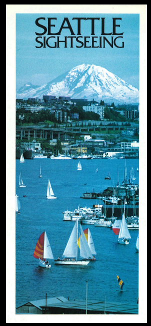
New Techniques for New Physics in Large-scale Structure

Marilena Loverde
Stony Brook University (—> University of Washington Fall 2021)


images: wikimedia commons



Outline

- New physics in large-scale structure
- New computational tools
- New observables

New physics in large-scale structure

New physics in large-scale structure

Goal: new physics from galaxy and intensity mapping surveys

observables $n_{galaxies}(x,a)$, $n_{voids}(x,a)$, $n_{HI}(x,a)$, $\kappa(\theta,a_{source})$, . . .

examples of new physics

- evidence for primordial non-Gaussianity
- detect m_ν (or axions or nonstandard neutrinos or thermal history)
- deviations from GR + Λ

New physics in large-scale structure

Goal: new physics from galaxy and intensity mapping surveys

observables $n_{galaxies}(x,a)$, $n_{voids}(x,a)$, $n_{HI}(x,a)$, $\kappa(\theta,a_{source})$, . . .

examples of new physics

- evidence for primordial non-Gaussianity

produce tiny changes to observables

- detect m_ν (or axions or nonstandard neutrinos or thermal history)

- deviations from GR + Λ

New physics in large-scale structure

Goal: new physics from galaxy and intensity mapping surveys

observables $n_{galaxies}(x,a)$, $n_{voids}(x,a)$, $n_{HI}(x,a)$, $\kappa(\theta, a_{source})$, . . .

examples of new physics

produce tiny changes to observables

- evidence for primordial non-Gaussianity

  $f_{NL} \sim 1$, nothing else modulates $n_{galaxies}(x,a)$ at 10^{-4}

- detect m_ν (or axions or nonstandard neutrinos or thermal history)

  $\sum m_\nu = 0.06$, $\delta\rho_{cdm+b}/\rho_{cdm+b}$ accurate to ~0.4%

- deviations from GR + Λ

  no firm threshold, likely strong prior!

New physics in large-scale structure

How is physics imprinted in large-scale structure?

Inflation encoded in primordial fluctuations $\hat{\mathcal{R}}(x)$ $(\hat{\mathcal{I}}(x), \ldots)$

$$\langle \mathcal{R}\mathcal{R} \rangle \quad \langle \mathcal{R}\mathcal{R}\mathcal{R} \rangle \quad \ldots$$

$$\langle \mathcal{R}\mathcal{I} \rangle$$

$\delta\rho_{cdm}/\rho_{cdm}$,. . . etc $\propto \mathcal{R}$

$\delta_X \equiv \delta\rho_X/\rho_X = T_X(k,a)\,\mathcal{R}$

Info about types of energy (e.g. m_ν) encoded in $T_X(k,a)$

New physics in large-scale structure

Observables more complicated, always nonlinear

e.g. $n_{galaxies}(x,a) = n_{galaxies}\,[\rho_{cdm}, \rho_b, \ldots]$

$\Rightarrow$ $\delta n_{galaxies}(x,a) = \delta n_{galaxies}/\delta\rho_{cdm}\ \delta\rho_{cdm}(x) + \delta n_{galaxies}/\delta\rho_b\ \delta\rho_b(x)$

(ρ_{cdm}, ρ_b values within say, $R_{galaxy} \sim (M/\rho_{cdm})^{1/3}$ scale of objects)

Fluctuations in $\delta n_{galaxies}(x,a)$ then follow fluctuations in matter so, e.g. $\langle \delta n_{gal} \delta n_{gal} \rangle \propto \langle \delta\rho_{cdm} \delta\rho_{cdm} \rangle$

New physics in large-scale structure

Observables more complicated, always nonlinear

e.g. $n_{galaxies}(x,a) = n_{galaxies}\,[\rho_{cdm},\ \rho_b,\ .\ .\ .]$

$\Rightarrow$ $\delta n_{galaxies}(x,a) = \delta n_{galaxies}/\delta\rho_{cdm}\ \delta\rho_{cdm}(x) + \delta n_{galaxies}/\delta\rho_b\ \delta\rho_b(x)$

(ρ_{cdm}, ρ_b values within say, $R_{galaxy} \sim (M/\rho_{cdm})^{1/3}$ scale of objects)

Fluctuations in $\delta n_{galaxies}(x,a)$ then follow fluctuations in matter so, e.g. $\langle \delta n_{gal} \delta n_{gal} \rangle \propto \langle \delta\rho_{cdm} \delta\rho_{cdm} \rangle$

the proportionality coefficient is referred to as the “bias” of the observable

New computational tools

Separate Universe/Response Approach

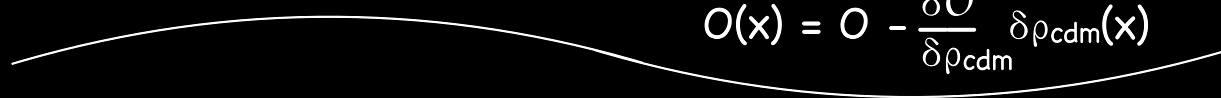
New computational tools

Separate Universe/Response Approach

A subset of nonlinear quantities involve *responses* of observables to long-wavelength fluctuations $\delta\rho_{cdm}(k_L)$

$$O(x) = O + \frac{\delta O}{\delta\rho_{cdm}}\delta\rho_{cdm}(x)$$

$$O(x) = O - \frac{\delta O}{\delta\rho_{cdm}}\delta\rho_{cdm}(x)$$



$\delta\rho_{cdm}\ (k_L)$

(e.g. $O = n_{gals},\ n_{voids},\ \kappa,\ . . .$)

New computational tools

Separate Universe/Response Approach

A subset of nonlinear quantities involve *responses* of observables to long-wavelength fluctuations $\delta\rho_{cdm}(k_L)$

$$O(x) = O + \frac{\delta O}{\delta \rho_{cdm}} \delta\rho_{cdm}(x)$$

$$O(x) = O - \frac{\delta O}{\delta \rho_{cdm}} \delta\rho_{cdm}(x)$$

$\delta\rho_{cdm}\ (k_L)$

(e.g. $O = n_{gals}, n_{voids}, \kappa, \ldots$)

Observer measures

$$\langle O(x)\, \delta_{cdm}(x') \rangle \sim \frac{\delta O}{\delta \delta_{cdm}} \langle \delta_{cdm}(x) \delta_{cdm}(x') \rangle$$

$$\langle O(x)\, O(x') \rangle \sim \left(\frac{\delta O}{\delta \delta_{cdm}} \right)^2 \langle \delta_{cdm}(x) \delta_{cdm}(x') \rangle$$

New computational tools

Separate Universe/Response Approach

A subset of nonlinear quantities involve *responses* of observables to long-wavelength fluctuations $\delta\rho_{cdm}(k_L)$

$$O(x) = O + \frac{\delta O}{\delta \rho_{cdm}} \delta\rho_{cdm}(x)$$

$$O(x) = O - \frac{\delta O}{\delta \rho_{cdm}} \delta\rho_{cdm}(x)$$

$\delta\rho_{cdm}\ (k_L)$

(e.g. $O = n_{gals}, n_{voids}, \kappa, \ldots$)

Observer measures

$$\langle O(x)\, \delta_{cdm}(x')\rangle \sim \frac{\delta O}{\delta \delta_{cdm}} \langle \delta_{cdm}(x) \delta_{cdm}(x')\rangle$$

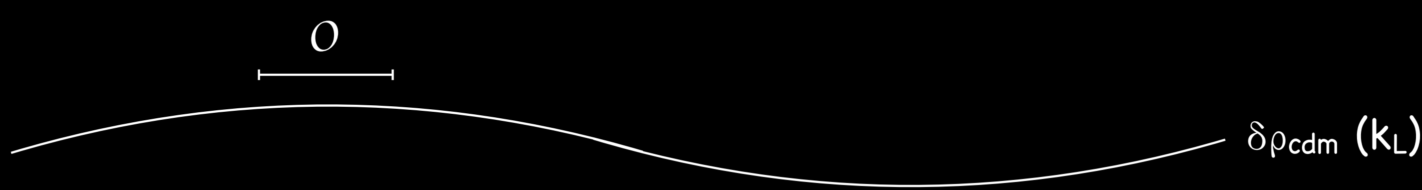
$$\langle O(x)\, O(x')\rangle \sim \left(\frac{\delta O}{\delta \delta_{cdm}}\right)^2 \langle \delta_{cdm}(x) \delta_{cdm}(x')\rangle$$

If characteristic size of O, $k_O \gg k_L$, can absorb $\delta\rho_{cdm}(k_L)$ into background

New computational tools

Separate Universe/Response Approach

If characteristic size of $\mathcal{O}$, $k_O \gg k_L$, can absorb $\delta\rho_{cdm}(k_L)$ into background



local scale factor and Hubble rate near O:

$$a_L = a(1 - 1/3\ \delta\rho_{cdm}/\rho_{cdm}), \quad H_L = H\ (1 - 1/3\ d/d\ln a(\delta\rho_{cdm}/\rho_{cdm})\ )$$

New computational tools

Separate Universe/Response Approach

If characteristic size of $\mathcal{O}$, $k_O \gg k_L$, can absorb $\delta\rho_{cdm}(k_L)$ into background

local scale factor and Hubble rate near O:

$$a_L = a(1 - 1/3\ \delta\rho_{cdm}/\rho_{cdm}), \quad H_L = H\,(1 - 1/3\ d/d\ln a(\delta\rho_{cdm}/\rho_{cdm})\,)$$

particle eom for stuff in O usual w/modified expansion:

$$\ddot{x} + 2\,H_L\,\dot{x} + 1/a_L^2\,\nabla\Phi = 0$$

New computational tools

Separate Universe/Response Approach

can predict
responses by
cosmology
dependence of O

$$\frac{\delta O}{\delta \delta_{cdm}} = \frac{O(a_L, H_L) - O(a, H)}{\delta_{cdm}}$$

New computational tools

Separate Universe/Response Approach

can predict responses by cosmology dependence of O

$$\frac{\delta O}{\delta \delta_{cdm}} = \frac{O(a_L, H_L) - O(a, H)}{\delta_{cdm}}$$

Compare to those measured via clustering

$$\langle O(x)\, \delta_{cdm}(x') \rangle \sim \frac{\delta O}{\delta \delta_{cdm}} \langle \delta_{cdm}(x) \delta_{cdm}(x') \rangle$$

New computational tools

Separate Universe/Response Approach

can predict responses by cosmology dependence of O

$$\frac{\delta O}{\delta \delta_{cdm}} = \frac{O(a_L, H_L) - O(a, H)}{\delta_{cdm}}$$

Compare to those measured via clustering

$$\langle O(x)\, \delta_{cdm}(x') \rangle \sim \frac{\delta O}{\delta \delta_{cdm}} \langle \delta_{cdm}(x) \delta_{cdm}(x') \rangle$$

* looks similar to "consistency relations" derived from residual symmetries of eom

Kehagias & Riotto 2013, Valageas 2013, Peloso & Pietroni 2013

New computational tools

Separate Universe/Response Approach

Compute responses via analytic methods or simulations

$$\frac{\delta O}{\delta \delta_{cdm}} = \frac{O(a_L, H_L) - O(a, H)}{\delta_{cdm}}$$

e.g.

$$a_L = a(1 - 1/3\ \delta\rho_{cdm}/\rho_{cdm})$$
$$H_L = H\ (1 - 1/3\ d/d\ln a(\delta\rho_{cdm}/\rho_{cdm})\ )$$

measure O in sims

movie: Kravtsov

New computational tools

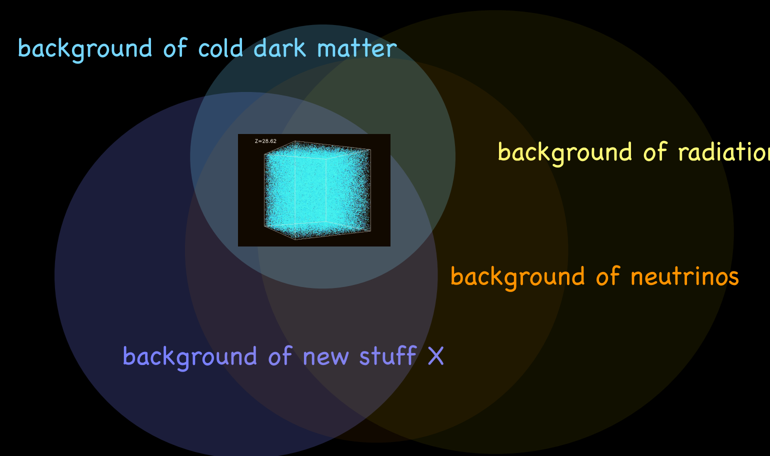
Separate Universe/Response Approach

Validate responses & clustering
w/simulations

$$\frac{\delta O}{\delta \delta_{cdm}} = \frac{O(a_L, H_L) - O(a, H)}{\delta_{cdm}}$$

Advantages:

- Cleaner measurements
- Easy method to compute responses to different types of matter and for different large-scale correlations
- Identify new signatures of new physics



movie: Kravtsov

New computational tools

Separate Universe/Response Approach

Validate responses & clustering w/simulations

$$\frac{\delta O}{\delta \delta_{cdm}} = \frac{O(a_L, H_L) - O(a, H)}{\delta_{cdm}}$$

Advantages:

- Cleaner measurements
- Easy method to compute responses to different types of matter and for different large-scale correlations
- Identify new signatures of new physics

Scenarios:

- ν CDM, γCDM
  ML 2014; Chiang, Hu, Li, ML 2017; Chiang, ML, Villaescusa-Navarro 2018; Shiveshwarkar, Jamieson & ML 2020
- clustered dark energy
  Chiang, Hu, Li, ML 2016
- isocurvature + CDM
  Jamieson & ML 2018
- compensated isocurvature
  Barriera, Cabass, Nelson, Schmidt 2019

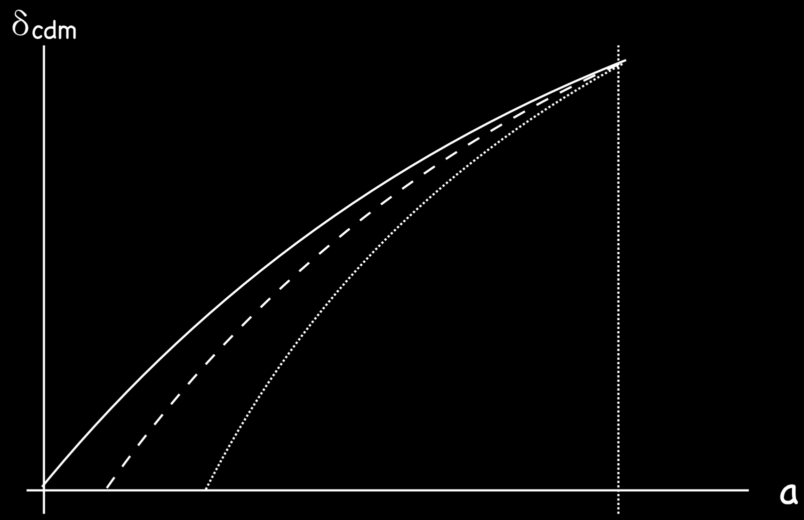
movie: Kravtsov

New computational tools

Separate Universe/Response Approach

Validate responses & clustering w/simulations

$$\frac{\delta O}{\delta \delta_{cdm}} = \frac{O(a_L, H_L) - O(a, H)}{\delta_{cdm}}$$



δ_{cdm} with different k_L, initial conditions have different evolutionary histories

Scenarios:

- ν CDM, γCDM

  ML 2014; Chiang, Hu, Li, ML 2017; Chiang, ML, Villaescusa-Navarro 2018; Shiveshwarkar, Jamieson & ML 2020

- clustered dark energy

  Chiang, Hu, Li, ML 2016

- isocurvature + CDM

  Jamieson & ML 2018

- compensated isocurvature

  Barriera, Cabass, Nelson, Schmidt 2019

movie: Kravtsov

New computational tools

Separate Universe/Response Approach

Validate responses & clustering w/simulations

$$\frac{\delta O}{\delta \delta_{cdm}} = \frac{O(a_L, H_L) - O(a, H)}{\delta_{cdm}}$$

Advantages:

- Cleaner measurements
- Easy method to compute responses to different types of matter and for different large-scale correlations
- Identify new signatures of new physics

Observables:

- n_{halos}, $P(k_s)$

  Wagner, Schmidt, Chiang, Komatsu 2014; Baldauf, Seljak, Senatore, Zaldarriaga 2015; Li, Hu, Takada 2014

- n_{voids}

  Jamieson, ML 2019; Chan, Li, Biagetti, Hamaus 2019

- PDF of matter and halos

  Jamieson & ML 2020; Jamieson & ML 2020

movie: Kravtsov

New computational tools

Separate Universe/Response Approach

Validate responses & clustering
w/simulations

$$\frac{\delta O}{\delta \delta_{cdm}} = \frac{O(a_L, H_L) - O(a, H)}{\delta_{cdm}}$$

Advantages:

- Cleaner measurements
- Easy method to compute responses to different types of matter and for different large-scale correlations
- Identify new signatures of new physics

Observables:

- n_{halos}, $P(k_s)$

  Wagner, Schmidt, Chiang, Komatsu 2014; Baldauf, Seljak, Senatore, Zaldarriaga 2015; Li, Hu, Takada 2014

- n_{voids}

  Jamieson, ML 2019; Chan, Li, Biagetti, Hamaus 2019

- PDF of matter and halos

  Jamieson & ML 2020; Jamieson & ML 2020

movie: Kravtsov

New Observables

Position-dependent probability distribution function (PDF)

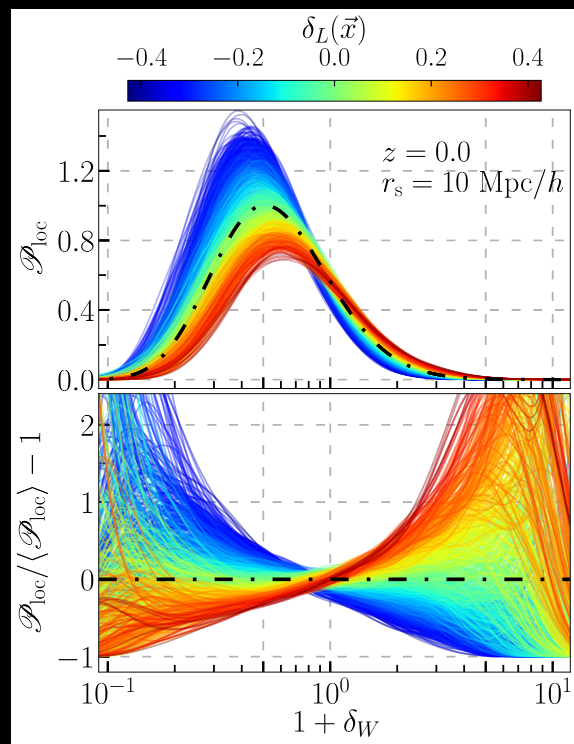
Jamieson & ML 2020; Jamieson & ML 2020

New Observables

Position-dependent probability distribution function (PDF)

Jamieson & ML 2020; Jamieson & ML 2020

Eulerian PDF

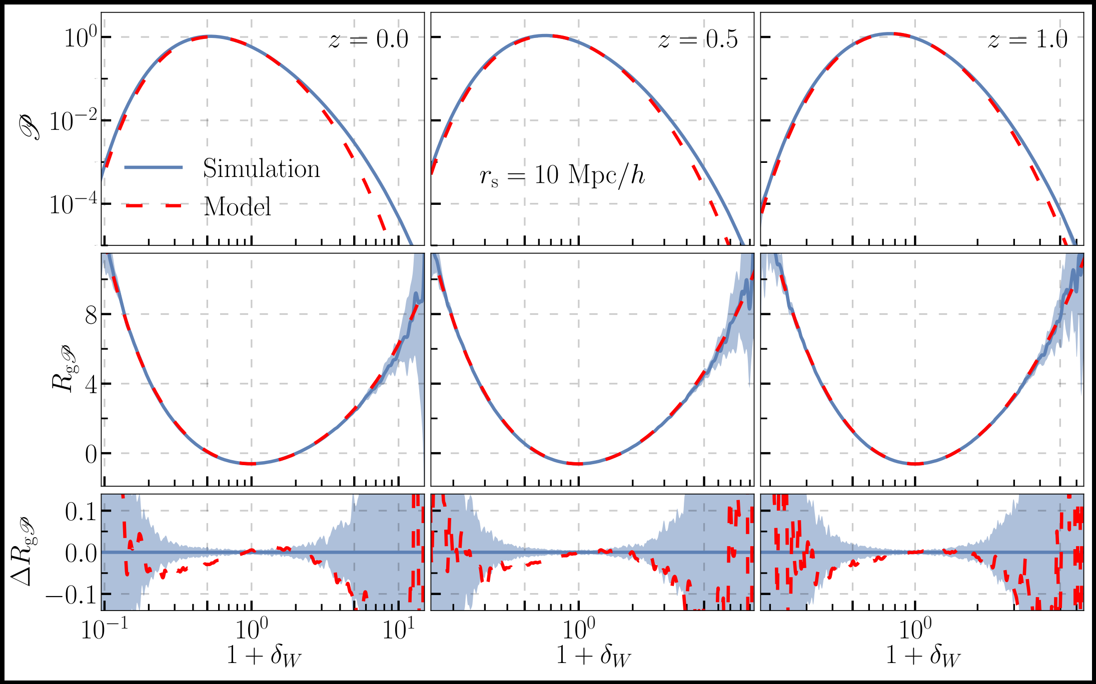


New Observables

Position-dependent probability distribution function (PDF)

Jamieson & ML 2020; Jamieson & ML 2020

Eulerian PDF



Response much more accurately modeled than PDF itself

(and "bias" of PDF more accurately predicted than bias of e.g. galaxies)

New Observables

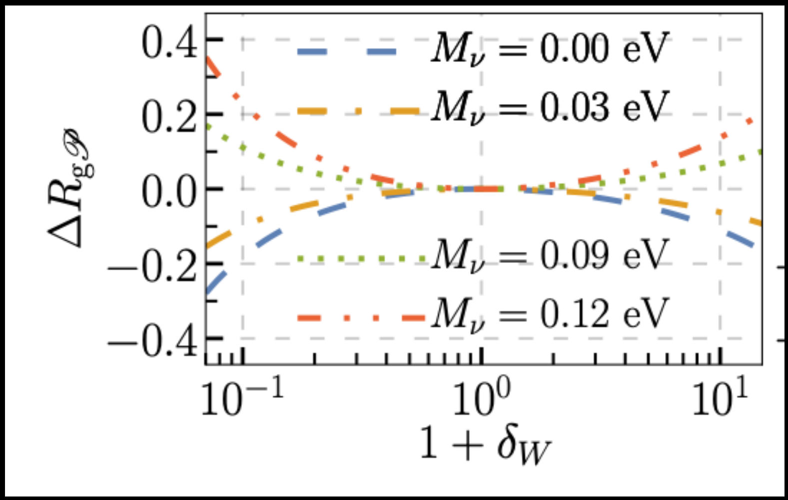
Position-dependent probability distribution function (PDF)

Jamieson & ML 2020; Jamieson & ML 2020

Response much more accurately modeled than PDF itself

(and "bias" of PDF more accurately predicted than bias of e.g. galaxies)

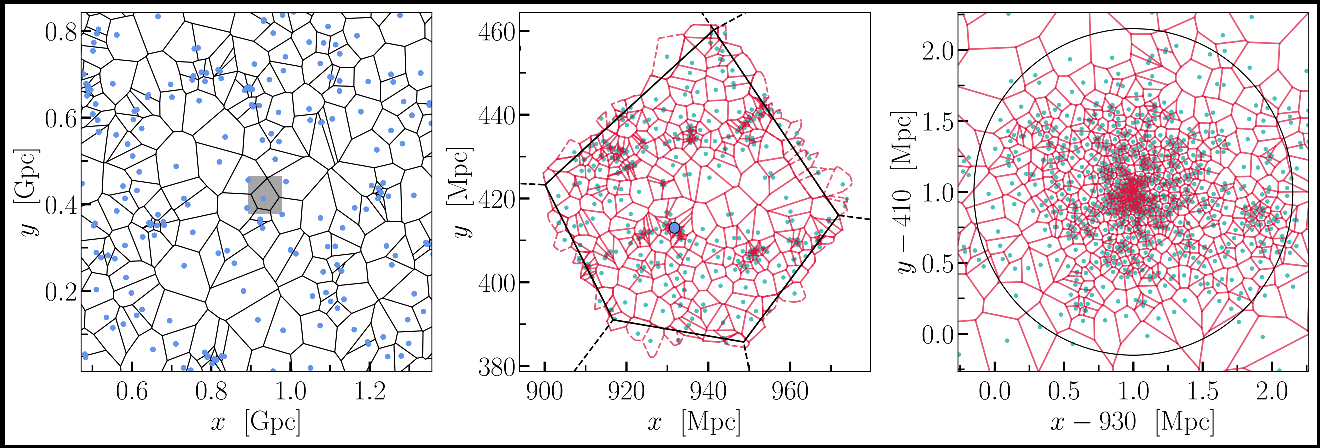
Sensitivity of Eulerian PDF to neutrino mass



New Observables

Position-dependent **Voronoi** probability distribution function (PDF)

Jamieson & ML 2020; Jamieson & ML 2020



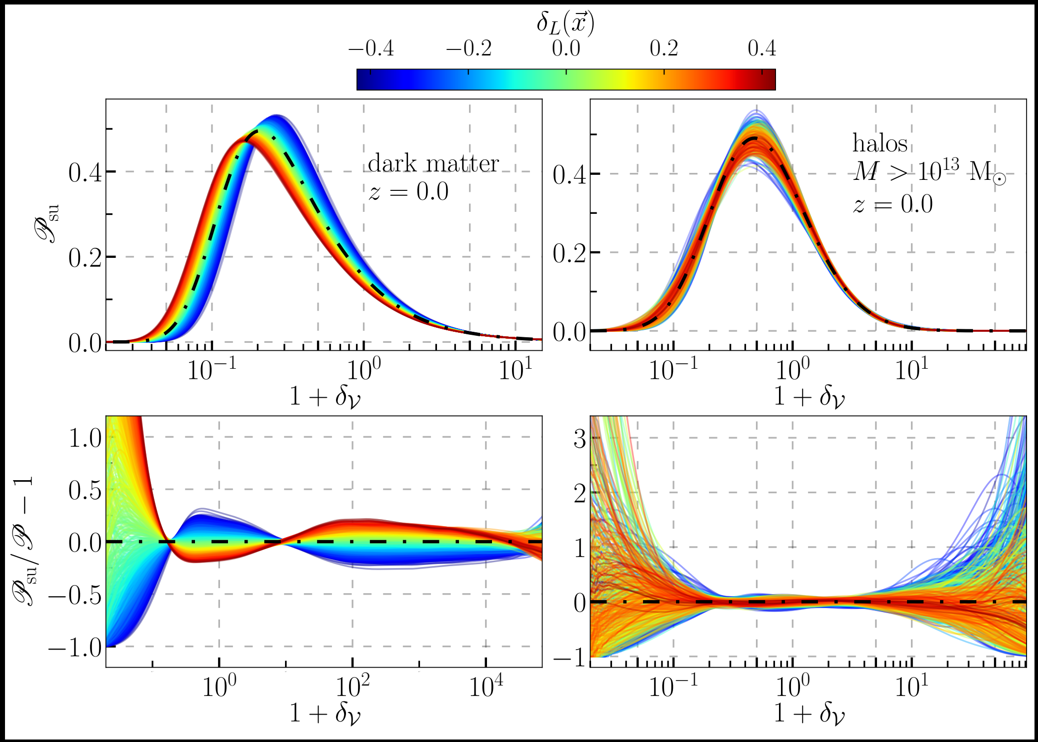
measure PDF of density in regions w/ fixed amount of mass or number of halos

New Observables

Position-dependent **Voronoi** probability distribution function (PDF)

Jamieson & ML 2020; Jamieson & ML 2020

Voronoi PDF



New Observables

Position-dependent **Voronoi** probability distribution function (PDF)

Jamieson & ML 2020; Jamieson & ML 2020

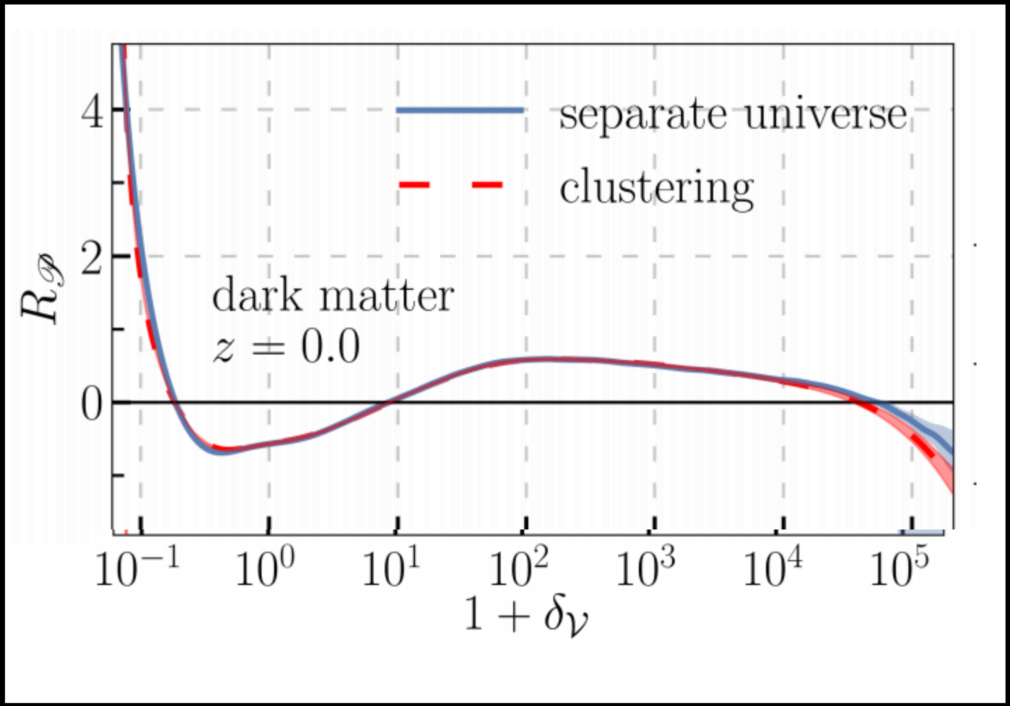
$R_{\mathcal{P}} =$

$$= \frac{\mathcal{P}(a_L, H_L) - \mathcal{P}(a, H)}{\mathcal{P}\ \delta_{cdm}}$$

vs

$$= \frac{\langle \mathcal{P}(x)\, \delta_{cdm}(x') \rangle}{\mathcal{P} \langle \delta_{cdm}(x) \delta_{cdm}(x') \rangle}$$

Voronoi PDF



New Observables

Position-dependent **Voronoi** probability distribution function (PDF)

Jamieson & ML 2020; Jamieson & ML 2020

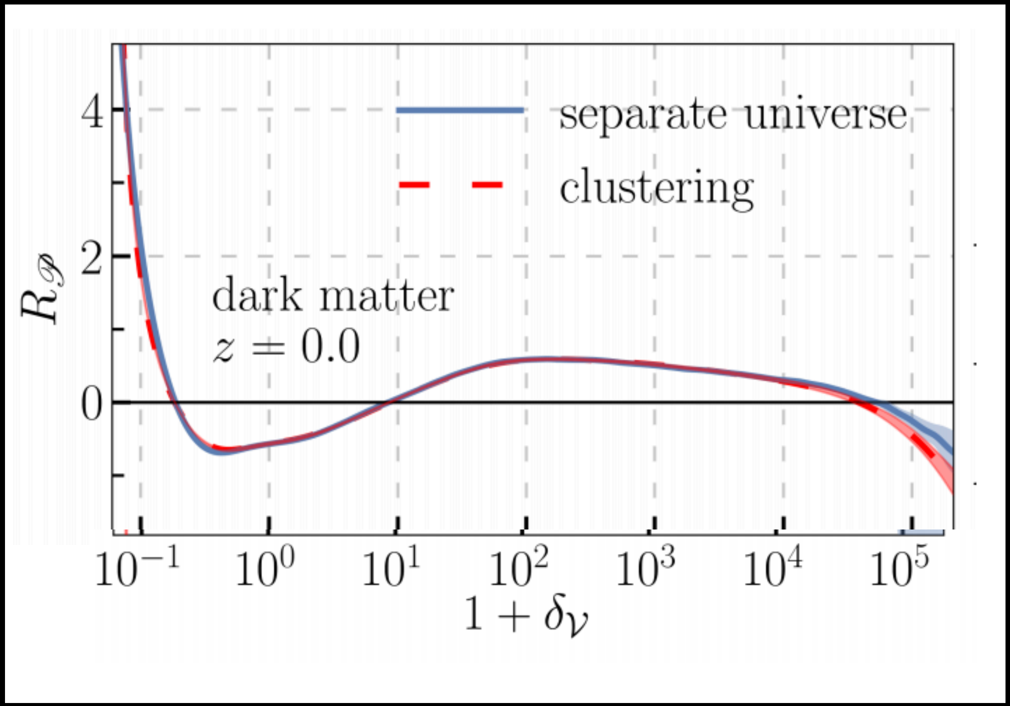
Voronoi PDF

$$R_{\mathcal{P}} =$$

$$= \frac{\mathcal{P}(a_L, H_L) - \mathcal{P}(a, H)}{\mathcal{P}\ \delta_{cdm}}$$

vs

$$= \frac{\langle \mathcal{P}(x)\, \delta_{cdm}(x') \rangle}{\mathcal{P} \langle \delta_{cdm}(x) \delta_{cdm}(x') \rangle}$$



agree across 5-6 orders of magnitude!

strongest test of separate universe approach to date

Summary

- Need extraordinarily accurate predictions to isolate new physics from large-scale structure data
- Separate universe/response method:
  - Provides clean predictions for "bias factors" and helps identify robust observables
  - Allows one to simulate a limited set of important observables in cosmologies with multiple fluids and non-gravitational forces
  - Allows one to compute bias of more general observables
  - Survives very strong tests!