Field Level Inference of Voids and Galaxy Clusters

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based upon 2304.09193 & 2107.06903

Motivation / Objective

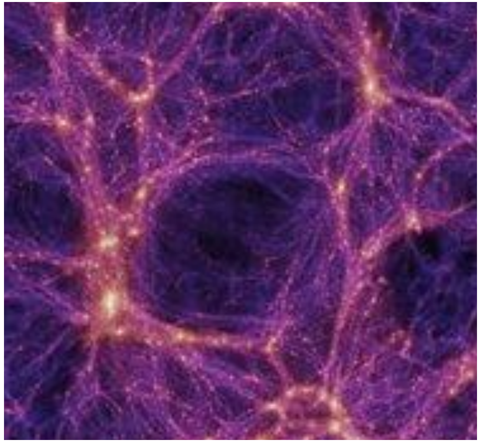
- Cosmology w/ Large scale structures

- Galaxy cluster masses from full surveys
- Void definition as anti-halos

- Automating research
- Quality of inference through
  - posterior predictive tests
  - accuracy tests w/ N-body

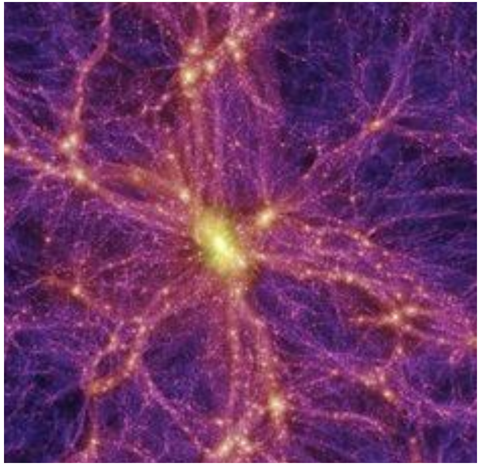
Cosmic Structures: positive aspects

Voids



- Linear on scales > 5 Mpc/h
- Shapes can probe cosmology (Alcock-Paczynski test)
- Density-profile can be used to probe modified gravity/neutrinos

Clusters

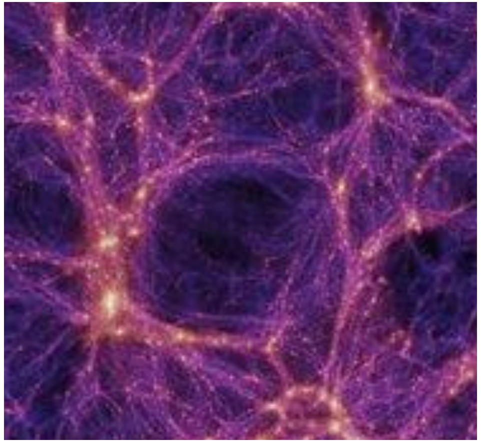


- Non-linear after collapse
- Abundance/mass can probe cosmological parameters (halo mass function).
- Can probe small-scales.

Image credit: Millennium Simulation Project

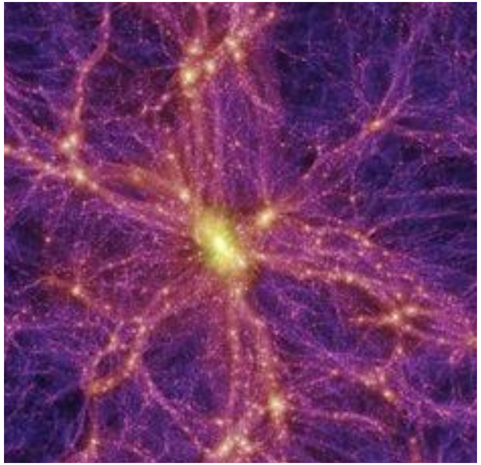
Cosmic Structures: **limits**

Voids



- Apply void finders to galaxy distribution
  (variety of methods/definition)
- Abundance hard to model
  (recent progress on this).

Clusters



- Estimate masses via proxies
  (velocity dispersion, X-ray emission, SZ-effect, weak-lensing).
- Often disagreements, even on nearby clusters.

Common theme: hard to get at dark matter distribution directly. Can we infer it?

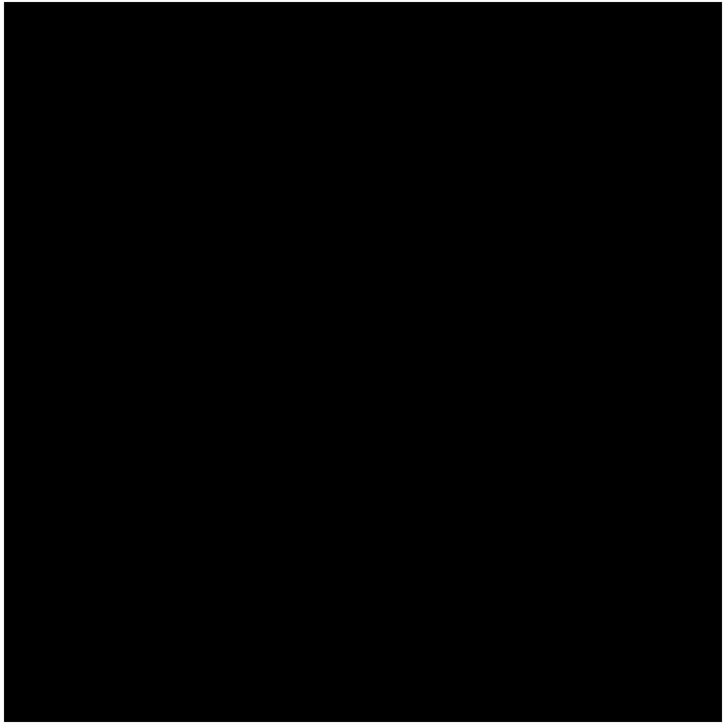
Image credit: Millennium Simulation Project

Achieving complete characterization of cosmic structure

'What I cannot create, I do not understand.'
Richard P. Feynman, 1988

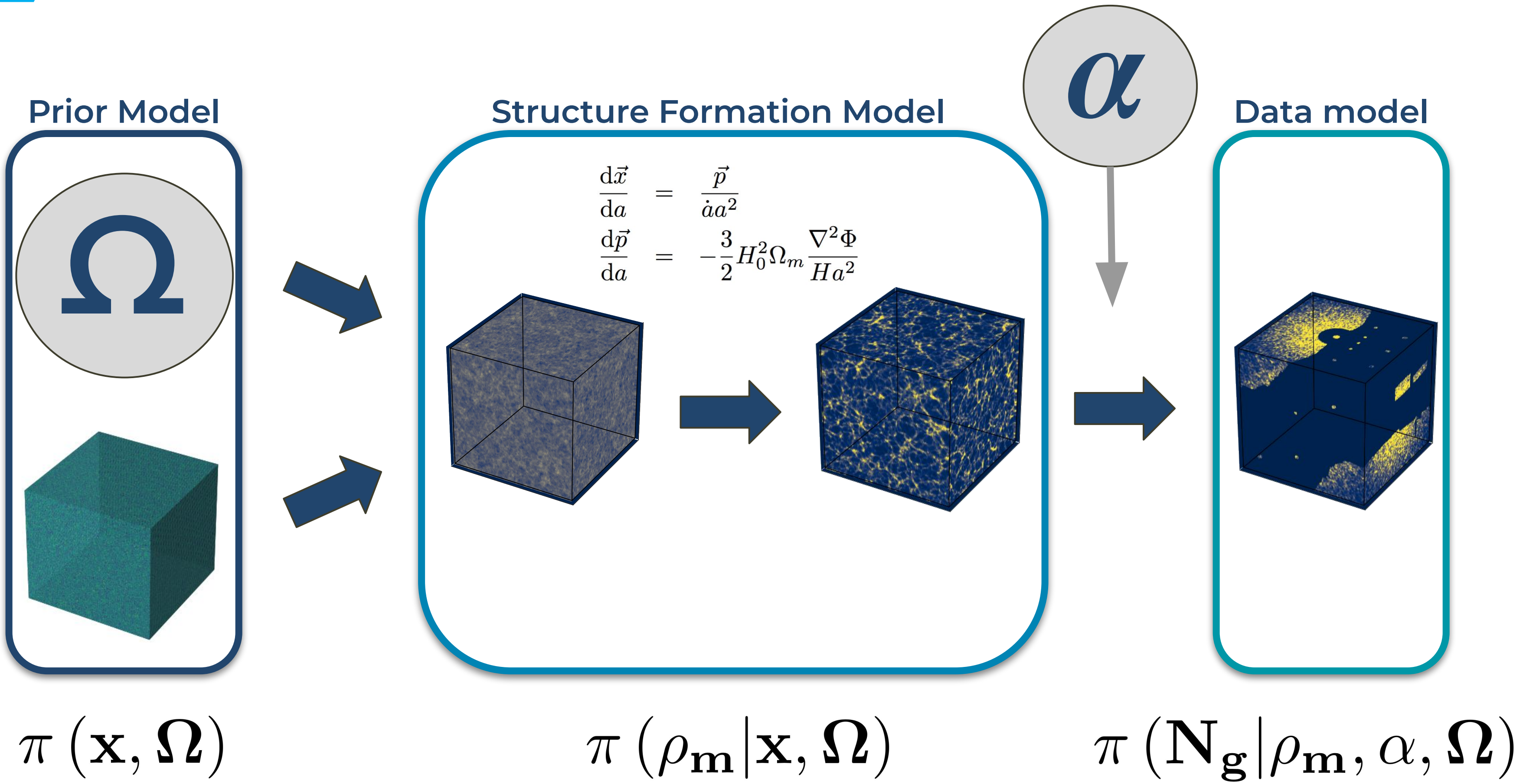
Bayesian Physical forward modeling

- **Field-level inference**
  - Beyond summary statistics
  - Beyond random realizations
- **Non-linear and dynamical inference**
  - Beyond linear structure growth
  - Redshift Distortions
  - Light-Cone effects
- **Causal inference**
  - Beyond associative analyses



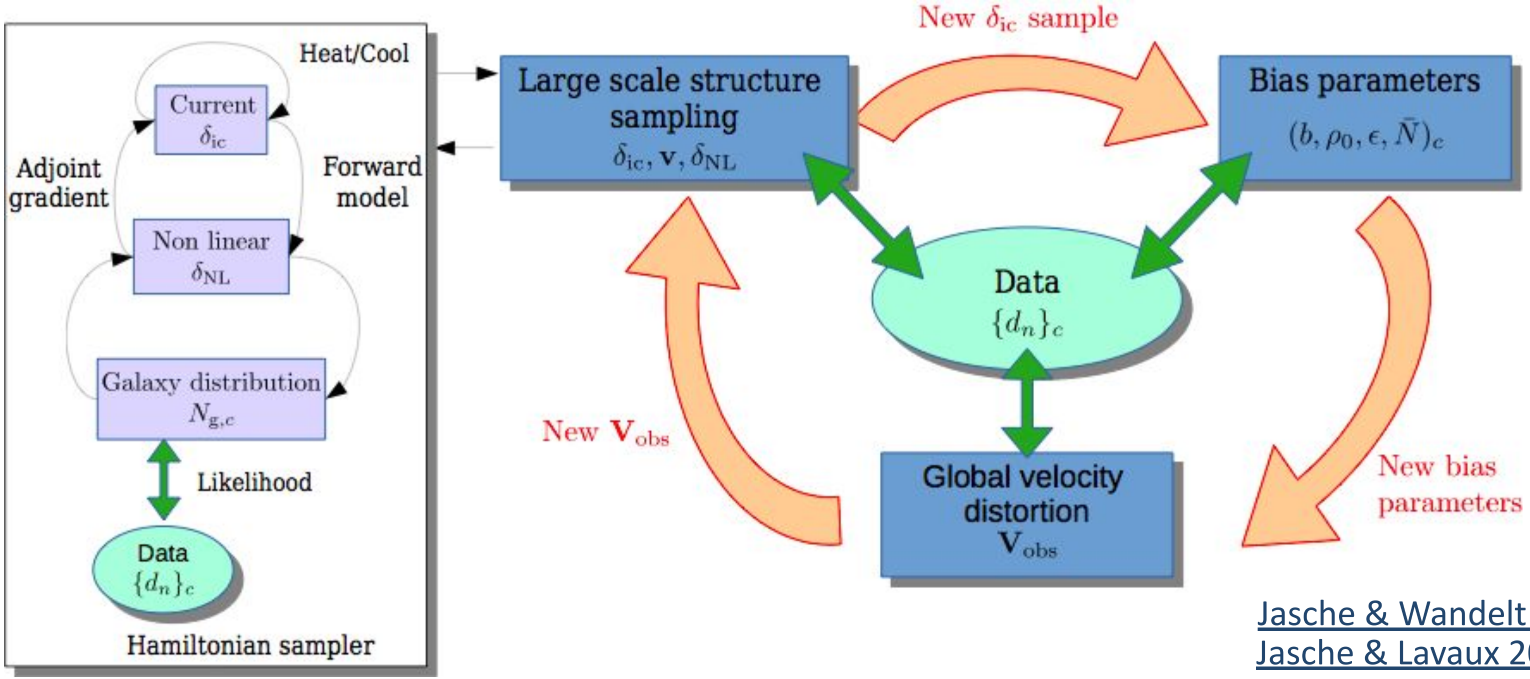
Jasche & Lavaux 2019

Bayesian Forward modeling cosmic structure surveys with BORG



BORG: A large scale MCMC framework

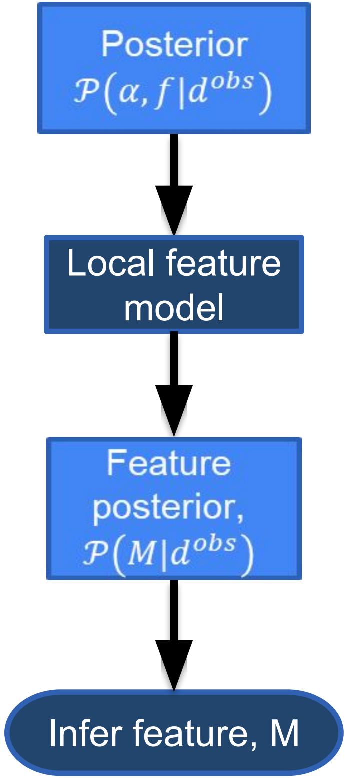
- **BORG's MCMC framework allows building flexible data models**
  - Hierarchical Bayes and block sampling
  - Efficient Hamiltonian Monte Carlo **(HMC)** technique
  - Fully differentiable physics forward model



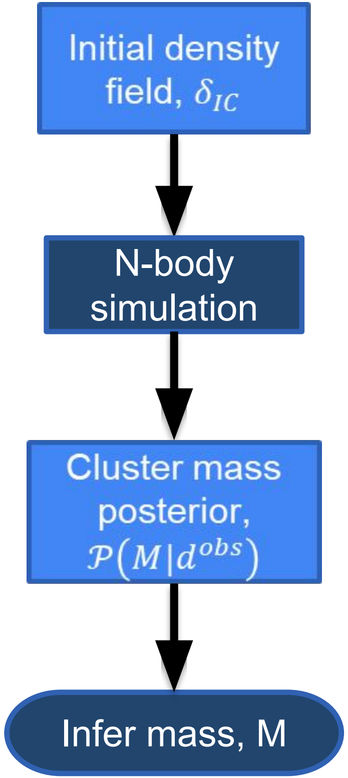
Jasche & Wandelt 2014
Jasche & Lavaux 2019

After the inference: Posterior resimulation

<u>Generic Feature extraction:</u>

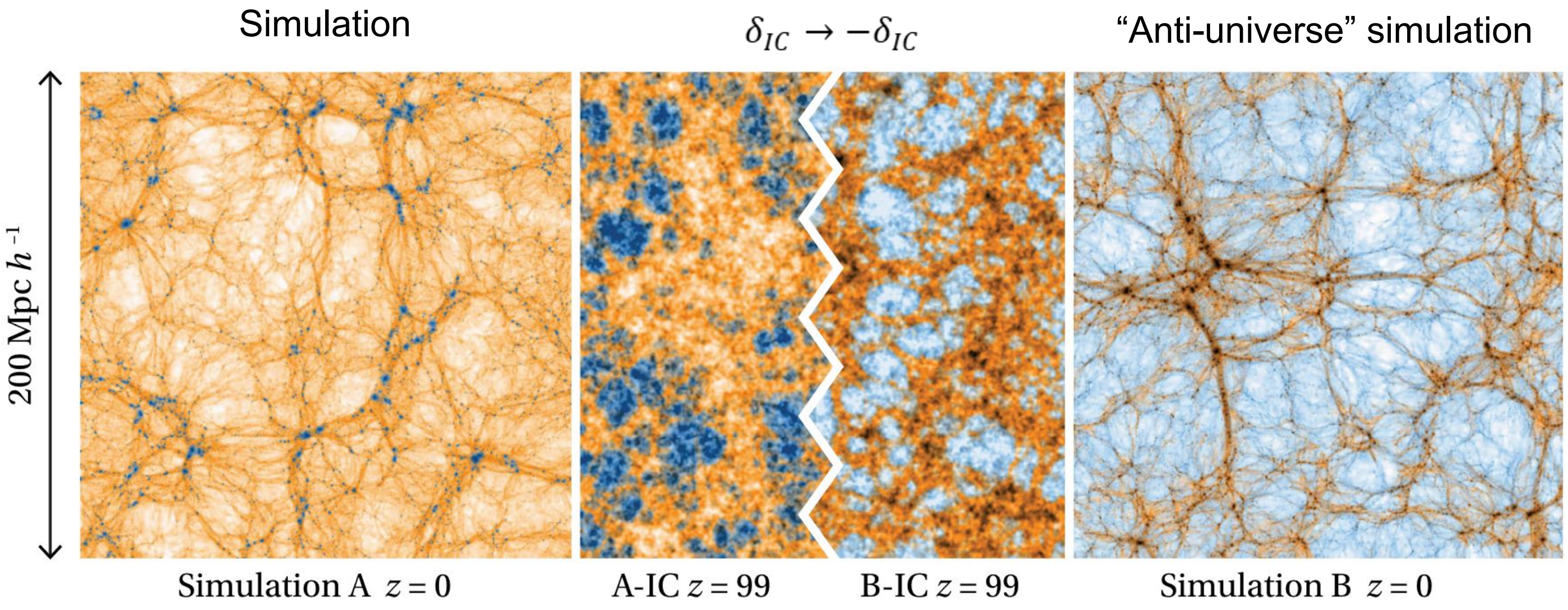


<u>Example – Cluster Mass</u>



- Can also infer local features in data.
- Need **NOT** be the same model used for field inference.
- E.g., information on cluster masses held in initial density over a large Lagrangian patch.
- But need a full N-body simulation to extract it.

Anti-halo Voids

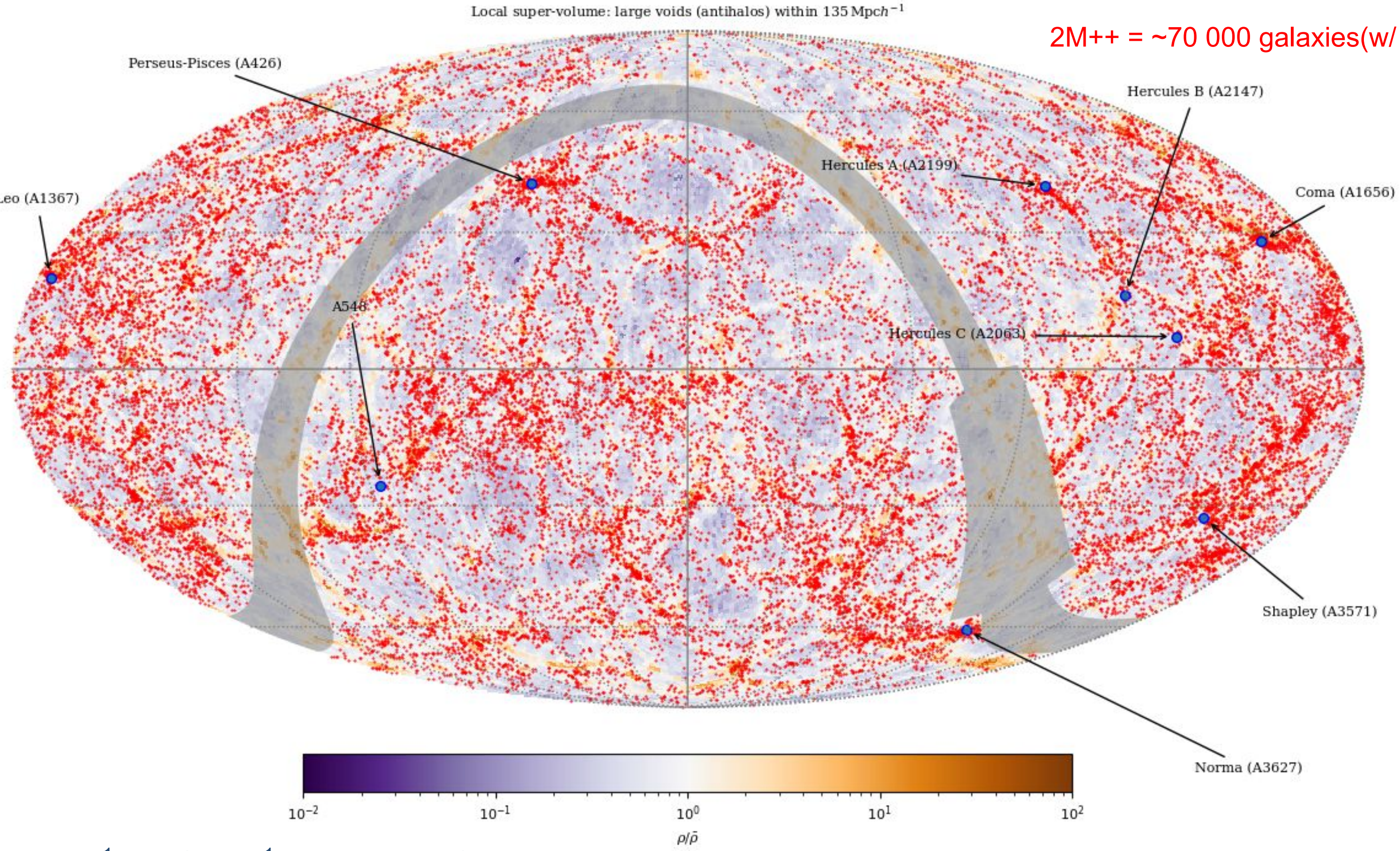


- Can also use posterior resimulations to study voids.
- Model voids as **Anti-halos**[1]: voids = halos from an "anti-universe" simulation.
- Mass function well-defined. Clear connection to initial conditions.
- Cover up to 25 Mpc/h radius regime of voids.
- May only be done if you **HAVE** initial conditions, provided by Field Level Inference

[1] Pontzen A., Slosar A., Roth N., Peiris H. V., 2016, Phys. Rev., D93, 103519

Field Level Inference with BORG: the case of 2M++, a new inference run

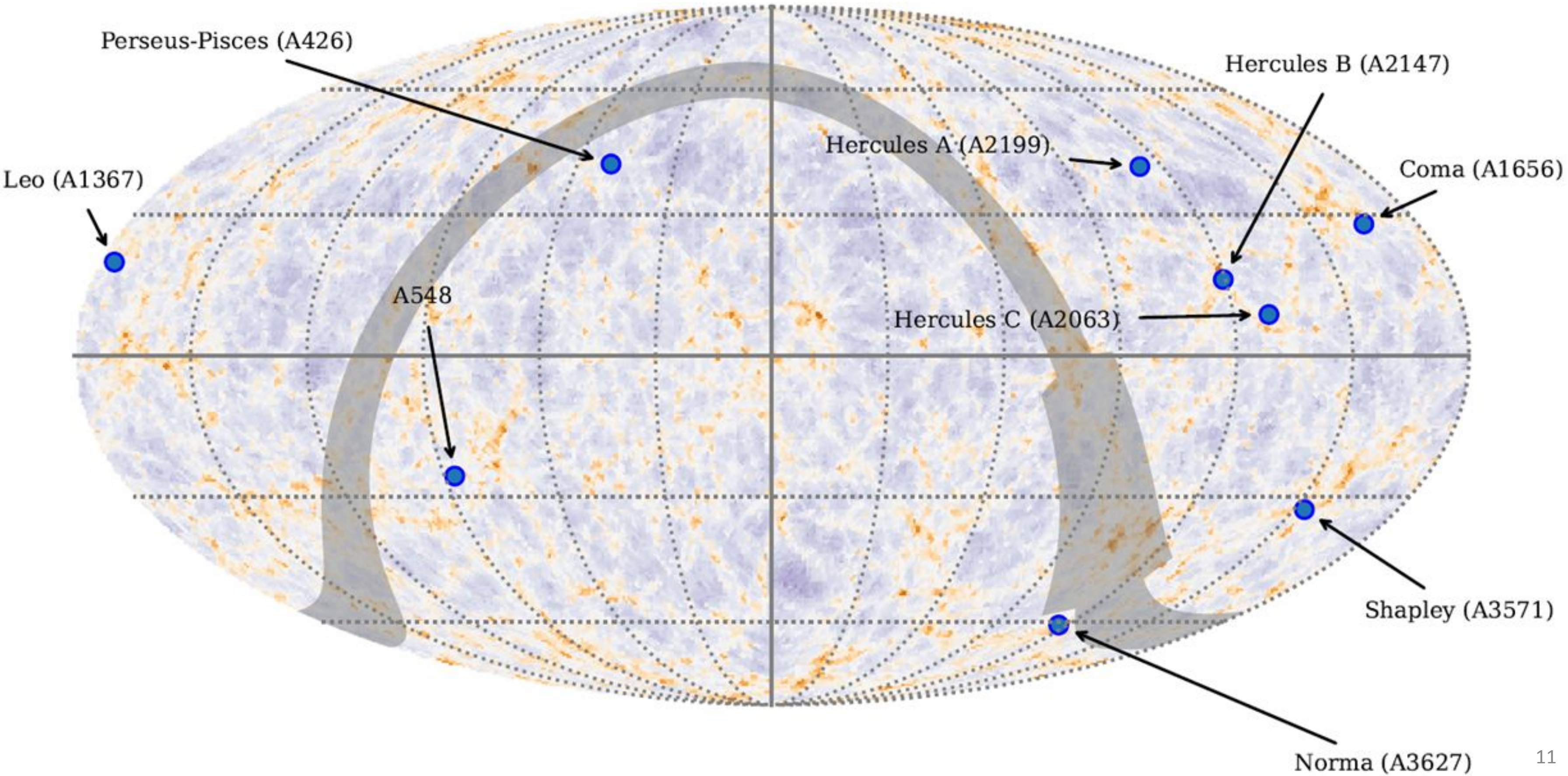
2M++ = ~70 000 galaxies(w/ spec-z)



ICs: 256^3 grid, 676.7h^{-1} Mpc (2.65h^{-1} Mpc resolution)

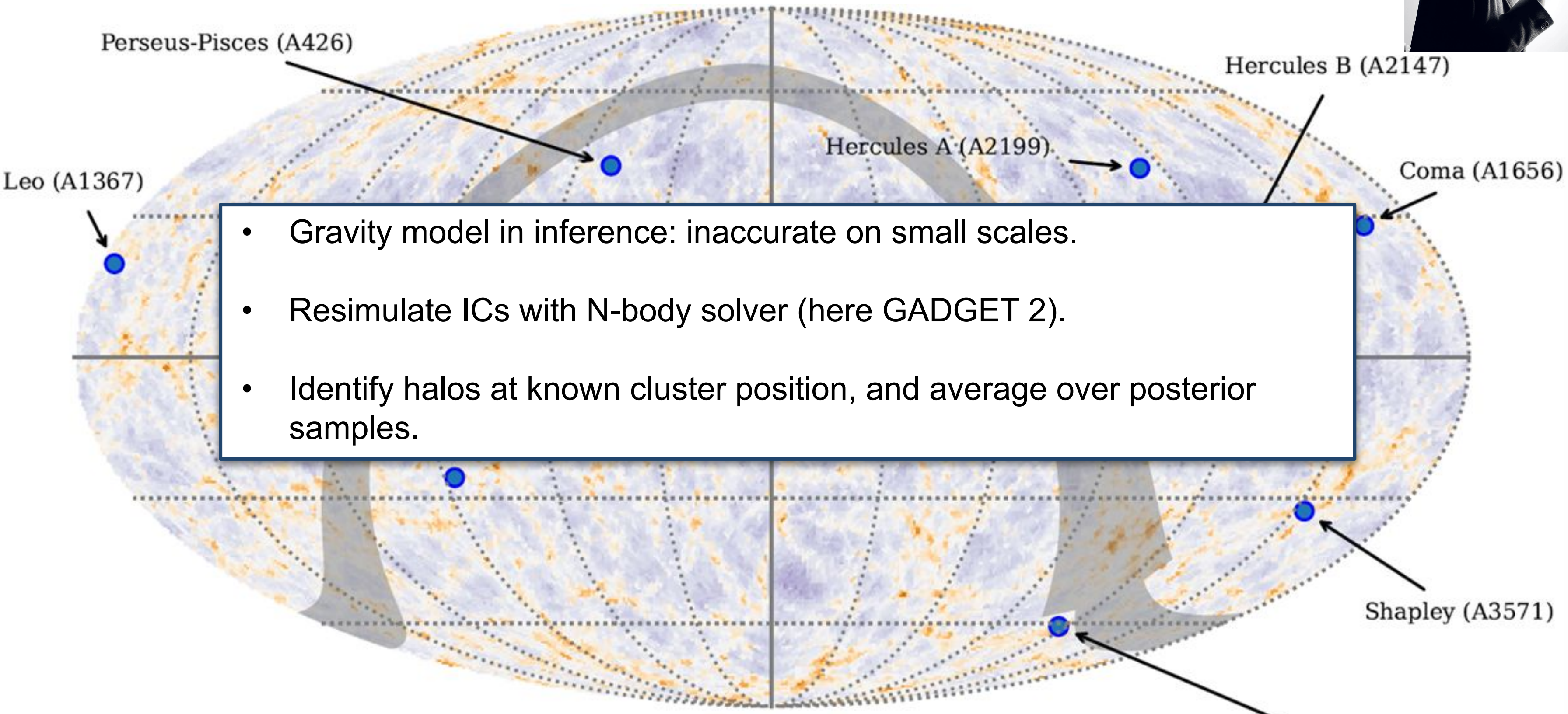
[1] Lavaux G., Hudson M. J., 2011, MNRAS, 416, 2840

Some galaxy clusters of interest to check masses



Stopyra S., Peiris H. V., Pontzen A., Jasche J., Natarajan P., 2021, *Monthly Notices of the Royal Astronomical Society*, 507, 5425

Two features of interest: 1/ accuracy of the N-body solver



- Gravity model in inference: inaccurate on small scales.
- Resimulate ICs with N-body solver (here GADGET 2).
- Identify halos at known cluster position, and average over posterior samples.

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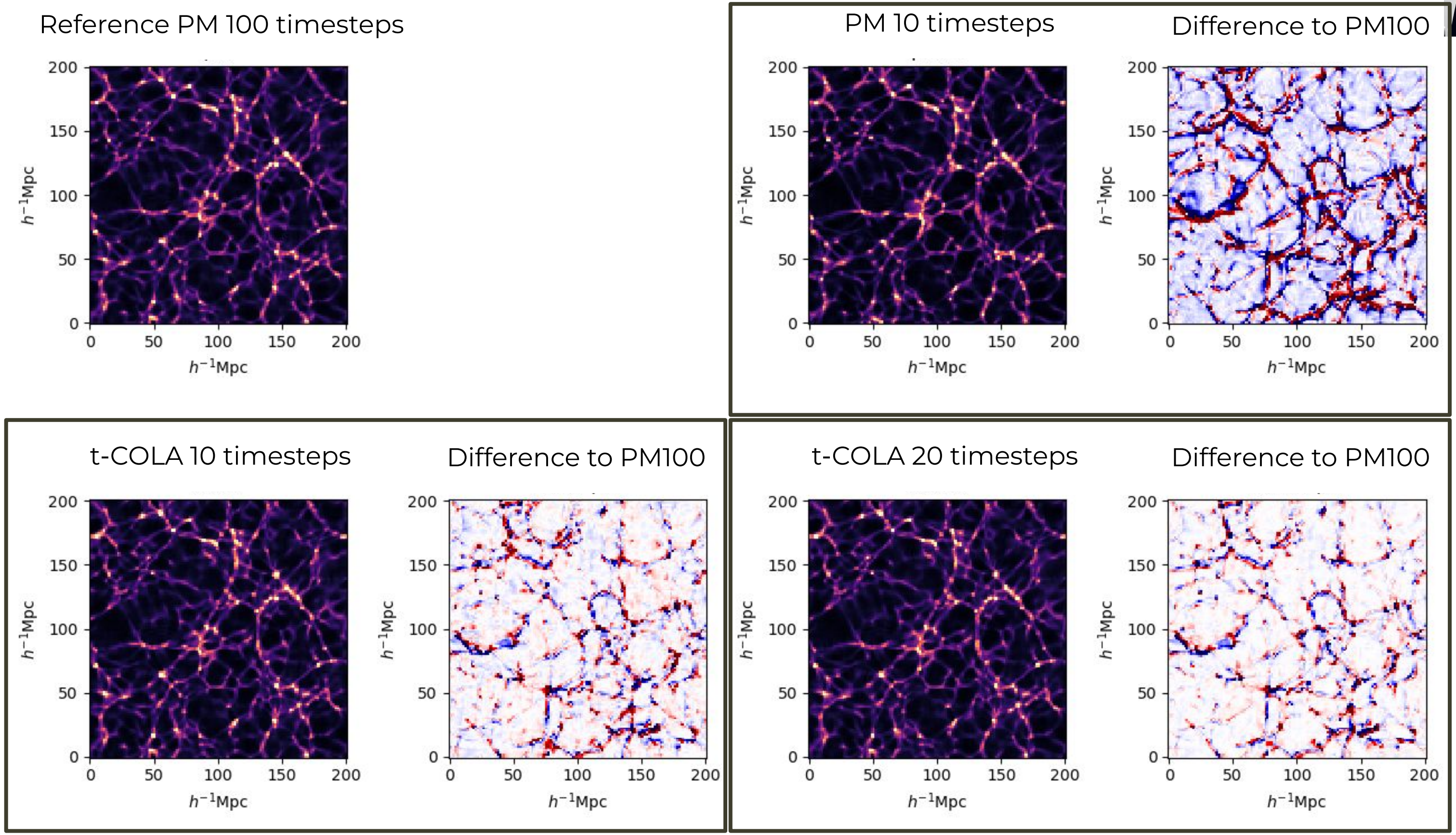
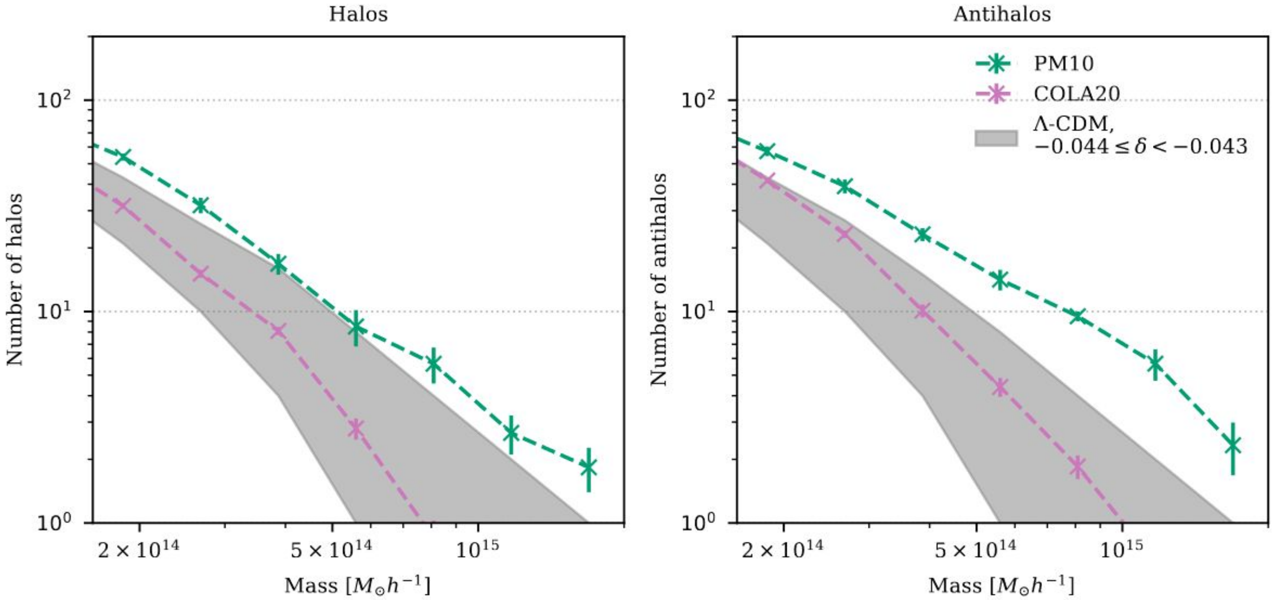


Accuracy requirements



However, inference model accuracy matters.

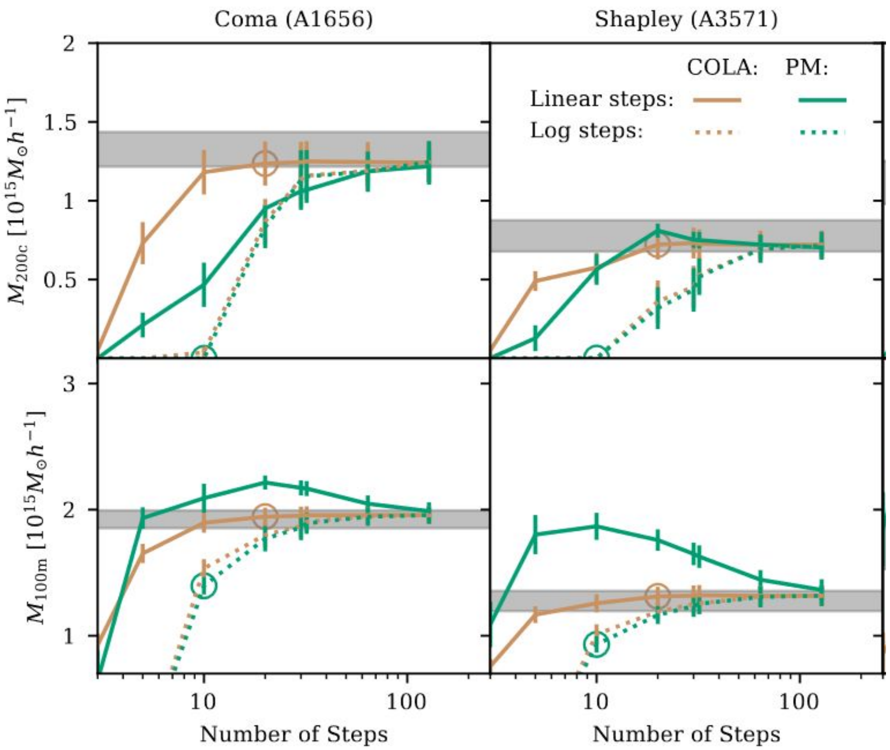
E.g., 10-step particle mesh underestimates core density at 10^15 Msol/h.

BORG compensates by inferring higher initial density.

Leads to overestimate masses!

[1] Stopyra S., ..., GL, 2023, *Monthly Notices of the Royal Astronomical Society*

Accuracy requirements

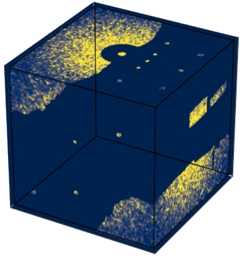


- Must choose models that are compatible at the virial radius scale.
- Investigated COLA/PM models with different time-step resolutions.
- COLA with 20 linearly-spaced steps could reproduce masses for most massive clusters.
- Insufficient for constraining ~10^14 Msol/h clusters, but mass functions are correct.

[1] Stopyra S., ..., GL, 2023, *Monthly Notices of the Royal Astronomical Society*

Two features of interest: 2/ resilience to systematics

Data model



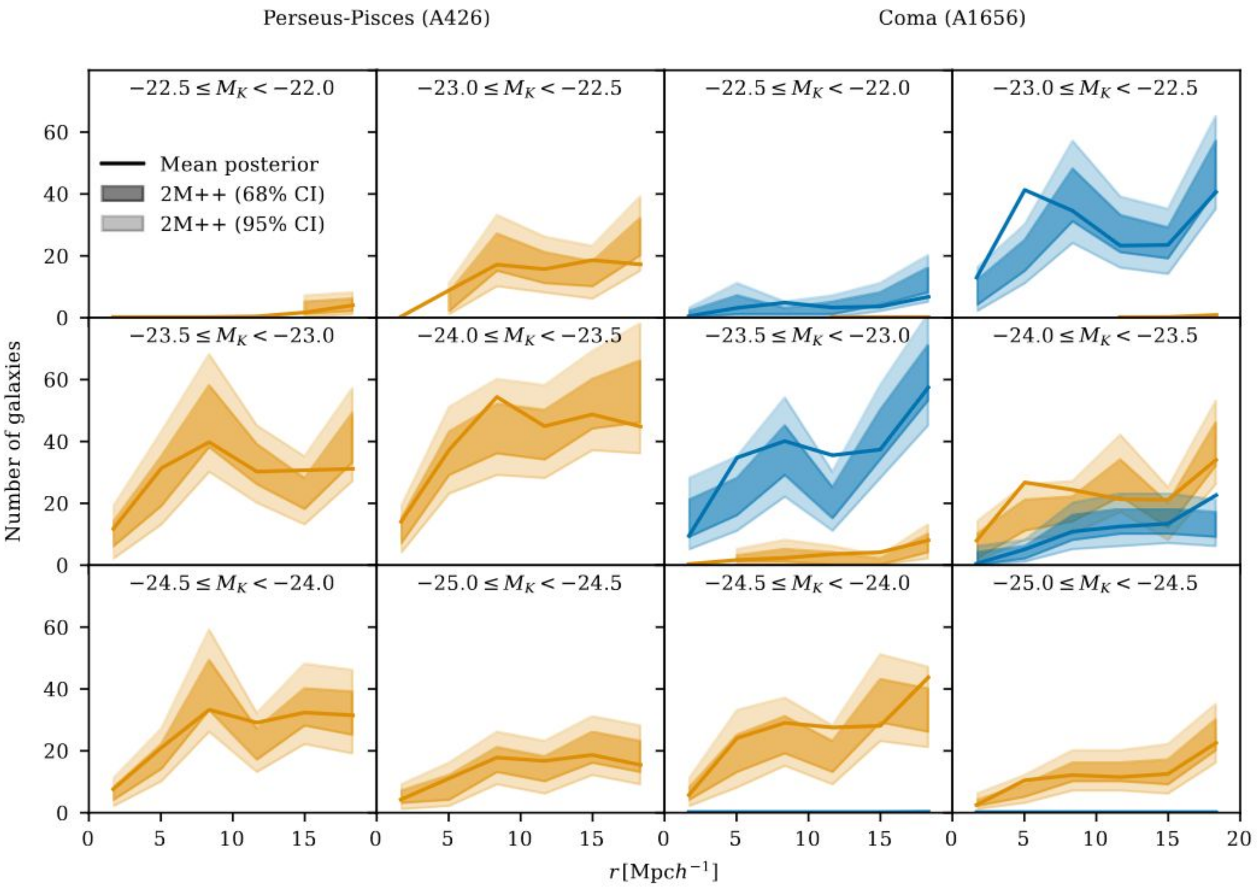
$$\pi\left(\mathbf{N_g} \middle| \rho_{\mathbf{m}}, \alpha, \boldsymbol{\Omega}\right)$$

$$\mathbf{N}_g = \mathbf{A} \odot \boldsymbol{\lambda}_g$$

A = foreground map, (+ Jeffreys prior)

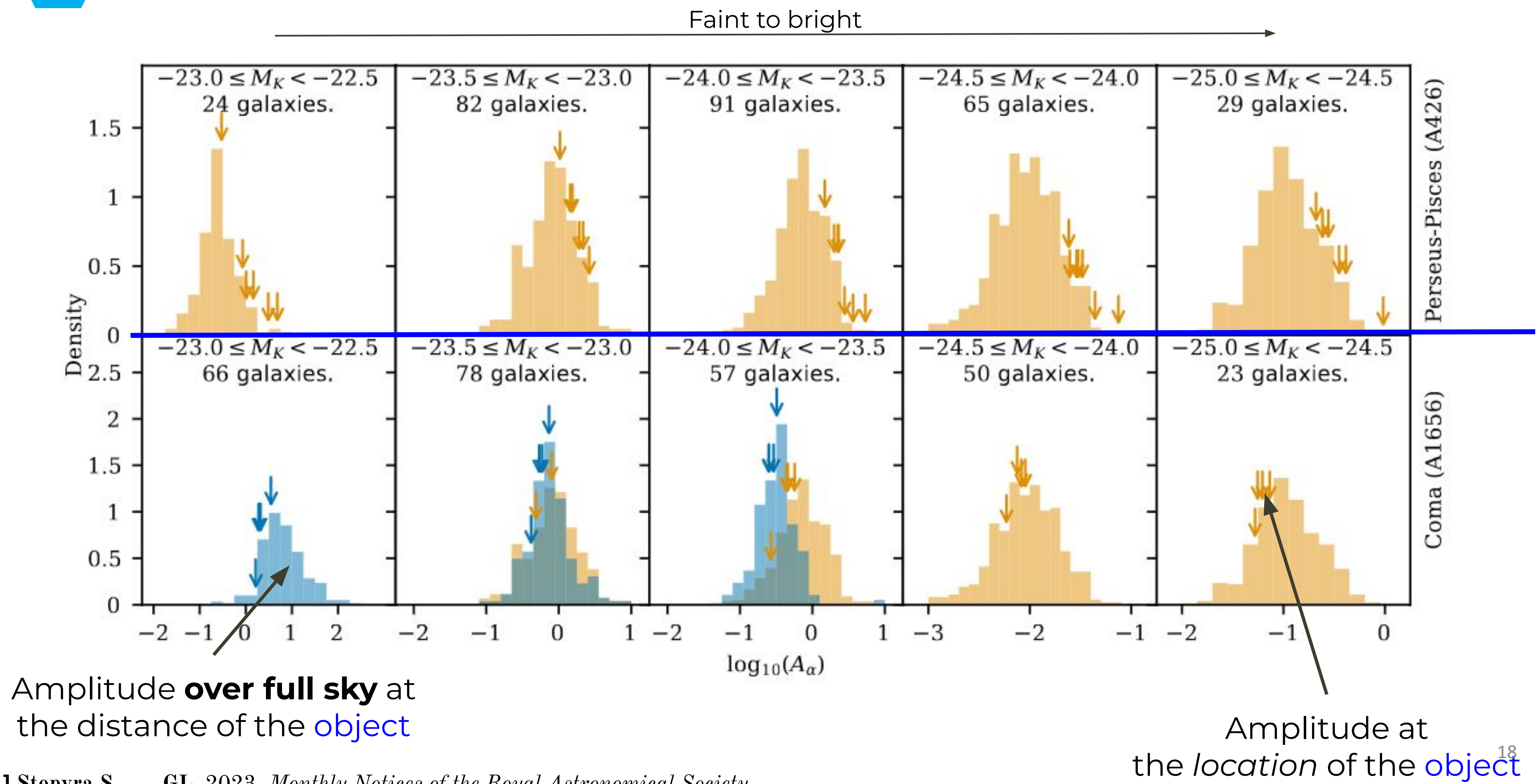
λ = output of galaxy bias model

Posterior predictive tests: galaxy abundances



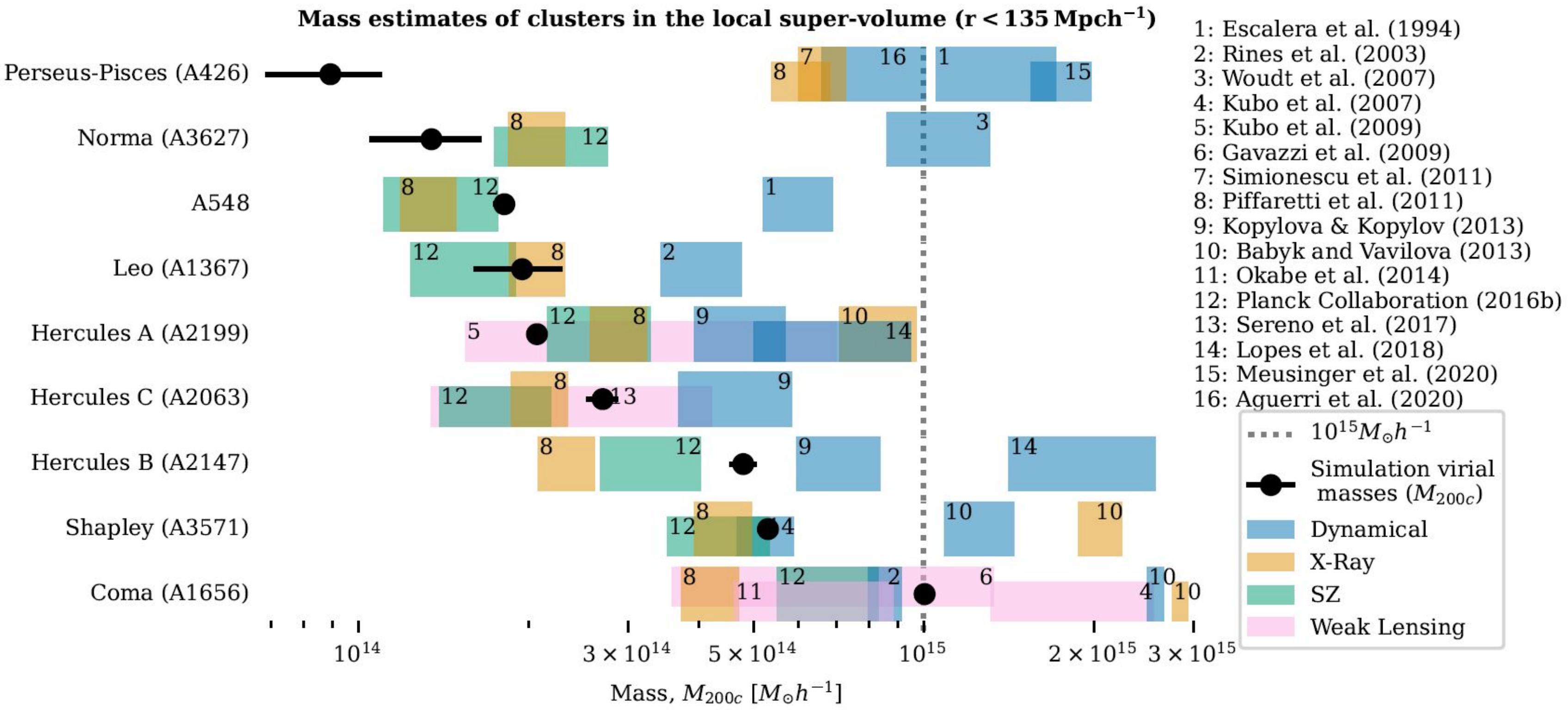
[1] **Stopyra S., ..., GL,** 2023, *Monthly Notices of the Royal Astronomical Society*

Posterior predictive tests: amplitude of systematic pixels



[1] Stopyra S., ..., GL, 2023, *Monthly Notices of the Royal Astronomical Society*

Mass Estimates with BORG Posterior Resimulation

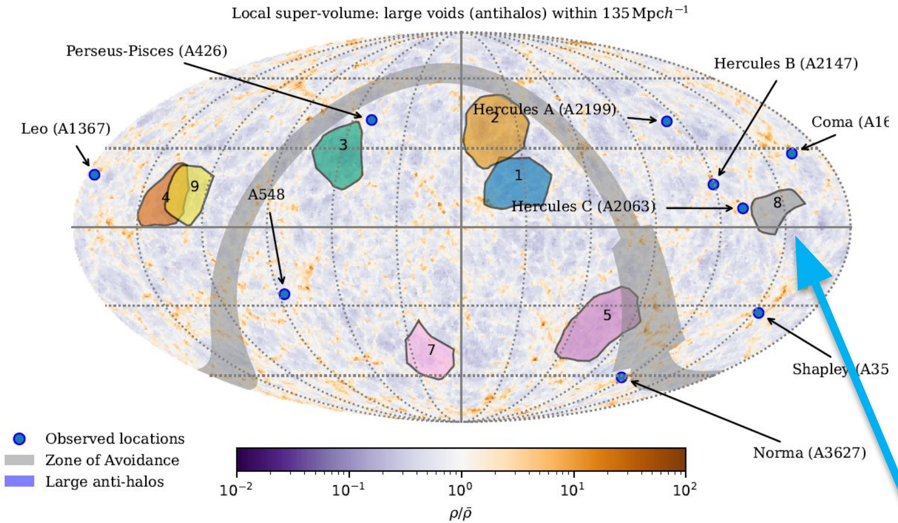


[1] Stopyra S., Peiris H. V., Pontzen A., Jasche J., Natarajan P., 2021, *Monthly Notices of the Royal Astronomical Society*, 507, 5425

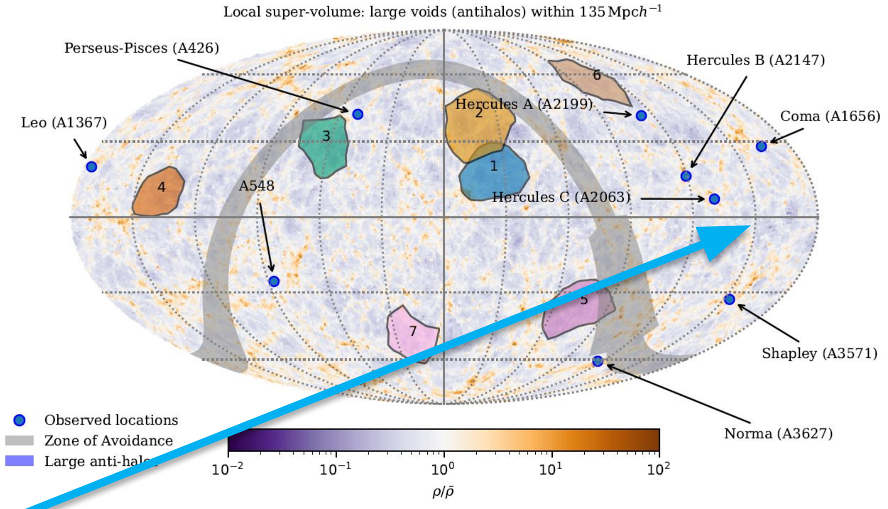
Anti-halos with BORG

- N samples from posterior. N anti-halo catalogues. How to combine them?
- What is the ‘same’ void in different MCMC samples?
- How do we know if an anti-halo is reliably constrained?

MCMC Sample 8500



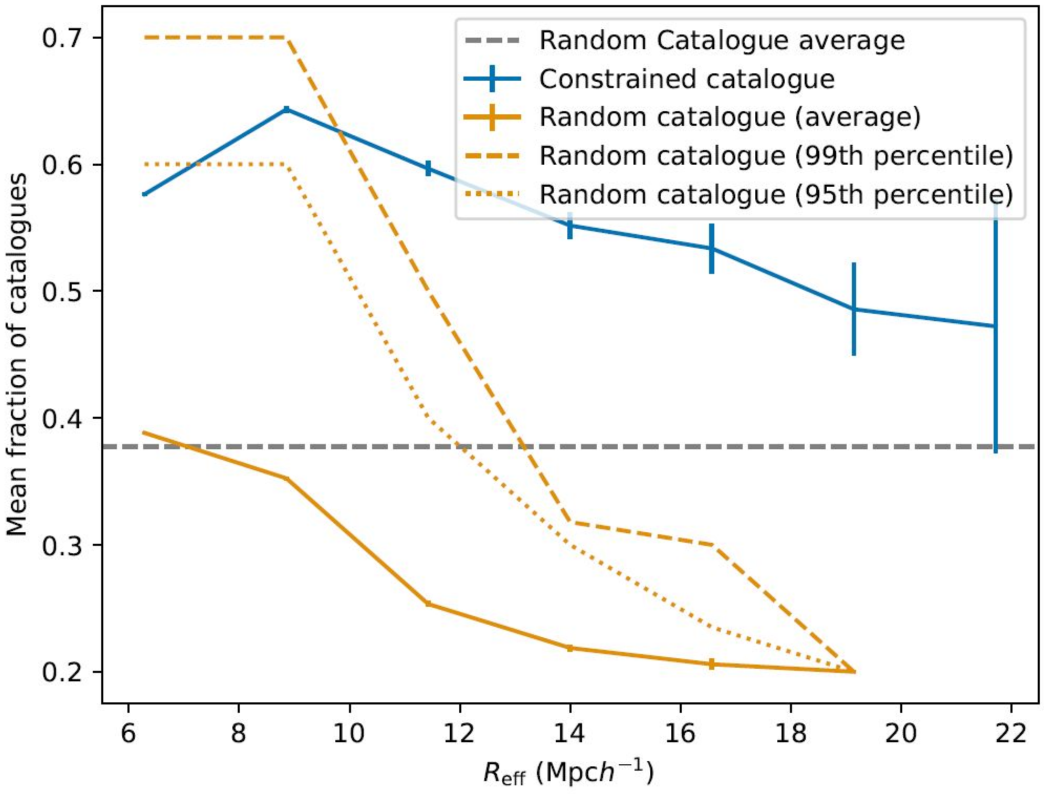
MCMC Sample 8800



Inconsistent appearance between MCMC samples indicates less-constrained anti-halos.

Anti-halos with BORG

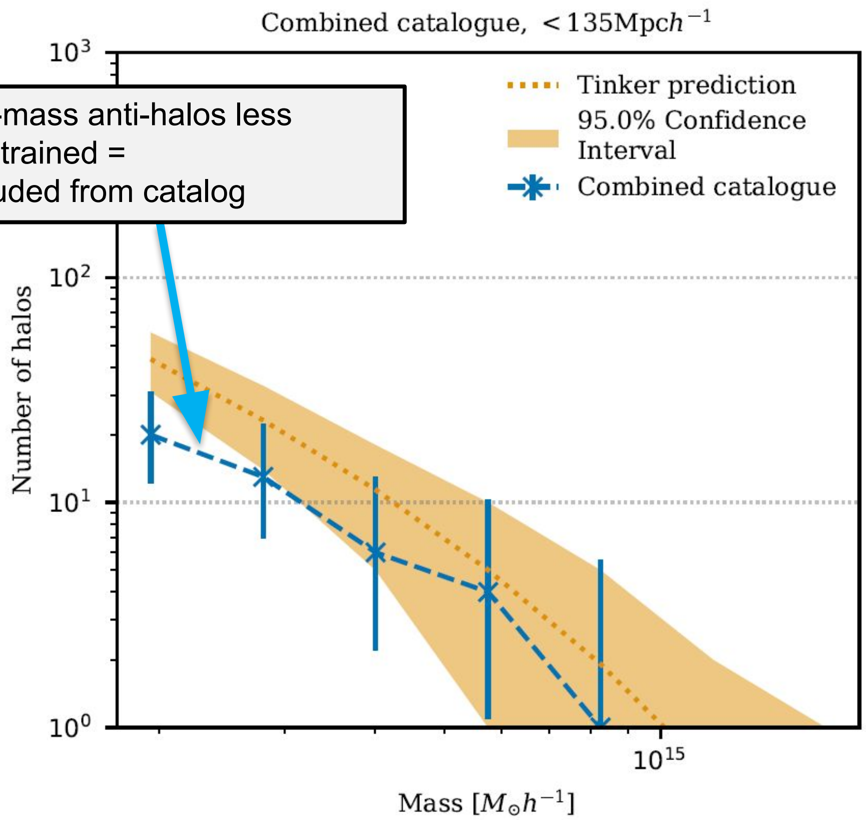
- Cut void from all catalogues with low signal-to-noise (SNR).
- Match remaining voids on distance (<1 void radii), and size.
- Exclude ambiguous matches.
- Retain voids appearing in high fraction of samples.

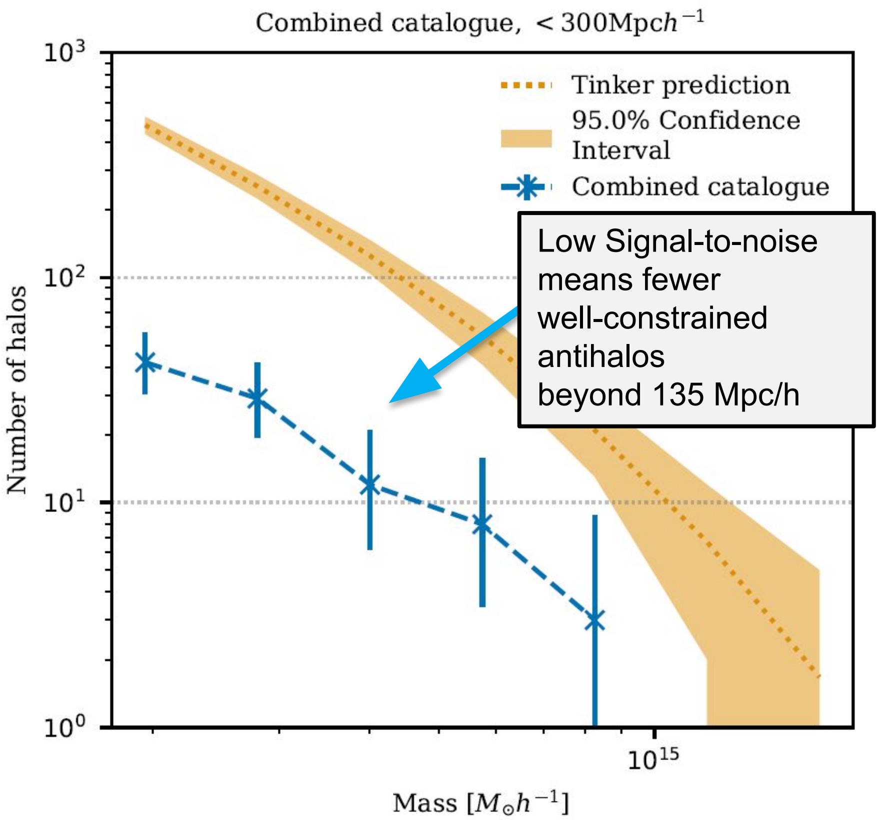


Voids = Anti-halos with BORG

PRELIMINARY RESULTS!

Low-mass anti-halos less constrained = excluded from catalog



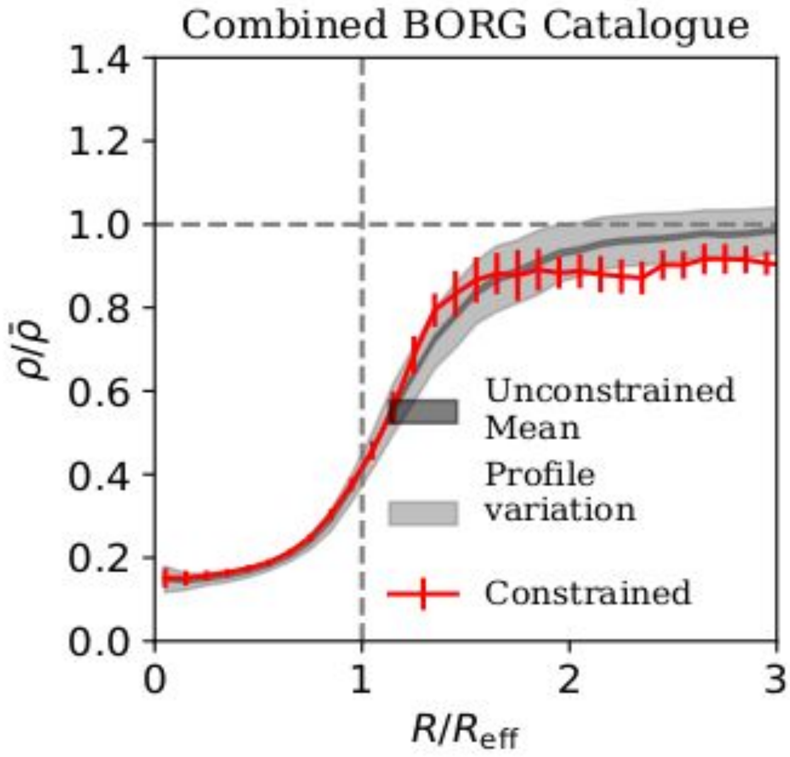


Low Signal-to-noise means fewer well-constrained antihalos beyond 135 Mpc/h

Constraining Physics with Voids

PRELIMINARY RESULTS!

- Test physics using mean void profile
- Slightly low profile observed, but within variance of similar regions in simulations.
- Modified gravity may change void evolution.
- Massive neutrini also affect void size-distribution.



Conclusions

- Estimated masses of the largest clusters w/ resimulation of BORG initial conditions.
- Method for combining catalogues from different MCMC samples into one catalogue.
- Agreement with X-ray/SZ data.
- Abundance consistent with Lambda-CDM.
- Removes voids with low signal-to-noise and retains high-confidence voids.
- Void profiles compatible with Λ-CDM