Planes of dwarf galaxies and the cosmic web in the local universe

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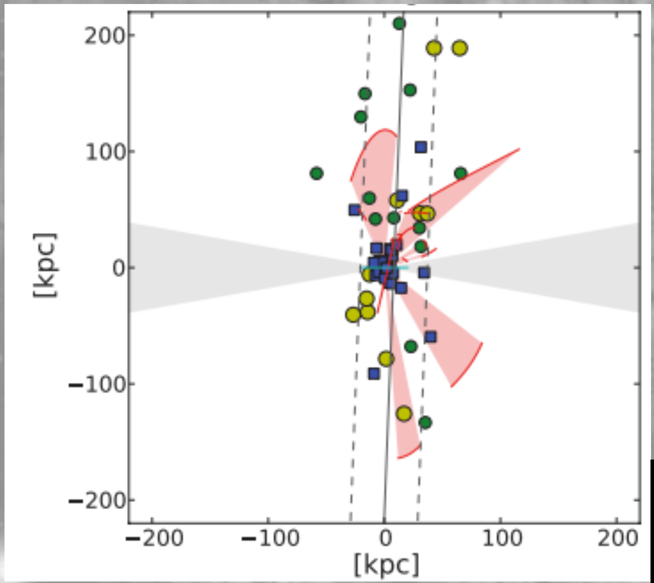
Stefan Gottlöber, Matthias Steinmetz (Potsdam)

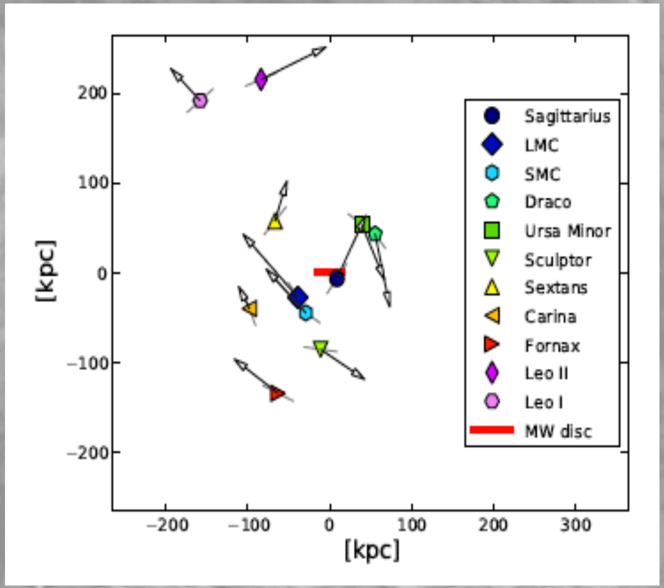
Milky Way – Vast Polar Orbiting structure (VPOS)



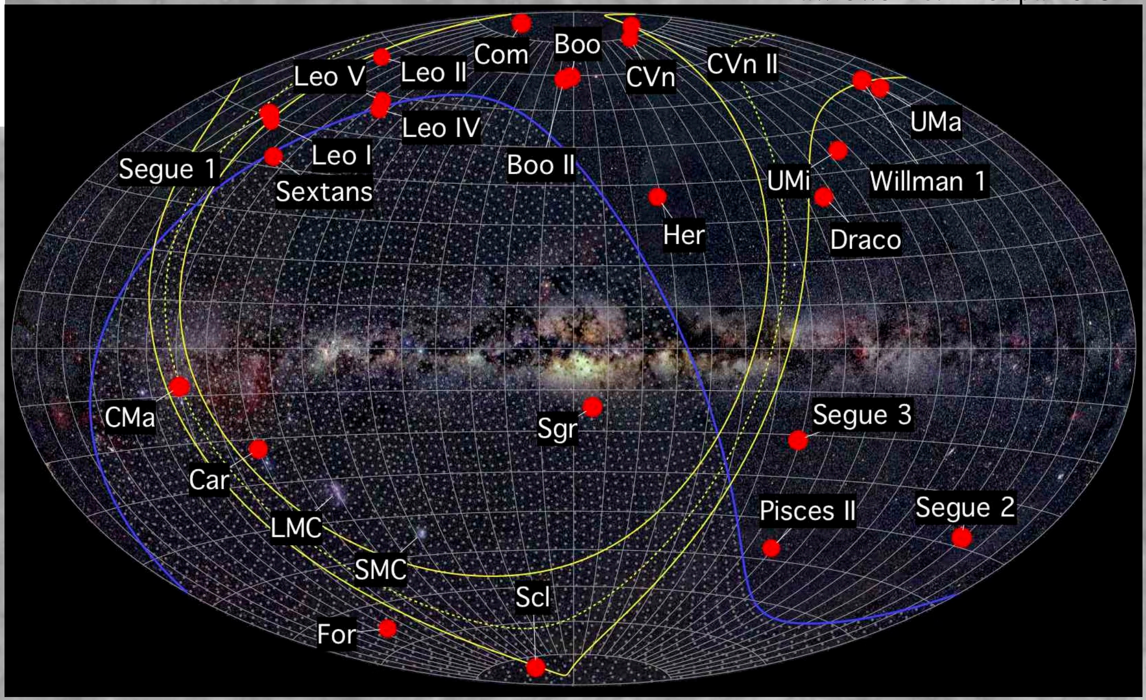
Pawlowski et al 2012
Metz, Kroupa & Jerjen 2007
Kroupa, Theis, Boily 2005

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

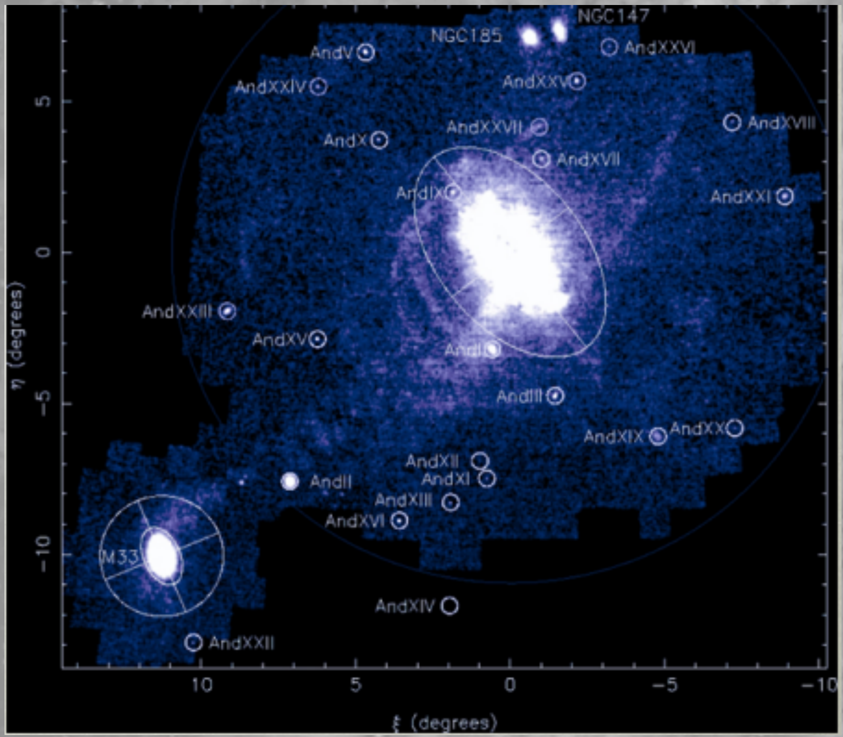
$c/a \sim 0.15$
Δ_{rms}=24kpc

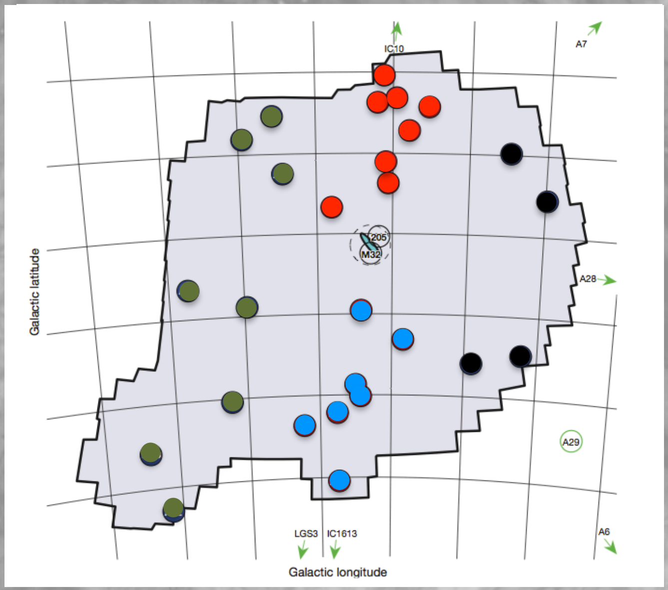


Metz, Kroupa & Libeskind 2007
Pawlowski & Kroupa 2013



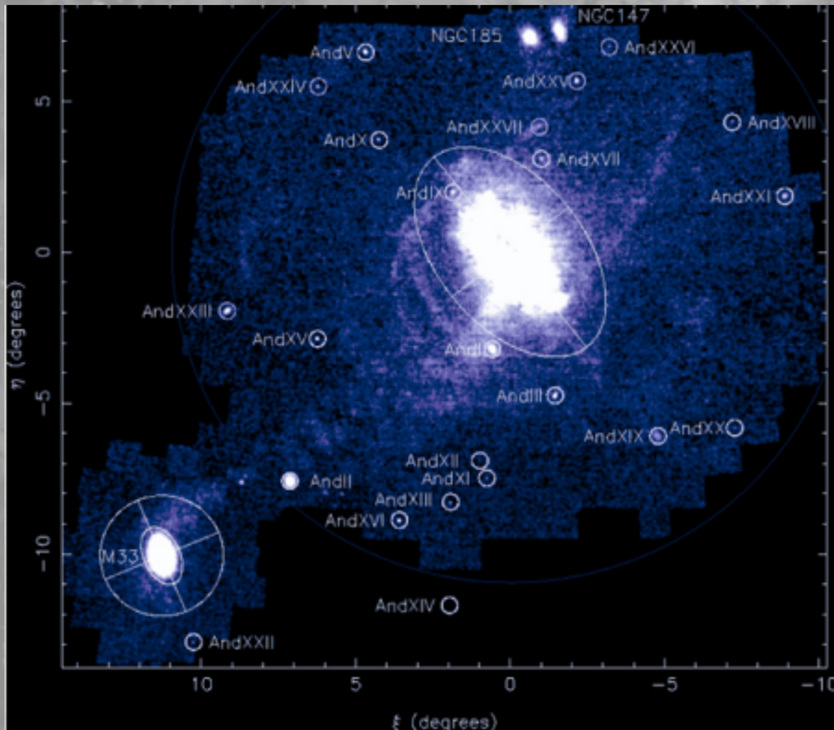
Sloan Digital Sky Survey (SDSS)

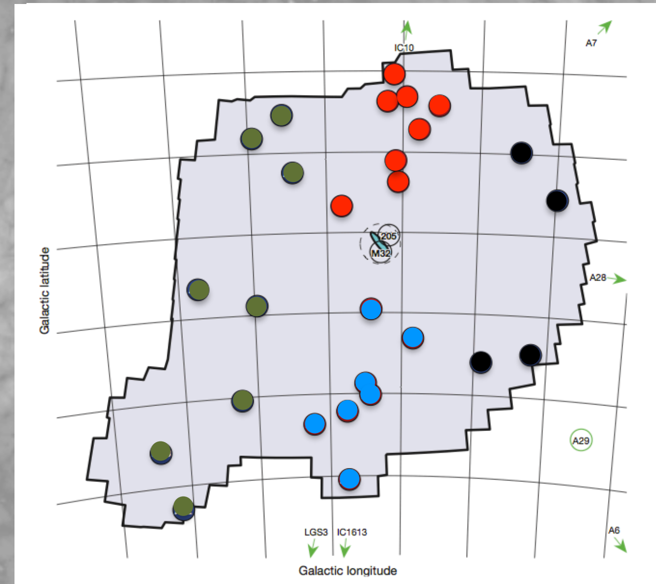




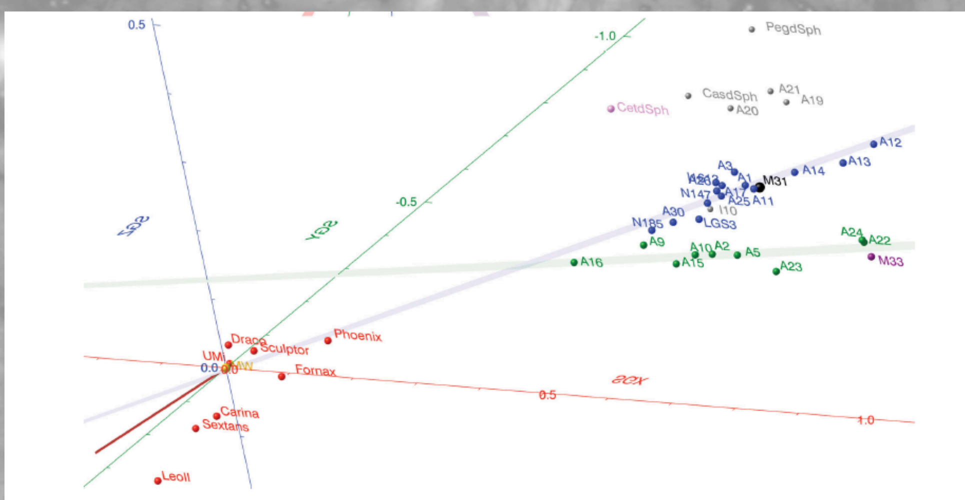
Andromeda

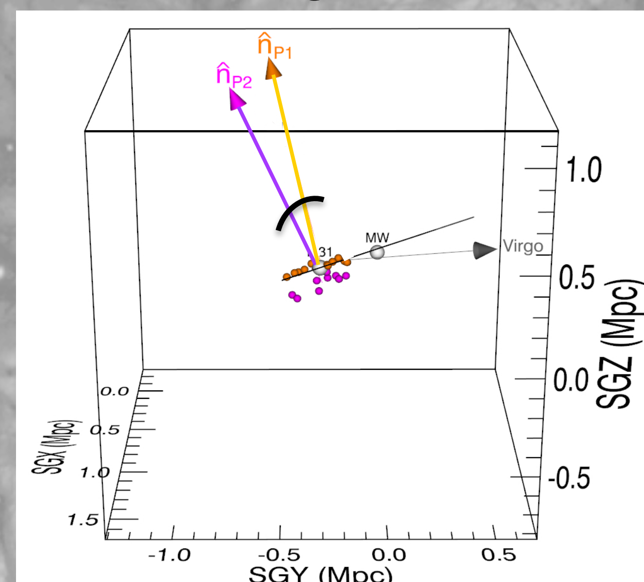
Ibata et al 2013, Conn et al 2013





14 deg

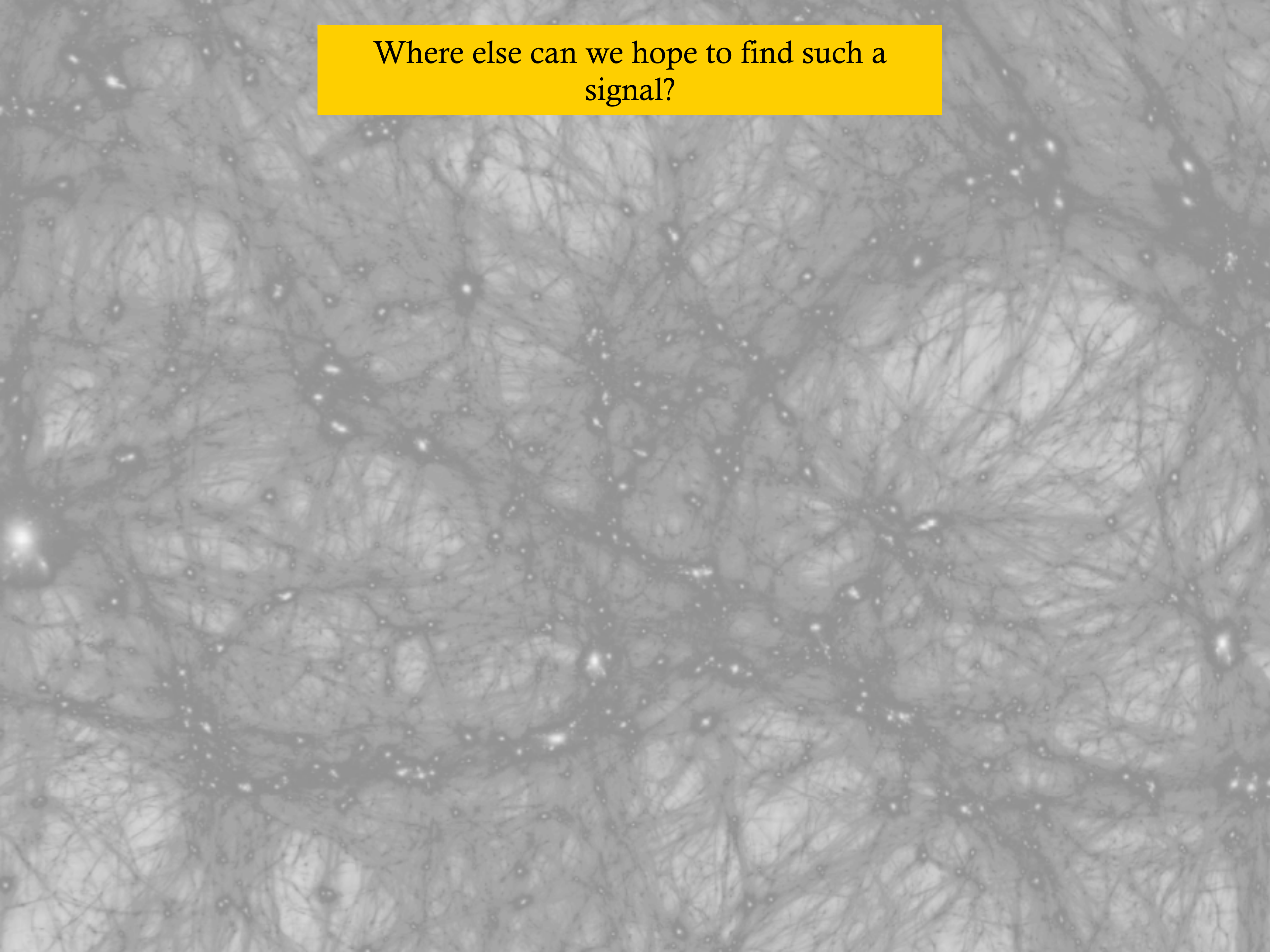




Andromeda – 2 planes, one co-rotating.

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

Where else can we hope to find such a signal?



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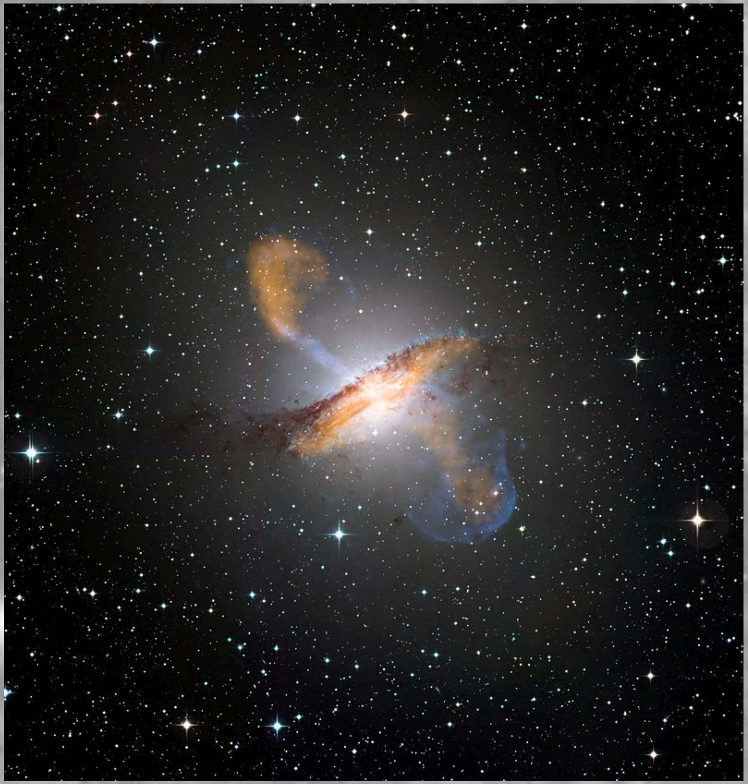
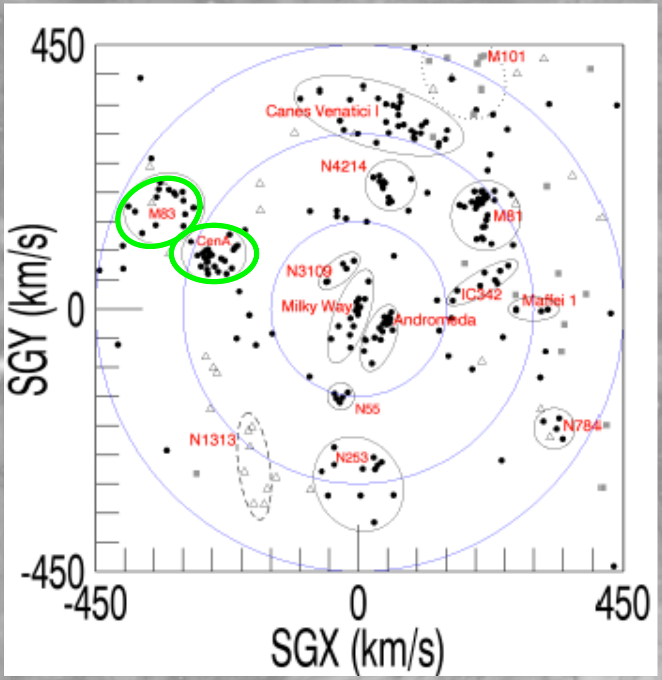


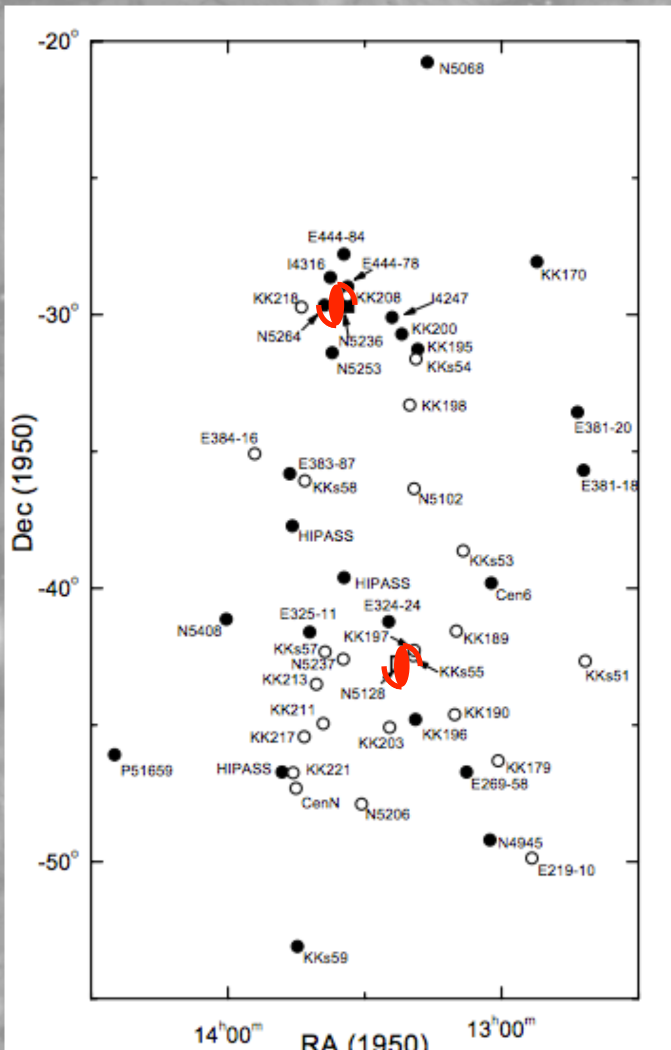
Cen A
$\sim 8\times10^{12}$ M_{sol}
3.8Mpc

Tully 2015

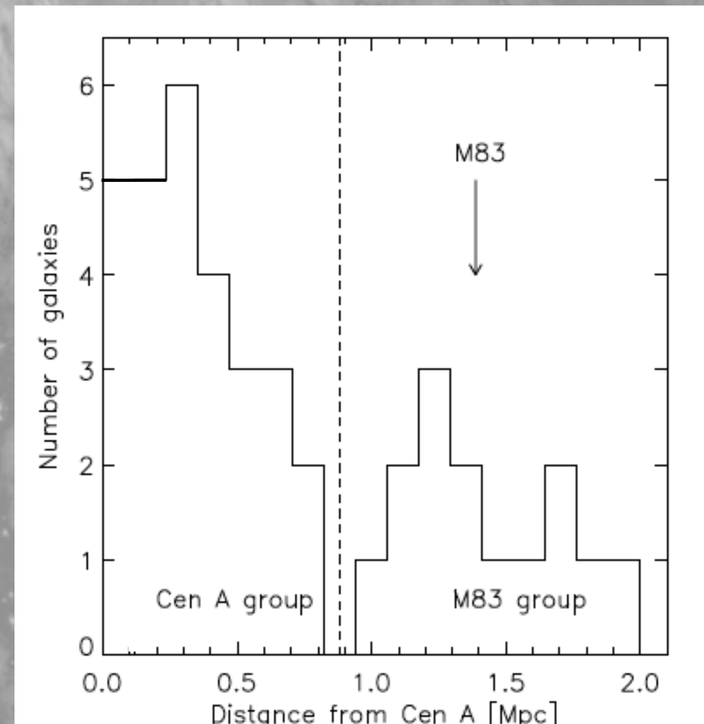
M83
$\sim 10^{12}$ M_{sol}
4.8Mpc

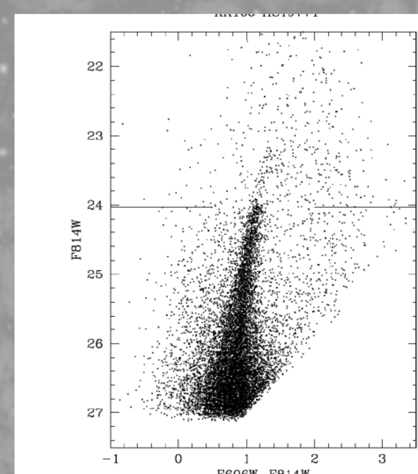


Centaurus A Complex



Karatchensev *et al* 2013

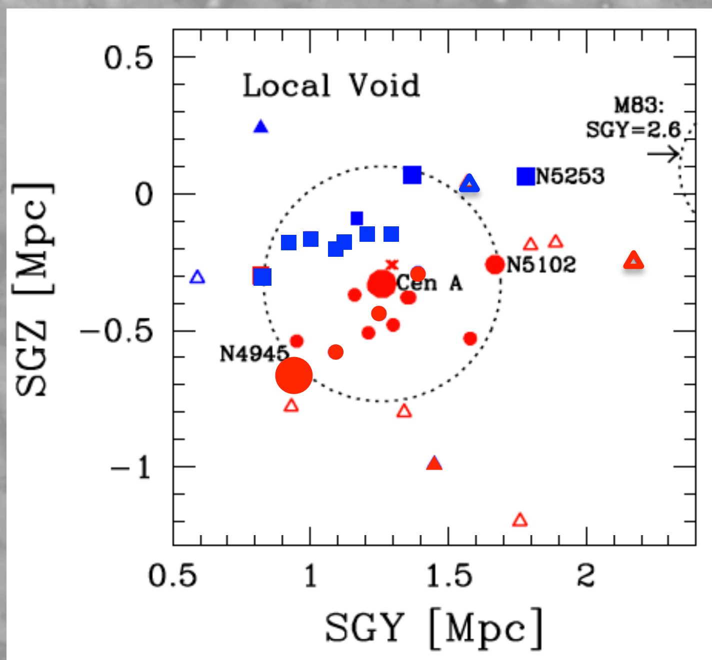


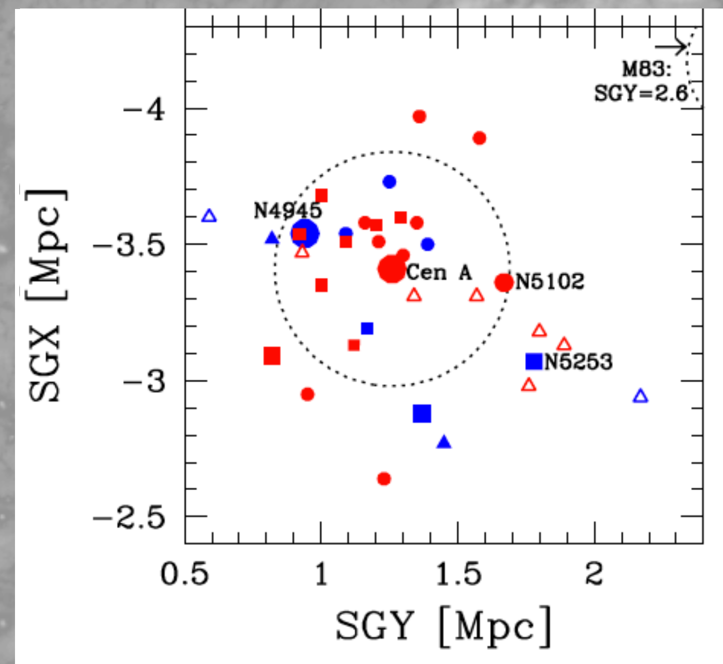


Tully 2015

Tip of the Red Giant Branch distances with HST are needed

Centaurus A Planes



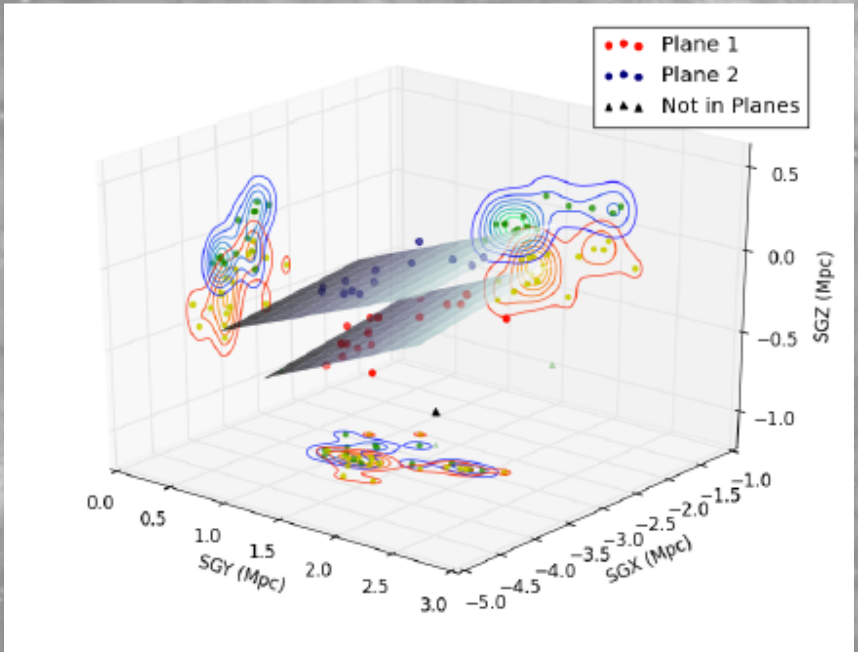


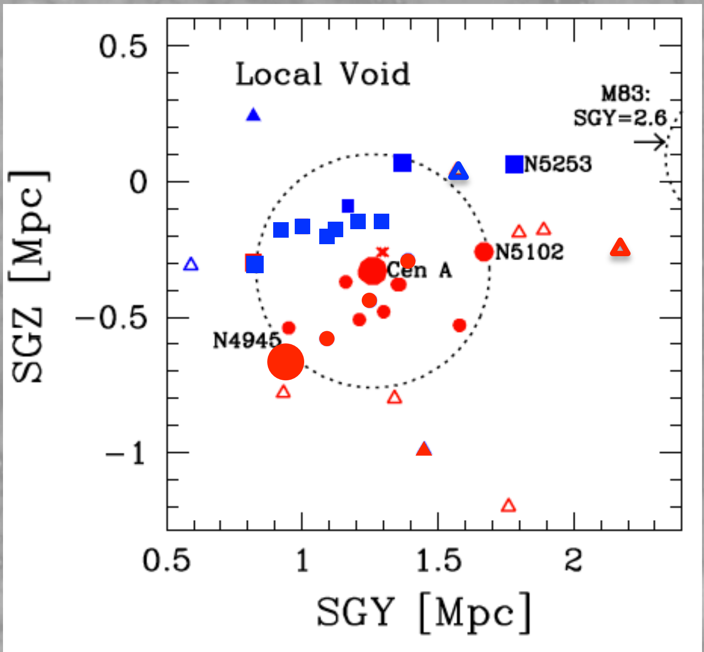
Not in Plane

No known distance

Tully, NL *et al* (2015)

Centaurus A Planes





	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	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)

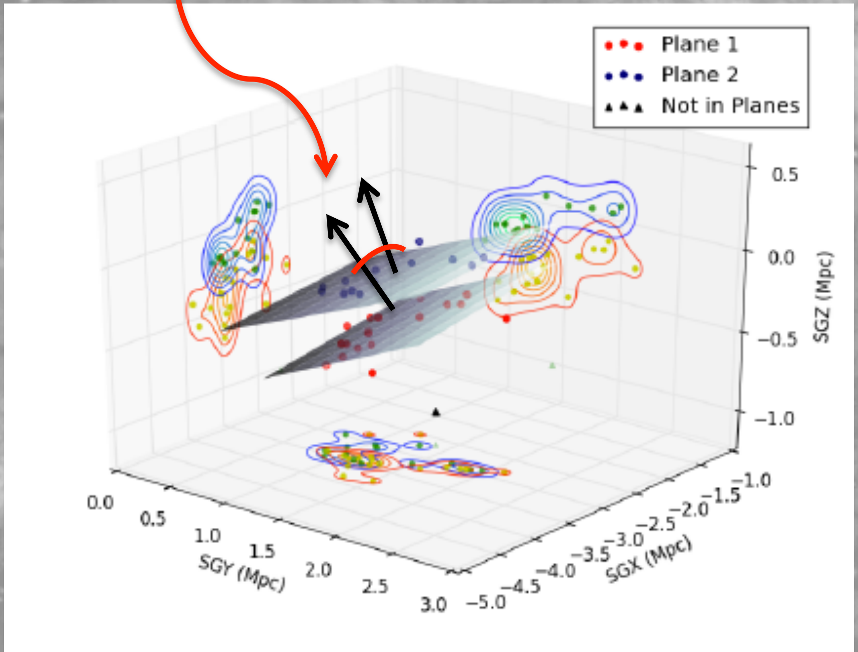
36 galaxies in total, 29 with distances

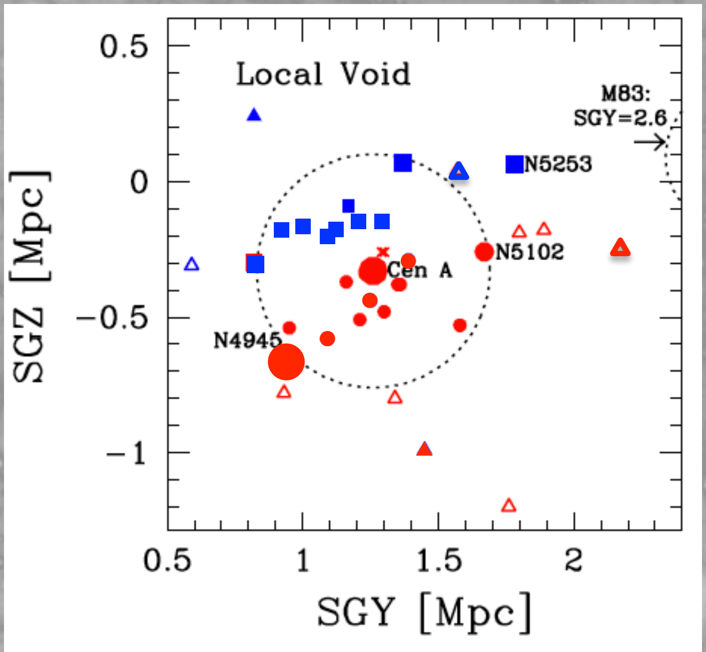
16 in plane 1
11 in plane 2
2 not in either

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

Centaurus A Planes

7 deg





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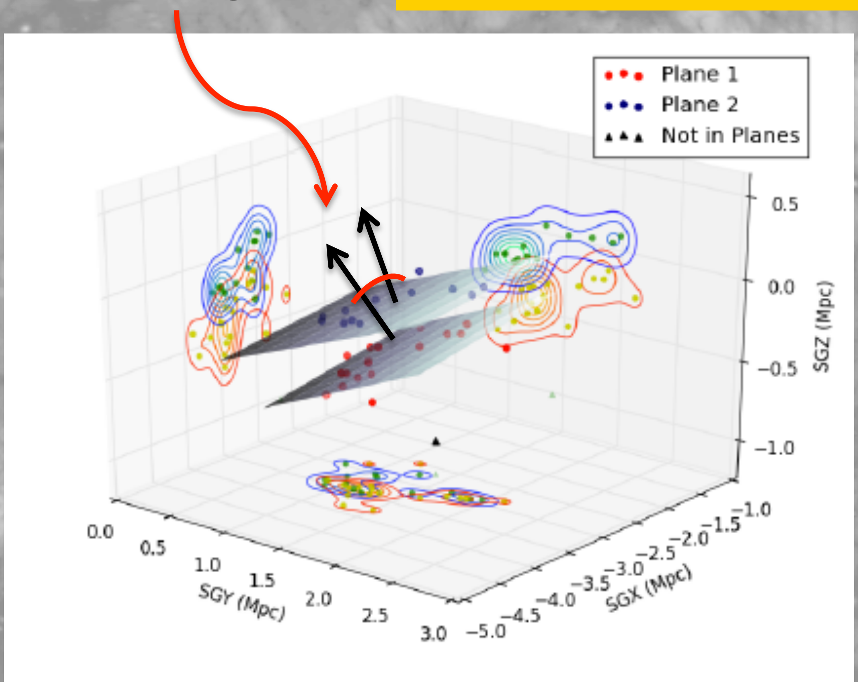
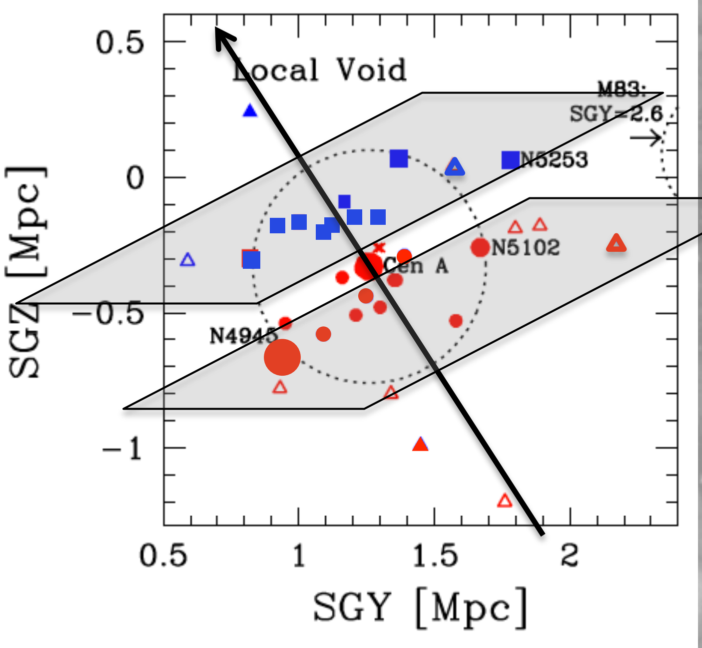
Distance errors are 5% along the line of sight

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

Tully, NL *et al* (2015)

Centaurus A Planes





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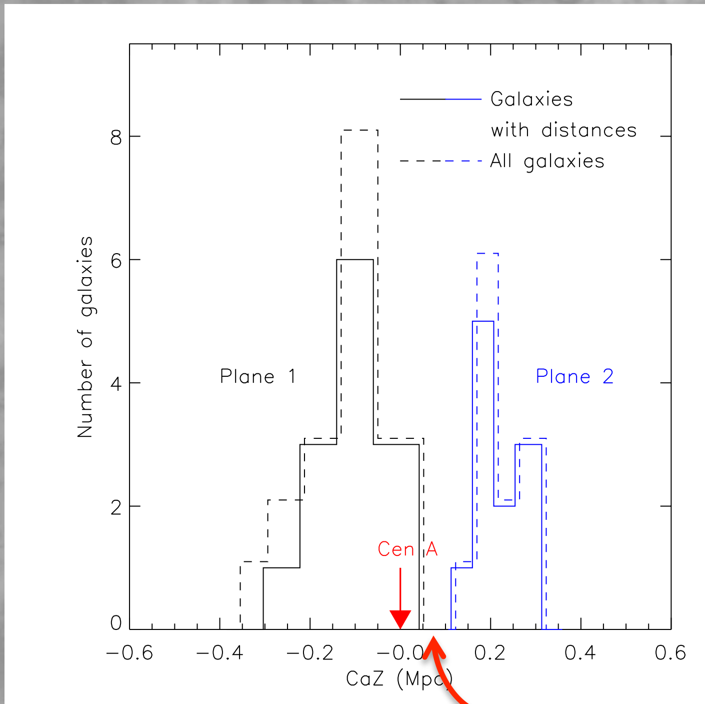
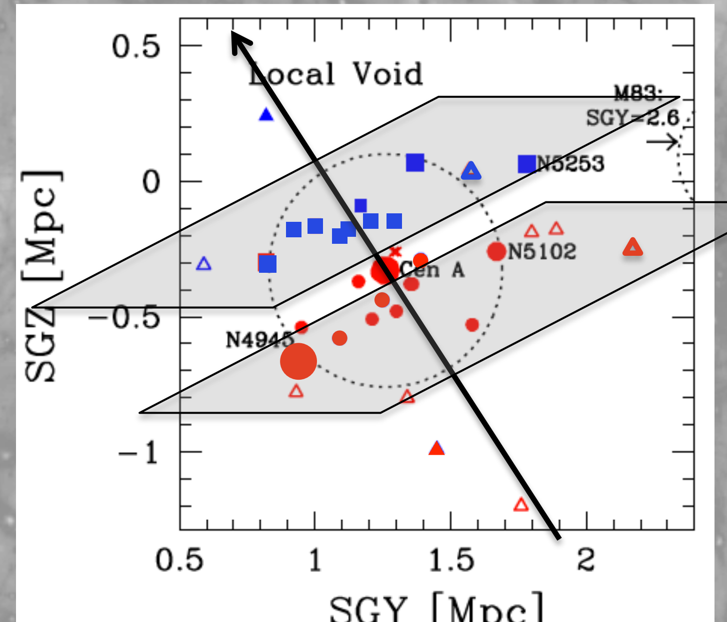
Can fit a single normal to the two parallel planes

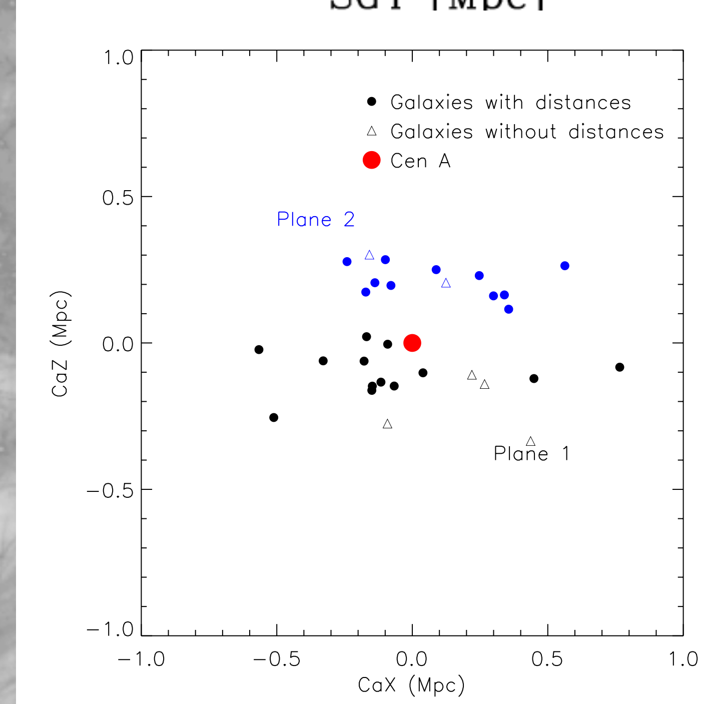
Tully, NL *et al* (2015)

Centaurus A Planes



Around 100kpc between planes





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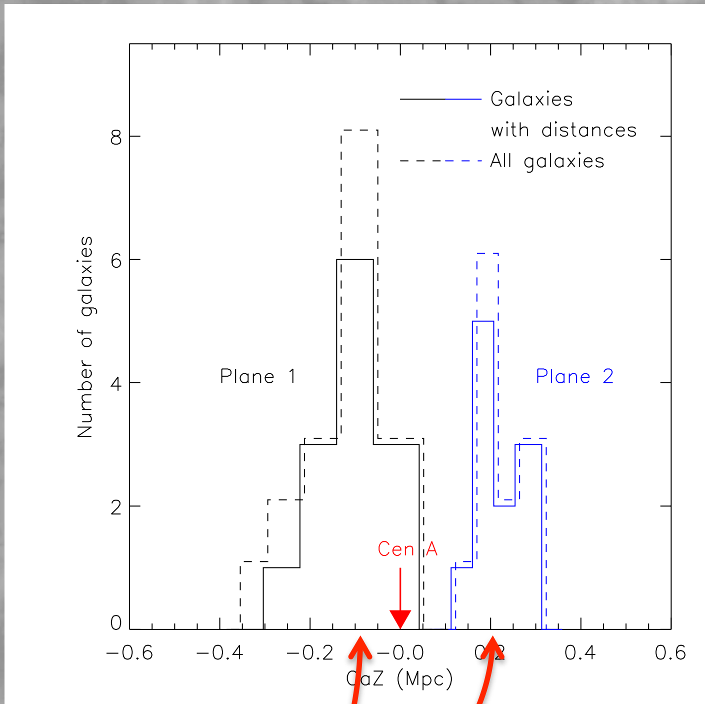
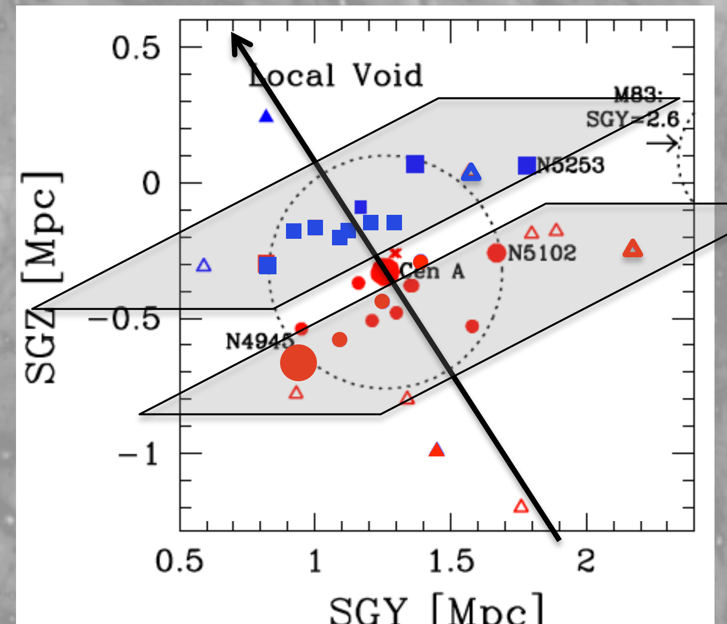
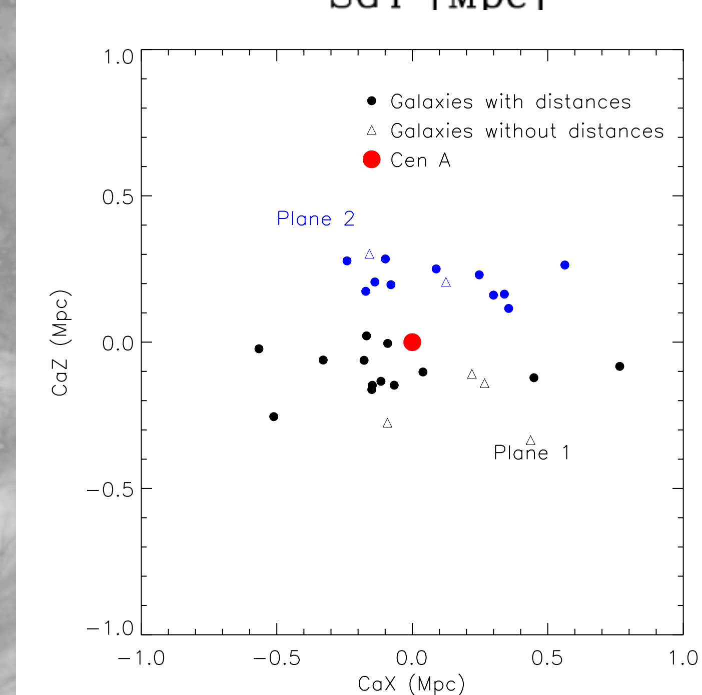


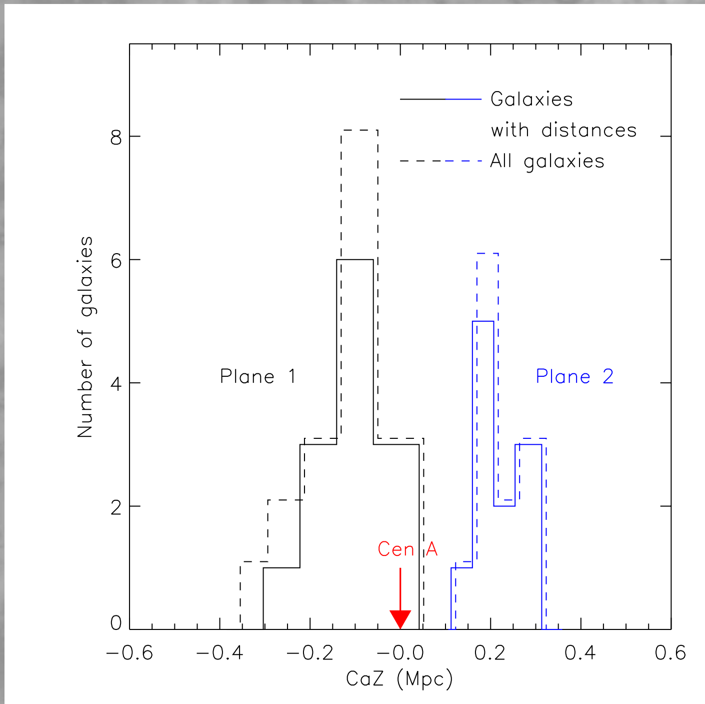
Around 100kpc between planes

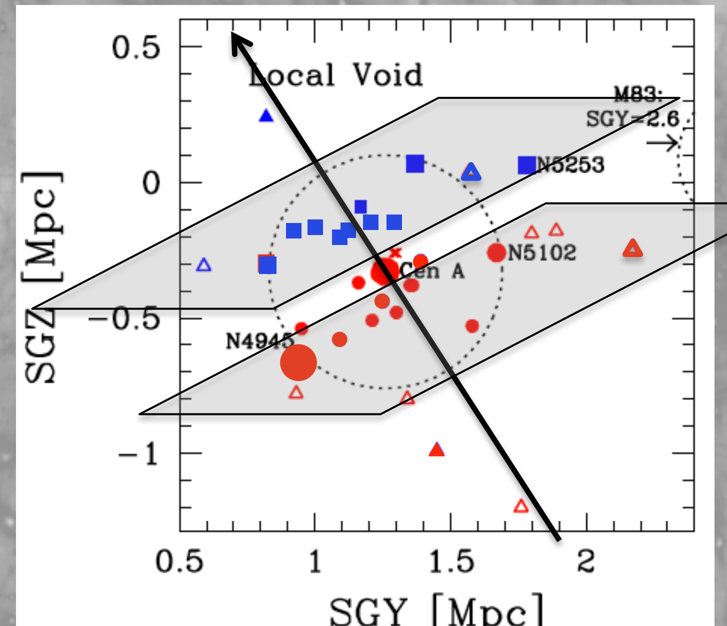
Offset between the means is around 300kpc

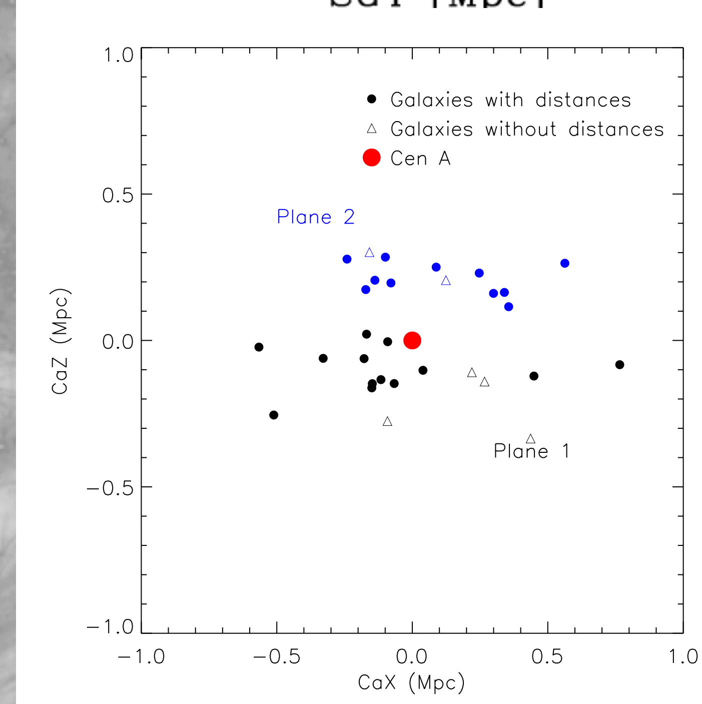




Centaurus A Planes







Around 100kpc between planes

Offset between the means is around 300kpc

Each plane is around 50-60kpc in rms

What is the likelihood to get such a set from a random distribution of 29 points?

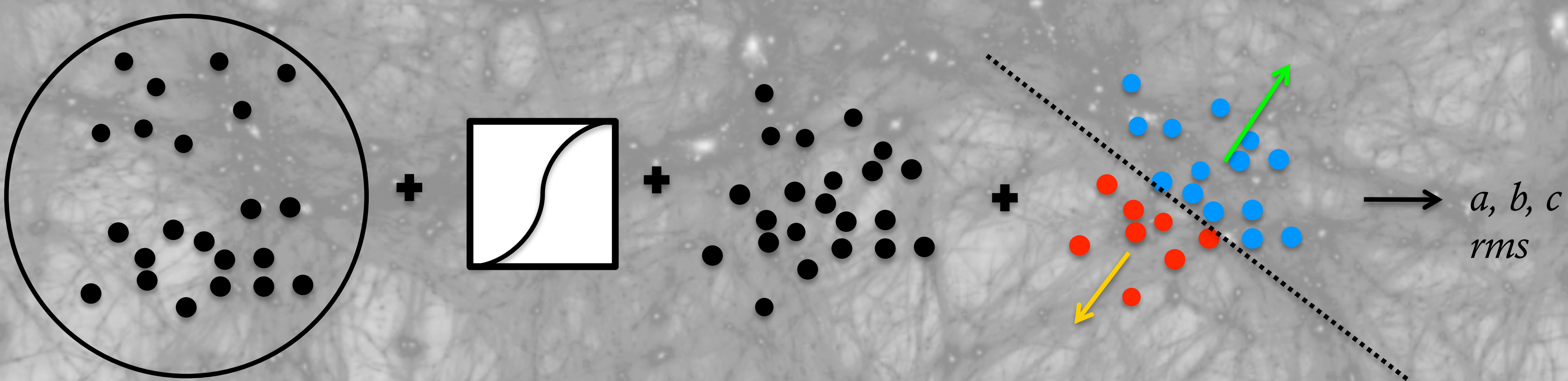
+ that follow the same radial distribution
+ that are as flattened as the entire CenA group

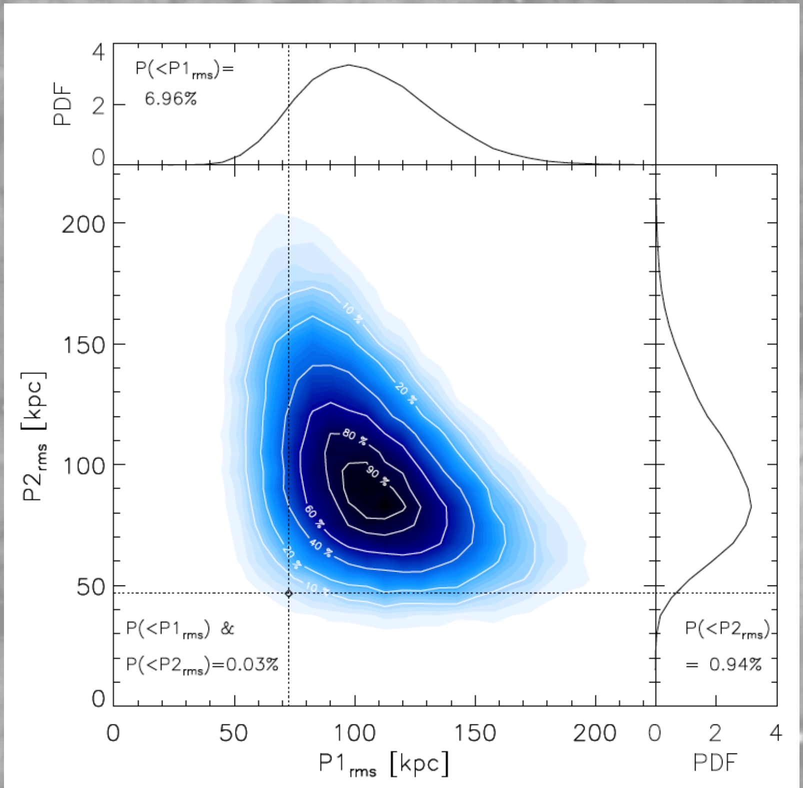
What is the likelihood to get such a set from a random distribution of 29 points?

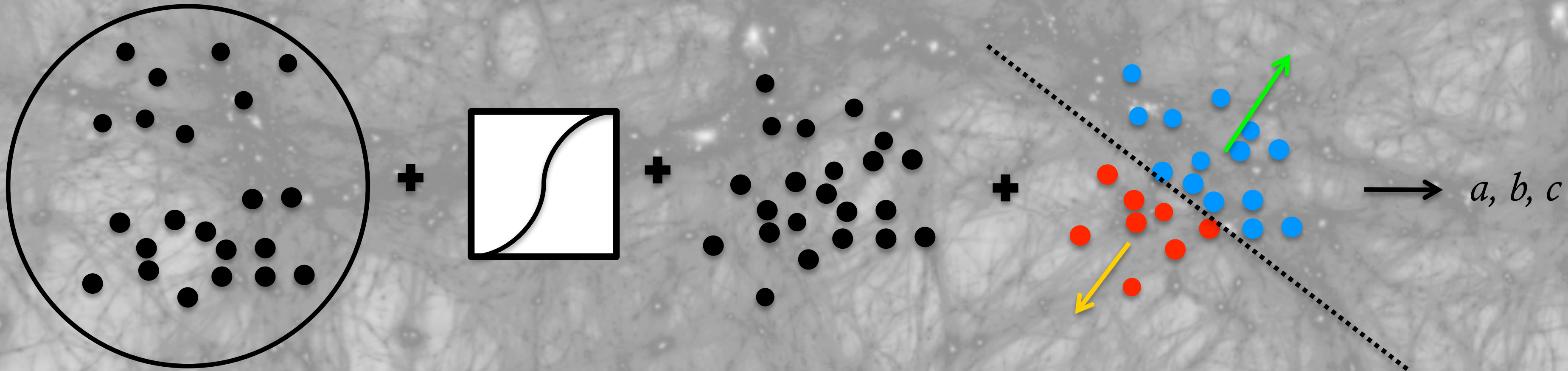
+ that follow the same radial distribution
+ that are as flattened as the entire CenA group

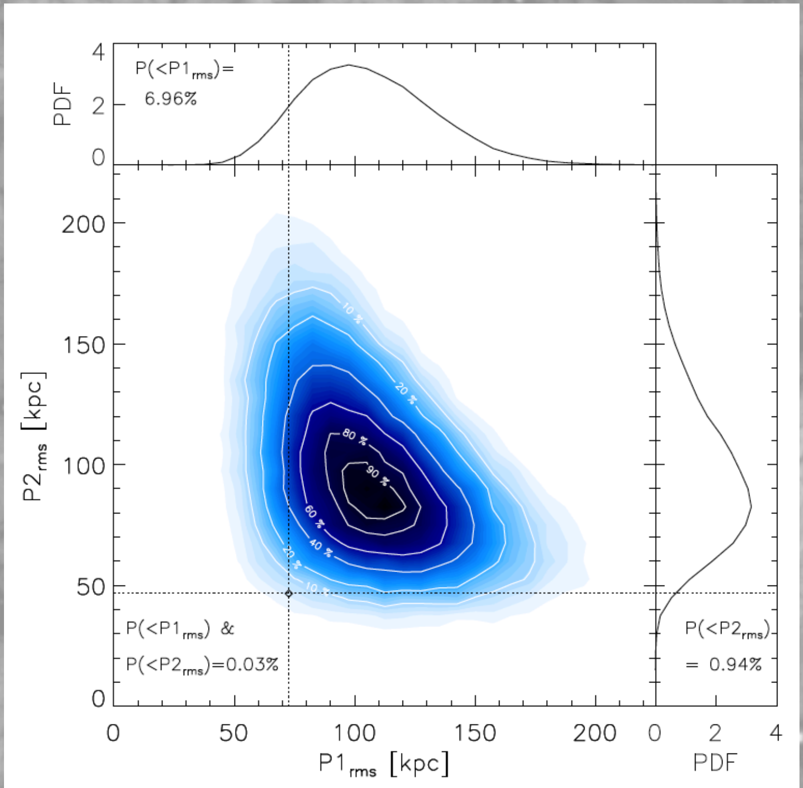
Create *N* sets of 29 galaxies (points) with the same *radial distribution* as the Cen A group but with randomized (Φ , θ)

For each set, separate the satellites into two groups, that have the same number of members as plane 1 and plane 2, but which also minimizes the r.m.s. about two best fit parallel planes.




P(<P1$_{rms}$)=
6.96%
PDF
P2$_{rms}$ [kpc]
P1$_{rms}$ [kpc]
P(<P1$_{rms}$) &
P(<P2$_{rms}$)=0.03%
P(<P2$_{rms}$)
= 0.94%
PDF

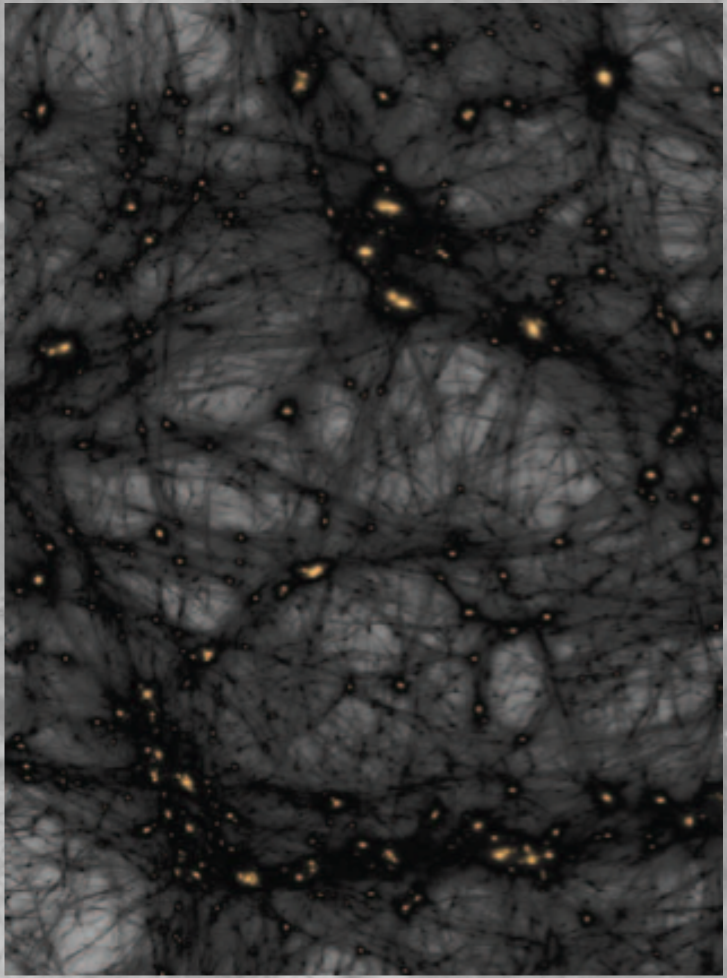

a, b, c



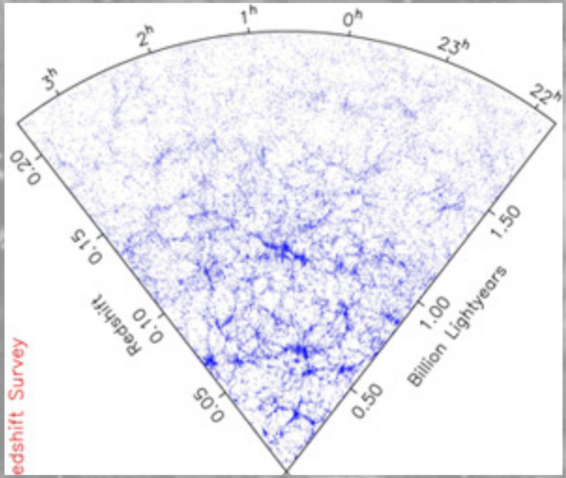
Probability of finding such set ups "by chance" are exceedingly low

What about the Large Scale Structure?

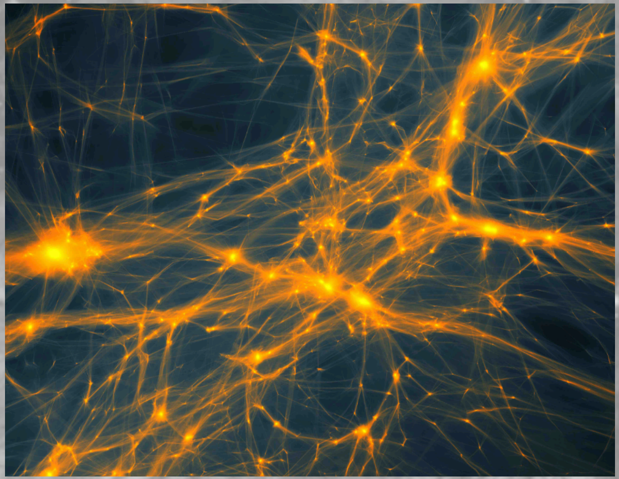
Hypothesis: is the *cosmic web* responsible for these non-linear planes



Libeskind 2014

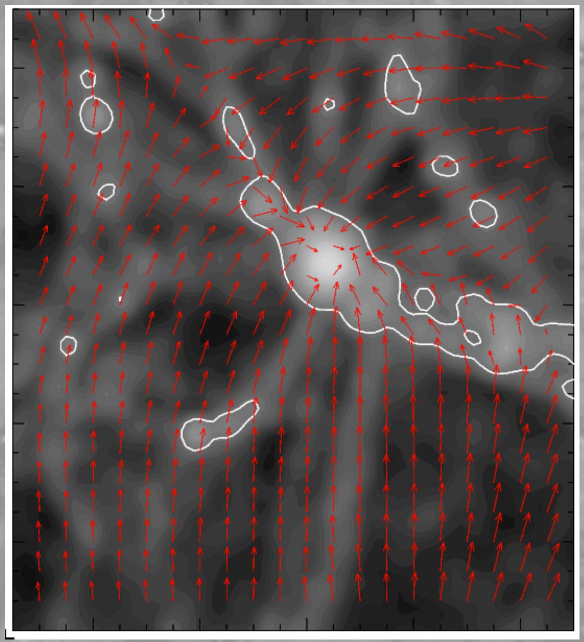


2df GRS



Kahler, Hahn & Abell 2013

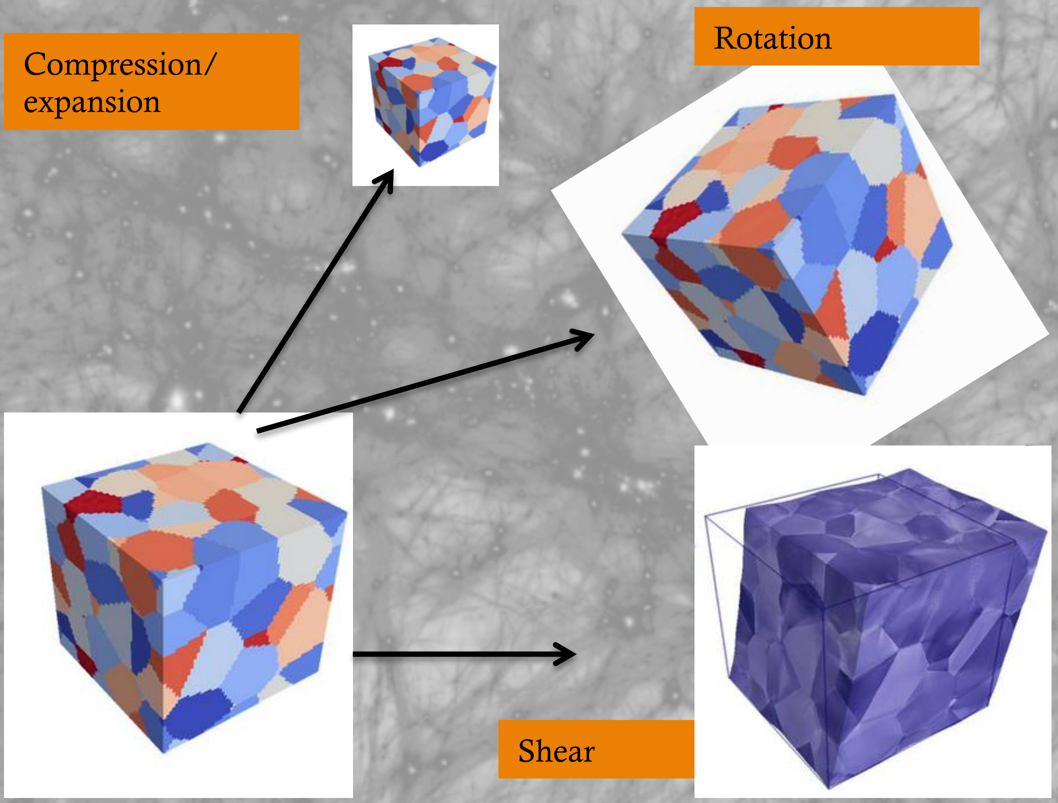
Velocity Shear Tensor

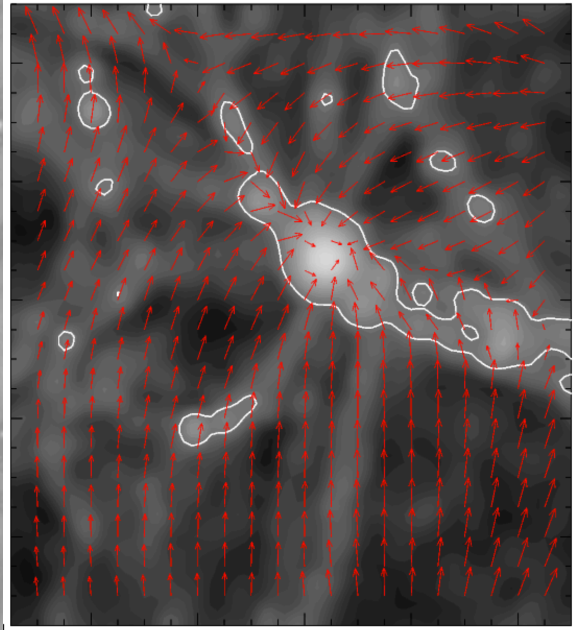


Hoffman et al 2012
Libeskind et al 2012, 2013

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

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





Symmetric part is the "Shear" tensor + Divergence

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

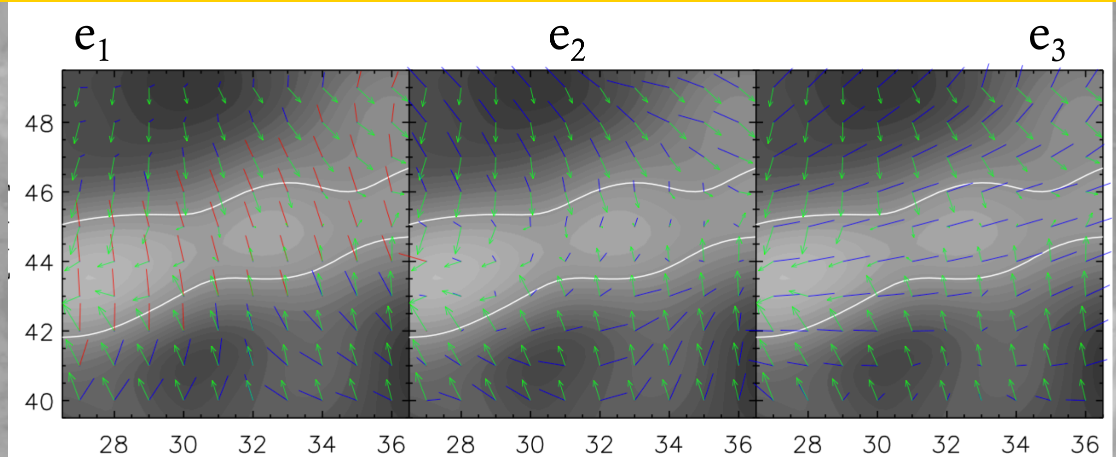
$$\begin{aligned}
\mathbf{v}(\mathbf{r}) &= \mathbf{v}(\mathbf{r}_0) + \frac{\partial \mathbf{v}(\mathbf{r})}{\partial r} \mathrm{d}\mathbf{r} \\
&= \mathbf{v}(\mathbf{r}_0) + \begin{bmatrix} \frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z} \\ \frac{\partial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

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

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

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

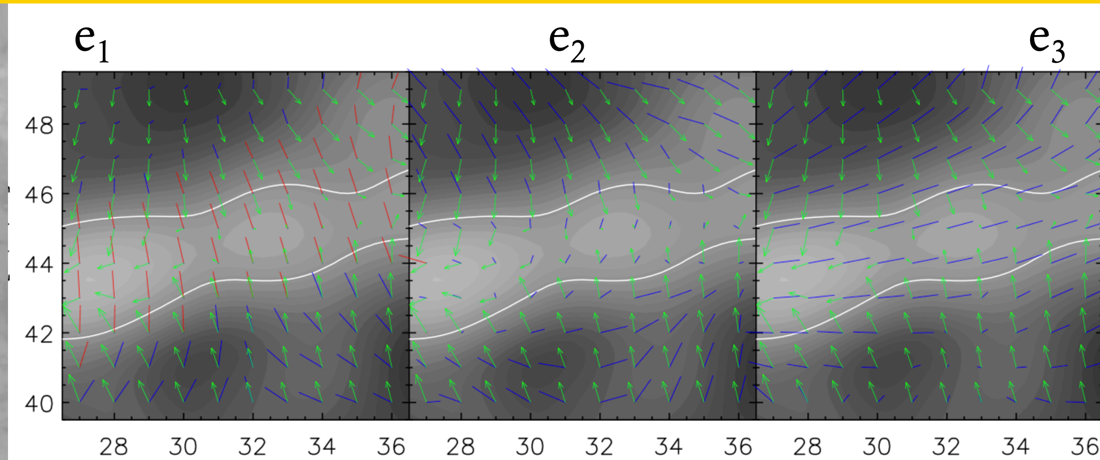
Full (3D) velocity & density field from Wiener filter reconstructions of the cosmic flows-2 survey



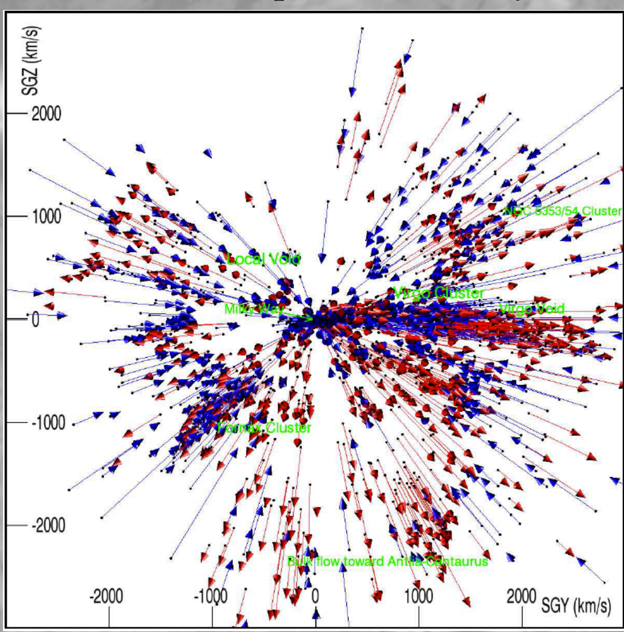
Axis of fastest collapse
Sheet normal

Axis of slowest collapse

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



radial peculiar velocity



Courtois et al 2013

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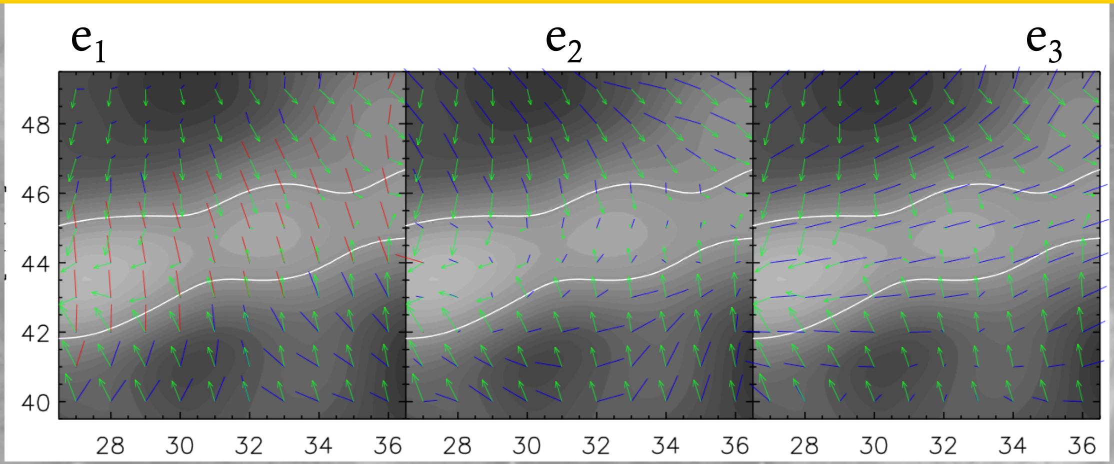

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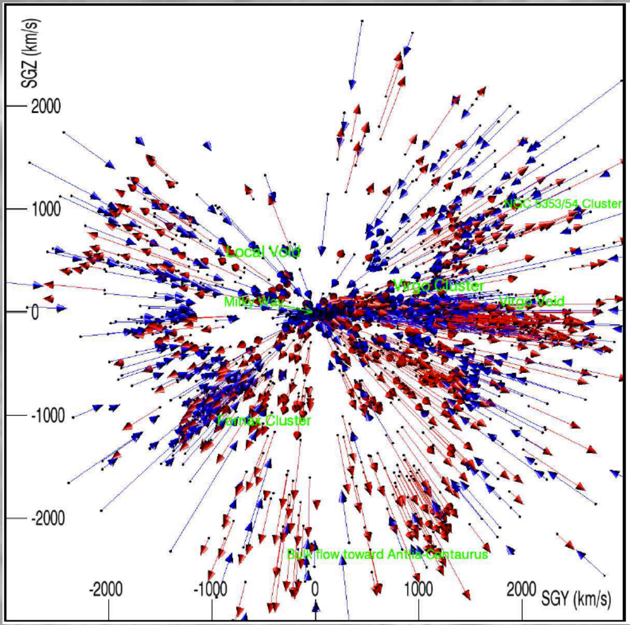
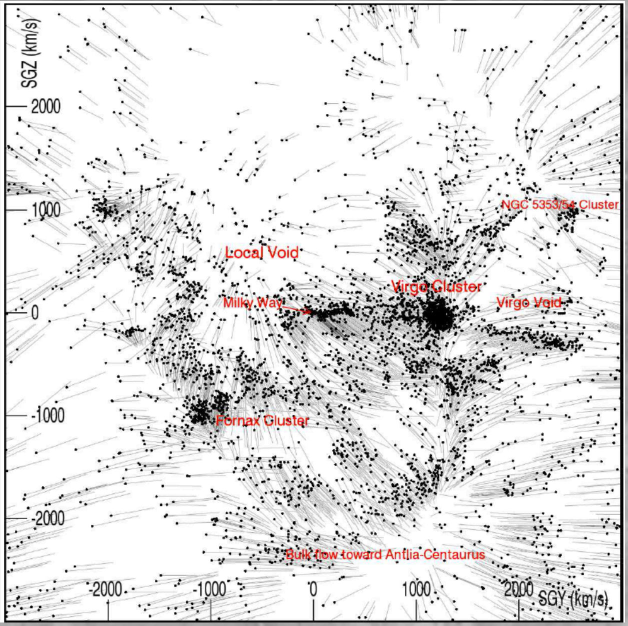


reconstructed 3D peculiar velocity



Courtois et al 2013

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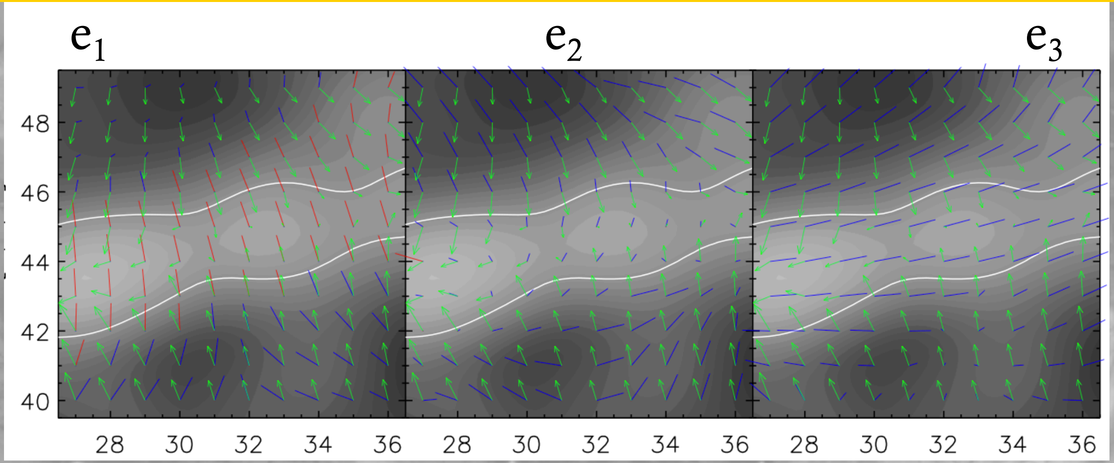

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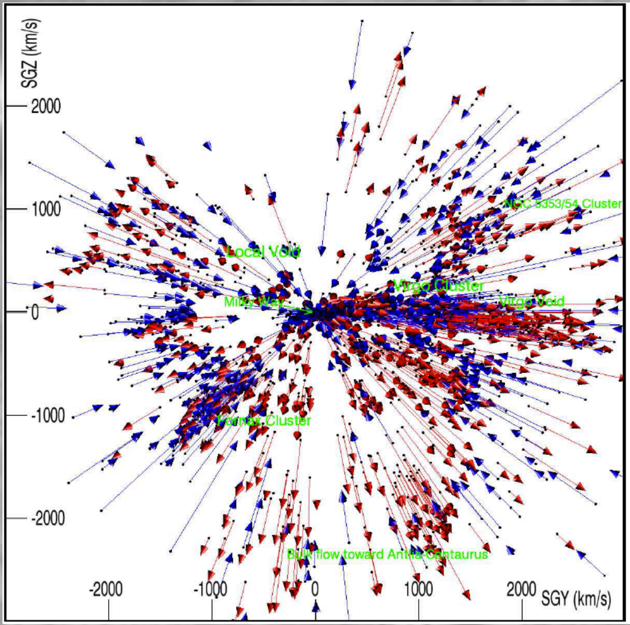

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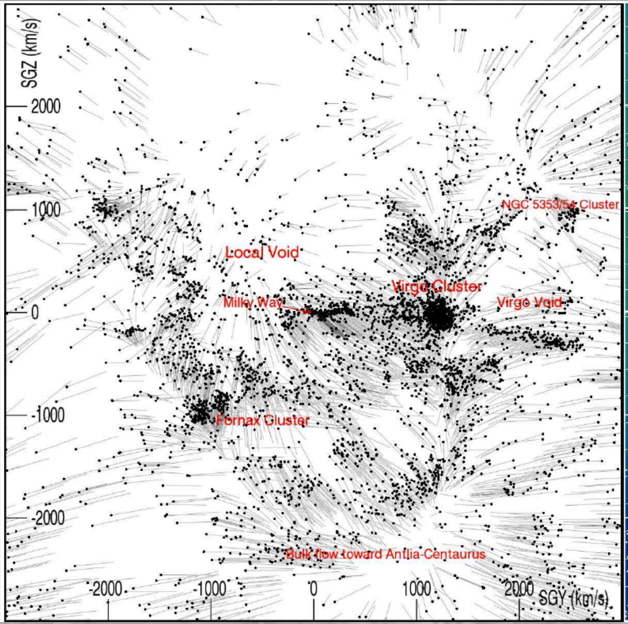
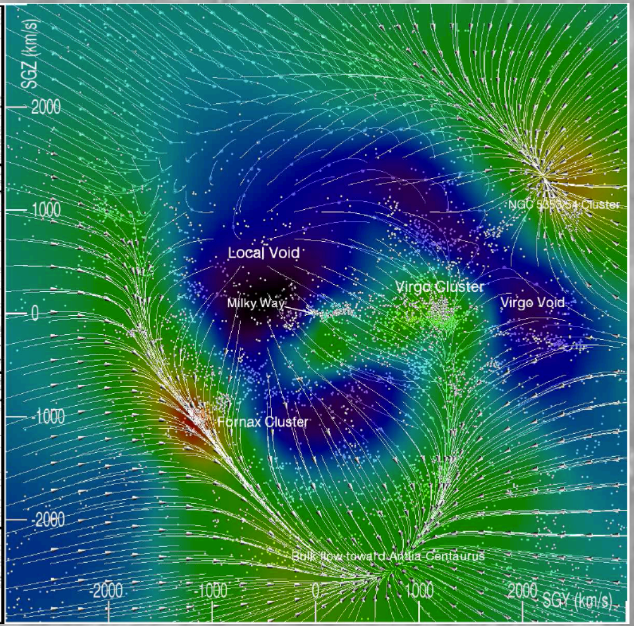


Corresponding 3D density field



Courtois et al 2013

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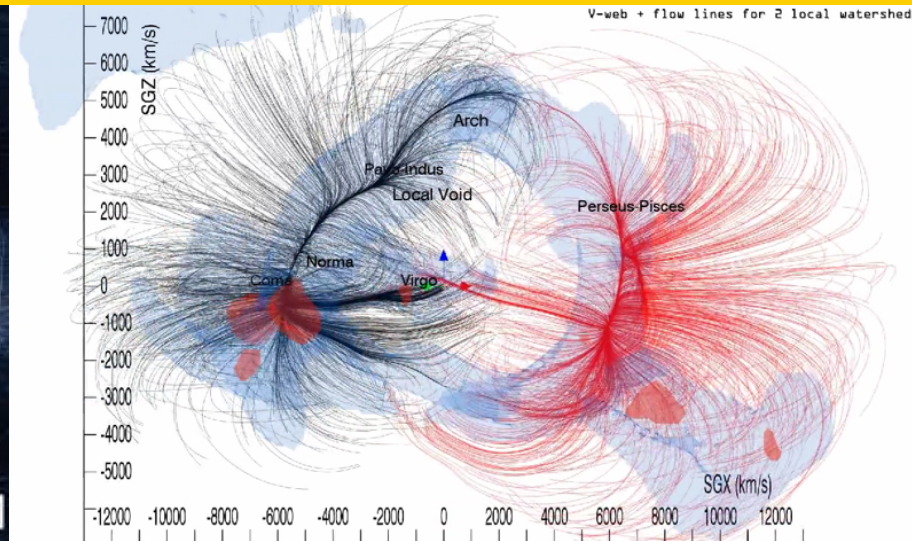
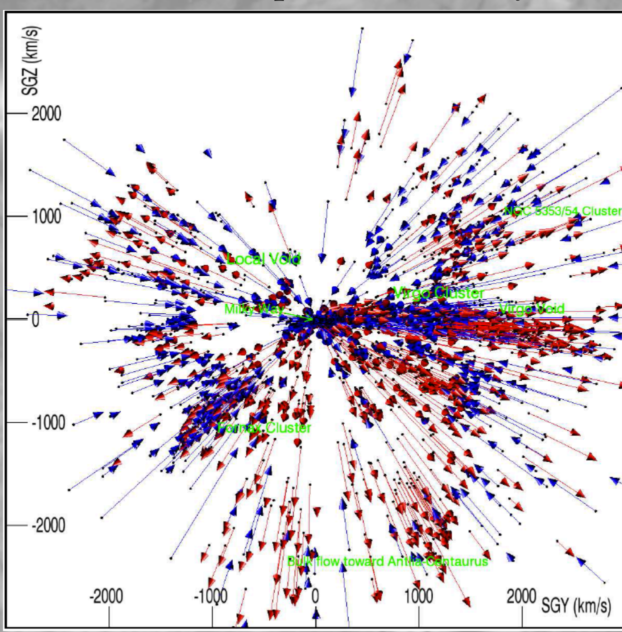
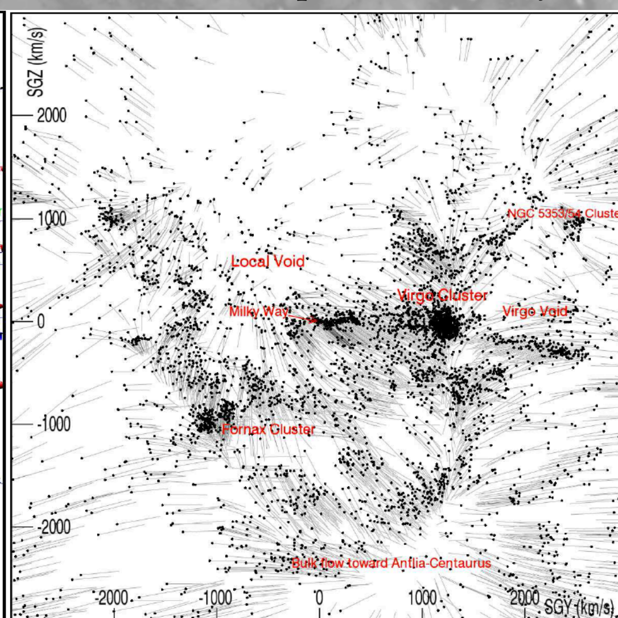


Tully et al 2014

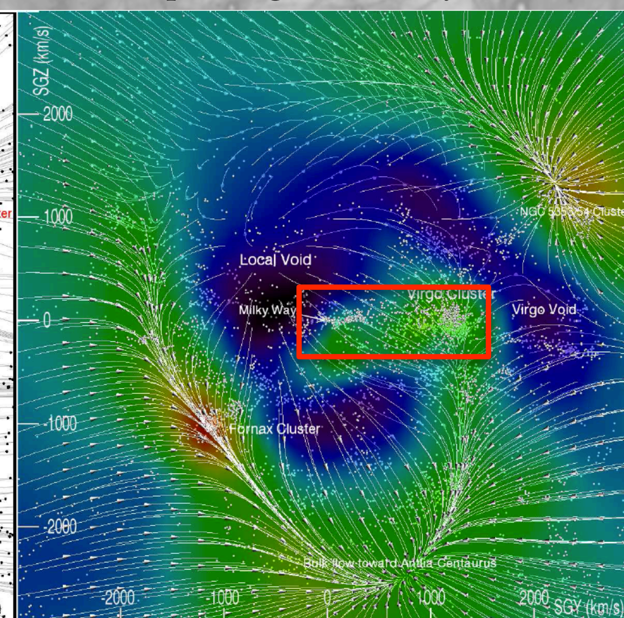
radial peculiar velocity



reconstructed 3D peculiar velocity

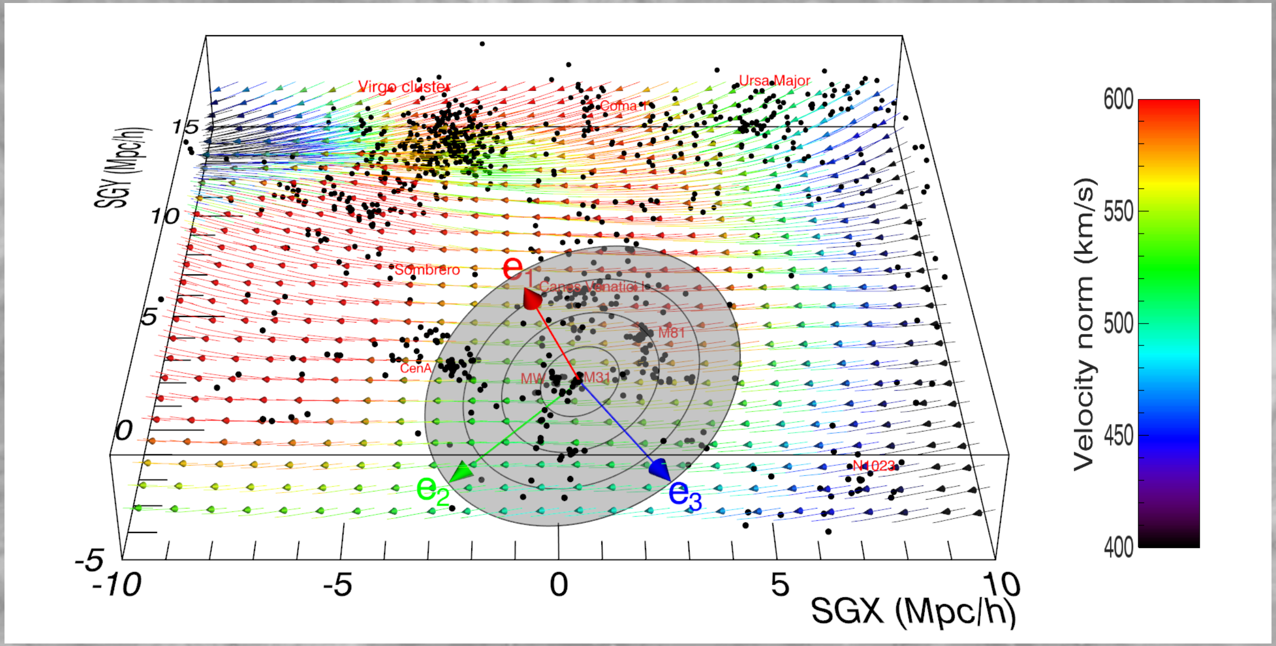


Corresponding 3D density field



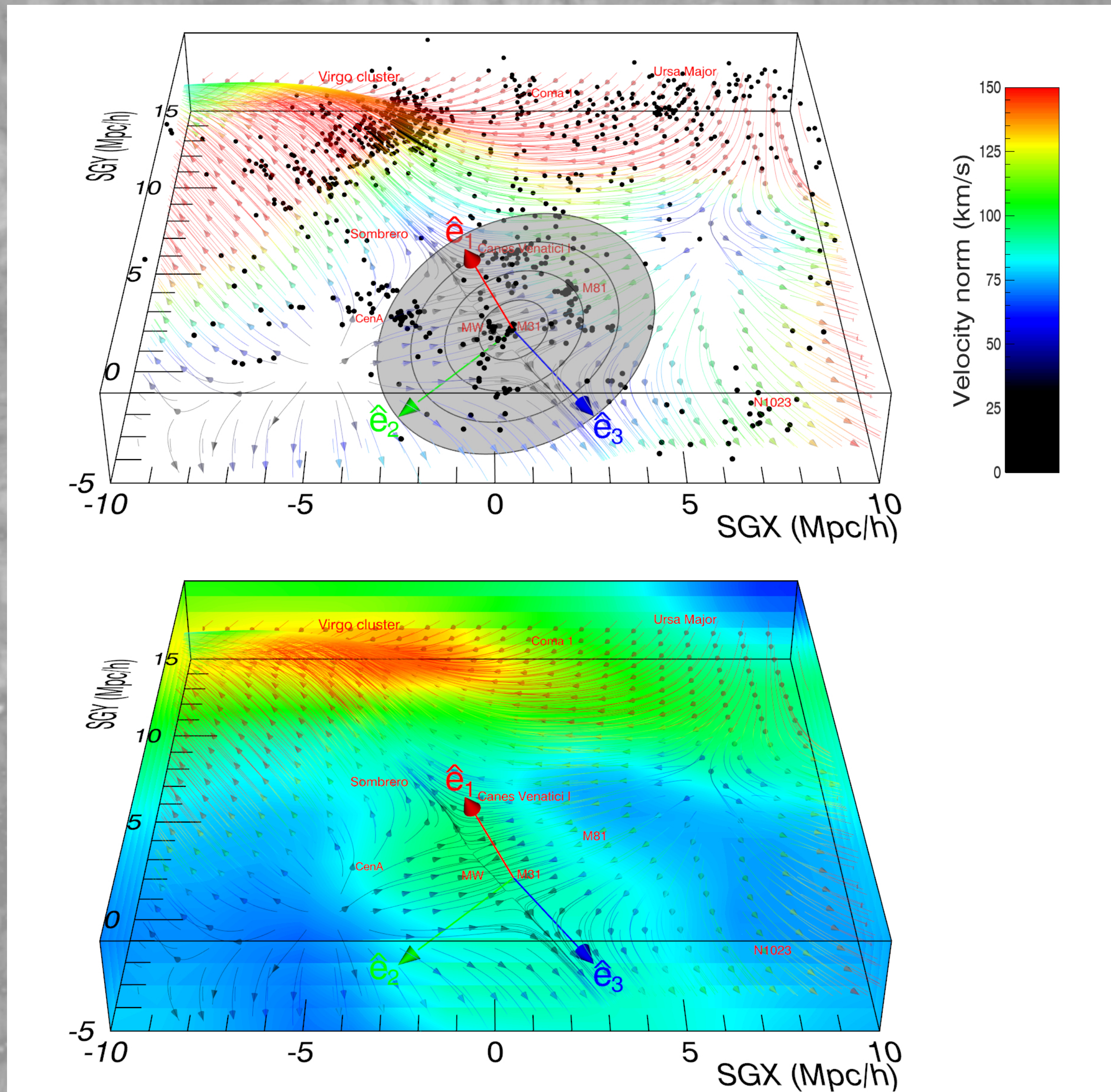
Courtois et al 2013

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



Libeskind *et al* 2015
Submitted

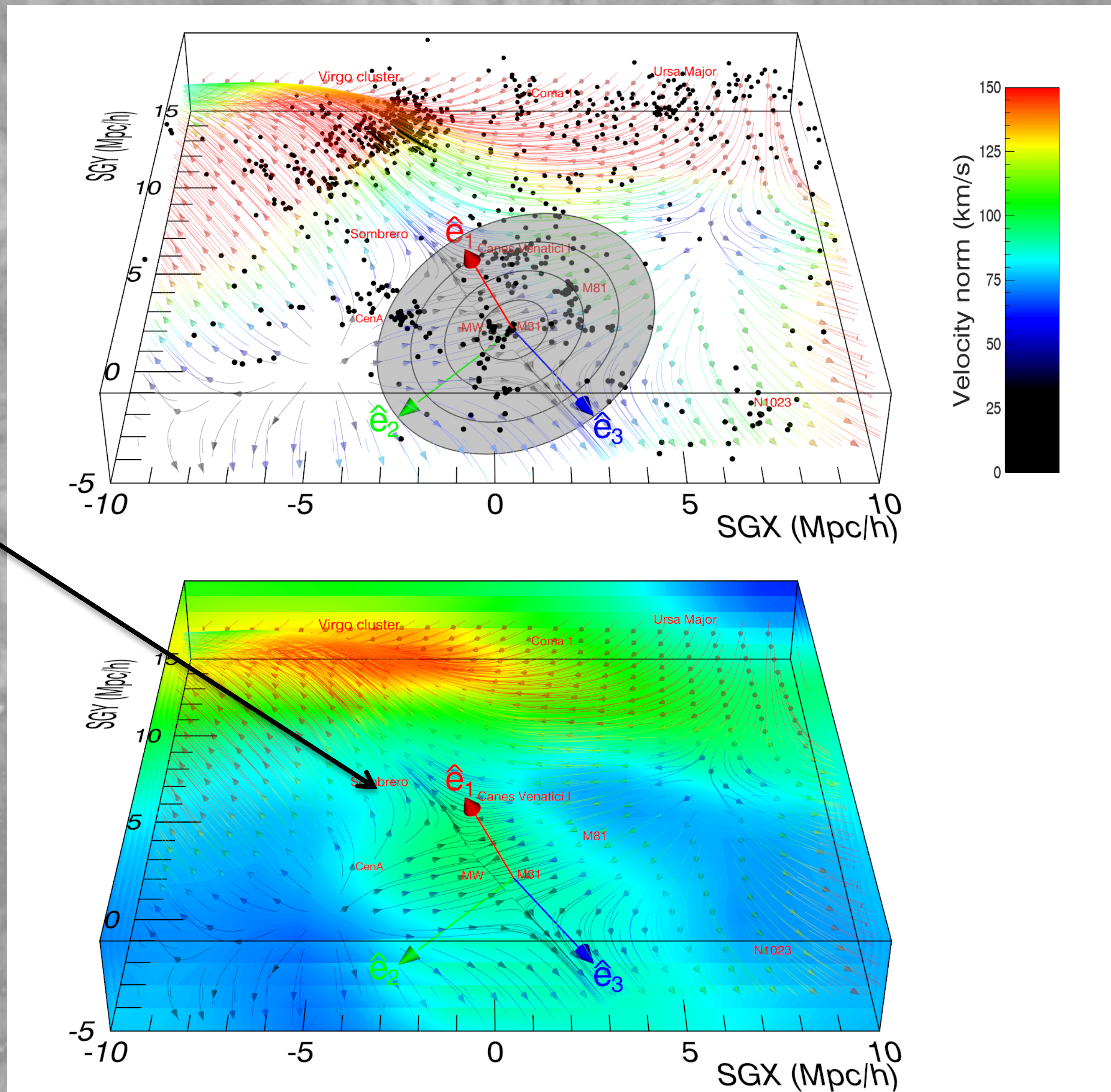
"Local" velocity field, from cosmic-flows-2



Libeskind *et al* 2015
Submitted

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

"Local Filament" stretched by Virgo

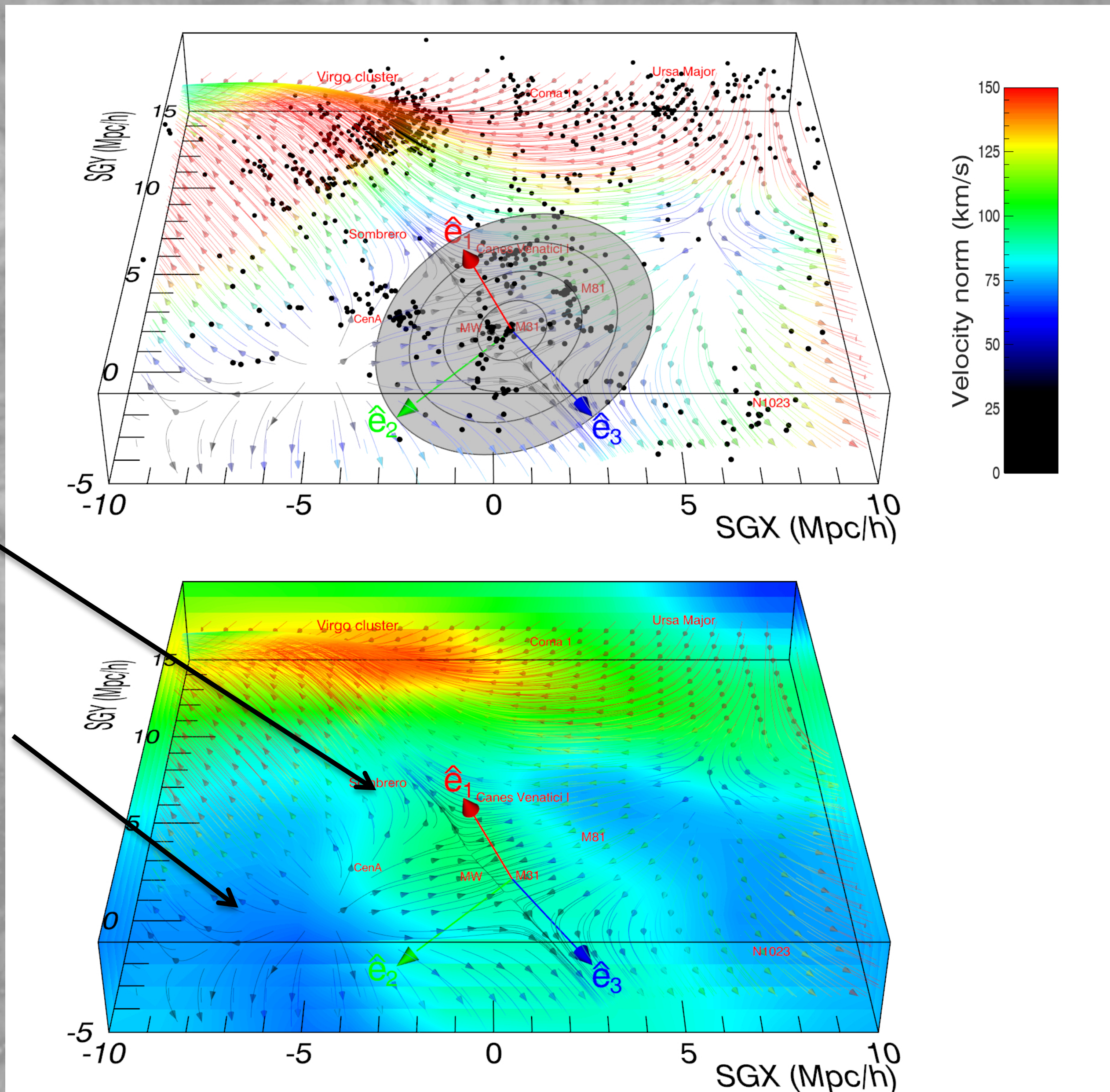


Libeskind *et al* 2015
Submitted

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

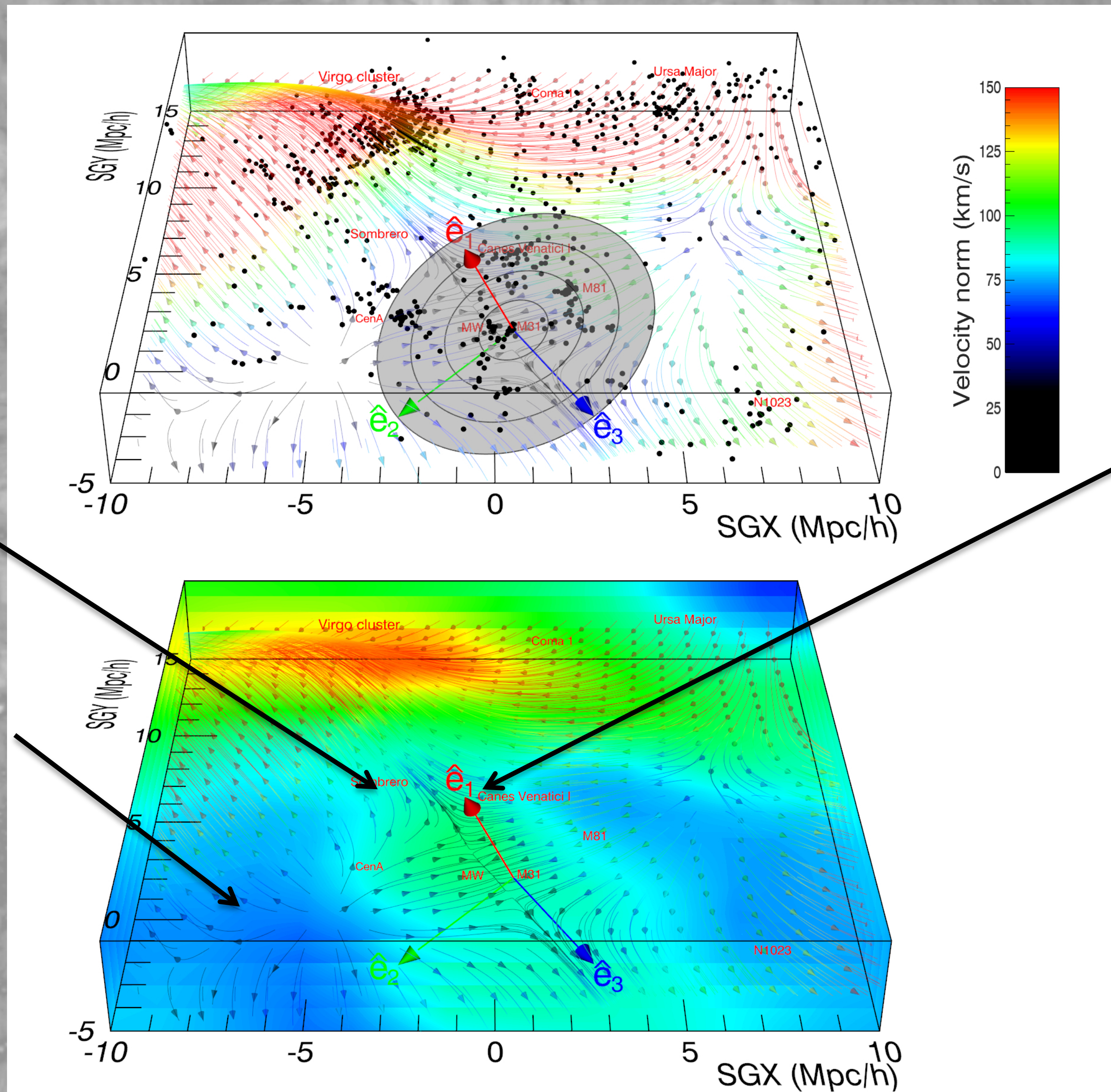
"Local Filament" stretched by Virgo

Laterally squashed by a "mini-repeller"



Libeskind *et al* 2015
Submitted

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



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Laterally squashed by a "mini-repeller"

e_1 sheet normal, points to the local void

Libeskind *et al* 2015 Submitted

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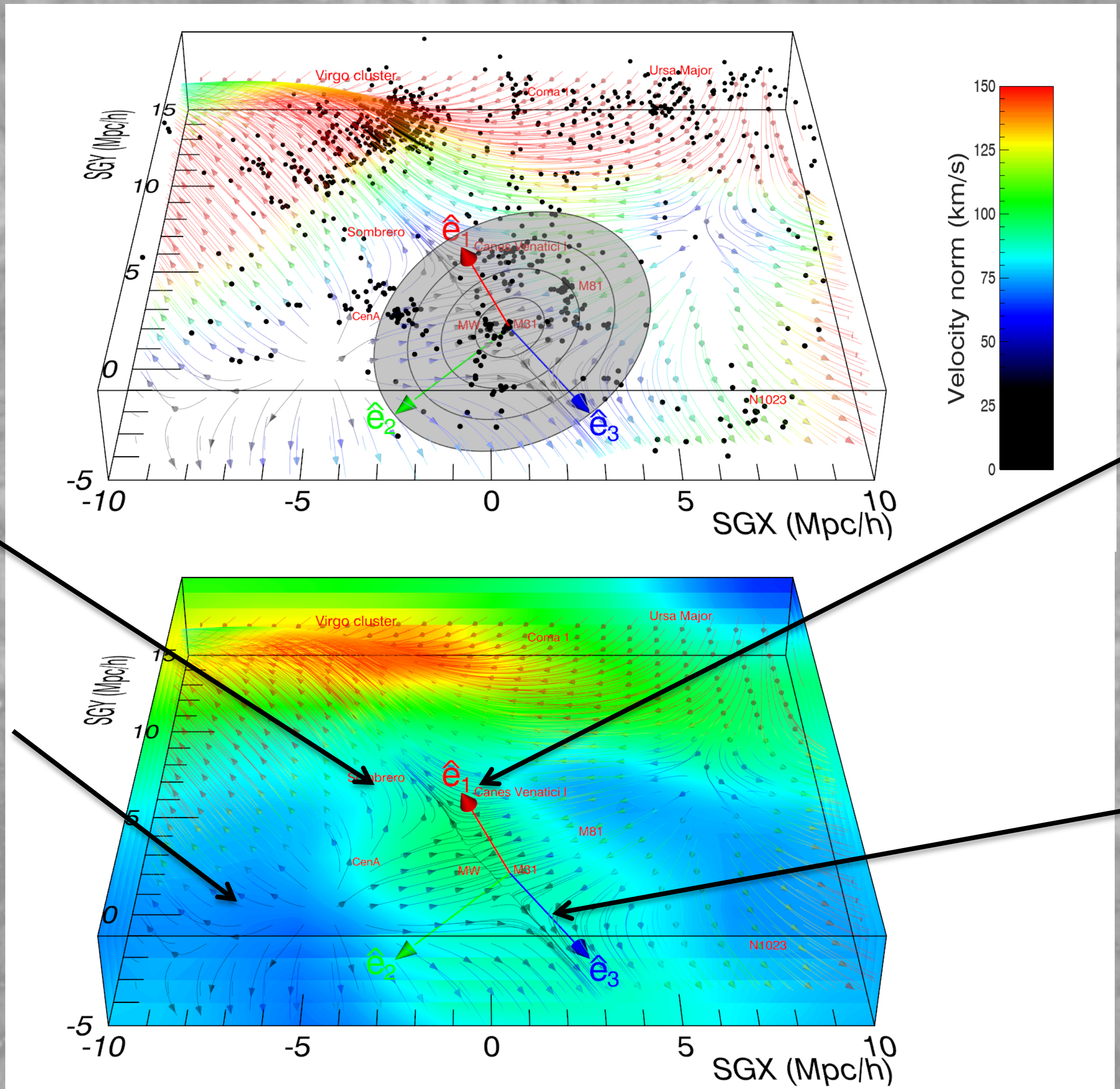


"Local Filament" stretched by Virgo

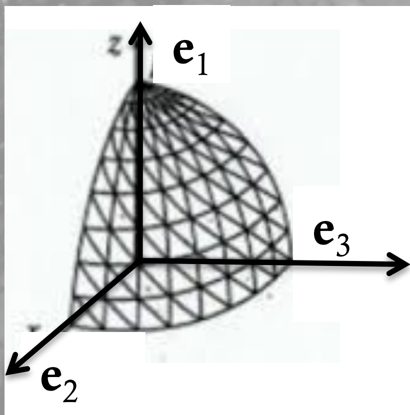
Laterally squashed by a "mini-repeller"

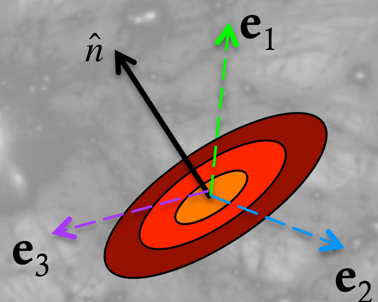
e_1 sheet normal, points to the local void

e_3 filament axis, points to Virgo

Libeskind *et al* 2015 Submitted

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





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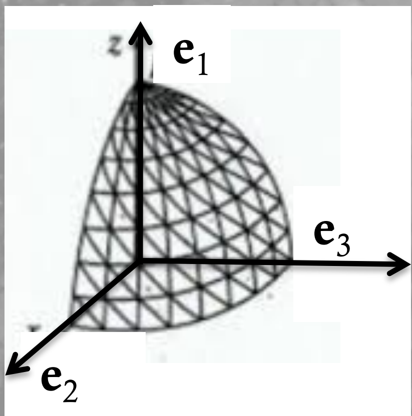

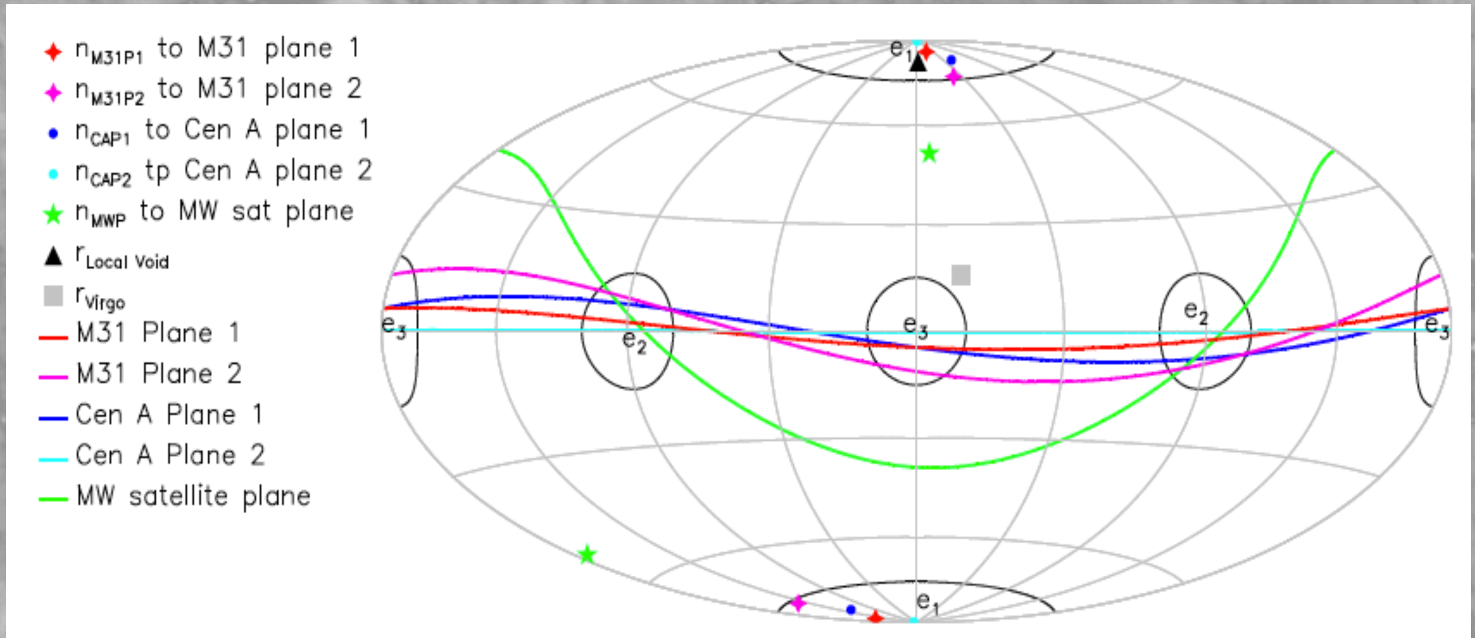

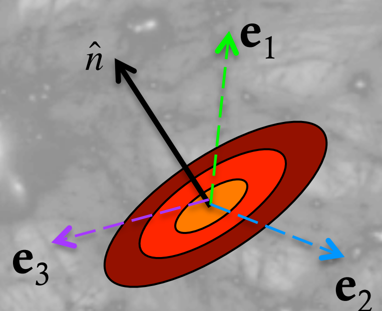

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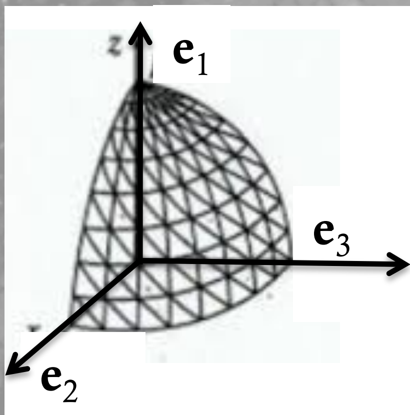
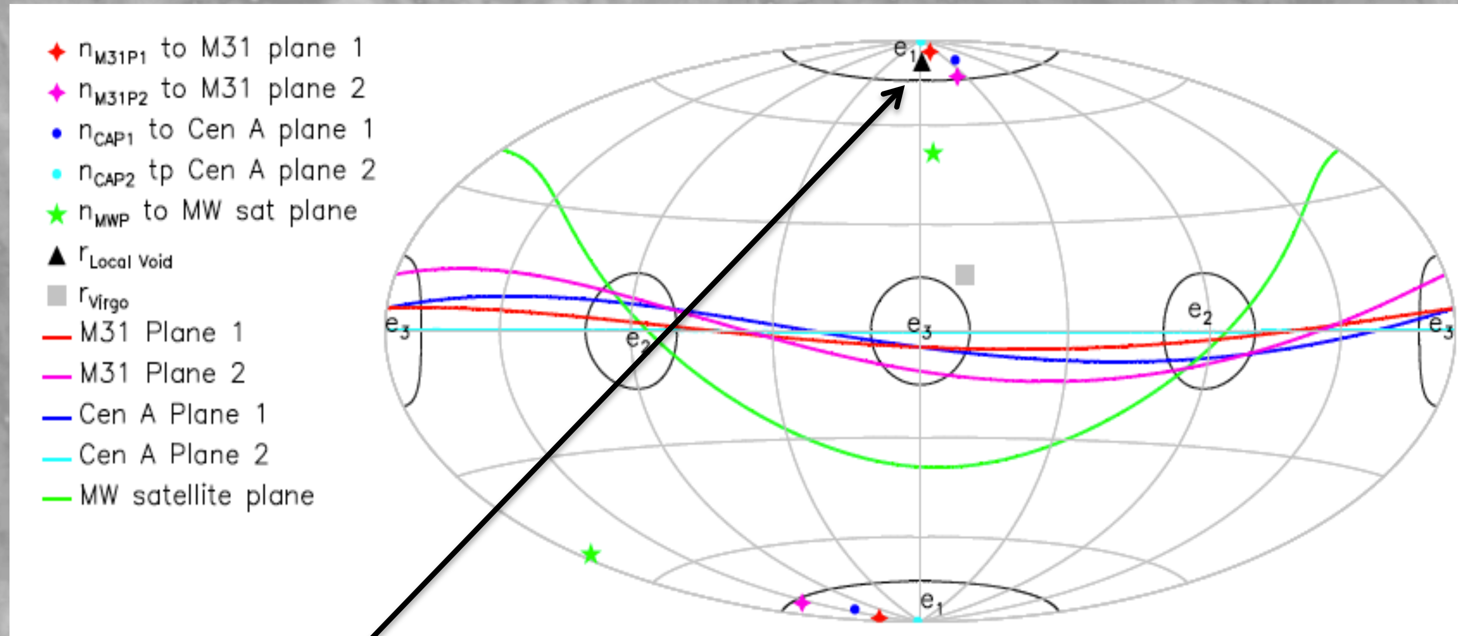
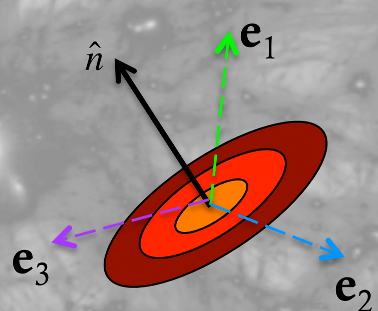
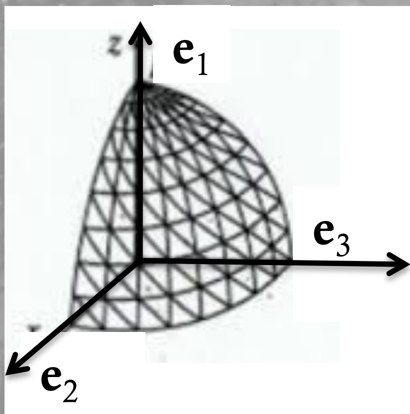


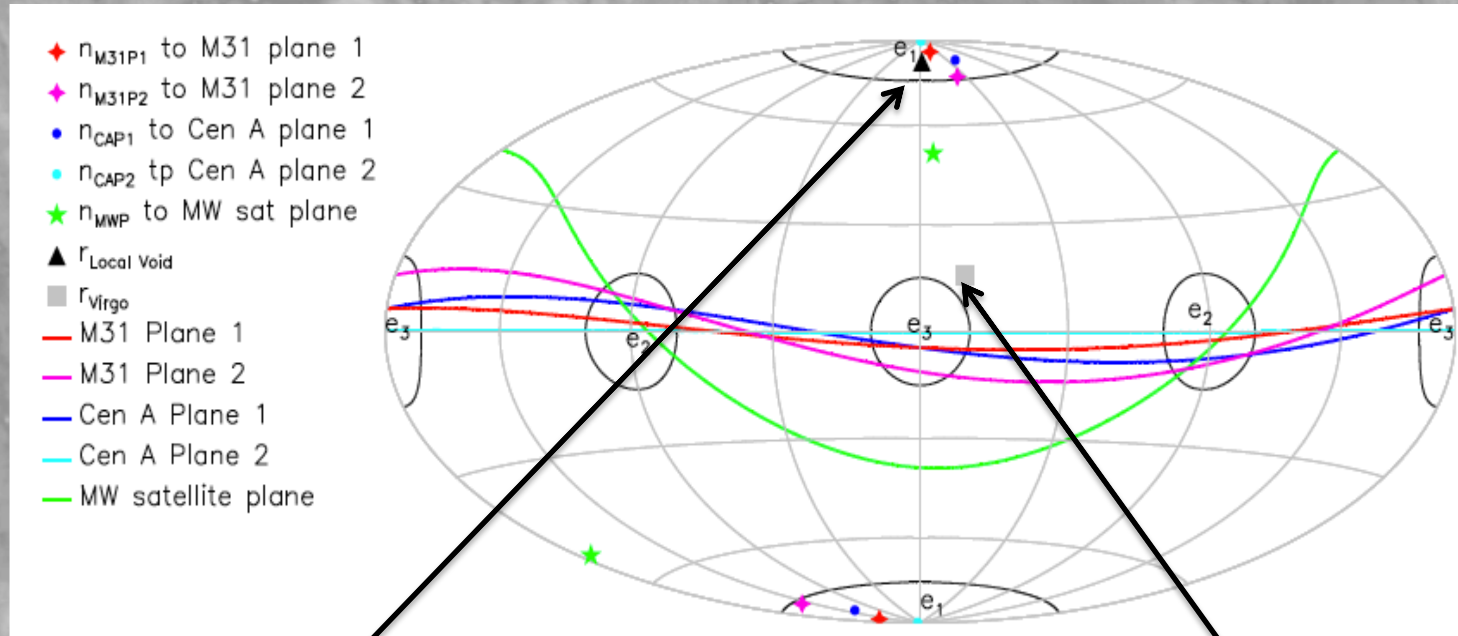


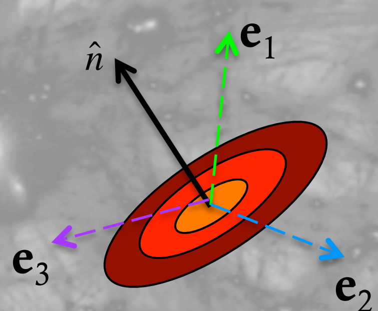


e_1 sheet normal, points to the local void

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







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e_3 filament axis, points to Virgo

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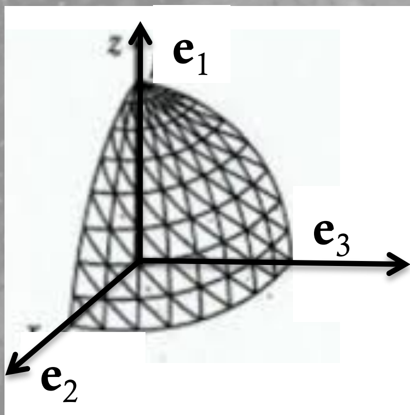
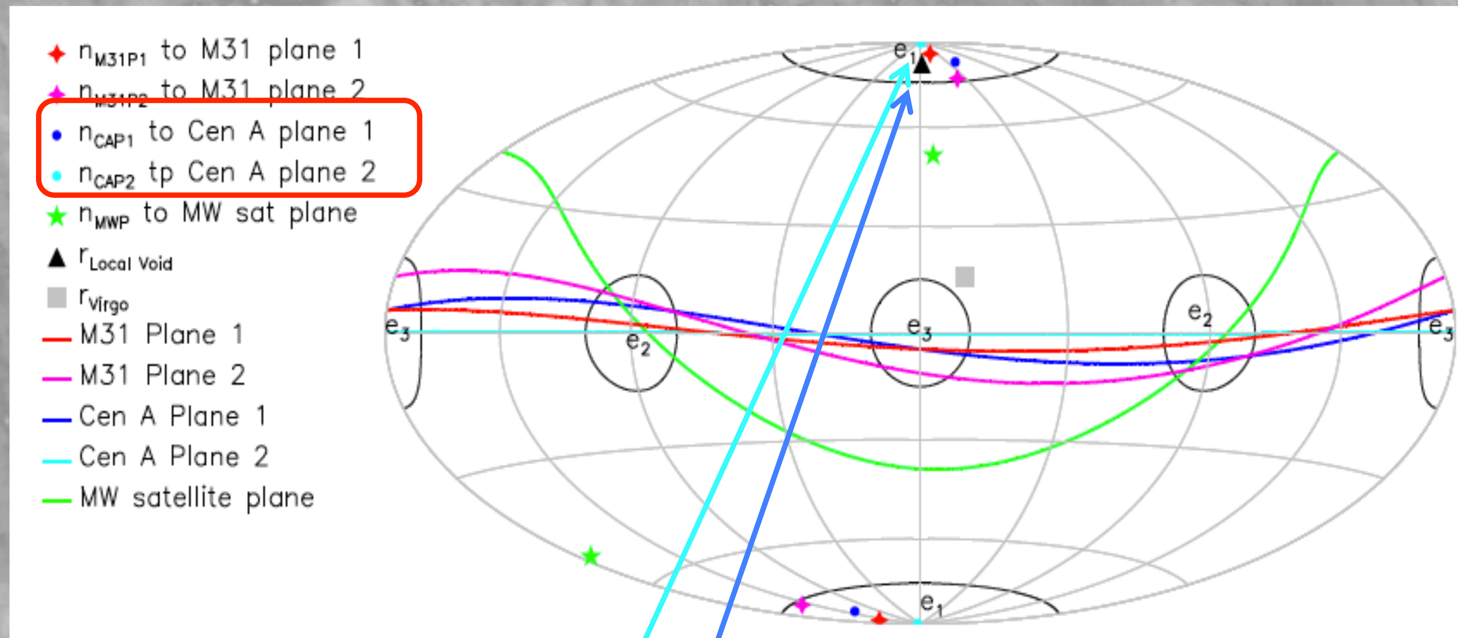
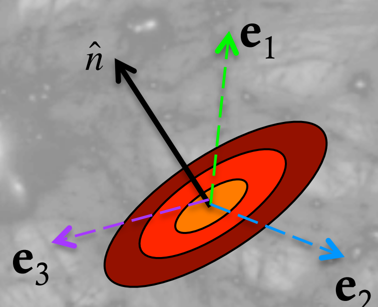


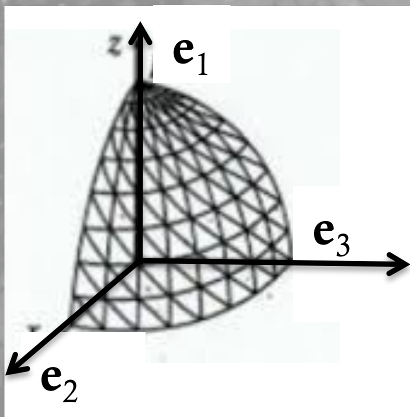


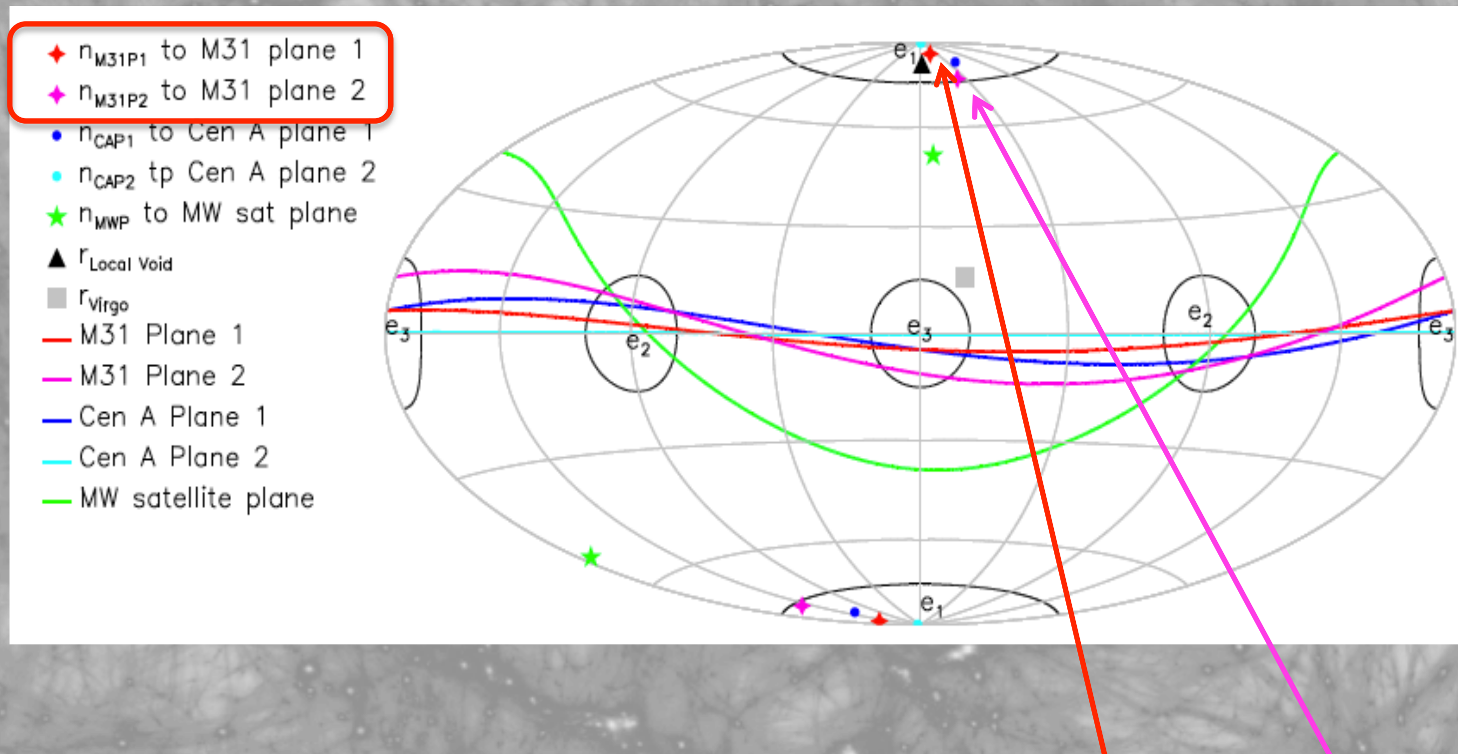


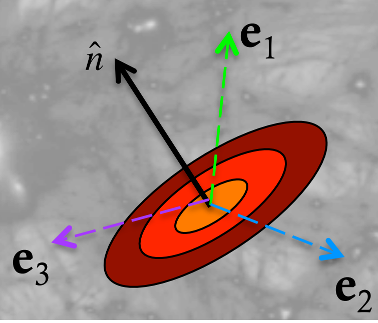
2 planes in CenA are well aligned

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

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







property	$\lvert\cos\theta\rvert$	degrees apart
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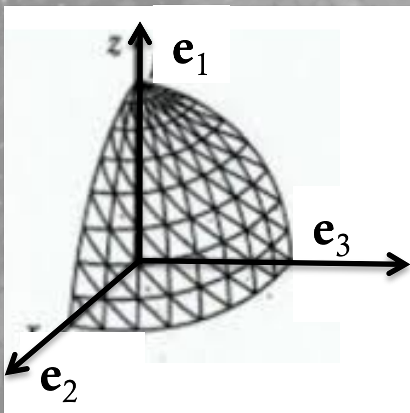
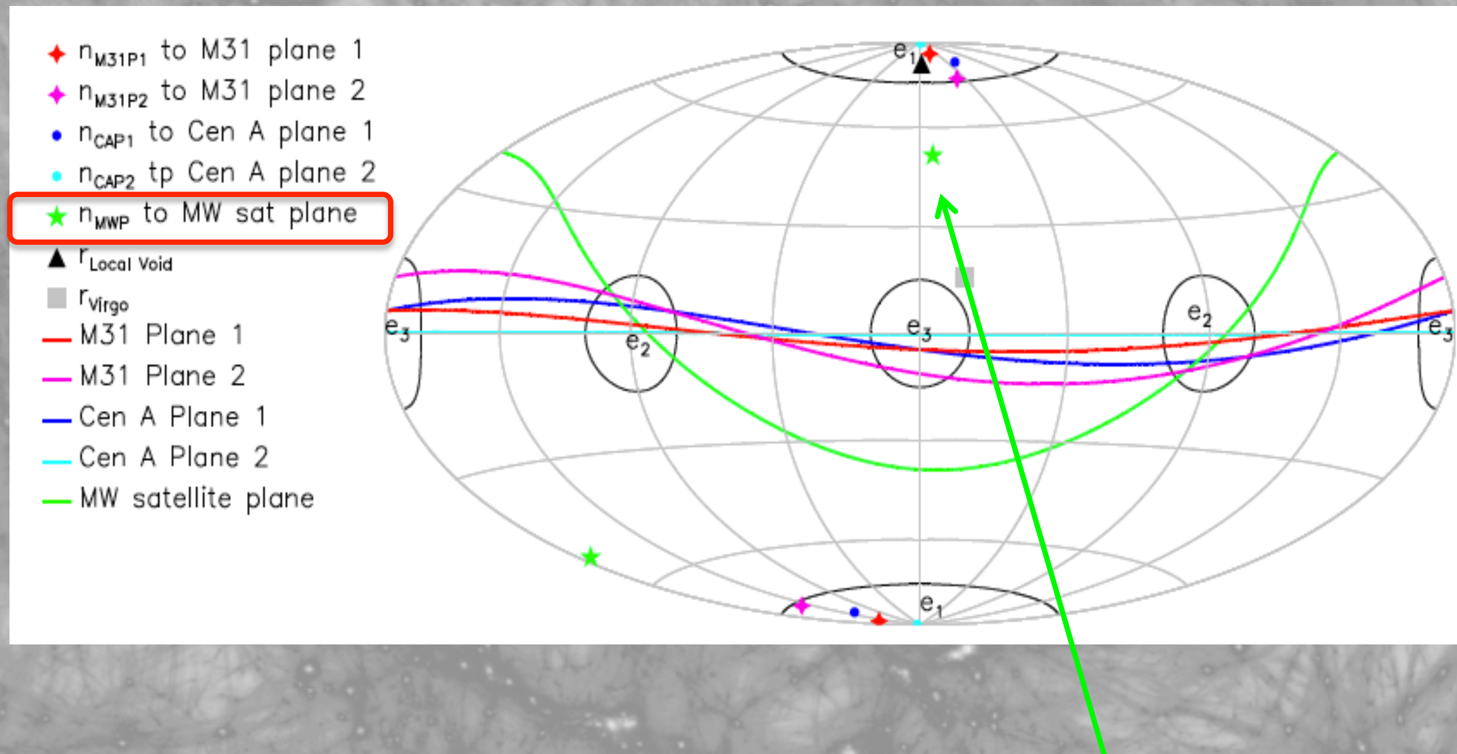
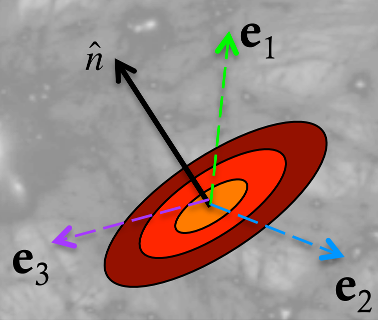
2 planes in M31
are well aligned

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







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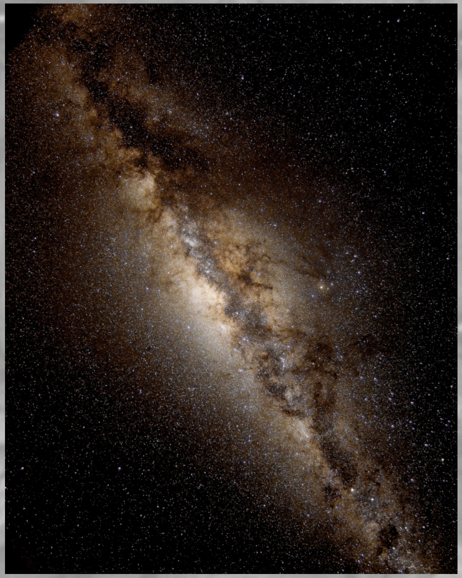
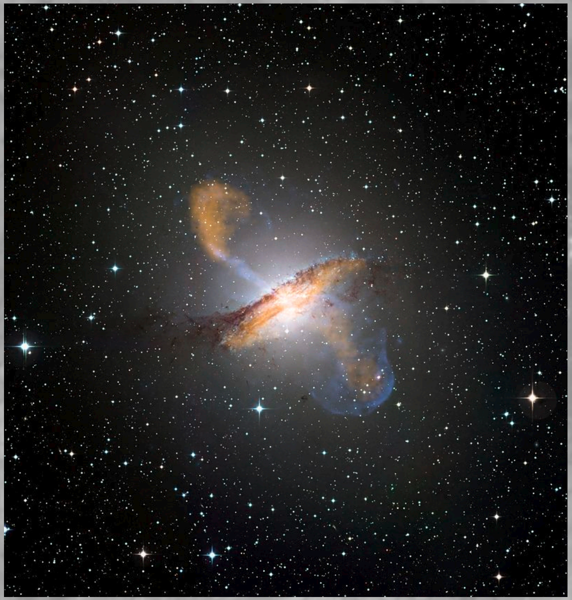
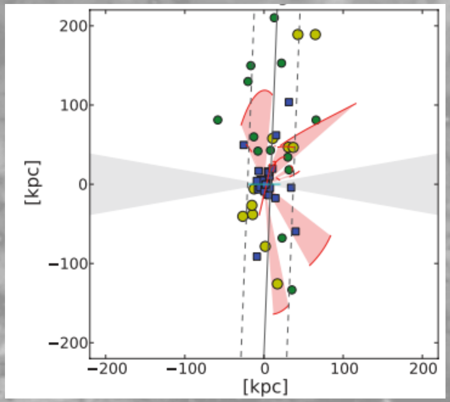
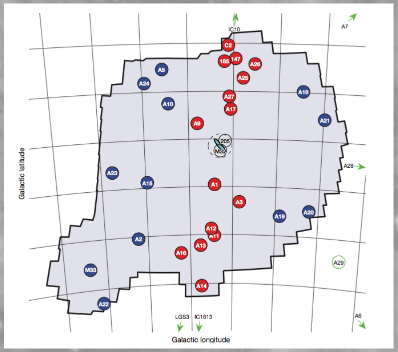
MW plane is off by ~38 deg, appears to have been torqued about the e_2 axis

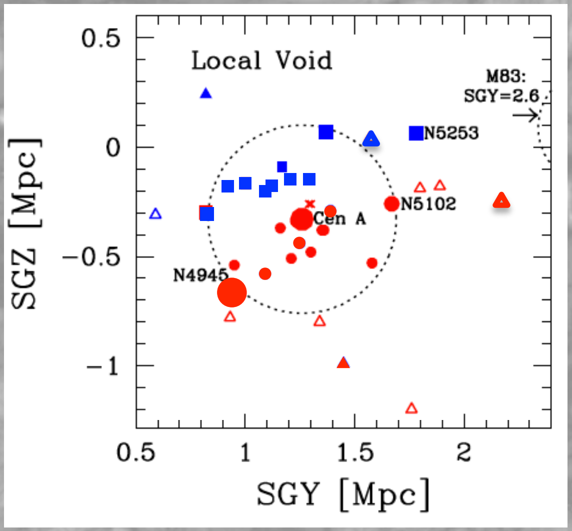
Summary of Local Volume Planes:









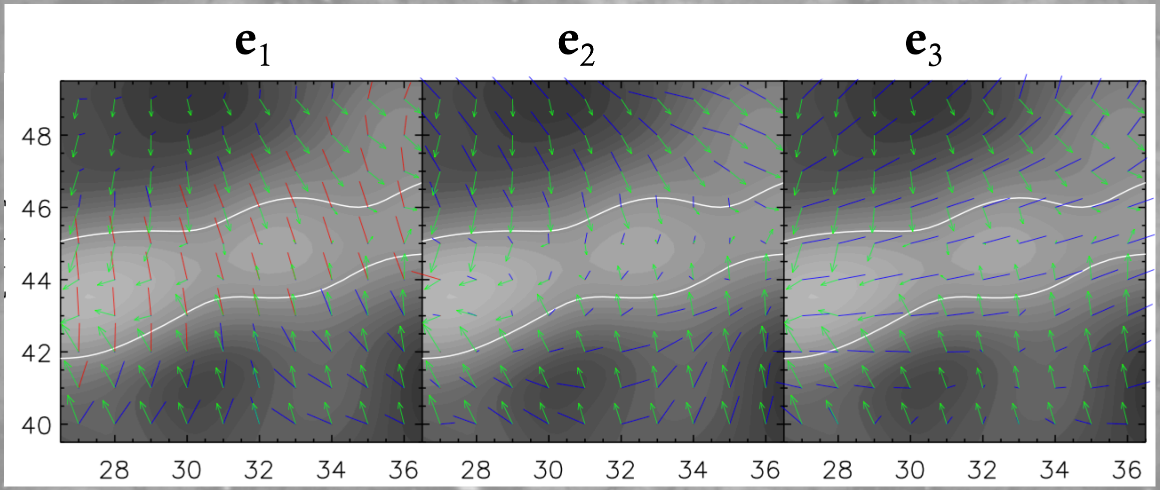


4 out 5 satellite planes are well aligned!

~35°

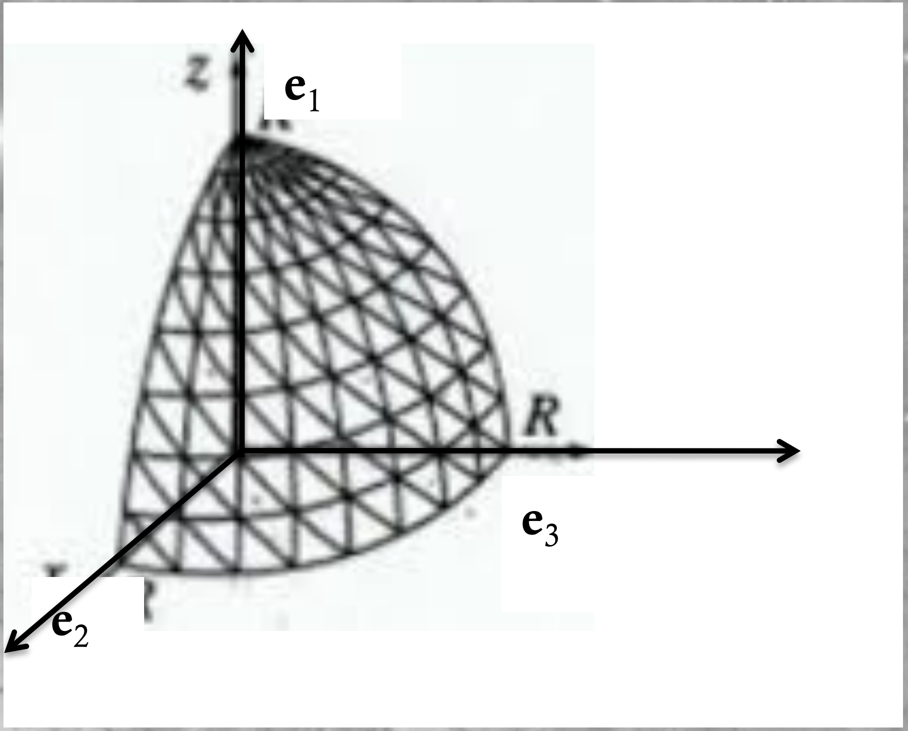
~4-7°

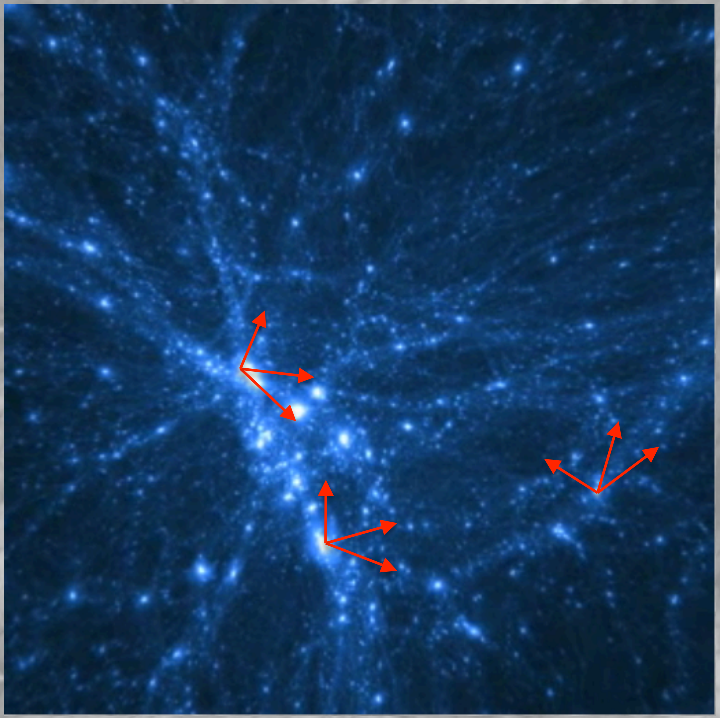
~1-9°



What can simulations tell us?

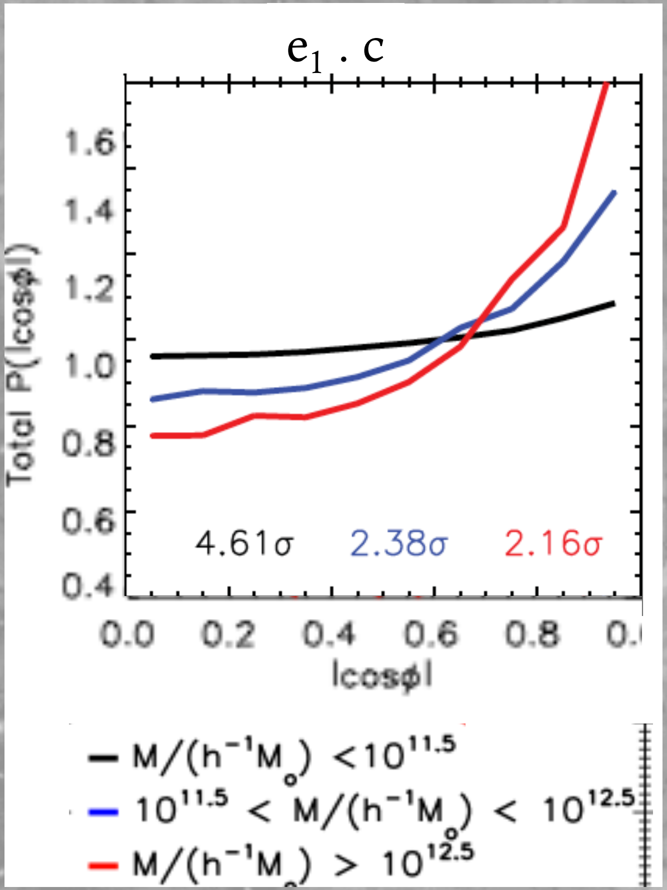
Are such alignments *generic* consequences of the LCDM model?

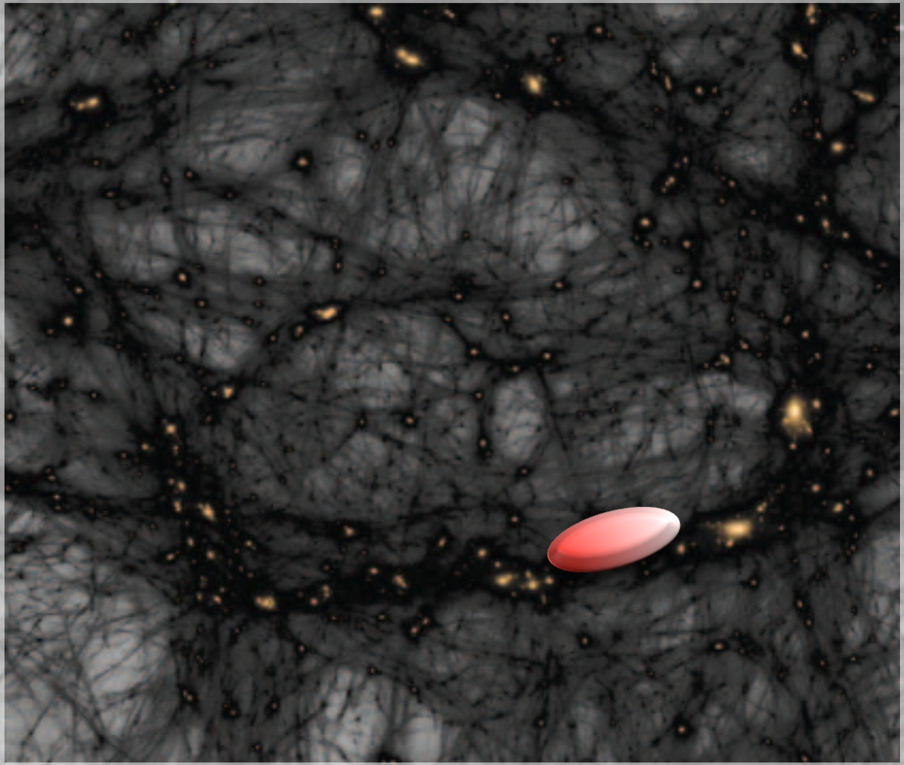




Alignment between the shear field and dark matter halos.

Strongest for most massive haloes





Libeskind et al 2013

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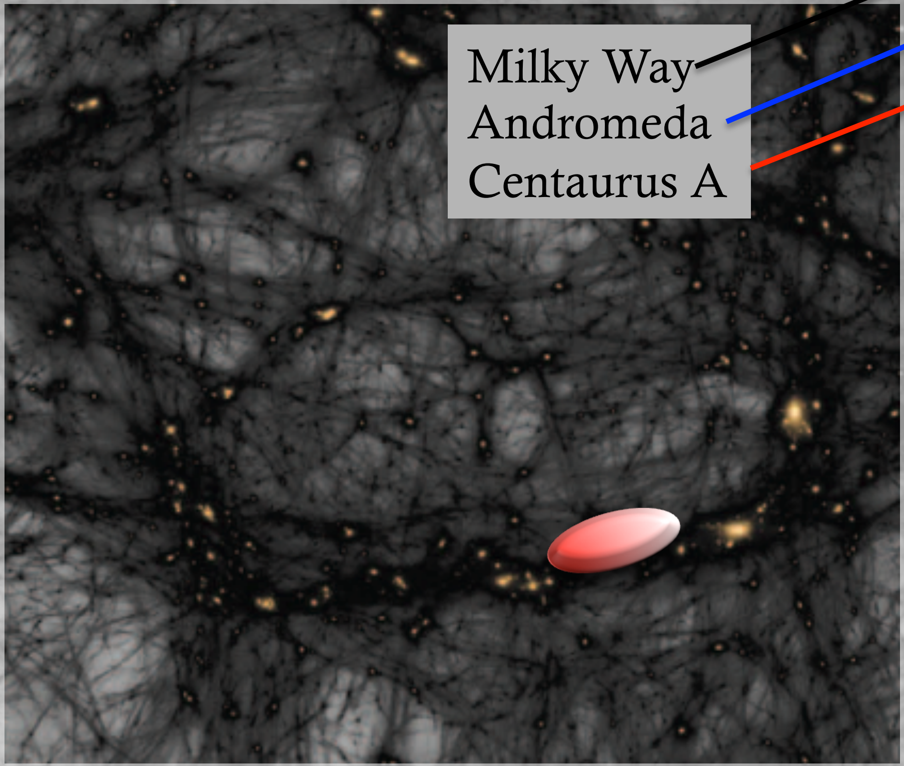
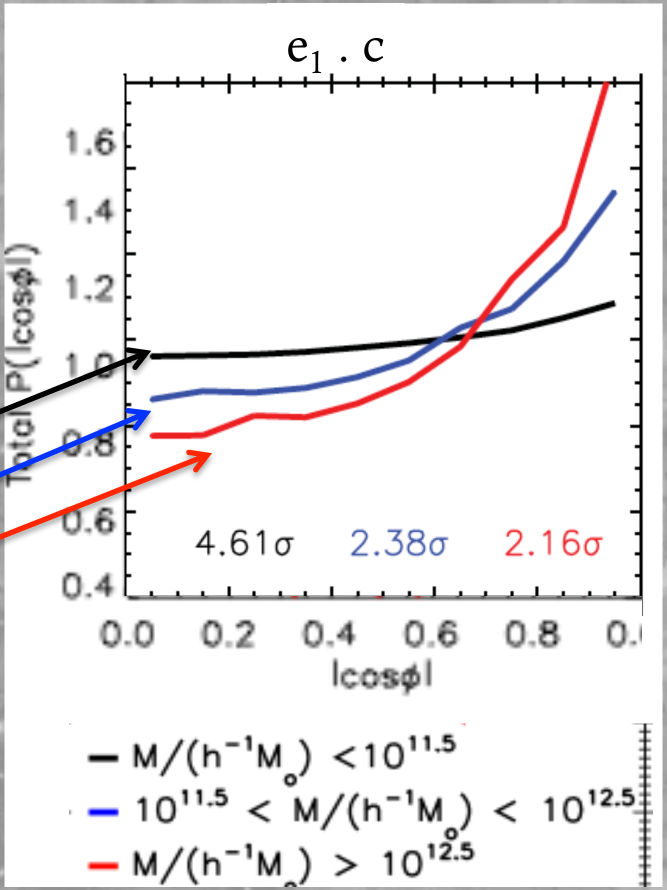
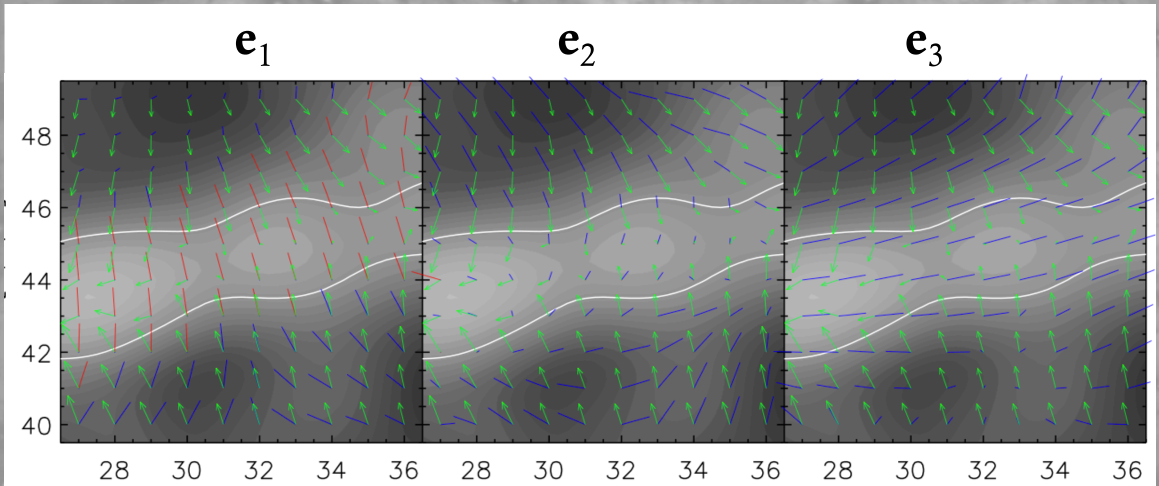




Libeskind et al 2013



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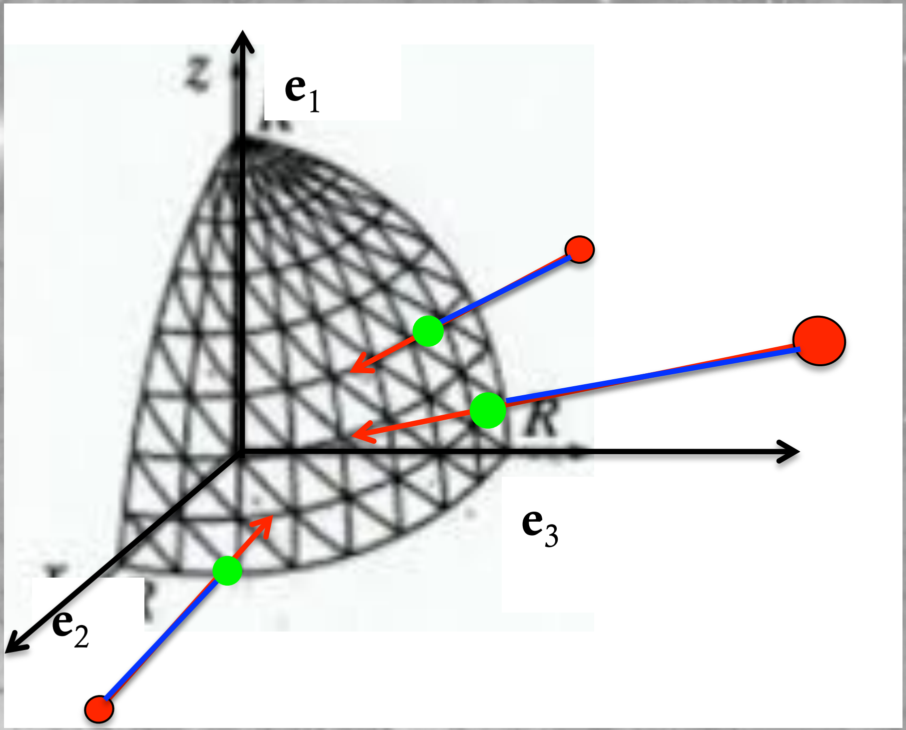

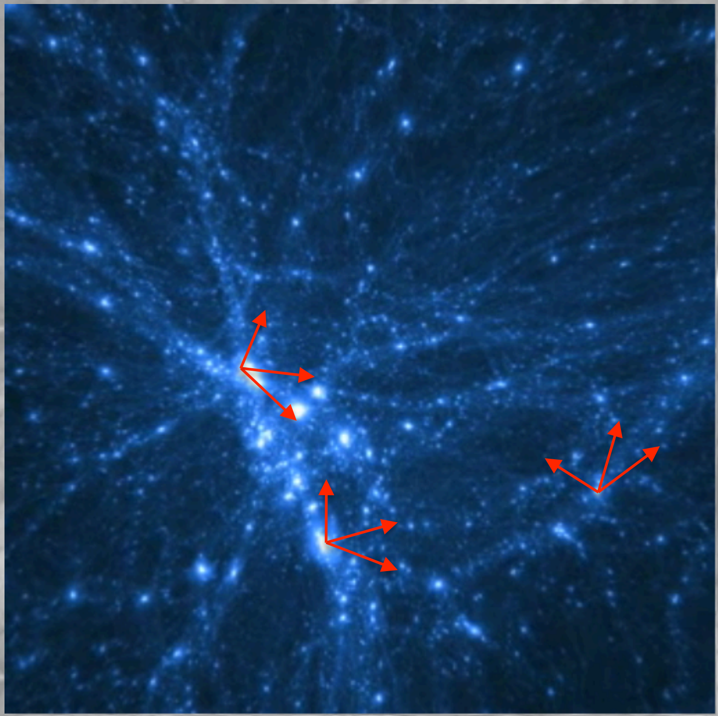

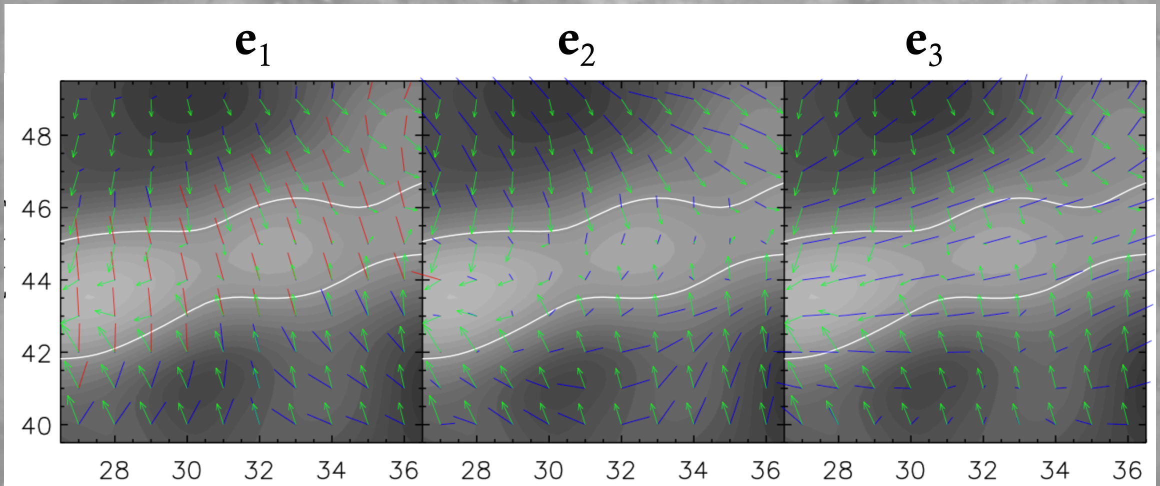

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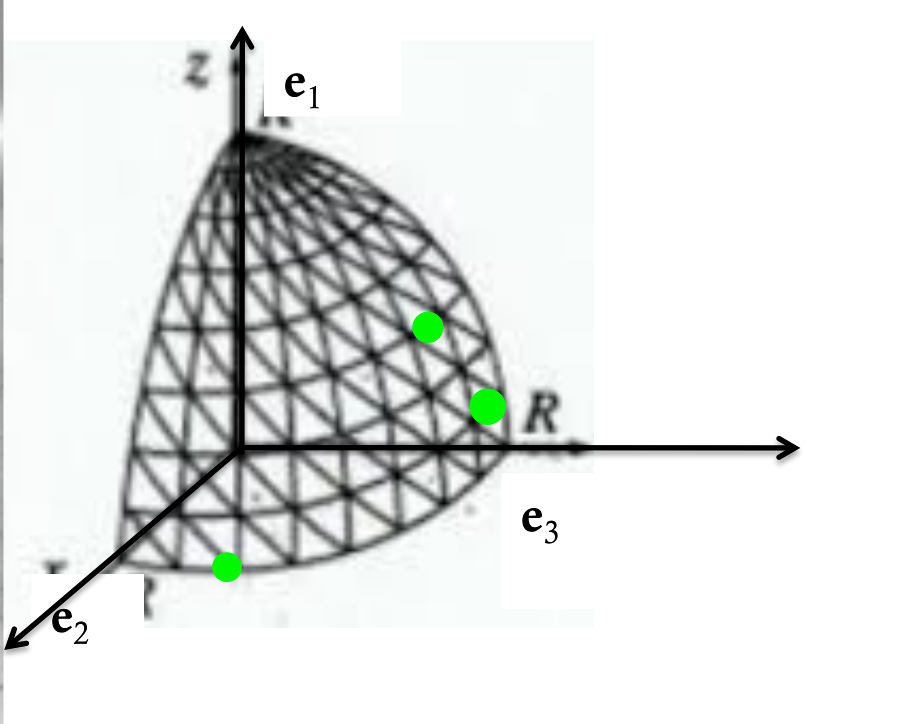
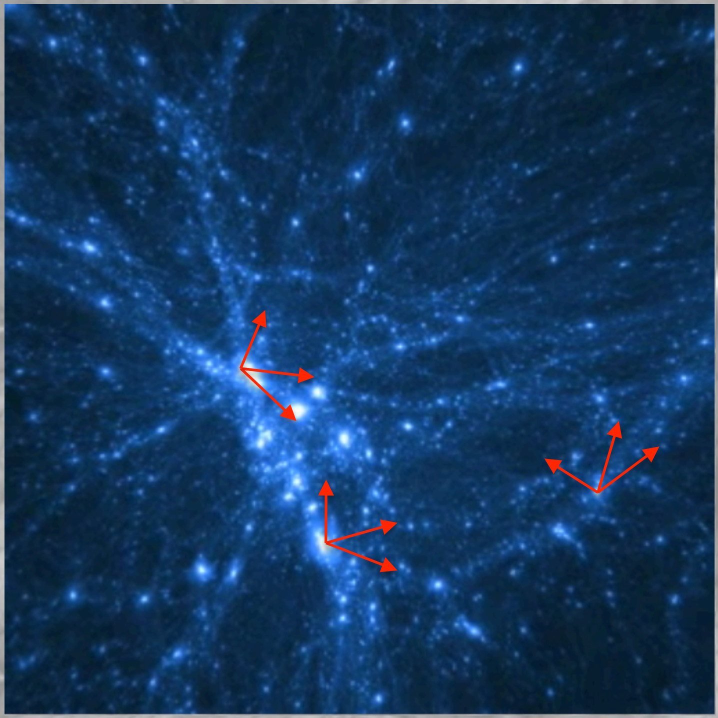
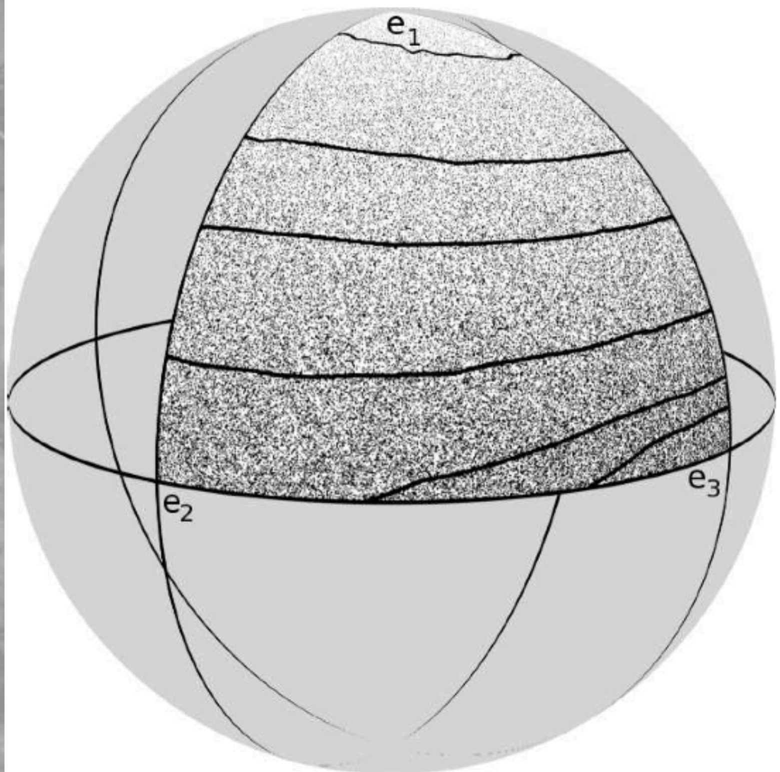




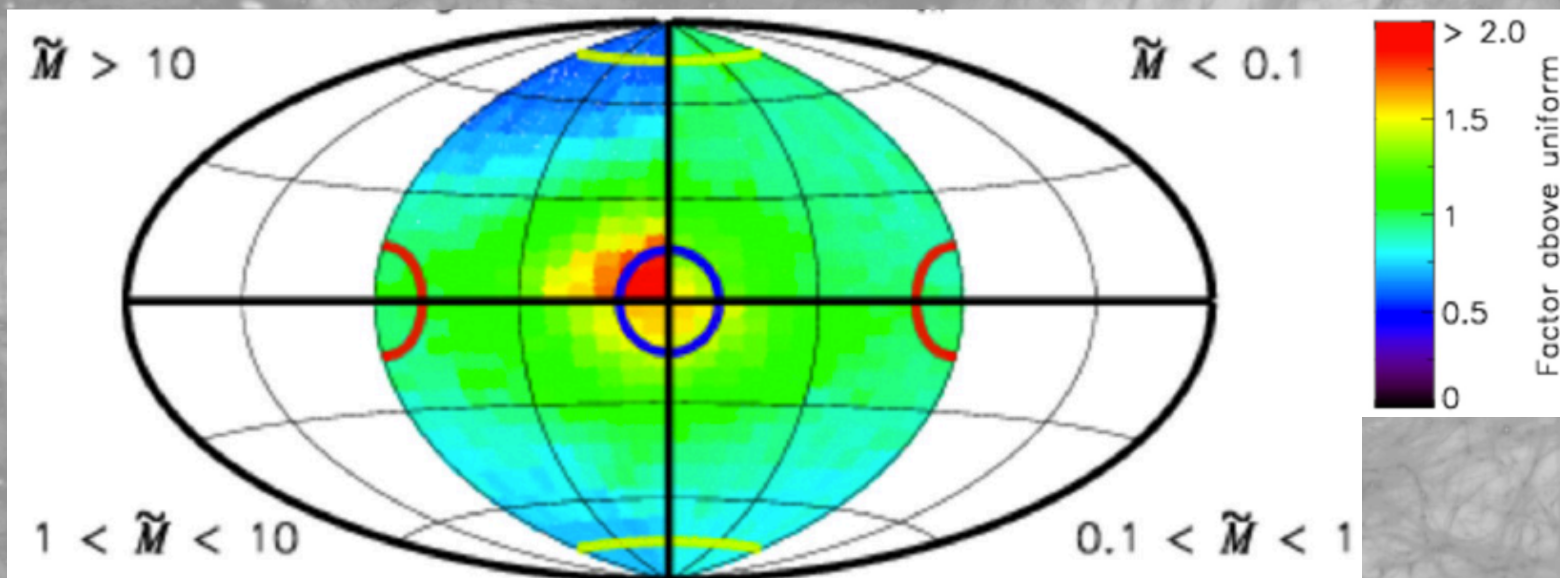
Track all infall points of subhaloes in the Shear eigenframe

1024^3 DM only simulation WMAP9
64Mpc box, Mres~ 2e7Msol

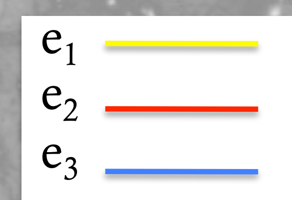


Libeskind et al 2014

Infall points of subhaloes in the Shear eigenframe



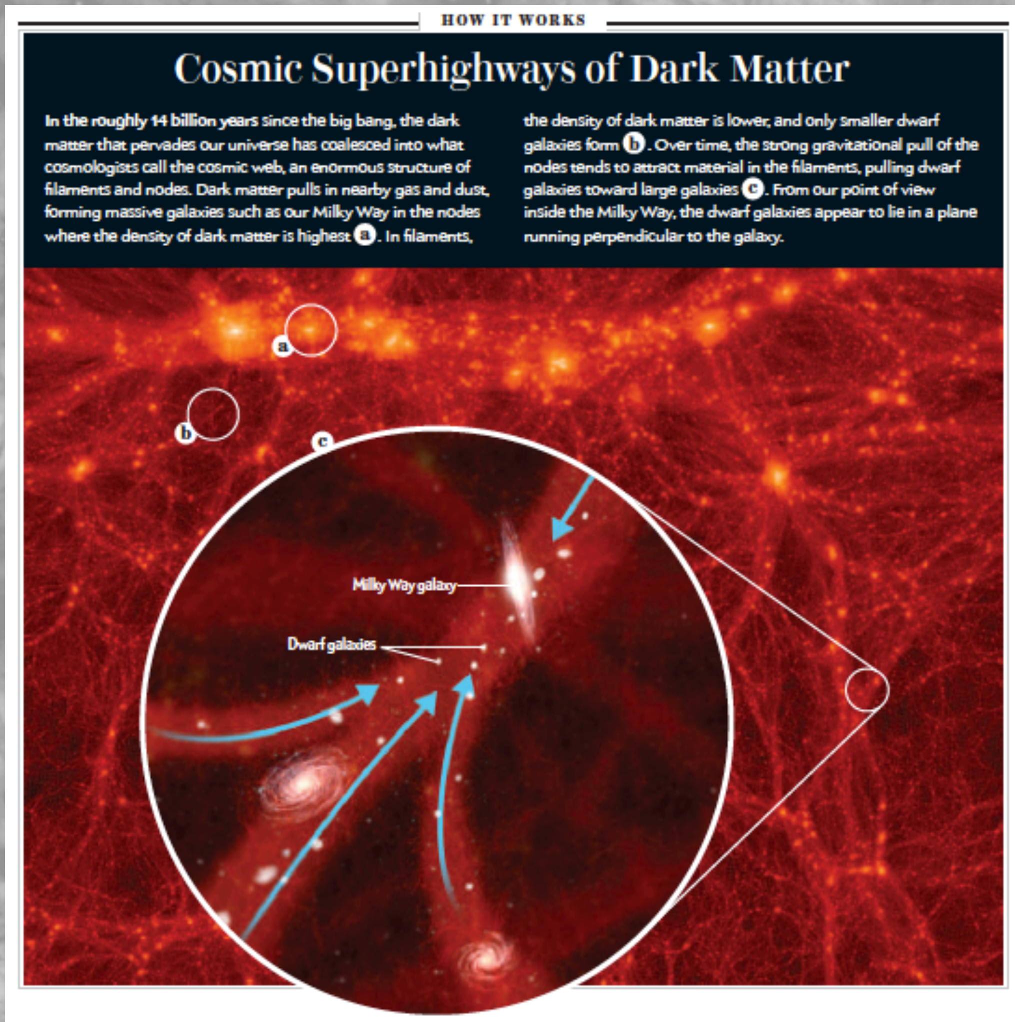
Shear field leads to beamed halo accretion



All mergers

Libeskind et al 2014

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*

Satellites within r_{vir} are oriented in a way that directly reflects the large scale structure.

Linear scales defined by the velocity field can still be “seen” close to hosts.

Conclusions

1. New HST distance measures of dwarfs around Centaurus A indicate a pair of satellite planes

2. The two satellite planes around Centaurus A and the pair around M31 are well aligned with the shear computed from Wf reconstruction of Cosmic Flows2

3. In simulations, the shear field beams satellites towards host haloes

Large Scale shear field on scales that are still linear appears to have a direct influence on the sub-Mpc position of dwarfs