Bayesian reconstruction of the cosmic DM flow

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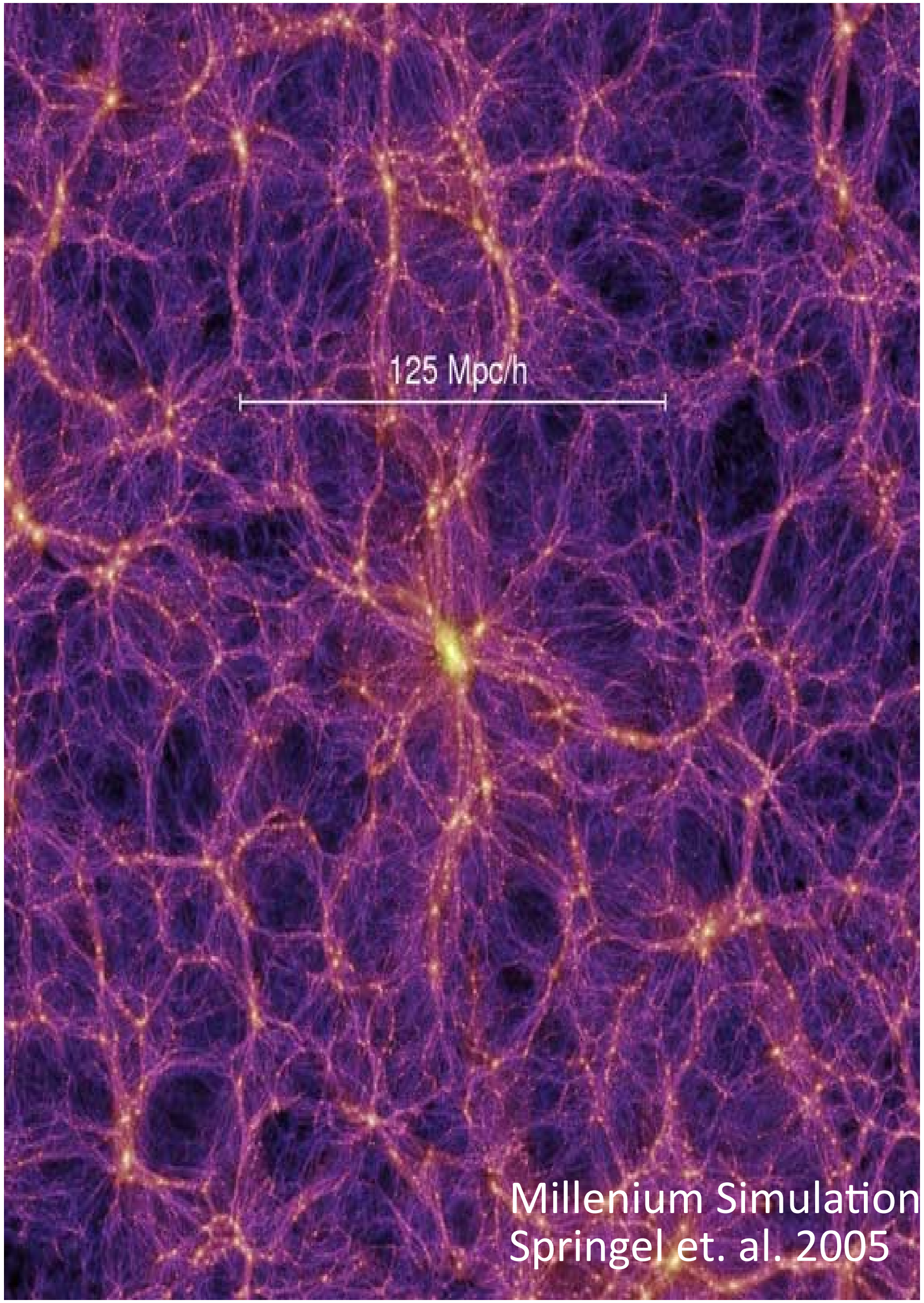
Cosmological large-scale structure

- Small initial conditions, approximate scale free and Gaussian
- Today still linear on large scales, non-linear on small scales
- Use to test of Dark Energy, Dark Matter, Gravity, Neutrino mass ...
- DM not directly observable: use galaxies as tracers, lensing, …



Large-scale structure reconstruction

- Typically one tries to measure summary statistics like density Power Spectrum
- A complete treatment requires a reconstruction of the density/velocity field itself
- A fully Bayesian treatment requires obtaining the high dimensional posterior
- A lot of progress on density reconstruction

  Jasche, Kitaura 2010,
  Jasche, Wandelt 2013, Modi et. al. 2018
  Jasche, Lavaux 2018 and many more
- In this talk: Direct reconstruction of the DM velocity field

  See also Lavaux 2013

The DM velocity field

The DM velocity can be inferred from density

Leclerqc et. al. 2017

Direct reconstruction,
allows to test Euler equation

$$\partial_t \delta + \nabla \cdot ((1+\delta)\mathbf{v}) = 0$$

$$\partial_t \mathbf{v} + H\mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla \Phi$$

Measured galaxy redshifts combine
cosmic expansion and local velocity

$$\frac{(1+z)}{(1+\bar{z})} = (1 + \mathbf{v} \cdot \mathbf{n})$$

Need to incorporate distance measurements $\bar{z} = d_L(\bar{z})$

Velocity bias

Galaxies are no perfect tracers of the DM density

$$\delta(z, \mathbf{x}) = b\, n_{gal}(z, \mathbf{x})$$

Galaxies do not perfectly trace the DM velocity neither

$$\mathbf{v} \cdot \mathbf{n} = \frac{z - \bar{z}}{1 + \bar{z}} + \epsilon_{\mathrm{NL}}$$

Stochastic contribution

Error-model:

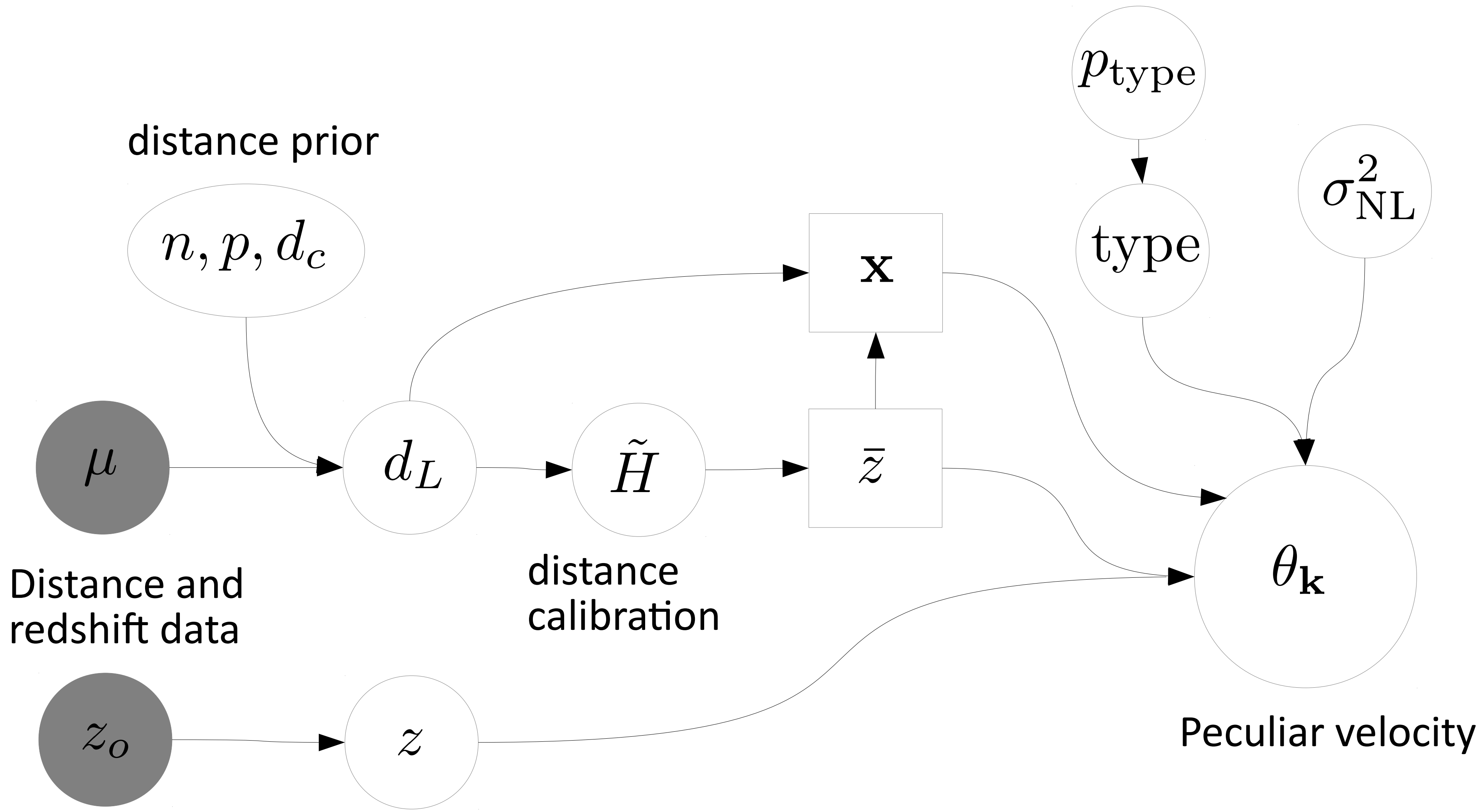
Assume ϵ_{NL} to be gaussian

σ^2_{NL} can be different for different galaxies

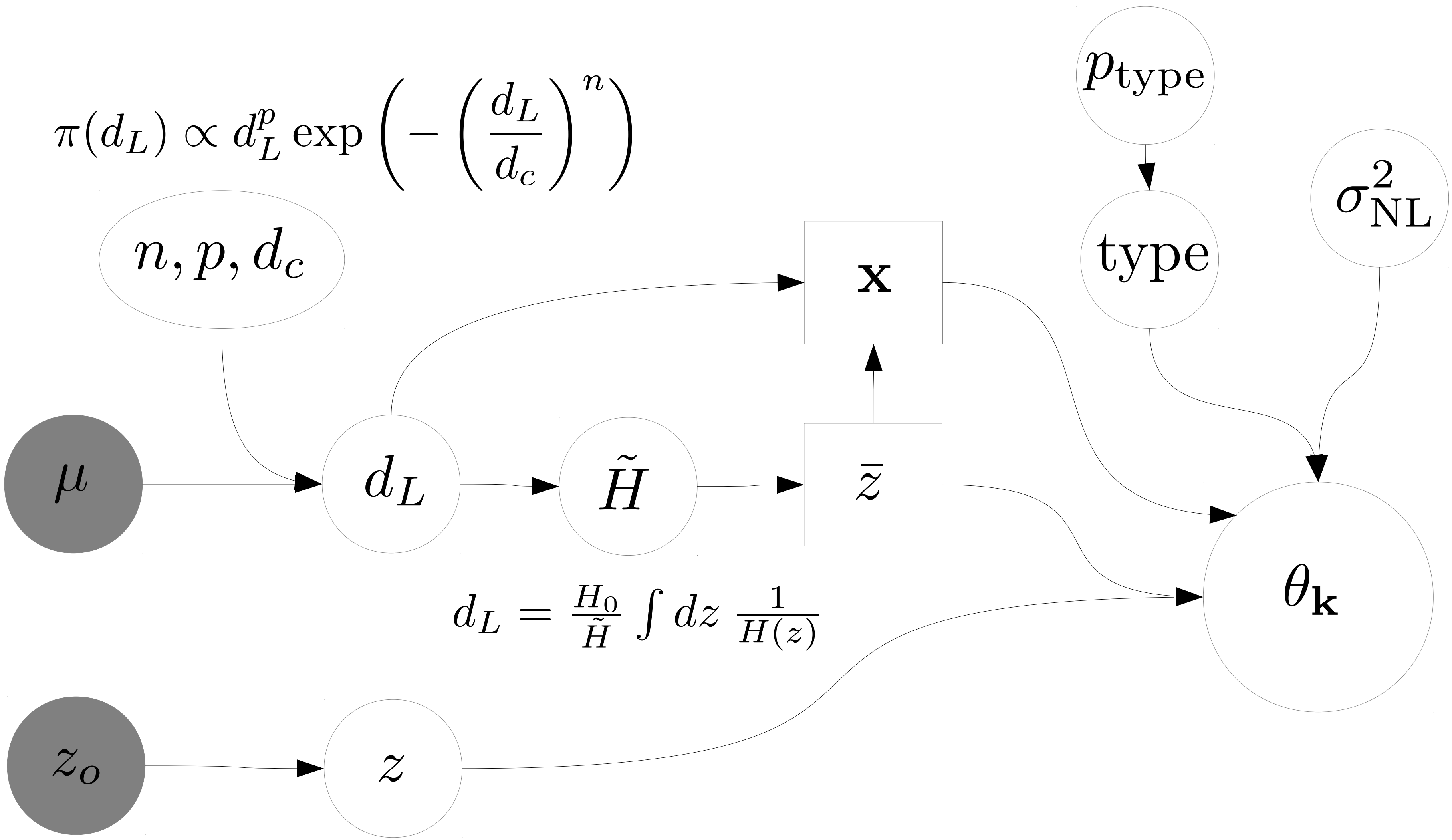
→ classify galaxies into types with different

→ determine self-consistently

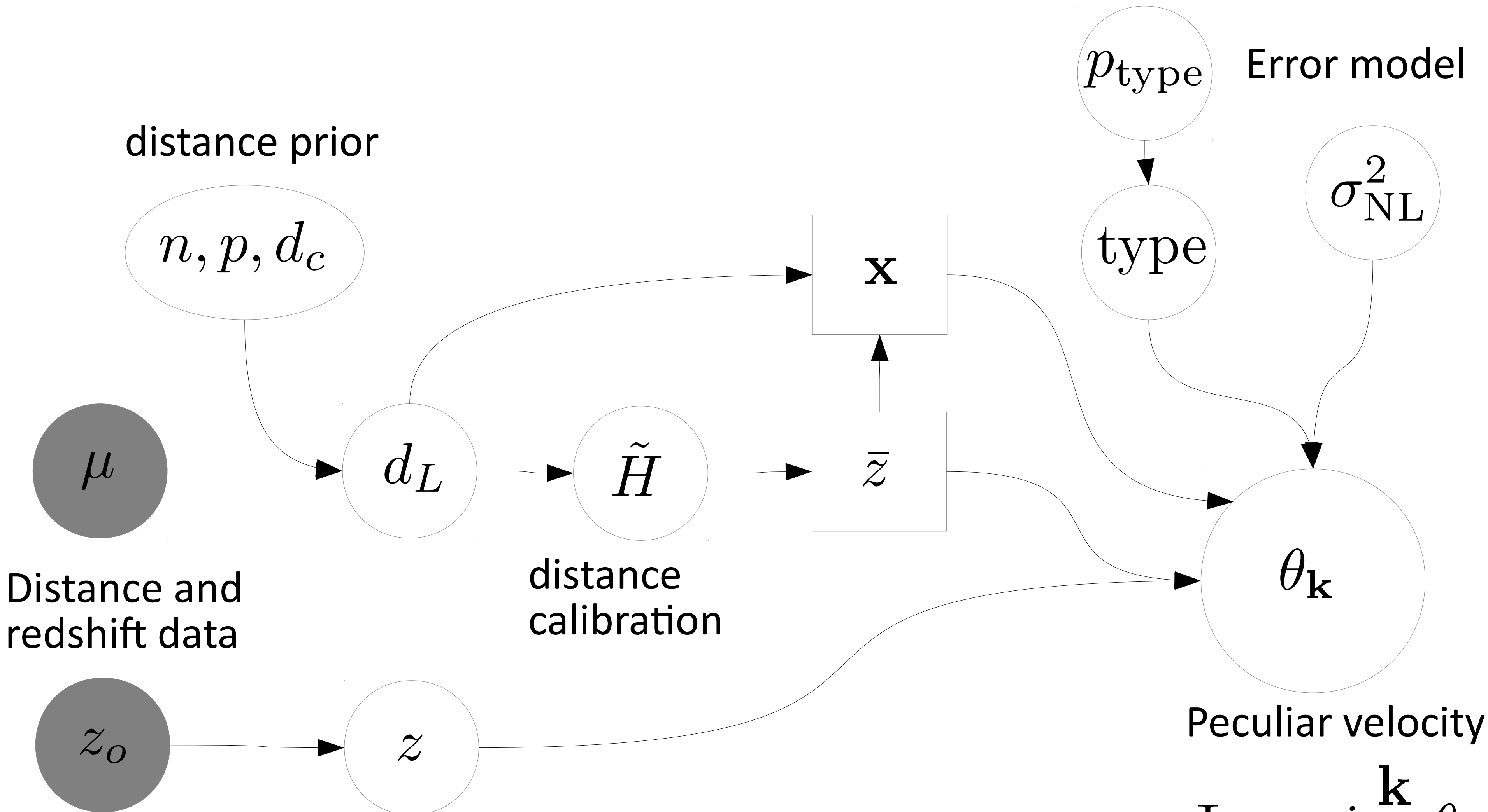
Statistical model and likelihood



Statistical model and likelihood



Statistical model and likelihood



$$\Psi_{\mathbf{k}} = i\frac{\mathbf{k}}{k^2}\theta_{\mathbf{k}}$$

$$\mathcal{L} \propto \prod_{\mathrm{galaxies}} \exp\left(-\frac{(v(z,\bar{z}) - Hf\Psi(\mathbf{x}))^2}{2\sigma^2_{\mathrm{NL,type}}}\right)\frac{1}{\sqrt{\sigma^2_{\mathrm{NL,type}}}}$$

Hamilton Monte Carlo

Reformulate as Hamiltonian particle system, with auxiliary variables (momentum) $\mathbf{p}$

Neal 2011
Jasche, Kitaura 2010

$$H = \frac{1}{2}\mathbf{p} \cdot \mathbf{M} \cdot \mathbf{p} - \log\left(P\left(\theta|\mathcal{D}\right)\right)$$

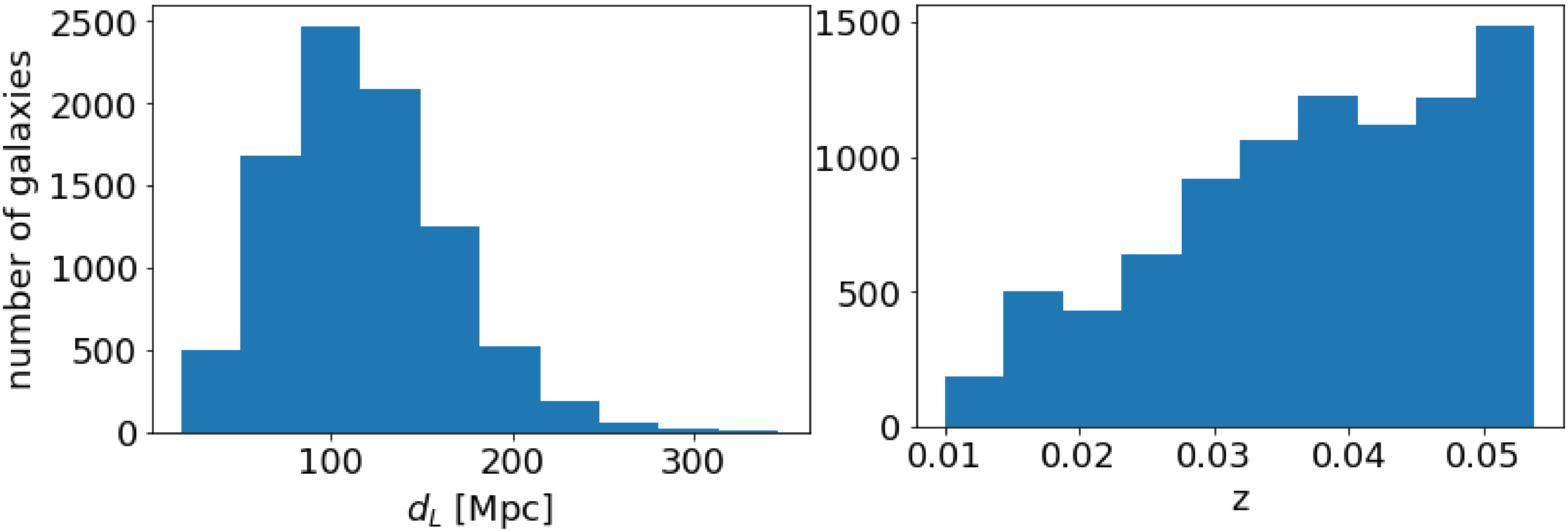
Samples obtained by solving Hamiltonian E.o.M.

$$\dot{\theta} = \mathbf{M}^{-1} \cdot \mathbf{p} \qquad \dot{\mathbf{p}} = -\partial_\theta \log\left(P\left(\theta|\mathcal{D}\right)\right)$$

Hamiltonian Monte Carlo is well suited to sample from high dimensional distributions

- Travel large distances in parameter space
- High acceptance rate
- Use gradient information

6dF distance data



- About 9000 galaxies
- Only the southern sky

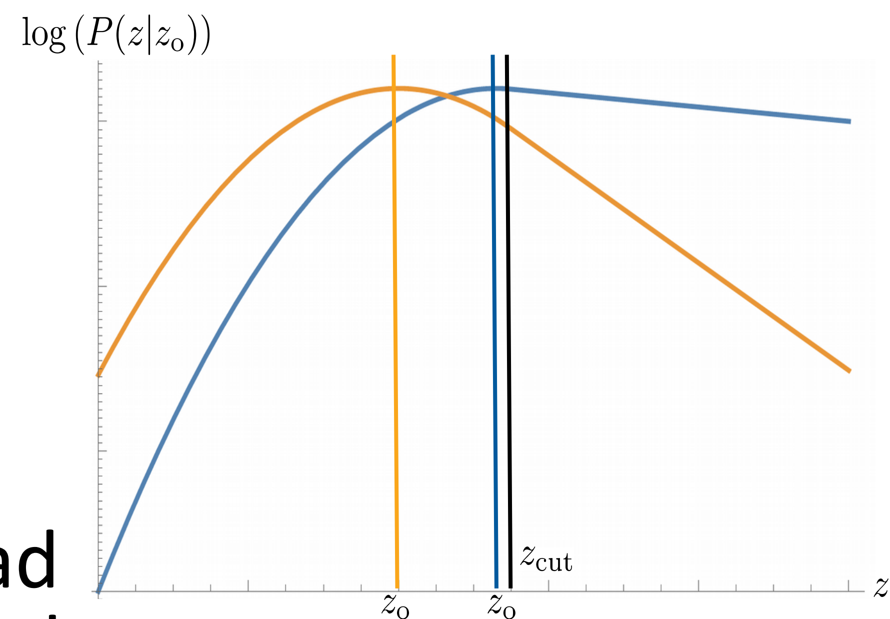
Redshift selection

Redshift likelihood gaussian, but typically surveys are cut a at maximal redshift

$$P(z|z_o) \propto \mathcal{N}(z_o|z)\theta(z_o - z_{\rm cut})\frac{1}{Z(z, z_{\rm cut})}$$

Posterior not gaussian, due normalization

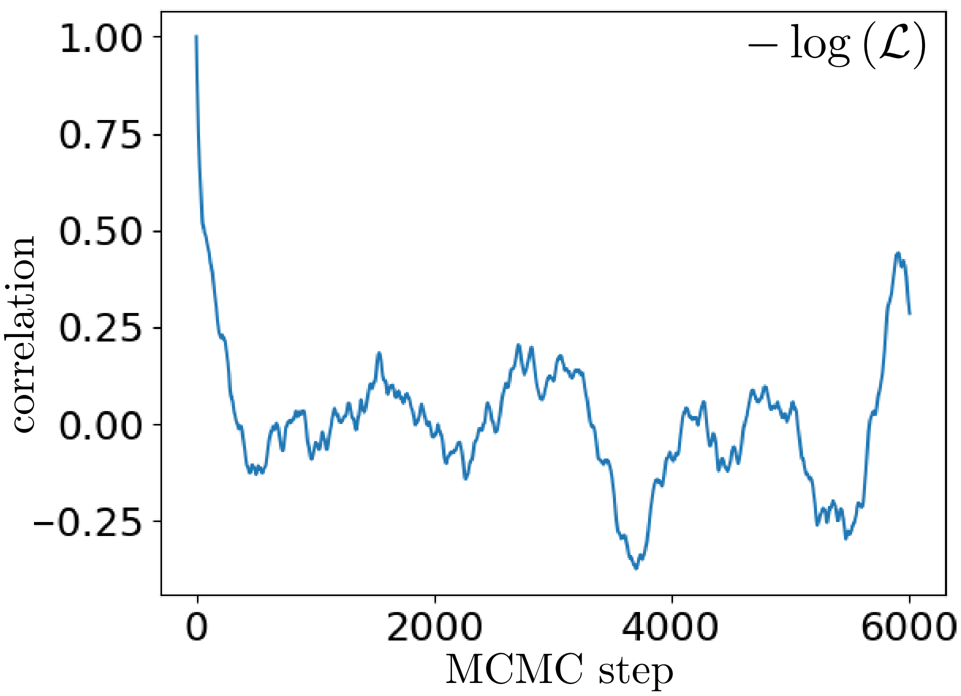
$$Z(z, z_{cut}) \propto \text{erfc}\left(\frac{z_{\rm cut} - z}{\sigma_z}\right)$$

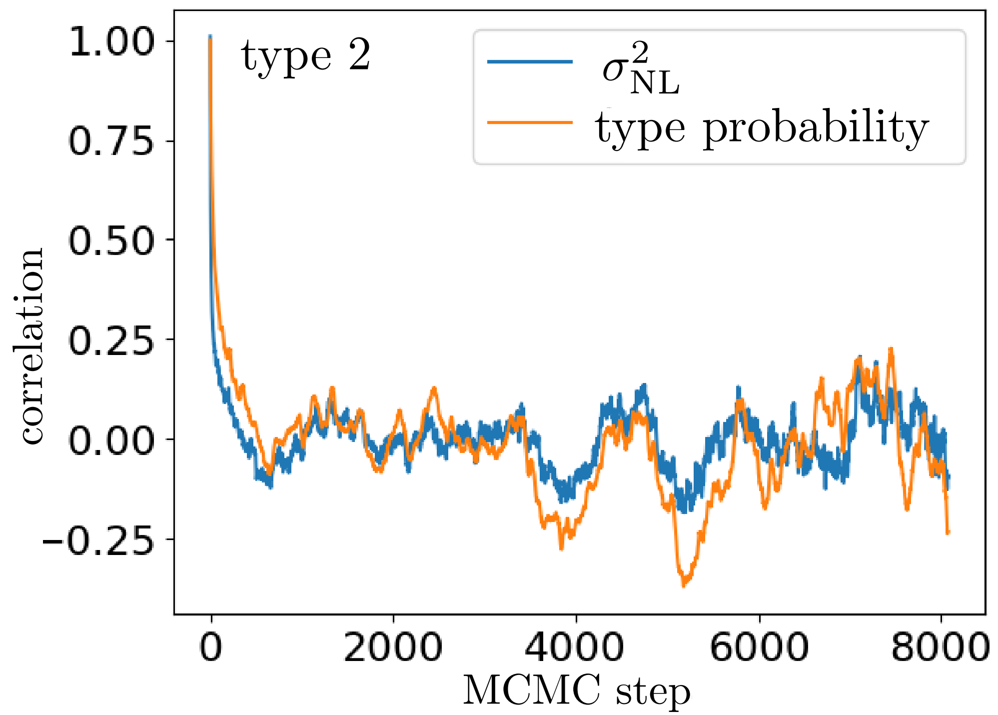


Not taking into account would lead to in falling of galaxies on large scales

Convergence analysis

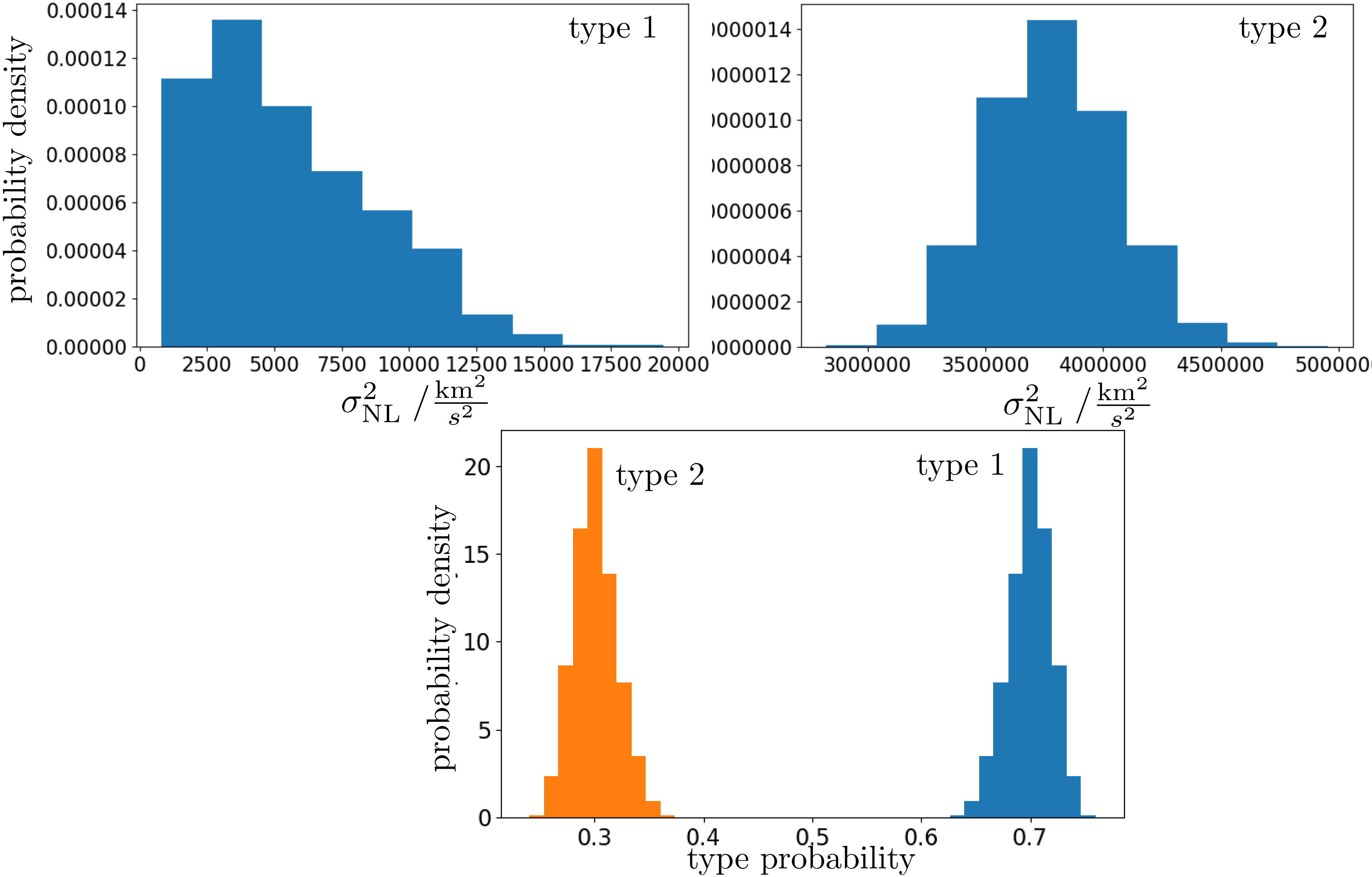
Preliminary





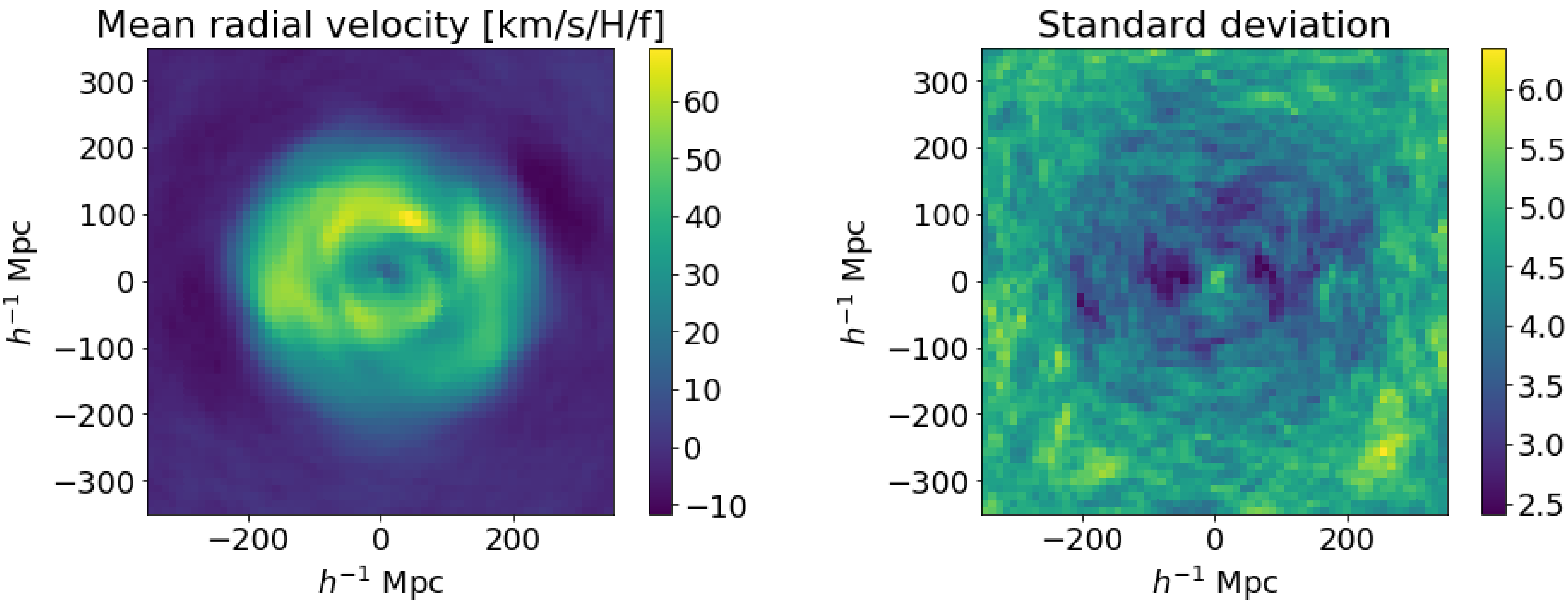
Error-model distribution

Preliminary



Radial velocity field

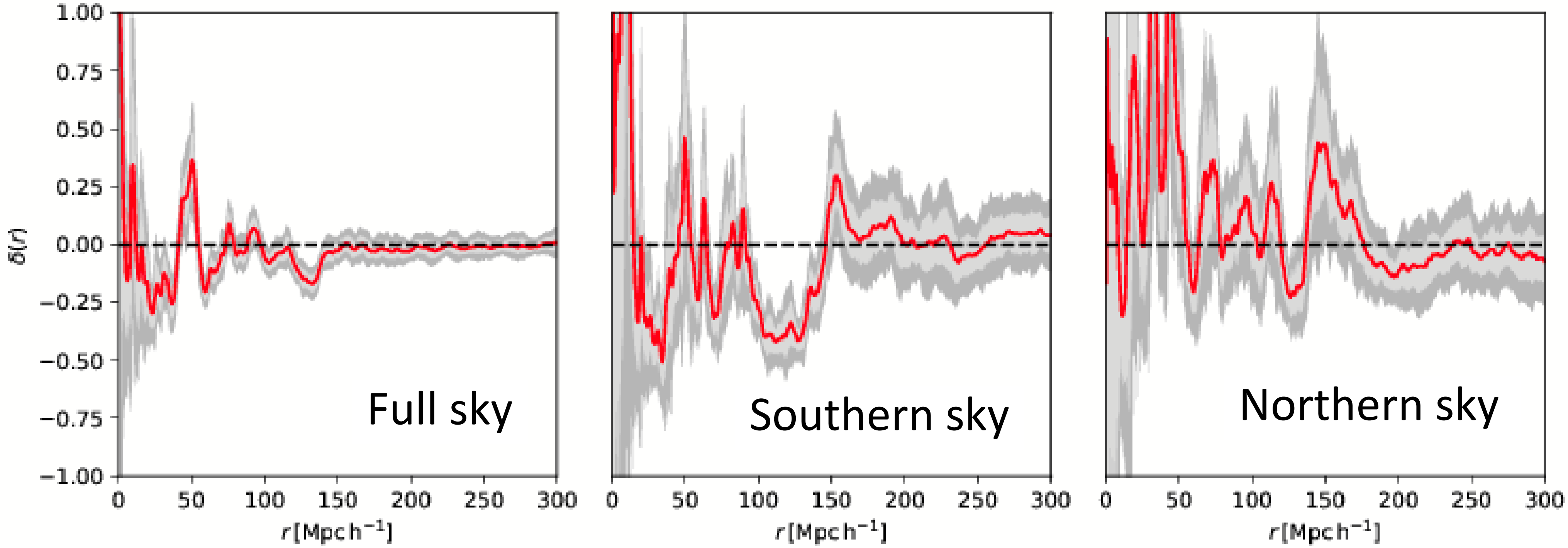
Preliminary



Density fluctuations in 6dF

Radial density profile of density fluctuations

From Lavaux & Jasche 2018



Conclusion and Outlook

- Direct reconstruction of 3D velocity field
  - 9000 galaxies from 6df in southern hemisphere
  - In future: Add 2000 Spitzer galaxies to analysis
- Implement in BORG framework Jasche, Wandelt 2013
  - Joined reconstruction with density
  - Reconstruction of the non-linear field
- How can we use the velocity field
  - Test gravity?
  - Implications for Hubble constant measurements?