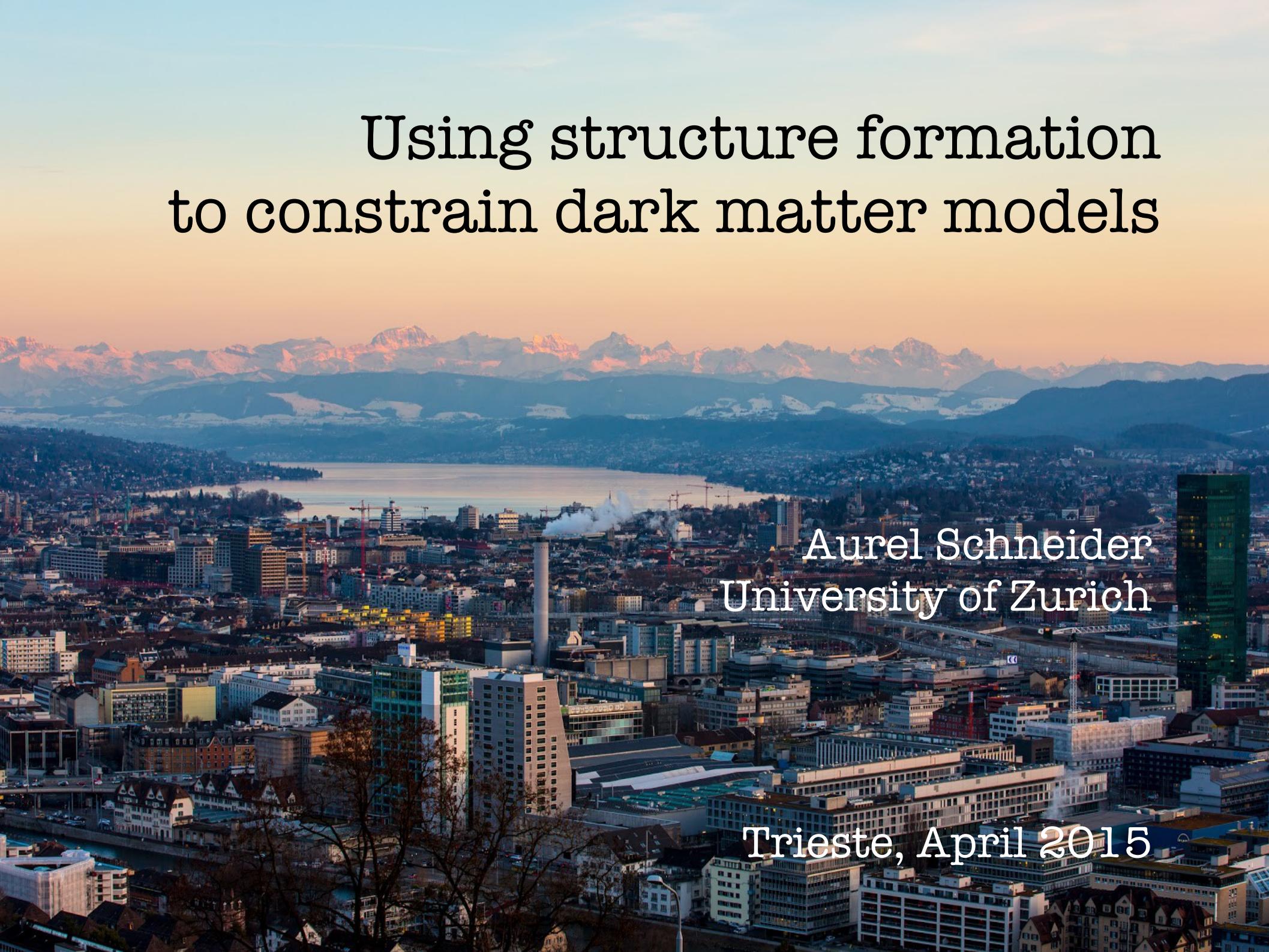


# Using structure formation to constrain dark matter models

The background image shows a panoramic view of the Zurich city skyline at sunset. In the foreground, the city's dense urban area with numerous buildings and infrastructure is visible. A prominent white cylindrical chimney or tower stands near the center. Behind the city, a large body of water, likely Lake Zurich, stretches towards a range of mountains. The mountains in the distance are heavily covered in snow, with their peaks catching the warm light of the setting sun, which creates a vibrant orange and yellow glow across the sky.

Aurel Schneider  
University of Zurich

Trieste, April 2015

# Probing DM scenarios with Astrophysics

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Direct detection  
Local density

Dark matter affects  
linear perturbations

Indirect detection  
Haloes and inner densities

# Probing DM scenarios with Astrophysics

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Direct detection  
Local density

Dark matter affects  
linear perturbations

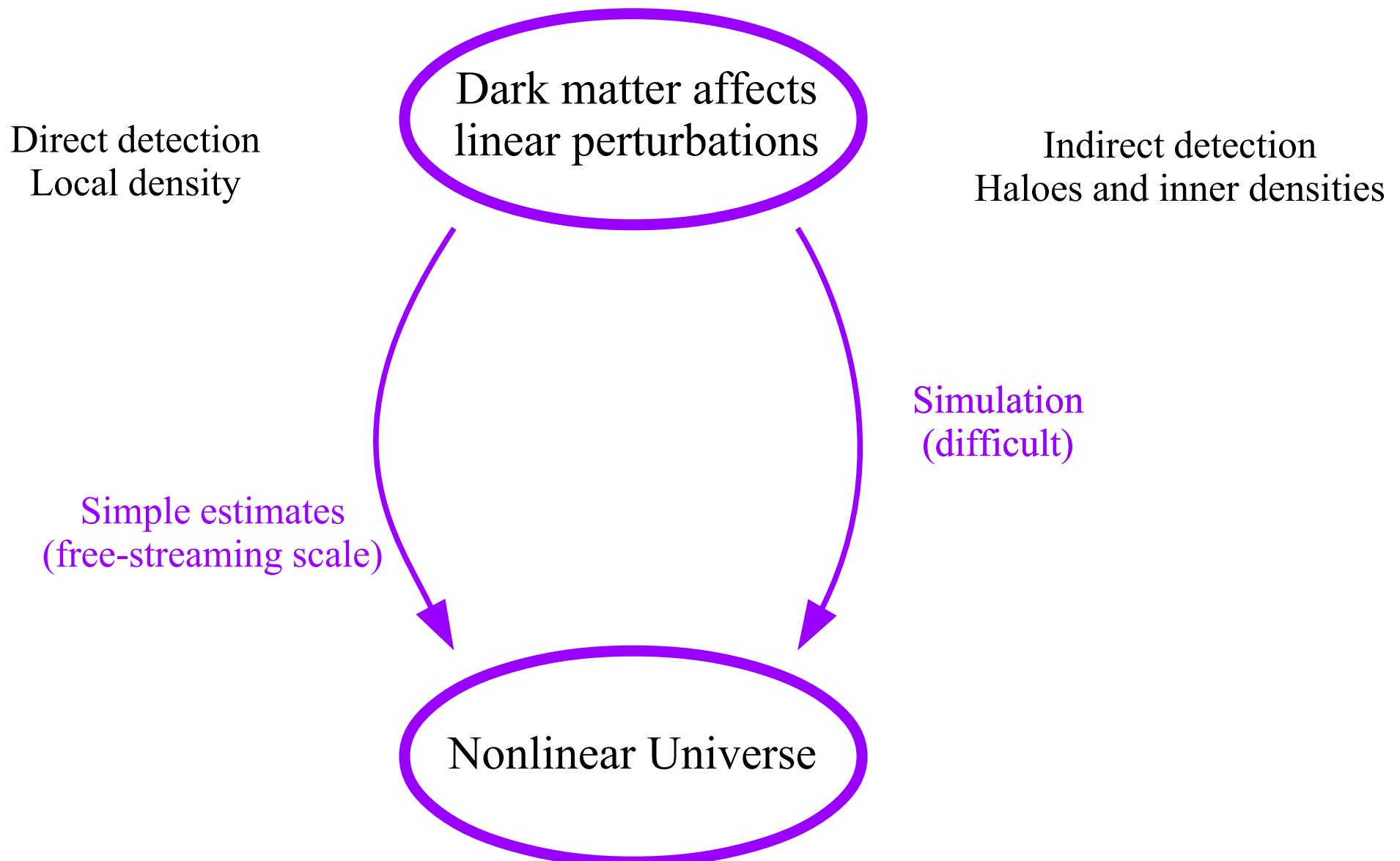
Indirect detection  
Haloes and inner densities

Simple estimates  
(free-streaming scale)

Nonlinear Universe

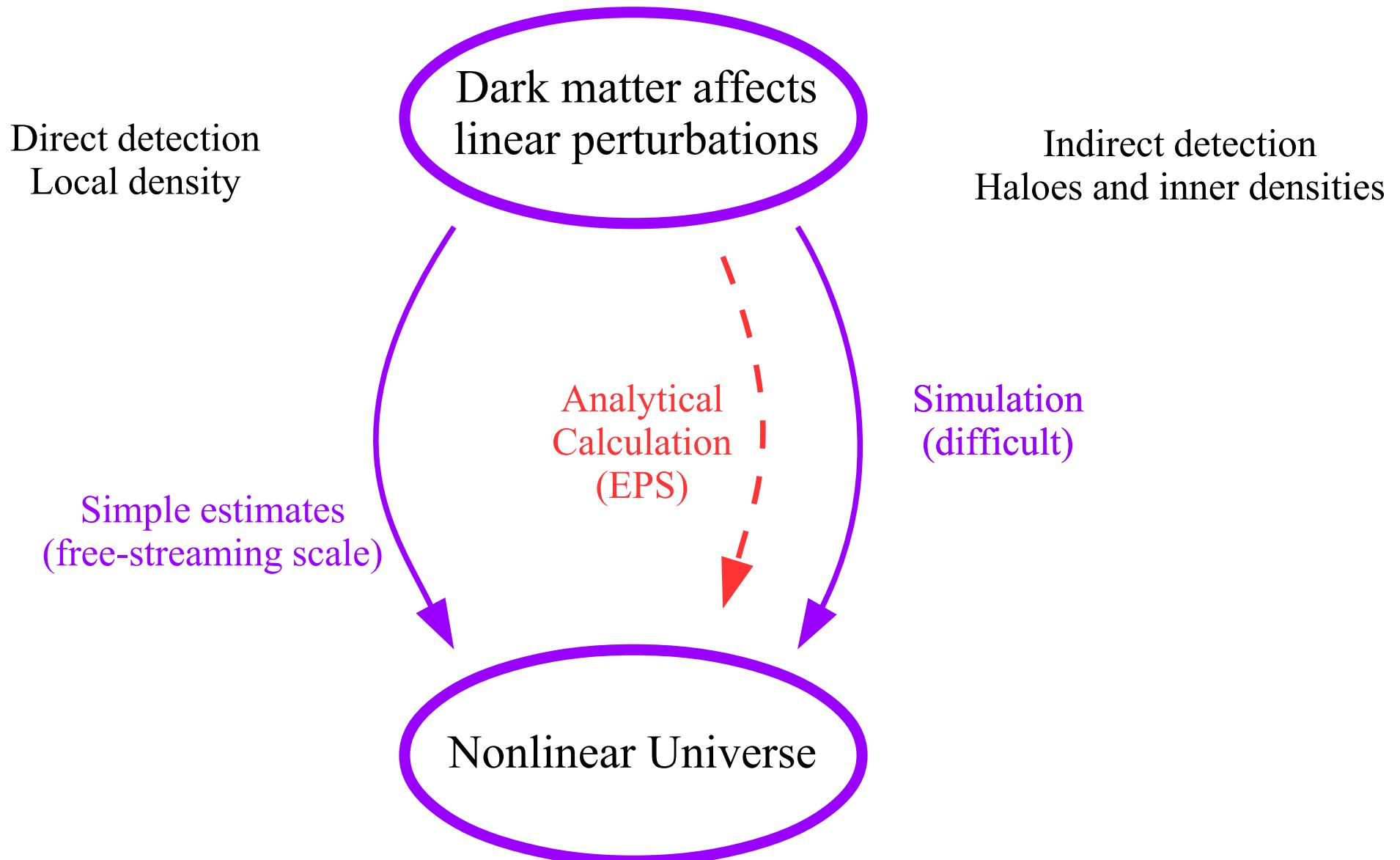
# Probing DM scenarios with Astrophysics

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# Probing DM scenarios with Astrophysics

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# Outline

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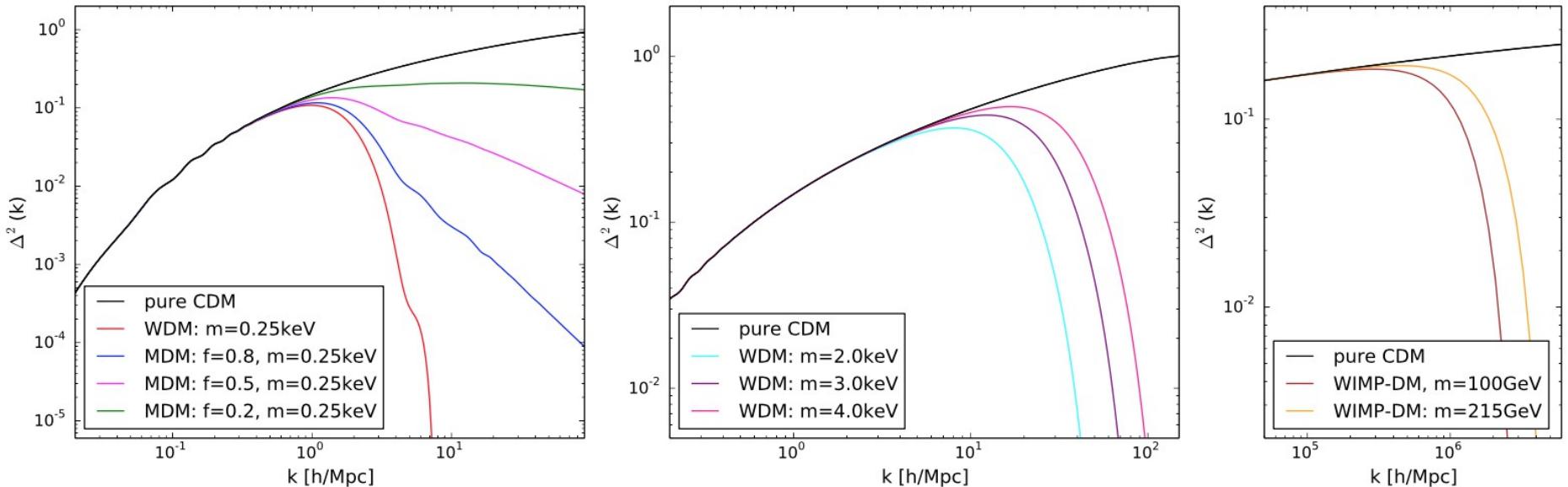
Modeling (suppressed) Structure Formation.

Constraining Dark Matter Models

Heading for a beer!

# Modeling Structure Formation: Overview

All dark matter scenarios suppress perturbations !



Examples with strong suppression:

- warm DM (Bode et al 2001)
- interacting DM (Boehm et al 2005)
- self-interacting DM (Cyr-Racine et al 2012)
- ultra-light axion DM (Marsh and Silk 2013)
- mixed DM (Boyarsky et al 2009)
- decaying DM (Kaplinghat 2005)

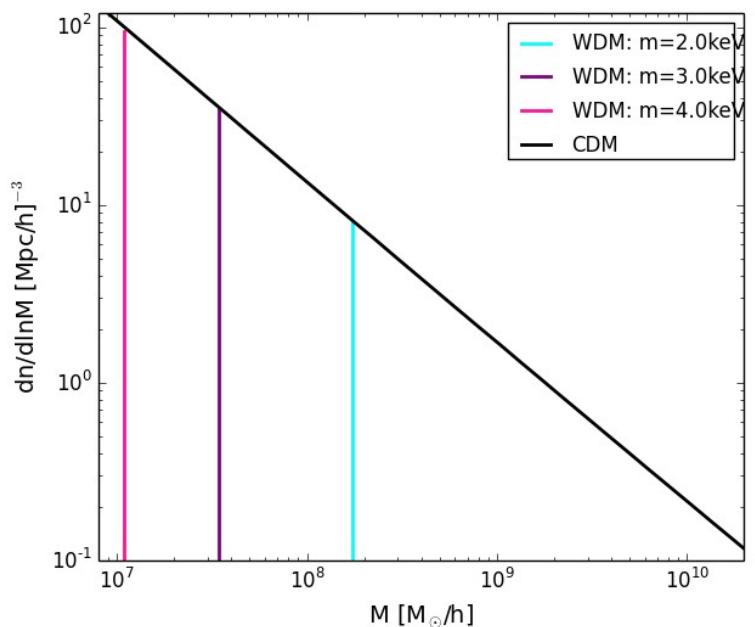
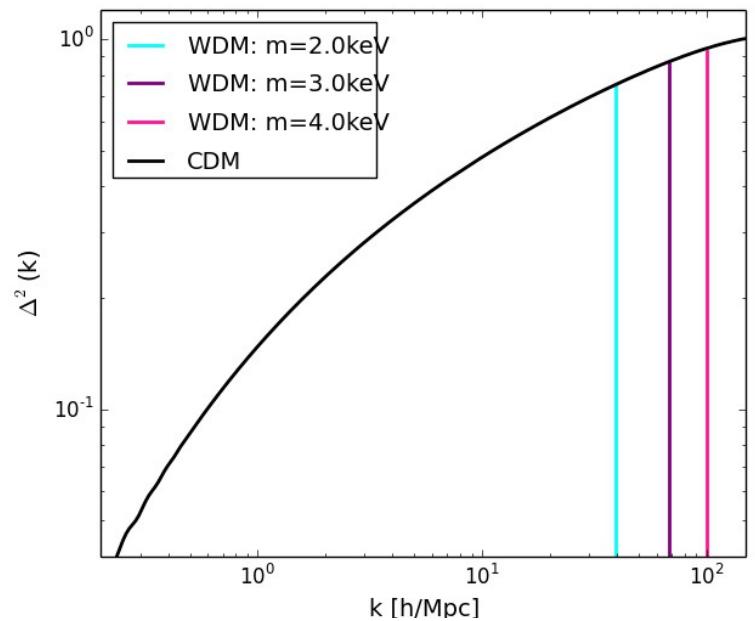
# Modeling Structure Formation : Free-Streaming

Free-streaming estimate :

$$\lambda_{FS} = \int \frac{\langle v(t) \rangle}{a(t)} dt$$

Or equivalent:

$$\lambda_s = \max(\lambda_J, t), \quad \lambda_J = \sqrt{\frac{\pi c_s^2}{4G\bar{\rho}}}$$



# Modeling Structure Formation: Boltzmann solver

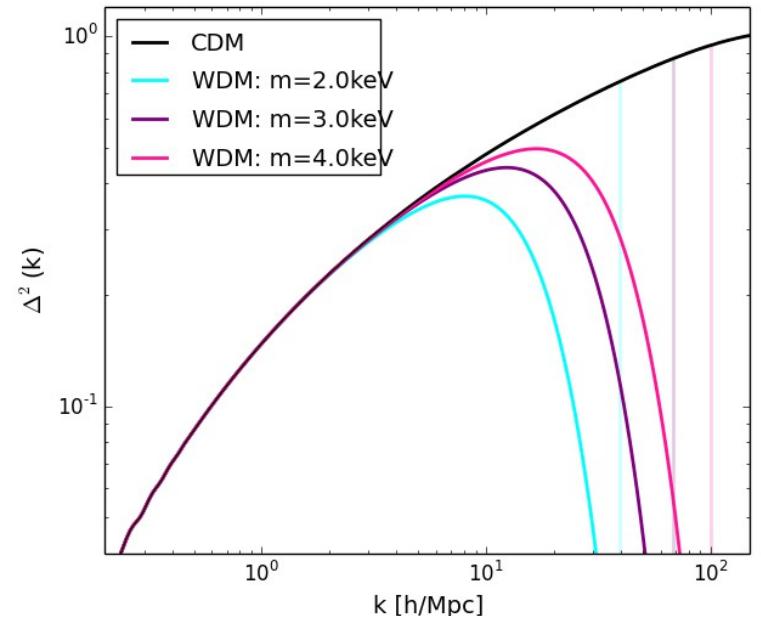
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The proper Boltzmann calculation:

Codes:    **cmbfast**    (Seljak & Zaldarriage, 1996)

**camb**        (Lewis 2002)

**class**        (Lesgourgues, 2011)



# Modeling Structure Formation: Sharp-k Model

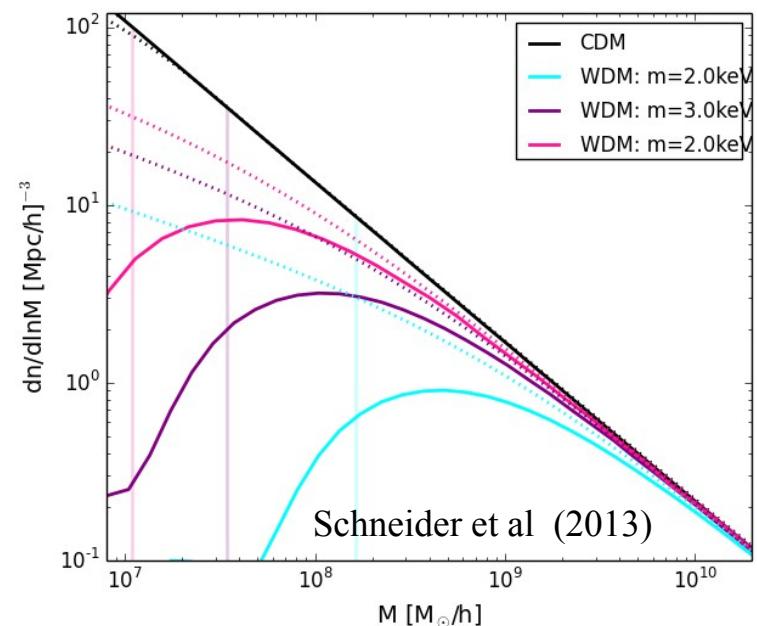
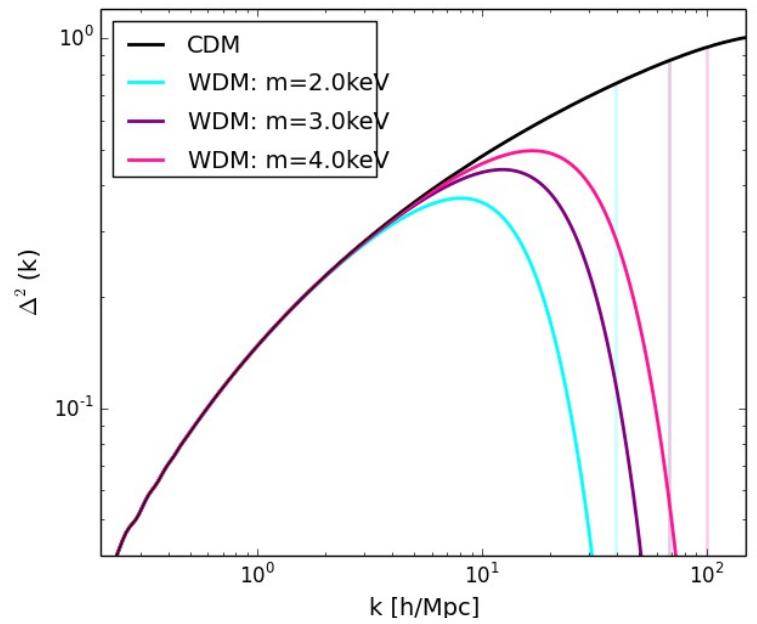
Extended Press-Schechter:

Requires sharp- $k$  modification!

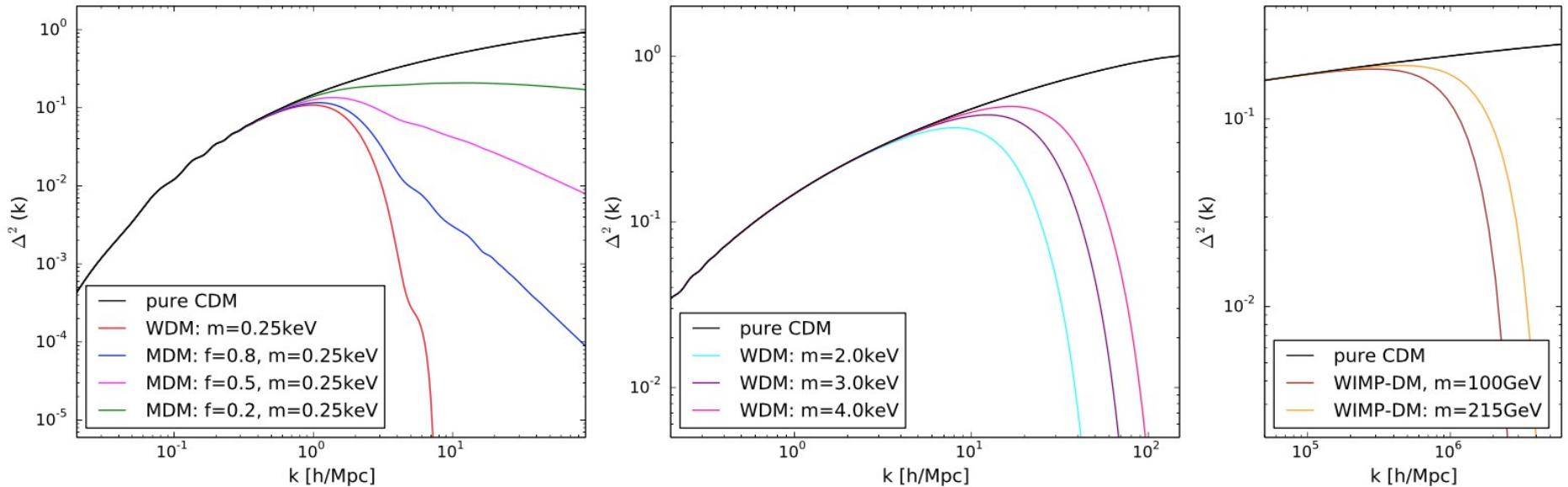
$$\frac{dn}{d \ln M} = \frac{1}{12\pi^2} \frac{\bar{\rho}}{M} \nu f(\nu) \frac{P(1/R)}{\delta_c^2 R^3}$$

$$f(\nu) = A \sqrt{\frac{2\nu}{\pi}} [1 + \nu^{-p}] e^{-\nu/2},$$

$$M = \frac{4\pi}{3} \bar{\rho} (cR)^3, \quad c = 2.5$$

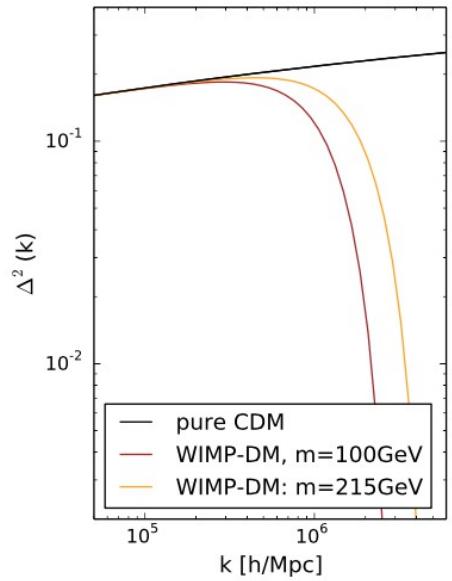
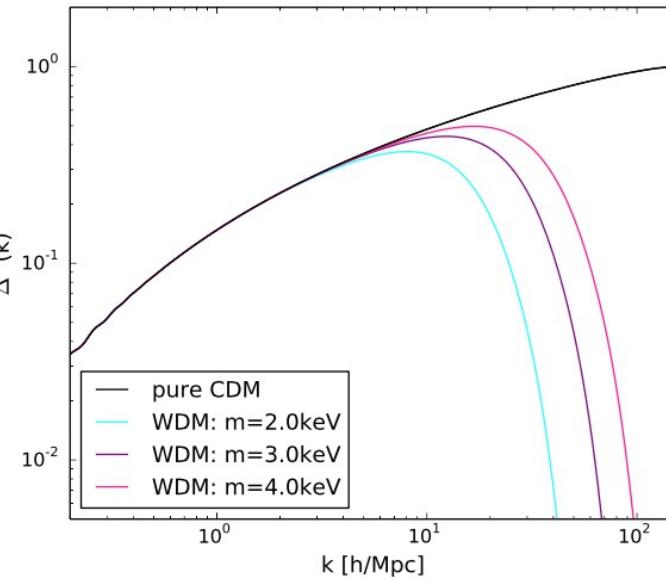
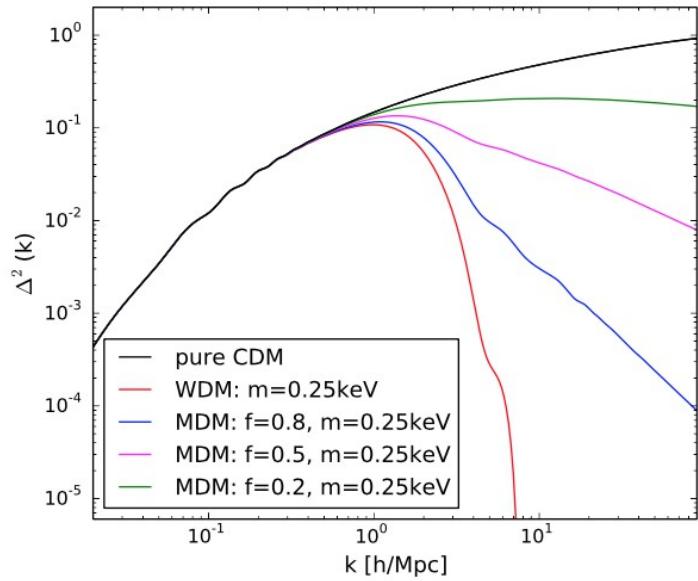


# Modeling Structure Formation: Overview

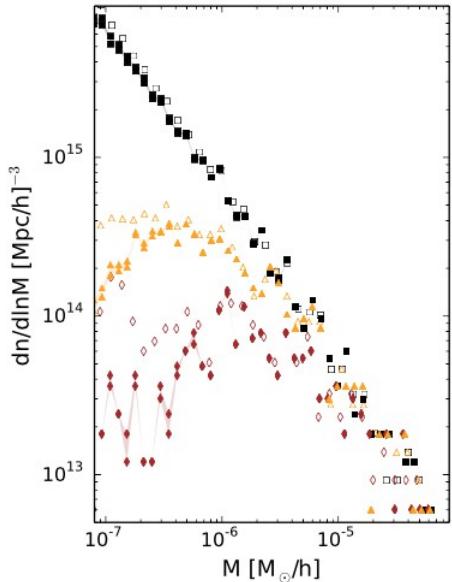
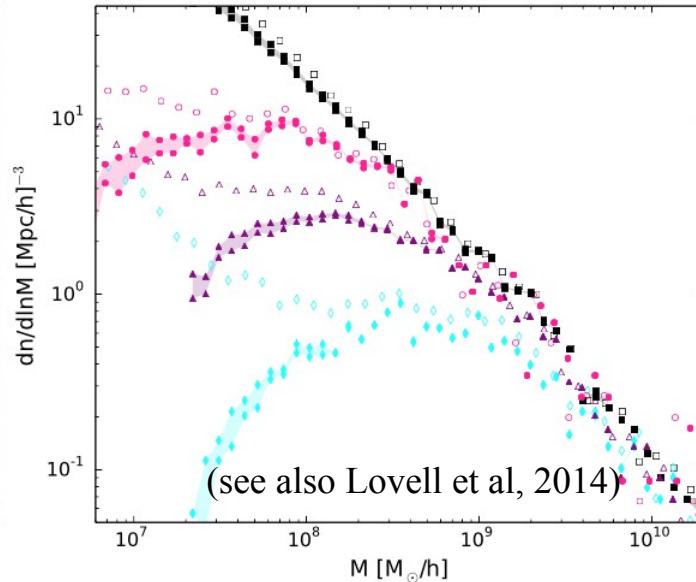
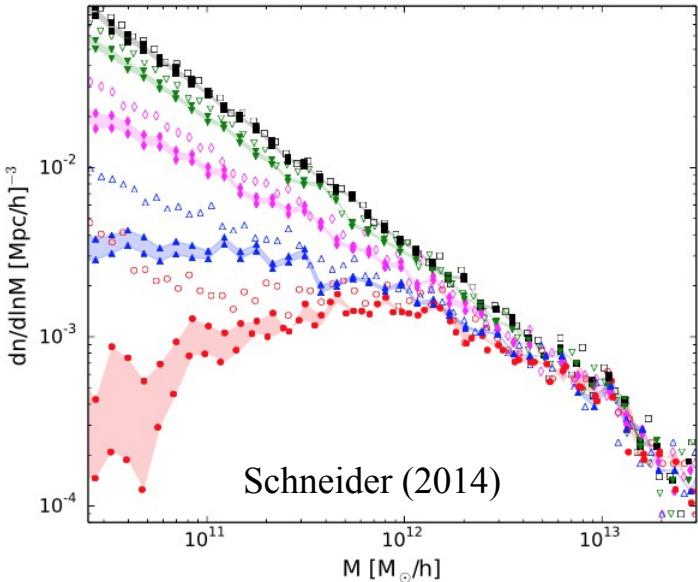


- Simulations: Best option but very painful (artificial clumping!)
- EPS: Sheth-Tormen model (does not work)
- EPS: sharp- $k$  model (works)

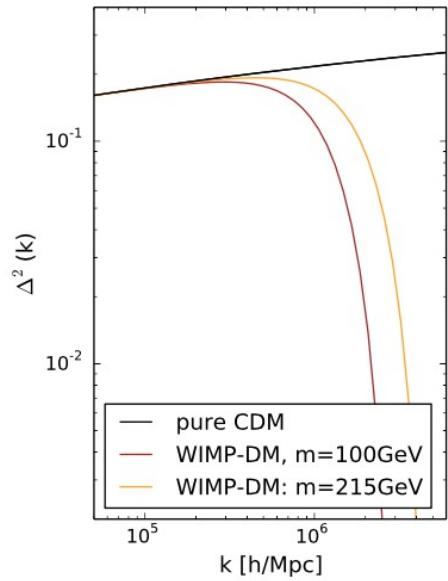
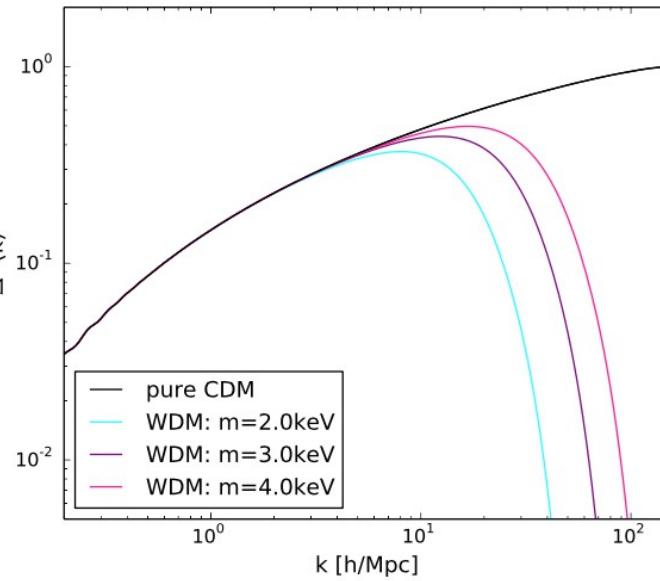
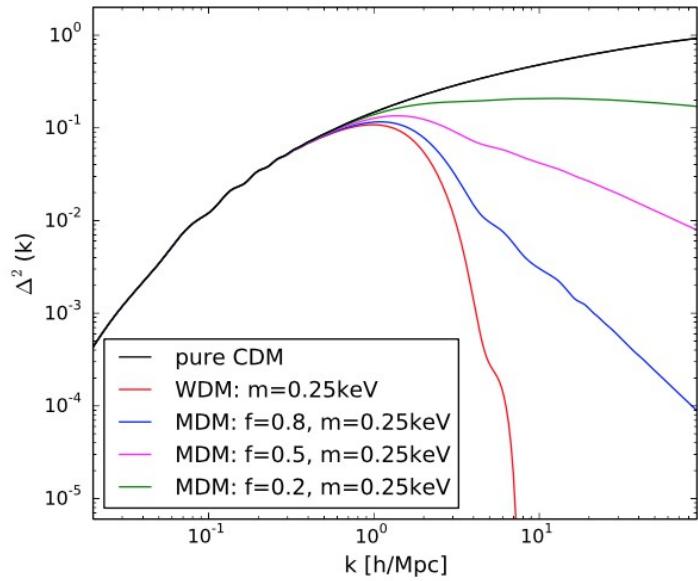
# Modeling Structure Formation: Simulations



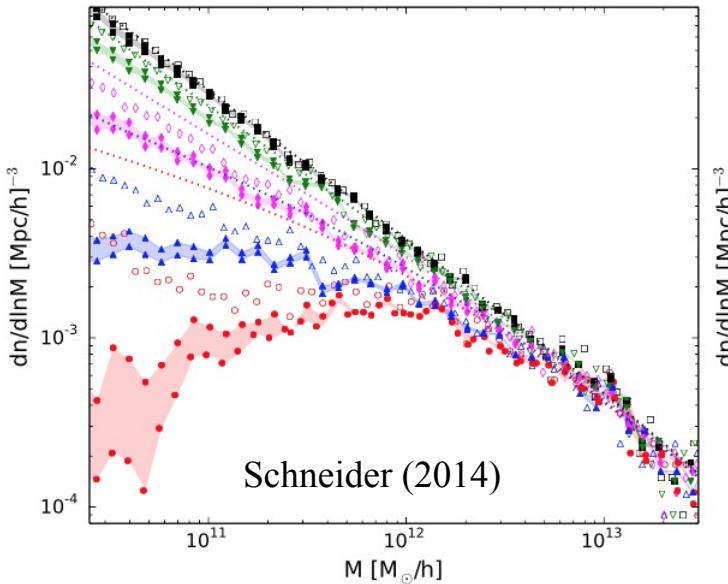
Numerical Simulations ...



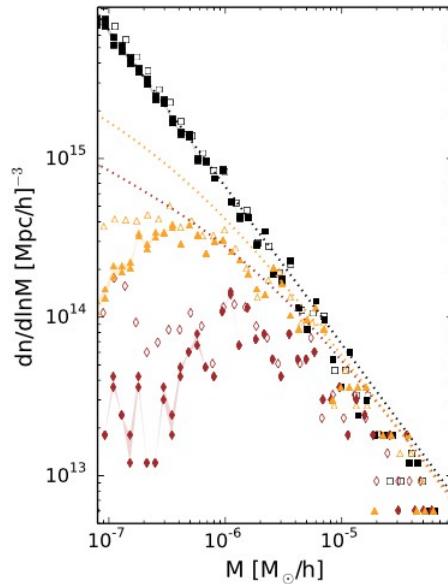
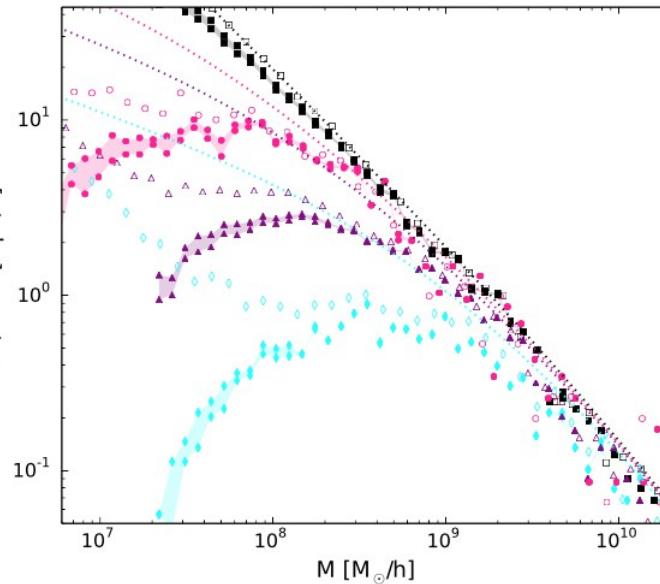
# Modeling Structure Formation: ST model



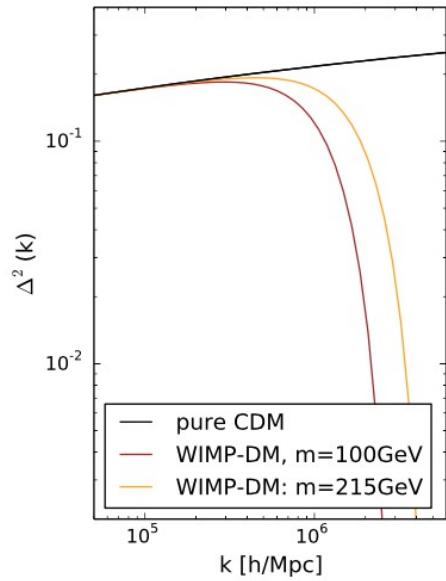
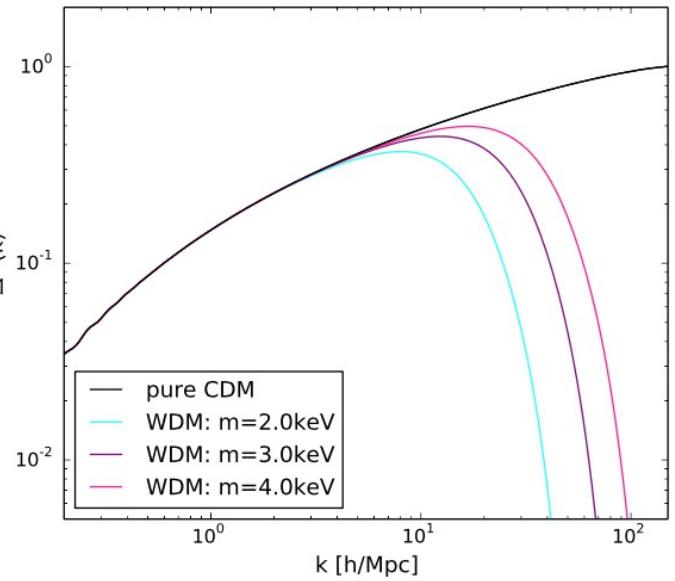
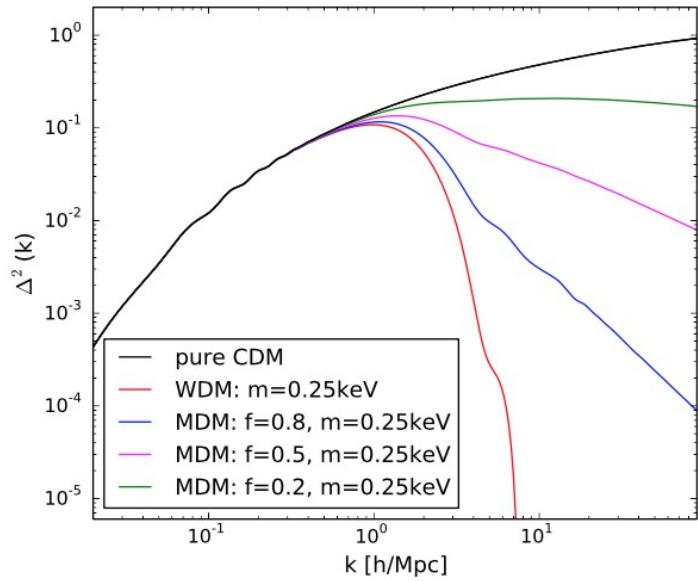
Sheth-Tormen model ...



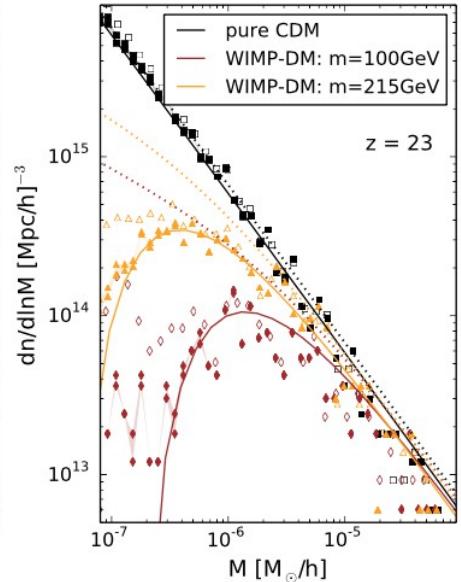
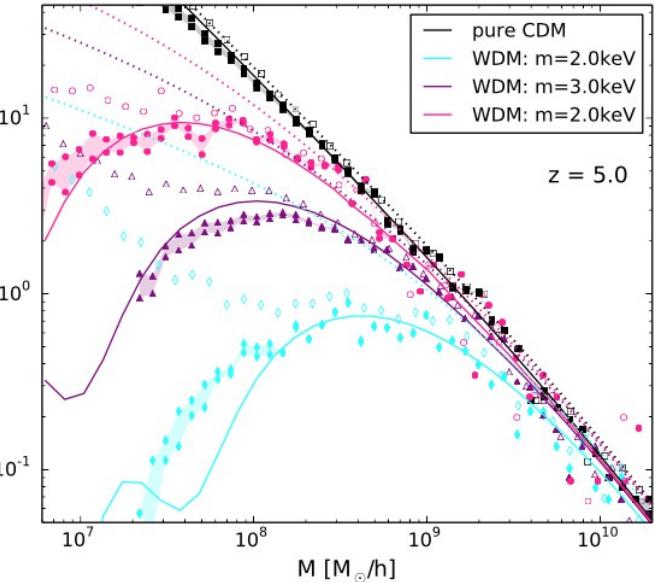
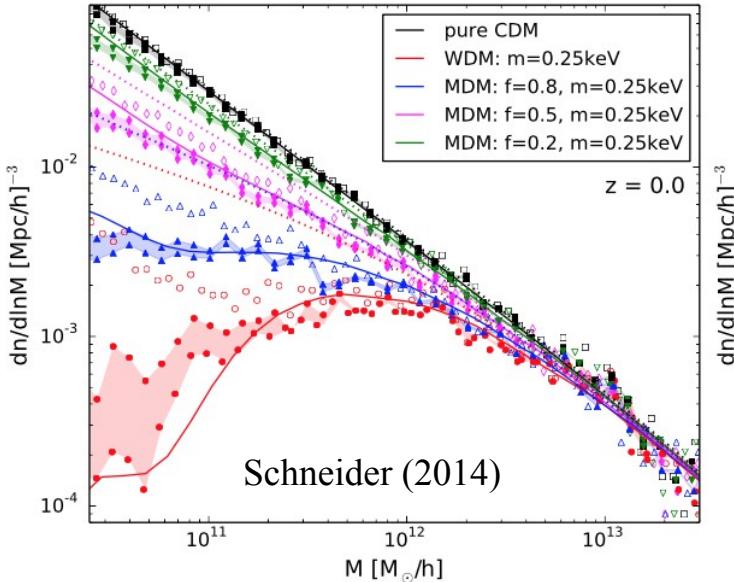
Schneider (2014)



# Modeling Structure Formation: Sharp-k model



↓  
Sharp- $k$  model ...  
↓  
↓



# Outline

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Modeling (suppressed) Structure Formation.

Constraining Dark Matter Models

Heading for a beer!

# Constraining Dark Matter : Overview

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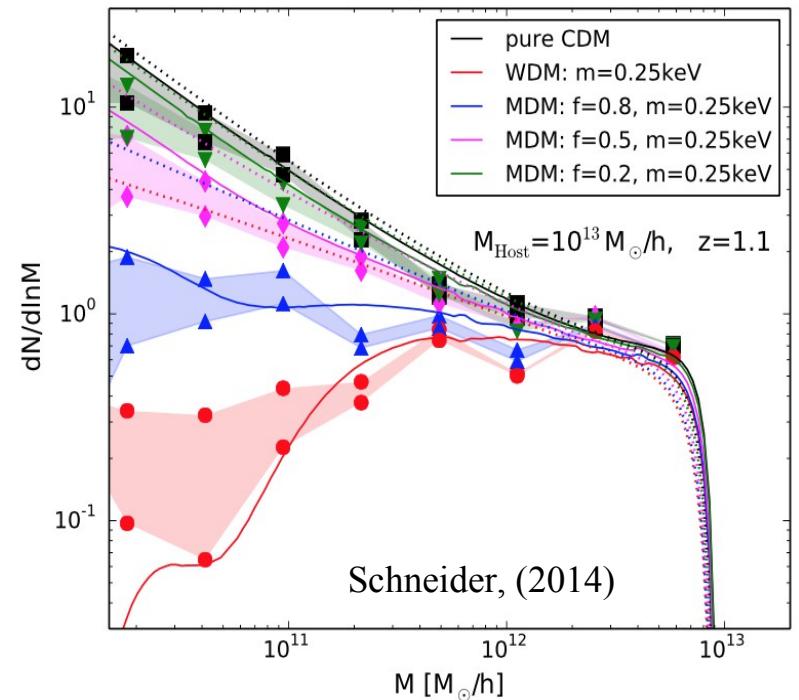
What can be used to constrain dark matter models:

- Dwarf galaxy counts
- Velocity functions
- Dwarf galaxy profiles
- Lyman-alpha forest
- ...

# Constraining Dark Matter : Dwarf Galaxy Counts

Conditional mass function:

Number count of haloes ending up  
in a (Milky-Way) host.



$$\frac{dN(M|M_0)}{d \ln M} = \frac{1}{6\pi^2} \frac{M_0}{M} f(\delta_c, S|\delta_{c,0}, S_0) \frac{P(1/R)}{R^3}$$

$$f(\delta_c, S|\delta_{c,0}, S_0) = \frac{(\delta_c - \delta_{c,0})}{\sqrt{2\pi(S - S_0)}} \exp \left[ -\frac{(\delta_c - \delta_{c,0})^2}{2(S - S_0)} \right]$$

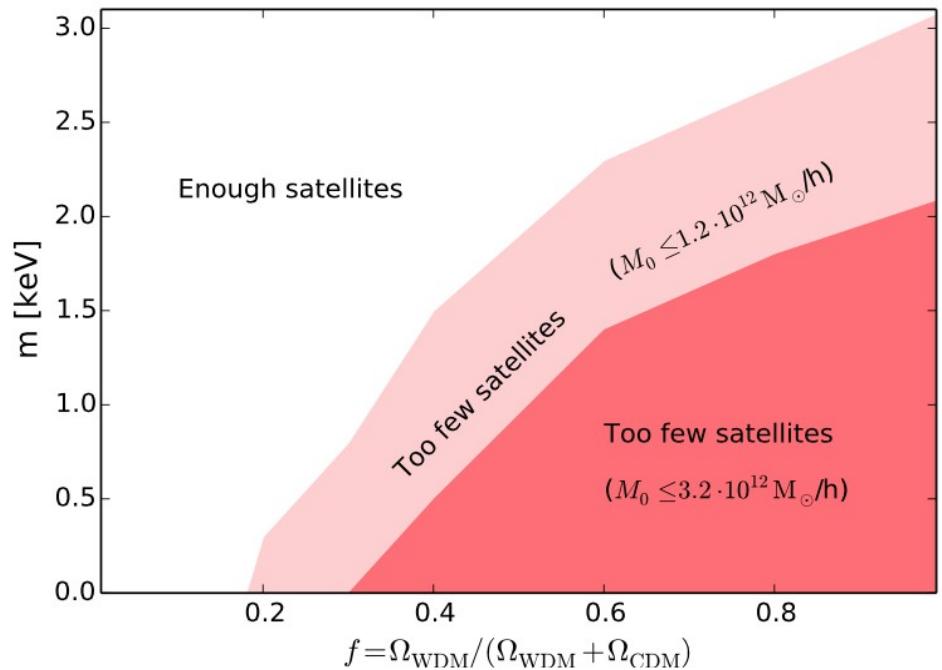
# Constraining Dark Matter : Dwarf Galaxy Counts

EPS model to estimate satellites  
(integrating cond. mass function):

$$\frac{dN_{\text{Sat}}}{d \ln M} = \frac{1}{44.5} \frac{1}{6\pi^2} \left( \frac{M_0}{M} \right) \frac{P(1/R)}{R^3 \sqrt{2\pi(S - S_0)}}$$

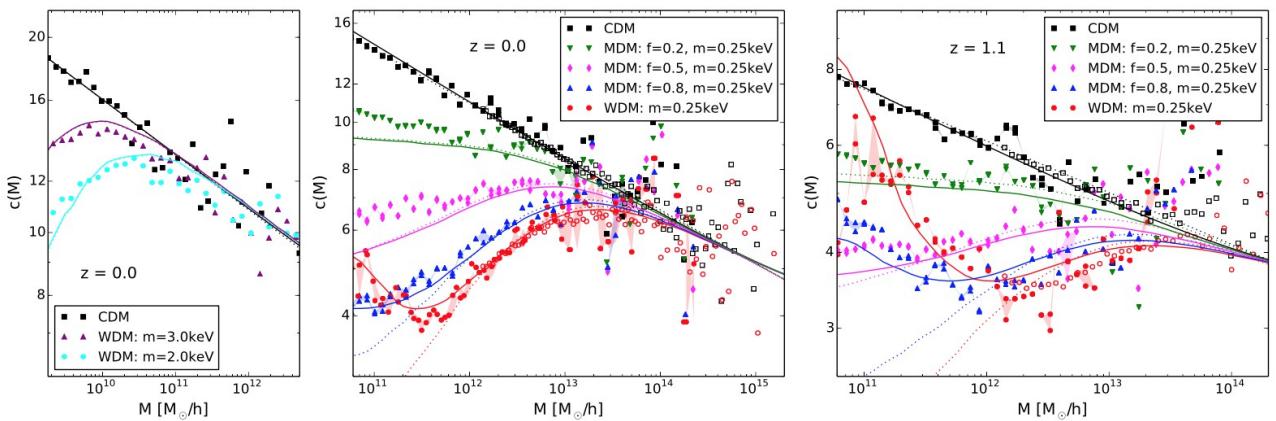
Method from Giocoli et al (2008)  
(see Schneider, 2014)

| Scenario       | $N_{\text{Sat}}$<br>(EPS model) | $N_{\text{Sat}}$<br>(Simulation) |
|----------------|---------------------------------|----------------------------------|
| WDM: m=1.5 keV | 9                               | 12                               |
| WDM: m=2.0 keV | 25                              | 27                               |
| WDM: m=2.3 keV | 32                              | 30                               |
| CDM: pure      | 158                             | 158                              |

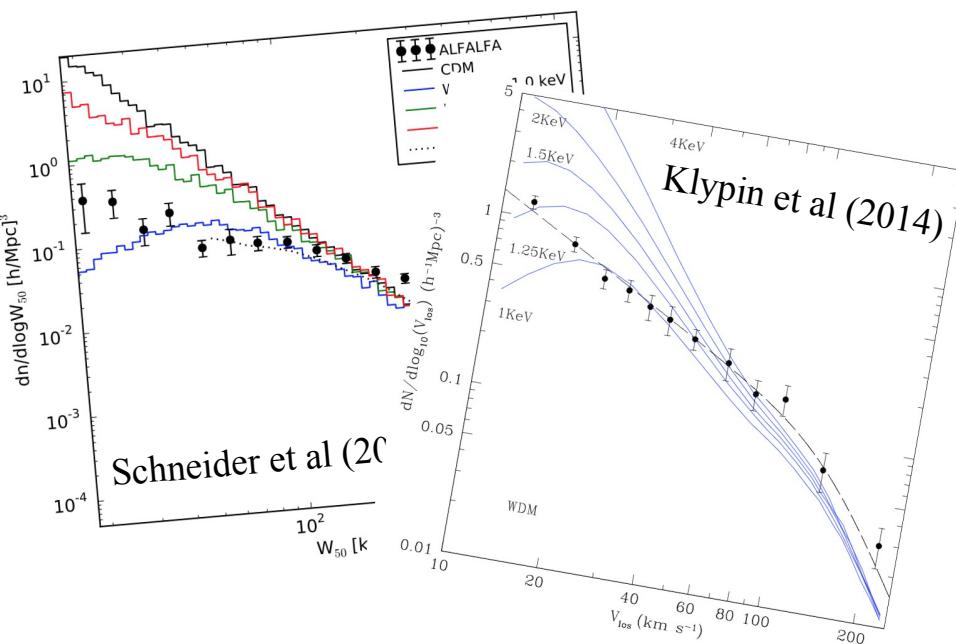


# Constraining Dark Matter : Other possibilities...

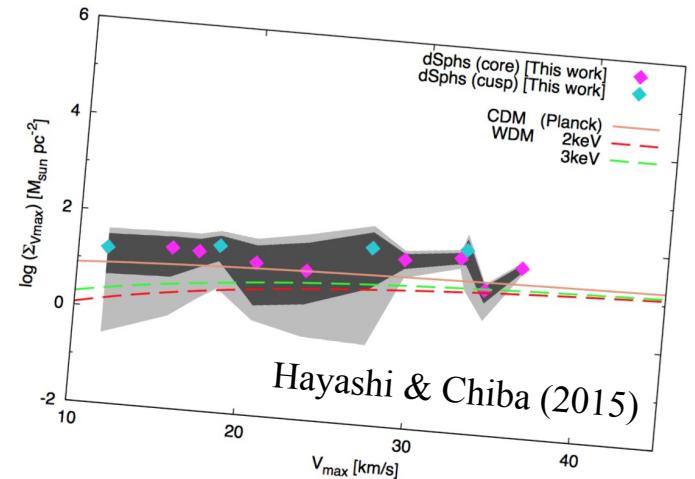
... Concentrations  
(profiles) with  
EPS:



... Velocity functions:



... Surface densities:



# Conclusions :

Suppressed perturbations lead to suppressed halo formation

EPS is a fast/simple yielding good estimates of:

Mass function

Number of satellites

Concentrations

... this can be used to constrain various DM scenarios