# Modern reconstruction techniques of the non-linear dynamics of Large Scale Structures

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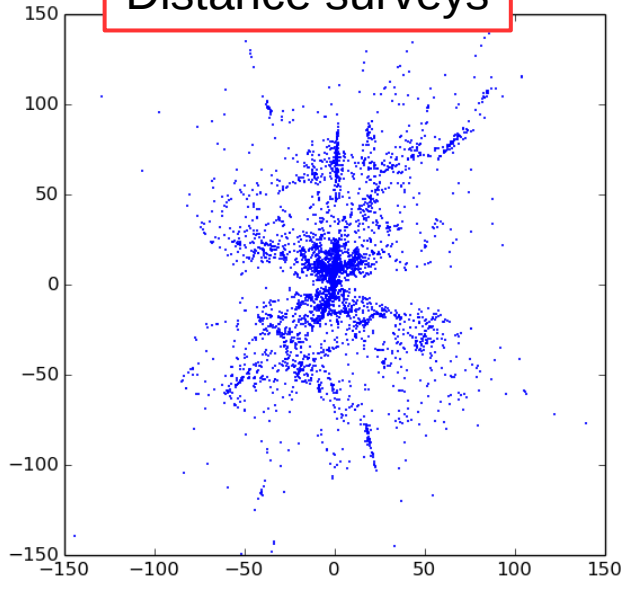
Stephen Turnbull (UoW), Jonathan Carrick

1st Roman Juszkiewicz symposium

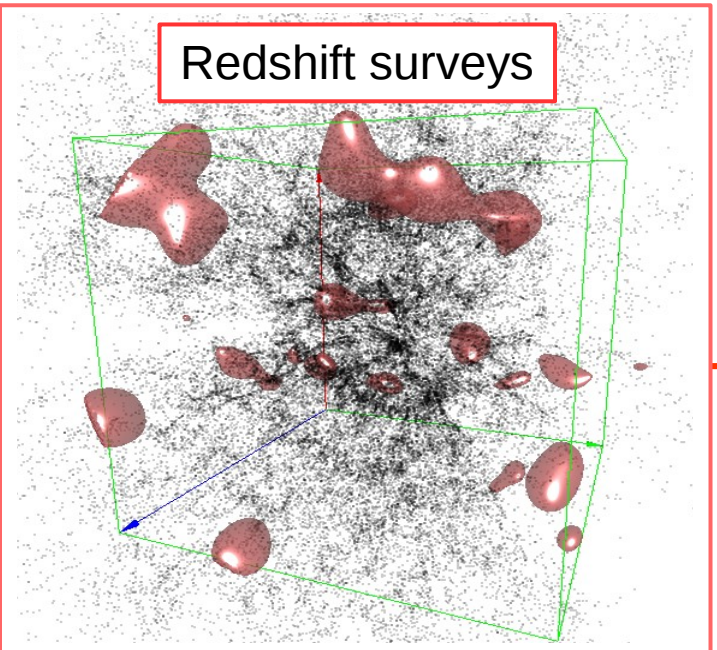
August 25th 2015

# What is "reconstruction"?

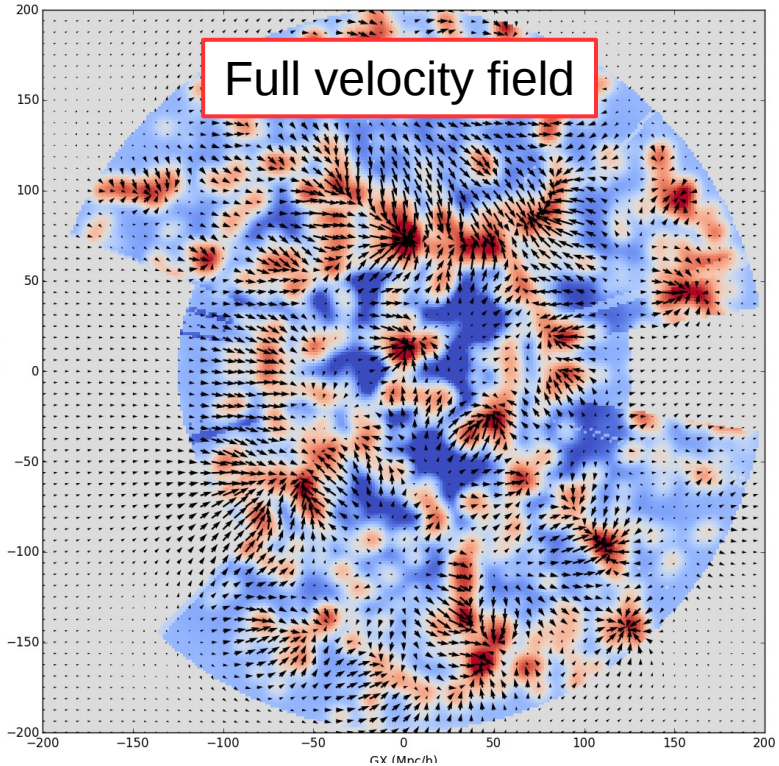
Distance surveys



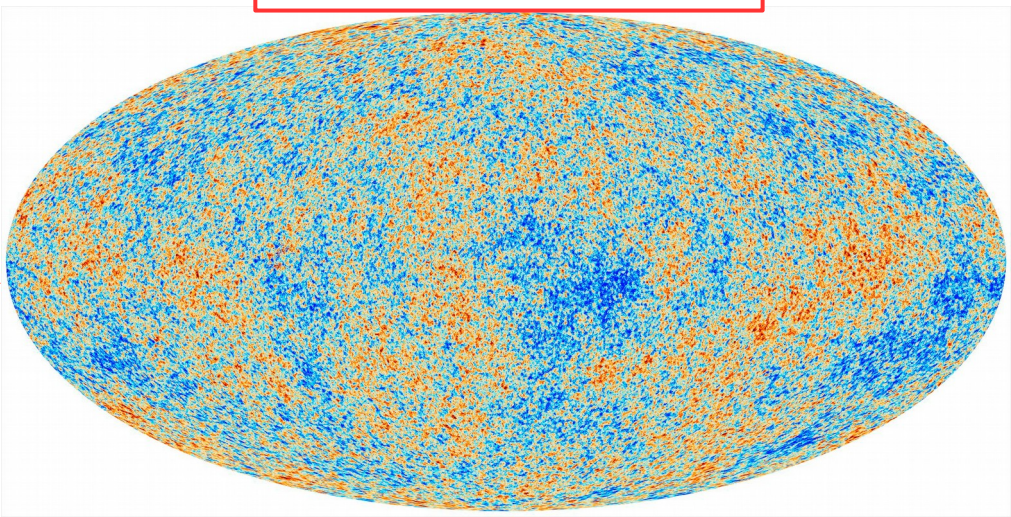

Redshift surveys



Full velocity field




Local initial conditions



# What is "reconstruction"?

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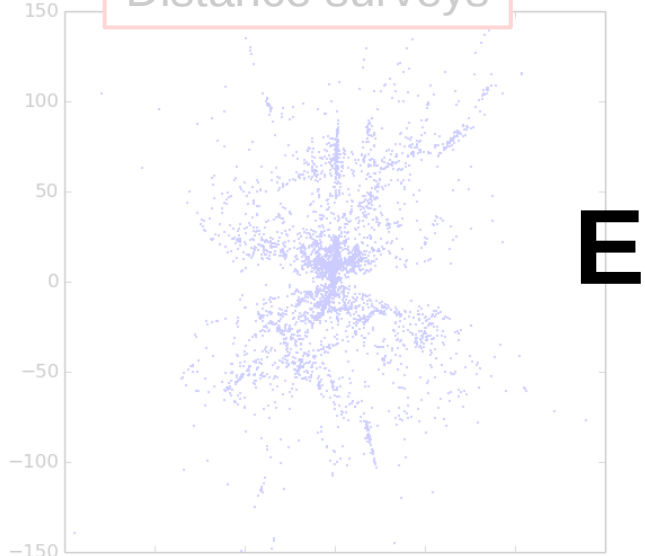
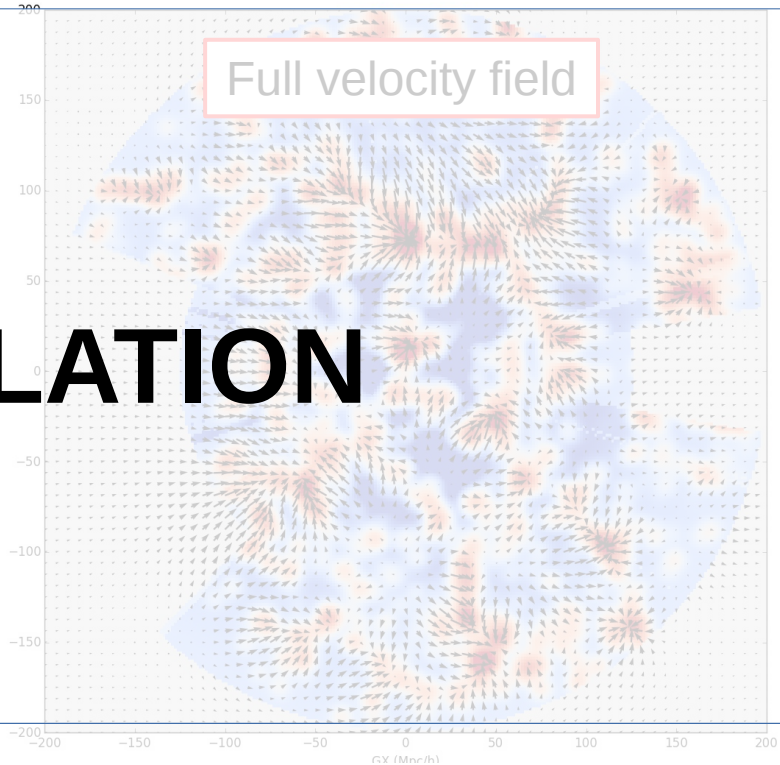



**EXTRAPOLATION**

Full velocity field

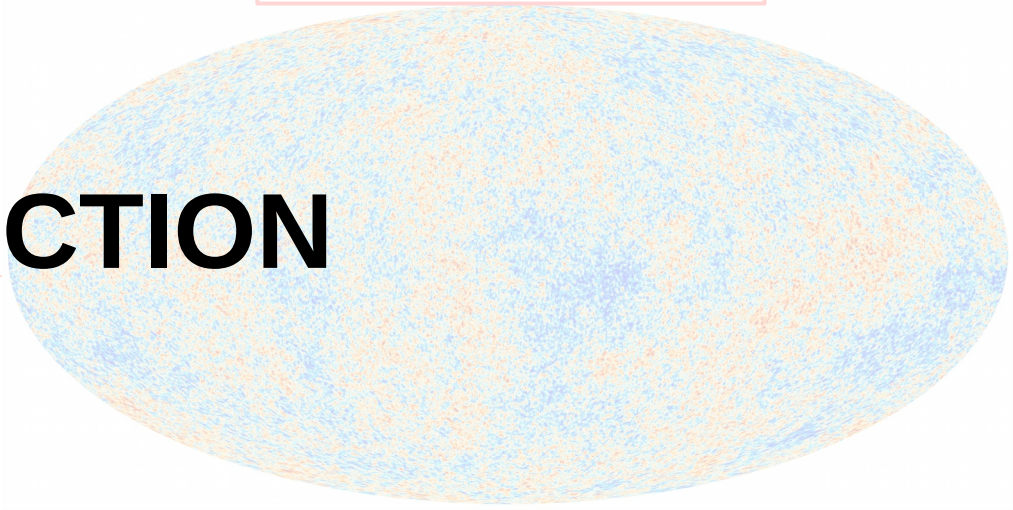



Redshift surveys



**PREDICTION**

Local initial conditions



# What is "reconstruction"?

- **Extrapolation** from the observed velocities
  (POTENT,Wiener,UMV method)

  Bertschinger & al (1990), Dekel & al (1999), Branchini & al (2000)
  Zaroubi & al (1999, 2002)

- **Prediction** from the observed fluctuation
  (Linear theory, Least action, MAK)
  ⇒ velocity-velocity comparison

  e.g. Peebles (1980); Peebles (1989); Brenier & al (2003),
  Shaya, Peebles, Tully (1995); Lavaux, Tully & al (2010);
  etc.

# Outline

- ~~Introduction~~
- Earlier methods
  - Linear theory/POTENT
  - Least action/MAK
  - Recent results
- New statistical reconstruction methods
  - ARES/VIRBiUS
  - BORG
  - Results on data
- Conclusion / Summary

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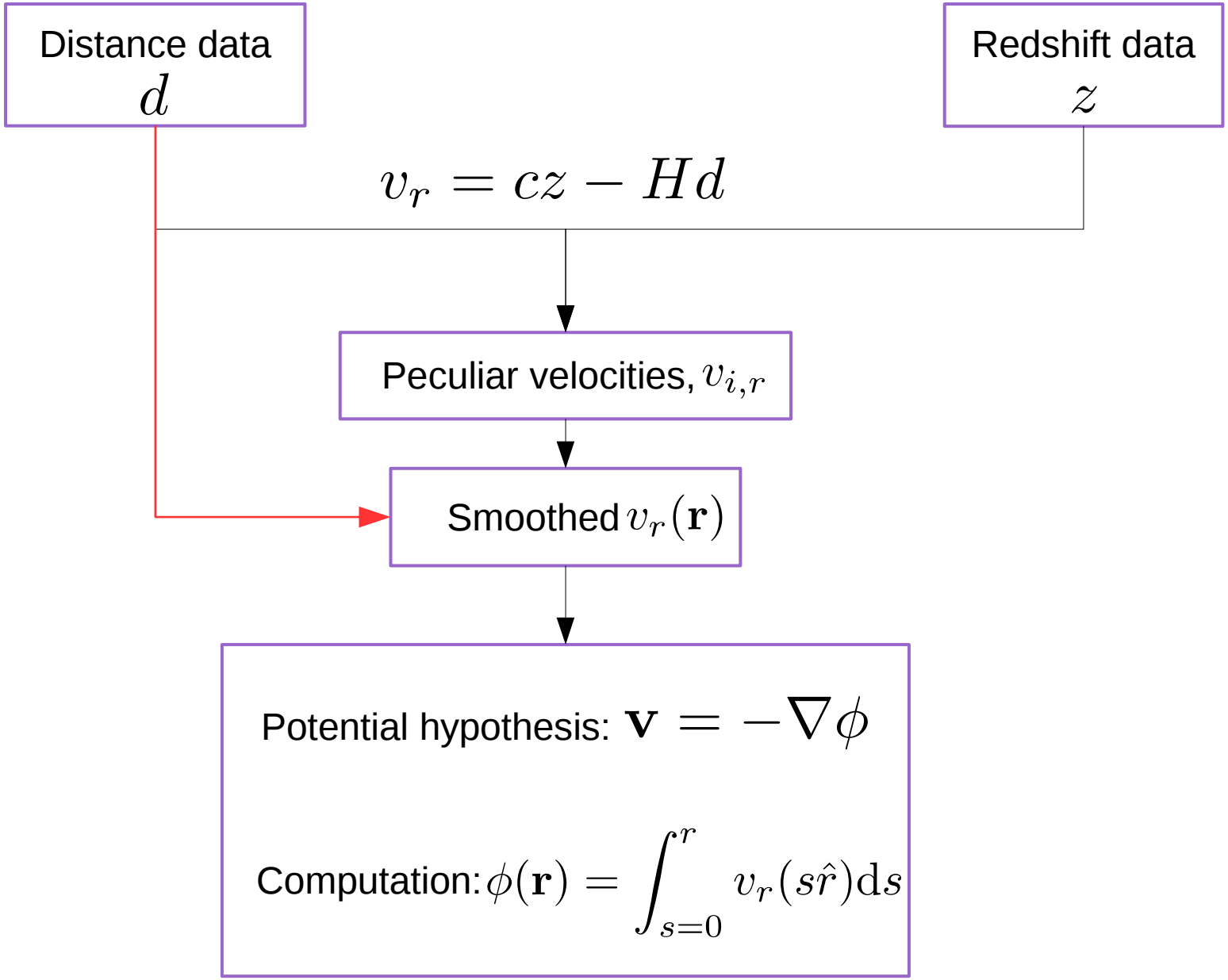
NOT EXHAUSTIVE!

# 1. Earlier reconstruction methods

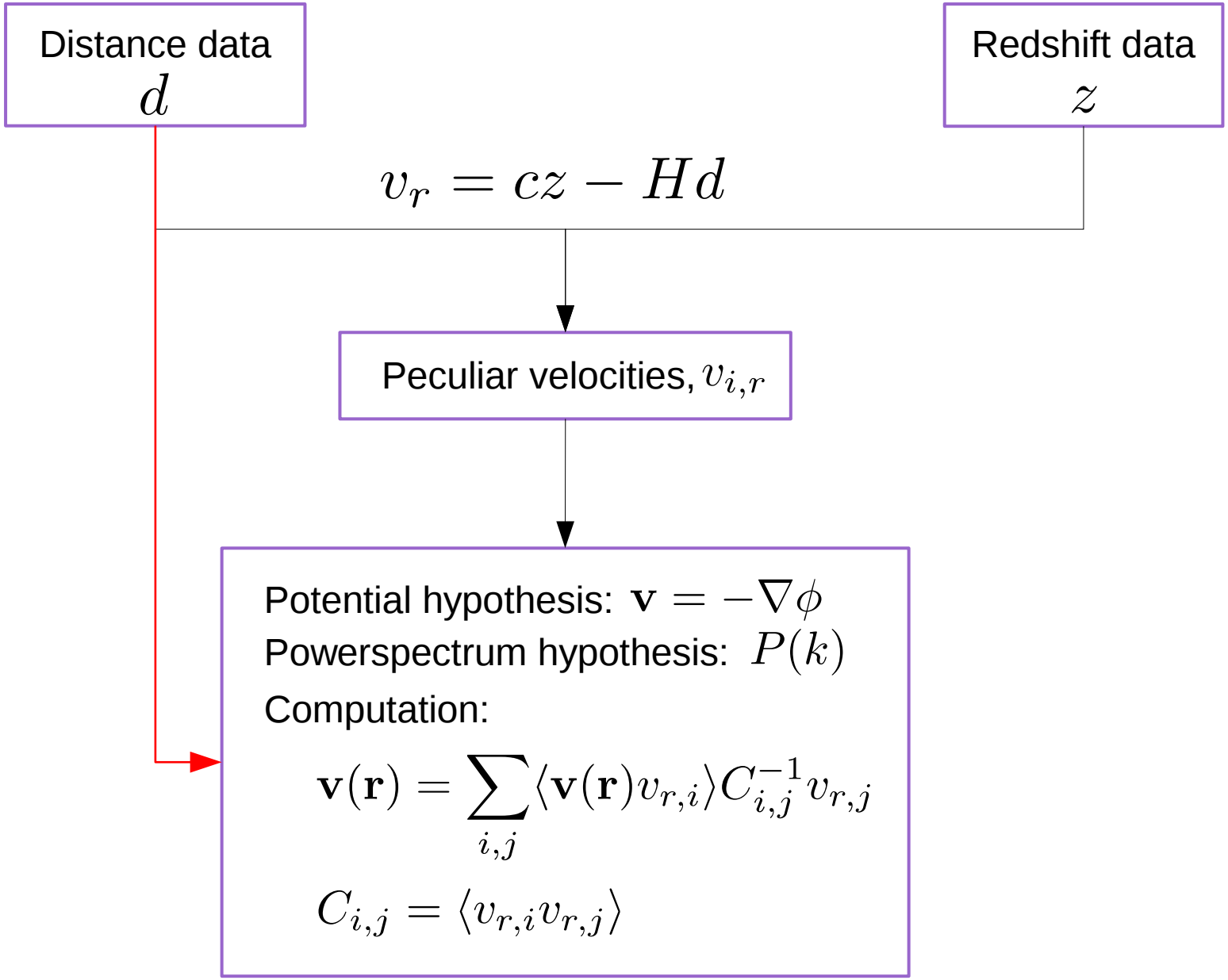
POTENT, Linear theory, MAK & friends

# Extrapolation methods (Eulerian POTENT)




Dekel et al. (1990), Bertschinger et al. (1990), Nusser & Dekel (1992)

# Extrapolation methods (Wiener filter)




Zaroubi et al. (1995), and later

# Prediction method (Linear reconstruction)

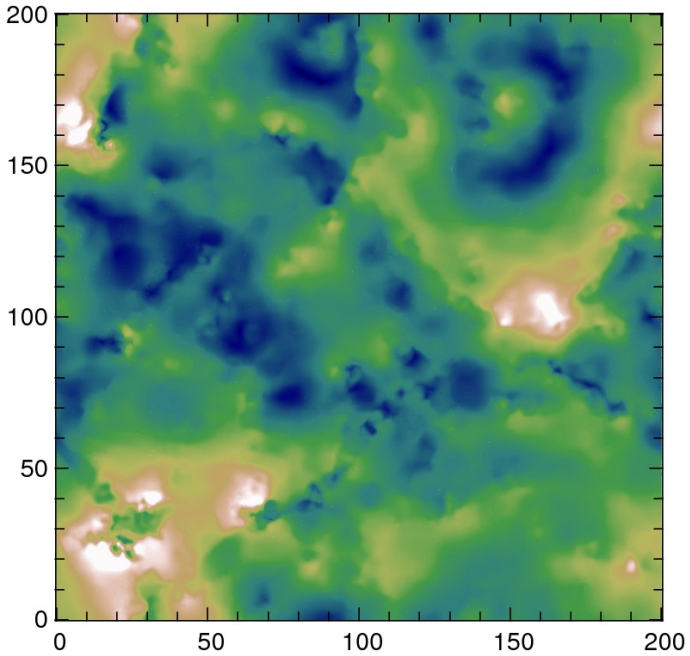
Redshift data
$z$

$$\Delta\phi = \delta(\mathbf{x})$$

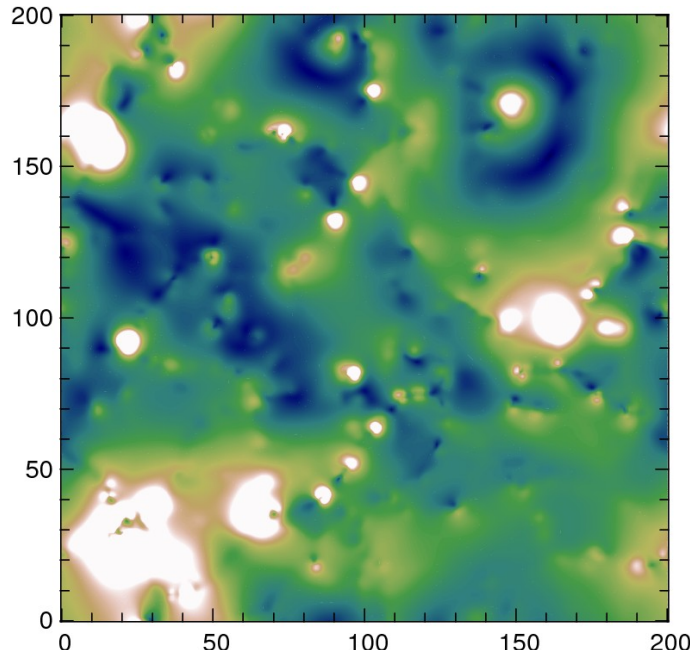
$$\mathbf{v}(\mathbf{r}) = afH\nabla\phi(\mathbf{r})$$

$$f = \frac{\mathrm{d}\log D_+}{\mathrm{d}\log a}$$

Simulation




Reconstruction




e.g. Peebles (1980)

# Prediction method (MAK reconstruction)

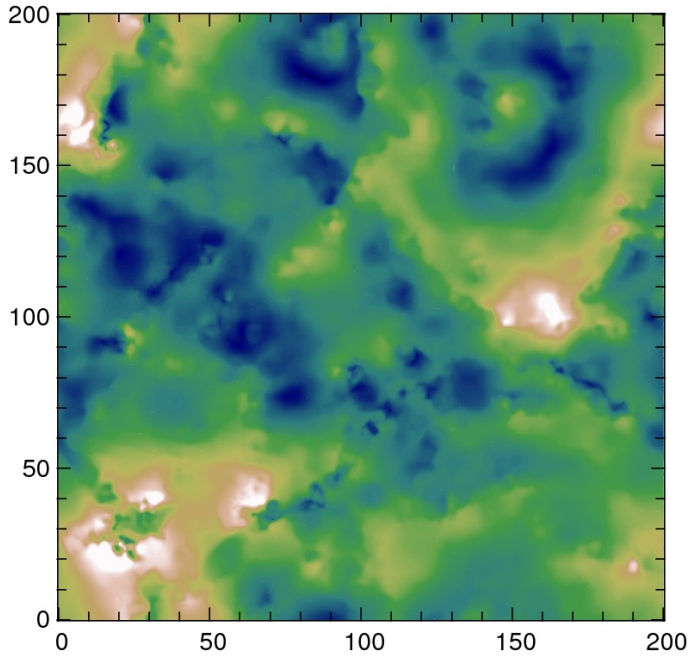
Redshift data
$z$

$$\det\left(\delta^K_{i,j} + \frac{\partial\Phi}{\partial x_i \partial x_j}\right) = \delta(\mathbf{x})$$

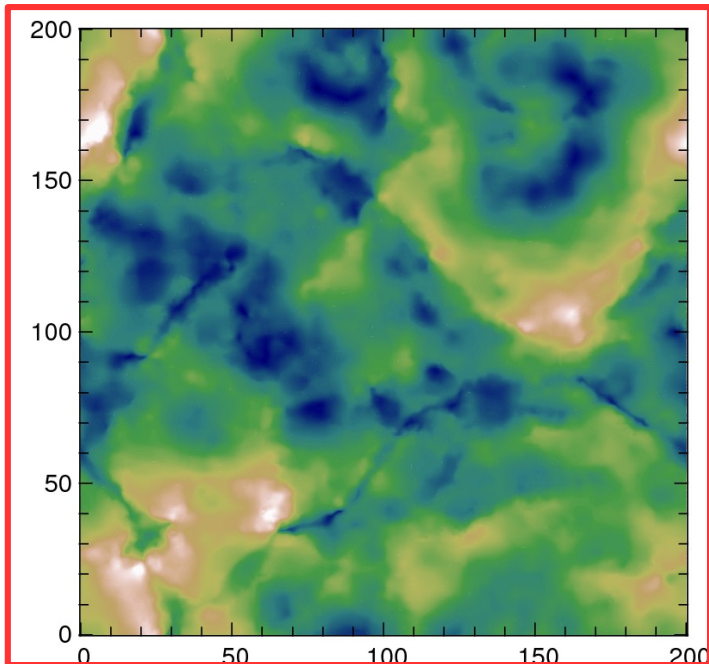
$$\mathbf{v}(\mathbf{r}) = afH\nabla\phi(\mathbf{r})$$

$$f = \frac{\mathrm{d}\log D_+}{\mathrm{d}\log a}$$

Simulation



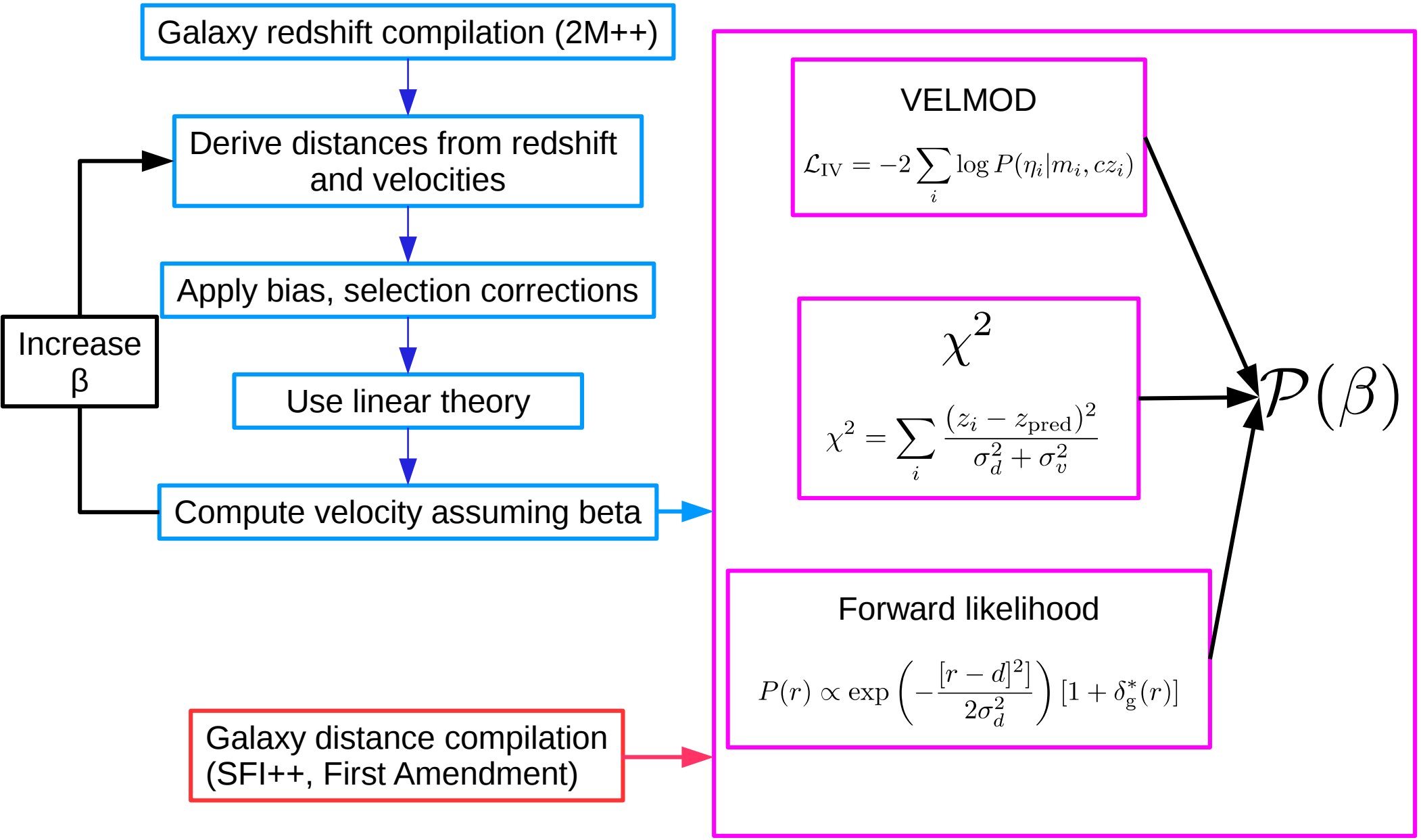

Reconstruction




**Brenier et al. (2003)**,
Mohayaee et al. (2005),
Lavaux et al. (2008),
Lavaux et al. (2010)

# Updated analysis framework for linear theory

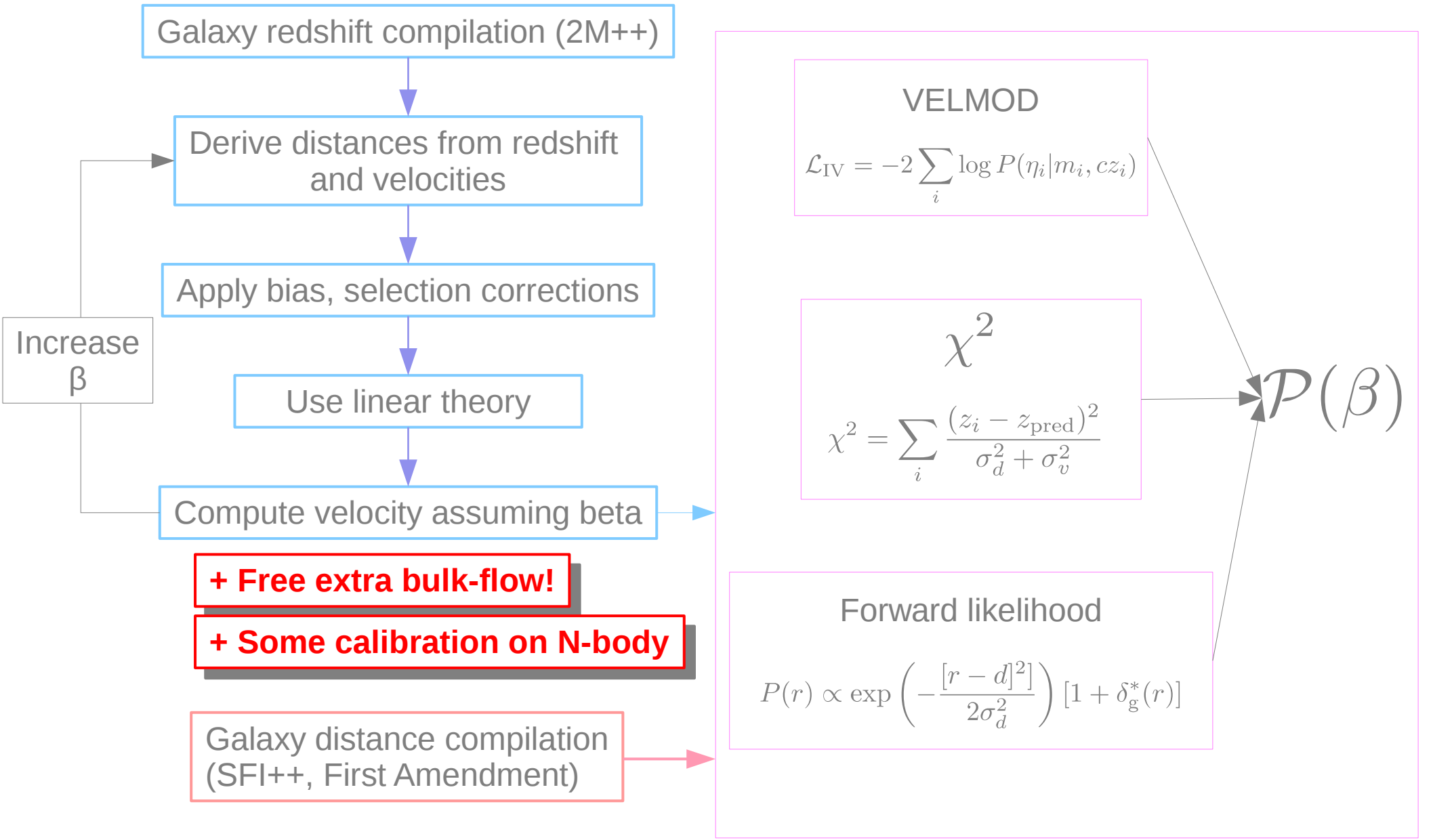
## velocity field reconstruction from density




**Carrick, Turnbull**, Lavaux & Hudson (2015, MNRAS)

# Analysis framework

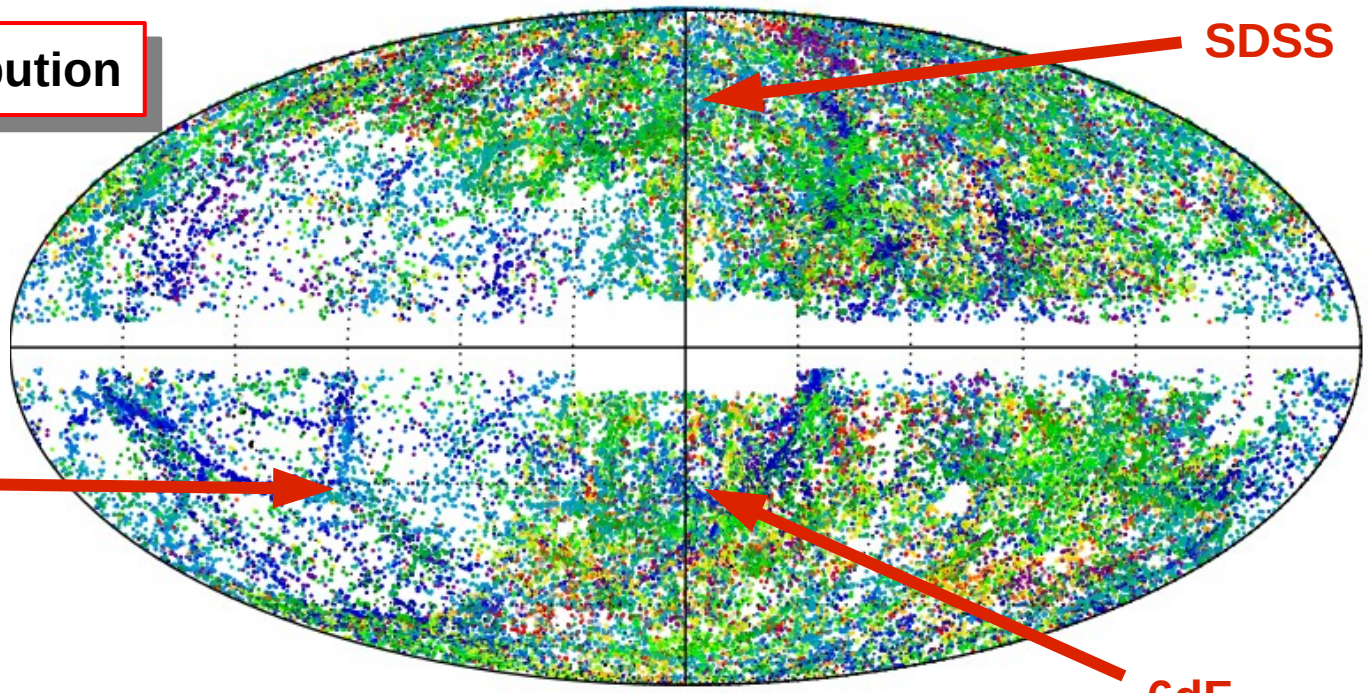
## velocity field reconstruction from density



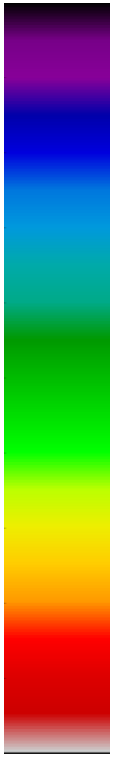

**Carrick, Turnbull**, Lavaux & Hudson (2015, MNRAS)

# The 2M++ catalog

**Galaxy distribution**



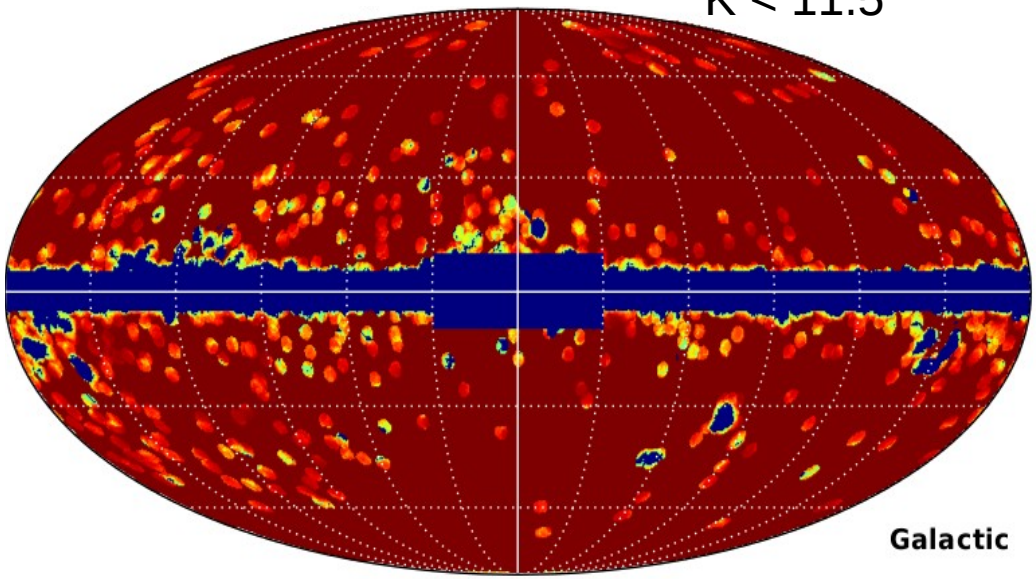

0 Mpc/h



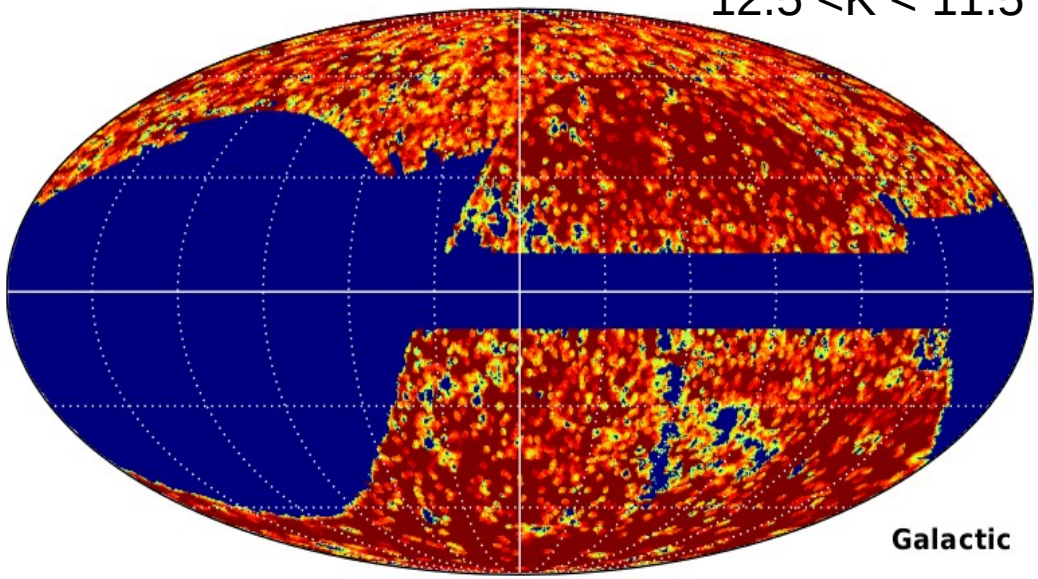
250 Mpc/h

**Redshift completeness**

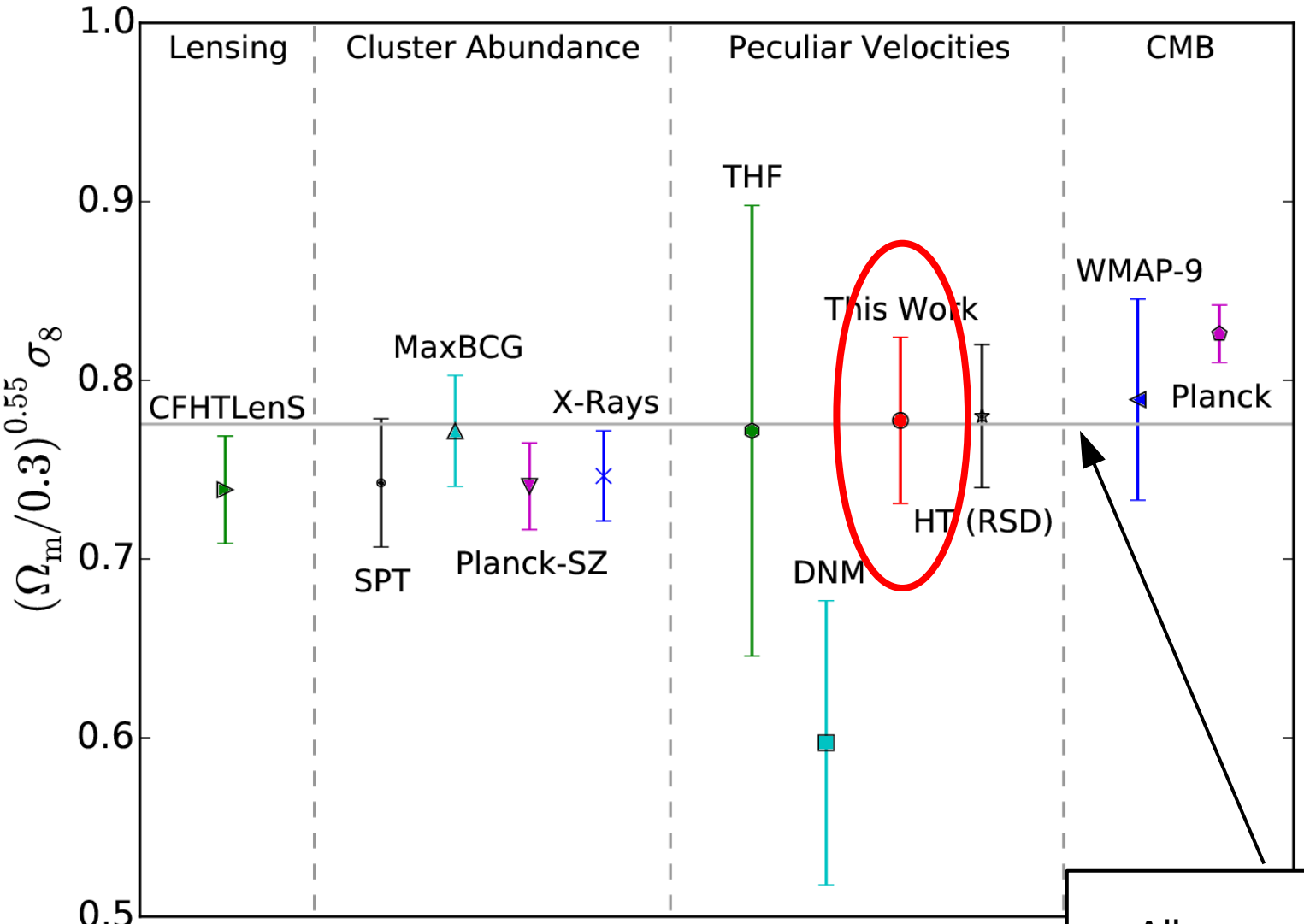
K < 11.5




12.5 <K < 11.5



# Results: gravity

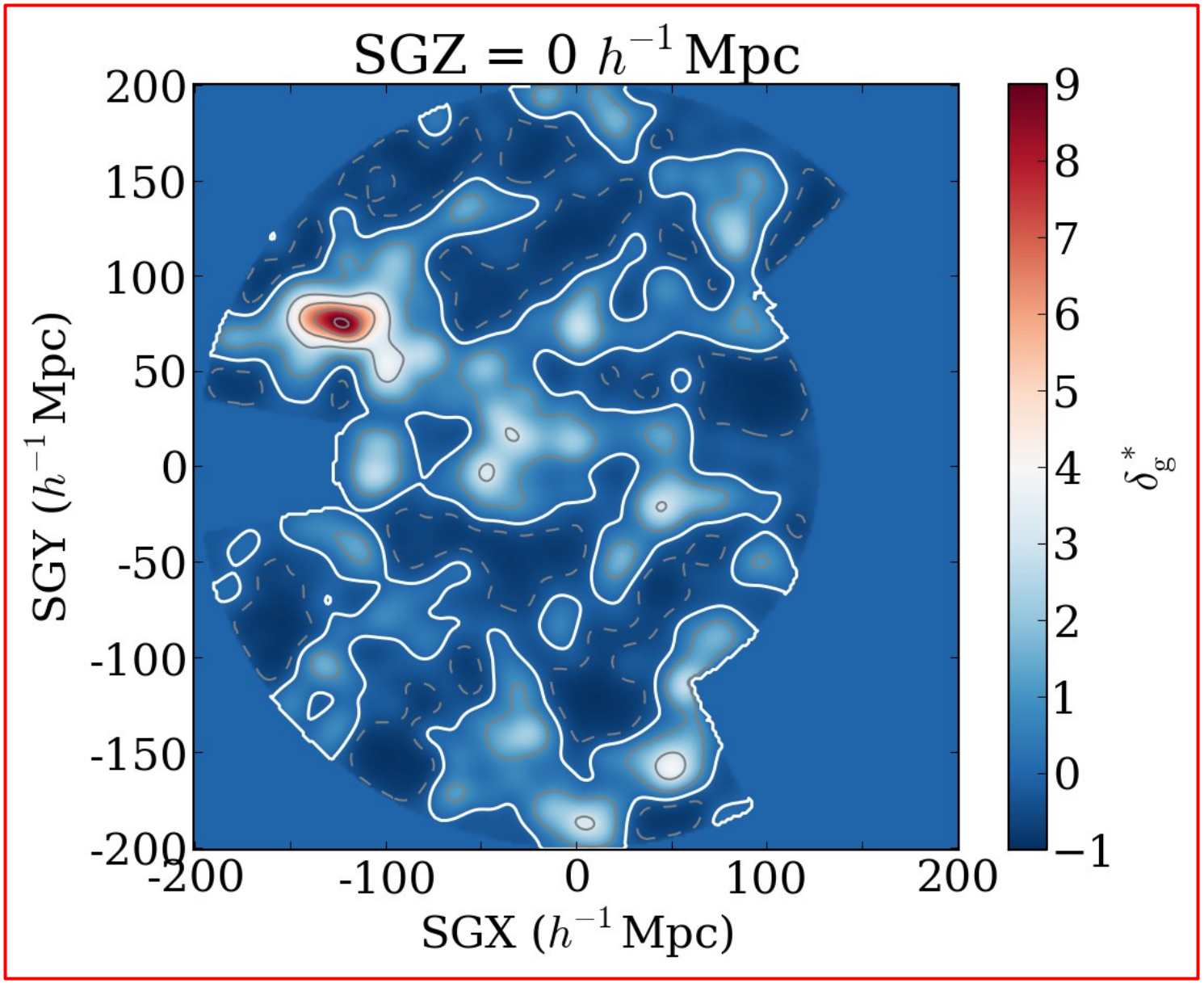



All measurements mean value

$f\sigma_8 = 0.400 \pm 0.005$

**Carrick, Turnbull**, Lavaux & Hudson (2015, MNRAS)

# Large scale structure calibrated map




**Carrick, Turnbull**, Lavaux & Hudson (2015, MNRAS)

# Summaries of results

- LG convergence as **expected** by LCDM
- Misalignment fluctuations **within** LCDM predictions
- $f\sigma_8$ in **agreement** with results from other probes
- **Bulk flow** still **high** but in **good agreement** with both observations and expectations

Calibrated velocities and maps at
http://cosmicflows.iap.fr and http://cosmicflows.uwaterloo.ca .

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- New statistical reconstruction methods
  - ARES/VIRBiUS
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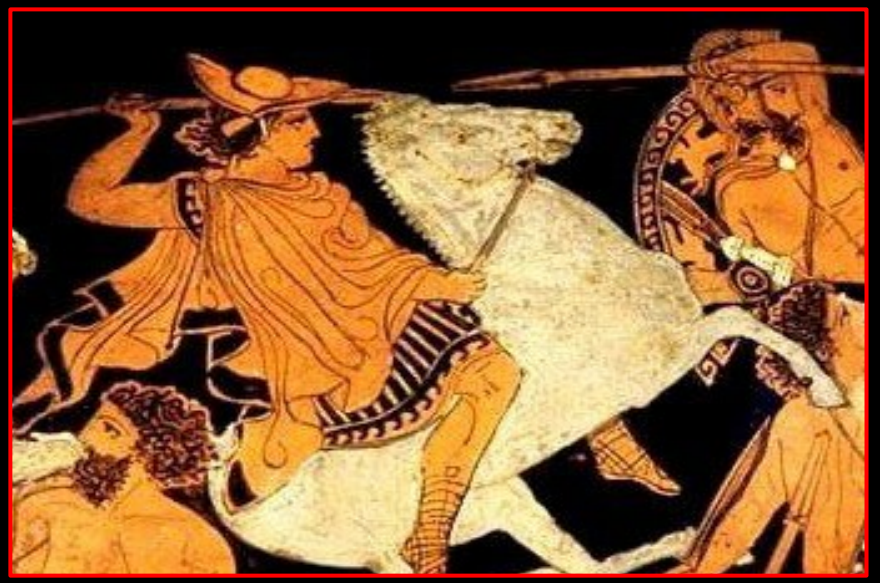
# New statistical reconstruction methods ("linear" approaches)


**Velocity Reconstruction using Bayesian Inference Scheme**

**VIRBIuS**

Lavaux (2015, submitted, in review)



**A**lgorithm for **RE**construction and **S**ampling (ARES)

Jasche & Wandelt (2013),
Jasche & Lavaux (2014),
Lavaux & Jasche (2015, submitted)
Jasche & Lavaux (2015, submitted)

# The VIRBIuS model

**Two observational constraints:**

Redshift → $v_r = \widetilde{H} d + \mathbf{v}^W \left( \frac{\widetilde{H}}{H} d\mathbf{u} \right) .\mathbf{u} + \varepsilon$

Distance modulus → $\mu_{\rm obs} = 5 \log_{10} \left( \frac{\widetilde{H} d}{H \times 1{\rm pc}} \right) + \varepsilon_\mu$

**Simplifying assumptions:**

Curl-free velocity field $\theta(\mathbf{x}) = \nabla . \mathbf{v}(\mathbf{x})$ (POTENT-like)

Velocity tracers are not biased

Isotropic radial selection effect for distances

Residual ε uncorrelated

**Priors:**

Velocity field $\theta$ Gaussian Random field $\langle \hat{\theta}(\mathbf{k}) \hat{\theta}(\mathbf{k}') \rangle = (2\pi)^3 \delta(\mathbf{k} + \mathbf{k}') P(k)$

Distances $\pi(d) \propto d^{p} \exp \left[ - \left( \frac{d}{d_{\rm cut}} \right)^{n} \right]$ Extra free parameters

Lavaux (submitted, 2015)

# Numerical issues: The problem

Huge posterior: > $10^7$ parameters

$$P\left(\{d_i\},\{\hat{\theta}_{i,j,k}\},\sigma_{\rm NL},A_S,H,\tilde{H},n,p,d_{\rm cut}\,|\,\{z_i\},\{\mu_i\},\{\sigma_{z,i}\},\{\sigma_{\mu,i}\}\right)$$

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$$P\left(\{d_i\},\{\hat{\theta}_{i,j,k}\},\sigma_{\rm NL},A_S,H,\tilde{H},n,p,d_{\rm cut}\,|\,\{z_i\},\{\mu_i\},\{\sigma_{z,i}\},\{\sigma_{\mu,i}\}\right)$$

+

Totally non-gaussian

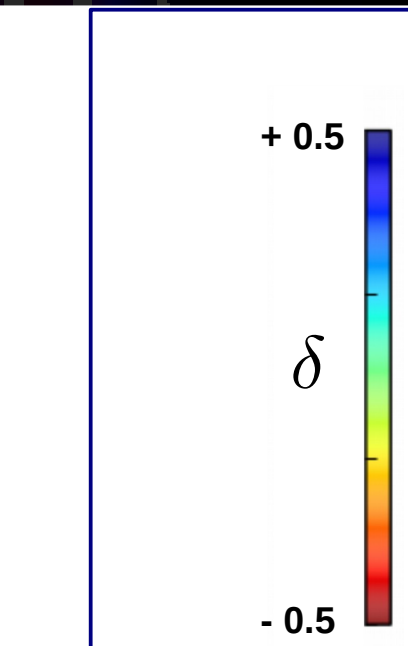
↓

Cannot evaluate a gridded posterior

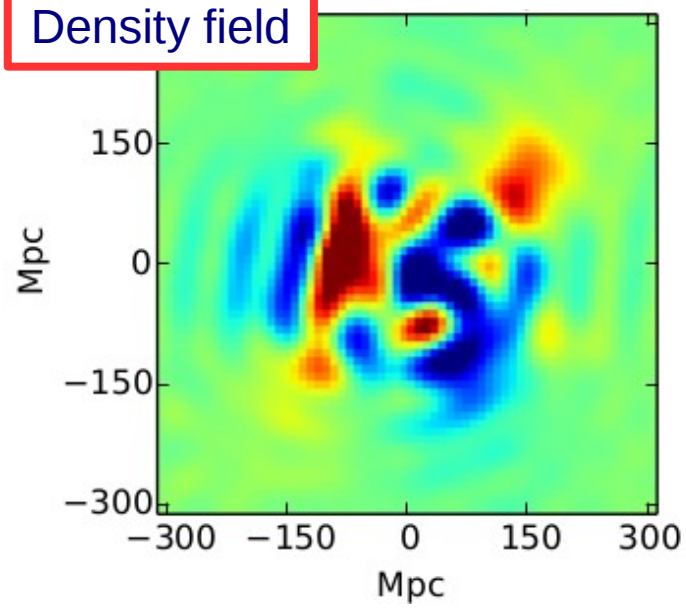
Cannot run a classical Metropolis-Hasting Markov-Chain algorithm

**BUT if we have a good proposal for a step of the chain it is doable**

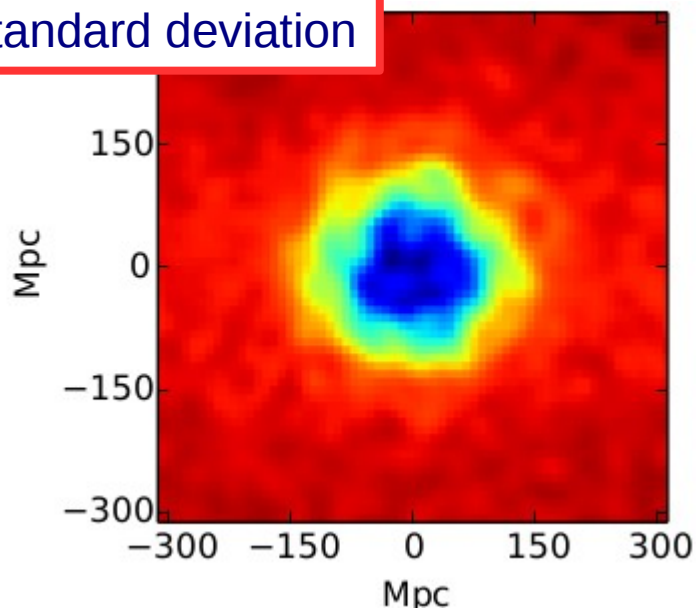
# Reconstructed « density » and velocity field

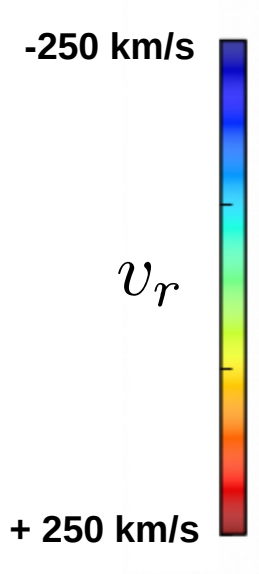



Density field

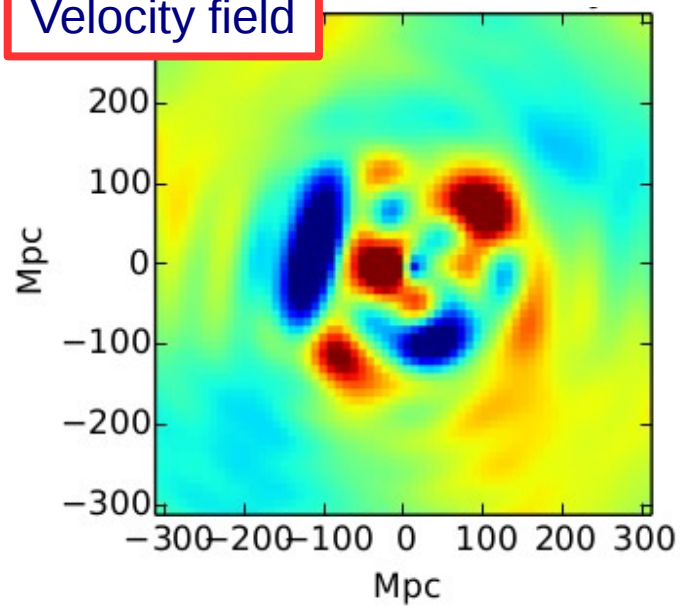



Standard deviation

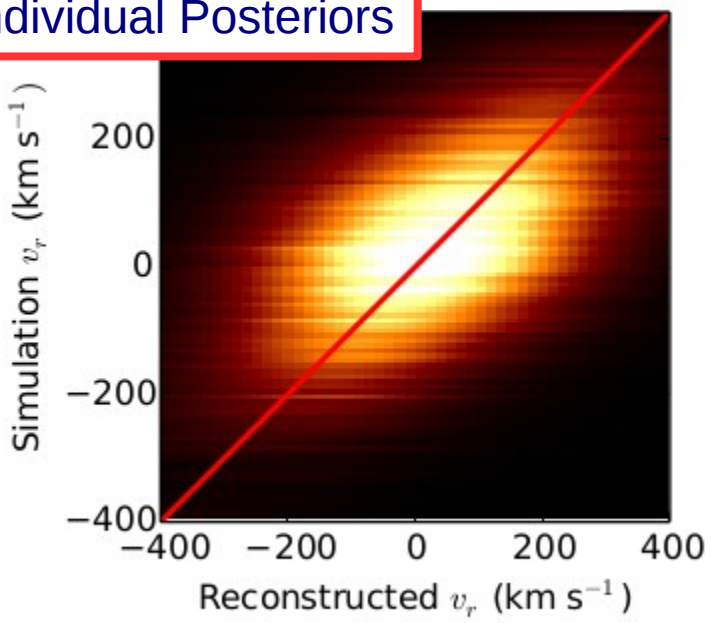


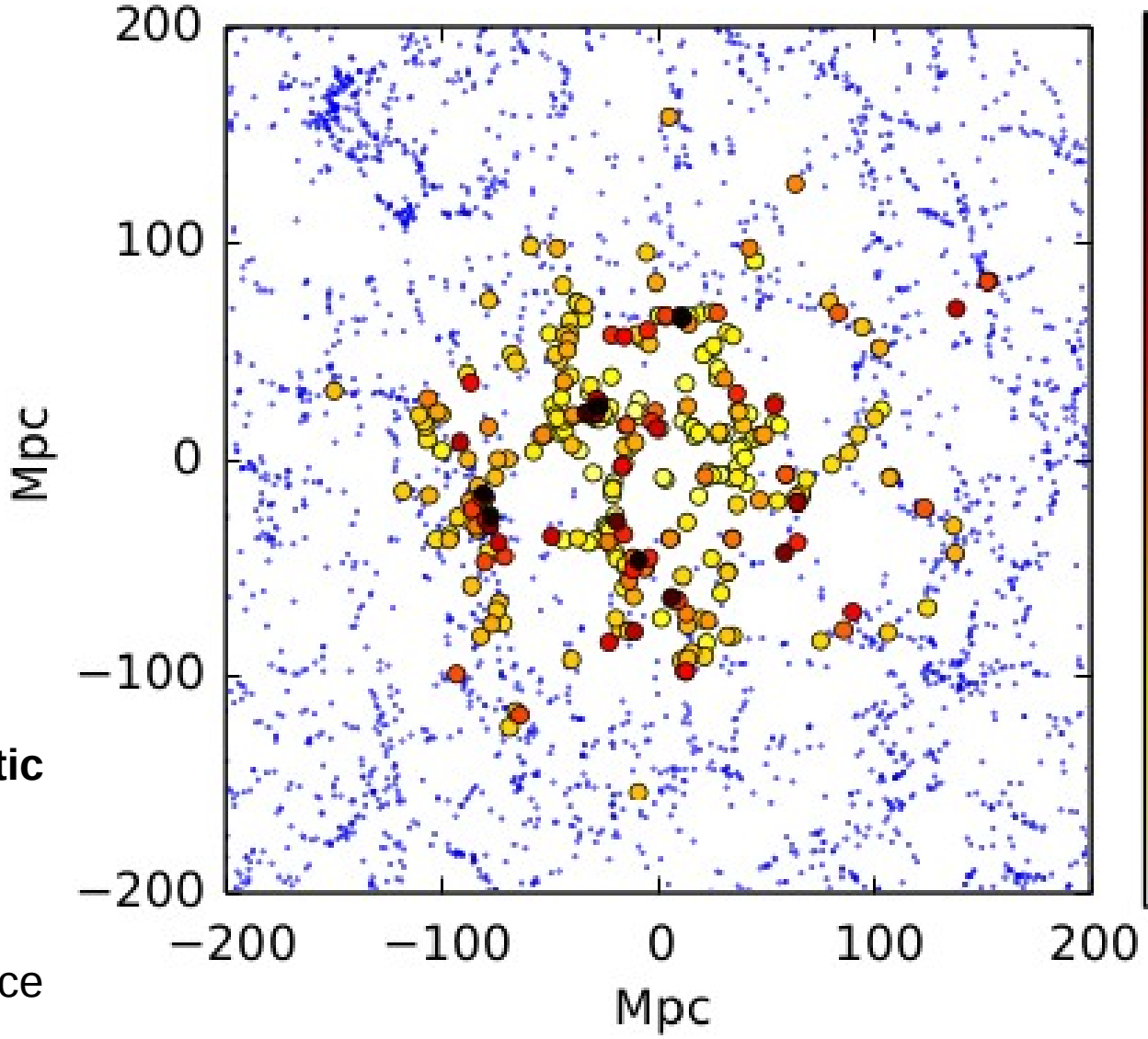

Velocity field




Individual Posteriors



# Application: halo mock catalog




Probably **high** velocity dispersion

Threshold is 100 km/s

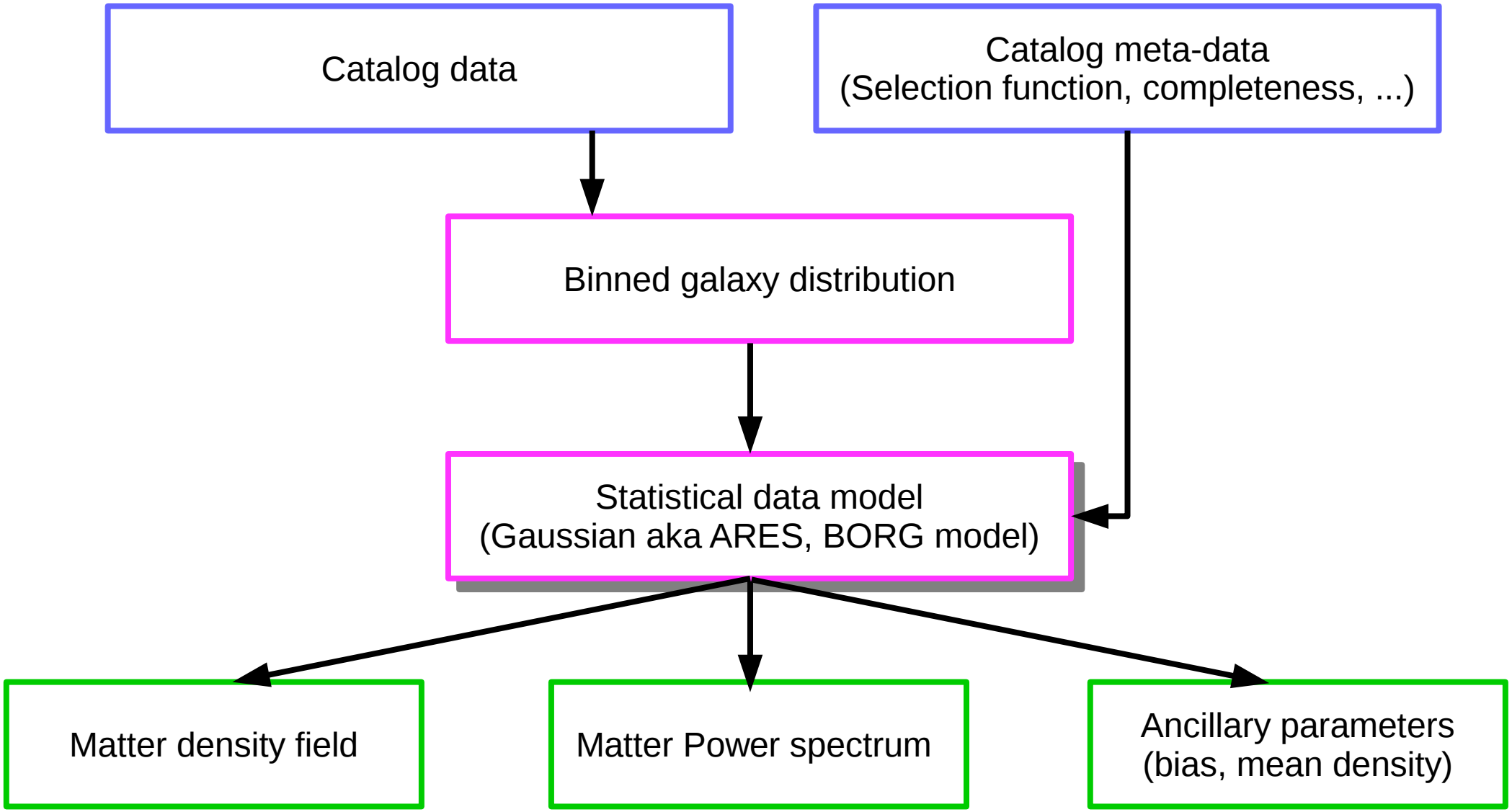
Probably **low** velocity dispersion

3000 tracers

**Complex realistic** radial selection

**Typical** observational **errors** on distance

# ARES analysis procedure



# The ARES data model

Linear response operator (mask, radial selection)

« Mean » density of tracers

bias

$$-\log P(\delta, b, \widetilde{N}) = A + \sum_i \frac{\left(N_i - \widetilde{N} R_i (1 + b\delta_i)\right)^2}{2\tilde{N} R_i} + \sum_k \frac{|\hat{\delta}_k|^2}{2P(k)}$$

NGP binned data

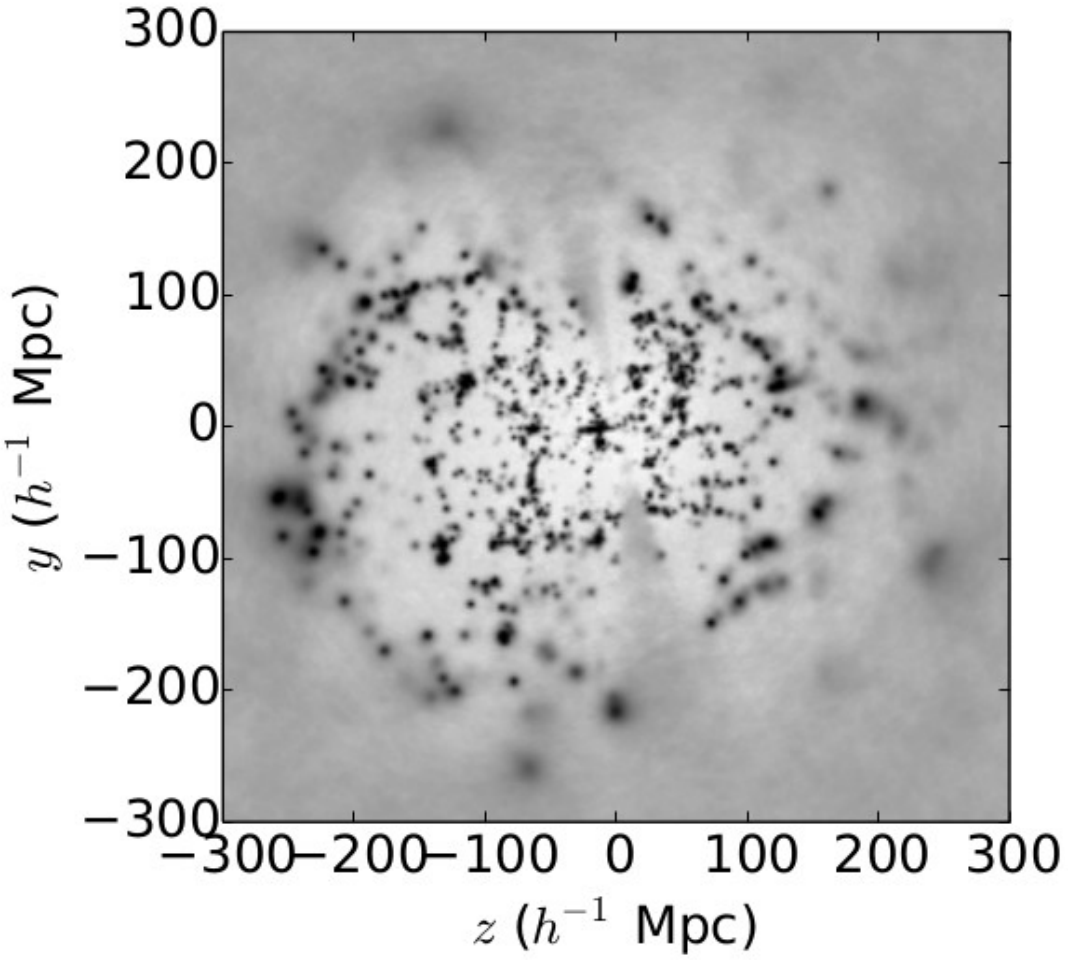
Gaussian probability

Gaussian prior

Jasche et al. (2010)

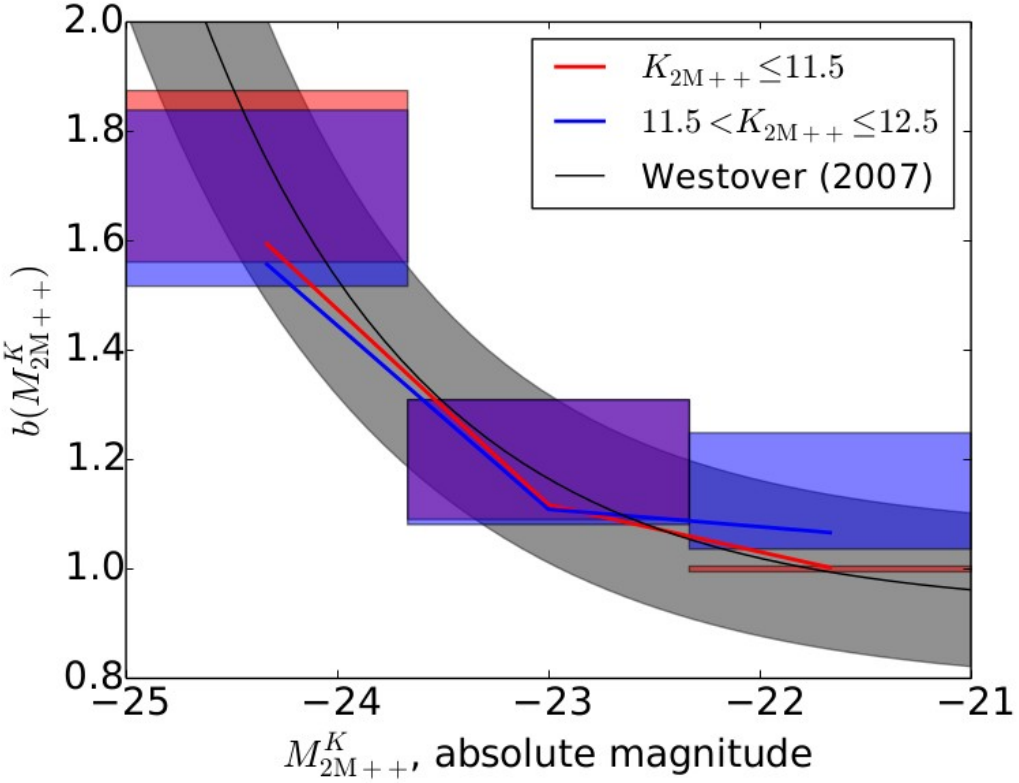
# ARES on 2M++: Map and Bias

Blind mean density reconstruction




Equatorial y-z plane (ra=0)

Blind galaxy bias measurement

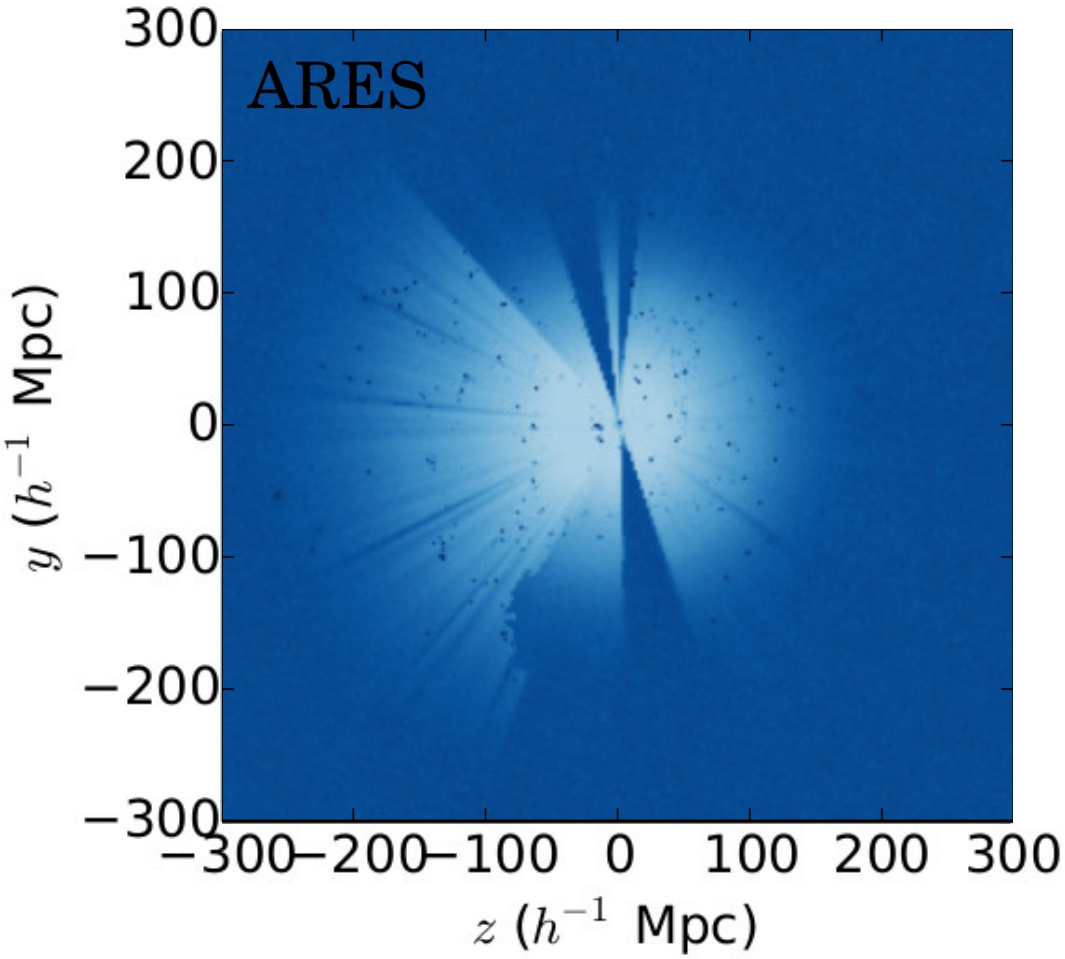



**2 apparent** magnitude bins
**3 absolute** magnitude bins

Lavaux & Jasche (2015, submitted)

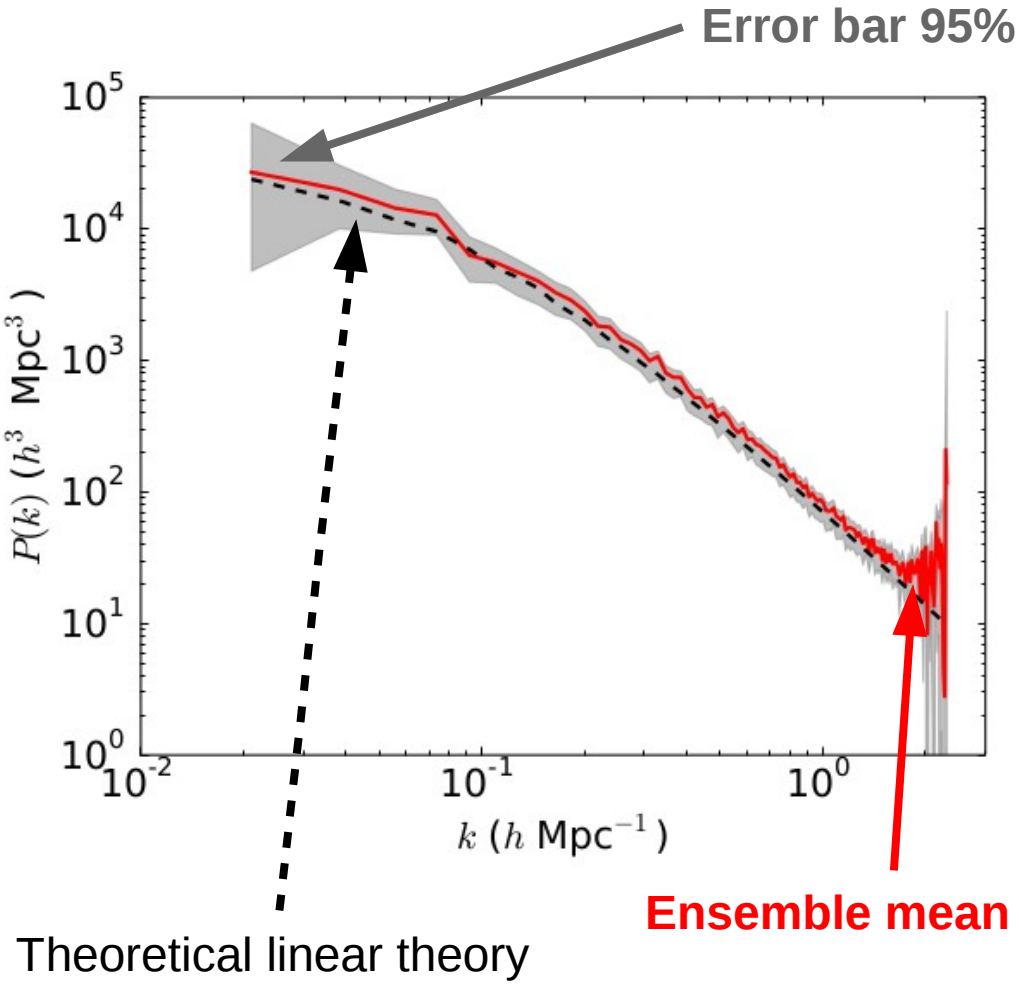
# ARES on 2M++: Map and Power spectrum

Blind density error estimation




Equatorial y-z plane (ra=0)

Blind power spectrum measurement



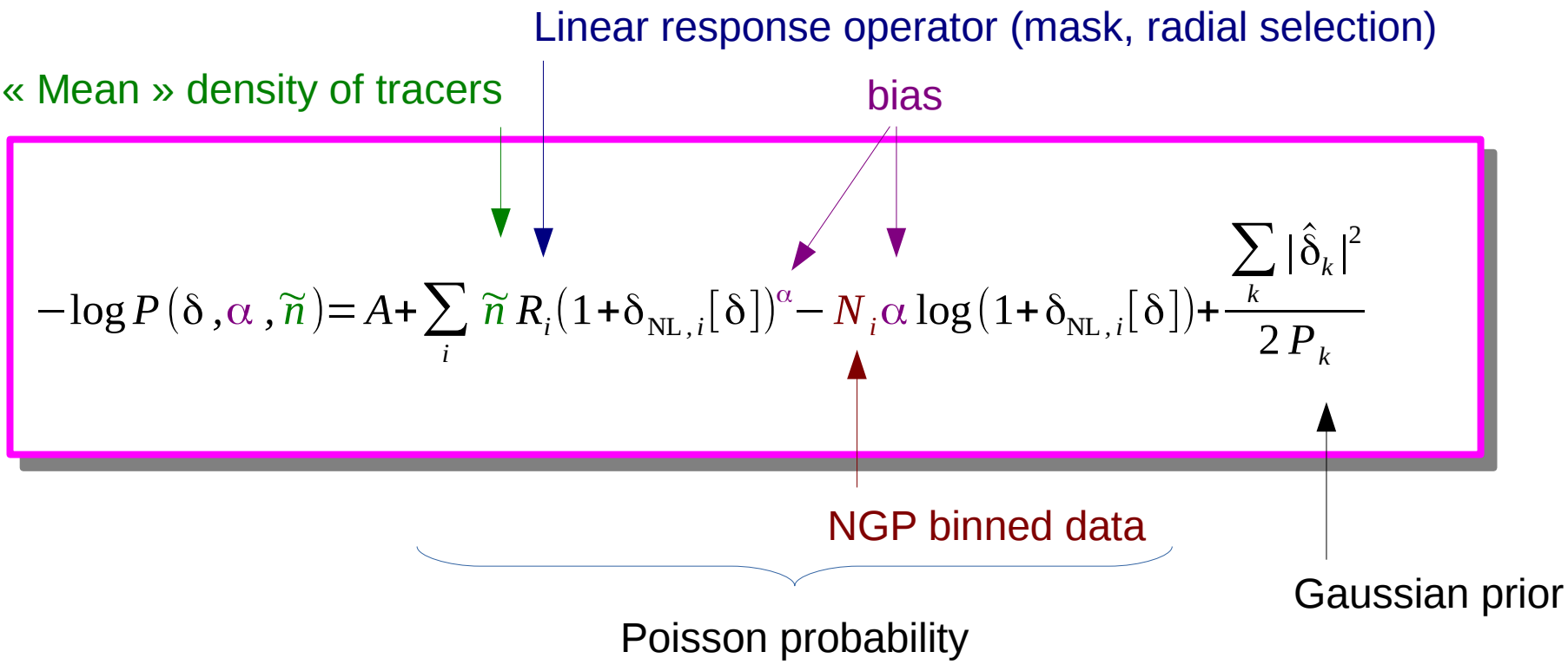

Lavaux & Jasche (2015, submitted)

# New statistical reconstruction methods (fully non-linear approaches)

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

Jasche & Wandelt (2013), Jasche & Lavaux (2014), Lavaux & Jasche (2015, submitted)

# The **BORG** data model




Field $\delta_{\mathrm{NL}}[\delta]$ derived from Cloud-In-Cell + 2LPT dynamics

$\delta$ sampled using Hamiltonian Monte Carlo algorithm

Jasche & Wandelt (2013)

# Parameter exploration using HMC

Assimilate the posterior to a potential energy : $-\log P \equiv V(\{x_i\})$

Create an Hamiltonian : $\mathcal{H}(\{x_i\},\{p_i\}) = \frac{1}{2}\sum_{i,j} M^{-1}_{i,j} p_i p_j + V(\{x_i\})$

Evolve system with Hamiltonian dynamics

Compute acceptance : $a = \exp\left(\frac{1}{2}(\mathcal{H}_{\text{end}} - \mathcal{H}_{\text{start}})\right)$

Pump and dump energy in the system by varying $\{p_i\}$

Generate a MC sample dropping the state of $\{p_i\}$

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Create an Hamiltonian : $\mathcal{H}(\{x_i\},\{p_i\}) = \frac{1}{2}\sum_{i,j} M^{-1}_{i,j} p_i p_j + V(\{x_i\})$

**INVOLVE GRADIENT COMPUTATIONS !**

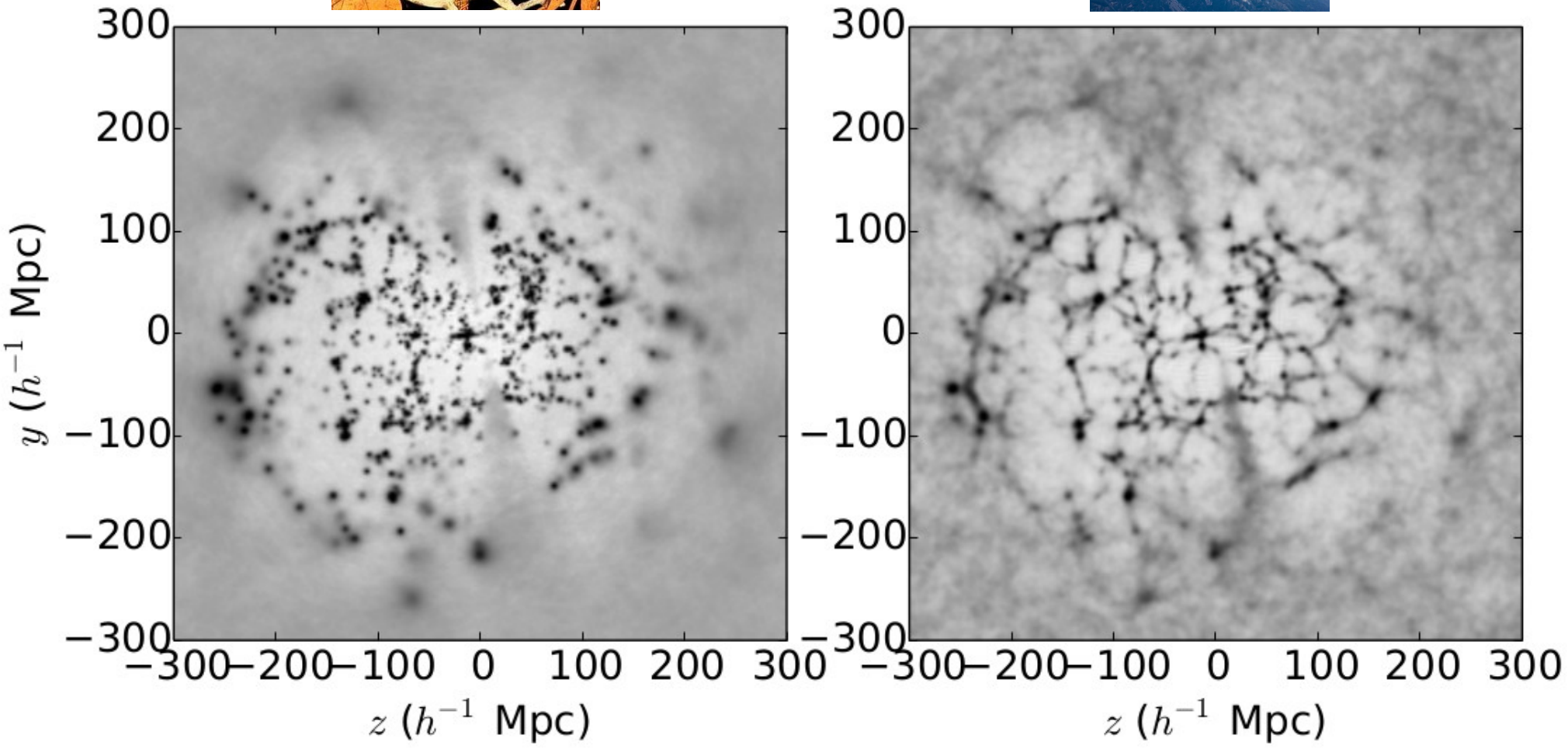
Evolve system with Hamiltonian dynamics

Compute acceptance : $a = \exp\left(\frac{1}{2}(\mathcal{H}_{\text{end}} - \mathcal{H}_{\text{start}})\right)$

Pump and dump energy in the system by varying $\{p_i\}$

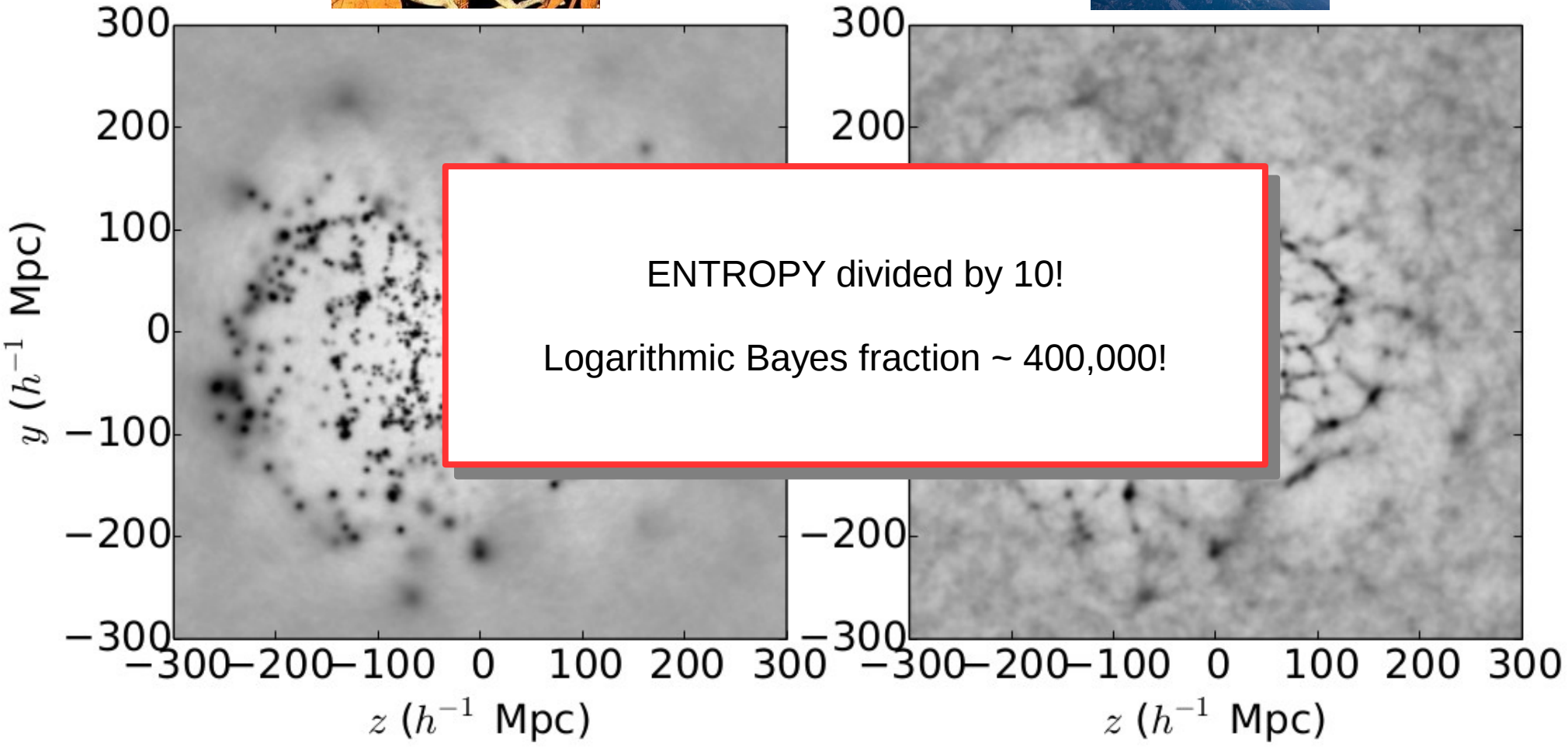
Generate a MC sample dropping the state of $\{p_i\}$

# Gaussian model vs BORG reconstruction




Jasche & Lavaux (2015, submitted)

# Gaussian model vs BORG reconstruction



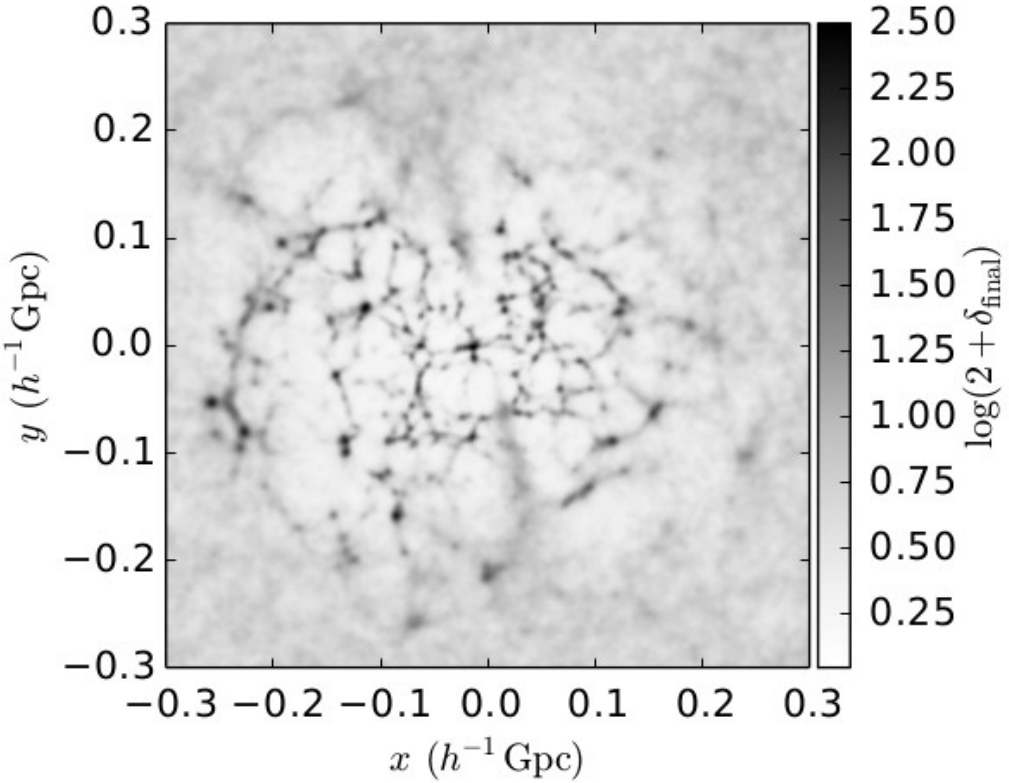

ENTROPY divided by 10!

Logarithmic Bayes fraction ~ 400,000!

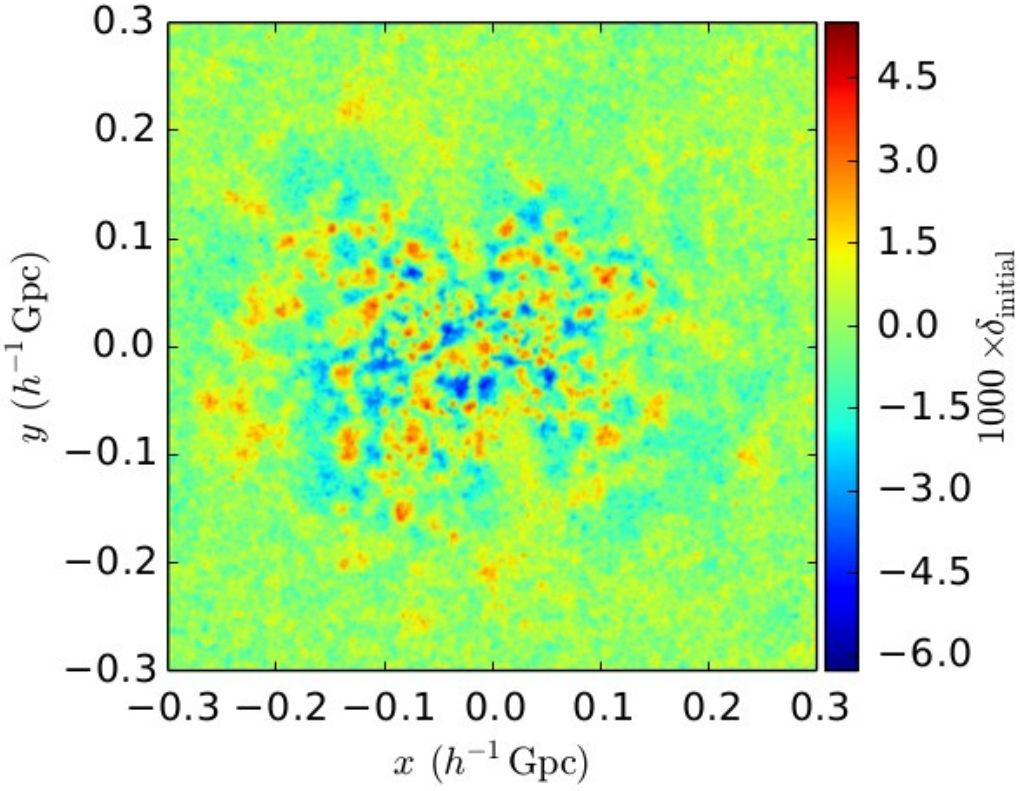
Jasche & Lavaux (2015, submitted)

# Initial condition reconstruction

Ensemble mean density field at present time




Ensemble mean density field at z=1000




Lavaux & Jasche (2015, submitted)

# Application to CMB cross-correlations

# Producing LSS/CMB observables

**Initial conditions from BORG**

Resimulations

**Hard to compute non-linear dynamics**

Momentum field
(kSZ effect)

$$\Delta T \propto \int (1+\delta)(r\hat{r}) v_r(r\hat{r}) \mathrm{d}r$$

Gas profile in cluster
(individual analysis of
tSZ pressure profile)

$$\Delta T \propto \int (1+\delta)(r\hat{r}) T_e(r\hat{r}) \mathrm{d}r$$

Rees-Sciama effect
(non linear density and
momentum field)

$$\dot{\Phi}(\vec{k},t) \propto \left( H(t)\hat{\delta}(\vec{k},t) + i\vec{k}.\hat{\vec{p}}(\vec{k},t) \right)$$

$$\Delta T \propto T \int \dot{\Phi}(r\hat{r}) \mathrm{d}r$$

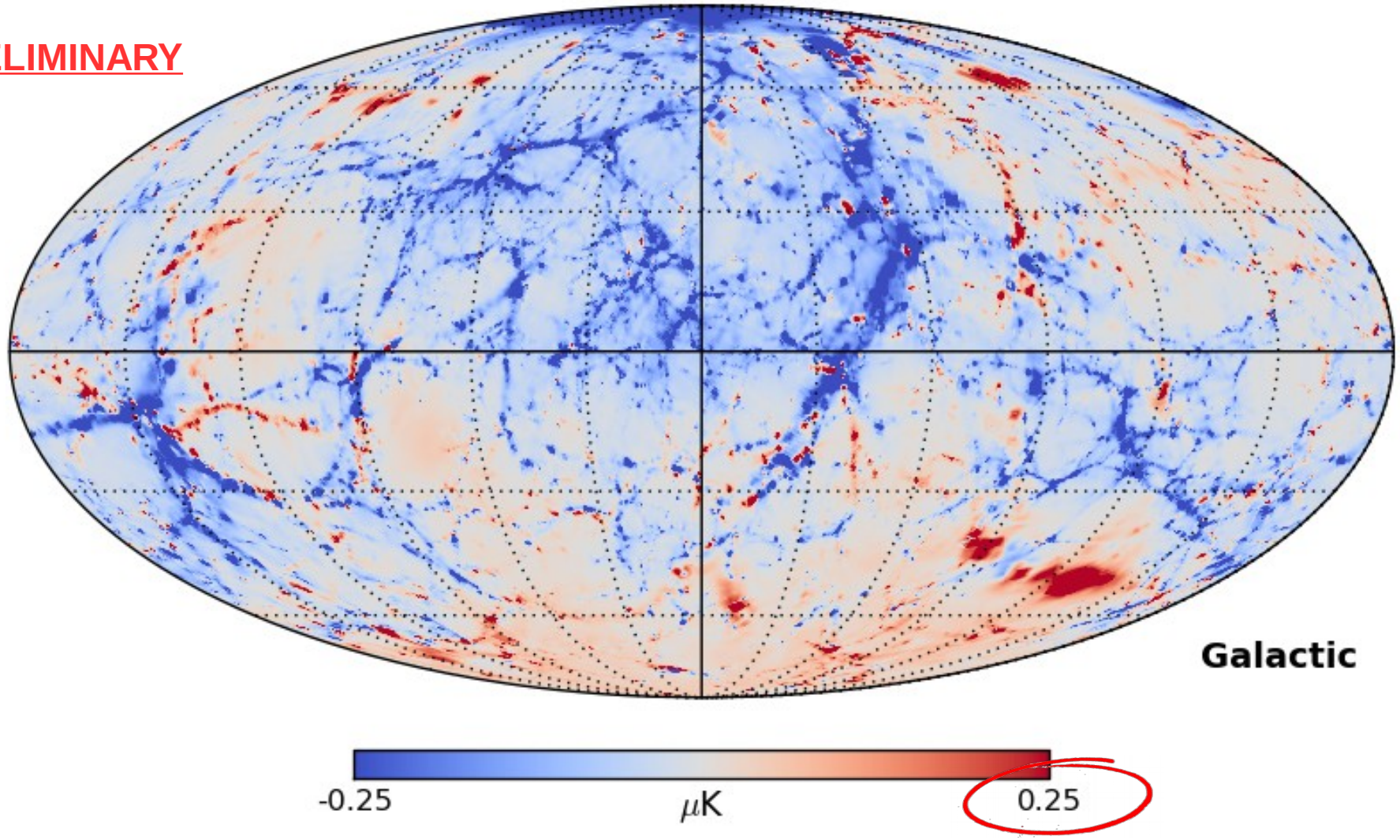
Better modeling yields higher
Signal/Noise

Two examples (PRELIMINARY MAPS)

Raytracing algorithm
Cai et al. (MNRAS, 2010)

# kSZ maps

**PRELIMINARY**



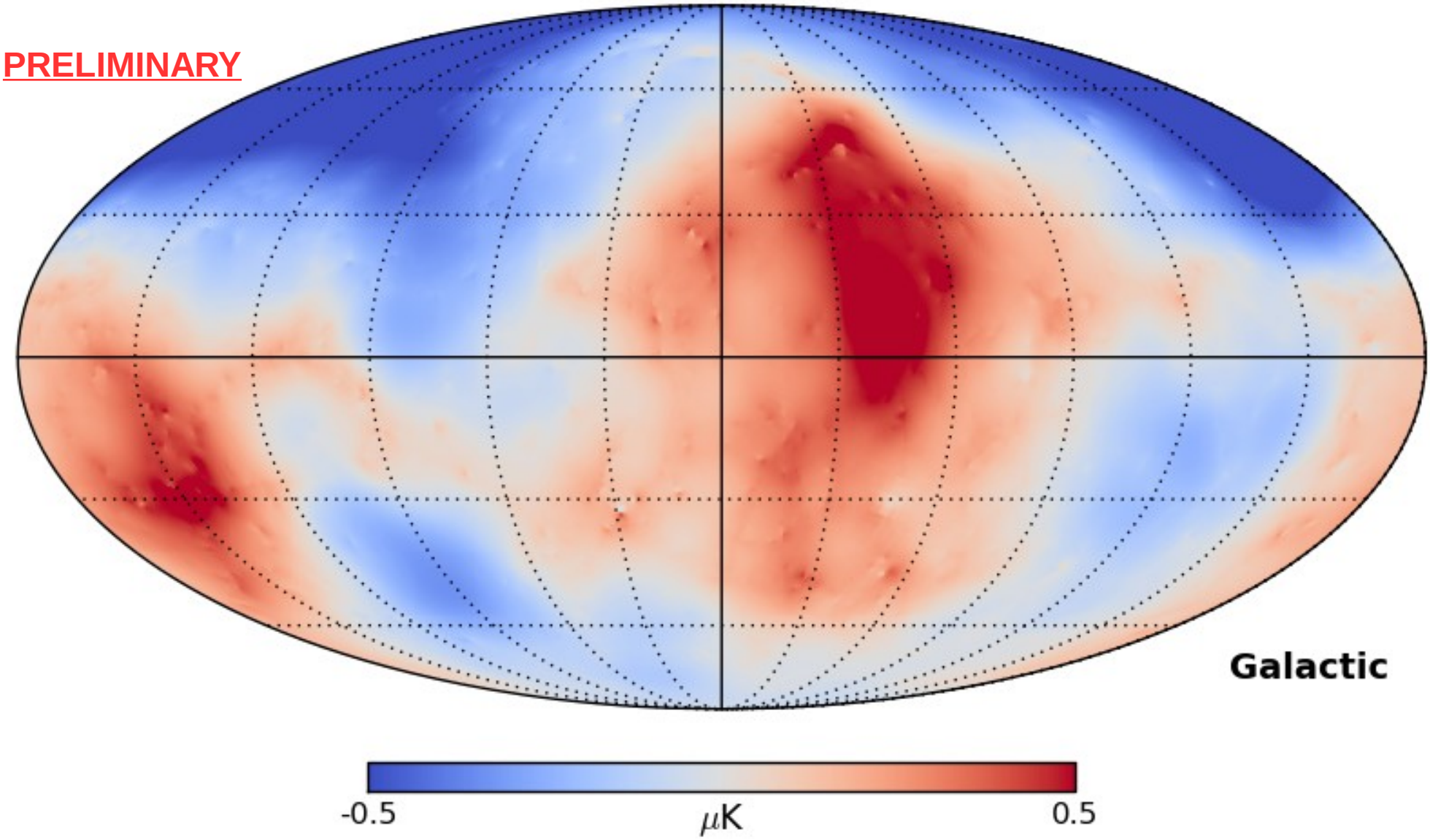

KSZ Simulation of **ONE(!)** BORG sample

Full posterior available for Hierarchichal Bayesian analysis

Raytraced from 0 to 100 Mpc/h

# Rees Sciama maps

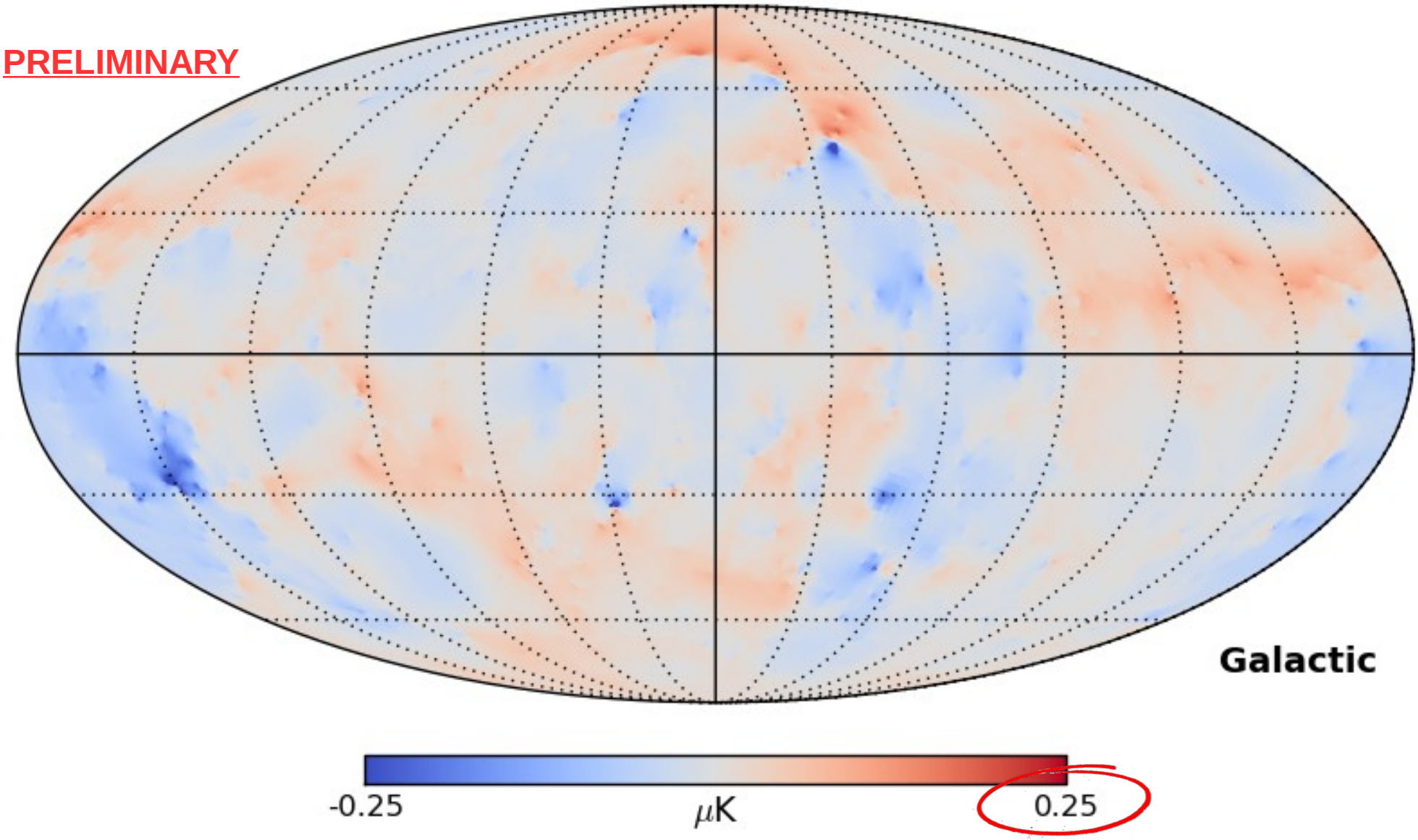
**PRELIMINARY**




Rees-Sciama+ISW effect, raytraced through the resimulation (0-100 Mpc/h)

# Only non-linear effects (RS - ISW)

**PRELIMINARY**

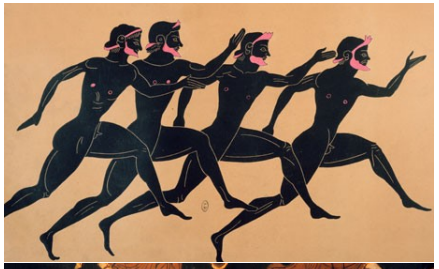



Pure Rees-Sciama effect, raytraced through the resimulation

# Conclusion

# Conclusion

**Modernizing the analysis of Large Scale Structures**



"Old" friends

VIRBIUS

**Extremely challenging!**

ARES

**BORG**

Understand the data collection

Proper statistical modeling

Develop analytical description of dynamics

**Numerical integration, scaling to large computing farms**

Posterior interpretation

**Chronocosmography +**
**Full non-linear analysis**