Kandinsky

Particles and the Universe,
Corfu, 20.09.2012

THE LARGE SCALE STRUCTURE OF WARM DARK MATTER

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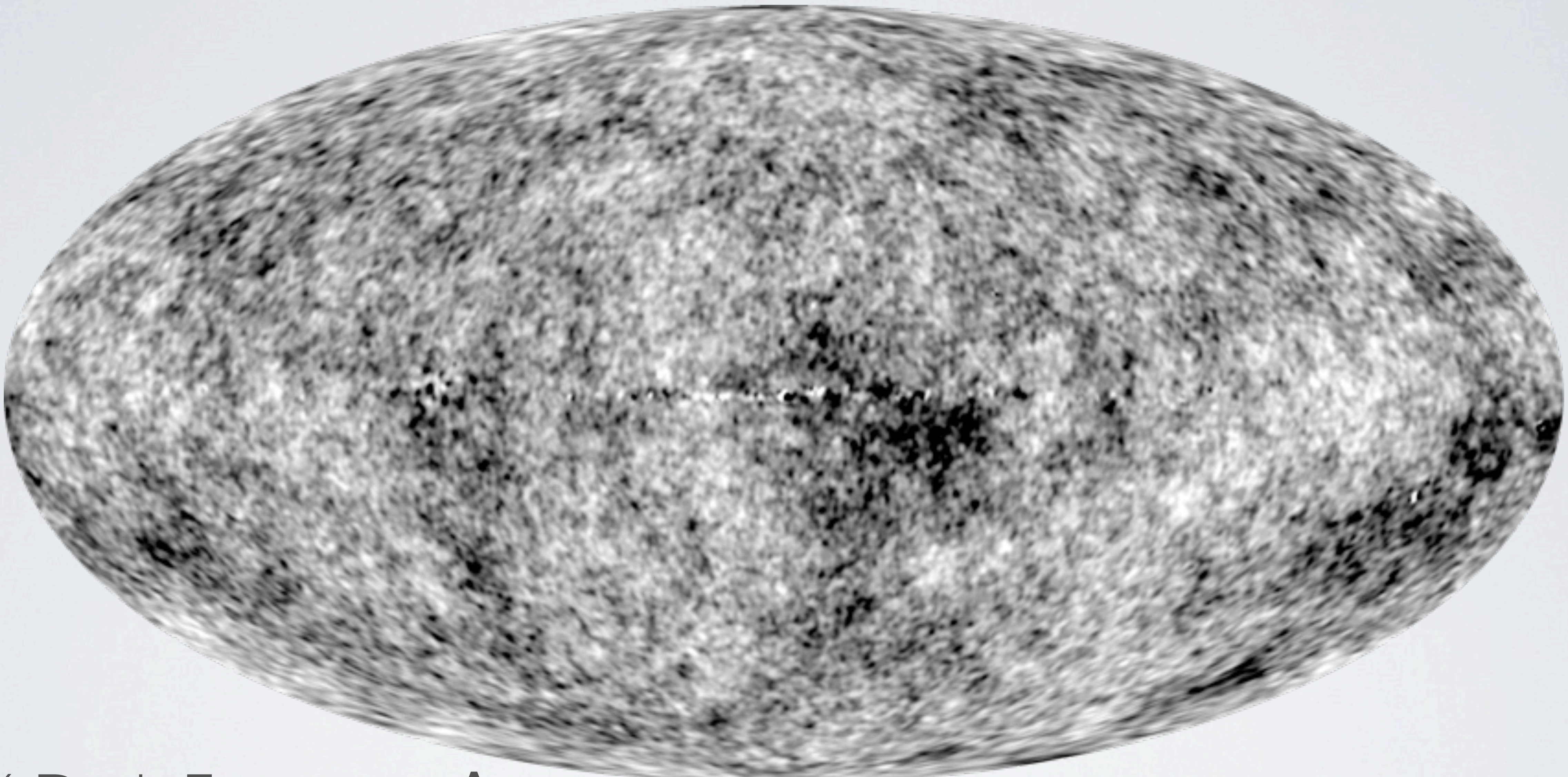
with Jochen Weller (USM),
Robert Smith (Zurich), Marco Baldi (USM), Matteo Viel (Trieste) and Martin Kilbinger (Paris)

OUTLINE

- free-streaming
- the halo model
- simulations - dark matter only
- degeneracies: WDM+b & WDM+ν

ΛCDM, PRESENT TIME



73% Dark Energy or Λ

23% Cold Dark Matter

4.5% Baryonic matter

negligible radiation and other standard model matter

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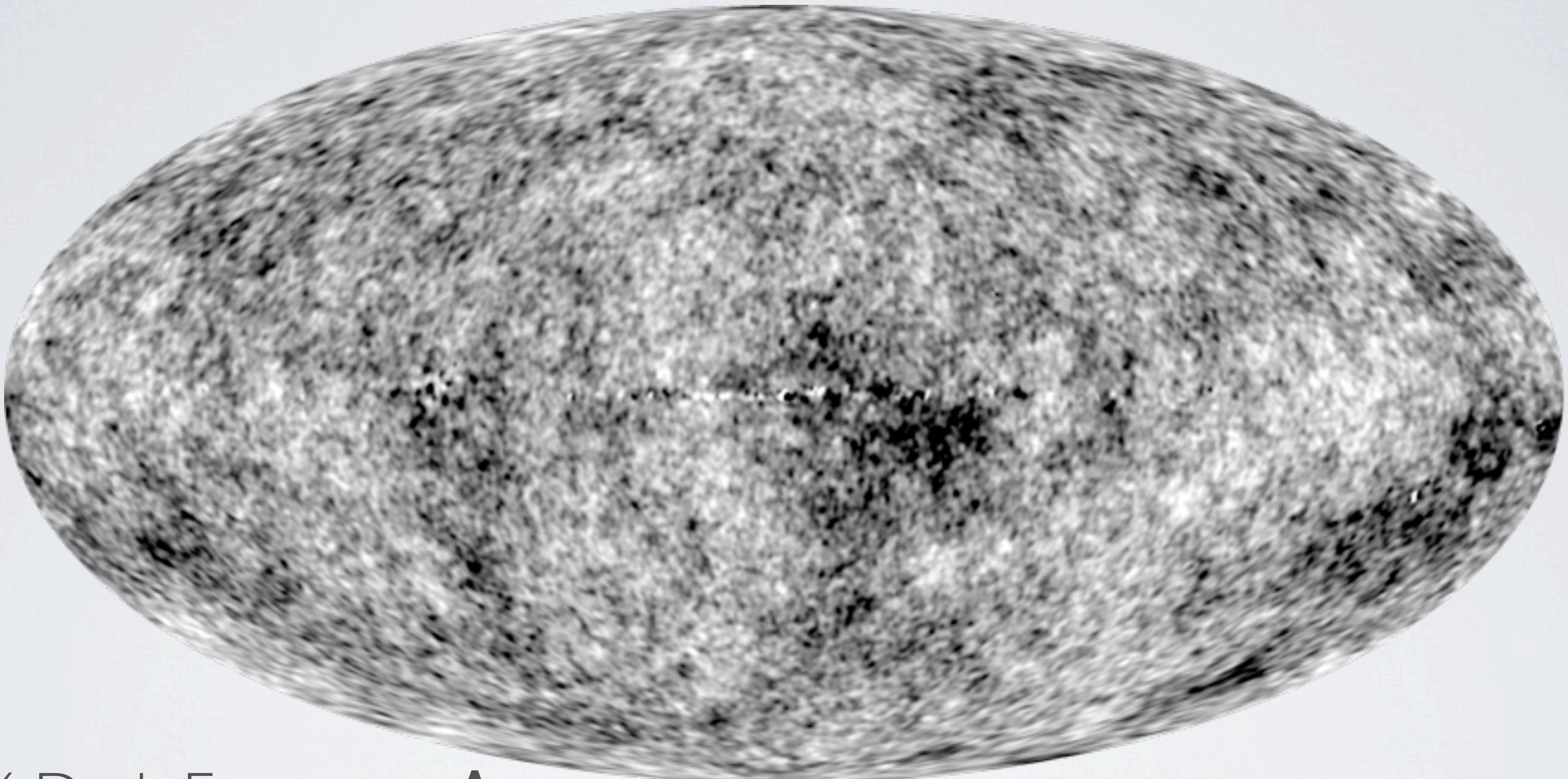

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WARM DARK MATTER PARTICLE

- DM: elementary particles
- DM: here assume thermal or sterile ν
- We have: $\Omega_{\rm dm}(m_{\rm dm}, g^*(T_{\rm d}), \langle\sigma v\rangle)$
- choose a DM model → get rid of one variable

CONSTRAINTS

- 1 measurement: Dark Matter abundance from CMB experiments (WMAP7, assuming standard ΛCDM):

$$\Omega_{\rm dm} = 0.227 \pm 0.014$$

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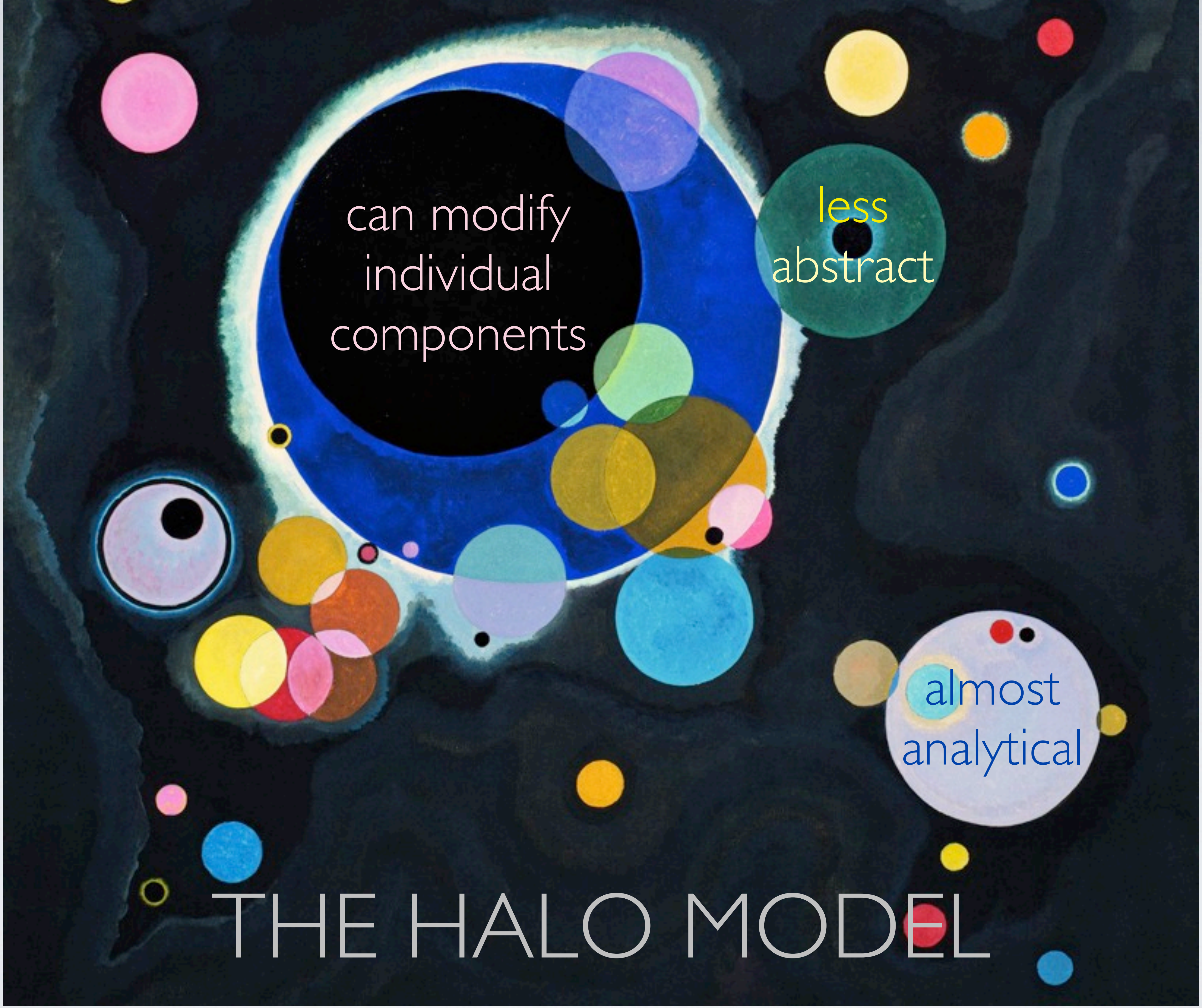
- 1 constraint: Choose a light particle (m ~ 1 keV)

  → Warm Dark Matter

  → constraints from Large Scale Structure

FREE-STREAMING

- early relativistic particles ⇒ free-streaming
- density field fluctuations ← smoothened
- ∴ the linear matter power spectrum ← small scale suppression
- How does this translate to non-linearities?


can modify individual components
less abstract
almost analytical
THE HALO MODEL

SPLITTING THE FIELD

Smith & Markovic (PRD; 2011)

- in CDM, assume:
  all of density field ← haloes

$$\rho(\boldsymbol{x}) = \sum_{i=1}^{N} M_i \, u_{\rm h}(|\boldsymbol{x} - \boldsymbol{x}_{0,i}|, M_i)$$

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- in WDM, split:
  clumped + smooth

SPLITTING THE FIELD

Smith & Markovic (PRD; 2011)

- volume average
- get background values

$$\langle \rho(\boldsymbol{x}) \rangle = \langle \rho_{\rm s}(\boldsymbol{x}) \rangle + \langle \rho_{\rm c}(\boldsymbol{x}) \rangle$$

- define a "clumped fraction"

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mass function (no. density of haloes per dM)

SPLITTING THE FIELD

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- we want statistic of clustering, so as always:

$$\langle \rho_i(\boldsymbol{x}) \rho_j(\boldsymbol{x}+\boldsymbol{r}) \rangle = \bar{\rho}_i \bar{\rho}_j \left(1 + \langle \delta_i(\boldsymbol{x}) \delta_j(\boldsymbol{x}+\boldsymbol{r}) \rangle \right)$$

$$\rho_i(\boldsymbol{x}) \equiv \bar{\rho}_i \left(1 + \delta_i(\boldsymbol{x})\right)$$

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$$\xi_{ij}(|\boldsymbol{r}|) \equiv \xi_{ij}(r) \equiv \langle \delta_i(\boldsymbol{x})\delta_j(\boldsymbol{x}+\boldsymbol{r})\rangle$$

+ statistical isotropy & homogeneity

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$$\Downarrow$$

$$\delta(\boldsymbol{x}) = (1-f)\delta_s(\boldsymbol{x}) + f\delta_{\mathrm{c}}(\boldsymbol{x})$$

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$$= \langle \rho_{\rm s}(\boldsymbol{x}) \rho_{\rm s}(\boldsymbol{x}+\boldsymbol{r}) \rangle + \langle \rho_{\rm c}(\boldsymbol{x}) \rho_{\rm c}(\boldsymbol{x}+\boldsymbol{r}) \rangle + 2 \langle \rho_{\rm c}(\boldsymbol{x}) \rho_{\rm s}(\boldsymbol{x}+\boldsymbol{r}) \rangle$$

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$$= \bar{\rho}_{\rm s}^2 \left(1 + \xi_{\rm ss}(r)\right) + \bar{\rho}_{\rm c}^2 \left(1 + \ \xi_{\rm cc}(r)\right) + 2 \bar{\rho}_{\rm c} \bar{\rho}_{\rm s} \left(1 + \xi_{\rm cs}(r)\right)$$

SPLITTING THE FIELD

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$$\Downarrow$$

$$\xi(r) = (1-f)^2\xi_{\rm ss}(r) + 2f(1-f)\xi_{\rm sc}(r) + f^2\xi_{\rm cc}(r)$$

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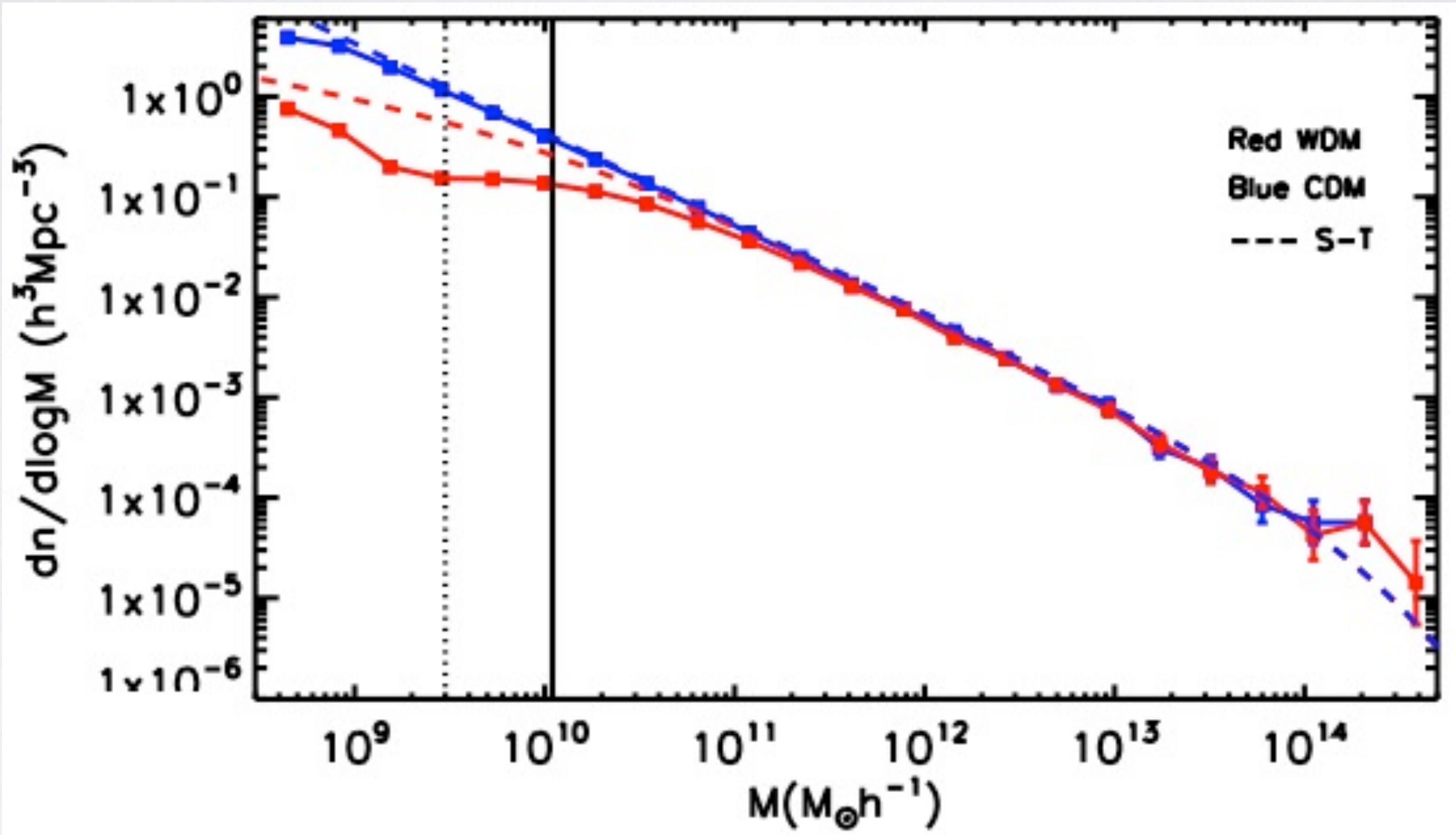
$$\Downarrow$$

$$P(k) = (1-f)^2 P_{\rm ss}(k) + 2(1-f)fP_{\rm sc}(k) + f^2 P_{\rm cc}(k)$$

$$P_{\rm cc}^{\rm 2h}(k) + P_{\rm cc}^{\rm 1h}(k)$$

CALIBRATING THE HALO MODEL

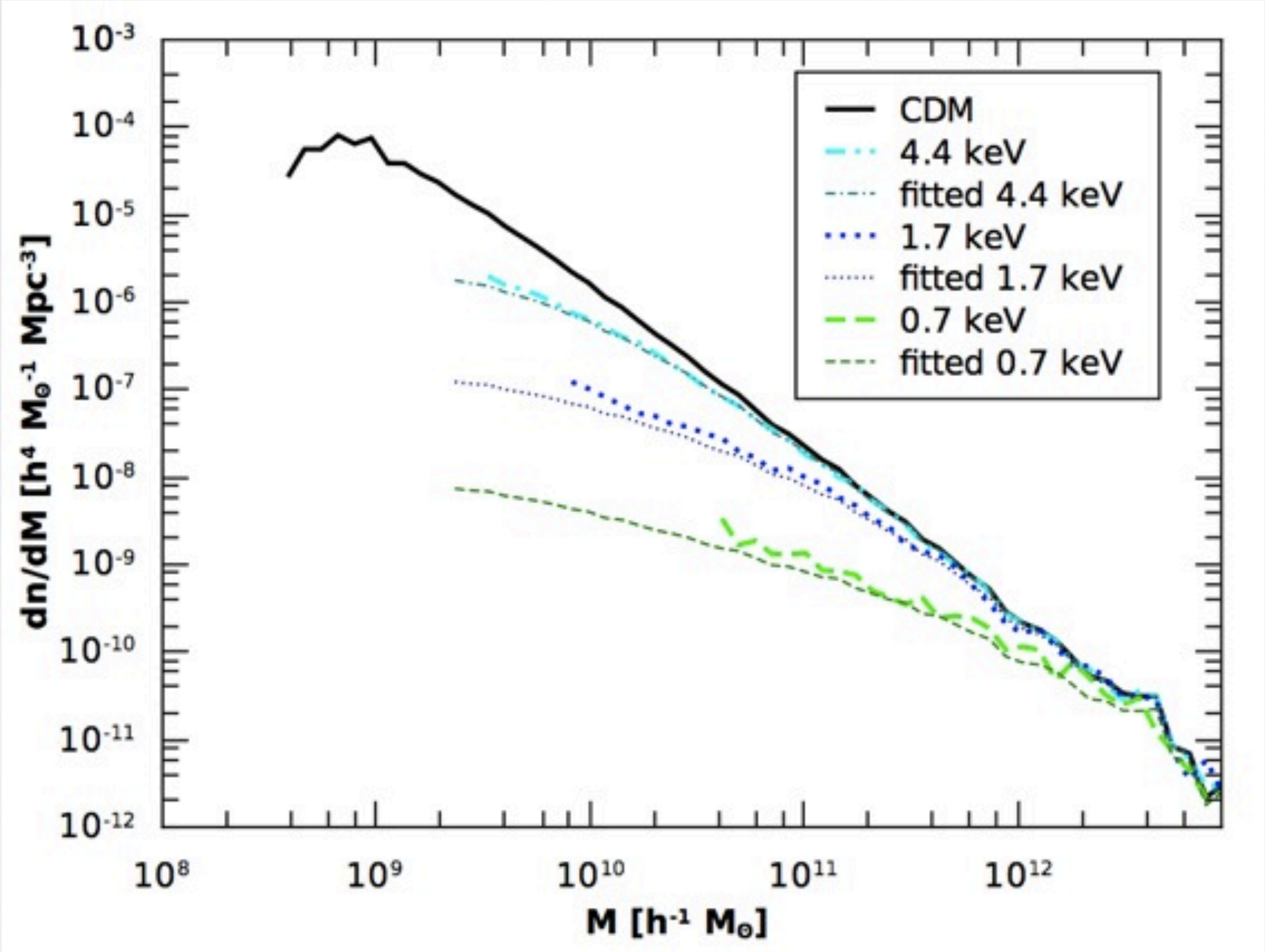
Zavala et al. (2009)



$$f = \bar{\rho}_{\rm c}/\bar{\rho} = \frac{1}{\bar{\rho}} \int_{M_{\rm cut}}^{\infty} dM M \frac{dn}{dM}$$

CALIBRATING THE HALO MODEL

Dunstan, Abazajian, Polisensky & Ricotti (2011)



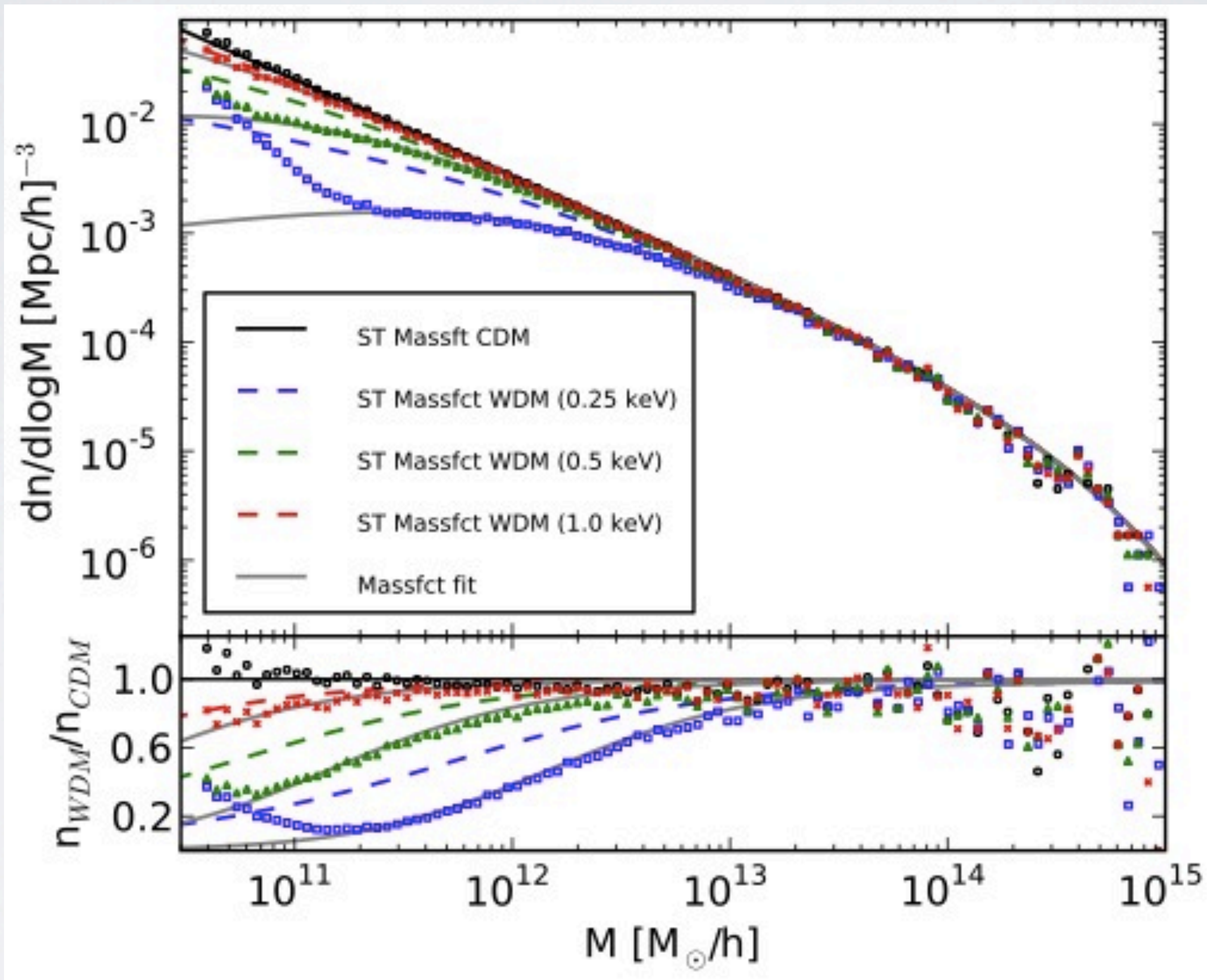
$\eta = 1.2$

$$\frac{dn}{dM}\Big|_{\mathrm{WDM}} = \left(1 + \frac{M_{1/2}}{M}\right)^{-\eta} \frac{dn}{dM}\Big|_{\mathrm{CDM}}$$

CALIBRATING THE HALO MODEL

Schneider, Smith, Maccio & Moore (2012)

$\eta = 1.16$

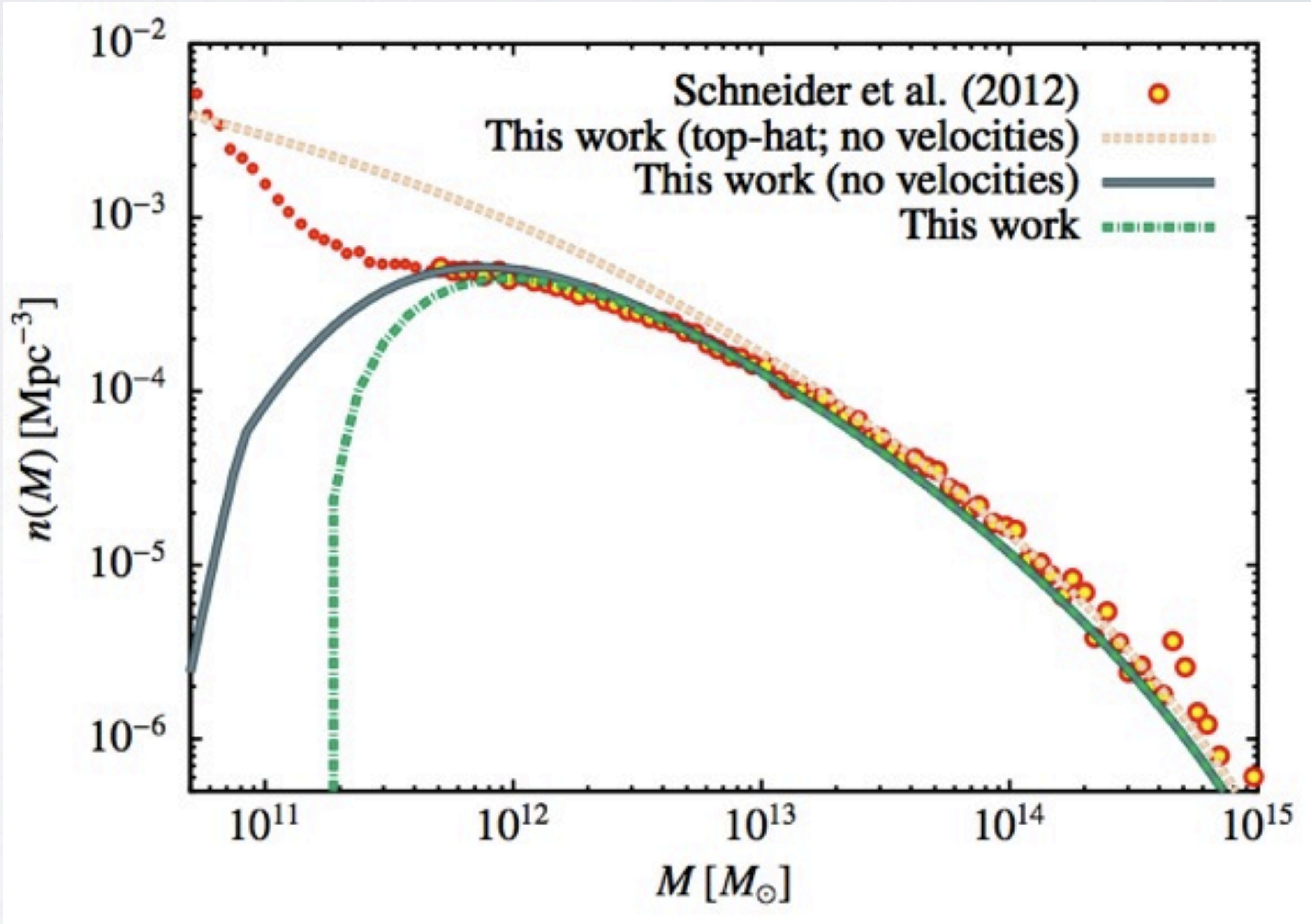


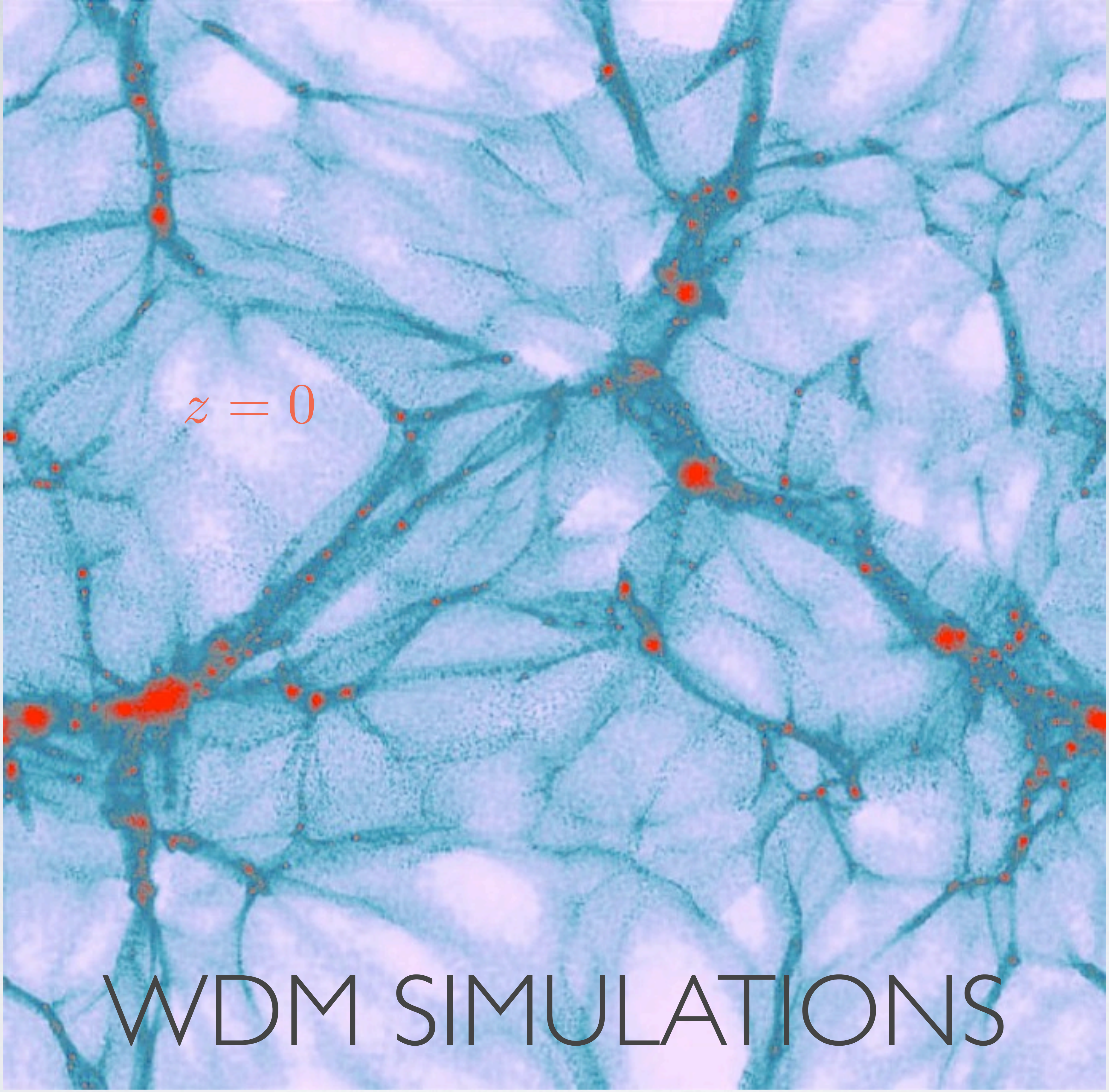
$$\left.\frac{dn}{dM}\right|_{\mathrm{WDM}} = \left(1 + \frac{M_{1/2}}{M}\right)^{-\eta} \left.\frac{dn}{dM}\right|_{\mathrm{CDM}}$$

CALIBRATING THE HALO MODEL

Benson et al. (2012)

- arXiv, Monday
- merger trees
- no top-down
- *smooth accretion!*





WDM SIMULATIONS

Viel, Markovic, Baldi & Weller (MNRAS; 2012)

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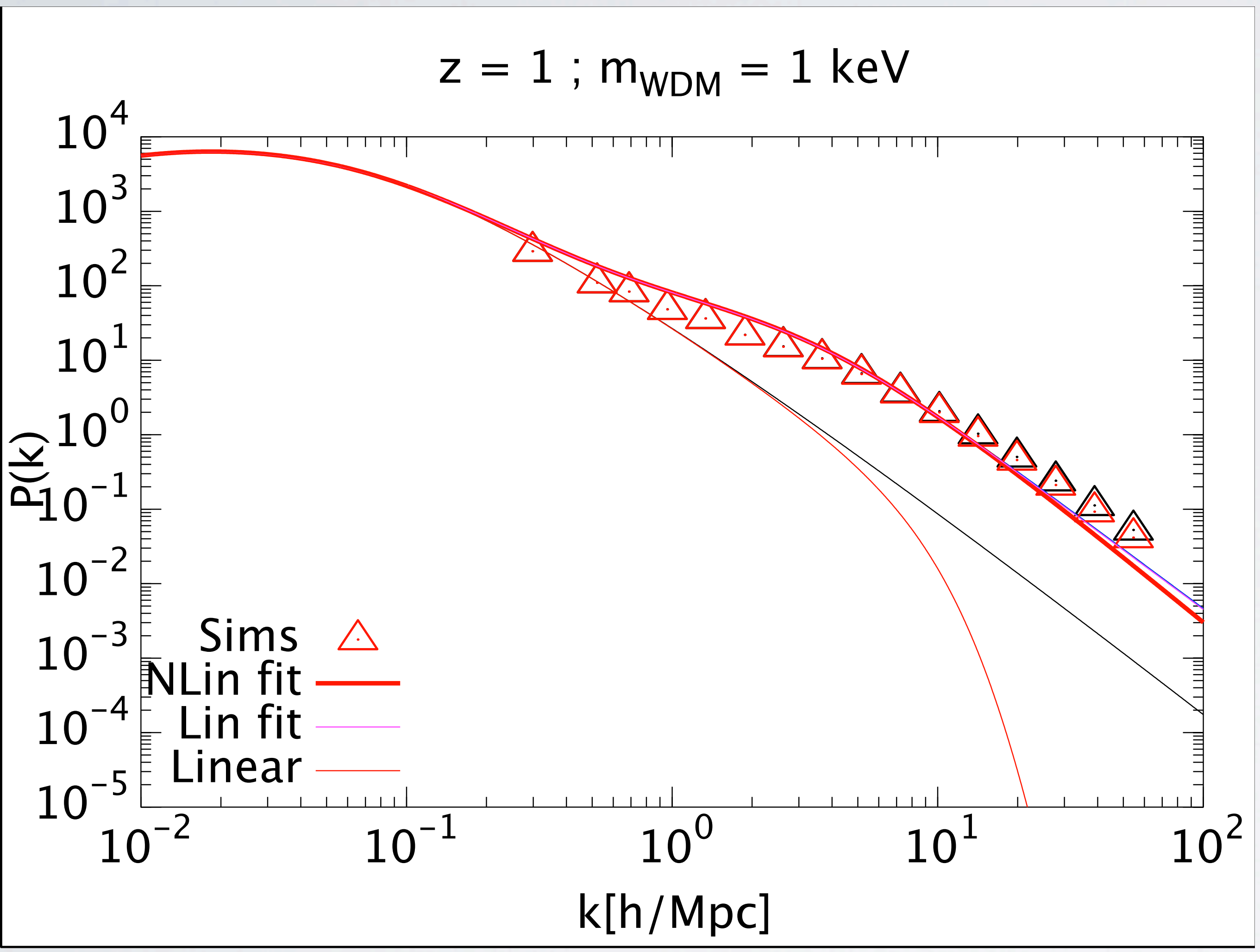
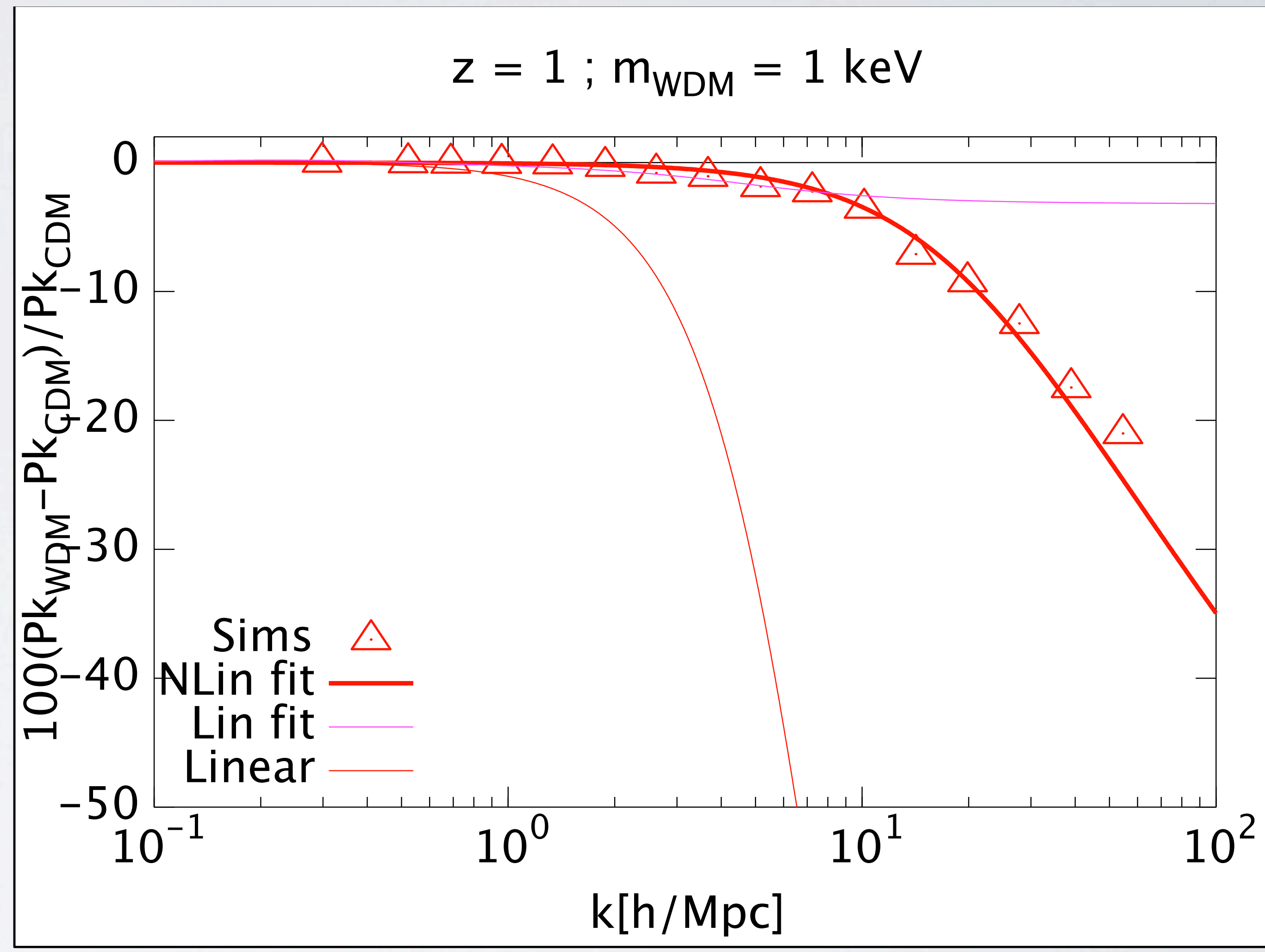


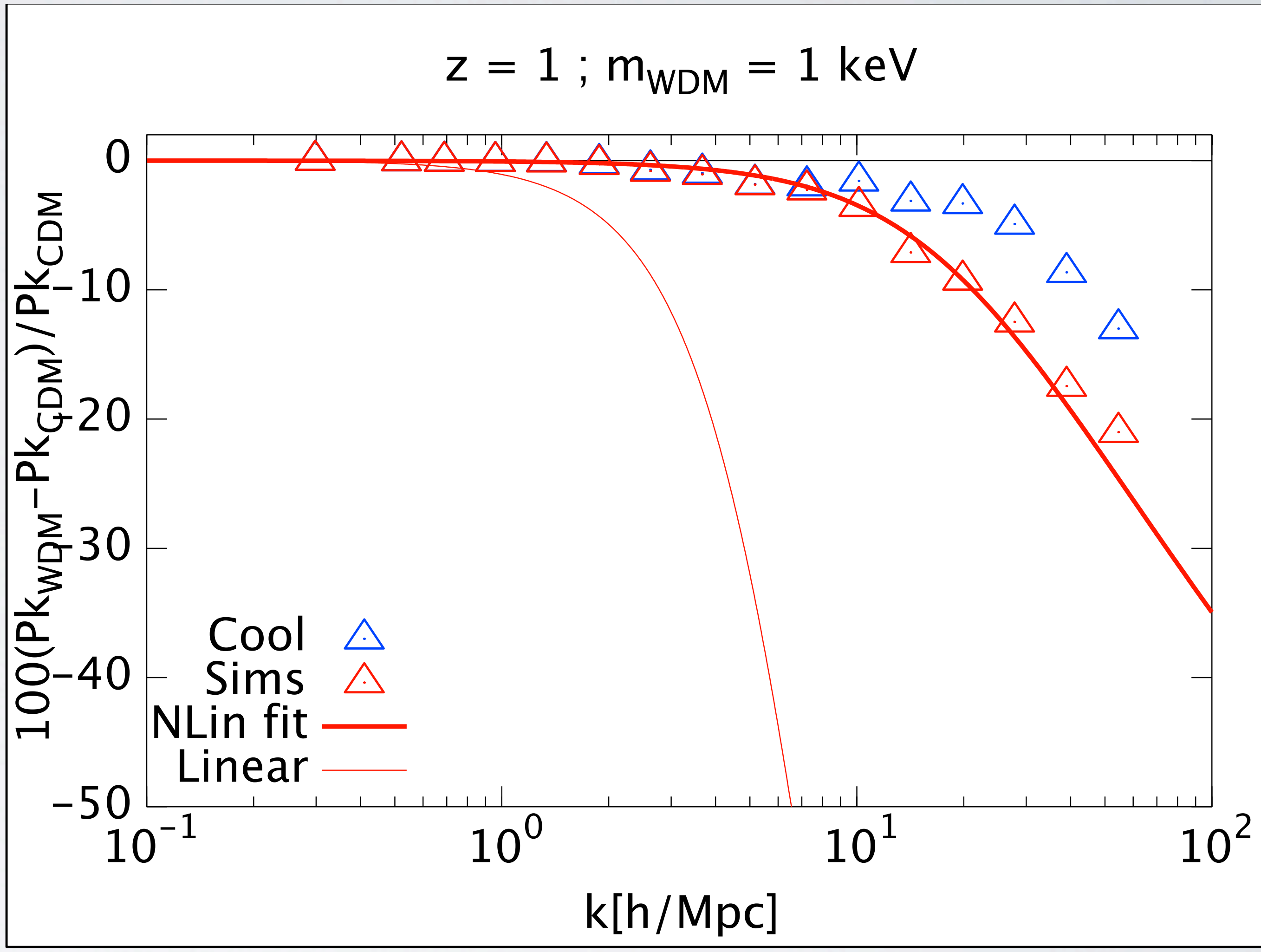


$$T^2_{\rm nlin}(k) \equiv P_{\rm WDM}(k)/P_{\Lambda{\rm CDM}}(k) = (1 + (\alpha\, k)^{\nu l})^{-s/\nu}$$

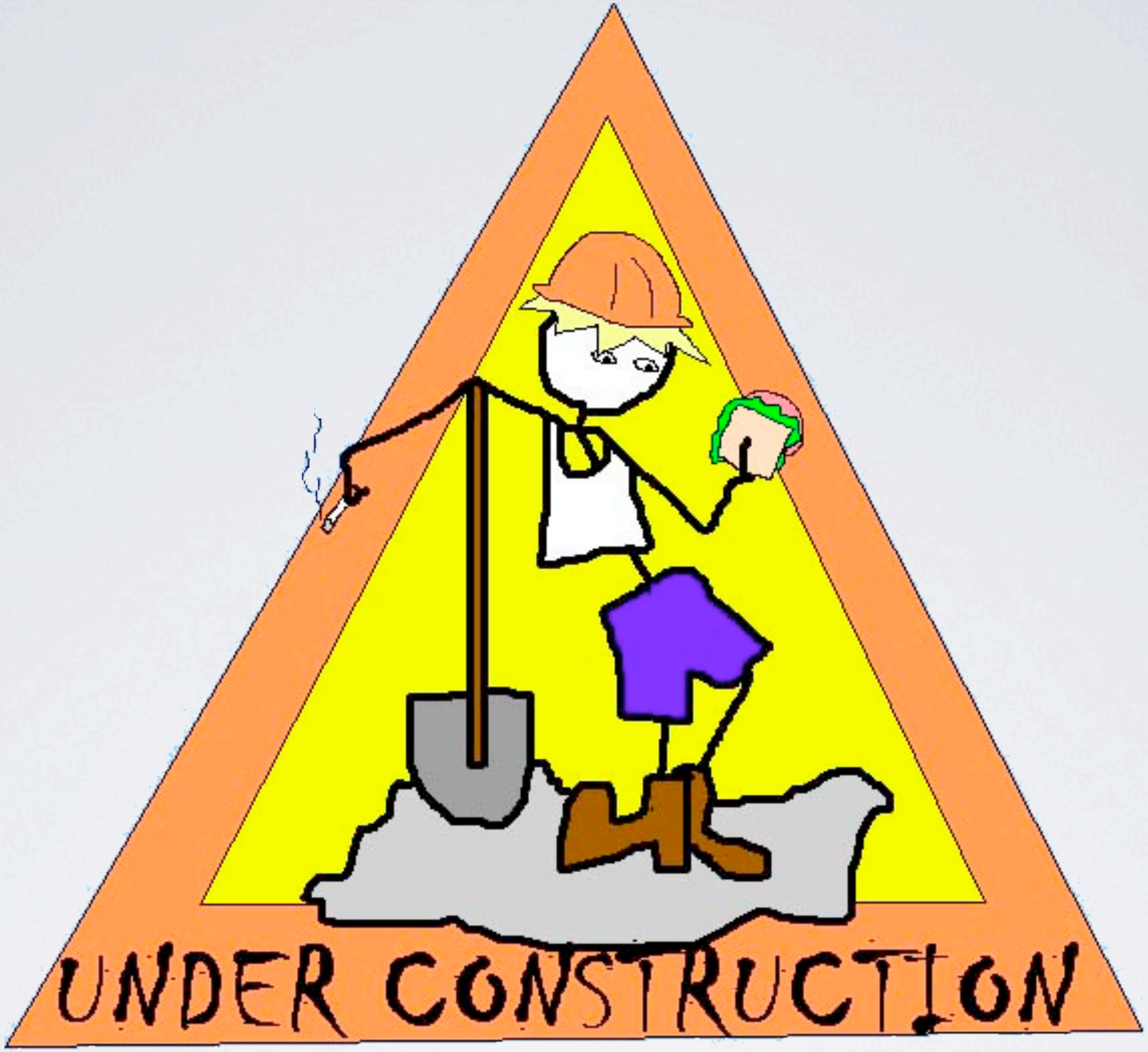
Depends on particle mass

WDM+b

Viel, Markovic, Baldi & Weller (MNRAS; 2012)



- blue: SF, winds
- cooling erases WDM effect



WORK IN PROGRESS...

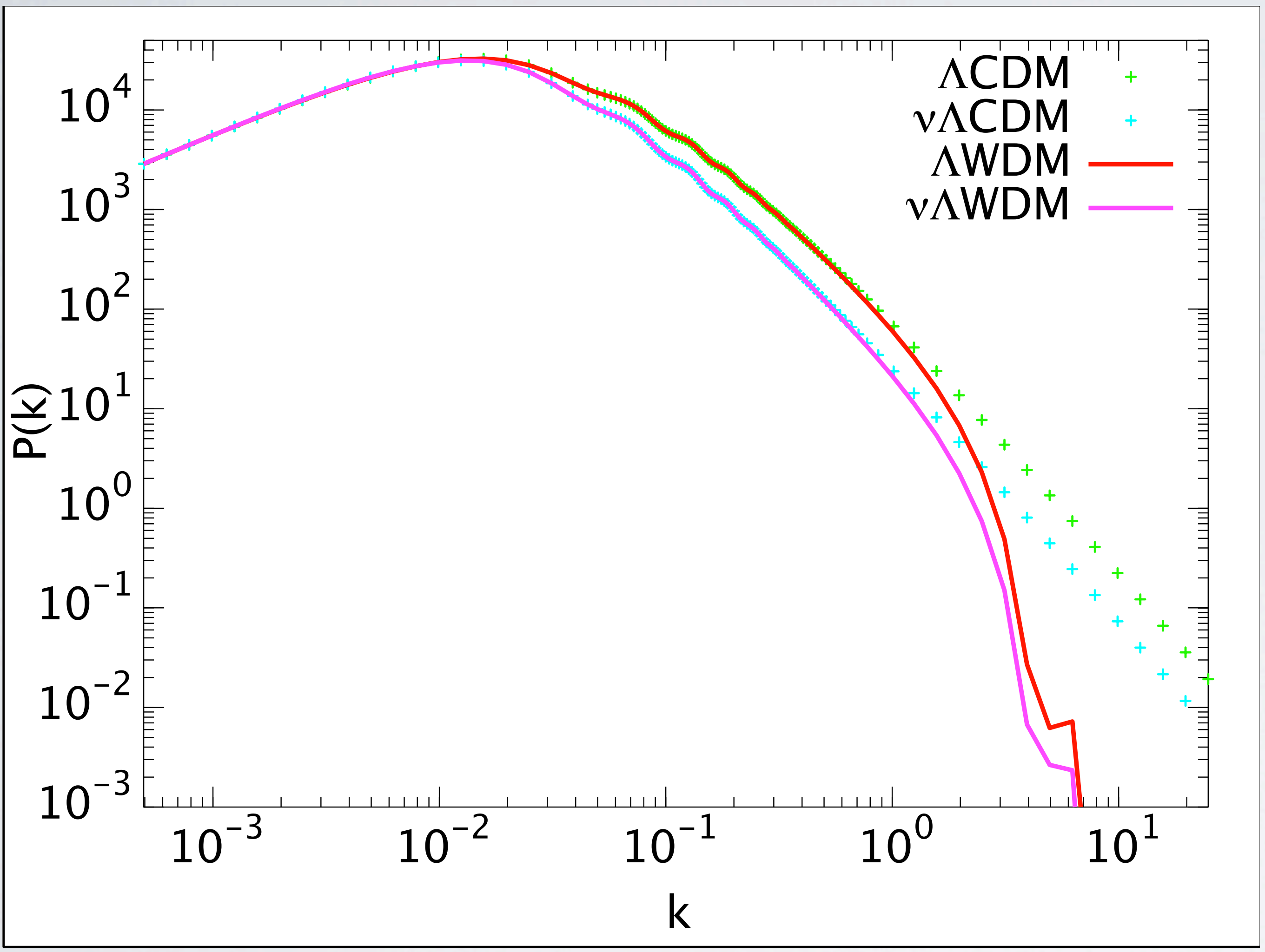
WDM+ν

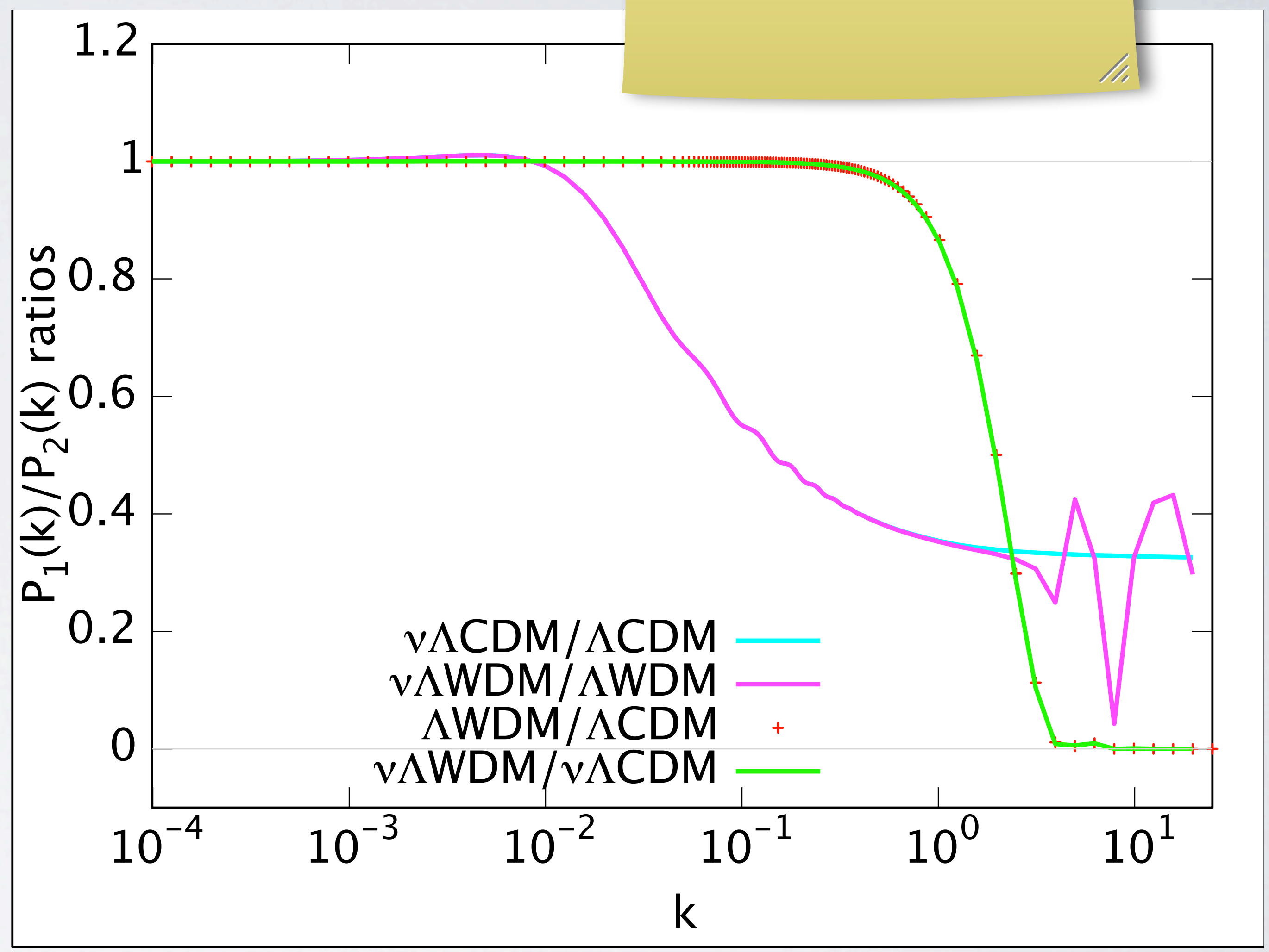
Markovic, Abdalla, Lahav & Weller (in prep)

- neutrinos = HDM
- CLASS code (Lesgourgues, 2011)
- halofit (CDM-based)
- ... new, calibrated halo model

WDM+ν

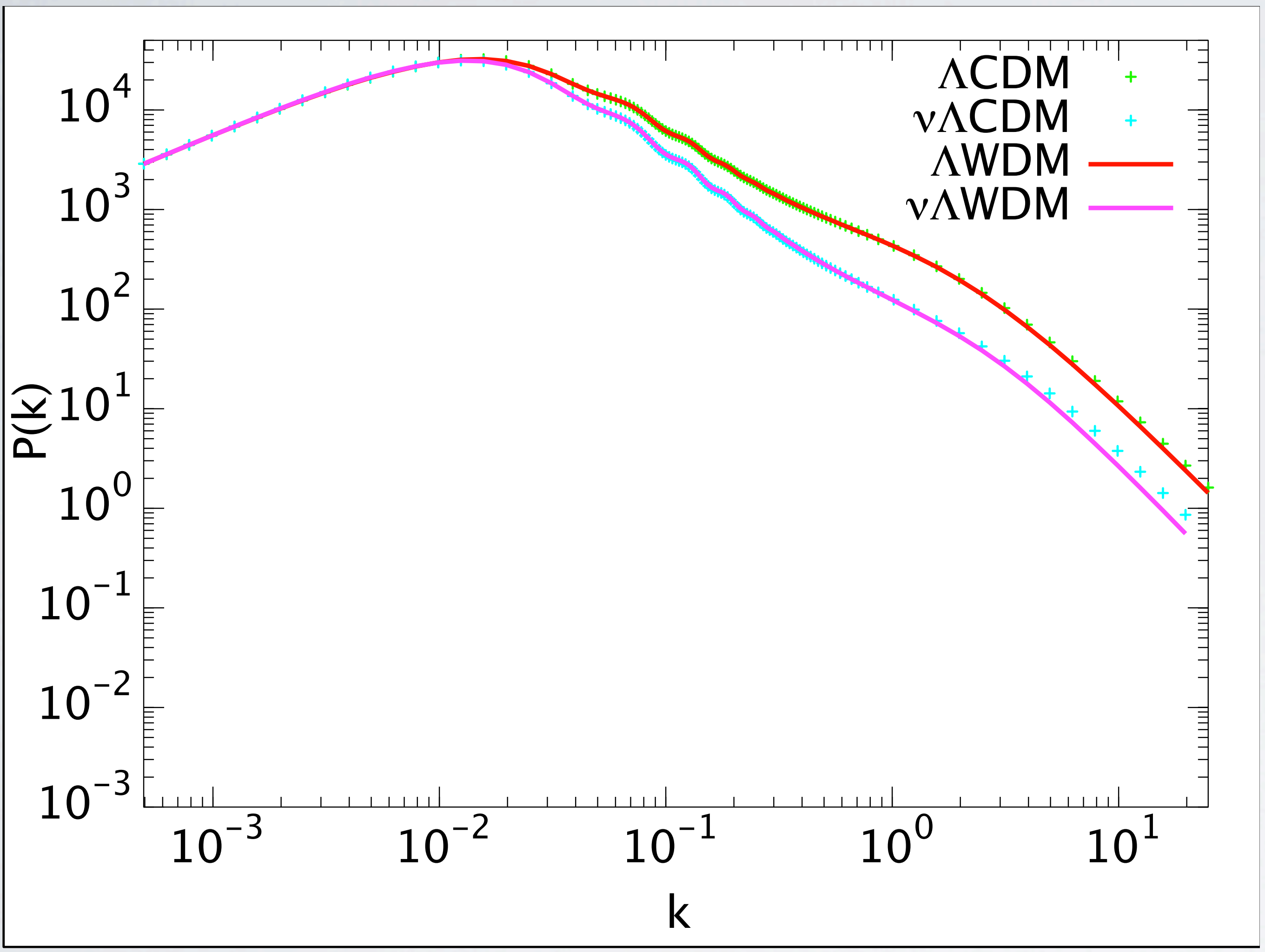
free-
streaming
scale

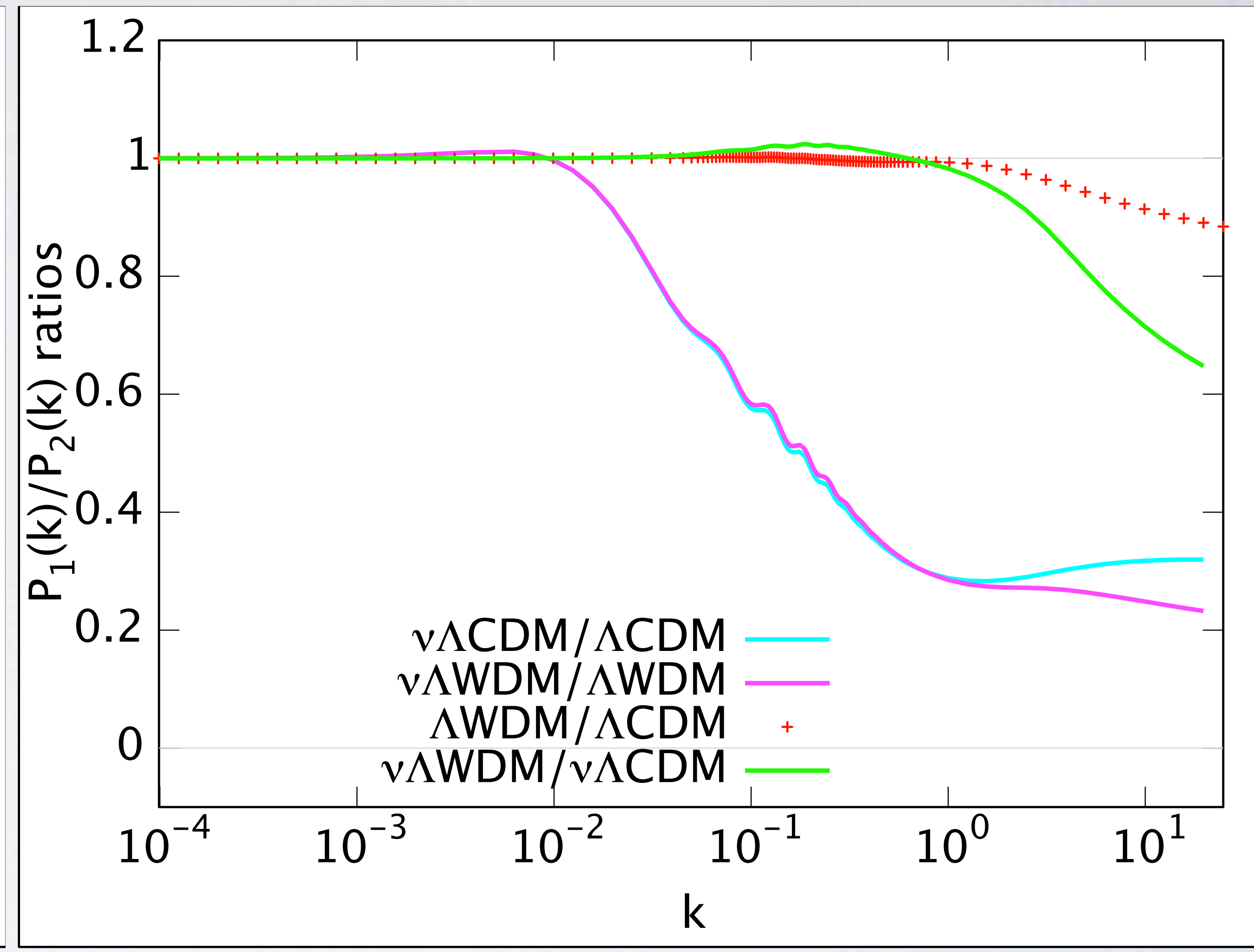




Linear

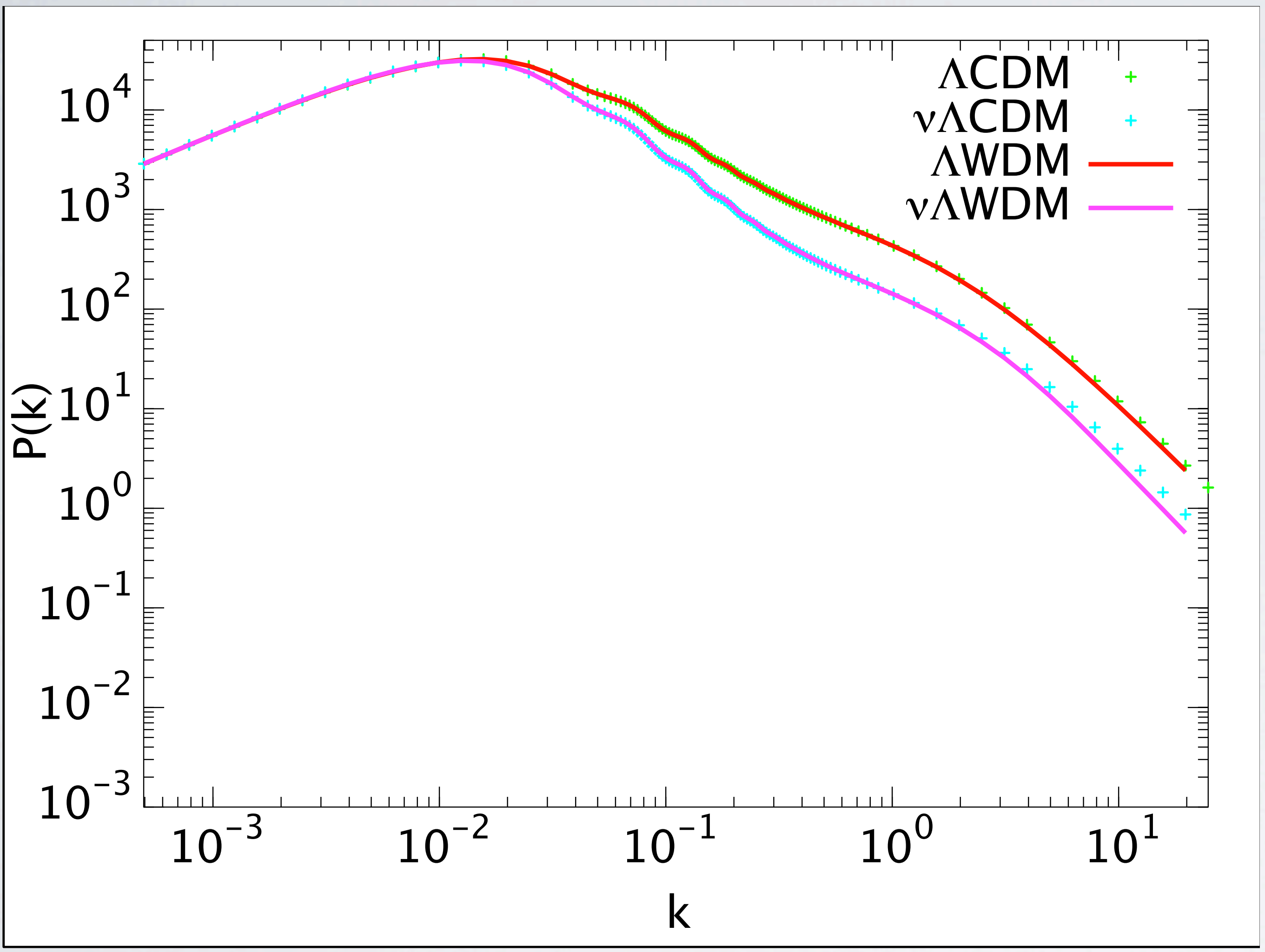
WDM+ν

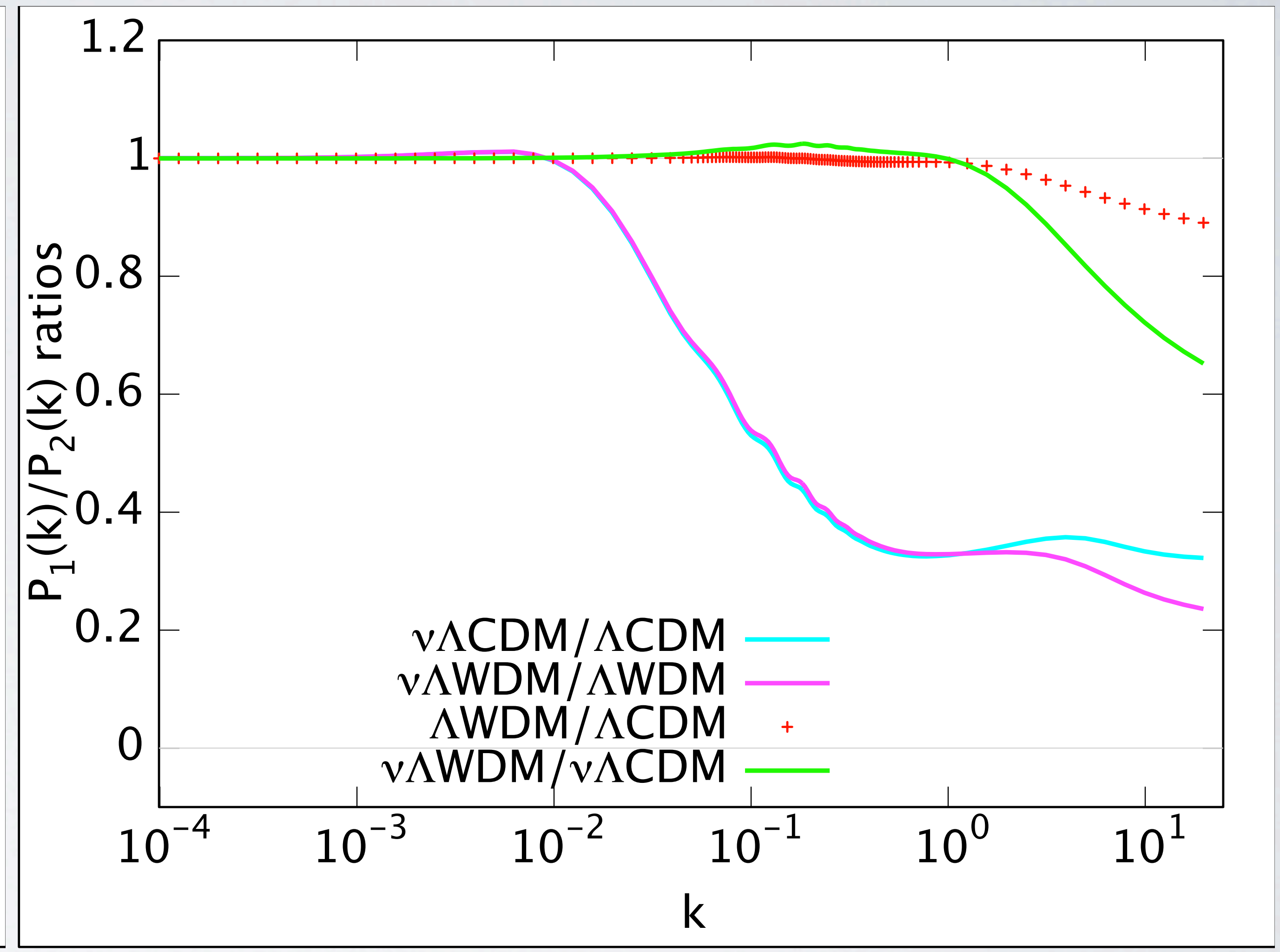




halofit

WDM+ν





halofit

+correction

TL;DR

- WDM is a generalisation of CDM.
- We know good prescriptions to calculate non-linear corrections in ΛWDM.
- BUT we need to know baryonic effects!

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