The CO Tully-Fisher relation of early-type galaxies

Timothy A. Davis, M. Bureau, K. Alatalo, L. Blitz, L. M. Young and the ATLAS^{3D} Team
(R. Bacon, M. Bois, F. Bournaud, R. Davies, T. de Zeeuw, J. Falcon-Barroso, H. Kuntschner, R. Morganti, T. Naab, N. Scott, T. Oosterloo, S. Khochfar, M. Sarzi, P. Serra, R. van den Bosch, G. van de Ven, G. V. Kleijn, A-M. Weijmans)

Abstract: The Tully-Fisher relation (TFR), relating the light of galaxies to their rotation velocities, has been extensively studied in gas-rich systems and provides a wealth of kinematic and stellar population information, as well as being important for the cosmic distance ladder. In gas-poor systems, such as early-type galaxies (ETGs), the relation is hard to study, requiring detailed dynamical modelling of the stellar kinematics. We demonstrate here using both single-dish and interferometric observations that CO molecules are an excellent kinematic tracer, even in high-mass galaxies, allowing us to investigate the TFR of ETGs relatively easily. We also find that the early-type TFR is offset from that of spirals by ≅1 magnitude at K band, in line with other results. Next generation facilities such as the LMT and ALMA should allow this technique to be extended to high-redshift systems, providing a new simple tool to trace the mass-to-light ratio (M/L) evolution of the most massive galaxies over cosmic time.

ATLAS^{3D}:

- Complete, volume-limited survey of all northern ETGs within 40 Mpc
- Direct follow-on from the SAURON project (de Zeeuw et al., 2002)
- Attempts to understand the nature of galaxies in the red sequence at z=0

For all 263 galaxies we have obtained:
- Optical integral-field spectroscopy (from SAURON/WHT)
- Multi-band optical photometry (from SDSS/INT)
- Integrated CO(1-0) and CO(2-1) spectra (from IRAM-30m)
- Interferometric HI line-imaging (from WSRT; DEC>10 deg only)
- Interferometric CO(1-0) line-imaging (CARMA; CO detections only)

The Tully-Fisher relation of early-type galaxies:

- The TFR gives clues about galaxy mass assembly history and evolution
  -> E.g. are S0 galaxies faded high-redshift spirals? If so, would be dimmer, for the same dynamical mass -> offset TFR
- Studying the TFR in ETGs is problematic, often no extended/relaxed HI
  -> Stellar tracers of galactic rotation are generally used
  PROBLEM! Stellar kinematics challenging (need high S/N at large radii)
  PROBLEM! Pressure support important; stellar dynamical modeling or asymmetric drift correction required
- Recent work: S0s offset from spirals by around 0.5 - 1 mag at K-band (e.g. Bedregal et al. 2006; Williams et al. 2010,)

CO as a kinematic tracer:

- In this work we use CO as tracer of the circular velocity of ETGs
  -> Usually found in relaxed, centrally concentrated structures
  -> Present in approximately 23% of ETGs (Young et al. 2010)
- Detection rate independent of galaxy luminosity and environment
  -> Direct probe of the potential in HI-poor high-mass galaxies

Potential pitfalls:

- Molecular gas may not reach flat part of the rotation curve:
  -> Profile shape! Doubled-horned galaxies should reach V_{flat}
  -> Confirmed by models (see Figure 1)
- CO often misaligned w.r.t. stars - need reliable (gas-based) inclination measures!
  -> Compare inclinations from:
  - Stellar axial ratios
  - Dust fits
  - Tilted-ring fits

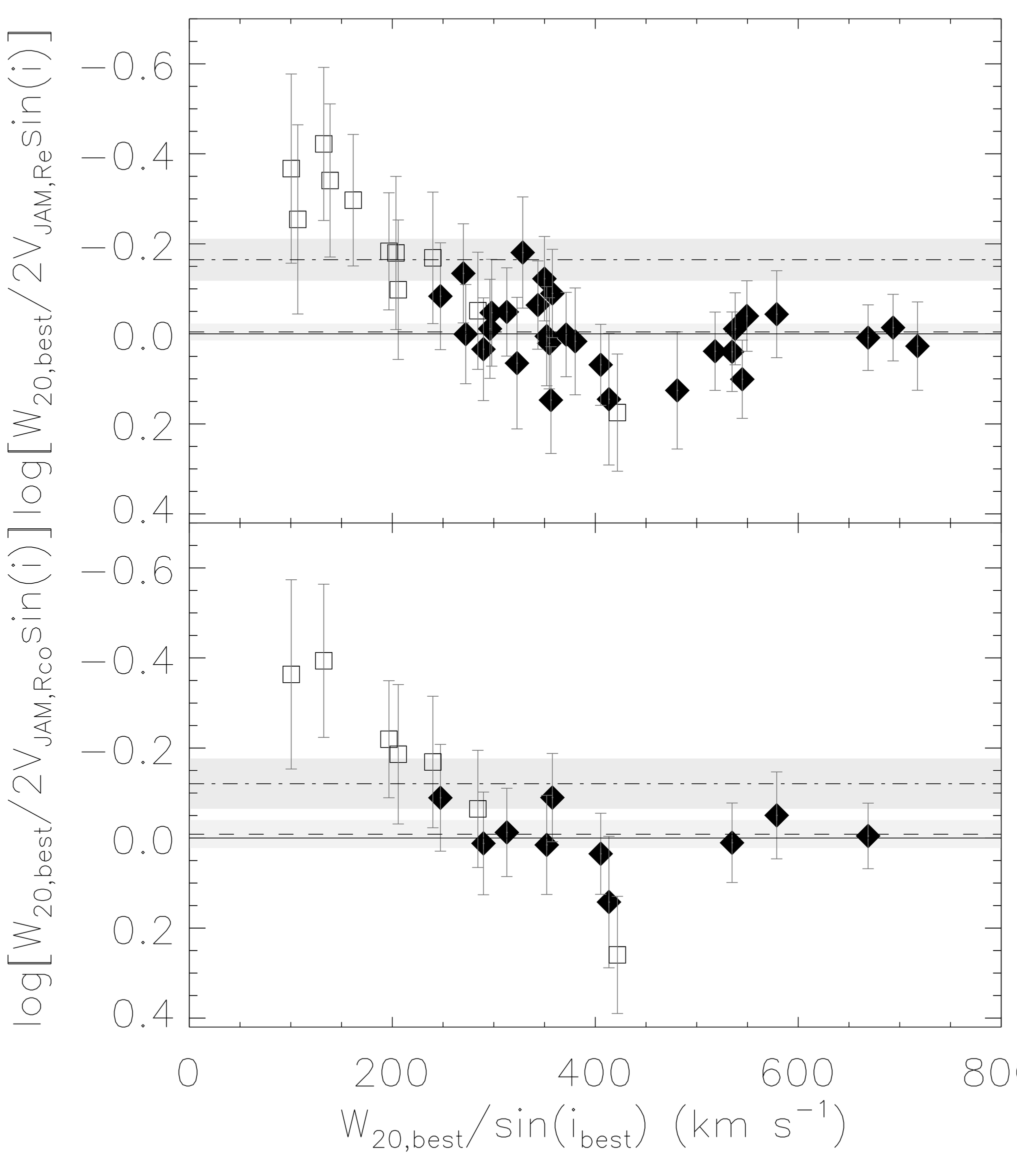


Figure 1: Differences between de-projected CO linewidths and twice the model circular velocities, measured at one effective radius (top) and the radius of maximum CO extent (bottom), plotted against the deprojected CO velocities. Galaxies with double-horned CO profiles are plotted as filled diamonds, others as squares. The solid line is a guide where the model and CO velocities are identical. The dashed and dot-dashed lines are least squares fit offsets from zero for the double-horned galaxies and the other galaxies, respectively. The errors on the fits are indicated as shaded regions around the best fit lines.

CO Tully-Fisher relations:

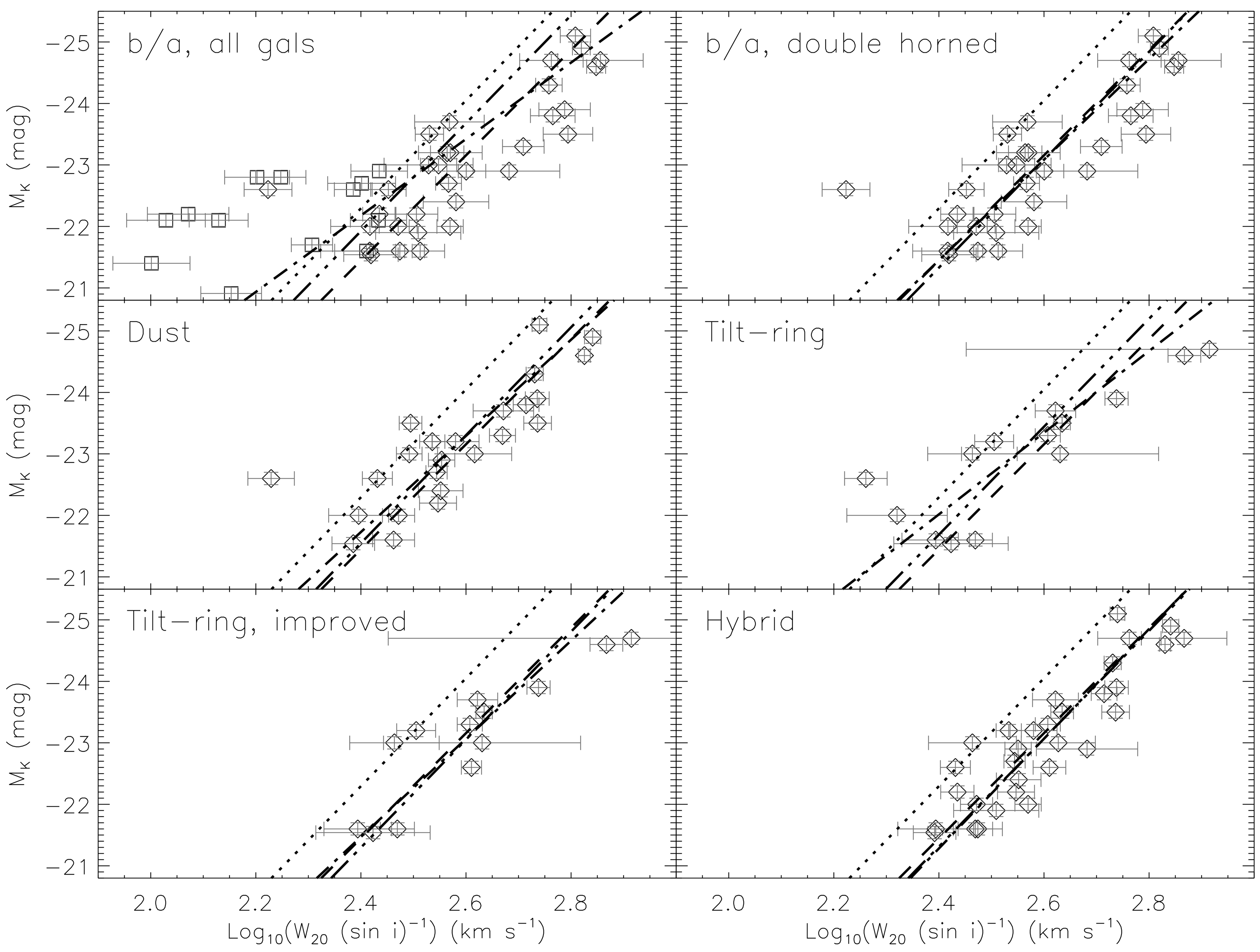


Figure 2: CO TFRs constructed using various velocity and inclination measures. The correlations shown in each plot are the spiral TFR of Tully (2000) and the S0 TFR of Williams et al. (2010). Also plotted are the best-fit relations to our own data, both for an unconstrained fit (dot-dashed) and a fit where the gradient is fixed to that found by Tully (2000) (triple dot-dashed). The inclination method used is indicated in the top-left of each panel. CO detections with double-horned profiles are shown as diamonds, all other galaxies as squares. Panels 1, 2, 3 and 4 use single-dish velocity measures, while 5 uses interferometric data. The hybrid relation in panel 6 uses the best velocity and inclination measures available. The best-fit relations agree well with that of Williams et al. (2010).

Conclusions:

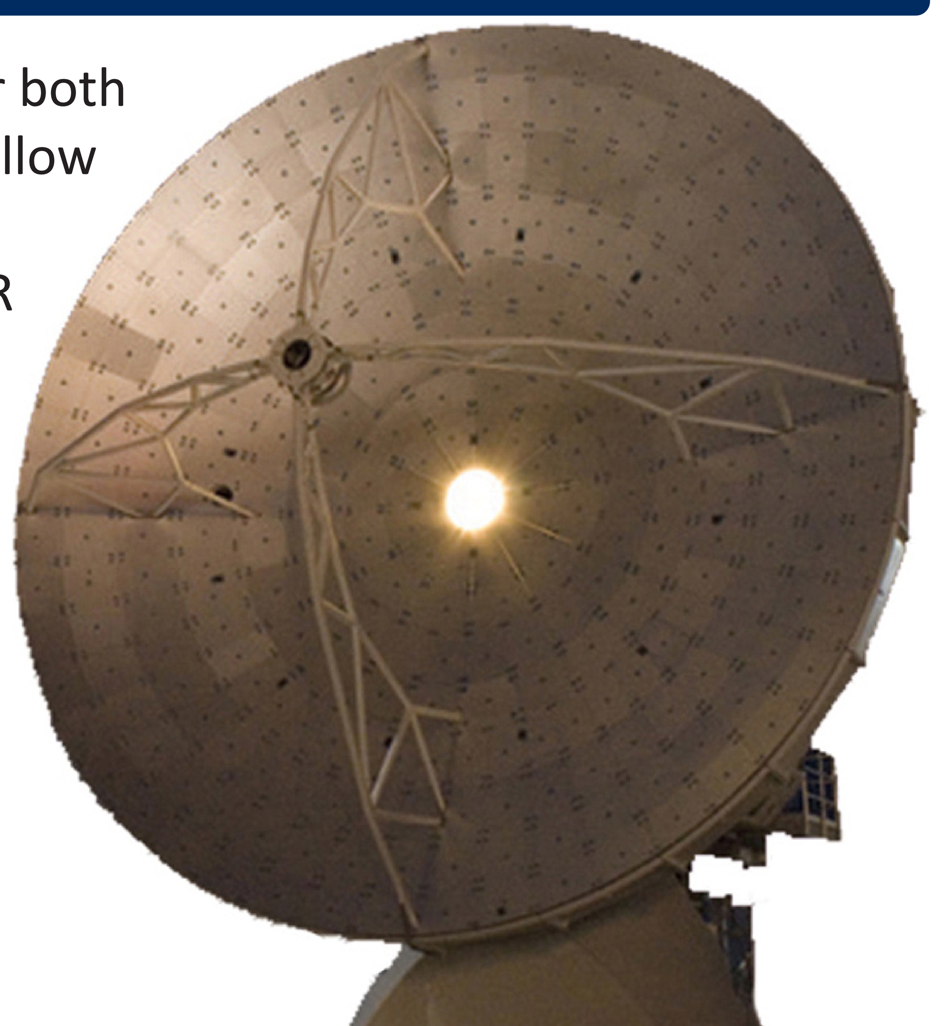
- A reliable early-type TFR is easily obtained from CO single-dish and/or interferometric observations
- Relation tightens when using inclinations measures that accurately trace the molecular component (e.g. dust, CO tilted-ring fits)
- CO TFRs are consistent with that found by Williams et al. (2010) for S0s:

$$\mathrm{M_K} = (-8.83 \pm 0.78)[\log_{10}(\frac{\mathrm{W_{20}}}{\mathrm{km\ s^{-1}}}) - 2.6) - (23.06 \pm 0.09)$$

- Intrinsic scatter for hybrid TFR is 0.4 mag, similar to that found for spirals
- Crucially, CO allows to probe the morphological evolution of the TFR using the same tracer for spiral and ETGs (identical systematics)
- Early-type CO TFR offset from that of spirals by 1.12 ± 0.12 mag, consisent with previous work but larger than Williams et al. (2010)

Future prospects:

- Large samples of CO linewidths for both spiral and early-type galaxies will allow further investigation of the morphological evolution of the TFR
- Future facilities (e.g. ALMA and LMT) will allow us to extend this work to high redshift and probe the M/L evolution of galaxies over cosmic time
- [CII] emission may be a useful kinematic tracer that can be used to study the TFR at high redshift



References: Bedregal et al., 2006, MNRAS, 373, 1125; Williams et al., 2010, MNRAS, submitted
Young et al., 2010, in preparation; de Zeeuw et al., 2002, MNRAS, 329, 513

Oxford Physics