NoiseChisel: Noise-based detection of diffuse signal
and its host GNU Astronomy Utilities (Gnuastro)

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H2020 Innovative Training Network

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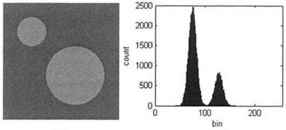
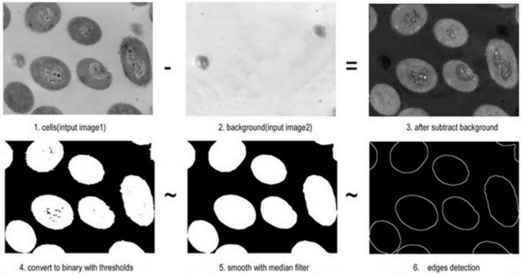
Slides available at http://akhlaghi.org/pdf/noisechisel.pdf

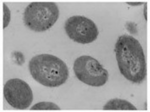
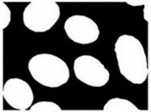
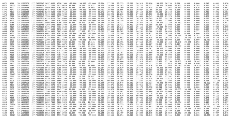
Traditional detection (sharp edges, high S/N)

When there are sharp and high S/N edges, a sufficiently high threshold can avoid the noise, so we can call them Signal-based detection.

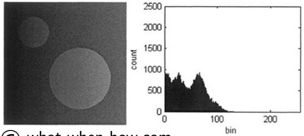




Outline is:

 → Threshold →  → Measure → 

This isn't sufficient for astronomical objects



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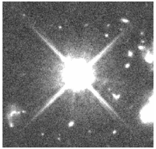
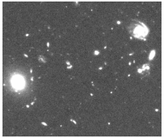
... don't have such sharp edges.
... can have a huge diversity of shapes and sizes.

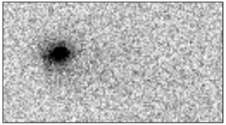
A star:



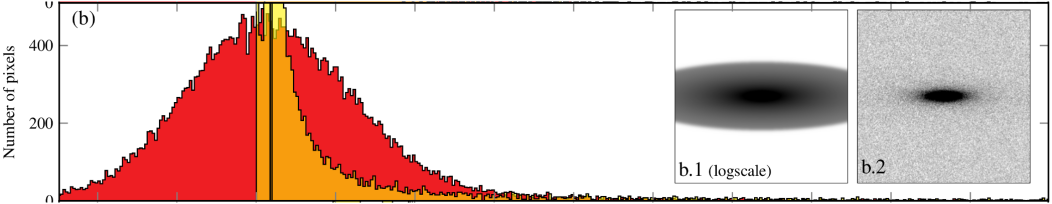
Some galaxies:



A main-belt comet:



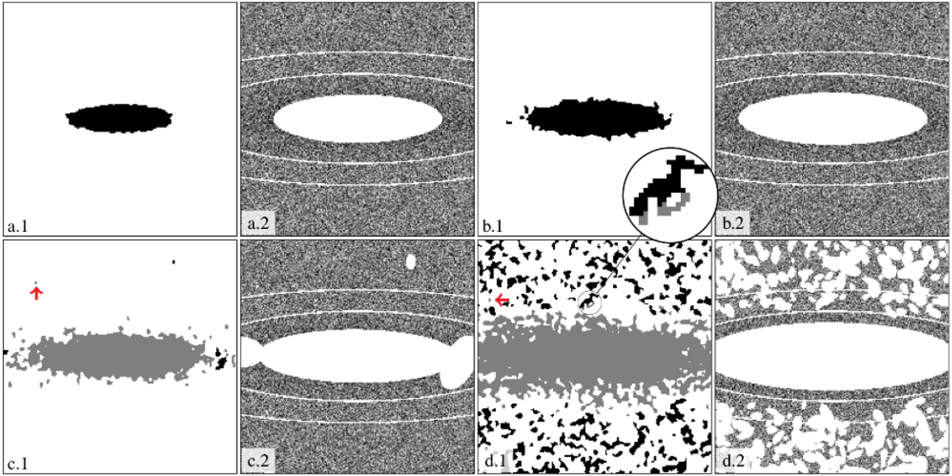
A mock galaxy: (Yellow/left-image: only signal. Red/right-image: signal and noise.)



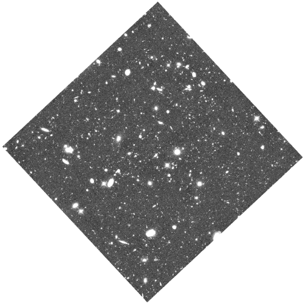
So for astronomical objects ...

... a threshold designed to avoid the noise (signal-based detection) will miss a lot of the signal. Decreasing the threshold will result in many false detections.

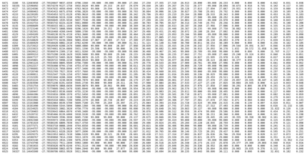
So our only hope is to try modeling the brighter parts.



Outline of most common detection software in astronomy



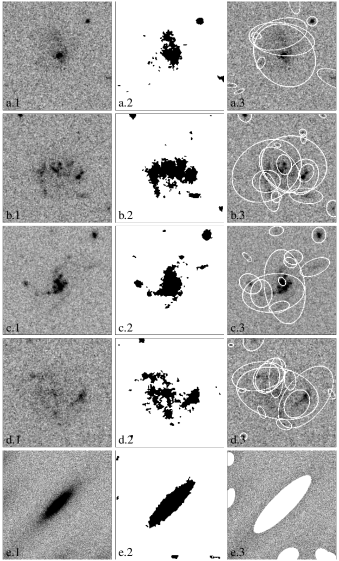
→ Software/Pipeline →



As a result:

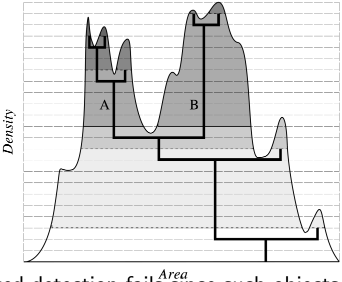
- Catalog production is computationally expensive.
- Decreases modularity, or creativity, and thus scientific objectivity.

Examples on real galaxy images



Real observed galaxies:

- Are not a clean ellipse.
  - Can be clumpy.
  - Can be diffuse.
  - Can have spiral arms.
  - Can be on the edge of the image.
- SExtractor's deblending uses layers and the parent is used to identify true peaks (systematic biases):



Signal-based detection fails since such objects do not satisfy its *a priori* assumptions.

Examples from Bacon et al (2017)

Rafelski+2015 (arXiv:1505.01160) use muliple runs of SExtractor on UDF.

Parameter	Deep	Shallow	Deep Deblend[a]	Shallow Deblend[a]	NUV	NUV Deblend[a]
detect_thresh	1.1	3.5	1.1	3.5	1.0	1.0
analysis_thresh	1.1	3.5	1.1	3.5	1.0	1.0
deblend_nthresh	32	32	8	8	32	8
deblend_mincont	0.01	0.01	0.3	0.3	0.01	0.3
detect_minarea	9	9	9	9	9	9
back_size	128	128	128	128	128	128
back_filtersize	5	5	5	5	5	5
back_photo_thick	26	26	26	26	26	26

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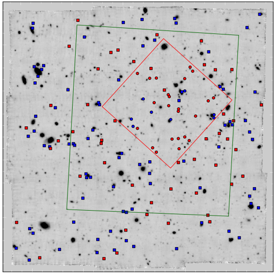
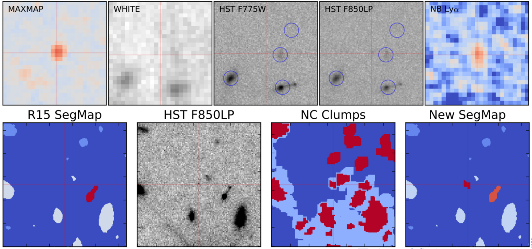
`deblend_mincont`	0.01	0.01	0.3	0.3	0.01	0.3
`detect_minarea`	9	9	9	9	9	9
`back_size`	128	128	128	128	128	128
`back_filtersize`	5	5	5	5	5	5
`back_photo_thick`	26	26	26	26	26	26

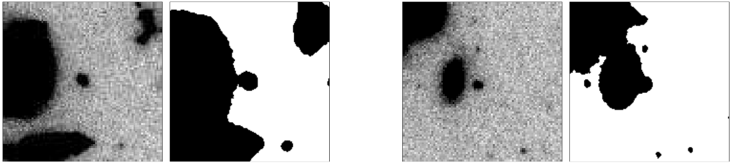
Bacon+2017 (arXiv:1710.03002) found 160 MUSE emission line objects not in Rafelski+2015. 88 (55%) had $> 5\sigma$ flux in a fixed aperture, and 57 (35.62%) were covered by SExtractor's segmentation maps (deblending problem).





In the segmentation map, but not in the catalog...

Failure to deblend near bright objects (75.44%).



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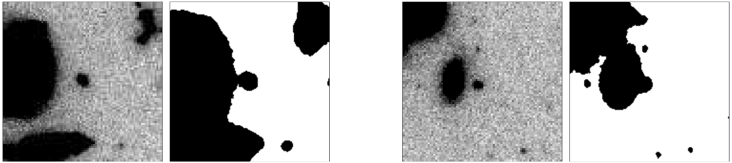
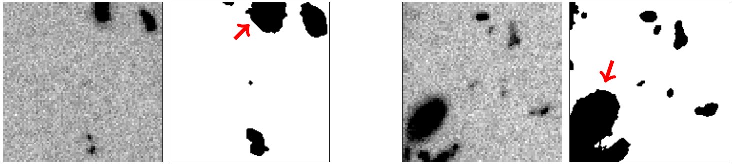
Failure to deblend near bright objects (75.44%).



Identify distant objects as one (8.77%).



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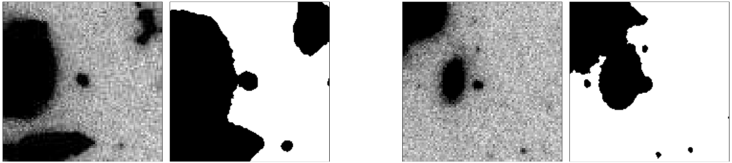

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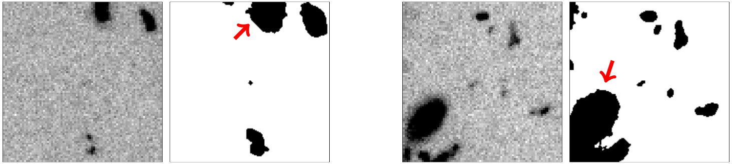
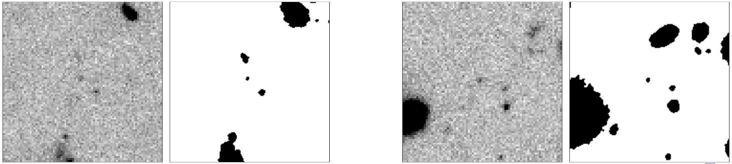


Manually removed from catalog (present in segmentation map. 15.79%).

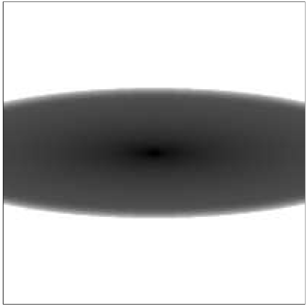


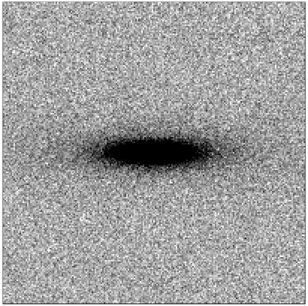
NoiseChisel – Detection – Basics

Aims:

- Threshold must be independent of the Sky.
- Impose negligible assumptions on signal.
- Accurately remove false detections.
- Use the actual data, not *a priori* models.

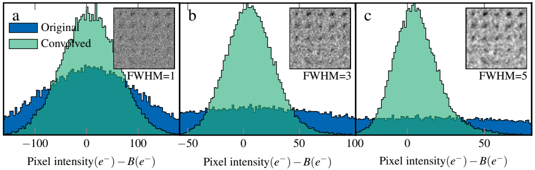
Model profile for demonstration:

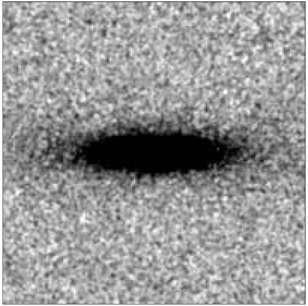




NoiseChisel – Detection – Convolution

- Convolution decreases dynamic range.
- **So:** Gaussian kernel, FWHM= 2pixels.



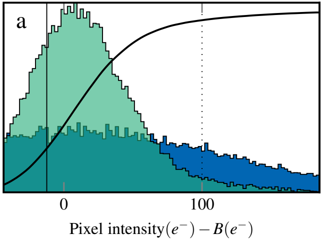


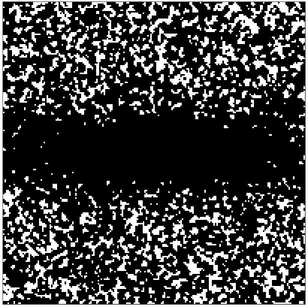
Since we are concerned with the sampling (noise) a-priori knowledge of the PSF (which relates to the signal) is no longer necessary and the same parameters work accurately on space-based and ground-based images.

An assumption removed. Works on any image.

NoiseChisel – Detection – Threshold

- Use the cumulative pixel distribution.
- The threshold is set to the 0.3 quantile of the image.





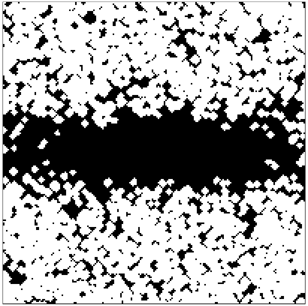
Since the threshold is now independent of Sky, we can accurately estimate the Sky once detection is complete.

✓ Threshold no longer defined by Sky.

NoiseChisel – Detection – Erode

Erosion: Foreground becomes background if touching.

- **Or:** we expand the holes.
- **Or:** we carve off the signal.



NoiseChisel name: a tool to carve off noise

No assumption on the shape of the object.

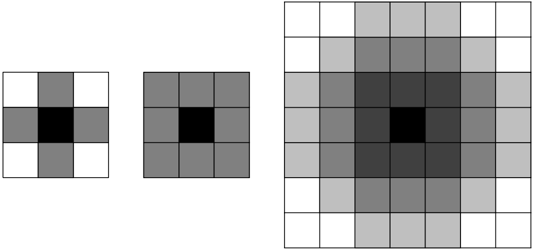
NoiseChisel – Detection – Open

Definitions:

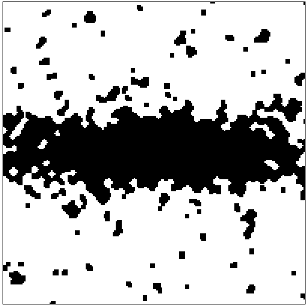
- **Dilation:** Inverse of erosion.
- **Opening:** Erosion followed by dilation.

In practice:

- Separates all the steps below.
- We use eight connectivity here (and four connectivity in the previous step.)

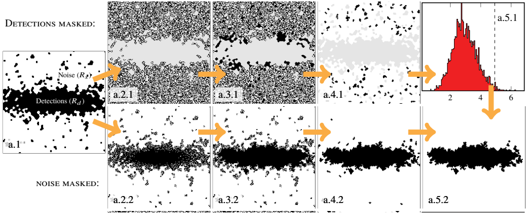


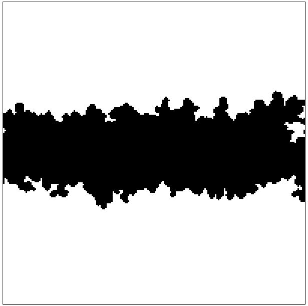
a b c



NoiseChisel – Detection – Remove false detections

- Use the ambient noise as a reference.
- The S/N of definite false detections is used:

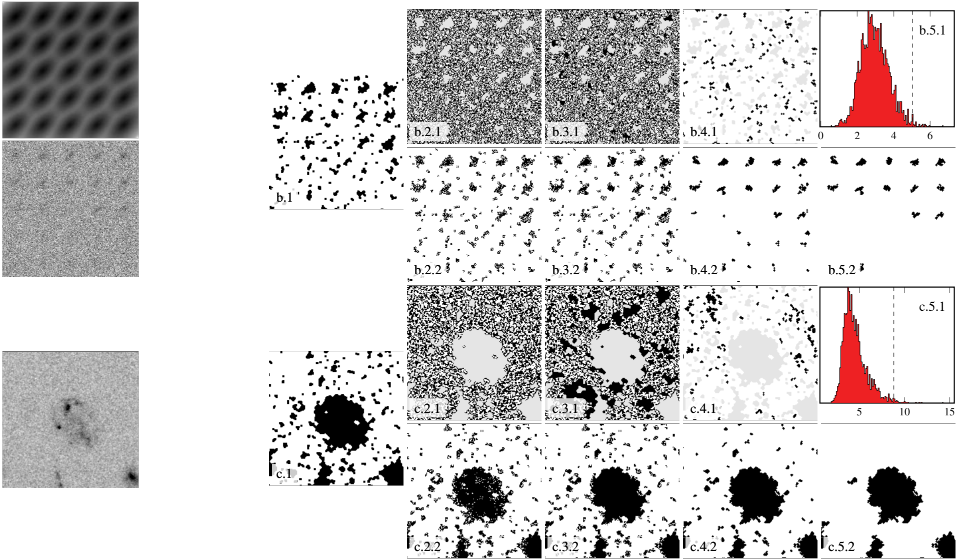




False detections are successfully removed with high accuracy.

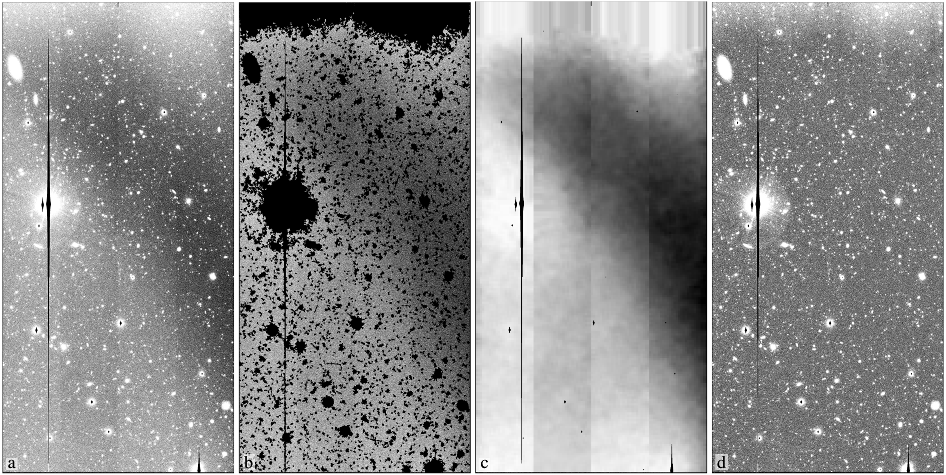
False detections are now identified for any image without hand-input values.

NoiseChisel – Detection – Remove false detections – Two more examples

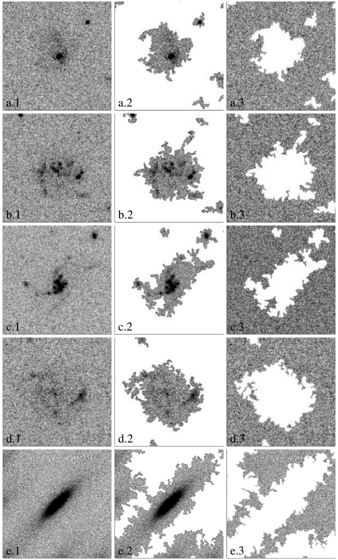


NoiseChisel - Accurate Sky estimation (after detection)

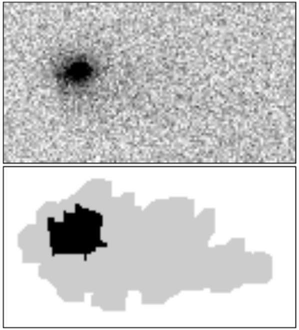
- Subaru SuprimeCam image after basic reduction and early HSCPipe processing.
- Sources are first detected, then the Sky value is measured (non-parametrically).
- CCD amplifier signature (bias subtraction residuals) removed.



NoiseChisel – Detection – Other real targets

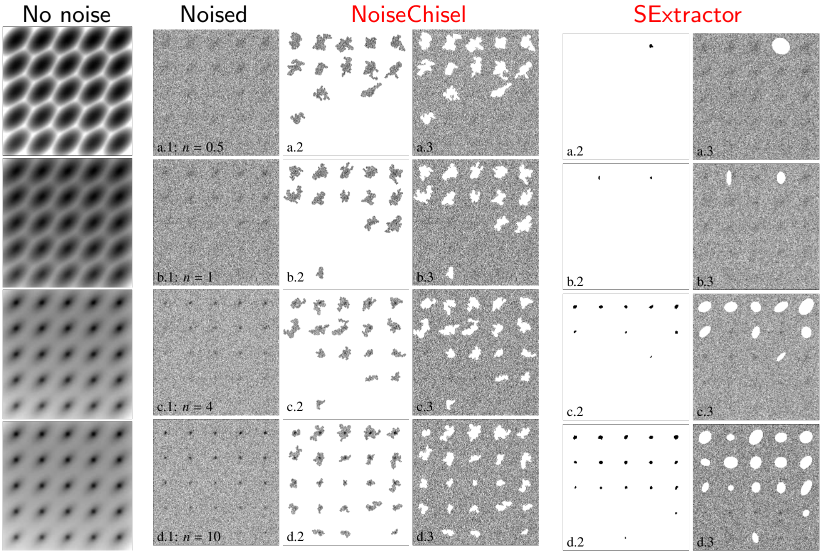


Detection of the diffuse and ultra-low surface brightness tail of a main-belt comet.

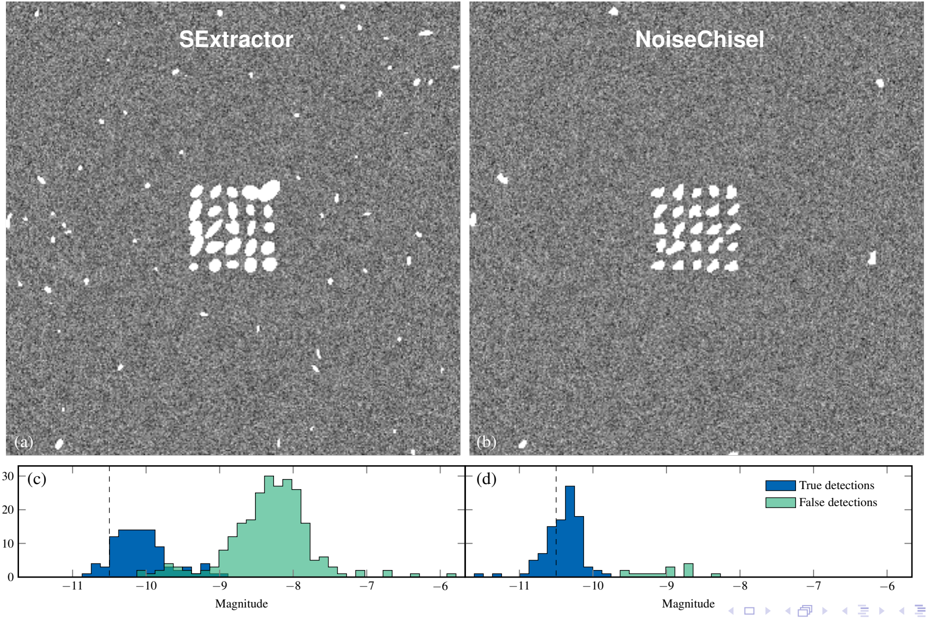


Noise-based detection: Works on any image with any target shape.

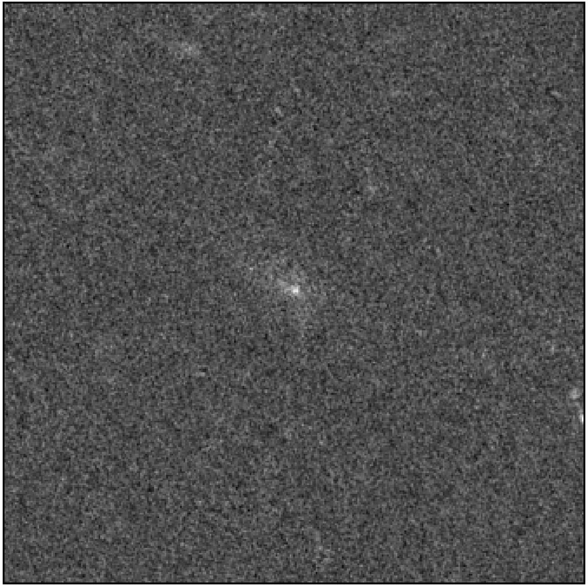
Rough completeness demo on mocks: NoiseChisel/SExtractor



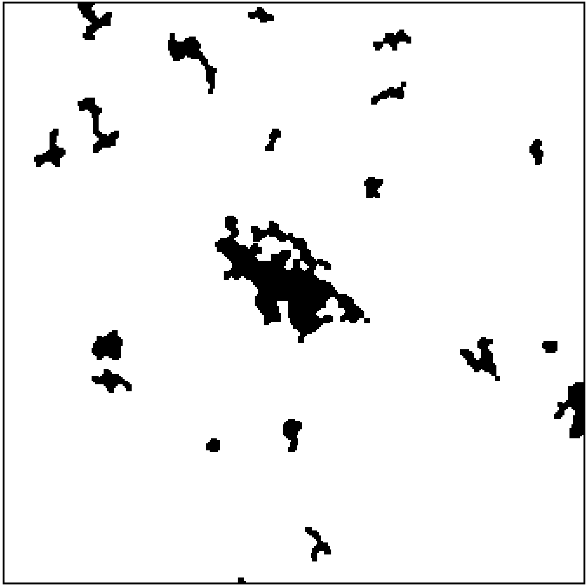
Purity and Magnitude dispersion test



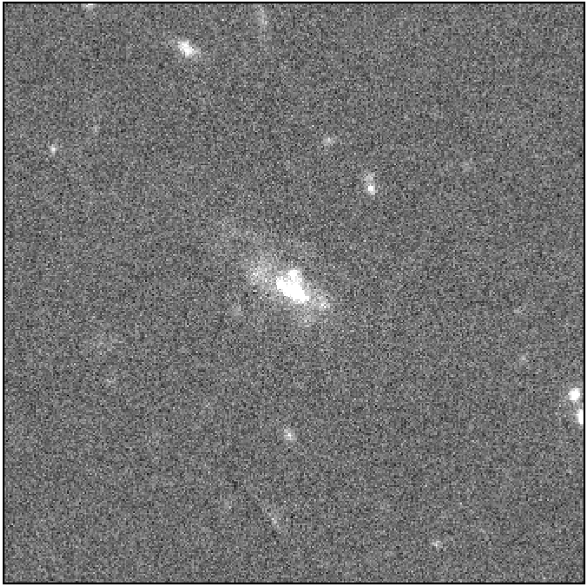
New growth demo: input (F435W, $\sim$ 700sec HST exposure)



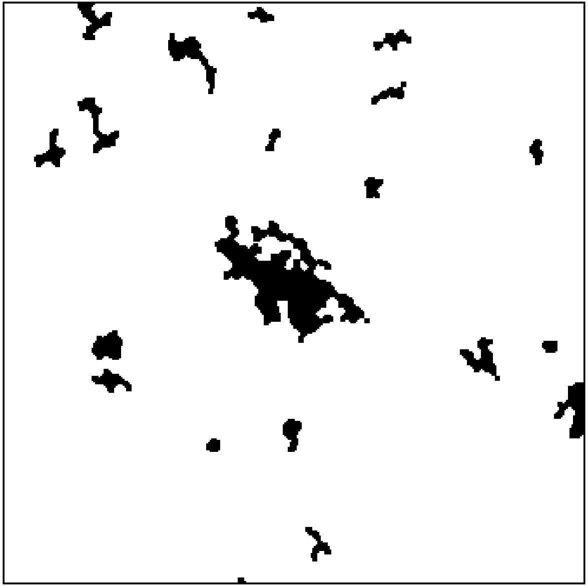
New growth demo: No growth



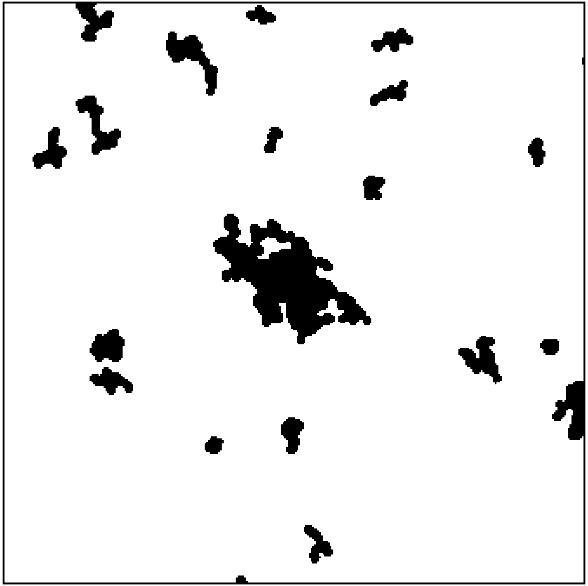
HST F435W ($\sim$ 1600sec exposure)



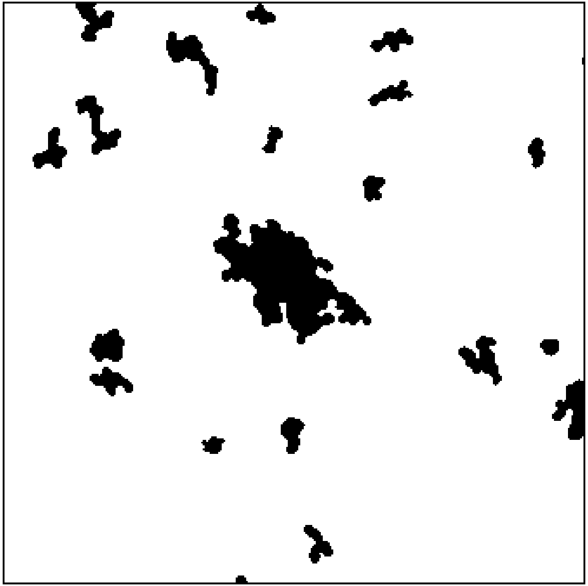
New growth demo: No growth



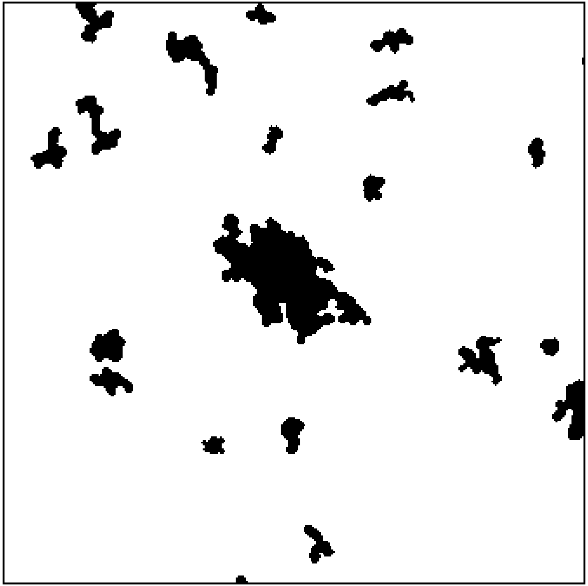
New growth demo: growth quantile: 0.99



New growth demo: growth quantile: 0.97

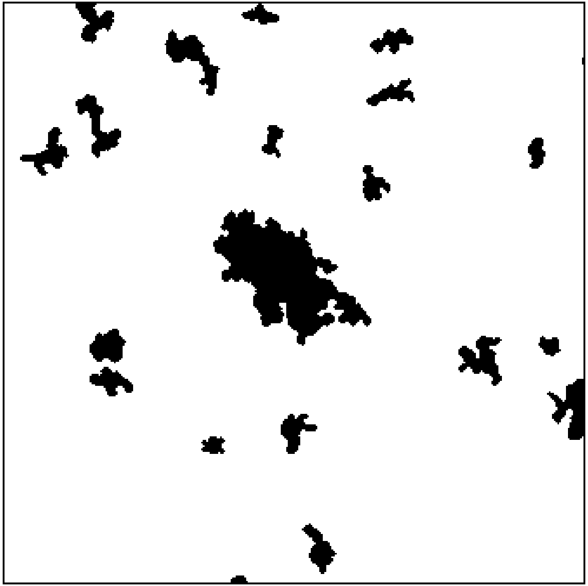


New growth demo: growth quantile: 0.95

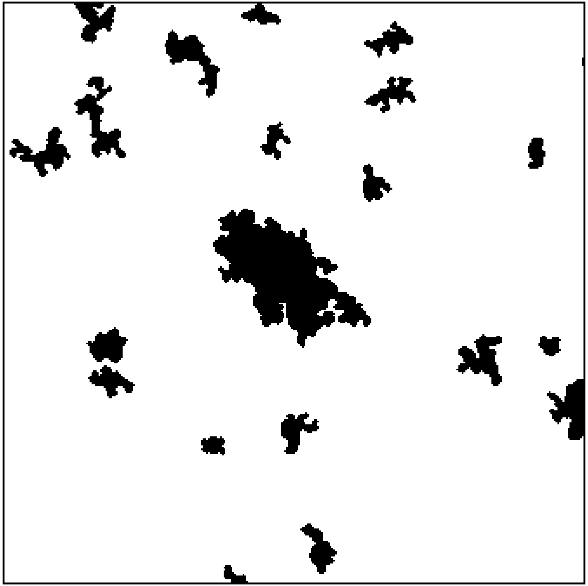


New growth demo: growth quantile: 0.92

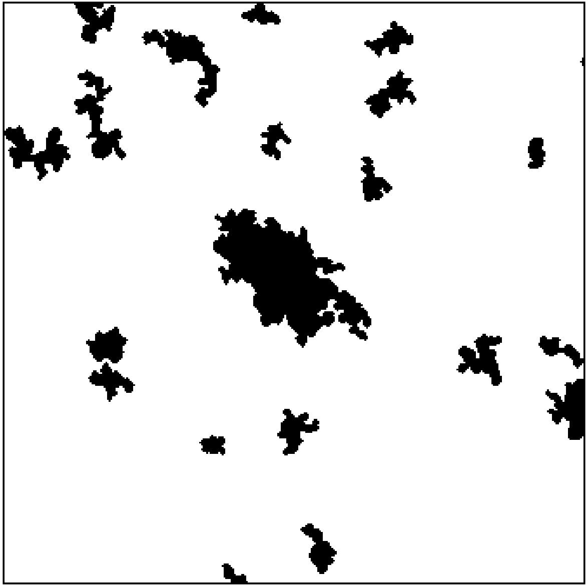
New growth demo: growth quantile: 0.90



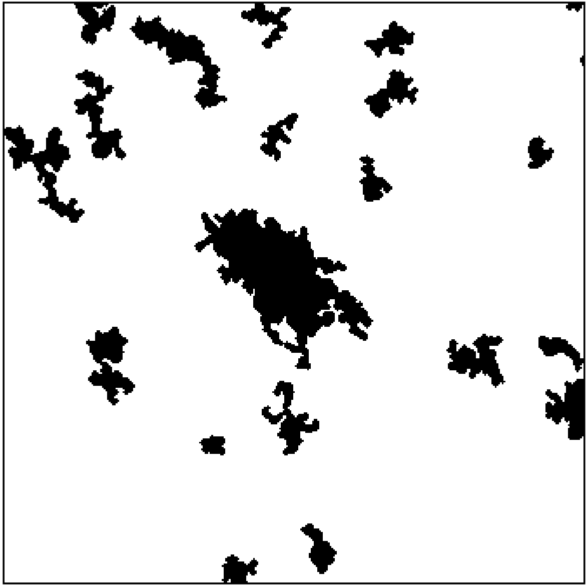
New growth demo: growth quantile: 0.85



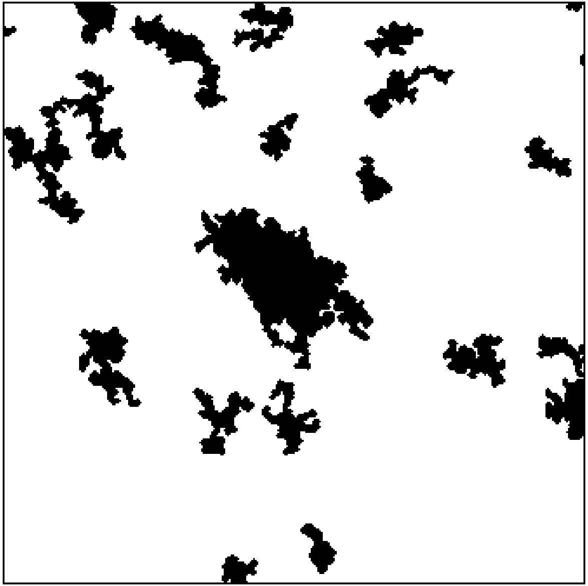
New growth demo: growth quantile: 0.80



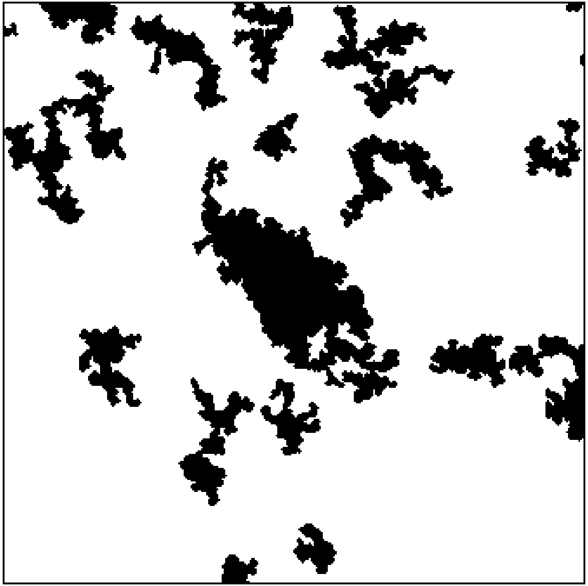
New growth demo: growth quantile: 0.75



New growth demo: growth quantile: 0.70



New growth demo: growth quantile: 0.65



New growth demo: growth quantile: 0.60

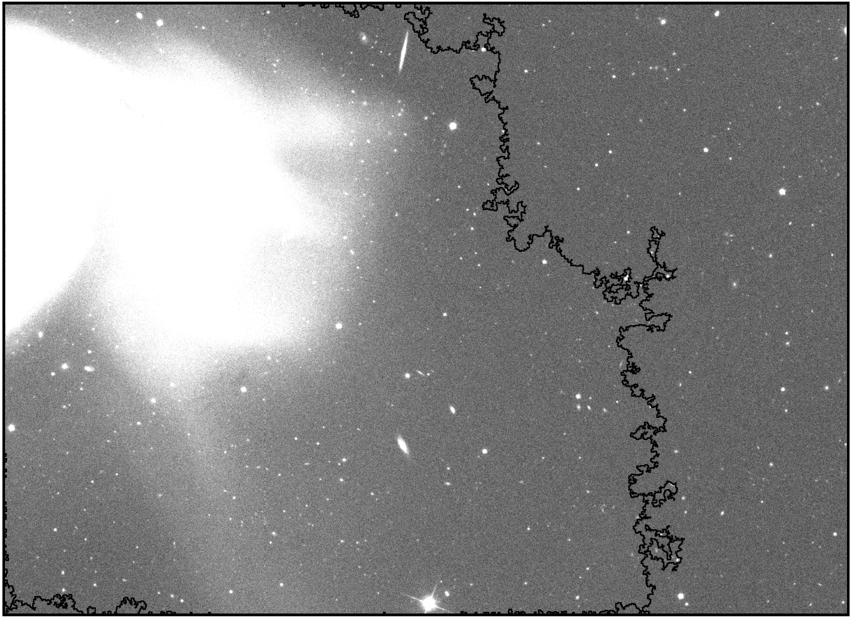
M51 with 12-inch telescope (10hr): `https://i.redd.it/jfqgpqg0hfk11.jpg`

M51 (single exposure SDSS image: $\sim$ 1min, 2.5m telescope)

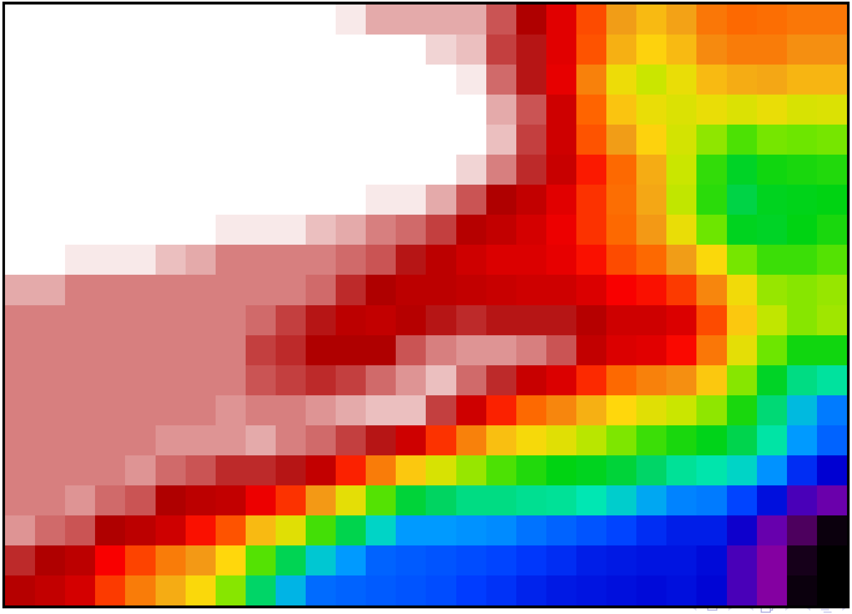
M51 (flux truncated to see the outskirts)

M51 Detected pixels

M51 detected edge (S/N$\approx$ 0.25 = 1/4 or 28.3 mag/arcsec^2)



M51 sky: undetected signal still remains!



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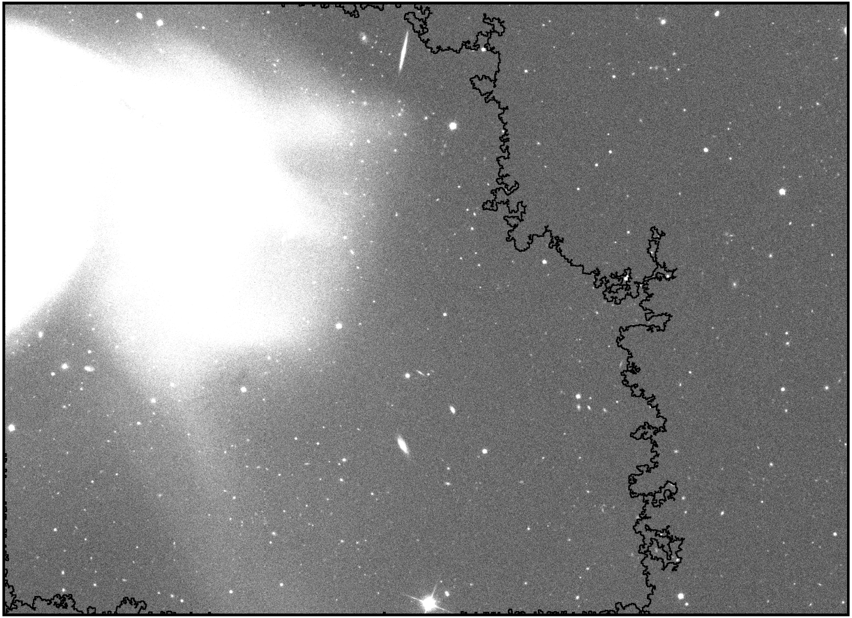
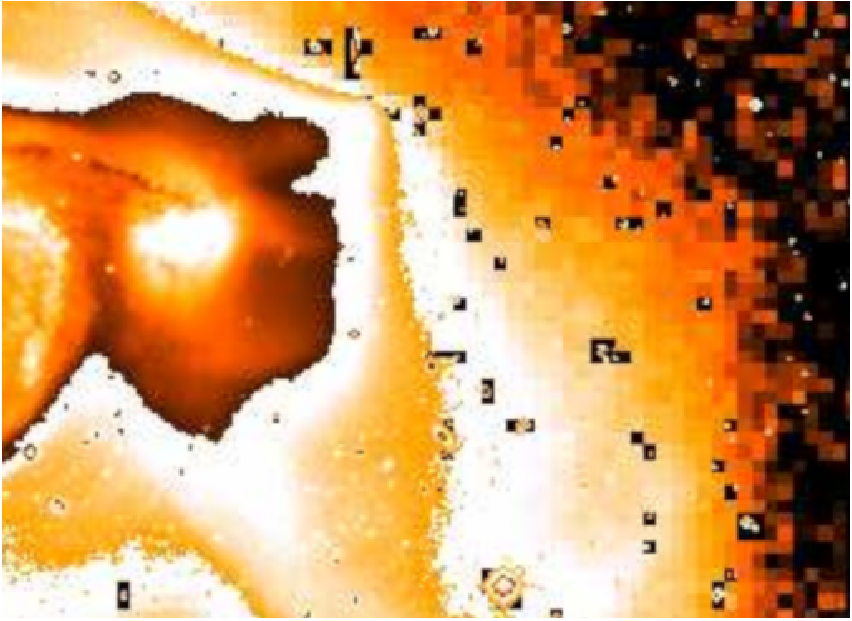
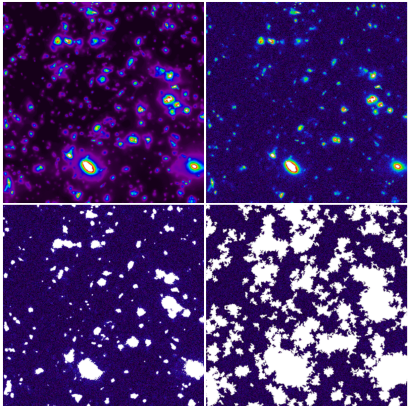
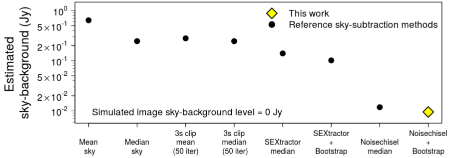


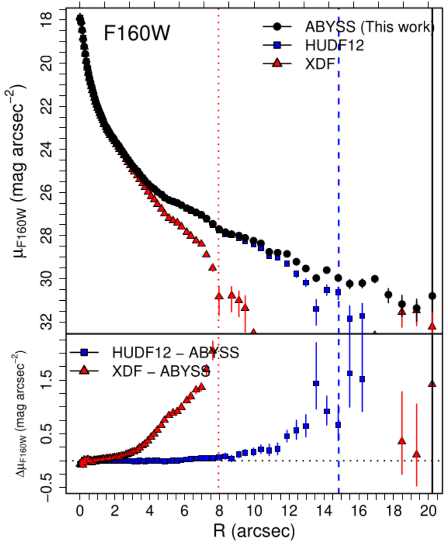
M51 by Watkins et al. 2015 (10hr with 1m Burrell Schmidt)



Re-processing HST images with NoiseChisel (Borlaff et al. 2019, arXiv:1810.00002)







GTC/OSIRIS spectroscopy of a $z = 6.5$ protocluster (Calvi et al. 2019: arXiv:1908.01827)

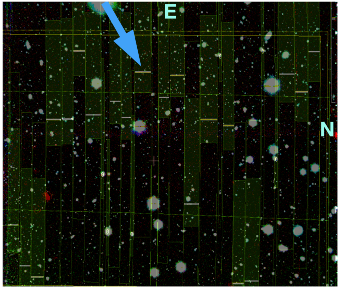
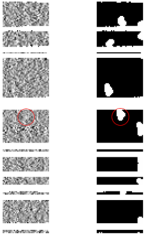


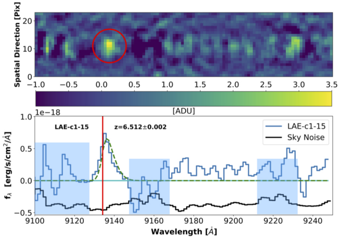
Figure 2. The mask used for the MOS in the OSIRIS/GTC observations. The mask includes 20 science objects and 6 guiding stars. The blue arrow indicates the slit associated with C1-01, one of the confirmed LAEs from Ouchi et al. (2010), included for comparison.



(a) Sky mask on the noise image

(b) Clumps detection

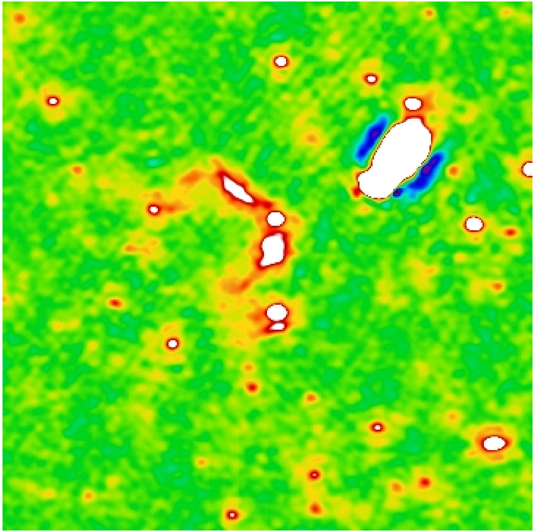
Figure 4. Example of *Noise Chisel* detection process on LAE-c1-15. **Left:** a part of the 2D spectrum with the sky emission lines masked. **Right:** the detected clumps with S/N larger than the preset threshold. The grey-scale shows higher ADU counts in lighter region. The red circles indicate the detected source.



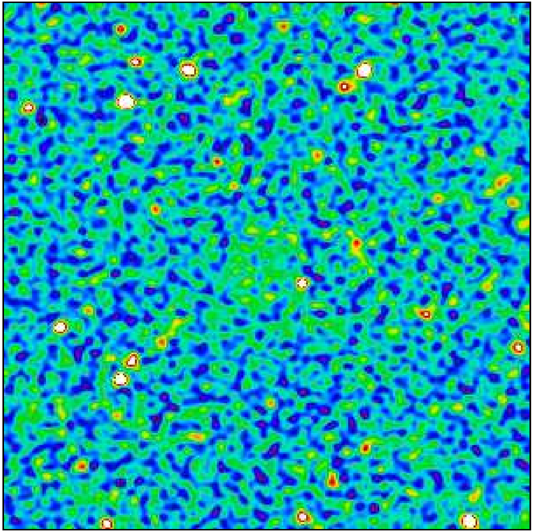
(b) C1-15

EMU examples

Abell S1136 (Thanks to Peter)

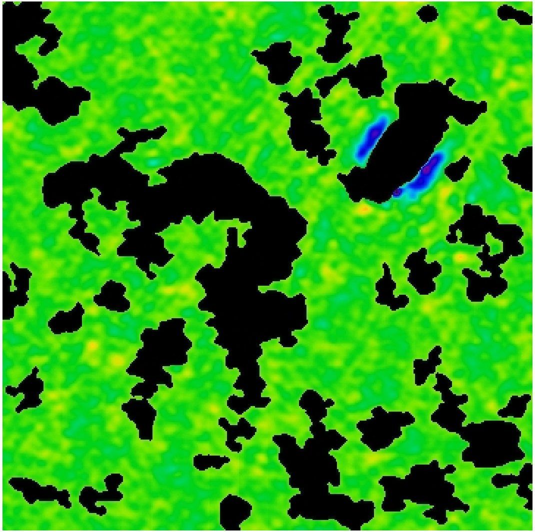


Diffuse blob (Thanks to Rami)

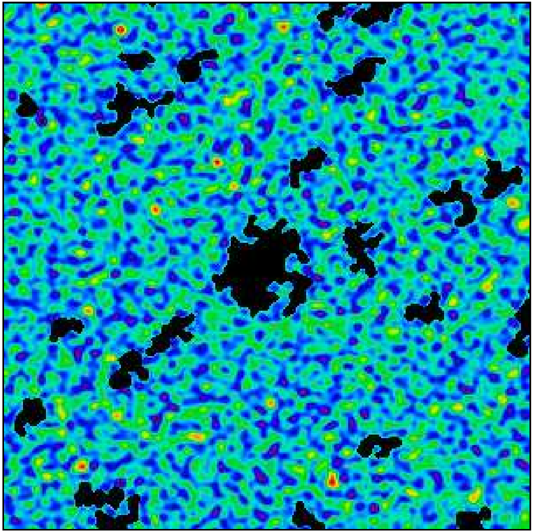


EMU examples (NoiseChisel detections masked)

Abell S1136

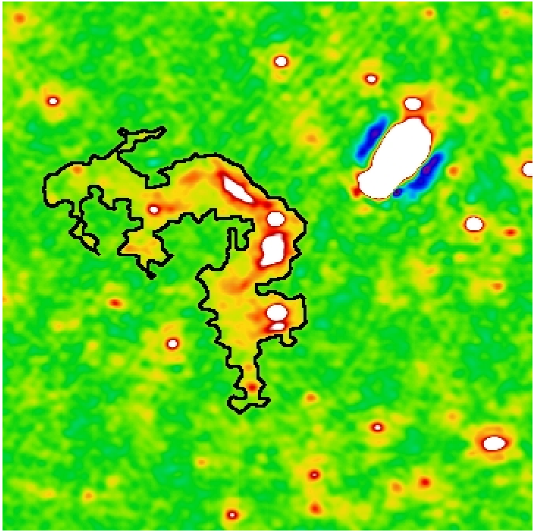


Diffuse blob

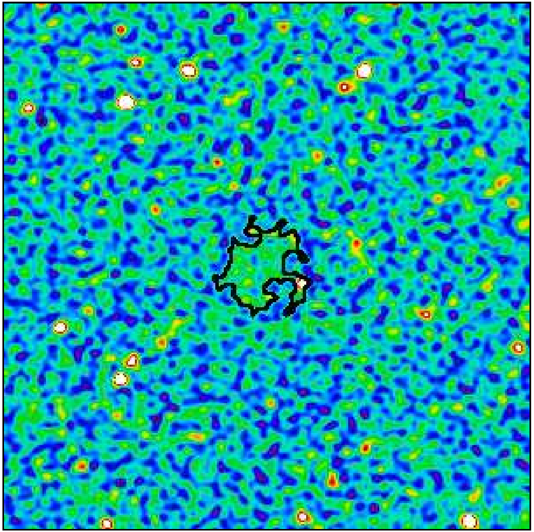


EMU examples (outer edges)

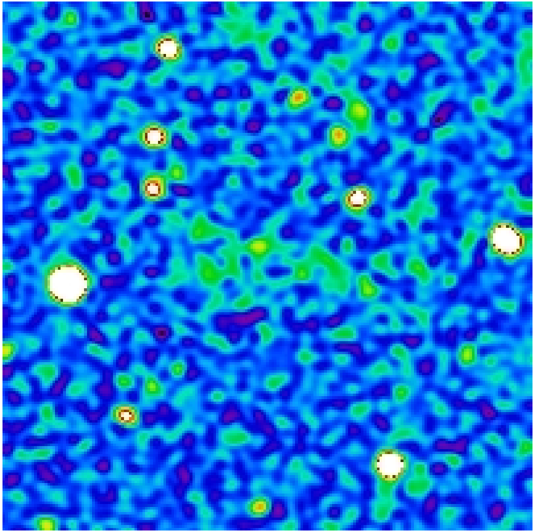
Abell S1136 (outer SB: 6.16×10^{-5}Jy/beam)

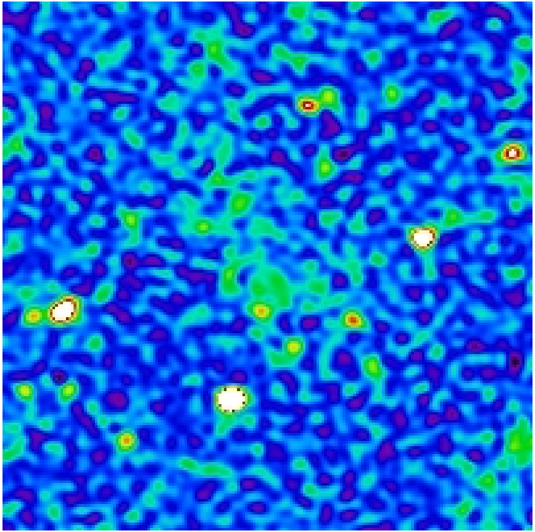


Diffuse blob

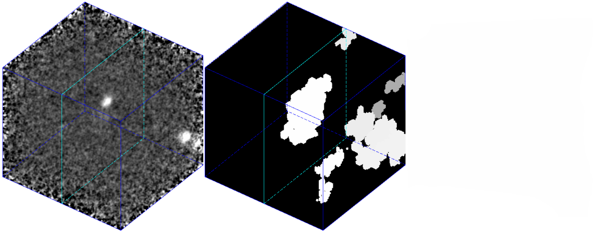


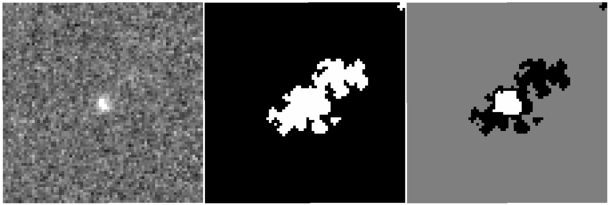
Objects with similar SB as the diffuse blob





Comming soon: 3D NoiseChisel (shown here: a Lyman-α emitter in the MUSE UDF10)



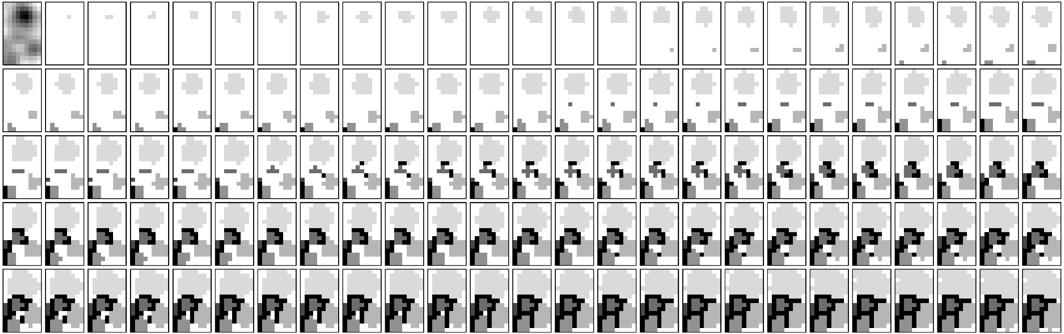


Subscribe to Gnuastro's announcement mailing list to be informed when 3D-enabled NoiseChisel is released:
https://lists.gnu.org/mailman/listinfo/info-gnuastro

"Coming soon" image from http://www.colprop.com

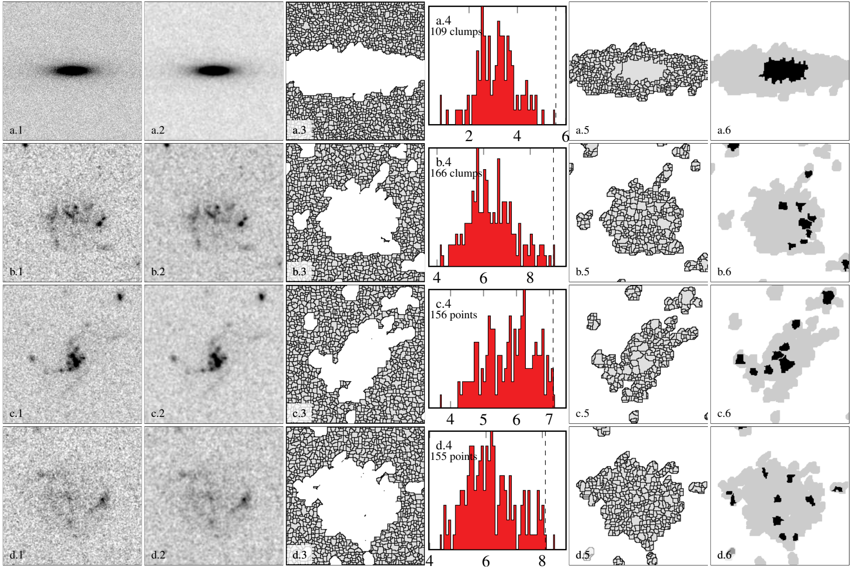
Segment: clumps through the watershed algorithm

A clump is found using the maximum resolution of the convolved image:



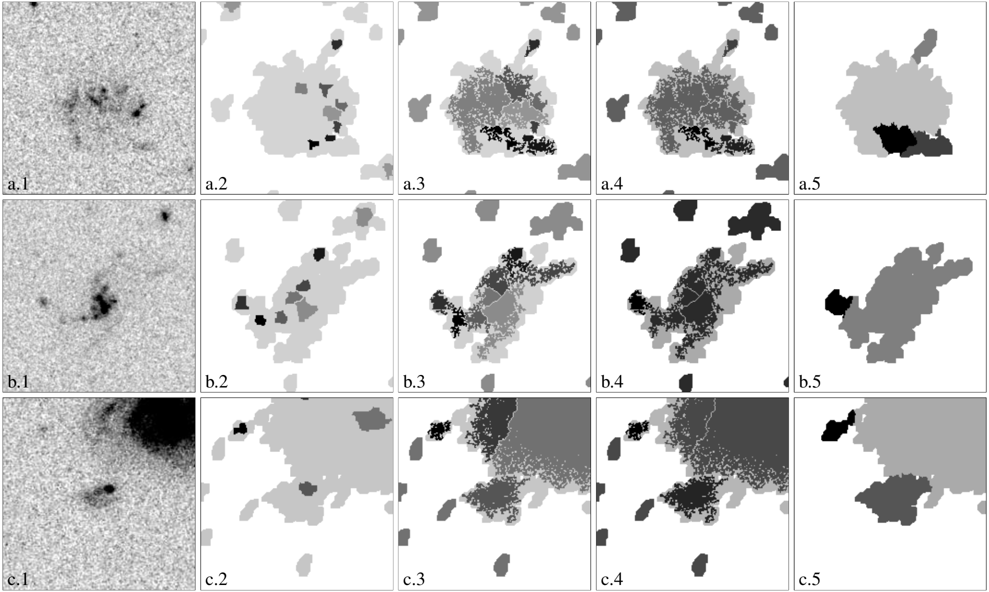
No more layers

Segment: True clumps using ambient noise as reference

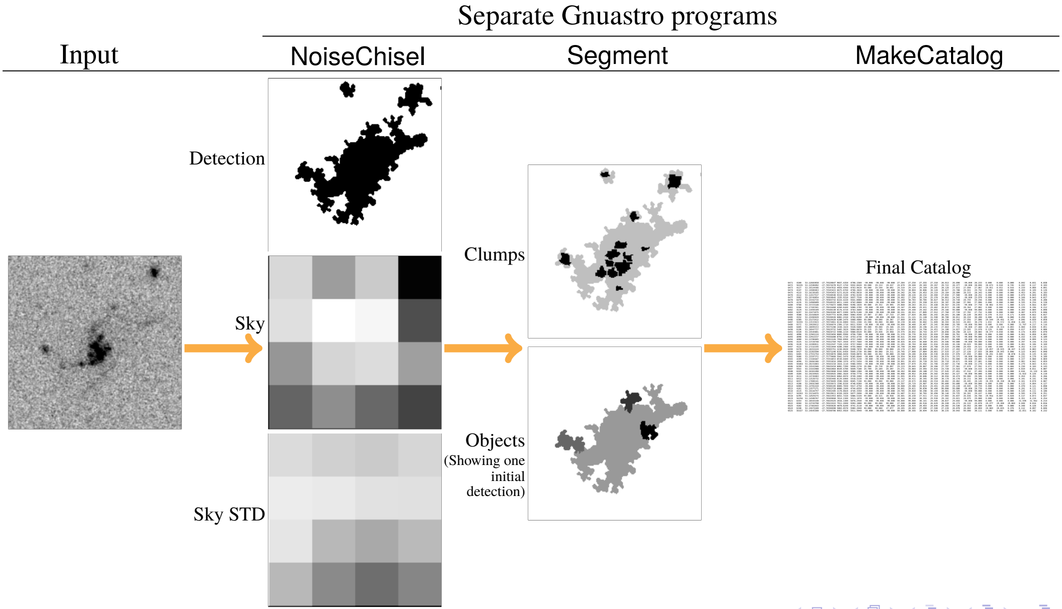


True clumps are found independent of user input.

Segment: objects



Summary of catalog generation process



GNU Astronomy Utilities (Gnuastro): NoiseChisel's parent software

- Gnuastro is a large collection of programs and libraries for astronomical data manipulation and analysis.
- Programs are run directly on the command-line with no mini-environment (unlike Python or IRAF).
- They are thus fast and easy to combine with other command-line programs. For example:

```
$ astnoisechisel image.fits
$ asttable binary-table.fits | awk '$4>10'
```

- The Gnuastro experience is thus very familiar and similar to basic Unix-like command-line tools (e.g., `ls` and `cat`).
- Gnuastro has a complete and up-to-date manual (like many GNU software).

GNU (+35 years old) is one of the oldest free or open-source software communities. For the GNU label, a software has to be refereed by the GNU Evaluation Committee, and has to abide by the time-tested GNU Coding Standards.

Current list of Gnuastro programs (sorted alphabetically)

- Arithmetic: arithmetic operations on multiple datasets (images).
- BuildProgram: Compile, link and run C/C++ code with Gnuastro's library.
- ConvertType: FITS images to and from text, JPEG, TIFF, EPS or PDF.
- Convolve: Convolve data with a given kernel.
- CosmicCalculator: Cosmological calculations.
- Crop: Crop region(s) from an image and stitch several images if necessary.
- Fits: View and manipulate FITS file extensions and header keywords.
- MakeCatalog: Make catalog of labeled images, see arXiv:1611.06387.
- MakeNoise: Make (add) noise to an image.
- MakeProfiles: Make mock 2D profiles (e.g., Sérsic, Gaussian, Moffat).
- Match: Match two given catalogs in 1D or 2D within an aperture.
- NoiseChisel: Detect signal in noise, see arXiv:1505.01664.
- Segment: Segment detections.
- Statistics: Statistical calculations on the input dataset.
- Table: Read/write FITS (binary or ASCII) or plain text tables.
- Warp: Warp image to new pixel grid.

Summary

- *NoiseChisel* is a method/tool to detect signal very deep into the noise.
- *Segment* is a method/tool to identify peaks independent of the parent and do a first order watershed segmentation.
- *MakeCatalog* is a program to generate a catalog from the output of NoiseChisel or MakeCatalog.
- GNU Astronomy Utilities (Gnuastro) is a highly robust and refereed set of tools containing the programs above (along with many other useful programs) that is guaranteed to be free to use for the future.
- For these slides, see `http://akhlaghi.org/pdf/noisechisel.pdf`.