Rapidly spinning gas disks observed towards massive z~4.5 red sequence progenitors

Alexander Karim (AIfA Bonn/EU ARC Network)

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Team Copenhagen: S. Toft, C. Gomez-Guijarro, G. Magdis
Team Socorro: C. Carilli, G. Jones
Others: Fraternali, Smolcic, Schinnerer, Capak, Riechers, Aravena, Sheth, Sargent, Swinbank, Smail, Koekemoer, van Kampen, Staguhn
How to form the first massive galaxies?

Toft et al. (2014): \( z > 3 \) SMGs as progenitors of \( > 10^{11} \) M\(_{\odot} \) compact \( z \sim 2 \) quiescent galaxies

- Space densities of populations consistent if mean duty cycle of bursts < 100 Myr
- Roughly half the Toft et al. (2014) SMG-sample at \( z > 4 \) (\([\text{CII}]158\mu\text{m} \) redshifted into ALMA's band-7)

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Evidence for a $z>4$ SMG population

See also Weiß et al. (2013); Note: Some found among optical dropouts with radio counterpart

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z>4 field sample in central COSMOS
Mix of morphologies, mostly IRAC & radio-detected, flat/red in SPIRE (Smolcic, AK+ 2015)

- Massive (~5x10^{10}-2x10^{11} M_{\text{Sun}}) Ultra/High-LIRGs > generally starbursts
- Covering top OR bottom end of sub-mm deep field selection function

<table>
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<tr>
<th>Name</th>
<th>$t_{\text{form}}$ [Myr]</th>
<th>$\tau_{\nu}$ [mag]</th>
<th>$M_*$ [M_{\odot}]</th>
<th>$L_{\text{dust}}$ [L_{\odot}]</th>
<th>$M_{\text{dust}}$ [M_{\odot}]</th>
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<tr>
<td>AzTEC1</td>
<td>199</td>
<td>2.897</td>
<td>7.4x10^{10}</td>
<td>2.2x10^{13}</td>
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<td>AzTEC/C159</td>
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<td>1.1x10^{11}</td>
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<td>J1000+0234</td>
<td>149</td>
<td>31.644</td>
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<td>9.1x10^{8}</td>
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<td>AK03-N*</td>
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<table>
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<tr>
<th>$S_{100\mu m}$ [mJy]</th>
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<th>$S_{250\mu m}$ [mJy]</th>
<th>$S_{350\mu m}$ [mJy]</th>
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<td>&lt; 6.8</td>
<td>&lt; 13.6</td>
<td>19.5 ± 6.0</td>
<td>29.8 ± 7.6</td>
<td>28.8 ± 9.0</td>
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<td>&lt; 13.6</td>
<td>22.3 ± 7.1</td>
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<td>12.3 ± 2.4</td>
<td>13.0 ± 3.7</td>
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<tr>
<td>&lt; 6.8</td>
<td>&lt; 13.6</td>
<td>&lt; 8.0</td>
<td>&lt; 12.0</td>
<td>&lt; 20.0</td>
</tr>
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</table>

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Concerted follow-up: total mass & distribution and conditions of gas/dust/stars (PI: AK)

Results in the following for 3 of our z>4 objects with [CII]158um line detections (papers being drafted)

- Distribution of young stellar populations.  
  **C. Gómez-Guijarro**+

- Gas/dust distribution and kinematics.  
  **A. Karim**+

- Molecular gas properties  
  **E.F. Jiménez-Andrade**+

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**See Poster #22!**

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**Alex Karim** (AIIfA Bonn) - Rapidly spinning gas disks around z~4.5 red sequence progenitors
All objects show steep [CII] velocity gradient

A star forming gas disk 1.3Gyr after the Big Bang seen in [CII] emission by ALMA?

- No robust information on stellar distribution
- Asymptotic velocity \(\sim 500\text{km/s}\)
- 2.4kpc intr. eff. radius; 130pc intr. turnover radius
- Likely highly rotation-supported

See also Chapman talk!

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Simple tilted ring modelling - (expon.) disk
3D modelling using GalPaK and 3D-Barolo (Bouche et al. 2015; Teodoro & Fraternali 2015)

- Relatively low inclination (~45 deg)
- Difficult to determine intrinsic velocity dispersion given strong velocity gradient
- Additional 2D modelling using GIPSY/rotcur consistent with these results (Jones et al. in prep.)

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However, disk signatures also in "mergers"

Data delay: carry-over and QA2-fail; HST analysis from Gomez-Guijarro, AK+ (in prep.)

- Asymptotic velocity ~800km/s
- 760pc intr. eff. radius

Ongoing minor merger perhaps not the trigger for the starburst. If previous major merger started the process, dynamical time is short enough to regularise the gas.

Alex Karim (AIIfA Bonn) - Rapidly spinning gas disks around z~4.5 red sequence progenitors
However, disk signatures also in "mergers"

3D modelling using GalPaK and 3D-Barolo (Bouche et al. 2015; Teodoro & Fraternali 2015)
Almost doesn’t fit into spectral window; geometric challenges for energy balance SED fitting

- Asymptotic velocity ~600km/s
- 2kpc intr. eff. radius; 170pc intr. turnover radius
- [CII] properties overall very similar to first object
- Young stellar emission offset from gas/dust; hints for partial foreground UV-emission (IRX/beta analysis: see poster #22)

**Figure 4.**

**Figure 5.**

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Relatively high inclination (closer to edge-on view)
Somewhat better spatial deblending of steep velocity gradient, still challenging to determine intrinsic dispersion

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Rest-frame 160um/16.5GHz continuum
20min on-target, 0.3”-0.4” beam (<0.3” in uniform weighting for high-SNR continuum)

- Far-IR Continuum generally more compact compared to [CII] extent (factor ~2)
- Radio continuum centroid shows small but significant offset in most cases
- where it shows an offset, radio emission either largely extended or tentatively multi-component
- Perhaps hinting to radio-AGN driving the mild offset from the observed far-IR/radio trend

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Implications for high-z [CII]-deficit

see also, e.g., de Breuck et al. (2014), Oteo et al. (2016), Diaz-Santos et al. (2016)

- Integrated [CII]/LIR comparable to Swinbank, AK+ (2012)
- At outer part of disk more in line with “normal” galaxies
Possible evolutionary tracks to $z \sim 2$

Plausible connection (from full sample of 6 from COSMOS); Gomez-Guijarro, Toft, AK+ (in prep.)

- Found 1.3 satellites (mass ratio ~1:5) on average; some hints for additional 1:10 mergers (up to 5; upper trends)
- Assumes size growth through minor mergers according to Bezanson et al. (2009) - simple scaling given the observed mass ratios
- Solid/dashed arrows assume 50/100Myr gas depletion timescales (see also upcoming slides)

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Kinematically compatible with descendants!

Toft+ suggesting a massive dead lensed disk (from 2.7hr XSHOOTER and 14-band HST)

- Typical z~2 compact post starburst galaxy (1.5x10^{11} M_{Sun}, age ~1Gyr, r_{eff}~1.7kpc)
- Compact exponential disk light and surface mass density profile (n=1)
- V_{max}~500km/s, 500pc turnover radius, v/σ>3

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Potential well similar to local giant ETGs

z~0 ellipticals with residual star formation (10x below main sequence; ATLAS$^{3D}$/Davis et al. 2016)

- Includes Oteo et al. (2015) z~4.4 source; plot being updated currently for clearer picture
- Trend below that for spirals; but be aware that spirals do not reach such high velocities (<400km/s)
- $M_{H2} \sim$ few $10^9$ $M_{\odot}$ within inner 1-2kpc in massive ETGs - similar potential well to our z~4.5 sources

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Mol. gas thermalized to J=5, unusually high

Jimenez-Andrade et al. (in prep.) with data from Schinnerer et al. (2008)

Fraction of peak

Velocity [km s⁻¹]

0.0 0.2 0.4 0.6 0.8 1.0 1.2

0 0.2 0.4 0.6 0.8 1.0 1.2

1 2 3 4 5 6 7

Sₖ/Sₖ(1-0)

10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷

AzTEC/C159
J1000+0234
GN20
Average SMGs
Disk Galaxies z~1.5
Milky Way GC
Thermalized

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Molecular gas content from CO

Jimenez-Andrade et al. (in prep.); 19/17hr total for NOEMA/JVLA (PI AK)

\[ M_{\text{gas}} \propto L_{\text{CO}} \]

\[ \tau_{\text{gas}} = \frac{M_{\text{gas}}}{\text{SFR}} = 16 \text{ Myr} \]

- Very low, but assumes \( \alpha = 0.8 \)
- from dynamical mass, \( M^* \) limit OR gas from dust could accommodate for 4x more gas
- Then \( M_{\text{gas}}/M_{\text{bar}} \sim 40\% \) (\( M_{\text{gas}} \sim 6 \times 10^{10} \) \( M_{\odot} \))
- Realistic depletion time hence \( \sim 86 \) Myr (see evolutionary considerations above)

Jiménez-Andrade et al. (in prep.)

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Hints for expanding halo gas

Using COSMOS intermediate band filters (continuum-subtracted); see also Capak et al. (2008)
Open question: How did these early starbursts come into being (major mergers?) and what is their fate?

Conclusions/outlook

ALMA, HST, NOEMA and JVLA reveal

• Complex rest-frame UV-morphologies (mostly minor mergers)
• Large velocity gradients in surrounding [CII], likely in Keplerian rotation
• Hints for young stellar emission projected in front of dust/gas
• High molecular gas excitation, efficient star formation

Progenitors of z~2 massive compact quiescent galaxies?

• Residual total mass and depletion timescale compatible
• Size-growth plausible given ongoing minor mergers
• Similar potential well as observed towards local massive early type galaxies
• Very tentative hints for radio-mode feedback

Some possible next steps for this sample

• Disk substructure? Gas turbulence? > higher resolution ALMA needed
• MUSE would be very valuable to study halo gas