Deciphering the dynamical Universe via non-linear Bayesian inference

Jens Jasche

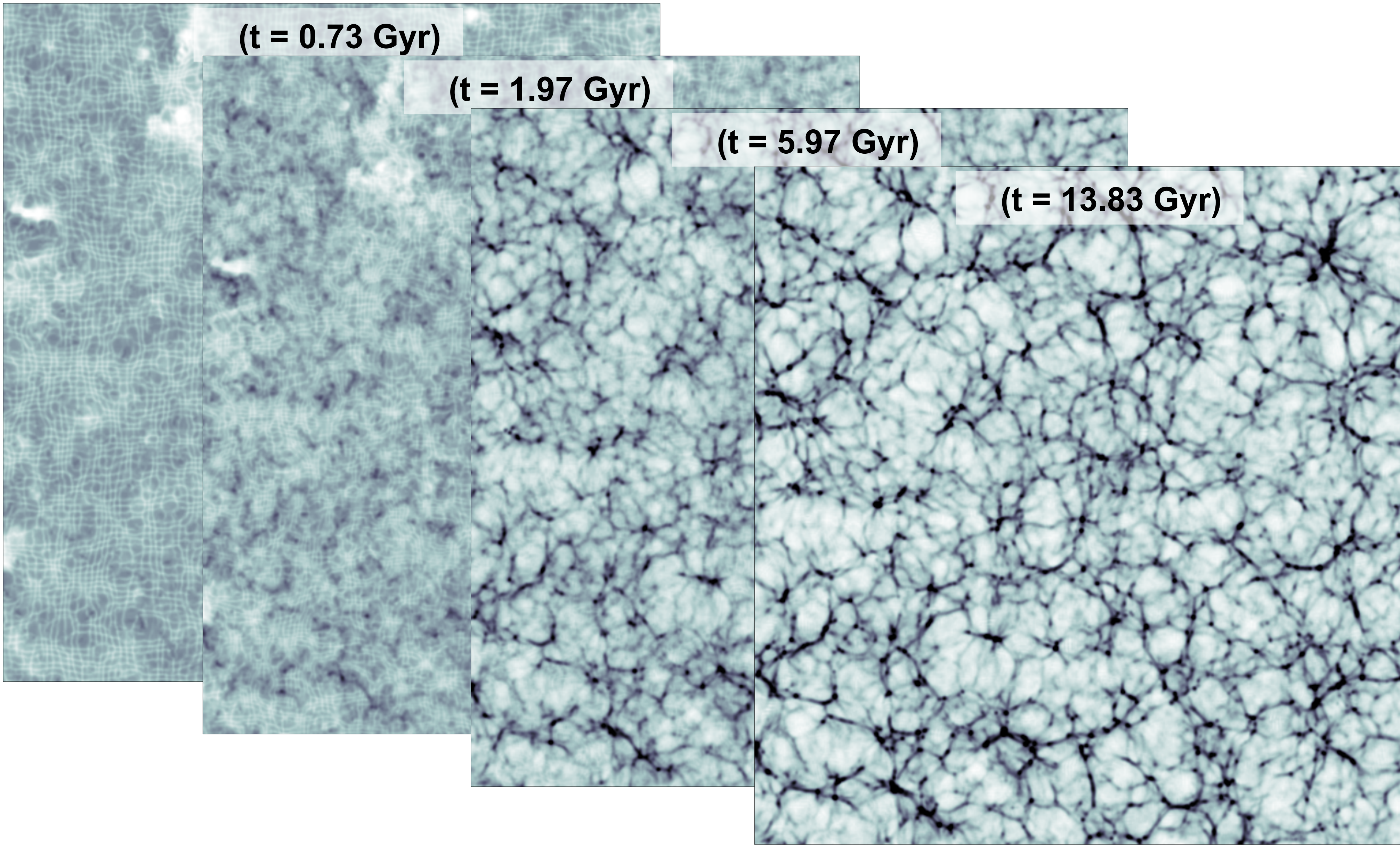
Guilhem Lavaux, Florent Leclercq,
Benjamin Wandelt

Statistical challenges for large-scale structure in the era of LSST

Oxford, 18 April 2018

The cosmic large scale structure...

... A source of knowledge!



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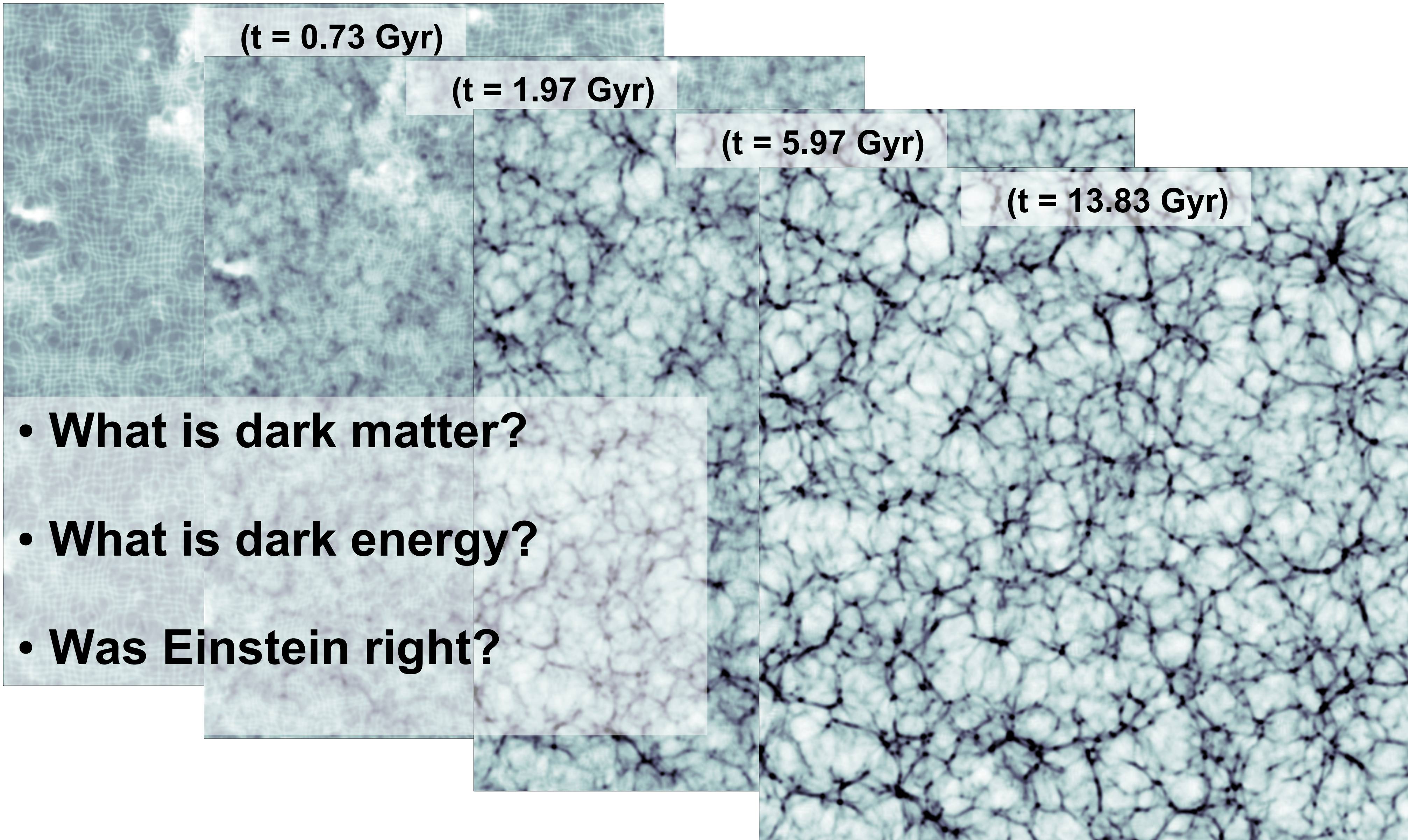
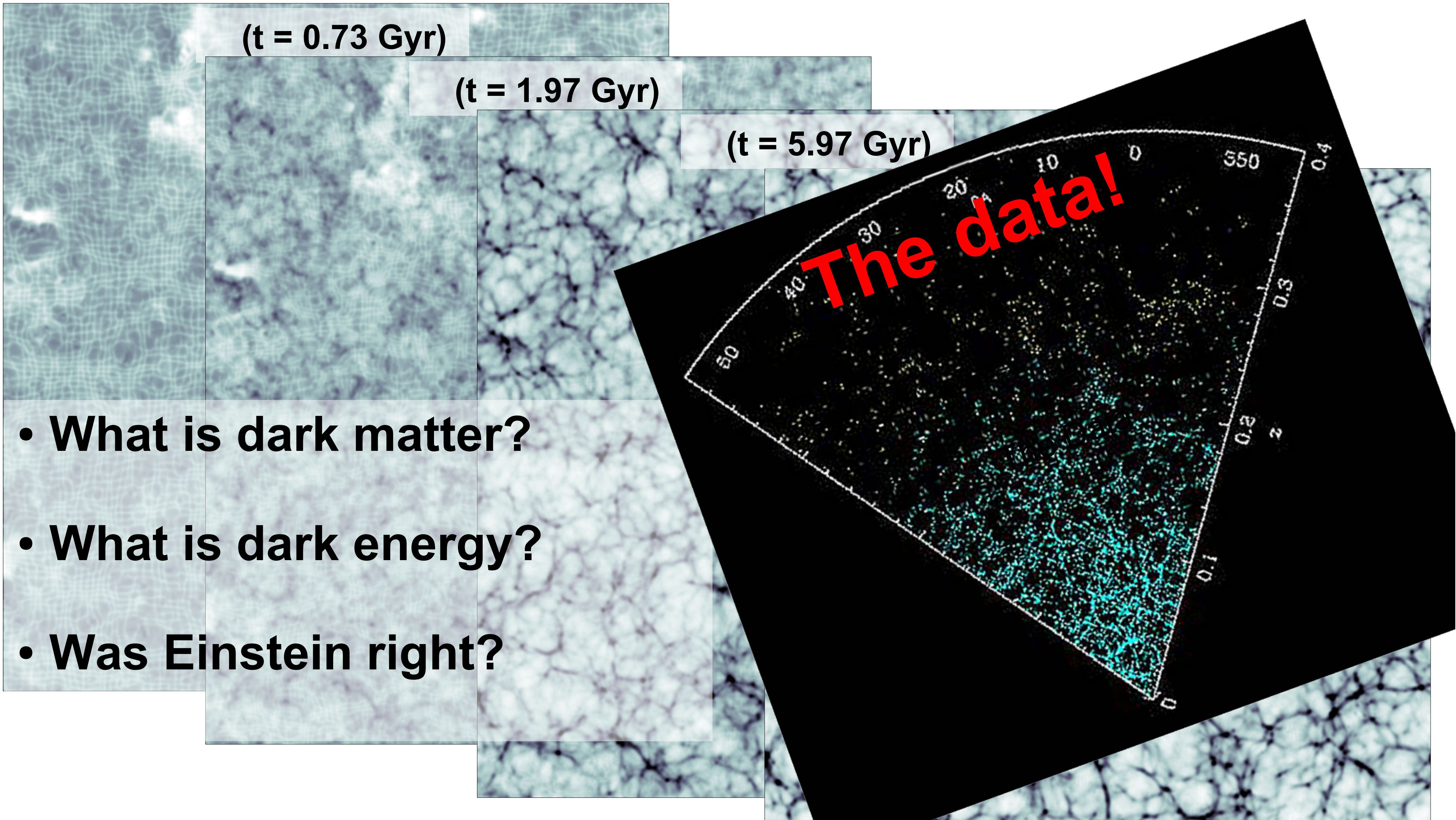


- **What is dark matter?**
- **What is dark energy?**
- **Was Einstein right?**

The cosmic large scale structure...

... A source of knowledge!



- **What is dark matter?**
- **What is dark energy?**
- **Was Einstein right?**

<u>No</u> unique recovery possible!!! We need an statistical approach.

Bayesian Statistics

"If your experiment needs statistics, you ought to do a better experiment."

Lord Ernest Rutherford

Bayesian Statistics

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Reasoning under uncertainty

Bayesian Statistics

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Reasoning under uncertainty

- Bayesian Statistics

$$\mathcal{P}(s|d) = \mathcal{P}(s)\,\frac{\mathcal{P}(d|s)}{\mathcal{P}(d)}$$

Bayesian Statistics

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Lord Ernest Rutherford

Reasoning under uncertainty

- Bayesian Statistics

$$\mathcal{P}(s|d) = \mathcal{P}(s)\,\frac{\mathcal{P}(d|s)}{\mathcal{P}(d)}$$

Get a computer representation of the full posterior distribution!

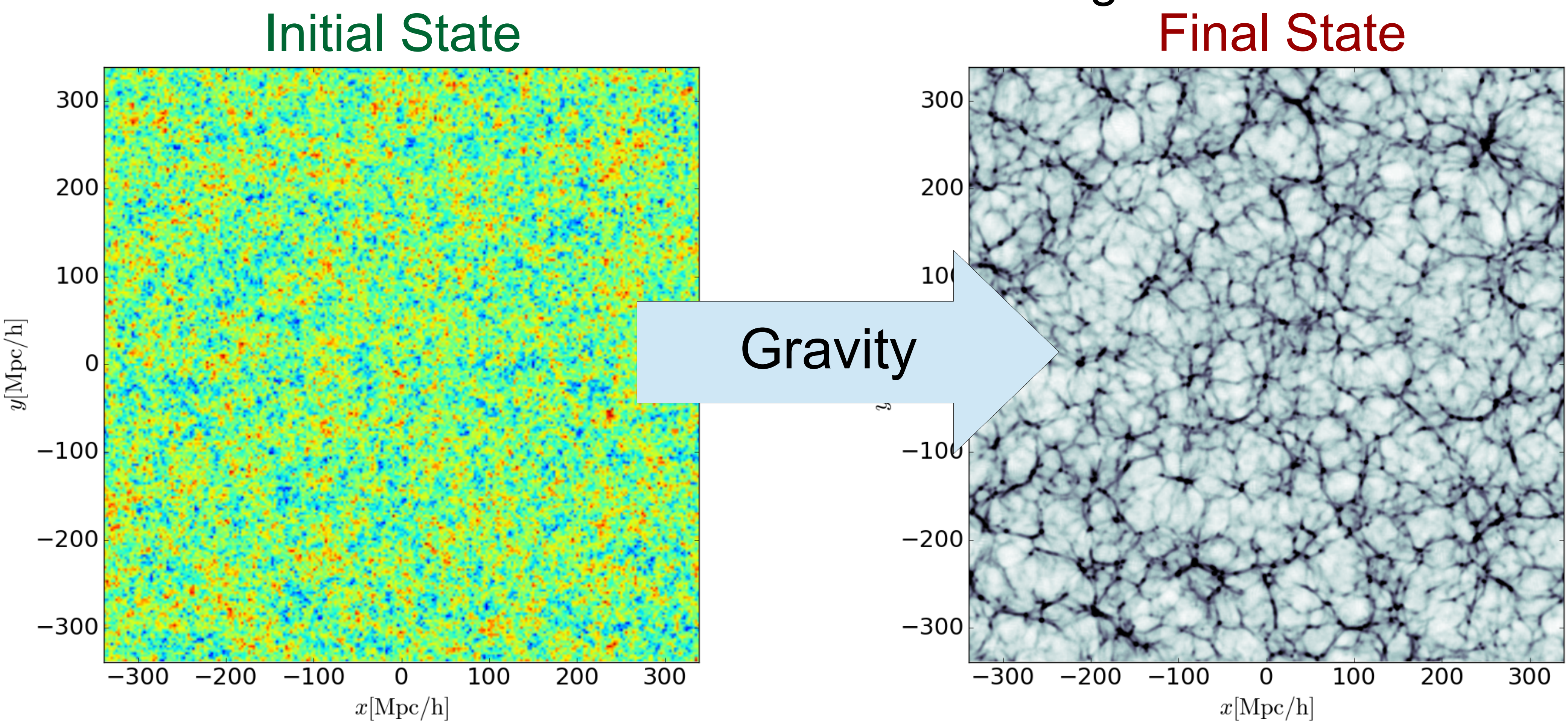
- Model tests
- Parameter studies
- Report statistical summaries
- Non-linear and Non-Gaussian uncertainty propagation

Motivation

Bayesian physical inference

Jasche, Wandelt (2013)

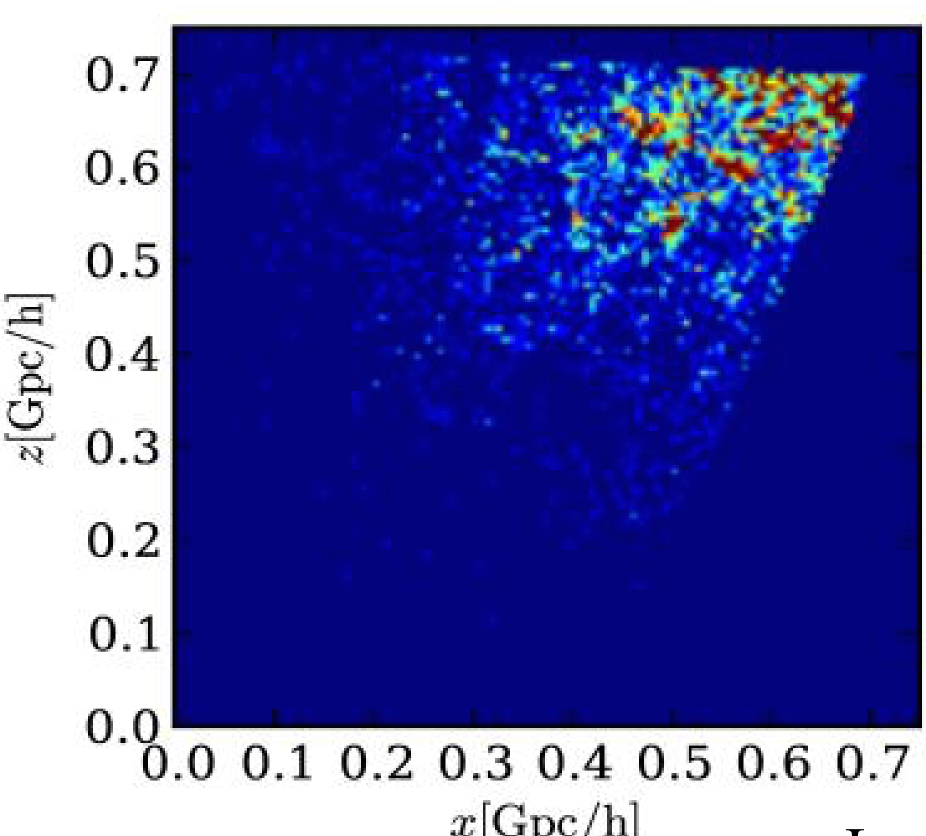
- Statistically complex final state
- Statistically simple initial state
- Solve inverse Problem via forward modeling

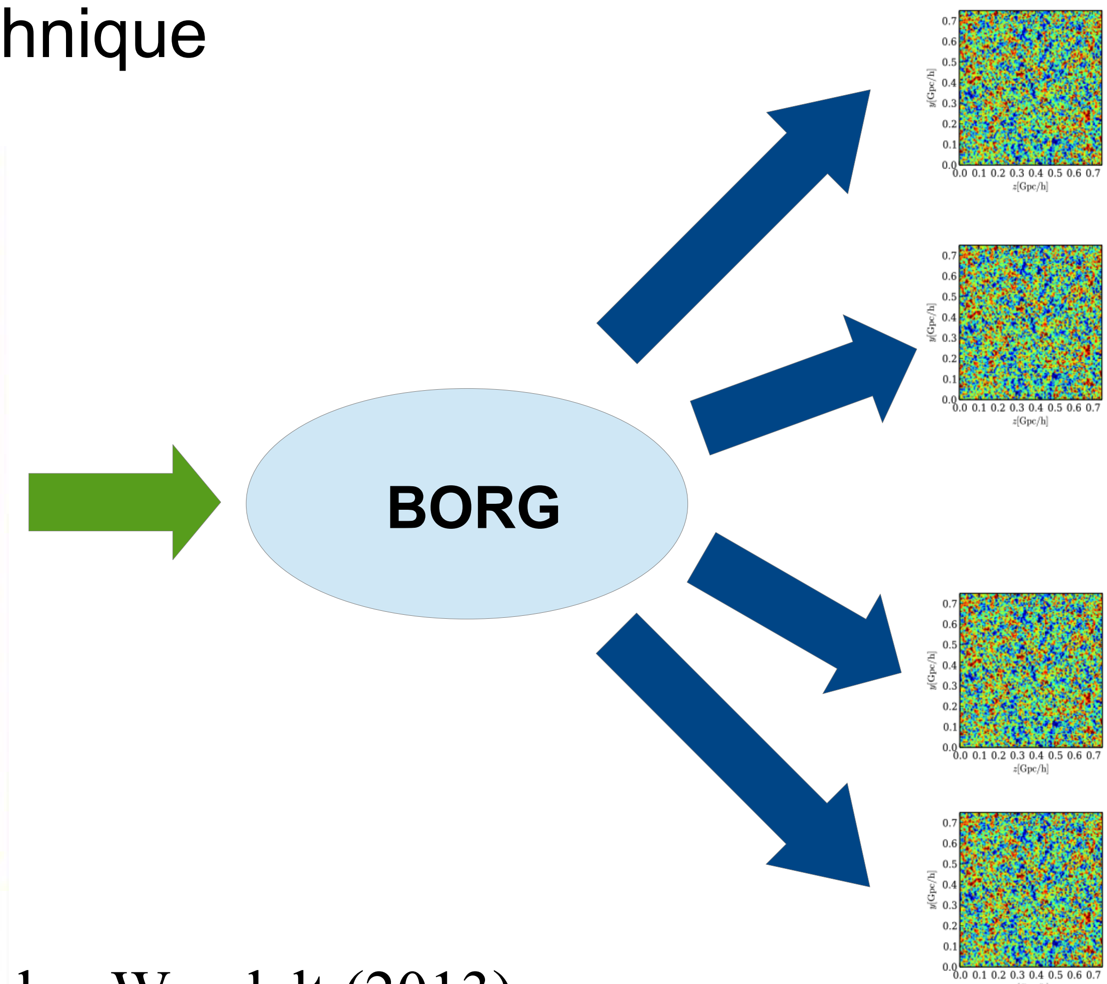


Bayesian Inference of initial conditions

BORG (**B**ayesian **O**rigin **R**econstruction from **G**alaxies)

- Uses dynamical LSS model (2LPT, PM) within Likelihood
- Solves a statistical initial conditions problem
- Exploits HMC sampling technique





Jasche, Wandelt (2013)

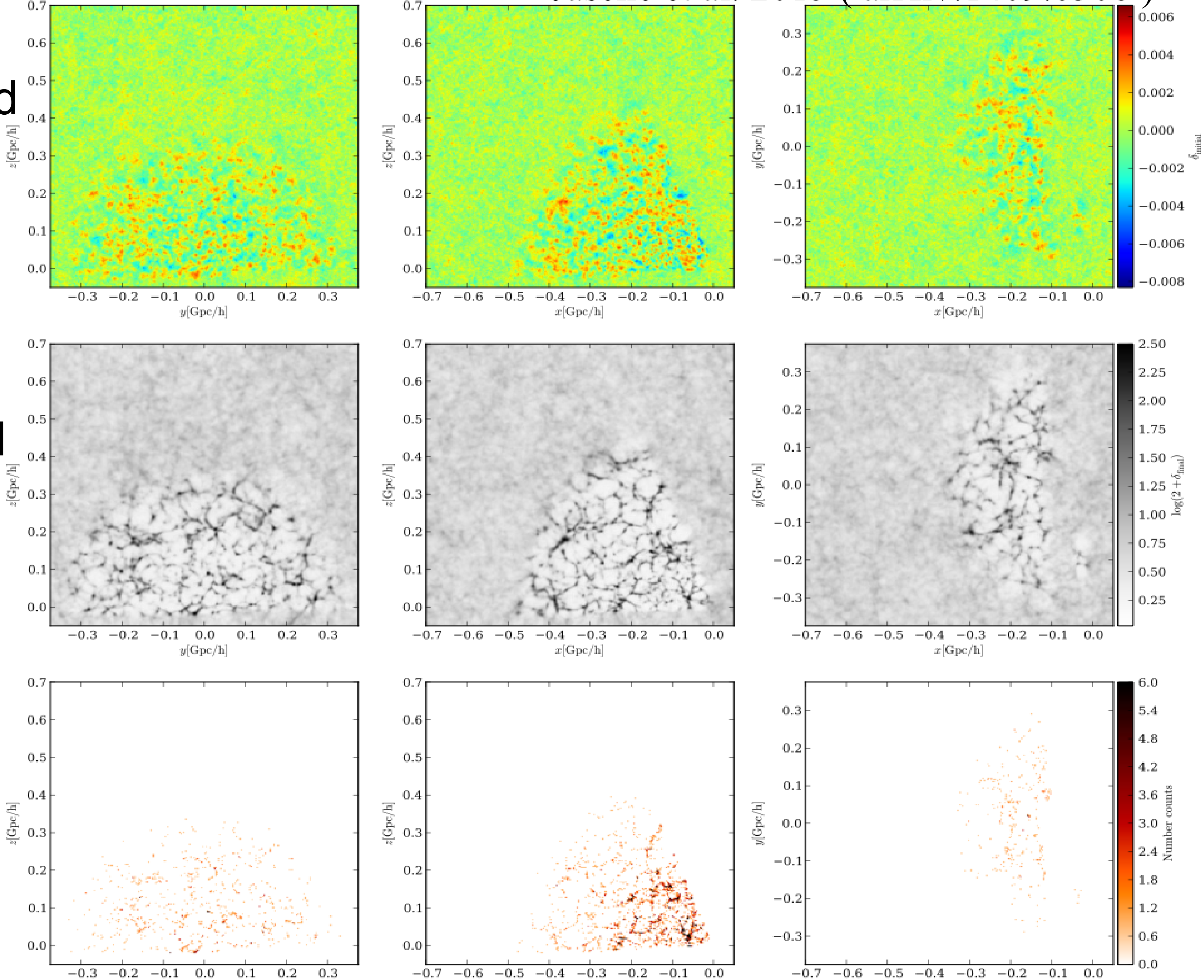
Bayesian analysis of the SDSS DR7

Jasche et al. 2015 (arXiv:1409.6308)

Initial density field
z ~ 1000

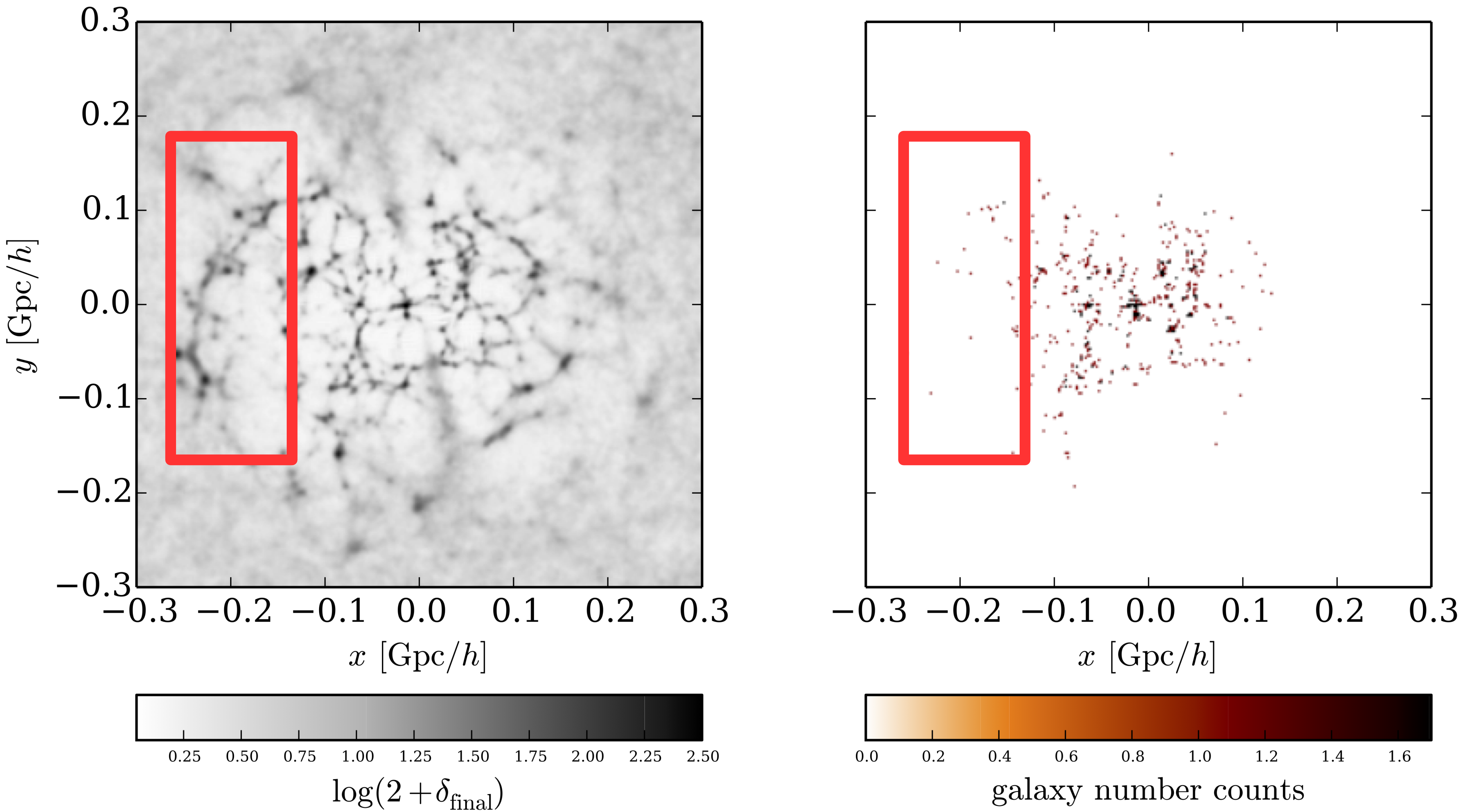
final density field
z=0

SDSS
number counts
z=0



The LSS in noisy regimes

Recovering the Sloan Great Wall in 2M++ data



Lavaux & Jasche 2016 (arXiv:1509.05040)

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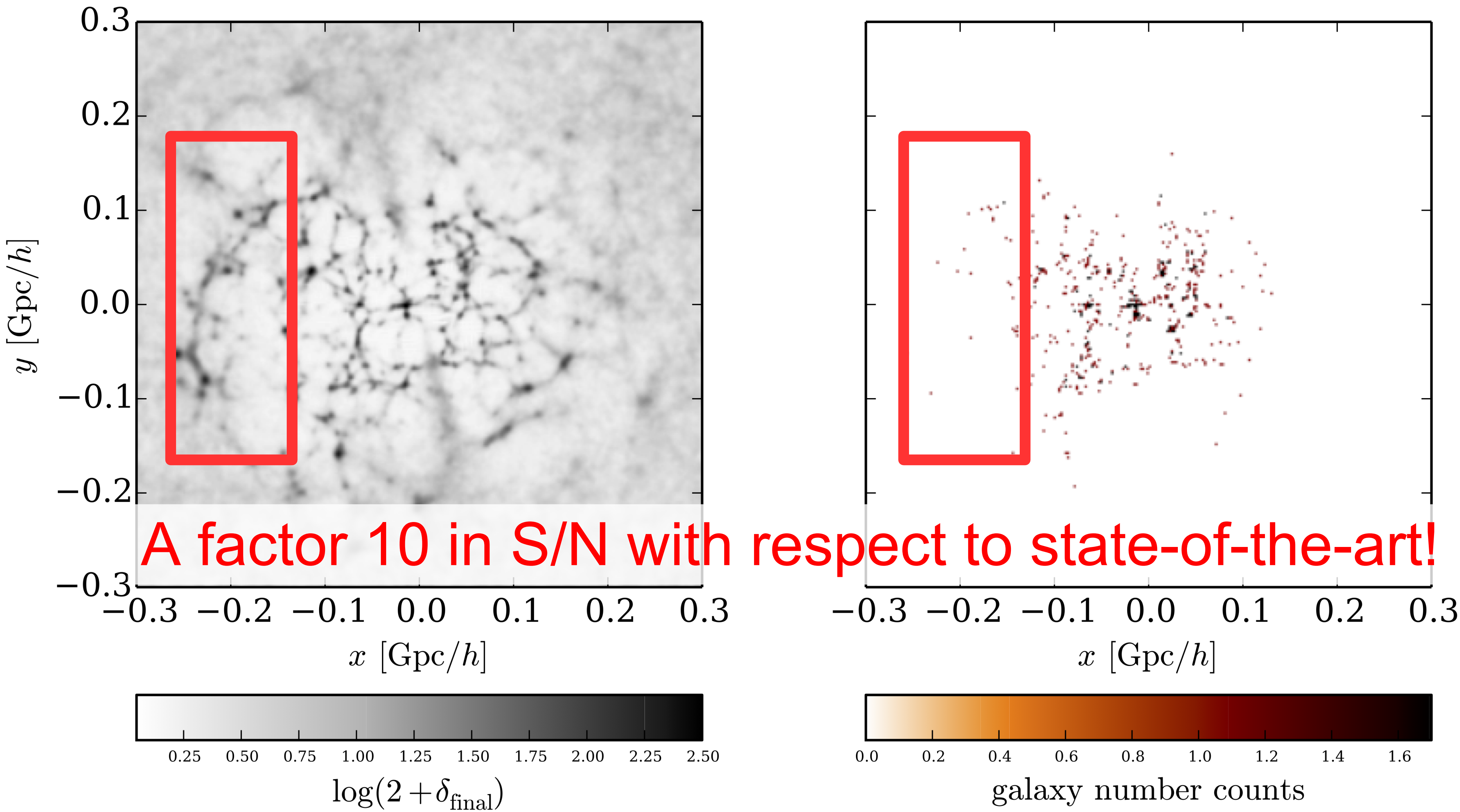
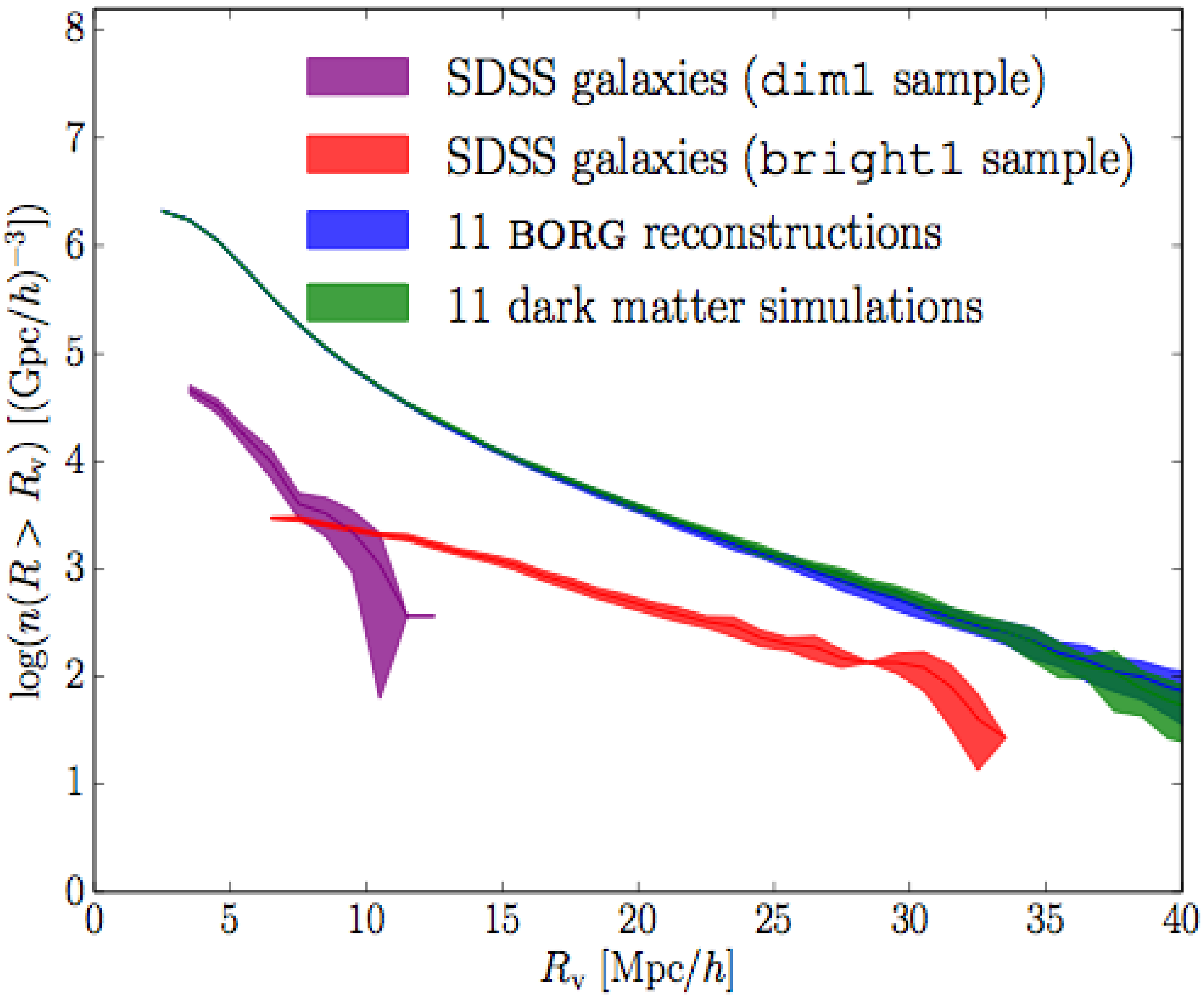


Lavaux & Jasche 2016 (arXiv:1509.05040)

Dark matter voids in the SDSS

Cumulative void number functions

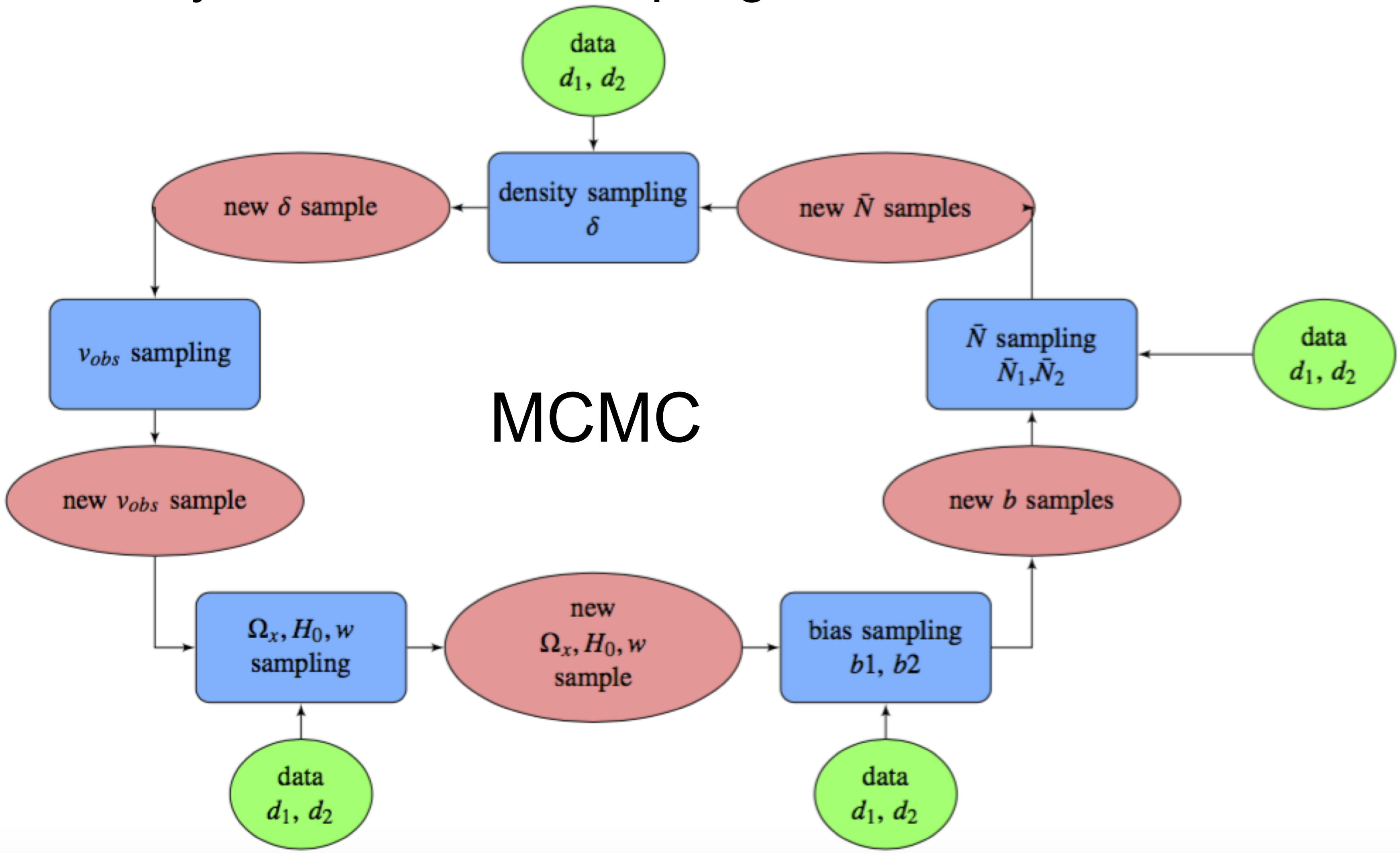


Leclercq et al. 2015 (arXiv:1410.0355)

BORG^3: A Modular statistical programing engine

Build flexible data models

- Hierachical Bayes and block sampling



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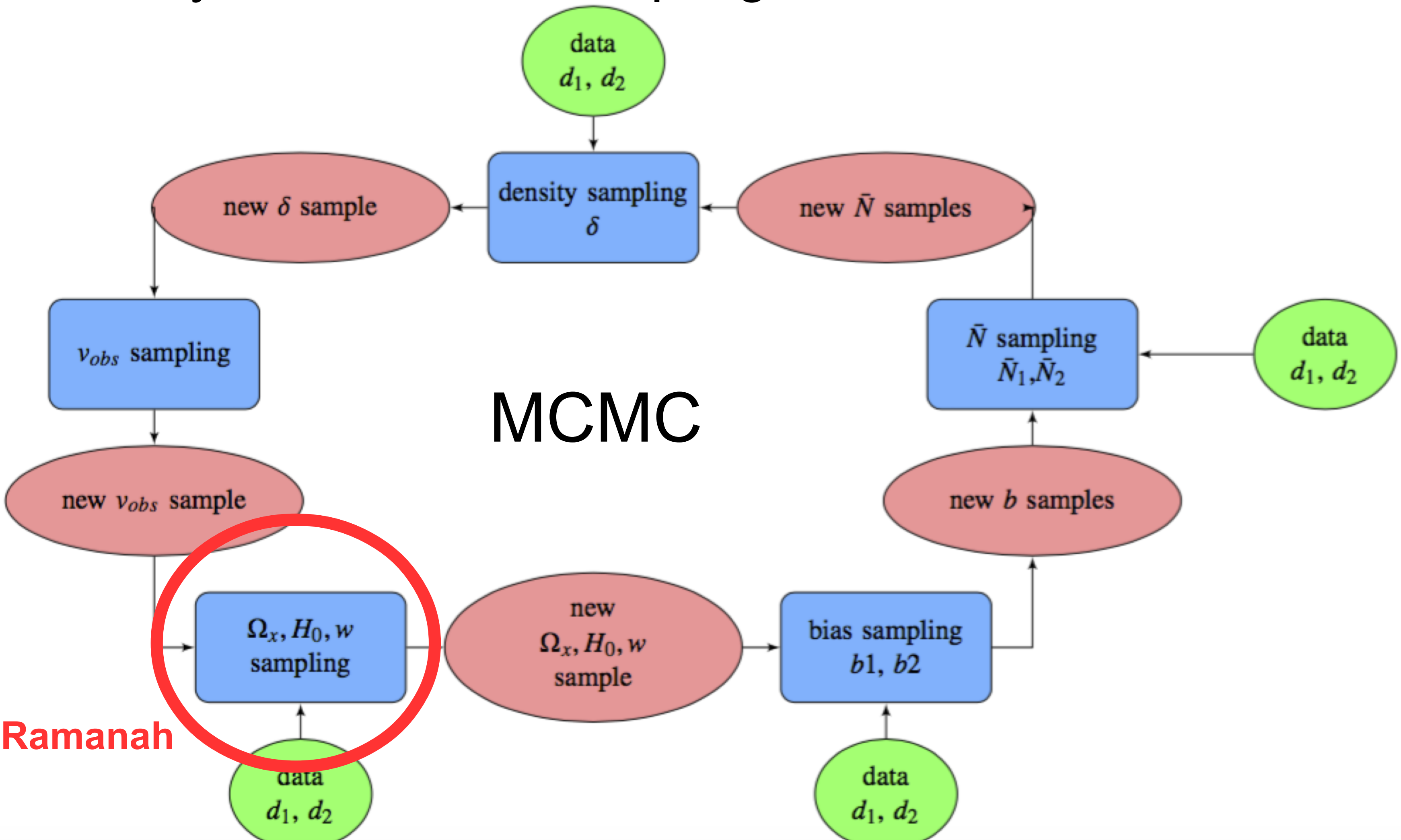
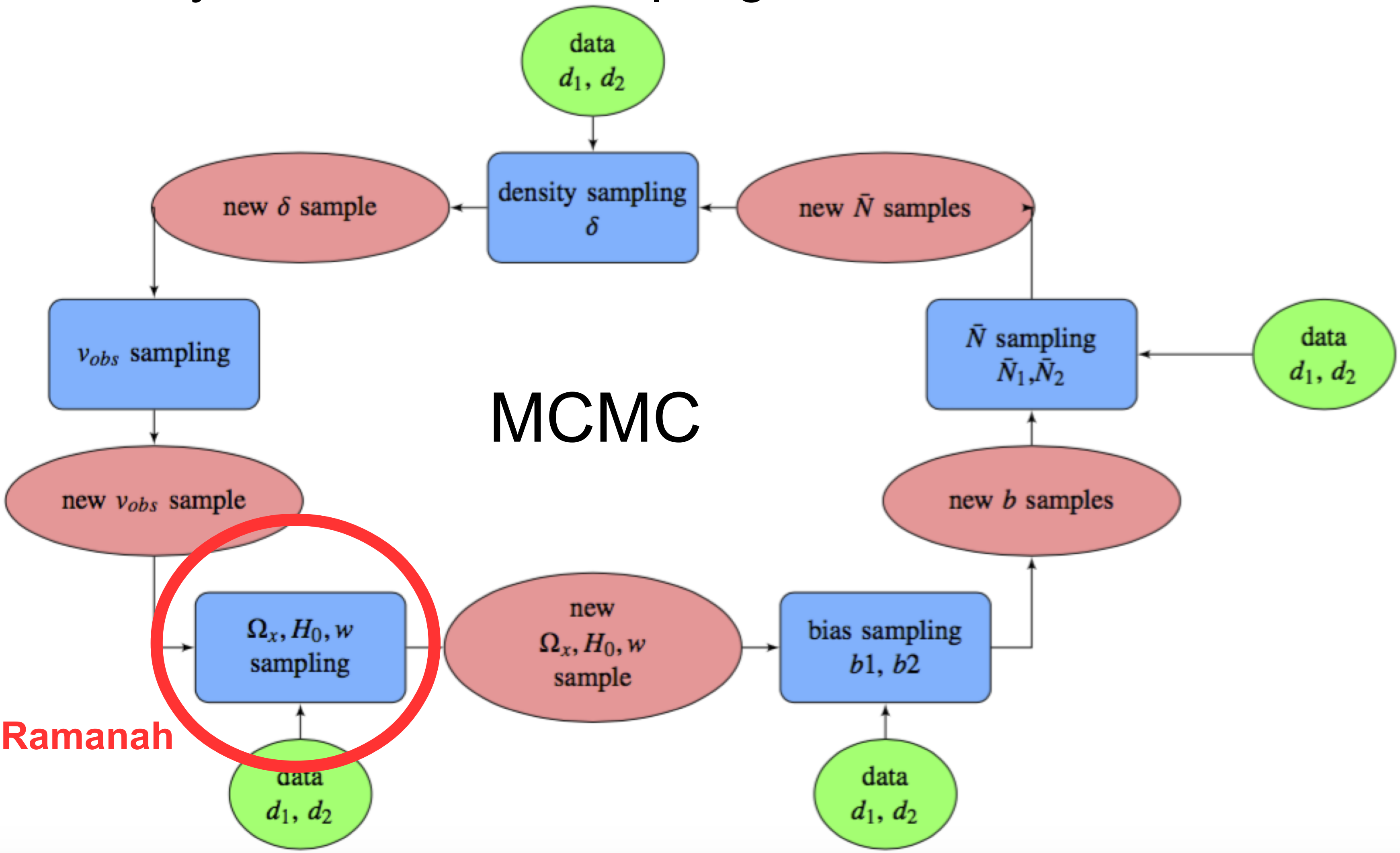


See talk by
Doogesh Kodi Ramanah

BORG[3]: A Modular statistical programing engine

Build flexible data models

- Hierachical Bayes and block sampling

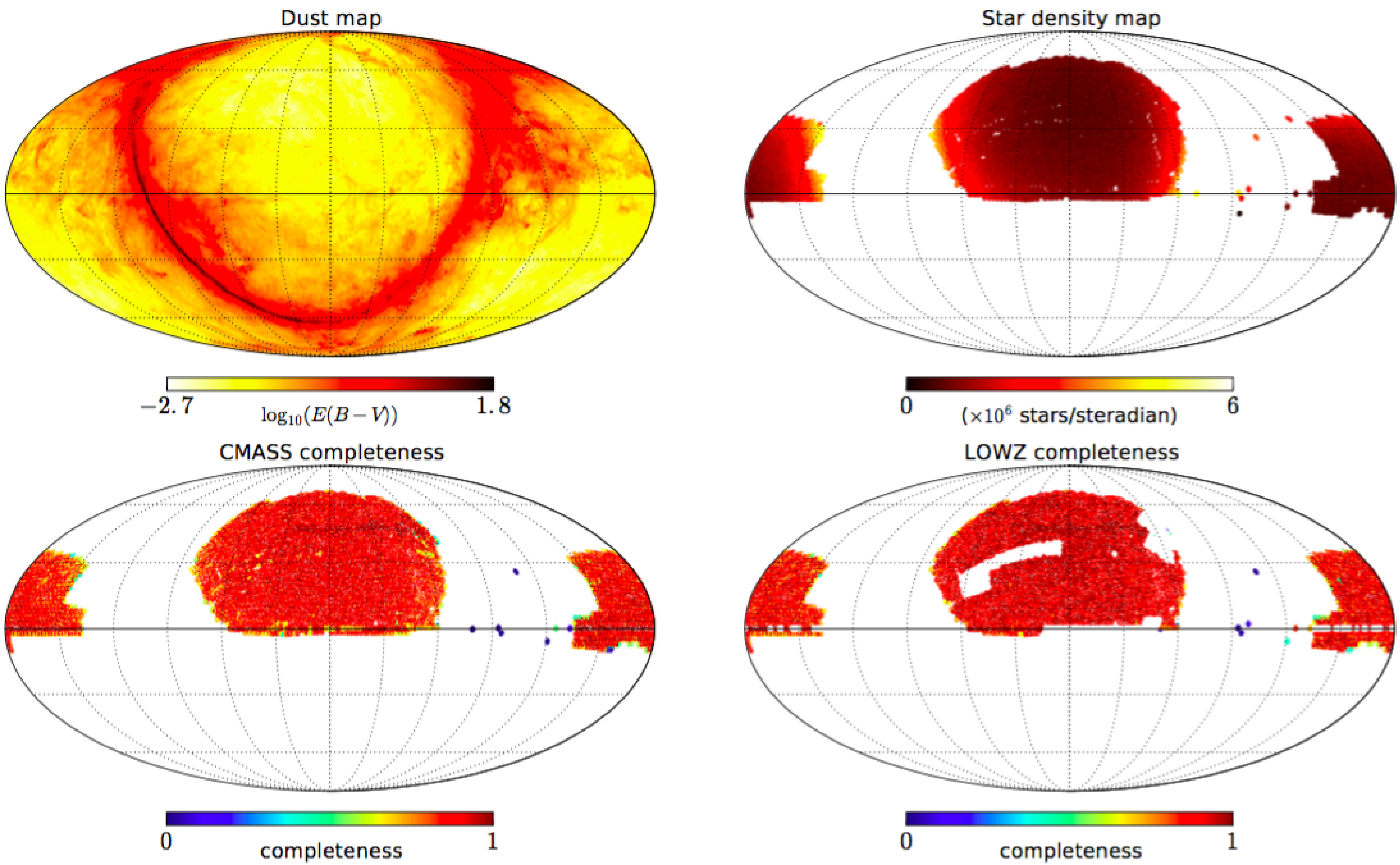


See talk by
Doogesh Kodi Ramanah

Marginalize out nuisance parameters.

Foreground contaminations

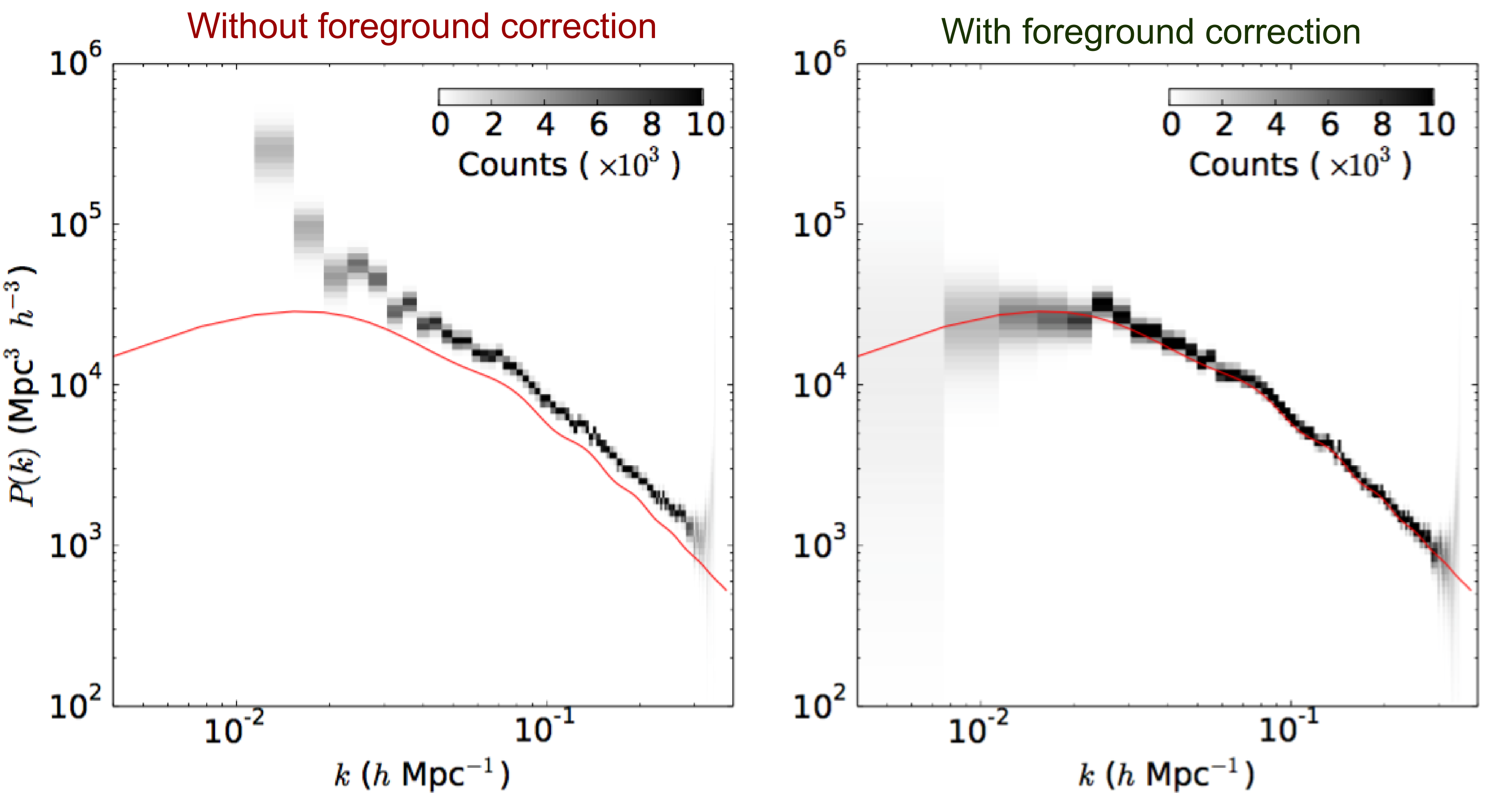
Foreground effect contaminate the inference (see e.g. Leistedt & Peiris (2014))



Jasche & Lavaux 2017 (arXiv:1706.08971)

Foreground contaminations

Mock data emulating LOWZ + CMASS



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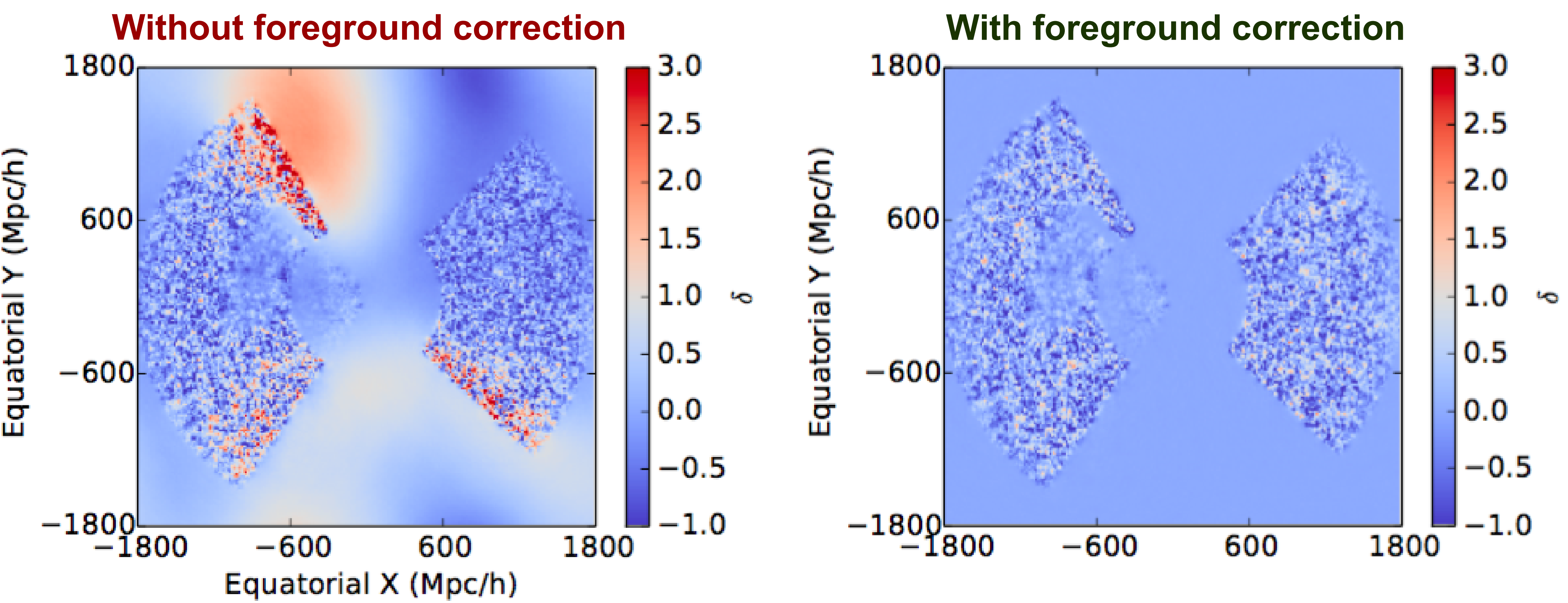


Use inferred 3D density field as diagnostics.

Jasche & Lavaux 2017 (arXiv:1706.08971)

Photometric redshift uncertainties

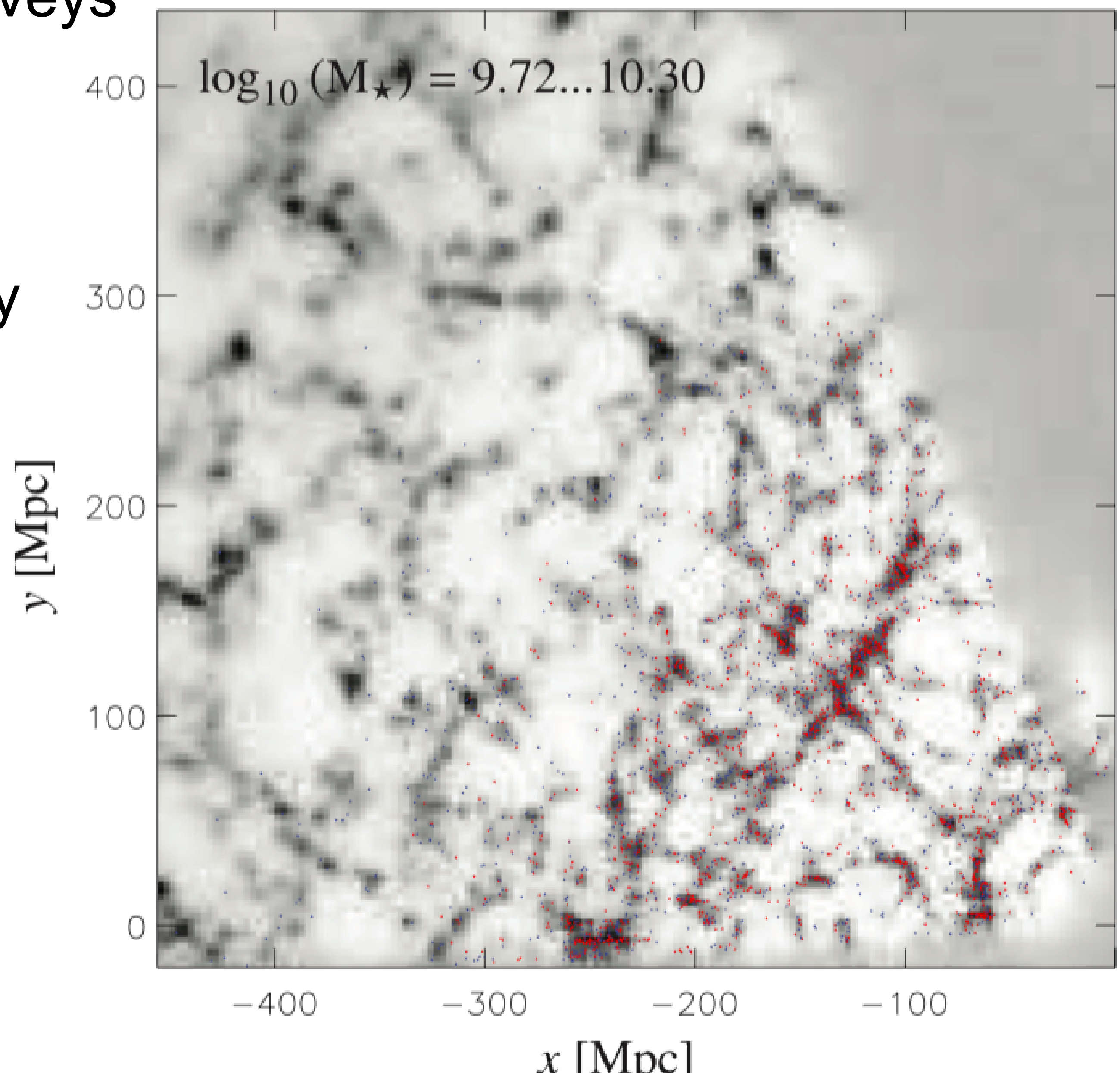
Photometric redshift surveys

- Deep volumes
- Millions of galaxies
- Low redshift accuracy

➡ **affects density fields and cosmological analyses**

See e.g. Blake, Bridle 2005

But:
Galaxies trace the matter distribution!!



Jasche et al 2010 (arXiv:0911.2498)

Photo-z sampling

Jasche, Wandelt 2012 (arXiv:1106.2757)

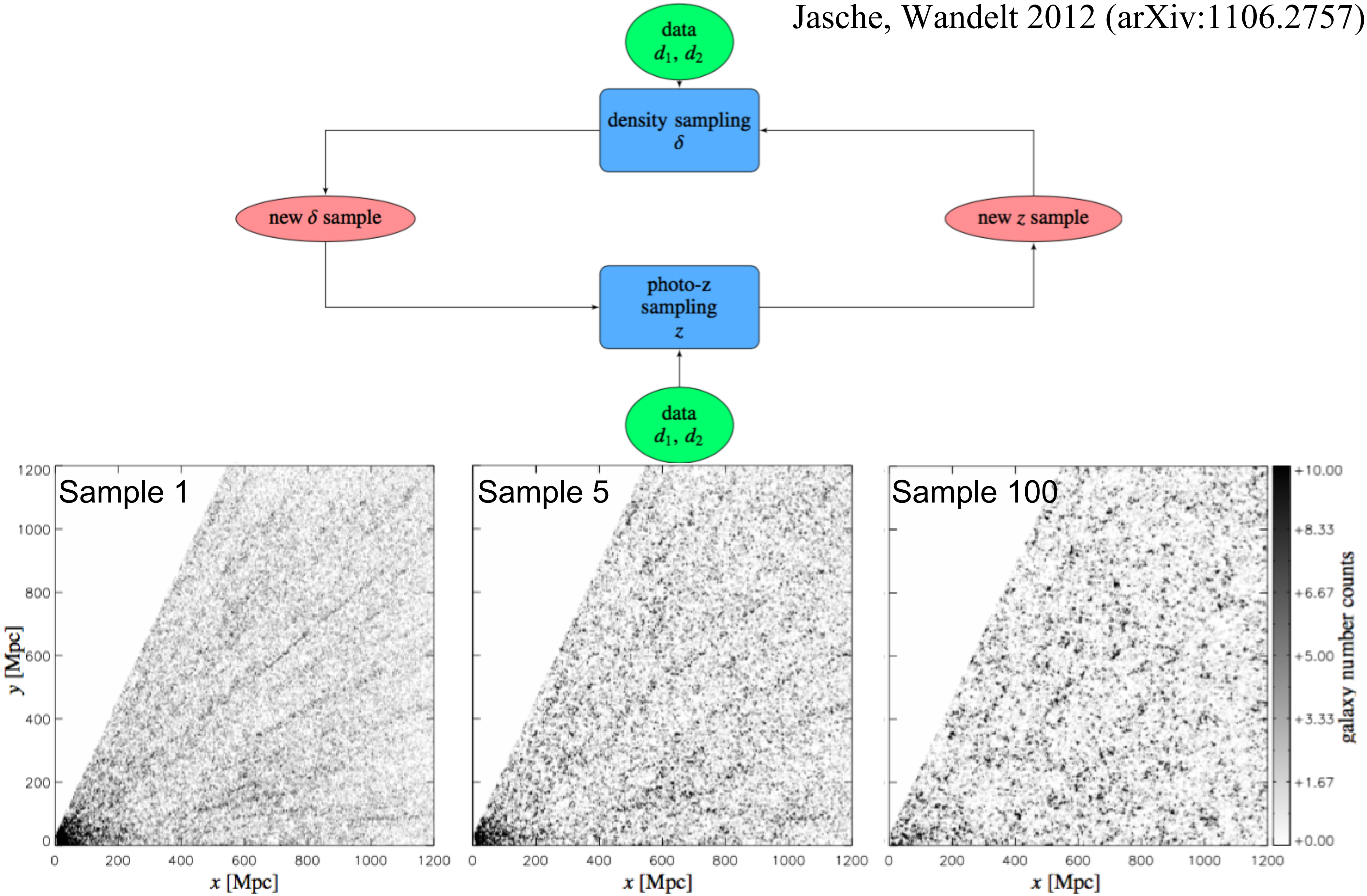
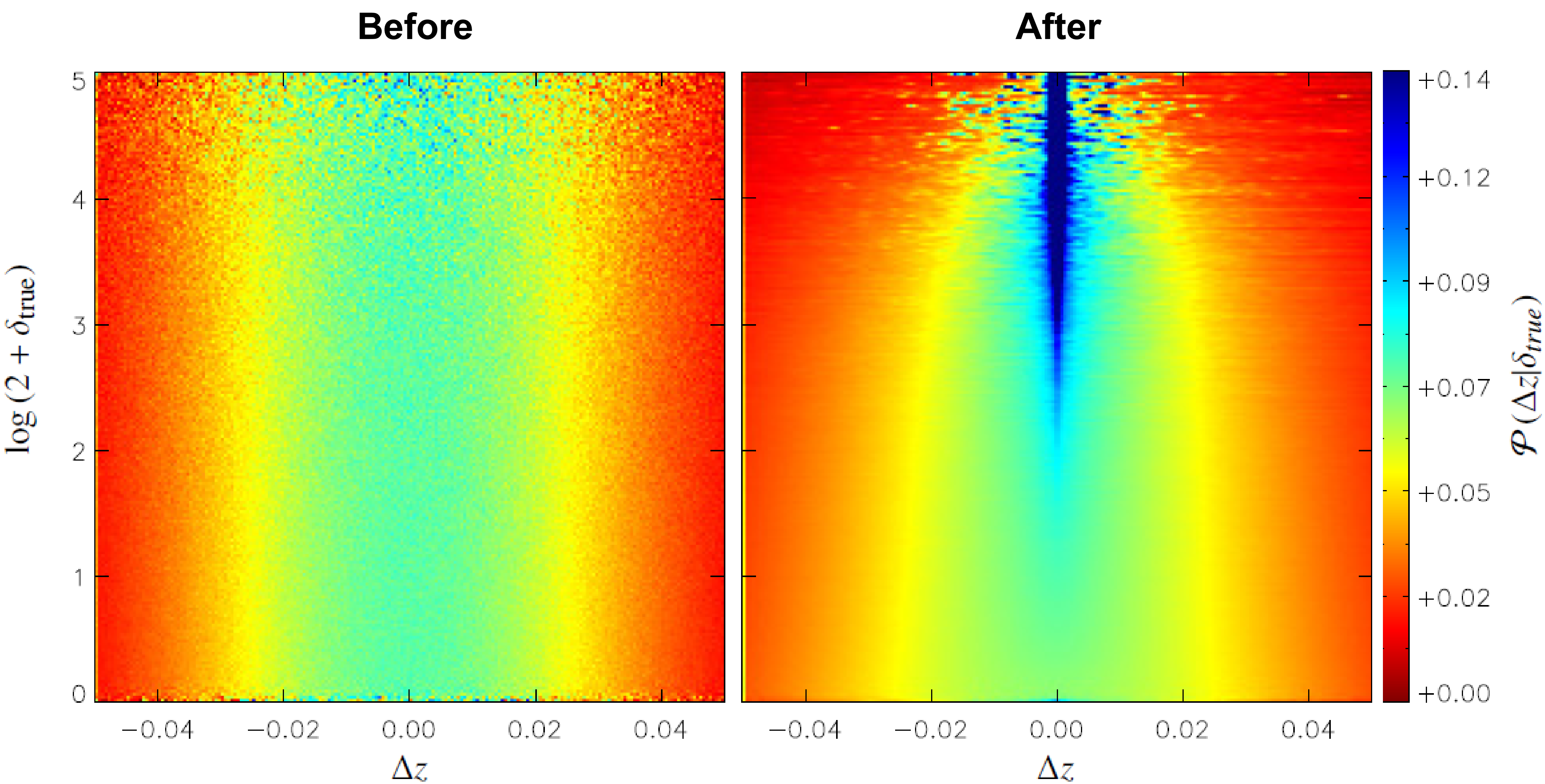


Photo-z sampling

Application to mock data



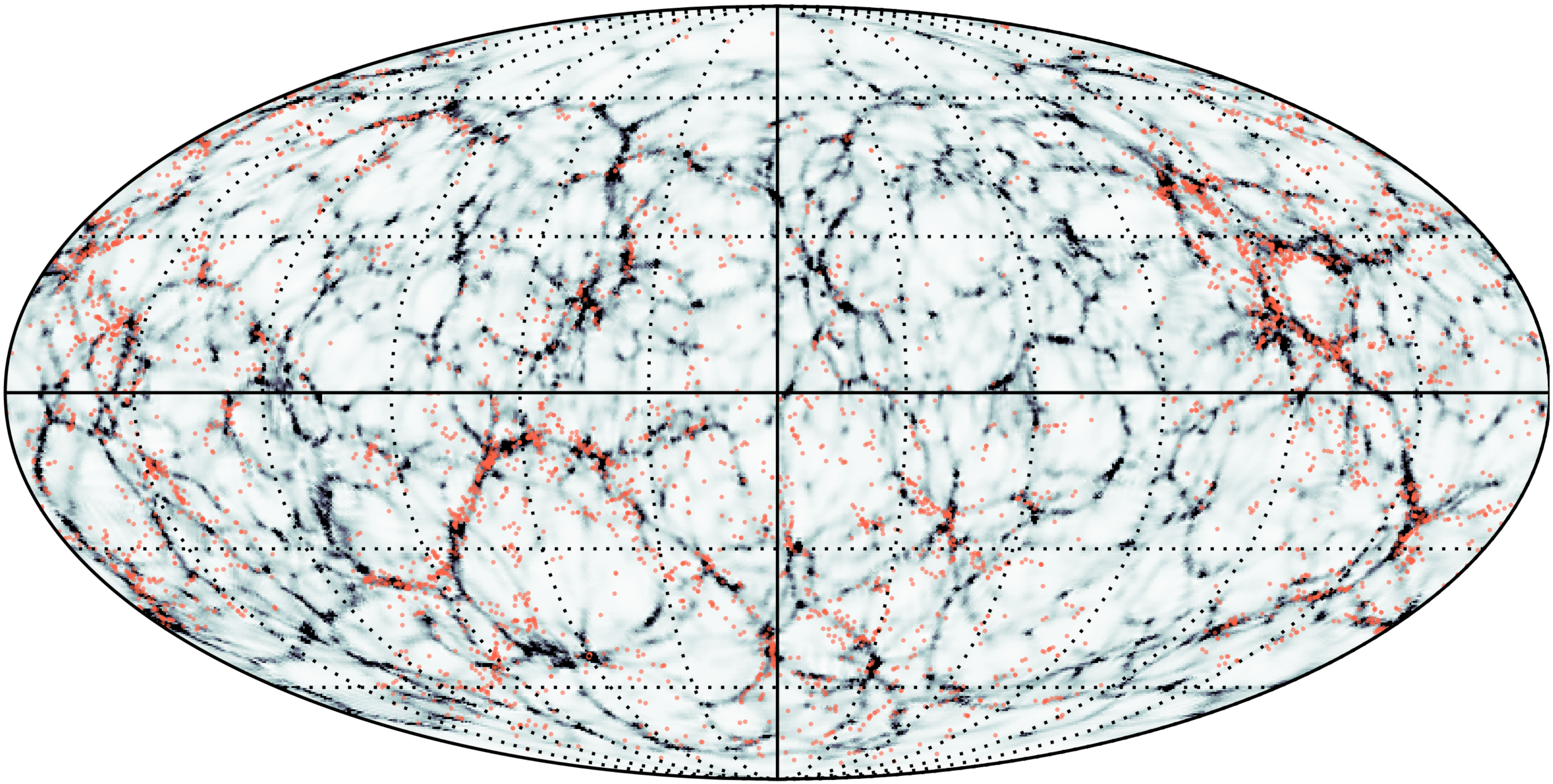
$\delta z \sim 0.03$ $\qquad$ $\delta z_f \sim 0.003$

Jasche, Wandelt 2012 (arXiv:1106.2757)

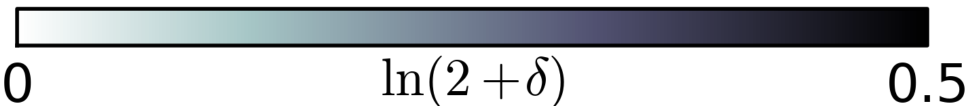
The non-linear LSS of our Universe

Preliminary work!

Final conditions inferred from 2M++ data



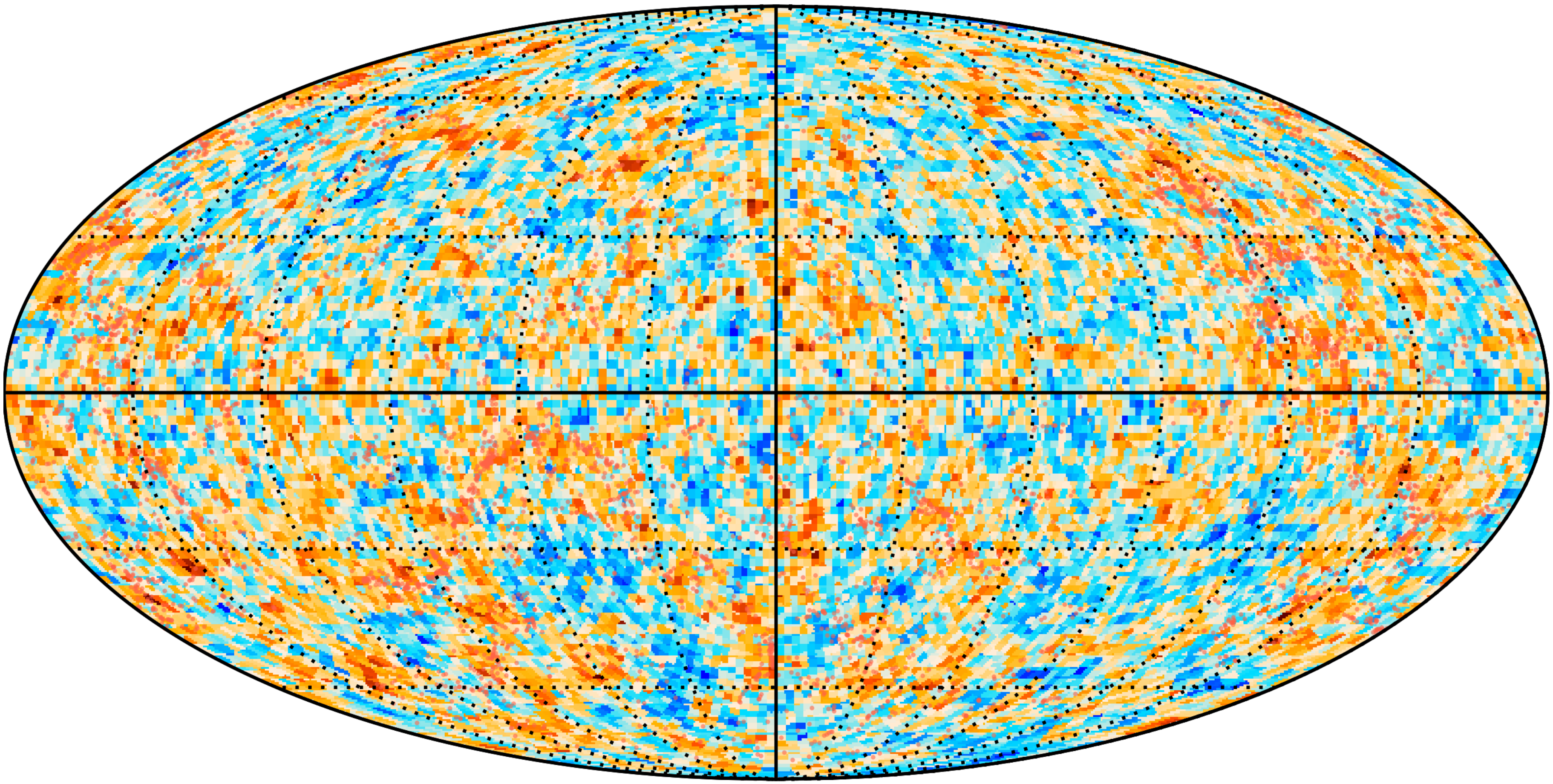
Jasche & Lavaux 2018 (in prep)



The non-linear LSS of our Universe

Preliminary work!

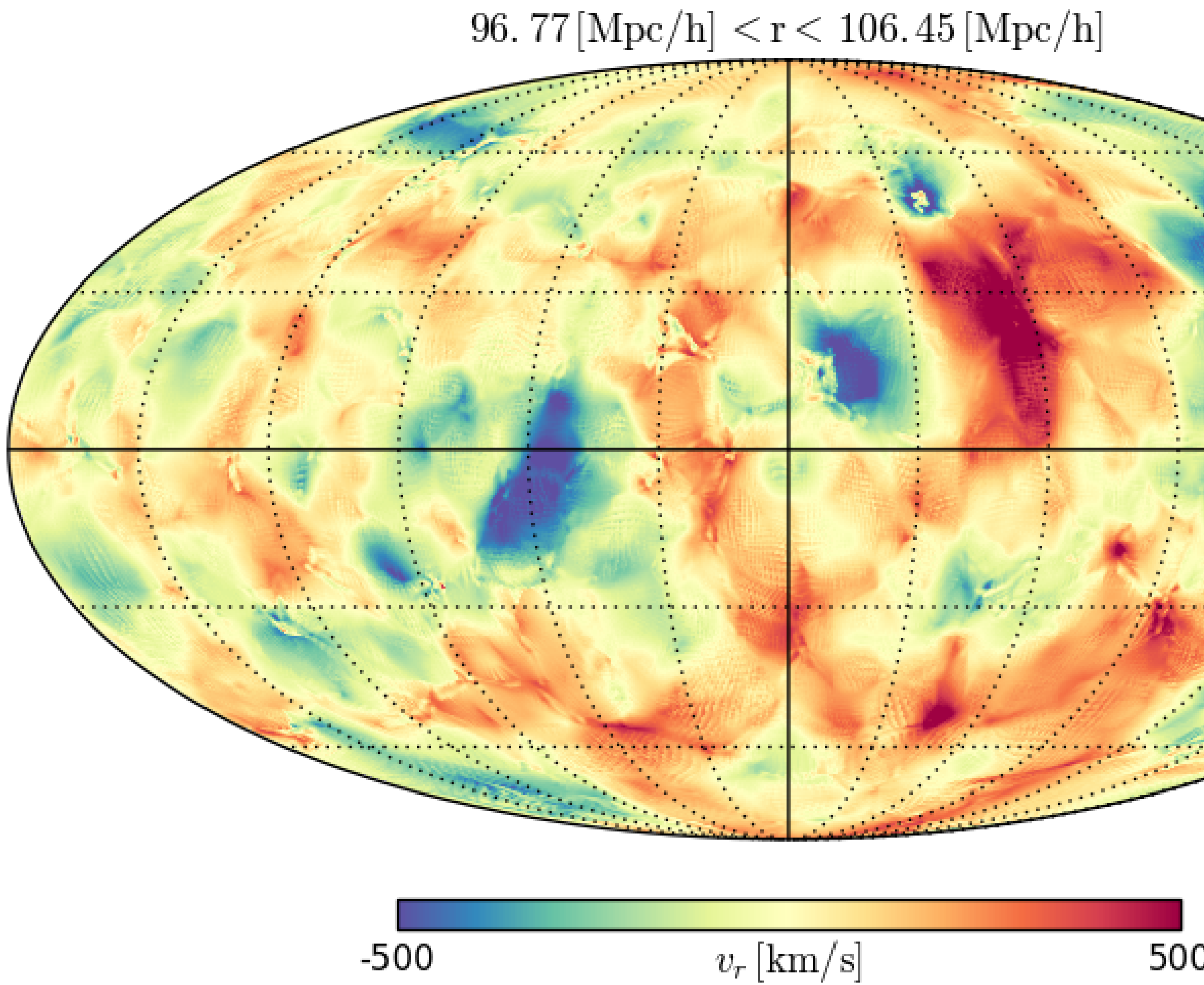
Initial conditions inferred from 2M++ data



Jasche & Lavaux 2018 (in prep)

Peculiar velocities and the Hubble flow

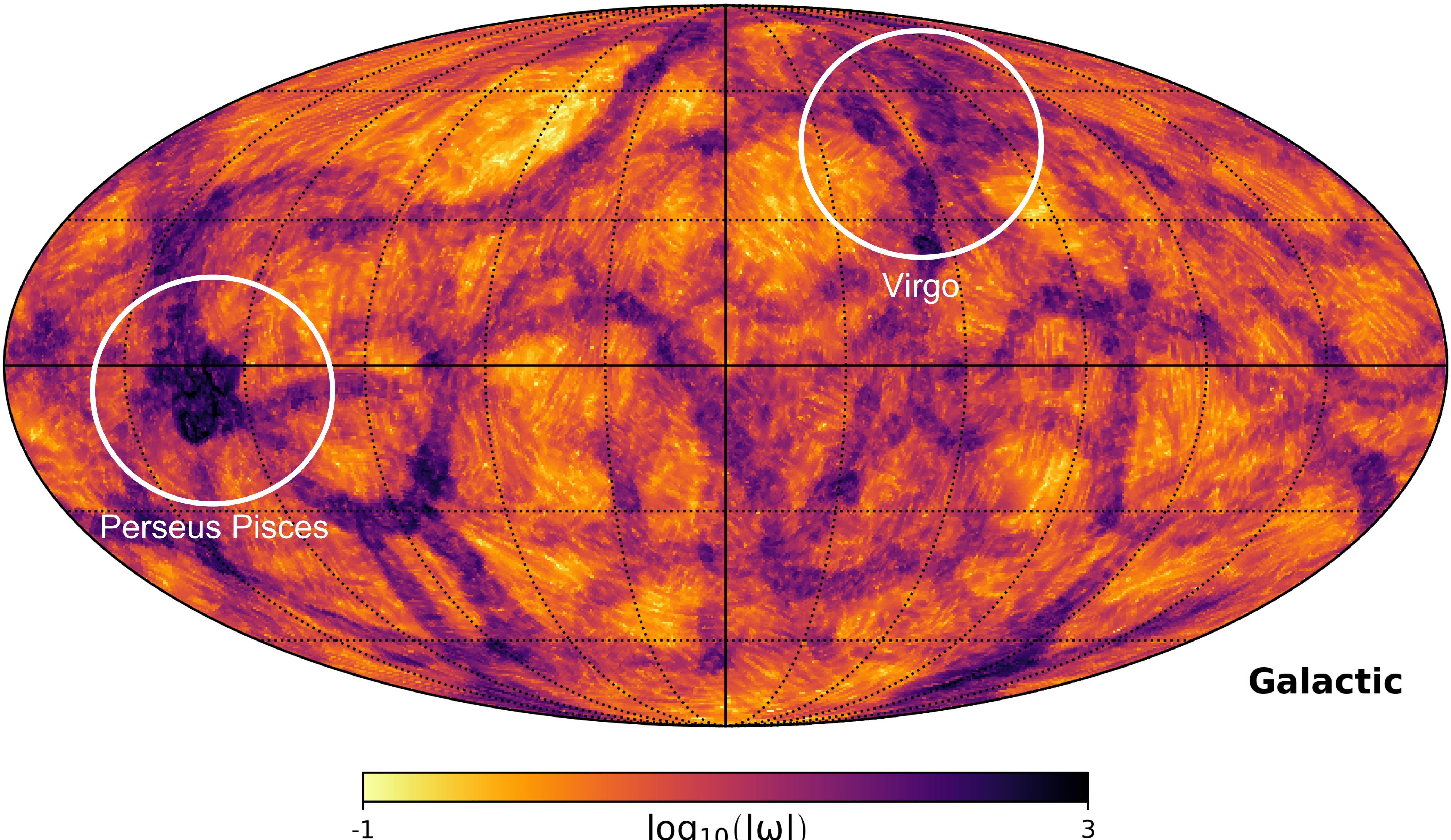
Preliminary work!



Jasche & Lavaux 2018 (in prep)

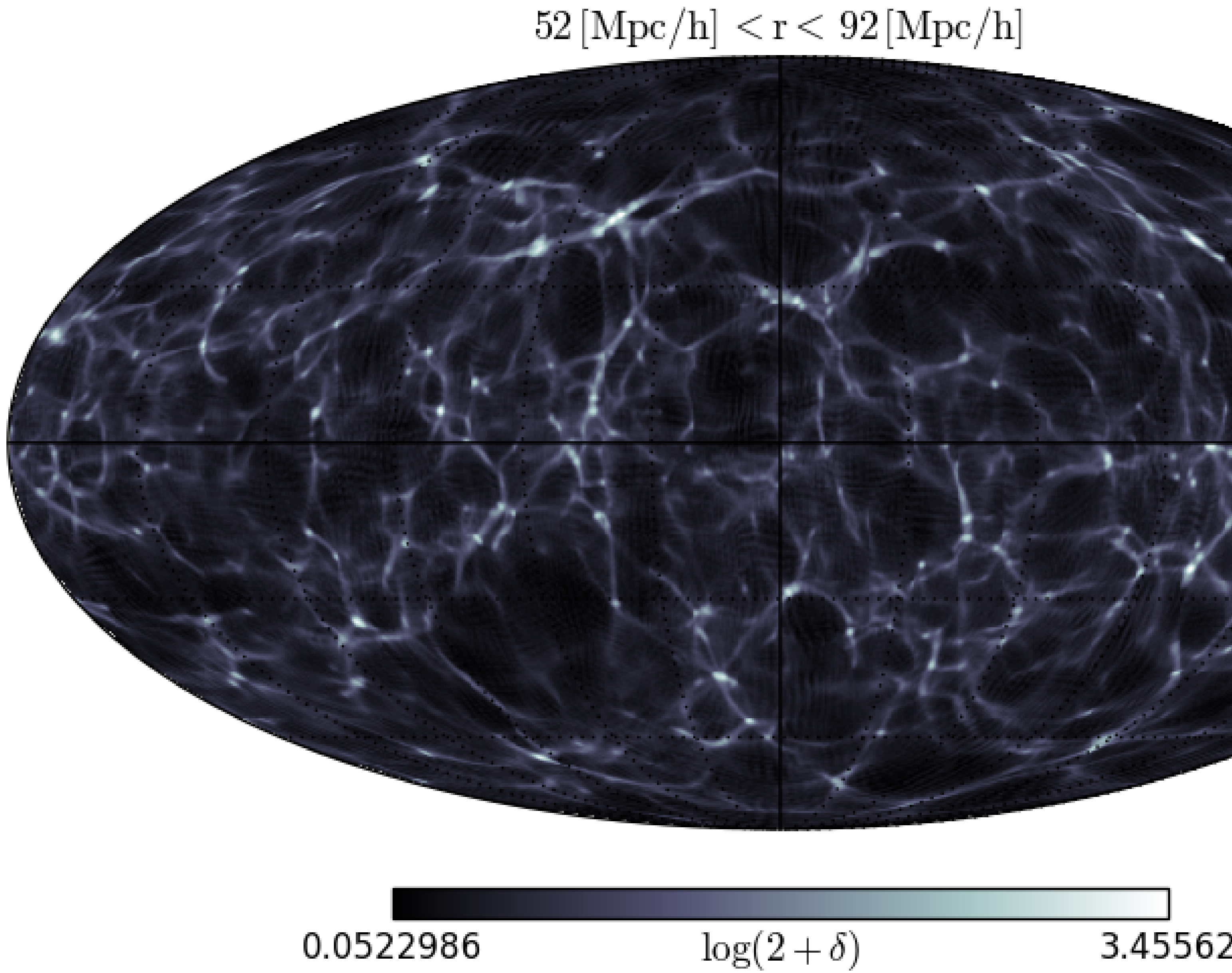
Vorticity of the velocity field

Preliminary work!

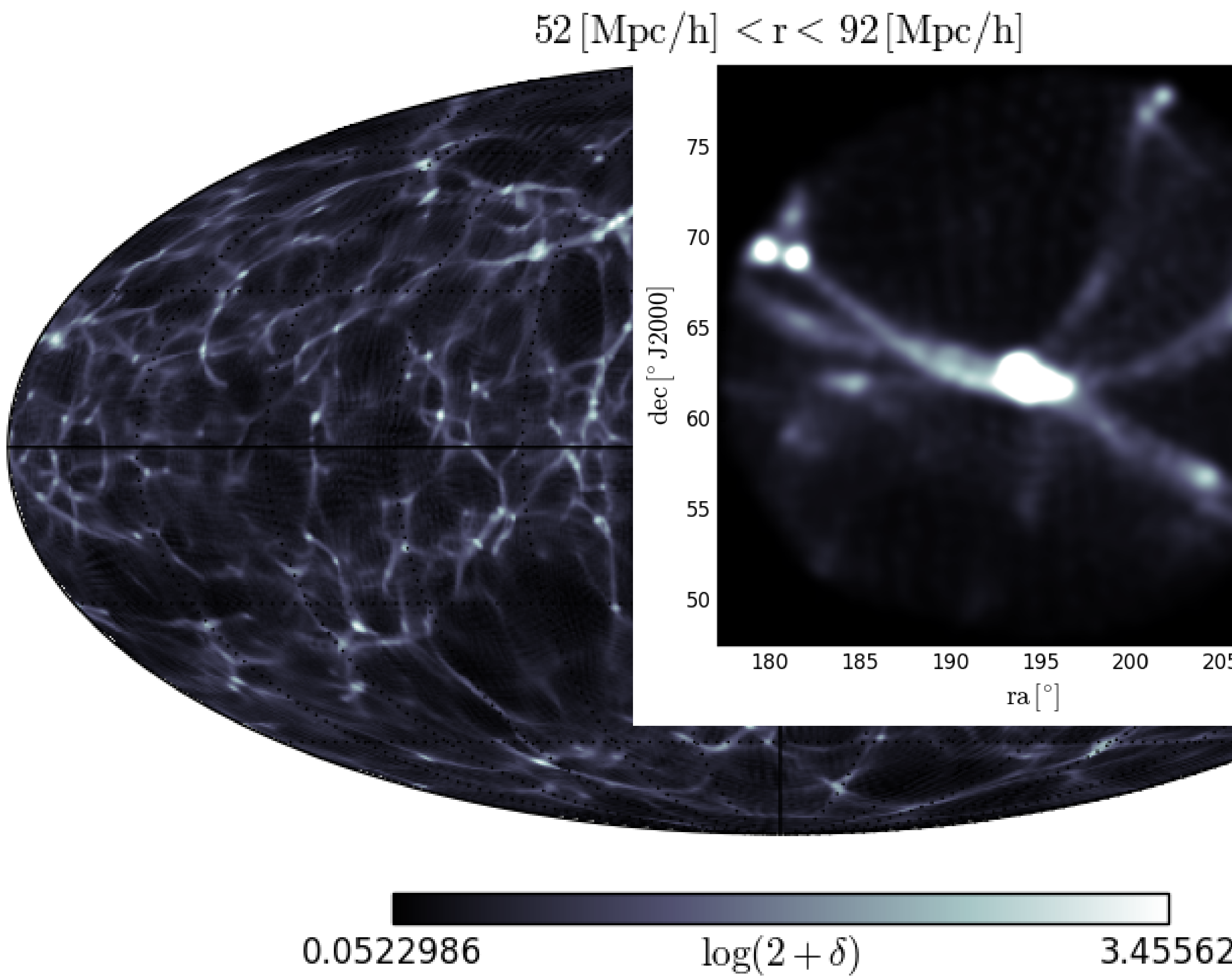


Jasche & Lavaux 2018 (in prep)

The Coma Cluster

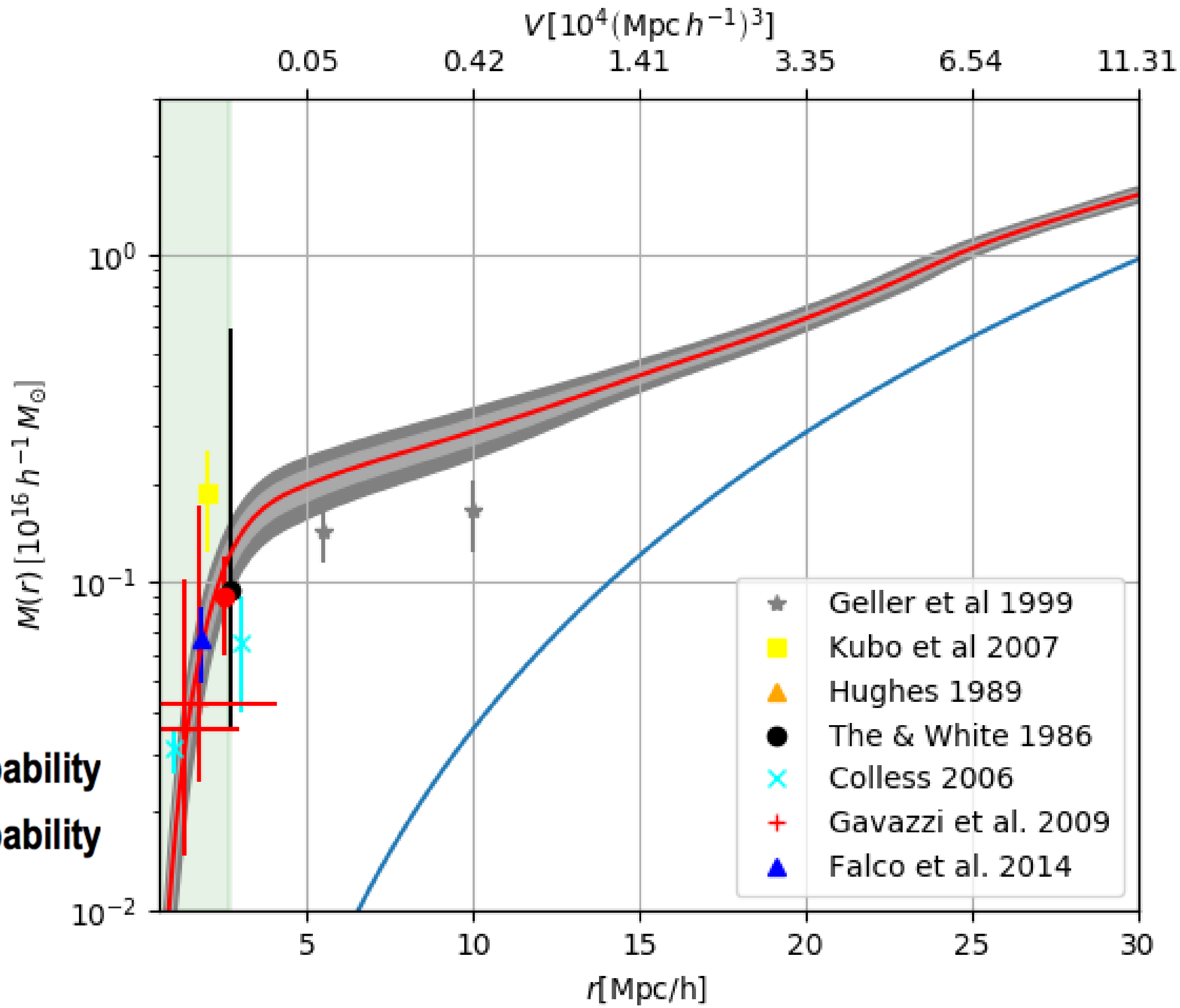


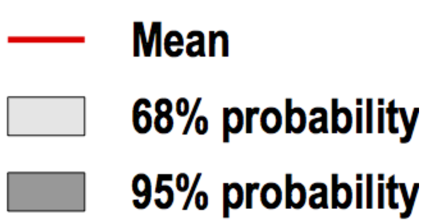
The Coma Cluster



Coma mass profile

Lavaux & Jasche 2018 in prep.





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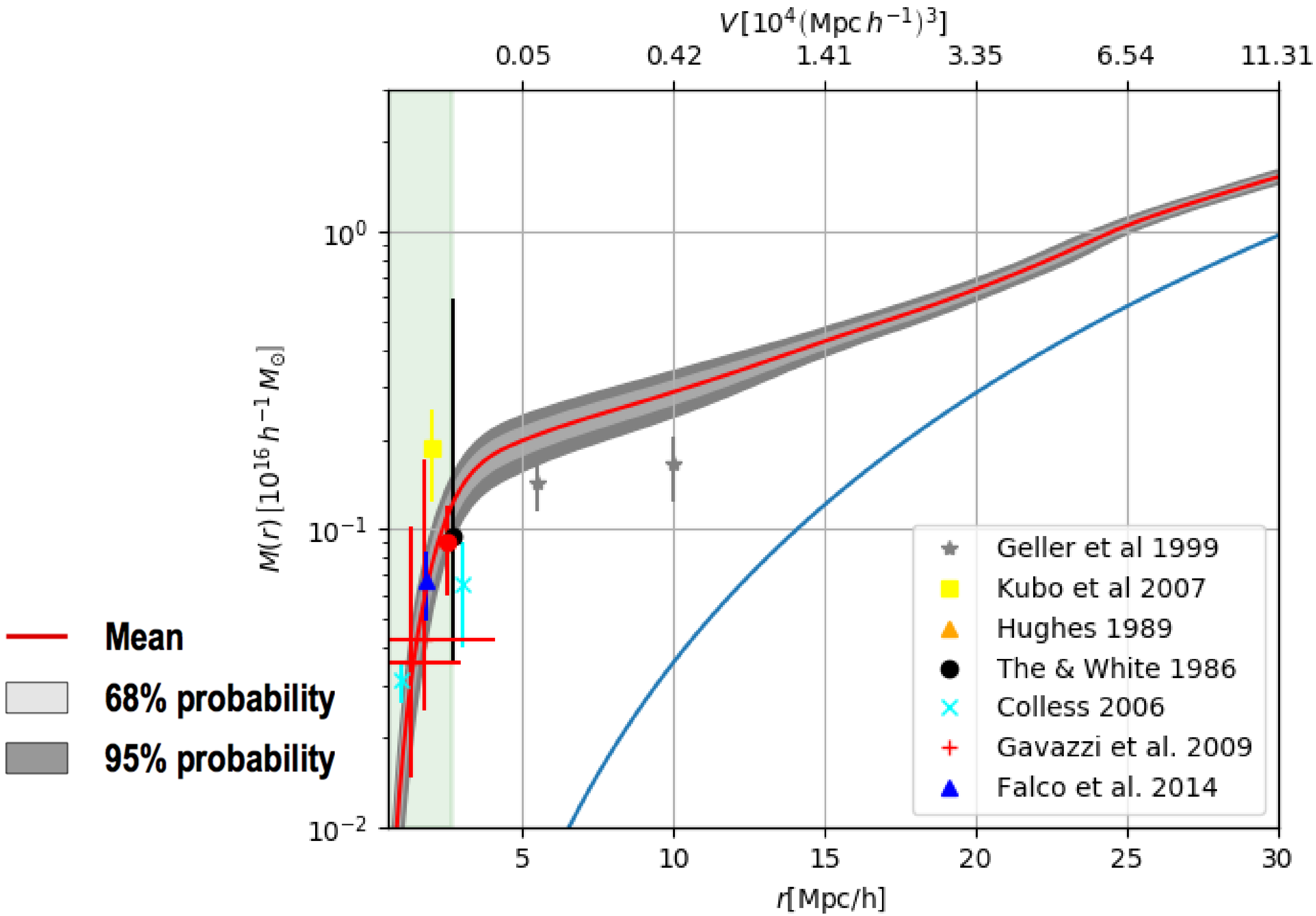


Also see talk by Guilhem Lavaux

Summary & Conclusion

BORG combines physical modeling with data science:

- Dynamical modeling accounts for non-Gaussian statistics
- Flexible data modeling via HMC and block sampling
- Solves complex high dimensional statistics problems
- Improves photo-z estimates

Scientific results:

- Characterization of initial conditions
- Accurate & Detailed reconstructions of the DM field
- Complementary mass estimates
- Dynamical reconstructions (velocity + vorticity)
- **We arrive at a consistent dynamical picture of our Universe**

The end...

Thank You!

Selected Bibliography:

Jasche, J. & Kitaura, F. S. *MNRAS* **407,** 29–42 (2010).

Jasche, J., Kitaura, F. S., Li, C. & Enßlin, T. A. *MNRAS* **409,** 355–370 (2010).

Jasche, J. & Wandelt, B. D. *MNRAS* **425,** 1042–1056 (2012).

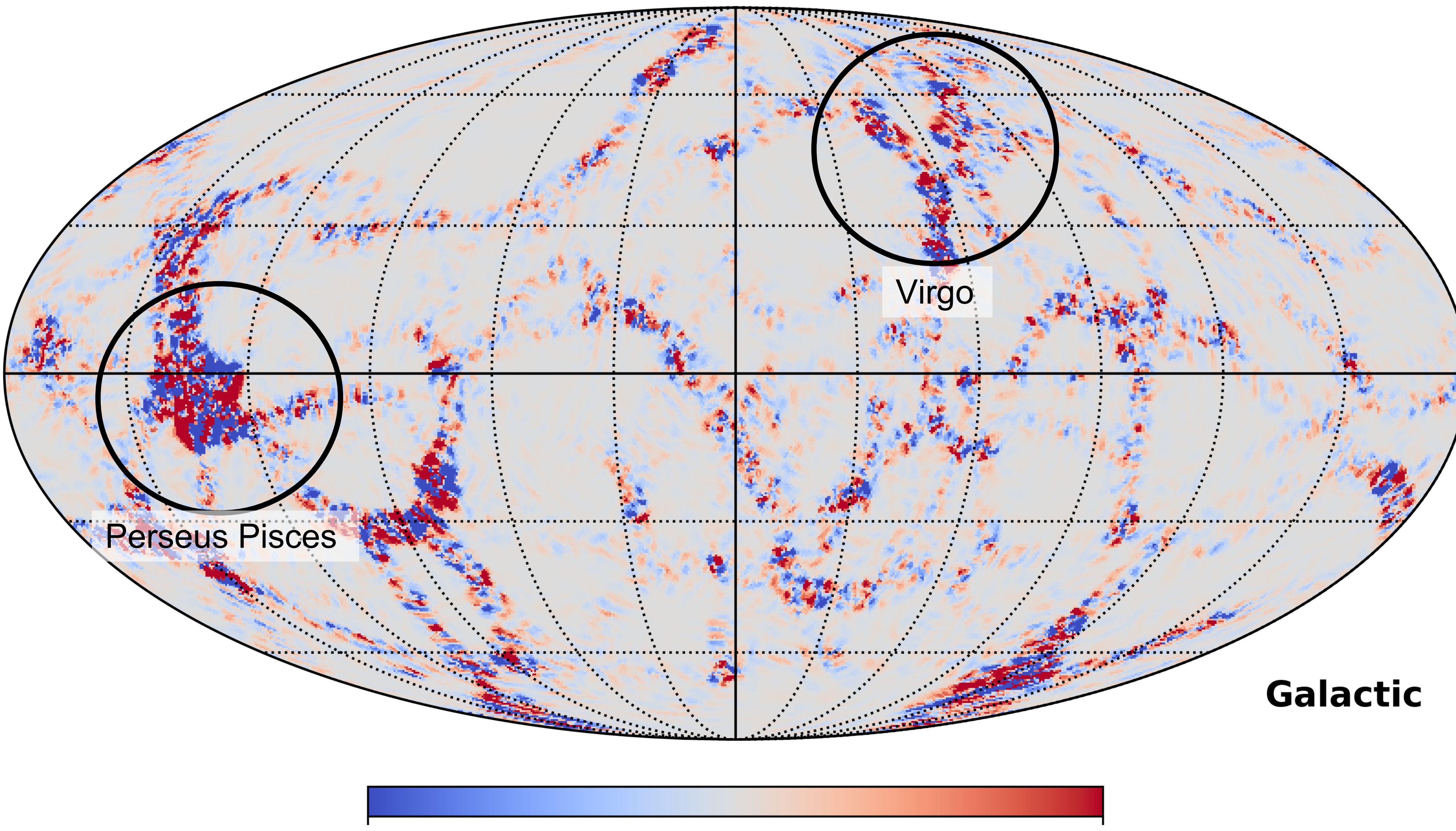
Jasche, J. & Wandelt, B. D. *MNRAS* **432,** 894–913 (2013).

Jasche, J., Leclercq, F. & Wandelt, B. D. *JCAP* **01,** 036 (2015).

Lavaux, G. & **Jasche**, J. *MNRAS* **455,** 3169–3179 (2016).

Vorticity of the velocity field

Preliminary work!



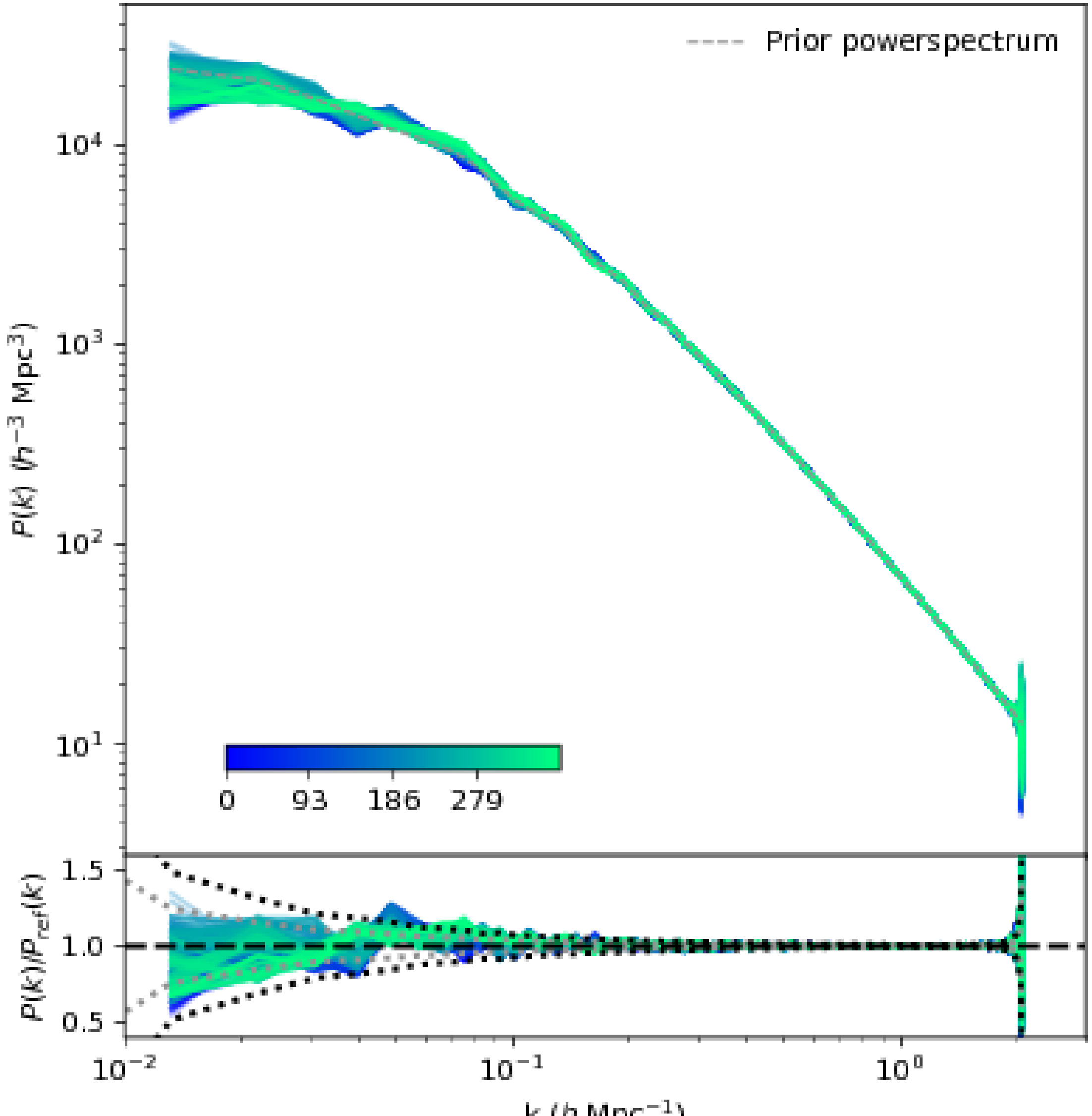
Jasche & Lavaux 2018 (in prep)

The non-linear LSS of our Universe

Preliminary work!

Consistency check

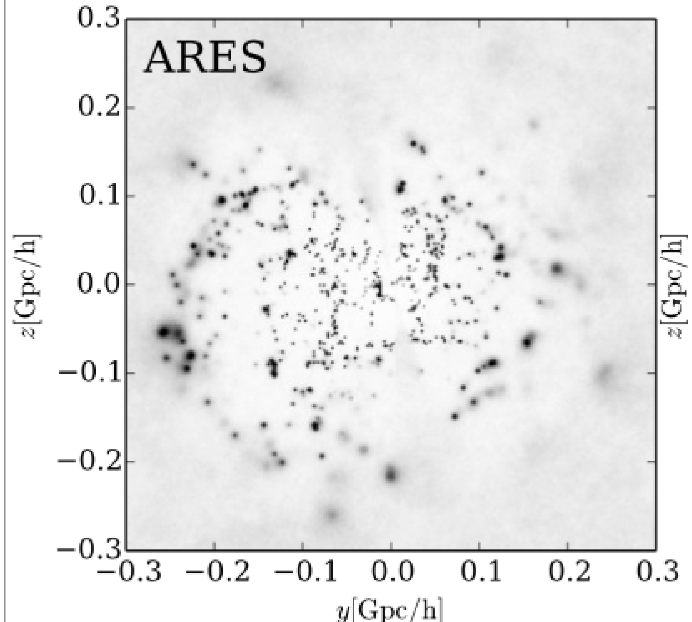
- Posterior estimate of the initial power-spectrum



Jasche & Lavaux 2018 (in prep)

Comparing inference schemes

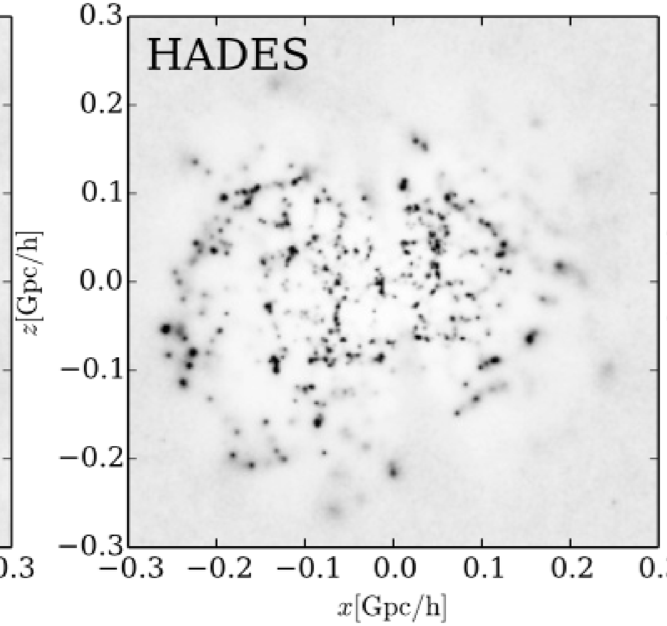
Gaussian



a.k.a: Wiener-filtering

Zaroubi et al. 1994
Erdogdu et al. 2004
Kitaura & Ensslin 2008
Grannet et al. 2015

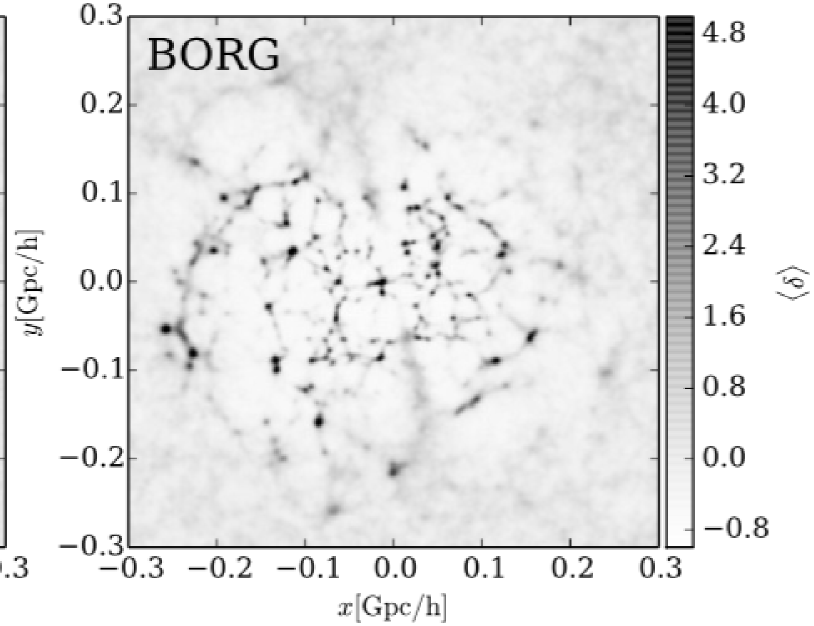
Log-normal-Poisson



log-normal-filtering

Kitaura 2010
Jasche&Kitaura 2010

2LPT-Poisson



Jasche&Wandelt 2012

Which scheme performs best?

Ask the data!

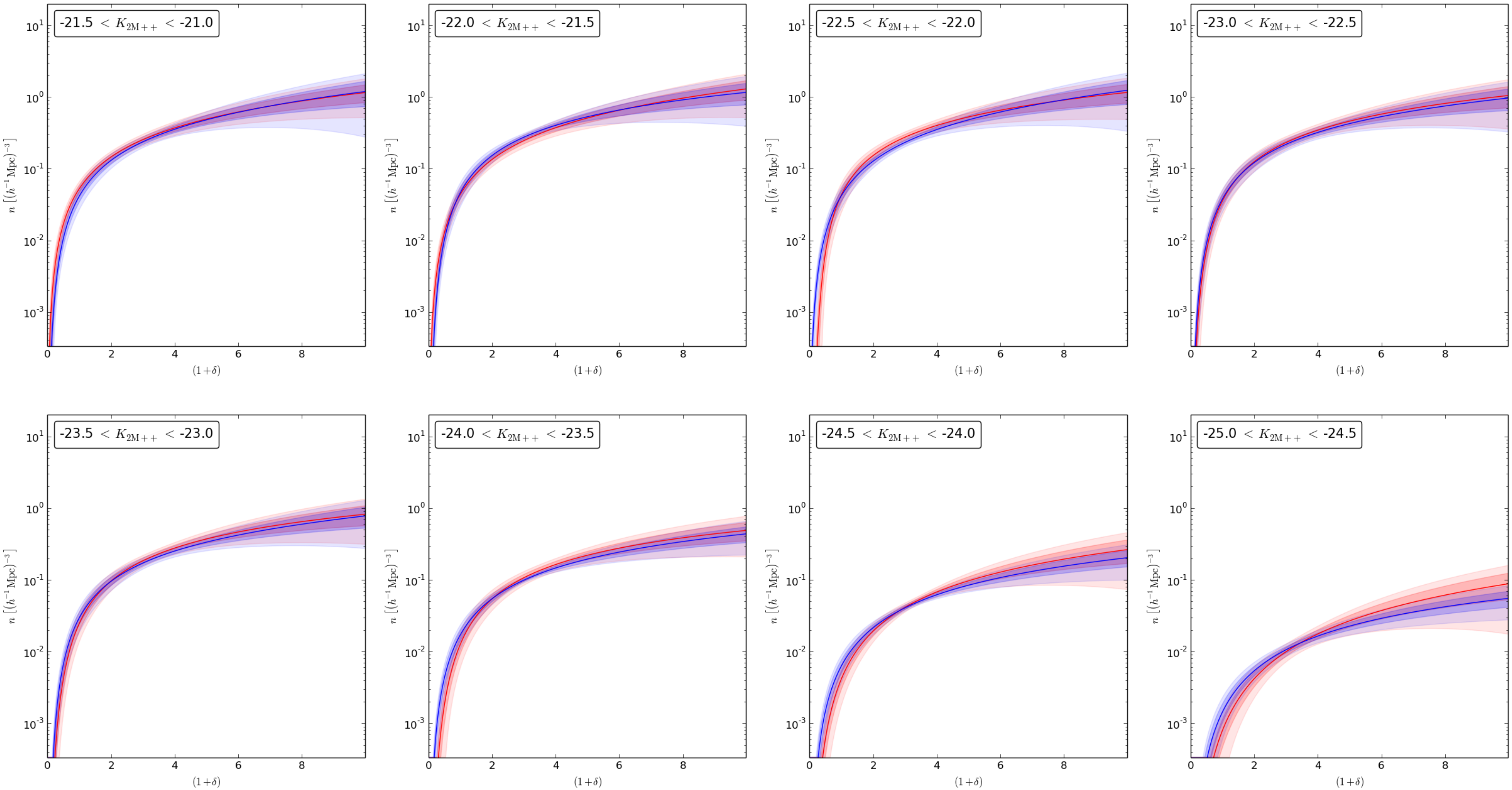
$$A_{ij} = \ln\left(\mathcal{P}(d|\delta_i)\right) - \ln\left(\mathcal{P}(d|\delta_j)\right)$$

	ARES	HADES	BORG
ARES	0	-219580.31	-383482.25
HADES	219580.31	0	-163901.94
BORG	383482.25	163901.94	0.

Jasche & Lavaux (in prep)

Astrophysics: The galaxy bias

Jasche & Lavaux 2018 (in prep)



Bias model: local generalized power-law

$$n^g(\delta, \bar{N}, \beta, \rho_g, \epsilon_g) = \bar{N}\,(1+\delta)^\beta\, \mathrm{e}^{-\rho_g\,(1+\delta)^{-\epsilon_g}}$$

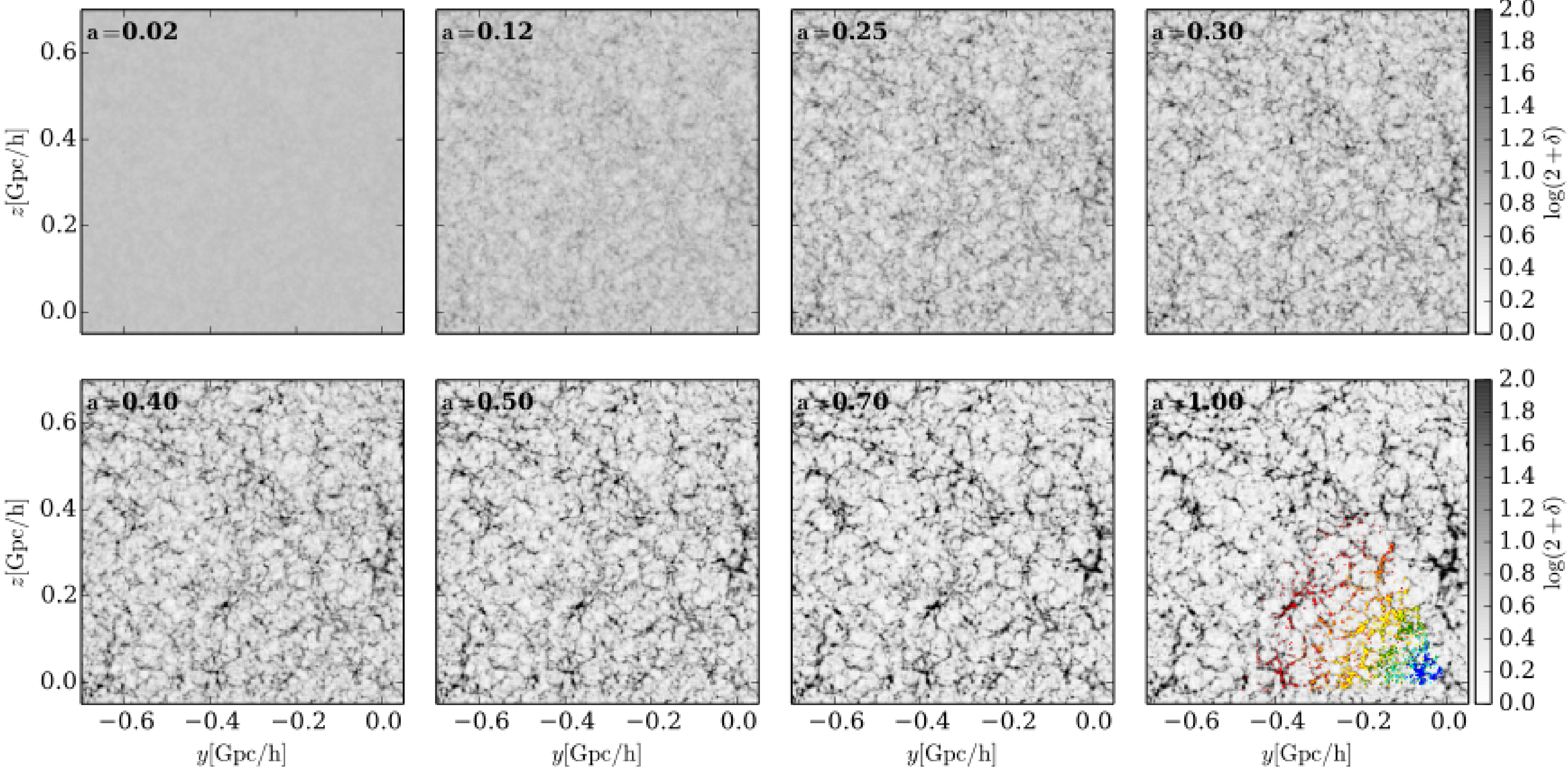
Neyrinck et al. 2014

Reconstructing formation histories

Dynamic Information

- Plausible LSS formation history

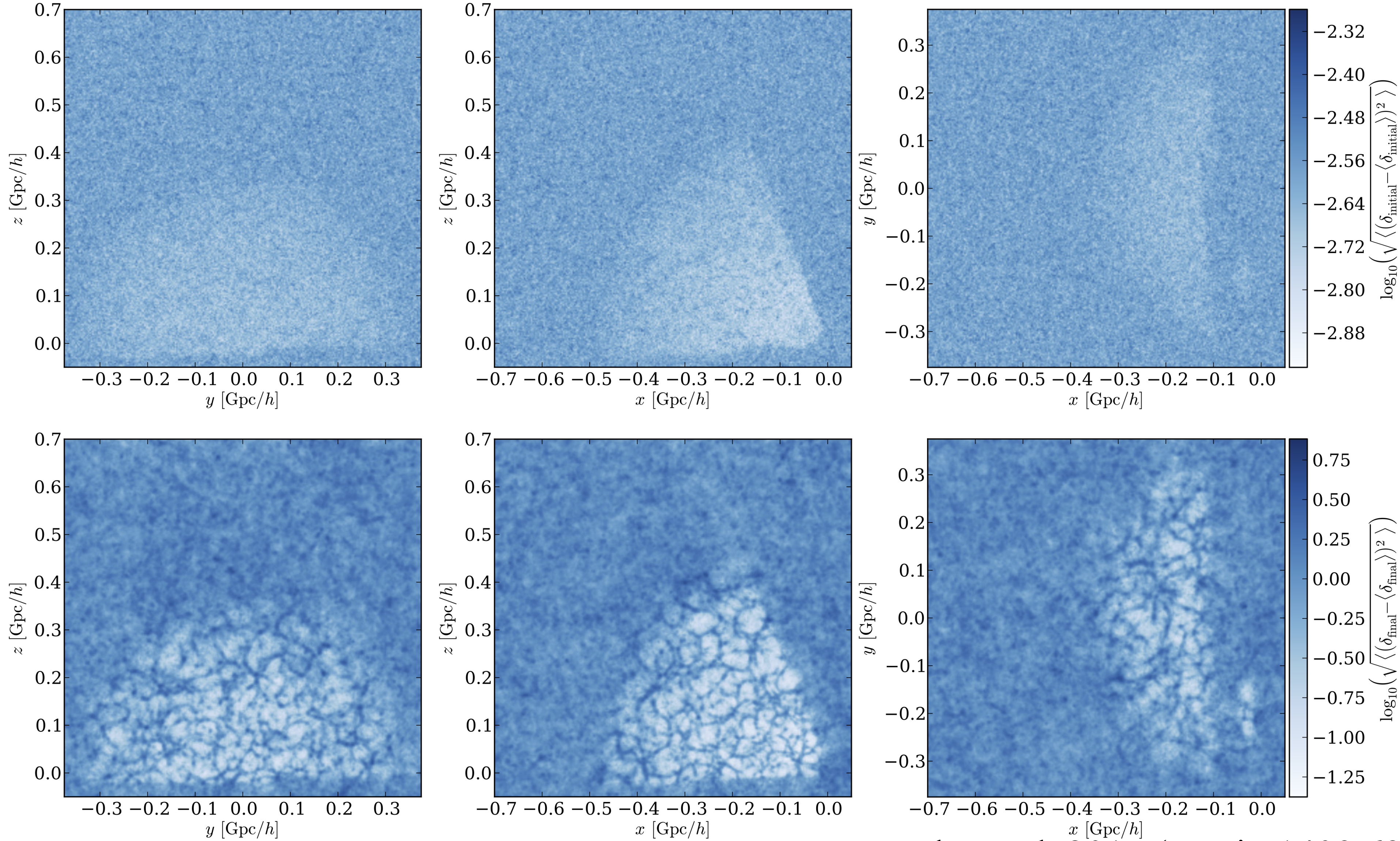
Jasche et al. 2015 (arXiv:1409.6308)



Bayesian analysis of the SDSS DR7

Uncertainty quantification

- Voxel-wise standard deviations for initial and final states

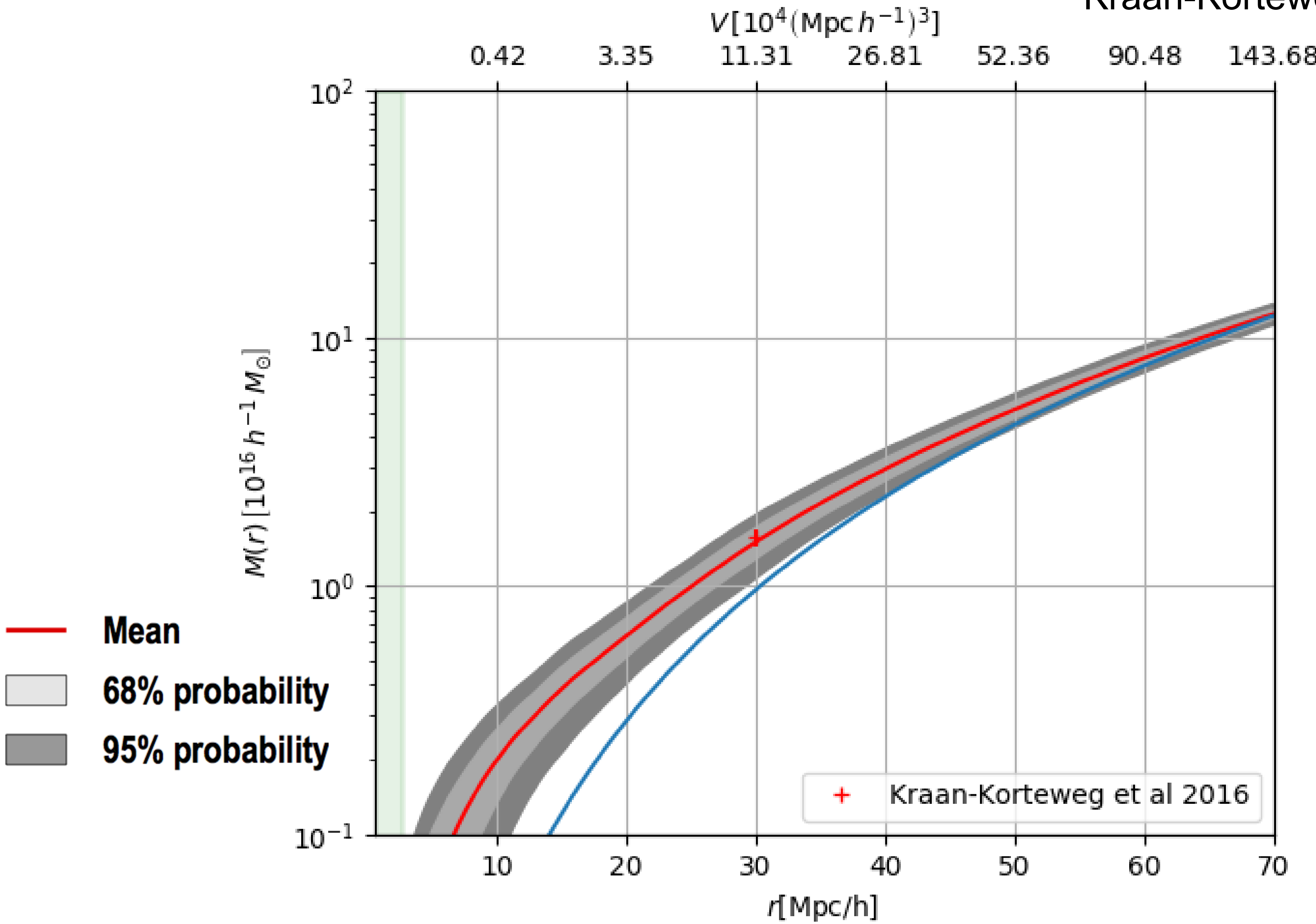


Jasche et al. 2015 (arXiv:1409.6308)

Mass of Vela Supercluster

2016 Discovery of a supercluster in the ZOA in Vela

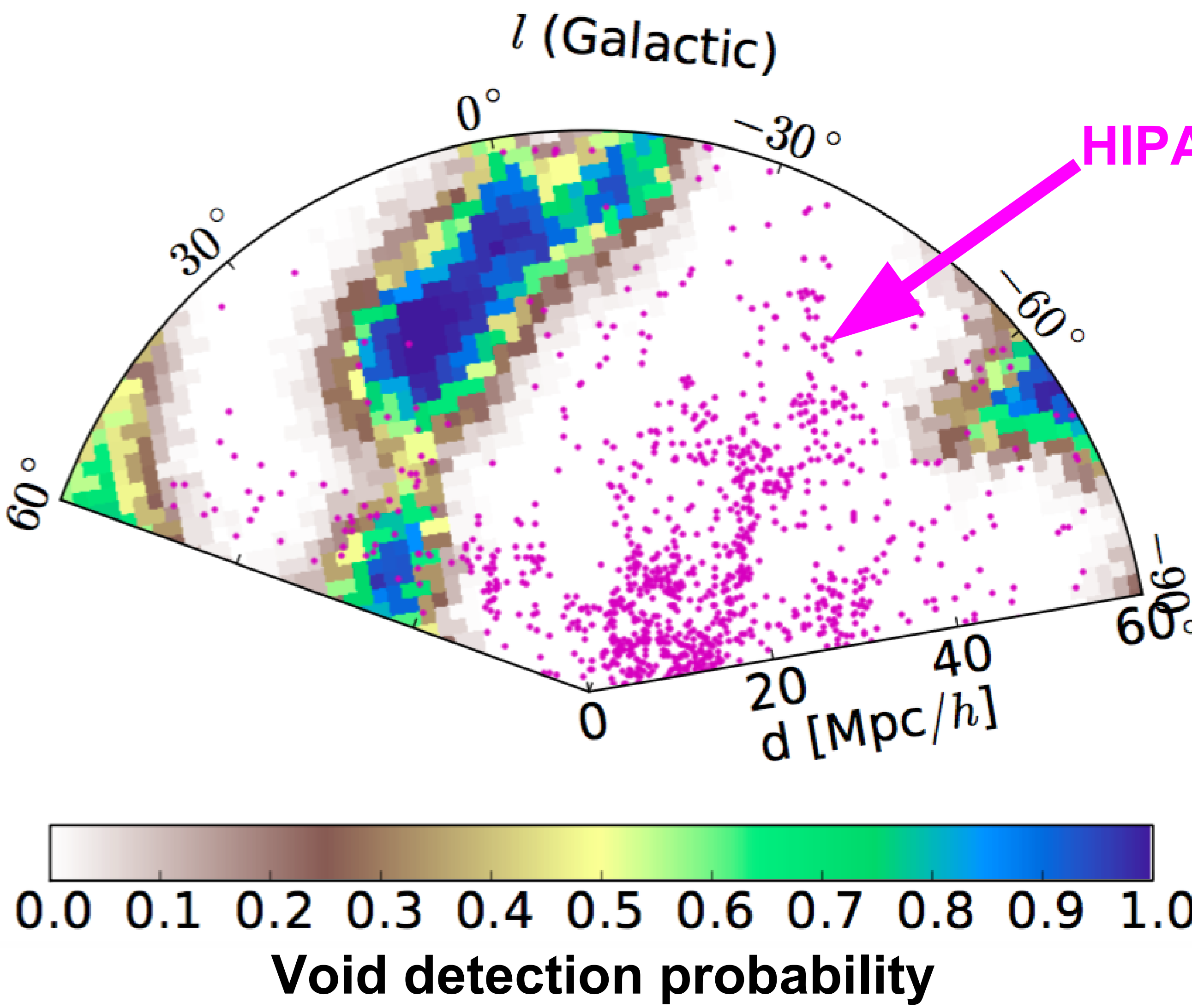
Kraan-Korteweg et al 2016



Lavaux & Jasche 2018 in prep.

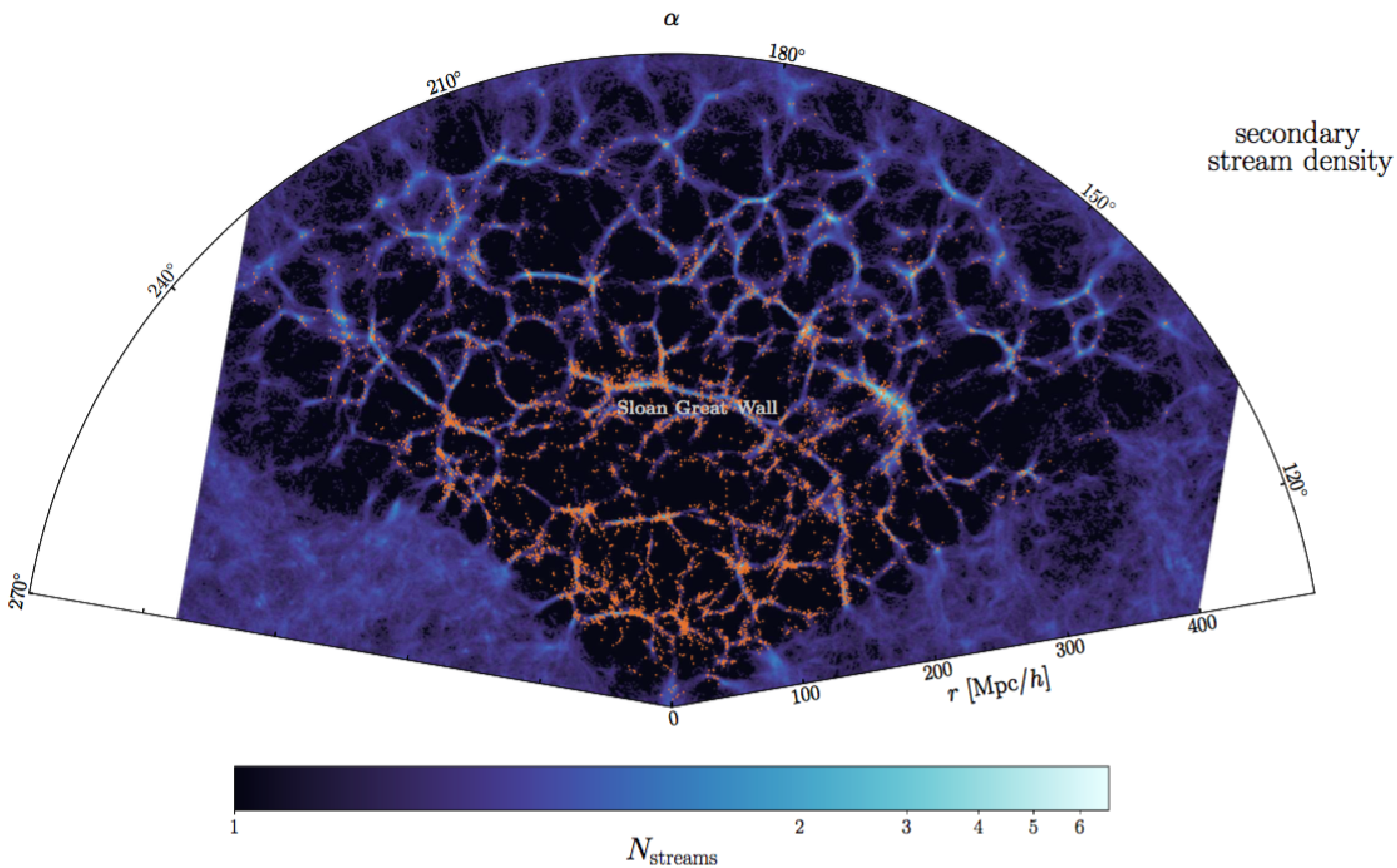
Detecting the local void

Testing with complementary HI data (HIPASS, Meyer et al. 2014):



Lavaux & Jasche 2016 (arXiv:1509.05040)

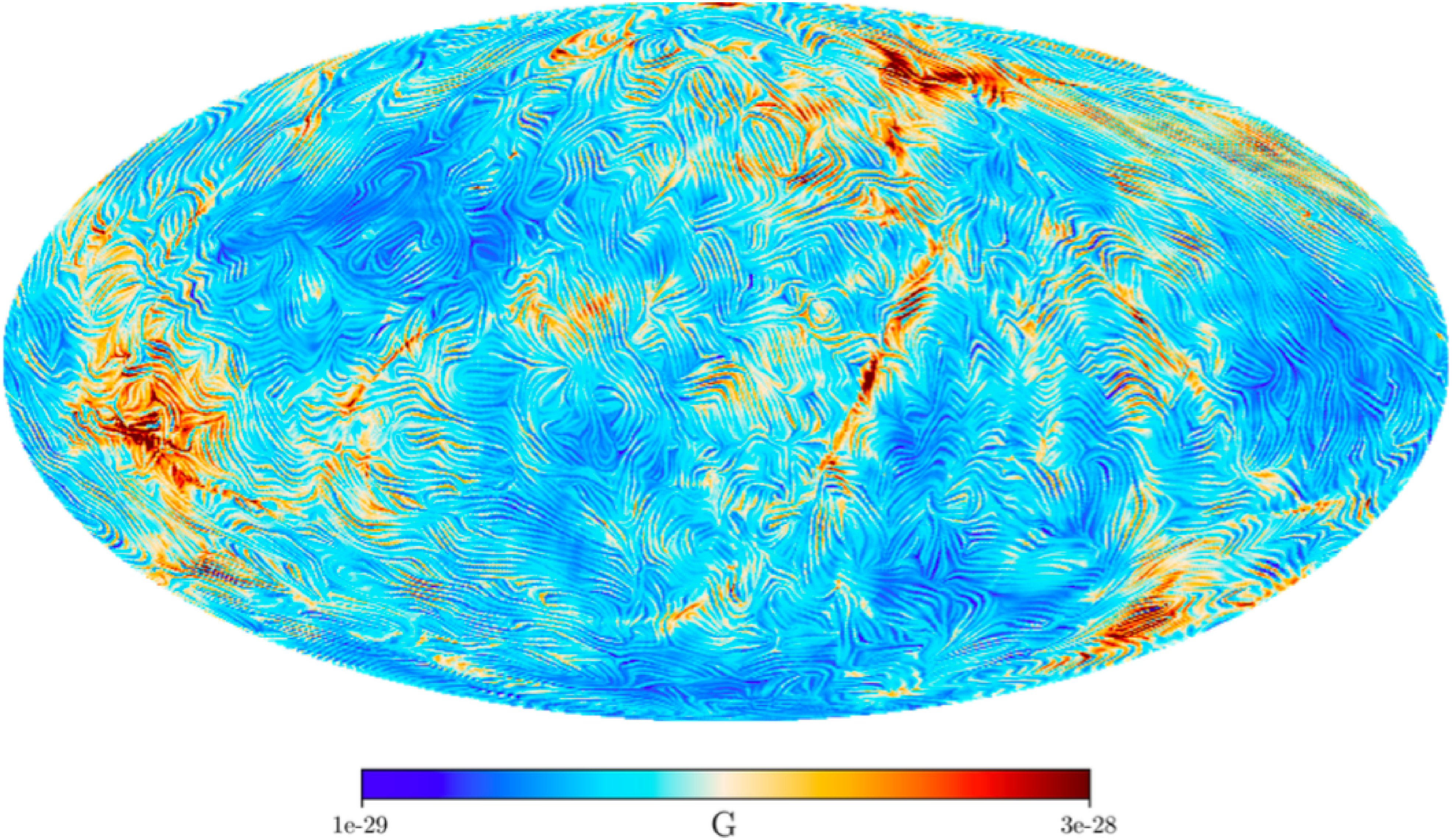
The Future: Stream densities



Leclercq et al 2017

Remnants of primordial Magnetic fields

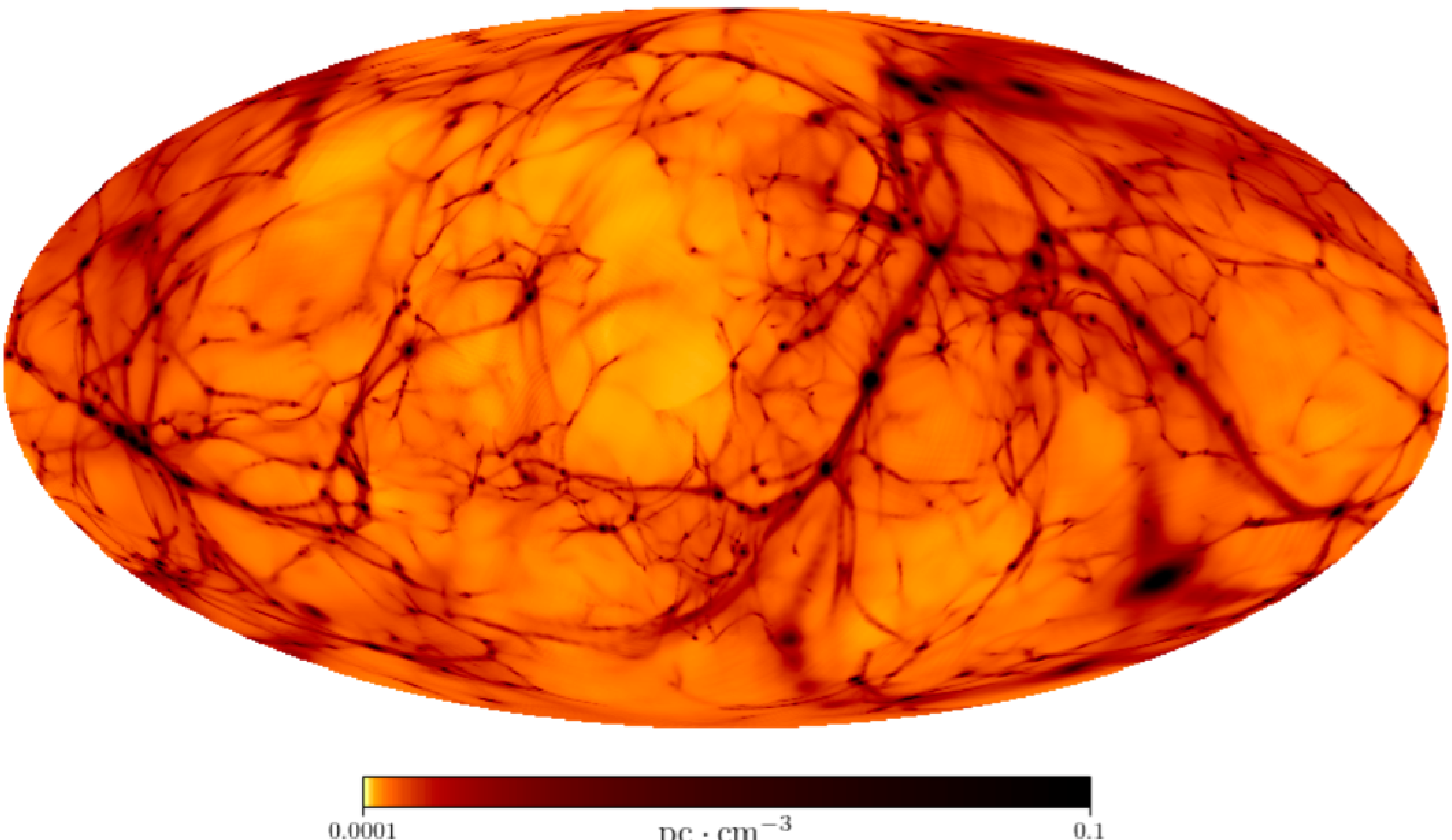
- Generate primordial MF via Harrison mechanism
- Evolve with MHD sim (ENZO)



Hutschenreuter et al. 2018 (arXiv:1803.02629)

Remnants of primordial Magnetic fields

- Electron dispersion measure



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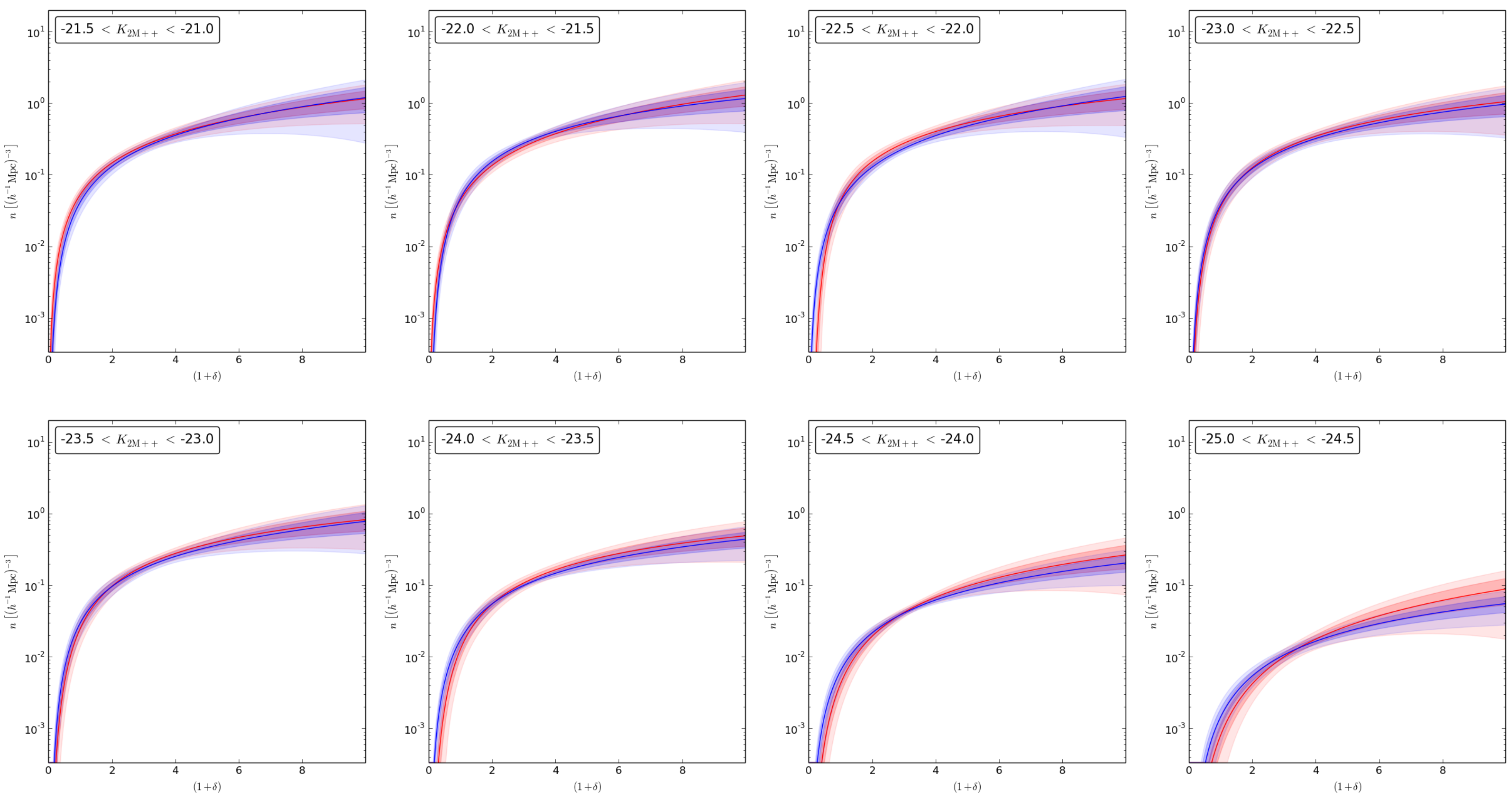
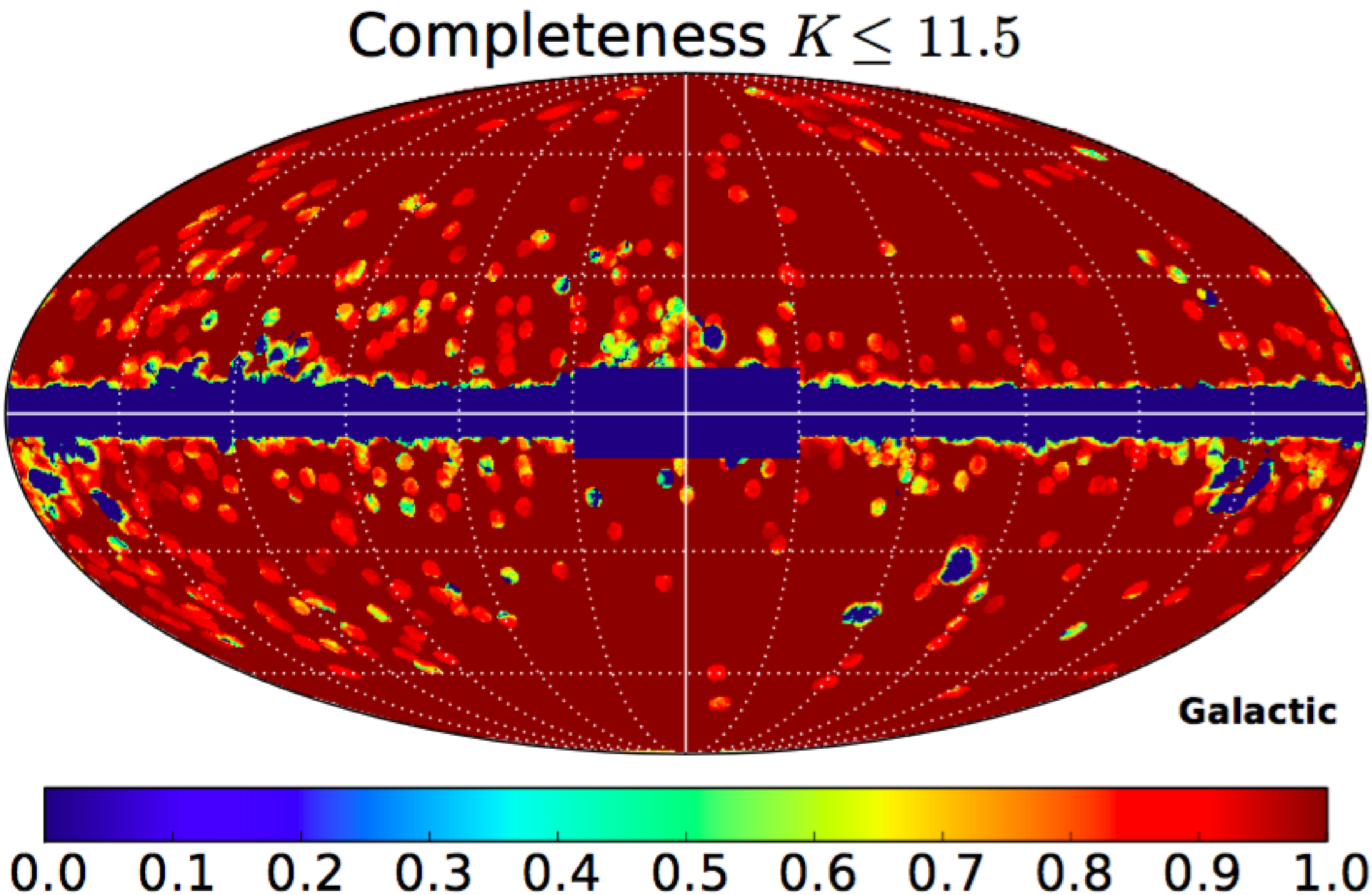


Jasche & Lavaux 2018 (in prep)

Detecting the local void

Analyzing the 2M++ galaxy survey (Lavaux et al. 2011):



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