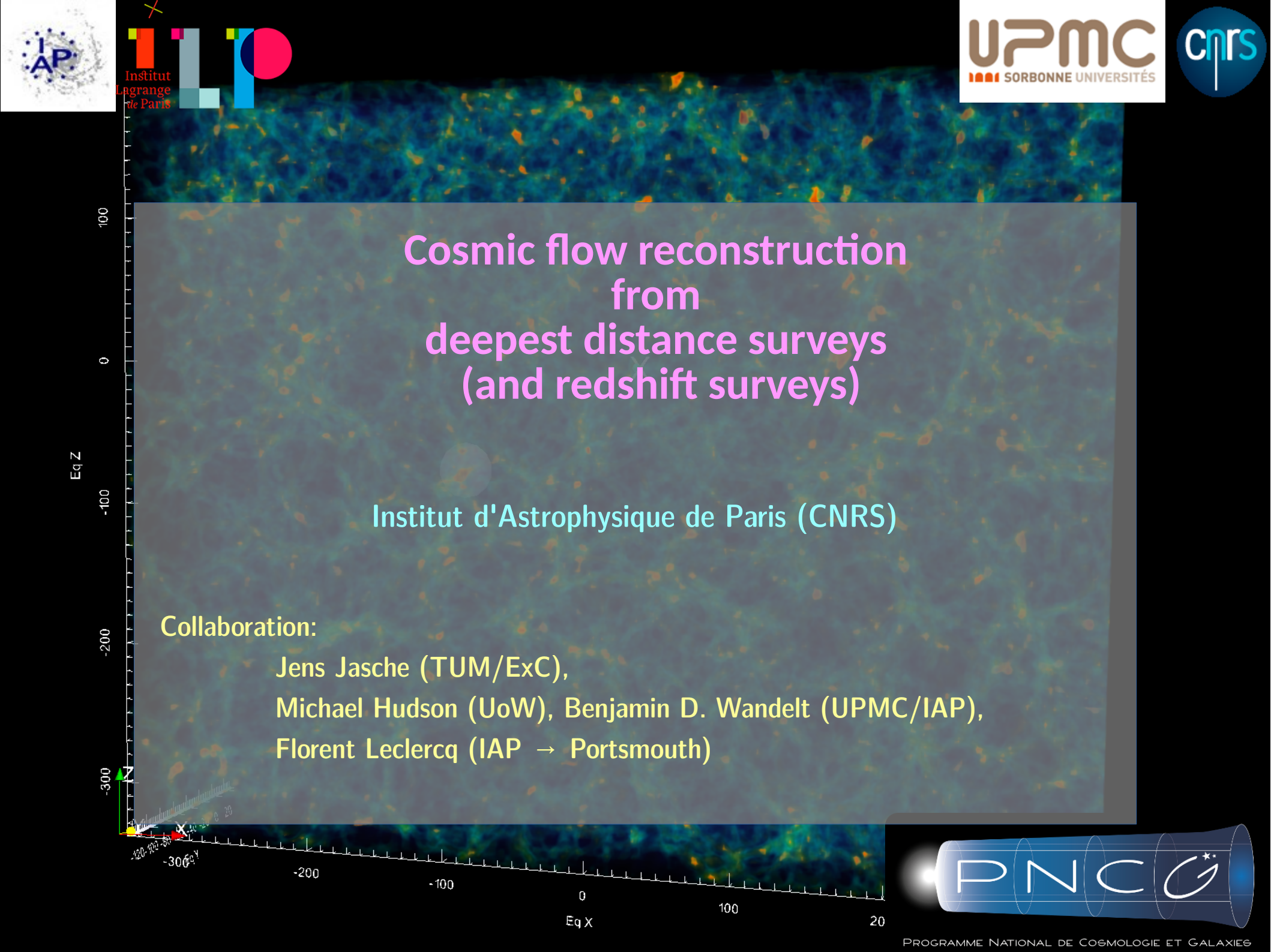


Cosmic flow reconstruction from deepest distance surveys (and redshift surveys)

Institut d'Astrophysique de Paris (CNRS)

Collaboration:

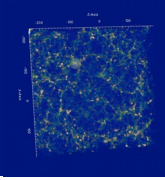
Jens Jasche (TUM/ExC),

Michael Hudson (UoW), Benjamin D. Wandelt (UPMC/IAP),

Florent Leclercq (IAP → Portsmouth)

Programme National de Cosmologie et Galaxies

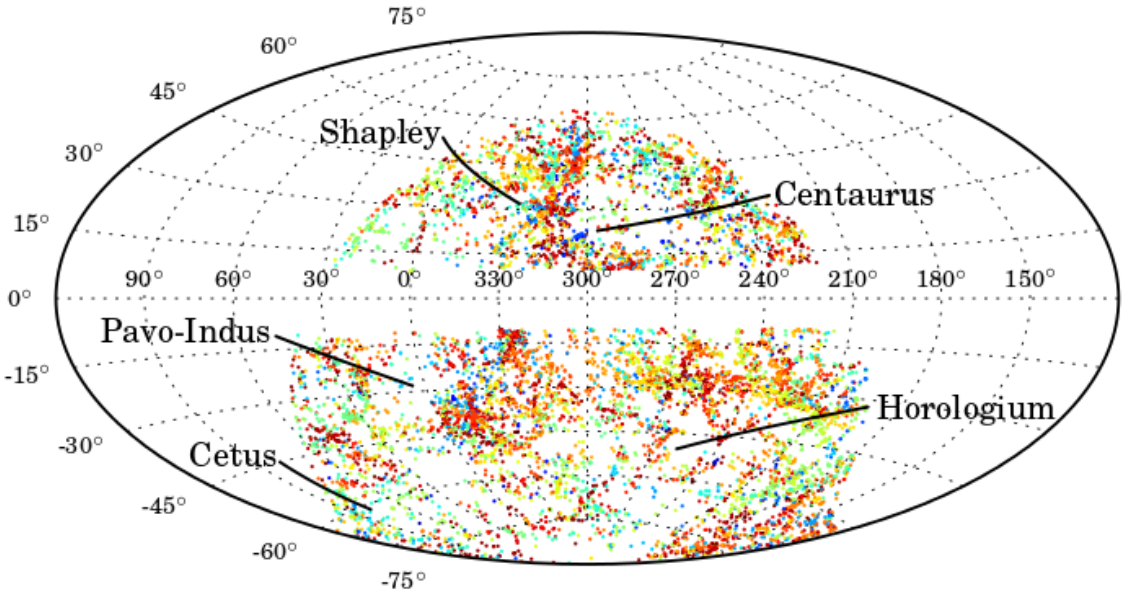
Outline



- Context and problems
- The statistical models: BORG (spectroscopic) and VIRBIUS (distance+spectroscopic)
- Application to CosmicFlows, COMPOSITE and 2M++
- Results
- Conclusion

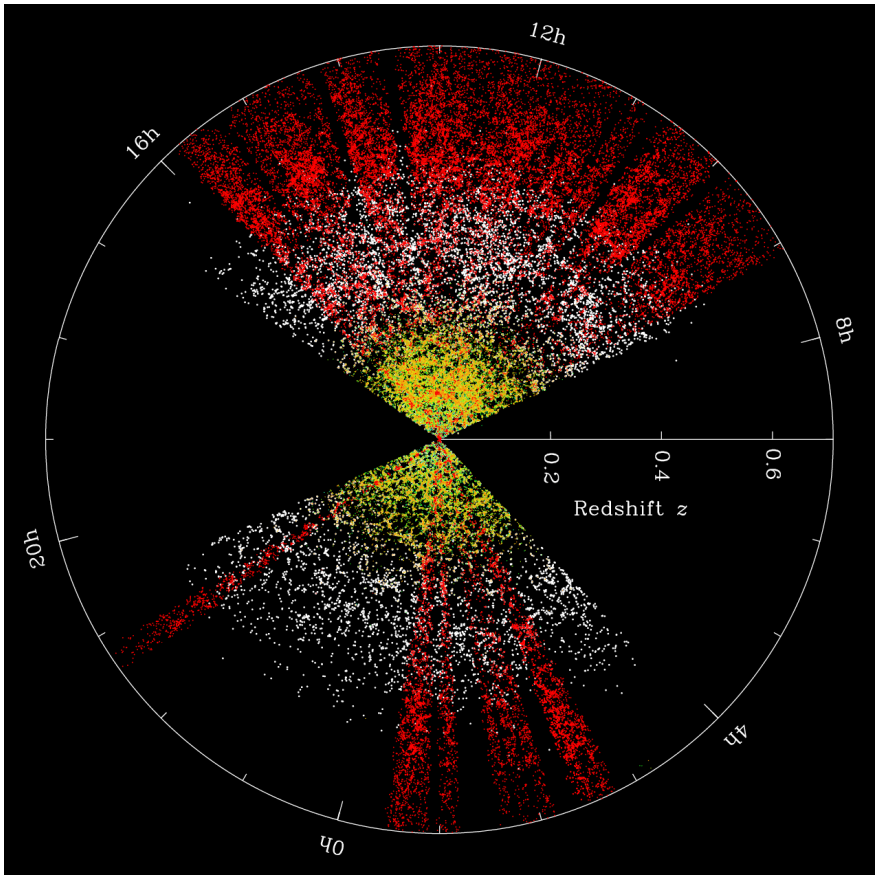
Context

- Cosmic distance surveys coming out of infancy
- Superb spectroscopic surveys



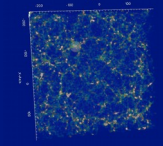
6dFv survey (Springob et al. 2014)

Cosmicflows 3 (Tully et al. 2016)



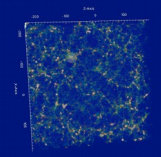
SDSS3 / BOSS (SDSS website)

Context



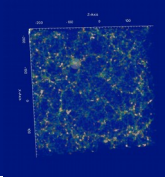
- Cosmic distance surveys coming out of infancy
- Superb spectroscopic surveys
- Still naive data analysis

Context



- Cosmic distance surveys coming out of infancy
- Superb spectroscopic surveys
- Still naive data analysis
- Is it possible to do a full and statistically accurate analysis of surveys? Obtain velocity fields?

Outline



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Bayesian **O**rigins **R**econstruction from **G**alaxies (BORG)

BORG2 model

Cosmological prior

Galaxy redshifts survey

Initial conditions
→ particles

Forward model:
- Perturbation Theory
- Particle Mesh

Matter Density building
particles → density

Galaxy density:
galaxy position → density

Bias model

$$\rho_g = A\rho_m^\alpha$$

Poisson statistics

~OpenMP parallel

Lavaux & Jasche, 2015, MNRAS
Jasche & Wandelt, 2013, MNRAS

BORG3 model

Cosmological prior

Galaxy redshifts survey

Initial conditions
→ particles

Forward model:
- Perturbation Theory
- Particle Mesh
- Redshift Space Distortion

Matter Density building
particles → density

Galaxy density:
galaxy position → density

Bias model

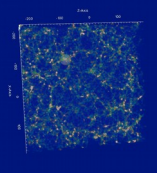
$$\rho_g = A\rho_m^{\alpha}\exp\left[-\left(\frac{\rho_m}{\rho_0}\right)^{-\epsilon}\right]$$

Poisson statistics

MPI + OpenMP parallel, exact supersampling, entire code rewriting

Lavaux & Jasche, 2016, in prep.
Jasche & Lavaux, 2016, in prep.

BORG3 model (effectively)



Linear response operator (mask, radial selection)

« Mean » density of tracers

bias

$$-\log P(\delta,\alpha,\tilde{n}) = A + \sum_i \tilde{n} R_i[(1+\delta_{\mathrm{NL},i}[\delta])^{\alpha} \times ...] - N_i[\alpha \log(1+\delta_{\mathrm{NL},i}[\delta]) + ...] + \frac{\sum_k |\hat{\delta}_k|^2}{2 P_k}$$

NGP binned data

Poisson probability

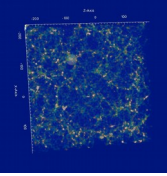
Gaussian prior

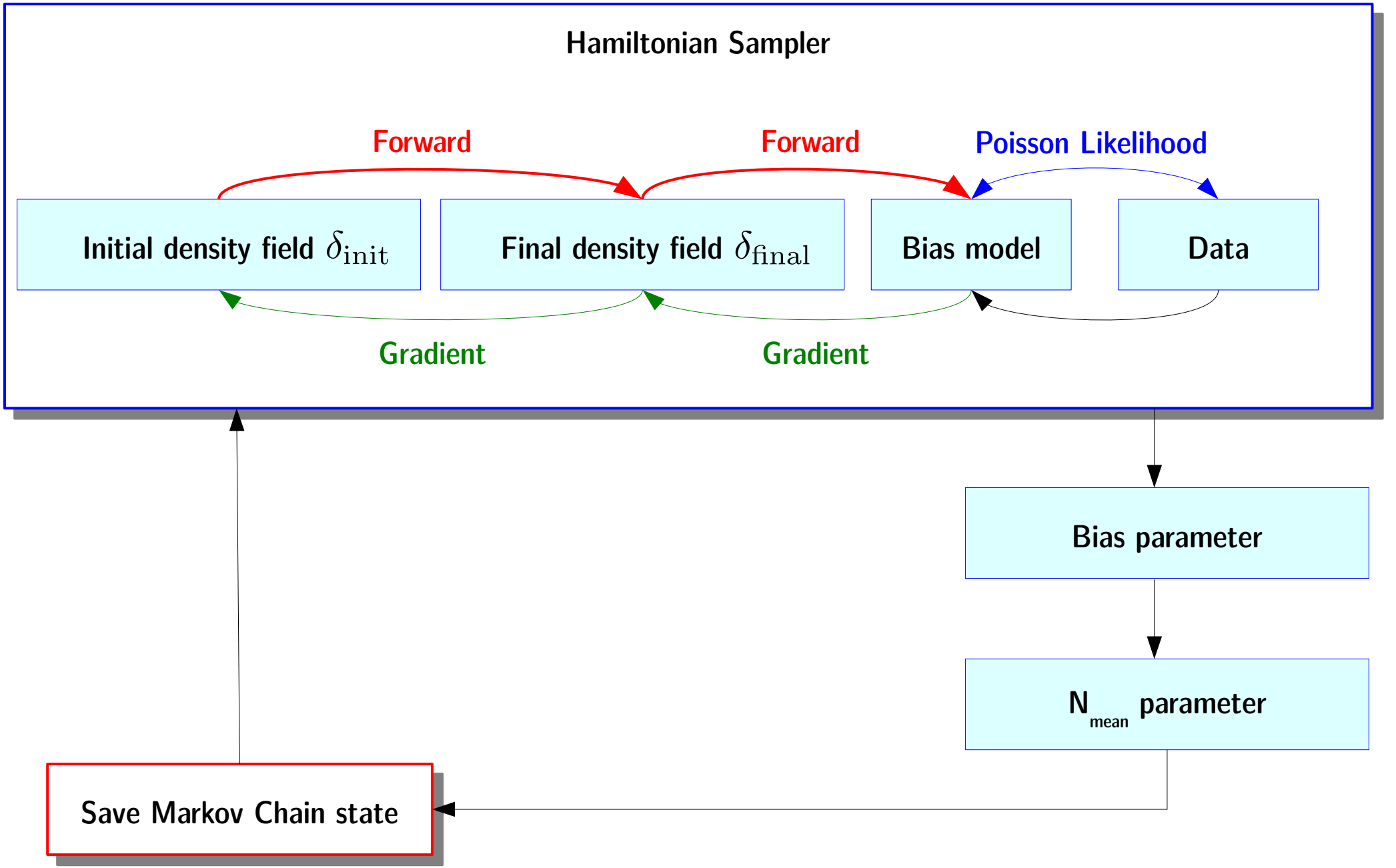
δ sampled using Hamiltonian Monte Carlo algorithm

LJ, JL, 2016 in prep.

Jasche & Wandelt (2013)

BORG3 sampling technique





Red-figured volute-krater showing Hippolytus. Apulia c. 340 BC. Photo © Maicar Förlag - GML

Velocity Reconstruction using Bayesian Inference Scheme

VIRBIUS model

Cosmological prior

Velocity field prior:
Potential, Gaussian

Velocity/density field

Bulk flow:
uniform prior

Distance prior

True Distances

Distance moduli / Indicators

Galaxy survey

Redshifts (+errors)

Lavaux, 2016, MNRAS

VIRBIUS model

Cosmological prior

Distance moduli / Indicators

Galaxy survey

Velocity field prior: Potential, Gaussian

Bulk flow: uniform prior

Redshifts (+errors)

Distance prior

Velocity/density field

True Distances

Log normal model

Predicted velocities

$$\vec{v} = -\vec{\nabla}\phi$$

Gaussian error model

Meta parameters (calibration, errors, classification)

OpenMP parallel

Lavaux, 2016, MNRAS

VIRBIUS model

Cosmological prior

Distance moduli / Indicators

Galaxy survey

Redshifts (+errors)

Velocity field prior: Potential, Gaussian

Bulk flow: uniform prior

Distance prior

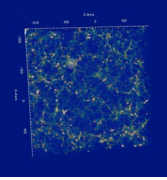
No LCDM assumptions

Velocity/density field

LCDM assumptions

OpenMP parallel

VIRBIUS model (effectively)



Hard to write completely here...

The following is only the core part:

Likelihood

$$\mathcal{L} = P(\{\mu_i, z_i\}|\{d_i^L\}, \{\sigma_{z,i}, \sigma_{\mu,i}\}, \{\hat{\Theta}(\boldsymbol{k}_q)\}, H, \widetilde{H}, \Sigma_{\rm NL}, \mathcal{T}, \{p_t^{type}\})$$

$$\propto \prod_{i=1}^{N_d} \left(\sigma_{z,i}^2(1+\bar{z}_i)^{-2} + \sigma_{{\rm NL},type(i)}^2\right)^{-1/2} \times$$

$$\exp\left\{-\frac{1}{2}\sum_{i=1}^{N_d} \frac{\left[v_i^r(z_i,d_i) - Hf\Psi_{r,i}(q^h)\right]^2}{\left[(\sigma_{z,i}^2(1+\bar{z}_i(d_i))^{-2} + \sigma_{{\rm NL},type(i)}^2\right]} - \frac{(\mu_i - 5\log_{10}(d_i^L/10\ {\rm pc}))^2}{\sigma_{\mu,i}^2}\right\}$$

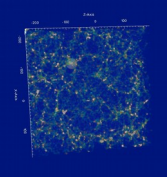
Posterior distribution

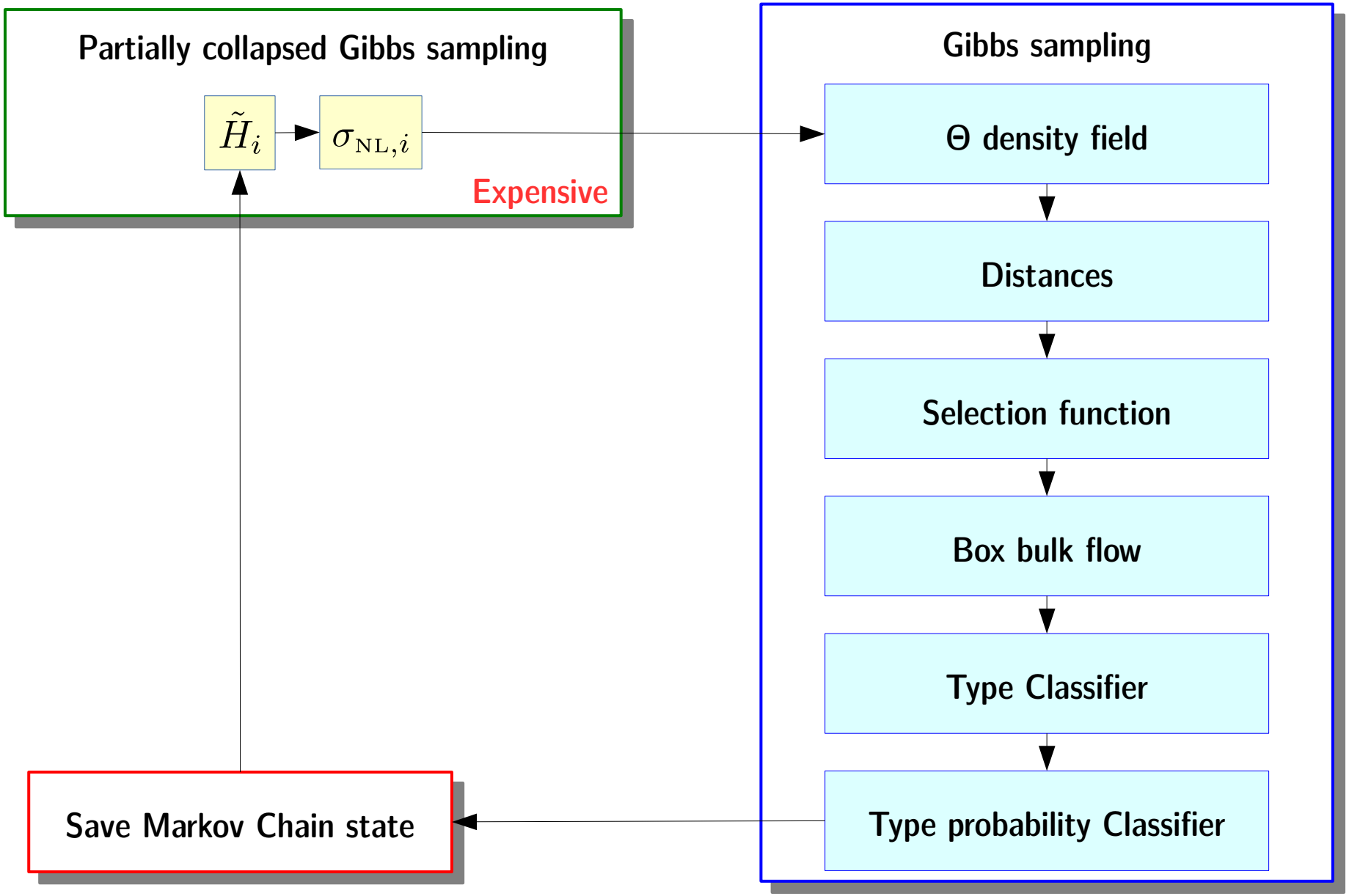
$$P(\mathcal{D}^L = \{d_i^L\}, \hat{\Theta} = \{\hat{\Theta}(\boldsymbol{k}_q)\}, \widetilde{H}, H, A_S, \{\sigma_{{\rm NL},t}\}, \mathcal{T}|$$

$$\mathcal{M} = \{\mu_i\}, \mathcal{Z} = \{z_i\}, \Sigma_z = \{\sigma_{z,i}\}, \Sigma_\mu = \{\sigma_{\mu,i}\}) =$$

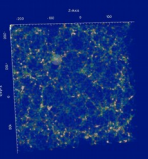
$$\frac{\mathcal{L} \times \pi(\mathcal{D}^L)\pi(\hat{\Theta})\pi(\Sigma_{\rm NL})\pi(H)\pi(\{type(i)\})\pi(A_S)}{\sum_{\mathcal{T}'} \int {\rm d}H{\rm d}\hat{\Theta}{\rm d}\mathcal{D}^L{\rm d}\Sigma_{\rm NL}\ \mathcal{L} \times \pi(\mathcal{D}^L)\pi(\mathcal{T}')\pi(\hat{\Theta})\pi(\{\sigma_{{\rm NL},t}\})\pi(H)};$$

VIRBIUS sampling technique





VIRBIUS sampling technique



Partially collapsed Gibbs sampling

$\tilde{H}_i$ → $\sigma_{\mathrm{NL},i}$

Gibbs sampling

Θ density field

Distances

Code fully tested on N-body simulation + mock catalogs

Box bulk flow

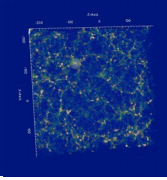
Type Classifier

Type probability Classifier

Save Markov Chain state

Lavaux, 2016, MNRAS

Outline



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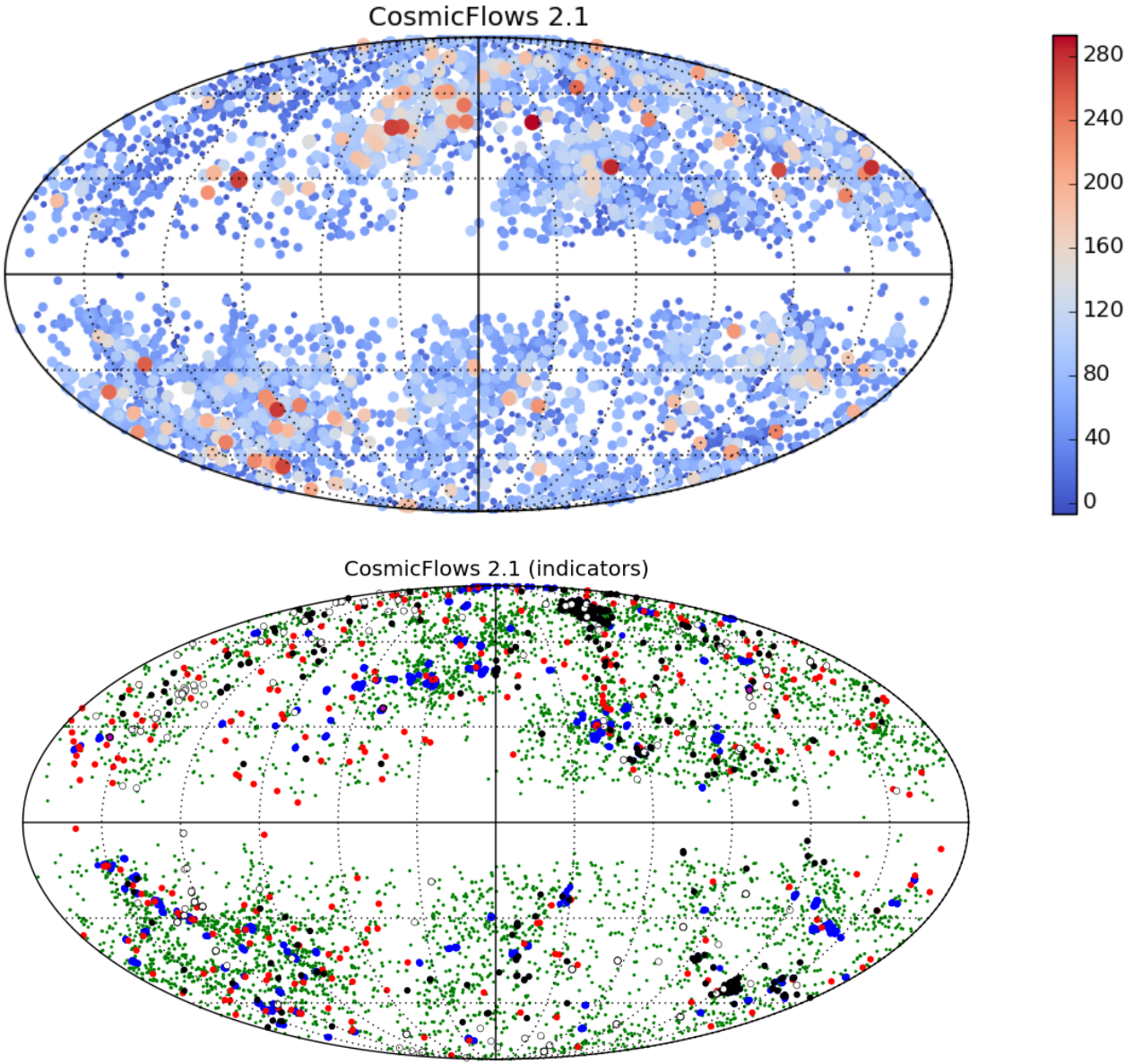
CosmicFlows 2.1 data



8188 galaxies

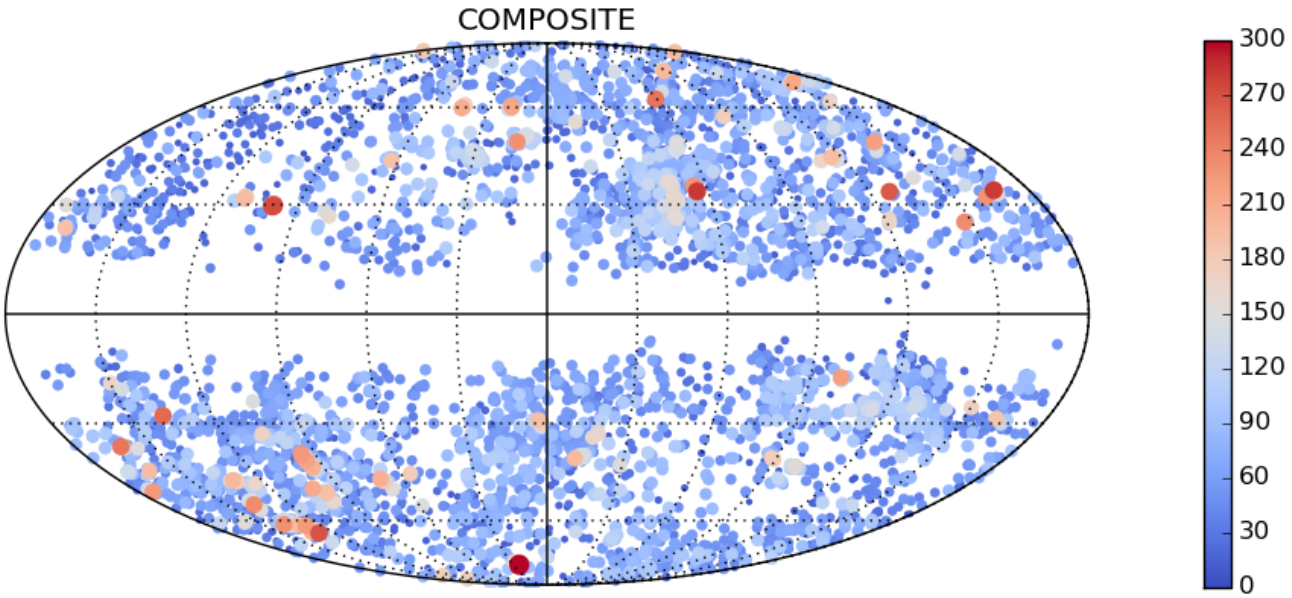
4 subsets:

- "High precision": 558
- Supernovae: 221
- Fundamental plane: 1455
- Tully-Fisher: 5954

Max velocity: 29 313 km/s

Tully et al. (AJ, 2013)

COMPOSITE data



4481 galaxies

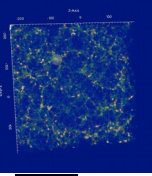
1 subset:

- Mixed bag

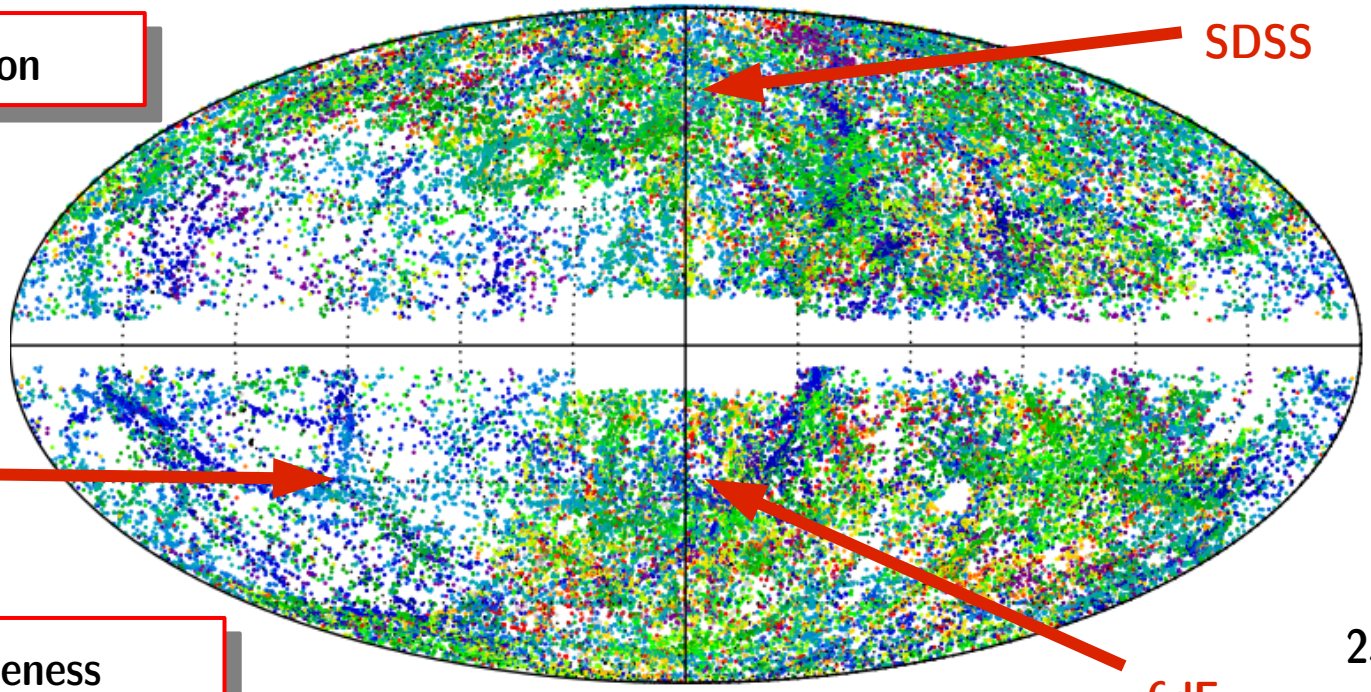
<u>Max velocity:</u> 42 580 km/s

Watkins, Feldman & Hudson (MNRAS, 2009)

2M++ compilation



Galaxy distribution

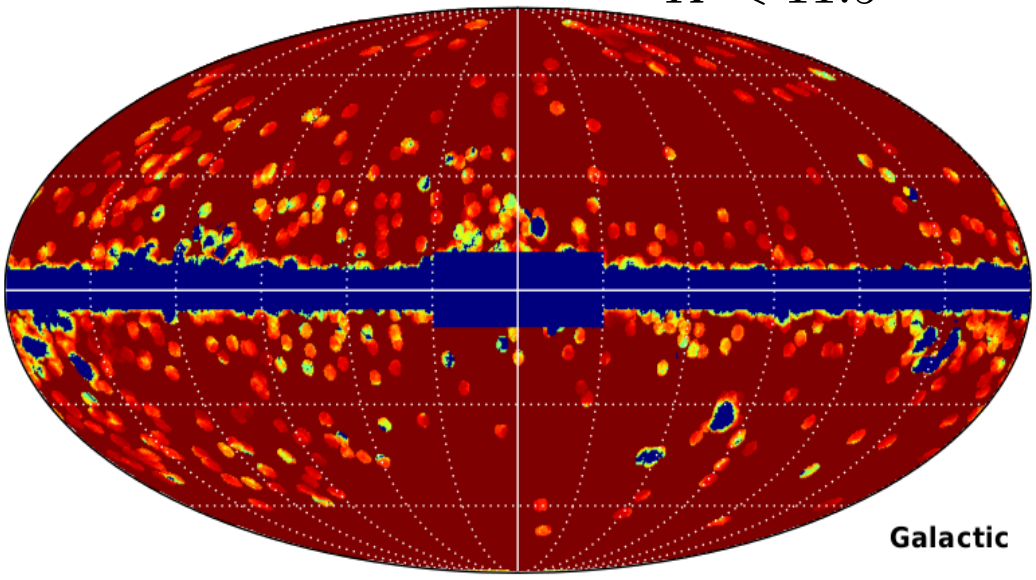


0 Mpc/h

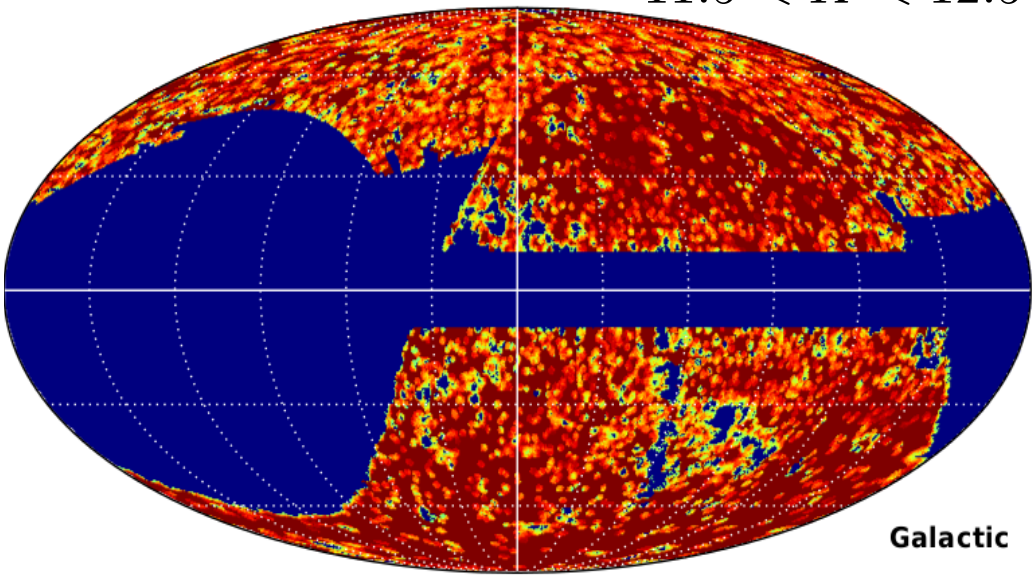
250 Mpc/h

Redshift completeness

$K < 11.5$



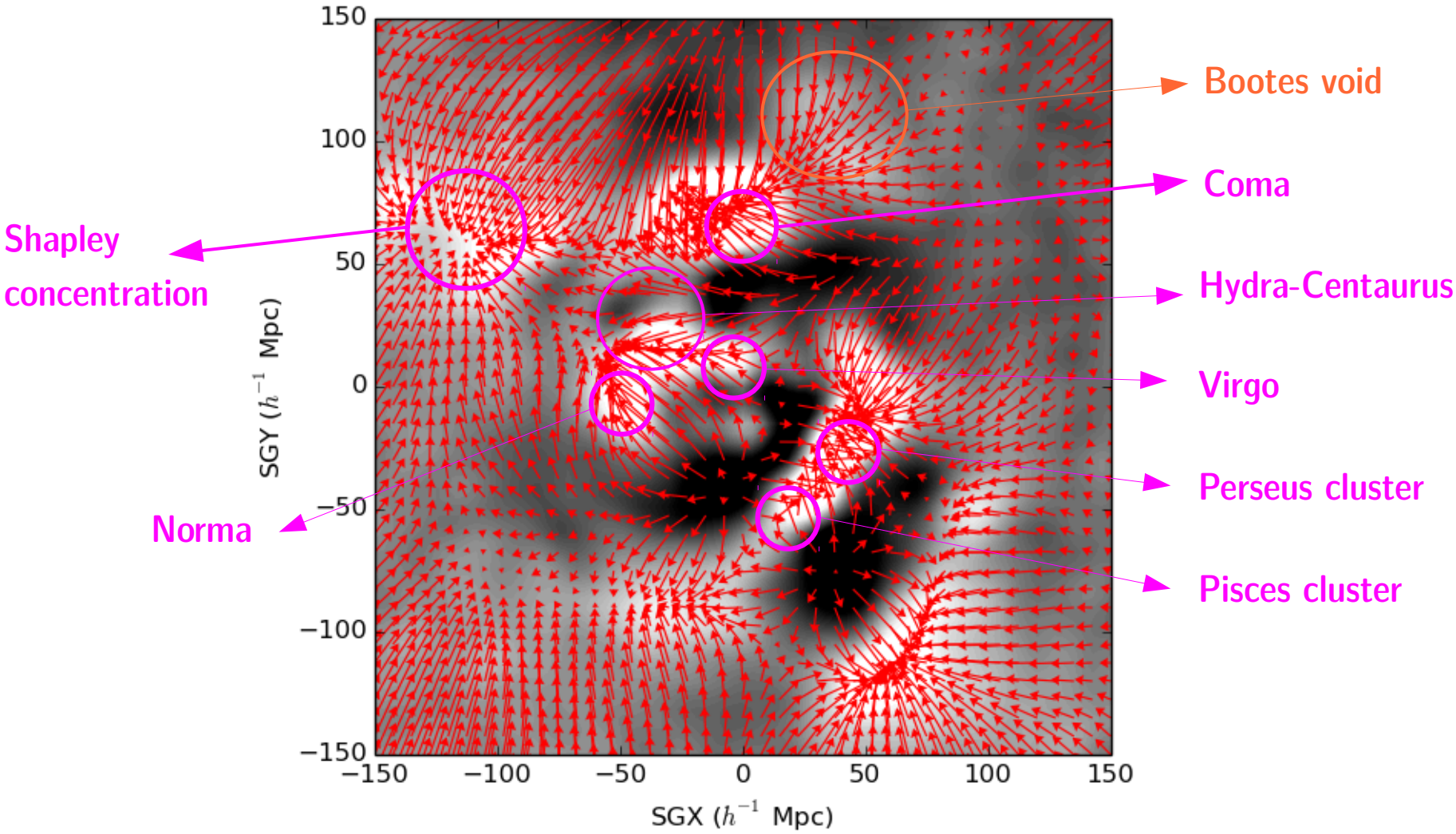
$11.5 < K < 12.5$



Lavaux & Hudson (MNRAS, 2011)

VIRBIUS reconstructed fields

PRELIMINARY (!)



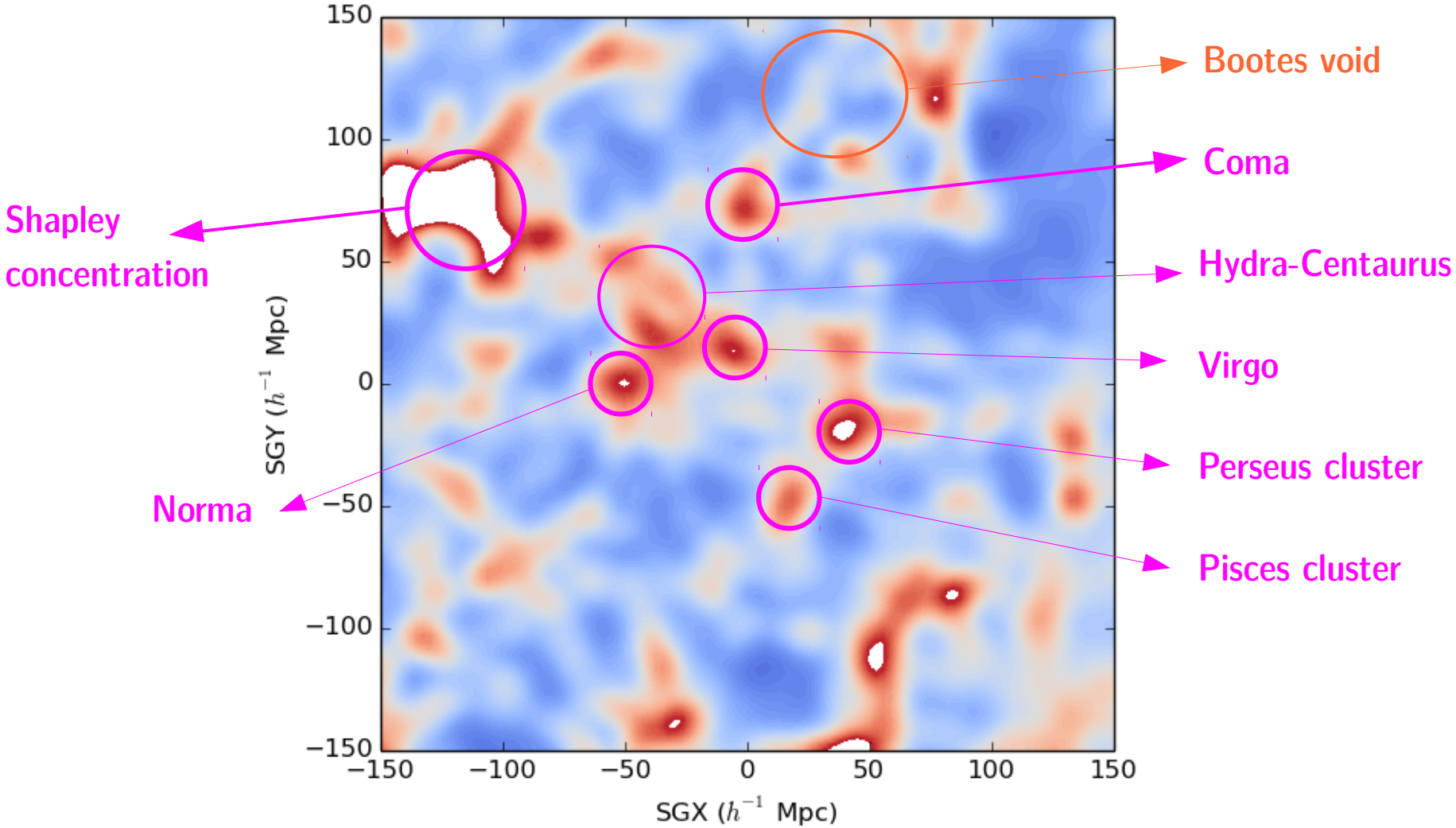
CF2.1, mean density and velocity field given data

Supergalactic plane

BORG3 density field

Supergalactic plane, final density field smoothed to 5 Mpc/h (Gaussian)

PRELIMINARY



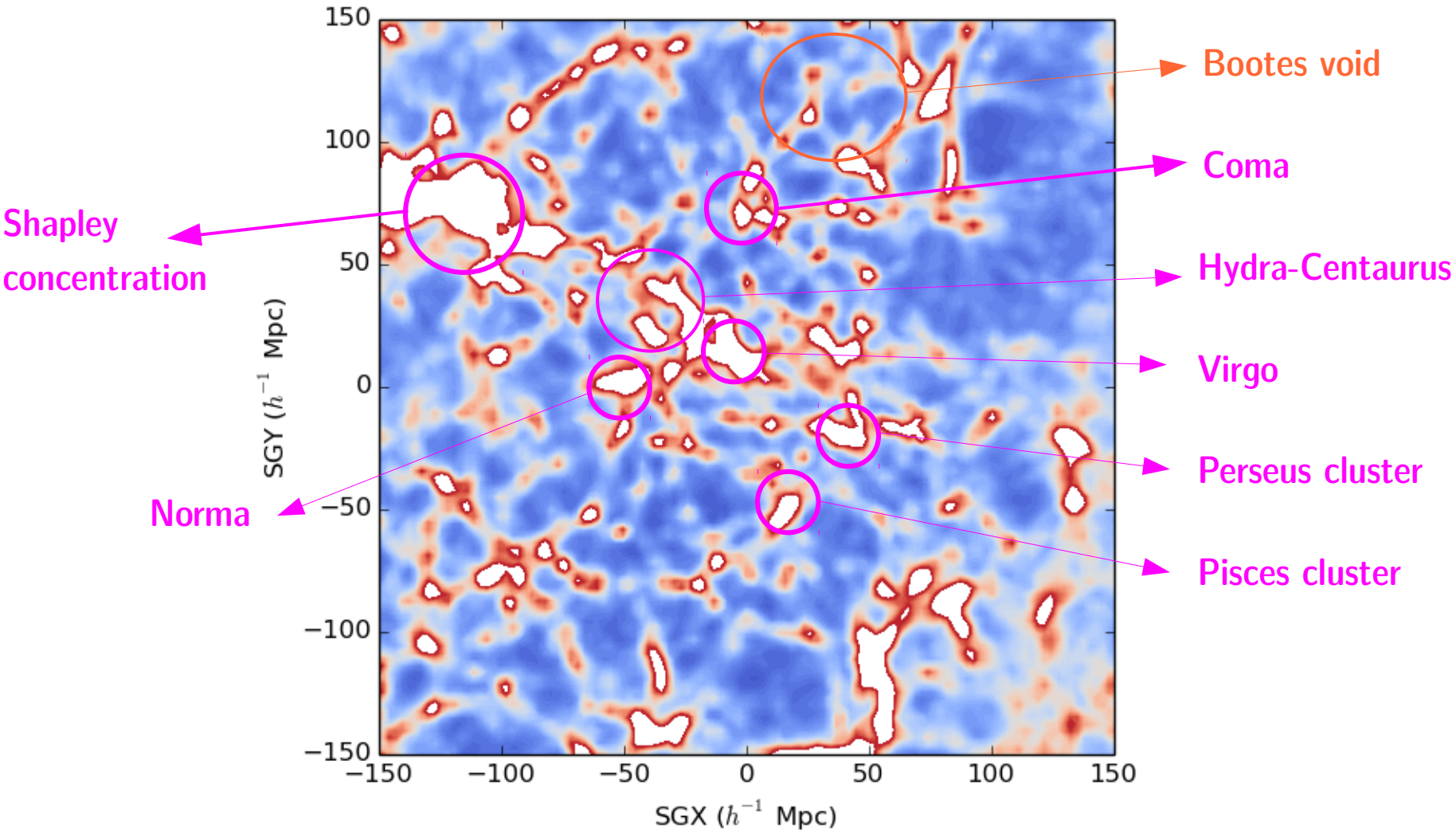
2M++, mean final matter density field

Supergalactic plane

BORG3 density field

Supergalactic plane, final density field, no smoothing

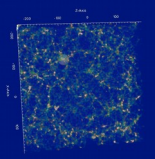
PRELIMINARY



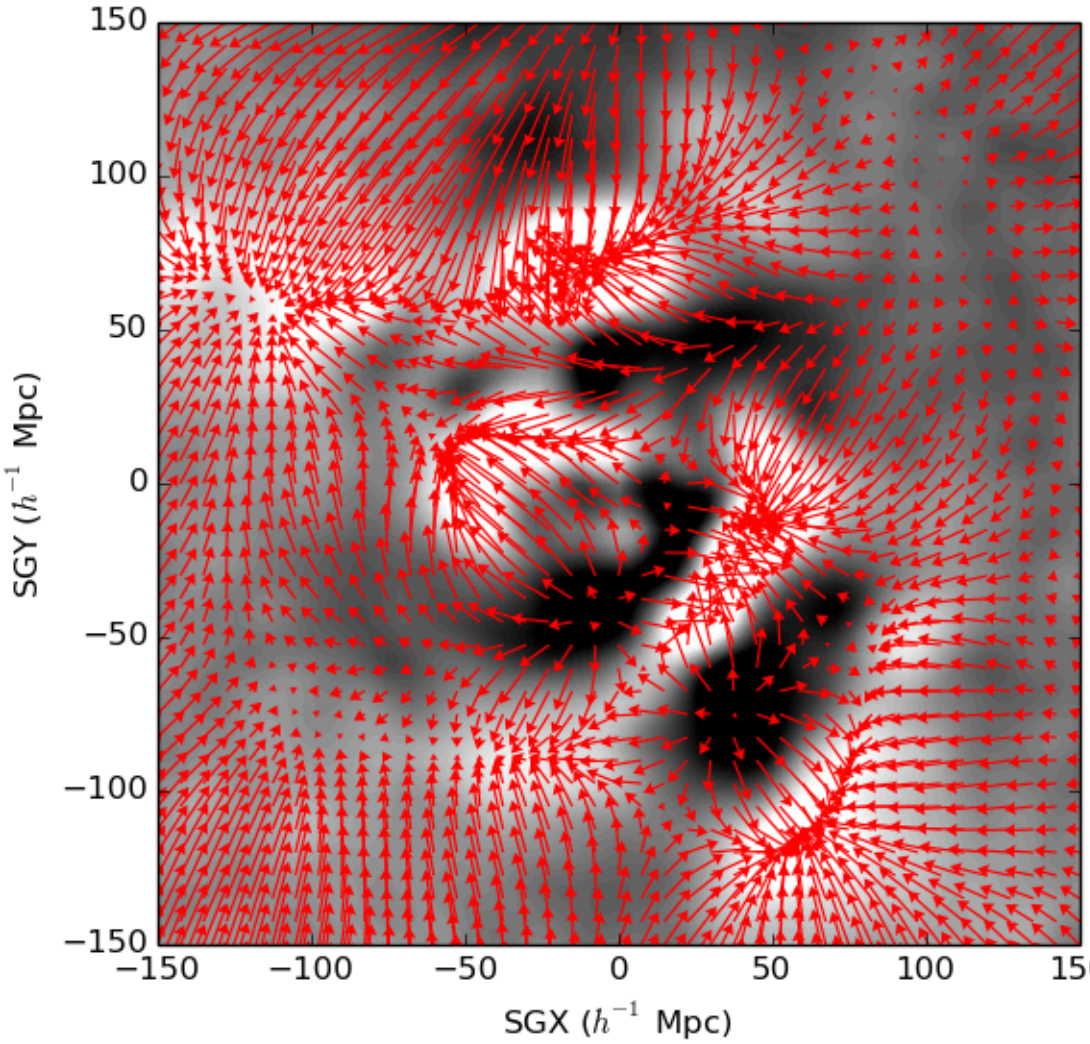
2M++, mean final matter density field

Supergalactic plane

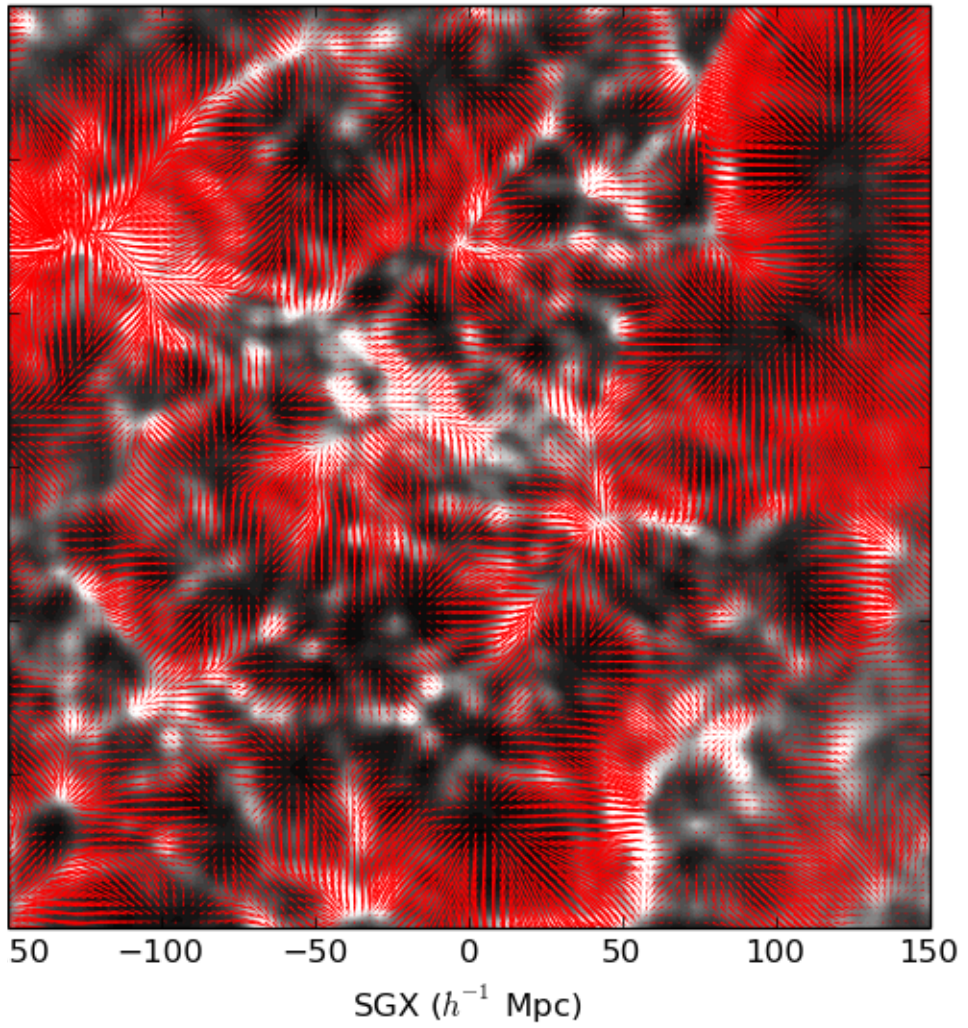
Density + velocity field



PRELIMINARY



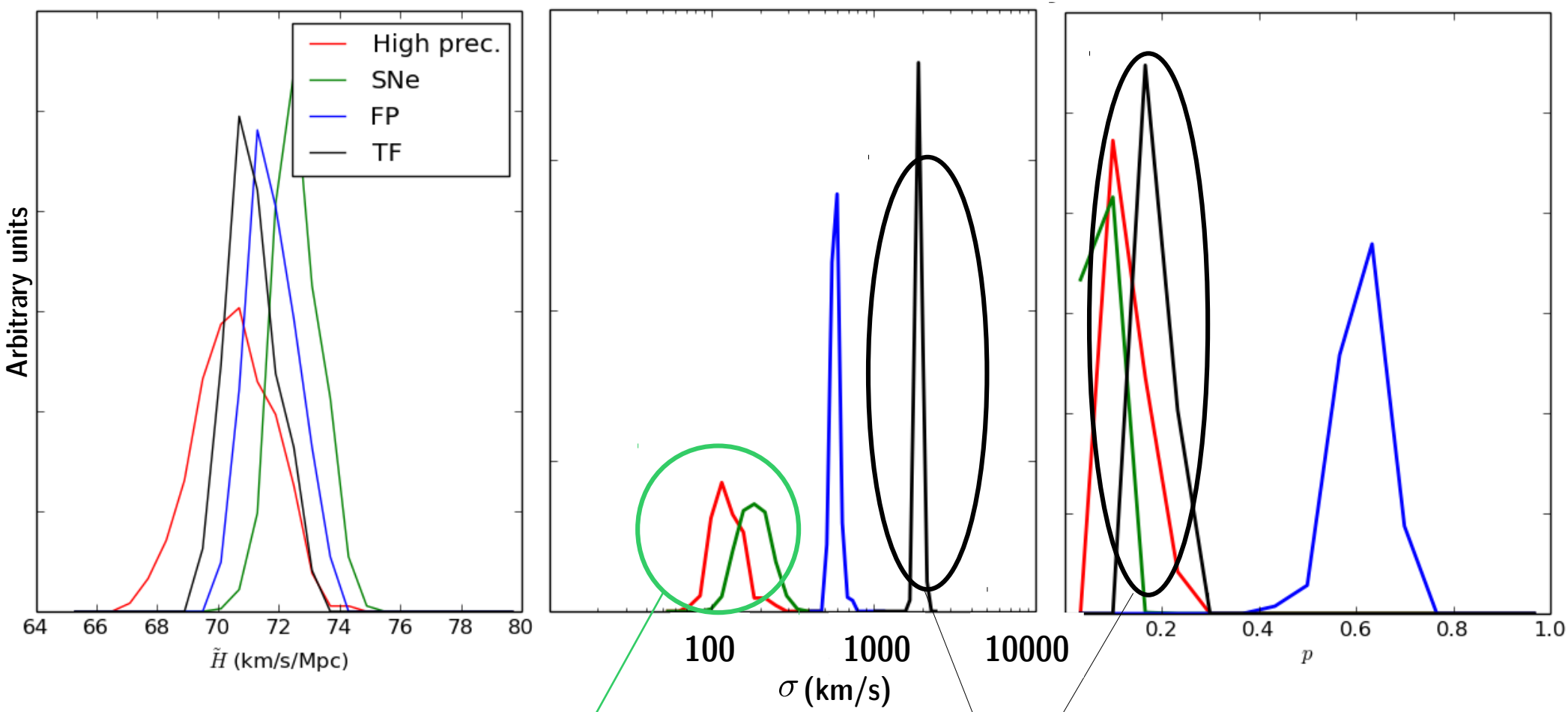
CF2.1, mean divergence field + velocity



2M++, mean final matter density field

Supergalactic plane

Meta-characteristics found by VIRBIUS



Zero point Calibration

Hubble constant

Additional error

Population fraction

Very high noise = no constraints

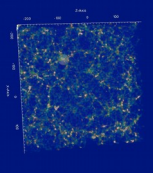
~20% of the whole sample

A lot of TFs

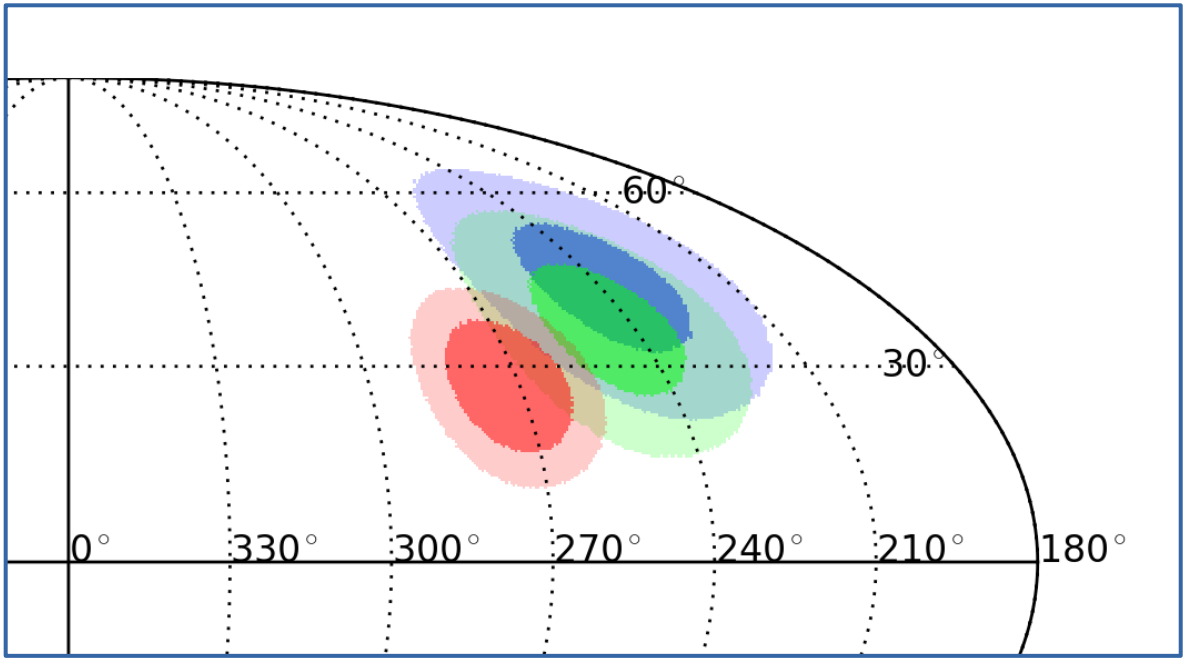
Significant number

of low velocity dispersion

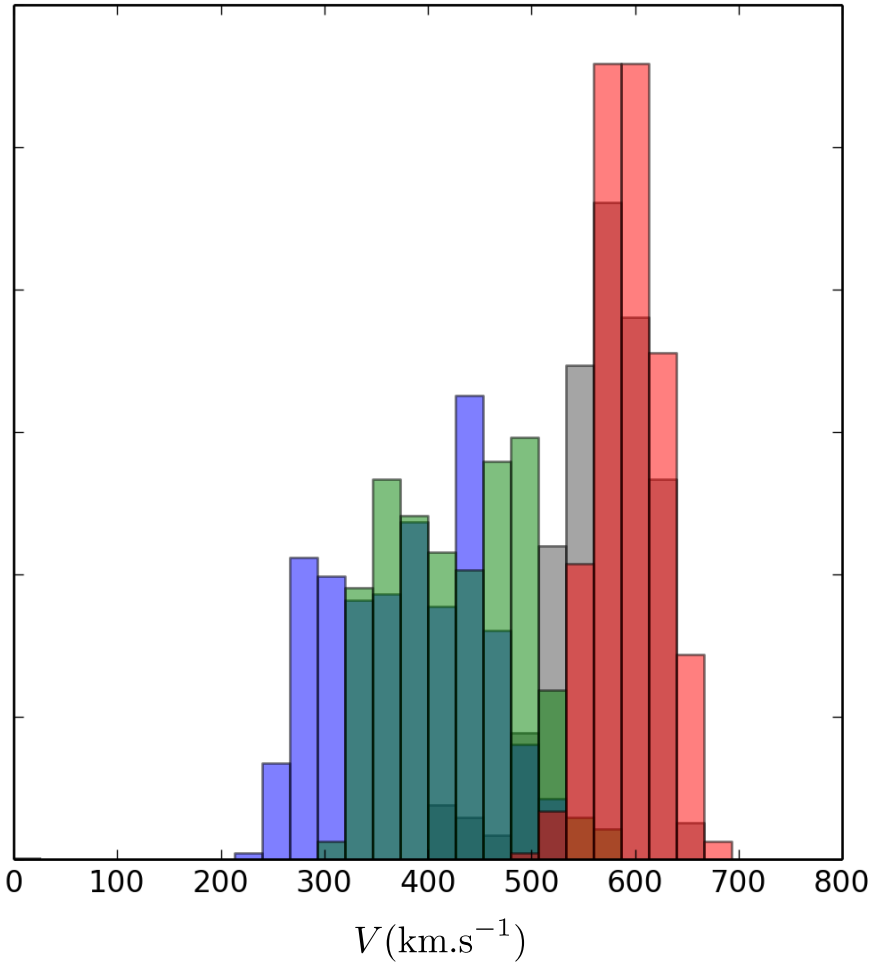
Bulk flows (Cosmic Flows 2.1)



PRELIMINARY

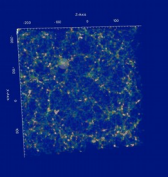


$10h^{-1}$ Mpc
$30h^{-1}$ Mpc
$60h^{-1}$ Mpc
} Gaussian kernel
∞

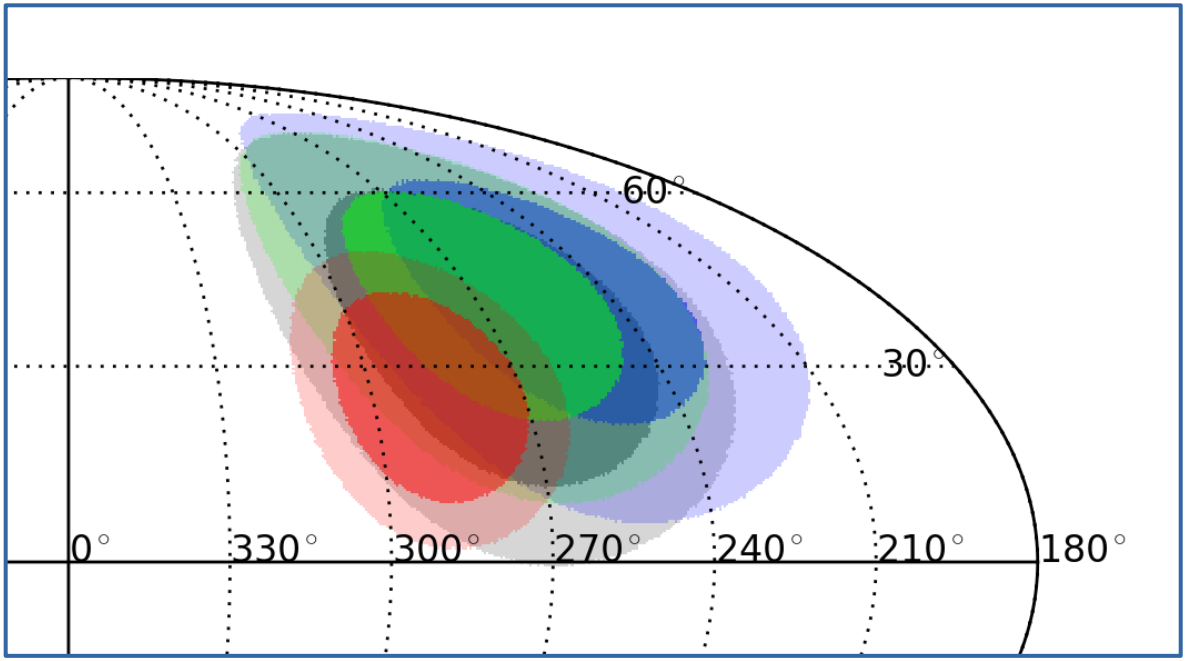


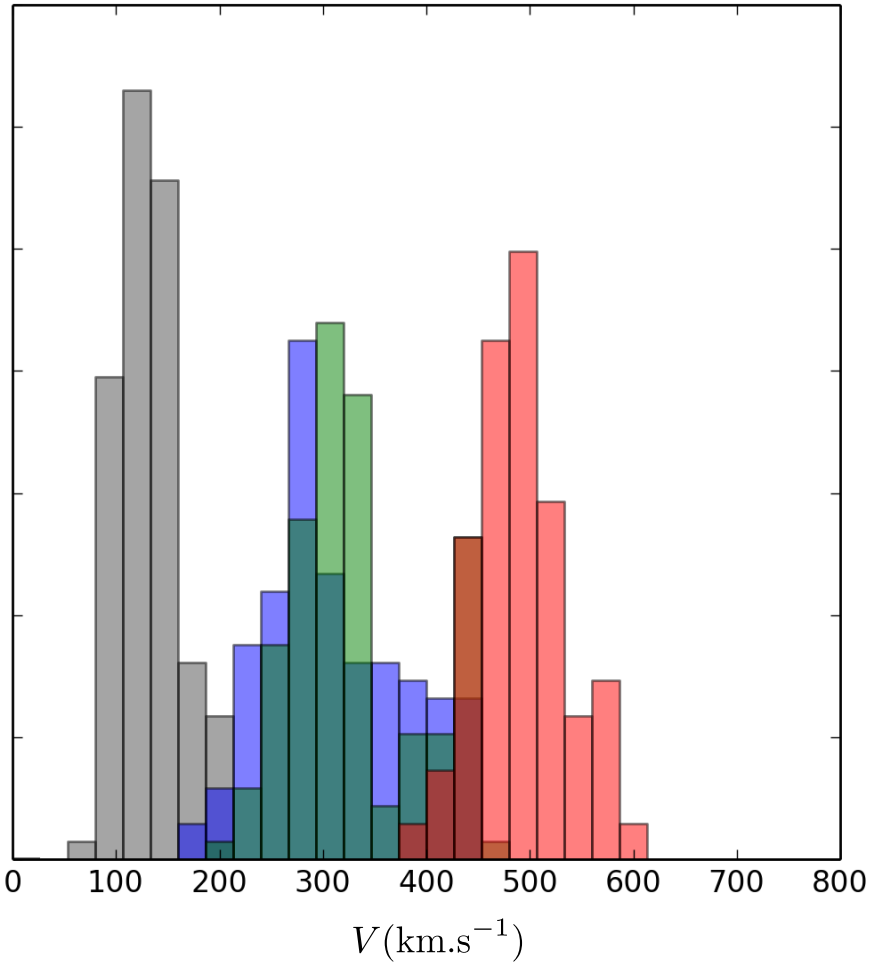
Compatible with Hoffman, Courtois & Tully (2015)

Bulk flows (COMPOSITE)



PRELIMINARY

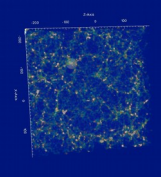




$10h^{-1}$ Mpc
$30h^{-1}$ Mpc
$60h^{-1}$ Mpc
} Gaussian kernel

∞

Conclusion



- ✔ Possibility of finding outliers
- ✔ Consistent analysis of different distance data
- ✔ Hubble constant in CF2.1 is more like ~70 km/s/Mpc
- ✔ Comparison with BORG, similar topology but details are still sorted out
- ✔ BORG3 opens new possibilities of fully non-linear reconstruction, including also distance data

- ✔ Bulk flows still high in CF2.1, not compatible with LCDM
- ✔ COMPOSITE has no residual non-LCDM bulk flow
- ✔ Both surveys compatible in the inner ~60 Mpc/h (Gaussian) region

- ✔ No cosmological parameters fitting yet