The separate universe from low to high densities

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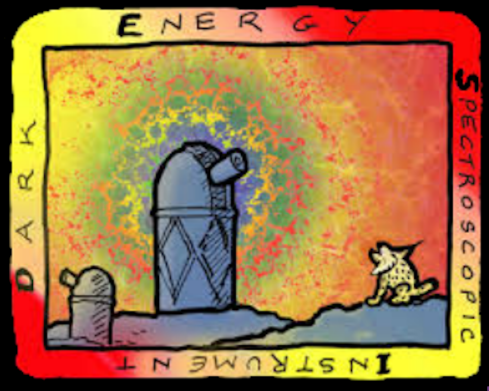
D. J. and M. Loverde arXiv:1812.08765
D. J. and M. Loverde arXiv:1909.05313
D. J. and M. Loverde (in preparation)

BSM Pandemic, 2020

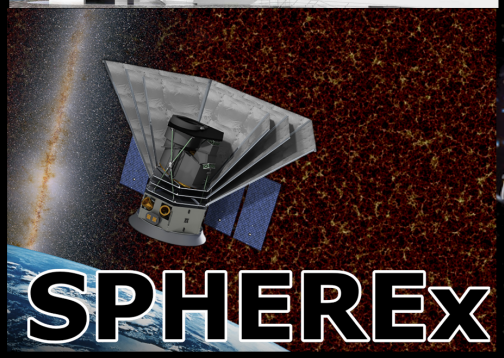
Goals for large scale structure

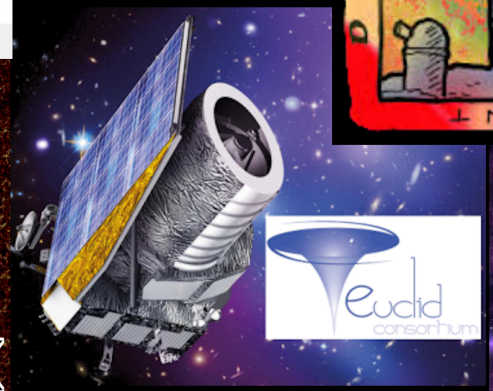
Learn about dark energy : Λ, w?

SDSS



DARK ENERGY SURVEY





Detect primordial non-Gausianity : f_{NL}?

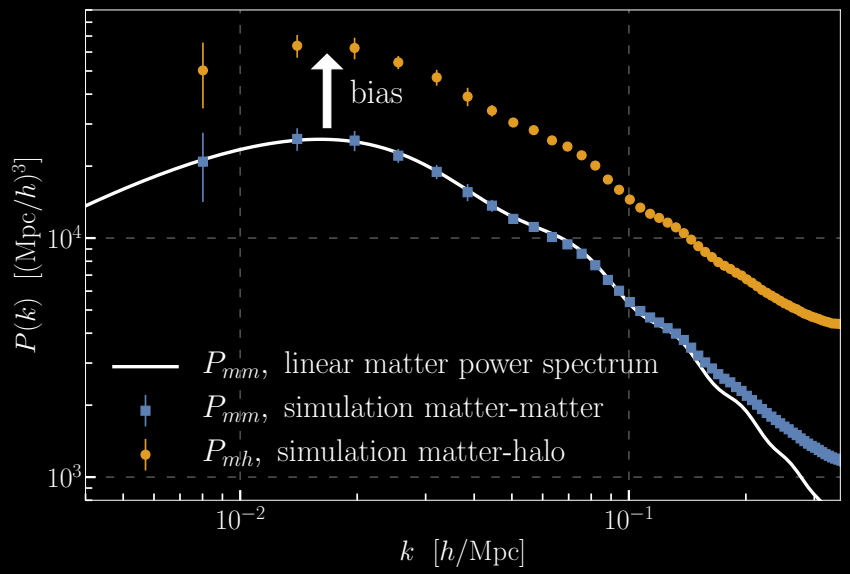
Weigh the neutrinos : $\sum m_\nu$?

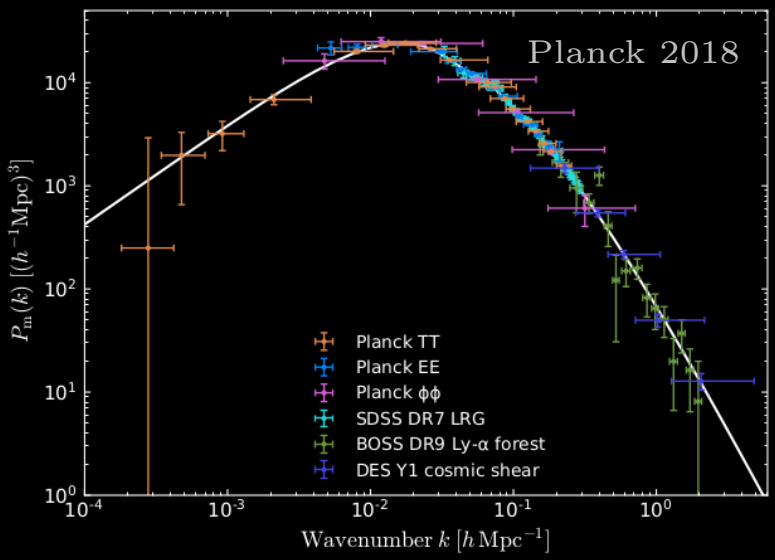
Challenges for large scale structure

What we predict	What we observe
→ matter field	→ galaxies
→ perturbation theory	→ voids
→ simulations	→ intesity maps

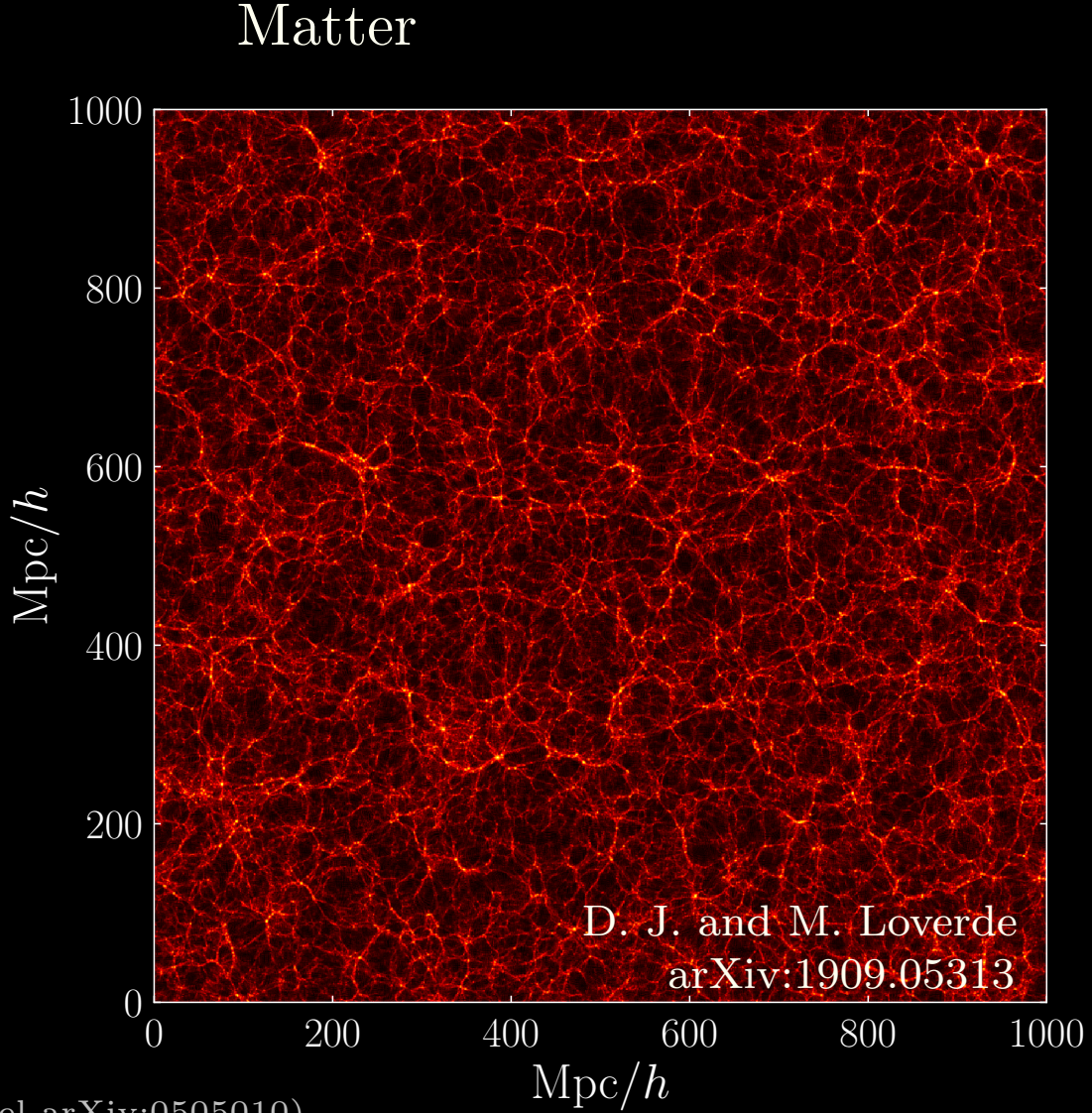
For example, for the power spectrum

$$\left\langle \delta(\vec{k})\delta(\vec{k}') \right\rangle = (2\pi)^3 \delta_D^3(\vec{k}+\vec{k}') P(k)$$



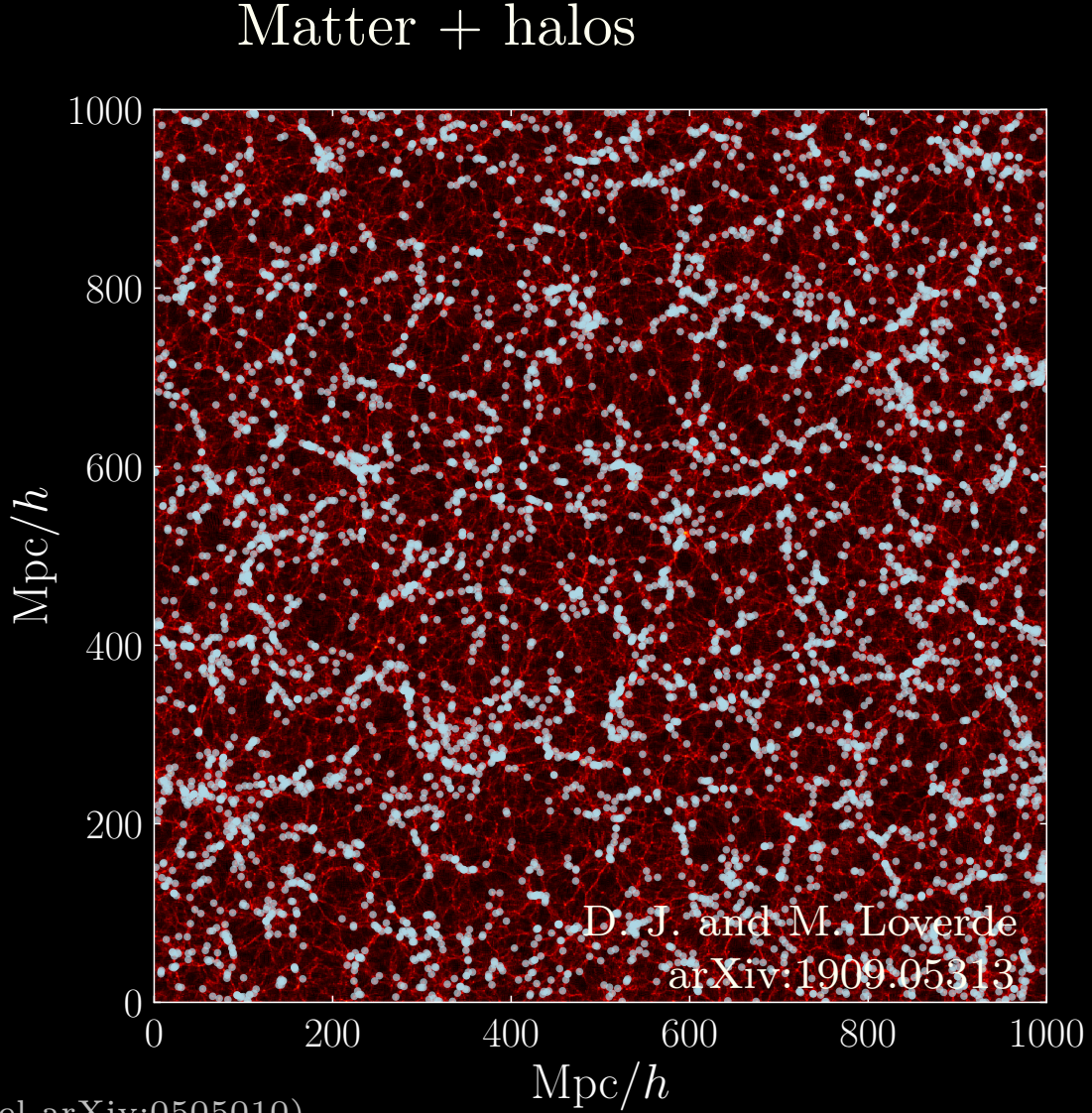


The matter field



Gadget2 (Springel arXiv:0505010)

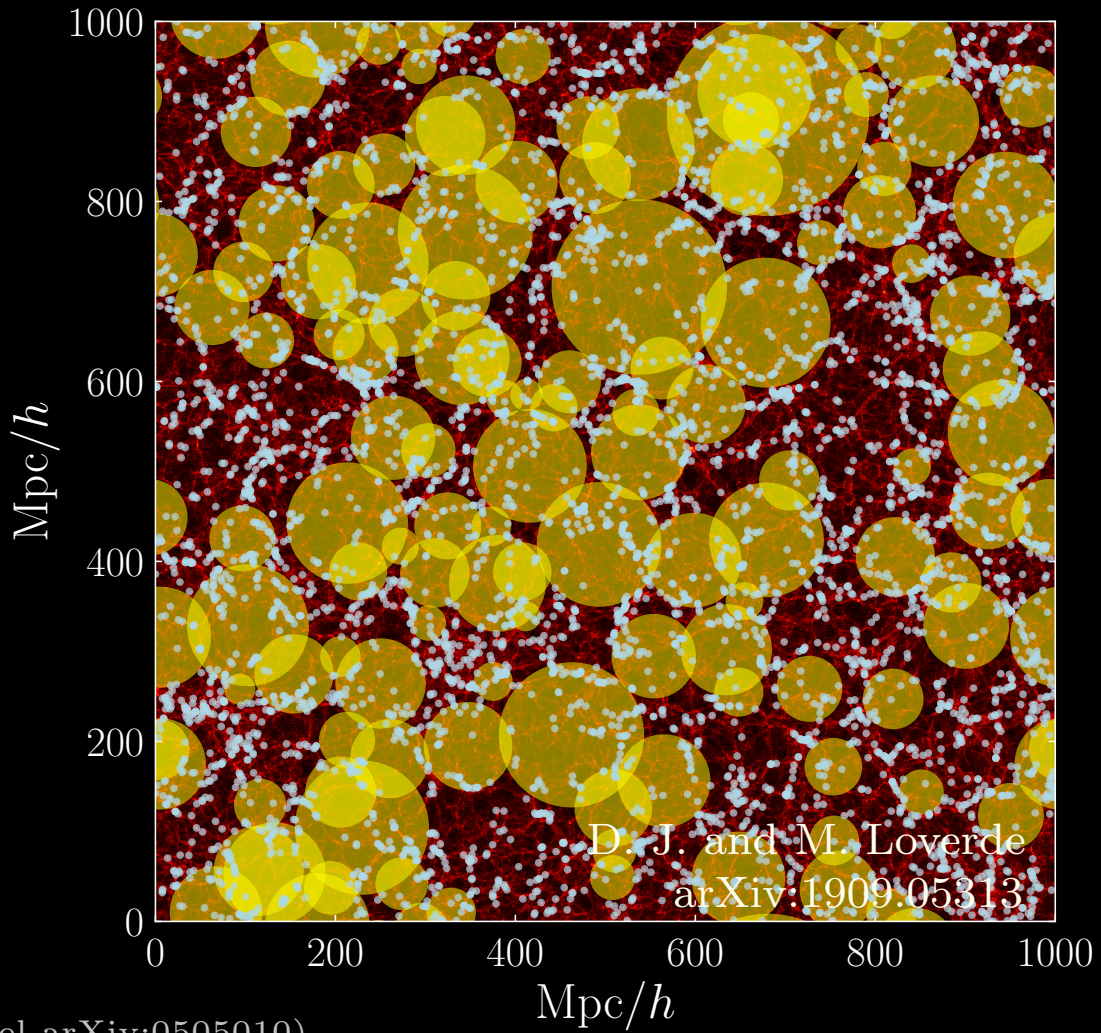
Halos in the matter field



Gadget2 (Springel arXiv:0505010)
Rockstar (Behroozi, Wechsler, Wu arXiv:1110.4372)

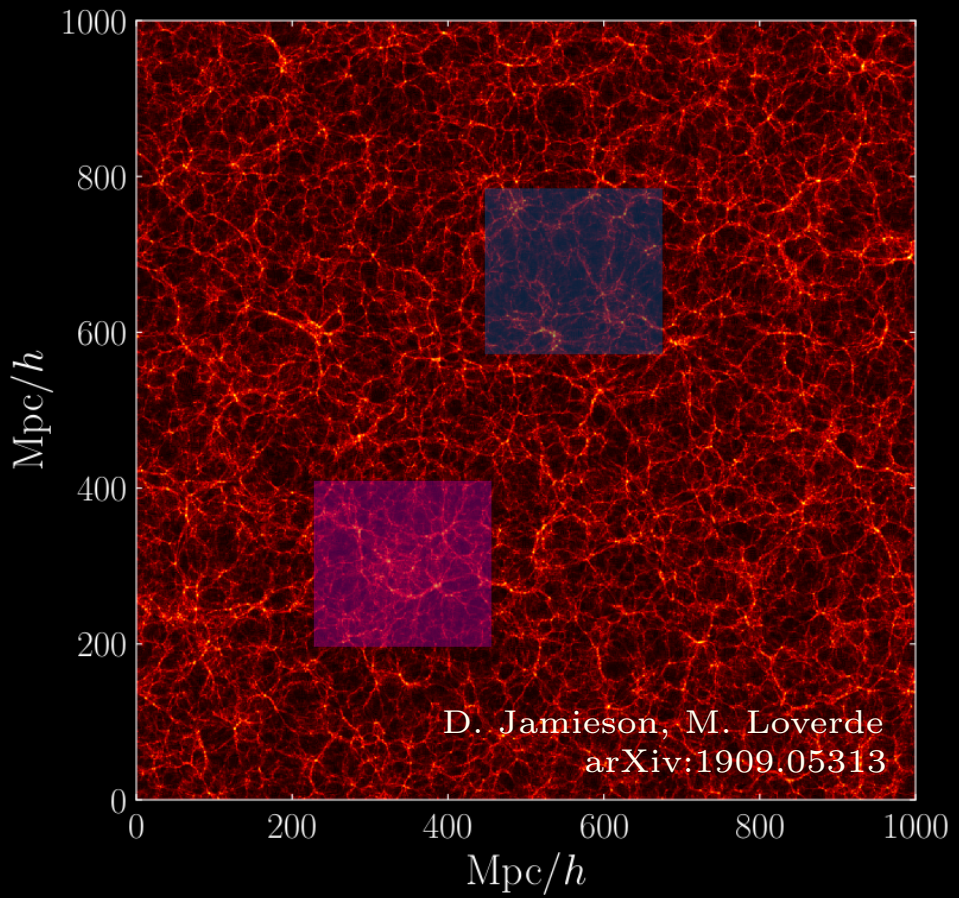
Voids in the halo field

Matter + halos + voids



Gadget2 (Springel arXiv:0505010)
Rockstar (Behroozi, Wechsler, Wu arXiv:1110.4372)
VIDE (P. M. Sutter *et al.* arXiv:1406.1191)

Local observables in the matter field



Underdense region:
→ Fewer massive halos
→ More large voids
→ Lower power

Overdense region:
→ More massive halos
→ Fewer large voids
→ Higher power

Separate universe simulations

Linear mode $\rightarrow$ shift in background,

$$\bar{\rho}_{su} = \bar{\rho}\,(1 + \delta_L)$$

$$a_{su} = a\left(1 - \frac{1}{3}\delta_L\right)$$

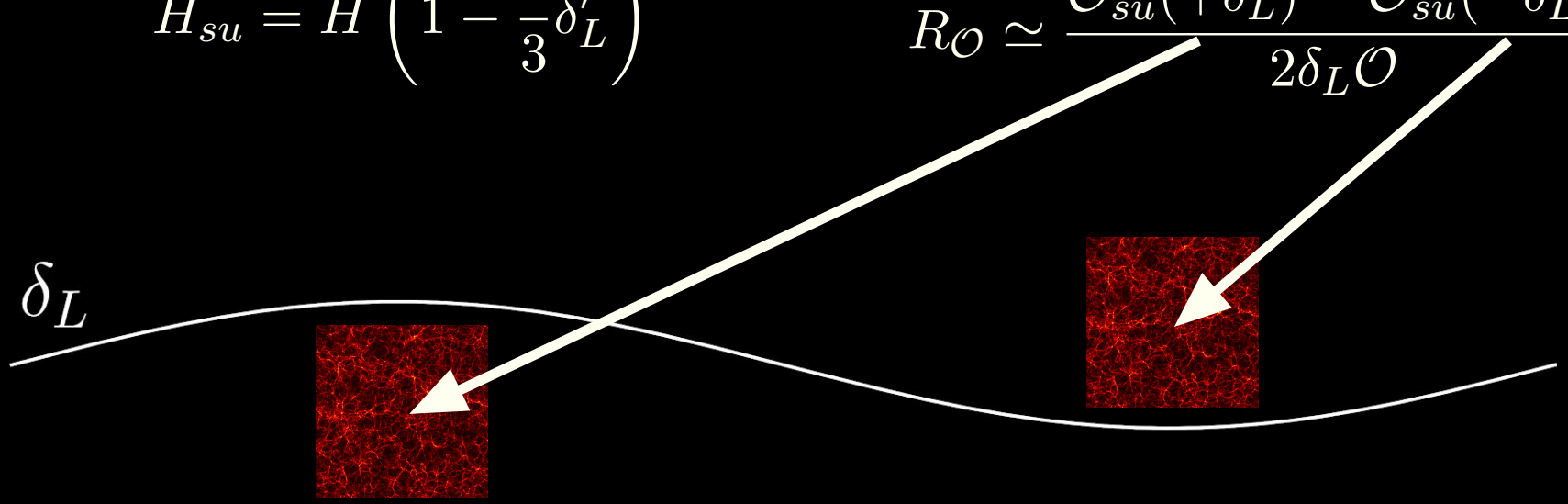
$$H_{su} = H\left(1 - \frac{1}{3}\delta'_L\right)$$

Run pairs of simulations,

$$H_{su}(a_{su}|\,\pm\,\delta_L)$$

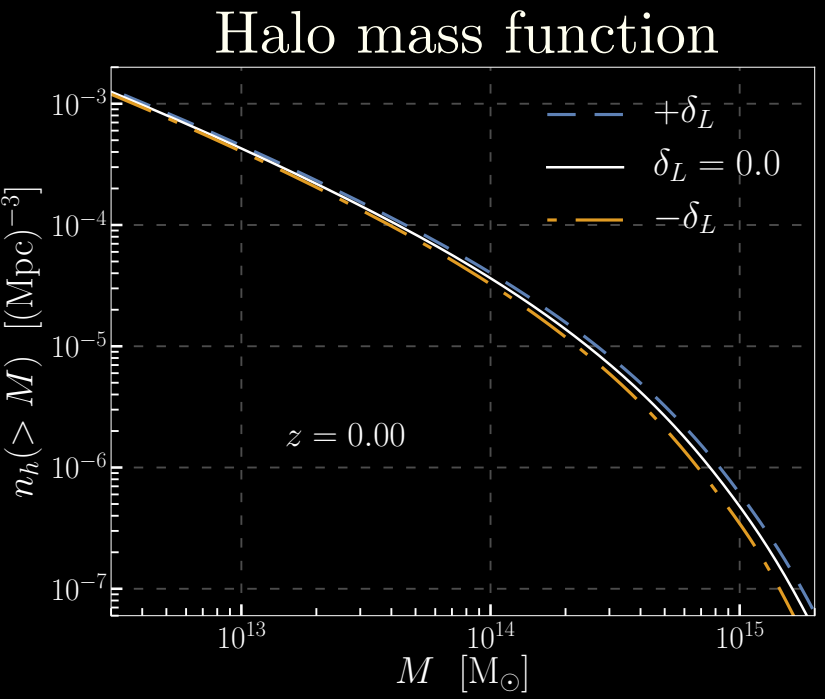
Measure the response of small-scale observables,

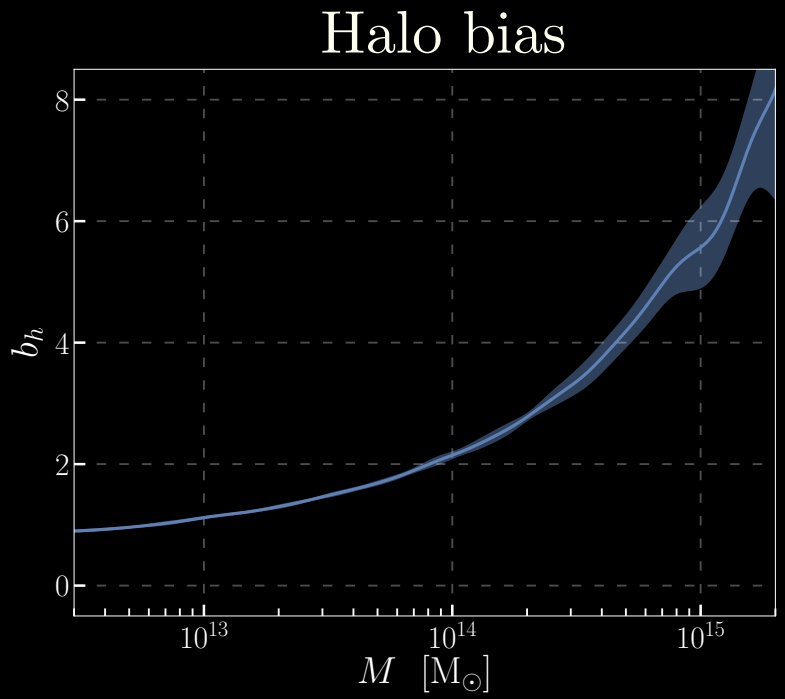
$$R_{\mathcal{O}} \simeq \frac{\mathcal{O}_{su}(+\delta_L) - \mathcal{O}_{su}(-\delta_L)}{2\delta_L \mathcal{O}}$$



Li, Hu, Takada arXiv:1401.0385
Wagner, Schmidt, Chiang, Komatsu arXiv:1409.6294

Local halo mass function → halo bias

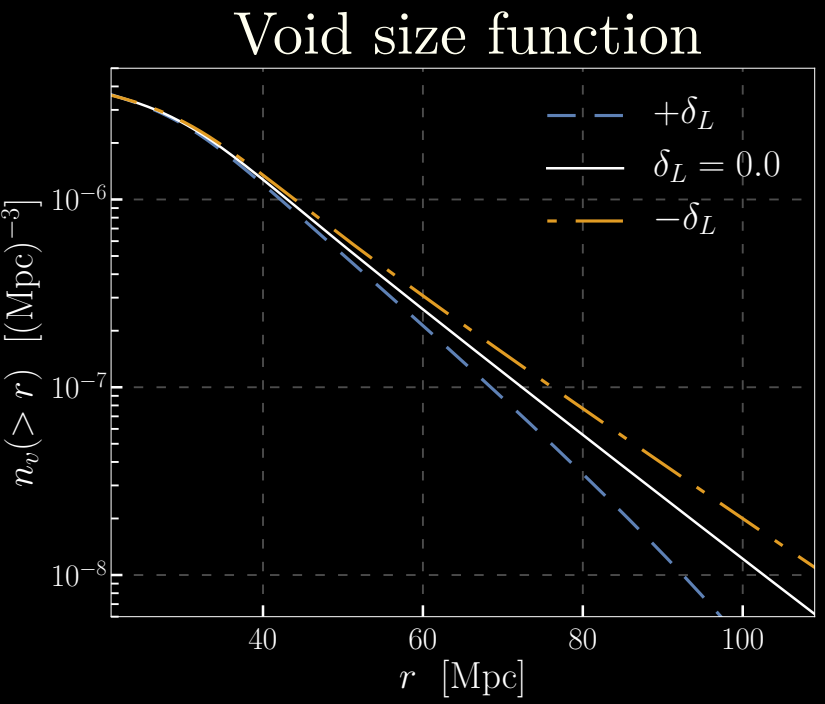


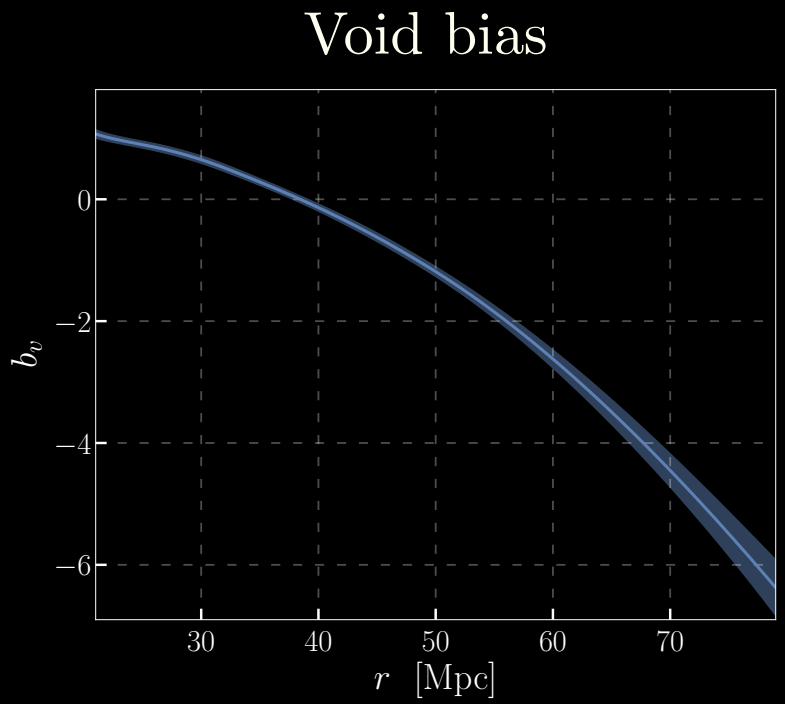


$$b_h(M) = \lim_{k \to 0} \frac{P_{hm}(k; M)}{P_{mm}(k)} = \frac{d \log n_h(M)}{d\delta_L}$$

Li, Hu, Takada arXiv:1511.01454
Baldauf, Seljak, Senatore, Zaldarriaga arXiv:1511.01465

Local void size function → void bias





$$b_v(r) = \lim_{k \to 0} \frac{P_{vm}(k;r)}{P_{mm}(k)} = \frac{d \log n_v(M)}{d\delta_L}$$

D. J. and M. Loverde arXiv:1909.05313
Chan, Li, Biagetti, Hamaus arXiv:1909.03736

Advantages of the separate universe

$\rightarrow$ Only need to know evolution of linear mode δ_L

$\rightarrow$ Small scale physics is simulated using standard N-body codes

$\rightarrow$ Include beyond ΛCDM physics through effects on δ_L

Massive neutrino cosmologies

Chiang, Hu, Li, Loverde arXiv:1609.01701

Dynamical dark energy fluctuations

Chiang, Hu, Li, Loverde arXiv:1710.01310

D. J. and M. Loverde arXiv:1812.08765

Radiation

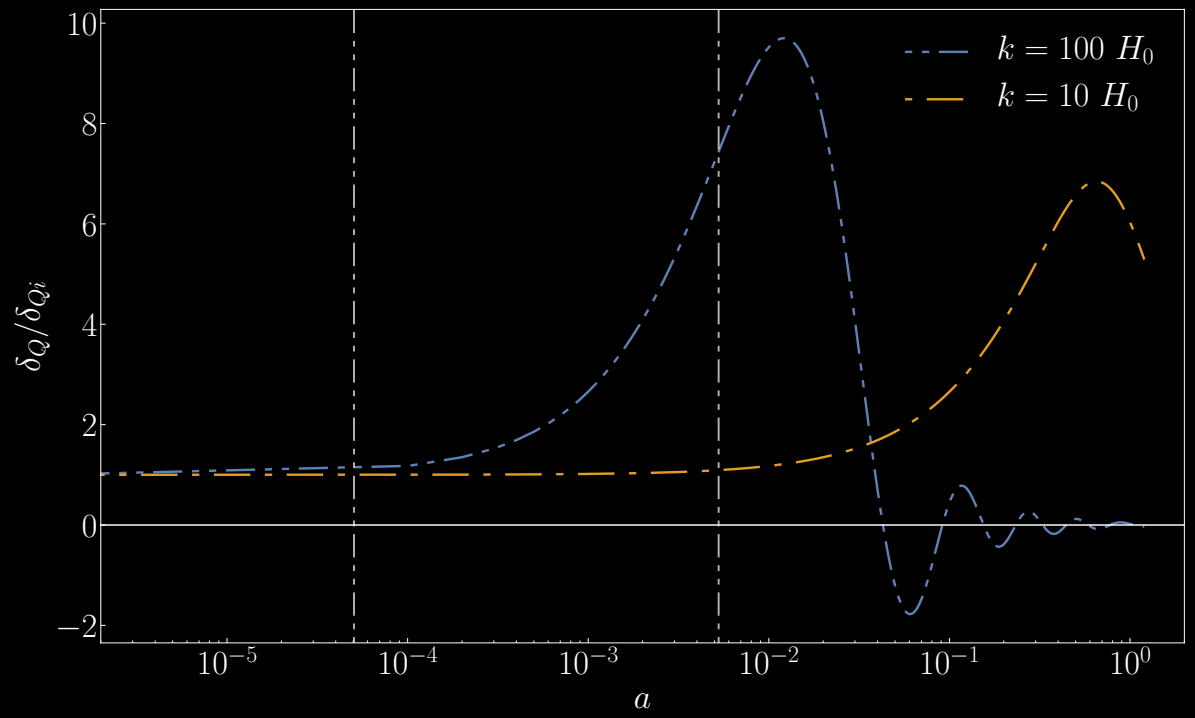
C. Shiveshwarkar, D. Jamieson, M Loverde (in preparation)

Dark energy perturbations and scale dependent growth

Gordon, Hu arXiv:0406496

Scalar field dark energy with sound speed c_Q,

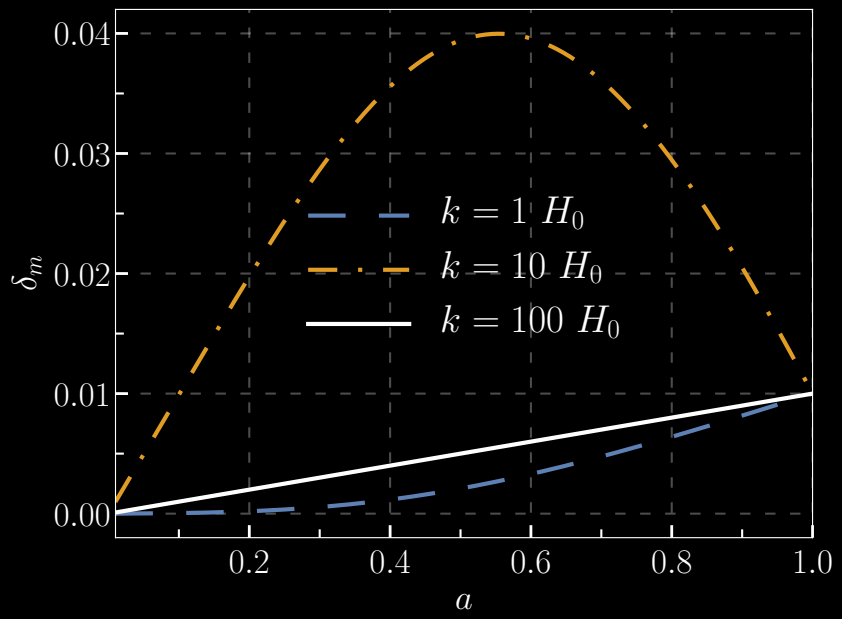
$$\mathcal{L}_Q = \frac{2c_Q^2\Lambda}{1+c_Q^2}\left(-\frac{1}{2\Lambda}g^{\mu\nu}\nabla_\mu Q\nabla_\nu Q\right)^{\frac{1+c_Q^2}{2c_Q^2}} - V(Q)$$

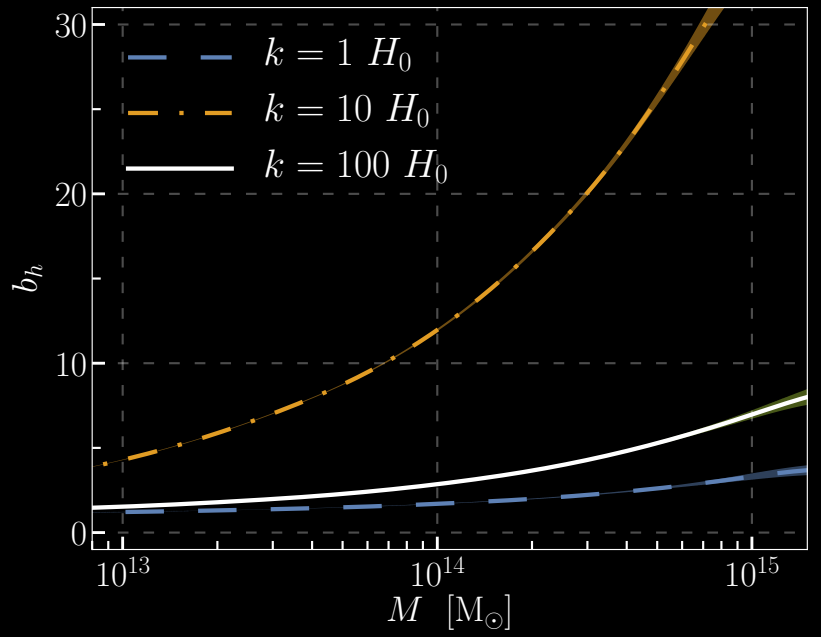


Scale dependent bias from quintessence isocurvature

Clustering dark energy perturbations
$\rightarrow$ scale dependent matter growth
$\rightarrow$ scale dependent bias

D. J. and M. Loverde arXiv:1812.08765





Can predict k-dependence of bias
from effect on <u>linear</u> power spectrum

Questions for large scale structure

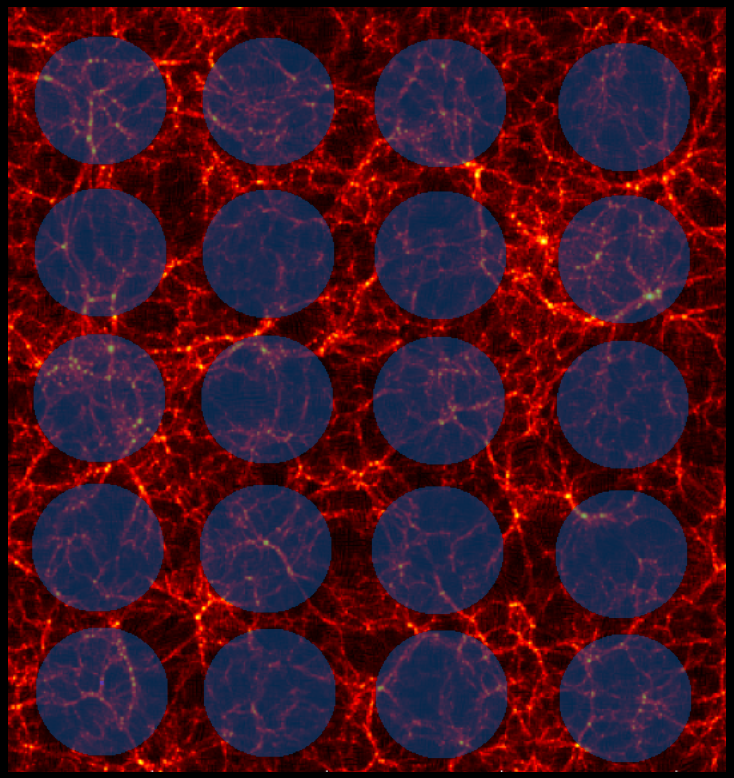
Effects of new physics on large scale structure may be small

1) How do we obtain optimal constraints?

2) Which regions/features/environments are most sensitive?

3) How do long wavelength modes affect the small scale density field?

The matter density PDF



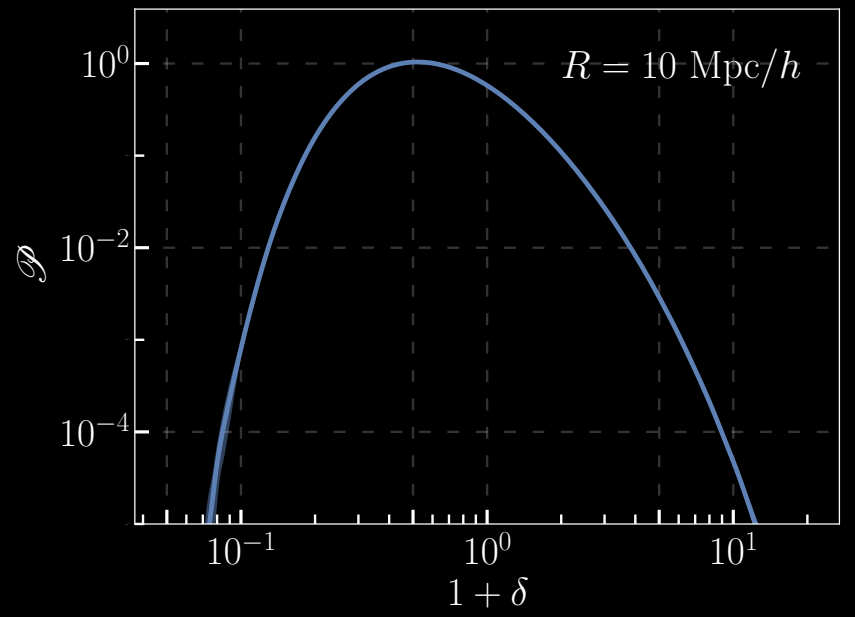
$$\rho(\vec{x})/\bar{\rho} = 1 + \delta(\vec{x})$$

Density field smoothed over radius R.

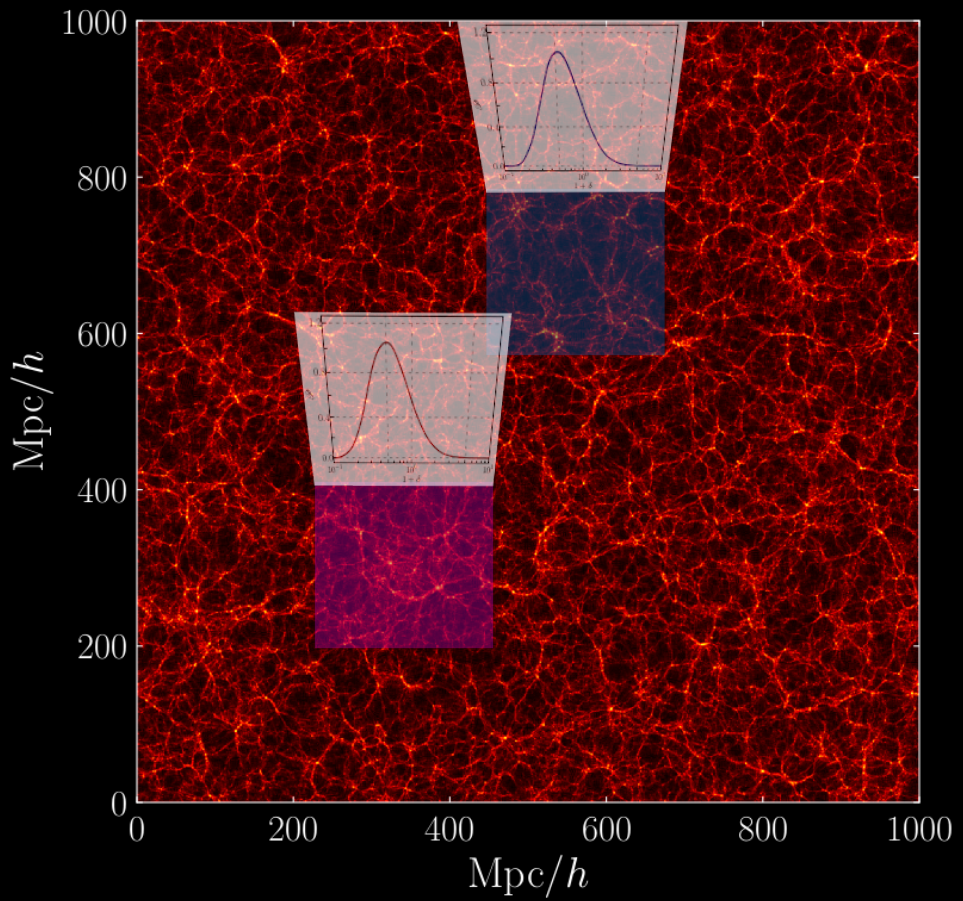
Estimate probability distribution function (PDF),

$$\mathscr{P}(1+\delta)$$

D. J. and M. Loverde (in preparation)



The local PDF

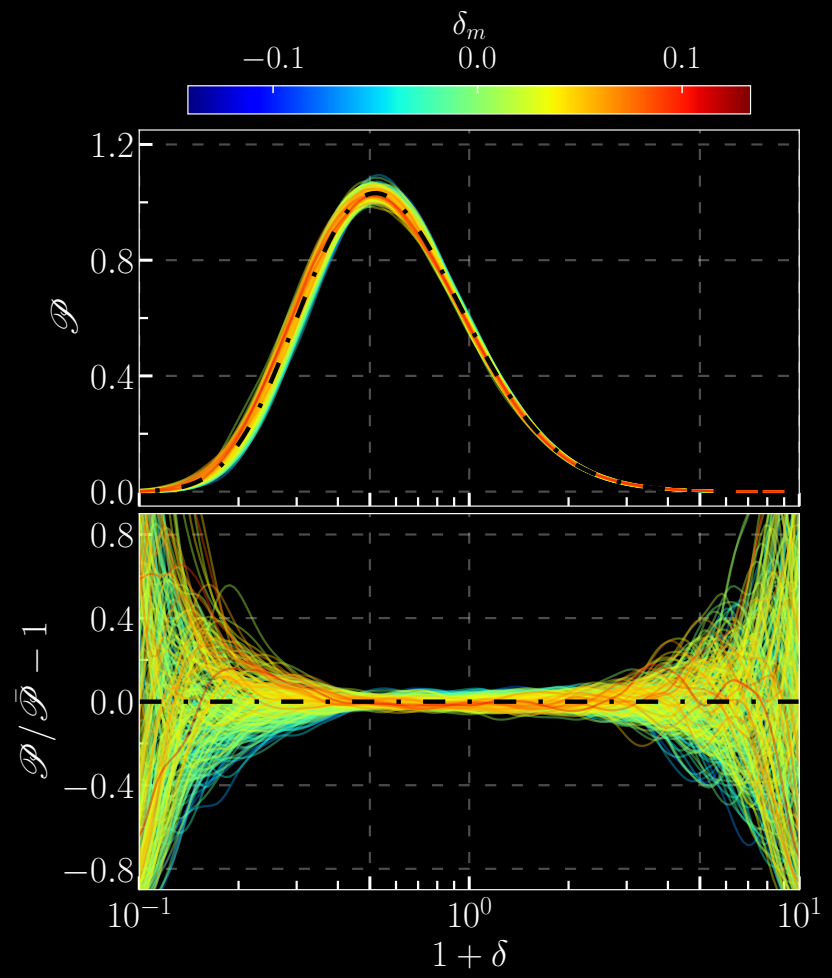


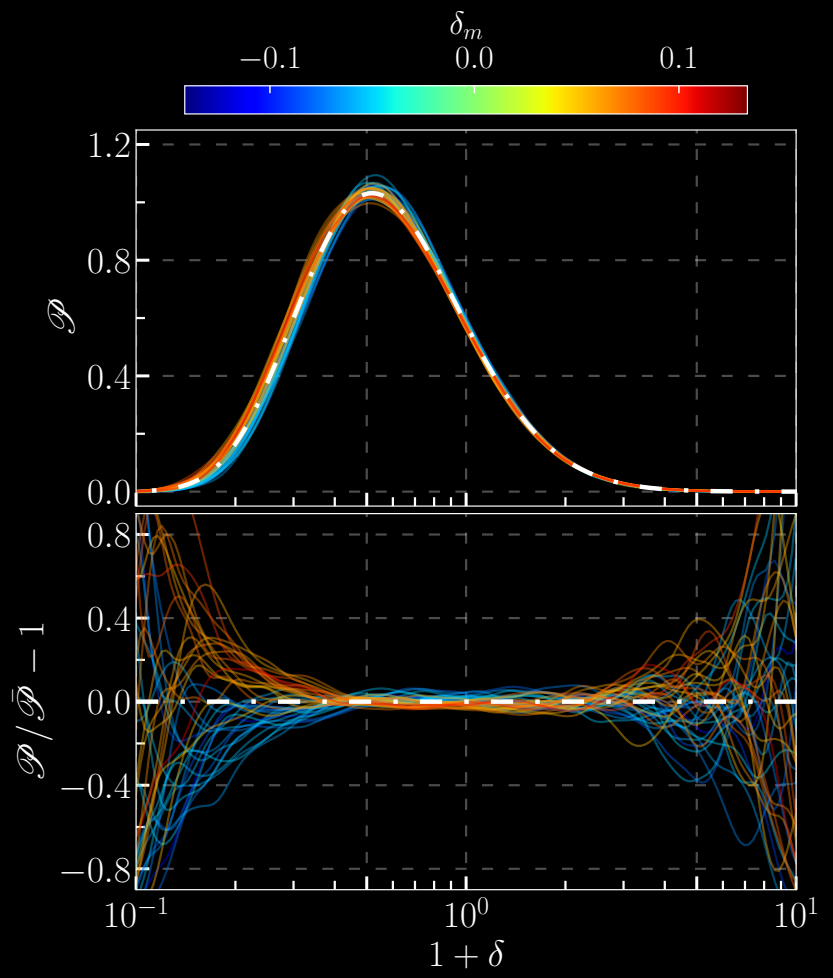
Underdense region:
→ Reduced clustering
→ Narrower distribution

Overdense region:
→ Enhanced clustering
→ Broader distribution

The local PDF

D. J. and M. Loverde (in preparation)

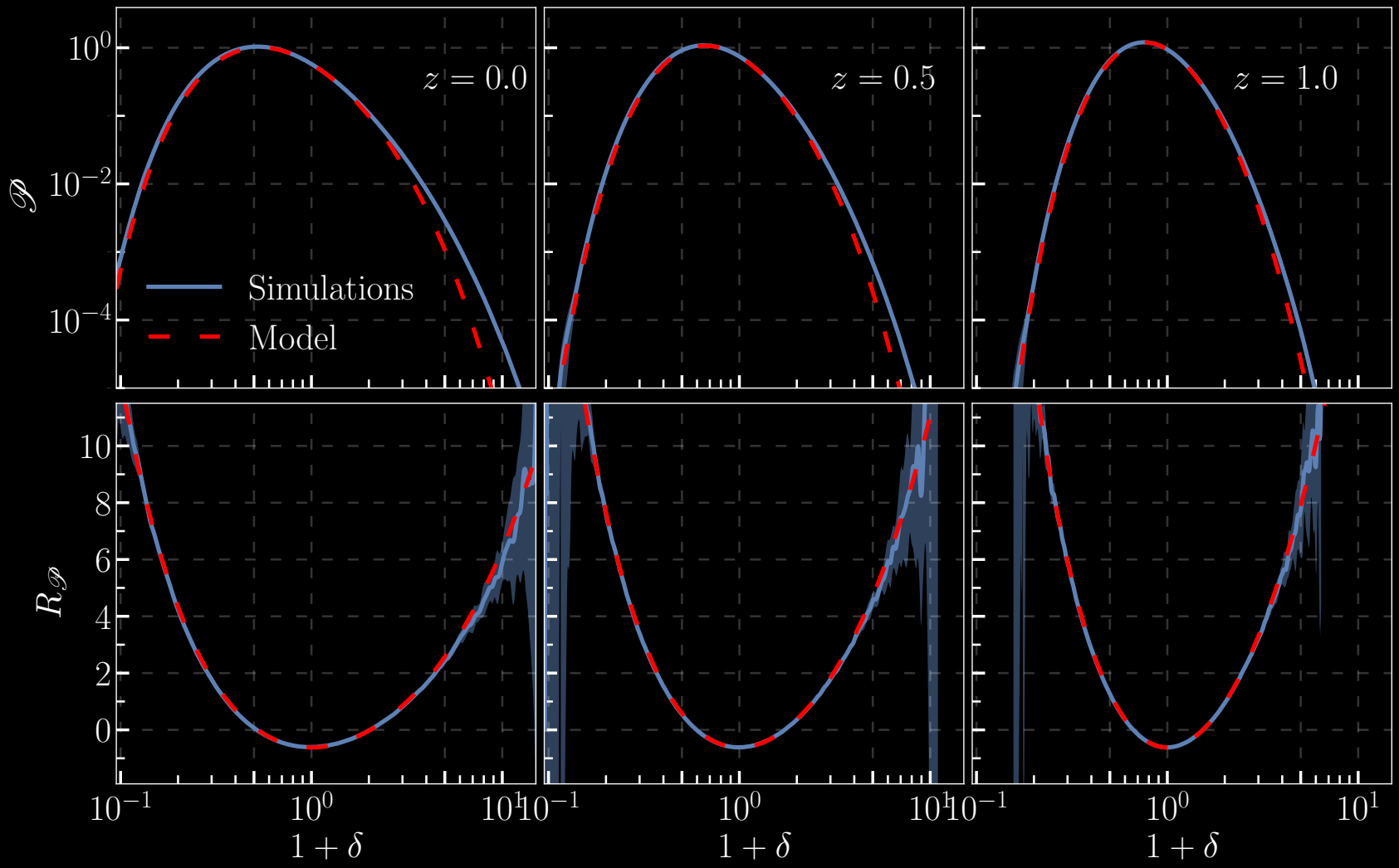




PDF response from separate universe simulations

Model from,
Ivanov, Kaurov, Sibiryakov arXiv:1811.07913

D. J. and M. Loverde (in preparation)



Conclusion

$\rightarrow$ Effects of beyond ΛCDM physics may be detectable on large scales through scale dependent bias

$\rightarrow$ These effects can be characterized using separate universe simulations

$\rightarrow$ We have made the first measurement of the separate universe response of the matter density PDF in simulations

$\rightarrow$ This new observable may be useful for obtaining optimal constraints on cosmological parameters

Thank you!