Towards galaxy formation simulations of Milky Way satellites with alternative dark matter models

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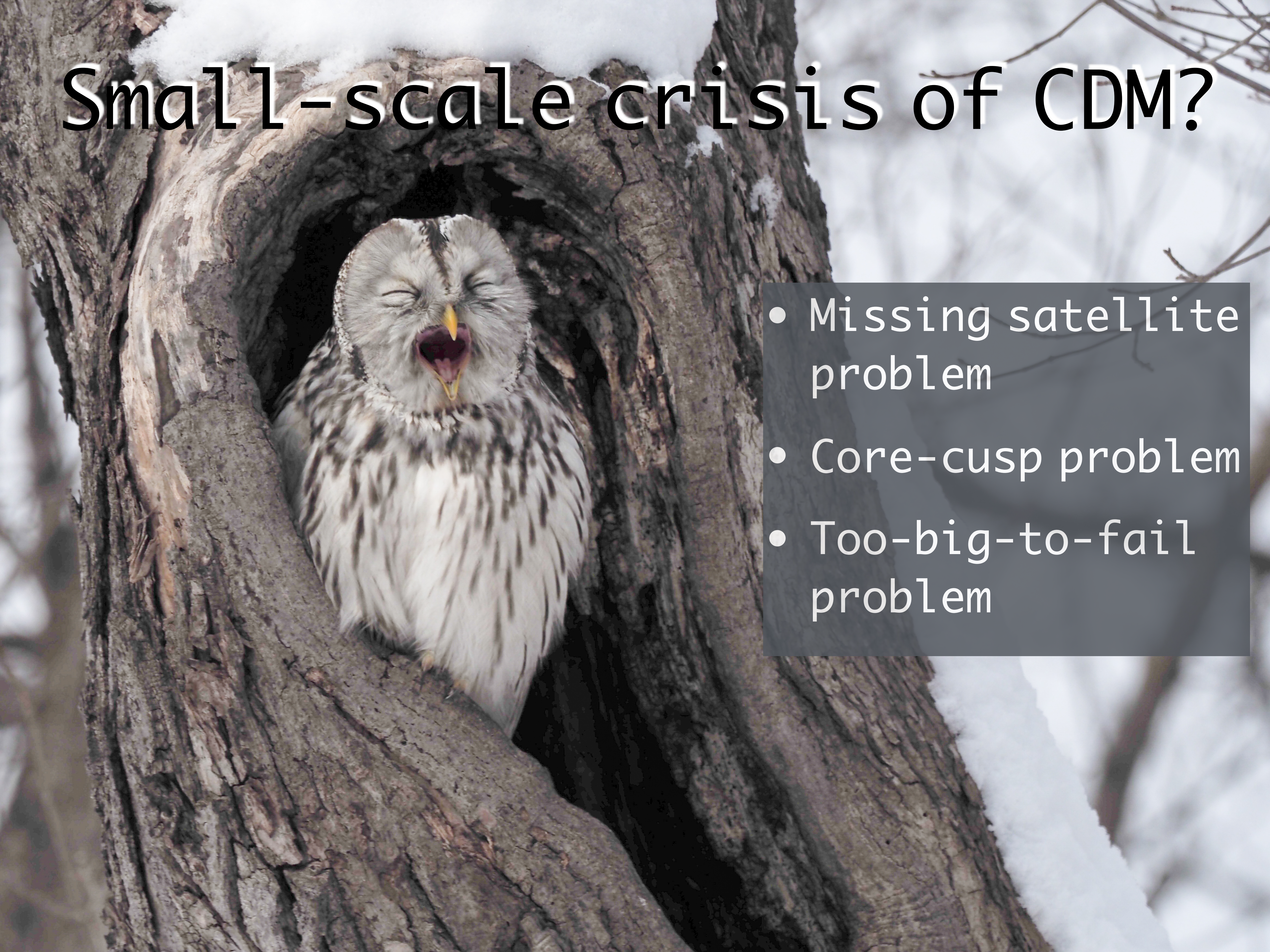
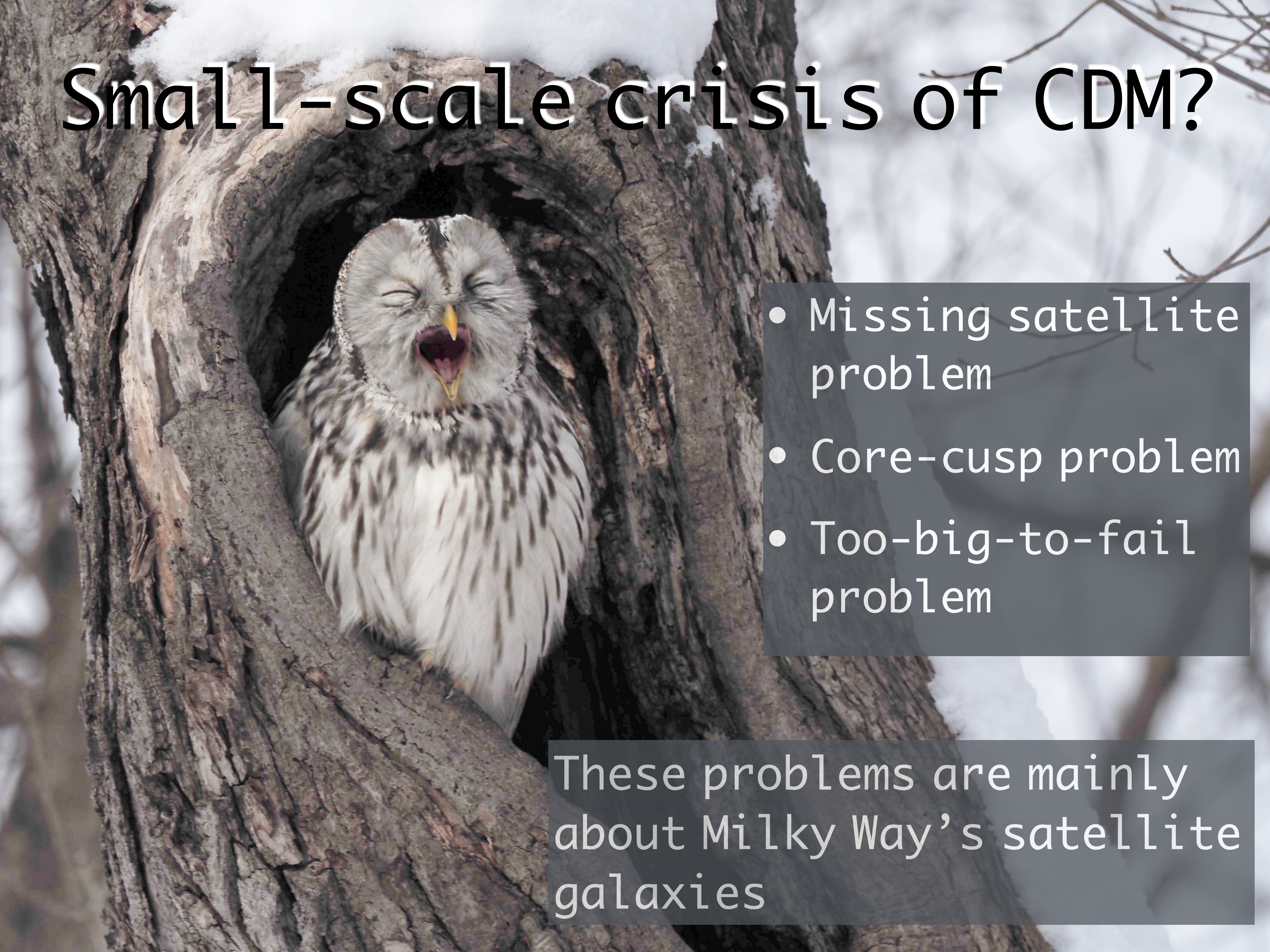
公募研究

Small-scale crisis of CDM?



- Missing satellite problem
- Core-cusp problem
- Too-big-to-fail problem

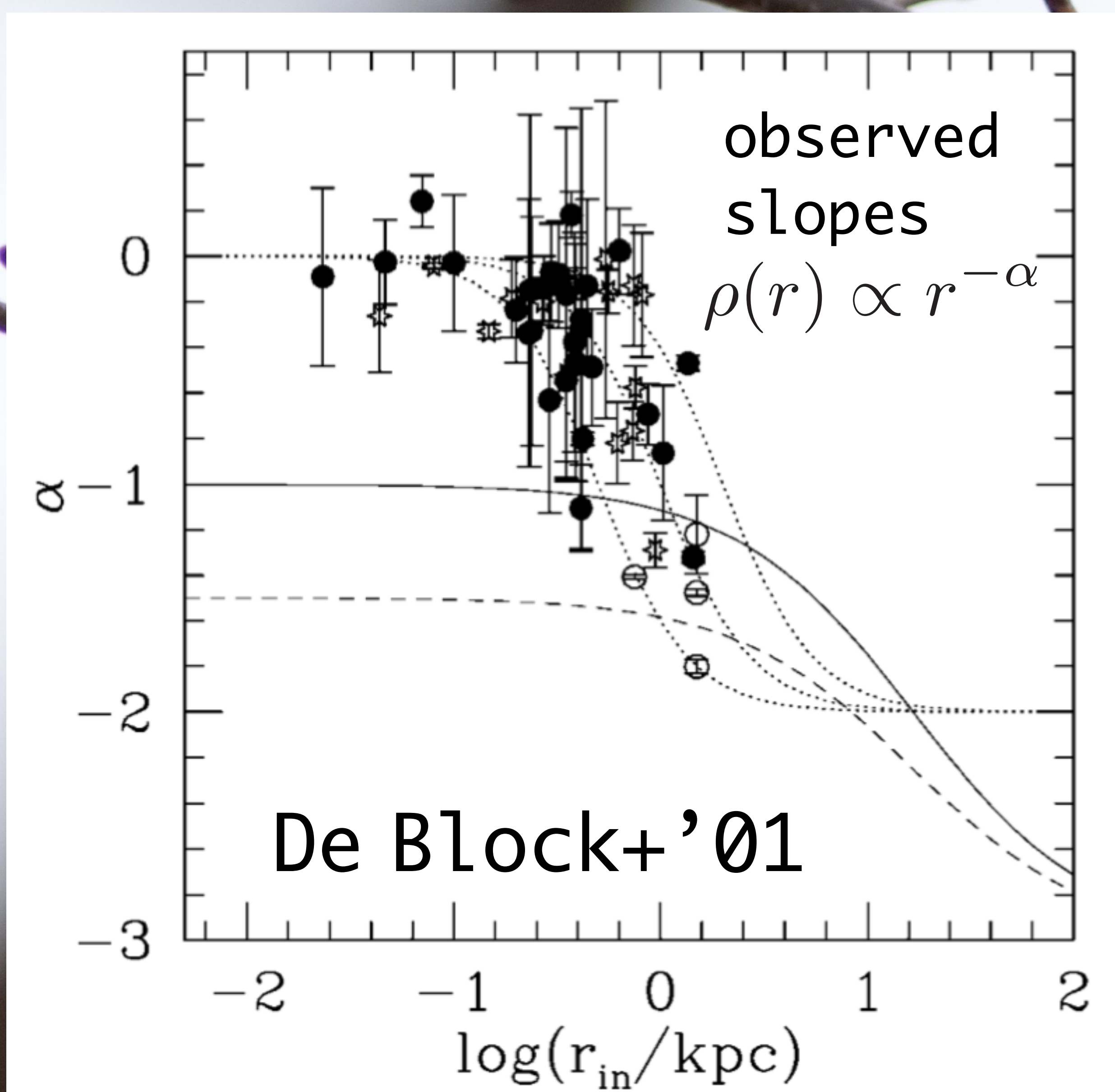


Small-scale crisis of CDM?

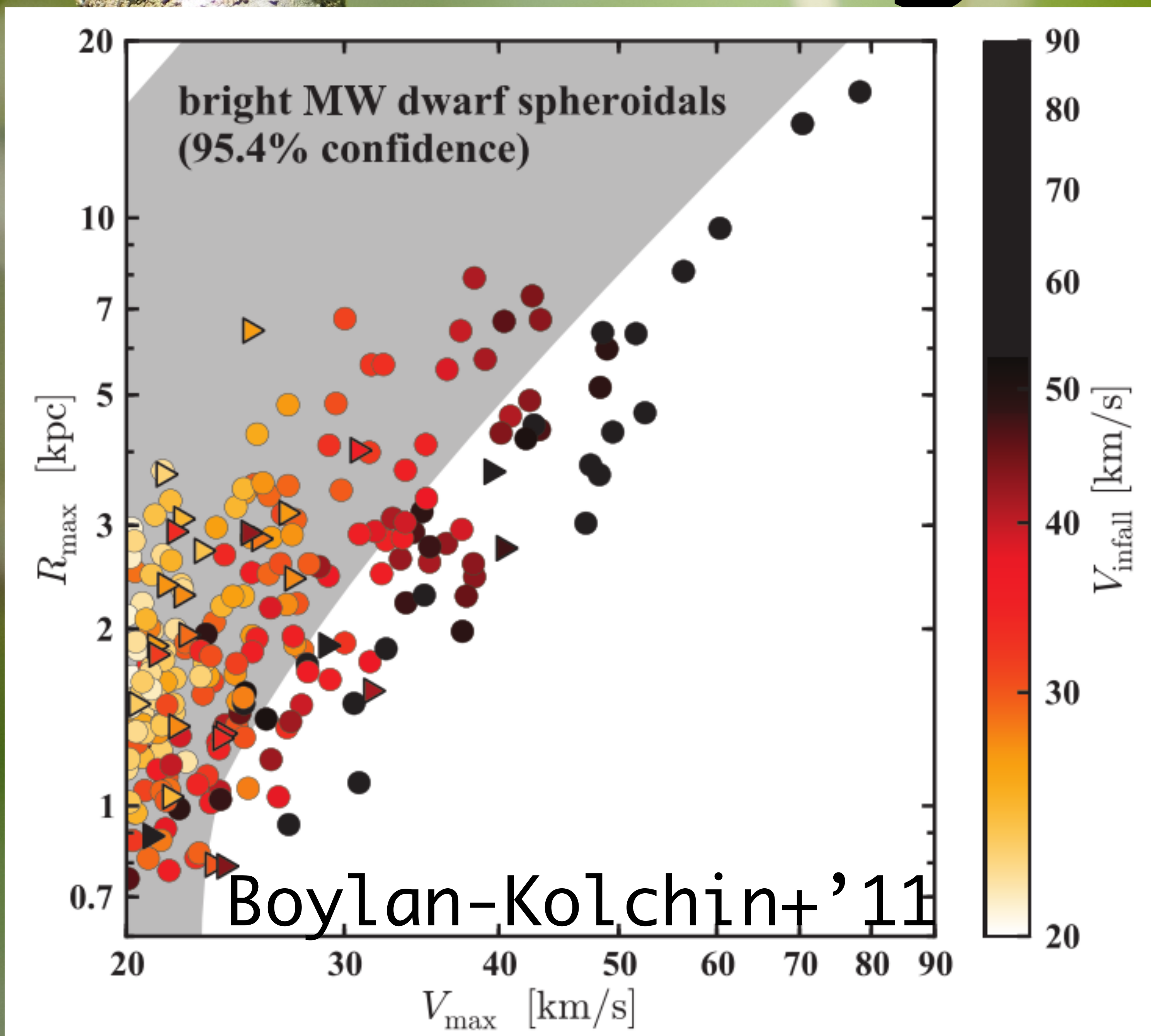
- Missing satellite problem
- Core-cusp problem
- Too-big-to-fail problem

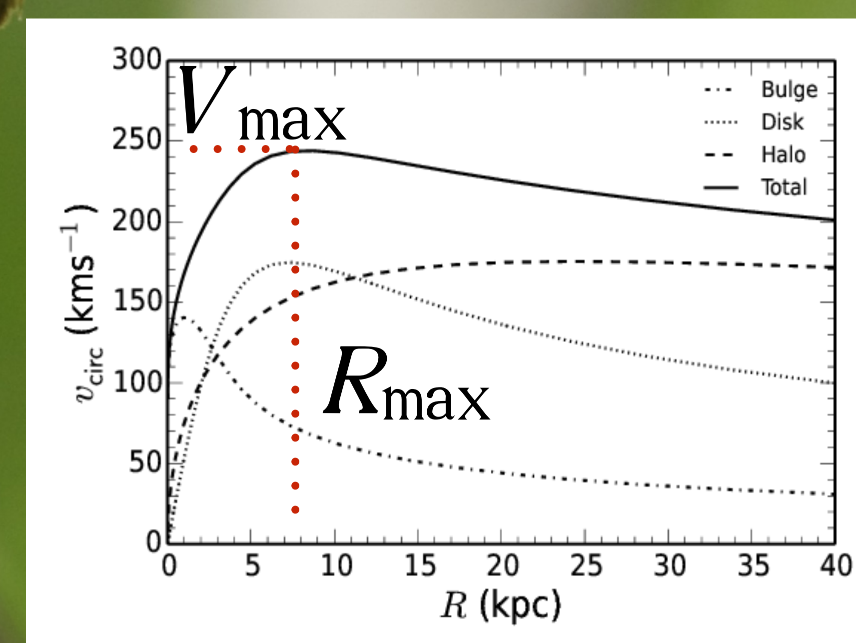
These problems are mainly about Milky Way's satellite galaxies

Central DM halo density profile of low surface brightness galaxies



Too-Big-To-Fail





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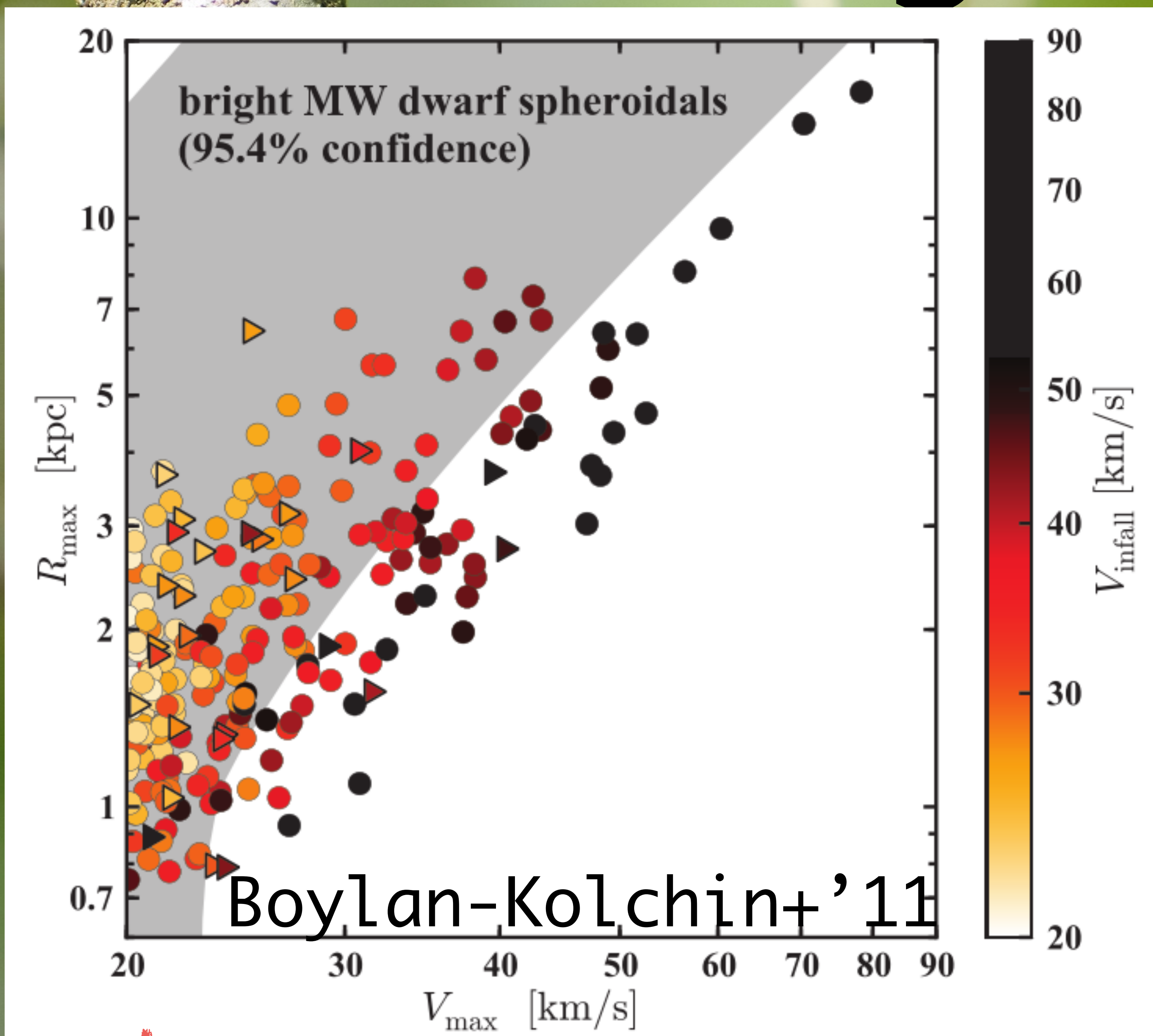
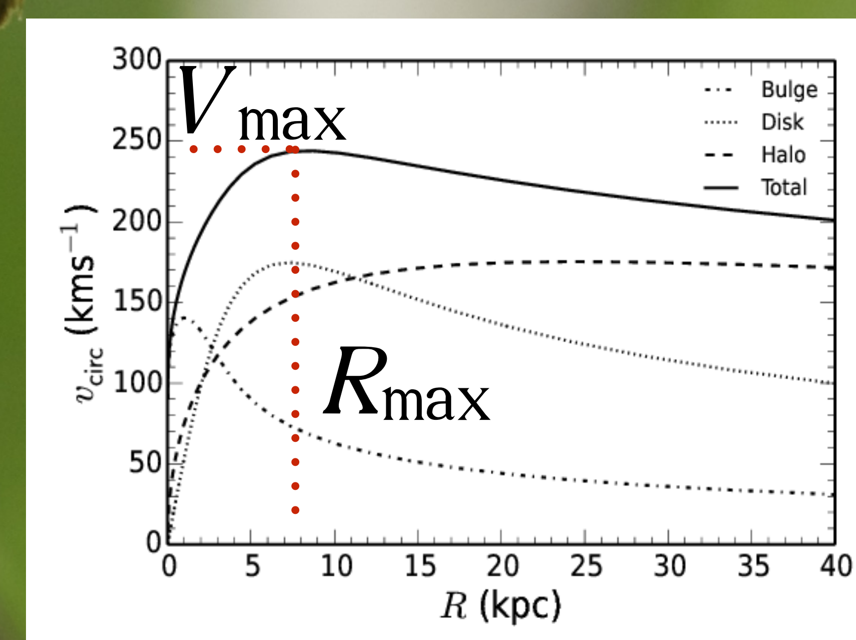


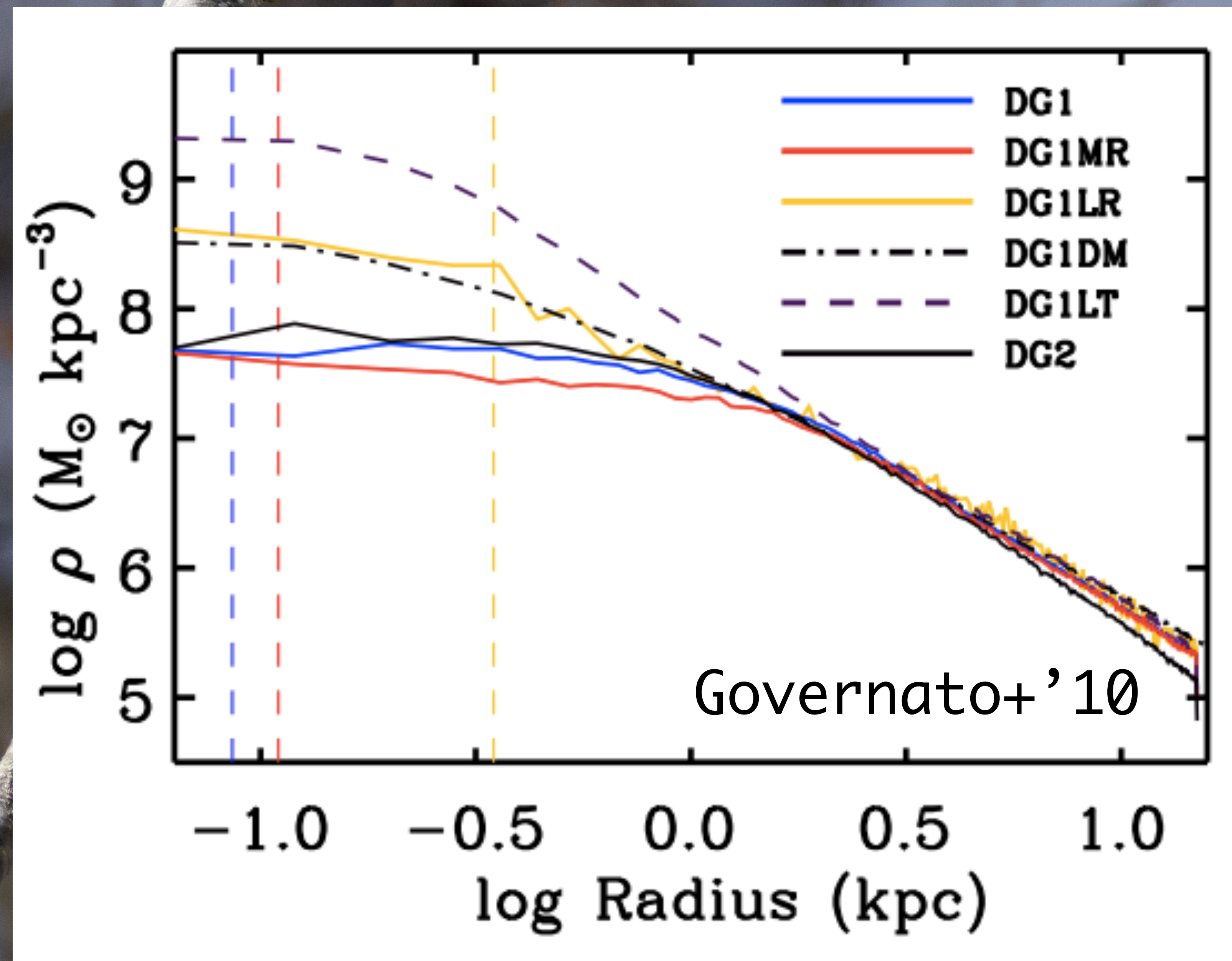
Galaxy formation is suppressed
by a UV-background (TO+'08, 09)




Baryonic solution

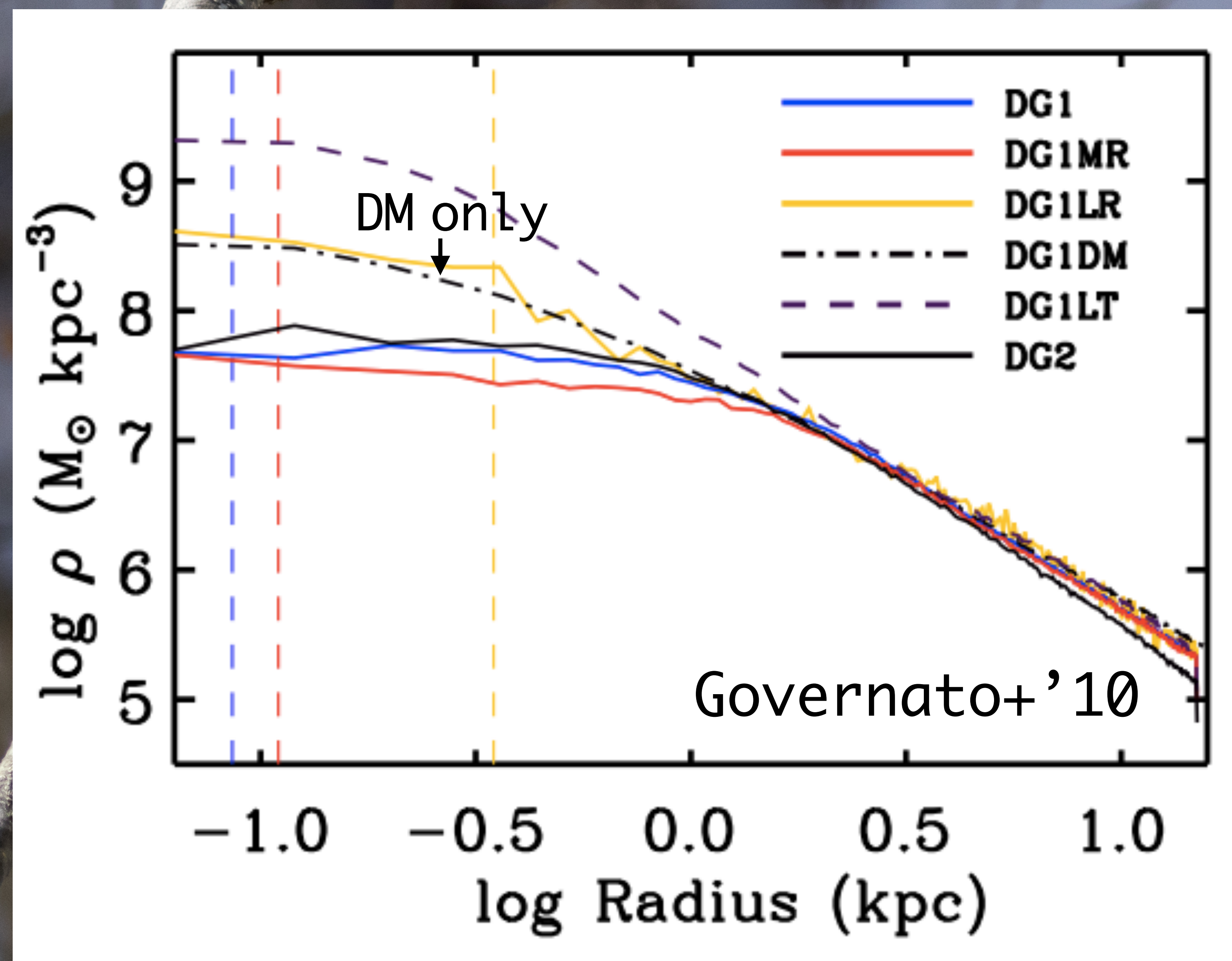
Core creation by stellar feedback

DM halo profile



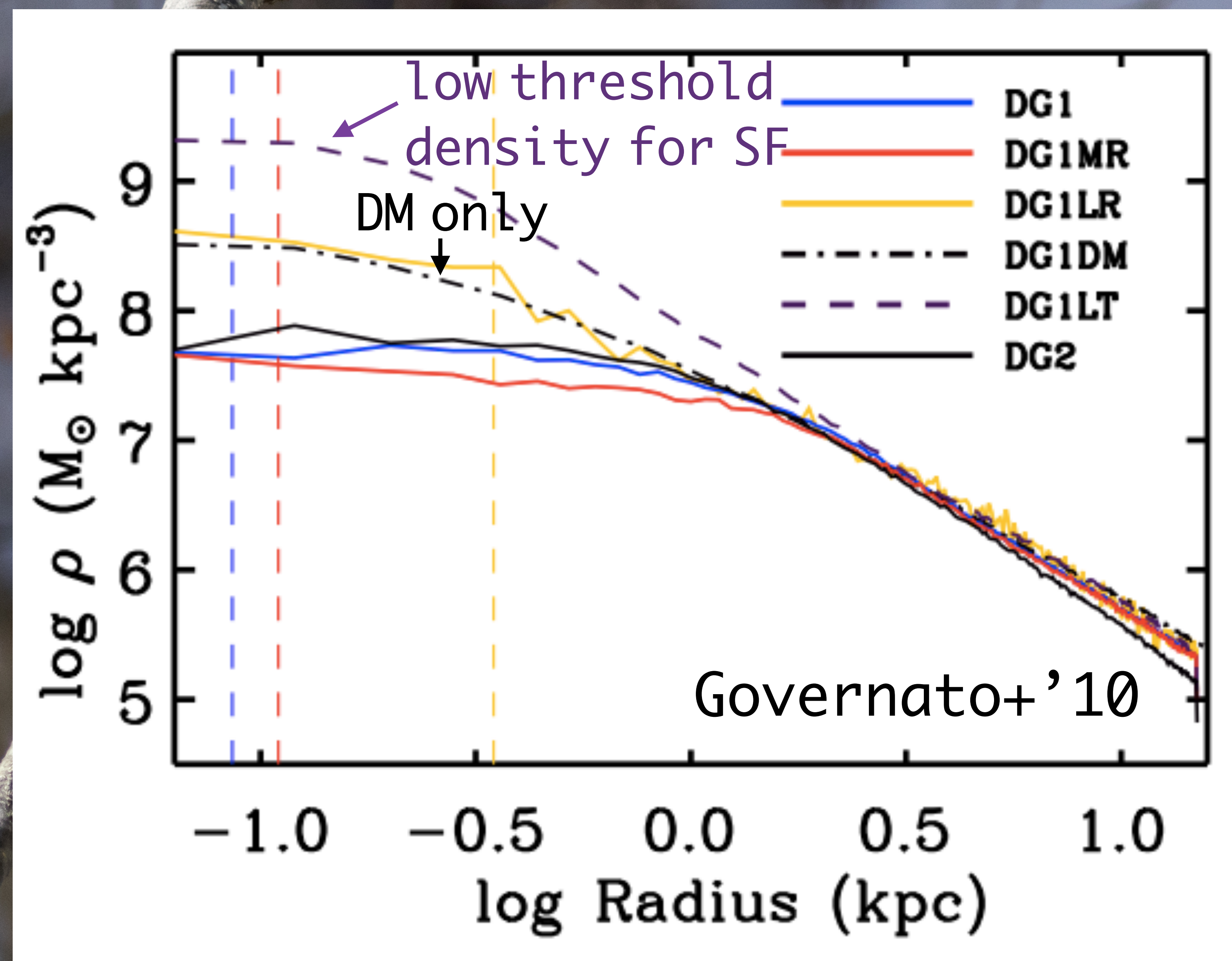
Core creation by stellar feedback

DM halo profile



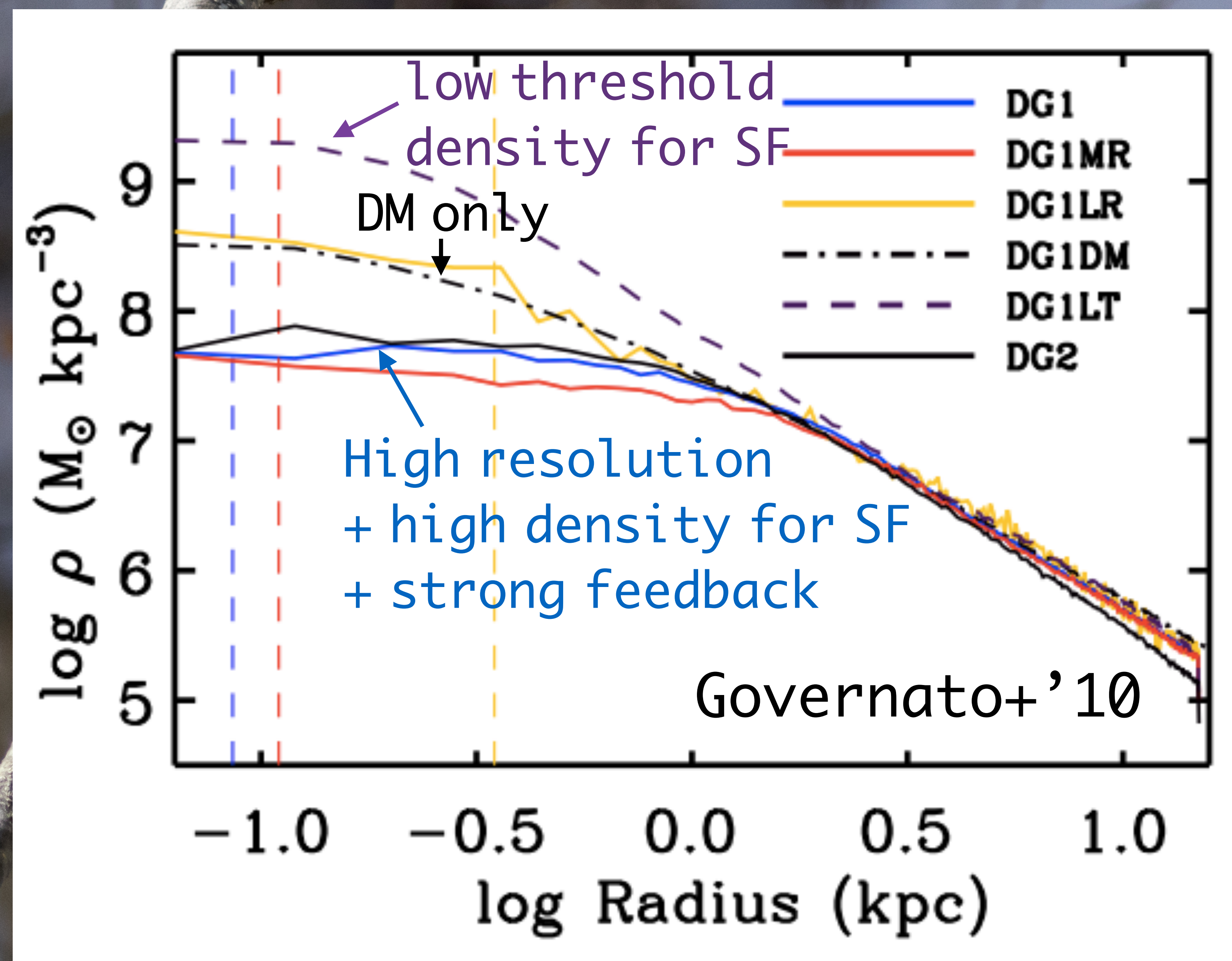
Core creation by stellar feedback

DM halo profile

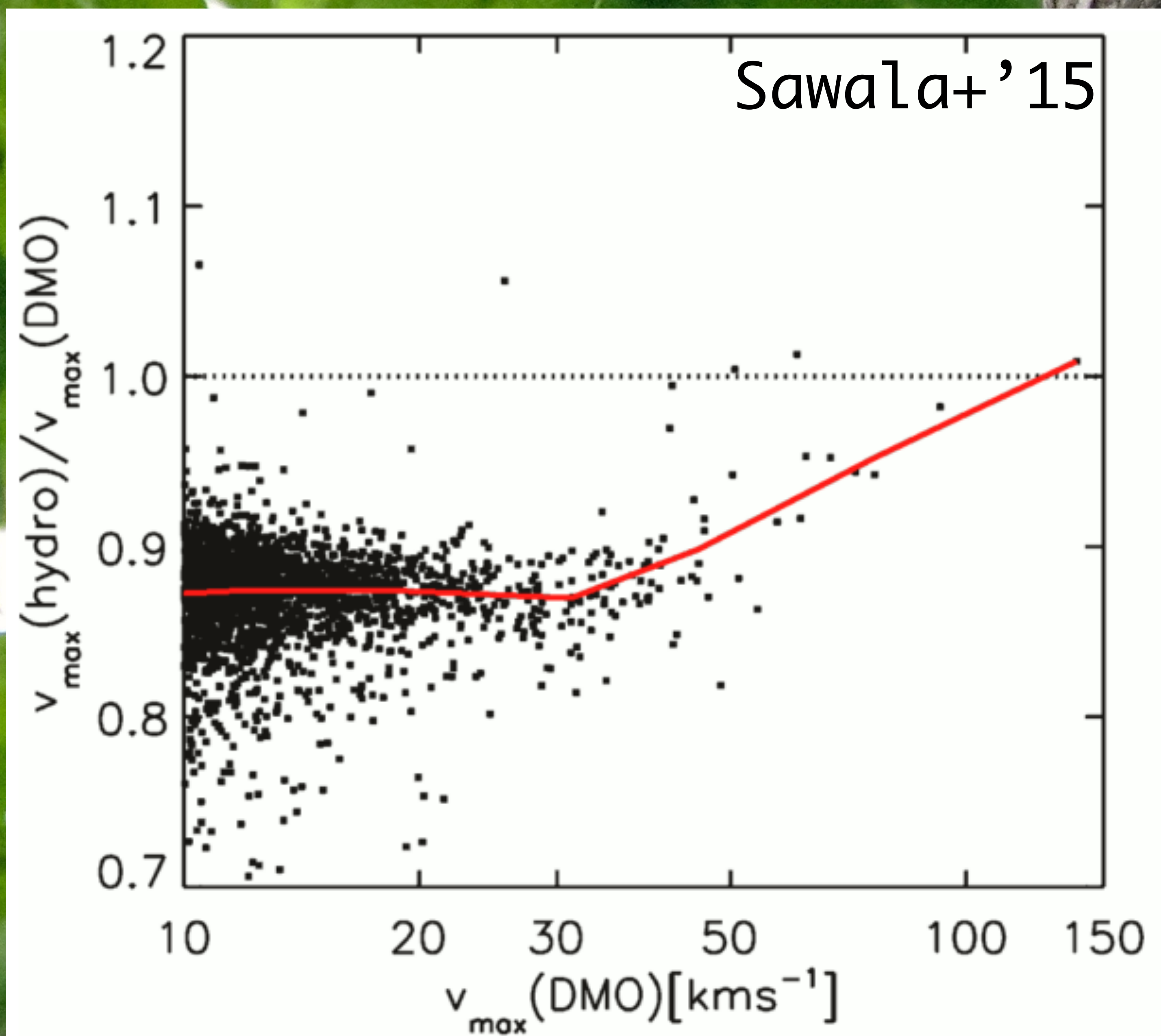


Core creation by stellar feedback

DM halo profile



Reduction of V_{max} by FB



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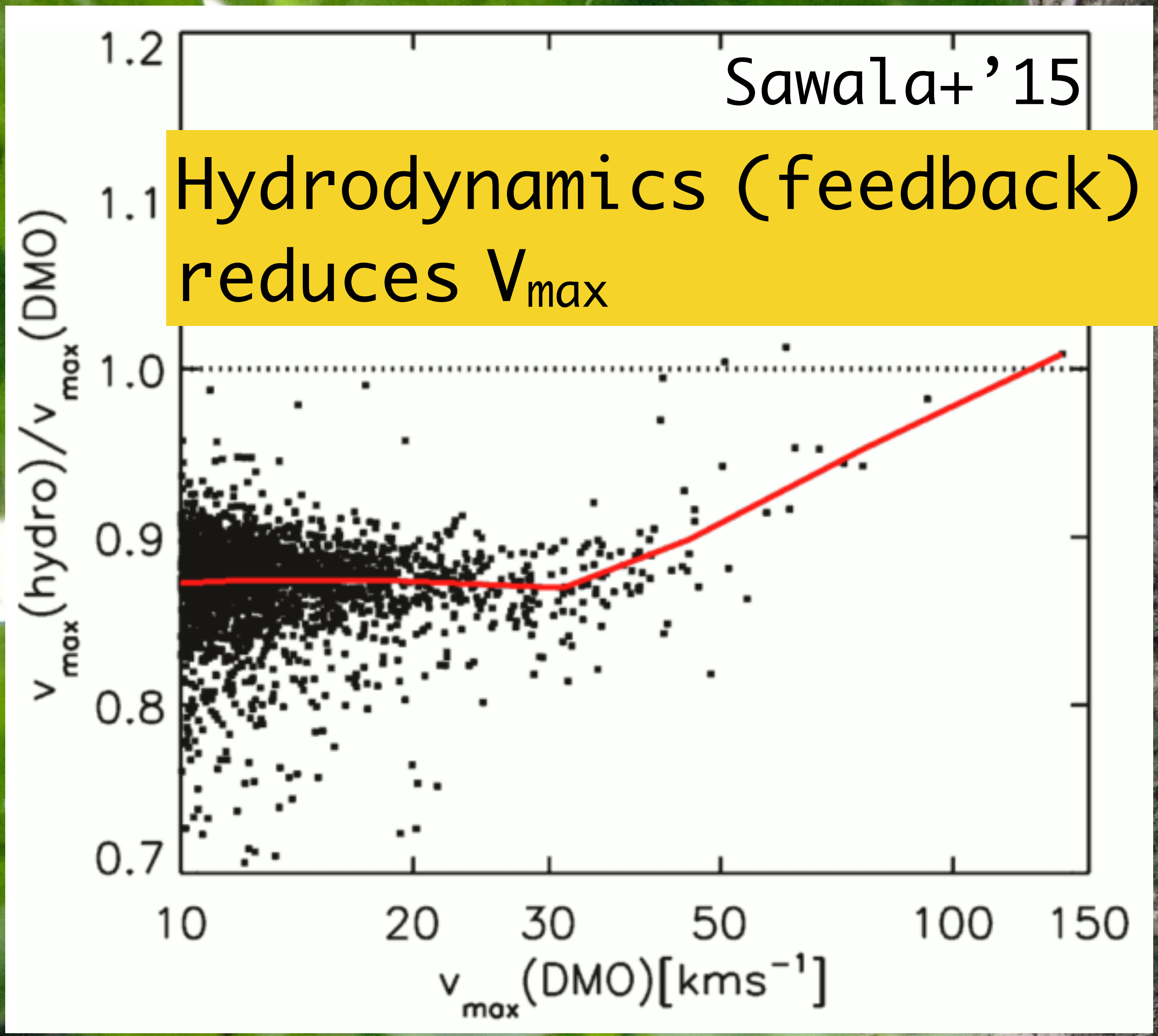
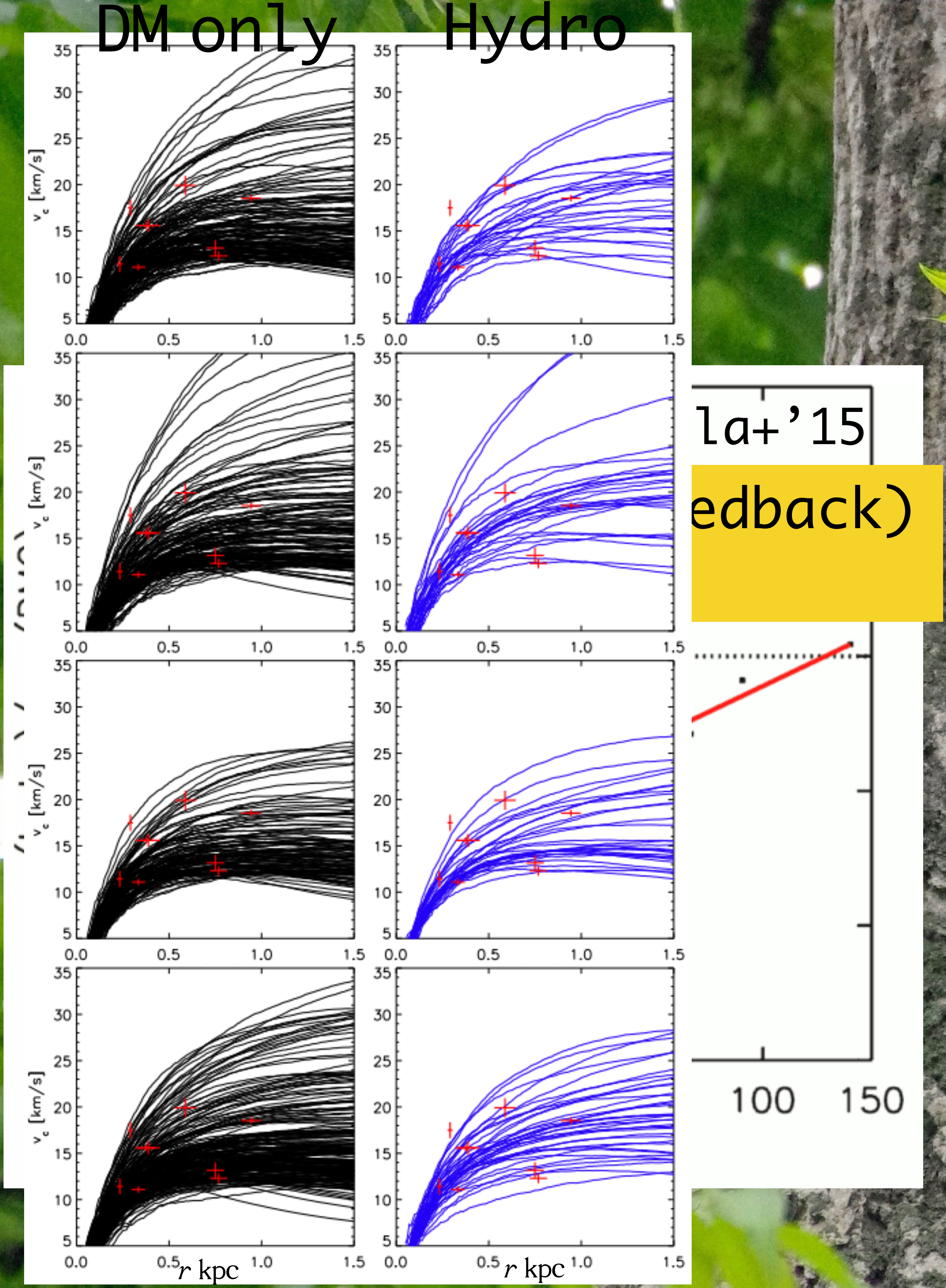
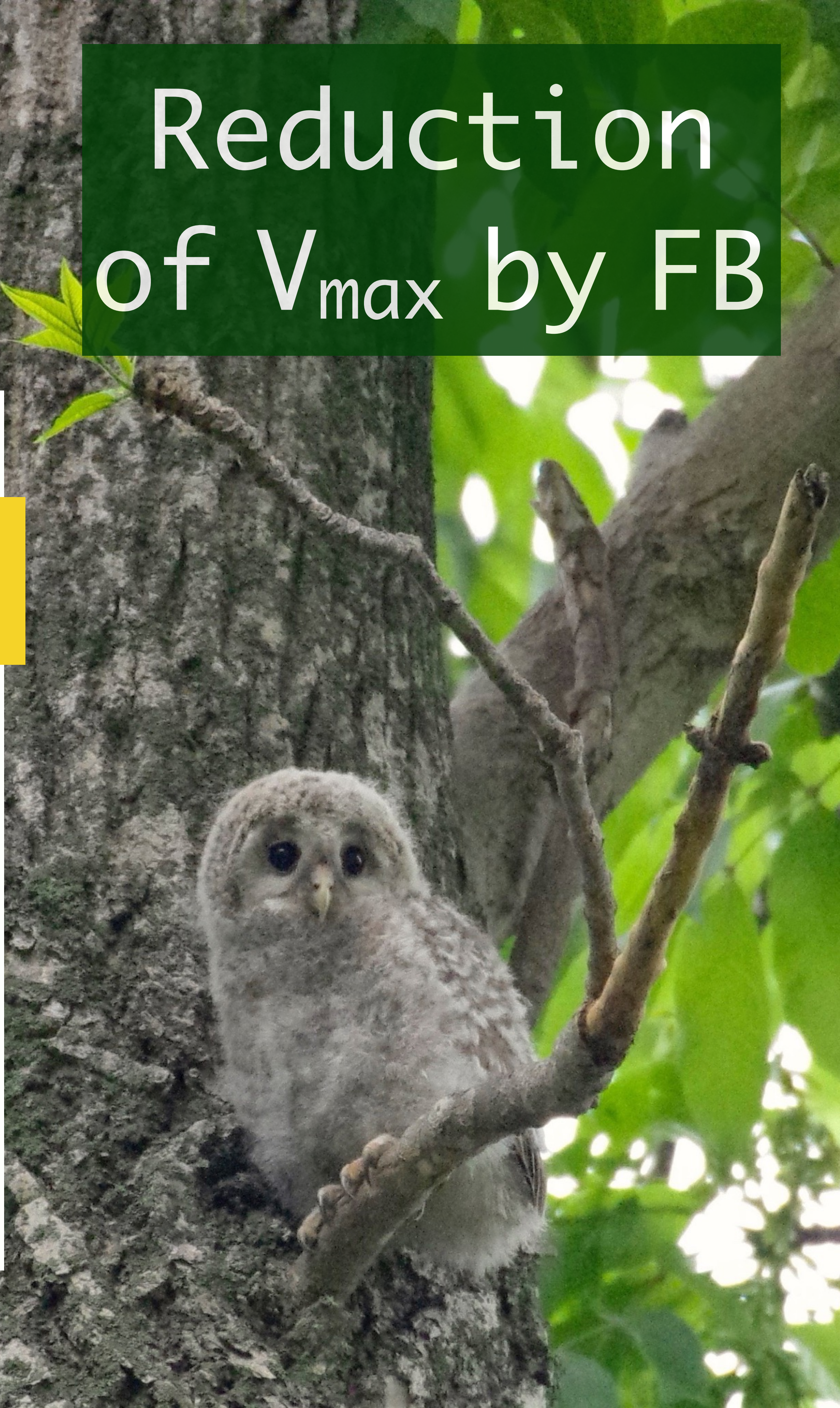


Hydrodynamics (feedback) reduces V_{max}

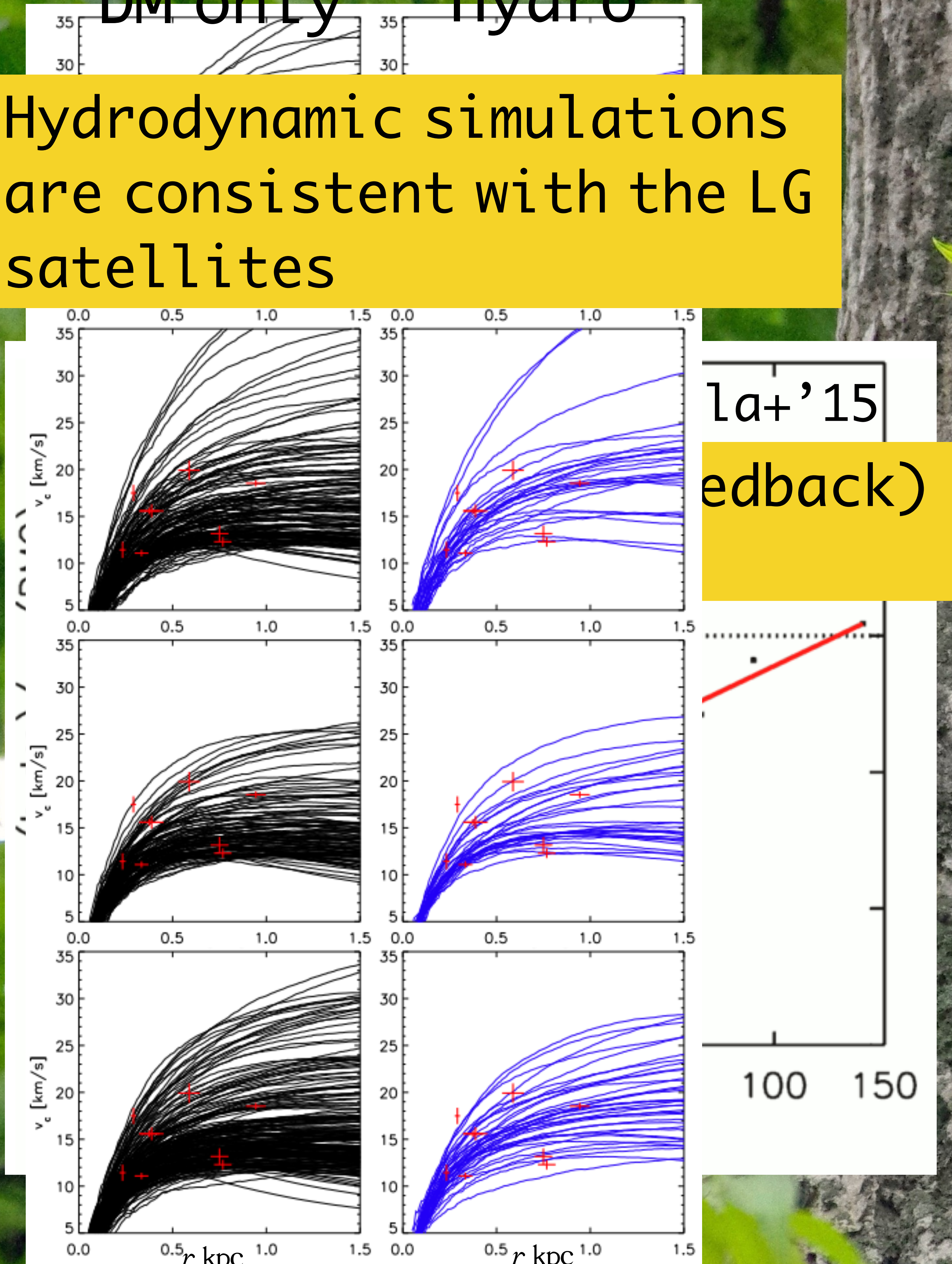
Reduction of V_{max} by FB





Reduction of V_{max} by FB

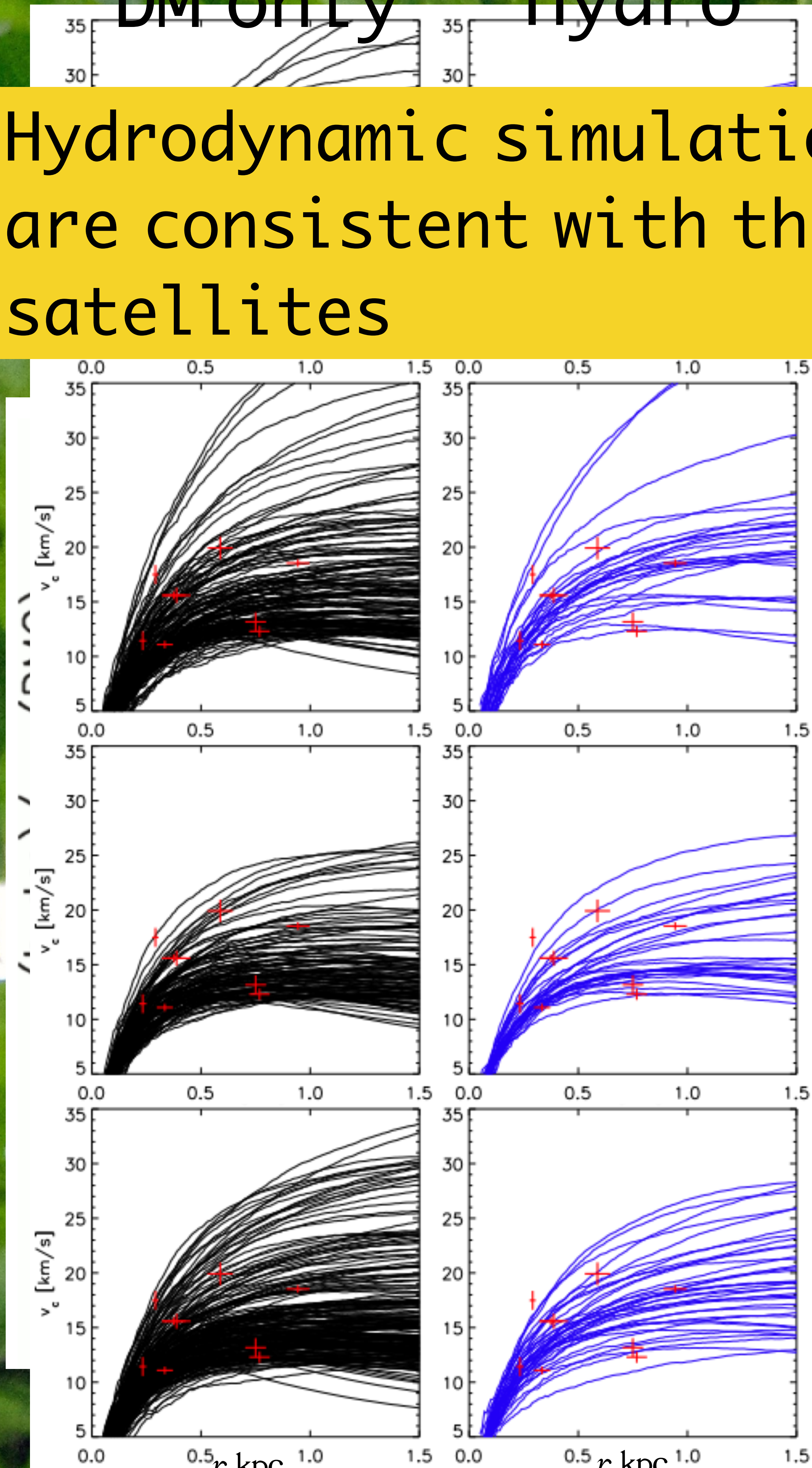
Hydrodynamic simulations are consistent with the LG satellites

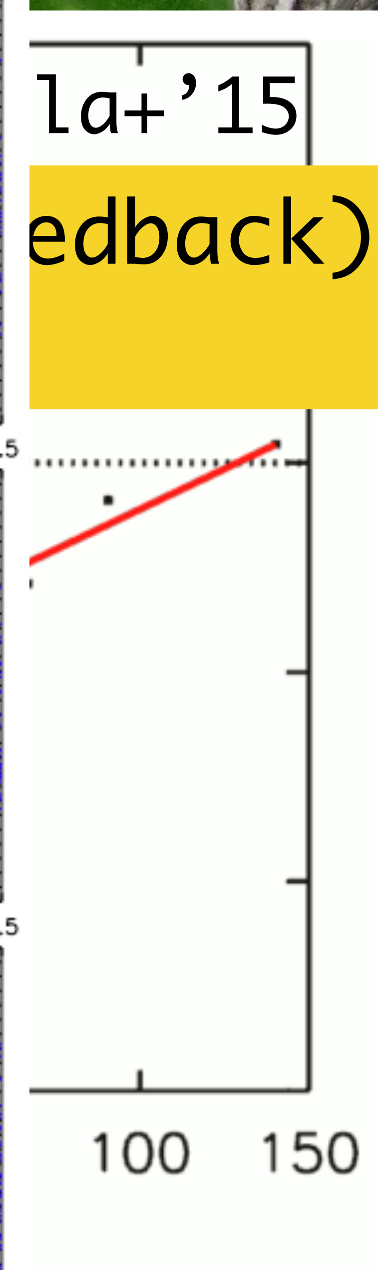


Reduction of V_{max} by FB

The same process that creates cored profile reduces V_{max}.

Hydrodynamic simulations are consistent with the LG satellites

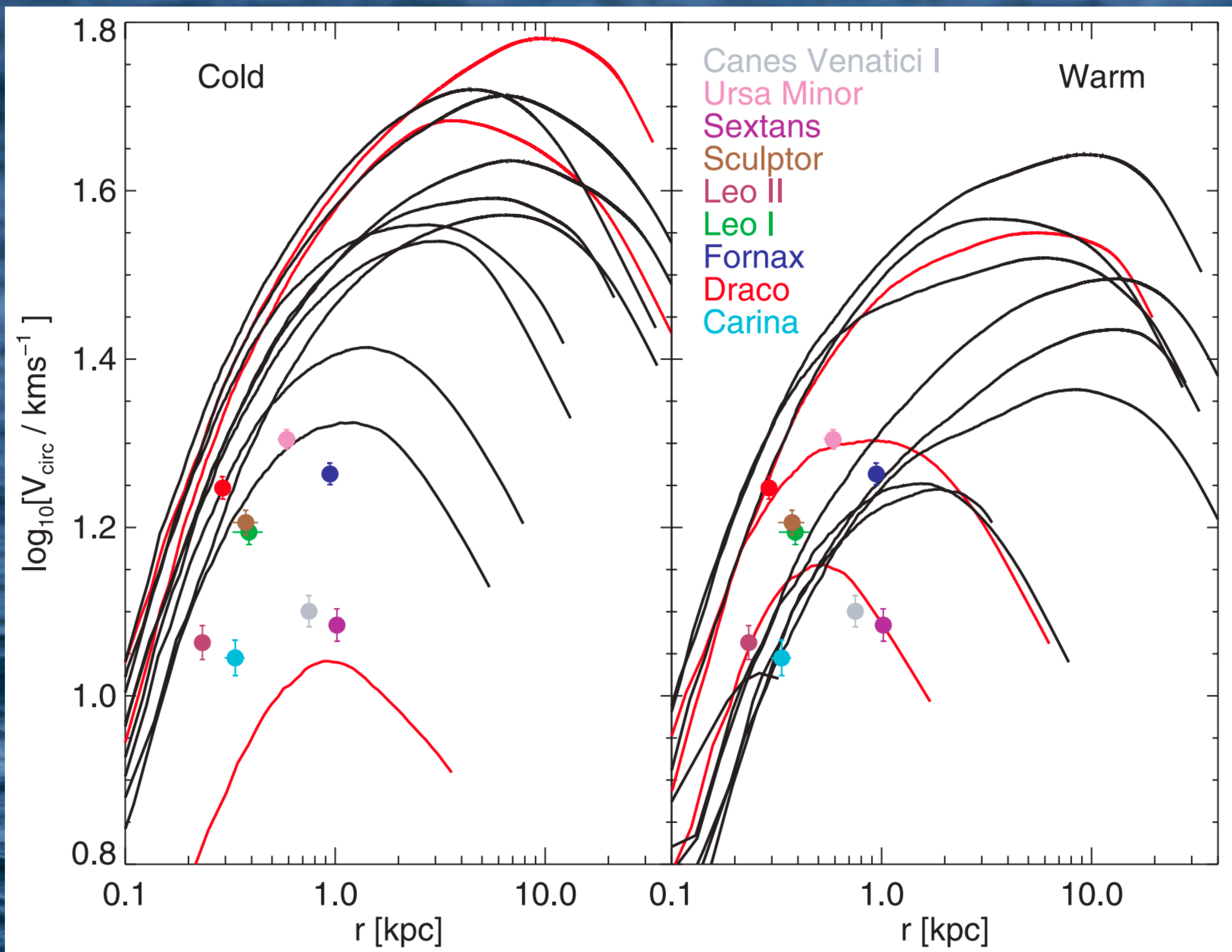




Alternative DM models

- Warm dark matter (WDM)
  - Initial density perturbations do not have small-scale power
- Self-interacting dark matter (SIDM)
  - Allow elastic scattering between DM particles

WDM

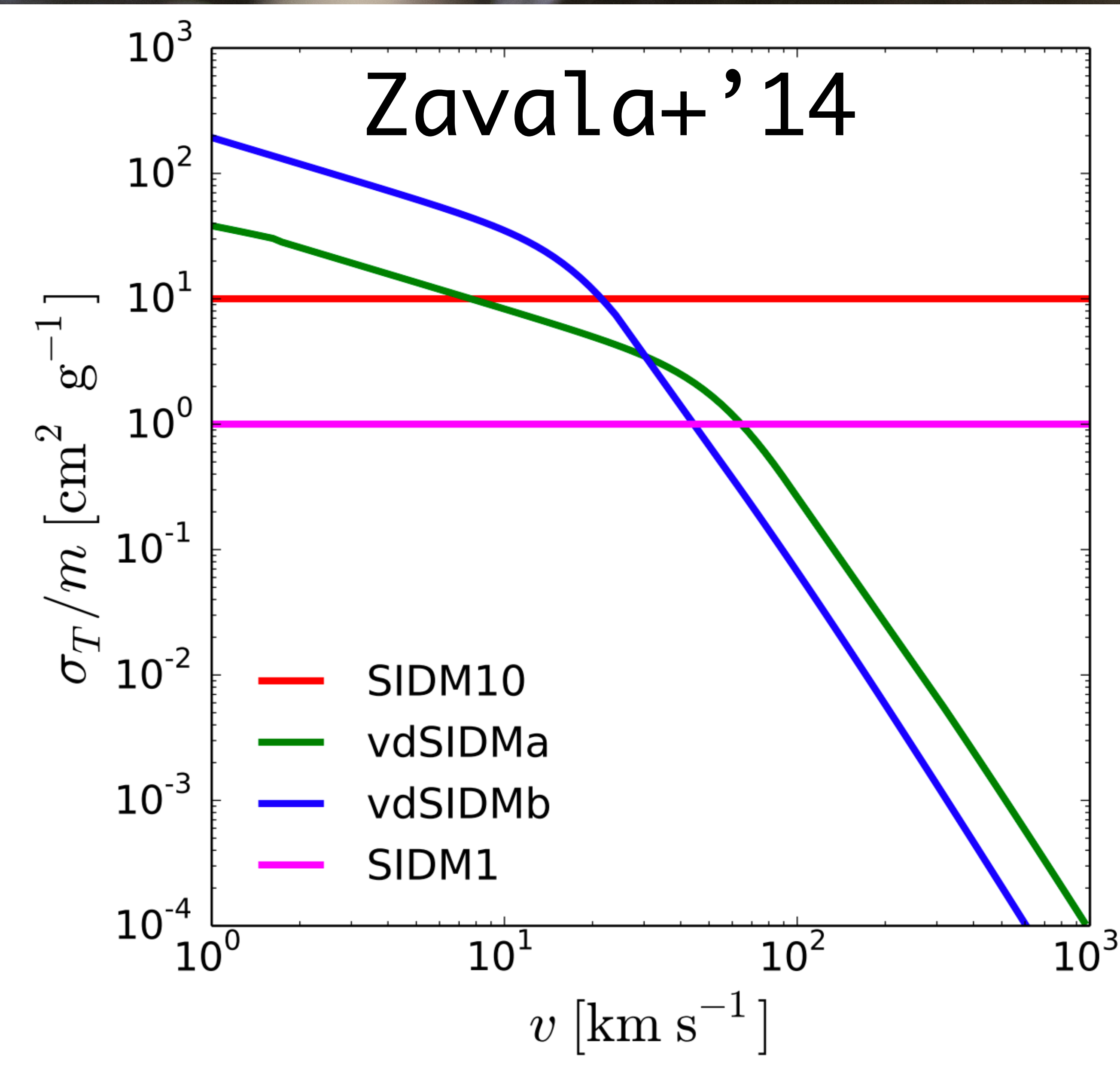


Lovell+'12

But, WDM halos have cuspy profiles.

SIDM

- $\sigma/m_x < 1$ cm^2 g^{-1} not to make clusters too round (e.g. Loeb & Weiner'11)
- This cross-section is too small to make any difference from CDM (Fry+15)
- Velocity dependent cross-section is promising (e.g. Loeb & Weiner'11)



IDM

make clusters too
ner'11)

s too
ference

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IDM

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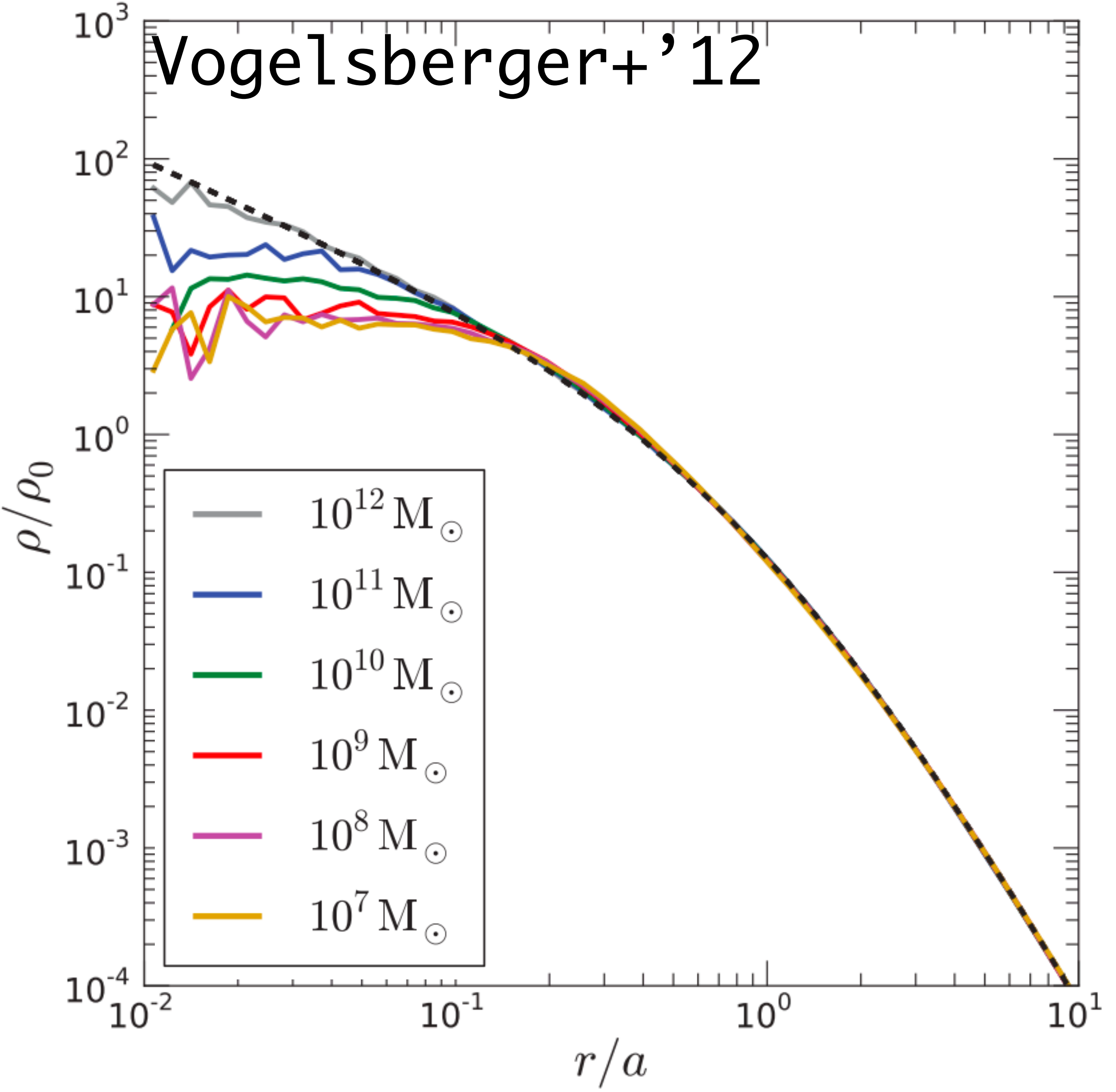
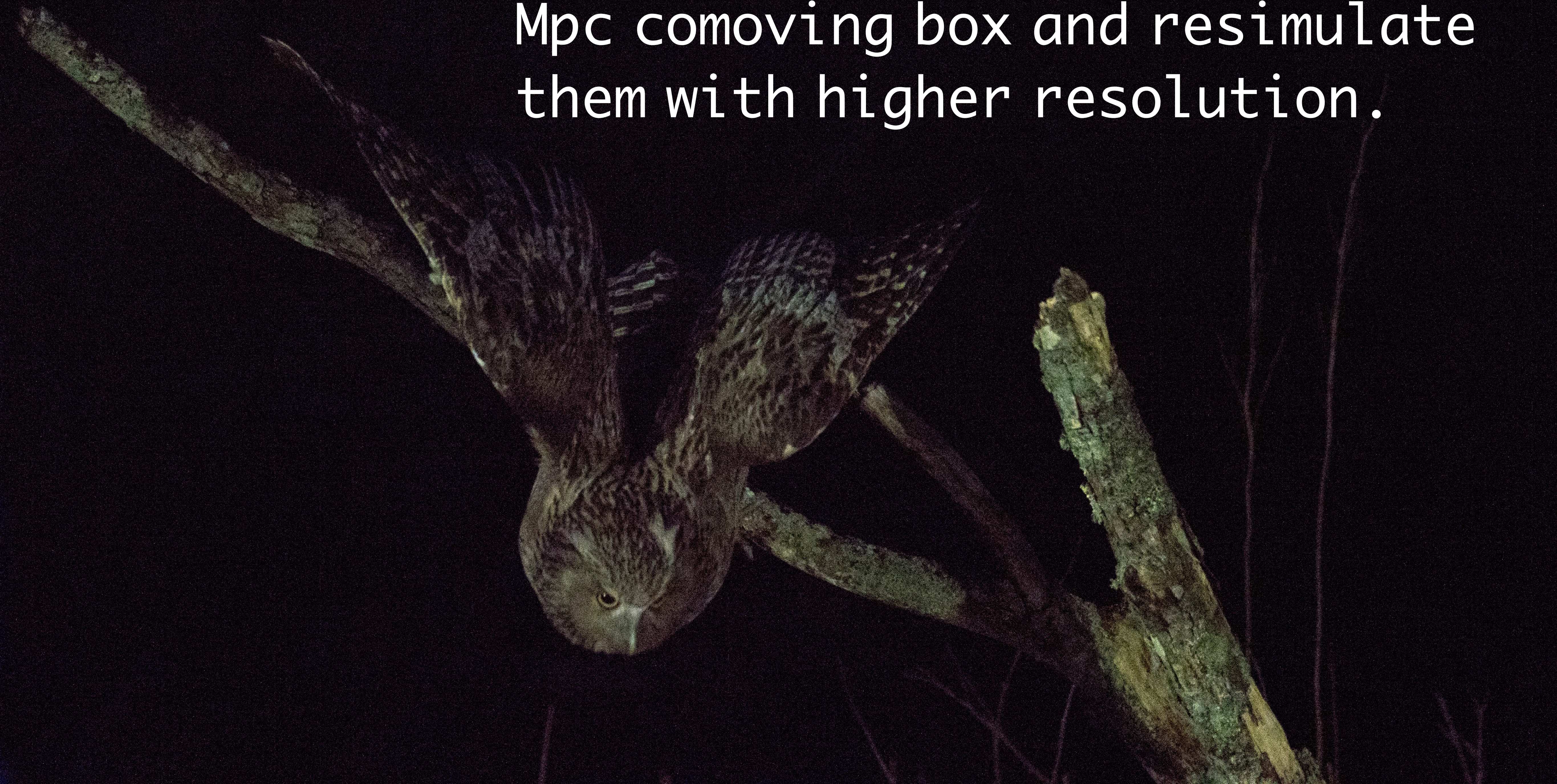


- Velocity dependent cross-section is promising (e.g. Loeb & Weiner’11)

Simulations

- Select MW-mass halos from a 50 Mpc comoving box and resimulate them with higher resolution.



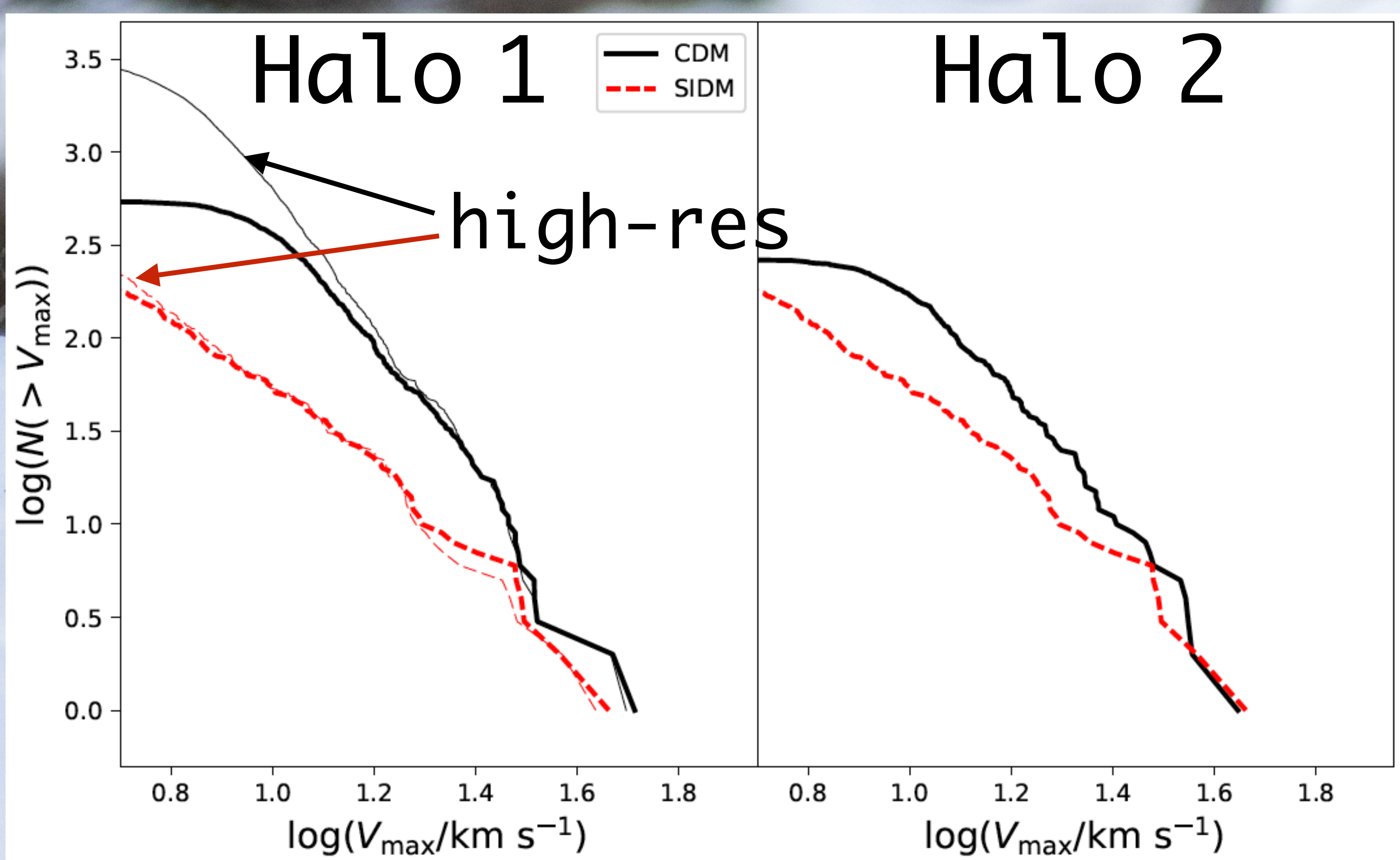
Halos

- Halo 1:
  $M_{vir} = 1.75 \times 10^{12}\ M_{\odot}$
- Halo 2:
  $M_{vir} = 9.01 \times 10^{12}\ M_{\odot}$

- Resolutions
  - Standard
    $m_{DM} = 5.72 \times 10^{5}\ M_{\odot}$
  - High-resolution
    $m_{DM} = 7.15 \times 10^{4}\ M_{\odot}$

Velocity functions

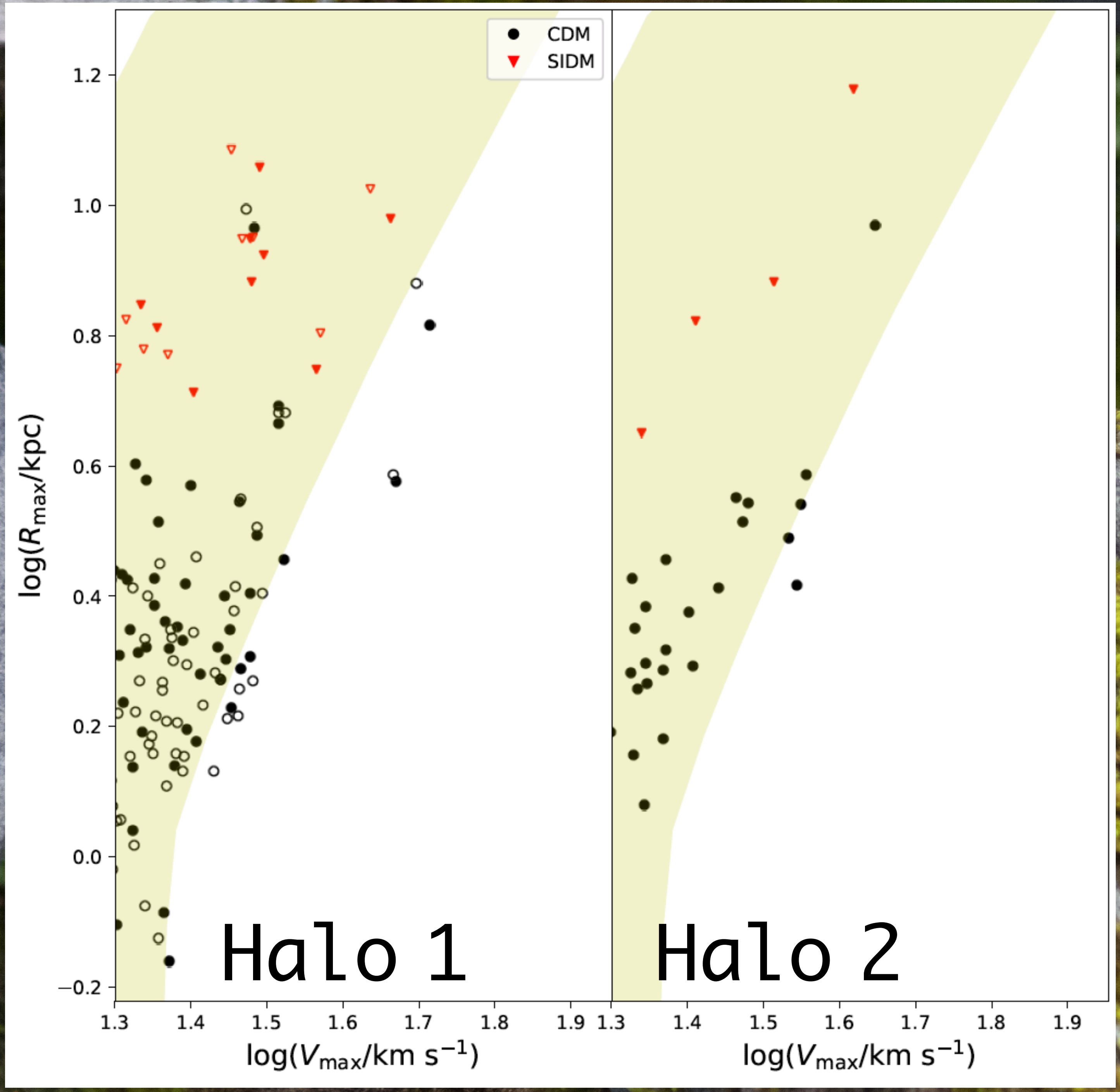
- Velocity functions of subhalos in Halo 1 and 2.



- The subhalo abundance is substantially reduced in SIDM

R_{max} v.s. V_{max}

- SIDM subhalos are much less centrally concentrated.



Summary of N-body part

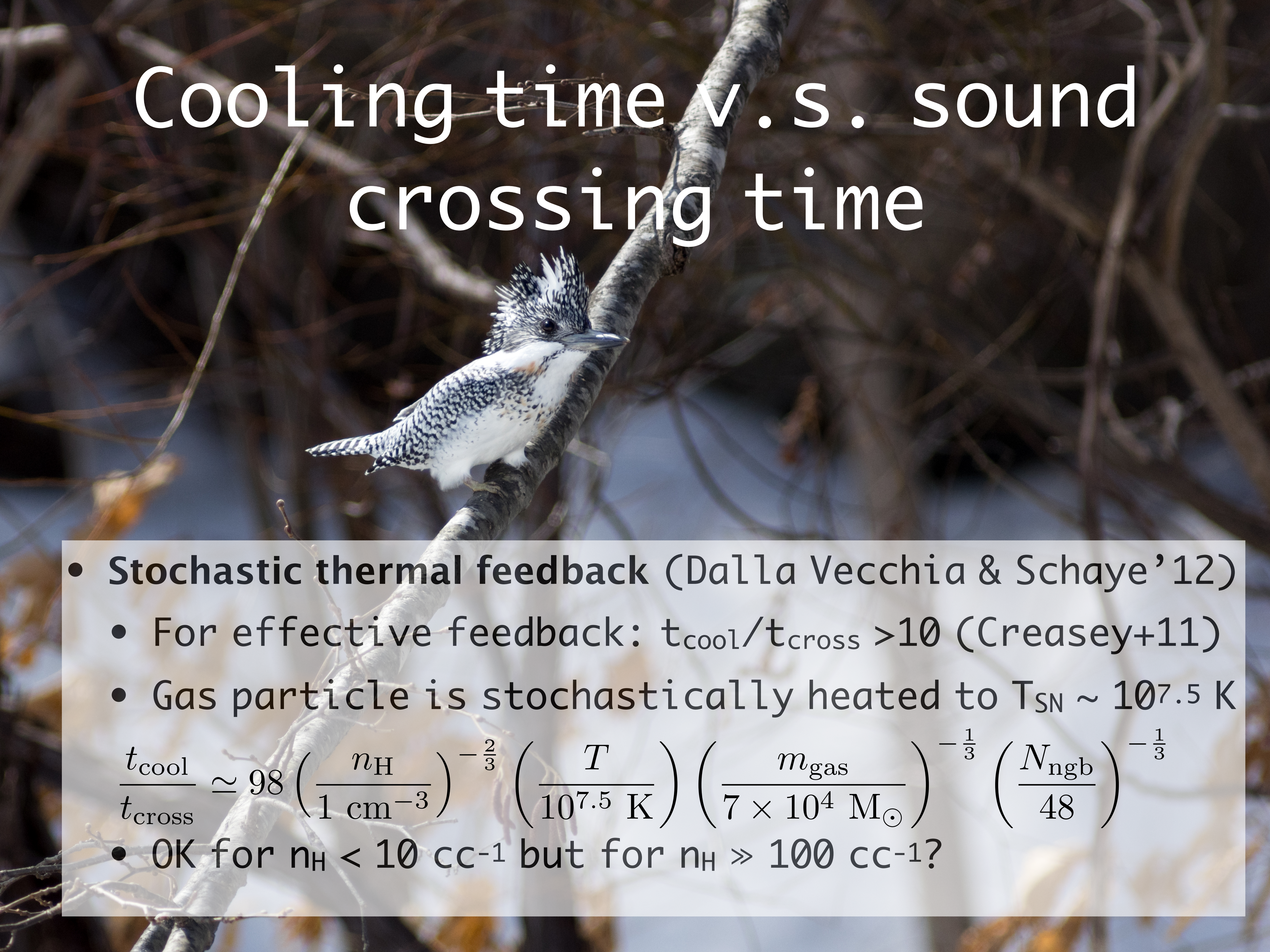
- SIDM subhalos are much less abundant than CDM subhalos.
- They are also less centrally concentrated
- We need much weaker feedback in SIDM than in CDM to explain observations.
- We should expect much weaker baryonic effects in SIDM
- Can we distinguish two models after baryonic effects are taken into account?

Feedback for high-resolution simulations

Gas cooling

- Cooling rate Λ [erg/cm^3] $\propto n_H^2$
- Star formation and supernova occur in dense environments with $n_H \gg 100$ cc^{-1}

- Feedback energy is quickly radiated away if we naively distribute it.



Cooling time v.s. sound crossing time

- **Stochastic thermal feedback** (Dalla Vecchia & Schaye'12)
  - For effective feedback: t_{cool}/t_{cross} >10 (Creasey+11)
  - Gas particle is stochastically heated to $T_{SN} \sim 10^{7.5}$ K

$$\frac{t_{\rm cool}}{t_{\rm cross}} \simeq 98 \left(\frac{n_{\rm H}}{1\ {\rm cm}^{-3}}\right)^{-\frac{2}{3}} \left(\frac{T}{10^{7.5}\ {\rm K}}\right) \left(\frac{m_{\rm gas}}{7\times10^{4}\ {\rm M}_\odot}\right)^{-\frac{1}{3}} \left(\frac{N_{\rm ngb}}{48}\right)^{-\frac{1}{3}}$$

  - OK for n_H < 10 cc^{-1} but for $n_H \gg$ 100 cc^{-1}?

New multiphase model

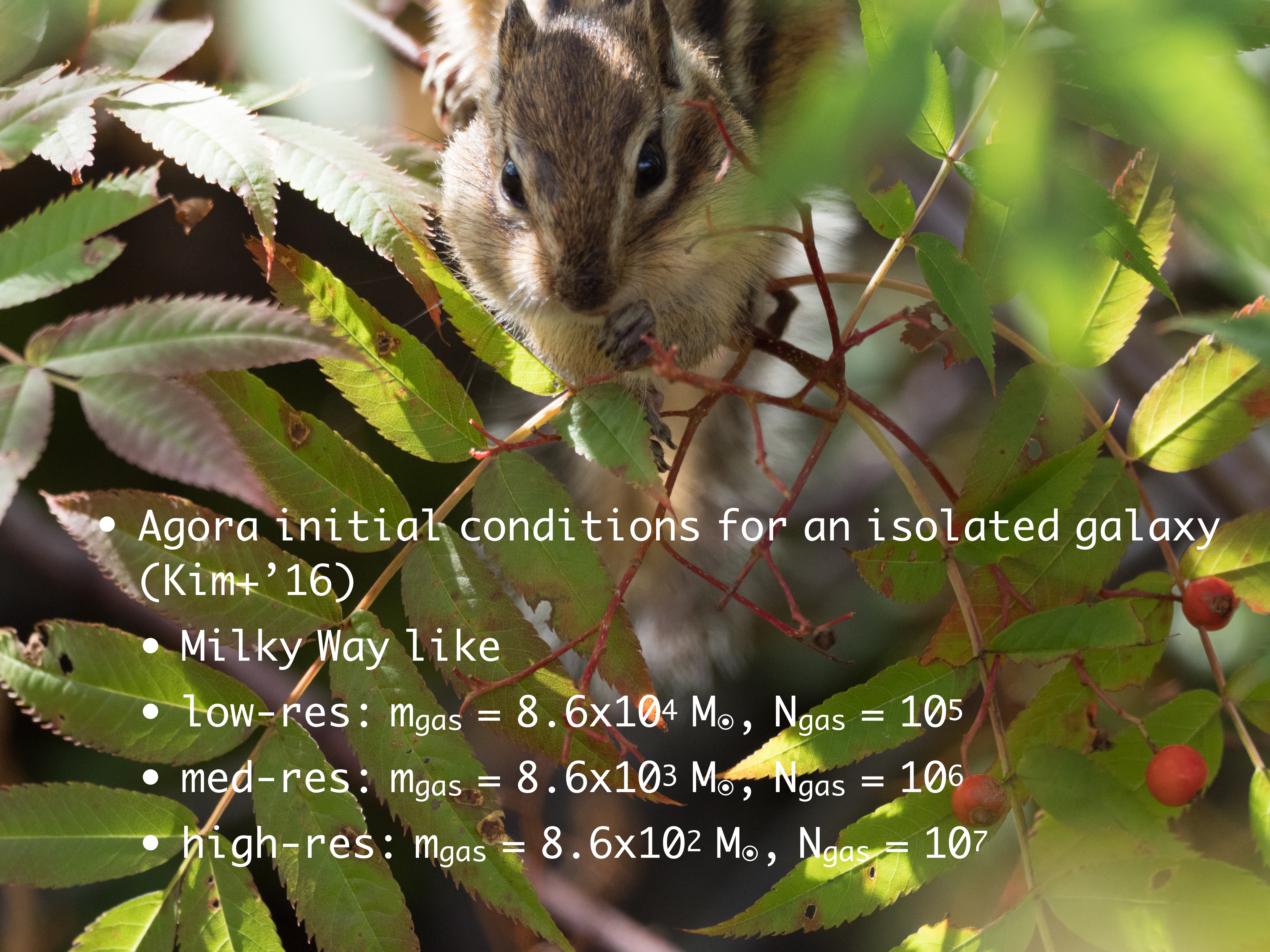
- When $t_{\mathrm{cool}}/t_{\mathrm{cross}} < \chi$ (=10), we compute the hot phase temperature so that $t_{\mathrm{cool}}(\rho_{\mathrm{hot}}, T_{\mathrm{hot}})/t_{\mathrm{cross}}(\rho, T) = \chi$: $u_{\mathrm{hot}} = u_{\mathrm{hot}}(T_{\mathrm{hot}})$ and $m_{\mathrm{hot}} = \Delta E/u_{\mathrm{hot}}$.

$$m = m_{\mathrm{hot}} + m_{\mathrm{cold}}$$

$$mu = m_{\mathrm{hot}} u_{\mathrm{hot}} + m_{\mathrm{cold}} u_{\mathrm{cold}}$$

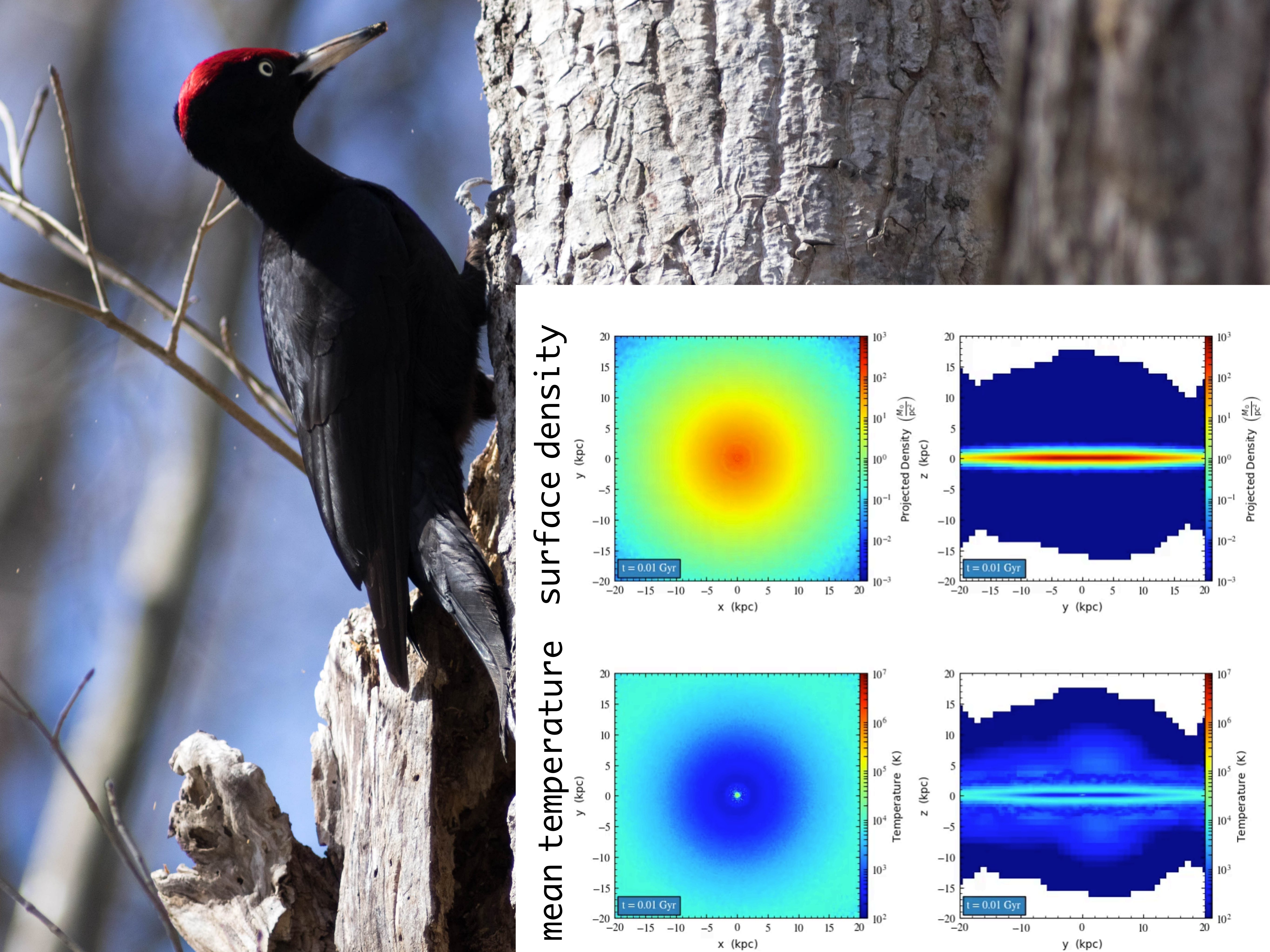
$$\rho u = \rho_{\mathrm{hot}} u_{\mathrm{hot}} = \rho_{\mathrm{cold}} u_{\mathrm{cold}}$$


Test
simulations

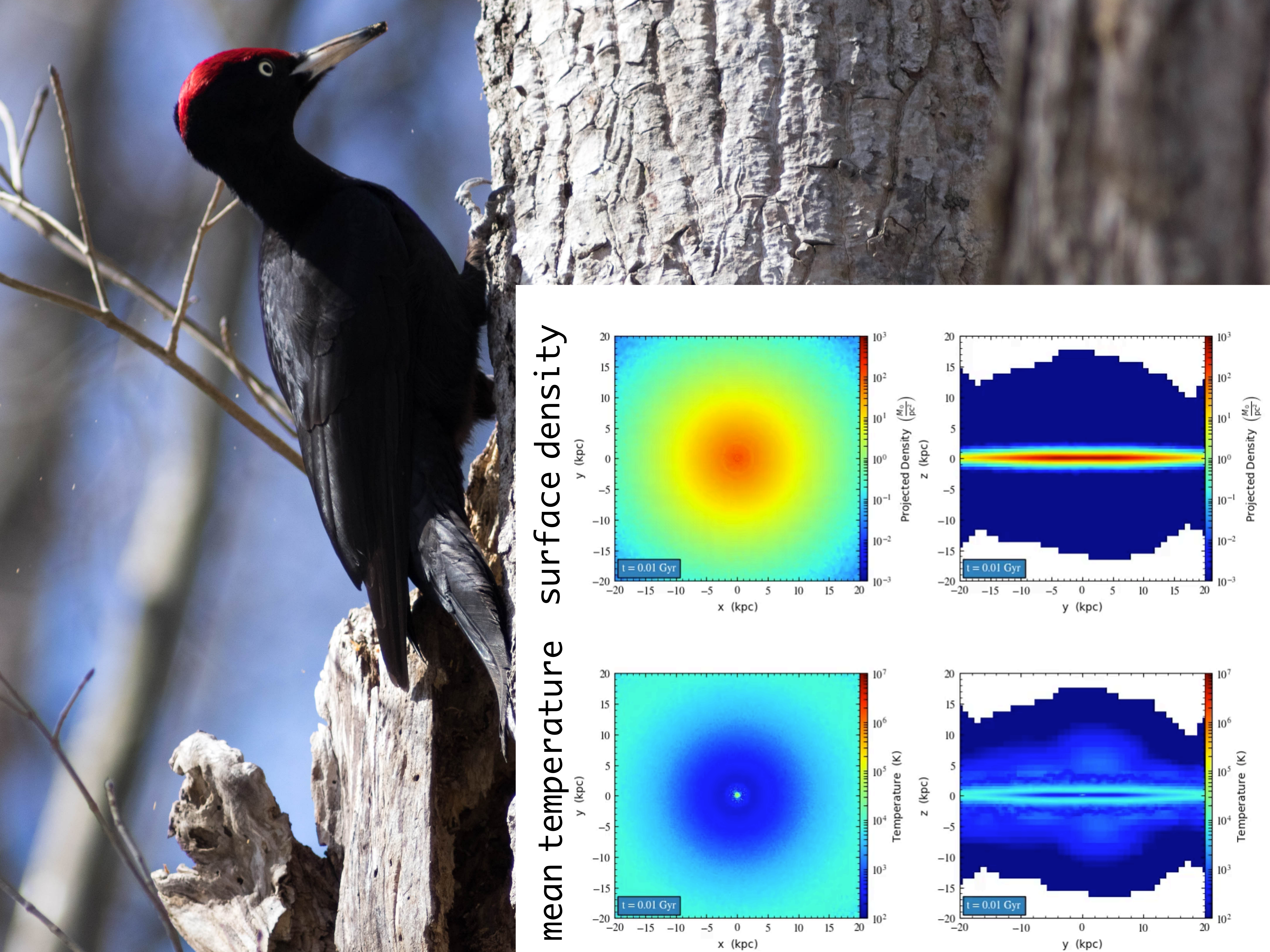


- Agora initial conditions for an isolated galaxy (Kim+'16)
  - Milky Way like
  - low-res: $m_{gas} = 8.6\mathrm{x}10^4\ M_\odot$, $N_{gas} = 10^5$
  - med-res: $m_{gas} = 8.6\mathrm{x}10^3\ M_\odot$, $N_{gas} = 10^6$
  - high-res: $m_{gas} = 8.6\mathrm{x}10^2\ M_\odot$, $N_{gas} = 10^7$


Results



surface density
mean temperature
t = 0.01 Gyr
x (kpc)
y (kpc)
z (kpc)
Projected Density $\left(\frac{M_\odot}{pc^2}\right)$
Temperature (K)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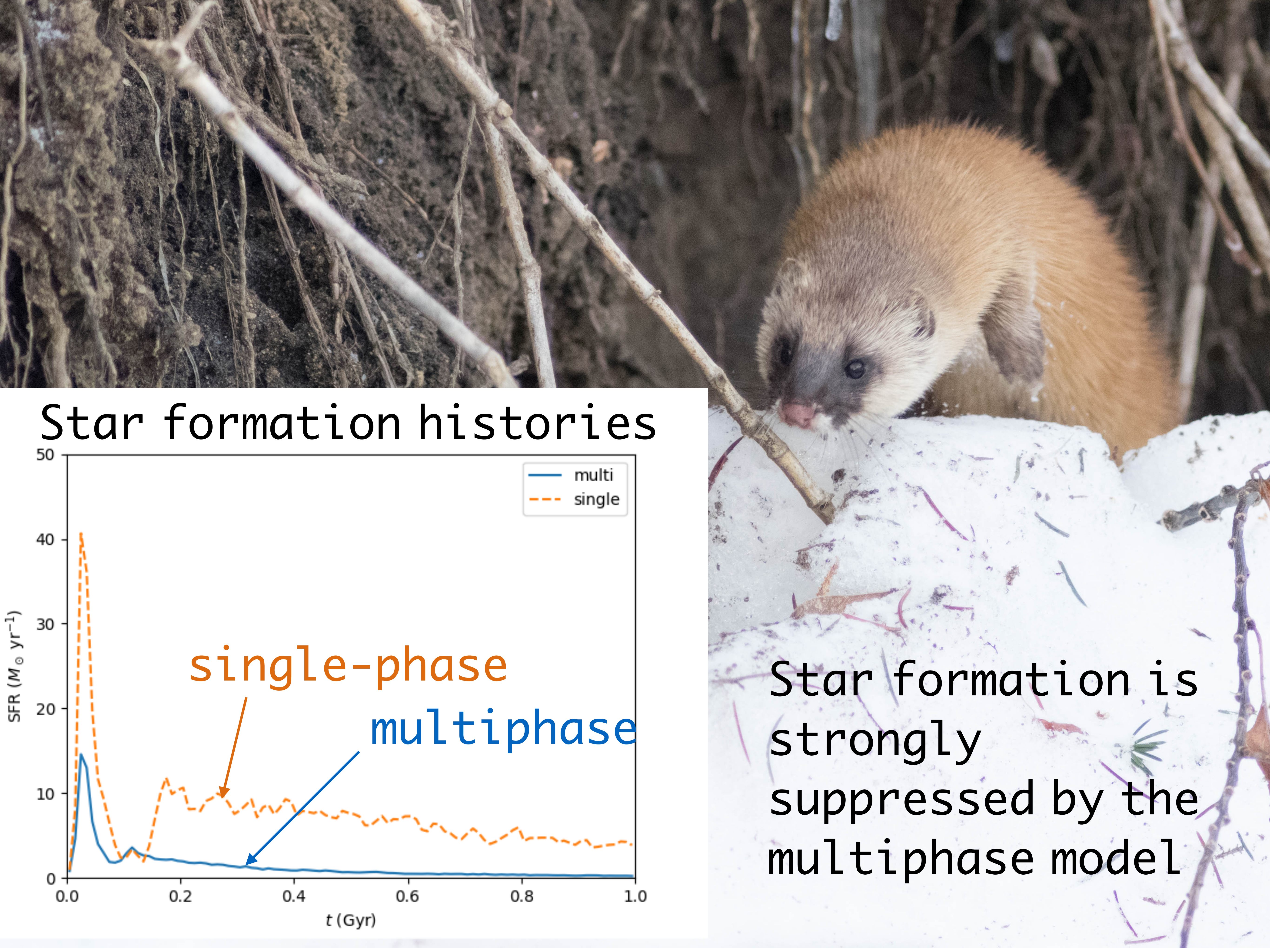
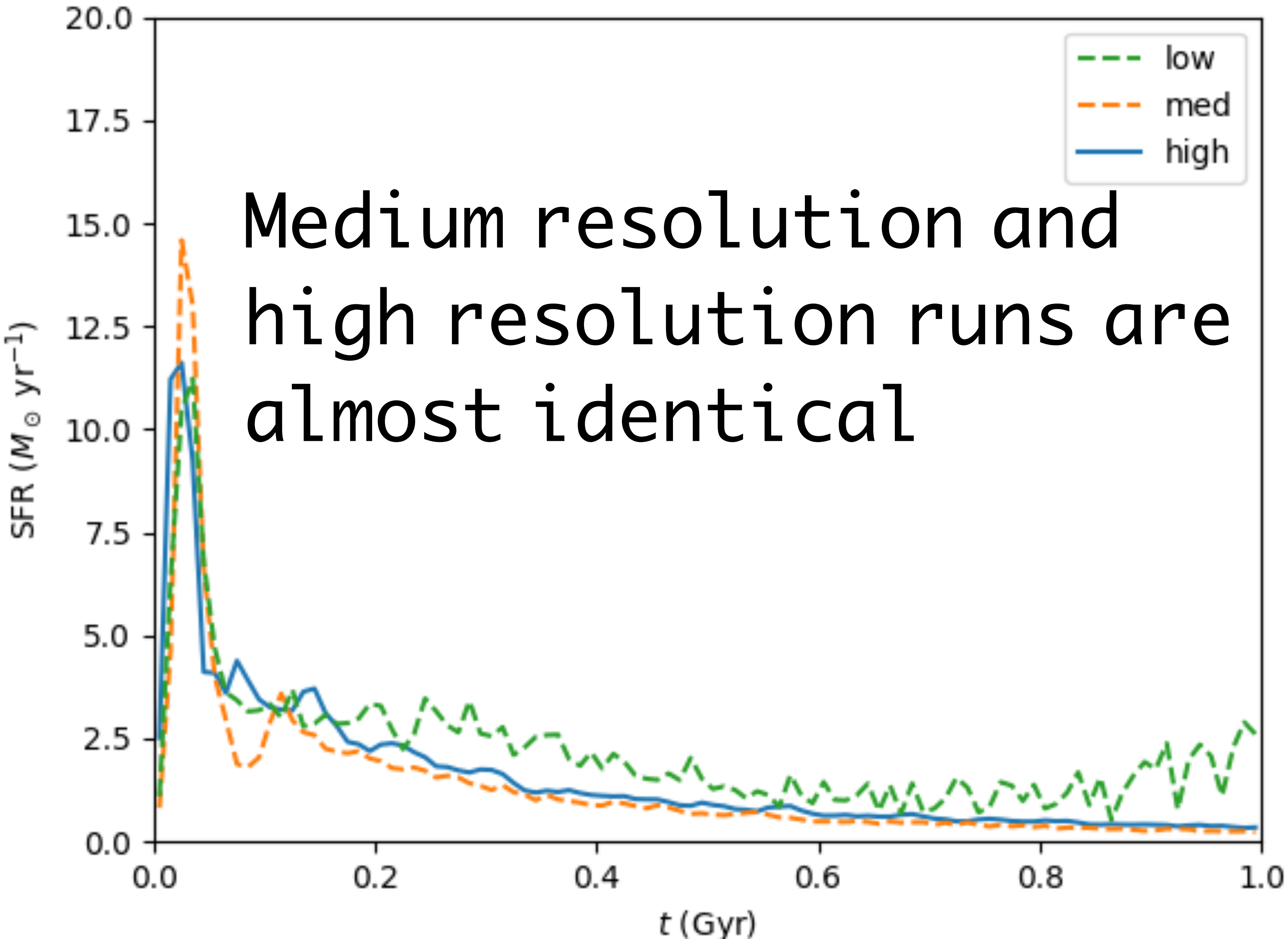

Star formation histories
50
40
30
20
10
0
SFR ($M_\odot$ yr^{-1})
0.0
0.2
0.4
0.6
0.8
1.0
t (Gyr)
multi
single
single-phase
multiphase
Star formation is strongly suppressed by the multiphase model

Convergence



Medium resolution and high resolution runs are almost identical


Summary

- The new scheme
  - effectively suppresses star formation even with $n_{th} > 100\ cc^{-1}$
  - can drive outflows
  - insensitive to numerical resolution
  - yet very simple
  - does not erase galactic structure such as spiral arms
- Ready for the cosmo-sims!