BERKELEY CENTER *for*
COSMOLOGICAL PHYSICS

Towards detecting neutrino mass using non-linear cosmic structure

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COSMOLOGICAL PHYSICS

Outline

- Introduction
- Cosmological simulations with massive neutrinos
- Non-linear information in the matter field
- Towards optimal constraints
- Where does neutrino mass information come from?

INTRODUCTION

Evidence for massive neutrinos

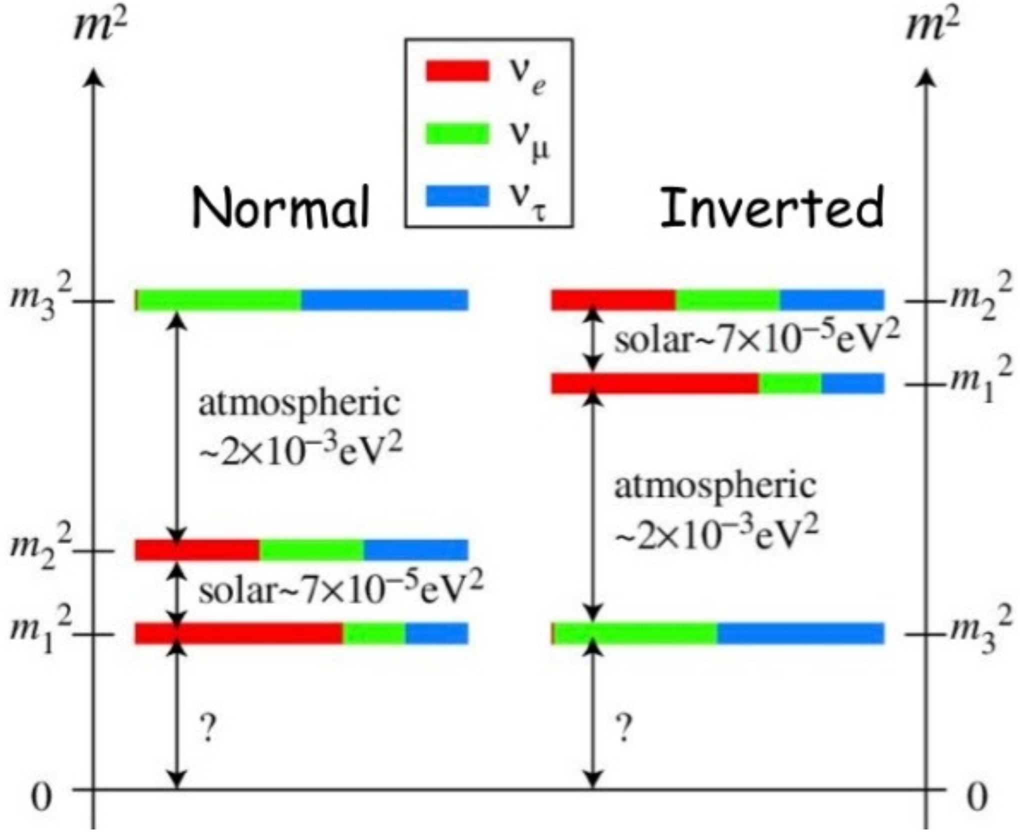
SOLAR NETRINOS:

Only 1/3 of expected solar neutrinos are electron neutrinos

ATMOSPHERIC NETRINOS:

Neutrino flux different in upward and downward direction

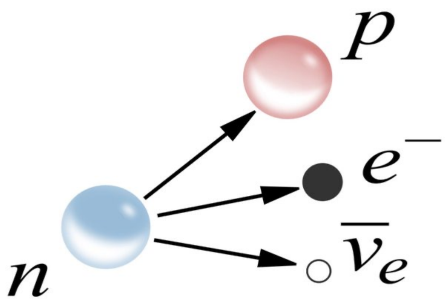
- Implies neutrinos can change flavor (oscillate)
- Requires neutrinos to have mass



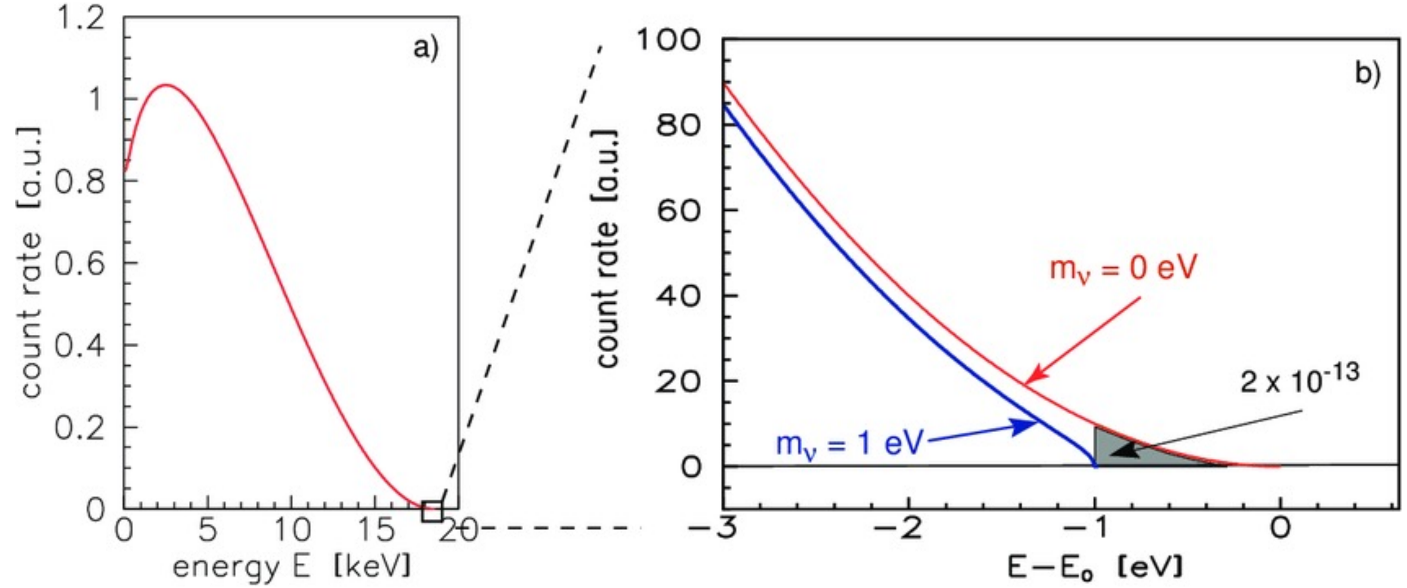
$M_\nu > 0.06$eV $M_\nu > 0.1$eV

Measuring neutrino mass using beta decay

- Massive neutrinos change maximum electron energy in beta decay

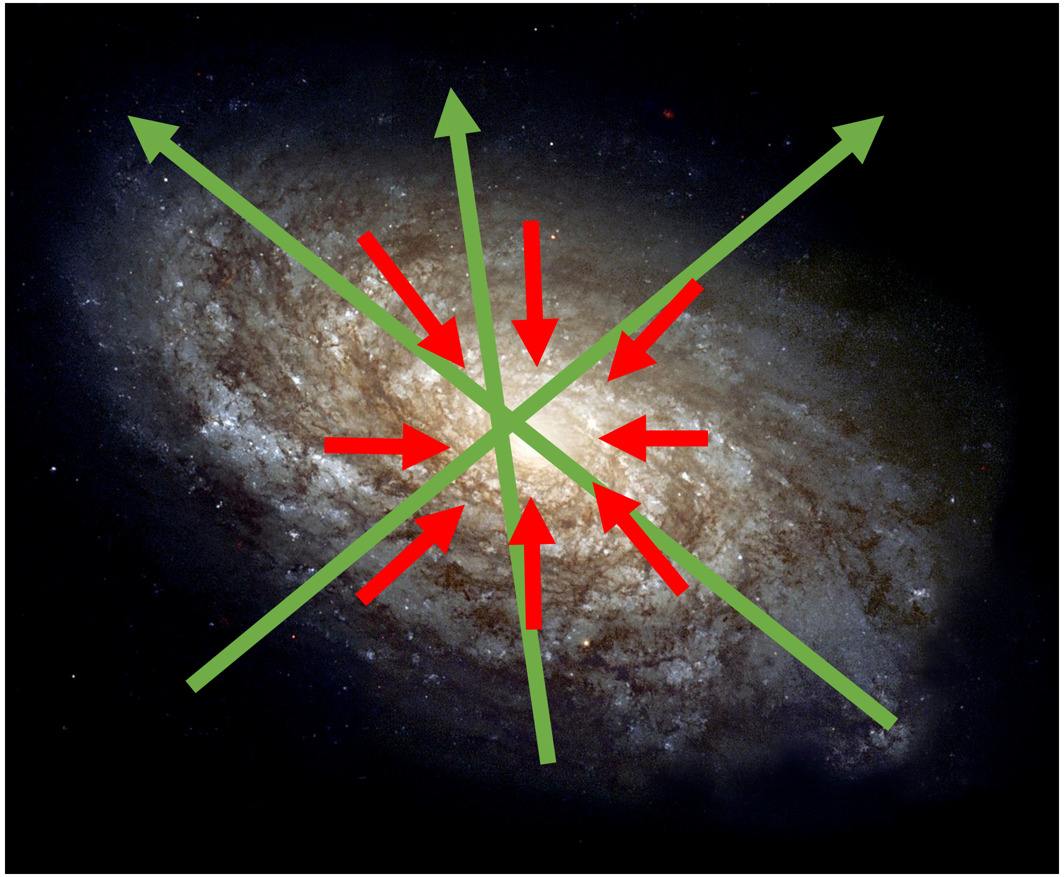


- Upper bound from **KATRIN**: $m_{\bar{\nu}_e}^{eff} < 0.8$eV (90% CL).
- Lower bound from **theory**: $M_\nu > 0.06$eV
- Can **cosmology** bridge the gap?



Why cosmology?

- Neutrinos produced in Big Bang
- Neutrinos have low mass and thus high thermal velocities compared to cold dark matter
- Difficult for gravity to make neutrinos cluster
- Neutrino mass causes reduction of structure formation on small scales



Cold Dark Matter **Neutrinos**

Cosmological correlation function

- Measure correlation between overdensity at different points in space

$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$$

$$\xi_2(|\mathbf{x}_1 - \mathbf{x}_2|) = \langle \delta(\mathbf{x}_1)\delta(\mathbf{x}_2) \rangle$$

- Massive neutrino effect will be seen on small scales

Linear theory

MASSIVE NEUTRINOS suppress small scale power

LINEAR CONSTRAINTS:

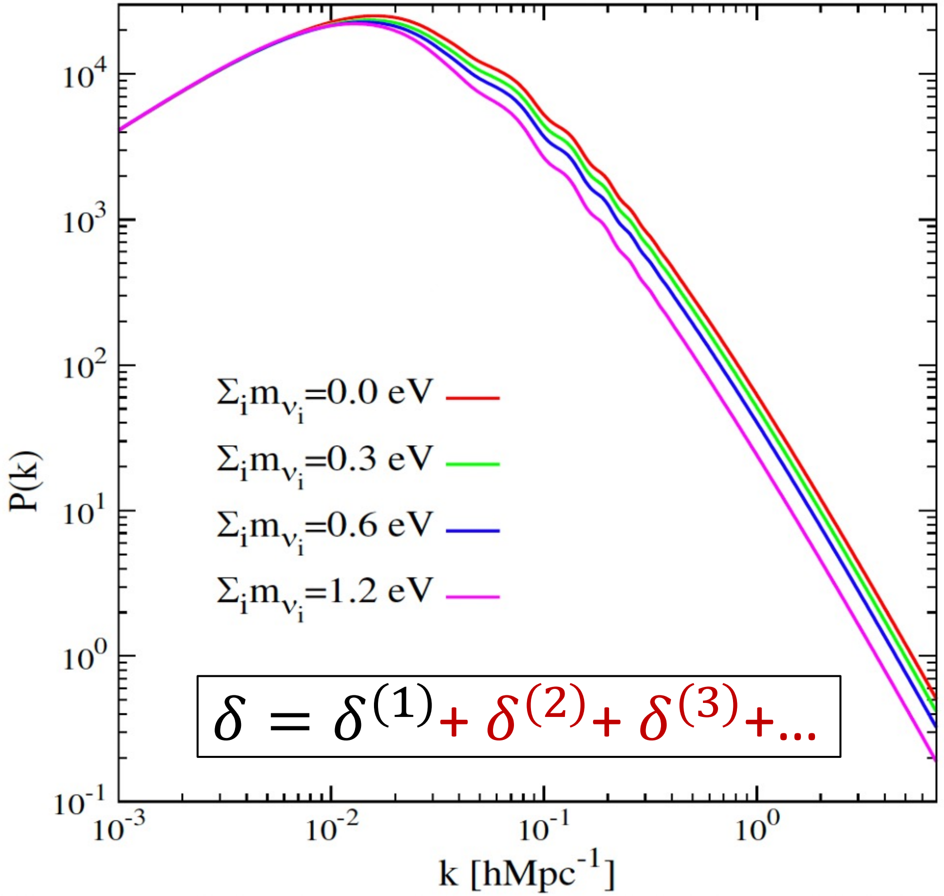
- Planck 2018 (95%): 0.26 eV,

  \+ BAO: 0.13 eV,

  \+ CMB lensing: 0.12 eV.
- CMB STAGE IV + LSST: 0.02 eV

BUT

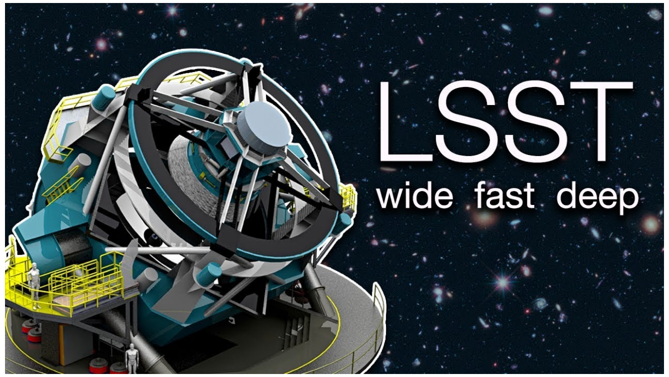
- Gravity causes non-linearities on small scales
- Is there more information in the **nonlinear regime**?

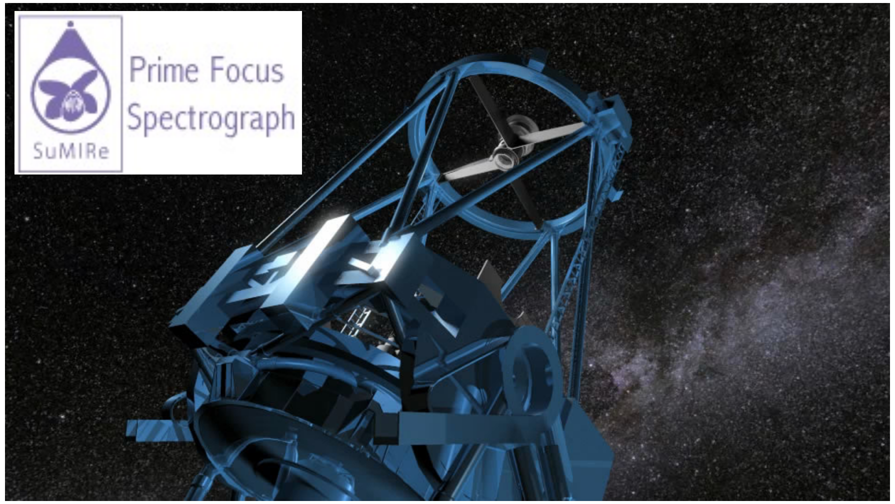


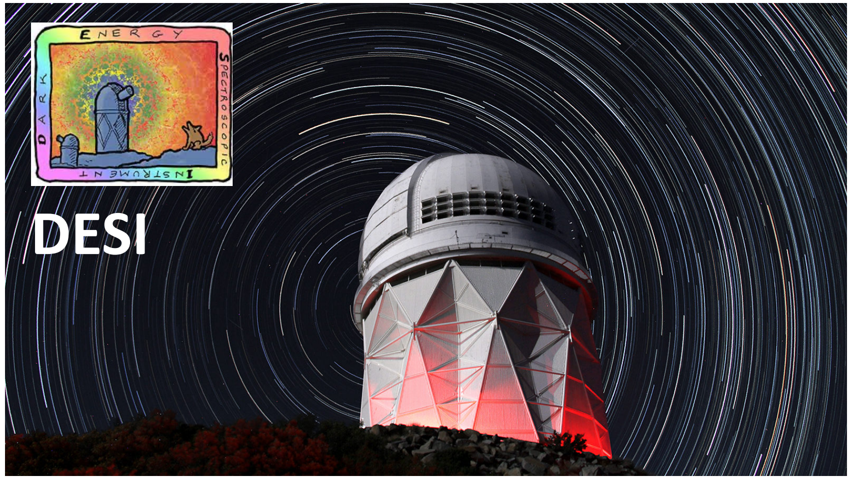
$$\delta = \delta^{(1)} + \delta^{(2)} + \delta^{(3)} + \ldots$$

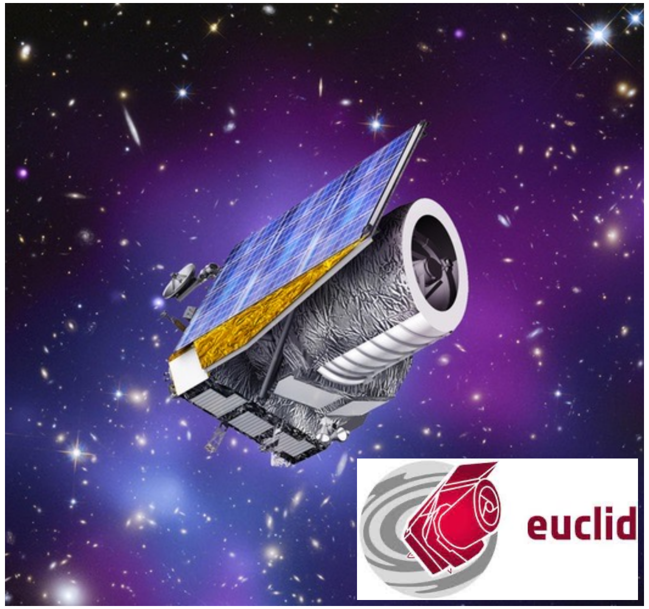
smaller scales
more non-linearity

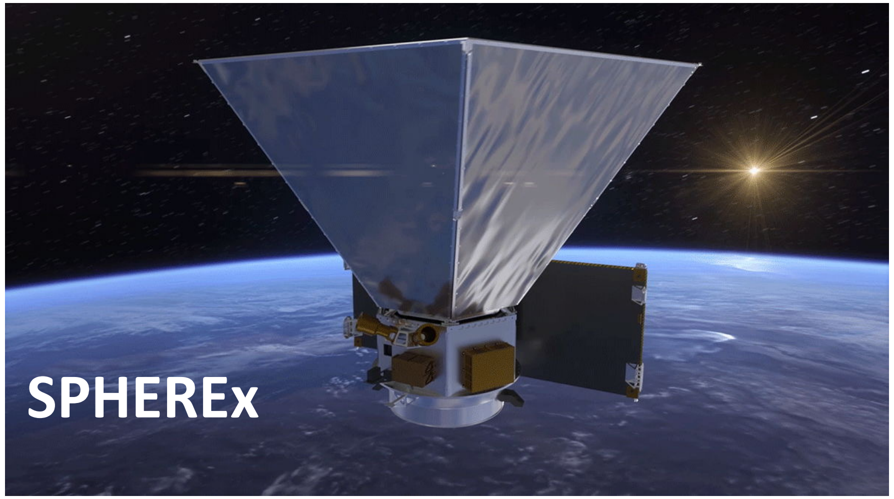
Many galaxy surveys will probe small scales





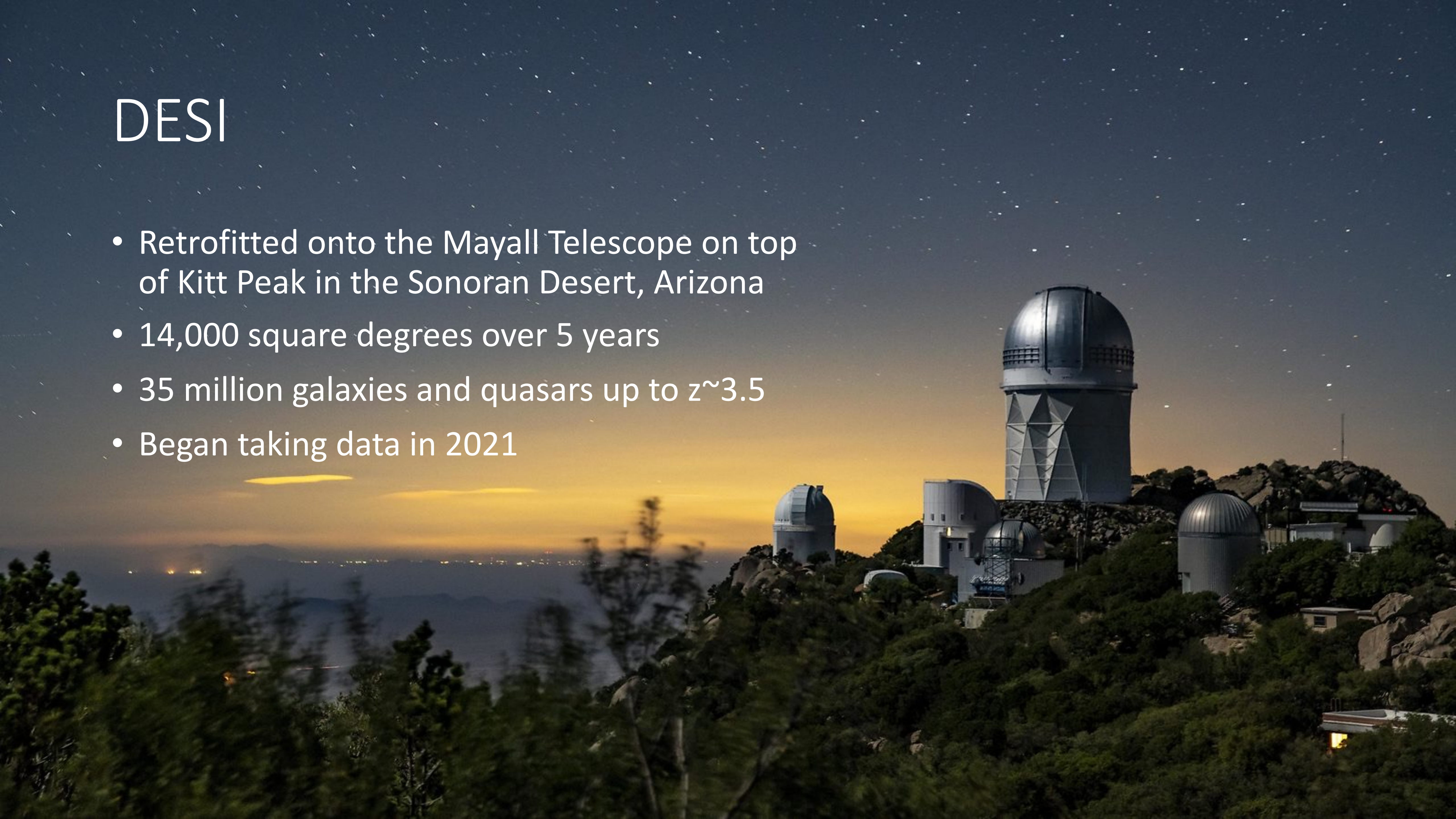






DESI

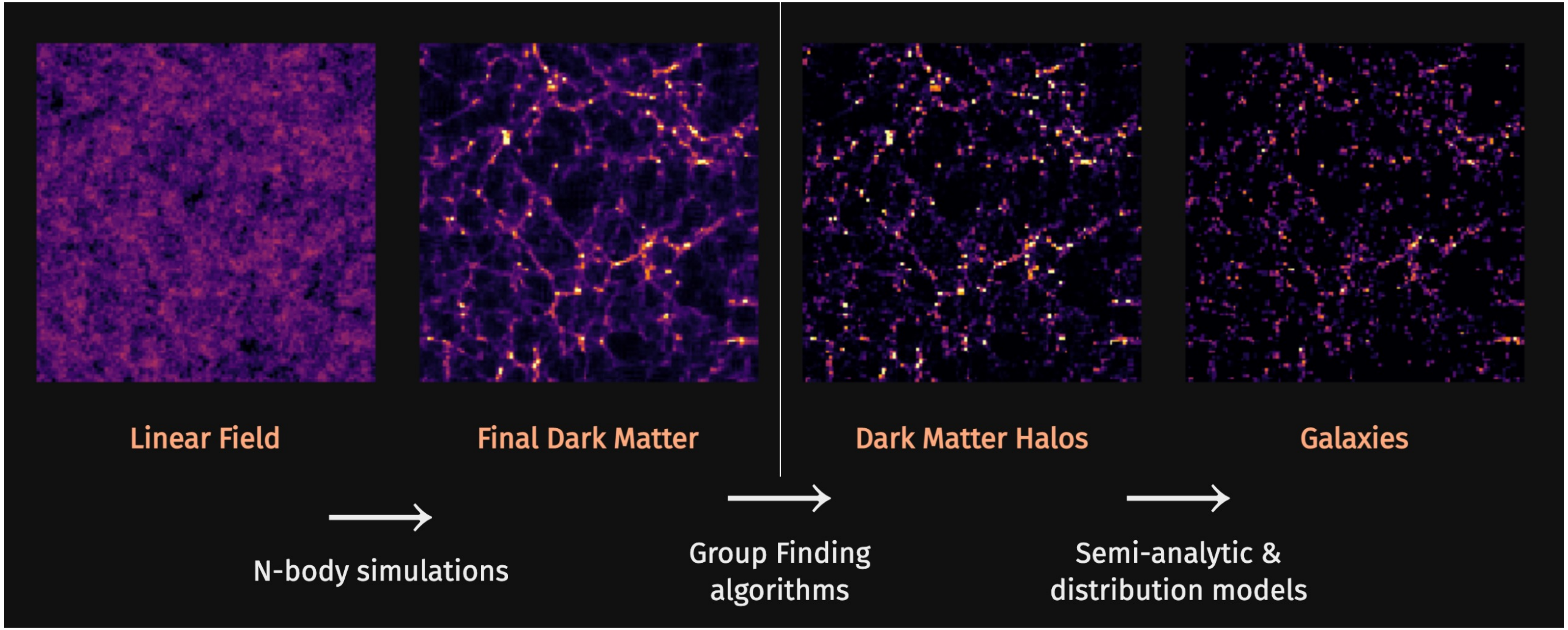
- Retrofitted onto the Mayall Telescope on top of Kitt Peak in the Sonoran Desert, Arizona
- 14,000 square degrees over 5 years
- 35 million galaxies and quasars up to z~3.5
- Began taking data in 2021



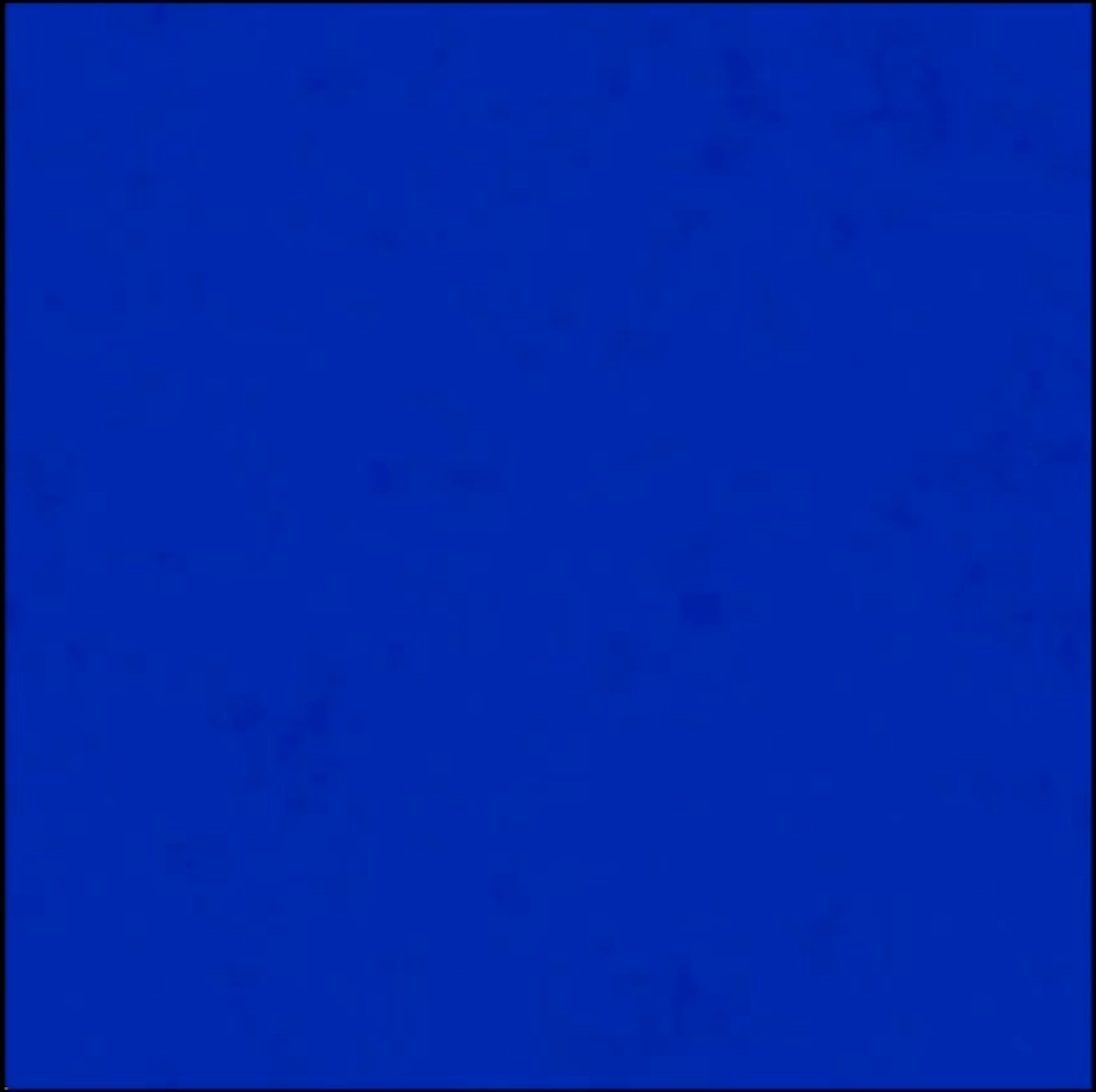
COSMOLOGICAL SIMULATIONS

Simulating non-linear structure formation

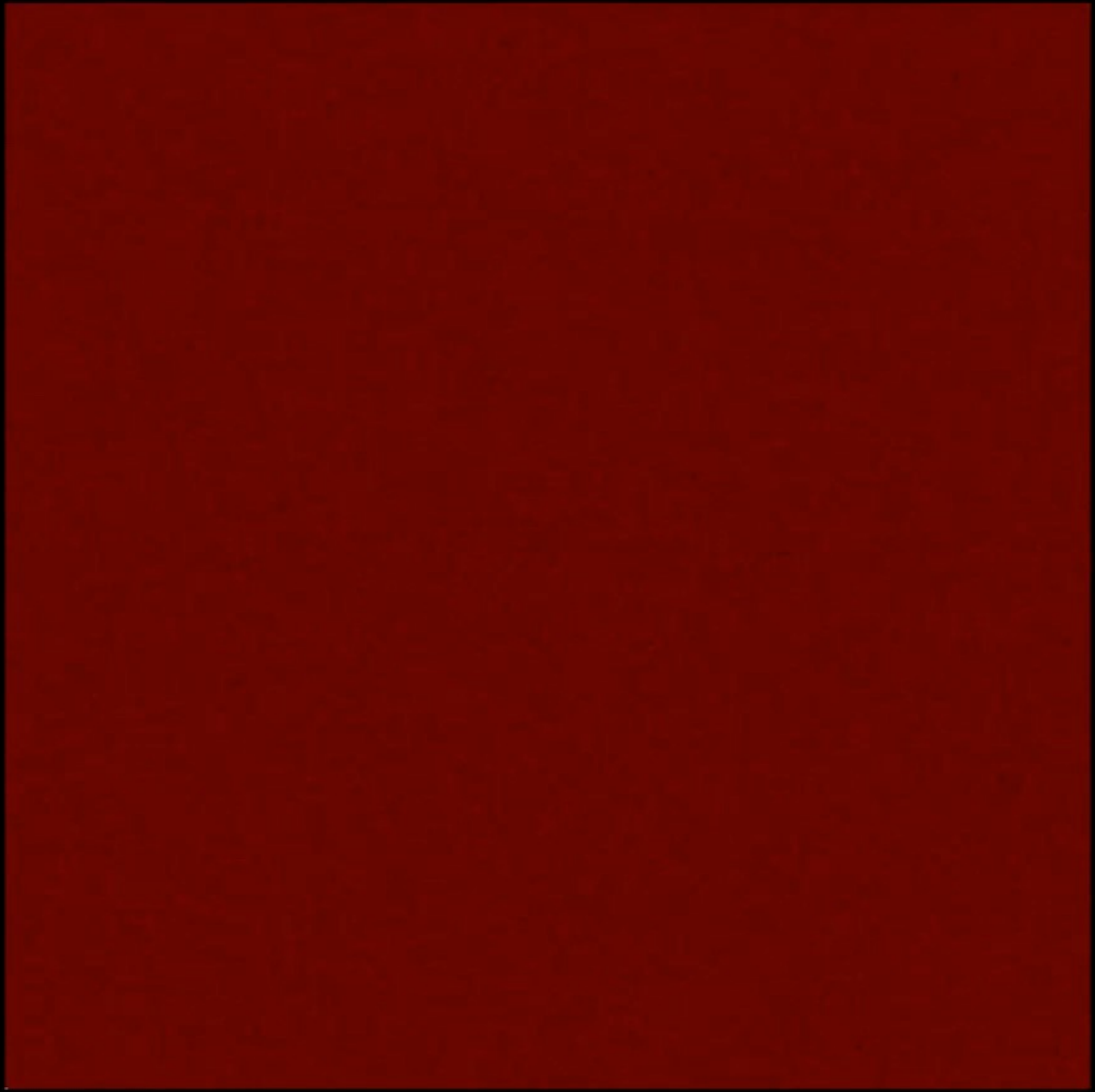
- Initialize particles at high redshift where perturbations are approximately linear, then allow particles to evolve under gravity, then compute observables



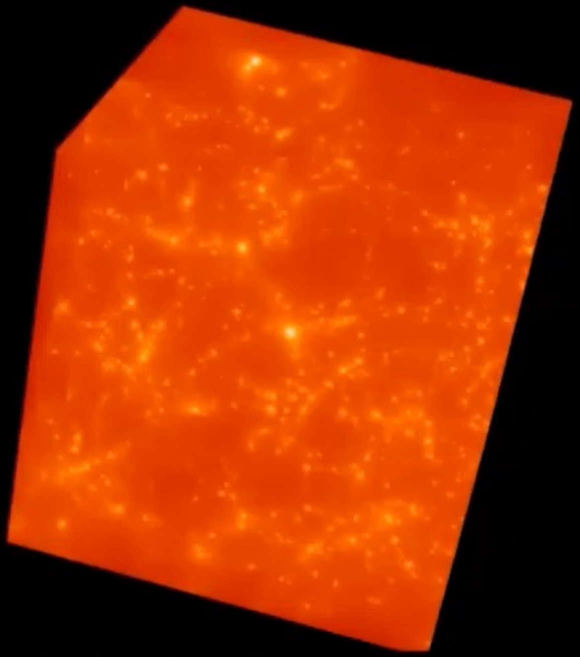
Dark Matter



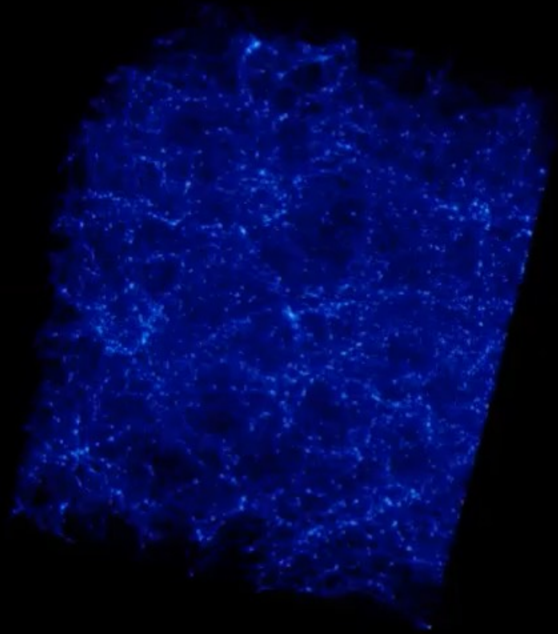
Neutrino



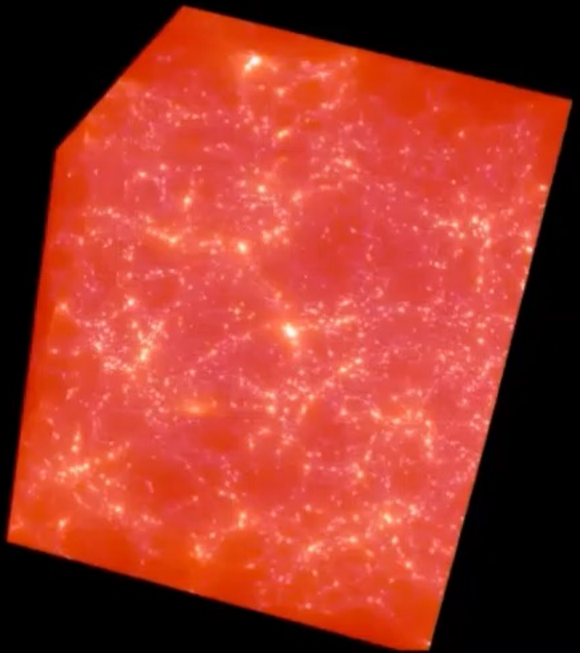
a=0.02



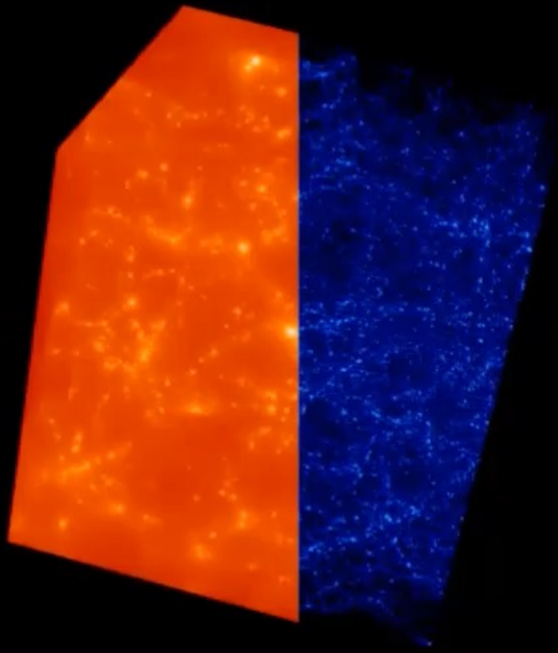
Neutrino



Dark Matter



Blending Neutrino and Dark Matter

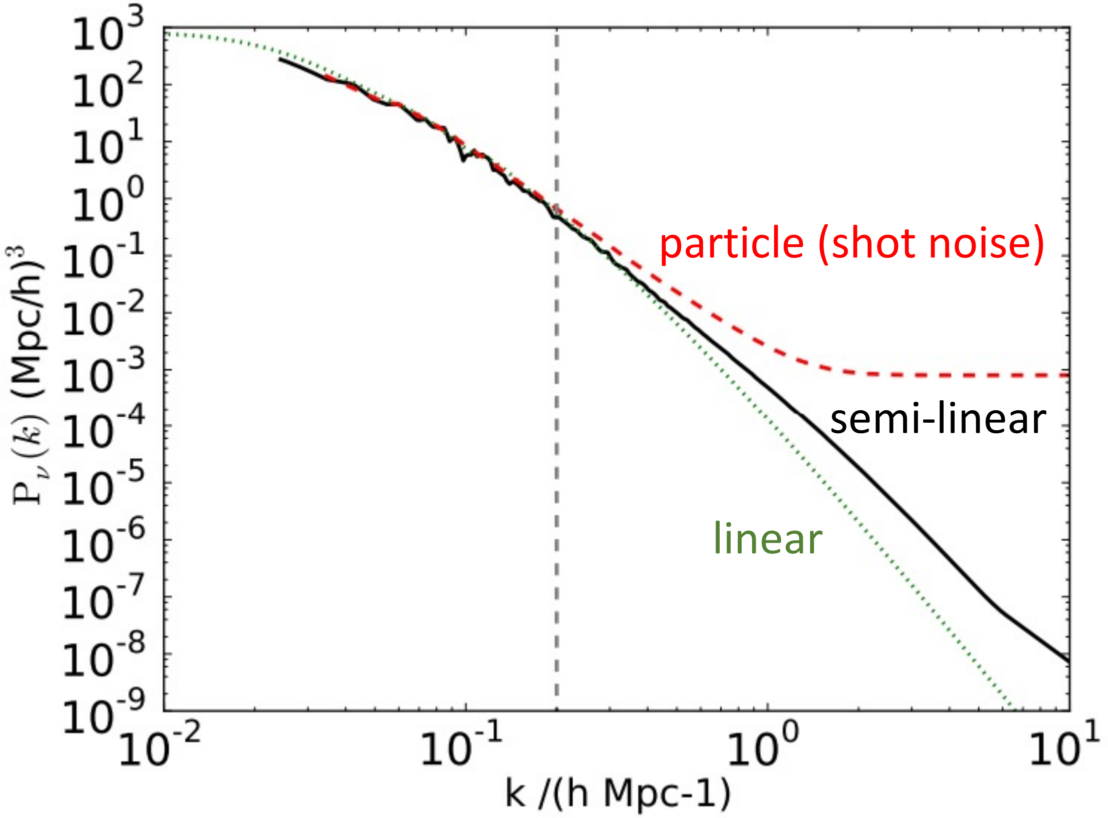


Cropping Neutrino and Dark Matter

Including neutrinos in N-body simulations

- Using particles suffers from shot noise, which is inversely related to the number of neutrino particles

- Cheap way to reduce shot noise
  Banerjee+2018, Bayer+2021



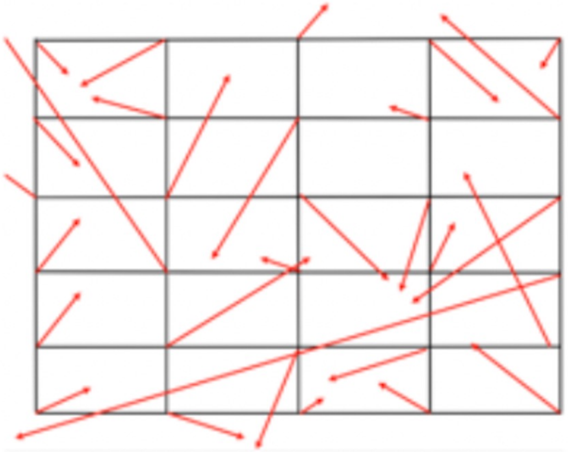
- Various other methods:

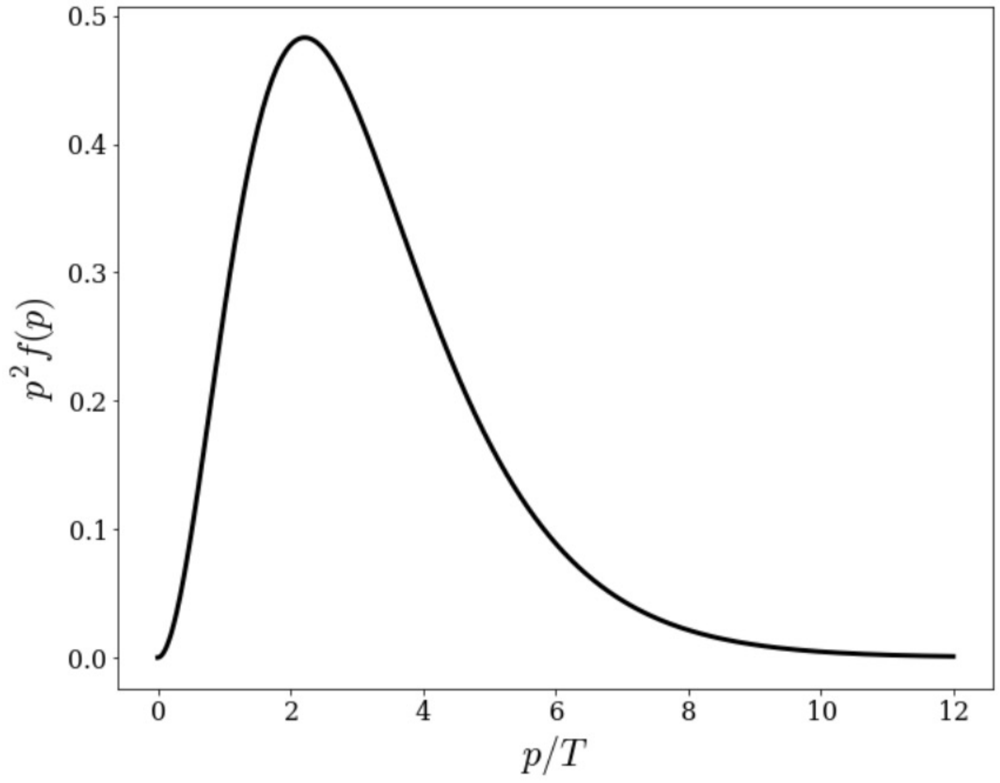
Semi-linear approximations (Bird+2012), Hybrid approach (Bird+2018), Poisson-Vlassov (Yoshikawa+2020)

Shot noise arises from randomness

- The origin of shot noise is the **random** sampling of the Fermi-Dirac distribution for the initial velocities

$$f(\mathbf{p}) = \frac{4\pi g_\nu}{(2\pi\hbar)^3}\frac{1}{e^{\frac{pc}{k_B T_\nu (1+z)}}+1}$$

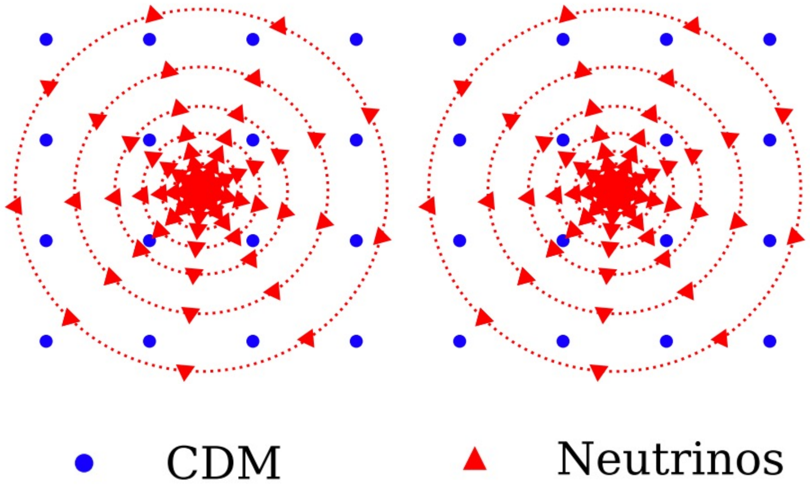


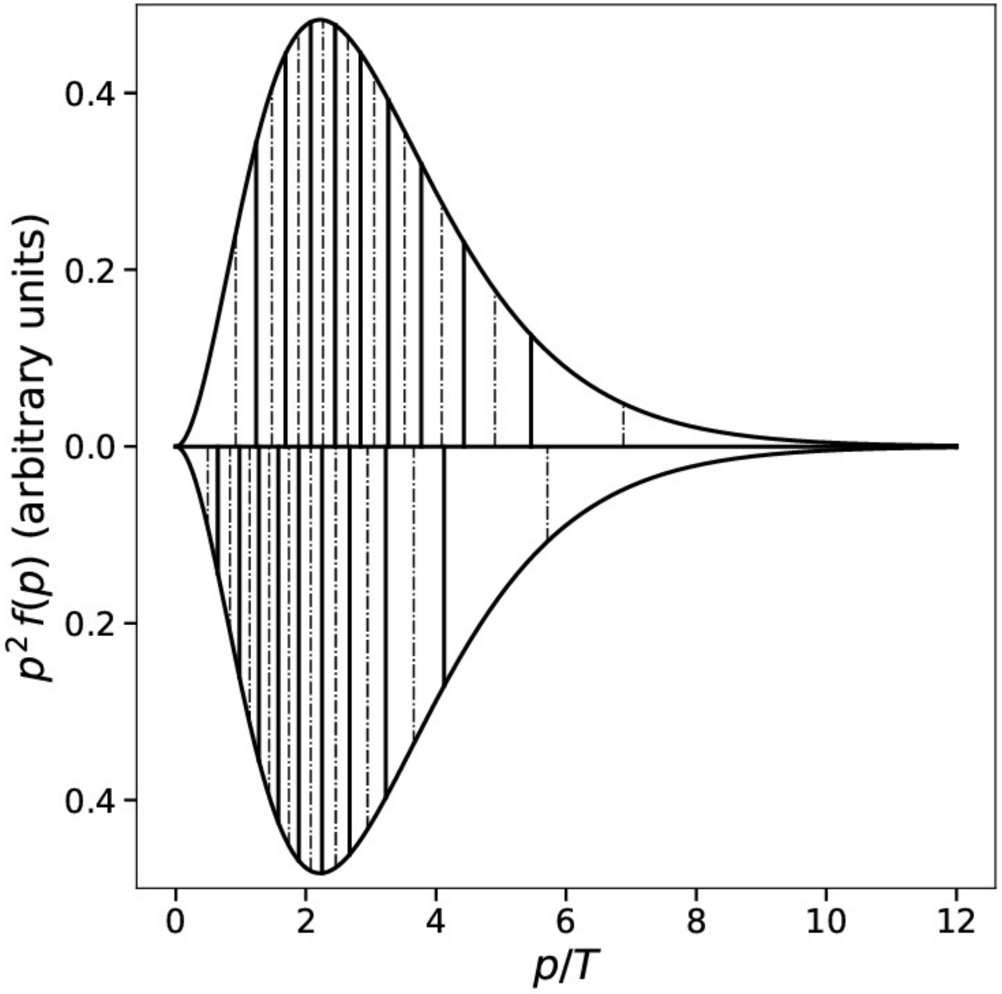


Reducing shot noise

Bayer, Banerjee, Feng (2021)

- Use “ordered” sampling (Banerjee+2018)
- Can extend to small scales by spreading out neutrino particles





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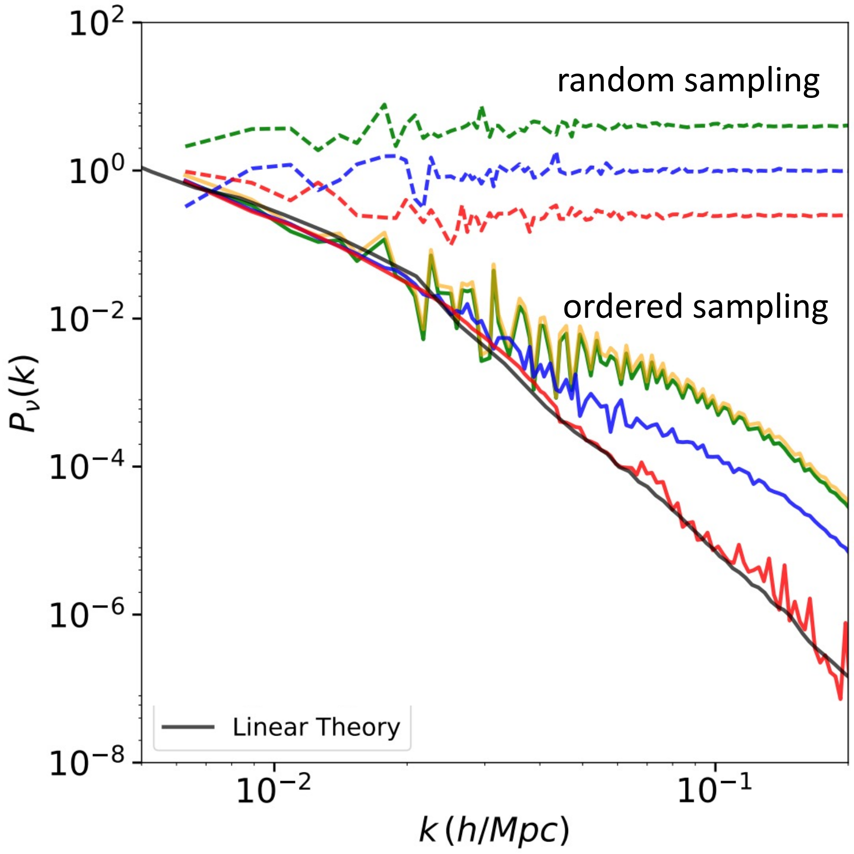
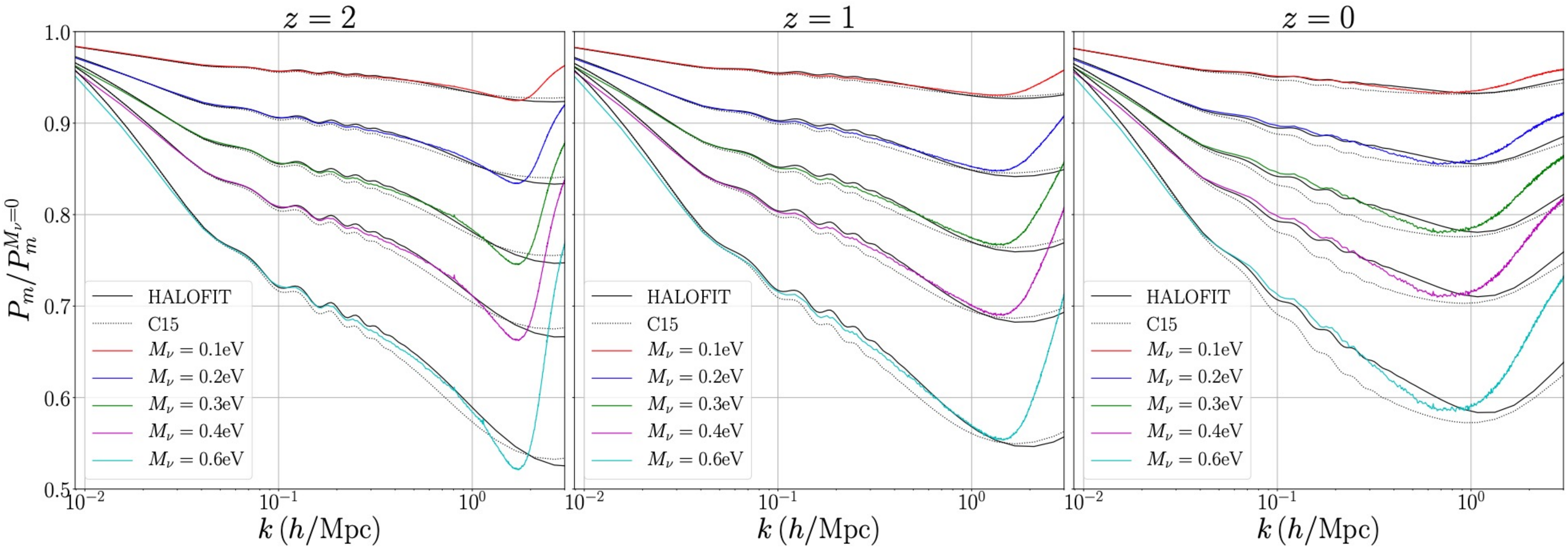


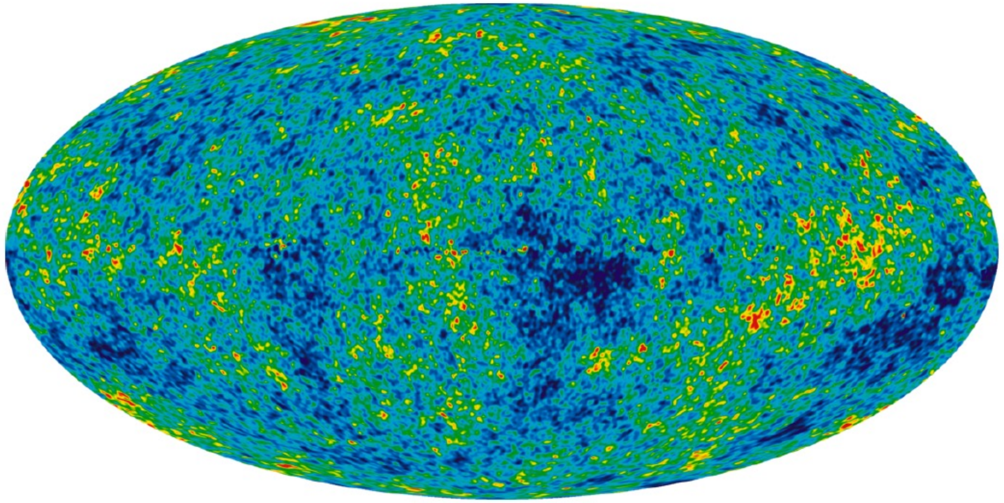
Implemented in FastPM

Bayer, Banerjee, Feng (2021)

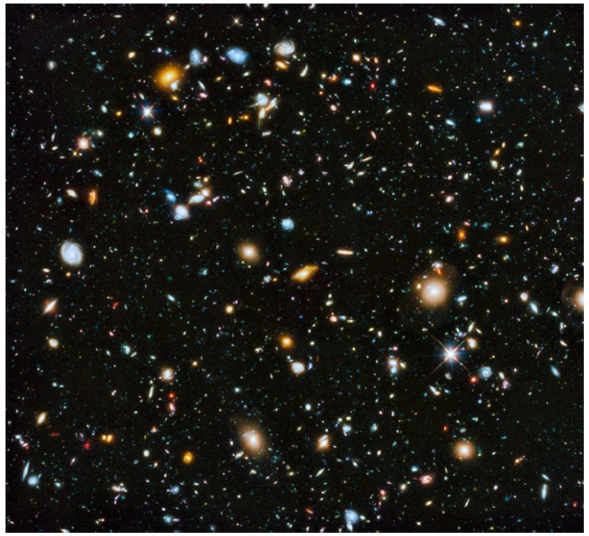


NON-LINEAR INFORMATION IN THE MATTER FIELD

Information from non-linearities



Gaussian density field
Fully described by the power spectrum



Non-Gaussian density field
Mathematically “intractable”
P(k), B(k), peaks, voids, …

Fisher Information

$$\mathrm{F}_{\alpha\beta} = \frac{\partial \vec{d}}{\partial \theta_\alpha} C^{-1} \frac{\partial \vec{d}}{\partial \theta_\beta}$$

$\vec{d}$ is the vector with the data
$\vec{d} = \{\mathrm{P}(\mathrm{k}_0), \mathrm{P}(\mathrm{k}_1), \mathrm{P}(\mathrm{k}_2) \ldots \mathrm{P}(\mathrm{k}_n), \ldots\}$

$\vec{\theta}$ is the vector with the model parameters
$\vec{\theta} = \{\Omega_m, \Omega_b, h, n_s, \sigma_8, M_\nu\}$

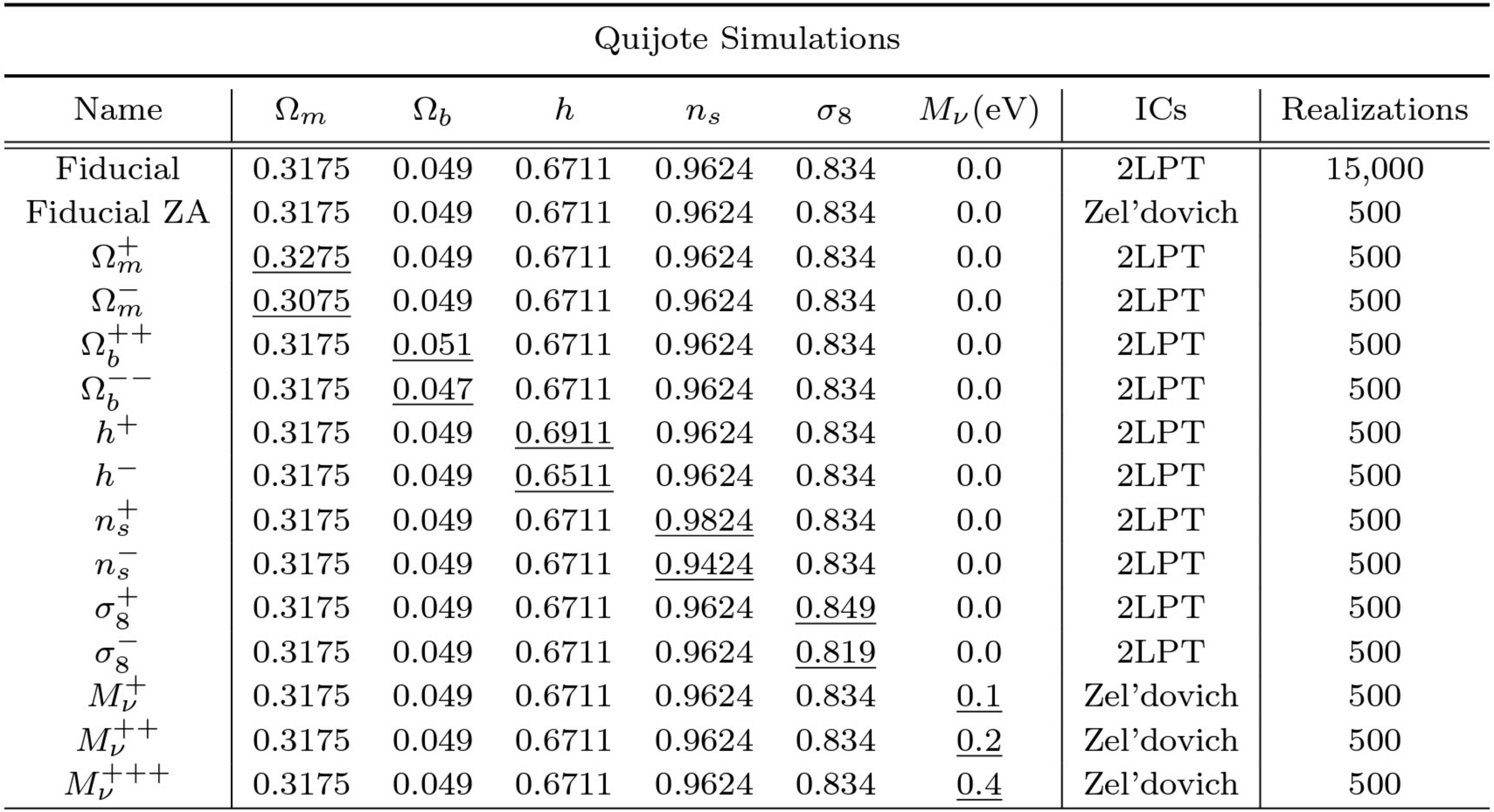
$$\delta\theta_\alpha \geq \frac{1}{\sqrt{(F^{-1})_{\alpha\alpha}}}$$

The Quijote Simulations

Villaescusa-Navarro, et al. (2020)

1 $(\mathrm{Gpc}/h)^3$

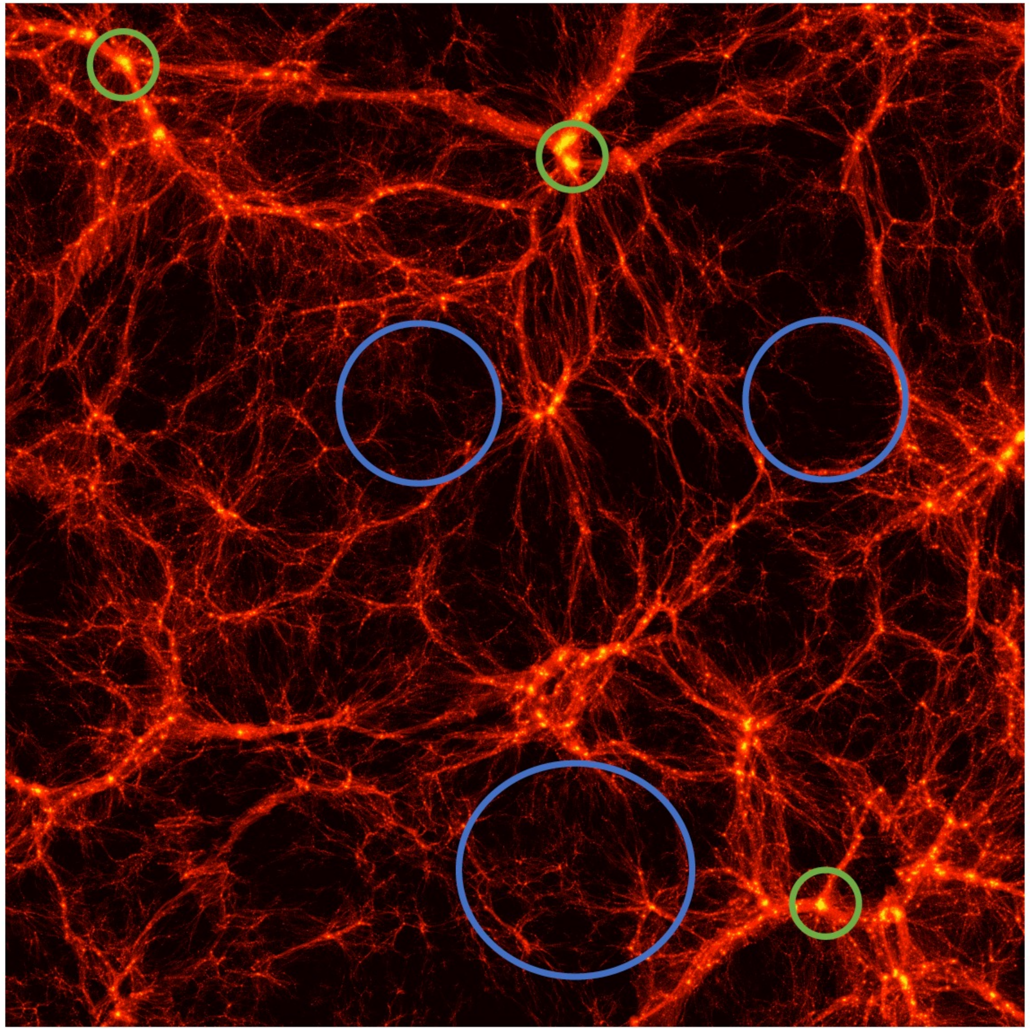
512^3 particles



Quijote Simulations

Name	Ω_m	Ω_b	h	n_s	σ_8	M_ν(eV)	ICs	Realizations
Fiducial	0.3175	0.049	0.6711	0.9624	0.834	0.0	2LPT	15,000
Fiducial ZA	0.3175	0.049	0.6711	0.9624	0.834	0.0	Zel'dovich	500
Ω_m^+	0.3275	0.049	0.6711	0.9624	0.834	0.0	2LPT	500
Ω_m^-	0.3075	0.049	0.6711	0.9624	0.834	0.0	2LPT	500
Ω_b^{++}	0.3175	0.051	0.6711	0.9624	0.834	0.0	2LPT	500
Ω_b^{--}	0.3175	0.047	0.6711	0.9624	0.834	0.0	2LPT	500
h^+	0.3175	0.049	0.6911	0.9624	0.834	0.0	2LPT	500
h^-	0.3175	0.049	0.6511	0.9624	0.834	0.0	2LPT	500
n_s^+	0.3175	0.049	0.6711	0.9824	0.834	0.0	2LPT	500
n_s^-	0.3175	0.049	0.6711	0.9424	0.834	0.0	2LPT	500
σ_8^+	0.3175	0.049	0.6711	0.9624	0.849	0.0	2LPT	500
σ_8^-	0.3175	0.049	0.6711	0.9624	0.819	0.0	2LPT	500
M_ν^+	0.3175	0.049	0.6711	0.9624	0.834	0.1	Zel'dovich	500
M_ν^{++}	0.3175	0.049	0.6711	0.9624	0.834	0.2	Zel'dovich	500
M_ν^{+++}	0.3175	0.049	0.6711	0.9624	0.834	0.4	Zel'dovich	500

Can study specific non-linear statistics

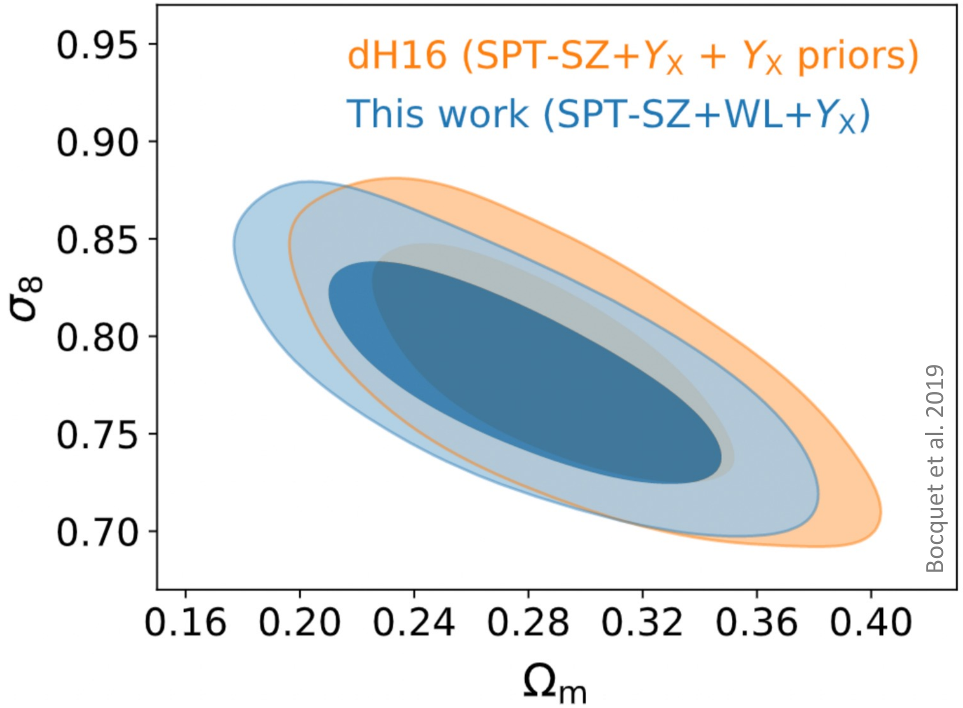


HMF
(Halo Mass Function)

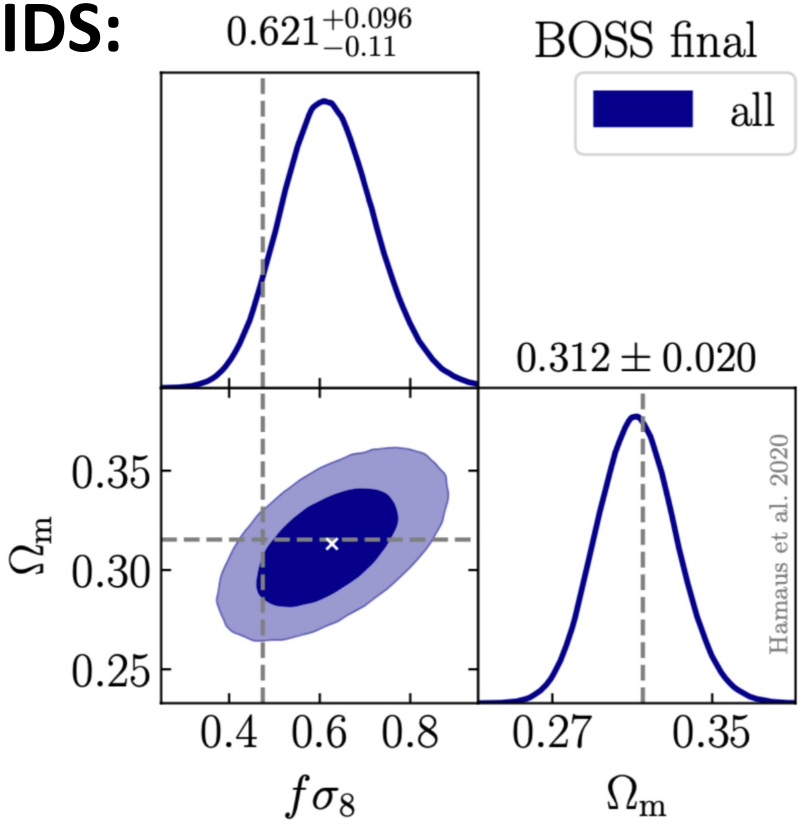
VSF
(Void Size Function)

Both have been used with real data to constrain cosmology

HALOS:

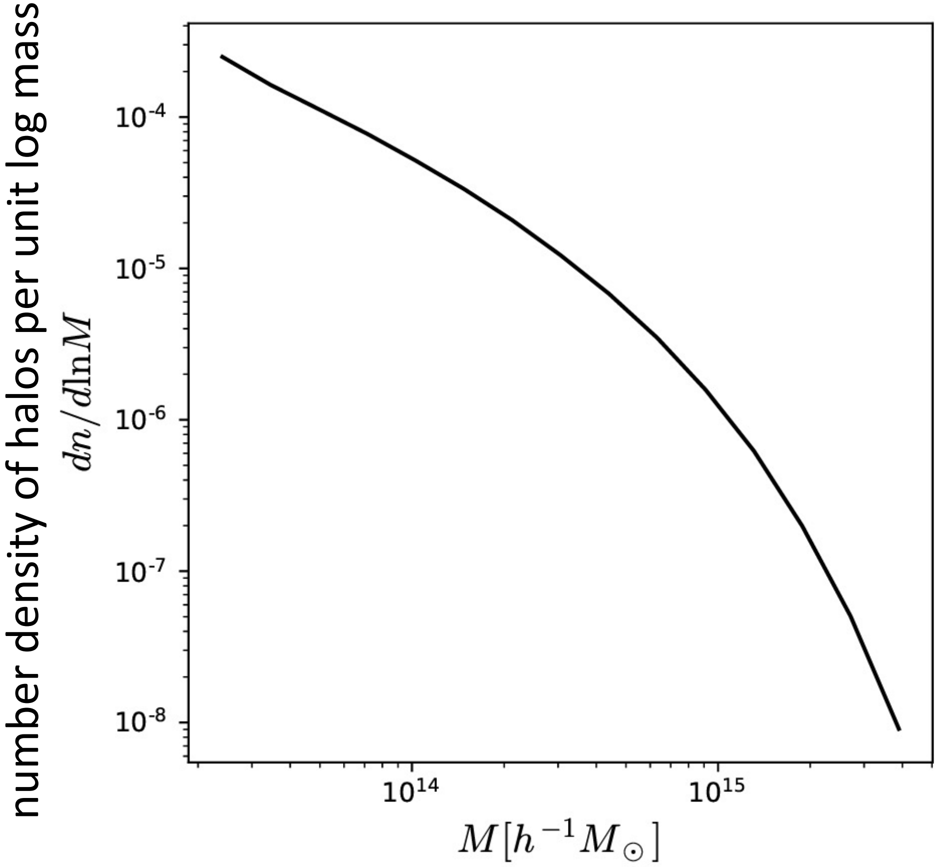


VOIDS:

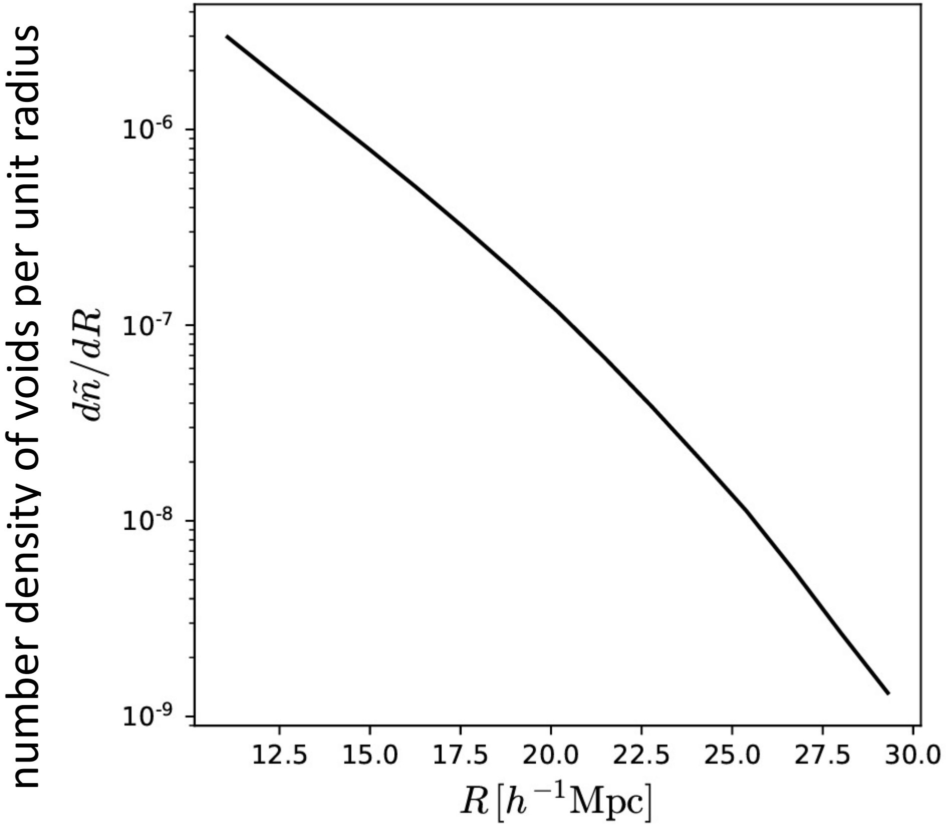


What do they look like?

HALO MASS FUNCTION:



VOID SIZE FUNCTION:

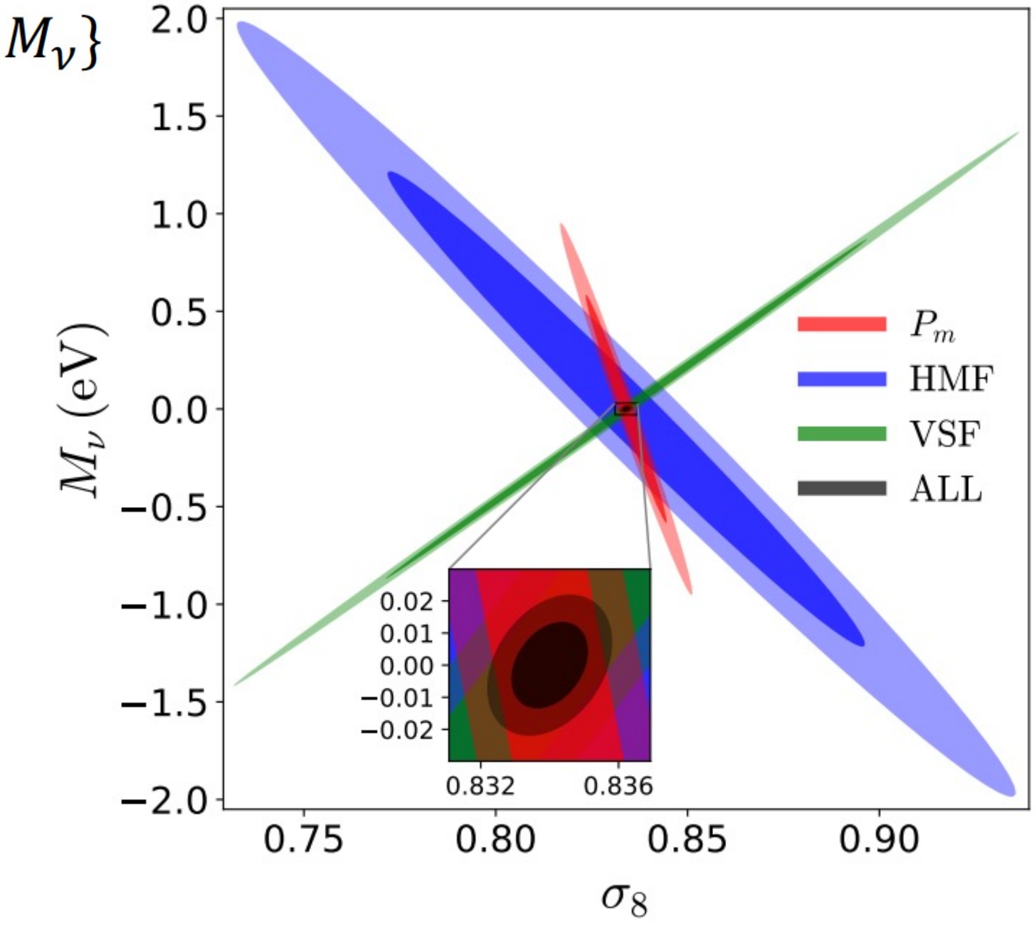


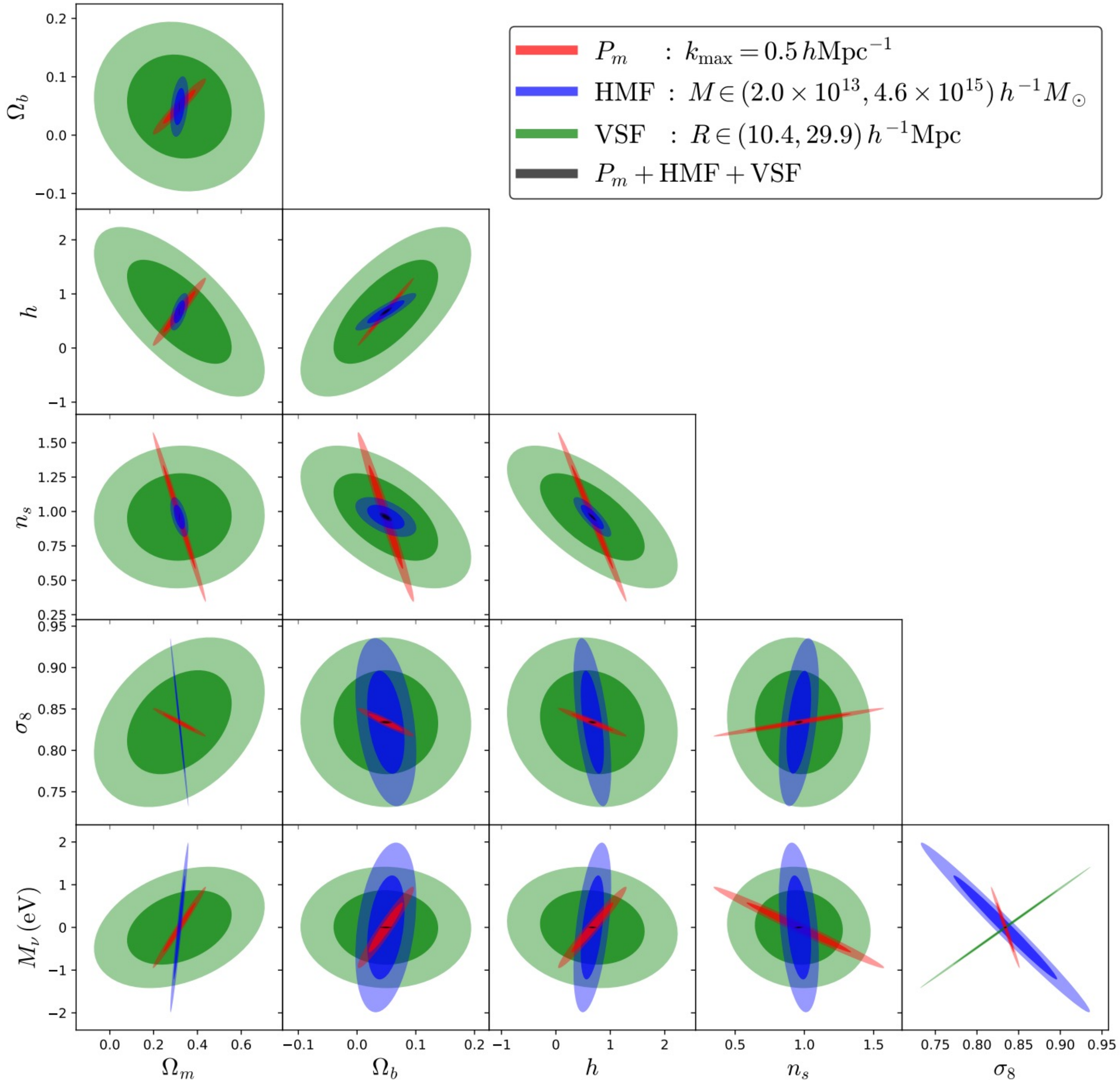
Fisher Analysis

Bayer, Villaescusa-Navarro, Massara, Liu, Spergel, et al. (2021)

- Combine matter clustering, halos, and voids
- Consider 6d parameter space: $\{\Omega_m, \Omega_b, h, n_s, \sigma_8, M_\nu\}$
- Strong degeneracy breaking
- For 1 (Gpc/h)^3
  - 0.77 eV using power spectrum only
  - 0.018 eV from combination
  - Factor 43 improvement!

🟥 P_m : $k_{\mathrm{max}} = 0.5\,h\mathrm{Mpc}^{-1}$
🟦 HMF : $M \in (2.0 \times 10^{13}, 4.6 \times 10^{15})\,h^{-1}M_\odot$
🟩 VSF : $R \in (10.4, 29.9)\,h^{-1}\mathrm{Mpc}$
⬛ $P_m + \mathrm{HMF} + \mathrm{VSF}$

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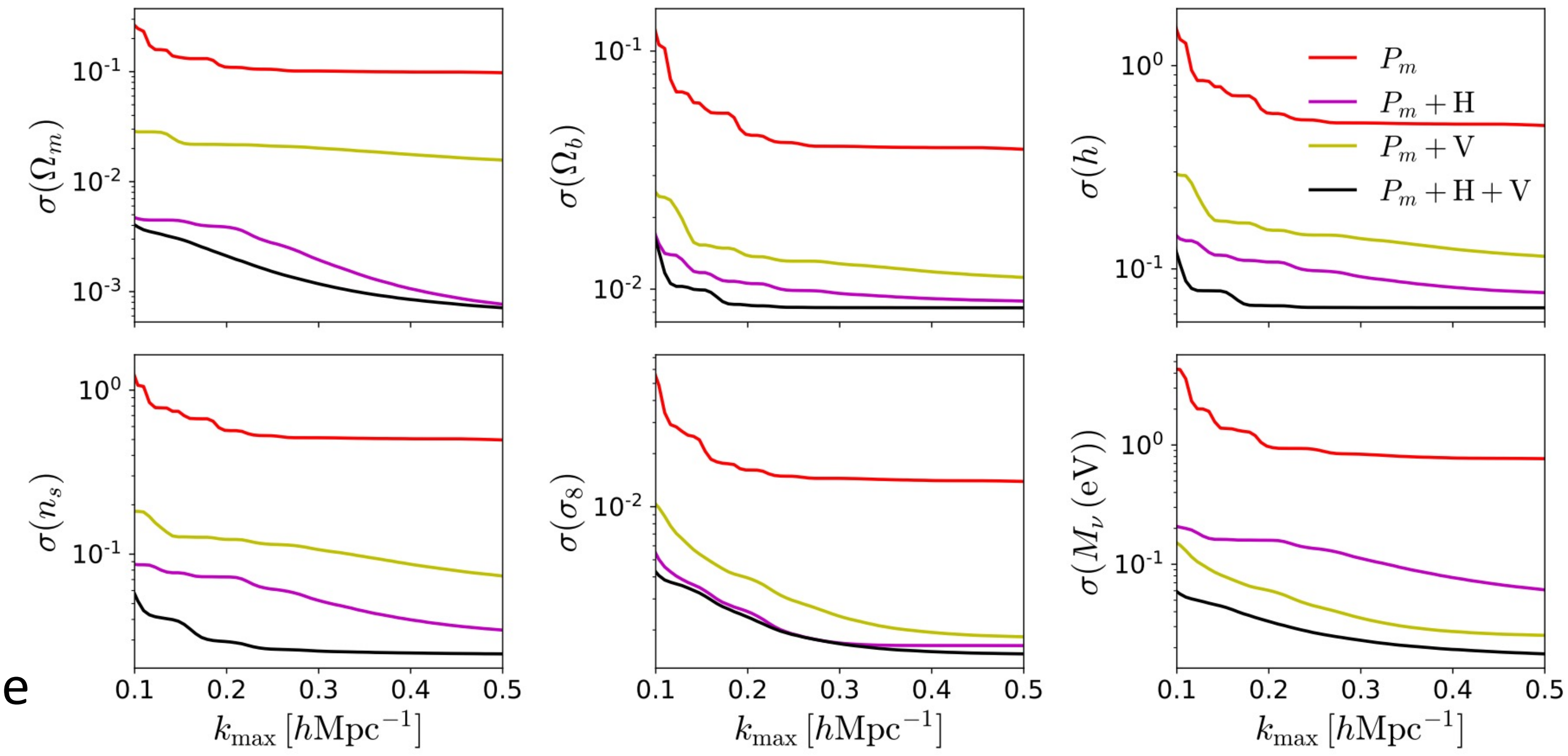
HMF : $M \in (2.0\times10^{13}, 4.6\times10^{15})\,h^{-1}M_\odot$
VSF : $R \in (10.4, 29.9)\,h^{-1}{\rm Mpc}$
$P_m + {\rm HMF} + {\rm VSF}$
Ω_b
0.2
0.1
0.0
−0.1
h
2
1
0
−1
n_s
1.50
1.25
1.00
0.75
0.50
0.25
σ_8
0.95
0.90
0.85
0.80
0.75
M_ν (eV)
2
1
0
−1
−2
0.0
0.2
0.4
0.6
Ω_m
−0.1
0.0
0.1
0.2
Ω_b
−1
0
1
2
h
0.5
1.0
1.5
n_s
0.75
0.80
0.85
0.90
0.95
σ_8

The power of small scales

Bayer, Villaescusa-Navarro, Massara, Liu, Spergel, et al. (2021)

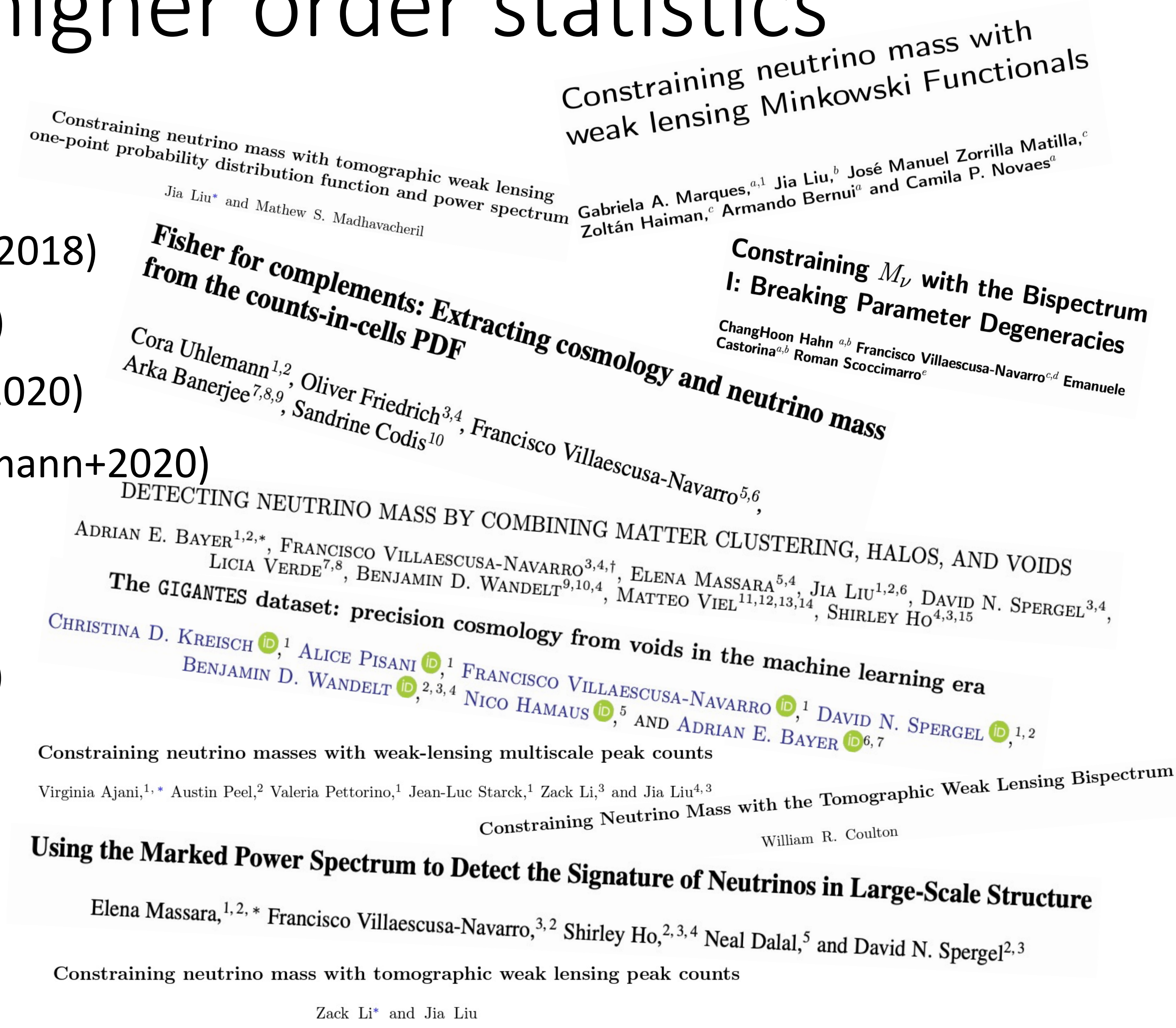
- Power spectrum saturates, but other probes do not

- Caveats:
  - Halos, lensing
  - Baryonic effects
  - Systematic noise
  - Super-sample variance



Many proposals for higher order statistics

- Lensing bispectrum (Coulton+2018)
- Lensing Minkowski functionals (Marques+2018)
- Lensing peak counts (Li+2018, Ajani+2020)
- Lensing probability density function (Liu+2020)
- Matter probability density function (Uhlemann+2020)
- Redshift-space bispectrum (Hahn+2020)
- Marked power spectrum (Massara+2021)
- Wavelets (Cheng+2021, Valogiannis+2021)
- Voids (Bayer+2021, Kreisch+2021)
- …



Constraining neutrino mass with weak lensing Minkowski Functionals

Gabriela A. Marques,[a,1] Jia Liu,[b] José Manuel Zorrilla Matilla,[c] Zoltán Haiman,[c] Armando Bernui[a] and Camila P. Novaes[a]

Constraining neutrino mass with tomographic weak lensing one-point probability distribution function and power spectrum

Jia Liu[*] and Mathew S. Madhavacheril

Fisher for complements: Extracting cosmology and neutrino mass from the counts-in-cells PDF

Cora Uhlemann[1,2], Oliver Friedrich[3,4], Francisco Villaescusa-Navarro[5,6], Arka Banerjee[7,8,9], Sandrine Codis[10]

Constraining M_ν with the Bispectrum I: Breaking Parameter Degeneracies

ChangHoon Hahn[a,b] Francisco Villaescusa-Navarro[c,d] Emanuele Castorina[a,b] Roman Scoccimarro[e]

DETECTING NEUTRINO MASS BY COMBINING MATTER CLUSTERING, HALOS, AND VOIDS

Adrian E. Bayer[1,2,*], Francisco Villaescusa-Navarro[3,4,†], Elena Massara[5,4], Jia Liu[1,2,6], David N. Spergel[3,4], Licia Verde[7,8], Benjamin D. Wandelt[9,10,4], Matteo Viel[11,12,13,14], Shirley Ho[4,3,15]

The GIGANTES dataset: precision cosmology from voids in the machine learning era

Christina D. Kreisch[1], Alice Pisani[1], Francisco Villaescusa-Navarro[1] David N. Spergel[1,2] Benjamin D. Wandelt[2,3,4], Nico Hamaus[5] and Adrian E. Bayer[6,7]

Constraining neutrino masses with weak-lensing multiscale peak counts

Virginia Ajani,[1,*] Austin Peel,[2] Valeria Pettorino,[1] Jean-Luc Starck,[1] Zack Li,[3] and Jia Liu[4,3]

Constraining Neutrino Mass with the Tomographic Weak Lensing Bispectrum

William R. Coulton

Using the Marked Power Spectrum to Detect the Signature of Neutrinos in Large-Scale Structure

Elena Massara,[1,2,*] Francisco Villaescusa-Navarro,[3,2] Shirley Ho,[2,3,4] Neal Dalal,[5] and David N. Spergel[2,3]

Constraining neutrino mass with tomographic weak lensing peak counts

Zack Li[*] and Jia Liu

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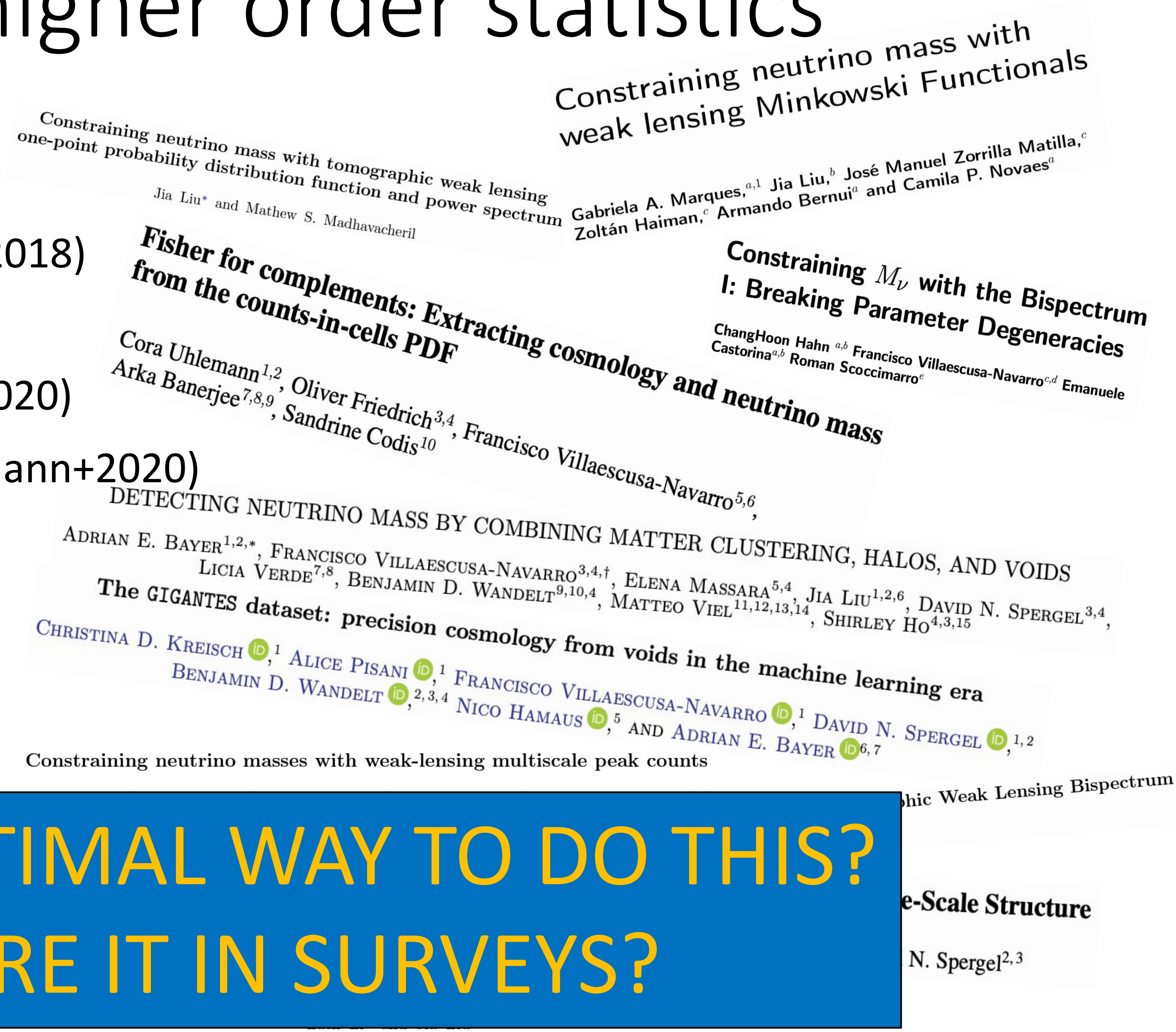
- Voids (Bayer+2021, Kreisch+2021)
- …



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Adrian E. Bayer[1,2,*], Francisco Villaescusa-Navarro[3,4,†], Elena Massara[5,4], Jia Liu[1,2,6], David N. Spergel[3,4], Licia Verde[7,8], Benjamin D. Wandelt[9,10,4], Matteo Viel[11,12,13,14], Shirley Ho[4,3,15]

The GIGANTES dataset: precision cosmology from voids in the machine learning era

Christina D. Kreisch[1], Alice Pisani[1], Francisco Villaescusa-Navarro[1], David N. Spergel[1,2], Benjamin D. Wandelt[2,3,4], Nico Hamaus[5] and Adrian E. Bayer[6,7]

Constraining neutrino masses with weak-lensing multiscale peak counts

hic Weak Lensing Bispectrum

e-Scale Structure

N. Spergel[2,3]

1. IS THERE AN OPTIMAL WAY TO DO THIS?

2. CAN WE MEASURE IT IN SURVEYS?

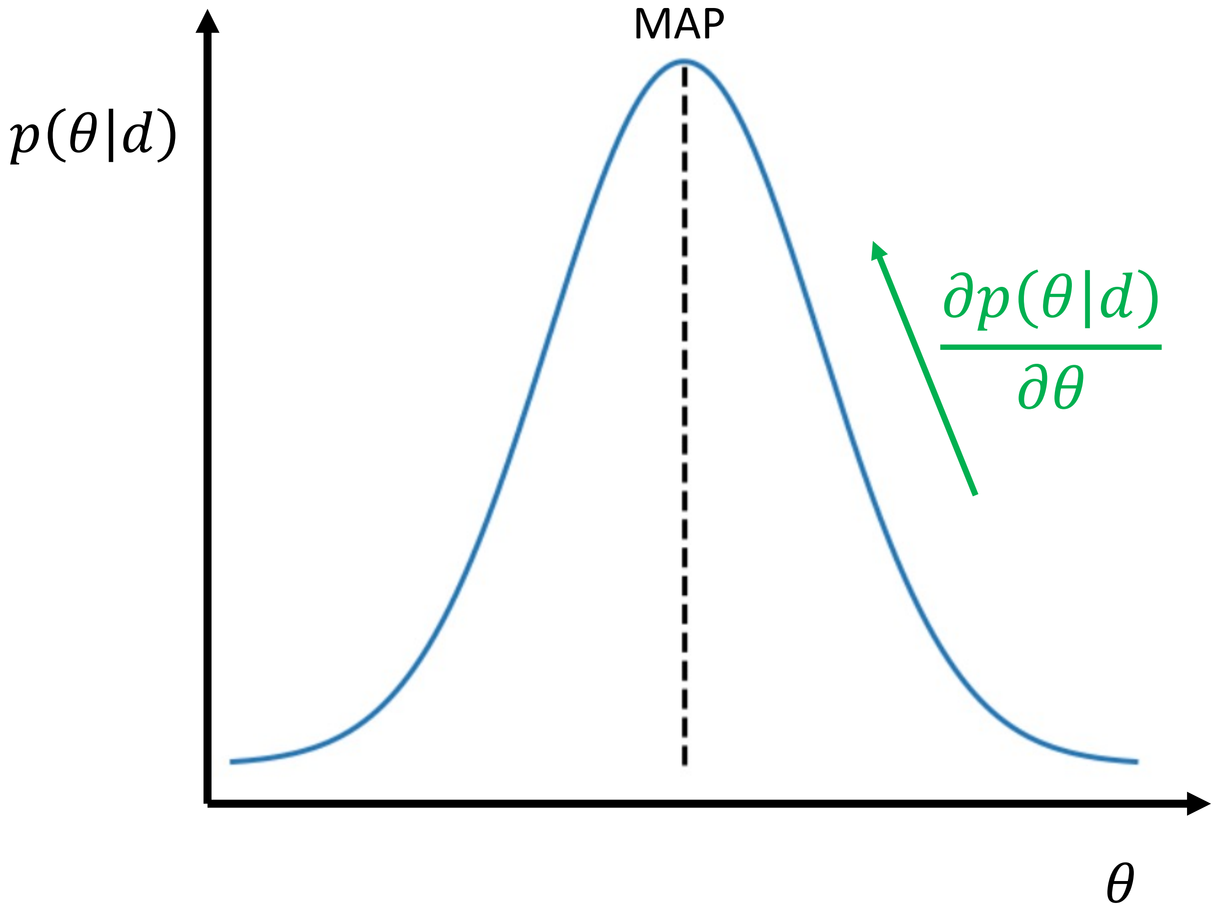
TOWARDS OPTIMAL CONSTRAINTS

Bayesian Inference

- Given data d, infer parameters θ

$$\underset{\text{posterior}}{p(\theta|d)} \propto \underset{\text{likelihood}}{p(d|\theta)} \; \underset{\text{prior}}{p(\theta)}$$

- Maximum a posteriori (MAP) gives estimate of θ
- Shape (width) of posterior gives error on θ



Towards Optimal Constraints

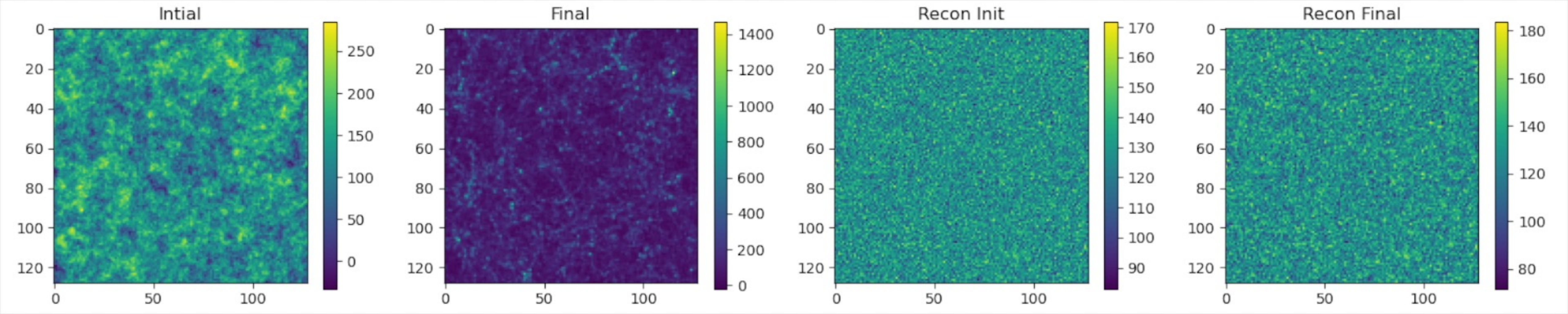
Seljak+2017, Modi+2018, 2020, Böhm+2020

- **Reconstruction**: formulate as a Bayesian inference problem at the field level
- Given field data, d, and forward model, f, infer parameters:
  - Initial modes: s
  - Forward model (e.g. cosmological) parameters: λ

$$\underset{\text{posterior}}{-2\log p(s,\lambda|d)} = \underset{\text{likelihood}}{[d - f(s,\lambda)]^{\dagger} N^{-1} [d - f(s,\lambda)]} + \underset{\text{prior}}{s^{\dagger} S^{-1} s}$$

- Need fast forward model (FastPM; Feng+2017)
- Need differentiable forward model using GPUs (FlowPM; Modi+2020)

Reconstruction from halo field (fixed cosmo)



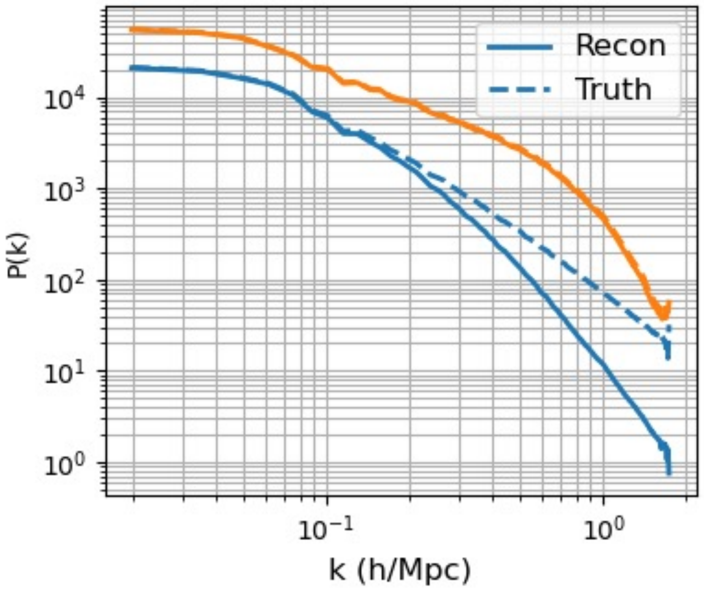
s_{true} d s $f(s)$

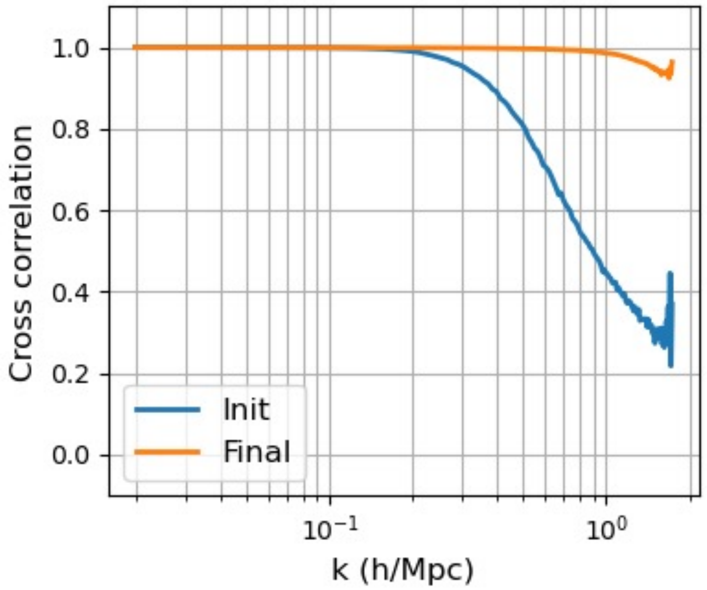
$$-2\log p(s|d) = [d - f(s)]^{\dagger} N^{-1} [d - f(s)] + s^{\dagger} S^{-1} s$$

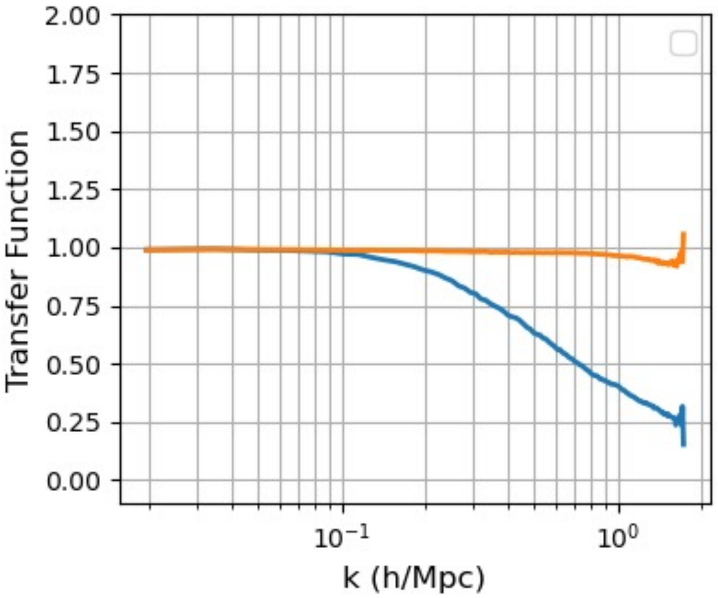
Reconstruction from halo field (fixed cosmo)

2 MAIN CHALLENGES:

- Great agreement on large scales, computationally expensive to push to small scales
- Expensive to sample posterior

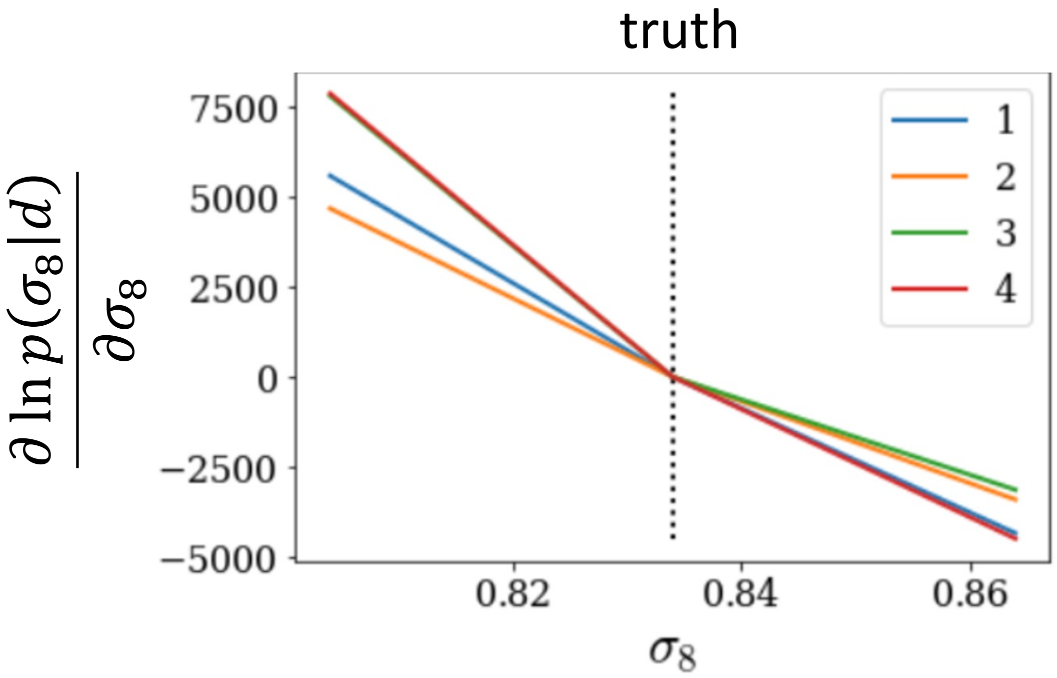


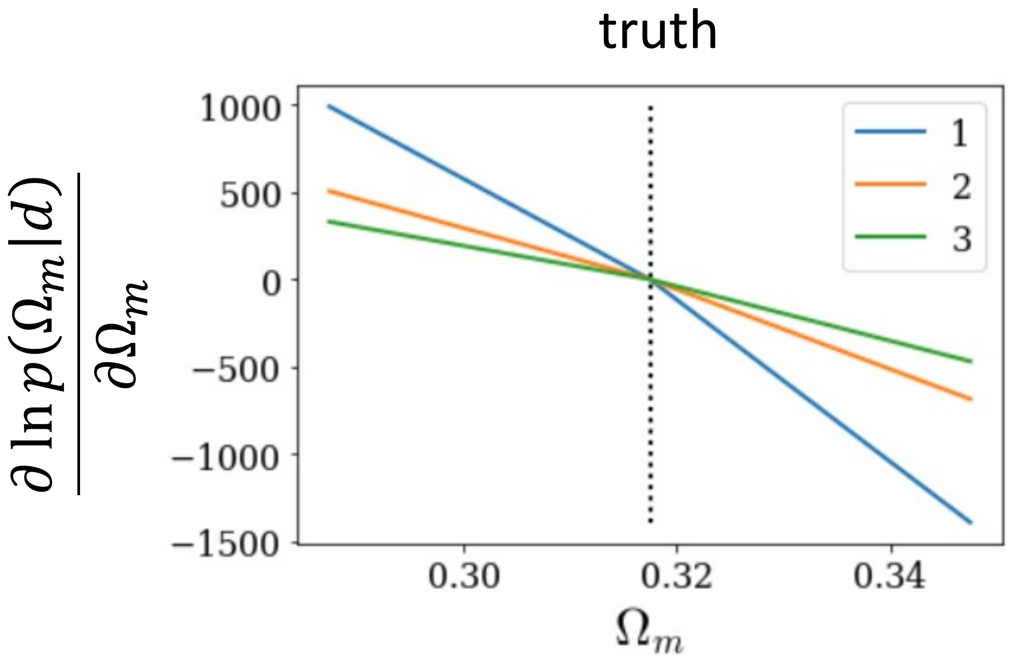




Varying cosmological parameters

Bayer, Modi, Seljak (in prep)





WHERE DOES NEUTRINO MASS INFORMATION COME FROM?

Non-linear neutrino mass information

Bayer, Banerjee, Seljak (2021)

- Run two N-body simulations using **matched linear physics** at z=0:
  1. δ with massive neutrinos (**real**)
  2. $\tilde{\delta}$ with<u>out</u> massive neutrinos (**fake**)

- Can the **nonlinear** effects of massive neutrinos be **faked by CDM**?

- Differing phases implies information beyond the power spectrum

$$\delta = |\delta| e^{i\varphi}$$

$$P_{\delta\delta} = \langle \delta^* \delta \rangle = \langle |\delta|^2 \rangle$$

$$P_{\delta\tilde{\delta}} = \left\langle \delta^* \tilde{\delta} \right\rangle = \left\langle |\delta||\tilde{\delta}|\, e^{-i(\varphi - \tilde{\varphi})} \right\rangle$$

What do surveys measure?

Bayer, Banerjee, Seljak (2021)

$$\delta_m = (1 - f_\nu)\delta_{cb} + f_\nu \delta_\nu$$

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- Halos/Galaxies: $\delta_g = b_1 \delta_{cb}$

What do surveys measure?

Bayer, Banerjee, Seljak (2021)

$$\xcancel{\delta_m} = (1 - f_\nu)\xcancel{\delta_{cb}} + f_\nu \xcancel{\delta_\nu}$$

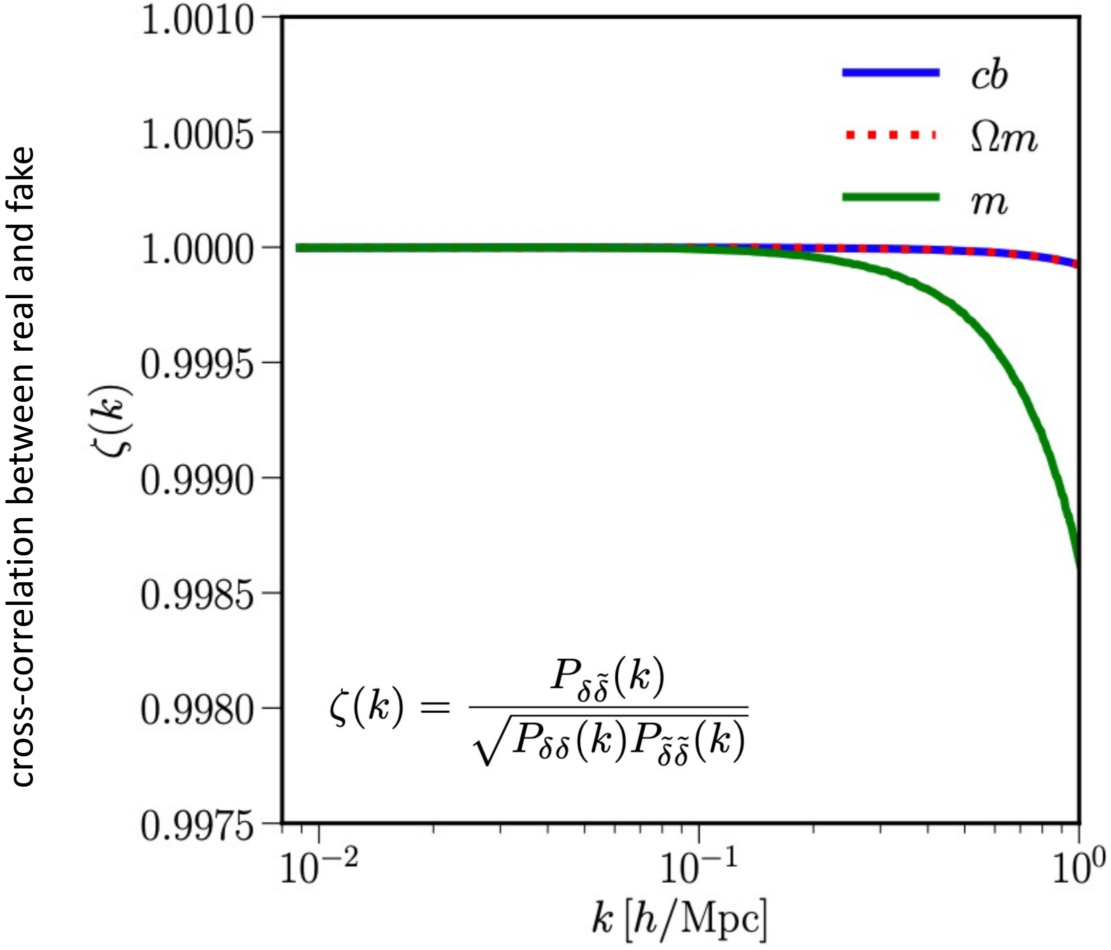
- Halos/Galaxies: $\delta_g = b_1 \delta_{cb}$

- Lensing:

$$\kappa(\chi_*, \hat{\boldsymbol{n}}) = \frac{3H_0^2\Omega_m}{2c^2} \int_0^{\chi_*} d\chi \, \frac{\chi}{a(\chi)} \left(1 - \frac{\chi}{\chi_*}\right) \delta_m(\chi\hat{\boldsymbol{n}})$$

Is non-linear information fake νs?

Bayer, Banerjee, Seljak (2021)



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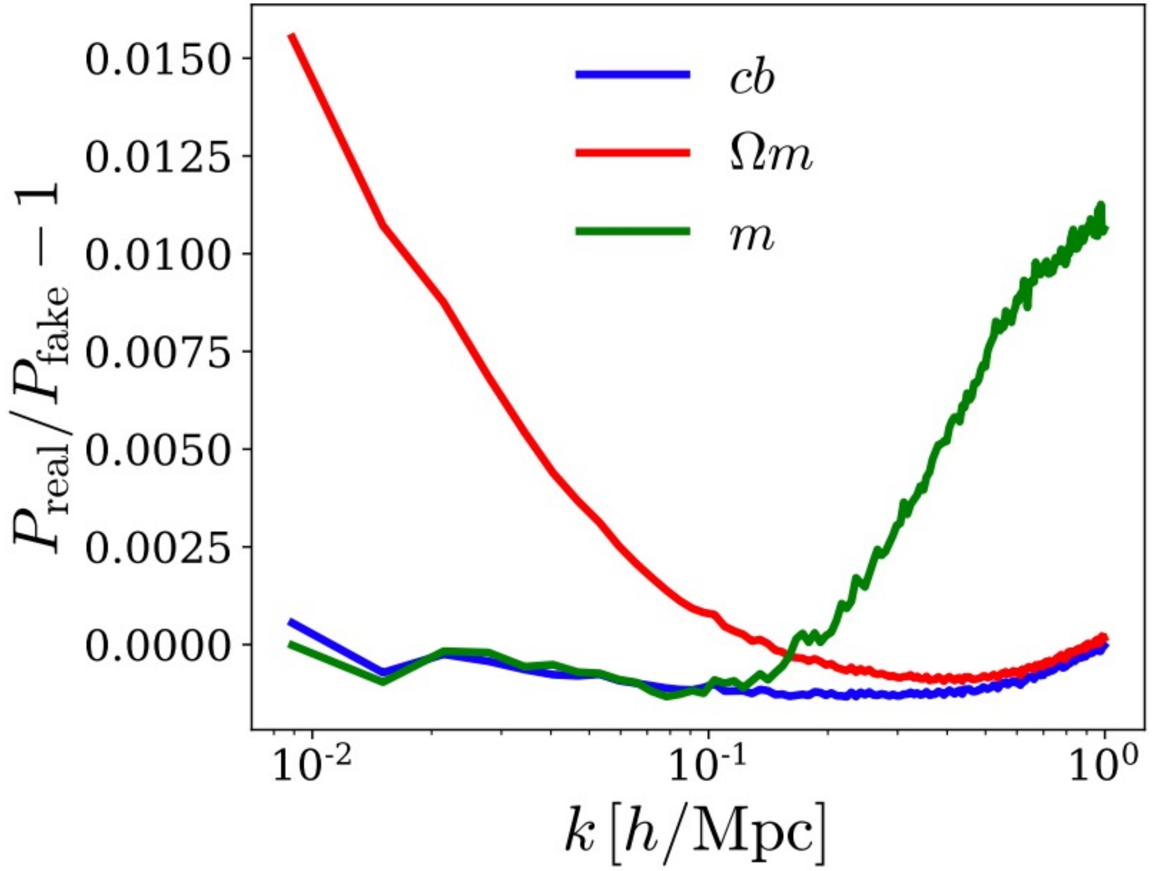
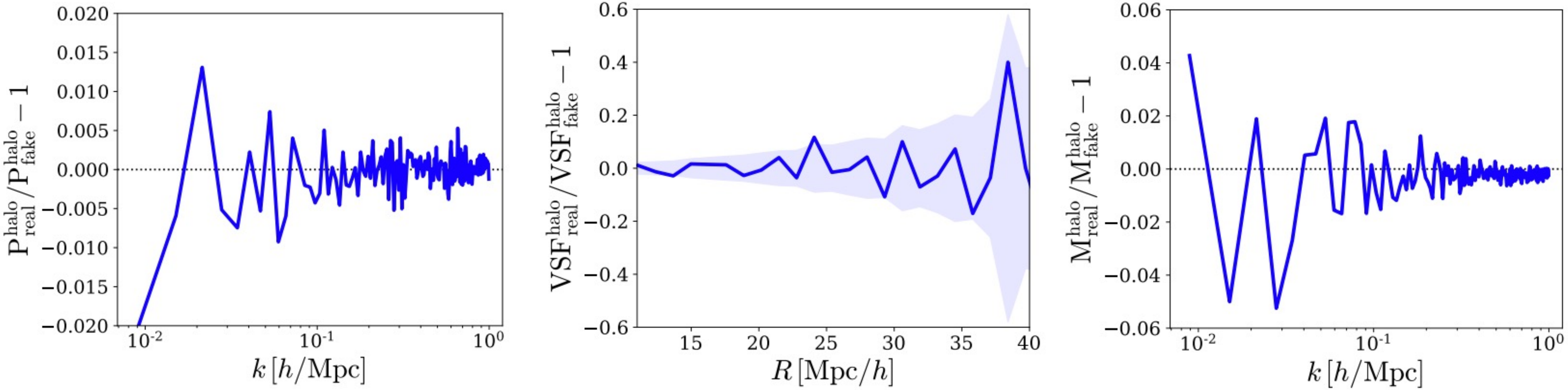


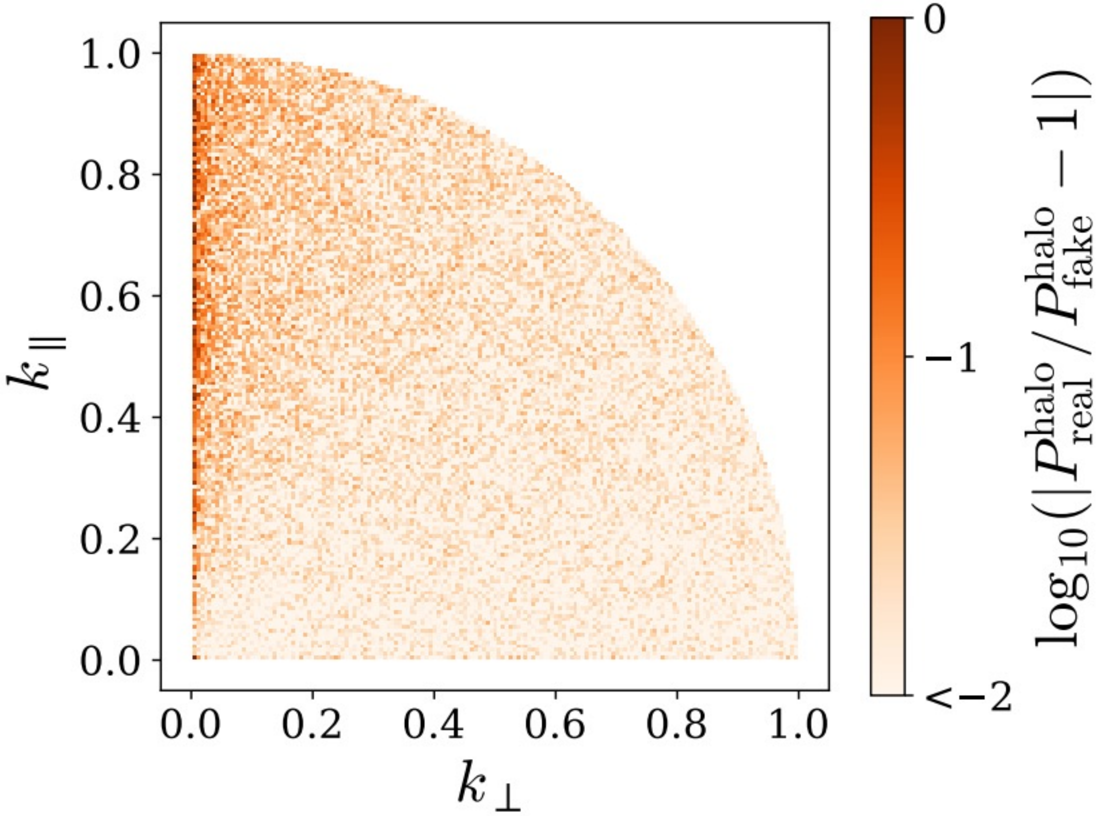
What about the halo field?

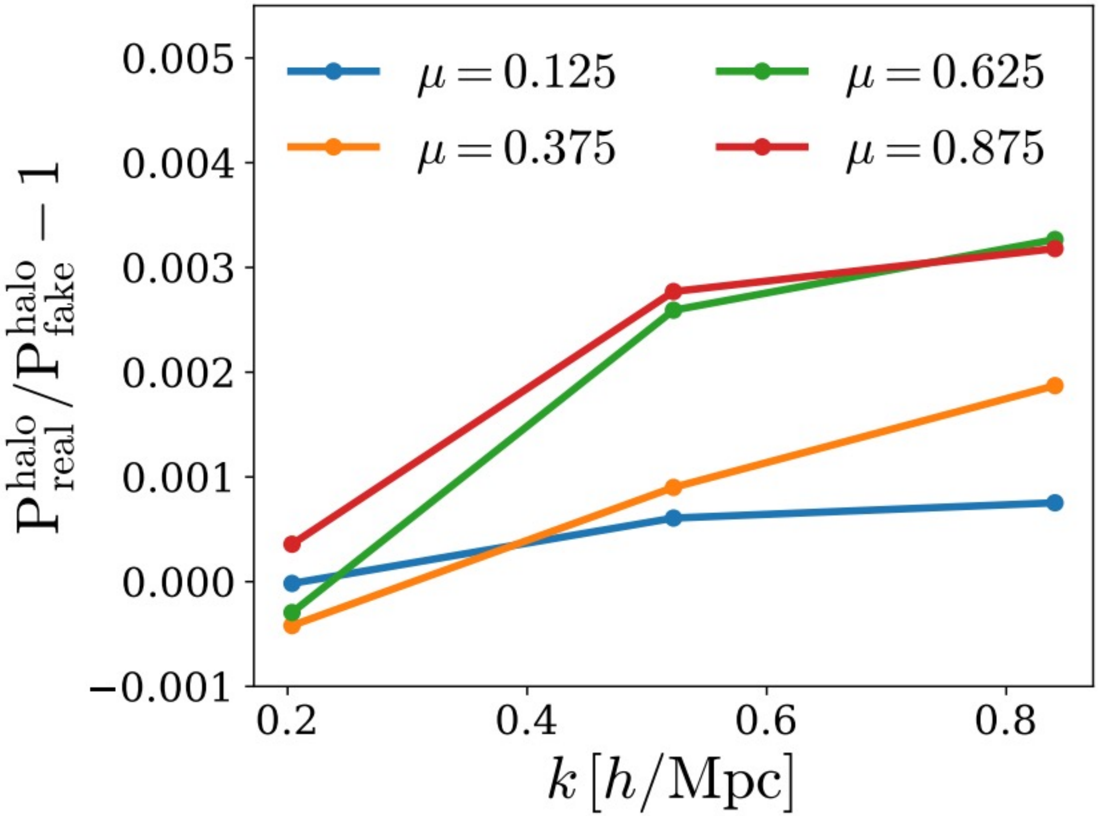
Bayer, Banerjee, Seljak (2021)



Velocity to the rescue?

Bayer, Banerjee, Seljak (2021)

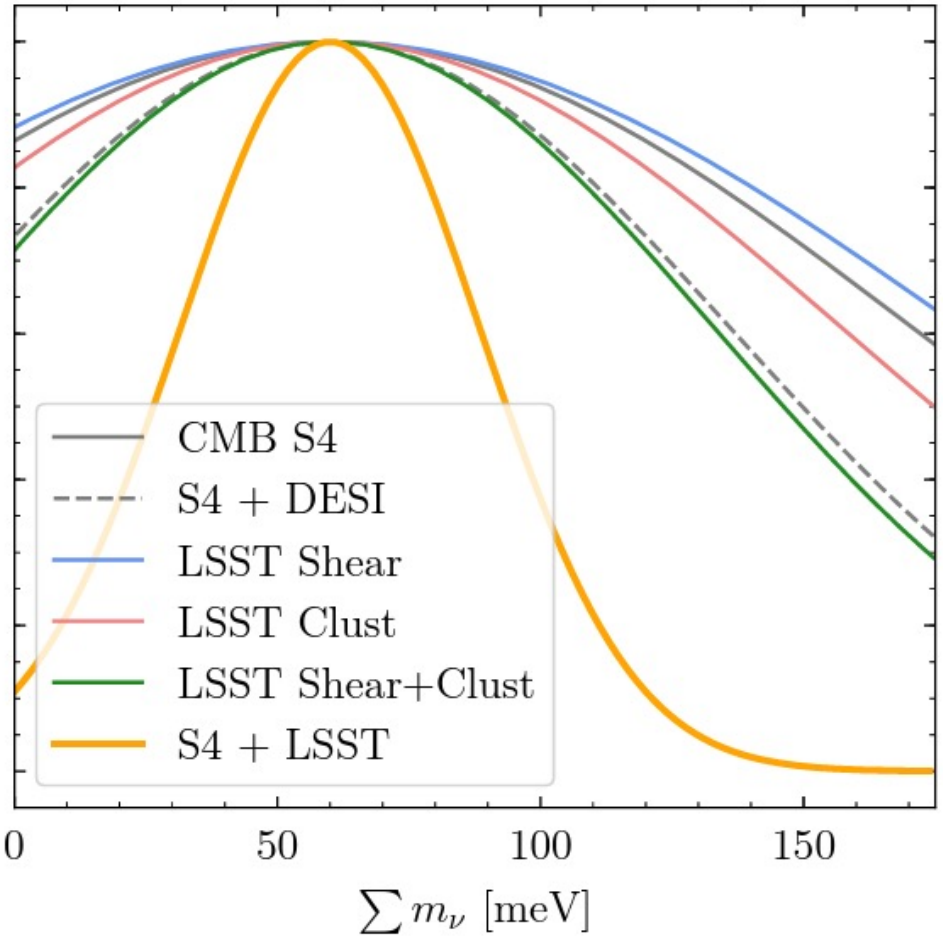




Combining different probes will be important

- With bias cancelling method can get constraints of $M_\nu \sim$ 0.02eV from linear analysis of LSST + Stage IV CMB (Schmittfull, Seljak (2017))

- Will there be more information in the non-linear regime?



Mishra-Sharma+2018

Conclusions

Much information in **matter** field, but not as much in **galaxy** or **lensing** fields at single redshift

Will be degraded further by **baryonic effects**, **systematic noise**, and **super-sample covariance**

Velocity / redshift space adds information

Combining multiple redshifts (tomography) and **multiple tracers** important to break degeneracies

Future Work: Apply full reconstruction framework on redshift space galaxies and weak lensing

Thank you!

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COSMOLOGICAL PHYSICS

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