Galaxy-collision simulation between dark satellite and dwarf galaxy

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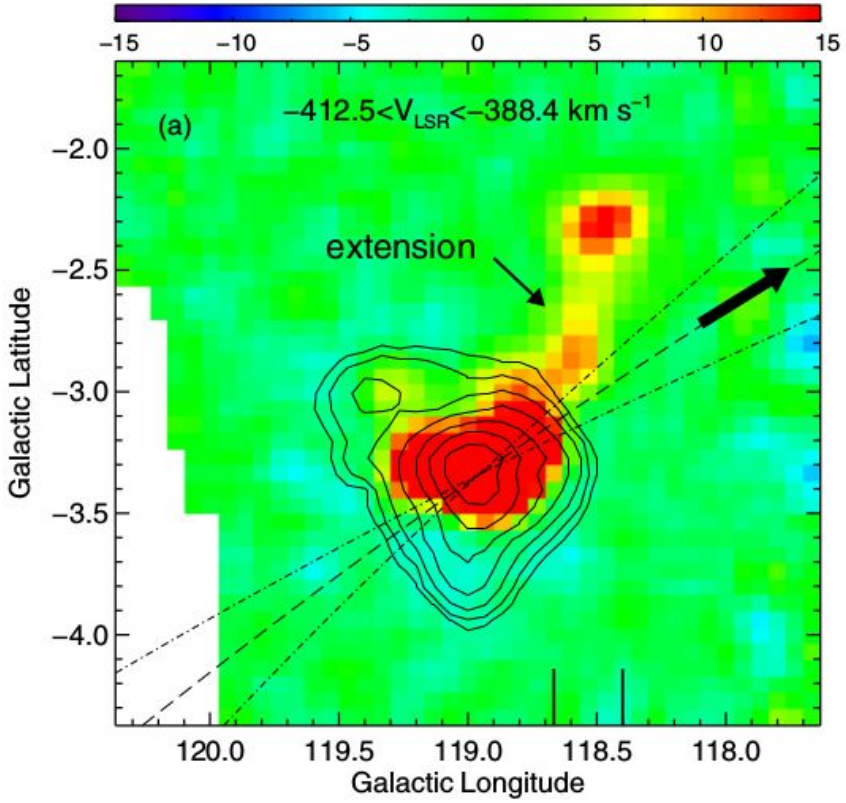
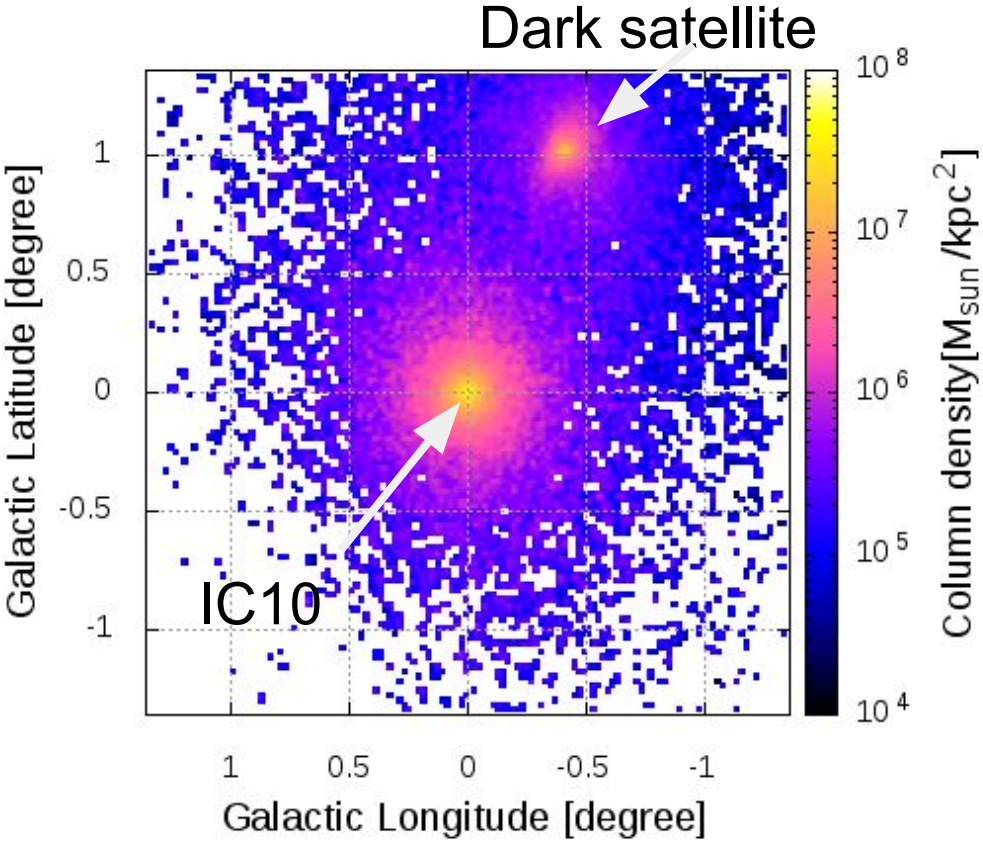
Preliminary result : Dark matter only test

- We performed N-body simulation of collision between a model of IC10 and a dark satellite.
- It is assumed that IC10 gas is stripped along with extended dark matter halo of dark satellite.

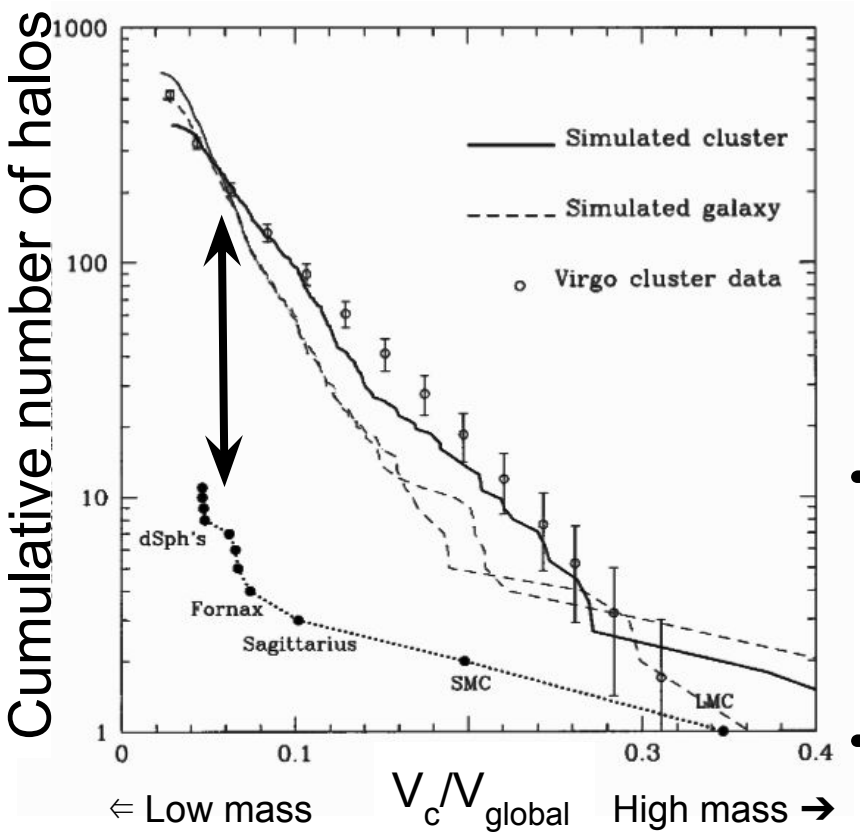


Observation (Nidever et al. 2013)



Missing satellite problem

- The expected number of dark matter halo(DMH) by theoretical simulation is **much less than observations** within our Local Group of galaxies (Klypin et al. 1999, Moore et al. 1999).



- The existence of **"dark satellite"** is a possible solution (Gnedin 2000).

➔ There are many satellite galaxies which are too dark to observe(Sawara et al. 2013).

➔ Only DMH and/or gas

What's origin of IC10 H_I gas stream??

IC10 : Starbursting-Irr galaxy in M31 system (~250 kpc from M31)

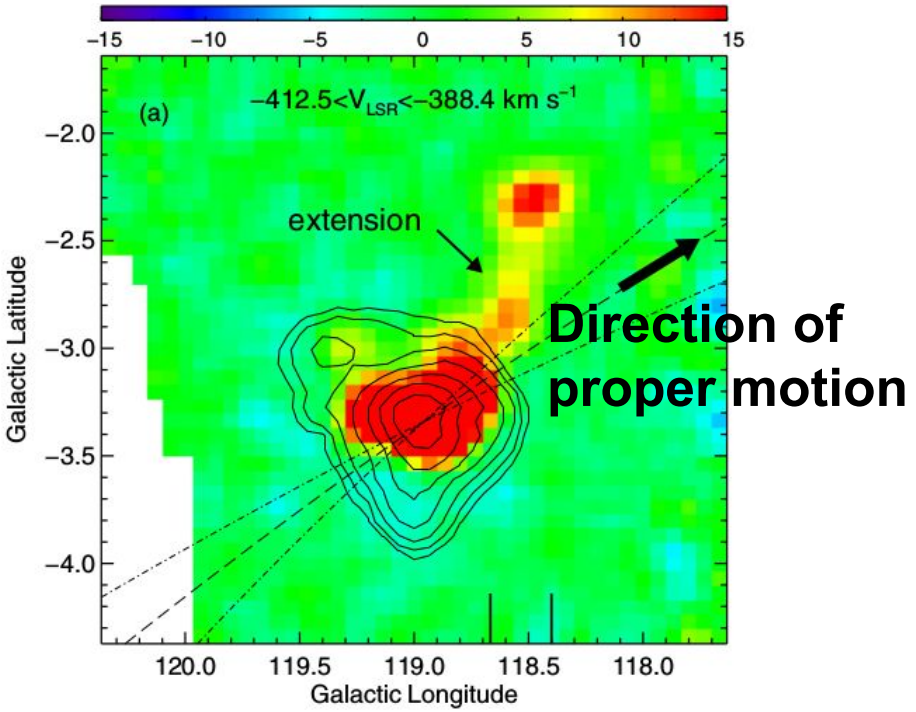
- Nidever et al. (2013) observed H_I gas stream associated with IC10.

However, **there is no optical counterpart** along with IC10 stream.

c. Interaction with companion galaxy.

Table 1
Properties of IC 10 and New H I Extension

Parameter	Value
GBT observations	
Resolution	9.′1
RMS noise	~21 mK per channel
3σ sensitivity over 20 km s^{-1}	~6.5×10^{17} atoms cm^{-2}
IC 10 galaxy	
Coordinates (J2000)	$\alpha = 00{:}20{:}23.16, \delta = +59{:}17{:}34$
Coordinates (Galactic)	$l = 118.°97, b = -3.°334$
Distance	805 kpc
$M_{\rm H\,I}$	$9.5 \times 10^7\ M_\odot$
New northern extension	
Length	~1.°3, ~18.3 kpc
Width	~0.°37, ~5.2 kpc
Orientation	~25° west of north
Velocity offset	~65 km s^{-1} below systemic
$\langle N_{\rm H\,I} \rangle$	~7×10^{17} atoms cm^{-2}
$M_{\rm H\,I}$	~$7.1 \times 10^5\ M_\odot$



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- Nidever et al. (2013) observed H_I gas stream associated with IC10.

However, **there is no optical counterpart** along with IC10 stream.

- We assume that this no optical counterpart is **"dark satellite"** around M31.
  - Previous works showed that the stream-like structure formed by merger between gas-rich dwarf galaxy and dark satellite (Starkenburg et al. 2015, 2016).
  - Proper motion of IC10 is already observed by Brunthaler et al. (2007), so IC10 is suitable for modeling.

M_{HI} ~7.1 × 10^5 $M_\odot$

120.0 119.5 119.0 118.5 118.0
Galactic Longitude

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- **Purposes of our study**
  a. **Study of dark satellite orbits by test-particle simulation. ← Today's talk**
  b. To explore the existence of dark satellites, we try to reproduce the H_I gas stream around IC10 by **N-body** and hydrodynamical simulation.

We examine the dark satellite hypothesis of the missing satellite problem.

M_{HI} ~7.1 × 10^{8} $M_{\odot}$

120.0 119.5 119.0 118.5 118.0
Galactic Longitude

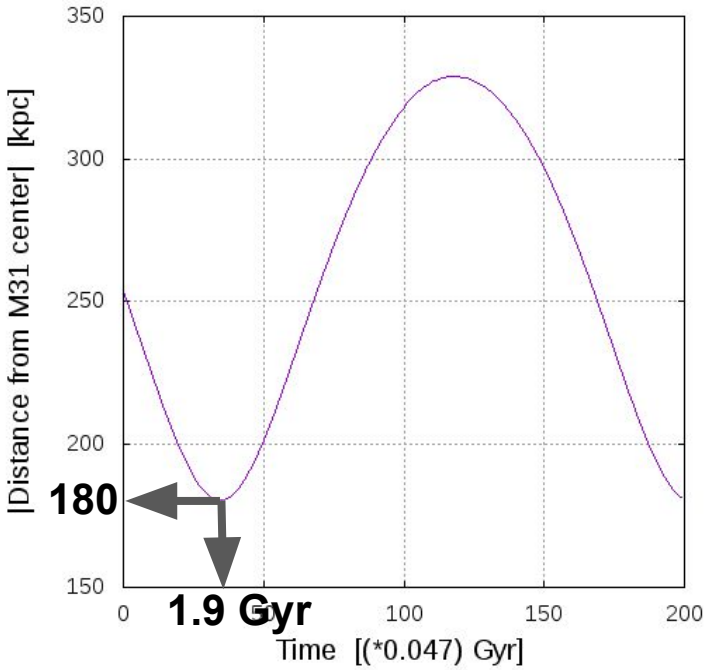
Parameter survey of dark satellite orbits

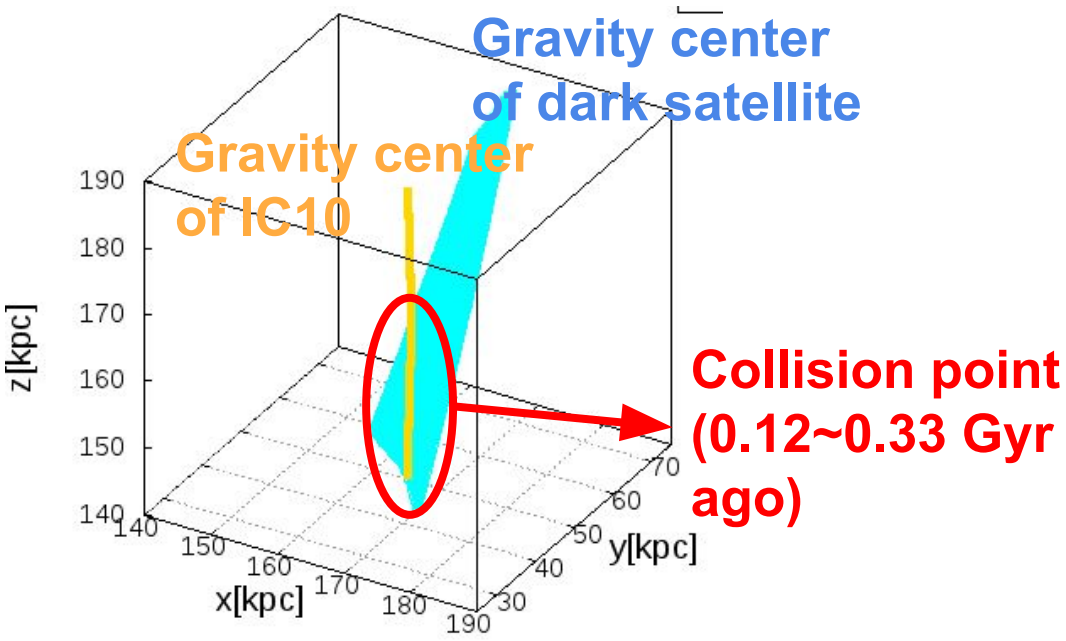
- Constraint in 6-d phase space
  - Current position of tip of HI gas stream
    1. Galactic longitude : 118°.53 (Nidever et al. 2013)
    2. Galactic latitude : -2°.35 (Nidever et al. 2013)
  3. Relative LoS velocity : -65.0 km/s (Nidever et al. 2013)

- Parameters to determine a orbit of dark satellite
  4. **Distance from Earth** : D
  5. **Proper motion toward to East** : V_E
  6. **Proper motion toward to North** : V_N
- **<u>Assumption</u>**
  - ✓ Dark satellite is bound to DMH potential of M31.
  - ✓ Dark satellite approaches within radius of 1 kpc (~ effective radius of stellar distribution) from the gravity center of IC10.

Result : Parameter survey

- Apoapsis of IC10 is distant from M31 about 180 kpc.
  - ➜ Tidal force of M31 is not effective for IC10 core.
- **Derived parameter ranges for the collision**
  - ➜ D = 783~797 kpc (< 805 kpc of IC10)
  - ➜ V_E = -191.6~-161.2 km/s; V_N= 168.8~244.7 km/s
  - ➜ Collision occurred 0.12~0.33 Gyr ago.





Method : N-body simulation

- N-body simulation is often used in study of theoretical astrophysics.
  - **Equation of motion** of ith particle

$$\frac{d^2\boldsymbol{x}_i}{dt^2} = \sum_{j\neq i}^{N\,particle} G m_j \frac{(\boldsymbol{x}_j - \boldsymbol{x}_i)}{\left[(\boldsymbol{x}_j - \boldsymbol{x}_i)^2 + \epsilon^2\right]^{3/2}} + \boldsymbol{a}_{DMH}(\boldsymbol{x}_i)$$

  - **External gravitational force of M31 DMH**

    : NFW profile (Navarro et al. 1996)

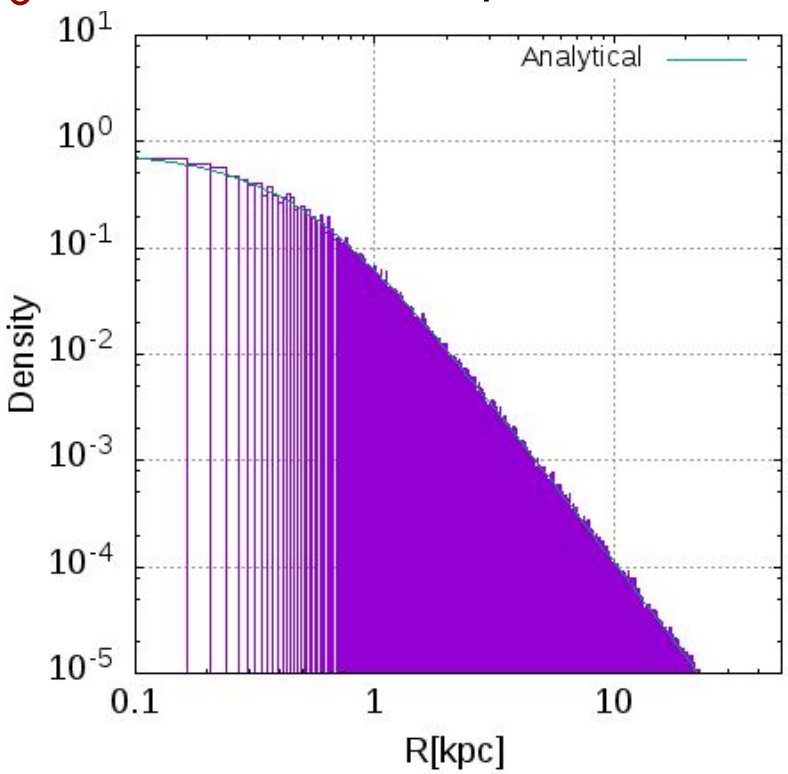
    - Scale radius : r_s = 34.6 kpc (Sofue 2015)
    - Scale density: $\rho_s = 2.23\times10^6 M_\odot kpc^{-3}$ (Sofue 2015)

$$\boldsymbol{a}_{DMH}(r) = -\frac{4\pi\rho_s G r_s^3}{r}\left(\ln(1+r/r_s) - \frac{r/r_s}{1+r/r_s}\right)$$

  - **Time integration method** : Leap-Frog method

Simple model test (dark matter only)

- Parameters of IC10/dark satellite modeling
  - IC10 DMH : Burkert profile(Burkert et al. 1995)
    - **Mass : $5.54\times10^8\ M_\odot$**
    - Core radius : 0.51 kpc
    - Concentration : 18.9
    - # of particles : 2^{16}=65536
    - Softening length : 15.625 pc
  - Dark satellite : NFW profile
    - **Mass : $0.2M_{IC10}$**
    - Scale radius : 1.0 kpc
    - # of particles : 2^{16}=65536
    - Softening length : 15.625 pc



  - Fiducial orbit : D = 797 kpc, (V_E, V_N)=(-179.7, 238.0) km/s
  - Integration time: ±1 Gyr (Time step ~0.2 Myr)

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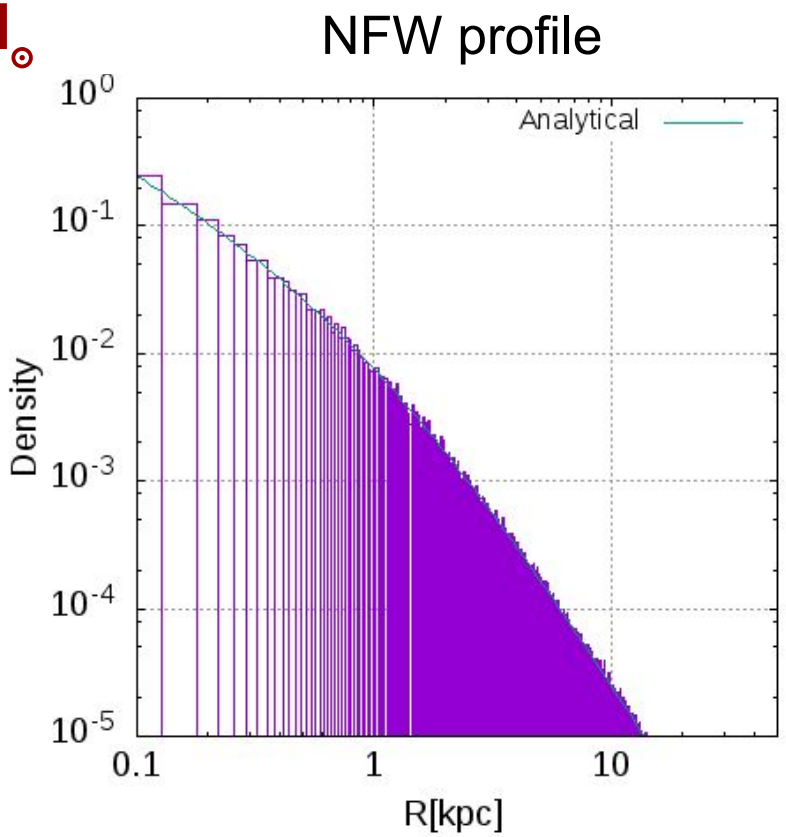
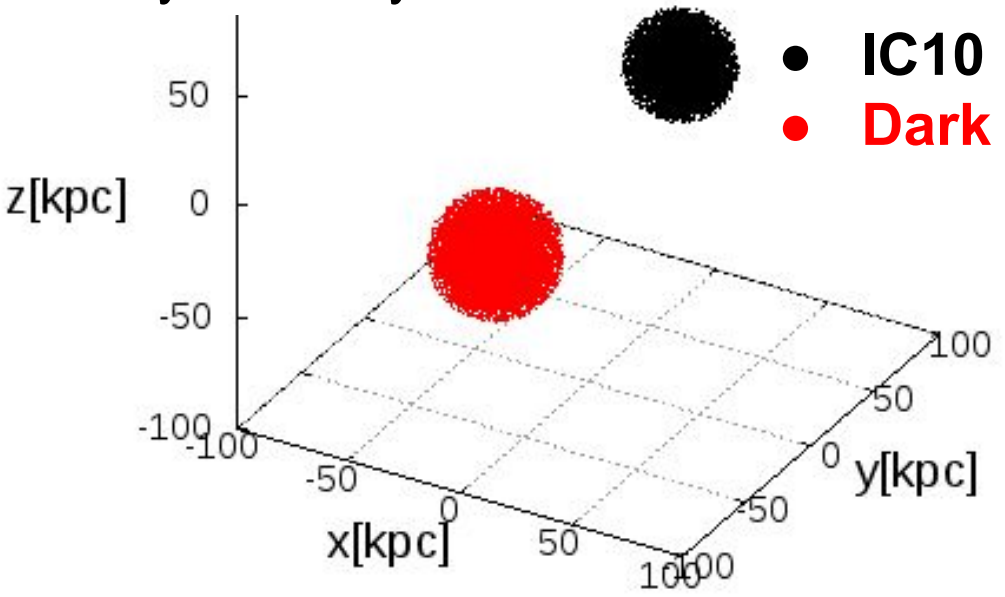


Preliminary result : Simple model test

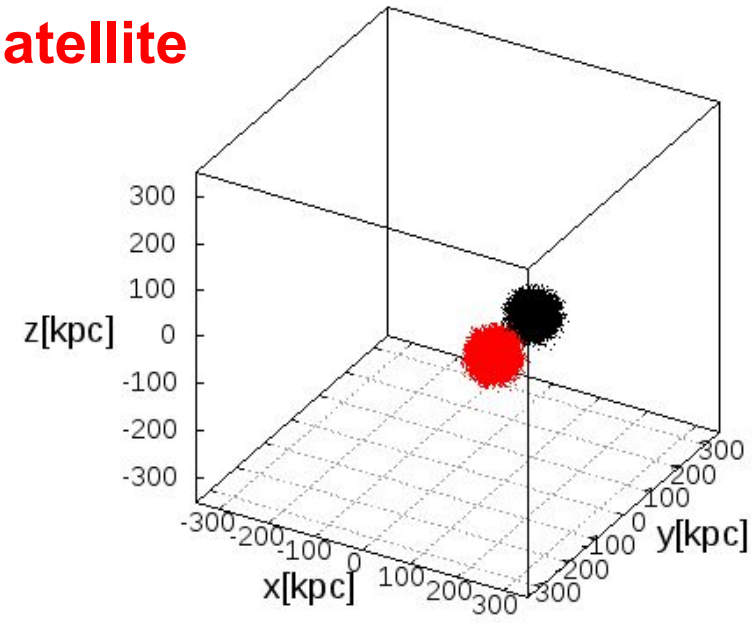
- Relative velocity is **~70 km/s** in collision.
- **There is not major morphological change in IC10 center region** due to collision with dark satellite.
  - ➜ In the case of low relative velocity, it is suspected that the morphological change clearly reveals.

Gravity center system



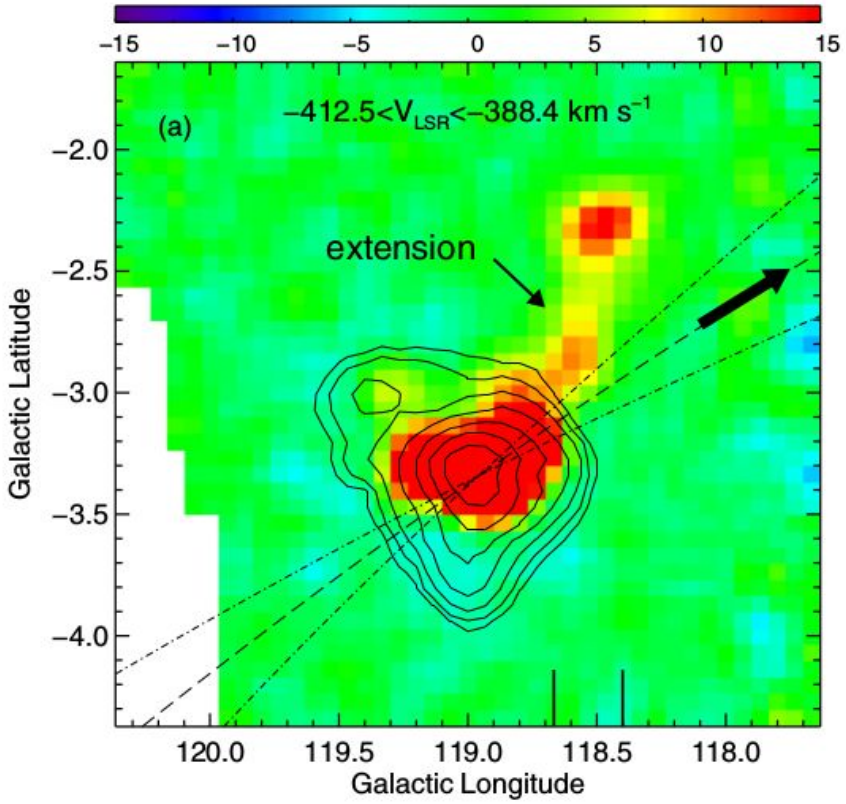
80% of the # of particles with small distances from each gravity center.

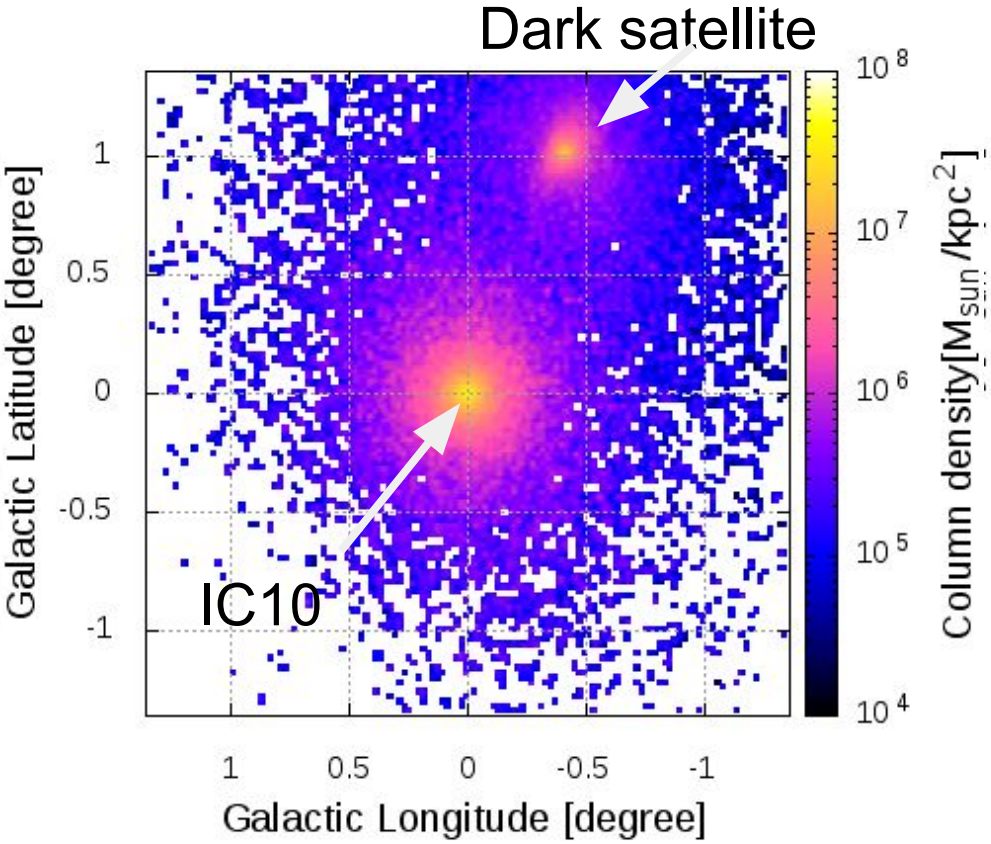
M31 center system



Preliminary result : Column density profile

- Column density profile of **dark satellite is extended toward to IC10**.
  - Gas is easily moved by tidal and ram-pressure stripping and extended along with DMH stream.





Summary and future work

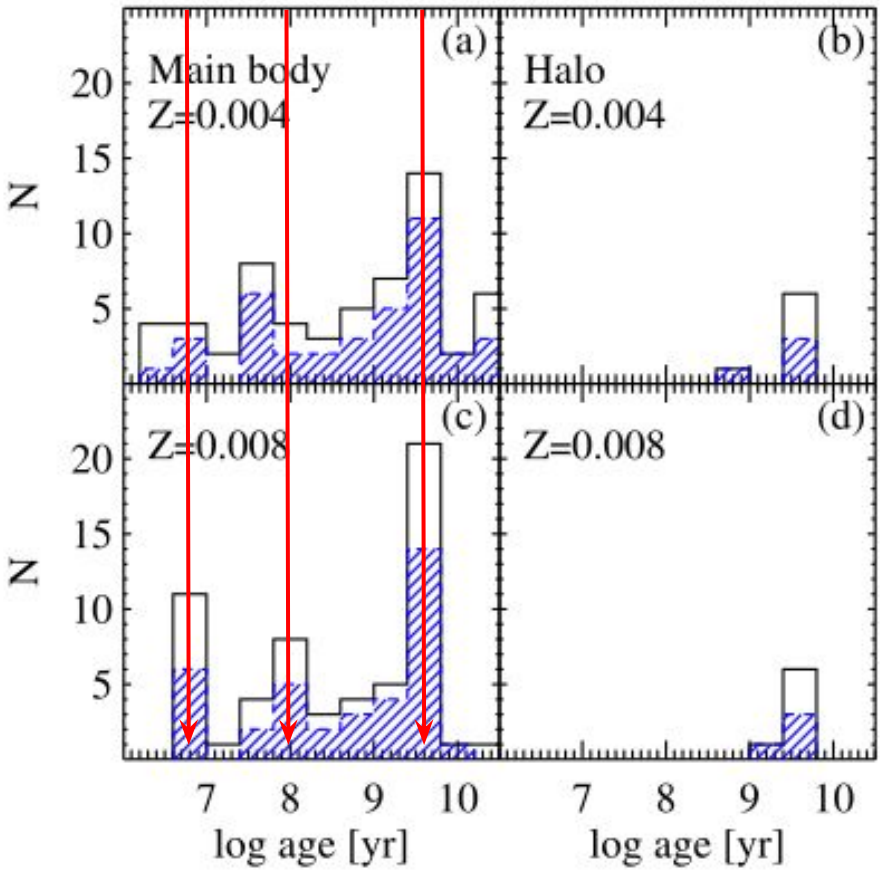
- **Summary**
  - Derived parameter ranges for the collision
    - ➜ D = 783~797 kpc
    - ➜ V_E = -191.6~-161.2 km/s; V_N= 168.8~244.7 km/s
  - According to DM only simulation, there is not major morphological change in IC10. But, density profile of **dark satellite DMH is extended toward to IC10.**
  - ➜ Gas stream possibly grow along with extension.
- **Future work**
  - Construct models of multi-component IC10.
    - Gas component / Stellar disk component
  - Parameter survey of IC10 / dark satellite variables.
    - Initial position / velocity of IC10 and dark satellite.
    - Mass / Concentration parameter of dark satellite.

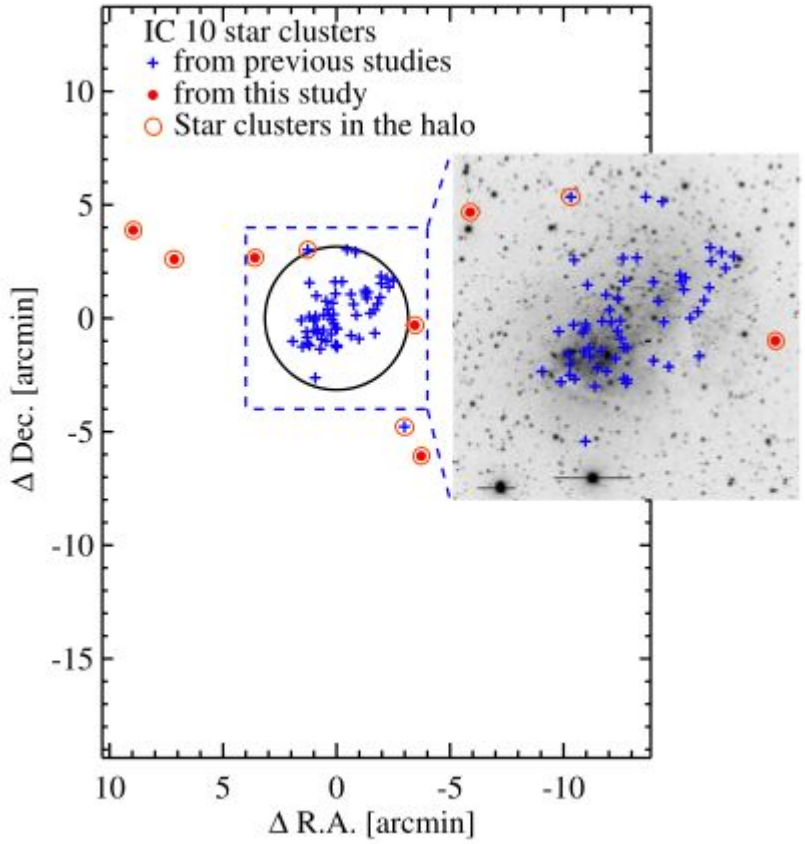
Appendix

Age of star clusters in IC10

- Lim et al. (2015) observed star clusters in IC10.
  - They estimated the age distributions of the star clusters in the main body and halo region.

6Myr 100Myr 4Gyr



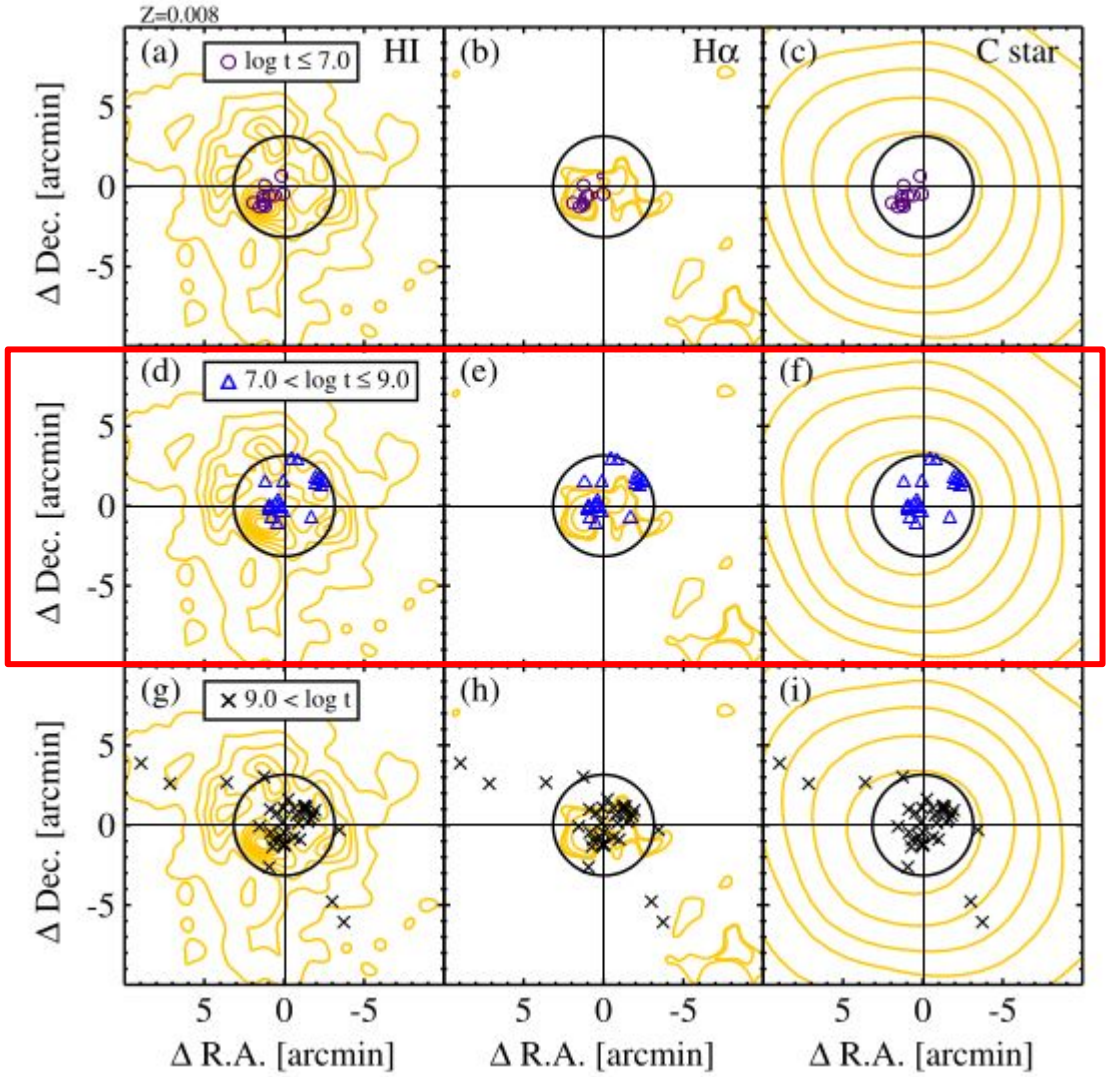


Spatial distribution of the star clusters with different ages in IC 10.

The first burst at 100 Myr produced star clusters mostly in two regions.

1. In the central star-forming region
2. In the **northwest star-forming region**

➜ **Collision is trigger of star formation?**

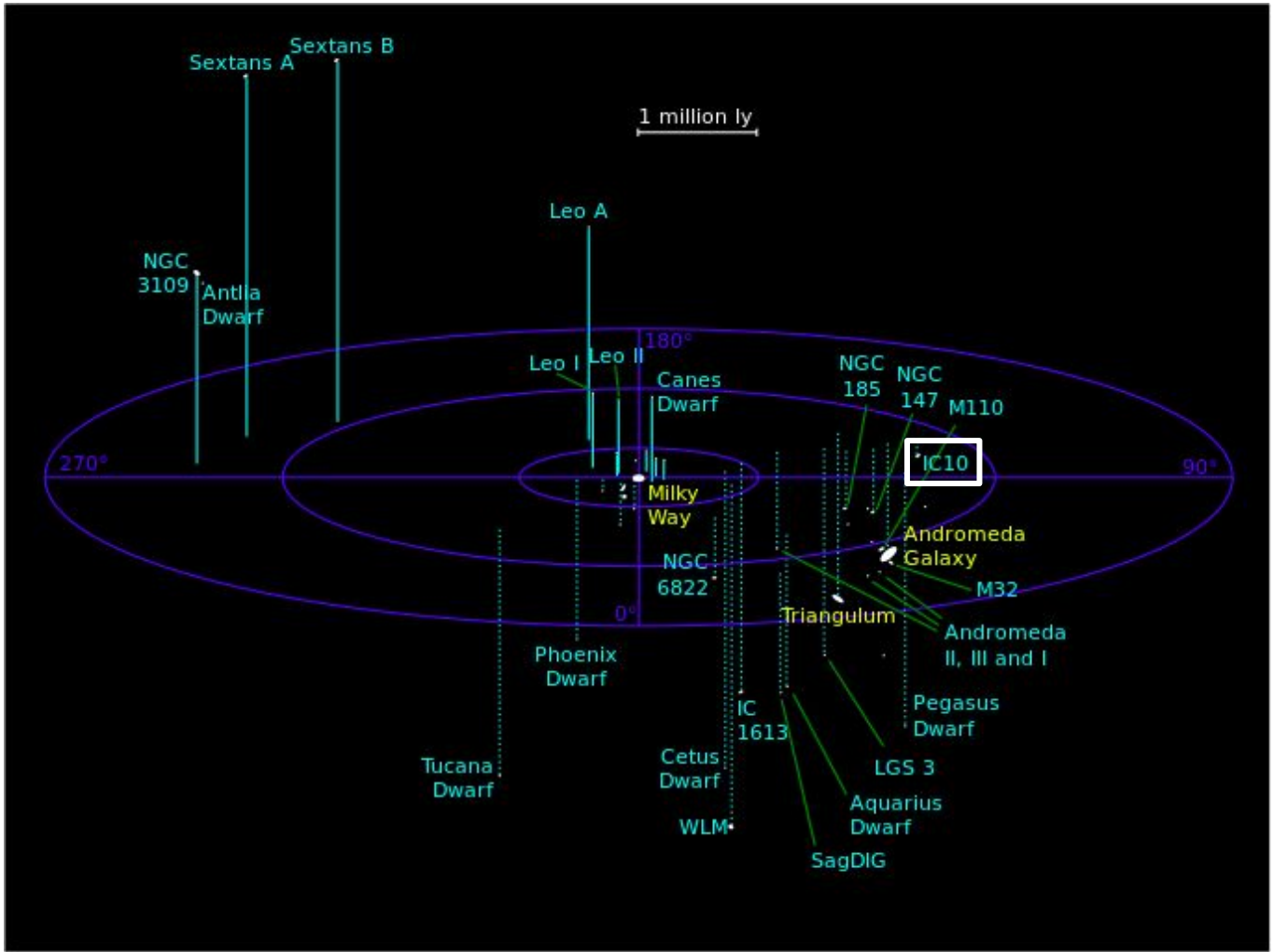


N-body simulation setup

- Code : Framework for Developing parallel Particle Simulator(Iwasawa et al. (2016), Namekata et al. in prep)
  - Using tree algorithm
    - Opening angle : 0.5
    - # of min particles in leaf : 4
    - # of max particles in cell : 64
    - Span of domain decomposition : 4
  - Using x86 Phantom-GRAPE(Tanikawa et al. (2012))
- Initial condition of galaxies : many-component galaxy initializer (Miki & Umemura (2018))
  - Final time of initialization : 23.5(~1.175Gyr)
- Time step : 1/256 = ε / 8

Local Group of galaxies

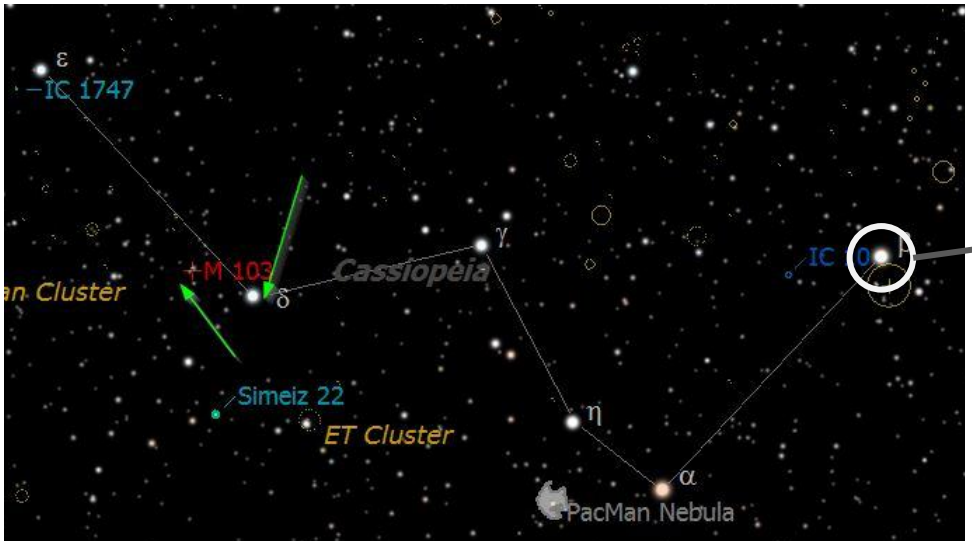
- Radius : ~ 1.5 Mpc
- The # of galaxies : MW (39) / M31 (27) / Others

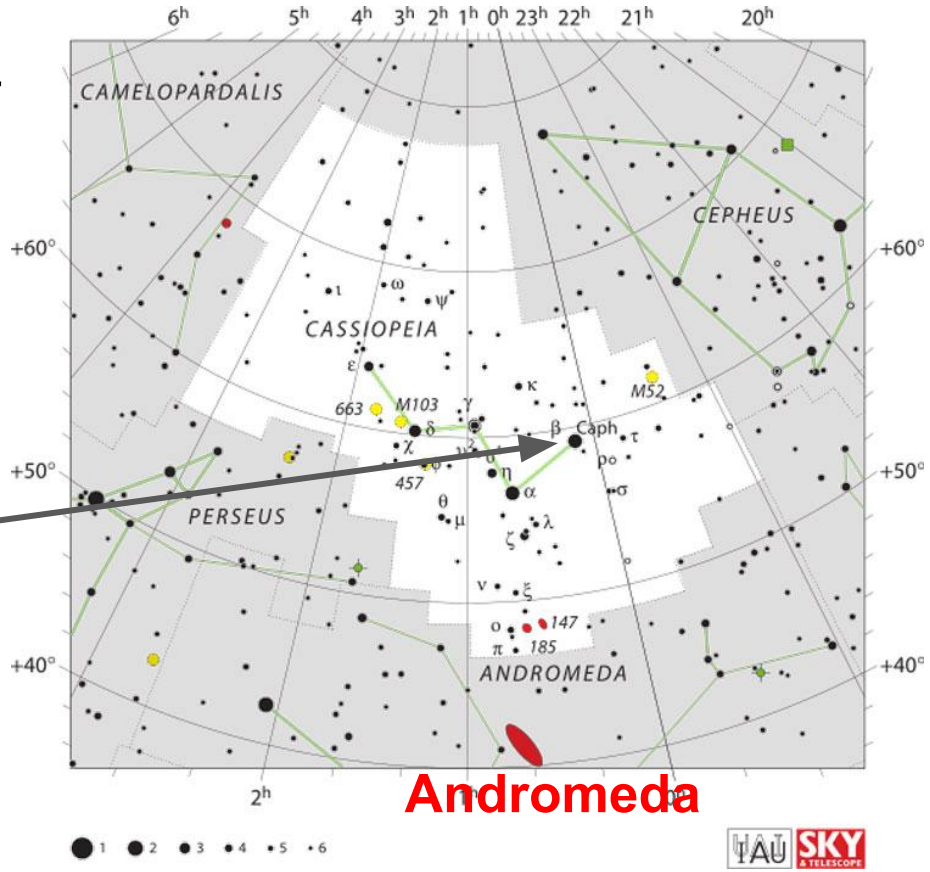


IC10 information

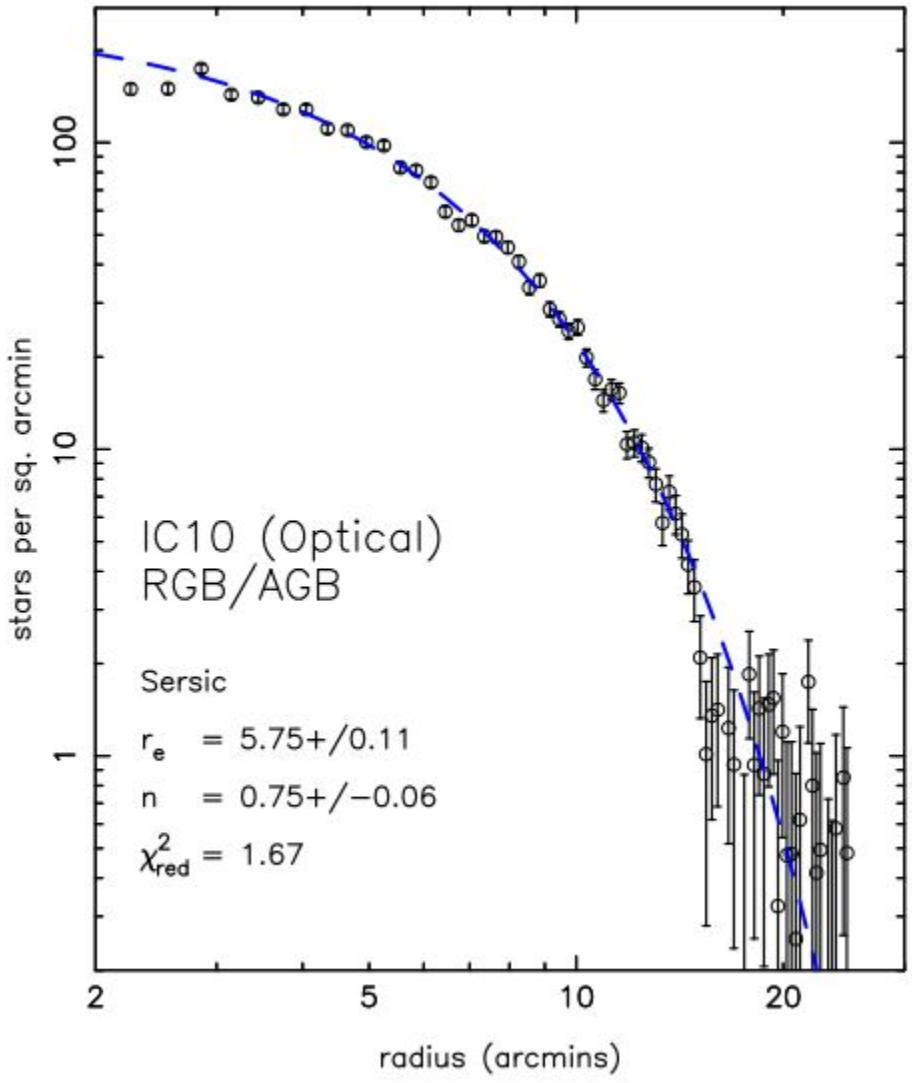
- IC10 model(Sanna et al. (2008), Nidever et al. (2012), Brunthaler et al. (2007))
  - Proper motion :

    (v_{LoS}, v_E, v_N) = (-148 km/s, -39 μsec, 31 μsec)
  - Distance : 805 kpc
  - Galactic longitude : 118°.87
  - Galactic latitude : -3°.334

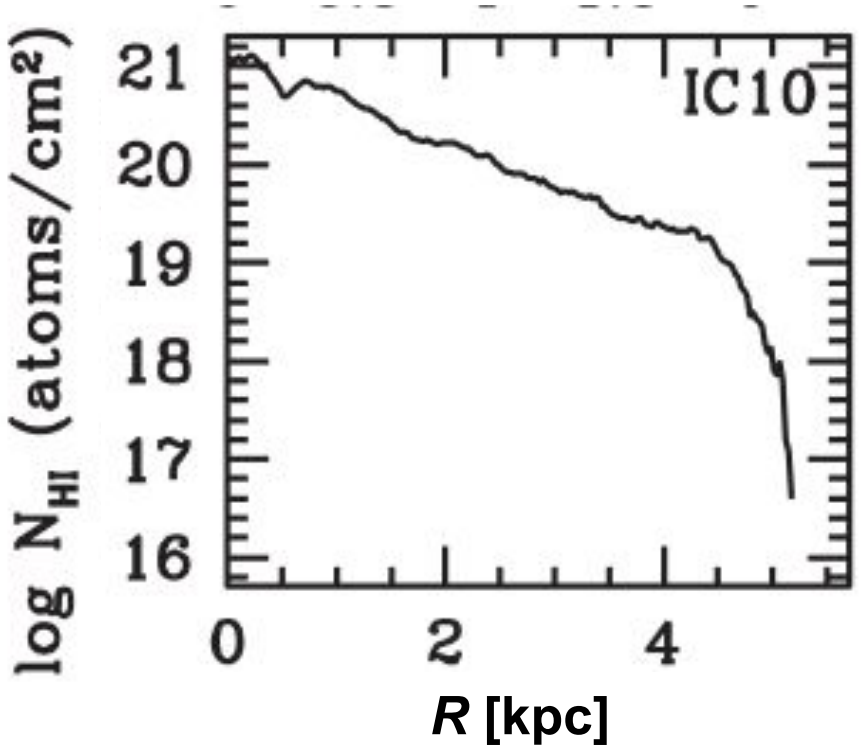




Stellar / gas distribution of IC10



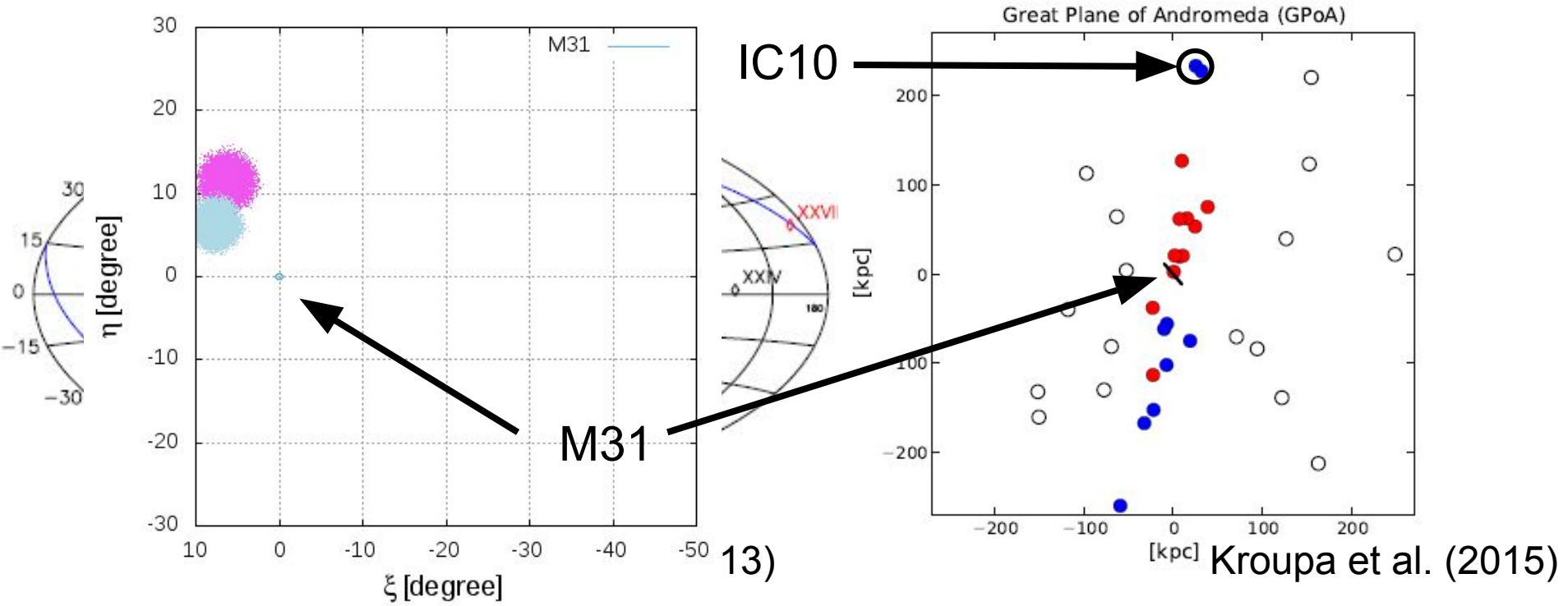
Stellar distribution of IC10
Stephanie et al. (2015)



Gas distribution of IC10
Hunter et al. (2012)

Dark satellite on the Great Plane of Andromeda

- Some of satellite galaxies around Local Group host galaxies (Milky Way,M31) are seem in “One Plane”.
- One candidate of origin of IC10 HI gas stream.
  - ➢ Dark satellite on this Plane of Satellites?



13)

Kroupa et al. (2015)

Another thenario of H_I gas stream

- Ashley et al.(2014)によると，IC10のmain bodyに視線速度の2ピークをがある.
  - これがmergerのcounter partだとすると，Nidever et al.(2013)のHI stream の先端にconter partがいないことも説明できる.
  - この場合，dark satelliteの出番としてはPoS上に乗っているultra faintなdwarfの候補として扱うことになる.