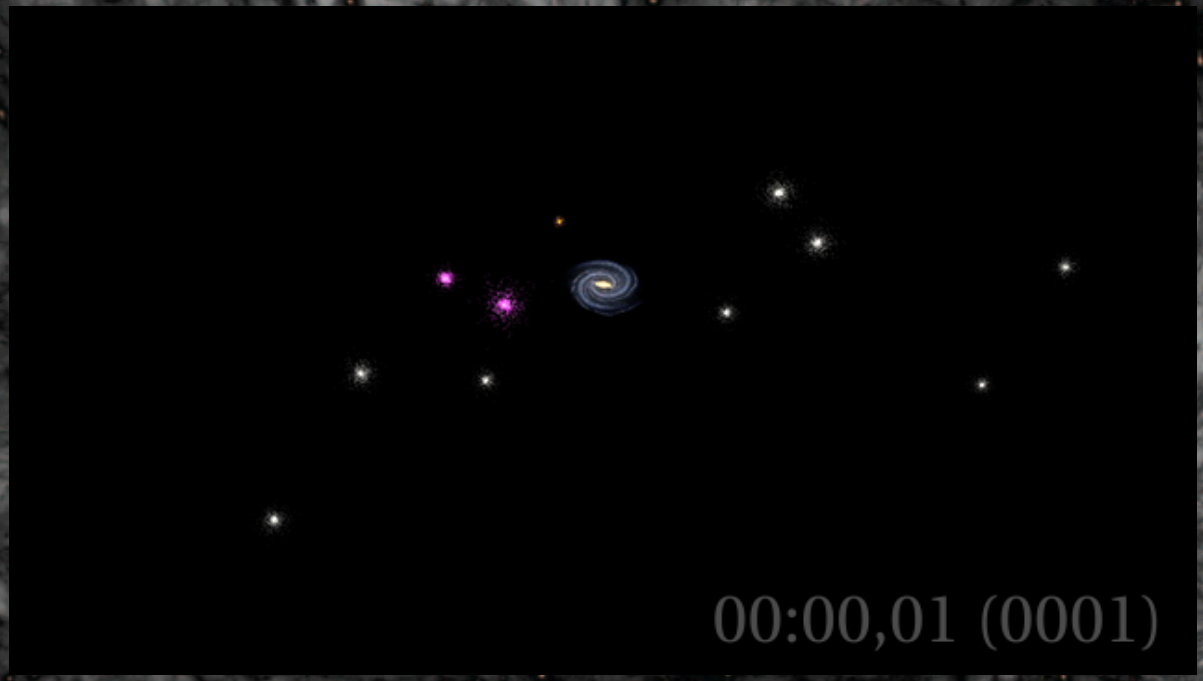
Planes of dwarfs and peculiar velocity fields



Noam I Libeskind

Leibniz Institute for Astrophysics, Potsdam, Germany

Yehuda Hoffman (Jerusalem)
Brent Tully (Hawaii)
Helene Courtois (Lyon)
Daniel Pomerade (Saclay)
Stefan Gottlöber, Matthias Steinmetz (Potsdam)

Dwarf galaxies on Planes

THE MAGELLANIC PLANE

WILLIAM E. KUNKEL

Cerro Tololo Inter-American Observatory,[3] Casilla 63-D, La Serena, Chile

SERGE DEMERS[1,2]

University of Chile, Casilla 36-D, Santiago de Chile

Abstract. A group of globular clusters and dwarf spheroidal galaxies with anomalous colour–magnitude diagrams first described by Sandage and Wildey (1967) is interpreted as relics of tidal interaction between the Magellanic Clouds and the Galaxy on the occasion of an early encounter. A projection of the orbital plane of the group members on to the sky coincides closely with the Magellanic Stream.

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Publication Date: 00/1976
Origin: ADS
Bibliographic Code: 1976RGOB..182..241K

Abstract

Not Available

Kunkel & Demers (1976)

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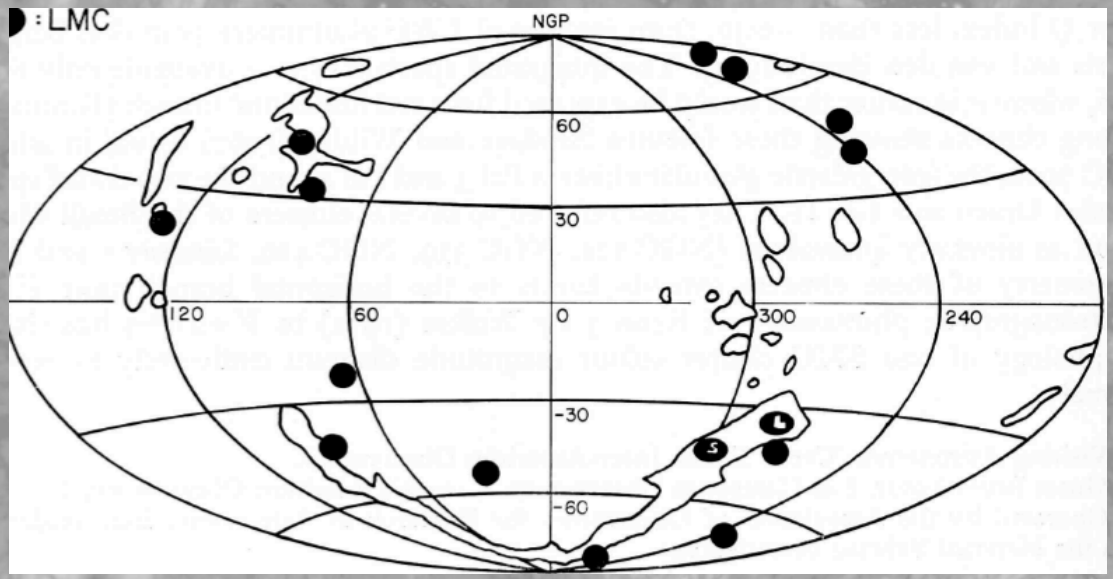


Kunkel & Demers (1976)

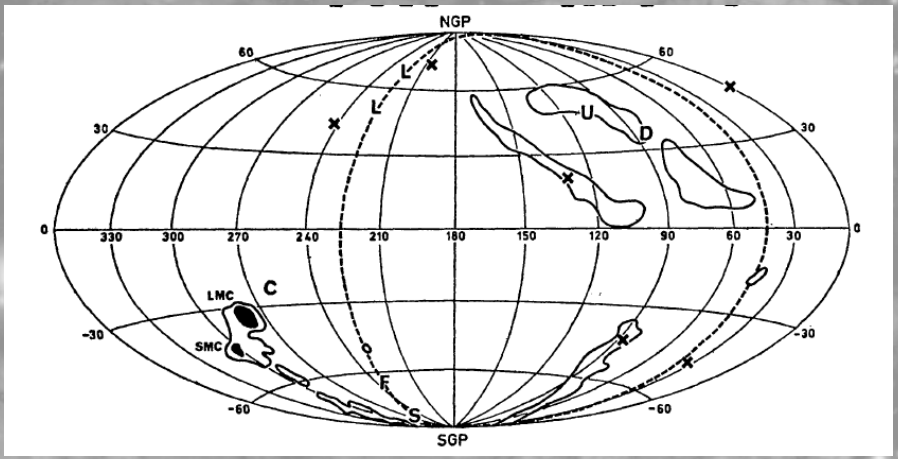
Magellanic stream and association with dwarfs

DWARF GALAXIES AND GLOBULAR CLUSTERS IN HIGH VELOCITY HYDROGEN STREAMS

D. Lynden-Bell

Institute of Astronomy, The Observatories, Madingley Road, Cambridge

(Received 1975 July 11)



Lynden-Bell (1976)

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Affiliation:	AA(Cambridge University, Observatoires, Cambridge, England)
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Publication Date:	03/1976
Category:	Astrophysics
Origin:	STI
NASA/STI Keywords:	Galactic Nuclei, Galaxies, Globular Clusters, Hydrogen Clouds, Magellanic Clouds, As Velocity, Stellar Evolution
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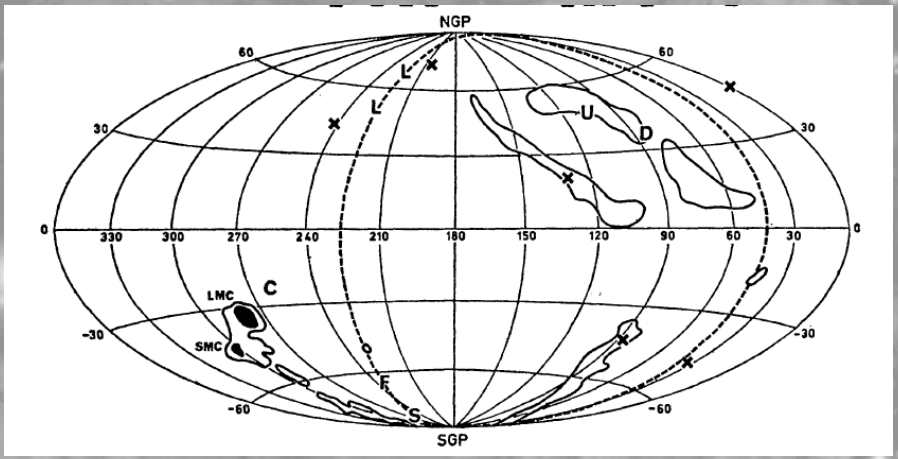

Lynden-Bell (1976)

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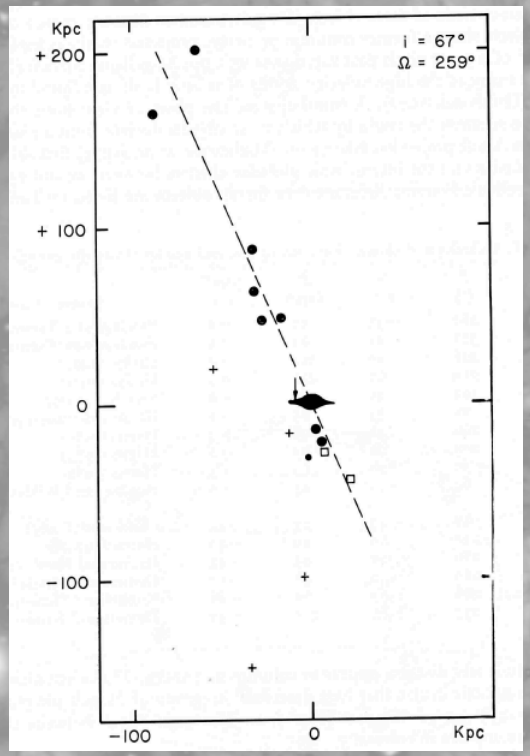
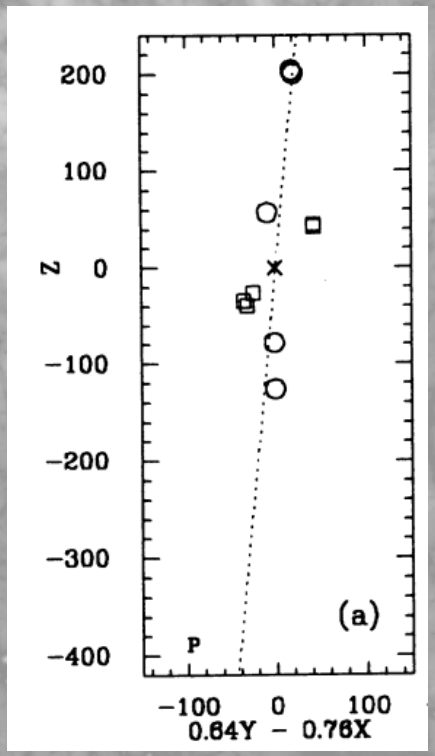
Planes of dwarfs – a problem since 1976

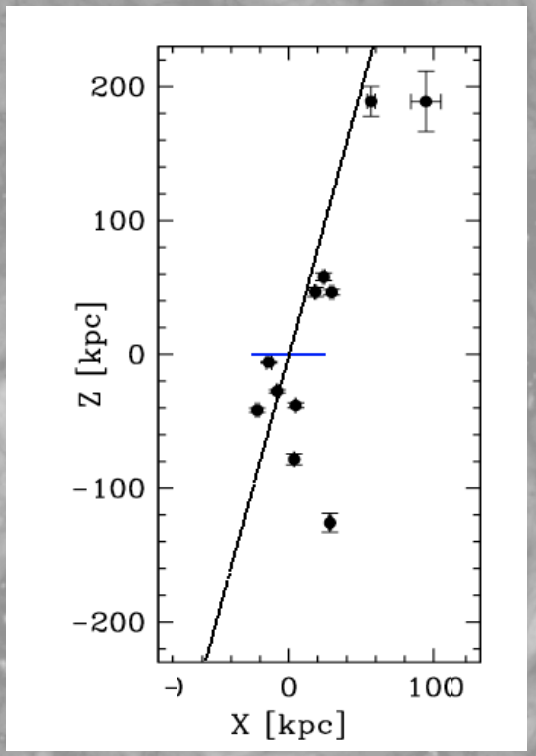
Kunkel & Demers (1976)



Majewski 1994



Kroupa, Theis & Boily 2005



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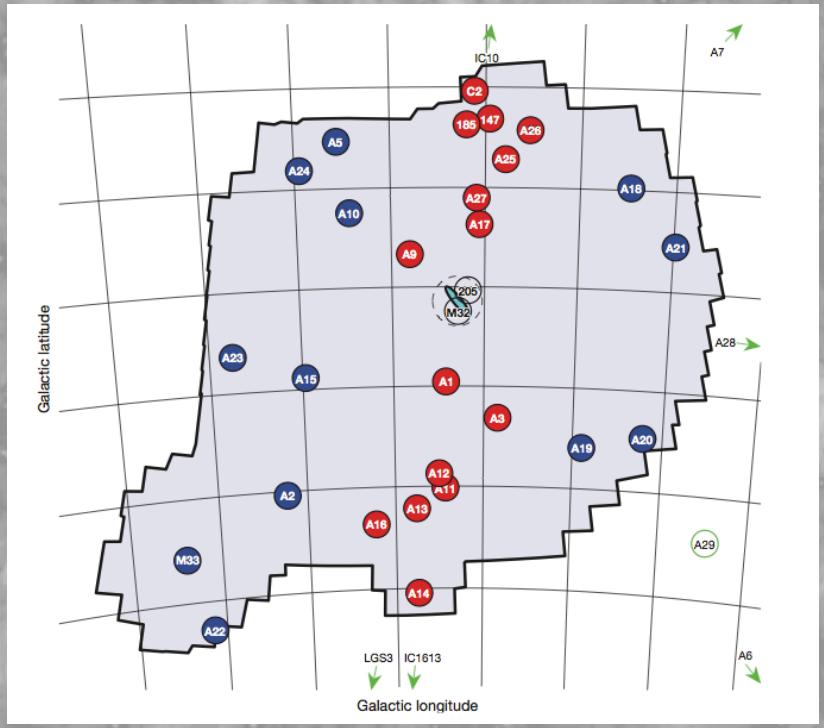
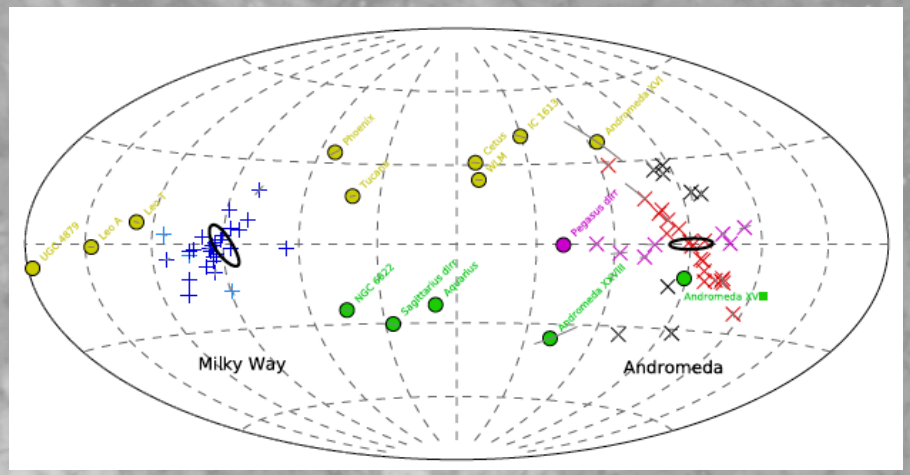
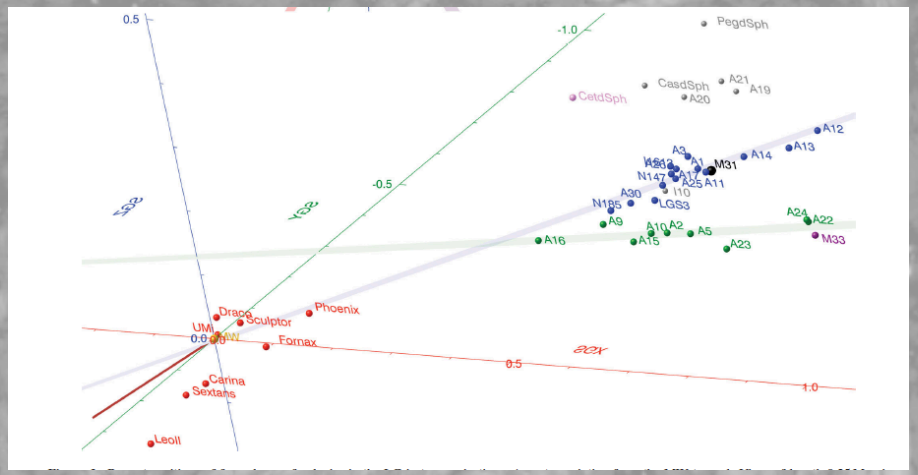


Ibata et al 2013, Conn et al 2013

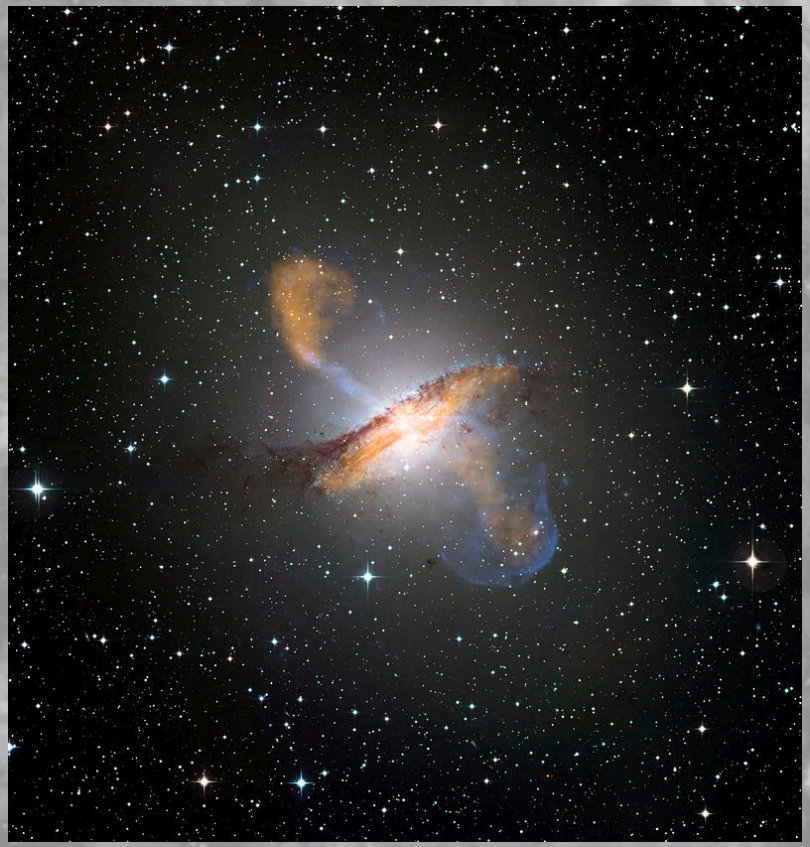


Pawlowski et al 2013

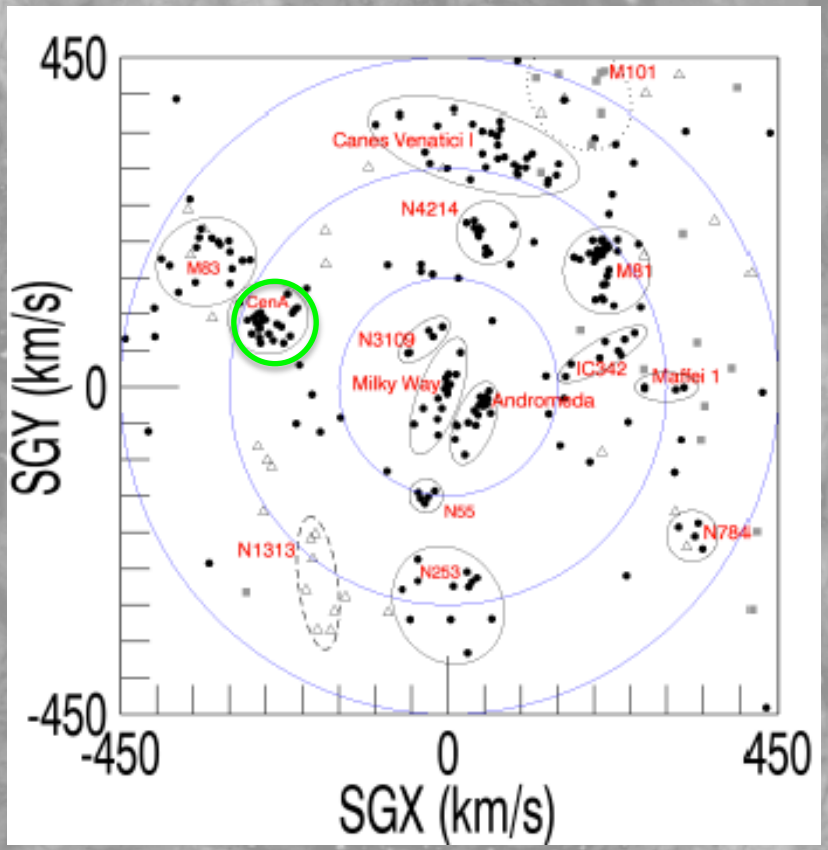


Shaya & Tully 2013

Where else can we hope to find planes of satellites?



ESO image



Courtois et al (2013)

Centaurus A, ~8×10^{12} M_{sol}, 3.8Mpc

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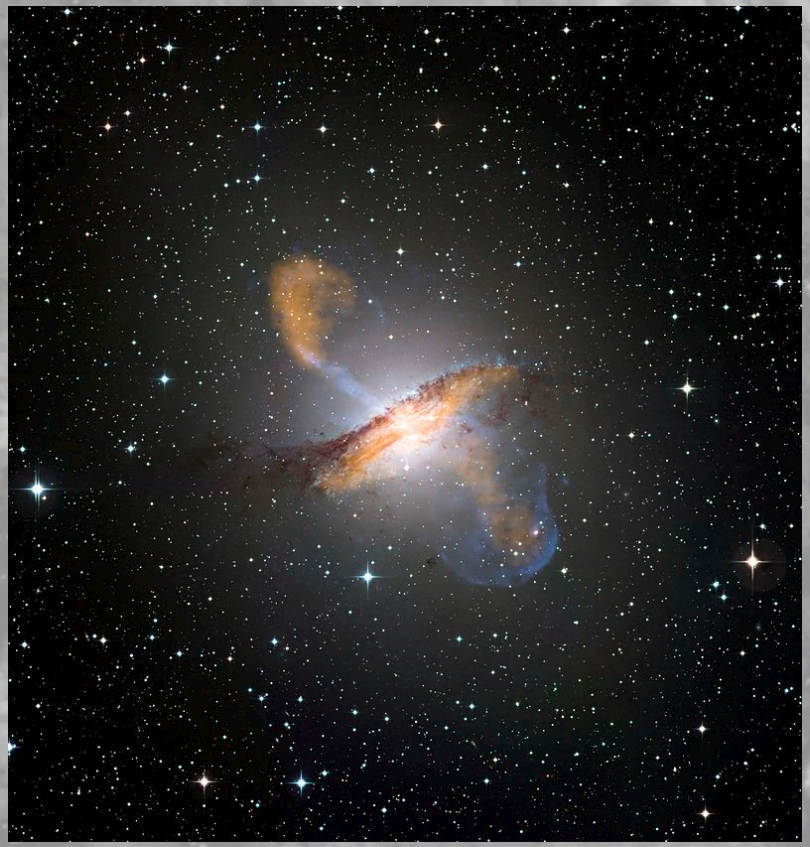
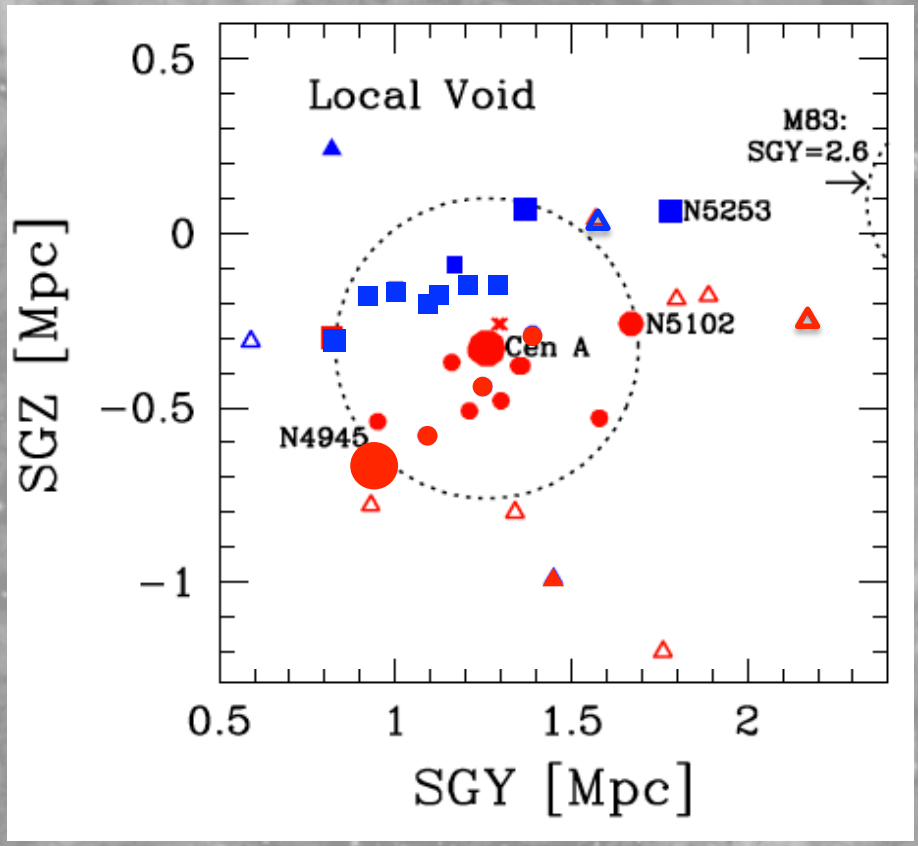
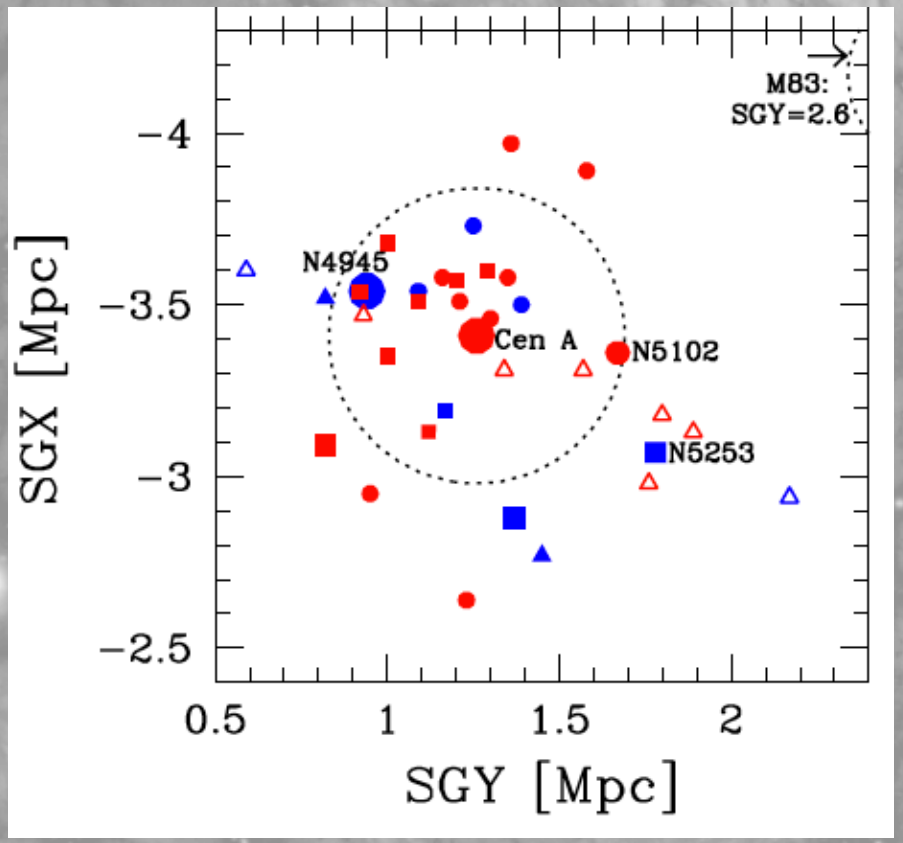
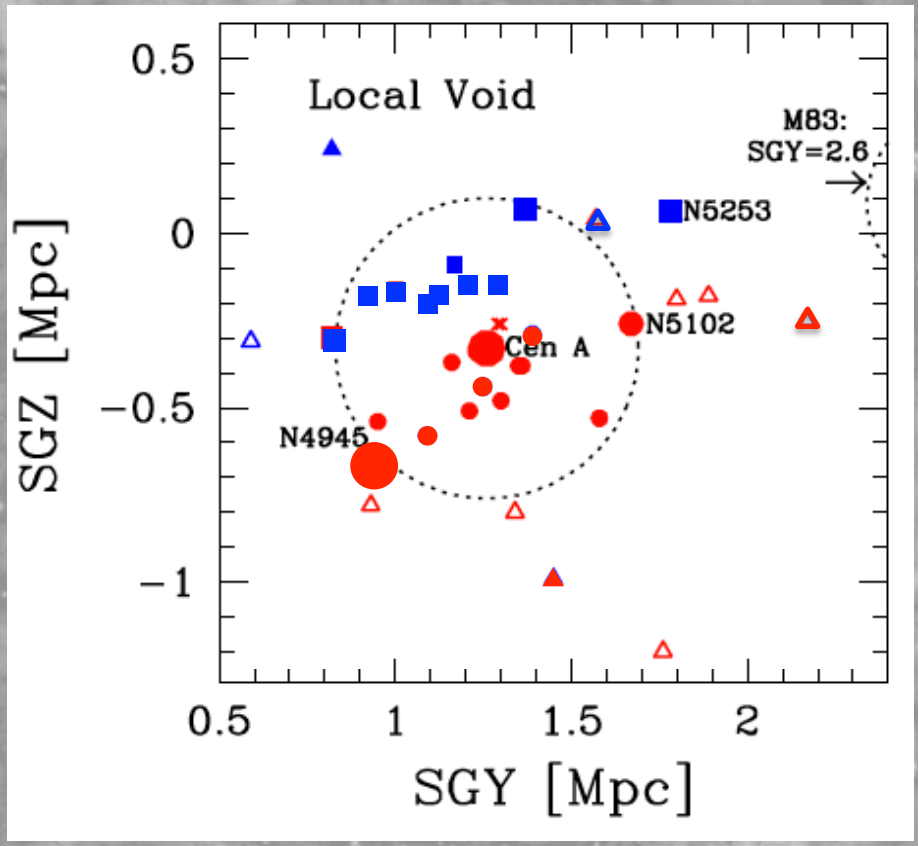




Centaurus A, ~$8 \times 10^{12}\, M_{sol}$, 3.8Mpc

Centaurus A Planes



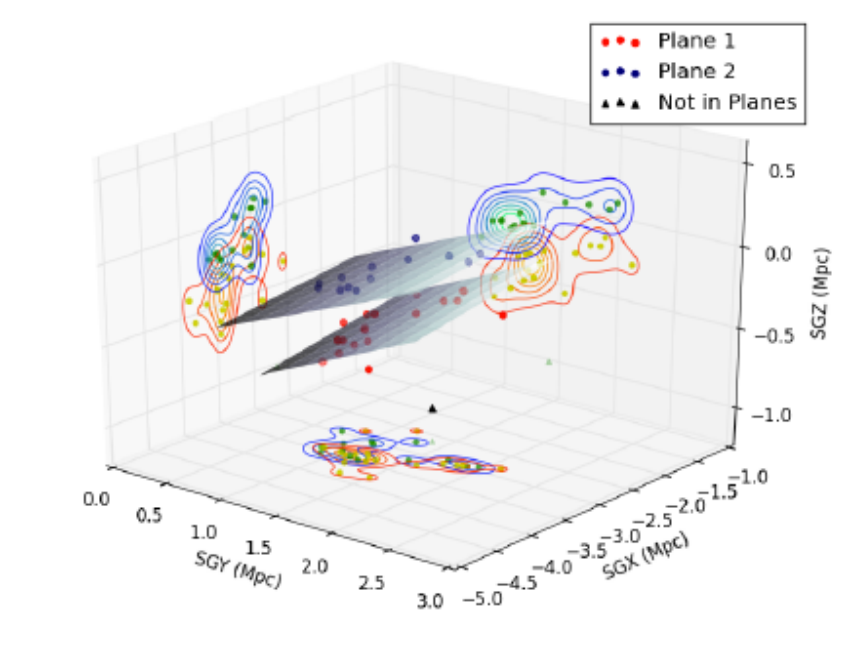


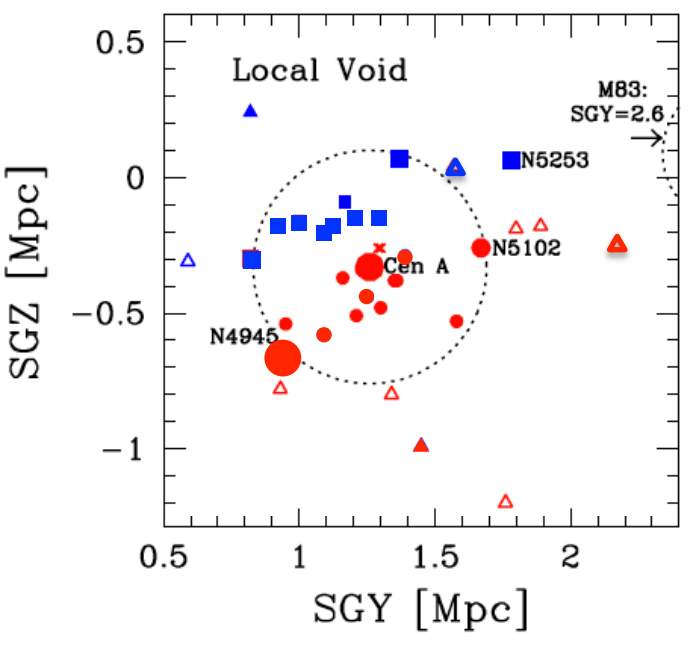
Tully, NL *et al* (2015)

Not in Plane

No known distance

Centaurus A Planes





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

Tully, NL *et al* (2015)

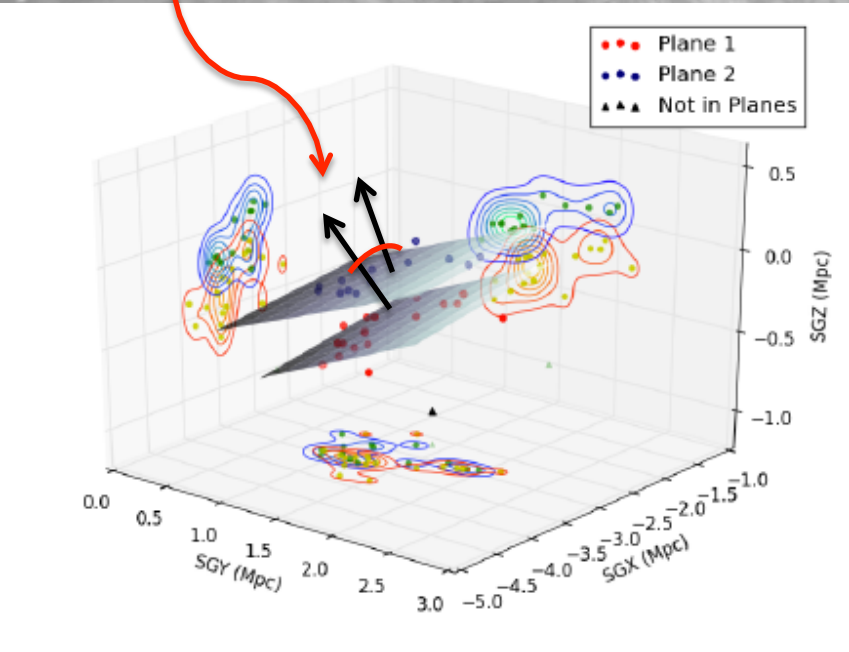
36 galaxies in total, 29 with distances

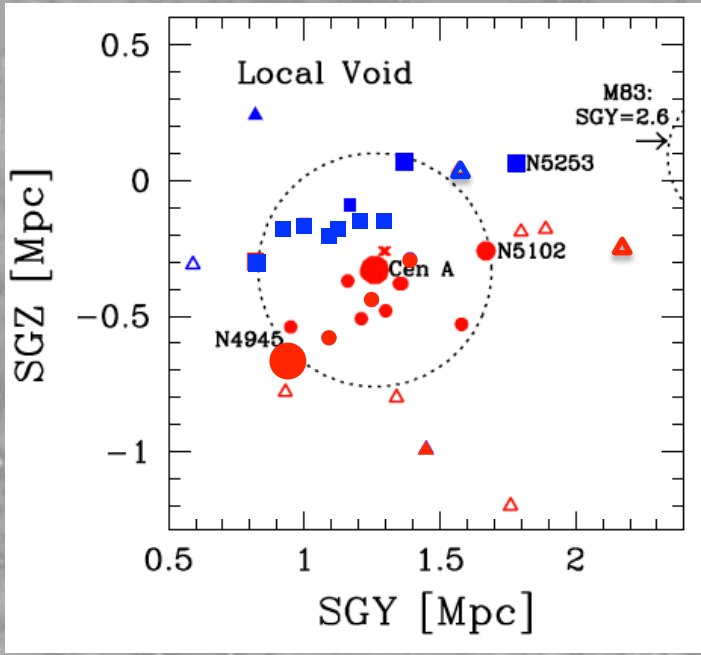
16 in plane 1
11 in plane 2
2 not in either

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

Centaurus A Planes

7 deg





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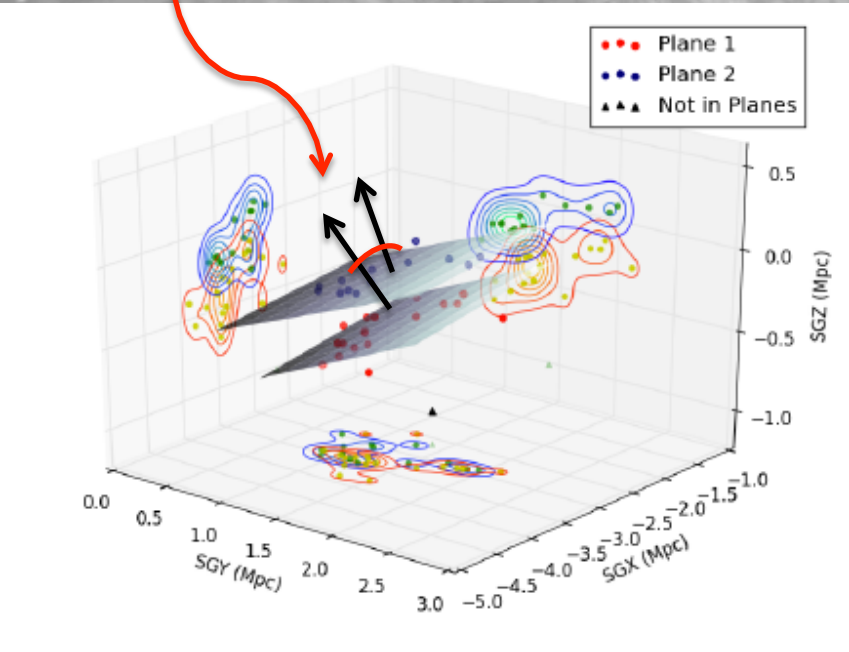
Distance errors are 5% along the line of sight

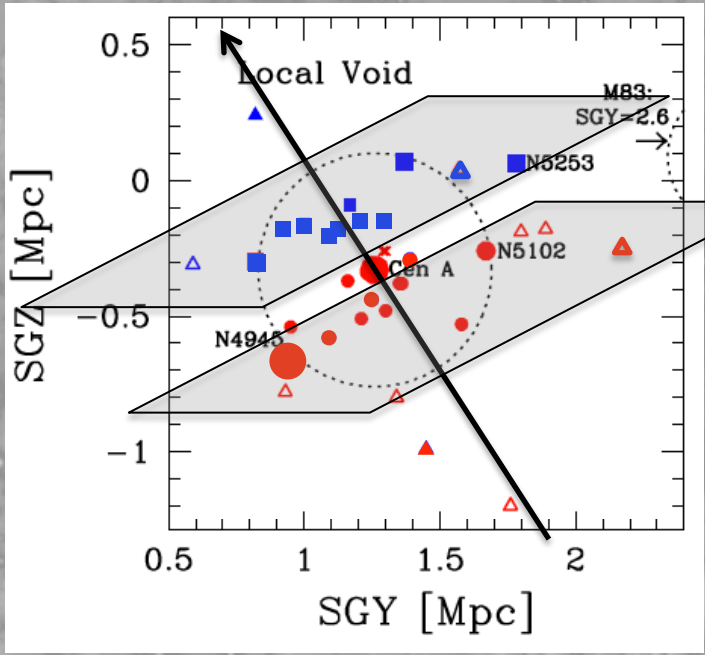
3 σ accuracy of the $n_{\rm CenA}$ is ~ ±2 degrees

Tully, NL *et al* (2015)

Centaurus A Planes

7 deg





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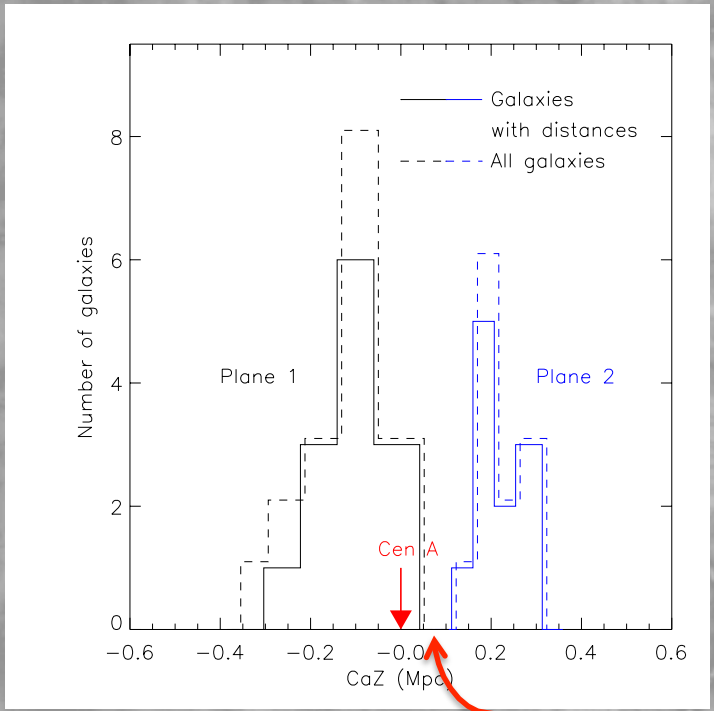
Can fit a single normal to the two parallel planes

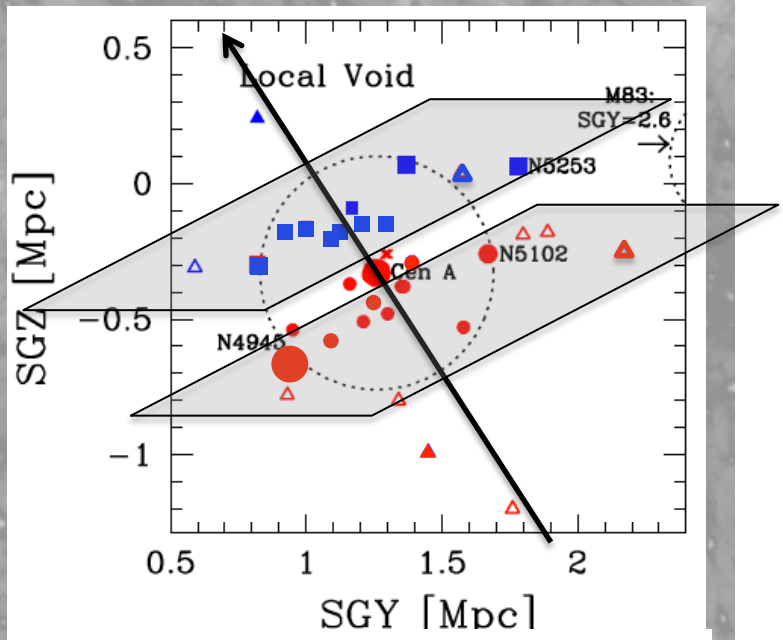
Tully, NL *et al* (2015)

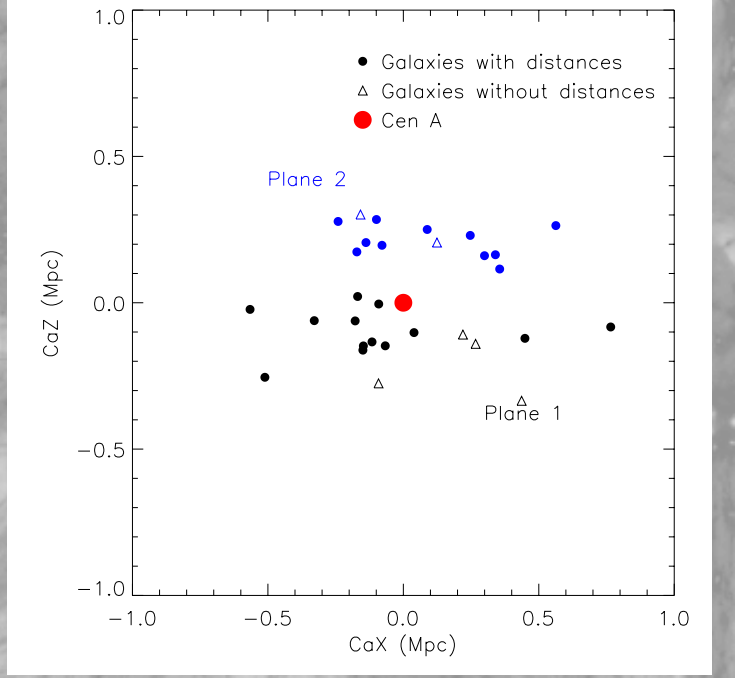
Centaurus A Planes



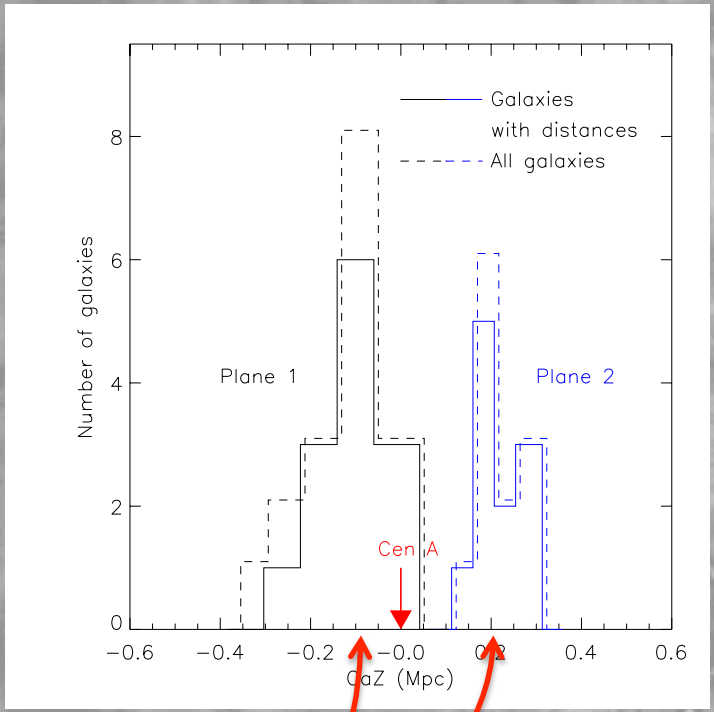
Tully, NL *et al* (2015)

Around 100kpc between planes





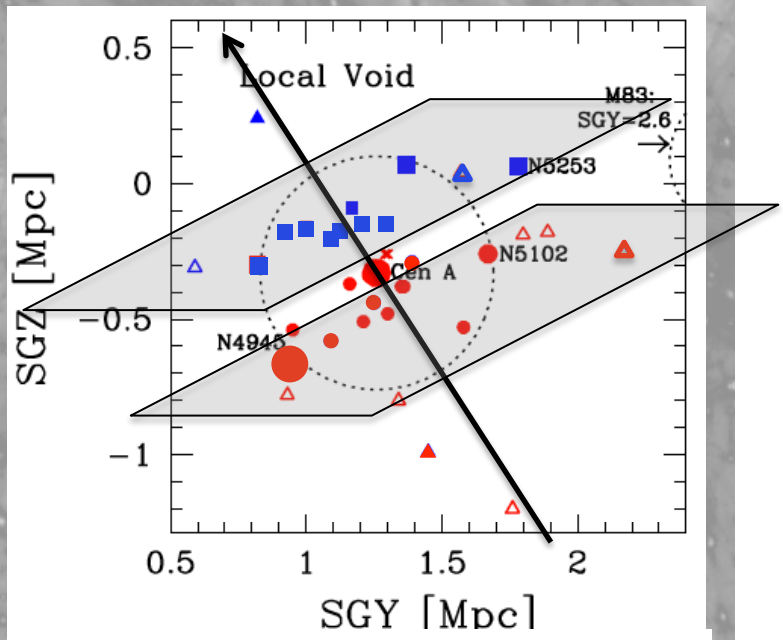
Centaurus A Planes

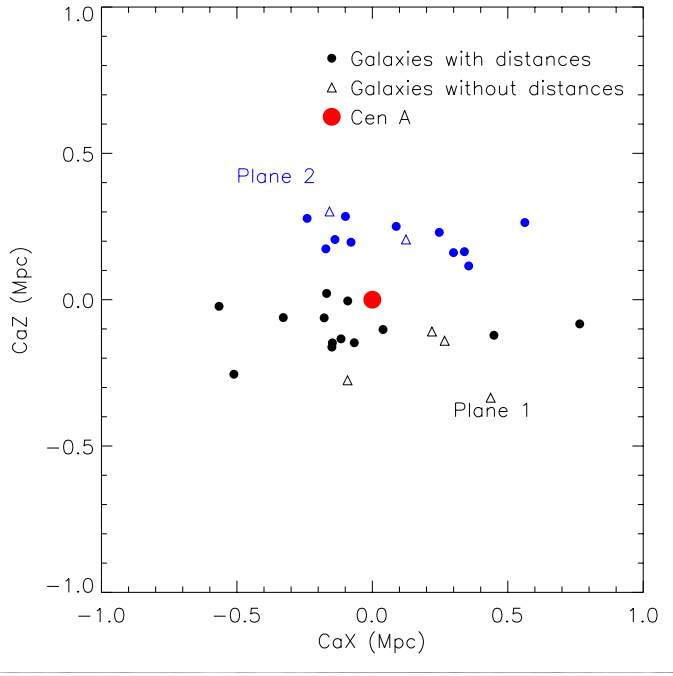


Tully, NL *et al* (2015)

Around 100kpc between planes

Offset between the means is around 300kpc





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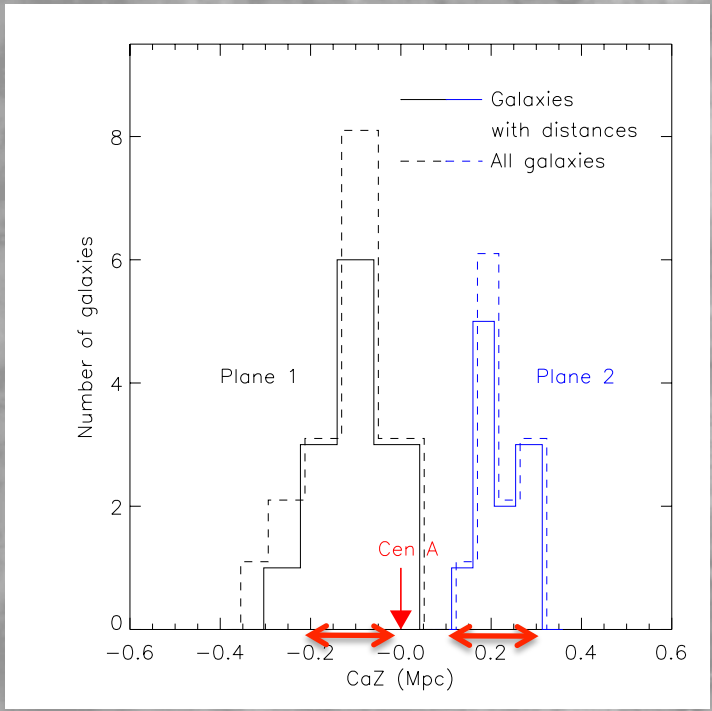
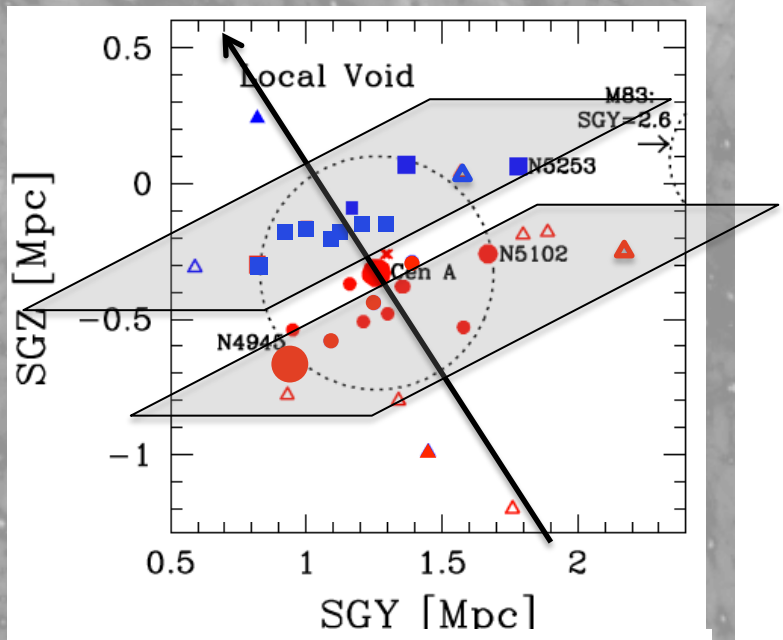
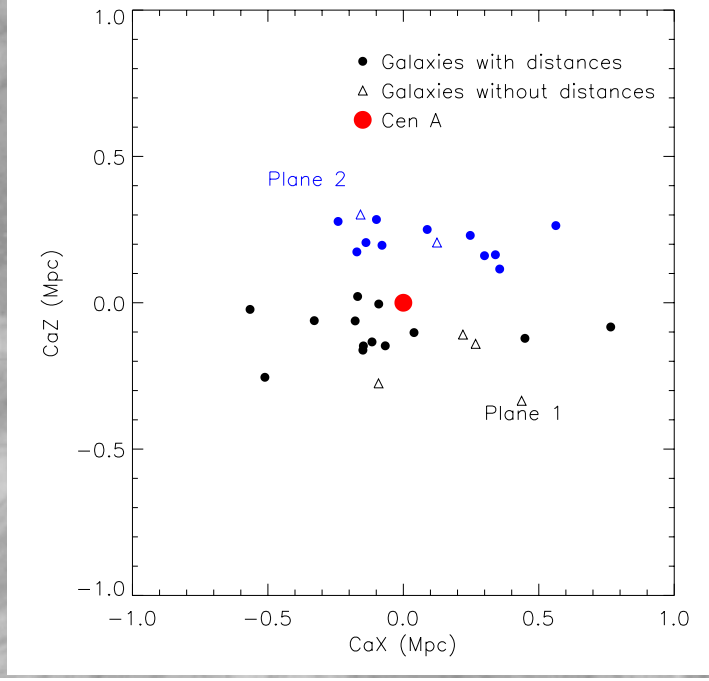


Tully, NL *et al* (2015)



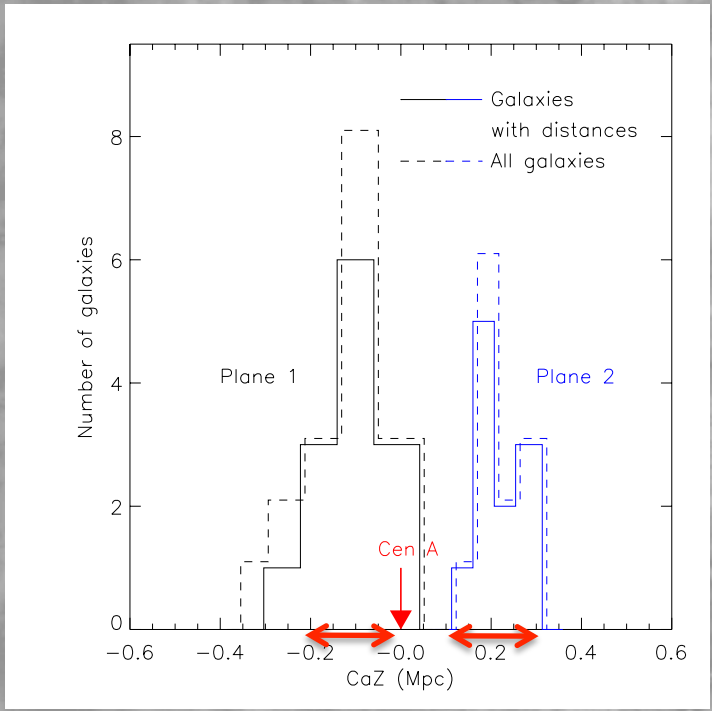


Around 100kpc between planes

Offset between the means is around 300kpc

Each plane is around 50-60kpc in rms

Centaurus A Planes



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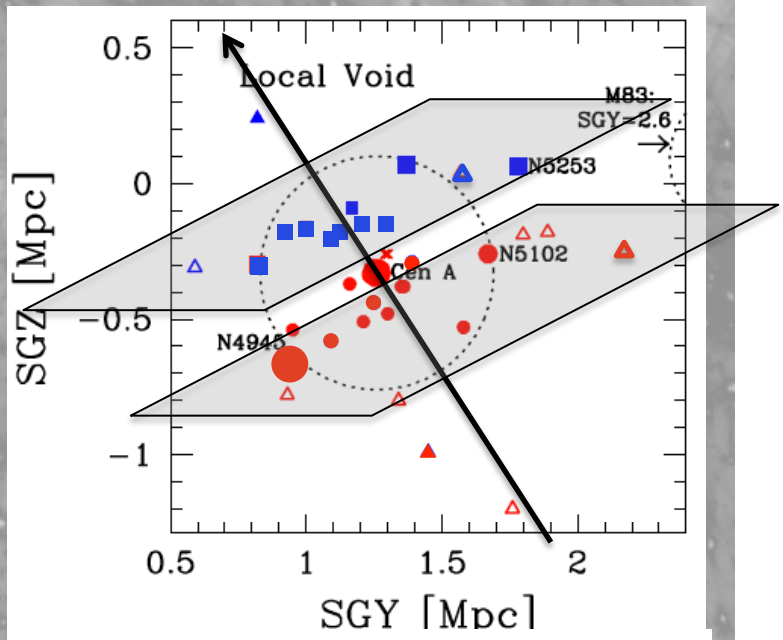

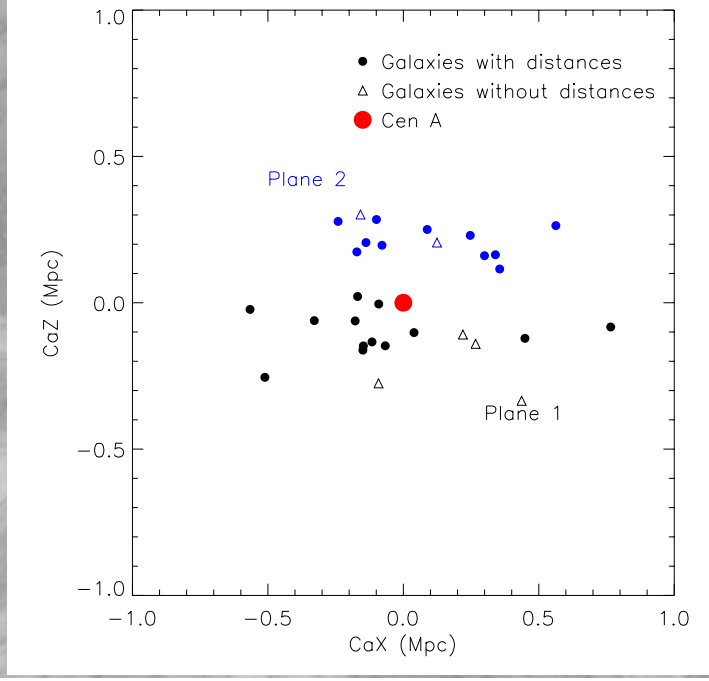

Around 100kpc between planes

Offset between the means is around 300kpc

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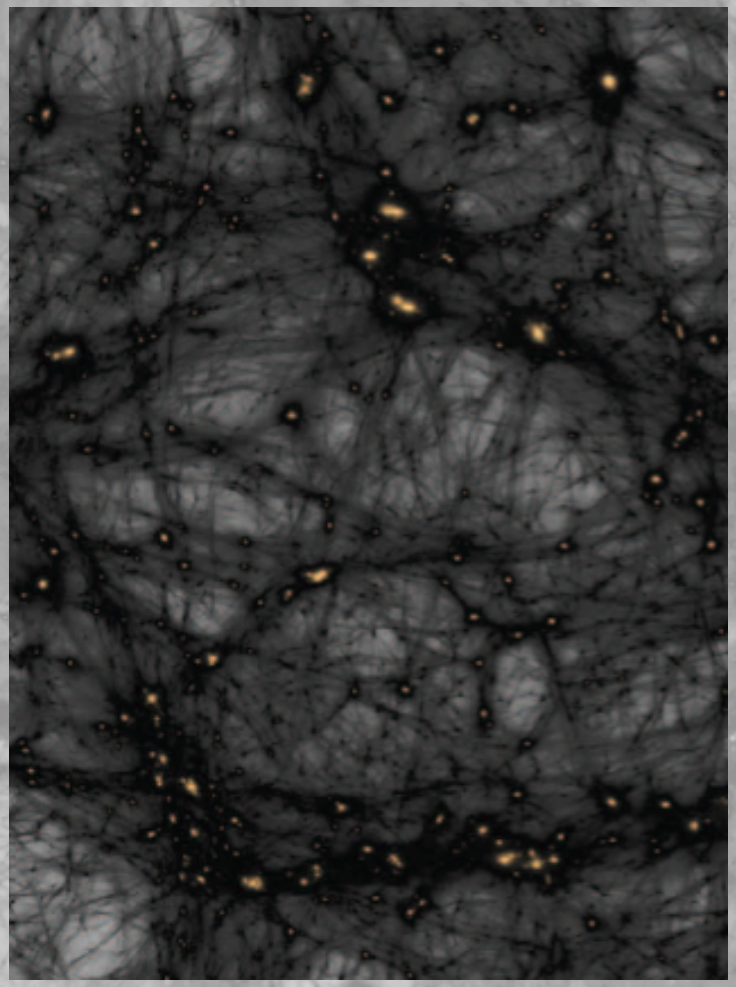
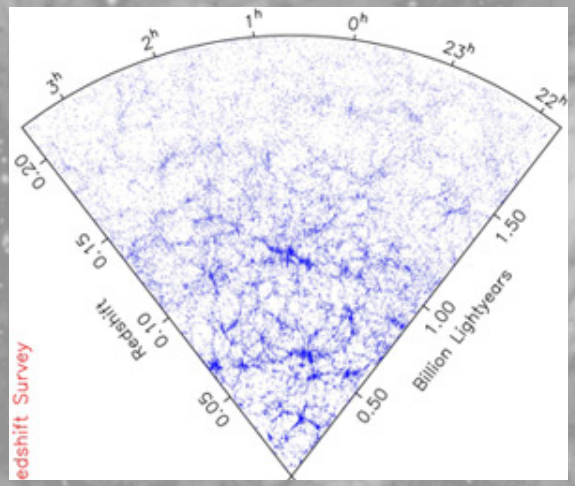
Probability of finding such set ups "by chance" are exceedingly low ~3 out of 10,000

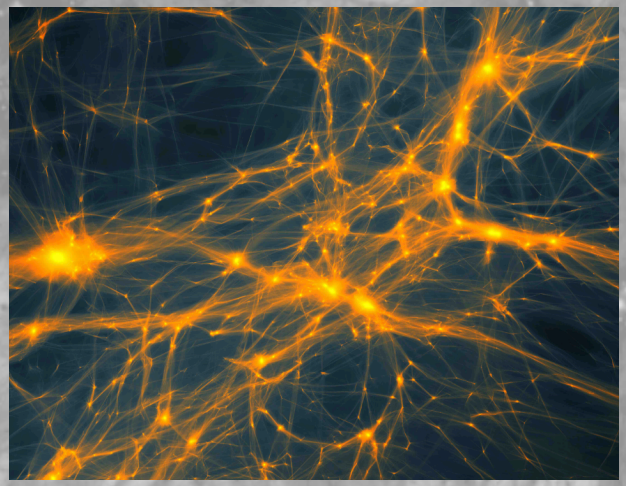
Is the *cosmic web* responsible for these planes of satellite galaxies



Libeskind 2014

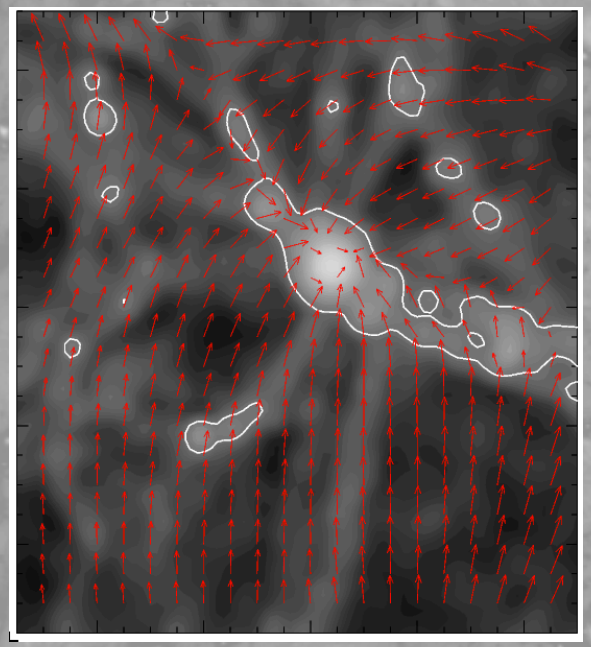


2df GRS



Kahler, Hahn & Abell 2013

Velocity Shear Tensor



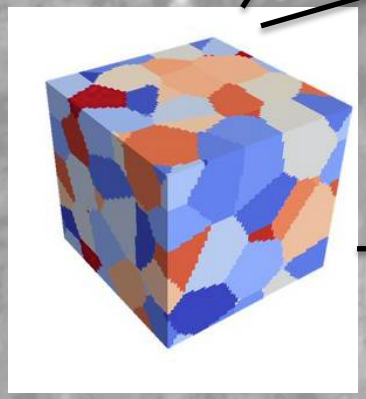
Hoffman et al 2012
Libeskind et al 2012, 2013

Looking at LSS from the point of view of (*peculiar*) velocity.

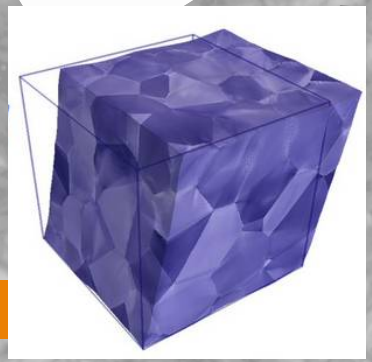
Specifically the deformation of the velocity field – shear, compression and rotation:

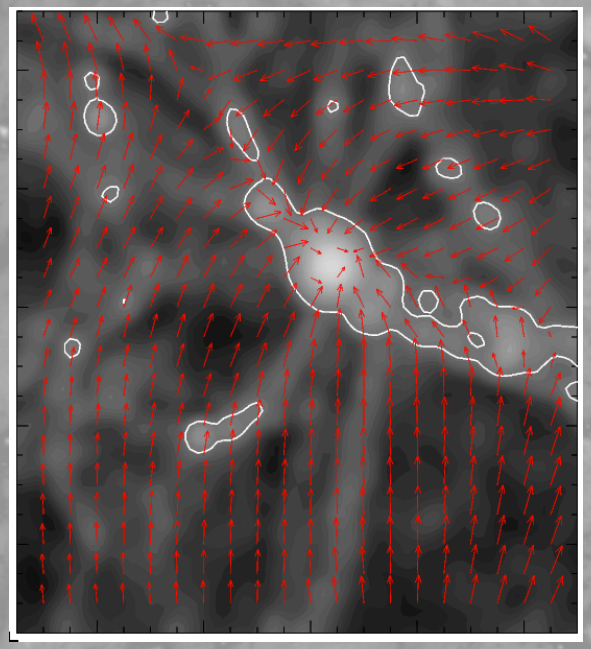
Compression/ expansion

Rotation



Shear





$$\mathbf{u} = H_0 \mathbf{r} \left(1 + \frac{\mathbf{v}}{H_0}\right)$$

$$\begin{aligned}
\mathbf{v}(\mathbf{r}) &= \mathbf{v}(\mathbf{r}_0) + \frac{\partial \mathbf{v}(\mathbf{r})}{\partial r} \mathbf{dr} \\
&= \mathbf{v}(\mathbf{r}_0) + \begin{bmatrix} \frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z} \\ \frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} & \frac{\partial v_y}{\partial z} \\ \frac{\partial v_z}{\partial x} & \frac{\partial v_z}{\partial y} & \frac{\partial v_z}{\partial z} \end{bmatrix} \begin{bmatrix} \mathbf{dx} \\ \mathbf{dy} \\ \mathbf{dz} \end{bmatrix} \\
&= \mathbf{v}(\mathbf{r}_0) + \mathbf{S}_{\alpha\beta}\ \mathbf{dr}
\end{aligned}$$

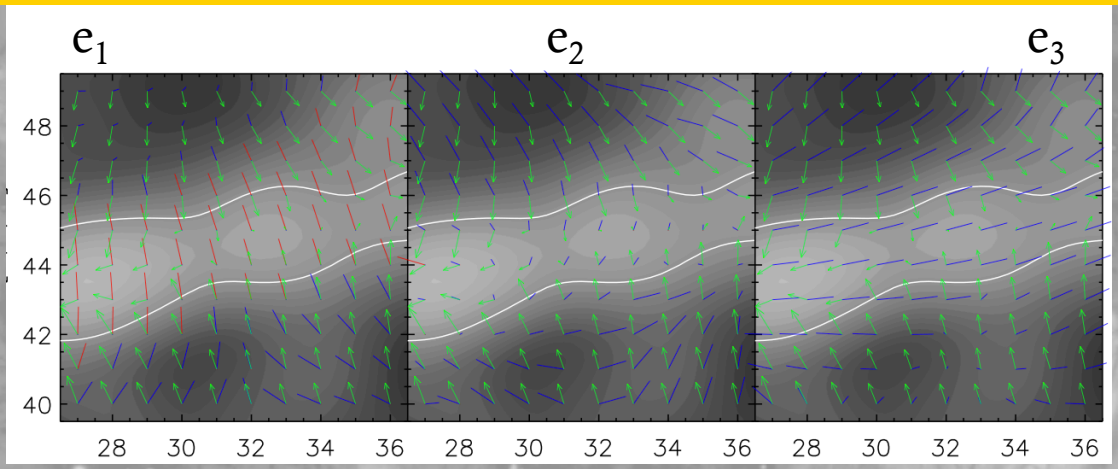
Symmetric part is the "Shear" tensor + Divergence

$$\mathbf{S}_{ij} = \Sigma_{ij} + \Omega_{ij}$$

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

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

Full (3D) velocity & density field from Wiener filter reconstructions of the cosmic flows-2 survey



Axis of fastest collapse
Sheet normal

Axis of slowest collapse

$$\Sigma_{ij} = -\frac{1}{2H(z)}\left(\frac{\partial v_i}{\partial r_j} + \frac{\partial v_j}{\partial r_i}\right)$$

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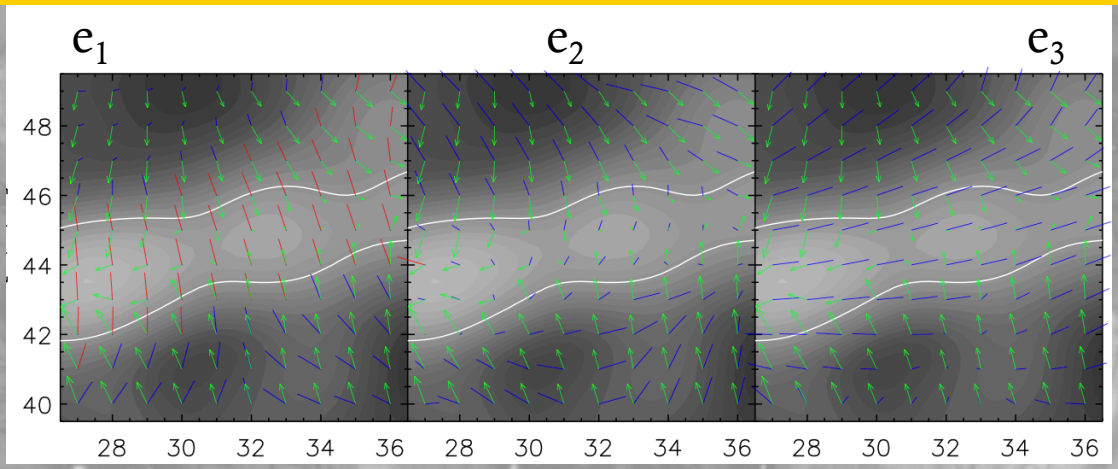
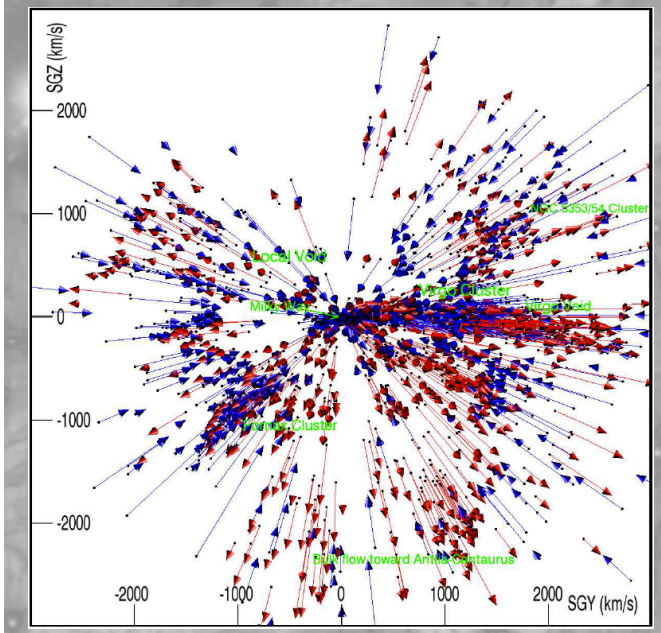


radial peculiar velocity



Courtois *et al* 2013

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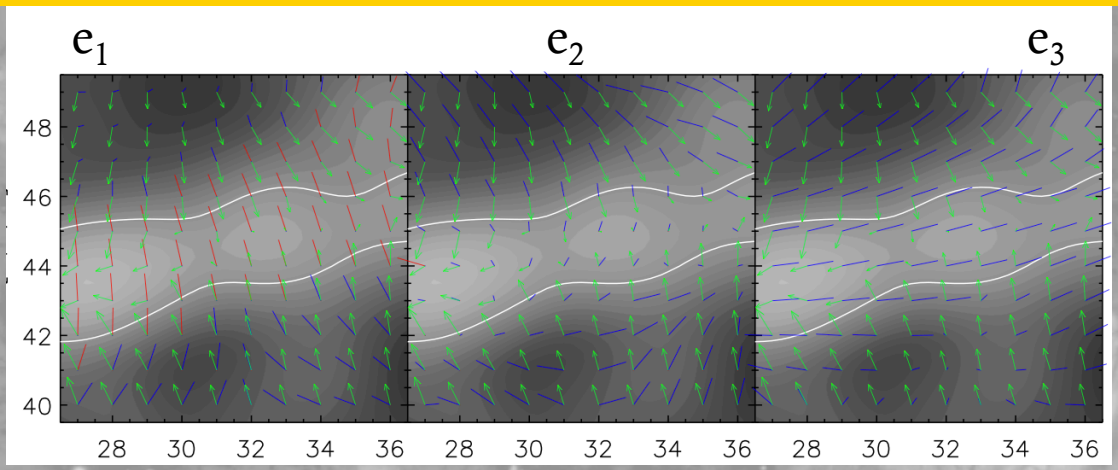

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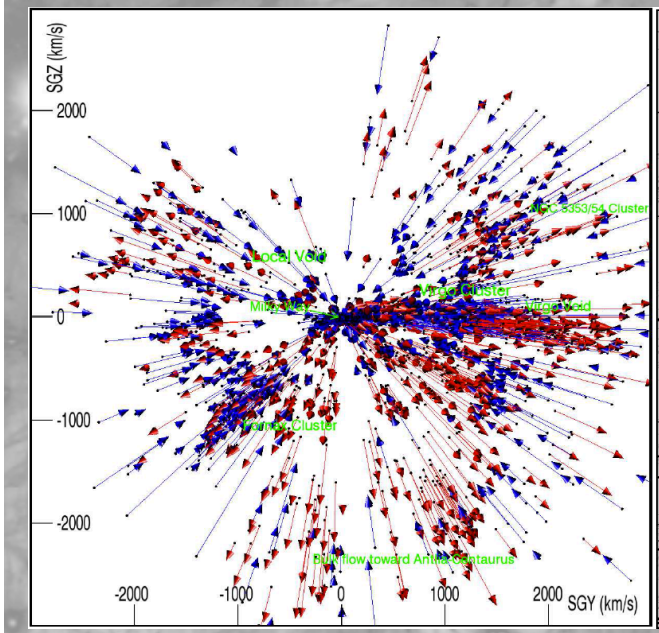
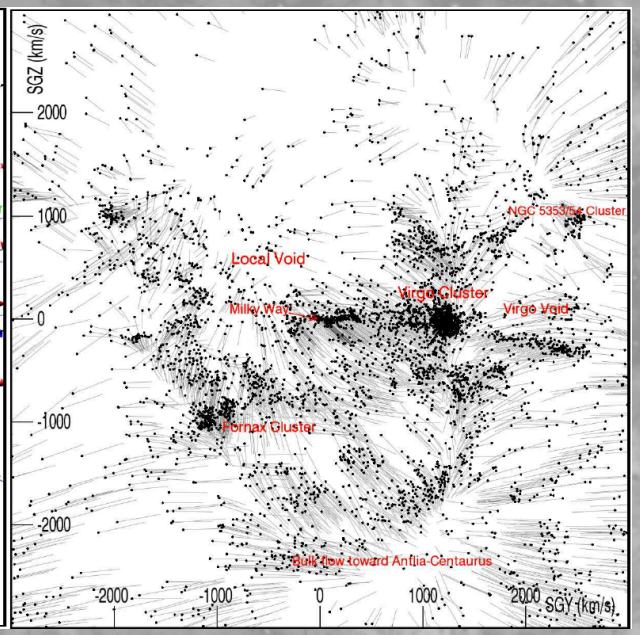


reconstructed 3D peculiar velocity



Courtois *et al* 2013

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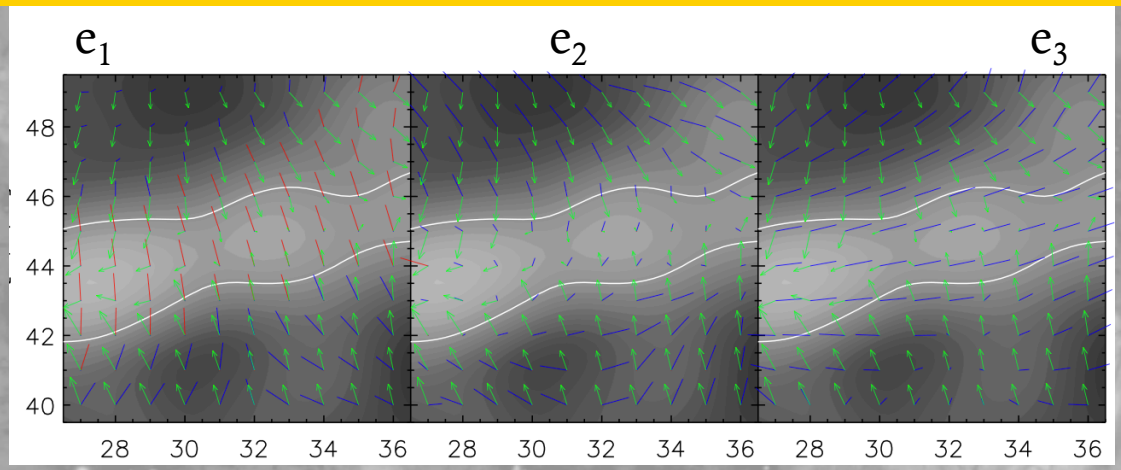
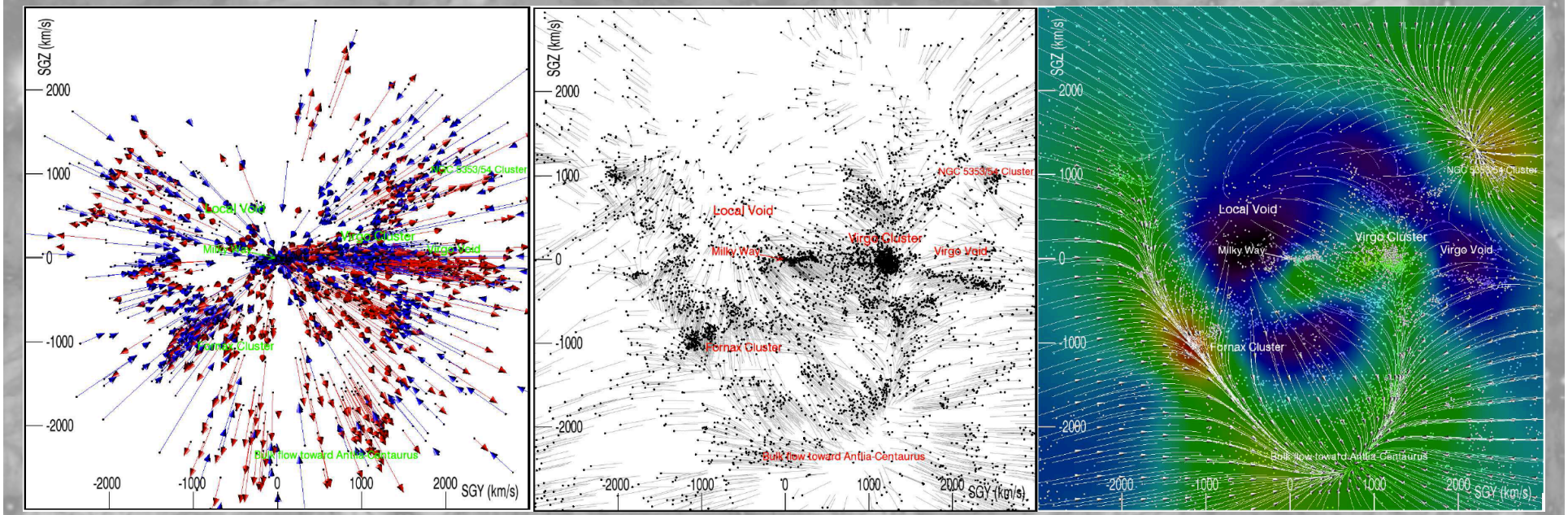


radial peculiar velocity

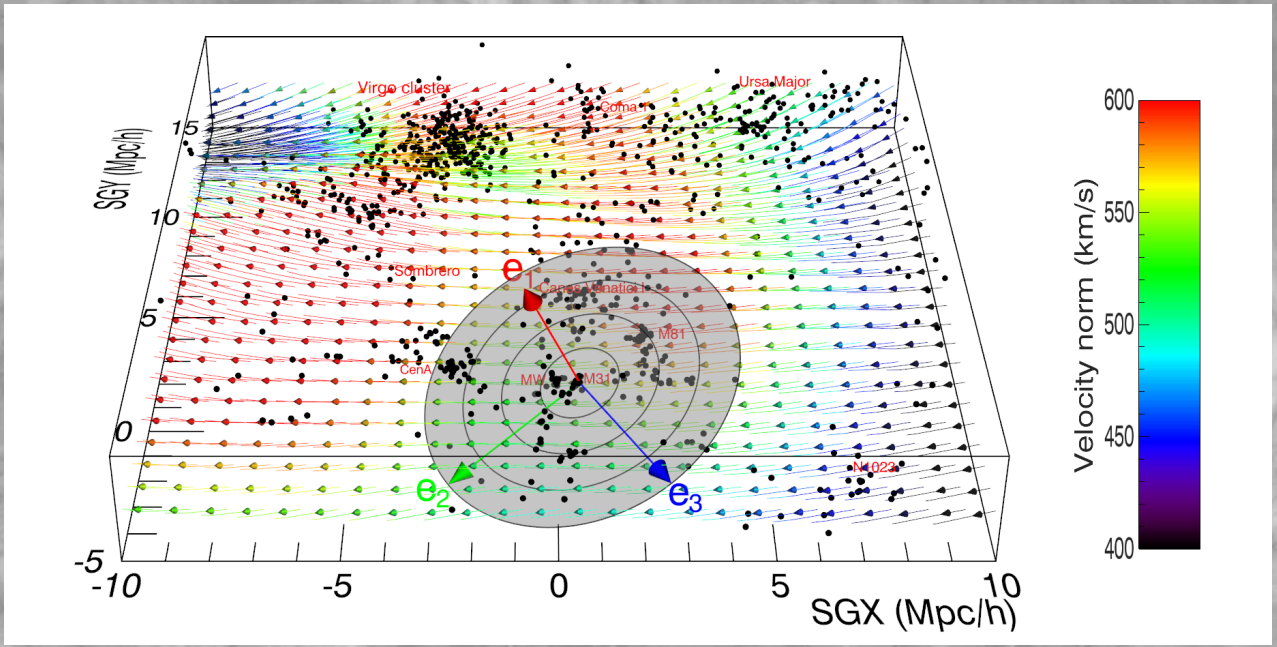
reconstructed 3D peculiar velocity

Corresponding 3D density field



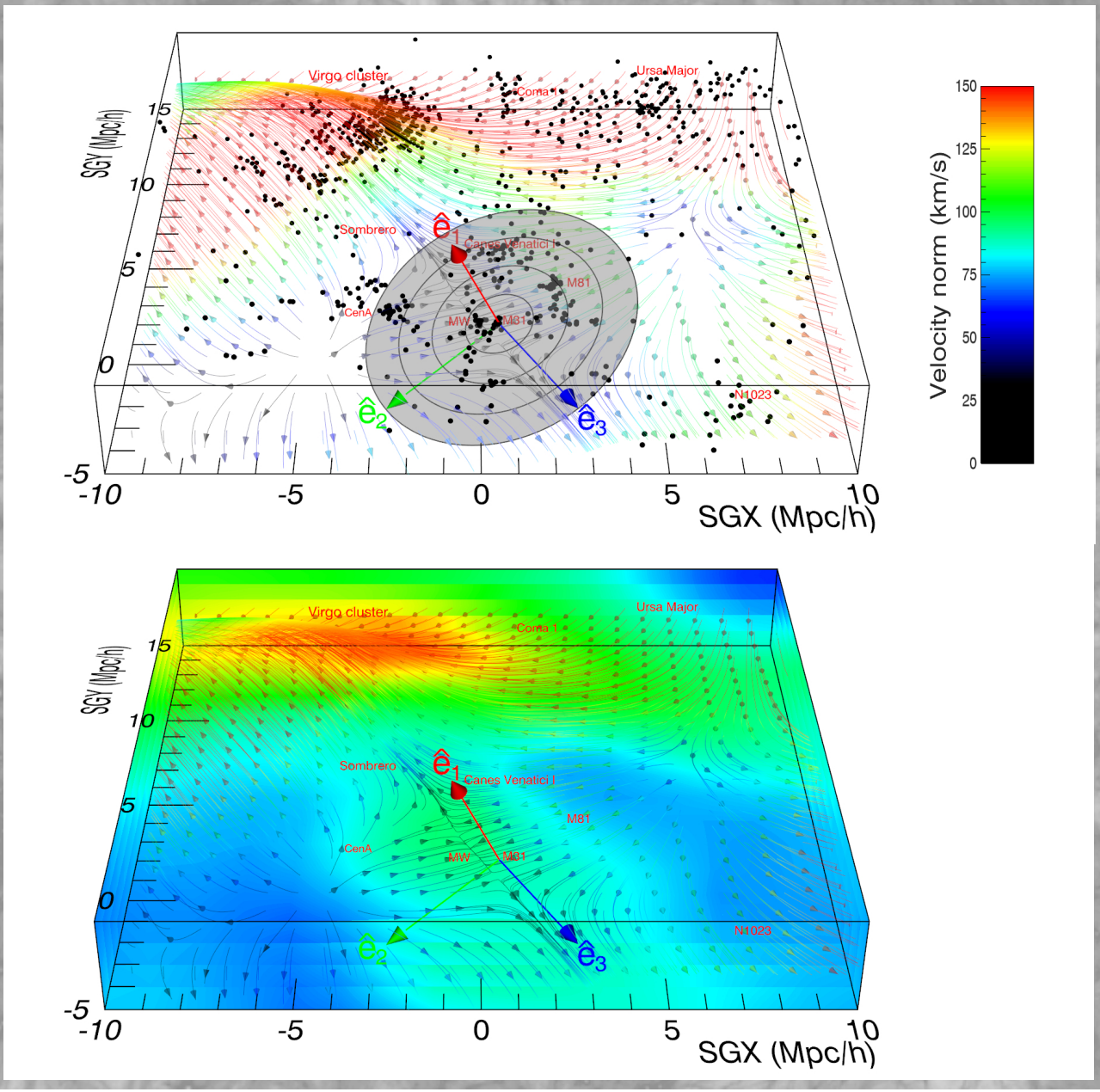
Courtois *et al* 2013

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



Libeskind *et al* 2015

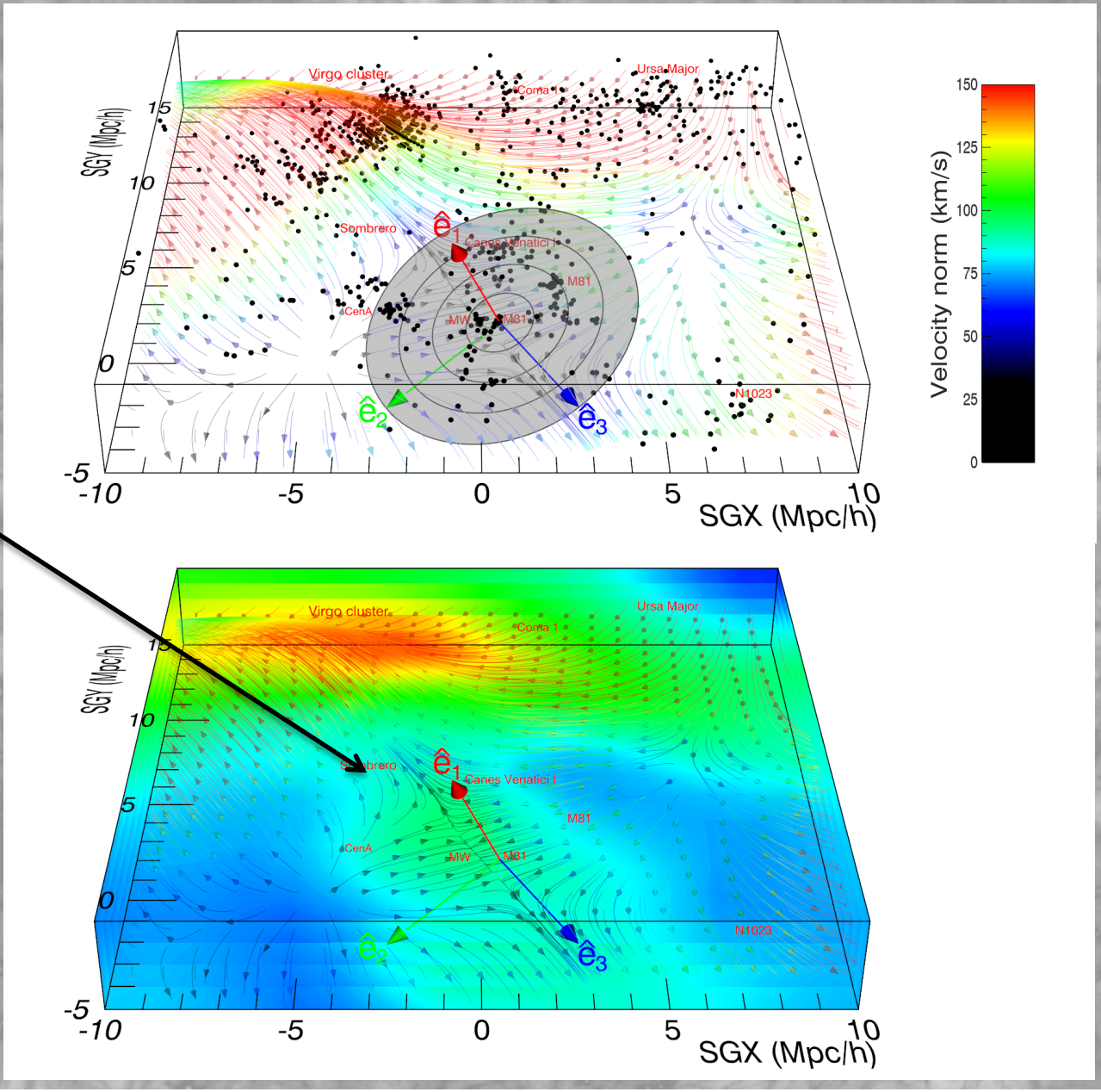
“Local” velocity field, from cosmic-flows-2



Libeskind *et al* 2015

"Local" velocity field, from cosmic-flows-2

"Local Filament" stretched by Virgo

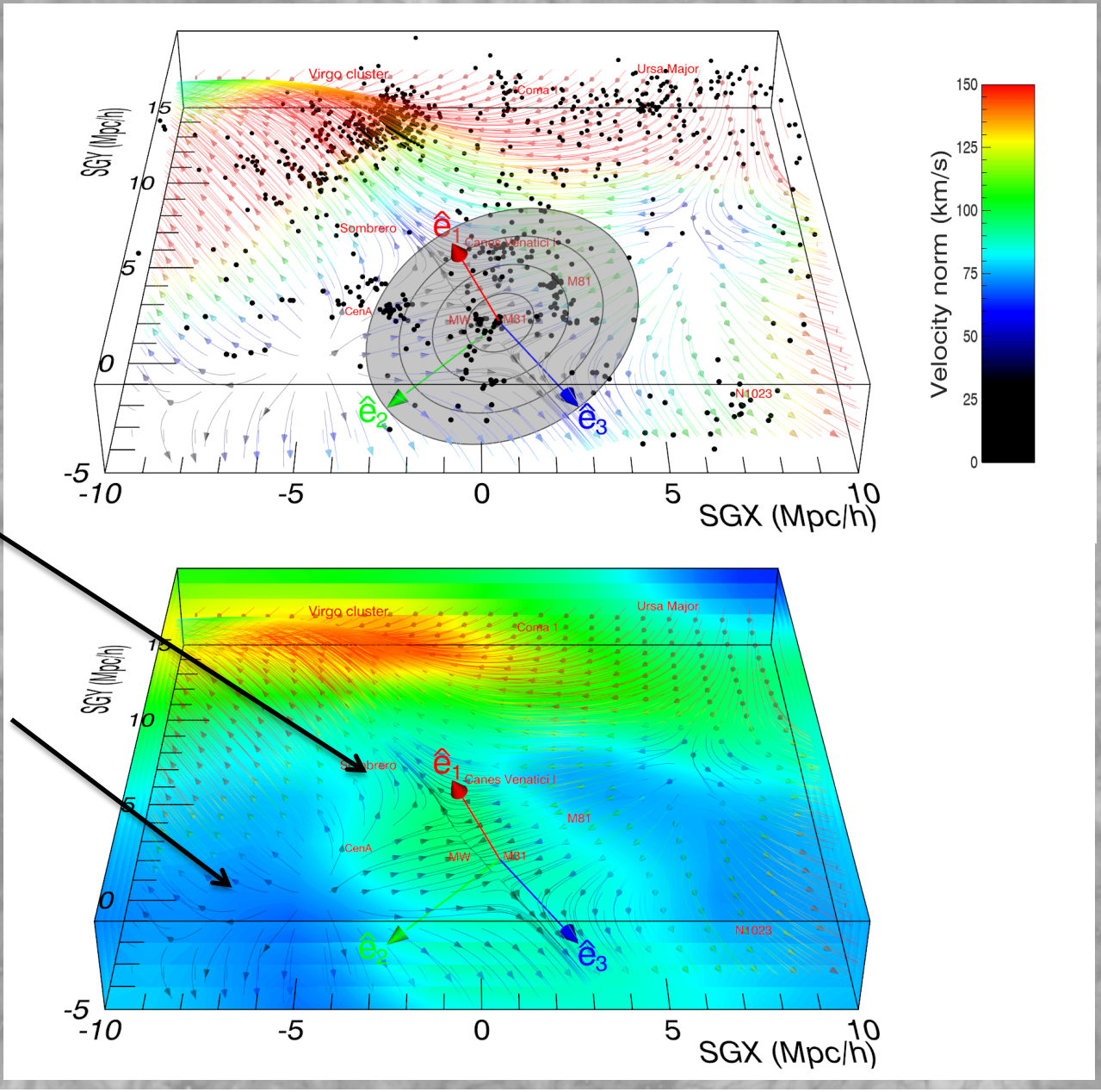


Libeskind *et al* 2015

"Local" velocity field, from cosmic-flows-2

"Local Filament" stretched by Virgo

Laterally squashed by a "mini-repeller"



Libeskind *et al* 2015

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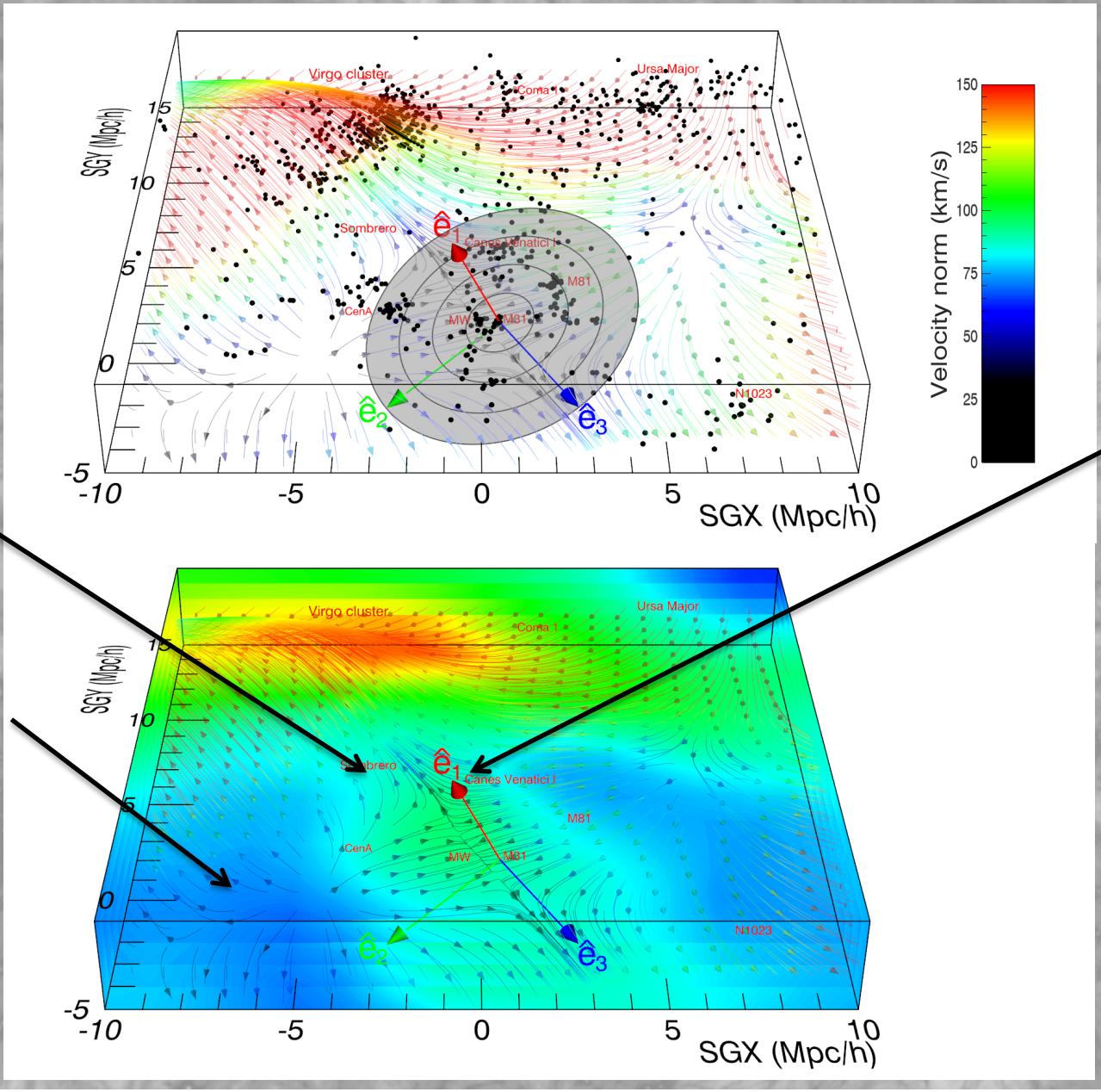

e_1 sheet normal, points to the local void

Libeskind *et al* 2015

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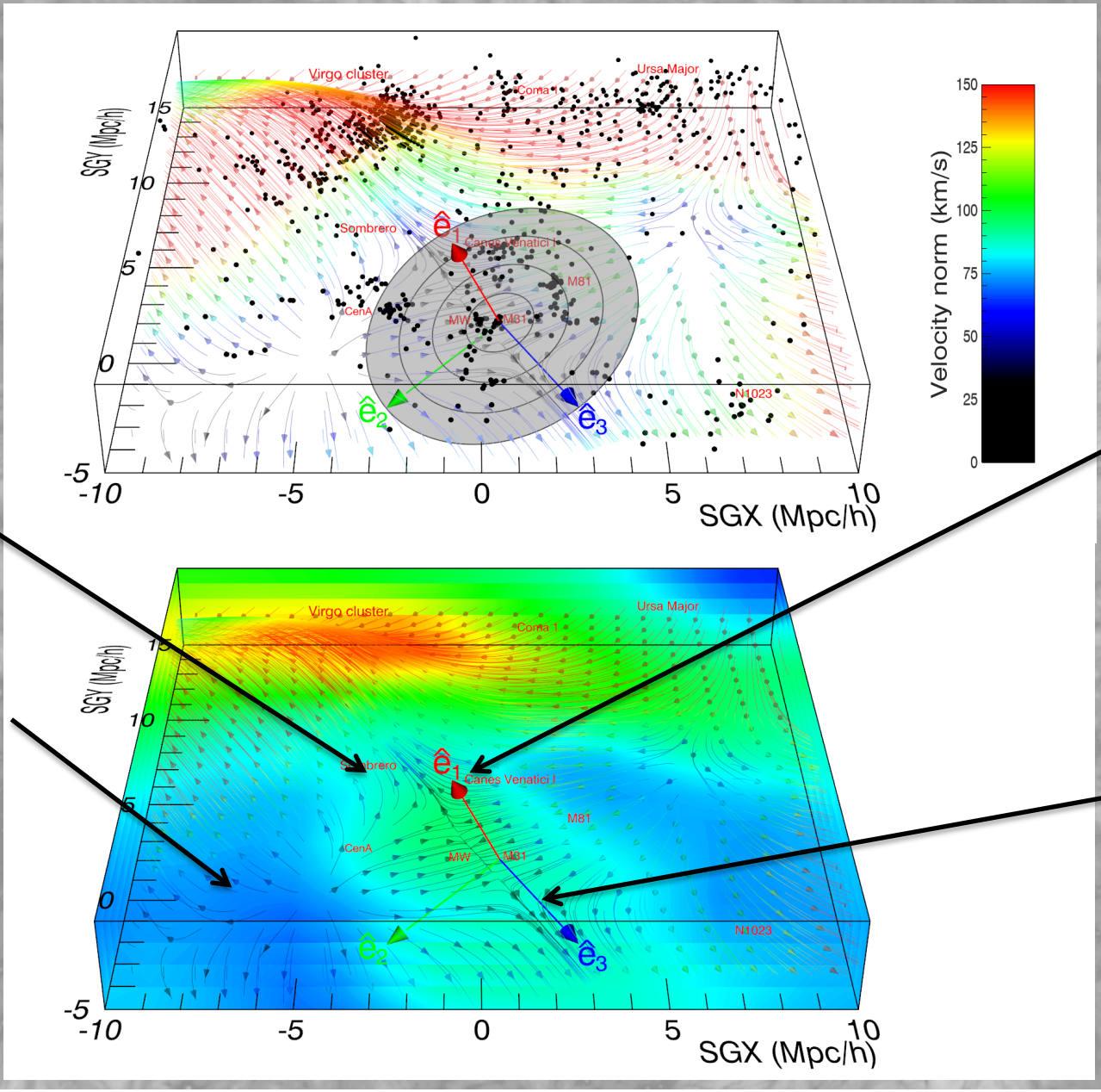


"Local Filament" stretched by Virgo

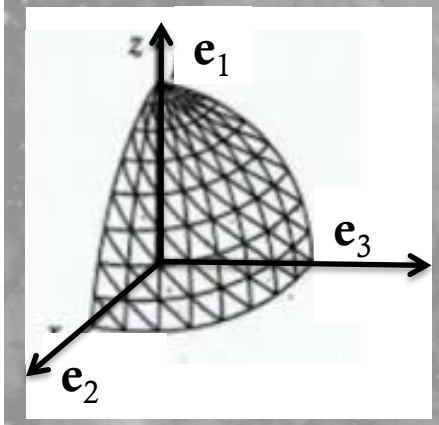
Laterally squashed by a "mini-repeller"

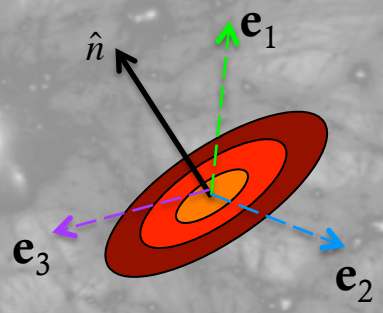
e_1 sheet normal, points to the local void

e_3 filament axis, points to Virgo

Libeskind *et al* 2015

How are the satellite planes of Cen A, M31, and the MW oriented with respect to the shear





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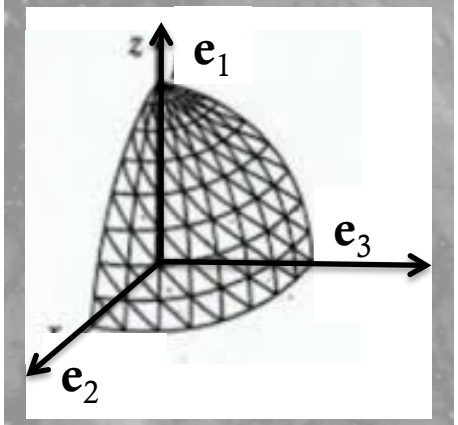

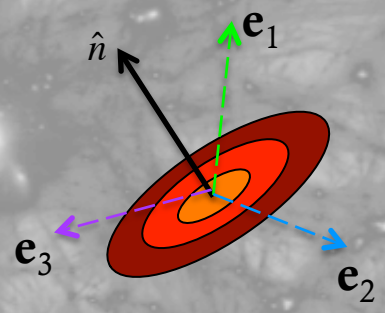

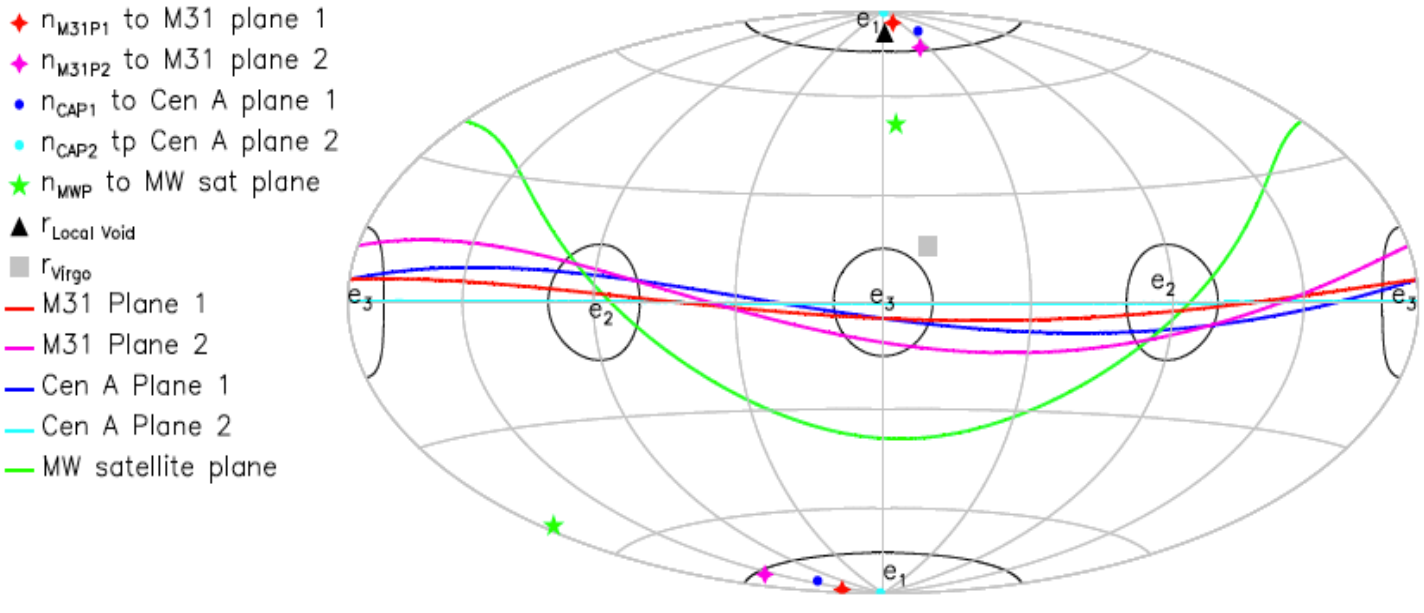

Libeskind *et al* 2015

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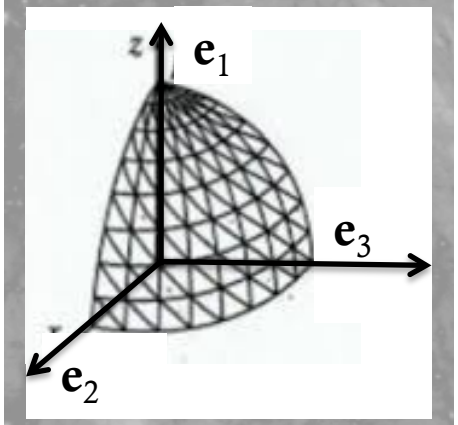

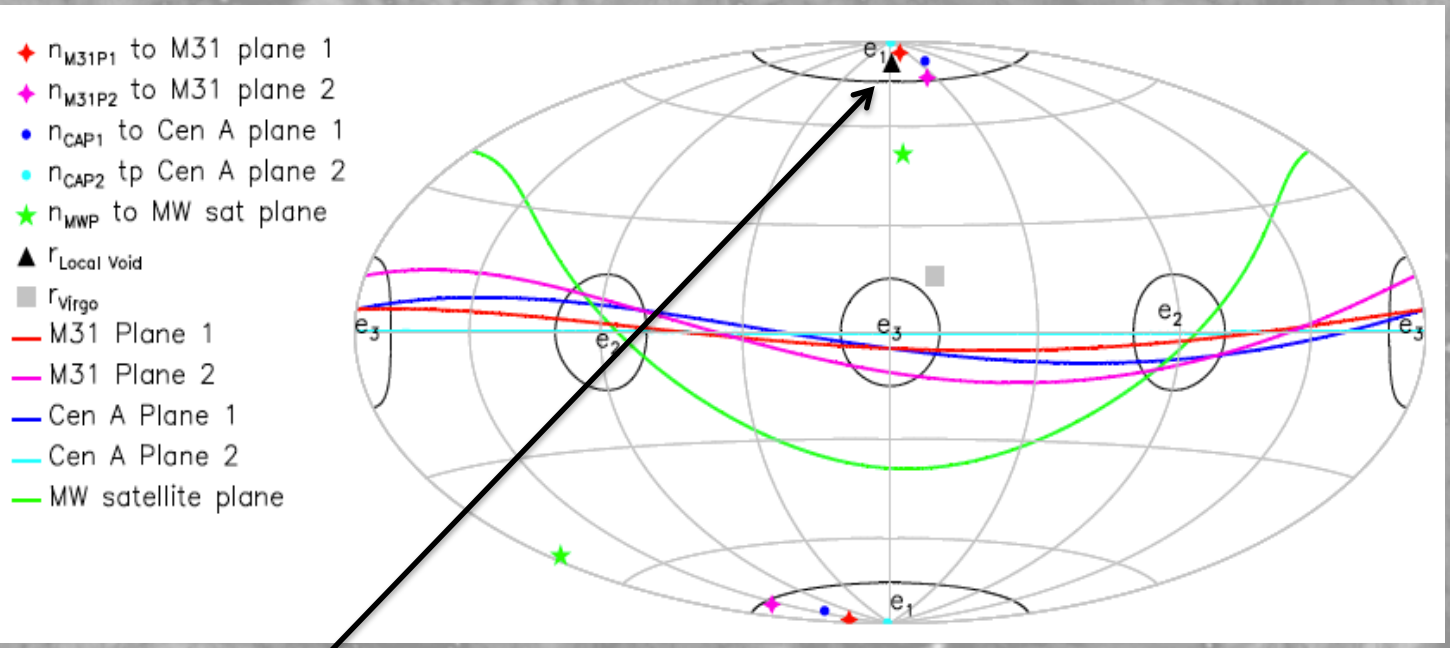

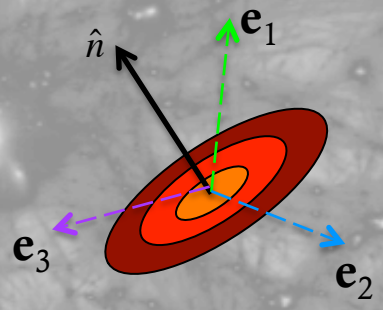

e_1 sheet normal, points to the local void

Libeskind *et al* 2015

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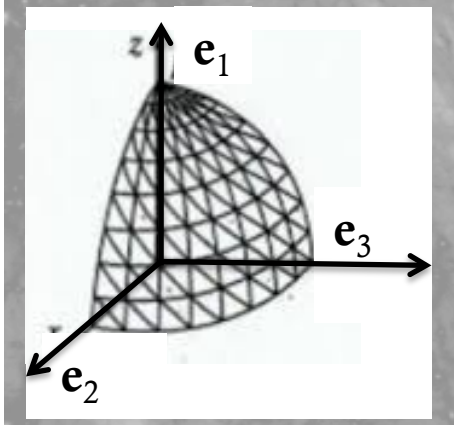

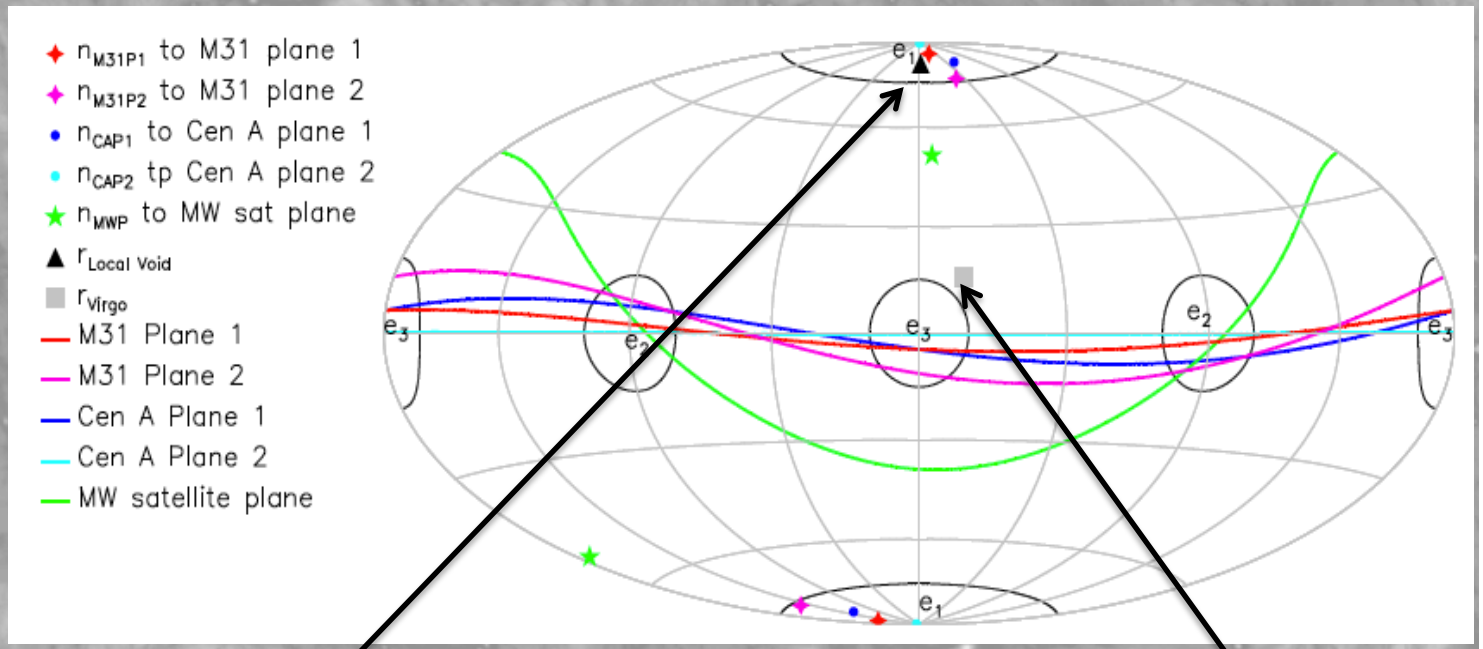

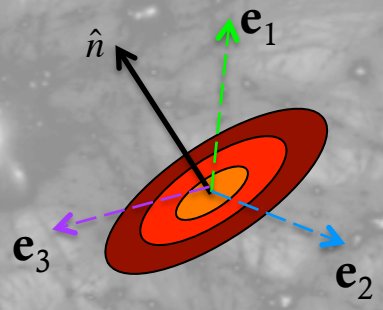

e_1 sheet normal, points to the local void

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Libeskind *et al* 2015

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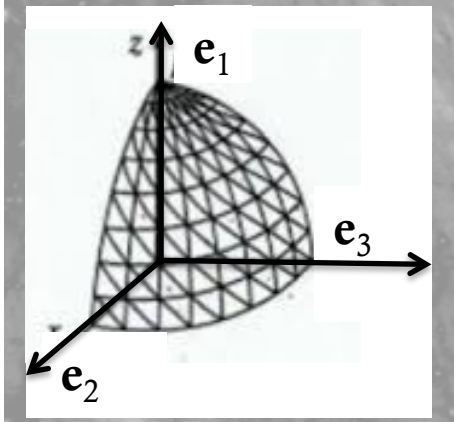
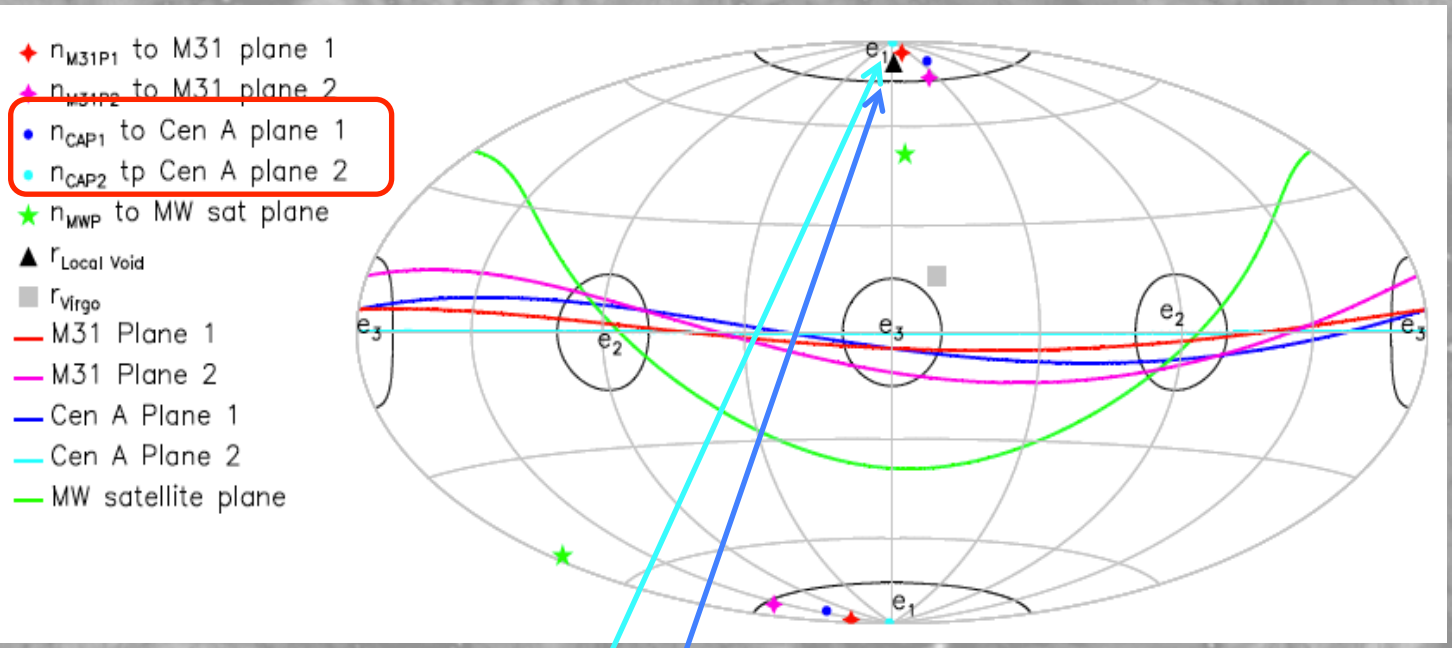
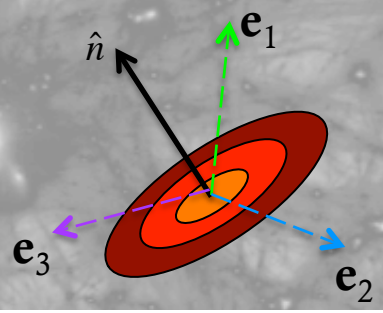




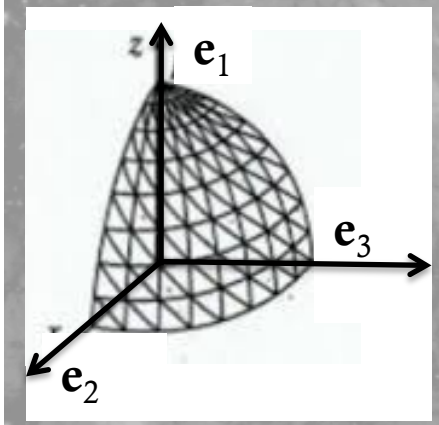


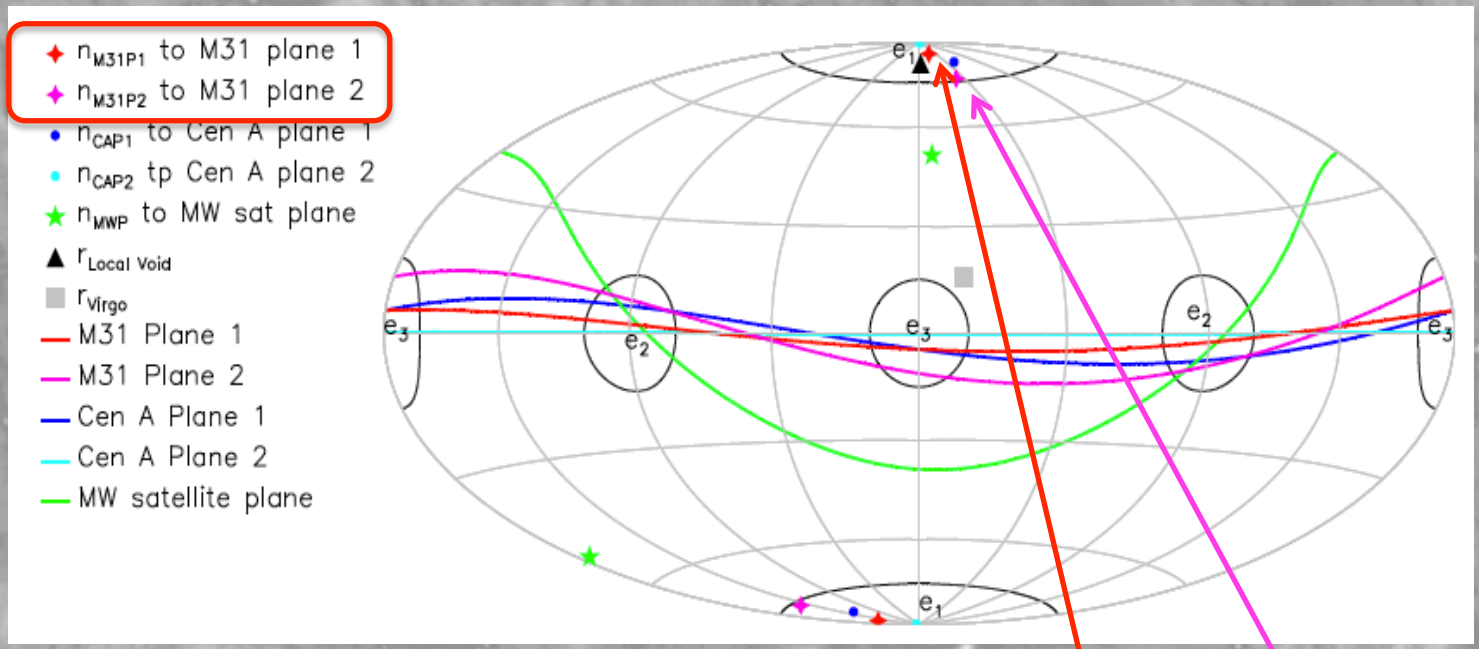
property	$\lvert\cos\theta\rvert$	degrees apart
$\mathbf{e}_3 \cdot \hat{r}_{\rm Virgo}$	0.9330	~21.1
$\mathbf{e}_1 \cdot \hat{r}_{\rm Virgo}$	0.2733	~74.1
$\mathbf{e}_1 \cdot \hat{r}_{\rm LV}$	0.9898	~8.17
$\mathbf{e}_1 \cdot \hat{n}_{\rm M31P1}$	0.9968	~4.5
$\mathbf{e}_1 \cdot \hat{n}_{\rm M31P2}$	0.9704	~13.9
$\mathbf{e}_1 \cdot \hat{n}_{\rm CAP1}$	0.9879	~8.9
$\mathbf{e}_1 \cdot \hat{n}_{\rm CAP2}$	0.9999	~0.3
$\mathbf{e}_1 \cdot \hat{n}_{\rm MWP}$	0.7801	~38.7

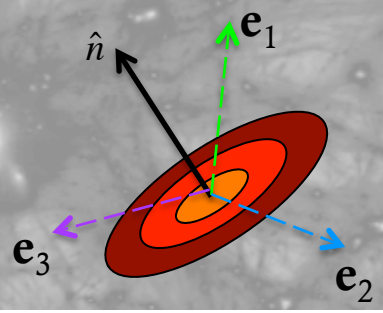
2 planes in CenA
are well aligned

Libeskind *et al* 2015

How are the satellite planes of Cen A, M31, and the MW oriented with respect to the shear







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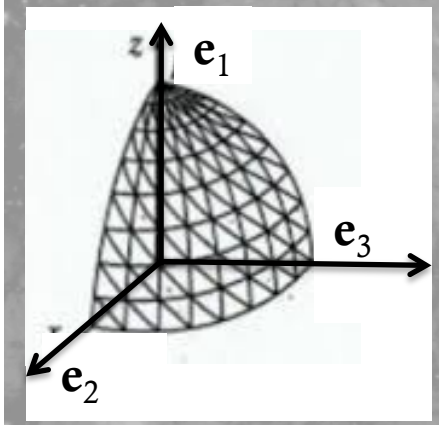
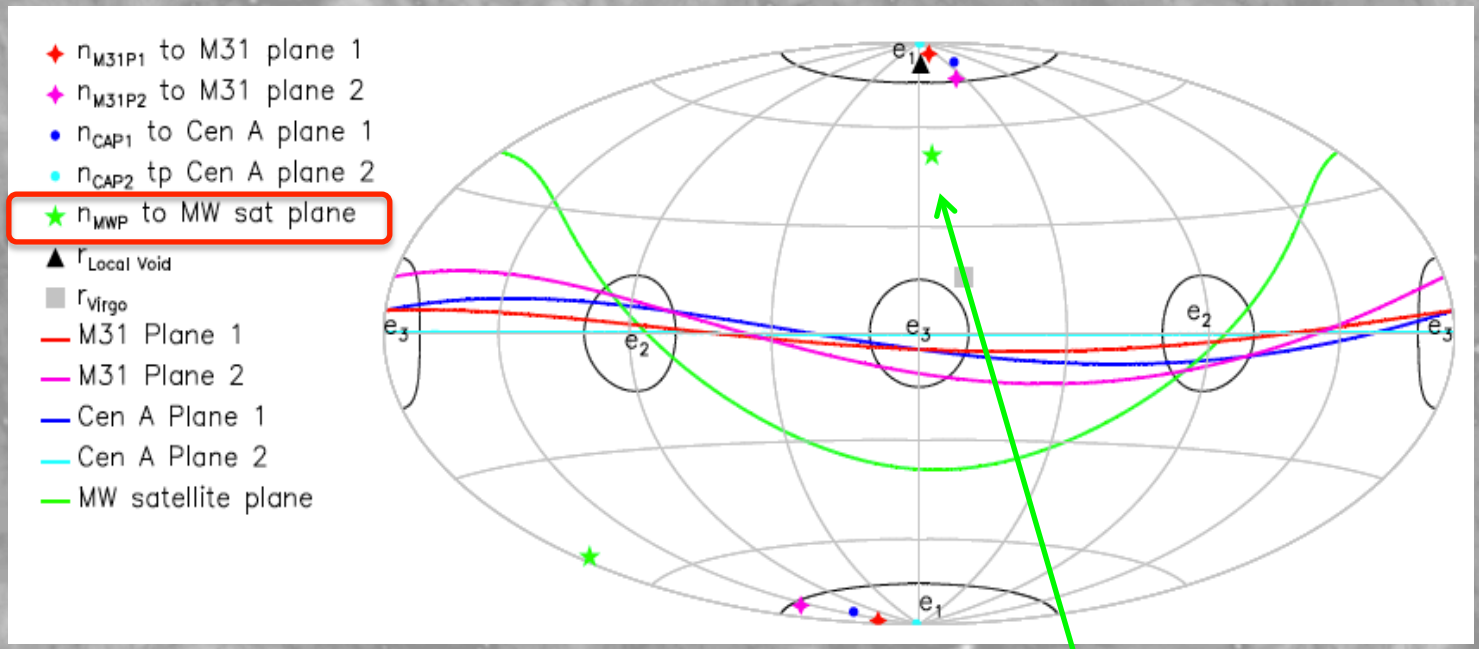
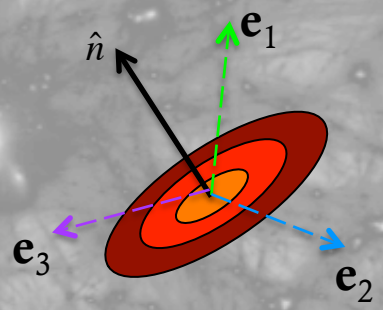
2 planes in M31 are well aligned

Libeskind *et al* 2015

How are the satellite planes of Cen A, M31, and the MW oriented with respect to the shear







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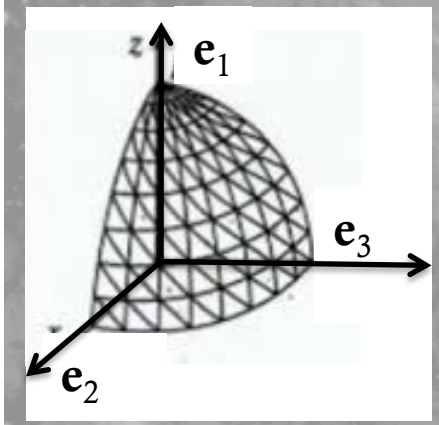
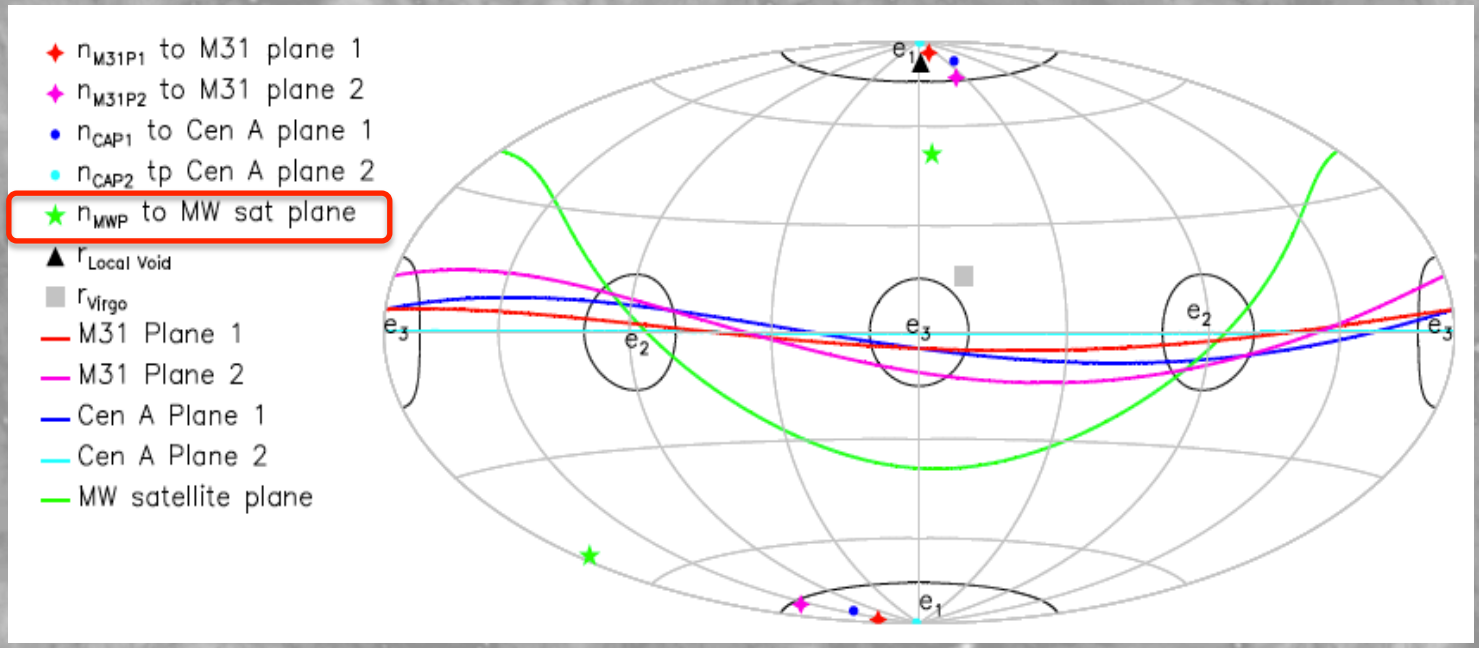
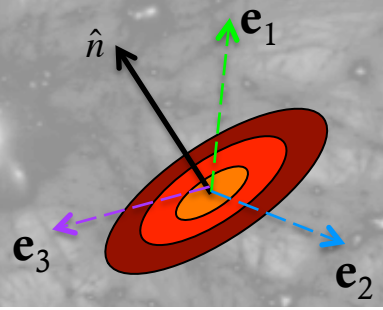
MW plane is off by ~38 deg, appears to have been torqued about the e_2 axis

Libeskind *et al* 2015

How are the satellite planes of Cen A, M31, and the MW oriented with respect to the shear







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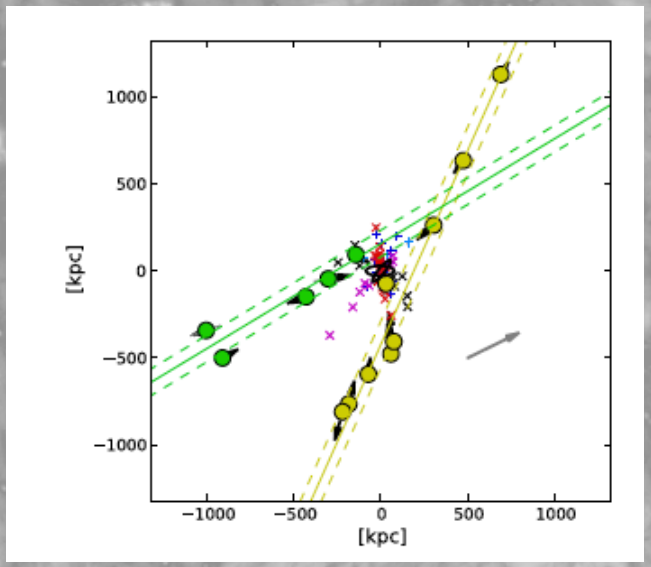


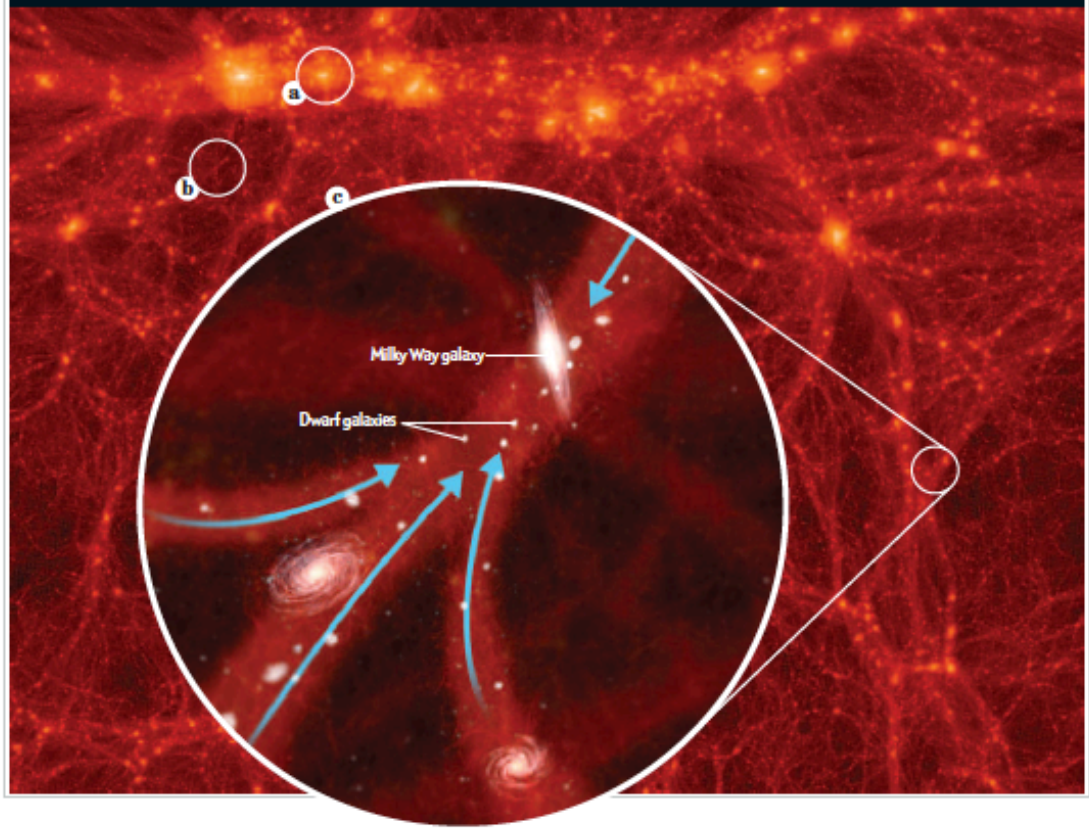
Pawlowski *et al* 2013

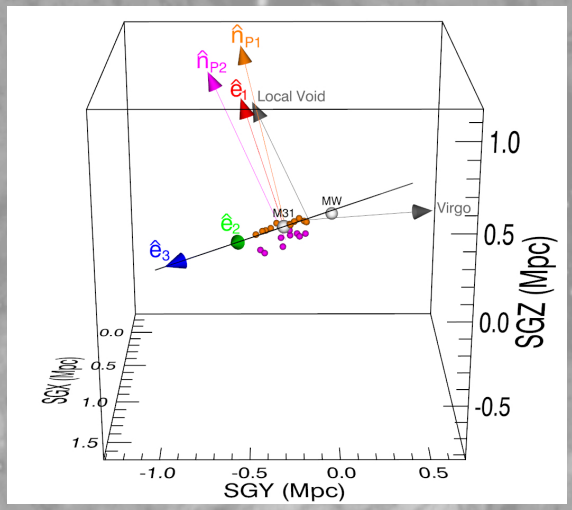
Satellites and cosmic filaments

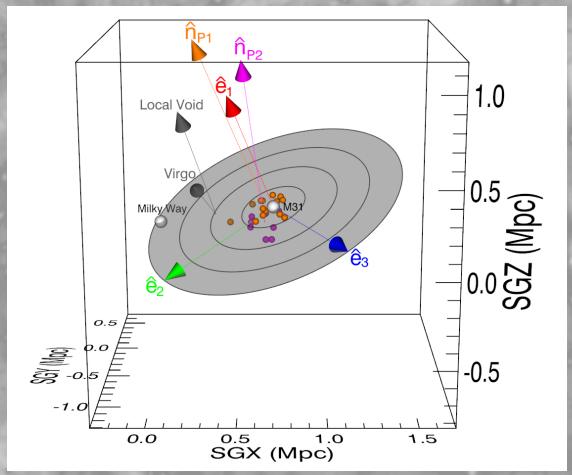
HOW IT WORKS

Cosmic Superhighways of Dark Matter

In the roughly 14 billion years since the big bang, the dark matter that pervades our universe has coalesced into what cosmologists call the cosmic web, an enormous structure of filaments and nodes. Dark matter pulls in nearby gas and dust, forming massive galaxies such as our Milky Way in the nodes where the density of dark matter is highest (a). In filaments, the density of dark matter is lower, and only smaller dwarf galaxies form (b). Over time, the strong gravitational pull of the nodes tends to attract material in the filaments, pulling dwarf galaxies toward large galaxies (c). From our point of view inside the Milky Way, the dwarf galaxies appear to lie in a plane running perpendicular to the galaxy.







Libeskind 2014, *Scientific American*

Conclusions

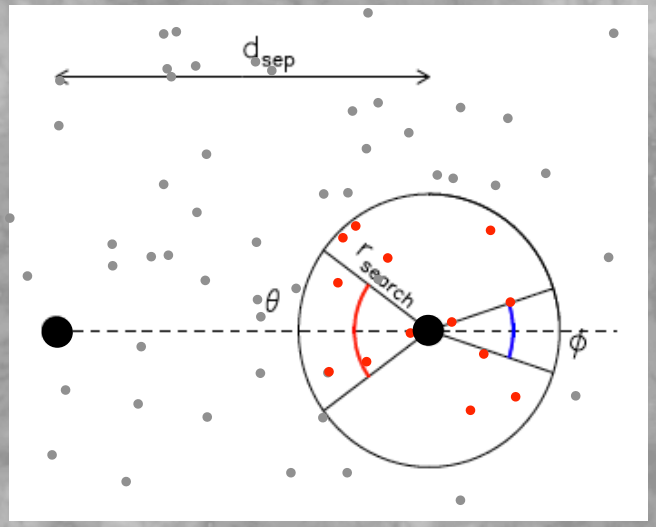
1. Dwarfs around Centaurus A indicate that they are located on two nearly parallel but fairly thin planes

2. By exploiting the cosmic flows -2 survey of peculiar velocities we have found a new feature in the local universe – a flattened filament stretching all the way to Virgo

3. This particular geometry may be responsible for forming these satellite planes

4. The shear field on scales that are still linear have a direct influence on the sub-Mpc position of dwarfs

Lopsided satellites in SDSS Local Groups



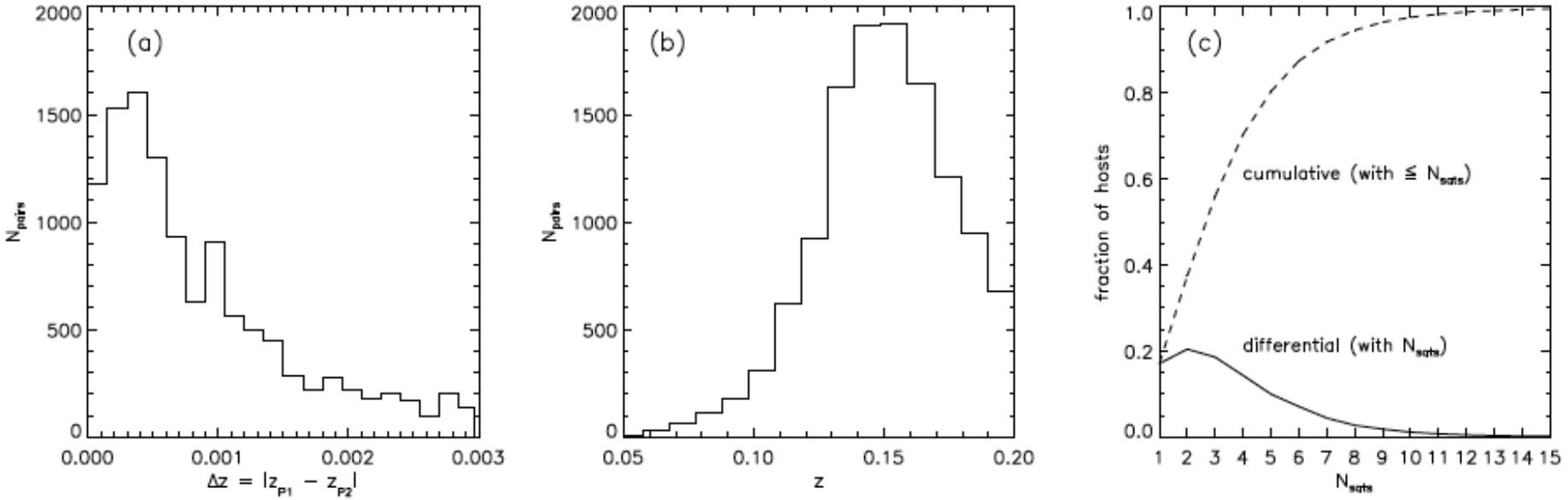
Start by identifying pairs of galaxies in the SDSS that "look" like the Local Group

Begin with group finder (FOF) – Tempel et al 2014

- find those FOF groups of size 2
- $-22.5 < M < -21.5$
- $0.5\text{Mpc} < d_{sep} < 1.5$ Mpc
- Identify a search radius $r_{search} = 250$kpc
- Find all (photometric) satellites within r_{search}
- Count how many are within (θ , Φ) and compare with how many you expect from a random distribution

Libeskind *et al* (2015/2016) Submitted

Lopsided satellites in SDSS Local Groups



What the sample looks like