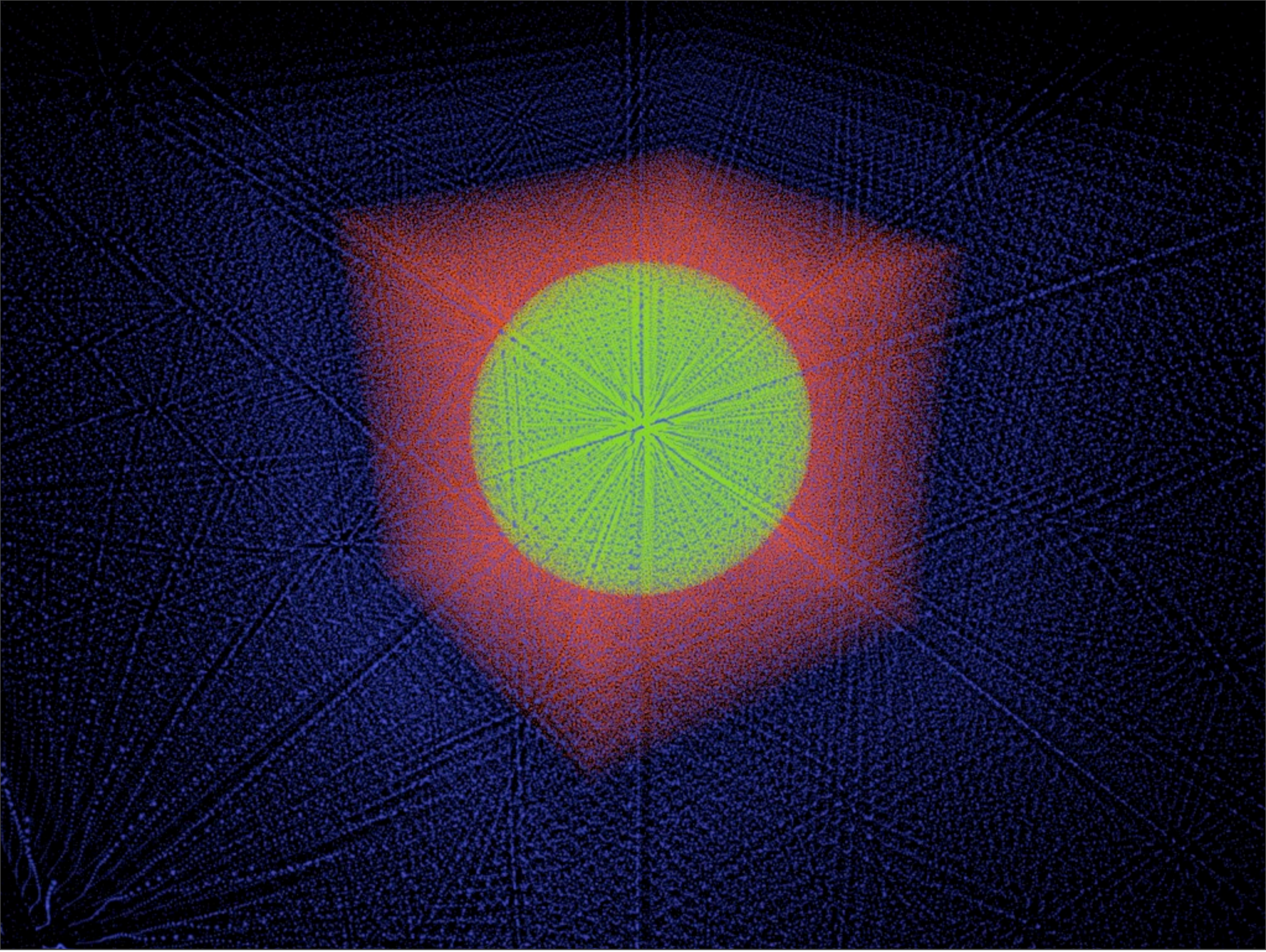
SN1a (delay times as per Maoz et al. 2012)

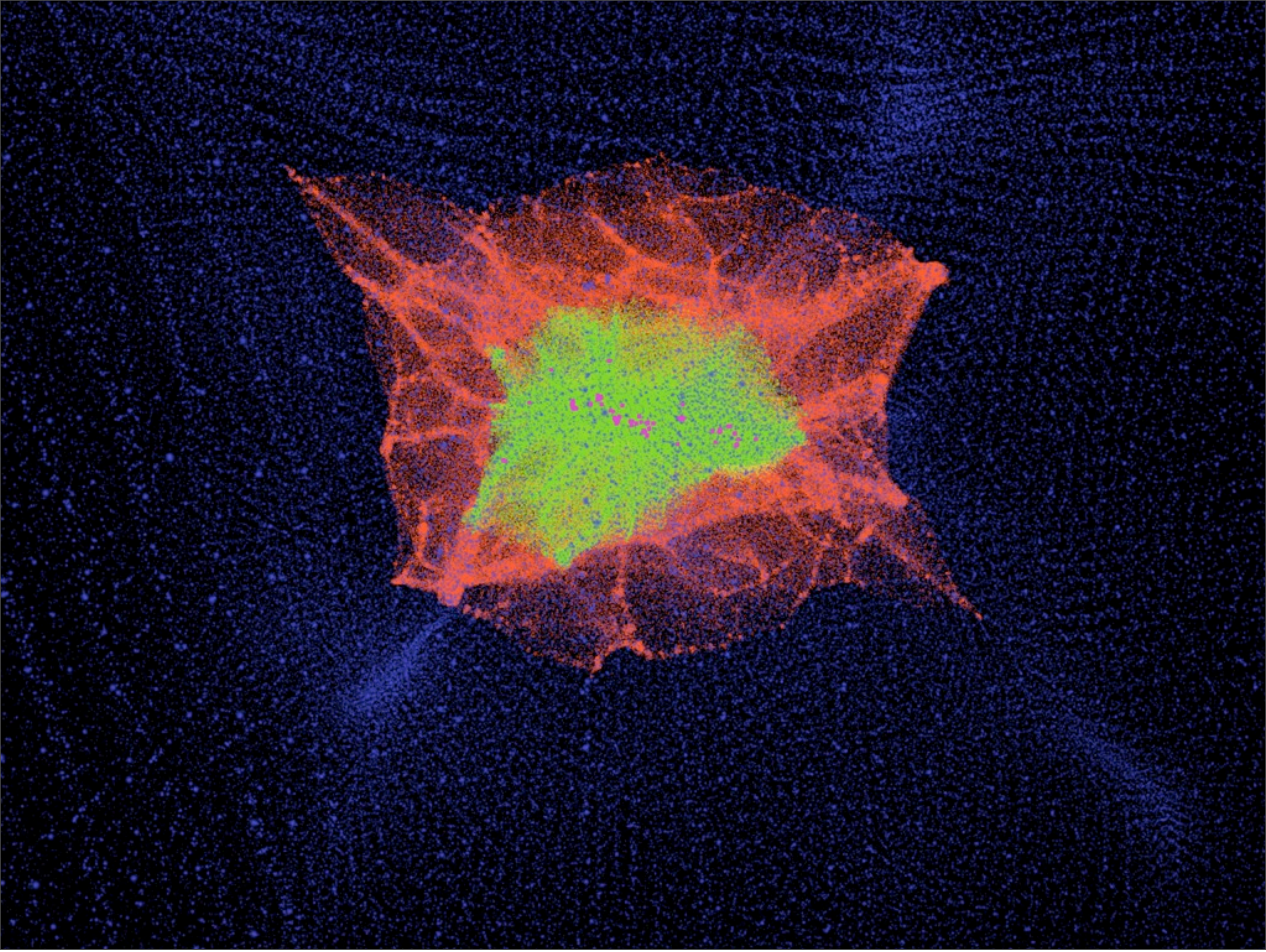
(iv) Injection of thermal energy

metals (m_{Fe} & m_O as per AGORA)

mass (AGORA)

mixing through diffusion





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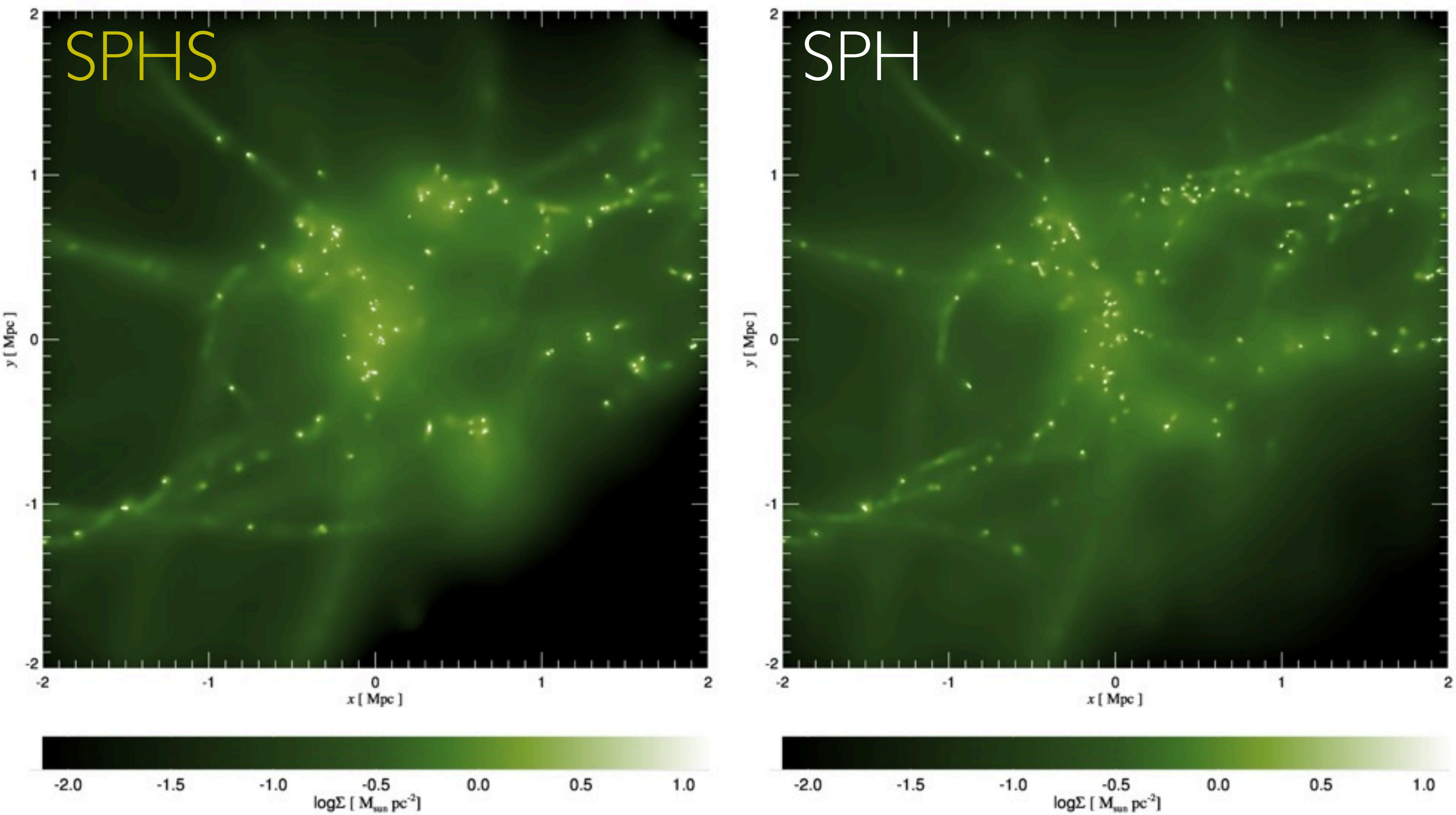
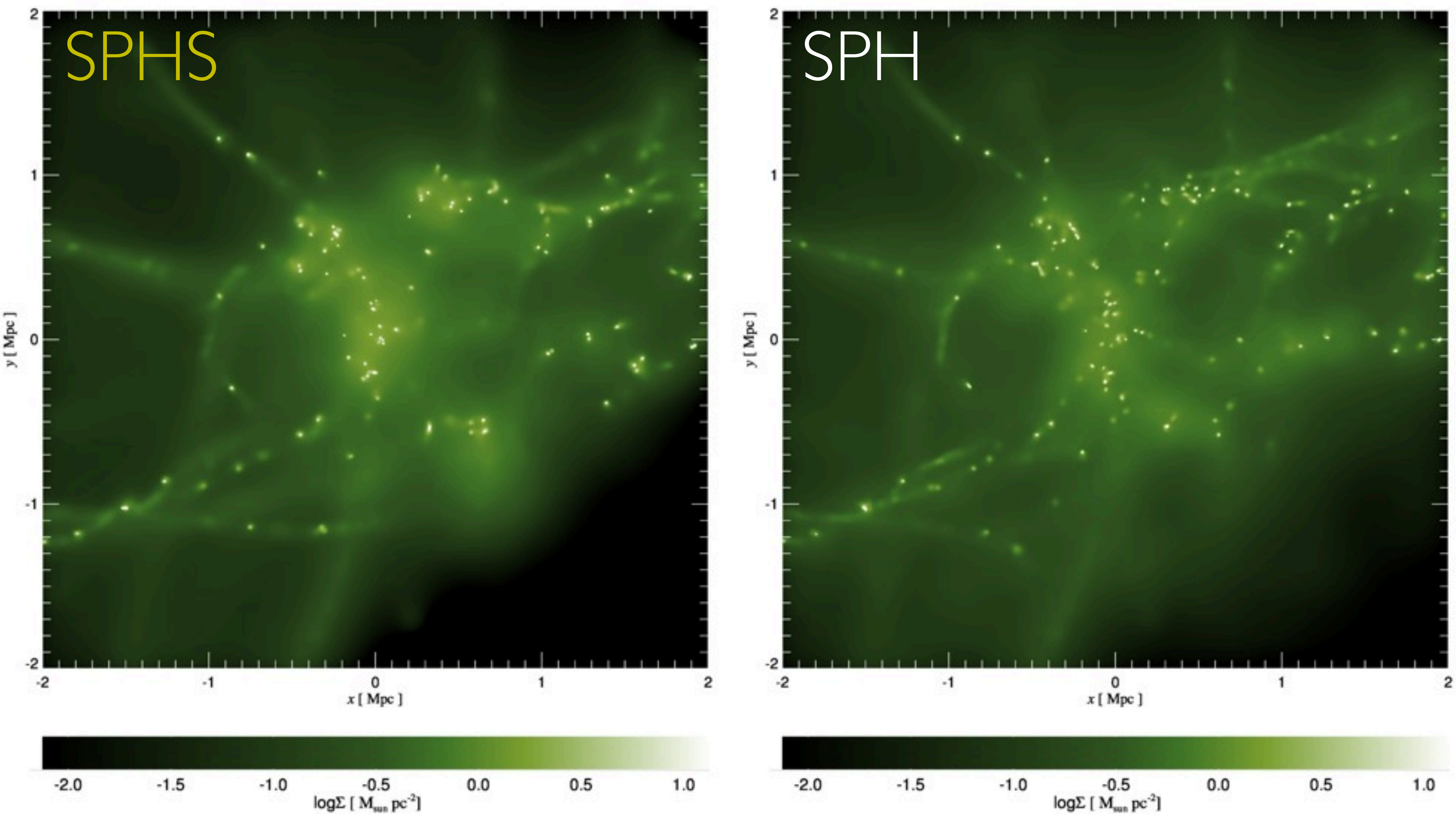


SPHS: Cosmological setting



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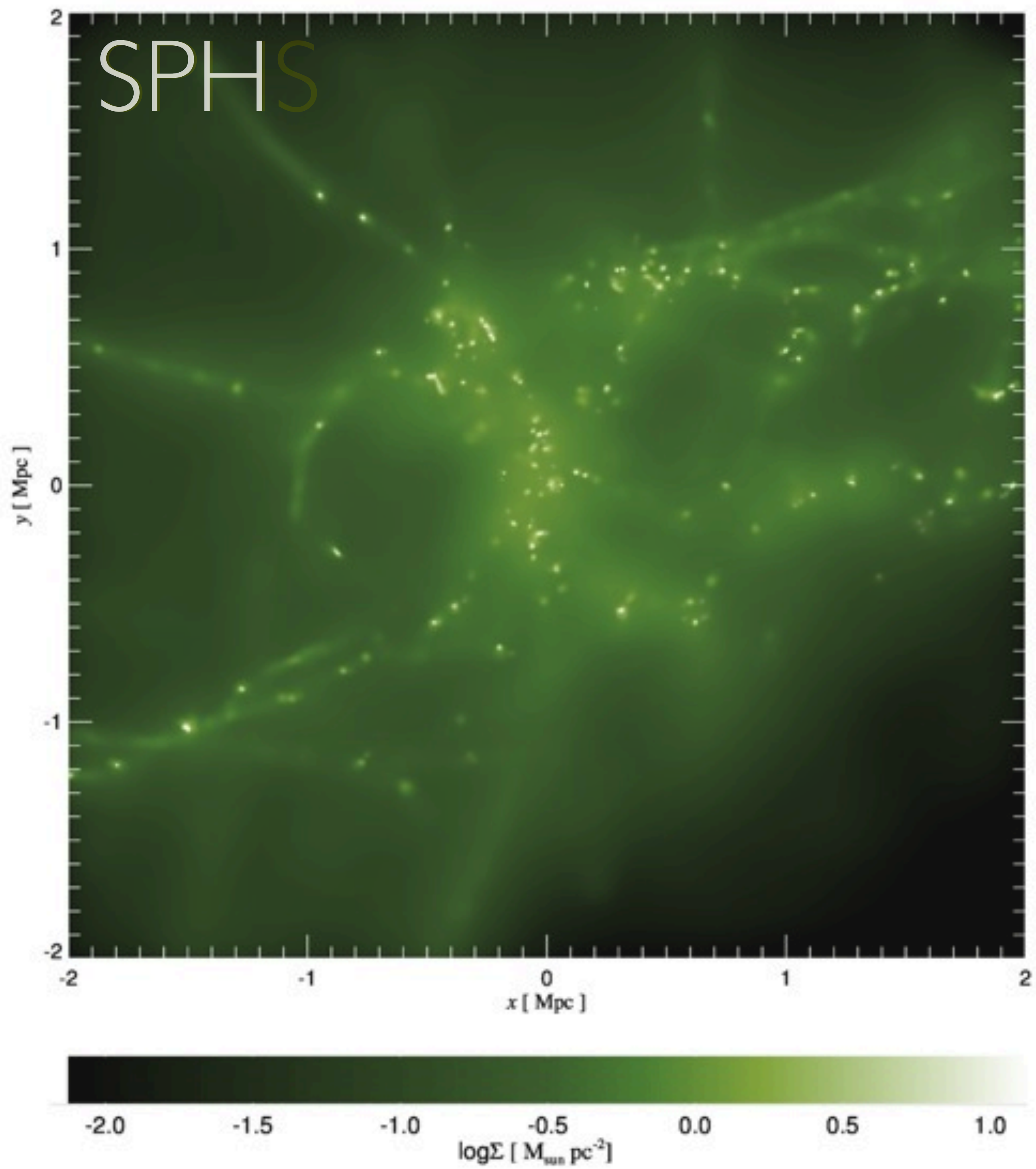

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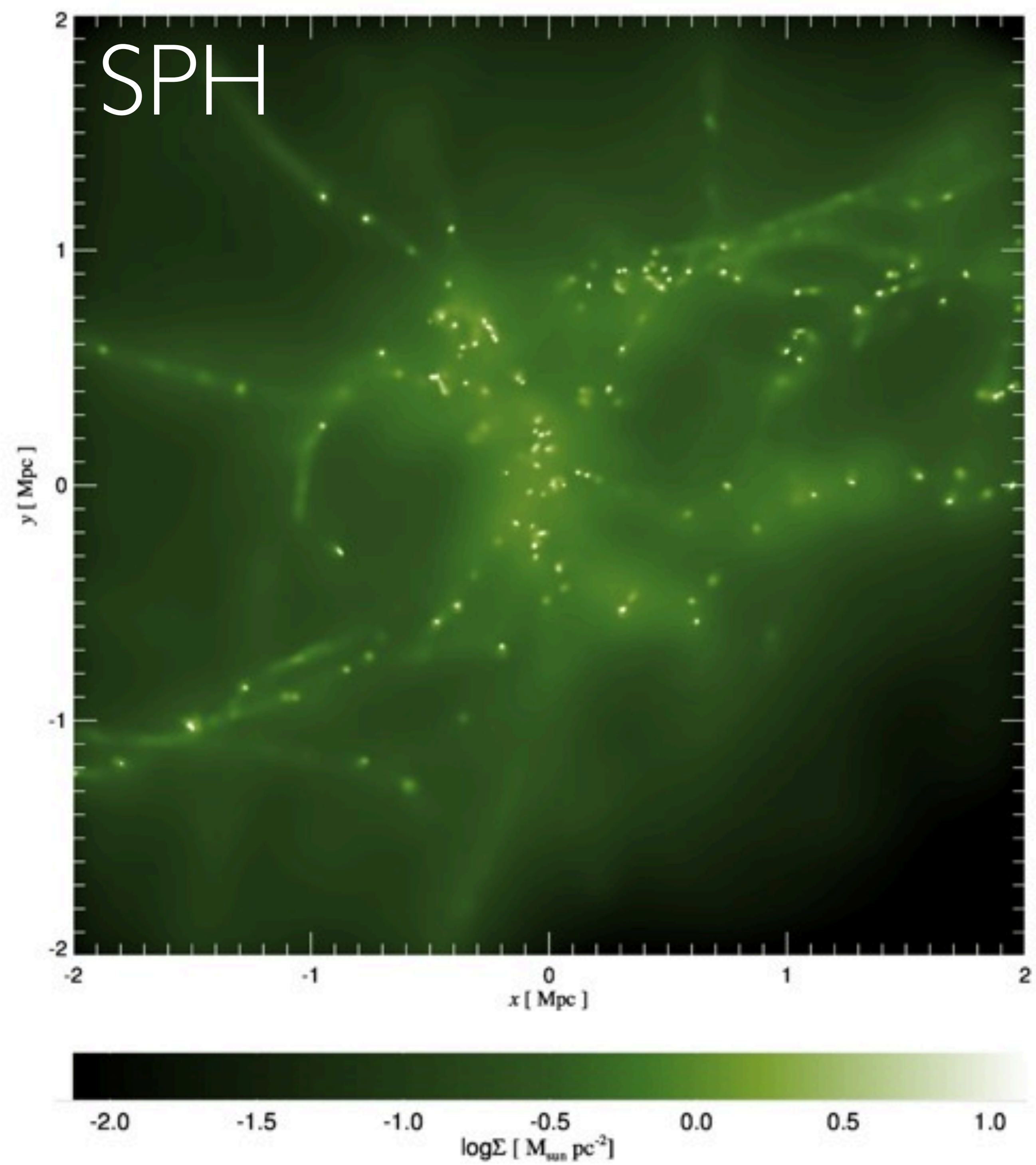

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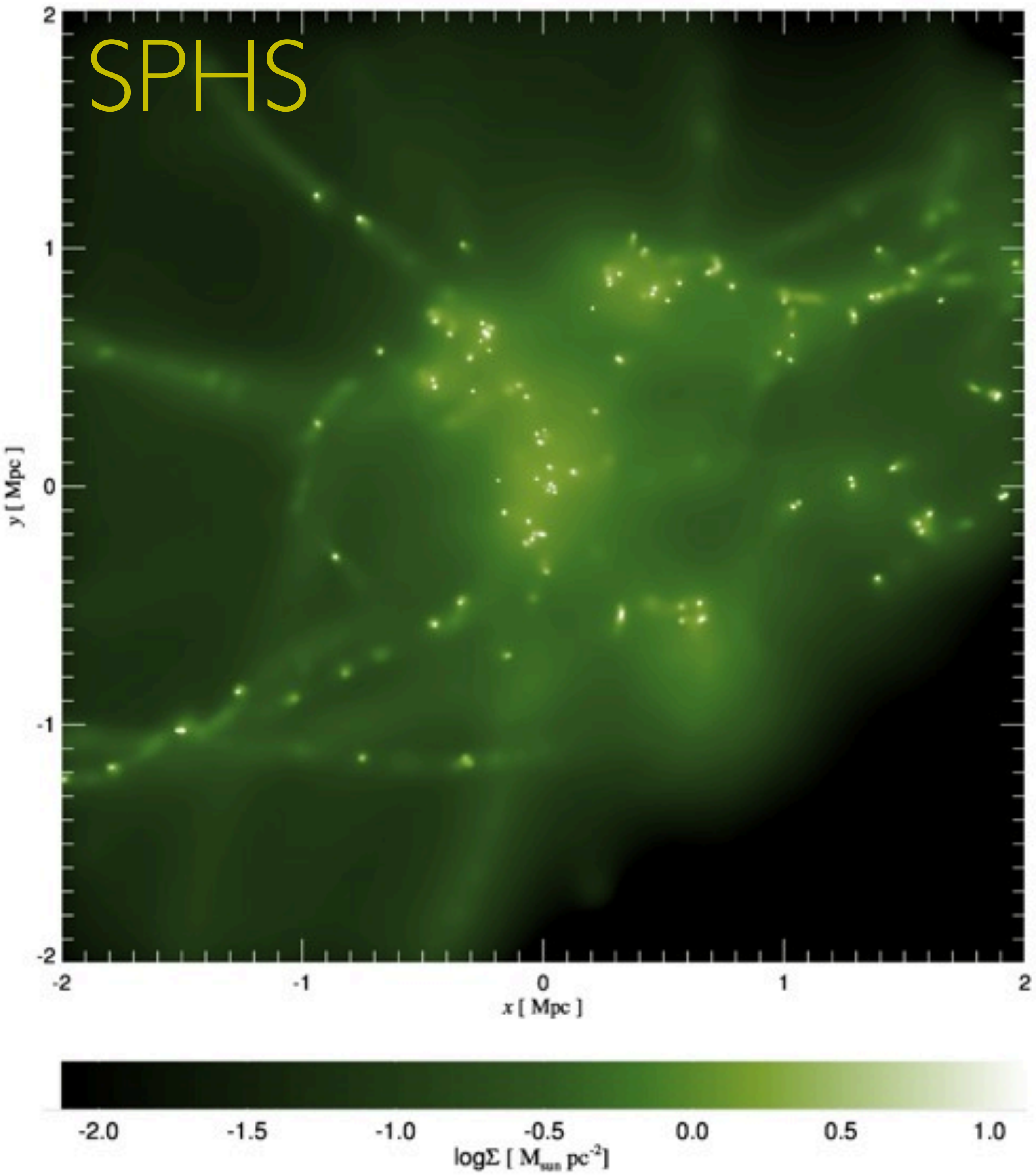

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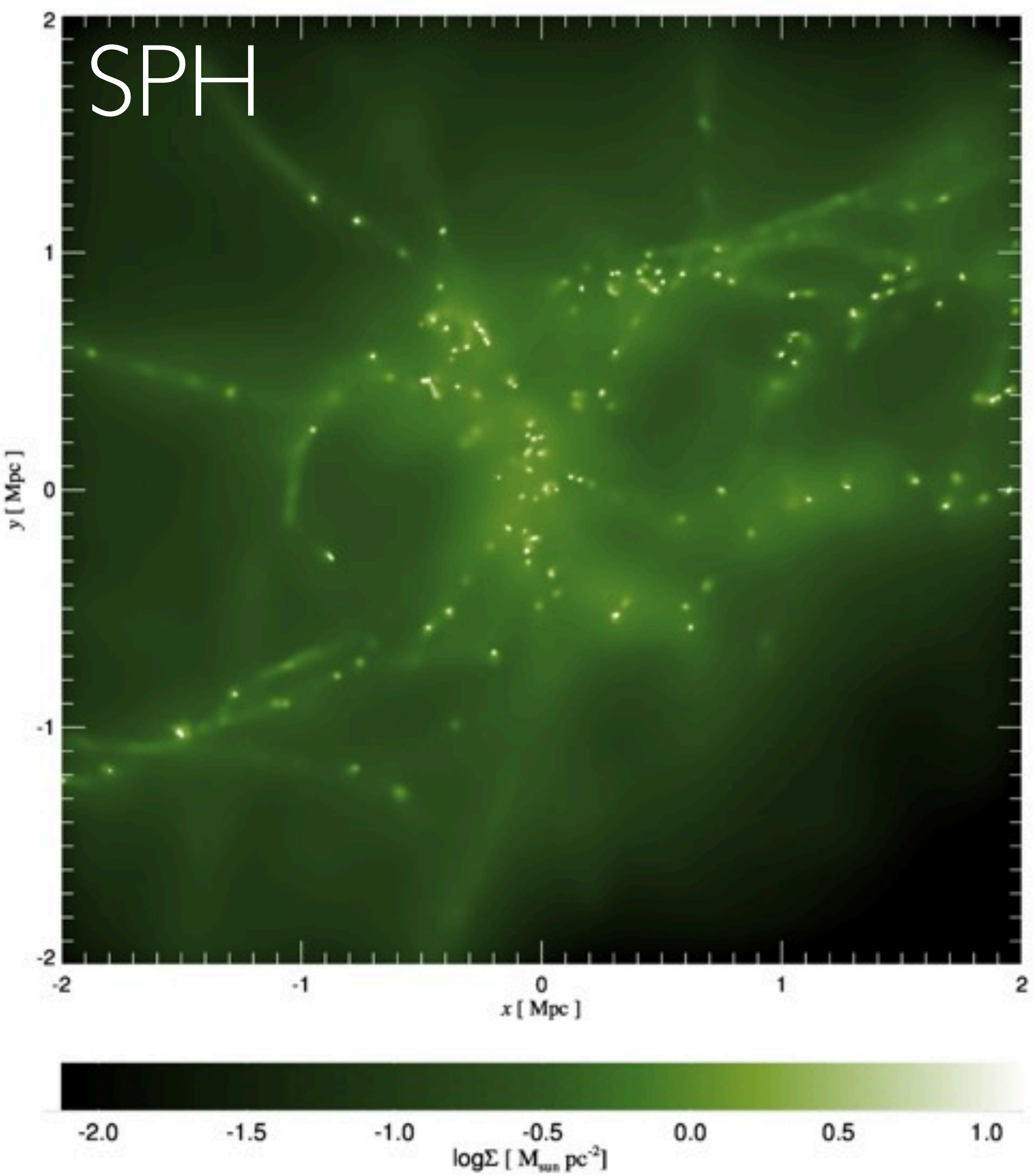

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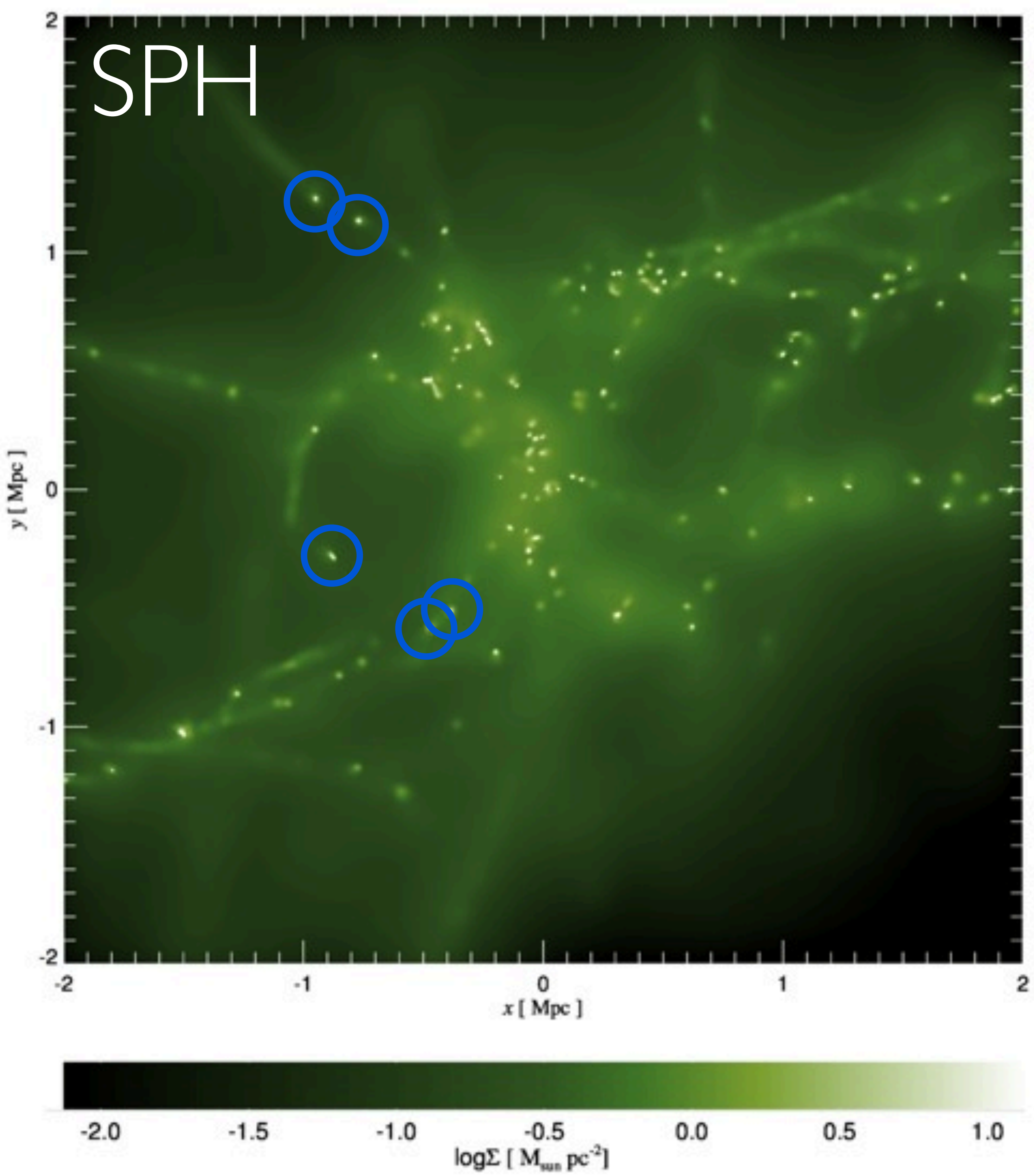

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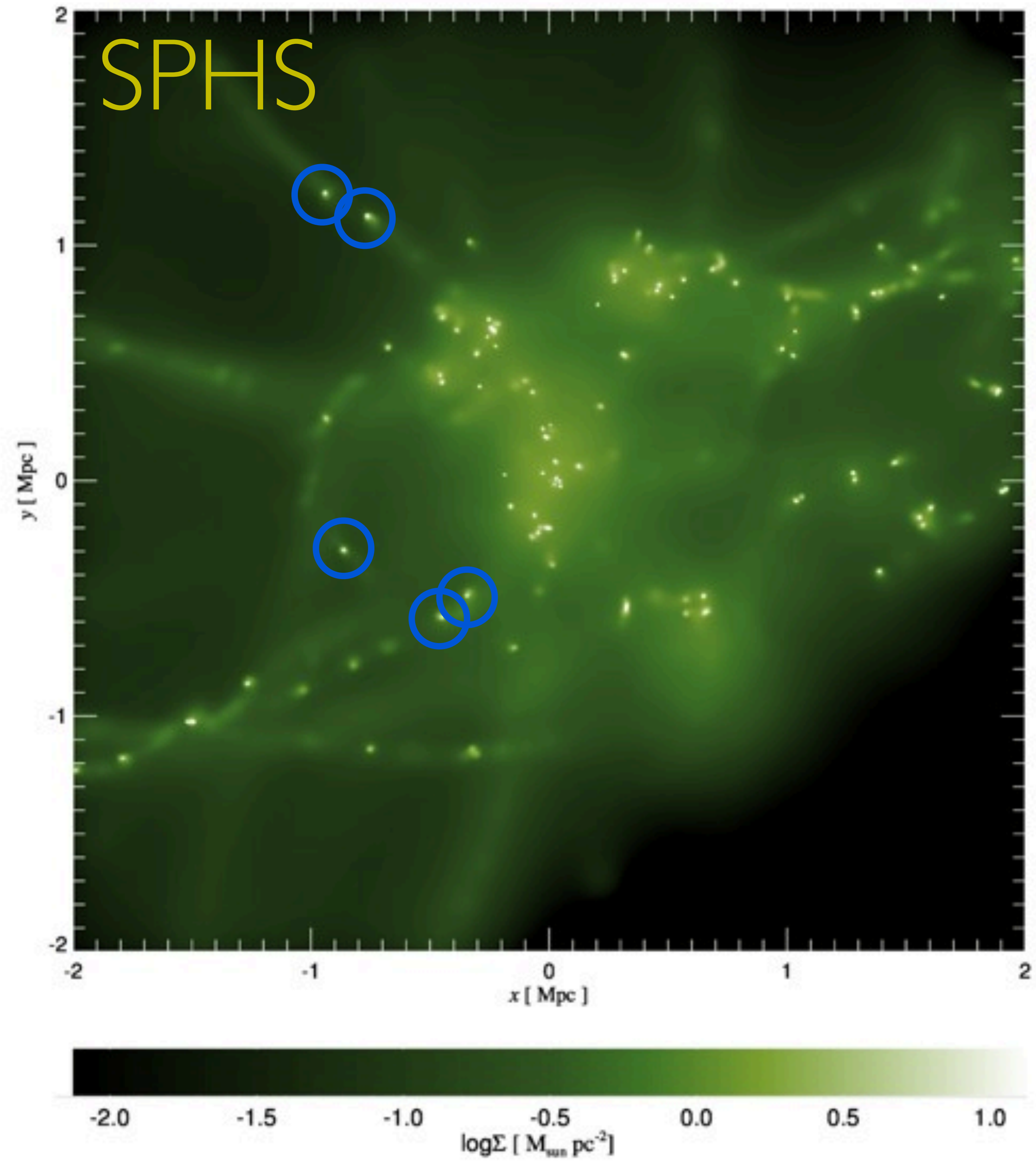

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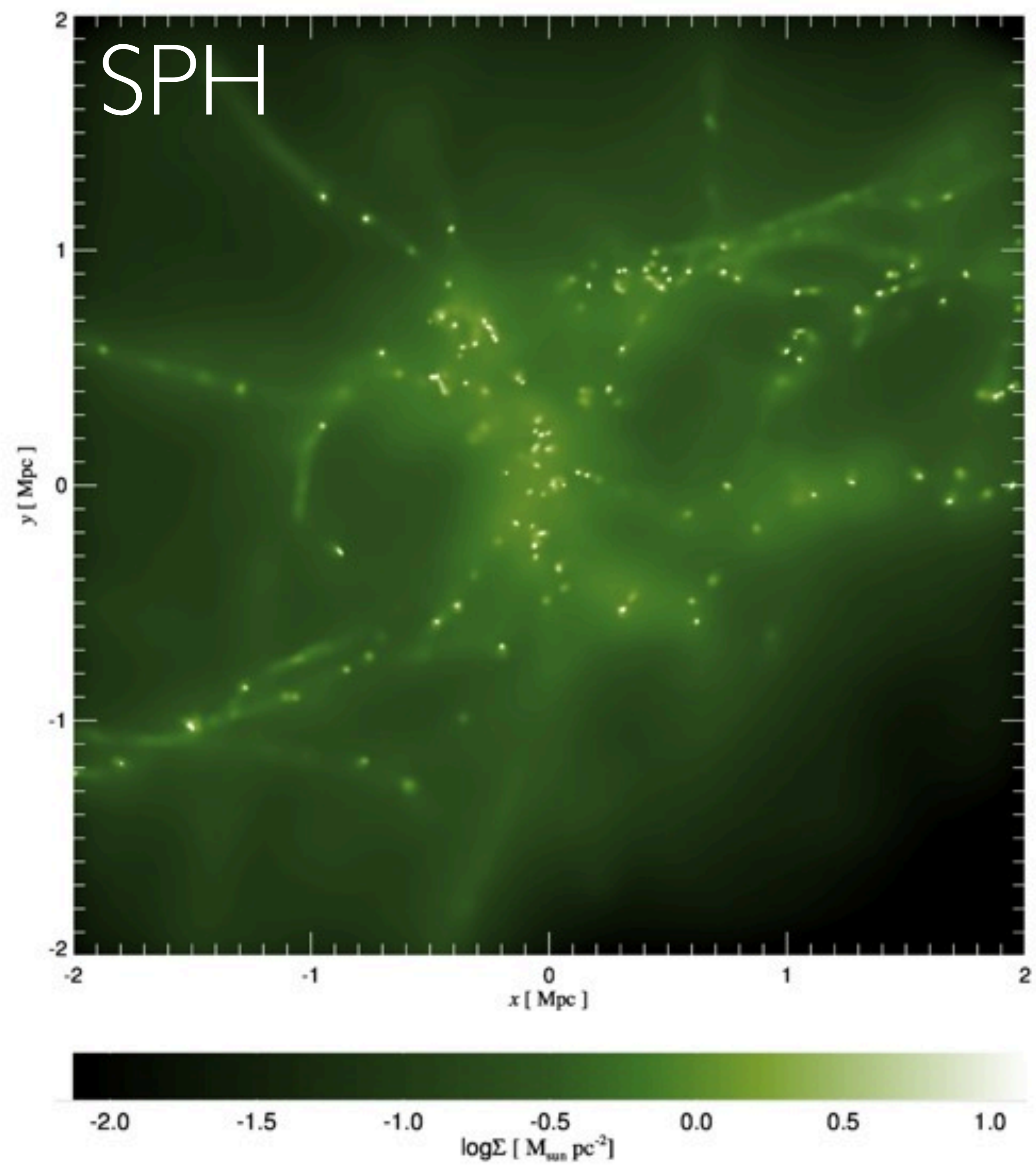

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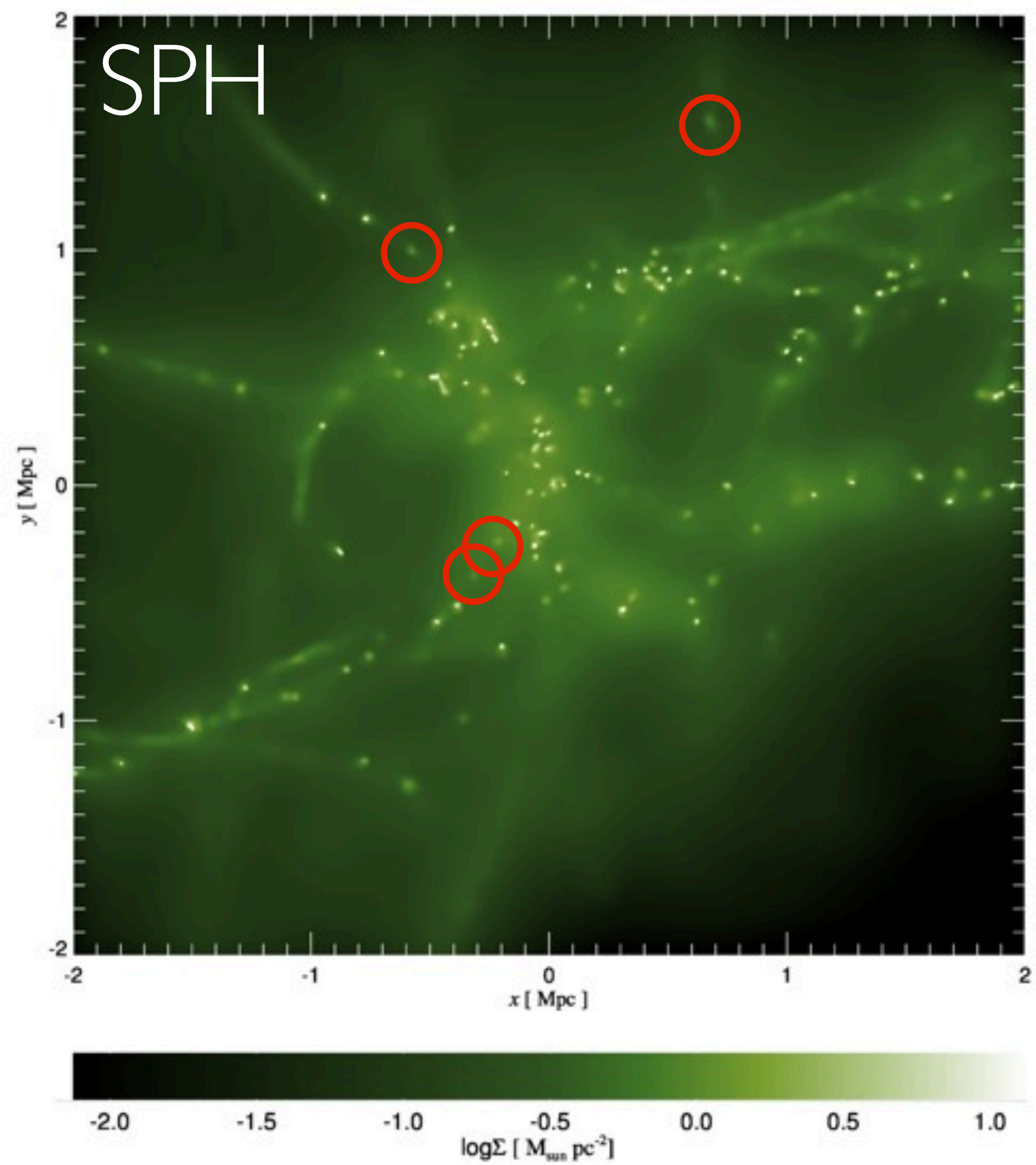

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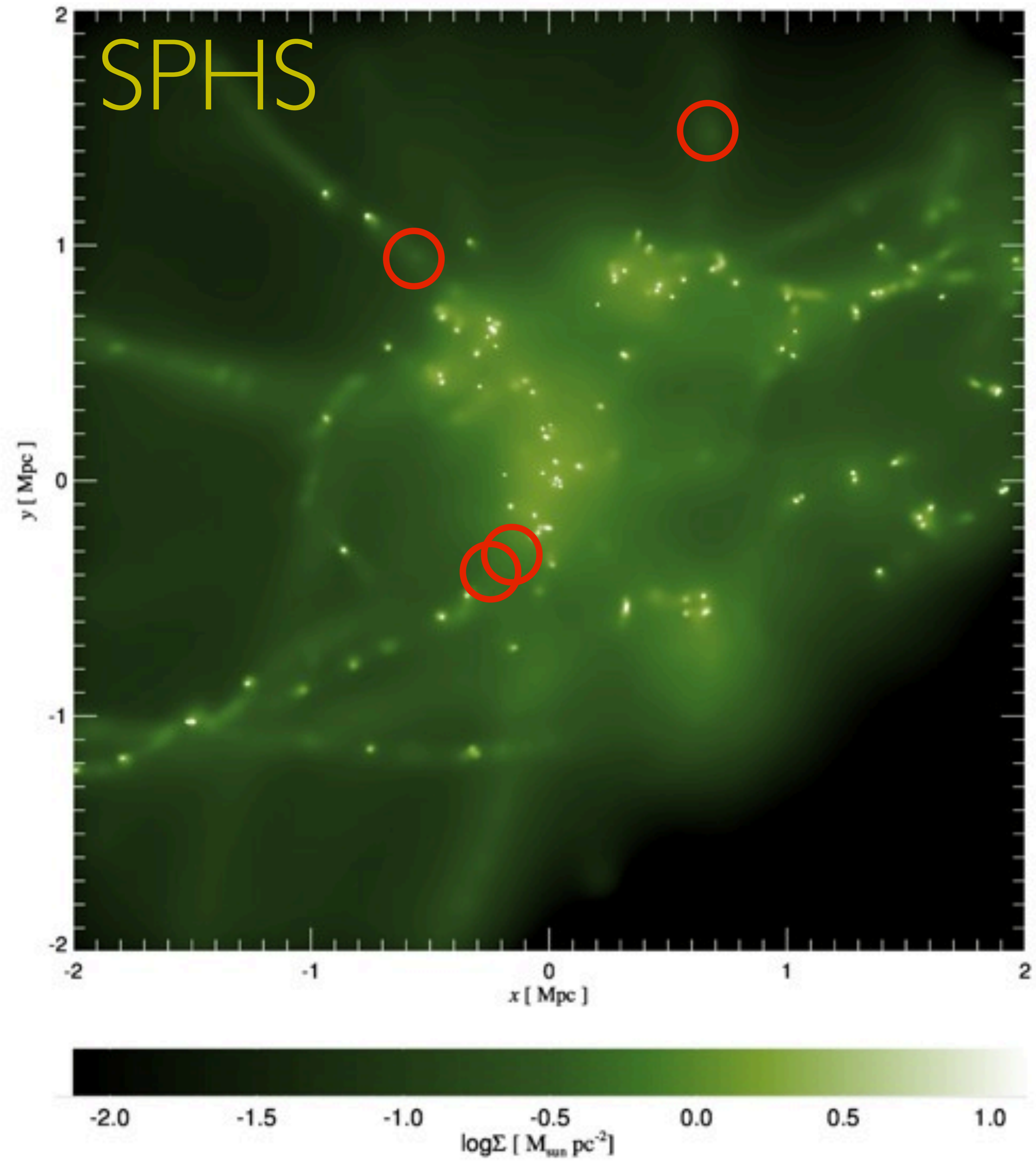

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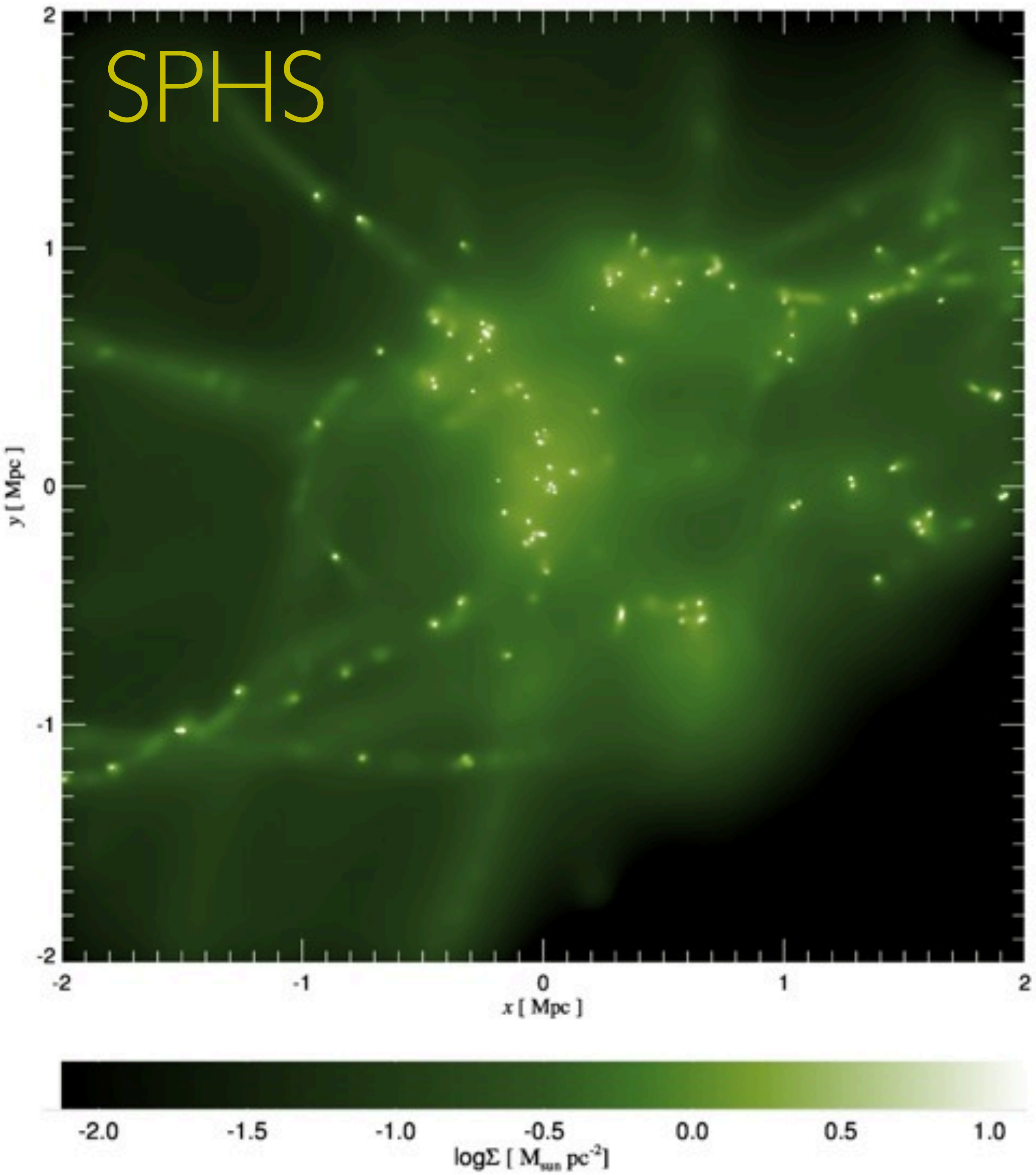

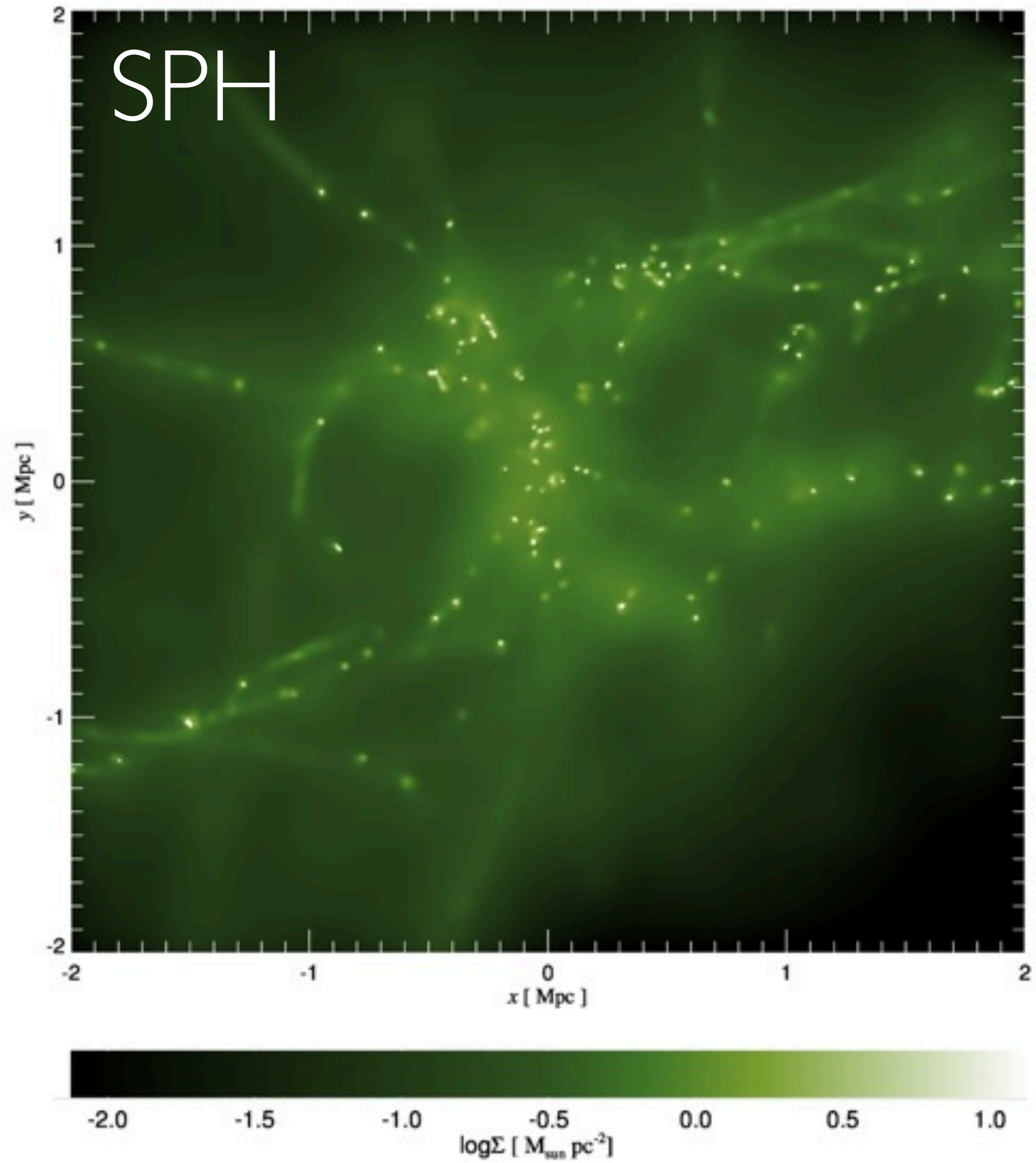

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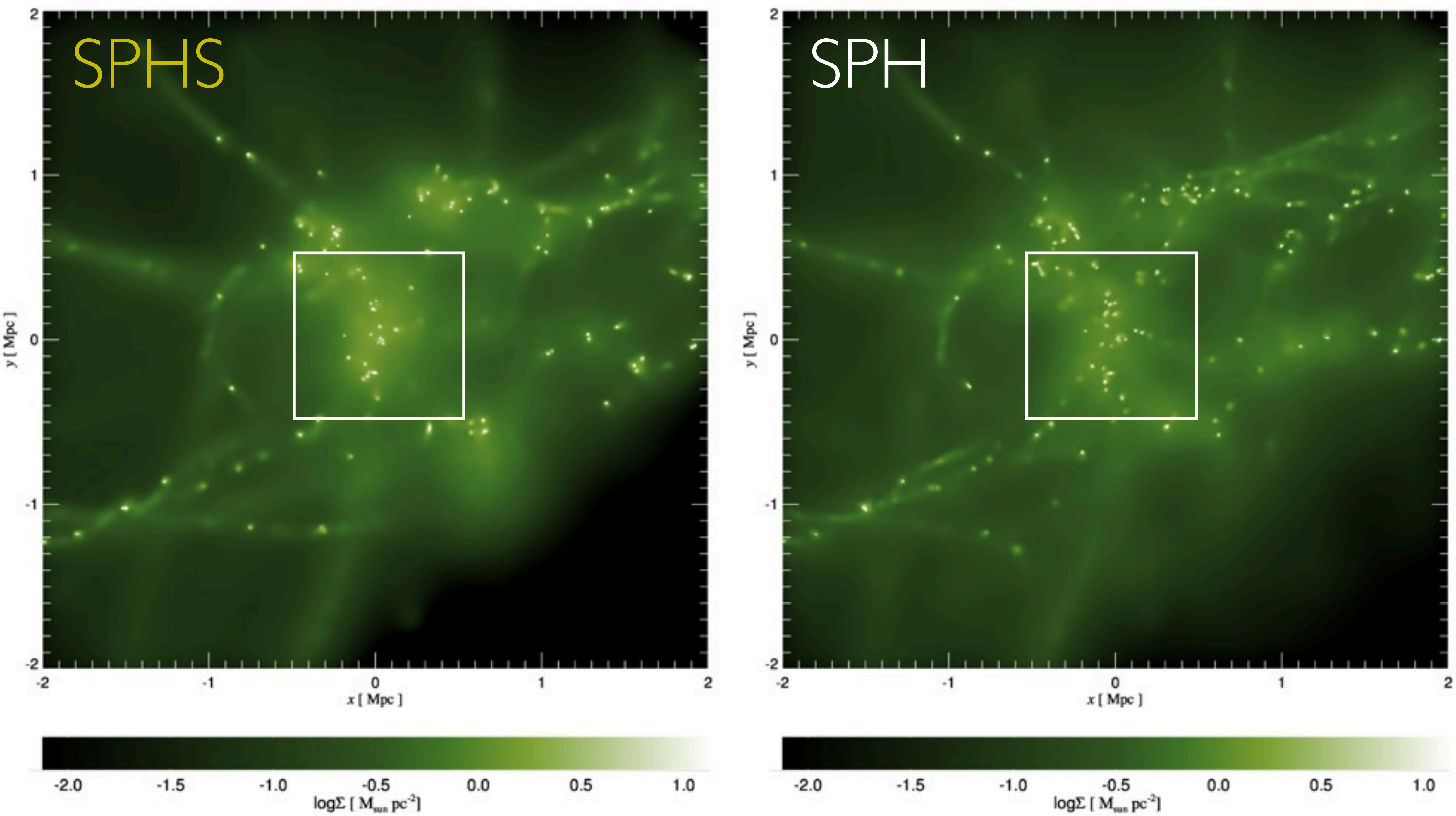

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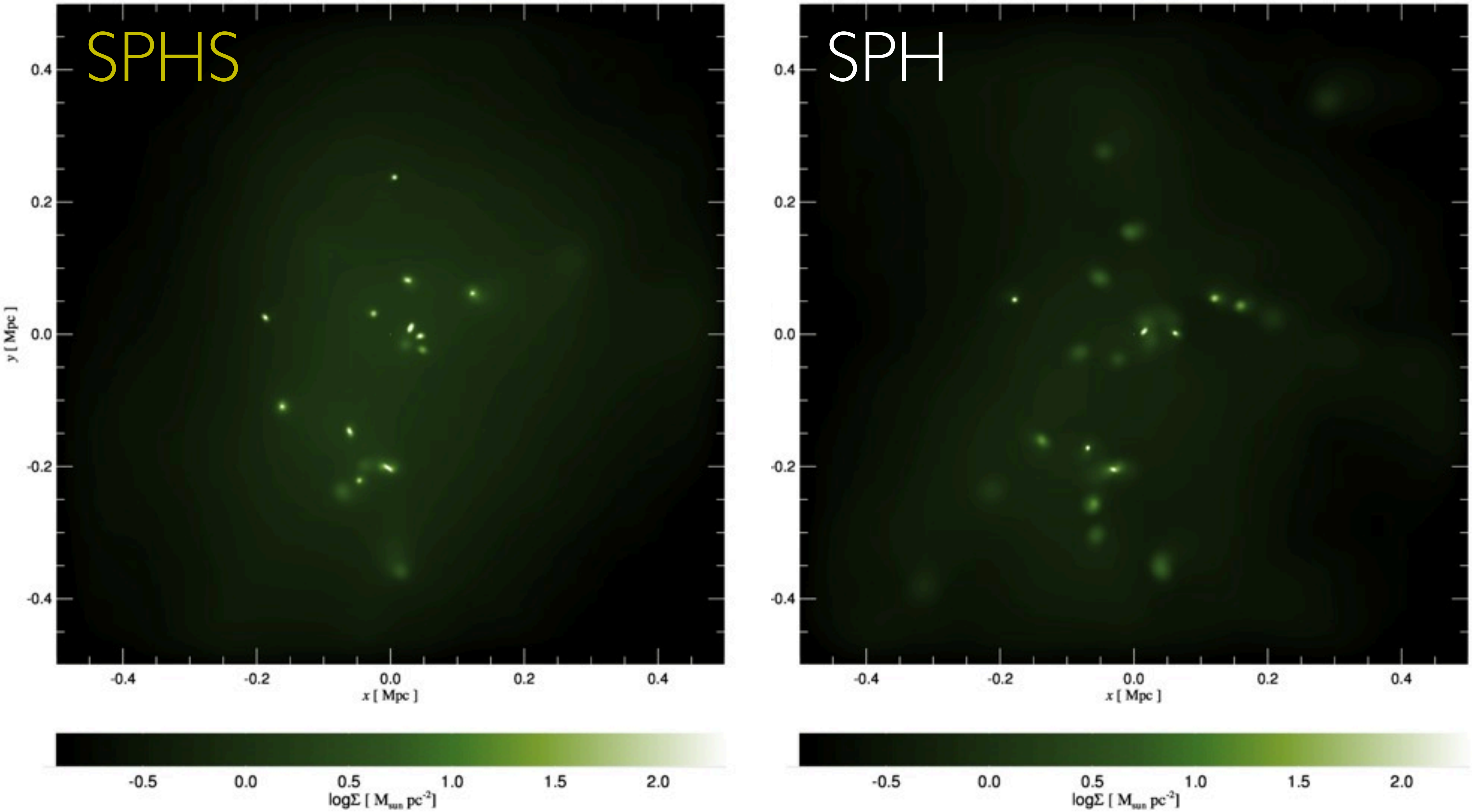

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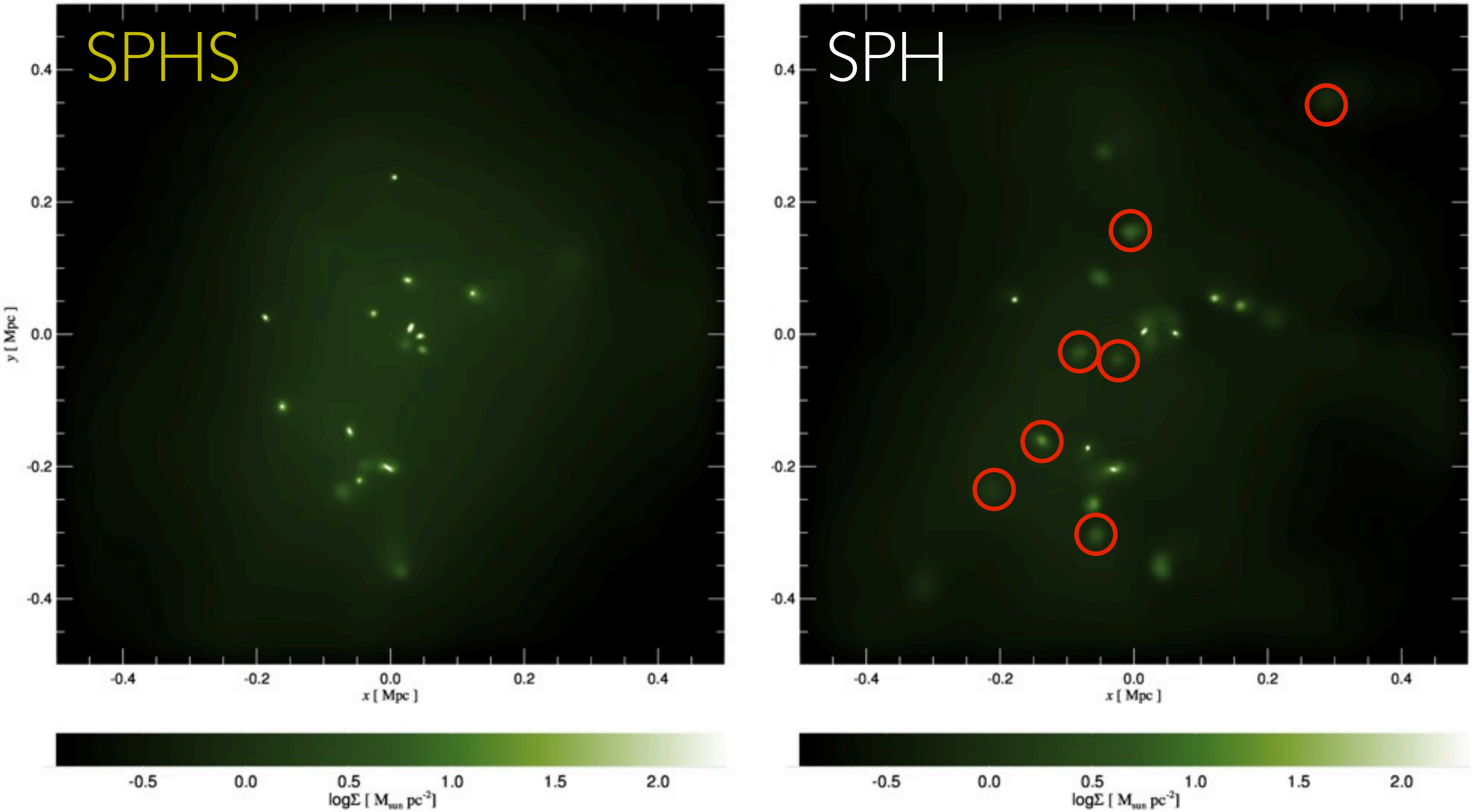

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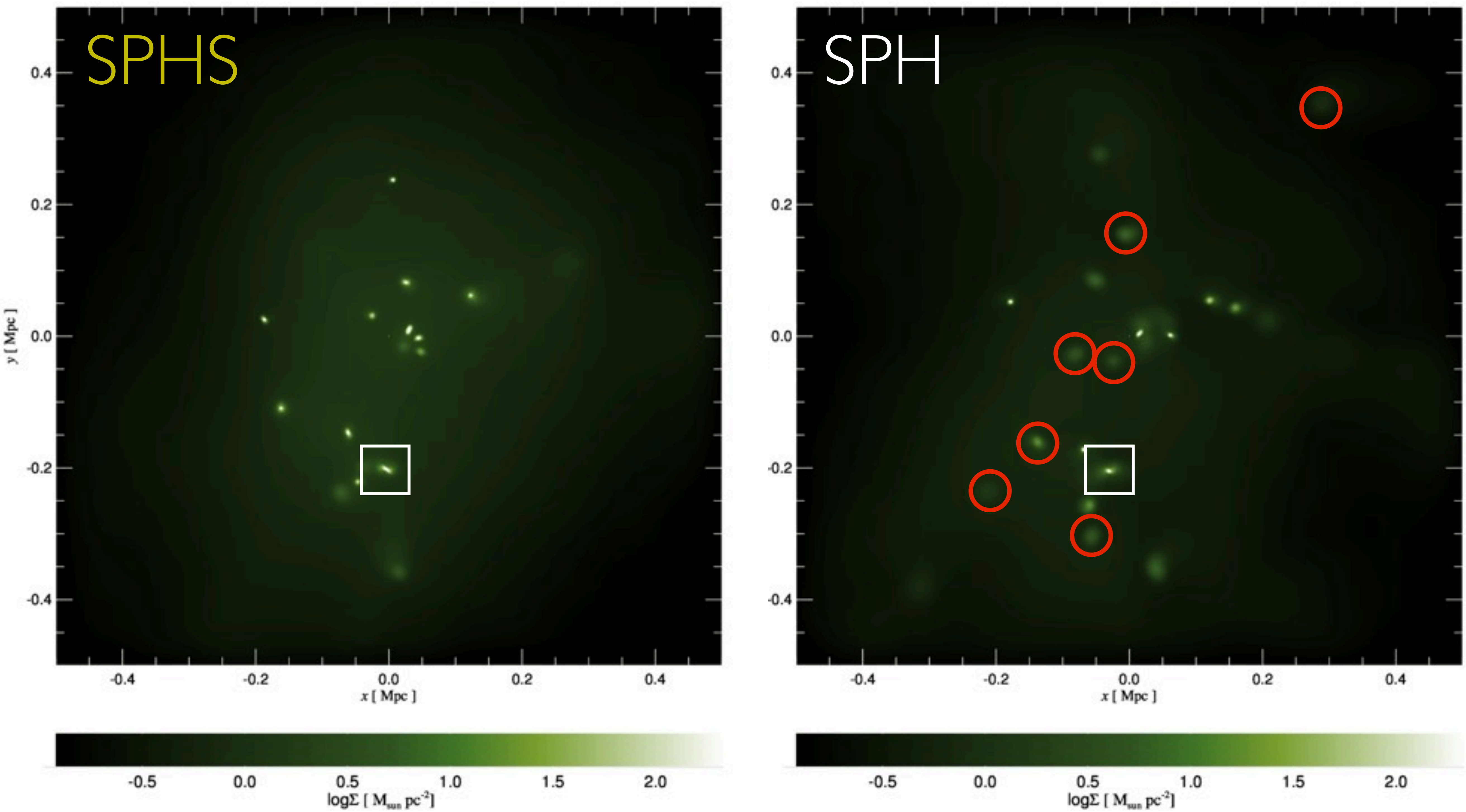

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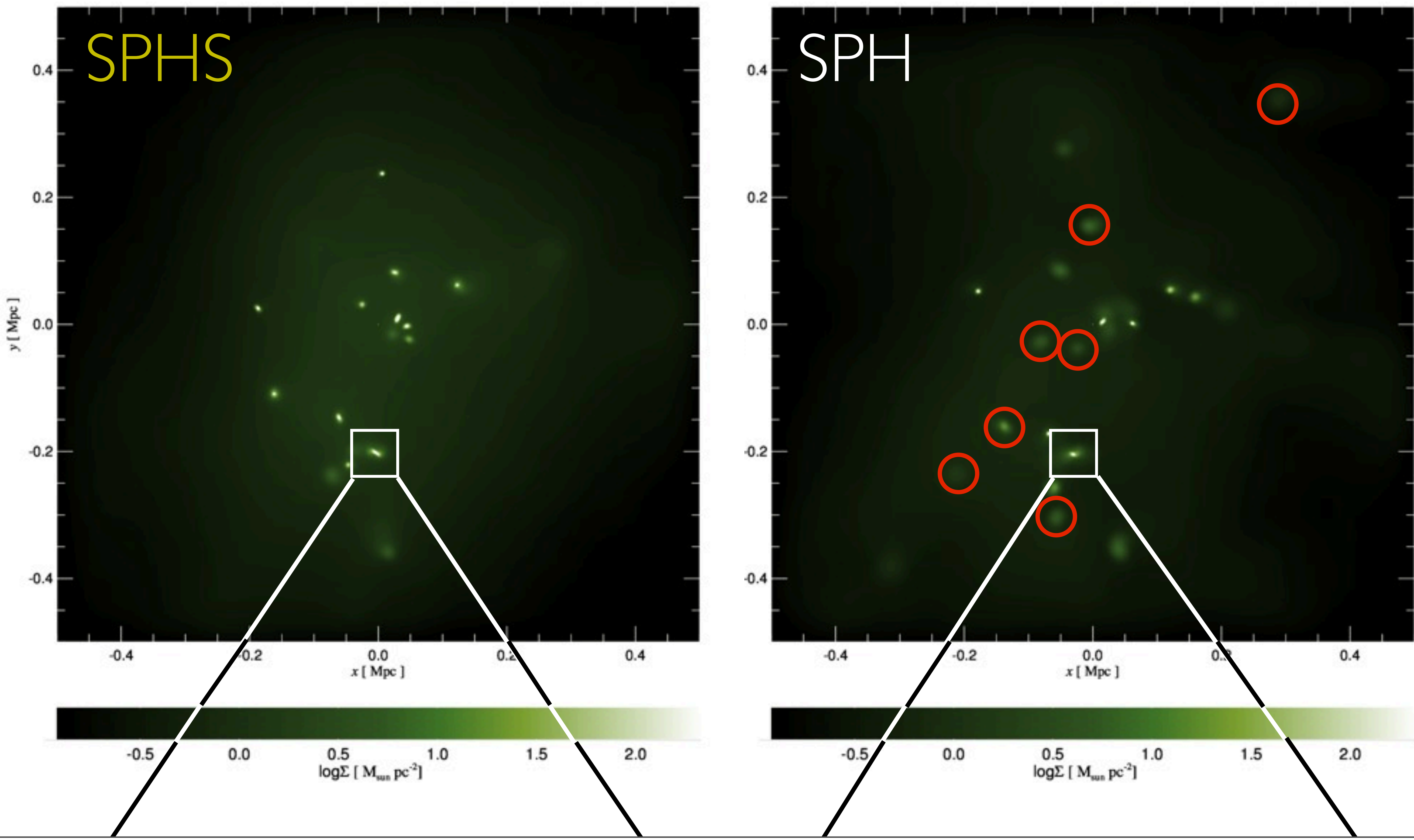

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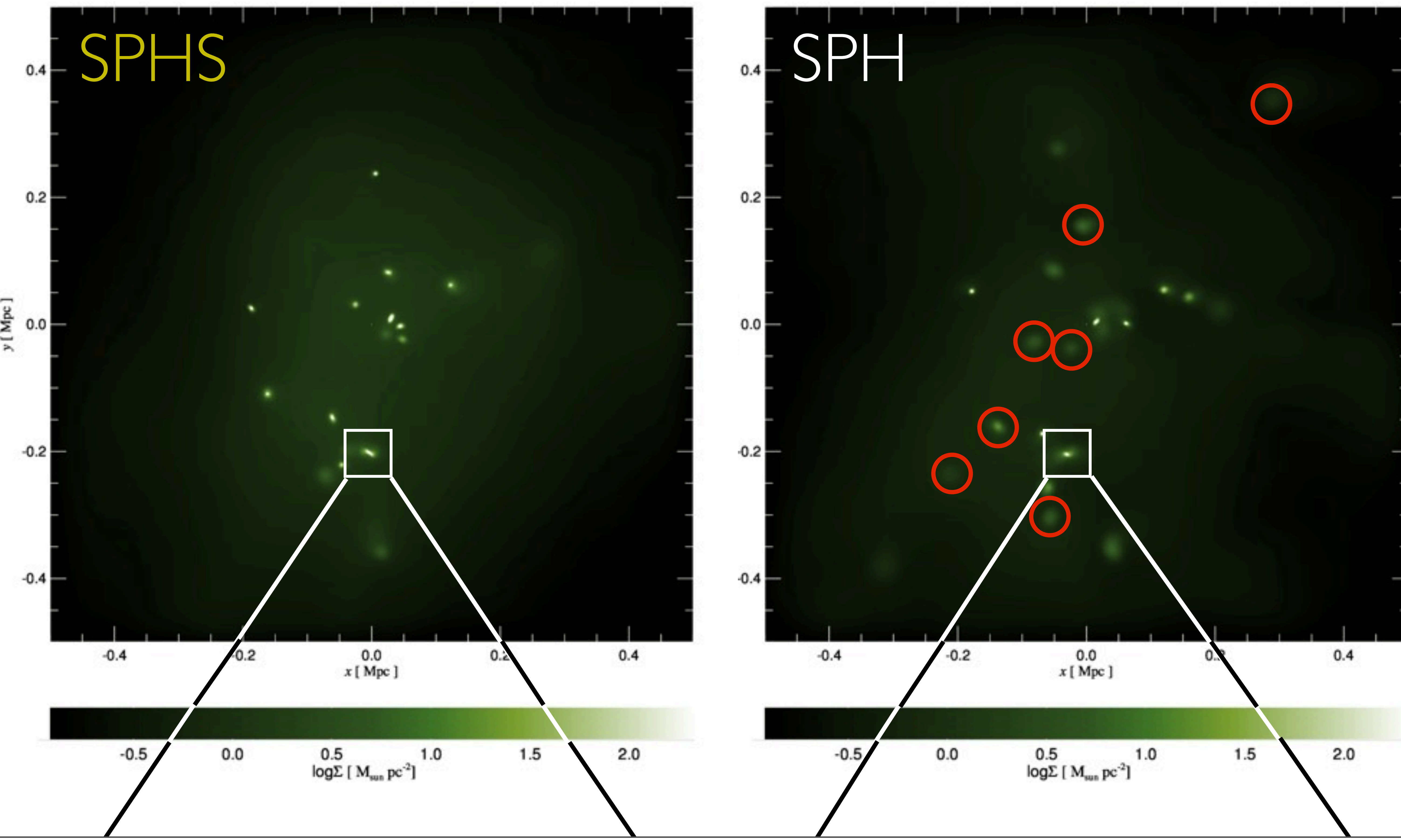

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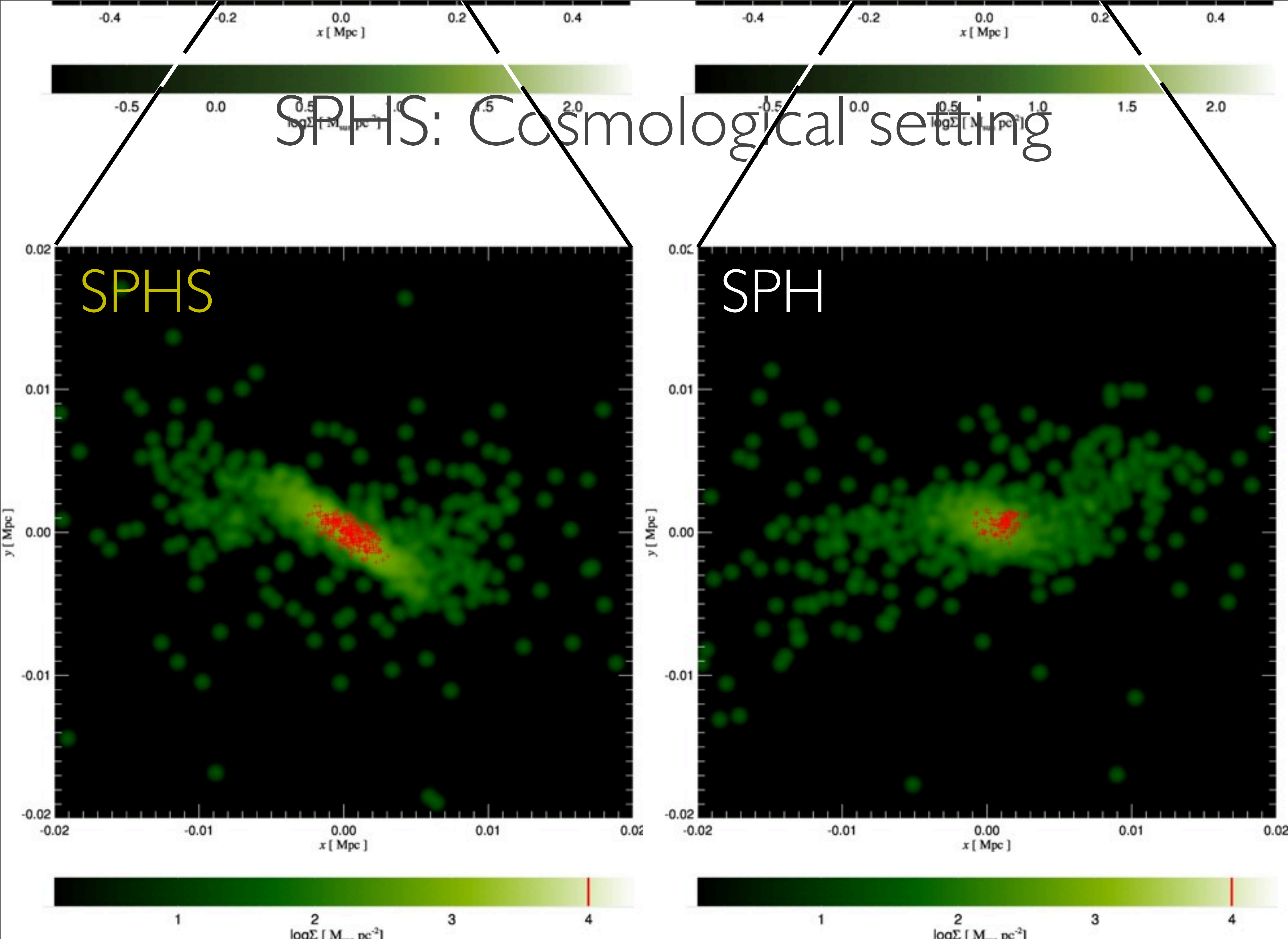

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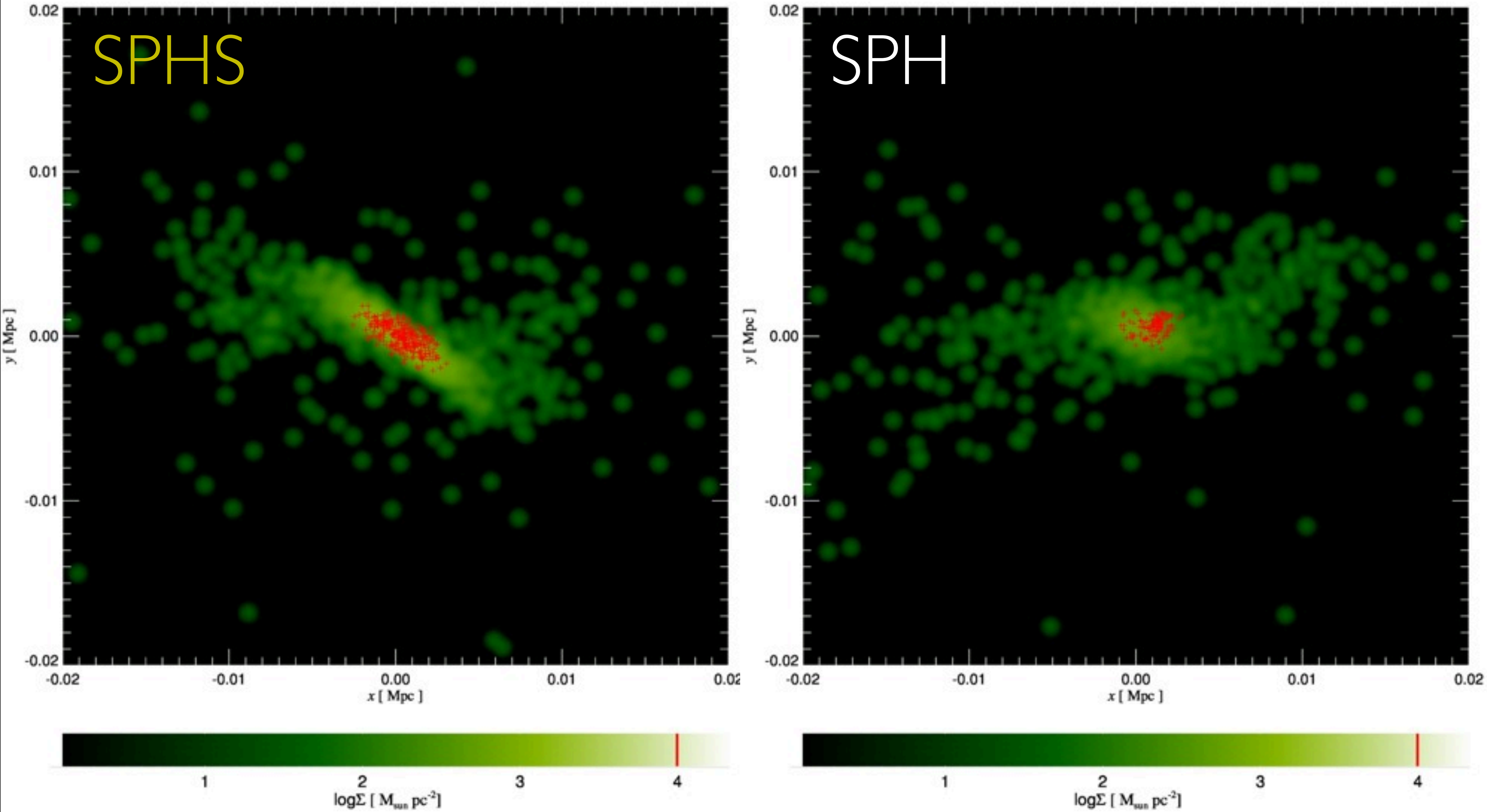

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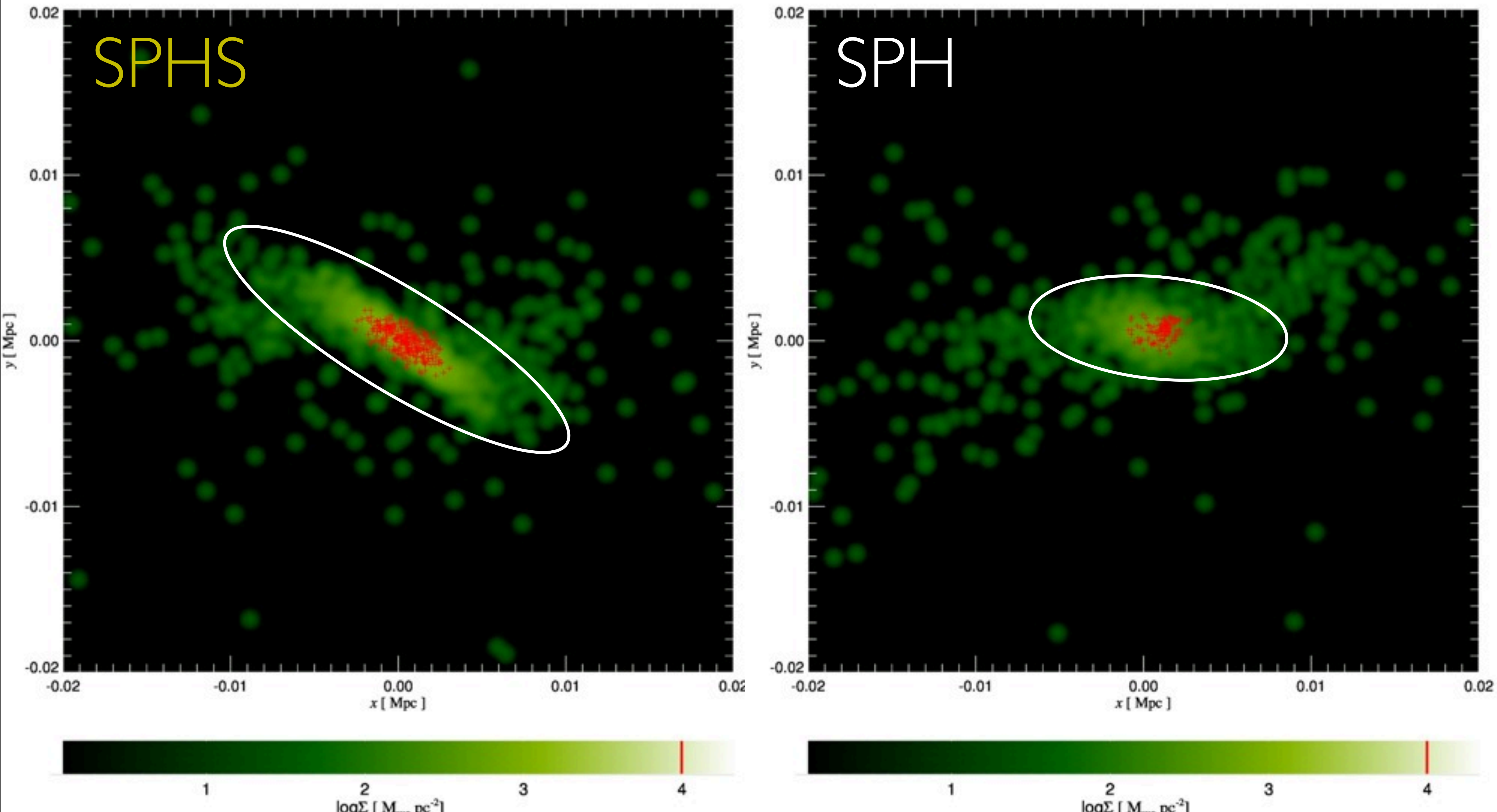

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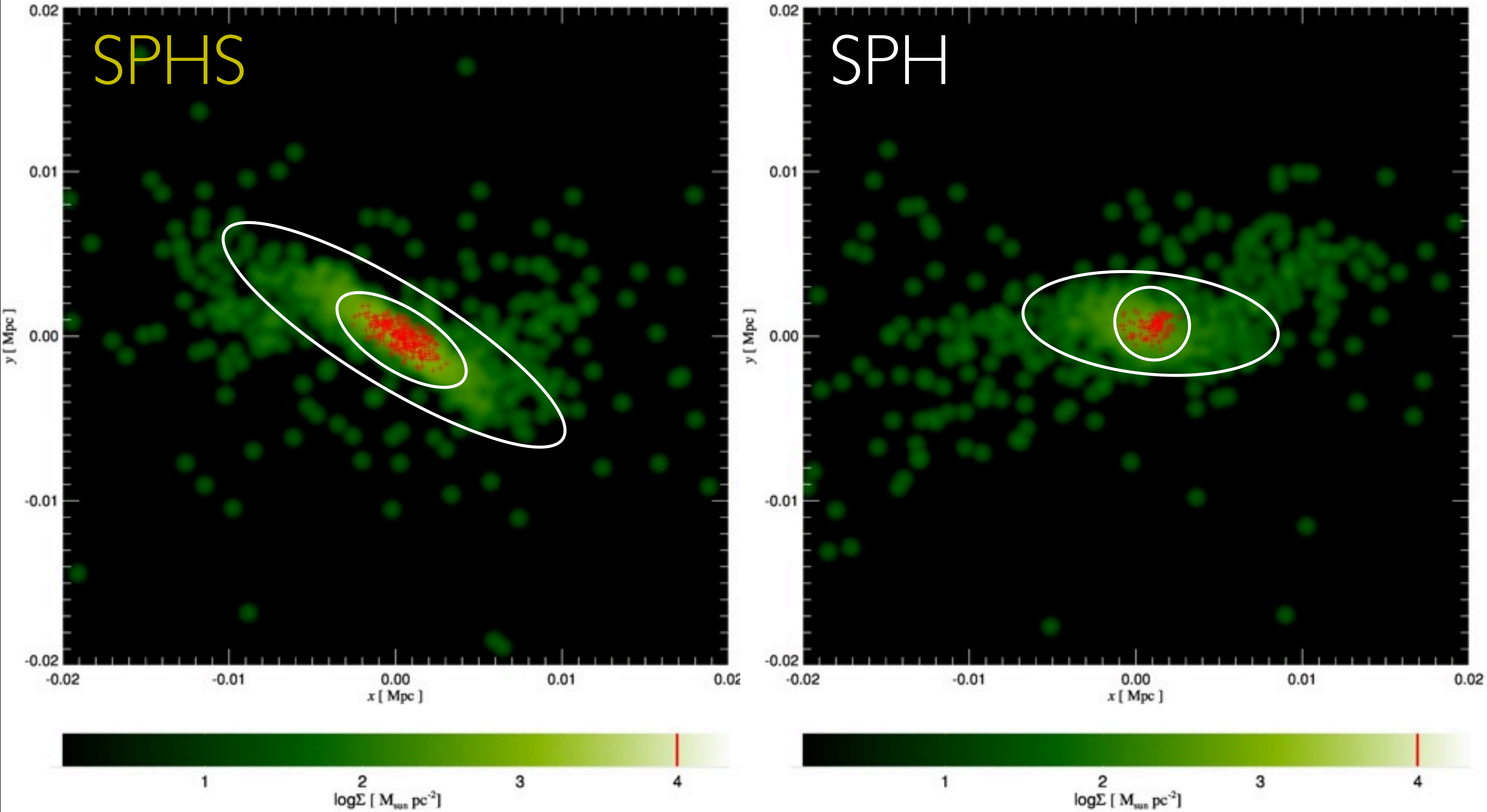

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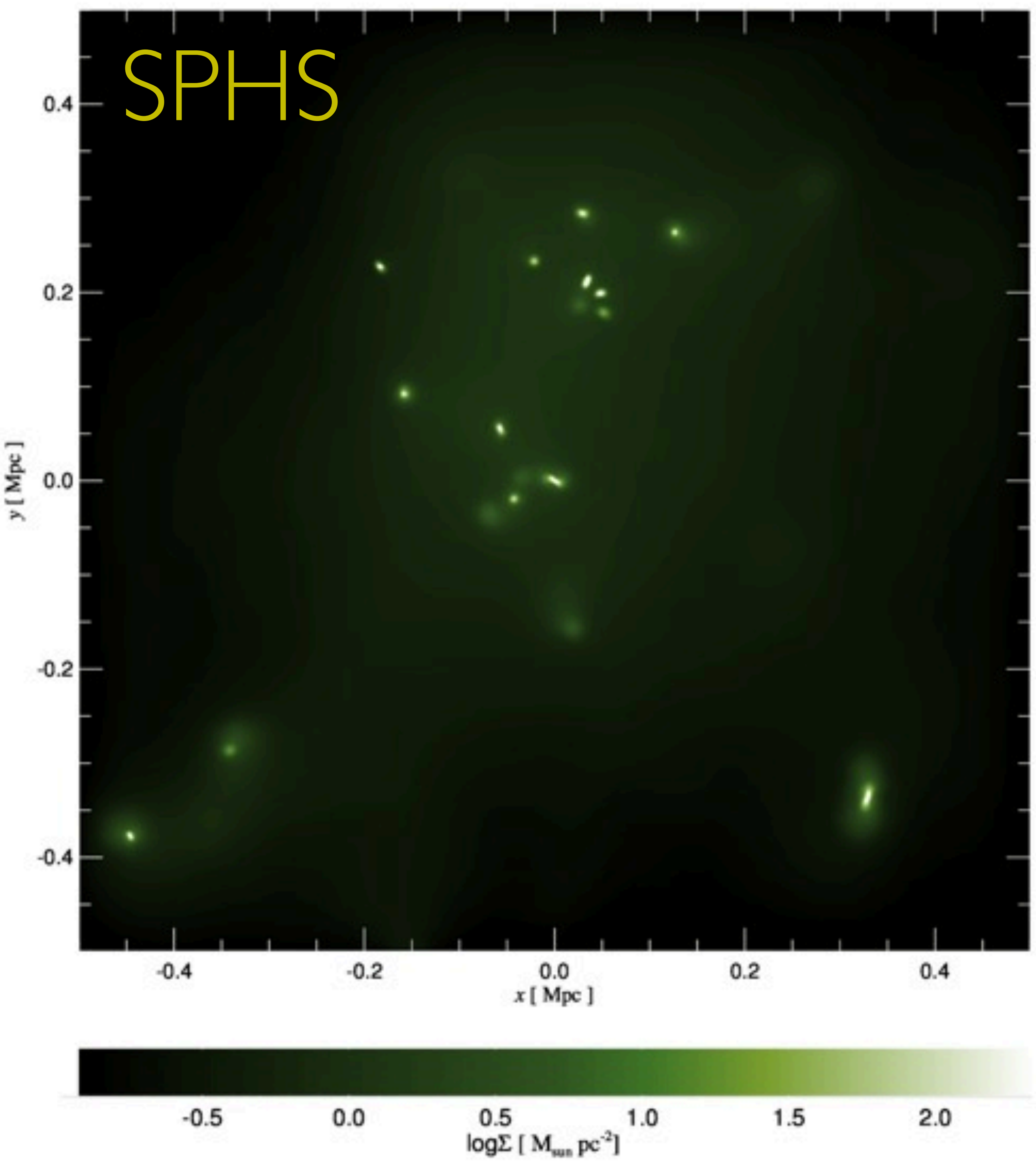

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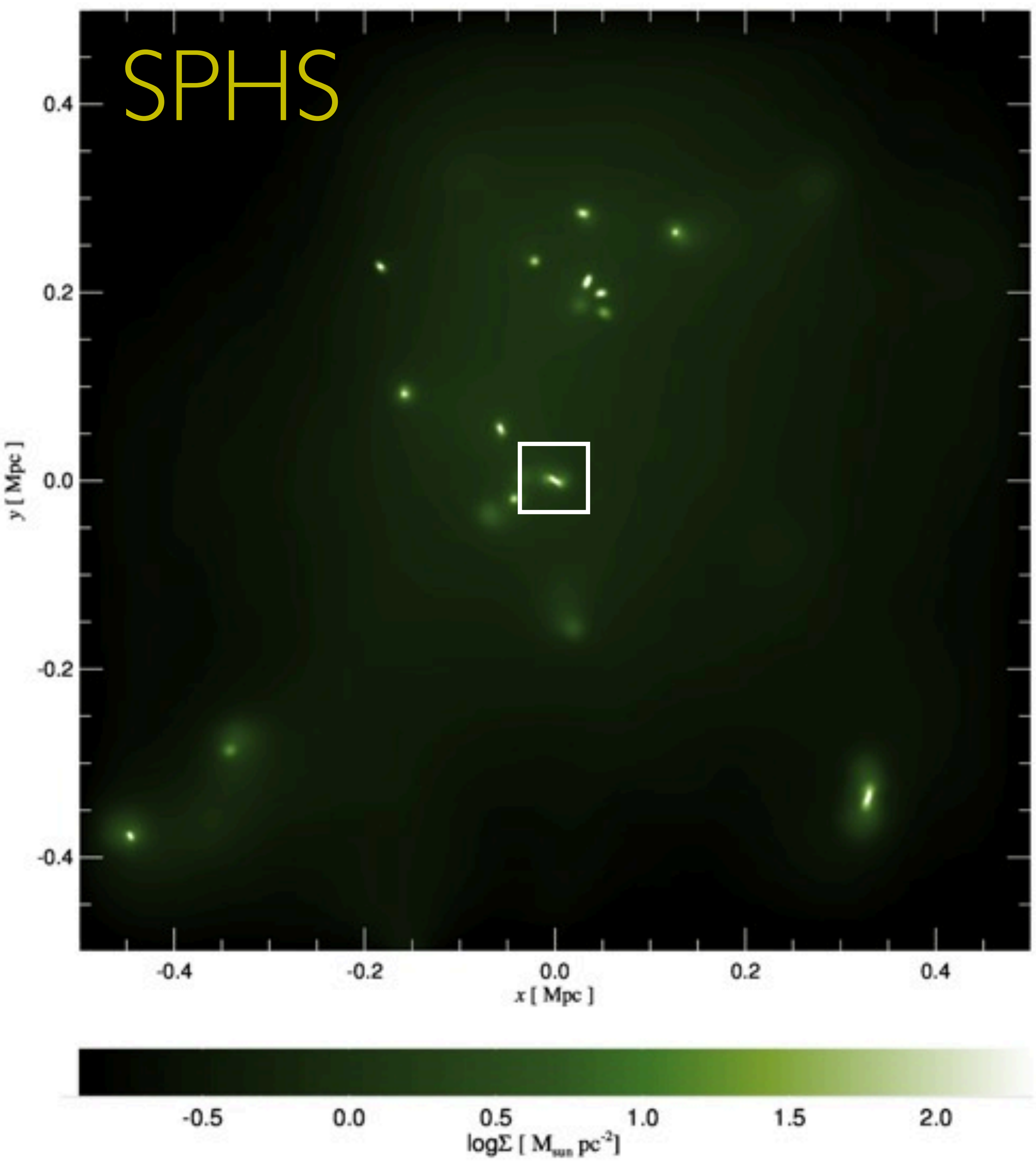

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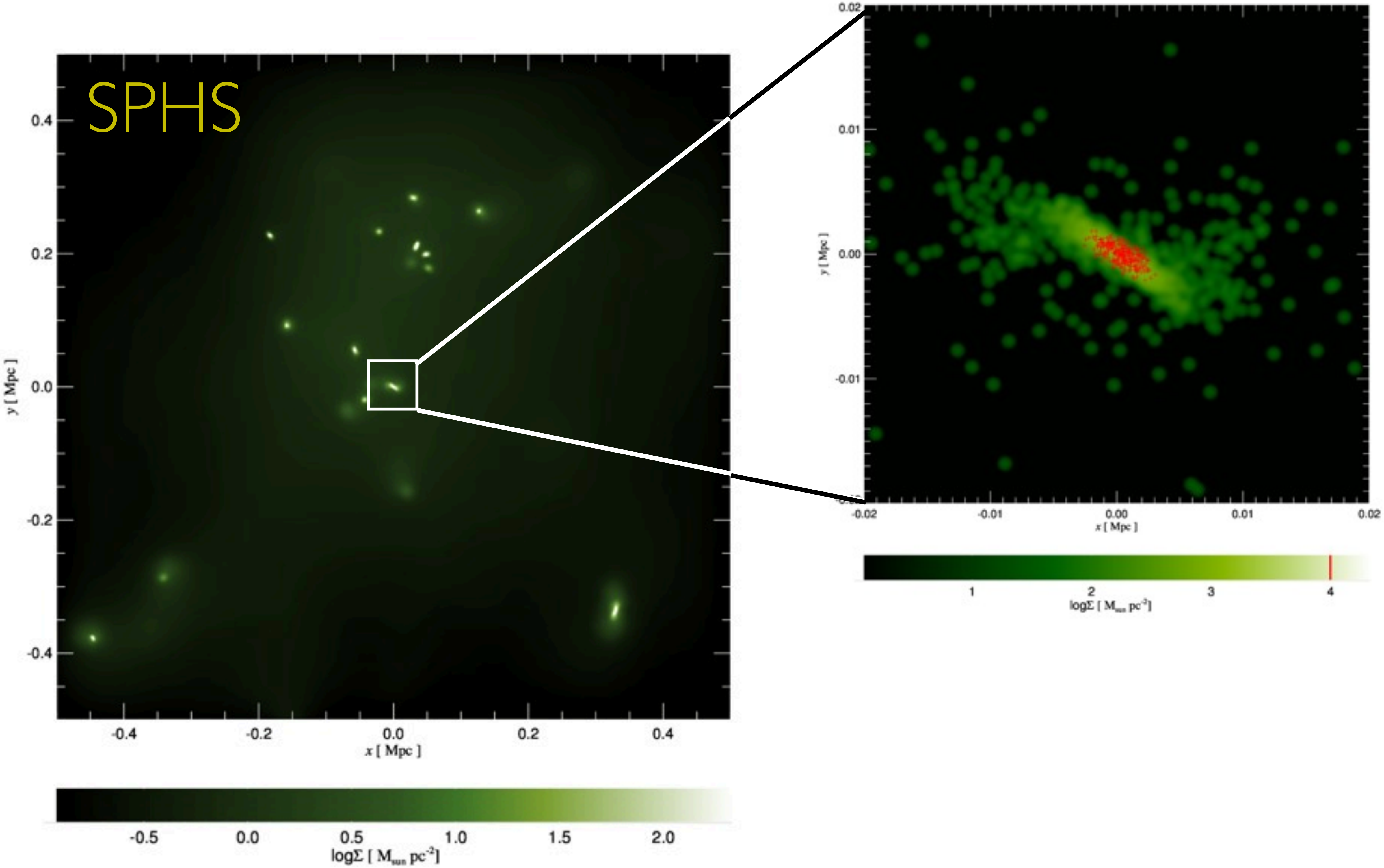
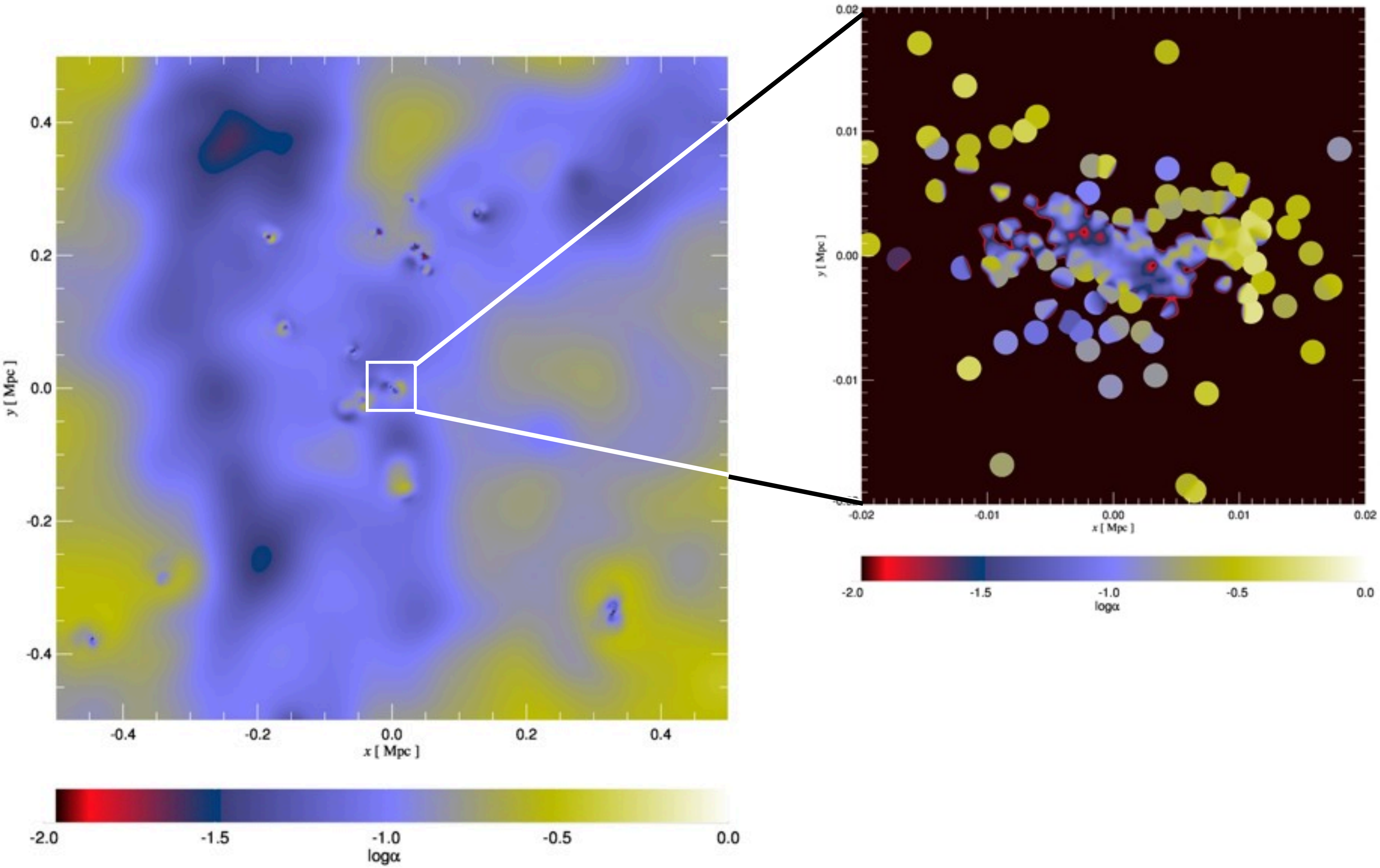
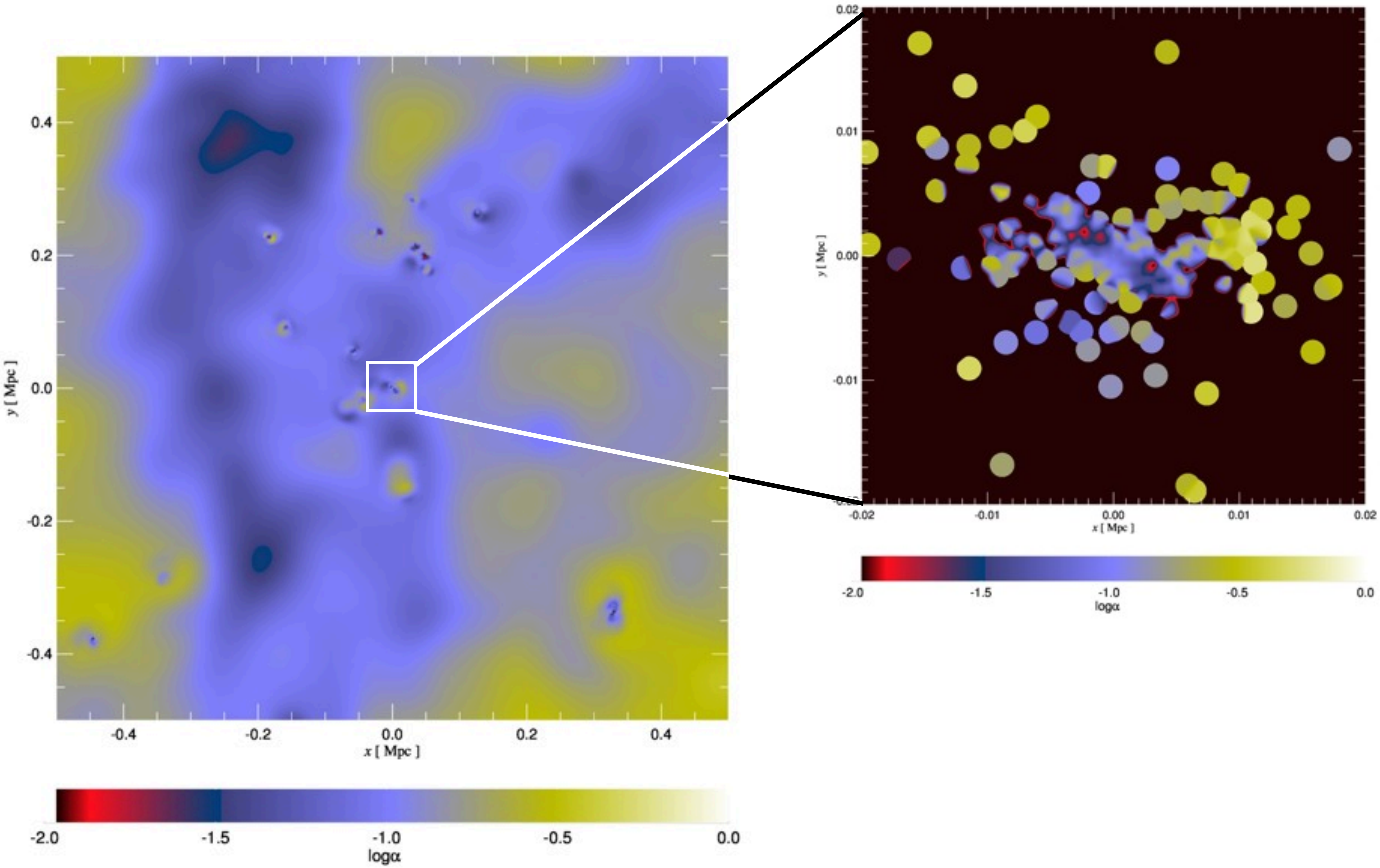


SPHS: ‘Early warning’ viscosity switch



SPHS: 'Early warning' viscosity switch



SPHS: 'Early warning' viscosity switch

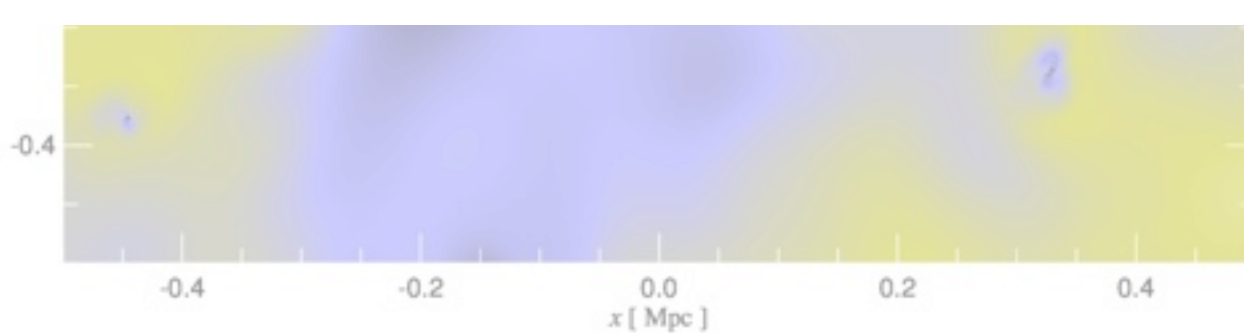
$$\alpha_{\mathrm{loc},i} = \begin{cases} \dfrac{h_i^2|\nabla(\nabla\cdot\mathbf{v}_i)|}{h_i^2|\nabla(\nabla\cdot\mathbf{v}_i)|+h_i|\nabla\cdot\mathbf{v}_i|+n_s c_s}\alpha_{\max} & \nabla\cdot\mathbf{v}_i < 0 \\ 0 & \text{otherwise} \end{cases}$$

[i.e. going to converge]

[i.e. converging]

[Requires high order gradient estimator]

-2.0 -1.5 -1.0 logα -0.5 0.0



SPHS: 'Early warning' viscosity switch

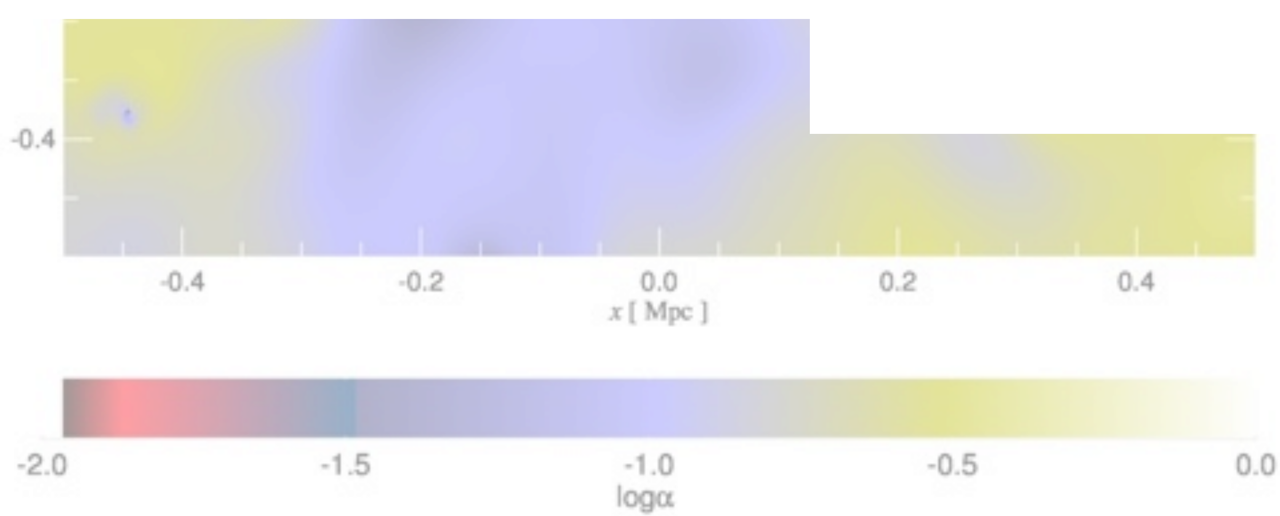
$$\alpha_{\mathrm{loc},i} = \begin{cases} \dfrac{h_i^2|\nabla(\nabla\cdot\mathbf{v}_i)|}{h_i^2|\nabla(\nabla\cdot\mathbf{v}_i)|+h_i|\nabla\cdot\mathbf{v}_i|+n_s c_s}\alpha_{\mathrm{max}} & \nabla\cdot\mathbf{v}_i < 0 \\ 0 & \mathrm{otherwise} \end{cases}$$

[i.e. converging]

[i.e. going to converge]

[Requires high order gradient estimator]

$$\nu = \alpha\frac{c_s^2}{\Omega_K}$$ viscosity



-0.5 0.0

SPHS: ‘Early warning’ viscosity switch

$$\alpha_{\mathrm{loc},i} = \begin{cases} \dfrac{h_i^2 |\nabla(\nabla \cdot \mathbf{v}_i)|}{h_i^2 |\nabla(\nabla \cdot \mathbf{v}_i)| + h_i |\nabla \cdot \mathbf{v}_i| + n_s c_s} \alpha_{\max} & \nabla \cdot \mathbf{v}_i < 0 \\ 0 & \text{otherwise} \end{cases}$$

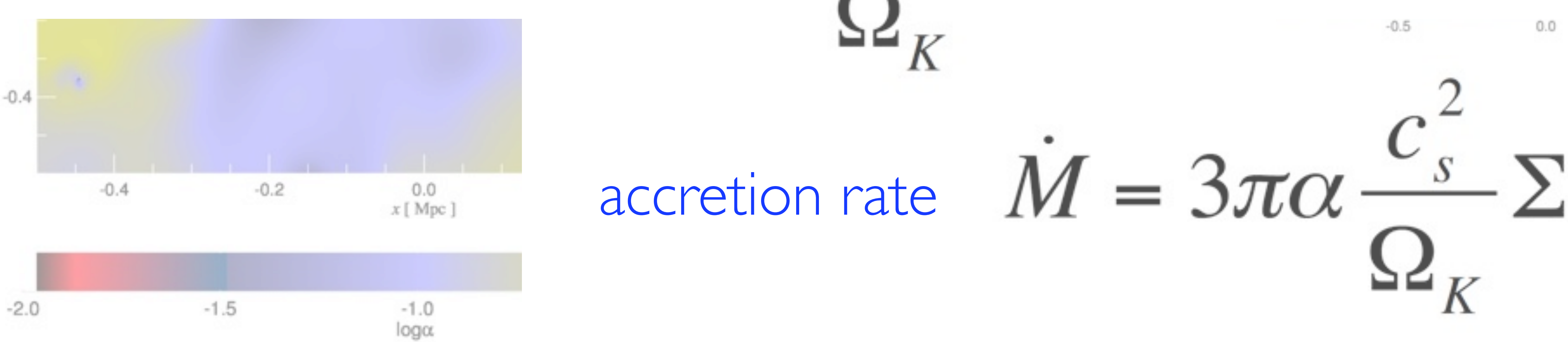
[i.e. going to converge]

[i.e. converging]

[Requires high order gradient estimator]

$$\nu = \alpha \frac{c_s^2}{\Omega_K}$$ viscosity

accretion rate $$\dot{M} = 3\pi\alpha \frac{c_s^2}{\Omega_K}\Sigma$$



Conclusions

- SPHS corrects for fundamental limitations in 'classic' SPH relating to mixing of multiple phases within the fluid (Agertz et al. 2007)

- Eliminates spurious cold clumps in SPH simulations

- Paves the way toward a new mode of disc feeding via SNe-driven accretion flow (Hobbs et al. 2013)

First results from cosmo sims suggest promising behaviour

- Disks more 'disky'? Due to structure formation differences + improved viscosity

Thank you