One point PDF from Spherical Collapse: Early Dark Energy vs. LCDM

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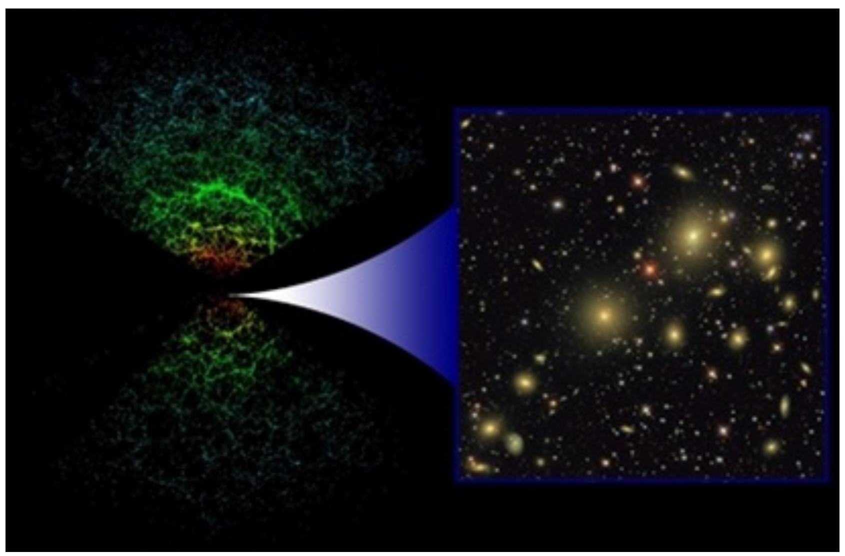

Figure Credit: http://sci.esa.int/planck/47693-large-scale-structure-in-the-universe/

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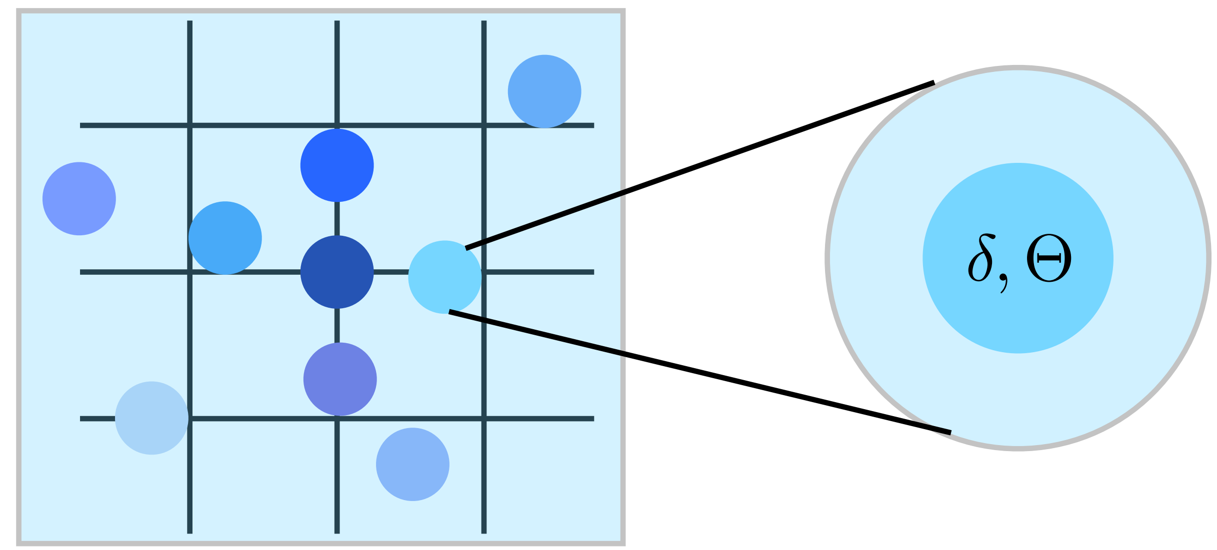

References:

1. A. Mandal and S. Nadkarni-Ghosh, **MNRAS 498** 2020 (arXiv: 1910.14347)
2. S. Nadkarni-Ghosh **MNRAS 428** 2013 (arXiv: 1207.2294)

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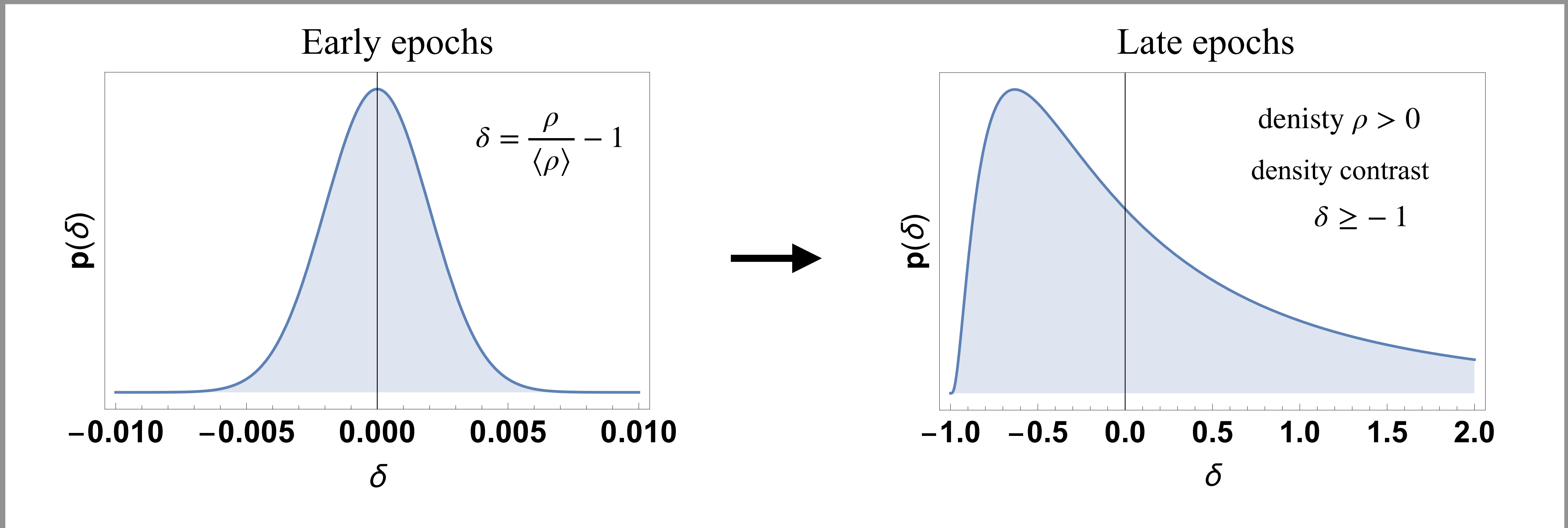
Motivation



- Gaussian fluctuations laid down during inflation (**Planck 2018**).
- Gaussian distribution picks up (secondary) non-Gaussian features. Thus, the one-point PDF carries information about the evolution history and can be used to constrain cosmological parameters.
- It has been of interest since the early 1930s - Hubble in 1934 first examined the frequency distribution of about 44000 galaxies.
- More recently, it has been measured from large scale surveys **VIPERS (Bel et al. 2016), the SDSS (Hurtado-Gil et al. 2017) and DES (Bel et al. 2016; Clerkin et al. 2017; Gruen et al.2018)**
- Can provide complimentary constraints which break parameter degeneracies **(Liu et al. 2016; Patton et al. 2017)**.

Theoretical modelling of the PDF

Phenomenological:

- Models based on equilibrium thermodynamics: **Saslaw & Hamilton 1984, Suto et al 1990, Lahav et al 1993**
- Log-normal model, motivated by the continuity equation: **Coles & Jones 1991**
- **Skewed log-normal model (SLN)** **Colombi 1994**: Log-normal + Edgeworth expansion.

Perturbative Methods:

- Eulerian and Lagrangian estimates: **Bernardeau 1994 (B94), Bernardeau & Kofman 1995, Colombi et al 1997**
- Extensions to make it more efficient and versatile: **Fosalba & Gaztanaga 2000 Juzkiewicz *et al* 1995**

Numerical Simulations: **Ueda &Yokoyama 1996, Szapudi & Pan 2004, Repp & Szapudi 2018, Klypin *et al* 2018,Shin *et al* 2017** **Generalised Normal distribution, version 2** N_{v2}

Non-Perturbative Methods: *

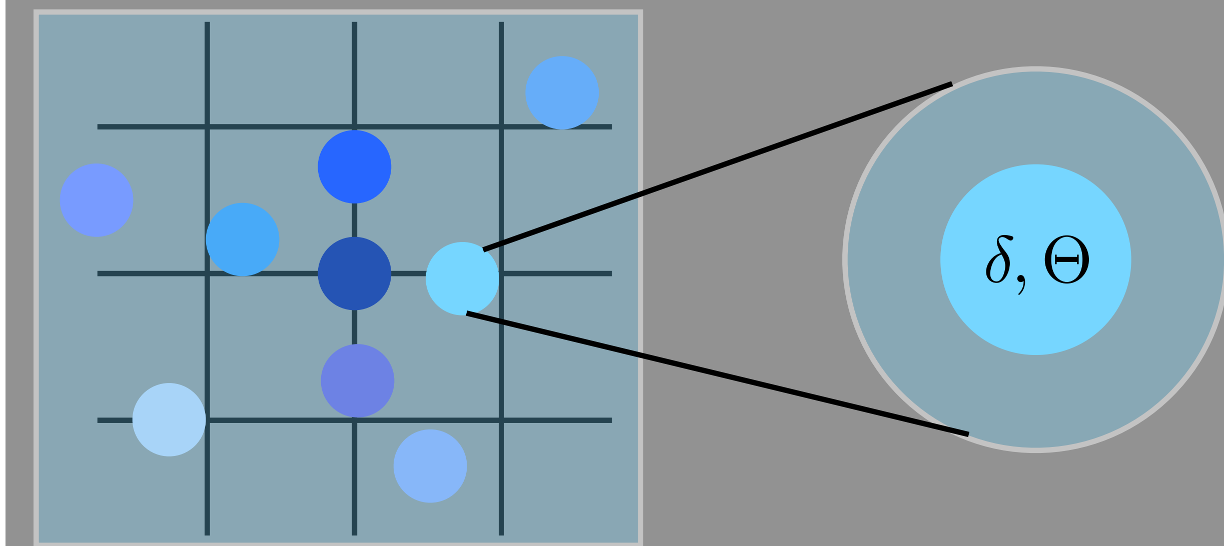
- Excursion Sets: **Lam & Seth 2008**
- Differential equations for the PDF evolution: **Ohta et al 2003, 2004.**
- Path Integral Formulation: **Valageas 1998, 2001, 2002**; recent extensions **Ivanov *et al* 2019**
- Large Deviation Theory: **Bernardeau & Reimberg 2016** and their collaborators

* Couple some non-local method with local approximations like spherical or ellipsoidal collapse

This work:

1. How well does spherical collapse perform compared to these methods ?
2. Obtain the PDF for models other than LCDM: early dark energy model and compare to LCDM

Spherical top-hat



Fractional density $\delta = \dfrac{\rho}{<\rho>} - 1$

Scaled velocity divergence $\Theta = \dfrac{\nabla_r \cdot \mathbf{v}}{H}$

Two first order equations

$$\delta' = -(1+\delta)\Theta$$

$$\Theta' = -\frac{3}{2}\Omega_m(a)\delta - \Theta\left(2 + \frac{H'}{H}\right) - \frac{\Theta^2}{3}$$

Non-autonomous dynamical system

One second order equation

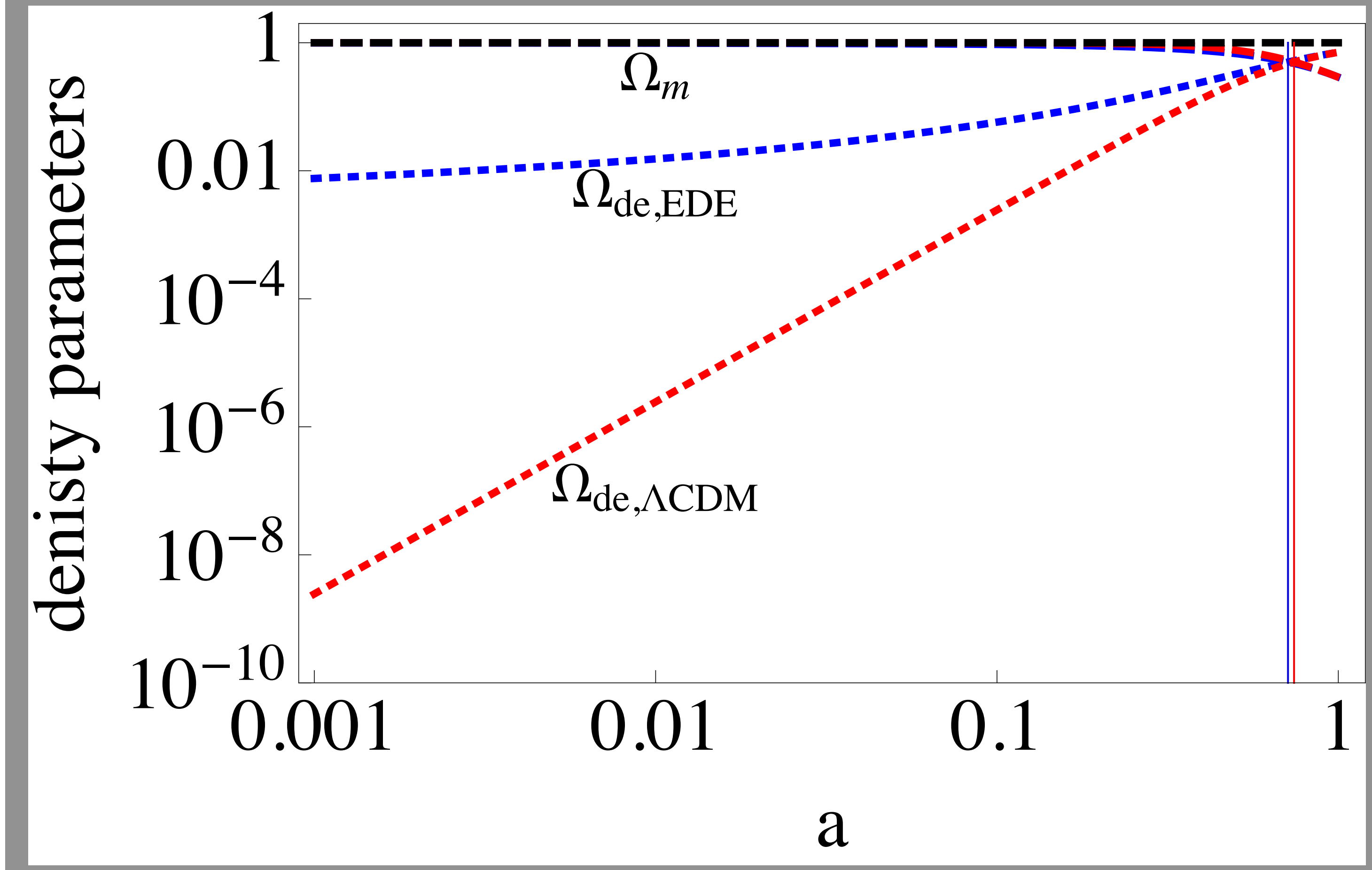
$$\delta'' + \frac{1}{2}\left\{1 - 3w(a)\Omega_{de}(a)\right\}\delta' - \frac{4}{3}\frac{\delta'^2}{1+\delta} - \frac{3}{2}\Omega_m(a)\delta(1+\delta) = 0$$

non-linear terms

- Assumptions: isolated spherical top-hat, top-hat remains a top-hat.
- Assumptions: scales below the horizon, non-relativistic, no shell-crossing.
- Employ `generalized Newtonian hydrodynamics' i.e. the weak field limit of the conservation of the stress-energy tensor + spherical symmetry **Lima et al. 1997, Abramo et al. 2009, Pace et al. 2010, 2017**.

The cosmological models

Cosmological models:



1. ΛCDM : $\Omega_{m,0} = 0.29,\ \Omega_{\Lambda,0} = 0.71,\ w_0 = -1.$

2. EDE (Early dark energy):
   Wettrich 2004, Doran and Robbers 2006

$$w(a) = \frac{w_0}{(1 - b\ln a)^2}$$

$$b = -\frac{3w_0}{\ln\left(\frac{1-\Omega_{de,e}}{\Omega_{de,e}}\right) + \ln\left(\frac{1-\Omega_{m,0}}{\Omega_{m,0}}\right)}$$

$\Omega_{m,0} = 0.29,\ \Omega_{\Lambda,0} = 0.71$

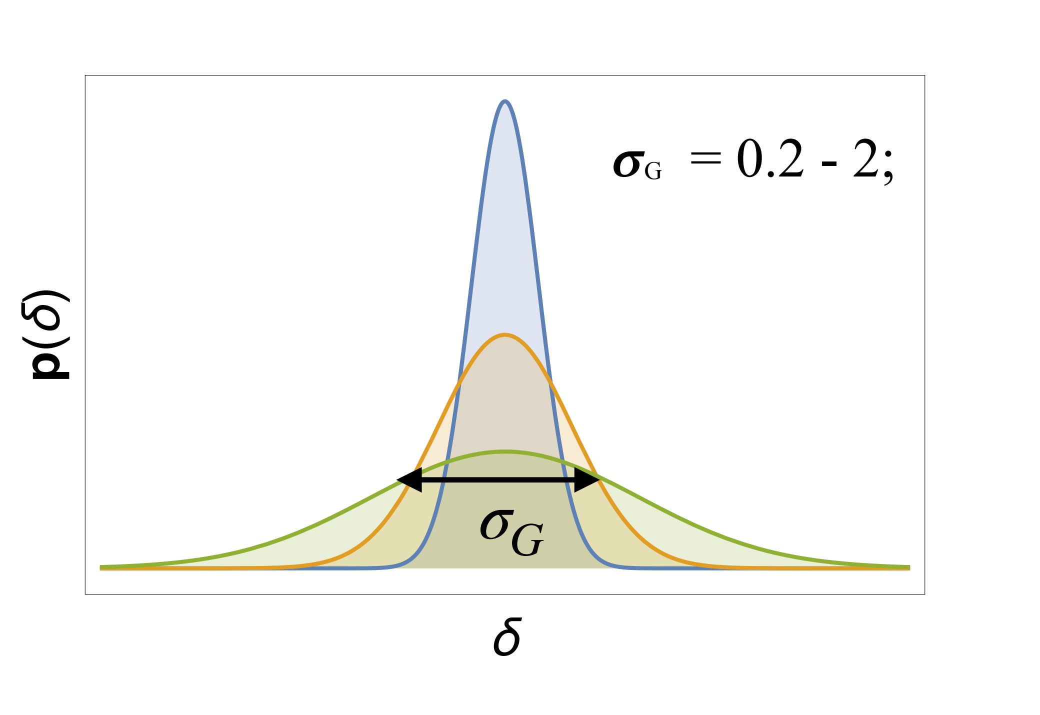
$w_0 = -0.99,\ \Omega_{de,e} = 8 \times 10^{-4}$

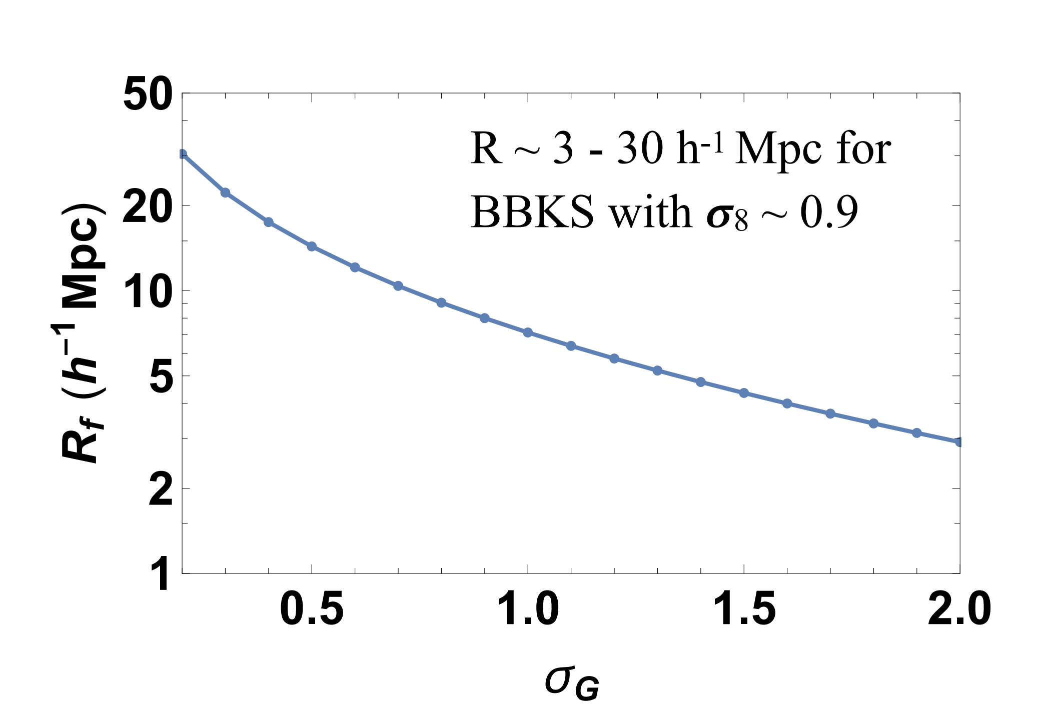
3. EdS : $\Omega_m = 1.$

All models are flat $\Omega_m + \Omega_{de} = 1$

- All models are assumed to be flat.
- Dark energy onsets early in the EDE model.
- Structure is expected to grow slower

Ensemble of initial conditions





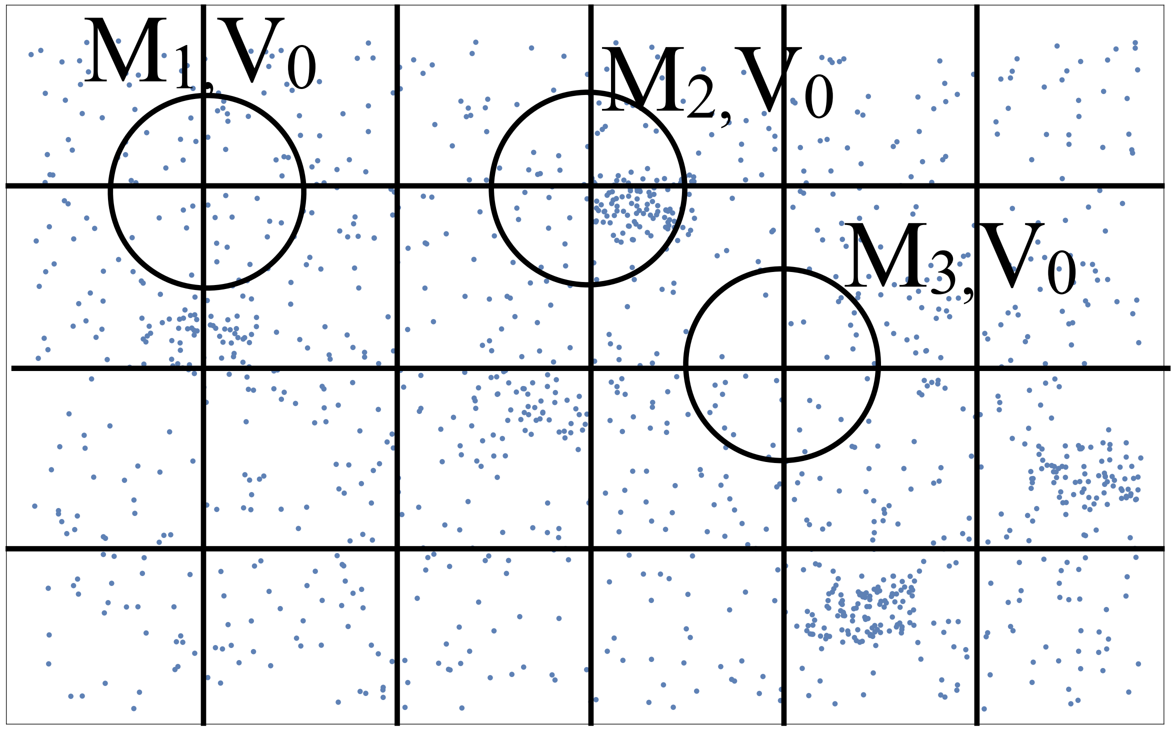
- Initial density: **50,000 points drawn from a Gaussian with width σ_G**
- Initial velocity: **Zeldovich initial conditions**
- Evolve each initial condition with the equations above and compute the late time distribution
- Five realisations with 50,000 points for each value of σ_G
- Linear PDF same for all models; obtain initial distribution by multiplying by growth factor

$$\delta(a = 0.001) = \frac{\delta(a = 1)}{\text{Growth factor}}$$

- Sph. Coll. gives Lagrangian PDF - convert to Eulerian PDF

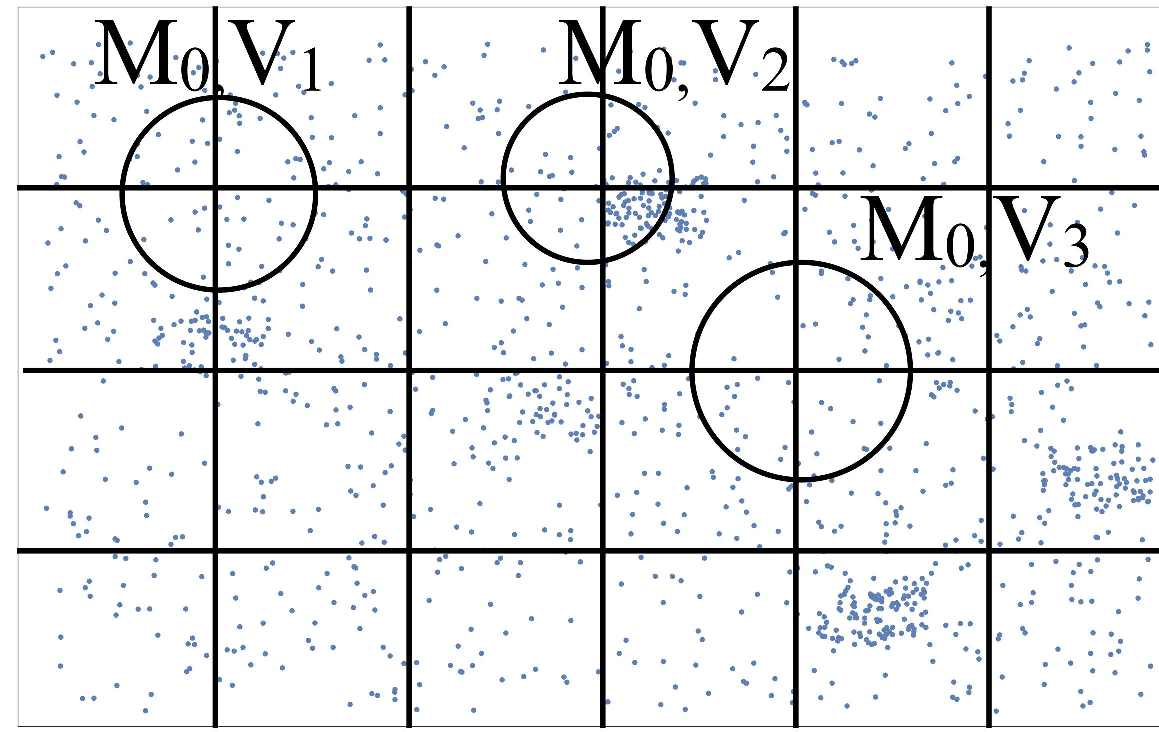
Eulerian vs. Lagrangian PDF

Eulerian density field



Define $(1+\delta)\bar{\rho} = \dfrac{M}{V_0}$

Lagrangian density field



Define $(1+\delta)\bar{\rho} = \dfrac{M_0}{V}$

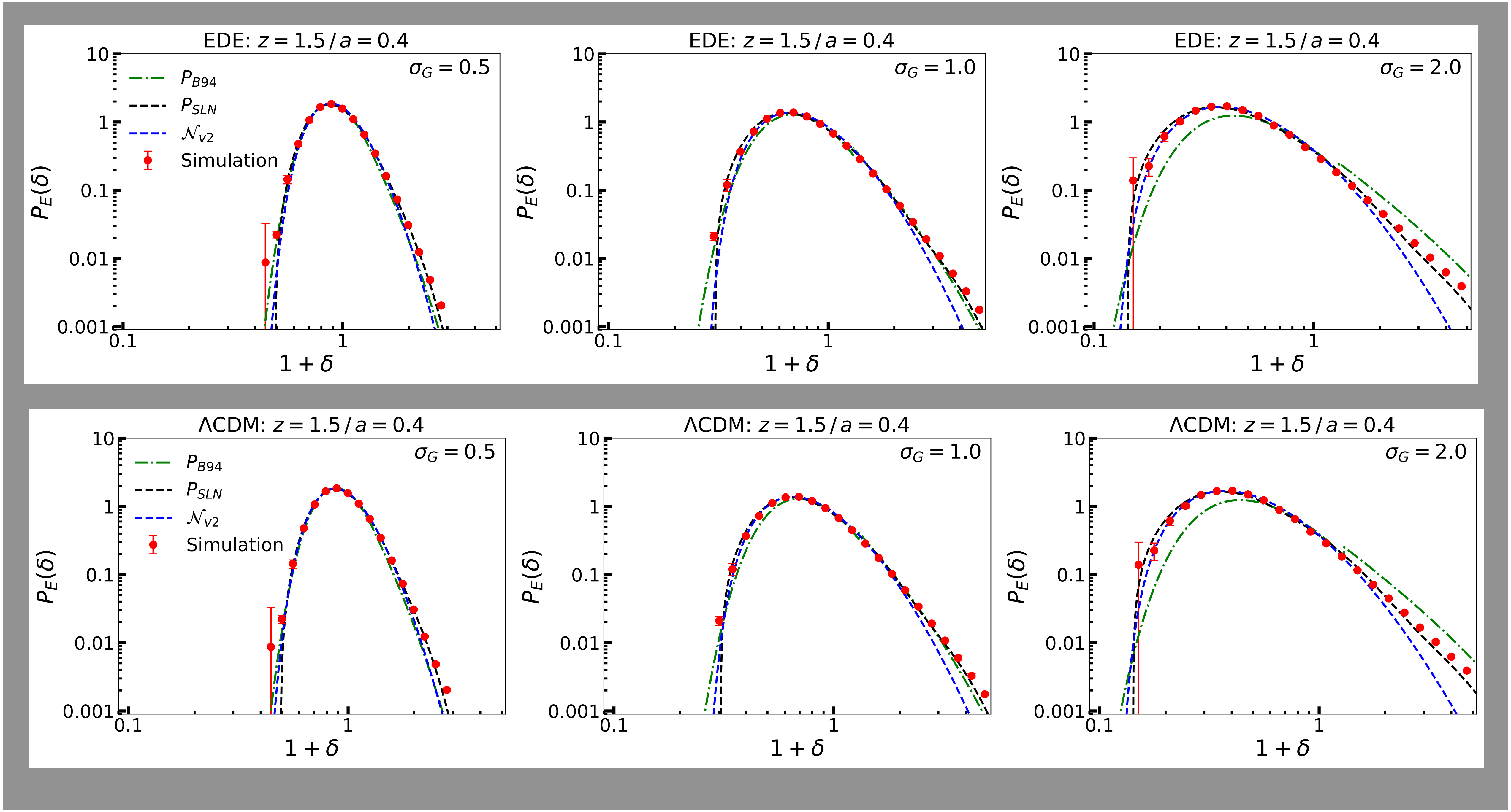
Convert from Lagrangian to Eulerian PDF
Bernardeau 1994,
Nadkarni-Ghosh and A. Singhal, MNRAS 2016

$$\int_{M_0}^{\infty} p_E(V_0, M)\,dM = \int_0^{V_0} p_L(V, M_0)\,dV$$

Two primary questions are:

- How well is the PDF reproduce the known forms when evolved to the non-linear regime ?
- What is the effect of cosmology ?

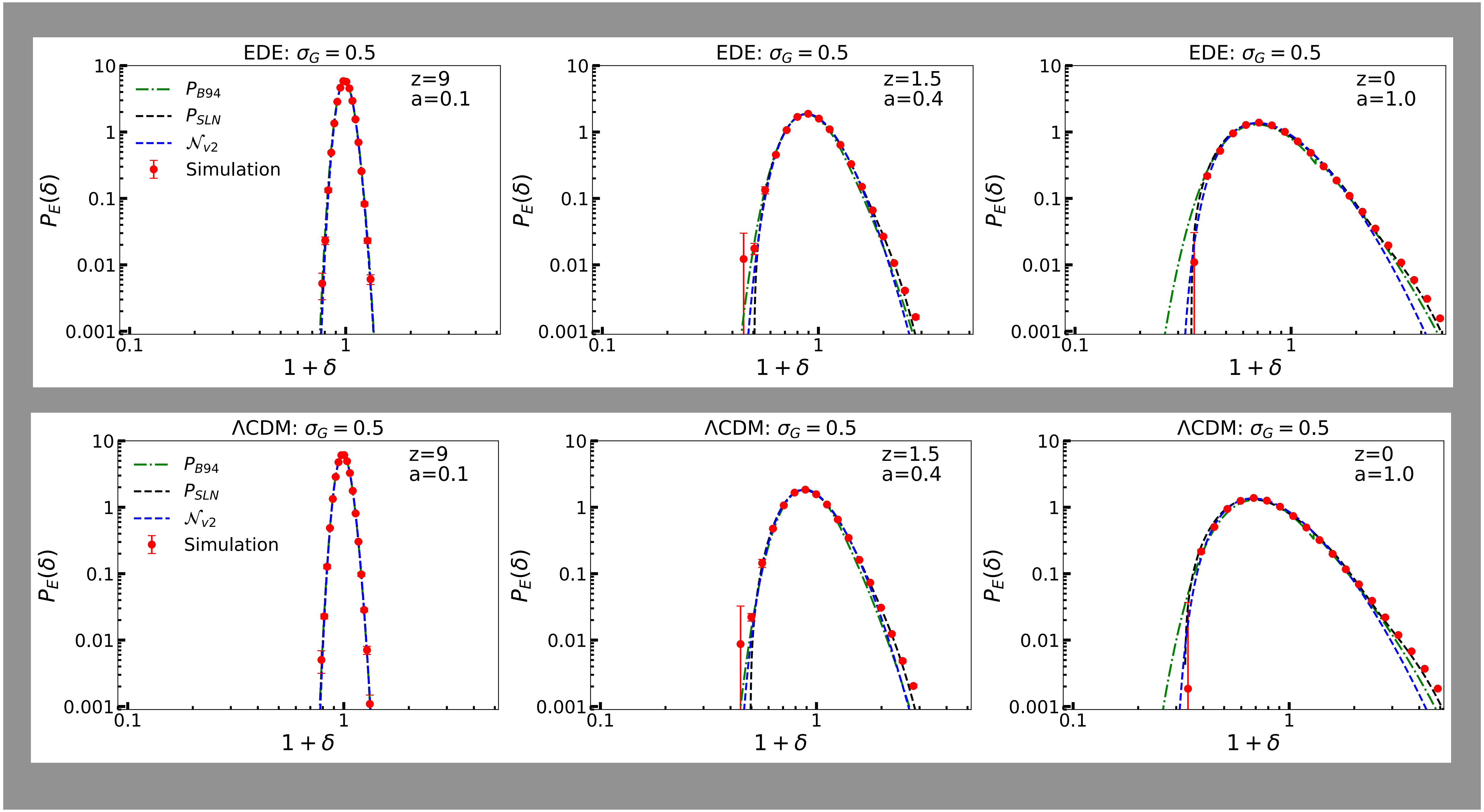
The non-linear PDF: as a function of scale



- **Skewed log-normal model (SLN)** **Colombi 1994**
- **Eulerian PT Estimate (B94)** **Bernardeau 1994**
- **Generalised Normal distribution, version 2** $\mathcal{N}_{v2}$ **Shin *et al* 2017**

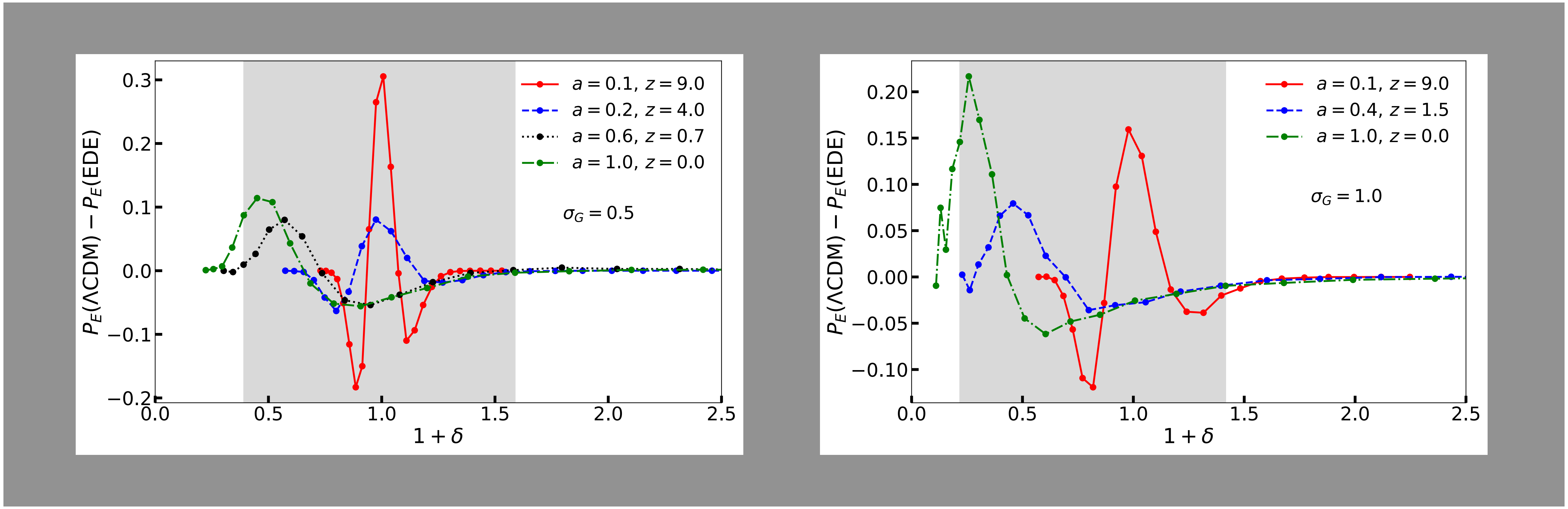
Fit is better for smaller scales and earlier redshifts

The non-linear PDF: as a function of redshift



Over the range of scales, cosmologies and epochs considered SLN is the best fit for the Eulerian PDF.

Difference of the PDF



Linear regime
Early epochs

$$\delta(a = 0.001) = \frac{\delta(a = 1)}{\text{Growth factor}} \Longrightarrow$$

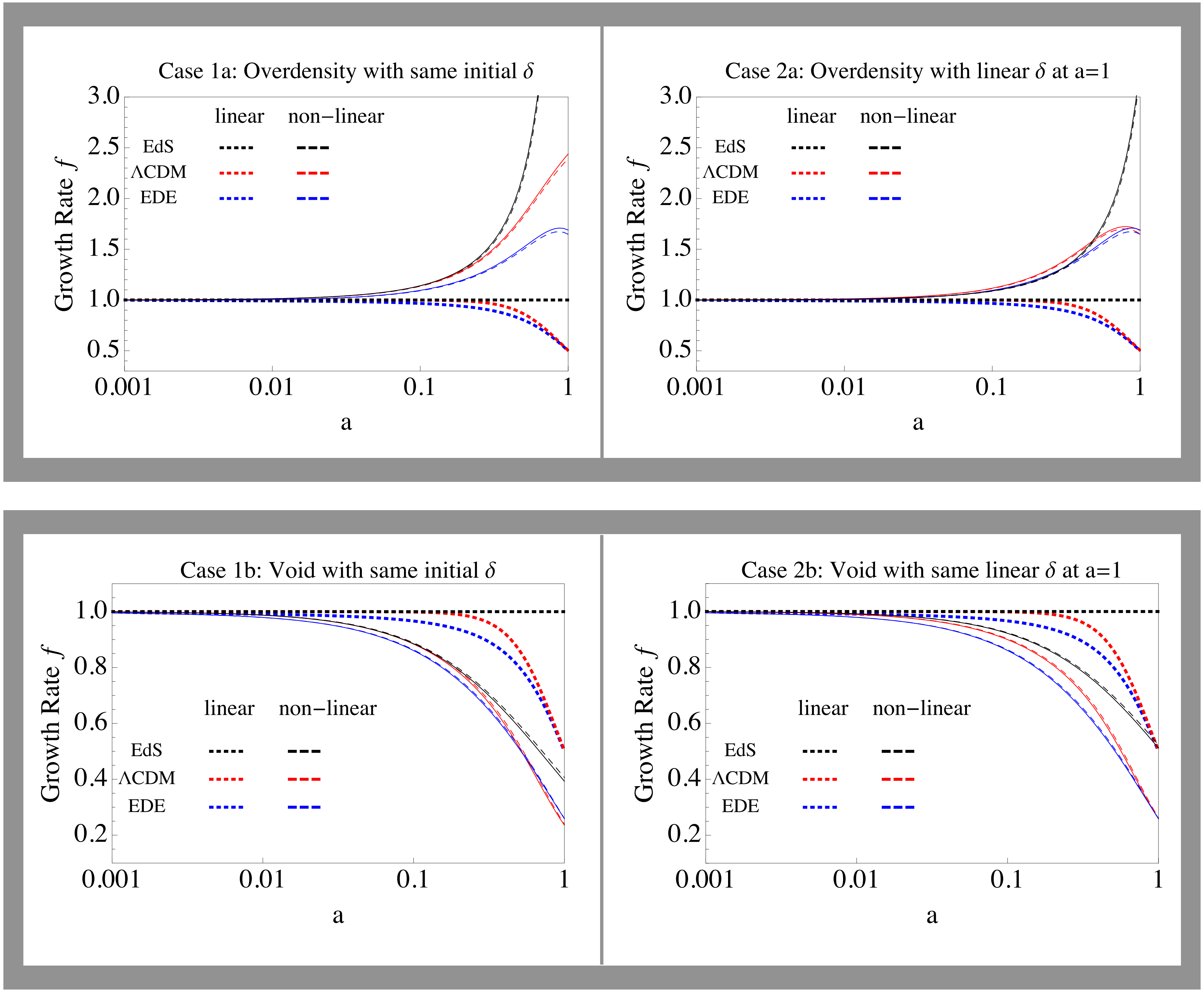
More points with lower values of δ

Higher for ΛCDM

Non-linear regime
Late epochs

- For bins near δ ~0 or 1+ δ ~1, EDE model has more points since growth factor is smaller - difference in PDF is negative.
- Voids are more sensitive than over densities because of the cut-off at 1+ δ ~ -1.

Non-linear Growth rates: self-regulation in voids



$$f = -\frac{(1+\delta)\Theta}{\delta}; \qquad \lim_{\delta\to -1} f = 0$$

Non-linear density-velocity divergence relation

- A tertiary aim of this paper was to check the non-linear relation between the density and velocity divergence derived in **Nadkarni-Ghosh MNRAS 2013**

- Linear continuity equation

Linear growth index

$$\Theta = -f(\Omega_m)\delta = -\Omega_m^{\gamma}\delta$$

definition

Zeldovich Initial conditions

No decaying mode in the linear solution.

Growth Rate

$$f = \frac{d\ln\delta}{d\ln a}$$

- Non-linear regime: Impose the same requirement: no perturbations at the big bang. This means given an initial density, there exists a unique velocity which assures that there are no perturbations at the big bang.

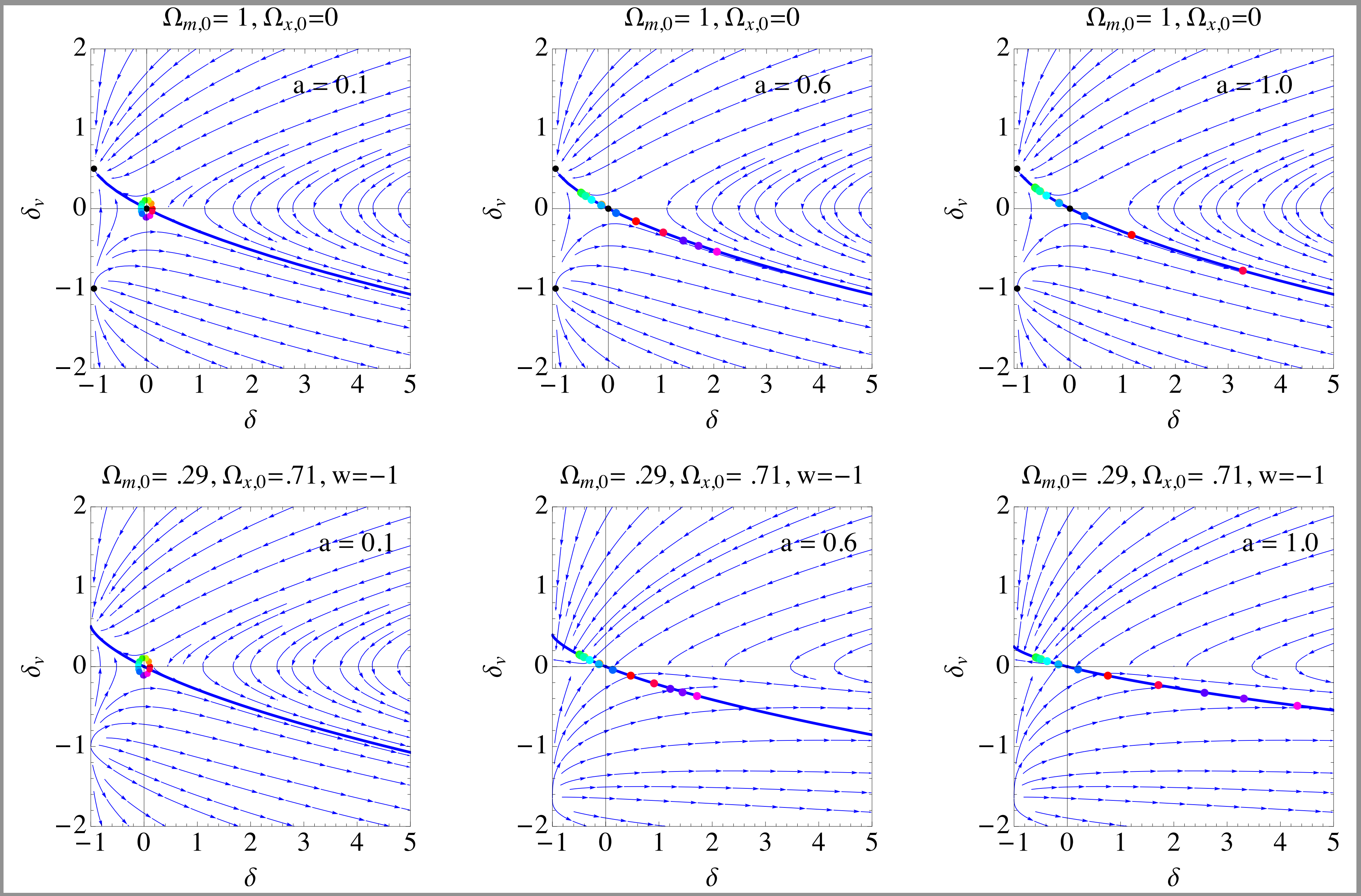
Non-linear fit
Extension of forms by
Bilicki & Chodorowski 2008
Bernardeau 1992

$$\Theta_{fit}(\Omega_m, w, \delta) = \begin{cases} 3A(\Omega_m, w)\left(1-(1+\delta)^{B(\Omega_m,w)}\right), & -1 \le \delta \le 1 \\ 3\Omega_m^{\gamma_1(w)+\gamma_2(w)}\left[(1+\delta)^{1/6}-(1+\delta)^{1/2}\right], & 1 \le \delta \le 10 \end{cases}$$

$$A(\Omega_m, w) = \frac{1}{2}\Omega_m^{\gamma_1(w)},\ B(\Omega_m, w) = \frac{2}{3}\Omega_m^{\gamma_2(w)},\quad \gamma_1(w) = -0.56(-w)^{-0.08} \text{ and } \gamma_2(w) = -0.01(-w)^{-1.18}.$$

Non-linear growth rate

$\Theta = 3\delta_v$



Nadkarni-Ghosh, MNRAS, 428 2013

- Non-linear density velocity curve: Invariant of the dynamical system
- But formula also holds true for the EDE model considered here with 3% accuracy.
- Simulations show a scatter; but mean is given by spherical collapse - better agreement with spherical collapse than ellipsoidal collapse

Discussion and Future directions

Ignored:

- Galaxy bias
- Shot noise: theoretical PDF convolved with a window function
- Parameter degeneracies

Looking ahead:

- Modified Gravity f(R) models: **Nadkarni-Ghosh, Chaudhury and Sarkar (in prep).**
- Understand PDF evolution for non-Gaussian initial conditions.
- Understand it in the context of 3D perturbations - Perturbation Theory or simulations.

Thank you !

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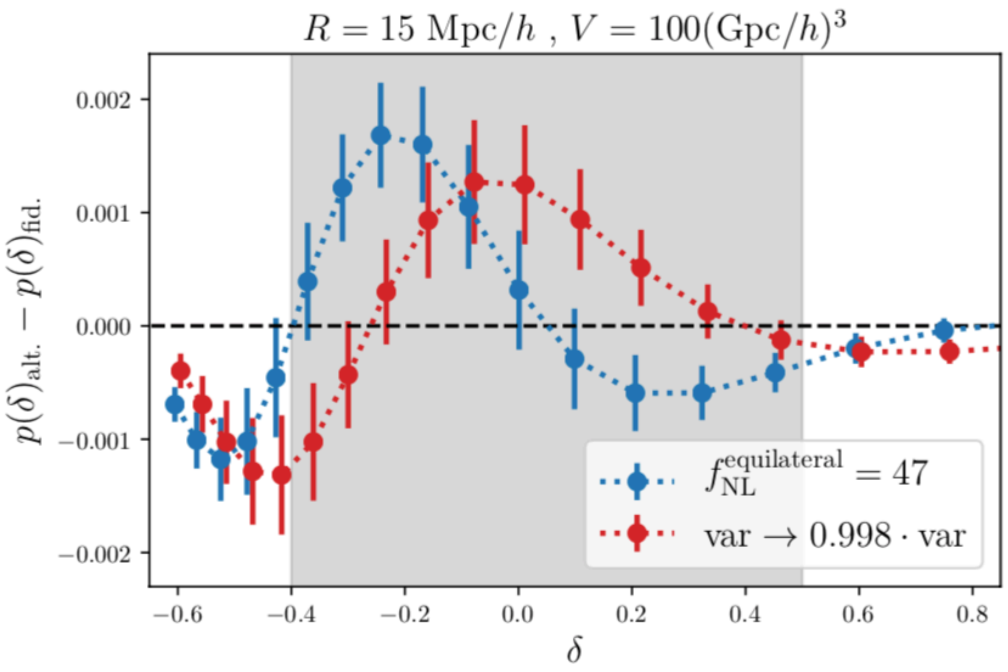
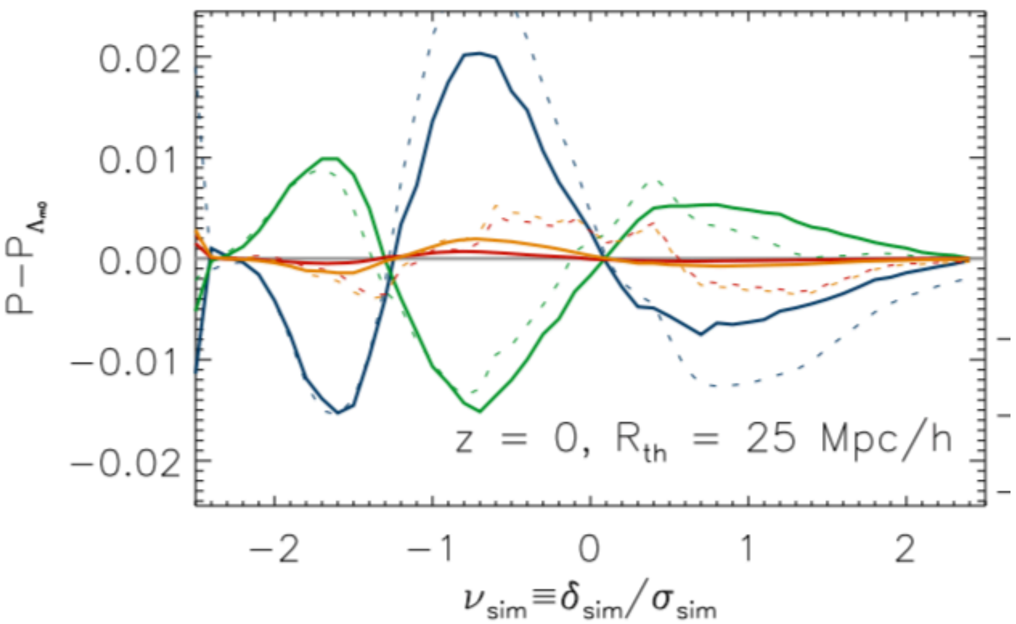
MNRAS, **498,** 2020
arXiv: 1910.14347

Difference of the PDF



Friedrich *et al* **MNRAS** *2020*



Shin *et al* ***Ap J*** *2017*

- Both show similar enhancement in voids