High-resolution mass models of the Large Magellanic Cloud

Shinna Kim

with Se-Heon Oh, Bi-Qing For, and Yun-Kyeong Sheen

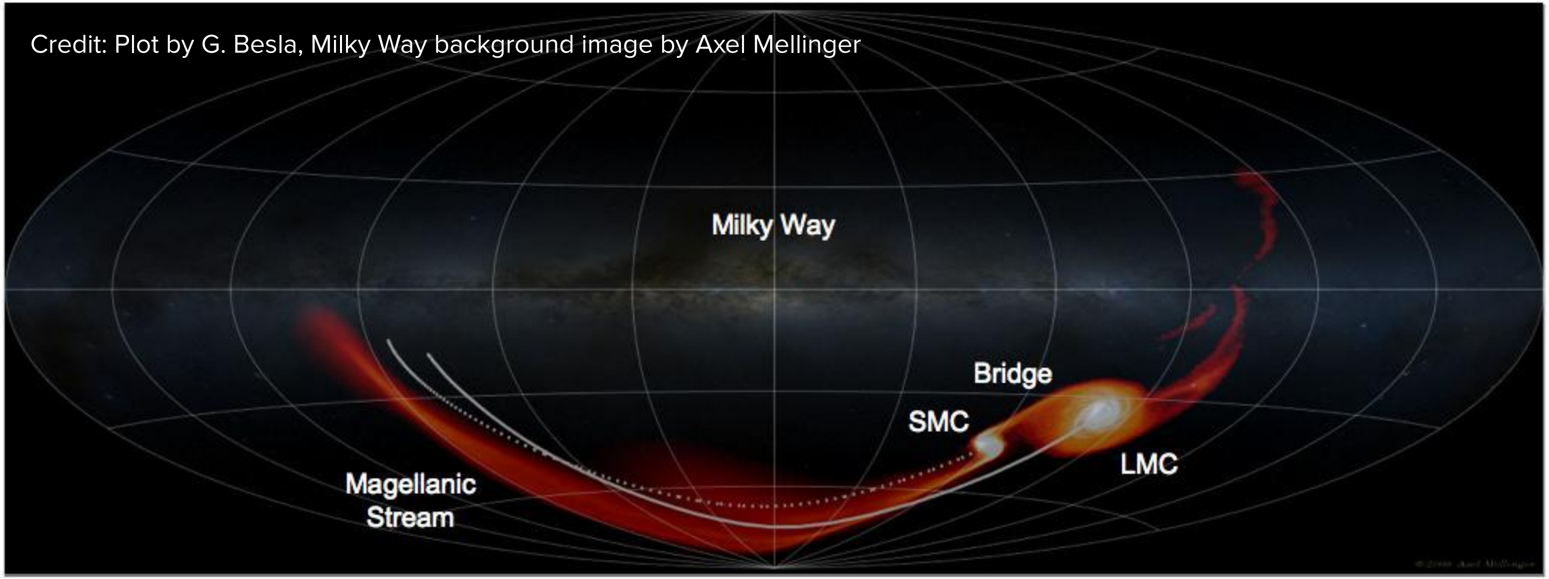
© ESO's La Silla Observatory

kimsn9711@gmail.com

Contents

1. Introduction
2. Rotation curve analysis of the LMC
3. Mass models of the stellar and gaseous components of the LMC
4. Mass distribution in the LMC
5. Summary

Introduction

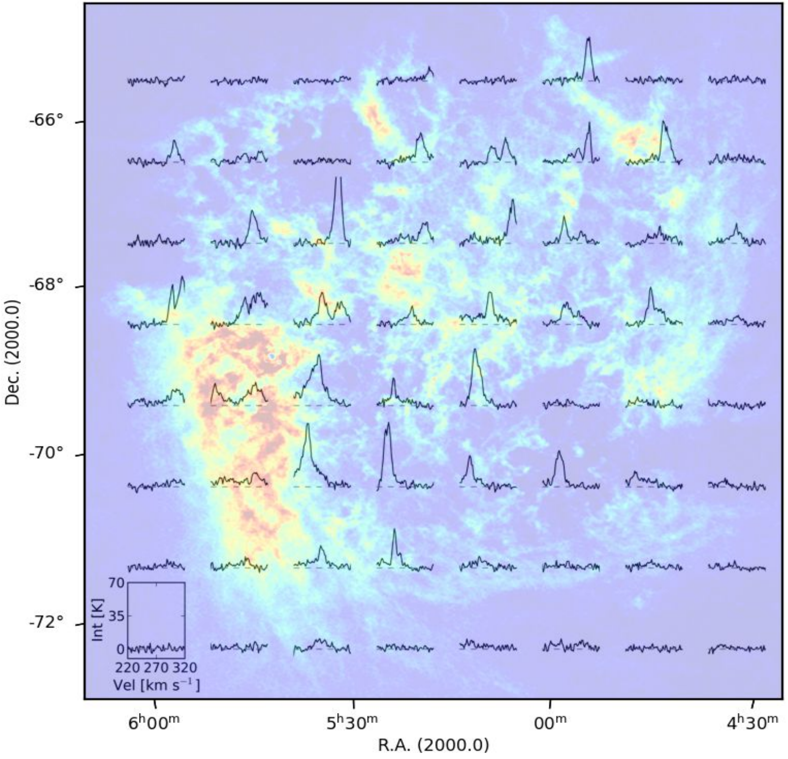

Credit: Plot by G. Besla, Milky Way background image by Axel Mellinger

- The Large Magellanic Cloud (LMC) is one of the closest galaxies to the Milky Way at a distance of ~50 kpc
- Gravitational interactions between the LMC and the Small Magellanic Cloud (SMC) and the Milky Way

kimsn9711@gmail.com

Introduction

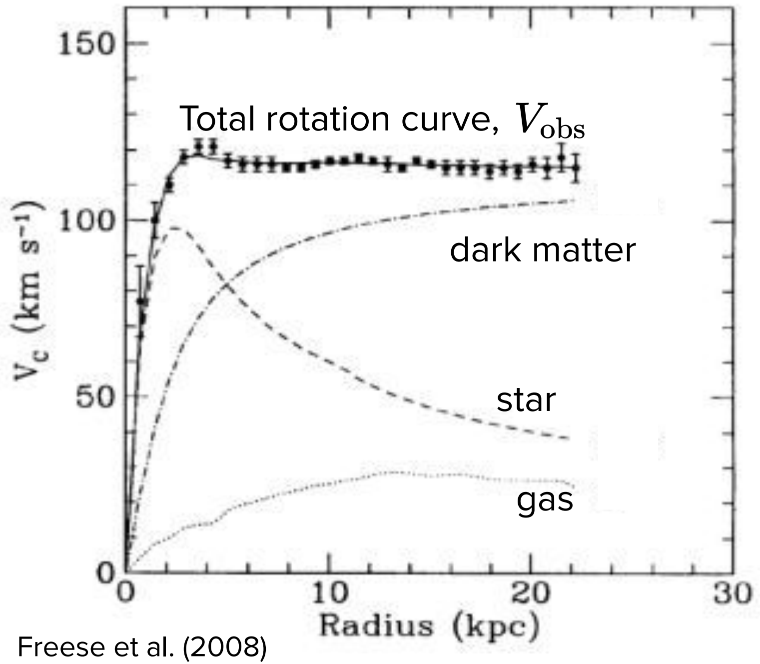
HI velocity profiles overlaid on the HI intensity map of the LMC



- LMC's gas component has complex HI structure by recent stellar feedback and gravitational interactions with other galaxies.
- Minimizing these effects is the first step in deriving more reliable HI kinematics of the galaxy.

Introduction

Example



Freese et al. (2008)

$$V_{\rm obs}^2 = V_{\rm gas}^2 + V_{\rm star}^2 + V_{\rm DM}^2$$

1. Total rotation curve (HI tracer) ➔ $V_{\rm obs}$
2. Stellar components ➔ $V_{\rm star}$
3. Gaseous components ➔ $V_{\rm gas}$
4. Dark matter component ➔ $V_{\rm DM}$

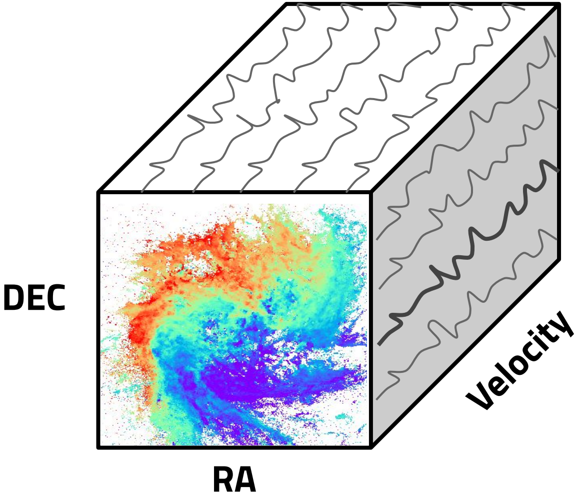
Deriving an accurate rotation curve is firstly required.

- ★ We aim to derive a **bulk HI** velocity field
  - ➔ global kinematics of the galaxy
  - ➔ non-circular gas motions removed

Combined ATCA and Parkes HI data cube

HI data cube

- Australia Telescope Compact Array (ATCA) + Parkes radio telescope (Kim et al. 2003)
- Angular resolution of ~60’’ which corresponds to a physical size of ~14.6 pc
- Velocity resolution of ~1.65 km/s

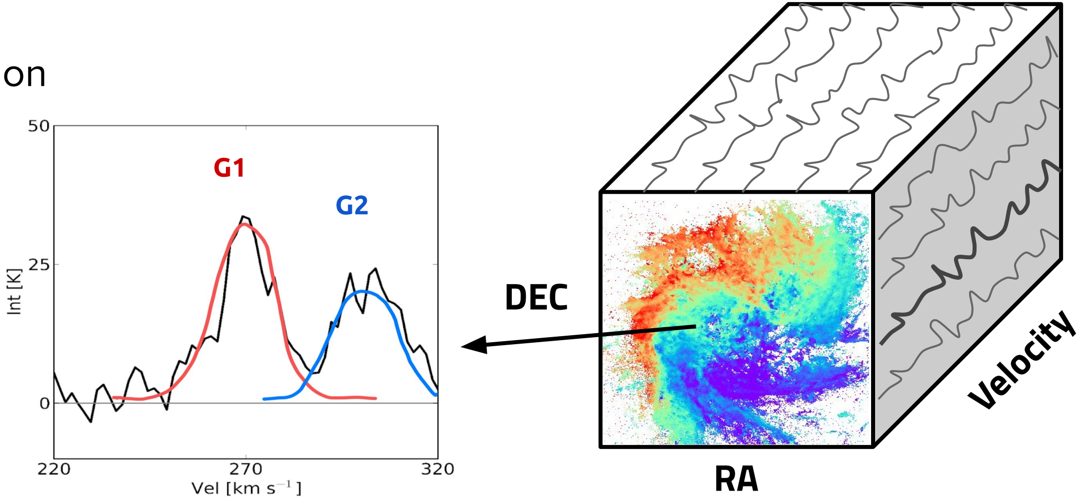


kimsn9711@gmail.com

Optimal decomposition of HI velocity profiles

a newly developed profile decomposition technique, **BAYGAUD** (Oh et al. 2008)

$$G(x) = \sum_{i=1}^{m} \frac{a_i}{\sqrt{2\pi}\sigma_i} \exp\left(\frac{-(x-\mu_i)^2}{2\sigma_i^2}\right) + \sum_{j=0}^{n} b_j\, x^j$$

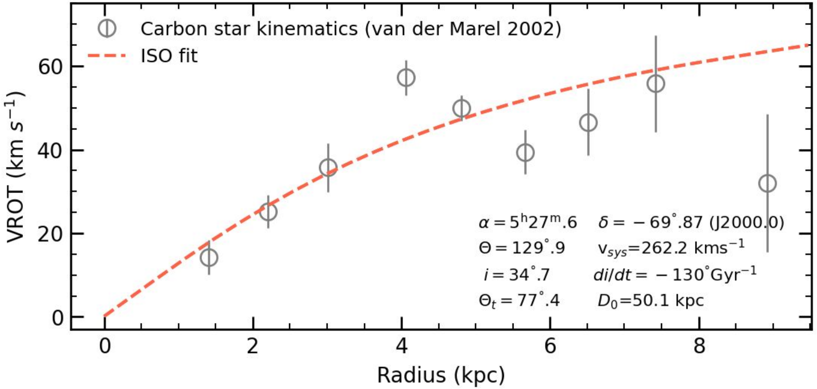


- ➔ Decompose each line-of-sight velocity profile of the data cube into an optimal number of Gaussian components based on Bayesian MCMC techniques
- ➔ Set the maximum number of Gaussian components with five
- ➔ Model selection using Bayes factor

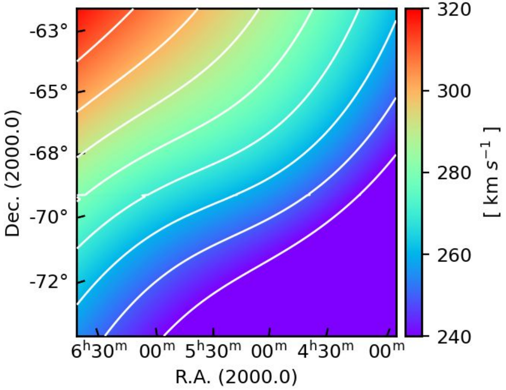
A global model velocity field based on stellar kinematics

- Model velocity field ; carbon star kinematics in van der Marel et al. (2002)
  - ➔ used for extracting the bulk component from the decomposed Gaussian components
- Why stellar kinematics?
  - ➔ global kinematics of the galaxy; less affected by recent stellar feedback or hydrodynamical forces

Carbon star kinematics (van der Marel et al. 2002)

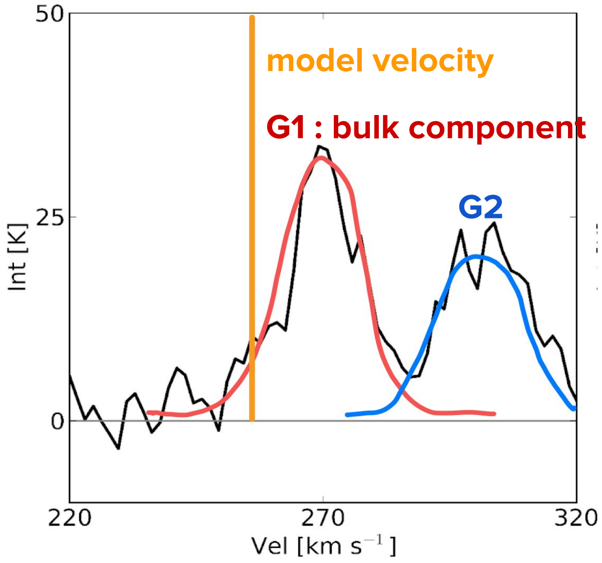


Model velocity field

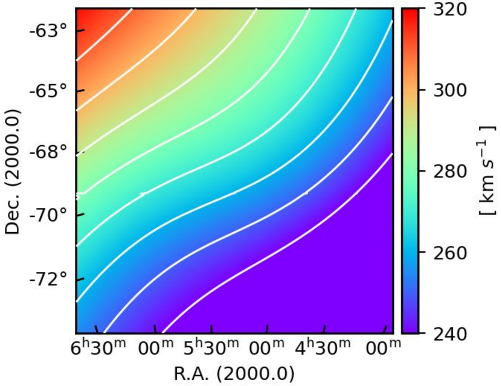


Extraction of HI bulk gas motions

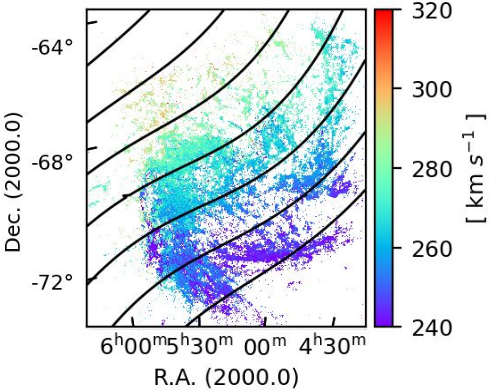
- We select co-rotating **HI bulk gas components** whose central velocities are **closest to the reference model velocity field** within a velocity limit.



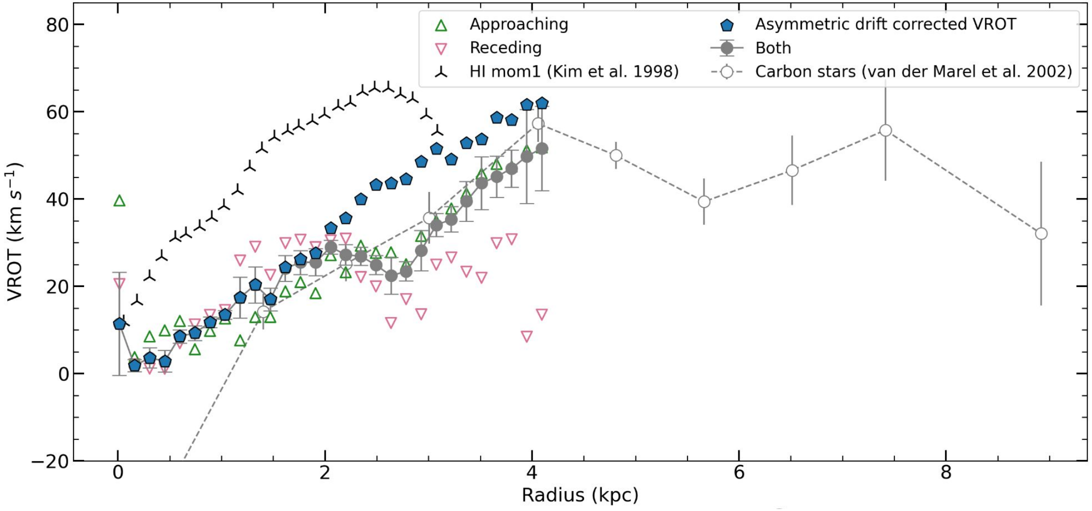
Model velocity field



Bulk velocity field



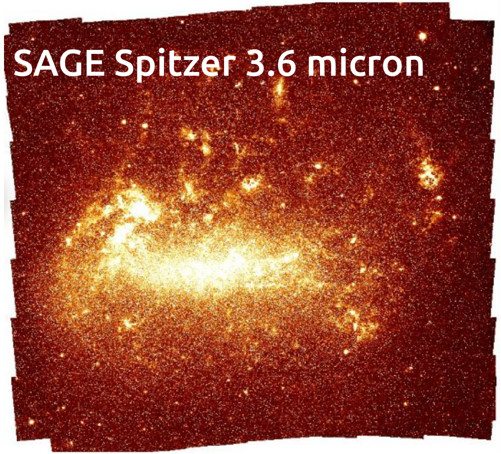
HI bulk rotation curve of the LMC

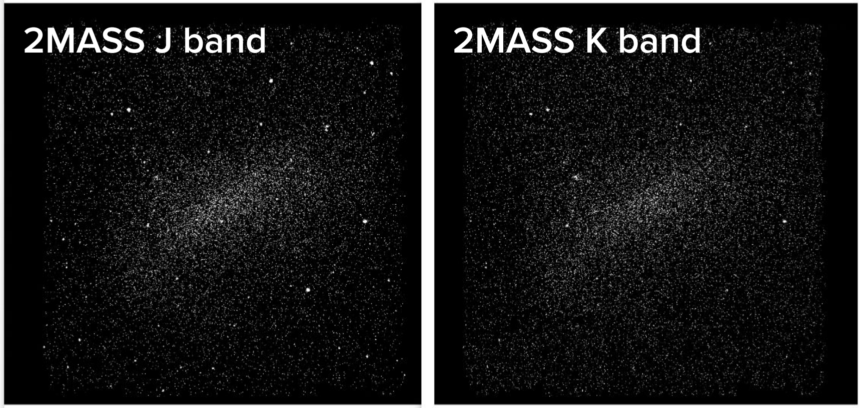


- HI bulk rotation curve; solid body-like, linearly rising in the central region compared to the conventional HI MOMENT1 rotation curve (Kim et al. 1998)
- consistent with carbon star kinematics (van der Marel et al. 2002)
  - ➔ less affected by the effect of random gas motions disturbed by recent gravitational and hydrodynamical processes

Mass model of the stellar component

- The total rotation curve : baryons (star and gas) and dark matter
- We quantify the dynamical contribution of the stellar component





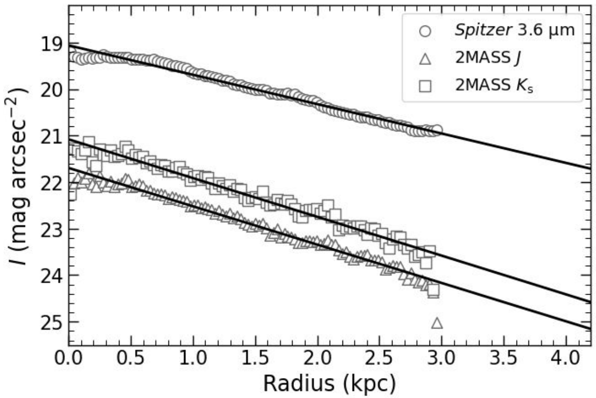
- trace old stellar populations; dominant
- less sensitive to dust extinction and recent star formation

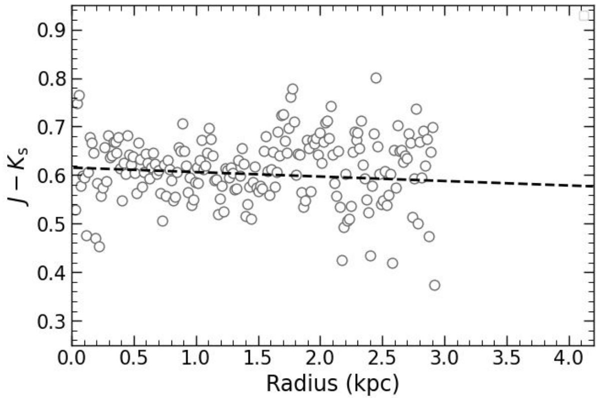
- stellar mass-to-light ratio
  - ➔ convert the 3.6 micron stellar light to the mass

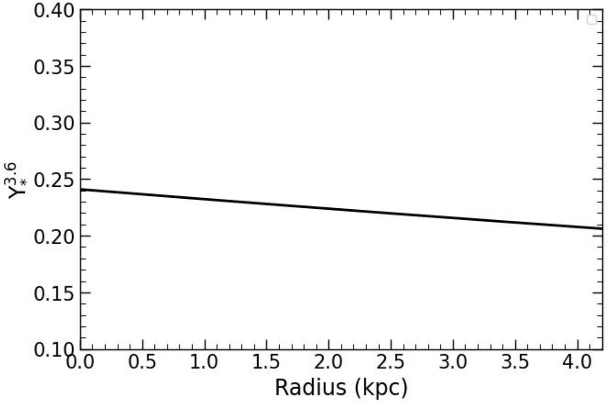
kimsn9711@gmail.com

Mass model of the stellar component

surface brightness profiles → J - K color → stellar mass-to-light ratio



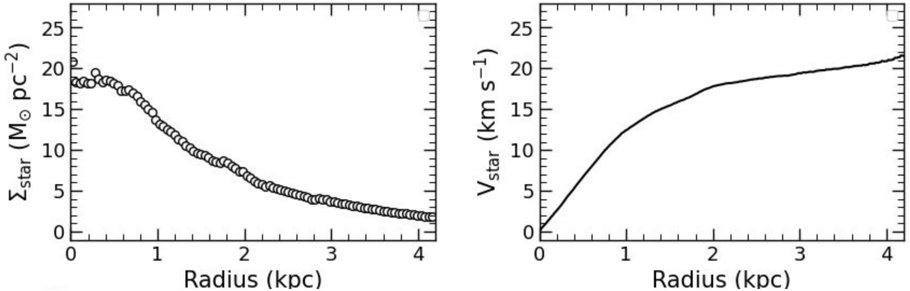




Mass models of the stellar and gaseous components

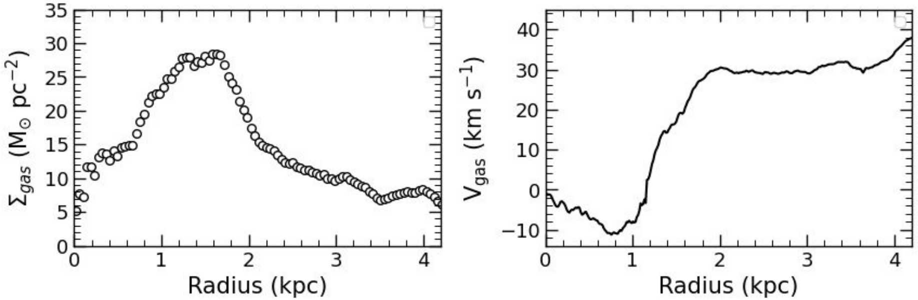
Stellar contribution

- ➔ Stellar surface mass density derived from the 3.6 micron surface brightness profile using $\Upsilon_\star^{3.6}$
- ➔ $V_{\rm star}$ assuming a stellar disk with $sech^2(z)$ distribution



Gas contribution

- ➔ Gas surface mass density derived from the HI intensity map
- ➔ $V_{\rm gas}$ assuming an infinitely thin gas disk



Disk-halo decomposition

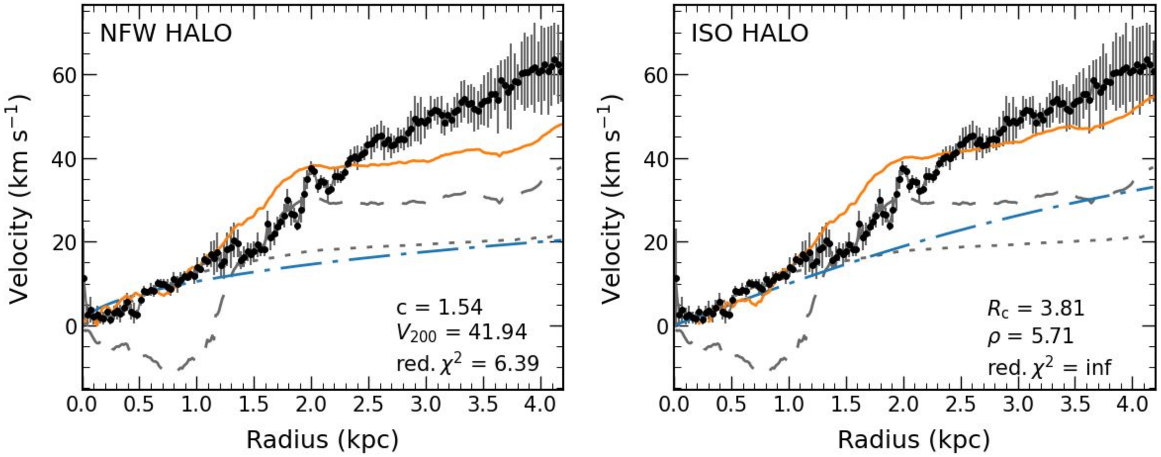
- The DM rotation curve can be derived as follows,

$$V_{\mathrm{DM}} = \sqrt{V_{\mathrm{obs}}^2 - V_{\mathrm{star}}^2 - V_{\mathrm{gas}}^2}$$

- Quantify the DM distribution by fitting two DM halo models

Navarro-Frenk-White (NFW) DM halo model (Navarro et al. 1996, 1997)	Pseudo-isothermal (ISO) DM halo model (Begeman et al. 1991)
$V_{\mathrm{NFW}}(R) = V_{200}\sqrt{\frac{\ln(1+\mathrm{cx}) - \mathrm{cx}/(1+\mathrm{cx})}{x[\ln(1+\mathrm{c}) - \mathrm{c}/(1+\mathrm{c})]}}$	$V_{\mathrm{ISO}}(R) = \sqrt{4\pi G \rho_0 R_C^2 \left[1 - \frac{R_c}{R}\,\mathrm{atan}\left(\frac{\mathrm{R}}{\mathrm{R_c}}\right)\right]}$
➔ inferred by LCDM N–body DM only simulations of galaxies	➔ used for describing observed rotation curves of galaxies

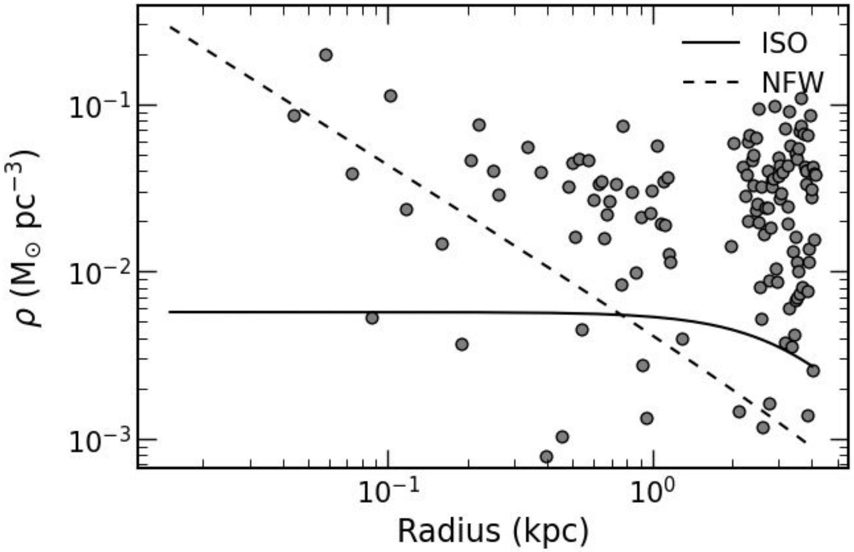
Disk-halo decomposition



Observed rotation curve: ●
Fitted rotation curve: —
DM: - — - — -
Stars: - - - - -
Gas: — —

- Both the NFW and ISO halo models do not well describe the DM rotation curve
- The fitted NFW concentration parameter c (~1) is unphysical for typical galaxies' DM halos which are predicted from the LCDM DM-only simulations.

DM density distribution in the LMC



- DM density profile assuming a spherical halo potential
- Both the NFW and ISO halo model do not well describe the DM density distribution

Mass modeling results of the LMC

- The total dynamical mass of the LMC, $M_{\rm dyn} = R_{\rm max} V_{\rm max}^2 / G$ within ~4.2 kpc
- The dynamical mass of the DM component, $M_{\rm DM} = M_{\rm dyn} - M_{\rm star} - M_{\rm gas}$

$M_{\rm star}$	$M_{\rm gas}$	$M_{\rm DM}$	$M_{\rm dyn}$
$2.89 \times 10^8 \, M_\odot$ (8 %)	$7.07 \times 10^8 \, M_\odot$ (19.9 %)	$2.56 \times 10^9 \, M_\odot$ (71.9 %)	$3.56^{+0.91}_{-0.80} \times 10^9 \, M_\odot$ (100 %)

- DM fraction of ~72 % indicates that LMC is largely DM dominated.

Summary

1. We separate turbulent non-ordered HI gas motions from the HI kinematics and produce an HI bulk velocity field which represents the global rotation of the LMC.
2. From a 2D tilted-ring analysis of the HI bulk velocity field, we derive a bulk rotation curve of the galaxy which corrects for its transverse, nutation and precession motions.
3. The dynamical contributions of baryons like stars and gaseous components which are derived using the Spitzer 3.6 micron image and the HI data are then subtracted from the total kinematics of the galaxy.
4. Both the NFW and ISO halo models do not well describe the DM distribution
5. LMC is largely DM dominated with a DM mass fraction of 72%.