Low-mass galaxy rotation curves that fail as dynamical mass tracers

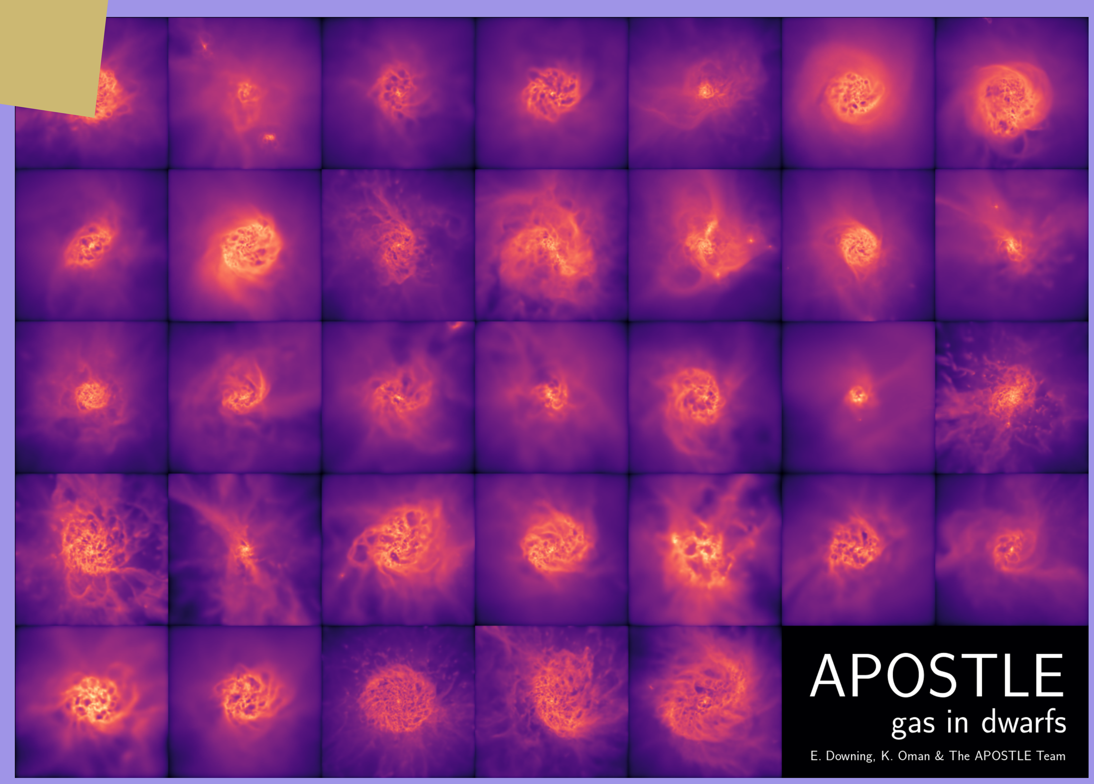
Kyle Oman & Eleanor Downing

Institute for Computational Cosmology – Durham University

arXiv: 2301.05242

Abstract

It is routinely assumed that galaxy rotation curves are equal to their circular velocity curves (modulo some corrections) such that they are good dynamical mass tracers. We took a somewhat unconventional, visualisation-driven approach to analysing 33 low-mass galaxies from the APOSTLE simulation suite exploring the limits of the validity of this assumption. Only 3 galaxies have rotation curves nearly equal to their circular velocity curves; the rest are undergoing a wide variety of dynamical perturbations. We used our visualisations to guide an assessment of how many galaxies are likely to be strongly perturbed by processes in several categories: mergers/interactions, bulk gas flows, non-spherical DM halo, warps, and IGM ram pressure. Most galaxies fall into more than one of these categories; only 5/33 are not in any of them. The sum of these effects leads to an underestimation of the low-velocity slope of the baryonic Tully-Fisher relation that is difficult to avoid, and could plausibly be the source of a significant portion of the observed diversity in low-mass galaxy rotation curve shapes.



The APOSTLE simulations

- Fully cosmological hydrodynamical zoom simulations of 12 volumes approx. 5 Mpc in diameter
- Best mass resolution of $10^4\,M_\odot$ (gas) or $10^5\,M_\odot$ (dark matter), with minimum force softening of 130 pc.
- Identical model and calibration as the EAGLE simulation project.

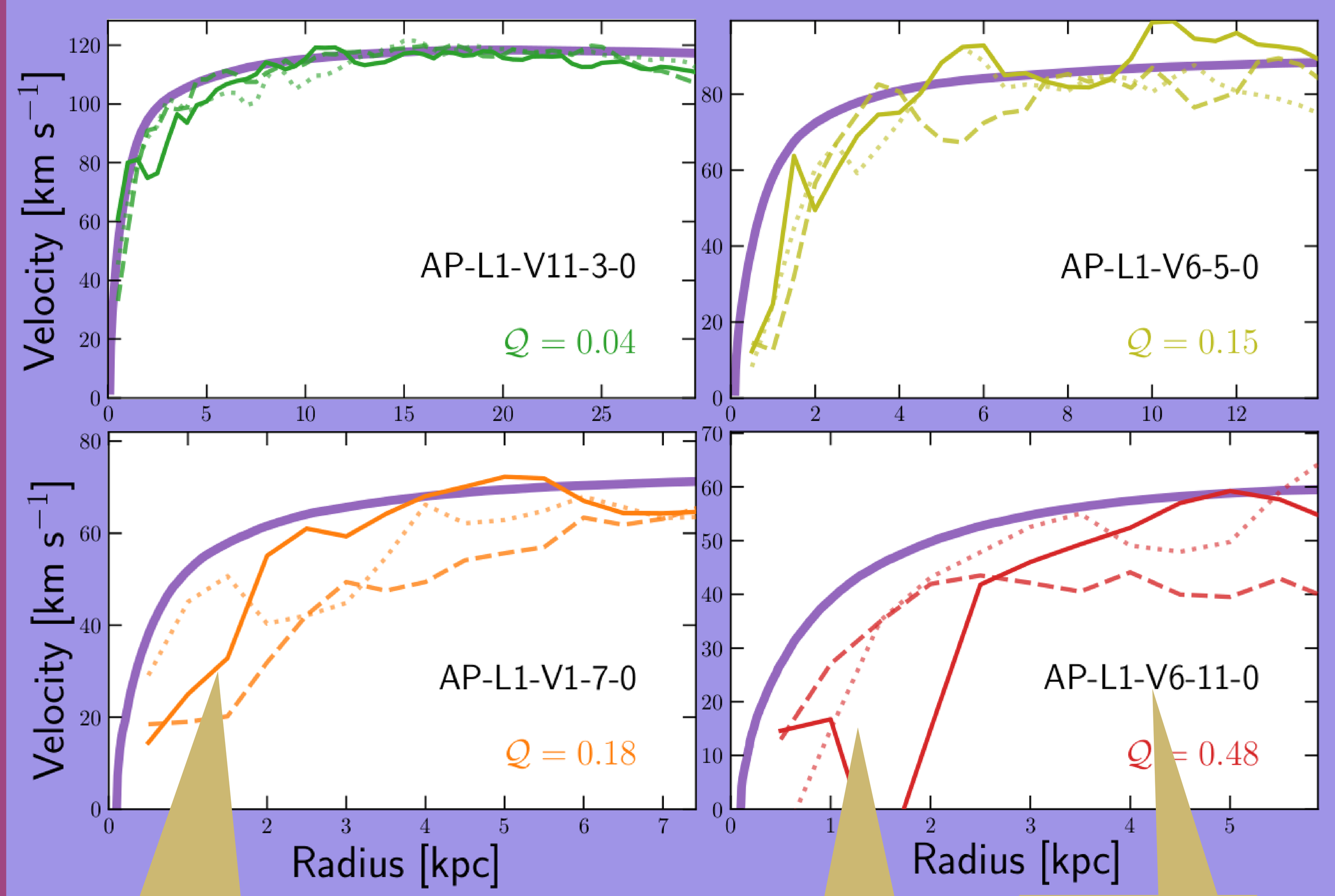
Images on this poster link to videos!

On Android+Chrome tap Share ➔ QR code ➔ Scan. On iOS use Camera app.

Rotation curves and circular velocity curves

- For every galaxy we calculated the orbital velocity expected from the potential: the circular velocity.
- We also measured the rotation curve (azimuthal velocity of the gas) at 300 Myr intervals.
- We defined a measure Q of the agreement between the rotation and circular velocity curves.
  *higher Q ➔ poorer agreement
- Galaxies were qualitatively classified excellent/good/fair/poor based on their Q.

Rotation curves for 4 example galaxies at the end of the simulation (solid lines) and 300 and 600 Myr earlier (dashed and dotted lines). The heavy purple lines show the circular velocity curves at the end of the simulation (these evolve only very slowly).



Q penalized for discrepancies between present-day rotation curve and circular velocity curve (over >25% of extent).

Q also penalised for more time-variability in rotation curve.

AP[OSTLE]
L1 – resolution level
V6 – volume identifier
11 – FOF group ID
0 – subhalo ID

Rotation curves
Solid – present day
Dashed – 300 Myr ago
Dotted – 600 Myr ago
Circular velocity curve
Heavy – present day

Quality "Q"
Green – excellent
Yellow – good
Orange – fair
Red – poor

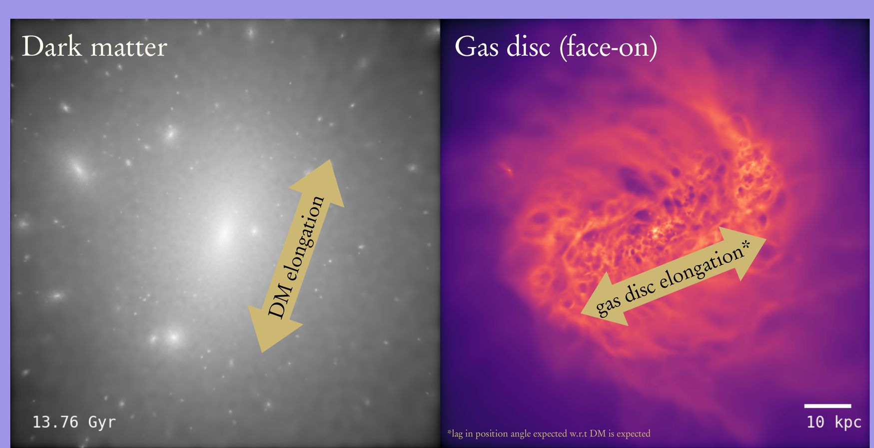
AP-L1-V11-3-0 · AP-L1-V6-5-0 · AP-L1-V1-7-0 · AP-L1-V6-11-0

Face-on (left video panel) and edge-on (right) views of the gas discs.

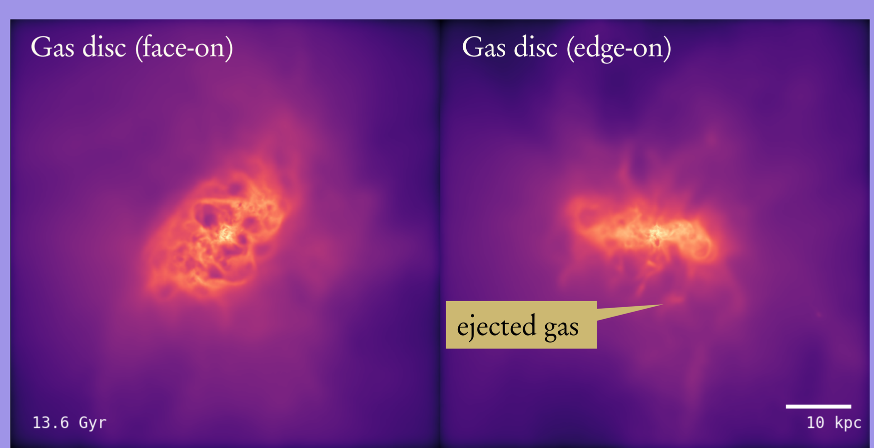
Kinematic perturbations

- For each galaxy, we made several videos visualising the gas and dark matter.
- We visually identified many features linked to perturbations of the gas disc: mergers/interactions with companions, bulk gas flows (radial and/or vertical), elongation of the DM halo, gas disc warps, and ram-pressure wind from the IGM.
- Our initial visual analysis guided a more quantitative follow-up analysis.

Face-on view of the gas disc (right), and the dark matter (left, same perspective) of galaxy AP-L1-V11-6-0. The DM halo is visibly elongated, driving transient lopsided ($m=1$ harmonic) and bisymmetric ($m=2$) deformations of the gas disc.



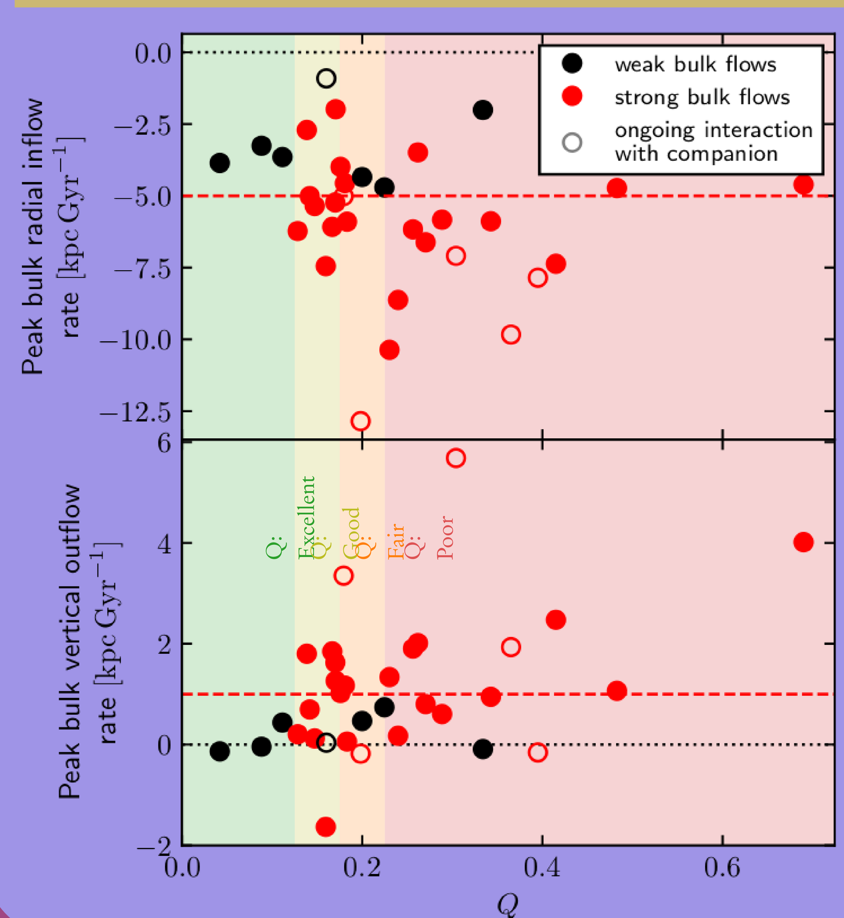
Face-on (left) and edge-on (right) views of the gas disc of galaxy AP-L1-V4-13-0. Several prominent whisps of vertically ejected gas are visible both above and below the disc in the interval from about 13.0 – 13.8 Gyr.



Bulk gas flows

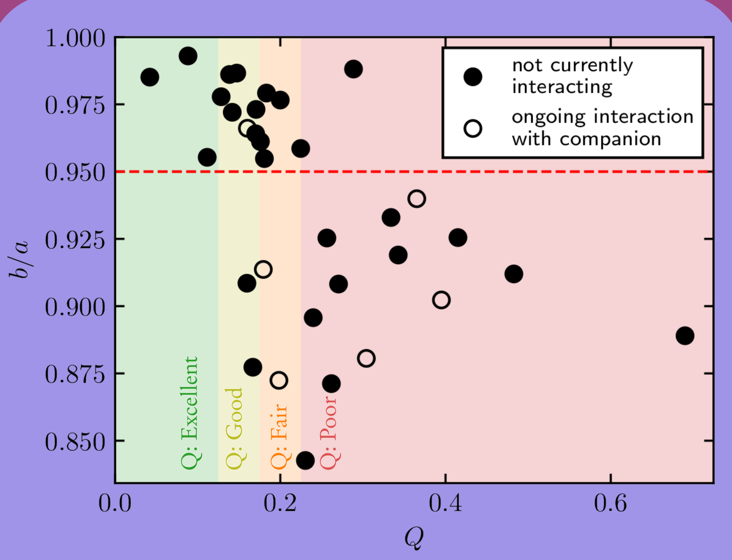
- The strength of non-circular bulk gas flows in the disc (radial or vertical) correlates with Q.
- Galaxies with strongly perturbed rotation curves tend to also have strong bulk gas flows.

Upper: Anti-correlation between peak (cylindrical) radial flow rate in the last 600 Myr of the simulation and the degree to which the rotation curve traces the circular velocity curve, Q. *Lower:* Correlation between peak vertical (out)flow rate and Q. Points which exceed a threshold for 'strong' flows (dashed line) in either panel are coloured red.



DM halo shape

- DM halo intermediate-to-major axis ratio (b/a) anti-correlates with Q.
- Even a mildly prolate or triaxial DM halo shape in the disc region ($b/a \lesssim 0.95$) can strongly perturb the gas.

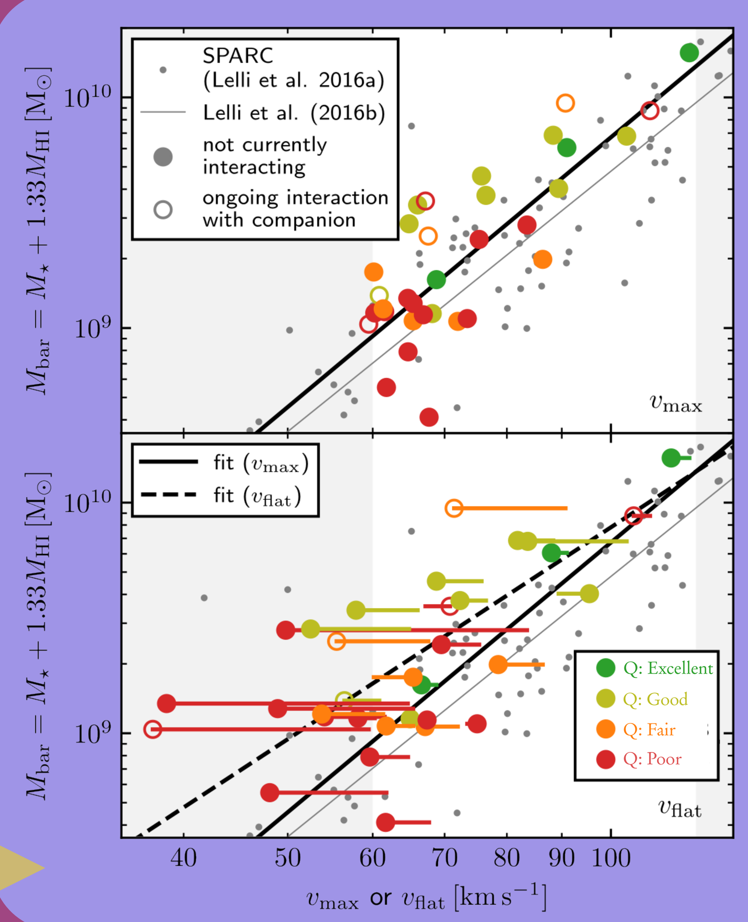


Anti-correlation between dark matter halo intermediate-to-major axis ratio b/a and the degree to which the rotation curve traces the circular velocity curve, Q.

Conclusions

- Only about 30% (12/33) of galaxies in our sample have rotation curves that trace their circular velocity curves reasonably well, and only about 10% (3/33) are close matches. Causes include:
  - megers/interactions with companions (6/33)
  - accretion-driven gas inflows (19/33)
  - supernova-driven gas outflows (15/33)
  - prolate/triaxial DM haloes (17/33)
  - gas disc warps (8/33)
  - IGM ram pressure (5/33)

  Most galaxies fall in more than one category.
- The baryonic Tully-Fisher relation and other kinematic scaling relations may suffer from severe biases.



Upper: The baryonic Tully-Fisher relation (BTFR) for our sample of low-mass galaxies where v_{max} is calculated from their circular velocity curves – the "true" BTFR, The heavy line is a fit to the filled coloured points.

Lower: The BTFR for the same sample of galaxies, but where v_{flat} is measured from their rotation curves. The points are joined to their positions in the upper panel by horizontal line segments.

The maximum gas rotation velocity (v_{flat}) systematically underestimates the maximum circular velocity (v_{max}), and the underestimates get systematically worse at lower v_{max}; this has the potential to bias both the normalisation and slope of the BTFR, as illustrated by the dashed fit line.