



Cosmic structure formation and dark matter

Aurel Schneider – ETH Zurich



Cosmic structure formation and dark matter

... using the example
of sterile neutrinos

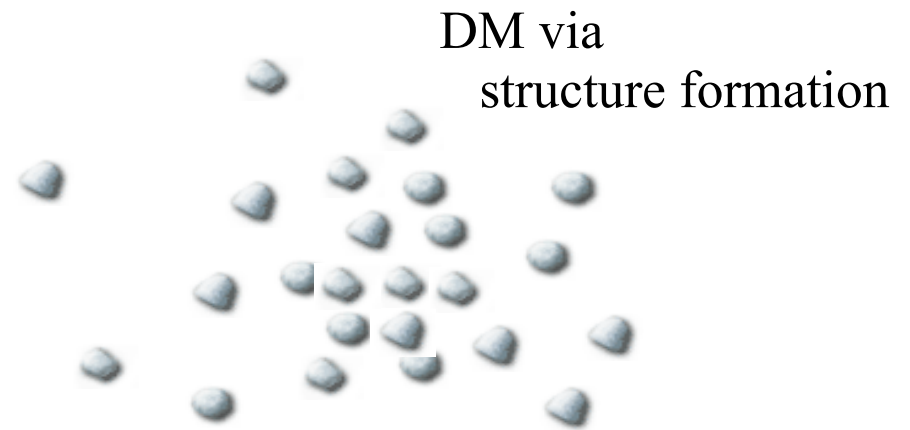
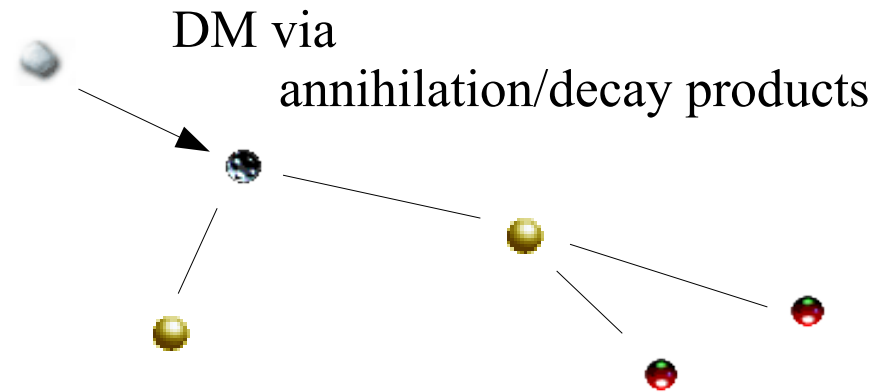
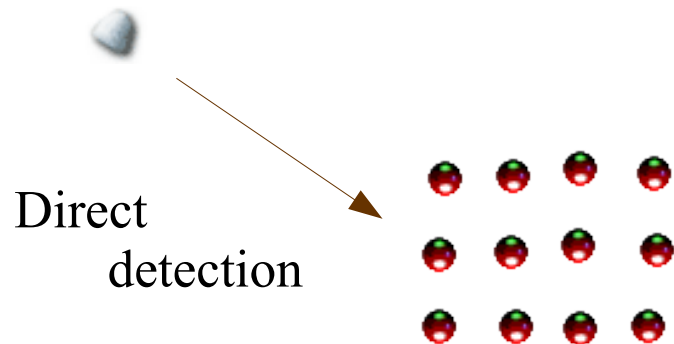
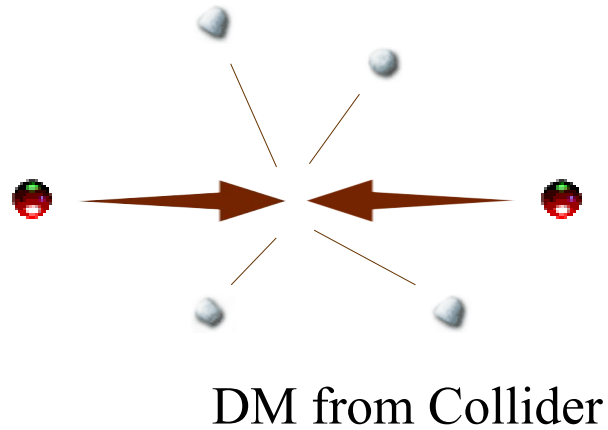
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Dark Matter: explore all possibilities

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

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Linear Structure Formation

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



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

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



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

Linear Structure Formation

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



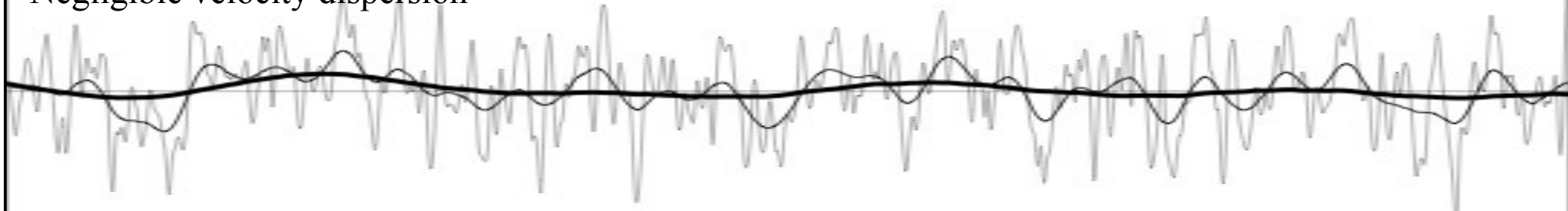
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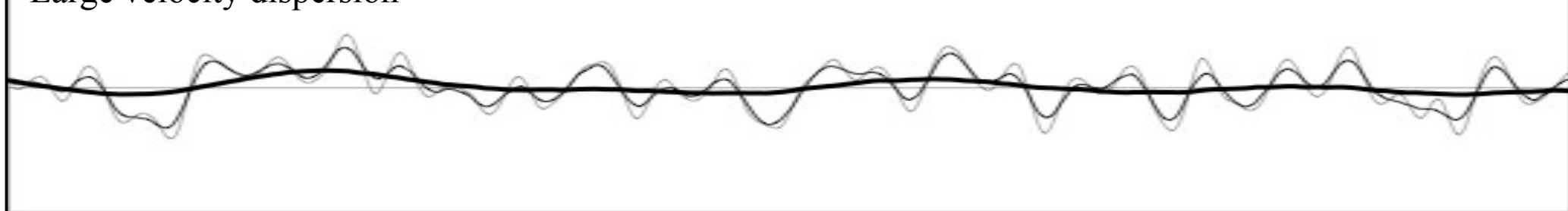


$$\ddot{\delta} + H\dot{\delta} = [4\pi G\bar{\rho} - k^2 c_s^2] \delta$$

Negligible velocity dispersion



Large velocity dispersion



Linear Structure Formation

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



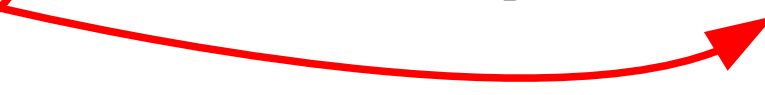
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$$\ddot{\delta} + H\dot{\delta} = [4\pi G\bar{\rho} - k^2 c_s^2] \delta$$

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



Linear Structure Formation – Fermi-Dirac (WDM)

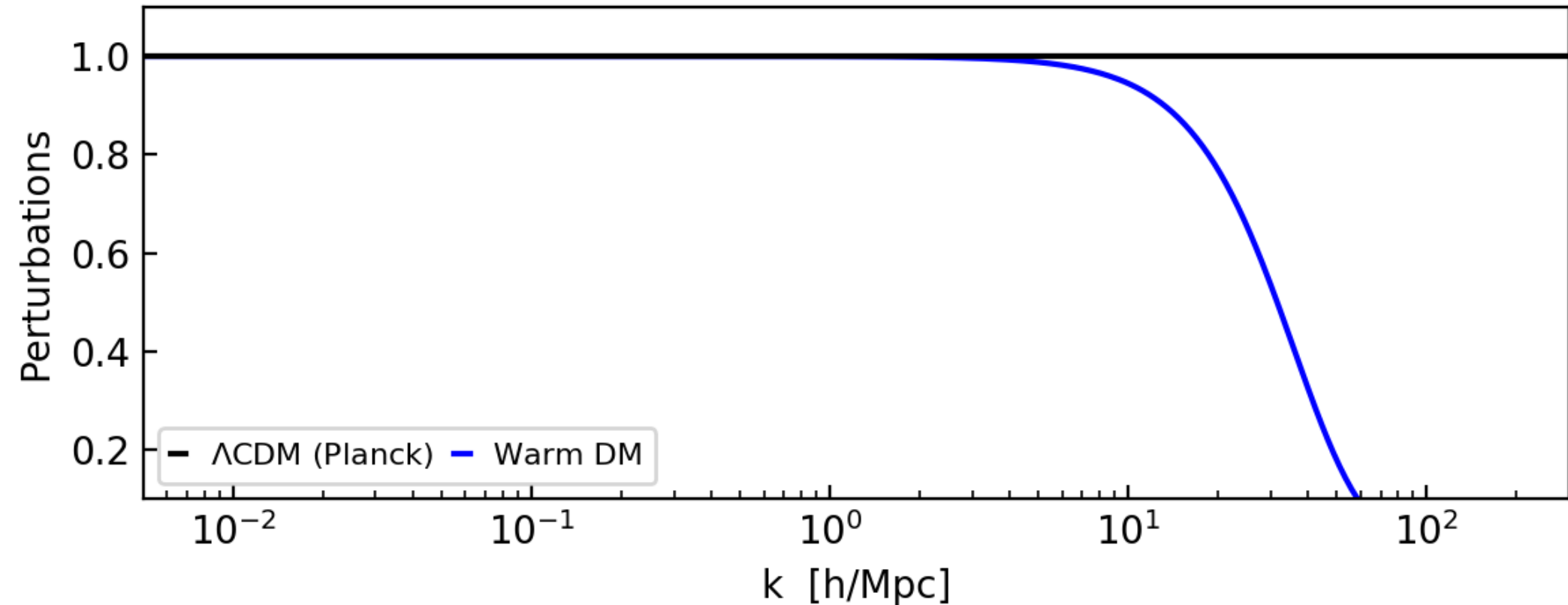
$$\frac{df(x, p, t)}{dt} = 0$$

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

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

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

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



Linear Structure Formation – Sterile Neutrino DM

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



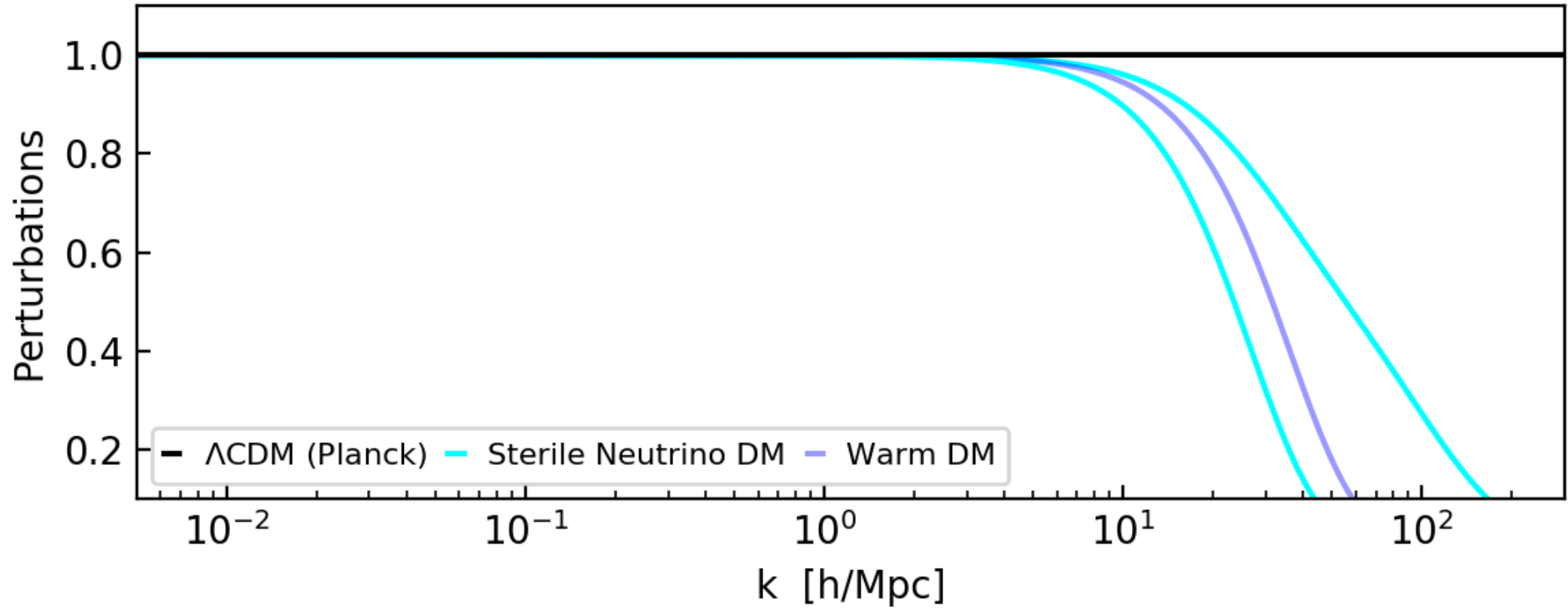
$$\dot{\delta} + \theta - 3\phi = 0,$$

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



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



Linear Structure Formation – Ultra-light Axion DM

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



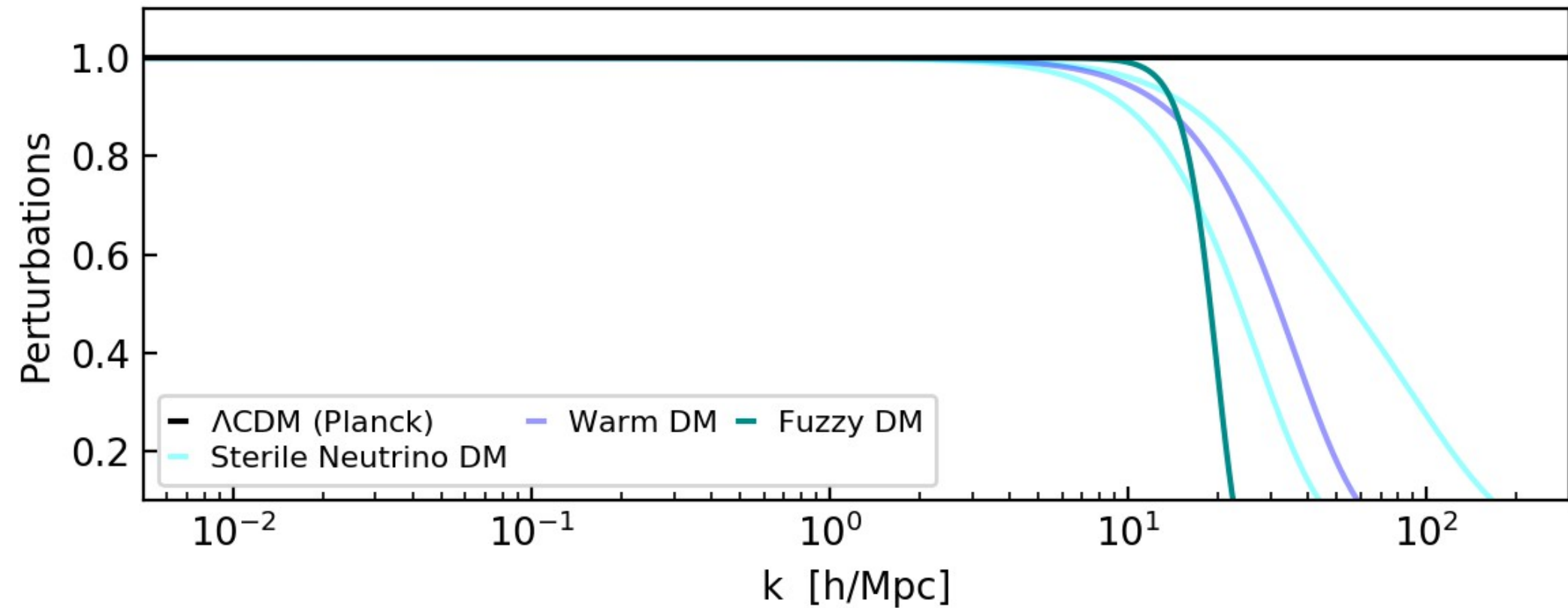
$$\dot{\delta} + \theta - 3\phi = 0,$$

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



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

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



Linear Structure Formation – Mixed DM

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



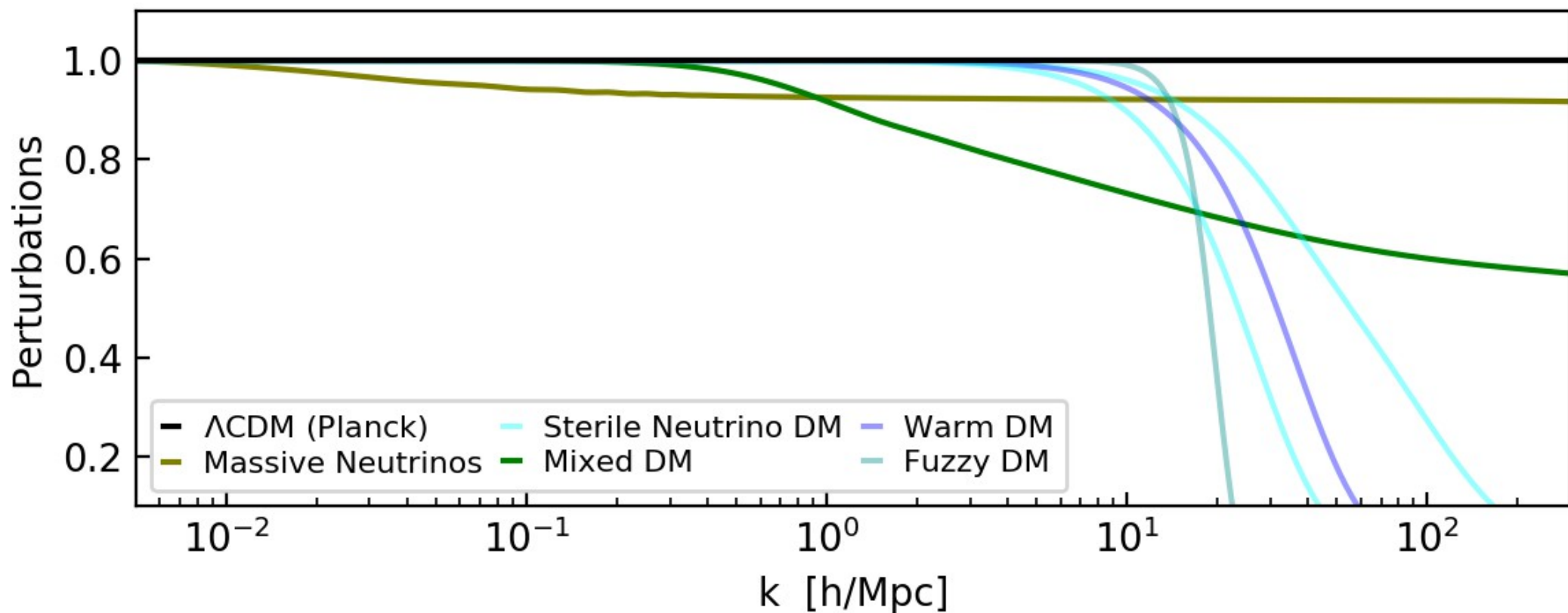
$$\dot{\delta} + \theta - 3\phi = 0,$$

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



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

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



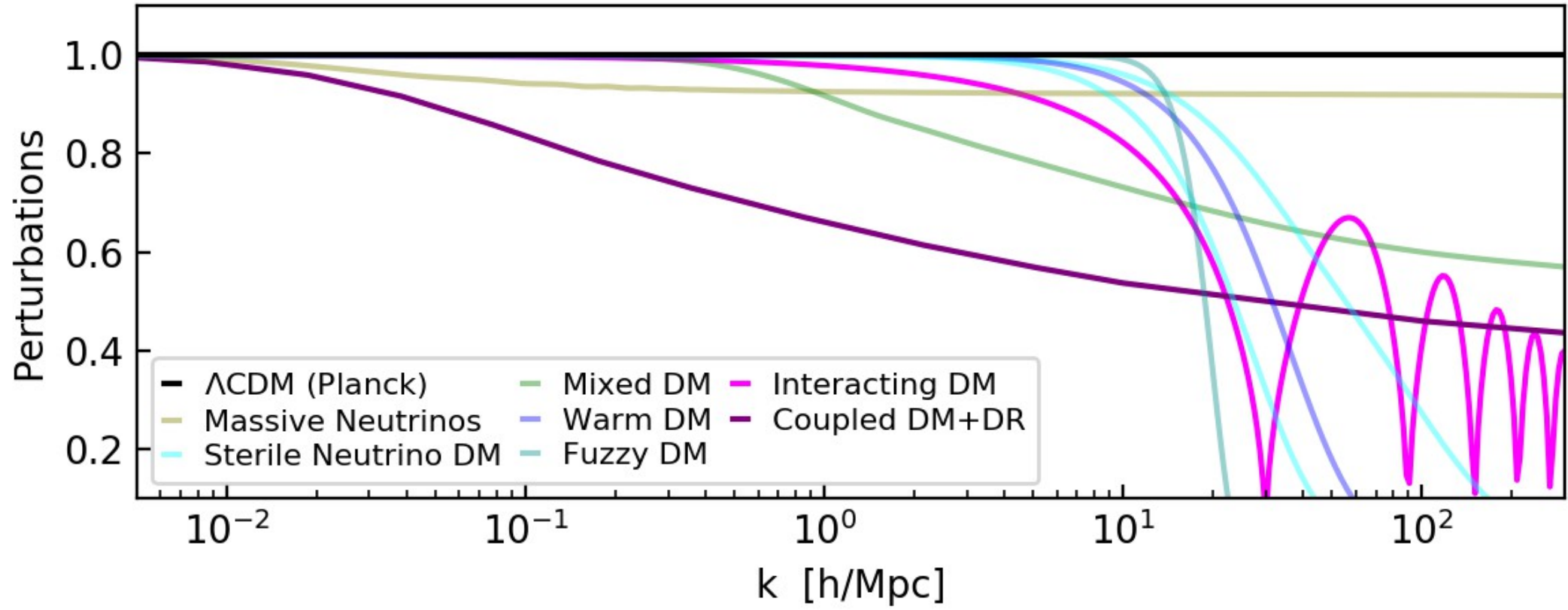
Linear Structure Formation – Interacting DM

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

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

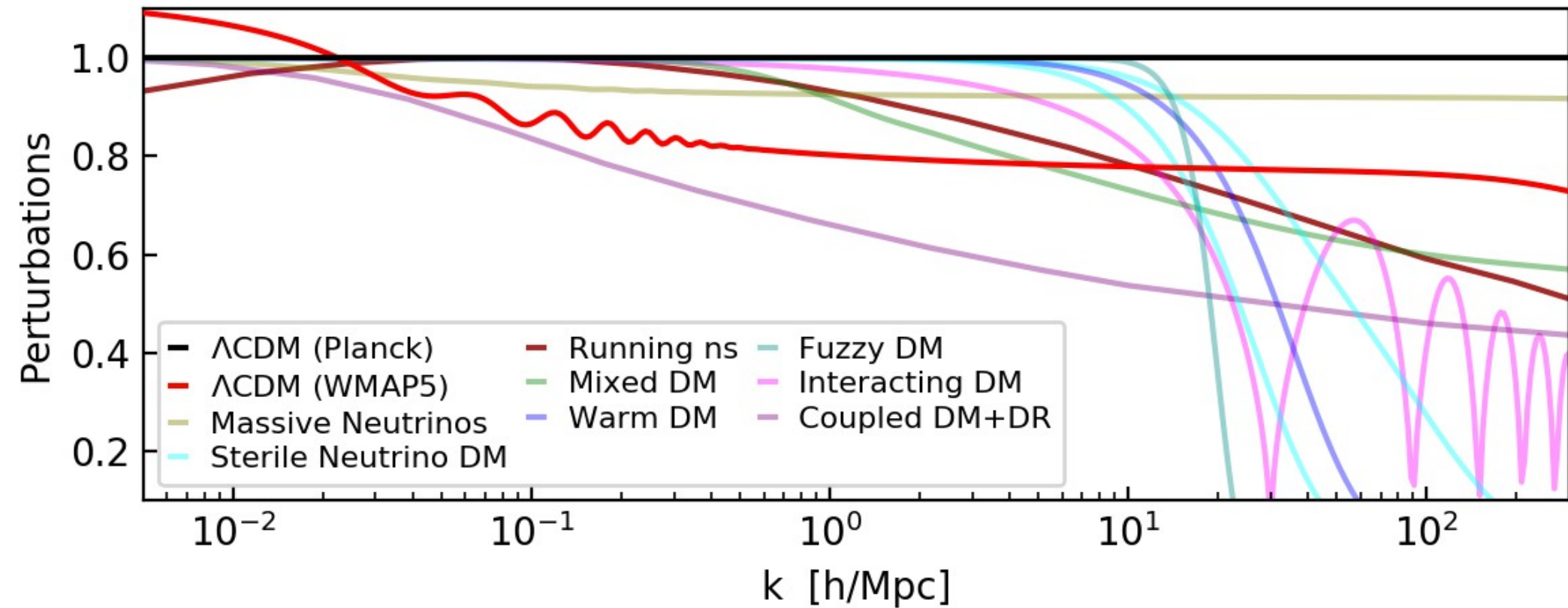
$$\dot{\theta} + H\theta - k^2 c_s^2 \delta - k^2 \psi = R(\theta_\chi - \theta)$$

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

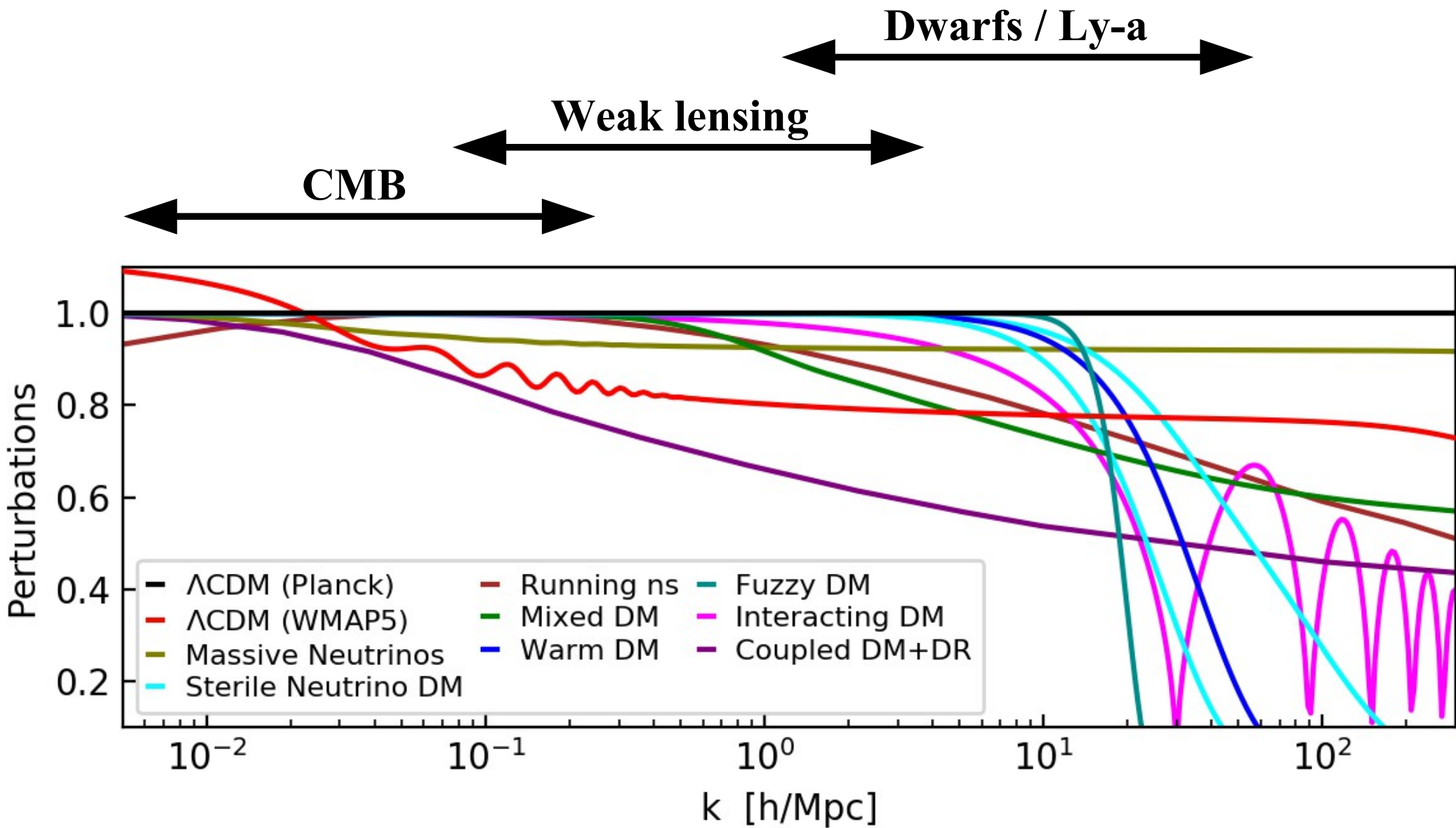


Linear Structure Formation – Non-DM effects

Changing / Extending Cosmological parameters



Linear Structure Formation – Non-DM effects



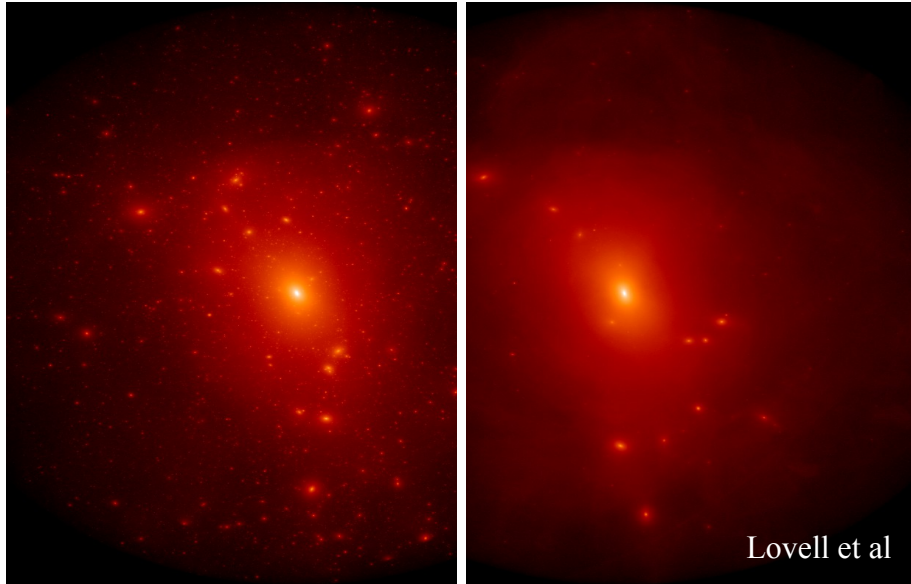
DM and structure formation: 2 options

Constraining DM models

Solving problems (?) of structure
formation

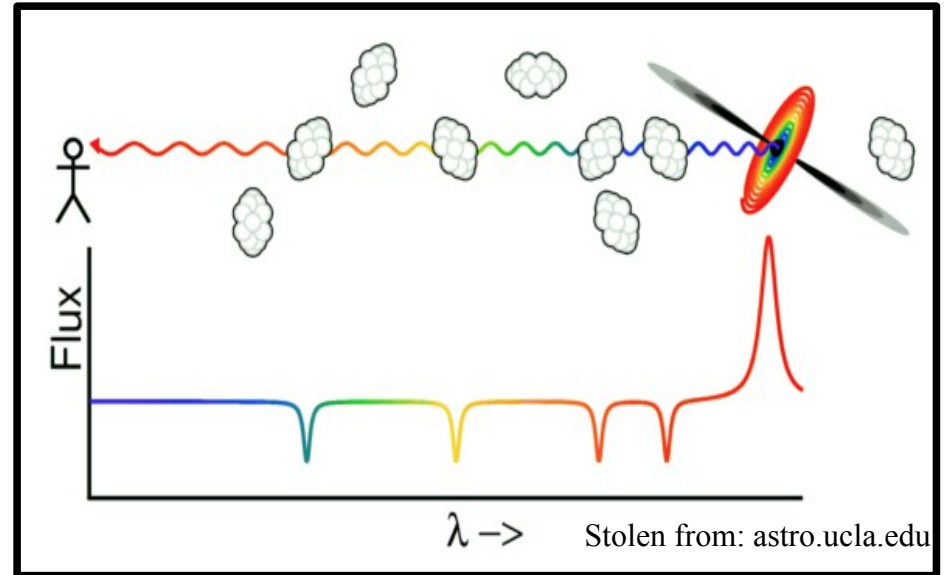
Constraining dark matter

Milky-Way satellites:



→ DM mass: $m > 2 \text{ keV}$ (e.g. AS 2015)

Lyman- α forest:



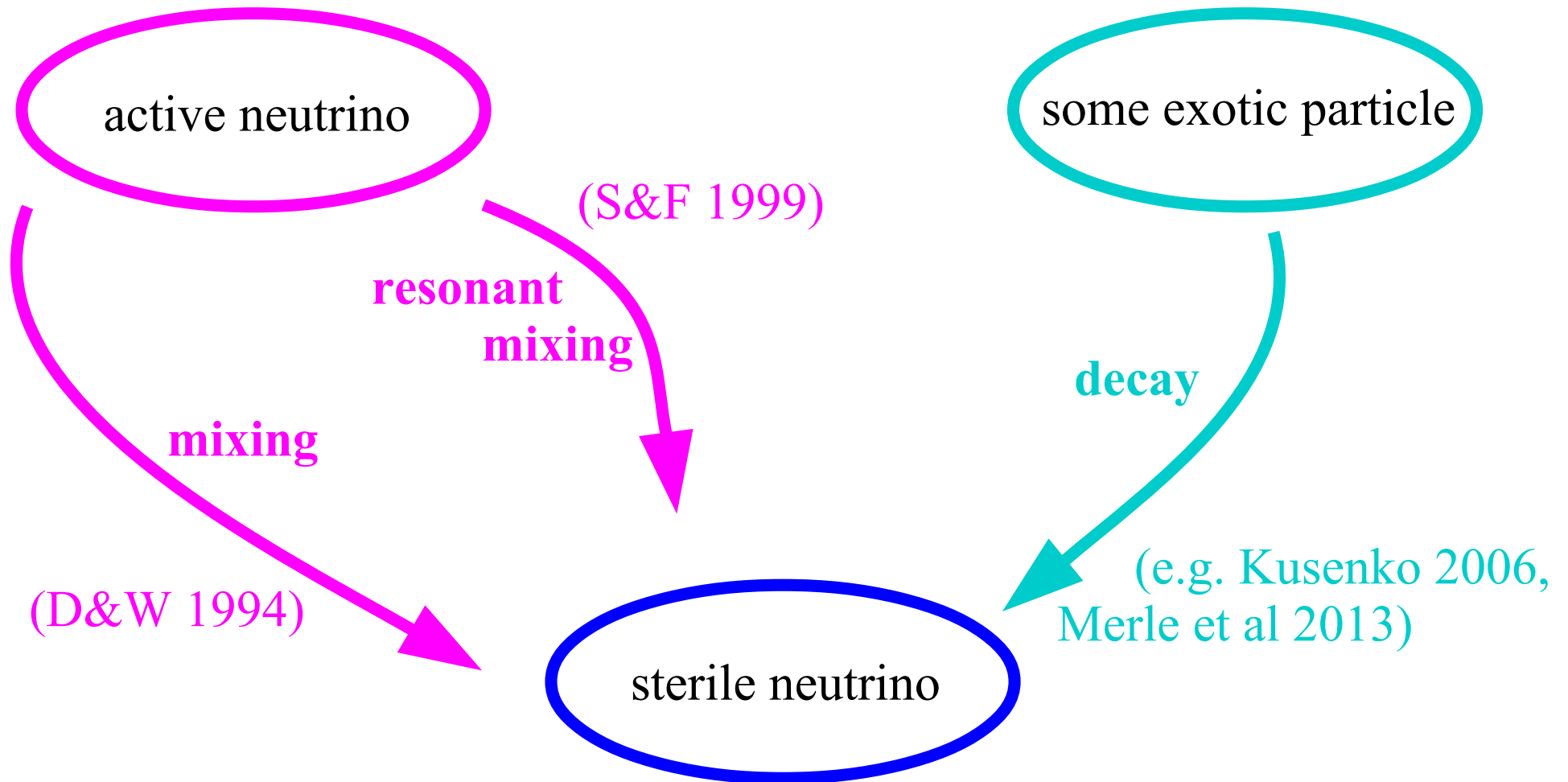
→ DM mass: $m > 3.3 \text{ keV}$ (e.g. Viel et al 2013)

Constraining DM: Sterile Neutrinos (**Example**)



sterile neutrino

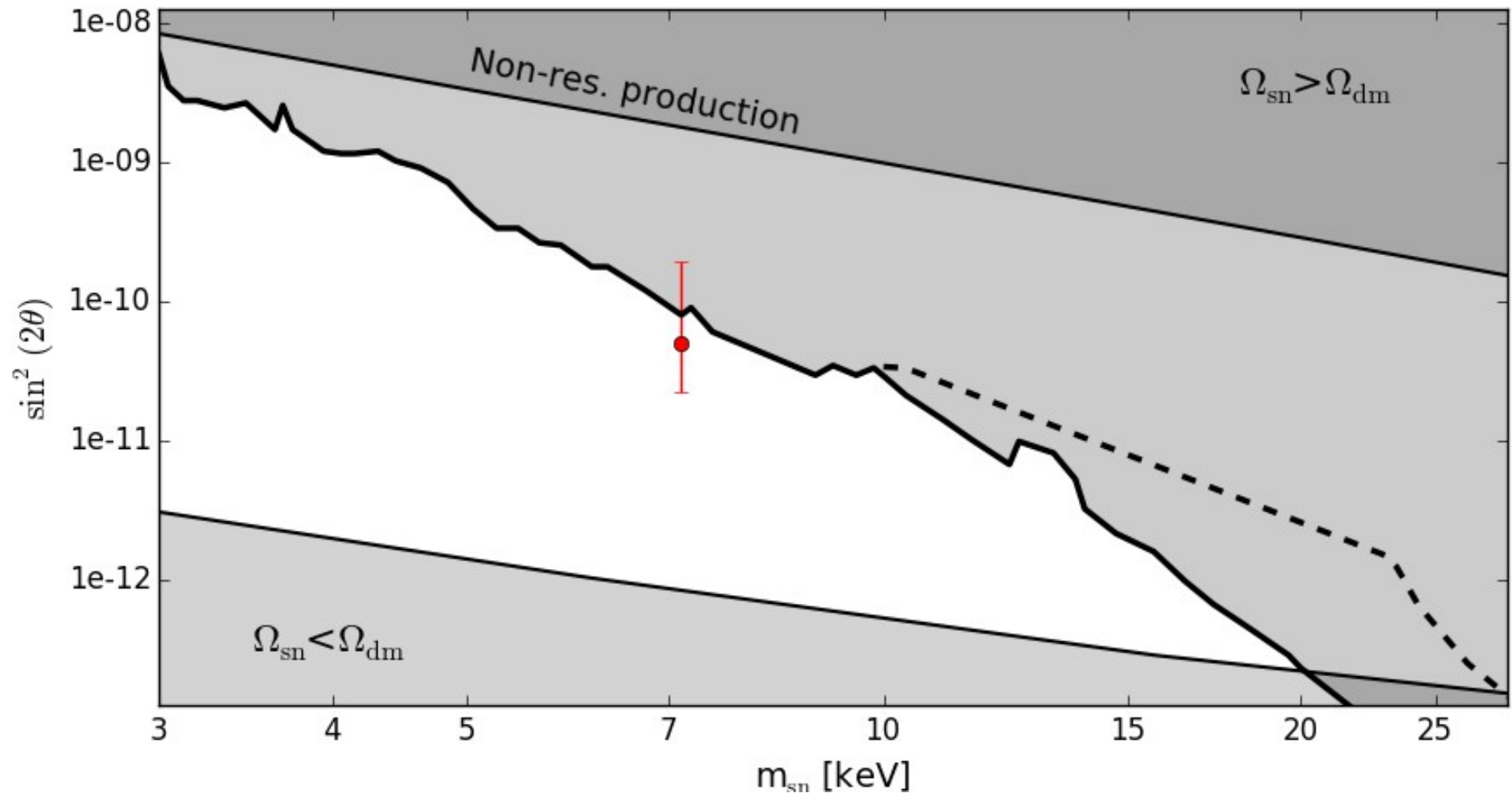
Constraining DM: Sterile Neutrinos (**Example**)



Constraining DM: Sterile Neutrinos (**Example**)

Production via mixing:

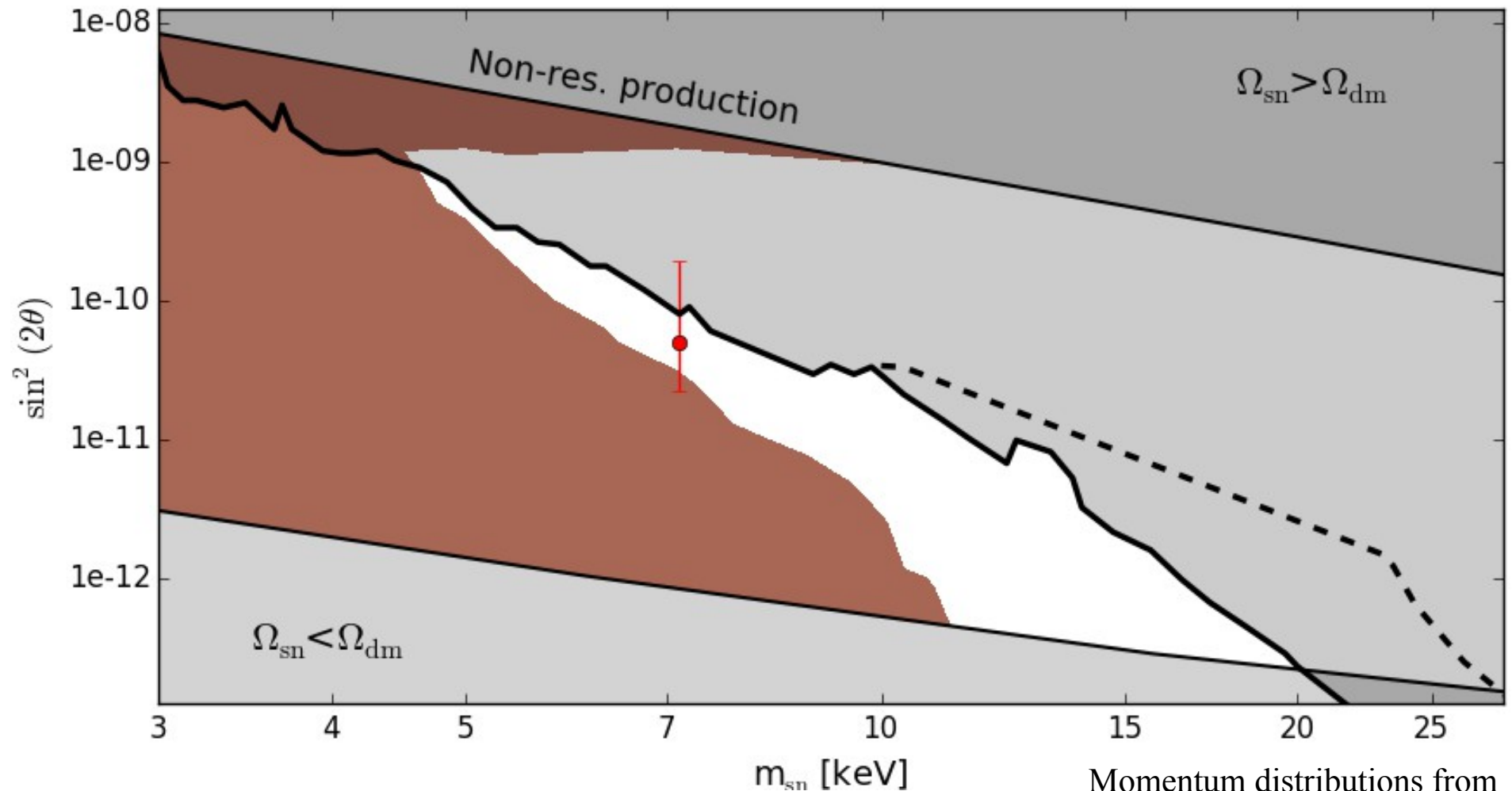
Schneider (2016)



Constraining DM: Sterile Neutrinos (**Example**)

Production via mixing: limits from satellites

Schneider (2016)

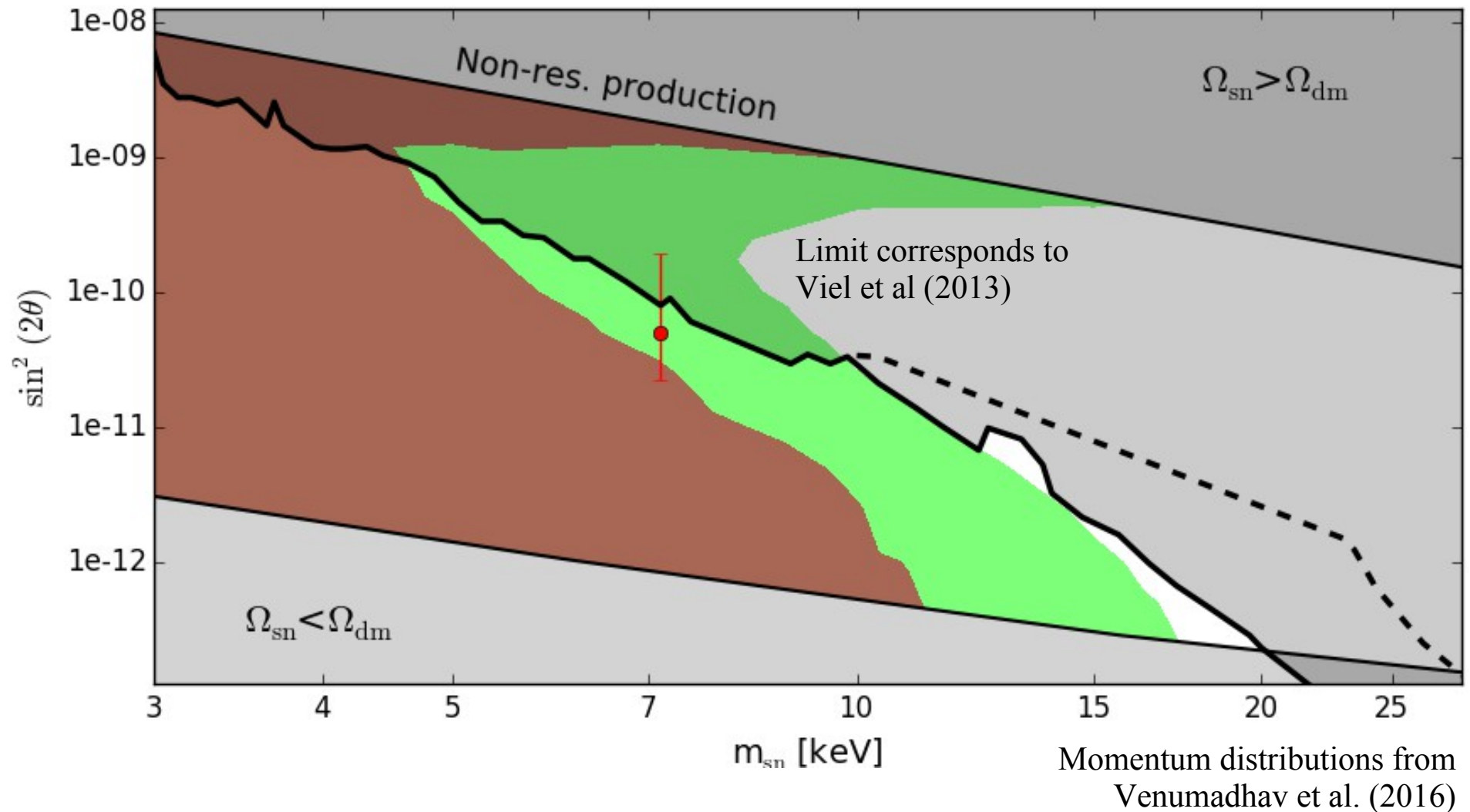


Momentum distributions from
Venumadhav et al. (2016)

Constraining DM: Sterile Neutrinos (**Example**)

Production via mixing: limits from Lyman- α

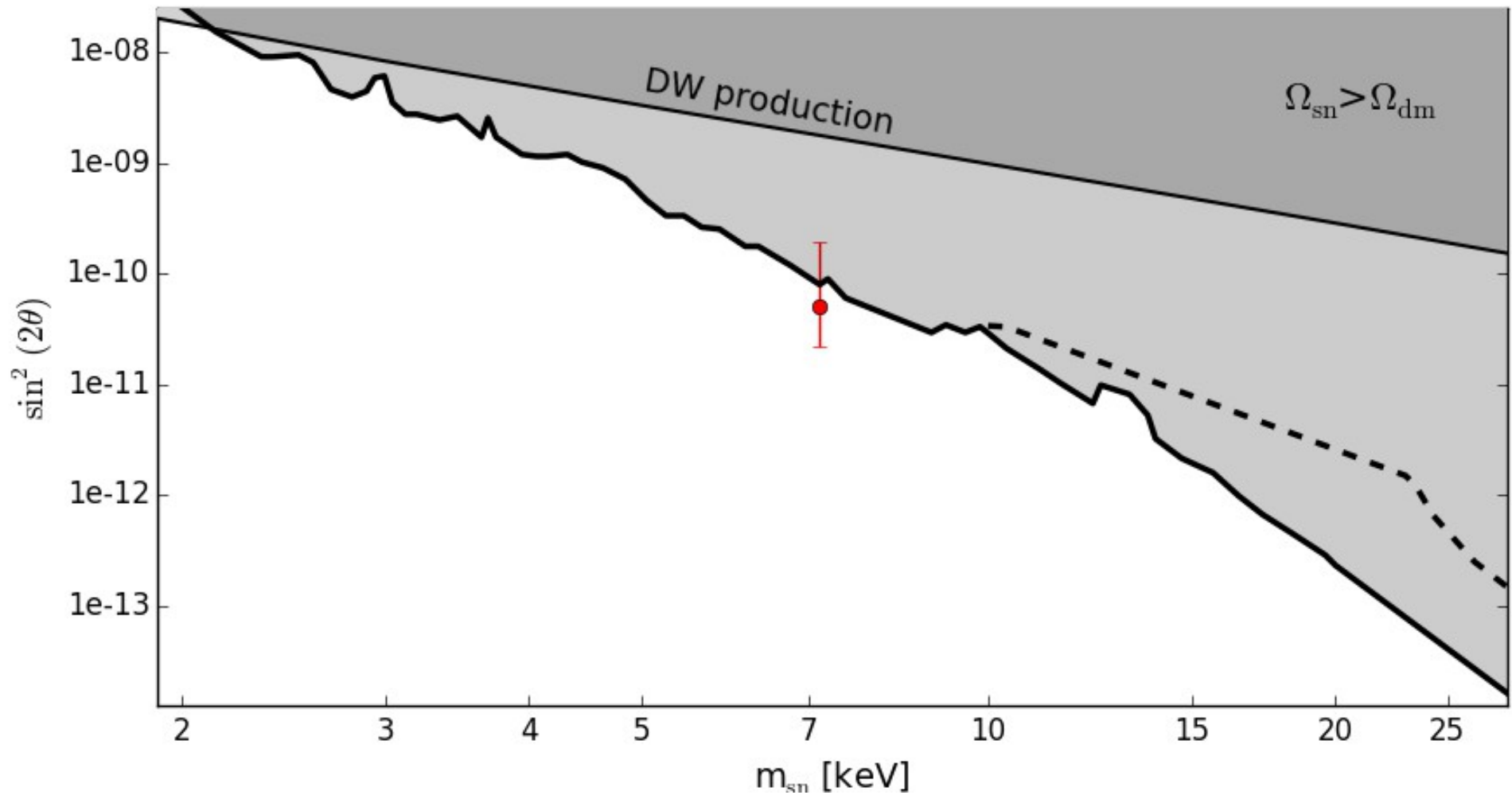
Schneider (2016)



Constraining DM: Sterile Neutrinos (**Example**)

Production via scalar decay:

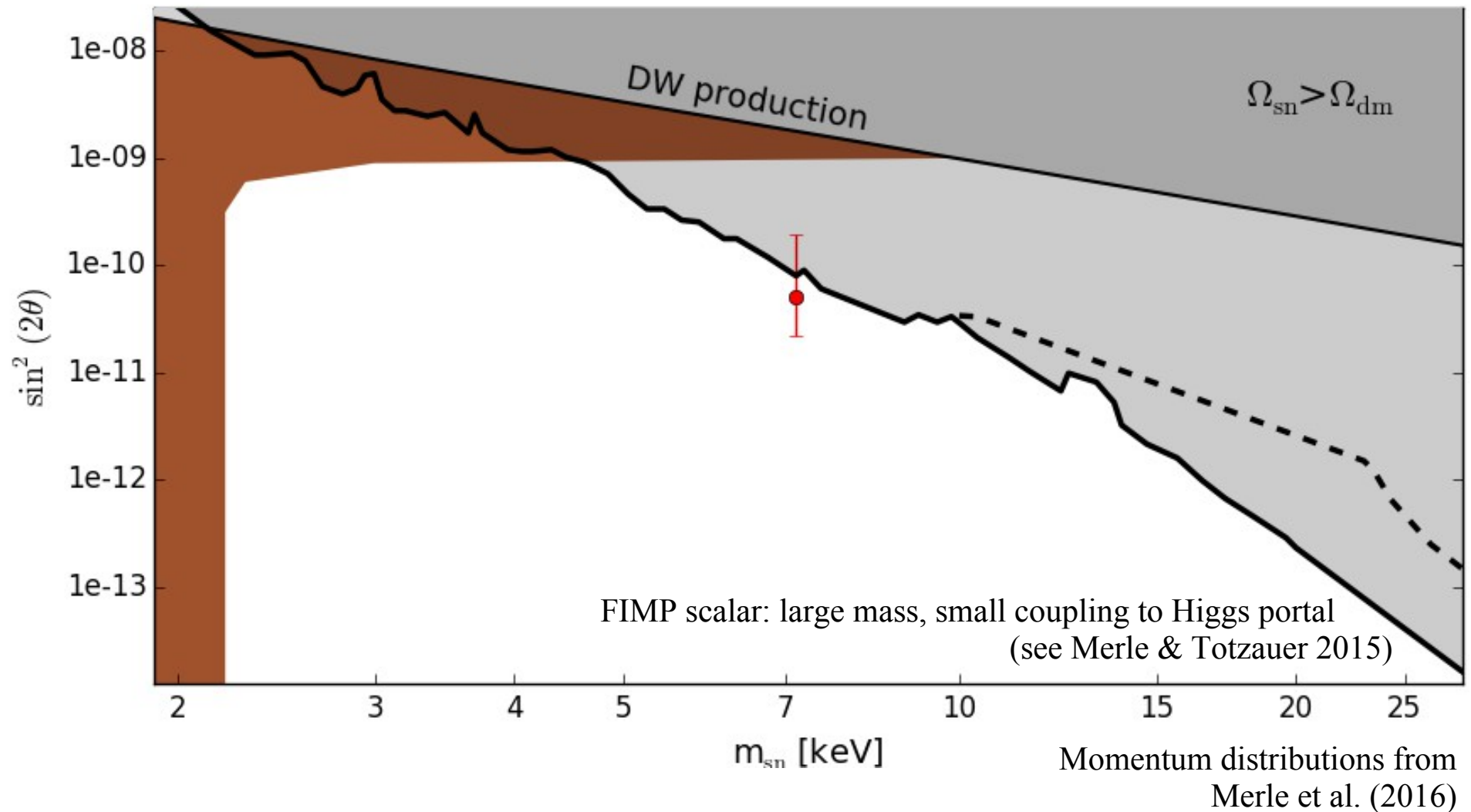
Schneider (2017)



Constraining DM: Sterile Neutrinos (**Example**)

Production via scalar decay: limits from satellites

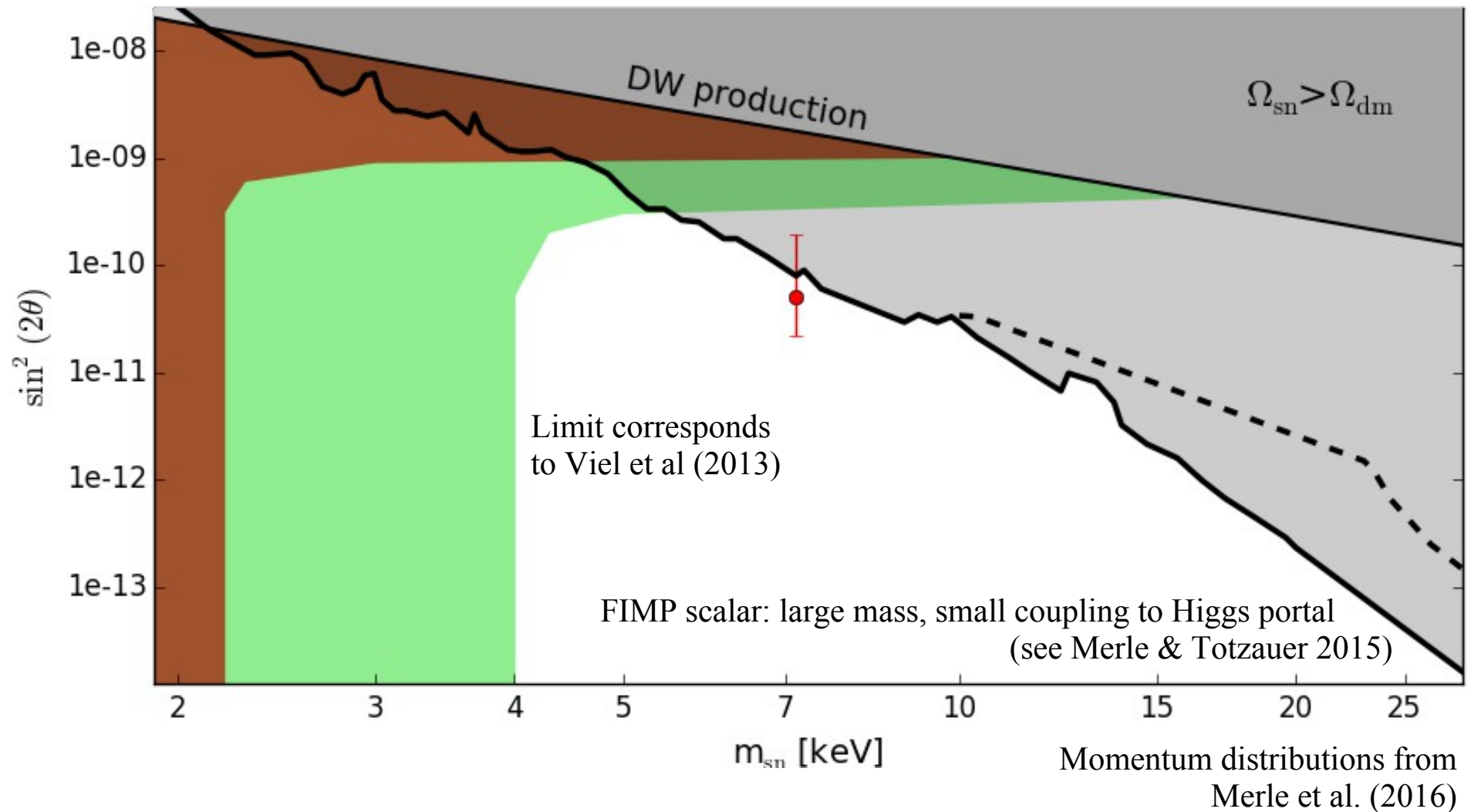
Schneider (2017)



Constraining DM: Sterile Neutrinos (**Example**)

Production via scalar decay: limits from Lyman- α

Schneider (2017)



DM and structure formation: 2 options

Constraining dark matter models

Solving problems (?) of structure
formation

DM and structure formation: 2 options

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Missing Satellites

Too Big To Fail

Cusp Core

Velocity function – including feedback

Small galaxies in the local volume:

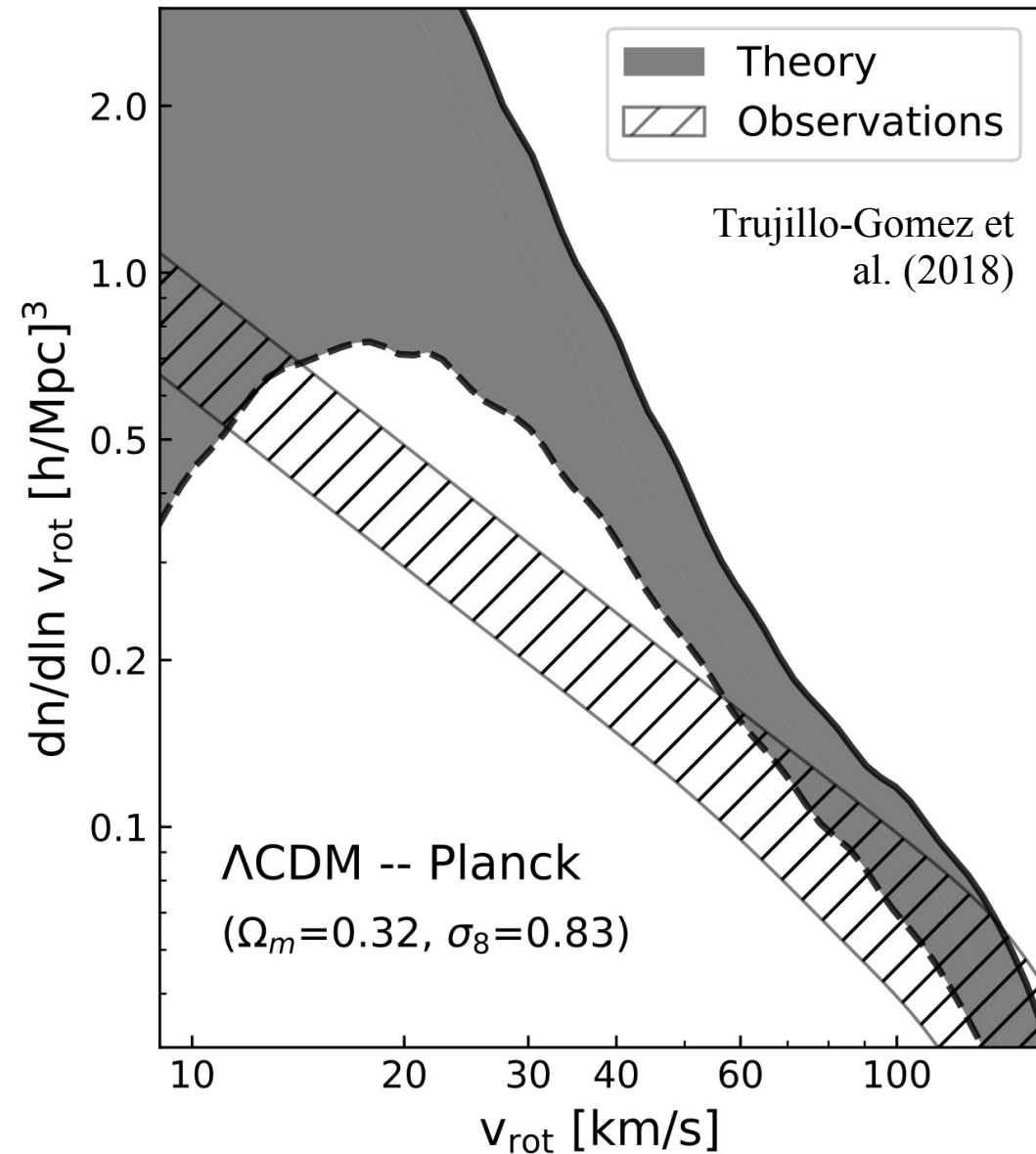
A powerful probe for dark matter
and cosmology !

Velocity function – including feedback

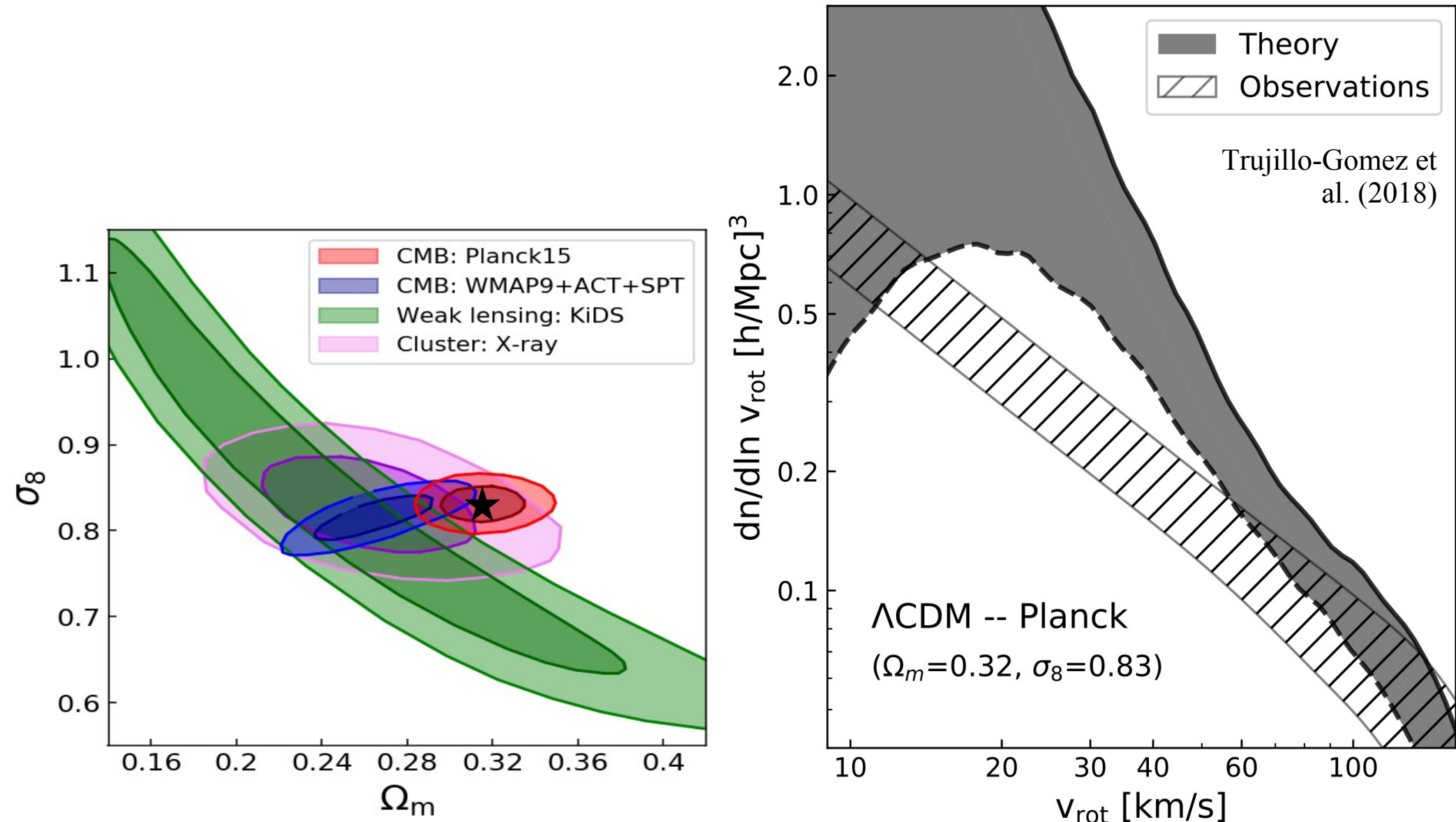
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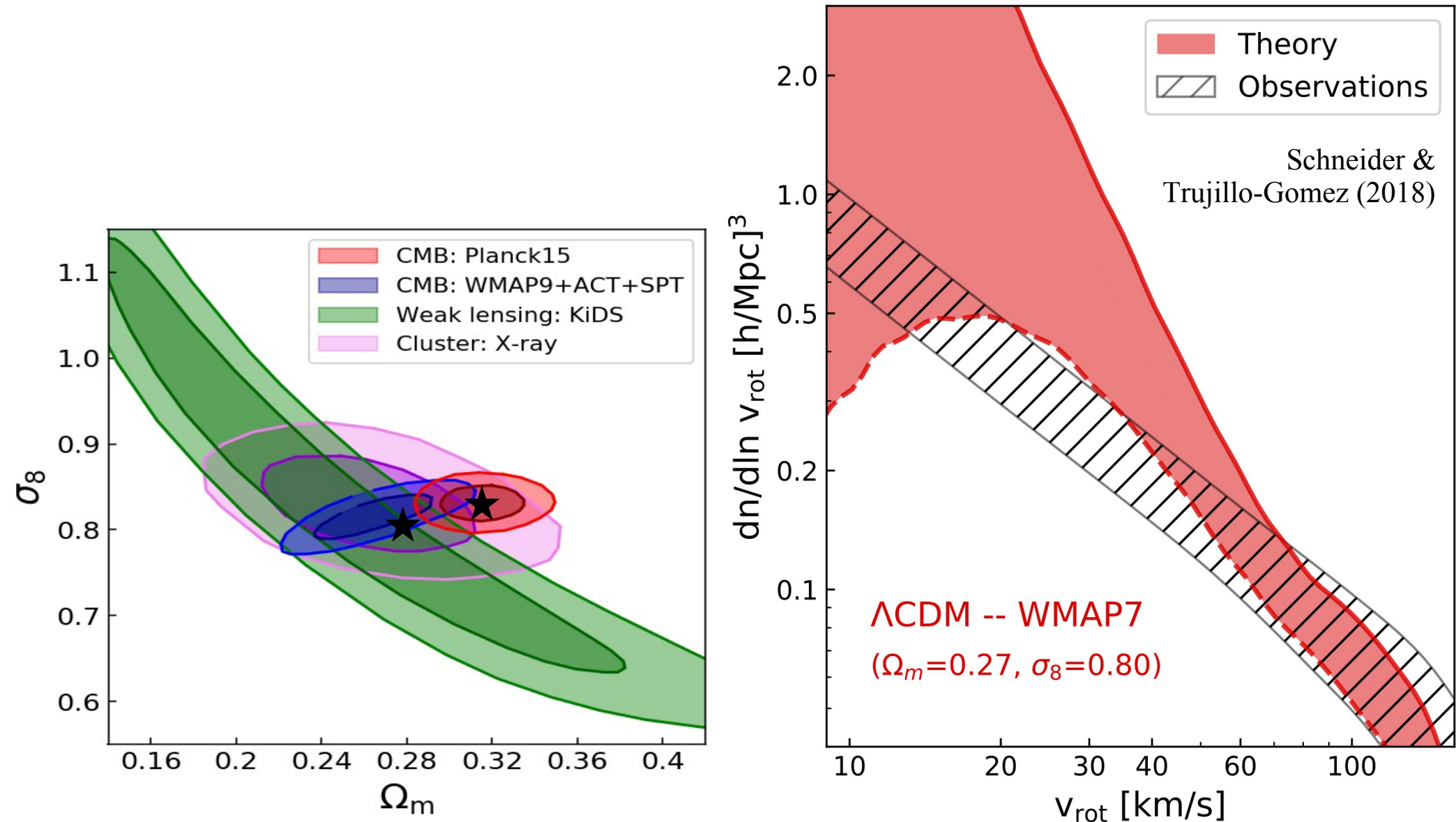
Grey band: area between zero and
maximum allowed feedback!



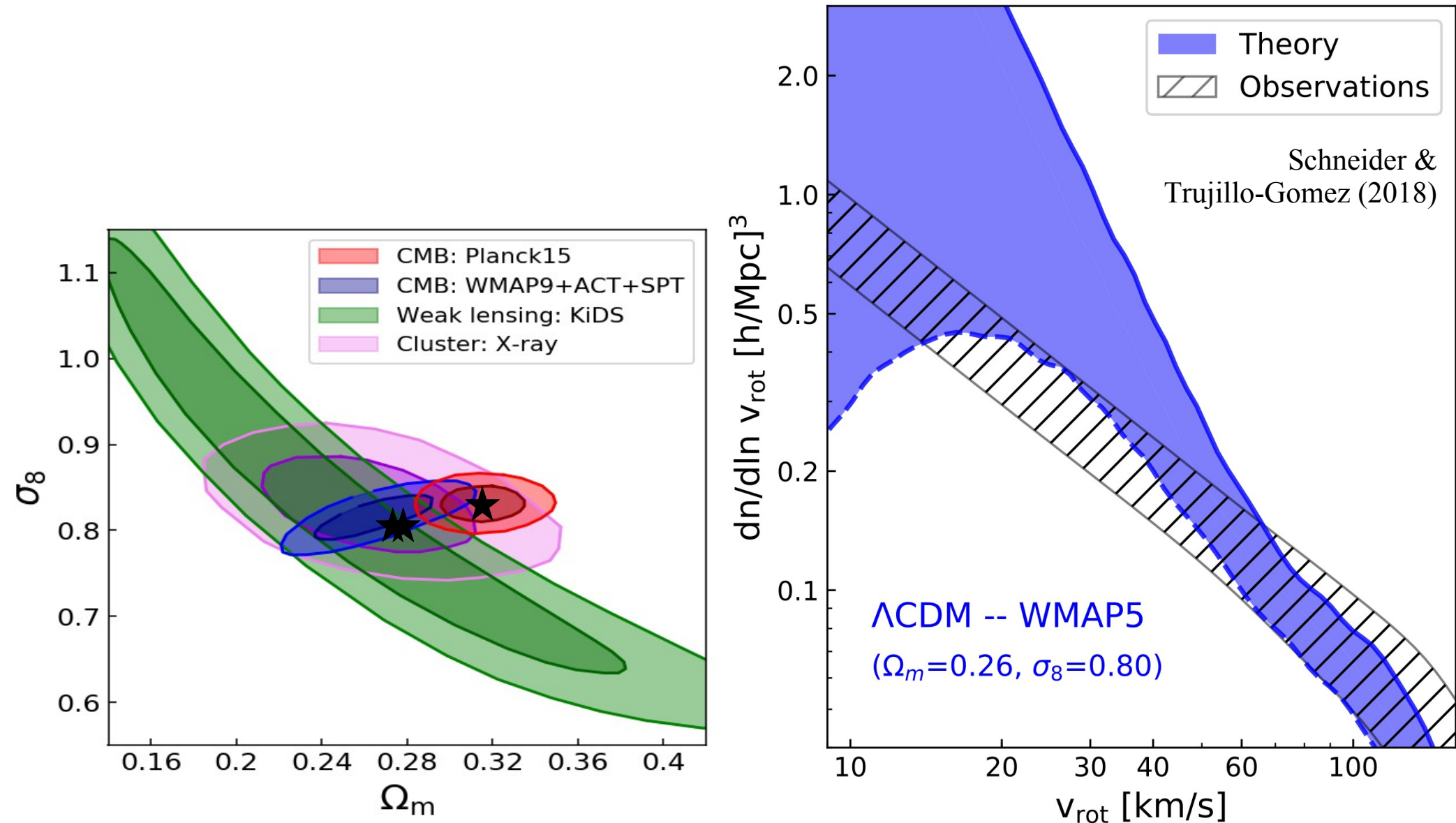
Velocity function – Cosmology



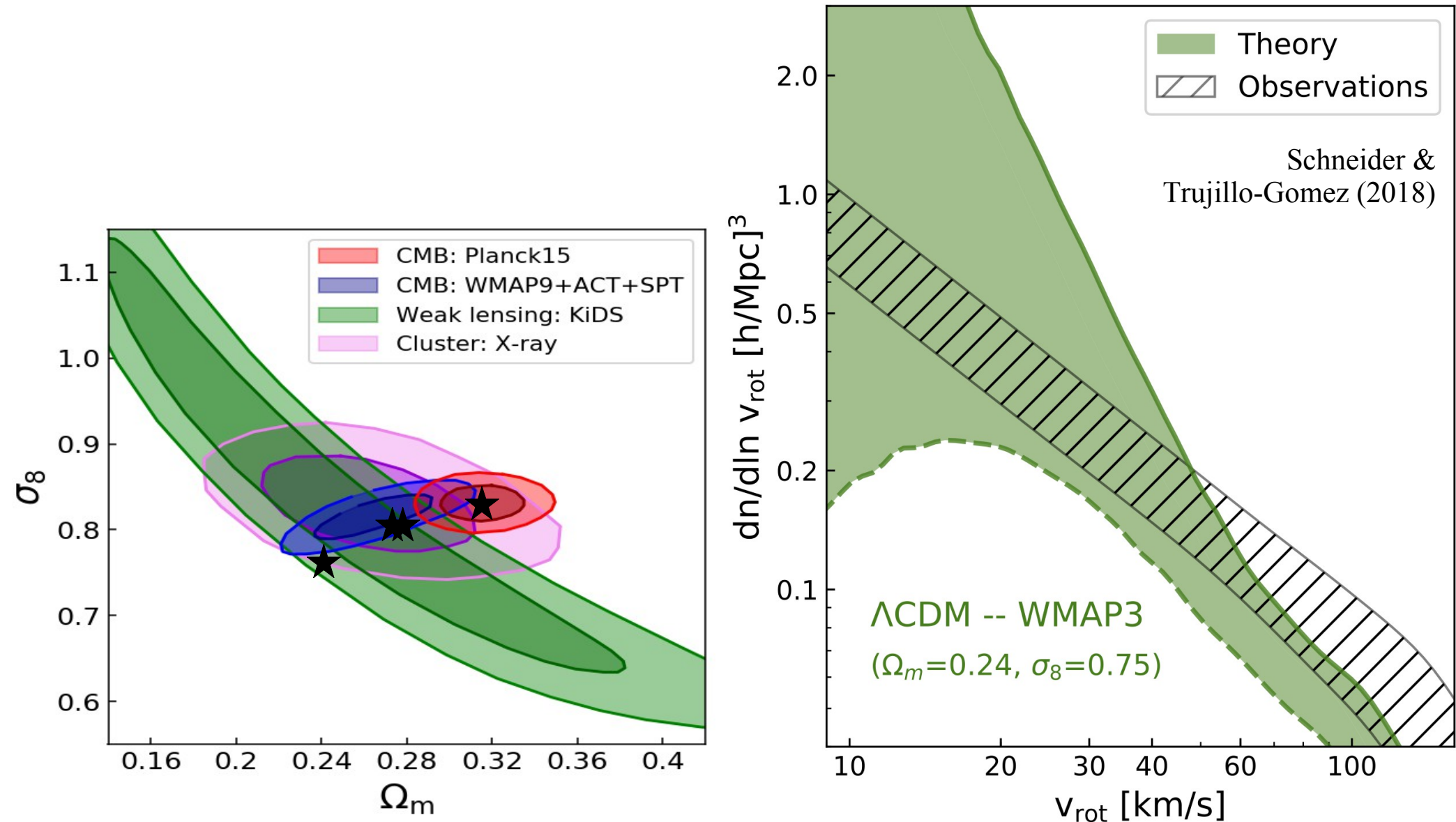
Velocity function – Cosmology



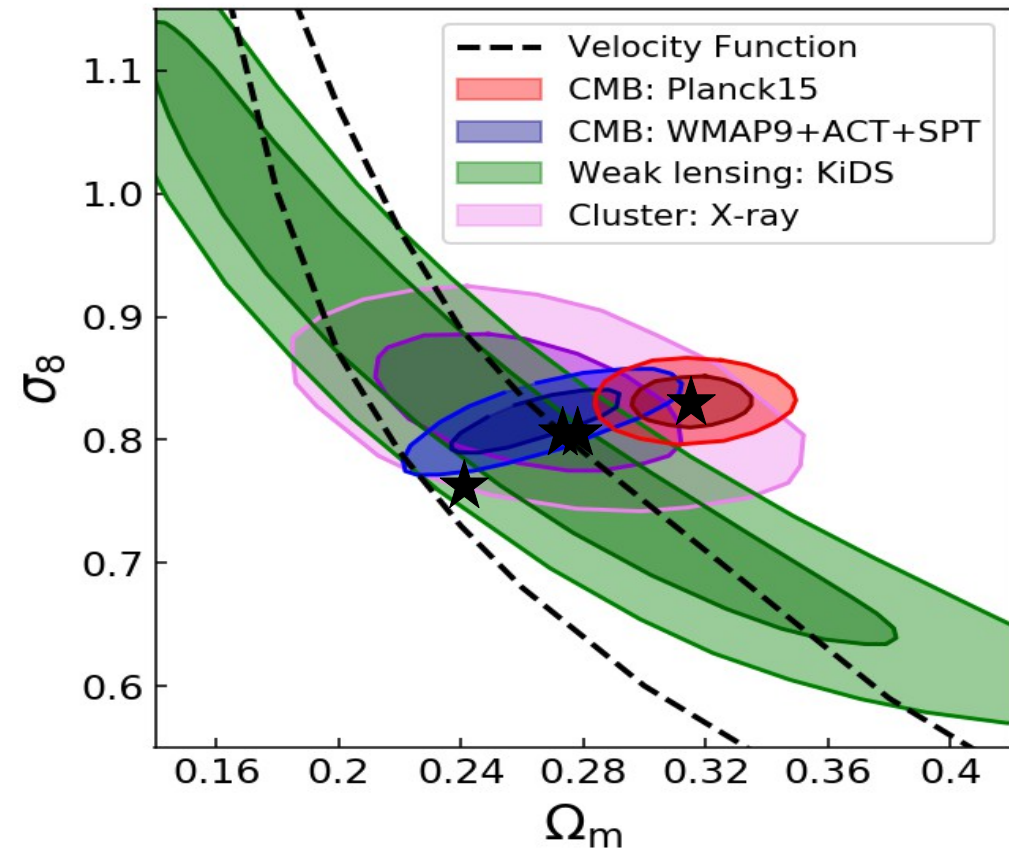
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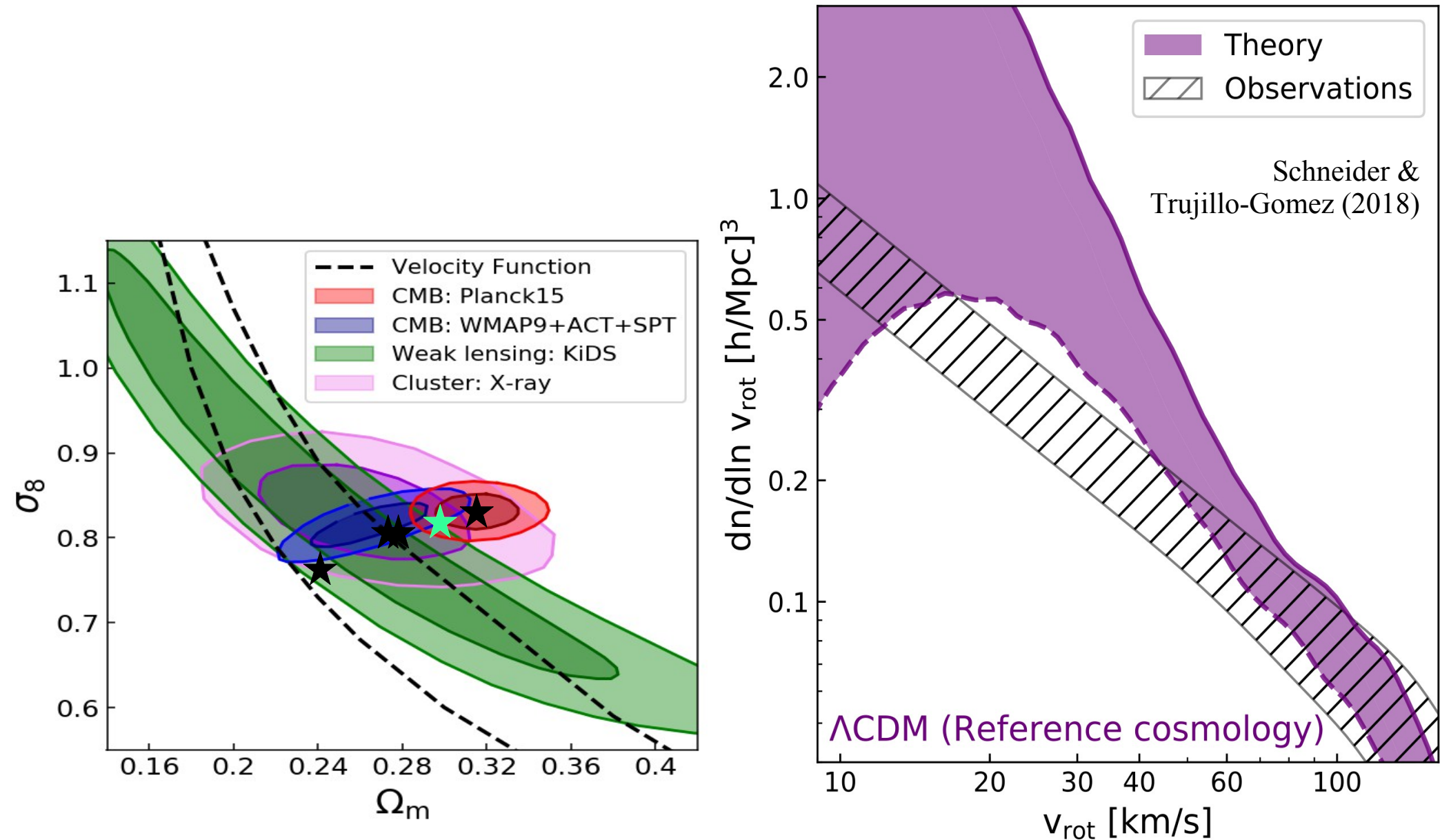
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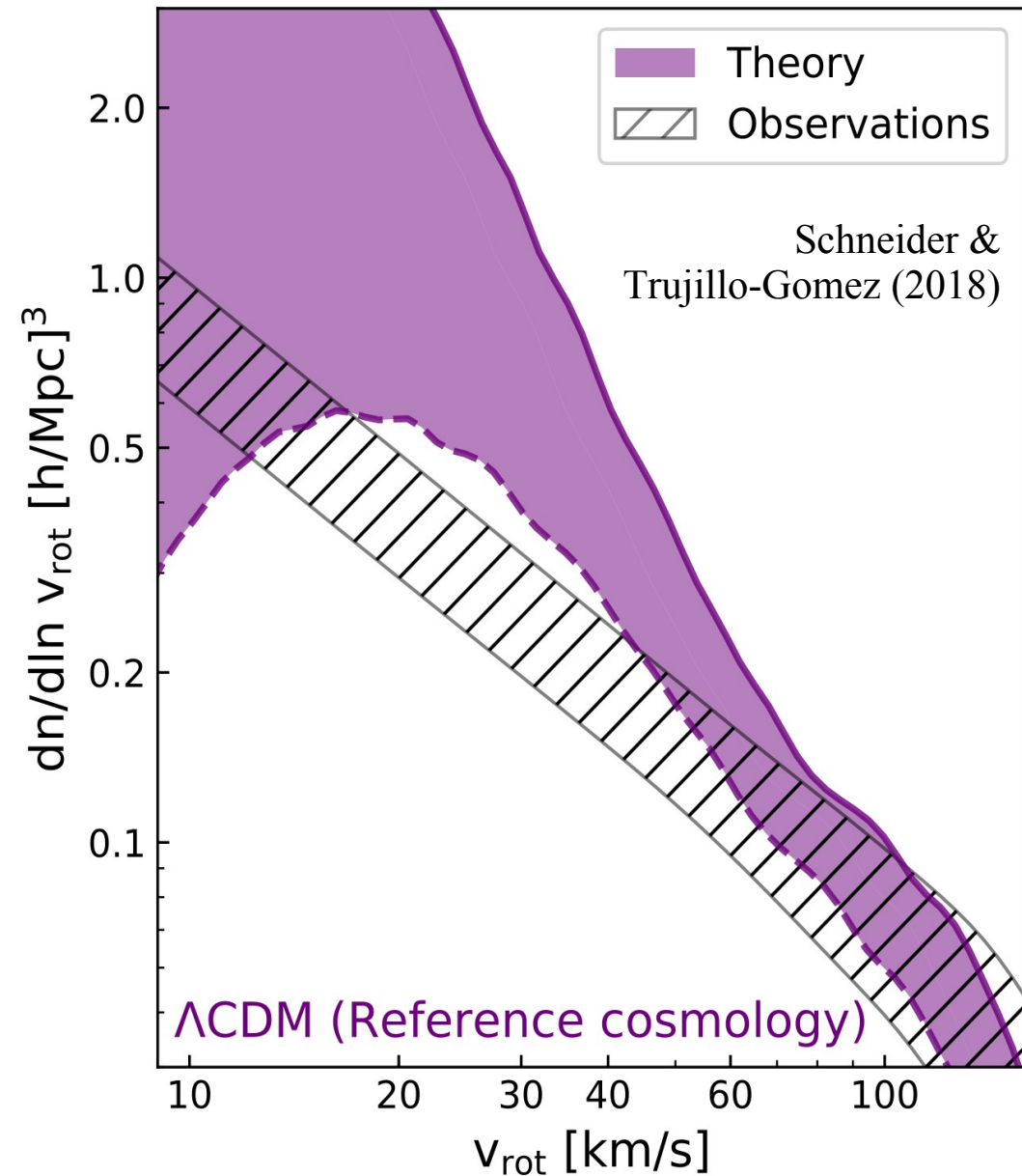


Velocity function – Dark Matter



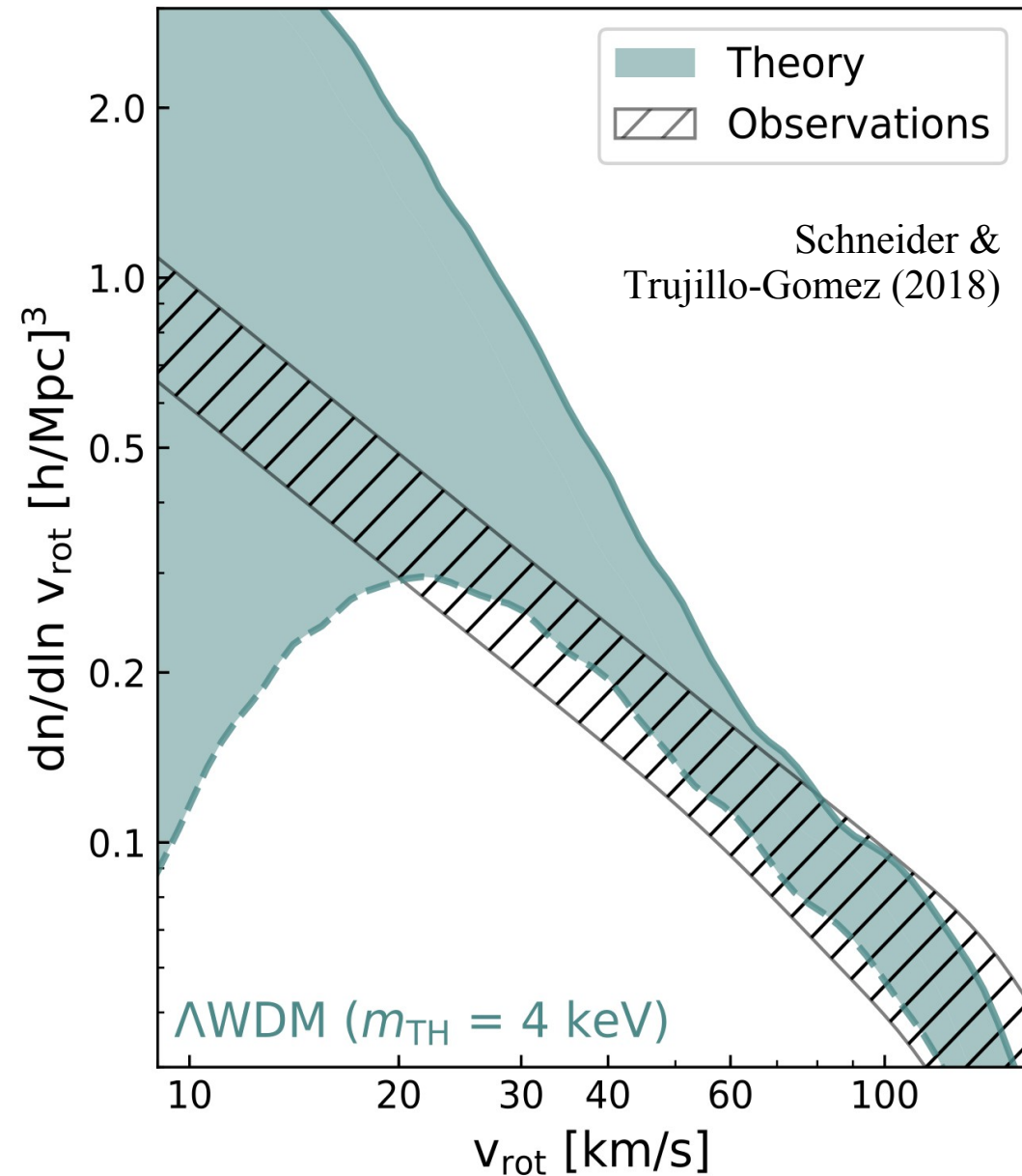
Velocity function – Dark Matter

... heating up
the dark matter sector



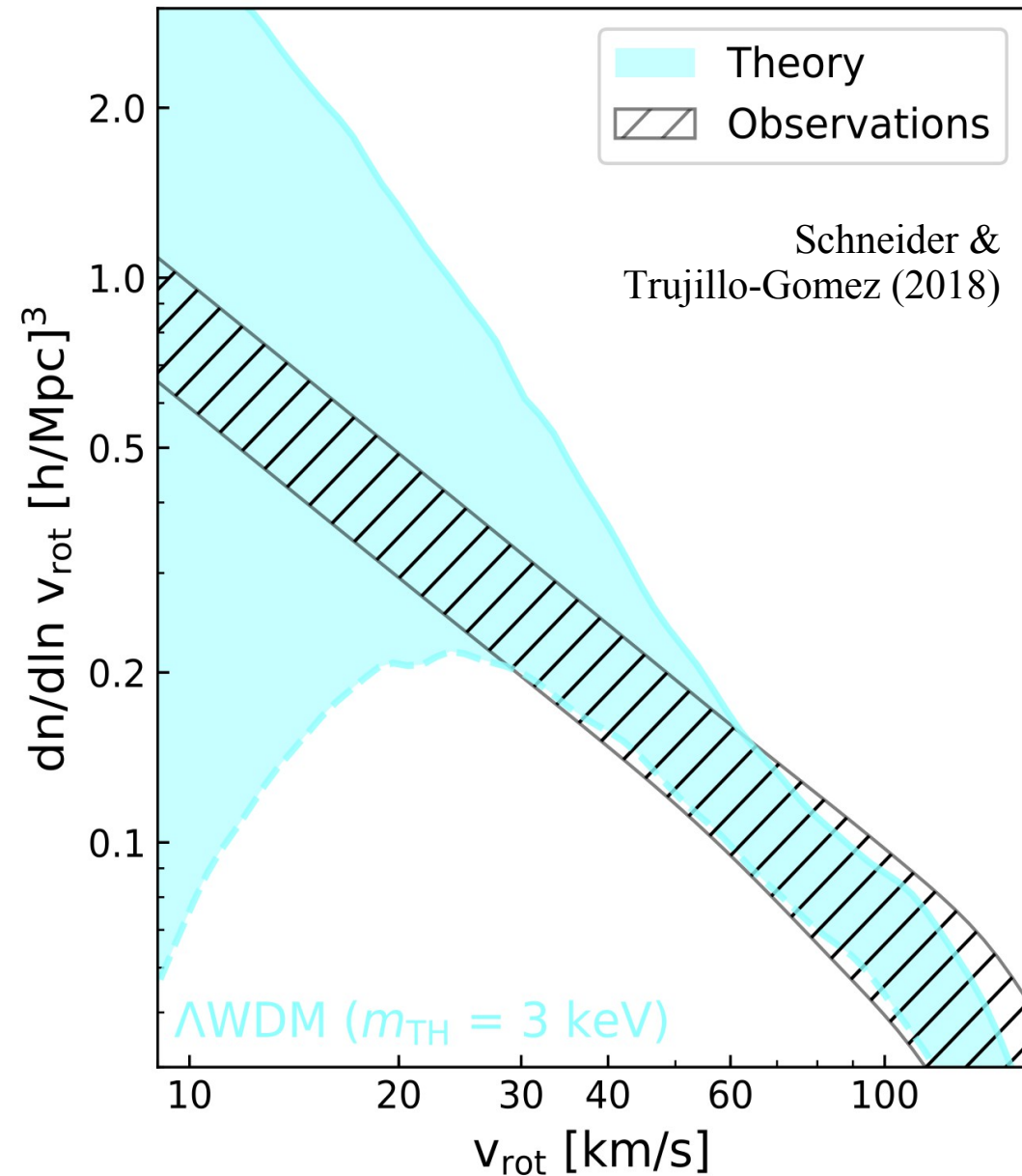
Velocity function – Warm Dark Matter

... heating up
the dark matter sector



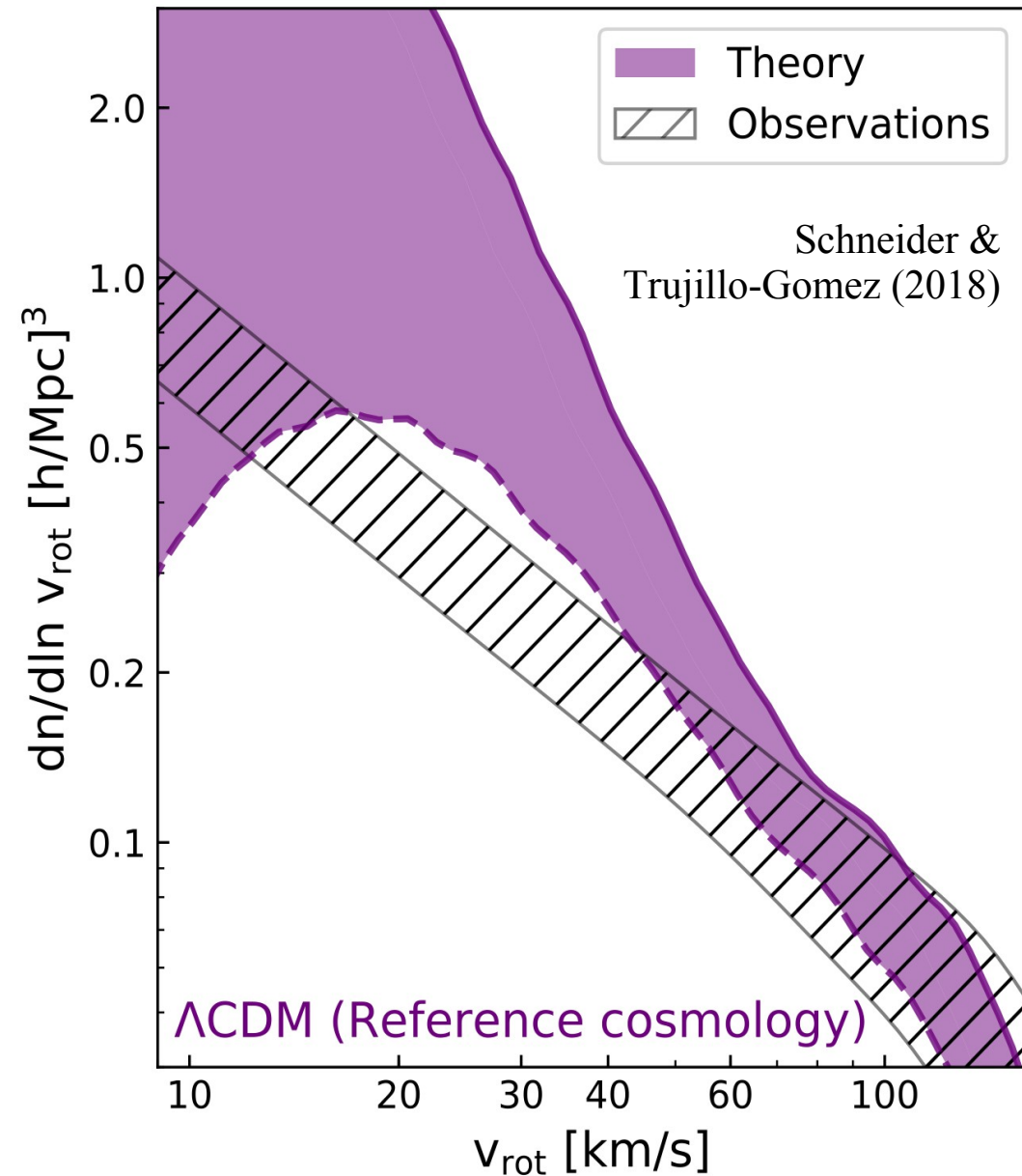
Velocity function – Warm Dark Matter

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the dark matter sector



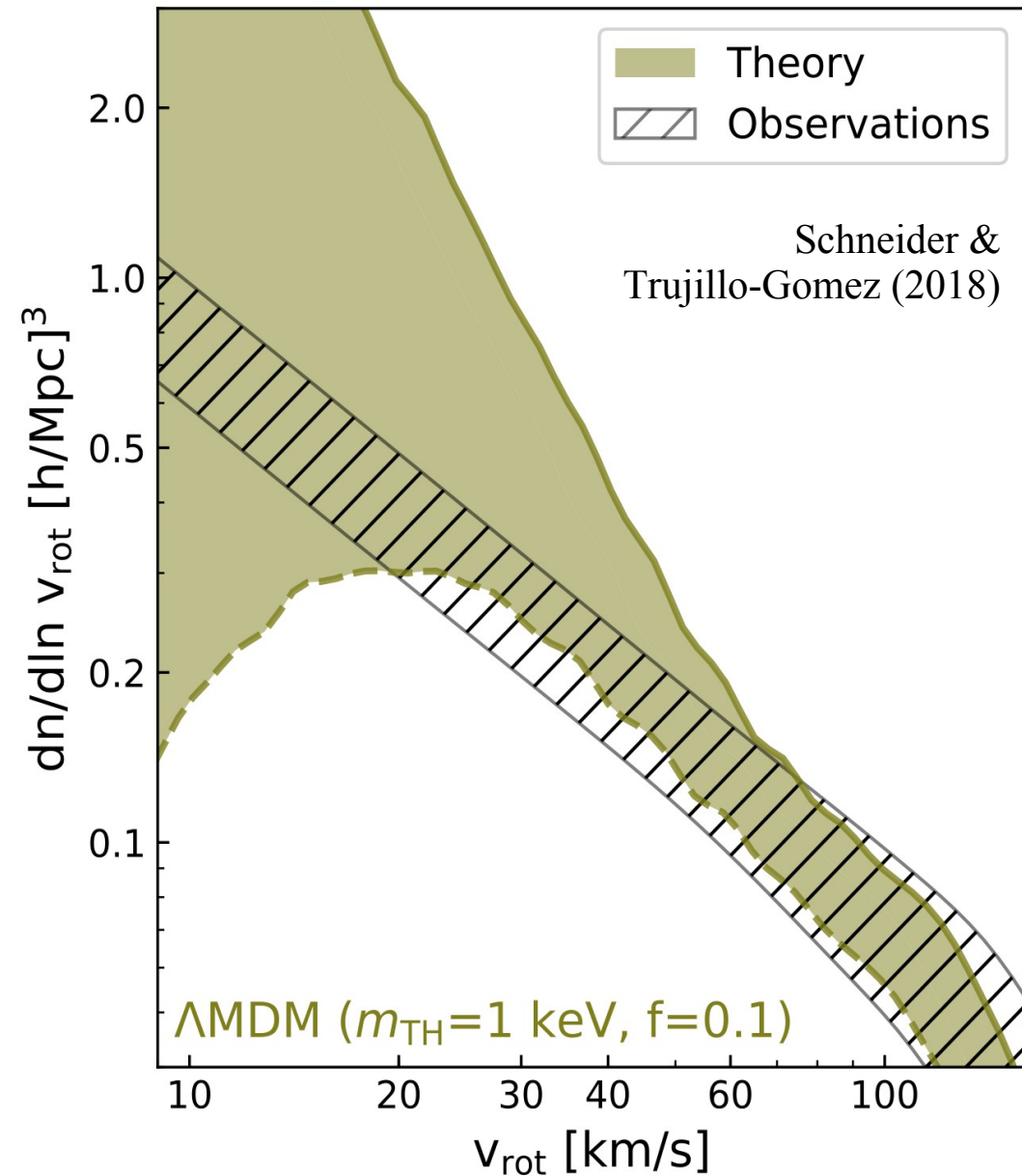
Velocity function – Mixed Dark Matter

... mixing up
the dark matter sector



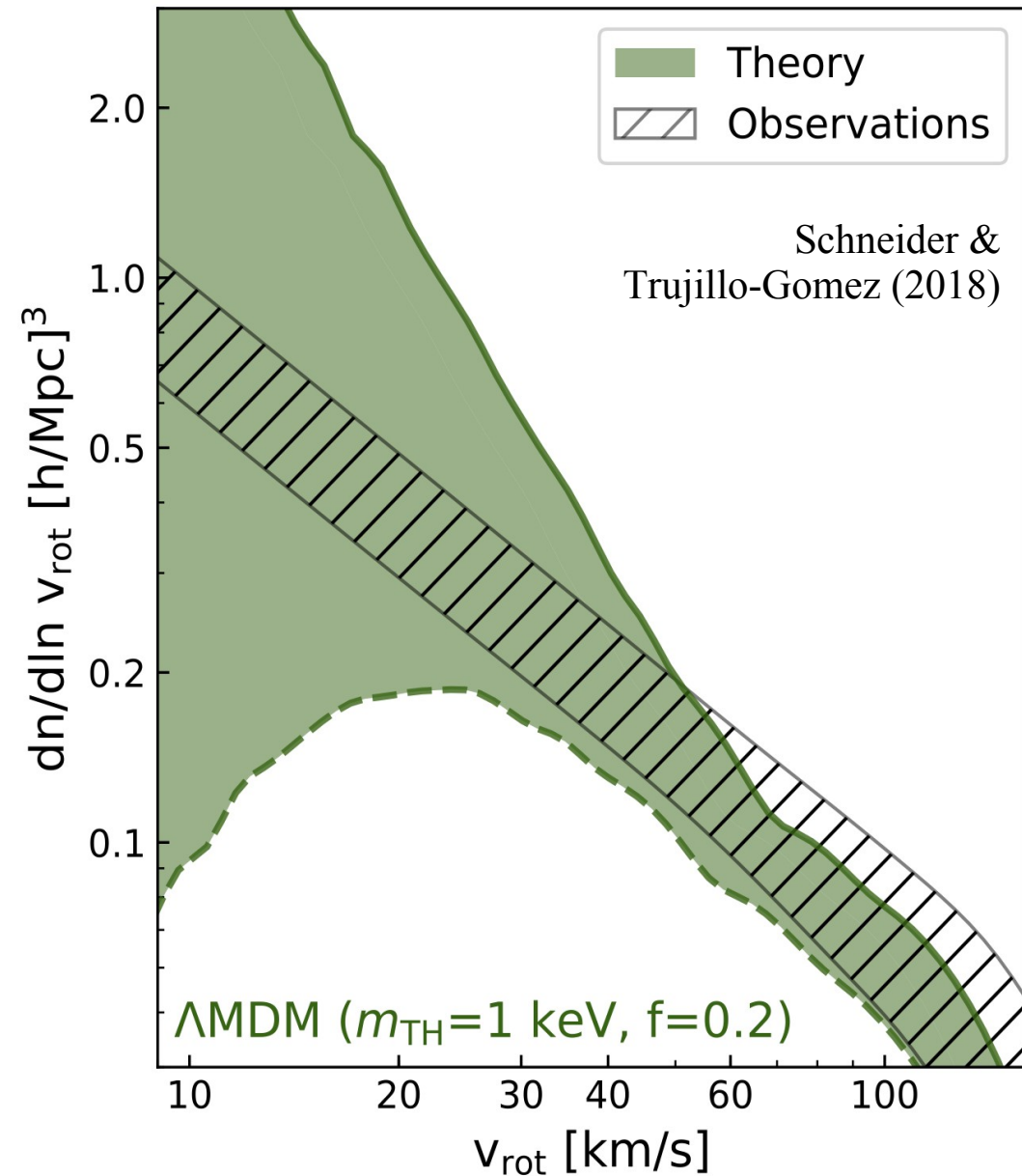
Velocity function – Mixed Dark Matter

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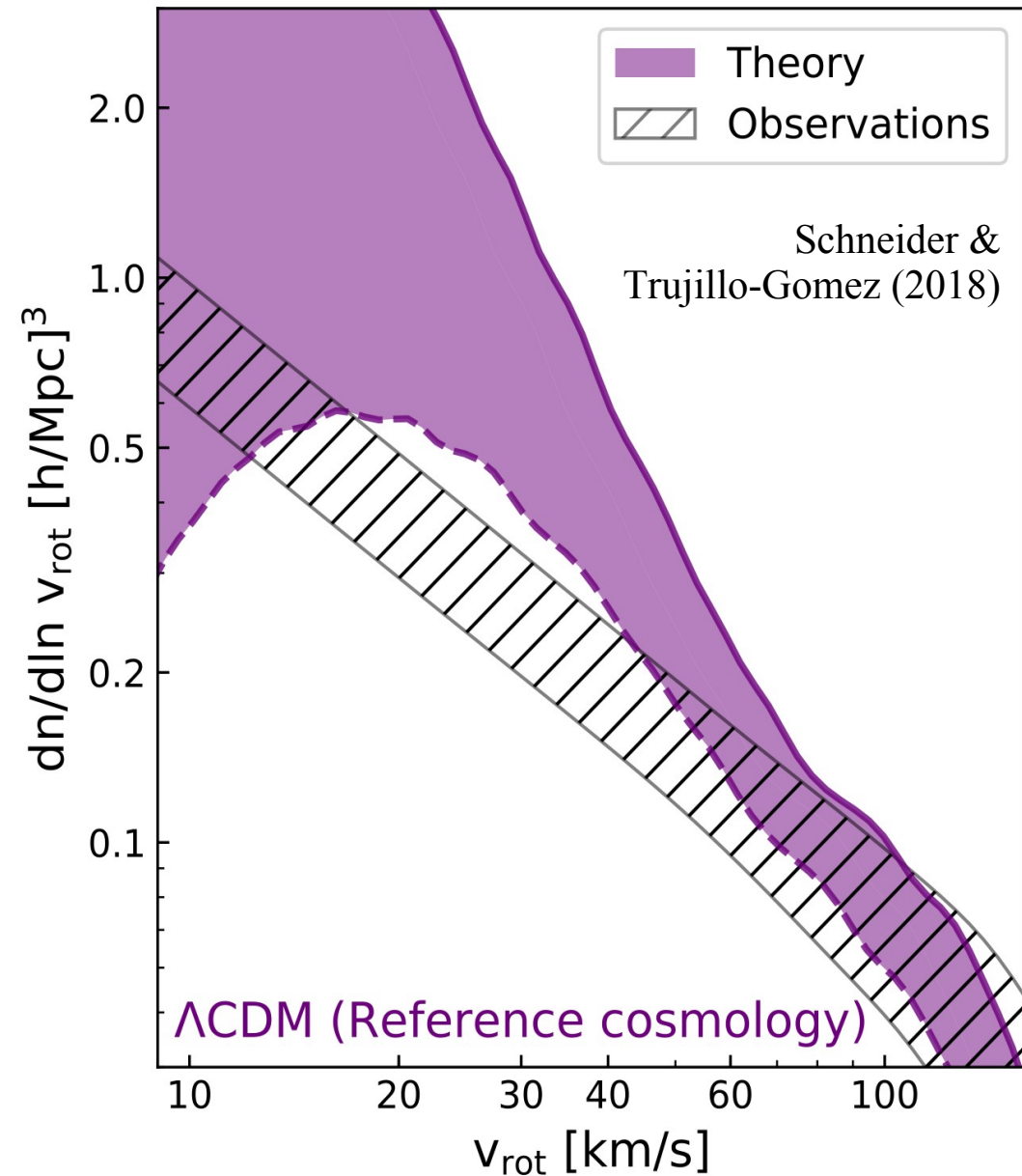
Velocity function – Mixed Dark Matter

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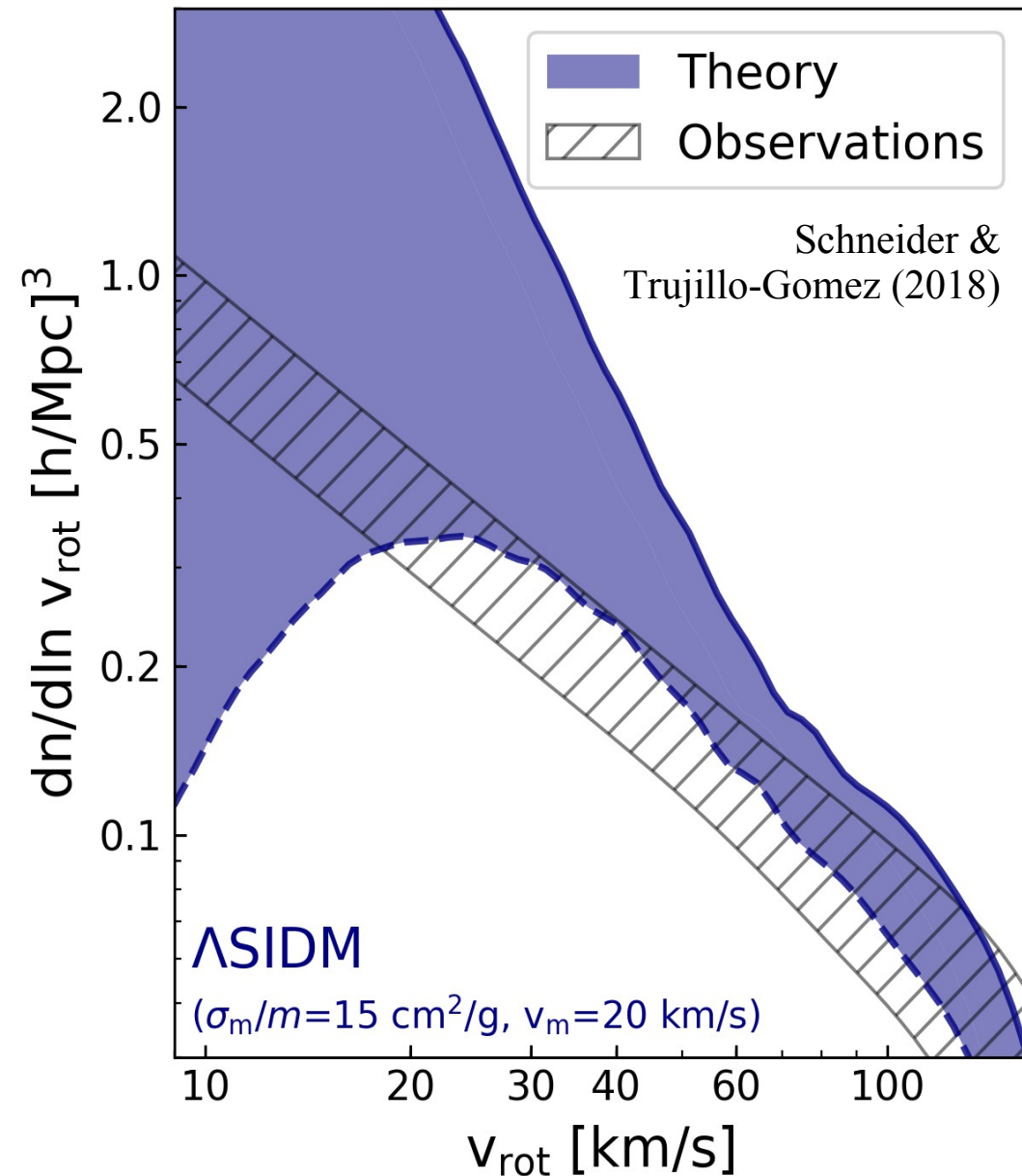
Velocity function – Mixed Dark Matter

... **self-interacting**
dark matter sector



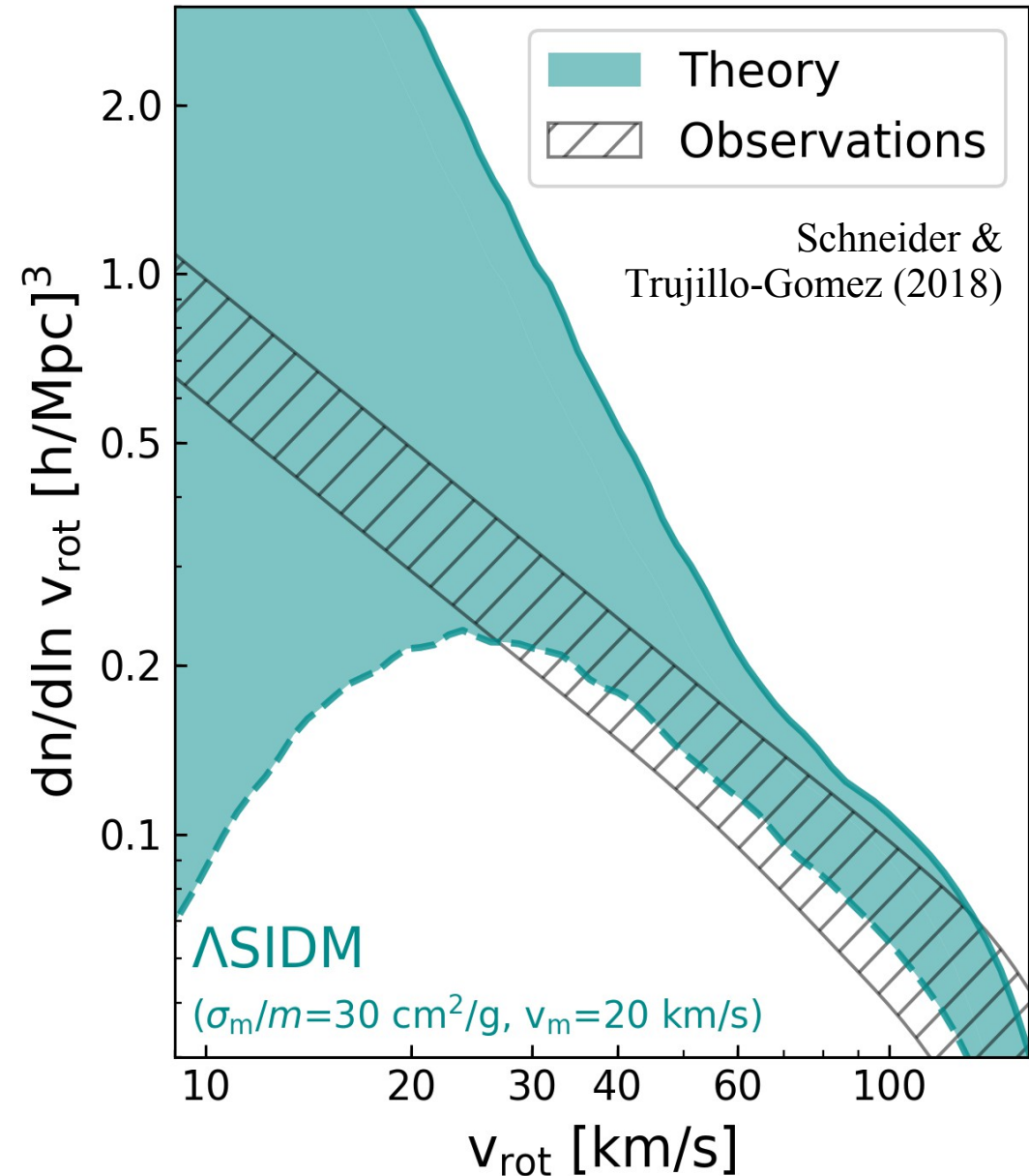
Velocity function – Mixed Dark Matter

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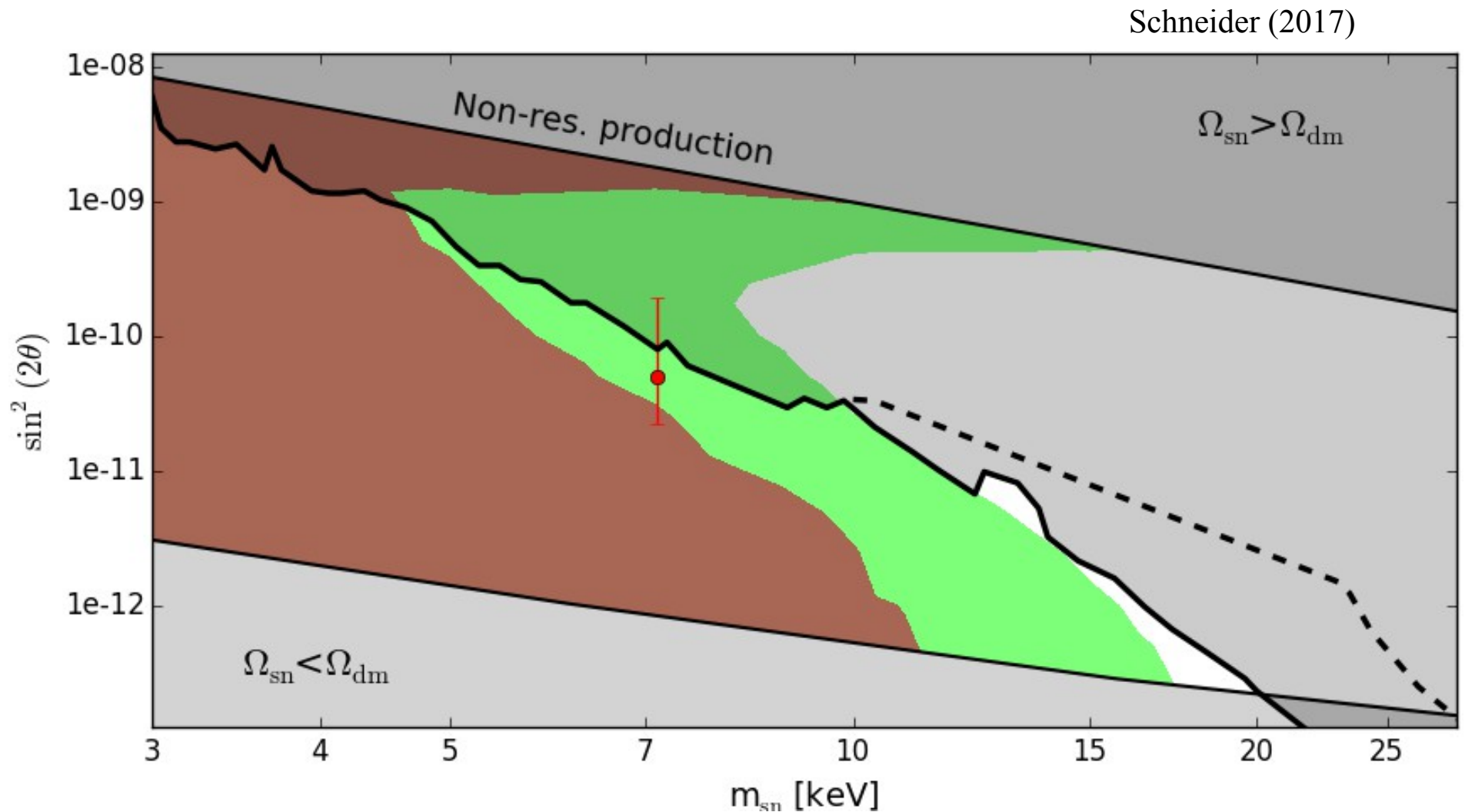


Velocity function – **Sterile Neutrino Dark Matter**

And what about sterile
neutrinos?

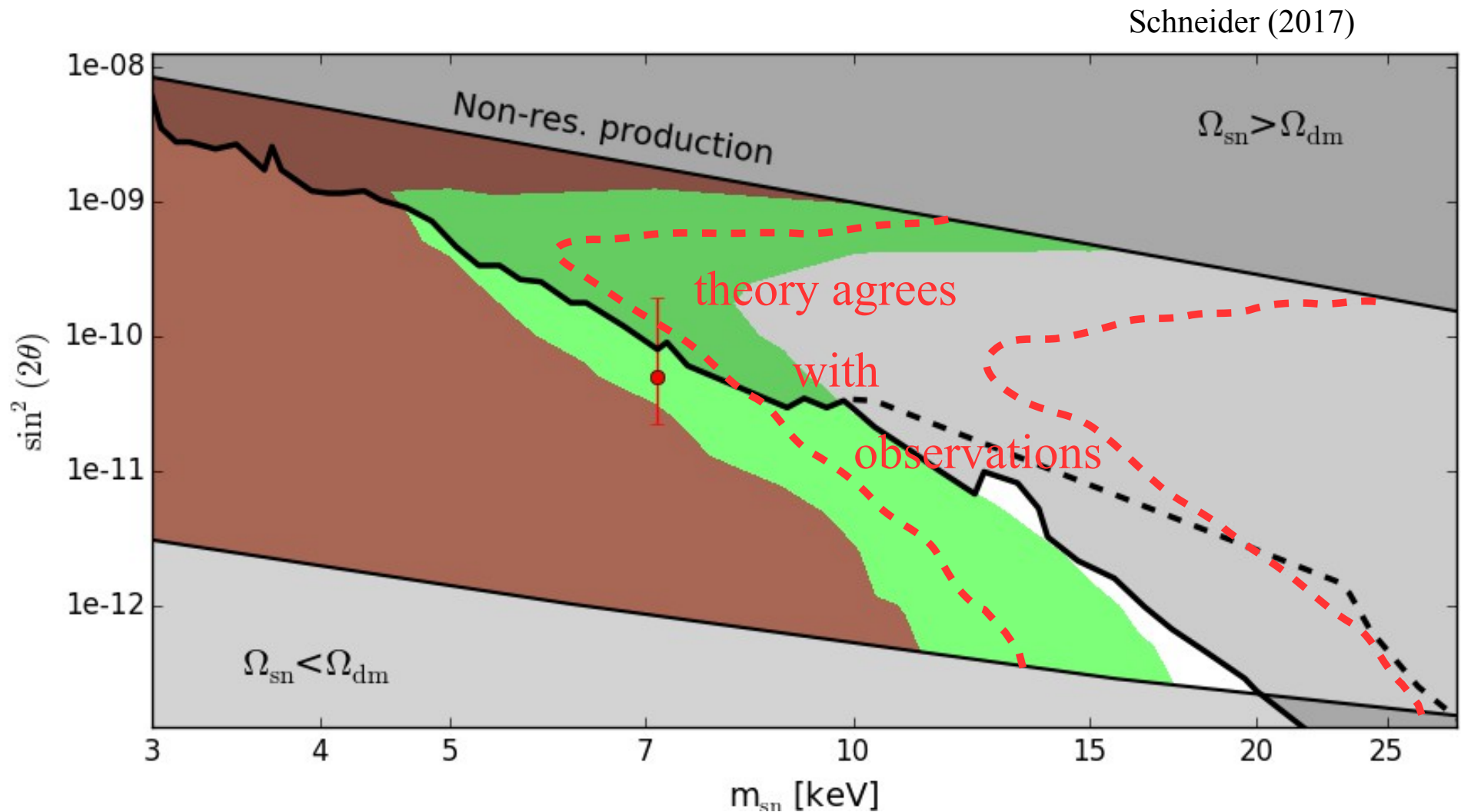
Velocity function – Sterile Neutrino Dark Matter

Assuming Planck cosmology ...



Velocity function – Sterile Neutrino Dark Matter

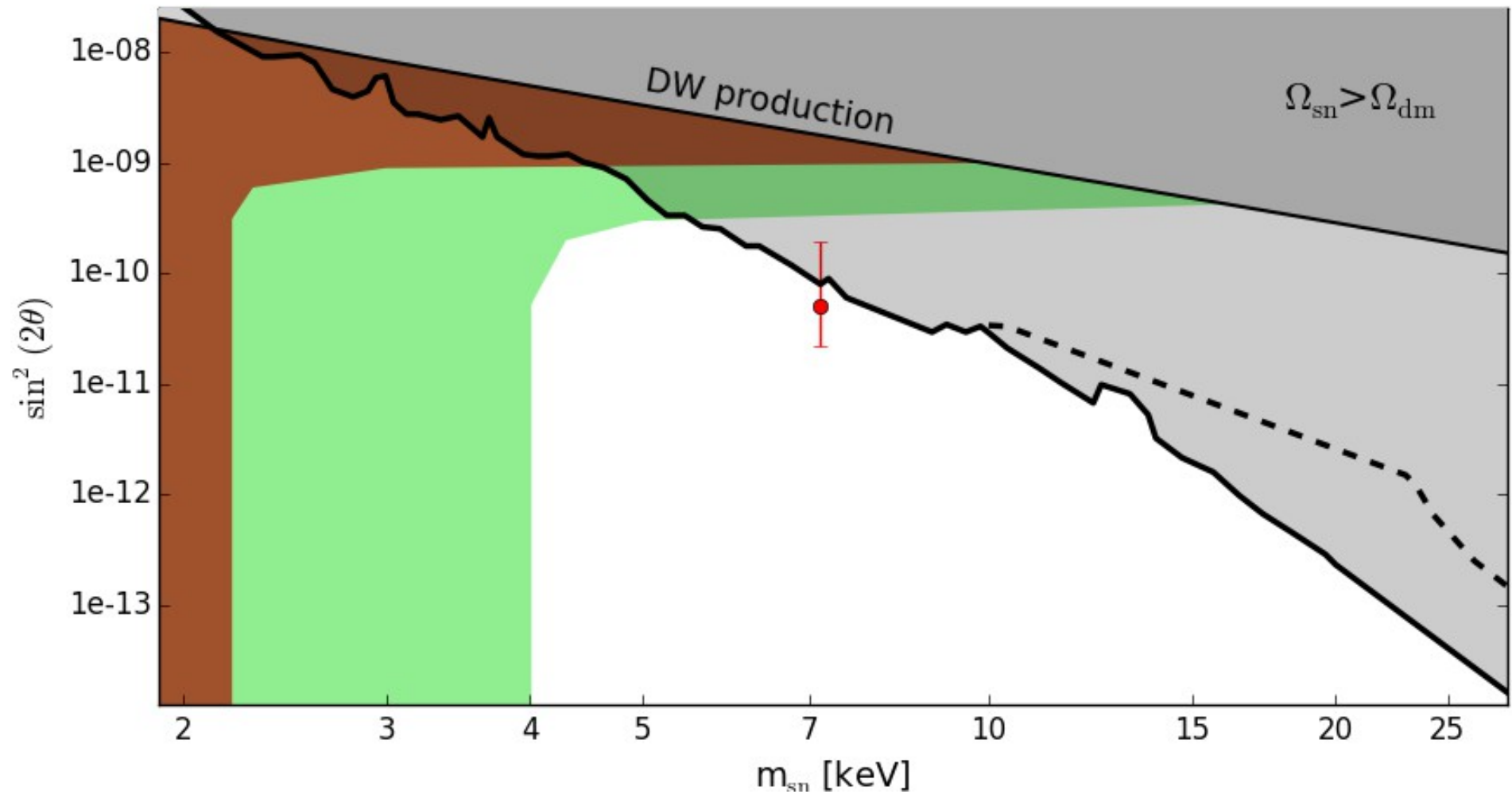
Assuming Planck cosmology ...



Velocity function – Sterile Neutrino Dark Matter

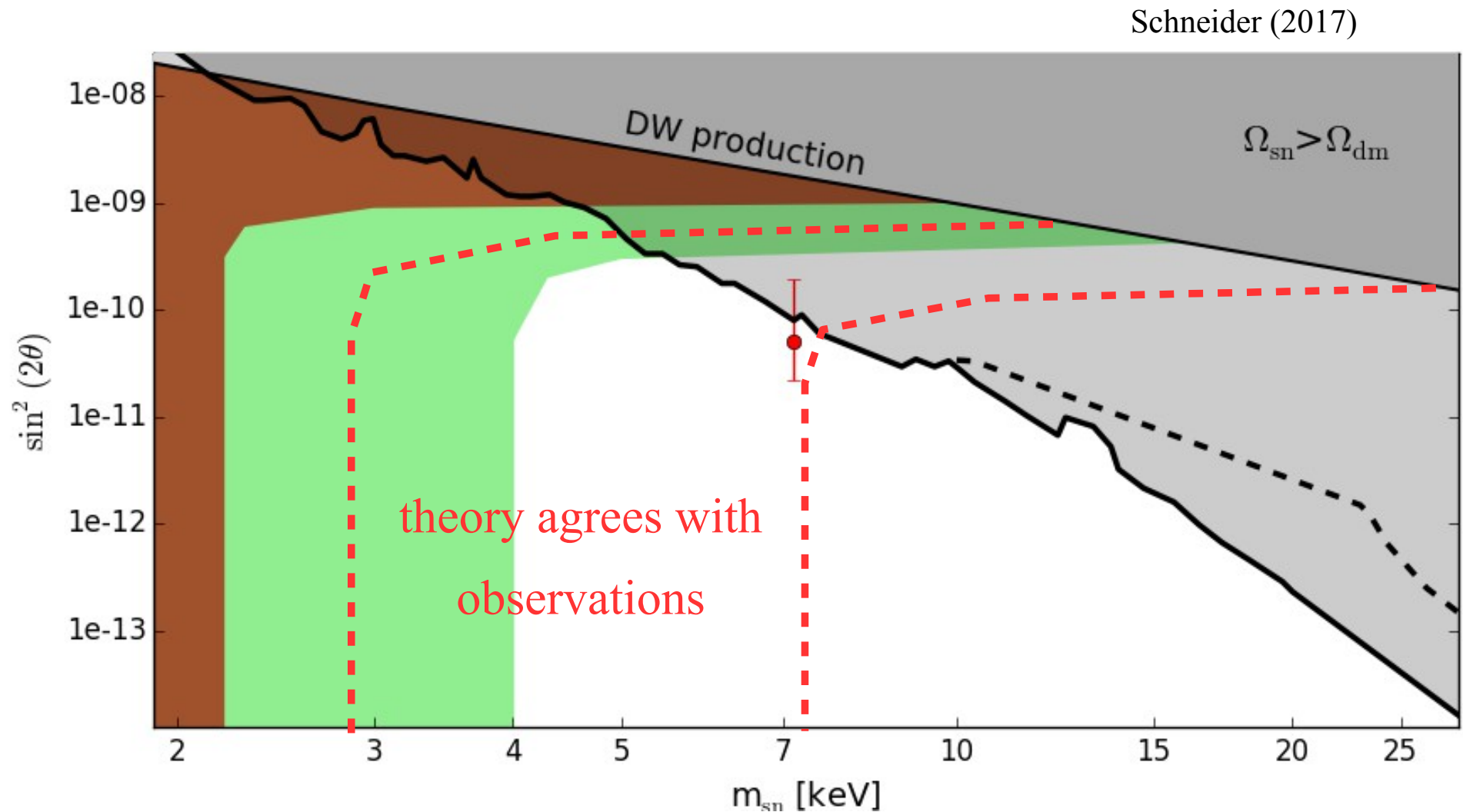
Assuming Planck cosmology ...

Schneider (2017)



Velocity function – Sterile Neutrino Dark Matter

Assuming Planck cosmology ...



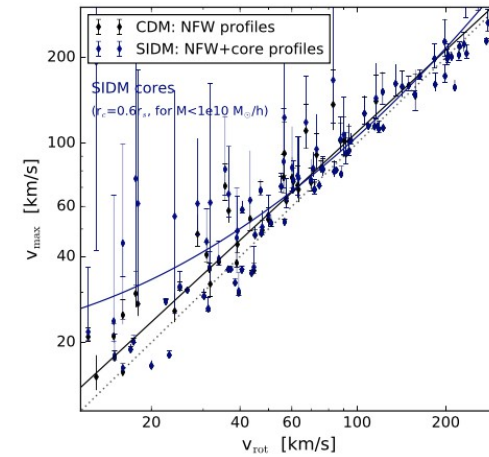
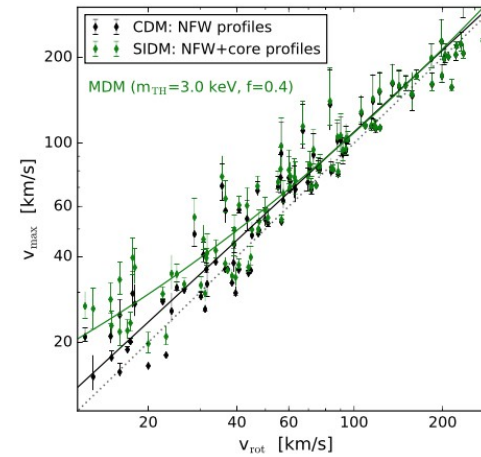
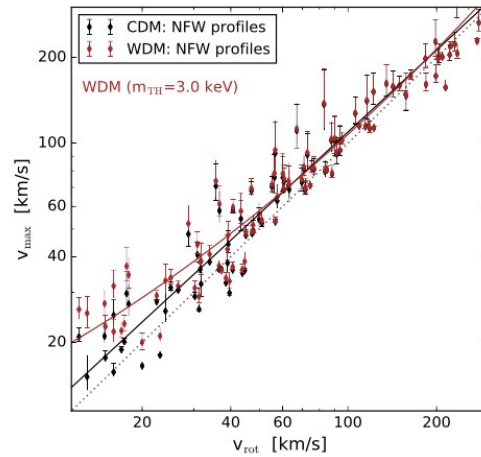
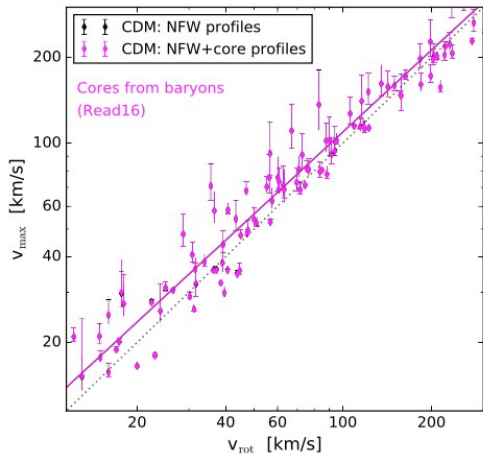
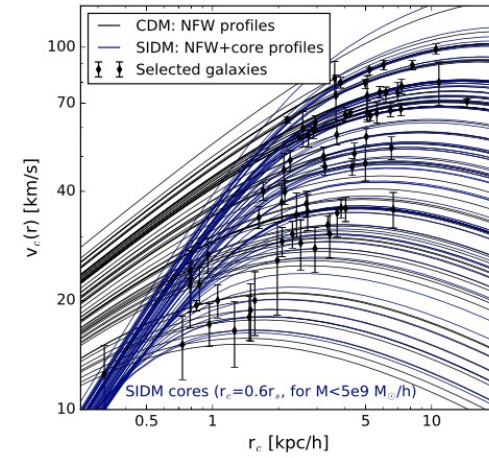
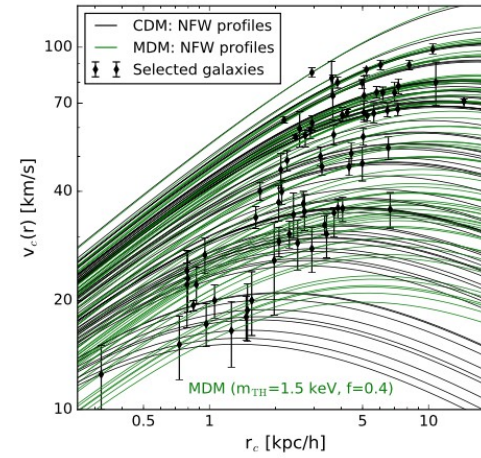
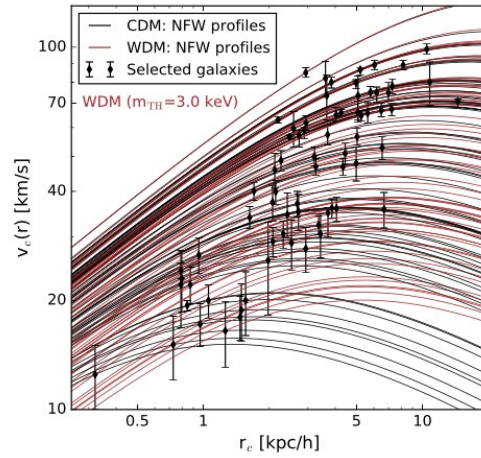
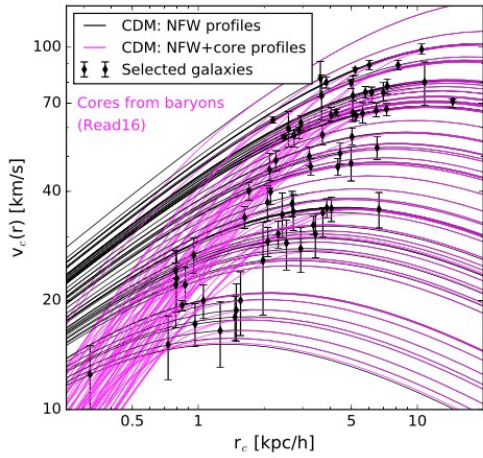
Conclusions:

Structure formation: a powerful tool
to constrain DM parameter space

Velocity function as a probe
of DM and cosmology

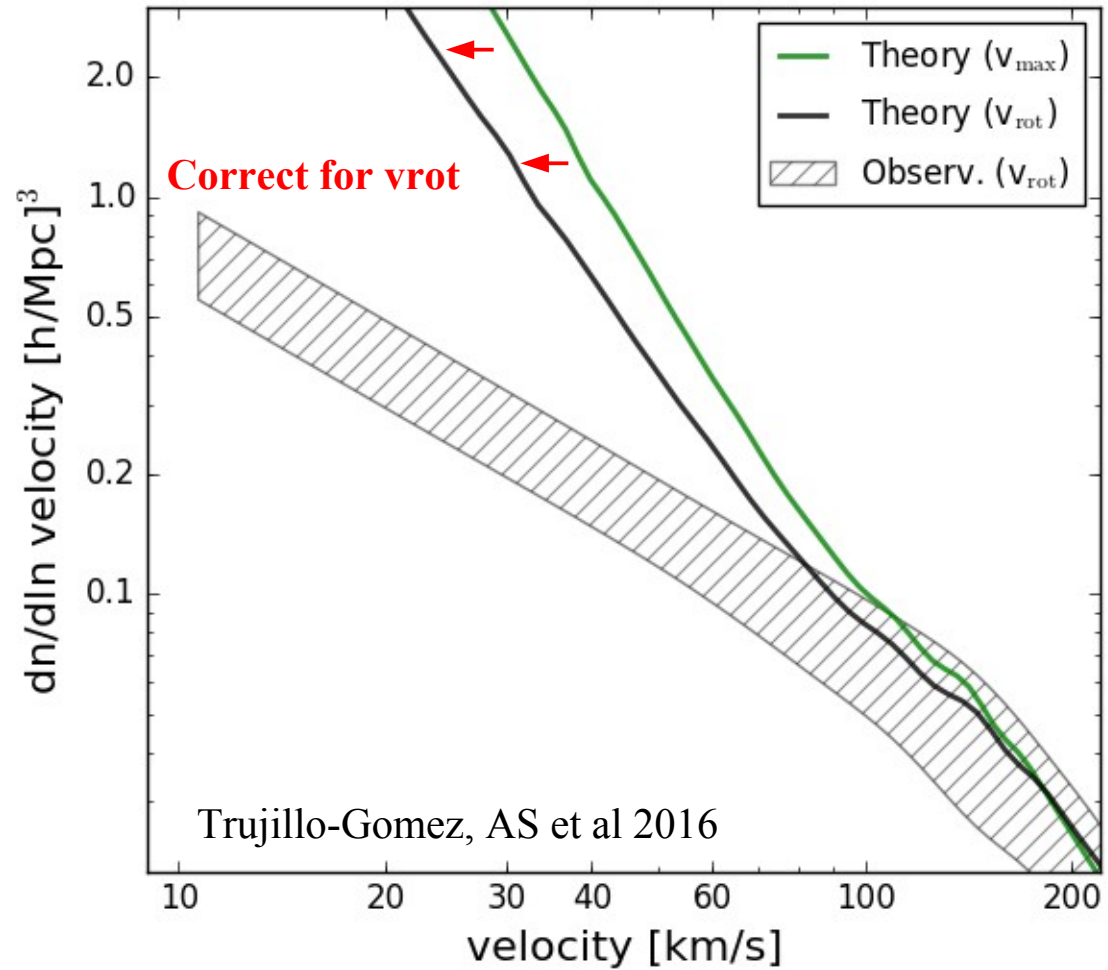
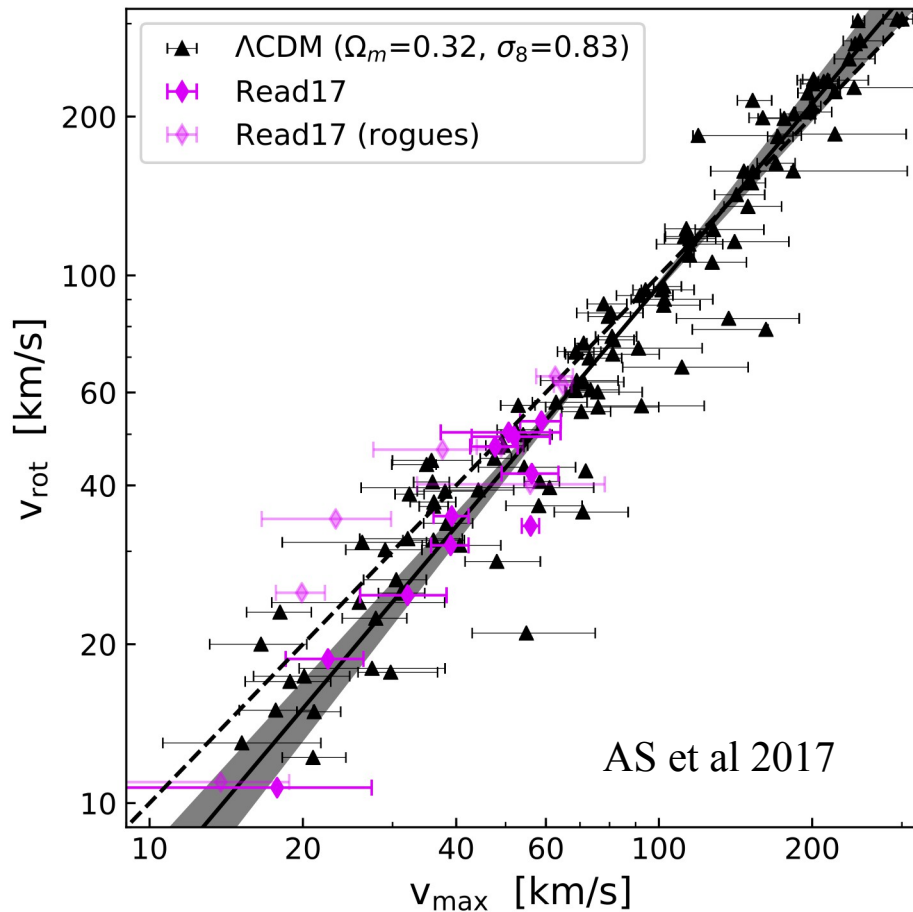
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Profile fitting



Velocity function of small galaxies

Find v_{rot} - v_{max} relation using dwarfs
with spatially resolved velocities



Velocity function of small galaxies

Include baryon effects:

- Maximum baryon depletion
- Maximum baryon suppression

