Falling outer rotation curves of star-forming galaxies at $0.6 < z < 2.6$ probed with KMOS$^3$D and SINS/zC-SINF

Philipp Lang

Natascha Förster Schreiber, Reinhard Genzel, Stijn Wuyts, Emily Wisnioski, Andreas Burkert, Dieter Lutz, Linda Tacconi

& KMOS$^3$D + SINS/zC-SINF - Teams
Individual rotation curves (RCs) of massive disks at $z \sim 1 - 2.5$

Genzel et al. 2017

Common outer fall-off of RCs hinting at a strong imprint of baryons
Typical rotation curves for high-z SFGs

Stacking needed to infer typical RC-shapes at $z = 1-3$!
### Extracted RCs

PV diagrams

- Position
- Velocity / $\lambda$

- $V_{\text{max}}$, $R_{\text{max}}$
- Velocity direction ($V/V_{\text{max}}$)
- $H\alpha$ surface brightness

Normalisation
- radial direction ($R/R_{\text{max}}$)
- velocity direction ($V/V_{\text{max}}$)
- $H\alpha$ surface brightness

KMOS@5, ESO Garching, December 4th 2018

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Selection for stacked sample

- rotation-dominated disks
- robust measurement of $V_{\text{max}}$, $R_{\text{max}}$
- no major interactions

Skelton et al. 2014, Whitaker et al. 2014, van der Wel et al. 2012, 2014

P. Lang et al. 2017
Galaxy stacking sample

Selection for stacked sample

- rotation-dominated disks
- robust measurement of $V_{\text{max}}, R_{\text{max}}$
- no major interactions

Final stacked sample: 92 KMOS$^{3\text{D}}$ + 9 SINS/zC-SINF

$0.6 < z < 2.6 \ (\langle z \rangle = 1.5)$

$9.3 < \log M_\star < 11.5 \ (\langle \log M_\star \rangle : 10.6)$

$\langle R_e \rangle: 4.6 \ kpc \ , \langle n \rangle = 1.1$

P. Lang et al. 2017
Skelton et al. 2014, Whitaker et al. 2014, van der Wel et al. 2012, 2014
Resulting stack

Stacked PV

Stacked normalized rotation curve

P. Lang et al. 2017
Resulting stacked RC

$R/R_e$

$V/V_{\text{max}}$

Stack
Zc400569
Zc406690
D3a15504

effective number of galaxies contributing

$R/R_{\text{turnover}}$

P. Lang et al. 2017

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Resulting stacked RC

\[ \frac{V}{V_{\text{max}}} \]

\[ R/R_\odot \]

- Stack
- Zc400569
- Zc406690
- D3a15504

\[ \langle V_{\text{rot}}/\sigma_0 \rangle \]

\[ \langle z \rangle \]

\[ \langle z \rangle \]

\[ R/R_{\text{turnover}} \]

P. Lang et al. 2017

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An independent calibration of $R_{\text{max}}$

**CANDELS H-band**
**HST/WFC3 Imaging**

van der Wel et al. 2012, 2014; Lang et al. 2014, Wuyts et al. 2016

Information on $R_e$ & $n$ for stellar distribution
An independent calibration of $R_{\text{max}}$

**CANDELS H-band HST/WFC3 Imaging**

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Exponential disk models

Information on $R_e$ & $n$ for stellar distribution

**Intrinsic, $R_e = 4$ kpc**

**observed**

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An independent calibration of $R_{\text{max}}$

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**Exponential disk models**

- observed, $R_e = 4\text{kpc}$
- observed, $R_e = 2\text{kpc}$
- observed, $R_e = 6\text{kpc}$

Information on $R_e$ & $n$ for stellar distribution

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Information on $R_e$ & $n$ for stellar distribution

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**Exponential disk models**

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- $\text{observed, } R_e = 6 \text{kpc}$
An independent calibration of $R_{\text{max}}$

**CANDELS H-band HST/WFC3 Imaging**

van der Wel et al. 2012, 2014; Lang et al. 2014; Wuyts et al. 2016

![Images of CANDELS H-band HST/WFC3 Imaging](COS3_04798 COS3_16954 COS4_06497 COS3_14411)

Information on $R_e$ & $n$ for stellar distribution

**Exponential disk models**

\[ \frac{V}{V_{\text{max}}} = \begin{cases} 
1 & \text{for } R < R_e \\
\exp\left(-\frac{R}{R_e}\right) & \text{for } R \geq R_e 
\end{cases} \]

Relation $R_e \rightarrow \text{`Observed` } R_{\text{max}}$
An independent calibration of $R_{\text{max}}$

**CANDELS H-band HST/WFC3 Imaging**

van der Wel et al. 2012, 2014; Lang et al. 2014, Wuyts et al. 2016

Comparison w/ $R_{\text{max}}$ measured on RCs

Information on $R_e$ & $n$ for stellar distribution

Relation $R_e$ --> ‘Observed‘ $R_{\text{max}}$
Fall-off independent of normalization

\[ \frac{V}{V_{\text{max}}} \]

\[ R_{\text{max}} \text{ from } R_{\text{e}} \]

\[ R_{\text{max}} \text{ from RCs} \]

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Comparison with baryonic + DM models

**Exponential baryonic disk** (Noordermeer 2008)

Set: $h_z/r_d = 0.2$  \[ R_e = 4.6 \text{ kpc} \quad \log(M_{\text{disk}}) = 11.0 \]
Comparison with baryonic + DM models

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**Dark Matter: NFW Halo** (Navarro et al. 1997)

\[
\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right) \left(1 + \frac{r}{r_s}\right)^2}
\]

\[
m_d = \frac{M_{\text{disk}}}{M_{200}} \quad c = \frac{r_{200}}{r_s}
\]

- \( m_d \sim 0.03 \) low-z disks \( \text{(Moster+13)} \) \( \Rightarrow \) \( f_{\text{DM}} (\leq R_e) \sim 50\% \)
- \( m_d \sim 0.05 \) high-z disks \( \text{(Burkert+16)} \) \( \Rightarrow \) \( f_{\text{DM}} (\leq R_e) \sim 25\% \)
- \( m_d \sim 0.17 \) cosmic \( = \Omega_{\text{bar}}/\Omega_{\text{DM}} \) \( \Rightarrow \) \( f_{\text{DM}} (\leq R_e) \sim 15\% \)
**Comparison with baryonic + DM models**

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**Pressure support in the disk:**

\[ V_{\text{rot}}(R)^2 = V_{\text{circ}}(R)^2 - 2\sigma^2 (R/R_d) \]

\[ 4.8 < V_{\text{rot}}/\sigma < 6.3 \]
**Comparison with baryonic + DM models**

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V_{\text{rot}}(R)^2 = V_{\text{circ}}(R)^2 - 2\sigma^2 (R/R_d)
\]

\( 4.8 < V_{\text{rot}}/\sigma < 6.3 \) \( \Rightarrow \) high baryon fraction \( (m_d \geq 0.05, f_{\text{dm}} < 25\%) \) + pressure support needed to explain fall-off!
Low vs. high V/σ galaxies

Pressure support in the disk:

\[ V_{rot}(R)^2 = V_{circ}(R)^2 - 2\sigma^2 (R/R_d) \]
Secondary dependencies in modeling

- Concentration of DM halo
- Adiabatic contraction of DM halo
- Central bulge mass fractions
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- Concentration of DM halo
- Adiabatic contraction of DM halo
- Central bulge mass fractions

Models predict fall-off independent of those assumptions!

P. Lang et al. 2017
Through stacking we can construct a **representative RC** reaching out to $\sim 2.5 R_{\text{max}} (\cong 4 Re , 6.5 Rd)$ with a **significant outer fall-off**, independent of method for normalization.

- **RC** consistent with **high baryon fraction** ($m_d \sim 0.17$, $f_{\text{DM}} (\leq R_e) \sim 15\%$) in combination with **pressure support** in the outer disk ($V_{\text{rot}}/\sigma_0 \sim 6.3$).

- Fall-off expected largely **independent** on DM halo concentration, adiabatic contraction and bulge fraction.