

# Vast planes of satellites in a simulation of the Local Group

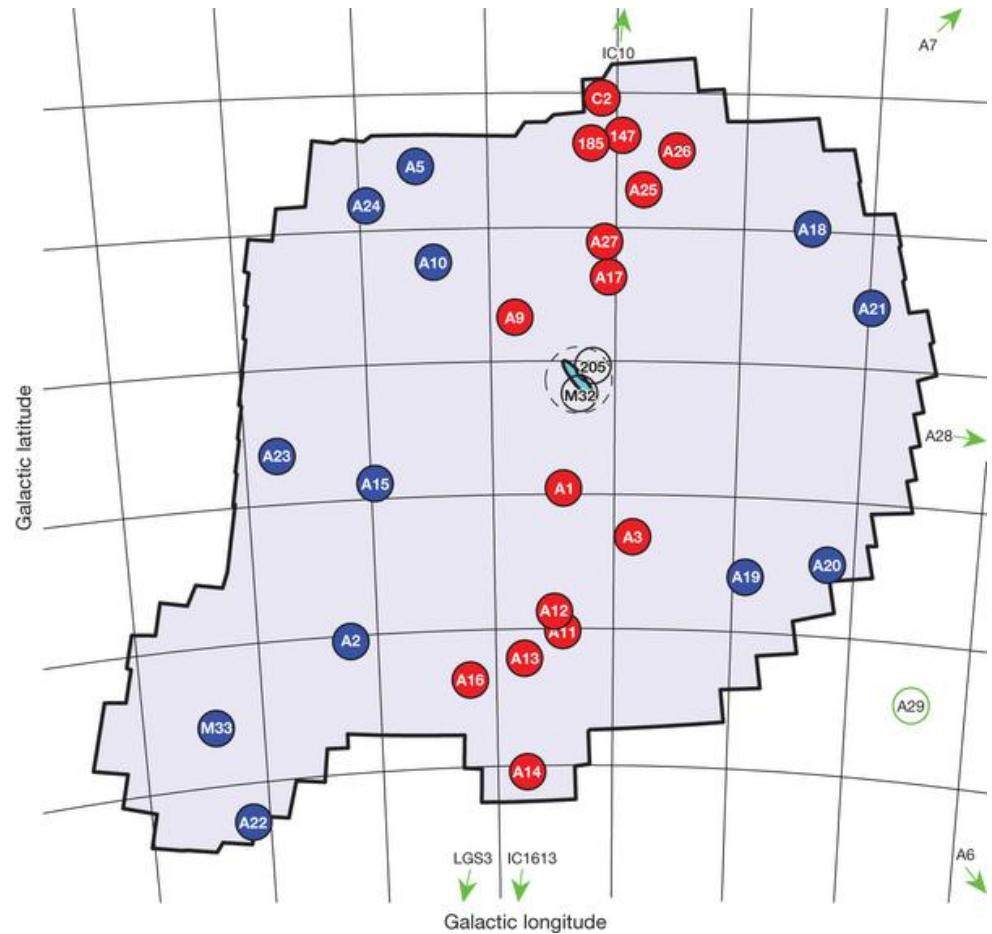
N. Gillet, P. Ocvirk and D. Aubert

Observatoire astronomique de Strasbourg

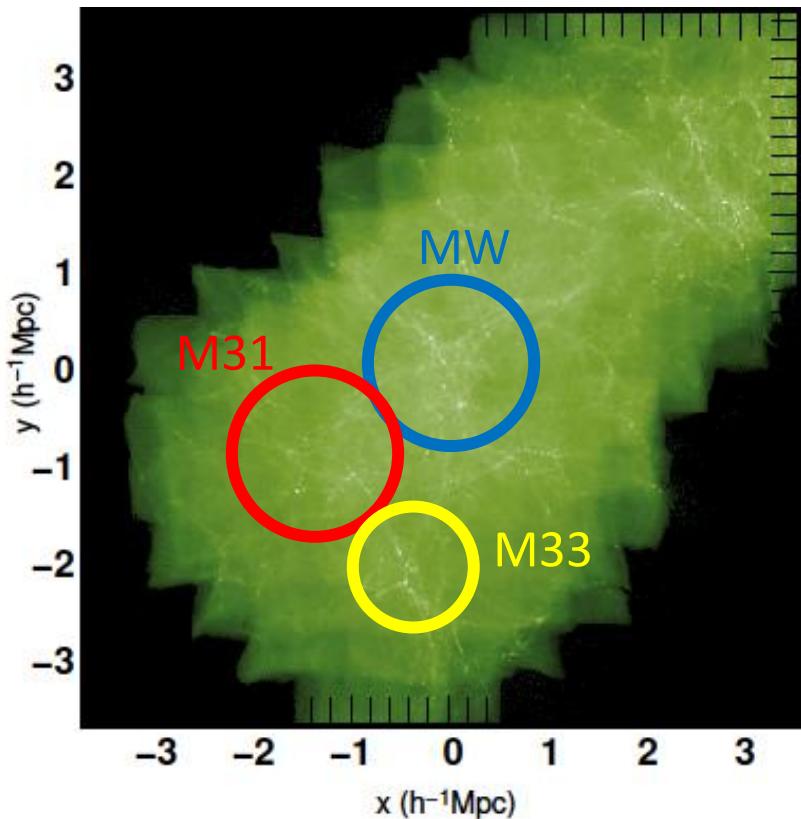
Gillet et al 2014 in prep

# Plane of Andromeda

- Ibata et al 2013
- 15 of 27 in Plane (0.13%)
- 400kpc diameter
- Less than 14kpc scatter
- 13 of 15 corotating (0.74%)
- ⇒ Probability to occur: 0.00096%
  
- In the simulation ?
  - Method of plane detection
  - Computing of a probability
  - Planes ?



# The CLUES simulation



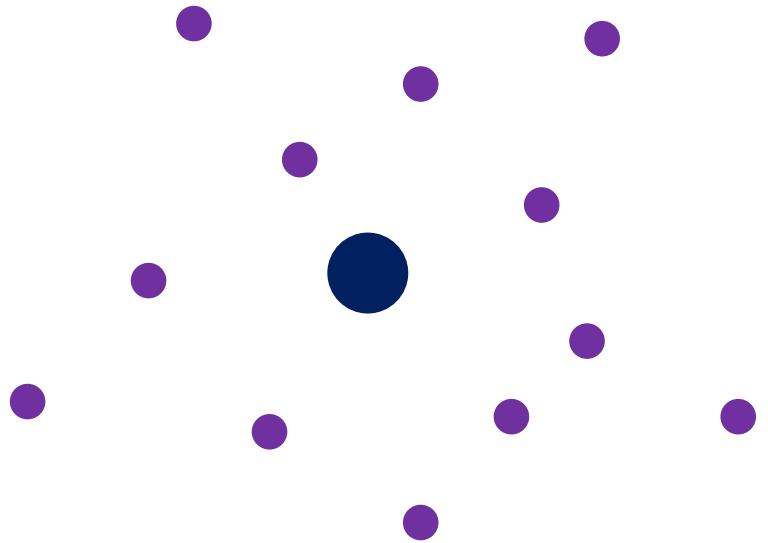
- ZOOM High resolution hydro simulation of the Local Group
- $11 h^{-1} \text{Mpc} @ 512^3$
- Resolution  $20 h^{-1} \text{kpc}$
- No live RT  
⇒ post-process: ATON

# Models of satellites at z=0

- 5 selections:
    - $M_{z=0}$  : more massive at  $z=0$
    - $M_{\max}$  : more massive at all  $z$
    - $M_{\star}$  : more stellar mass
    - $z_{\text{reio}}$  : reionise the latest
    - $z_{\text{reio}} M_{\max}$  :  $M > 10^9 M_{\odot}$  + reionise the latest
  - 2 hosts (MW and M31)
  - $\sim$ PAndAS volume (25 satellites)
  - PAndAS-bis volume (27 satellites)
  - Spherical volume, 25, 27, 30, 35, 50, 100, 150 satellites
- ⇒ 90 samples of satellites

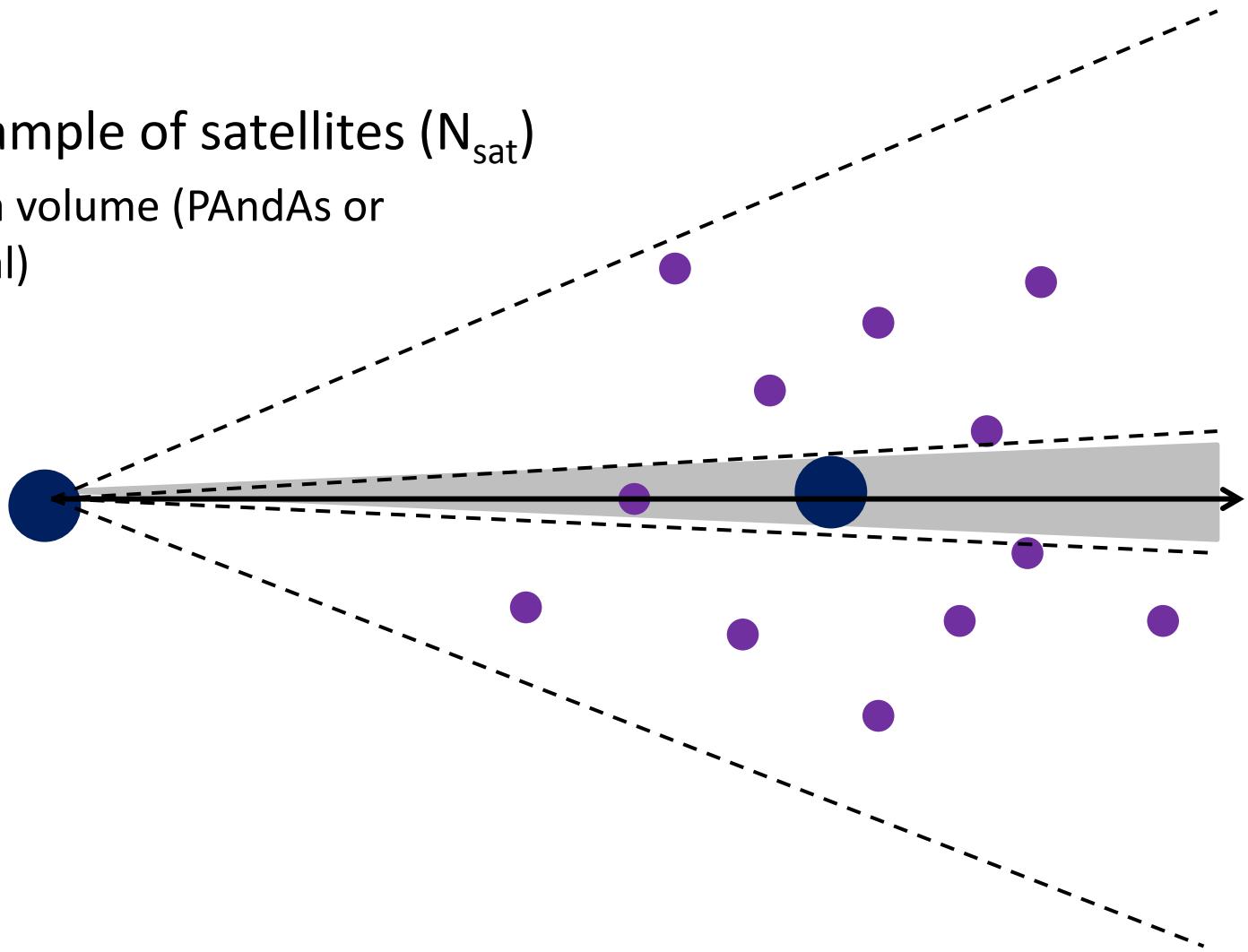
# Method of plane detection

- Select a sample of satellites ( $N_{\text{sat}}$ )



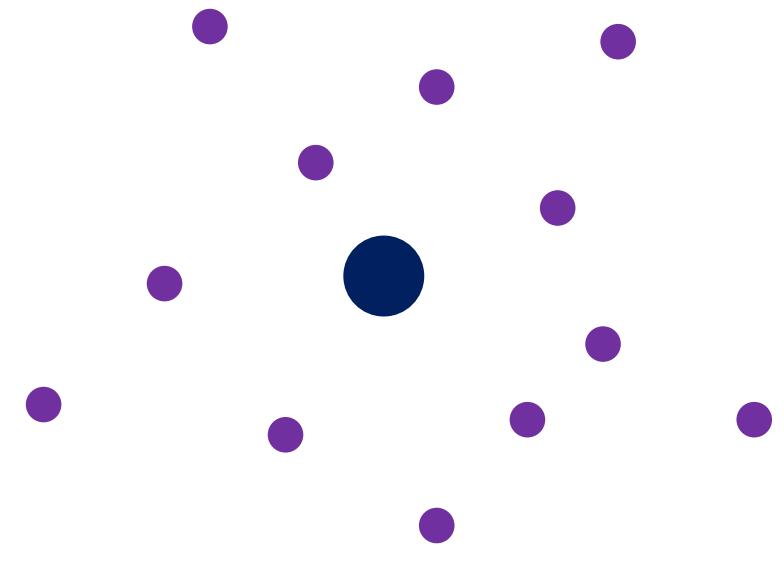
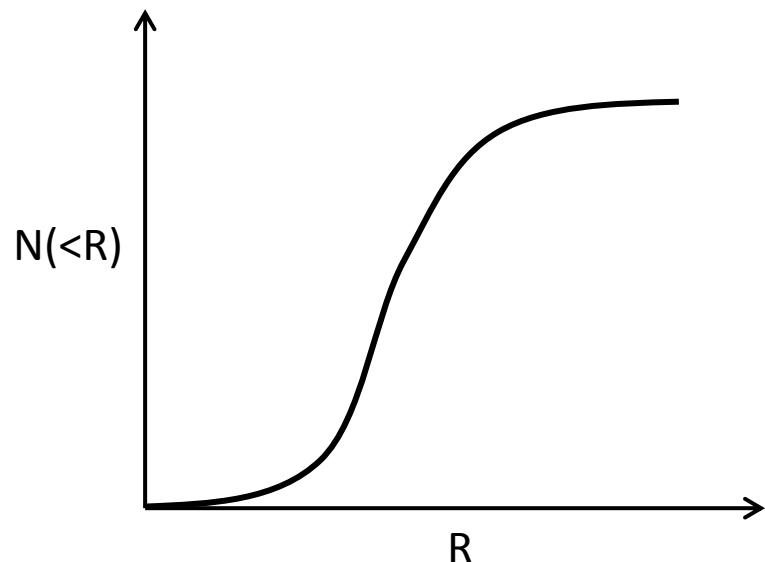
# Method of plane detection

- Select a sample of satellites ( $N_{sat}$ )
  - Within a volume (PAndAs or spherical)



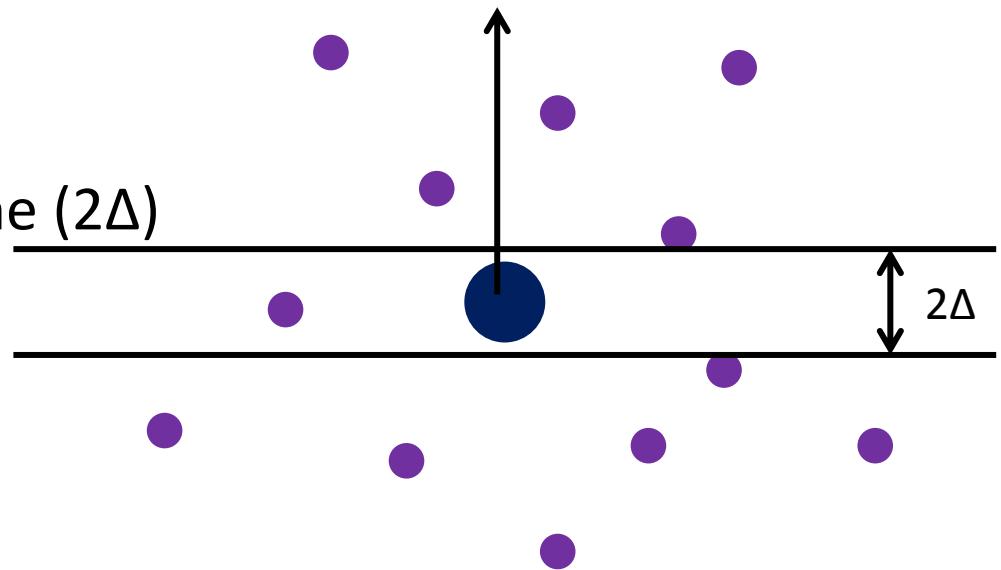
# Method of plane detection

- Select a sample of satellites ( $N_{\text{sat}}$ )
  - Within a volume (PAndAs or spherical)
  - Fixed radial distribution



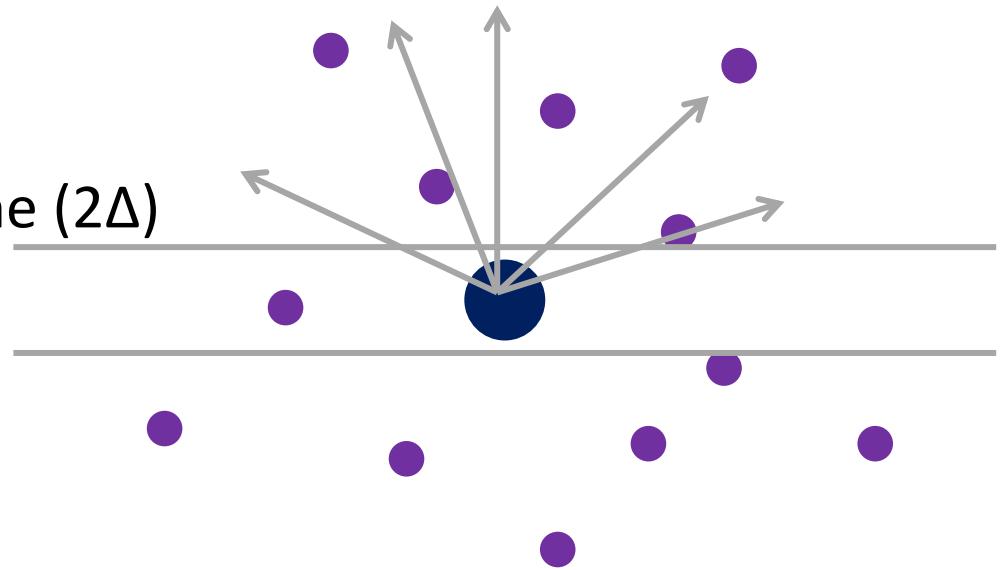
# Method of plane detection

- Select a sample of satellites ( $N_{\text{sat}}$ )
  - Within a volume (PAndAs or spherical)
  - Fixed radial distribution
- Count satellites in the plane ( $2\Delta$ )



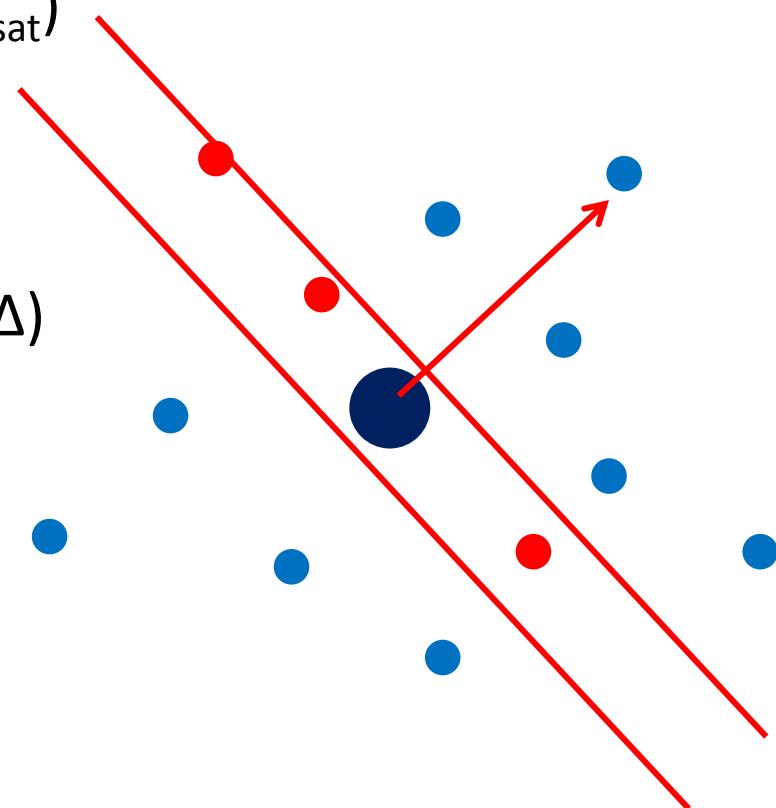
# Method of plane detection

- Select a sample of satellites ( $N_{\text{sat}}$ )
  - Within a volume (PAndAs or spherical)
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- Count satellites in the plane ( $2\Delta$ )
- For 100000 planes



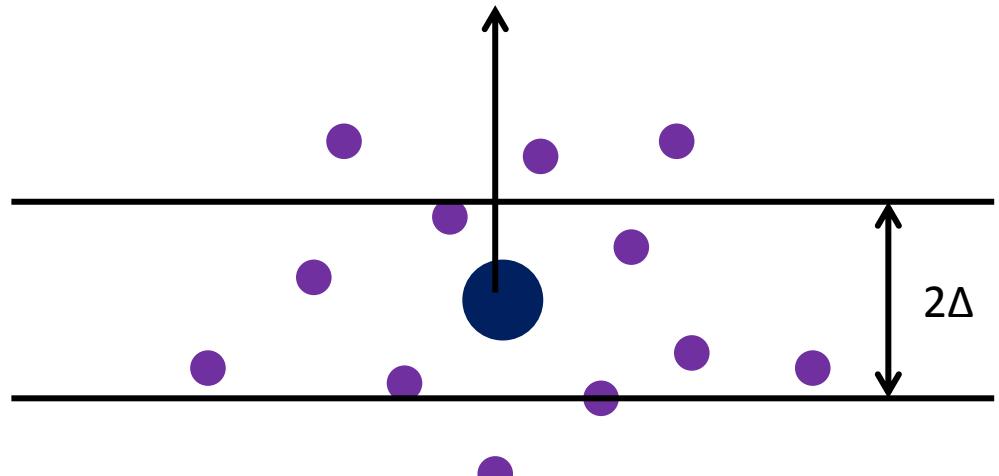
# Method of plane detection

- Select a sample of satellites ( $N_{\text{sat}}$ )
  - Within a volume (PAndAs or spherical)
  - Fixed radial distribution
- Count satellites in the plane ( $2\Delta$ )
- For 100000 planes  
=> The best plane



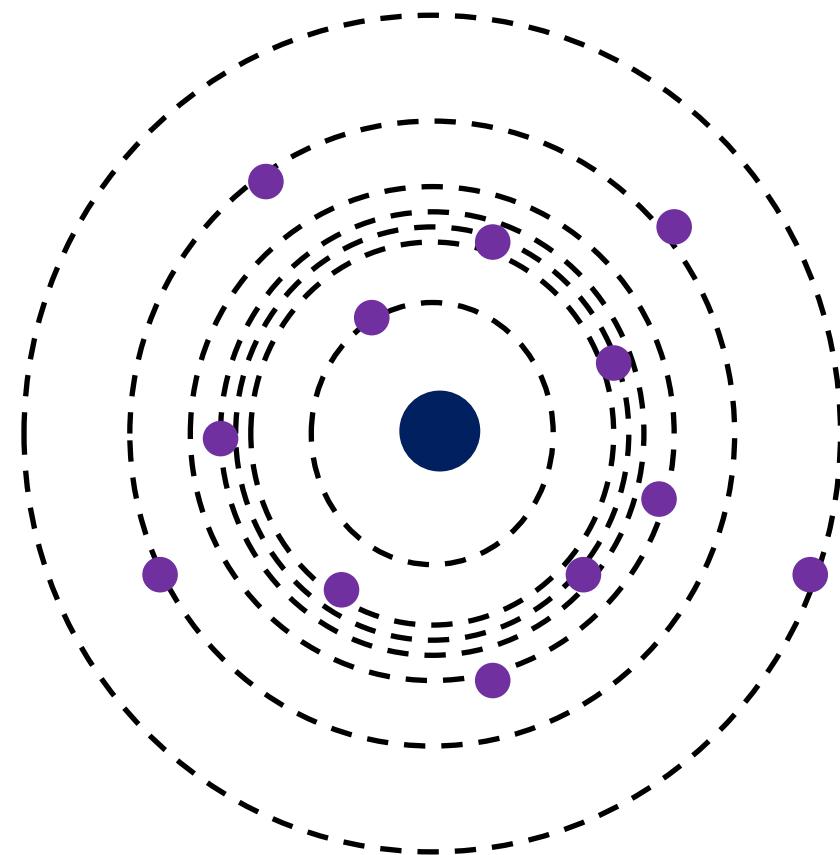
# Method of plane detection

- Strong dependence on the Radial Distribution
- Concentrate  
=> Easier to find big plane
- Probability to find a plane  
 $\Leftrightarrow$  radial distribution



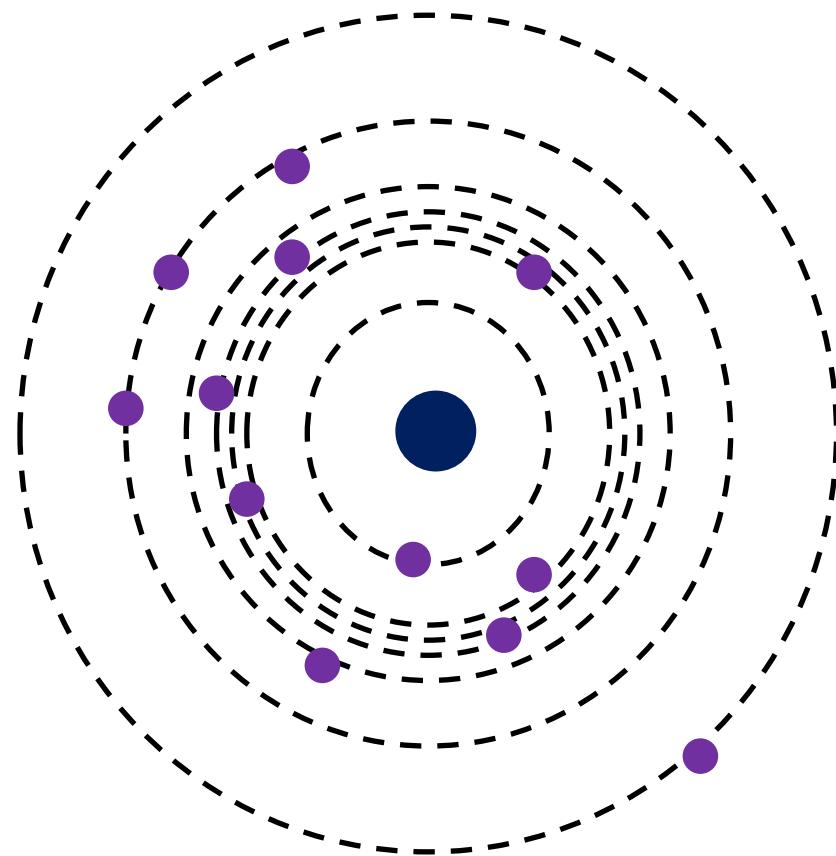
# Probability to find a plane at « $N_p$ » satellites

- Radial distribution fixed



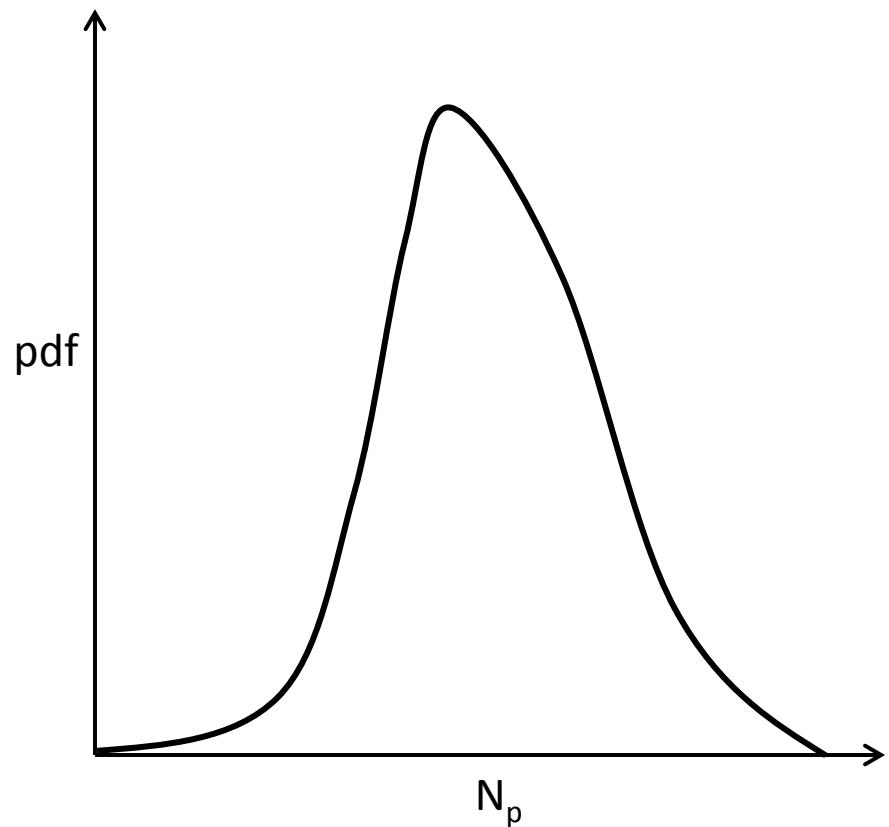
# Probability to find a plane at « $N_p$ » satellites

- Radial distribution fixed
- Random position  
⇒ Search the best plane



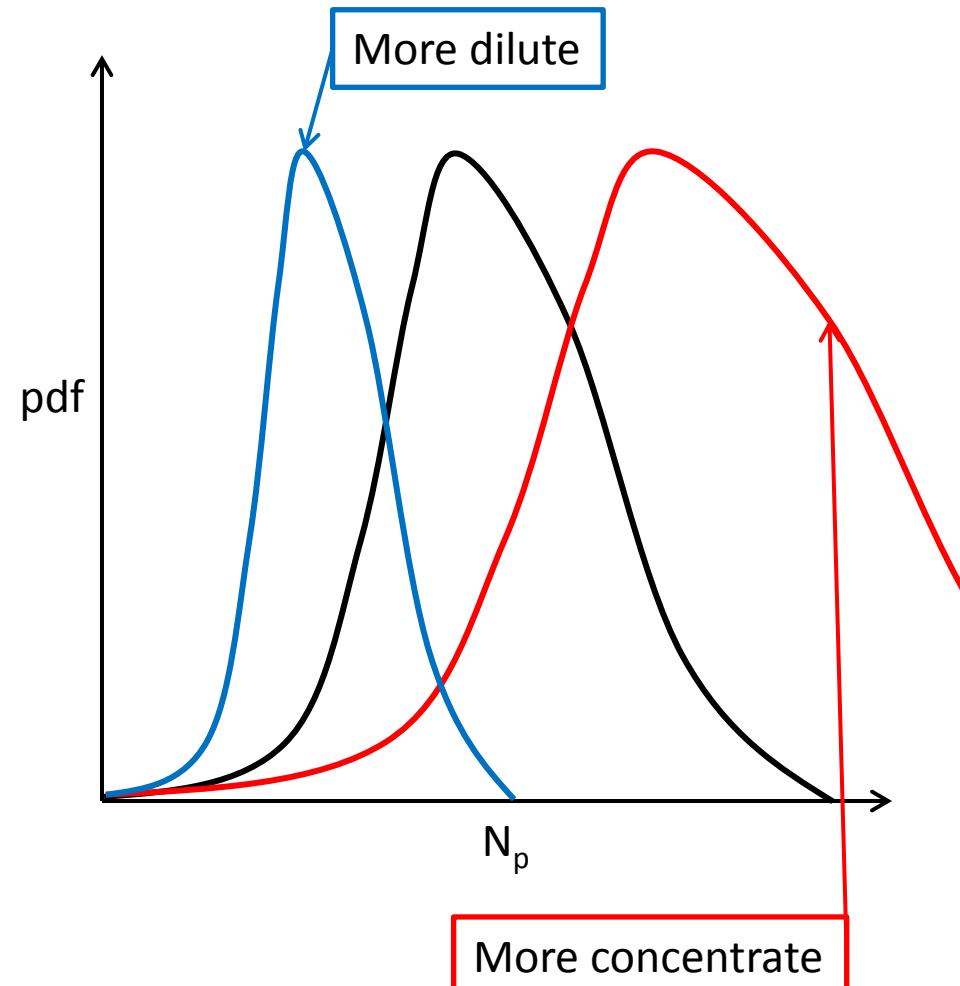
# Probability to find a plane at « $N_p$ » satellites

- Radial distribution fixed
- Random position
  - ⇒ Search the best plane
- 10000 times
  - ⇒ Probability distribution of the maximum number of satellites in a plane, for a fixed radial distribution.



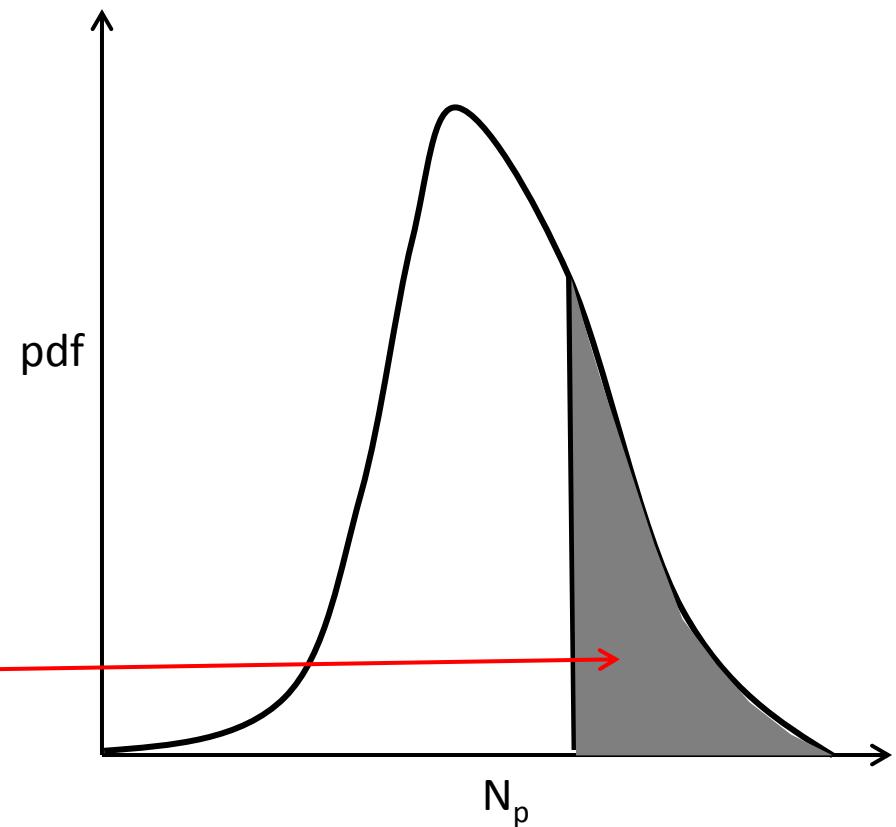
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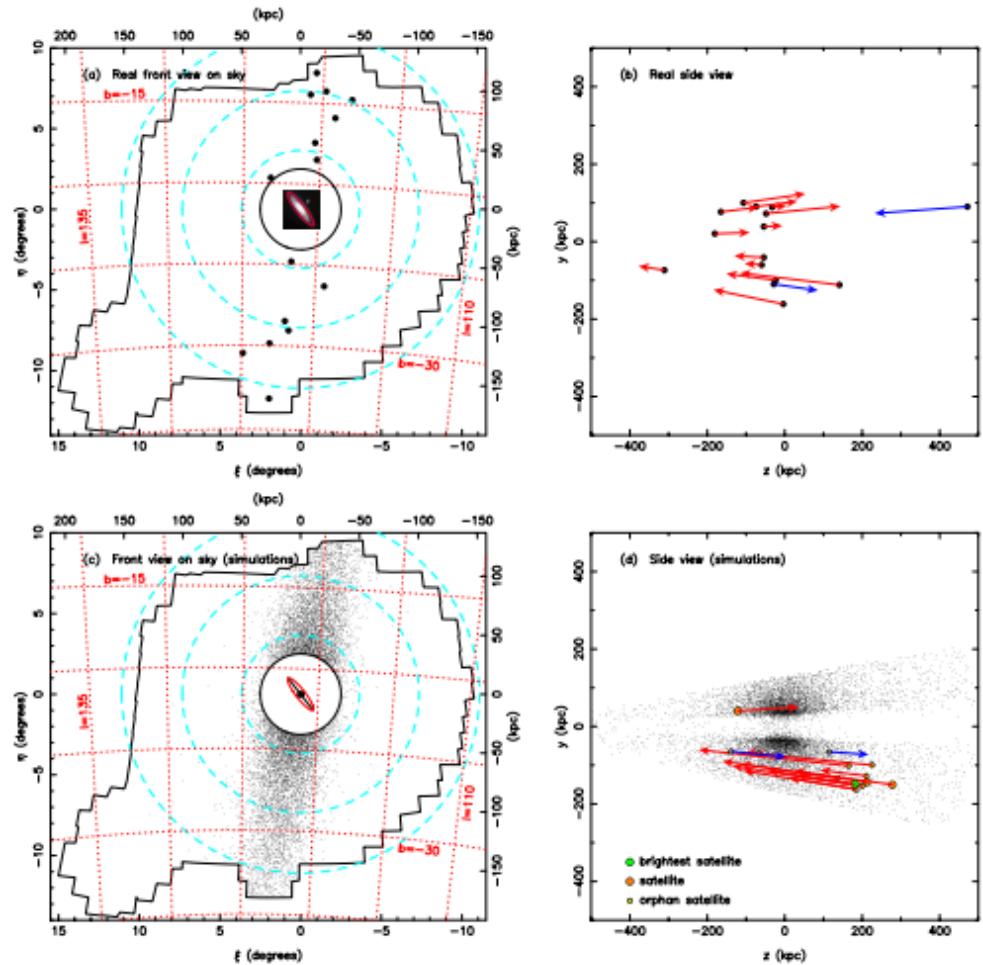
- Radial distribution fixed
- Random position
  - ⇒ Search the best plane
- 10000 times
  - ⇒ Probability distribution of the maximum number of satellites in a plane, for a fixed radial distribution.
- p-value =  $p(X>k)$



# Plane of Andromeda

Observations:

- 15 of 27 in Plane (0.13%)
  - 400kpc diameter
  - Less than 14kpc scatter
  - 13 of 15 corotating (0.74%)
- ⇒ Probability to occur in a random population: 0.00096%



Ibata et al 2014

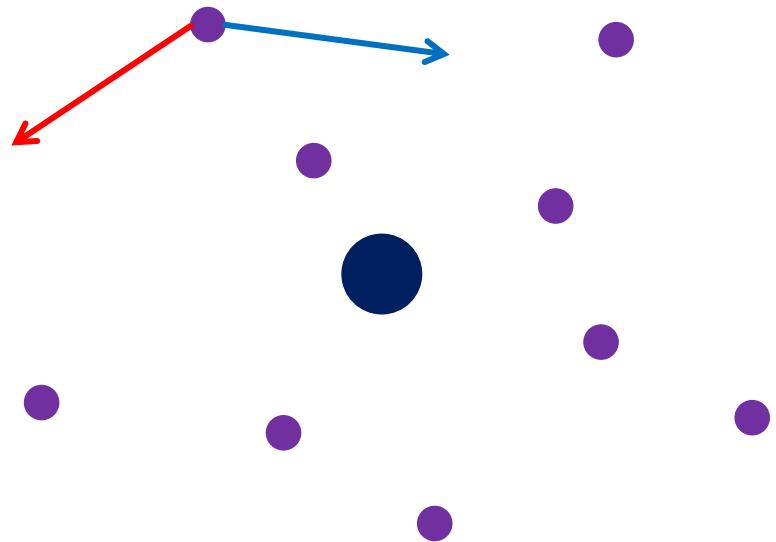
# Probability of co-rotation

- Velocities projected on the plane
- 50/50 probability rotation
- Probability = head or tail  
⇒ Binomial distribution

$$p(X = k) = \binom{k}{n} p^k (1-p)^{n-k}, p = 0.5$$

- Observation => Line of sight  
=> estimation of the rotation way

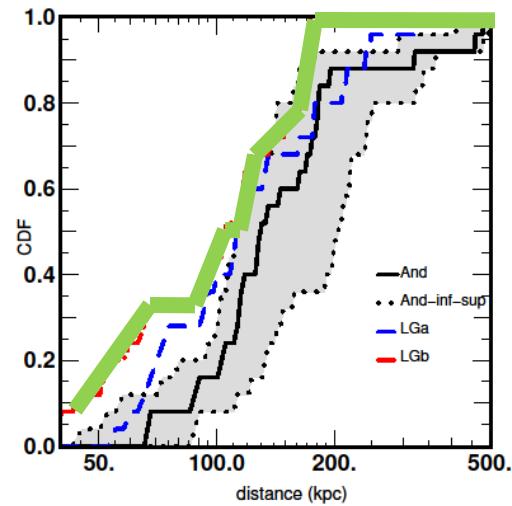
Face-on view of a plane



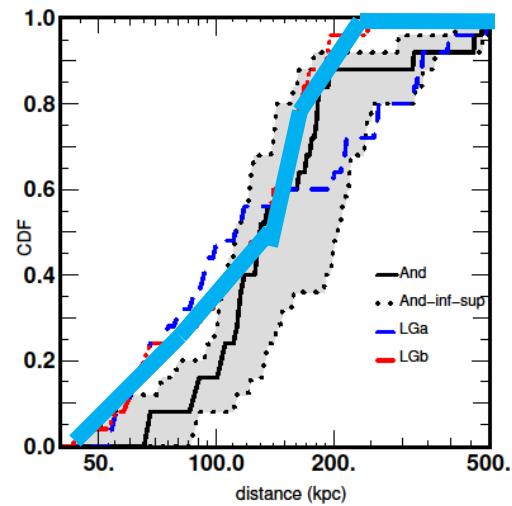
# PAndAS volume with 25 satellites

# $\sim$ PAndAS, 25 satellites

Radial Density:  $M_{\max}$

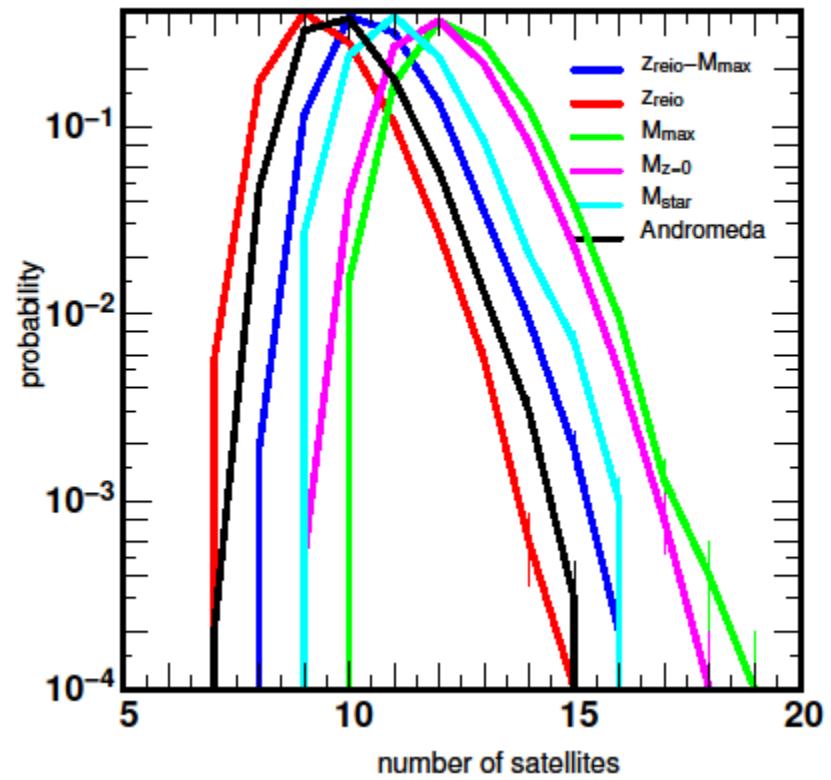


Radial Density:  $M_{\star}$

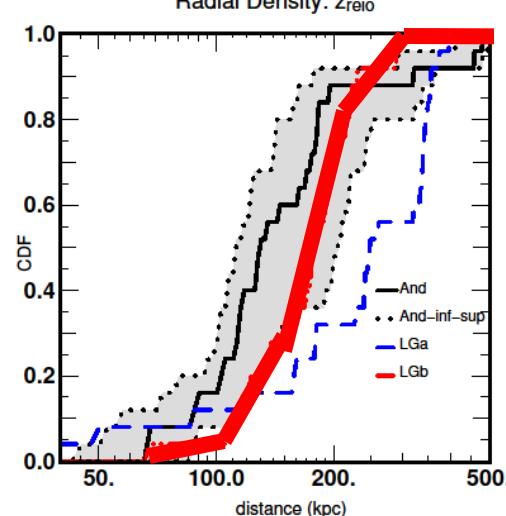


Probability of number of satellites in the maximal plane

MAX Plane probability: LGb



Radial Density:  $Z_{\text{reio}}$



# Results: ~PAndAS, 25 satellites

(1) Galaxy	(2) Selection of satellites	(3) Number satellites in the plane	(4) Number satellites co- rotating	(5) RD $\chi^2$	(6) Angle Plan/line of sight	(7) p-value planar structure (%)	(8) p-value co- rotation (%)	(9) Total signifi- cance (%)	(10) $\sigma_{\parallel}$ (kpc)	(11) $\sigma_{\perp}$ (kpc)	(12) $L_{LOS}^{max}$ ( $\times 10^4$ km s $^{-1}$ kpc)
LGa	$z_r M_{max}$	9	5	1.1514	54.3	93.75	100	93.75	187.4	13.4	$0.63_{-0.1}^{+0.99}$
	$z_r$	10	7	4.4042	57.7	37.8	34.3	12.9937	209.5	15.5	$0.62_{-0.37}^{+0.96}$
	$M_{max}$	12	7	1.807	15.4	28.47	77.4	22.0475	104.9	11.5	$0.59_{-0.32}^{+0.86}$
	$M_{z=0}$	11	7	1.7896	42.6	62.42	54.8	34.2578	125.3	11.2	$0.5_{-0.28}^{+0.76}$
	$M_{star}$	12	7	1.2899	62.5	20.31	77.4	15.7283	160.7	13.9	$0.6_{-0.23}^{+0.87}$
LGb	$z_r M_{max}$	11	10	1.8997	65.6	51.26	1.1	0.6007	176.5	15.6	$0.9_{-0.56}^{+1.55}$
	$z_r$	11	8	1.3851	102.1	13.91	22.6	3.1514	170.1	13.8	$0.56_{-0.22}^{+0.95}$
	$M_{max}$	14	10	4.3958	111.7	16.77	17.9	3.0113	126.3	11.6	$0.72_{-0.42}^{+1.03}$
	$M_{z=0}$	13	8	3.9583	114	32.6	58.1	18.9423	123	11.7	$0.79_{-0.42}^{+1.25}$
	$M_{star}$	11	7	2.8179	130.6	72.61	54.8	39.8504	116.8	15.4	$0.8_{-0.19}^{+1.2}$
M31	simu	14	12	X	88.5	1.60	1.3	0.0208	154.7	12.5	1.47
M31	I13	15	13	X	89	0.13	0.74	0.00096	191.9	12.6	1.3

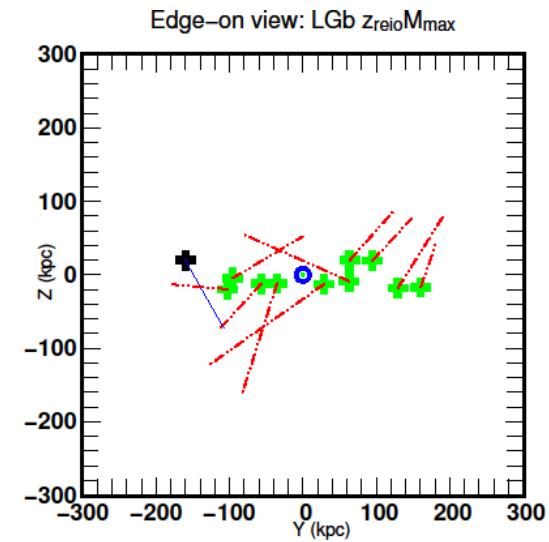
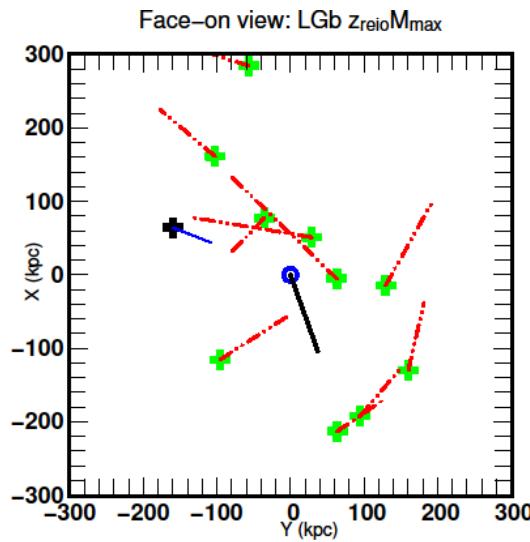
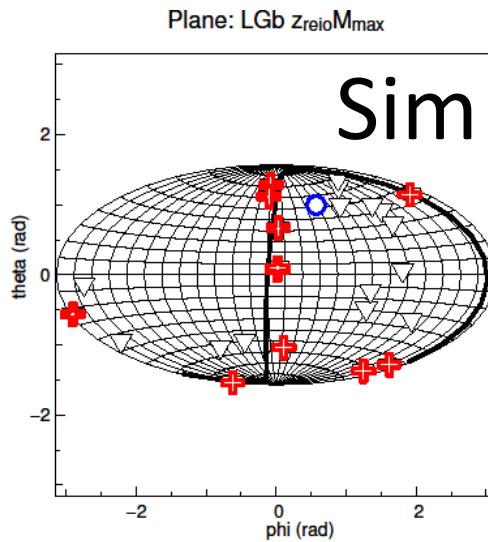
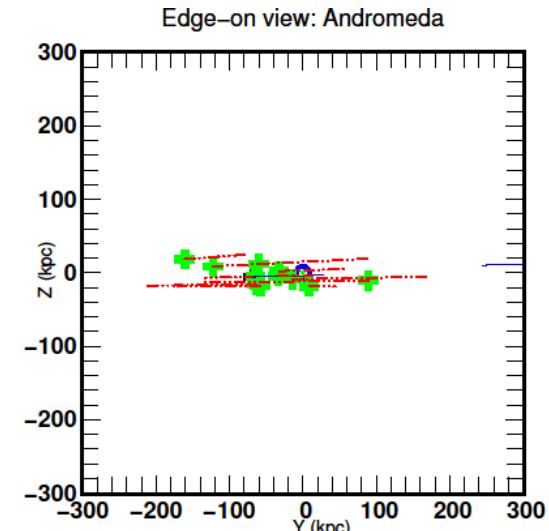
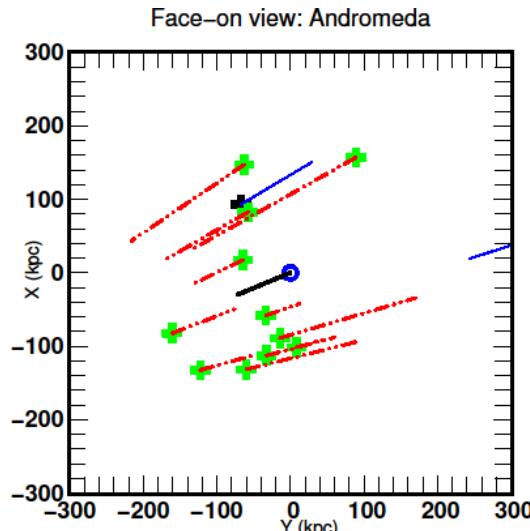
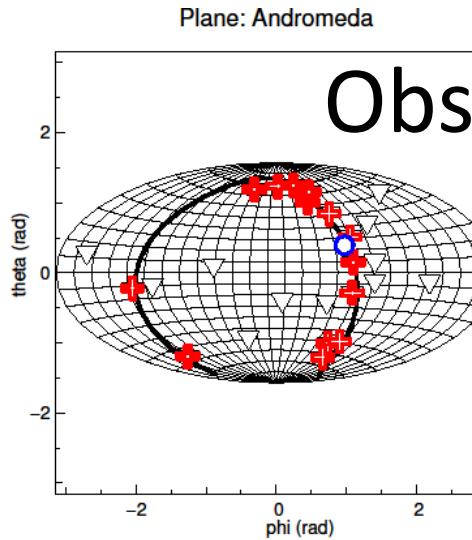
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M31	I13	15	13	X	89	0.13	0.74	0.00096	191.9	12.6	1.3

# Results: ~PAndAS, 25 satellites



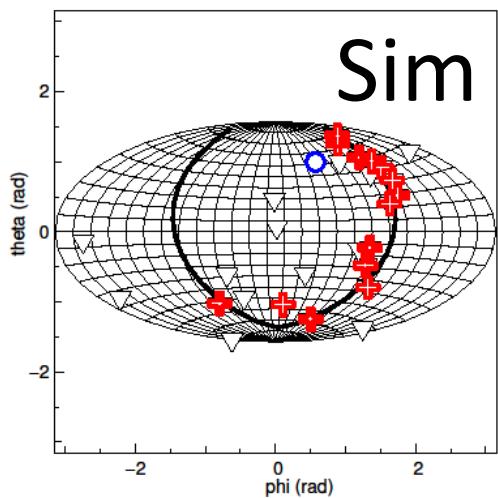
PAndAS-bis volume  
(bigger)  
with 27 satellites

# Results: PAndAS-bis, 27 satellites

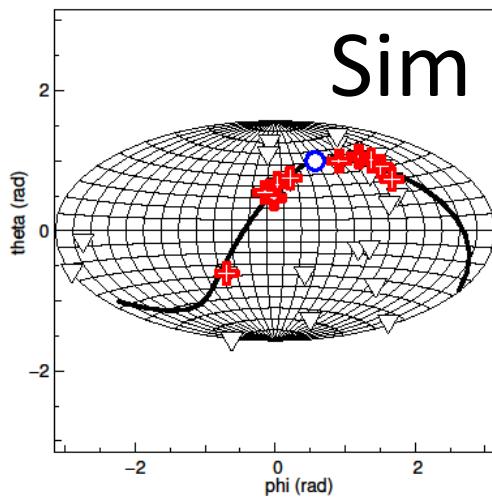
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LGa	$z_r M_{\max}$	9	6	2.66	125.3	84.2	25.4	21.4	222.7	12.0	$0.62^{1.0}_{0.09}$
	$z_{\text{reio}}$	9	6	7.88	126.3	47.3	25.4	12.0	266.1	13.3	$0.77^{1.08}_{0.18}$
	$M_{\max}$	10	7	0.54	129.0	90.2	17.2	15.5	125.0	14.6	$0.60^{0.90}_{0.15}$
	$M_{z=0}$	10	6	1.10	136.7	82.0	37.7	30.9	178.3	11.7	$0.79^{1.19}_{0.35}$
	$M_{\star}$	10	8	1.12	104.5	88.9	5.5	4.9	184.7	15.3	$0.54^{0.72}_{0.26}$
LGb	$z_r M_{\max}$	14	11	1.11	55.0	0.55	2.9	0.0160	176.3	14.1	$1.23^{1.98}_{0.42}$
	$z_{\text{reio}}$	10	10	4.49	90.5	24.4	0.1	0.0244	212.7	14.0	$0.98^{1.49}_{0.55}$
	$M_{\max}$	13	11	1.02	66.2	33.0	1.1	0.363	140.4	12.7	$0.72^{0.93}_{0.40}$
	$M_{z=0}$	14	9	0.71	69.6	3.96	13.3	0.527	145.1	13.7	$0.80^{1.38}_{0.40}$
	$M_{\star}$	12	7	0.76	49.6	45.8	38.7	17.7	123.8	15.4	$0.76^{1.11}_{0.32}$

# Results: PAndAS-bis, 27 satellites

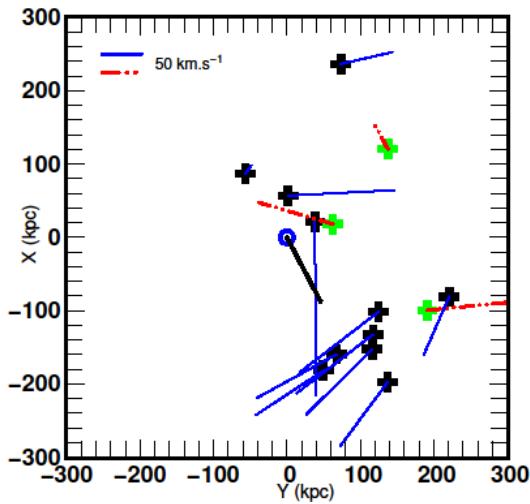
Detected plane: LGb  $z_{\text{reio}} M_{\text{max}}$



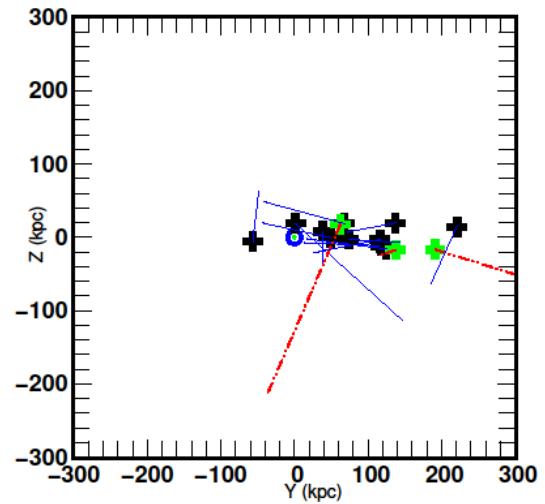
Detected plane: LGb  $z_{\text{reio}}$



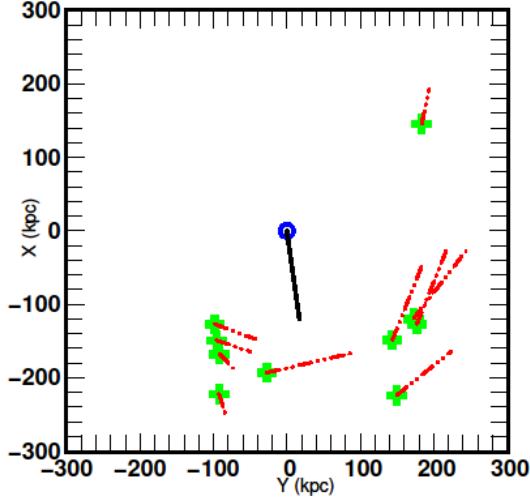
Face-on view: LGb  $z_{\text{reio}} M_{\text{max}}$



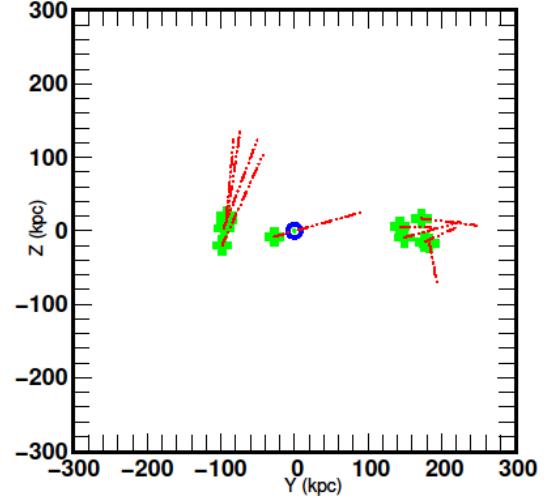
Edge-on view: LGb  $z_{\text{reio}} M_{\text{max}}$



Face-on view: LGb  $z_{\text{reio}}$

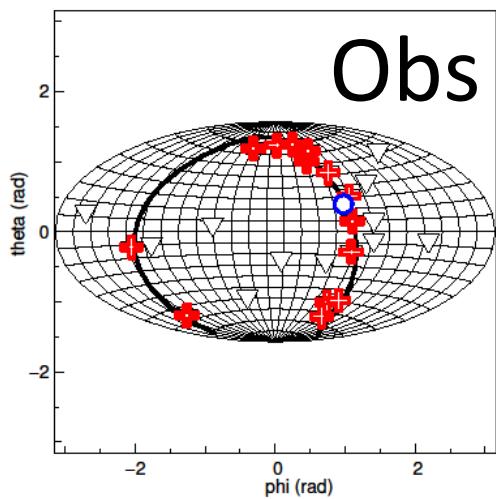


Edge-on view: LGb  $z_{\text{reio}}$

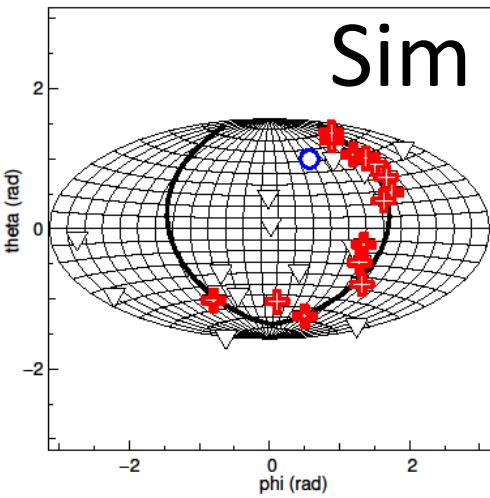


# Results: PAndAS-bis, 27 satellites

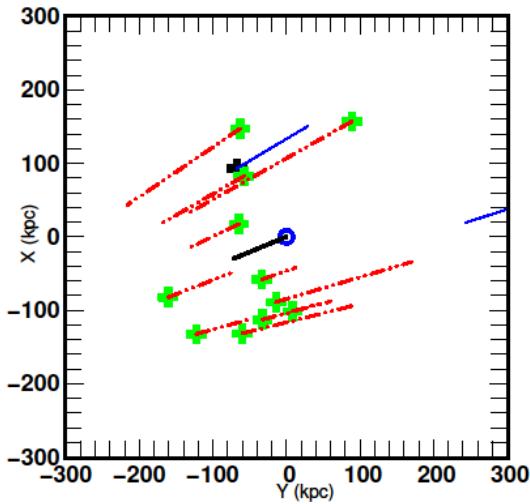
Plane: Andromeda



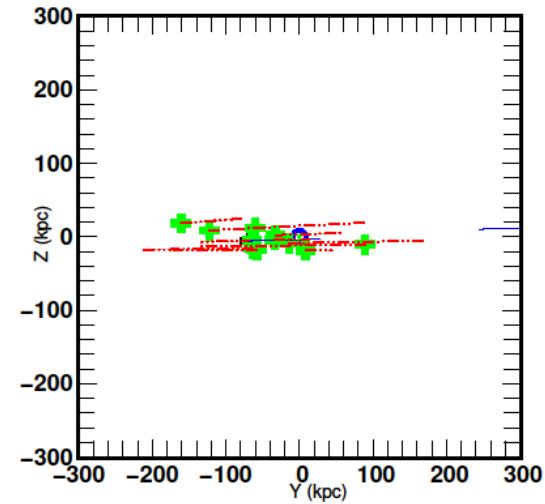
Detected plane: LGb  $z_{\text{reio}} M_{\text{max}}$



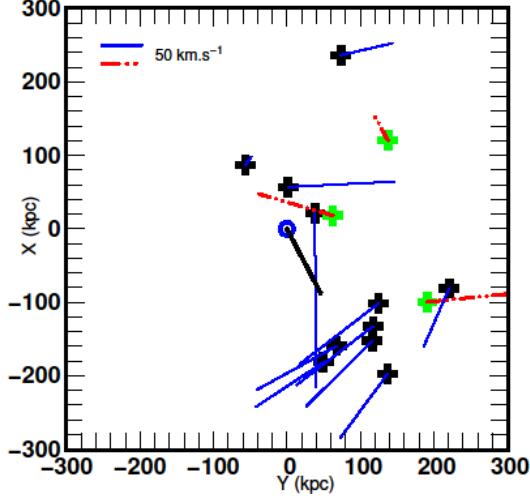
Face-on view: Andromeda



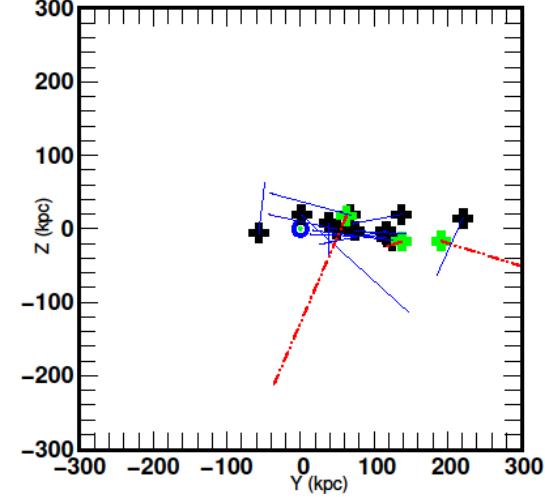
Edge-on view: Andromeda



Face-on view: LGb  $z_{\text{reio}} M_{\text{max}}$



Edge-on view: LGb  $z_{\text{reio}} M_{\text{max}}$



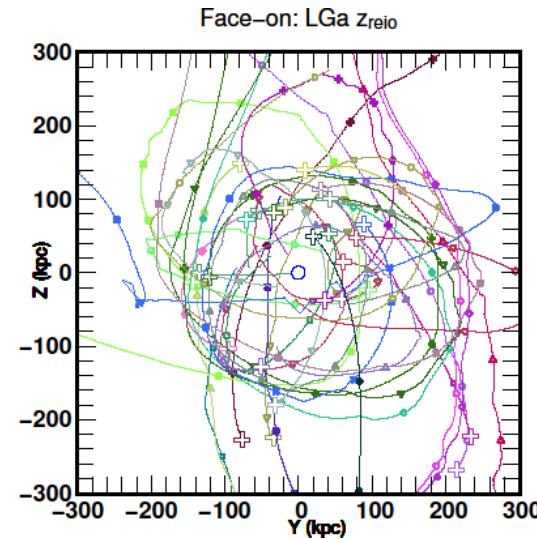
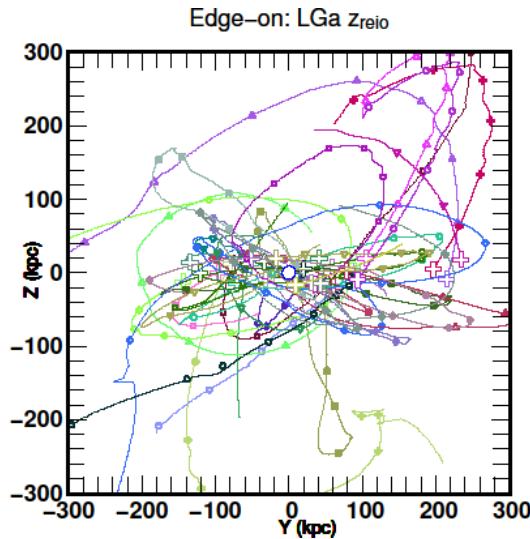
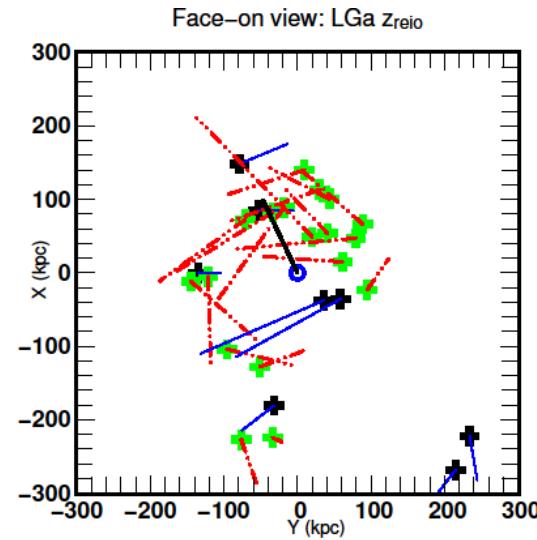
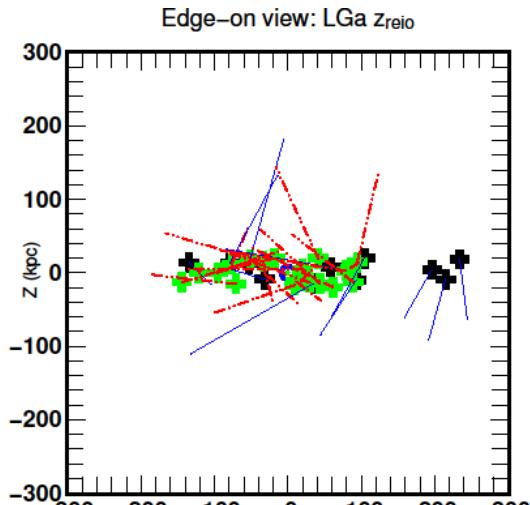
# Spherical volume with 100 satellites

# Results: spherical, 100 satellites

(1) Galaxy	(2) Selection of satellites	(3) Number satellites in the plane	(4) Number satellites co- rotating	(5) RD $\chi^2$	(6) Angle Plan/line of sight	(7) p-value planar structure (%)	(8) p-value co- rotation (%)	(9) Total signifi- cance (%)	(10) $\sigma_{\parallel}$ (kpc)	(11) $\sigma_{\perp}$ (kpc)	(12) LLOS <sub>min</sub> $(\times 10^4$ km s <sup>-1</sup> kpc)
LGa	z <sub>r</sub> M <sub>max</sub>	32	21	1.007	63.4	0.3	11	0.033	203.7	13.4	0.69 <sup>0.97</sup> <sub>0.31</sub>
	z <sub>r</sub>	32	21	1.251	63.4	0.07	11	0.0077	212.6	13.3	0.74 <sup>1.01</sup> <sub>0.31</sub>
	M <sub>max</sub>	32	20	0.6134	52.2	7.1	21.5	1.5288	138.5	12.8	0.72 <sup>0.86</sup> <sub>0.51</sub>
	M <sub>z=0</sub>	30	20	0.5863	69.3	20.65	9.8	2.0389	152.6	13.1	0.57 <sup>0.75</sup> <sub>0.43</sub>
	M <sub>star</sub>	27	16	0.6342	52.1	93.41	44.2	41.2936	174.2	11.8	0.75 <sup>1.1</sup> <sub>0.37</sub>
LGb	z <sub>r</sub> M <sub>max</sub>	28	19	1.5198	118.1	27.96	8.7	2.4369	140.2	13.8	0.93 <sup>1.26</sup> <sub>0.6</sub>
	z <sub>r</sub>	28	19	1.5352	118	21.55	8.7	1.8782	140.2	13.7	0.93 <sup>1.26</sup> <sub>0.6</sub>
	M <sub>max</sub>	33	19	1.6253	130.6	9.09	48.6	4.4254	129.7	13.1	0.74 <sup>0.99</sup> <sub>0.39</sub>
	M <sub>z=0</sub>	33	17	1.8036	130.9	9.99	100	9.9899	126.7	12.6	0.7 <sup>0.9</sup> <sub>0.46</sub>
	M <sub>star</sub>	30	20	1.378	101.4	18.79	9.8	1.8552	168	11.9	0.8 <sup>1</sup> <sub>0.63</sub>

# Results: spherical, 100 satellites

Sim



# Conclusions and discussions

- Method to properly compare observations and detections in the simulation => radial density
- Significant detections (probability > 1% and 0.1%)
  - Comparable properties: size, thickness, ~number of satellites
  - « Goup of satellites » + others accidentally align
  - No favorite selection of satellites
- No planes detected with an as extremely low probability as the observations

# Results: other significant planes in spherical selections

(1) $N_{sat}$ Galaxy	(2) Selection of satellites	(3) Number satellites in the plane	(4) Number satellites co- rotating	(5) RD $\chi^2$	(6) Angle plane / LoS	(7) p-value planar structure (%)	(8) p-value co- rotation (%)	(9) Total signifi- cance (%)	(10) $\sigma_{\parallel}$ (kpc)	(11) $\sigma_{\perp}$ (kpc)	(12) LLOS <sub>min</sub> ( $\times 10^4$ km s <sup>-1</sup> kpc)
25-LGb	$z_r M_{max}$	12	11	1.6316	65.6	6.57	0.6	0.0417	173.5	15.9	$0.89^{1.33}_{0.5}$
25-LGb	$M_{z=0}$	14	9	2.5785	105	1.6	42.3	0.6783	133.9	13.3	$0.70^{0.97}_{0.31}$
27-LGb	$z_r M_{max}$	12	11	1.6256	65.1	11.74	0.6	0.0745	173.6	15.3	$0.89^{1.33}_{0.49}$
27-LGb	$z_r$	12	9	1.4482	99.6	3.51	14.5	0.5124	170.7	15	$0.76^{1.11}_{0.45}$
27-LGb	$M_{z=0}$	15	10	2.67	104.8	1.27	30.1	0.3832	129.9	13.8	$0.62^{0.94}_{0.27}$
50-LGa	$z_r$	15	12	3.0351	115.5	20.82	3.5	0.7319	266	14.1	$0.8^{1.14}_{0.43}$
100-LGa	$z_r M_{max}$	32	21	1.007	63.4	0.3	11	0.033	203.7	13.4	$0.69^{0.97}_{0.31}$
100-LGa	$z_r$	32	21	1.251	63.4	0.07	11	0.0077	212.6	13.3	$0.74^{1.01}_{0.31}$
150-LGa	$z_r M_{max}$	44	26	0.6152	63.3	0.57	29.1	0.1659	183.2	12.7	$0.66^{0.93}_{0.41}$
150-LGa	$z_r$	42	26	0.6013	63	1.68	16.4	0.2757	186.3	12.6	$0.67^{0.96}_{0.41}$
150-LGa	$M_{z=0}$	41	29	0.5064	70	12.64	1.1	0.1454	157.9	12.3	$0.61^{0.78}_{0.45}$
150-LGb	$M_{star}$	43	29	1.5209	102.4	4.2	3.1	0.1324	158.7	11.5	$0.84^{1.07}_{0.55}$

# Radiative Transfert

## Post-process: ATON

- ATON (Aubert & Teyssier 2008)
- Grid-based method
- Multi-GPU: CUDATON
- Stellar/halos sources,  $T=50000K$ ,  $f_{esc}=0.2$
- Ocvirk et al 2013:
  - No photo-evaporation/feedback
- Ocvirk et al 2014:
  - Model of negative stellar feedback

# Radiative feedback

- DM halos as sources
- Mini-halos  $< 10^7$ :
  - suppressed by LW background
- Low-mass  $10^7 < M < 10^9$ :
  - ( $T_{vir} > 10^4$ K) sensitive to photo-heating => star formation suppression if  $x > 0.5$
- High-mass  $> 10^9$ :
  - from star continuously
- Ocvirk et al 2014

