

Reconstruction of peculiar velocities of galaxies: methods and application to observations

Guilhem Lavaux

Supervisor:

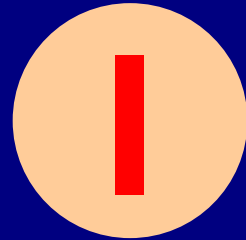
Francis Bernardeau,

Co-supervisor:

Stephane Colombi, Roya Mohayaee, Joseph Silk

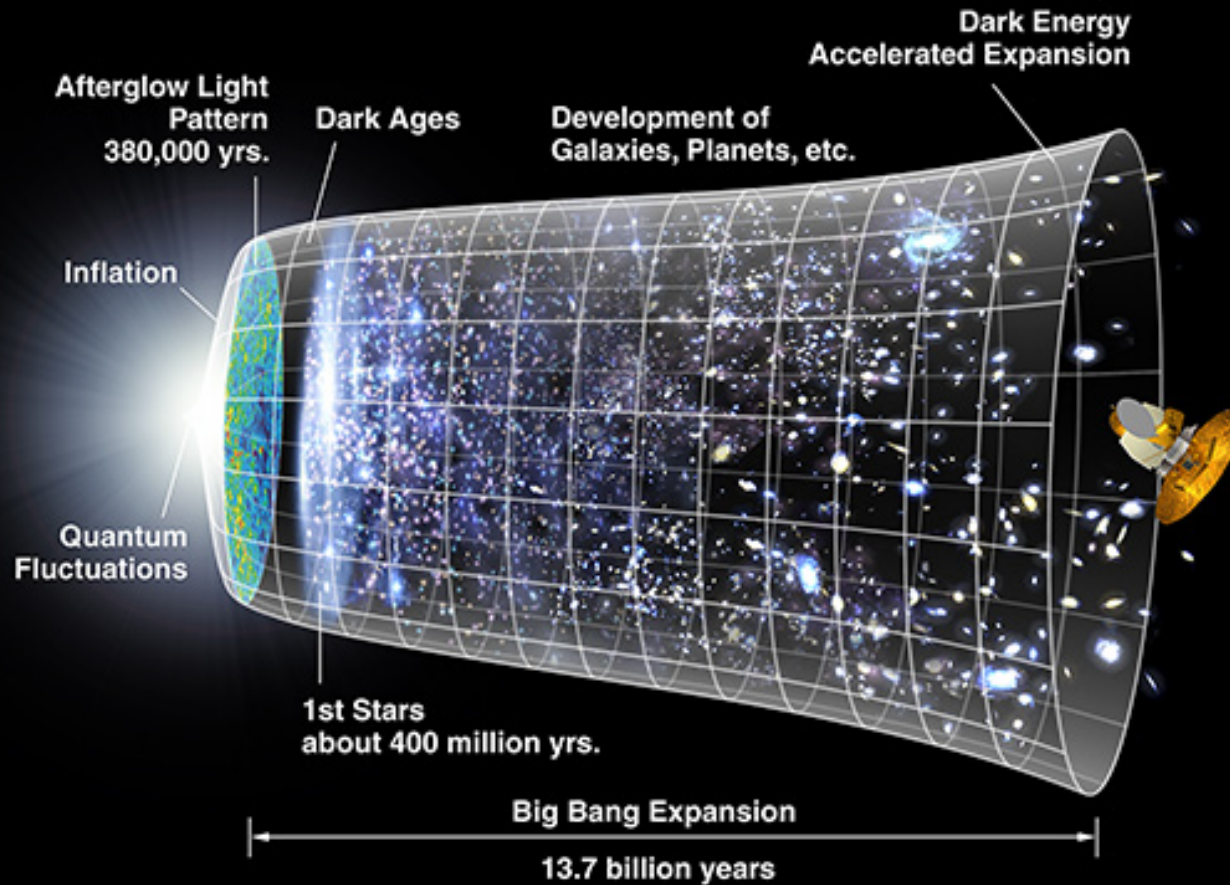
Collaborators:

Brent Tully, John Huchra, Dale Kocevski

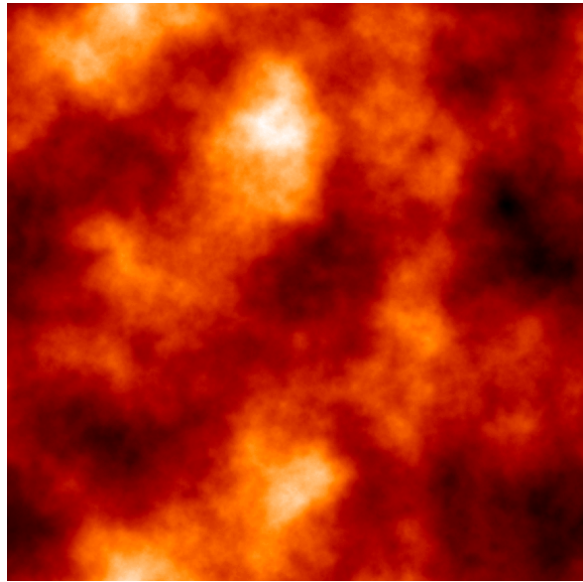


Cosmology, dark matter
and
peculiar velocities

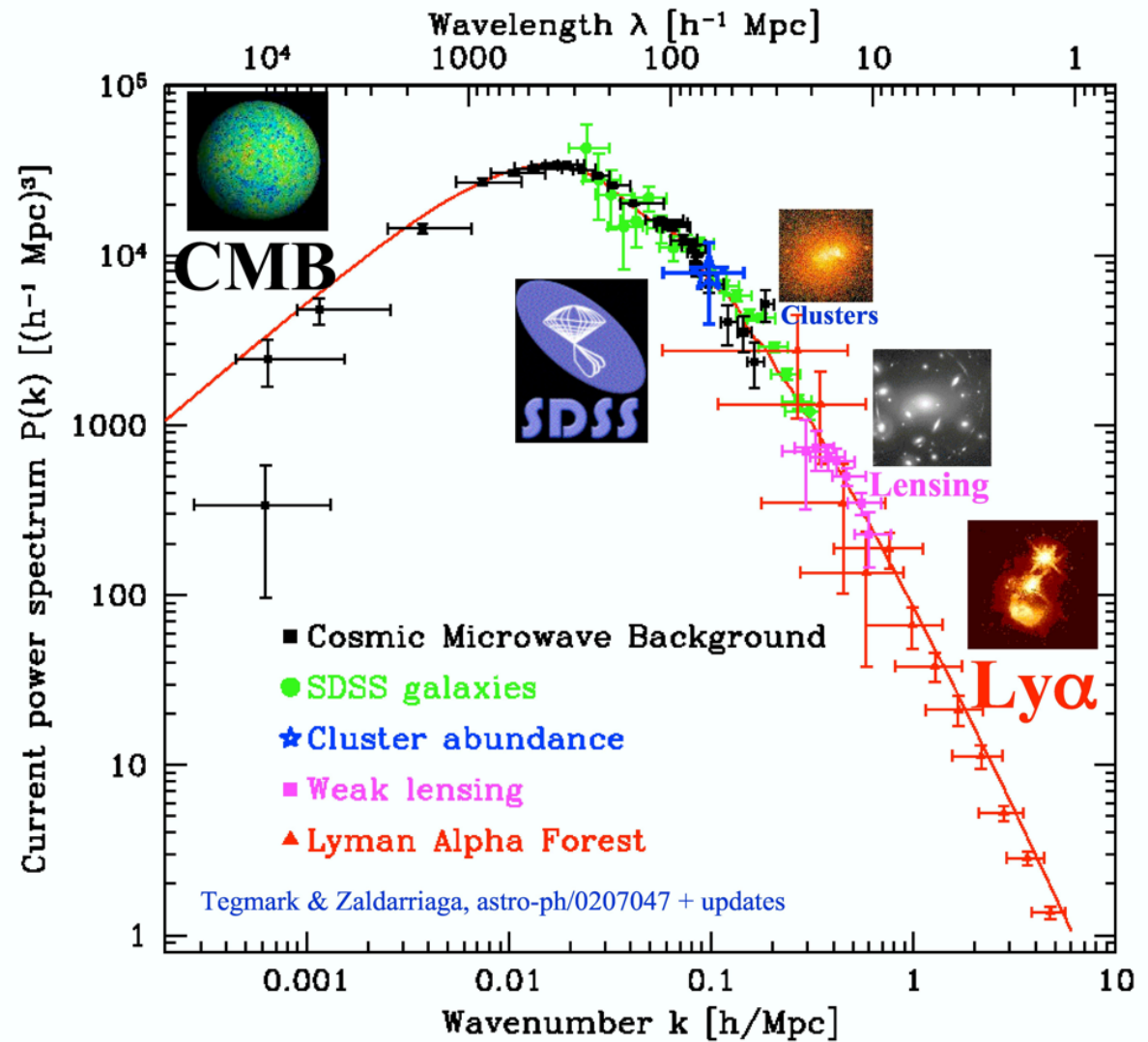
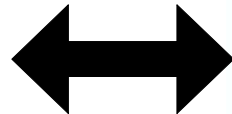
Current cosmological paradigm



Density fluctuations & cosmology

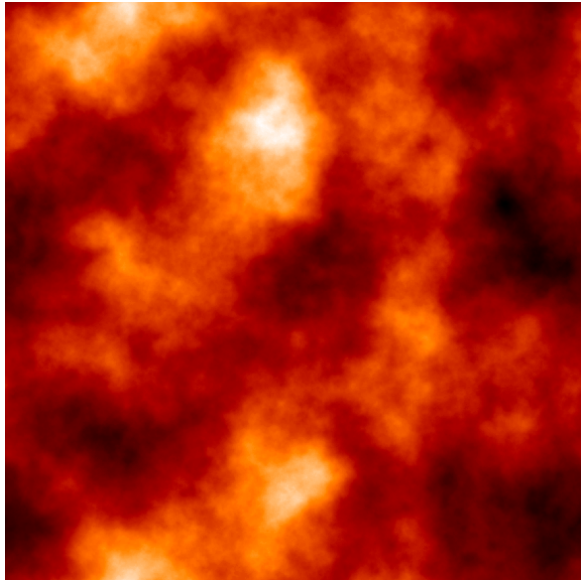


Matter density fluctuations



Power spectrum of matter density fluctuations

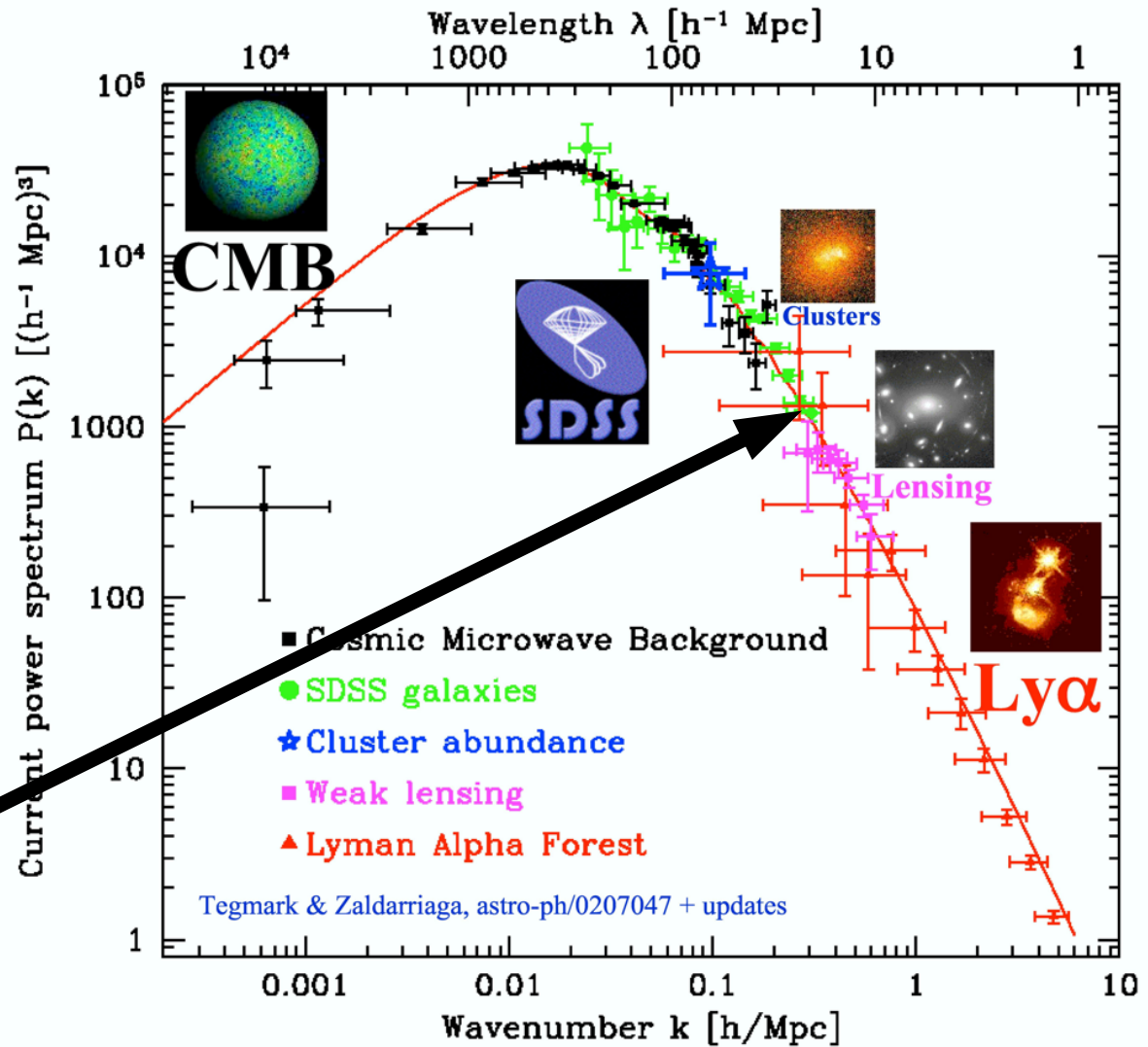
Density fluctuations & cosmology



Matter density fluctuations

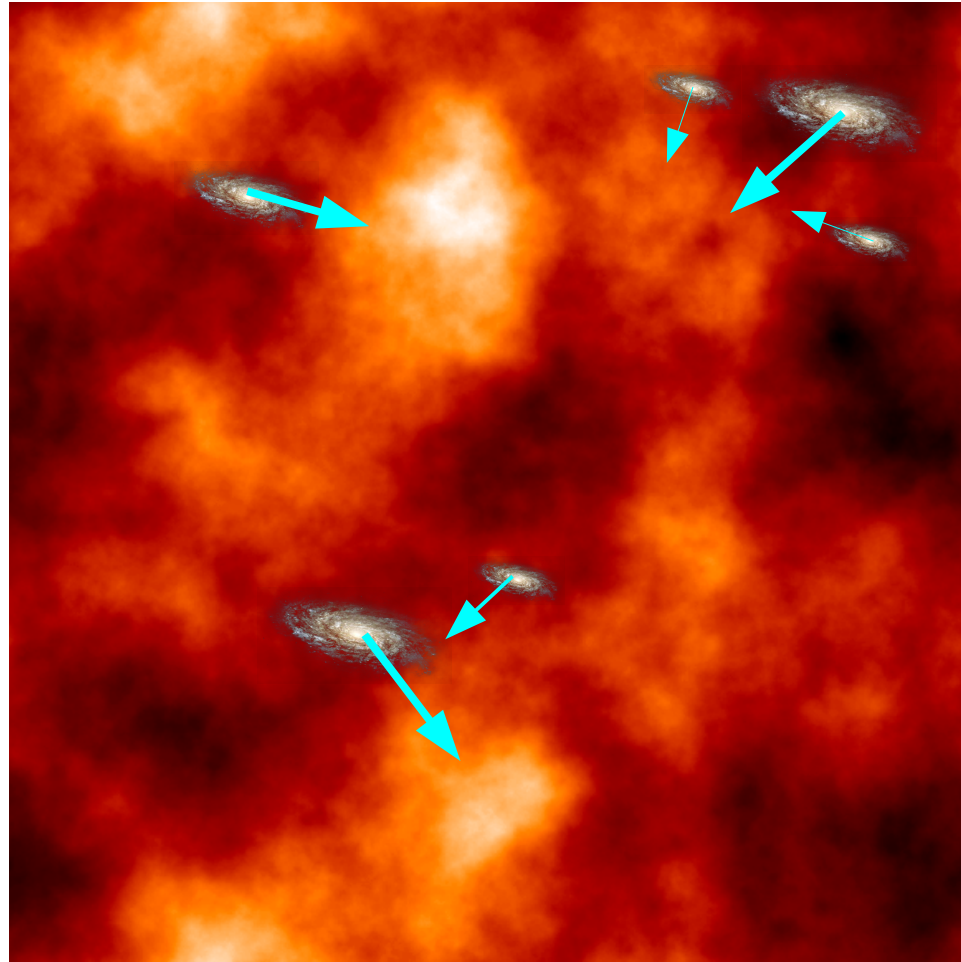


This curve contains most of the information on cosmology



Power spectrum of matter density fluctuations

Why studying velocities ?

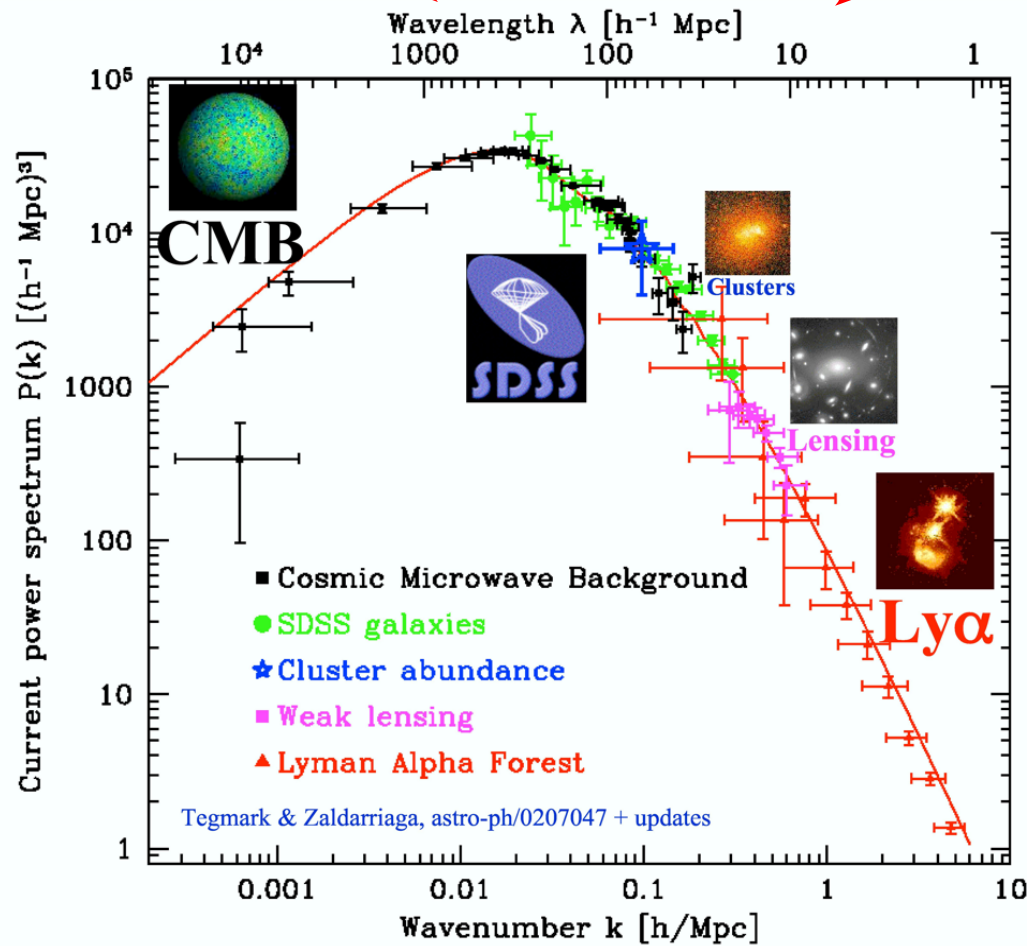


Related to the dynamics and so to the **absolute** matter density

Why studying velocities ?



Scale range where peculiar velocities are interesting



$$\left\langle \left(\frac{\delta v}{v} \right)^2 \right\rangle \propto \int_k P(k) dk$$

$$\left\langle \left(\frac{\delta \rho}{\rho} \right)^2 \right\rangle \propto \int_k P(k) k^2 dk$$

But using peculiar velocities proved to be in practice technically very difficult.

“Measuring” peculiar velocities



Total apparent velocity ($c z$)

Using the Doppler effect on the spectra of galaxies
⇒ the red shift z

+ Hubble constant

Line of sight component of peculiar velocities

$$v_r = c z - H d$$

Distance indicator (d)

- Tully-Fisher
- Tip of the Red Giant Branch
- Surface Brightness Fluctuation
- Fundamental plane
- Cepheids

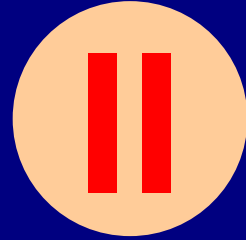
Very difficult to observe in practice !

Outline



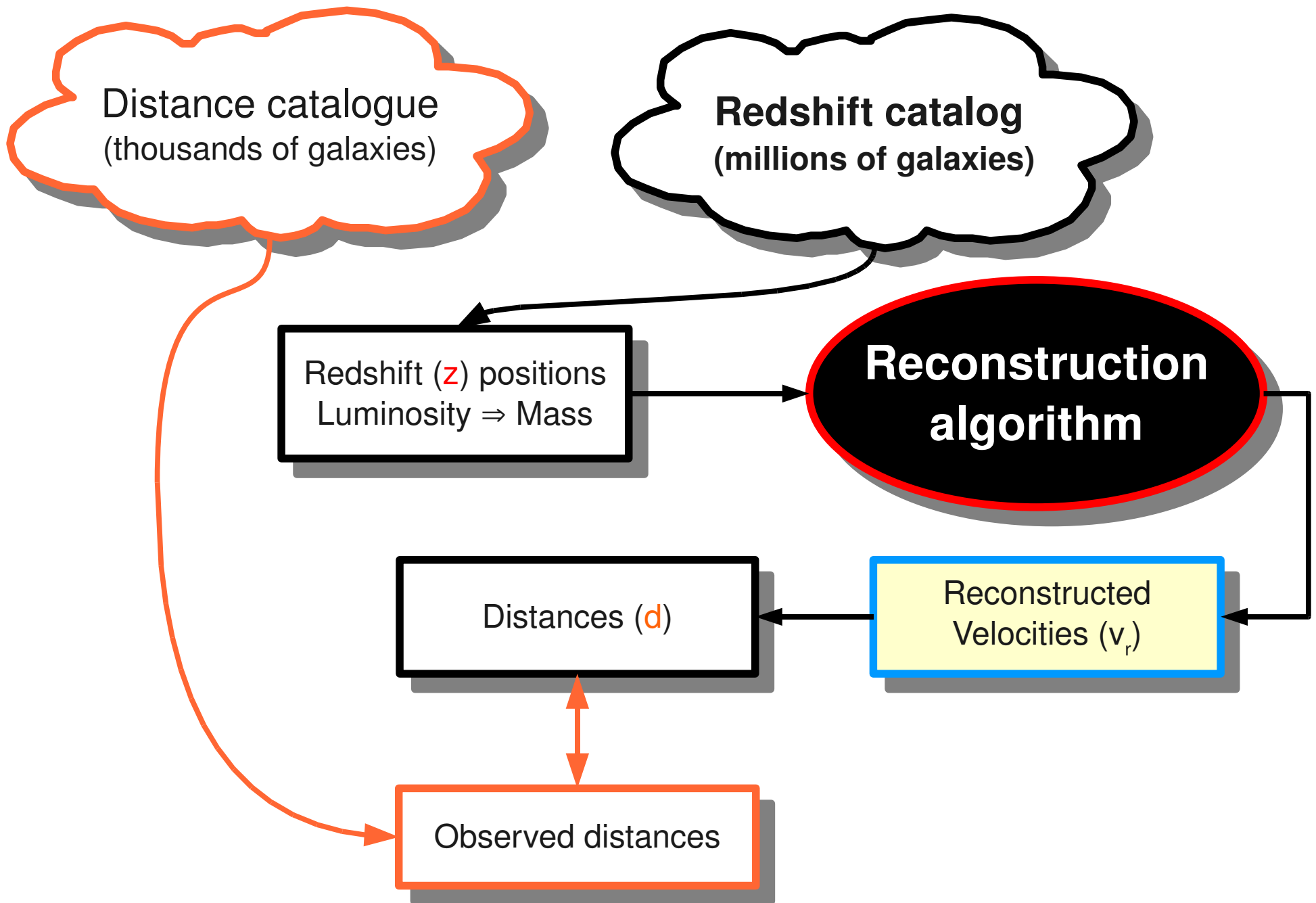
- I Cosmology, dark matter and peculiar velocities
- II Methods of reconstruction
- III Tests of the methods
- IV The peculiar velocities of our Local Universe
- C Conclusion

An alternative approach...



Methods of reconstructions

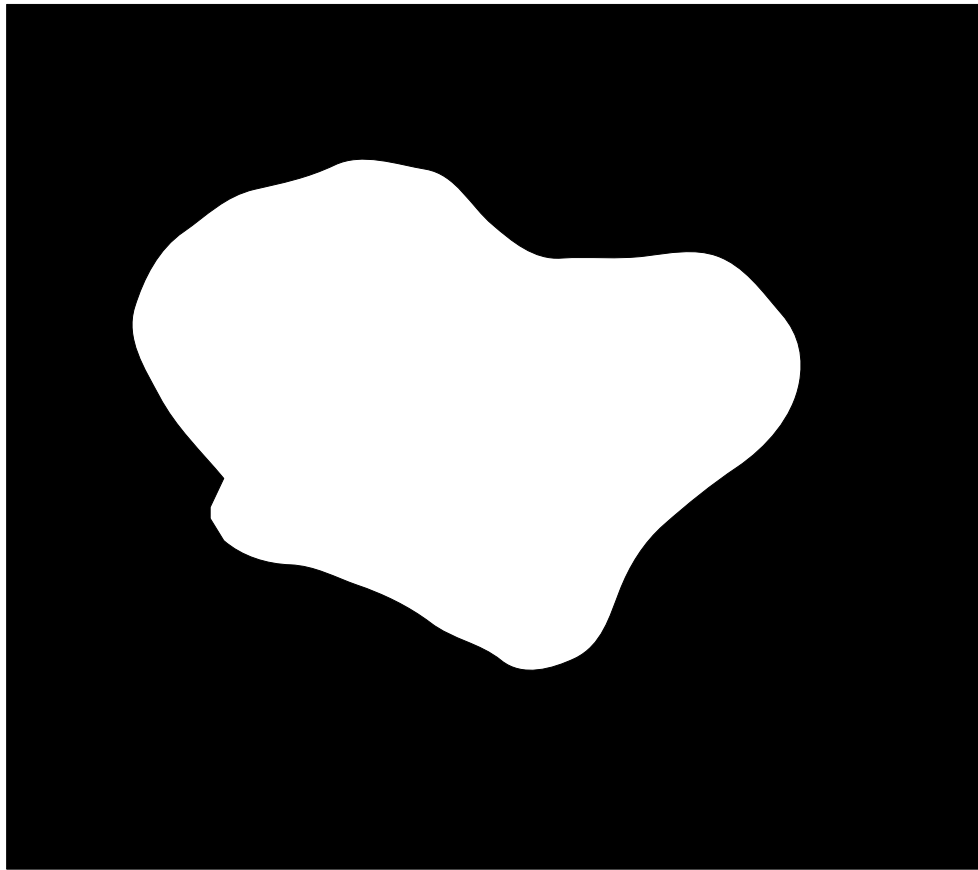
$$c z = H d + v_r$$



Two coordinate systems



Lagrangian coordinates



$t \rightarrow 0$

Eulerian coordinates

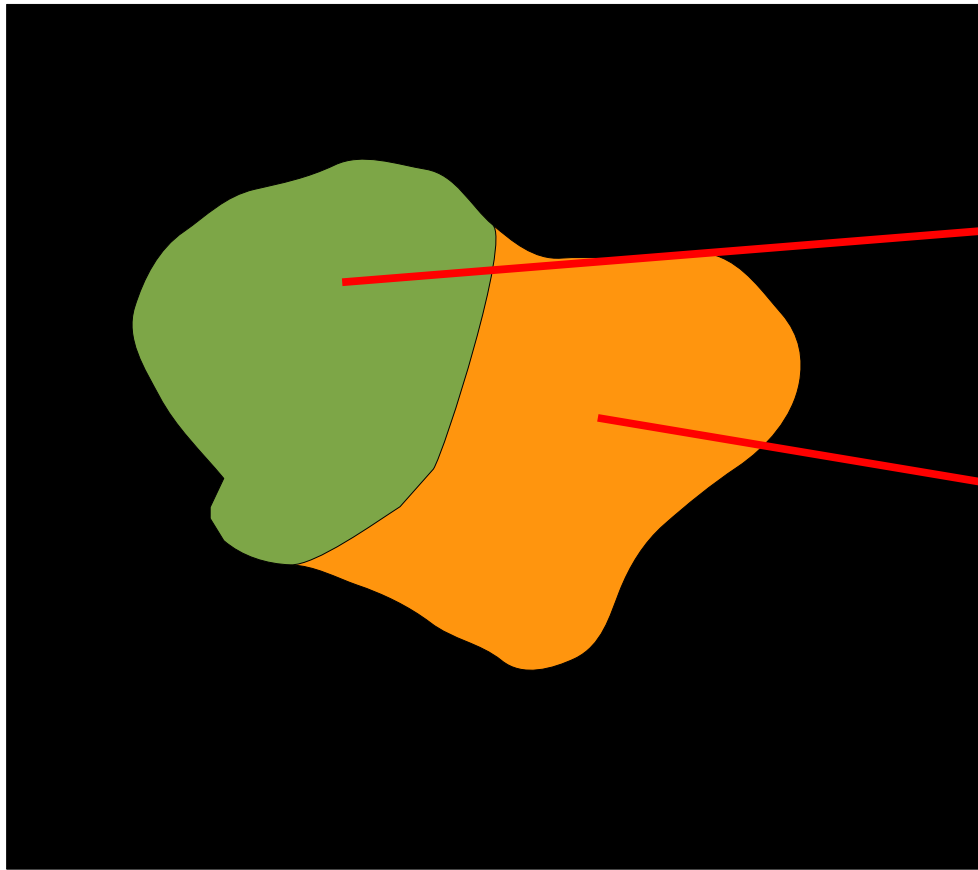


$t = \text{present time}$

Two coordinate systems

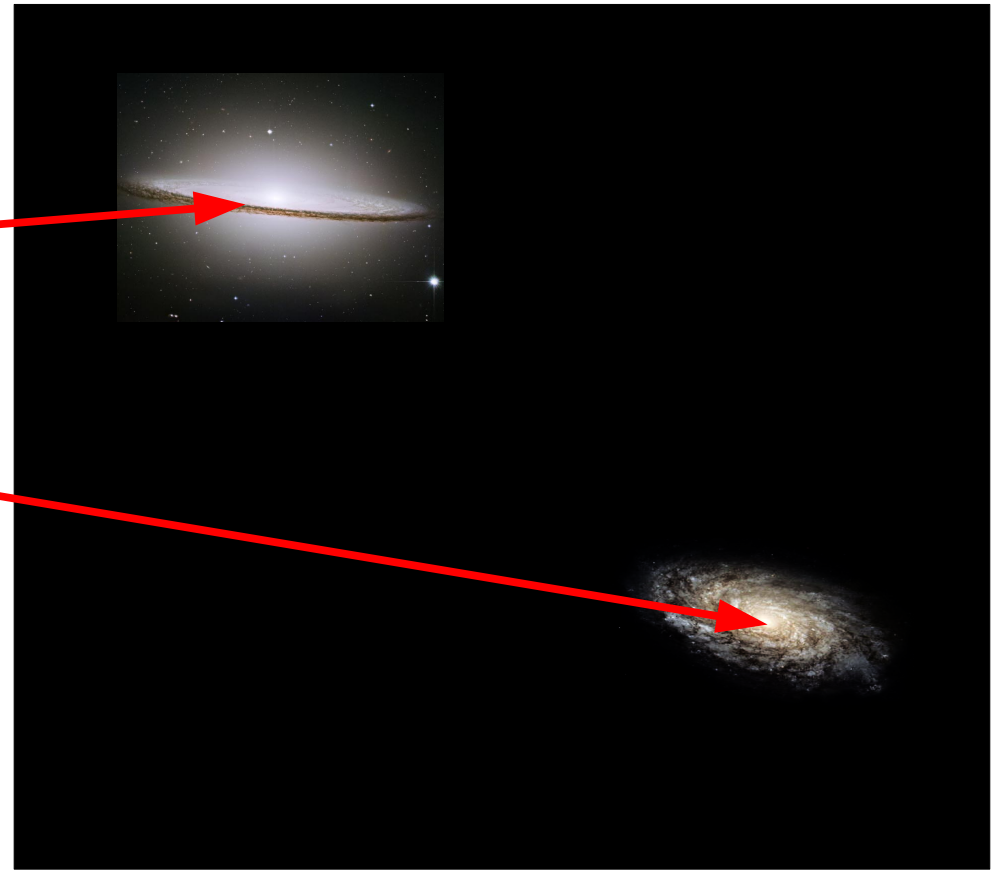


Lagrangian coordinates



$t \rightarrow 0$

Eulerian coordinates

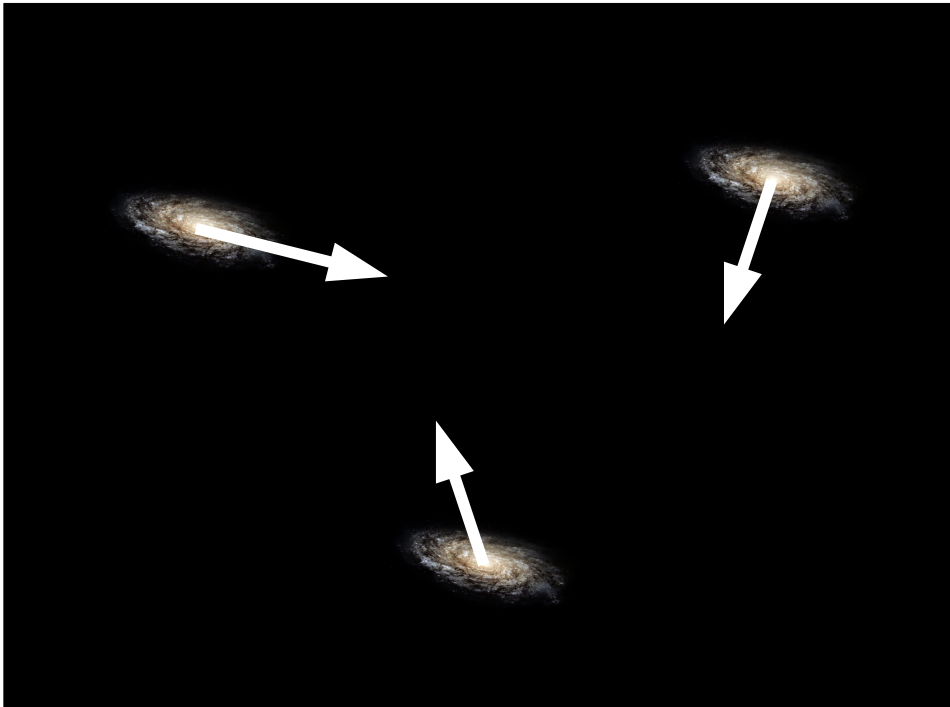


$t = \text{present time}$

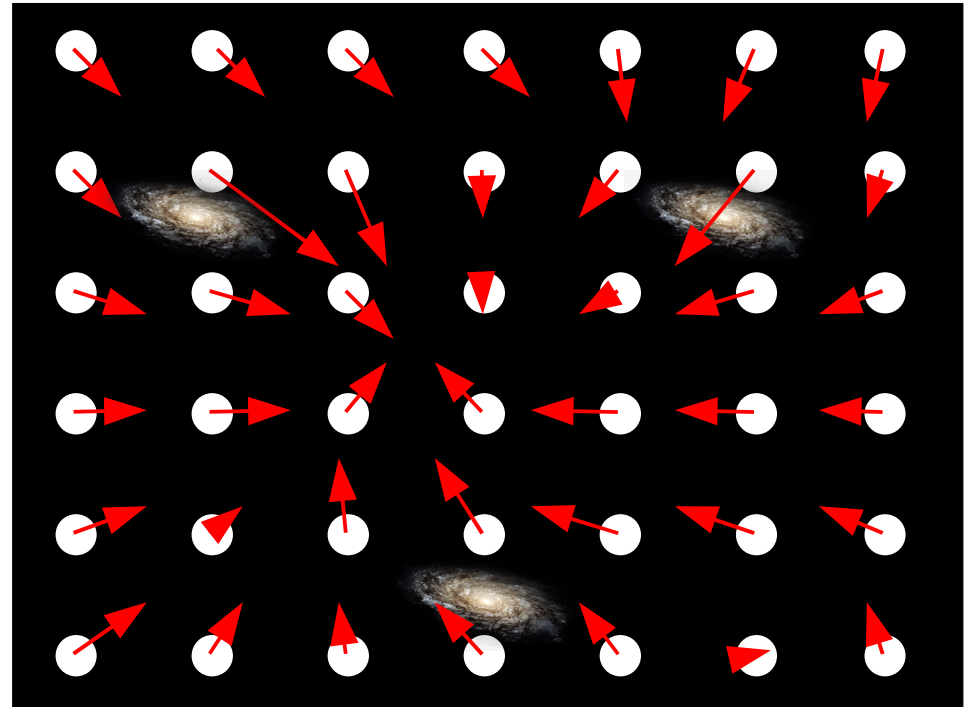
The algorithms



- Lagrangian reconstructions:
 - Least-Action (Peebles 1989)
 - MAK (Monge-Ampère-Kantorovitch) (Brenier et al. 2003, Lavaux et al. 2008a)



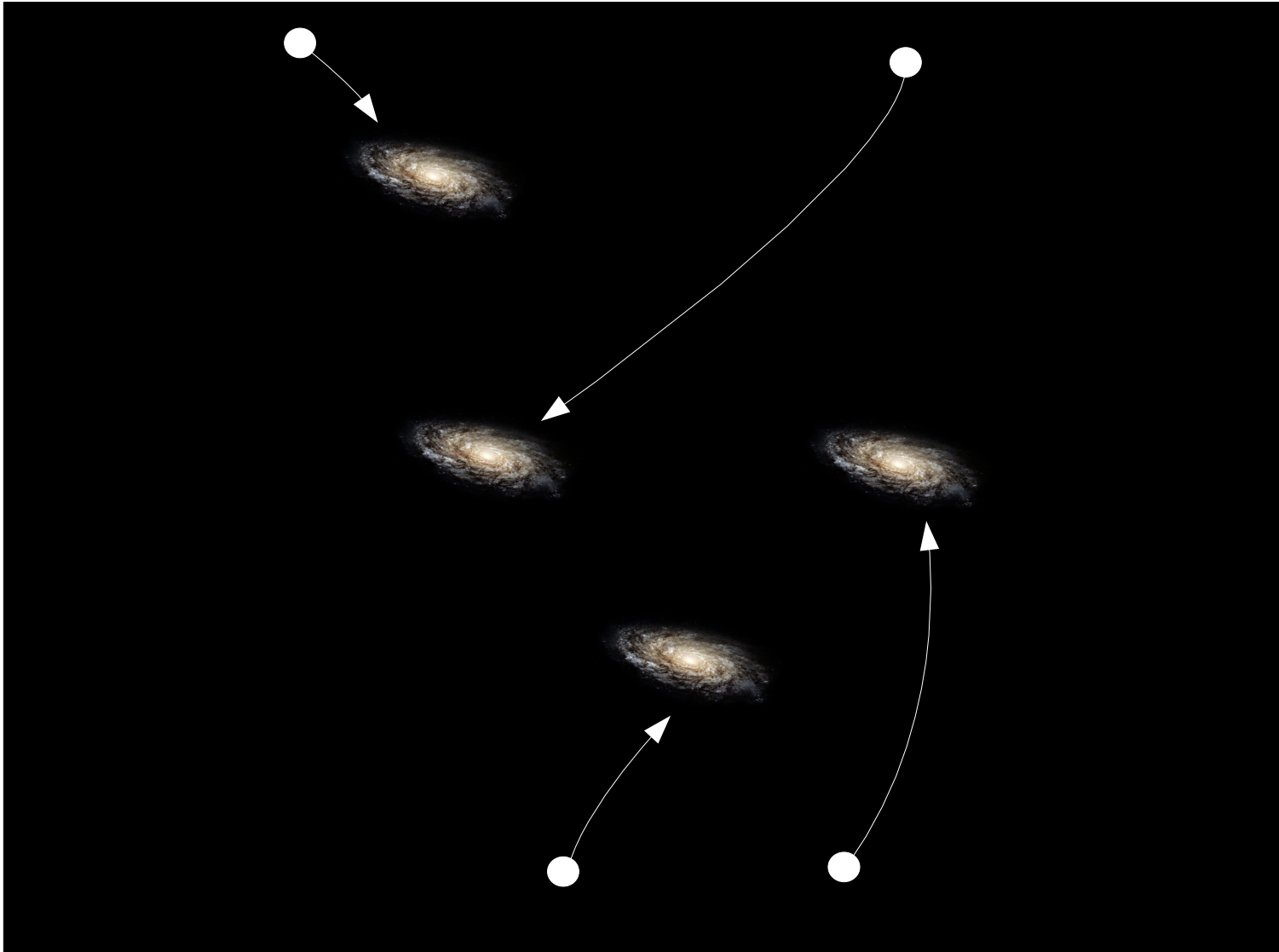
- Eulerian reconstructions (e.g. POTENT Bertschinger&Dekel 1989)



The MAK reconstruction



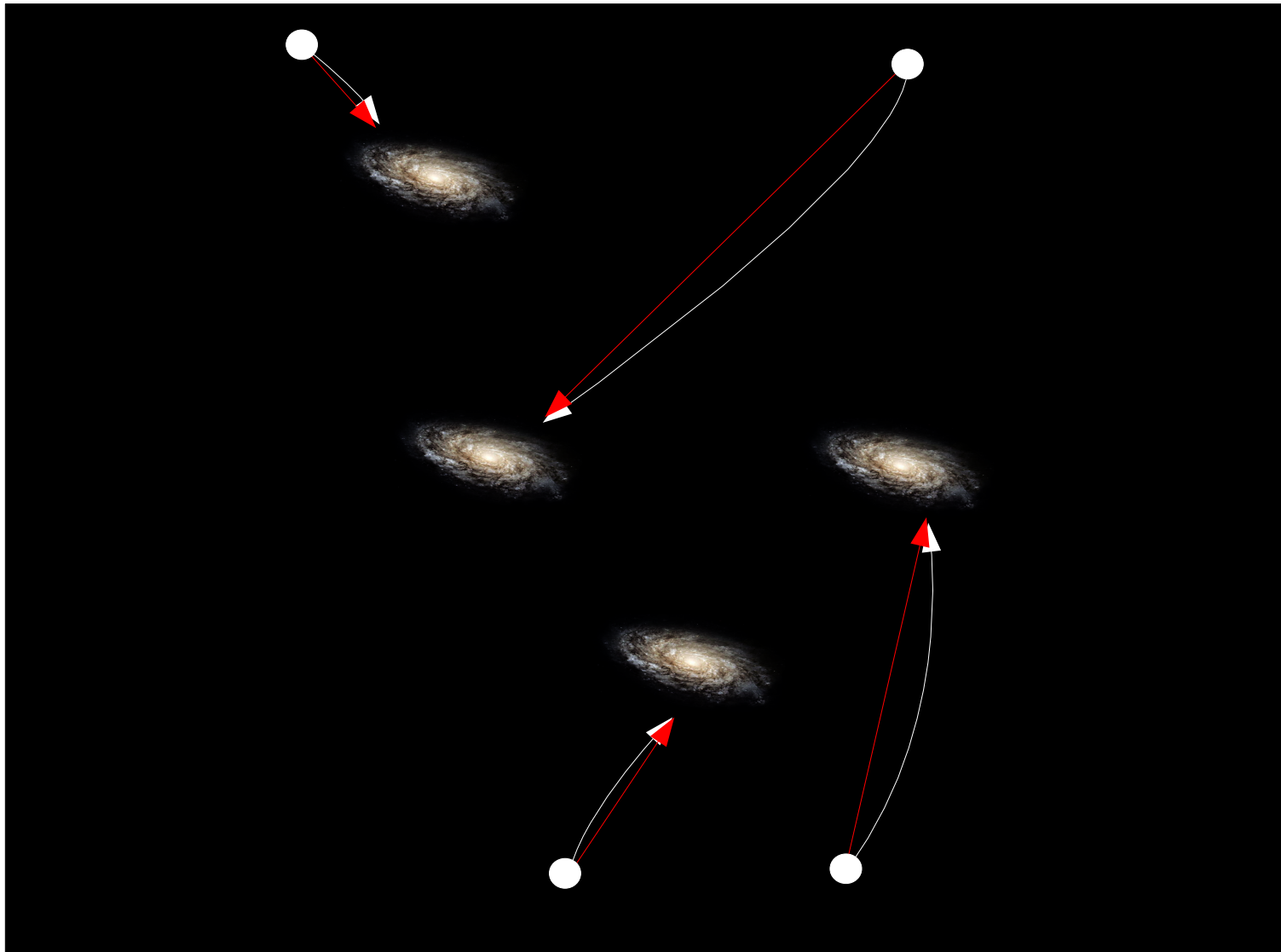
The true galaxy orbits



The MAK reconstruction



The **MAK** displacements



Comoving coordinates

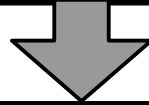
Hypothesis displacement field is convex potential \Leftrightarrow **no** shell crossing

motivated by Lagrangian perturbation theory, N-body simulation

+ Mass conservation

Hypothesis displacement field is convex potential \Leftrightarrow **no** shell crossing
motivated by Lagrangian perturbation theory, N-body simulation

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Brenier et al. 2003

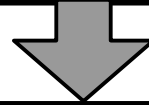
Monge-Ampère problem:
$$\left| \frac{\partial^2 \Phi}{\partial x_i \partial x_j} \right|_{i,j} = \frac{\rho(\mathbf{x})}{\rho_0}$$



Monge-Kantorovich problem:
$$I[\mathbf{q}(\mathbf{x})] = \int \rho(\mathbf{x}) |\mathbf{x} - \mathbf{q}(\mathbf{x})|^2 d^3 \mathbf{x}$$

Hypothesis displacement field is convex potential \Leftrightarrow **no** shell crossing
motivated by Lagrangian perturbation theory, N-body simulation

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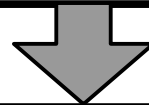


Brenier et al. 2003

Monge-Ampère problem: $\left. \frac{\partial^2 \Phi}{\partial x_i \partial x_j} \right|_{i,j} = \frac{\rho(\mathbf{x})}{\rho_0}$



Monge-Kantorovitch problem: $I[\mathbf{q}(\mathbf{x})] = \int \rho(\mathbf{x}) |\mathbf{x} - \mathbf{q}(\mathbf{x})|^2 d^3 \mathbf{x}$



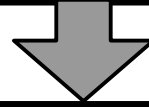
Discretization: $S_\sigma = \sum_i (\mathbf{x}_i - \mathbf{q}_{\sigma(i)})^2 \sim$ Inertial least-action principle



Gravity effects are yet included

Hypothesis displacement field is convex potential \Leftrightarrow **no** shell crossing
motivated by Lagrangian perturbation theory, N-body simulation

+ Mass conservation

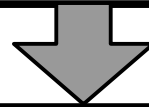


Brenier et al. 2003

Monge-Ampère problem: $\left. \frac{\partial^2 \Phi}{\partial x_i \partial x_j} \right|_{i,j} = \frac{\rho(\mathbf{x})}{\rho_0}$



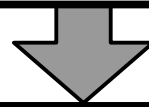
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Discretization: $S_\sigma = \sum_i (\mathbf{x}_i - \mathbf{q}_{\sigma(i)})^2 \sim$ Inertial least-action principle



Gravity effects are yet included



Zel'dovich approximation: $\mathbf{v}_i = H\beta(\mathbf{x}_i - \mathbf{q}_i)$ with $\beta \approx \Omega_m^{5/9}$

Only dependence on cosmology

Algorithmic

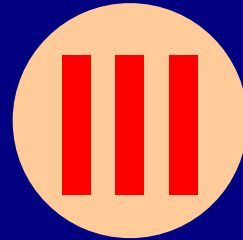


- Direct solving of the minimization problem is practically impossible ($O(N!)$ time complexity).

Algorithmic



- Direct solving of the minimization problem is practically impossible ($O(N!)$ time complexity).
- Use a better algorithm developed by Dimitri Bertsekas (originally to solve economics problem). $\Rightarrow O(N^{2.25})$ time complexity.
- MPI/OpenMP implementation (publicly available later on <http://www.iap.fr/users/lavaux/>)



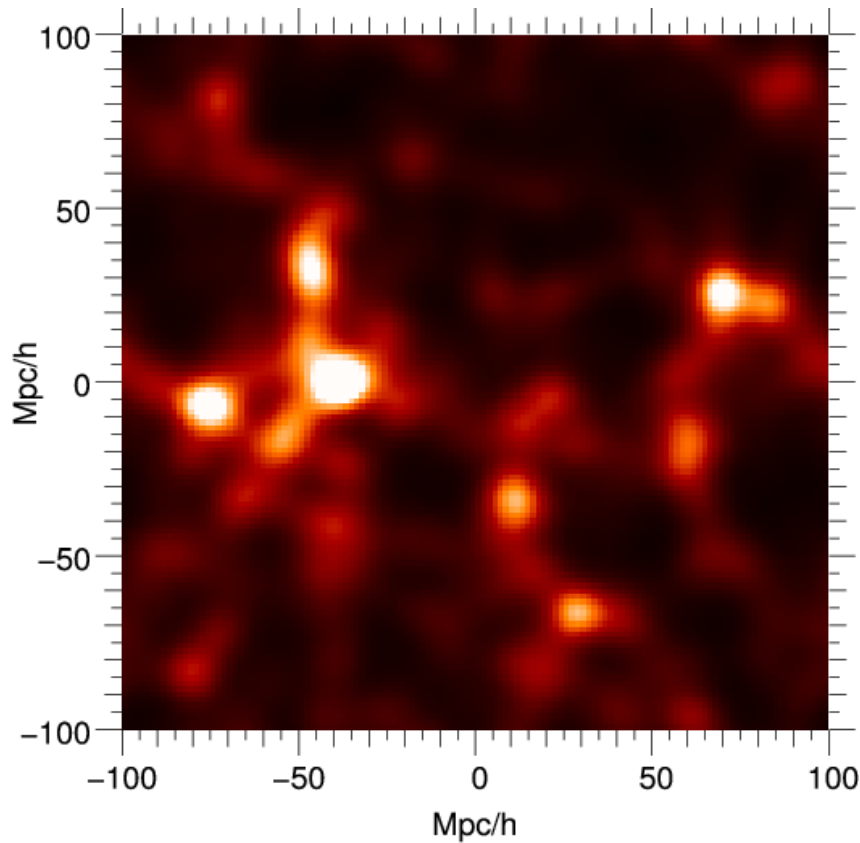
Test of
the Monge-Ampère-Kantorovitch
reconstruction

Direct testing on simulation

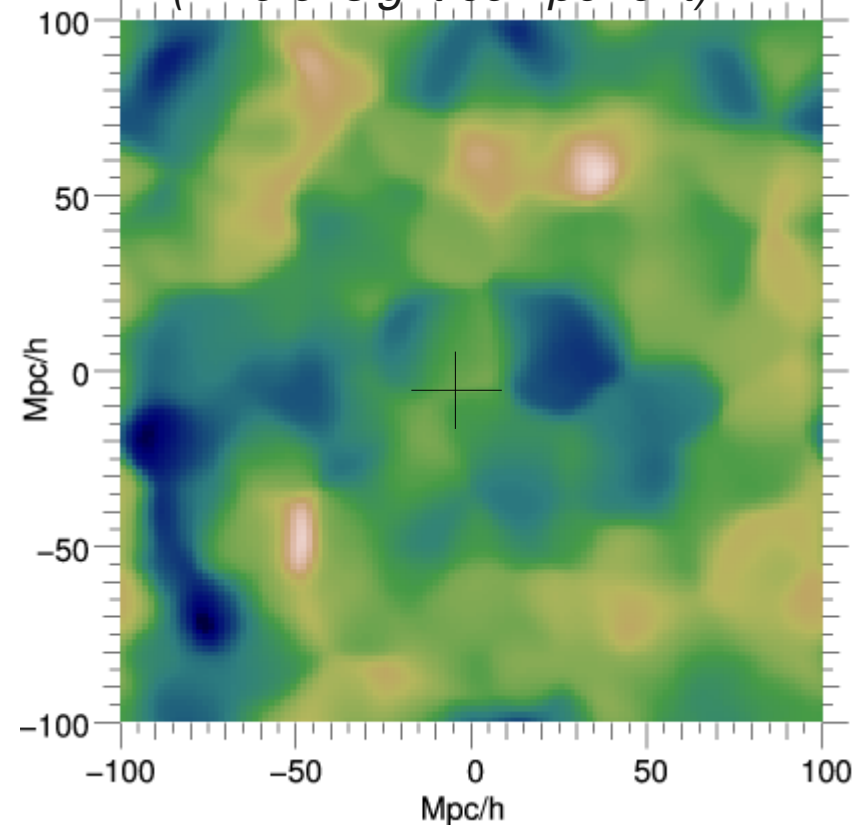


Simulation

Density field



Simulated velocity field
(Line of sight component)



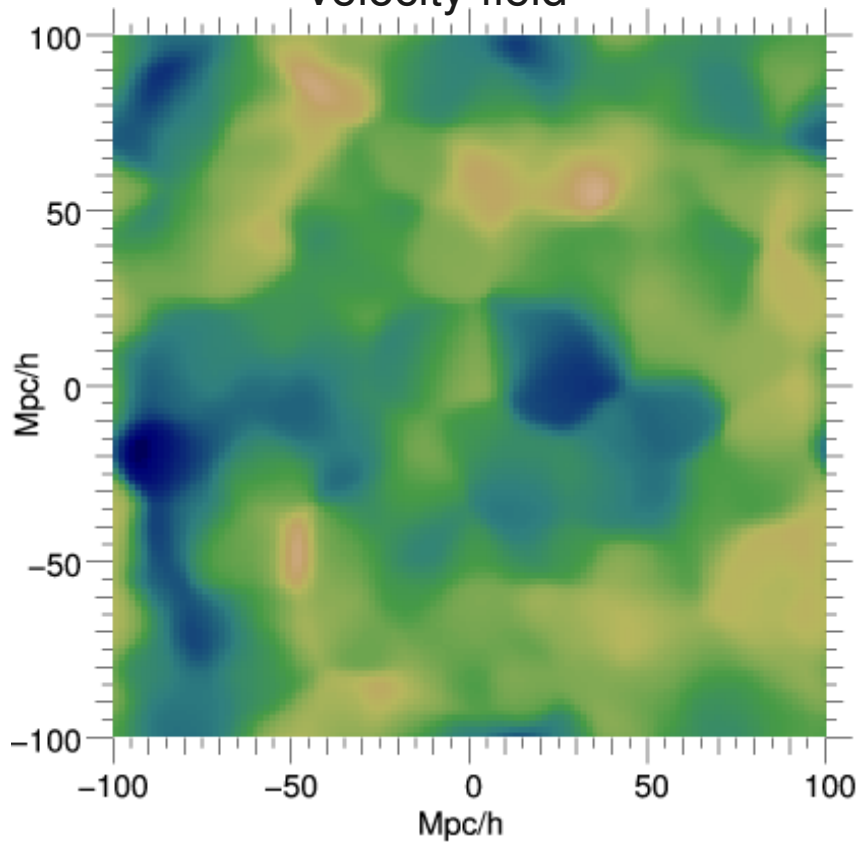
Brenier et al. 2003
Mohayaee et al. 2005
Lavaux et al., MNRAS, 2008

Λ CDM $\Omega_M=0.30$, $\Omega_\Lambda = 0.70$, $\sigma_8=1.0$, BBKS power spectrum
128³ particles (but results do not change with a 512³)

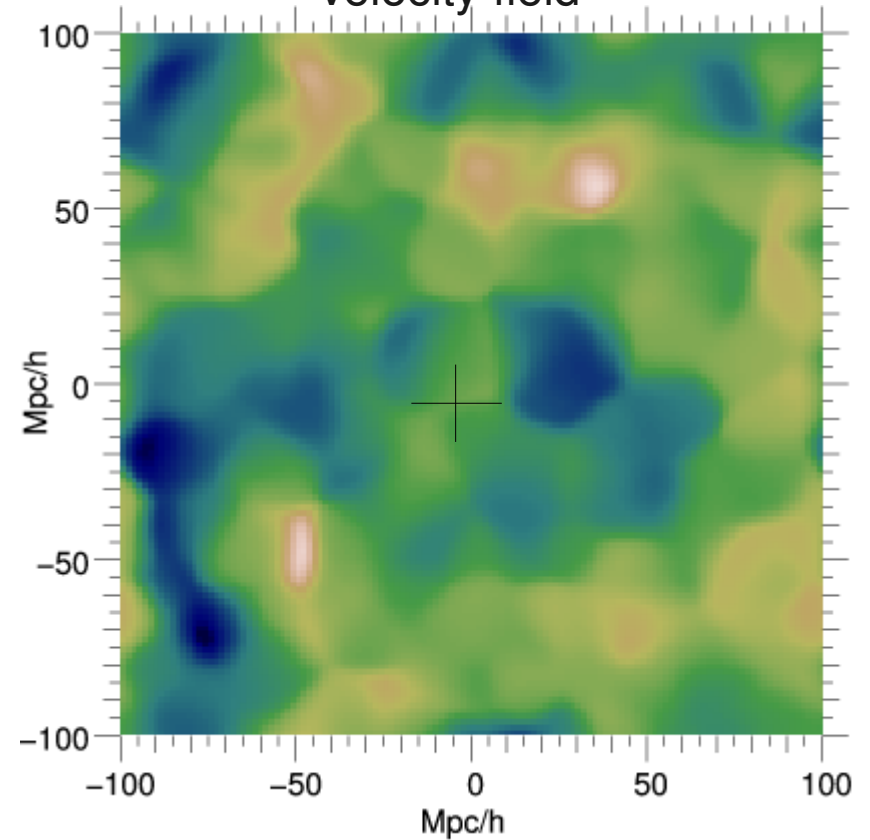
Direct testing on simulation



**Reconstructed
velocity field**



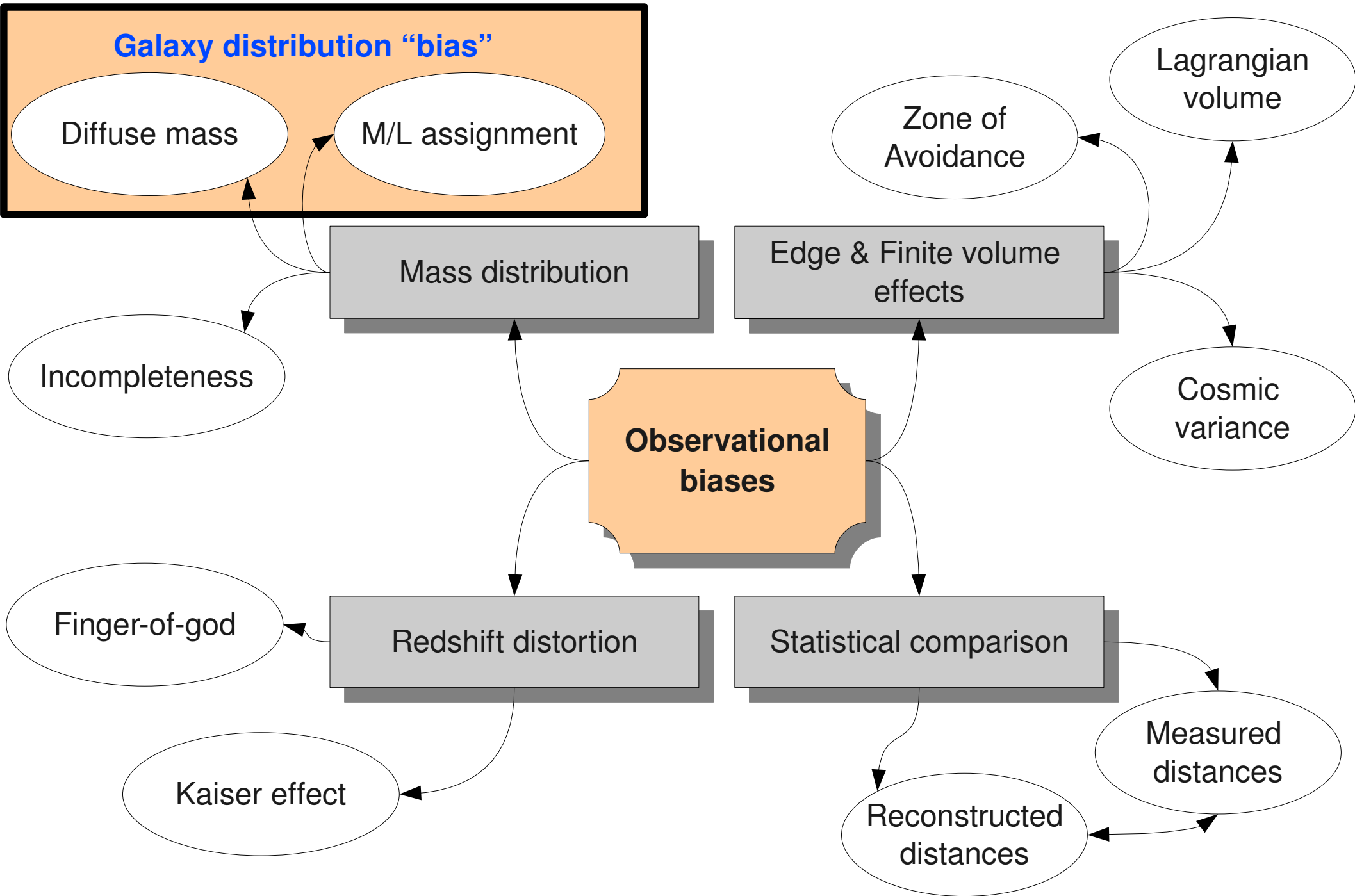
**Simulated
velocity field**



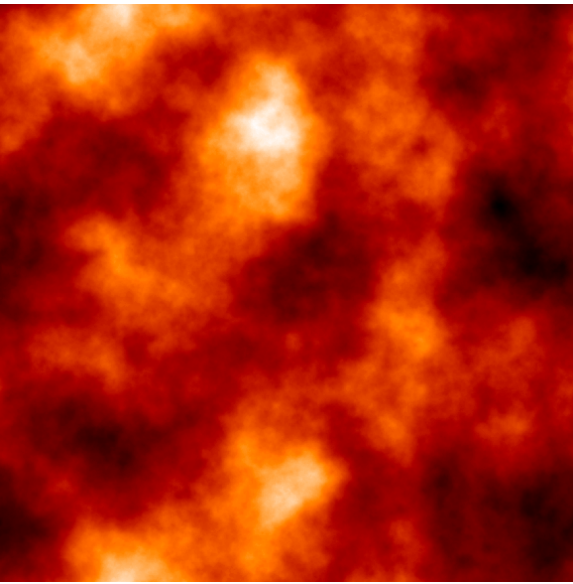
Brenier et al. 2003

Mohayaee et al. 2005

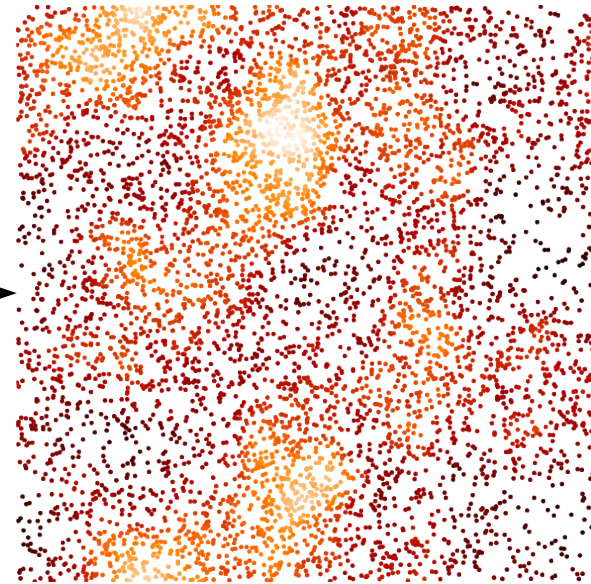
Lavaux et al., MNRAS, **383**, 1292 (2008)



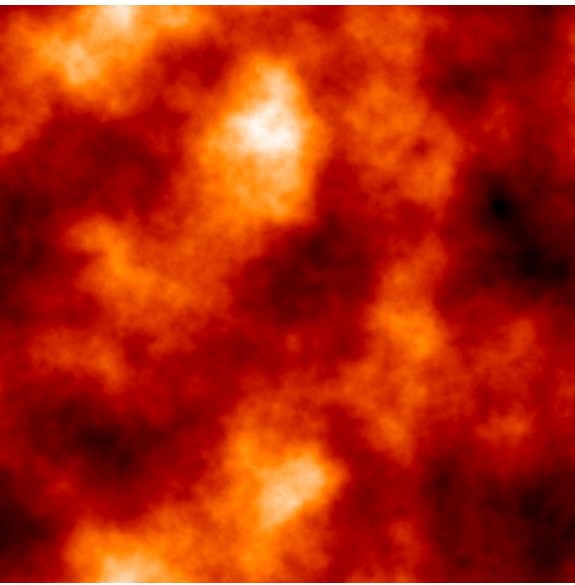
Distribution of mass



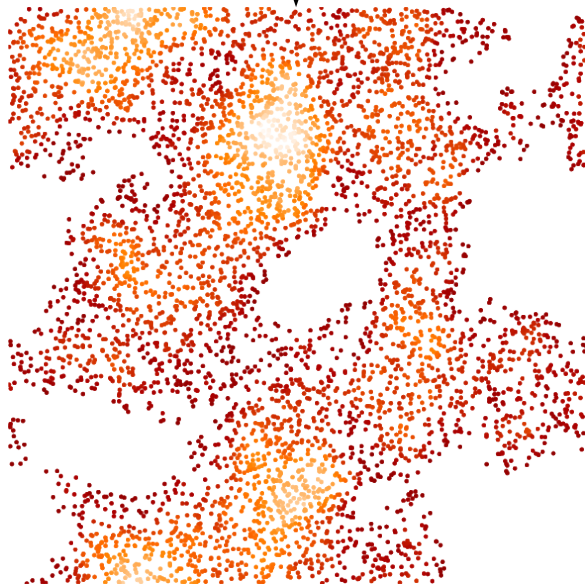
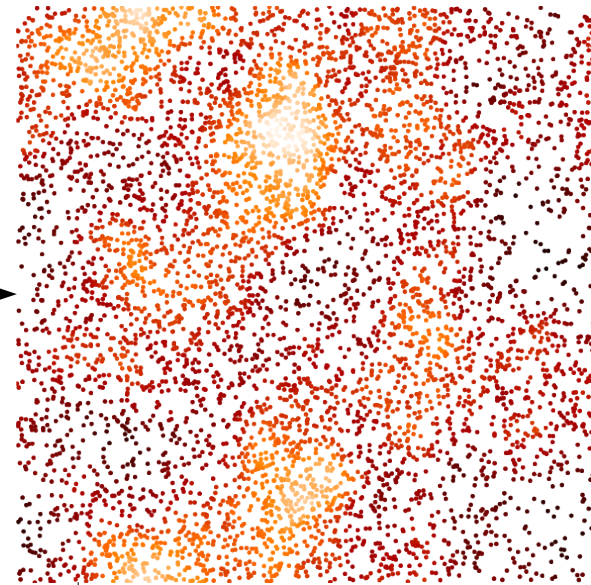
“Galaxy sampling”



Distribution of mass

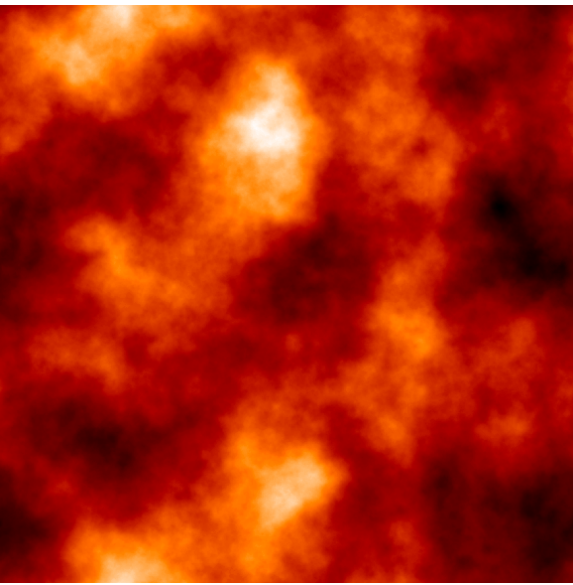


“Galaxy sampling”

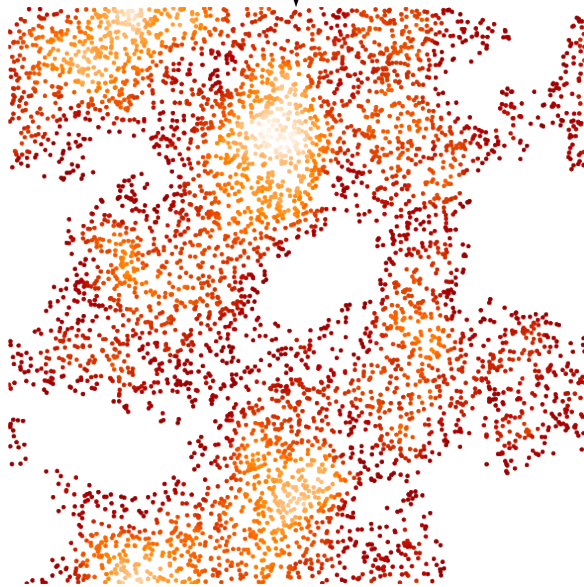
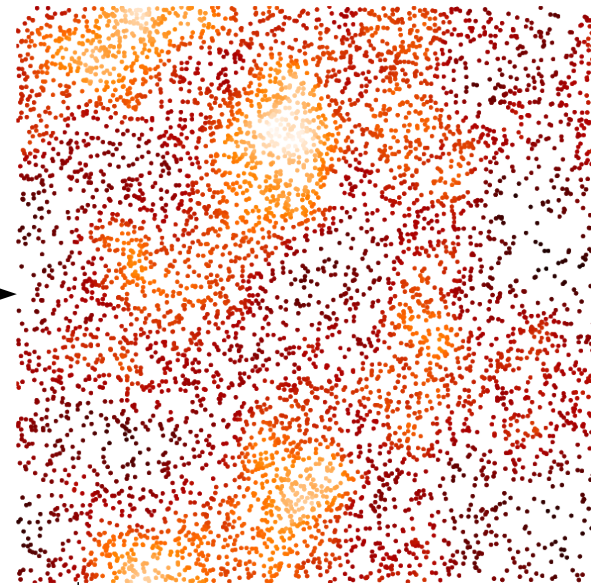


Diffuse mass

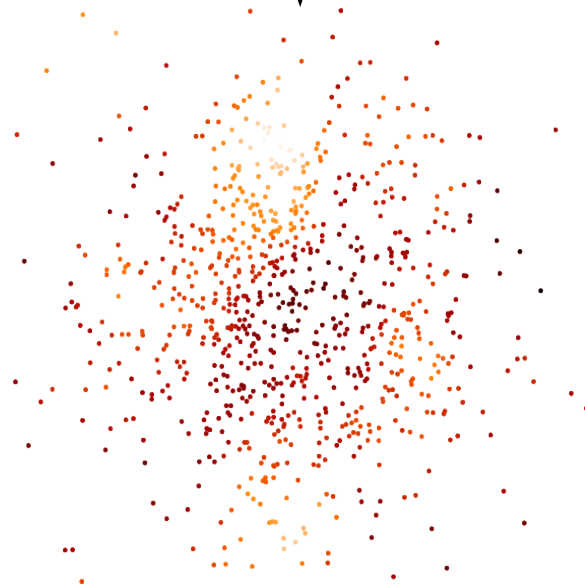
Distribution of mass



“Galaxy sampling”

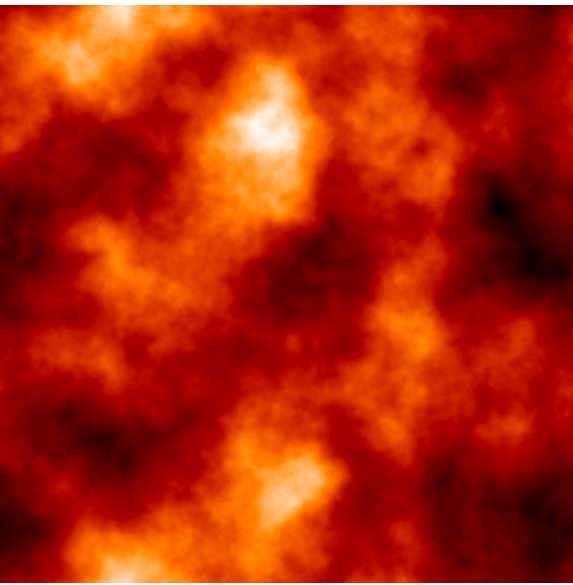


Diffuse mass

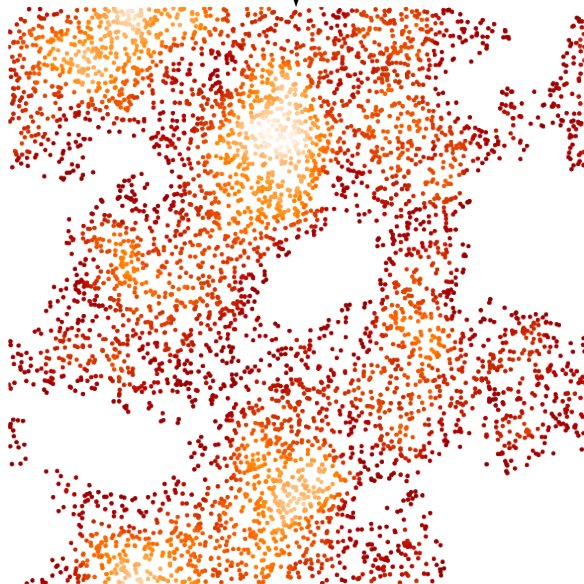
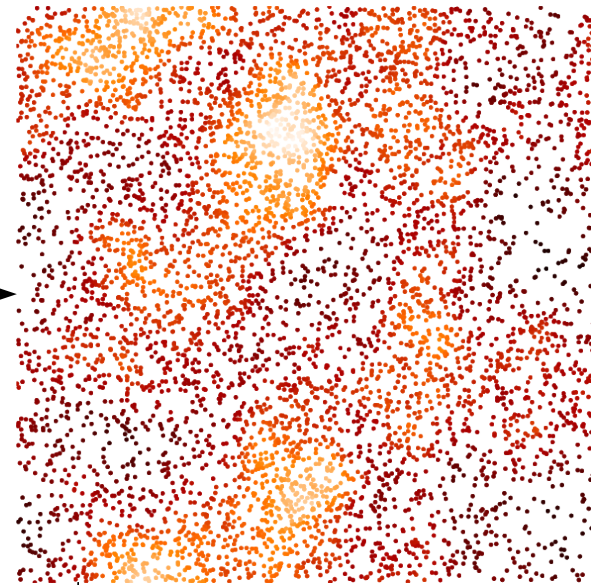


Incompleteness

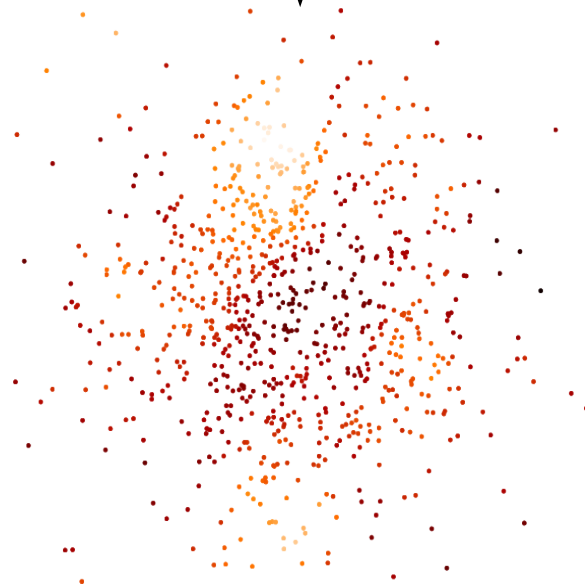
Distribution of mass



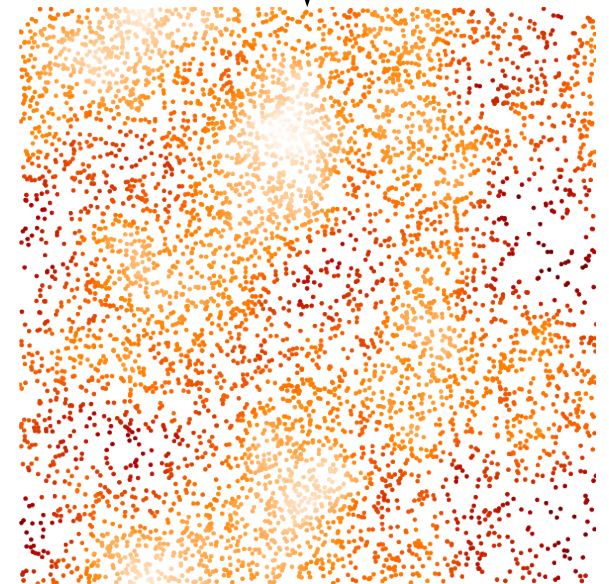
“Galaxy sampling”



Diffuse mass

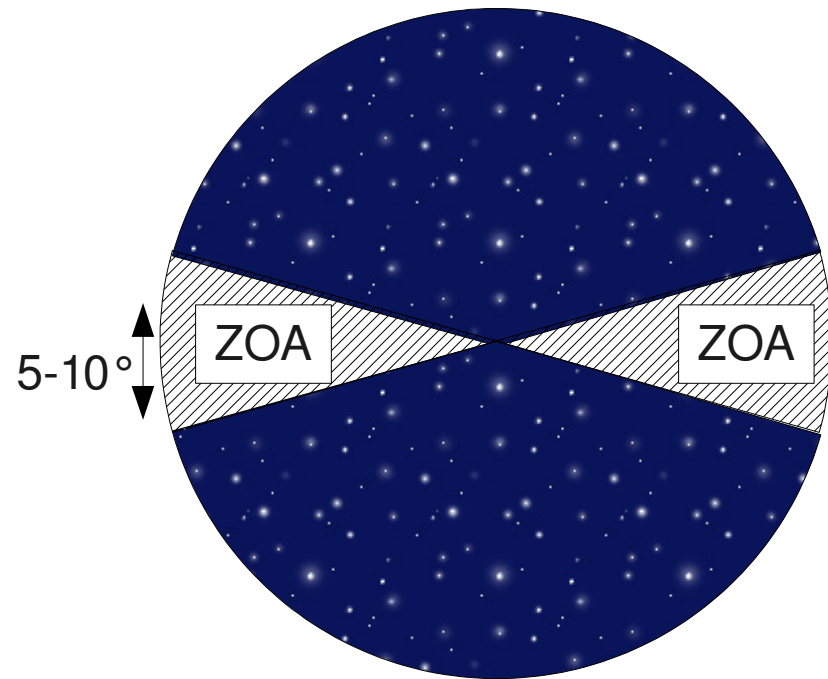
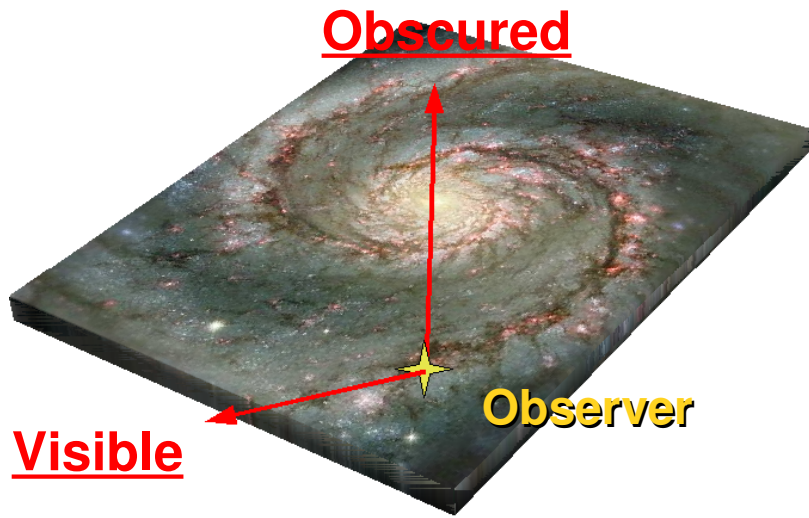


Incompleteness



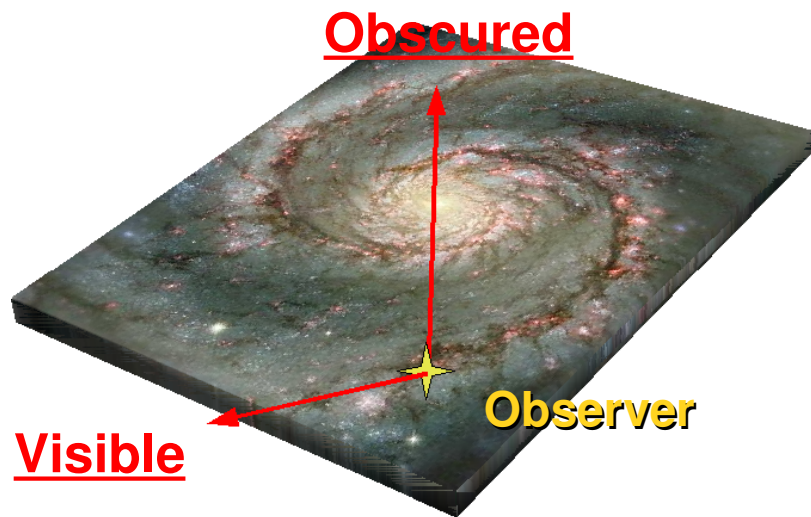
M/L

Edge & Finite volume effects

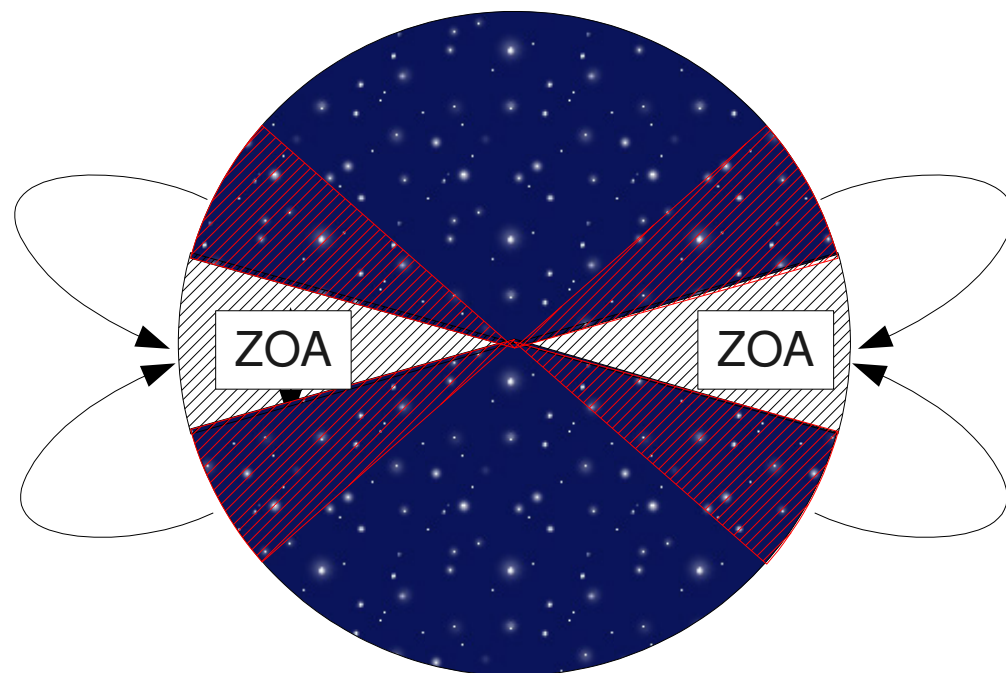


Zone of Avoidance

Edge & Finite volume effects



Objects folding into the cleared ZOA

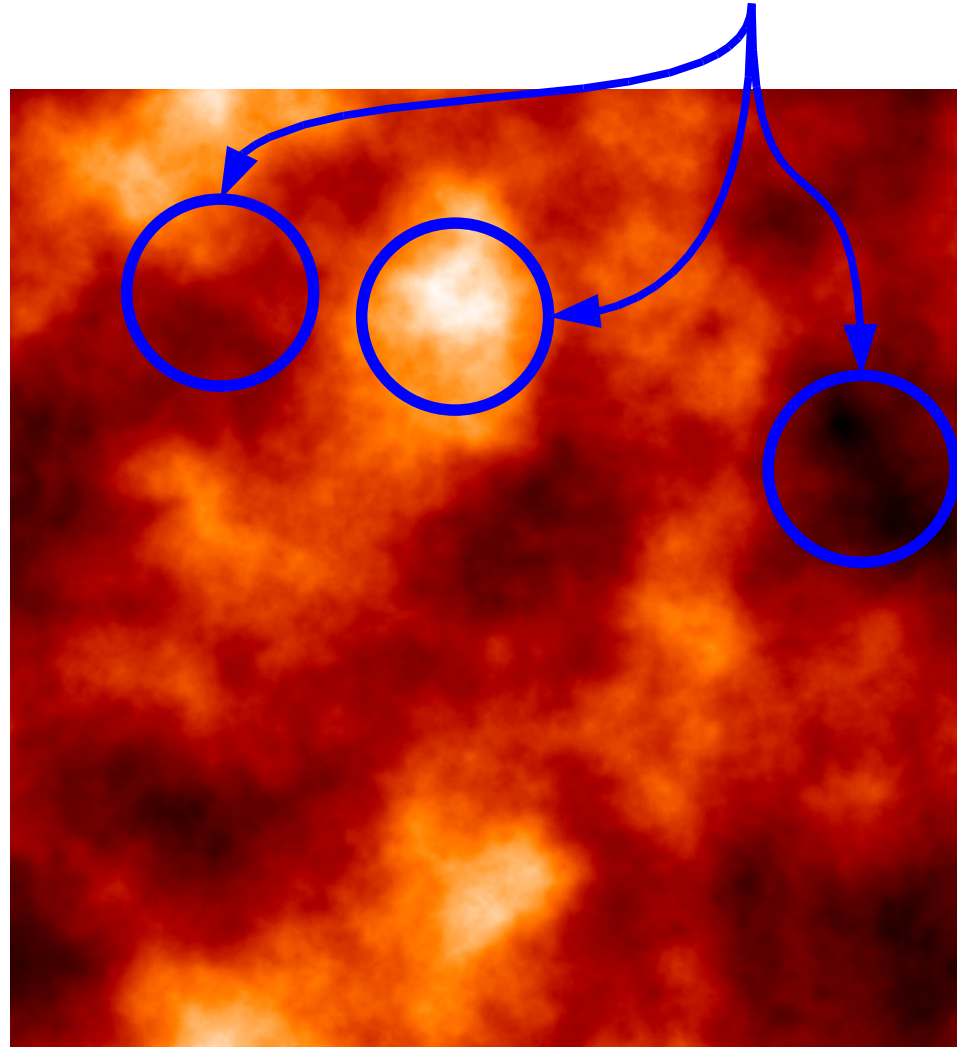


Zone of Avoidance

Edge & Finite volume effects



Portion of the universe
selected by chance

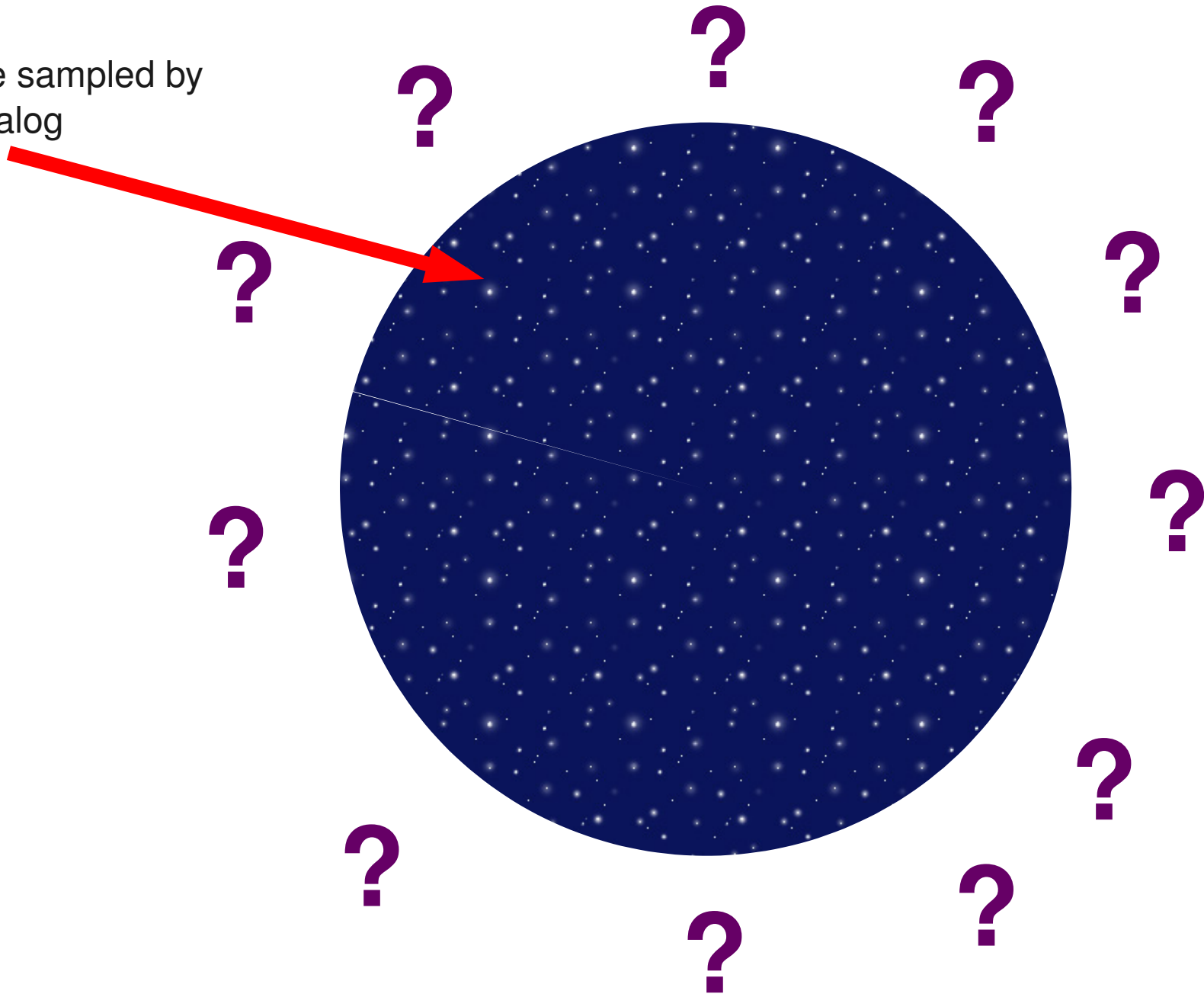


Cosmic variance

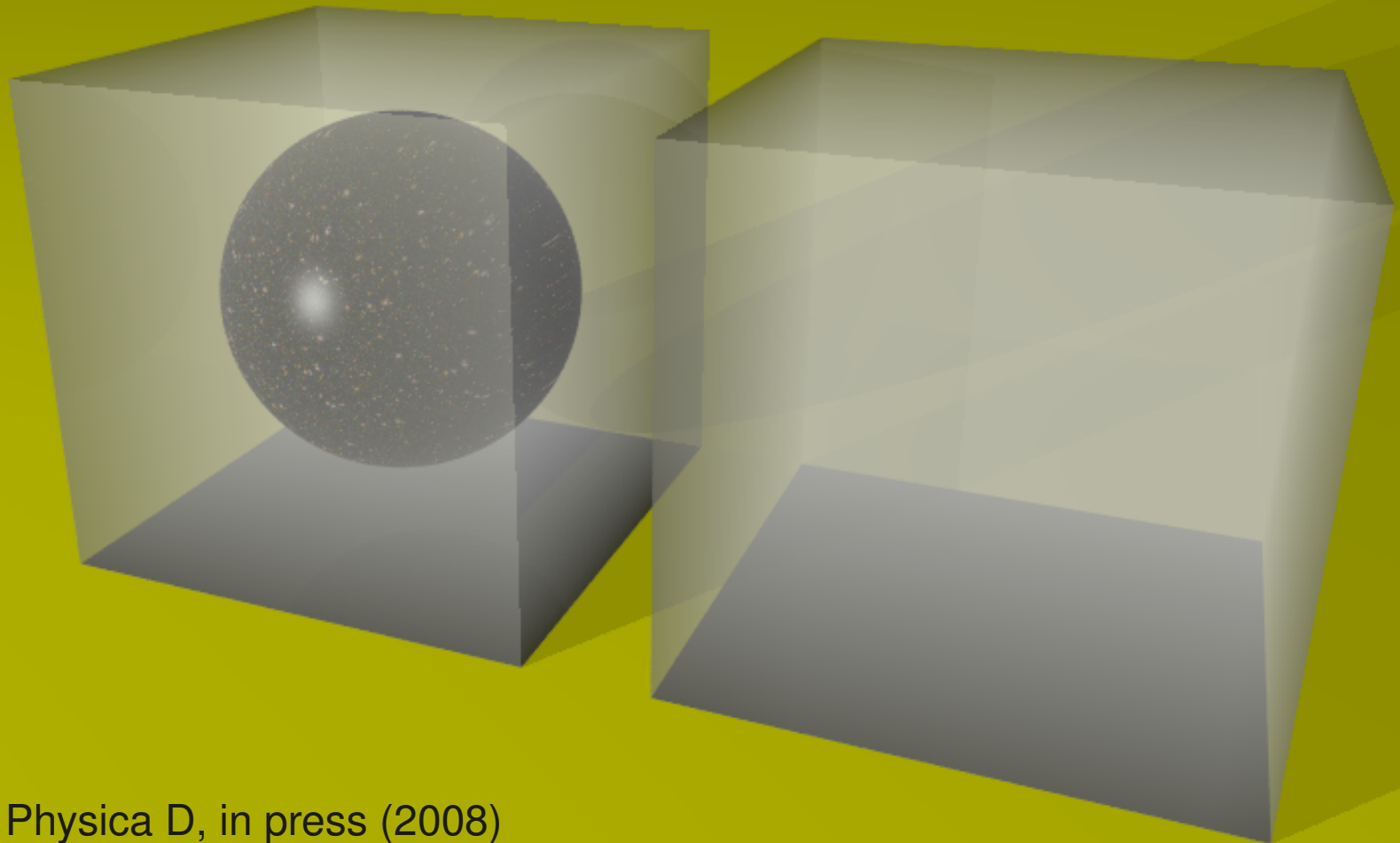
Edge & Finite volume effects



Volume sampled by
the catalog



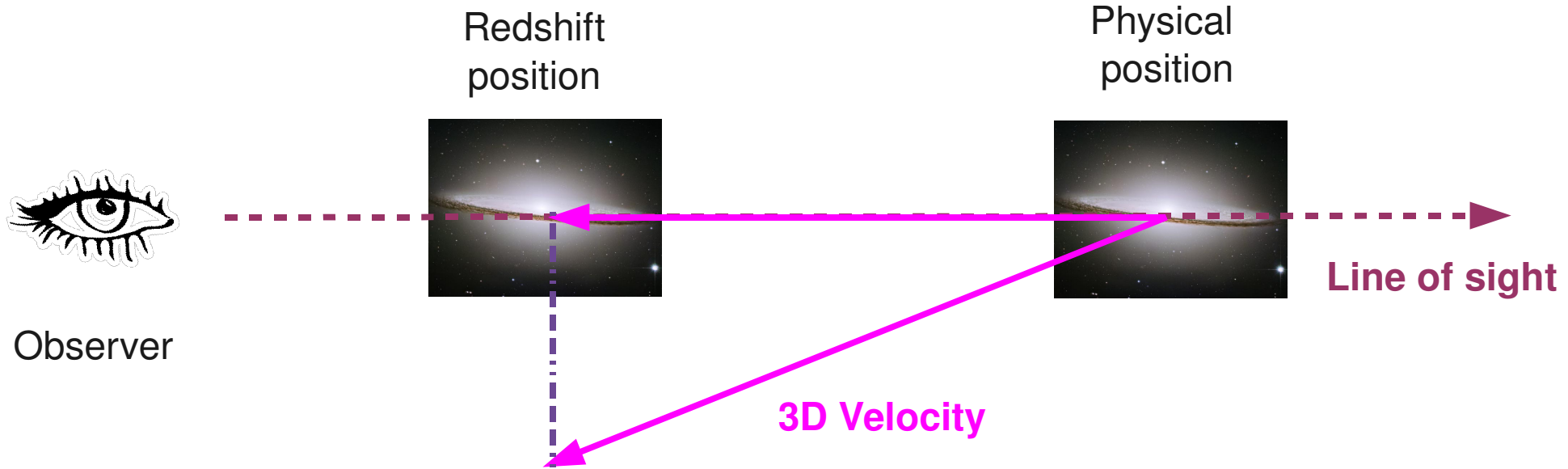
Edge & Finite volume effects



Lavaux, Physica D, in press (2008)

Lavaux et al., MNRAS, **383**, 1292 (2008)

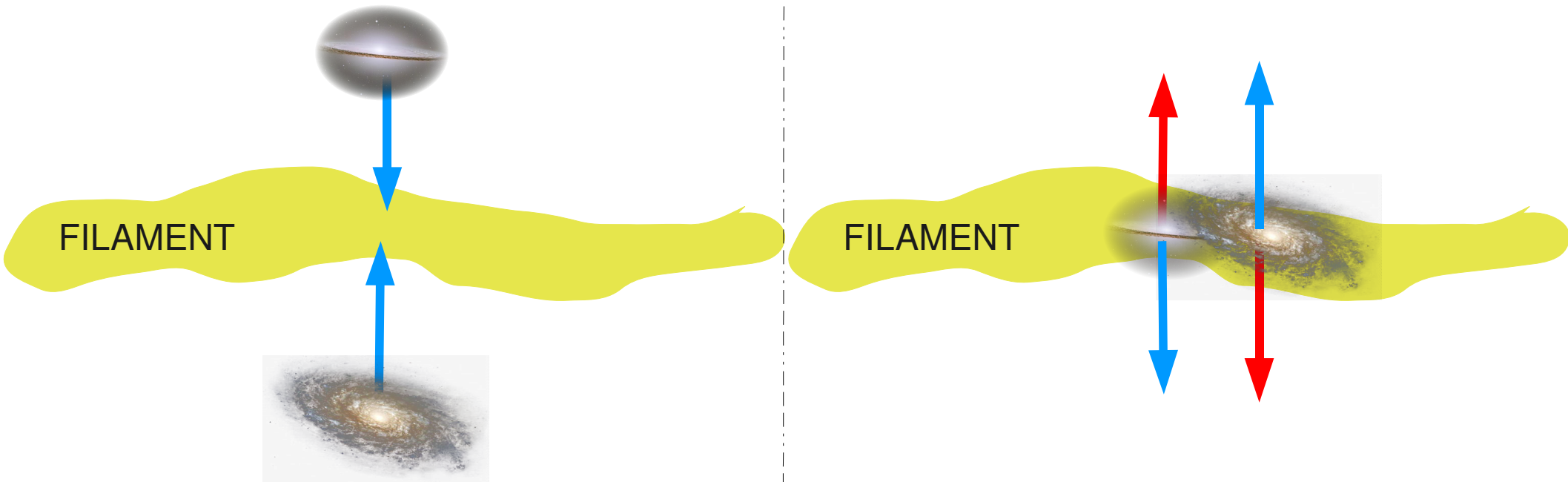
Redshift distortion



modification of MAK

$$S_{\sigma} = \sum_i \left(\left(\vec{s}_i - q_{\sigma(i)}^{\vec{}} \right)^2 - f(\Omega_m, \Omega_{\Lambda}) \frac{\left((\vec{s}_i - q_{\sigma(i)}^{\vec{}}) \cdot \vec{s}_i \right)^2}{\|\vec{s}_i\|^2} \right)$$

Redshift distortion



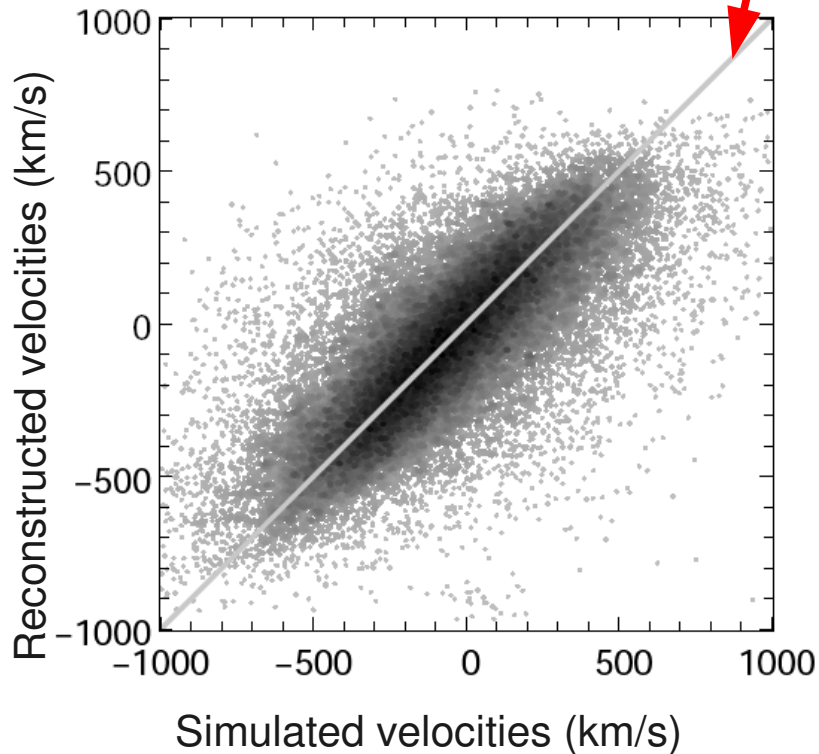
**NOT CORRECTIBLE
(SMALL SCALE EFFECT)**

Redshift distortion

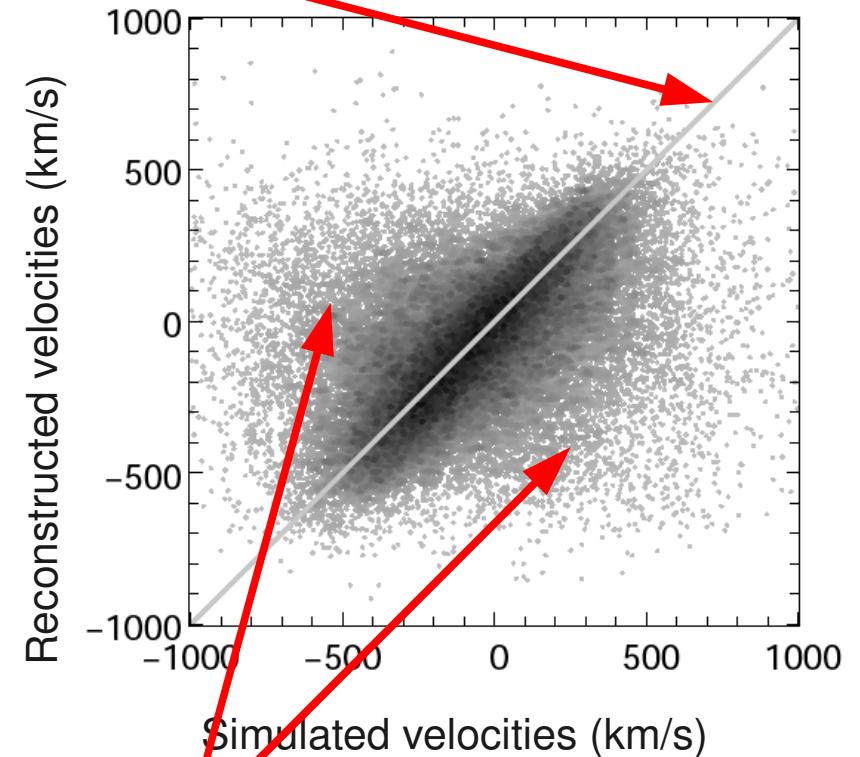


Ideal correlation

Without redshift distortion

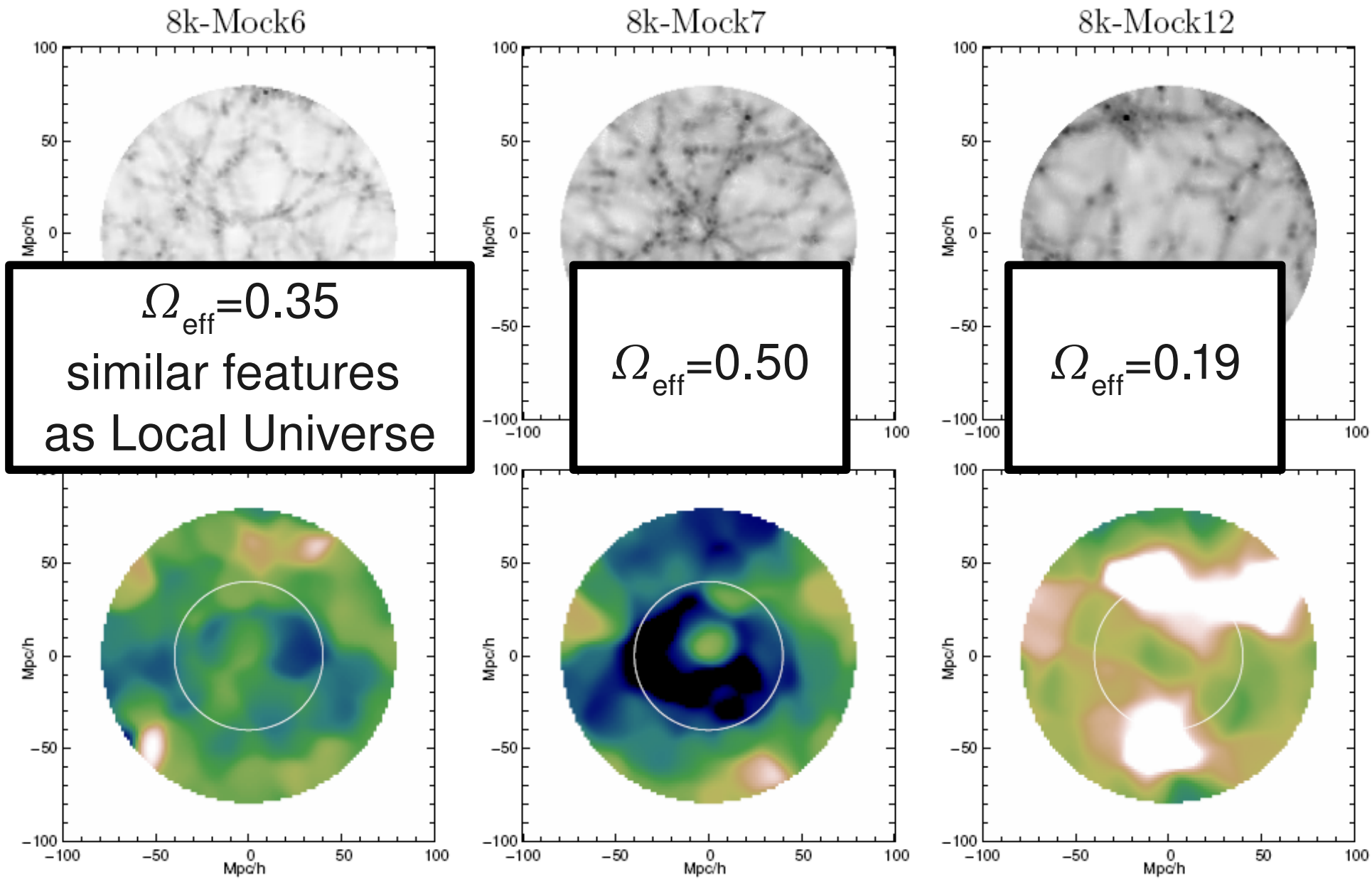


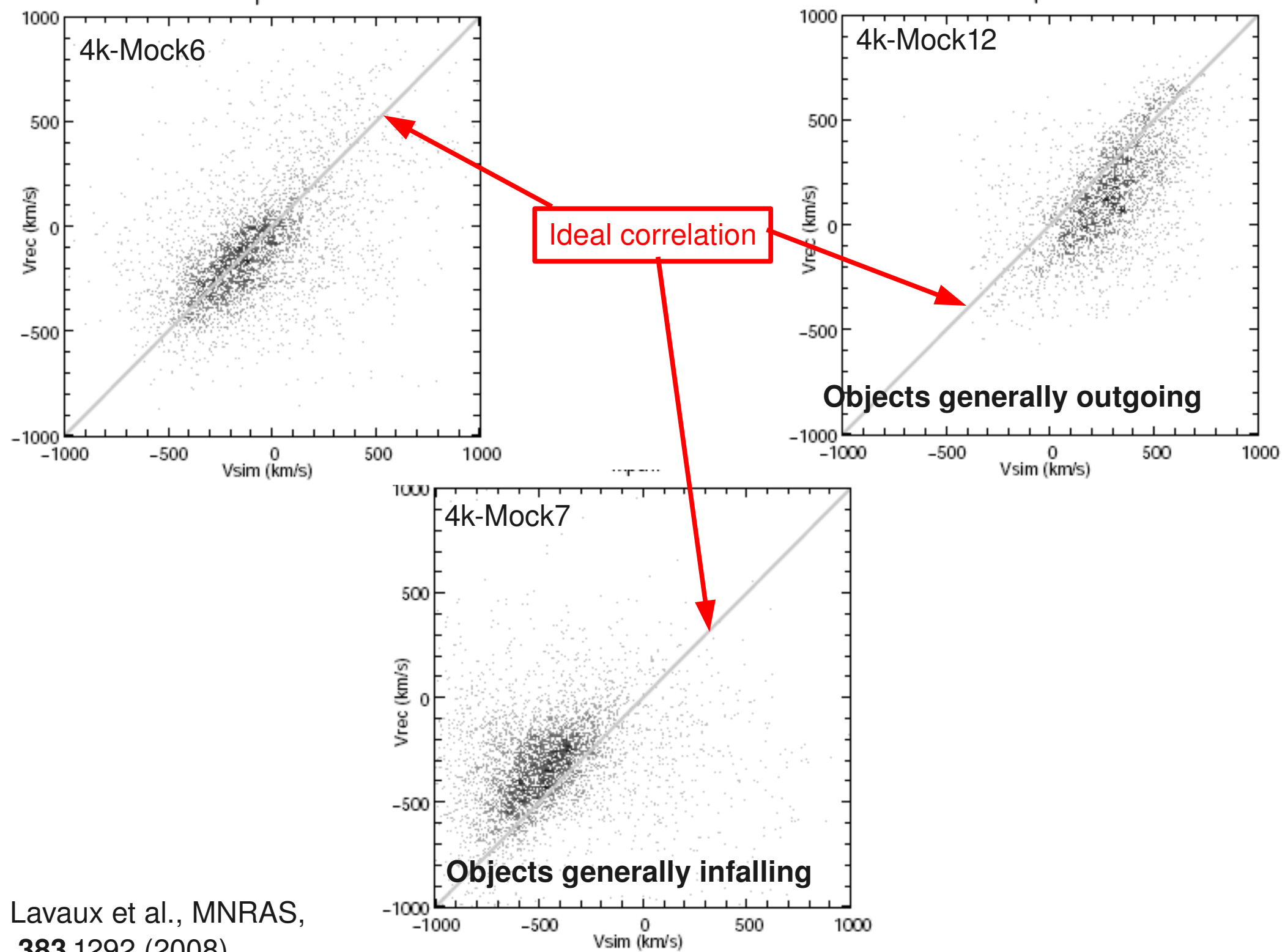
With redshift distortion

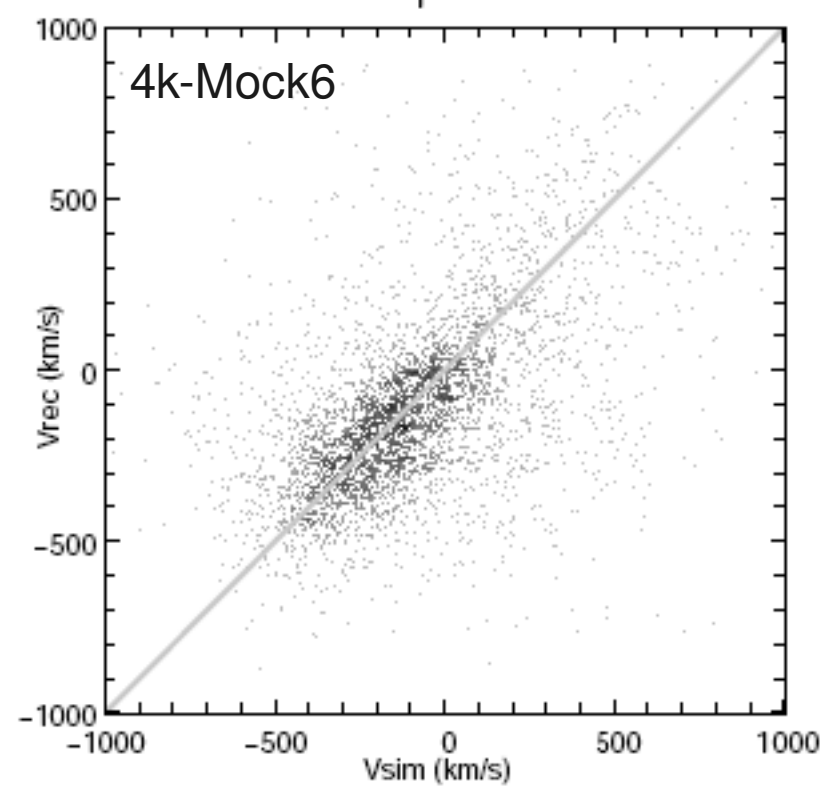


Shell crossings due to redshift distortion

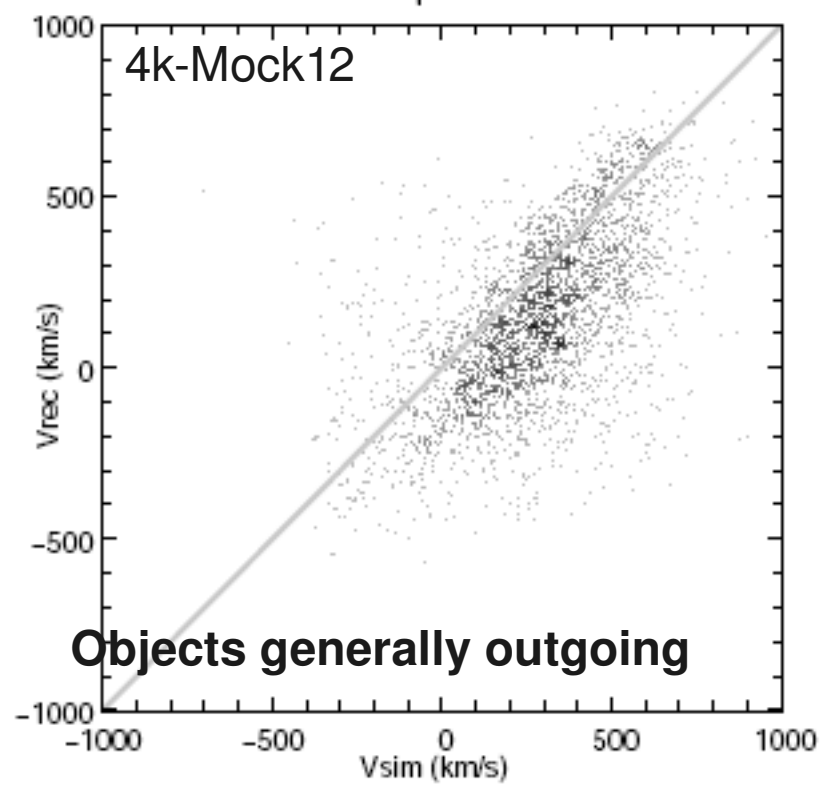
Three basic mock catalogs



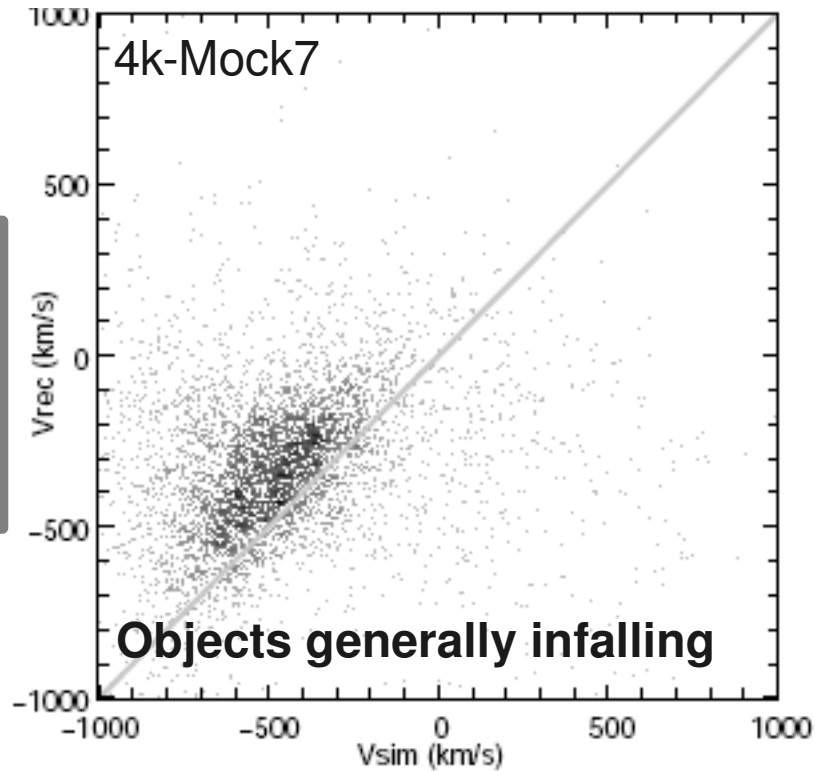




$\Omega_{M,\text{mes}} = 0.30$
 $\Omega_{\text{eff}} = 0.50$



$\Omega_{M,\text{mes}} = 0.31$
 $\Omega_{\text{eff}} = 0.35$

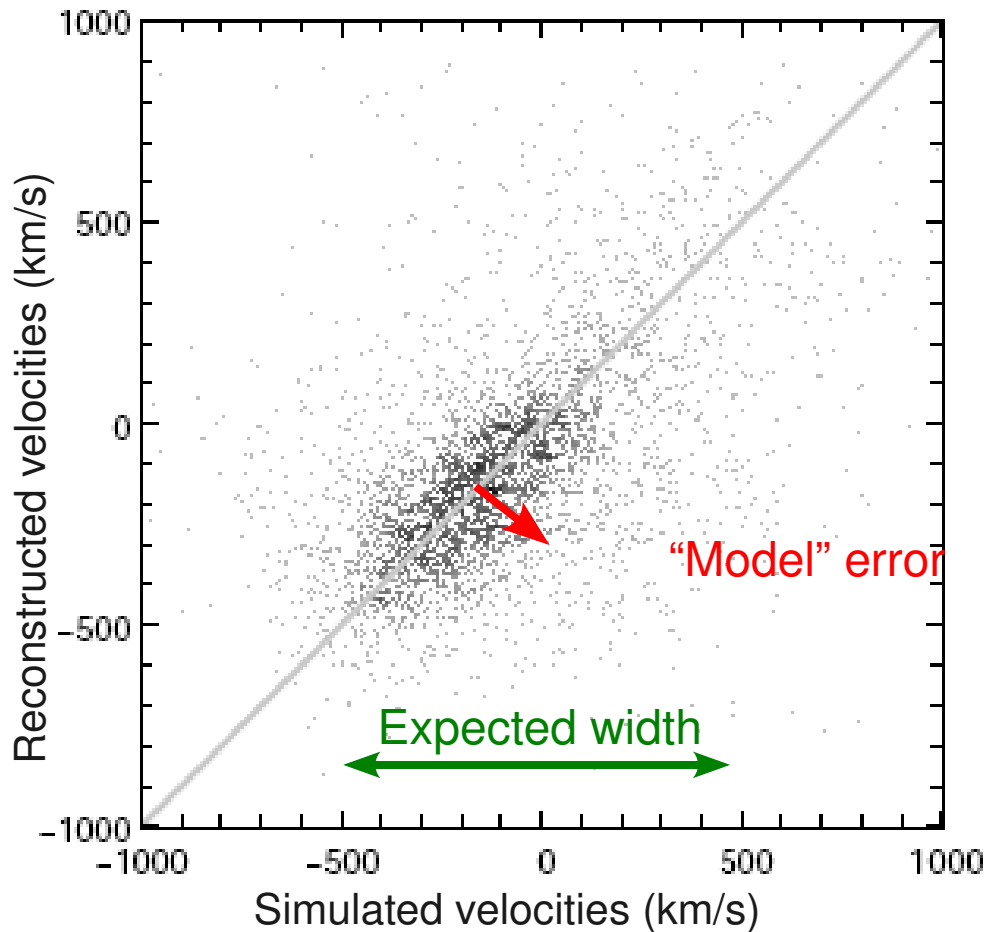


$\Omega_{M,\text{mes}} = 0.15$
 $\Omega_{\text{eff}} = 0.19$

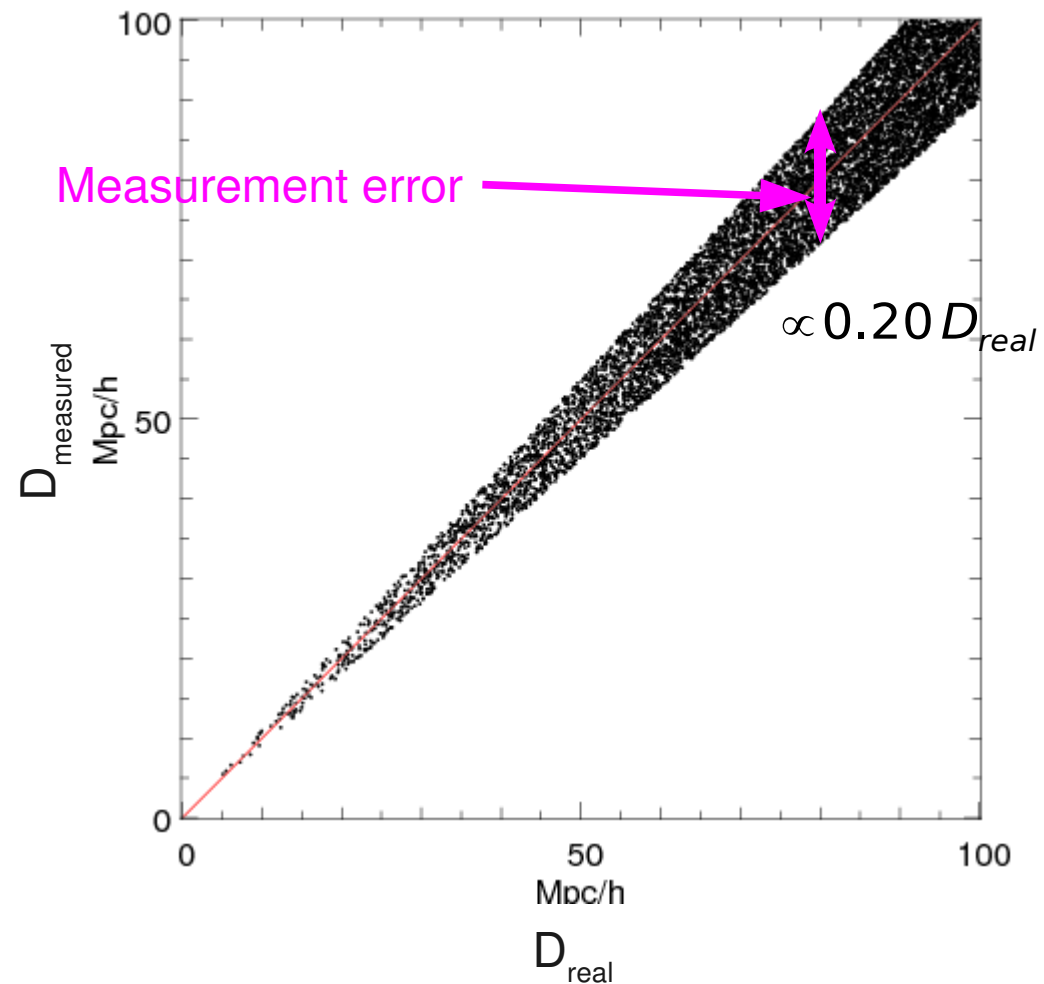
Statistical analysis of a scatter



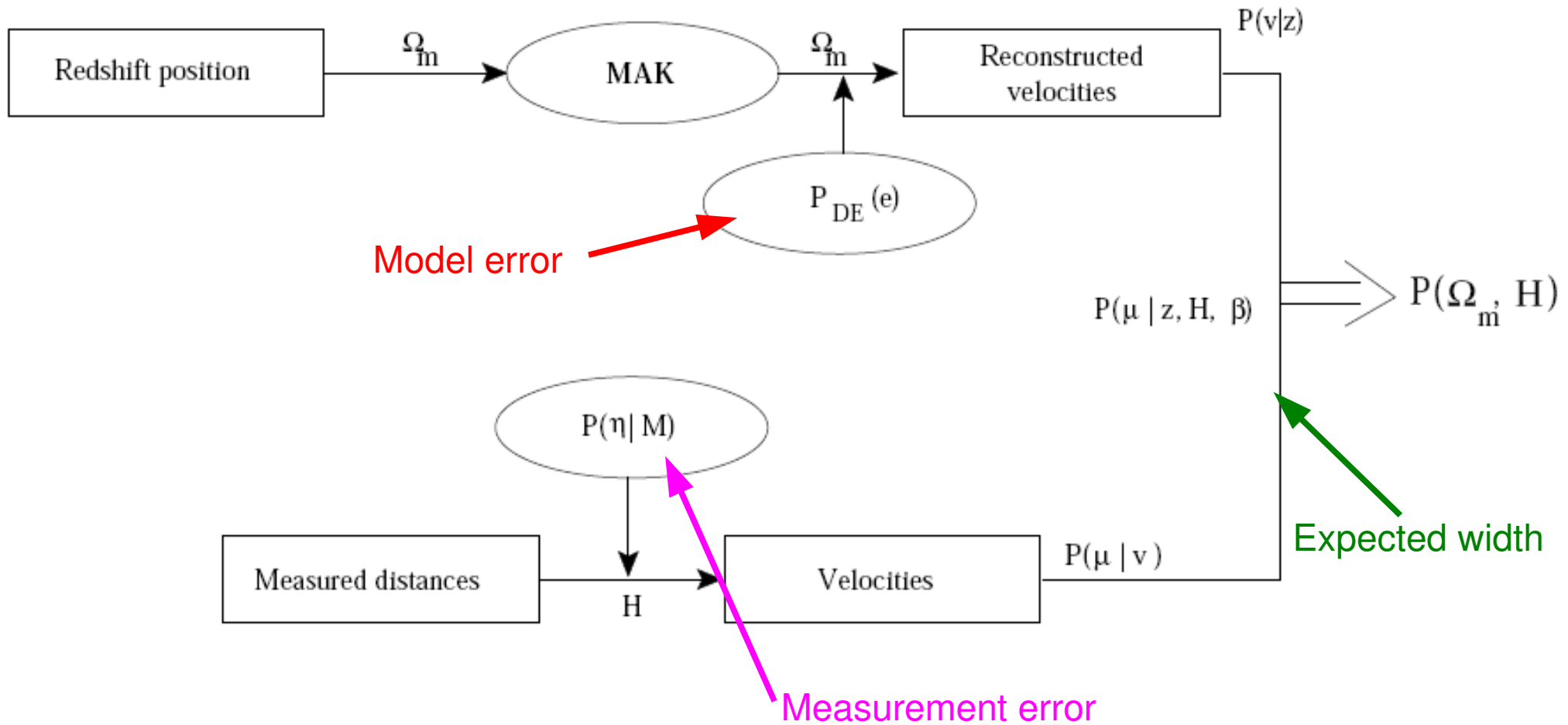
Class 1: "Model" error



Class 2: "Measurement" error



The bayesian chain



Lavaux, Physica D, in press (2008)

Lavaux et al., MNRAS, **383**, 1292 (2008)

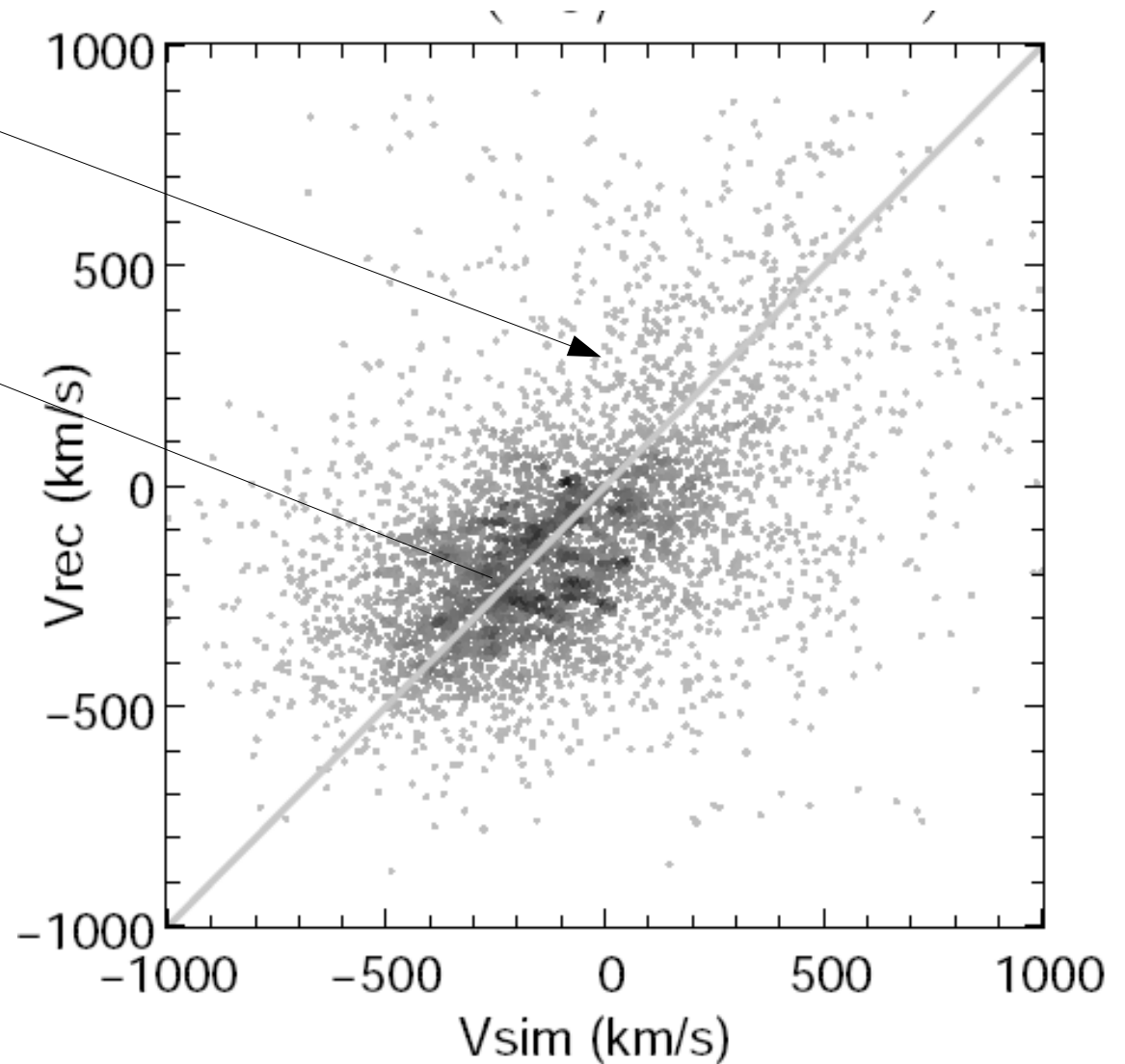
Example



Data points include
typical observational errors
8% distance

Max of $P(\Omega_M)$ yields

- 0.30 when width is known
- 0.10 if width is unknown



Example



Data points include
typical observational errors
8% distance

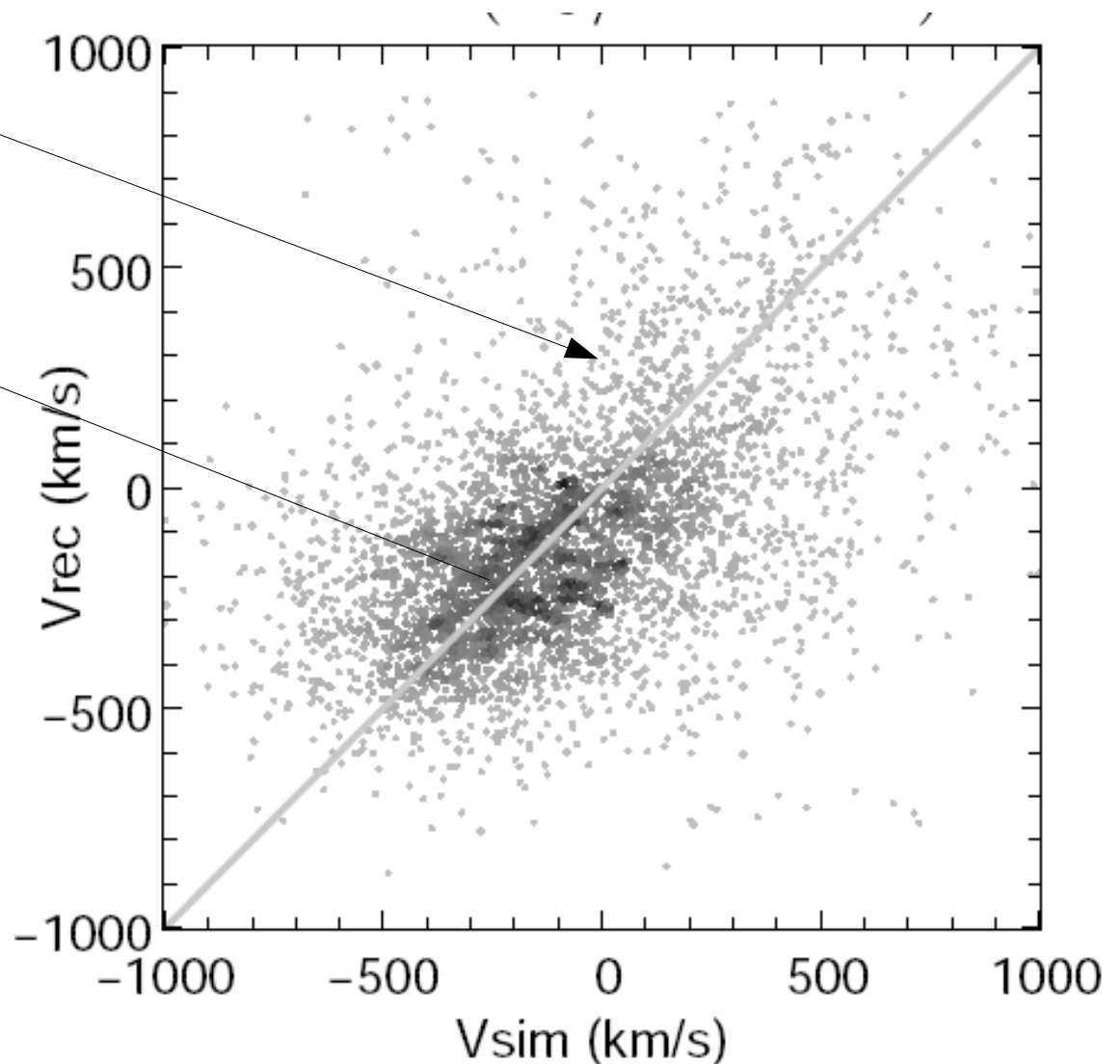
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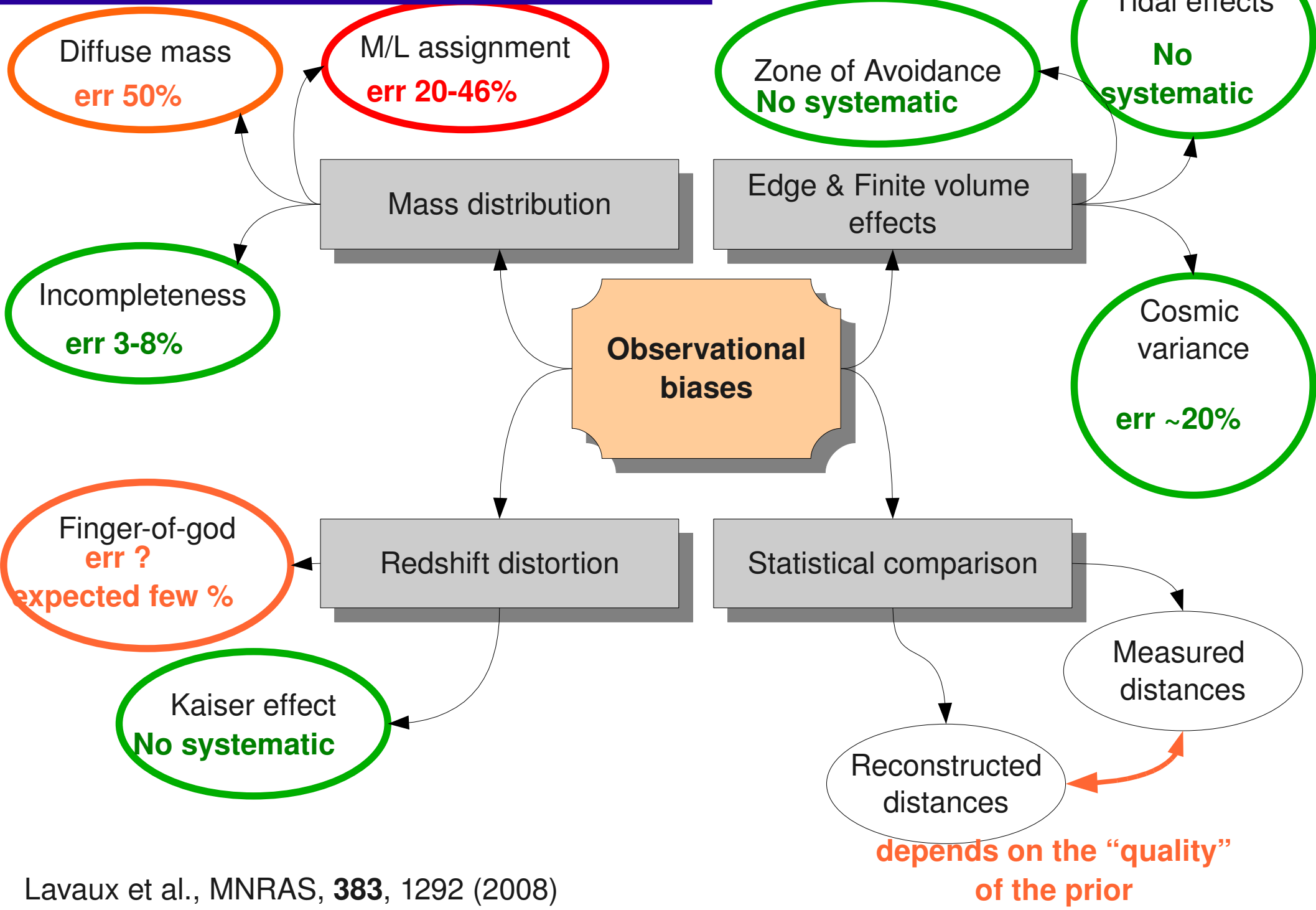


Insufficient !

Use of correlation function
may be mandatory



Summary of systematics (Ω_m)



Summary of systematics (Ω_m)

Diffuse mass
err 50%

M/L assignment
err 20-46%

Incompleteness
err 3-8%

May be tested using different corrections

Cosmic
variance
err ~20%

May be checked using
deeper galaxy catalogs



The peculiar velocities of our Local Universe

Catalogues of galaxies



Redshift catalogues

CfA/ZCAT, SDSS,
2MASS Redshift Survey ($K < 11.25$),
2dF, 6dFGS, SPACE

Distance catalogues

Mark III, NBG-3k, SFI, SFI++,
2MASS TF

⇒ Map making of the Local Universe

2MRS/NBG-3k catalogs



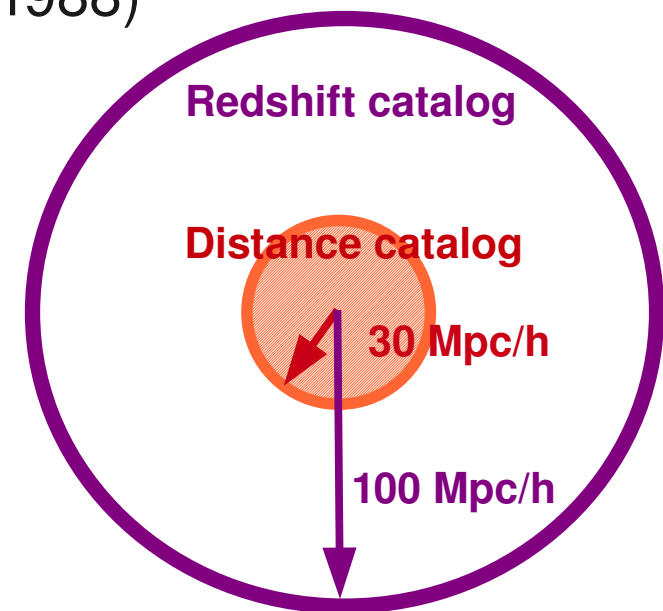
2MASS redshift catalog (Huchra et al. 2005)

- Based upon the 2MASS photometric galaxy catalog
- ~25000 galaxies, selected with $K_s < 11.25$
- **Full sky & Complete down to $|b| \sim 5$ degree**
- Distribution peaks at ~ 90 Mpc/h ($z \sim 0.03$)
- ~ 250 Mpc/h ($z \sim 0.08$) deep

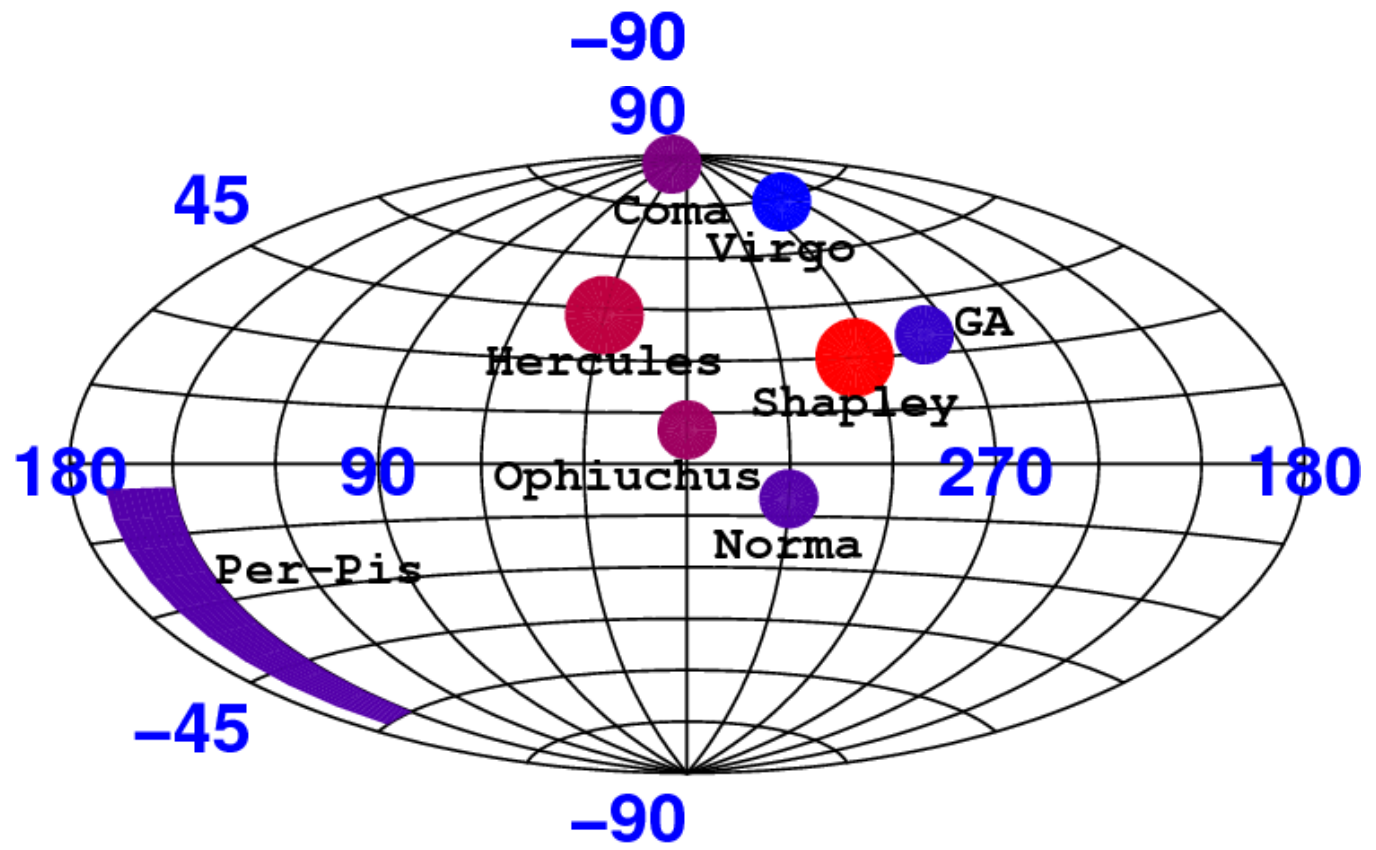
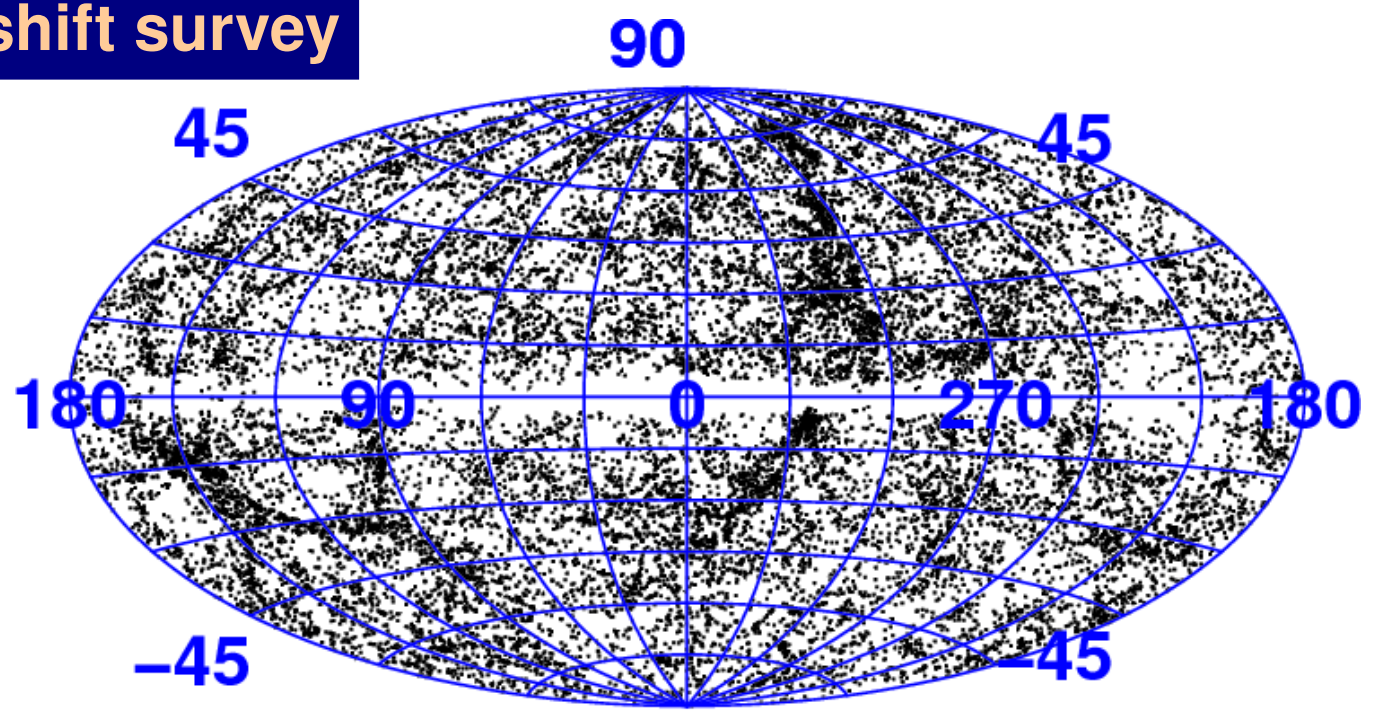
NBG-3k distance catalog (Tully et al. 2008)

- ~ 30 -40 Mpc deep, outgrowth of NBGC (Tully 1988)
- 1791 galaxies with high quality distances
 - › Tully-Fisher relation
 - › Tip of the red giant branch
 - › Surface brightness fluctuation
 - › Fundamental plane

⇒ What do we see ?

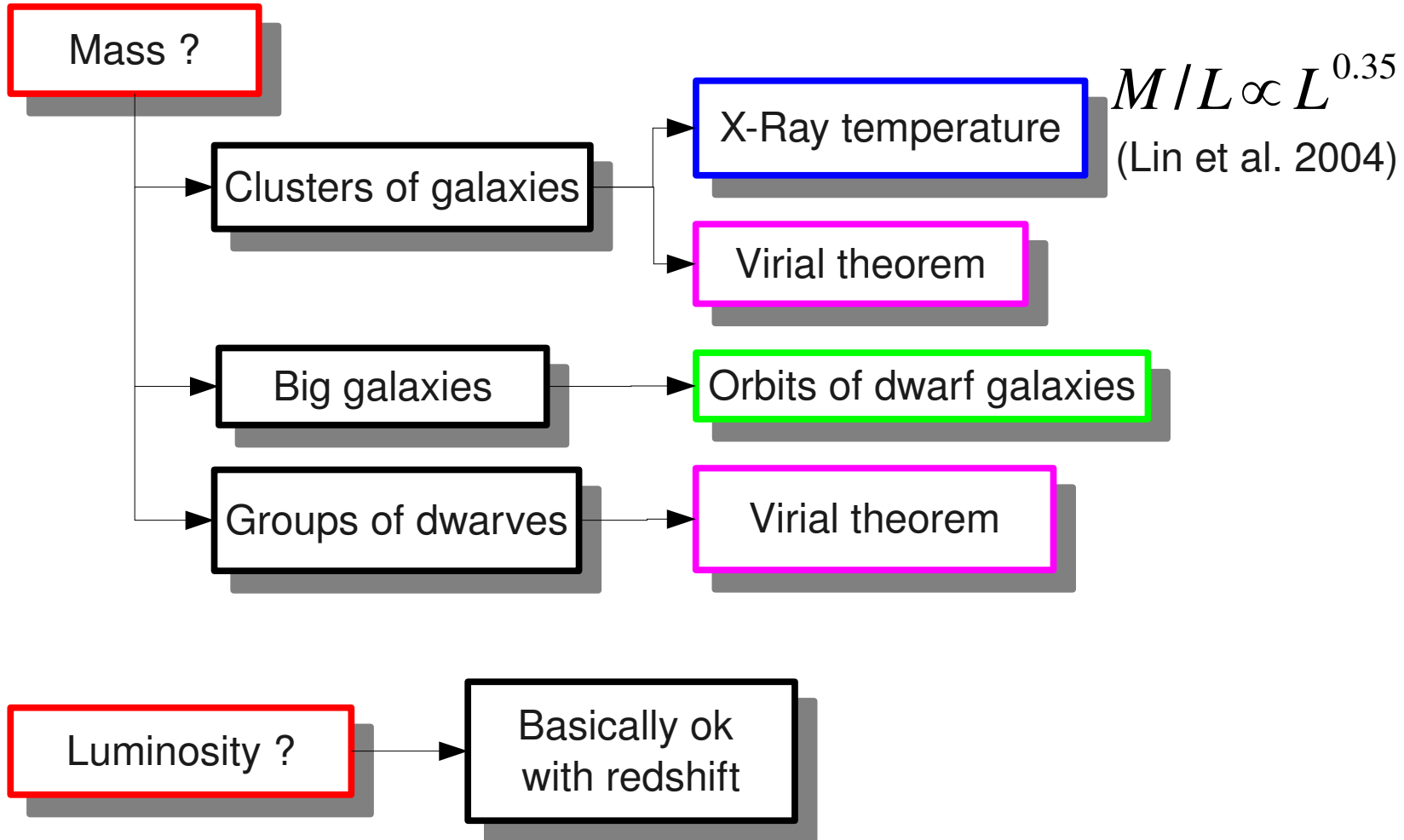


2MASS Redshift survey

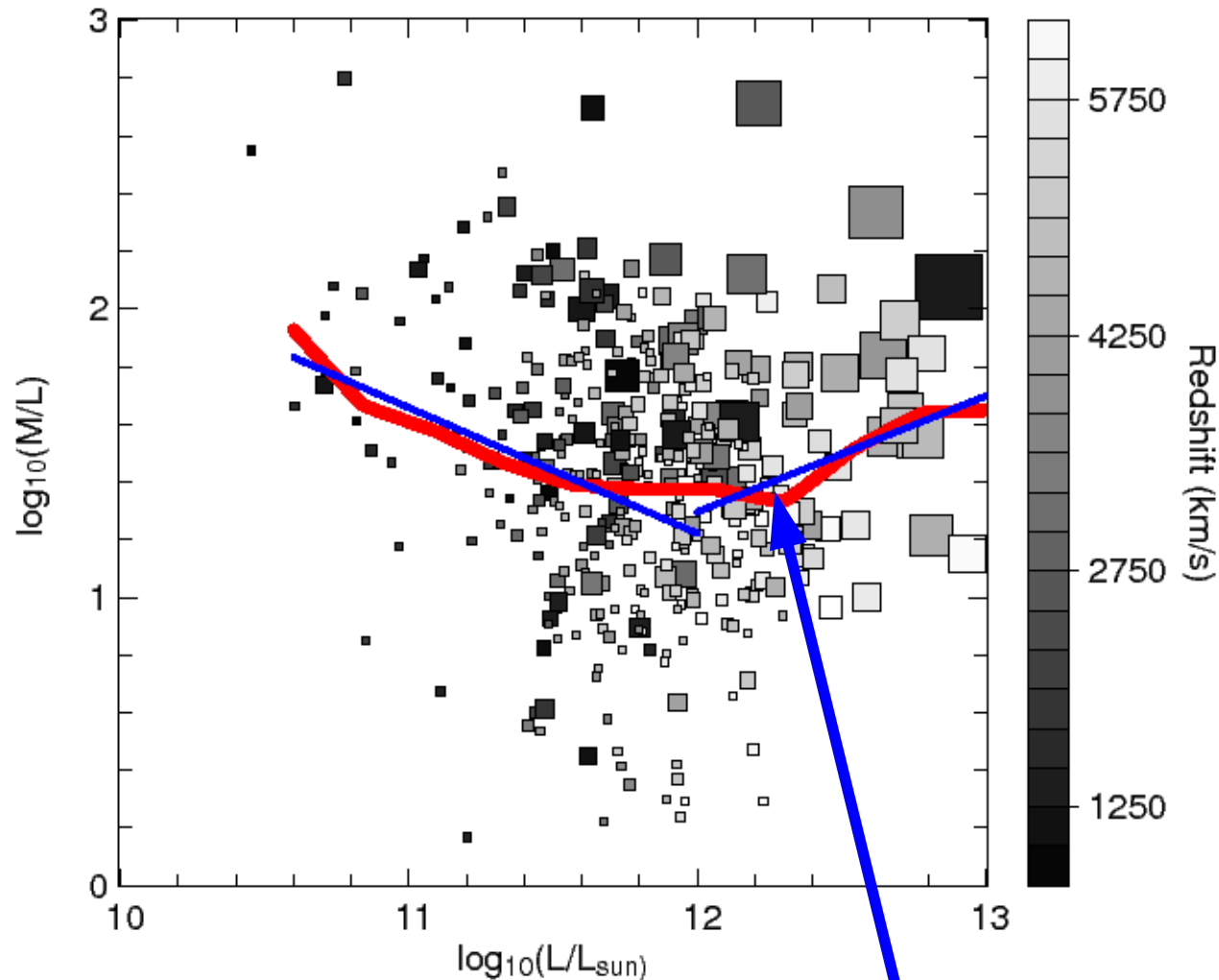




Estimation of M/L



Estimation of M/L (virial theorem)



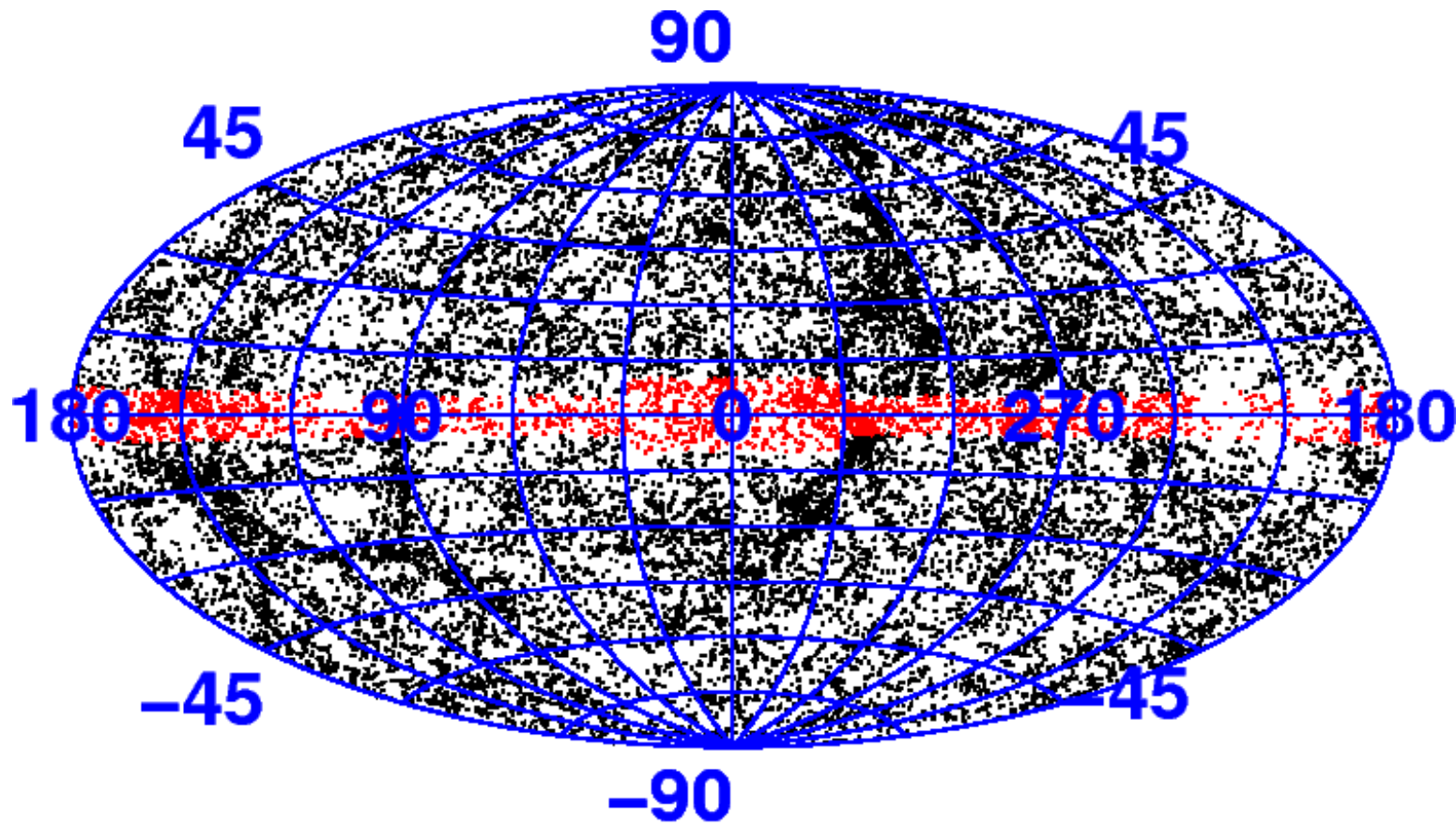
$$M_{200} / L \propto L^{0.35 \pm 0.02}$$

(Lin et al. 2004)

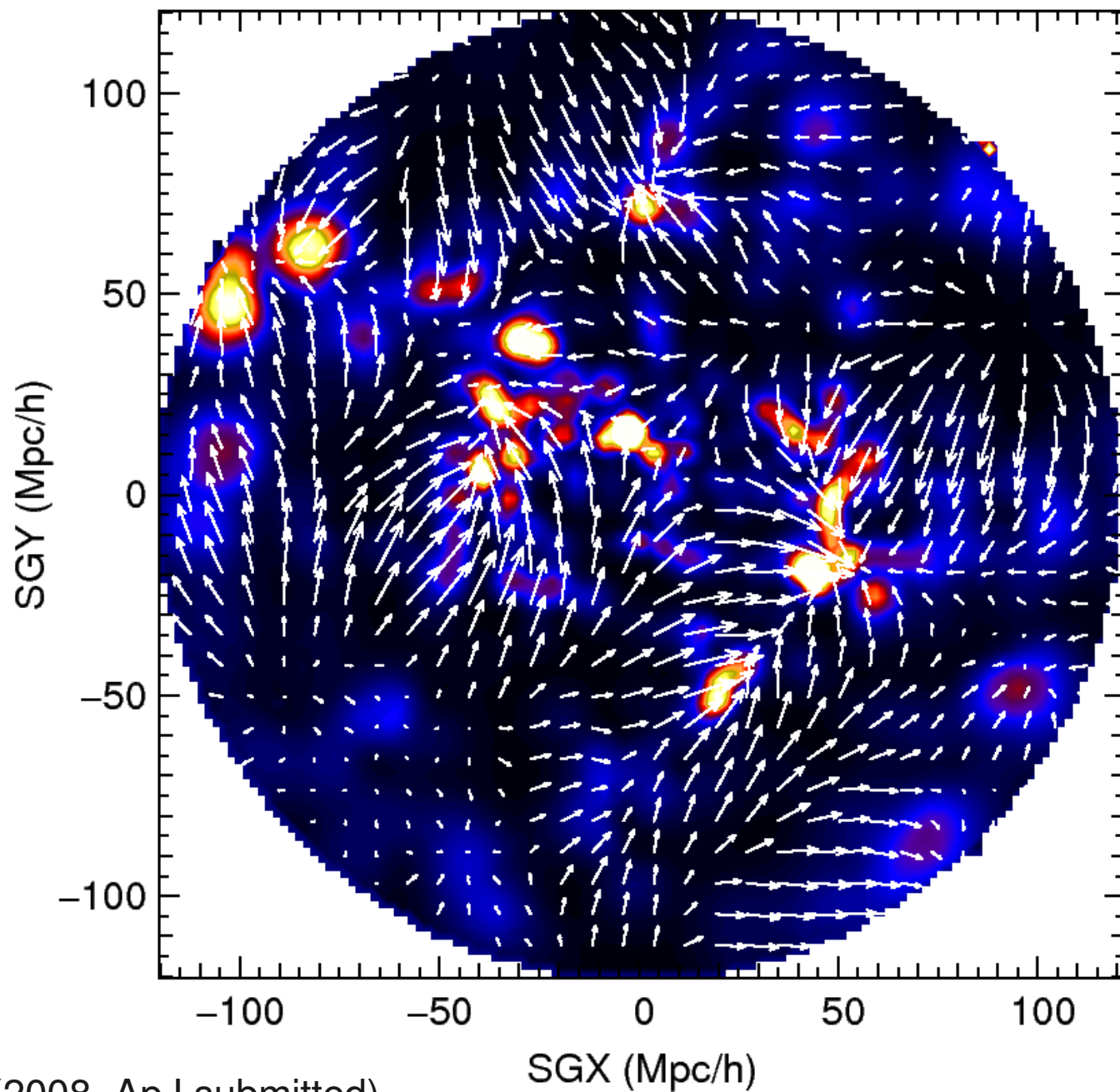


$$M / L \propto L^{0.40}$$

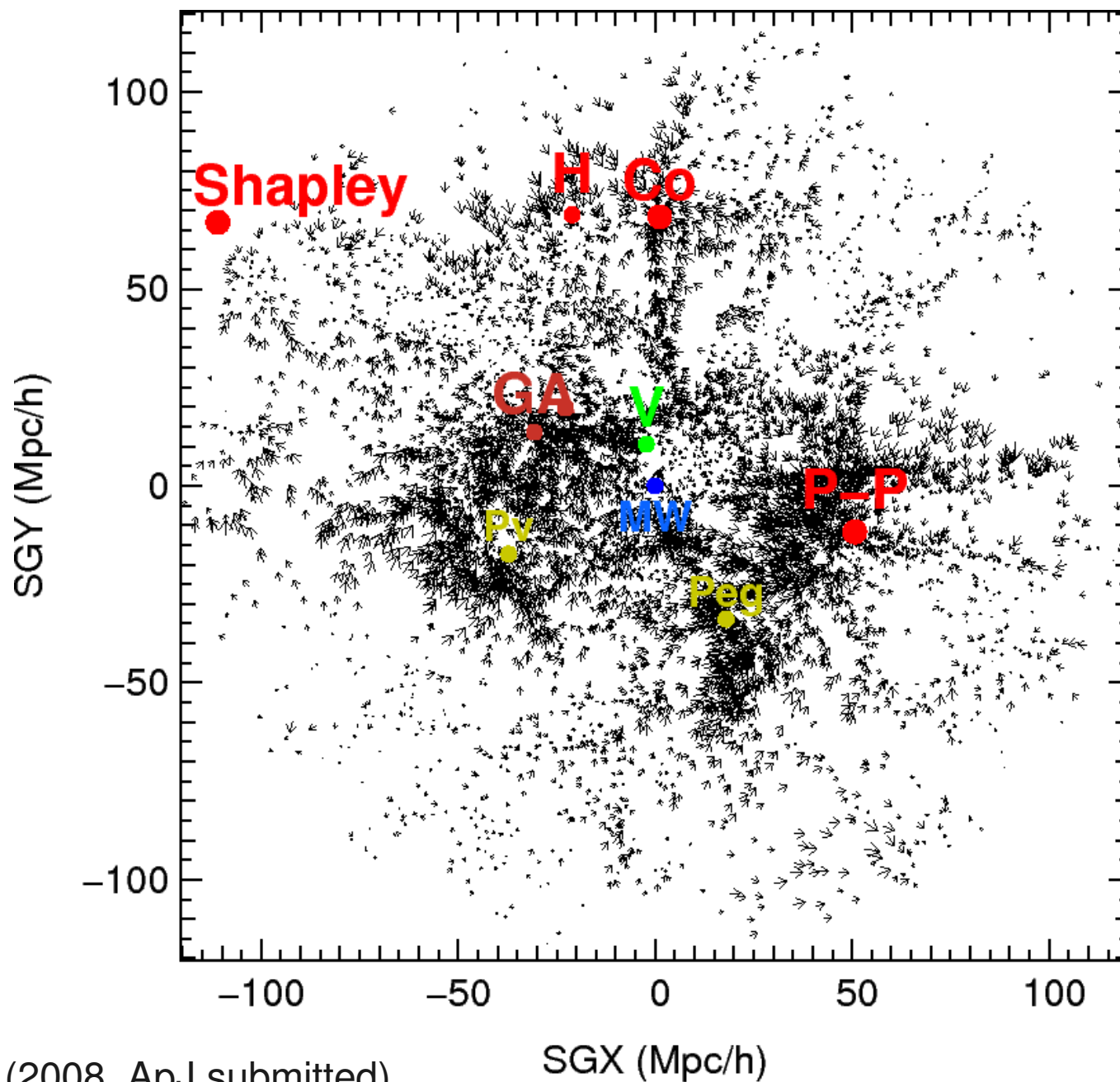
Filling the Zone of Avoidance



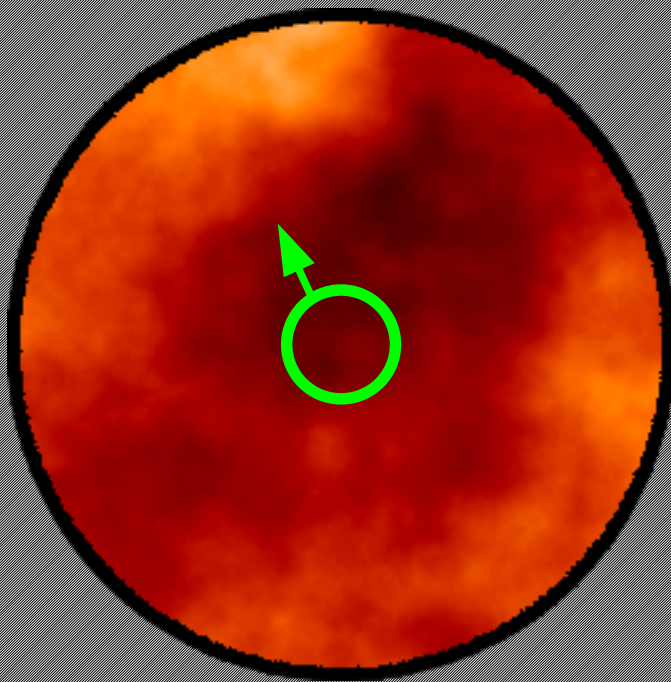
Reconstructed velocity field



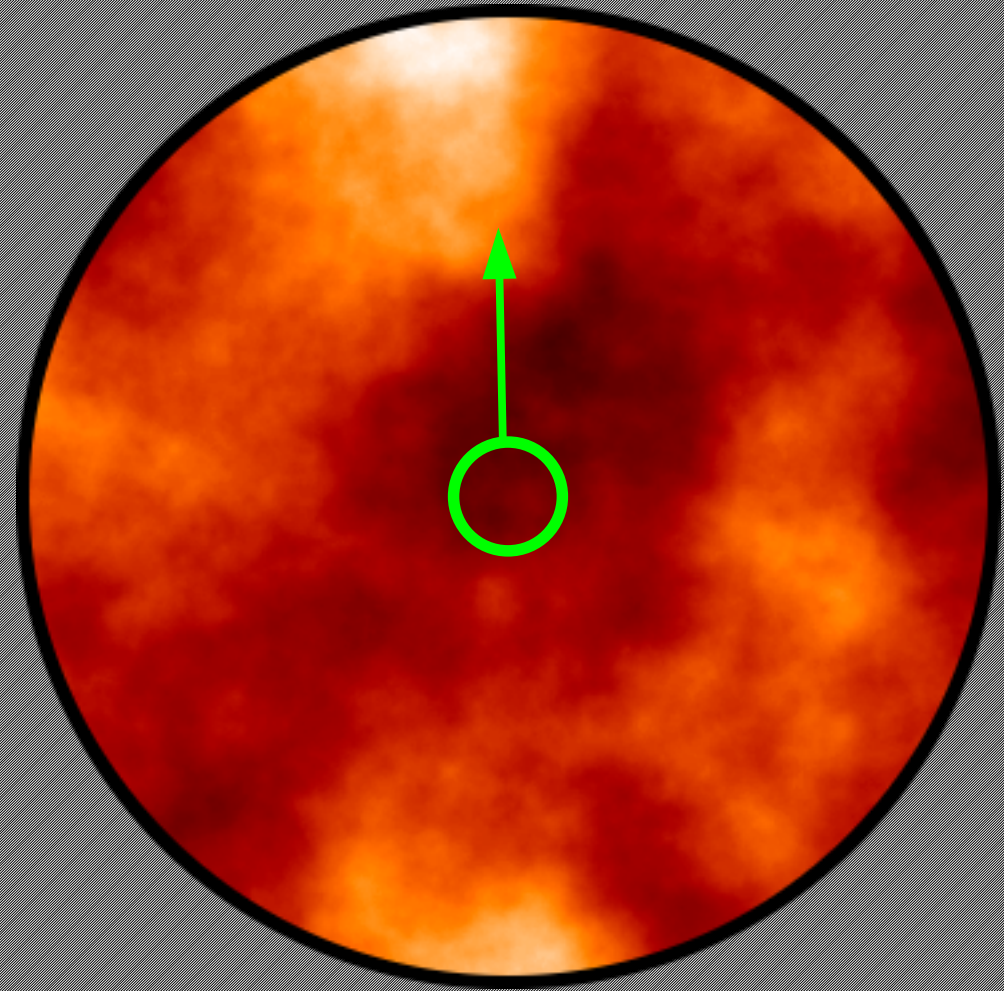
Reconstructed peculiar velocities



The NBG-3k bulk flow problem

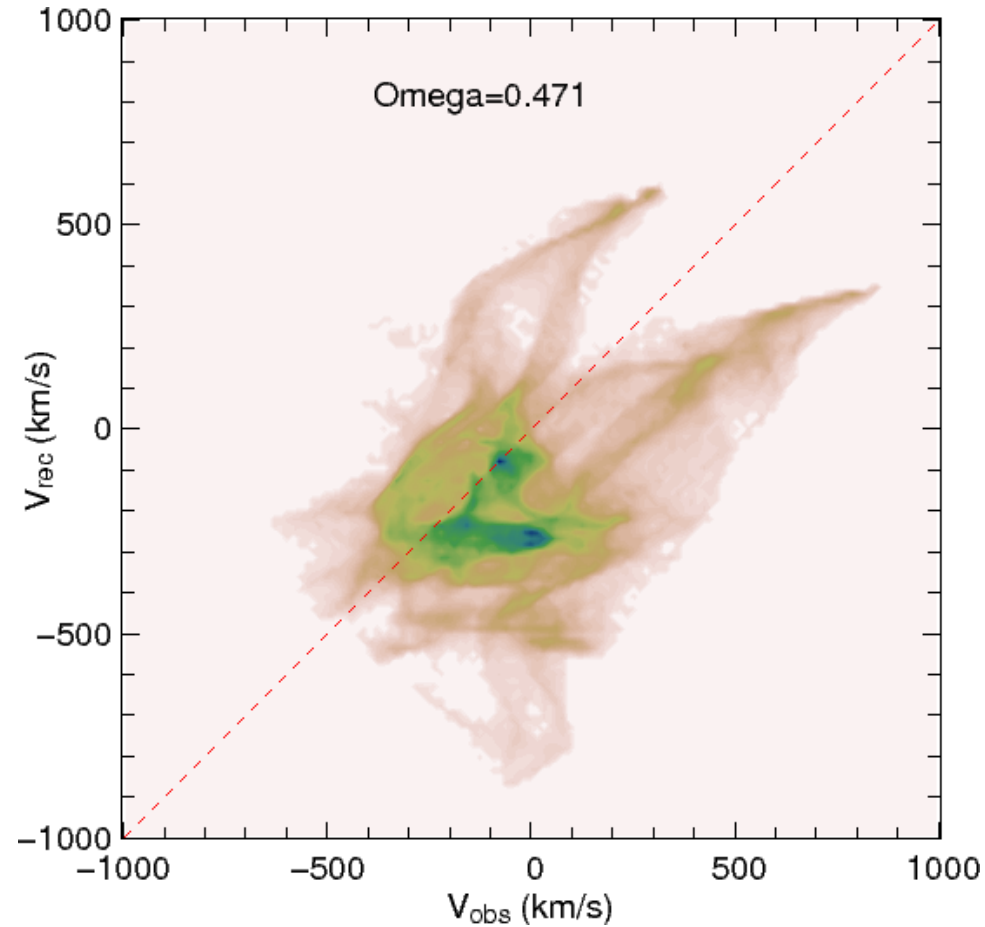


WRONG BULK FLOW

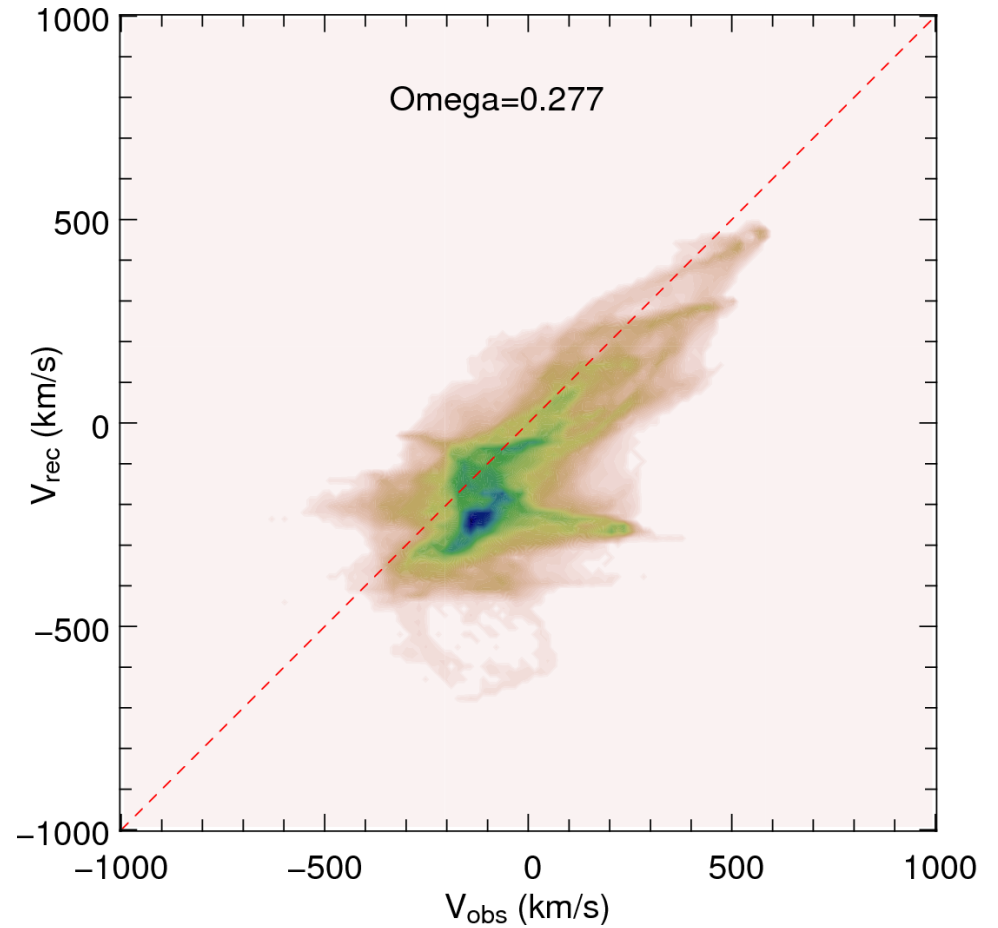


BETTER BULK FLOW

Wm estimation

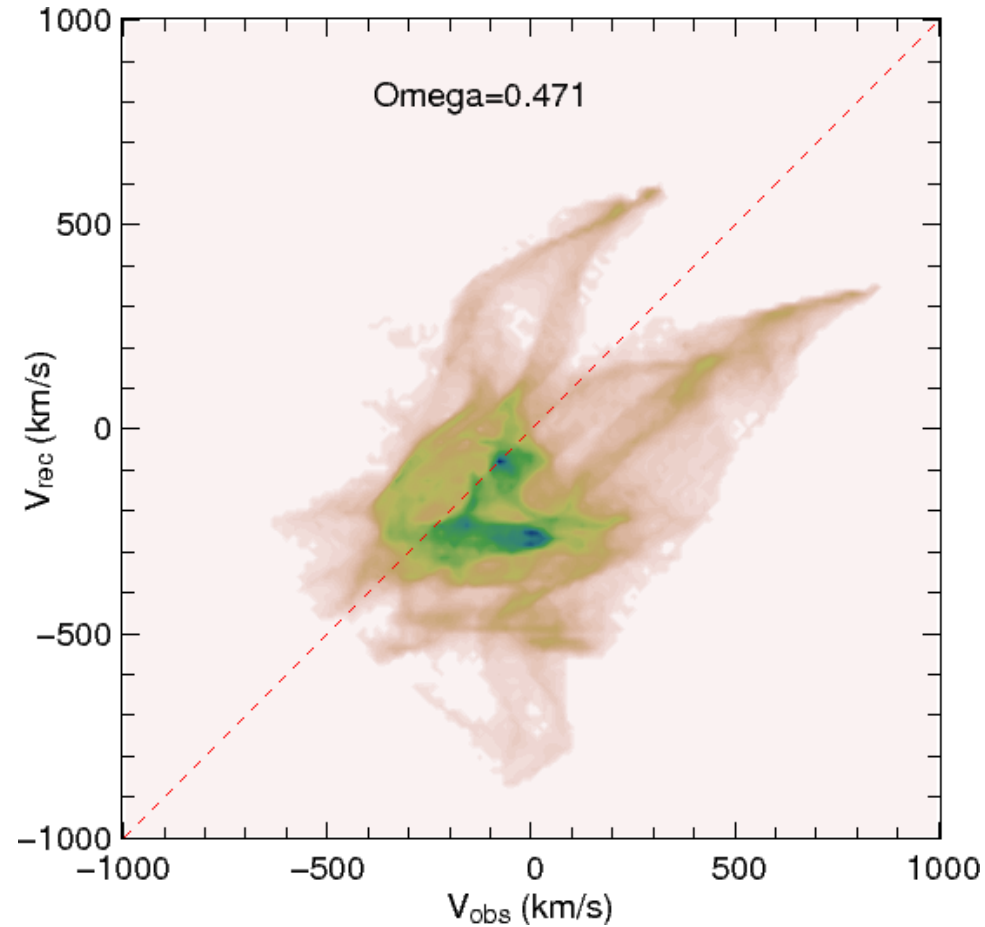


Without bulk flow correction

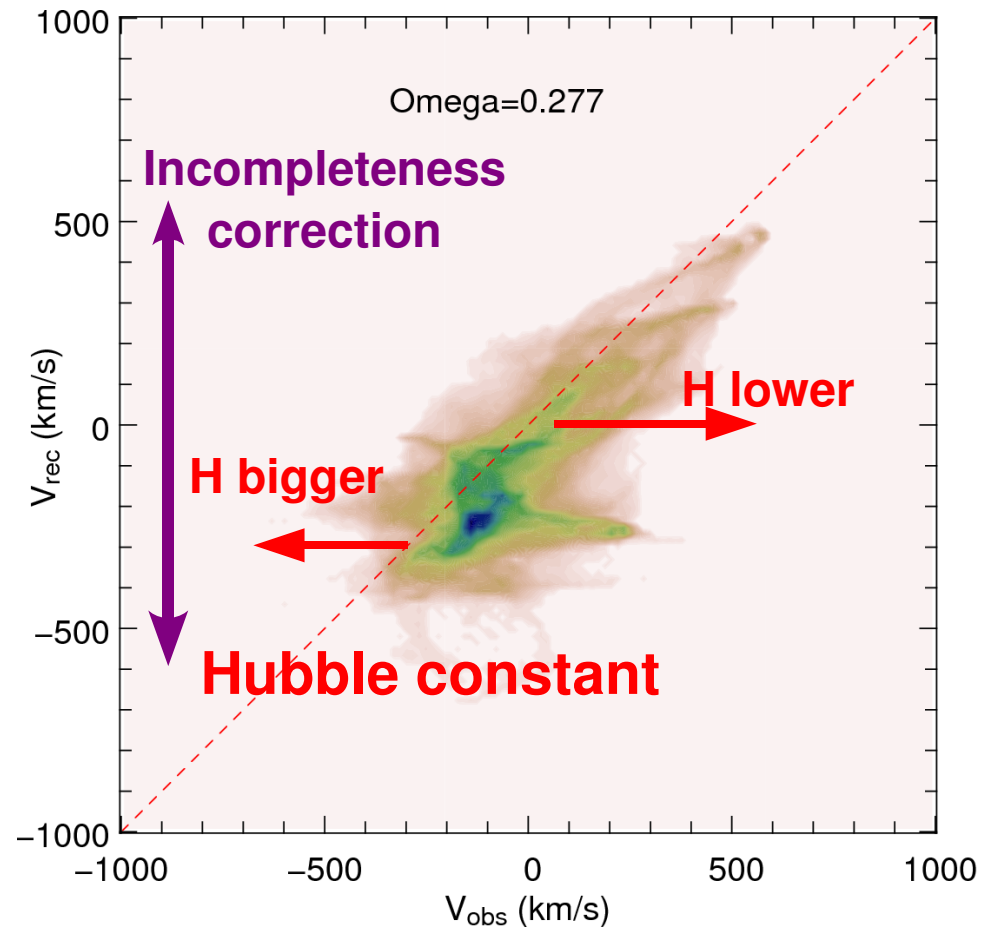


With bulk flow correction

Wm estimation



Without bulk flow correction



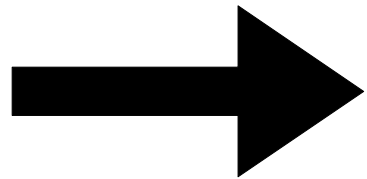
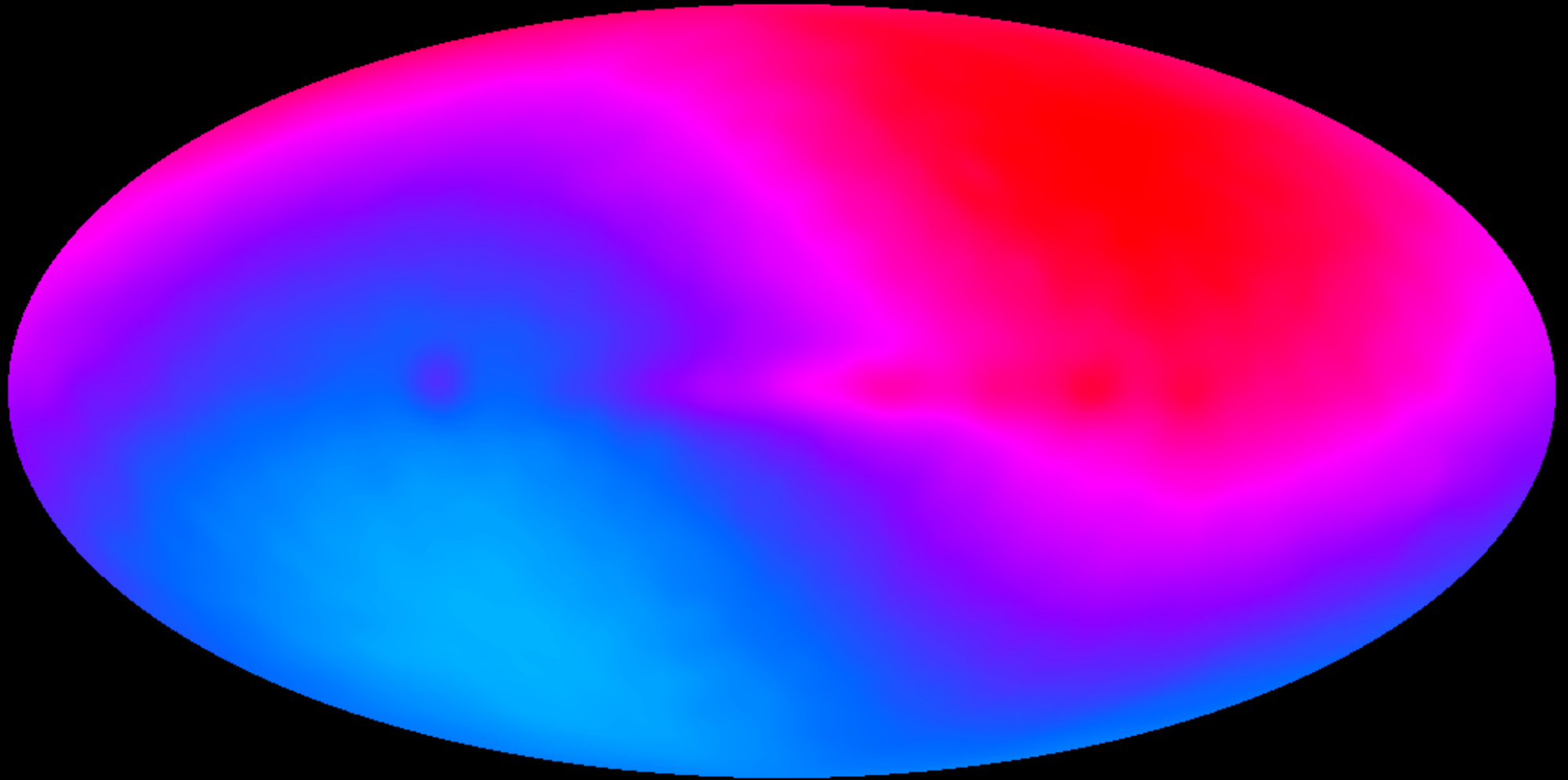
With bulk flow correction

$H=80 \pm 6$ km/s/Mpc

Lavaux et al., ApJ submitted, (2008)

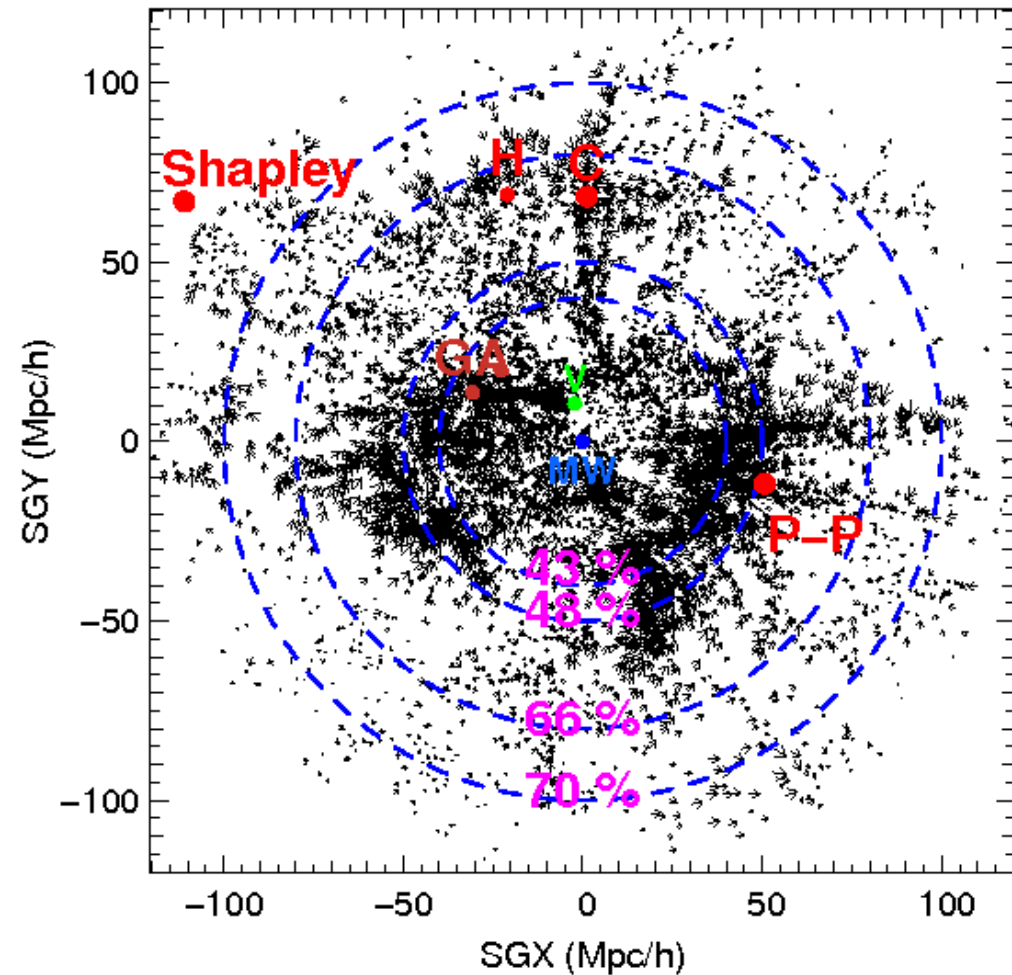
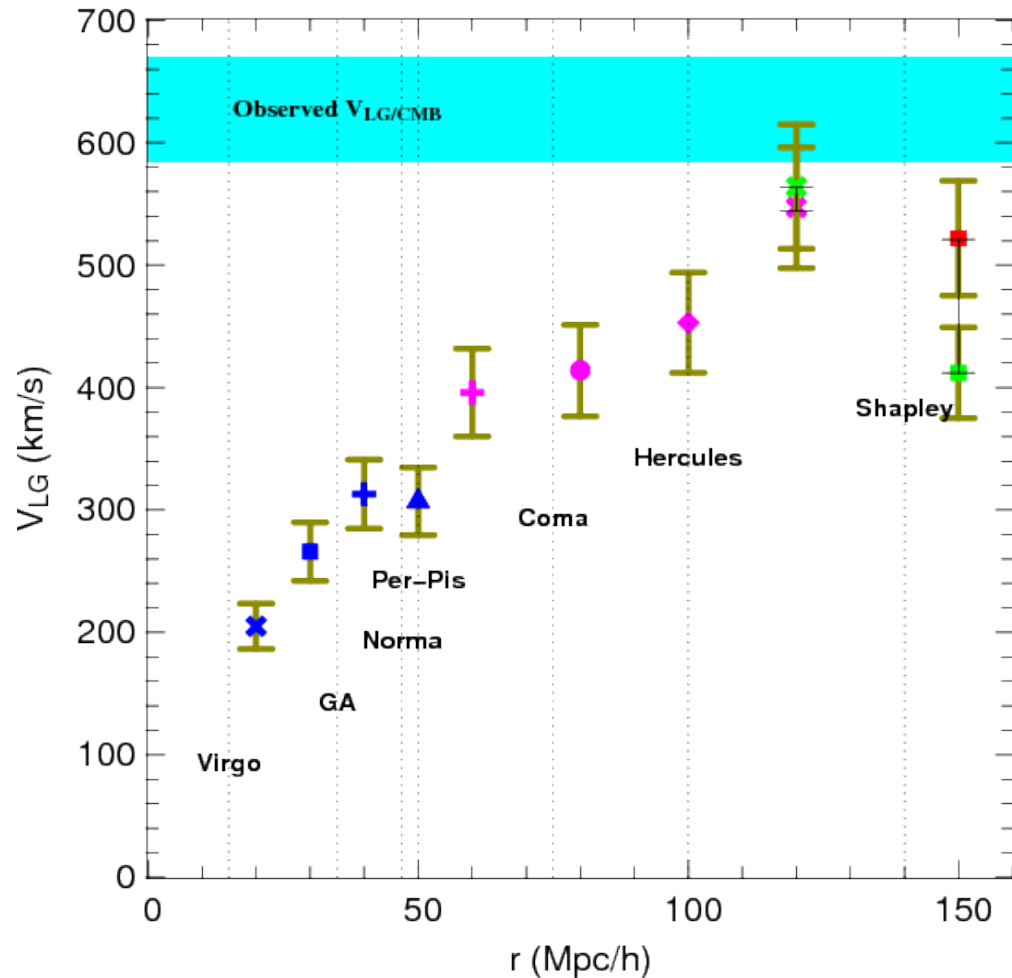
Comparison of smoothed velocity field \Rightarrow increase signal-to-noise

Local Group velocity: COBE observation

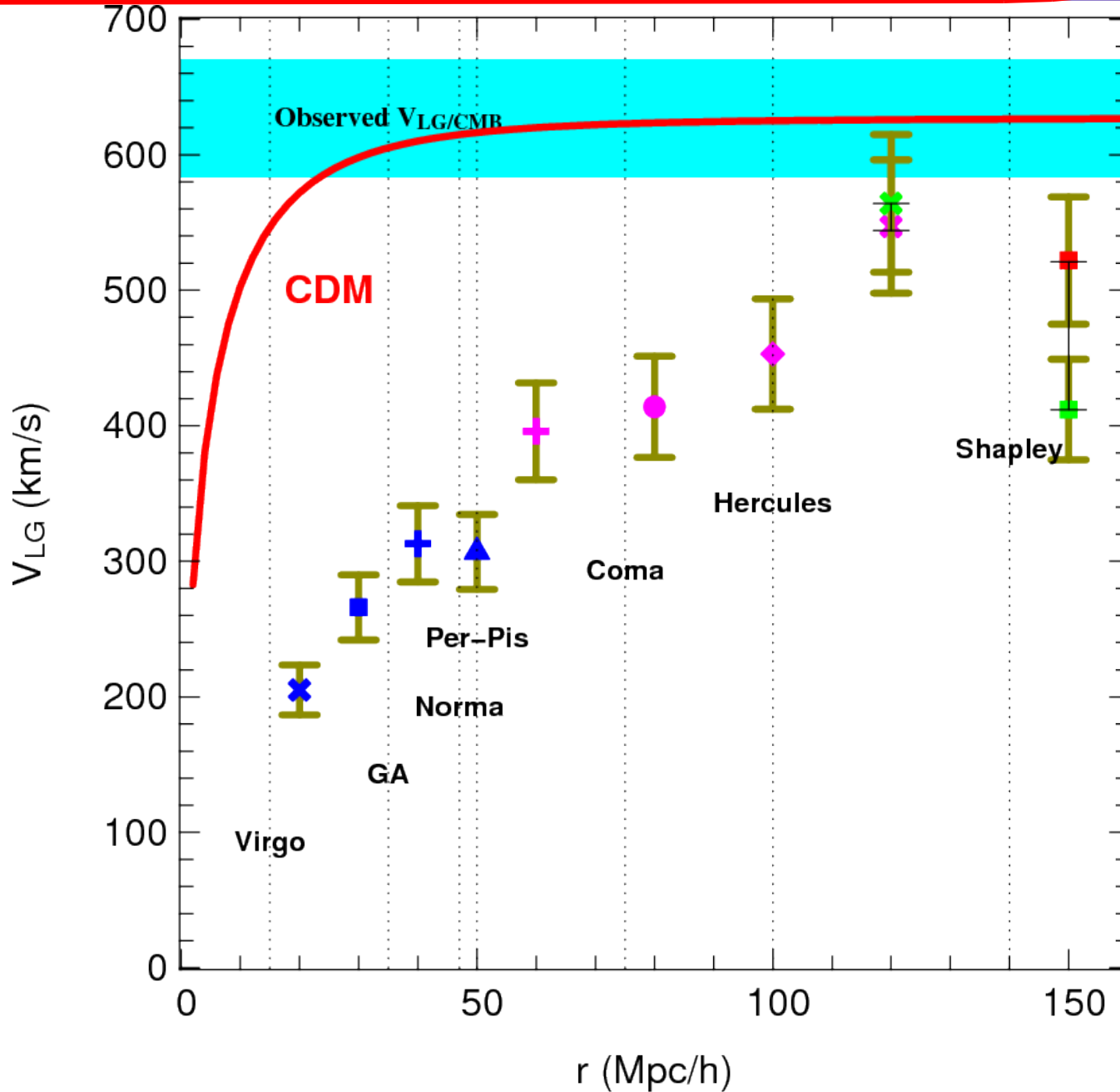


What is the origine of the CMB dipole ?

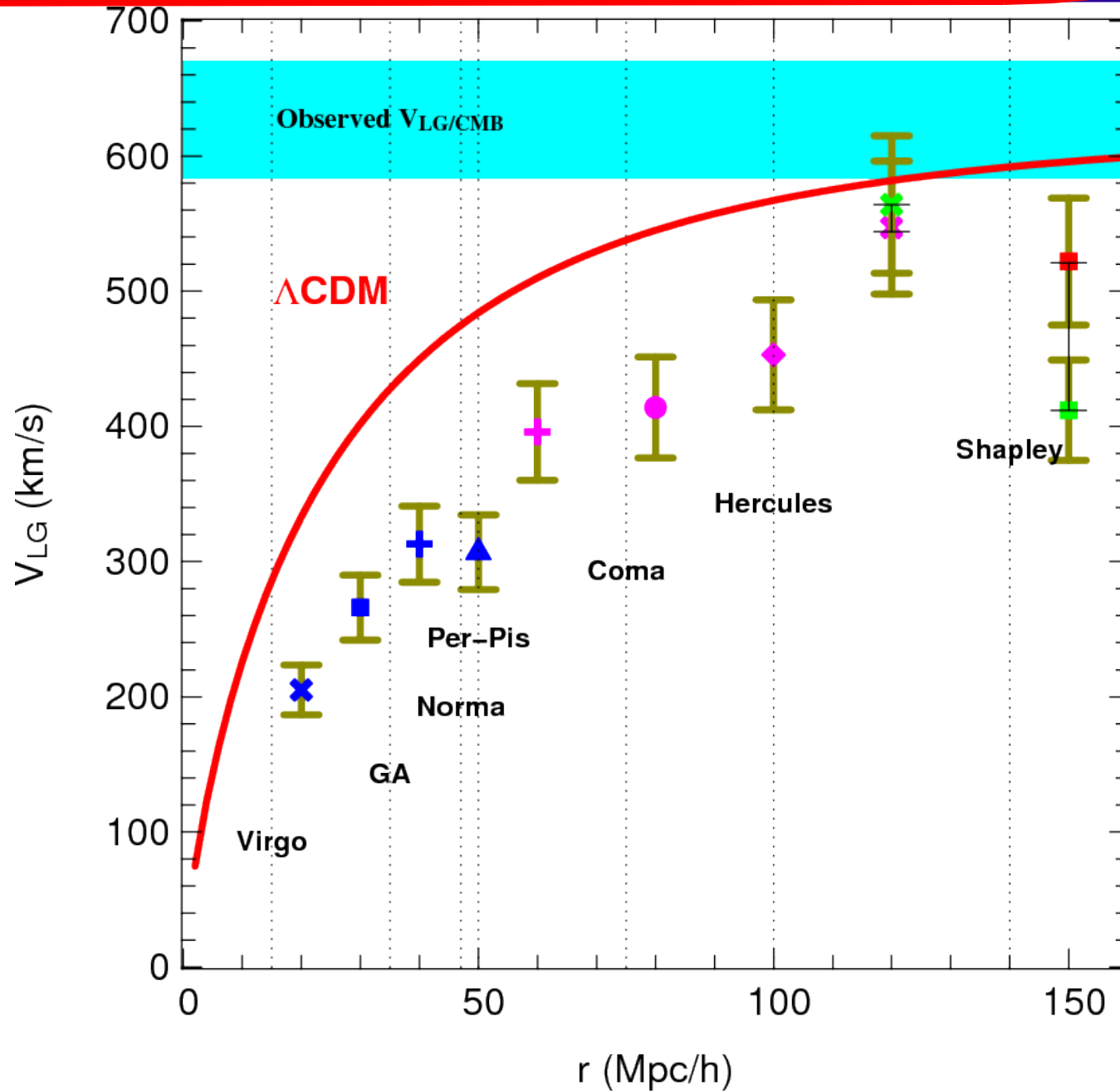
Local Group velocity: amplitude



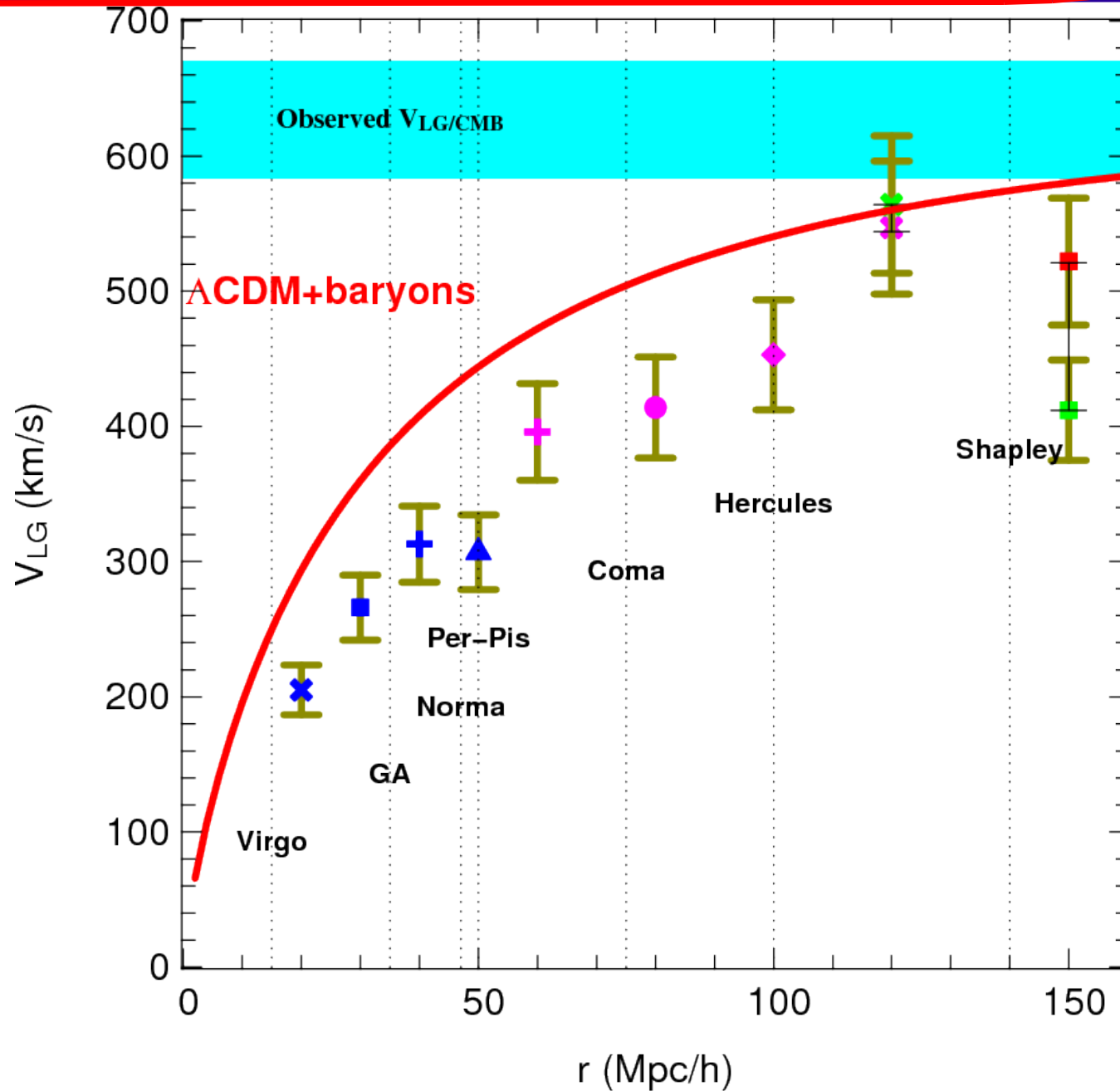
Local Group velocity: CDM



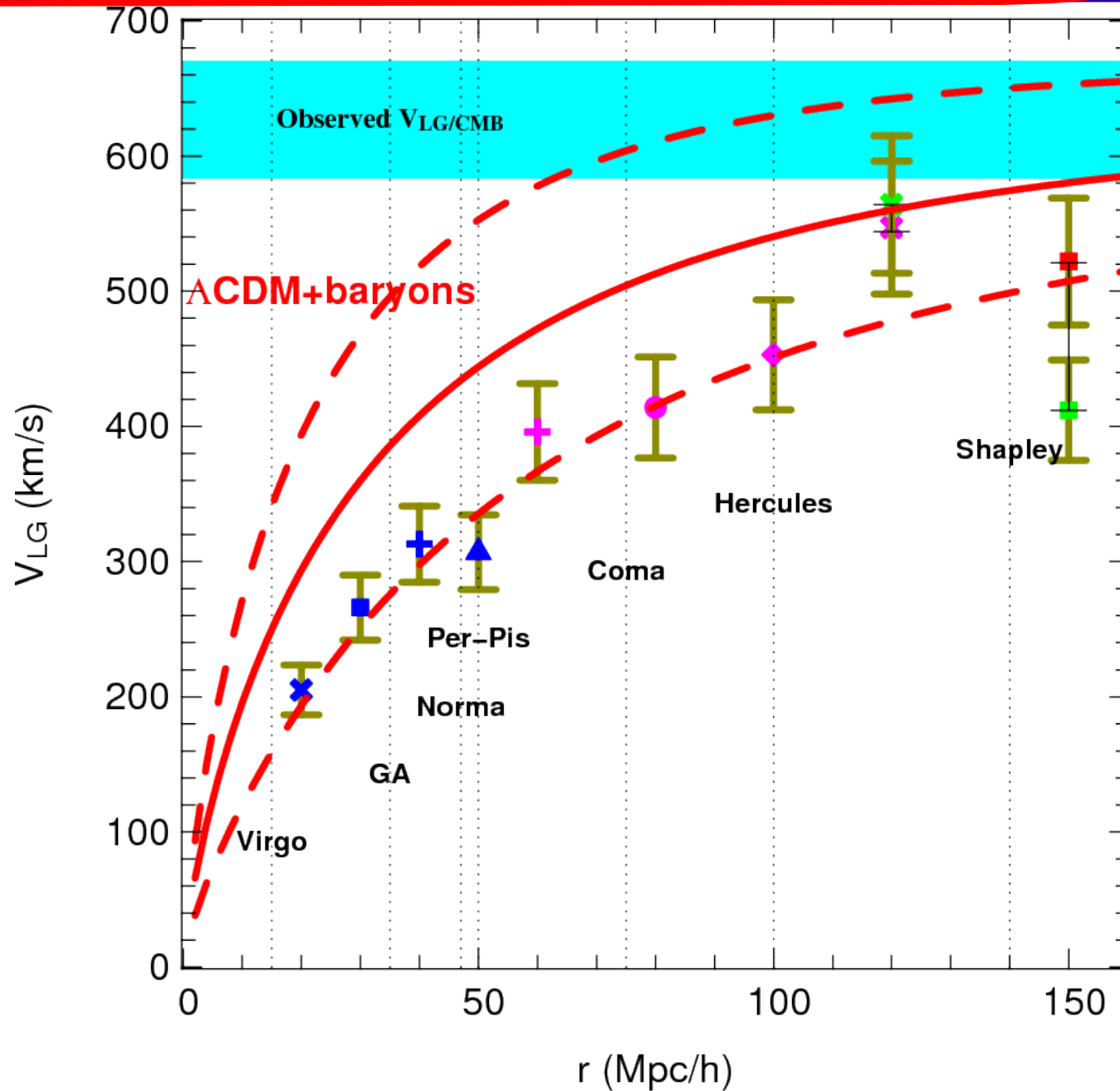
Local Group velocity: Λ CDM



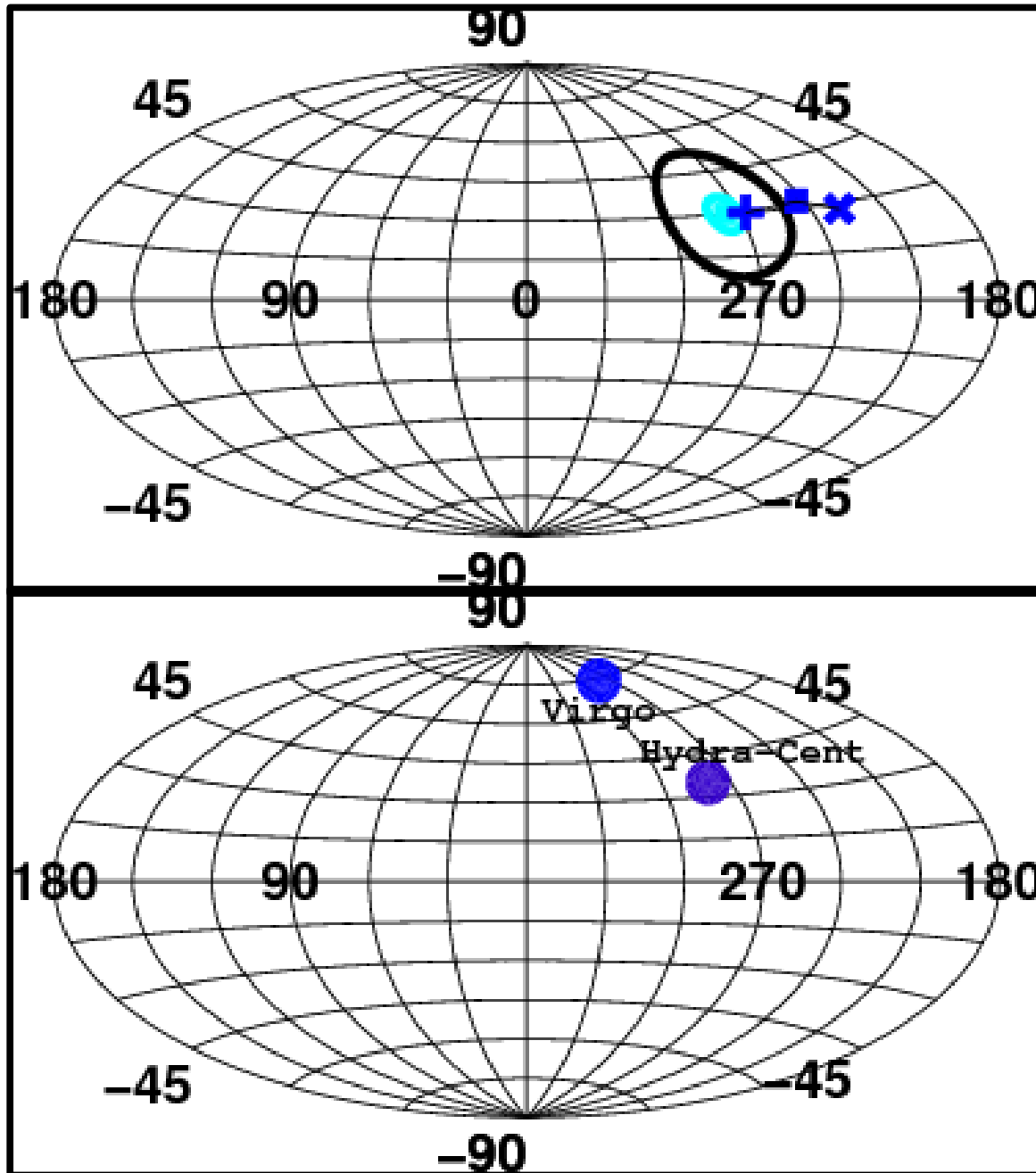
Local Group velocity: Λ CDM+baryons



Local Group velocity: Λ CDM+baryons



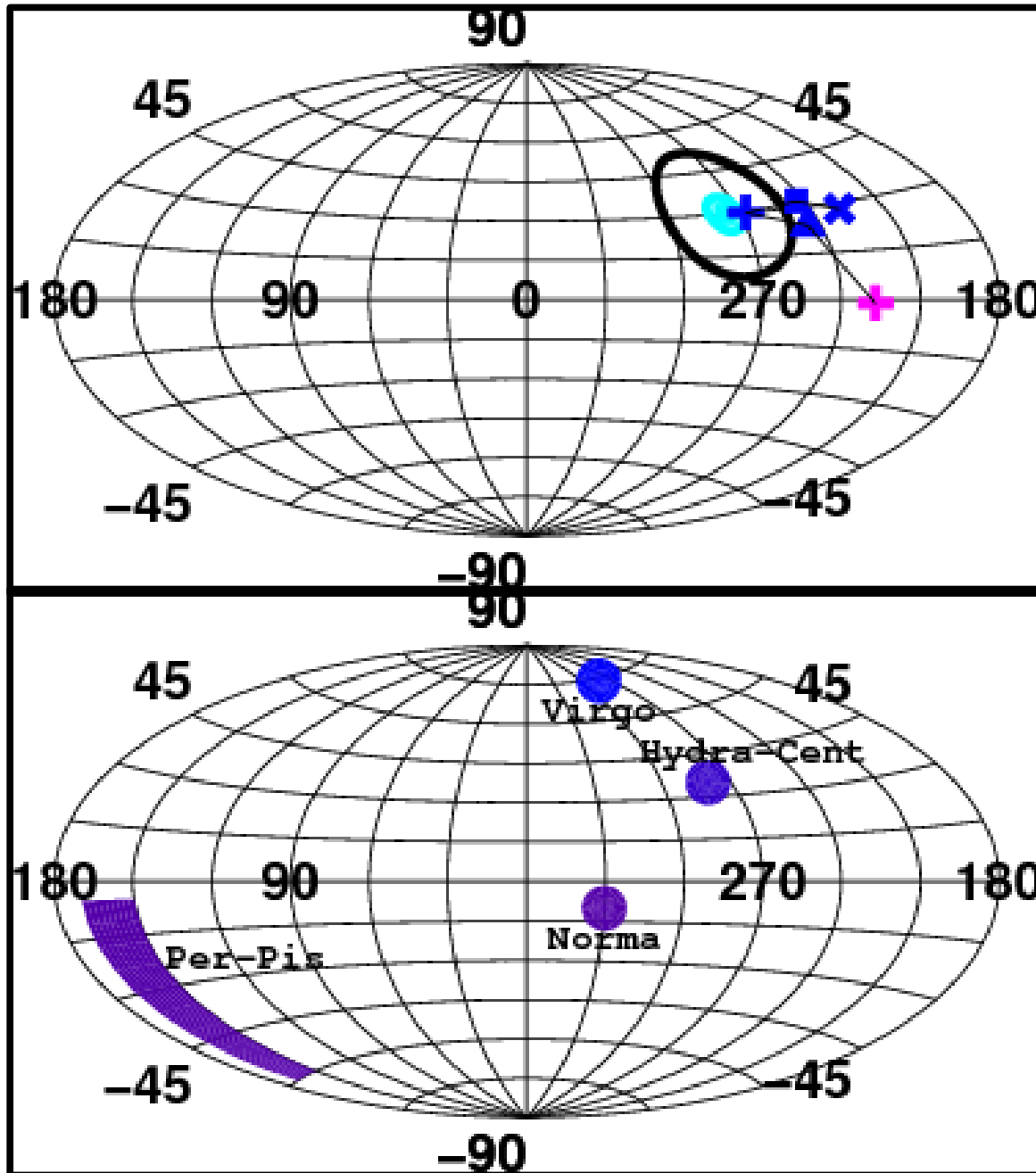
Local Group velocity: direction



40 Mpc/h

Lavaux et al. (2008)

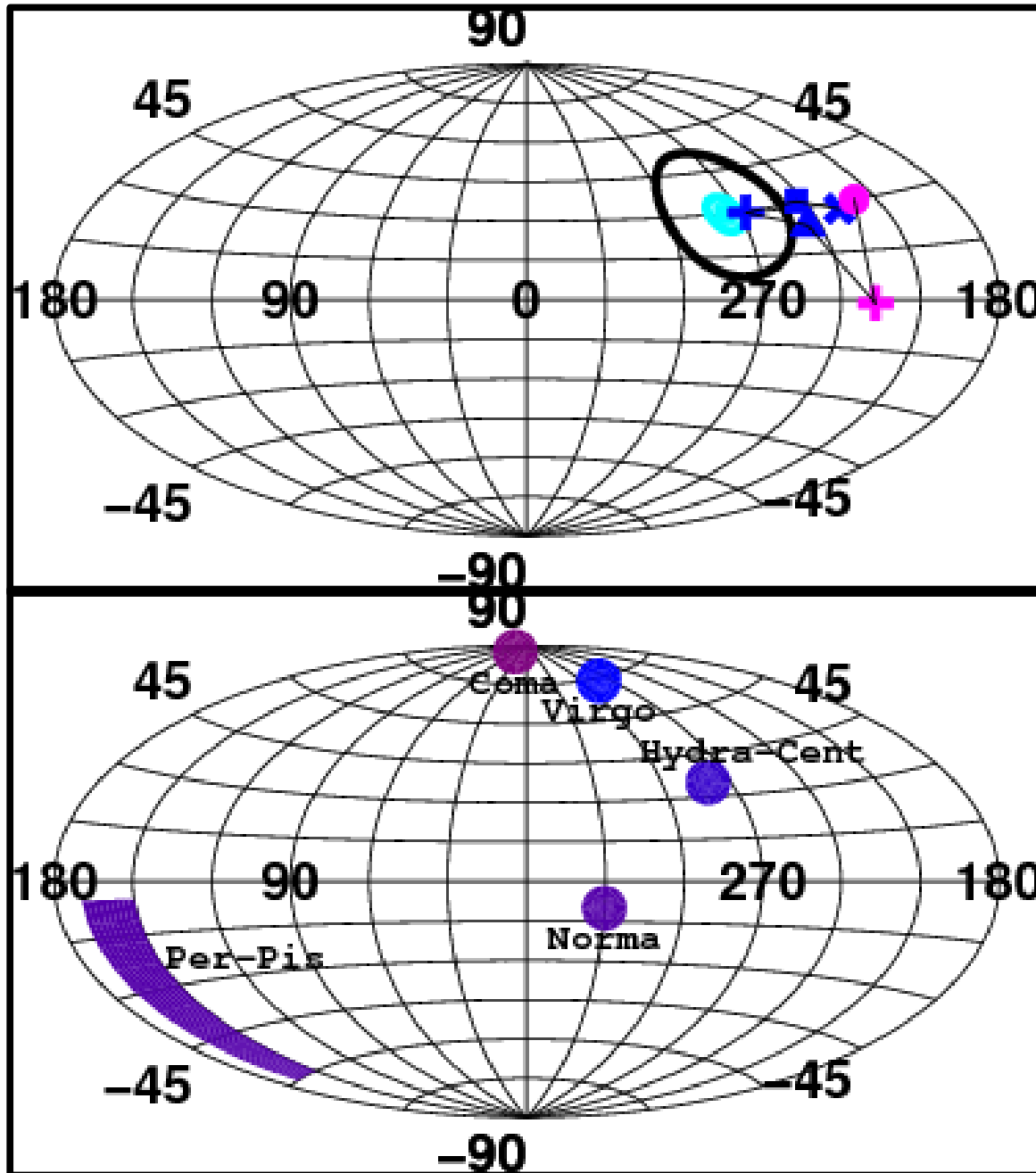
Local Group velocity: direction



60 Mpc/h

Lavaux et al. (2008)

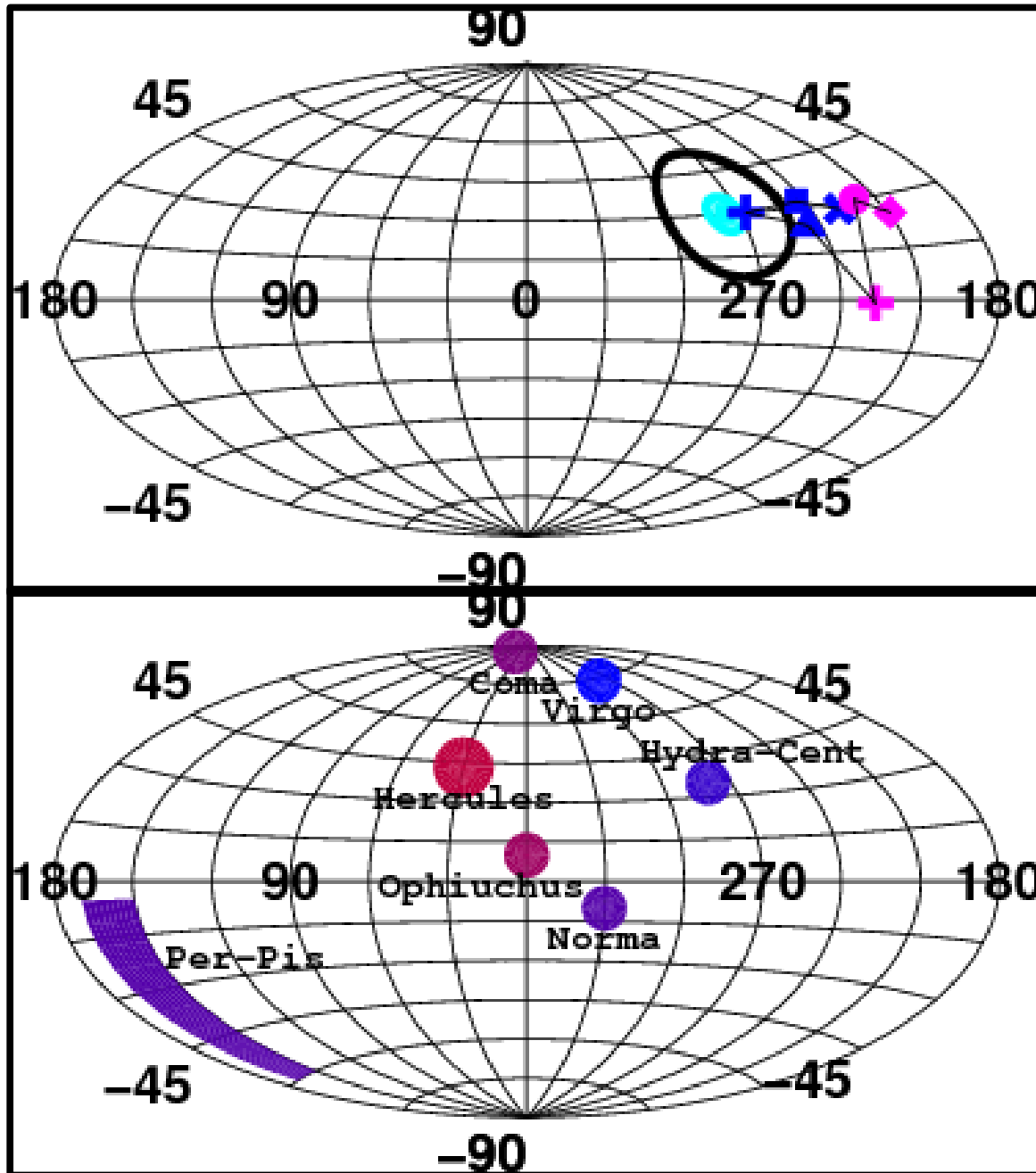
Local Group velocity: direction



80 Mpc/h

Lavaux et al. (2008)

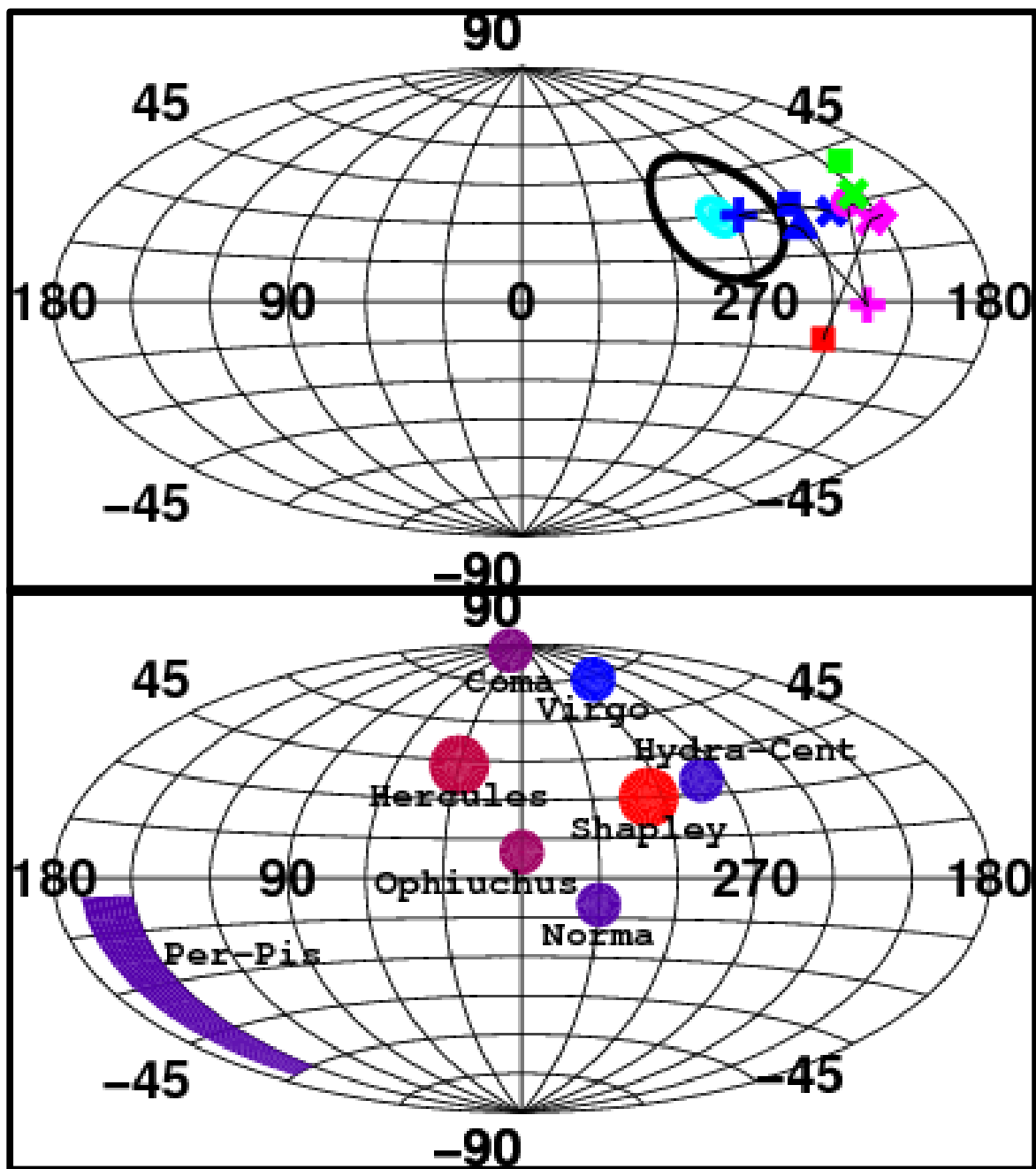
Local Group velocity: direction



100 Mpc/h

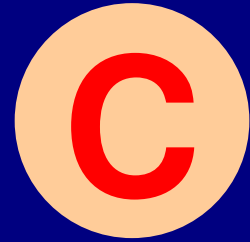
Lavaux et al. (2008)

Local Group velocity: direction



150 Mpc/h

Lavaux et al. (2008)



Conclusion

Conclusion



Lagrangian reconstruction
of peculiar velocities

Test of MAK reconstruction:
simulation & mock catalogs

Used it on 2MRS + NBG-3k

Convergence (or lack of) of the LG velocity

Likelihood formalism

Reconstructed \Leftrightarrow observed velocities:
successful comparison

Comparison with Λ CDM

Conclusion / Perspective



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2MRS + X-ray surveys (like RBC)

Improved modelling with
Euler-Poisson reconstruction

Vlasov-Poisson

More statistical analysis:
• correlation function
• improved likelihood analysis)

Constrained simulation of
the Local Universe

Conclusion / Future



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Constrained simulation of
the Local Universe

6dFGS, SDSS, LSST

Correlation kinetic Sunyaev-Zel'dovich

Correlation with ISW on CMB

Thank you for your attention !

Conclusion



Lagrangian reconstruction
of peculiar velocities

Test of MAK reconstruction:
simulation & mock catalogs

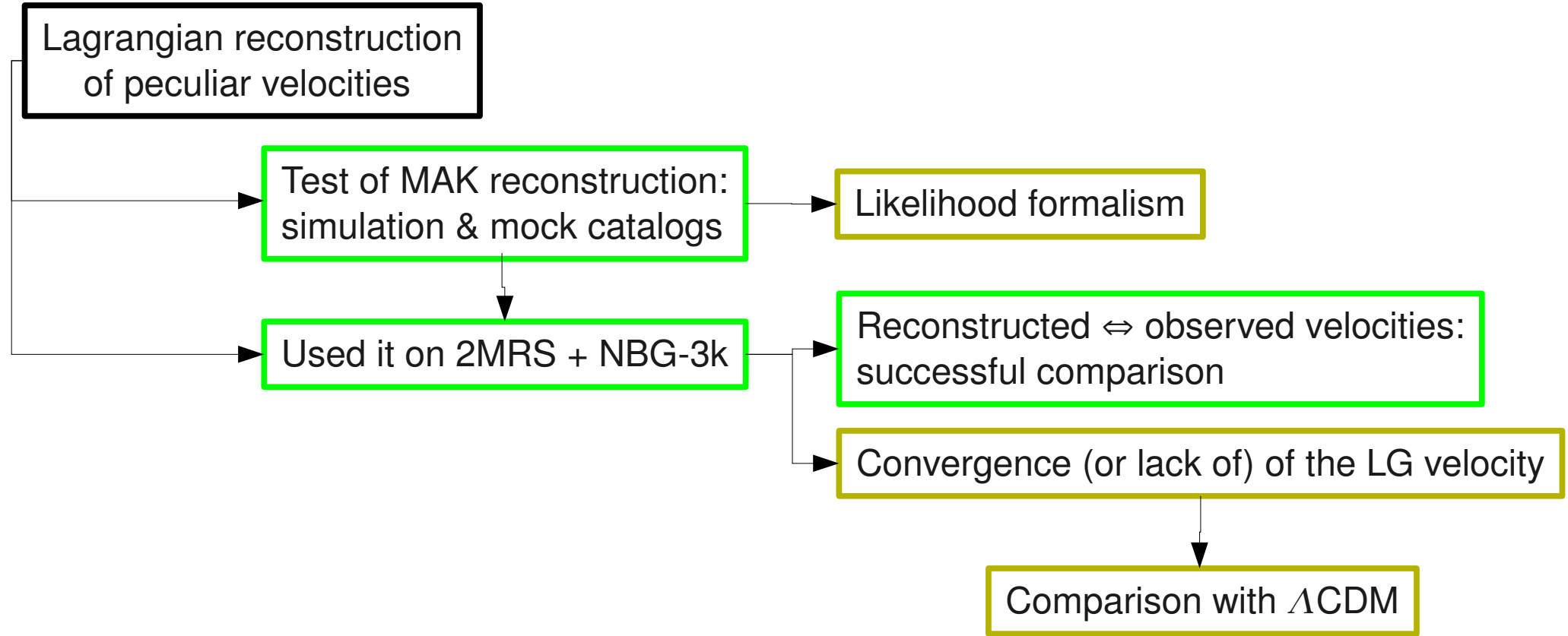
Likelihood formalism

Used it on 2MRS + NBG-3k

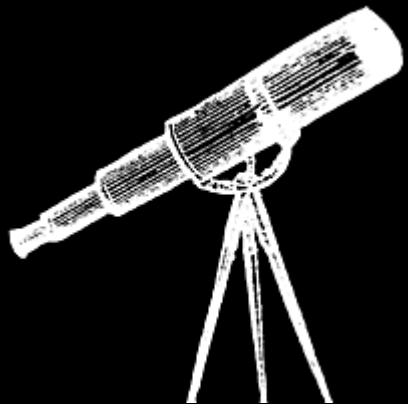
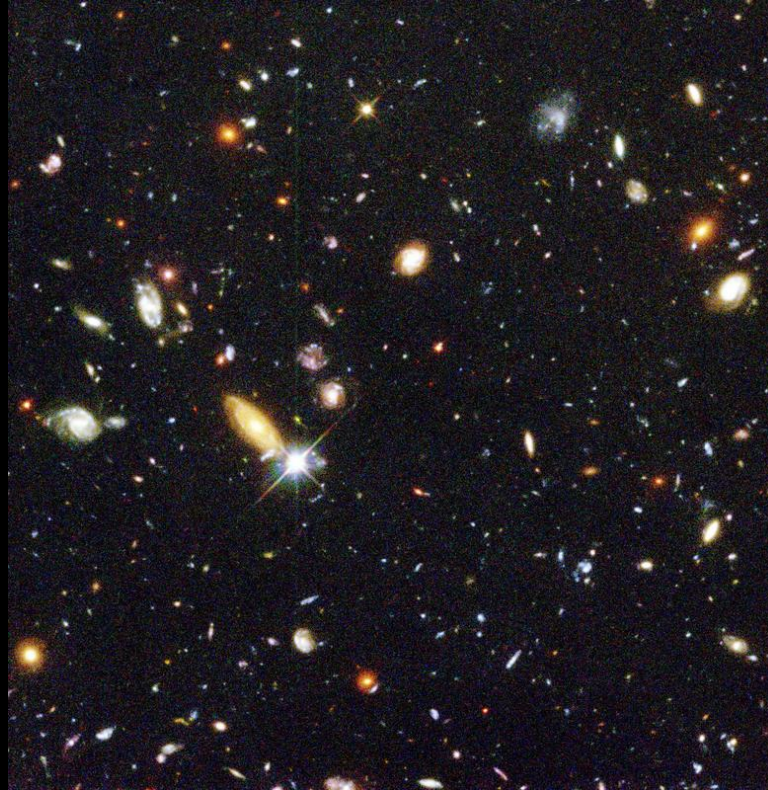
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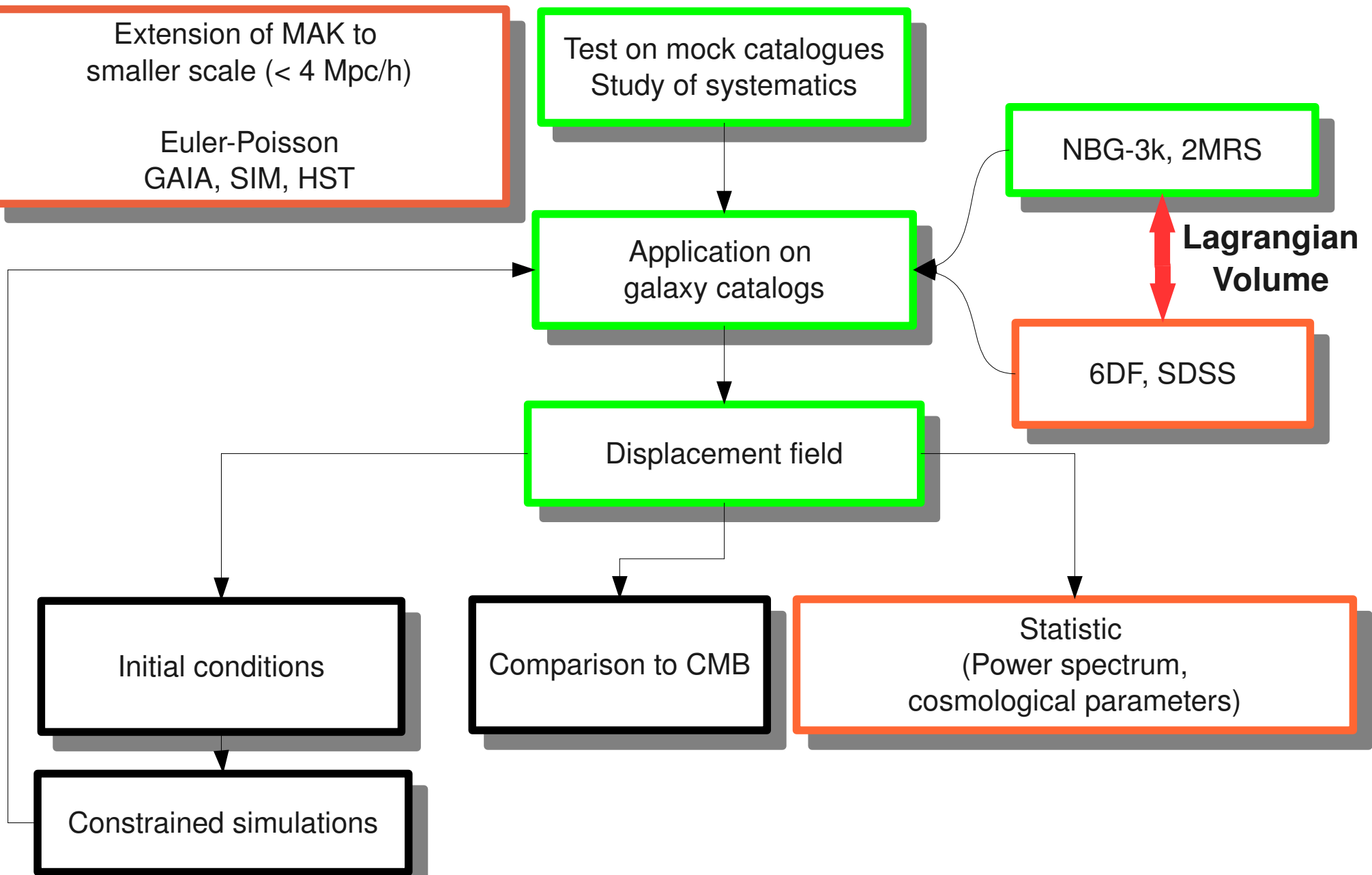


Catalogues of galaxies



Listing of global properties:
luminosity, distance, sky position, shape

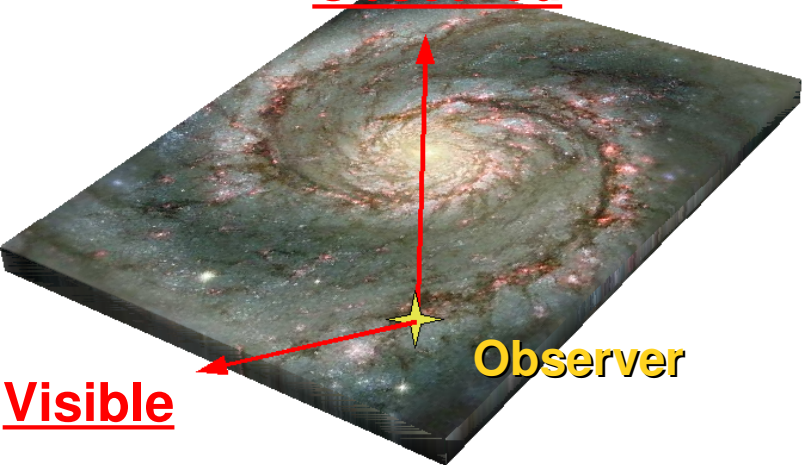
Conclusion / Perspectives



Edge & Finite volume effects

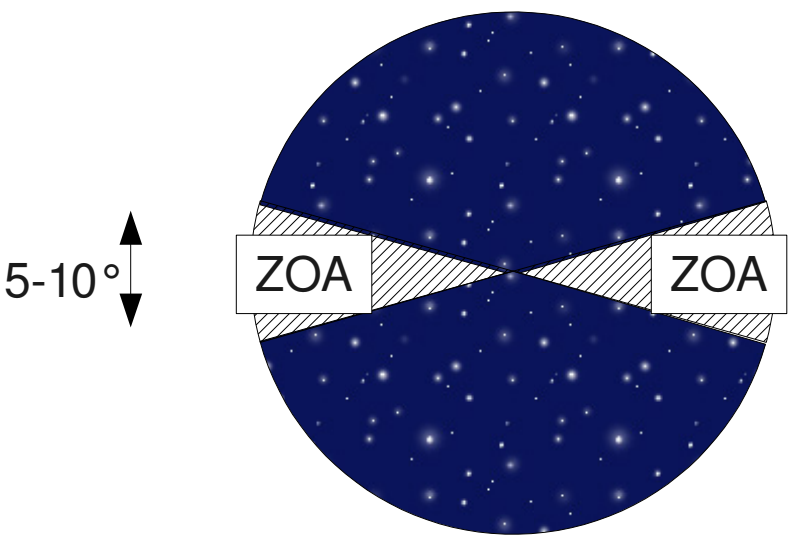


Obscured



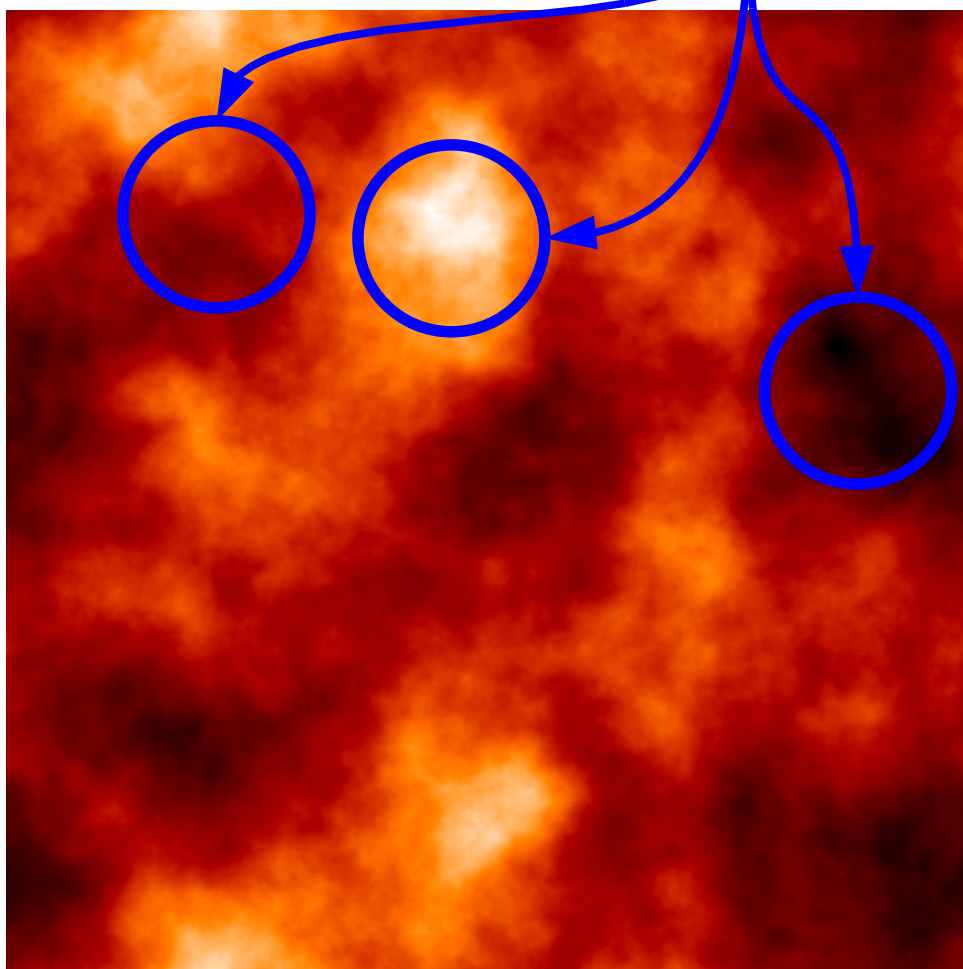
Visible

Observer



Zone of Avoidance

Portion of the universe selected by chance



Cosmic variance

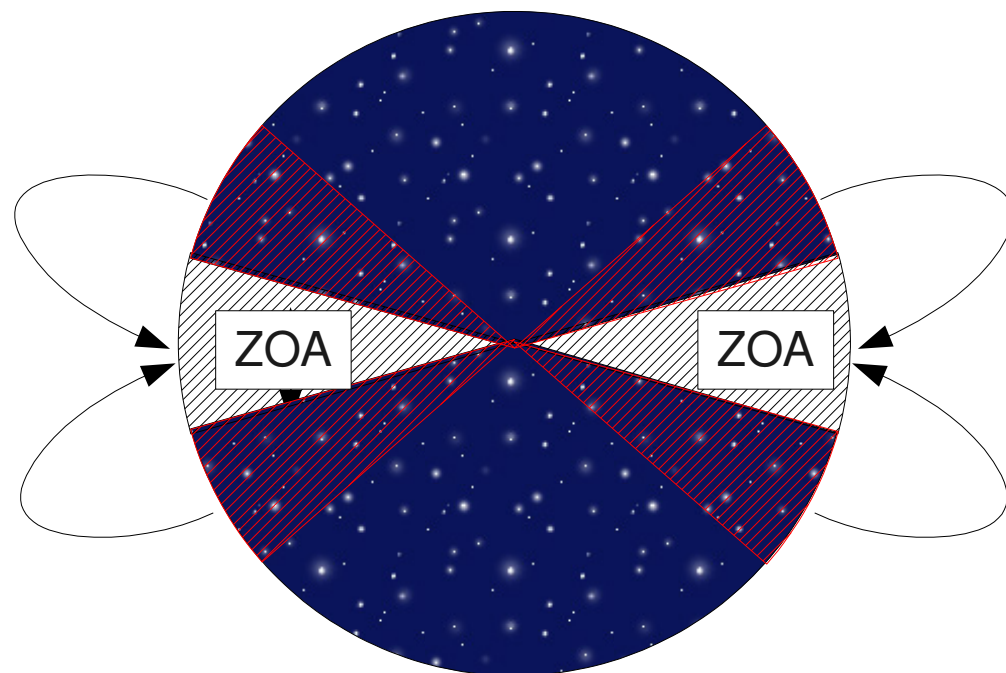
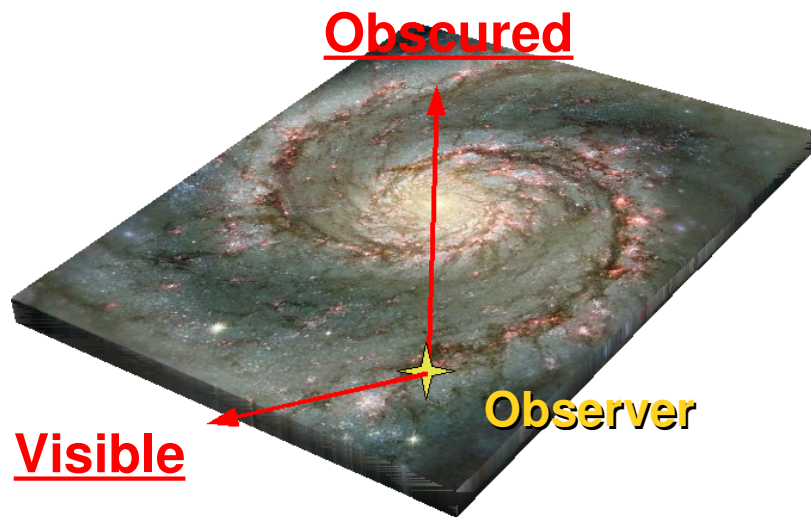
Edge & Finite volume effects



Methods:

- SPH filtering (Fontanot et al. 2003)
- Yahil method (Yahil et al. 1991)
- Shaya method (Shaya et al. 1995) \Rightarrow simplest

Objects folding into the cleared ZOA



Zone of Avoidance

(introduced in Shaya et al. 1995, ApJ)