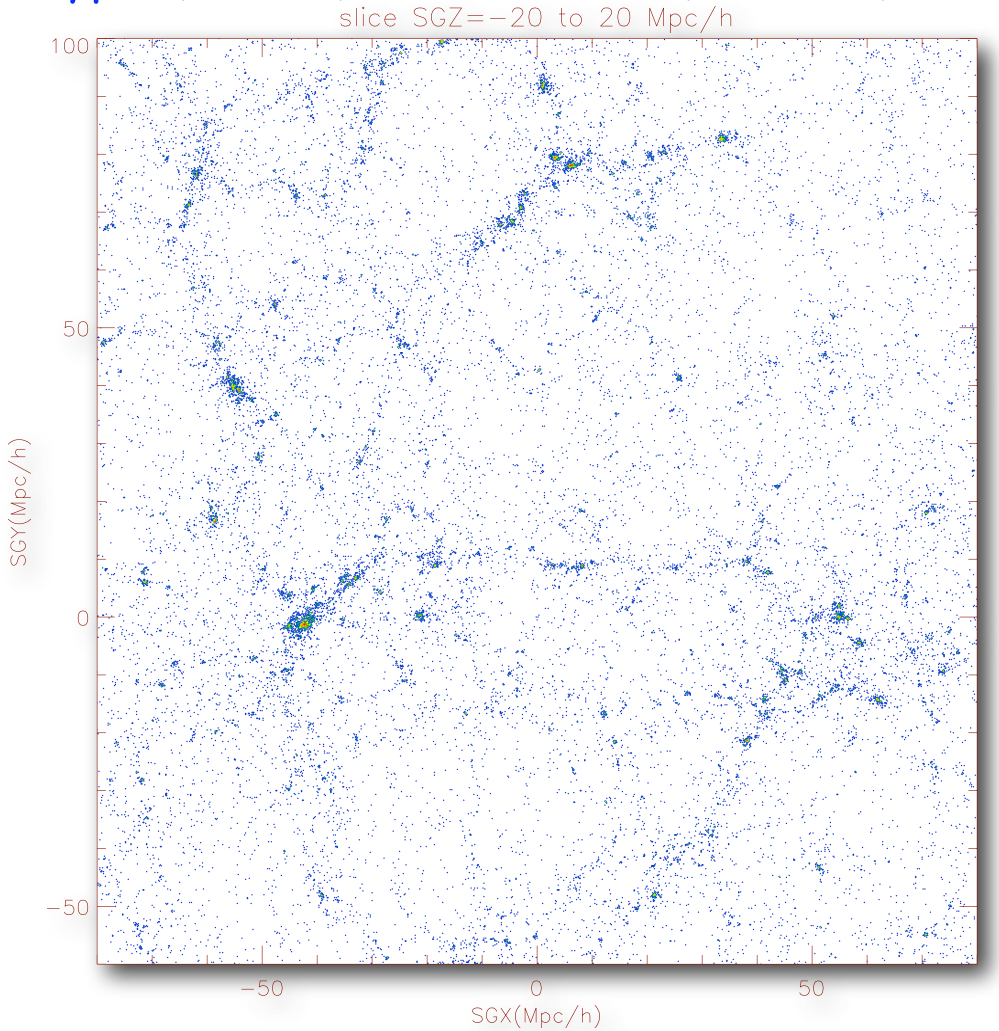
Constrained Simulations of the Local Universe:
Simulating Nearby Voids

Yehuda Hoffman - Hebrew University
Y. Dover, M. Sivan (HU)   E. Romano-Diaz (HU, Kentucky)
L.A. Martinez, G. Yepes (Madrid), A. Klypin (NMSU), S. Gottlober (Potsdam)

- Constrained simulations (CSs)
- Coldness of the local flow: environment, cosmological models
- Coldness of the flow and the ZOA
- Peculiar gravity vs velocity: cosmological implications?
- Formation of the Local Group in the local filament
- Populating DM halos with galaxies



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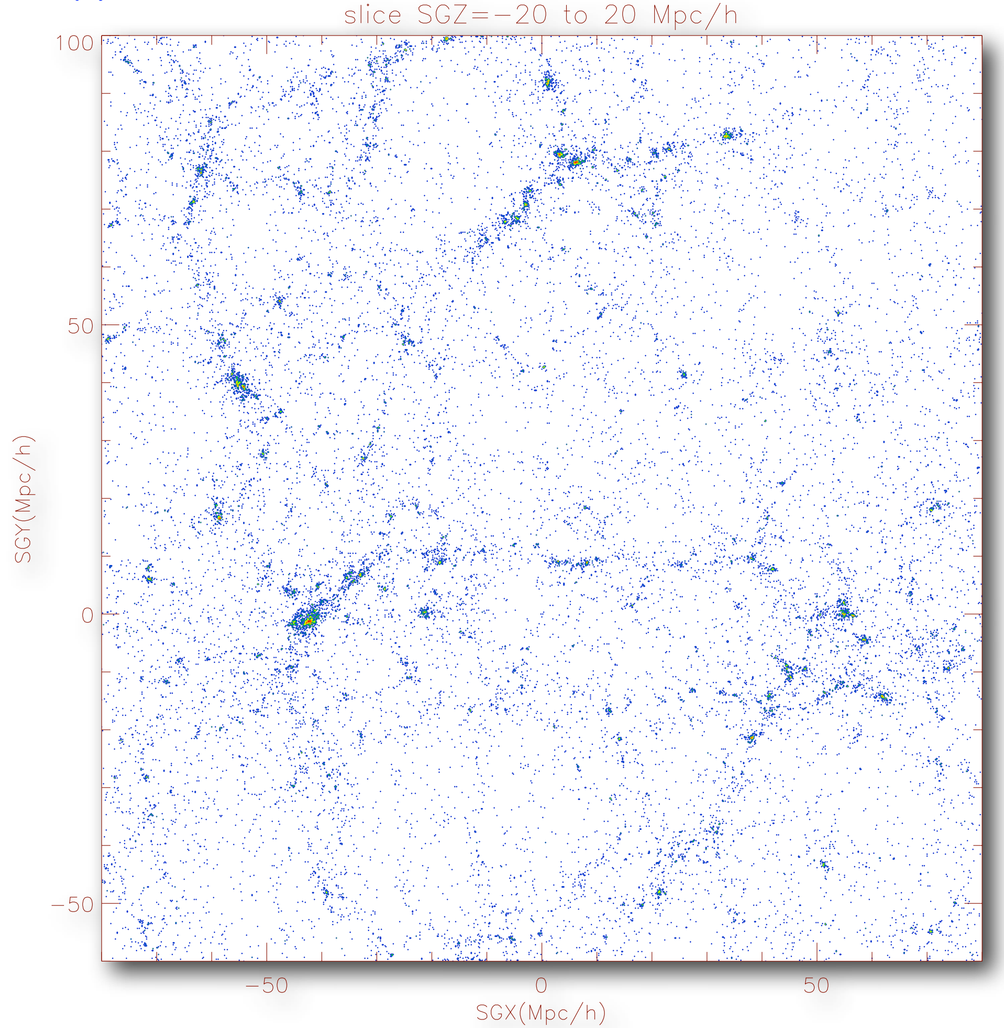

- CSs are simulations are designed to obey a set of constraints - in the present case observational data is used.

Why should one do CS?

- In doing NEAR FIELD COSMOLOGY the local volume cannot be treated as representative - the cosmic variance needs to be beaten.

- A tool of studying particular objects.

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Dictionary

con•strain |kənˈstrān|

verb [trans.] (often **be constrained**)

severely restrict the scope, extent, or activity of : *agricultural development is considerably constrained by climate | we can constrain data access.*

• compel or force (someone) toward a particular course of action : *children are constrained to work in the way the book dictates.*

• [usu. as adj.] (**constrained**) cause to appear unnaturally forced, typically because of embarrassment : *he was acting in a constrained manner.*

• poetic/literary confine forcibly; imprison.

• archaic bring about (something) by compulsion : *Calypso in her caves constrained his stay.*

See note at COMPEL .

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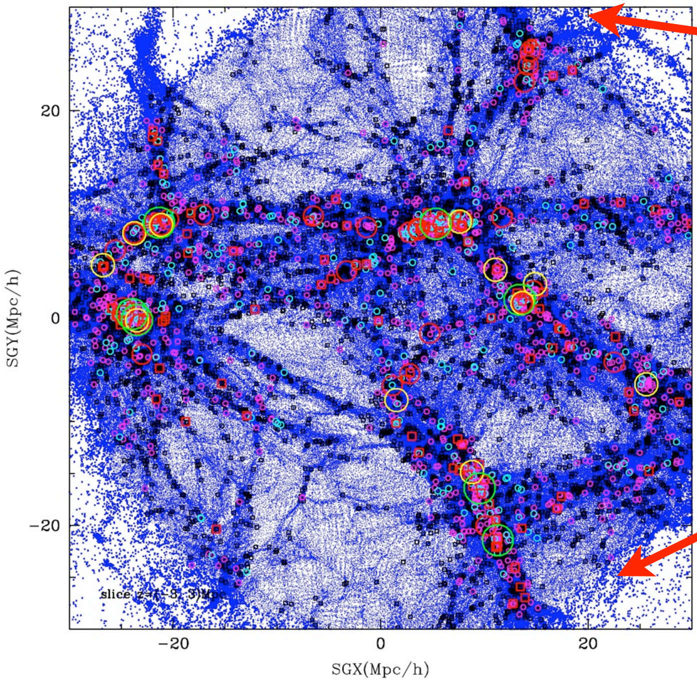
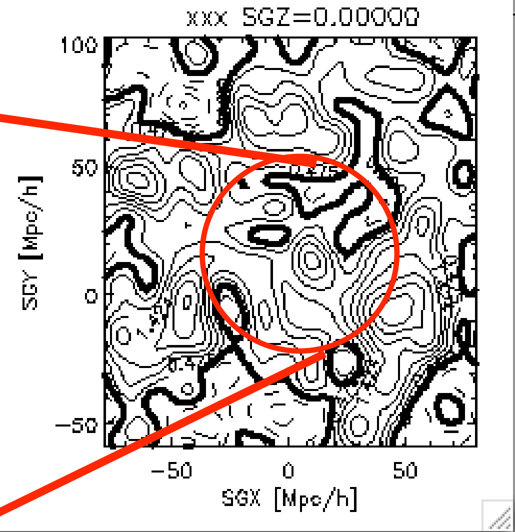
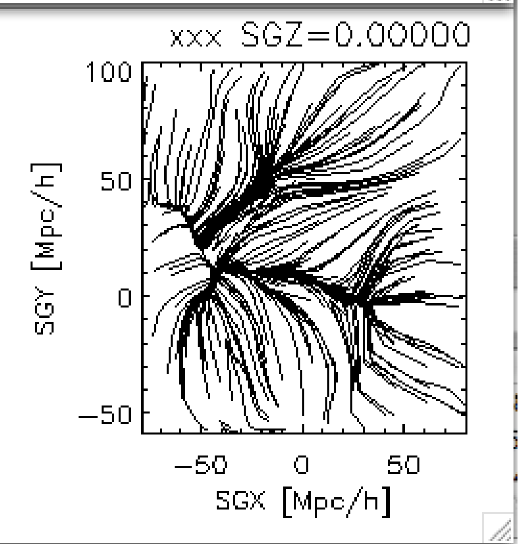
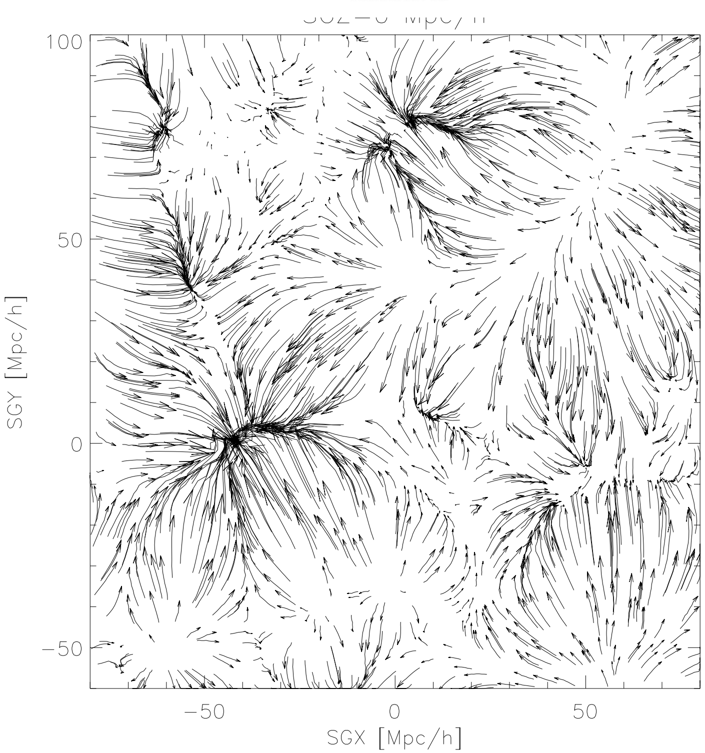
Constrained Simulation: ART

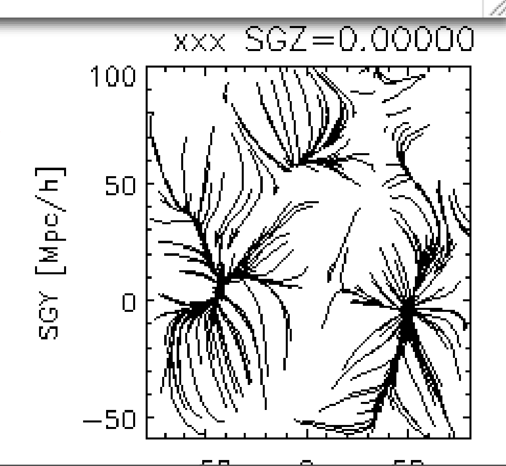
N=256^3 (inner R=30Mpc/h 1024^3) L=160Mpc/h











Initial Conditions:

Constrained Realization

Velocities: MARK3, SBF, Karachenstev et al

Nearby X-ray clusters (Reiprich & Bohringer 2002)

Cosmological Model:

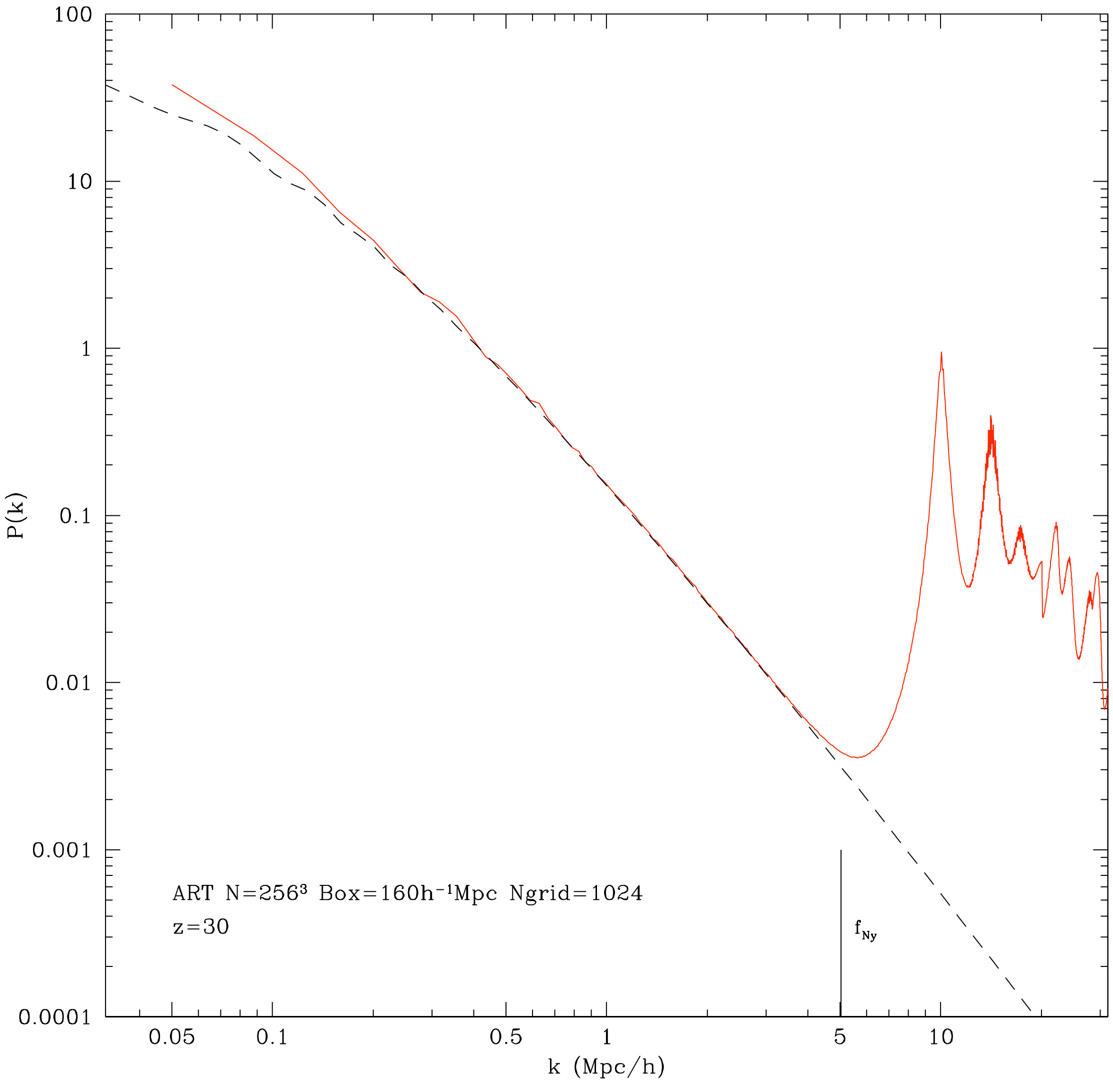
FLAT ΛCDM

$$\sigma_0 = 0.9, \;\; h = 0.7, \;\; \Omega_m = 0.3$$

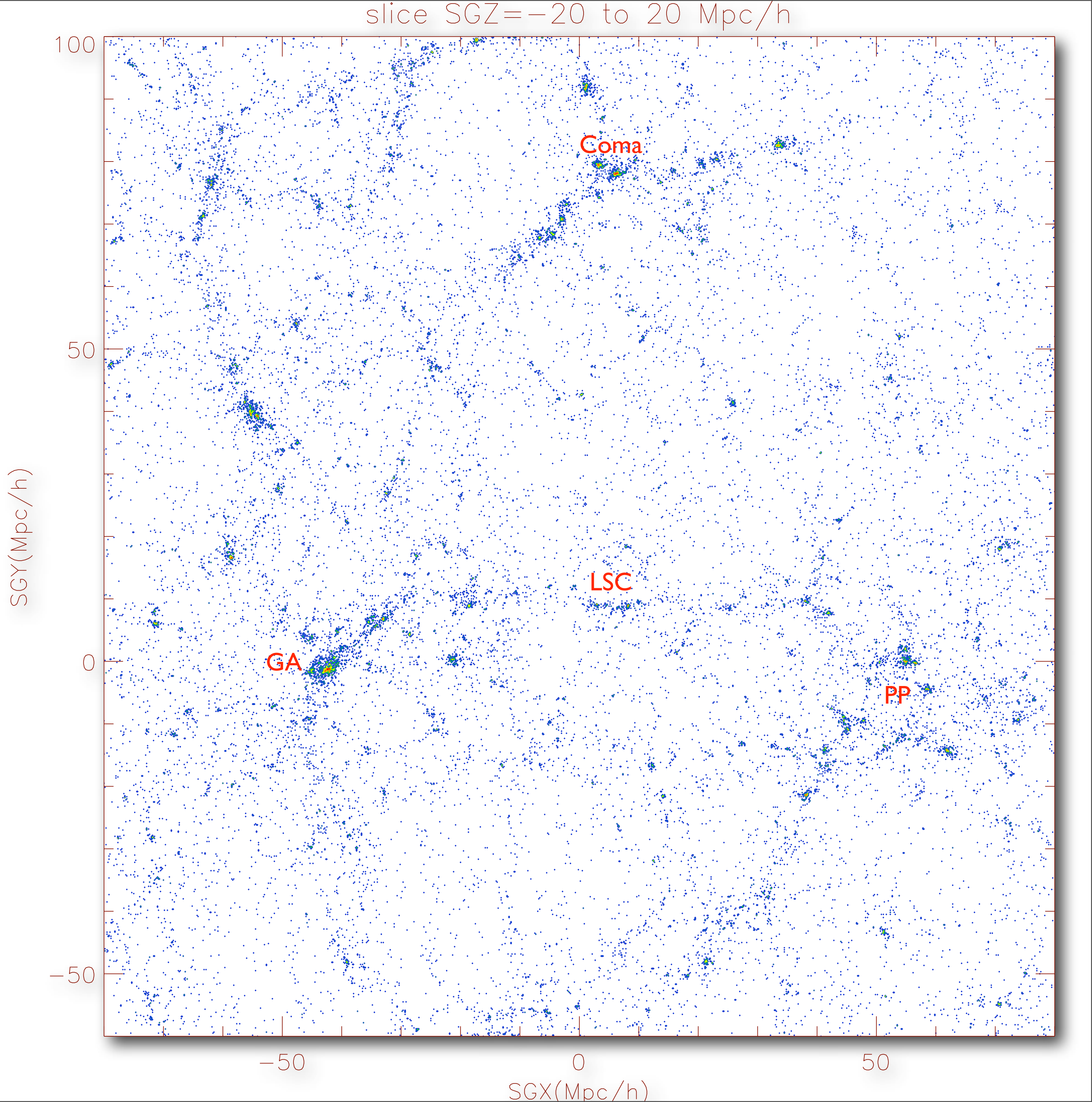
The 1-2-3 guide to making CSs

- Choose the cosmological model
- Construct a set of constraints to be imposed
- Linearize the constraints
- Construct a random realization of a Gaussian field
- impose the constraints on that field (YH & Ribak 1991) ==> initial conditions
- Feed it to an N-body and/or hydro code
- Simulate and observe the universe evolving

Imposing the constraints on the random realization increases P(k) at small k's



BOX 160Mpc/h
CODE ART
GRID 256^3
Standard ΛCDM
σ_8=0.9
m_p=2 $10^{10}M_{sun}$/h



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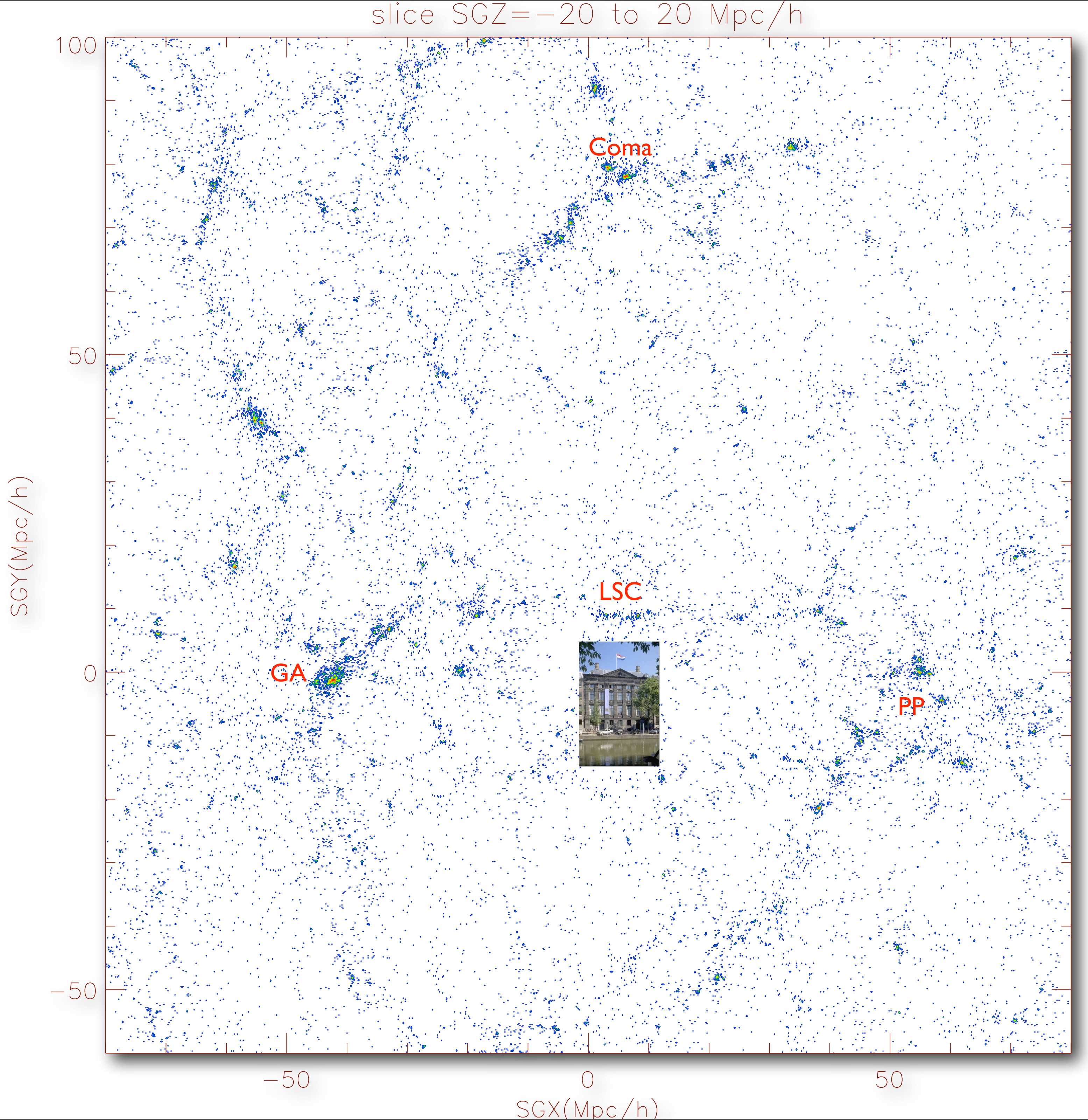
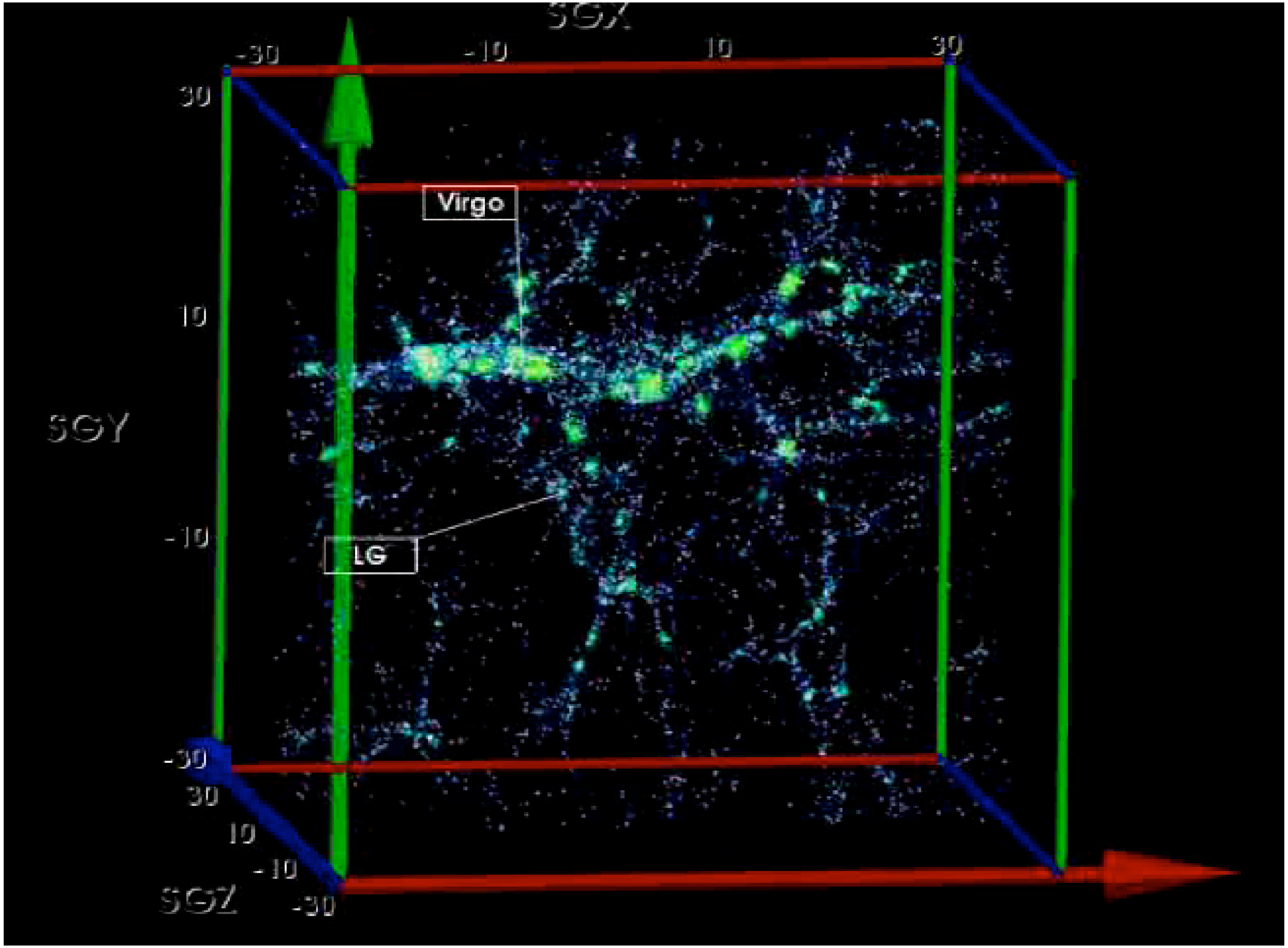


BOX=64 Mpc/h, N=256^3, mp=1.3 10^9 M_{sun}/h
GADGET, WMAP3 FLAT ΛCDM

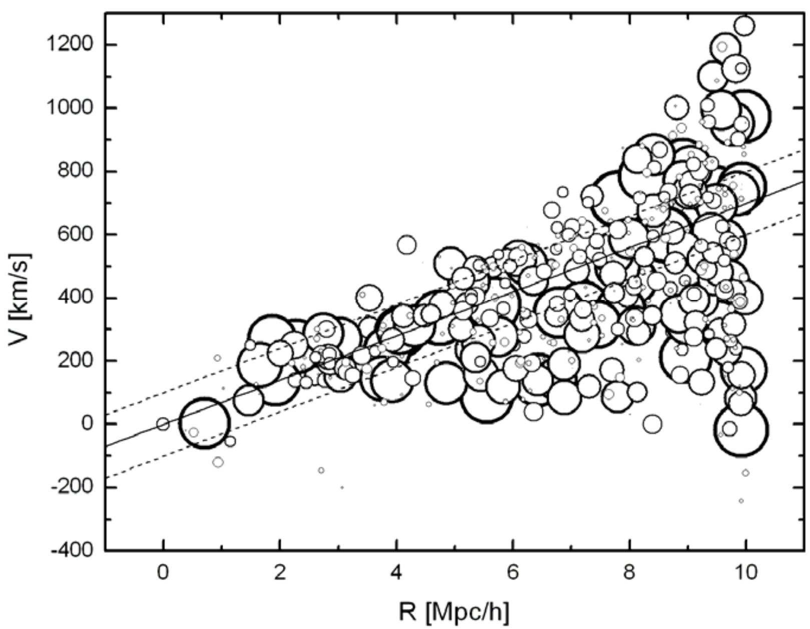


	SGX [Mpc/h]	SGY [Mpc/h]	SGZ [Mpc/h]	Vx [km/s]	Vy [km/s]	Vz [km/s]	Mass [M_sun]	
MW candidate	-9.05087	0.858379	-5.31218	259.2	469.4	125.260	5.93263e+011	
M31 candidate	-8.71955	1.15849	-4.48516	172.5	397.6	-24.8200	4.81896e+011	
Virgo (main halo)	-10.2004	10.4932	-9.83438				1.06553e+014	

Distance between M31 and MW = 0.94 [Mpc/h] (pairwise velocity: -185.5 km/s)
The distance to Virgo from M31 = 10.86 [Mpc/h]
The distance to Virgo from MW = 10.7 [Mpc/h]

Virgo is composed of several halos amounting to a total of ~1.8e14 M_sun.

The Mw candidate statistics:
Vel. Disp.:
R<2 [Mpc/h] 104.4 km/s (statistics is lousy – 4 halos)
R<4[Mpc/h] 100.5 km/s
R<6 [Mpc/h] 114.95 km/s
R<8[Mpc/h] 148.38 km/s



Things to do ...

- Find the "best"possible constrained realization that leads to a CS that best matches the observed sky.
- Run DM & "adiabatic' hydro 1024^3 simulations of BOX=64, 160 & 320 Mpc/h
- Zoom-in on individual objects (Virgo, Coma, ...) and run multi-mass simulations at an effective 4096^3 resolution
- Zoom-in on the LG with full hydro `gastrophysics' - formation of the MW & M31 - NEAR FIELD COSMOLOGY

The Coldness of the Local Hubble Flow

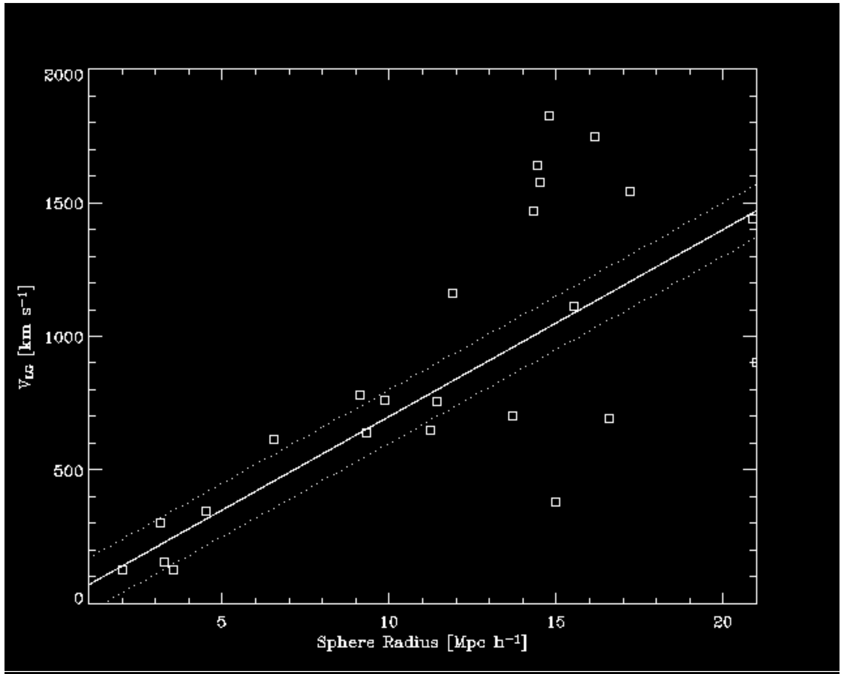
Of course, this result that the local velocity field is so unexpectedly quiet is of enormous practical importance. Because of it, one can estimate accurate distance ratios for even “local” galaxies, based on observed redshifts reduced to the Virgocentric kinematic system, or more locally to the barycenter of the Local Group. Nevertheless, the explanation of why the local expansion field is so noiseless remains a mystery. The two possibilities discussed by Sandage, Tammann, & Hardy (1972) of $q_0=0$ or a high-density, totally uniform distribution of matter at, say, near or at the closure density, remain valid.

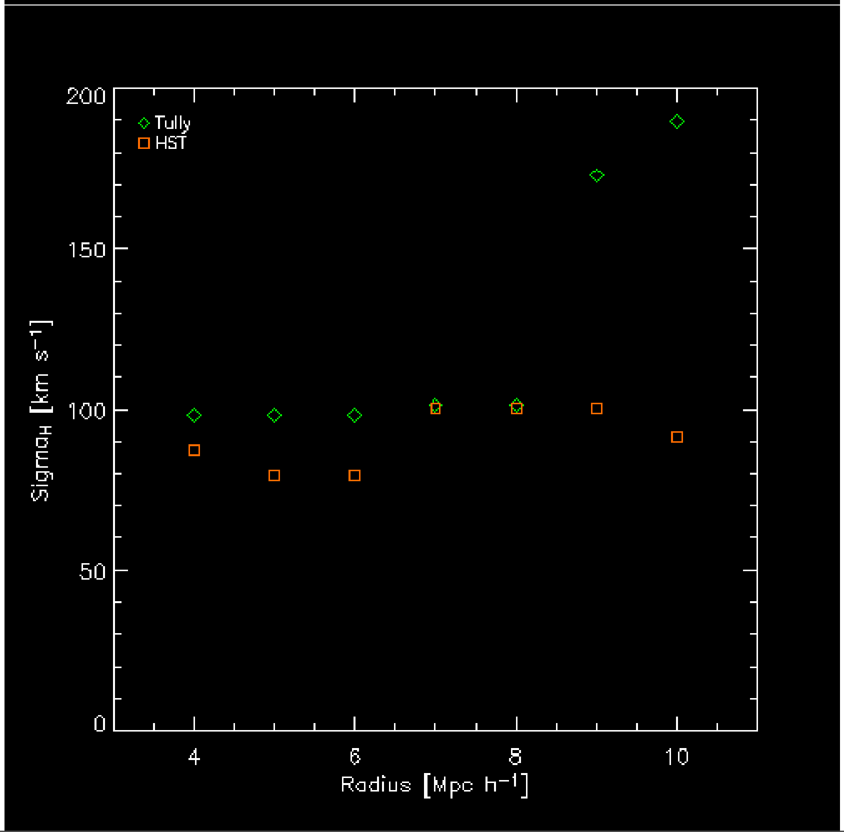
Sandage (1999)

- $\sigma_H = 88$ +/- 20 km/s (R/5 Mpc h^{-1})

(Maccio, Governato & Horellou 2005, based on HST, SBF & TF)

HST KEY PROJECT

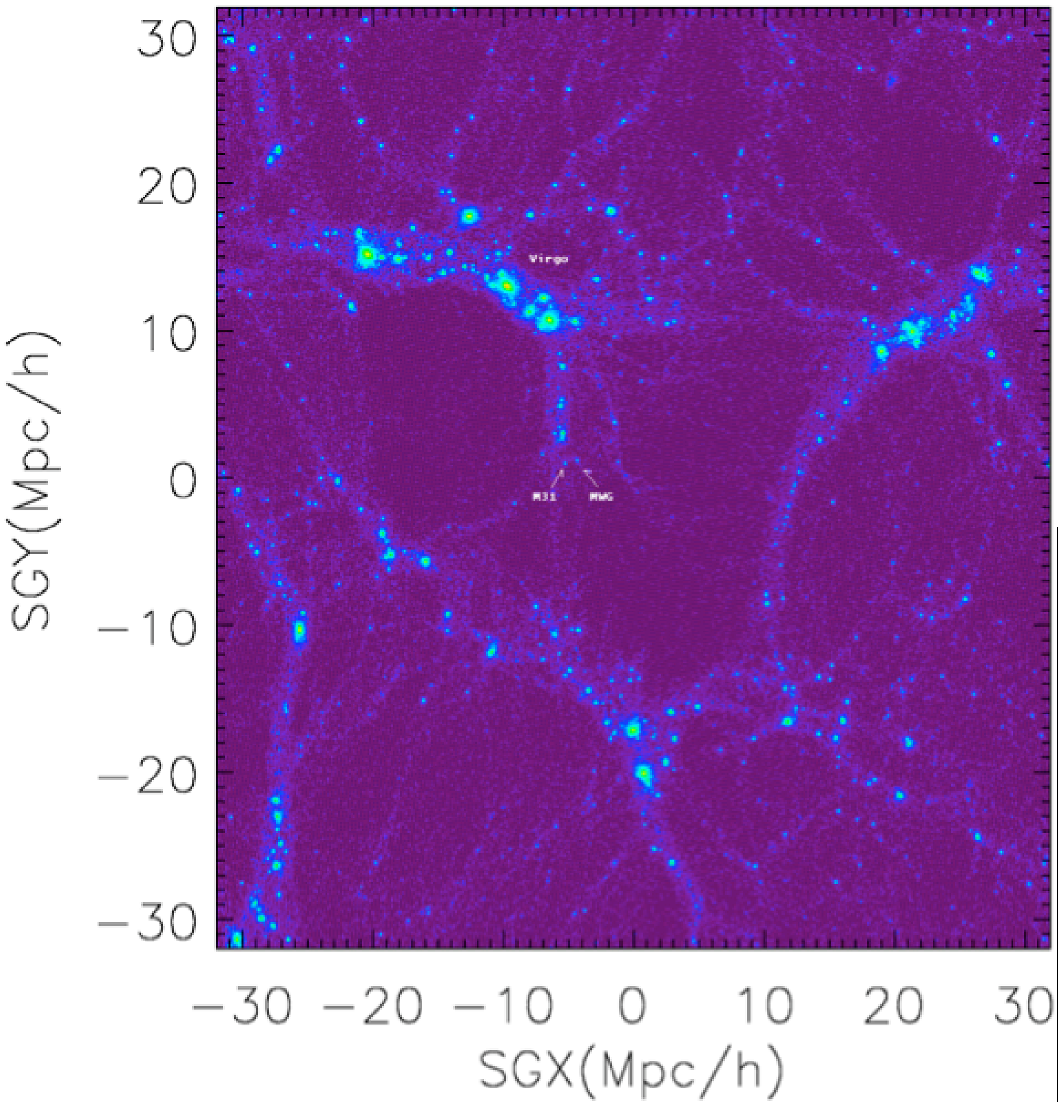


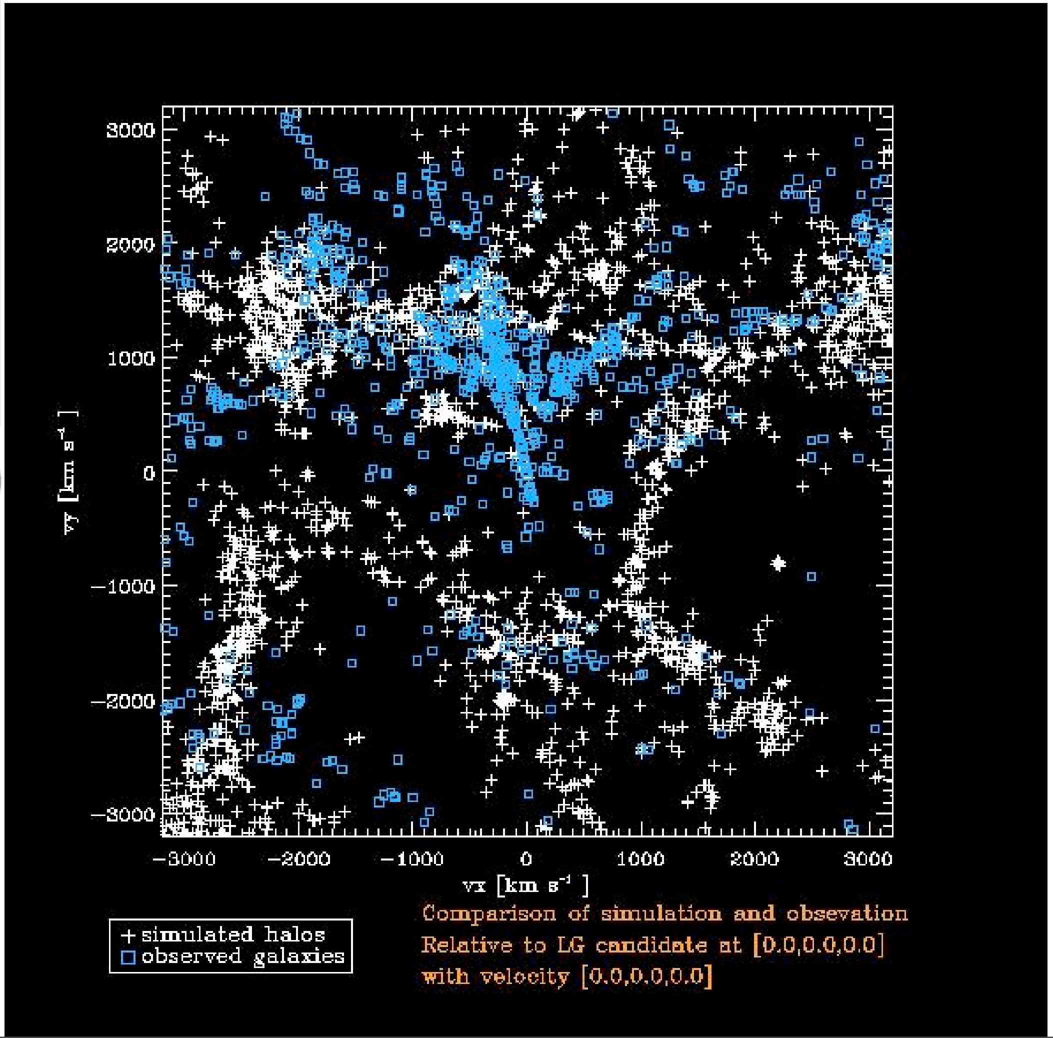


N-body constrained simulation:

Constraints: rad. vel. (MARK III, SBF), X-ray clusters

GADGET, DM, L=64Mpc/h, N=256^3, flat ΛCDM





Cold Local Hubble Flow

LG candidates

Two halos of ~1.e12M_{sun} /h

No similar halo within 2Mpc/h

More or less at the right location

Within ~12Mpc/h from the Virgo

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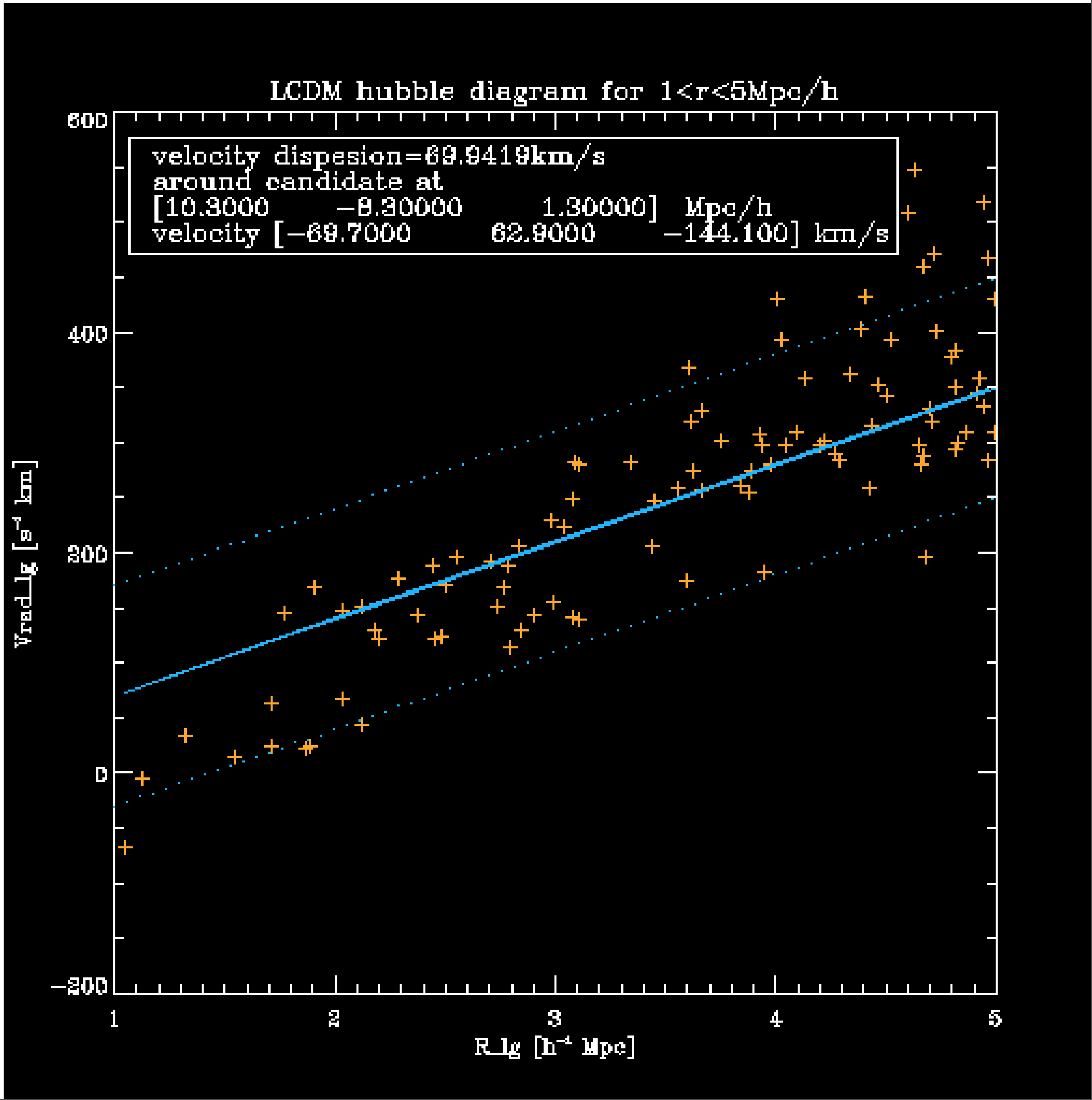

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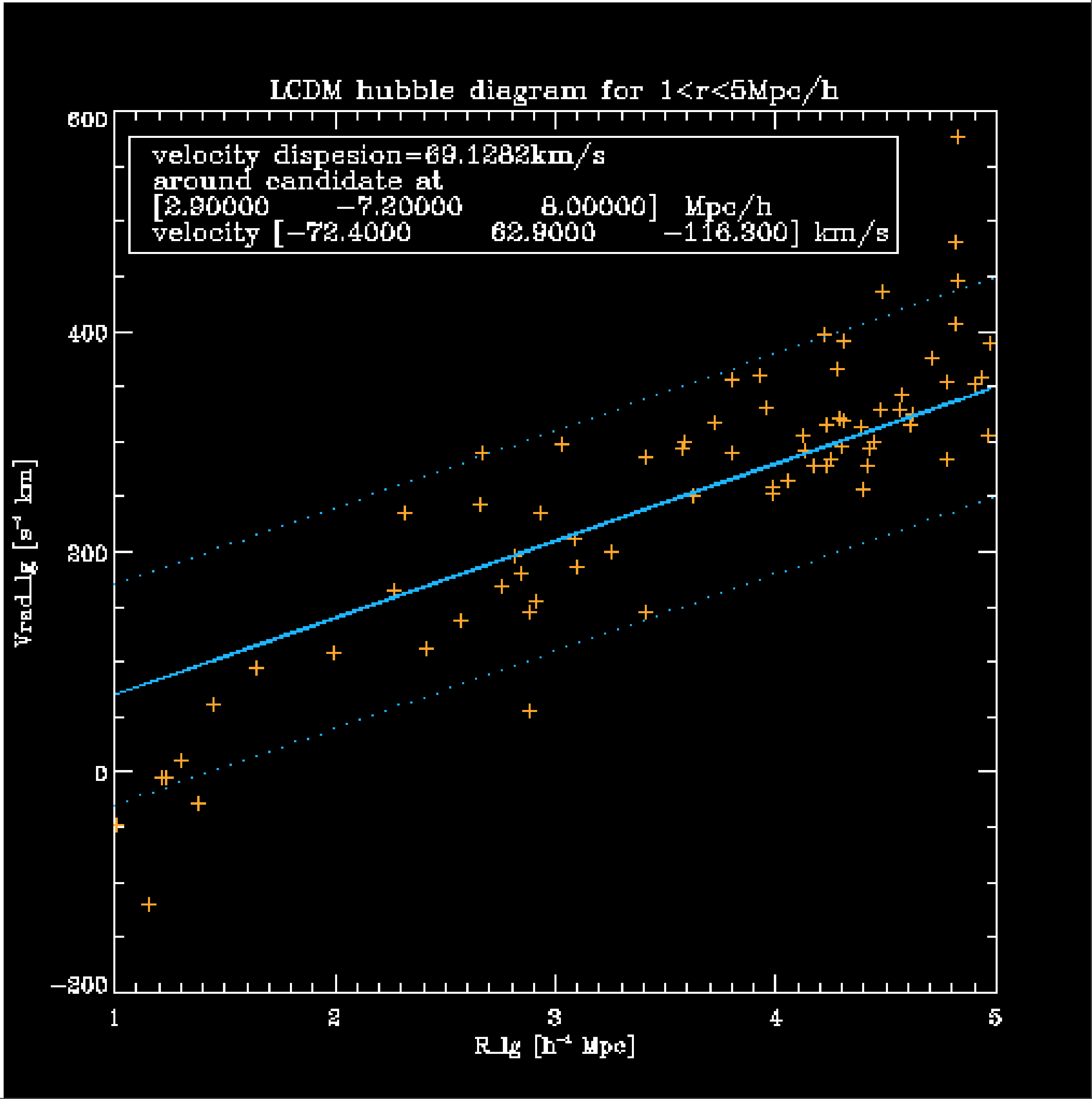

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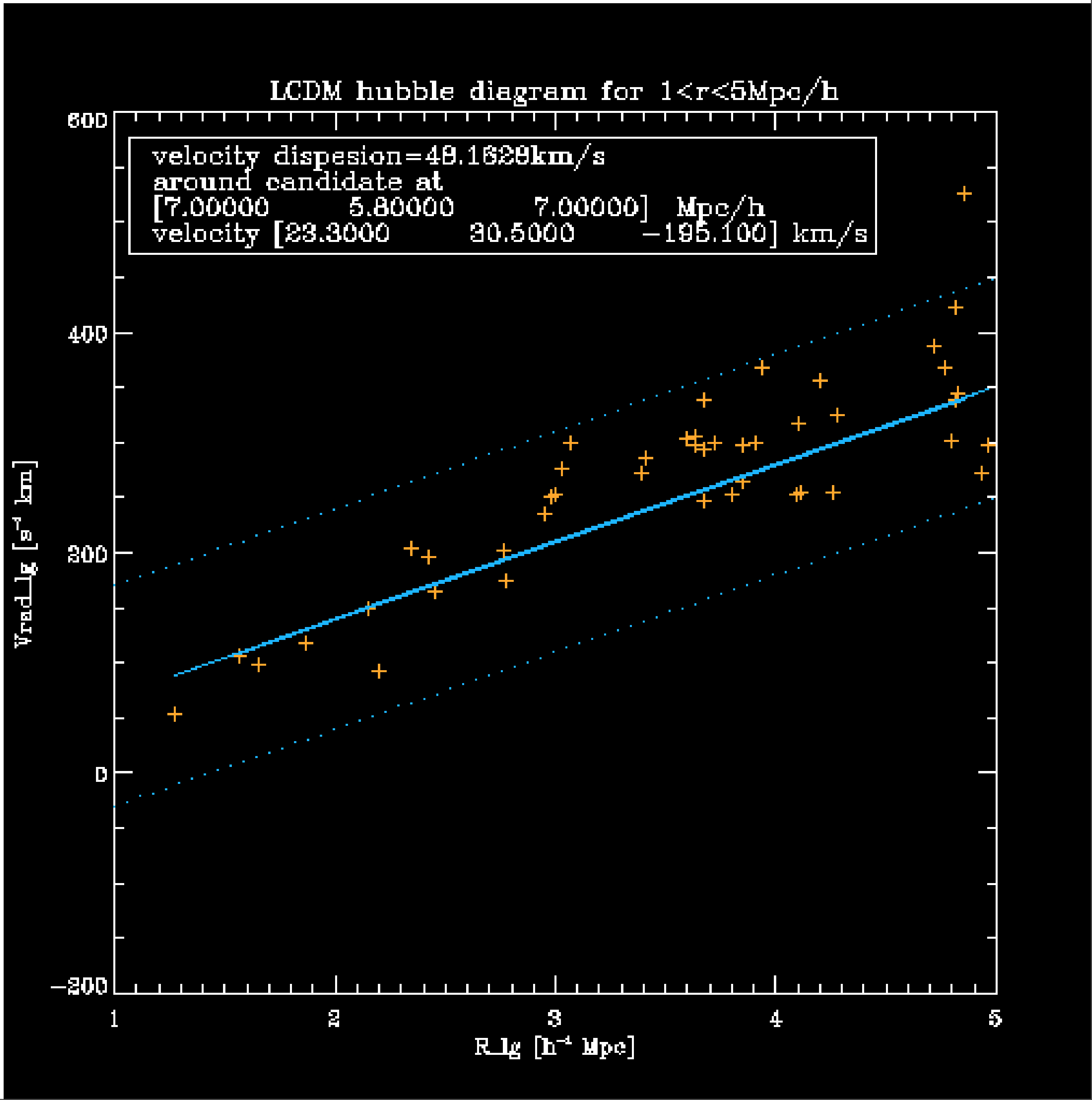


Cold Local Hubble Flow

LG candidates

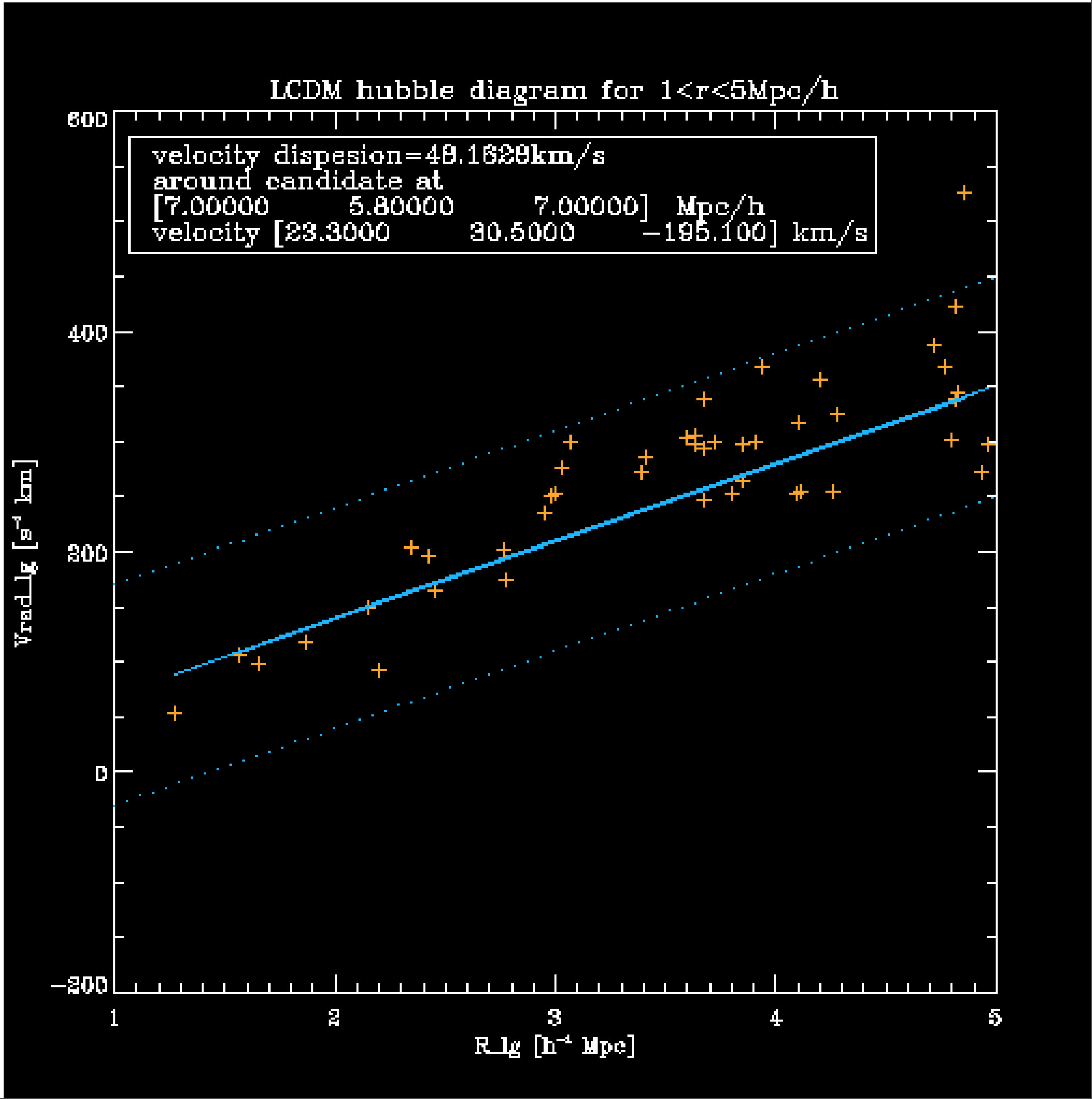
Two halos of ~1.e12M_{sun} /h

No similar halo within 2Mpc/h

More or less at the right location

Within ~12Mpc/h from the Virgo

Three LG candidates with cold Hubble flow, but some are NOT cold.

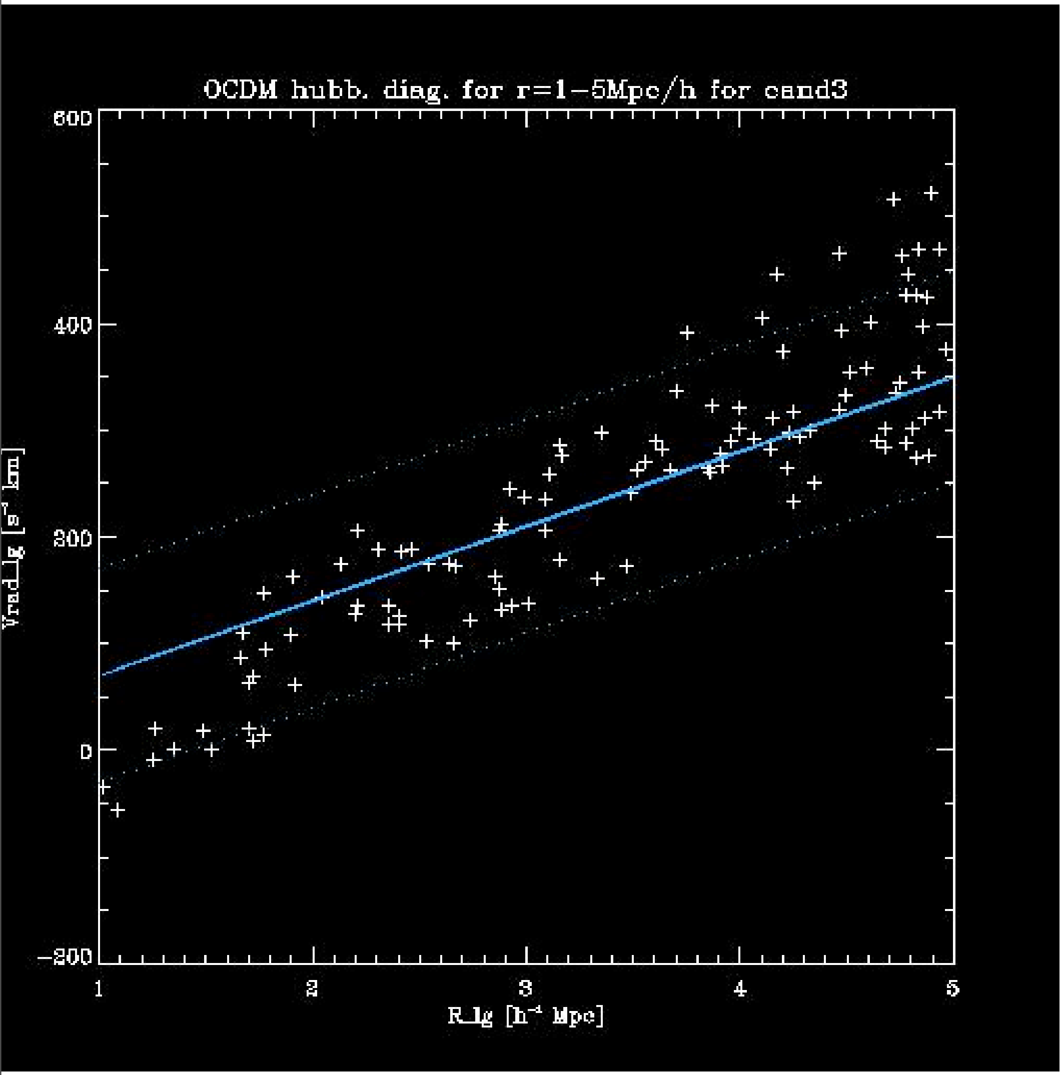


- Recently, it has been claimed that the coldness of the local flow is a manifestation of the **dark energy** (Maccio, Governato & Horellou 2005, Teerikorpi, Chernin & Baryshev 2005).

- Is it? Or maybe it is an environmental effect? Something else?

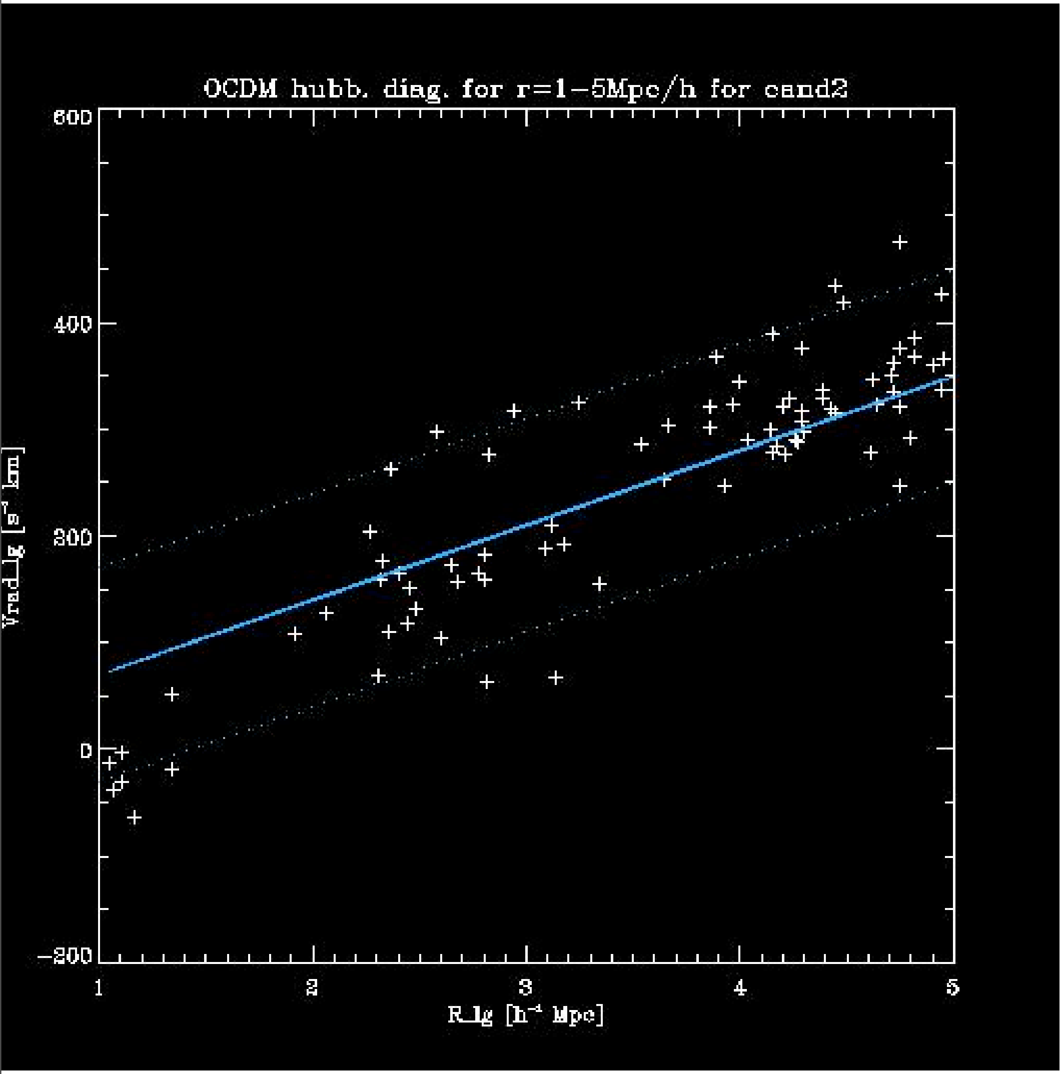
- Run constrained and unconstrained simulations for ΛCDM, OCDM and SCDM identify LG-like objects and study the coldness.

OCDM



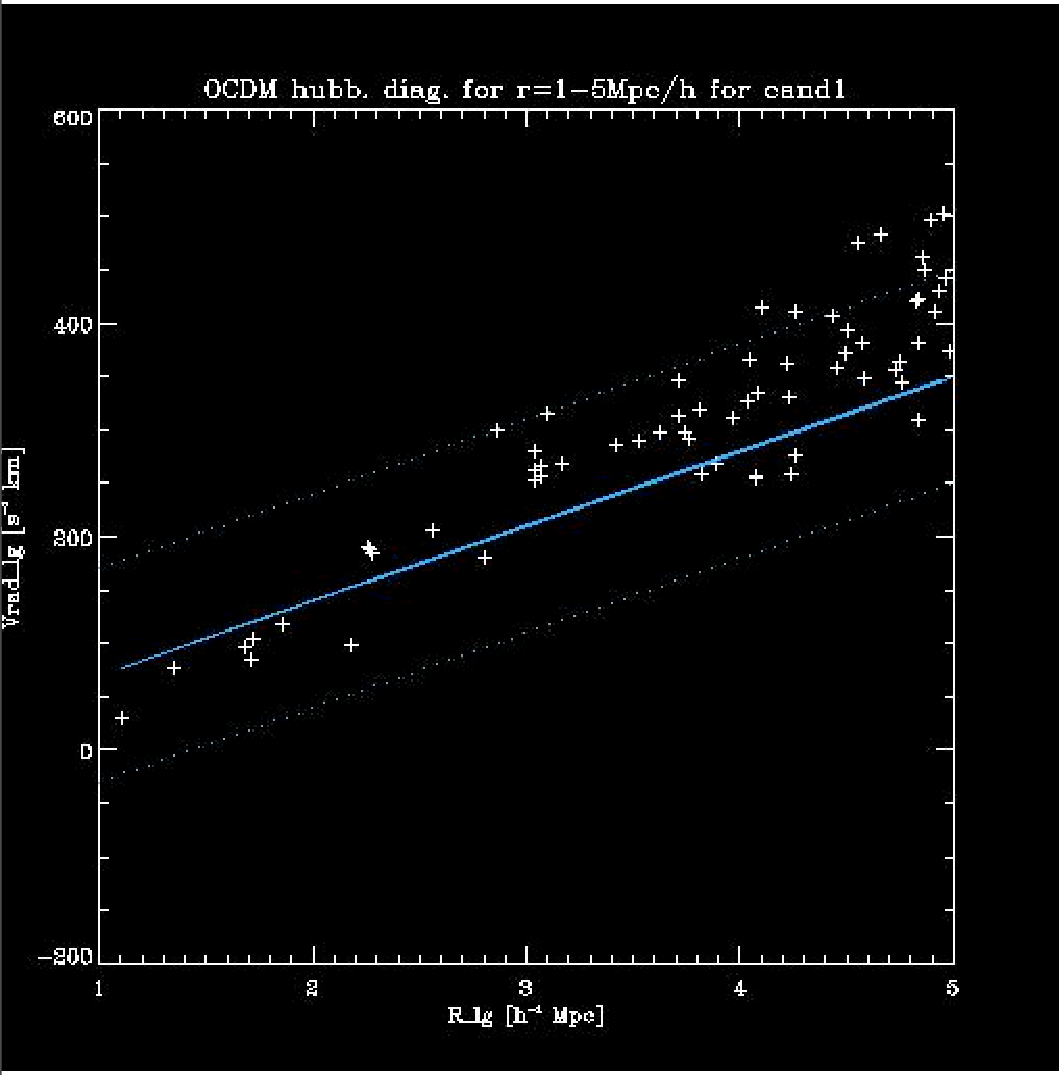
OCDM hubb. diag. for r=1-5Mpc/h for cand3
600
400
200
0
-200
1
2
3
4
5
Vrad_lg [s⁻¹ km]
R_lg [h⁻¹ Mpc]

OCDM



OCDM hubb. diag. for r=1-5Mpc/h for cand2
Vrad_lg [s⁻¹ km]
R_lg [h⁻¹ Mpc]
600
400
200
0
-200
1
2
3
4
5

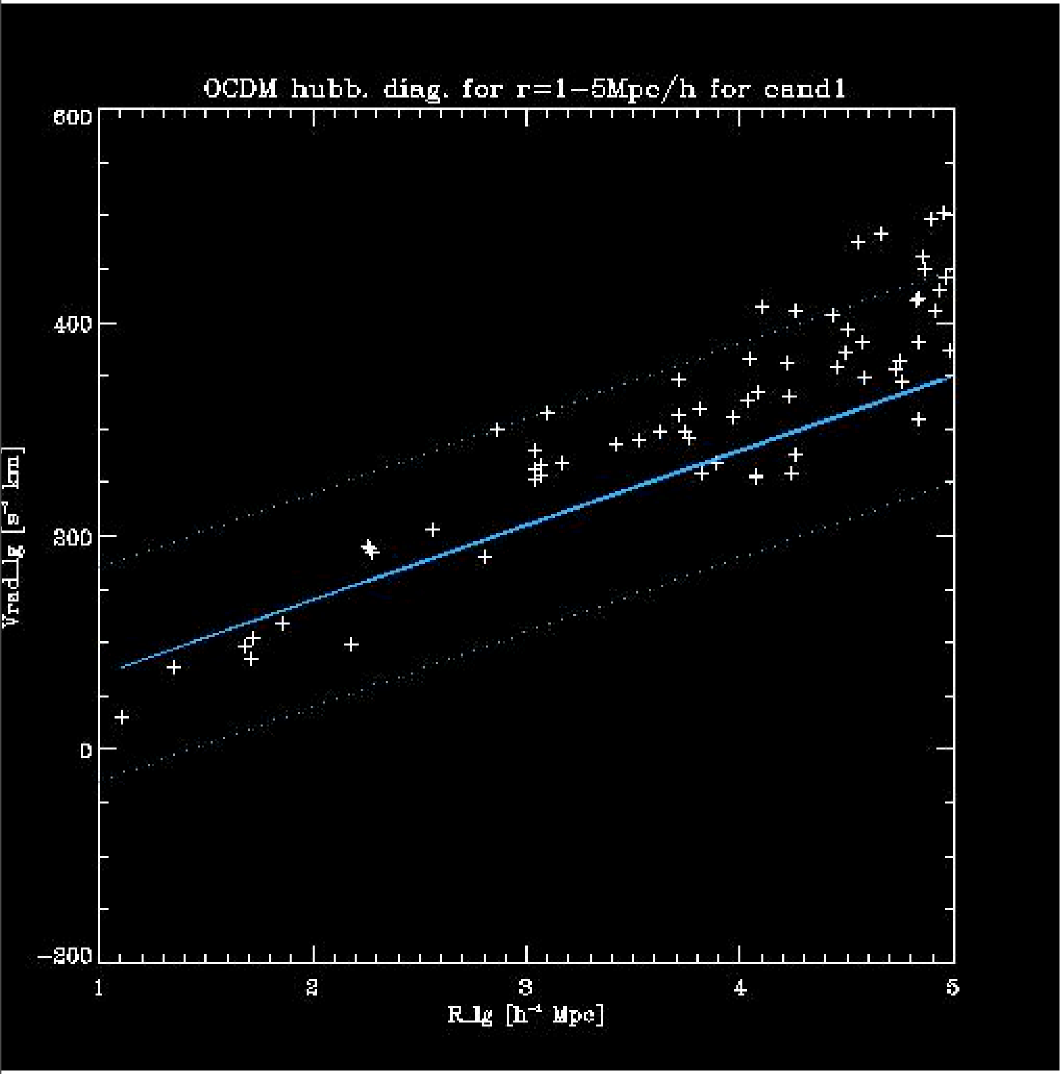
OCDM



OCDM hubb. diag. for r=1−5Mpc/h for cand1
600
400
200
0
−200
1
2
3
4
5
R_lg [h⁻¹ Mpc]
Vrad_lg [s⁻¹ km]

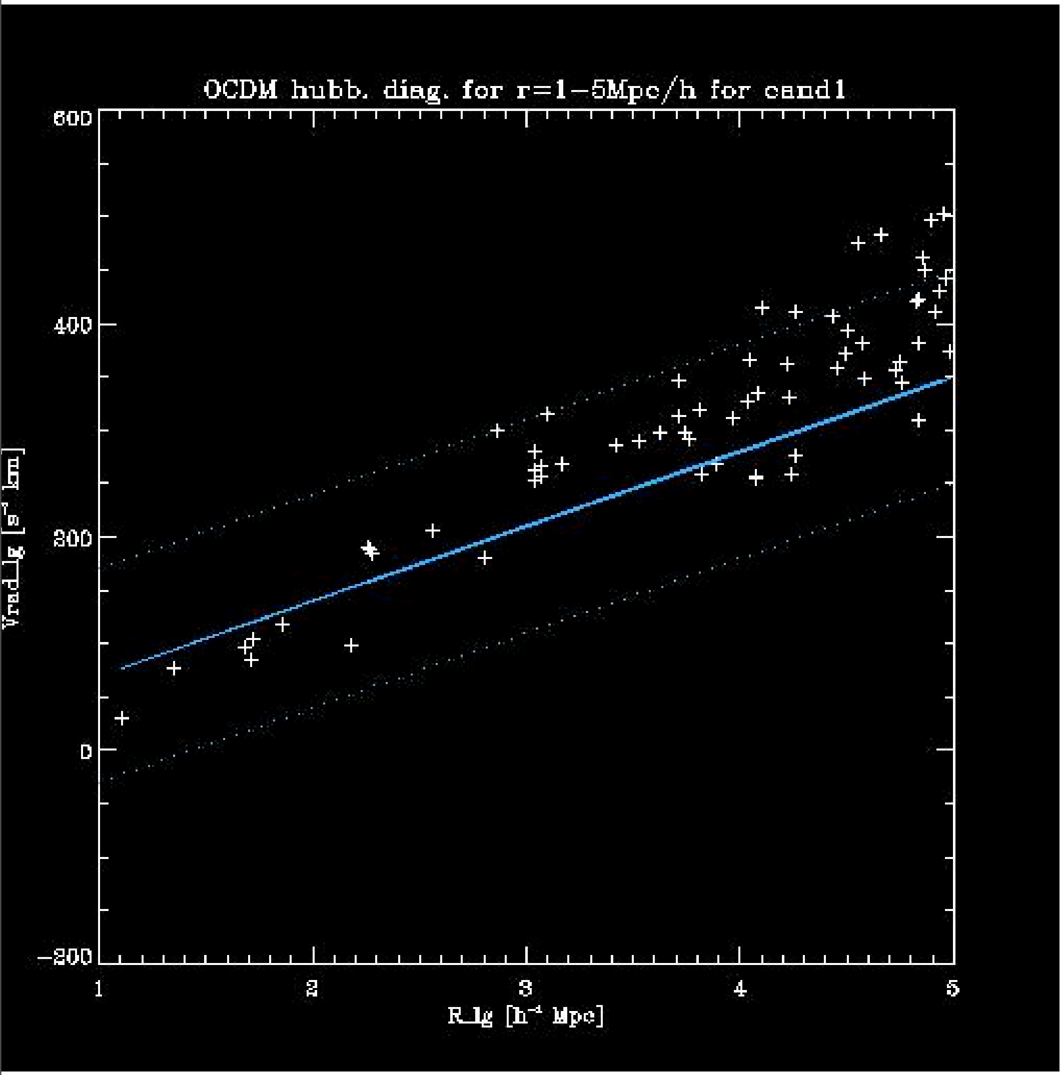
OCDM

SCDM

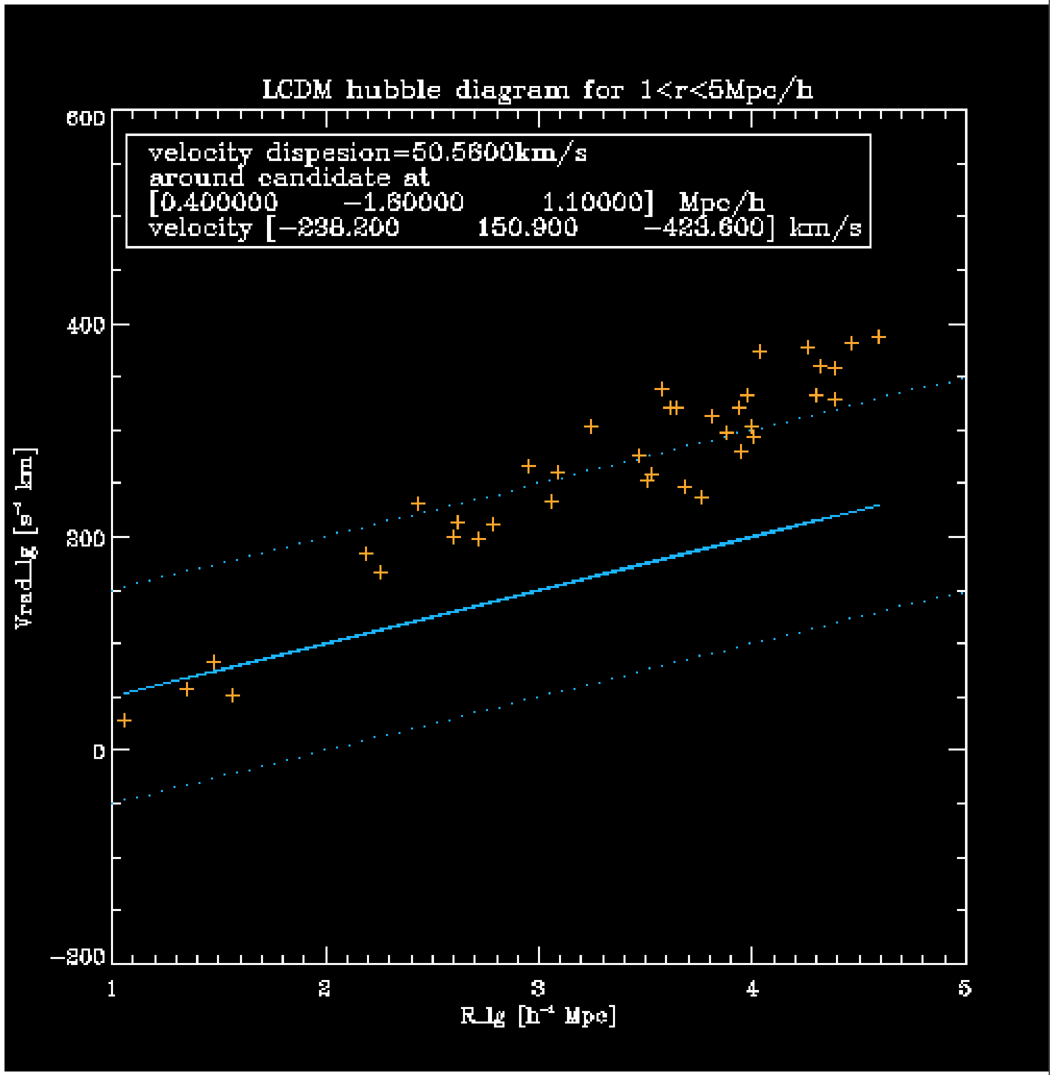

OCDM hubb. diag. for r=1−5Mpc/h for cand1
Vrad_lg [s⁻¹ km]
R_lg [h⁻¹ Mpc]
600
400
200
0
−200
1
2
3
4
5

OCDM

SCDM



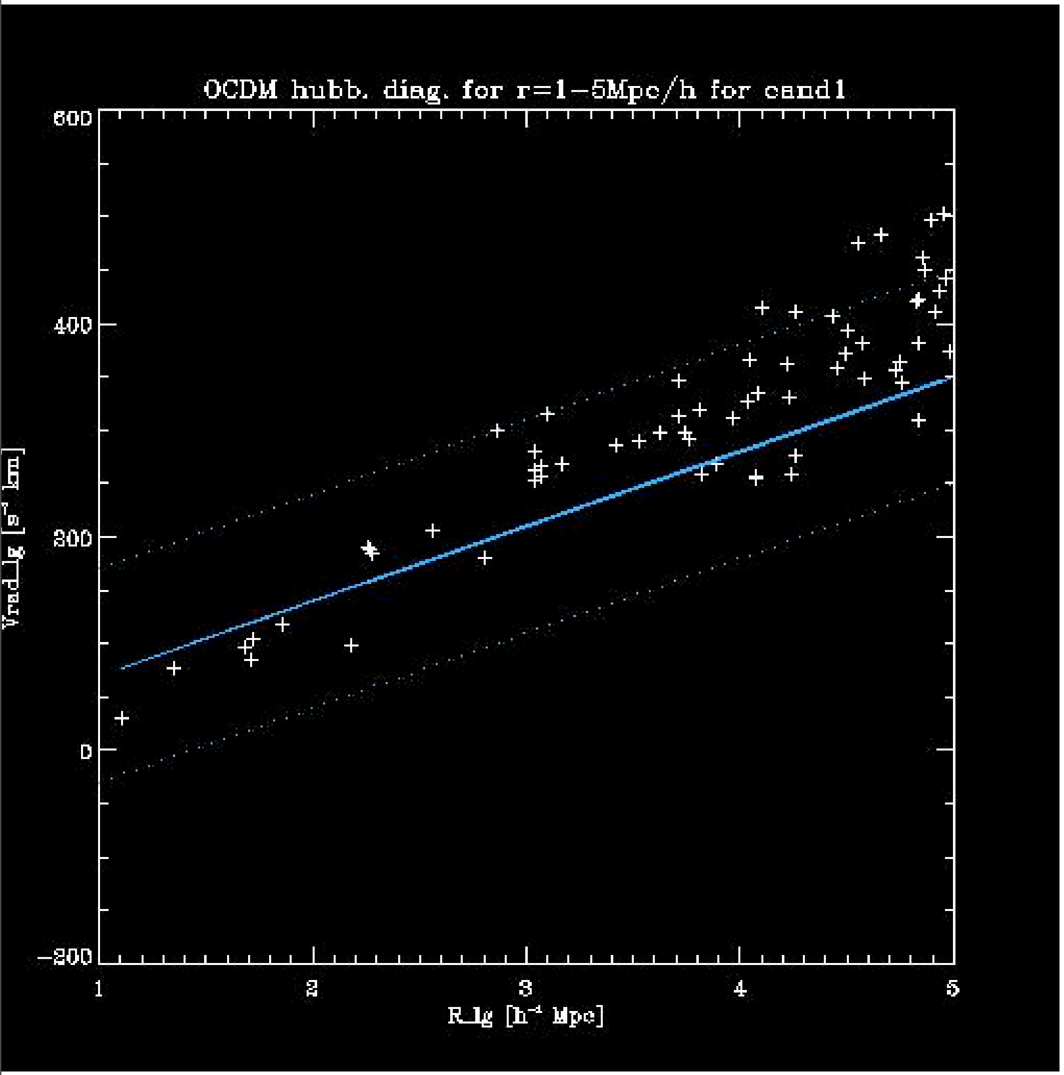
OCDM hubb. diag. for r=1-5Mpc/h for cand1
Vrad_lg [s^-1 km]
R_lg [h^-1 Mpc]

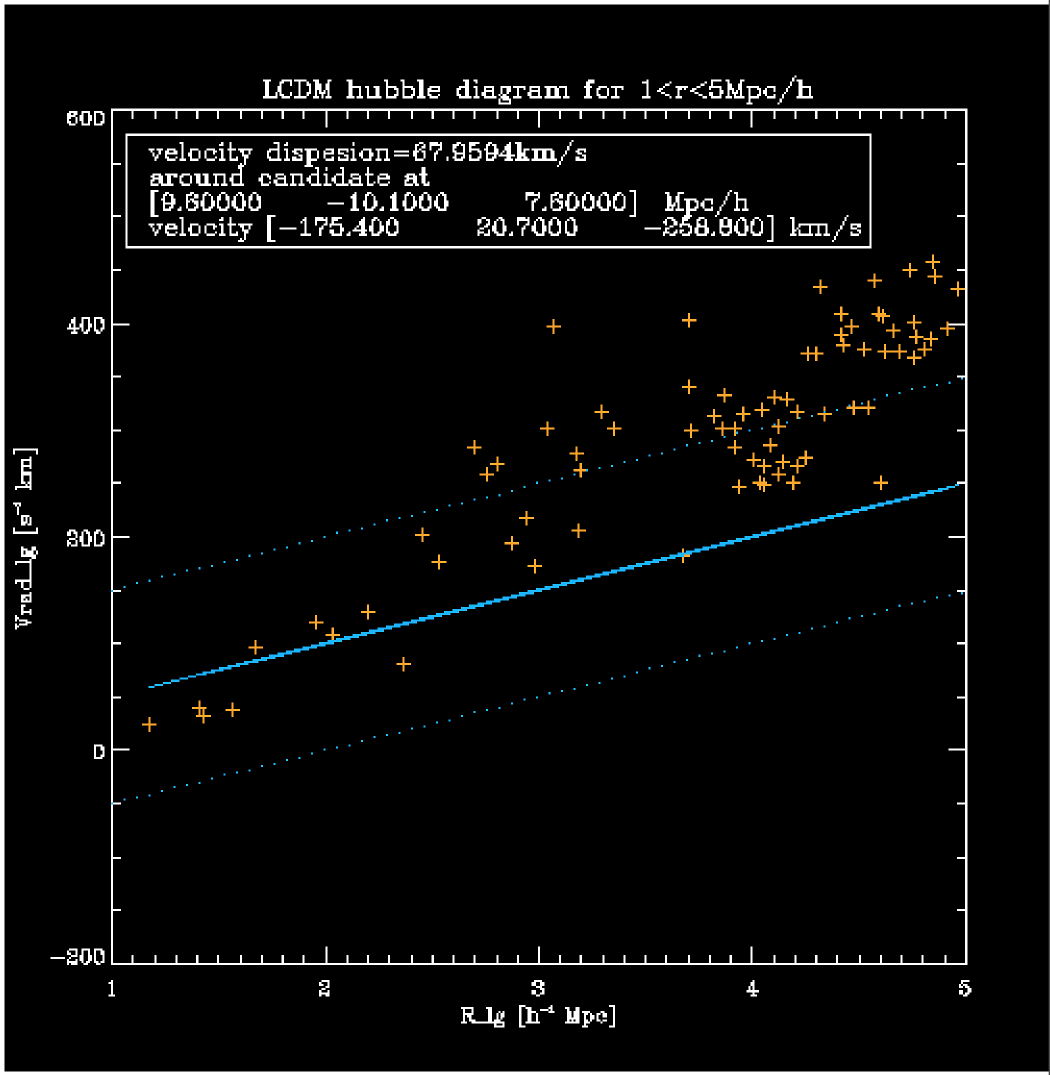


LCDM hubble diagram for 1<r<5Mpc/h
velocity dispesion=50.5600km/s
around candidate at
[0.400000 -1.60000 1.10000] Mpc/h
velocity [-238.200 150.900 -423.600] km/s
Vrad_lg [s^-1 km]
R_lg [h^-1 Mpc]

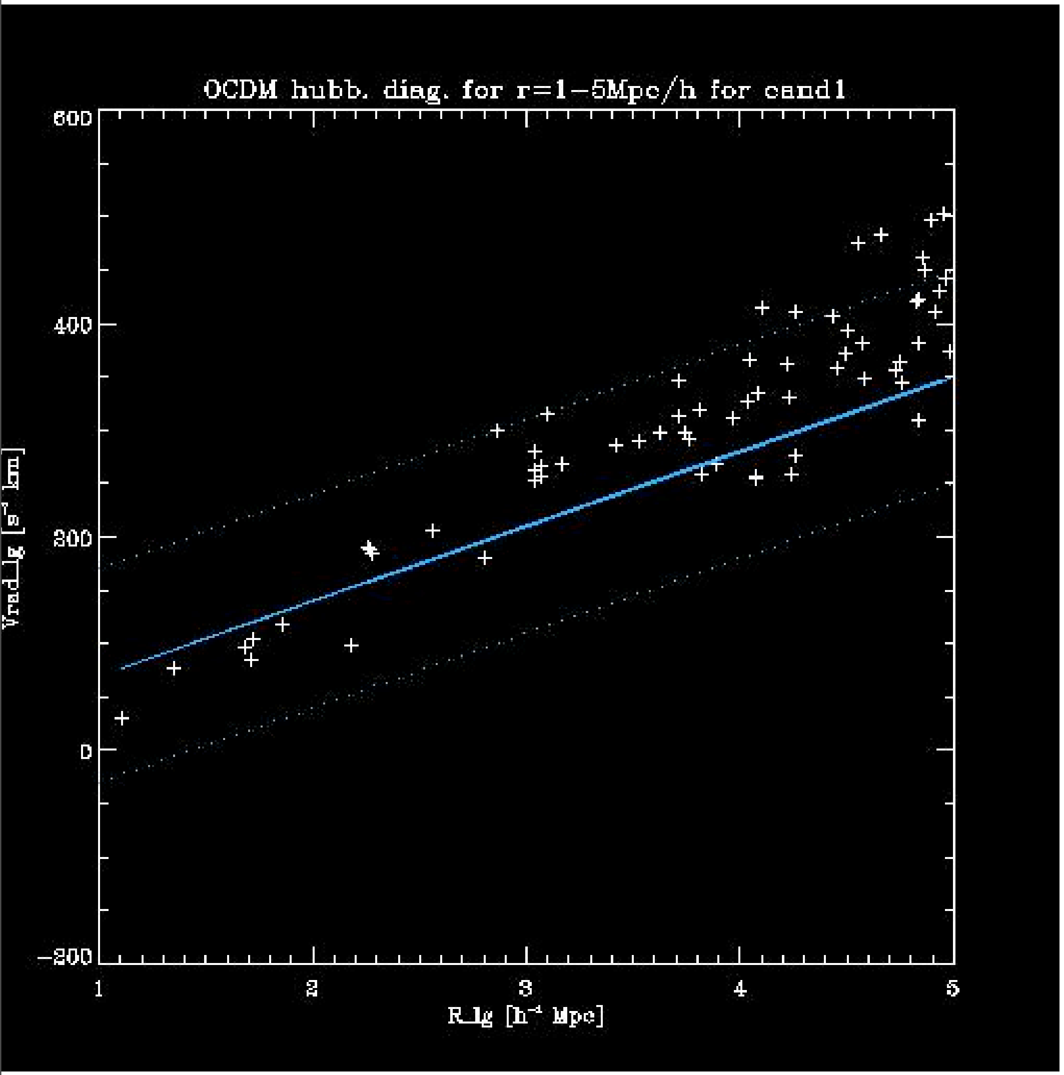
OCDM

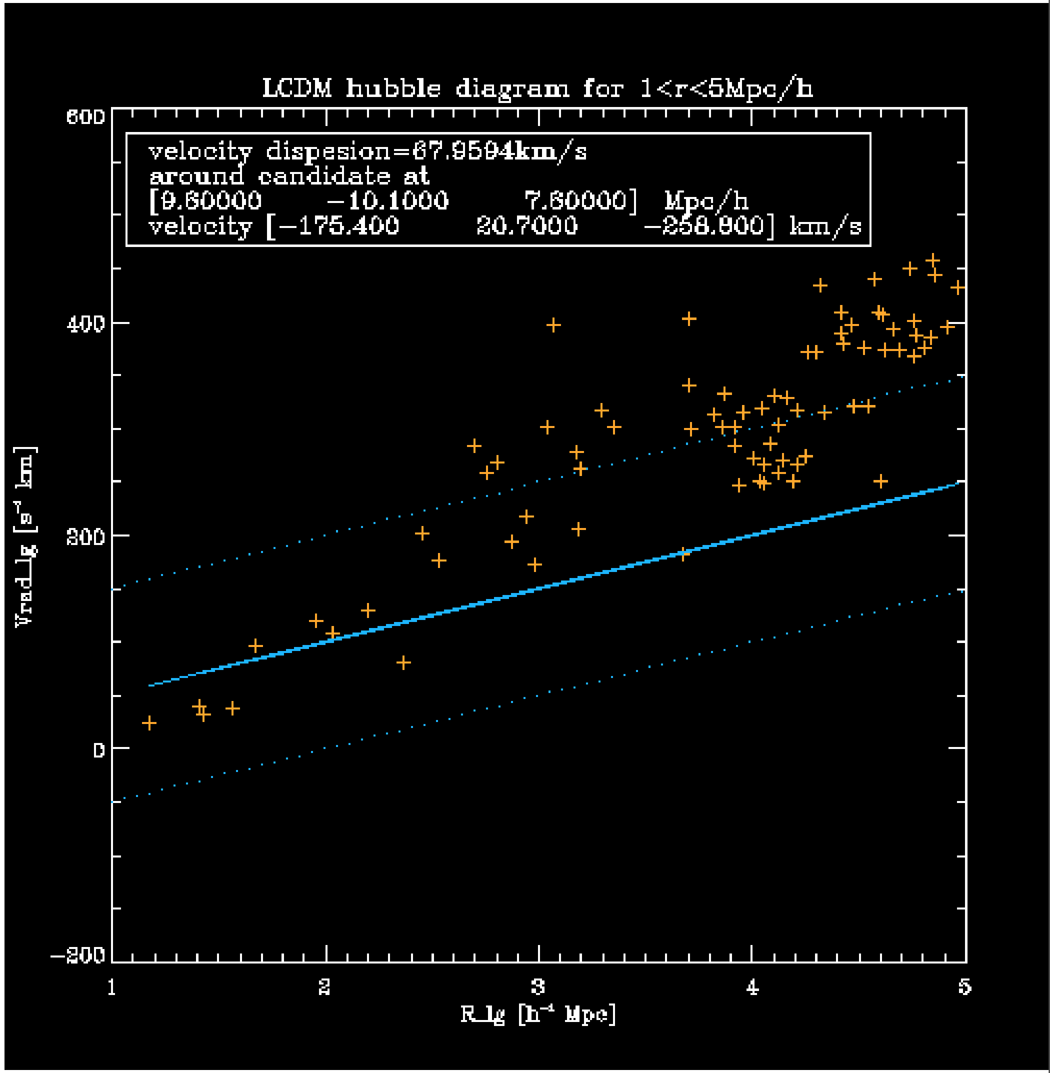
SCDM


OCDM hubb. diag. for r=1−5Mpc/h for cand1
600
400
200
0
−200
Vrad_lg [s^{-1} km]
1
2
3
4
5
R_lg [h^{-1} Mpc]


LCDM hubble diagram for 1<r<5Mpc/h
velocity dispesion=67.9594km/s
around candidate at
[9.60000 −10.1000 7.60000] Mpc/h
velocity [−175.400 20.7000 −258.900] km/s
600
400
200
0
−200
Vrad_lg [s^{-1} km]
1
2
3
4
5
R_lg [h^{-1} Mpc]

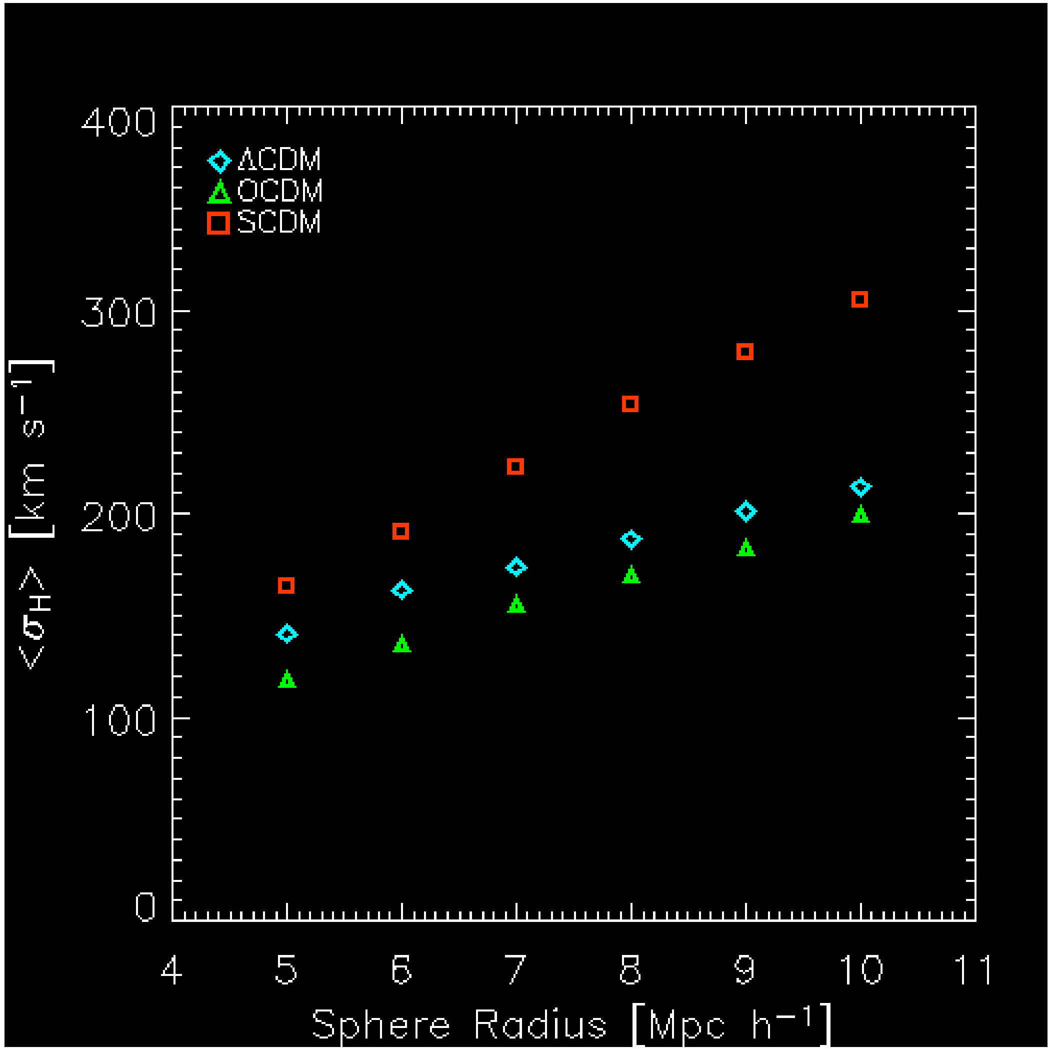
OCDM SCDM



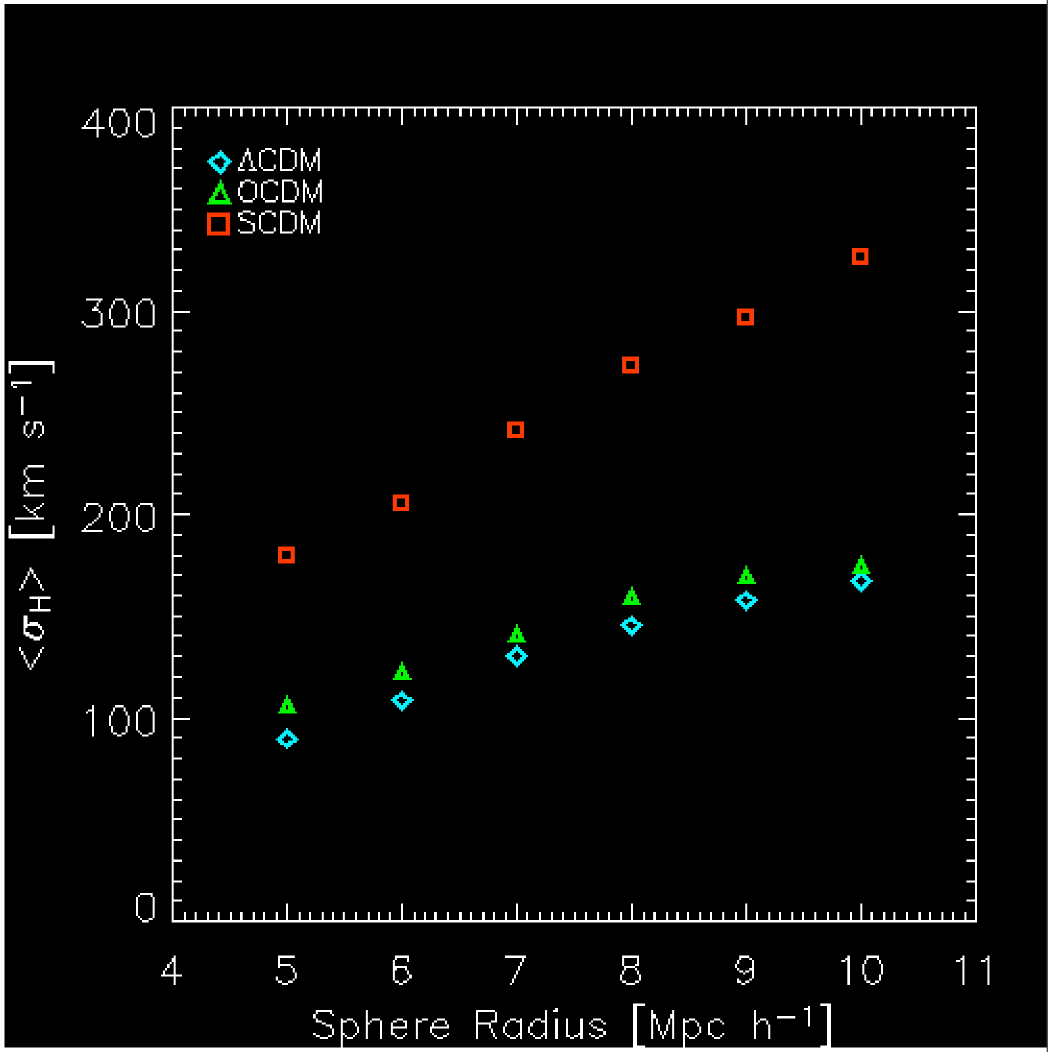


Cold flows emerge in other cosmologies as well!

Statistics of σ_H



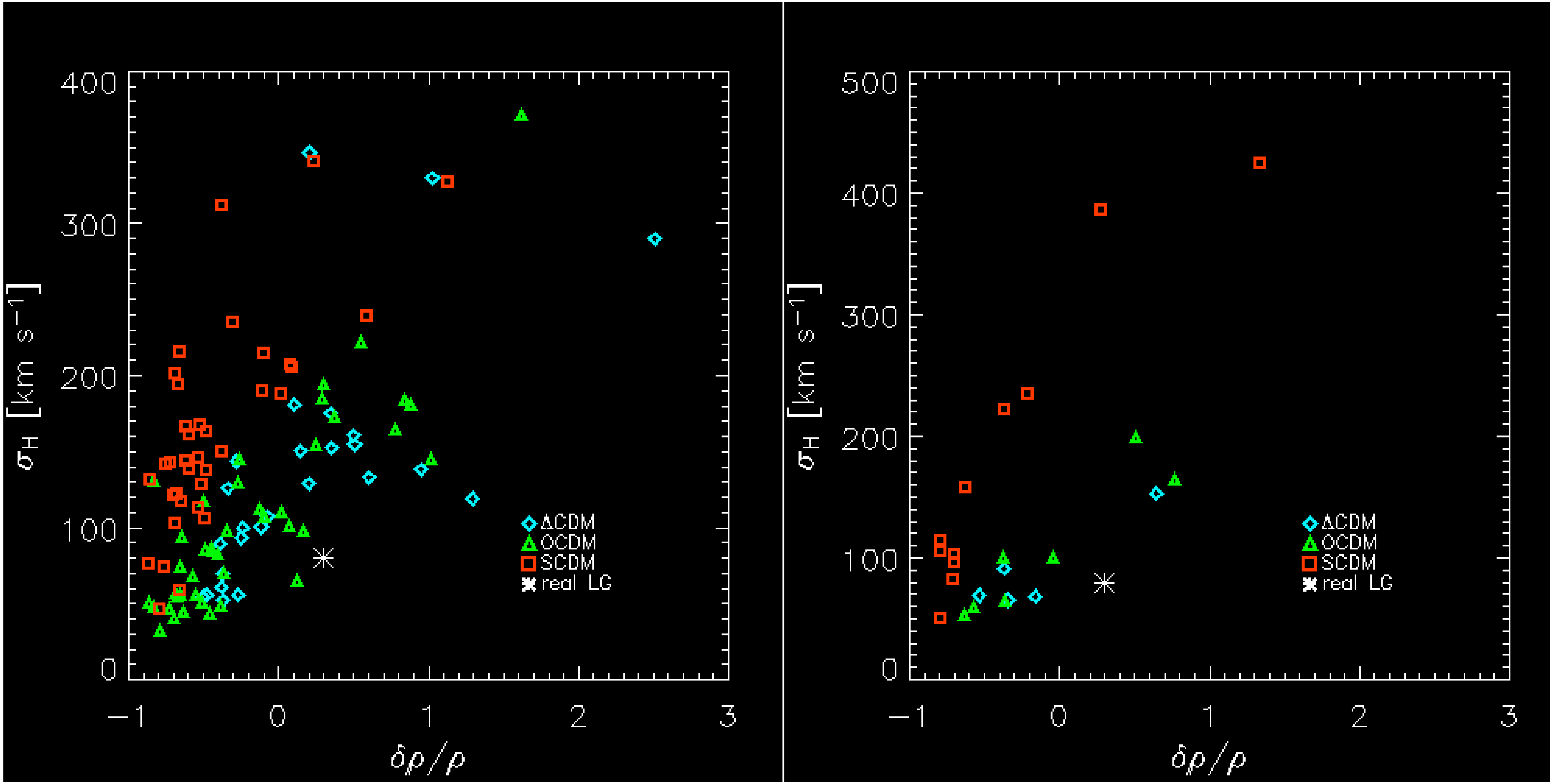
(Objects selected a la Maccio et al 2005)



(Objects selected our way)

Similar results are obtained in the ΛCDM and OCDM unconstrained simulations.

So, the issue is not the coldness of the local flow but rather ...



(Objects selected a la Maccio et al 2005)

(Objects selected our way)

The (over)density is measured within a sphere of R=5Mpc/h

Observations of galaxies: $\delta_{gal}(R<5Mpc/h) \sim 0.5 +/- 0.2$

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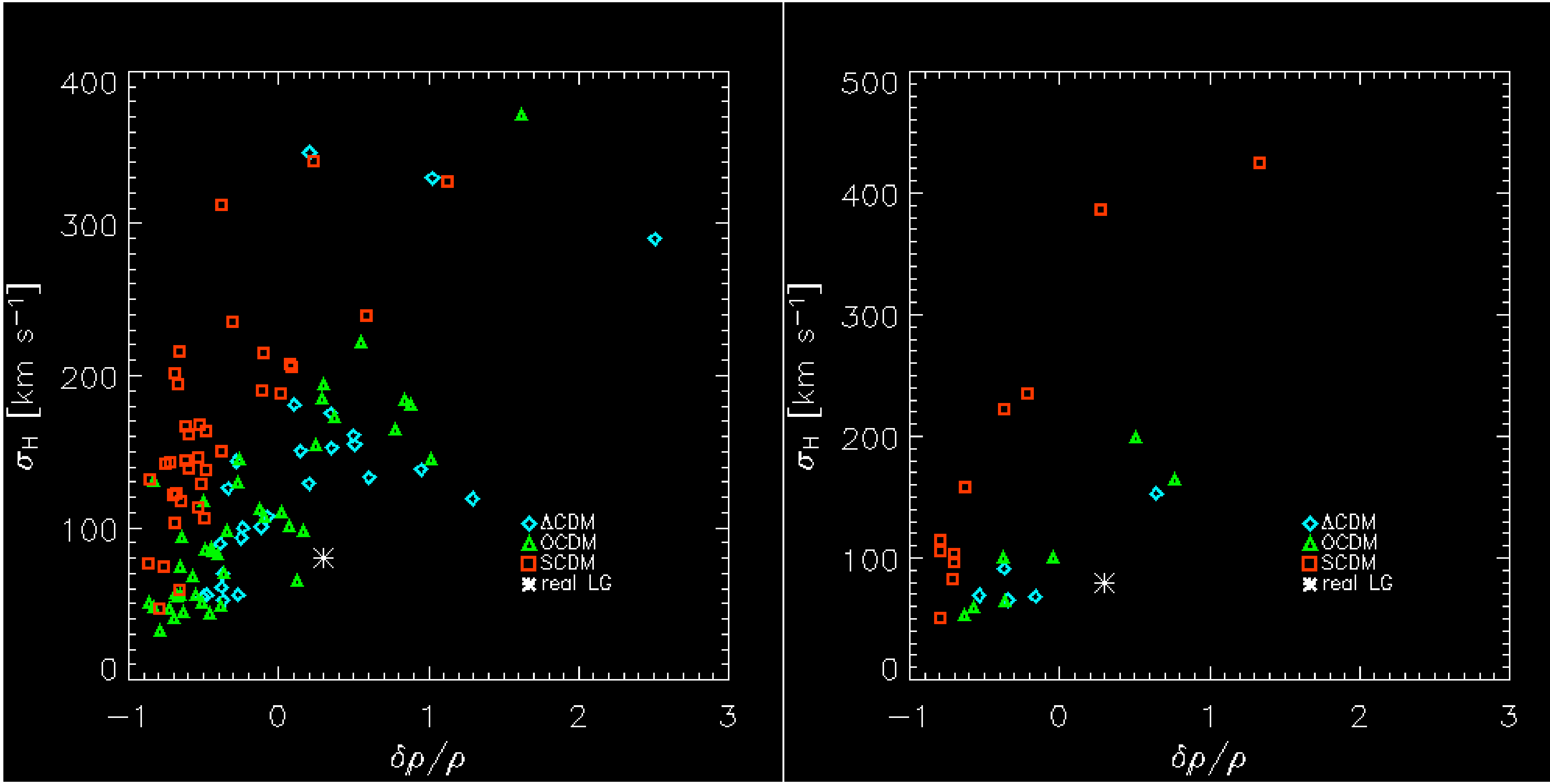

(Objects selected a la Maccio et al 2005) (Objects selected our way)

The (over)density is measured within a sphere of R=5Mpc/h

Observations of galaxies: δ_{gal}(R<5Mpc/h) ~ 0.5 +/- 0.2

...of cold LG-like objects in a mildly overdense environment.

Conclusions

- The problem is not of **'coldness'** but rather **'coldness' vs overdensity**.
- The peculiarity of the local neighborhood still remains. The LG is either too cold/overdense compared with theoretical expectations.
- Flat-ΛCDM & OCDM predict the same dynamics in the LG environment.
- Apart from the **(coldness of the flow | density)** the local region appears to be very typical for Flat-ΛCDM & OCDM

The Zone of Avoidance (ZOA) & the Coldness of the Local Flow

indisputable facts

- The Galactic ZOA contains the GA & PP supercluster
- The LG is caught in a 'tug of war' between the GA & PP
- The tidal field within the LSC is dominated by the GA & PP (Lilje, Yahil & Jones 1988)
- The tidal field in the LG environment is (at least partially) dominated by the GA & PP
- The tidal field constitutes a deviation from a pure isotropic expansion

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- The tidal field constitutes a deviation from a pure isotropic expansion

- A Galactic observer who measures the dispersion around a pure Hubble flow only outside of the ZOA is bound to underestimate it.
- Can it be that the local flow is hotter than what we think it is?

The LG Neighborhood

- σ_H = 88 +/- 20 km/s (R/5 Mpc h^{-1})

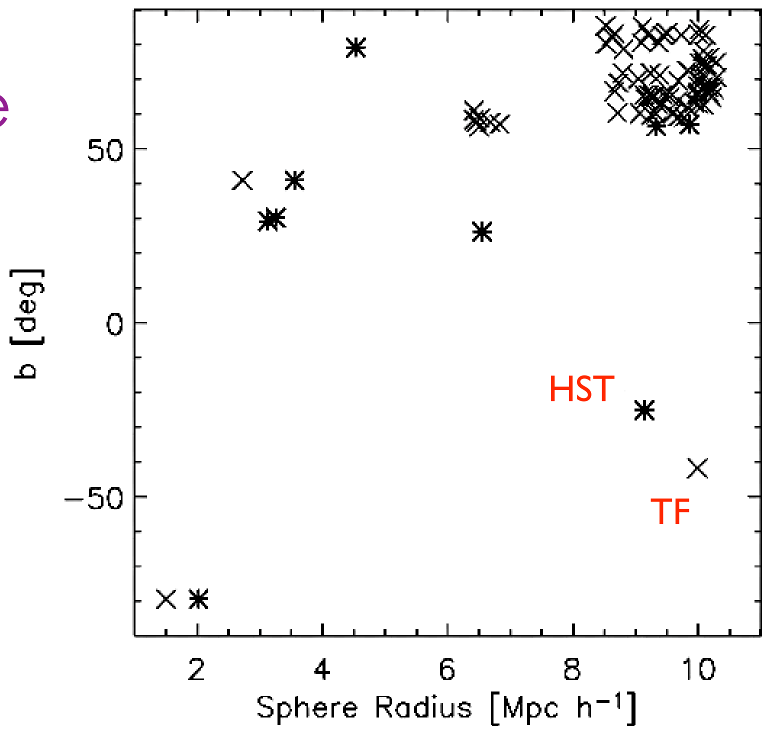
  (Maccio, Governato & Horellou 2005, based on HST, SBF & TF)

- The mean overdensity is:

  δ(R<5Mpc/h) ~ 0.5 +/- 0.2

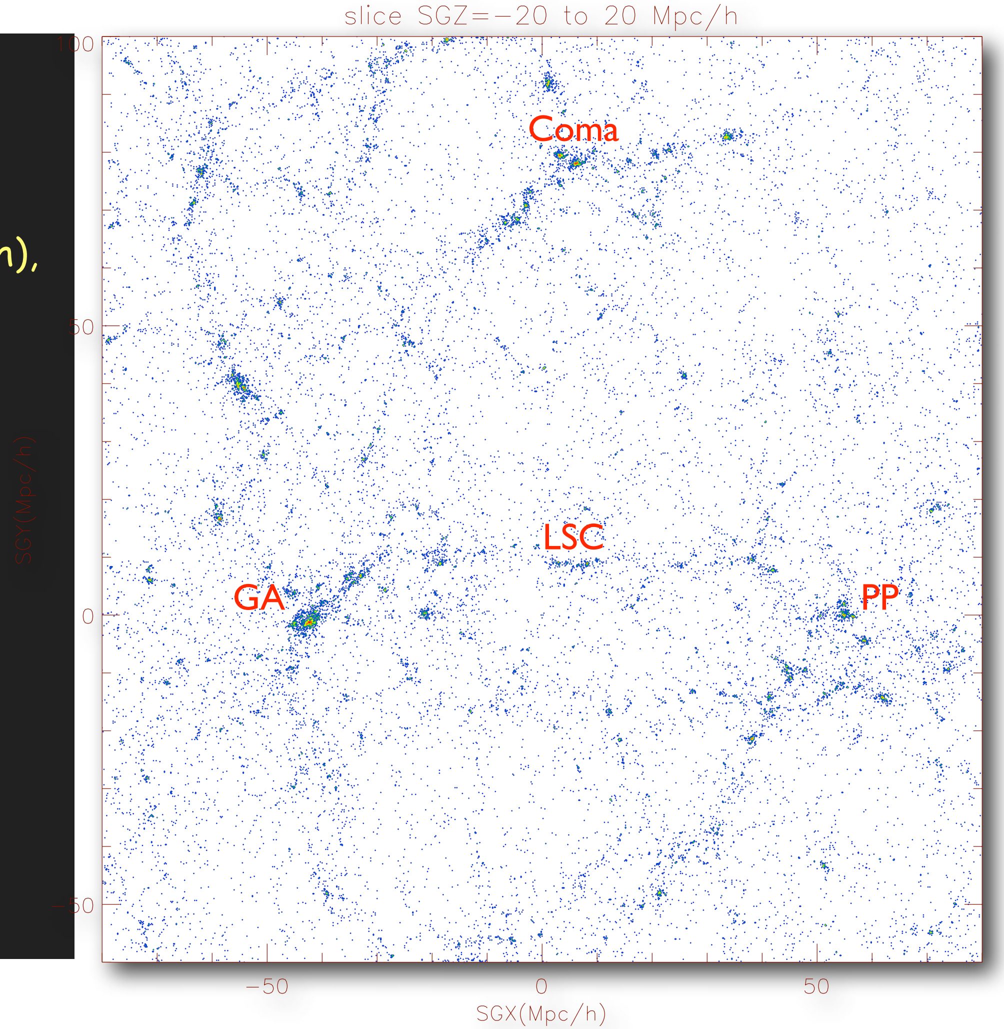
- The effective ZOA of these data base

  |b|~25°



Testing the Effect of the ZOA

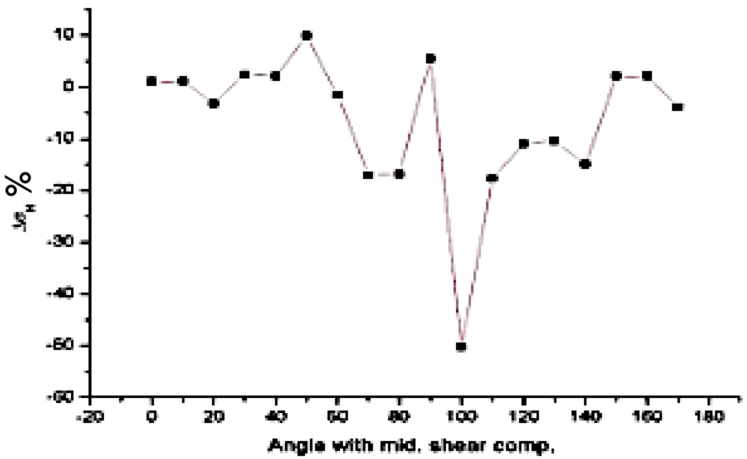
- Use a CS of the local universe
- CS: large box that contains the GA & PP (L=160Mpc/h), high resolution inner sphere (R=30Mpc/h) with effective $N=1024^3$ resolution (m_p=3.2e8M_{sun}/h)
- Pick up LG-like candidates
- Define a ZOA for each candidate and check how σ_H changes with its orientation
- Study the orientation of the ZOA relative to the eigenvectors of the shear tensor
- Compare with the actual LG



$$v_\alpha = U_\alpha + \frac{\partial v_\alpha}{\partial r_\beta} r_\beta + \epsilon_\alpha = U_\alpha + \left(\frac{1}{3}(\nabla \cdot \mathbf{v})\delta_{\alpha\beta} + \Sigma_{\alpha\beta} + \omega_{\alpha\beta}\right) r_\beta + \epsilon_\alpha$$

$\omega_{\alpha\beta}=0$ shear tensor

LG-like Candidate:
M_1=4.0e12M_{sun}/h, M_2=1.8e12M_{sun}/h
δ(R=5Mpc/h)=0.105, D=1.0Mpc/h, V_{rad}=-122km/s
Distance to simulated Virgo ~ 10Mpc/h
Located in a filament connected to "Virgo"
For a full sky observer σ_H =97km/s



Shear & Bulk

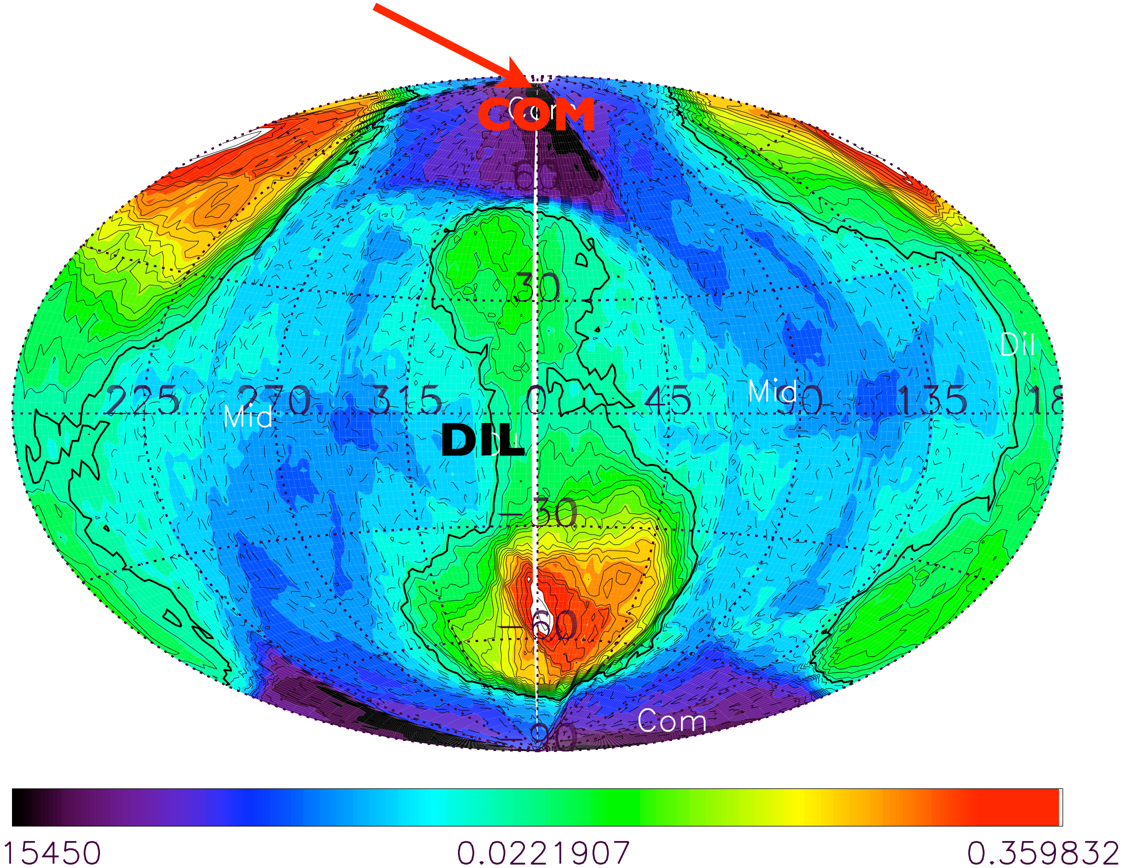
<u>eigenvalues</u>: 29, 15, -44 h km/s/Mpc

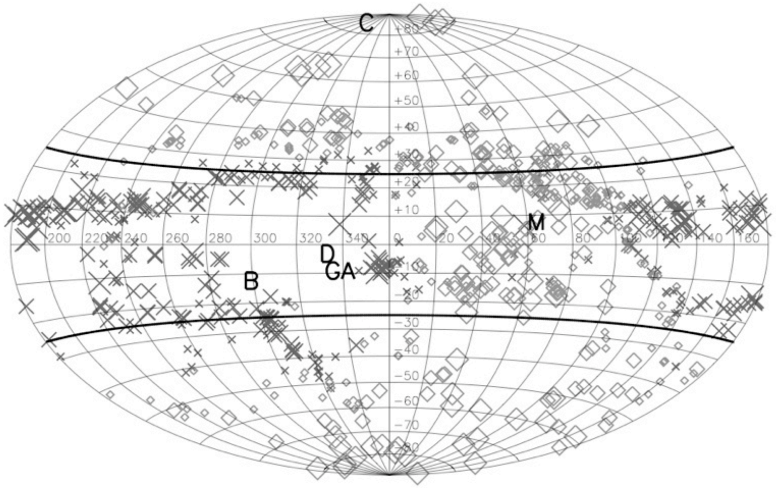
<u>eigenvectors</u>: (gl, gb)
dilational = ~(330, -5)
middle = ~(50, 5)
compresional = ~(330, 85)

<u>bulk</u>(v,gl,gb) = 250km/s, 300, -12

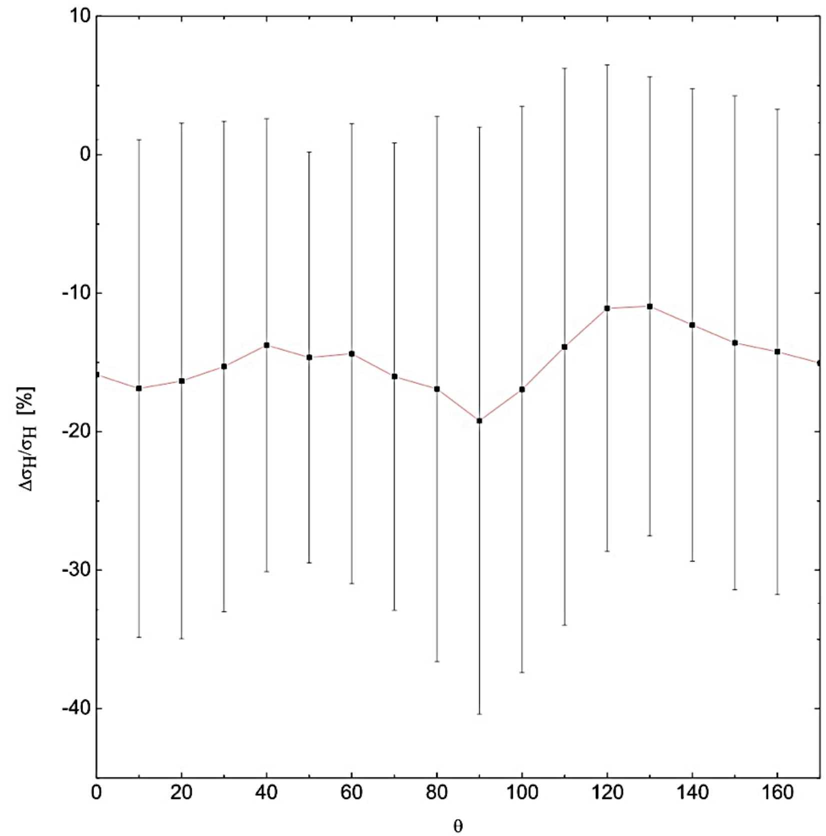
ZOA direction in galactic (l,b) relative to the LG-candidate

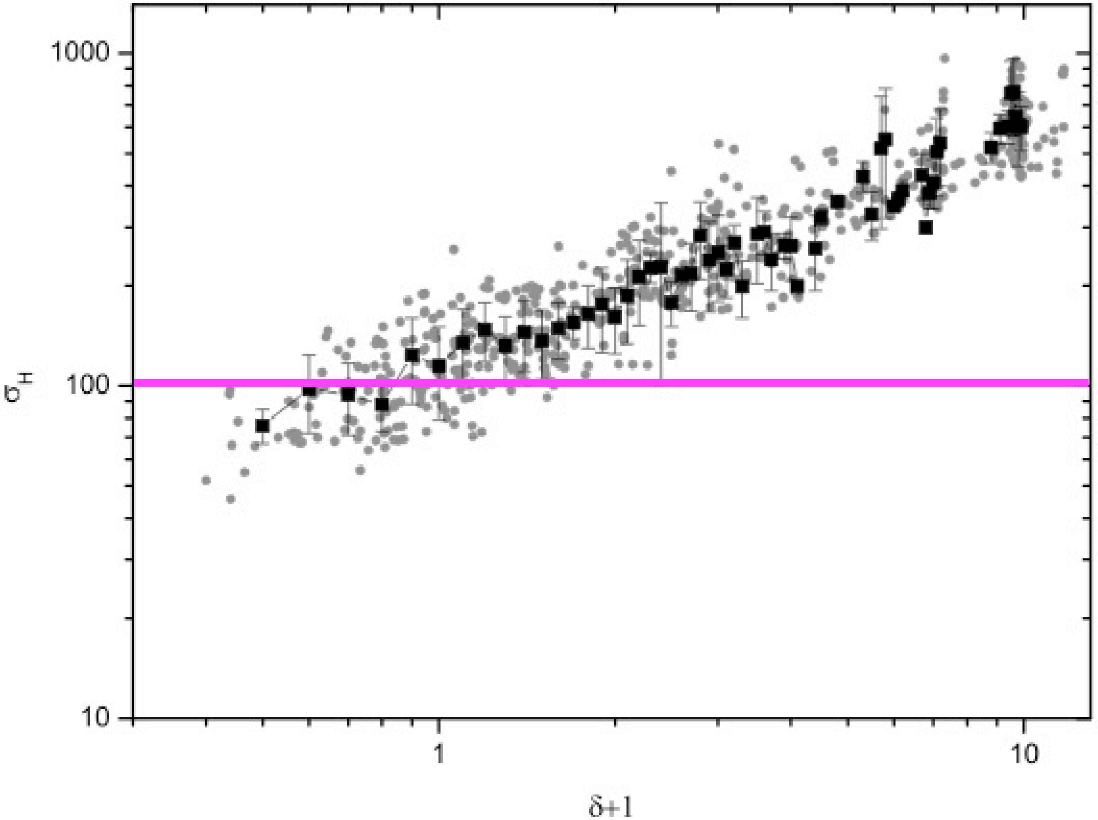
Maximum reduction of σ_H ~50%





Sample of galactic size DM halos:
Mass: (0.5 -> 10) 10^{12} M_{sun}/h
Location: Within 25Mpc/h from the center
and +/- 10Mpc/h from the
Supergalactic Plane
Sample: 606 halos





ZOA and the Coldness ...

- A 'galactic' ZOA that points roughly in the direction of the shear's compressional eigenvector leads to an underestimation of σ_H.
- For the best LG-like object we find a 50% reduction in σ_H.
- For a sample of galactic size halos near the Supergalactic plain we find a reduction in σ_H of ~(20 +/-20)%.
- The Galactic ZOA points close to the shear's compressional mode.

- Light and Motion in the Local Volume (Whiting, 2005)

- ABSTRACT:
- Using high-quality data on 149 galaxies within 10 megaparsecs (Mpc), I find no correlation between luminosity and peculiar velocity at all. There is no unequivocal sign on scales of 1-2 Mpc of the expected gravitational effect of the brightest galaxies, in particular infall toward groups; or of infall toward the Supergalactic Plane on any scale. Either dark matter is not distributed in the same way as luminous matter in this region, or peculiar velocities are not due to fluctuations in mass.

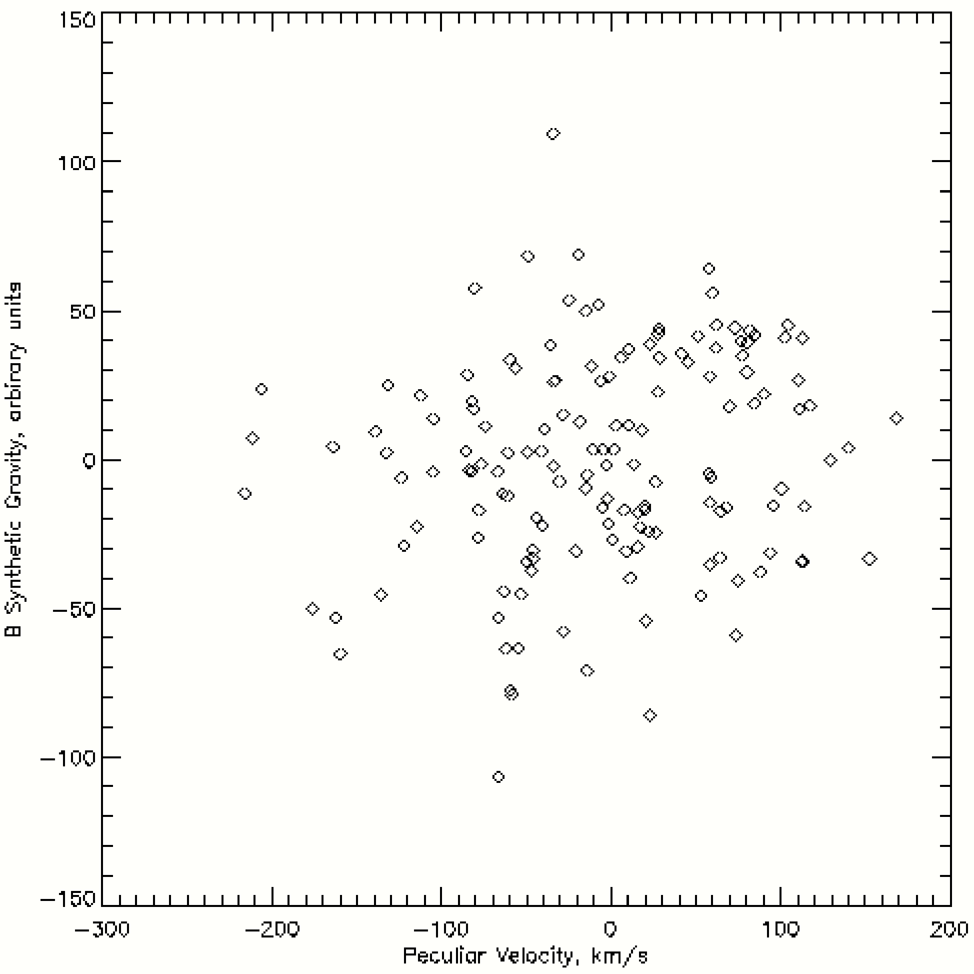
Study of velocity and gravitational fields of observed galaxies within 7 Mpc/h Local Volume

↓

No correlation between peculiar velocity & gravity

↓

Peculiar velocities could not be the result of mass fluctuations



Our(+) study

- ***Local g-field***: taking into account only haloes (treated as point particles) within the Local Volume (< 7 Mpc/h, following W05)
- ***Global g-field***: using all the matter distribution (as calculated by the N-body code)

Goals:

- Check the two hypotheses:

a. The local g-field reproduces the global one

b. Linear theory is valid within the Local Volume (namely $v \propto g$)

- Analyze relation between peculiar velocity and gravity for different cosmological models and initial conditions (constrained and unconstrained)

+ L. A. Martinez, G. Yepes & YH

LG-like candidate in a constrained ΛCDM simulation

$$\mathbf{g} = \frac{2f(\Omega_m, \Omega_\Lambda)}{3H_0\Omega_m}\,\tilde{\mathbf{g}}$$

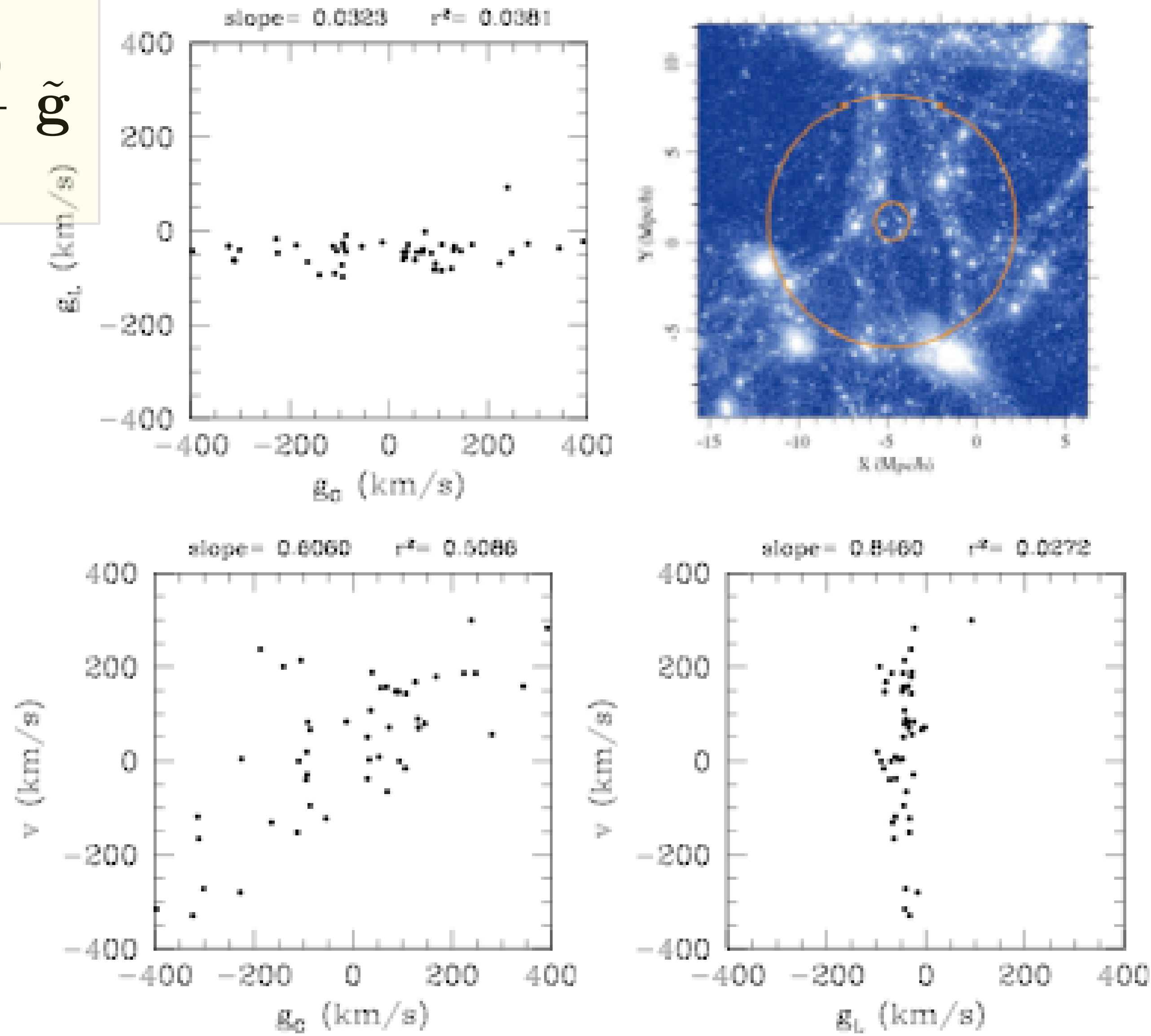


Figure 9. Plots of g_L^y vs. g_G^y, v vs. g_G^y and v vs. g_L^y for the *best* candidate in ΛCDM simulation. The distribution of matter nearby to the candidate (in the supergalactic plane) is also ploted, where the external orange circle limits the Local Volume and the small one points out the Local Group position.

Local vs Global g-field

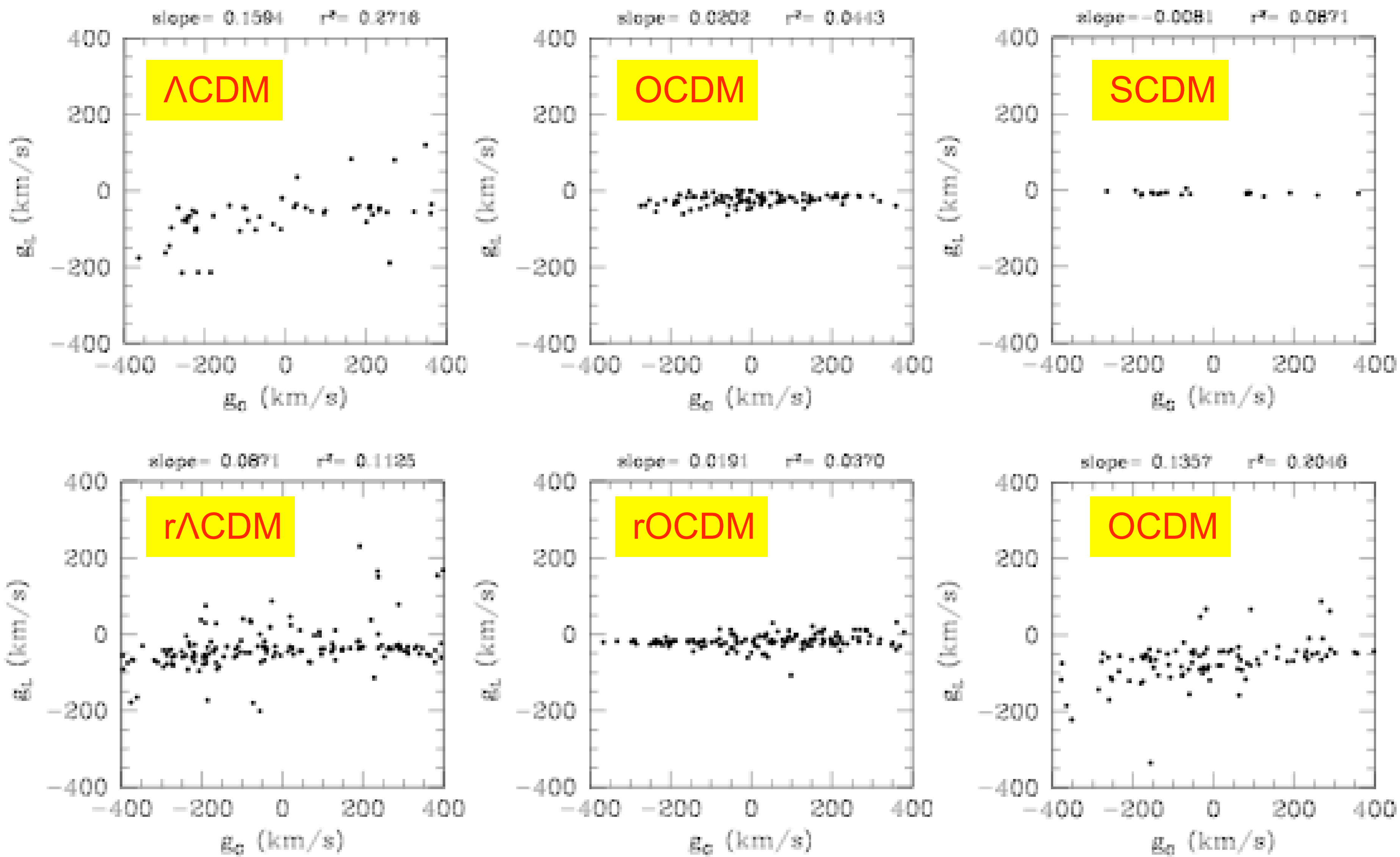
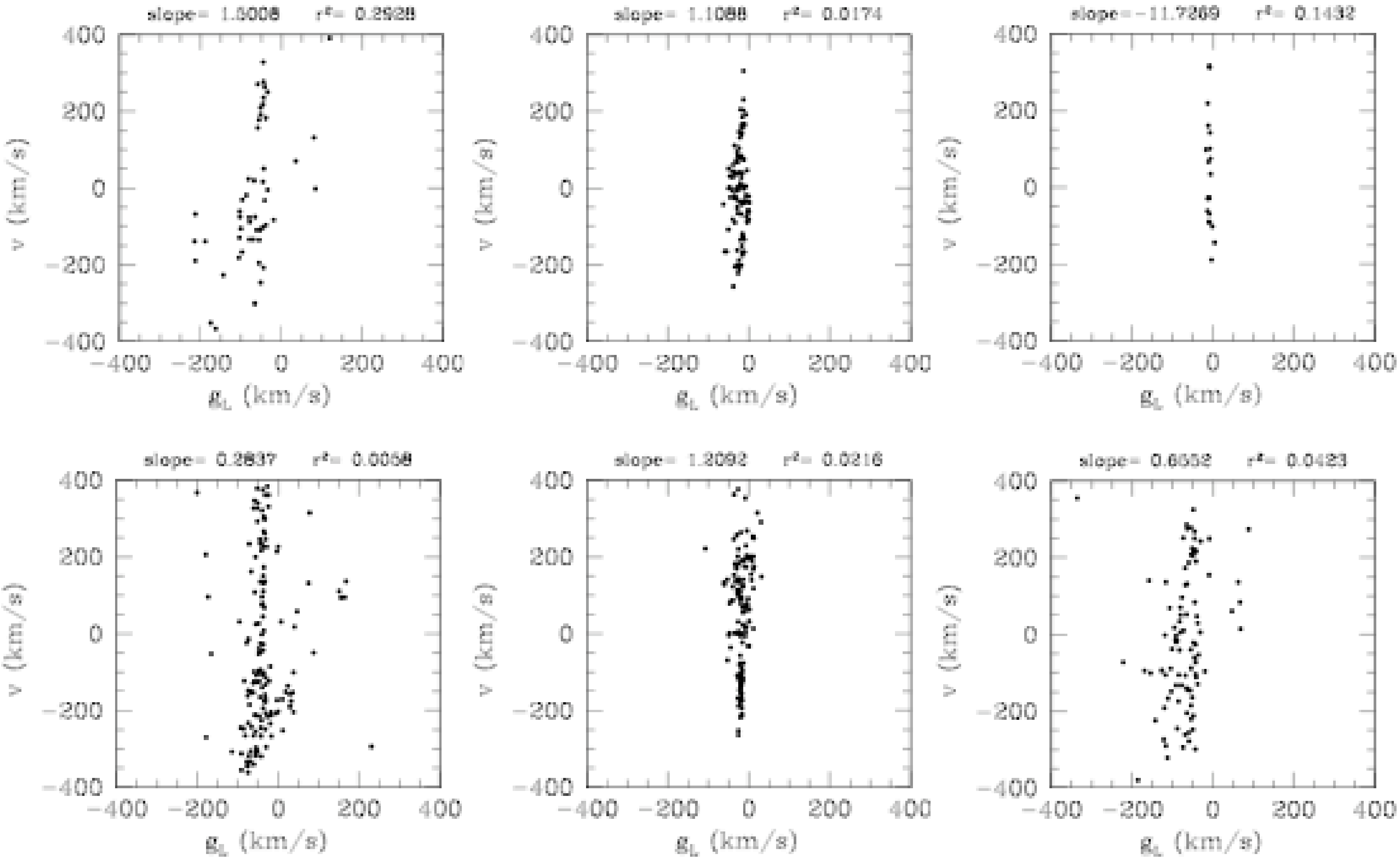


Figure 2. Local vs. global scaled acceleration for constrained ΛCDM, OCDM and SCDM (first row) and unconstrained ΛCDM and OCDM (second row and two first columns) Local Volumes. The last plot belongs to the same candidate that in the first one but for the constrained OCDM simulation.

Local g-field vs velocities



Global g-field vs velocities

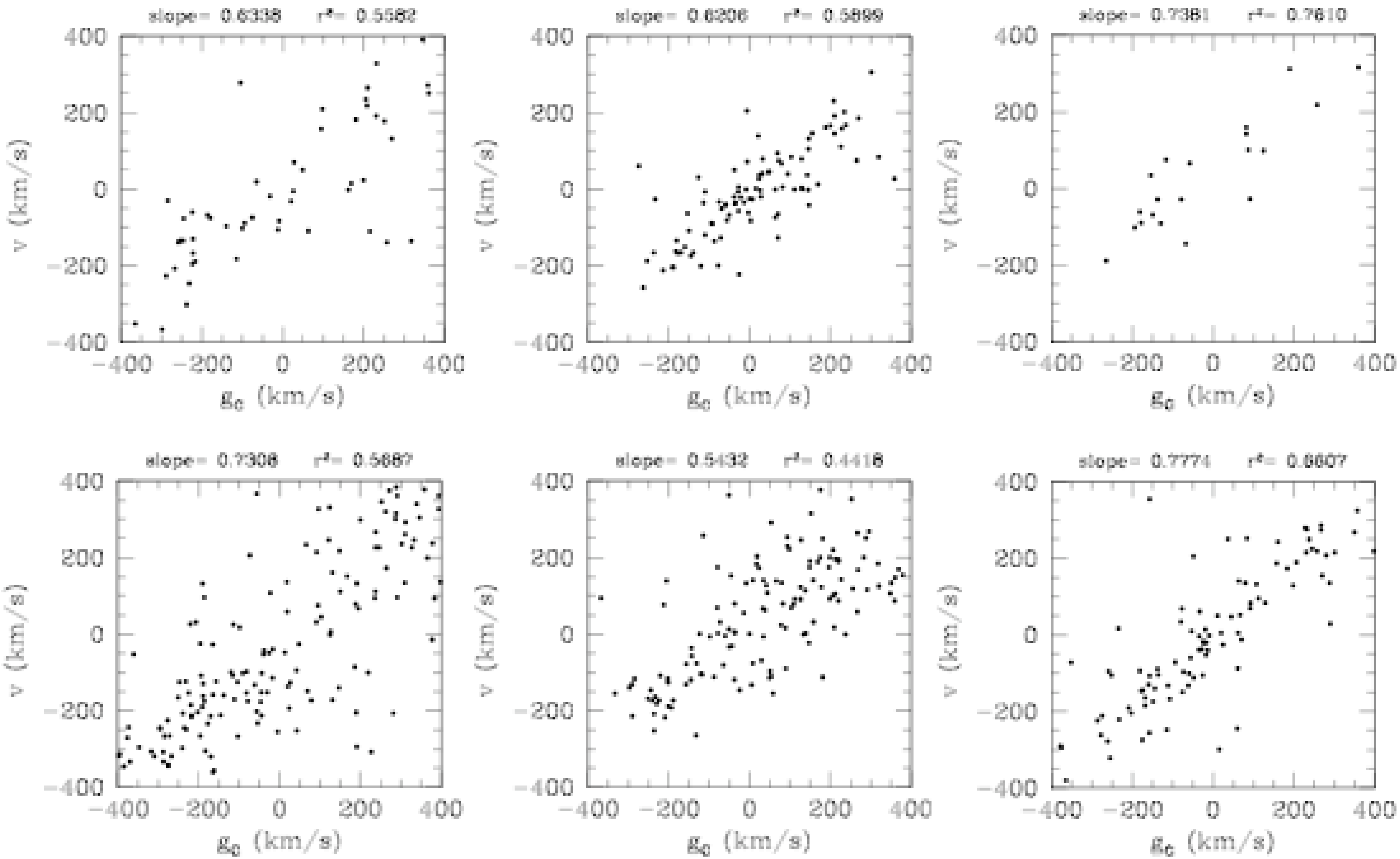


Figure 5. Peculiar velocity *vs.* global scaled acceleration for the same candidates of Figure 2.

Is the lack of correlation between the global and local field due to:

a. The sampling of g over finite volume?

b. The sampling of g by DM halos, treated as point particles?

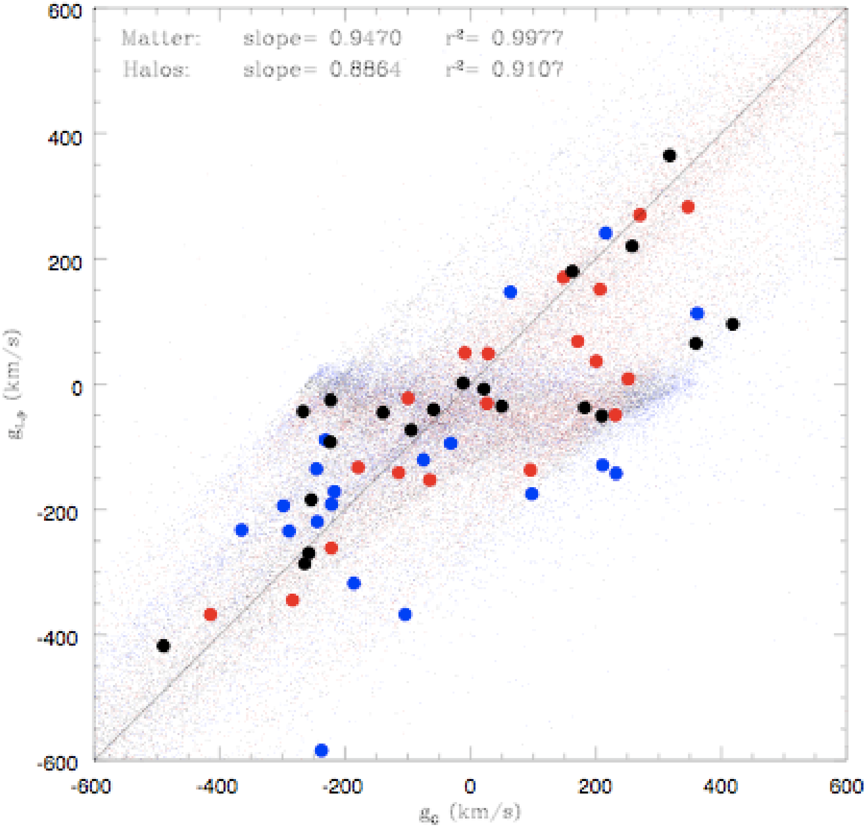
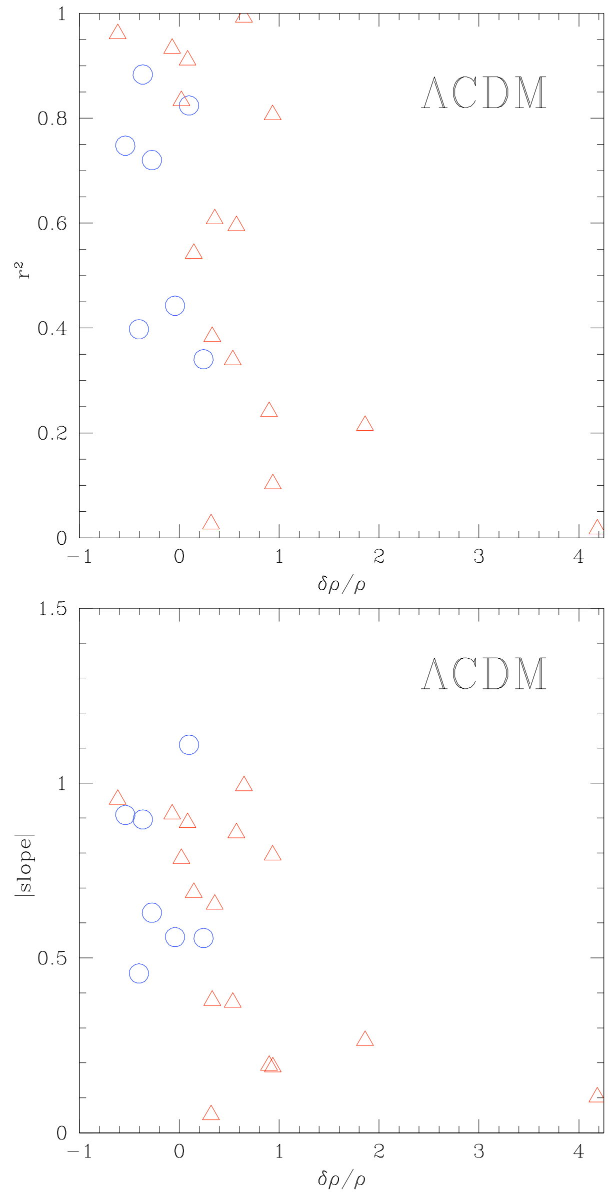


Figure 4. Local *vs.* global acceleration taking into account all the particles within the LV for the same first candidate of the Figure 2 in the ΛCDM simulation. The small points are relative to the particle-particle pairs and the thick ones to the halo-particle pairs. Colors represent the distance of the particle or the halo to the LG: close in *red*, intermediate in *black* and distant in *blue*. A black straight line with the slope equals to one is also plot.



Conclusions

- Local and global g-fields are not equivalent and they are uncorrelated.
- There is no significant correlation between the g-field and peculiar velocities in the simulated Local Volumes.
- The local dynamics does not seem to contradict the standard model of cosmology - no need for any new physics
- The lack of correlation between the local & global g-fields in the Local Volume around LG-like objects raises questions about the application of the 'least action' method to the local universe:

★ Sampling volume

★ Tracing the g-field by point-like particles

★ The method should be tested on LG-like objects

A side issue - the effect of shear

- Note the gravitational field is scaled by

$$\mathbf{g} = \frac{2f(\Omega_m, \Omega_\Lambda)}{3H_0\Omega_m}\ \tilde{\mathbf{g}}$$

- We find that **v_p ~ fac g_{global}** and **fac ~ (0.6 - 0.7)**

- **Implication: as a test on Ω_m this would underestimate its value**

The role of shear

Shear accelerates the collapse:
(Hoffman 1986, 1989, van den Weygaert & Babul 1994)

$$\frac{\partial}{\partial t}\delta = -\frac{1}{a}\nabla \cdot \boldsymbol{v}_p , \qquad (1)$$

$$\left(\frac{\partial}{\partial t} + 2\frac{\dot{a}}{a}\right)\theta = -\frac{4\pi G\rho\delta}{a^2} - \frac{\theta^2}{3} - \Sigma^2 , \qquad (2)$$

re the velocity field is assumed to be irrotational and it is ınded as:

$$v_{p,\alpha} = a(\tfrac{1}{3}\theta\delta_{\alpha\beta} + \Sigma_{\alpha\beta})r_\beta . \qquad (3)$$

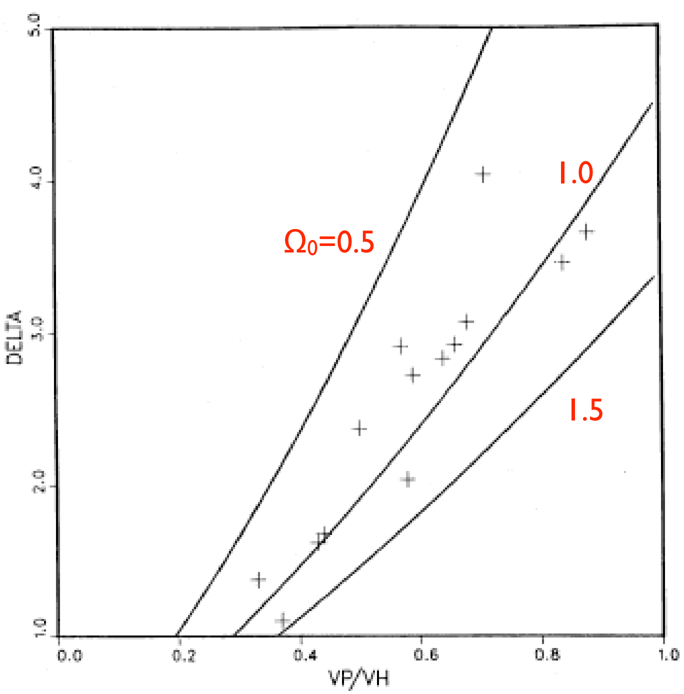
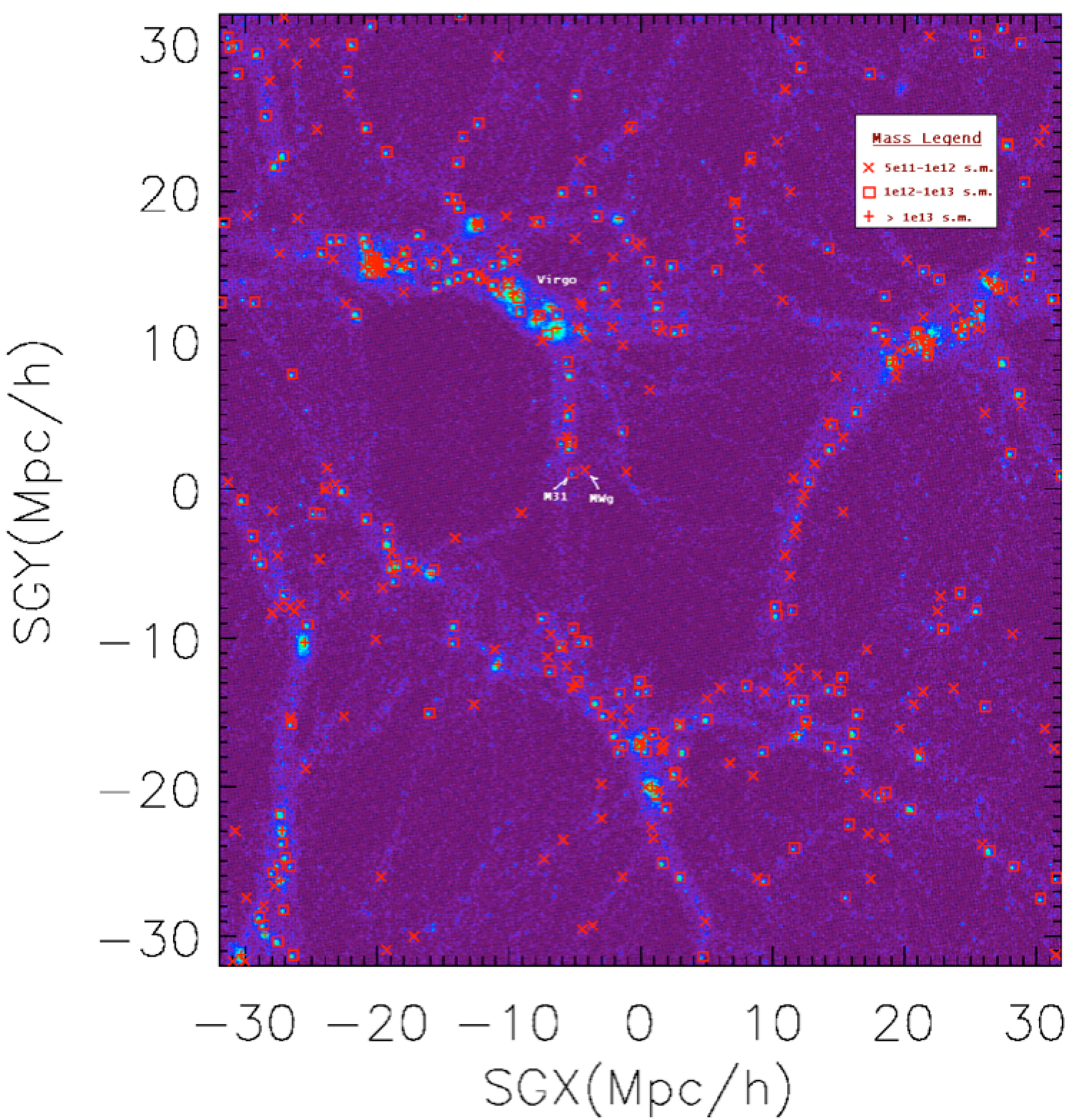


FIG. 1.—The $(\delta, v_p/v_H)$-relation predicted by the SNL model for the following values of Ω_0 (*left to right*): 0.5, 1.0, and 1.5. The predictions of the QL model of a flat universe are shown as plusses, which correspond to the values given in Table 1.

Ω_0 is underestimated

Evolution of LG Candidate



z=0   t=13.4e9 yrs

M_{MW} = 0.8e12 M_{sun}/h

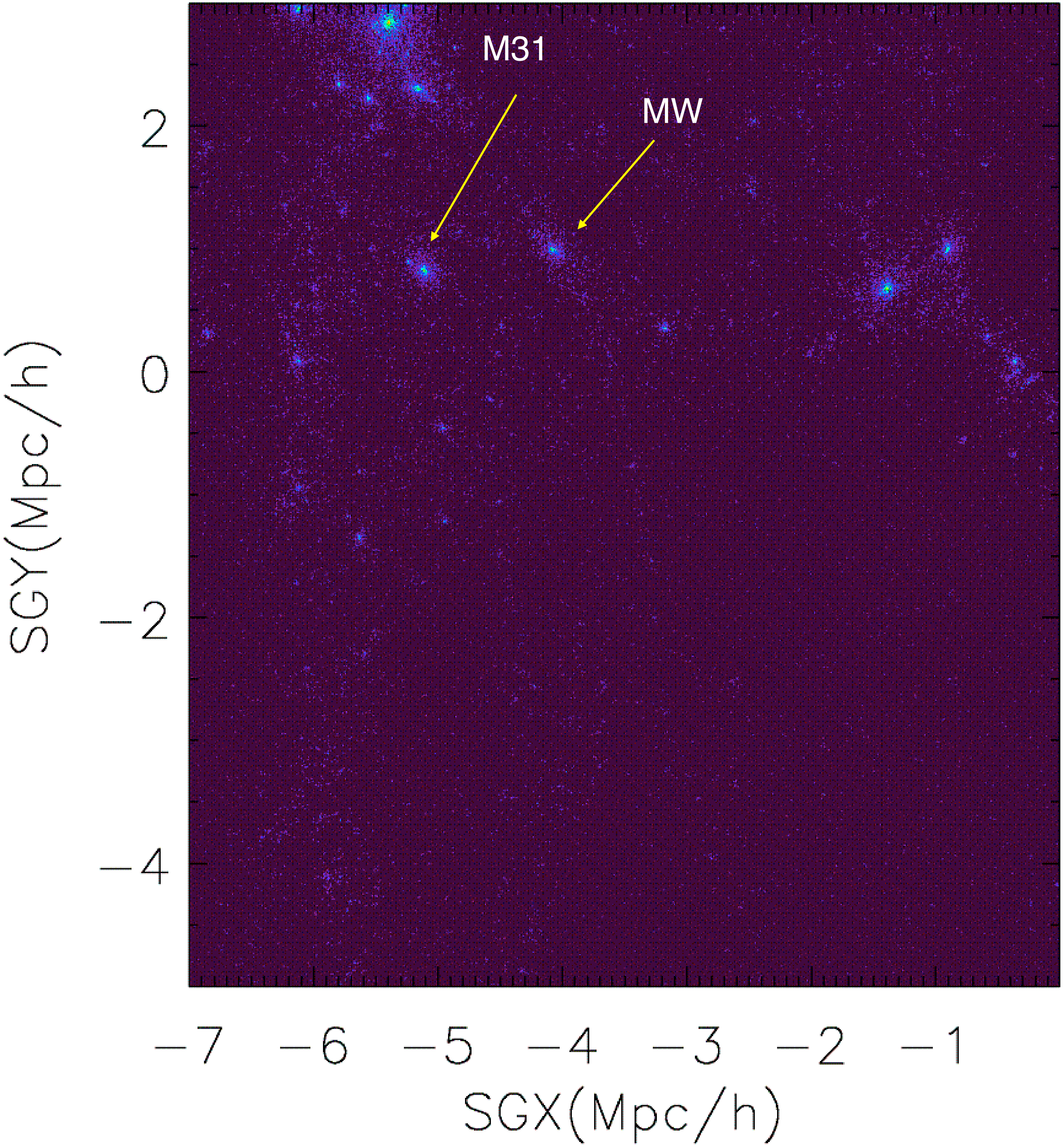
M_{M31} = 1.0e12 M_{sun}/h

M_{Virgo} = 1.7e14 M_{sun}/h

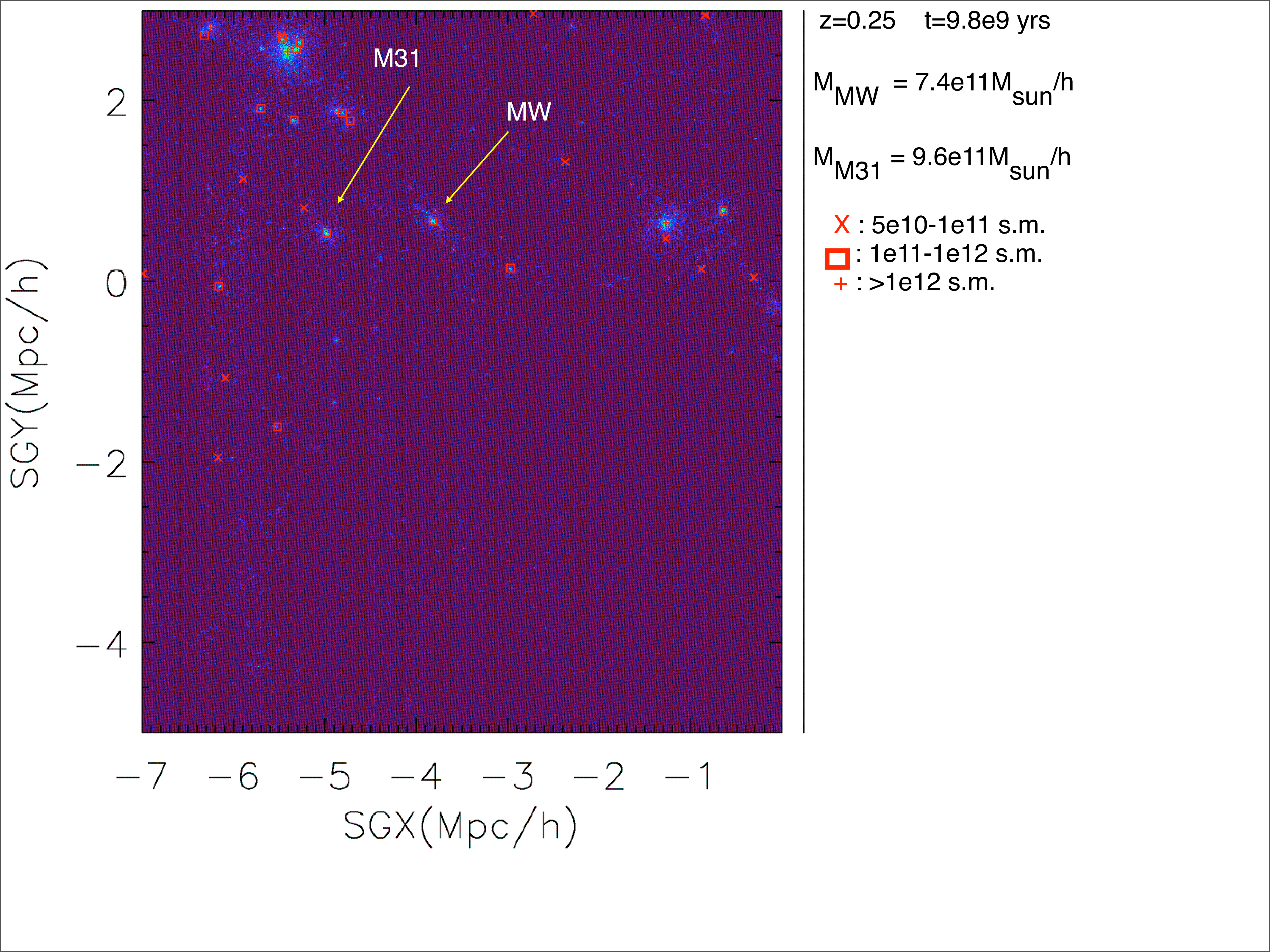
MW: (-4,1,-4) Mpc/h
M31: (-5,1,-5) Mpc/h
Virgo: (-10,13,-7) Mpc/h

D(MW-M31) =1.1 Mpc/h
D(MW-Virgo)=13 Mpc/h

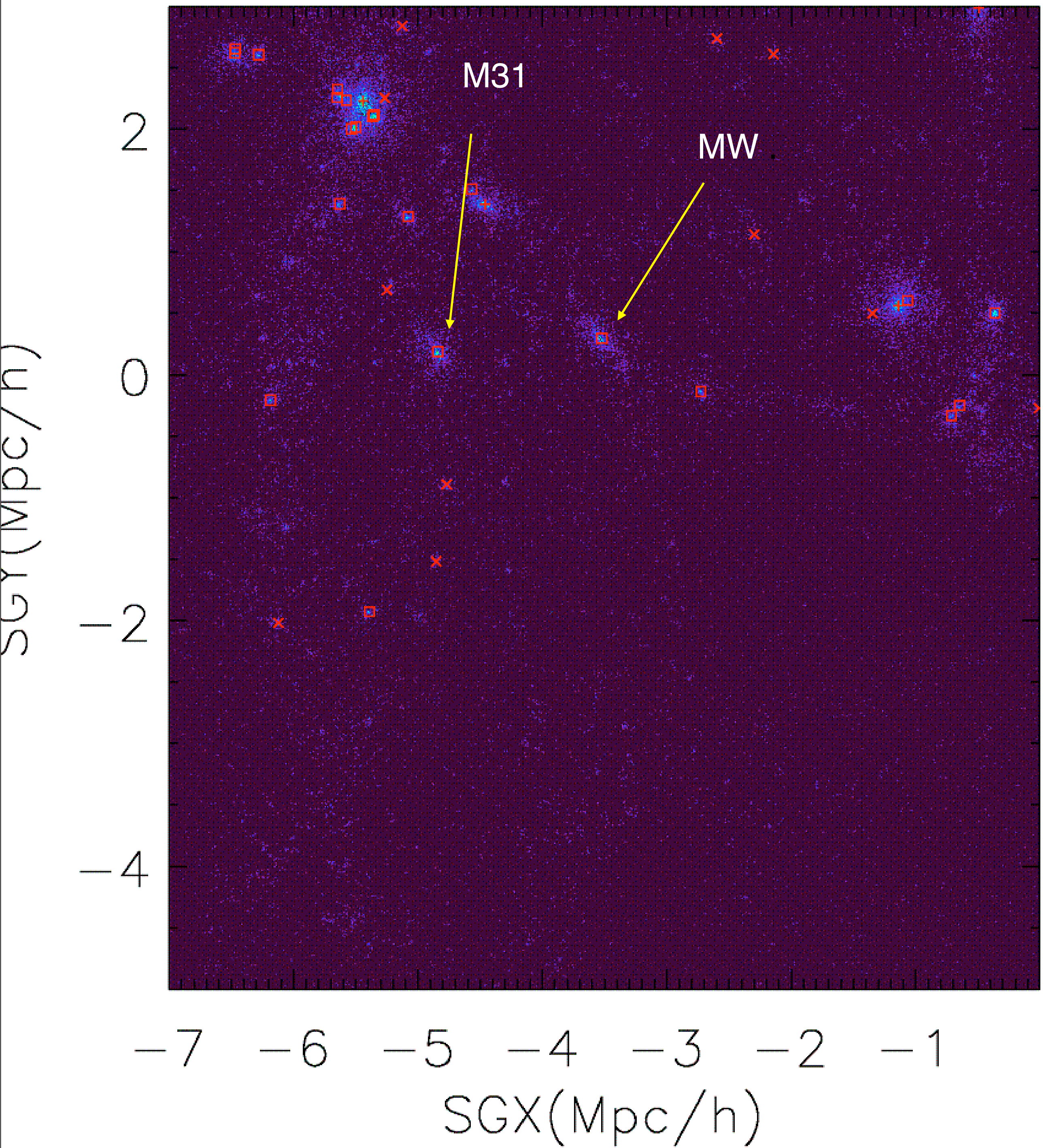
$\sigma_H \sim$ 160 km/s



z=0.11 t=1.1e10 yrs



z=0.25 t=9.8e9 yrs
M31
MW
M_{MW} = 7.4e11M_{sun}/h
M_{M31} = 9.6e11M_{sun}/h
X : 5e10-1e11 s.m.
: 1e11-1e12 s.m.
+ : >1e12 s.m.
SGY(Mpc/h)
SGX(Mpc/h)
2
0
−2
−4
−7
−6
−5
−4
−3
−2
−1



z=0.43 t=8.3e9 yrs

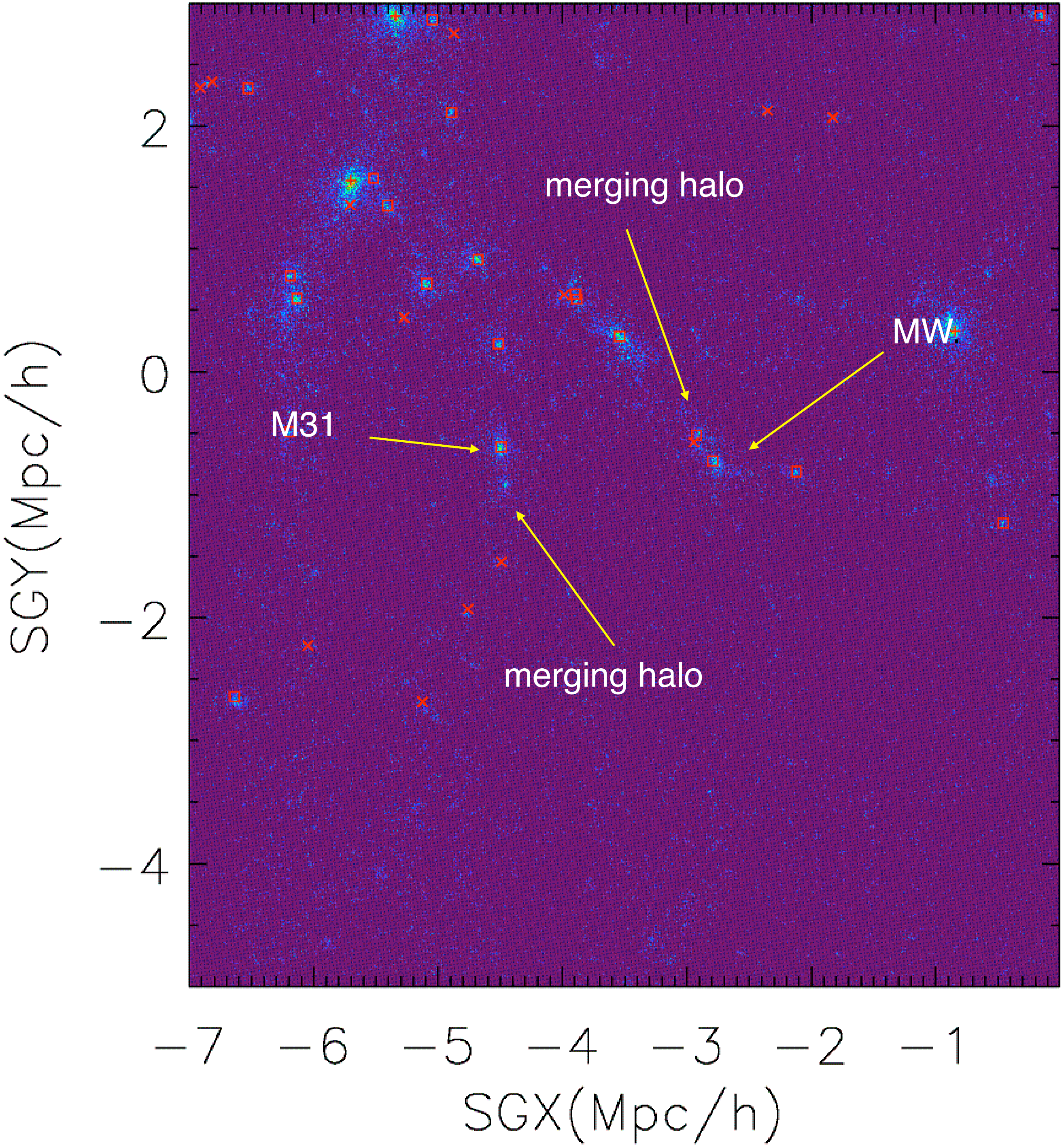
M_{MW} = 7.6e11M_{sun}/h

M_{M31} = 9.1e11M_{sun}/h

X : 5e10-1e11 s.m.

: 1e11-1e12 s.m.

\+ : >1e12 s.m.



z=0.66   t=5.3e9 yrs

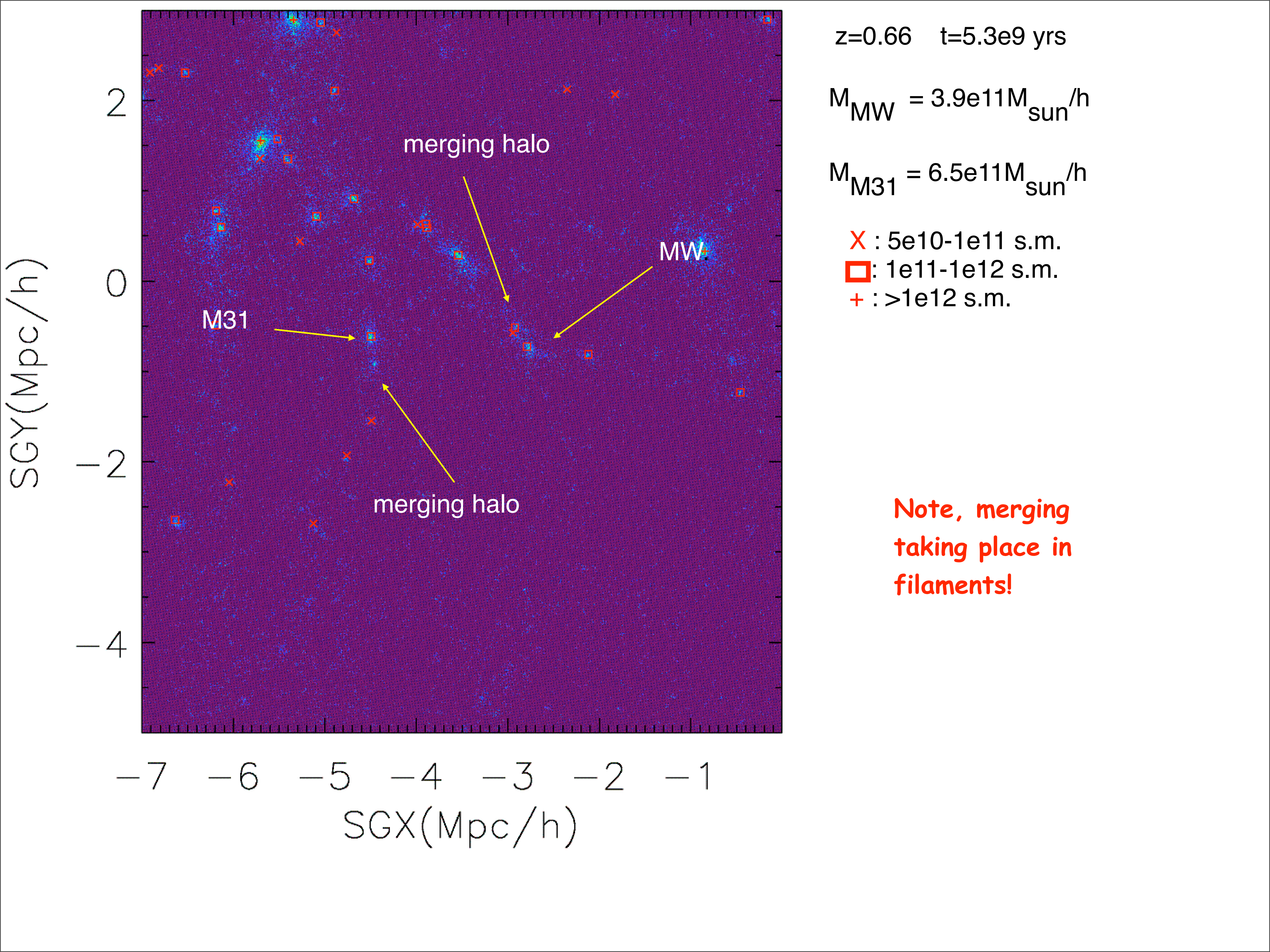
M_{MW} = 3.9e11M_{sun}/h

M_{M31} = 6.5e11M_{sun}/h

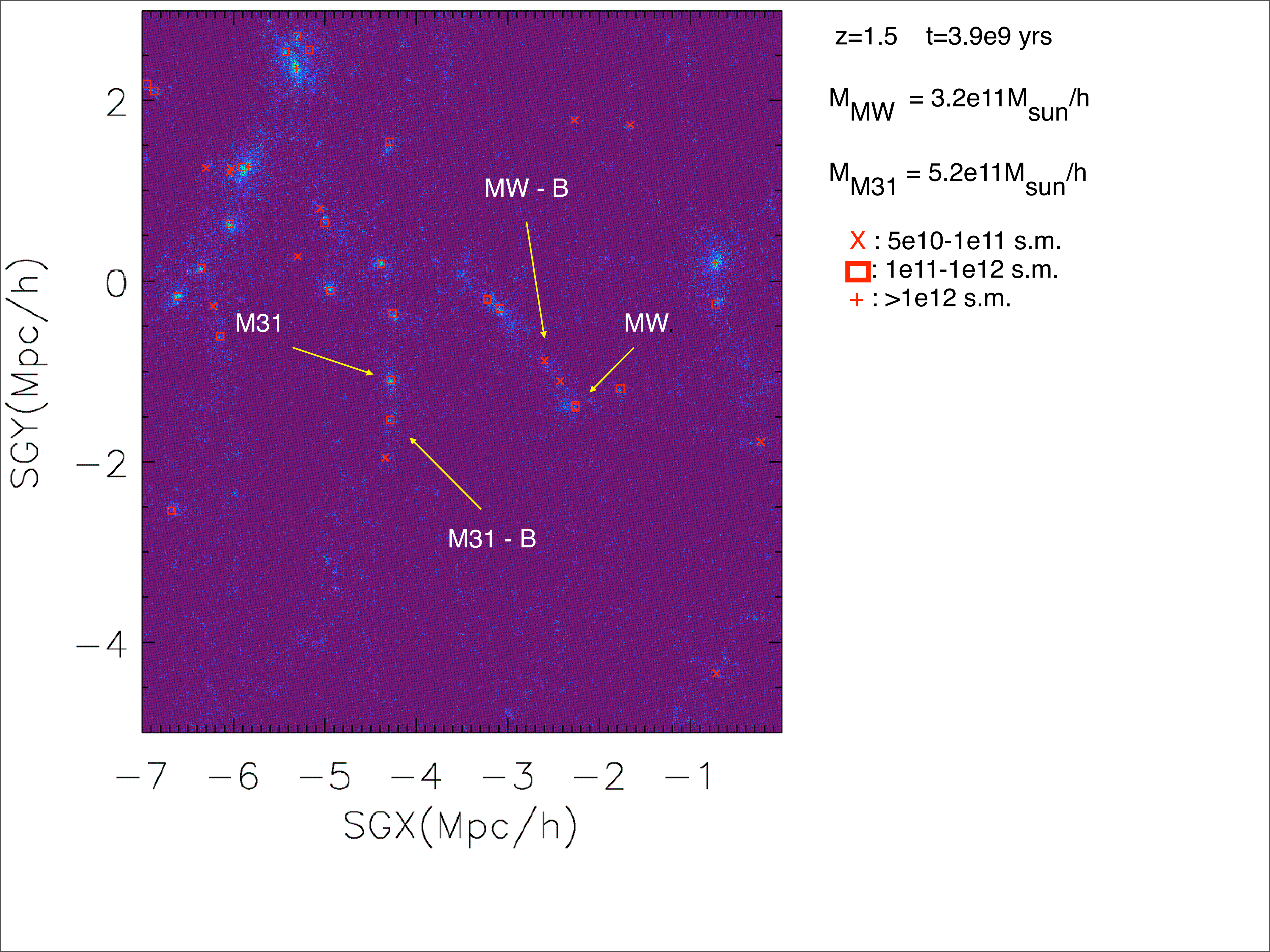
X : 5e10-1e11 s.m.

□: 1e11-1e12 s.m.

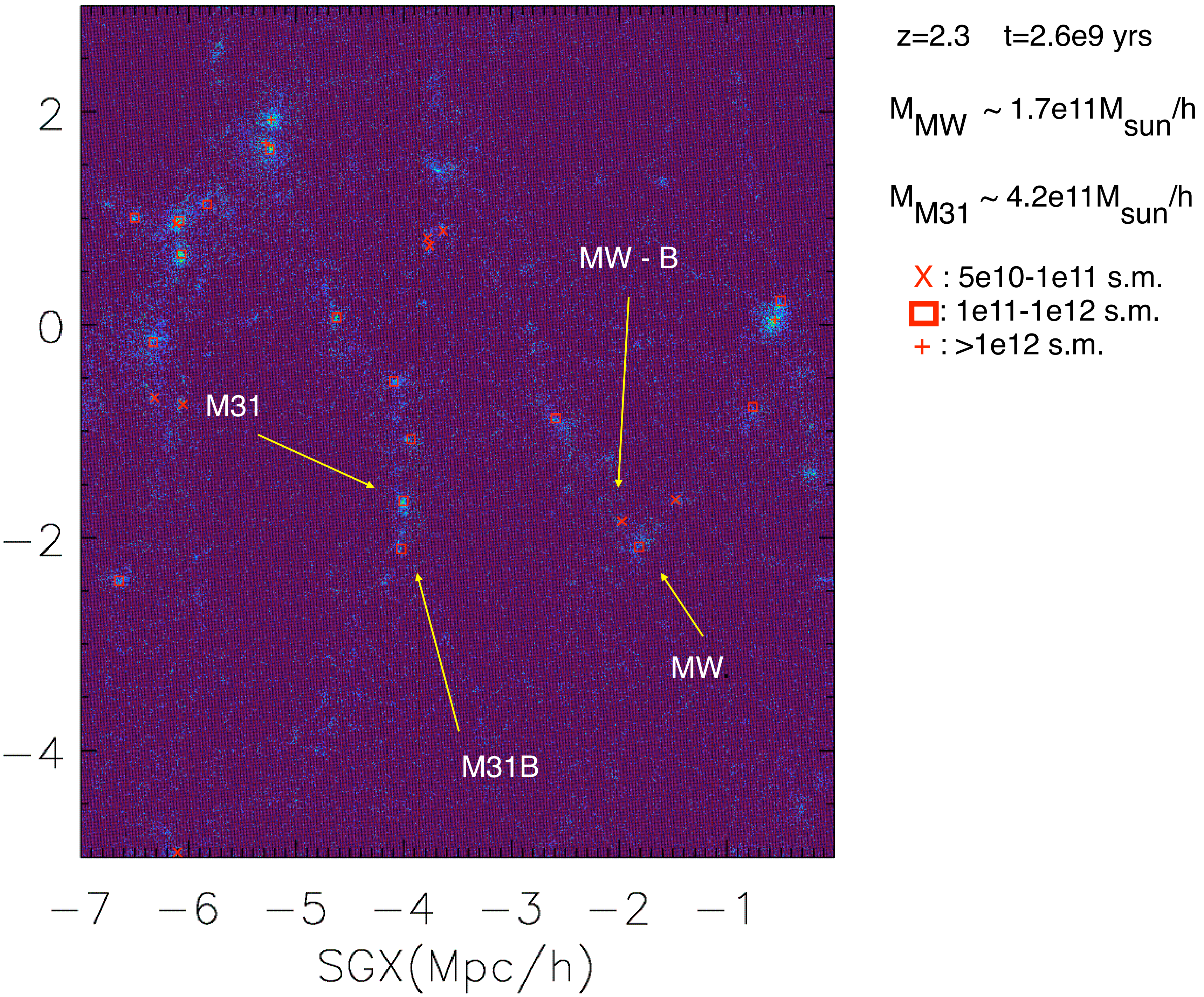
+ : >1e12 s.m.



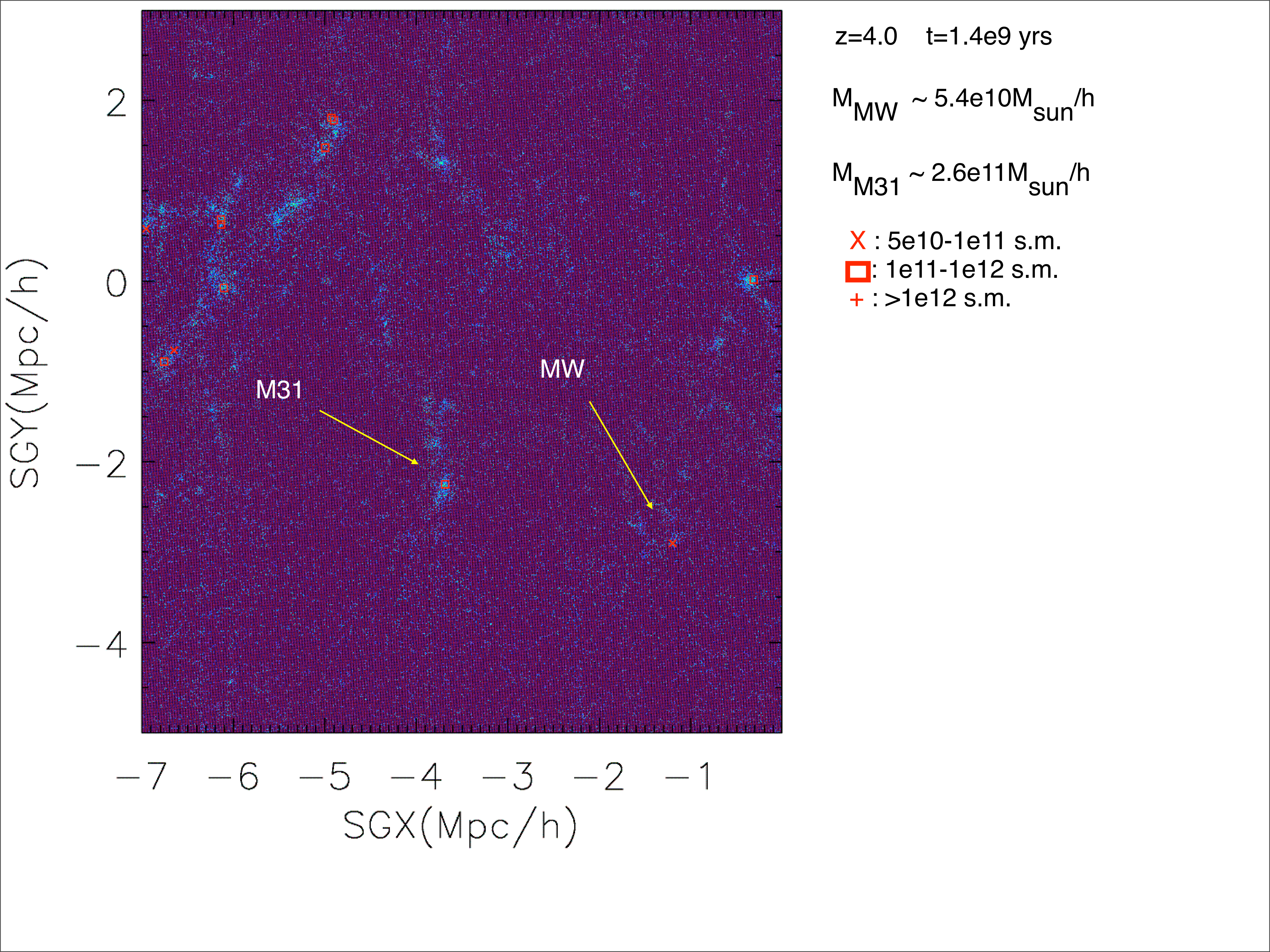
z=0.66 t=5.3e9 yrs
M_{MW} = 3.9e11M_{sun}/h
M_{M31} = 6.5e11M_{sun}/h
X : 5e10-1e11 s.m.
: 1e11-1e12 s.m.
+ : >1e12 s.m.
merging halo
MW
M31
merging halo
SGY(Mpc/h)
SGX(Mpc/h)
2
0
−2
−4
−7
−6
−5
−4
−3
−2
−1
Note, merging taking place in filaments!



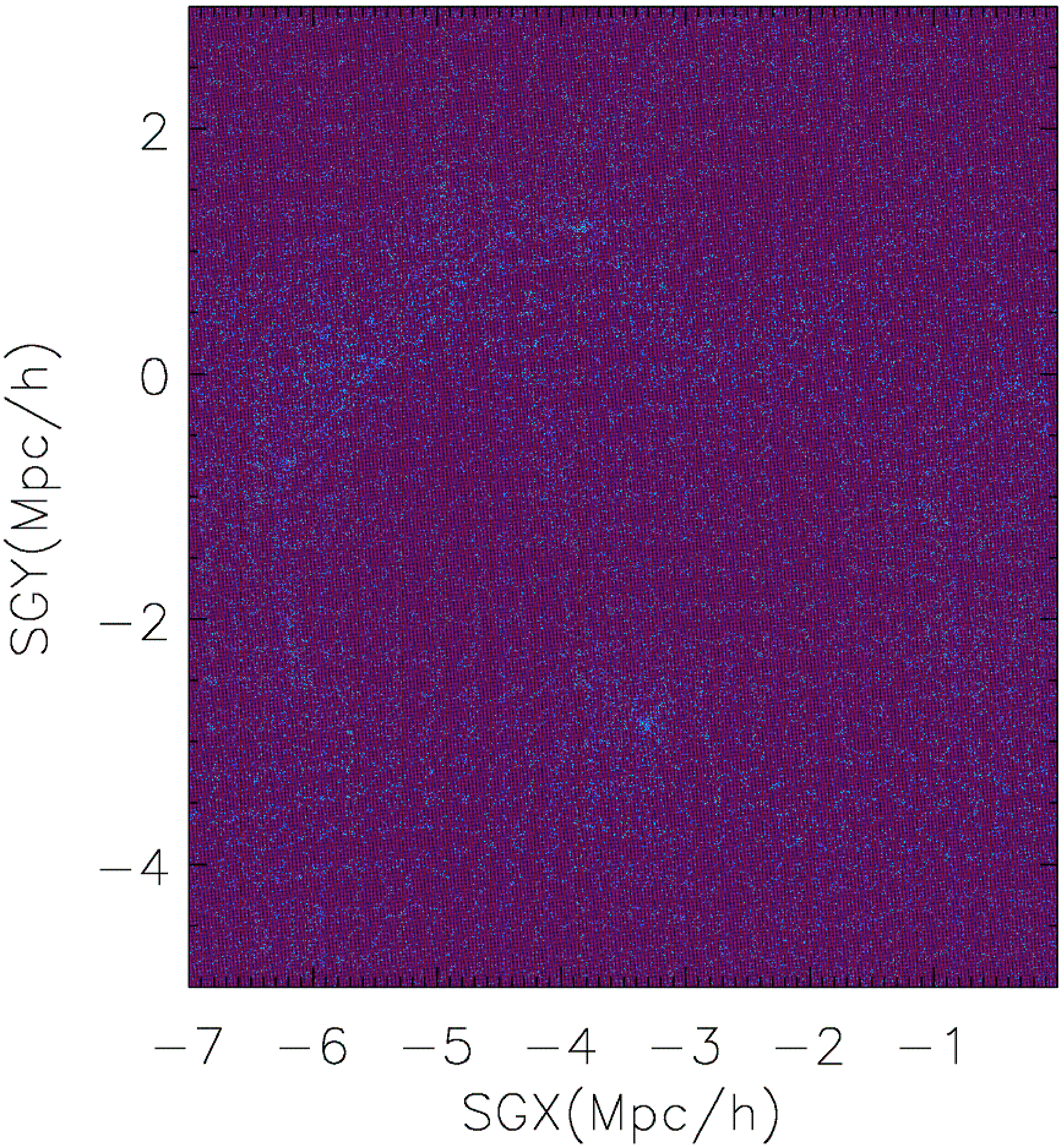
z=1.5 t=3.9e9 yrs
M_MW = 3.2e11M_sun/h
M_M31 = 5.2e11M_sun/h
X : 5e10-1e11 s.m.
: 1e11-1e12 s.m.
+ : >1e12 s.m.
MW - B
M31
MW
M31 - B
SGY(Mpc/h)
SGX(Mpc/h)
2
0
−2
−4
−7
−6
−5
−4
−3
−2
−1



z=2.3 t=2.6e9 yrs
M_MW ~ 1.7e11M_sun/h
M_M31 ~ 4.2e11M_sun/h
X : 5e10-1e11 s.m.
: 1e11-1e12 s.m.
+ : >1e12 s.m.
MW - B
M31
M31B
MW
SGY(Mpc/h)
SGX(Mpc/h)



z=4.0 t=1.4e9 yrs
M_{MW} ~ 5.4e10M_{sun}/h
M_{M31} ~ 2.6e11M_{sun}/h
X : 5e10-1e11 s.m.
: 1e11-1e12 s.m.
+ : >1e12 s.m.
M31
MW
SGY(Mpc/h)
SGX(Mpc/h)
2
0
−2
−4
−7
−6
−5
−4
−3
−2
−1

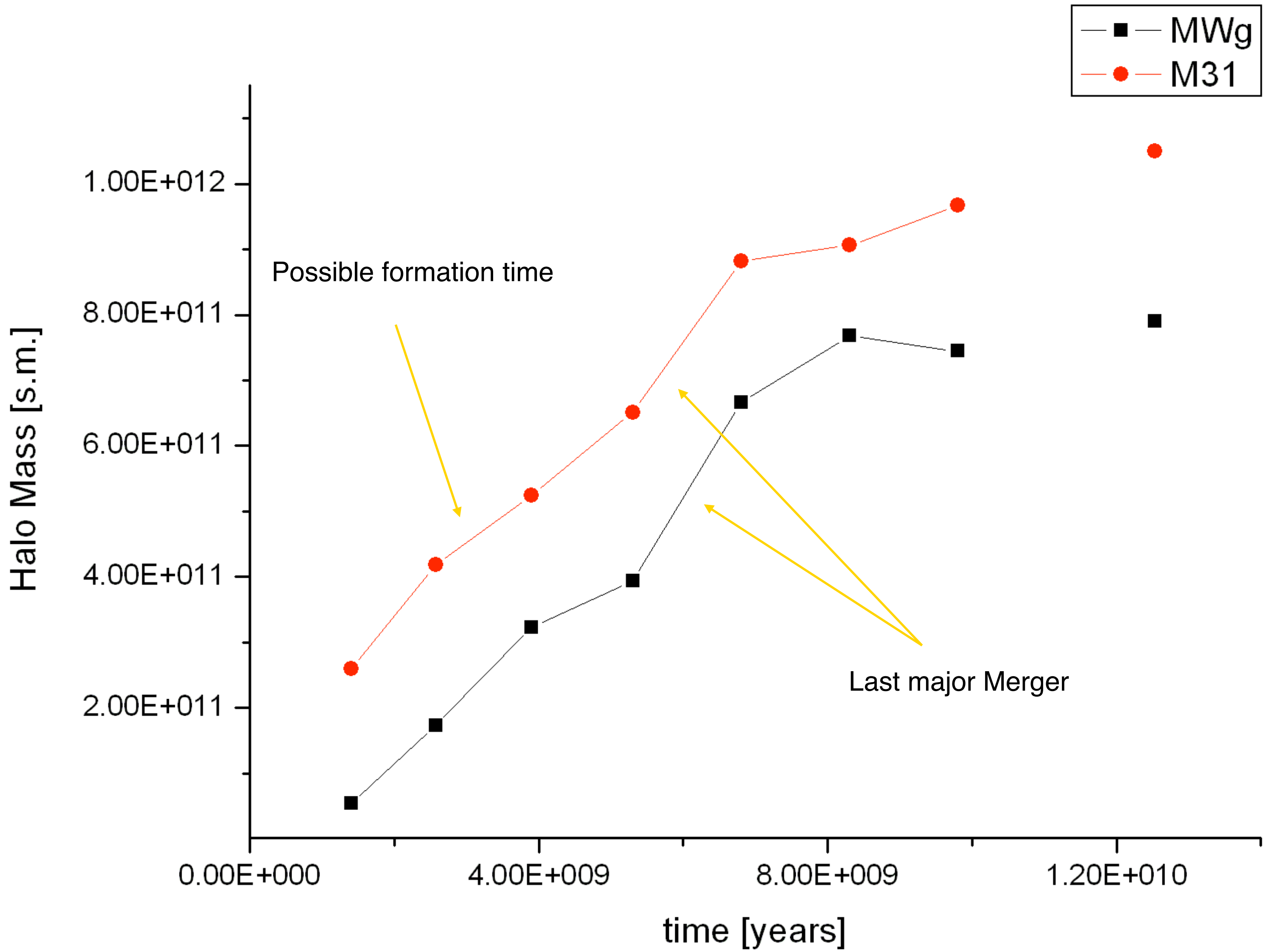


z=9.0   t=5.0e8 yrs

MW & M31 do not exist as virialized halos

(within the mass resolution)

Halos mass as a function of time



- We have an interesting & intriguing LG candidate.
- The LG might have formed out of two converging filaments.
- The LG dynamics does not necessarily follow a 'two-body problem'
- Timing arguments?
- Implications for galaxy formation?

Populating Dark Matter Halos With Galaxies

Full hydro - gastrophysics simulations:
Too CPU expensive to do such a simulation for the full box - will be done to selected regions.

Sami-analytical modeling (SAM)

Populate DM halos by statistical means:
Here the Conditional Luminosity Function (CLF; van de Bosch et al 2003) is used.

$$\phi(L|M)dL = \frac{\tilde{\phi}^*}{\tilde{L}^*}\left(\frac{L}{\tilde{L}^*}\right)^{\tilde{\alpha}} \exp(-L/\tilde{L}^*)dL$$

where $\tilde{\phi}^* = \tilde{\phi}^*(M)$, $\tilde{L}^* = \tilde{L}^*(M)$ and $\tilde{\alpha} = \tilde{\alpha}(M)$.

Note, for $M<10^9\ M_{sun}/h$ $\phi(L|M)=0$.

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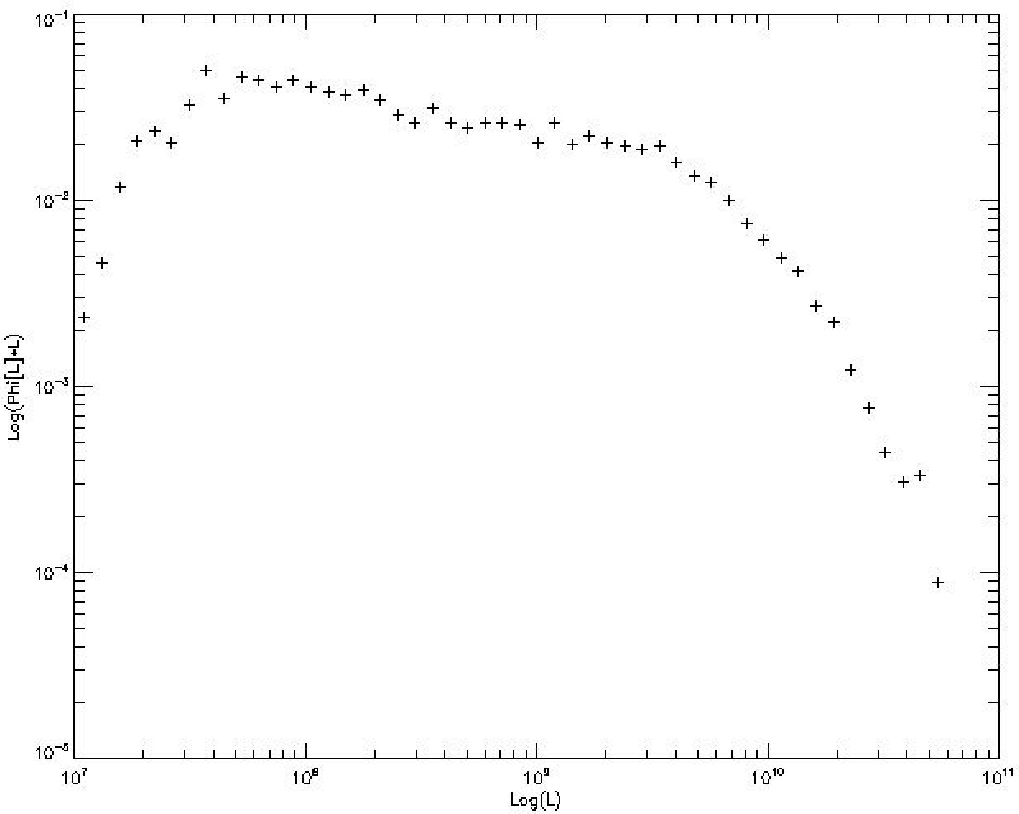


$$\phi(L|M)dL = \frac{\tilde{\phi}^*}{\tilde{L}^*}\left(\frac{L}{\tilde{L}^*}\right)^{\tilde{\alpha}} \exp(-L/\tilde{L}^*)dL$$

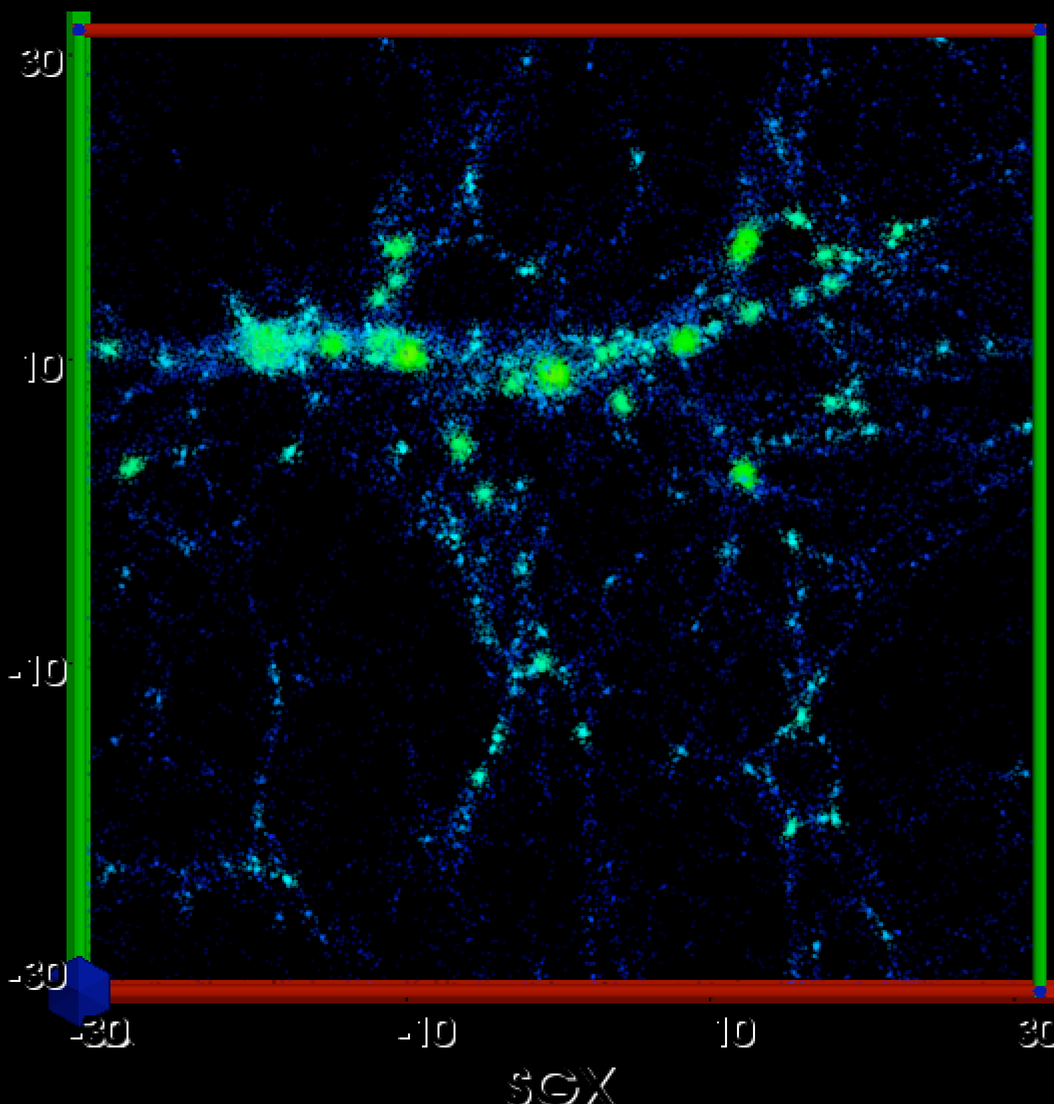
where $\tilde{\phi}^* = \tilde{\phi}^*(M)$, $\tilde{L}^* = \tilde{L}^*(M)$ and $\tilde{\alpha} = \tilde{\alpha}(M)$.

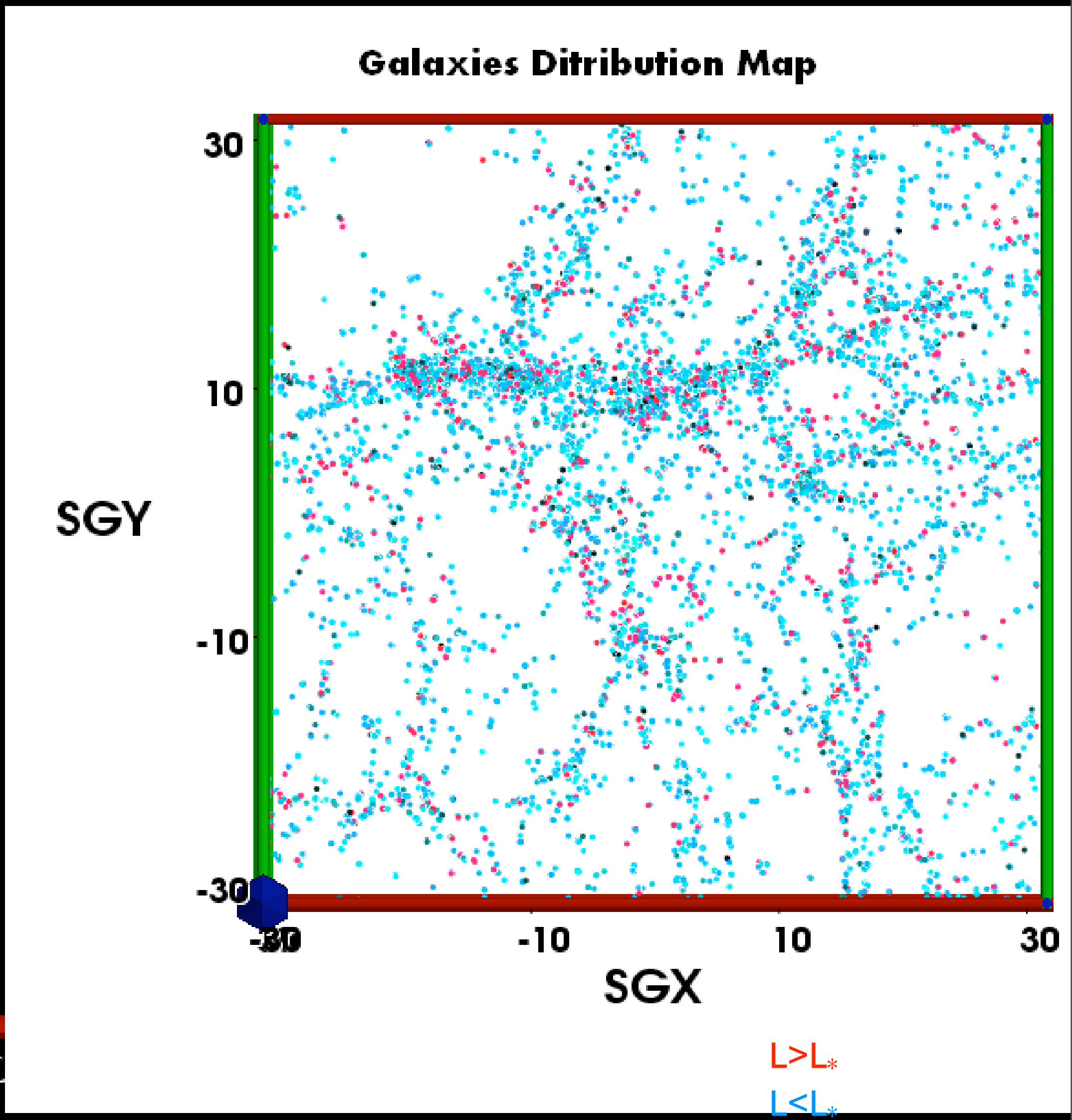
Note, for $M<10^9$ M_{sun}/h $\phi(L|M)=0$.

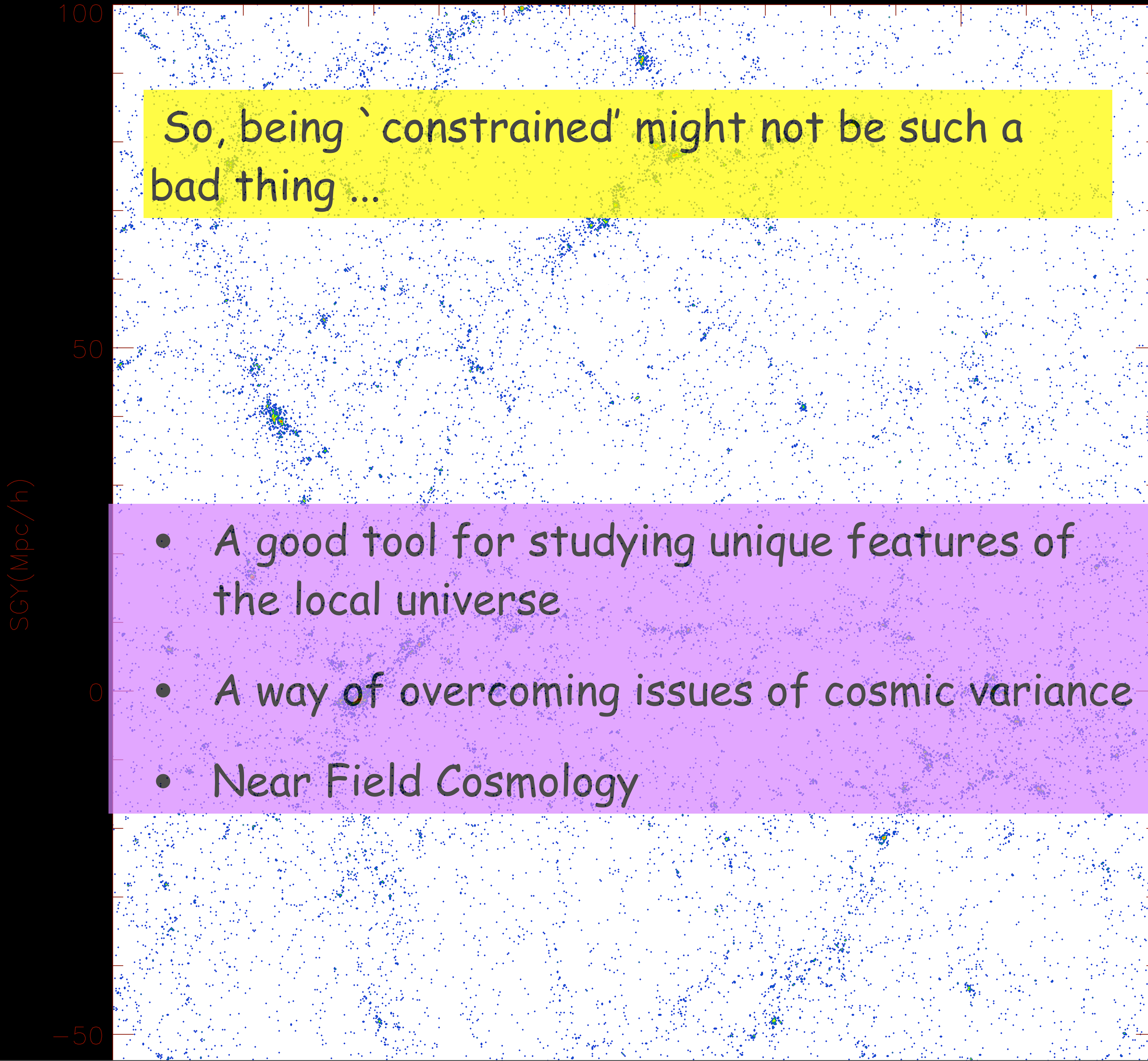
BOX64: DM vs galaxy distribution

20 2.48910 -27.7625 12.1034 -6.12885 A3526

DM Distribution Map







So, being `constrained' might not be such a bad thing ...

- A good tool for studying unique features of the local universe
- A way of overcoming issues of cosmic variance
- Near Field Cosmology