AIP Leibniz-Institut für Astrophysik Potsdam

Dark matter distribution on small scales

Matthias Steinmetz (AIP)

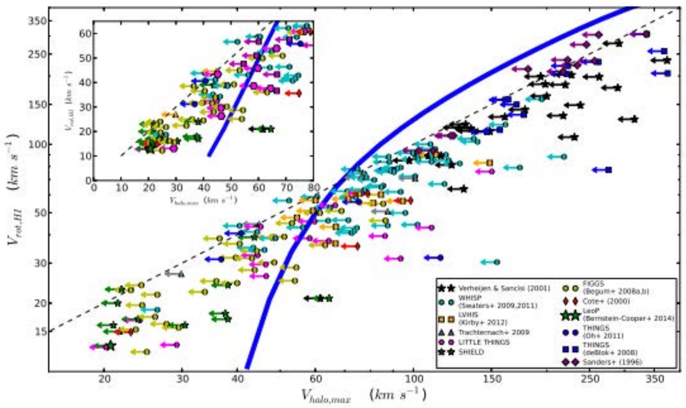
RAVE RADIAL VELOCITY EXPERIMENT

CLUES Constrained Local UniversE Simulations

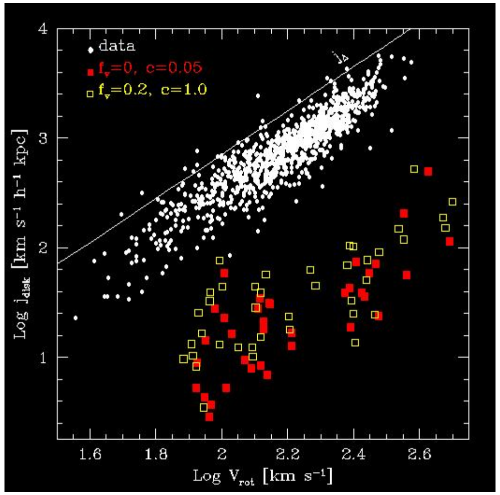
Agenda

- Issues of the LCDM model on small scales ($\lesssim$1Mpc)
- Vast planes of satellites
- Constrained Local UniversE Simulations (CLUES)
- The mass of the Milky Way's dark matter halo and the local dark matter density
- Summary and conclusions

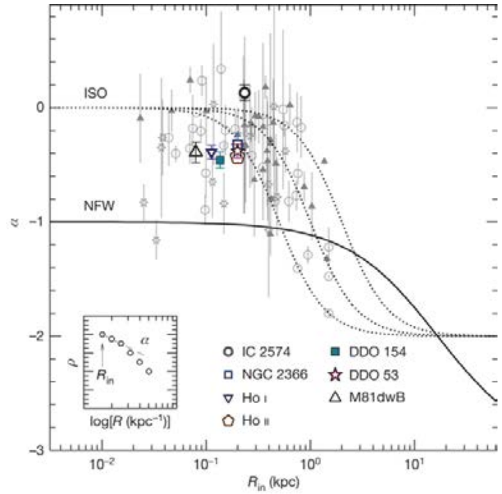
LCDM: Issues an small (≲1Mpc) scales



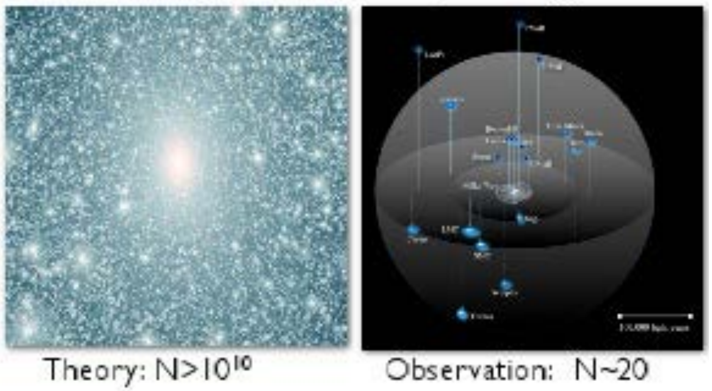
too big to fail



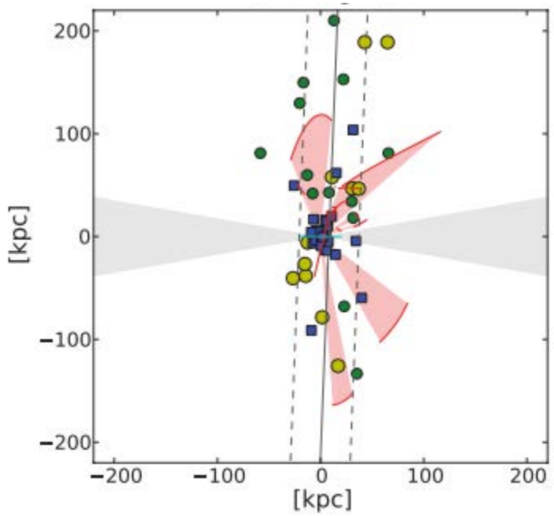
AM catastrophe



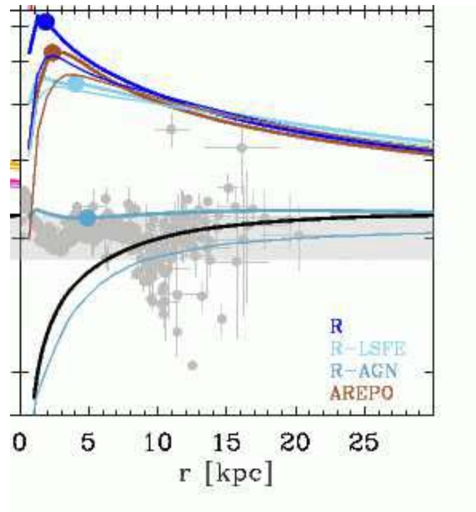
core vs cusp



Substructure crisis



Vast planes of satellites

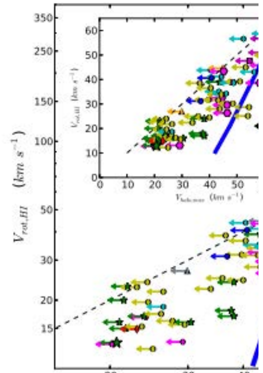


Massive old bulges

LCDM: Issues an small ($\lesssim$1Mpc) scales

- Astrophysics: We do not understand galaxy formation (ISM physics, feedback, AGN, cosmic rays ...)
- Cosmology: The structure formation paradigm is wrong or incomplete at small scales (WDM, SIDM, MOND ...)
- Observations: The observational data is biased or incomplete (Zone of avoidance, completeness limits, beam smearing ...)
- Comparison Theory vs Observations: comparing apples with oranges

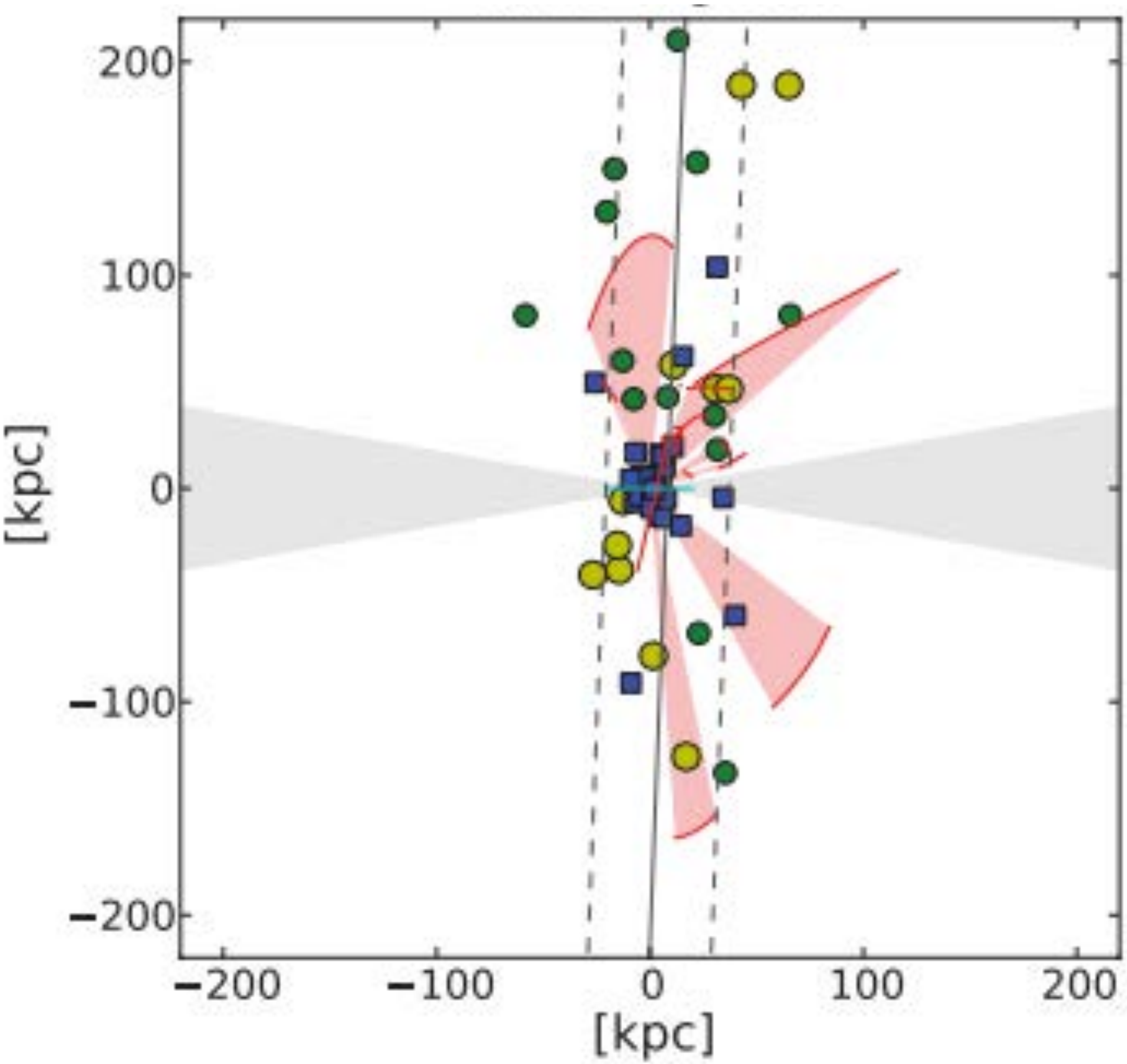
LCDM: Issues an small (≲1Mpc) scales

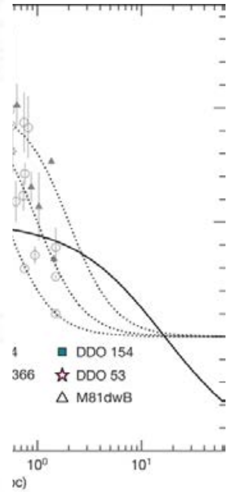


too

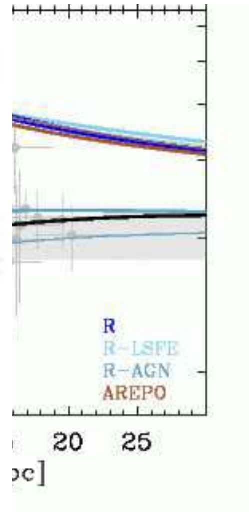
Theory: N>10^10

Sub





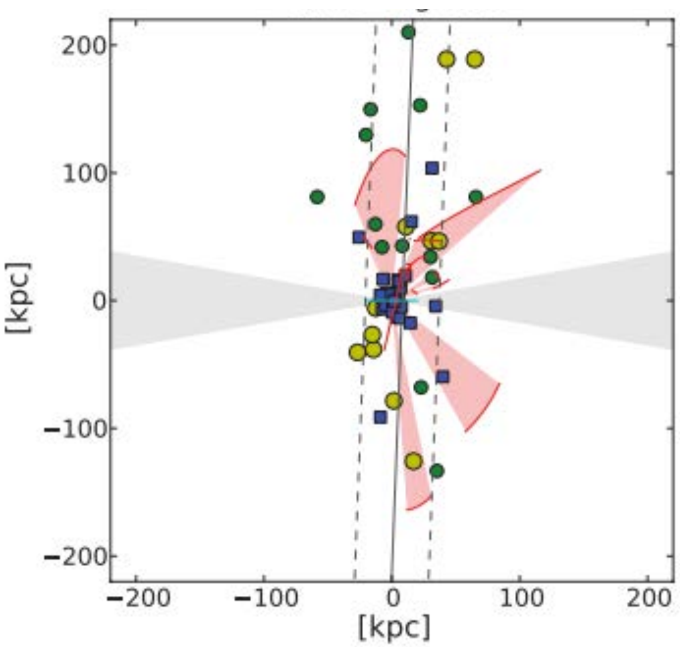
cusp



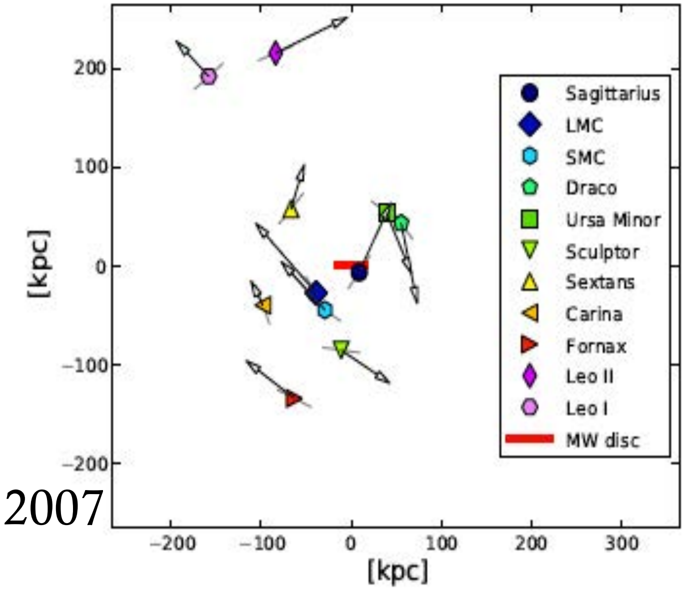
ve old

ges

Milky Way – Vast Polar Orbiting structure (VPOS)



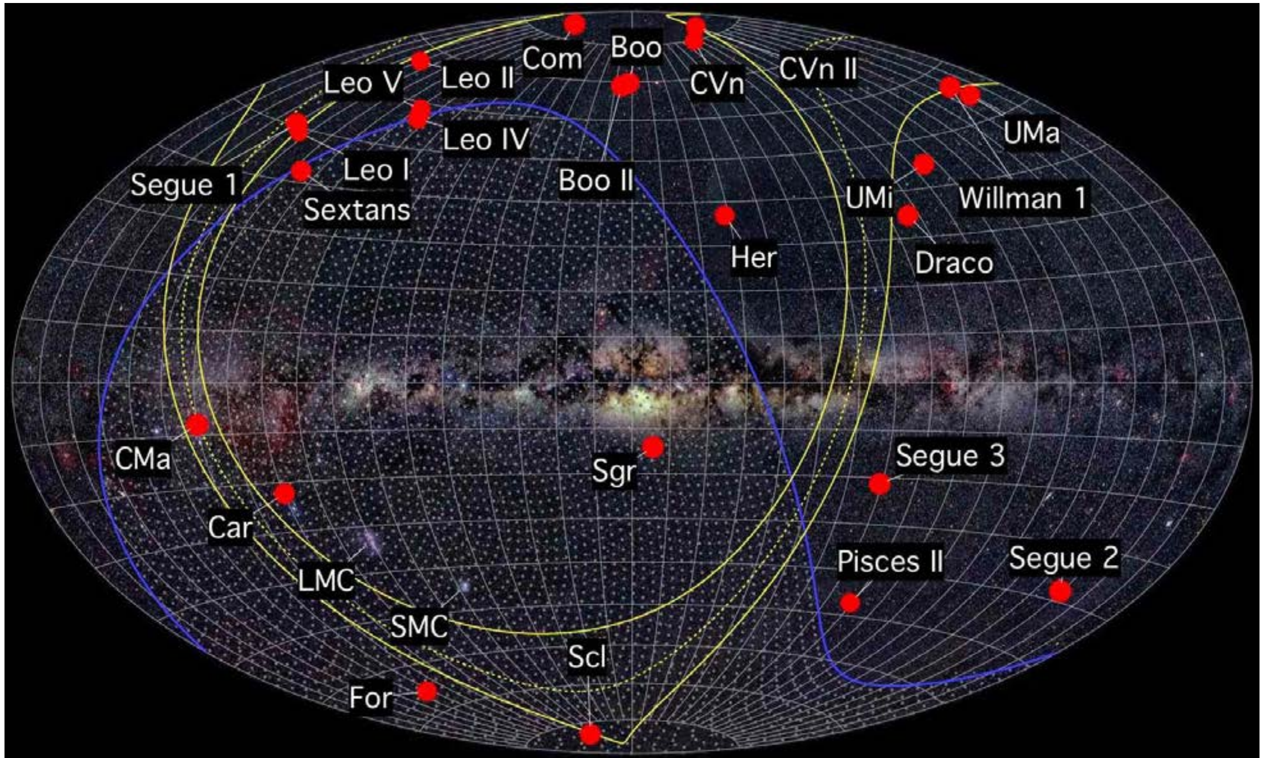
c/a ~ 0.15
Δ_{rms}=24kpc



Metz, Kroupa & Libeskind 2007
Pawlowski & Kroupa 2013

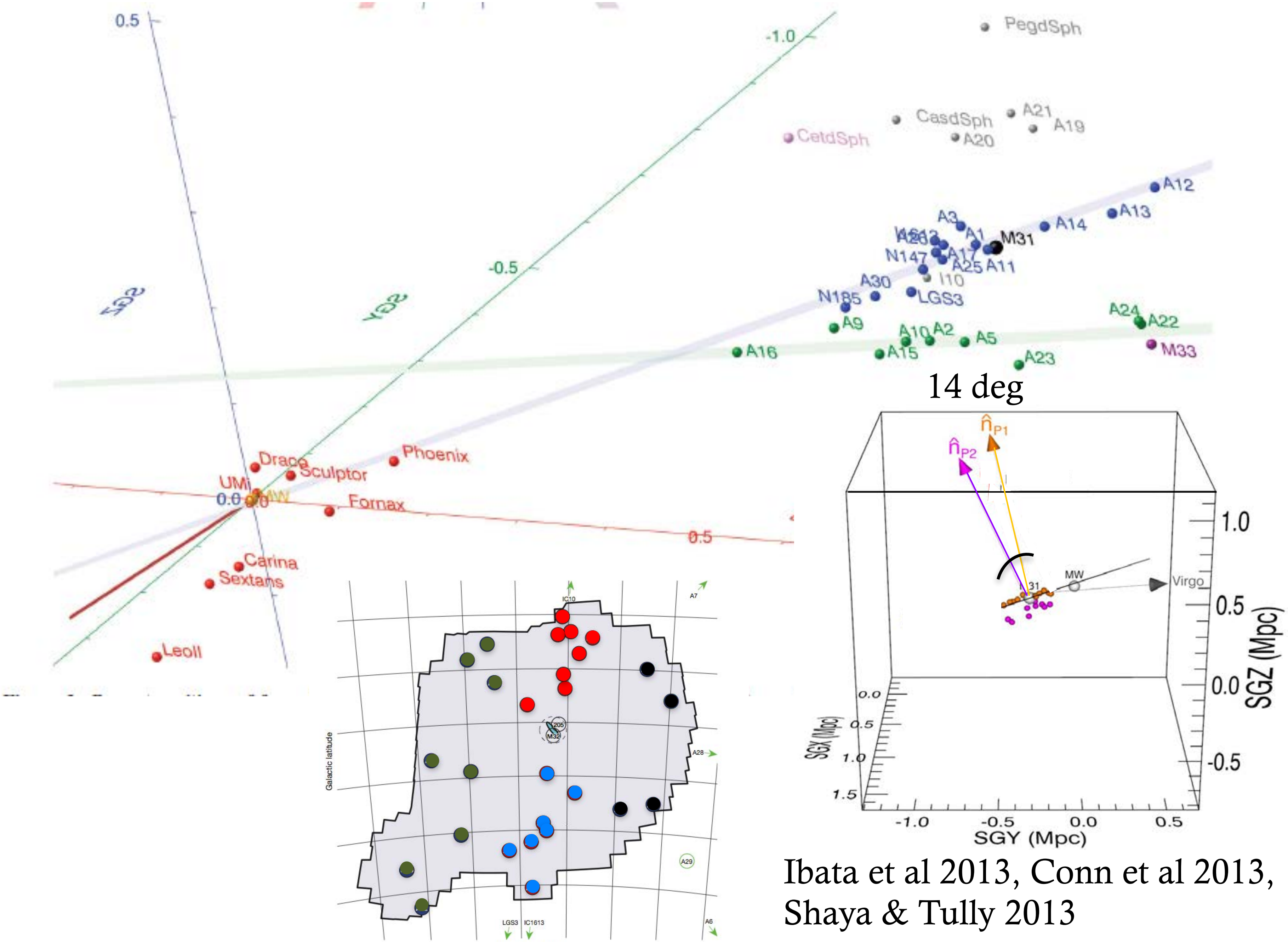
Pawlowski et al 2012
Metz, Kroupa & Jerjen 2007
Kroupa, Theis, Boily 2005

Kunkel & Demers 1975
Lynden-Bell 1976, 1982
Lynden-Bell & Lynden Bell 1982



Sloan Digital Sky Survey (SDSS)

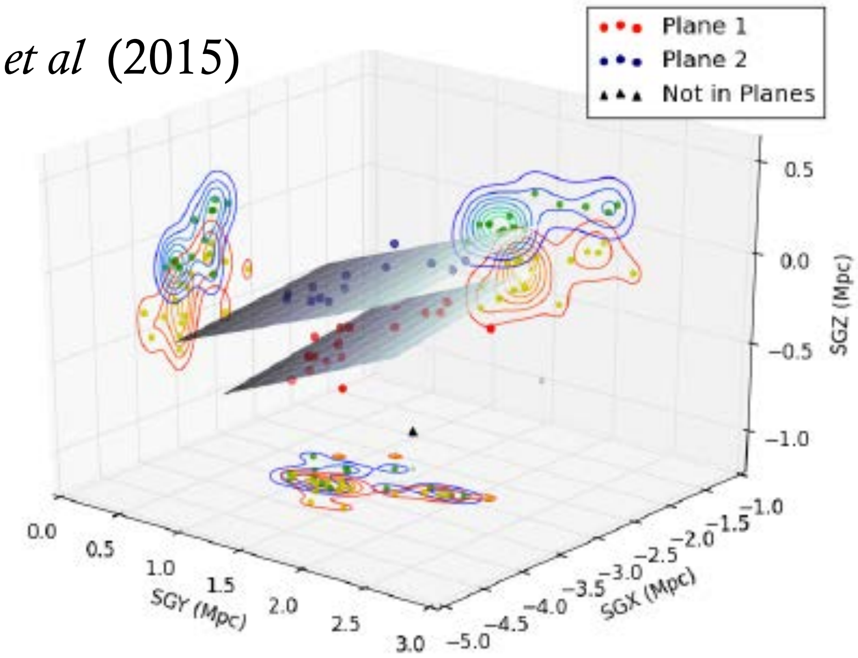
Andromeda – 2 planes, one co-rotating.

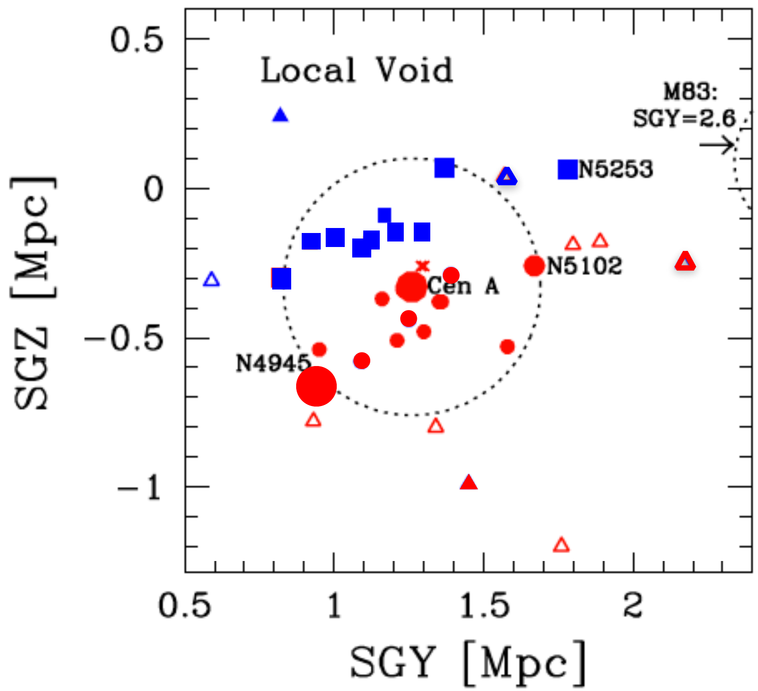


Ibata et al 2013, Conn et al 2013,
Shaya & Tully 2013

Centaurus A Planes

Tully *et al* (2015)





36 galaxies in total, 29 with distances

16 in plane 1
11 in plane 2
2 not in either

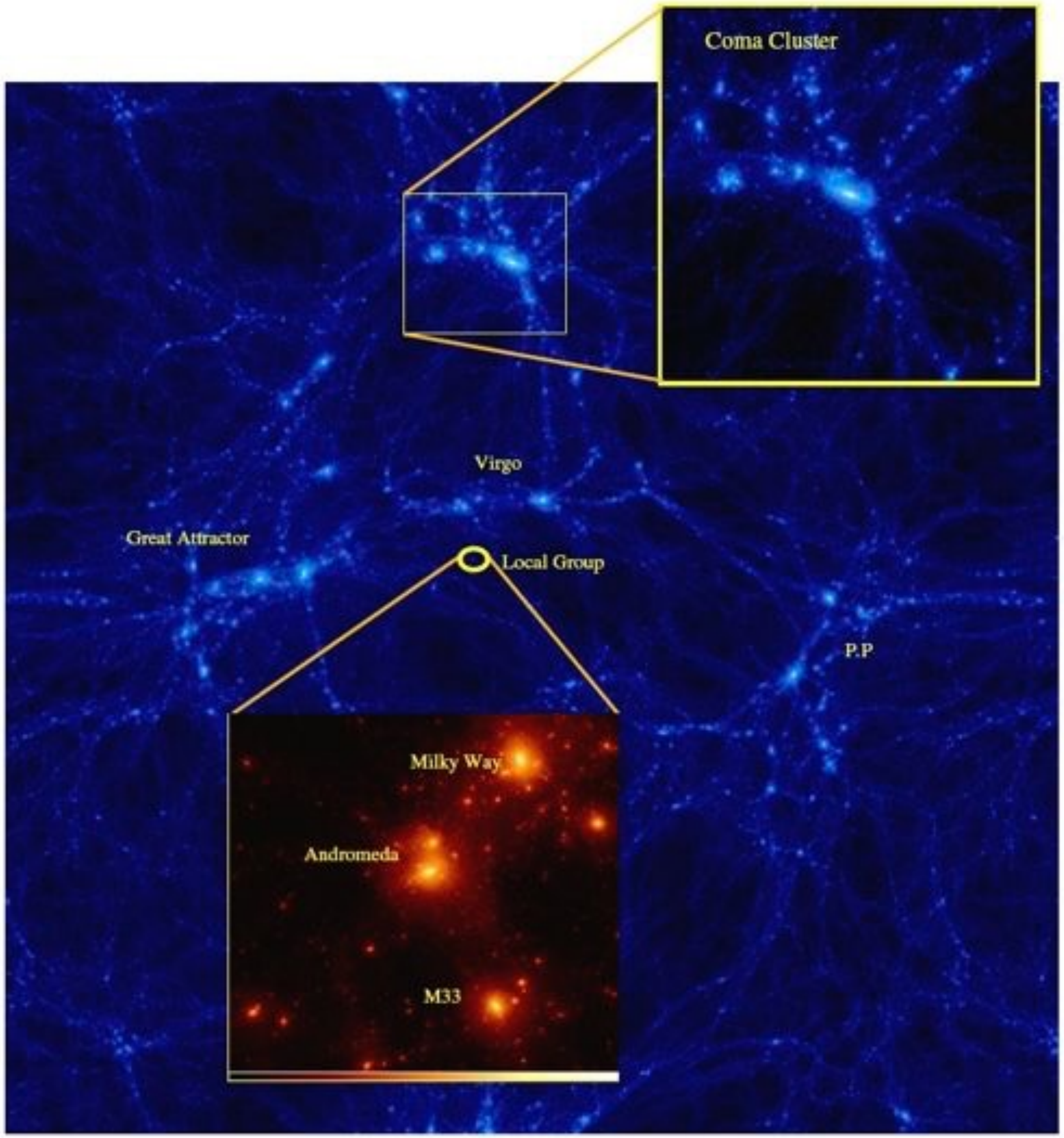
7 without distances of which
+4 could be Plane 1 and
+2 in plane 2

	Plane 1 (all)	Plane 1 (good)	Plane 2 (all)	Plane 2 (good)
a_{rms}	397 kpc	346 kpc	413 kpc	250 kpc
b_{rms}	287 kpc	203 kpc	200 kpc	236 kpc
c_{rms}	79 kpc	73 kpc	48 kpc	47 kpc
c/a	0.2	$\boxed{0.21}$	0.12	$\boxed{0.19}$
b/a	0.72	0.60	0.50	0.95
c/b	0.28	0.36	0.24	0.2

Vast planes of satellites

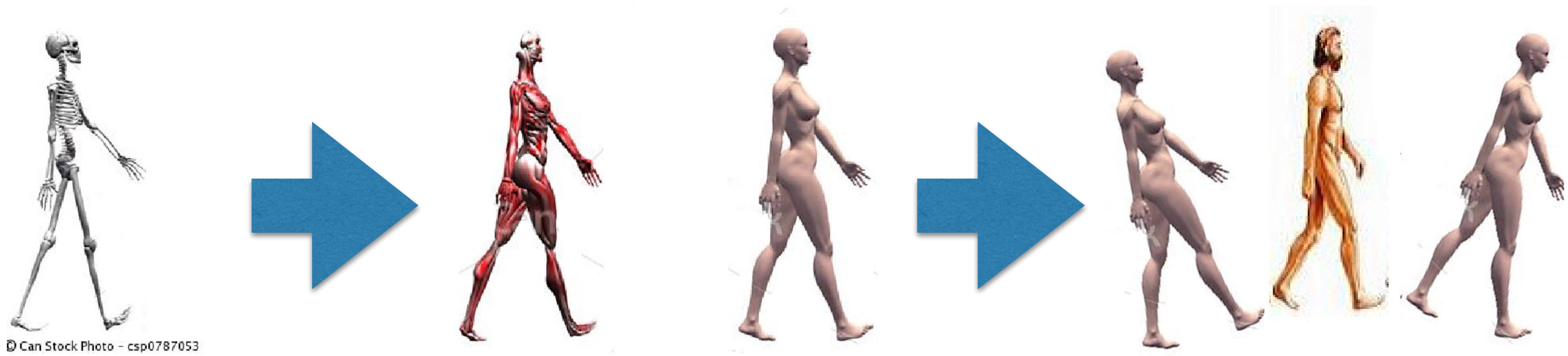
- 5 such planes discovered in the Local Group
  - they are very thin (~50kpc)
  - kinematically consistent (Andromeda: rotating?)
  - Dark Energy Survey: newly discovered satellites fall into the same plane
- Statistical fluke of the Local Group?
- If ubiquitous in the universe, then they pose an interesting challenge to LCDM
  - standard DM modification (SIDM, WDM) would not provide a solution (actually, it would be even more difficult)
  - Astrophysics:
    - tidal torque theory: disks tend to be perpendicular to the local sheet (Navarro, Abadi + MS, 2004)
    - correlations between large scale matter infall and „lighting up“ dwarf halos?

How to simulate the Local Universe?



$160h^{-1}$ Mpc

Constrained Simulations (from thesis J. Sorce)



Constraints from Observations

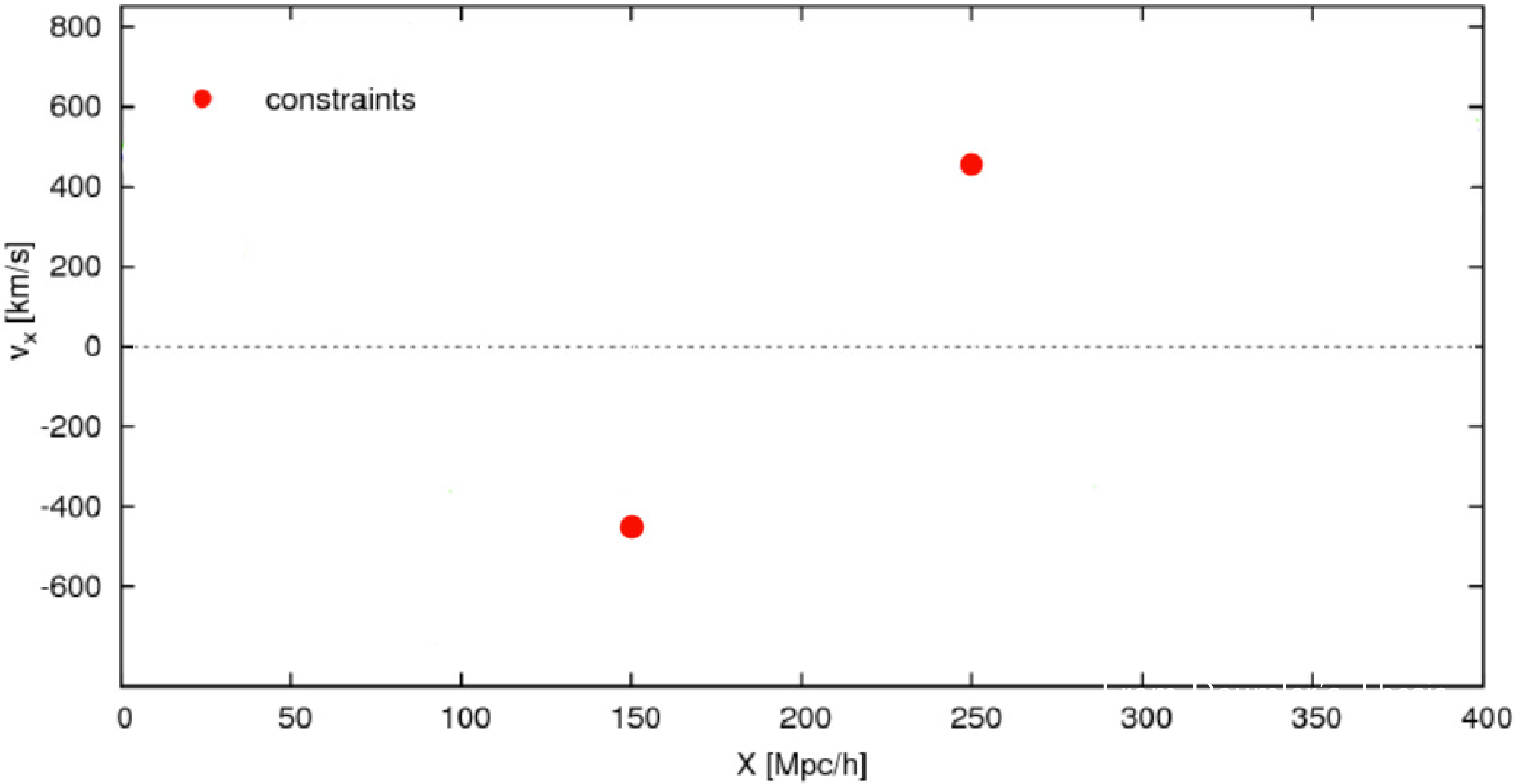
Reconstruction

Realizations

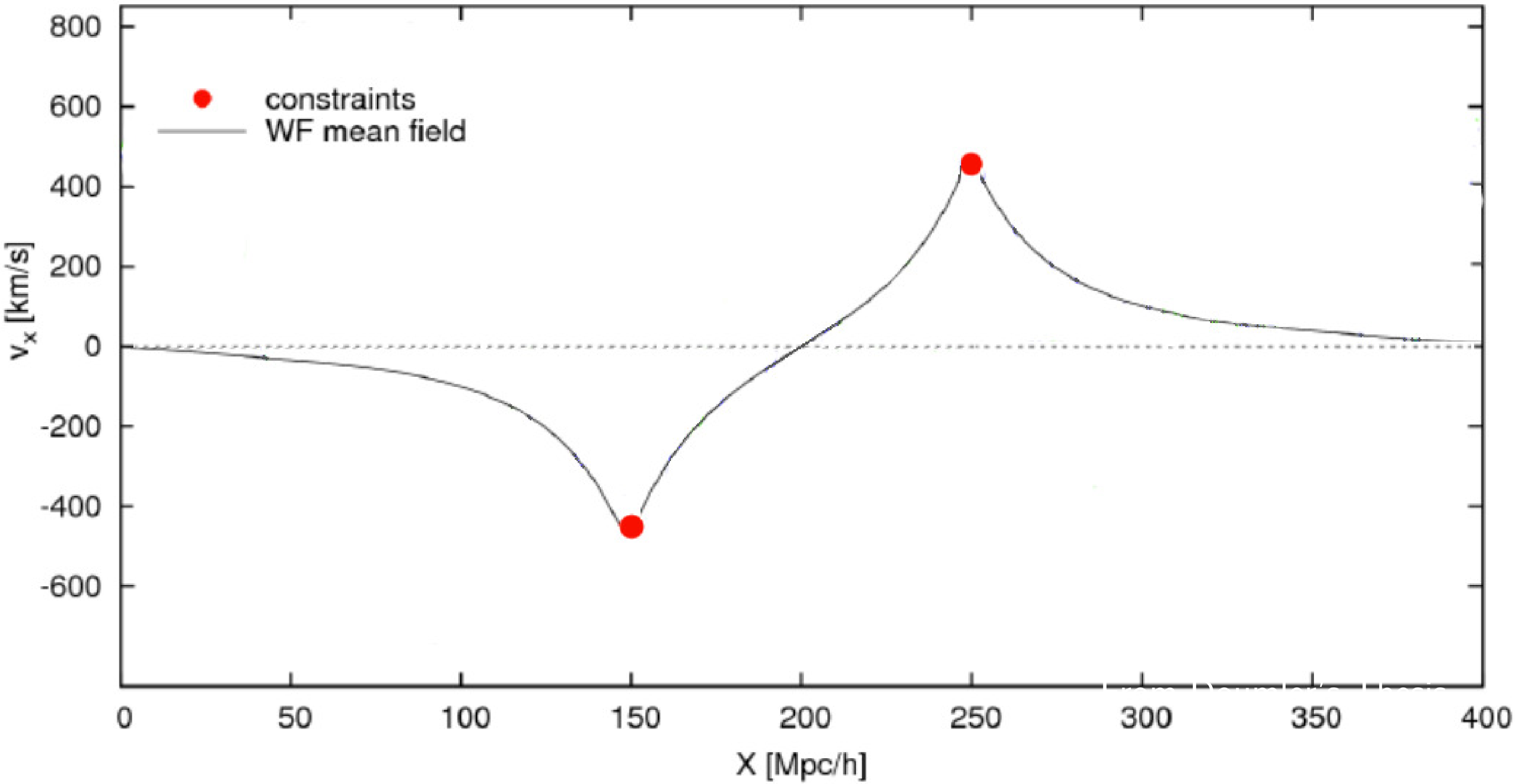
Initial Conditions

Constrained Simulation of Evolution

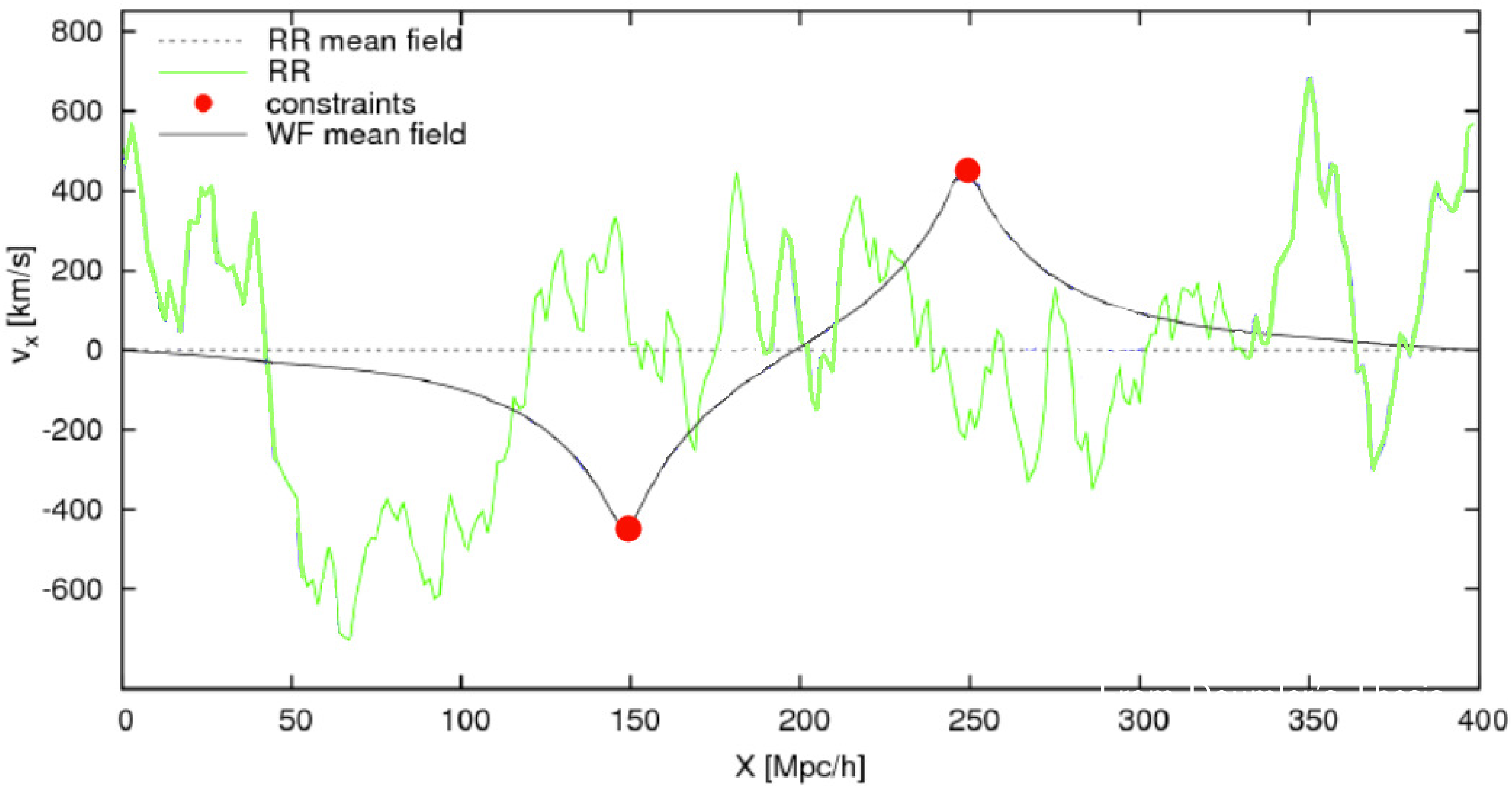
1D example - constraints



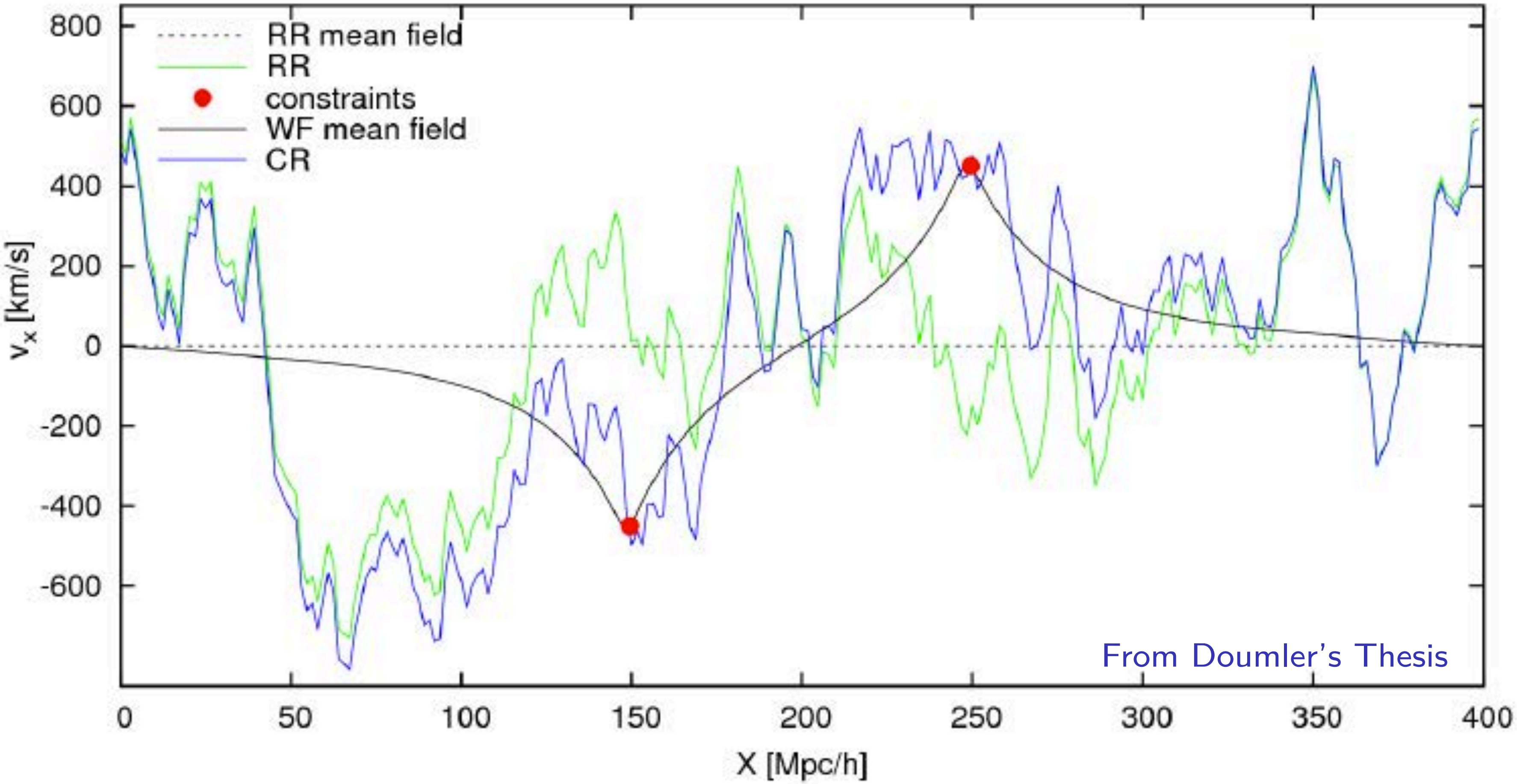
1D example - mean field



1D example - reduced power spectrum realization



1D example - constrained random field

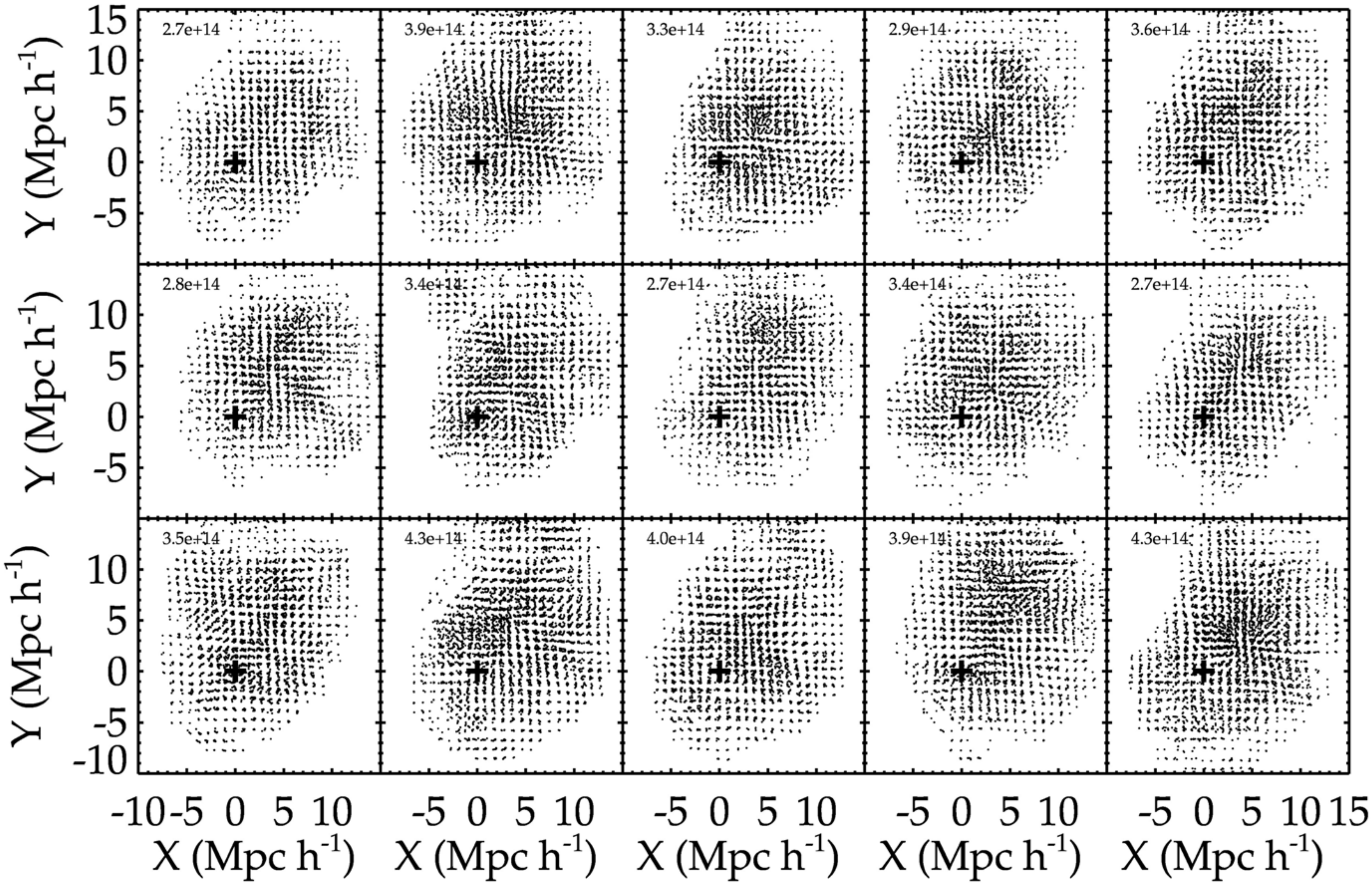


Hoffman & Ribak, 1991

Reconstruction and Resampling of Density Fields

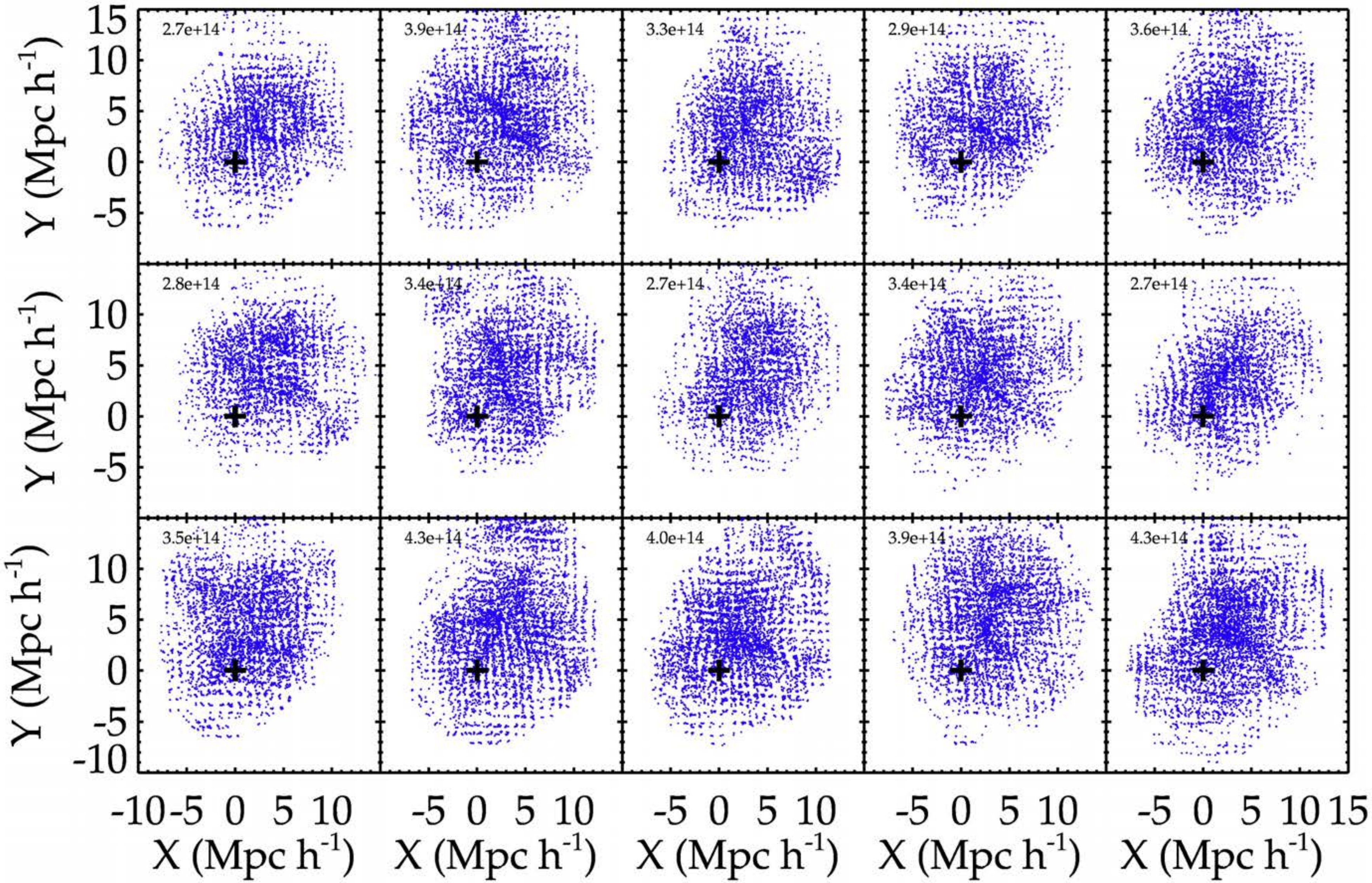
- constraining Gaussian random fields (Hoffman & Ribak, 1991)
- radial velocity field (MARK III, Willick et al., 1997, Tonry 2001, Karachentsev 2004, Tully+Courtois 2013)
- nearby cluster positions (Reiprich & Böhringer, 2002)
- 2MASS galaxy distribution
- reconstruct the underlaying density field
- create a Gaussian representation of this density field

Example Virgo (12 realizations) $z=10$

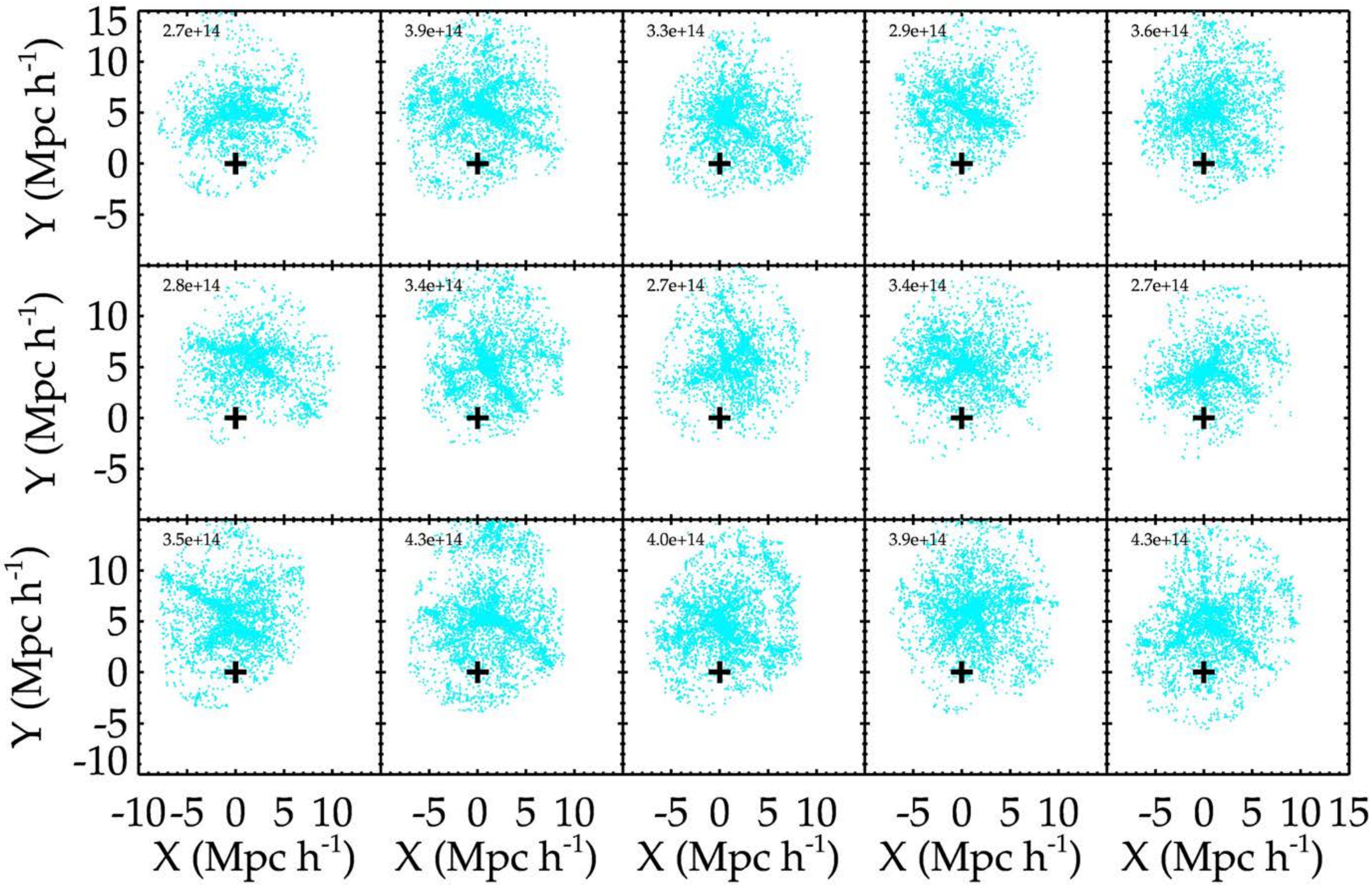


Example Virgo (12 realizations)

z=5

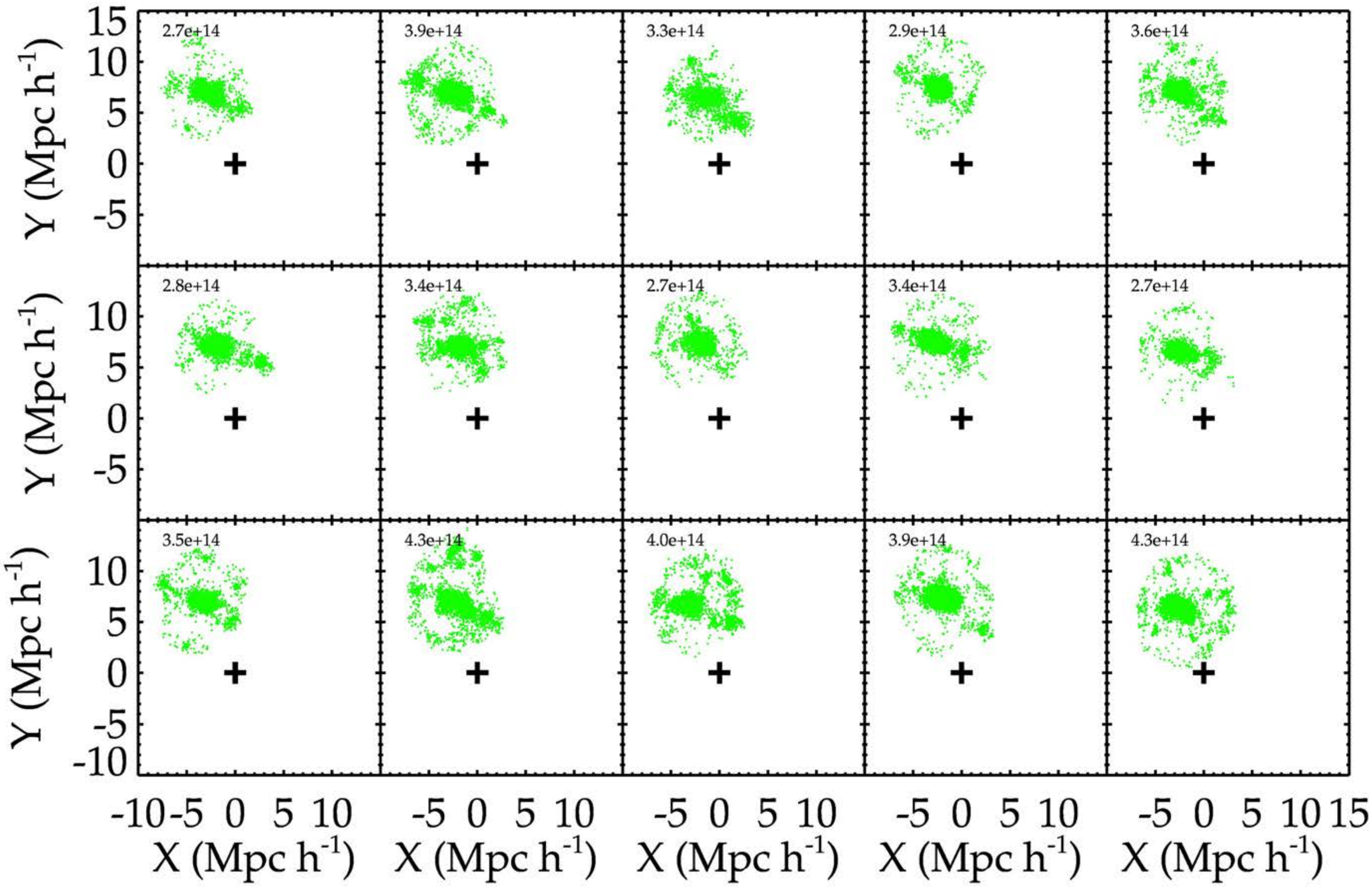


Example Virgo (12 realizations) $z=2$



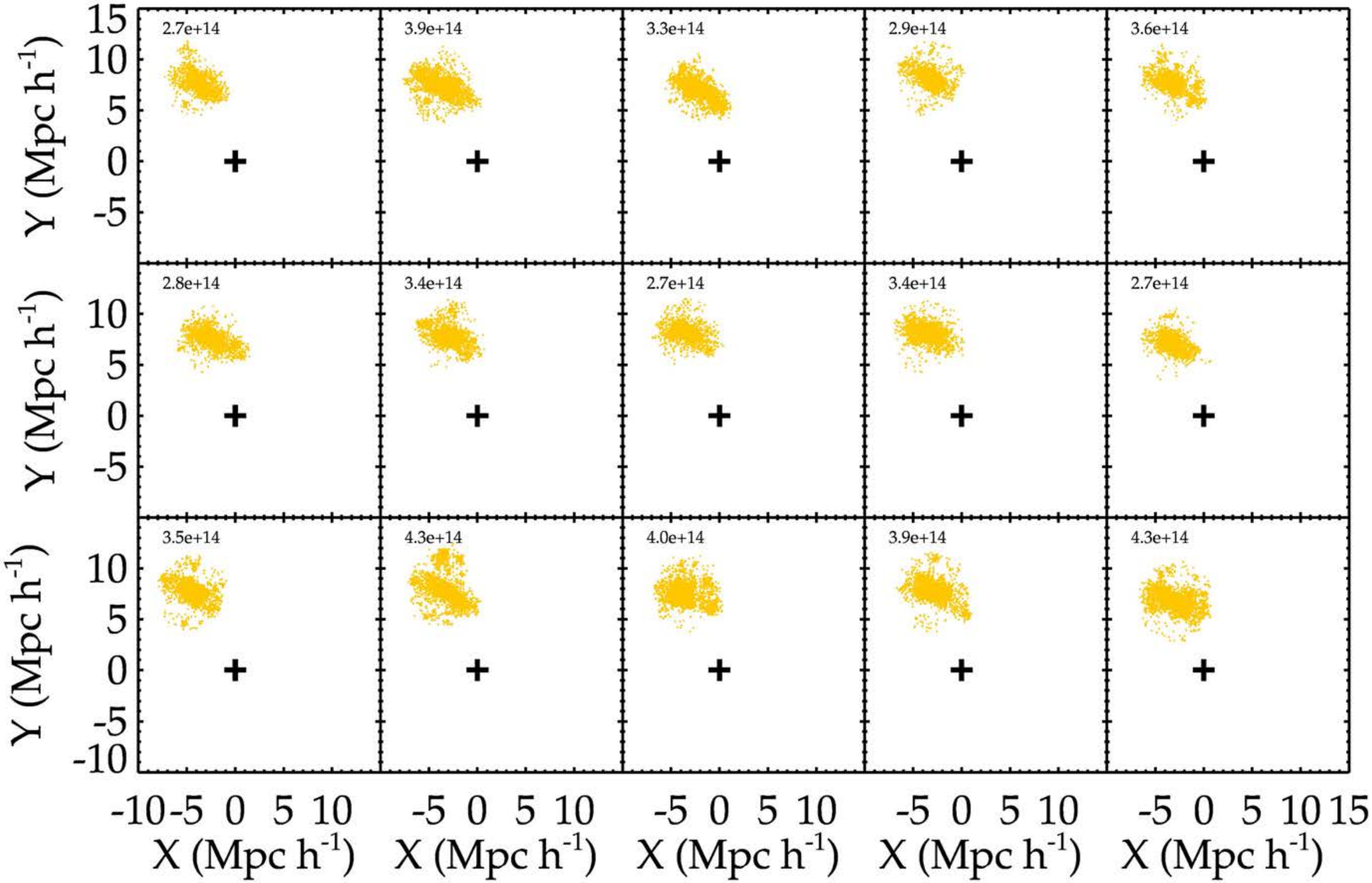
Example Virgo (12 realizations)

z=0.5



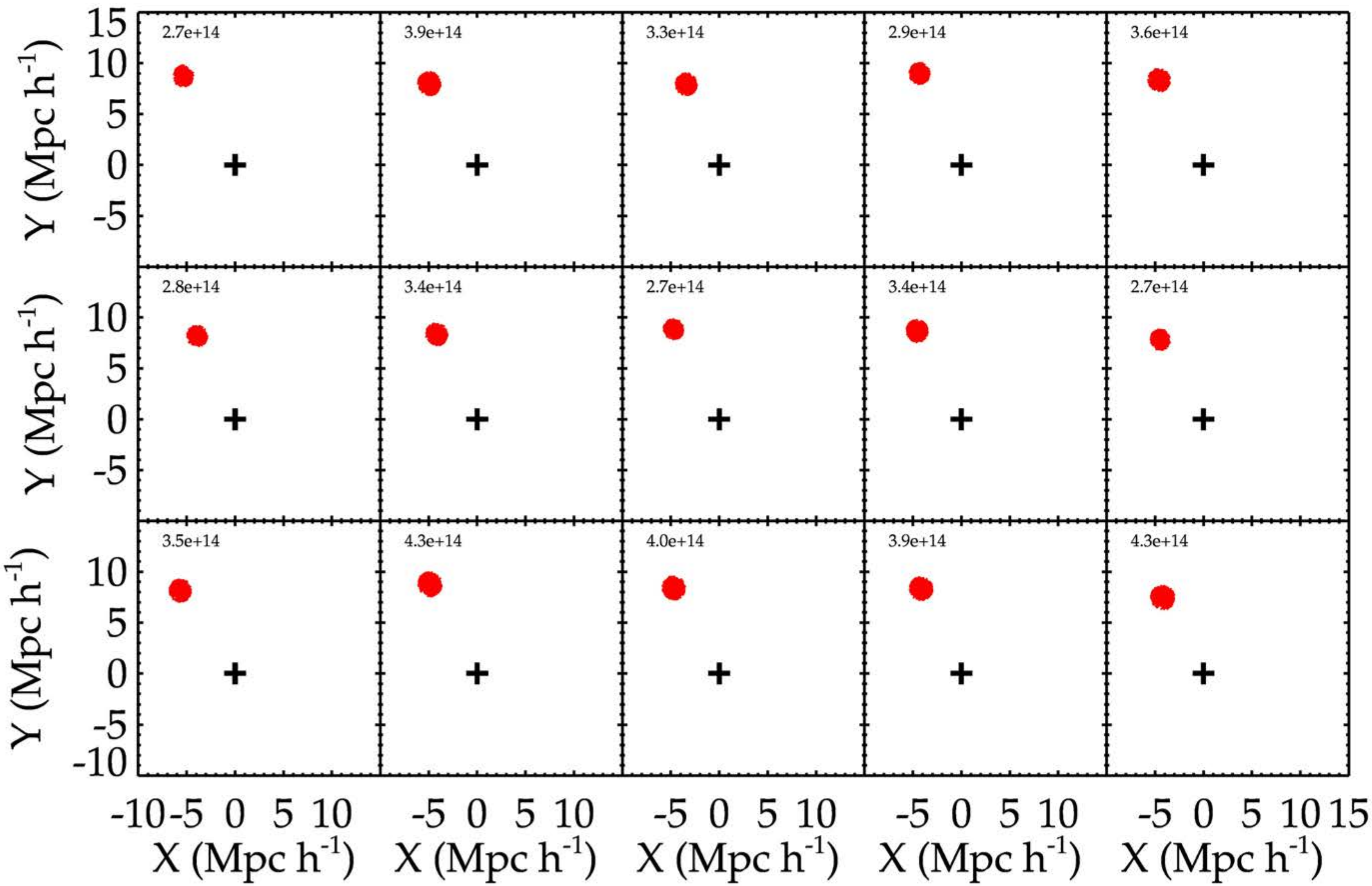
Example Virgo (12 realizations)

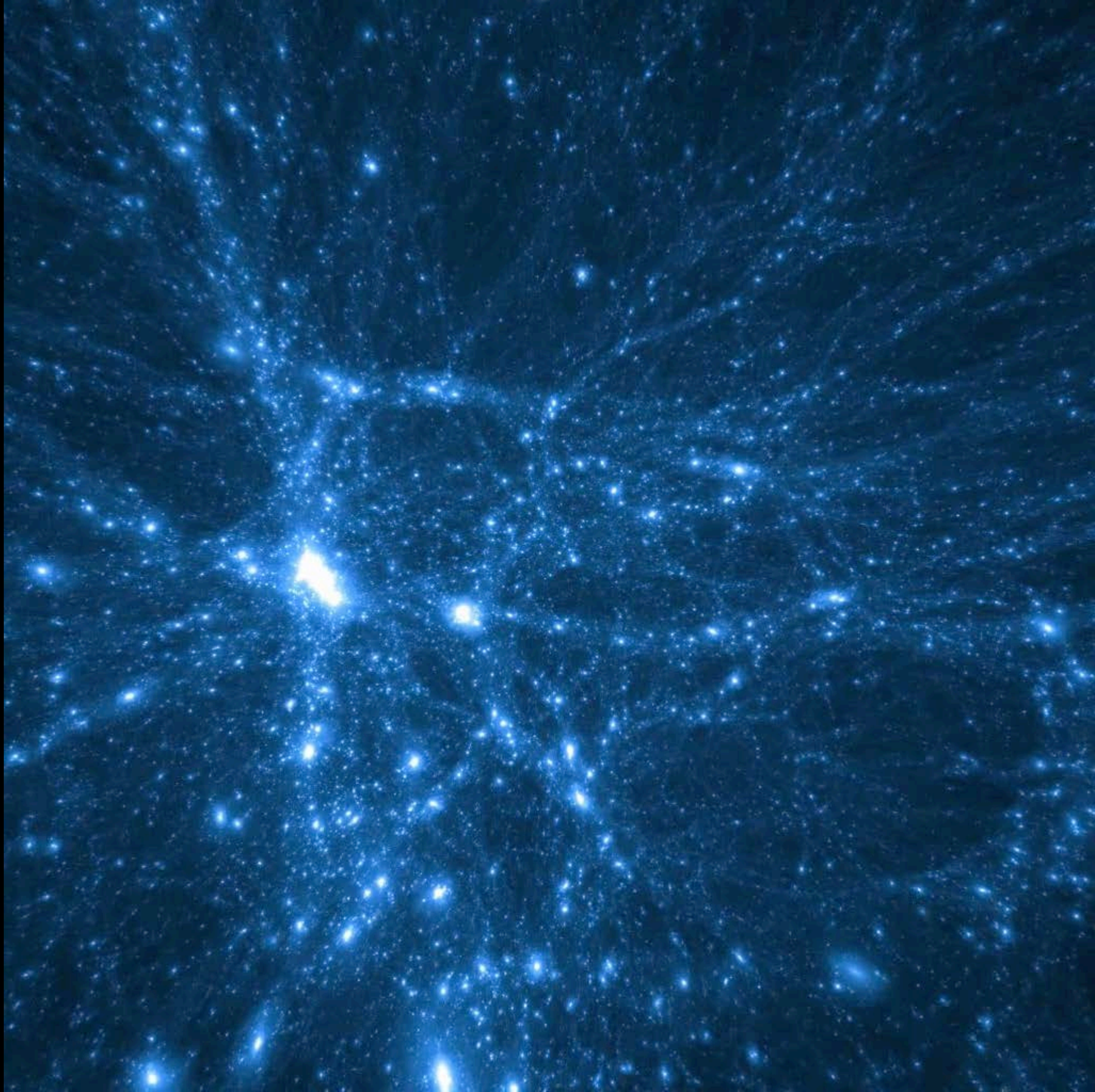
z=0.25



Example Virgo (12 realizations)

z=0



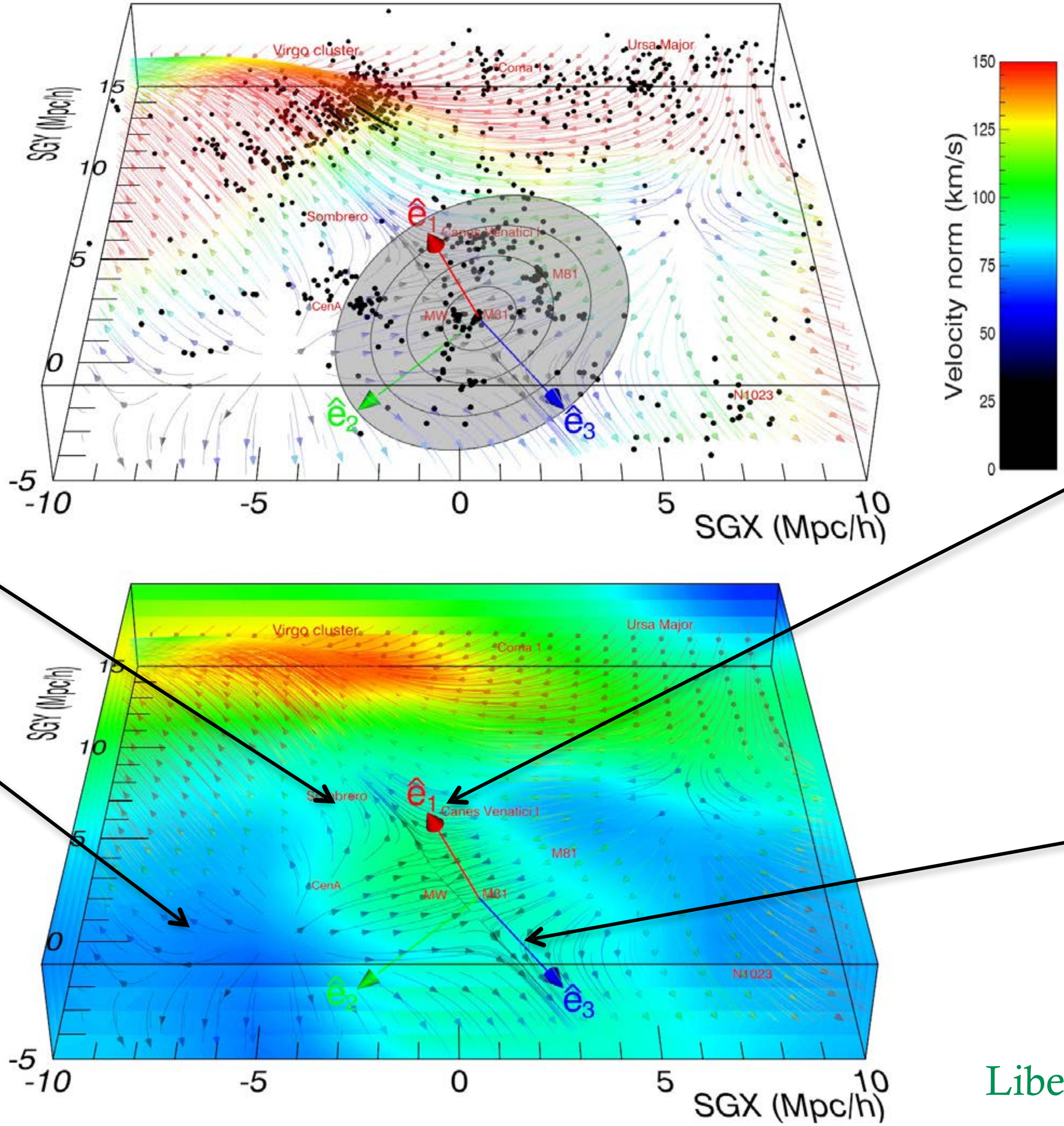


Vast planes of satellites compared to local LSS

“Local” velocity field, from cosmic-flows-2

“Local Filament” stretched by Virgo

Laterally squashed by a “mini-repeller”

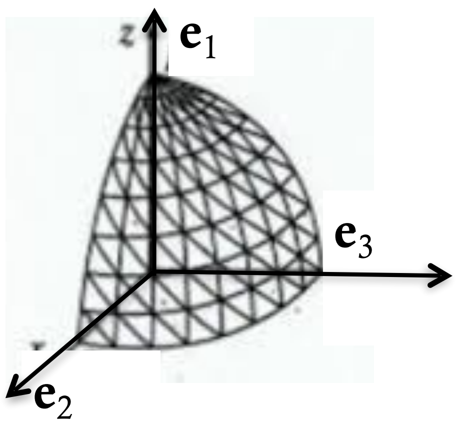


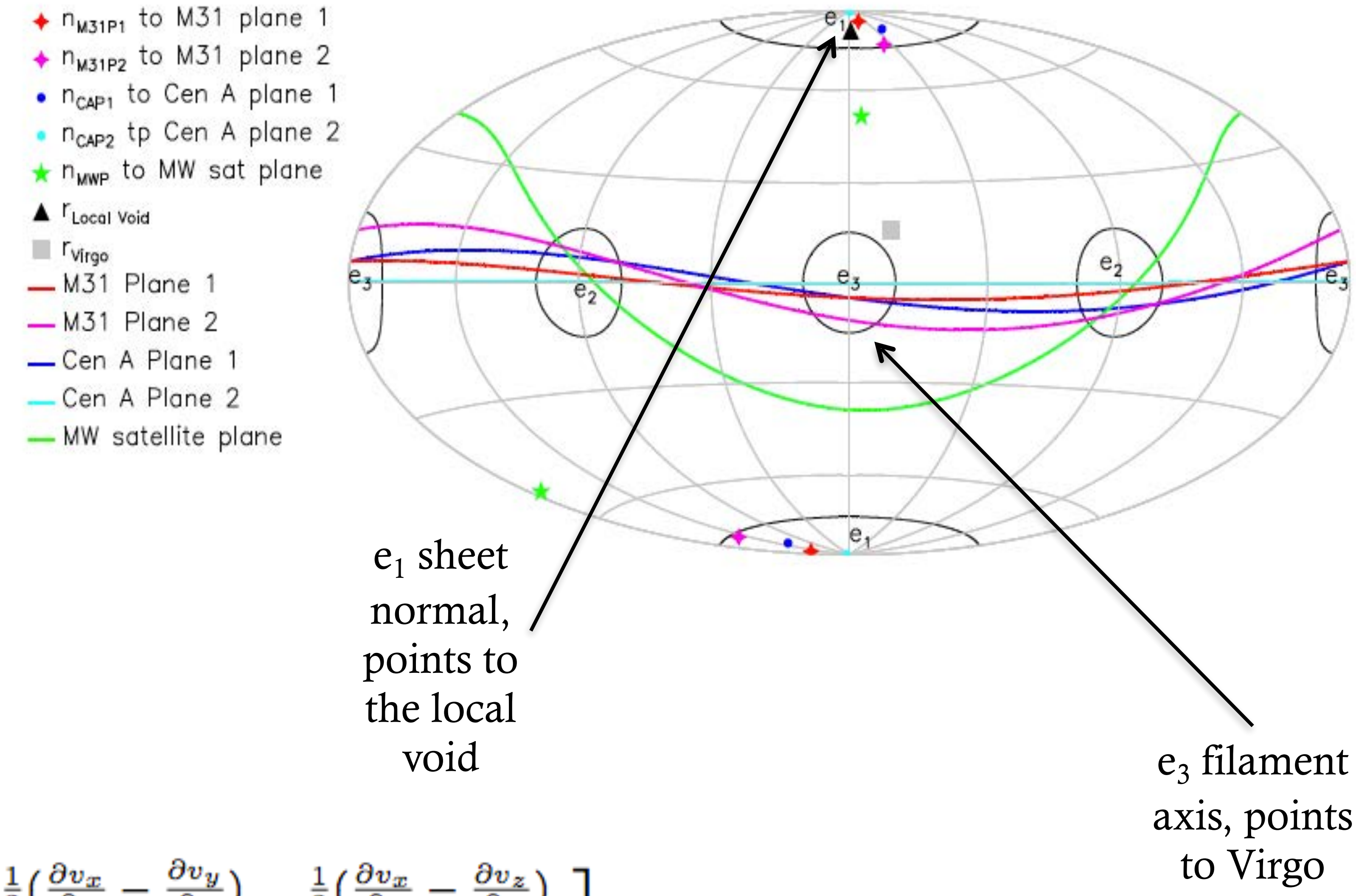
e_1 sheet normal, points to the local void

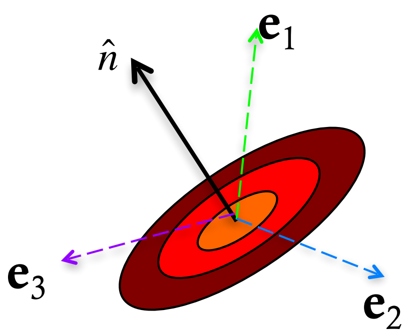
e_3 filament axis, points to Virgo

Libeskind *et al* 2015

Alignment of satellite planes w.r.t. the shear field

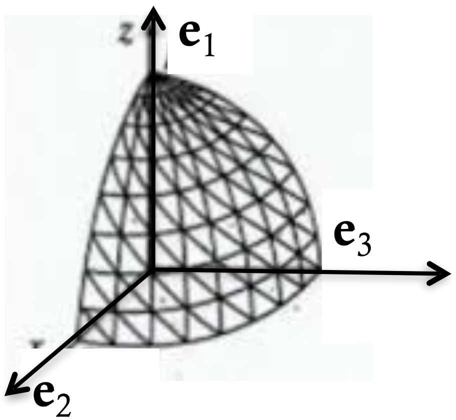


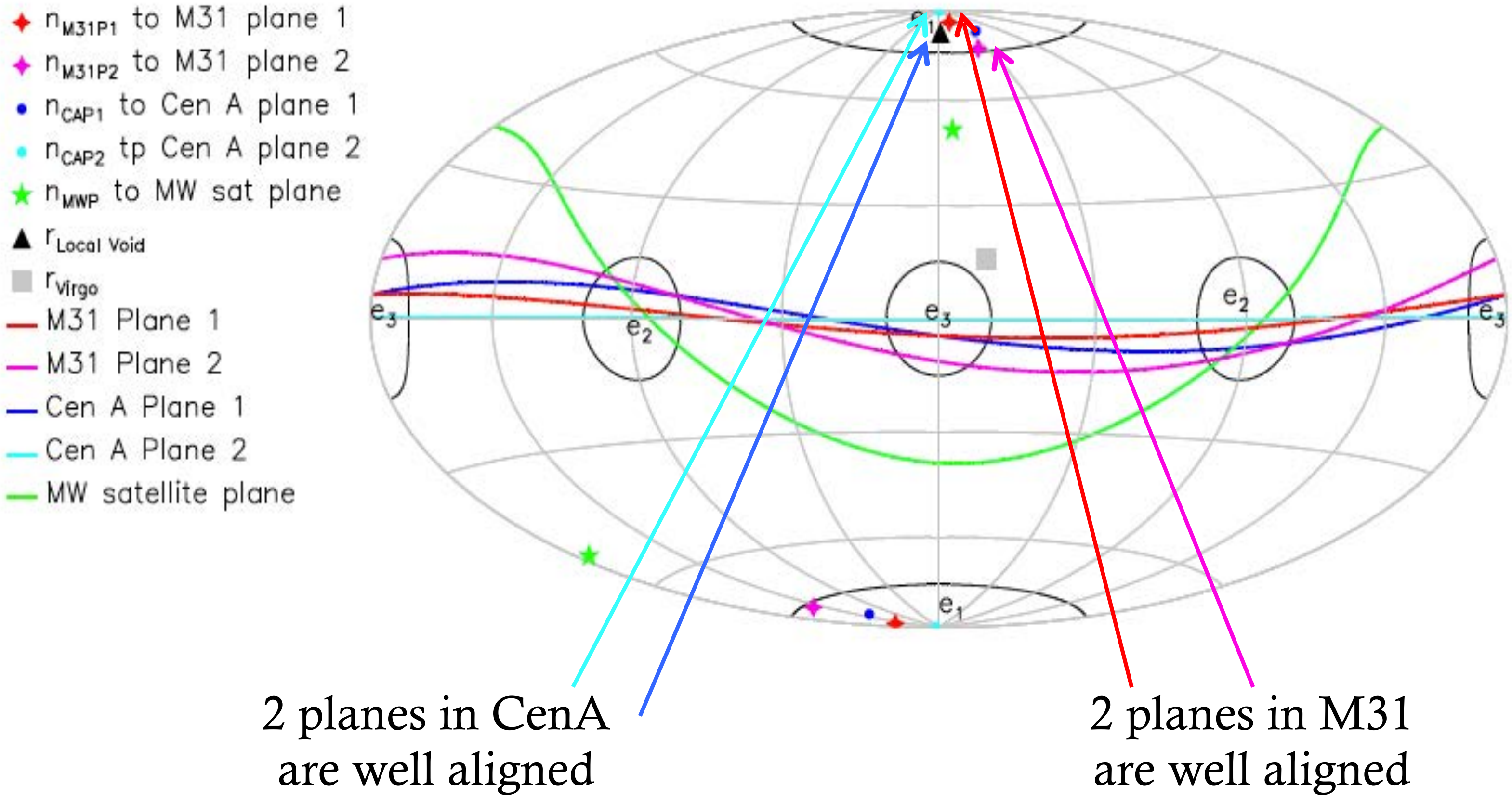


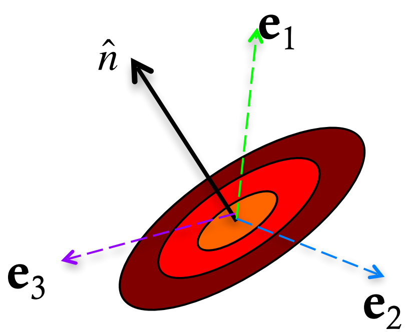


$$\begin{bmatrix} 0 & \frac{1}{2}\left(\frac{\partial v_x}{\partial y} - \frac{\partial v_y}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}\right) \\ -\frac{1}{2}\left(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right) & 0 & \frac{1}{2}\left(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}\right) \\ -\frac{1}{2}\left(\frac{\partial v_z}{\partial x} - \frac{\partial v_x}{\partial z}\right) & -\frac{1}{2}\left(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}\right) & 0 \end{bmatrix}$$

Alignment of satellite planes w.r.t. the shear field

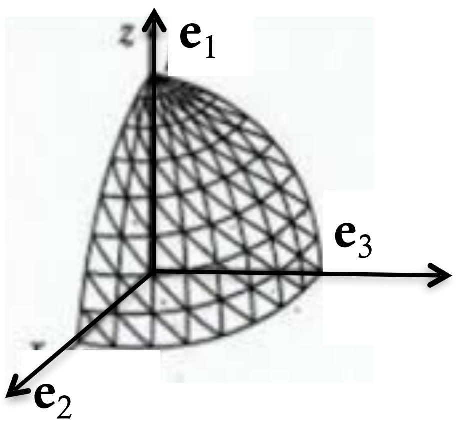


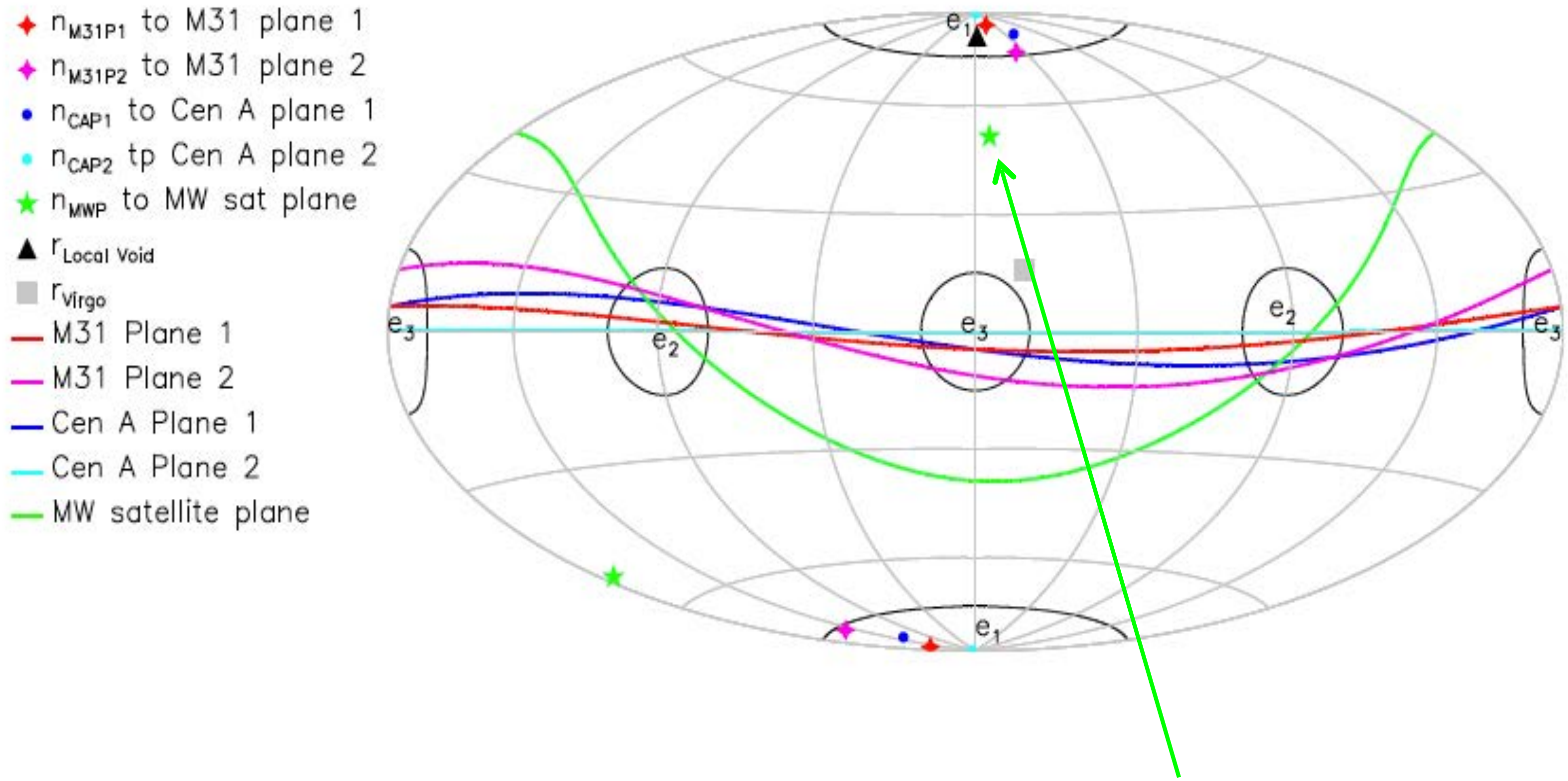


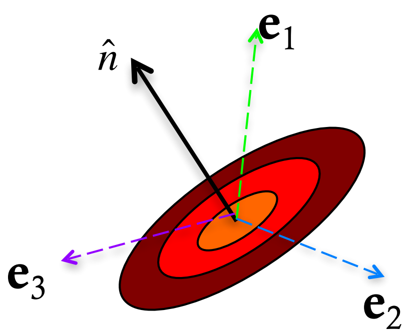


$$\begin{bmatrix} 0 & \frac{1}{2}\left(\frac{\partial v_x}{\partial y} - \frac{\partial v_y}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}\right) \\ -\frac{1}{2}\left(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right) & 0 & \frac{1}{2}\left(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}\right) \\ -\frac{1}{2}\left(\frac{\partial v_z}{\partial x} - \frac{\partial v_x}{\partial z}\right) & -\frac{1}{2}\left(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}\right) & 0 \end{bmatrix}$$

Alignment of satellite planes w.r.t. the shear field



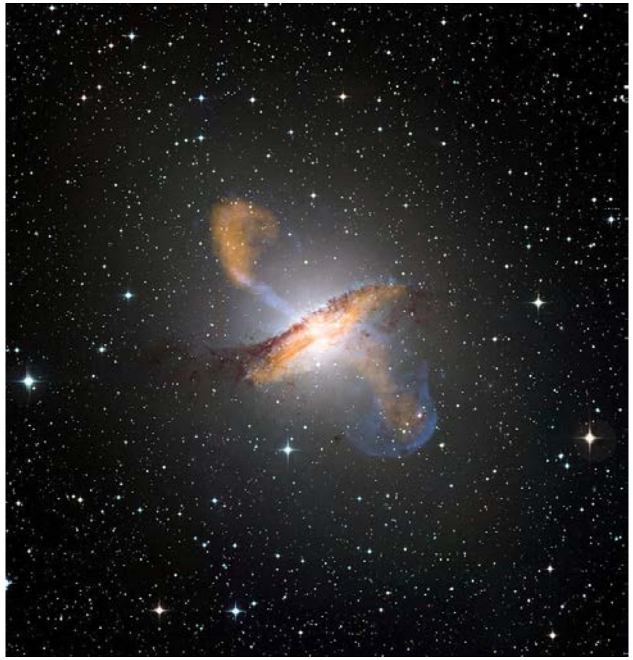


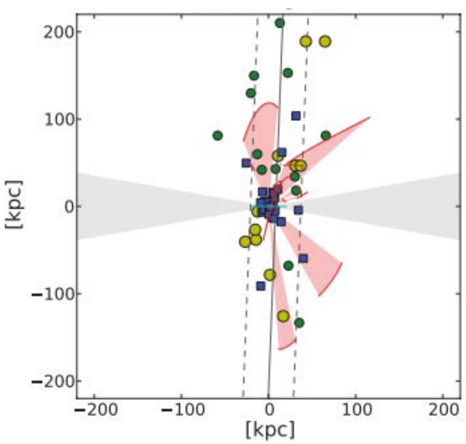


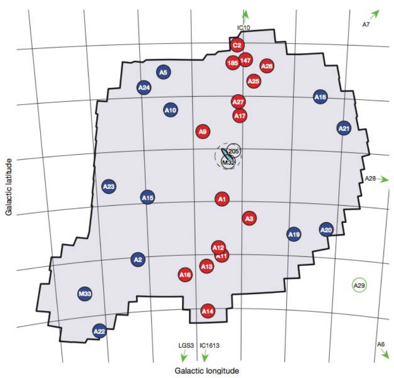
MW plane is off by ~38 deg, appears to have been torqued about the e_2 axis

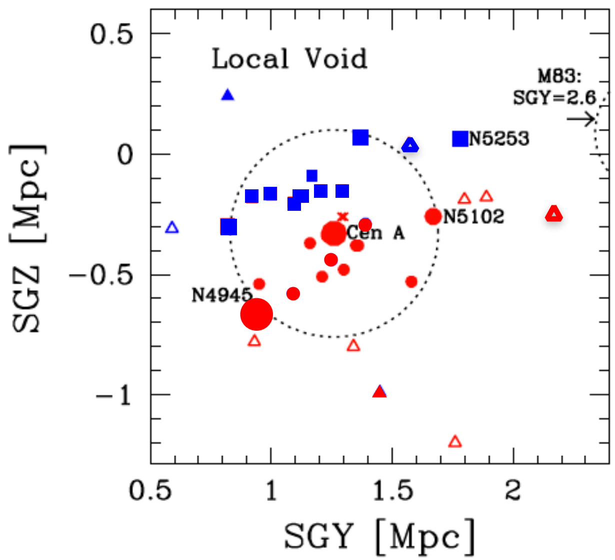
$$\begin{bmatrix} 0 & \frac{1}{2}\left(\frac{\partial v_x}{\partial y} - \frac{\partial v_y}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}\right) \\ -\frac{1}{2}\left(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right) & 0 & \frac{1}{2}\left(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}\right) \\ -\frac{1}{2}\left(\frac{\partial v_z}{\partial x} - \frac{\partial v_x}{\partial z}\right) & -\frac{1}{2}\left(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}\right) & 0 \end{bmatrix}$$

Summary of Local Volume Planes









4 out 5 satellite planes are well aligned
with shear field!

~1-9°

Haloes with Mass ~1-5 x10^{13}

Nothing bigger than itself within 3Mpc

Lets test for:

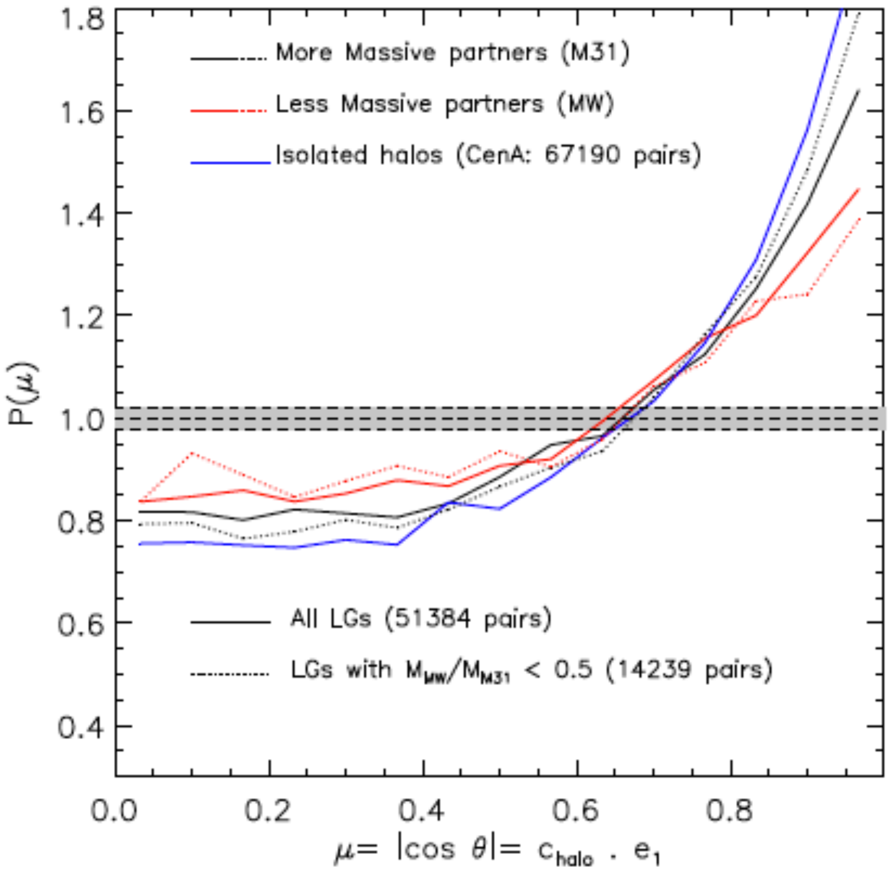
"Local Group" pairs

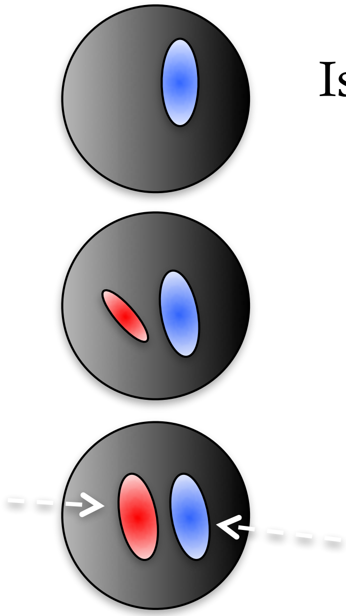
Cen A analogues

Two halos r ~ 1Mpc

Nothing else r < 1Mpc

Nothing M > M_{Virgo} within d~10Mpc





Isolated Massive

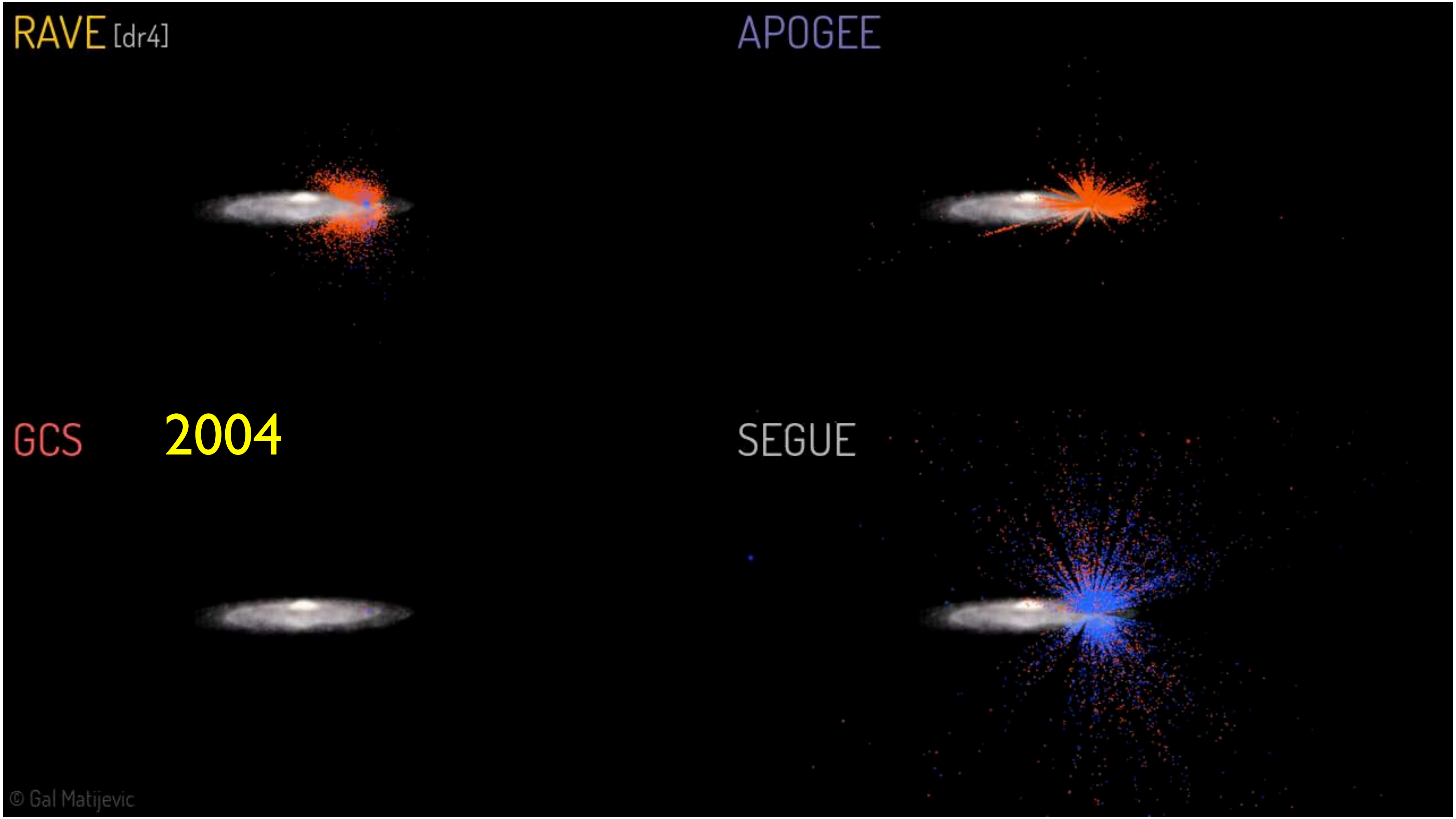
Less massive partner, not as well aligned

Libeskind et al *2015*

The mass of the Milky Way and the local dark matter density

Systematic spectroscopic surveys 2004

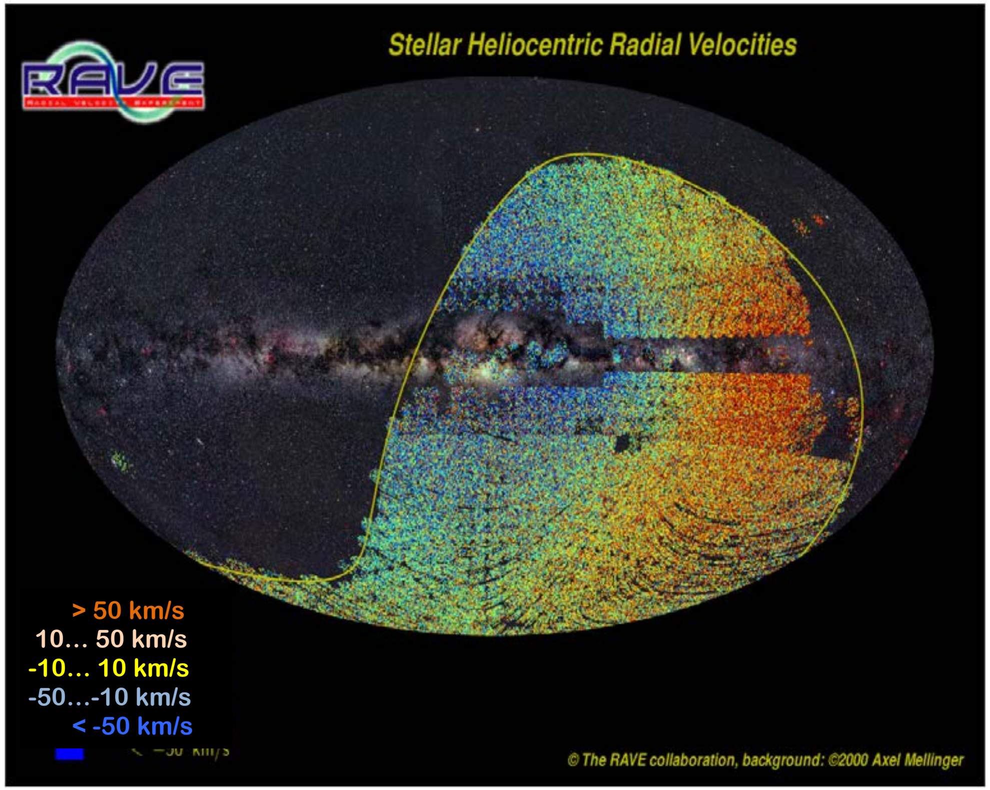
Systematic spectroscopic surveys 2014



Kordopatis et al. 2013

- Intermediate resolution (R~7500)
- 425 561 stars,
- 482 430 spectra

  (DR3: 77 461 stars)
- 9 < I < 12 mag



<u>Database:</u>

✓ Radial velocities

✓ Spectral morphological flags

✓ T_{eff}, logg, [M/H]

✓ Mg, *Al, Si, Ti, Ni, Fe*

✓ Line-of-sight Distances

✓ Photometry:

DENIS, USNOB, 2MASS, APASS

✓ Proper motions:

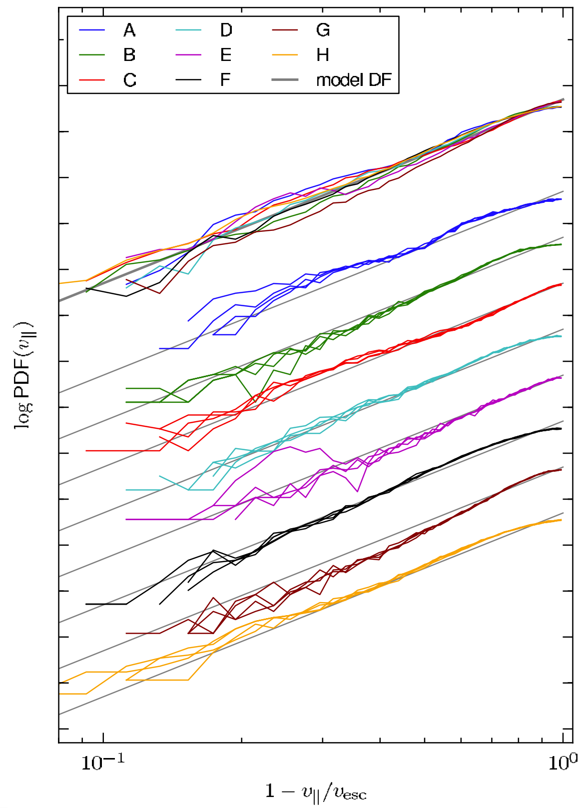
UCAC4, PPMX, PPMXL, Tycho-2, SPM4

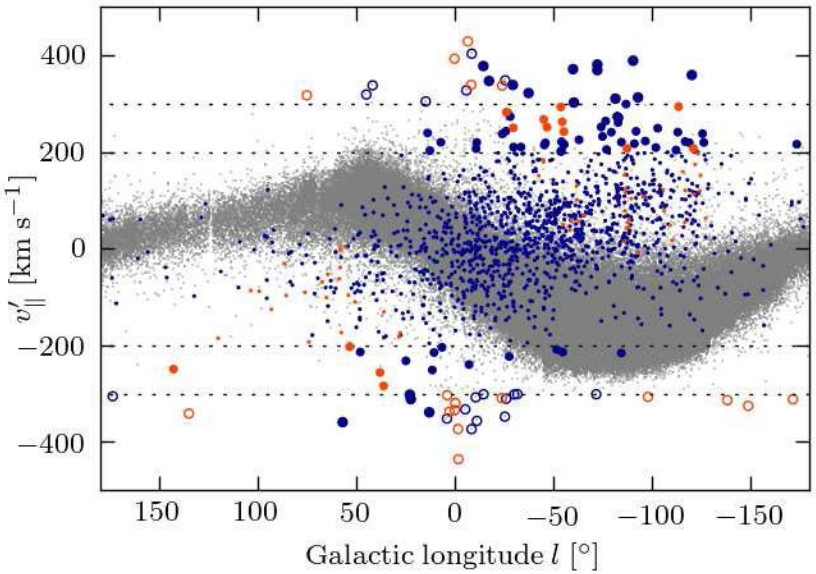
Escape speed of the Milky Way at the Solar Circle

- Leonard & Tremaine (1990):
  - consider distribution function f(E)
  - $f \rightarrow 0$ as $E \rightarrow \Phi(r_{vir}) \Rightarrow n(v) \propto (v_{esc}\text{-}v)^k$
- Consequently for line of sight:

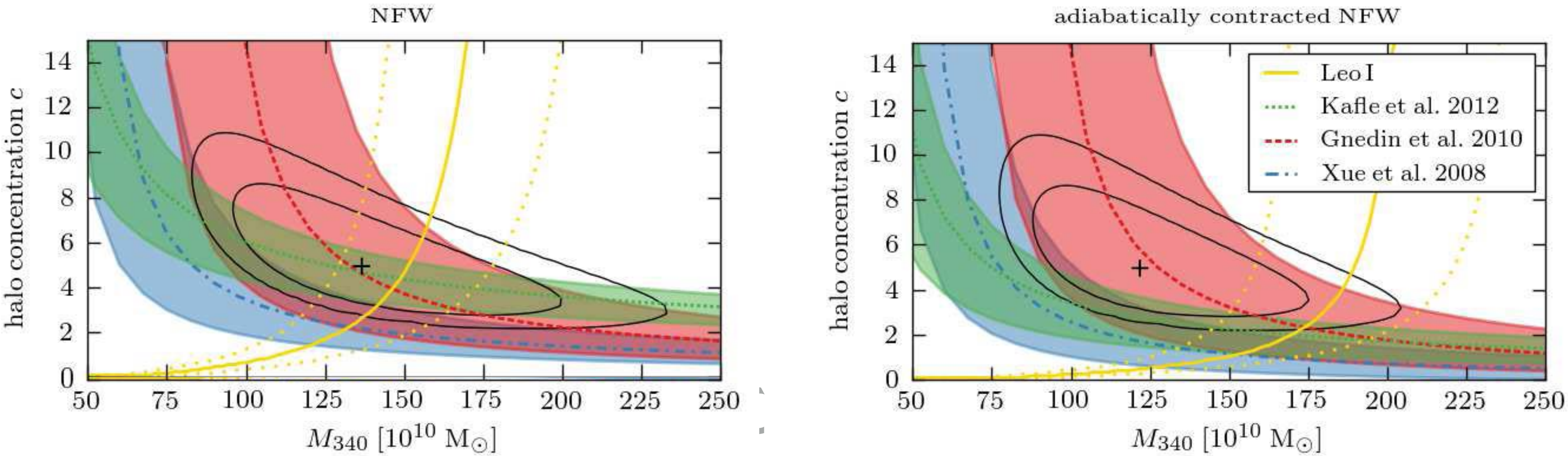
$$n(v_{||}) \propto (v_{esc}\text{-}v_{||})^{k+1}$$

- Dependence verified via cosmological simulations
- Measure distribution $n(v_{||})$ for high velocity stars with RAVE on counterrotating orbits
- Smith + RAVE (2007):
  $498\text{km/s} < v_{esc} < 608\text{km/s}$





Mass of the Milky Way with additional constraints



Kafle: Mass within 25kpc

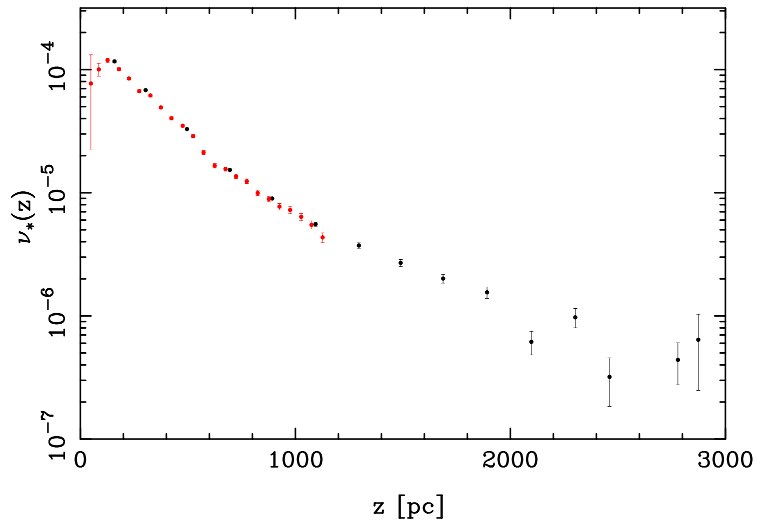
Xue: Mass within 60kpc

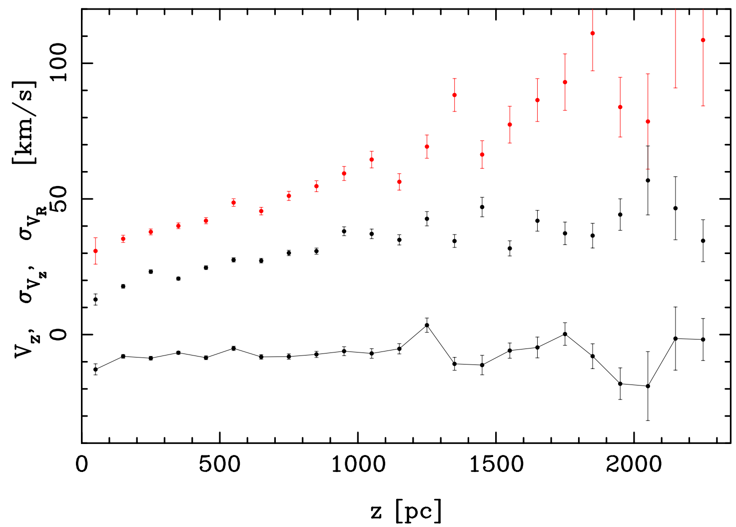
Gnedin: Mass within 85kpc

Piffl et al., 2014

Determining the local density by the K_z force

- Take a sample of RAVE stars in a 500pc radius cylinder towards the South Galactic Pole up to 2 kpc from the Galactic Plane.
- subset of red clump stars gives good distances.
- Change in kinematics with vertical distances gives total vertical force (in simplest approximation proportional to surface density)
- number counts of stars gives baryonic mass distribution





Determining the local density by the K_z force

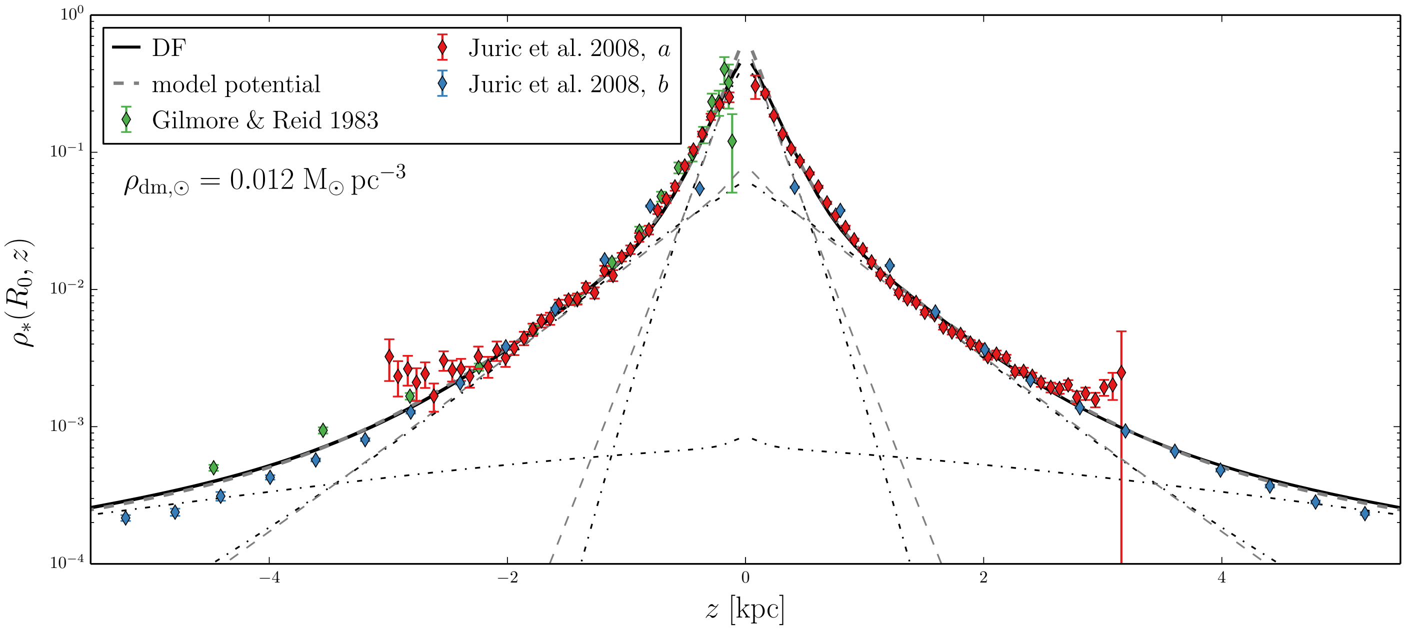
$$\frac{K_Z(1\mathrm{kpc})}{2\pi G} = 68.5 \pm 1.0\,\mathrm{M}_\odot\mathrm{pc}^{-2}$$
$$\frac{K_Z(2\mathrm{kpc})}{2\pi G} = 96.9 \pm 2.2\,\mathrm{M}_\odot\mathrm{pc}^{-2}$$

$$\boxed{\begin{aligned} \varrho_{\mathrm{DM}}(z=0) &= 0.0143 \pm 0.0011\,\mathrm{M}_\odot\mathrm{pc}^{-3} \\ &= 0.542 \pm 0.042\,\mathrm{GeV\,cm}^{-3} \end{aligned}}$$

- stronger increase of surface density between 1kpc and 2kpc, indicative for a flattened halo (q ≈ 0.8)
- distance errors, biases, selection effects ... ?

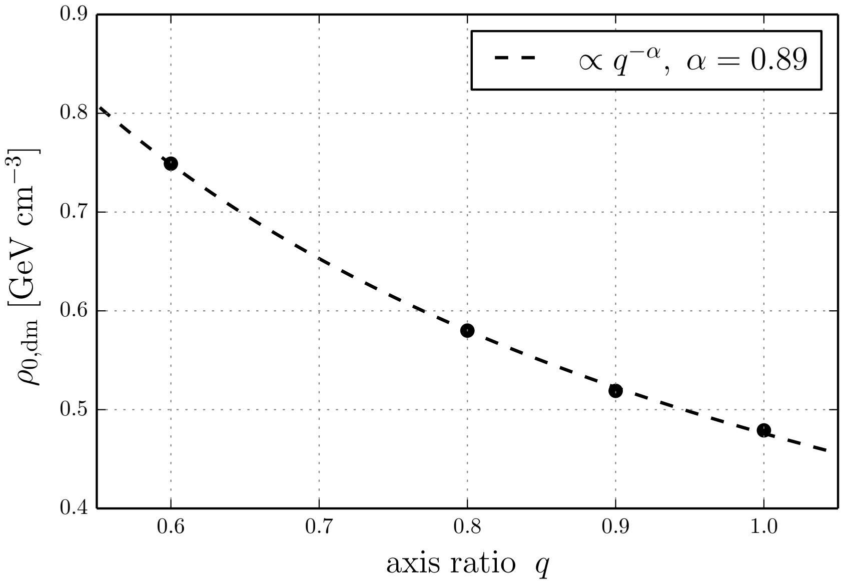
Dark mass in the solar neighborhood (Piffl et al 2014)

- Mass Model:
  - three exponential disks
  - flattened bulge
  - NFW dark matter halo
- Binney 2012 model for kinematics (incl. stellar halo)
- Model fit to vertical RAVE data



Results

$$\varrho_{\rm DM} = 0.48 \times q^{-0.89} {\rm GeV/cm}^3$$



Model potential parameters		
$\Sigma_{0,\rm thin}$	570.7	$\rm M_\odot\,pc^{-2}$
$\Sigma_{0,\rm thick}$	251.0	$\rm M_\odot\,pc^{-2}$
$R_{\rm d}$	2.68	kpc
$z_{\rm d,thin}$	0.20	kpc
$z_{\rm d,thick}$	0.70	kpc
$\Sigma_{0,\rm gas}$	94.5	$\rm M_\odot\,pc^{-2}$
$R_{\rm d,gas}$	5.36	kpc
$\rho_{0,\rm dm}$	0.01816	$\rm M_\odot\,pc^{-3}$
$r_{0,\rm dm}$	14.4	kpc
DF parameters		
$\sigma_{r,\rm thin}$	33.9	$\rm km\,s^{-1}$
$\sigma_{z,\rm thin}$	24.9	$\rm km\,s^{-1}$
$R_{\sigma,r,\rm thin}$	9.0	kpc
$R_{\sigma,z,\rm thin}$	9.0	kpc
$\sigma_{r,\rm thick}$	50.5	$\rm km\,s^{-1}$
$\sigma_{z,\rm thick}$	48.7	$\rm km\,s^{-1}$
$R_{\sigma,r,\rm thick}$	12.9	kpc
$R_{\sigma,z,\rm thick}$	4.1	kpc
$F_{\rm thick}$	0.460	
$F_{\rm halo}$	0.026	

$$\varrho_{\rm DM} = 0.0126 \times q^{-0.89} {\rm M_\odot\,pc^{-3}} \pm 10\%$$

$$\Sigma_{\rm DM}(< 0.9{\rm kpc}) = (69 \pm 10)\,{\rm M_\odot\,pc^{-2}}$$

$$M_{\rm DM}(< R_0) = (6.0 \pm 0.9) \times 10^{10}\,{\rm M_\odot}$$

$$M_{\rm vir} = (1.3 \pm 0.1) \times 10^{12}\,{\rm M_\odot}$$

- 46% of the radial force acting on the Sun provided by baryons
- Bienamyé et al (2014): RAVE stars towards Galactic Pole, red clump distances: $\varrho_{\rm DM}(R=R_0,z=0) = 0.0143 {\rm M_\odot pc^{-3}}$

Summary

- Vast planes of galaxies pose an interesting challenge to the LCDM structure formation scenario
  - so far 5 planes have been established in the Local Group system
  - Are such planes ubiquitous in the Universe or a cosmic fluke of our local environment?
- Comparison with LSS simulations designed to reproduce the Local Group environment
  - strong alignment of satellite planes with local shear field
  - indicative of correlation of the galaxy formation process with the inflow pattern in the cosmic suburb
- Mass estimates for the MW dark matter halo based on spectroscopic surveys indicative of a relatively low total mass/local DM density