Building up the Local Group: baryonic properties of MW and M31 in a CLUES simulation

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Nuza et al. (2014), MNRAS, 441, 2593 [arXiv:1403.7528]
Scannapieco et al. (2015), A&A, 577, A3 [arXiv:1503.00723]

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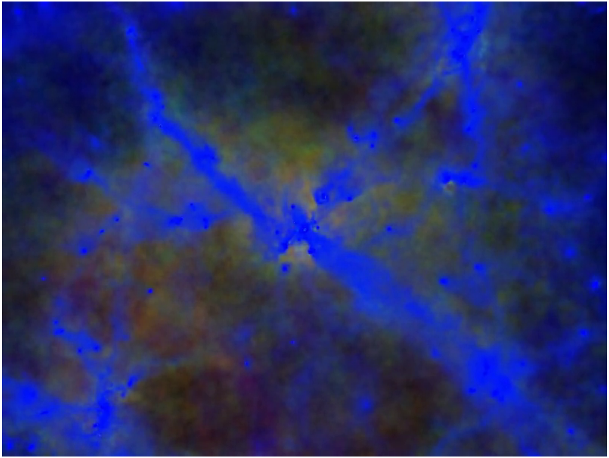
Outline

- Introduction
  - Accretion in galaxy formation
  - Gaseous haloes in Milky Way-like galaxies
- Cosmological simulations
  - CLUES project
  - Simulation code
  - Feedback mechanisms
- Gas properties (Nuza et al. 2014)
  - Gas phases
  - H I covering fractions
  - Comparison with observations
- Stellar discs (Scannapieco et al. 2015)
  - Star formation rates
  - Galaxy morphologies
  - Stellar disc fraction
- Conclusions

Introduction: Gas accretion through cosmic time

- Galaxy formation models predict the existence of quasi-spherical accretion of hot gas (*hot-mode*) and filamentary accretion of cold material penetrating inside the virial radius (*cold-mode*) supplying fresh gas for star formation

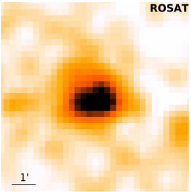
Formation of the M31 candidate



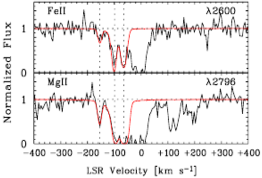
blue: cold gas; yellow/red: hot gas

Introduction: observations of galaxy gaseous haloes

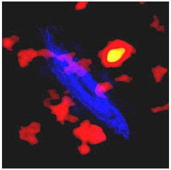
- Hot X-ray coronae surrounding some (massive) spiral galaxies (e.g. Bogdán et al. 2015)



- UV absorption features in low/intermediate and high ions reveal the existence of warm-cold and hot gas around the Milky Way respectively (e.g. Herenz et al. 2013)

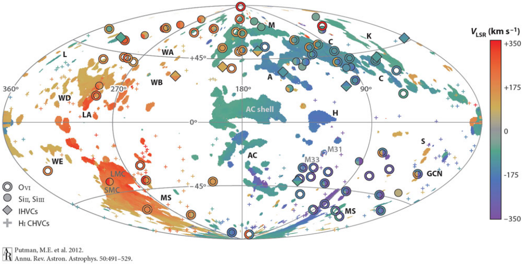


- Neutral H I clouds around Andromeda galaxy (e.g. Thilker et al. 2004)



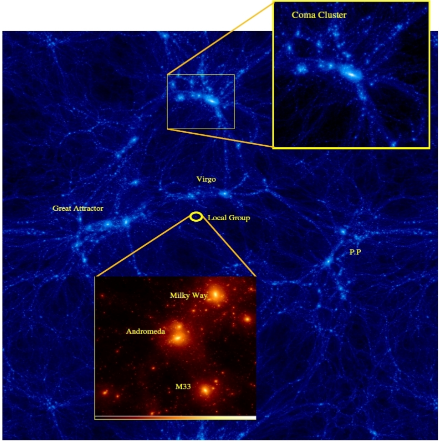
Introduction: Milky Way's gaseous halo

- Multiphase character of the circumgalactic medium within the virial radius:
  - ▷ Most of the neutral gas is located at $r \lesssim 50\,\mathrm{kpc}$ but different gas phases coexist (e.g. Richter 2012)



  - ▷ For larger distances gas is hotter ($T \sim 10^5 - 10^6$ K) and highly ionized (e.g. Lehner et al. 2014)

The Local Group in CLUES

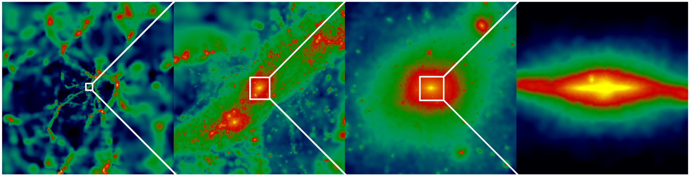


Credit: CLUES collaboration

- ▷ Simulation consistent with large-scale structure at $z = 0$
- ▷ At sub-Mpc scales the simulation is not constrained: perform random realizations to get MW and M31 halo candidates
- ▷ Halo masses, relative velocity, separation and disc orientation resembling those in the actual LG

Cosmological simulations

- Initial conditions consistent with WMAP5 cosmology
- High resolution sphere of $2\,h^{-1}\,\mathrm{Mpc}$ radius centred on the LG



- $M_{\mathrm{gas}} = 3.89 \times 10^5\,h^{-1}\,\mathrm{M}_\odot$ and $M_{\mathrm{DM}} = 1.97 \times 10^6\,h^{-1}\,\mathrm{M}_\odot$
- Simulation evolves initial condition to present time using GADGET3 (Springel et al. 2008) including extensions of Scannapieco et al. (2005, 2006) and Aumer et al. (2013)
- Include recipes for star formation, energy feedback and chemical enrichment

Feedback mechanisms

- Energetic and chemical:

  → *Supernova*: Return of chemical elements and energy to the gas

  → *Radiation pressure*: Return of energy by young stars

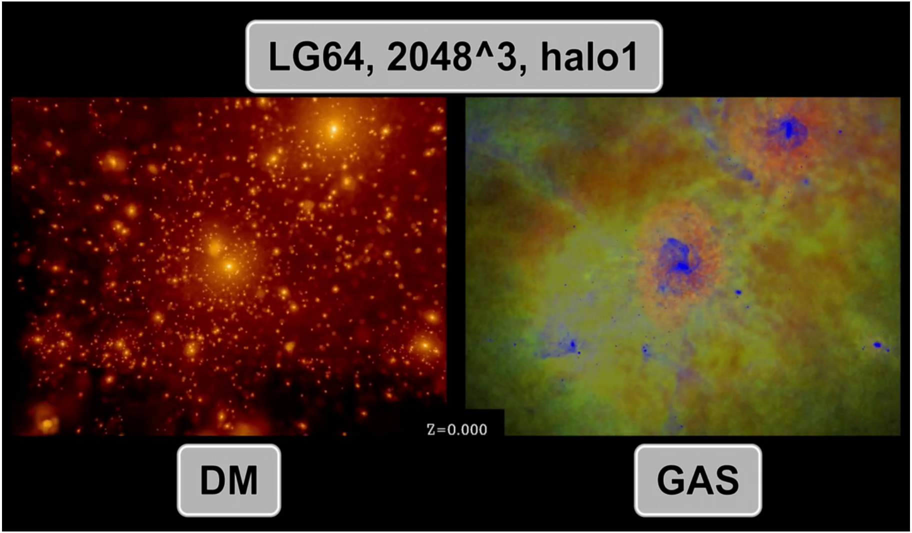
  → *Stars in AGB phase*: Return of given chemical elements

  → *AGN feedback*: Return of energy by central black hole

Still discussion on importance/relative efficiencies

▷ Note that feedback will have a larger impact in the central regions, and particularly in the stellar components

The formation of the Local Group



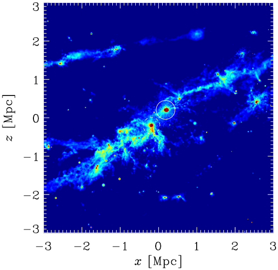
$L = 1.6\,\mathrm{Mpc}$, $3.4 < \log\ T/\mathrm{K} < 6.5$ *(blue-yellow-red)*

Gas properties

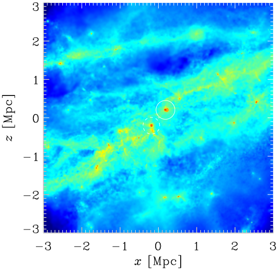
(Nuza et al. 2014)

Gas distribution in the LG

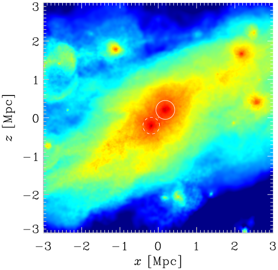
We split gas in H I, "Cold" ($T < 10^5$ K) and "Hot" ($T \geq 10^5$ K) phases



H I

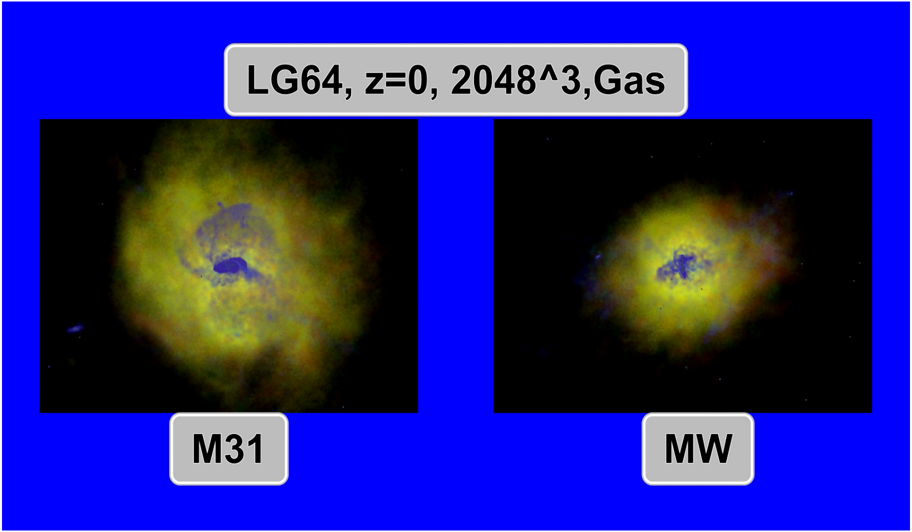


Cold

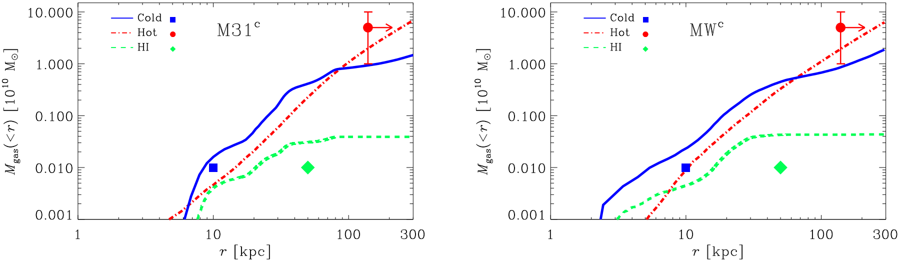


Hot

Gas distribution in M31 and MW

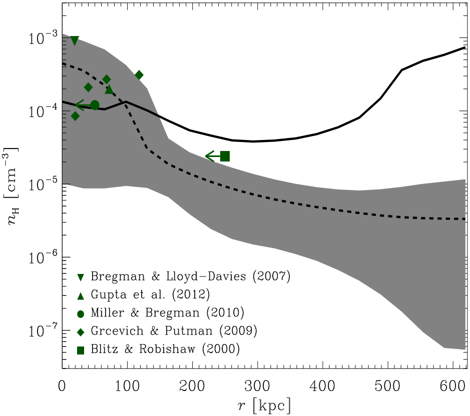


Cumulative gas mass profile for different phases



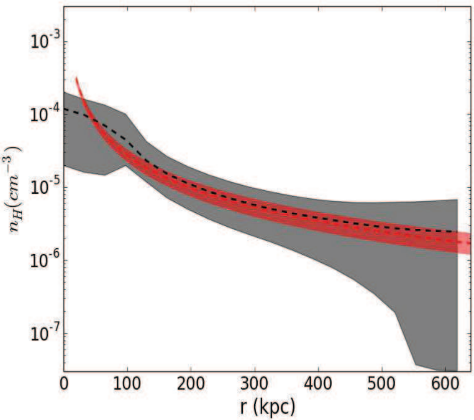
- Compare with available observations (e.g. Lehner et al. 2014)
- $M^{\rm obs}_{\rm cold}(r \lesssim 10\,{\rm kpc}) \sim 10^8\,{\rm M}_\odot$
- $M^{\rm obs}_{\rm HI}(r \lesssim 50\,{\rm kpc}) \sim 10^8\,{\rm M}_\odot$
- $M^{\rm obs}_{\rm hot}(r \lesssim R_{\rm vir}) \sim 5 \times 10^{10}\,{\rm M}_\odot$
- Amount of material in different phases similar to observed values

MW gas density profile



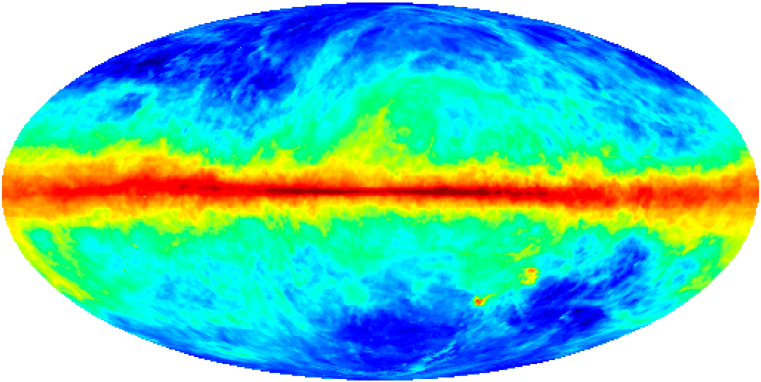
- ▷ Comparison with available Milky Way's electron density estimates
- ▷ Spherically-averaged density profile is given by the dashed line
- ▷ Typical scatter for the density profile in different directions is given by the shaded region
- ▷ MW is at the origin whereas M31 is located at $r = 652$ kpc
- ▷ Gas density excess toward M31

MW gas density profile: hot component



- At scales $r \gtrsim 50$ kpc the density profile remains unchanged as most of the material belongs to the hot phase
- Excellent agreement with the modelling of Milller & Bregman (2015) based on a sample of O VII & O VIII emission lines probing the Milky Way's halo (figure from their paper)

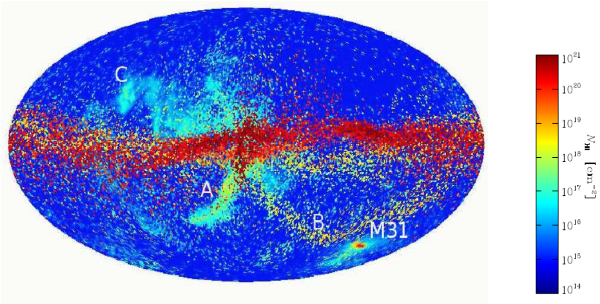
Leiden-Argentine-Bonn H I survey (Kalberla et al. 2005)



Credit: Lambda/NASA

- Simplest comparison with observations: compute covering fractions

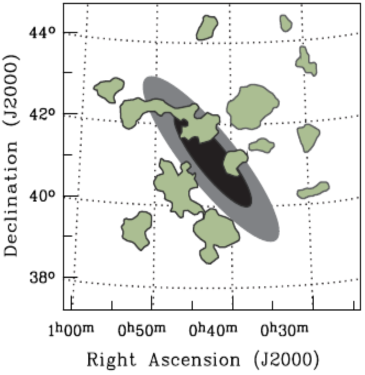
H I covering fractions: view from the MW



- Column densities: $N_{\rm HI} \gtrsim 10^{18}\,{\rm cm}^{-2}$
  - ▷ Simulated: $f_{\rm c} = 0.33$
  - ▷ Observed: $f_{\rm c} \simeq 0.3 - 0.37$ (e.g. Wakker 2004)
- Accreting neutral gas:
  - ▷ Simulated: $\dot{M}_{\rm HI}(r \leq 50\,{\rm kpc}) = 0.34\,{\rm M}_\odot\,{\rm yr}^{-1}$
  - ▷ Observed: $\dot{M}_{\rm HVC} \simeq 0.1 - 0.5\,{\rm M}_\odot\,{\rm yr}^{-1}$ (e.g. Putman et al. 2012)

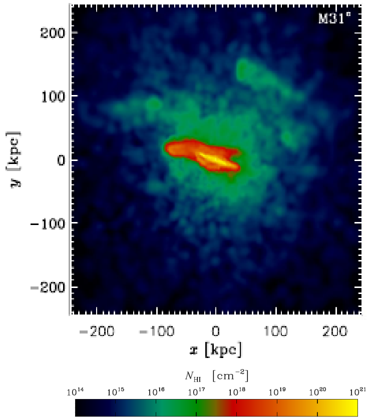
H I covering fractions: focusing on M31

Andromeda galaxy



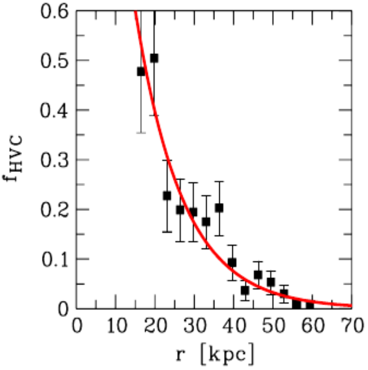
H I clouds with $N_{\rm HI} \gtrsim 5 \times 10^{17}{\rm cm}^{-2}$
(figure from Richter 2012)

M31 viewed from MW

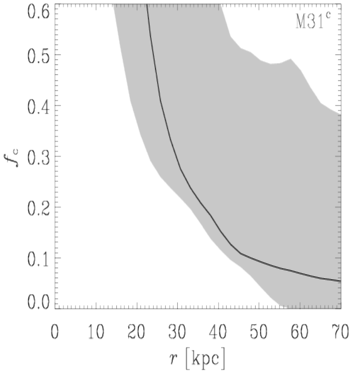


H I covering fractions: focusing on M31 (II)

Observation



Simulation



- Shaded region indicates all possible galaxy orientations
- Black solid line: M31 is seen almost edge-on

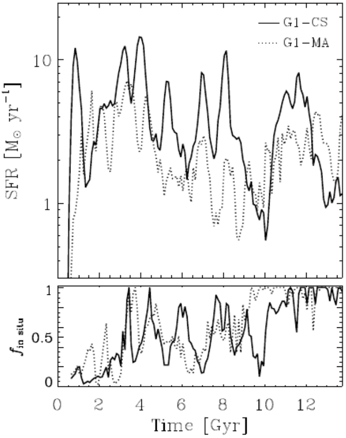
Stellar discs

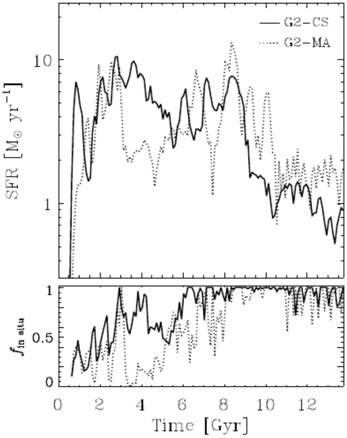
(Scannapieco et al. 2015)

Star formation through cosmic time

M31

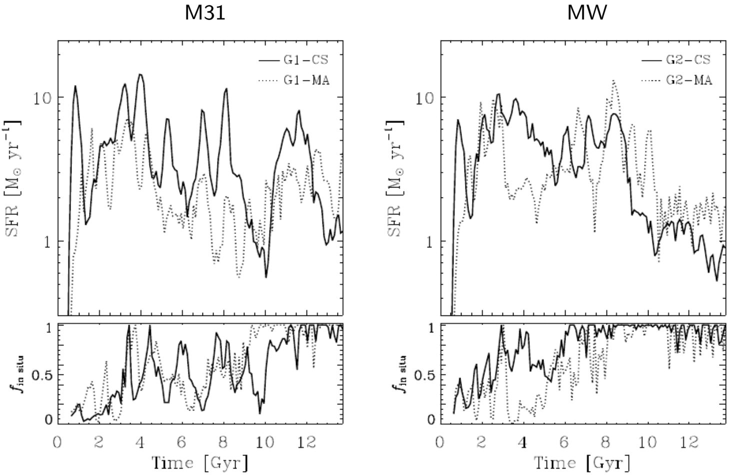
MW





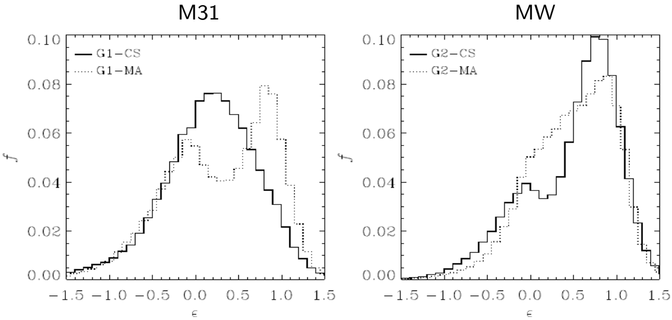
- M31 has a very bursty SFR, unlike MW that exhibits a much smoother SFR
- MW has very high in-situ fractions; in M31 these are smaller (indicative of its more active merger history)

Star formation through cosmic time



- This indicates that M31 probably ends up as a less disky galaxy than MW
- As SF process depends on feedback implementation, we run additionally a simulation with stronger feedback. Results are similar for the two simulations

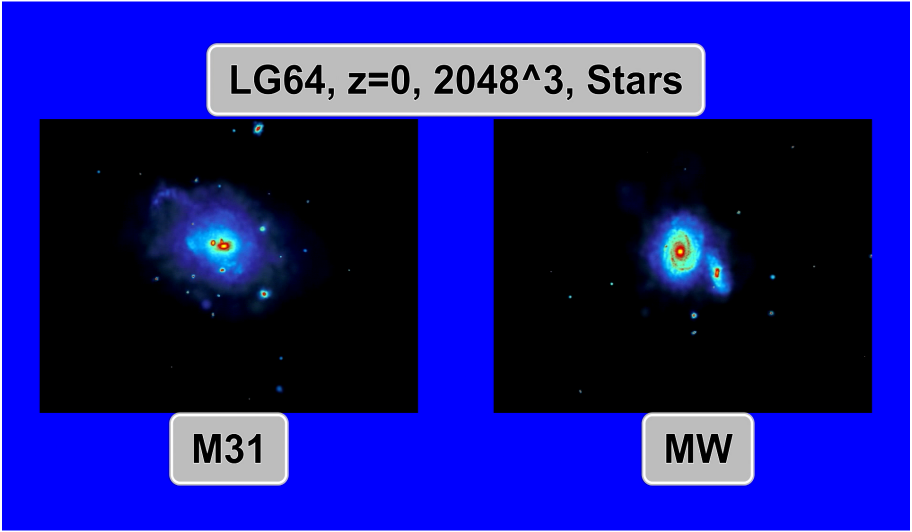
Galaxy stellar components at $z = 0$



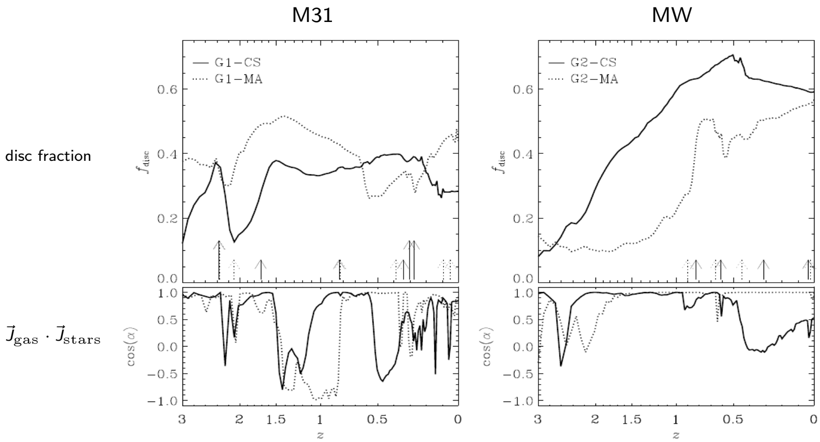
$$\epsilon_i \equiv \frac{j_{z,i}}{j_{\rm circ}(r_i)} = \begin{cases} \lesssim 0.5 & : \text{ bulge component} \\ \gtrsim 0.5 & : \text{ disc component} \end{cases}$$

- The M31 galaxy candidate has a dominant bulge
- The MW galaxy candidate has a massive, rotationally-supported disc

Stellar distribution in MW and M31

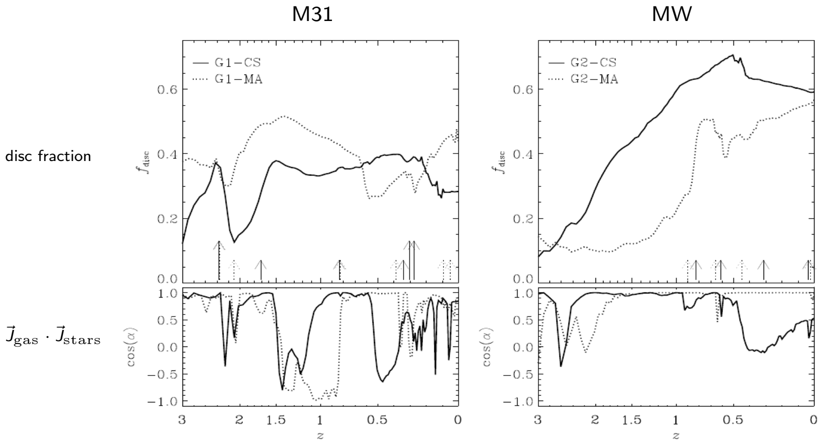


Stellar disc survival in a LG-like environment



- Mergers and misalignment between gas/stars induce disc destruction (similar results are found for isolated galaxies, Scannapieco et al. 2009)
- Merger/accretion history much more active and violent for M31 than for MW

Stellar disc survival in a LG-like environment



- M31 has two major mergers at $z < 0.5$; MW has less mergers and with lower merger ratio
- Similar results for the two models, but the MW disc forms significantly later in the stronger feedback model (i.e. including *radiation pressure*)

Conclusions

- Gas properties in the galactic haloes of our simulated LG are in reasonable agreement with observations
- In our simulation, we detect a gas density excess toward the direction of M31 owing to the presence of a gas bridge between the galaxies
- Only the simulated MW has a dominant stellar disc. In M31 a significant disc cannot develop as a result of its very active merger history, particularly at low redshift