The **odd** distribution of **dwarf** galaxies in the **Local** Neighbourhood

Noam I Libeskind

Leibniz Institute for Astrophysics, Potsdam, Germany

Yehuda Hoffman (Jerusalem)
Brent Tully (Hawaii)
Helene Courtois (Lyon)
Rodrigo Ibata (Strasbourg)
Daniel Pomerade (Saclay)
Stefan Gottlöber, Matthias Steinmetz, Quan Quo, Elmo Tempel (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]

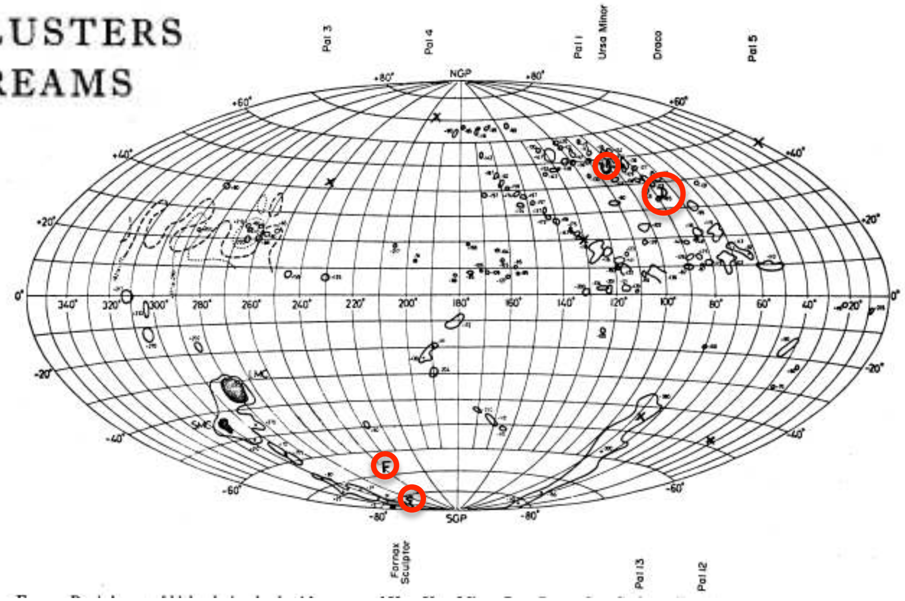
University of Chile, Casilla 36-D, Santiago de Chile

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.

Kunkel & Demers (1976)

Lynden-Bell 1976

DWARF GALAXIES AND GLOBULAR CLUSTERS IN HIGH VELOCITY HYDROGEN STREAMS



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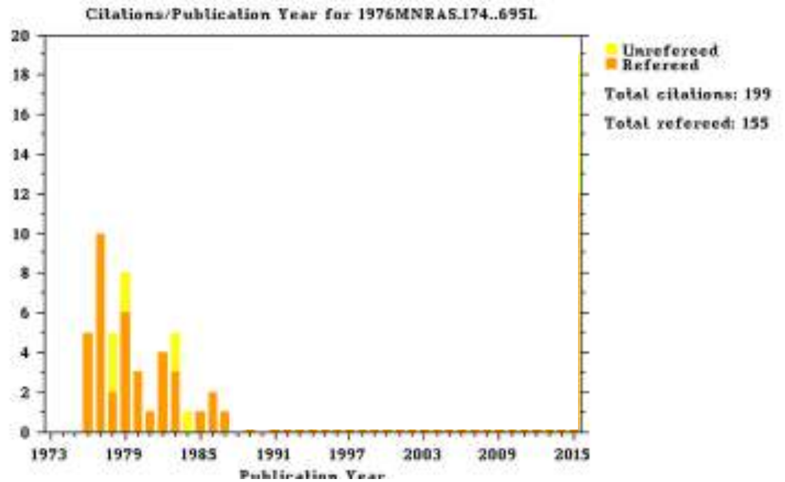

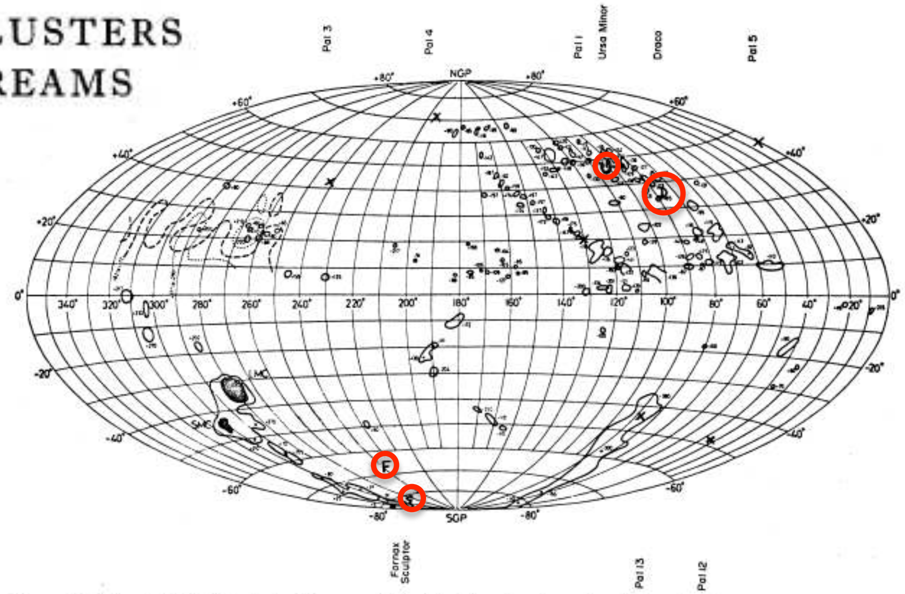

Dwarf galaxies on Planes

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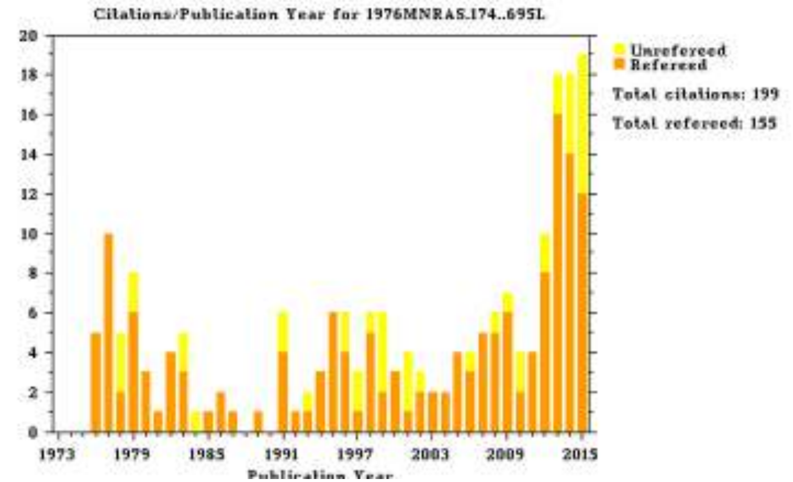

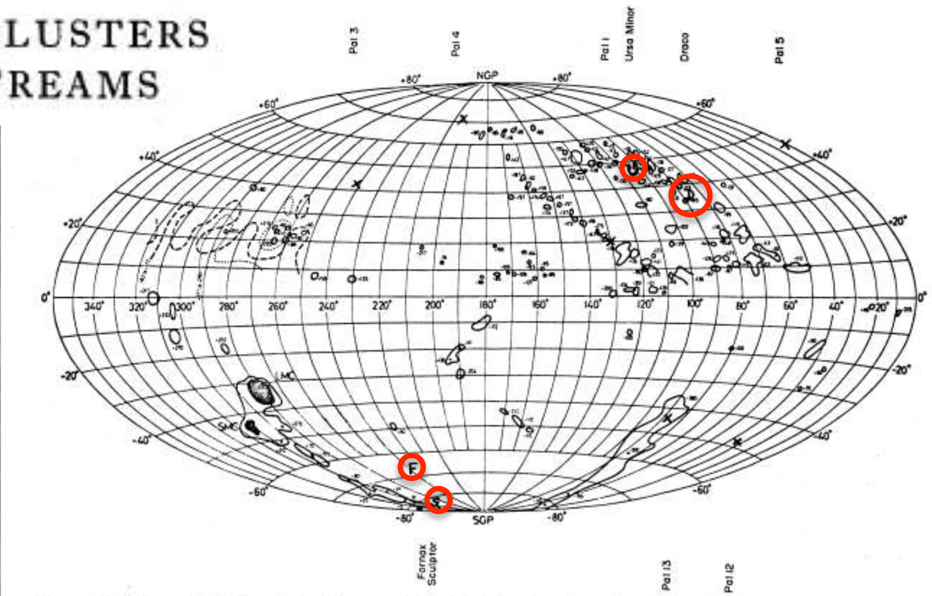

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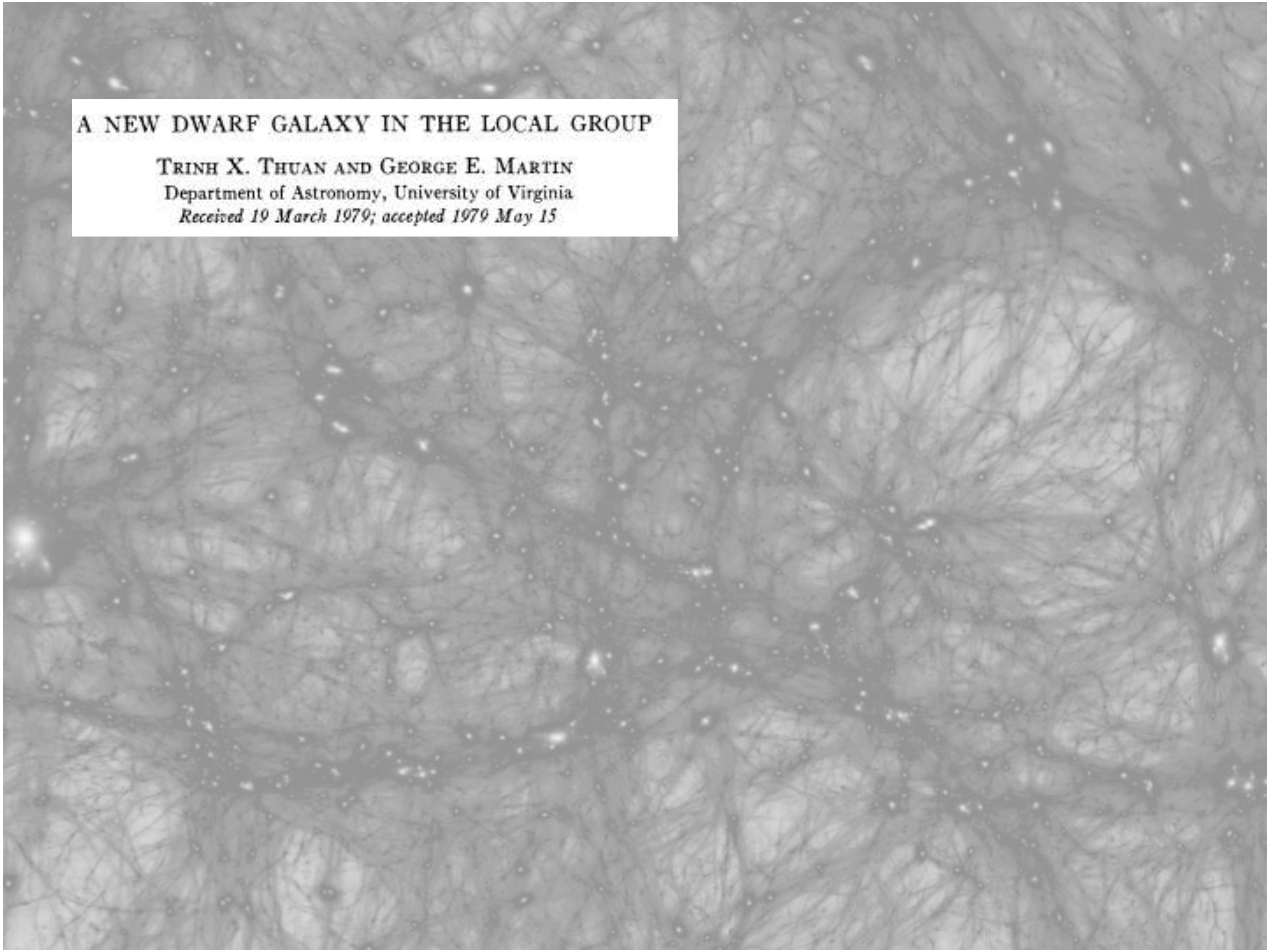
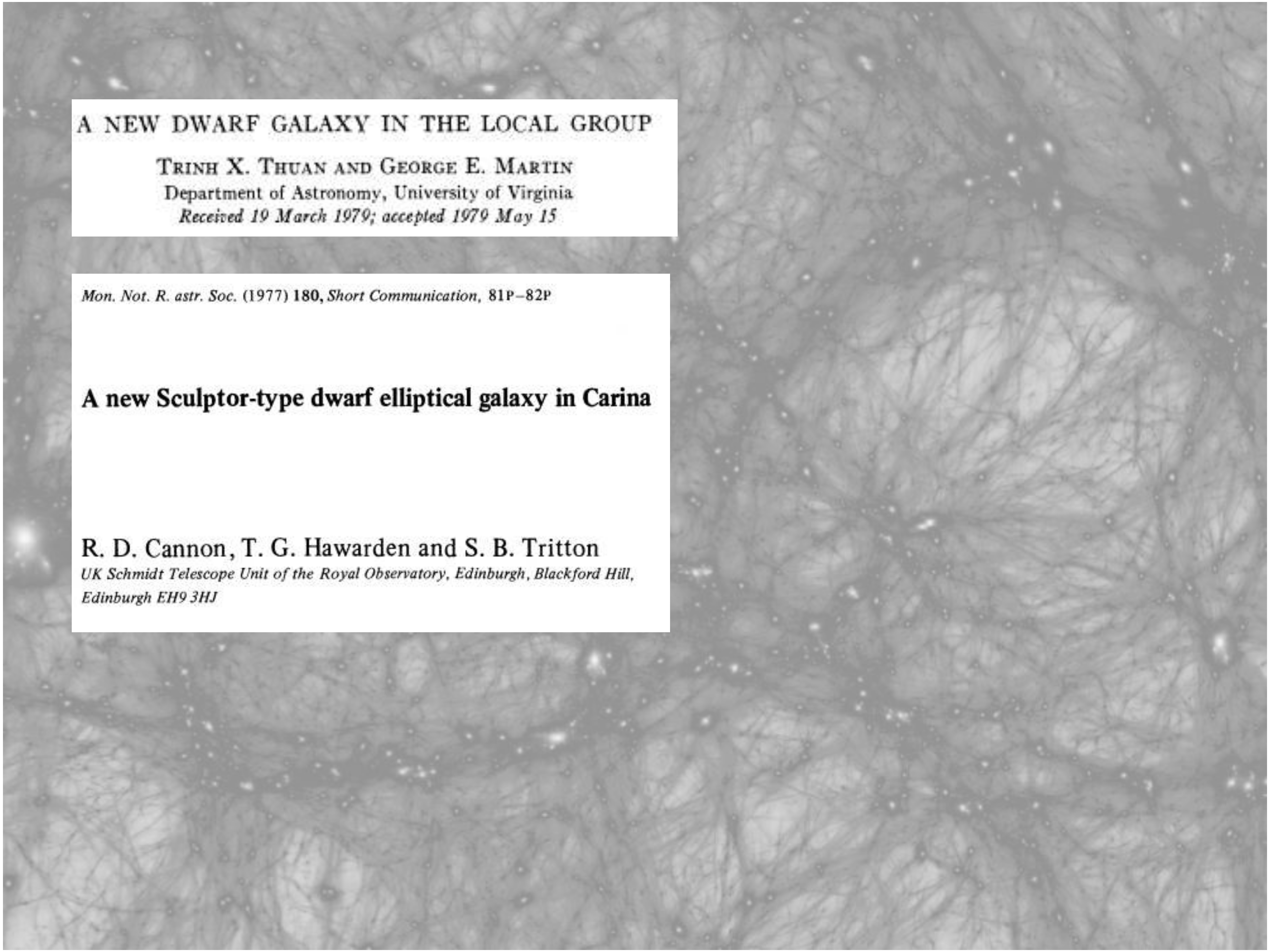
TRINH X. THUAN AND GEORGE E. MARTIN
Department of Astronomy, University of Virginia
Received 19 March 1979; accepted 1979 May 15





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1982 February *The Ursa Minor Dwarf Galaxy*

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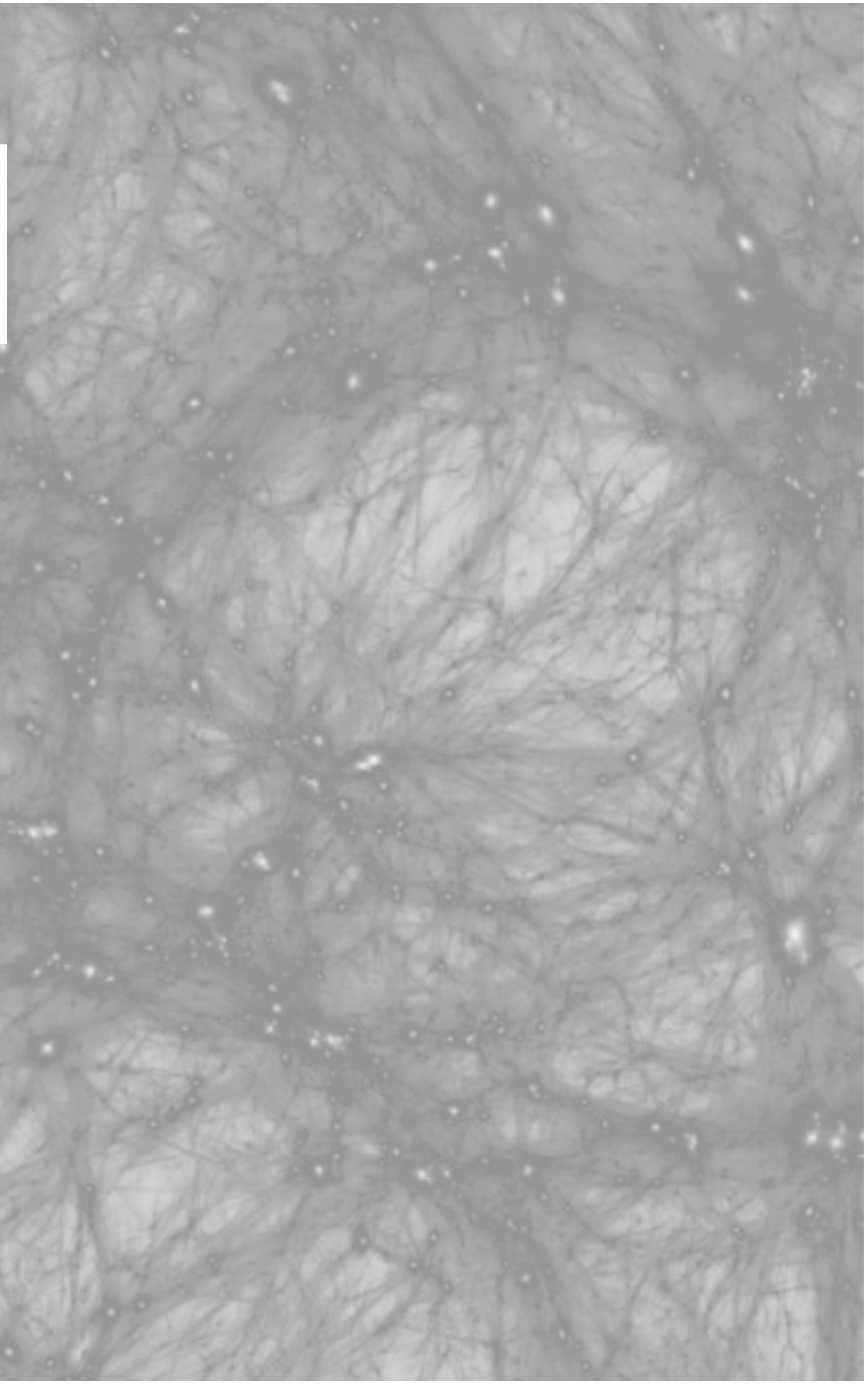
By D. Lynden-Bell
Institute of Astronomy, The Observatories, Cambridge



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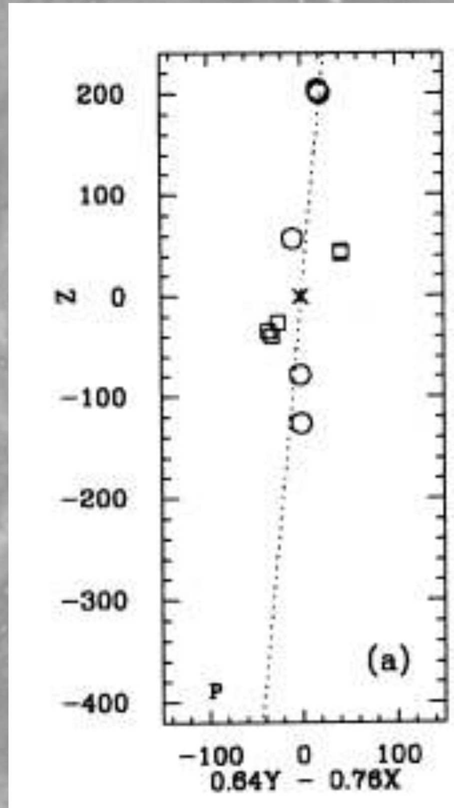
THE FORNAX-LEO-SCULPTOR STREAM REVISITED

STEVEN R. MAJEWSKI[1]
The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101
Received 1993 August 25; accepted 1994 May 16

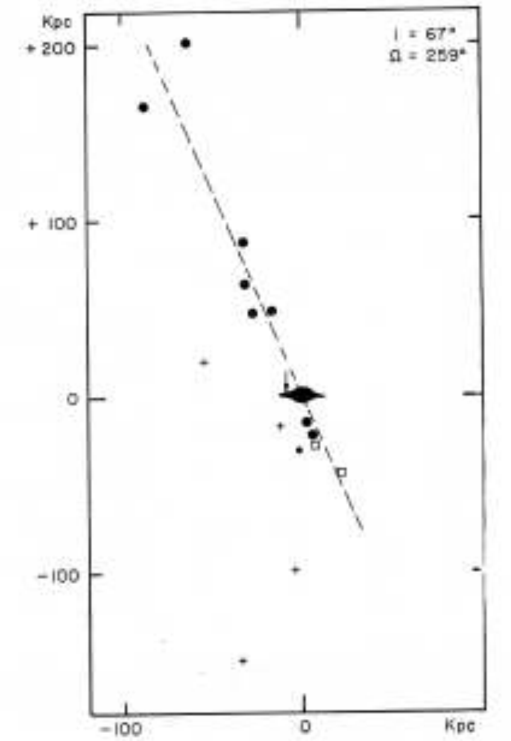


Majewski 1994

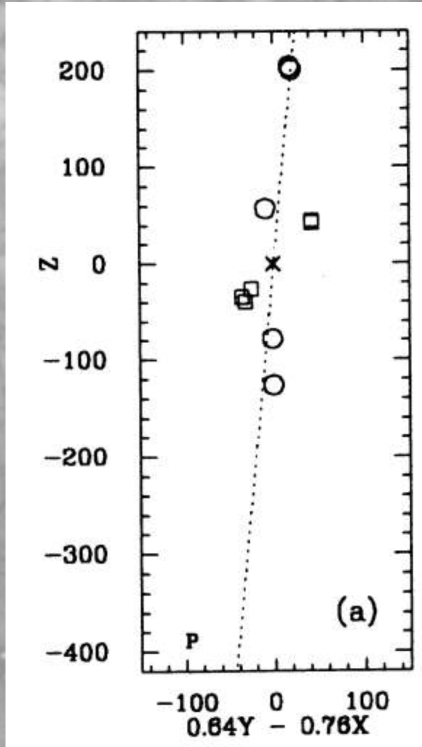
[6] The author is mindful that Nature has not always been kind in matters of spatial distribution. I thank Richard Kron and Allan Sandage for pointing out the important example that the first 10 QSOs discovered also lay in one plane.

Planes of dwarfs – a problem since 1976

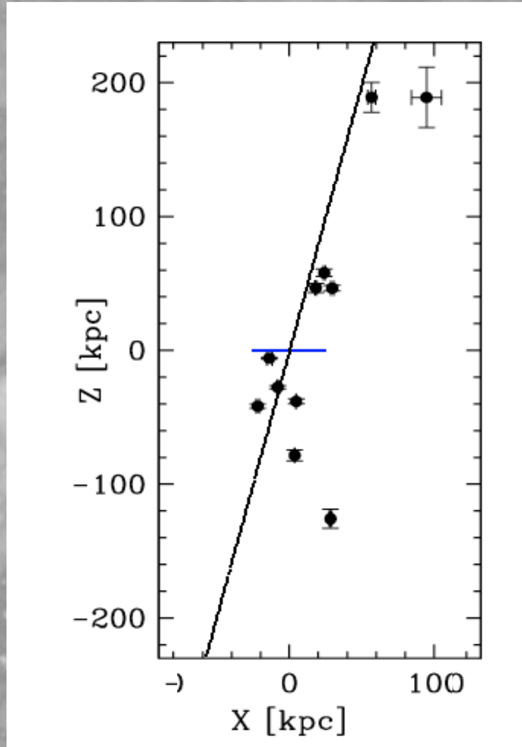
Kunkel & Demers (1976)



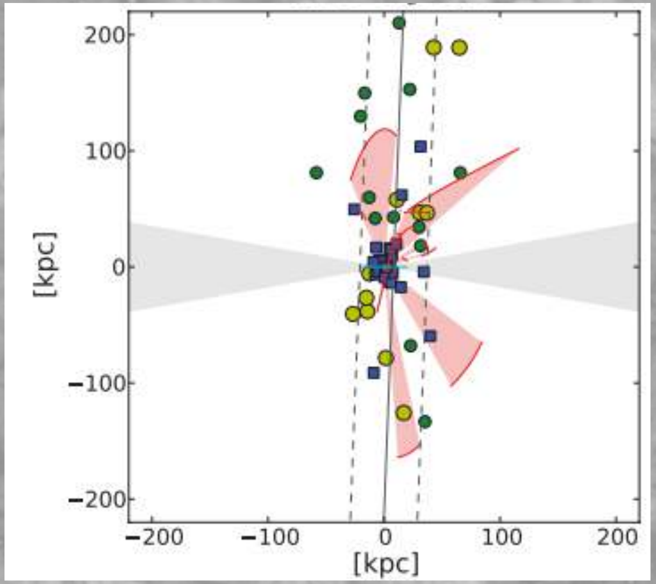
Majewski 1994



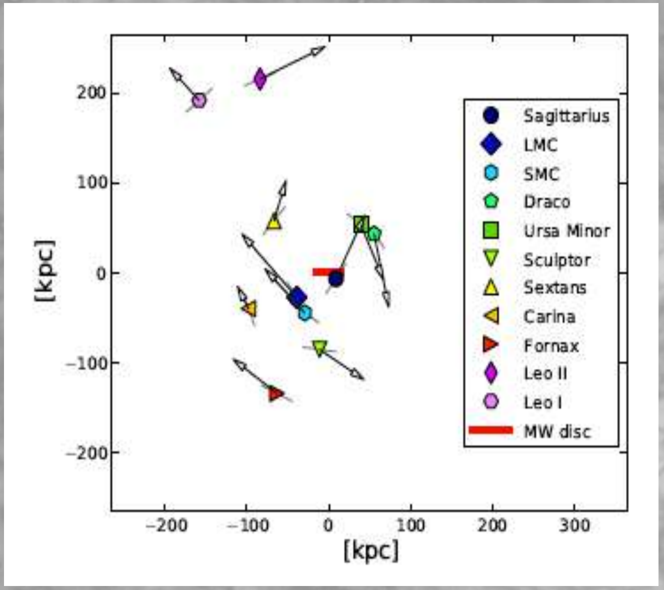
Kroupa, Theis & Boily 2005



Milky Way – Vast Polar Orbiting structure (VPOS)



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

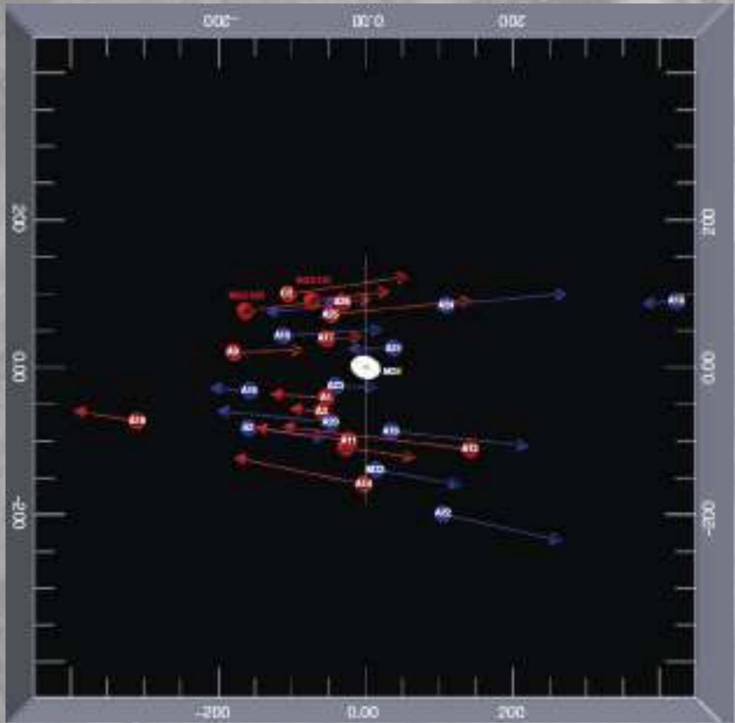


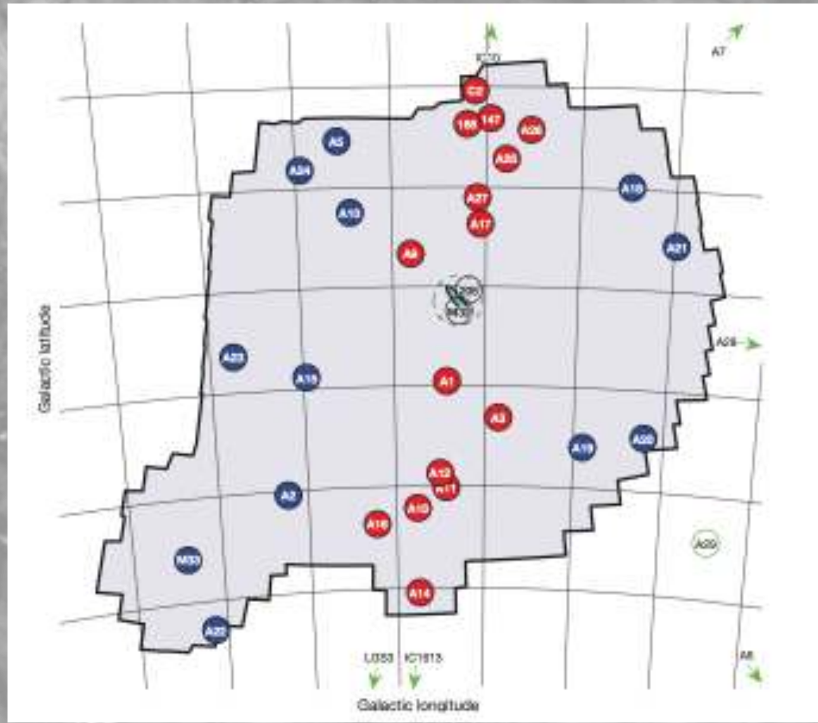
Metz, Kroupa & Libeskind 2007
Pawlowski & Kroupa 2013

c/a ~ 0.15

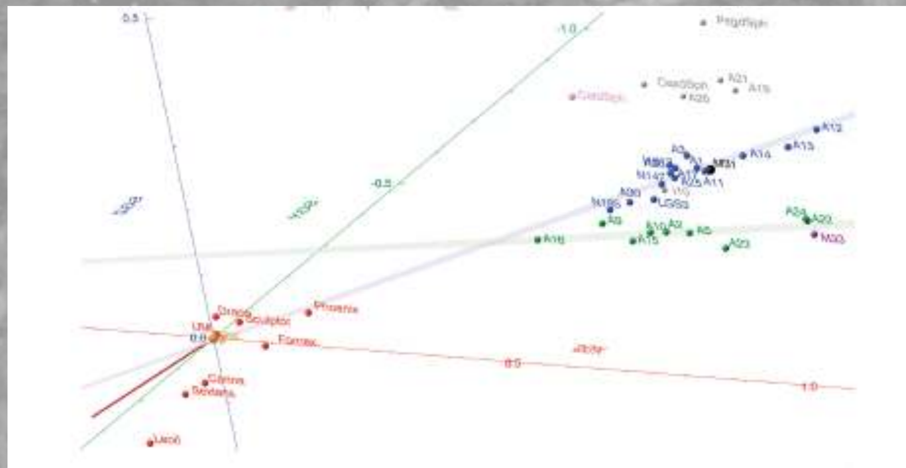
Δ_{rms}=24kpc

Planes of dwarfs – a problem since 1976





Ibata et al 2013, Conn et al 2013



Shaya & Tully 2013

See also Pawlowski et al

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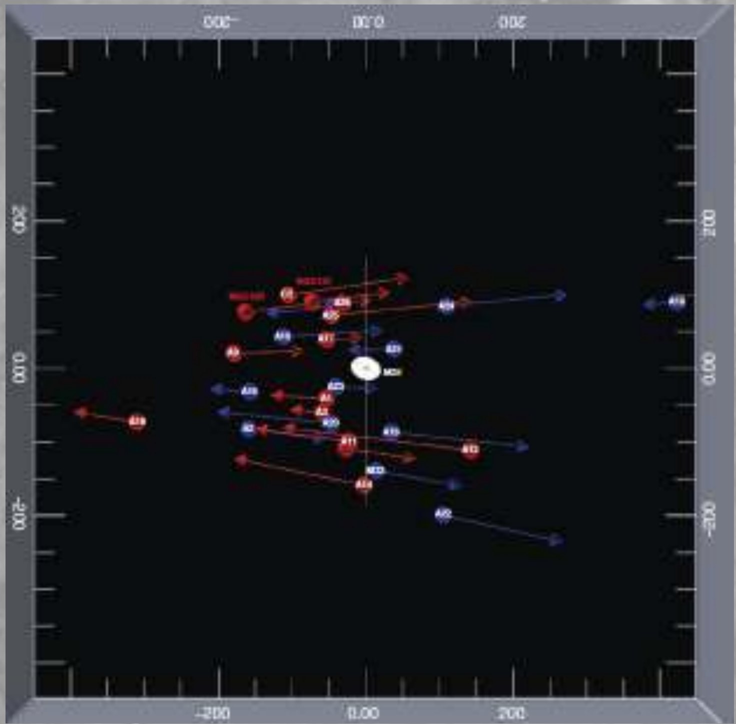

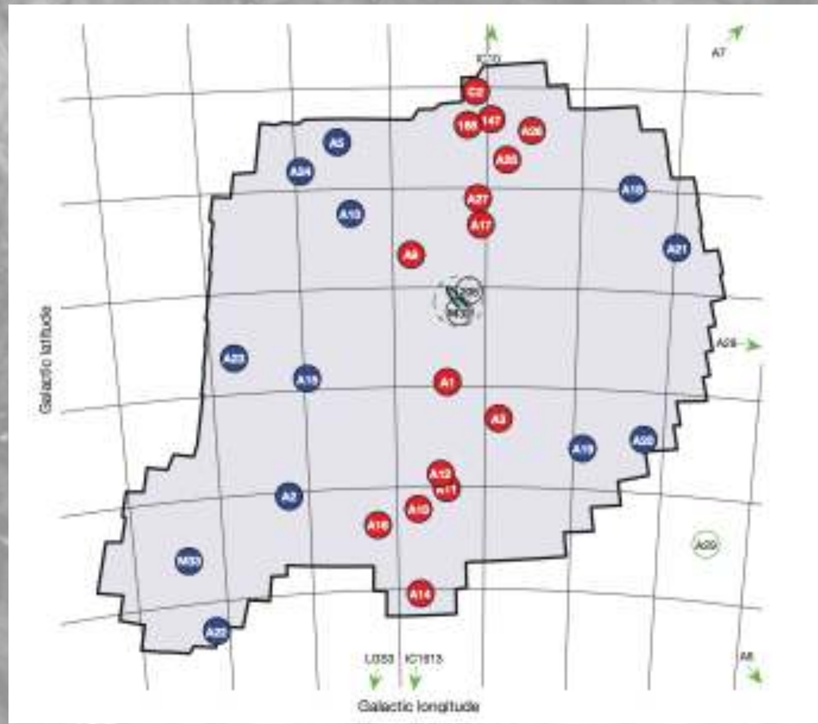

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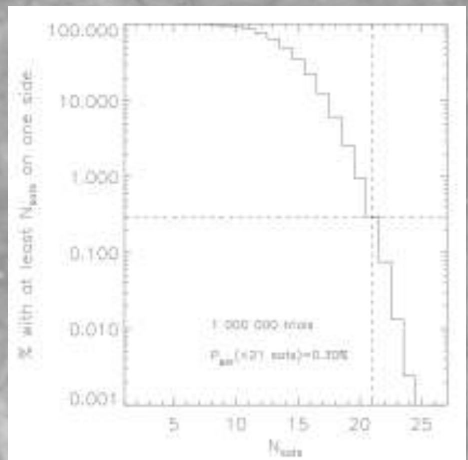
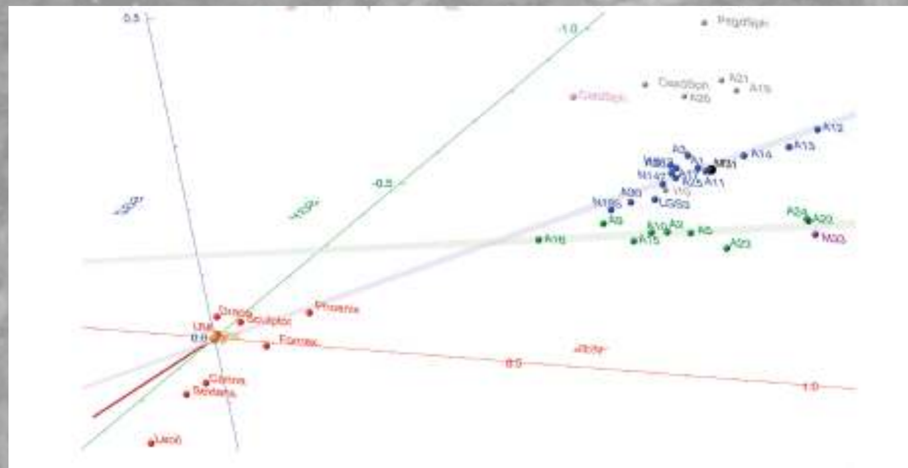
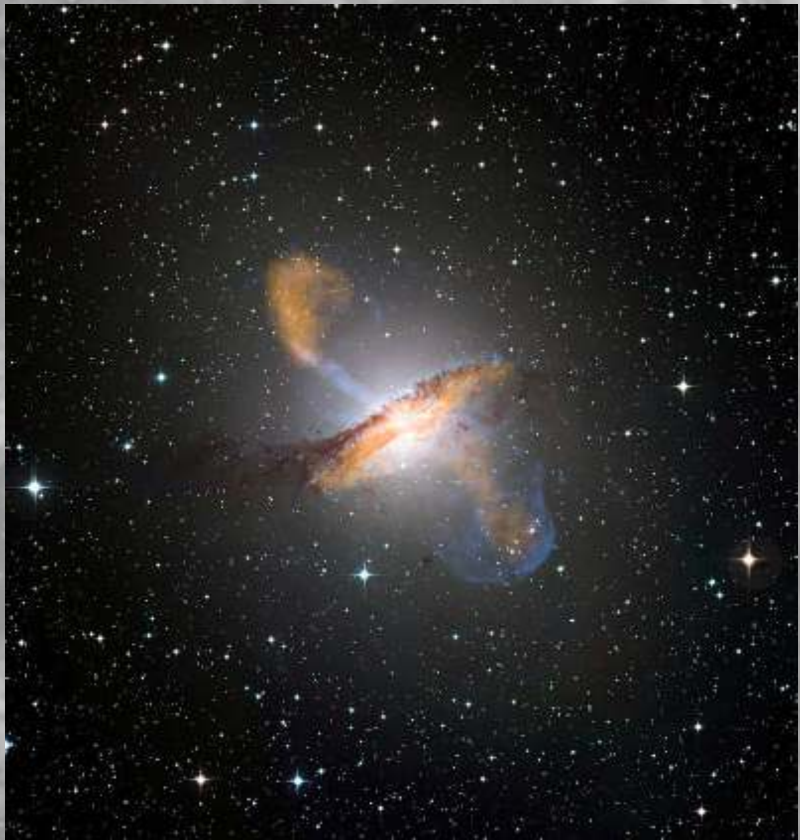




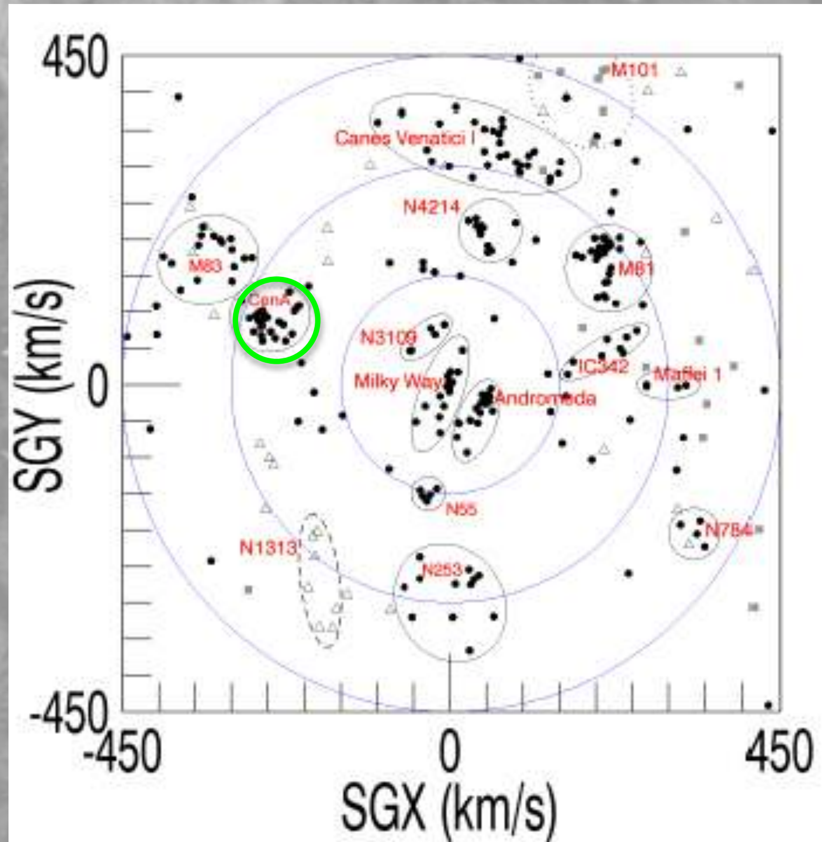
Shaya & Tully 2013

See also Pawlowski et al

Where else can we hope to find planes of satellites?



ESO image



Courtois et al (2013)

Centaurus A, ~8x10^{12} M_{sol}, 3.8Mpc

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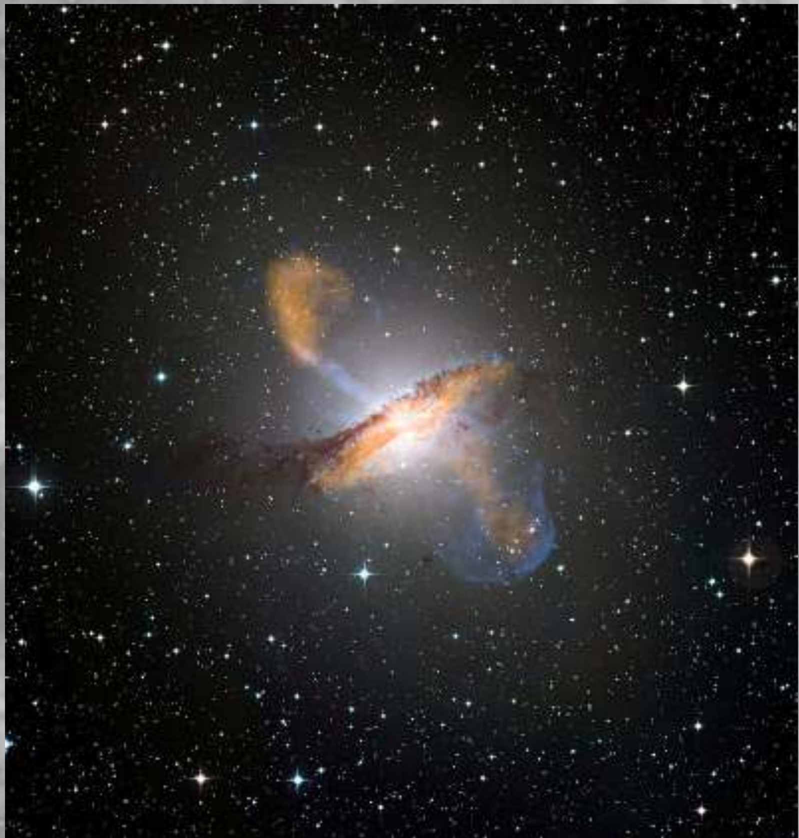
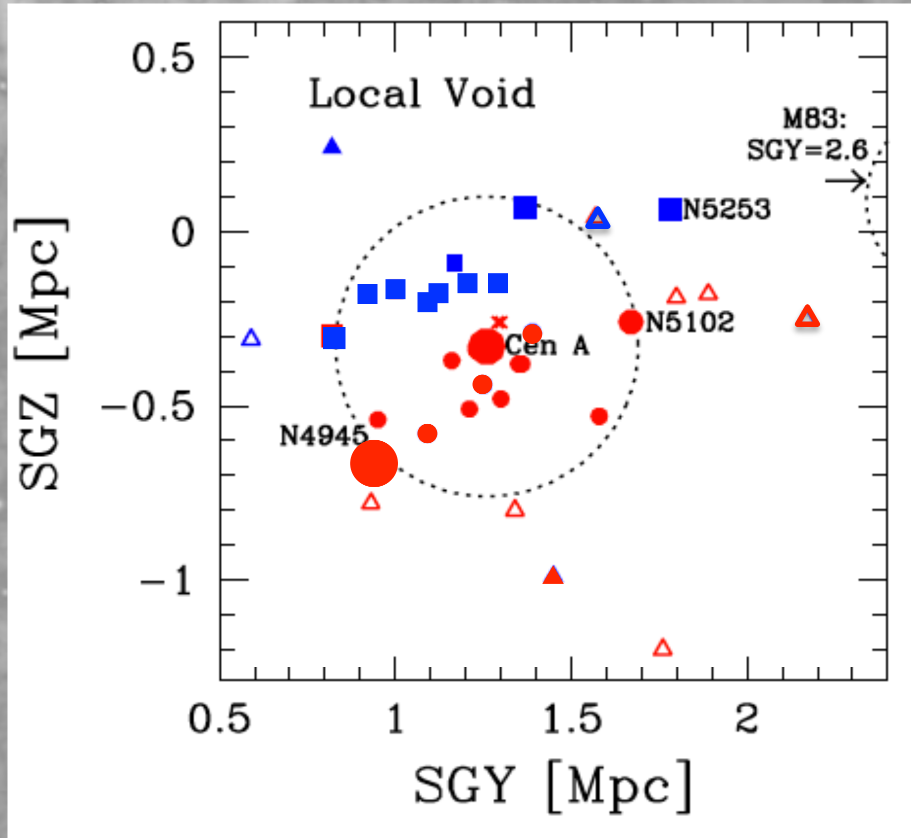
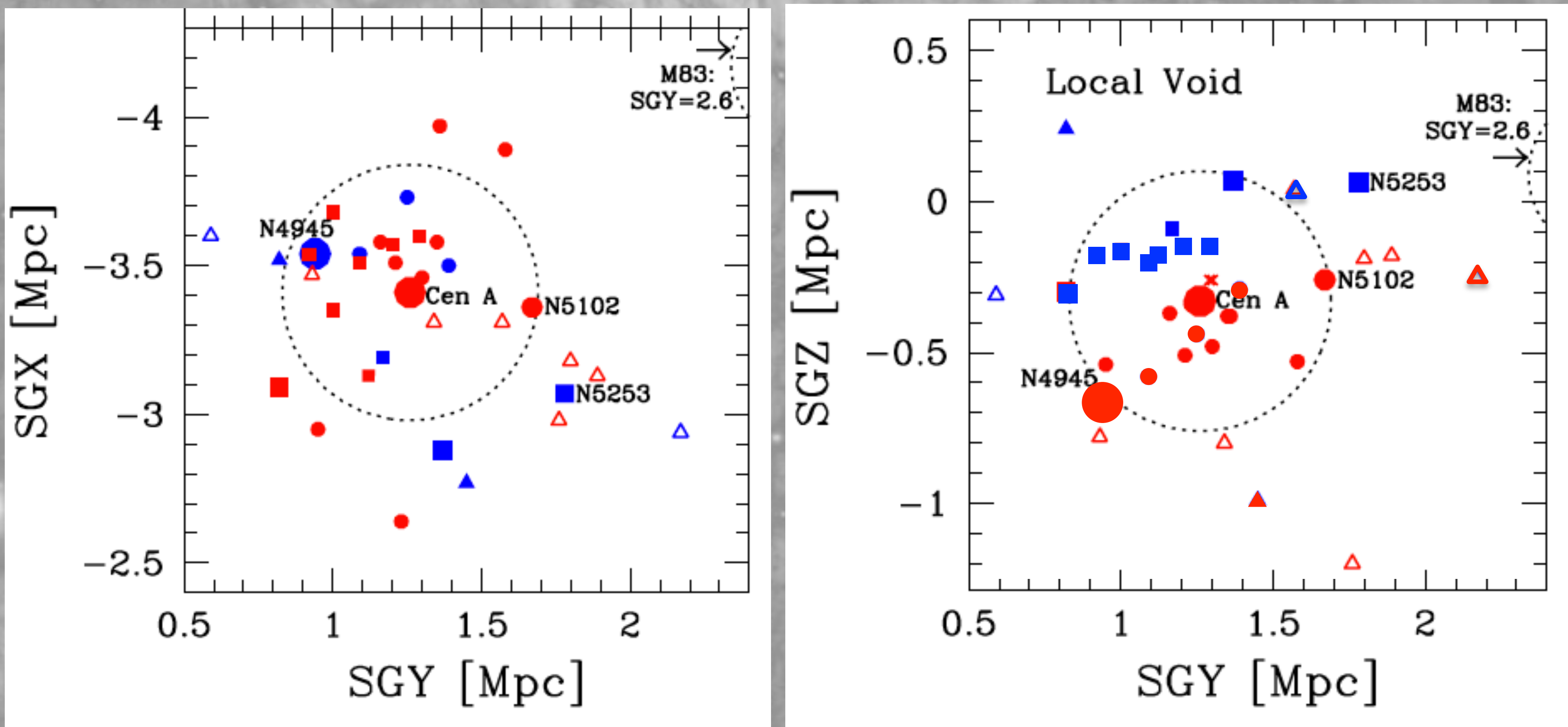




Tully, NL *et al* 2015

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

Centaurus A Planes

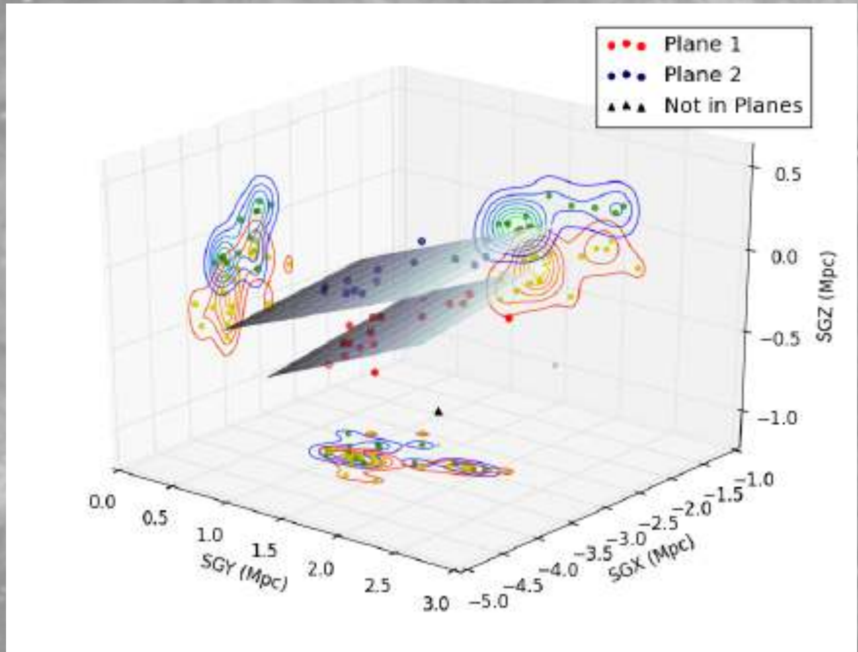


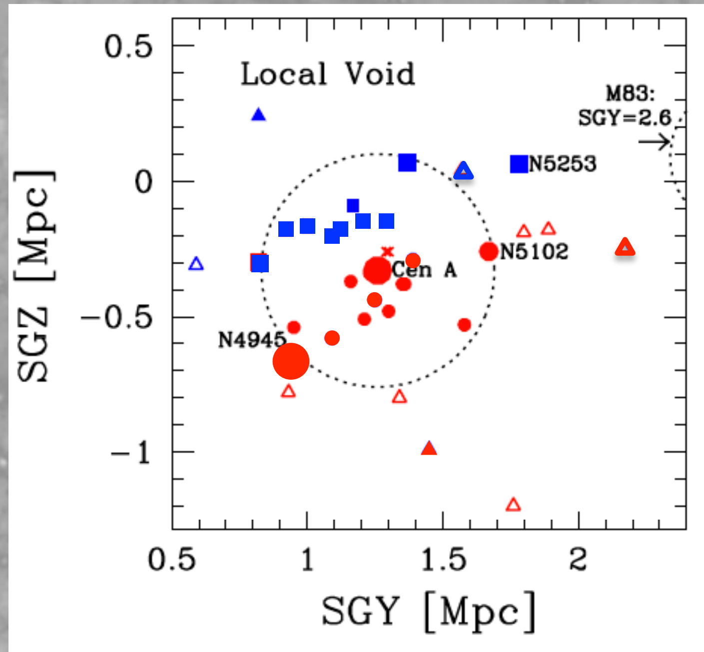
Tully, NL *et al* (2015)

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)

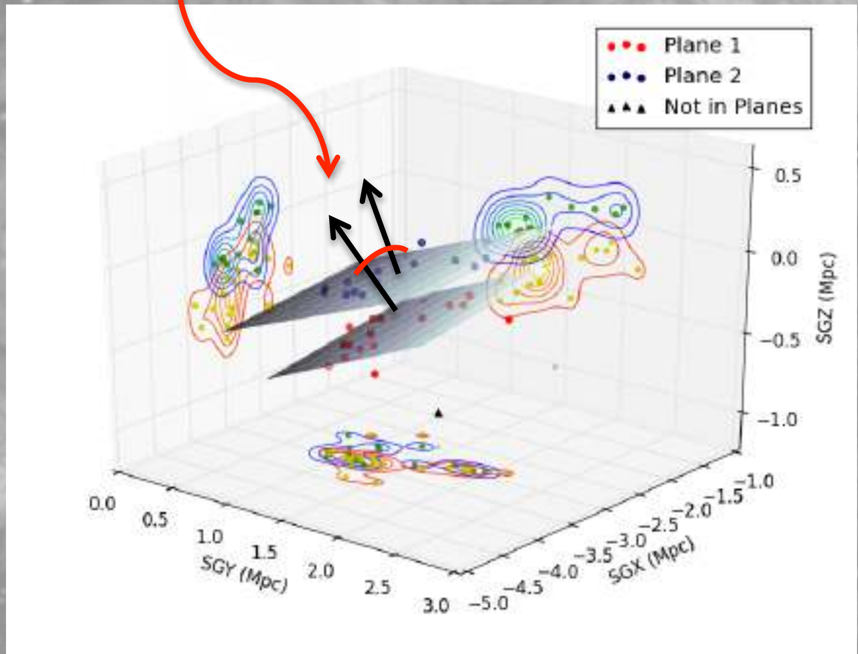
36 galaxies in total, 29 with distances

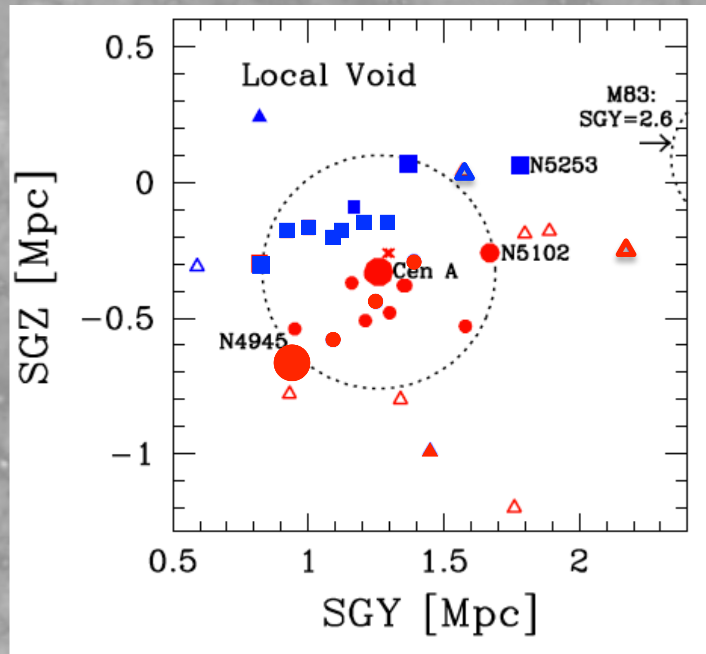
16 in plane 1
11 in plane 2
2 not in either

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

Centaurus A Planes

7 deg





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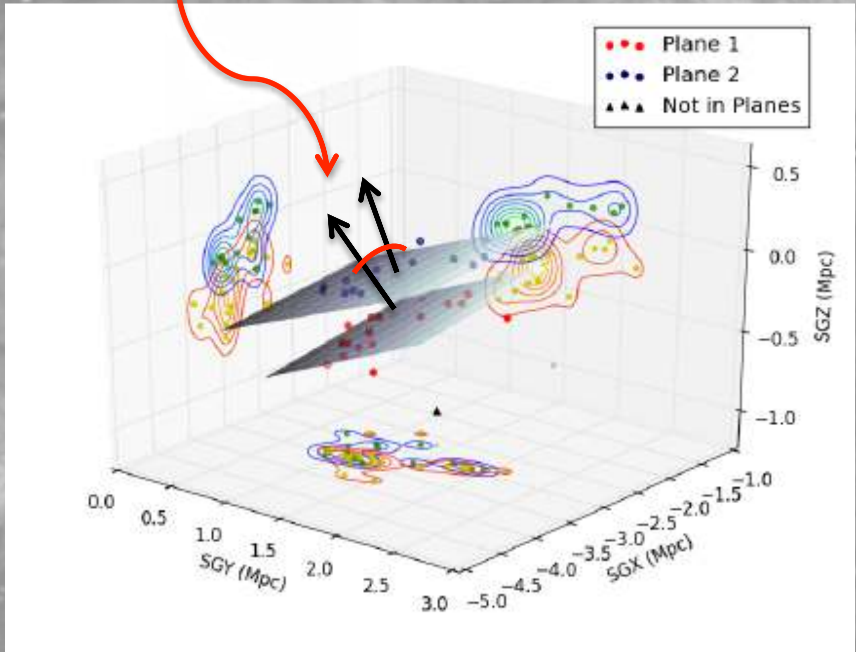
Distance errors are 5% along the line of sight

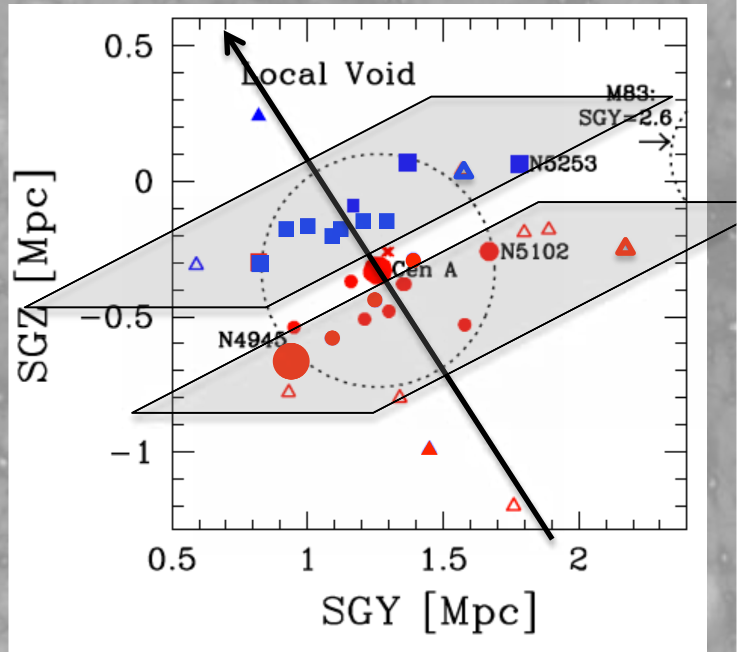
3 σ accuracy of the $n_{\rm CenA}$ is ~ ±2 degrees

Tully, NL *et al* (2015)

Centaurus A Planes

7 deg





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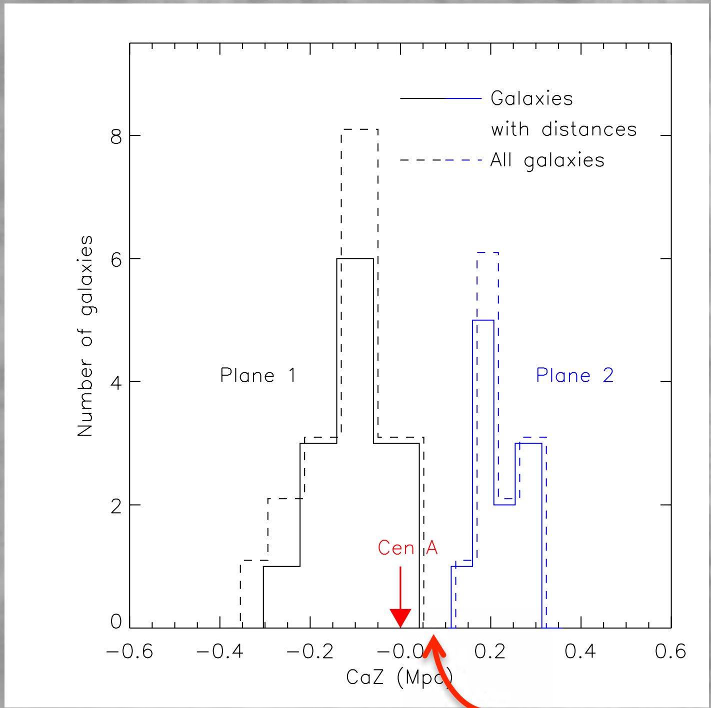
Can fit a single normal to the two parallel planes

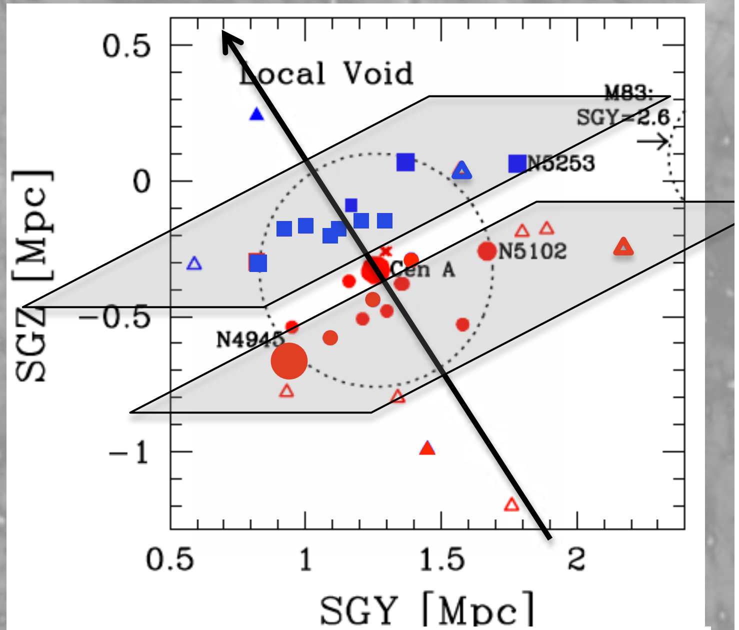
Tully, NL *et al* (2015)

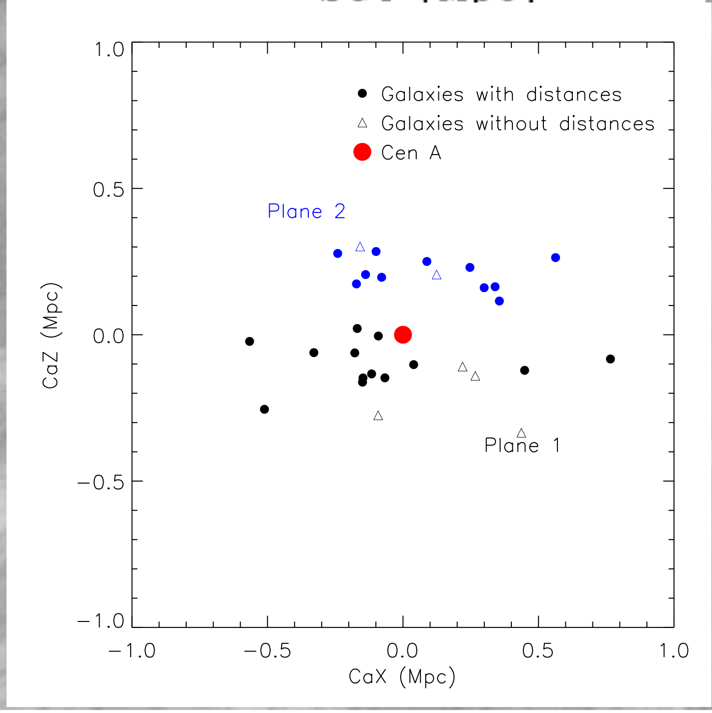
Centaurus A Planes



Tully, NL *et al* (2015)

Around 100kpc between planes





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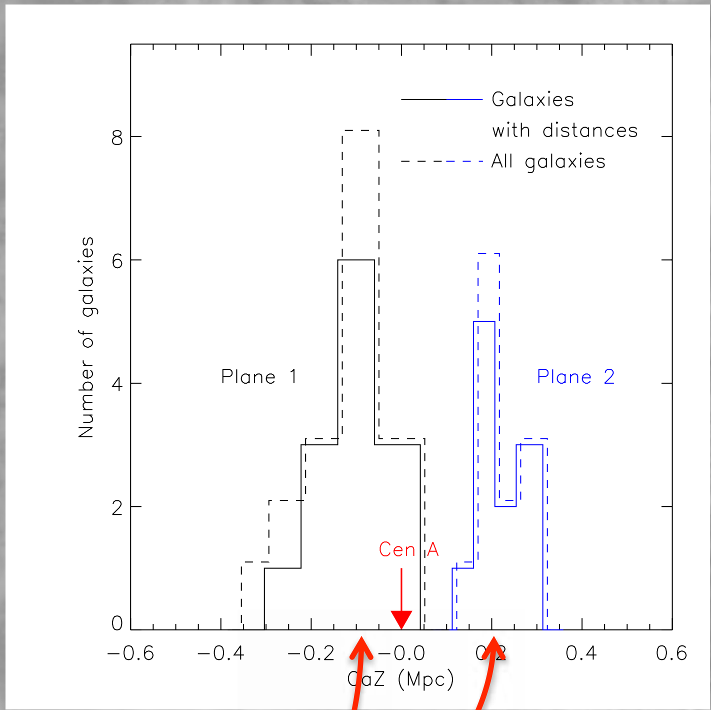
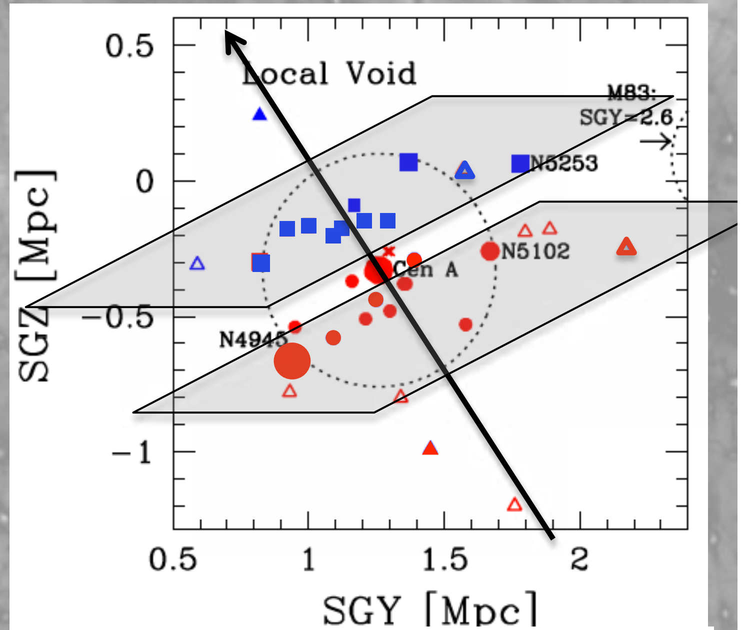
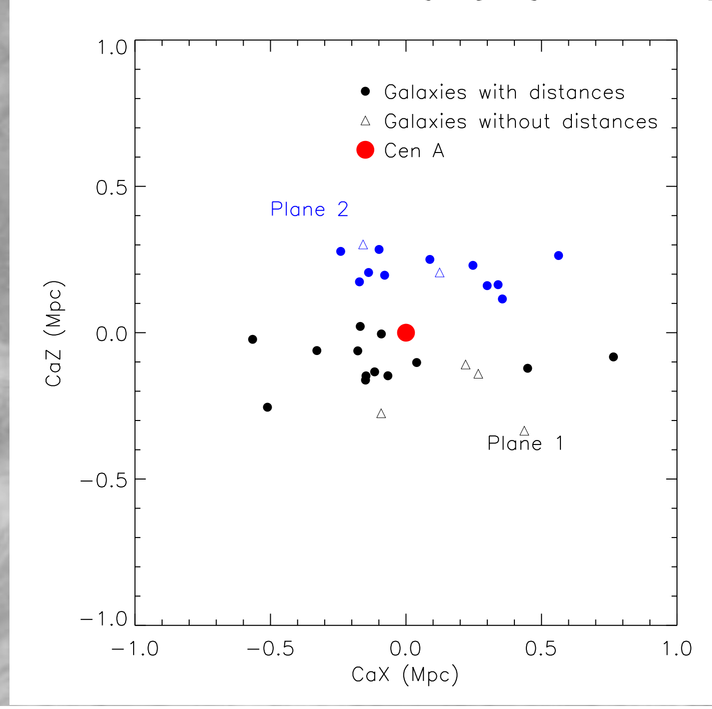


Tully, NL *et al* (2015)

Around 100kpc between planes

Offset between the means is around 300kpc





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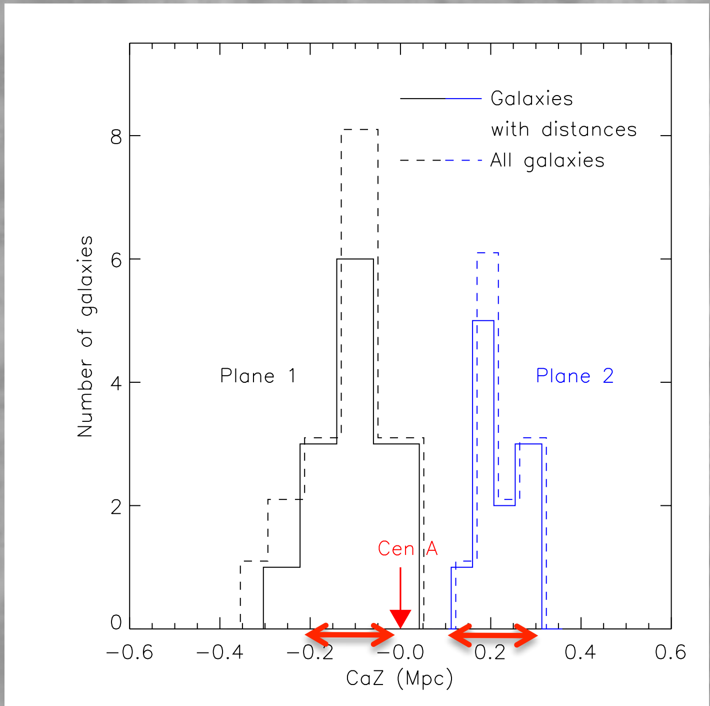

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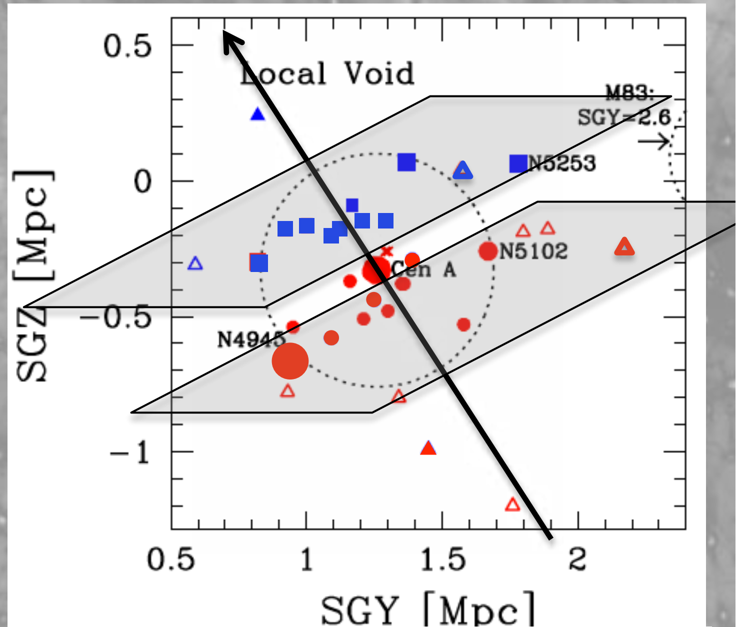
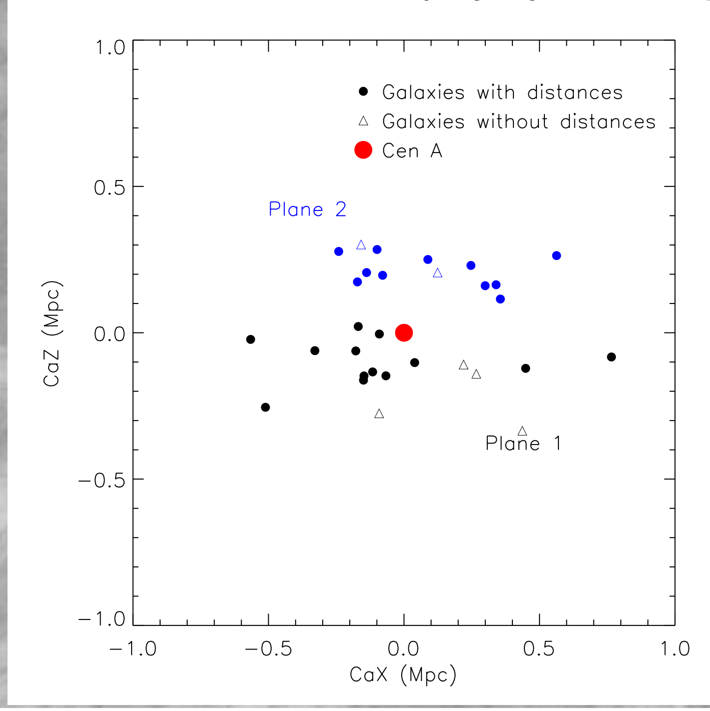


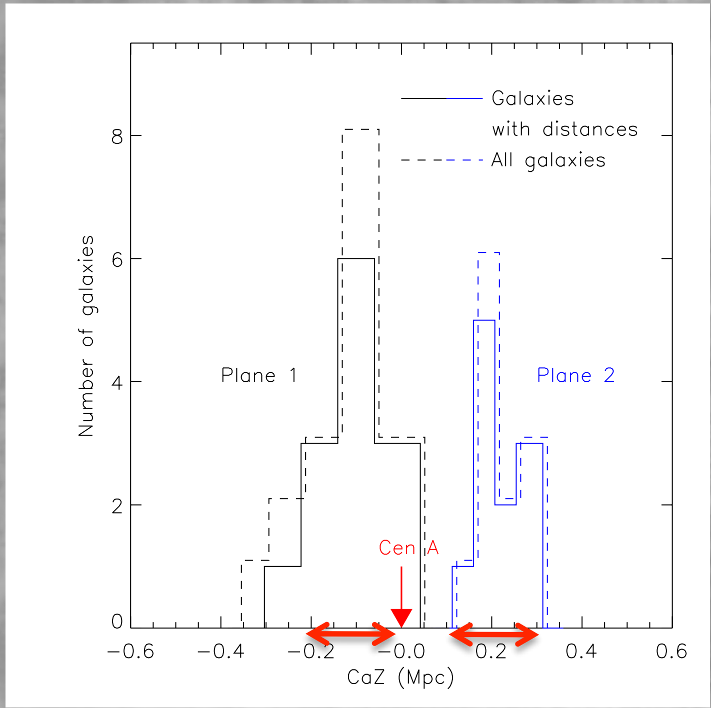


Around 100kpc between planes

Offset between the means is around 300kpc

Each plane is around 50-60kpc in rms

Centaurus A Planes



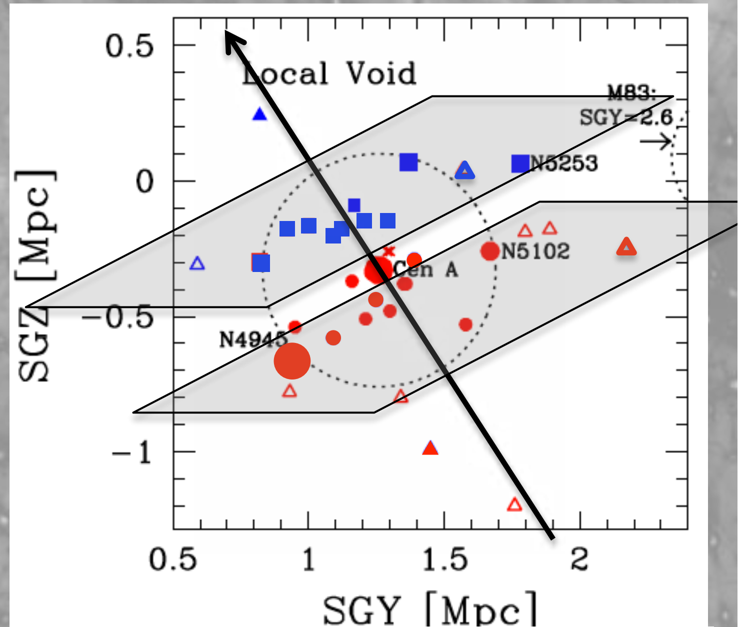
Tully, NL *et al* (2015)

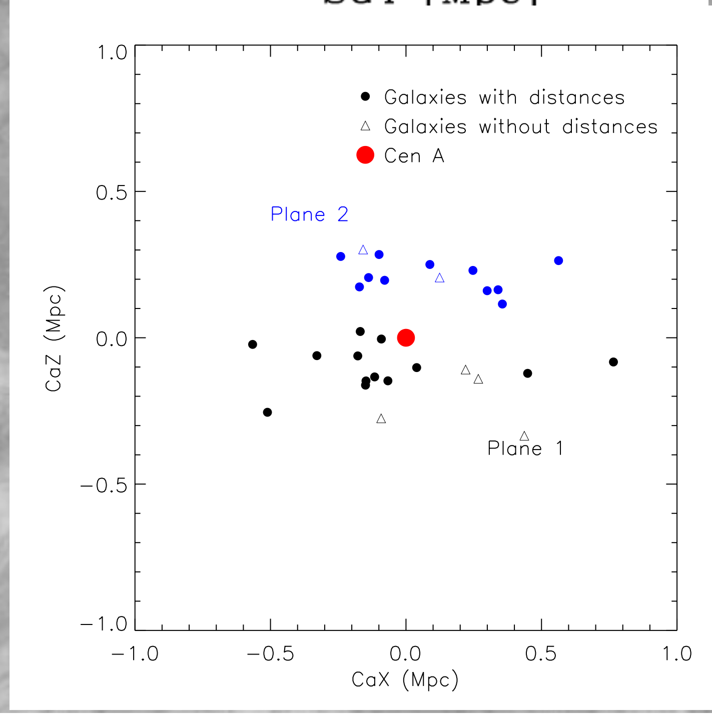
Around 100kpc between planes

Offset between the means is around 300kpc

Each plane is around 50-60kpc in rms

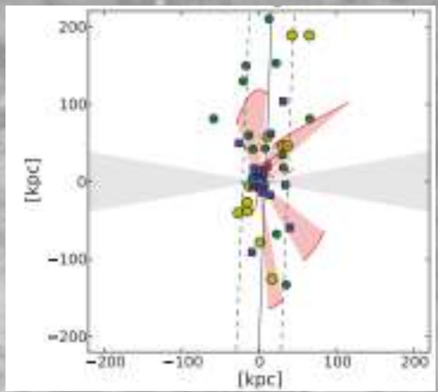
Probability of finding such set ups “by chance” are exceedingly low ~3 out of 10,000



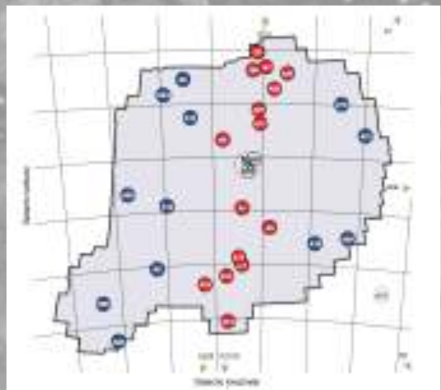


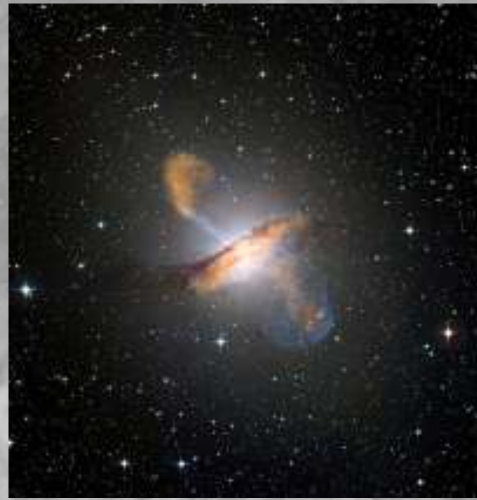
Summary of Local Volume Planes:

One plane
Co-rotating
c/*a*~0.15

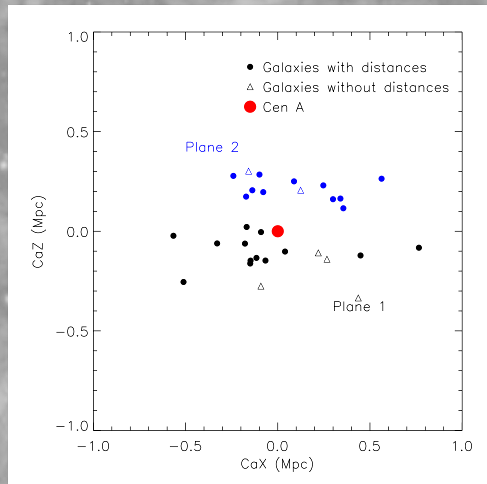


Two parallel planes
One co-rotating
c/*a*~0.17

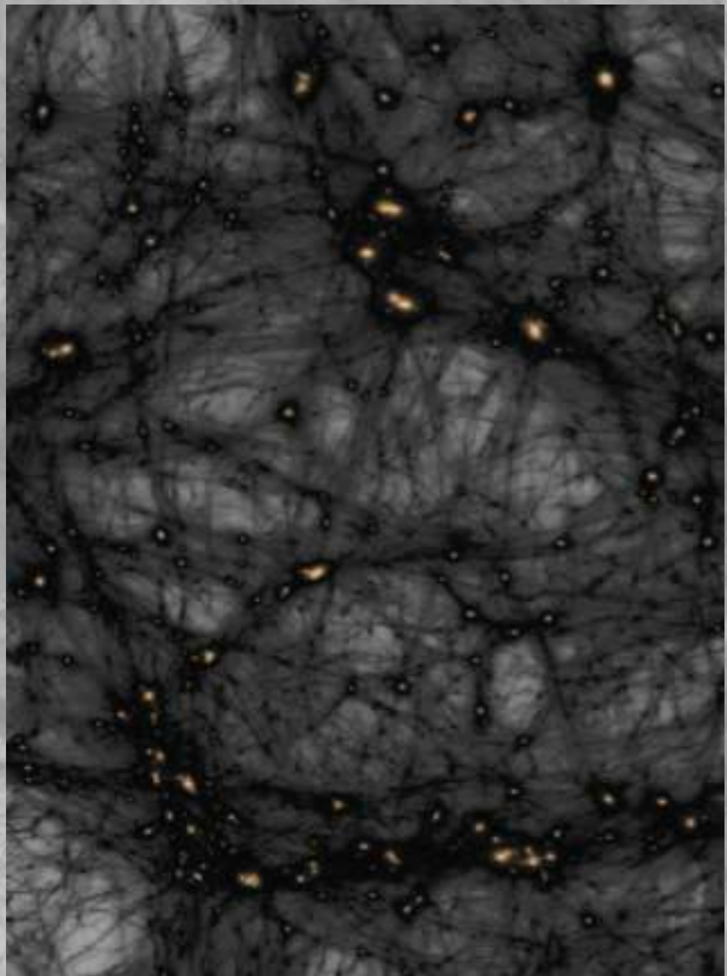




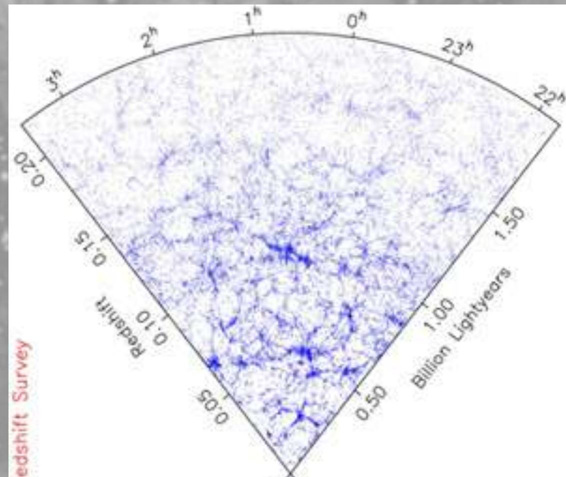
Two parallel planes
co-rotating?
c/*a*~0.2



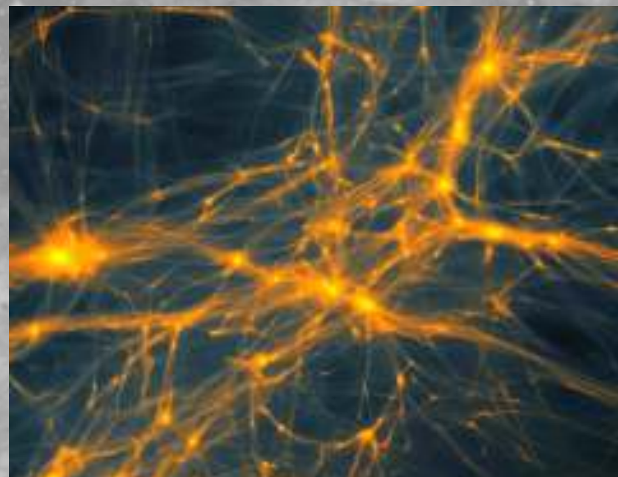
Is the *cosmic web* responsible for these planes of satellite galaxies



Libeskind 2014

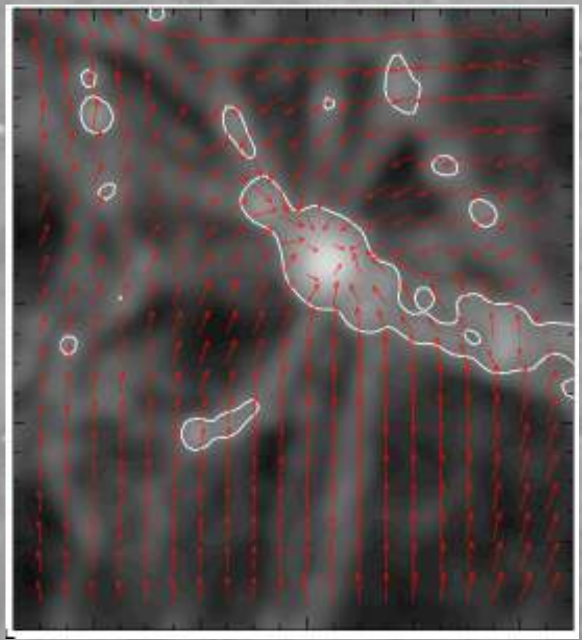


2df GRS



Kahler, Hahn & Abell 2013

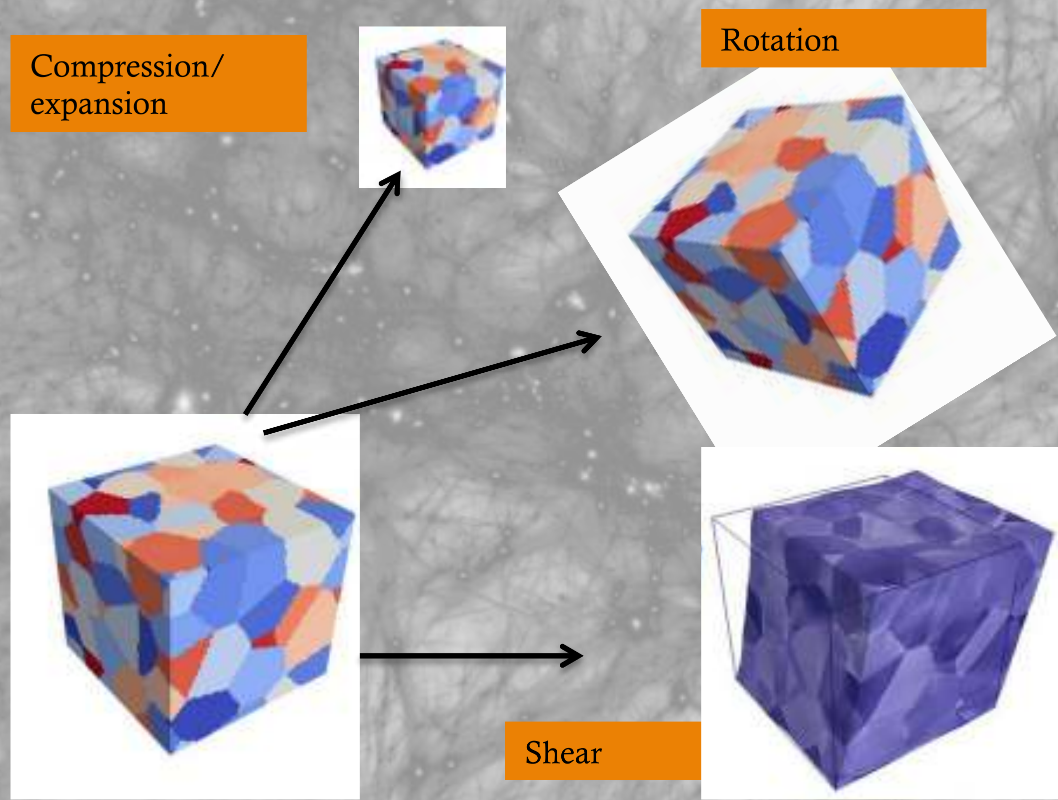
Velocity Shear Tensor

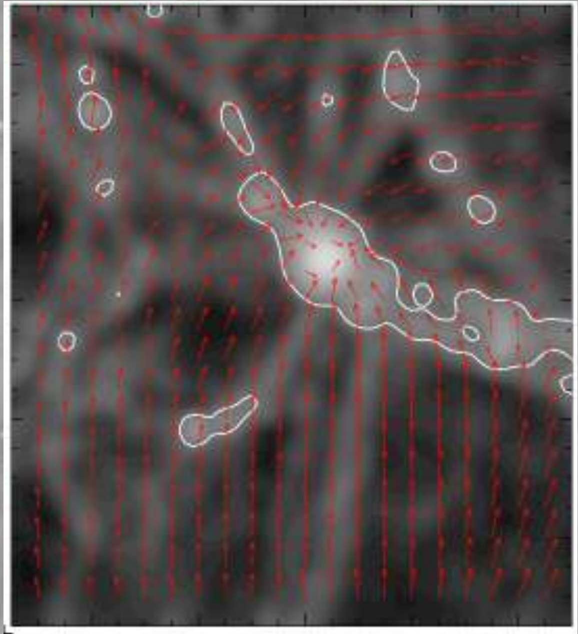


Hoffman et al 2012
Libeskind et al 2012, 2013

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

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





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

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

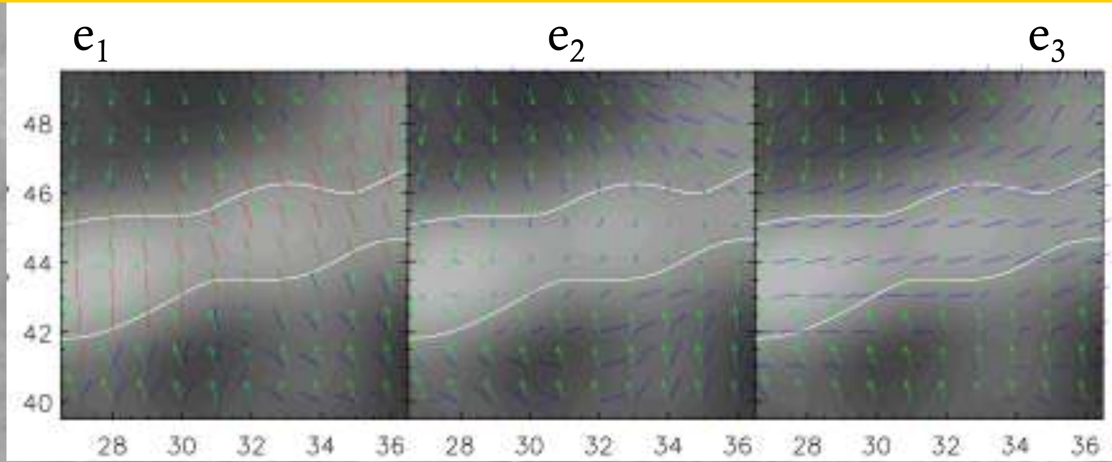
$$\mathbf{S}_{ij} = \boldsymbol{\Sigma}_{ij} + \boldsymbol{\Omega}_{ij}$$

Symmetric part is the "Shear" tensor + Divergence

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

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

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

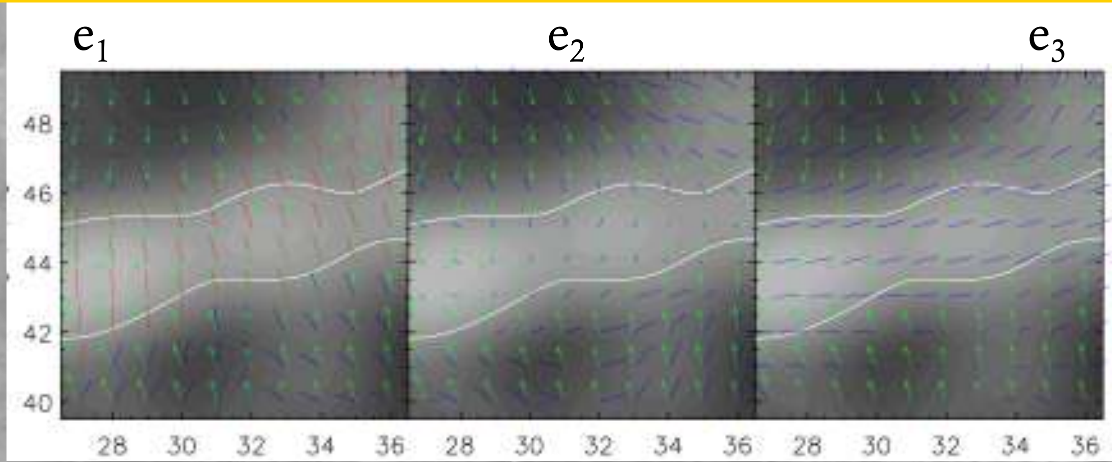


Axis of fastest collapse
Sheet normal

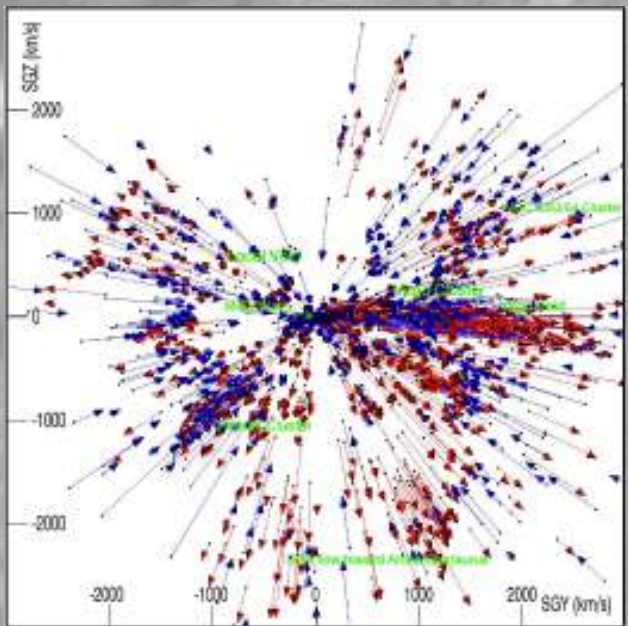
Axis of slowest collapse

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

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

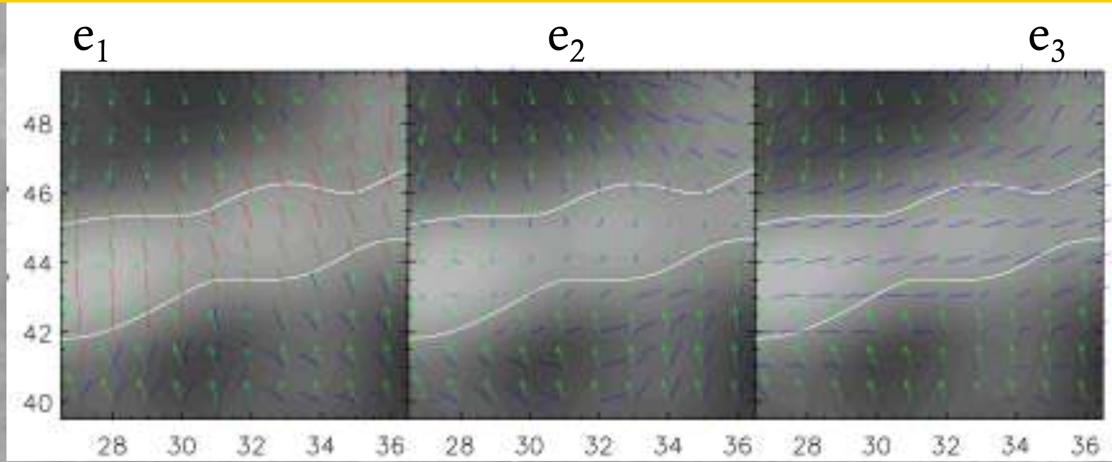


radial peculiar velocity



Courtois *et al* 2013

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



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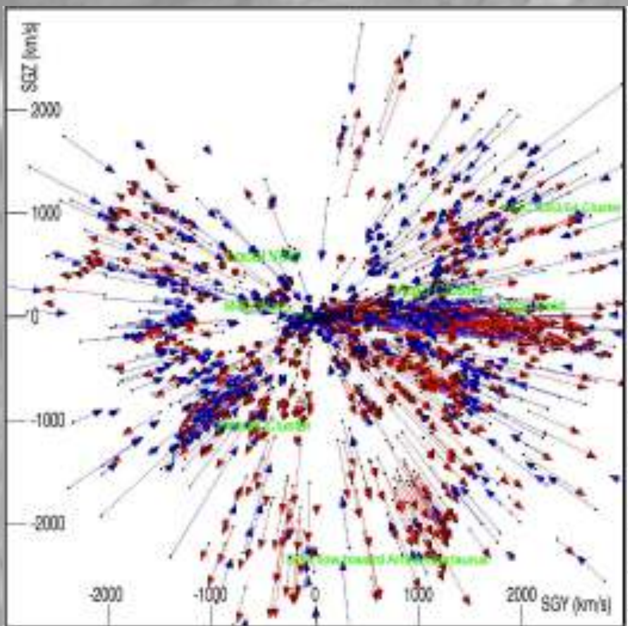
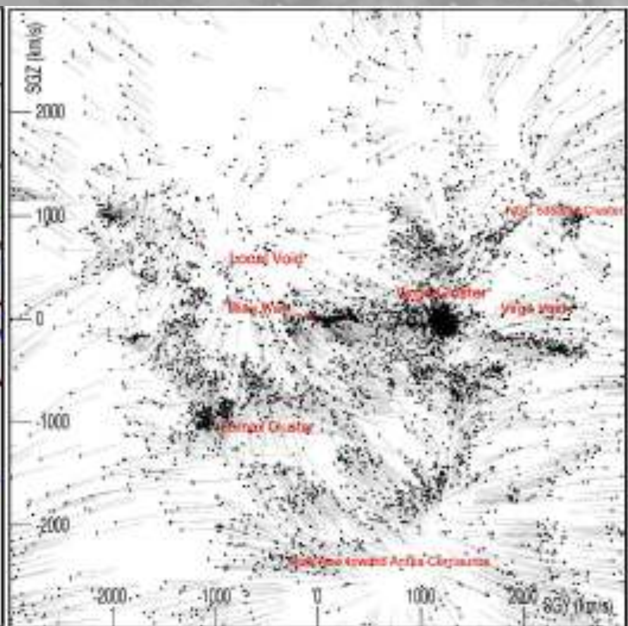
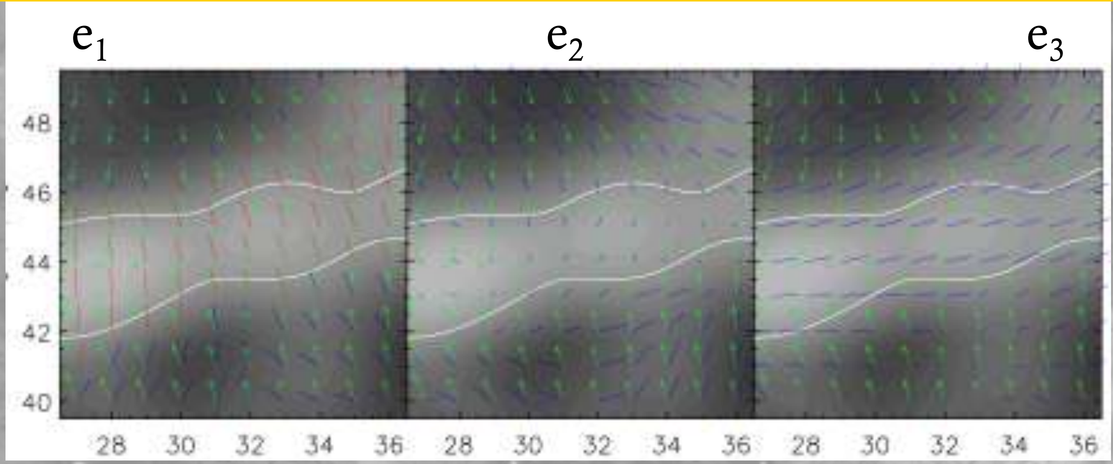


reconstructed 3D peculiar velocity

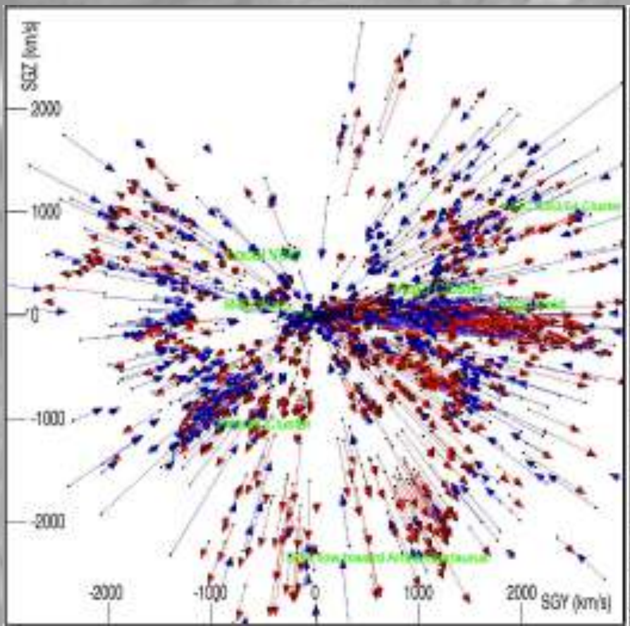


Courtois *et al* 2013

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



radial peculiar velocity



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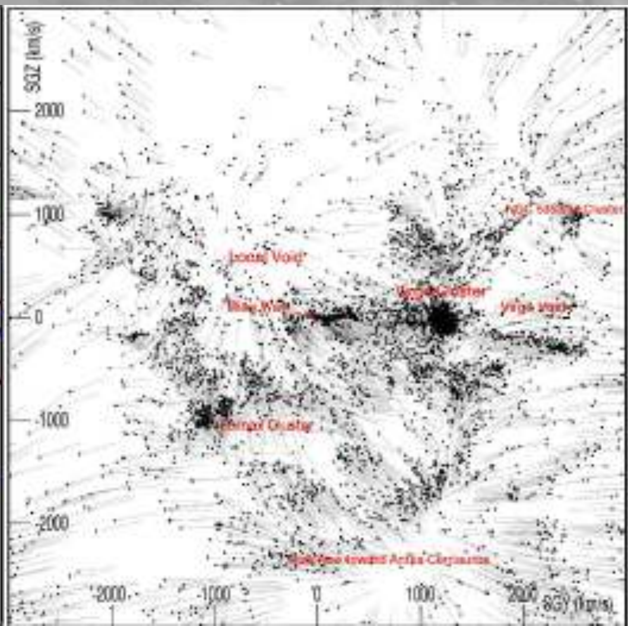
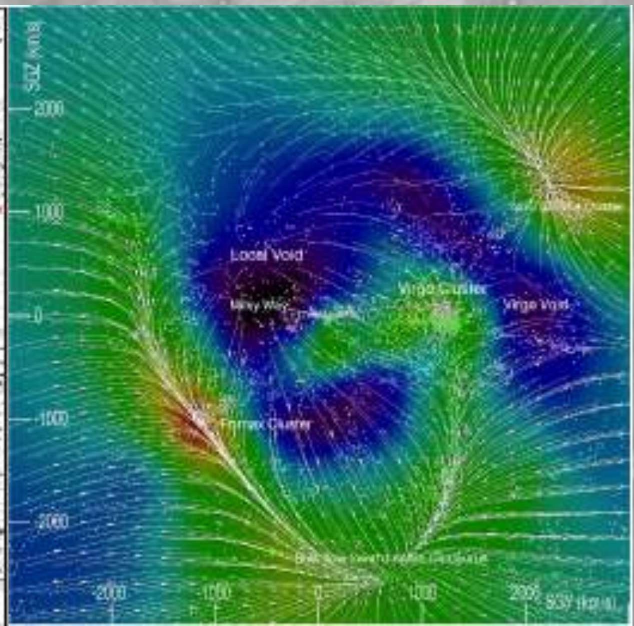
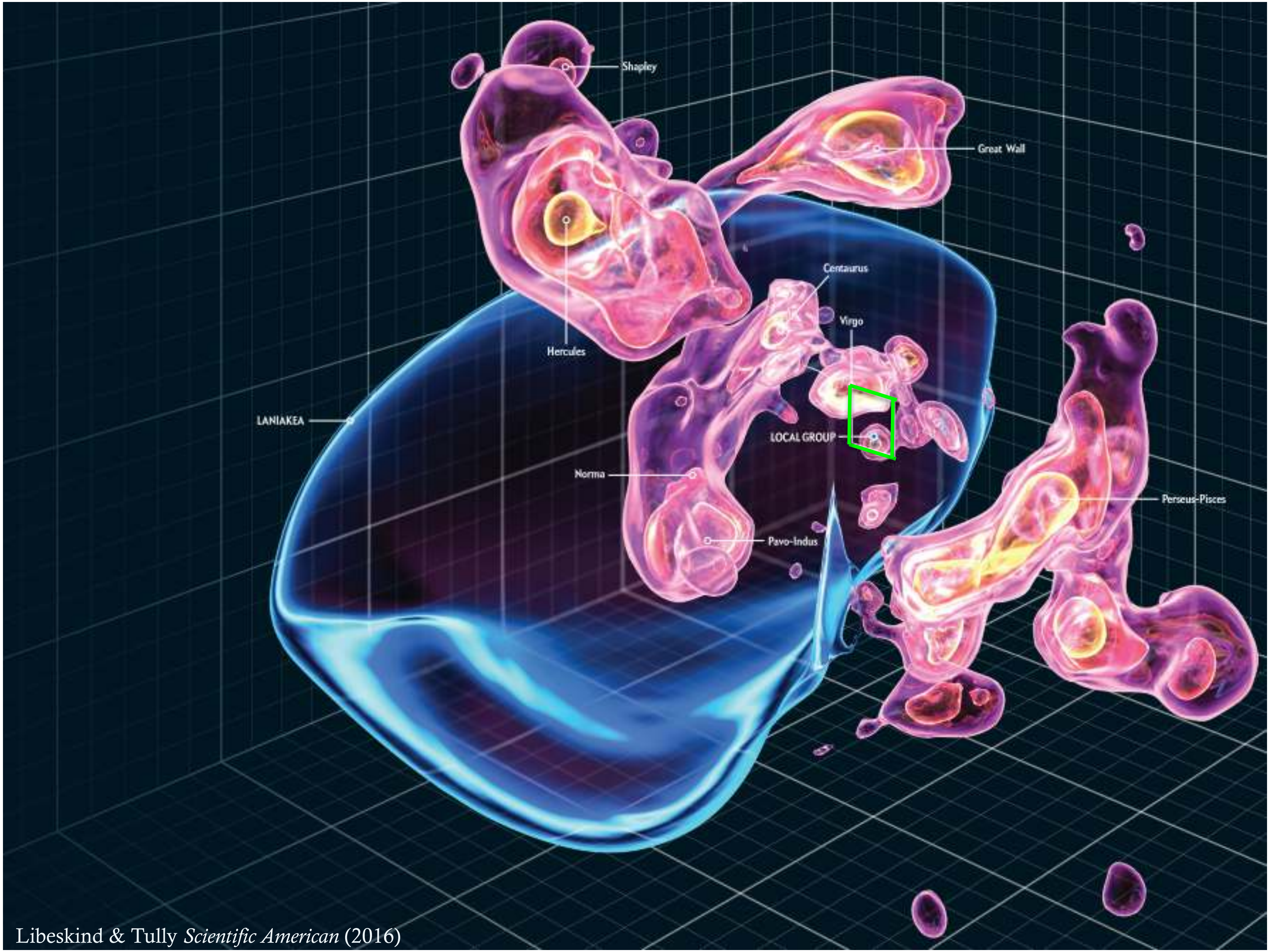


Corresponding 3D density field



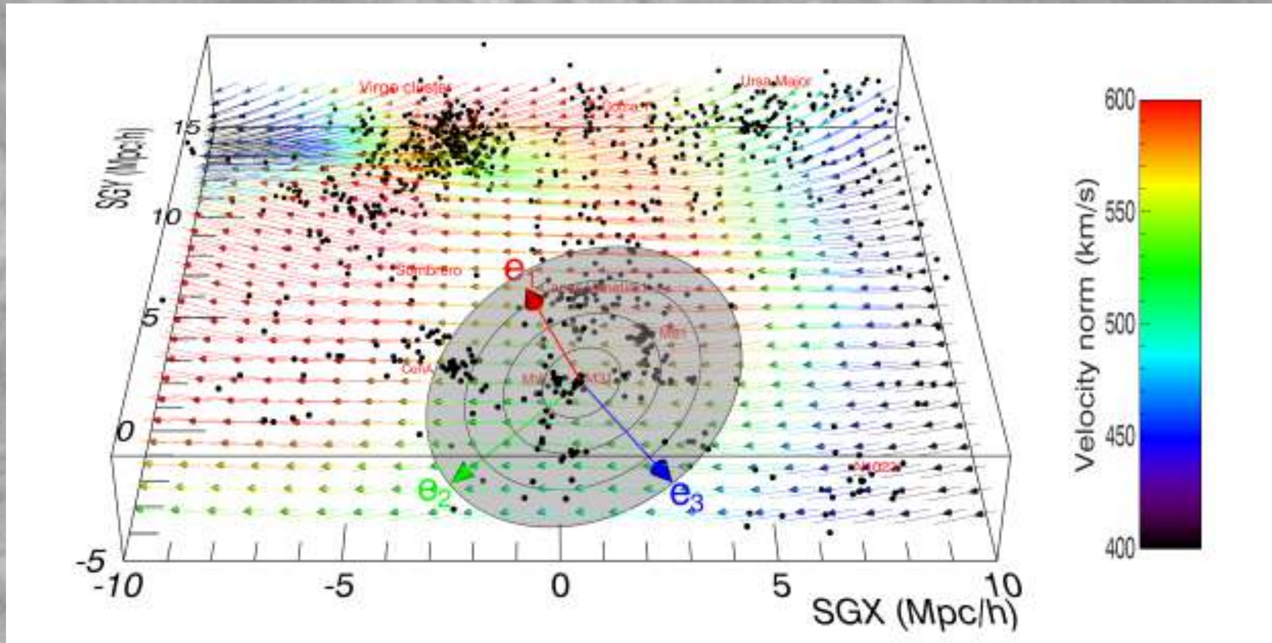
Courtois *et al* 2013

Libeskind & Tully *Scientific American* (2016)



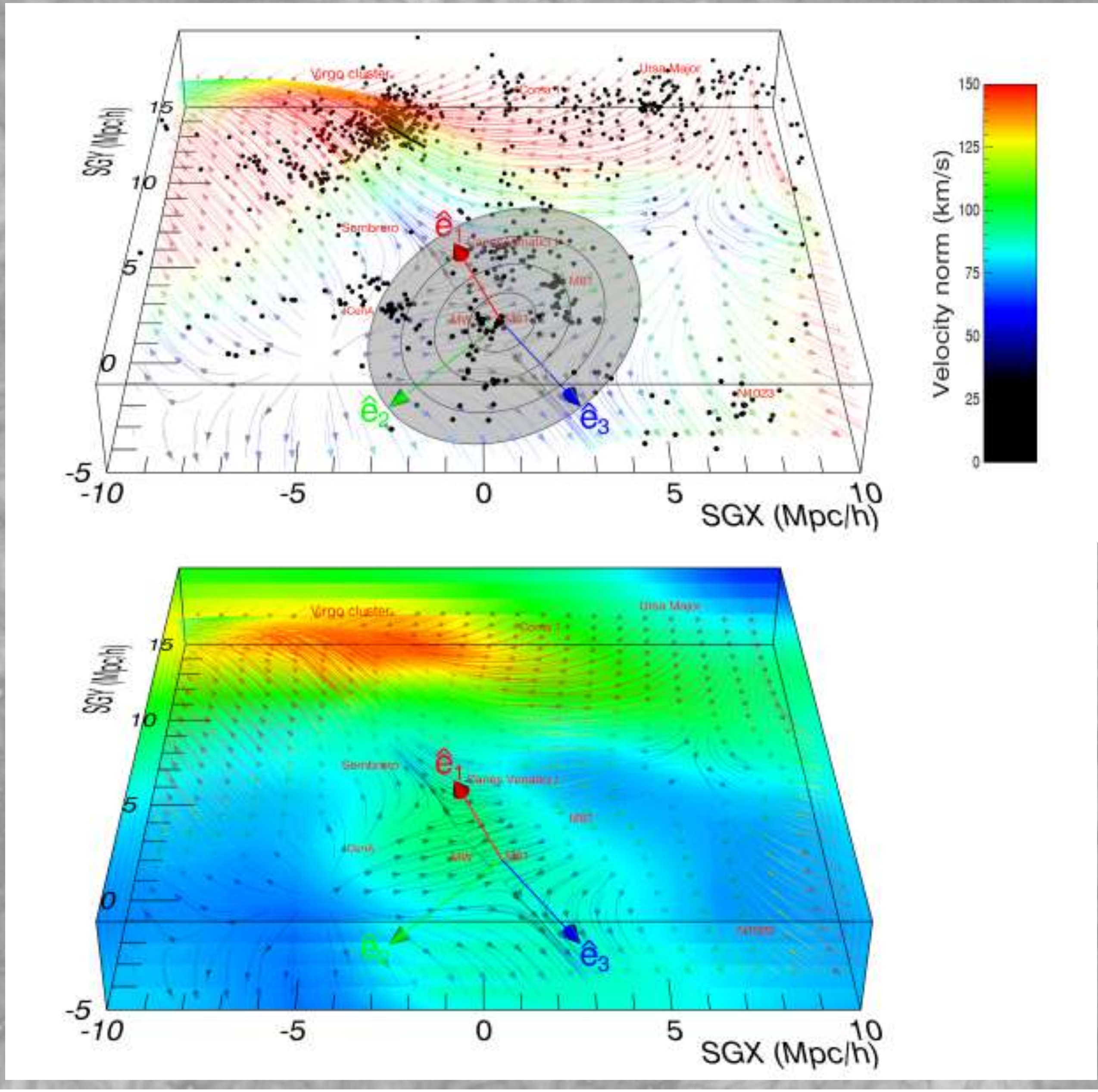
Libeskind & Tully *Scientific American* (2016)

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



Libeskind *et al* 2015

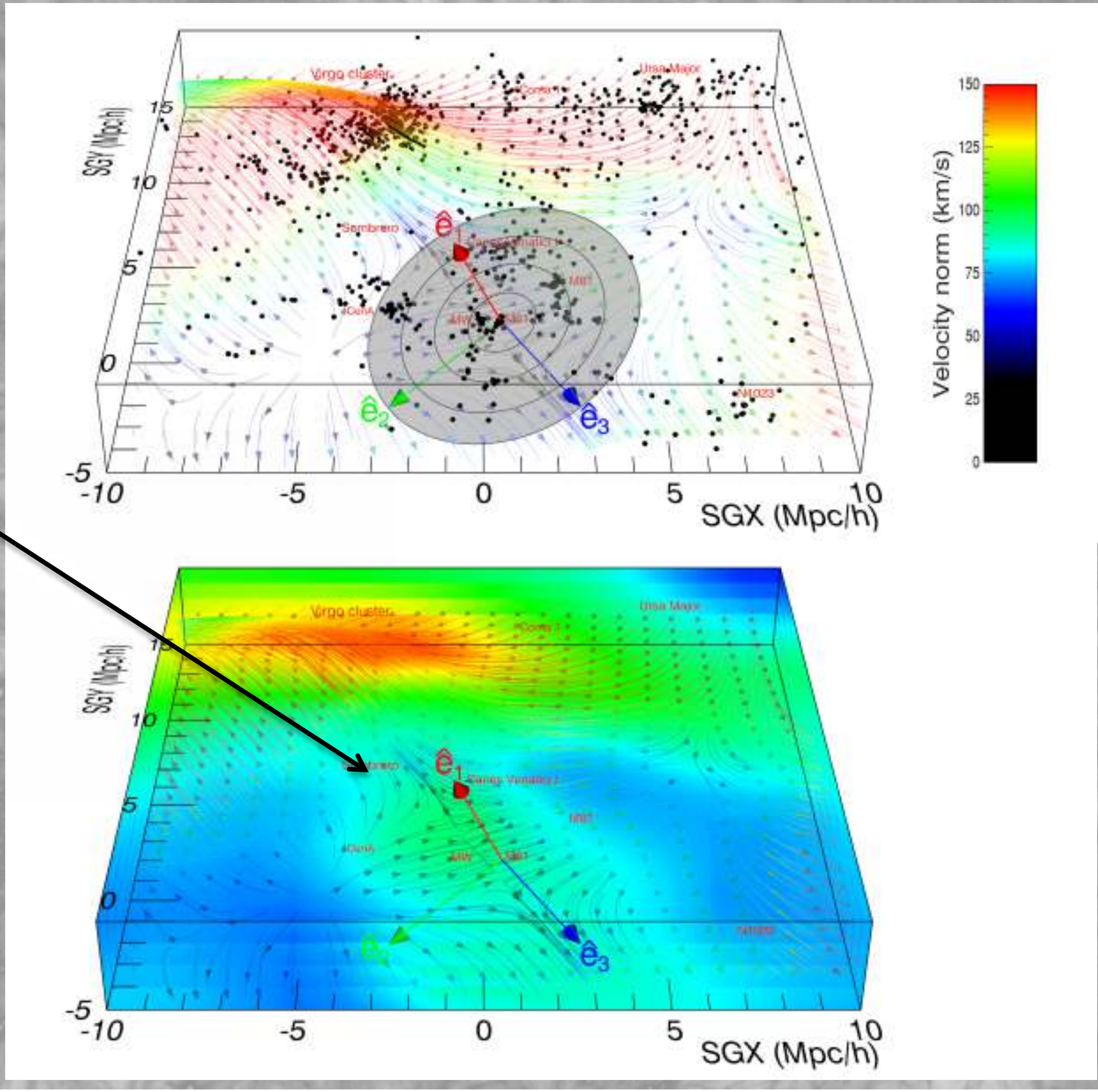
“Local” velocity field, from cosmic-flows-2



Libeskind *et al* 2015

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

“Local Filament” stretched by Virgo

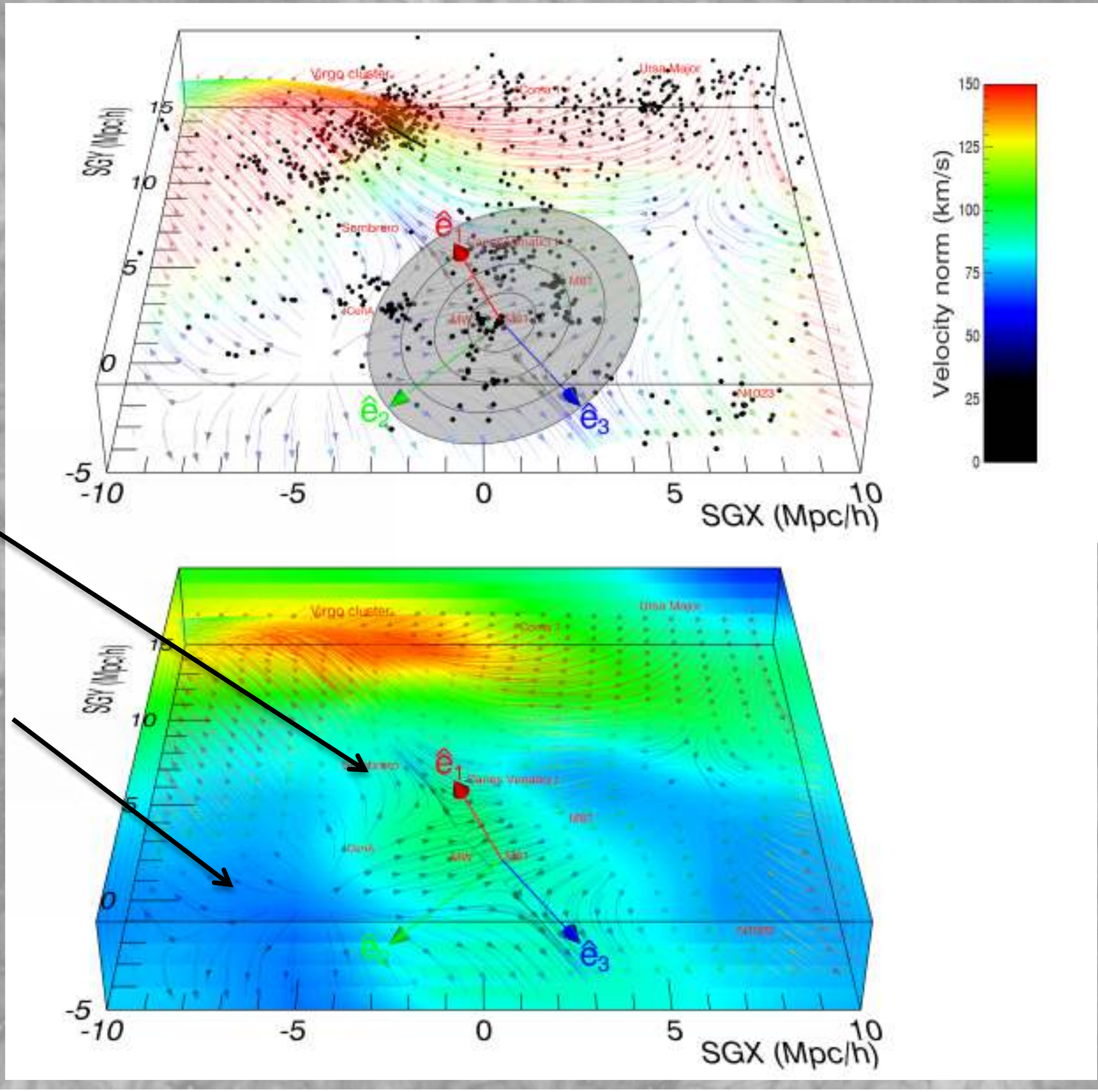


Libeskind *et al* 2015

"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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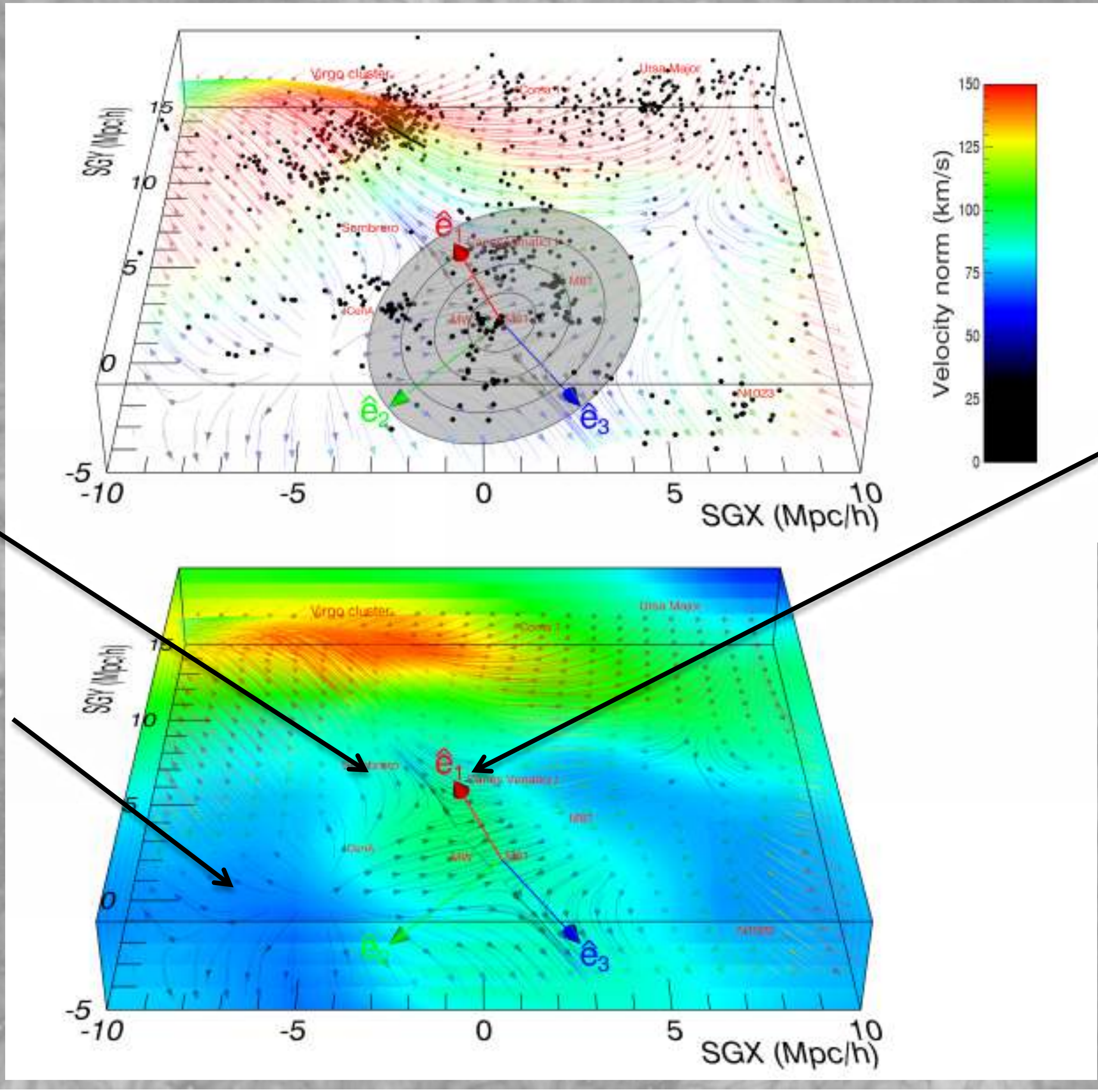

“Local Filament” stretched by Virgo

Laterally squashed by a “mini-repeller”

e_1 sheet normal, points to the local void

Libeskind *et al* 2015

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

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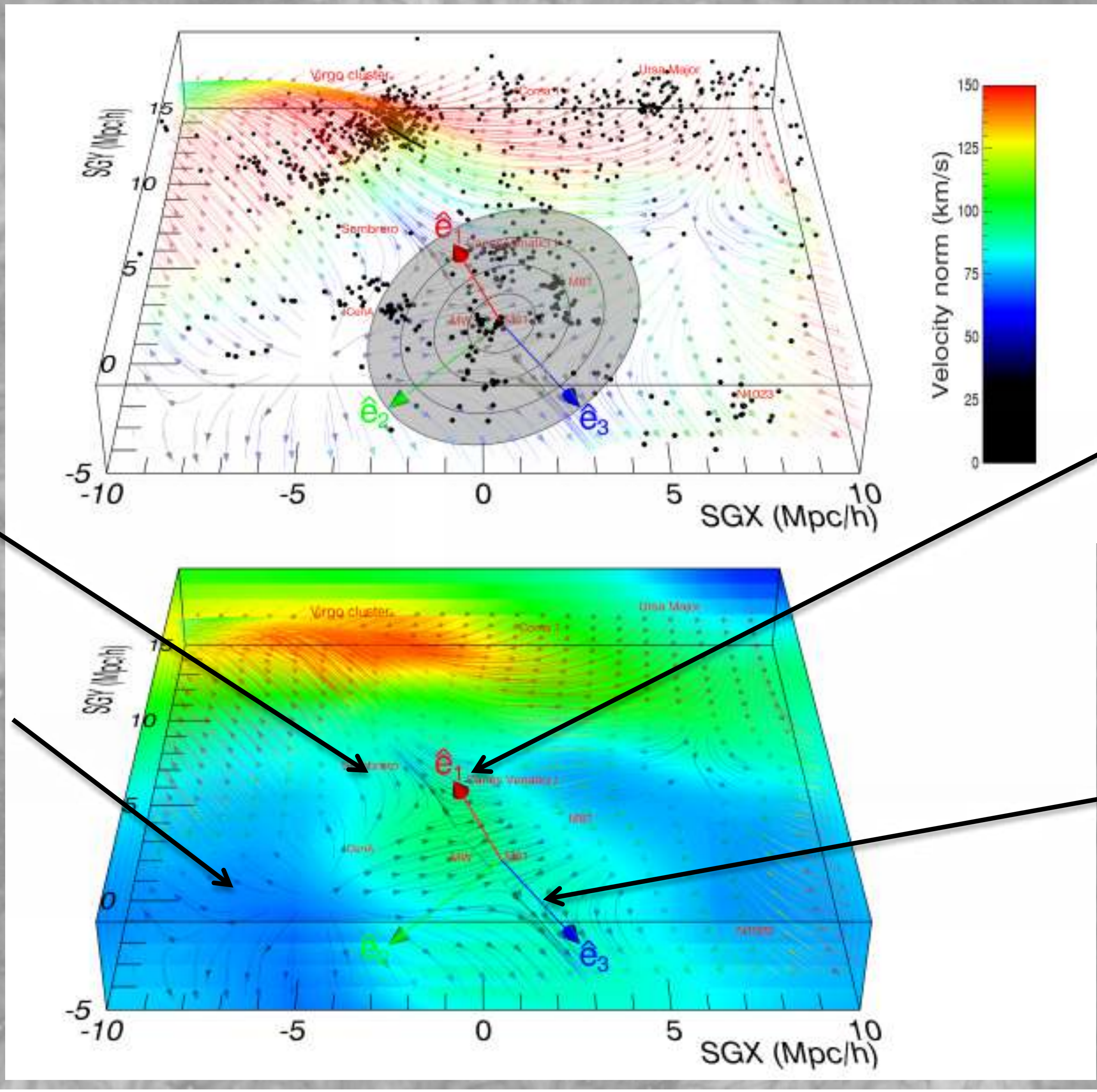
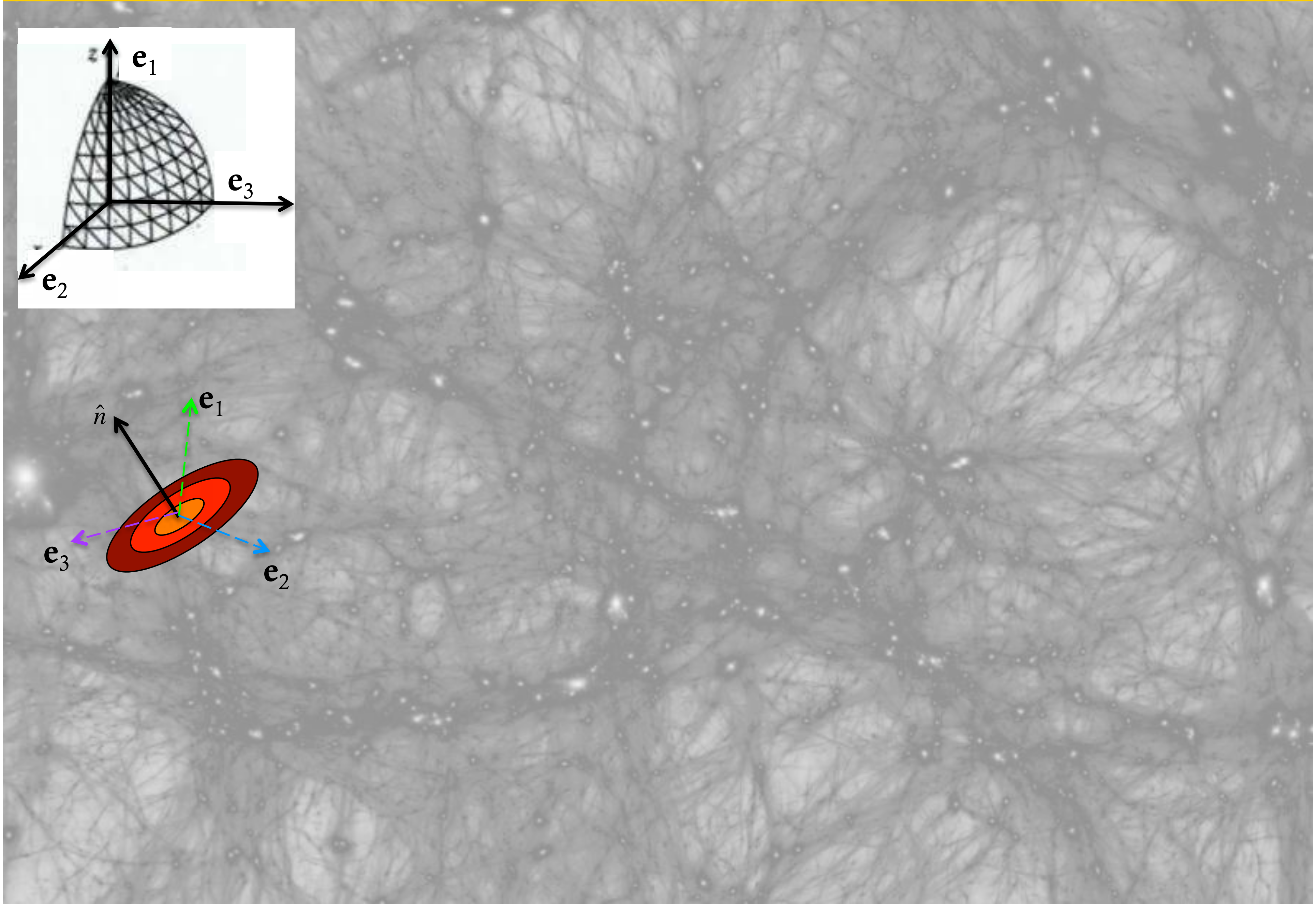


e_1 sheet normal, points to the local void

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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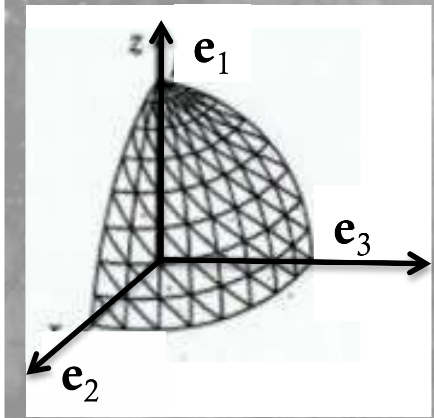

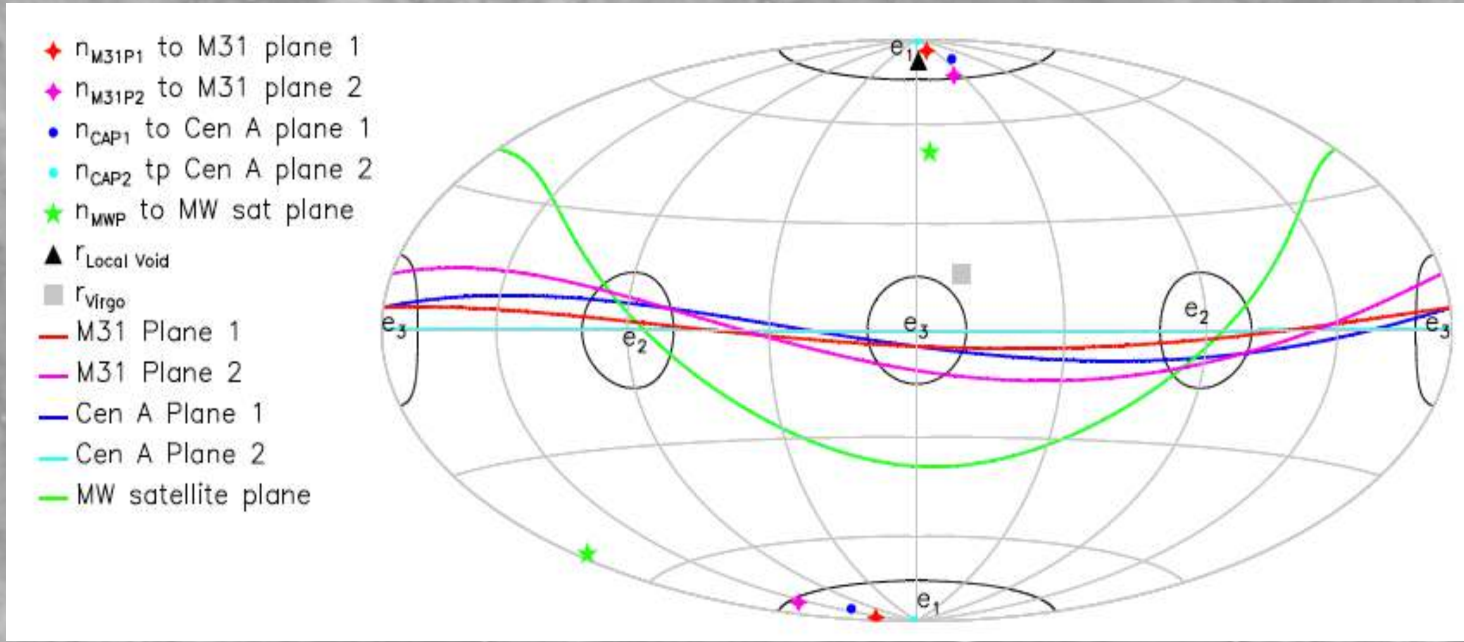

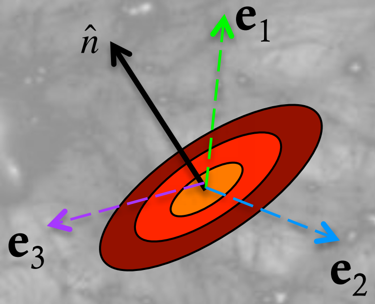

Libeskind *et al* 2015

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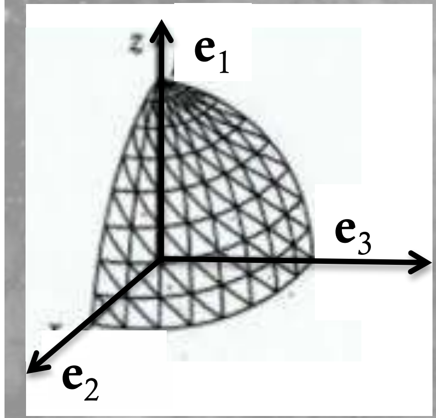

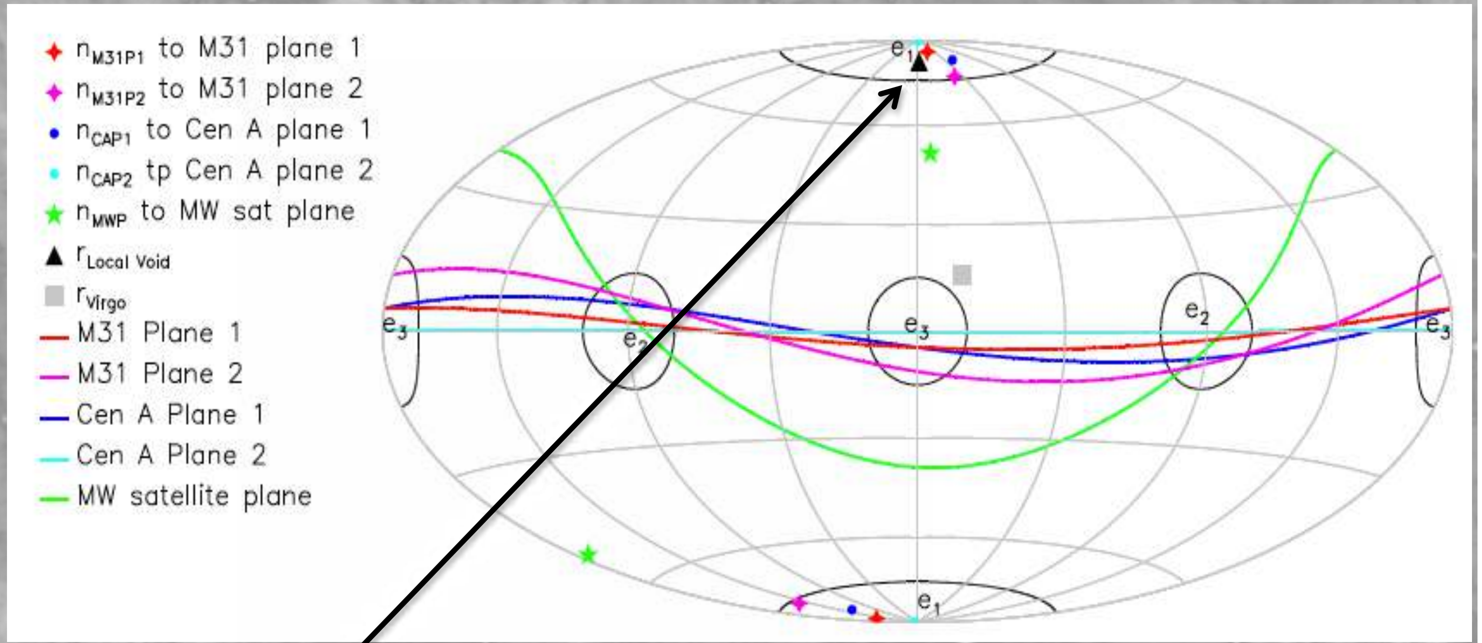

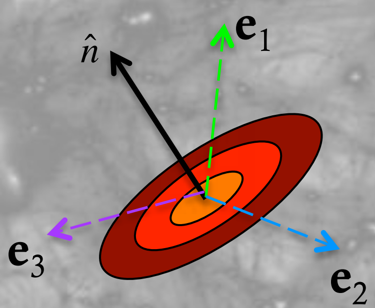

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Libeskind *et al* 2015

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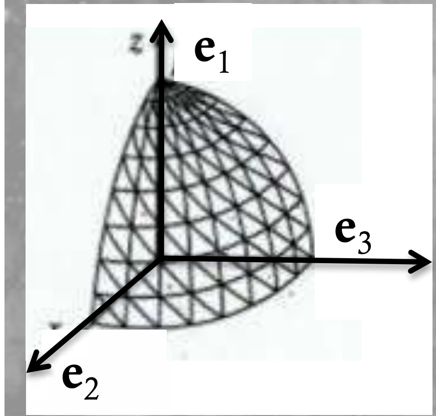

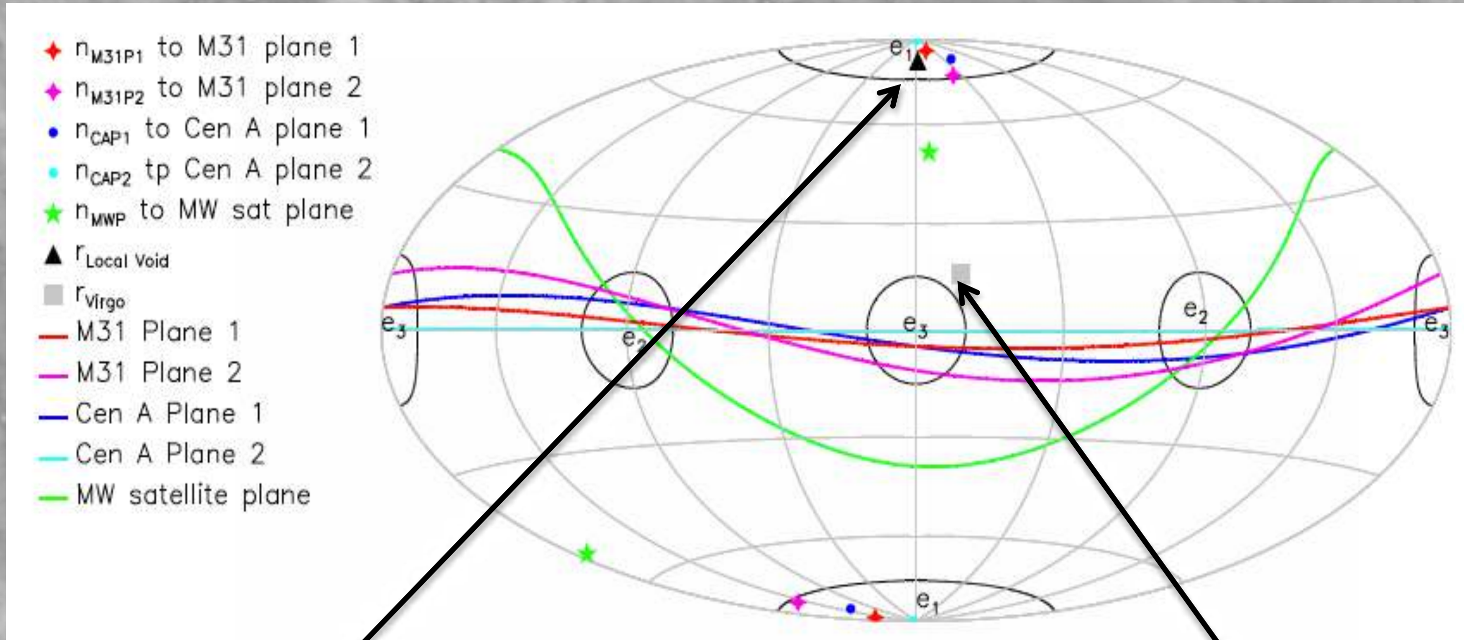

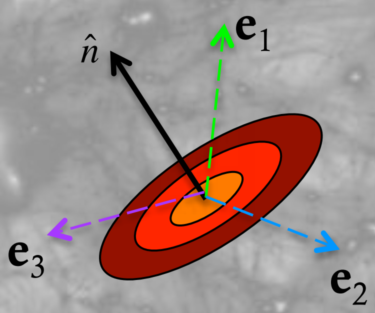

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Libeskind *et al* 2015

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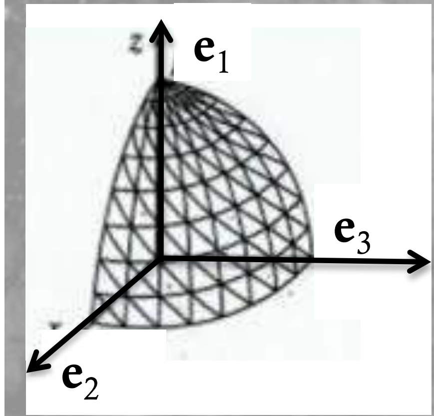
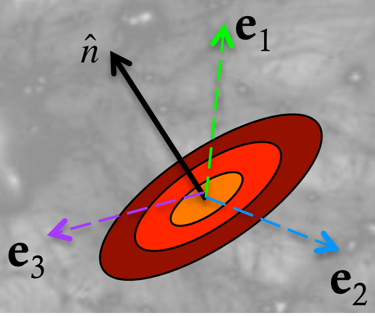
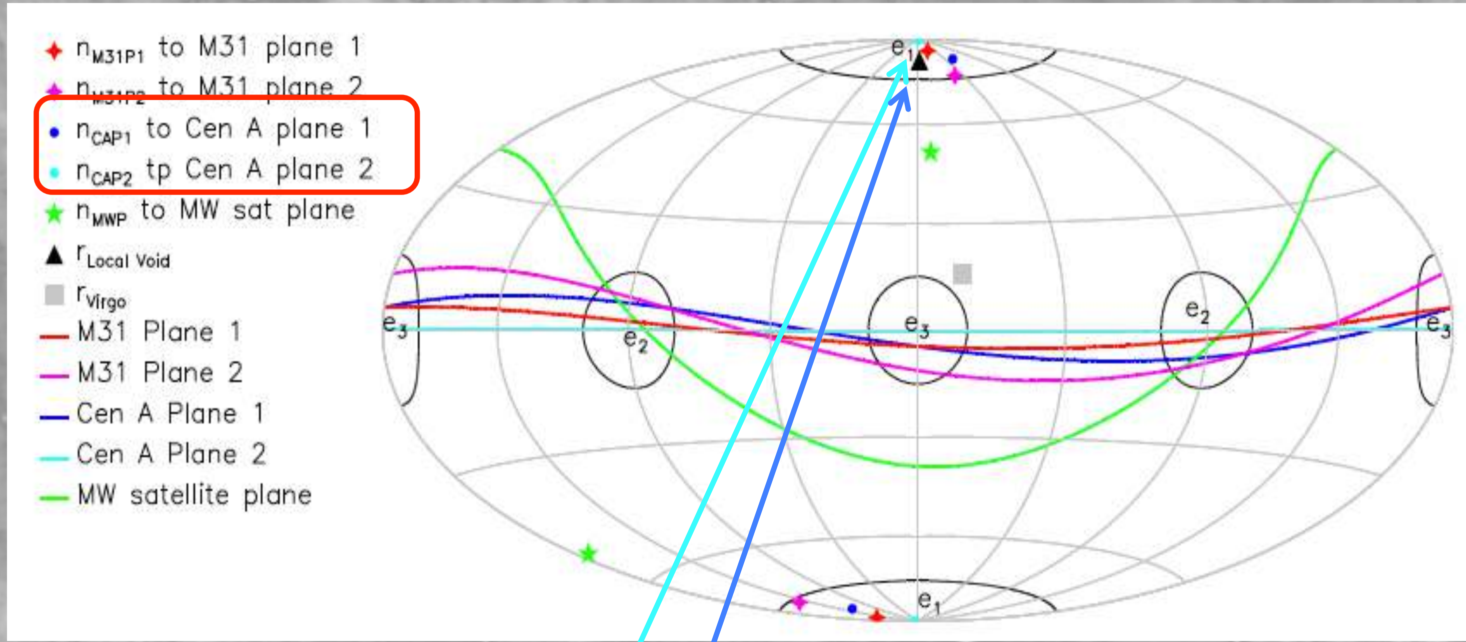




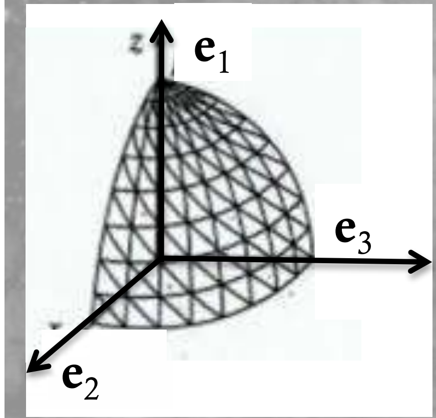


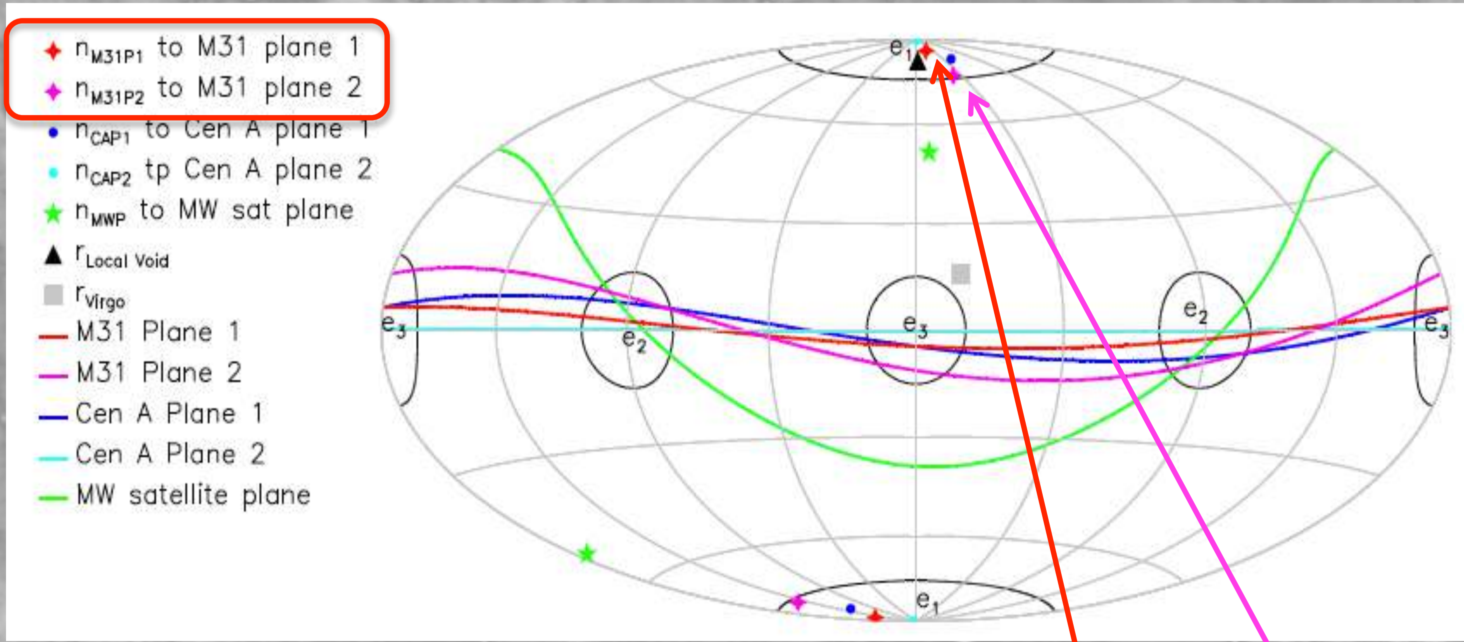
property	$\lvert\cos\theta\rvert$	degrees apart
$\mathbf{e}_3 \cdot \hat{r}_{\mathrm{Virgo}}$	0.9330	~21.1
$\mathbf{e}_1 \cdot \hat{r}_{\mathrm{Virgo}}$	0.2733	~74.1
$\mathbf{e}_1 \cdot \hat{r}_{\mathrm{LV}}$	0.9898	~8.17
$\mathbf{e}_1 \cdot \hat{n}_{\mathrm{M31P1}}$	0.9968	~4.5
$\mathbf{e}_1 \cdot \hat{n}_{\mathrm{M31P2}}$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

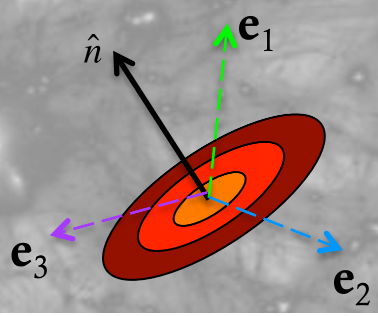
2 planes in CenA
are well aligned

Libeskind *et al* 2015

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







property	$\lvert\cos\theta\rvert$	degrees apart
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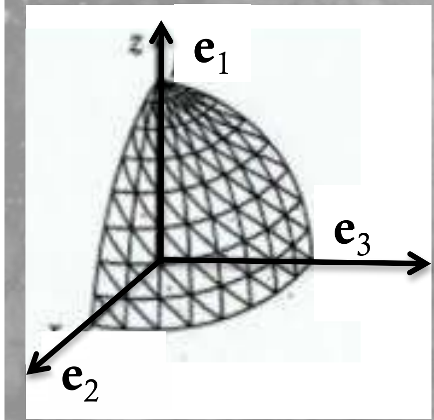
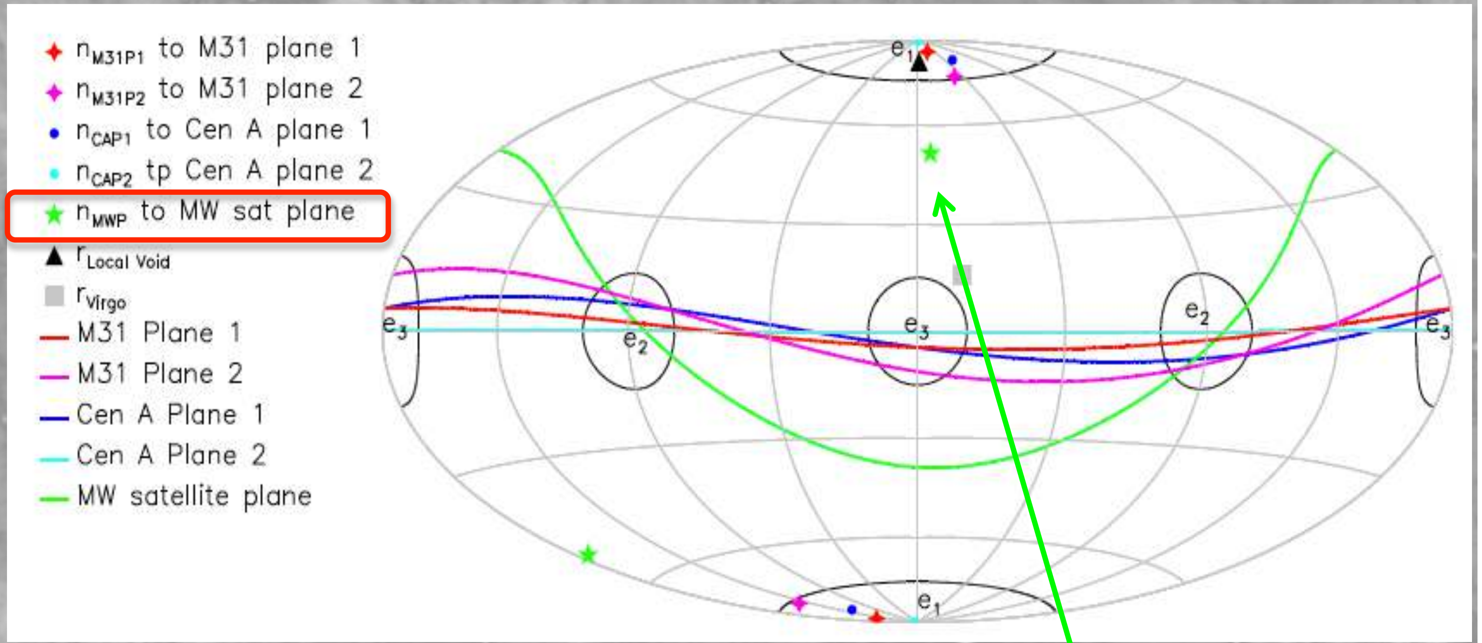
$\mathbf{e}_1 \cdot \hat{n}_{\rm CAP1}$	0.9879	$\sim$8.9
$\mathbf{e}_1 \cdot \hat{n}_{\rm CAP2}$	0.9999	$\sim$0.3
$\mathbf{e}_1 \cdot \hat{n}_{\rm MWP}$	0.7801	$\sim$38.7

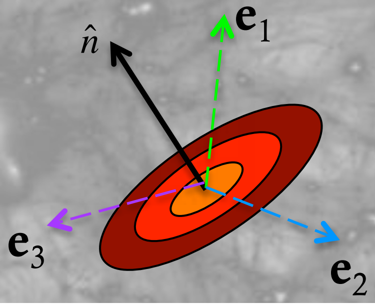
2 planes in M31 are well aligned

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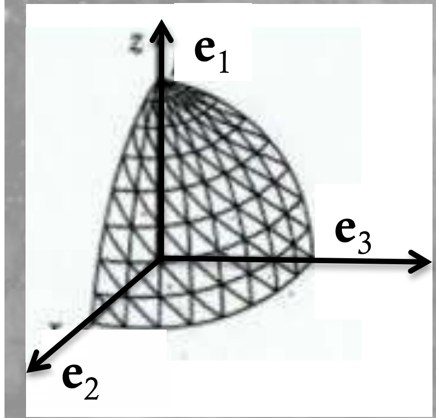
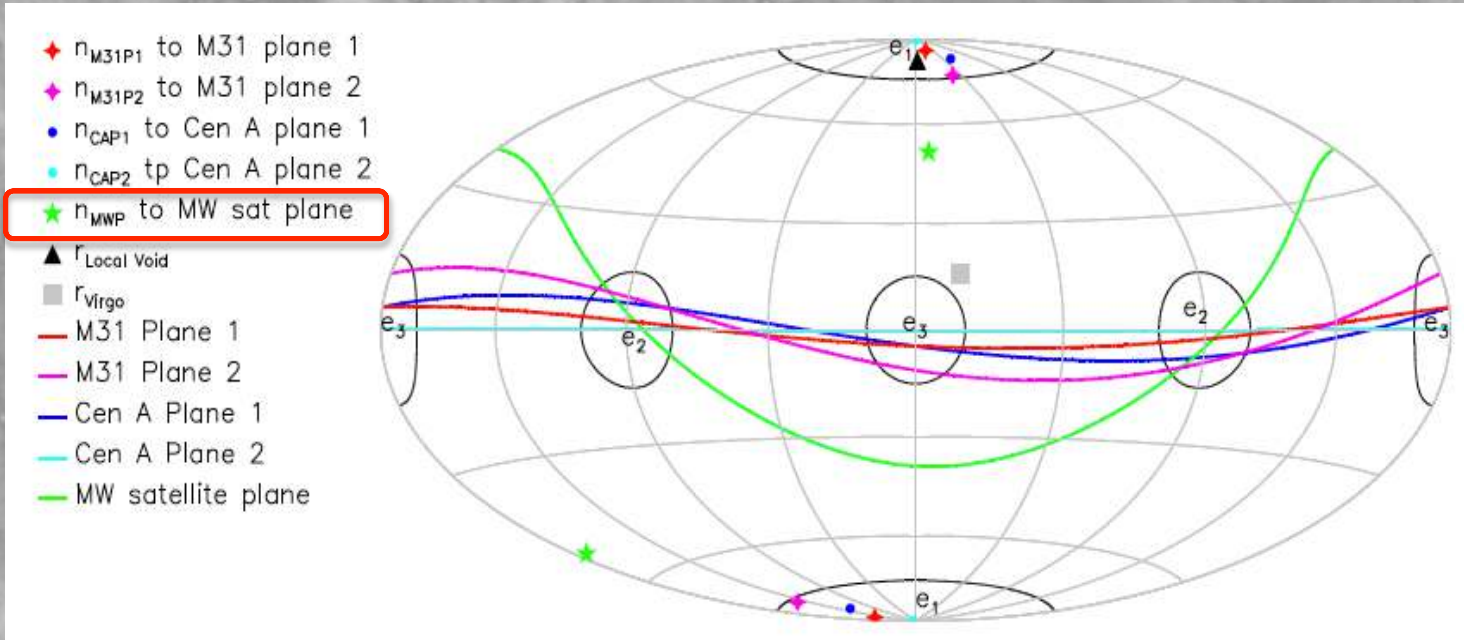
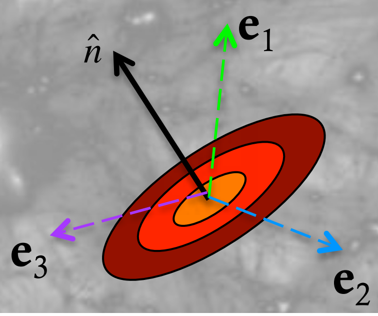
MW plane is off by ~38 deg, appears to have been torqued about the e_2 axis

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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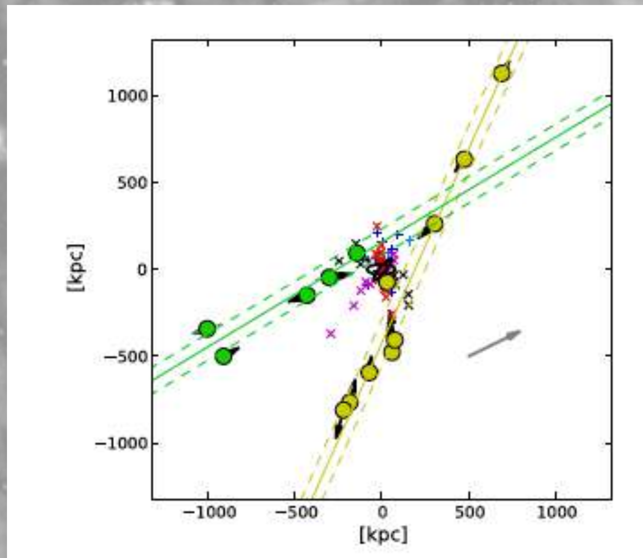
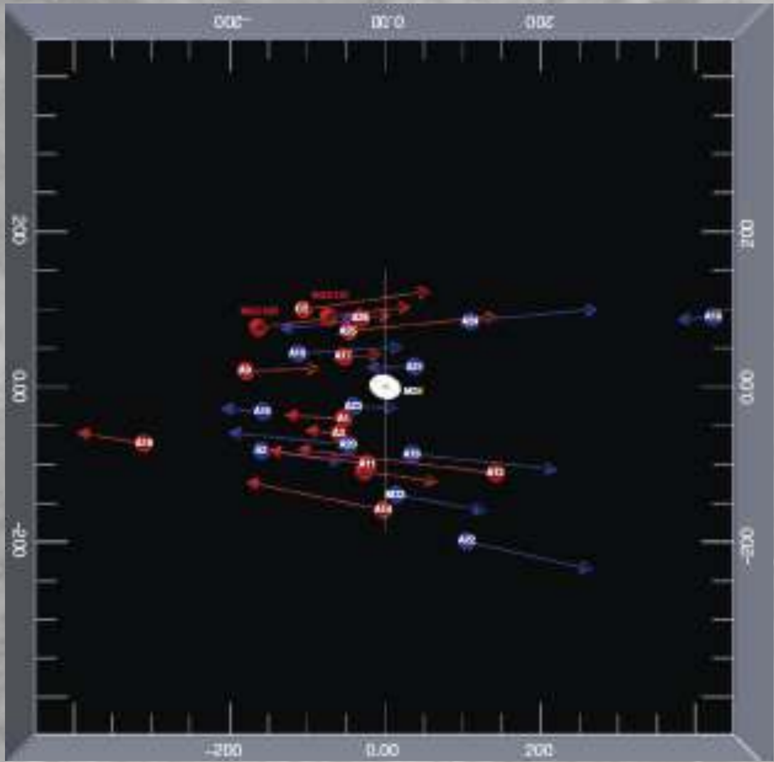
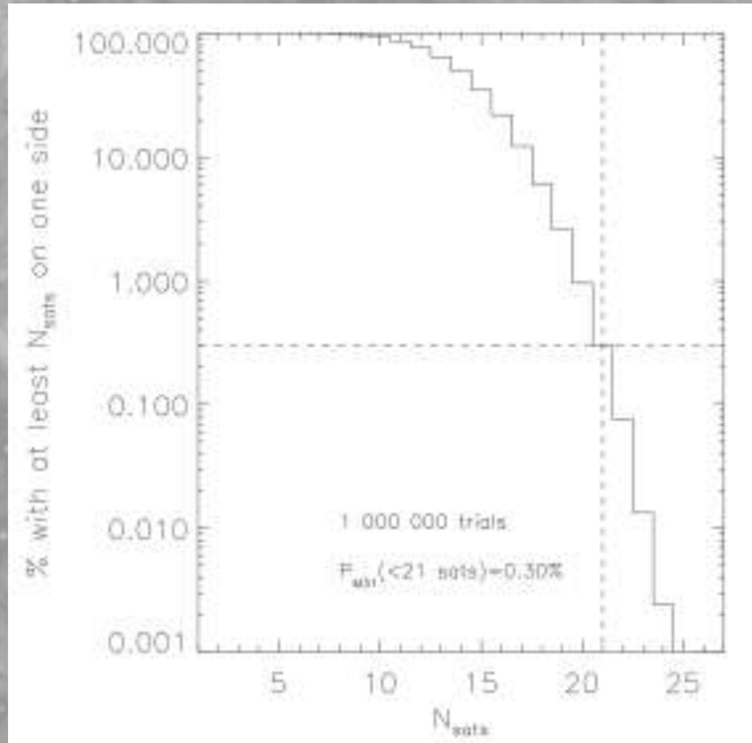


Pawlowski *et al* 2013

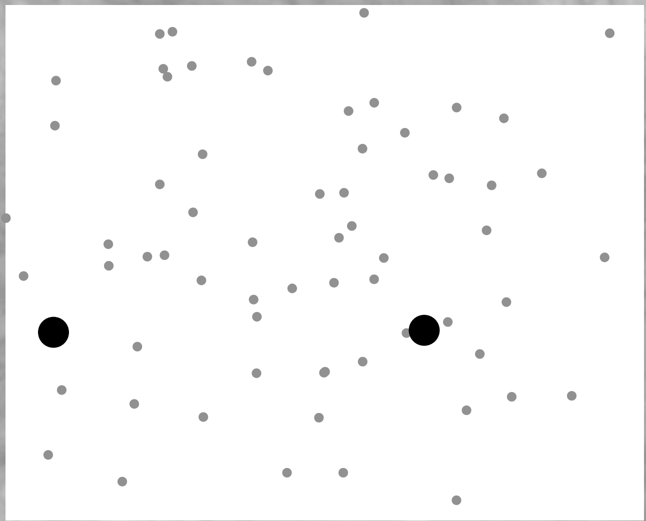




With 27 satellites 21 of which are on one side the chances are

$$P\left(\frac{n}{k}\right)=\frac{1}{2^n}\left(\frac{n!}{k!(n-k)!}\right)=\frac{1}{2^{27}}\left(\frac{27!}{6!(27-6)!}\right)=0.003=0.3\%$$

Lopsided satellites in SDSS Local Groups

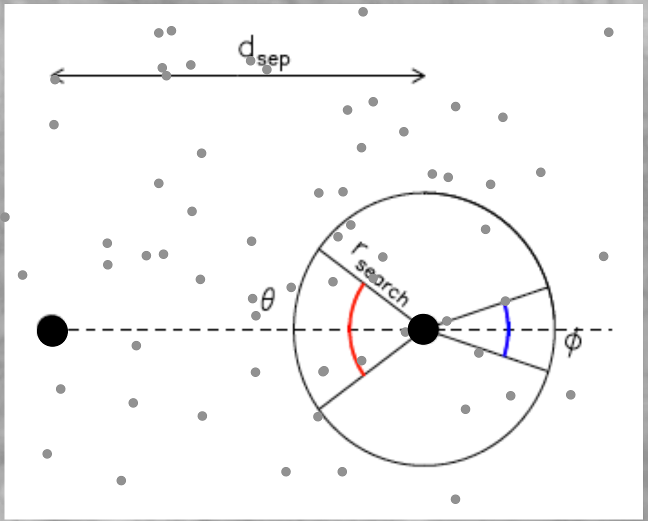


Start by identifying pairs of galaxies in the SDSS that "look" like the Local Group

- $-22.5 < M < -21.5$
- $0.5\text{Mpc} < d_{sep} < 1.5$ Mpc

Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups



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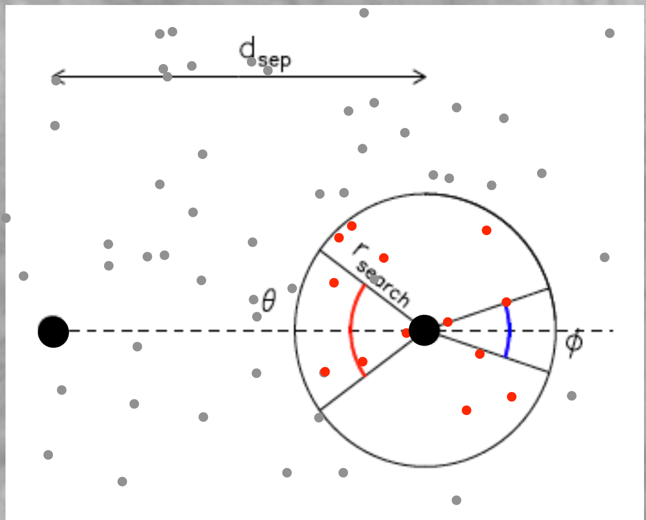
- Identify a search radius $r_{search} = 250\text{kpc}$

Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups



Start by identifying pairs of galaxies in the SDSS that "look" like the Milky Way

- $-22.5 < M < -21.5$
- $0.5\text{Mpc} < d_{sep} < 1.5\text{ Mpc}$

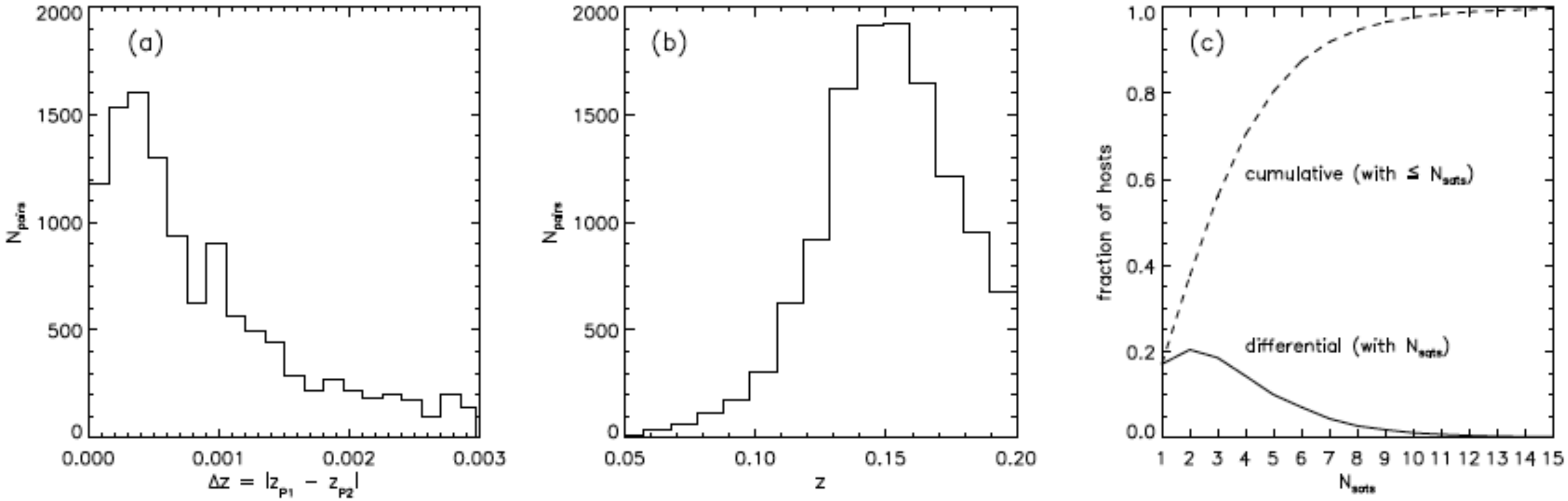
- Identify a search radius $r_{search} = 250\text{kpc}$

- Find satellites within r_{search} **ignore satellite photo-z**

- Count how many are within (θ , Φ) and compare with how many you expect from a random distribution

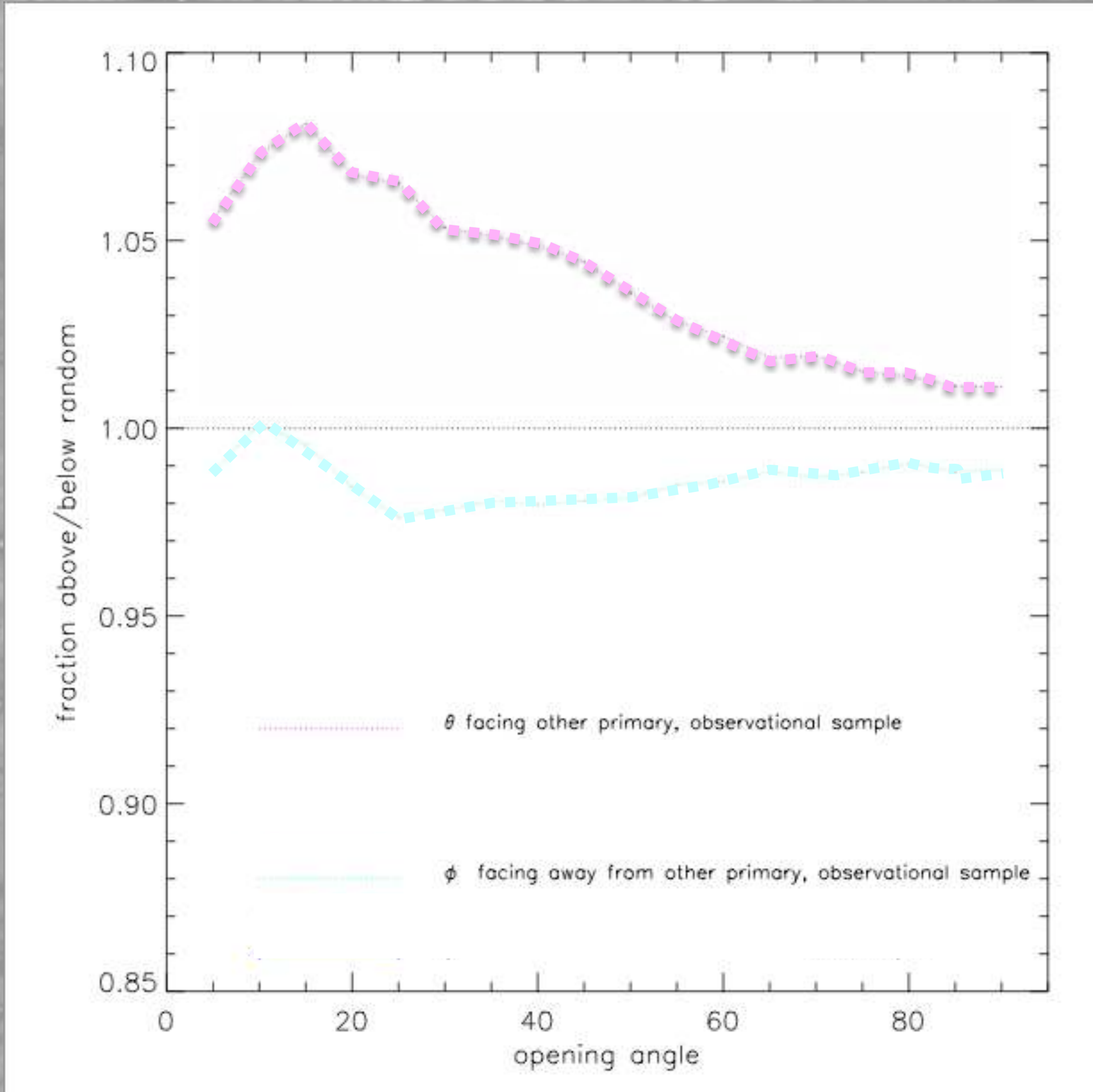
Libeskind *et al* 2016

Lopsided pairs – sample selection



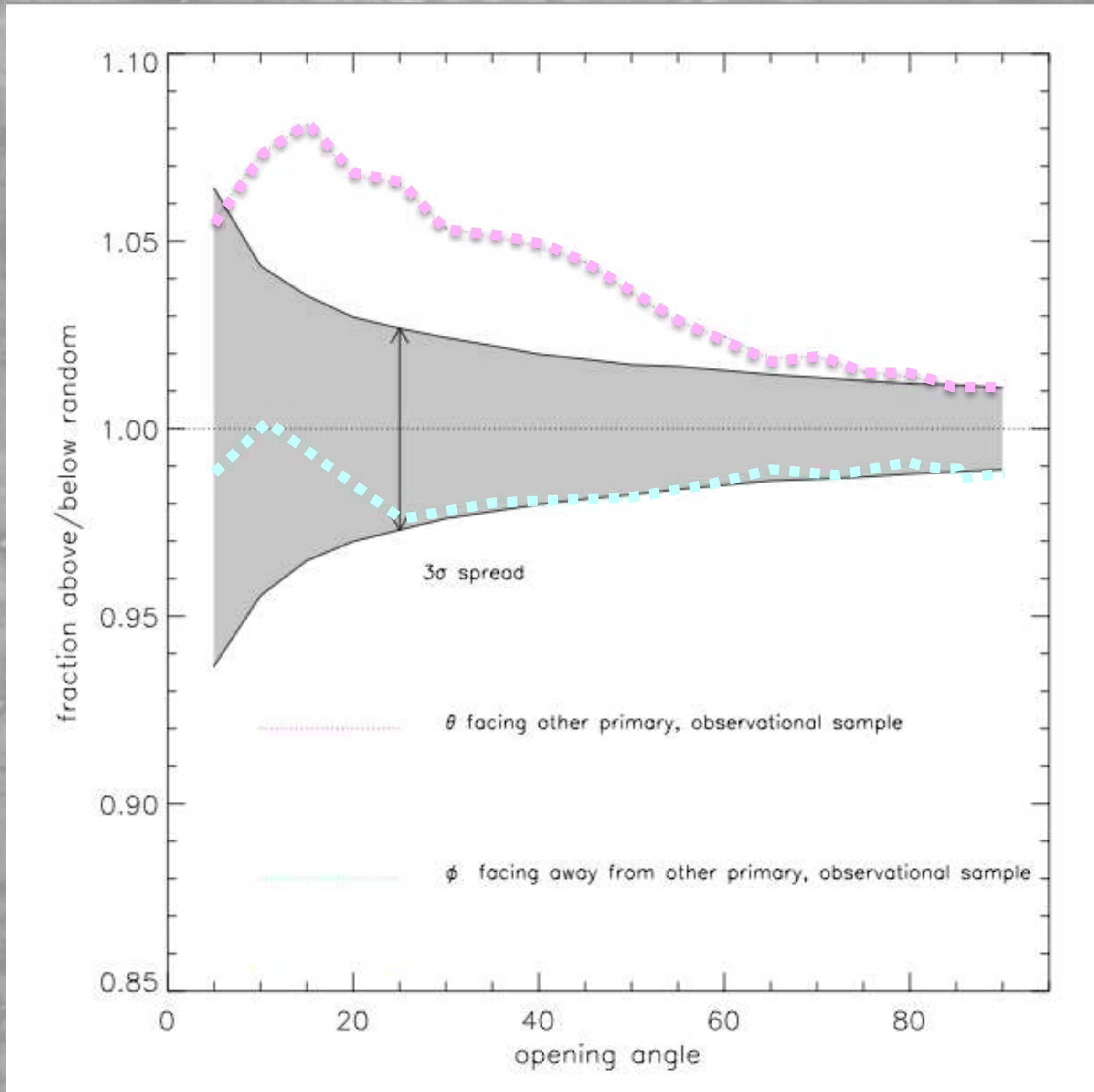
Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups



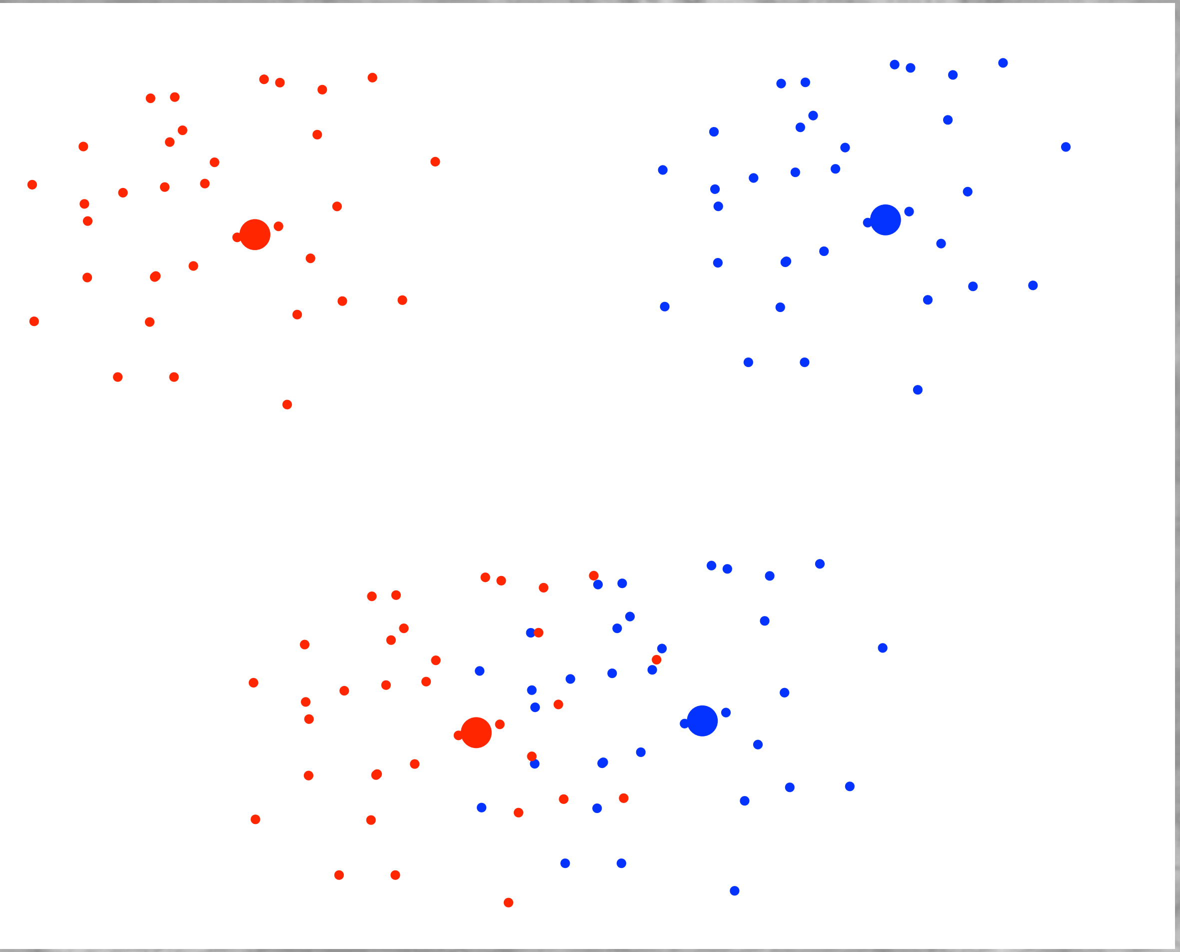
Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups



Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups
Issue of overlap:



What is the effect of extended satellite distributions?

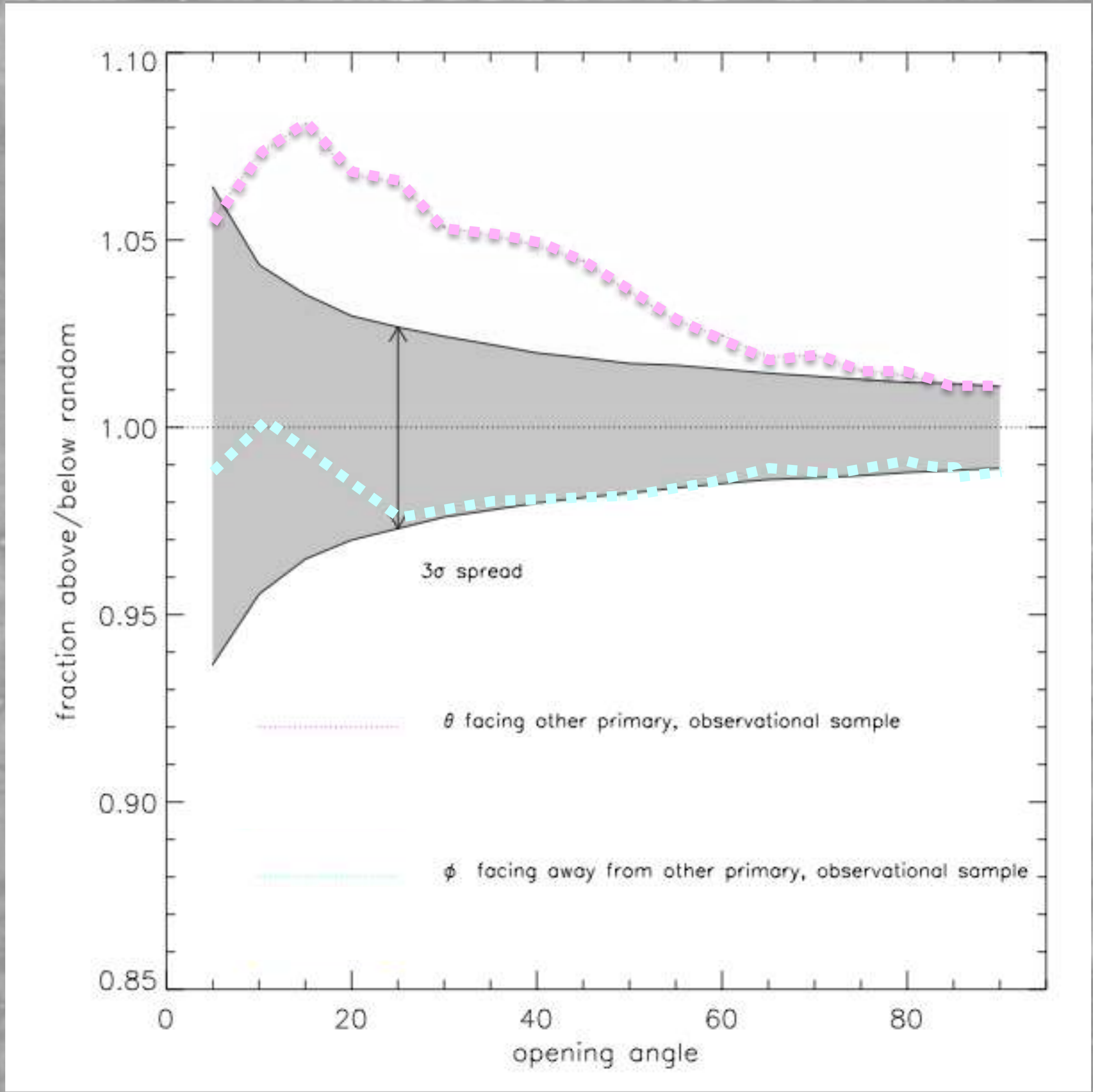
For each pair member, find an isolated galaxy at the same redshift with the same magnitude

Place it and its satellites and the same separation as each pair member, rotate N times

Compute overlap bias and subtract from observed signal

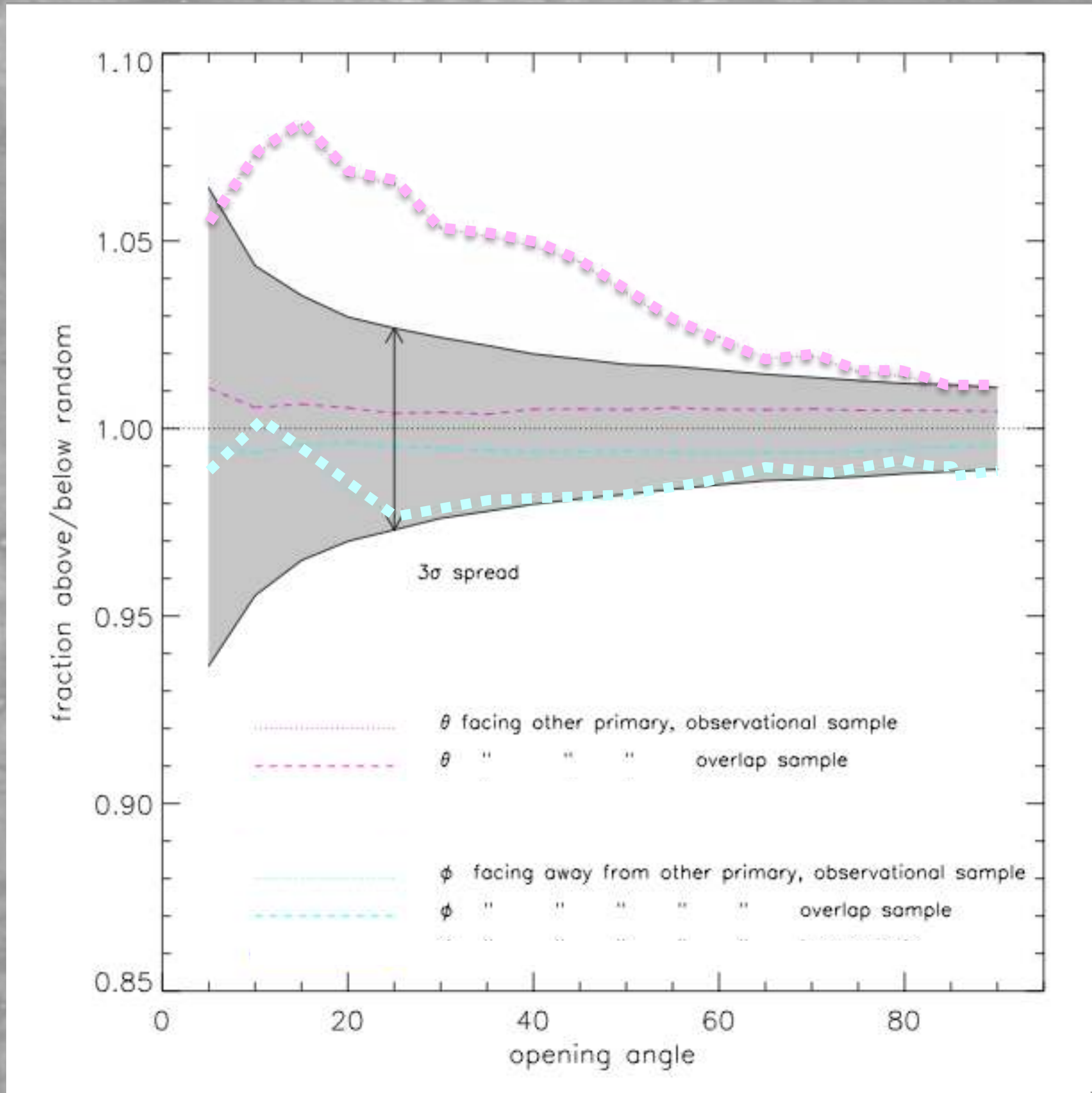
Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups



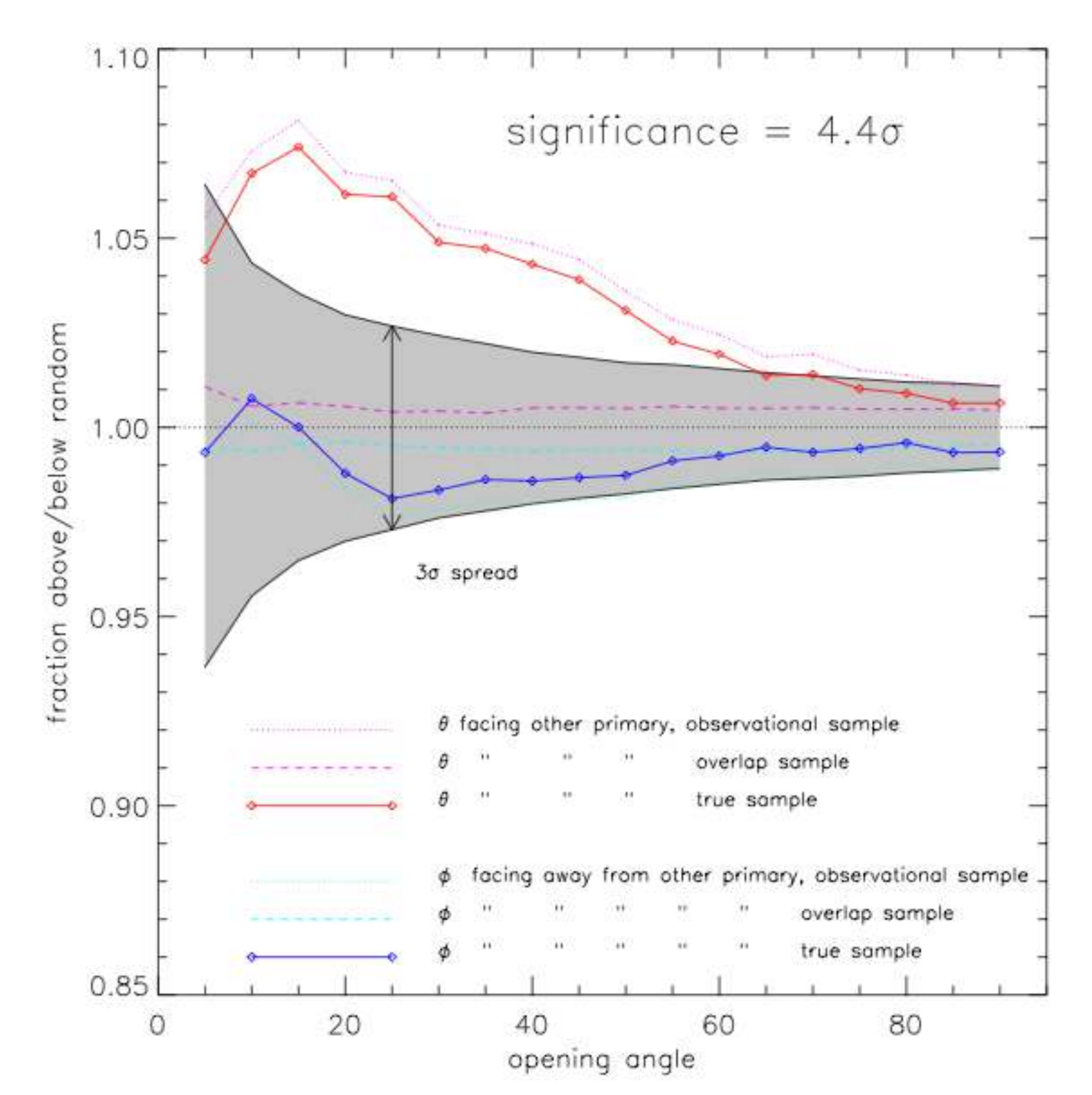
Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups



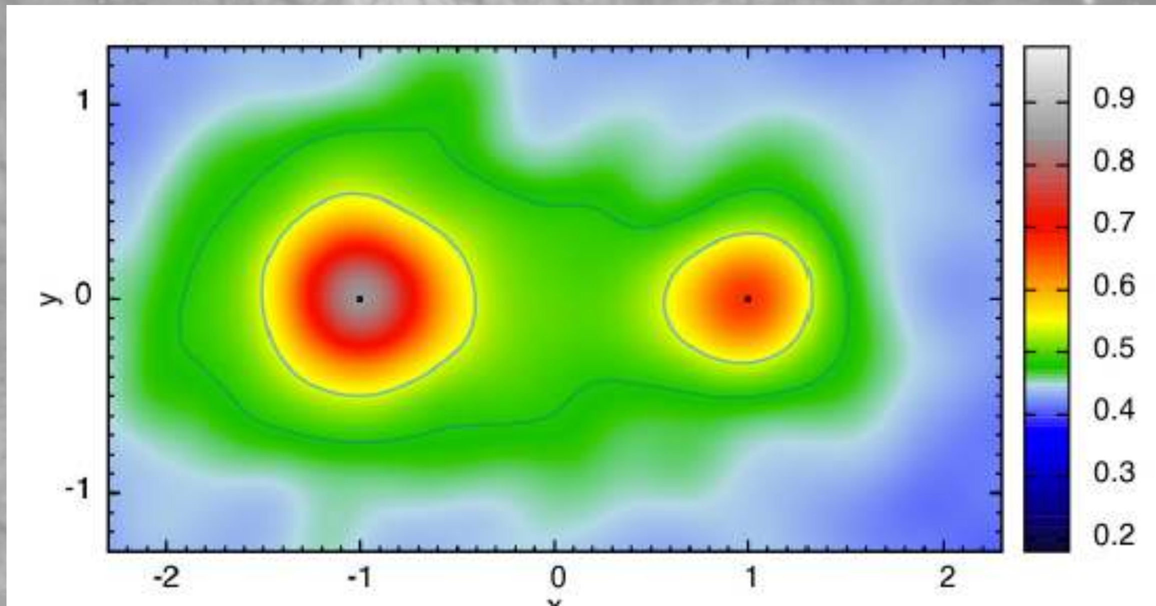
Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups



Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups

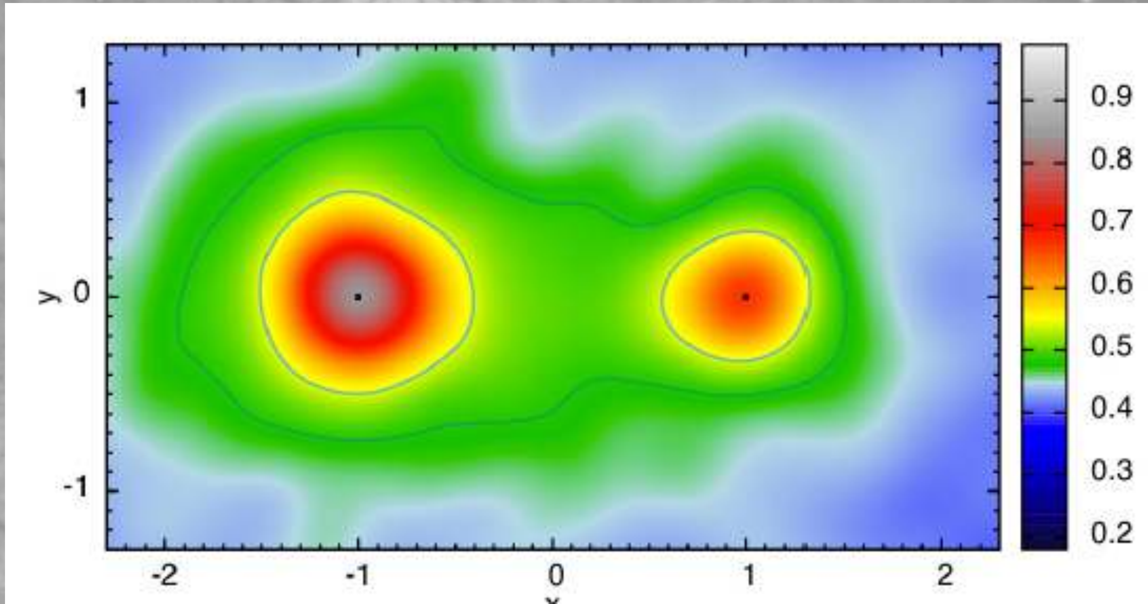


Stacking all systems reveals a bar-bell geometry

Examining similar set ups in simulations but results still inconclusive (Gong et al in prep)

Libeskind *et al* 2016

Lopsided satellites in SDSS Local Groups



Sensitive to pair selection criteria

Insensitive to how the satellites are chosen

Libeskind *et al* 2016

Conclusions

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

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

5. Satellites in galaxy pairs in surveys are lopsided