Field Level Inference of Voids and Galaxy Clusters

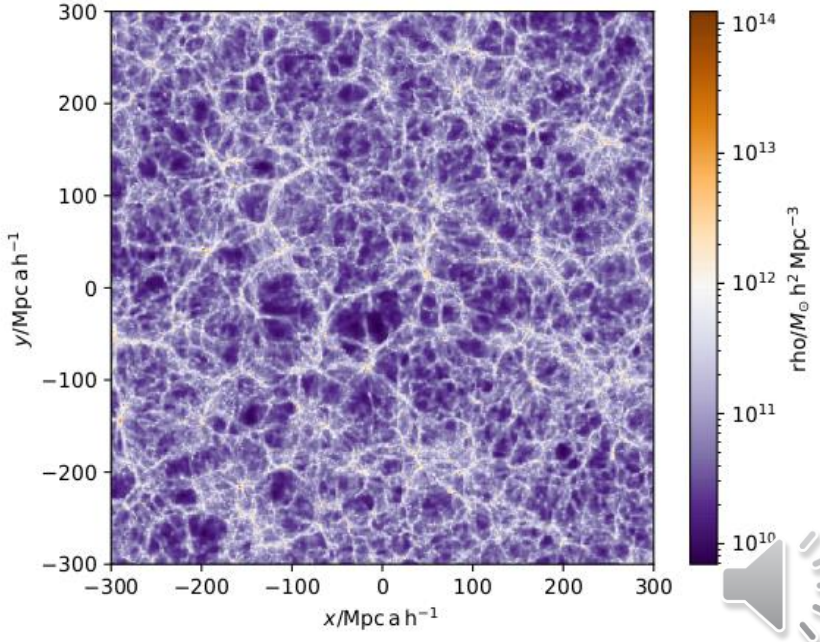
Stephen Stopyra

Cosmology from Home 2023

Based on arxiv:2304.09193
In collaboration with Hiranya V. Peiris, Andrew Pontzen, Jens Jasche and Guilhem Lavaux

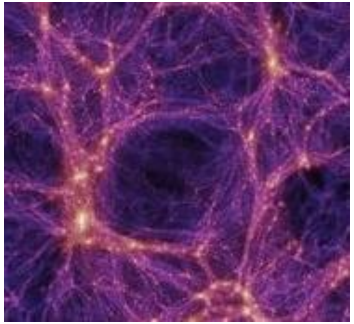
Cosmic Structures

- Large scale structure encodes information about the Universe's initial conditions.
- Cluster properties such as mass, abundance sensitive to new physics (e.g., primordial non-Gaussianity).
- Void size and abundance sensitive to modified gravity.



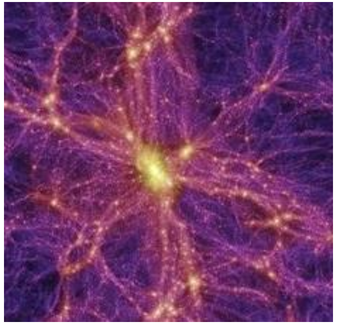
Cosmic Structures

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

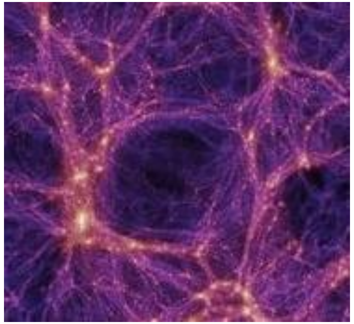


- Non-linear after collapse
- Abundance/mass can probe cosmological parameters (halo mass function).
- Can probe small-scales.

Image credit: Millennium Simulation Project

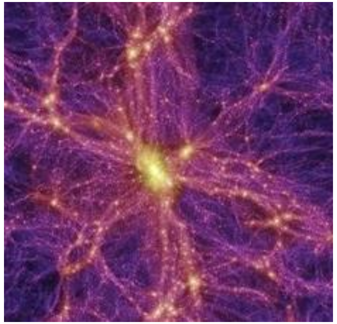
Cosmic Structures

Voids



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

Clusters

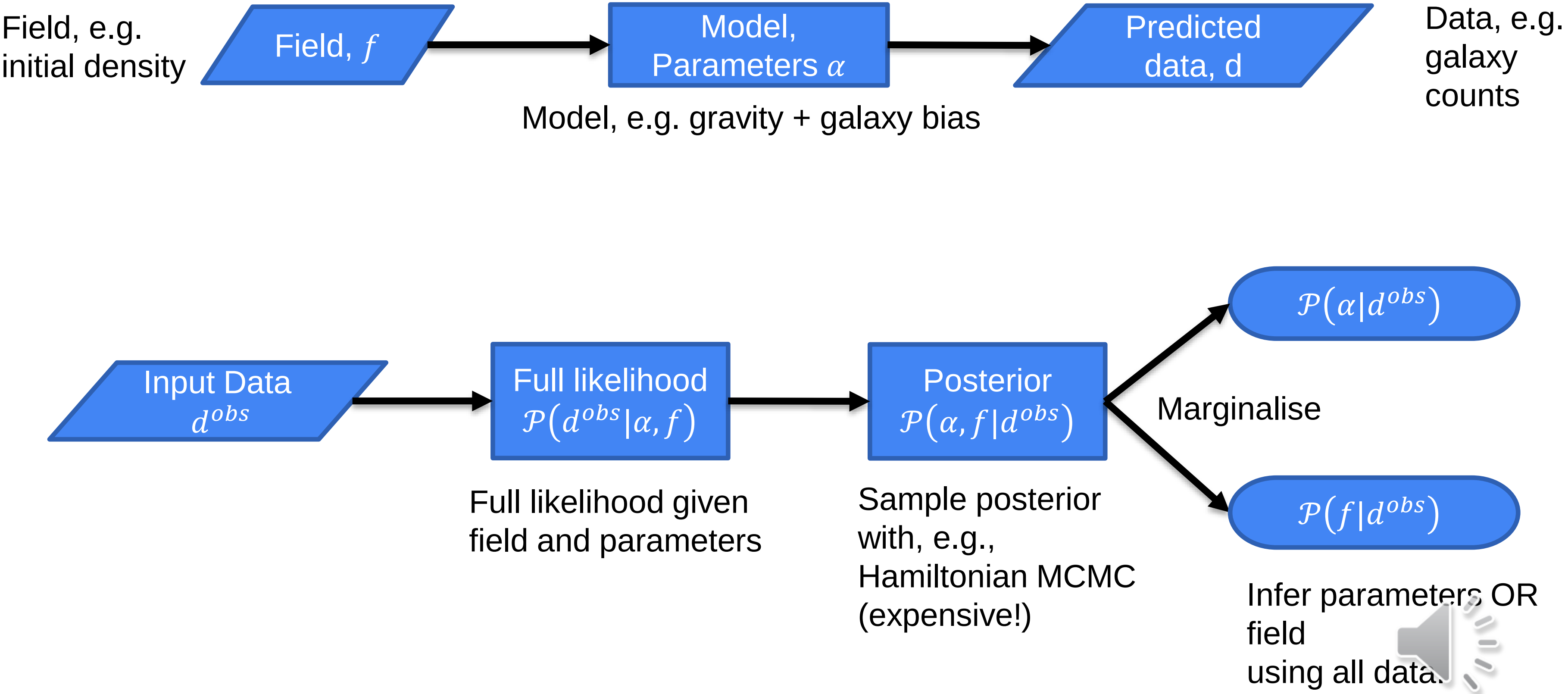


- Estimate masses via proxies (velocity dispersion, X-ray emission, SZ-effect, weak-lensing).
- Often disagreements, even on nearby clusters.

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

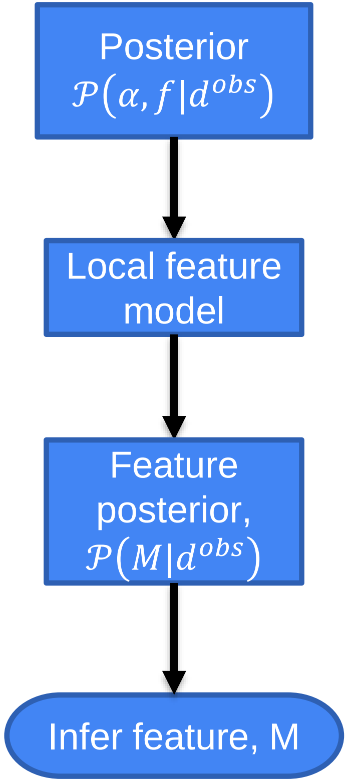
Image credit: Millennium Simulation Project

Field Level Inference

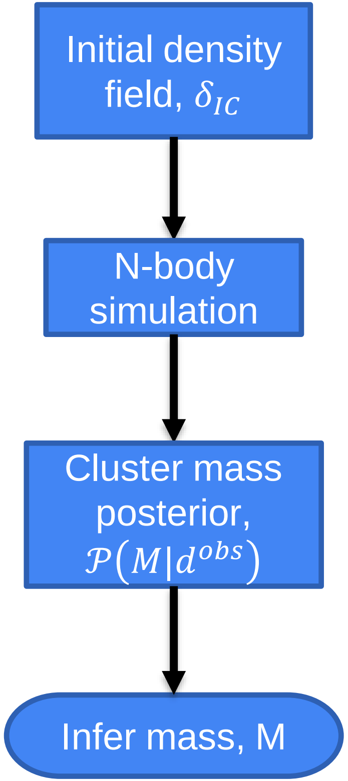


Posterior Resimulation

Generic Feature extraction:



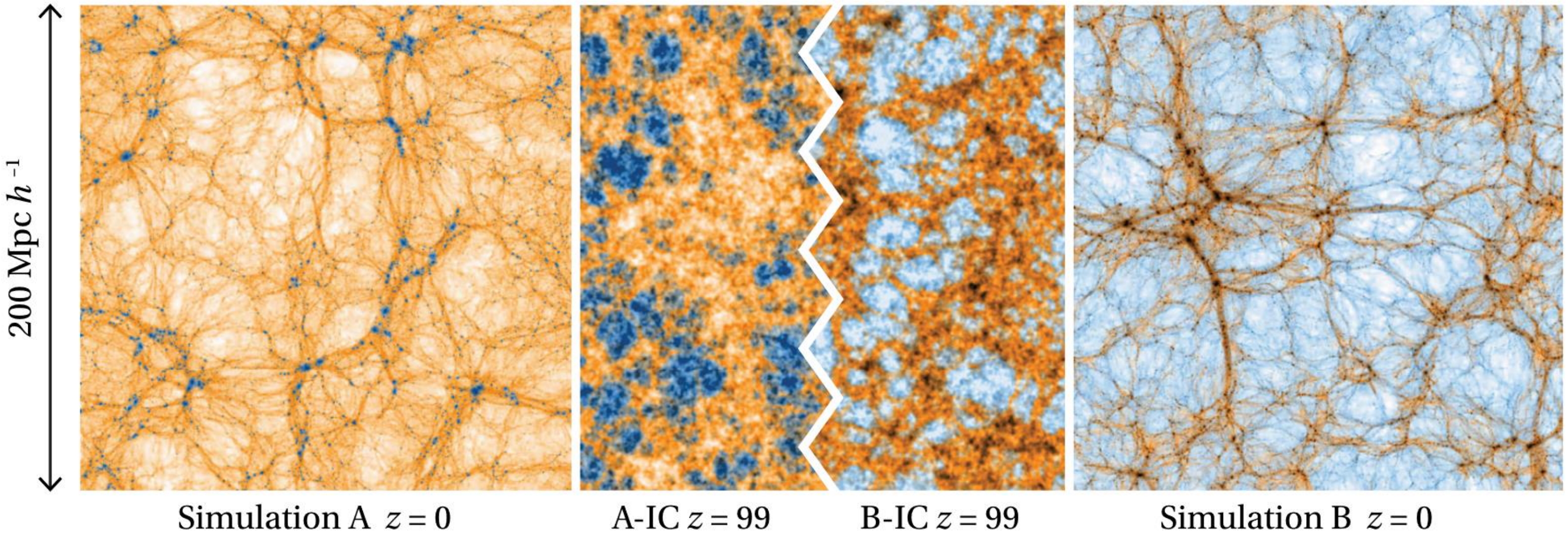
Example – Cluster Mass



- 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

Simulation $\delta_{IC} \rightarrow -\delta_{IC}$ "Anti-universe" simulation

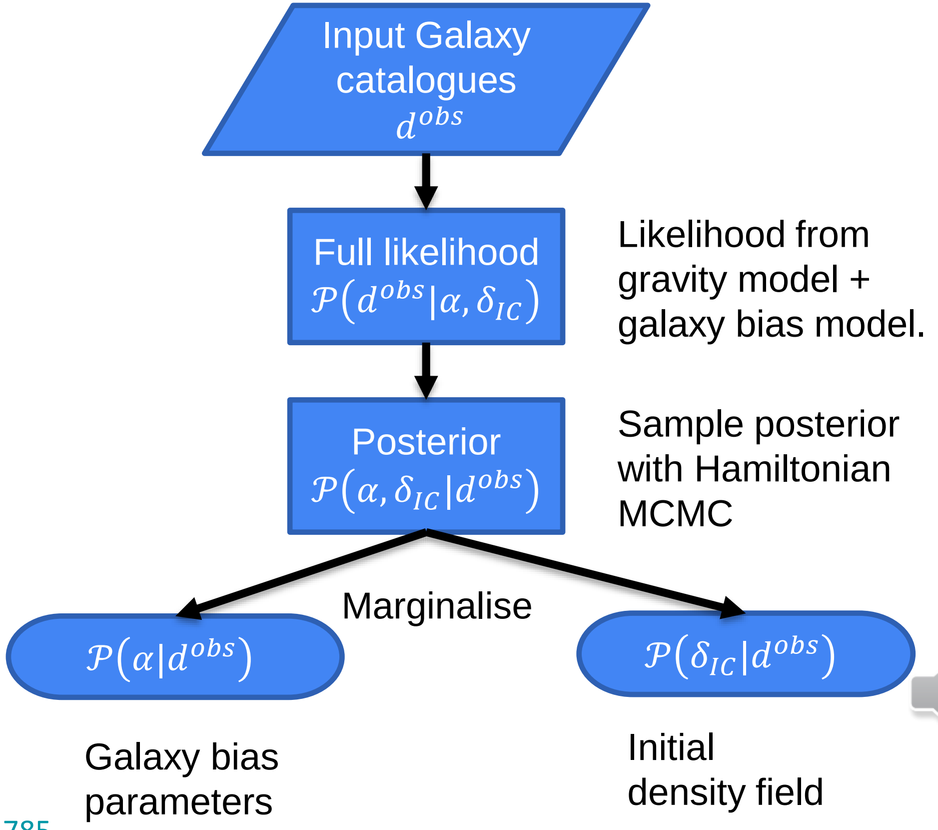


- Can also use posterior resimulations to study voids.
- Model voids as **Anti-halos**[1]: voids identified as halos from an "anti-universe" simulation.
- Mass function well-defined. Clear connection to initial conditions.
- Cover up to 25 Mpc/h radius regime of voids.

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

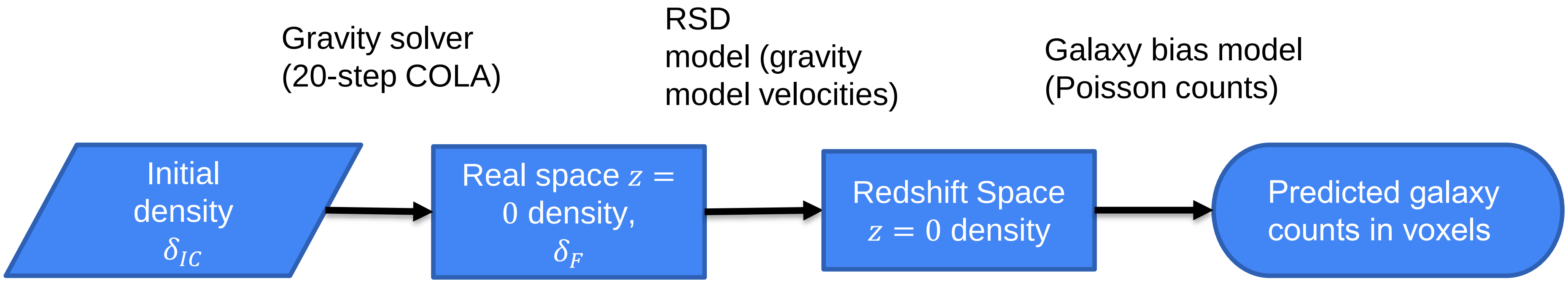
Field Level Inference with BORG

- BORG – Bayesian Origin Reconstruction from Galaxies [1].
- Tool for FLI of initial density field, from galaxies (and soon weak lensing, see [2]!)
- Samples the full posterior for δ_{IC}



[1] Jasche J., Lavaux G., 2019, A&A, 625, A64
[2] Porqueres et al. (2023) https://arxiv.org/abs/2304.04785

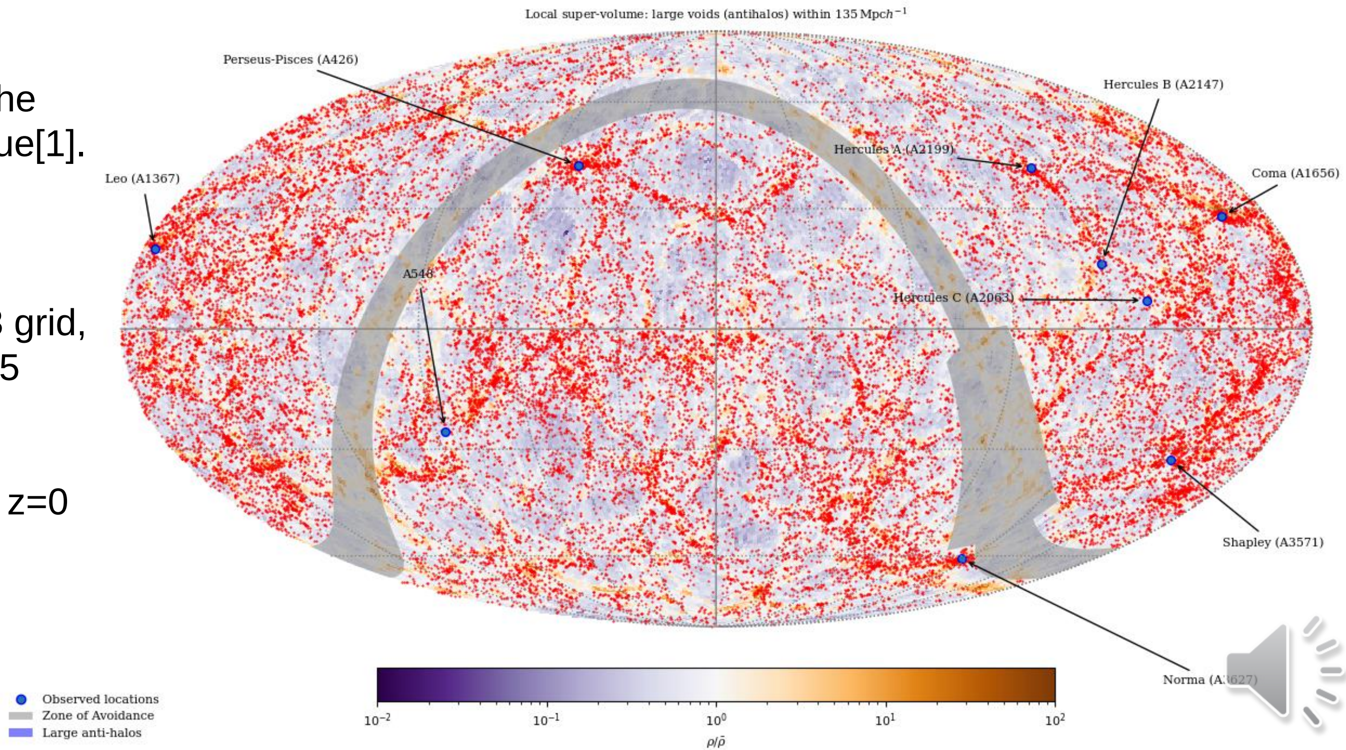
BORG Forward Model



- Gravity solver must be fast for efficient sampling: e,g, 20-step COLA.
- Sacrifices small-scale accuracy for computational tractability.
- N-body posterior resimulation therefore required to extract cluster masses.
- Flexible – can change gravity, RSD, or galaxy bias model to improve inference.

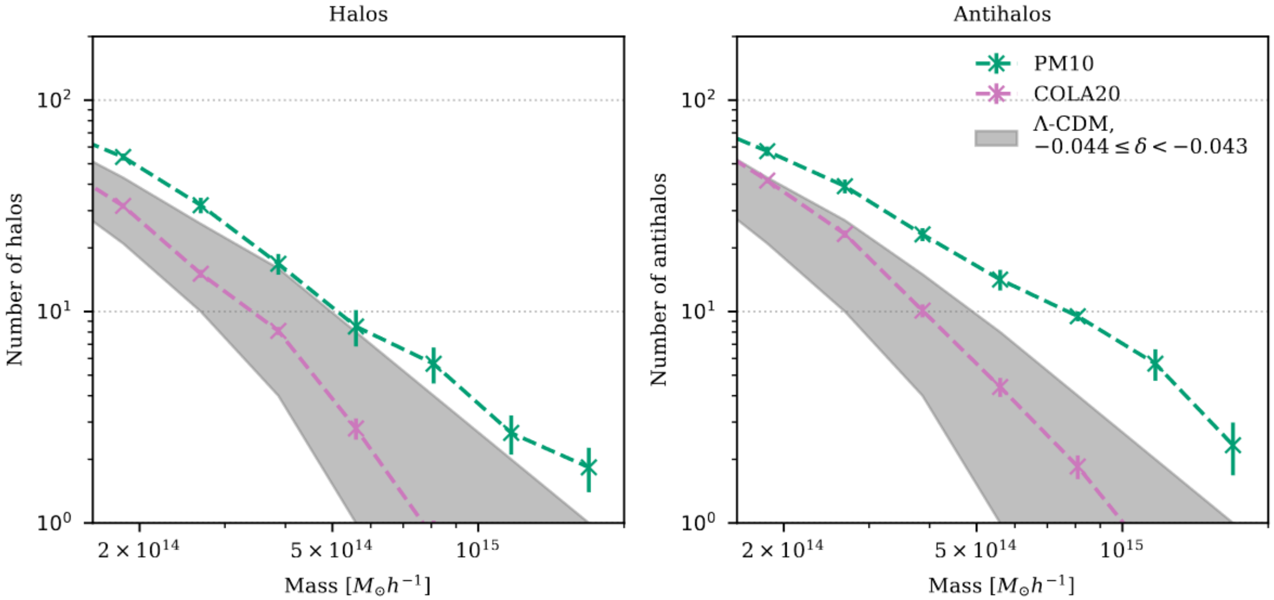
Field Level Inference with BORG

- Reconstruction with the 2M++ galaxy catalogue[1]. ~70000 galaxies, spectroscopic.
- ICs inferred on 256^3 grid, 676.7 Mpc/h box (2.65 Mpc/h resolution).
- Resimulated to study z=0 density field.



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

Accuracy Requirements



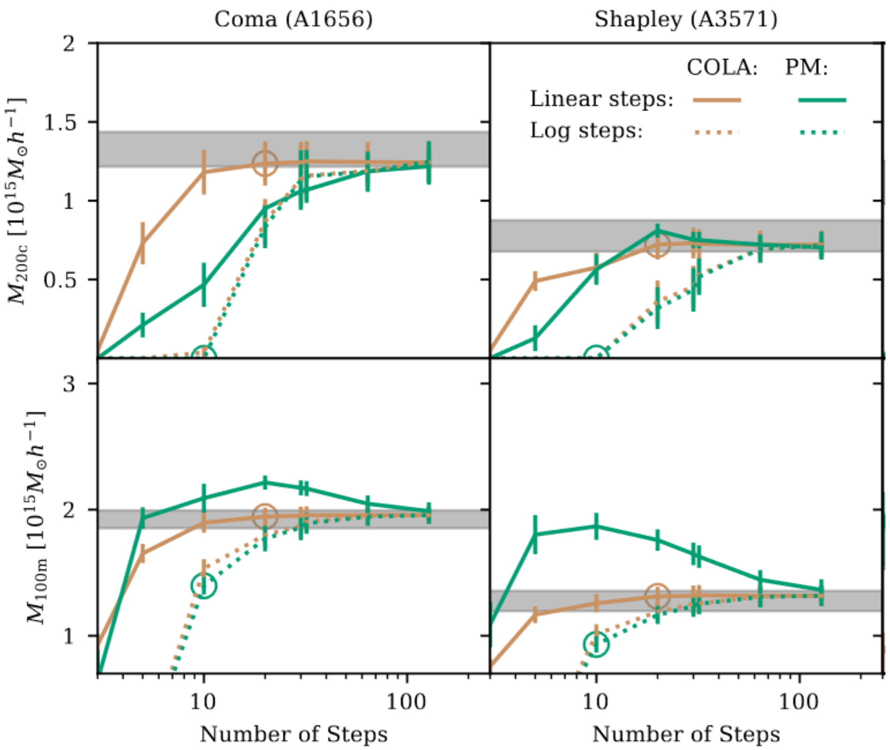
However, inference model accuracy matters.

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

BORG compensates by inferring higher initial density.

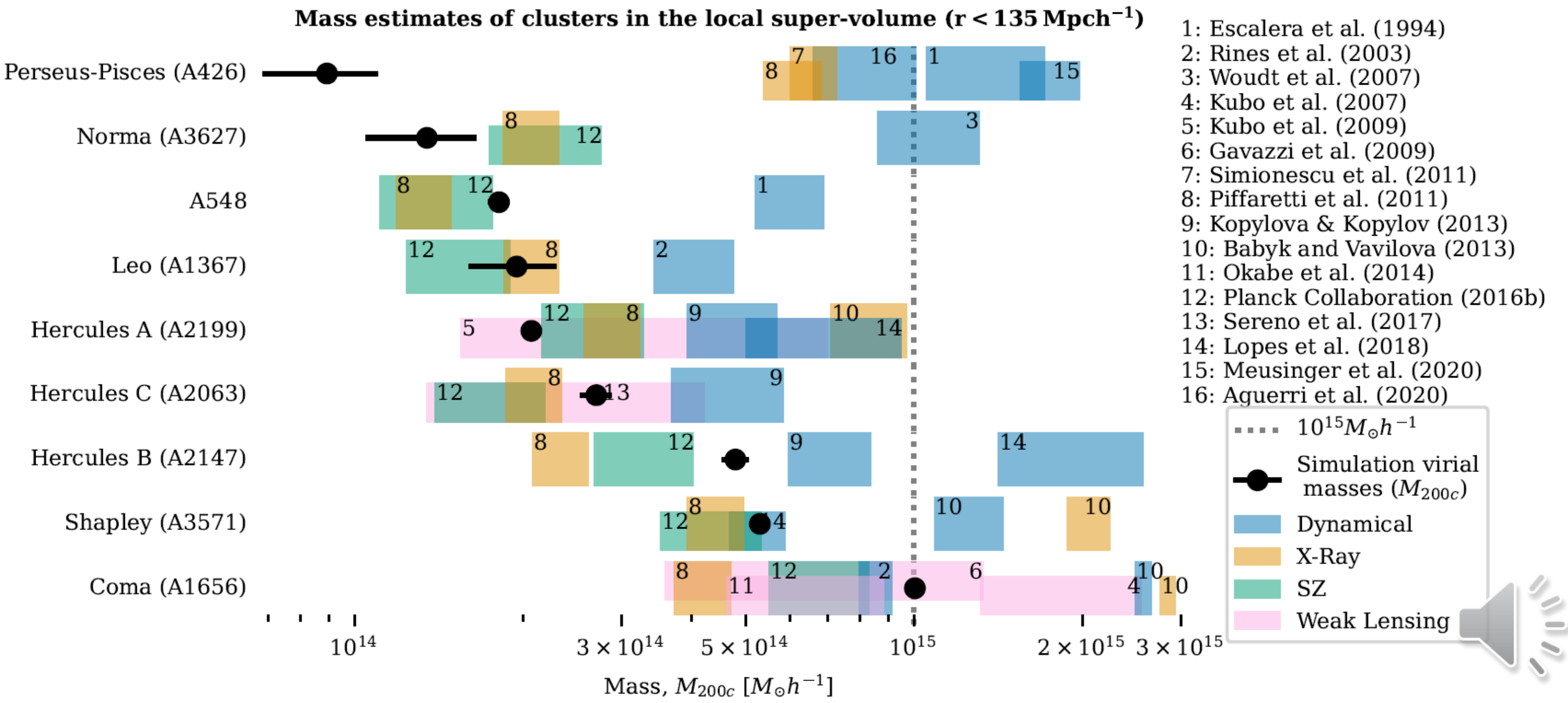
Leads to overestimate masses!

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.

Mass Estimates with BORG Posterior Resimulation

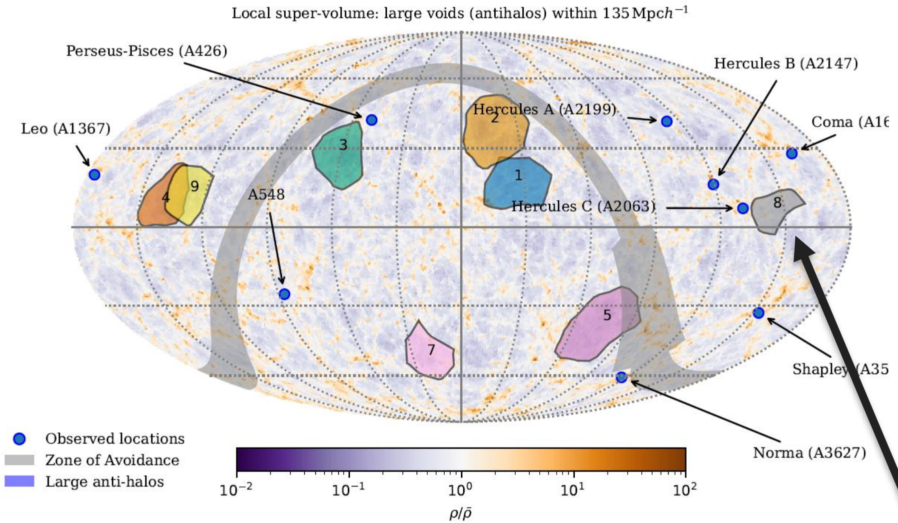


[1] Stopyra S., Peiris H. V., Pontzen A., Jasche J., Natarajan P., 2021, Monthly Notices of the Royal Astronomical Society, 507, 5425

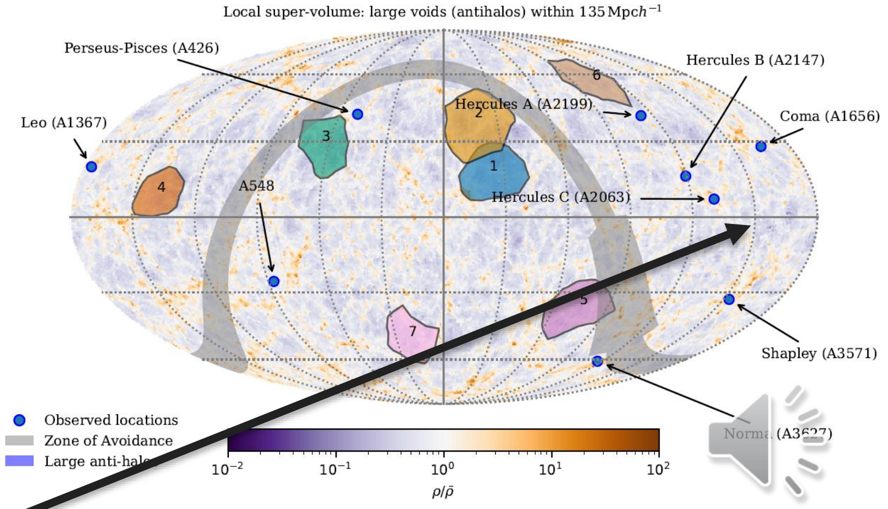
Anti-halos with BORG

- 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



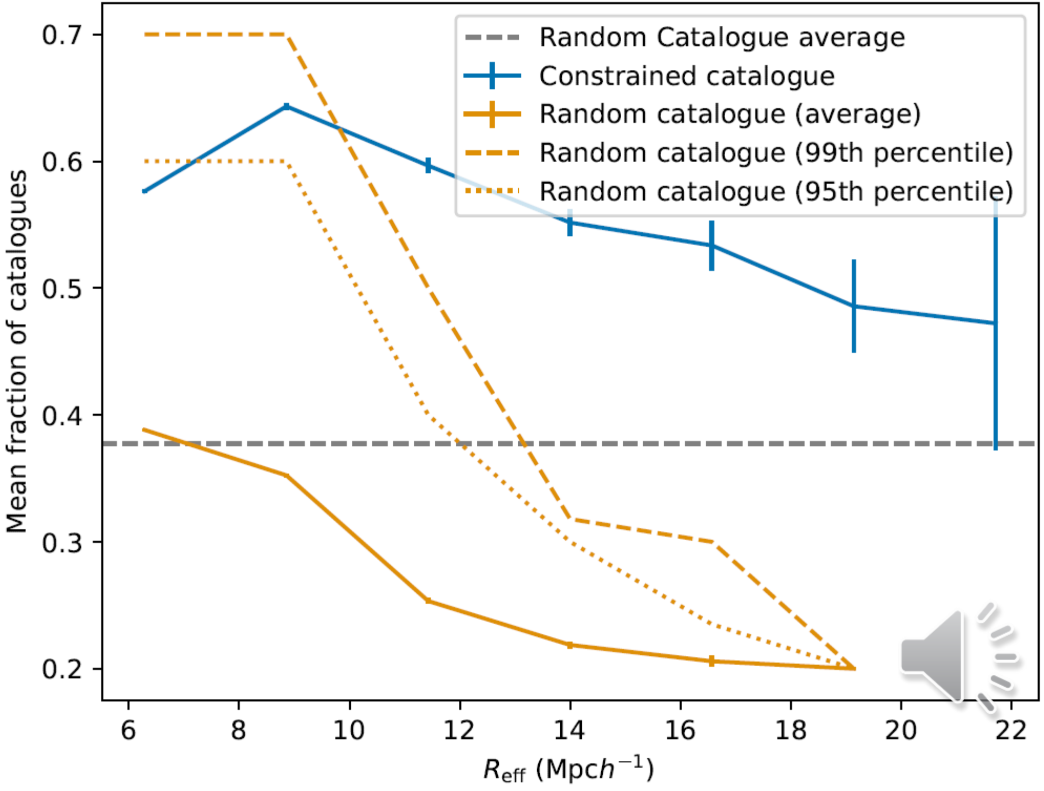
MCMC Sample 8800



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

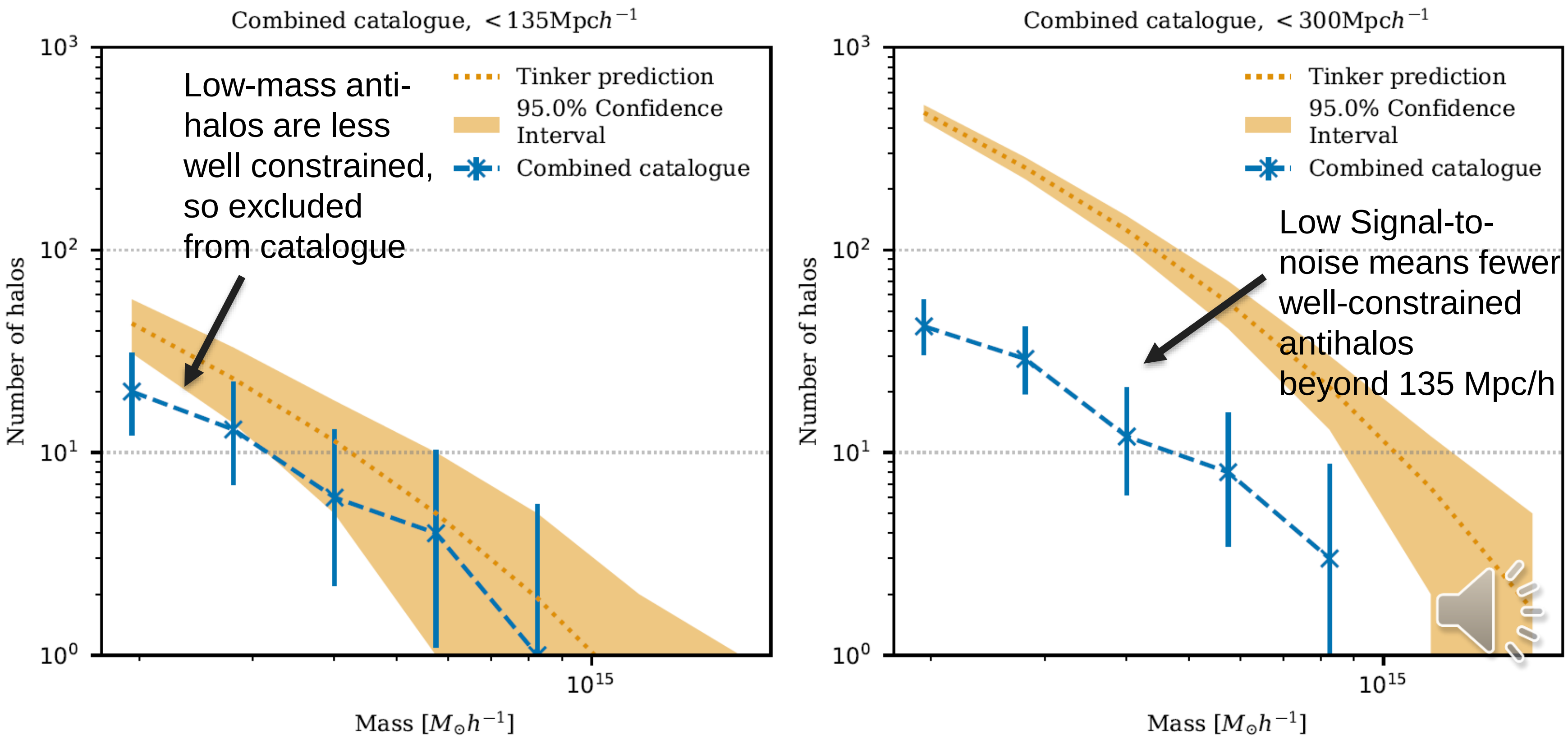
Anti-halos with BORG

- 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.



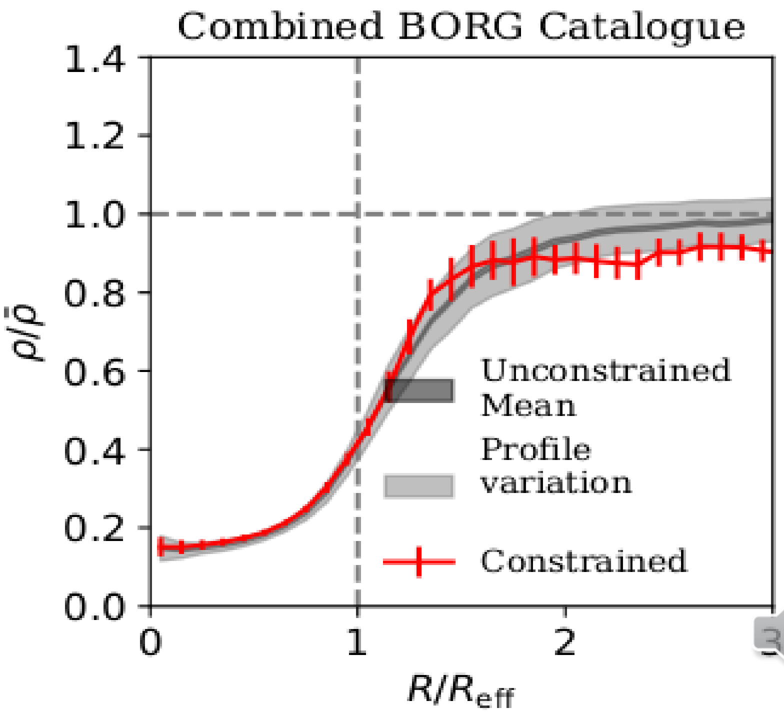
Anti-halos with BORG

PRELIMINARY RESULTS!



Constraining Physics with Voids

- Can get physics from the stacked density profile.
- Slightly low profile observed, but within variance of similar regions in simulations.
- Modified gravity should change void evolution.
- Massive neutrinos also affect void size-distribution.



PRELIMINARY RESULTS!

Challenges for the Future

- Can we do this with larger volume data-sets?
- What about photometric datasets (e.g., LSST)? See [1]
- Galaxy catalogue with lower-precision redshifts - but voids are large, so would it still work?
- Could use other tracers too to constrain velocities (e.g. supernovae).
- Cosmology constraints

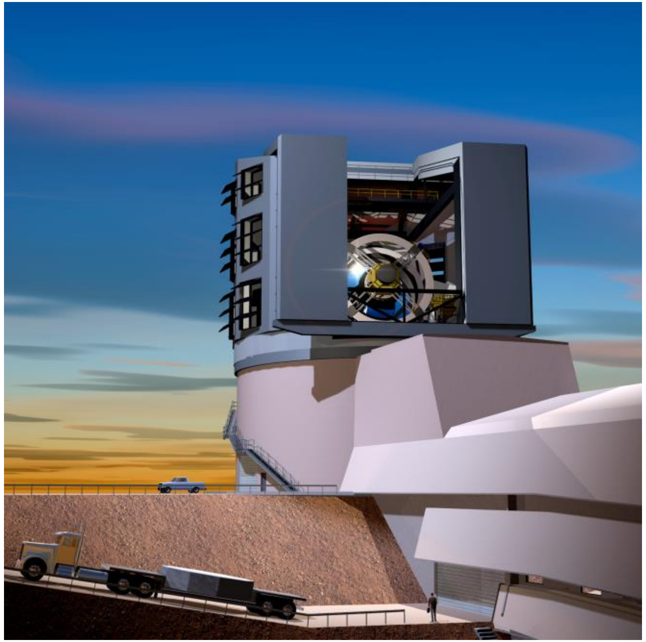


Image credit: Todd Mason, Mason Productions Inc. / LSST Corporation

[1] Tsaprazi et al. (2023) https://arxiv.org/abs/2301.03581