The Assembly of Disk Galaxies: From Keck to JWST

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- SIGMA survey of galaxy kinematics at $z=2$
- Mock observations of galaxy simulations
When/how are disks assembled?

When/how do disks settle into their current well-ordered state?
It is important to take into account the effects of seeing and beam smearing when measuring galaxy kinematics.

Weiner et al. 2006a,b; Kassin et al. 2007,12; Covington, Kassin et al. 2010; Simons, Kassin et al. 2016
Measurements of the kinematics of high z galaxies tell us about their physical state.

\[ V_{rot} \text{ dominated} \quad \text{mixed} \quad \sigma \text{ dominated} \]

\[ z \sim 1 \text{ HST} \]

\[ V_{rot} \sin{i} = 208 \text{ km/s} \]
\[ \sigma_{\text{gas}} = 40 \text{ km/s} \]
\[ 75 \text{ km/s} \]
\[ 55 \text{ km/s} \]
\[ 29 \text{ km/s} \]
\[ 59 \text{ km/s} \]

\( \sigma \) is a gas velocity dispersion

- integrates over all velocity gradients beneath the seeing
- quantifies the amount of disordered motions in galaxies (Weiner et al. 06, Kassin et al. 2007, Covington, Kassin et al. 2010, Kassin et al. 14)
- Does not indicate a “thick disk” (i.e., a disk that is simply puffier)
Kassin et al. 2007, 12

\[ S_{0.5} = \sqrt{0.5V_{rot}^2 + \sigma_{\text{gas}}^2} \]

\( S_{0.5} \) takes into account all the motions, not just rotation.

\( S_{0.5}^2 \sim \text{total mass} \) (see also Covington et al. 2010)

Stellar Mass Tully-Fisher Relation to \( z=1.2 \)

coincident with Faber-Jackson

\( S_{0.5} \) takes into account all the motions, not just rotation.
Tully-Fisher Relation at z~0.2

Ordered disks lie on ridge-line, Disturbed galaxies lie off
“Mass of Disk Formation”

Simons, Kasson et al. 2015 et al.; see also Bloom et al. 2017
High-z Galaxies are Mostly Peculiars
Still, more Ordered disks lie on ridge-line & more Disturbed galaxies lie off

Tully-Fisher Relation at z~1.0

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Does the relative importance of $V_{rot}$ and $\sigma$ evolve with time?
"Disk Settling"

\[
\log \sigma = -0.84 \left(1+z\right)^{-1} + 2.04
\]

Kassn et al. 12
Simons, Kassin et al. 2016 & 17
\(\sigma\) trend see also Wisnioski et al. 15, Turner et al. 2017
Linking galaxy populations in time with "abundance matching"

(our best shot, but far from perfect)
"Disk Settling"

Abundance matched galaxy populations
(Moster et al. 2013)

Kassn et al. 2012
Simons, Kassn et al. 2017
How does the fraction of disk galaxies evolve?

- \( \frac{V_{\text{rot}}}{\sigma} \sim 10 \)  
  local massive disks  
  like the one shown

- \( \frac{V_{\text{rot}}}{\sigma} > 3 \)  
  analog of local low mass disks

- \( \frac{V_{\text{rot}}}{\sigma} > 1 \)  
  rotation supported

NGC 4388, credit: ESA/Hubble & NASA
Fraction of galaxies with $V_{\text{rot}}/\sigma > 1$ increases with time.

"Disk Settling"

- $10^{10} - 10^{11} M_\odot$
- $10^{9.5} - 10^{10.5} M_\odot$
- $10^{9} - 10^{10} M_\odot$
Large IFU surveys of galaxy kinematics

$z \sim 3$:
- AMAZE/LSD: Gnerucci et al. 2011
- KDS: Turner et al. 2017

$z \sim 2$:
- KMOS$^{3D}$: e.g., Wisnioski et al. 2015
- SINS: e.g., Förster-Schreiber et al. 2006, 9, 11

$z \sim 1$:
- MASSIV: e.g., Epinat et al. 2012
- KROSS: e.g., Madgis et al. 2016, Harrison et al. 2017
- KMOS$^{3D}$: e.g., Wisnioski et al. 2015

$z<1$:
- IMAGES: e.g., Flores et al. 2006, Yang et al. 2008, Puech et al. 2008
Quantitatively, surveys agree that disks become more ordered with time.

Kassin et al. 12; Simons, Kassin et al. 2016 & 17

Redshift

fraction of galaxies with \( V/\sigma > 1 \)

\( 10^{10} - 10^{11} M_\odot \)
\( 10^{9.5} - 10^{10.5} M_\odot \)
\( 10^{9} - 10^{10} M_\odot \)

KMOs-3D
IMAGES
KROSS
MASSIV
KDS
AMAZE
Only ~30% of high mass galaxies at z=2 have V/σ > 3!

Kassin et al. 12; Simons, Kassin et al. 2016 & 17
$V_{\text{rot}}$ can be confused with orbital rotation of mergers in ground-based observations

$\Rightarrow$ Fraction of disks at $z \sim 2$ defined using $V/\sigma$ is likely even lower

VELA simulation
(Ceverino et al. 2014, 16)

Simons, Kassin, Snyder, Ceverino+ in prep
Conclusions:
• the vast majority of galaxies at high redshift are not disks

• galaxies increase in ordered rotation ($V_{\text{rot}}$) and decrease in disordered motions ($\sigma$) with time

• the average fraction of disk galaxies increases significantly with time

• higher mass galaxies arrive at an ordered state first ("kinematic downsizing")

• conclusions from high-z kinematic surveys depend on sample selections for mass and morphology