すばるPFSを用いた 矮小銀河ダークハロー構造への制限

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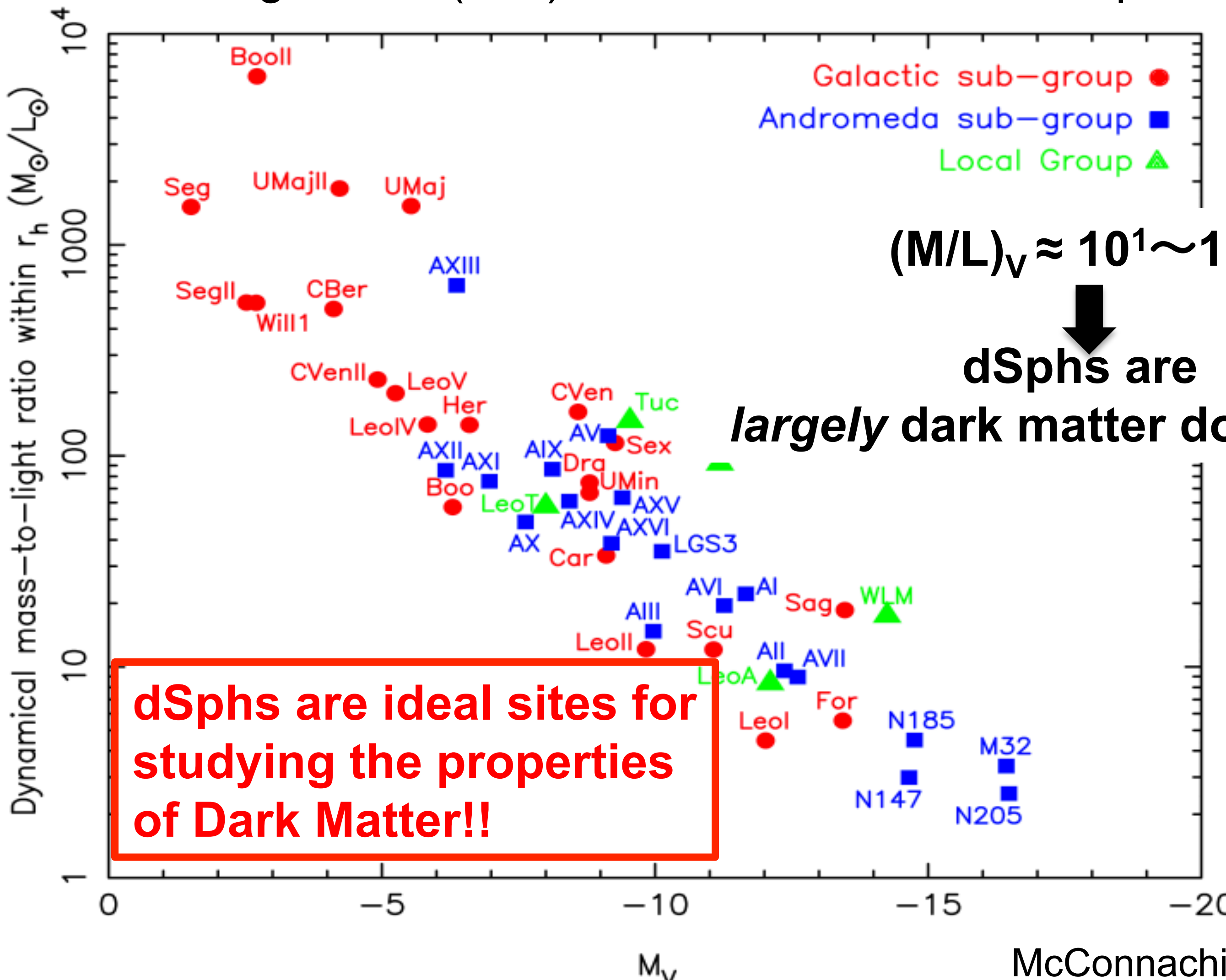
& Kavli IPMU PFS working group

Dynamical Properties of dSphs

Mass to Light ratio (M/L) within stellar extent in dSphs



$(M/L)_V \approx 10^1 \sim 10^3$

⬇

dSphs are
***largely* dark matter dominated!**

dSphs are ideal sites for studying the properties of Dark Matter!!

McConnachie 2012

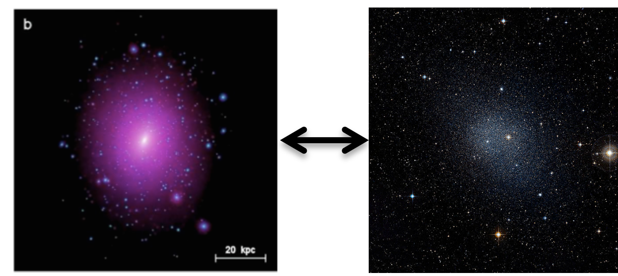
Science Goal

✓ **What is the distribution of dark matter of dSphs?**

✧ **Central density slope of a dark halo**
✧ **Global shape of a dark halo**

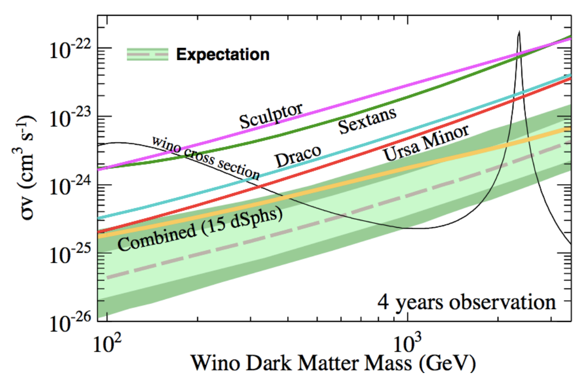
✓ **Testing ΛCDM theory on small mass scales.**

- Core-cusp problem & Too-big-to-fail problem
- How flattened are dark halos?
- Uncovering potential problems…



✓ **Constraining on the nature of dark matter**

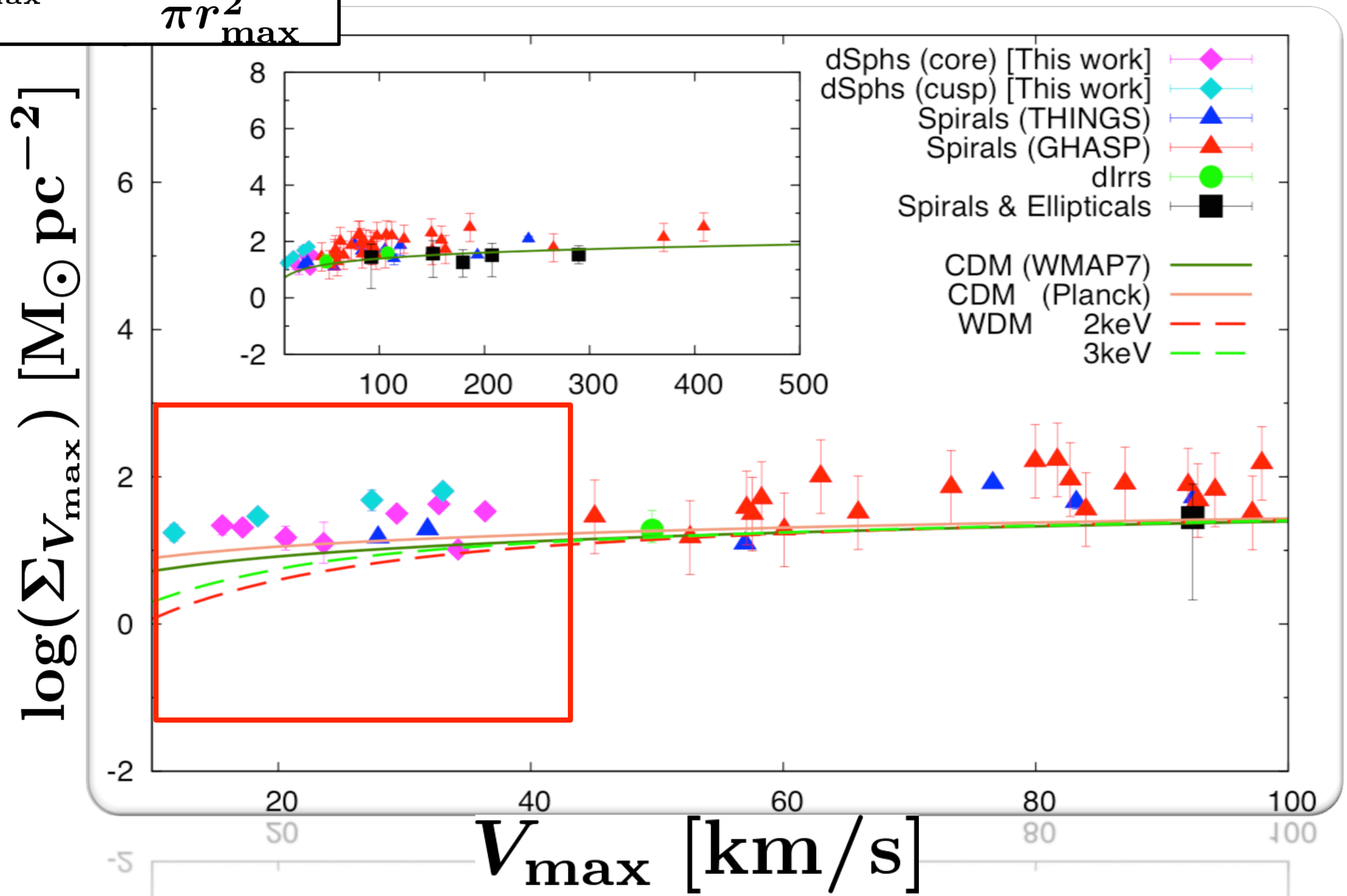
- γ-ray flux caused by annihilation of DM particles (市川くん's talk)
- Constancy of mean surface density of dark halos (KH & Chiba 2015a)



New astrophysical test on the nature of dark matter

KH & Chiba (2015a)

$$\Sigma_{V_{\max}} = \frac{M(r_{\max})}{\pi r_{\max}^2}$$



Non-spherical dark matter distribution of dSphs in the MW and M31

Hayashi & Chiba (2015b, in prep.)

※Assumptions※

- Stellar components are in dynamical equilibrium.
- Static gravitational potential is dominated by DM.
- DSphs are considered as a collisionless system.
- Axisymmetry in both stellar and DM components.

・**Axisymmetric Jeans equations**

$$\overline{v_z^2} = \frac{1}{\nu(R,z)} \int_z^\infty \nu \frac{\partial \Phi}{\partial z} dz \qquad \overline{v_\phi^2} = \frac{1}{1-\beta_z} \left[\overline{v_z^2} + \frac{R}{\nu} \frac{\partial (\nu \overline{v_z^2})}{\partial R} \right] + R \frac{\partial \Phi}{\partial R}$$

$$\beta_z = 1 - \overline{v_z^2} / \overline{v_R^2}$$: **velocity anisotropy**

・**Luminous component**

$$\nu(R,z) = \frac{3L}{4\pi b_*^3} \left[1 + \frac{m_*^2}{b_*^2} \right]^{-5/2}$$

$$m_*^2 = R^2 + \frac{z^2}{q^2}$$ **q : axial ratio**

$$q'^2 = \cos^2 i + q^2 \sin^2 i$$ **q' : projected q**

・**DM-halo component**

$$\rho(R,z) = \rho_0 \left(\frac{m}{b_{\mathrm{halo}}} \right)^\alpha \left[1 + \left(\frac{m}{b_{\mathrm{halo}}} \right)^2 \right]^{-(\alpha+3)/2}$$

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Free parameters

- **Luminous component**

$$\nu(R,z) = \frac{3L}{4\pi b_*^3}\left[1 + \frac{m_*^2}{b_*^2}\right]^{-5/2}$$

$$m_*^2 = R^2 + \frac{z^2}{q^2}$$ **q : axial ratio**

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- **DM-halo component**

$$\rho(R,z) = \rho_0 \left(\frac{m}{b_{\rm halo}}\right)^{\alpha} \left[1 + \left(\frac{m}{b_{\rm halo}}\right)^2\right]^{-(\alpha+3)/2}$$

$$m^2 = R^2 + \frac{z^2}{Q^2}$$ **Q : DM's axial ratio**

The observational dataset

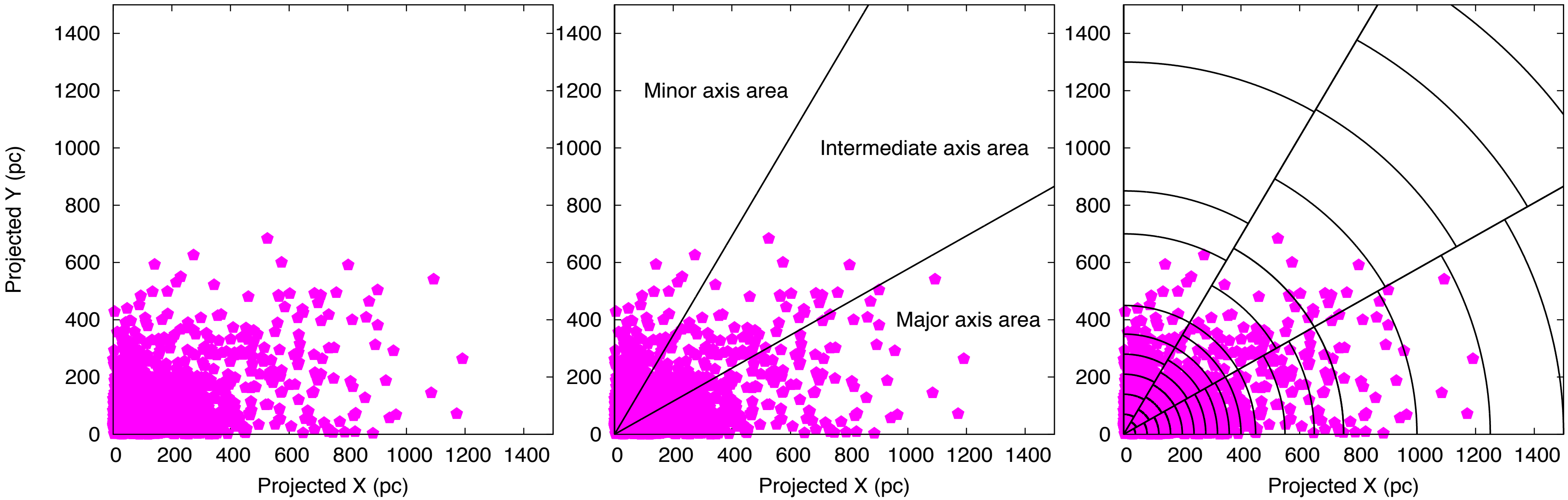
Table 1. The observational dataset for MW and M31 dSph satellites

Object	No. of stars	M_* ($10^6 M_\odot$)	M_V	$D_\odot$ (kpc)	$r_{\rm half}$ (pc)	q' (axial ratio)	$\tau_{0.7}$[a] (Gyr)	Ref.[b]
MW dSphs								
Carina	776	0.38	-9.1 ± 0.5	106 ± 6	241 ± 23	0.67 ± 0.05	4.5	1,3,7
Fornax	2523	20.0	-13.4 ± 0.3	147 ± 12	668 ± 34	0.70 ± 0.01	4.6	1,3,7
Sculptor	1360	2.3	-11.1 ± 0.5	86 ± 6	260 ± 39	0.68 ± 0.03	12.7	1,3,7
Sextans	445	0.44	-9.3 ± 0.5	86 ± 4	682 ± 117	0.65 ± 0.05	No data	1,3,7
Draco	185	0.29	-8.8 ± 0.3	76 ± 6	196 ± 12	0.69 ± 0.02	11.5	2,7
Leo I	328	5.5	-12.0 ± 0.3	254 ± 15	246 ± 19	0.79 ± 0.03	2.7	2,3,7
Leo II	200	0.74	-9.8 ± 0.3	233 ± 14	151 ± 17	0.87 ± 0.05	6.8	1,7
M31 dSphs								
And I	51	3.9	-11.7 ± 0.1	745 ± 24	670 ± 30	0.78 ± 0.04	7.6	5,6,7
And II	488	7.6	-12.4 ± 0.2	652 ± 18	1230 ± 20	0.90 ± 0.02	6.2	4,6,7
And III	62	0.83	-10.0 ± 0.3	748 ± 24	400 ± 30	0.48 ± 0.02	8.8	5,6,7
And V	85	0.39	-9.1 ± 0.2	773 ± 28	350 ± 20	0.82 ± 0.05	10.0	5,6,7
And VII	136	9.5	-12.6 ± 0.3	762 ± 35	770 ± 20	0.87 ± 0.04	12.8	5,6,7

[a]This value is the lookback time at achieving 70% of current stellar mass of dSphs, and is estimated by available data taken from Weisz et al. (2014).

[b]References: (1) Irwin & Hatzidimitriou (1995); (2) Martin et al. (2008); (3) Walker et al. (2009c); (4) Ho et al. (2012); (5) Tollerud et al. (2012); (6)McConnachie & Irwin (2006); (7) McConnachie (2012)

The observational dataset

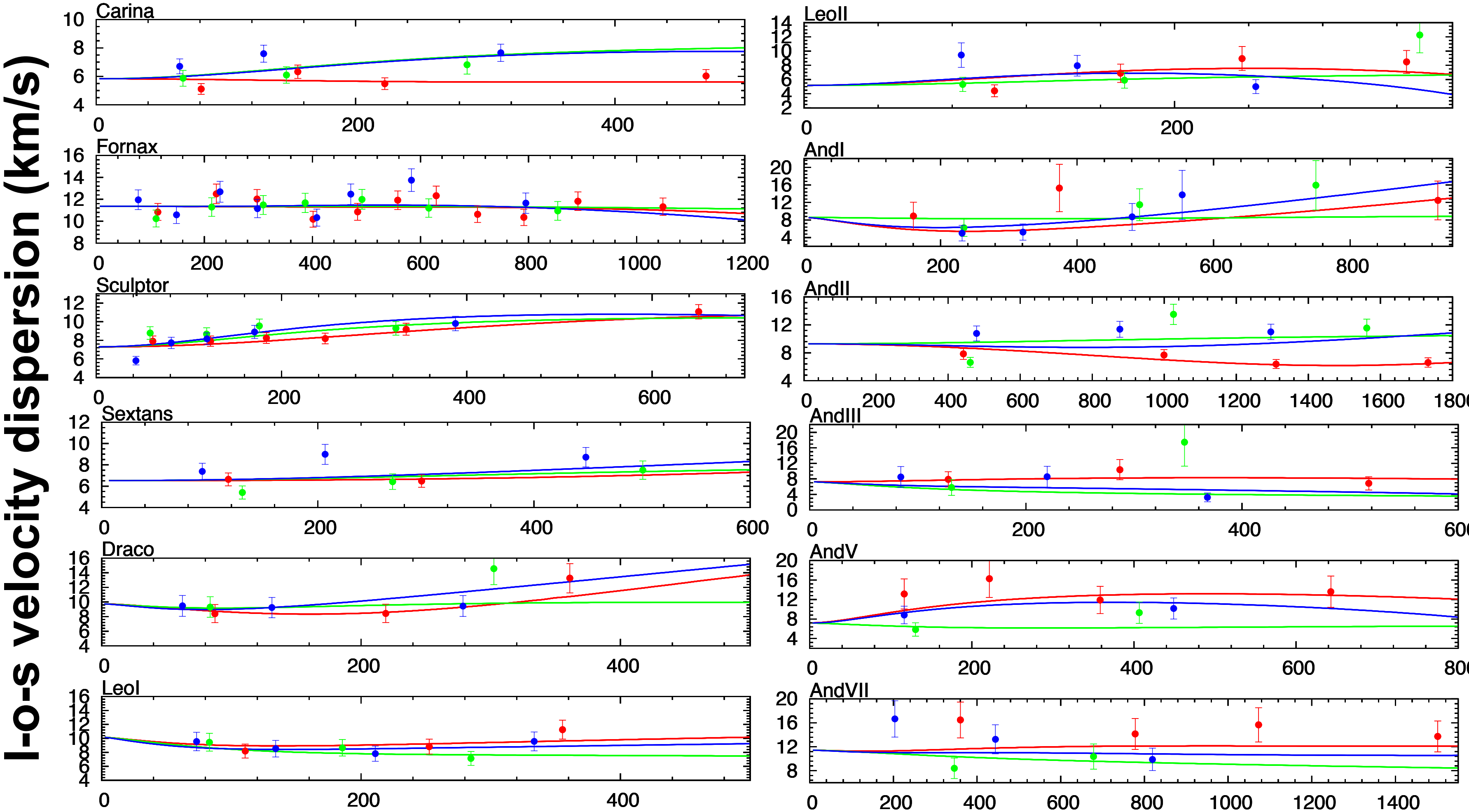


Fitting method: MCMC technique

$$P_i(\sigma_{\mathrm{los},i}|\mathbf{M}) = \frac{1}{\sqrt{2\pi \mathrm{Var}(\sigma_{\mathrm{los},i})}} \exp\left[-\frac{1}{2}\frac{(\sigma_{\mathrm{los},i}-\sigma_{t,i})^2}{\mathrm{Var}(\sigma_{\mathrm{los},i})}\right]$$

$$\mathbf{M} = (Q, b_{\mathrm{halo}}, \rho_0, \beta_z, \alpha, i)$$

Line-of-sight velocity dispersion profile



Major axis, **Minor axis**, **intermediate axis** **(pc)**

Best-fit parameters

Table 2. Results of MCMC analysis for twelve dSph galaxies.

Galaxy	Q	$b_{\rm halo}$[pc]	ρ_0 [$M_\odot$ pc^{-3}]	β_z	α	i [deg]
MW dSphs						
Carina	0.33 ± 0.02	$709.7^{+40.6}_{-44.3}$	0.107 ± 0.006	-0.05 ± 0.06	$-0.09^{+0.09}_{-0.05}$	$87.1^{+2.9}_{-9.1}$
Fornax	0.38 ± 0.03	$991.1^{+27.0}_{-21.4}$	0.086 ± 0.003	$-0.17^{+0.16}_{-0.07}$	$0.00_{-0.04}$	$90.0_{-10.6}$
Sculptor	0.45 ± 0.03	$637.7^{+32.6}_{-26.0}$	0.168 ± 0.008	$-0.03^{+0.06}_{-0.04}$	$0.00_{-0.09}$	$87.8^{+2.2}_{-9.1}$
Sextans	0.53 ± 0.06	$1126.7^{+93.5}_{-74.5}$	0.028 ± 0.008	$0.23^{+0.12}_{-0.18}$	$0.00_{-0.10}$	$89.8^{+0.2}_{-12.5}$
Draco	0.40 ± 0.05	$590.2^{+46.5}_{-43.9}$	0.153 ± 0.021	$0.31^{+0.08}_{-0.13}$	$-0.86^{+0.11}_{-0.11}$	$75.6^{+14.4}_{-8.8}$
Leo I	0.86 ± 0.10	$581.8^{+33.3}_{-26.1}$	0.037 ± 0.005	0.09 ± 0.14	$-1.40^{+0.06}_{-0.08}$	$70.5^{+19.5}_{-7.5}$
Leo II	0.91 ± 0.16	$281.8^{+35.3}_{-30.6}$	0.195 ± 0.031	$-0.62^{+0.56}_{-1.8}$	$0.00_{-0.11}$	$88.8^{+0.2}_{-34.3}$
M31 dSphs						
And I	$2.41^{+0.49}_{-0.39}$	$811.3^{+118.1}_{-112.7}$	0.037 ± 0.009	$0.79^{+0.03}_{-0.05}$	$-0.39^{+0.39}_{-0.29}$	$90.0_{-34.8}$
And II	0.57 ± 0.04	$2290.9^{+174.8}_{-84.1}$	0.010 ± 0.002	$0.22^{+0.05}_{-0.06}$	$0.00_{-0.04}$	$89.9^{+0.1}_{-15.6}$
And III	0.16 ± 0.04	$796.9^{+90.5}_{-96.8}$	0.043 ± 0.01	≤ -0.21	$-1.43^{+0.14}_{-0.23}$	$70.8^{+8.6}_{-3.3}$
And V	$4.75^{+4.54}_{-1.71}$	$369.9^{+35.6}_{-37.2}$	0.039 ± 0.007	≤ 0.13	$-1.33^{+0.21}_{-0.12}$	$78.2^{+11.8}_{-14.3}$
And VII	1.60 ± 0.39	$486.6^{+40.3}_{-28.8}$	0.062 ± 0.01	$0.12^{+0.19}_{-0.47}$	$-0.35^{+0.20}_{-0.46}$	$75.4^{+14.6}_{-18.6}$

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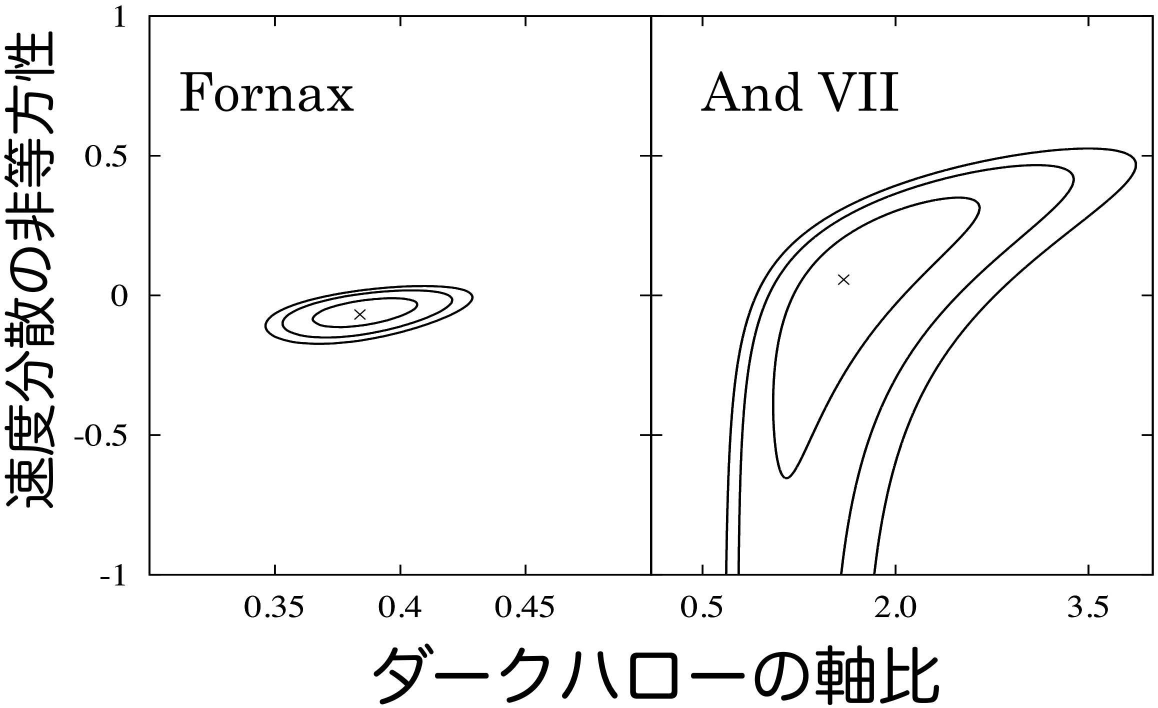
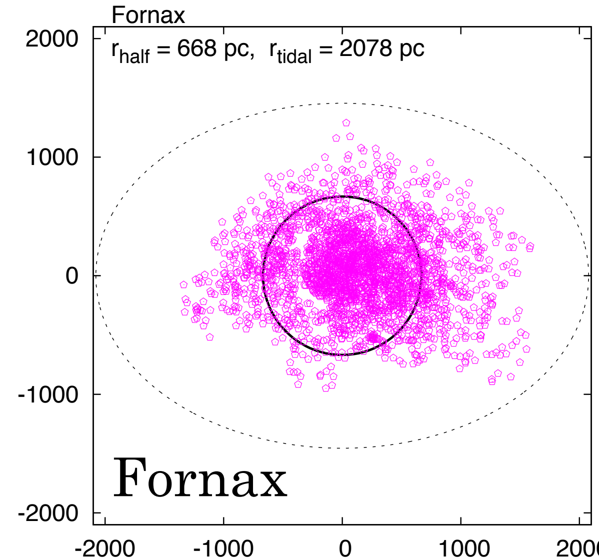
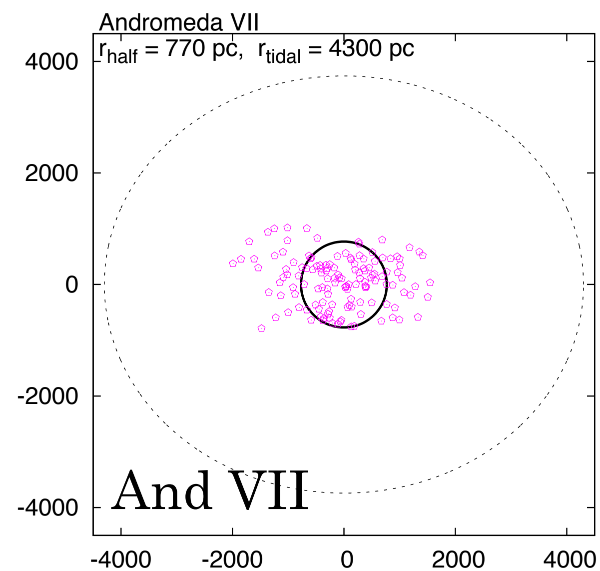
Degeneracy between Q and β_z



Fornax: good constraint ☺
And VII: strong degeneracy ☹

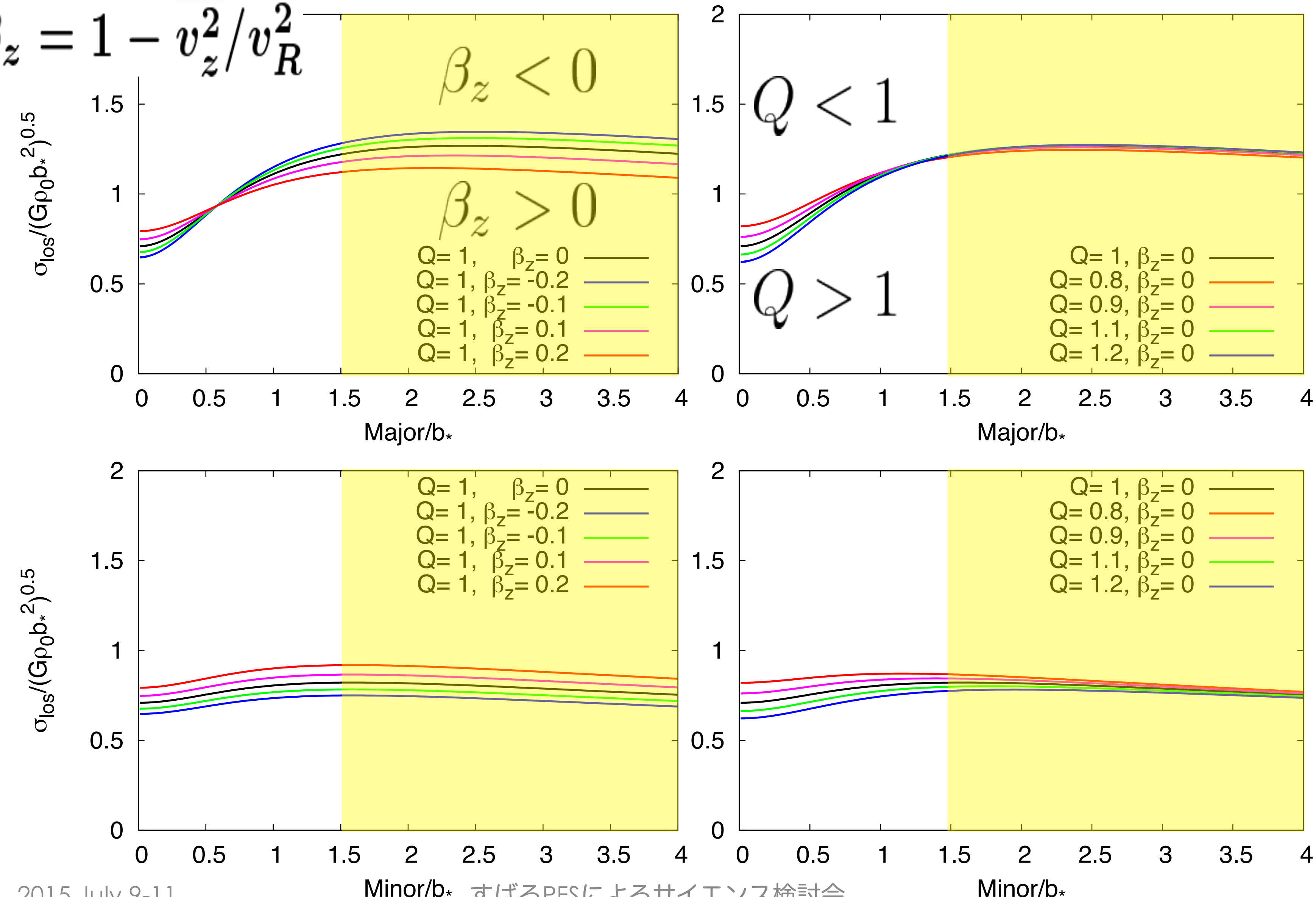
What is the origin of this degeneracy?



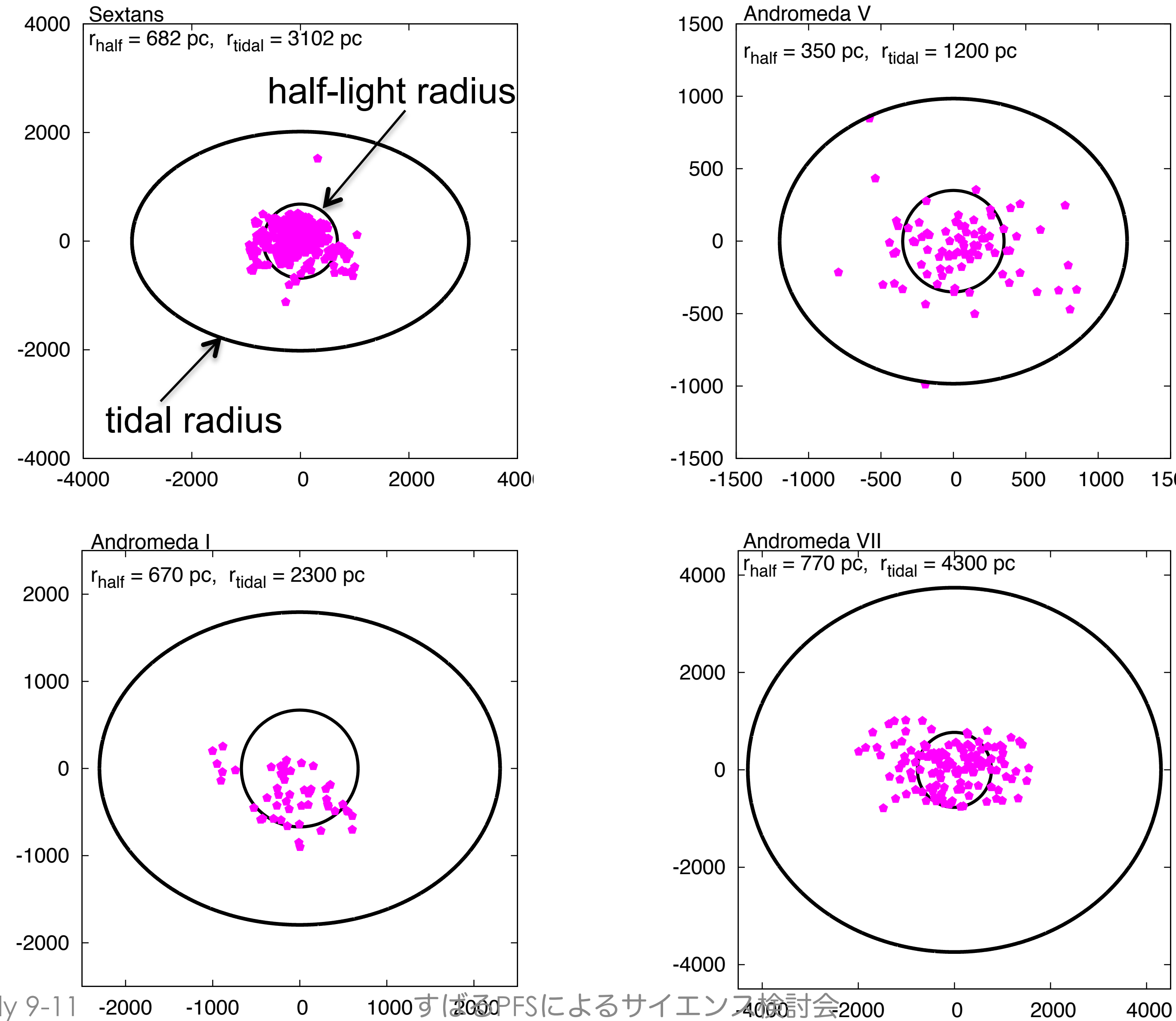


Degeneracy between Q and β_z …

$$\beta_z = 1 - \overline{v_z^2}/\overline{v_R^2}$$



The impact of sample selection



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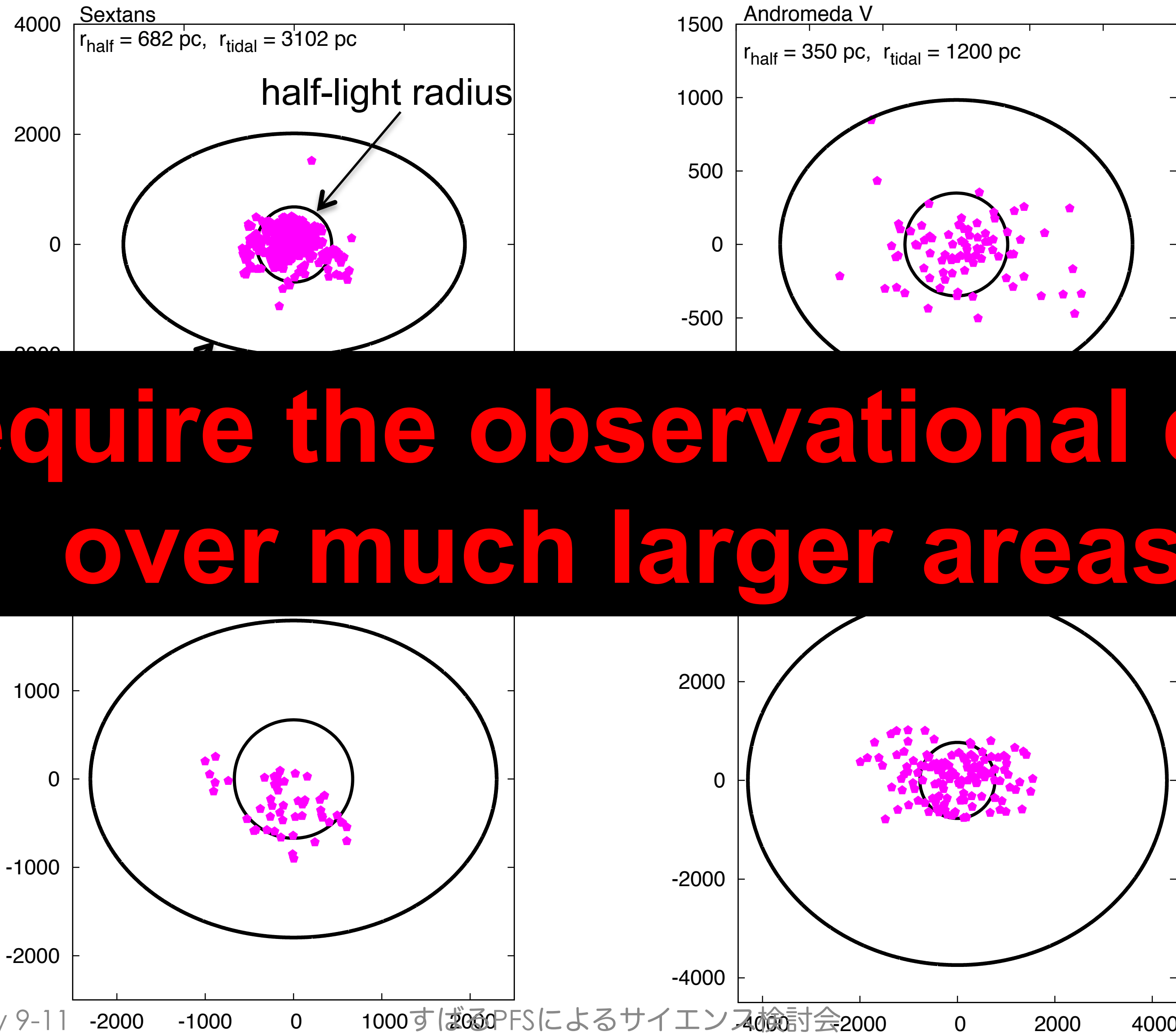
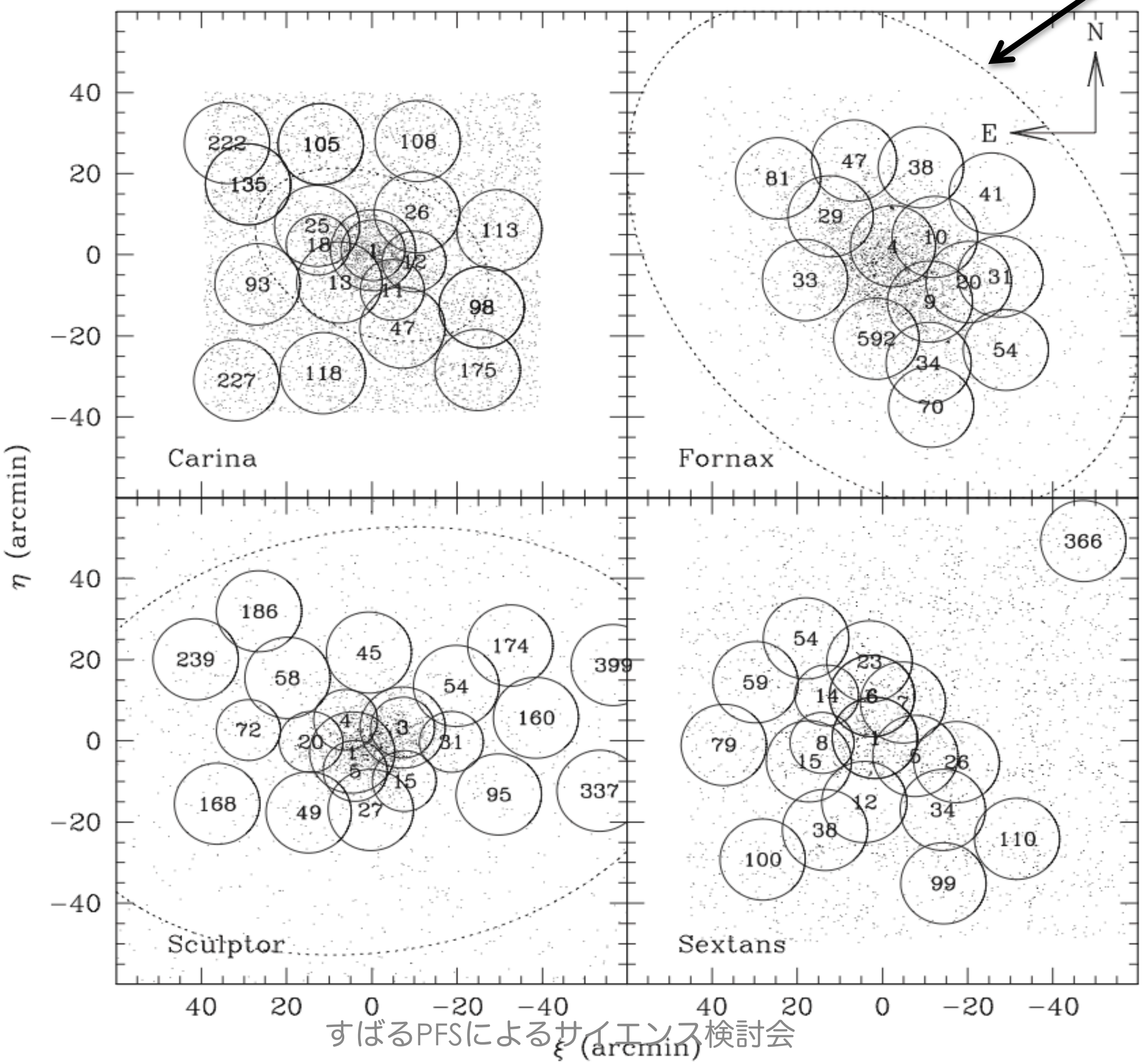


Require the observational data over much larger areas

Previous survey for dwarf spheroidal satellites

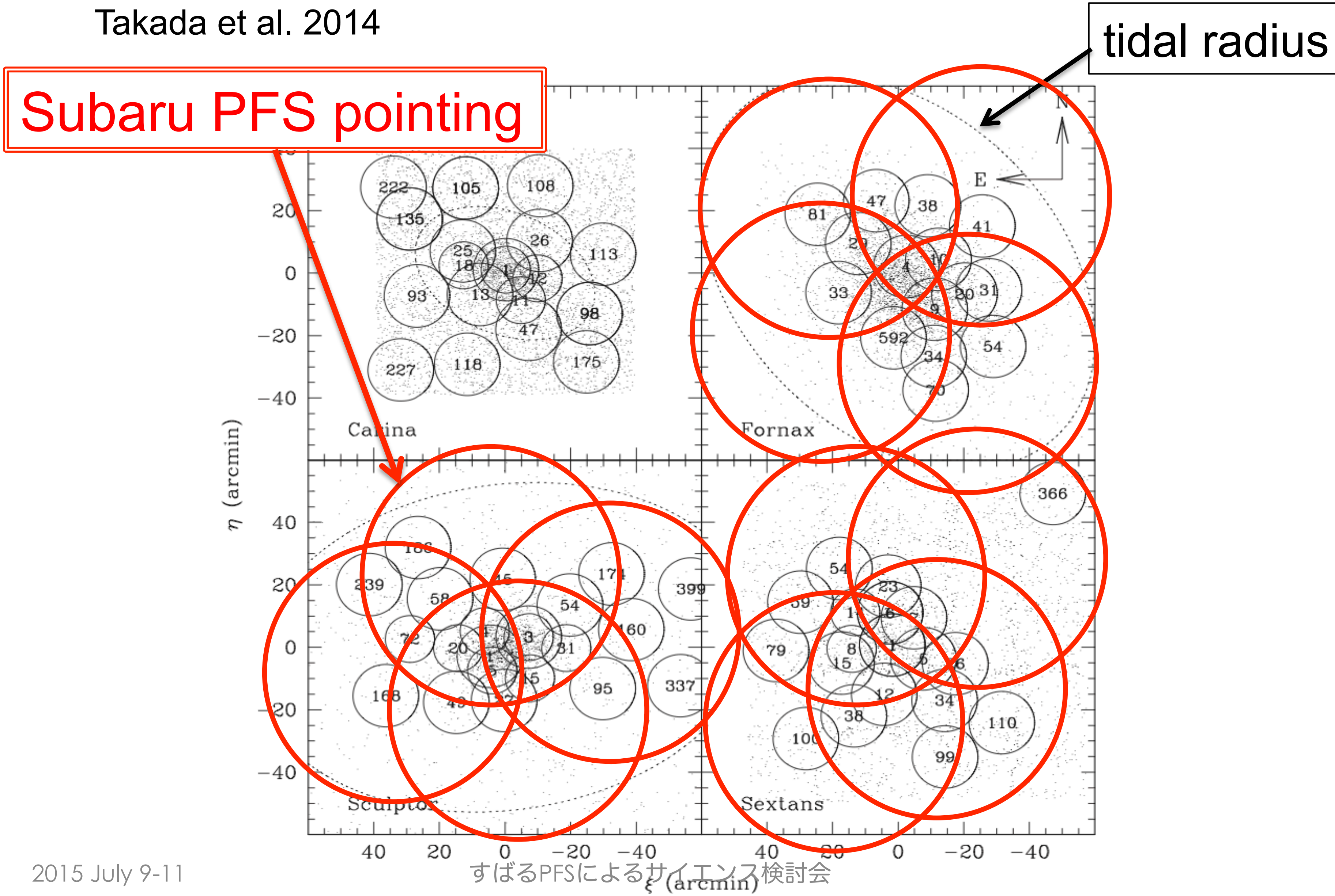
Walker et al. 2009

tidal radius



PFS survey for dwarf spheroidal satellites

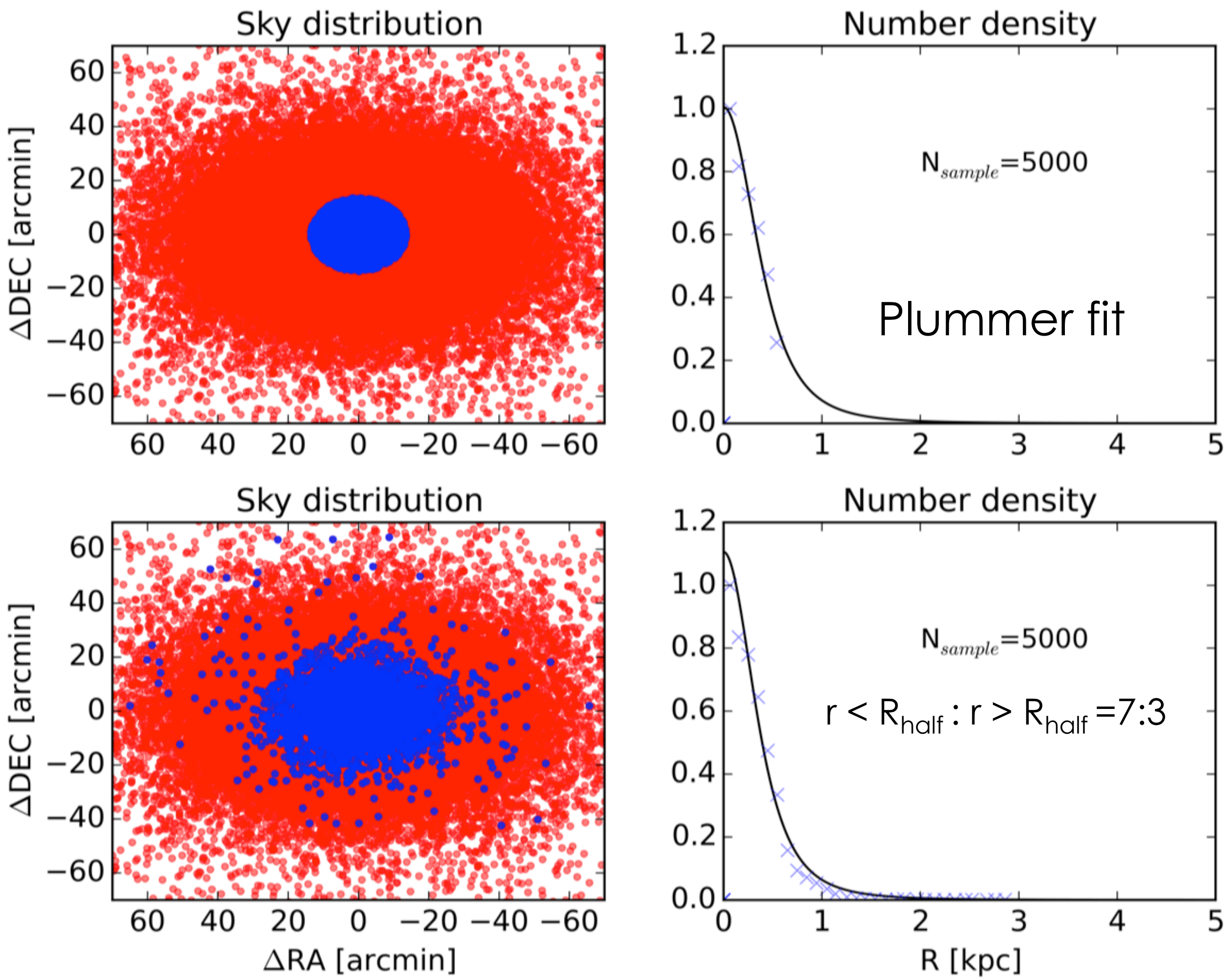
Takada et al. 2014



Gaia Challenge – Triaxial Data

Data within R_{half}

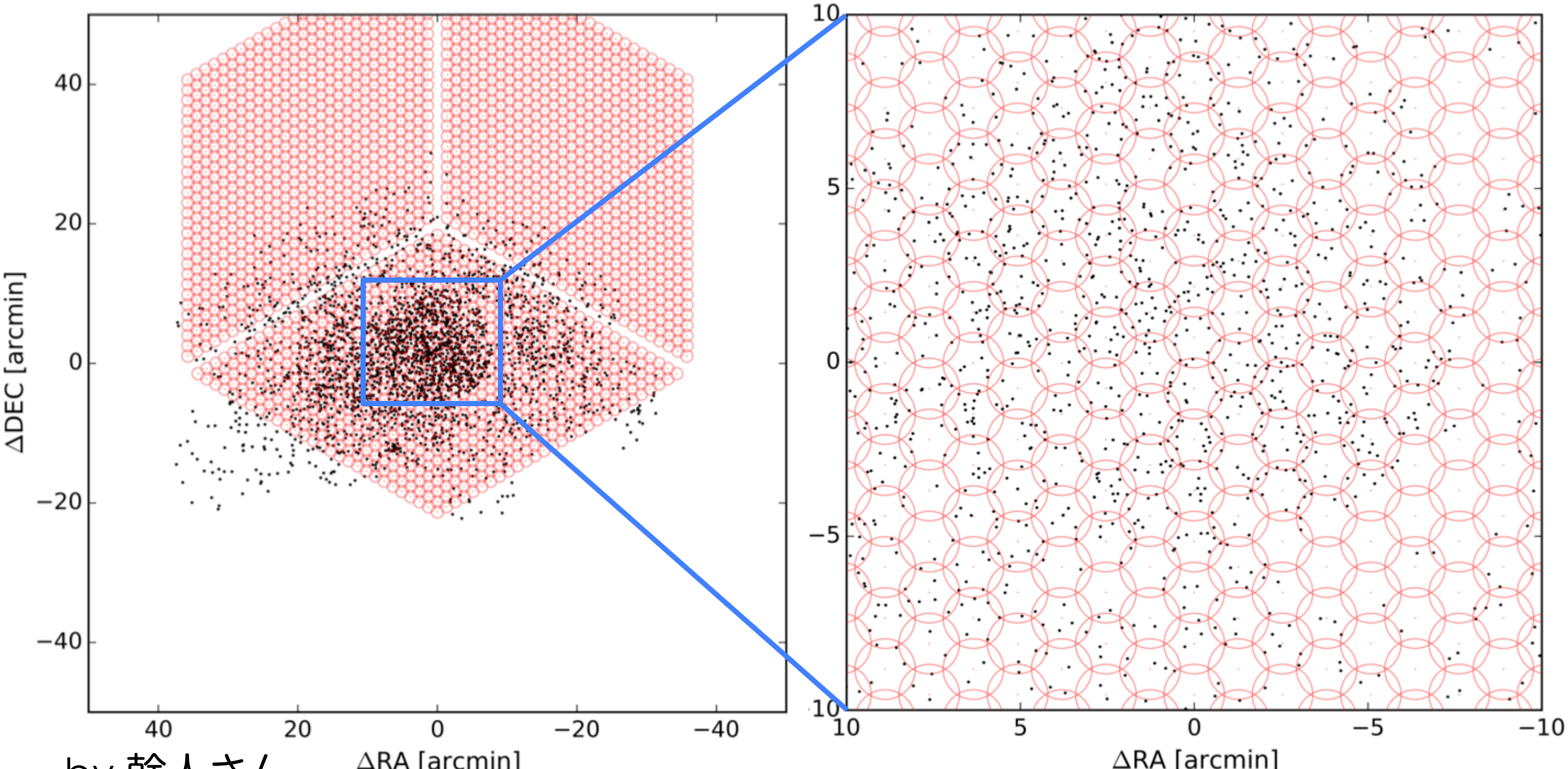
Data within $5*R_{half}$



誠意計算中。。。

What is an optimal observation for dSphs?

Black dots: Spectroscopic data of Fornax dSph (Walker+ 2009) # of stars= 2523



by 幹人さん

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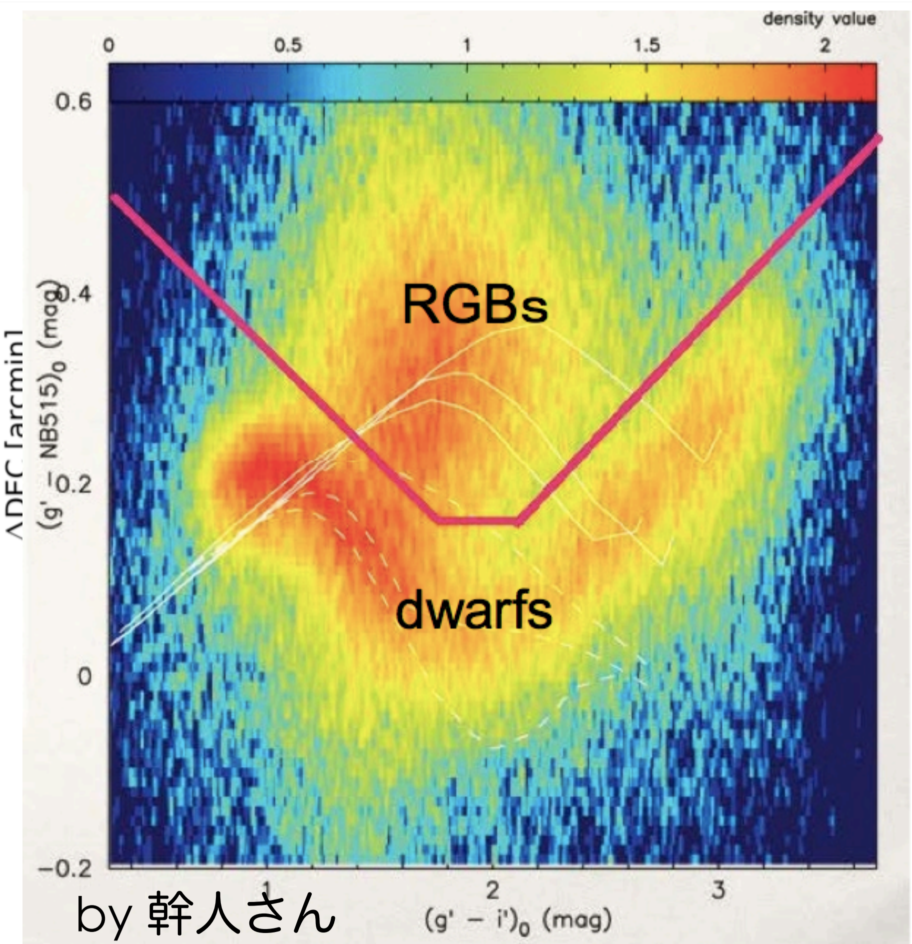
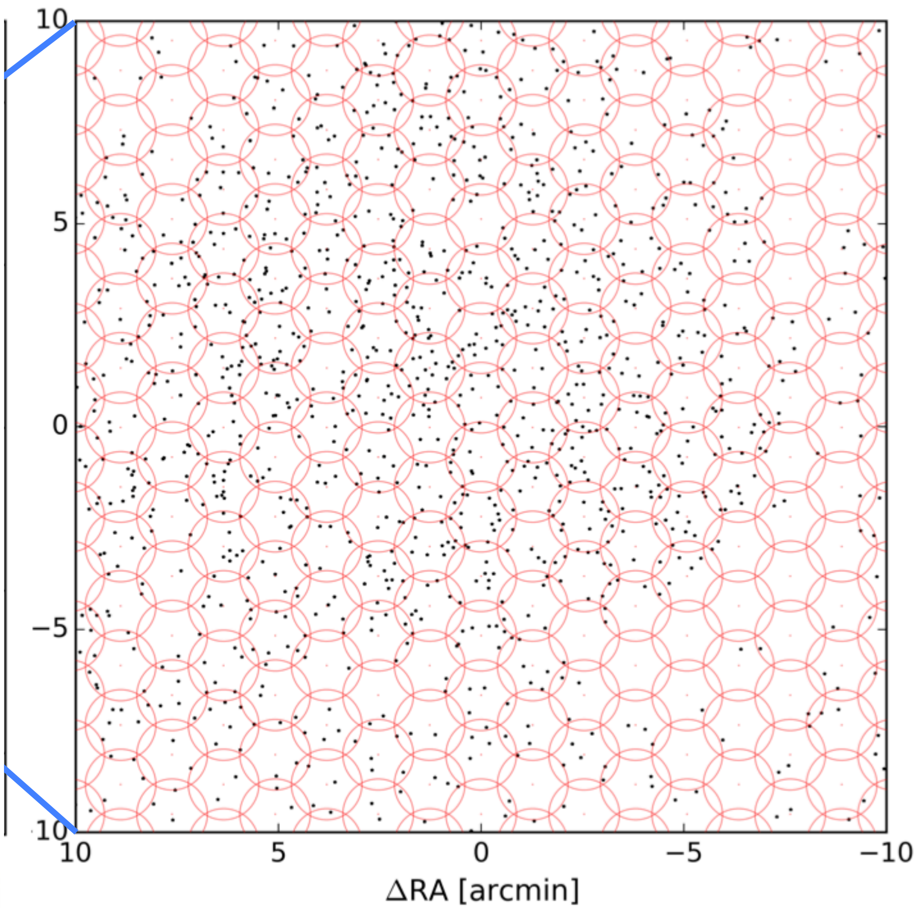
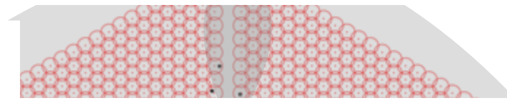




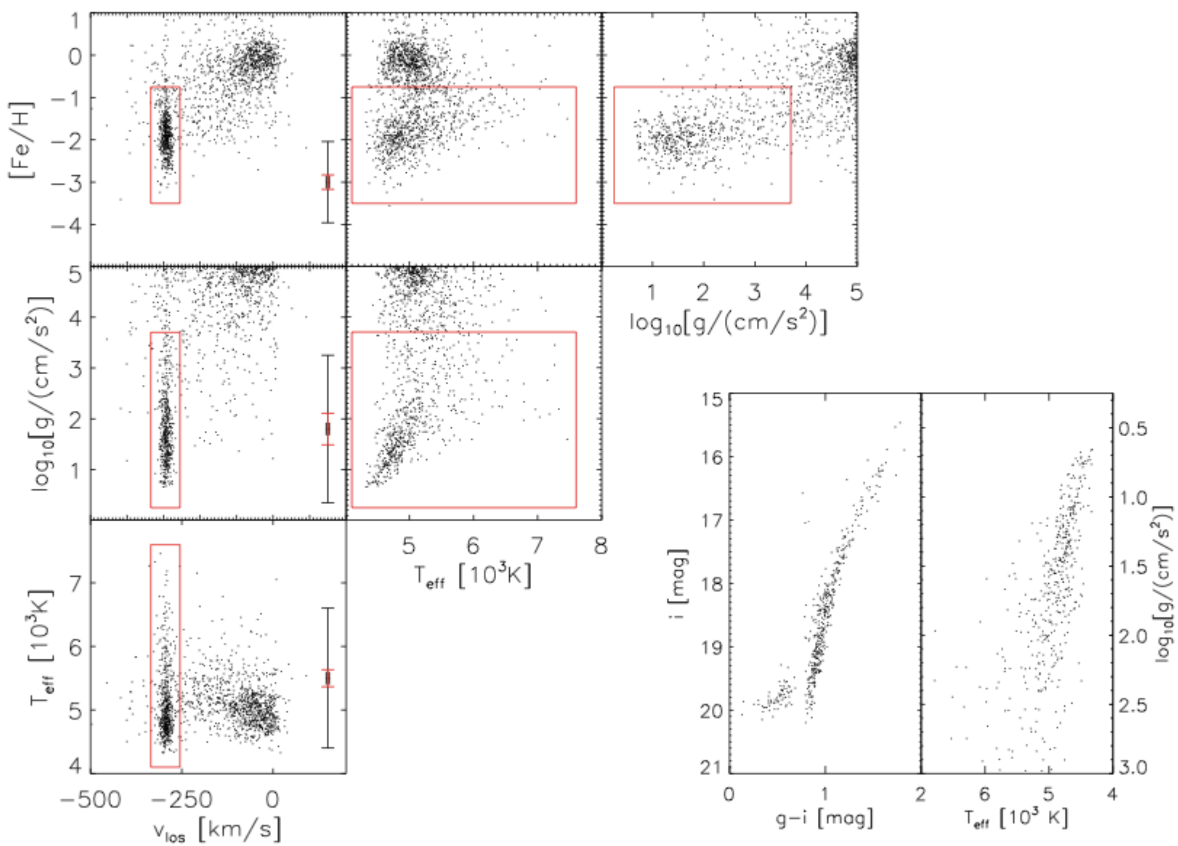
What is an optimal observation for dSphs?

outer (depopulated) region:

observe foreground stars and background galaxies simultaneously.



Walker+ (2015)



Summary

- The best-fitting cases for most of the dSphs yield not spherical but flattened halos. These axial ratios are smaller than the CDM-based N-body predictions.
- To set robust constraints on dark halo structures in dSphs, we require deep photometric data to assemble many sample stars down to faint magnitudes and spectroscopic data over large areas out to their tidal radii.
- ***Subaru HSC and PFS offer an unprecedented opportunities to investigate dark matter halo properties of the MW and M31 dSphs.***
- In order to do optimal observation, we should advance concrete discussion on GA survey plan.


Fin