Neutrino mass constraint from an Implicit Likelihood Analysis of BOSS voids

DESI lunch, 10/4/23

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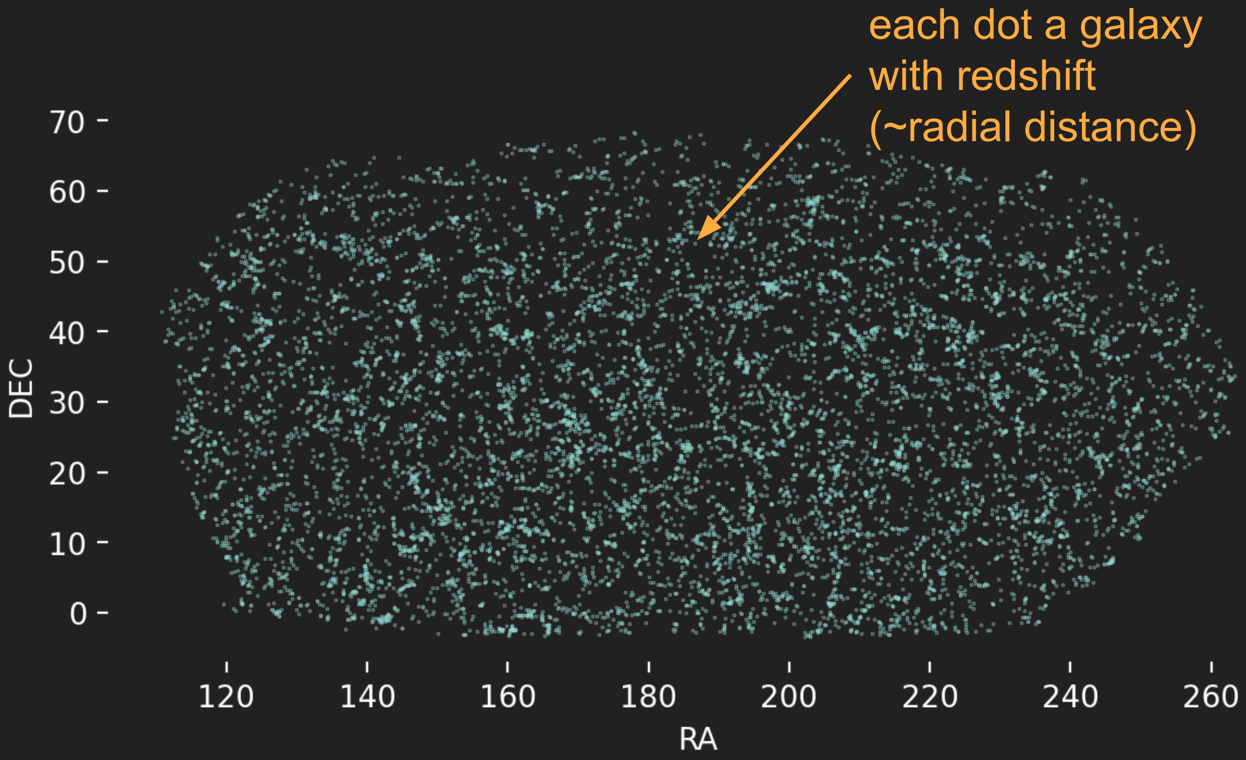
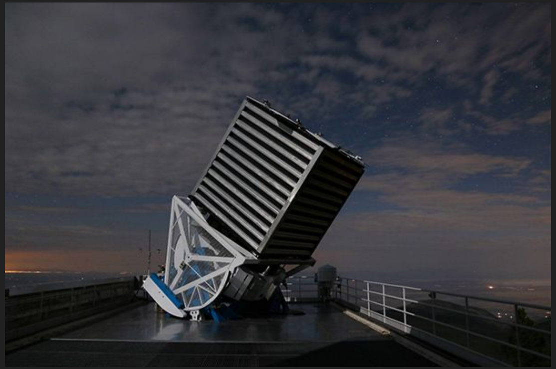
with Elena Massara, Alice Pisani, ChangHoon Hahn, David Spergel, Shirley Ho, Benjamin Wandelt

arXiv:2307.07555

A 3-D map of the universe



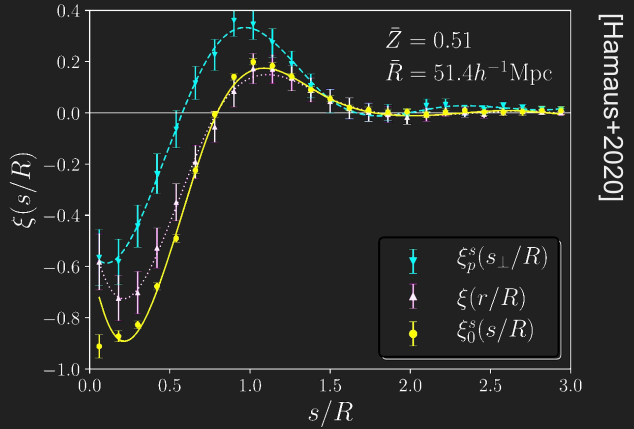
SDSS/BOSS survey

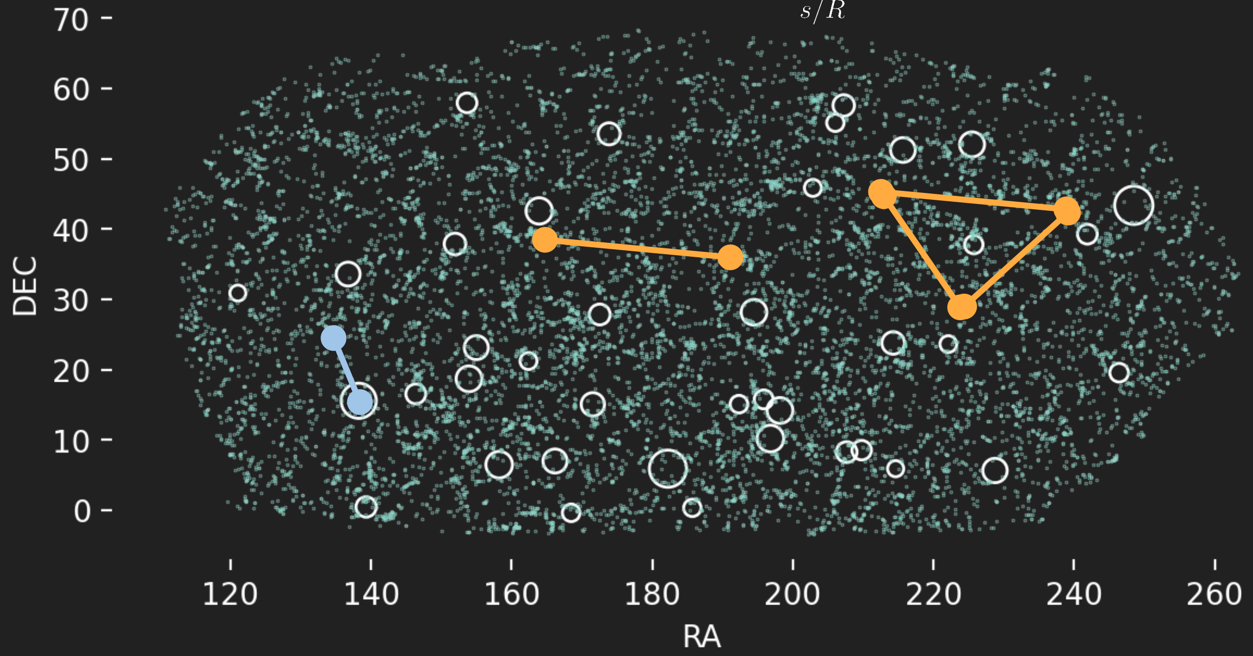


How to summarize this map?

1) pairs of galaxies (power spectrum)
2) triangles of galaxies (bispectrum)
3) …

4) "empty regions" (*cosmic voids*)
   – size distribution
   – void-galaxy pairs
   – …

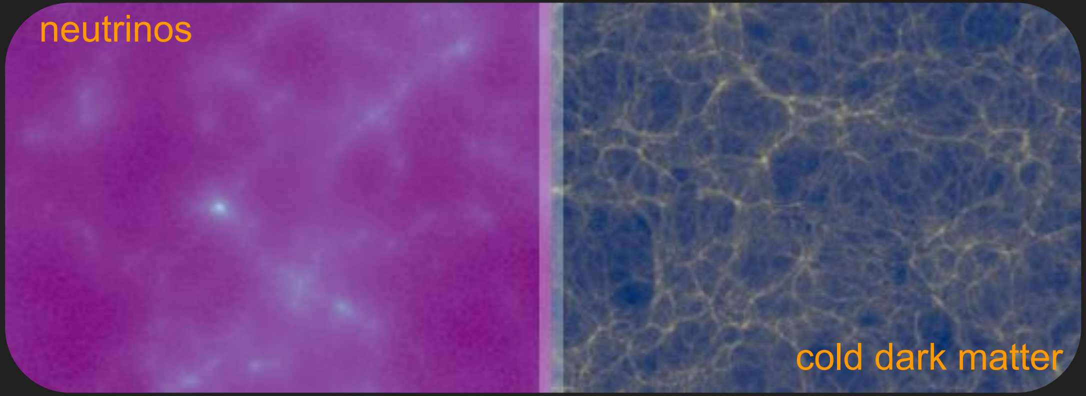


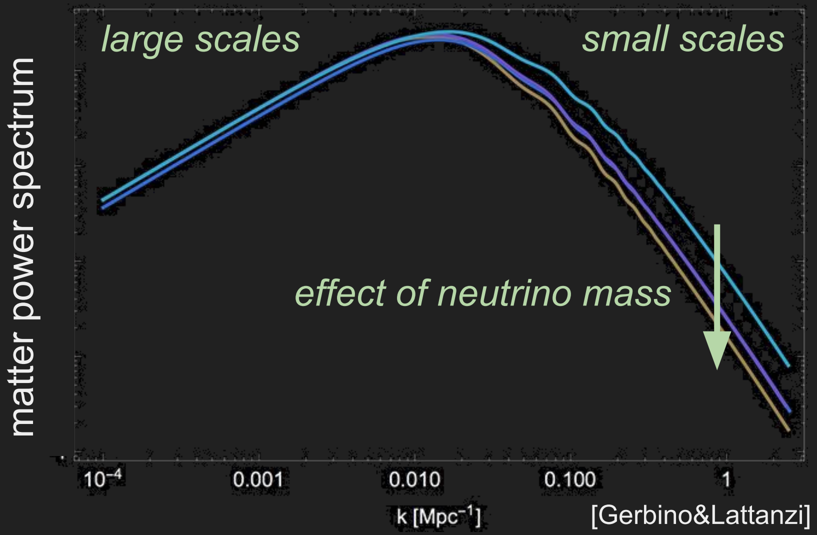


What can voids do for us?

- not virialized → ideal for redshift-space distortions, Alcock-Paczynski
  - matter density Ω_m
  - growth of structure *f/b*
- complementary to correlation functions since voids upweight *underdense* regions
  - corrections to general relativity
  - dark energy
  - neutrino mass

[FLAMINGO]

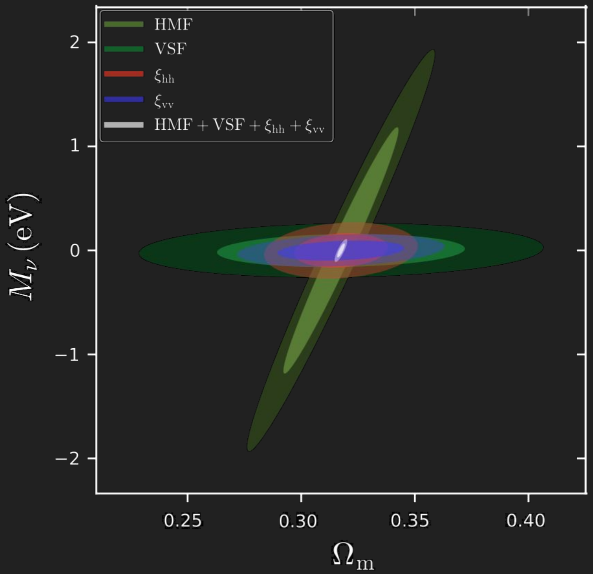




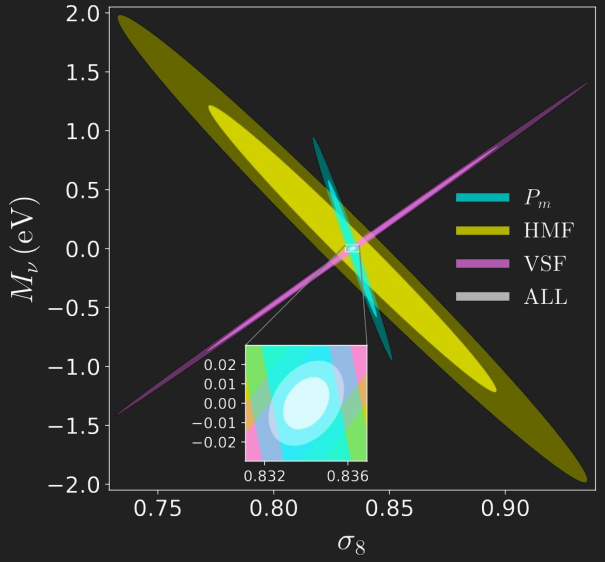
[Gerbino&Lattanzi]

Voids & neutrino mass: forecasts

QUIJOTE halos (1 Gpc/h)

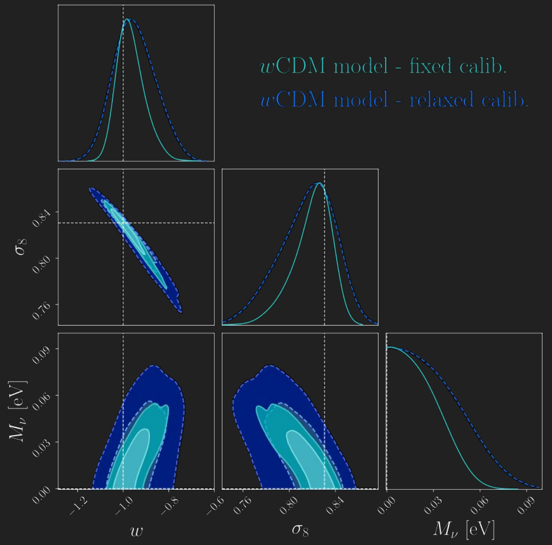


[Kreisch+2021]



[Bayer+2021]

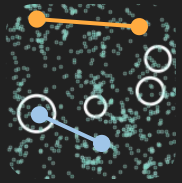
"Euclid" spec-z galaxies (Vdn+b)



[Contarini+2022]

Problem formulation

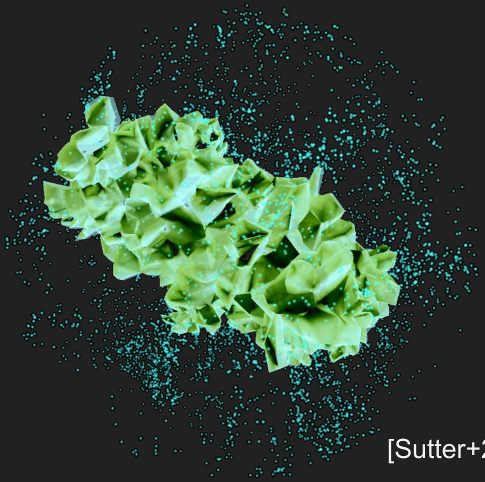
- obtain constraints on neutrino mass sum, Σm_{ν}
- using BOSS CMASS NGC
- summary statistics:
  - galaxy auto-power spectrum
  - void size function
  - void-galaxy cross power spectrum



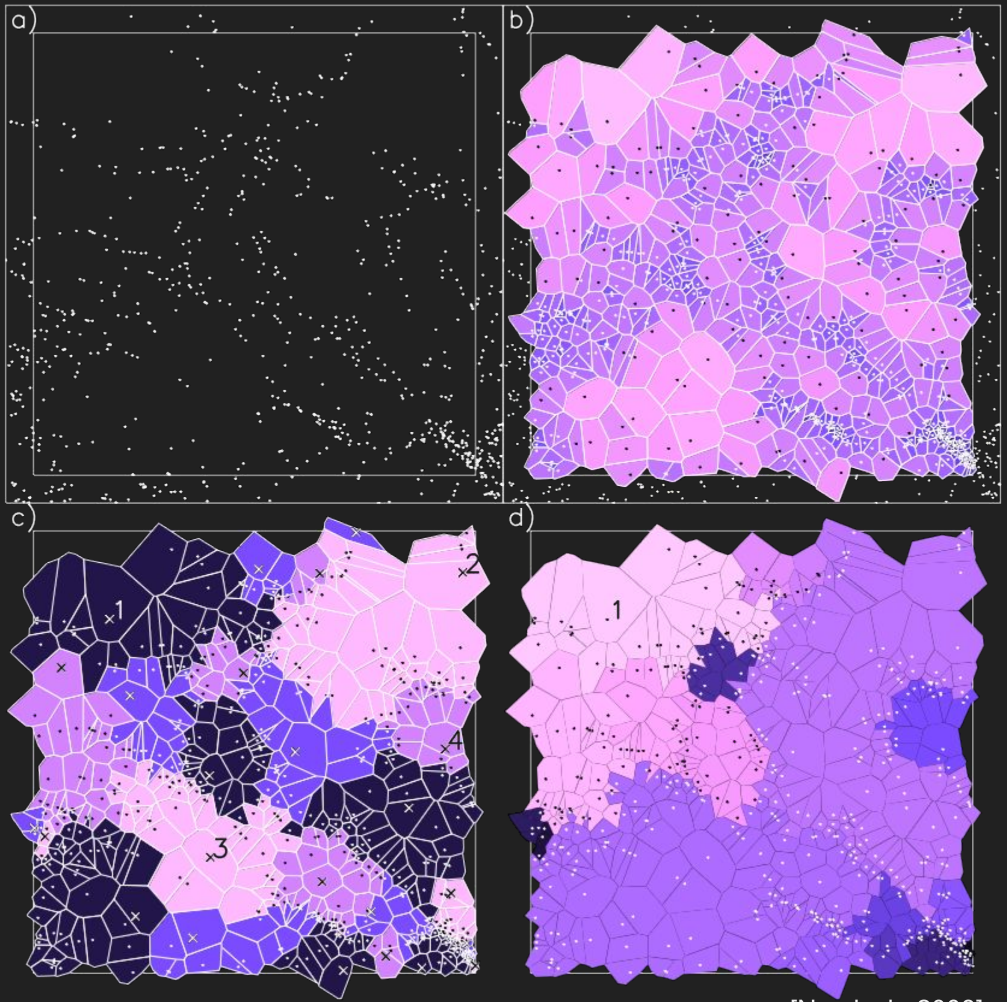
- model based on simulations
- perform implicit-likelihood inference

Void finding

- currently no universally accepted void definition
- simulation based analysis → can choose without biasing
- opt for ZOBOV / VIDE
- Voronoi tessellation, watershed transform



[Sutter+2012]



[Neyrinck+2008]

Why simulation-based & implicit-likelihood inference

- no analytic model currently available to describe galaxy auto power, void size function, void profiles consistently → need simulations
- likelihood function of Poisson/Gauss mixture unknown
- also: 17-D emulation w/ limited simulations difficult

Implicit Likelihood Inference

Assume that we have a simulator that can evaluate the model m(θ, η, ζ) *to required accuracy*.

Use simulated samples to train neural approximator:

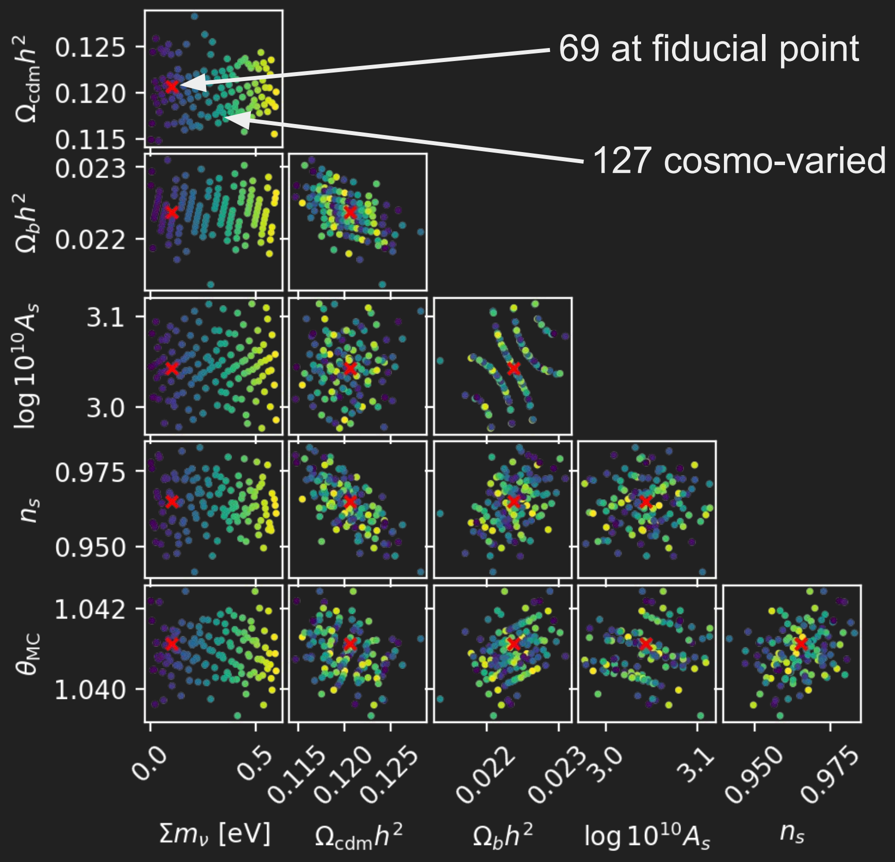
neural likelihood estimation

neural posterior estimation

$$P(\text{parameters} \mid \text{data}) = \frac{P(\text{data} \mid \text{parameters})\, P(\text{parameters})}{P(\text{data})}$$

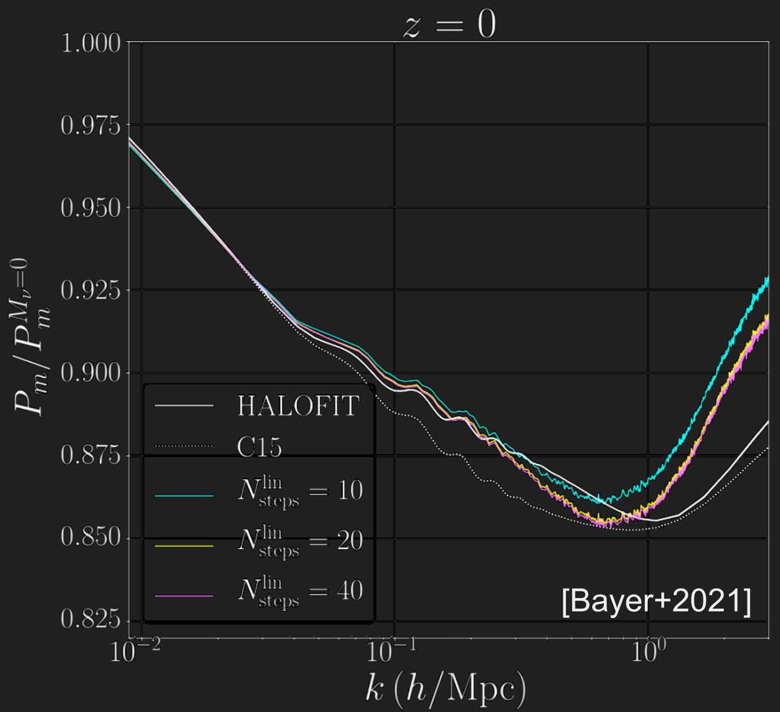
neural ratio estimation

Gravity-only simulations

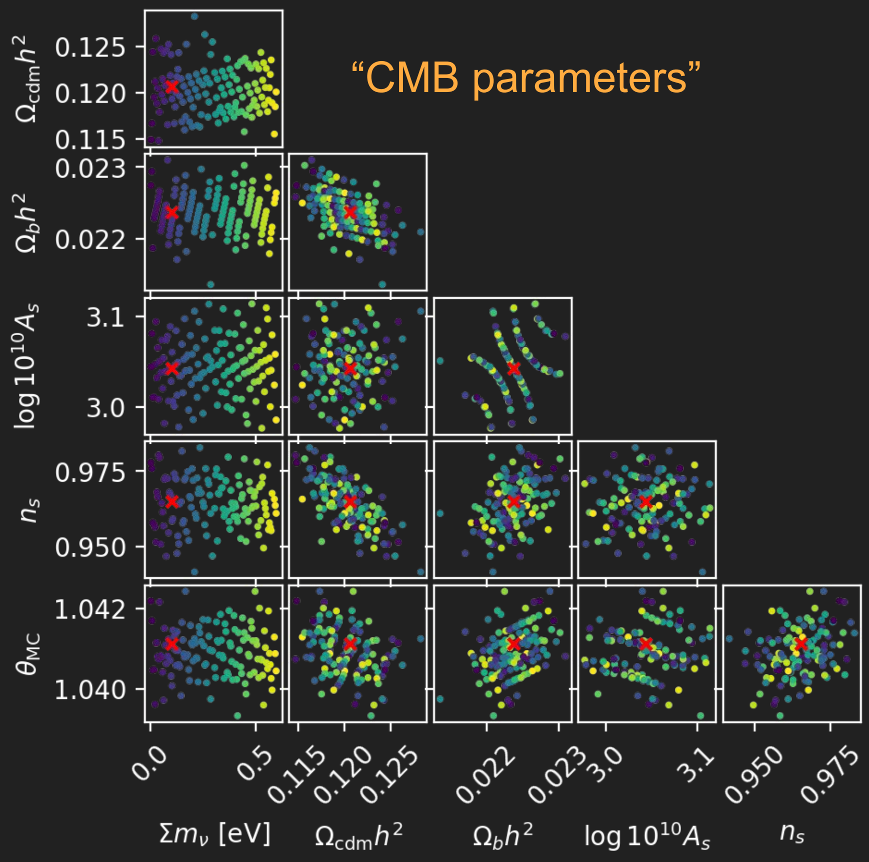


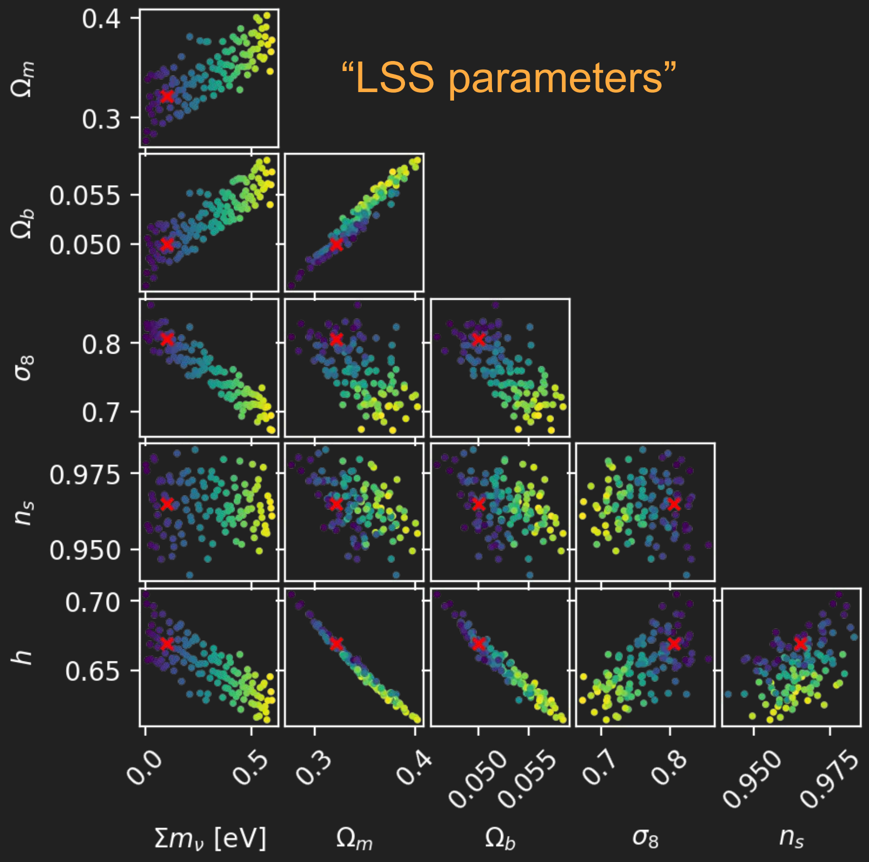
Need to simulate according to prior CMASS NGC

FastPM 2.5 Gpc/h sidelength
2800^3 CDM particles + neutrinos
ΛCDM prior: Gaussian *Planck* x 2



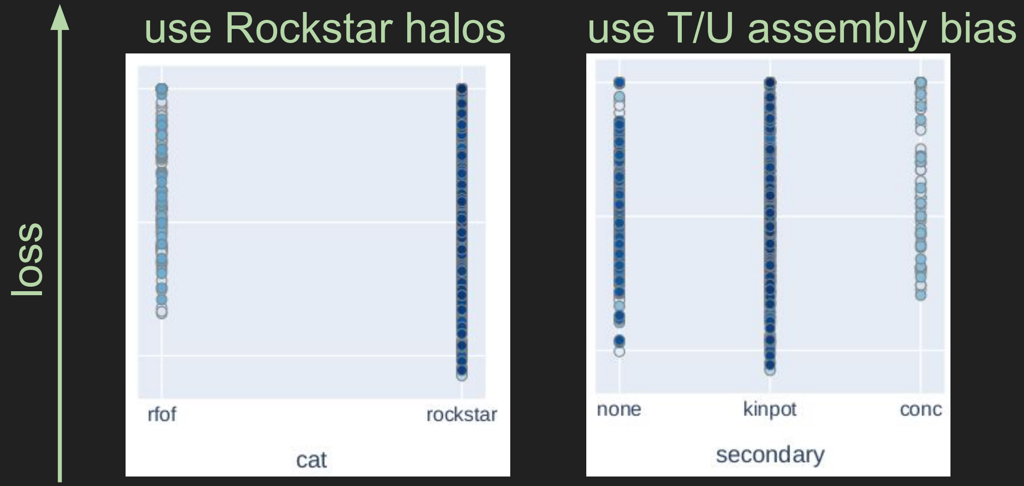
Gravity-only simulations





Choosing halo occupation distribution (HOD)

- global optimization over partly discrete spaces to identify parameterization & prior ranges
- 1st iteration: target=QUIJOTE, statistic=power spectrum
- 2nd iteration: target=data, statistic=void size function



Choosing halo occupation distribution (HOD)

Converged at 11-parameter model:

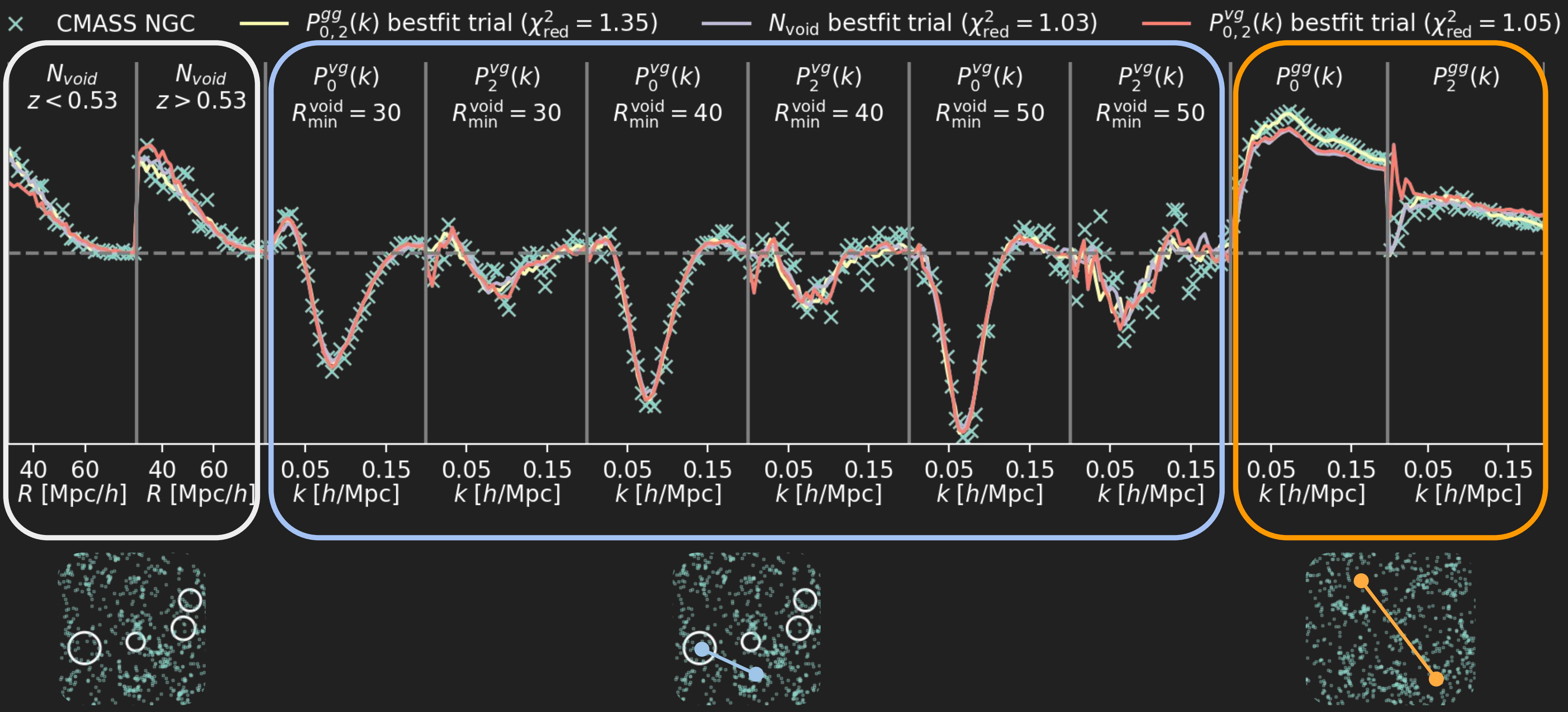
- M_{min} = minimum mass to host central, $\sigma_{\log M}$ = scatter in that relation
- M_0 = minimum mass to host satellite, M_1 = typical mass to host satellite, α = number of satellites
- η_{cen}, η_{sat} = velocity biases
- $\mu(M_{min})$, $\mu(M_1)$ = linearized redshift evolution
- P_1, a_{bias} = secondary bias parameters for centrals (based on kinetic to potential energy ratio)

Likely not ideal!

Lightcones

- 20 snapshots [probably excessive]
- extrapolate using host halo velocity
- cuboid remapping
- survey mask
- fiber collisions
- Downsample to n(z)

Data vector


CMASS NGC
$P^{gg}_{0,2}(k)$ bestfit trial ($\chi^2_{\rm red} = 1.35$)
$N_{\rm void}$ bestfit trial ($\chi^2_{\rm red} = 1.03$)
$P^{vg}_{0,2}(k)$ bestfit trial ($\chi^2_{\rm red} = 1.05$)
N_{void} $z < 0.53$
N_{void} $z > 0.53$
$P^{vg}_0(k)$ $R^{\rm void}_{\rm min} = 30$
$P^{vg}_2(k)$ $R^{\rm void}_{\rm min} = 30$
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$P^{vg}_2(k)$ $R^{\rm void}_{\rm min} = 40$
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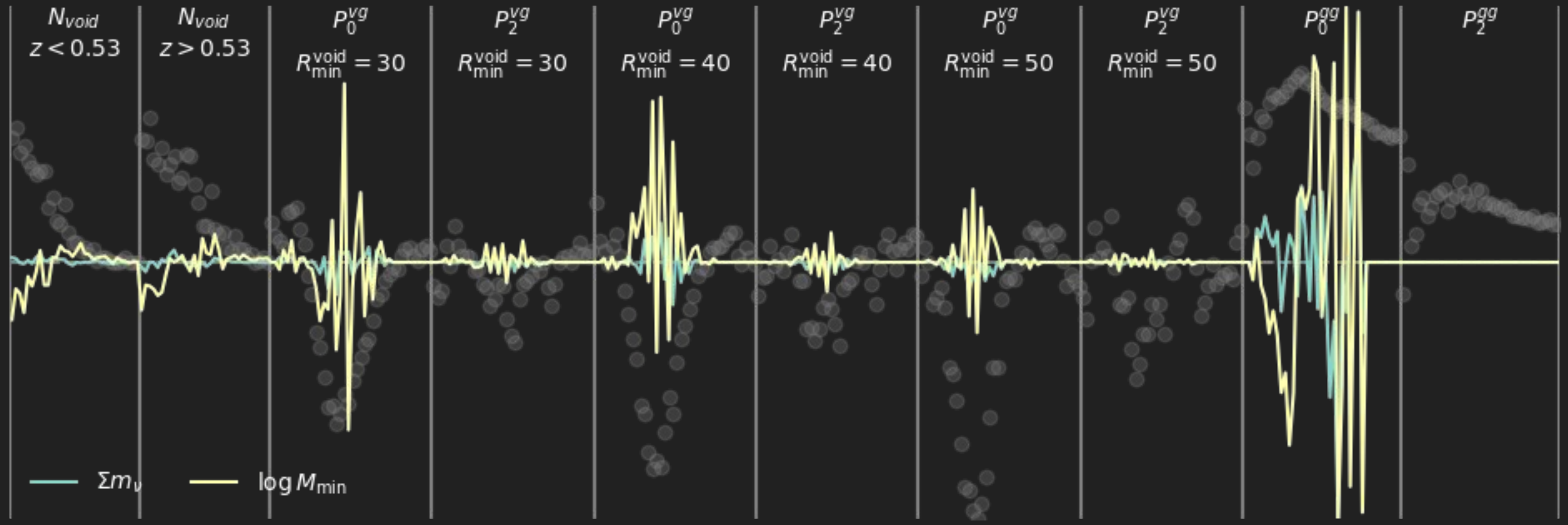
$P^{vg}_2(k)$ $R^{\rm void}_{\rm min} = 50$
$P^{gg}_0(k)$
$P^{gg}_2(k)$
40 60
R [Mpc/h]
0.05 0.15
k [h/Mpc]

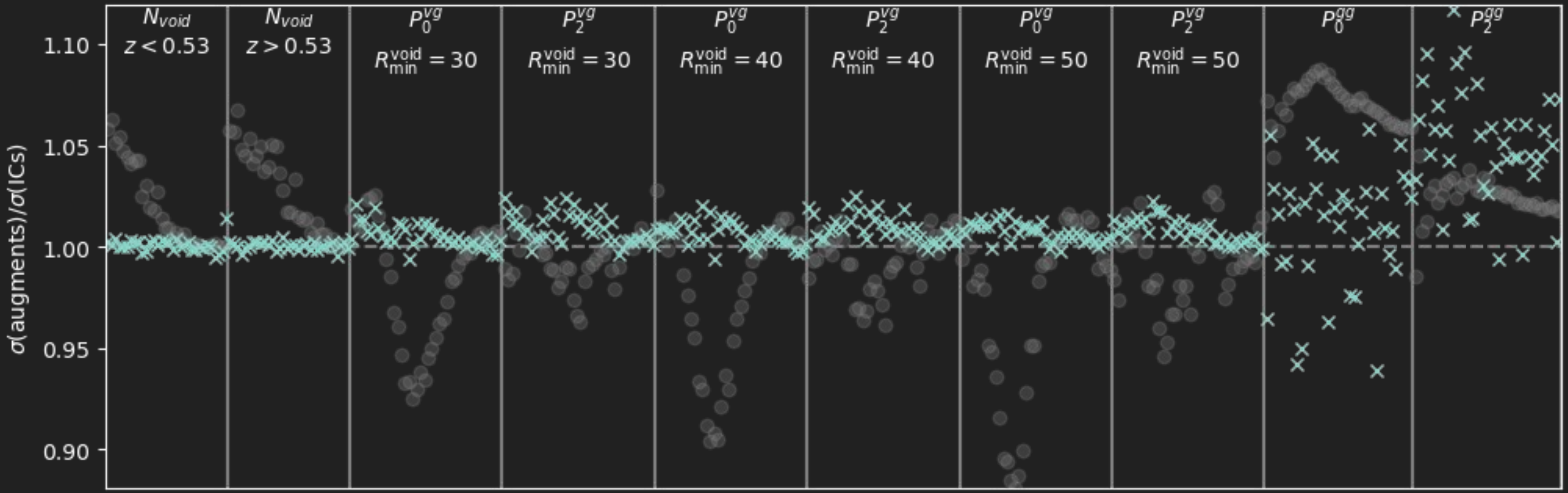
Compression

- linear score compression assuming Gaussian likelihood (MOPED)
- to 17-D (# parameters)



Augmentations

- cosmo-varied simulations have same random seed (historical reasons…)
- but we can generate quasi-independent realizations
- 2 remaps x 6 transpositions x 8 reflections = 96
- How independent? Check using simulations at fiducial point



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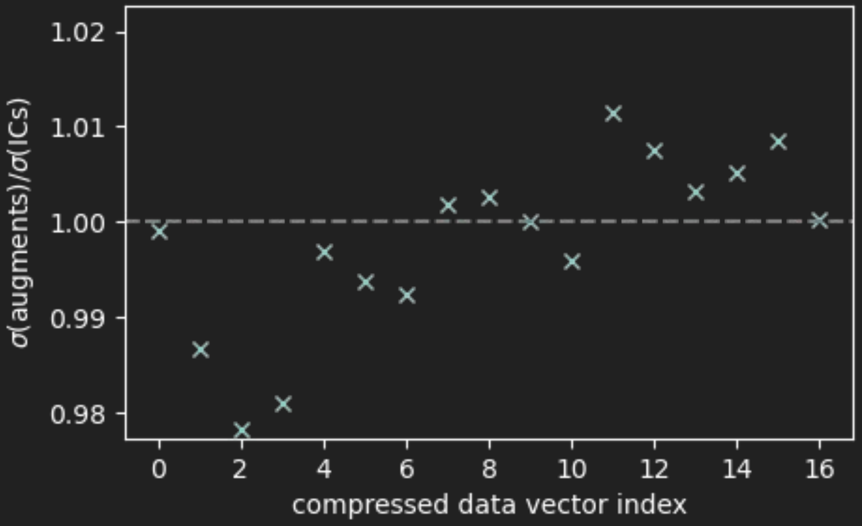
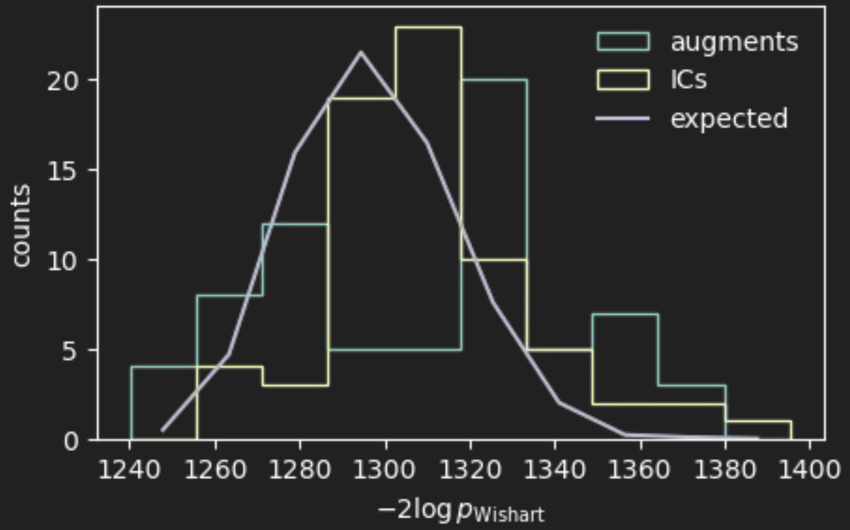




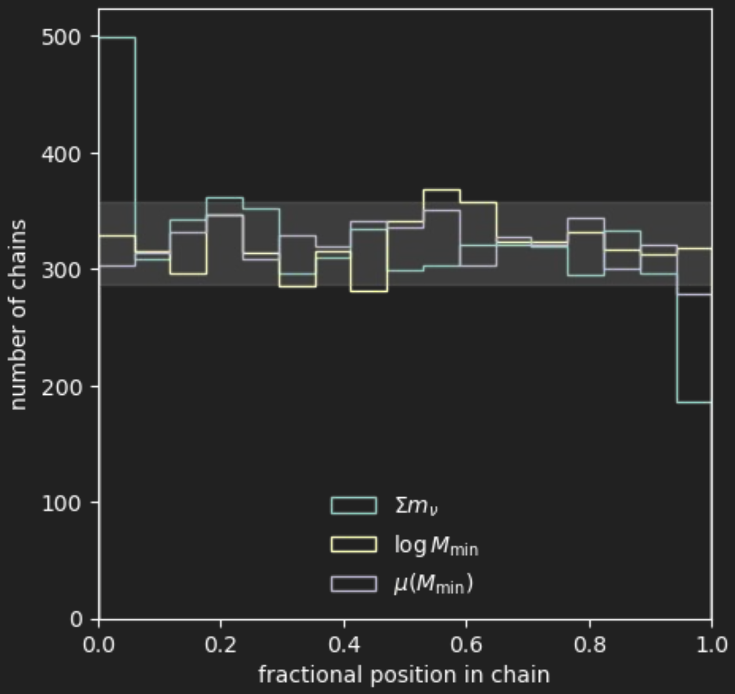
Training & inference

- Withhold 13 simulations for testing (covering M_ν prior well)
- For each simulation, draw ~230 HODs & 8 augmentations
- Gives ~170k training samples
- Train with $\Theta = \{ M_\nu, \log M_{min}, \mu(M_{min}) \}$ to have additional diagnostics (also did some runs with other HOD parameters)

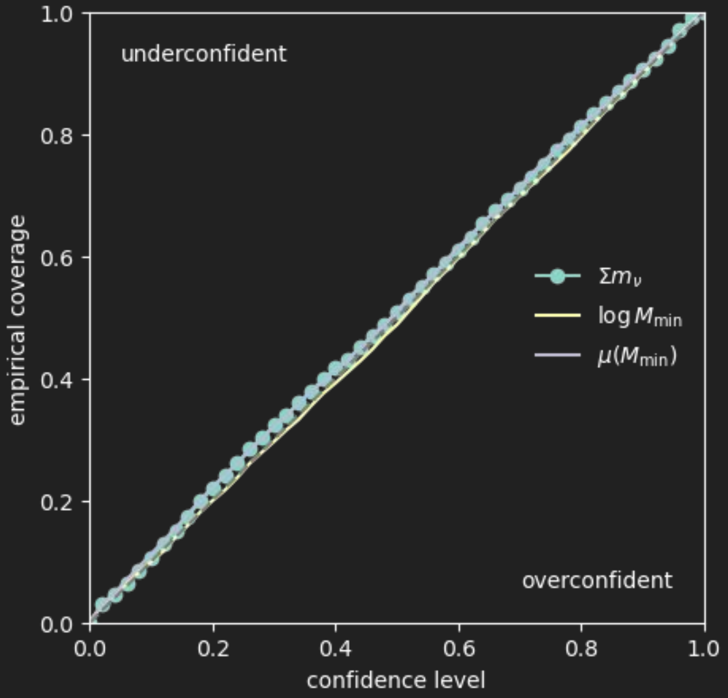
Internal consistency checks

test posterior calibration by running inference on mocks from prior

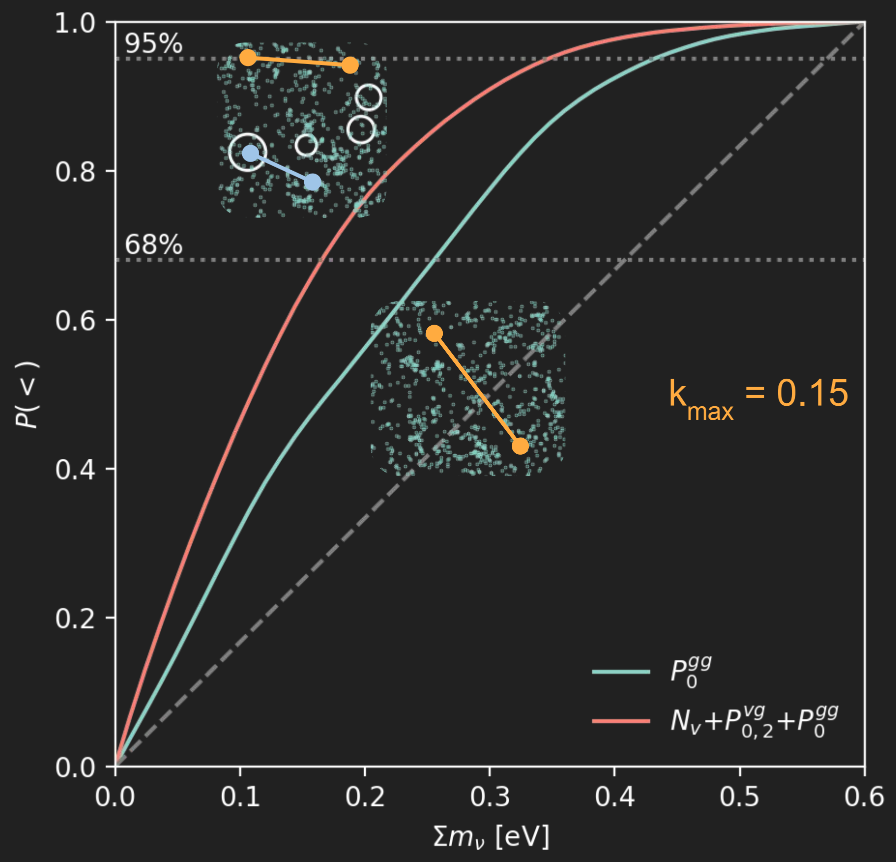
rank statistics

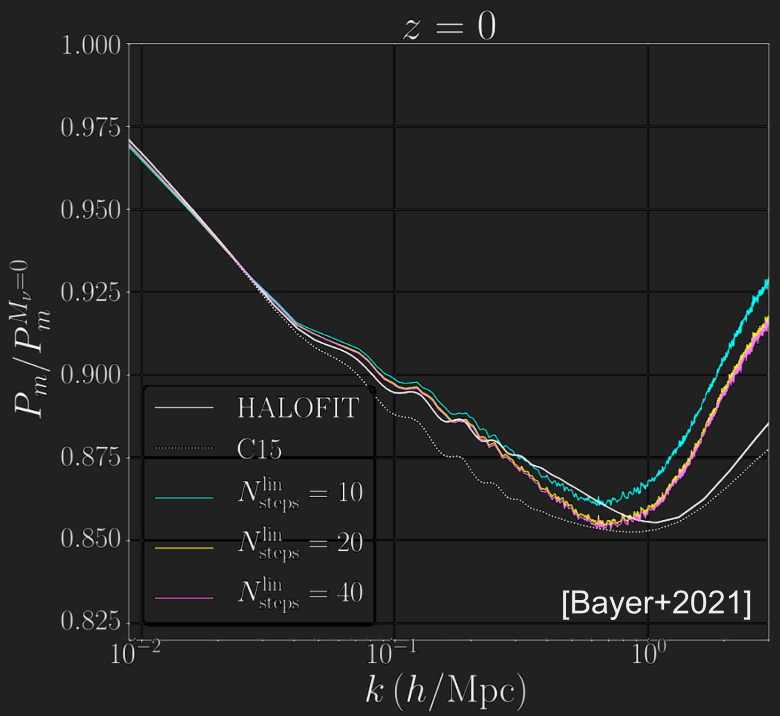


q-q plot



Main posteriors





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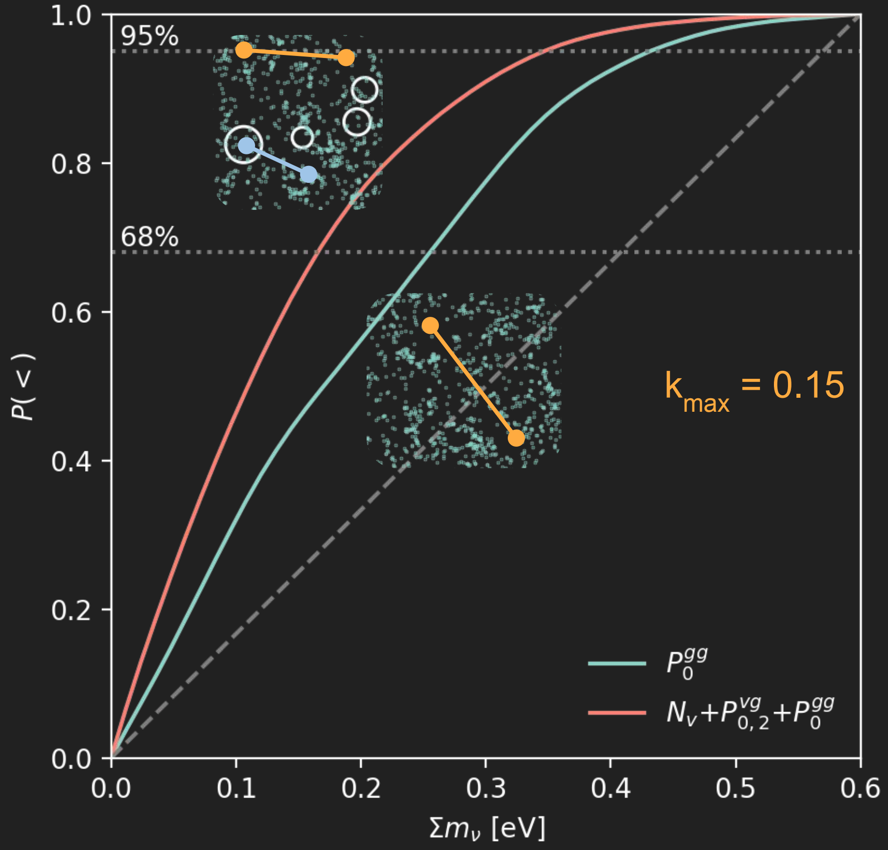
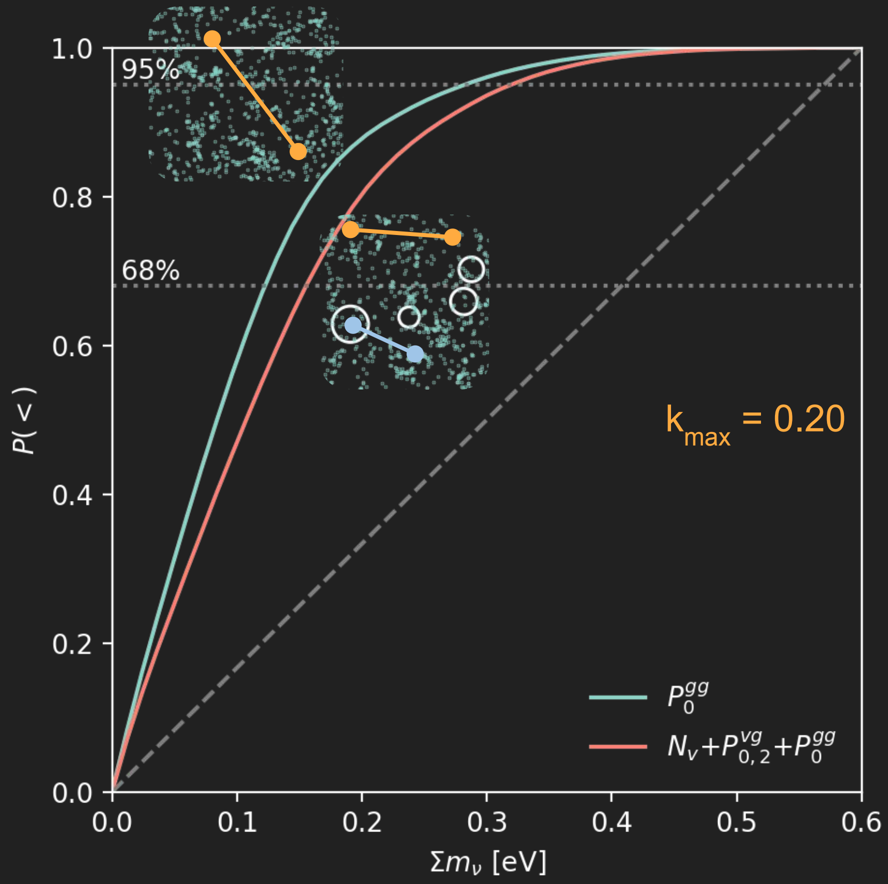
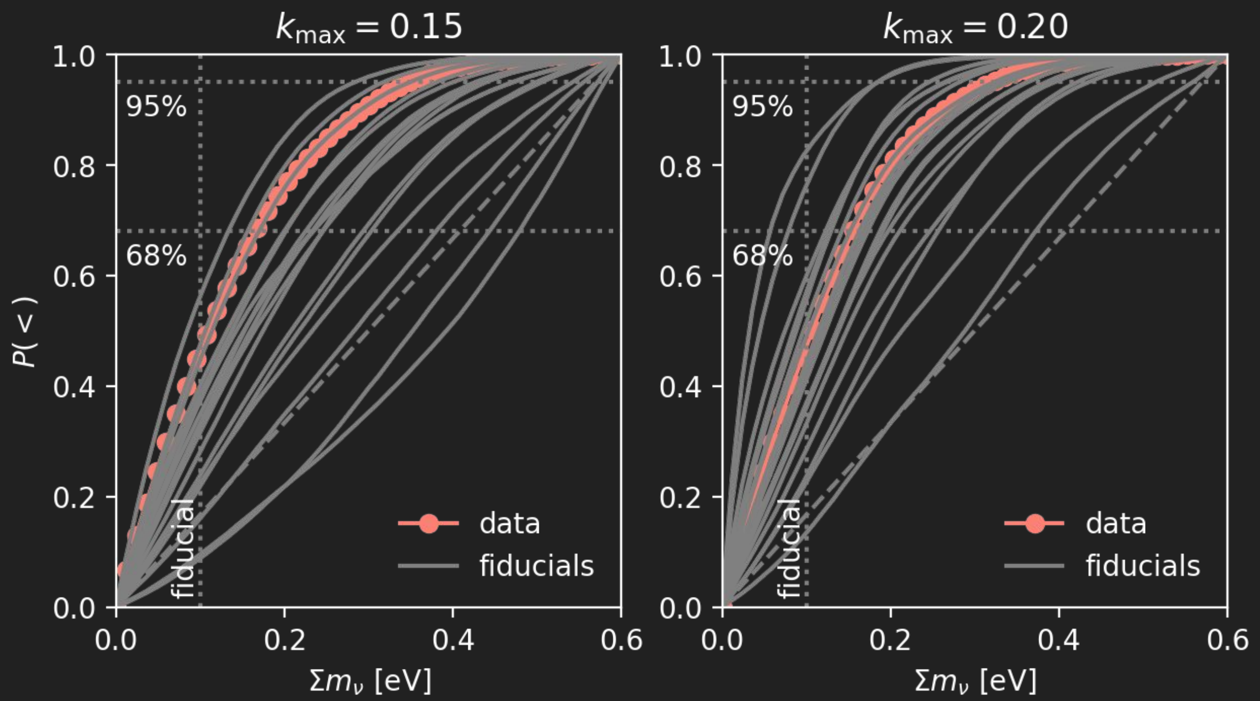




Compare to posteriors on fiducial mocks

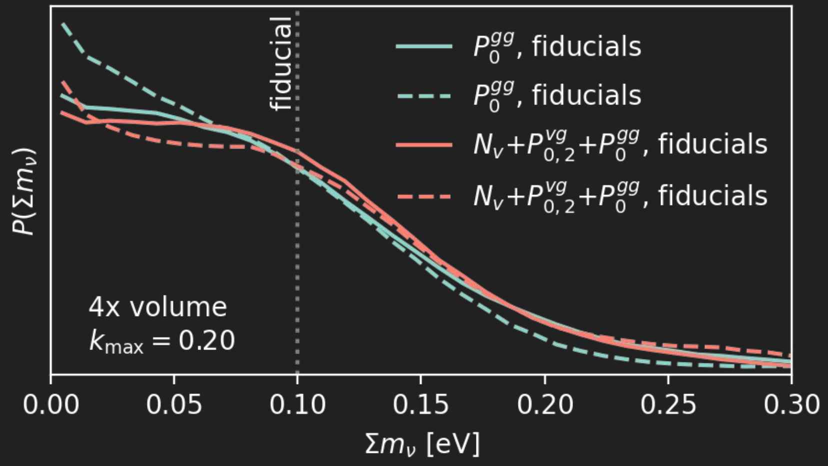


Not obviously wrong, but maybe systematics on large scales? (e.g., galaxy weights in void-galaxy cross power)
– Or: the "augmentations" don't work well enough

Broadening of posteriors

Including void statistics sometimes leads to larger upper bound on M_ν

statistical fluctuation?



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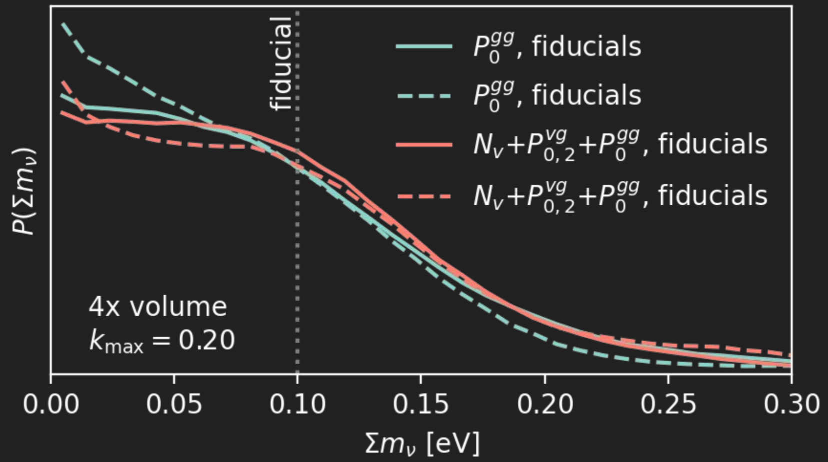
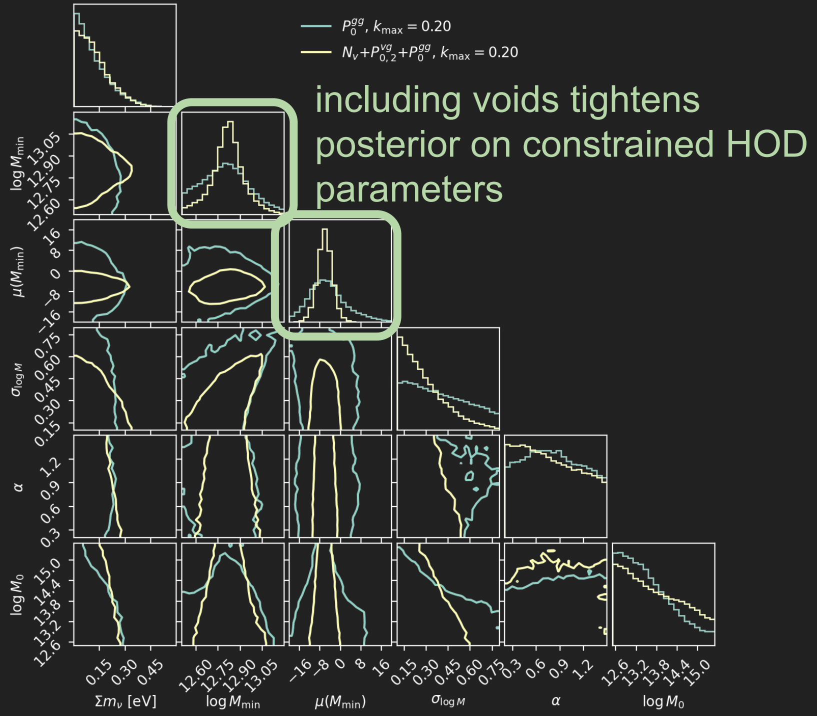


inefficient compression?



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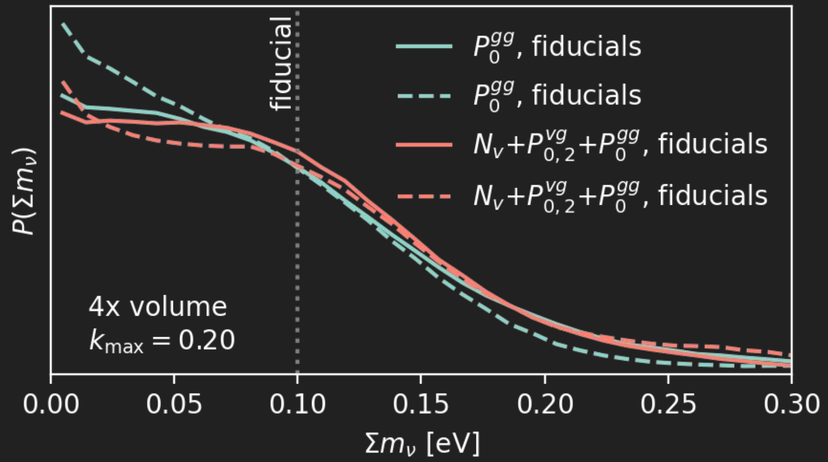
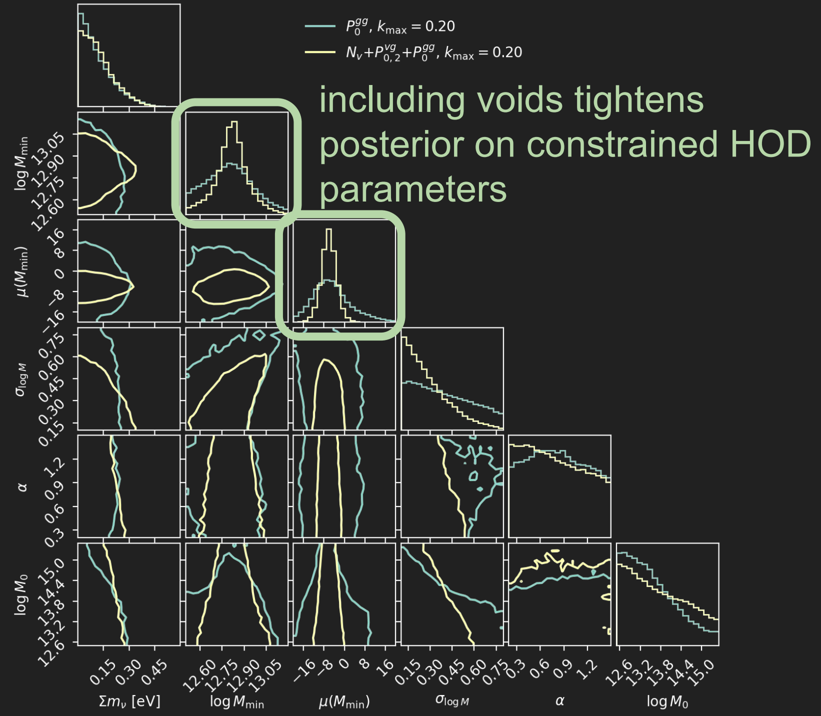
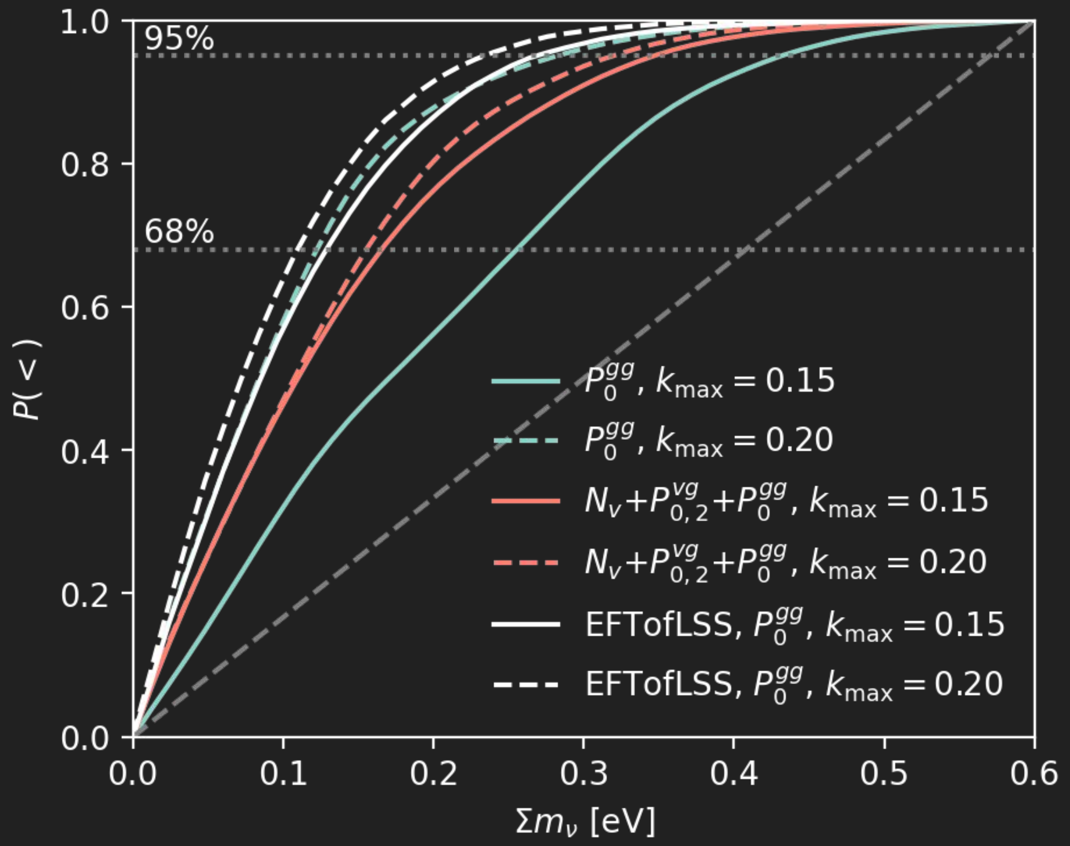


One-sided posteriors are different from "Gaussian" ones

inefficient compression?



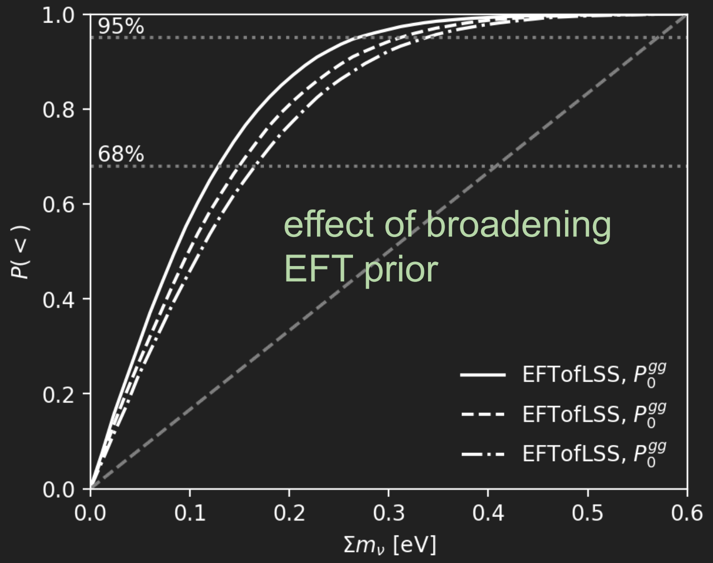
Comparison to EFTofLSS

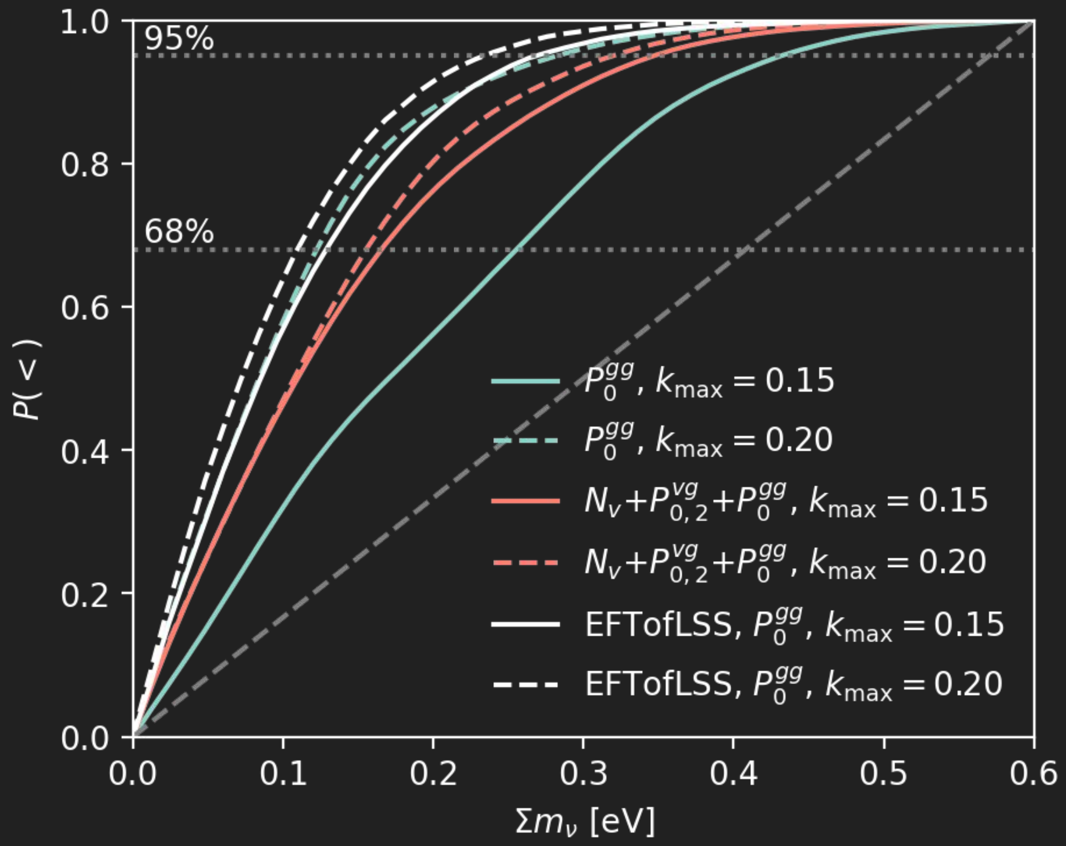


Comparison to EFTofLSS

EFT possible issues:

- prior dependence, volume effects
- redshift evolution?





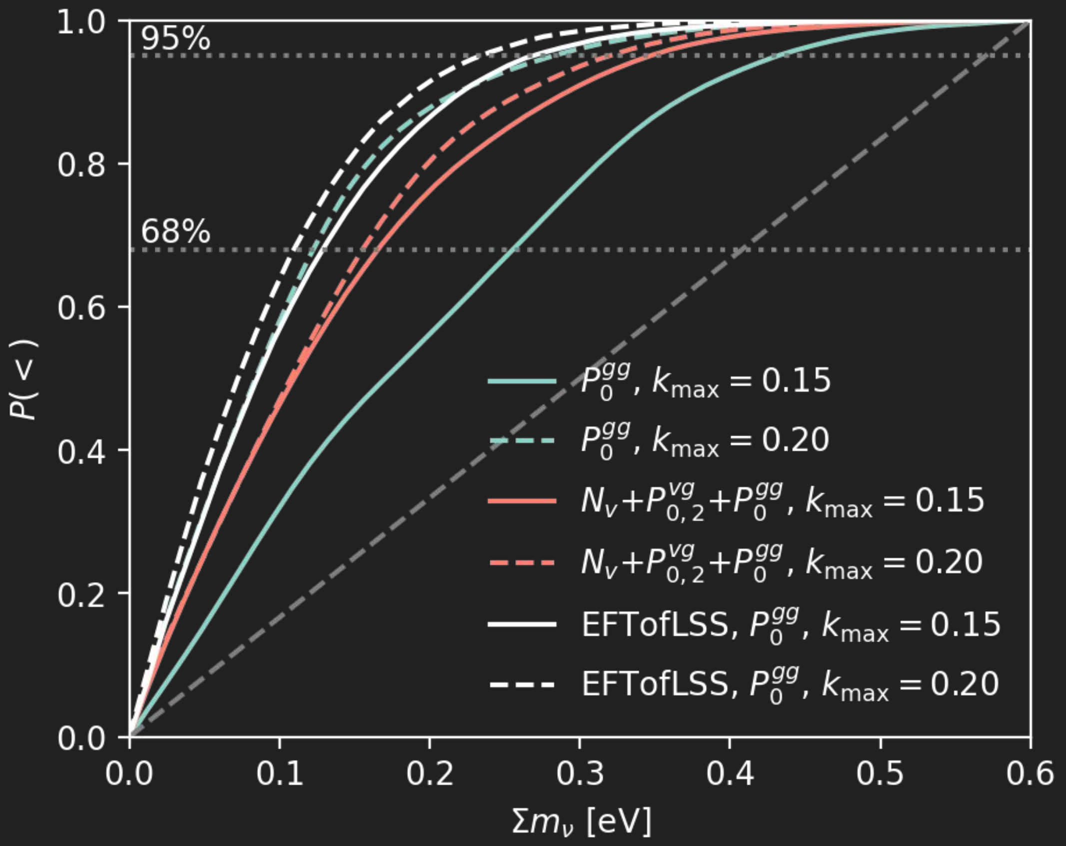
Comparison to EFTofLSS

EFT possible issues:

- prior dependence, volume effects
- redshift evolution?

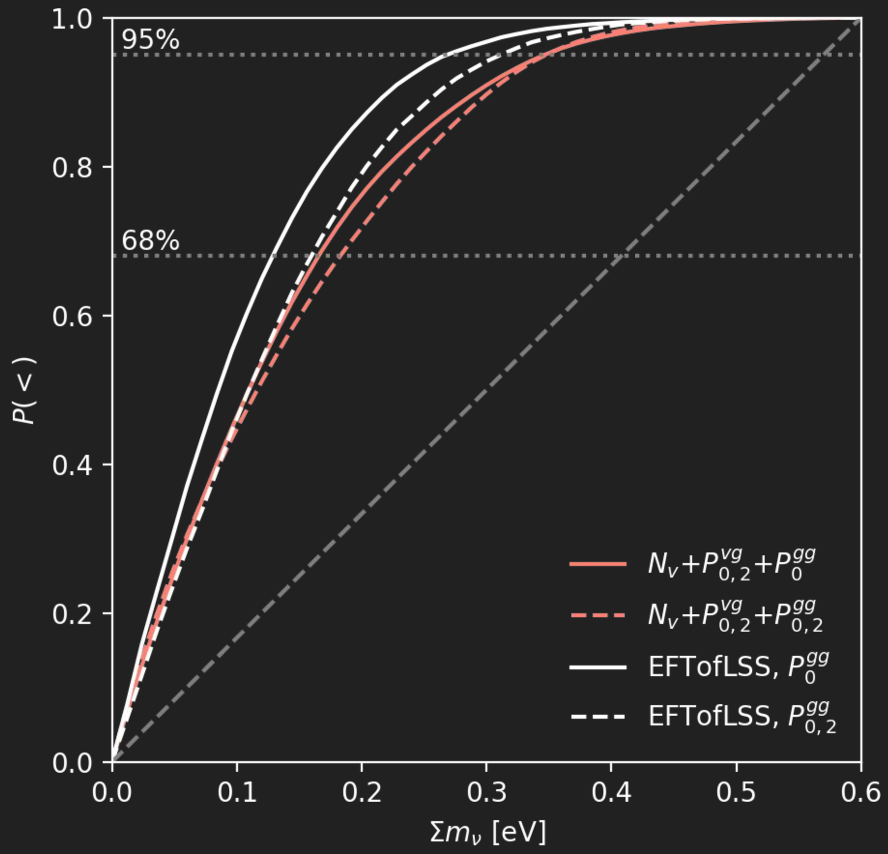
Our possible issues:

- prior volume effects
- inaccurate simulations (neutrino mass impact?)
- “augmentation” procedure
- …



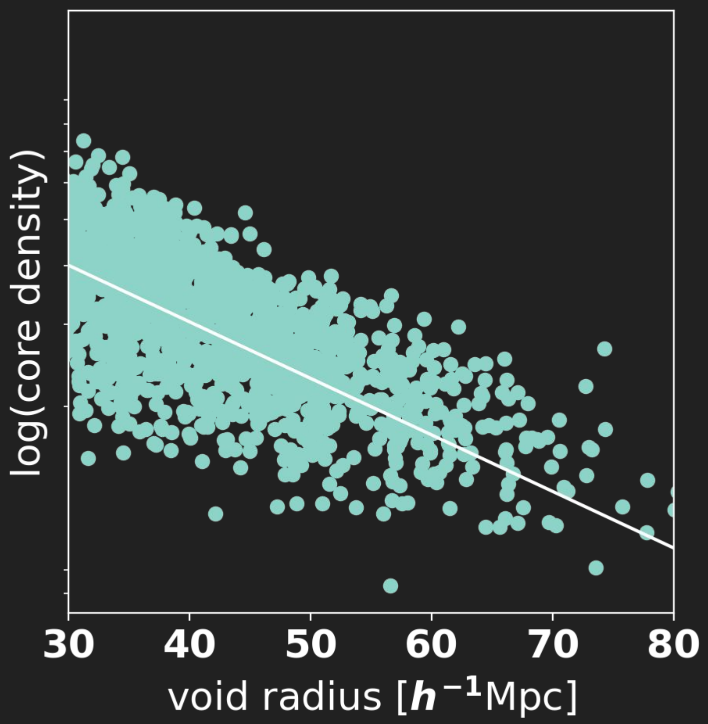
Quadrupole

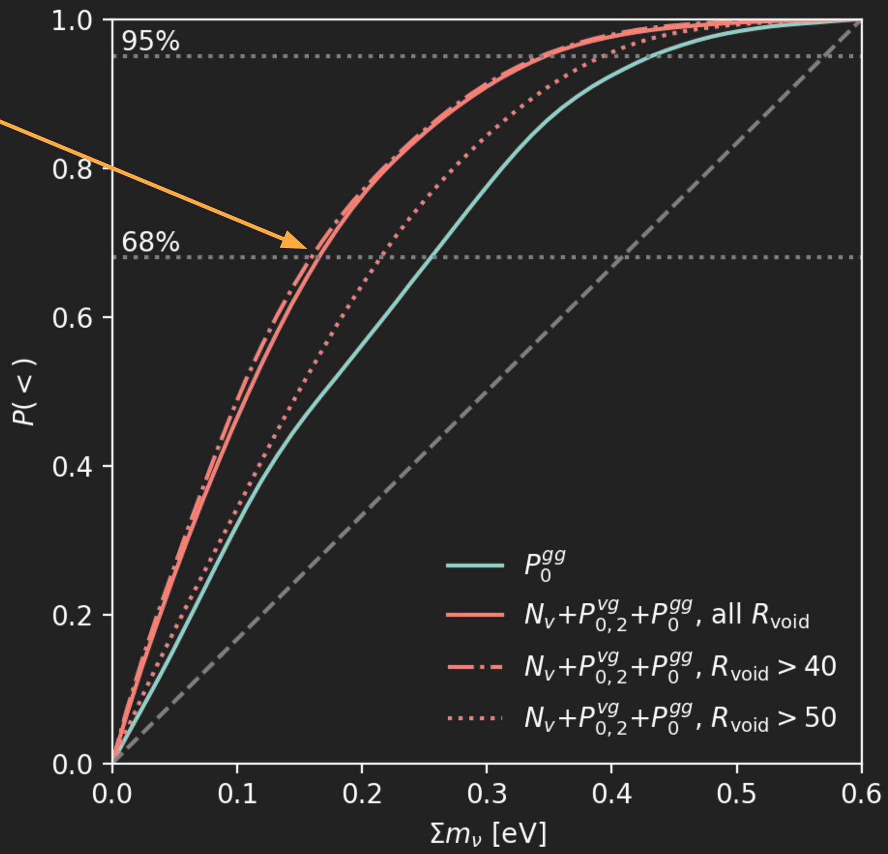
Qualitative agreement with EFT result
→ gives some confidence that simulations are accurate



Influence of void size

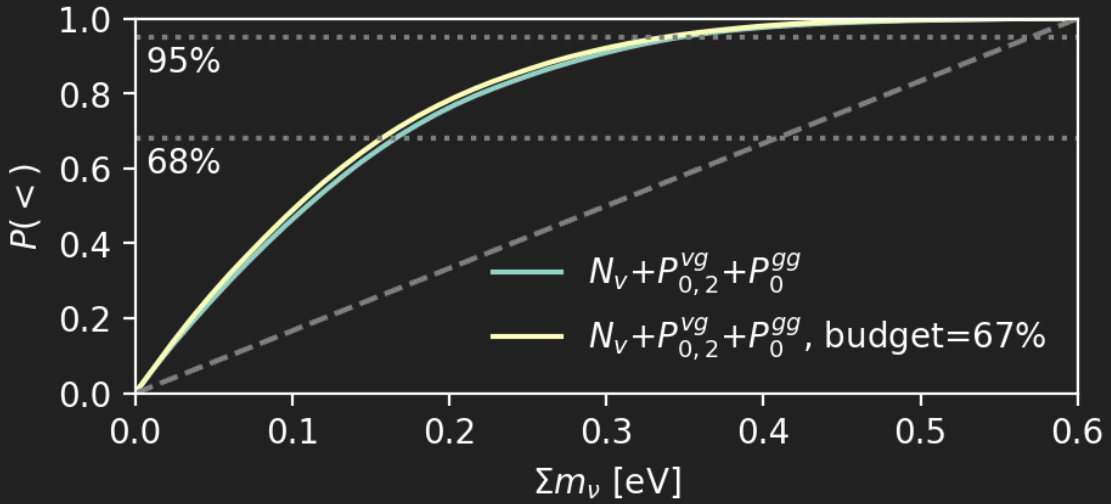
constraint dominated by voids
with 40 < radius / h^{-1} Mpc < 50





Simulation budget

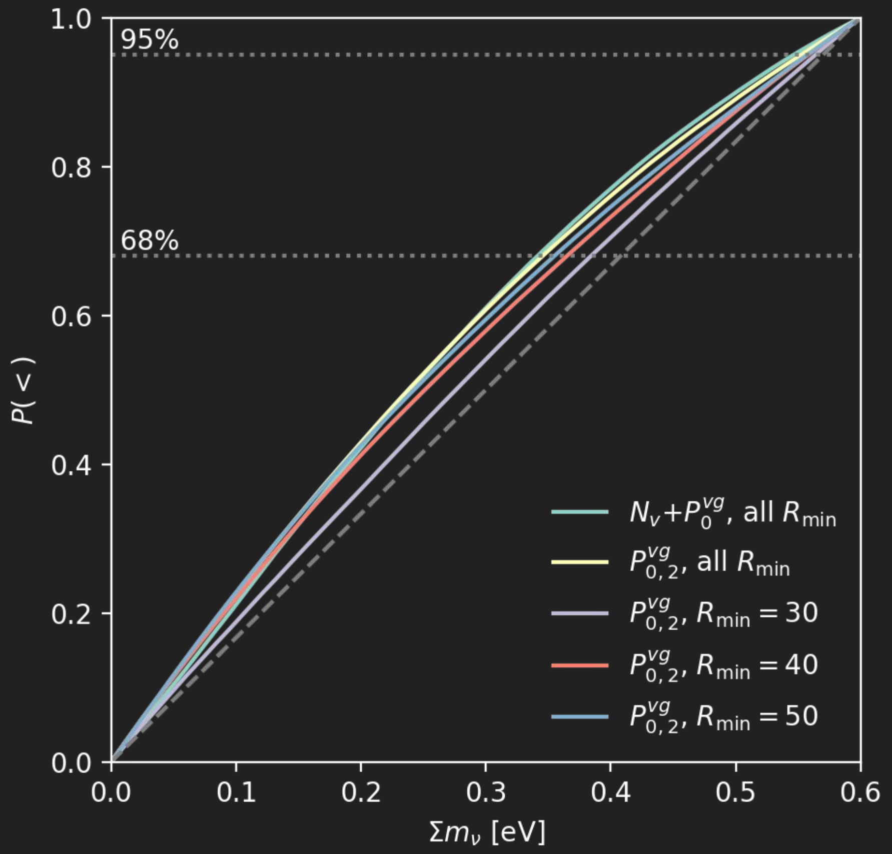
Appear to have enough simulations.
But “augmentation” is the critical point.



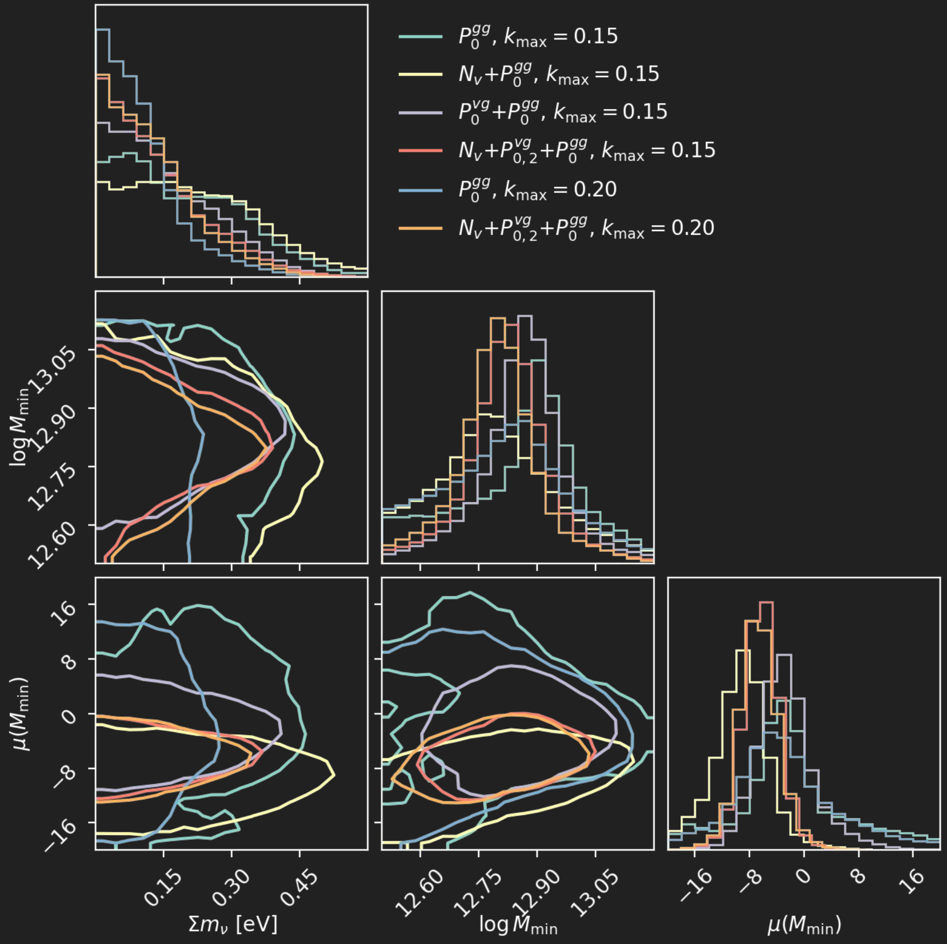
Summary

- constrained neutrino mass sum from BOSS CMASS NGC
- using galaxy auto power spectrum, void size function, void-galaxy cross power spectrum
- modeling based on FastPM+HOD simulations
- implicit likelihood inference with neural ratio estimation
- void statistics appear to contribute a little
- qualitative agreement with EFTofLSS results, but differences
- possible future improvements:
  - simulation layout
  - HOD parameterization
  - compression
  - “perturbative” implicit likelihood inference
  - survey systematics
  - …

Void only posteriors



Full posteriors



EFT posteriors