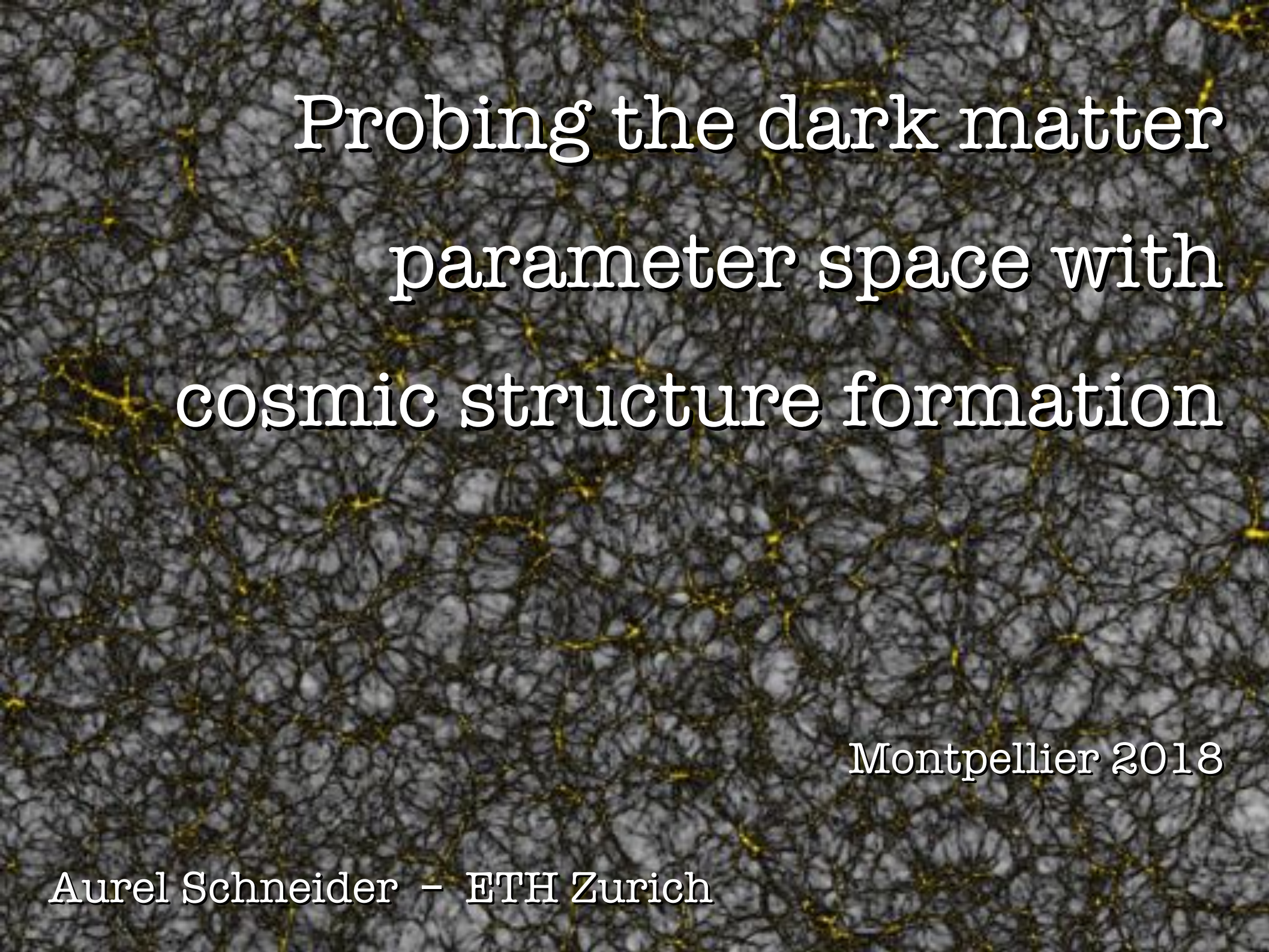

Probing the dark matter parameter space with cosmic structure formation

Montpellier 2018

Aurel Schneider – ETH Zurich

Dark Matter: explore all possibilities

- Overwhelming gravitational evidence
- Particle outside of standard model
- Many ideas and possibilities

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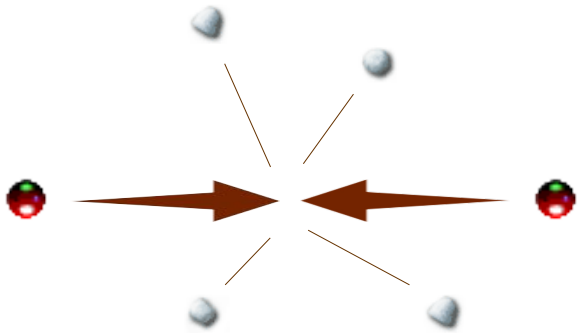

DM from Collider

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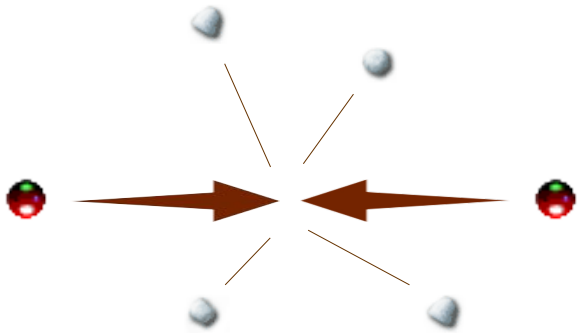

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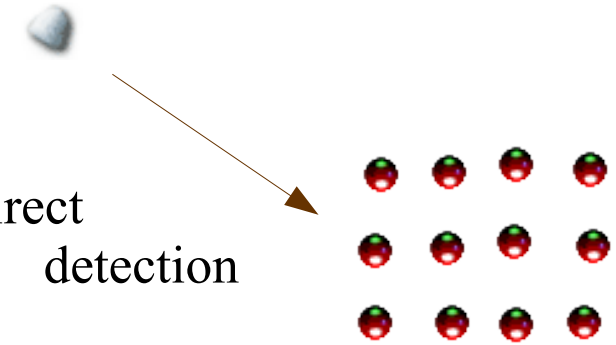

Direct
detection

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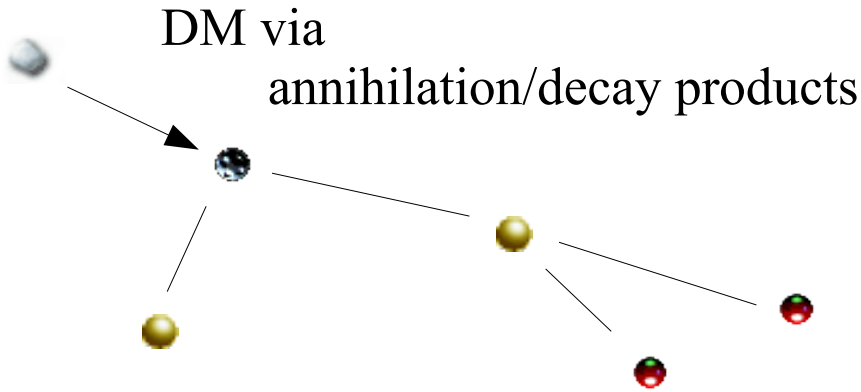

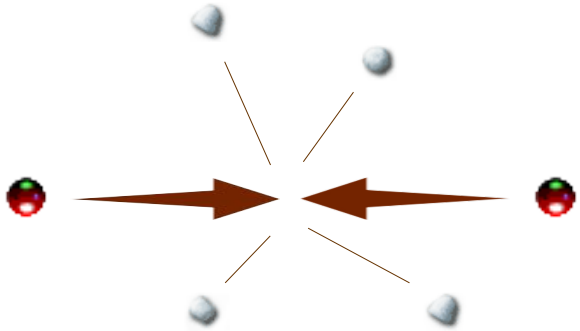

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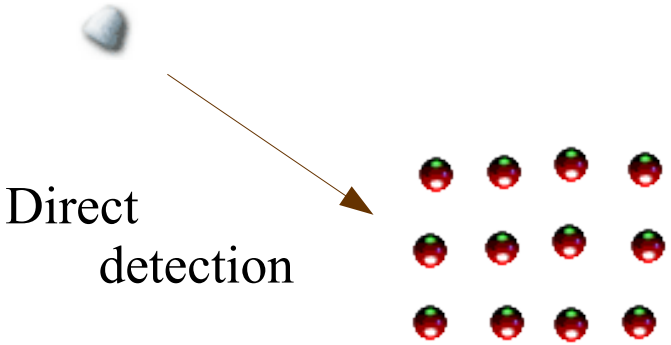

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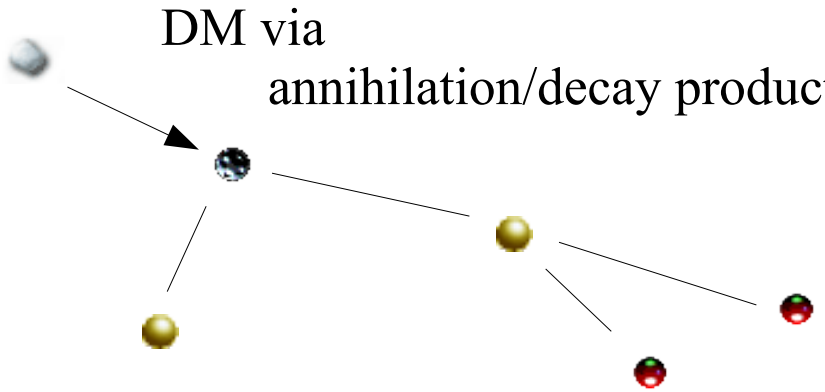
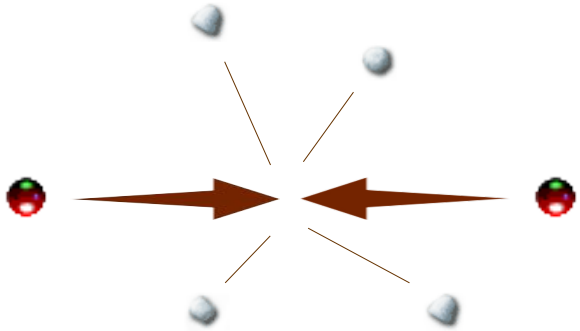


DM via
annihilation/decay products



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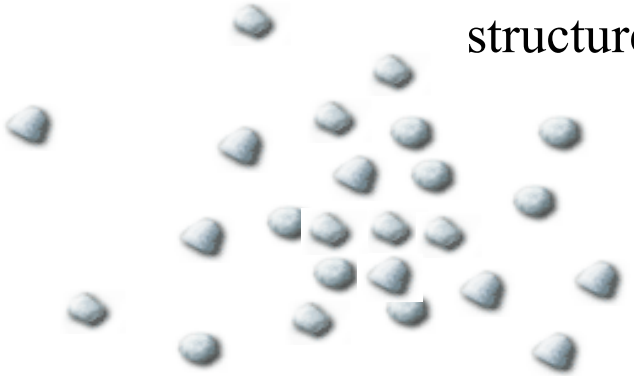
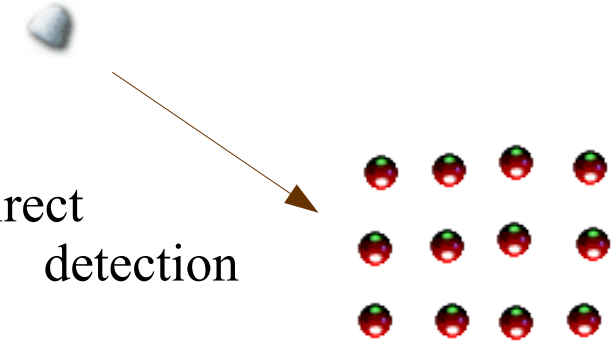


DM via
structure formation



Direct
detection

Linear Structure Formation

$$\frac{df(x,p,t)}{dt} = 0$$

$$\dot{\delta} + \theta - 3\phi = 0,$$

$$\dot{\theta} + H\theta - k^2 c_s^2 \delta - k^2 \psi = 0.$$

$$\ddot{\delta} + H\dot{\delta} = \left[4\pi G\bar{\rho} - k^2 c_s^2\right] \delta$$

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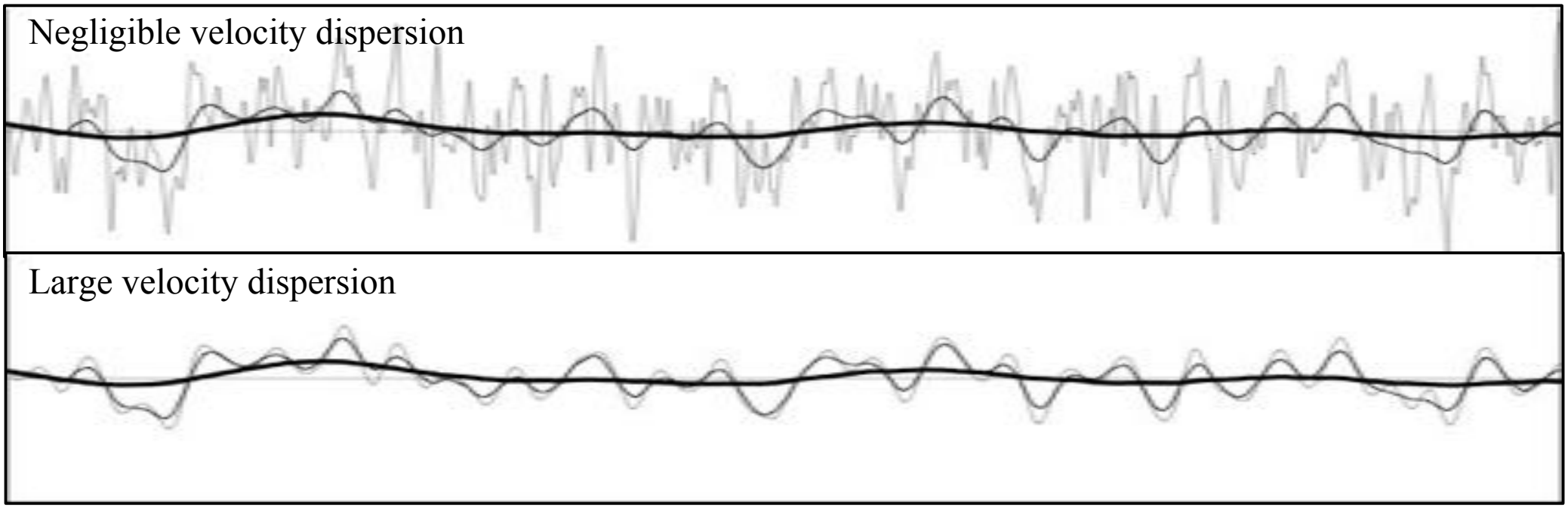

Linear Structure Formation

$$\frac{df(x,p,t)}{dt} = 0$$

$$c_s^2 = \frac{1}{m^2}\frac{\int dp p^2 f(p)}{\int dp f(p)}$$

$$\dot{\delta} + \theta - 3\phi = 0,$$

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Linear Structure Formation – **Fermi-Dirac (WDM)**

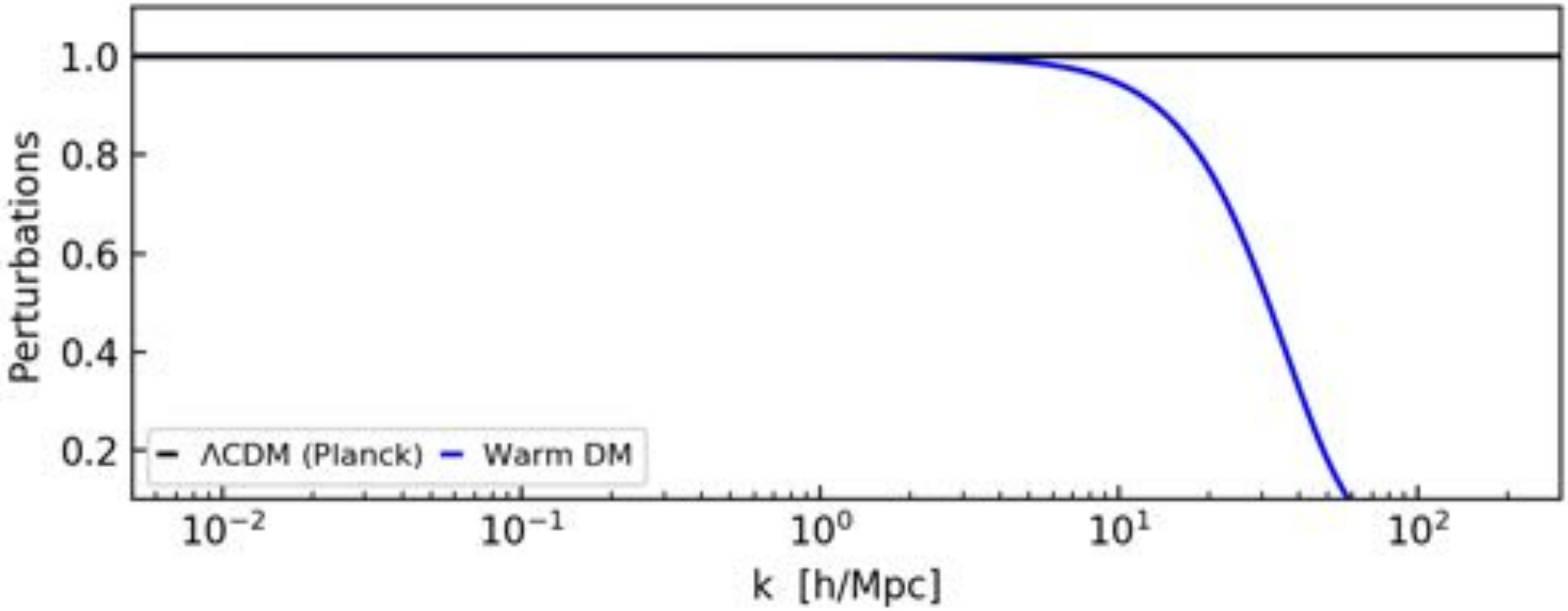
$$\frac{df(x,p,t)}{dt} = 0$$

$$\dot{\delta} + \theta - 3\phi = 0,$$

$$\dot{\theta} + H\theta - k^2 c_s^2 \delta - k^2 \psi = 0.$$

$$c_s^2 = \left(\frac{T}{m}\right)^2$$

$$\ddot{\delta} + H\dot{\delta} = \left[4\pi G\bar{\rho} - k^2 c_s^2\right]\delta$$



Linear Structure Formation – **Sterile Neutrino DM**

$$\frac{df(x,p,t)}{dt} = 0$$

$$\dot{\delta} + \theta - 3\phi = 0,$$
$$\dot{\theta} + H\theta - k^2 c_s^2 \delta - k^2 \psi = 0.$$

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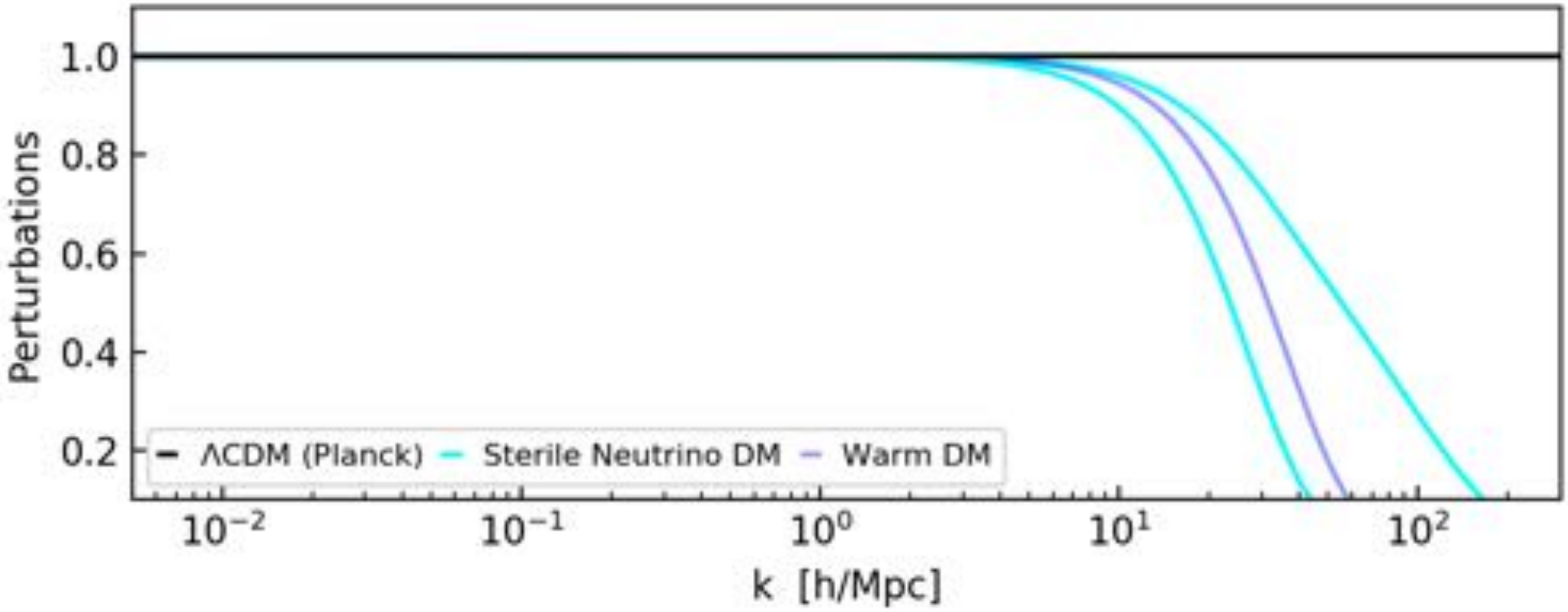


Linear Structure Formation – **Ultra-light Axion DM**

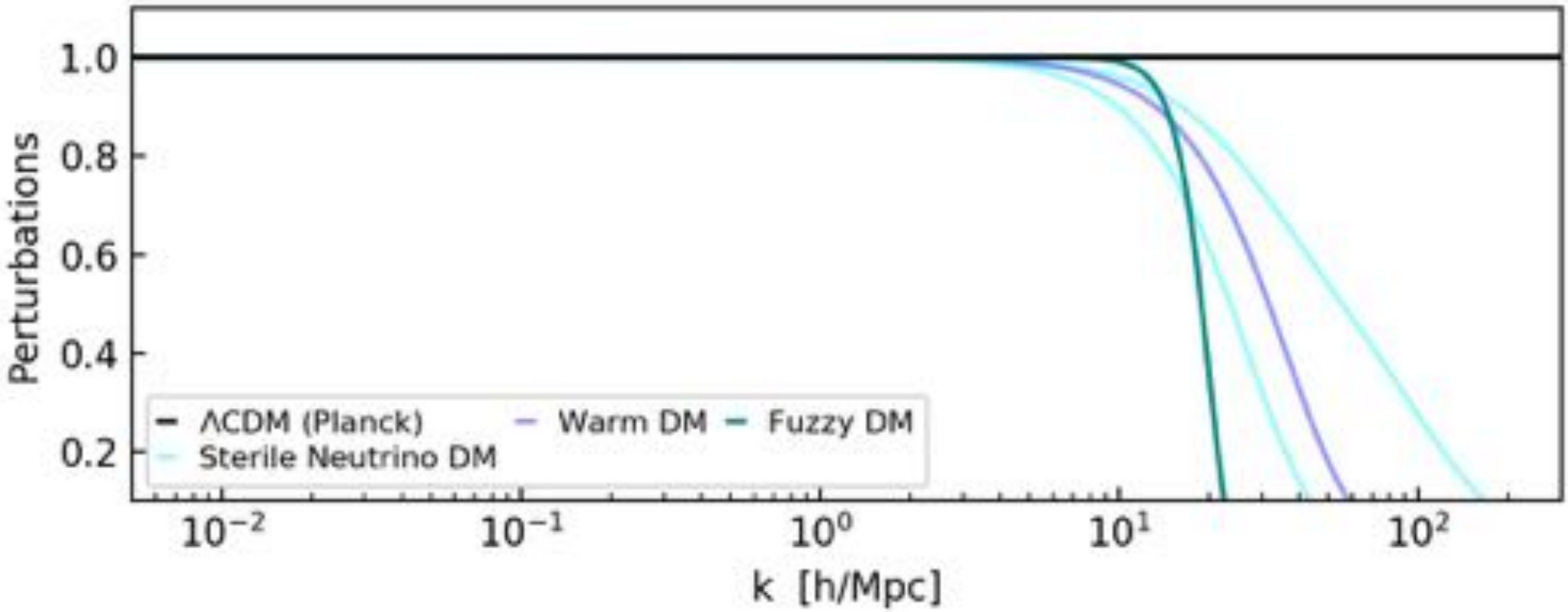
$$\frac{df(x,p,t)}{dt} = 0$$

$$\dot{\delta} + \theta - 3\phi = 0,$$

$$\dot{\theta} + H\theta - k^2 c_s^2 \delta - k^2 \psi = 0.$$

$$\ddot{\delta} + H\dot{\delta} = \left[4\pi G\bar{\rho} - k^2 c_s^2\right]\delta$$

$$c_s \propto \frac{k}{m}$$



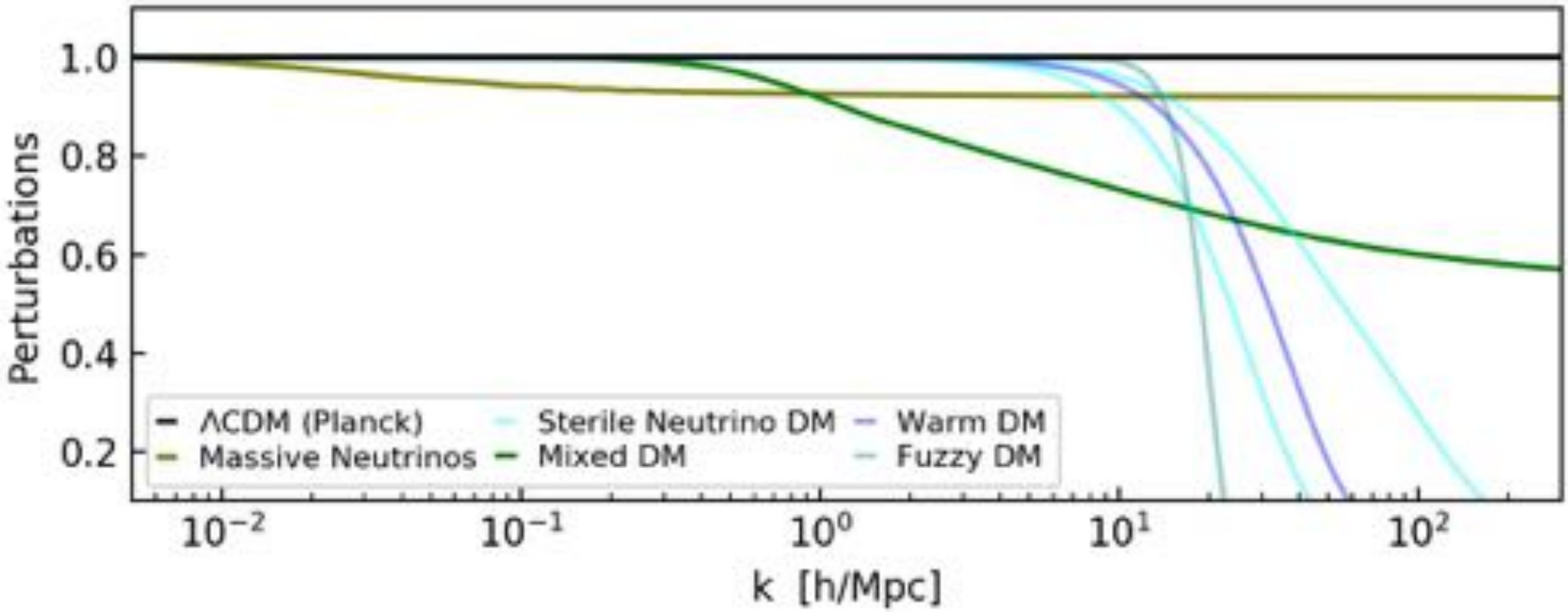
Linear Structure Formation – **Mixed DM**

$$\frac{df(x,p,t)}{dt} = 0$$

$$\dot{\delta} + \theta - 3\phi = 0,$$
$$\dot{\theta} + H\theta - k^2 c_s^2 \delta - k^2 \psi = 0.$$

$$\ddot{\delta}_c + H\dot{\delta}_c = 4\pi G\bar{\rho}\delta_c + 4\pi G\bar{\rho}\delta$$

$$\ddot{\delta} + H\dot{\delta} = \left[4\pi G\bar{\rho} - k^2 c_s^2\right]\delta + 4\pi G\bar{\rho}\delta_c$$



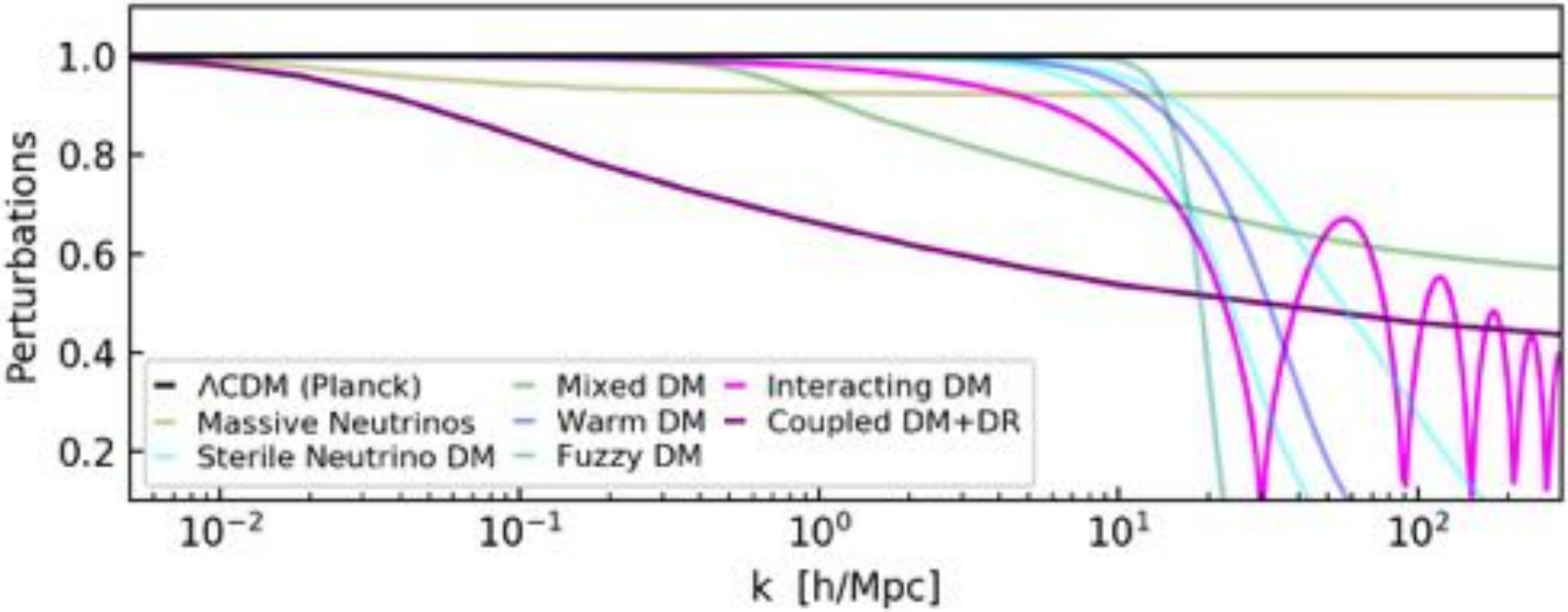
Linear Structure Formation – **Interacting DM**

$$\frac{d\,f(x,p,t)}{dt} = C[f(x,p,t),..]$$

$$\dot{\delta} + \theta - 3\phi = 0$$

$$\dot{\theta} + H\theta - k^2 c_s^2 \delta - k^2 \psi = R(\theta_\chi - \theta)$$

$$\ddot{\delta} + H\dot{\delta} + R(\dot{\delta} - \dot{\delta}_\chi) = \left[4\pi G\bar{\rho} - k^2 c_s^2\right]\delta$$



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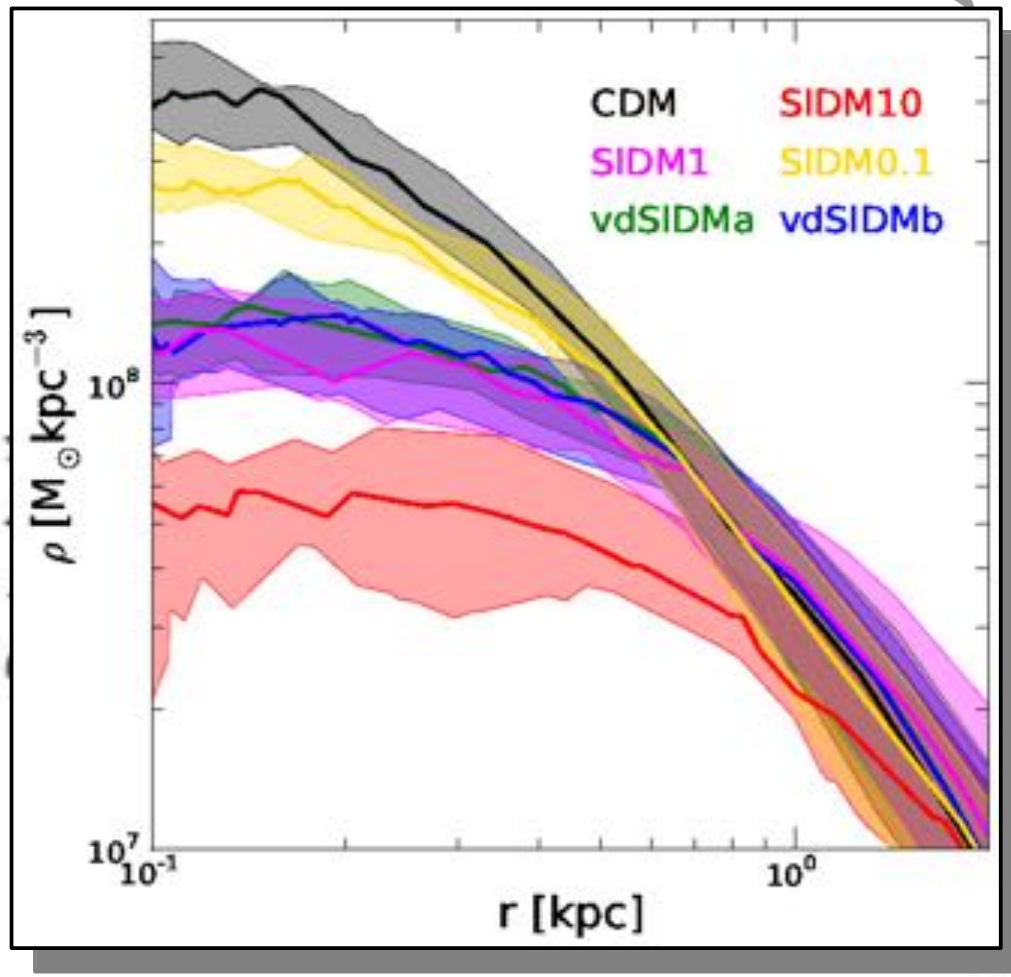
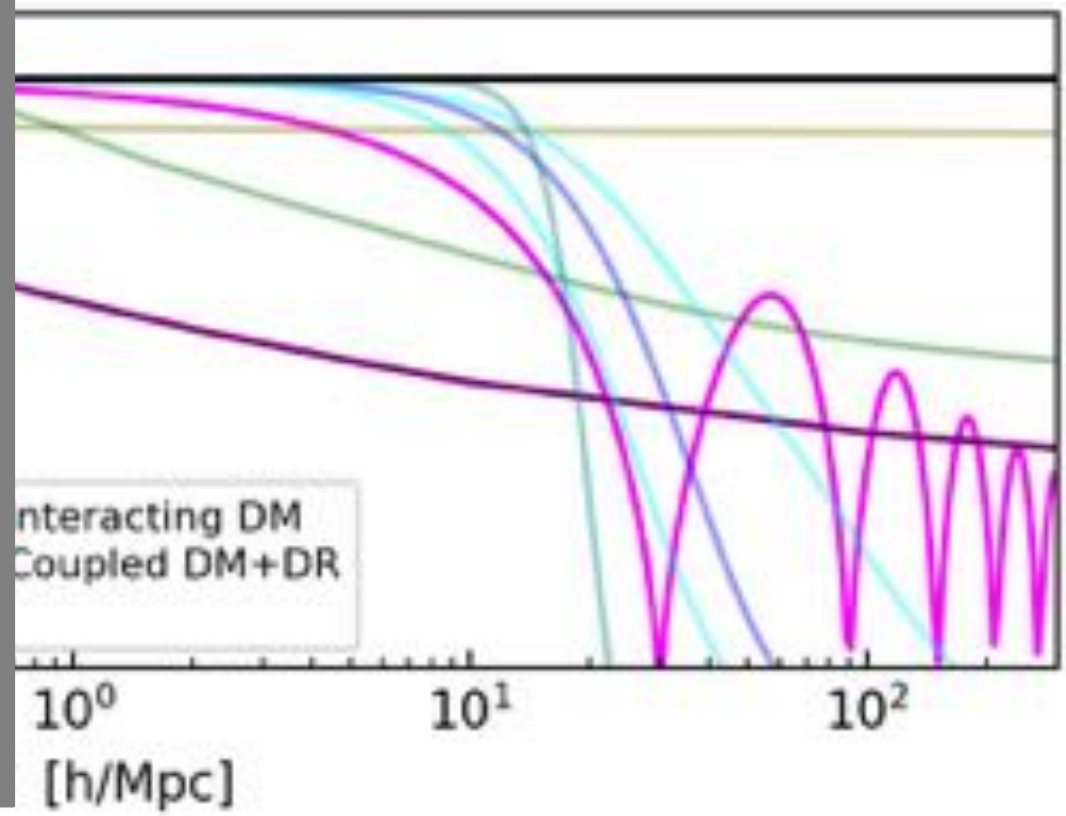
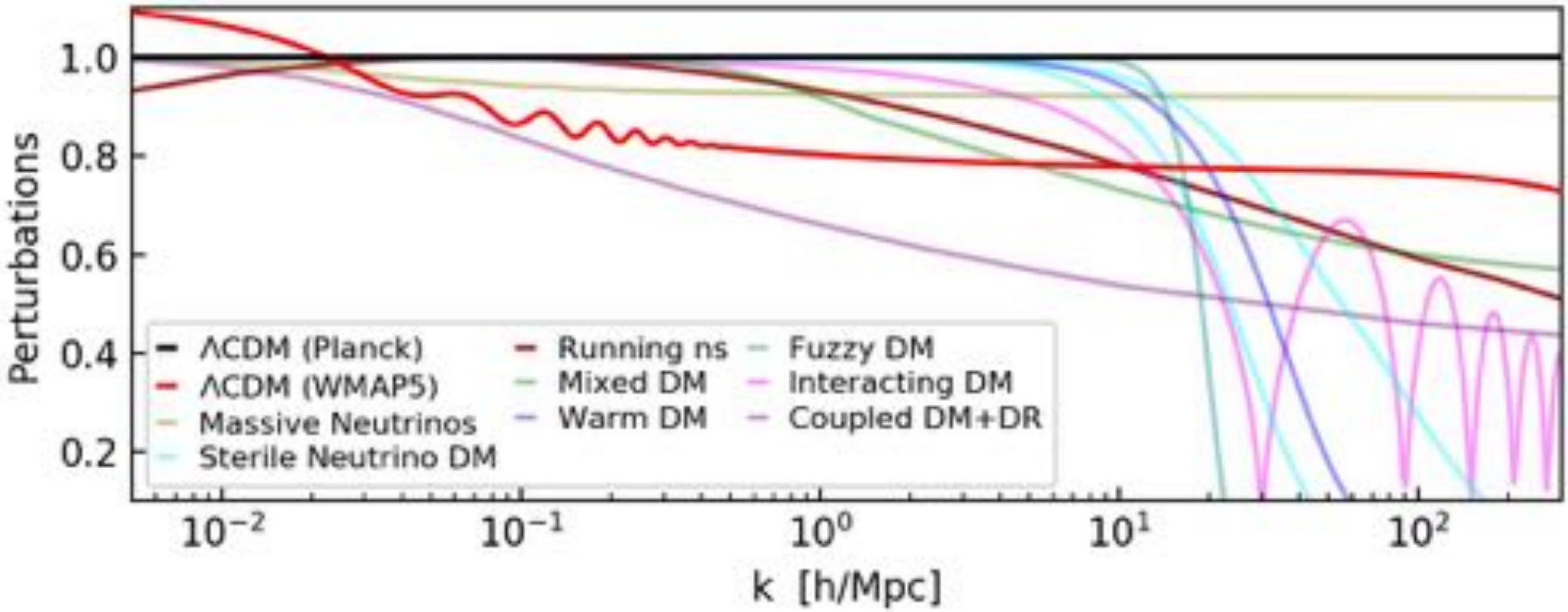




Linear Structure Formation – **Non-DM effects**

Changing / Extending Cosmological parameters



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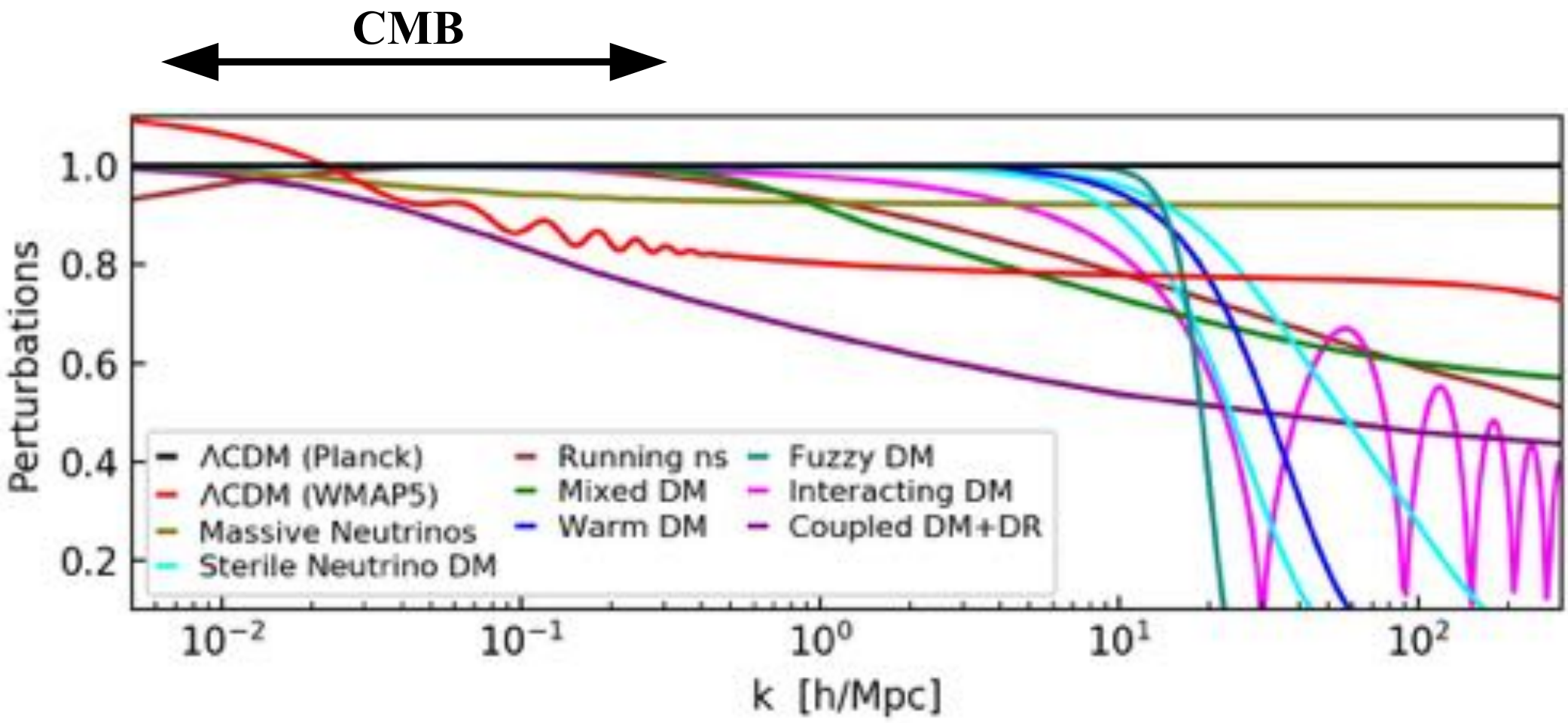

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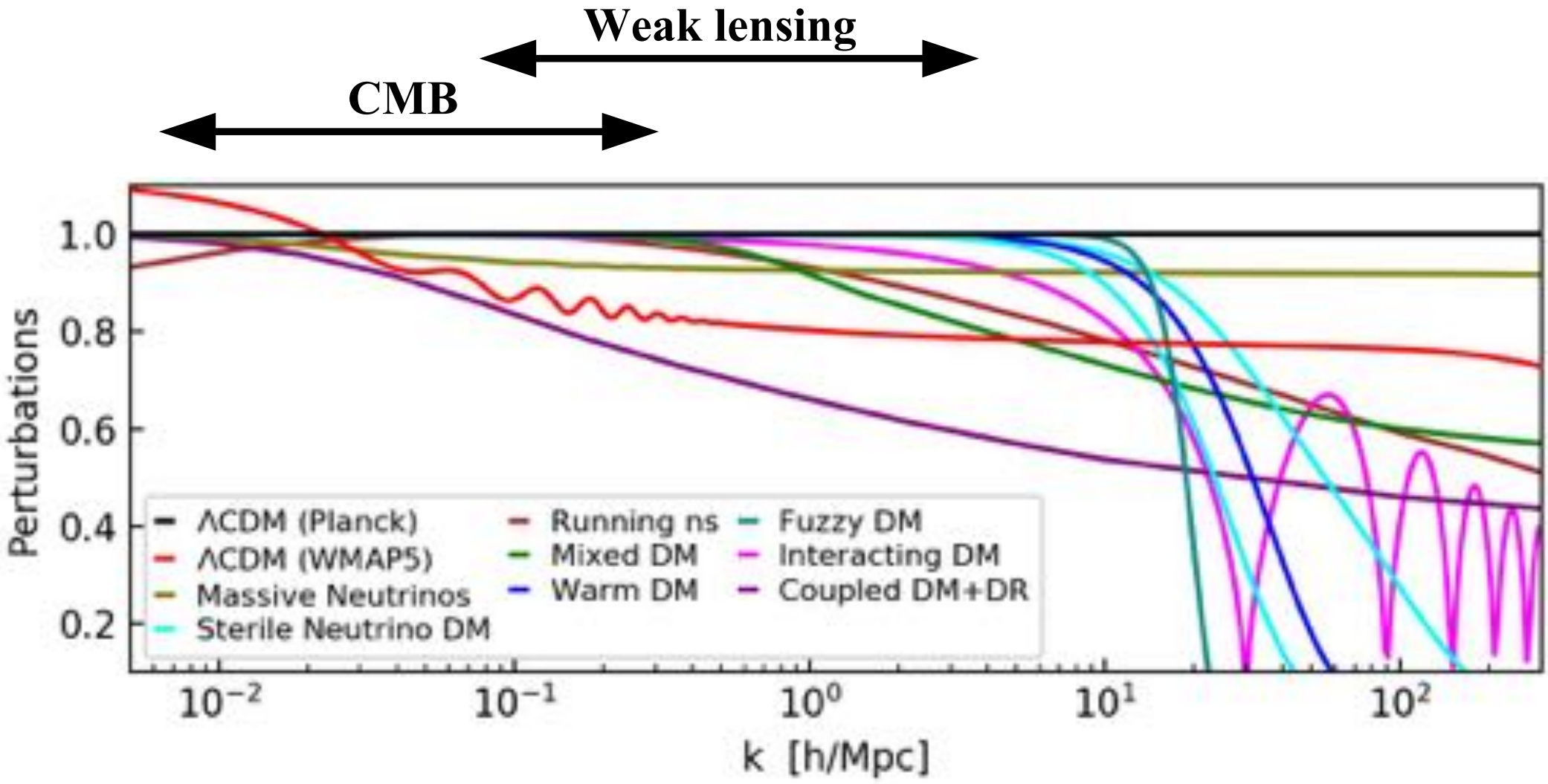

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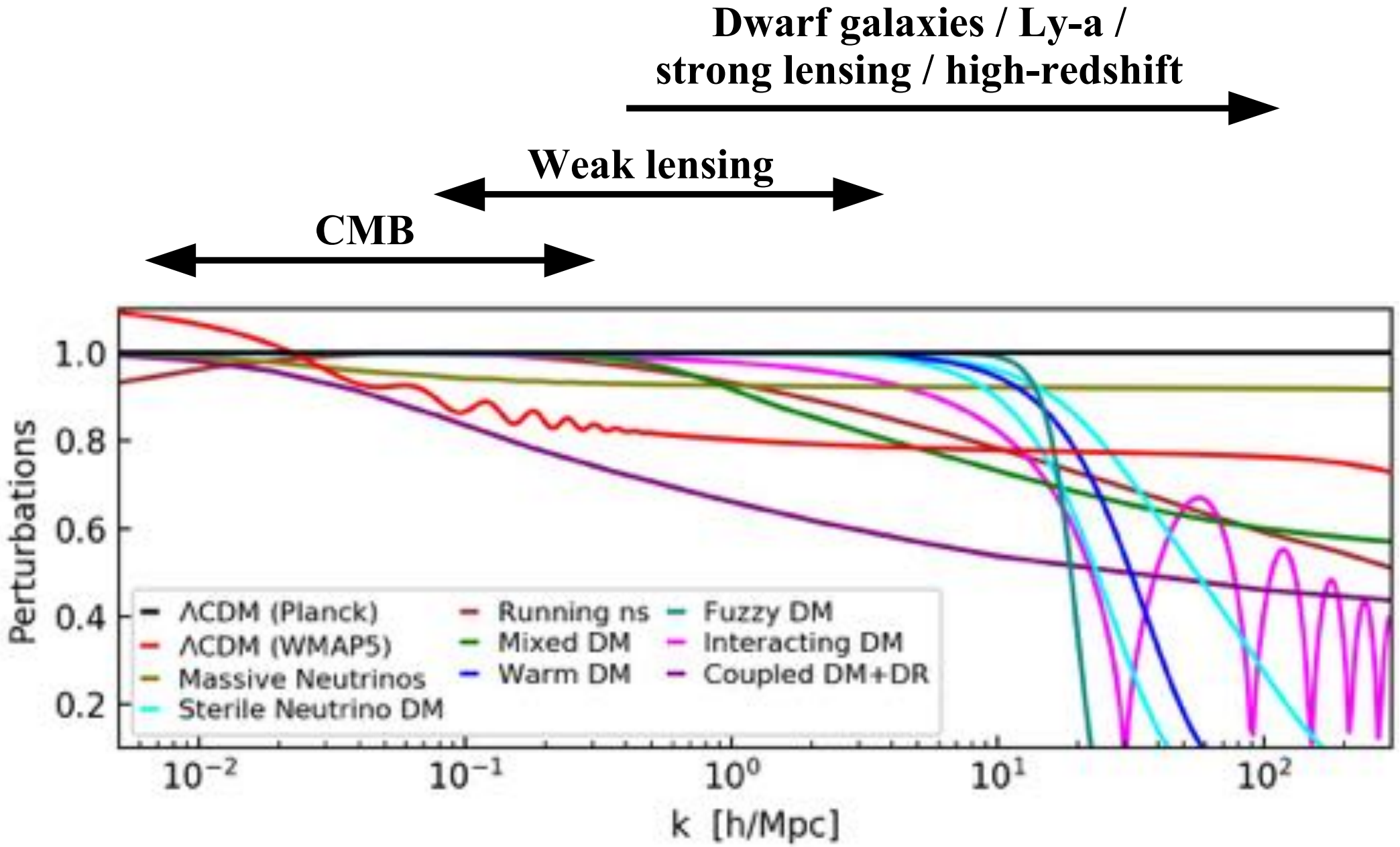

DM and structure formation: 2 options

Do dwarf galaxies disagree with the cold dark matter paradigm ?

Constraining dark matter models

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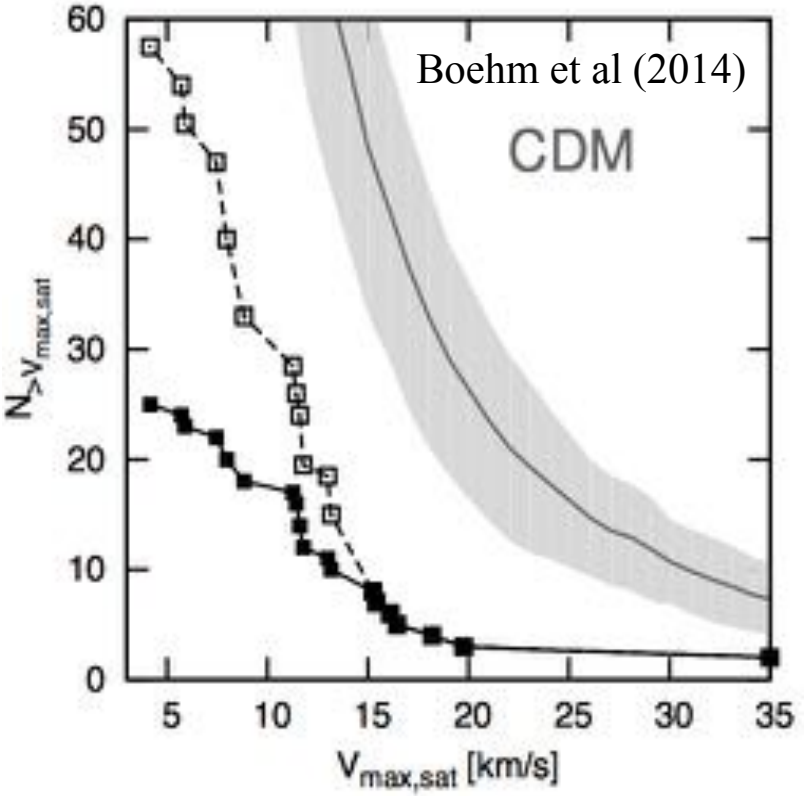
Small-scale problems

Missing satellites Too-big-to-fail Cusp-core

Gravity-only sims



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(warm, mixed, interacting DM, ...)

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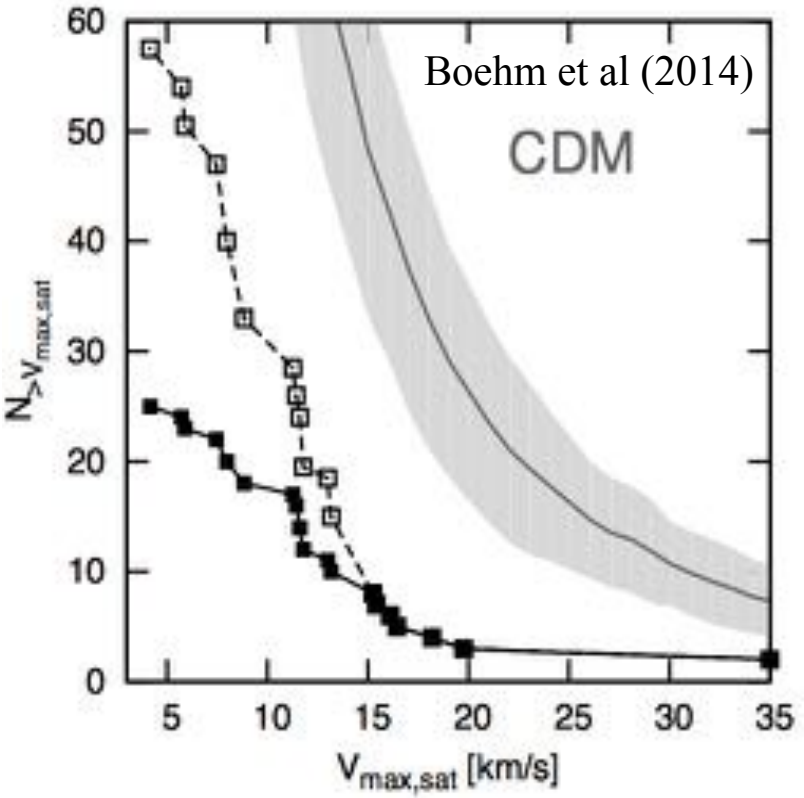

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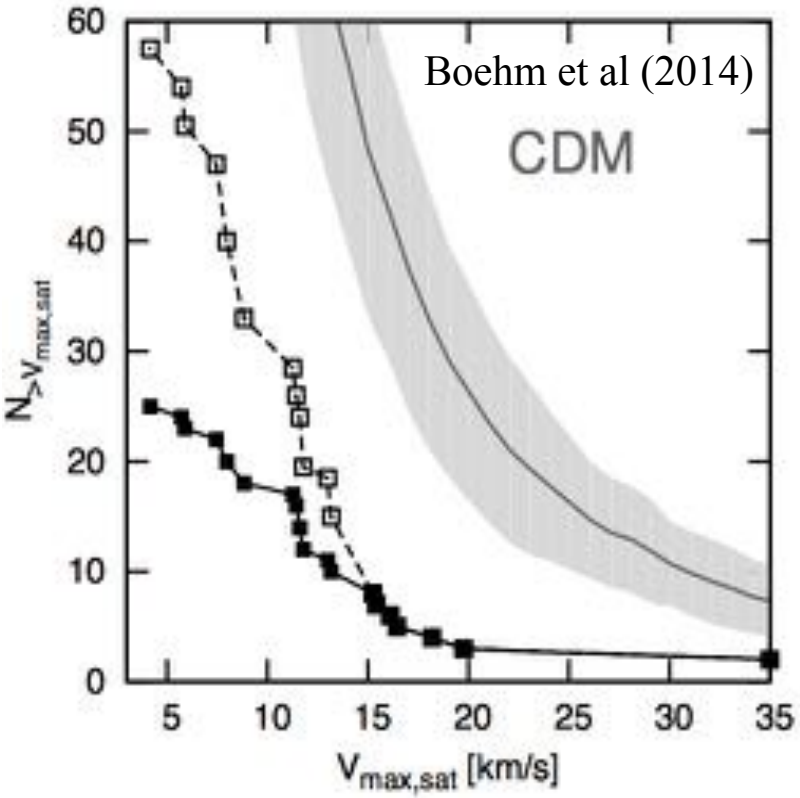
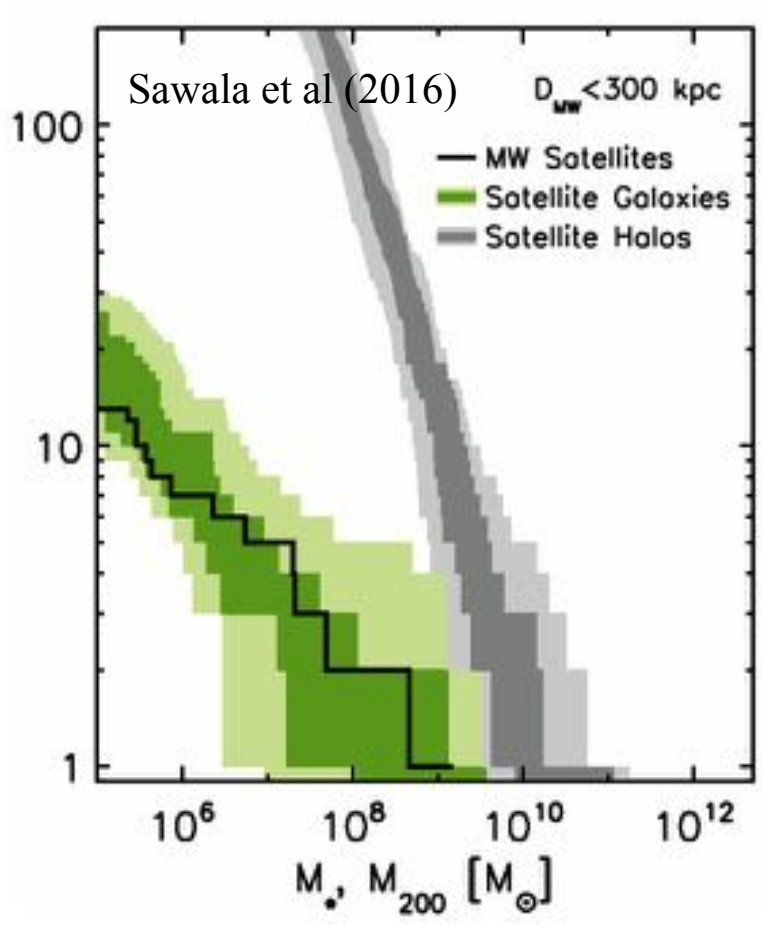


Hydro-sims



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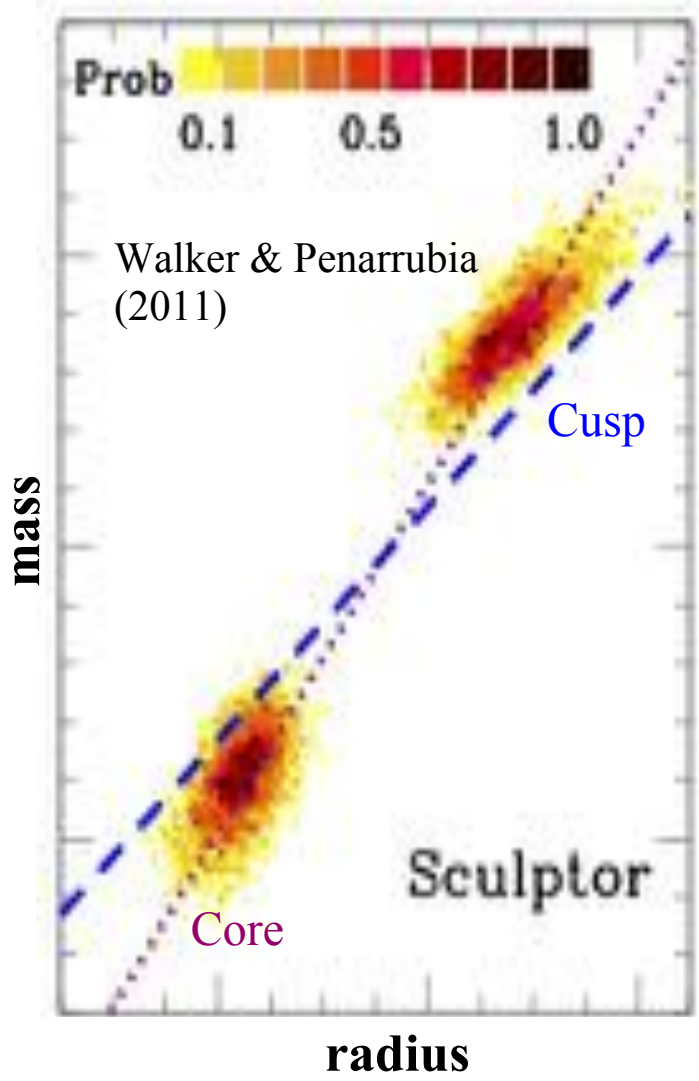

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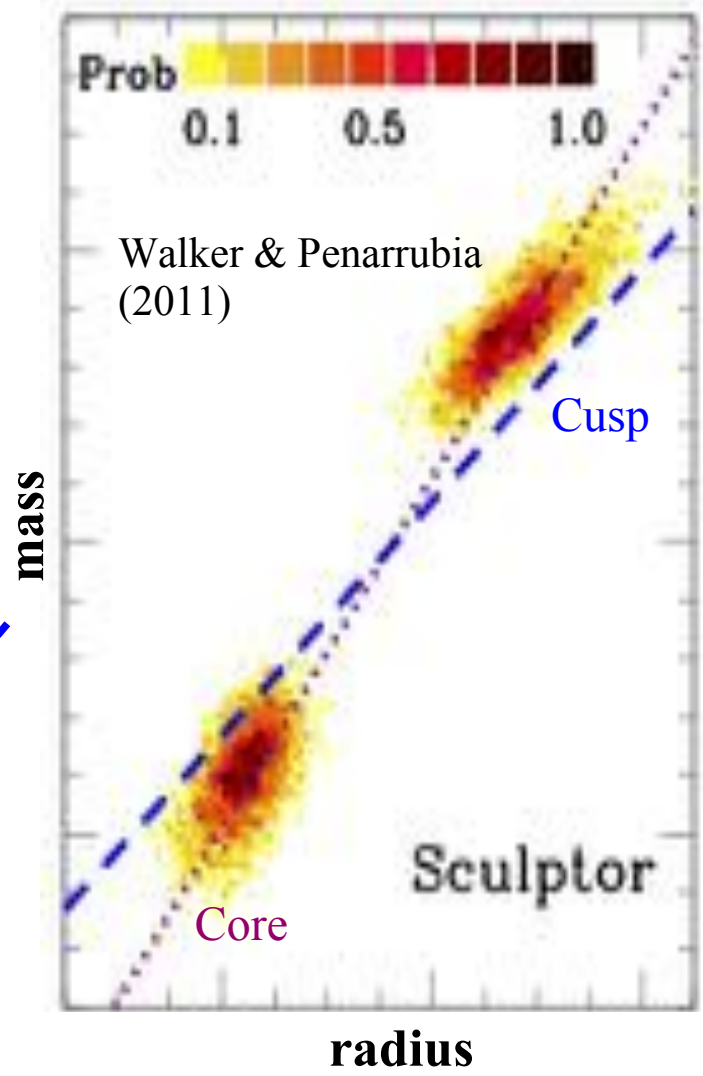

DM models affecting profiles

(self-interacting DM, fuzzy DM, …)

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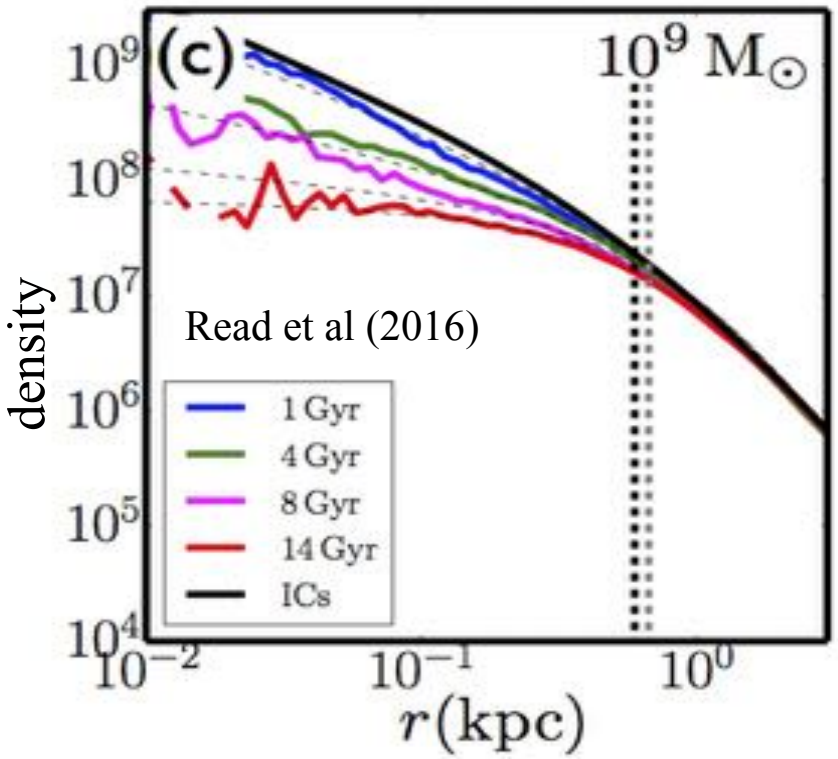
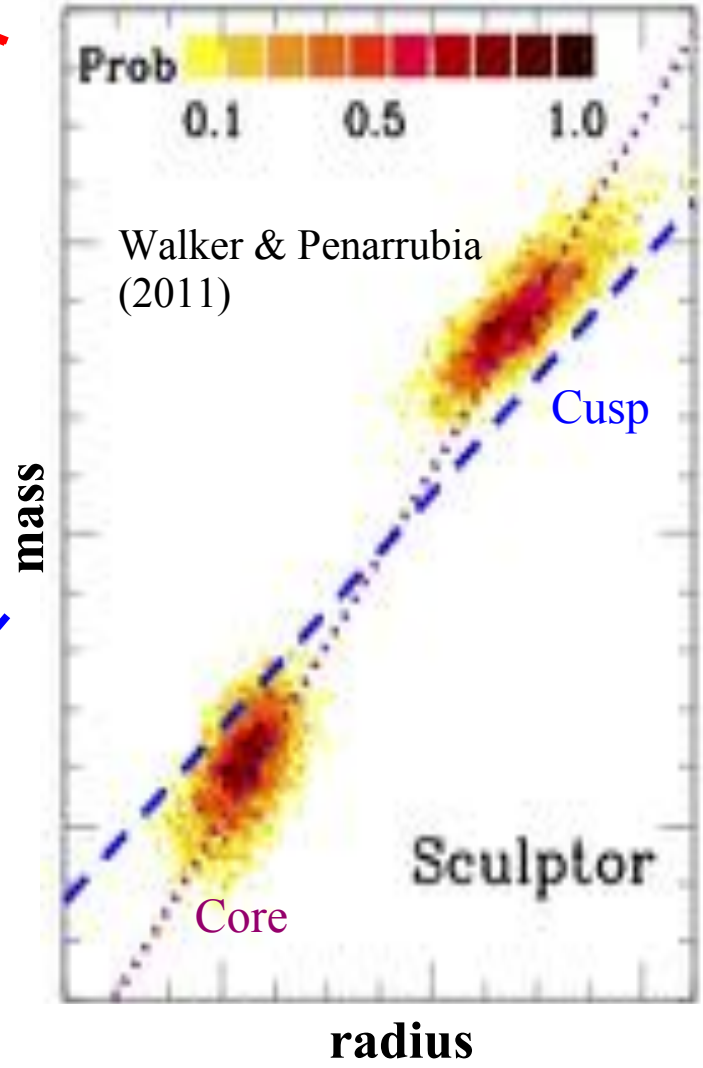


Observational systematics?

(Fattahi et al, 2016)



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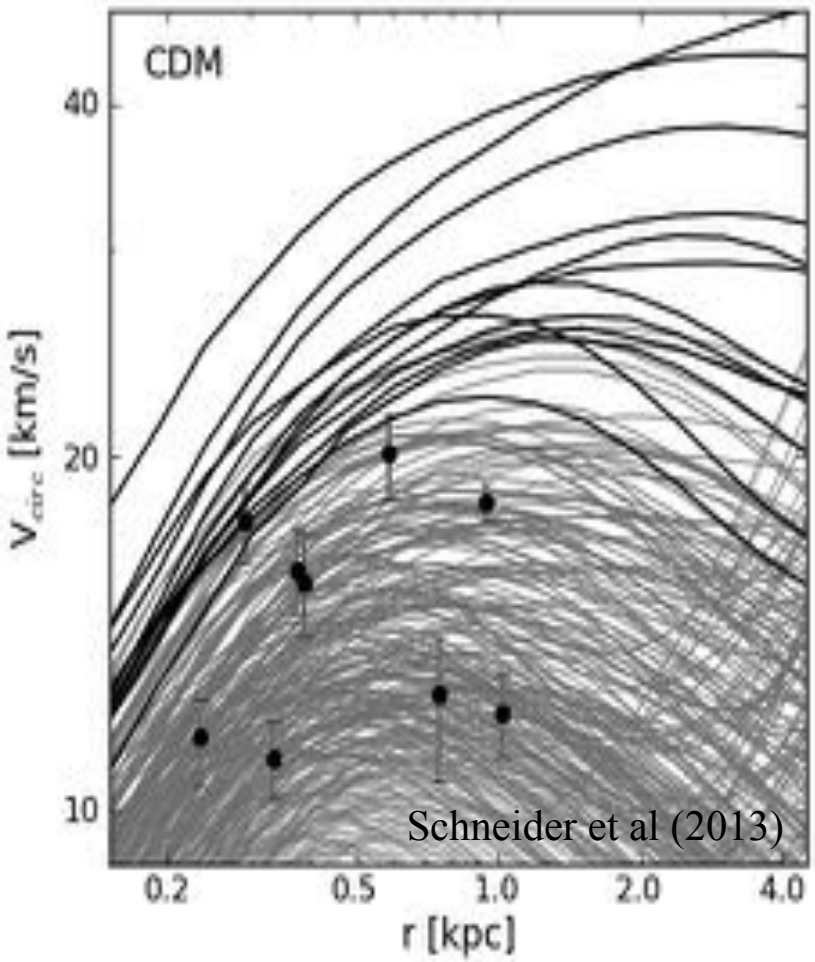

Schneider et al (2013)

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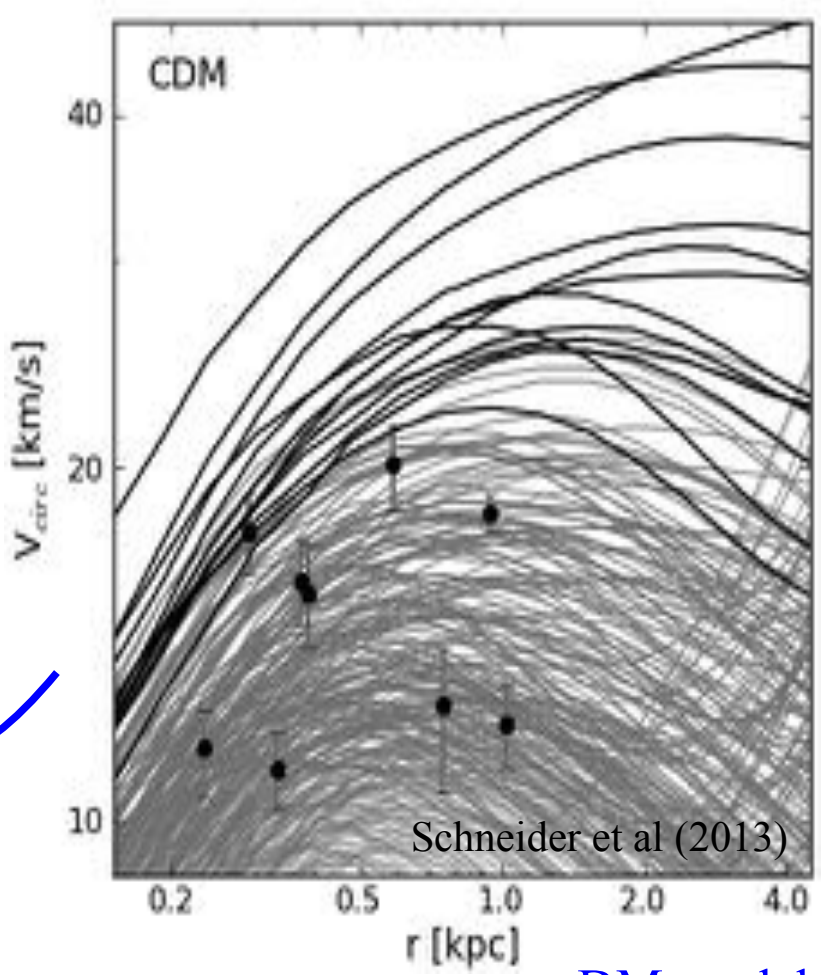

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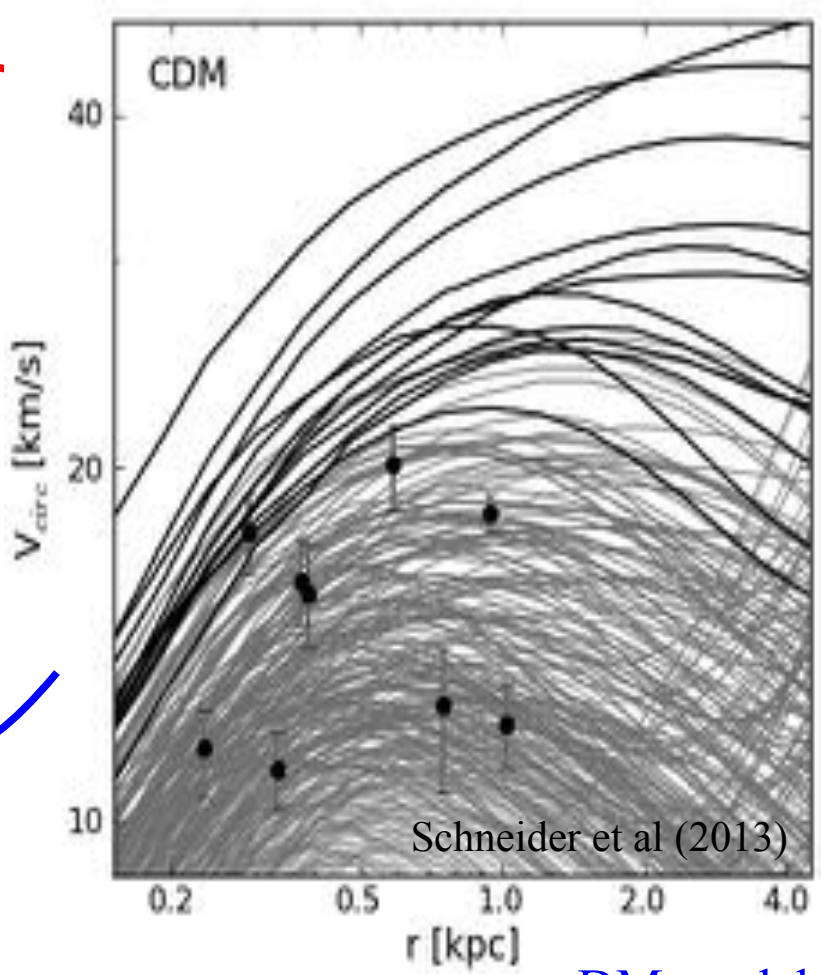
Hydro-sims,

Baryon cores,

…



Small Milky-Way mass,

Low clustering amplitude,

…

DM models affecting profiles (self-interacting DM, fuzzy DM, …)

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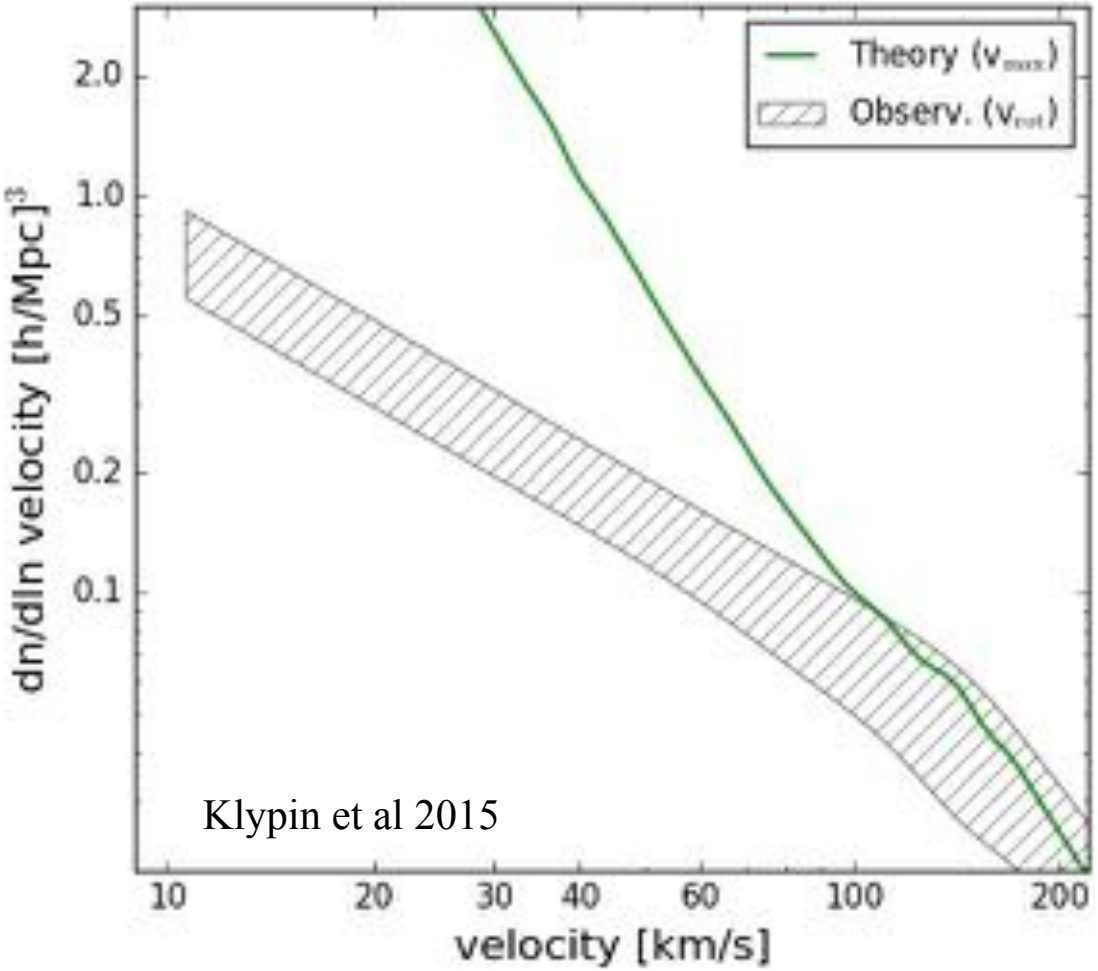
Velocity function of small galaxies

Velocity function of small galaxies

Large discrepancy between theory and observations … but is this a fair comparison ?



Klypin et al 2015

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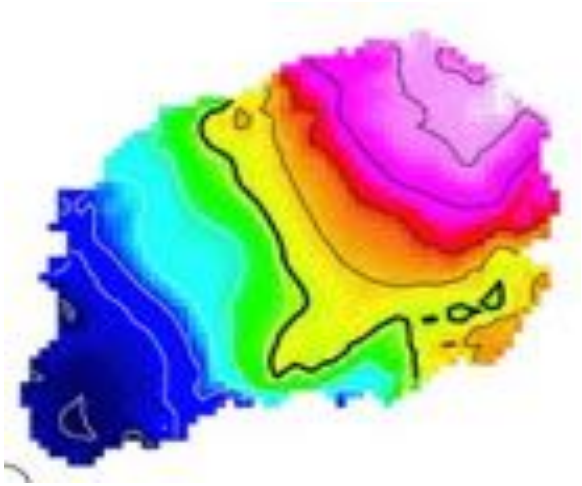

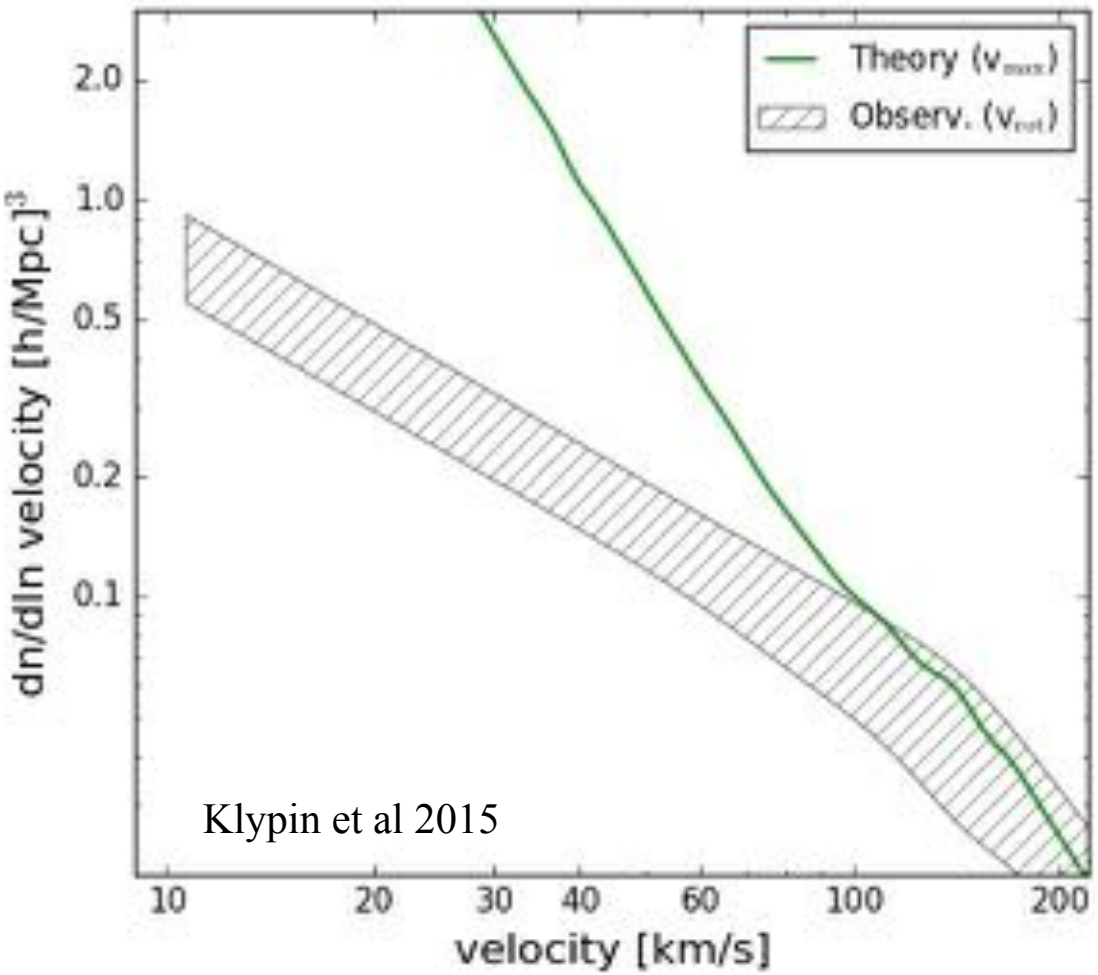

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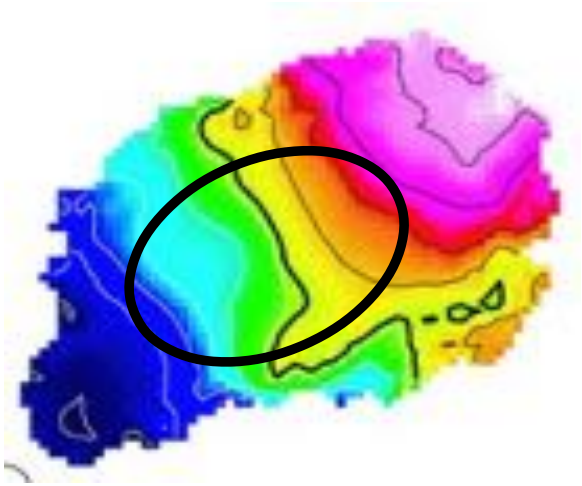
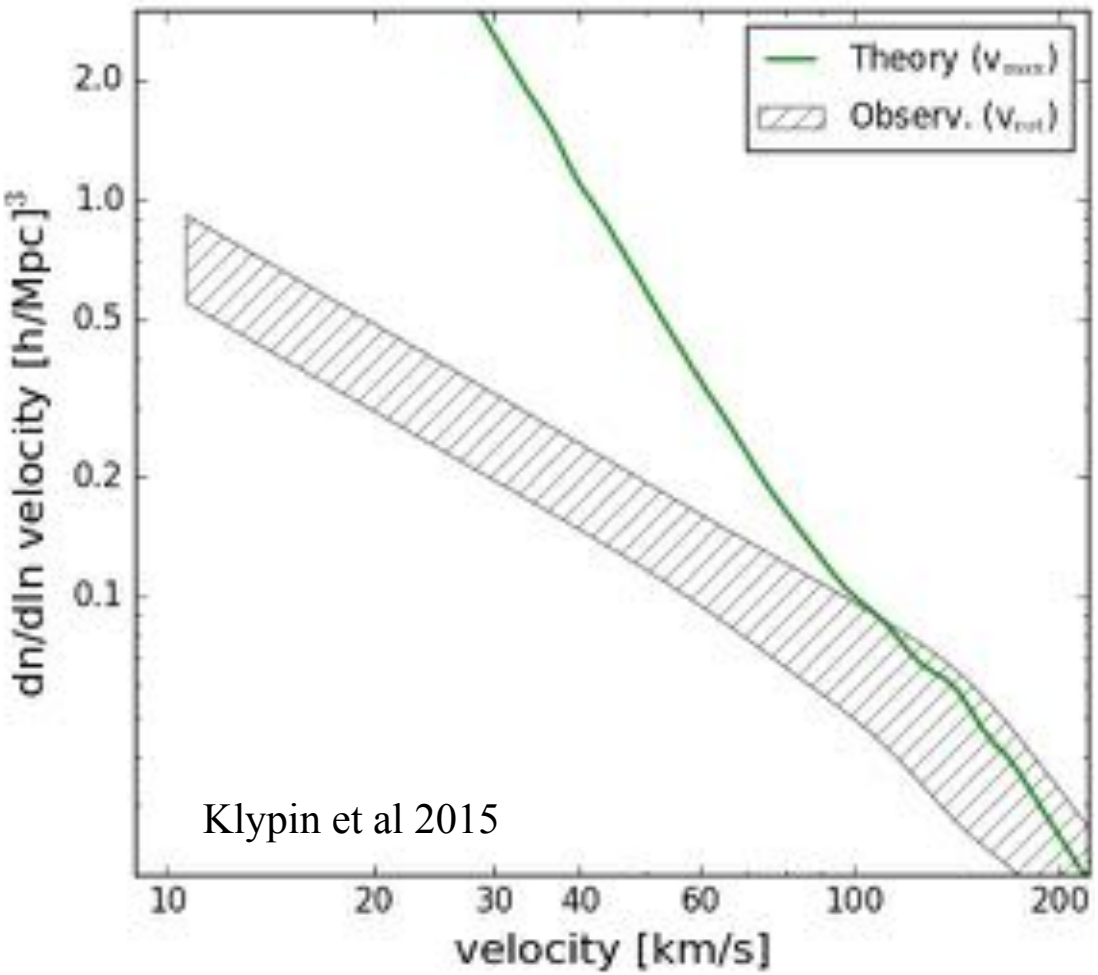
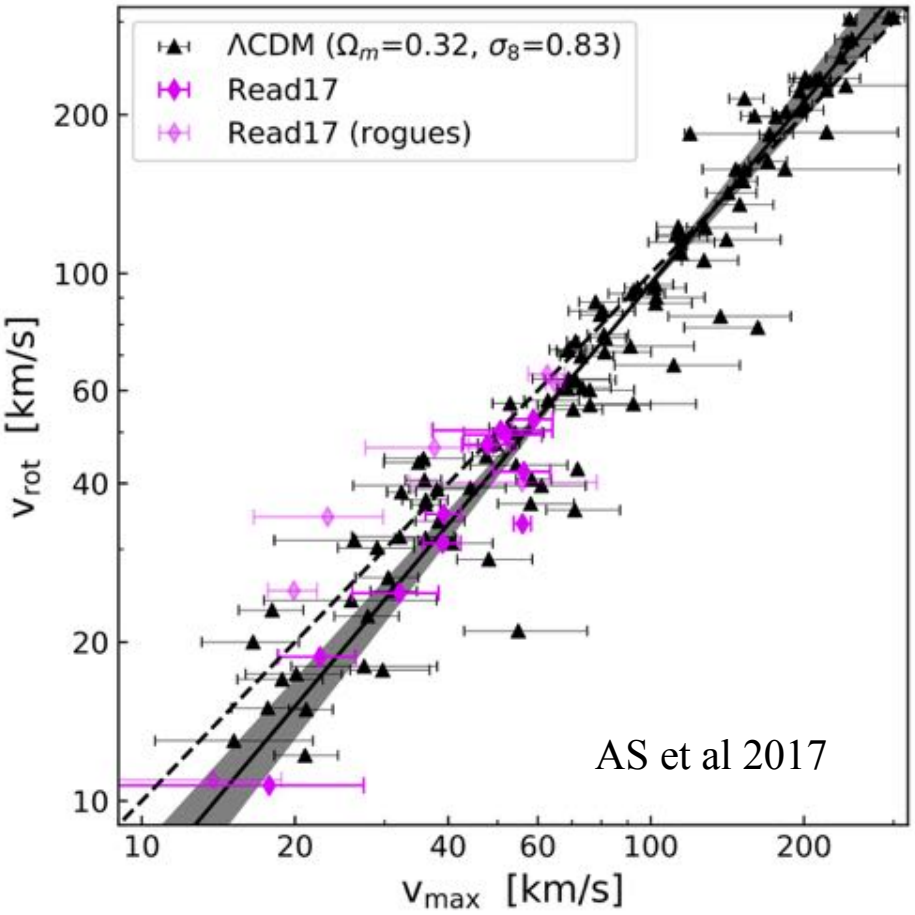
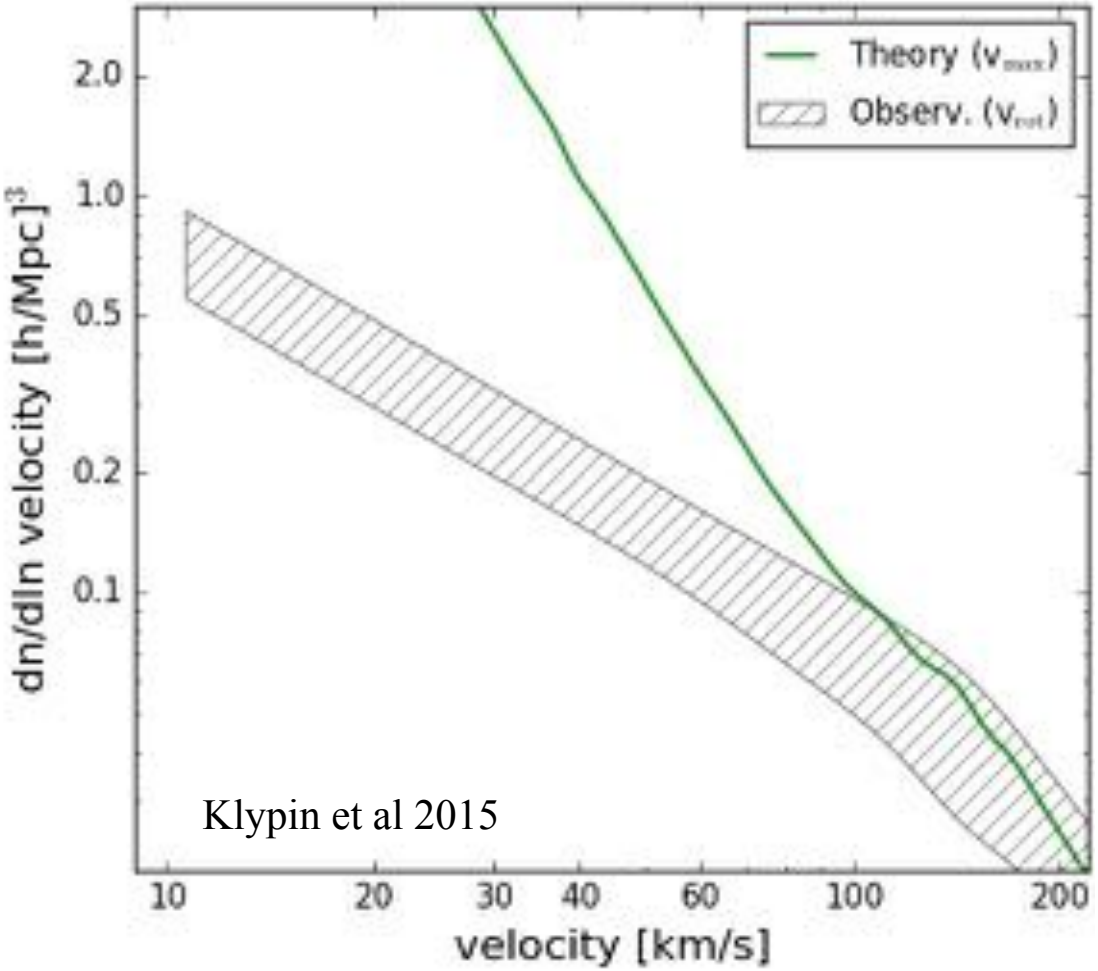




Velocity function of small galaxies

Find vrot-vmax relation using dwarfs with spatially resolved velocities





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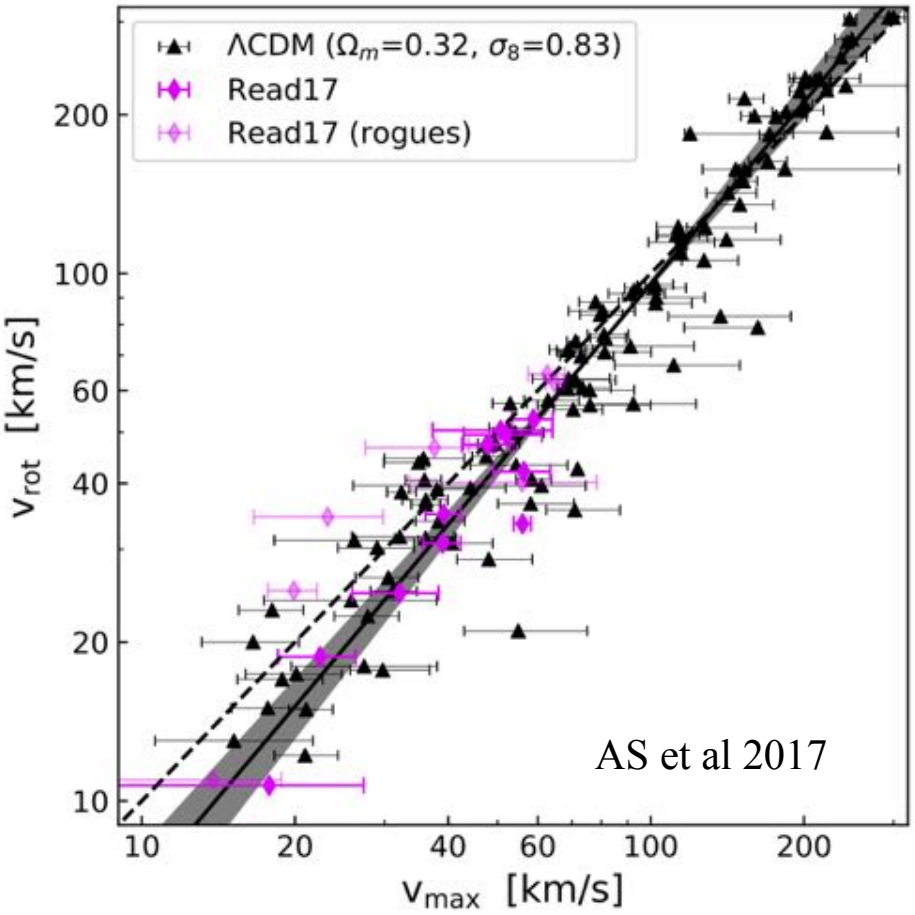

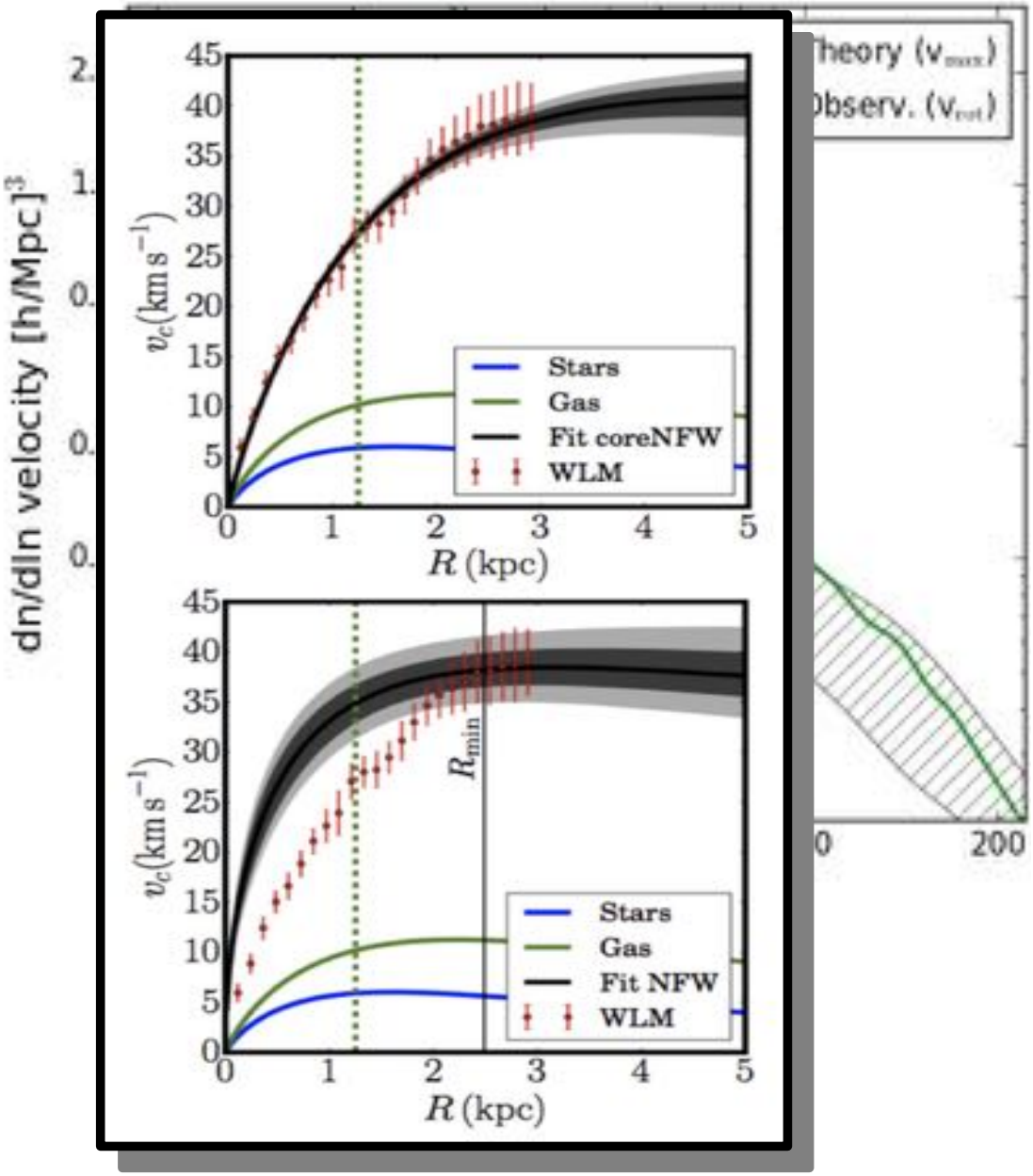

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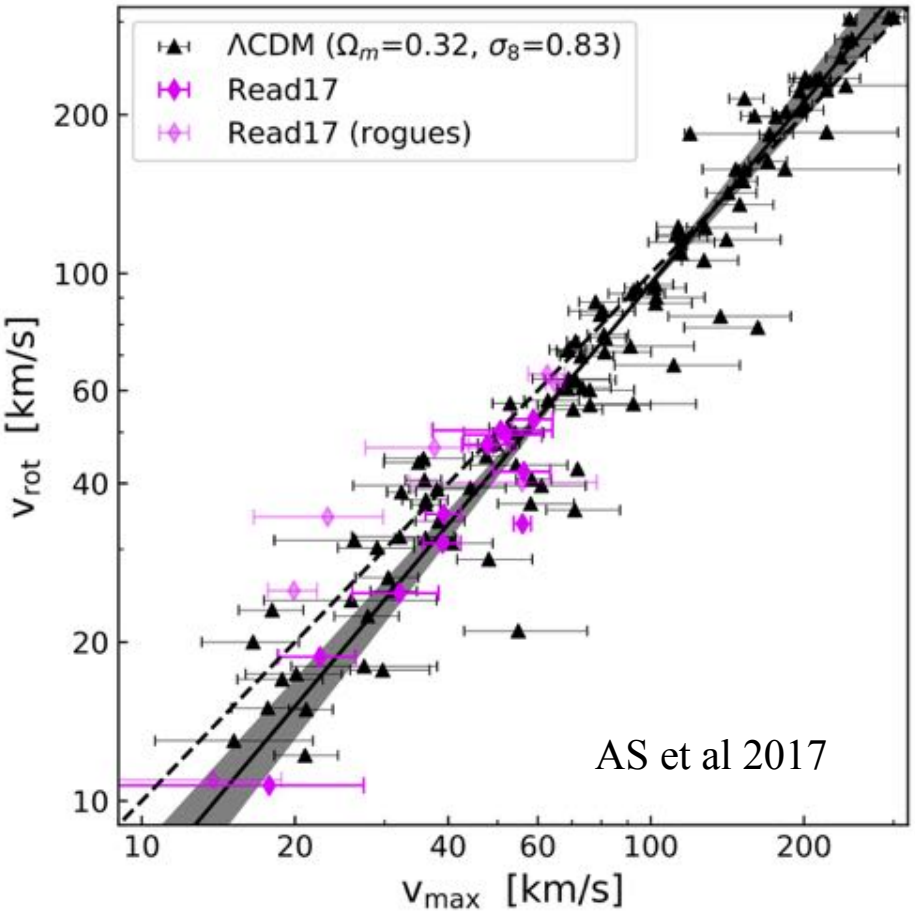
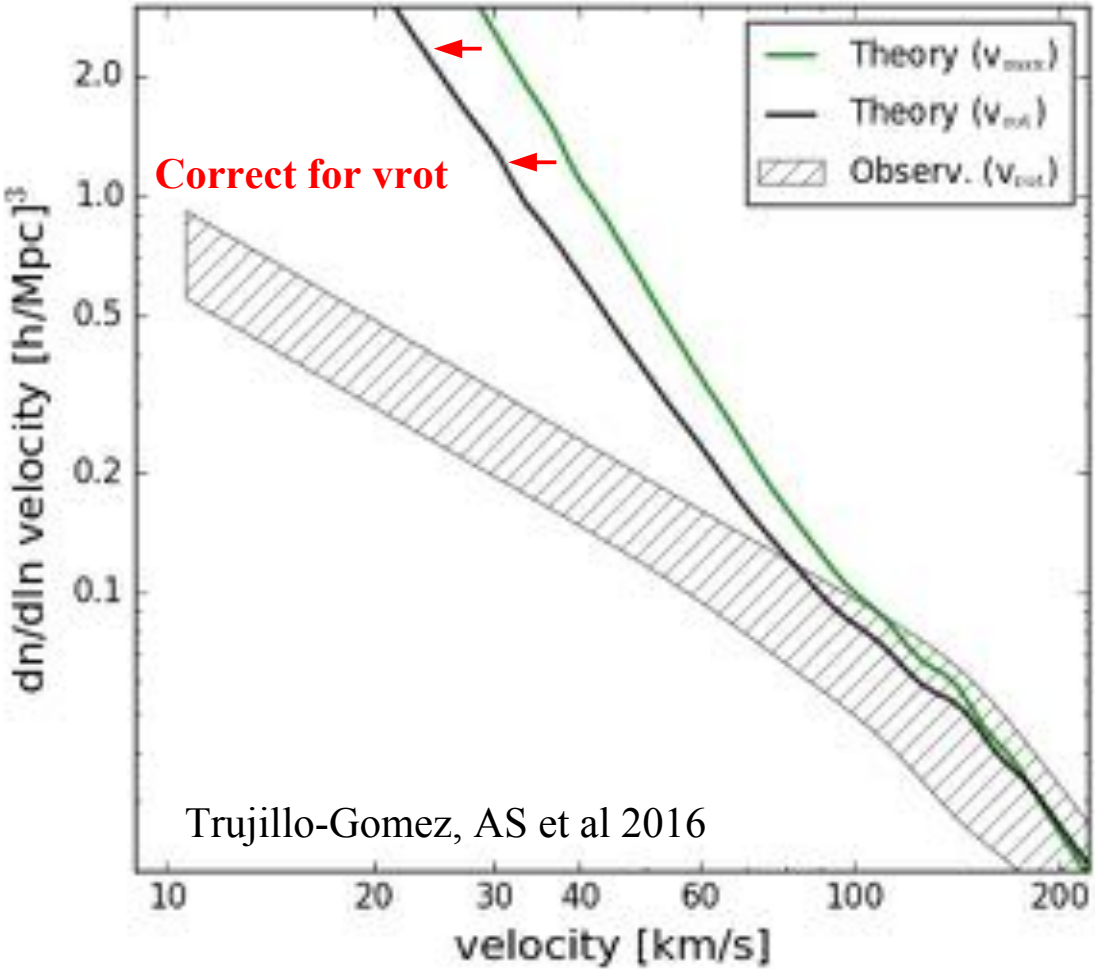
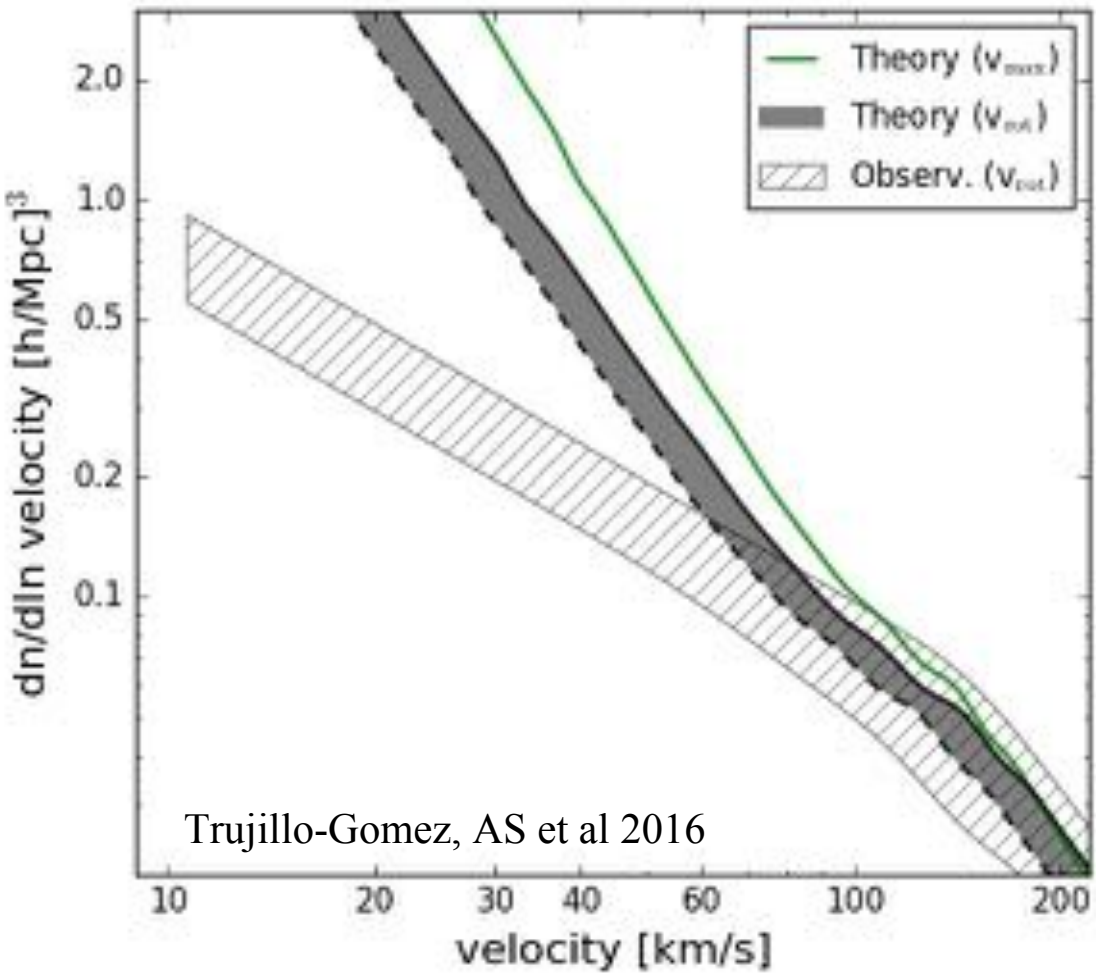




Velocity function of small galaxies

Include baryon effects:

- Maximum baryon depletion

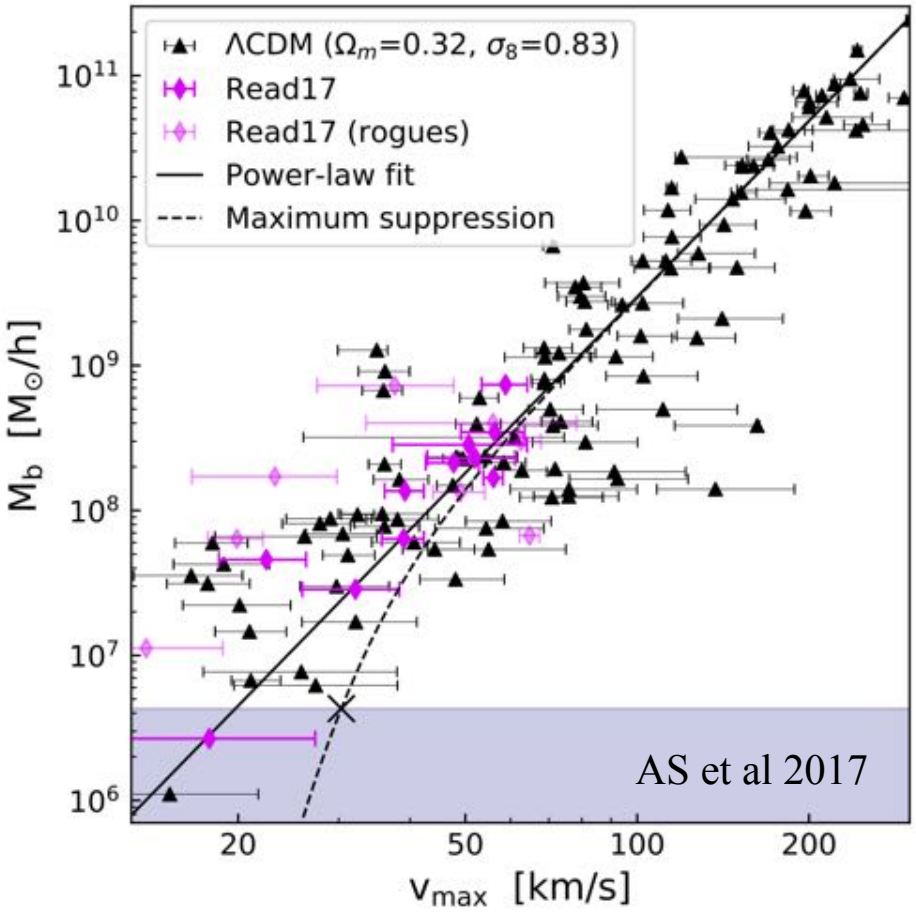


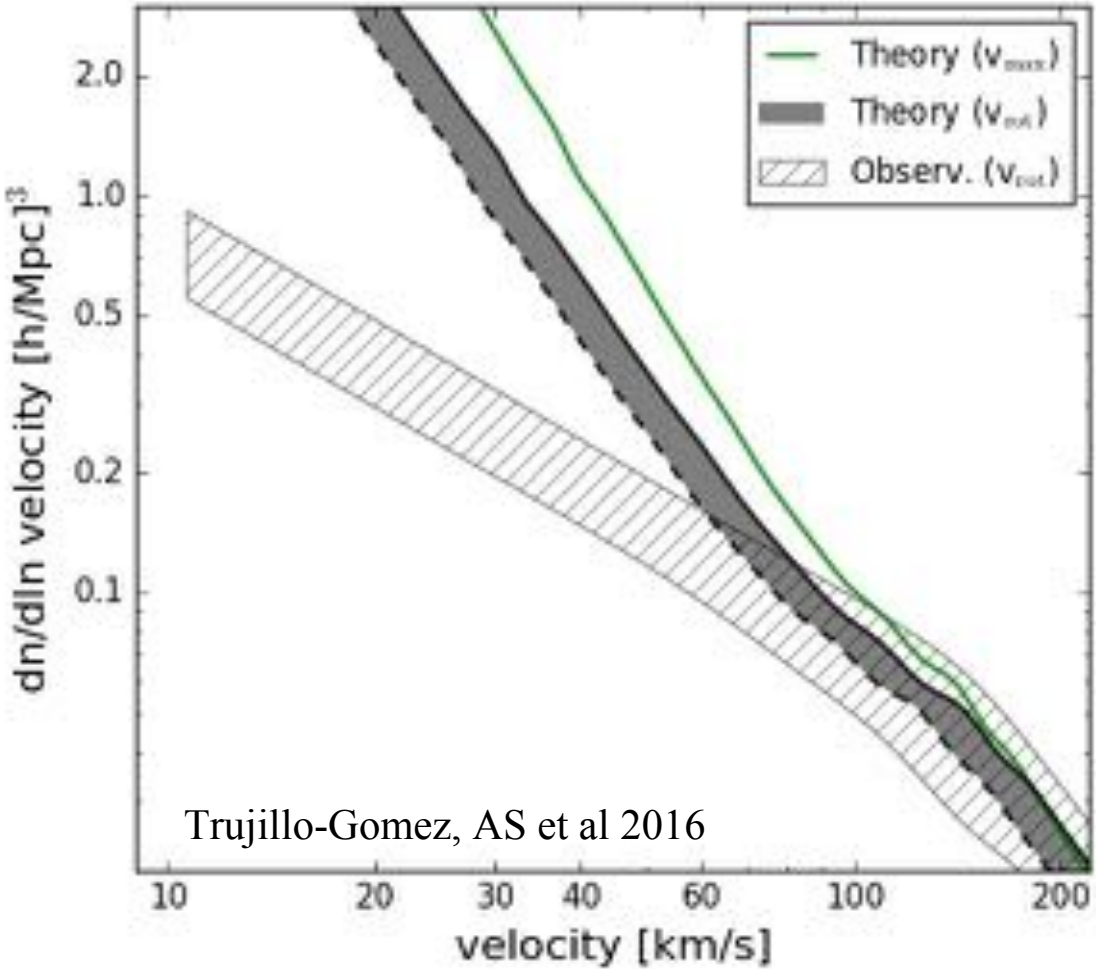
Trujillo-Gomez, AS et al 2016

Velocity function of small galaxies

Include baryon effects:

- Maximum baryon depletion
- Maximum baryon suppression





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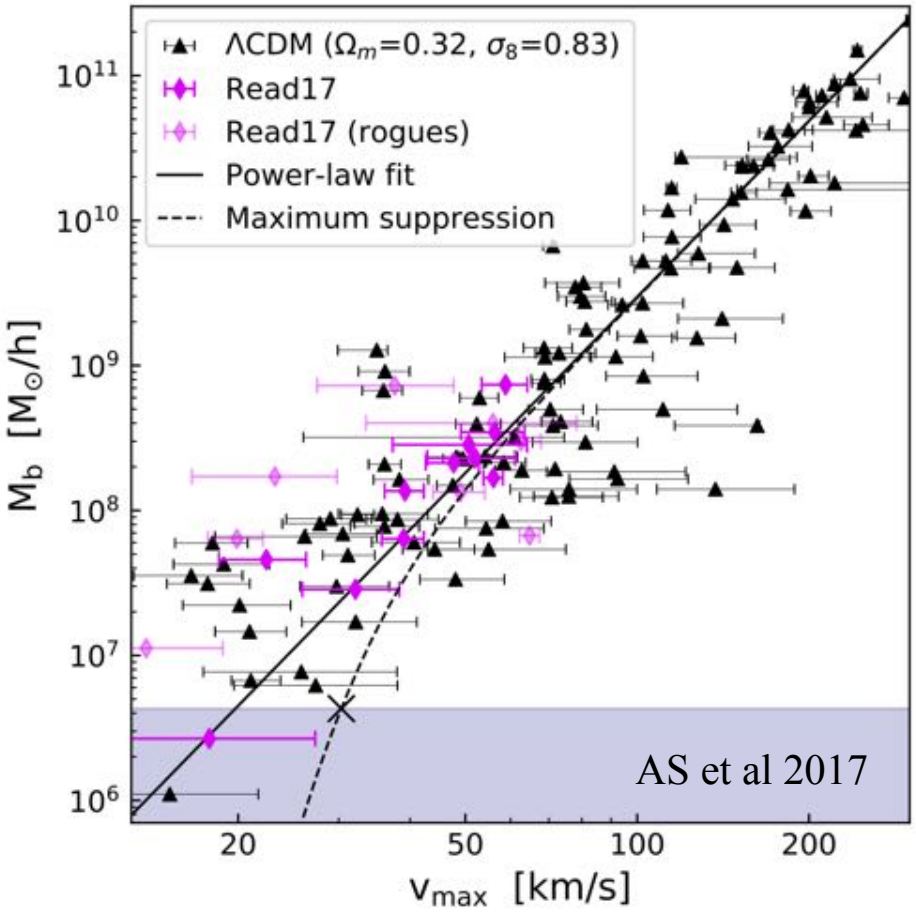

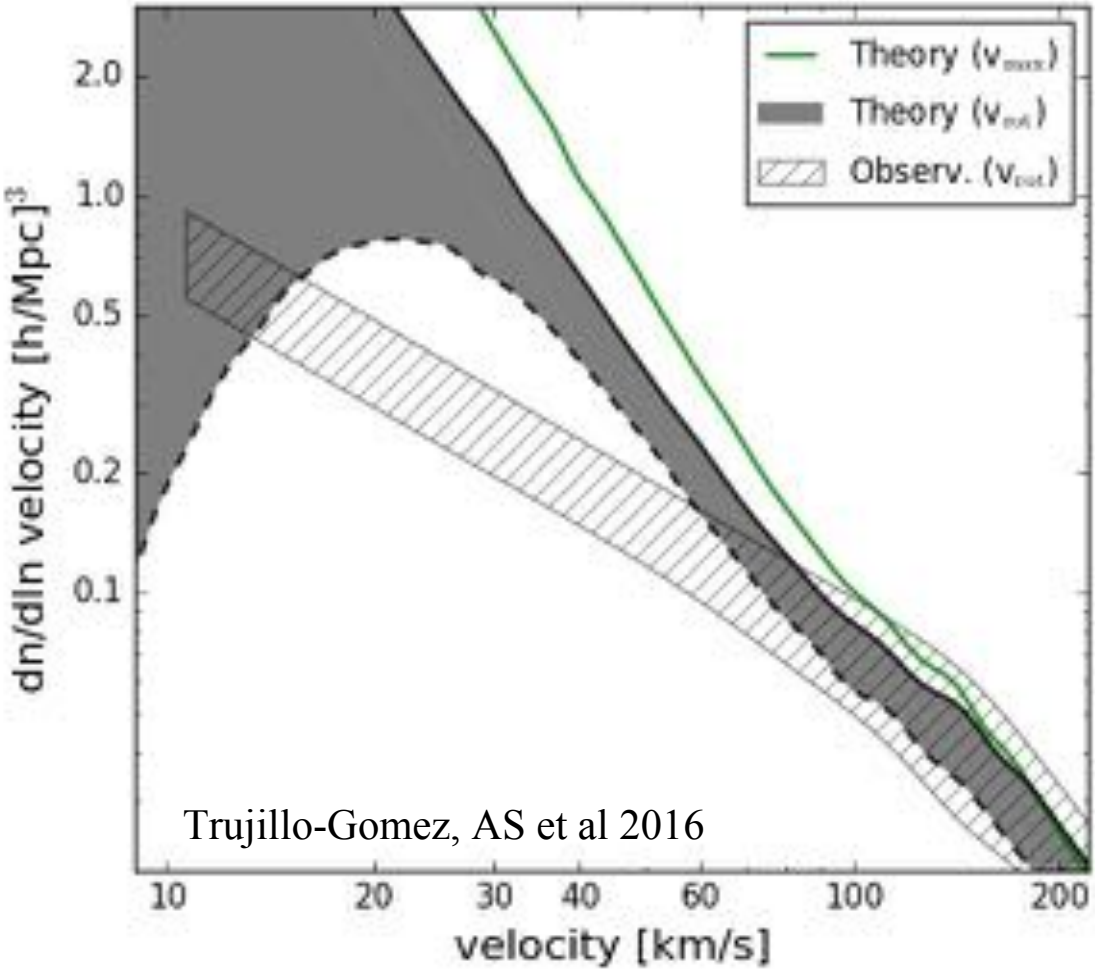

Velocity function – Solution with hydro sims ?

Recent hydro sims (**Maccio2016**, **Brooks2017**) find no tension ...

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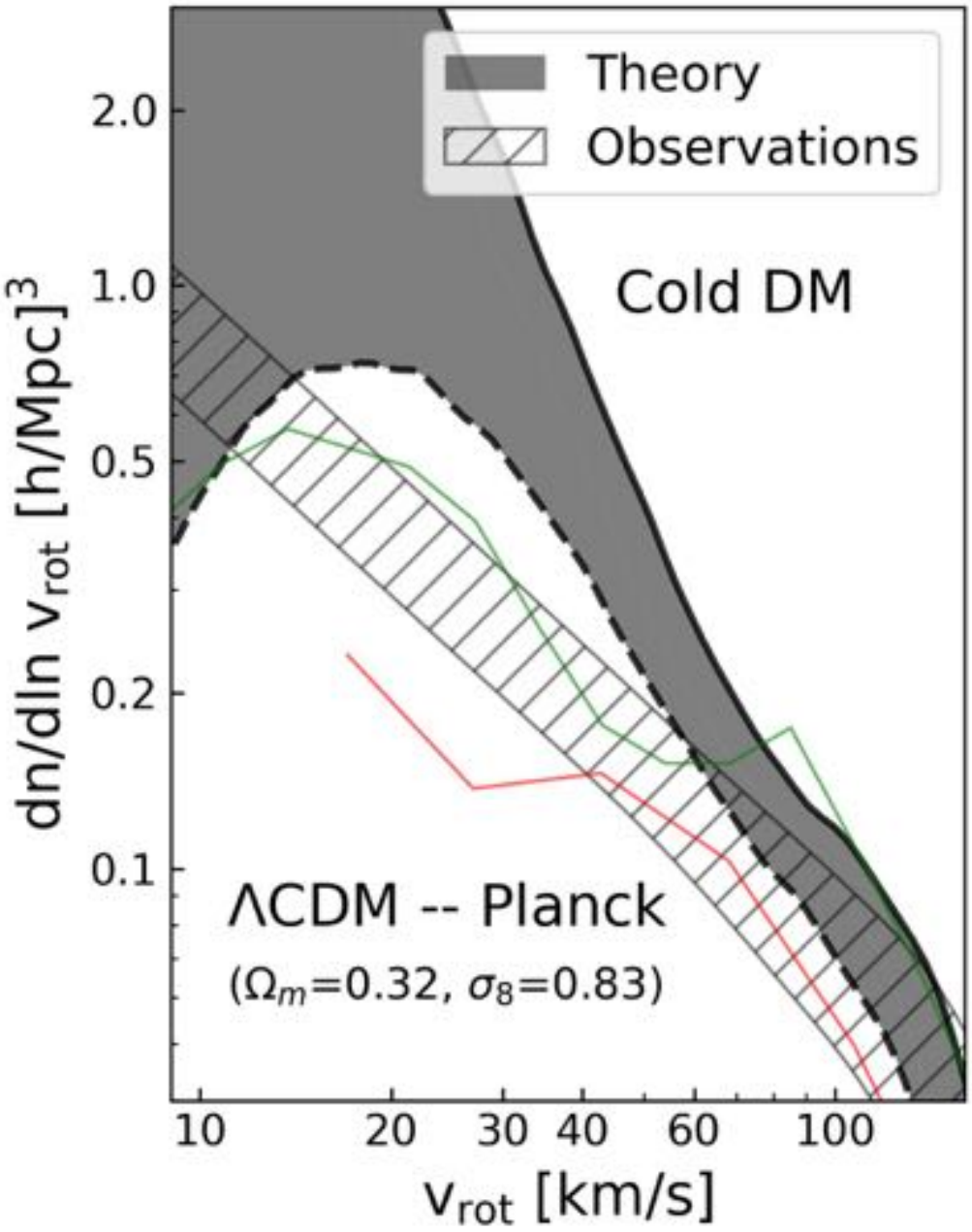
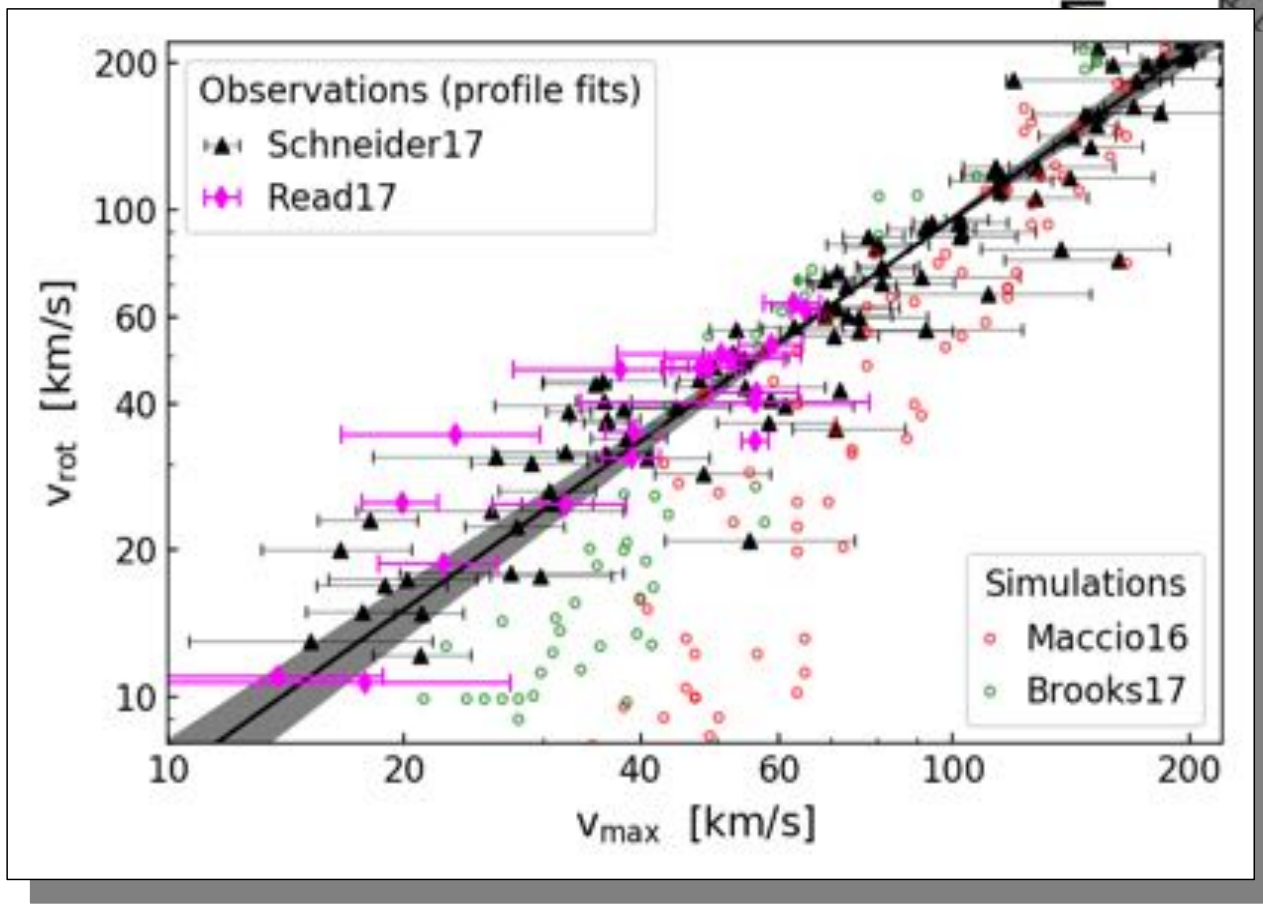
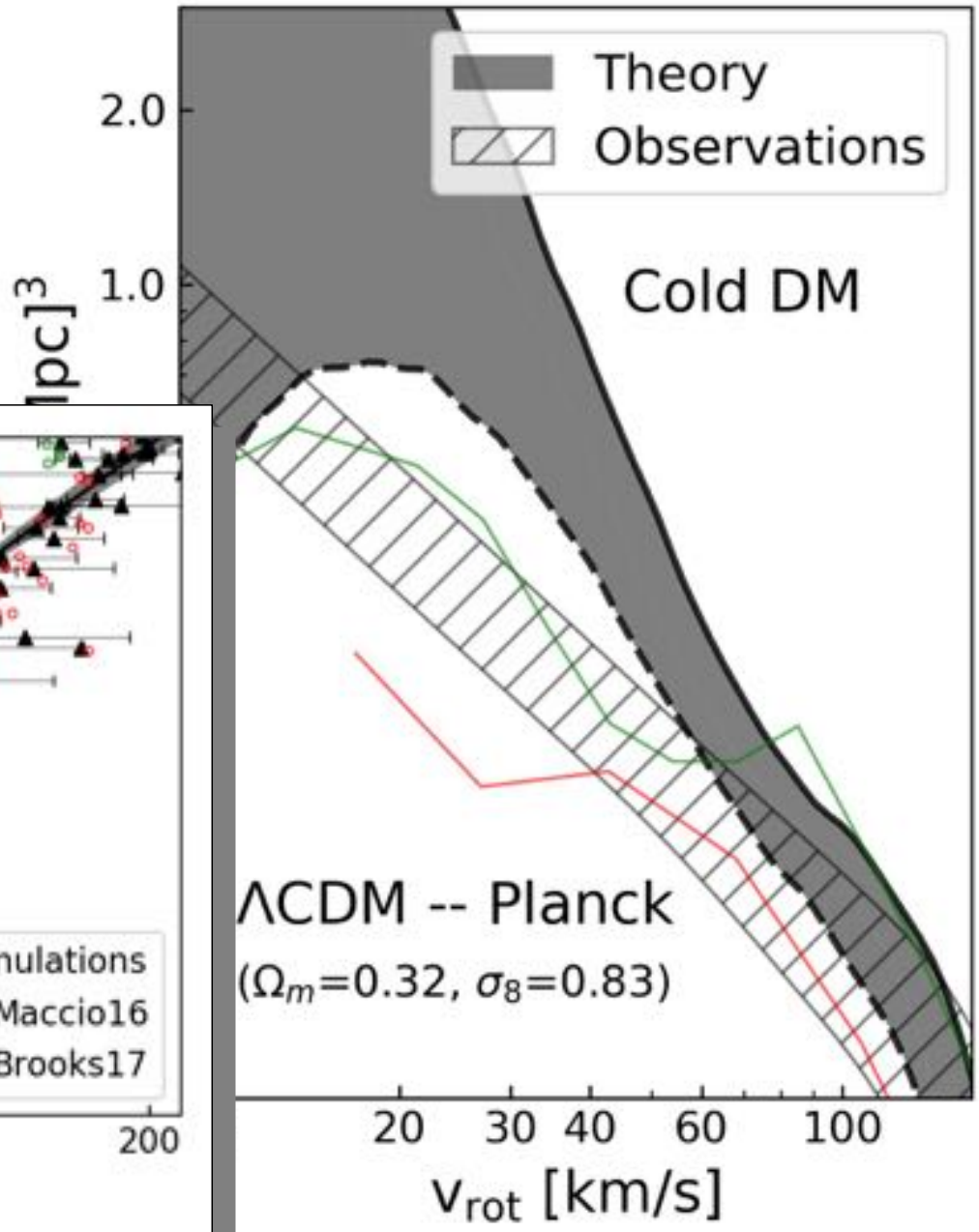


Velocity function – Solution with hydro sims ?

Recent hydro sims (**Maccio2016**, **Brooks2017**) find no tension …

… but at the prize of disagreeing with vmax-estimates from observed dwarfs





Velocity function – How to resolve the tension ?

Cosmology ?

Dark Matter ?

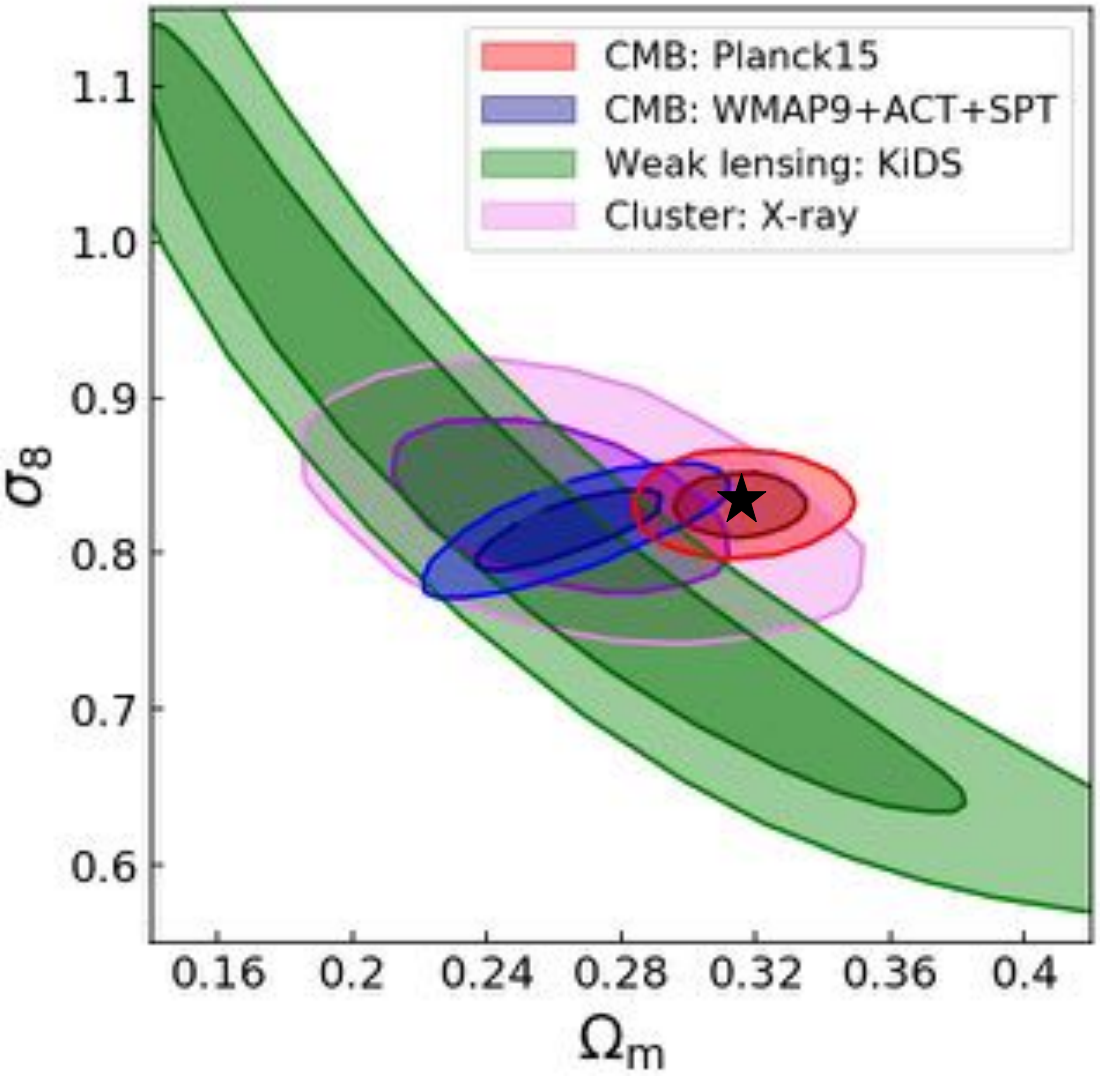
Systematics ?

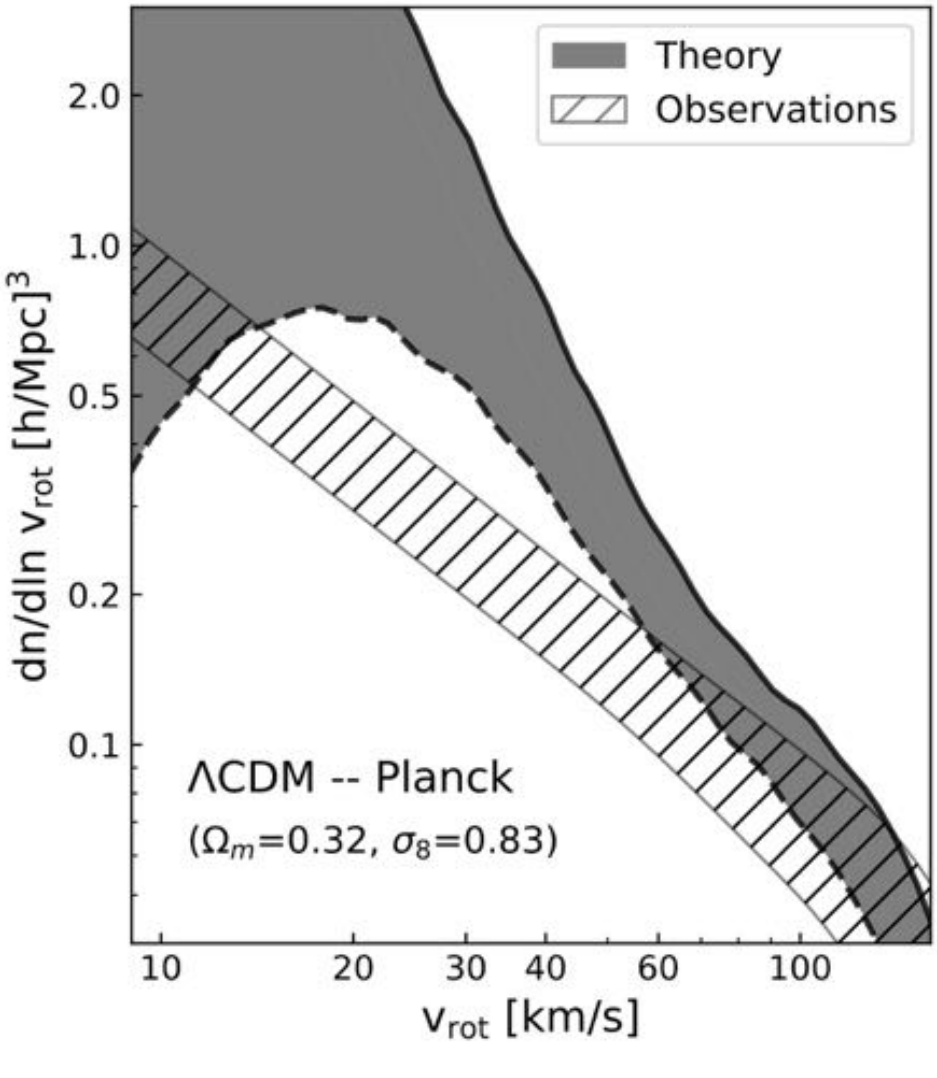
Velocity function – How to resolve the tension ?

Cosmology ? Dark Matter ? Systematics ?

Velocity function – How to resolve the tension ?

Cosmology ? Dark Matter ? Systematics ?





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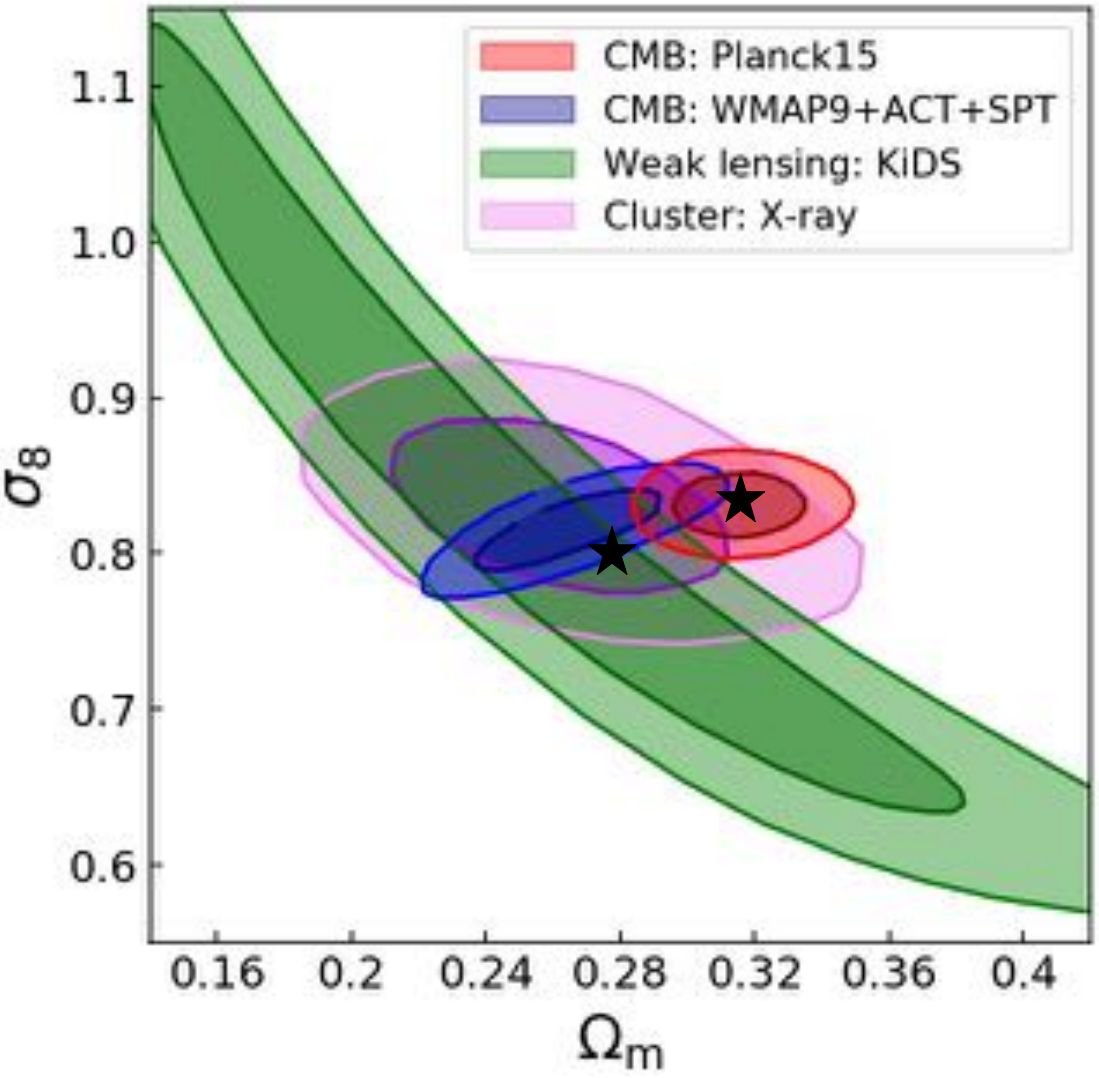
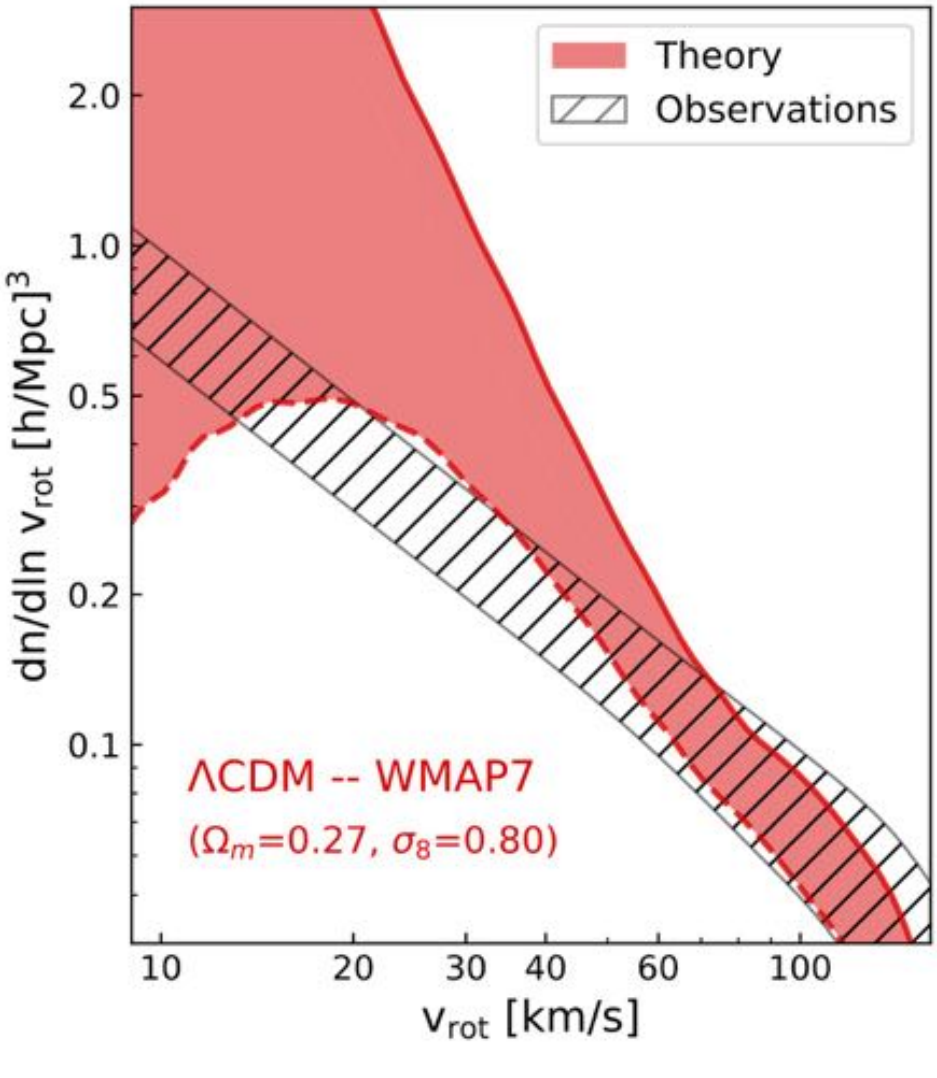
Cosmology ? Dark Matter ? Systematics ?





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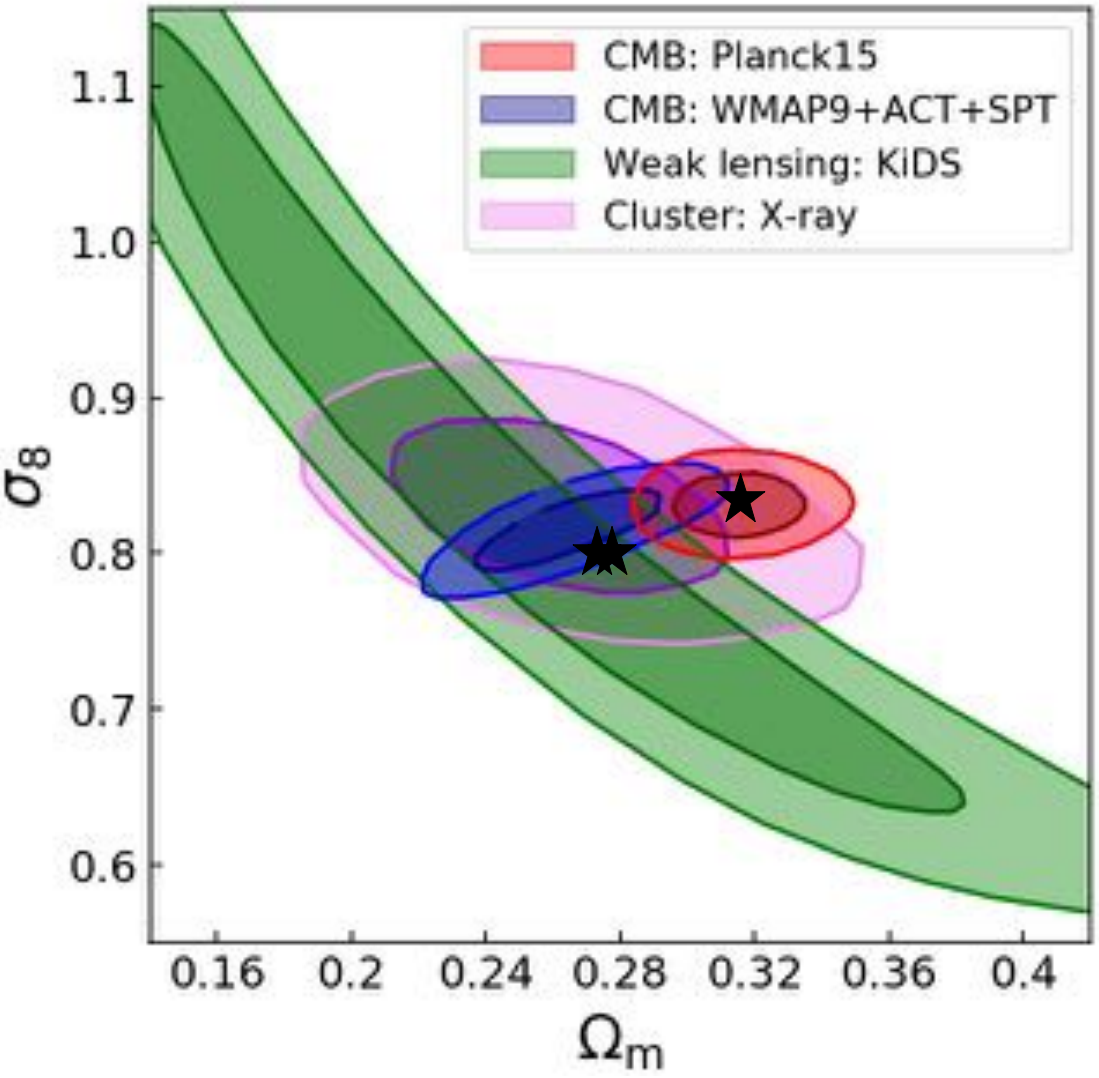

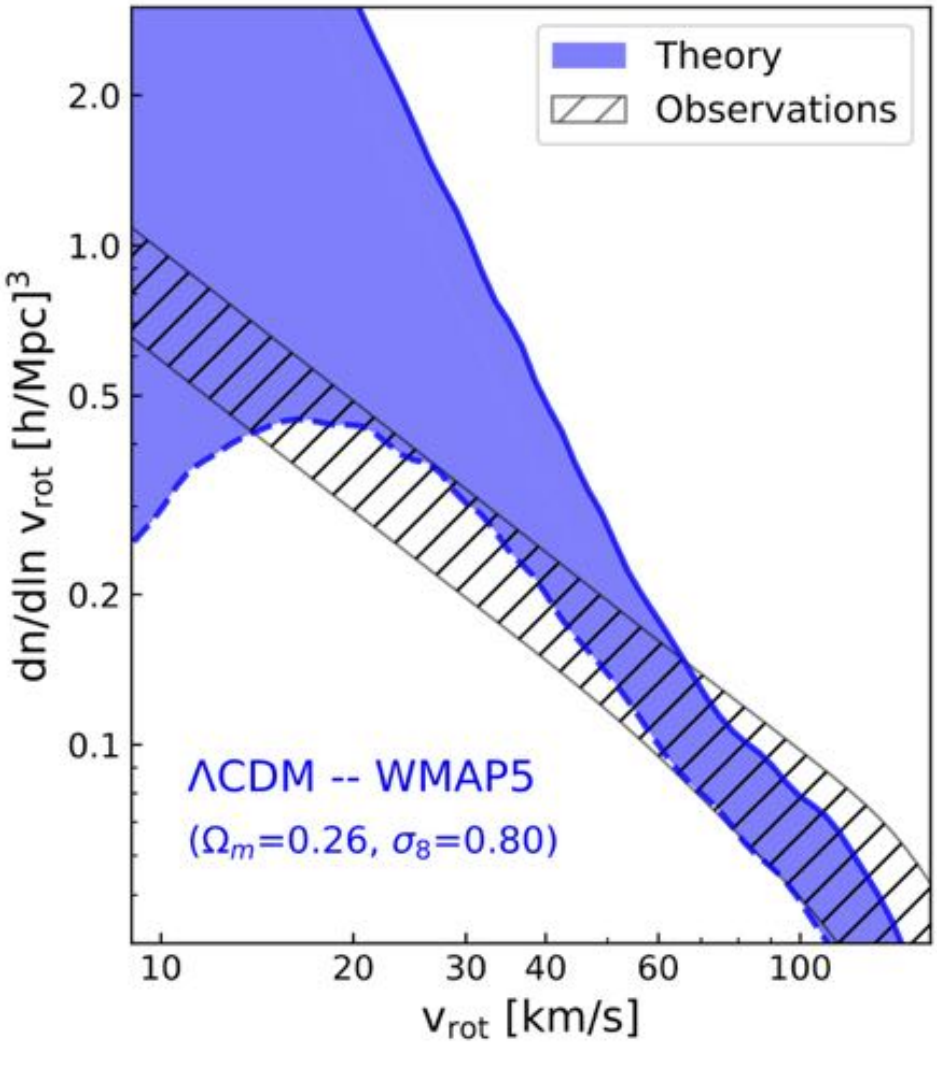

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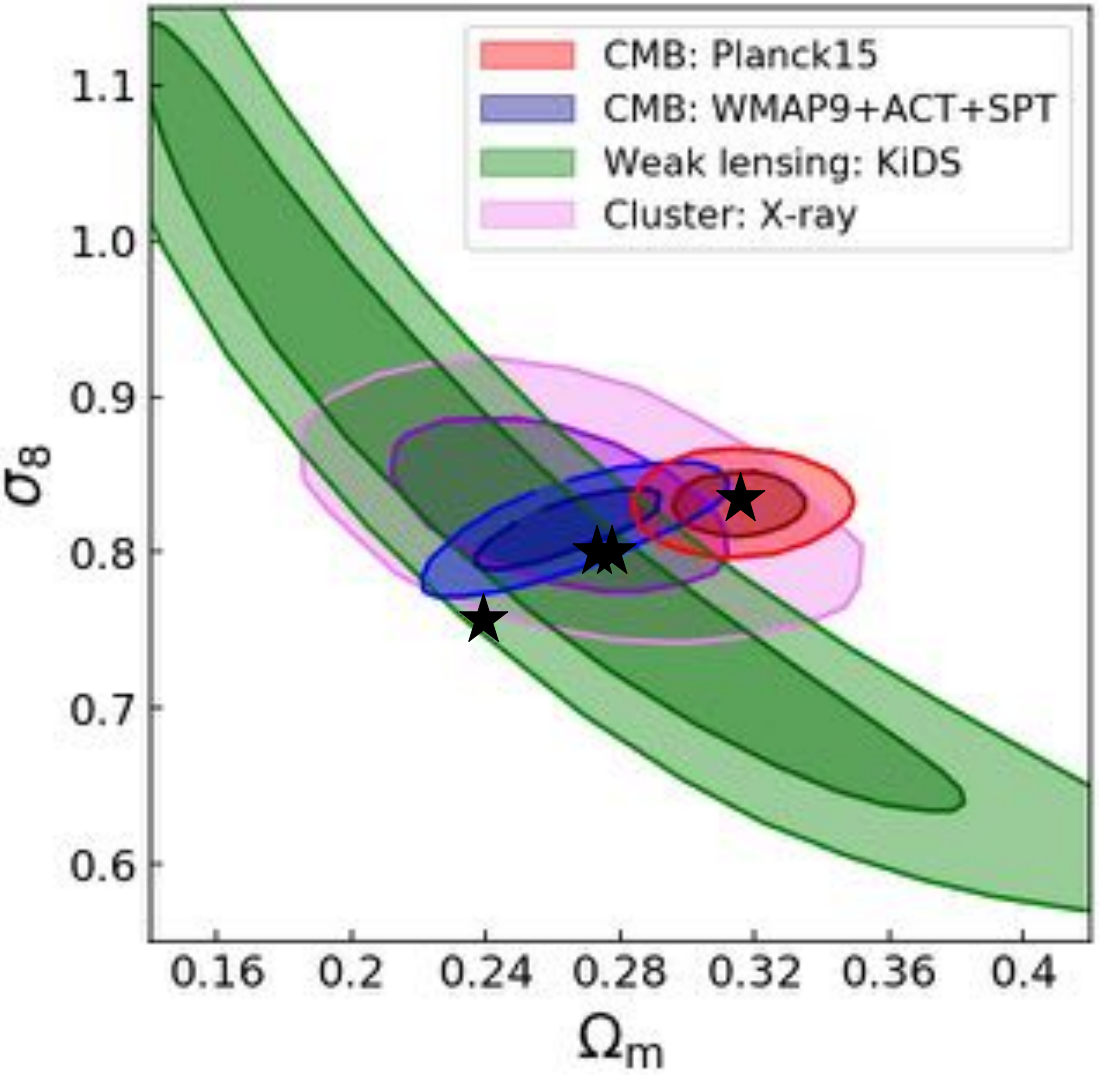

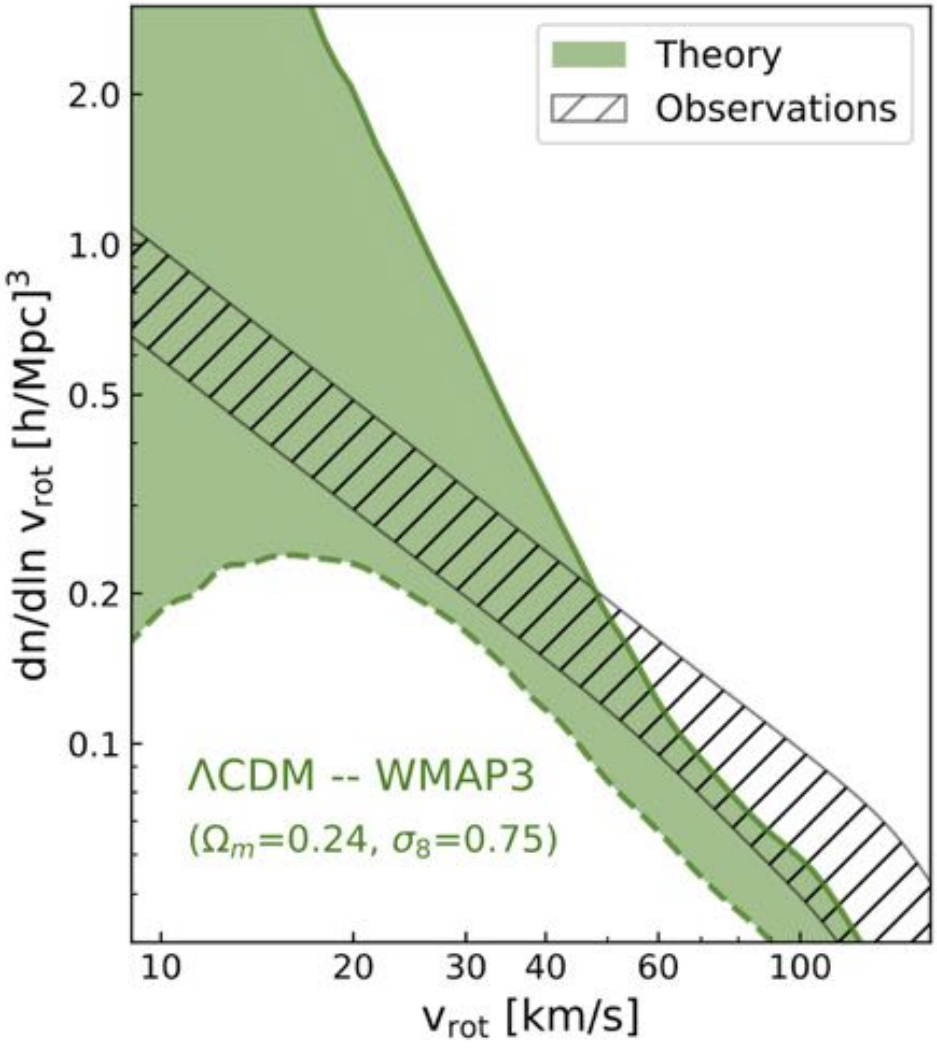

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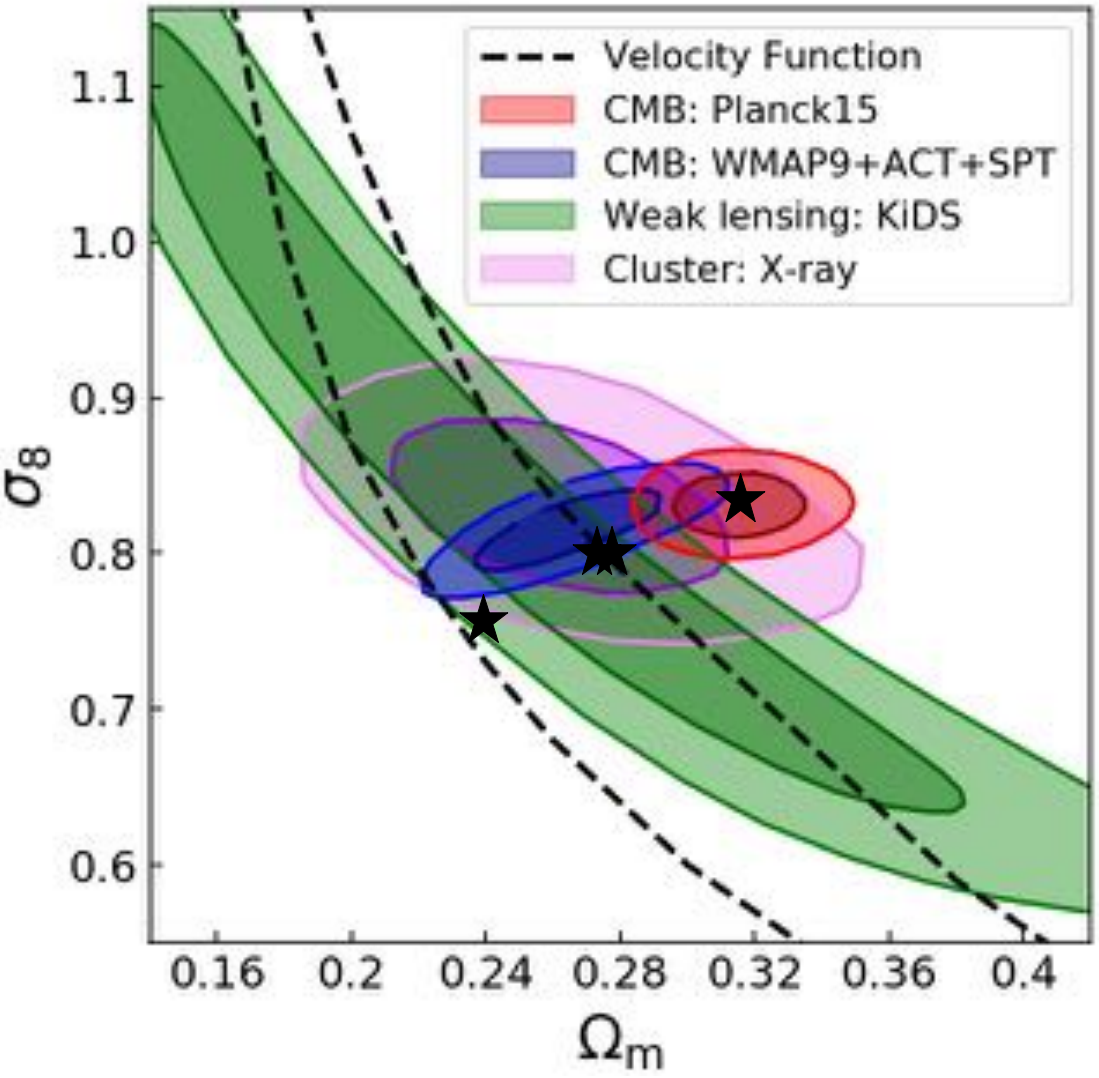

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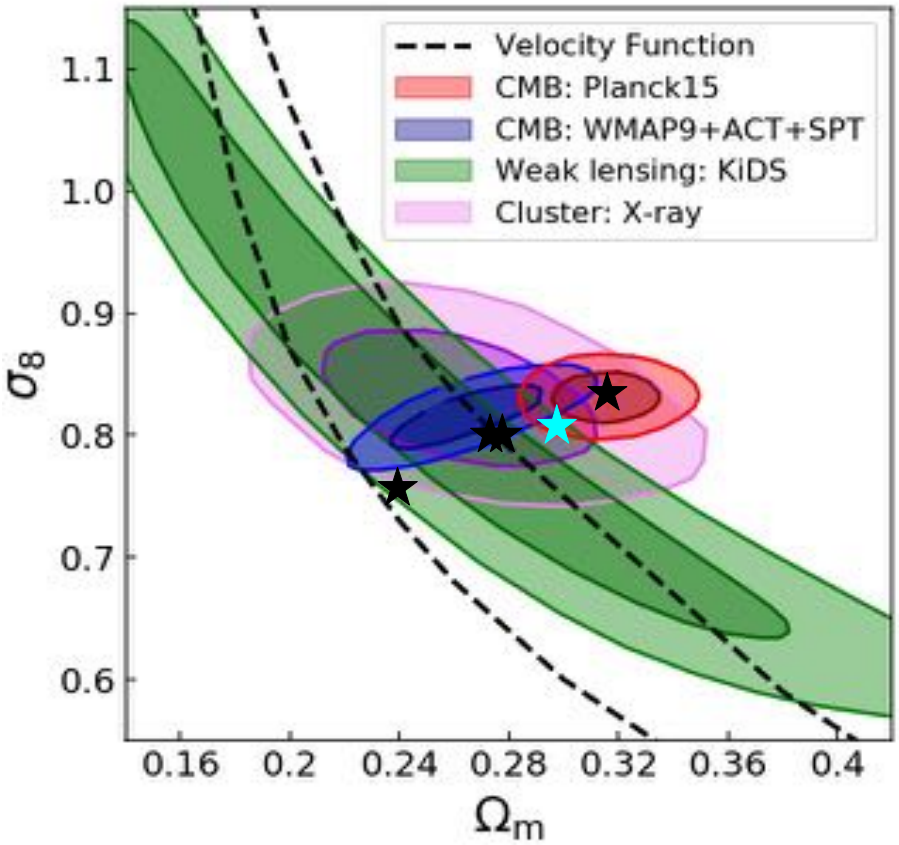
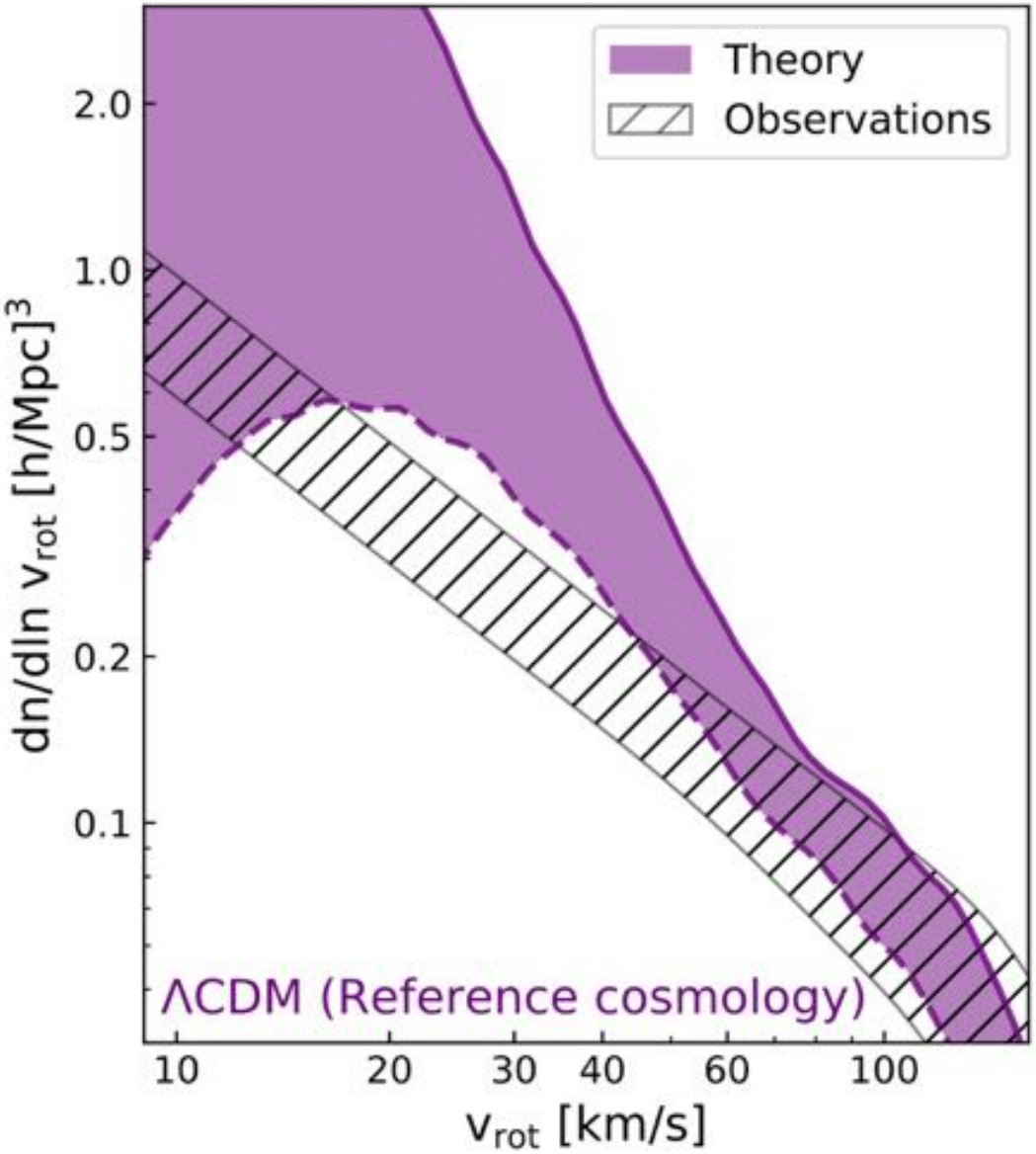


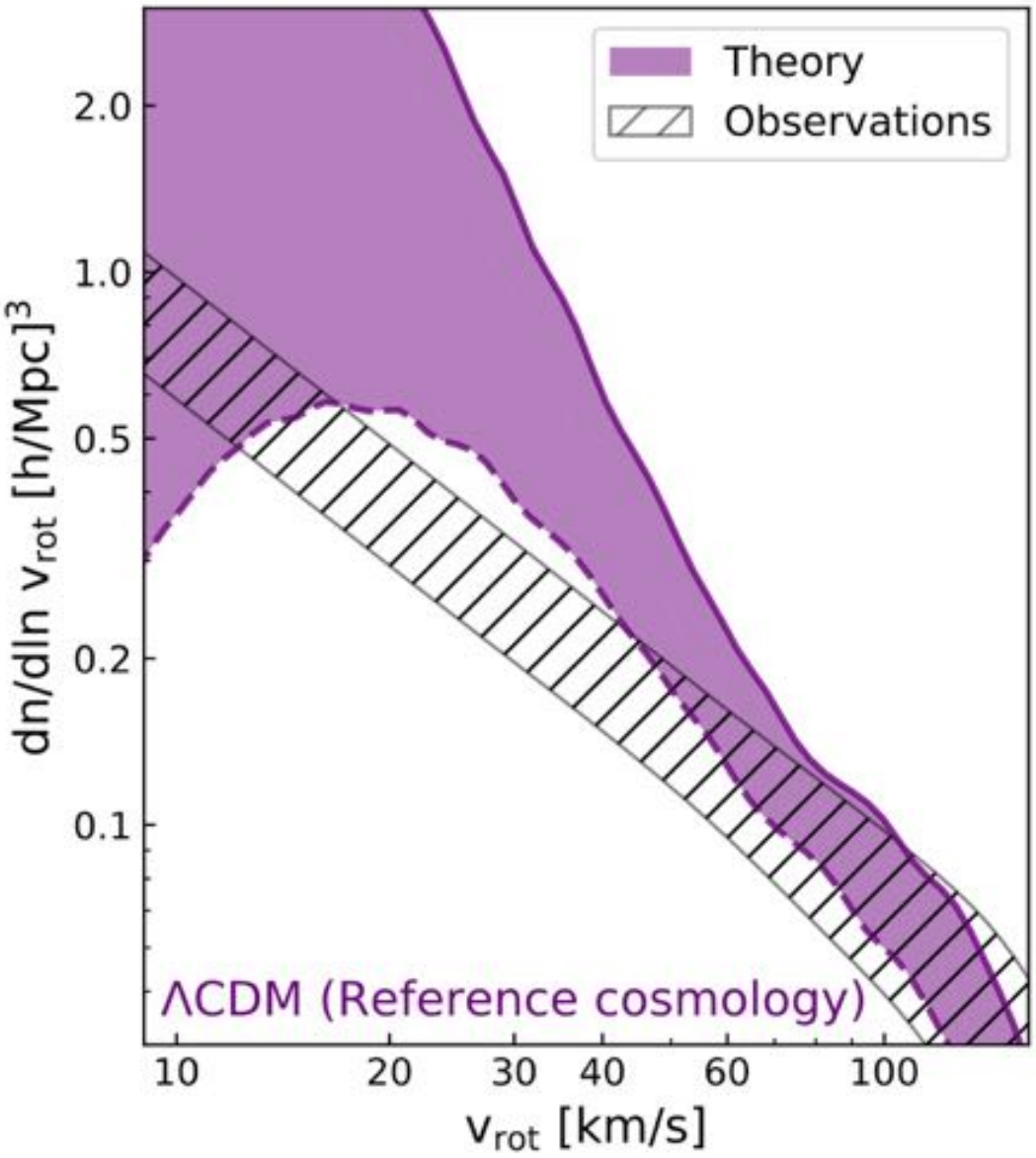


Velocity function – How to resolve the tension ?

Cosmology ? **Dark Matter ?** Systematics ?

… **heating up**

the dark matter sector



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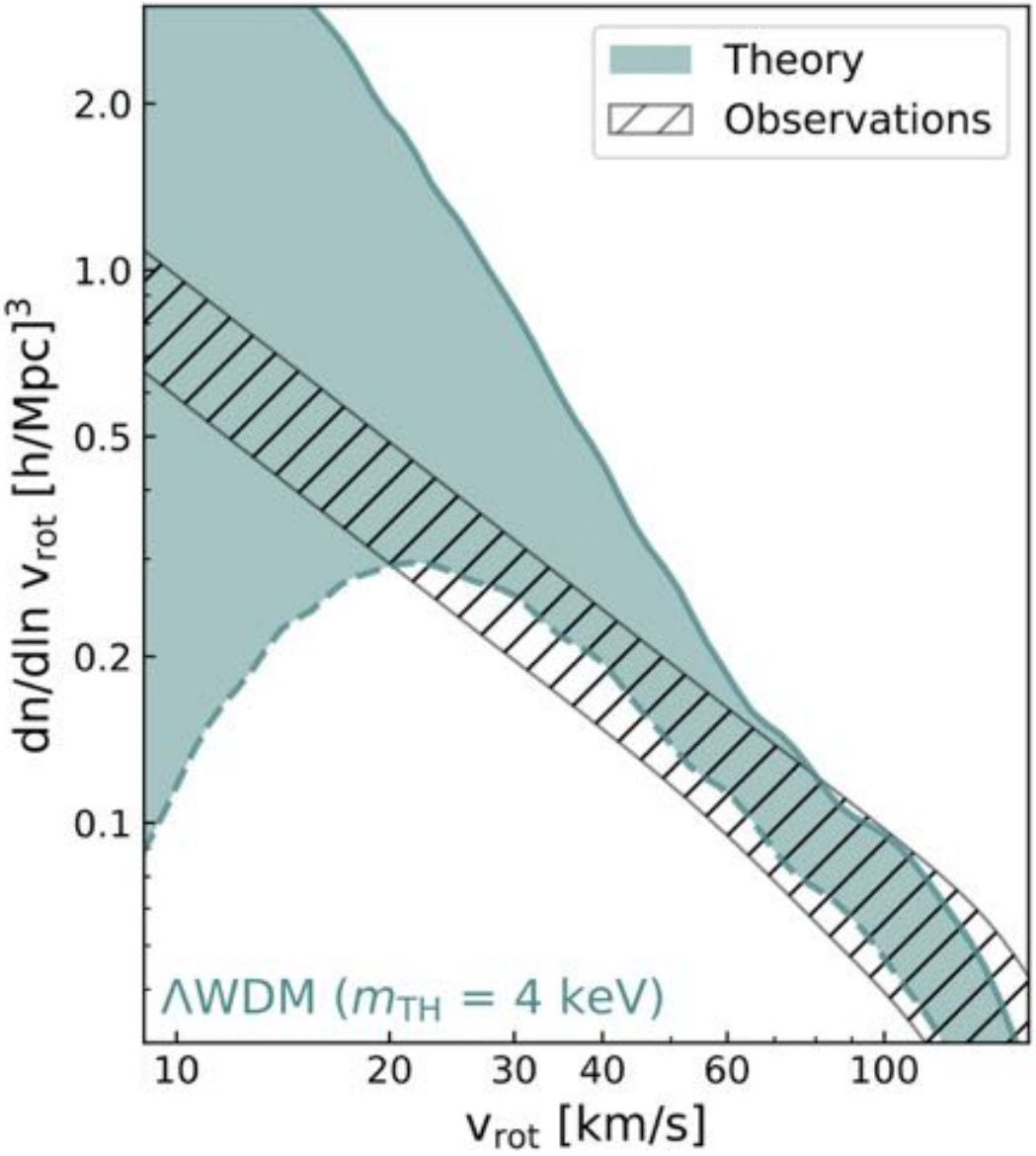

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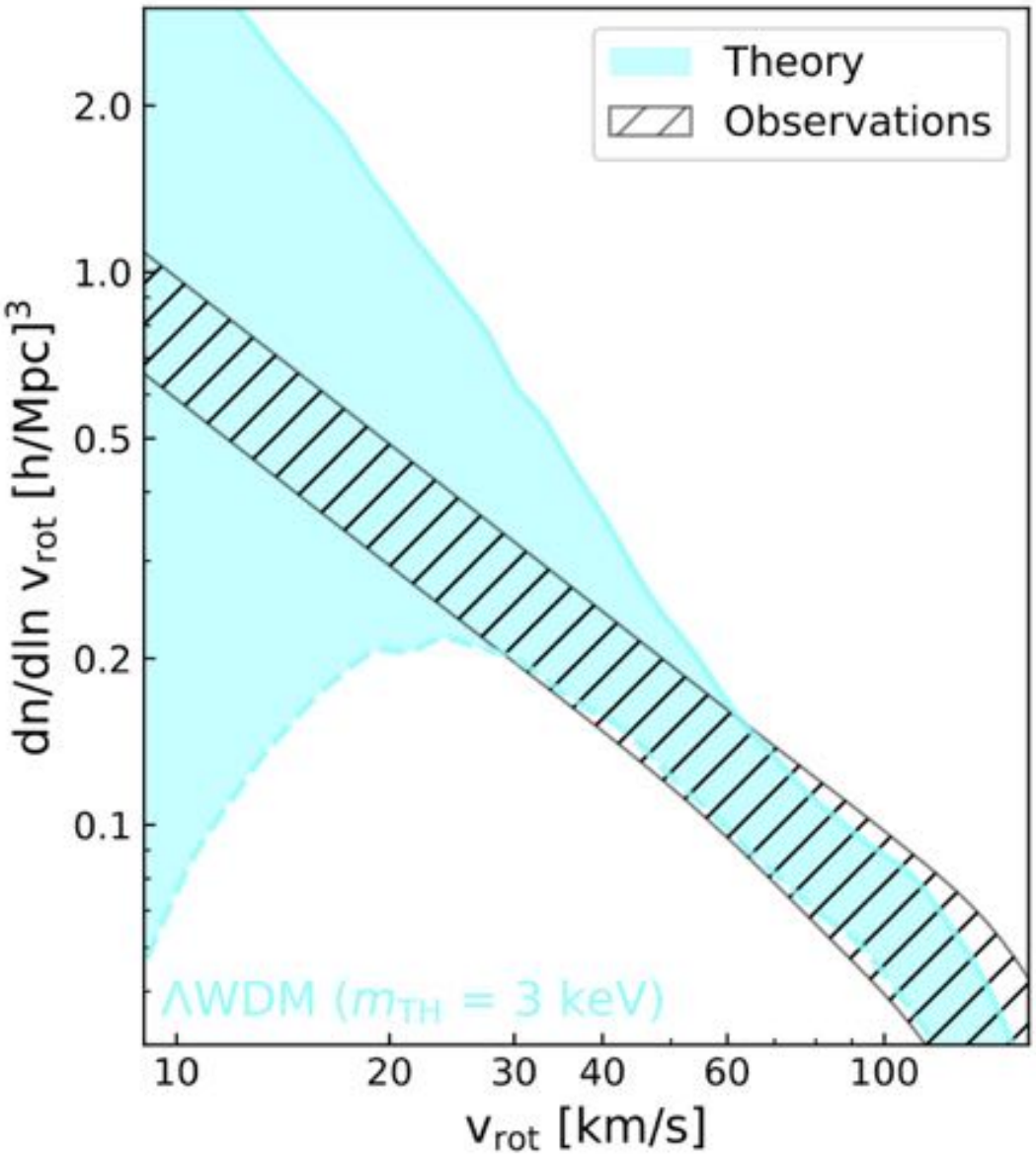

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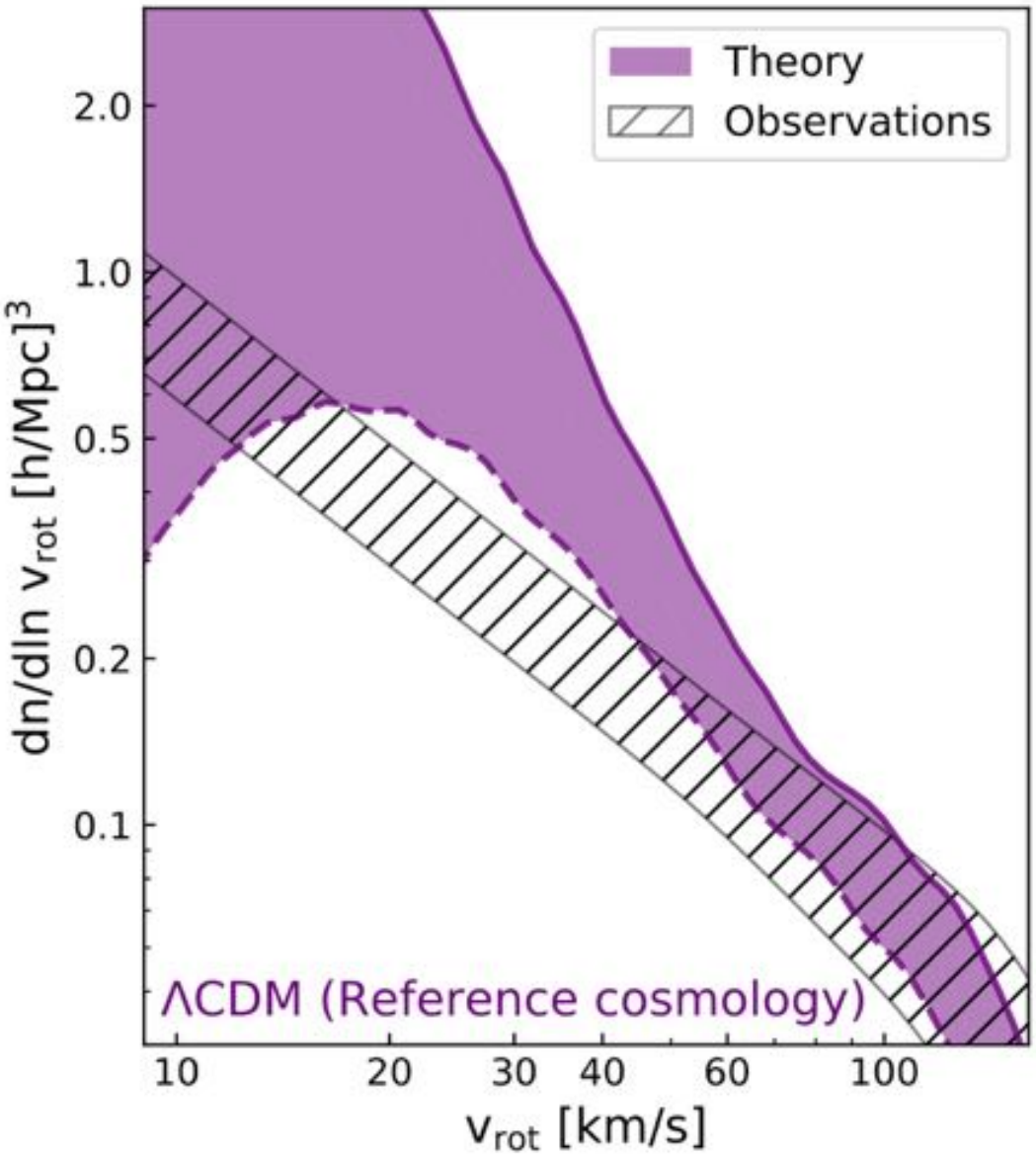

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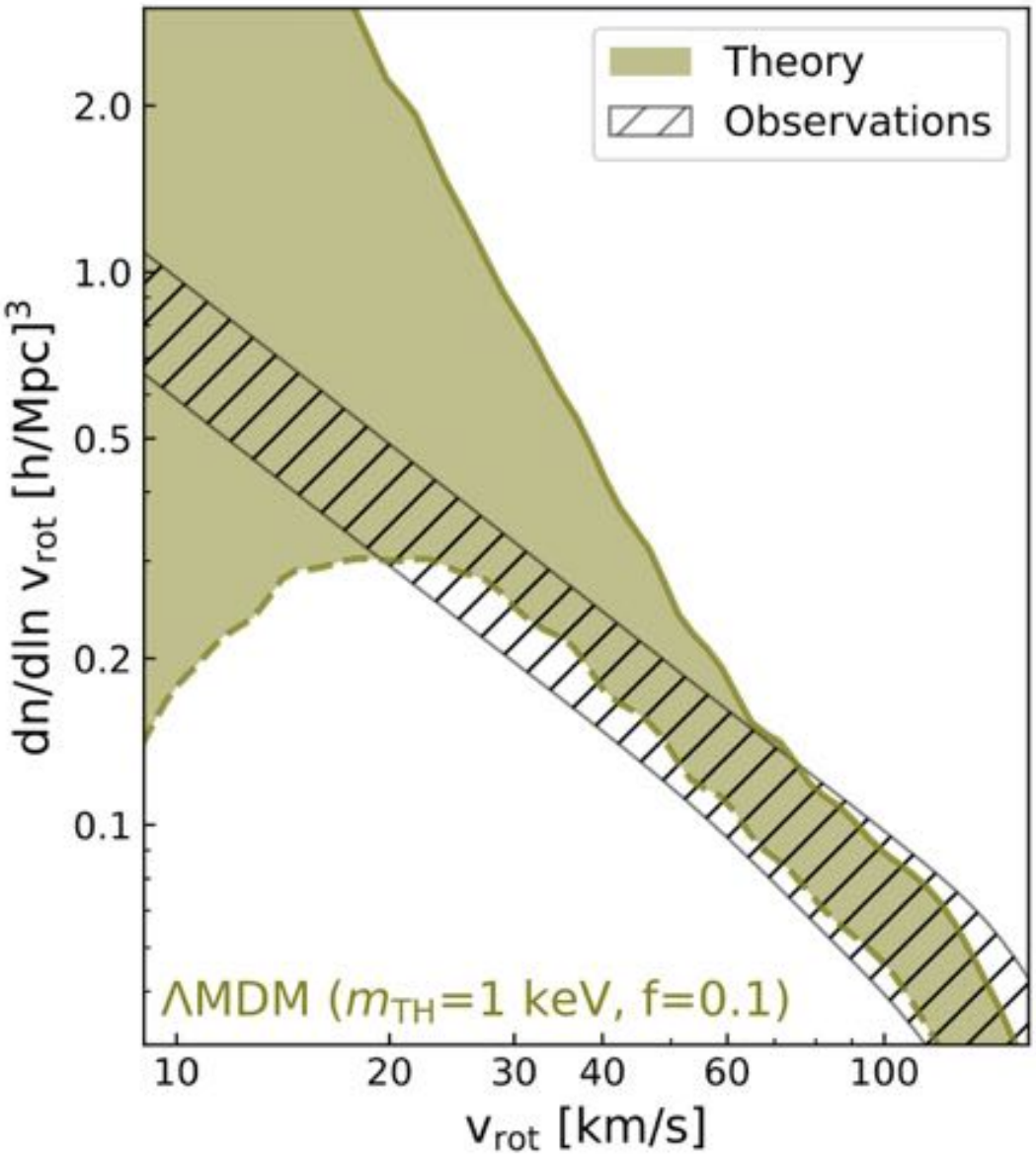

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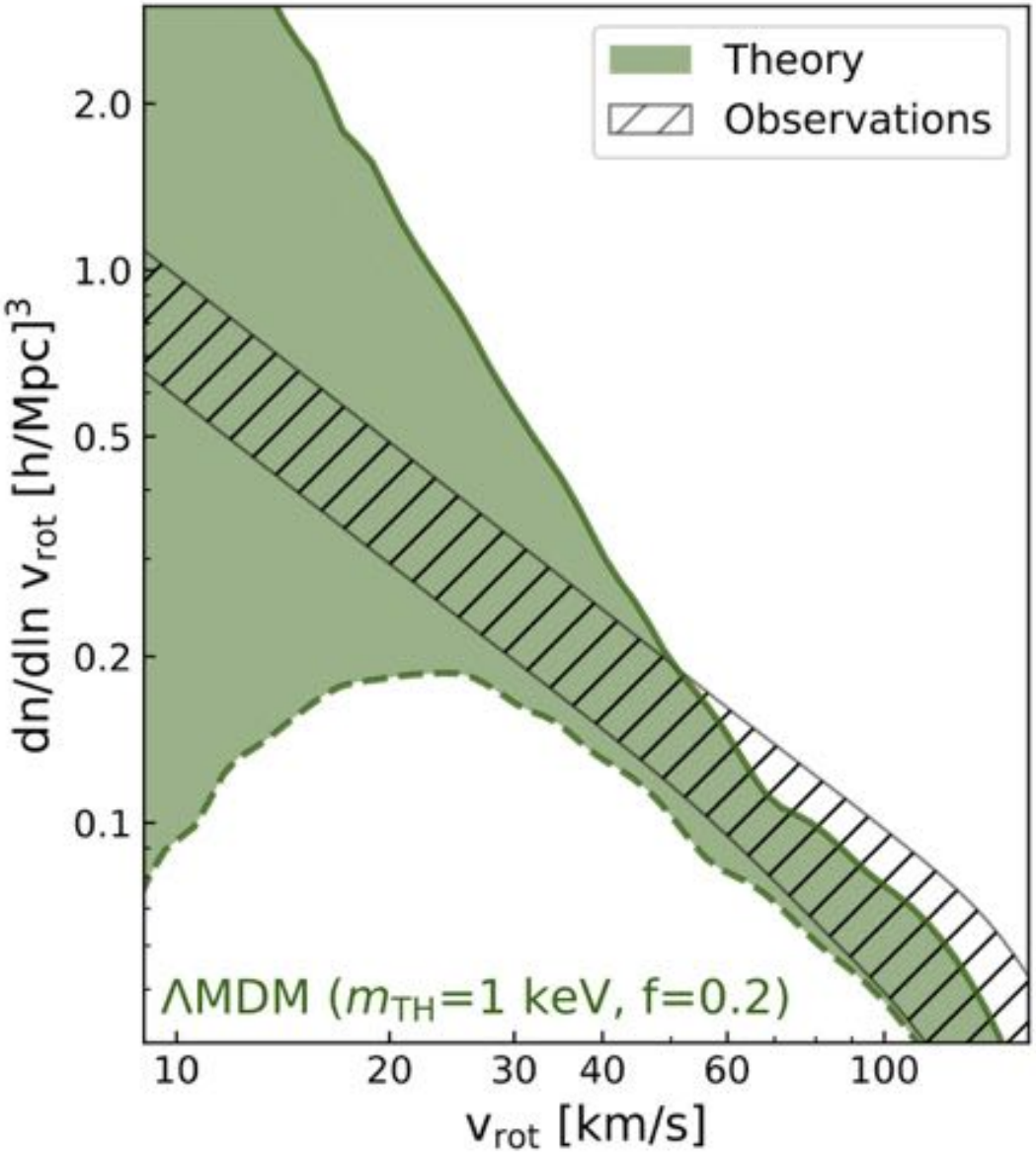

Velocity function – How to resolve the tension ?

Cosmology ? **Dark Matter ?** Systematics ?

… **self-interacting**

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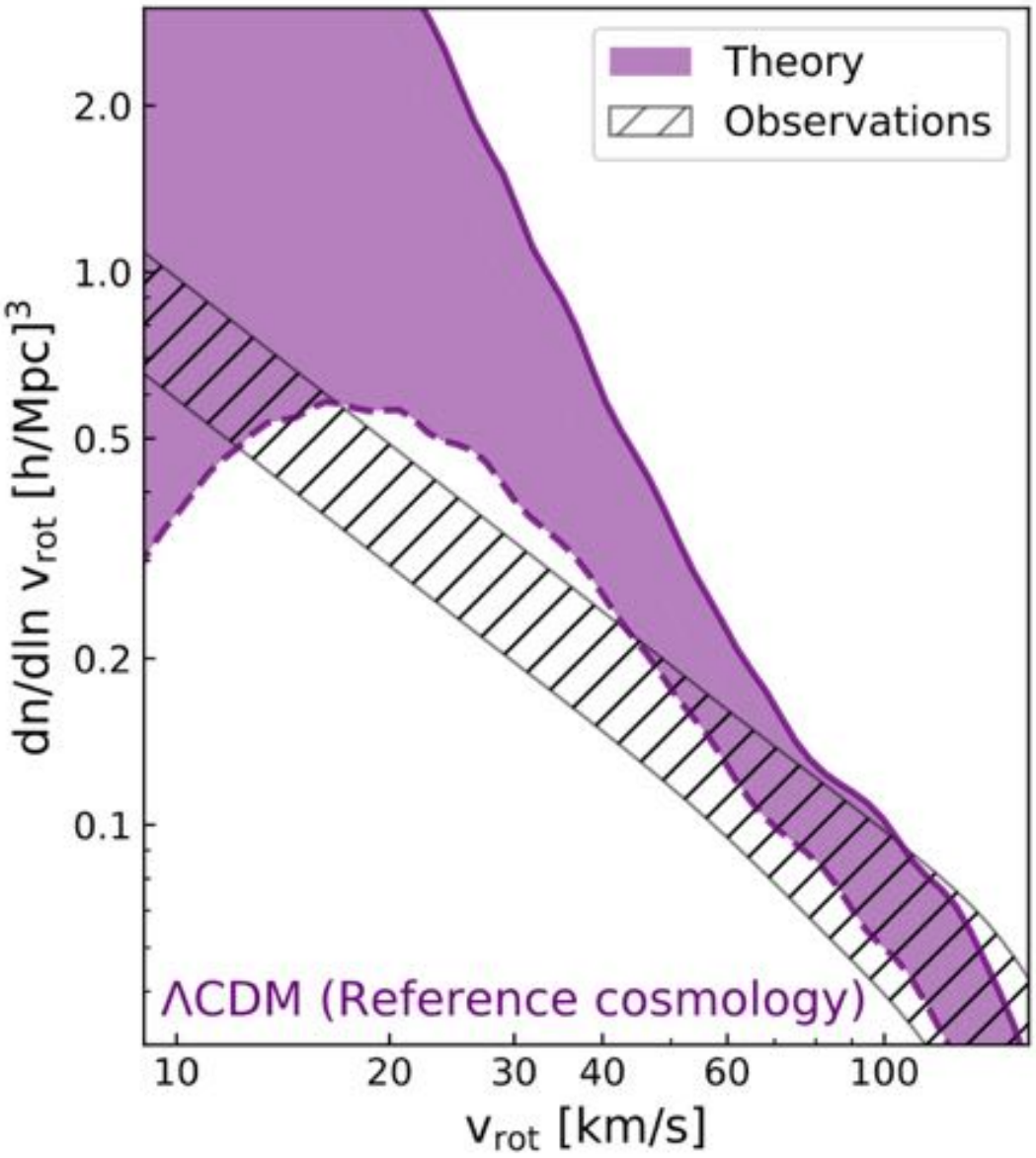

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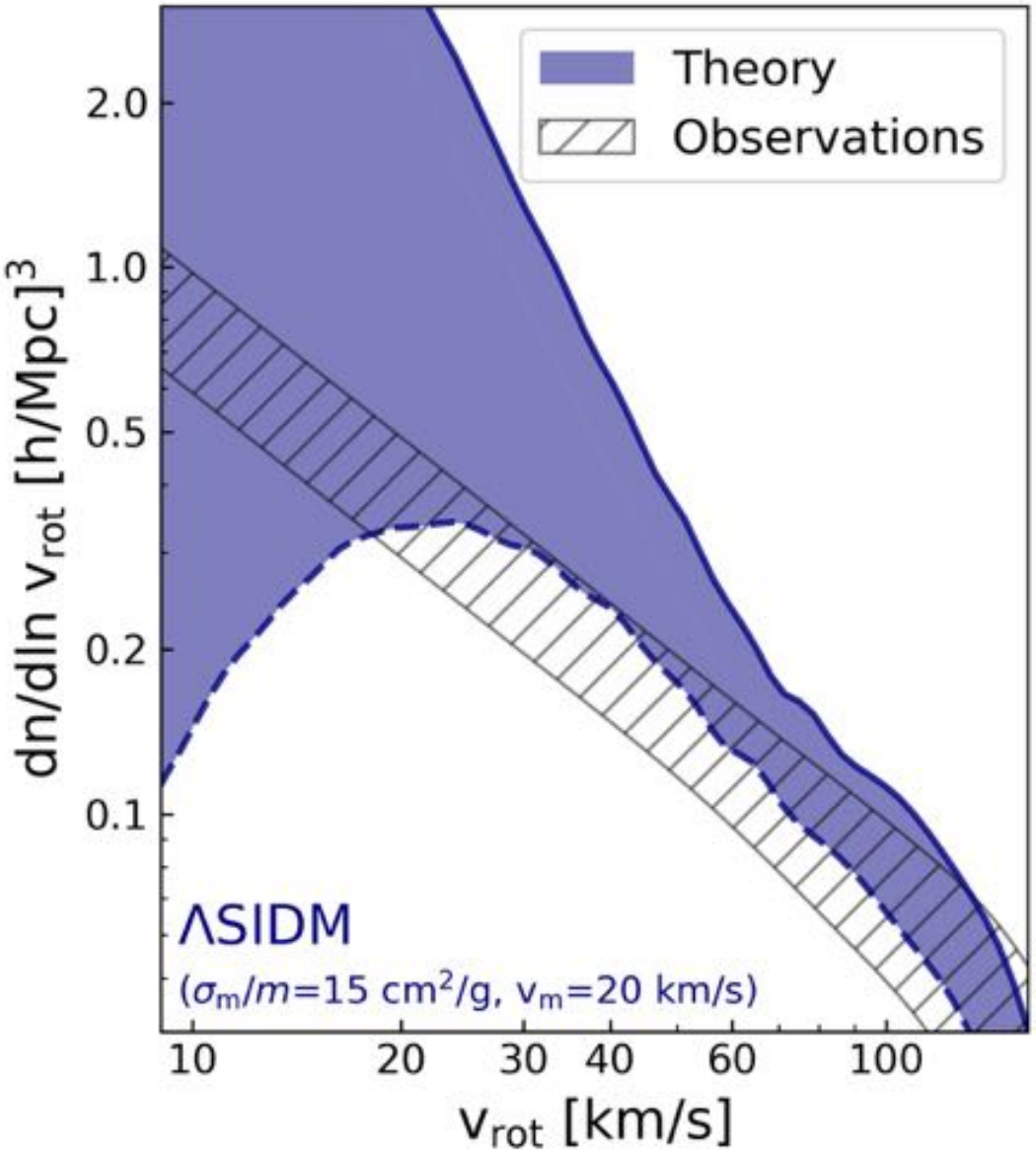

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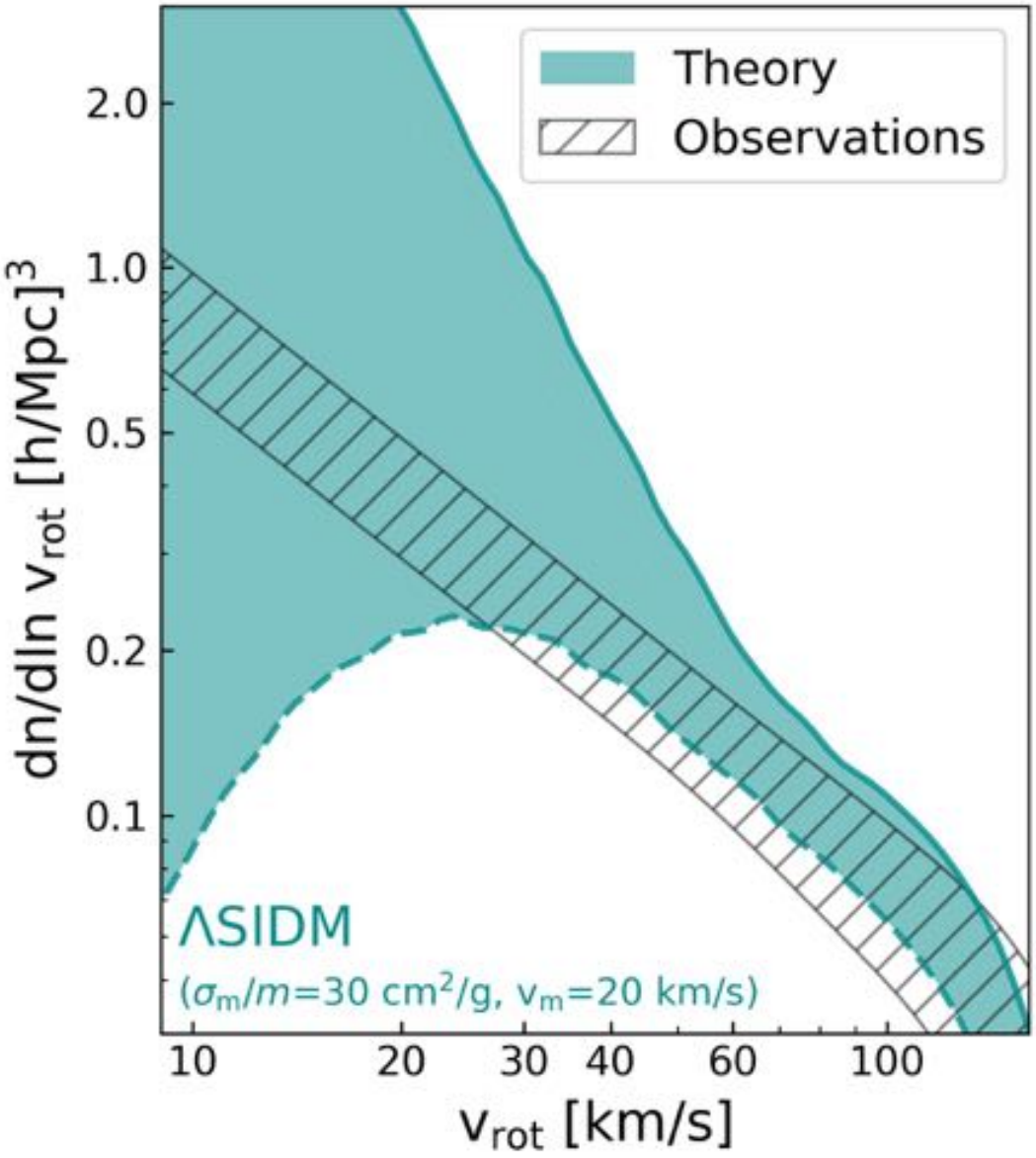

Velocity function – How to resolve the tension ?

Cosmology ? Dark Matter ? **Systematics ?**

… selection effects, inclination errors, non-spherical gas motions, asymmetric drift correction, …

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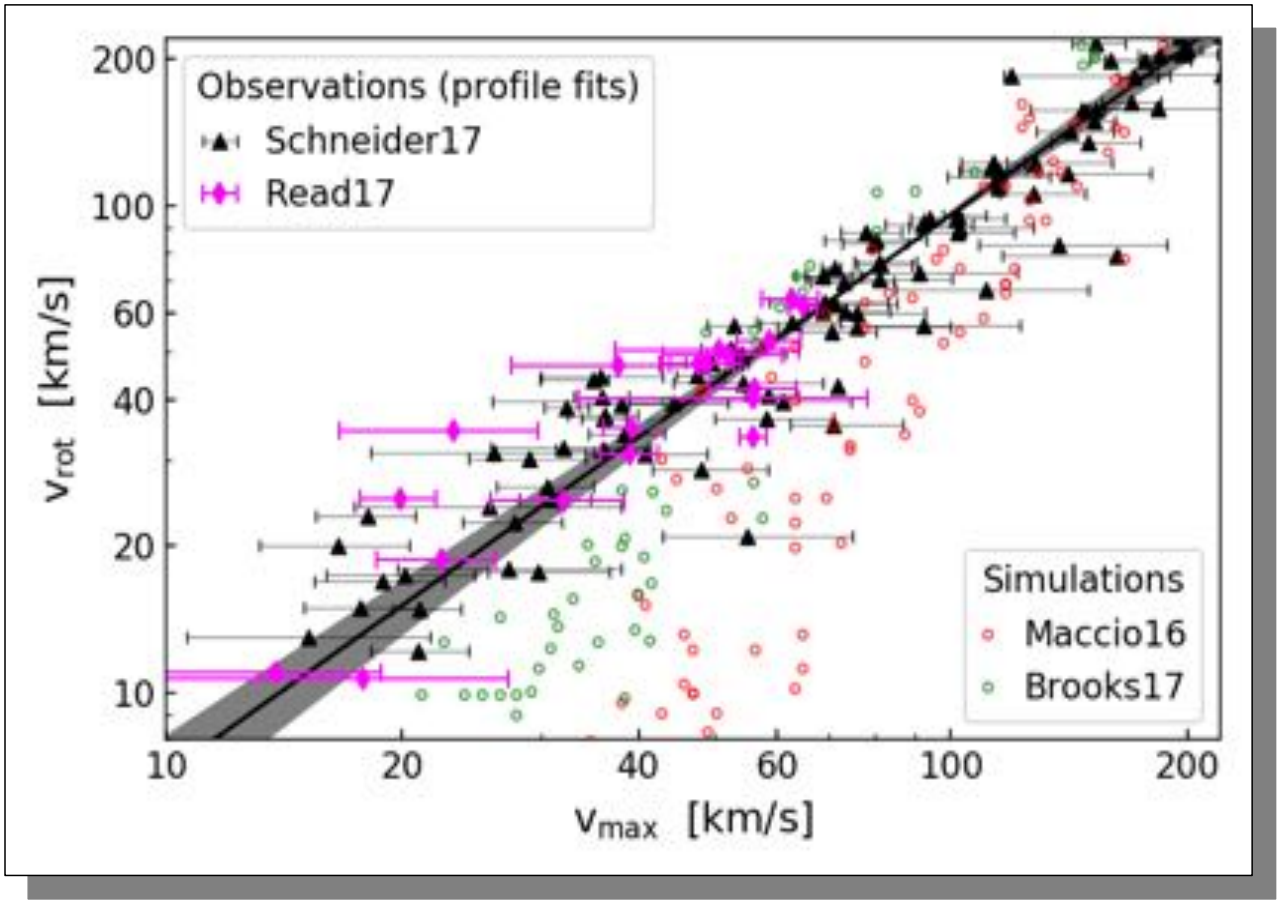


Velocity function – How to resolve the tension ?

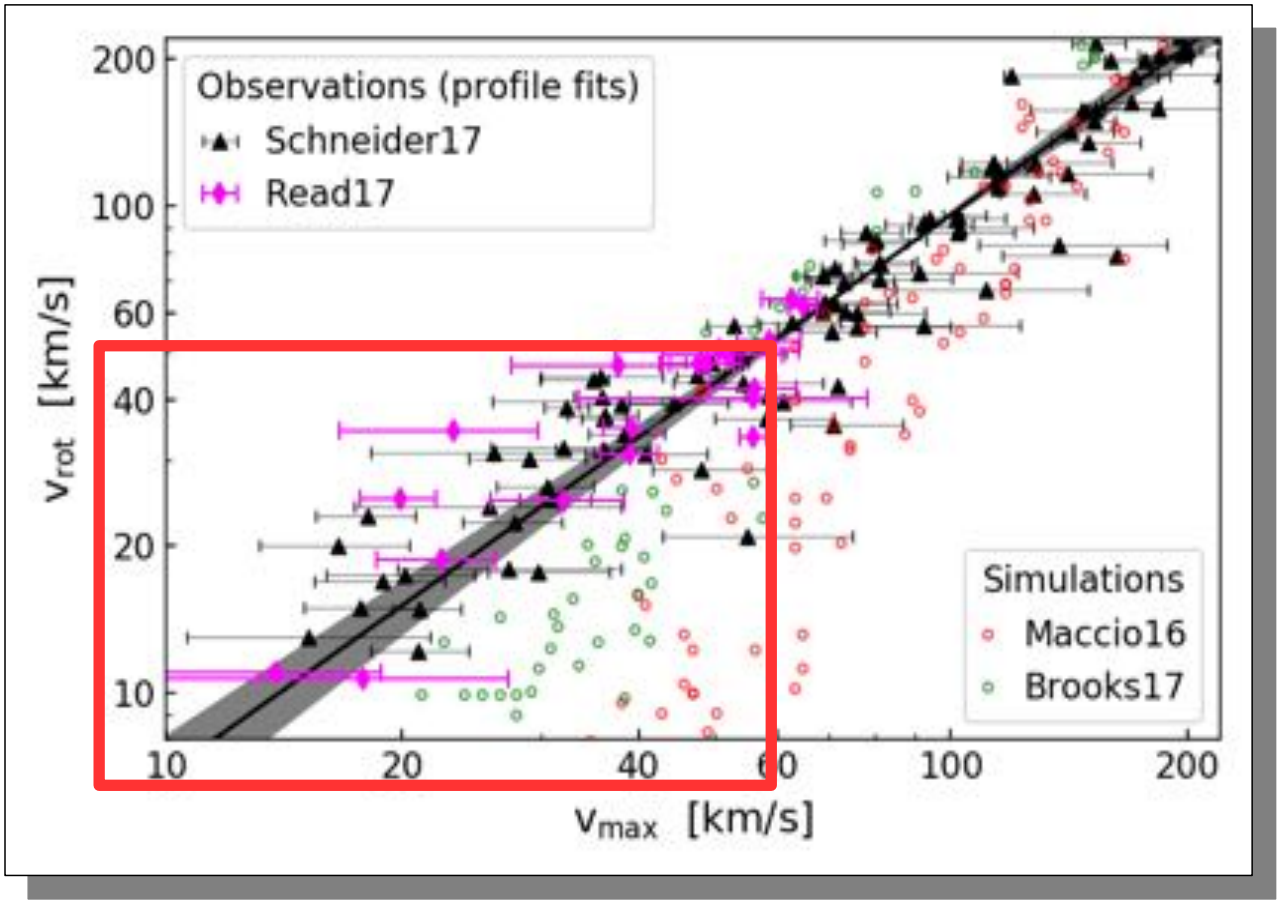
Cosmology ?

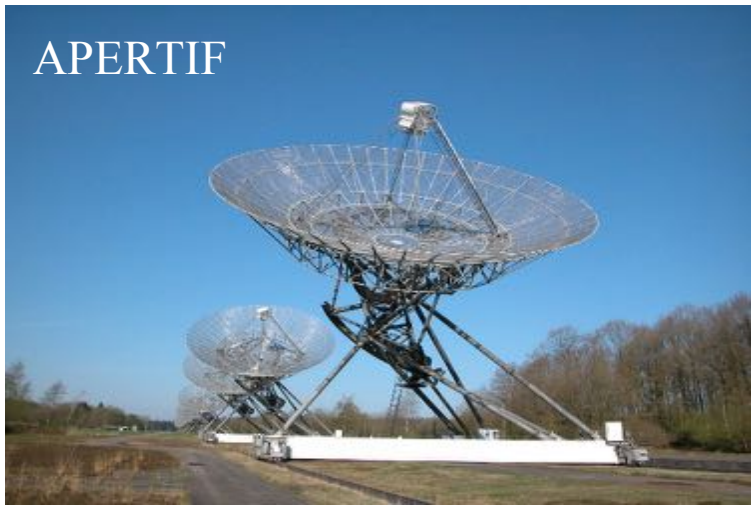
Dark Matter ?

Systematics ?

1000 – 2000 dwarfs with resolved velocities

50 – 100 dwarfs with high-res rotation curves





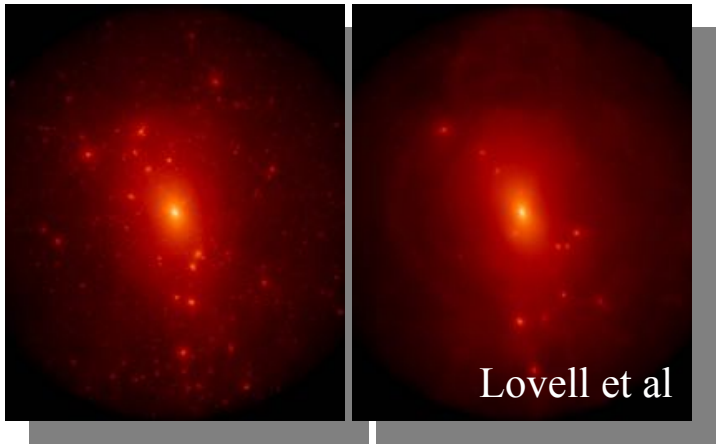
DM and structure formation: 2 options

Do dwarf galaxies disagree with the cold dark matter paradigm ?

Constraining dark matter models

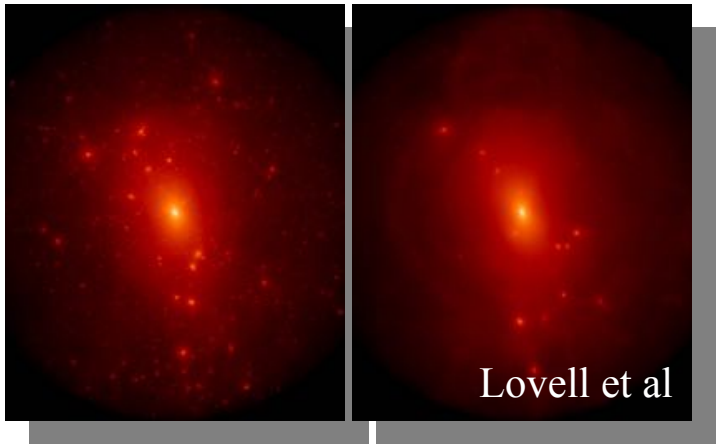
Constraining dark matter

Milky-Way satellites

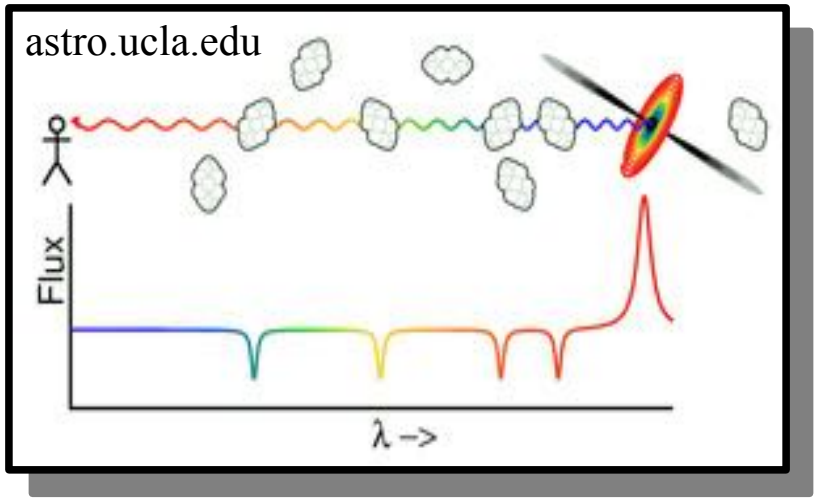


Constraining dark matter

Milky-Way satellites



Ly-alpha forest



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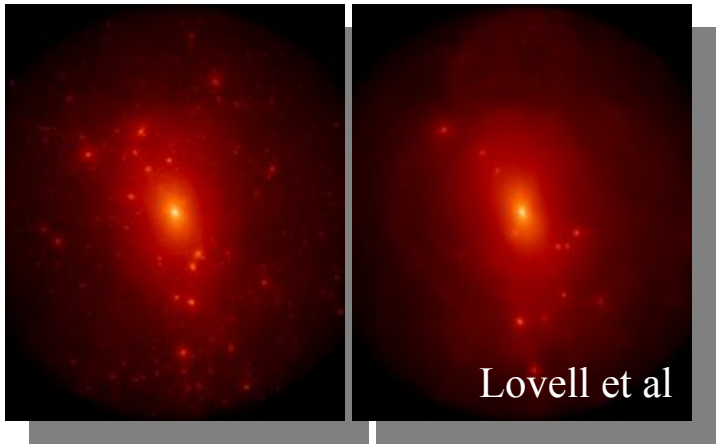
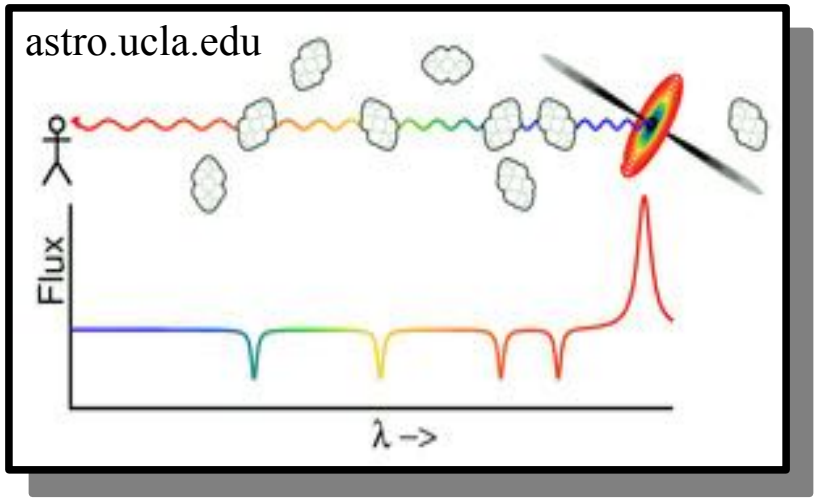


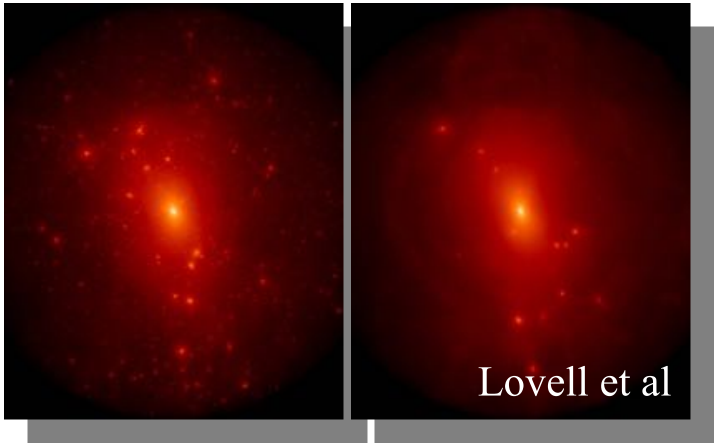
Strong lensing

Ly-alpha forest



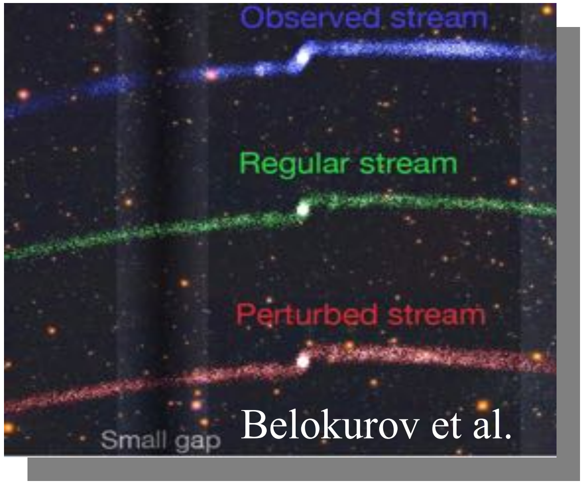
Constraining dark matter

Milky-Way satellites



Strong lensing

Stellar streams



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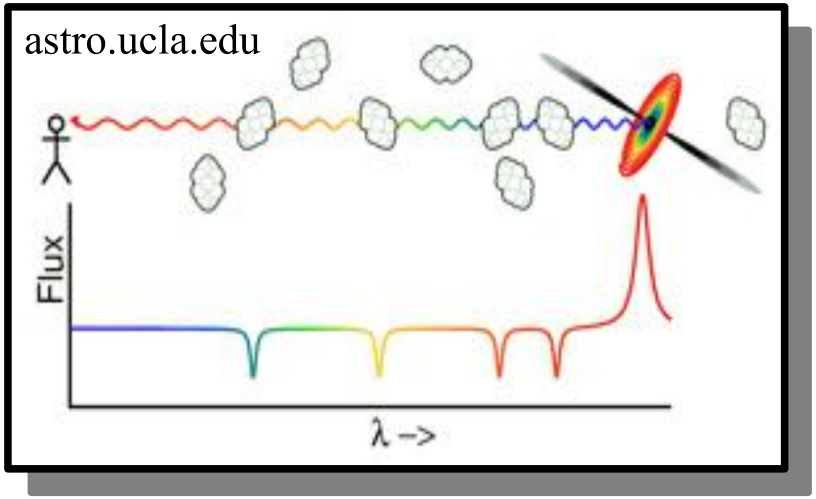
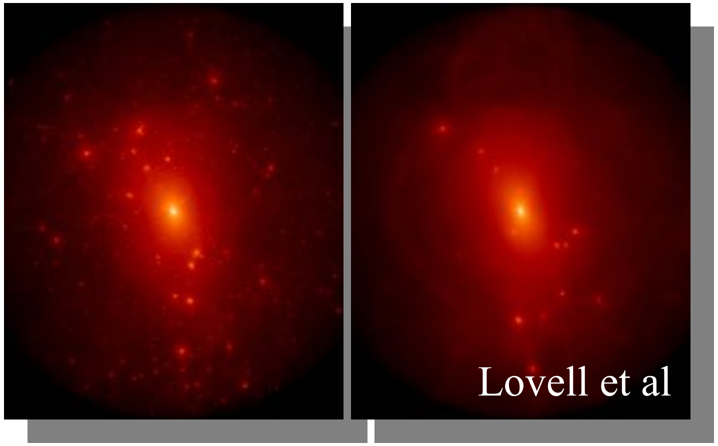


Constraining dark matter

Milky-Way satellites



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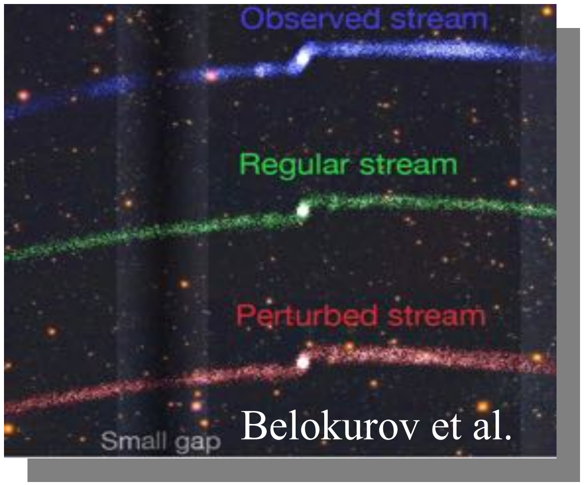
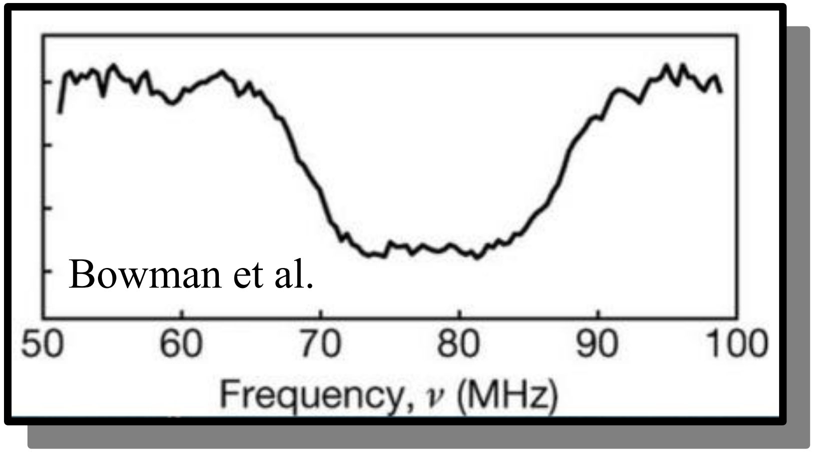


Global 21-cm signal



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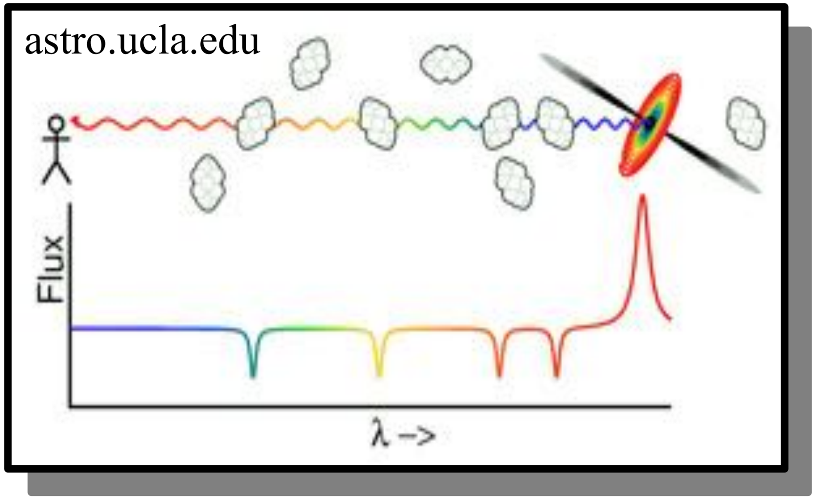
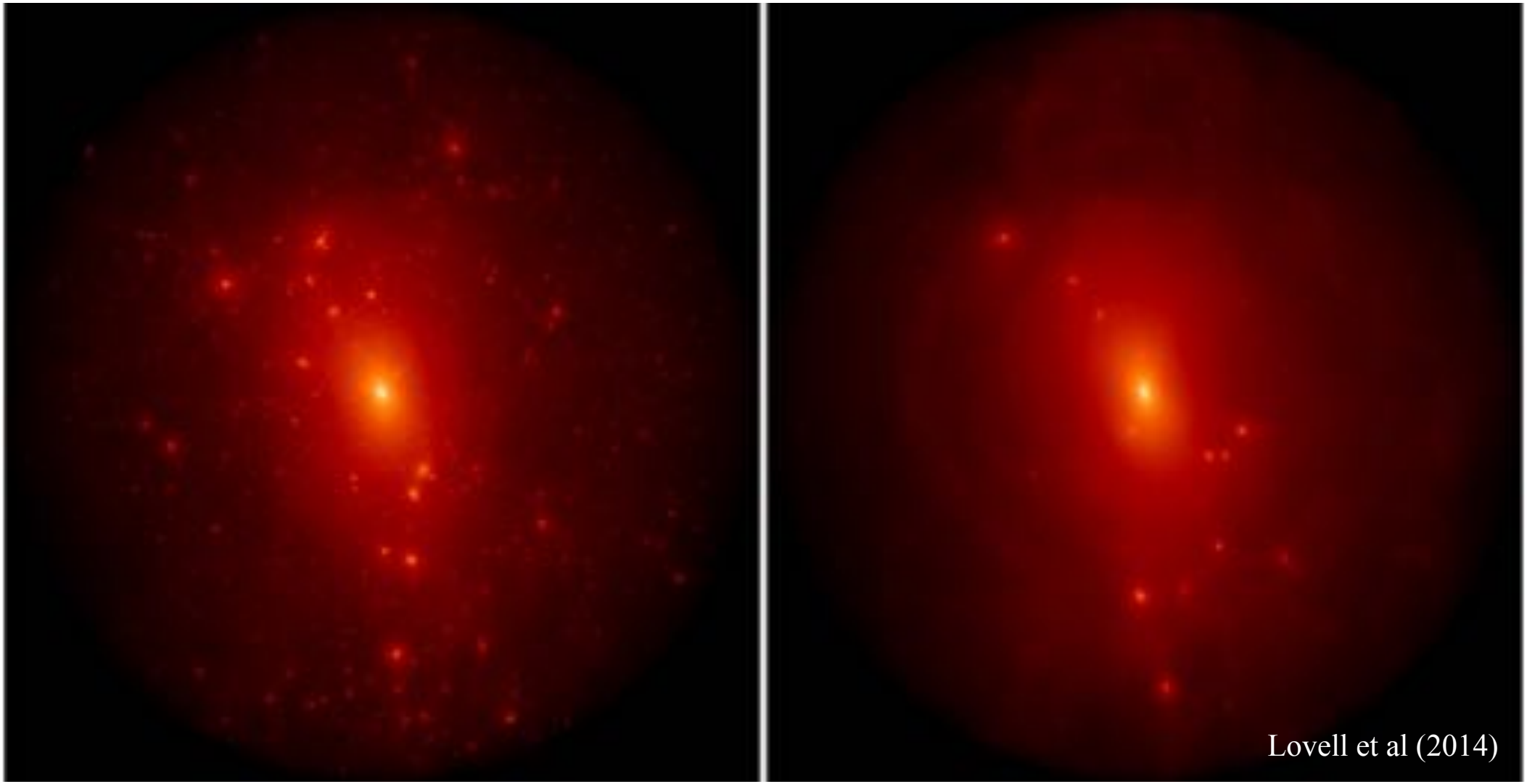
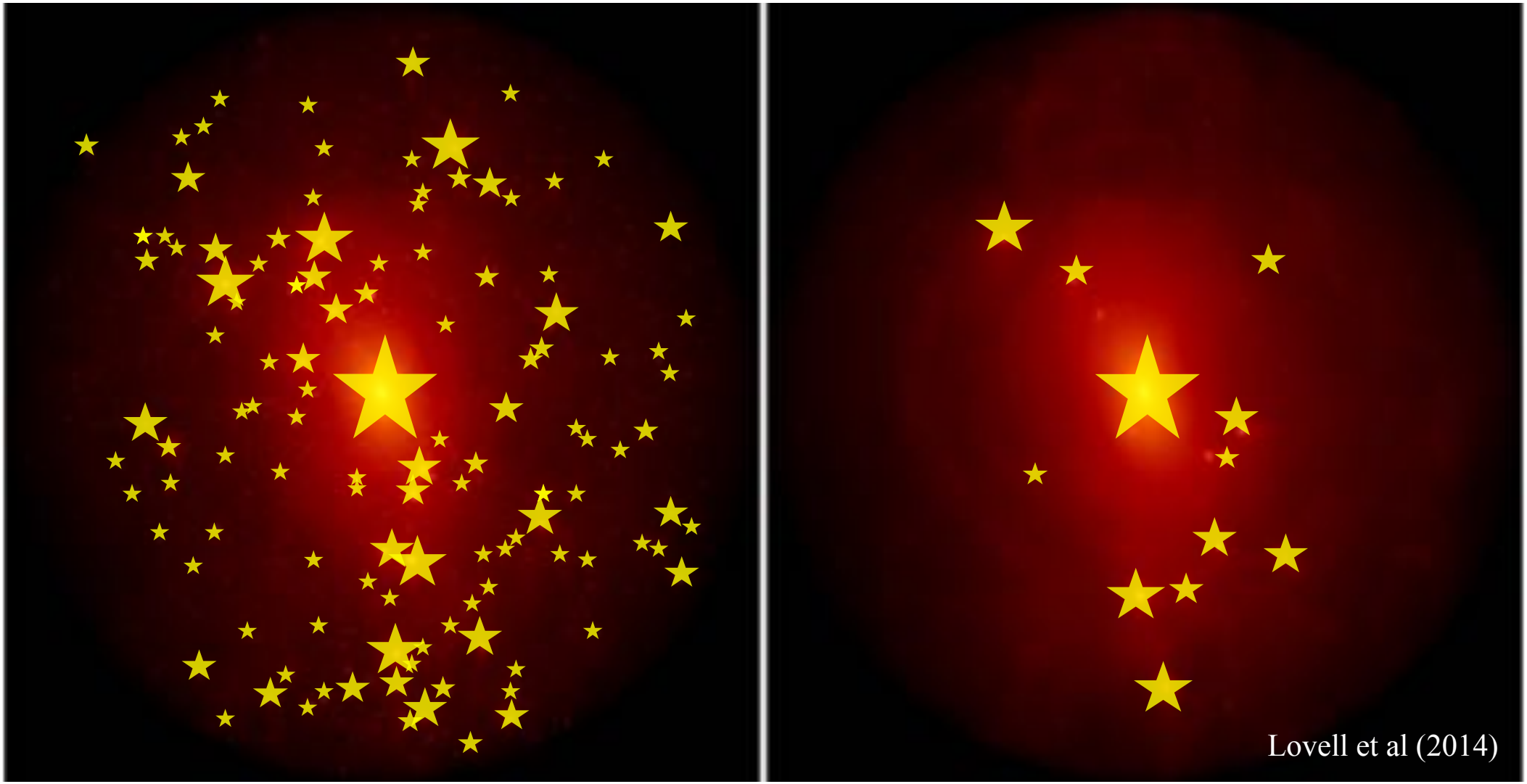


Constraining dark matter: **Milky-Way satellites**



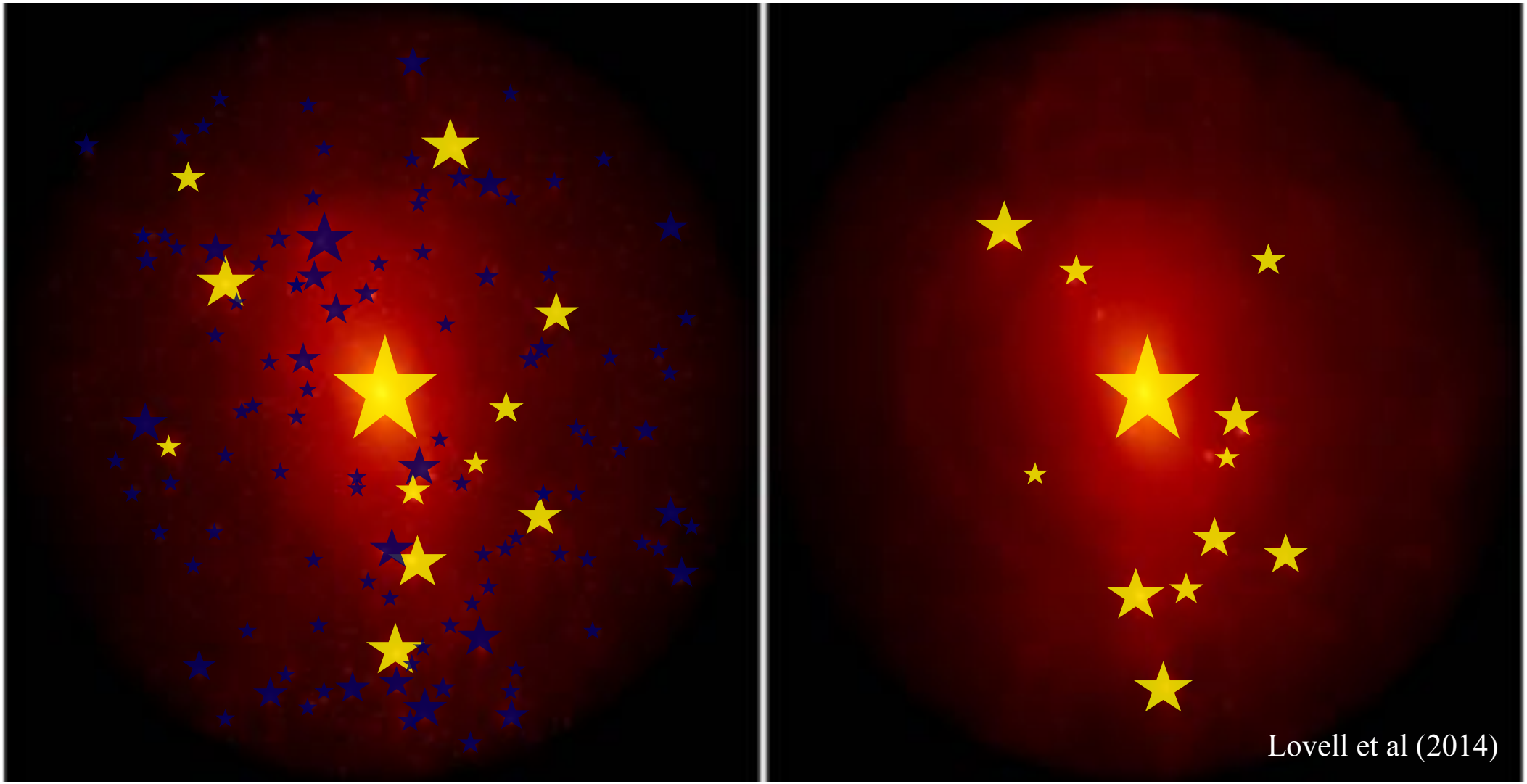
Known: 11 classical satellites, > 35 ultra-faint satellites

Constraining dark matter: **Milky-Way satellites**



… assuming simple halo-mass stellar mass relation.

Constraining dark matter: **Milky-Way satellites**



… assuming galaxy formation with the *right* stellar and radiation feedback.

Constraining dark matter: **Milky-Way satellites**

Warm DM: **m > 2-3 keV**

(Polisensky2011, Kennedy2014, ...)

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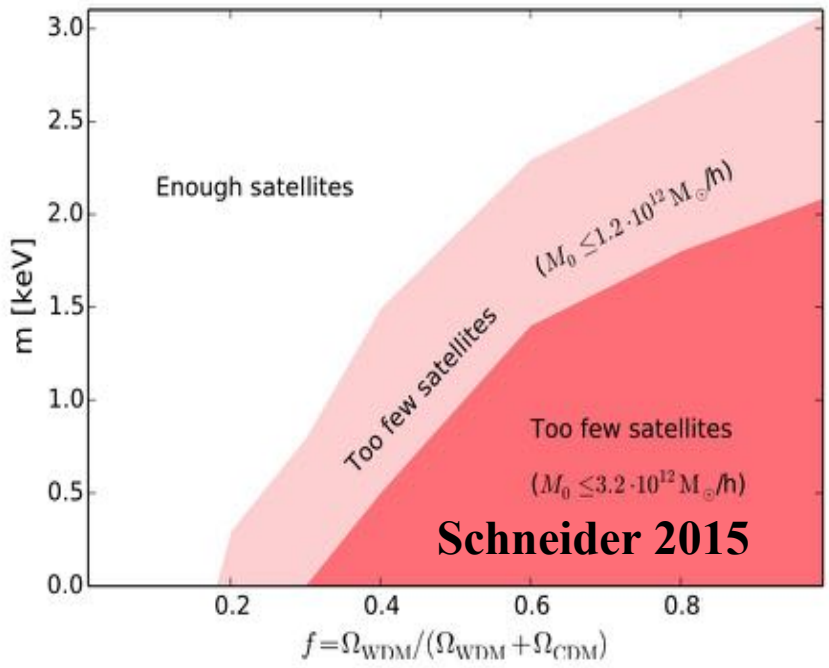

Constraining dark matter: **Milky-Way satellites**

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Fuzzy DM: **m > 1-3 x 10^{-22} eV**

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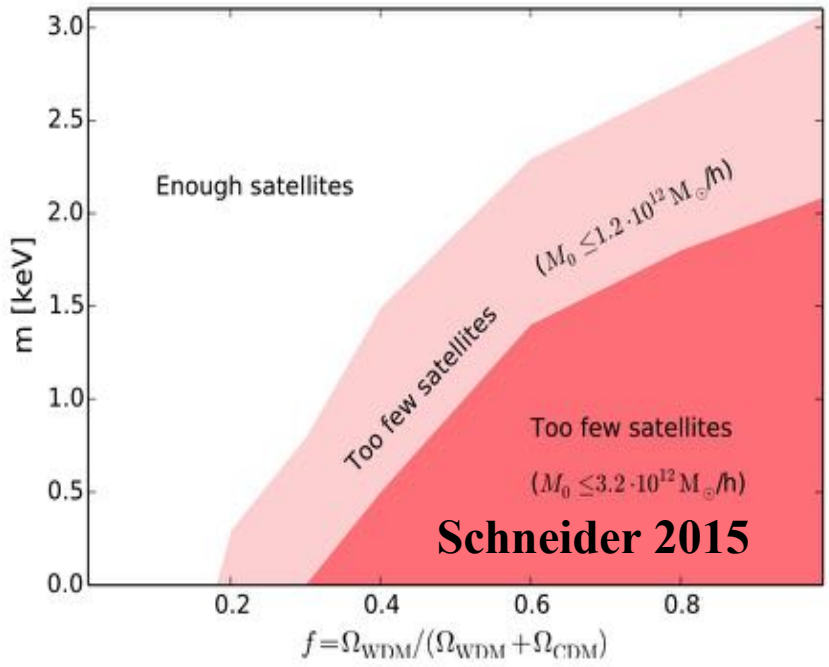

Constraining dark matter: **Milky-Way satellites**

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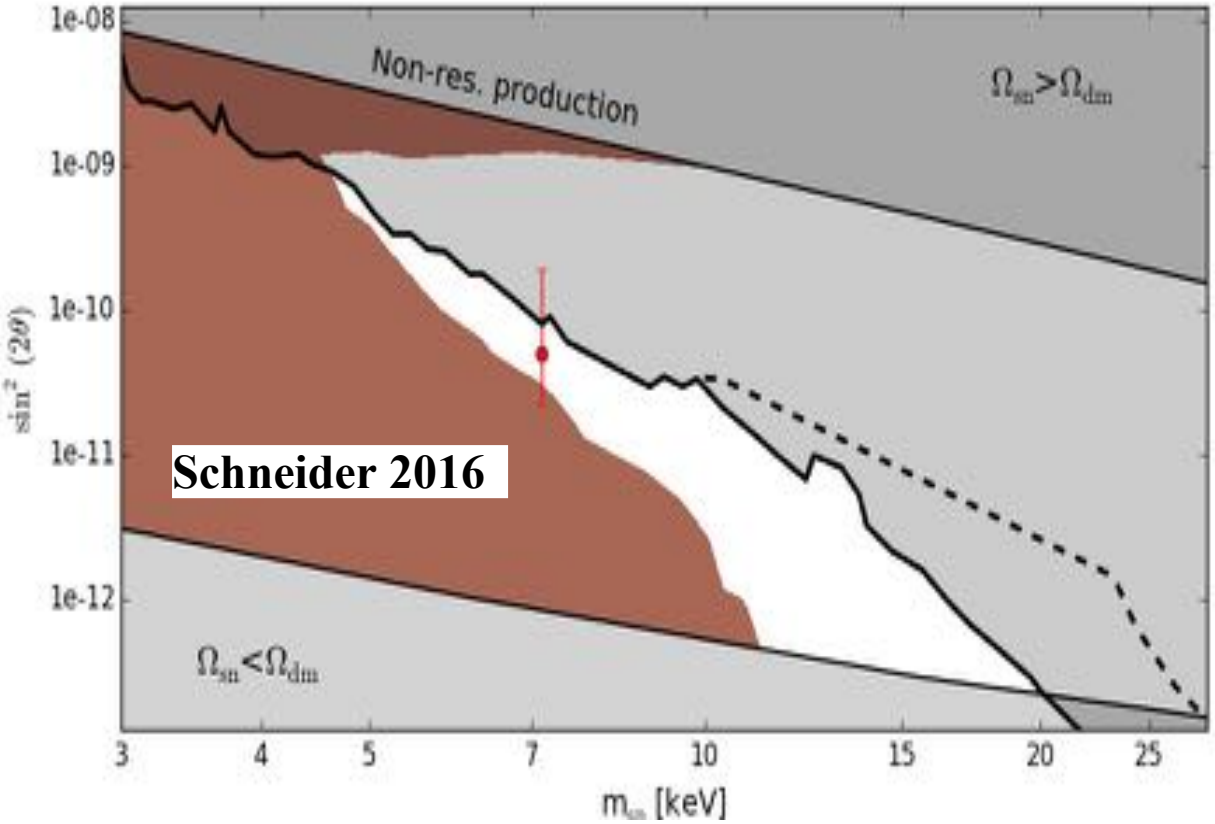
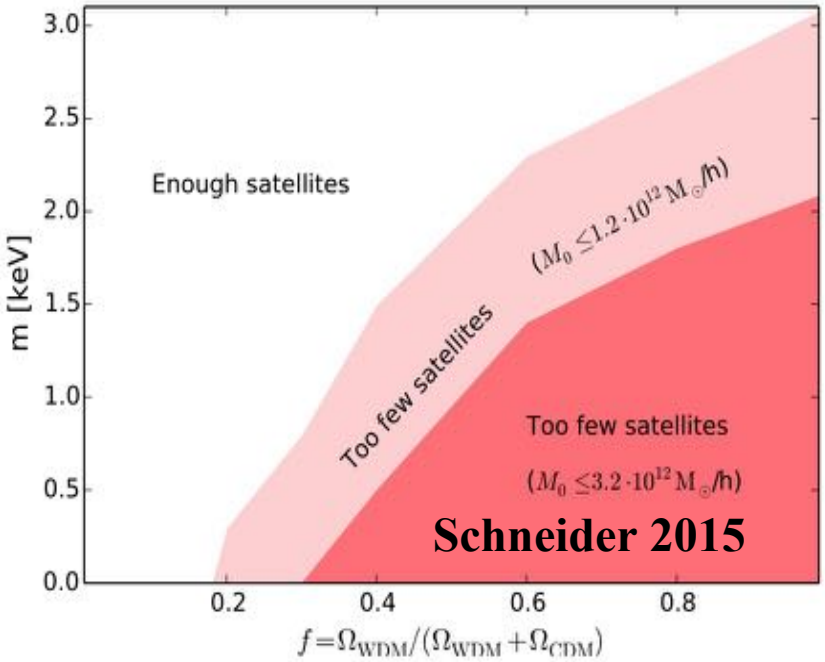
Sterile Neutrino DM (res. prod.)



Mixed DM



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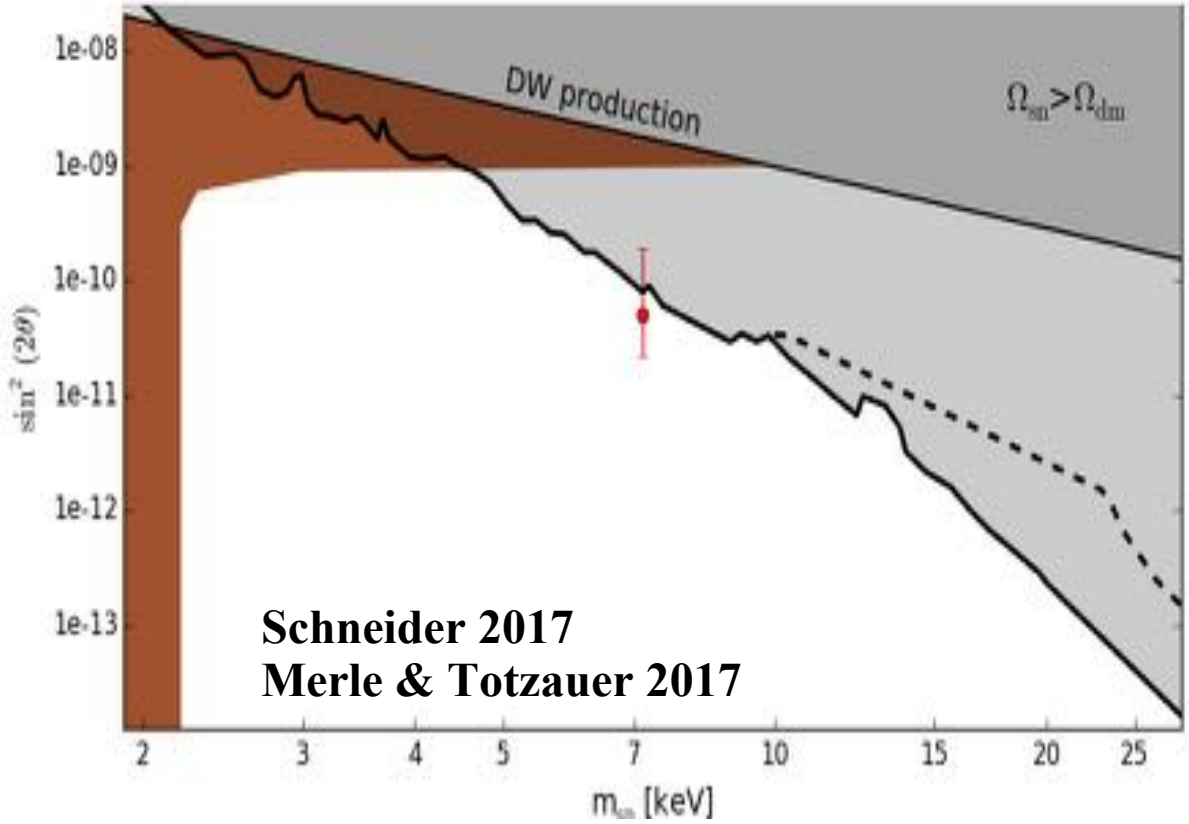
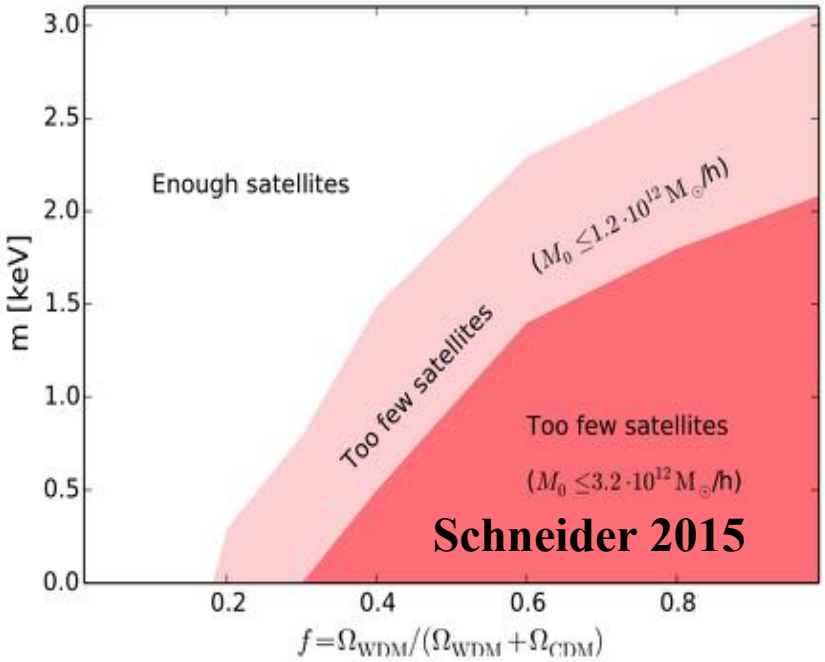
Fuzzy DM: **m > 1-3 x 10^{-22} eV**

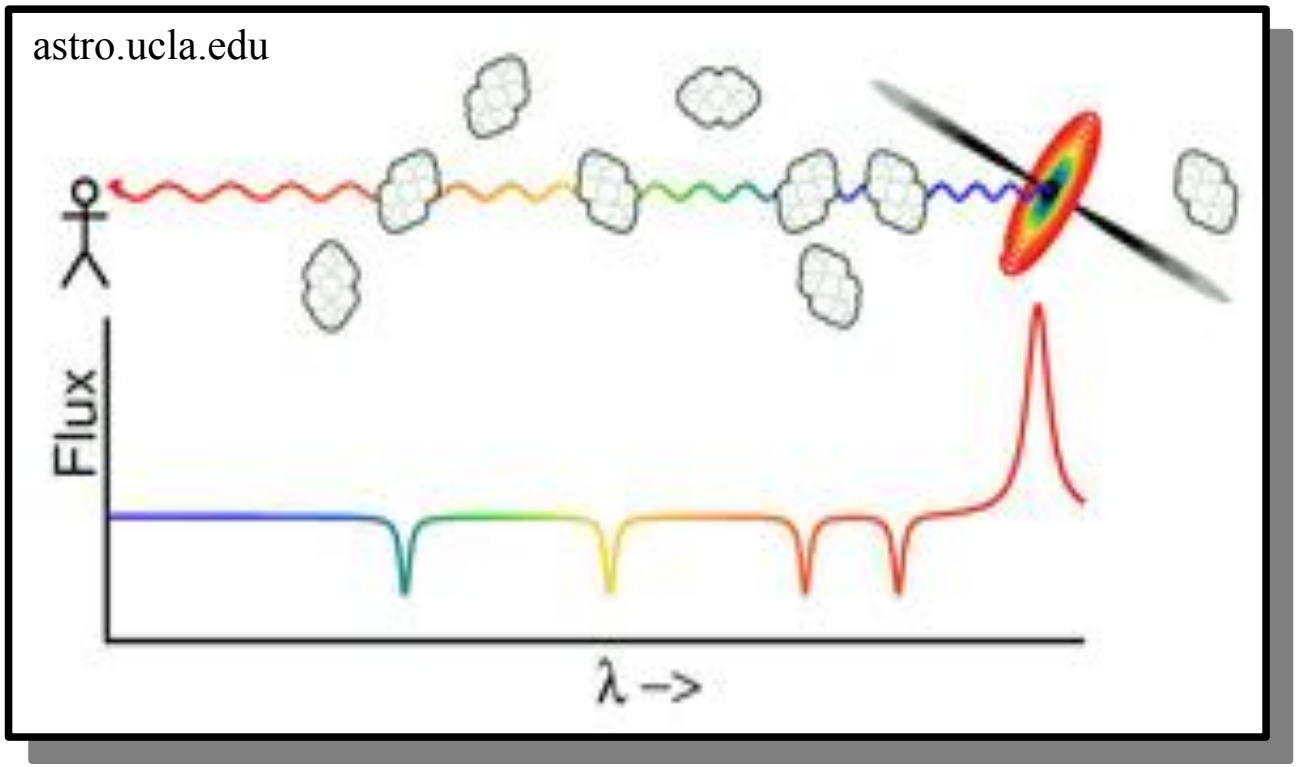
Sterile Neutrino DM (decay prod.)



Mixed DM



Constraining dark matter: **Lyman-alpha forest**



Constraining dark matter: **Lyman-alpha forest**

Warm DM: **m > 3-5 keV**

(Viel2013, Baur2016, Irsaic2016, ...)

Constraining dark matter: **Lyman-alpha forest**

Warm DM: **m > 3-5 keV**

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Fuzzy DM: **m > 3 -15 x 10^{-22} eV**

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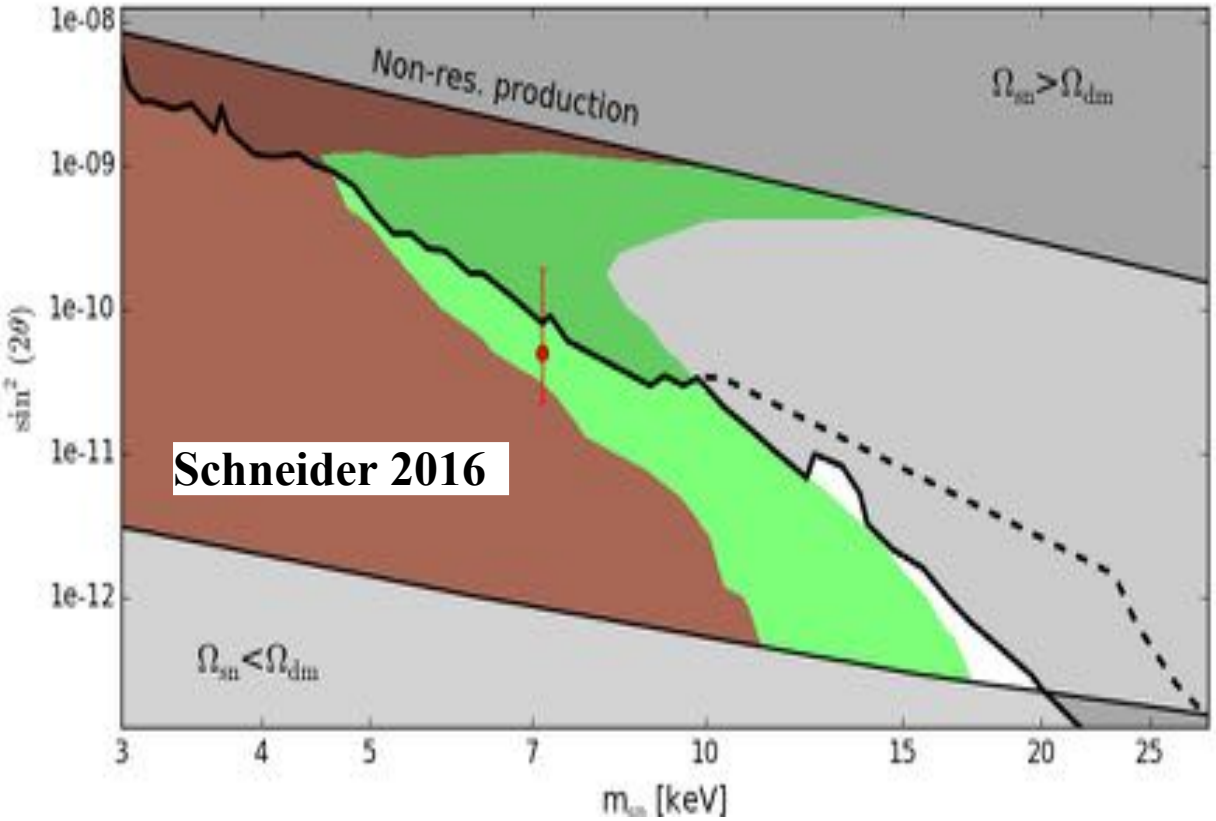
Sterile Neutrino DM (res. prod.)



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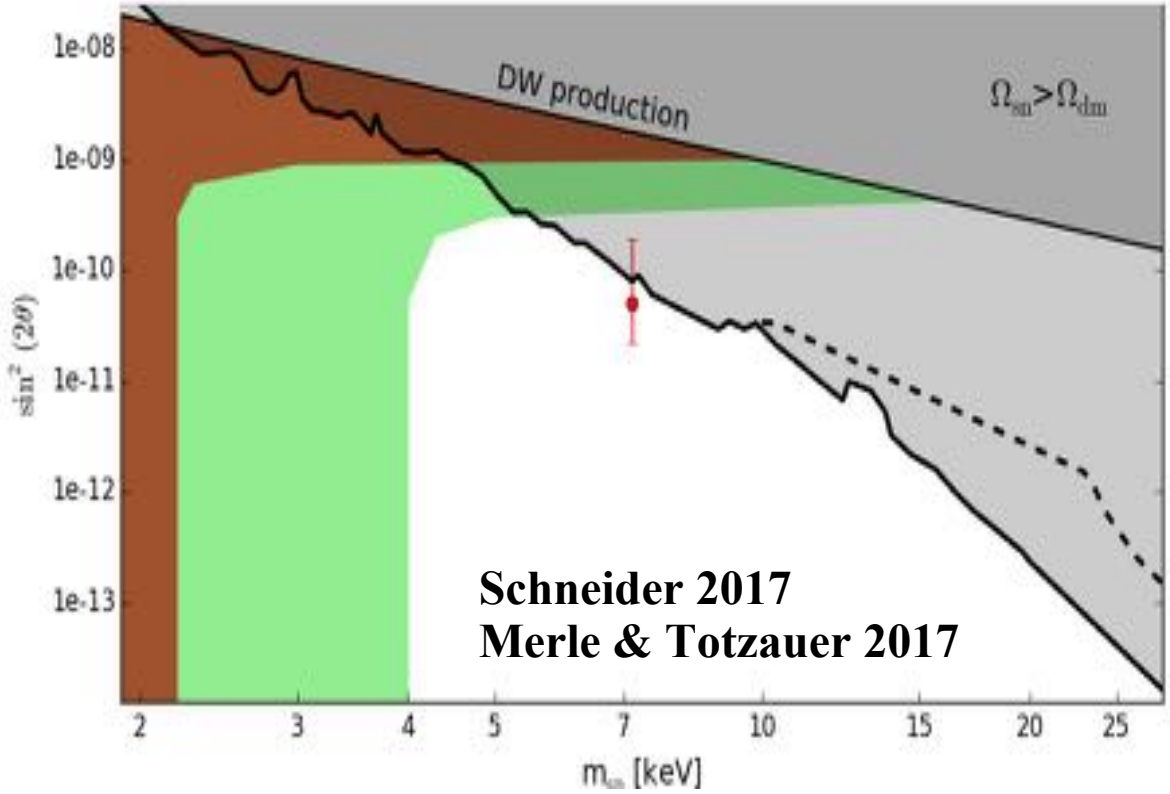

Constraining dark matter: **Global 21-cm signal**

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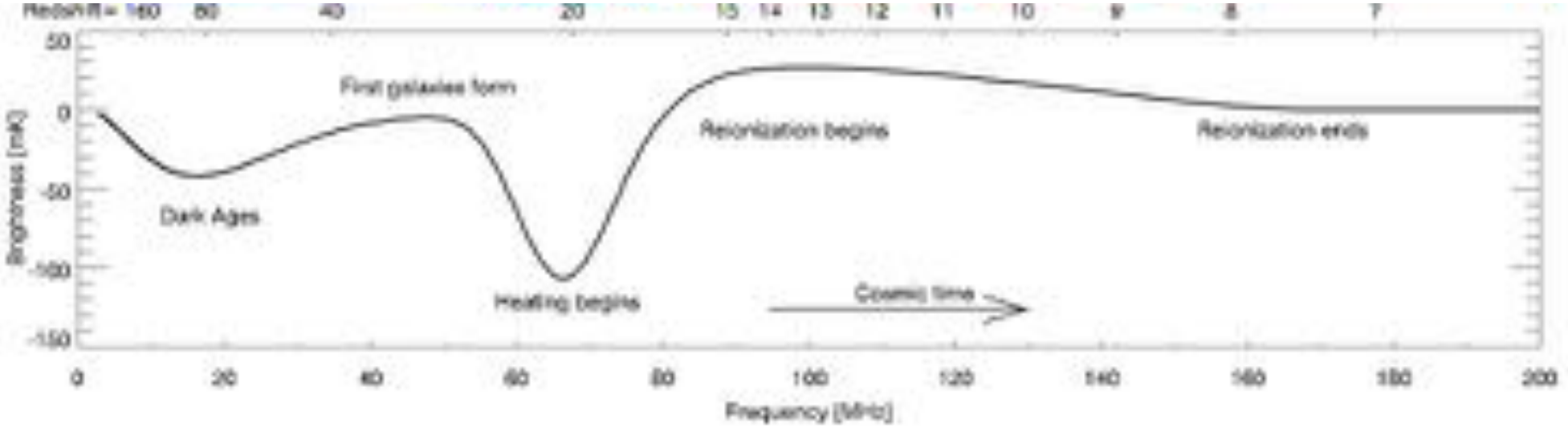

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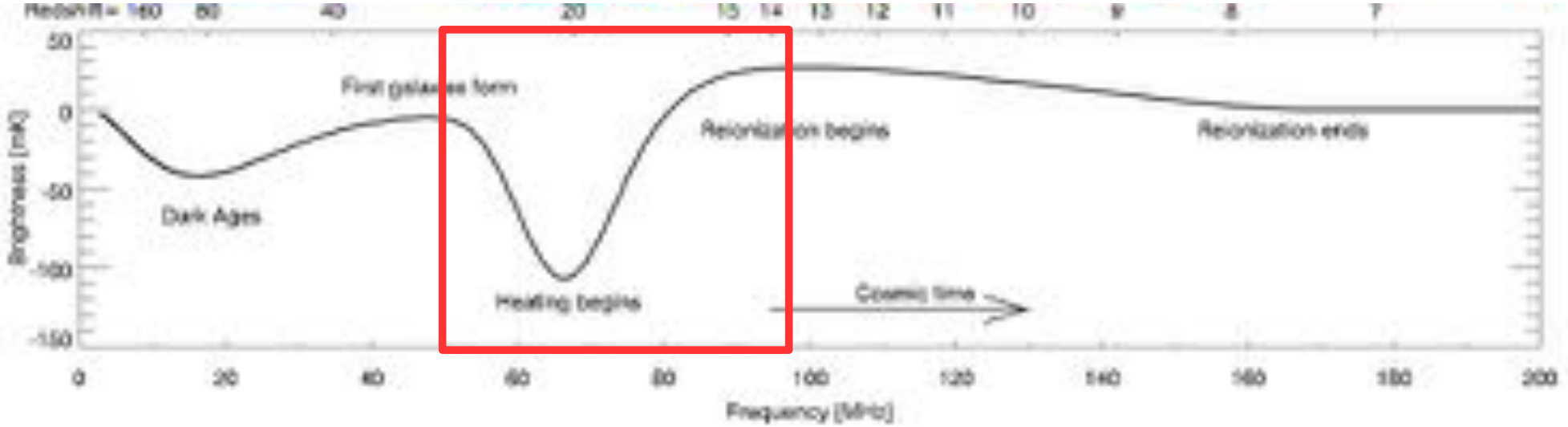

$$\delta T_b \propto \frac{x_{\rm tot}}{1+x_{\rm tot}}\left(1-\frac{T_{\rm cmb}}{T_{\rm gas}}\right)$$

$$x_{\rm tot} \propto f_* \frac{d}{dt} f_{\rm coll}$$

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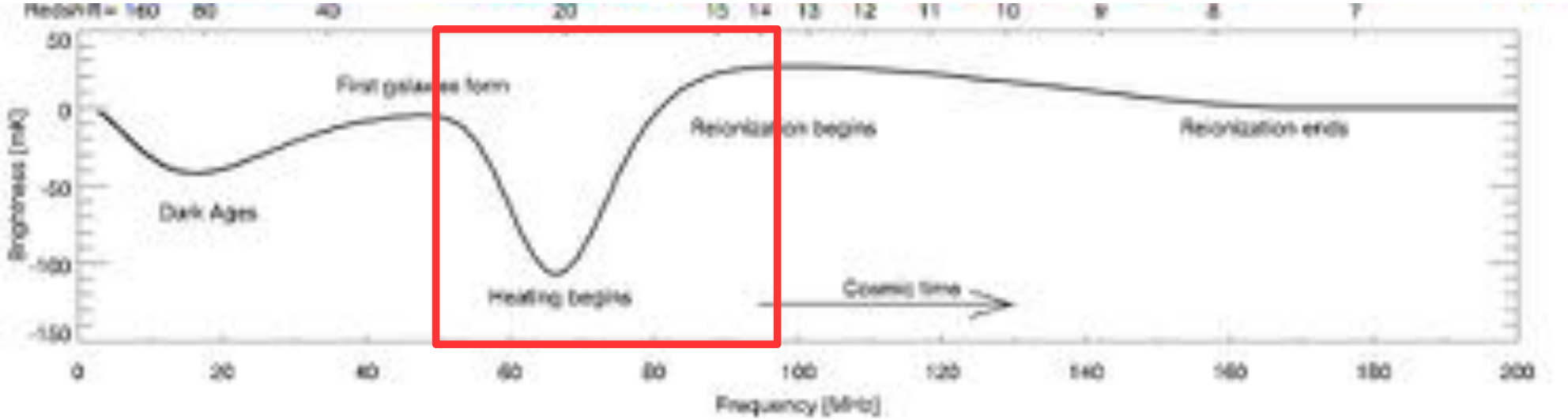

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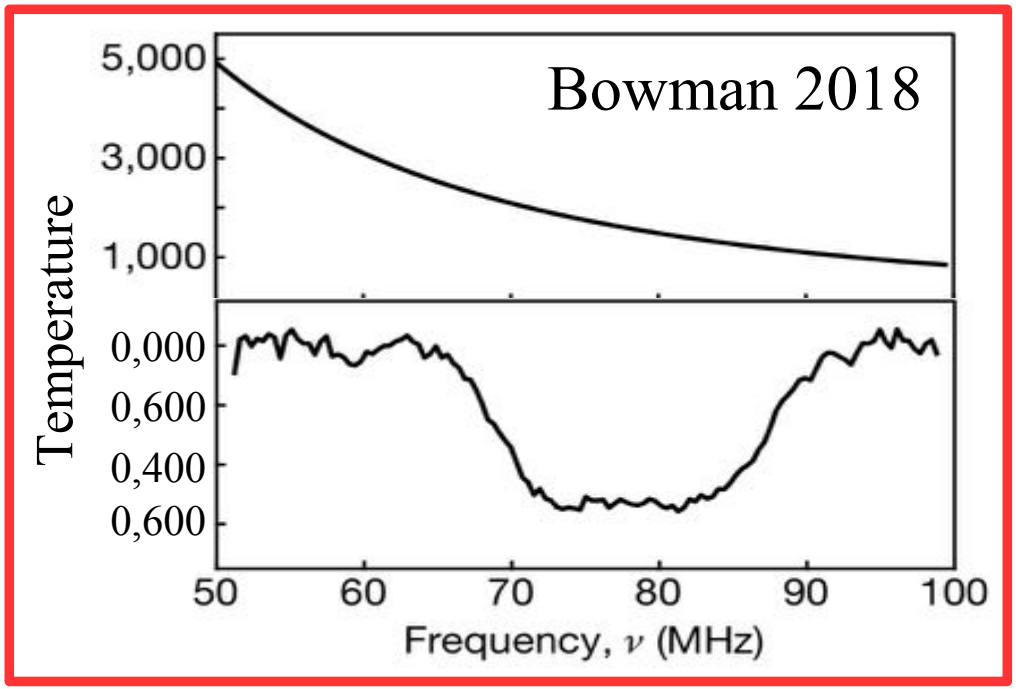

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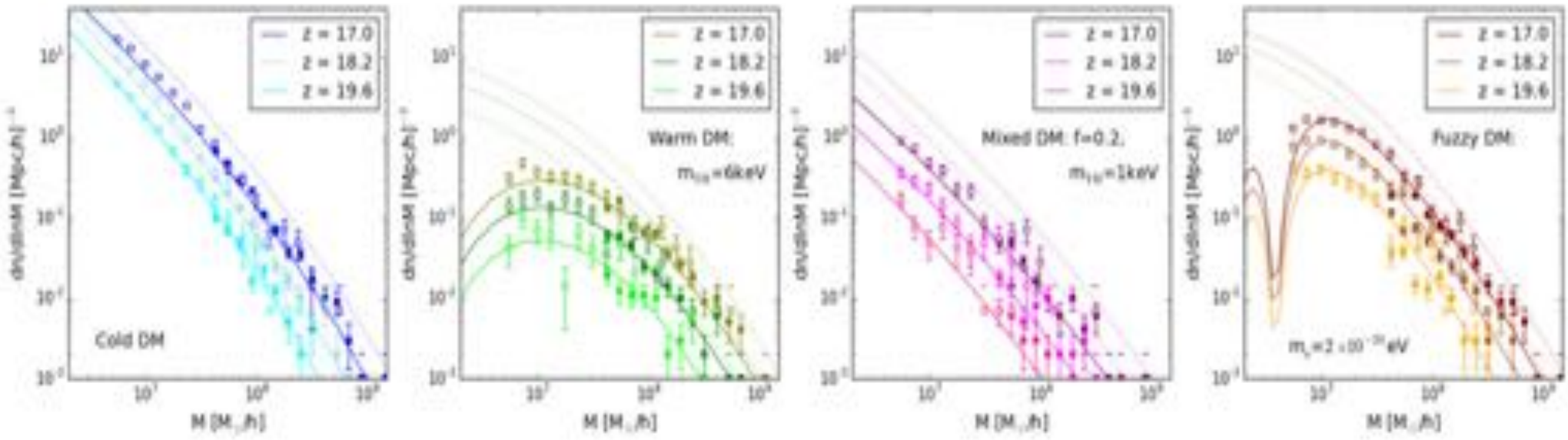

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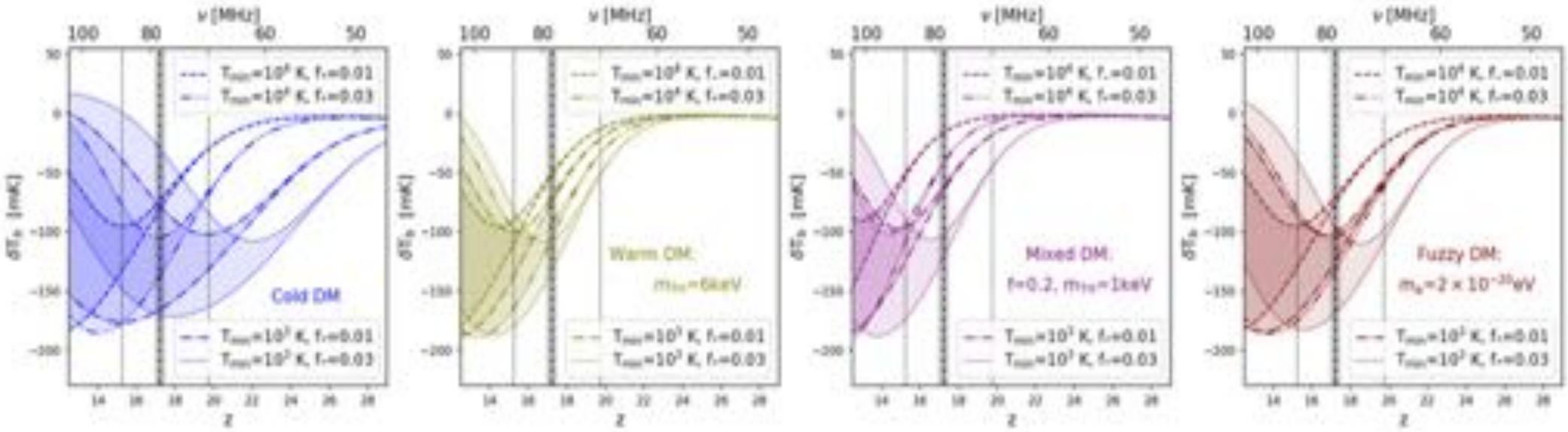

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$$f_* < 0.03$$

$$T_{\rm min} > 10^3\,{\rm K}$$

Constraining dark matter: **Global 21-cm signal**

Warm DM: **m > 6.1 keV**

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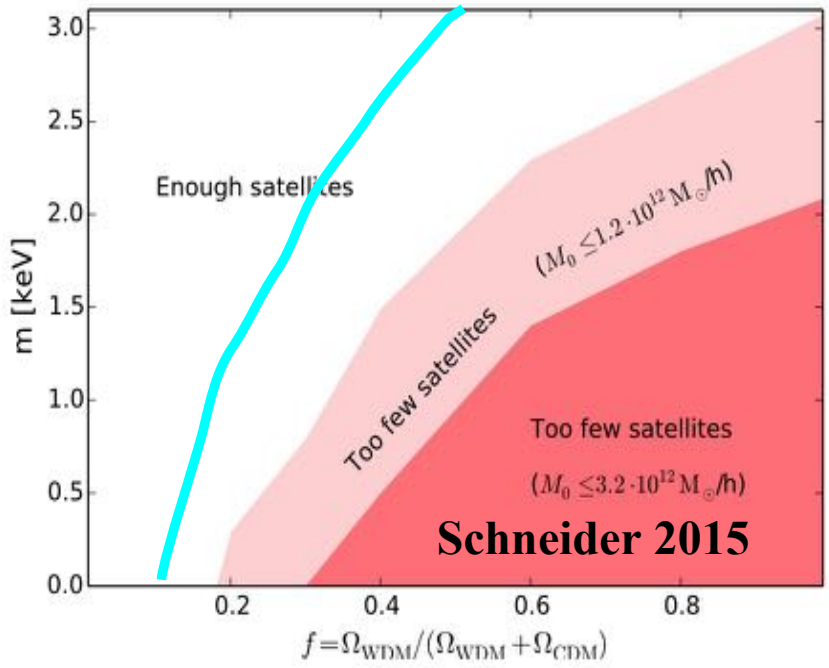
Mixed DM



Constraining dark matter: **Global 21-cm signal**

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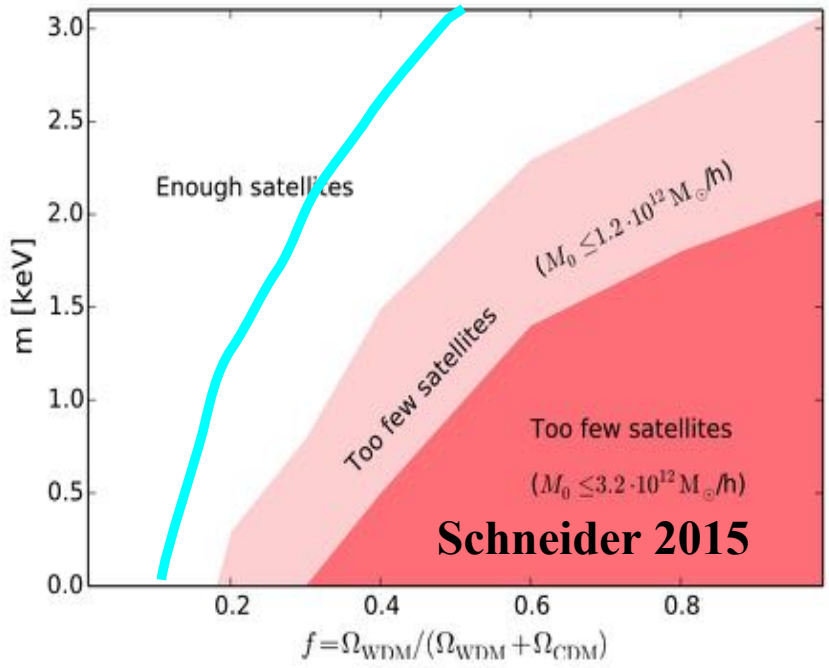
Fuzzy DM: **m > 8 x 10^{-21} eV**

Mixed DM



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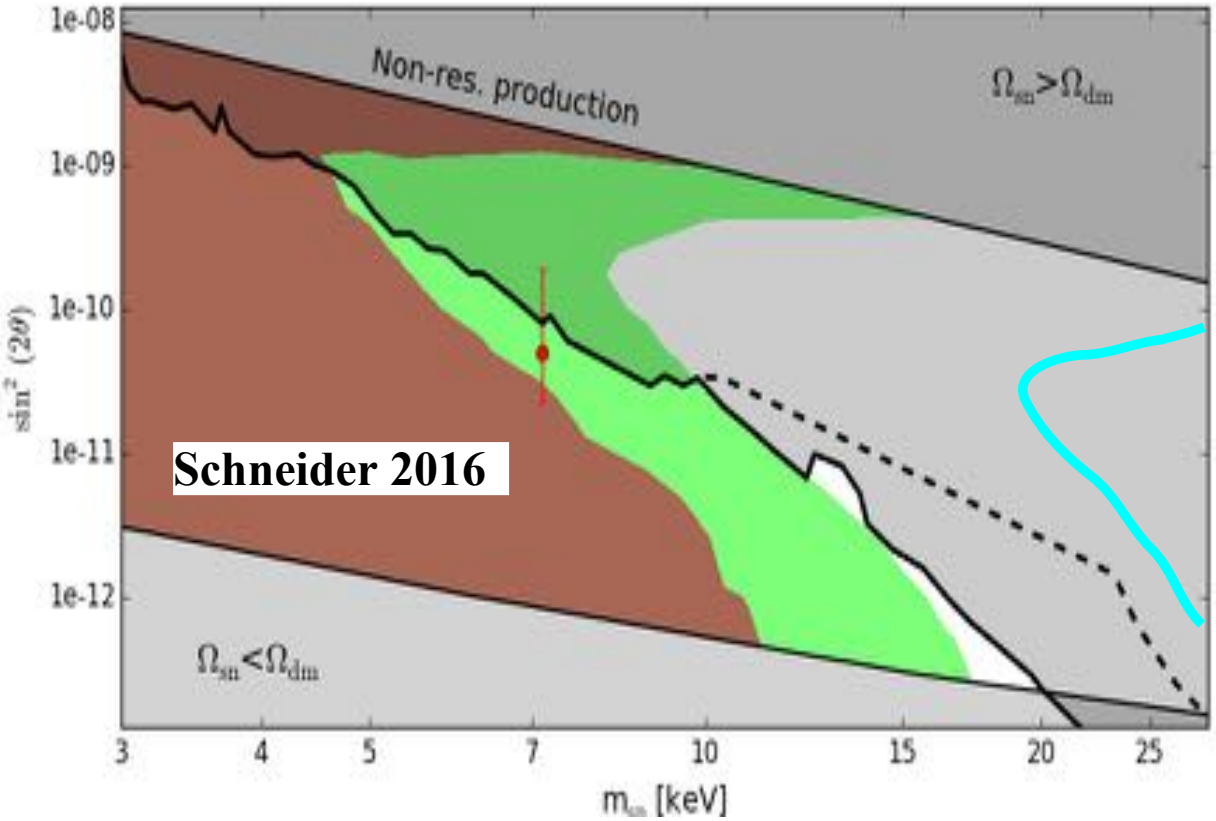

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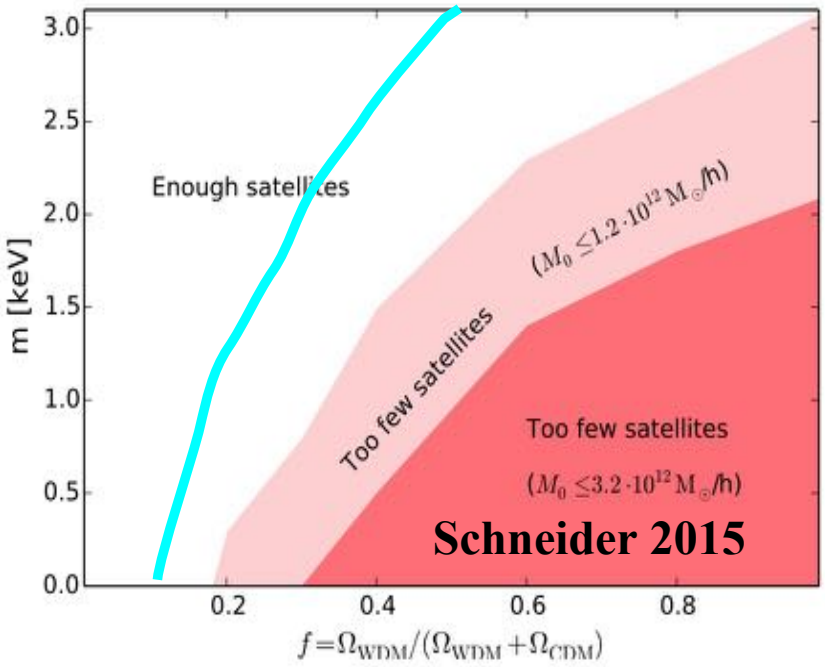

Conclusions:

Structure formation is a powerful tool

to constrain parts of the DM parameter space

Not everything is solved at small scales!

Profile fitting