Generalized Dark Matter Cosmological Observables & Constraints

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Dark Energy Colloquium – May 2020

Success of CDM ?

Dark matter : Density

$\rho_{cdm}(a) = \rho_{cdm,0} \cdot a^{-3}$

Dark matter :
equation of state parameter

$P_{cdm} = \omega \cdot \rho_{cdm} \cdot c^2$

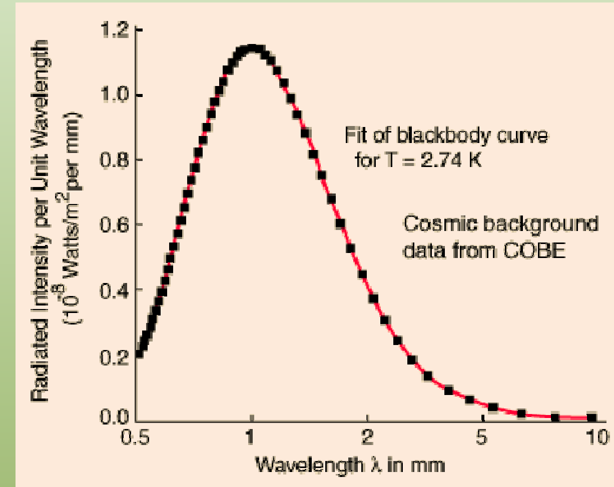
$\omega = 0$

Dark matter :
effective sound speed

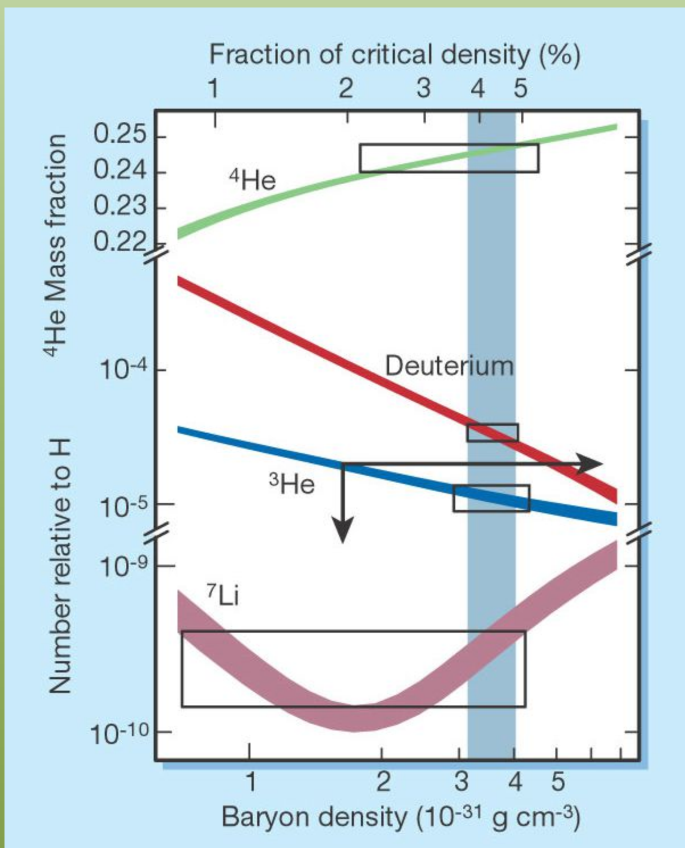
$c_s^2 = \delta P_{cdm} / \delta \rho_{cdm}$

$c_s^2 = 0$

Success of CDM ?



Black body CMB



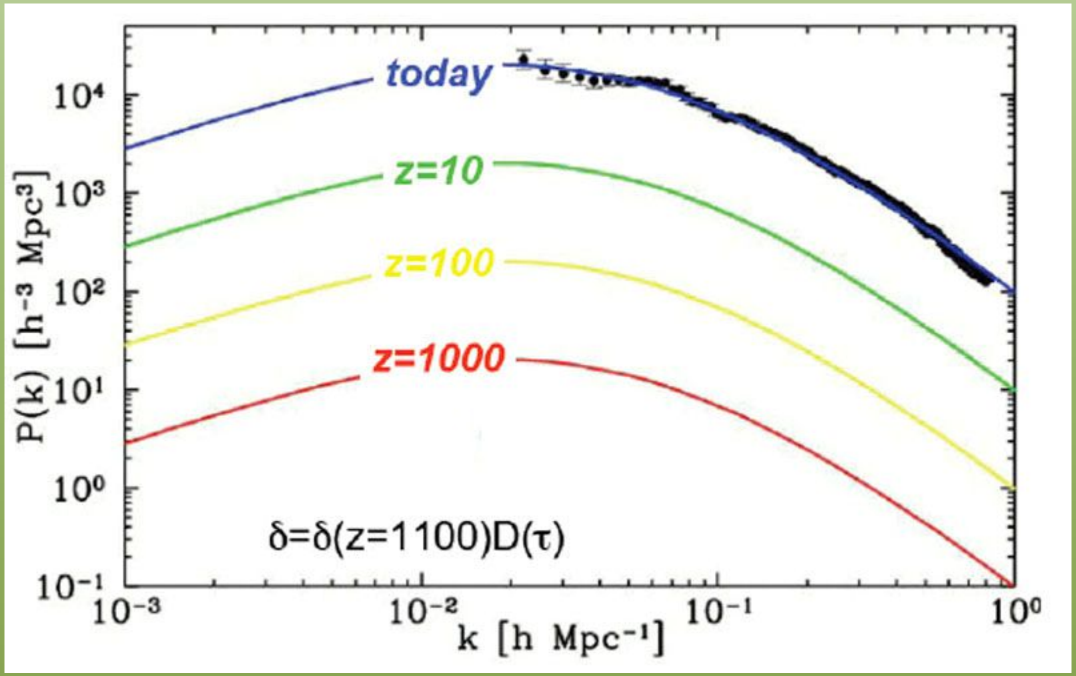
Mass-To-Light Ratios

Type of Object	Mass-to-Light Ratio
Sun	1
Matter in vicinity of Sun	2
Mass in Milky Way within 80,000 light-years of the center	10
Small groups of galaxies	50–150
Rich clusters of galaxies	250–300

Mass to light ratio

BBN

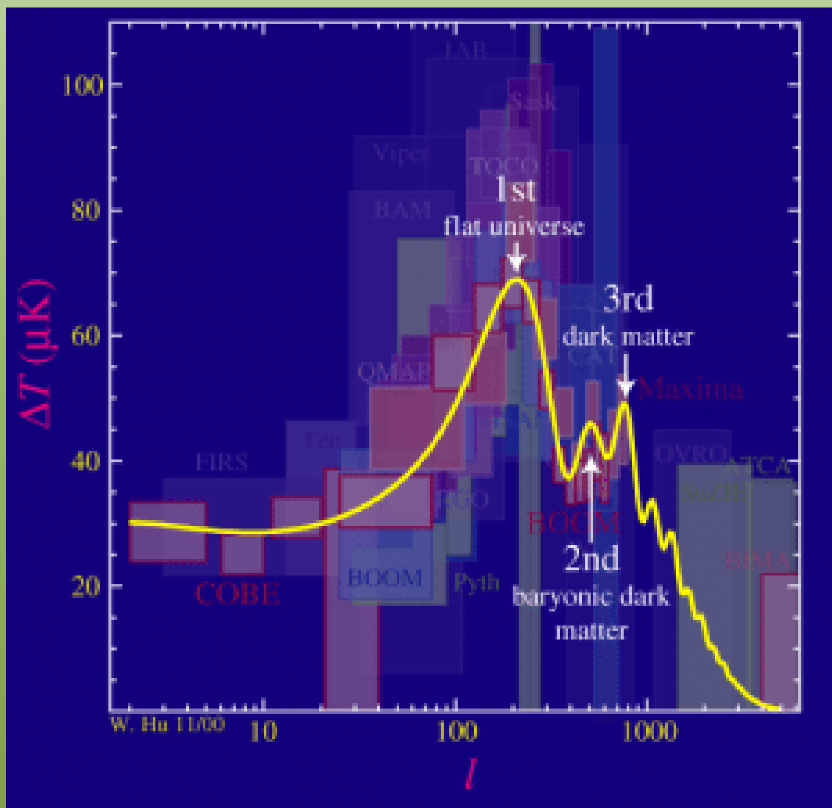
Success of CDM ? : ω null ??

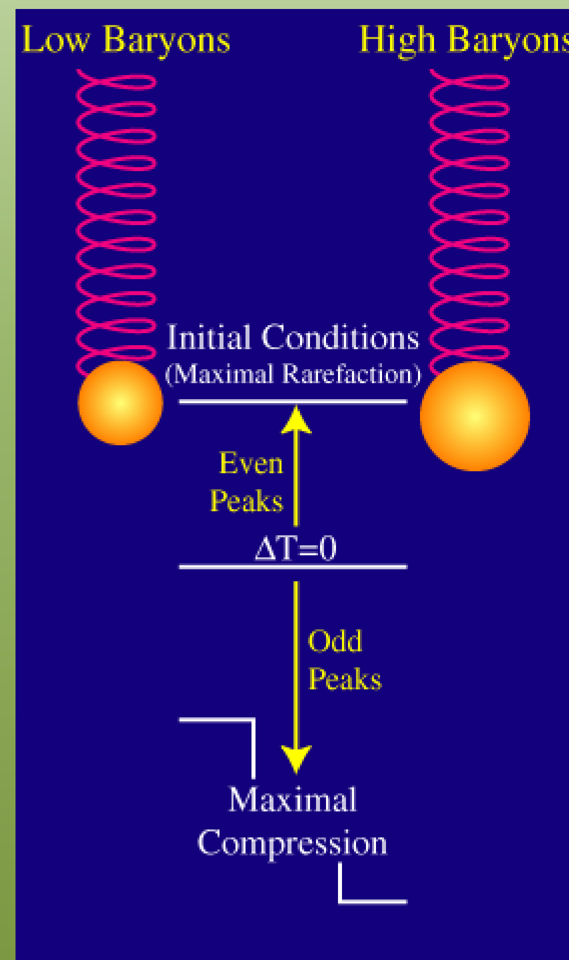


$$\delta \sim (1+z)^{-1}$$

$$\delta_f = 10^{-5}\left(\frac{1+1000}{1+5}\right) \sim 0.002$$

Success of CDM ? : cs null ??

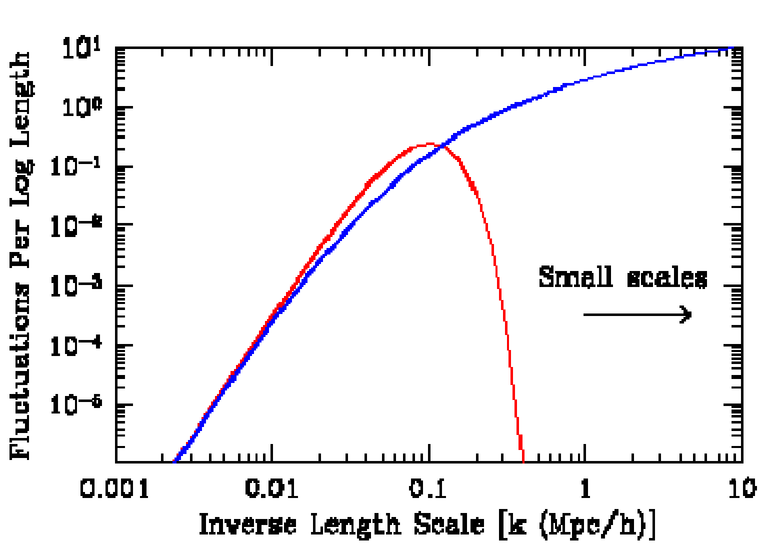


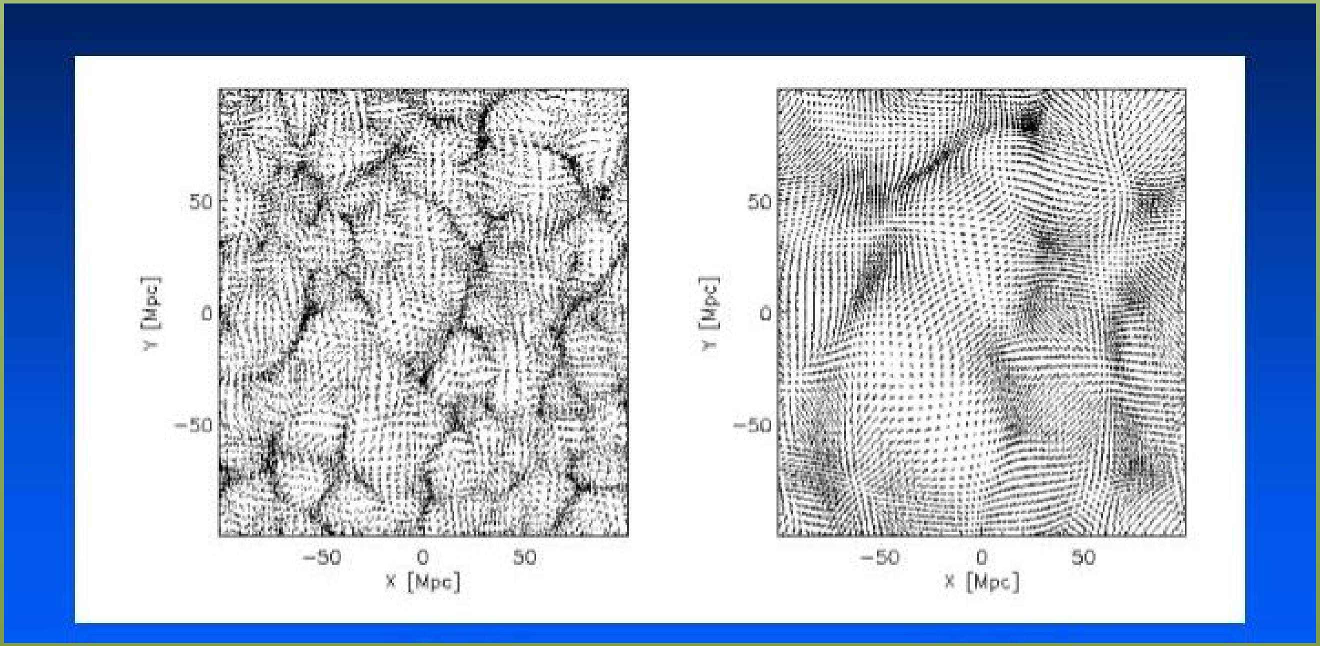


Cmb peaks

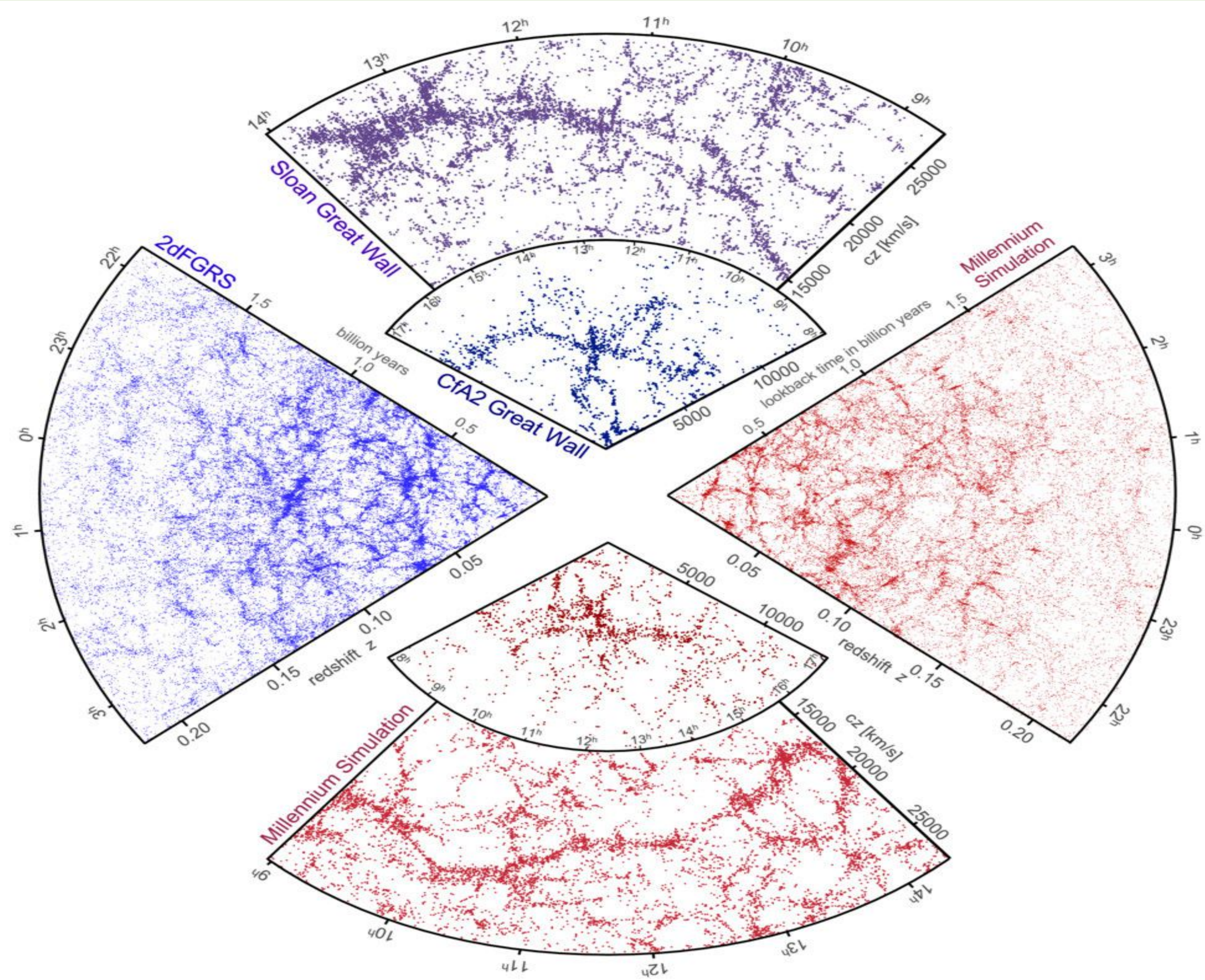
The C in LCDM ?

Peebles vs Zeldovitch





Simulations



Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
Millennium Simulation
cz [km/s]
lookback time in billion years
billion years
redshift z

Extensions of CDM ?

Hu 1998

Kopp 2016

$\omega_{gdm} = P_{gdm} / \rho_{gdm} \neq 0$

$c_s^2 = \delta P_{cdm} / \delta \rho_{cdm} \neq 0$

Warm Dark Matter

Neutrinos

DM Couplings

Chaplygin Gas

Equations of background and perturbations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$T_i^{\mu\nu} = (\rho_i c^2 + P_i) u^\mu u^\nu + P_i g^{\mu\nu}$$

$$\dot{\bar{\rho}}_i + 3H\left(\bar{\rho}_i + \frac{\bar{P}_i}{c^2}\right) = 0$$

$$\omega_{gdm} = P_{gdm} / \rho_{gdm} \neq 0$$

$$c_s^{\,2} = \delta P_{cdm} / \delta \rho_{cdm} \neq 0$$

$$\dot{\delta}_i + 3H\left(c_{s,i}^2 - w_i\right)\delta_i = - \left[1 + w_i + \left(1 + c_{s,i}^2\right)\delta_i\right] \vec{\nabla} \cdot \vec{u}_i$$

$$\dot{\vec{u}}_i + 2H\vec{u}_i + (\vec{u}_i \cdot \vec{\nabla})\vec{u}_i + \frac{\vec{\nabla}\phi}{a^2} = 0$$

$$\nabla^2 \phi = 4\pi G a^2 \sum_k \bar{\rho}_k \left(1 + 3c_{s,k}^2\right)\delta_k$$

Boltzmann code

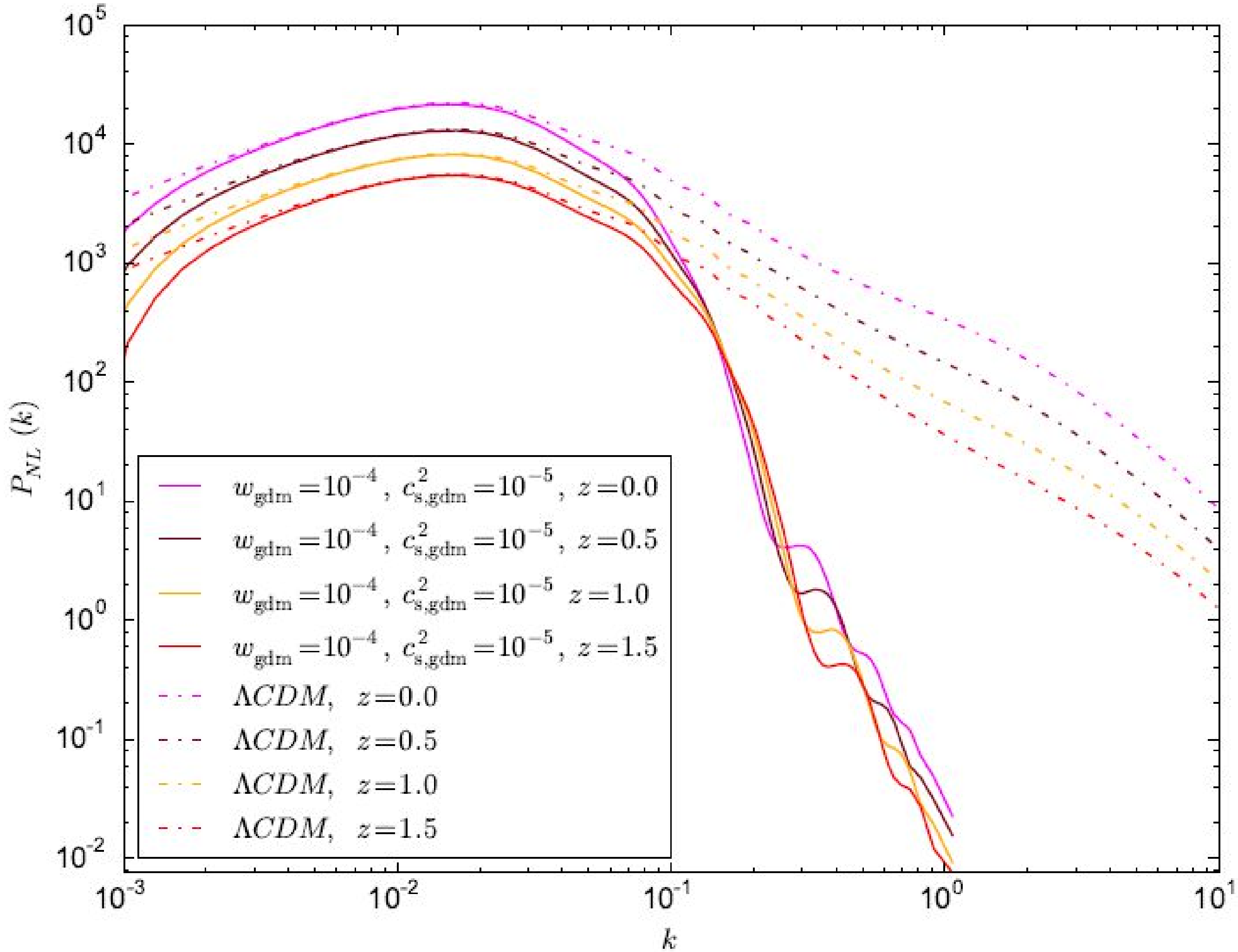
$$\dot{\delta} + (1 + w_{\mathrm{gdm}}) \left(\theta + \frac{\dot{h}}{2} \right) + 3H \left(\frac{\delta p}{\delta \rho} - w_{\mathrm{gdm}} \right) \delta = 0$$

$$\dot{\theta} + H(1 - 3w_{\mathrm{gdm}})\theta + \frac{\dot{w}_{\mathrm{gdm}}}{1 + w_{\mathrm{gdm}}}\theta - \frac{\delta p / \delta \rho}{1 + w_{\mathrm{gdm}}} k^2 \delta + k^2 \sigma = 0$$

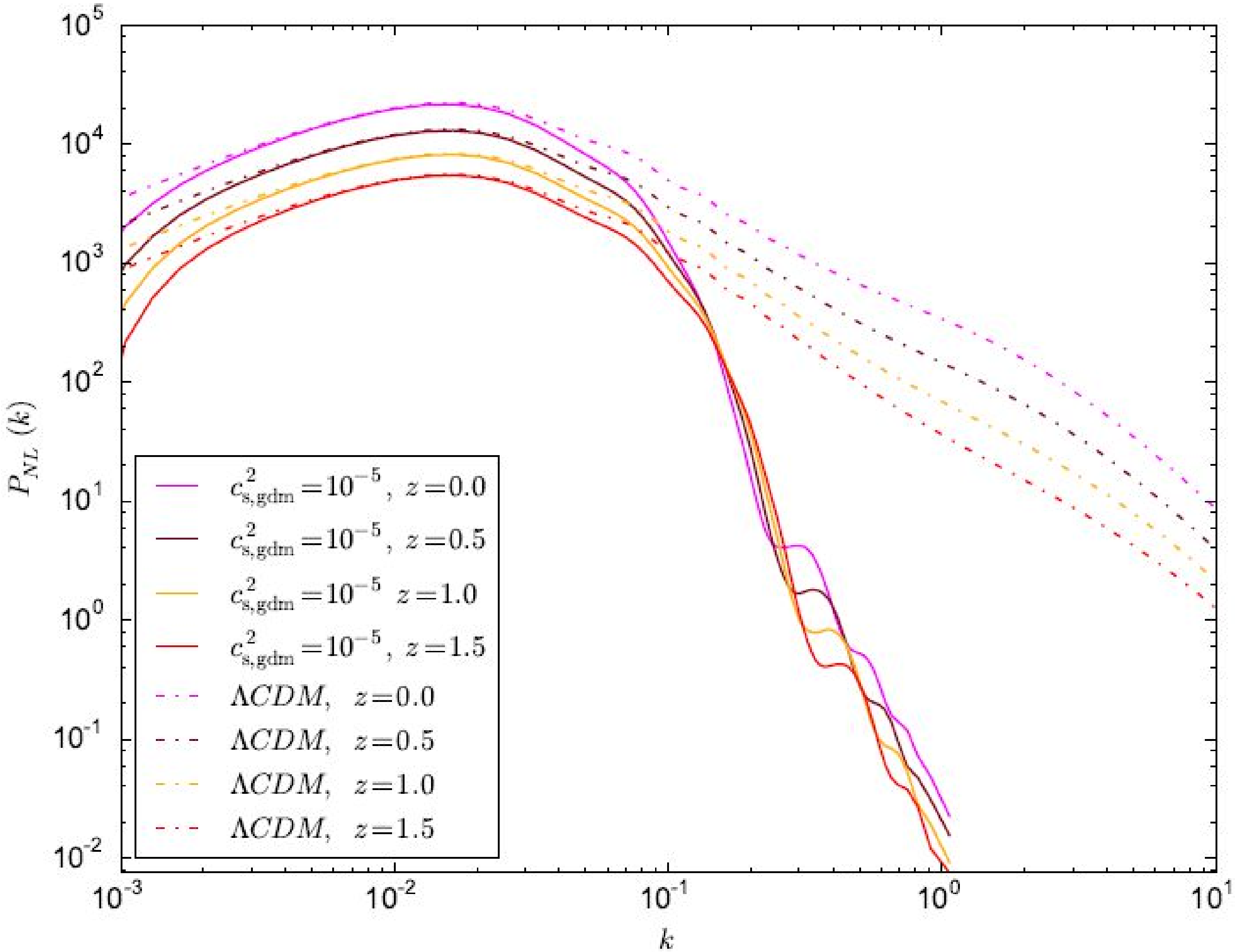
$$\delta p = c^2_{\mathrm{s,gdm}} \delta \rho - \dot{\rho} (c^2_{\mathrm{s,gdm}} - c^2_{\mathrm{a,gdm}}) \theta / k^2$$

$$\dot{\sigma} + 3H \frac{c^2_{\mathrm{a,gdm}}}{w_{\mathrm{gdm}}} \sigma = \frac{4}{3} \frac{c^2_{\mathrm{vis,gdm}}}{1 + w_{\mathrm{gdm}}} (2\theta + \dot{h} + 6\dot{\eta})$$

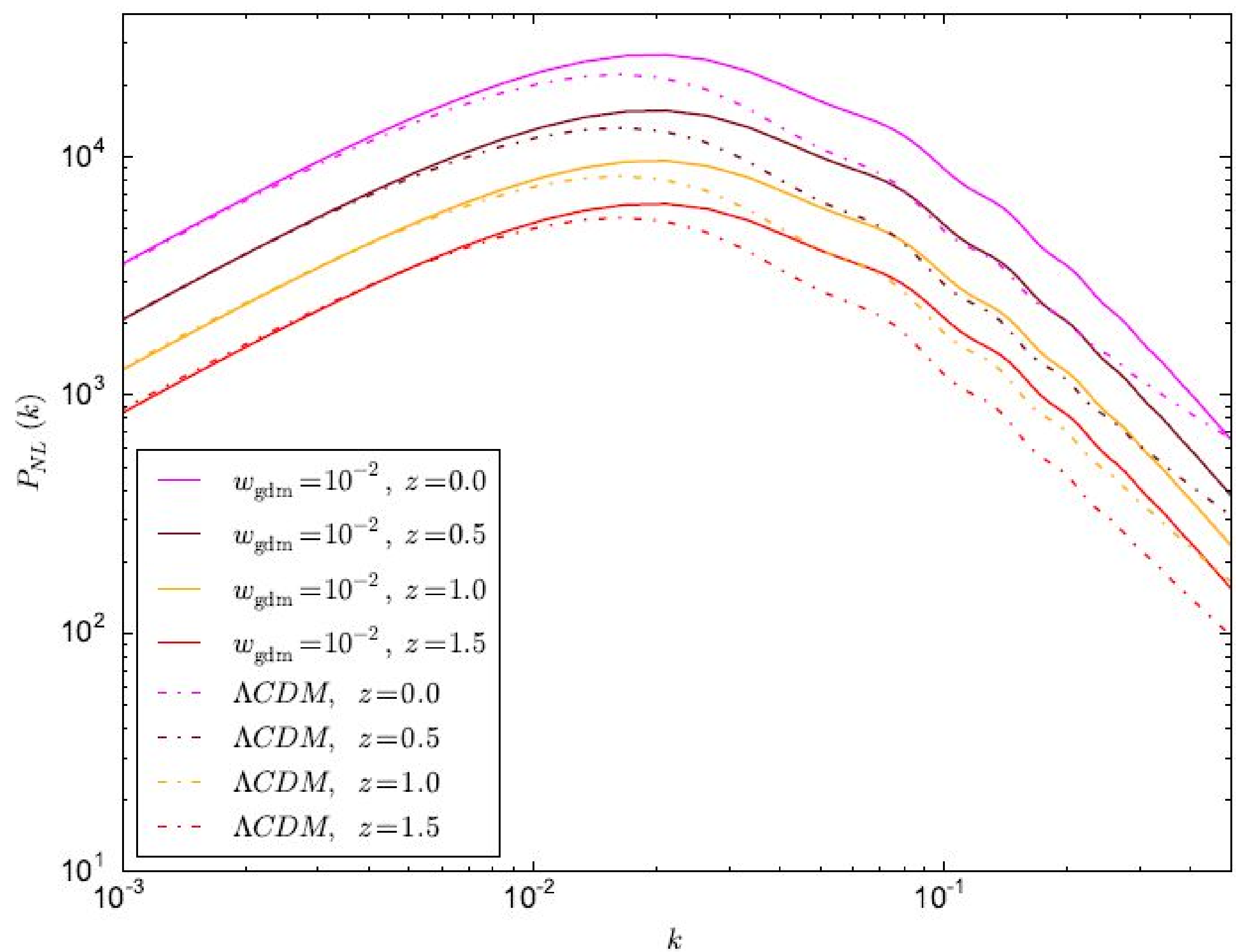
Boltzmann code – power spectrum



Boltzmann code – power spectrum



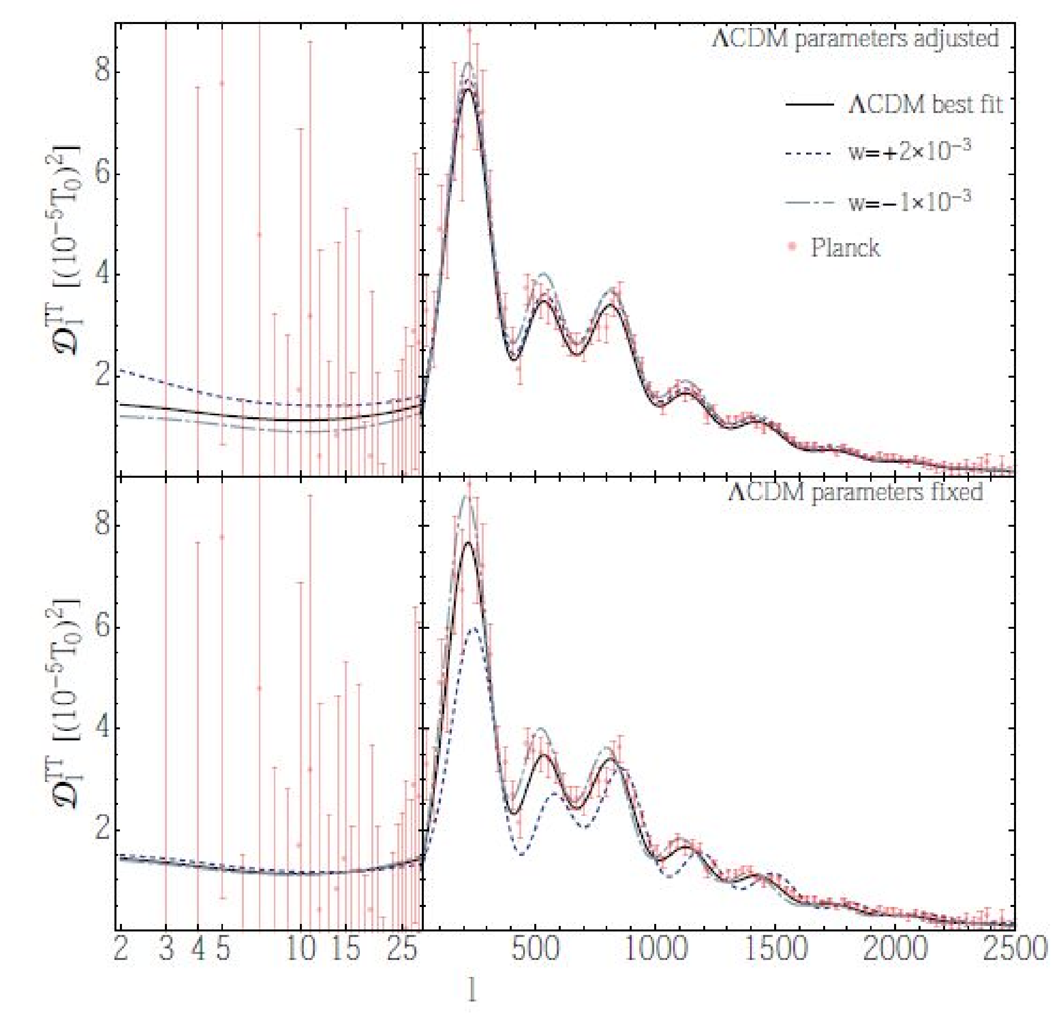
Boltzmann code – power spectrum



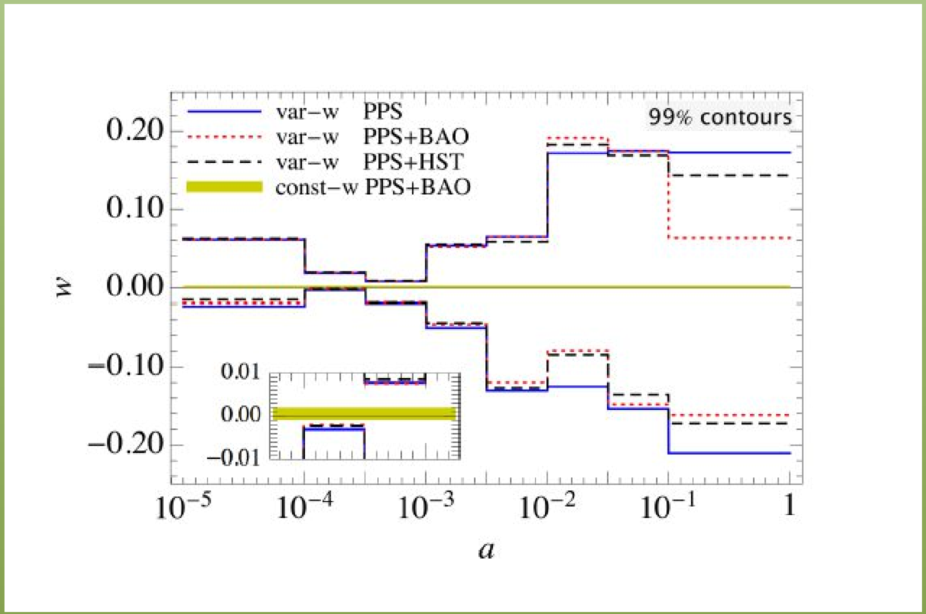
Linear constraints

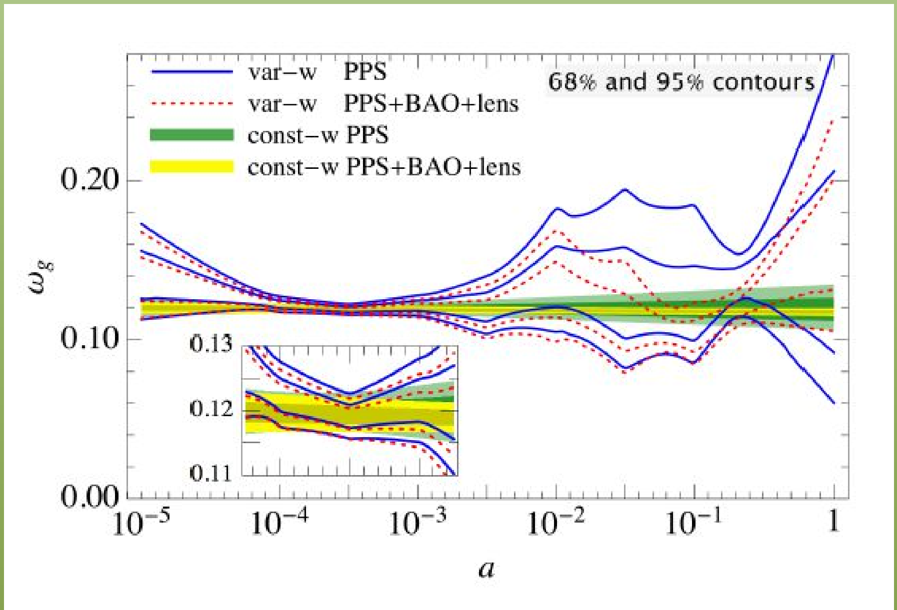
Likelihoods	Λ-wDM $10^2 w$ 95.5%	Λ-wDM $10^2 w$ 99.7%
PPS	$0.007^{+0.463}_{-0.466}$	$0.007^{+0.676}_{-0.673}$
PPS + Lens	$0.087^{+0.439}_{-0.448}$	$0.087^{+0.662}_{-0.648}$
PPS + Lens + HST	$0.256^{+0.217}_{-0.217}$	$0.256^{+0.322}_{-0.323}$
PPS + Lens + BAO	$0.063^{+0.108}_{-0.112}$	$0.063^{+0.163}_{-0.164}$

Thomas et al. 1601.05097



Linear constraints





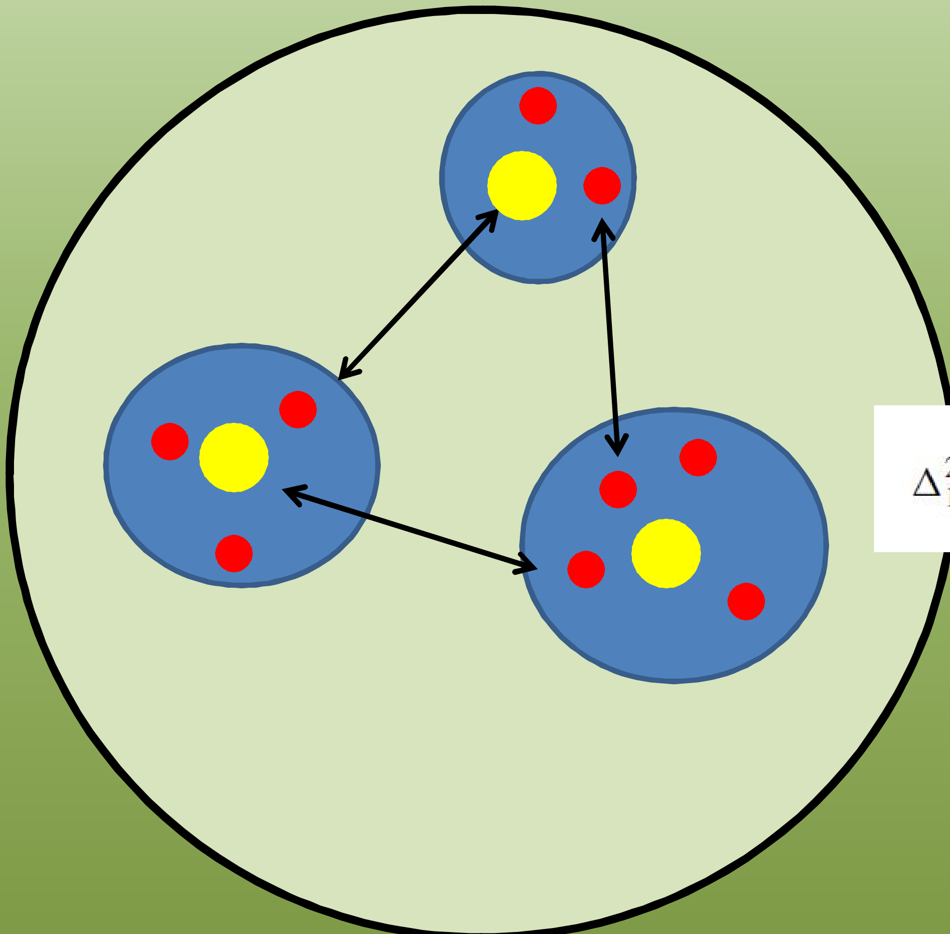
Ilic et al. 2004.09572v1

Linear constraints predictions

Model	Parameters	CMB+SNIa+BAO	CMB+SNIa+BAO+WL	Photometric Euclid
ΛCDM	$10^2 \times \Omega_b$	4.834 ± 0.054	4.815 ± 0.053	$(4.834) \pm 0.075$
	Ω_{dm}	0.2562 ± 0.0060	0.2539 ± 0.0057	$(0.2562) \pm 0.0074$
	h	0.6797 ± 0.0049	0.6816 ± 0.0048	$(0.6797) \pm 0.016$
	σ_8	0.8187 ± 0.0089	0.8142 ± 0.0090	$(0.8187) \pm 0.0088$
	n_s	0.9674 ± 0.0043	0.9686 ± 0.0043	$(0.9674) \pm 0.023$
	$10 \times \tau$	0.72 ± 0.13	0.68 ± 0.13	–
ΛGDM	$10^2 \times \Omega_b$	4.71 ± 0.12	4.69 ± 0.12	$(4.834) \pm 0.11$
	Ω_{dm}	0.2491 ± 0.0087	0.2458 ± 0.0088	$(0.2562) \pm 0.014$
	$10^2 \times w$	0.066 ± 0.054	0.055 ± 0.053	$(0.00) \pm 0.21$
	$10^6 \times c_s^2$	< 0.78	< 0.010	< 0.0018
	h	0.6873 ± 0.0082	0.6898 ± 0.0082	$(0.6797) \pm 0.020$
	σ_8	$0.7351^{+0.094}_{-0.041}$	0.8174 ± 0.016	$(0.8187) \pm 0.0096$
	n_s	0.9656 ± 0.0044	0.9682 ± 0.0042	$(0.9674) \pm 0.035$
	$10 \times \tau$	0.73 ± 0.15	0.58 ± 0.16	–

Tutusaus et al. 1805.06202

Non Linear constraints ?



$$\Delta^2(k) = 4\pi V \left(\frac{k}{2\pi}\right)^3 P(k)$$

1 halo term

$$\Delta^2_{1H}(k) = 4\pi \left(\frac{k}{2\pi}\right)^3 \frac{1}{\bar{\rho}^2} \int_0^\infty M^2 W^2(k, M) F(M)\, \mathrm{d}M$$

2 halos term

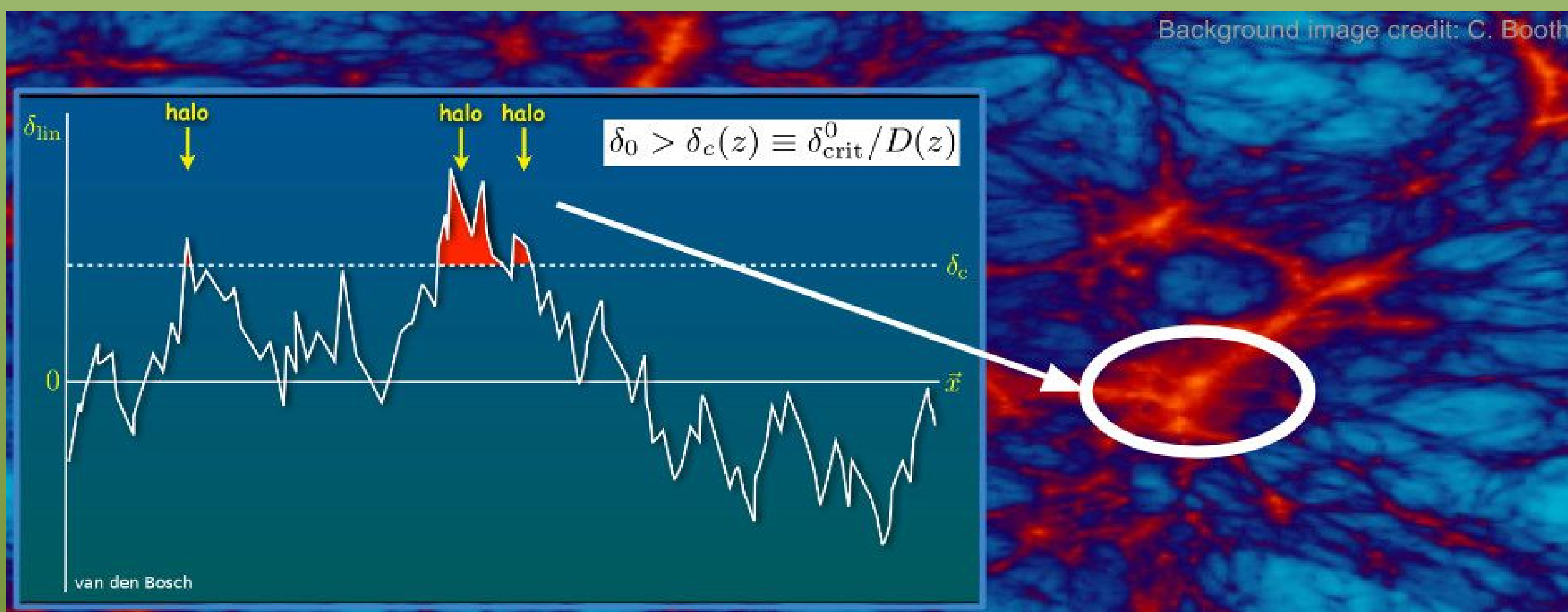
$$\Delta^2_{2H}(k) = \Delta^2_{\text{lin}}(k)$$

$$p(\delta \geq \delta_c) = \frac{1}{\sqrt{2\pi\sigma^2}} \int_{\delta_c}^{\infty} \exp\left(-\frac{\delta^2}{2\sigma^2}\right) d\delta$$

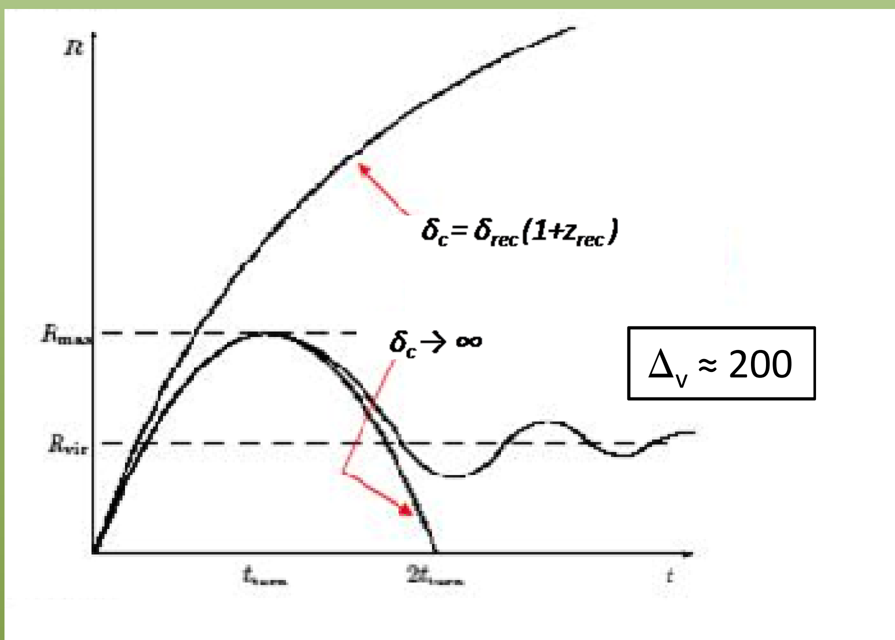
Press - Schechter formalism….

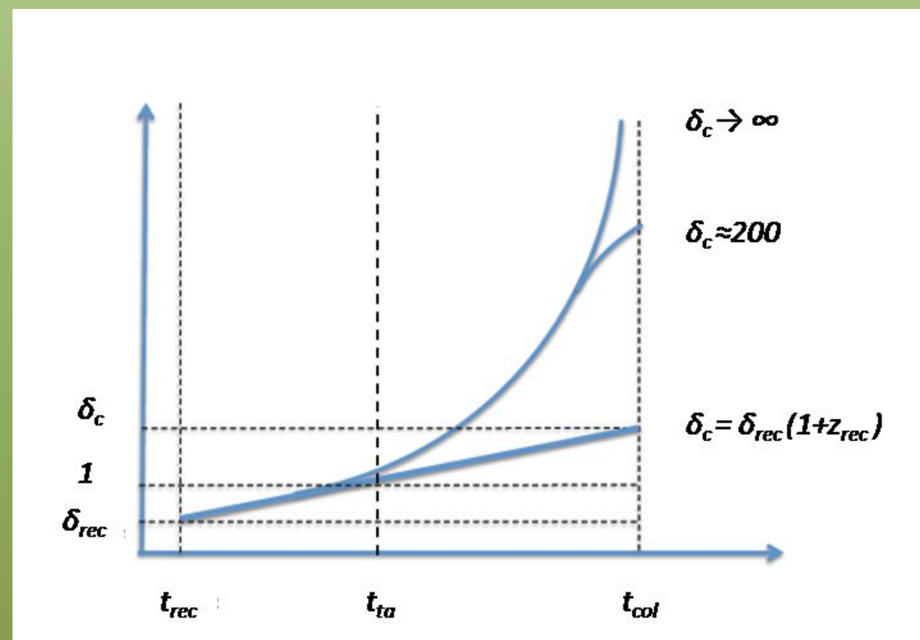
$$F(> M) = 2 \, . \, p(>\delta_c)$$

$$\int n(M)\, dM = \rho/M \, . \, F(>M)$$



Spherical collapse model





Spherical collapse model

Derivation and calculation of δ_c

$$A_i \equiv 3H\left(c_{s,i}^2 - w_i\right)\delta_i$$

$$B_i \equiv 1 + w_i + \left(1 + c_{s,i}^2\right)\delta_i$$

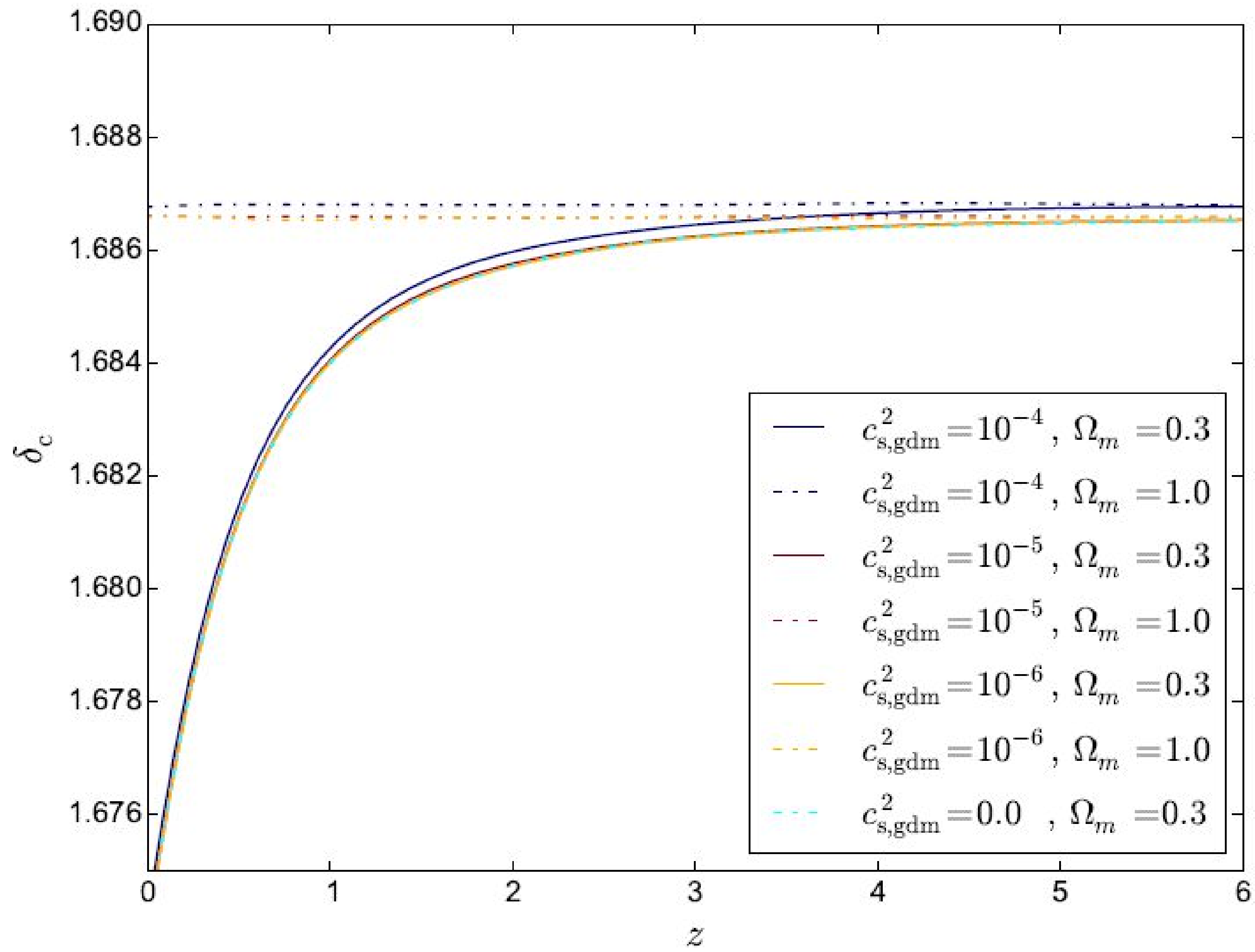
$$\dot{\delta}_i + A_i + B_i\theta_i = 0$$

$$\dot{\theta}_i + 2H\theta_i + \frac{1}{3}\theta_i^2 + \frac{\nabla^2\phi}{a^2} = 0$$

$$\ddot{\delta}_i + \dot{A}_i + \left(2H - \frac{\dot{B}_i}{B_i}\right)\left(A_i + \dot{\delta}_i\right) - \frac{1}{3}\frac{\left(\dot{\delta}_i + A_i\right)^2}{B_i} - \frac{B_i}{a^2}\nabla^2\phi = 0$$

δ_c in GDM

arxiv.1912.12250



δ_c in GDM

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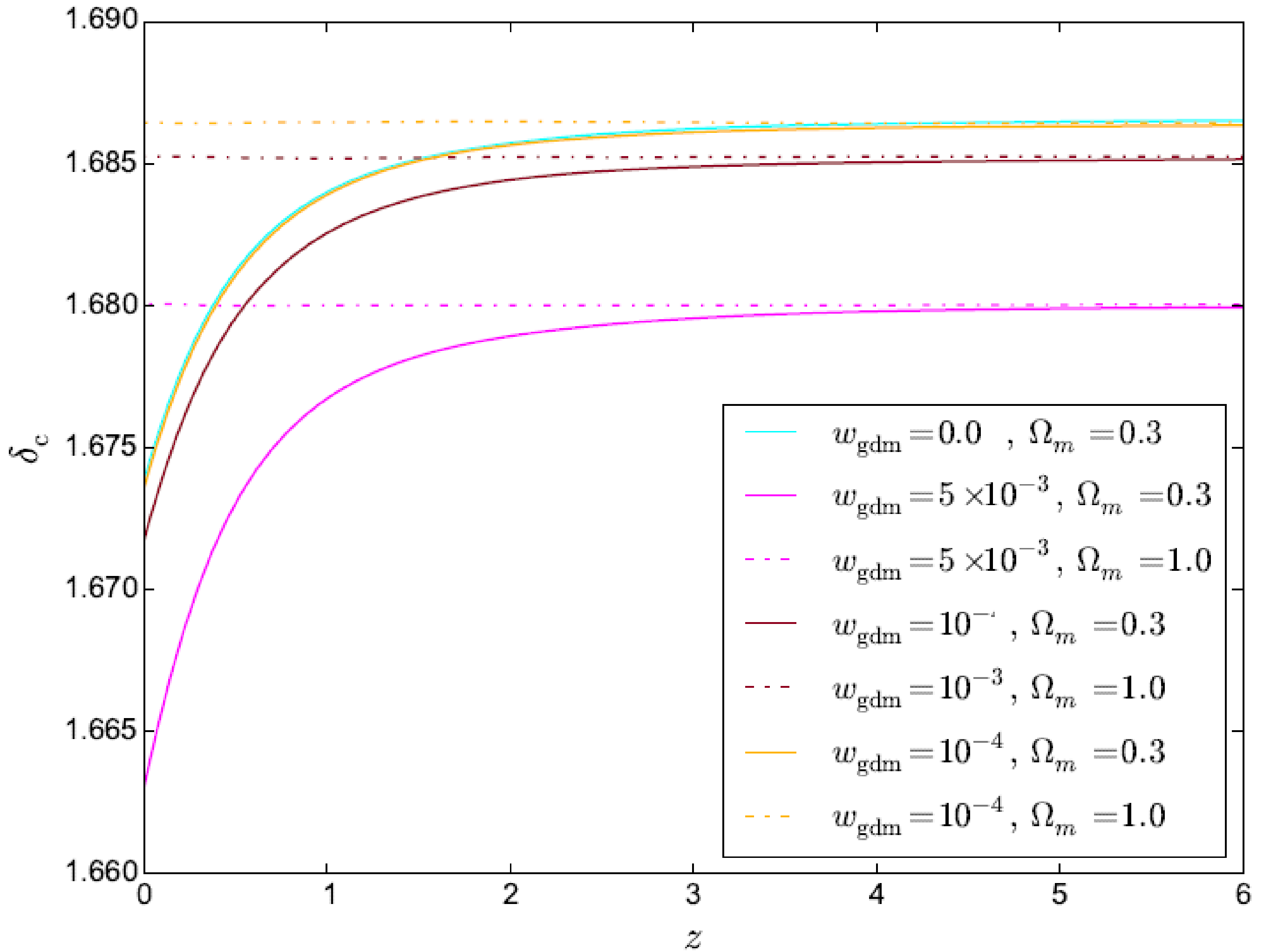
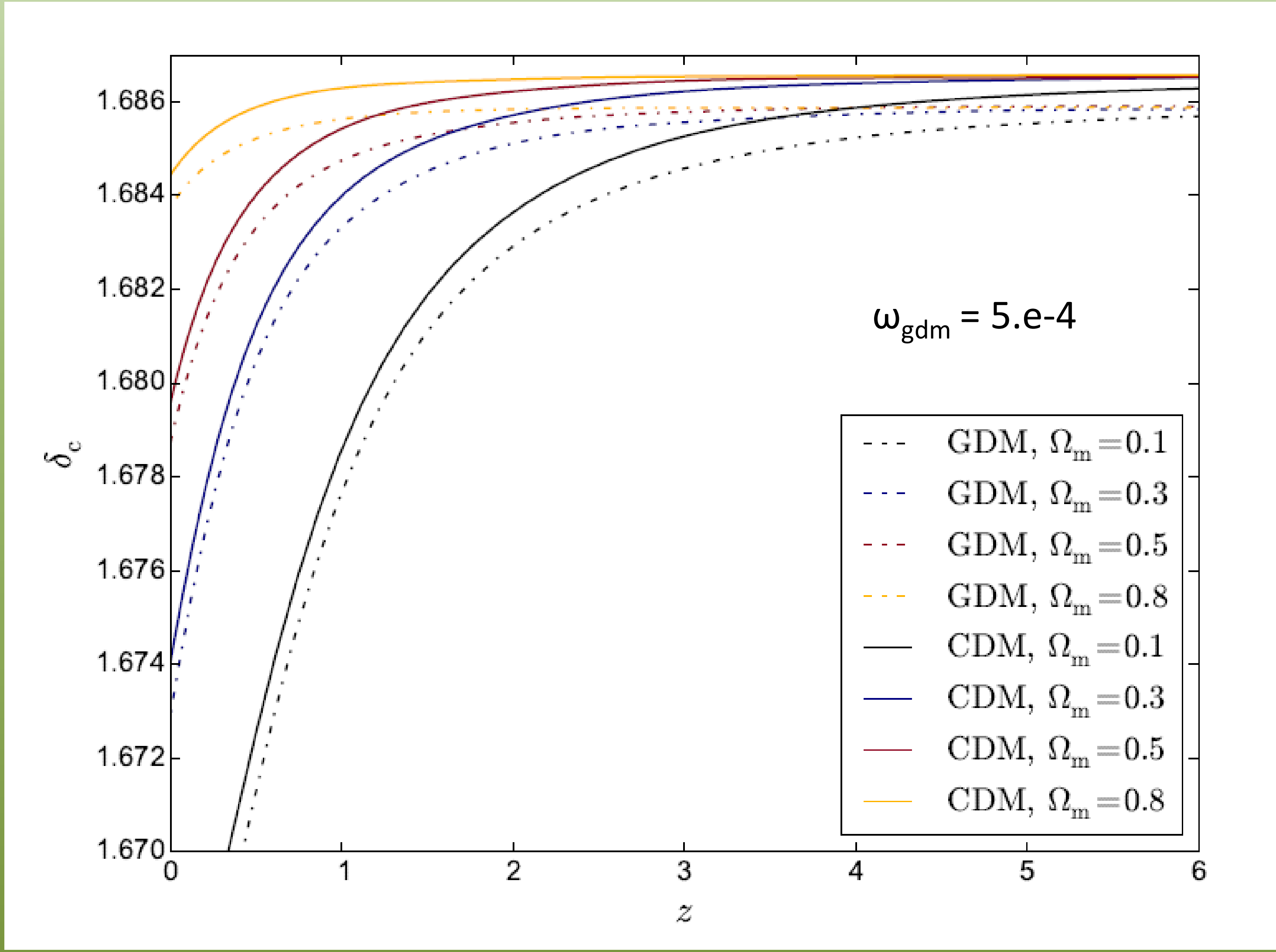
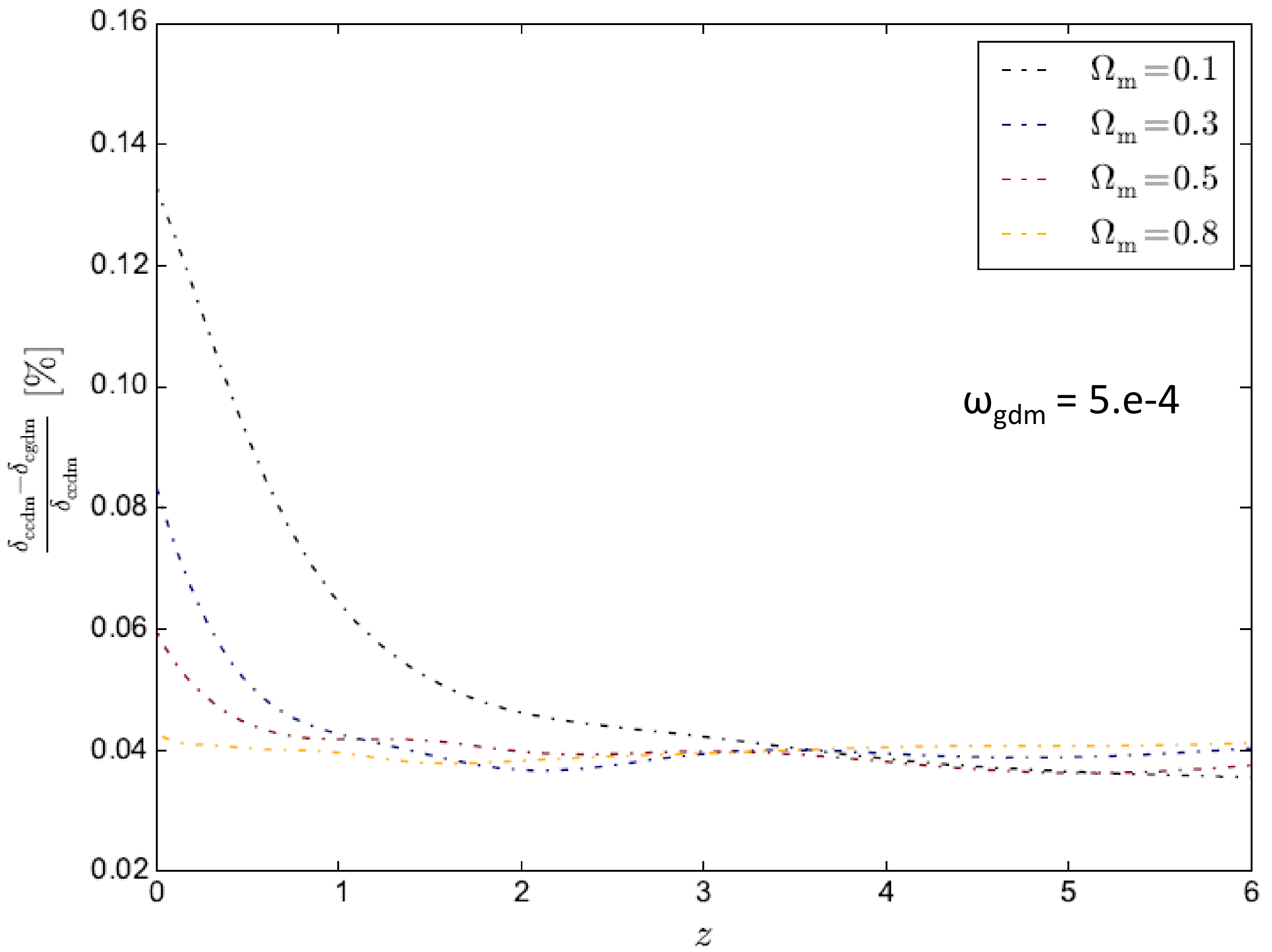


δ_c in GDM, vary Ω_M **arxiv.1912.12250**



δ_c in GDM, vary Ω_M

arxiv.1912.12250



Spherical collapse model

Calculation of Δ_{vir}

$$U_{\mathrm{gdm,ta}} + U_{\Lambda,\mathrm{ta}} = U_{\mathrm{gdm,vir}} + T_{\mathrm{gdm,vir}} + U_{\Lambda,\mathrm{vir}} + T_{\Lambda,\mathrm{vir}}$$

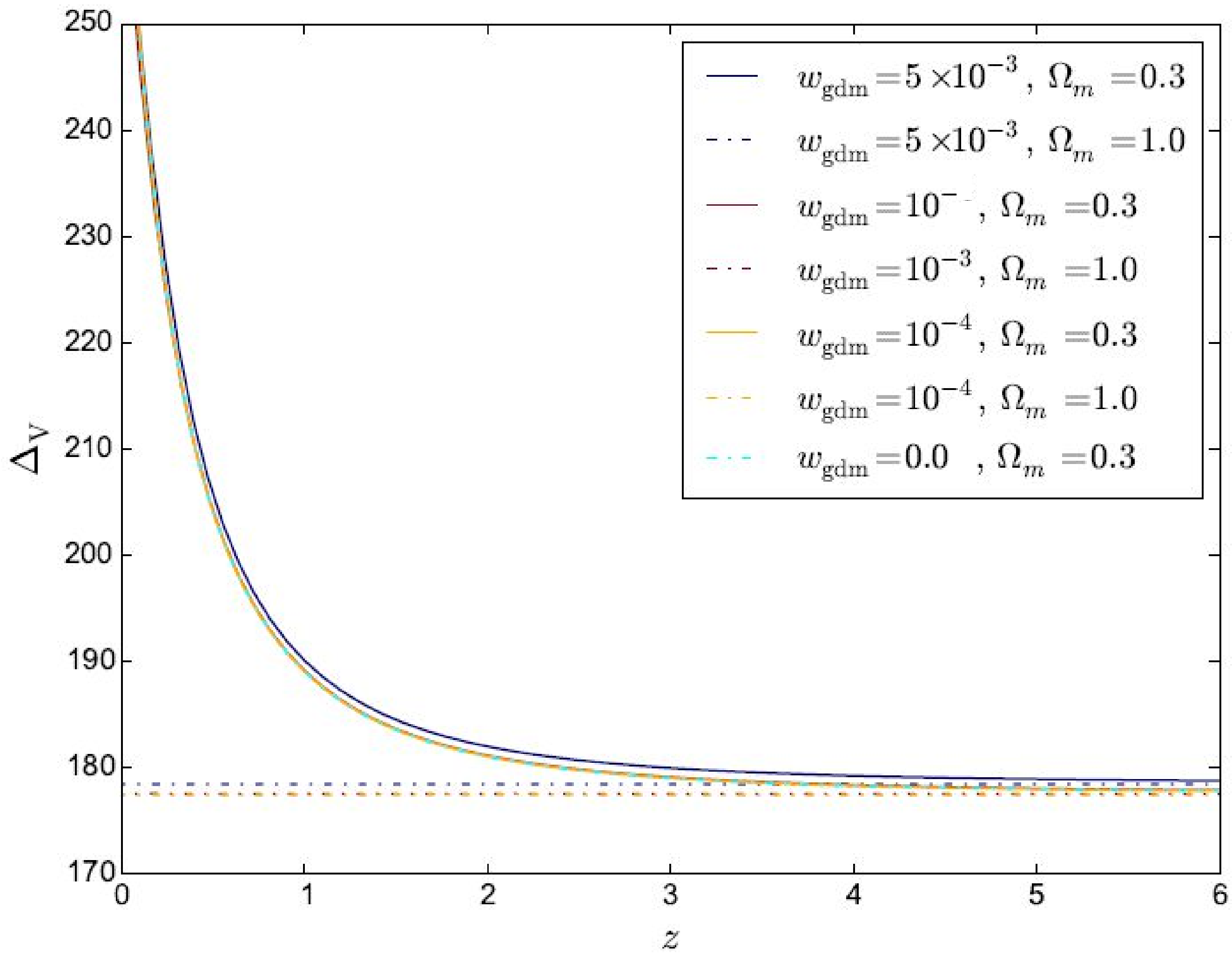
$$U_{\mathrm{gdm,ta}} + U_{\Lambda,\mathrm{ta}} = \frac{1}{2}U_{\mathrm{gdm,vir}} + 2U_{\Lambda,\mathrm{vir}}$$

$$\theta = \frac{\rho_\Lambda}{\rho_{\mathrm{gdm}}} \text{ and } \eta = \frac{r_{\mathrm{vir}}}{r_{\mathrm{ta}}}$$

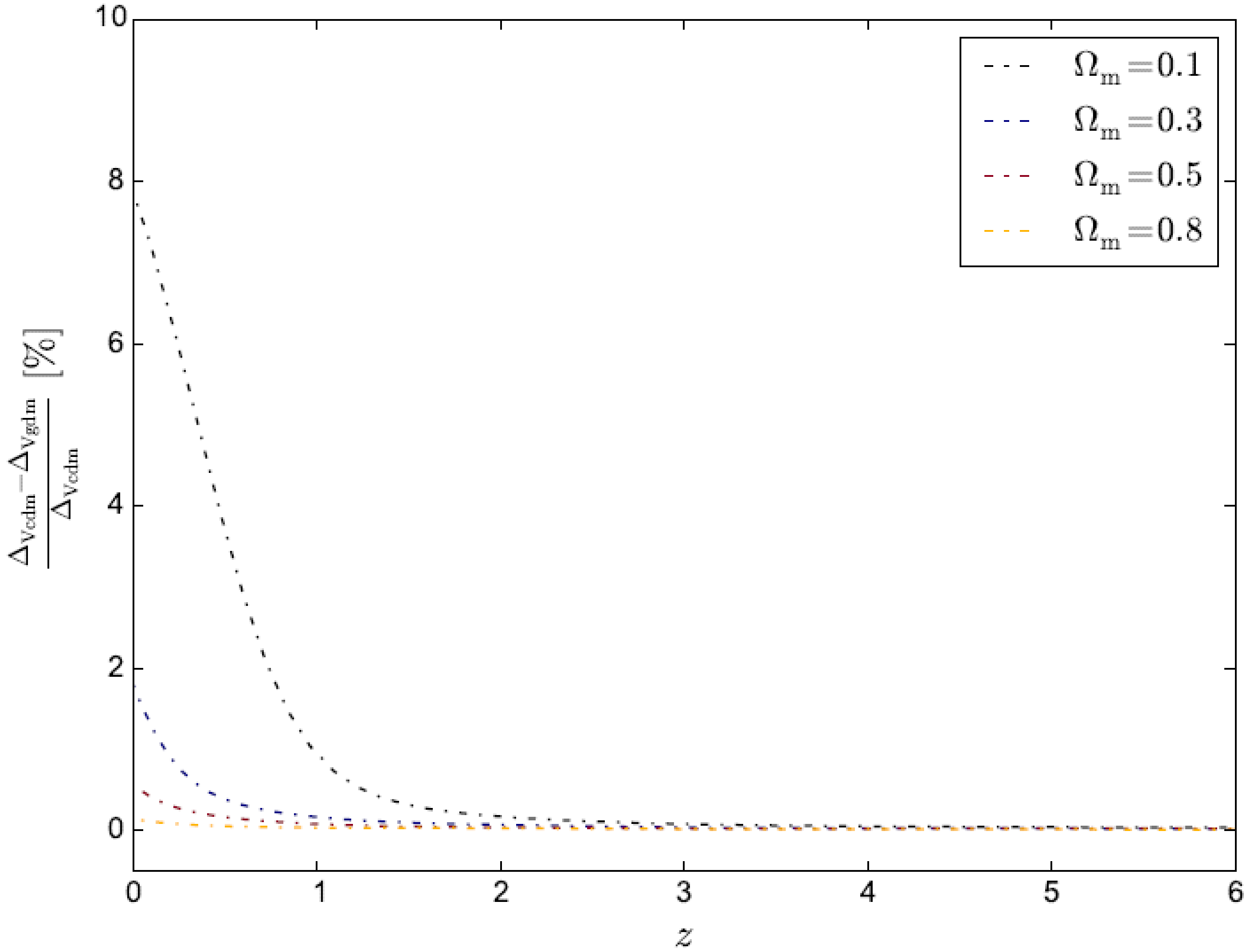
$$\theta\eta^3 + \left(1 + \frac{\theta}{2}\right)\eta - 1/2 = 0$$

Δ_{vir} in GDM

arxiv.1912.12250



Δ_{vir} in GDM, vary Ω_M **arxiv.1912.12250**



Halo mass function

$$\frac{dn(M)}{dM} = -\frac{\bar{\rho}}{M}\frac{\mathrm{d}\nu}{\mathrm{d}M}\mathcal{F}(\nu)$$

$$\nu\mathcal{F}_{\rm ST}(\nu) = A\sqrt{\frac{2a}{\pi}}\left[1+\left(\frac{1}{a\nu^2}\right)^p\right]\ \nu\ \exp\left\{\left[-\frac{a\nu^2}{2}\right]\right\}$$

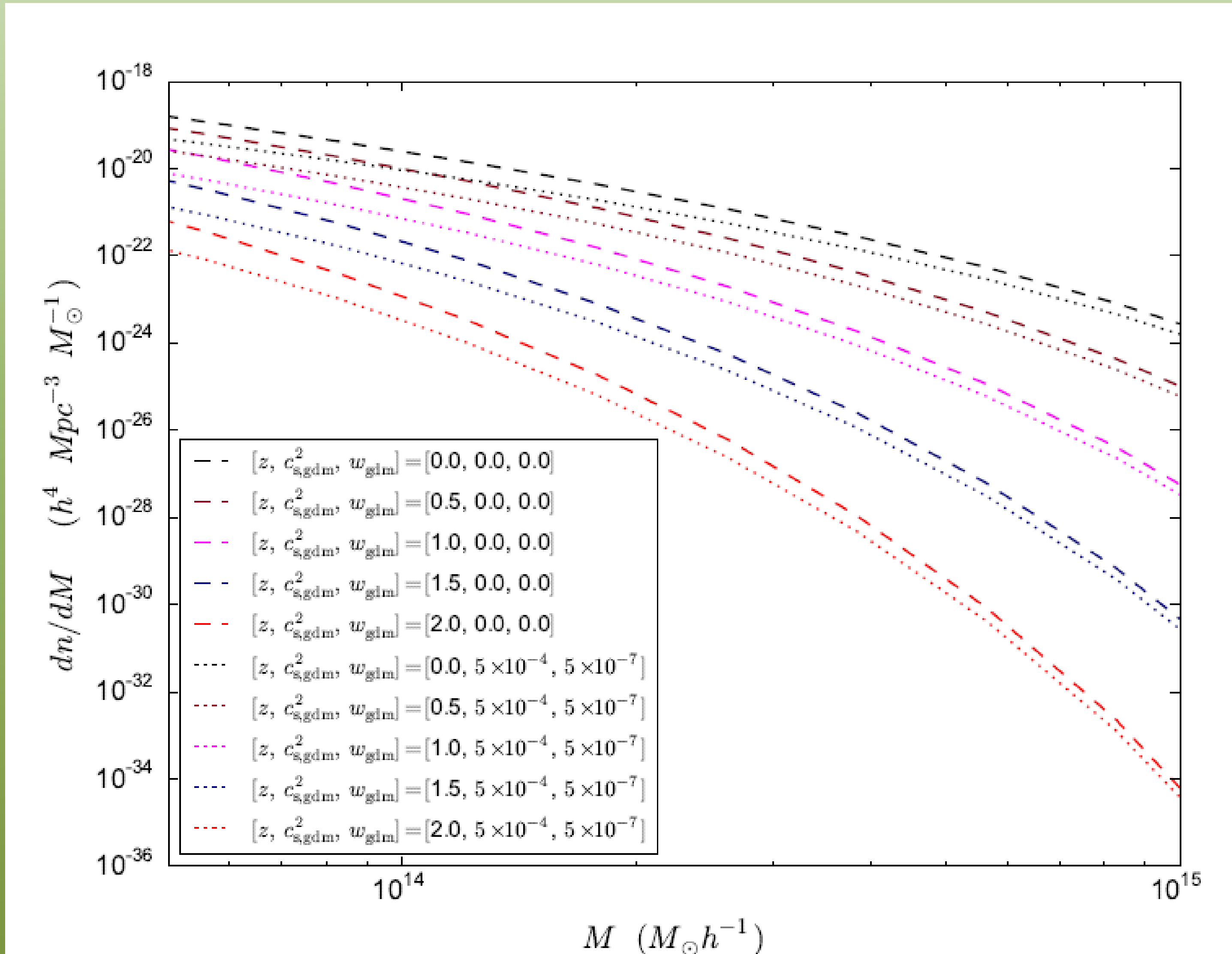
$$a = 0.4332x^2 + 0.2263x + 0.7665\,,$$
$$p = -0.1151x^2 + 0.2554x + 0.2488\,,$$
$$A = -0.1362x + 0.3292\,,$$

where $x = \log\left(\Delta(z)/\Delta_{\rm V}(z)\right)$

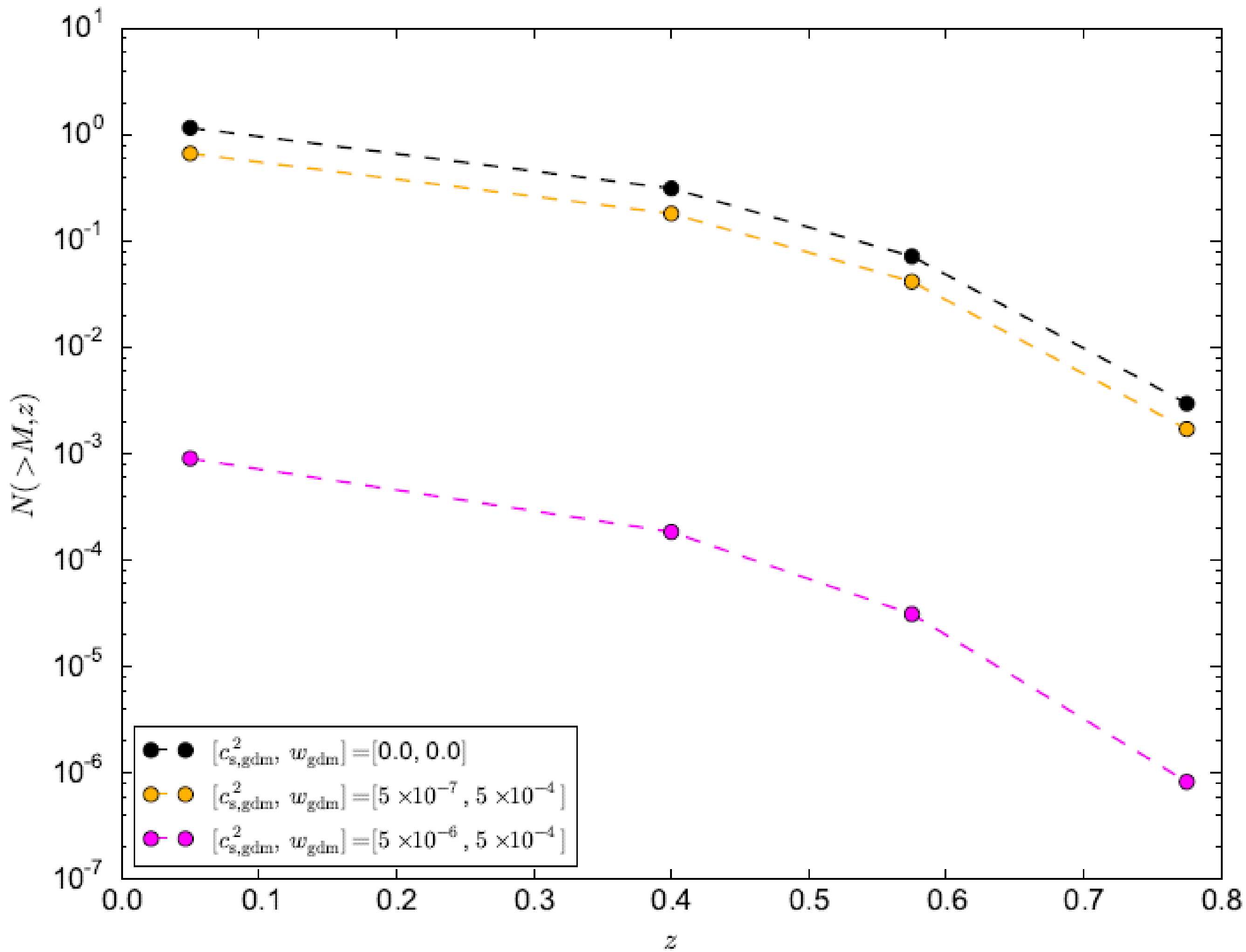
$\nu = \delta_c / \sigma_R(z)$

HMF in GDM

arxiv.1912.12250



Application : cluster counts



Application : cluster counts

$$\chi^2_{\rm num} = 2\sum_{i=1}^{4}\left[N_i - N'_{{\rm obs},i}\left(1 + \ln N_i - \ln N'_{{\rm obs},i}\right)\right] + \xi^2$$

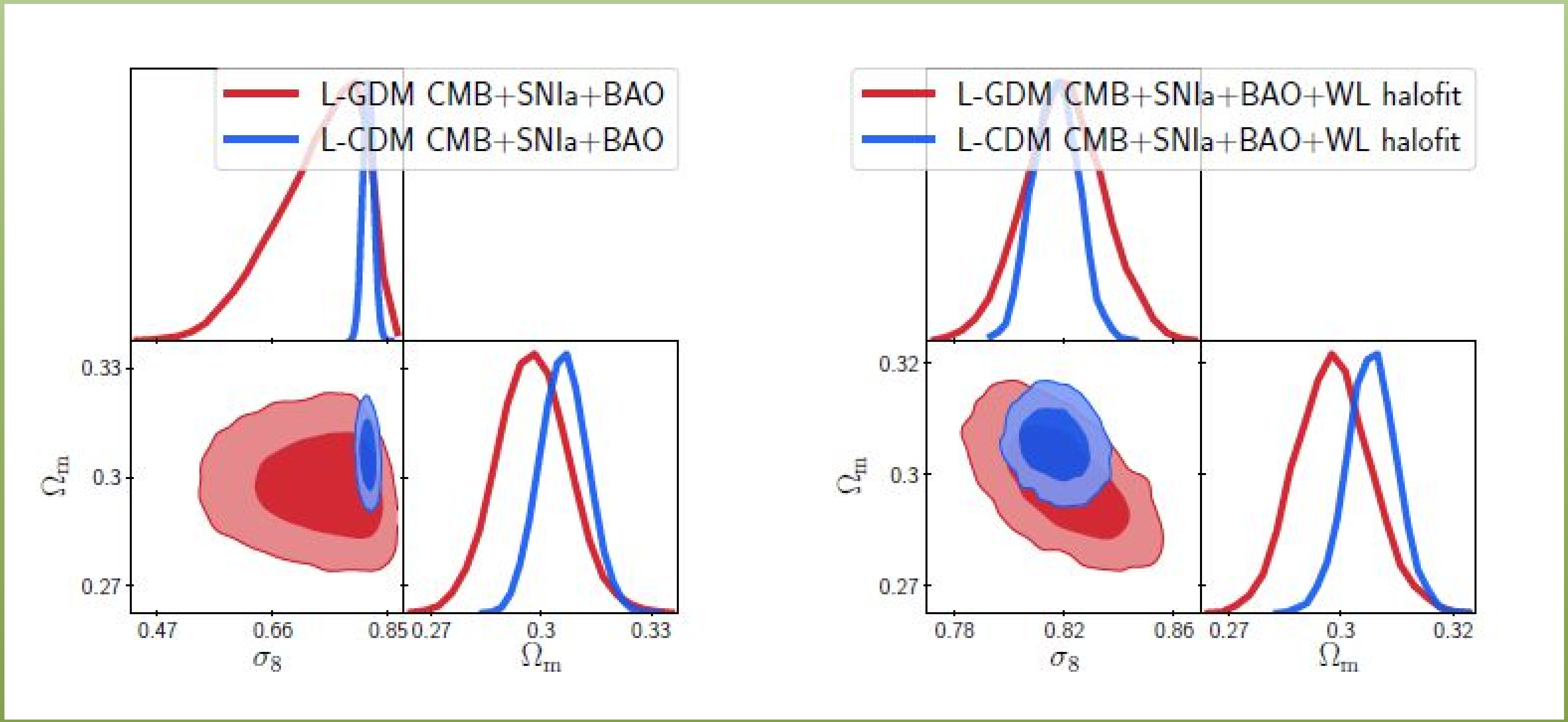
$X^2 \approx 11.2$ for ΛCDM

$X^2 \approx 15.44$ for ΛGDM with $c_s^2 = 5.\ e^{-7}$ and $\omega_{gdm} = 1.e^{-4}$

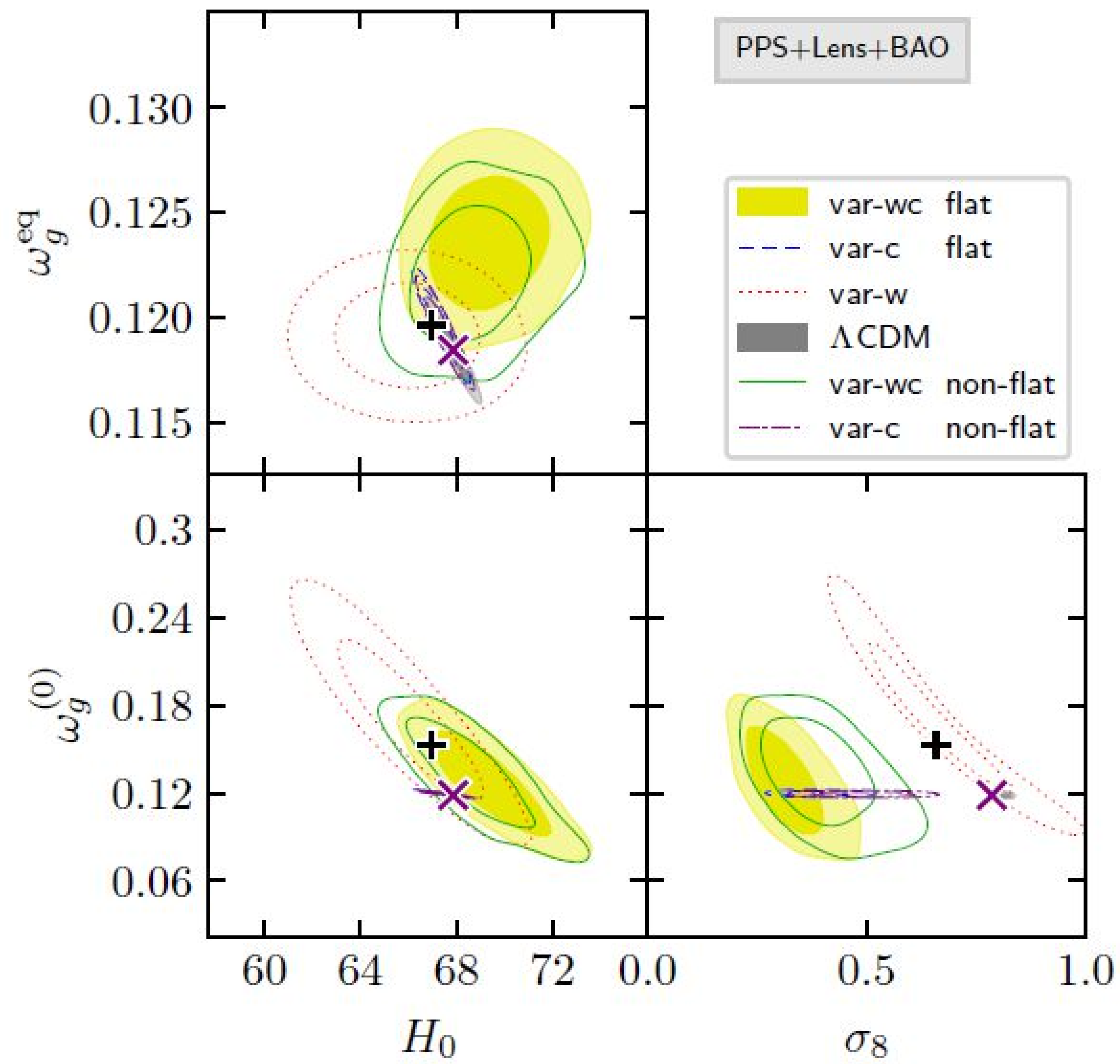
$X^2 \approx 79.57$ for ΛGDM with $c_s^2 = 5.\ e^{-6}$ and $\omega_{gdm} = 1.e^{-4}$

arxiv.1912.12250

Application σ_8 discrepancy



Tutusaus et al. 1805.06202



Ilic et al. 2004.09572v1

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