The Cosmic Skidmark:

witnessing galaxy transformation at z=0.19

David Murphy

FONDECYT postdoctoral fellow
Instituto de Astrofísica,
Pontificia Universidad Católica, Chile

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David N. A. Murphy[★1]

1. Institute of Astrophysics, Pontificia Universidad Catolica de Chile, Macul, Santiago, Chile

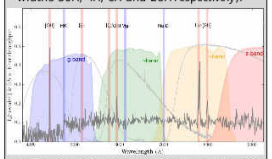
★FONDECYT Postdoctoral Researcher, dmurphy@astro.puc.cl

We present an early-look analysis of the "Cosmic Skidmark". Discovered following visual inspection of the Geach, Murphy & Bower (2011) SDSS Stripe 82 cluster catalogue generated by ORCA - an automated cluster algorithm searching for red-sequences (Murphy, Geach & Bower 2012), this z=0.19 1.4L★ galaxy appears to have been caught in the rare act of transformation while accreting onto an estimated 10^{13}-$10^{14}h^{-1}M_{\odot}$-mass galaxy group (Stott et al. 2012). Pending additional data from ALMA Cycle 2, we show here preliminary analysis of VLT/VIMOS IFU spectroscopy and deep SOAR Adaptive Module (SAM) LGS optical imaging.

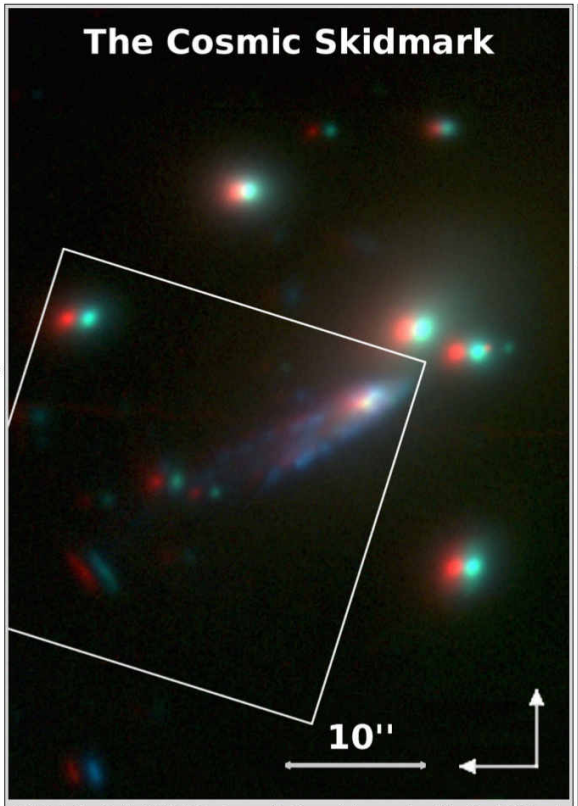
The study of galaxy populations reveals clearly bimodal properties such as morphology (Driver et al. 2006), star formation rates (Kauffmann et al. 2006) and the colour-magnitude distribution (Baldry et al. 2006). The origin of this dichotomy appears to be driven mainly by galaxy environment (Dressler et al. 1997); compared to those in the low-density field, spiral galaxies in clusters exhibit suppressed star formation, smaller cold-gas reservoirs and gaseous disk truncation of their (Boselli & Gavazzi 2006).

The redshift evolution of the colour-magnitude (CM) distribution into a progressively pronounced "red sequence" (Bower et al. 1992) at early times, indications of a transitional CM "green valley" and a lack of high-mass blue spirals point to the **transformation of late-type spirals into early-type ellipticals** (Stott et al. 2007) within cluster environments.

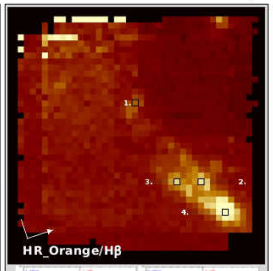
The SDSS spectroscopic catalogue provides a 3"-diameter fiber spectrum centred on the Cosmic Skidmark's core (red circle in bottom image) but also includes light from the blue component of the target. The spectrum shows a clear 4000Å break associated with early-type galaxies, but also strong [OII] (λ_{em}4420Å), Hβ (λ_{em}5767Å), [OIII] (λ_{em}5883Å) and Hα (λ_{em}7788Å) line emission (equivalent widths 30Å, 4Å, 6Å and 26Å respectively).

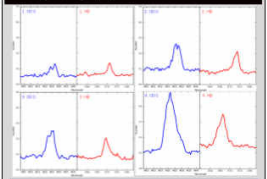


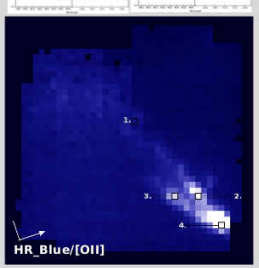
From measured equivalent widths, we determine a mean SFR based on three H and [OII]-derived calculations (using the Kewley et al. 2004 and Kennicutt et al. 2009 relations). Determining that the SDSS fiber covers the entire galaxy without significantly sampling the background, an SFR surface-density of $\log_{10}$SFR=-1.9$M_{\odot}yr^{-1}kpc^{-2}$ is estimated. This is used to determine the required sensitivity our ALMA Cycle 2 observations must reach to trace the H_2 gas.



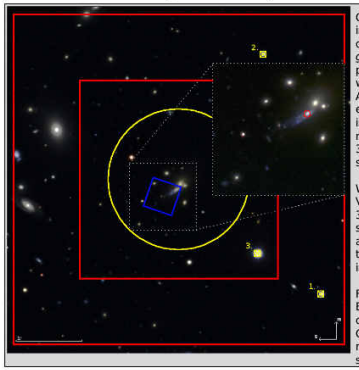
SOAR Adaptive Module (SAM) LGS *gri*-composite 3D anaglyph conversion of the Cosmic Skidmark along with the VIMOS/IFU FOV. The cometary plume, strongly star-forming, extends for ~50kpc.







Deep VLT/VIMOS IFU data provides a truly 3D measurement of the target, and permits spectral identification of three key star formation indicators ([OII],[OIII],Hβ). We find clear SF evidence throughout the plume, tracing out the dual-tail structure alluded to in the optical imaging. Detailed kinematic analysis will appear in Murphy et al. (2014)



Our Cosmic Skidmark investigation will consist of three datasets. Preliminary wide-field *gri*-band Magellan IMACS photometry (*left*) was followed up with deep (7hrs) *griz*-band SOAR Adaptive Module (SAM; Tokokini et al. 2004) photometry. This LGS instrument achieved 0.61"(0.57") median g(i)-band seeing in a 3'x3' FOV indicated by the smaller red square.

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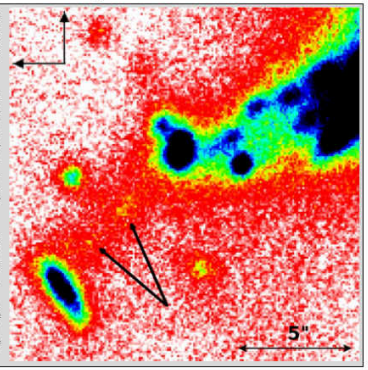

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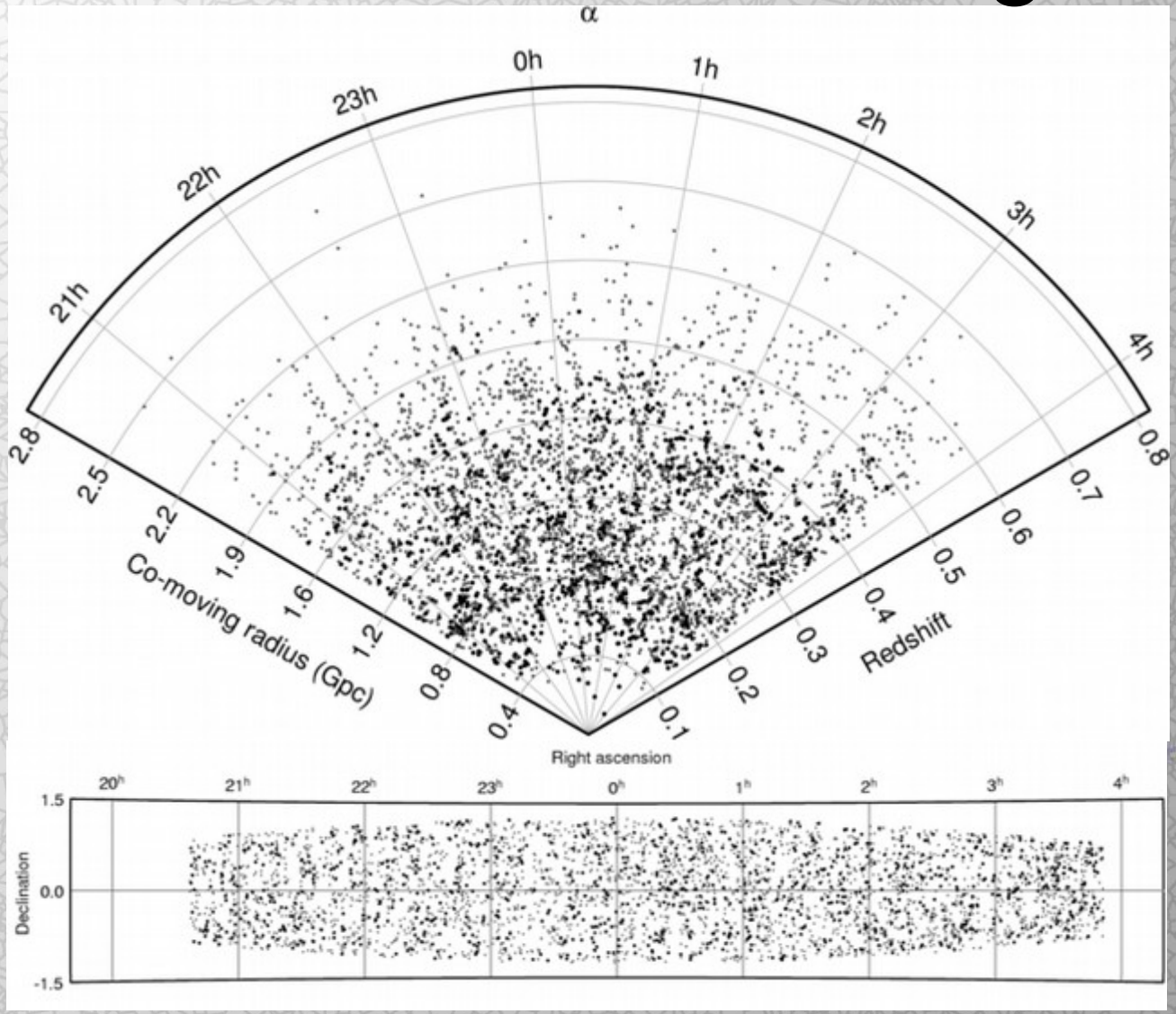
SDSS Stripe 82 ORCA cluster catalogue



Red-sequence-based optical cluster finder: ORCA (Murphy, Geach & Bower 2012)

Uses deep SDSS photometry in equatorial stripe

Covers 270 sq degrees

Finds 4098 clusters

Catalogue extends to z~0.6

Cluster redshifts and richnesses estimates (the latter a proxy for mass)

ORCA catalogues in the pipeline for Pan-STARRS, VST-ATLAS, SDSS DR10

Geach, Murphy & Bower 2011

Pan-Clusters: Cluster detection in Pan-STARRS

David Murphy*[1,2], Richard G. Bower[2], James E. Geach[2,3]
and the Pan-STARRS[4] science consortium
1. Department of Astronomy & Astrophysics, Pontificia Universidad Catolica de Chile, Macul, Santiago, Chile
2. Institute for Computational Cosmology, Durham University, South Road, Durham. DH1 3LE. UK
3. Department of Physics, McGill University, Ernest Rutherford Building, 3600 Rue University, Montréal, H3A 2T8, Canada
4. http://pan-starrs.ifa.hawaii.edu/

Pan-STARRS-1 (PS1) will produce two types of survey - 10 "Medium Deep Survey" fields covering a total of 84 sq deg, and a 3π survey covering over 27,000 sq deg of extragalactic sky. PS1 features deep 5-band photometric coverage capable of detecting clusters over z~1 in the Medium Deep Surveys. In addition to the traditional optical richness measures, in Pan-STARRS one may also exploit the *y*-band filter to estimate the cluster stellar mass. Coupled with a well-defined cluster selection function, this provides a useful, independent route to cluster mass estimation that can be calibrated to X-ray, SZ and weak-lensing measurements.

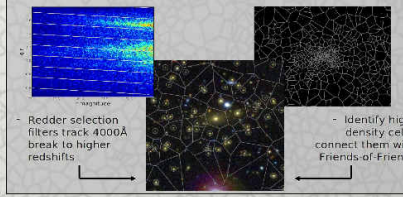
ORCA: Two detection requirements

1.Cluster red sequence

- Photometric selection filters: exhaustive search in CM space

2.Projected galaxy overdensity

- Voronoi mesh: unbiased, non-parametric density field estimator



- Redder selection filters track 4000Å break to higher redshifts

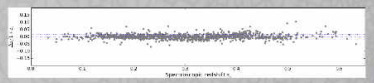
- Identify high-density cells, connect them with Friends-of-Friends

One way to identify clusters in the Pan-STARRS photometric data will be through "red sequence" (Bower et al. 1992) detection techniques (e.g. Gladders & Yee 2000). We present here **ORCA**: the "Overdense Red-sequence Cluster Algorithm" (Murphy, Geach & Bower 2012). This algorithm has been applied to the SDSS Stripe 82 (Geach, Murphy & Bower 2011) & Pan-STARRS MDS fields.

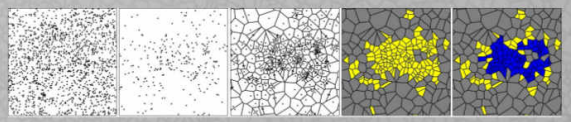
Expectations and Goals

- Medium Deep Surveys (MDS; ~9deg²/field):
  - Deep (i < 26.9) *grizy* photometry over 10 fields
  - Cluster detections to **z ≈ 1.2**
  - **~10³ distant clusters** / galaxy groups
- 3π Survey (~27,000deg²):
  - *grizy* photometry to at least single-epoch SDSS depth
  - Cluster detections to **z ≤ 0.6**
  - **~10⁵ clusters** / galaxy groups

Cluster redshift accuracy: Stripe 82



- 1137 ORCA BCGs from SDSS Stripe 82 catalogue (Geach, Murphy & Bower 2011) with spectroscopic measurements compared to photoz.
- After 3σ clip (removed 0.4%), find 1σ scatter in $\Delta z/(1+z_s)$ of 1.6%
- Mock MDS photometric redshifts (Cai et al. 2009) achieve 5%
- BCG photometric redshifts are accurate cluster redshift estimators

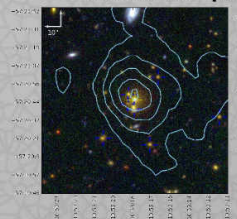


A depiction of the ORCA detector applied to a 9'x9' cut-out region of SDSS Stripe 82 (Abazajian et al. 2009). Starting with all galaxies in the box (*first* panel), a photometric selection isolates galaxies within a specific redshift range (*second* panel).

In the *third* panel, we compute the Voronoi diagram of the distribution to estimate the surface density of remaining galaxies. These are separated into overdense (yellow) and underdense (grey) cells in panel *four* according to how likely they are to belong to a random distribution.

In the *final* panel, we use a Friends-Of-Friends percolation algorithm to connect overdense cells until the density of the whole system falls below a density threshold. Galaxies in the blue cells become members of a cluster if there are at least N_{min} linked members.

XMMXCS J105318.5+57200.7: ORCA/PS1 optical counterpart



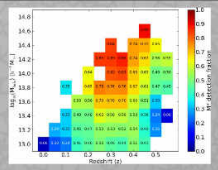
An ORCA analysis of PS1-MD8 (the Lockman Hole) yielded 133 clusters over 11.6sq degrees.

We compare this catalogue to the XCS (Romer et al. 2001) DR1 (Mehrtens et al. 2011). Shown left is the optical counterpart to XMMXCS J105318+57200.7, with X-ray contours added. In this cluster, ORCA finds:

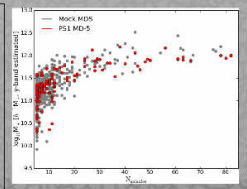
- 8 members (crosses, yellow is the BCG)
- z_{cl}=0.34±0.04 (c.f. XCS: z=0.34)
- $\log_{10}M_{500}$=11.41$h^{-2}M_{\odot}$ (*y*-band luminosity)

X-ray data from XCS will permit inter-calibration between cluster optical richness measures (such as B_{gc}; Yee & López-Cruz 1999), *y*-band and X-ray mass estimates.

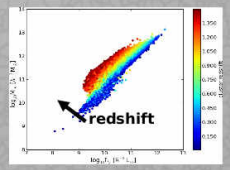
Connecting mass to richness

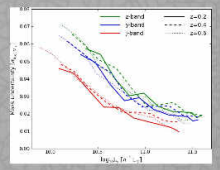


Working from y-band mass estimates, we have begun correlating cluster mass with other observables, including low-level (e.g. N_{gal} – see *lower* plot) and higher level estimators (e.g. A_{gc} and B_{gc}). To do so, however, requires an understanding of the **ORCA detection performance**, such as the fraction of stellar mass recovered in each Pan-STARRS MDS cluster (*left* plot – see Murphy, Geach & Bower 2011). As shown in the plot *below*, these early measurements compare well to predictions from mock MDS surveys.



PS-1 *y*-band cluster mass estimates

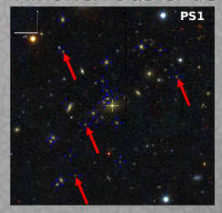




As with NIR bands, the PS-1 ***y*-filter traces stellar mass** with only minimal contribution from the star-forming population and dust (see e.g. Kodama & Bower 2003). The *left* plot shows the Bower et al. 2006 model L_y-M_y relation from a mock lightcone spanning a large redshift range. This simple analysis does not include survey flux limits or photometric errors, but nevertheless provides a useful preliminary correlation that can be tested against observational data.

The depth and wavelength probed with the *y*-band provides improved mass estimates over the SDSS *z*-band in the 3π survey. Using three redshift bins from the *left*, in the *right*-hand figure we plot the scatter in L_y-M_y compared to equivalent estimates from the *z*-band and UKIDSS *J*-band. The *y*-band mass uncertainties are smaller by between $0.01>\log_{10}M_y>0.005$ at each redshift range, with improved accuracy at lower luminosities.

An ORCA cluster detected in PS1 & SDSS



- PS-1 MDS *gri* imaging @ 1yr depth
- i_{lim}< 23.3: recovers more members
- 24 members (yellow = BCG)
- z_{cl} = 0.199 (from member photoz)

- SDSS DR7 *gri* single-epoch imaging
- i_{lim} < 21.7
- 8 members (yellow = BCG)
- z_{cl} = 0.198 (photoz)

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Cai et al. (2009) MNRAS, 395, 1185C
Geach, Murphy & Bower (2011) MNRAS, 413, 3059G
Gladders & Yee (2000) AJ, 120, 2148G
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Further information

***contact: dmurphy@astro.puc.cl**
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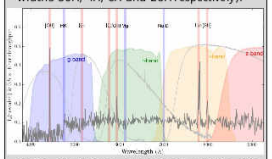

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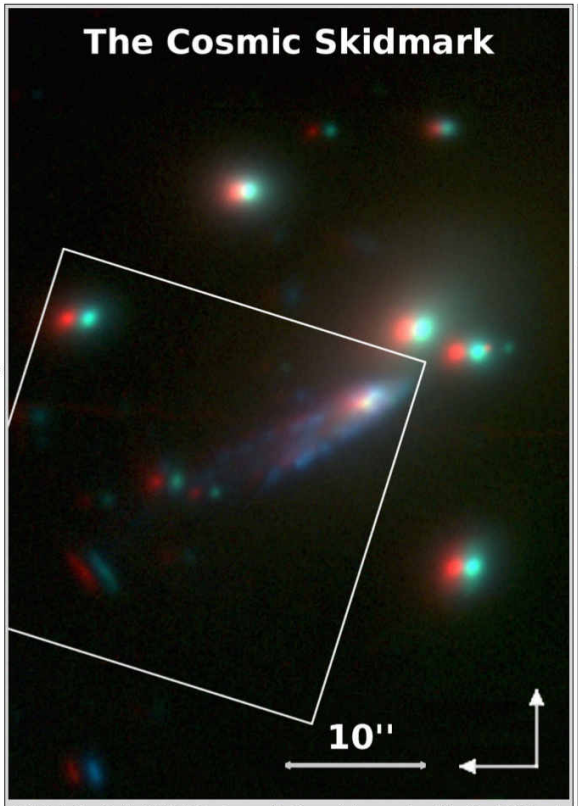

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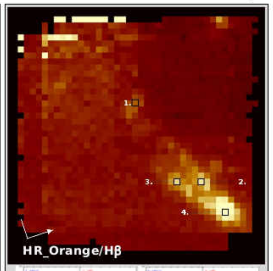

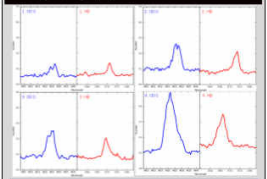

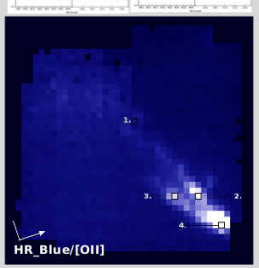

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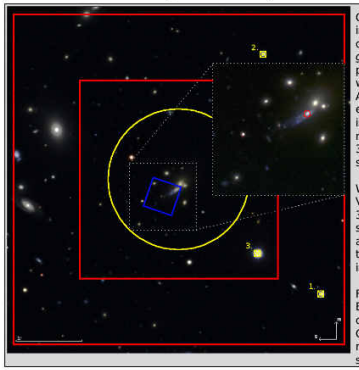

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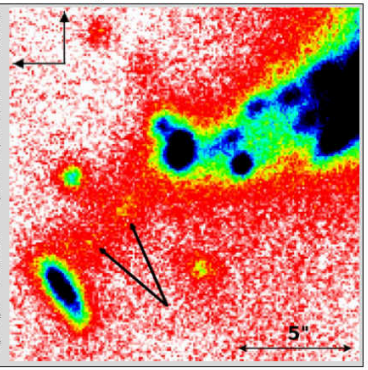

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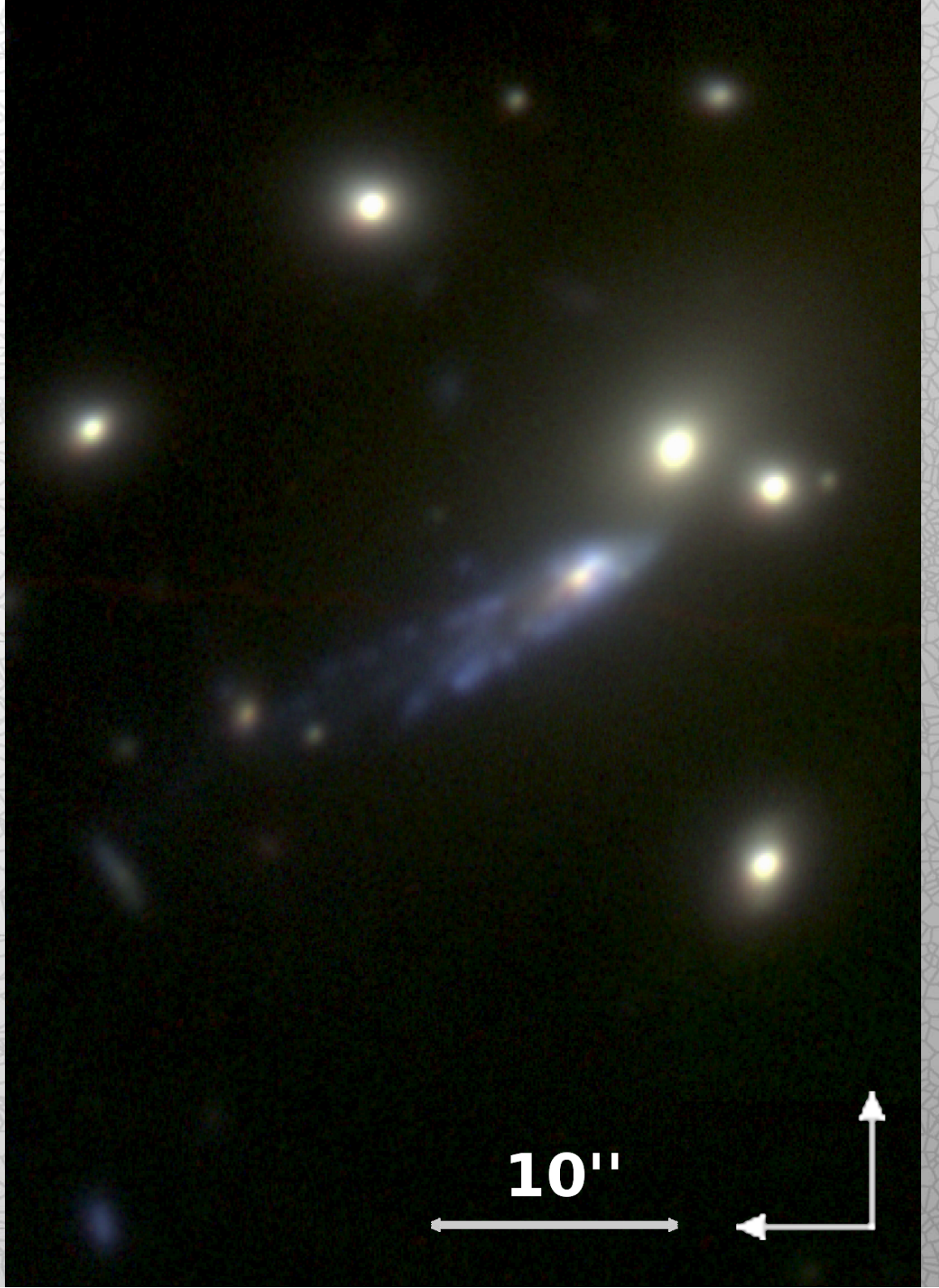
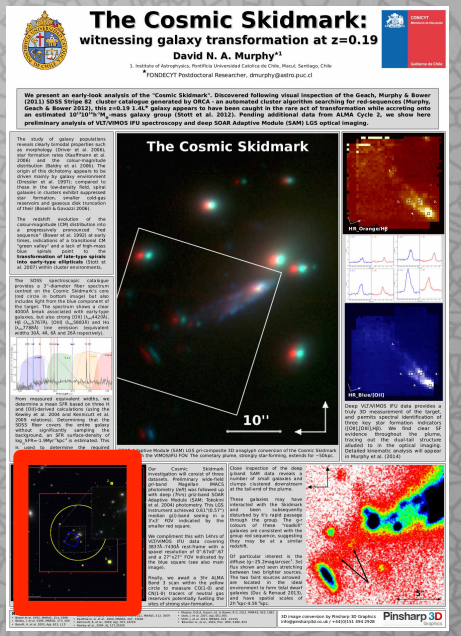
- Stott, J. et al. 2012, MNRAS, 422, 2213S
- Tokovinin A., et al., 2004, Proc. SPIE, 5490, 870





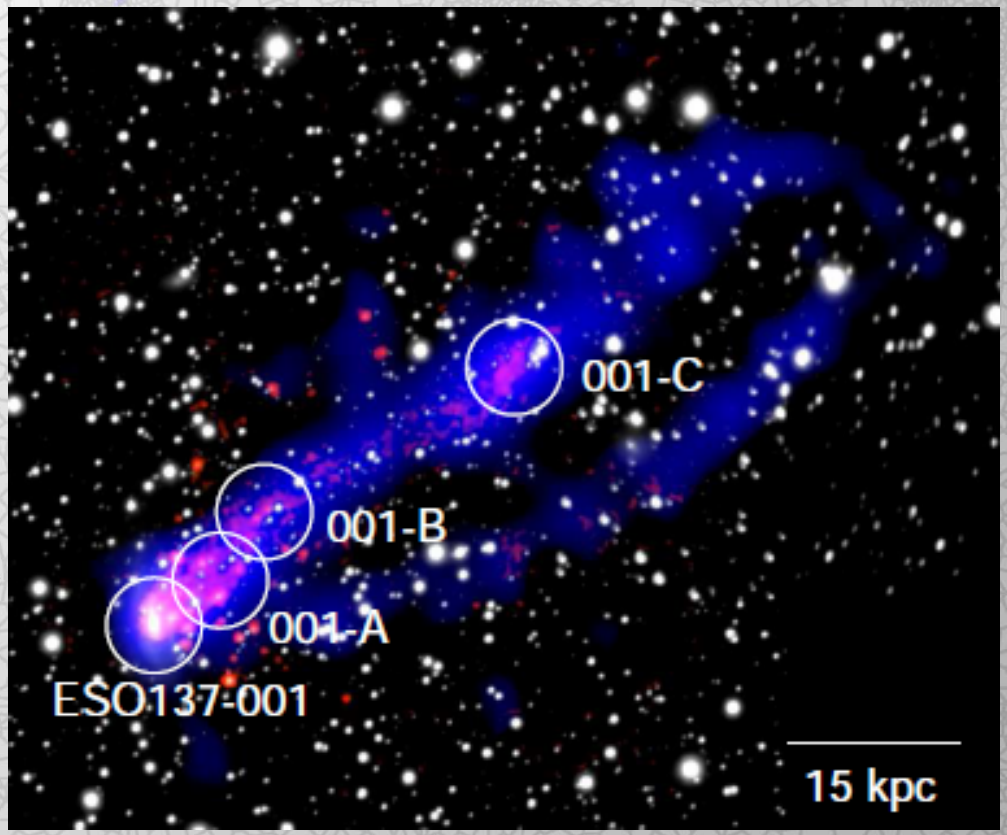
- SOAR Adaptive Module (SAM)
- LGS optical imaging
- deep griz photometry
- 0.61”(0.57”) in g(i) closed loop

SAM: Tokovinin et al. 2004

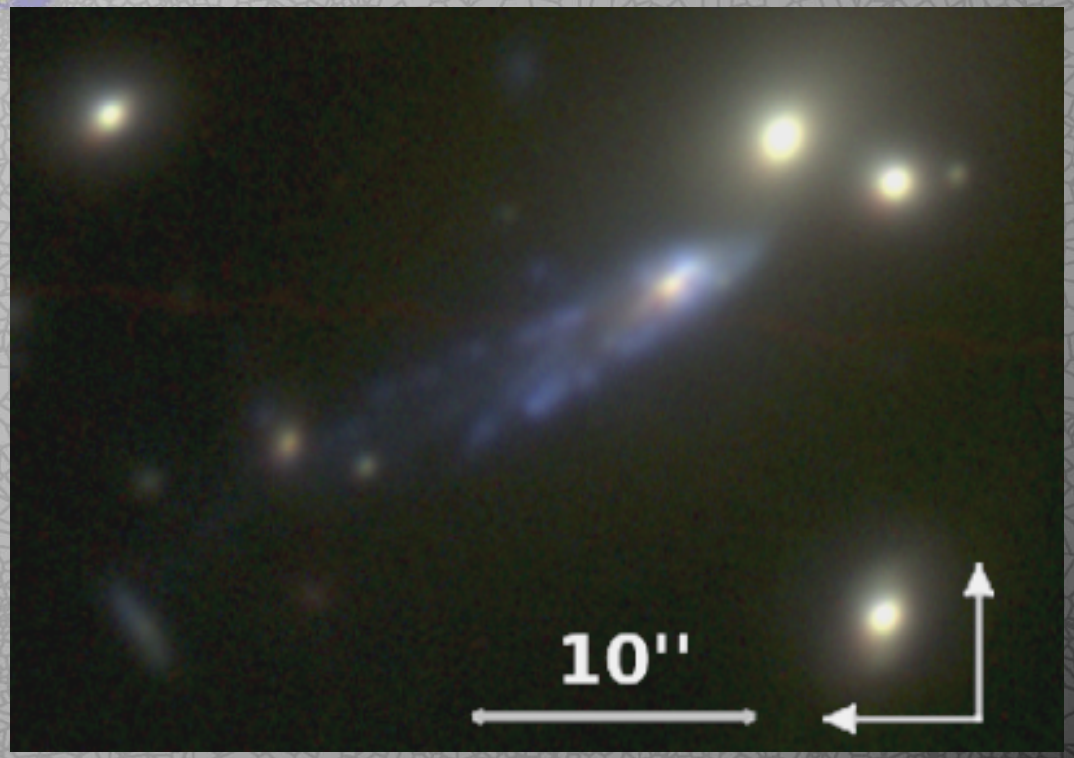
Please also note...

- ...poster by Veronica Menacho, Miguel Verdugo (A2163 @z=0.2)
- ...poster and talks by Pavel Jachym, Jeff Kenney:

z~0: ESO 137-001



z~0.2: Cosmic Skidmark



(to scale)

Please also note...

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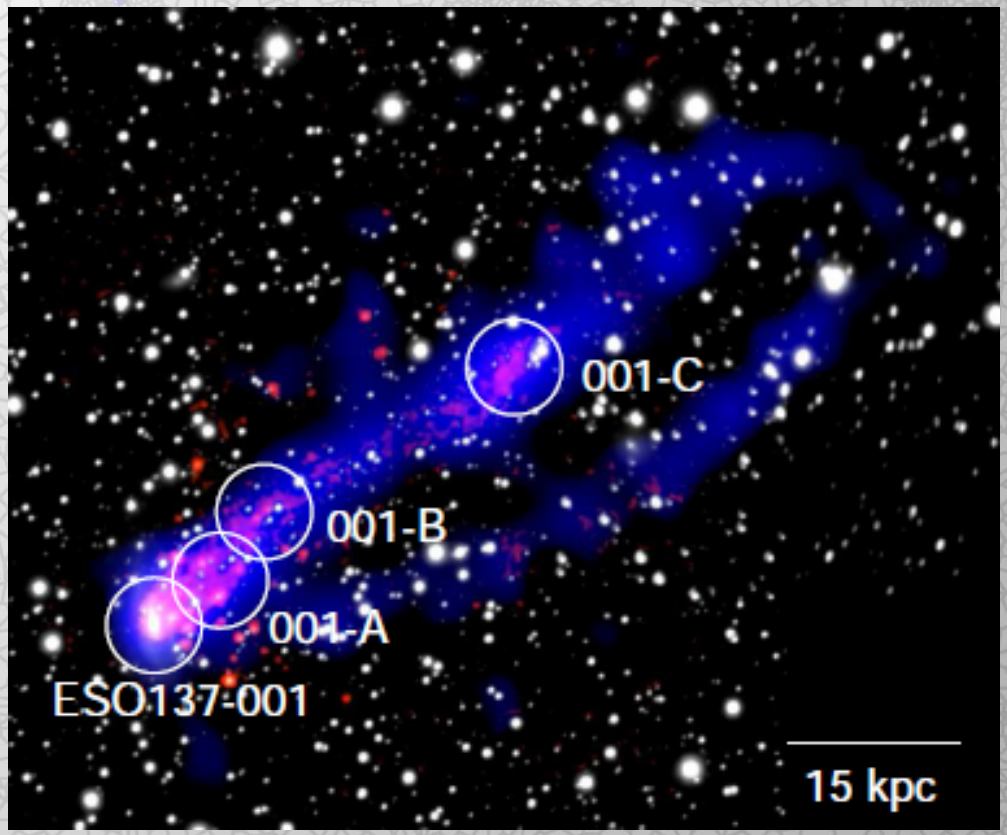
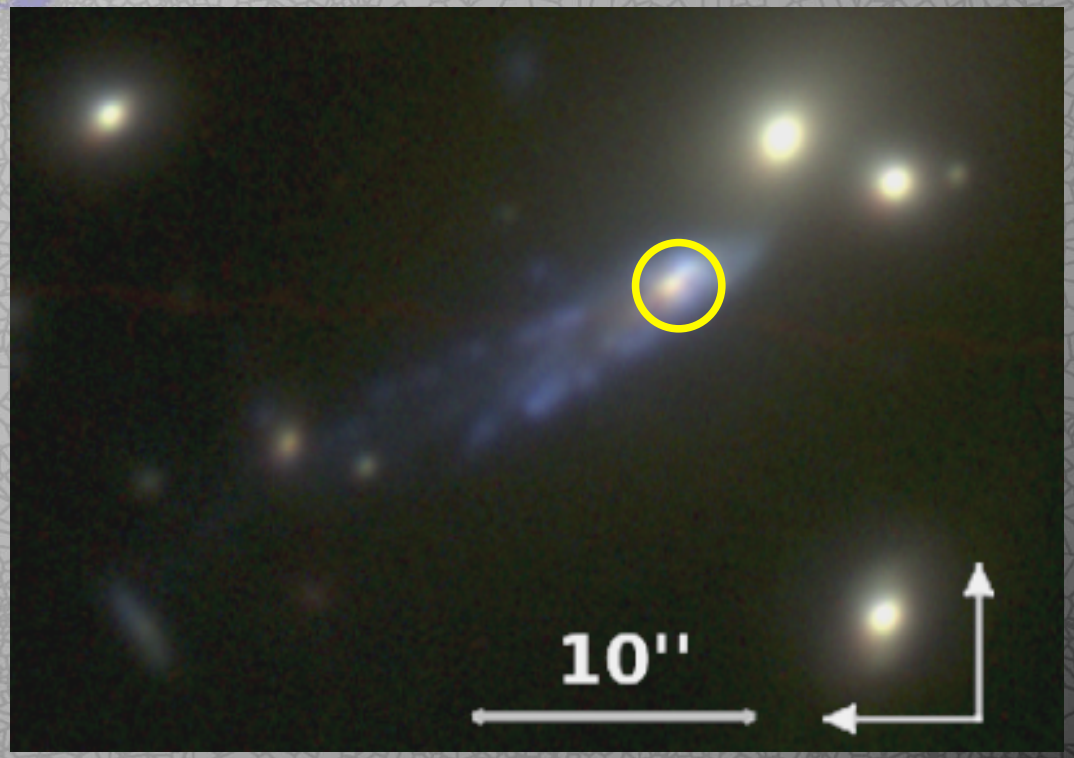
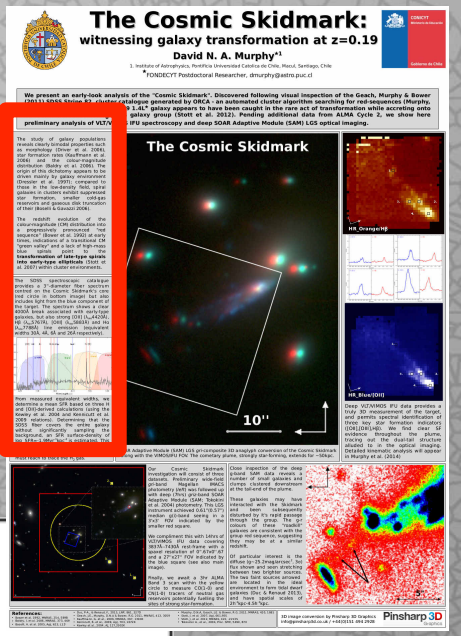


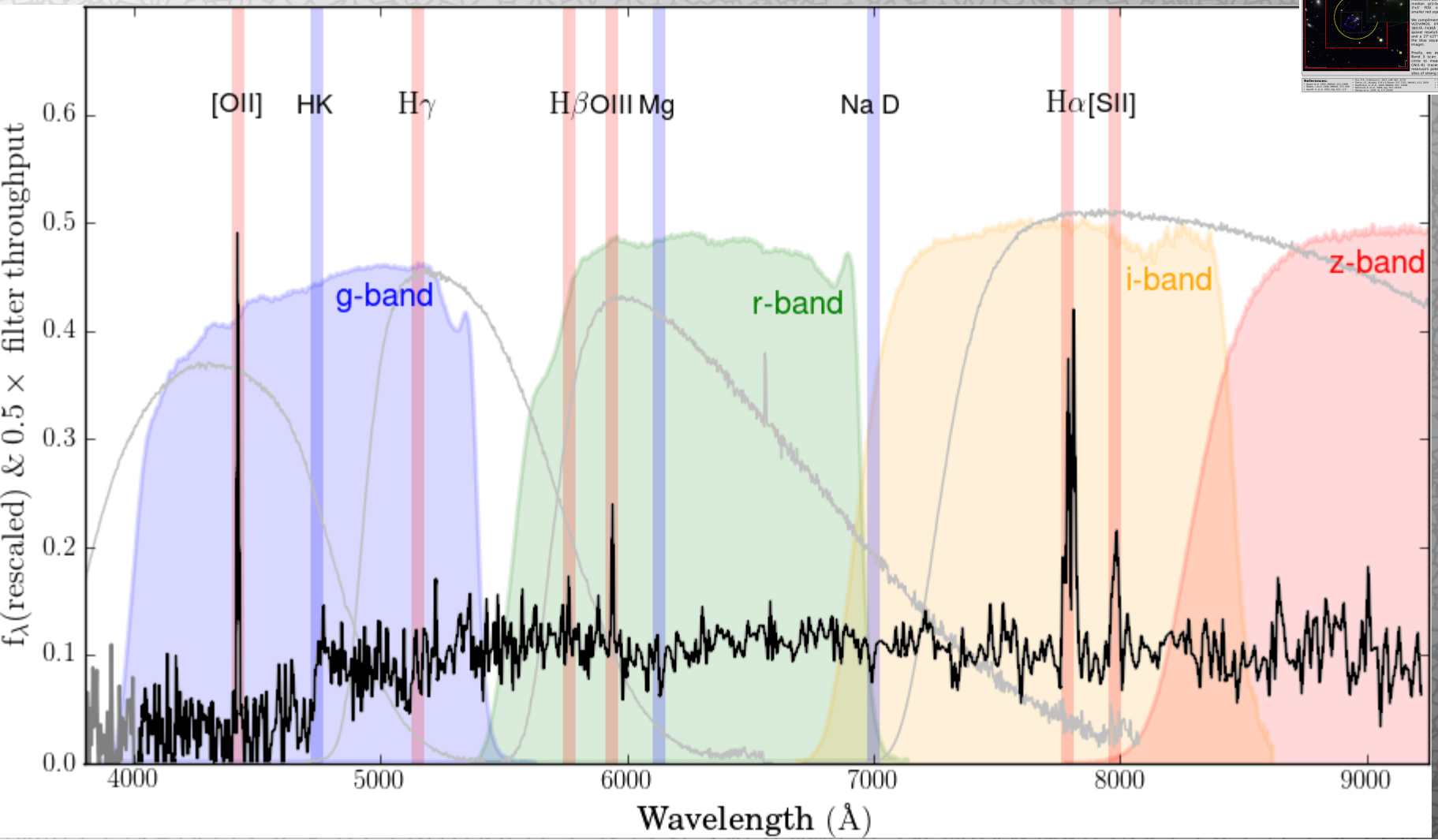
z~0.2: Cosmic Skidmark



(to scale)

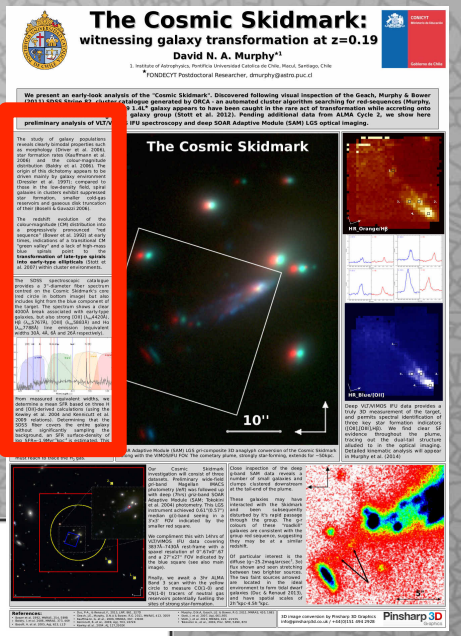
SDSS Target spectrum

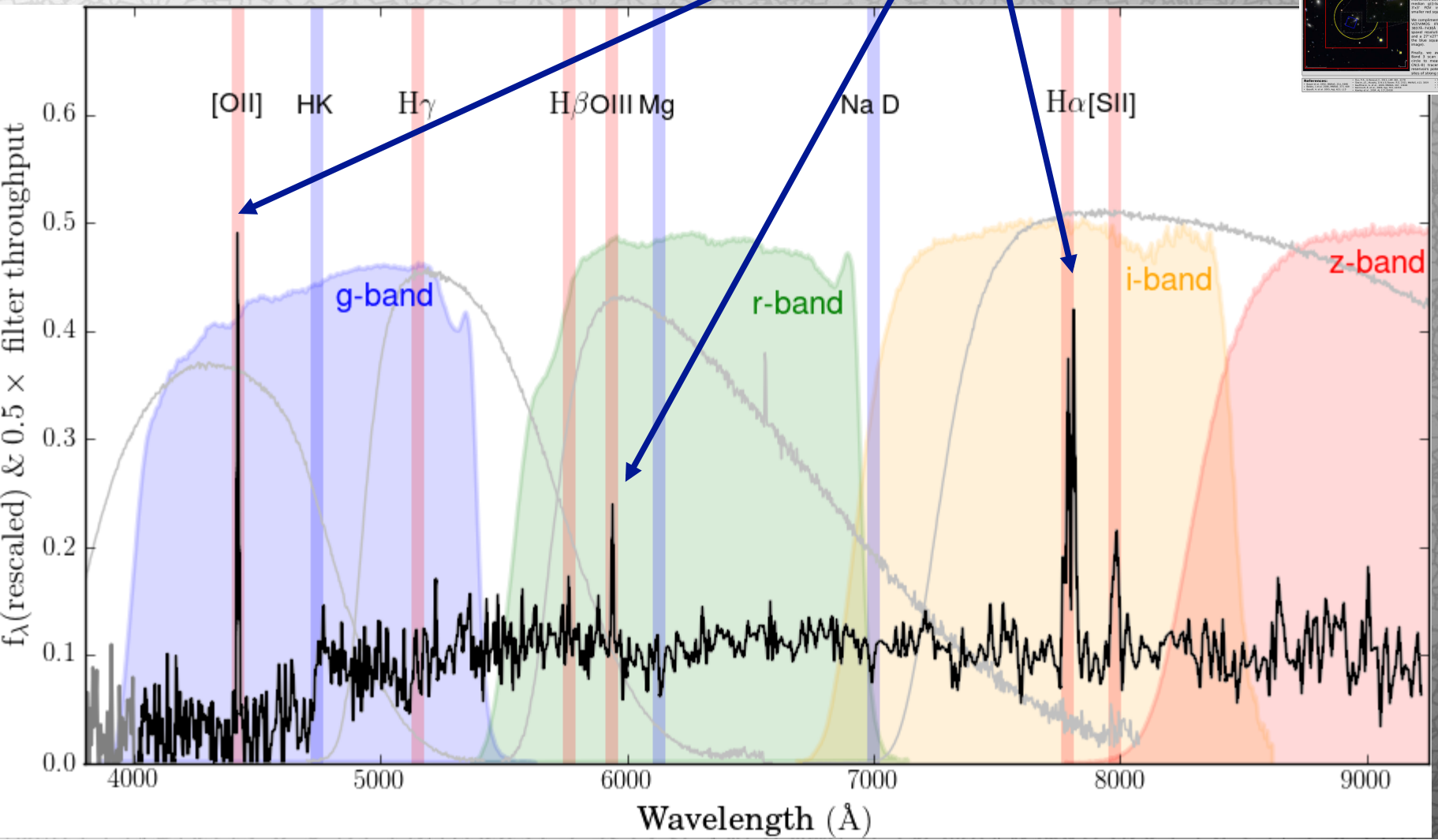




SDSS Target spectrum

Forming stars.....

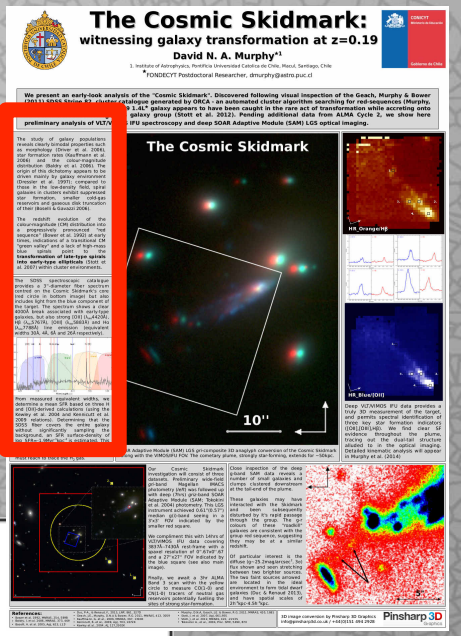


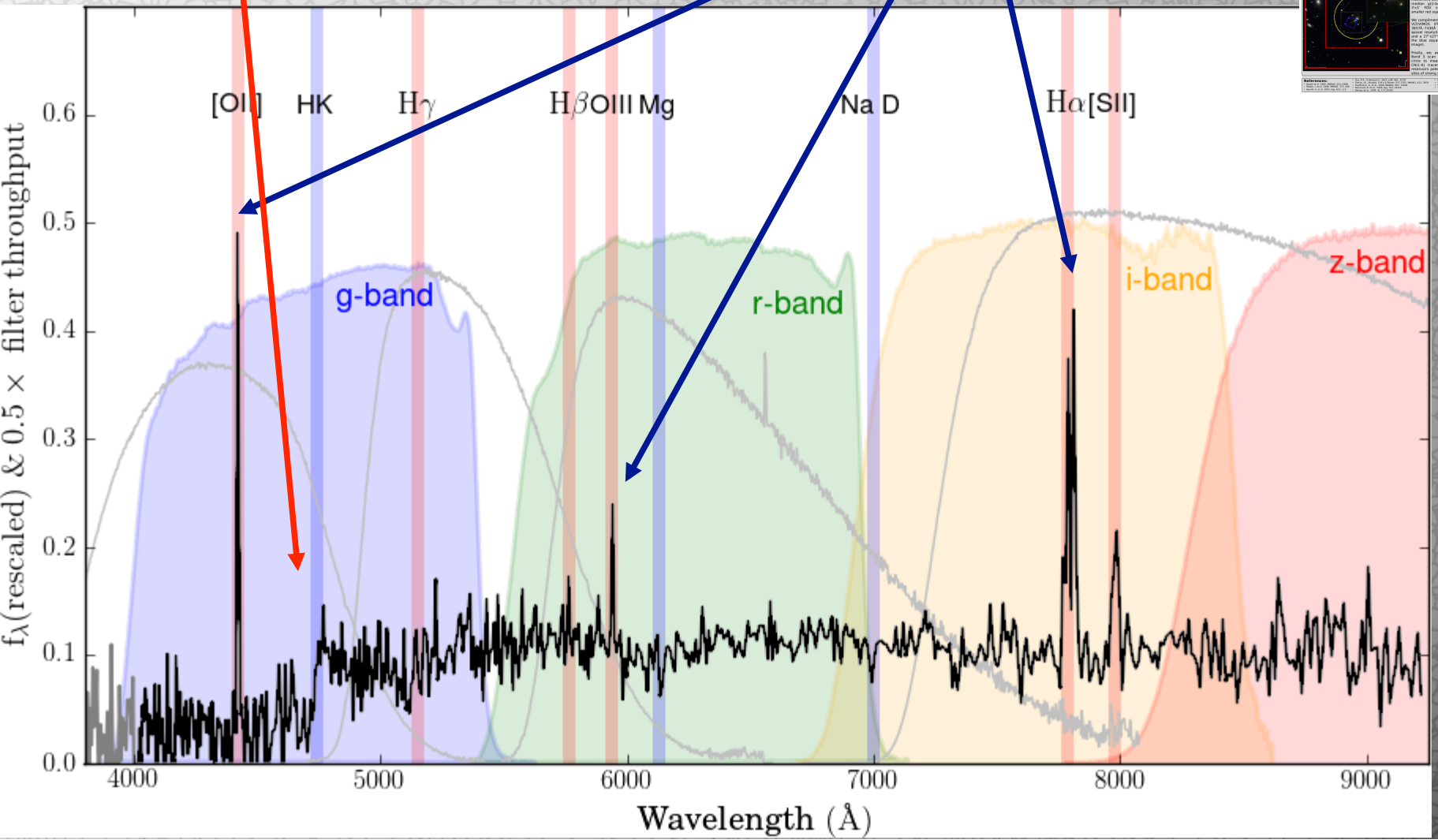


SDSS Target spectrum

...but also clear 4000A break

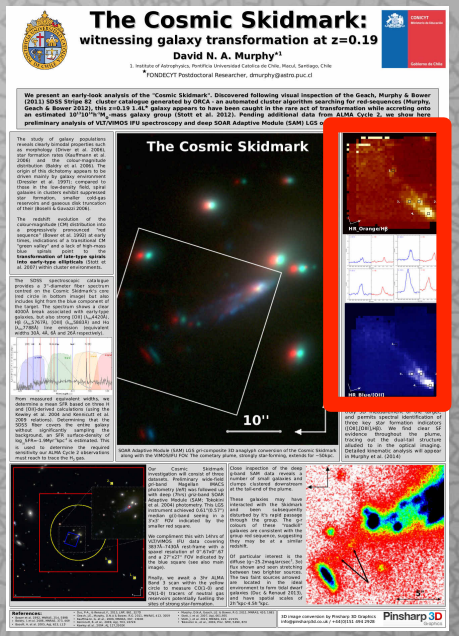
Forming stars.....

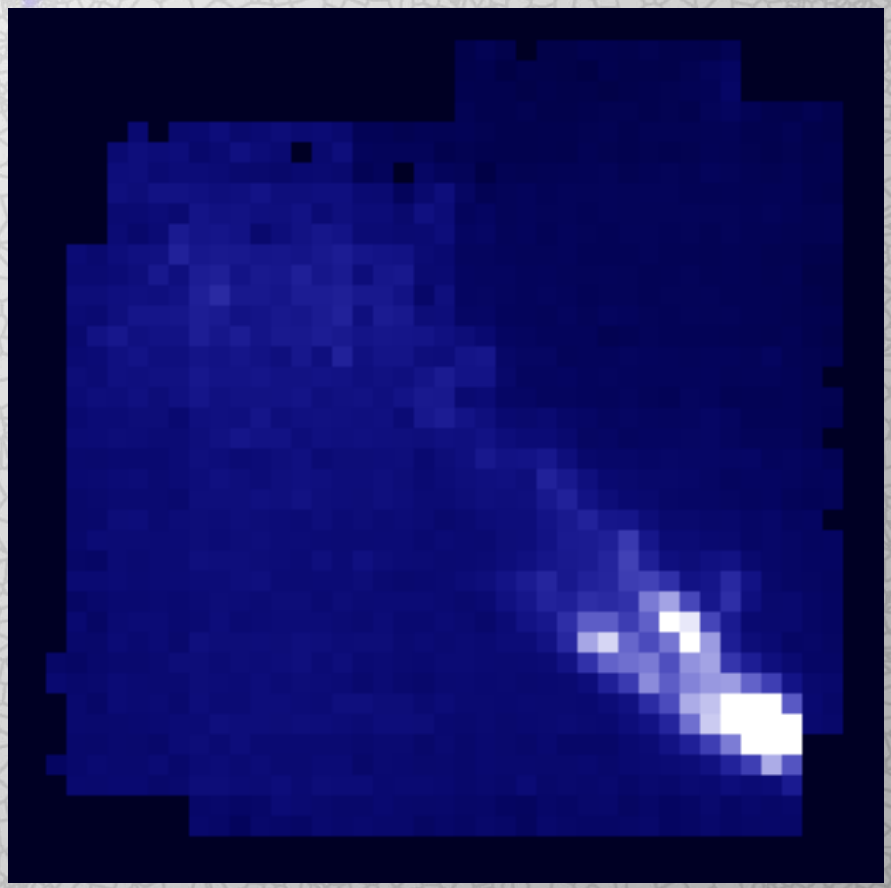


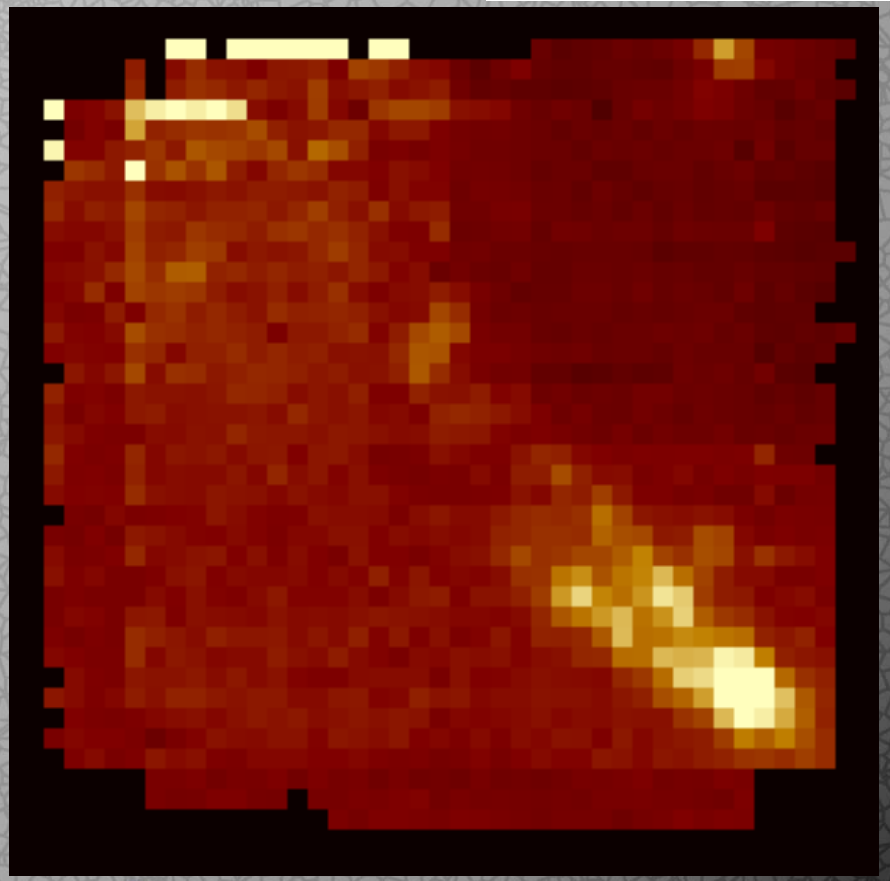


VIMOS IFU (Preliminary)

- 27”x27”, 0.66” spaxels
- Using new **H**igh-**R**es **B**lue grism (HRB; [OII]) and **H**igh-**R**es **O**range (HRO; Hbeta, [OIII])
- Awaiting full HRO depth before final analysis

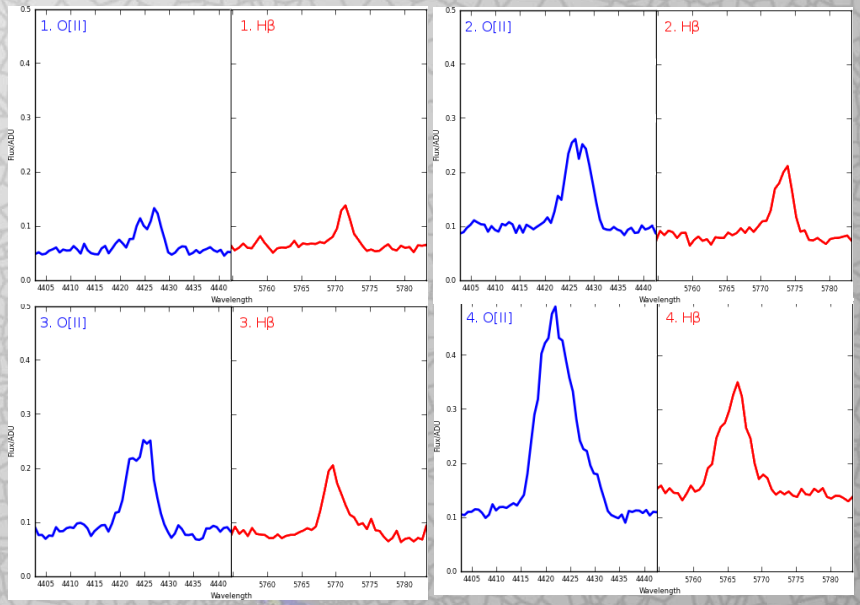


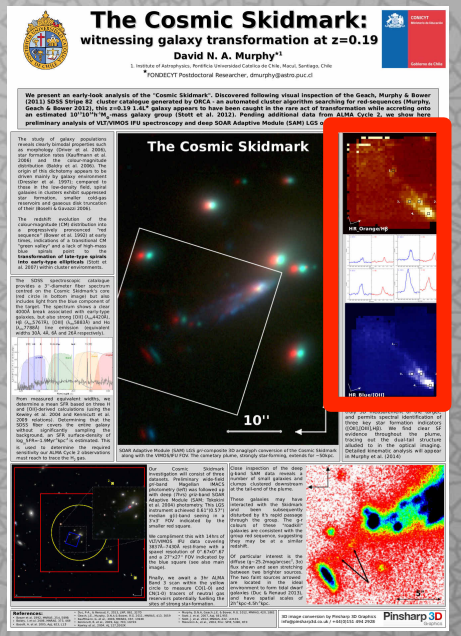


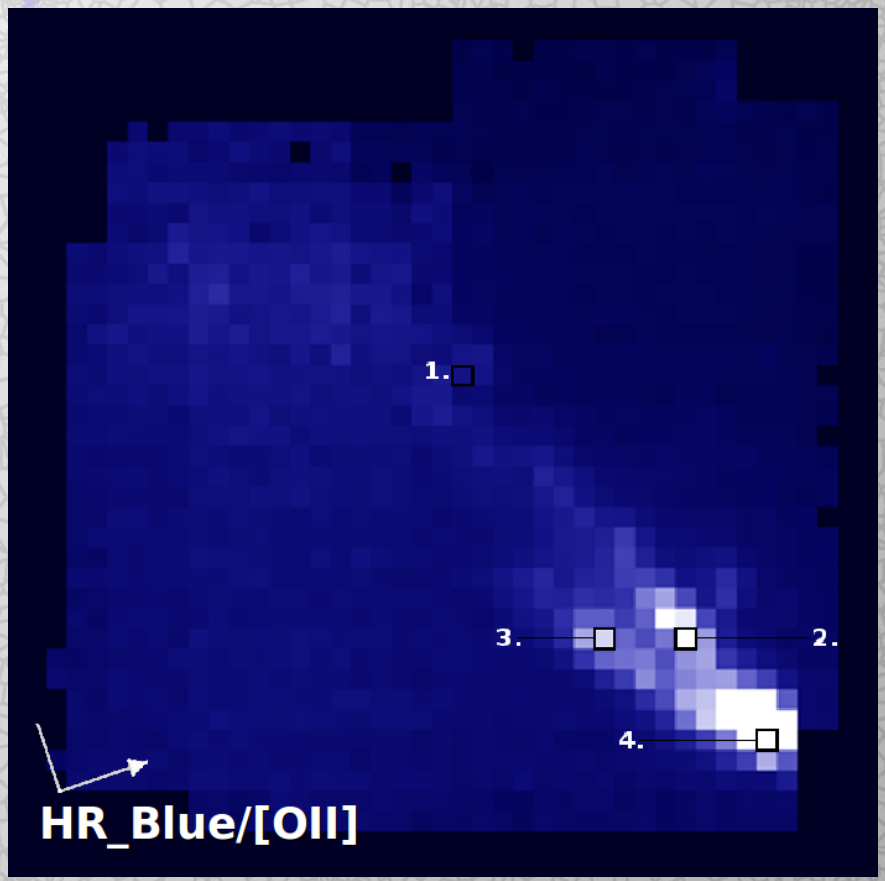


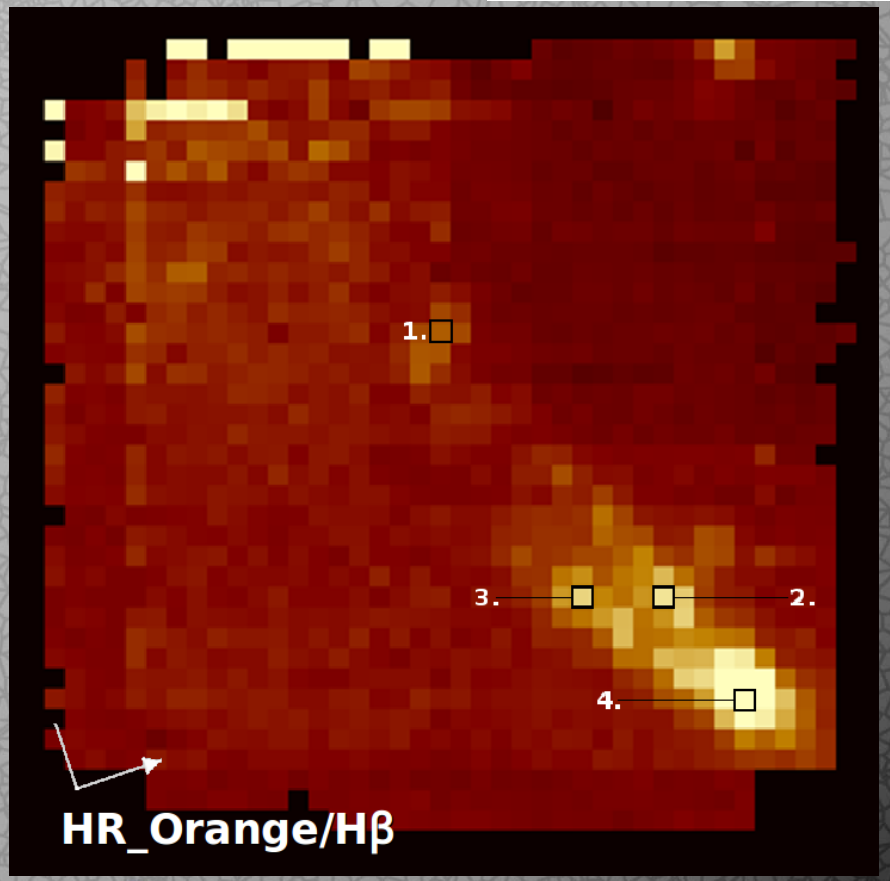
VIMOS IFU

- Emission-line tracers map the same structure as seen in optical imaging



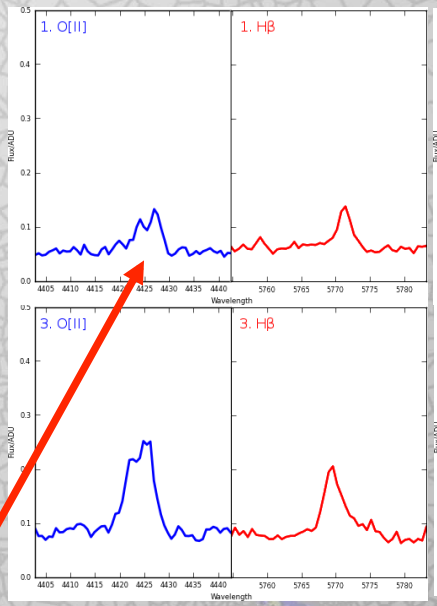


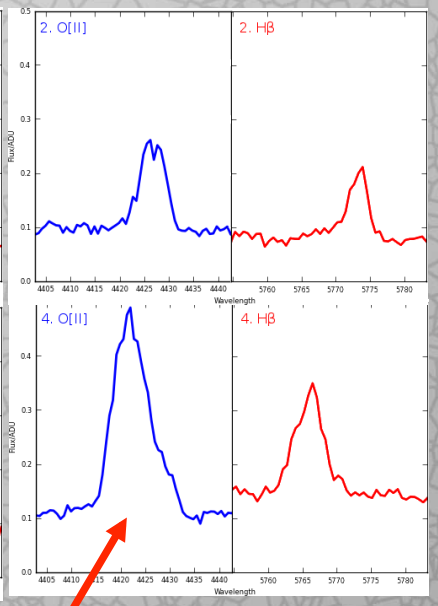


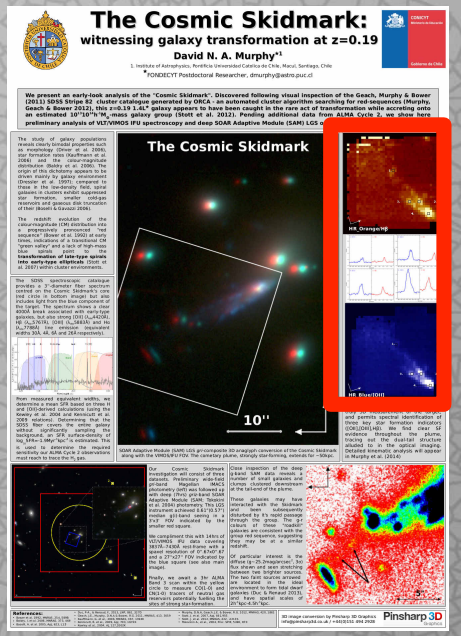


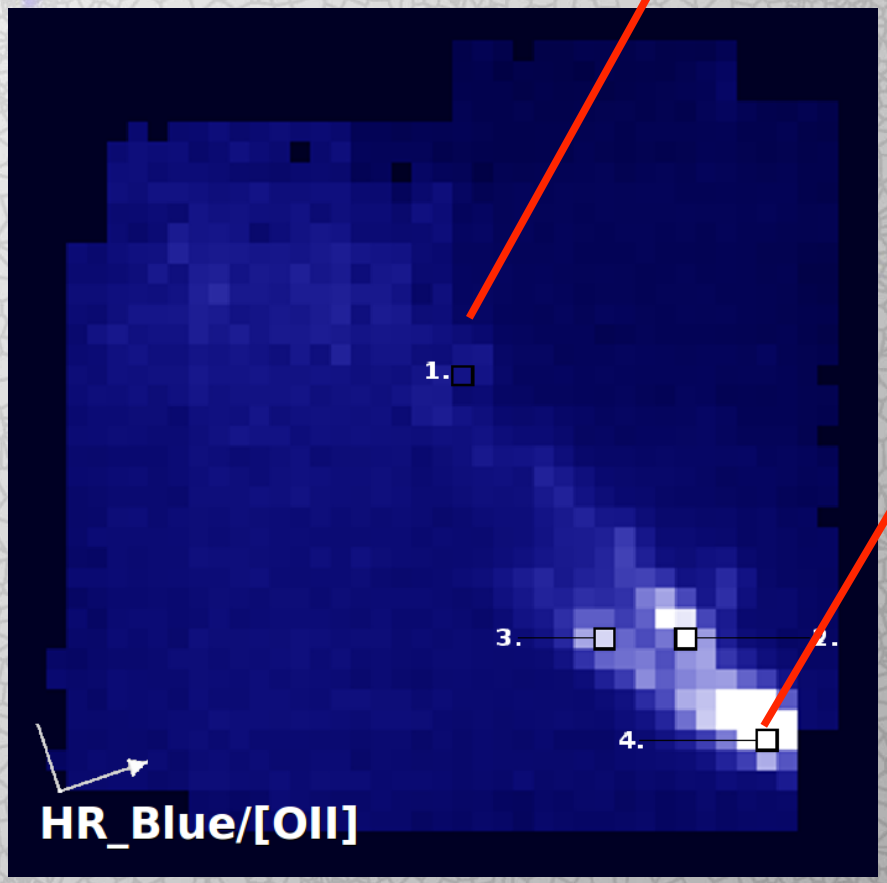
VIMOS IFU

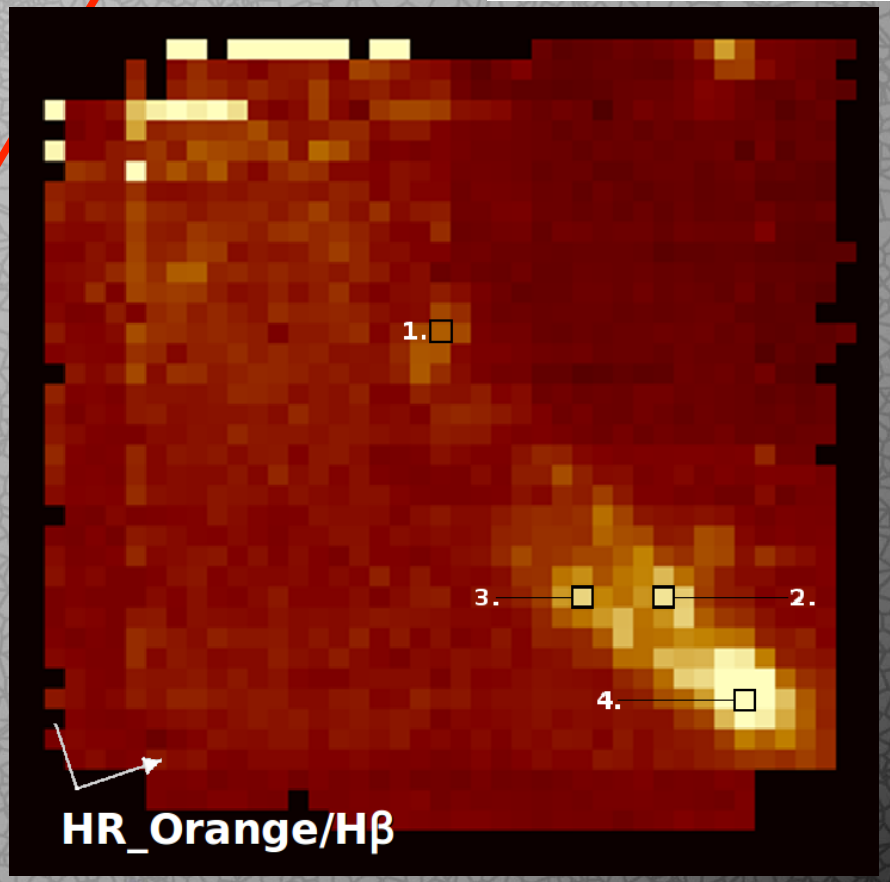
- Emission-line tracers map the same structure as seen in optical imaging
- SF throughout plume, out to 50kpc projected distance from core











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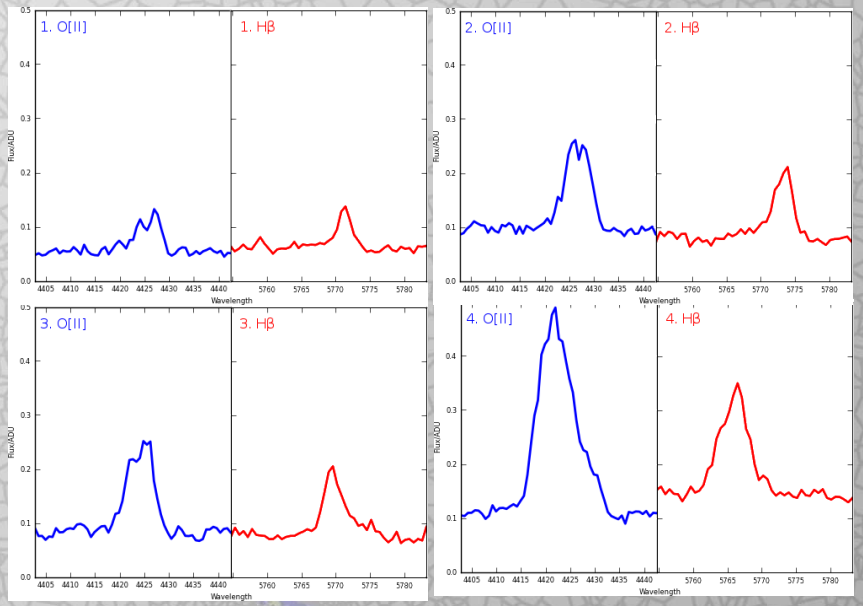
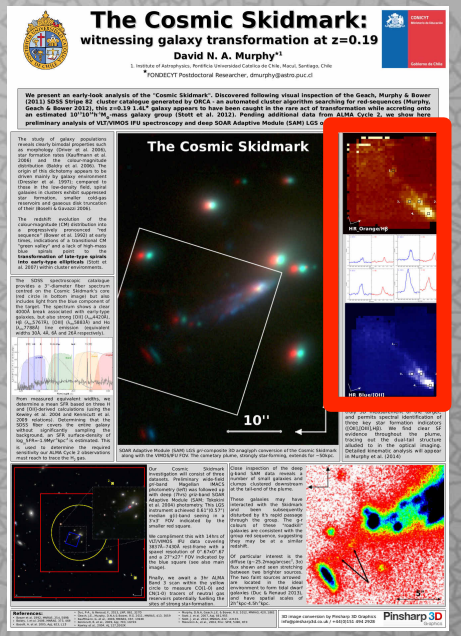
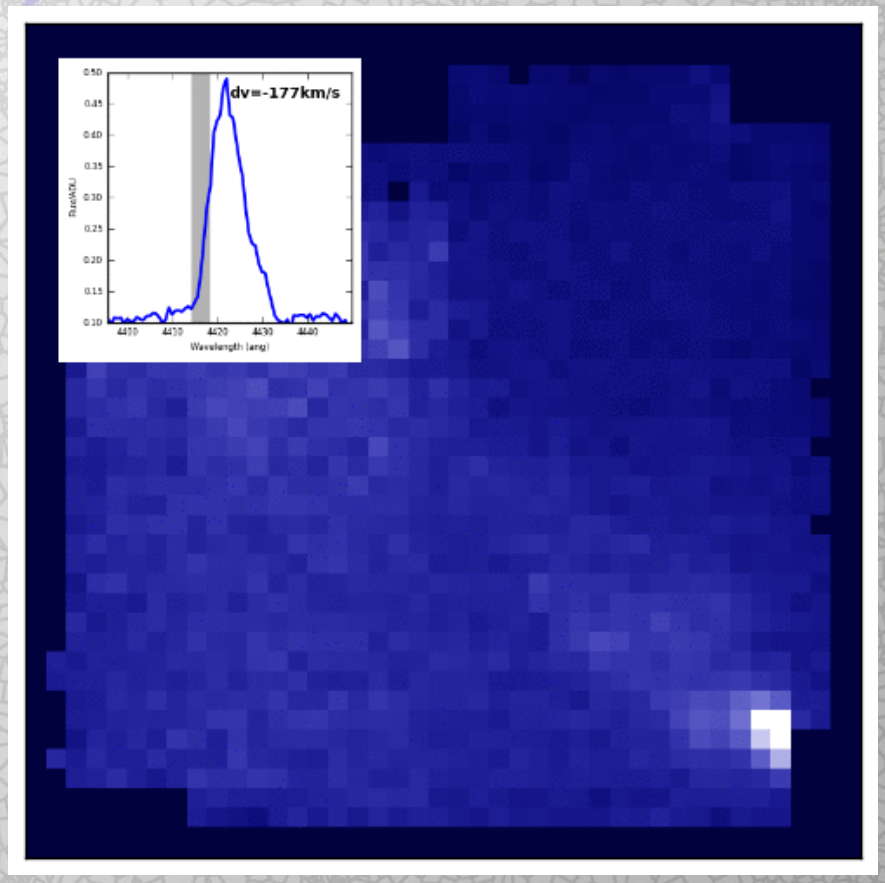
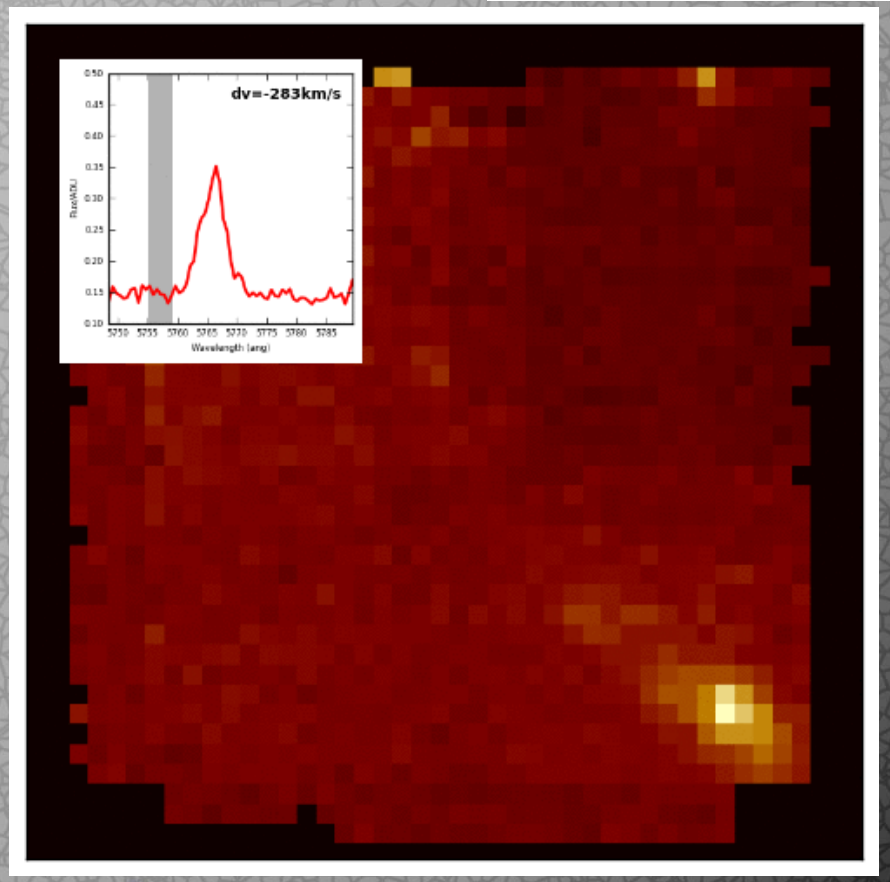


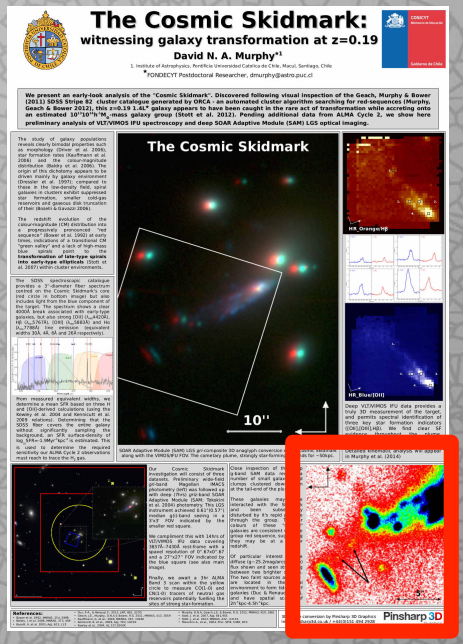


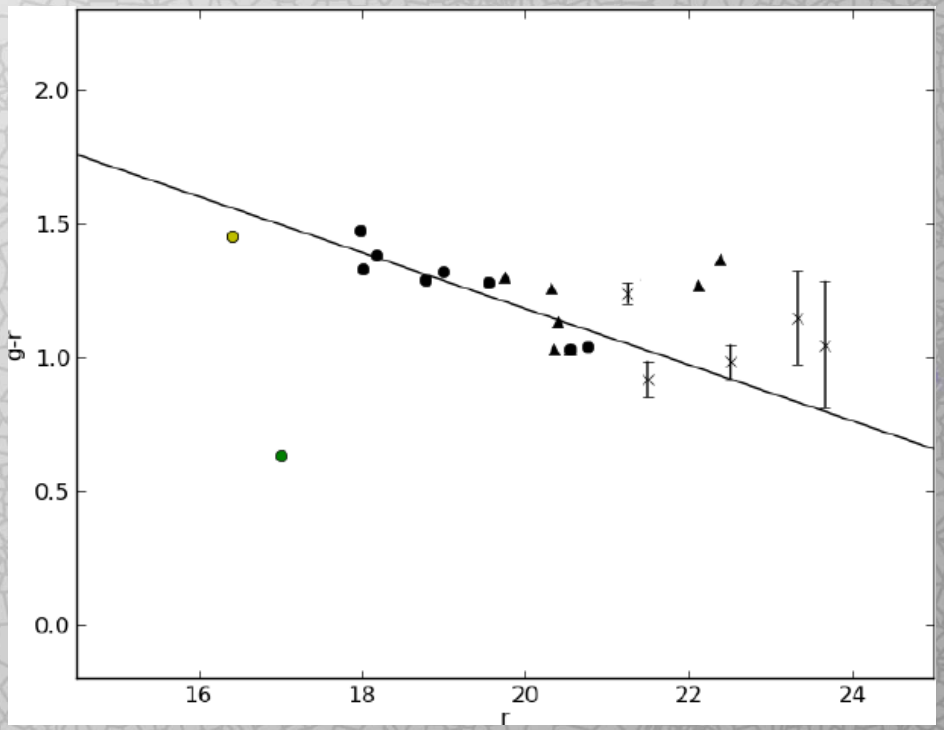


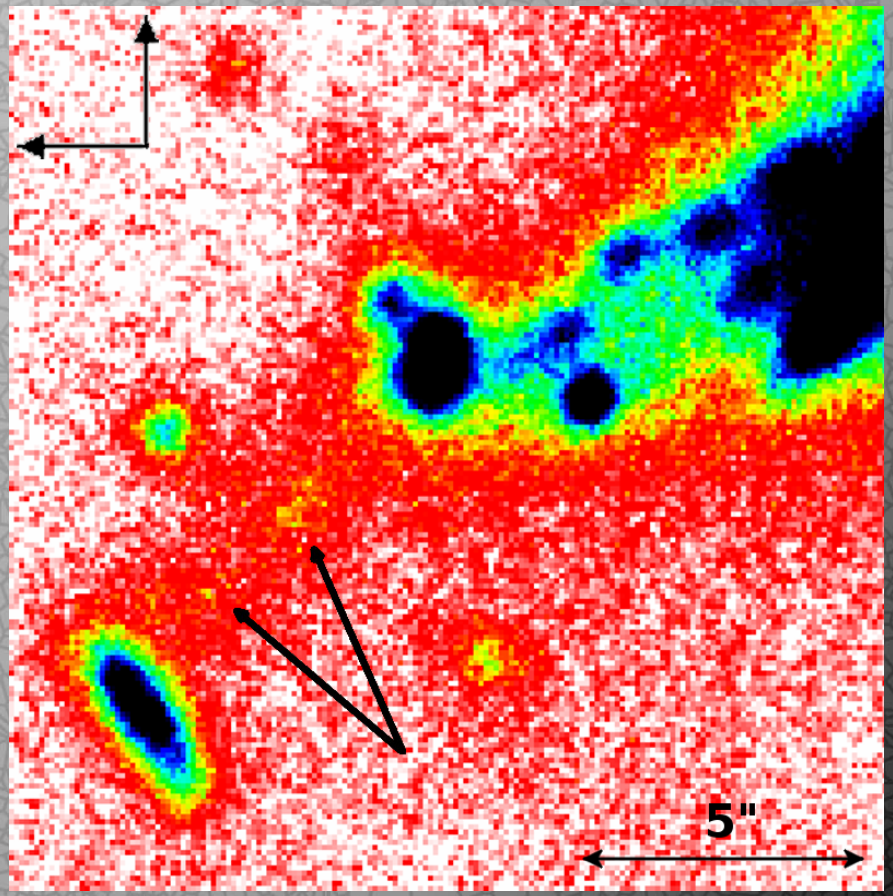


Deep SAM stacked imaging

- Stack both open and closed-loop g-band imaging
- Focus on the “tail” of the Skidmark
  - Roadkill: Galaxy harassment?
  - Diffuse flux between tail and disk galaxy
  - 3σ peak detections (faintest at 25.2mag/arcsec^2)
    - ~2-4kpc projected size
    - Possible tidal dwarf galaxies?







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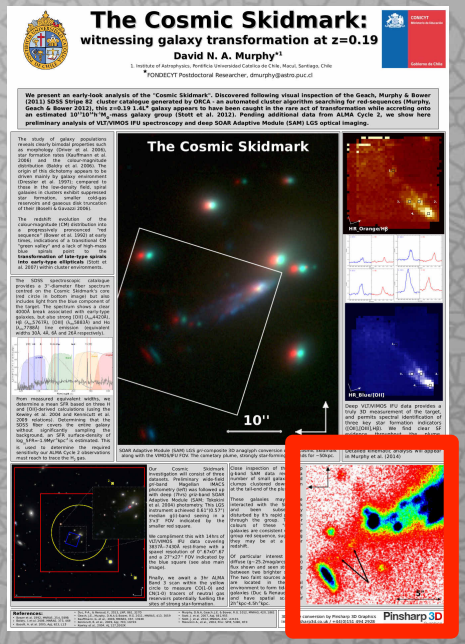
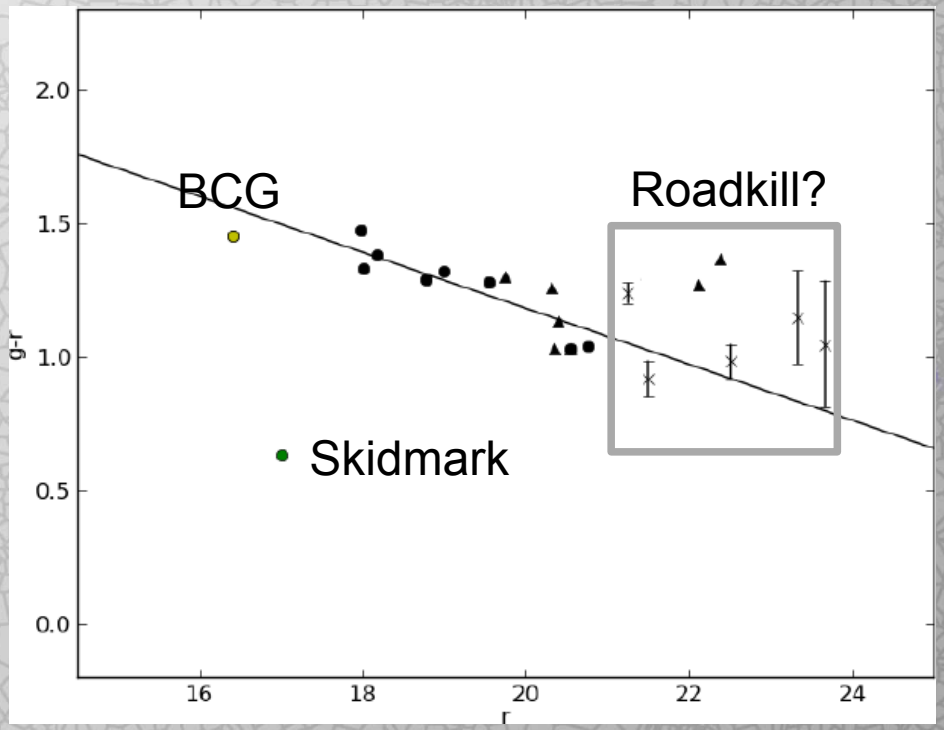
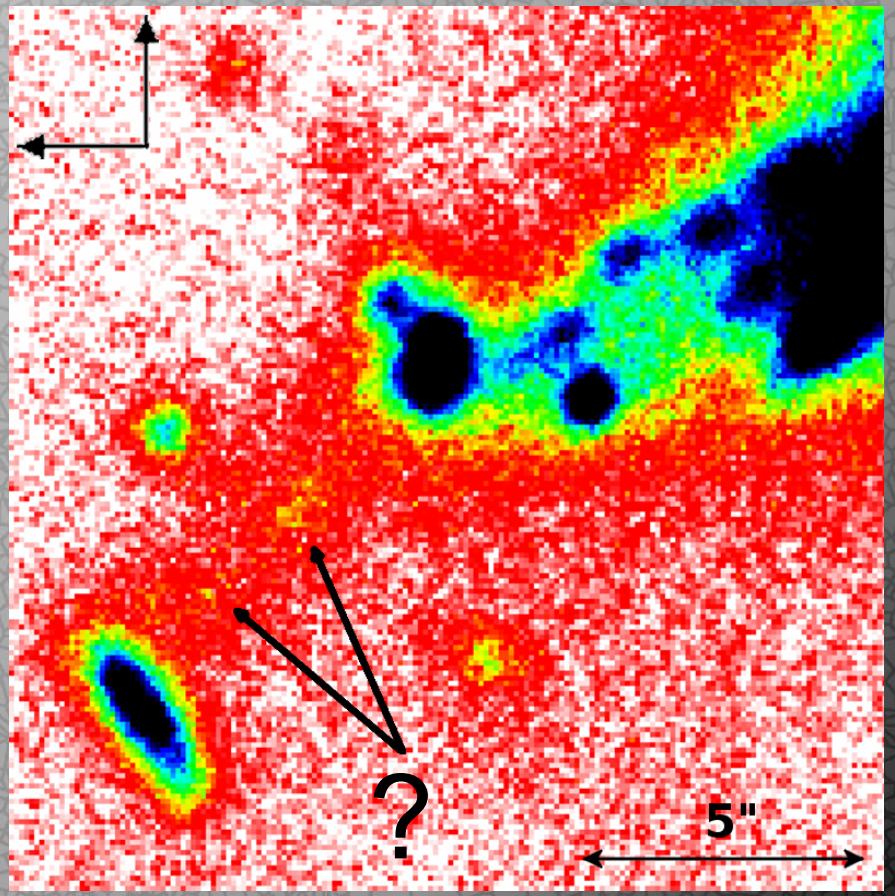
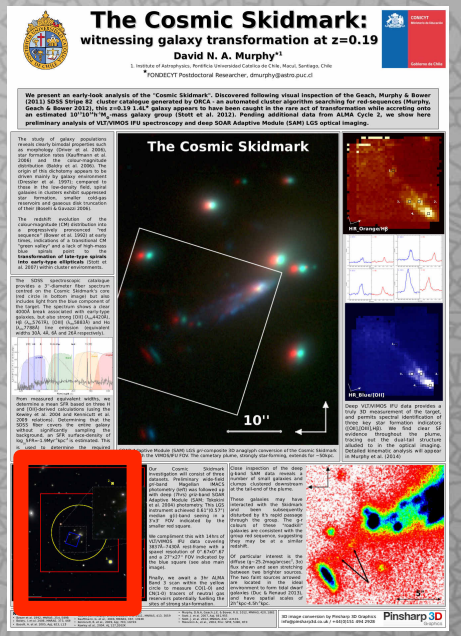
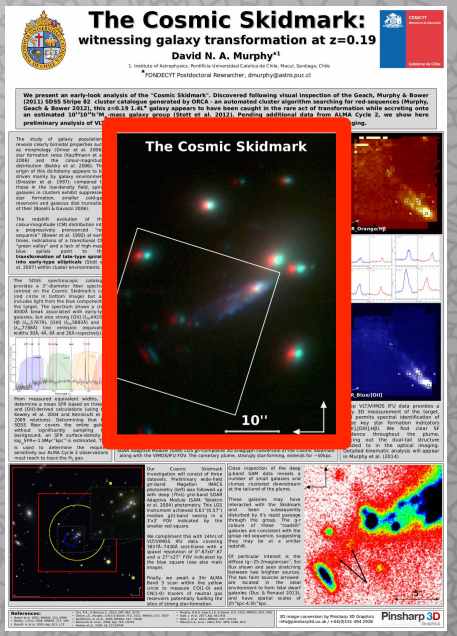




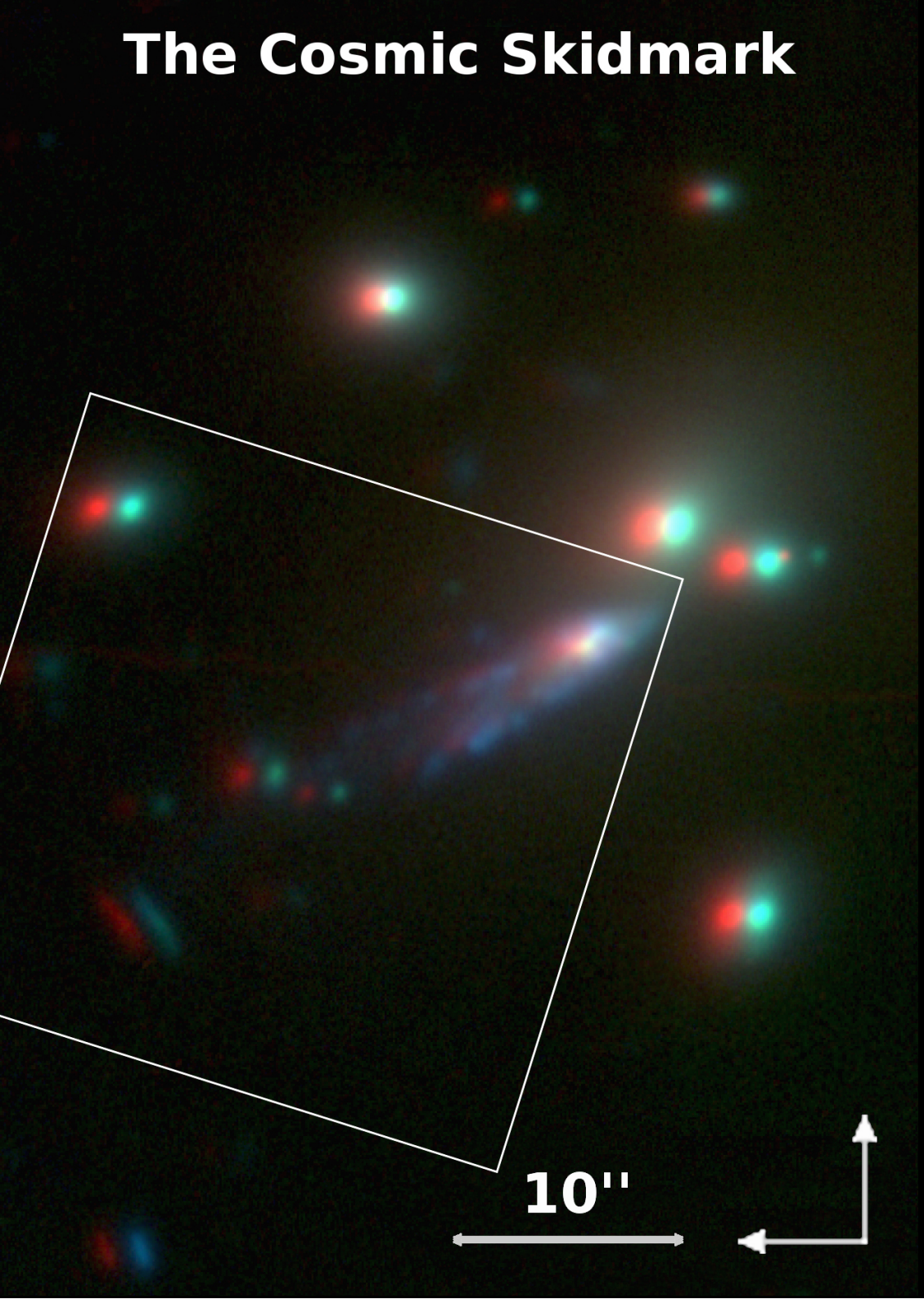


- Current and forthcoming Skidmark data highly complementary to “jellyfish”-type galaxies undergoing transformation
- IFU access to redshifted [OII]
- Tracking of SF over entire system
- In-queue: ALMA Band 3 CO(1-0), CN(1-0)
- Skidmark + group covered in single B3 pointing
- Couple cold gas (where it exists) to SF as identified with IFU: in-situ?
- ICM enrichment?
- Tidal dwarf galaxies?
- Stellar streams?




The Cosmic Skidmark:
witnessing galaxy transformation at z=0.19
David N. A. Murphy*1
1. Institute of Astrophysics, Pontificia Universidad Catolica de Chile, Macul, Santiago, Chile
*FONDECYT Postdoctoral Researcher, dmurphy@astro.puc.cl
We present an early-look analysis of the "Cosmic Skidmark". Discovered following visual inspection of the Geach, Murphy & Bower (2011) SDSS Stripe 82 cluster catalogue generated by ORCA - an automated cluster algorithm searching for red-sequences (Murphy, Geach & Bower, 2012), this z=0.19 1.4L* galaxy appears to have been caught in the rare act of transformation while accreting onto an estimated 10^13.5 M_sun galaxy group (Stott et al. 2012). Pending additional data from ALMA Cycle 2, we show here preliminary analysis of VLT/VIMOS IFU data revealing
The Cosmic Skidmark
10''
References:

The Cosmic Skidmark



- z~0.2 galaxy undergoing transformation
- 50kpc SF-tail
- IFU: two kinematically distinct plumes
- The future:
  - Stay tuned for papers on the CS
  - Awaiting ALMA C2 data for CO(1-0), CN(1-0)
  - Job-hunting
- dmurphy@astro.puc.cl