Milky Way dwarf spheroidal galaxies as a probe of dark matter properties

Kohei Hayashi (JSPS fellow)
ICRR, The University of Tokyo

Collaborators: Masahiro Ibe (ICRR, adviser), Shigeki Matsumoto (IPMU), Miho N. Ishigaki (IPMU), Hajime Sugai (IPMU) and Shun'ichi Horigome (IPMU)

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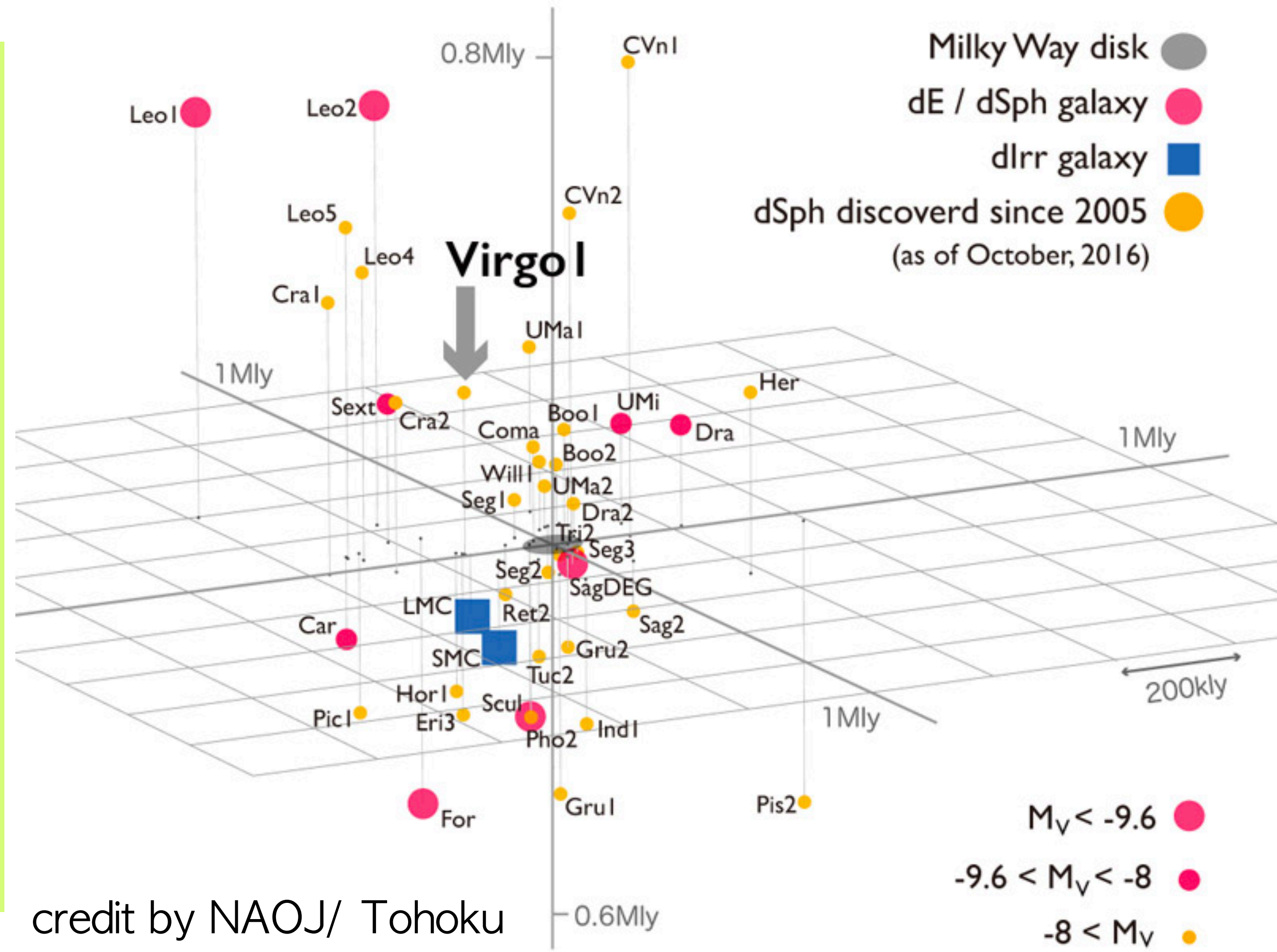
Introduction

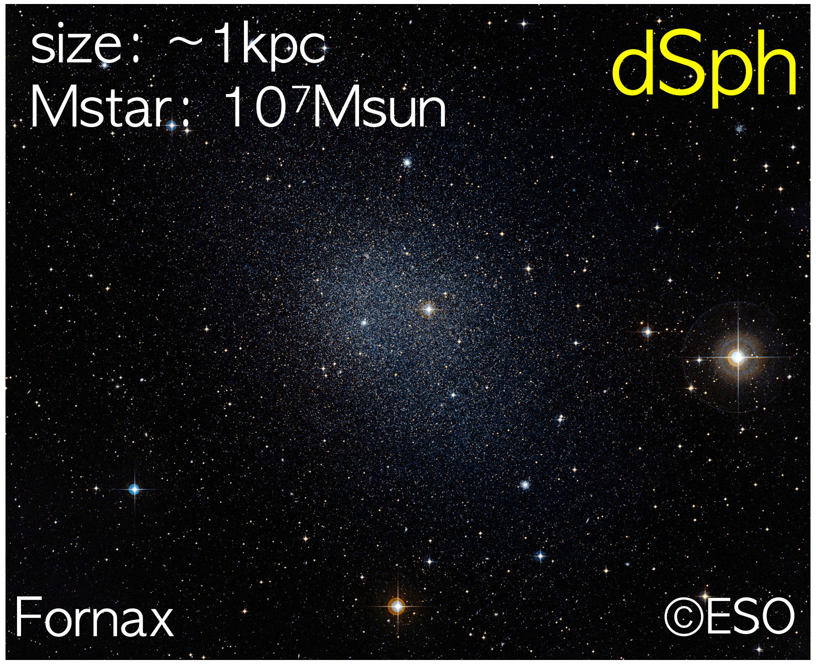
Dwarf Spheroidal Galaxy (dSph)

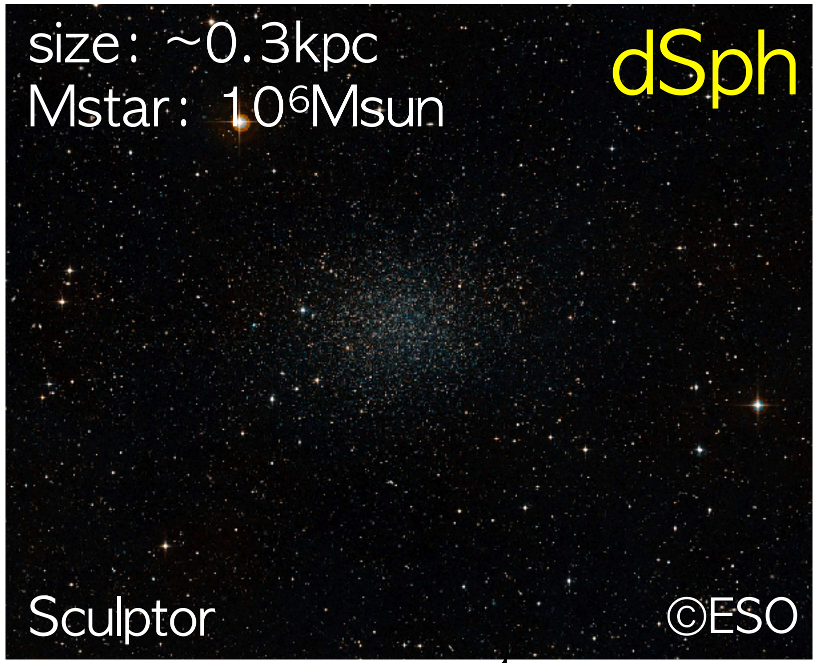
<u>Observational properties:</u>

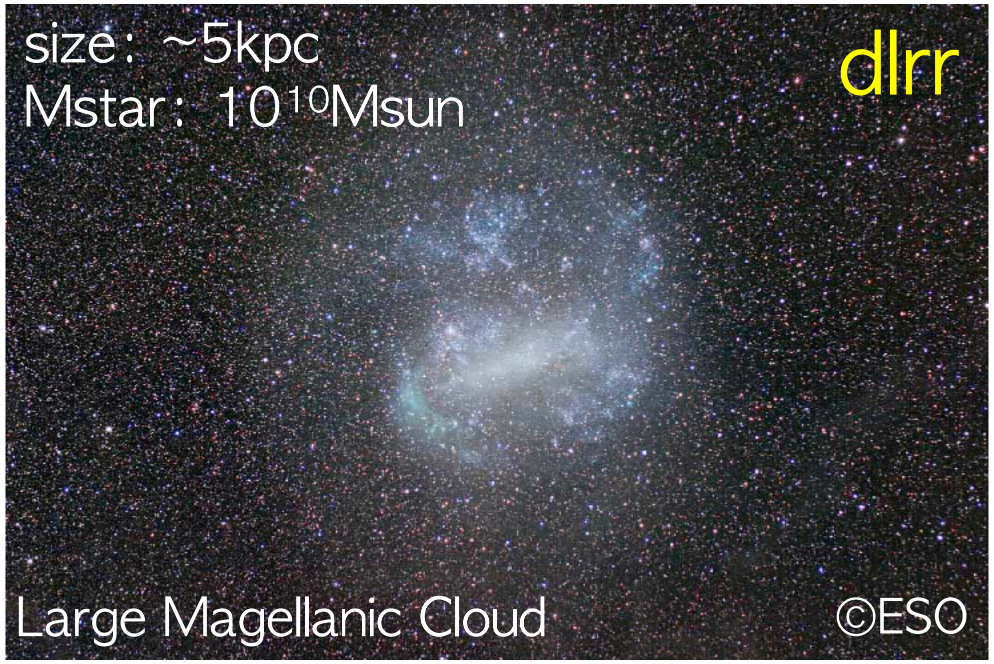
- ✤ the faintest, smallest and thus oldest galaxies in the Universe
- ✤ associate with luminous galaxies as satellites
- ✤ no gas, no current star formation
- ✤ spheroidal shape and no stellar rotation



credit by NAOJ/ Tohoku



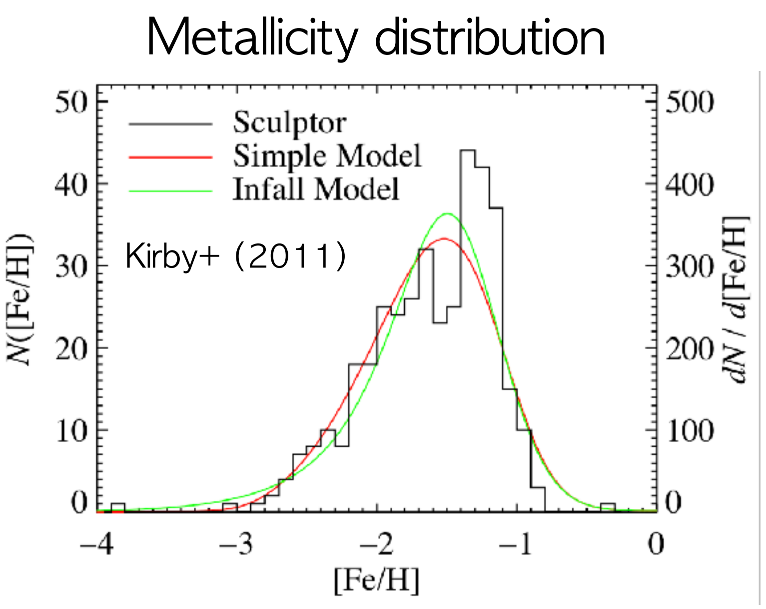


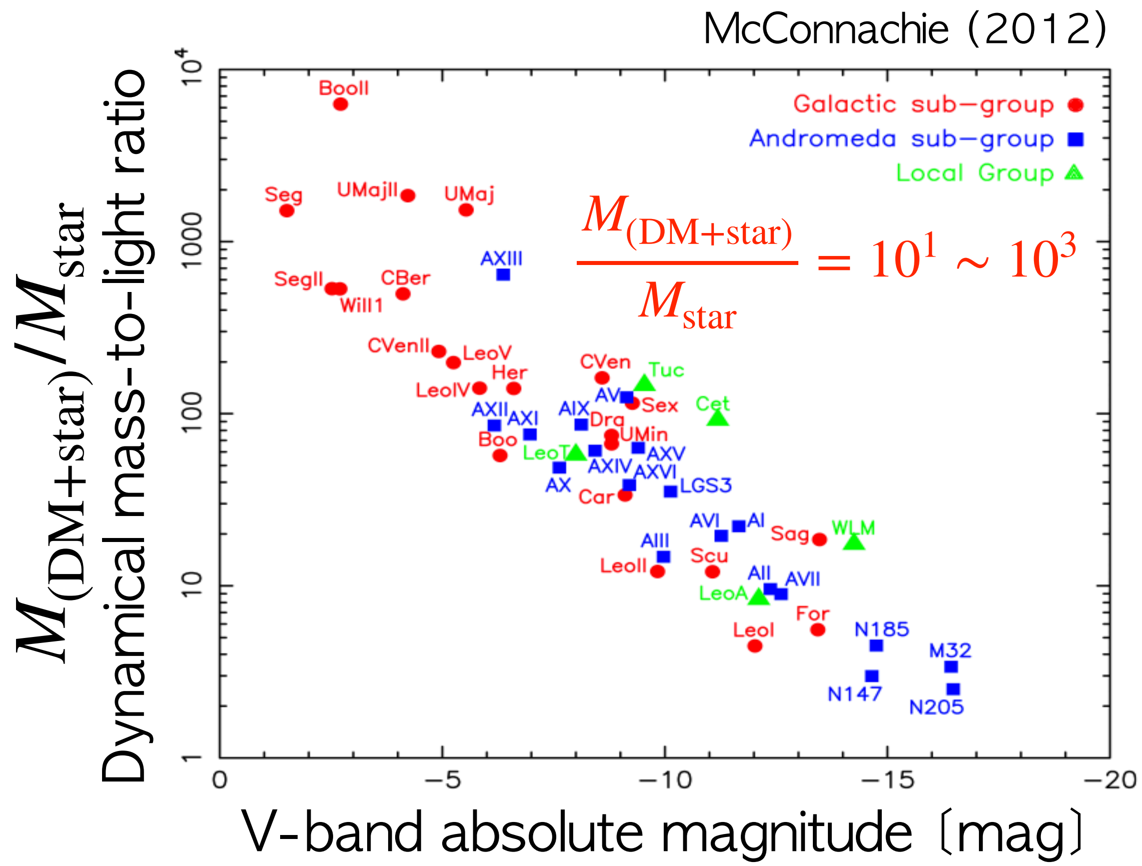


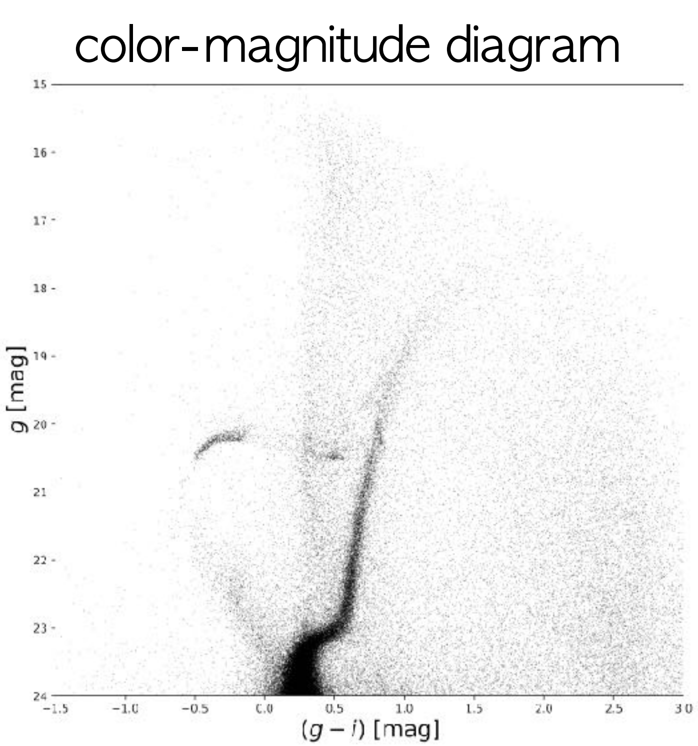
Dwarf Spheroidal Galaxy (dSph)

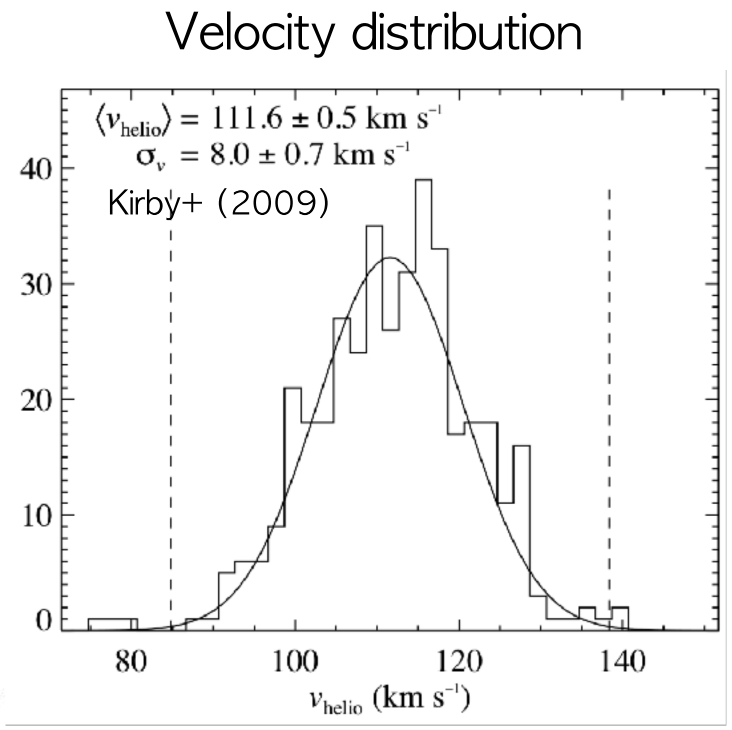
Important properties of dSphs:

- ✤ Detailed chemo-dynamical study through their resolved stars
- ✤ Dark matter rich









DSph galaxies are ideal sites for studying dark matter properties.

Small-scale challenges to Λ CDM paradigm

Definition of "small scales"

$$M_{\rm virial} < 10^{11} M_\odot, k > 3{\rm Mpc}^{-1}, r < 1{\rm Mpc}$$

$$\Longrightarrow r_{\rm vir} < 150{\rm kpc}, V_{\rm virial} < 50{\rm km/s}$$

i.e., galaxy and dwarf-galaxy scales

Bullock & Boylan-Kolchin (2017)

✦ Missing satellite problem

- Overabundance of dark subhalos

✦ Core-cusp problem

- Cuspy central density in CDM halos vs. cores in observed galaxies

✦ Too-big-to-fail problem

- Most massive subhalos are more concentrated than observed luminous satellites

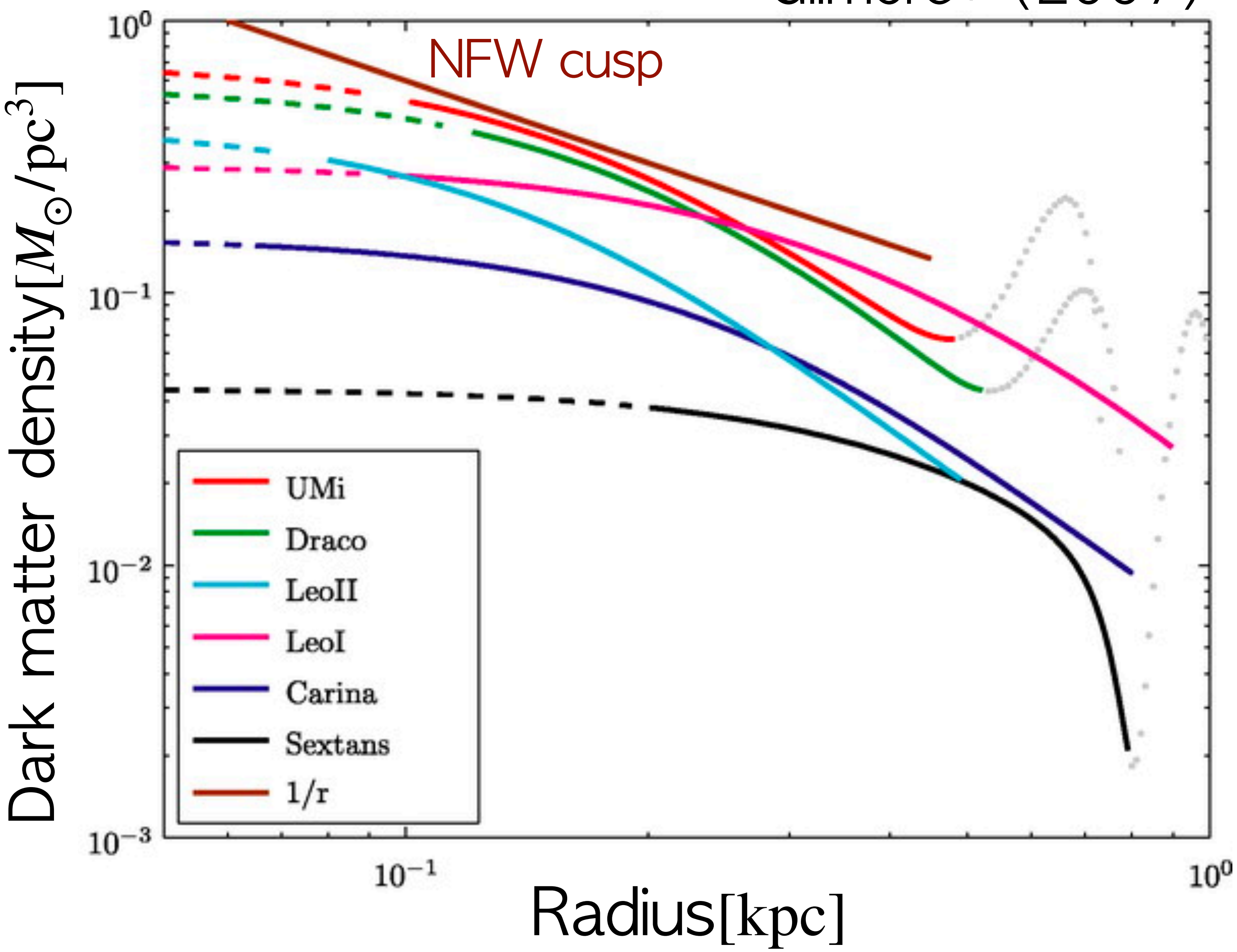
\+ the other problems (satellite planes, shapes of dark halo, and so on...)

Small-scale challenges to Λ CDM paradigm

✦ Core-cusp problem

- Cuspy central density in CDM halos vs. cores in observed galaxies

Gilmore+ (2007)



Possible solutions:

– Baryonic feedbacks
  Stellar feedbacks such as SNe can transform central cusp into cored dark matter profiles.
– Alternative dark matter models
  The other dark matter models motivated by particle physics (SIDM, SIMP, Axion..) can create a cored density profiles without relying on any baryon effects.

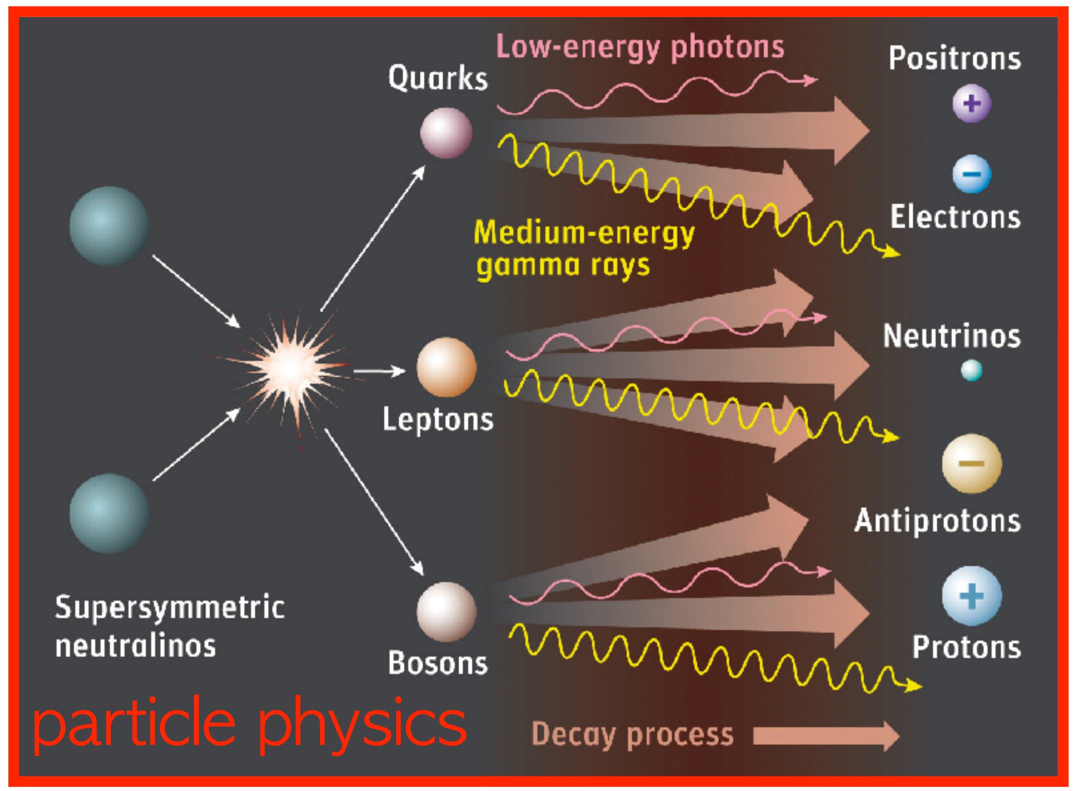
BUT…
- Uncertainties of dynamical models
- Incomplete observational data

Whether dSphs have cusped or cored dark halo is yet unclear because of many systematic uncertainties on estimates of their dark halo profiles.

Indirect search for dark matter particles

$$\Phi(E, \Delta\Phi) = \left[\frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2} \sum_f b_f \frac{dN_\gamma}{dE}\right] \times \int_{\Delta\Omega} \int_{\rm l.o.s} d\ell \, d\Omega \, \rho_{\rm DM}^2(\ell, \Omega)$$

Gamma-ray flux — Particle physics — Astrophysics (J-factor)



Gamma-ray observation

- Indirect searches for DM through its annihilation
- MW dSphs are ideal targets for detecting a DM signal
- Understanding the DM distribution of the dSphs is of very importance!

Dynamical modeling for dwarf spheroidal galaxy

How to derive DM profiles in the dSphs?

- The dSphs are not rotation but dispersion supported systems.
- Due to a DM dominated system, the effects of gravity of stars can be negligible small.
- Current observable data provide sky and l.o.s velocity distributions of the resolved stars.
- Jeans analysis is the most common way to derive DM profiles in the dSphs.

ex) Spherical Jeans Equation

$$\frac{1}{\nu(r)}\frac{d}{dr}[\nu(r)\overline{v_r^2}] + 2\frac{\beta_a(r)\overline{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

Stellar velocity anisotropy

$$\beta_a(r) = 1 - \frac{\sigma_\phi^2 + \sigma_\theta^2}{2\sigma_r^2}$$

Parameterized dark matter profile

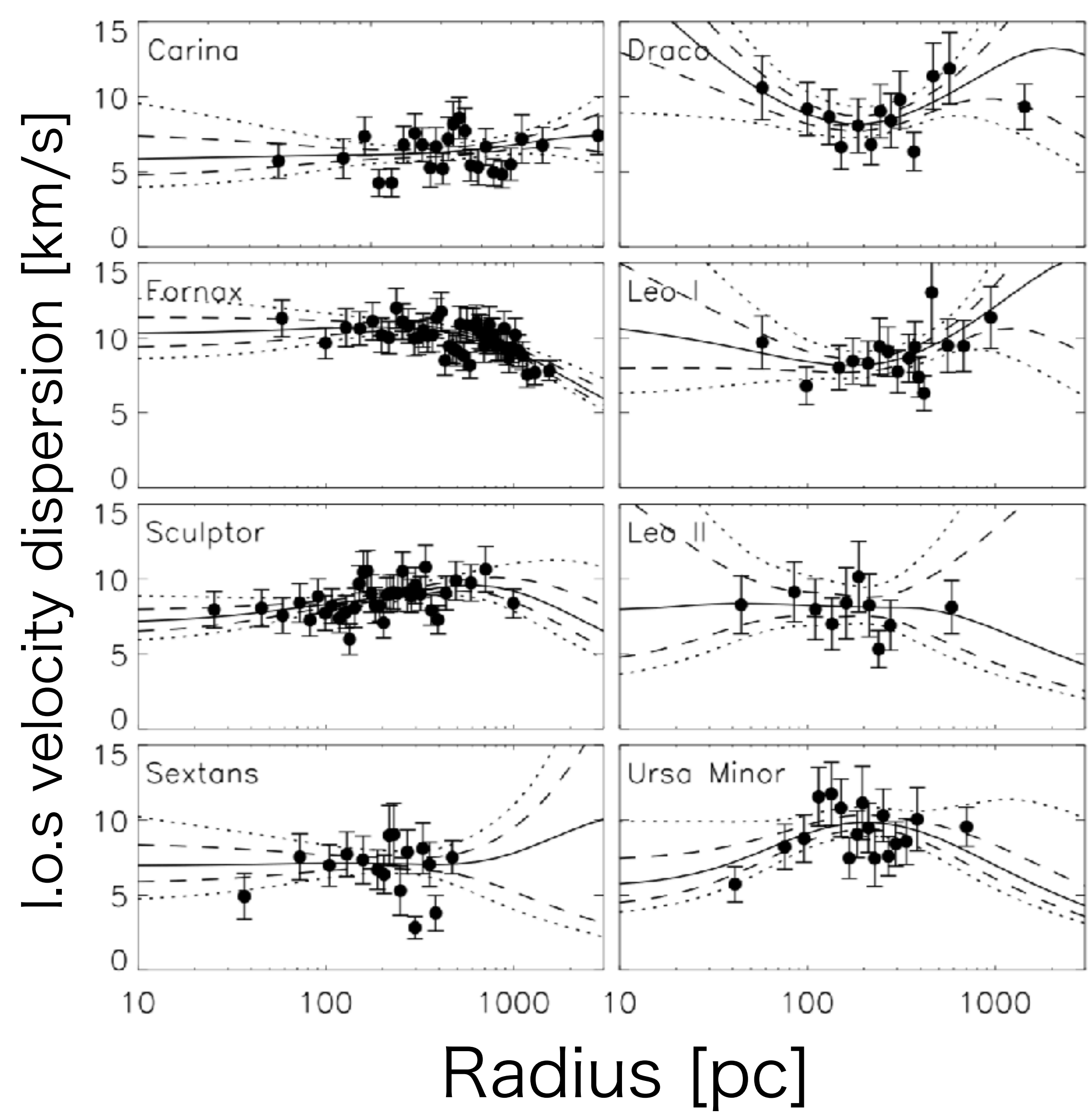
$$\rho_{\rm DM}(r) = \frac{\rho_s}{(r/r_s)^\gamma[1+(r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Unobservables ⇒ free parameter $(\rho_s, r_s, \alpha, \beta, \gamma, \beta_a)$

Comparing between derived and observed velocity dispersions, the best-fit parameters and their uncertainties can be estimated.

Line-of-sight velocity dispersion profile

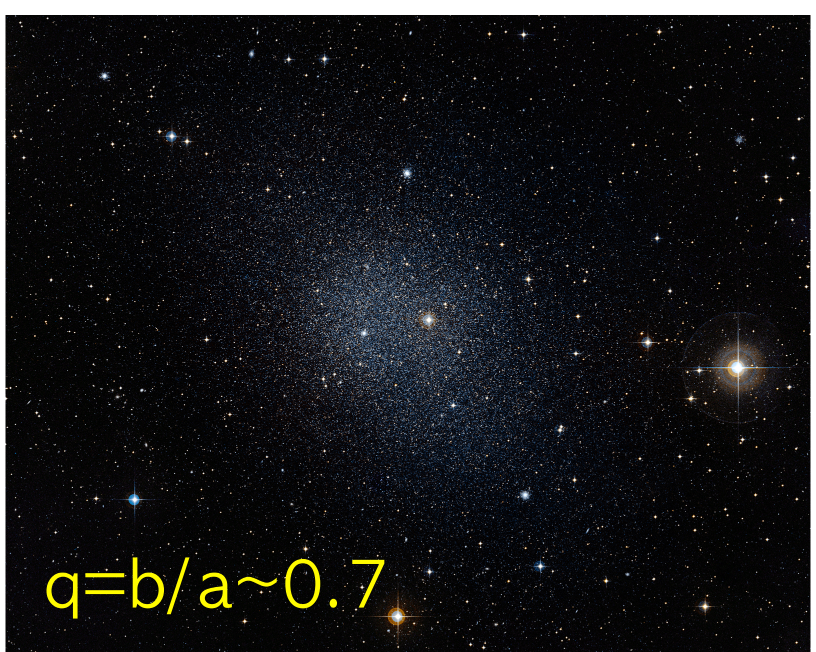
$$\sigma_p^2(R) = \frac{2}{I(R)}\int_R^\infty \left(1 - \beta_a\frac{R^2}{r^2}\right)\frac{\nu(r)\overline{v_r^2}}{\sqrt{r^2-R^2}}dr$$

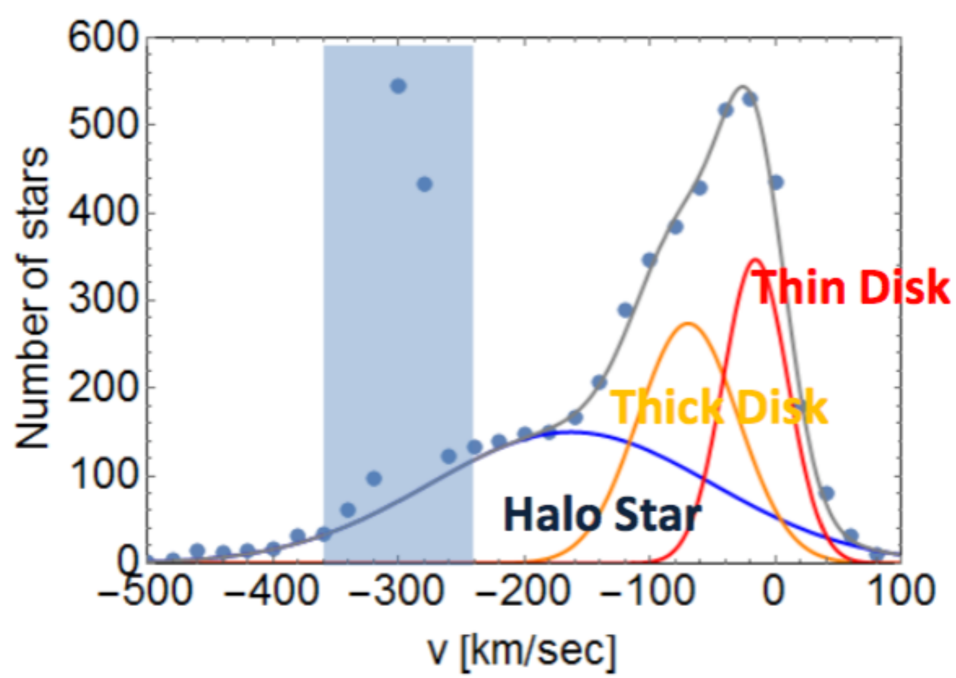


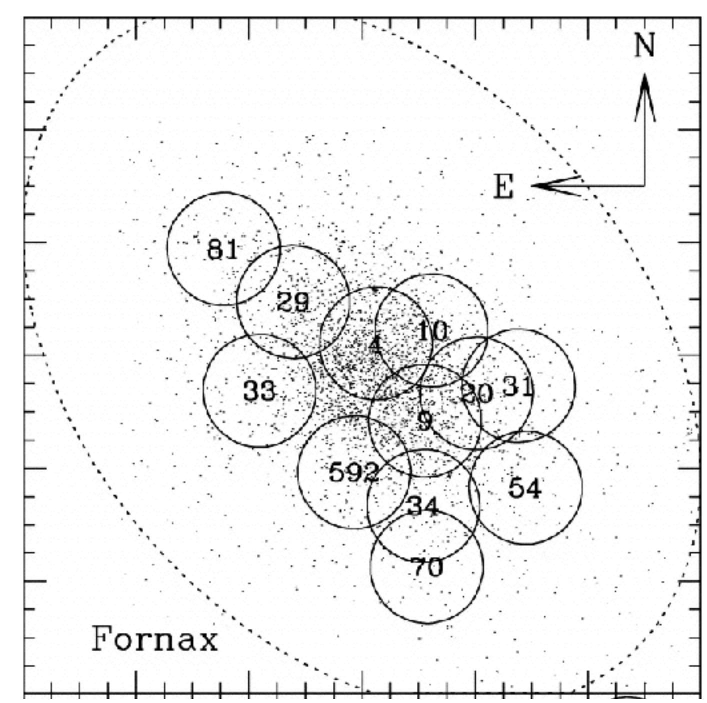
Geringer-Sameth et al. (2015)

Non-negligible systematic uncertainties on the estimates of DM distributions

- Non-spherical dark halo (Hayashi et al. 2016)
  Most previous works have assumed spherical mass models for simplicity, even though the distributions of luminous and dark components in dSph are actually not spherical.
- Foreground contaminations (Ichikawa (inc. KH) et al. 2017a,b)
  Foreground contaminations have largely impact on determining dark halo profiles, especially ultra faint dwarf galaxies.
- Sample volume (Subaru PFS)
  Due to insufficient number of available data especially in the outer regions of the dSphs, current dynamical analyses still place poor constraints on dark halo structures.







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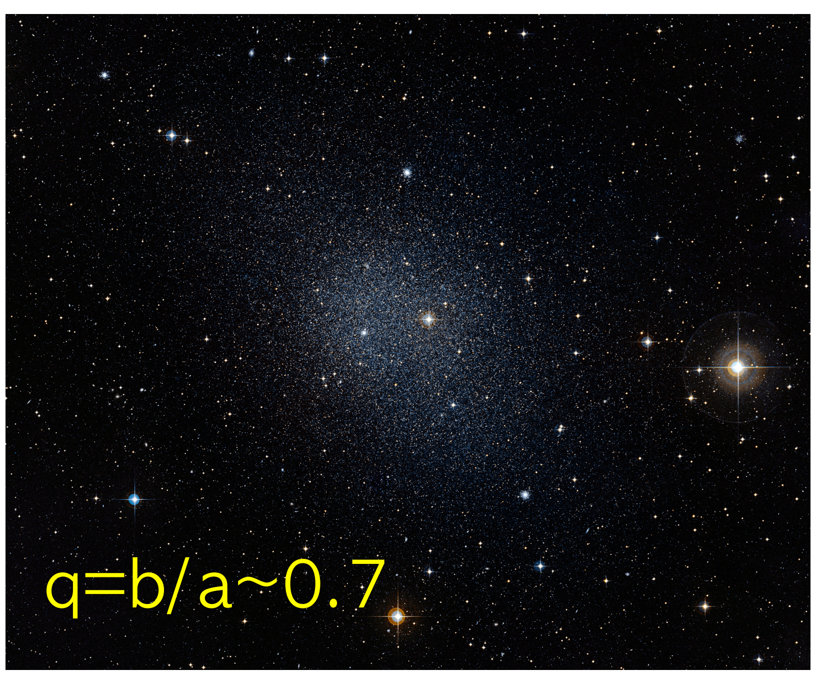
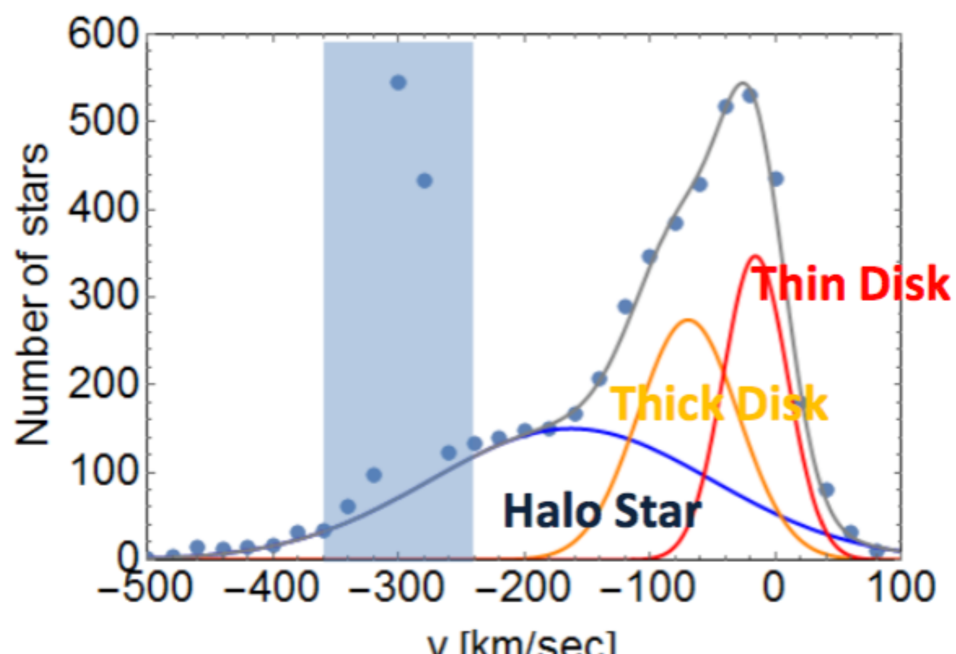
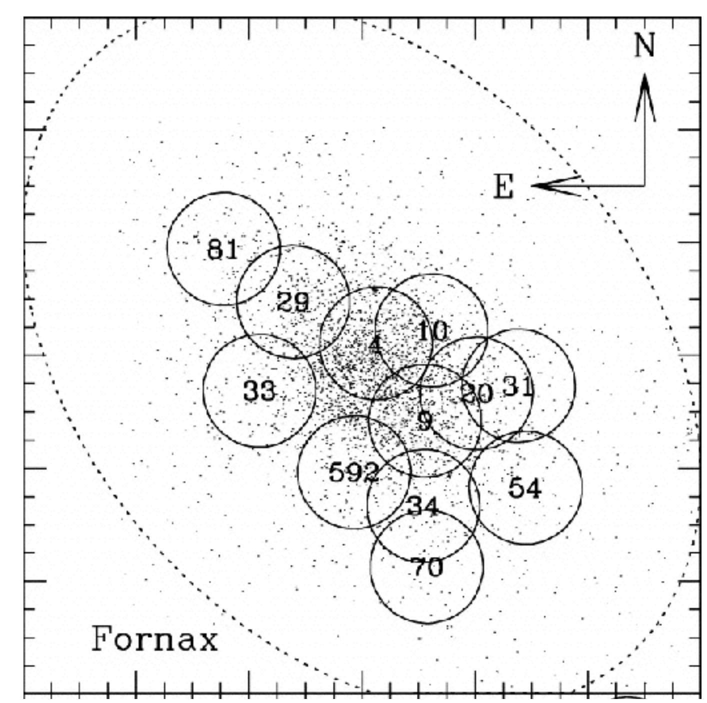






Non-spherical dynamical mass models

KH & Chiba (2012, 2015), KH et al. (2016)

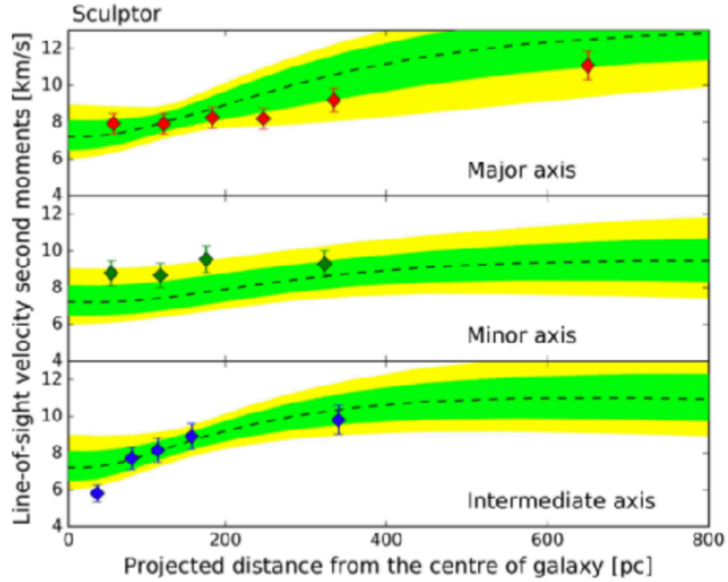
Axisymmetric Jeans eqs.

$$\overline{v_z^2} = \frac{1}{\nu(R,z)}\int_z^\infty \nu \frac{\partial \Phi}{\partial z} dz$$

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

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

→ Observable $\overline{v_{\rm l.o.s}^2}(x,y)$



Stellar profile: Plummer profile

Observable

$$I(x,y) \propto [1 + m_*^2/b_*^2]^{-2} \Longleftrightarrow \nu(R,z)$$

$$m_*^2 = x^2 + \frac{y^2}{q'^2} \qquad q'^2 = \cos^2 i + q^2 \sin^2 i$$ Unobservable

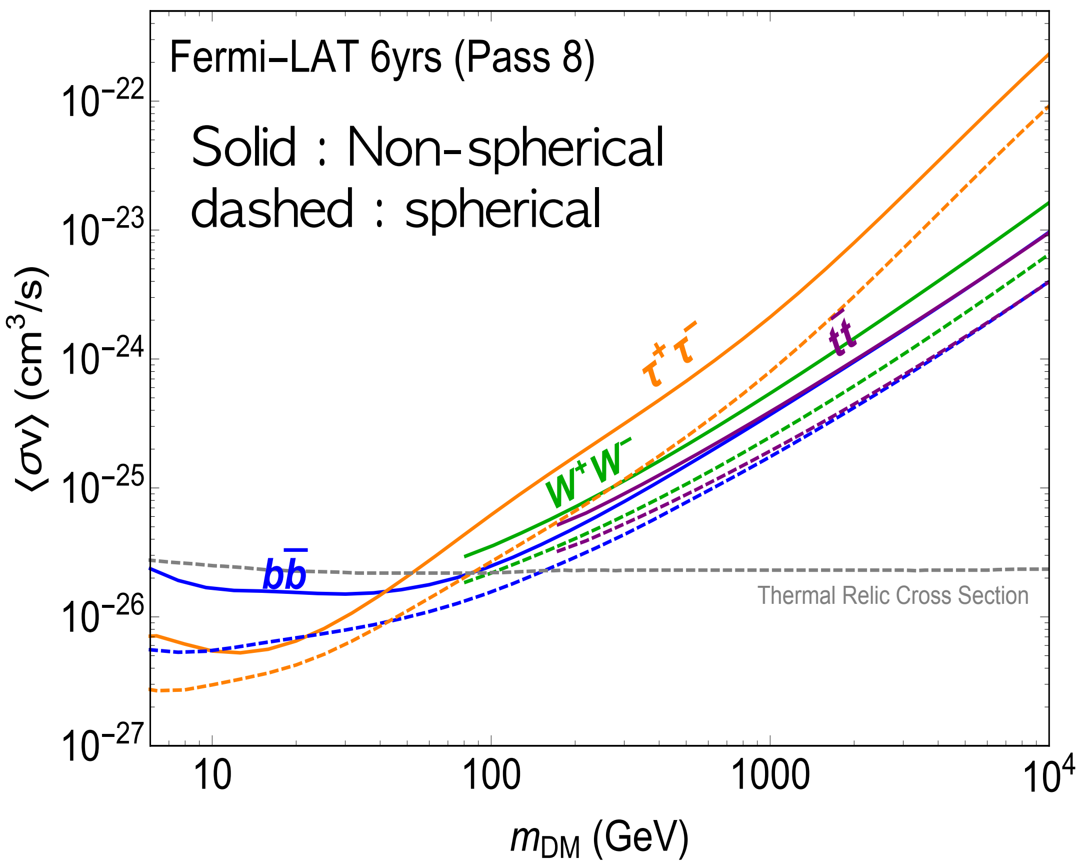
Dark matter profile Unobservable

$$\rho_{DM}(R,z) = \rho_0 \left(\frac{m_{DM}}{b_{halo}}\right)^{-\gamma}\left[1 + \left(\frac{m_{DM}}{b_{halo}}\right)^{-\alpha}\right]^{-\frac{\beta-\gamma}{\alpha}}$$

$$m_{DM}^2 = R^2 + \frac{z^2}{Q^2}$$

Free parameters

$(Q, b_{\rm halo}, \rho_0, \beta_0, \alpha, \beta, \gamma, i)$



- J-factors estimation with spherical models are overestimated.
- The uncertainties of non-sphericity should be important.

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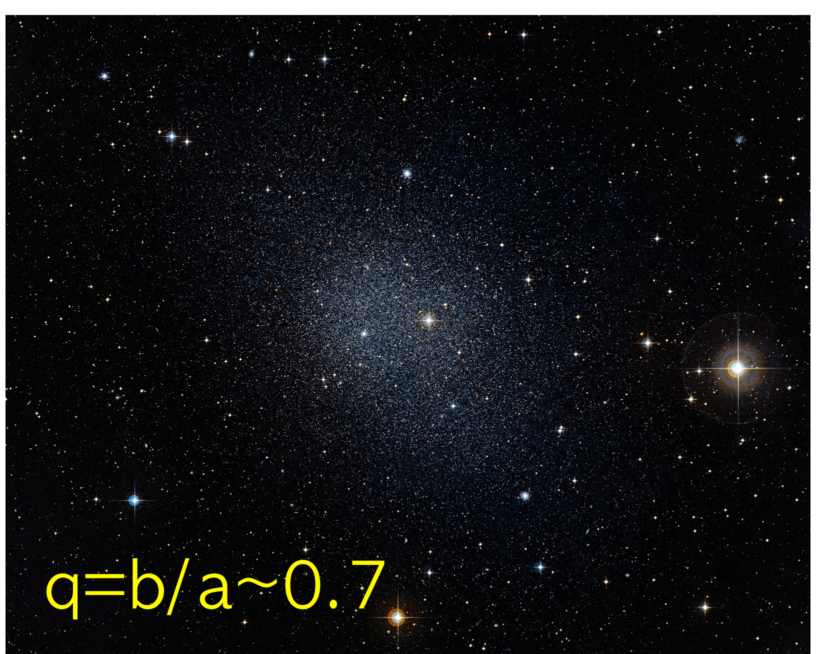
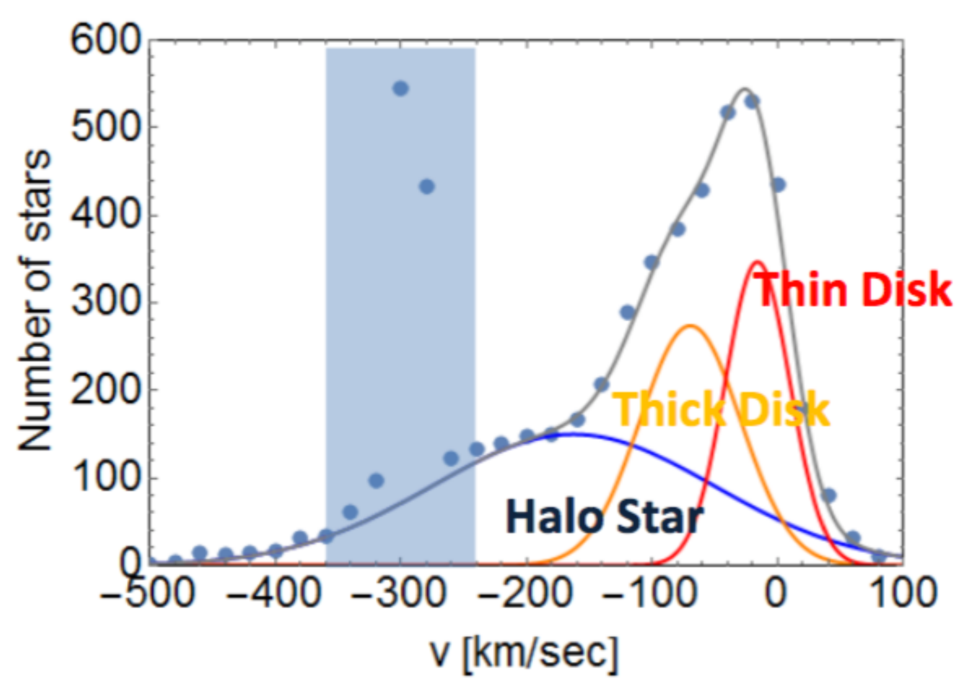
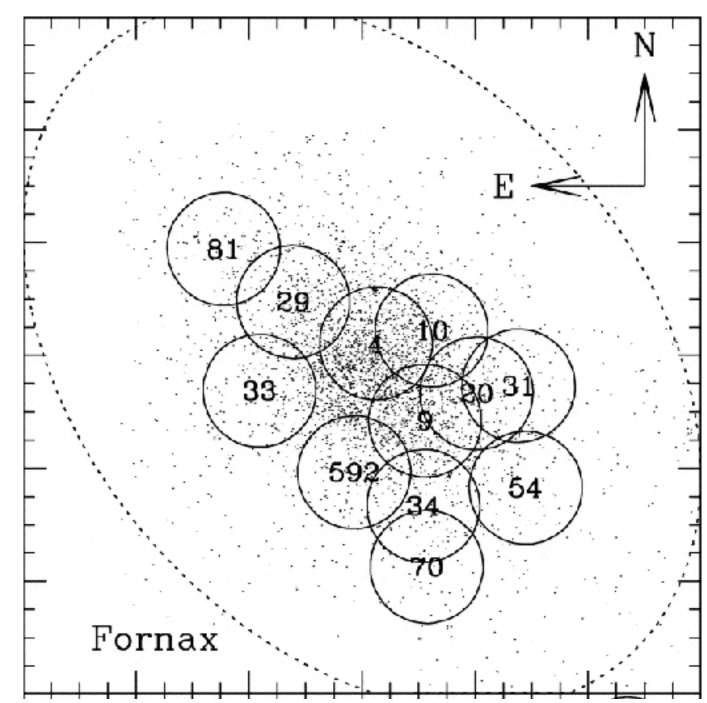




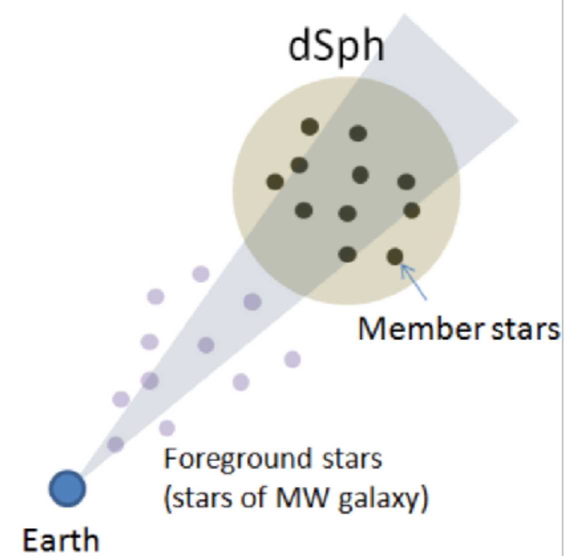


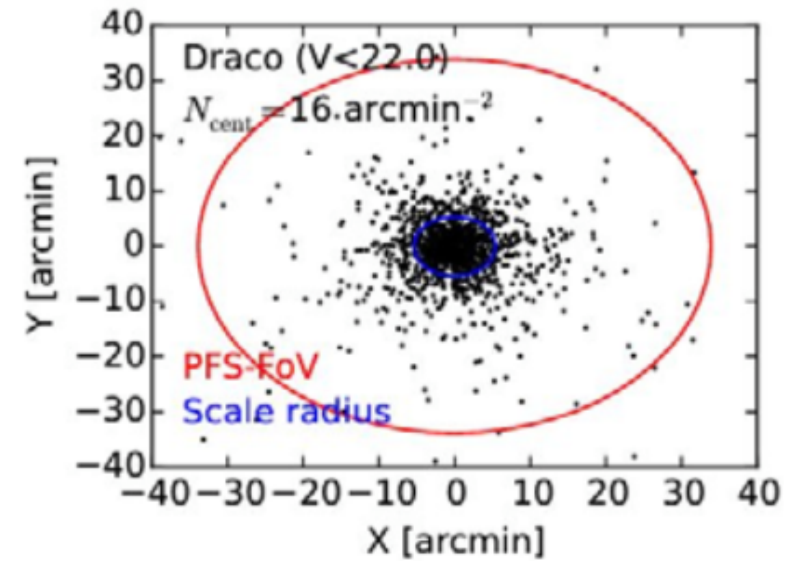
New fitting function including contamination effects

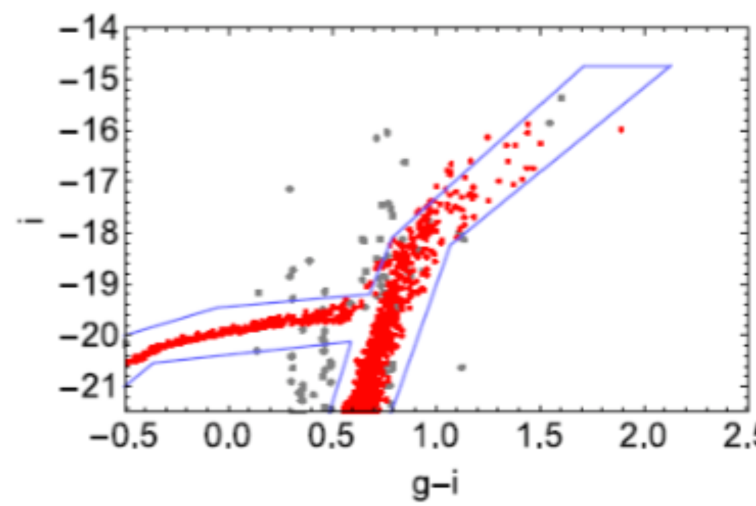
Ichikawa et al. (2017, 2018)

Big efforts to reduce contaminations…

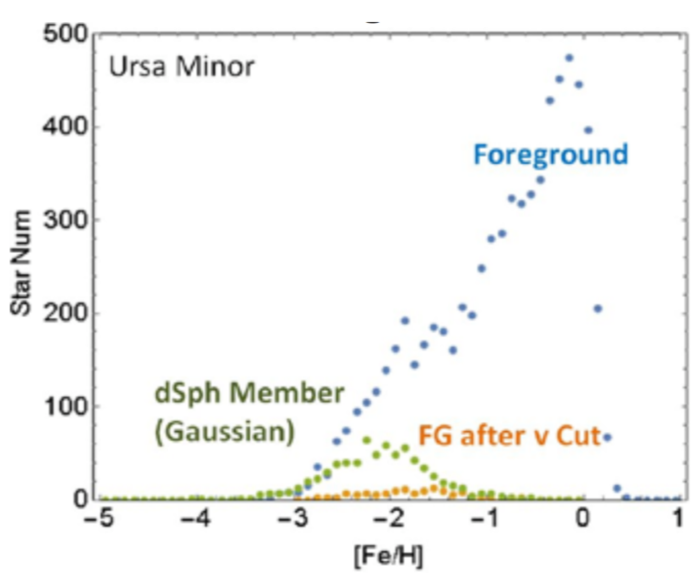
1. Region of interest cut
2. Color-magnitude cut
3. Velocity cut
4. Surface gravity cut
5. Effective temperature cut
6. Metallicity cut

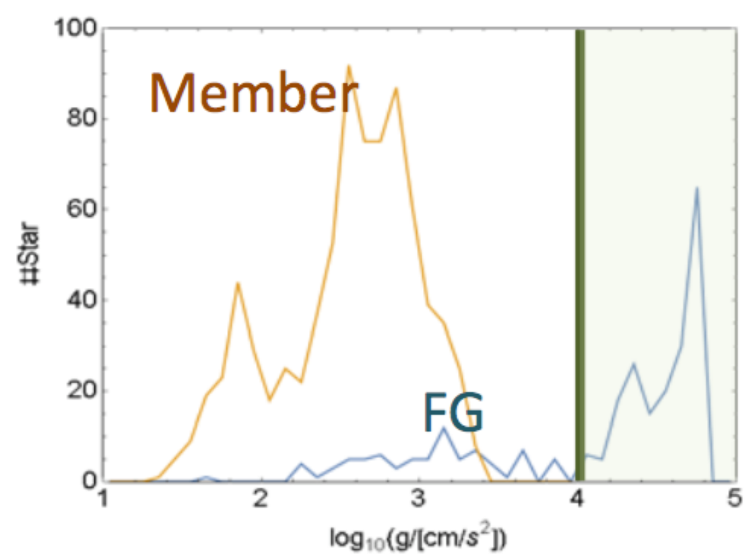


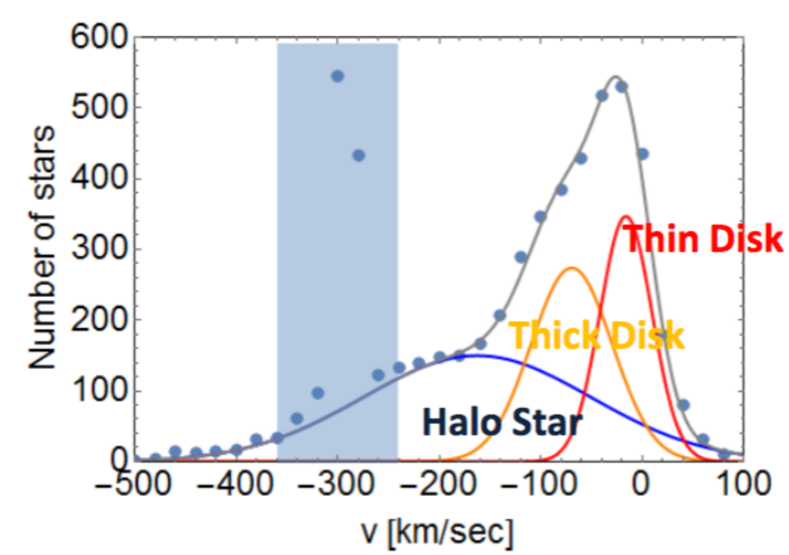




<u>Indistinguishable contaminations still remain…</u>







New fitting function including contamination effects

Ichikawa et al. (2017, 2018)

$$L = \prod_i [s f_{\rm Mem}(v_i, R_i) + (1-s) f_{\rm FG}(v_i, R_i)]$$

- Membership fraction parameter

$$s = \frac{\mathcal{N}_{\rm Mem}}{\mathcal{N}_{\rm Mem} + \mathcal{N}_{\rm FG}}$$

- Distribution functions

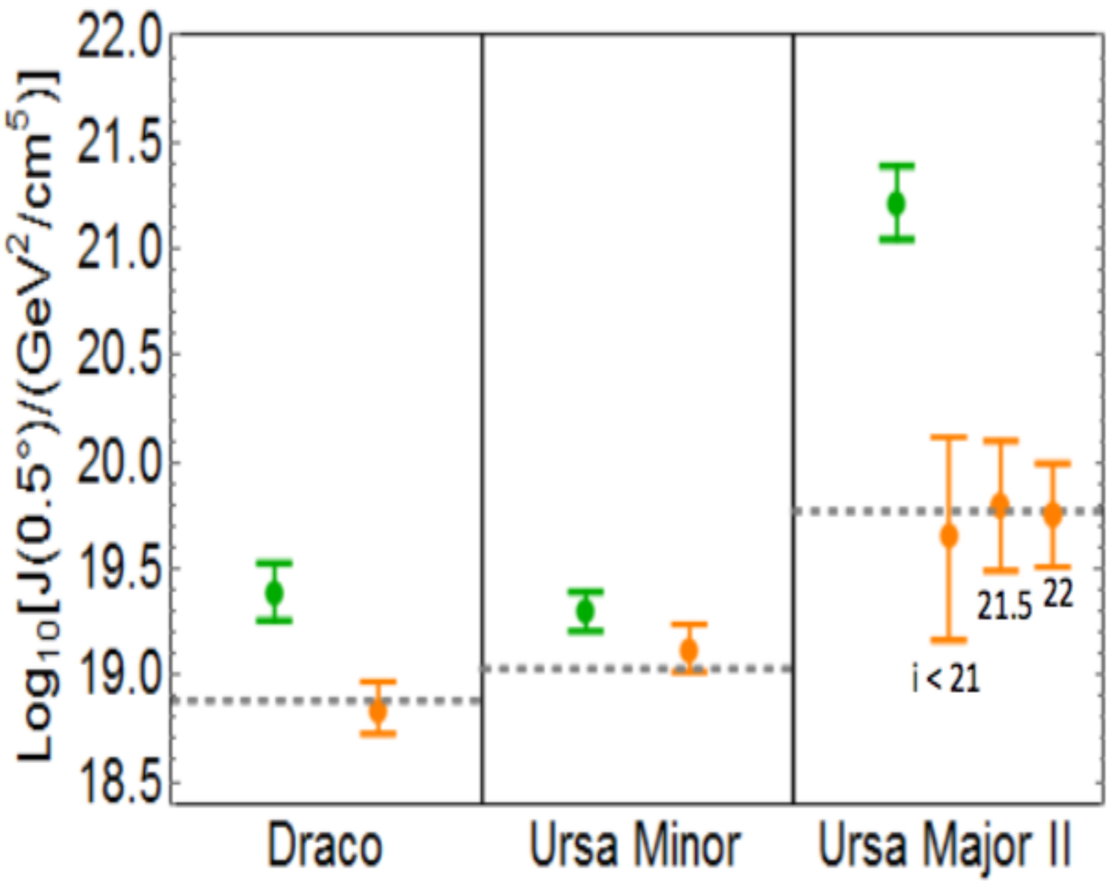
$$f_{\rm Mem}(v, R) = \mathcal{N}_{\rm Mem} 2\pi R I_*(R) \mathcal{G}[v; \bar{v}_{\rm Mem}, \sigma_p(R)]$$

$$f_{\rm FG}(v, R) = \prod_{i \in {\rm thin,thick,halo}} \mathcal{N}_{\rm FG} 2\pi R \mathcal{G}[v; \bar{v}_{\rm FG}, \sigma_{{\rm FG},i}]$$

- generate mock data of dSphs
- Dashed lines: true J-values from mock data
- Compare with three methods

  Orange: our work

  Green: Contaminated



- J-factors are affected strongly by contaminations.
- Our method can treat successfully contamination effects.
- A number of stellar spectra of contamination as well as member stars are required.
- Apply this method to real dSph data (Horigome (inc. KH) et al. in prep.).

Non-negligible systematic uncertainties on the estimates of DM distributions

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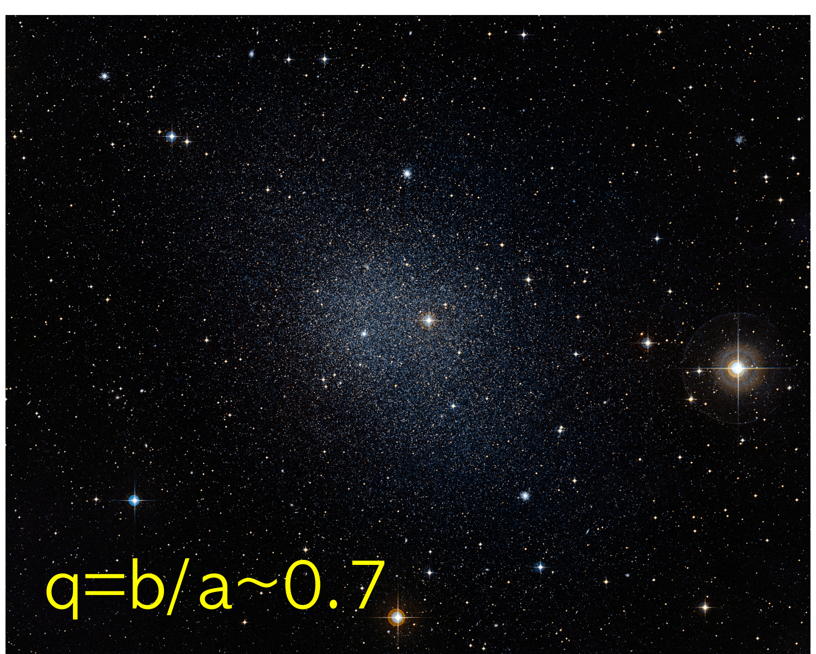
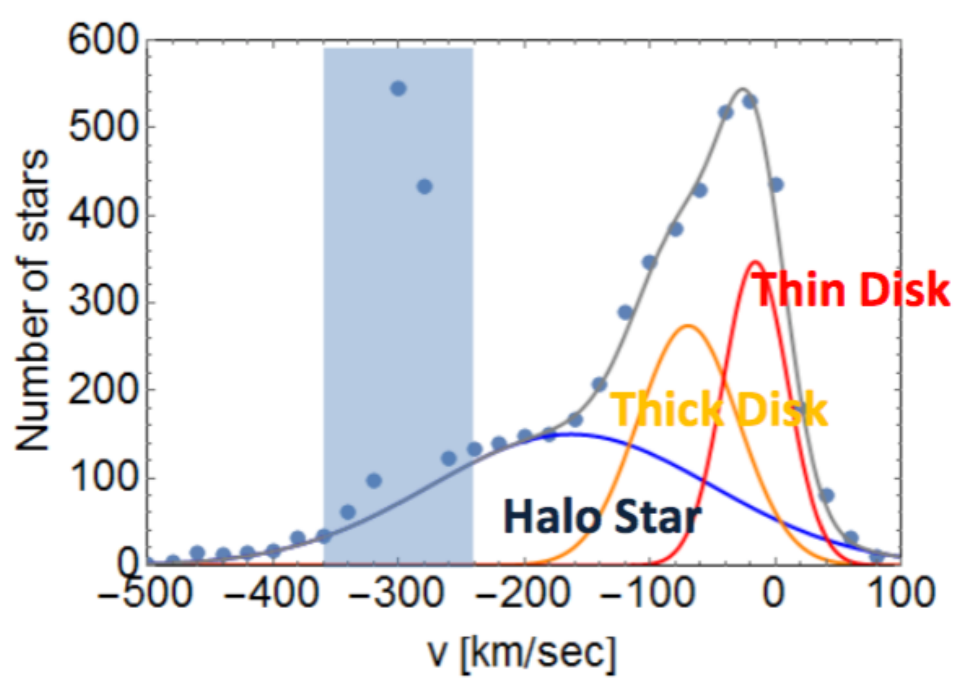
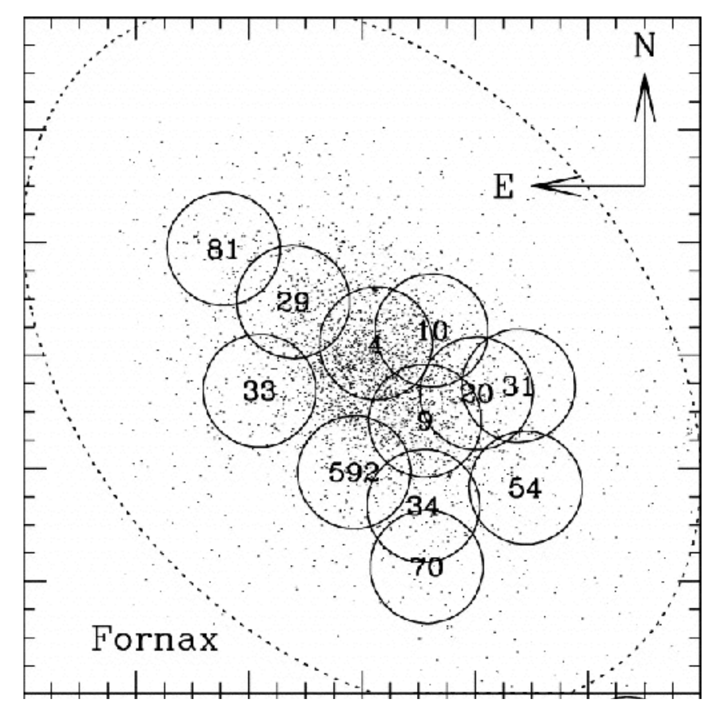


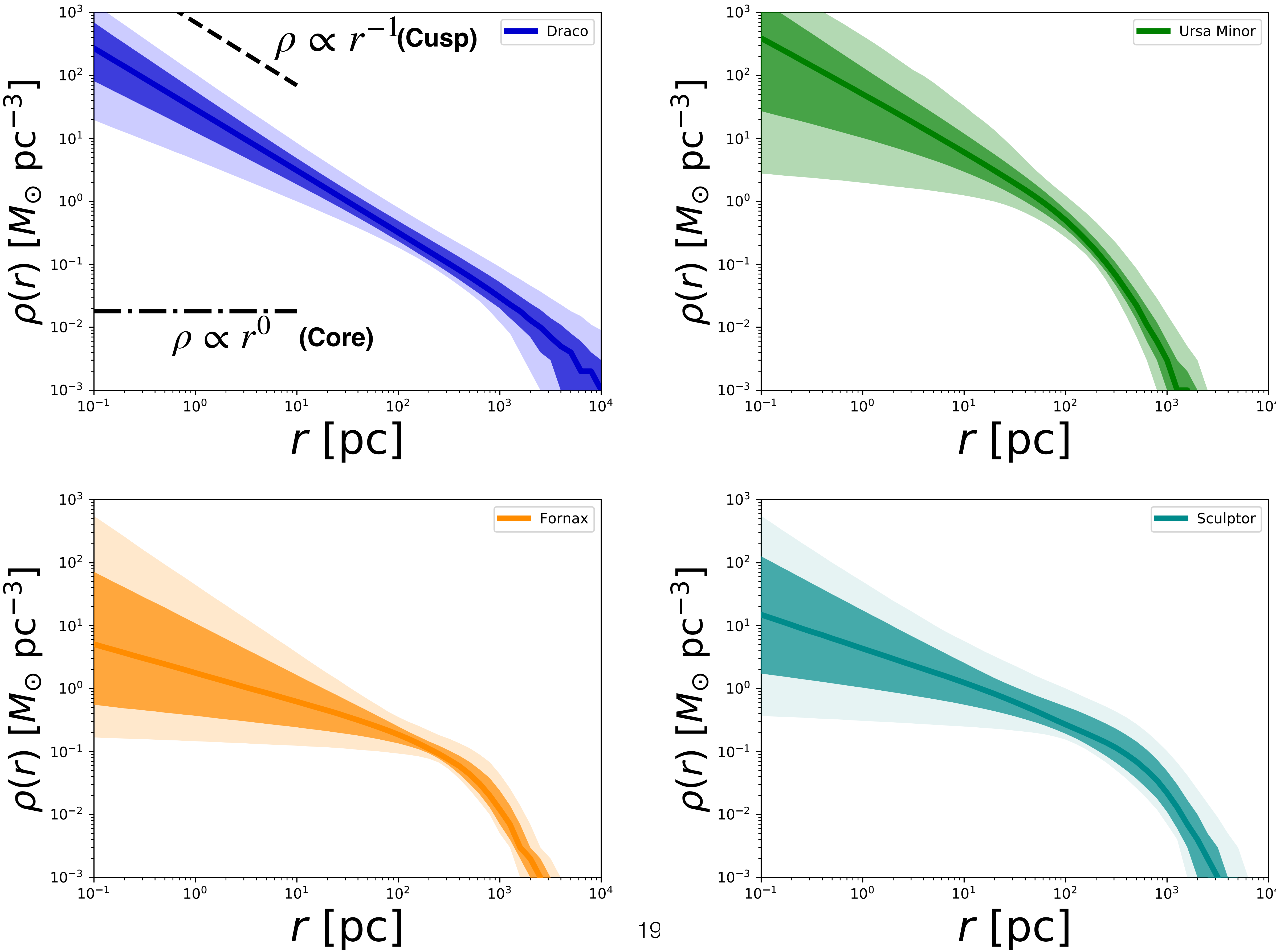




Dark matter distributions in the MW dSphs

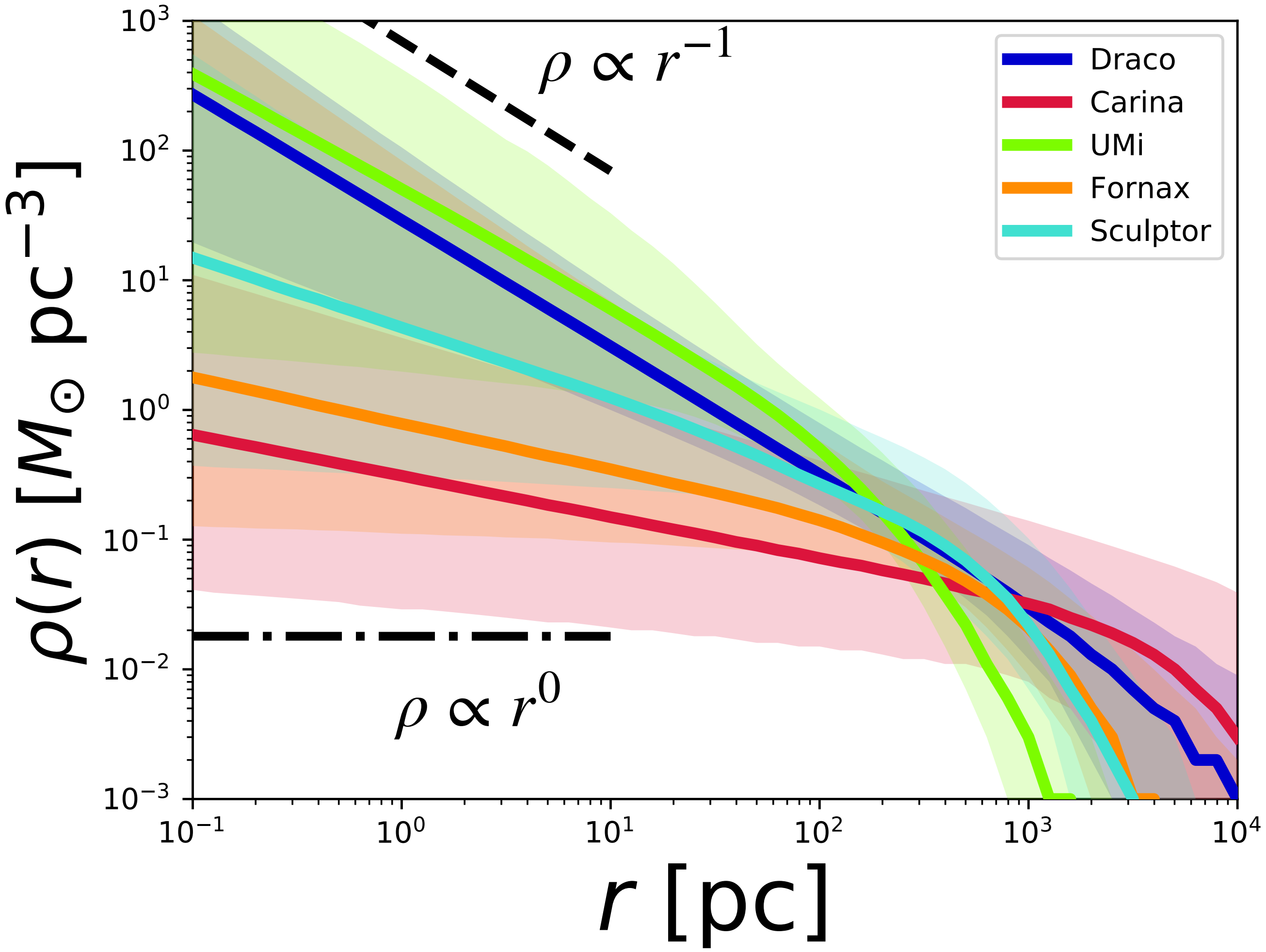
DM profiles of the classical dwarfs

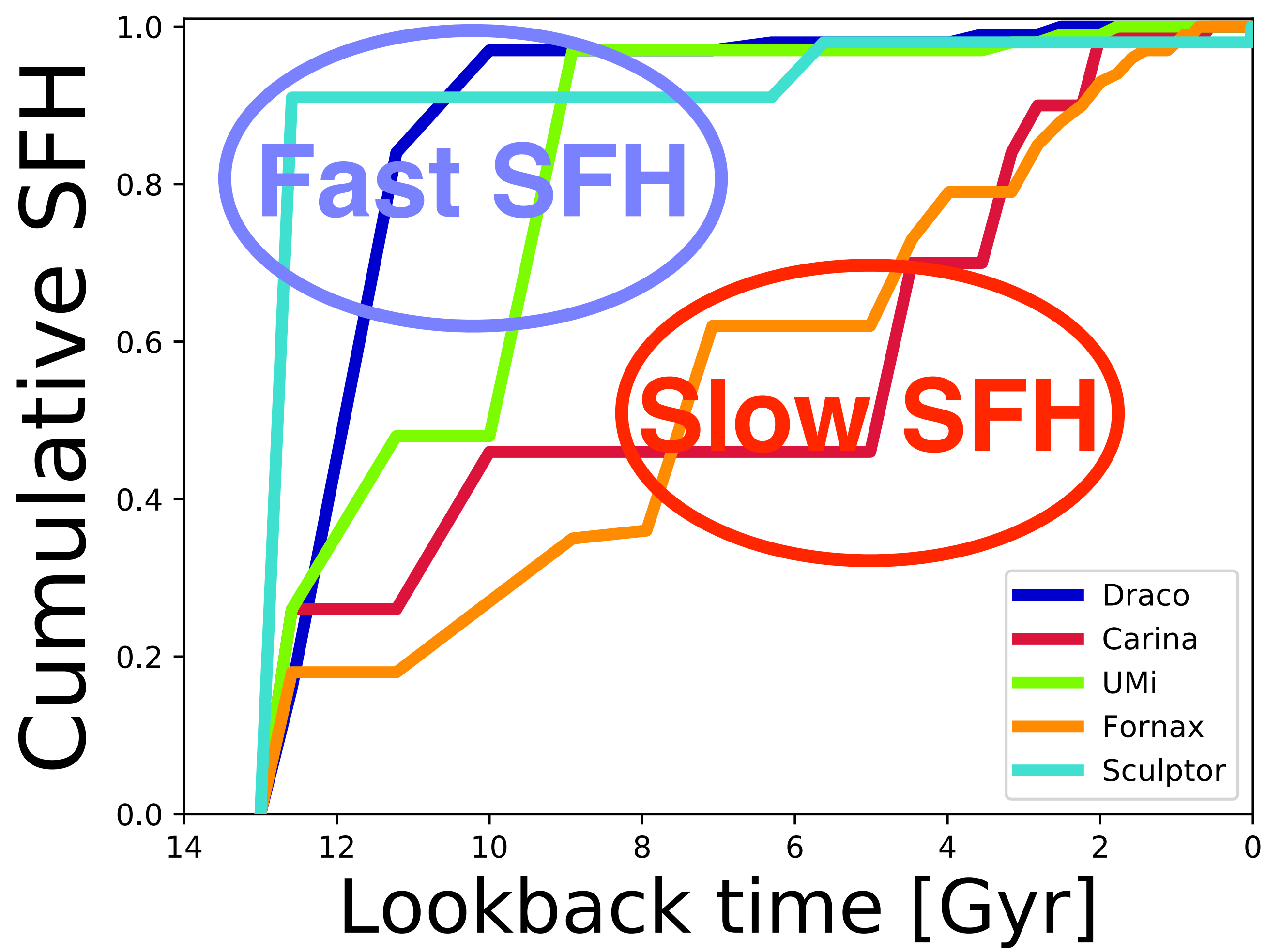
Hayashi et al. (in prep.)



NO core-cusp problem?

Inner slope of dark matter density profile could depend on star formation history.

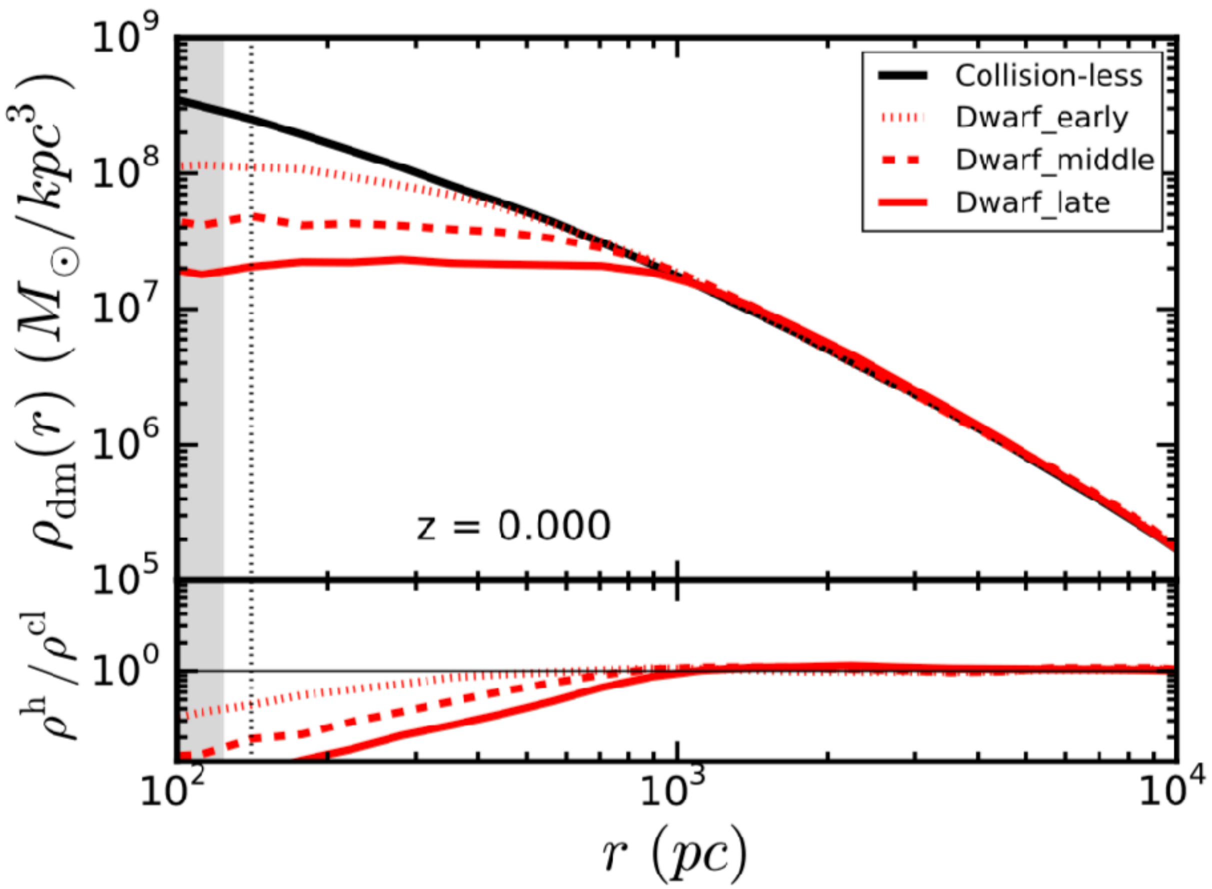


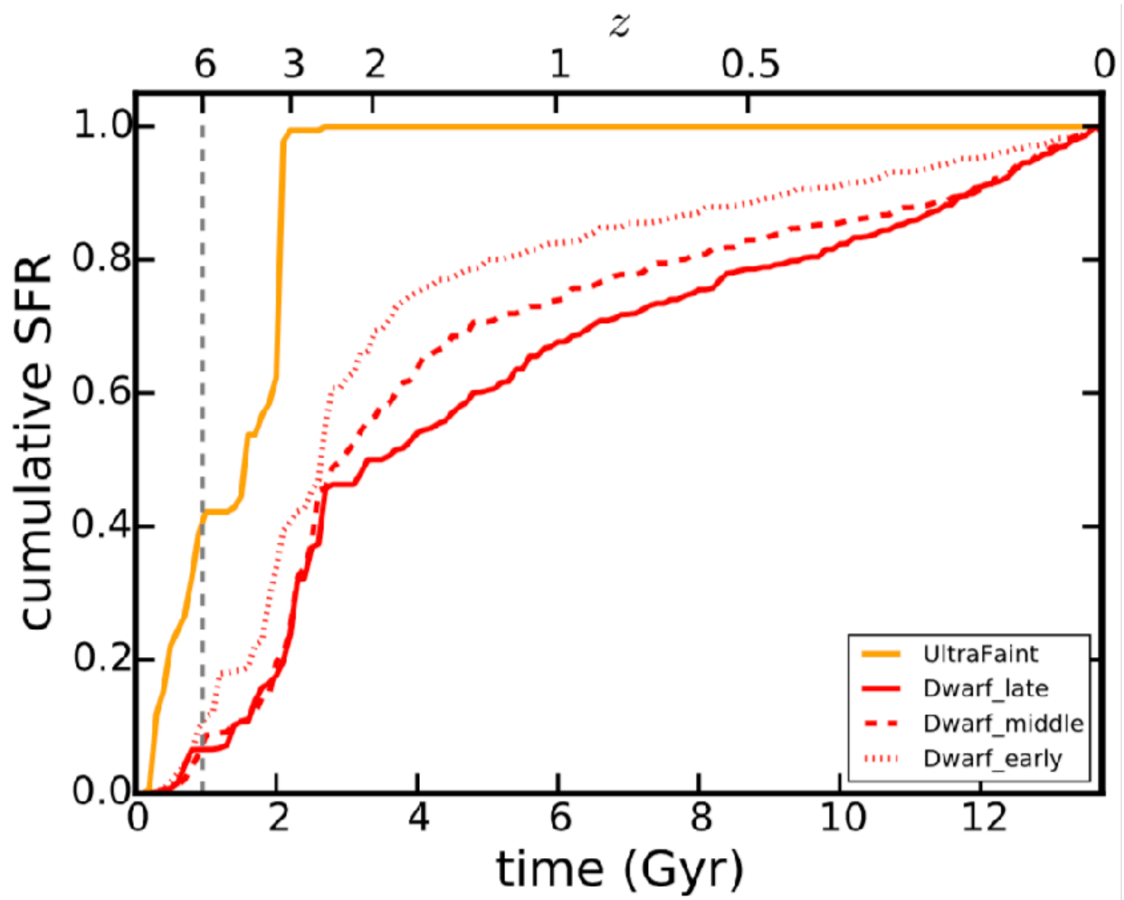


Slow SFH ⇒ shallower cuspy
Fast SFH ⇒ cuspy

What's the origin of this relation?

FIRE simulation (Onorbe et al. 2015)





"Dwarf_late" has successive SFH and thus has undergone periodical SN feedbacks.

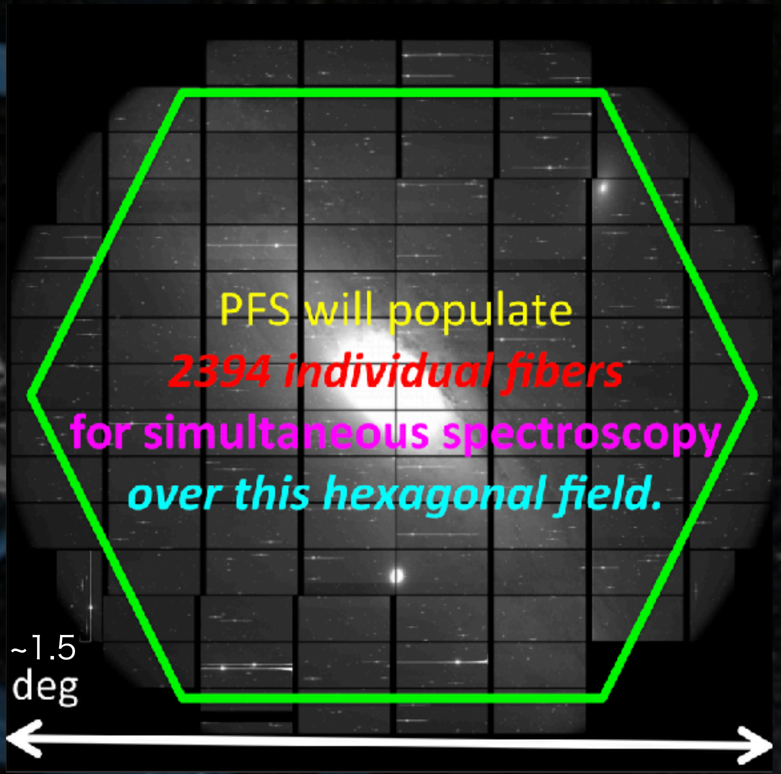
⇒ Feedback energy can be injected constantly into dark matters in the inner regions.

"Dwarf_early" has also successive SFH but its star formation activity at late epoch is not stronger than Dwarf_late.

⇒ Feedback energy is not enough to keep core, and its profile turns back cupsy.

Prospects for Subaru Prime Focus Spectrograph

SUBARU PRIME FOCUS SPECTROGRAPH



Fast facts

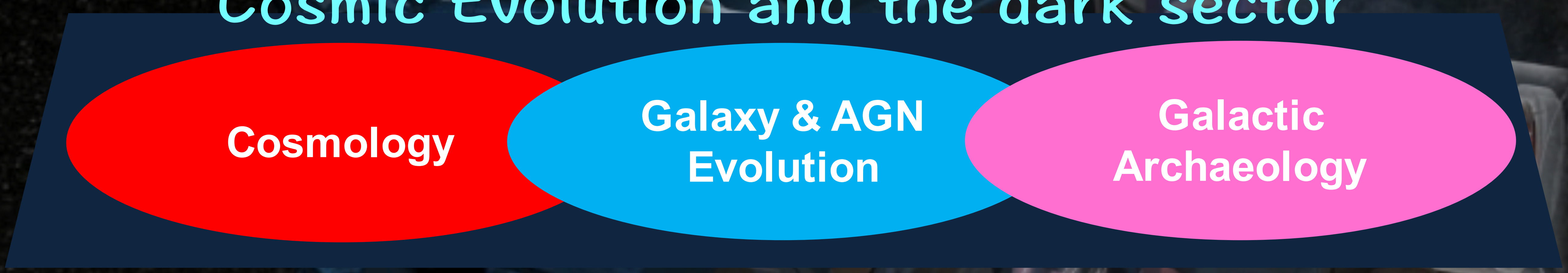
- Wide field: ~1.5deg diameter
- Massive multiplicity: 2394 fibers
  - fiber diameter: ~1.05 arcsec
  - fiber positioner pitch: ~85arcsec
  - minmum fiber separation: ~30 arcsec
- VIS-NIR coverage: 380-1260nm simultaneously
  - Low resolution mode: ~2.5Å resolution
  - Medium resolution mode (@~800nm): ~1.6Å resolution
- Aiming at start of science operation & survey program in 2021, as a facility instrument on Subaru Telescope

SUBARU PRIME FOCUS SPECTROGRAPH

Planing PFS large survey plan
Subaru Strategic Program (SSP; すばる戦略枠)

- HSC-SSP has been progressing since 2014
  300 nights out to ~2019 (2020?)
- PFS-SSP: A proposal (300~360 night) is in preparation.
  - Timely start by taking over the HSC-SSP
  - A survey program with the three “pillars”

Cosmic Evolution and the dark sector



Subaru Prime Focus Spectrograph

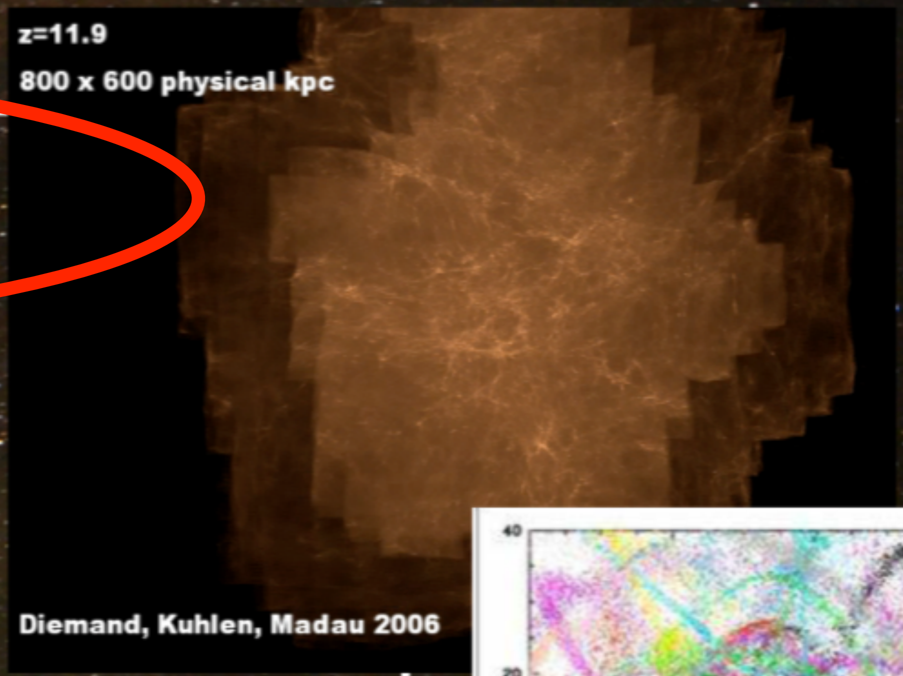
PFS Galactic Archaeology (GA) component

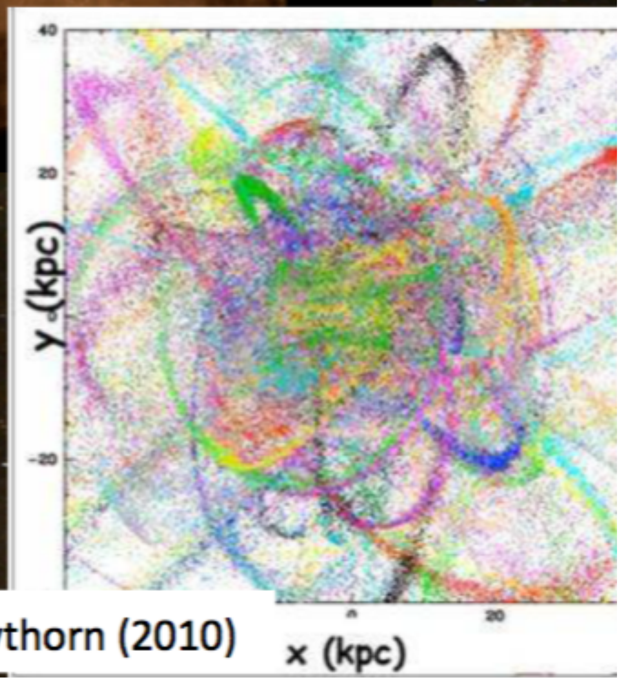
M. Chiba
(Tohoku U.)

Science objectives

We measure radial velocities & chemical abundances for a large number of stars in the Milky Way and Andromeda to constrain the nature of dark matter and its role in the formation of these galaxies

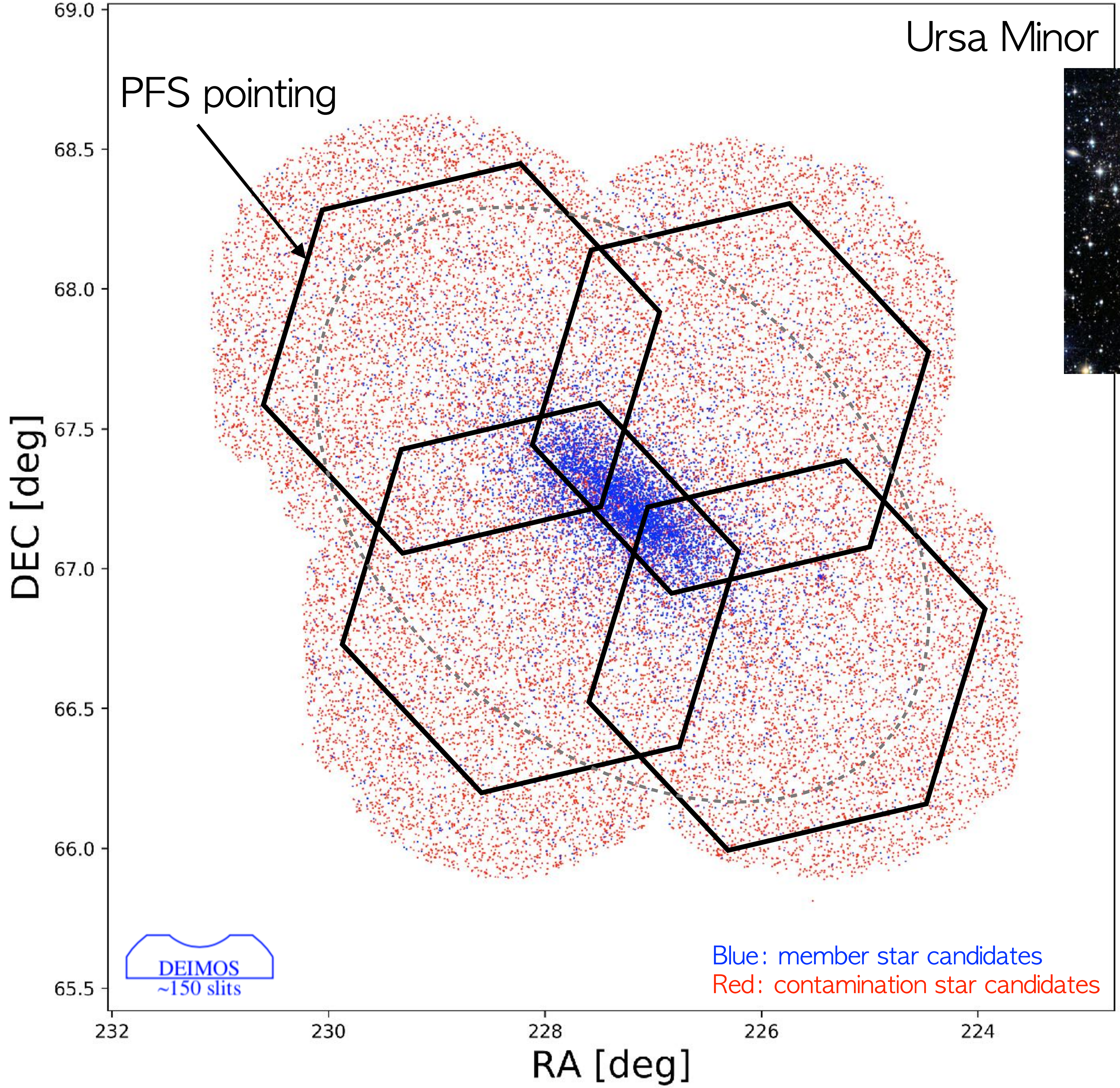
- MW dwarf satellites (Feb, May, Jun, Oct)
  - DM distribution, chemo-dynamics with [α/Fe]
- The M31 halo (Oct)
  - DM/stellar halo structure, chemo-dynamics with spectroscopic [Fe/H]
- MW halo/stream (Feb, Mar, May, Jun, Oct)
  - DM/stellar halo structure, chemo-dynamics
- MW disks (Dec for outer disk, any month for thick disk)
  - Chemo-dynamics with radial migration, disk structure



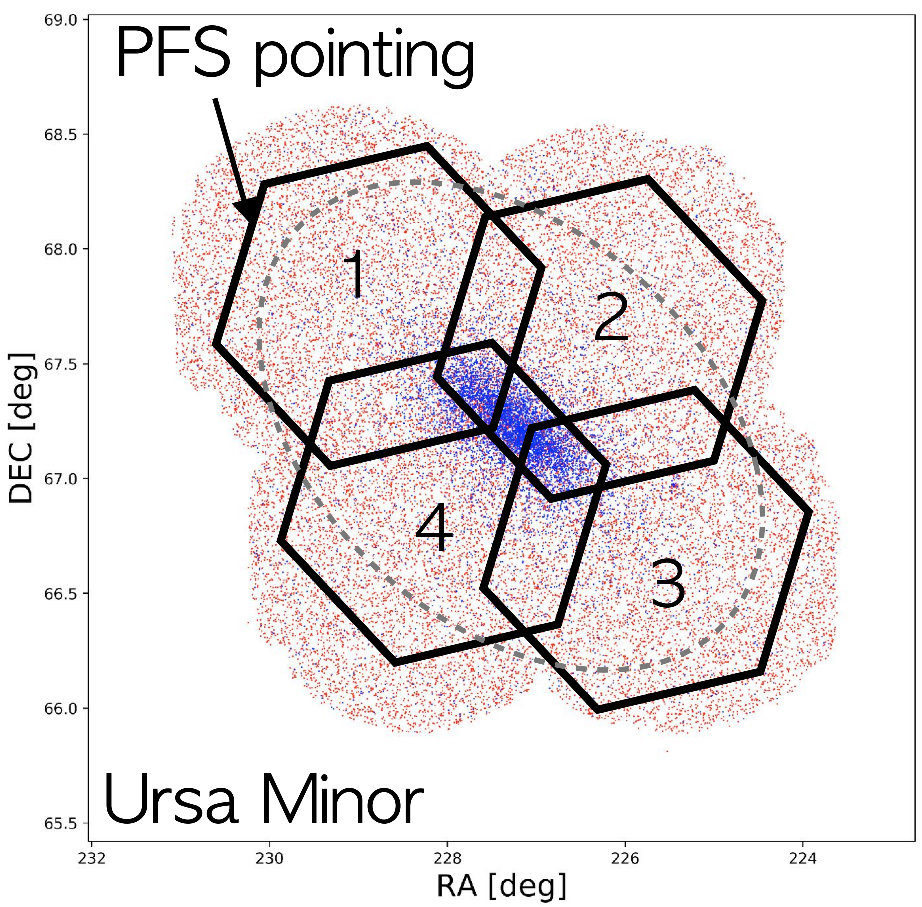


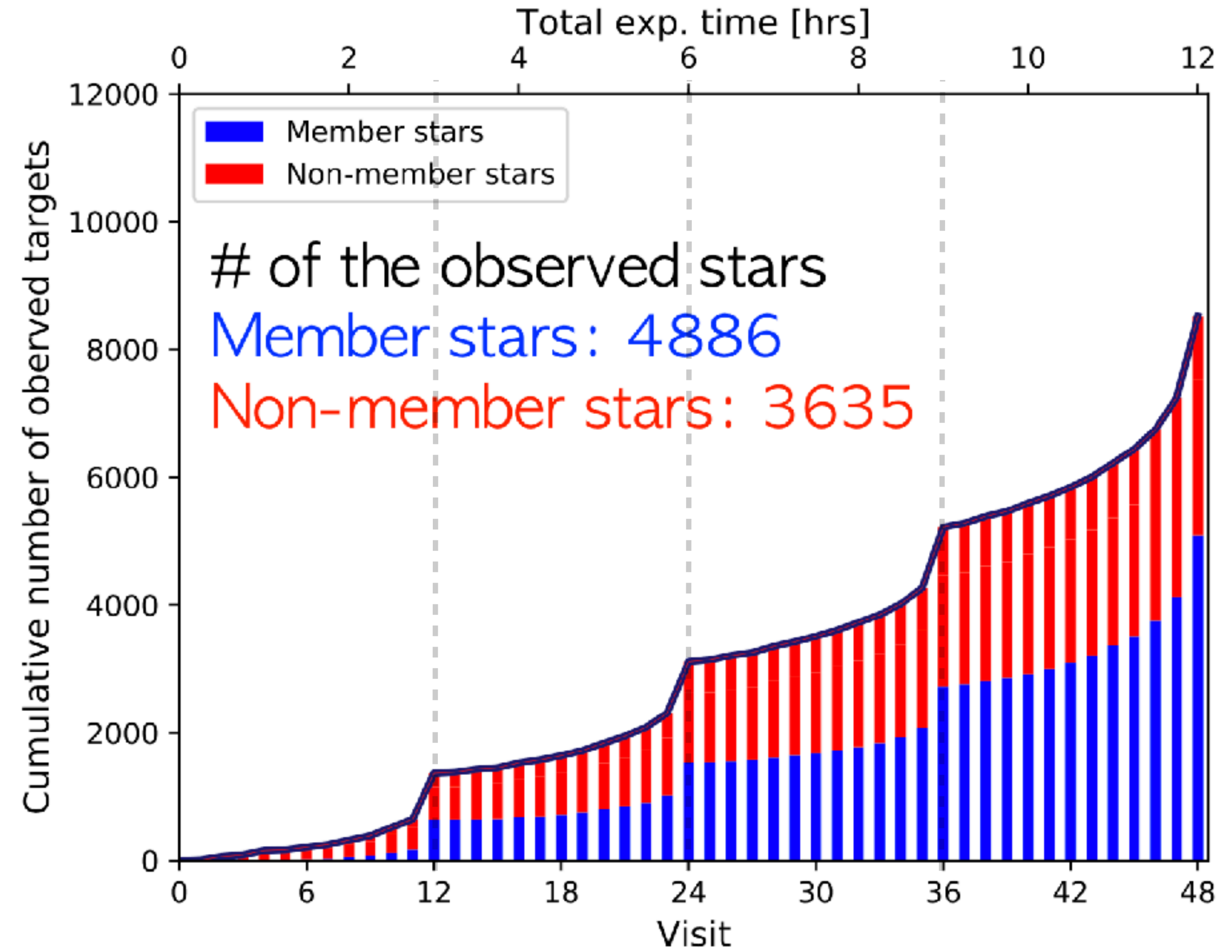
Freeman & Bland-Howthorn (2010)

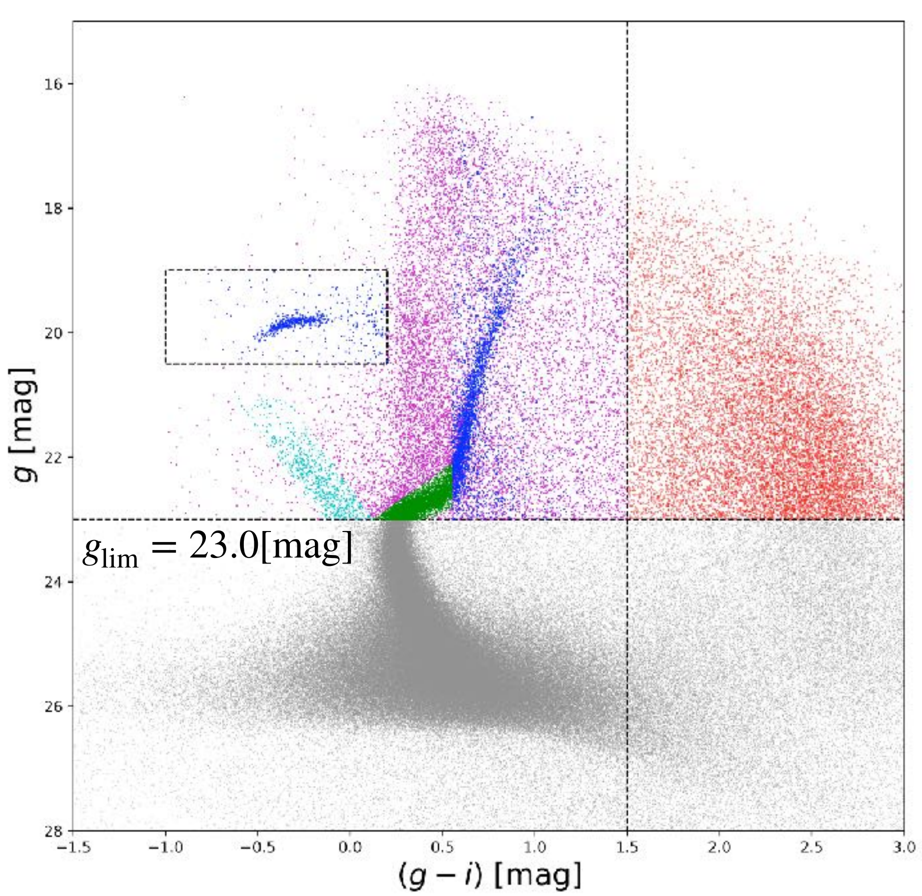
Uniqueness of PFS-dSph survey



Survey simulation for Ursa Minor dSph via PFS







- PFS can do observe about 5000 member stars in UMi dSph, while the number of current data is only ~300.
- PFS will be enable us to get an enormous number of stellar kinematic data out to the outskirts of dSphs.
- PFS will also obtain large volume of contamination stars, so that estimates of J-factors will be much more robust.
- In the current plan, Draco, Fornax, Sculptor, Sextans, Ursa Minor & BootesI are the primary targets of PFS-dSph survey.

Summary

- The MW dSphs are ideal sites for studying basic properties of dark matter.
- However, the major hidden systematic uncertainties on estimates of their dark halo structures still remain.
- In order to treat correctly and statistically these uncertainties, we constructed new dynamical models for the MW dSphs.
- Applying our models to the classical dSphs, we found a possible relation between inner slope of dark halo and star formation history.
- Subaru-PFS will have the remarkable capability to measure kinematic data of resolved faint stars in the dSphs and thus will allow us to determine robustly their dark matter structures.