Microlensing Pipelines: From Pixels to Lightcurves

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STScI

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Sagan Summer Workshop

Overview of Talk

1) Microlensing from space

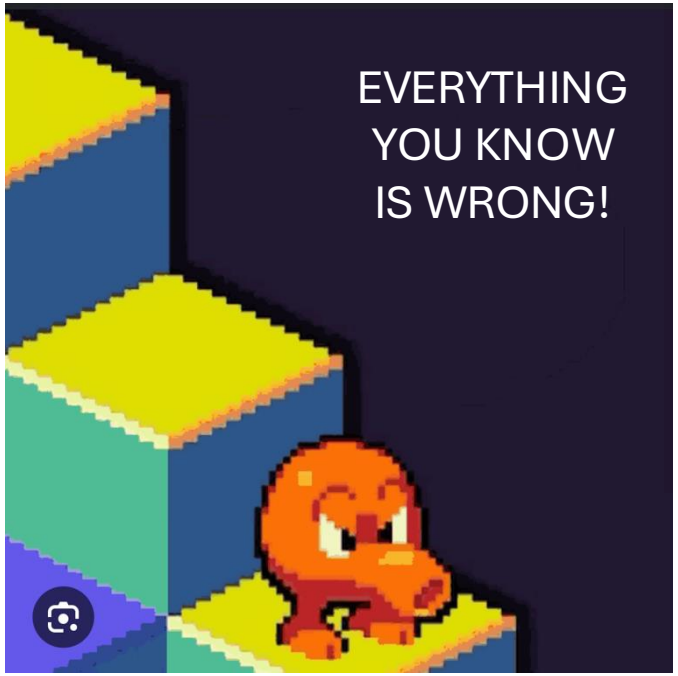
- Improvements from ground, but…
  - under-sampling
  - PSFs
  - proper motions
  - detailed fitting

2) New Pipeline, familiar products

- Rigorous stacks → DIs
- Fluxes + positions several ways

3) Additional products

- Cutouts
- Advanced DIA

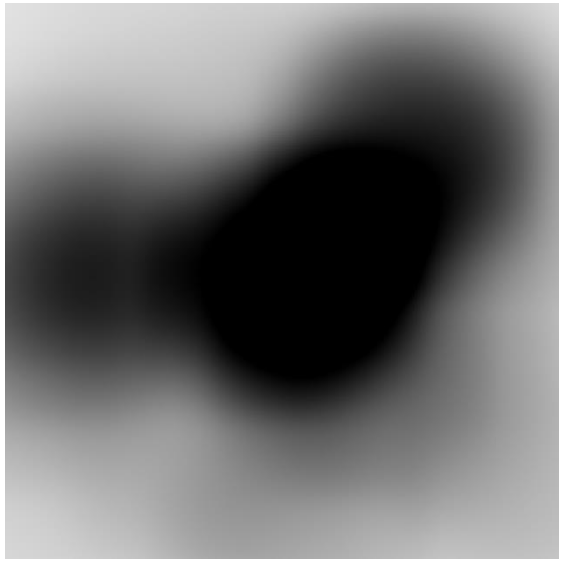


Q*BERT SCREEN 4

Ground vs Roman

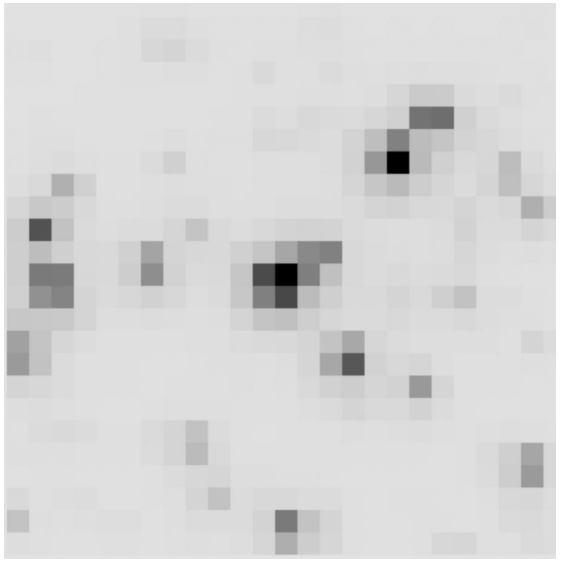
Ground:

- 0.25″ × 0.25″ pixels
- ≥ 0.5″ seeing, variable
- well sampled
  - easy to analyze



Roman:

- 0.1″ × 0.1 ″ pixels
- 0.1″ PSF
- under-sampled
  - need specialized s/w



HST –vs- JWST –vs- ROMAN

HST

undersampling?
astrometry?

- Single mirror ✅
- Low earth orbit
- breathing changes PSF over orbit
- 1-parameter family (focus)

JWST

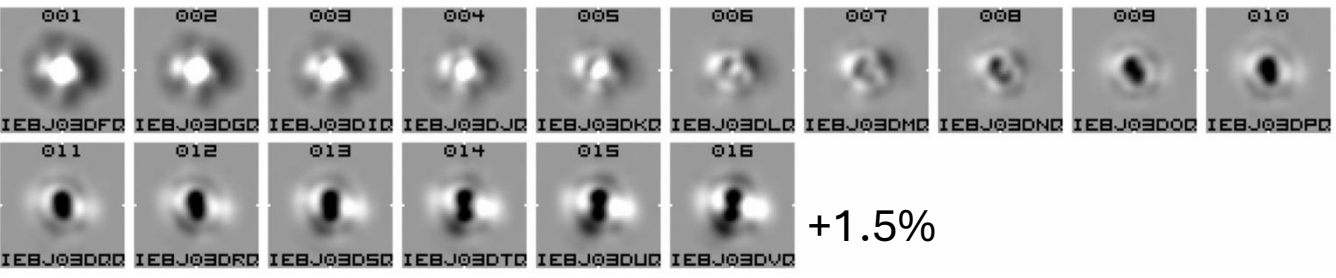
good enough for AstroDrizzle ?

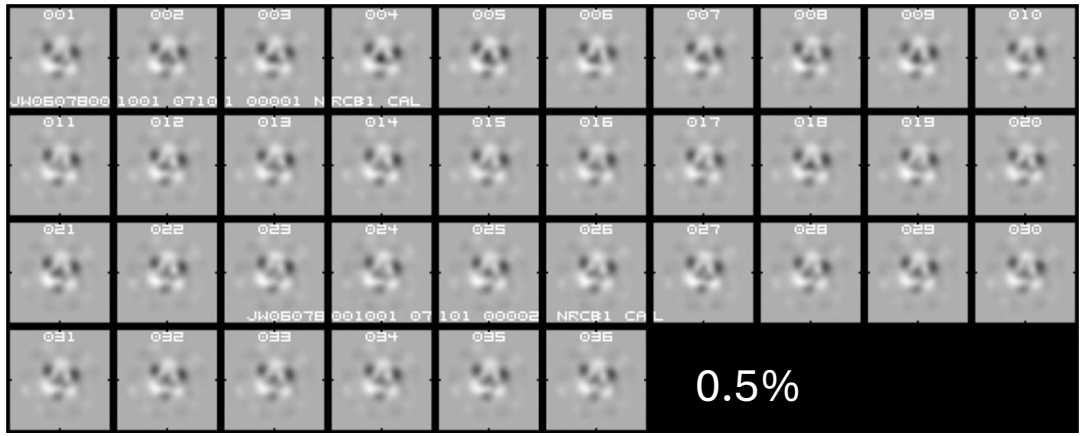
- 18 mirrors
- Stable L2 orbit ✅
- stable over days, slight PSF changes over months
- 18^2 param fam

ROMAN

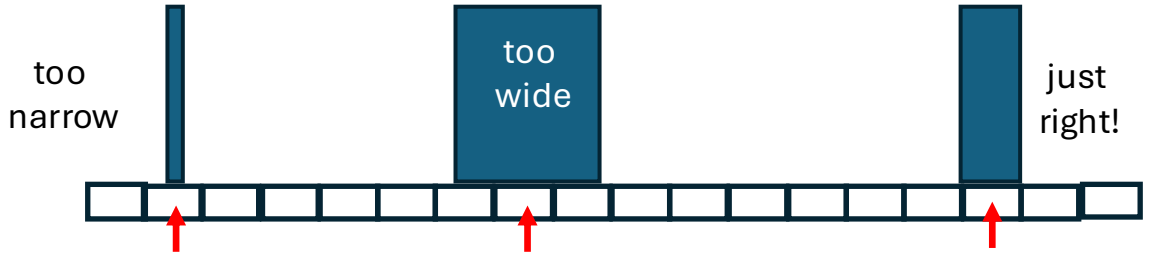
Very Tight Req'ts on PSFs and astrometry!

- Single mirror ✅
- Stable L2 orbit ✅
- Best of both worlds? ?

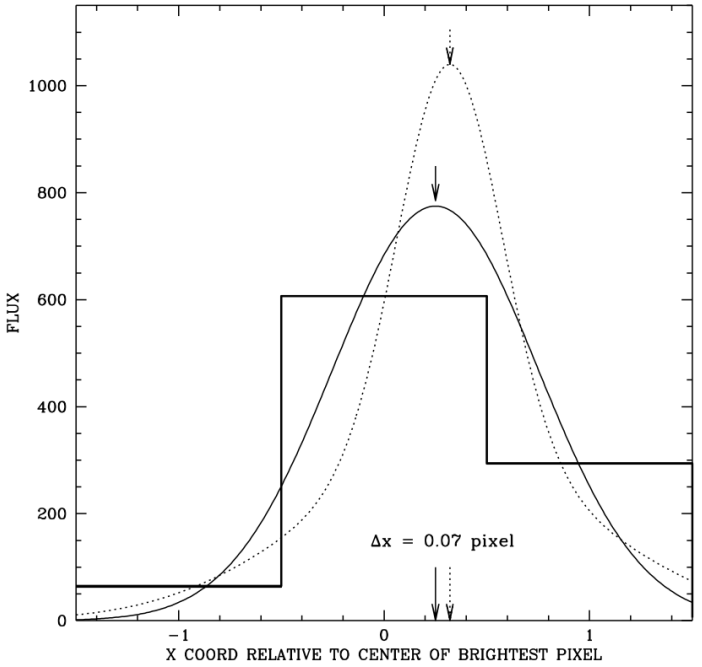




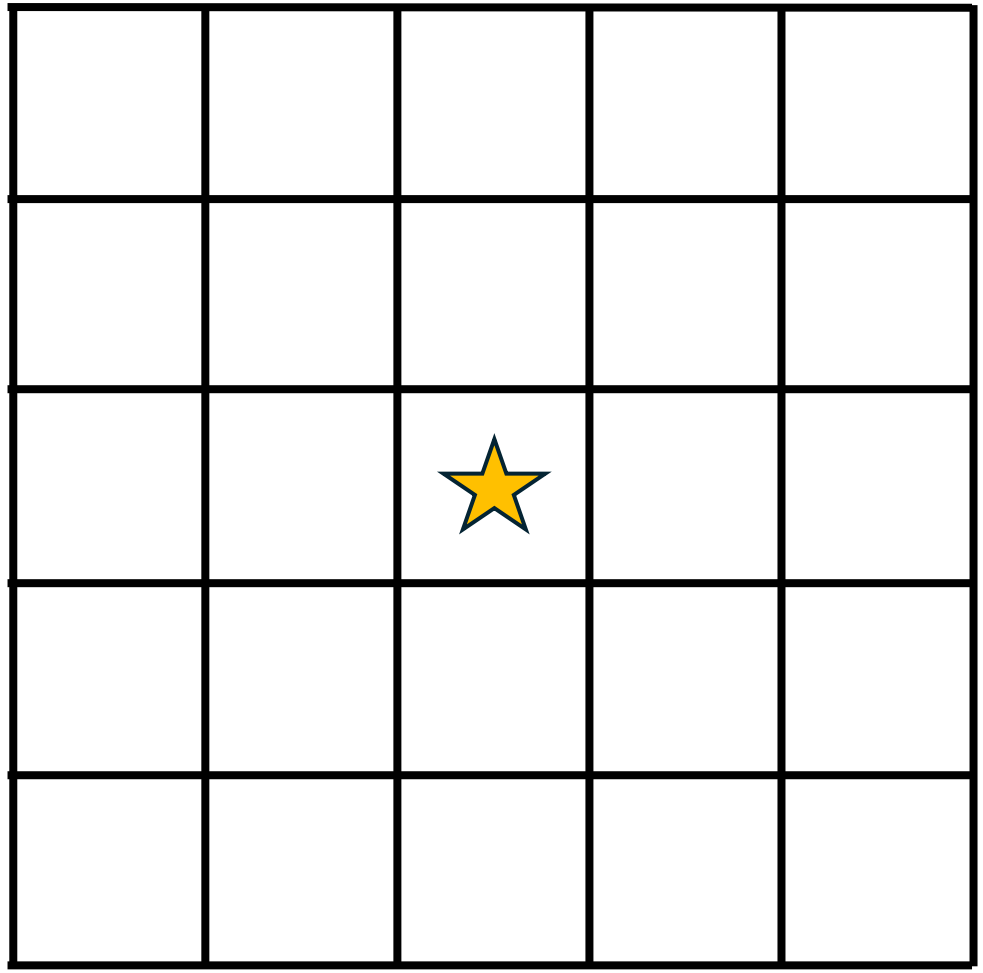
Under-Sampling? % Flux in central pixel



- Nyquist-sampled Gaussian: **13%**
- HST
  - WFPC2: **20% → 45%**
  - ACS/HRC got **9%**
  - ACS/WFC gets **23%**
  - WFC3/UVIS gets **18%**
  - WFC3/IR gets over **50%**
- JWST
  - NIRCam **15% → 60%**
- ROMAN **11% → 43%**



How does flux slosh from one pixel to the other?



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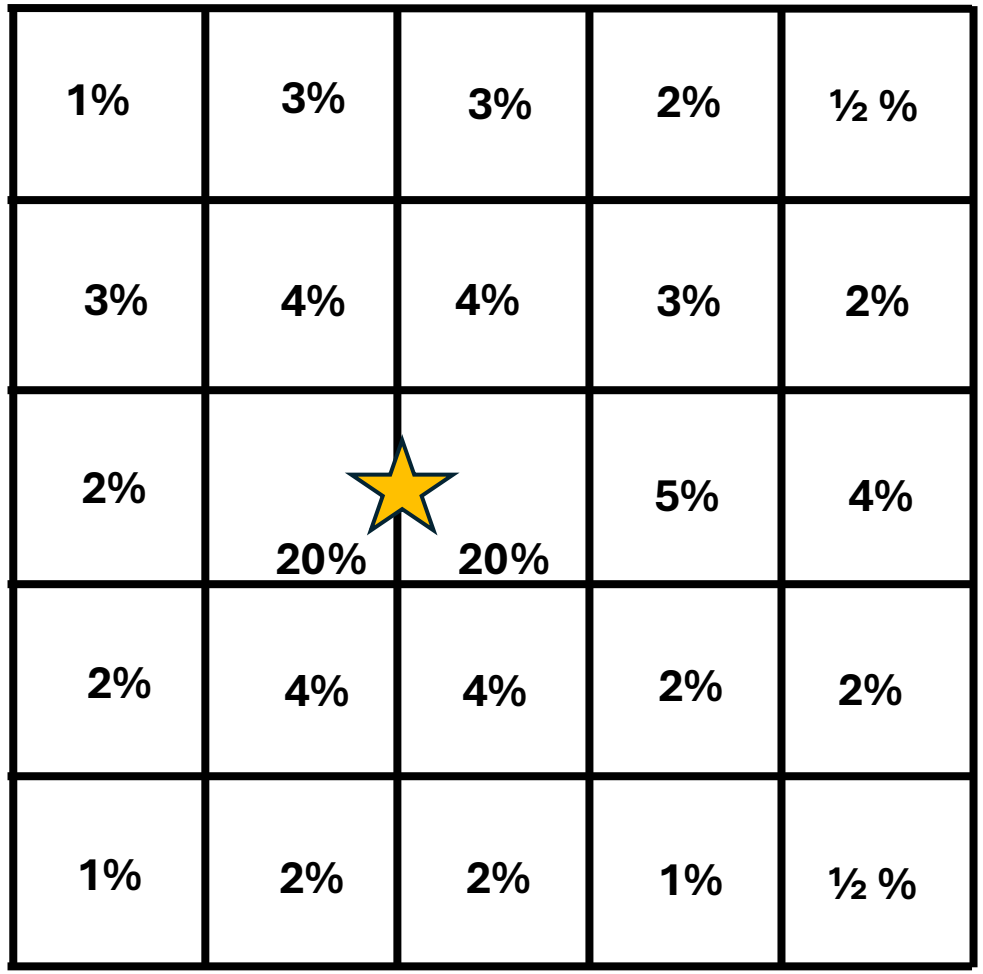
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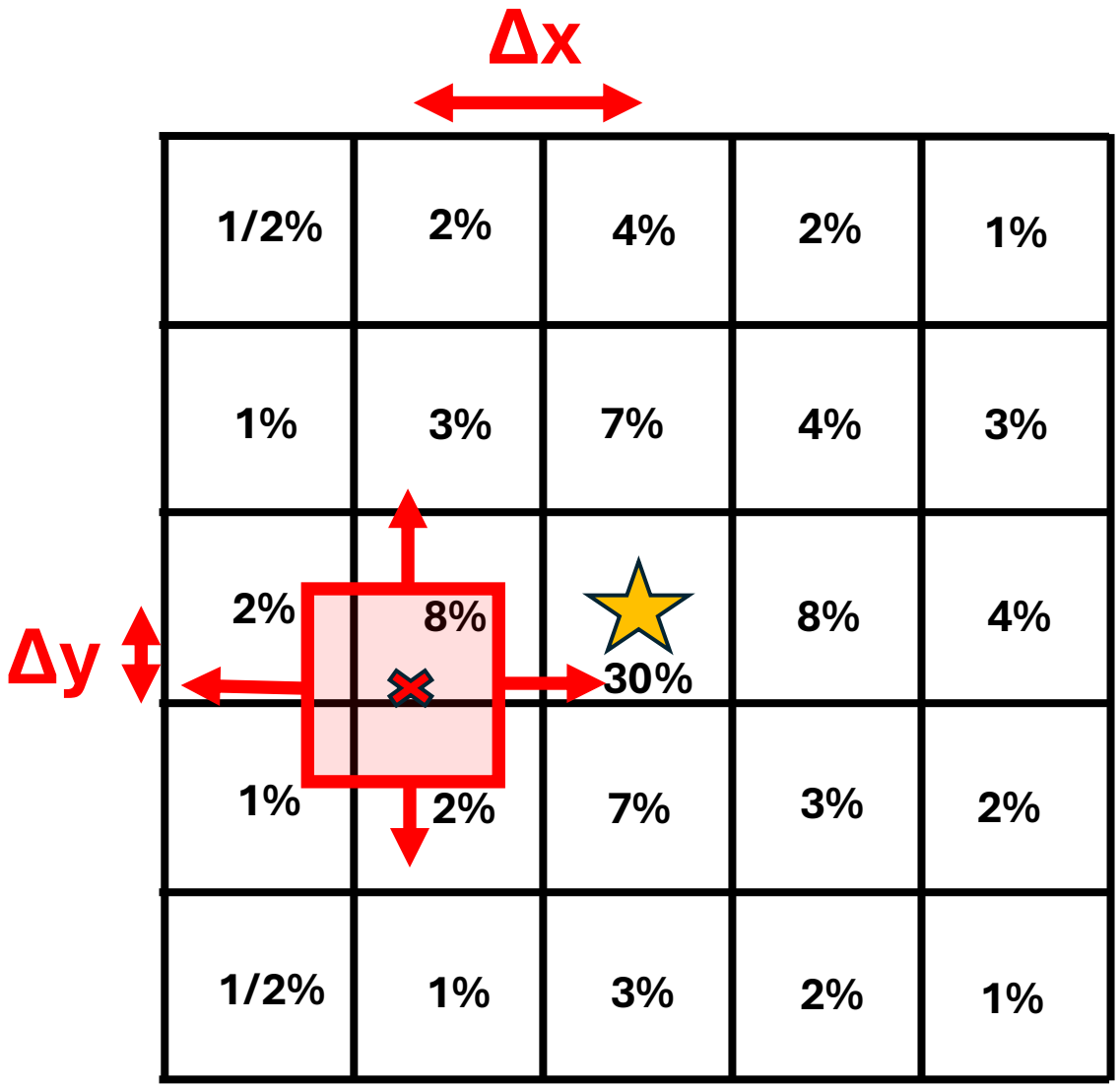
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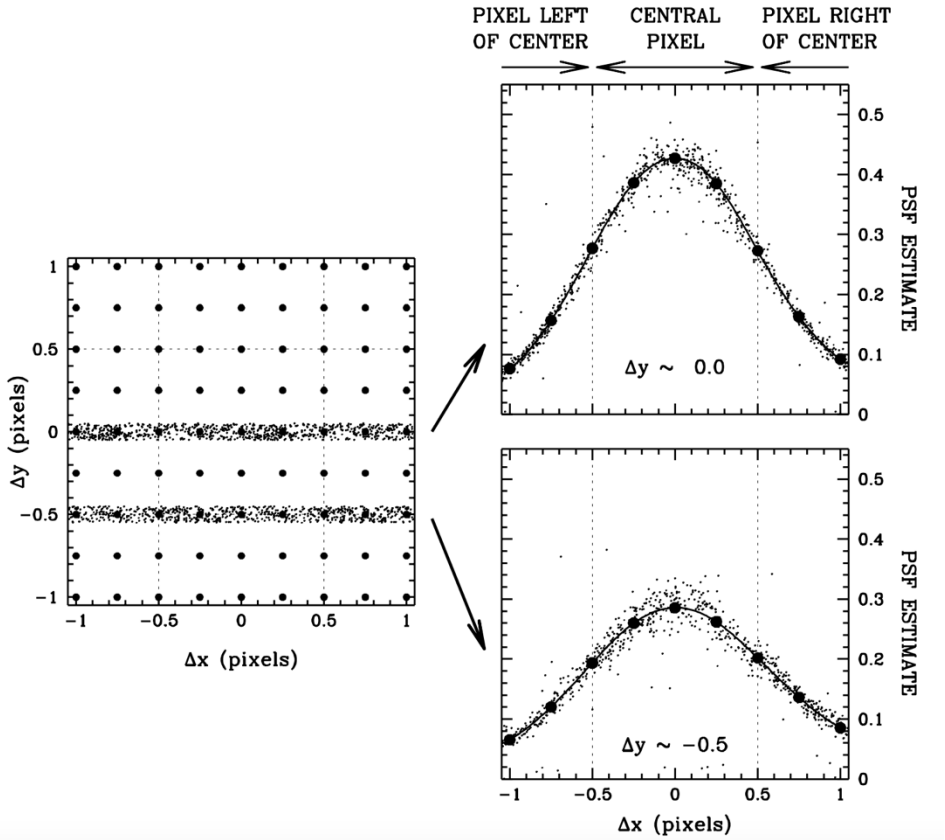
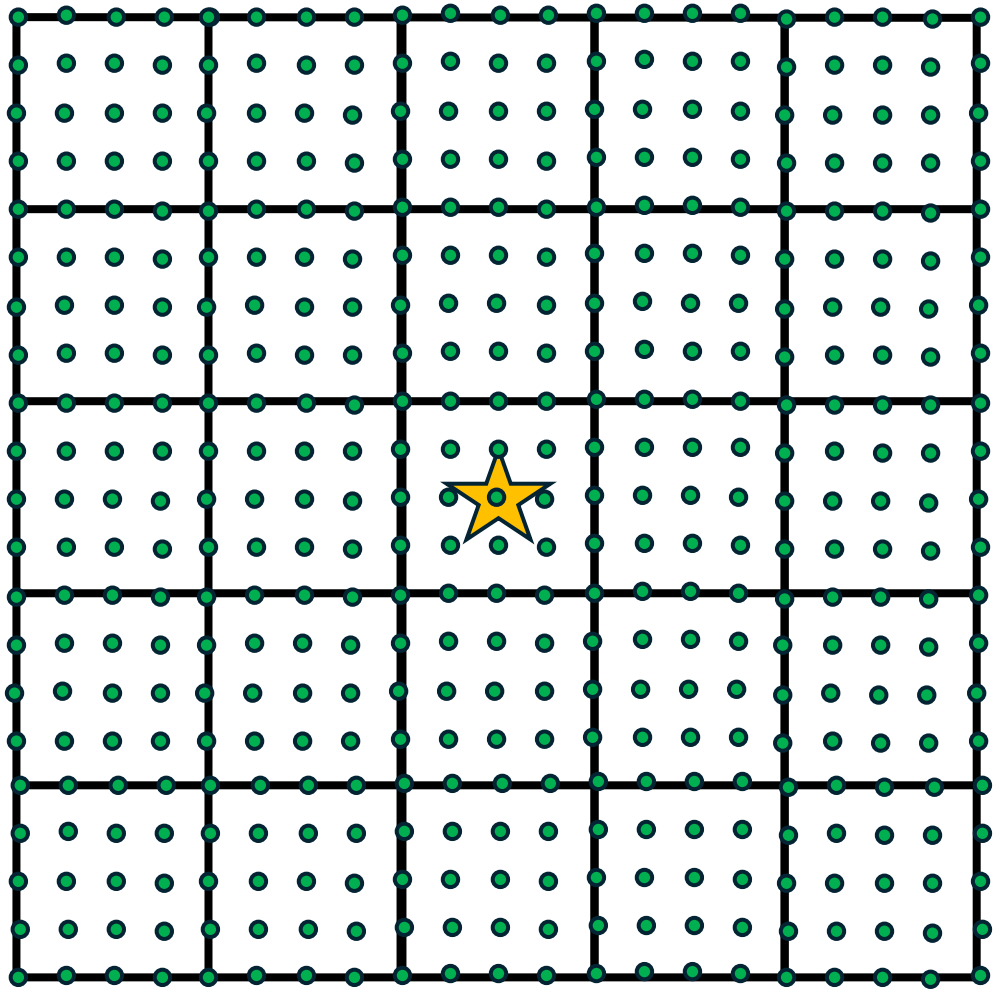
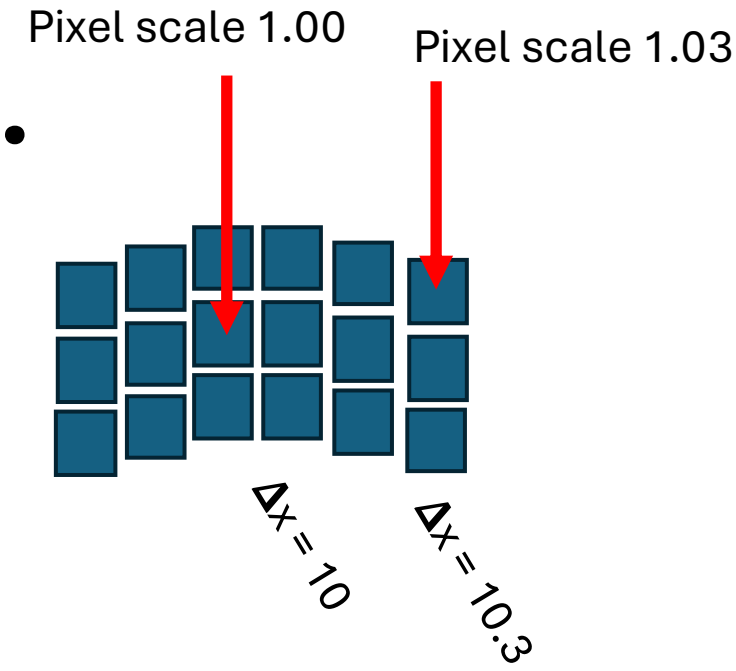


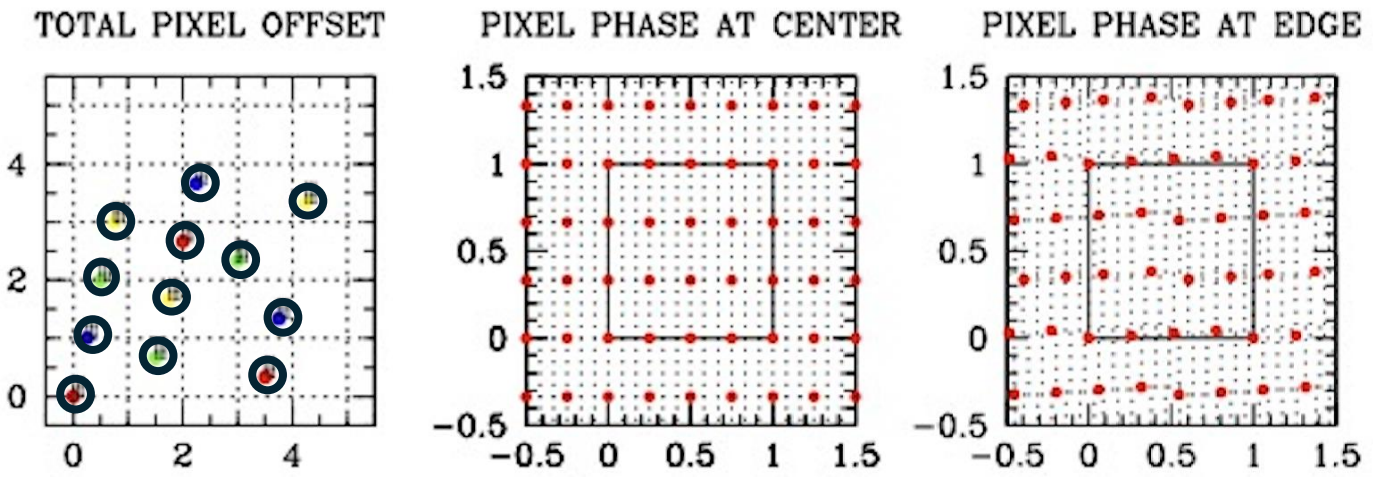


Need bi-cubic interpolation between grid-points!

We need a well-sampled scene…



- **`AstroDrizzle`** is focused on preserving FLUX
  - Needs positions good to 0.1 pixel
  - Does not require perfect dataset
- **Preserving sampling requires more care**
  - Requires particular dataset + iteration
    1) Dither coherence < 5 pixels
    2) Dither for transit trending
    3) Dither for sub-pixel cvg
- **APT constraints: 2-day blocks**
  - 9 sets of 12W-1B-12W-1R
  - 12 x 18 dither W146 (216 images)
  - Get 3 x 3 dither of B and R (9 each)
  - 234 total in a "dither block"



Some Vignettes…

1) Realization of scene with dithers

2) Hal, it's full of stars!

3) Visualizing DIs…

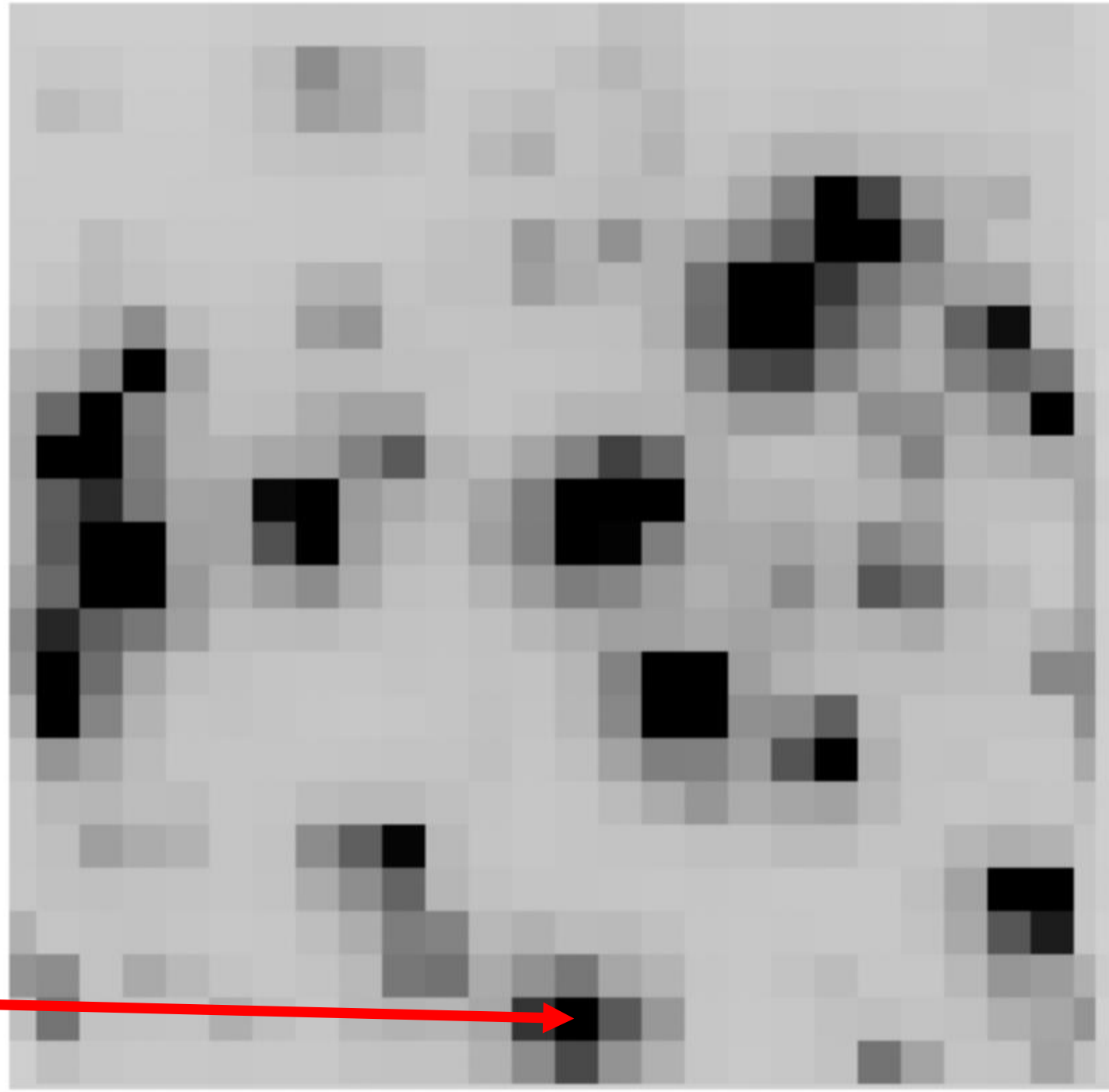
4) A microlensing event in DIs

5) SS Objects in DIs

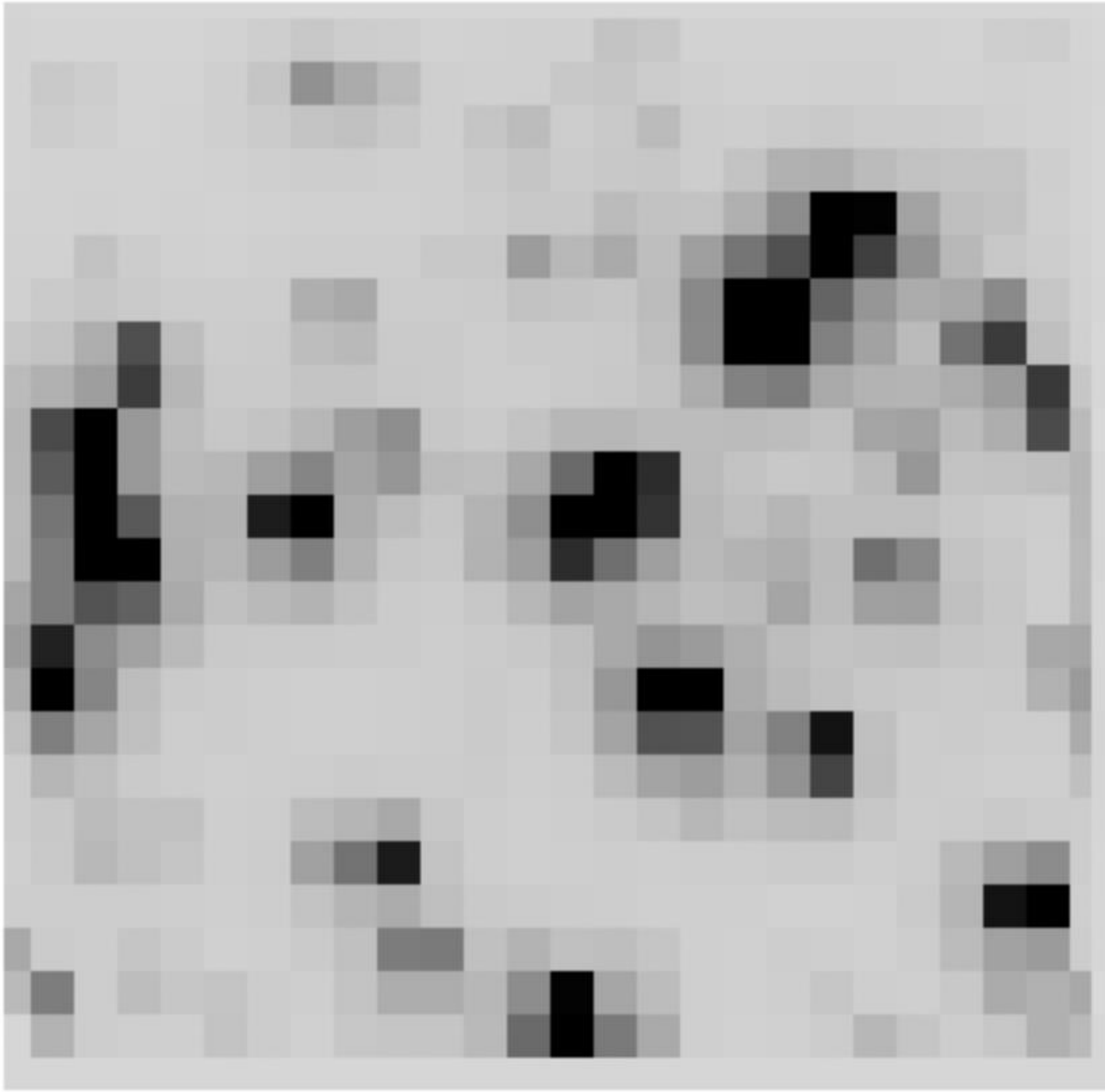
6) Color Dependence in Roman PSF

7) Fitting stars with undersampled PSFs

Realization of scene with dithers



Realization of scene with dithers



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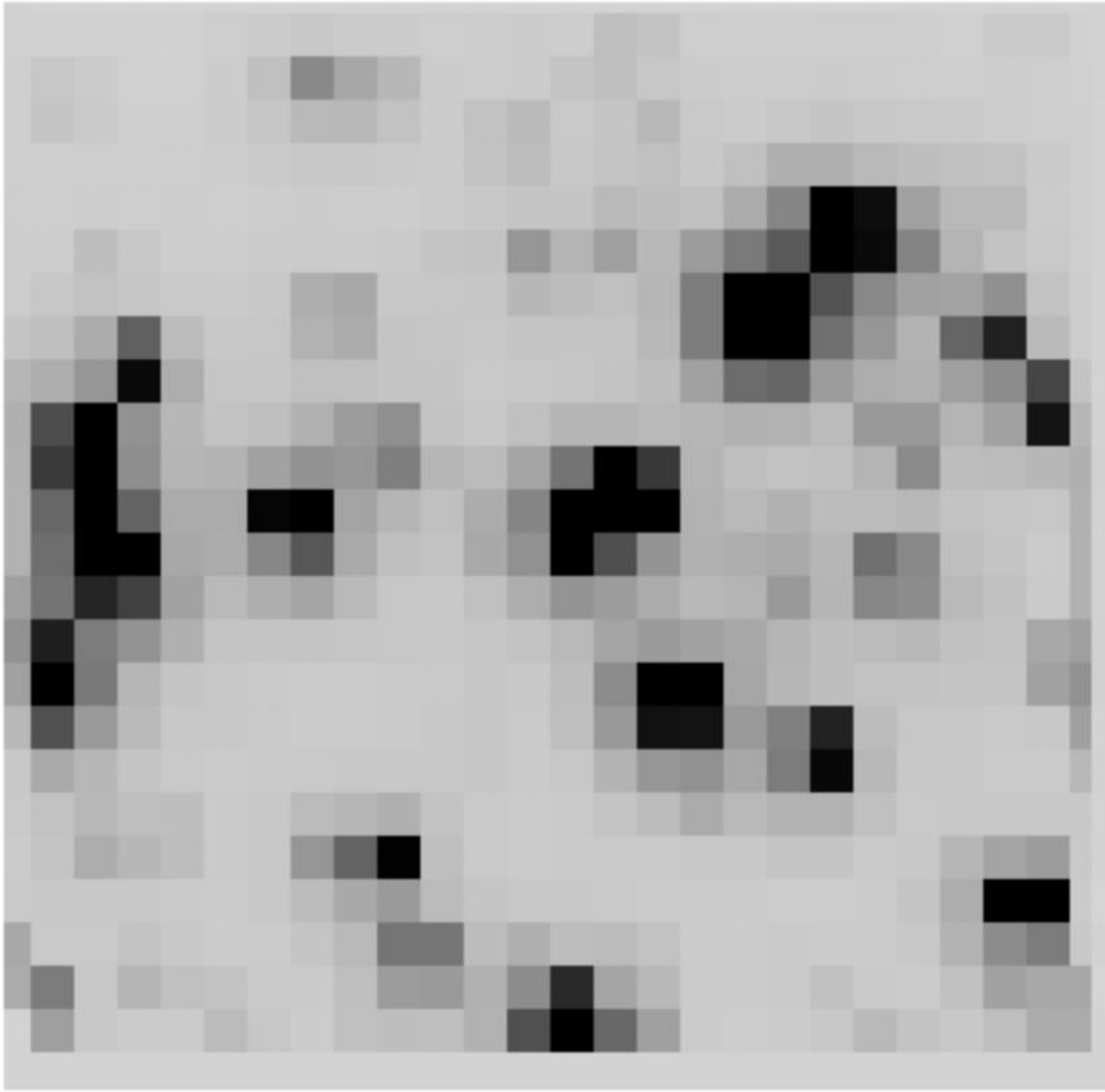
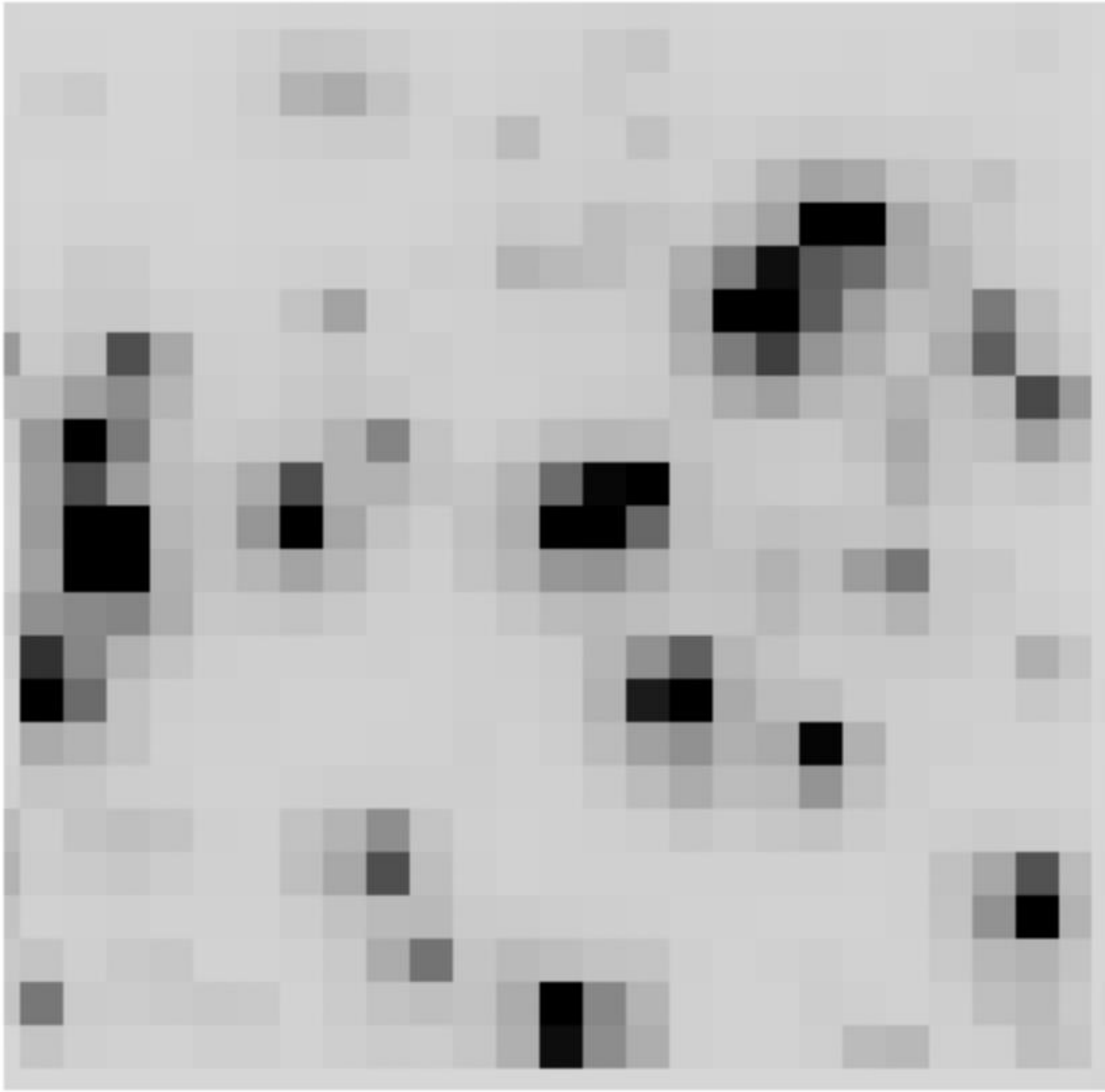
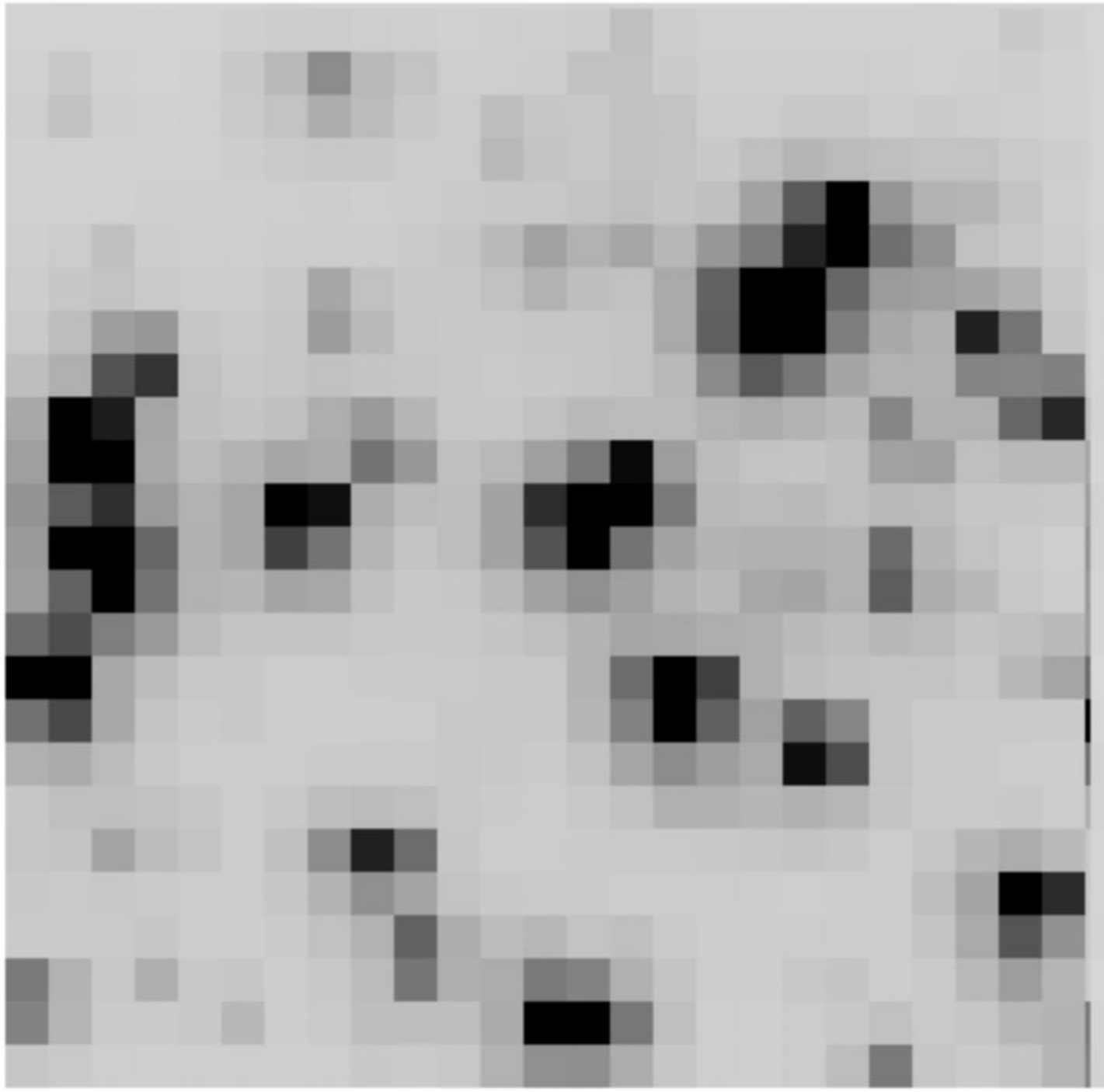


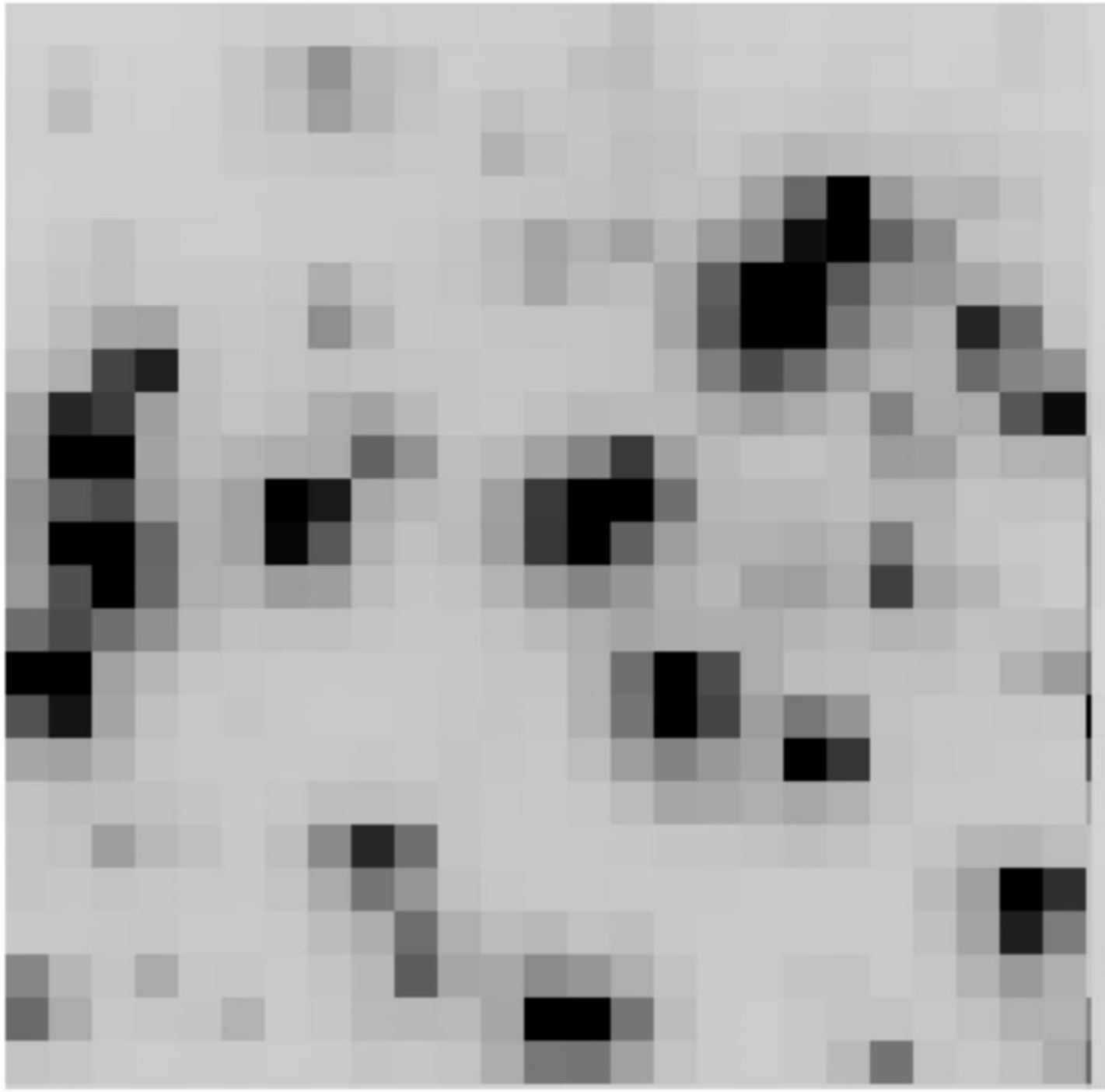
Realization of scene with dithers



Realization of scene with dithers



Realization of scene with dithers



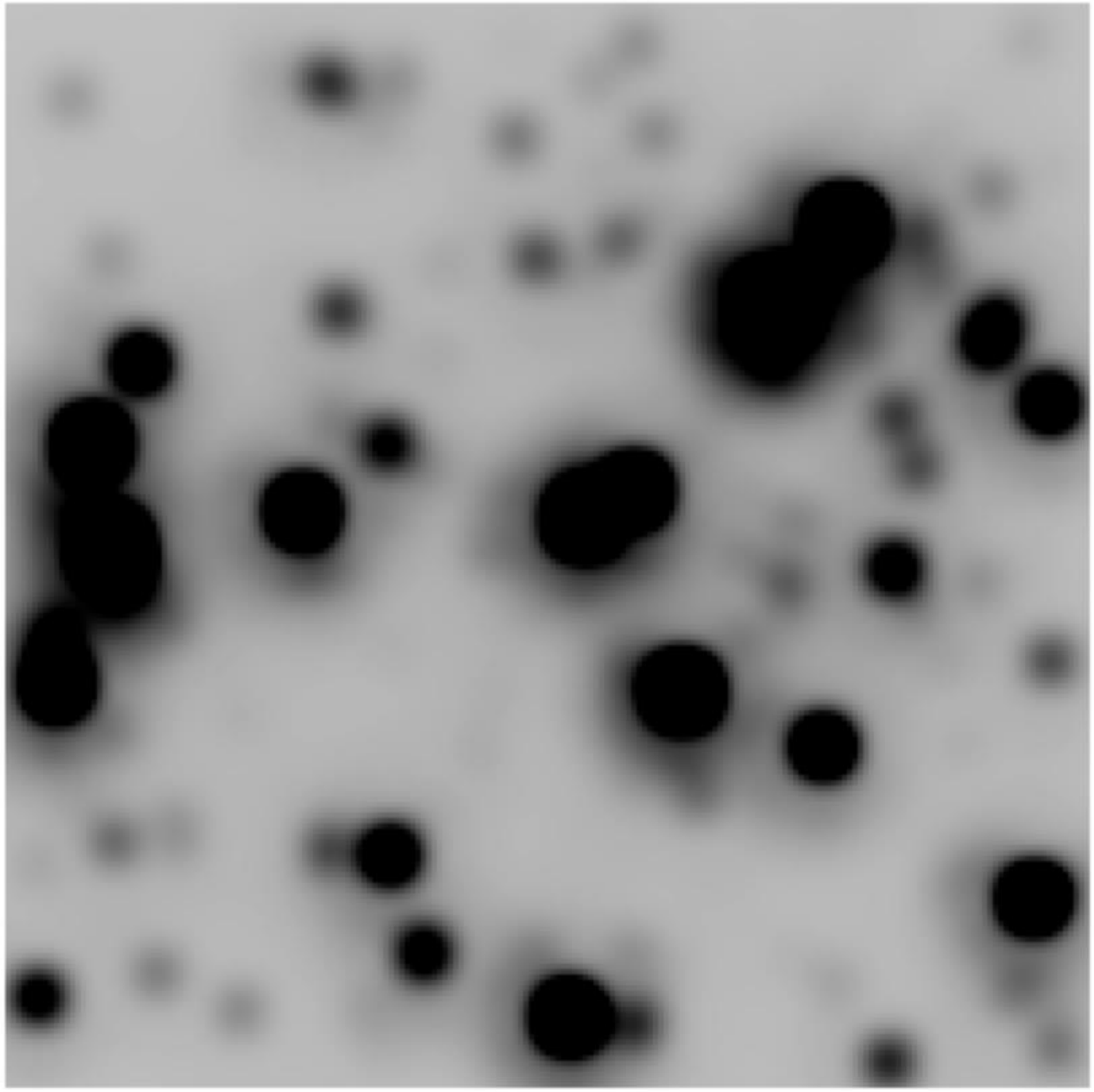
Full 8x resolution image

200x200 super pixels

25x25 real pixels

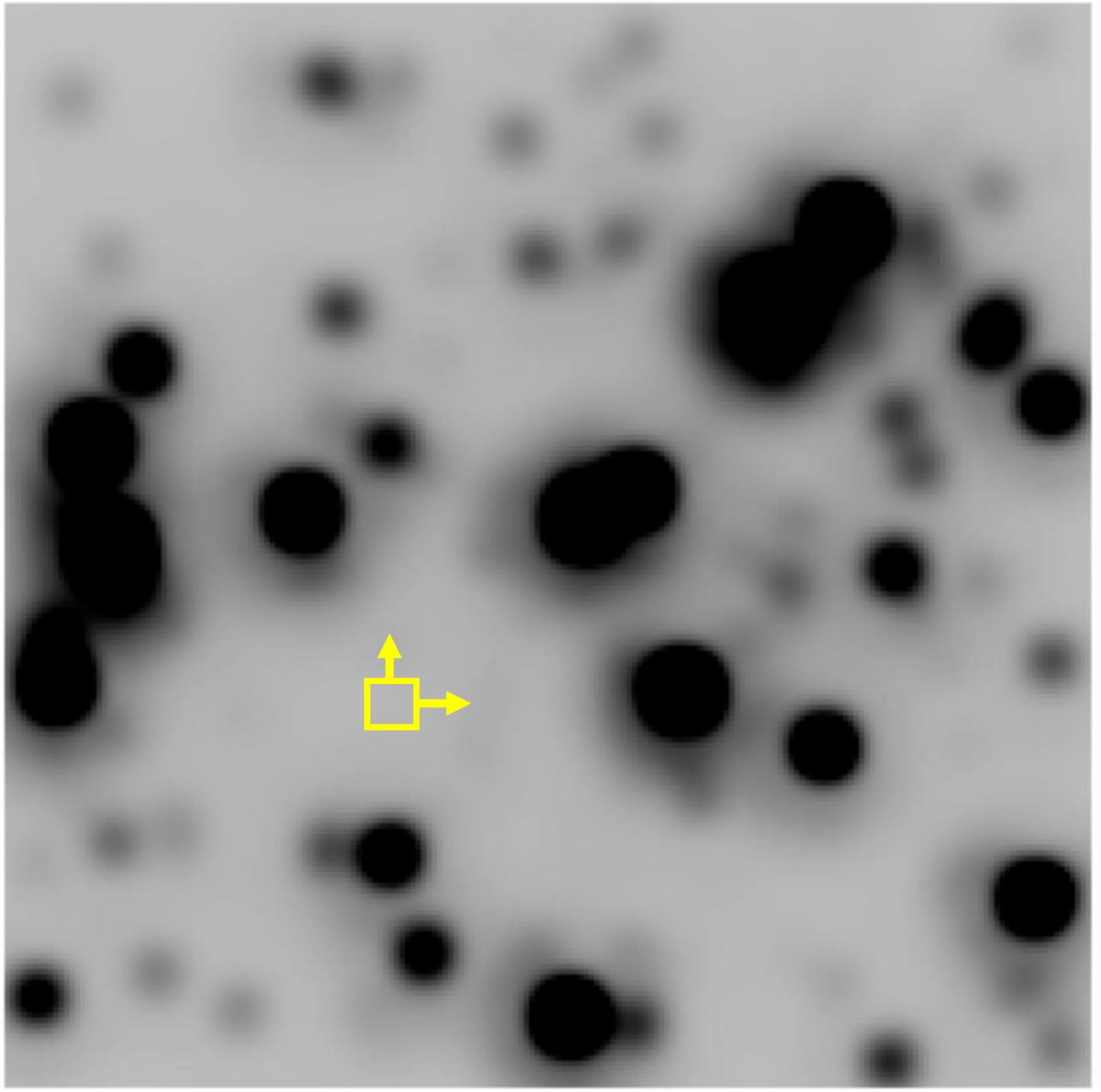
~125 stars
~ 5 pixels/star
r_{iso} ~ 1.25

Amenable to DAOPHOT-type crowded-source routines.



Samplings of the scene

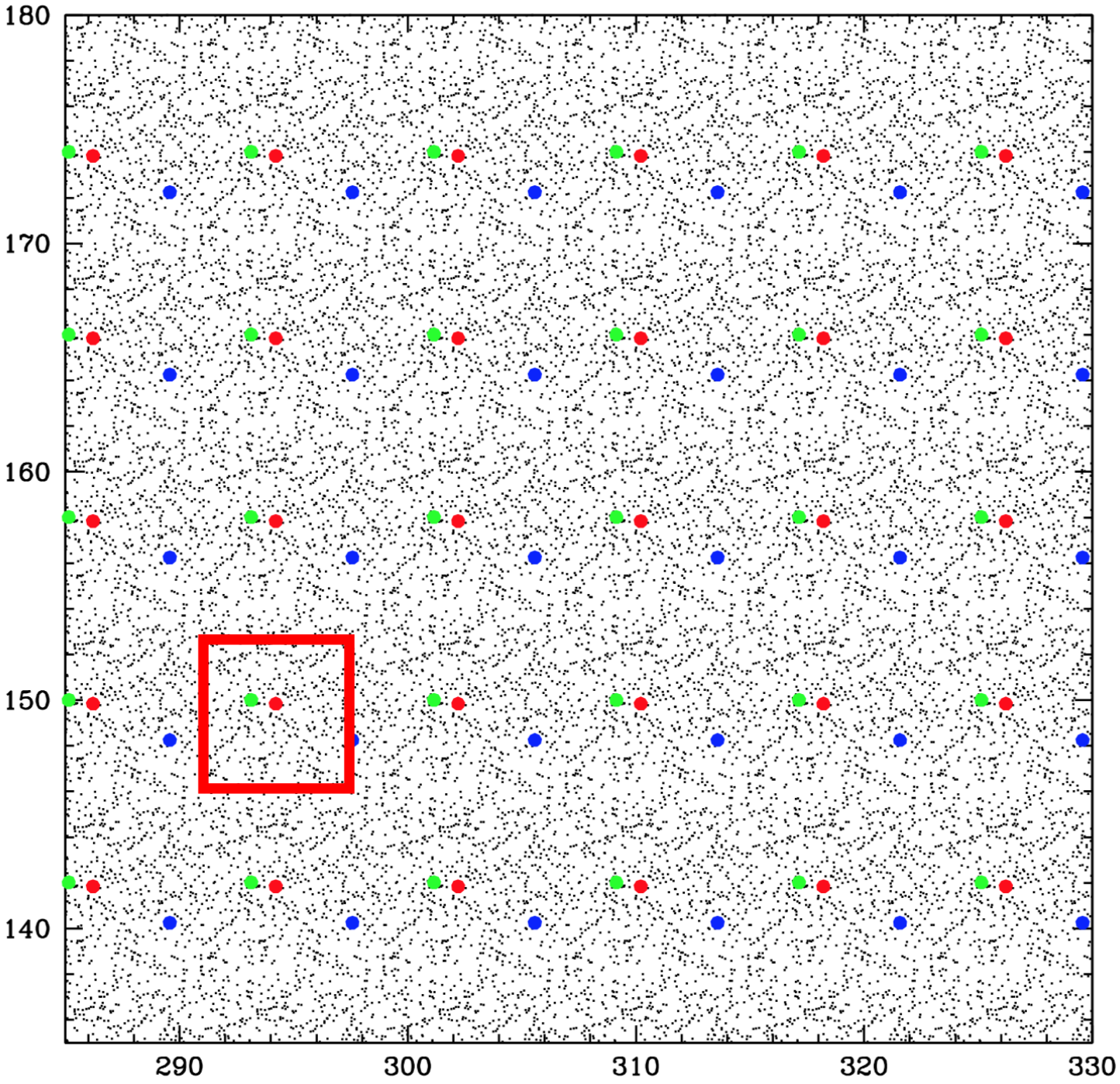
48x48-super-pixel region
(6x6–true-pixel region)

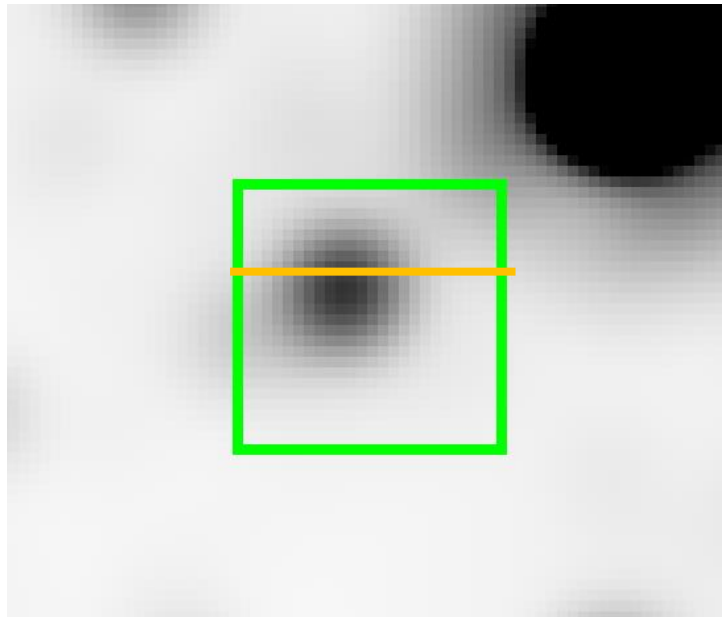


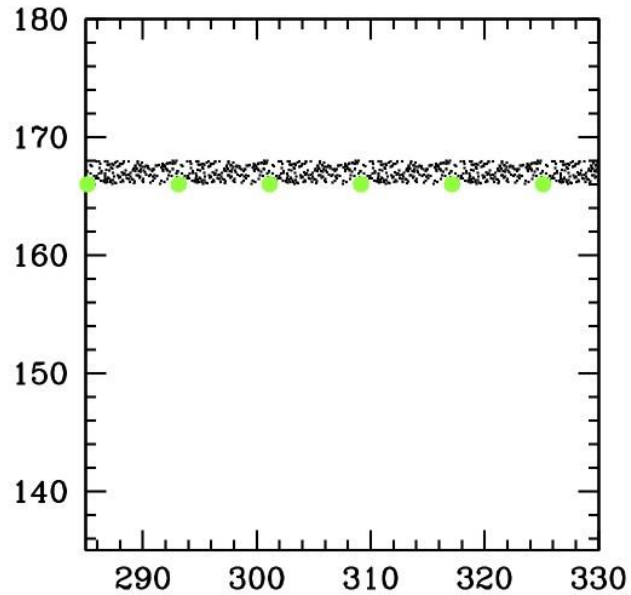
Samplings of the scene

48x48-super-pixel region
(6x6–true-pixel region)

IMAGE#1's samples
IMAGE#2's samples
IMAGE#3's samples



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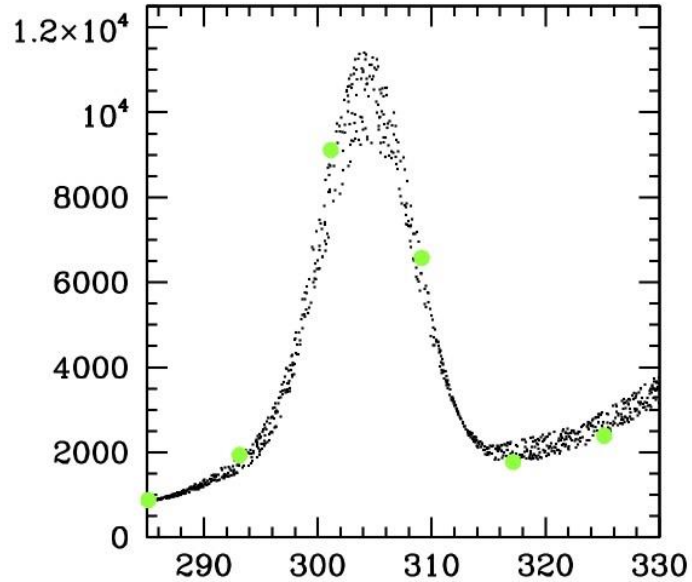
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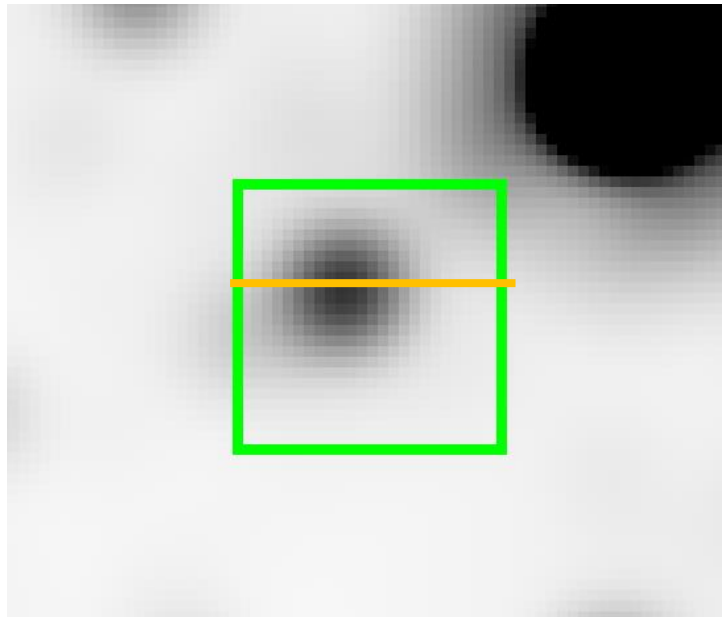

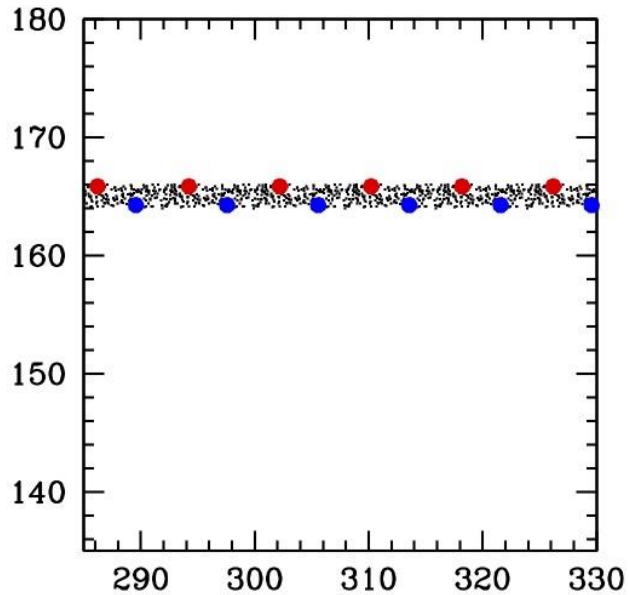
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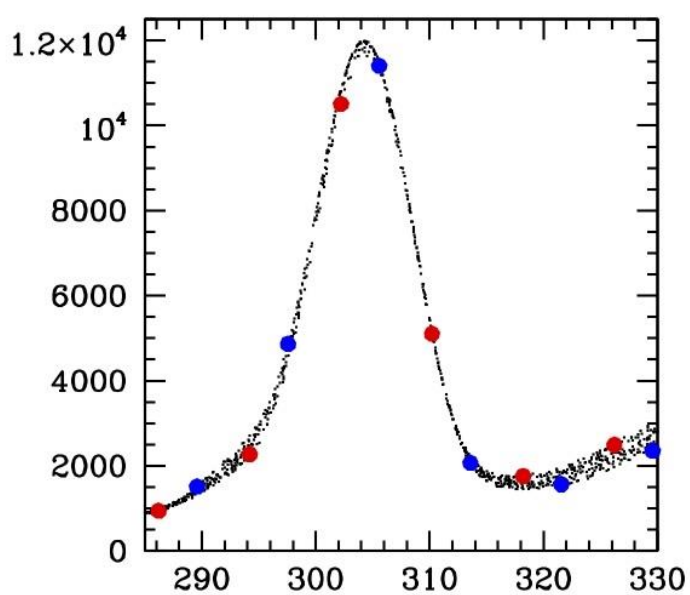
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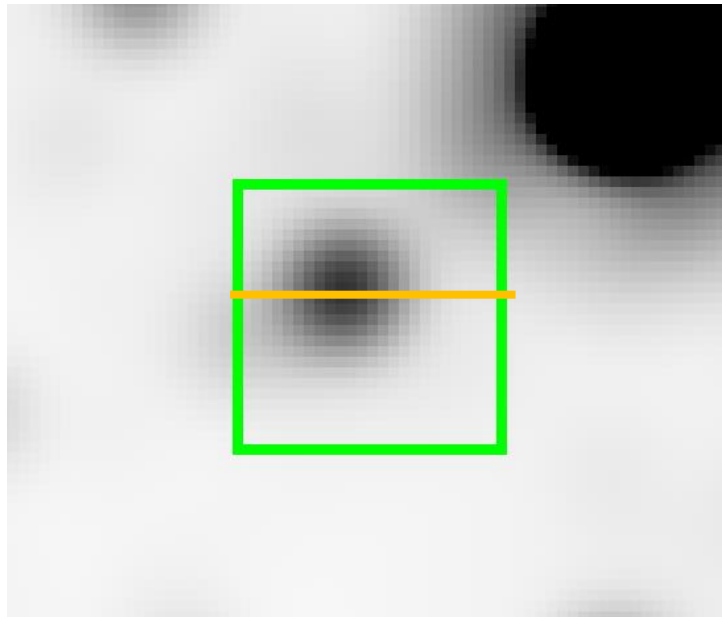

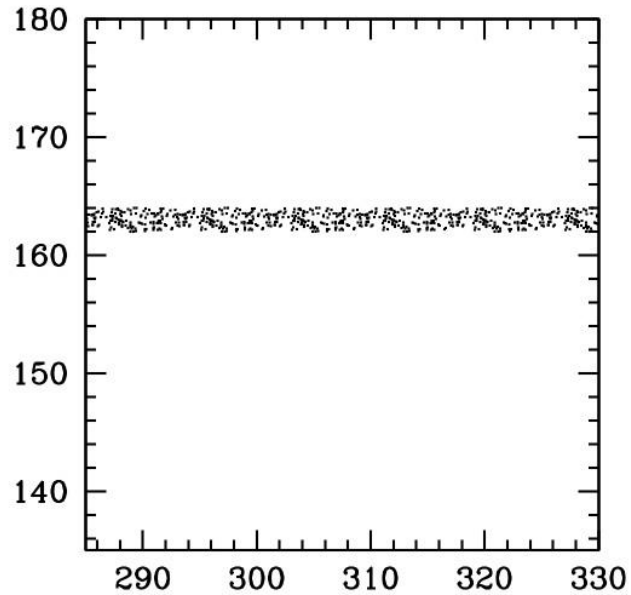
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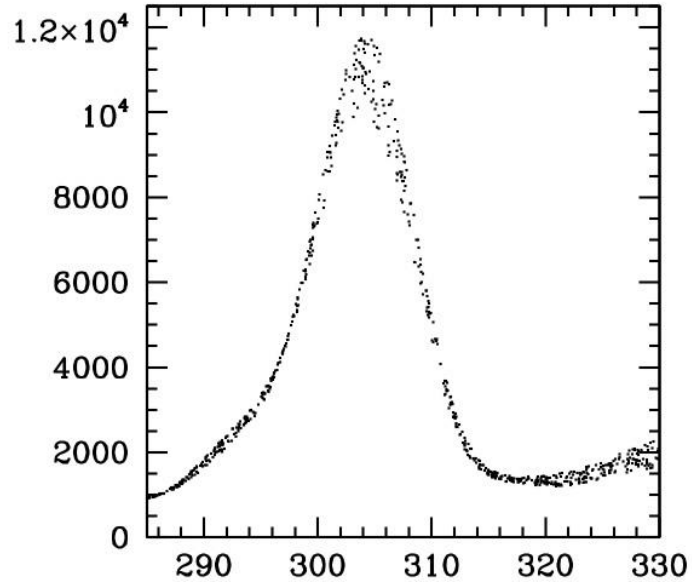
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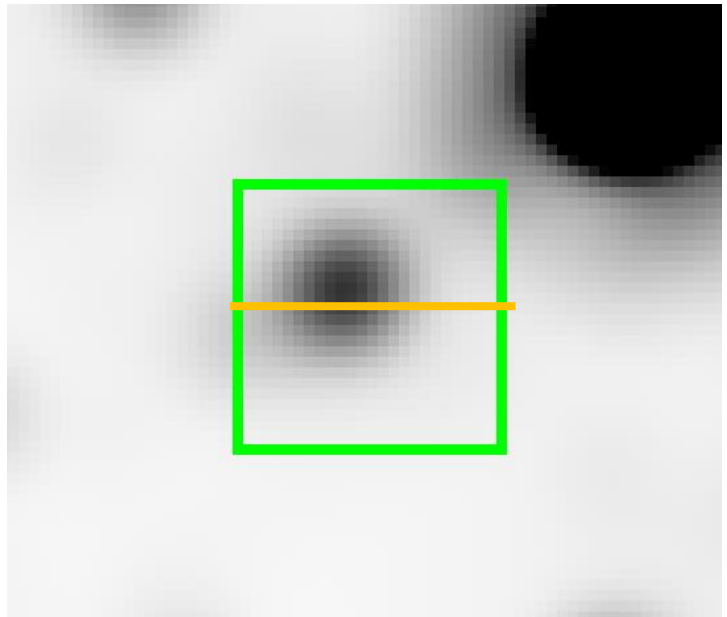

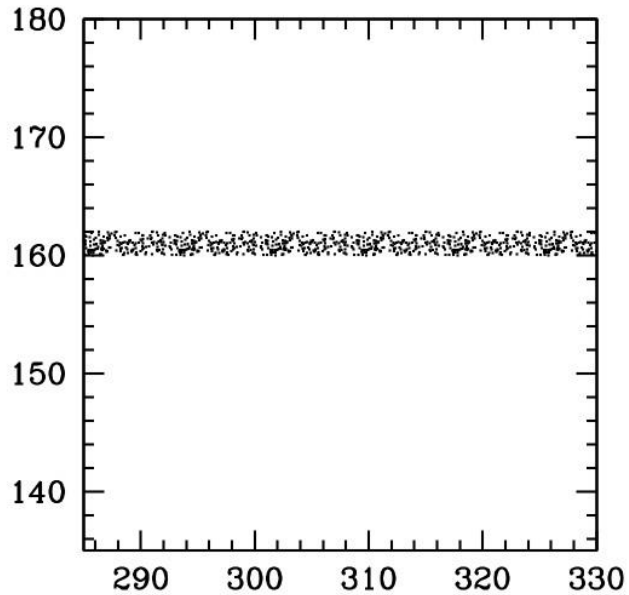
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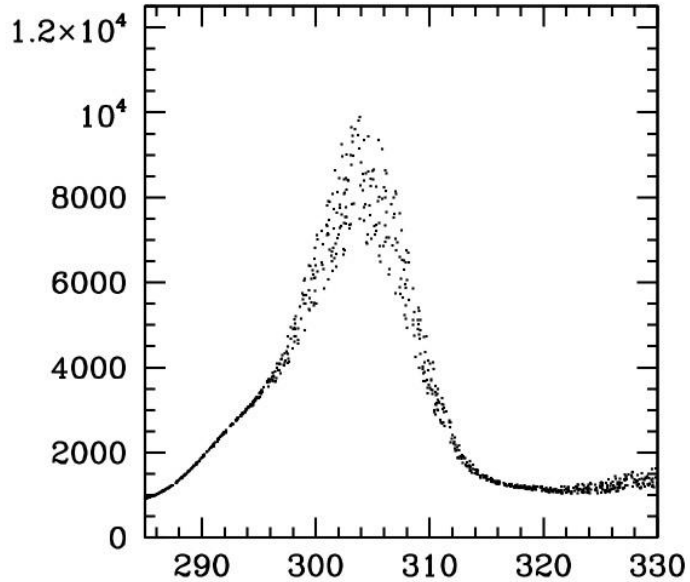
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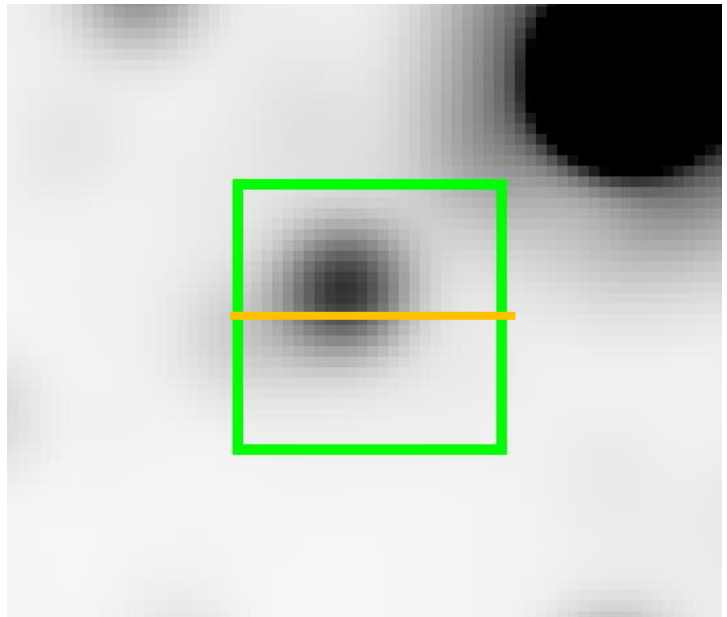

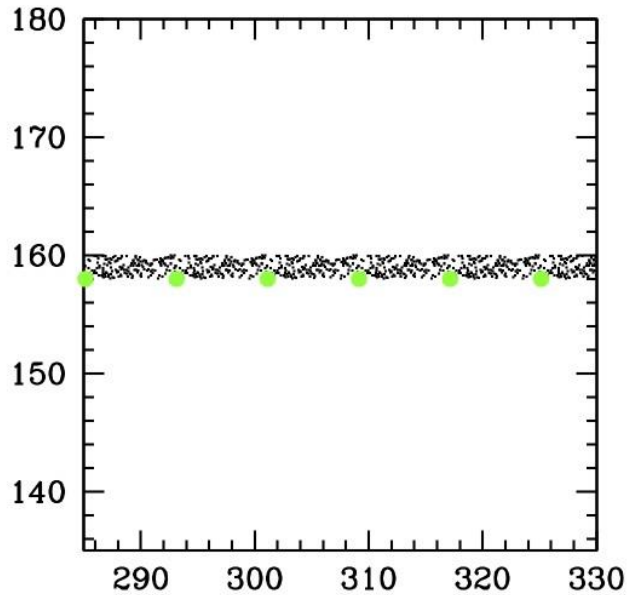
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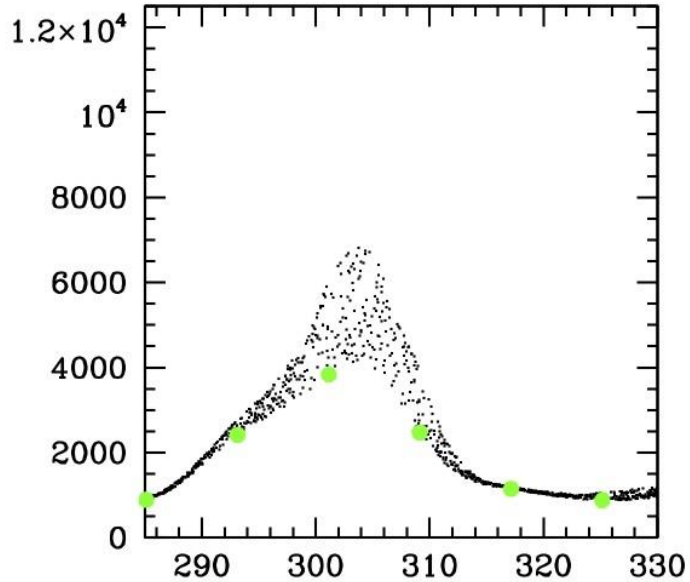
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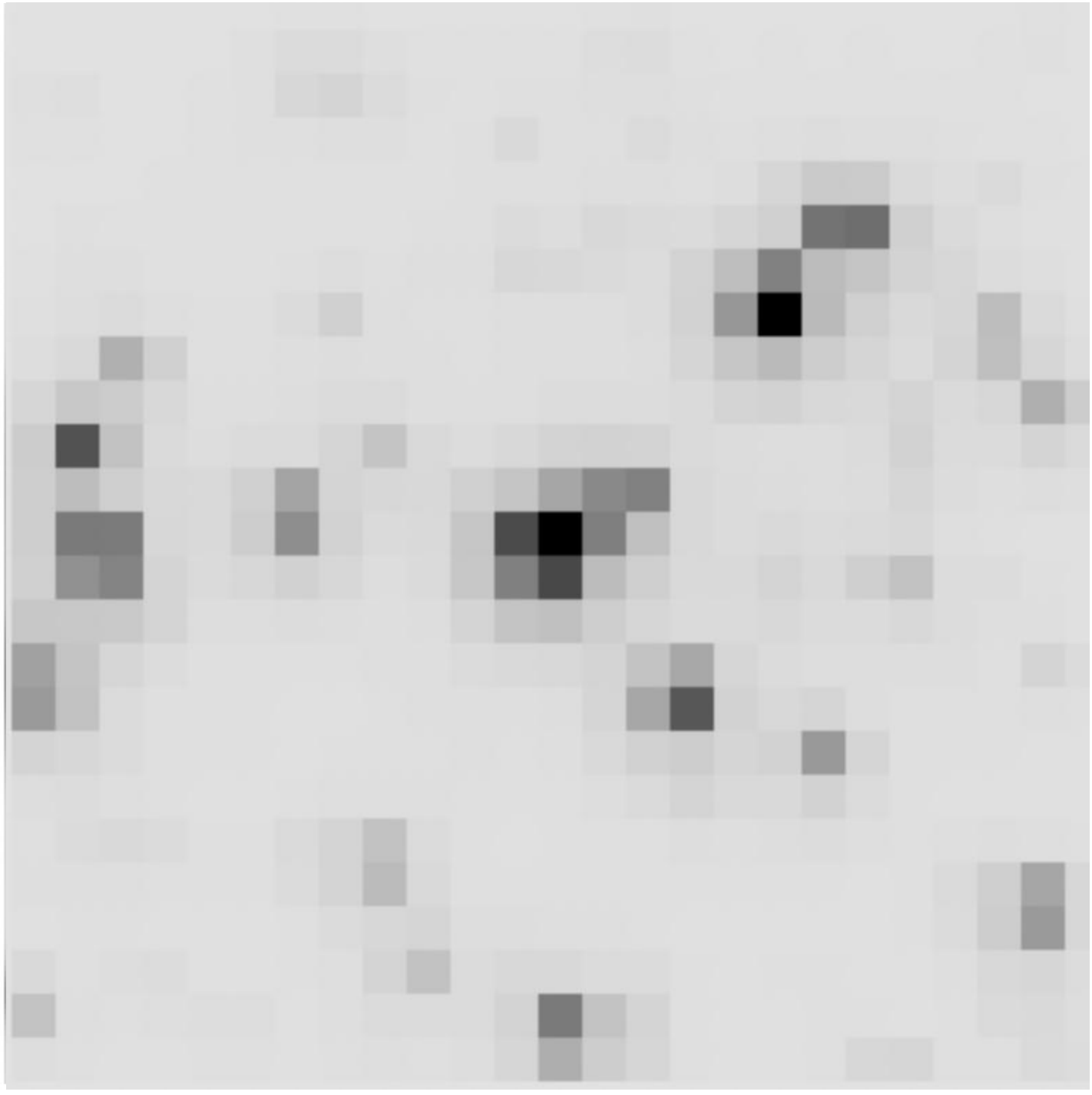
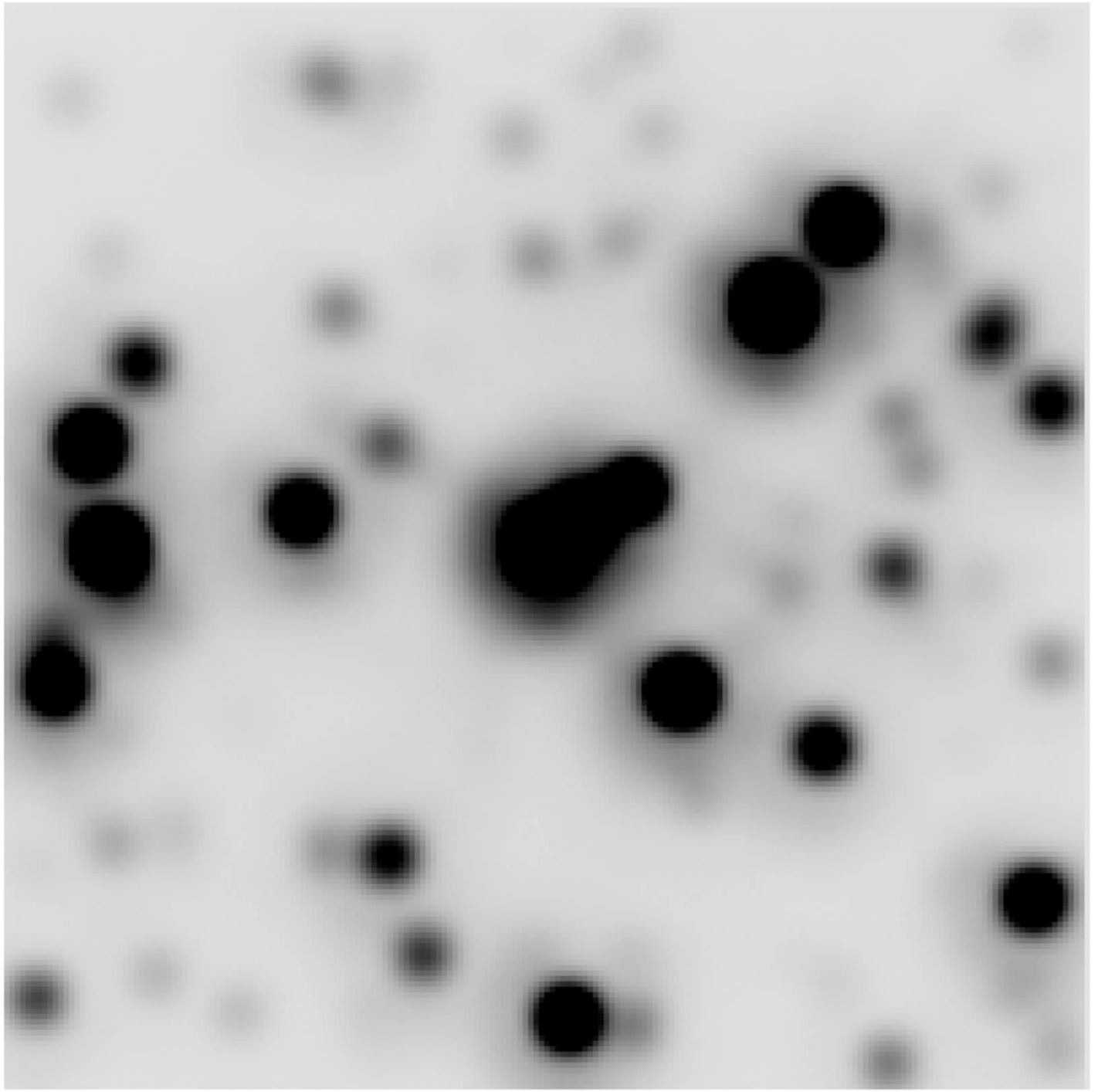
Single under-sampled exposure



Stack dithered set



Some Vignettes…

1) Realization of scene with dithers

2) Hal, it's full of stars!

3) Visualizing DIs…

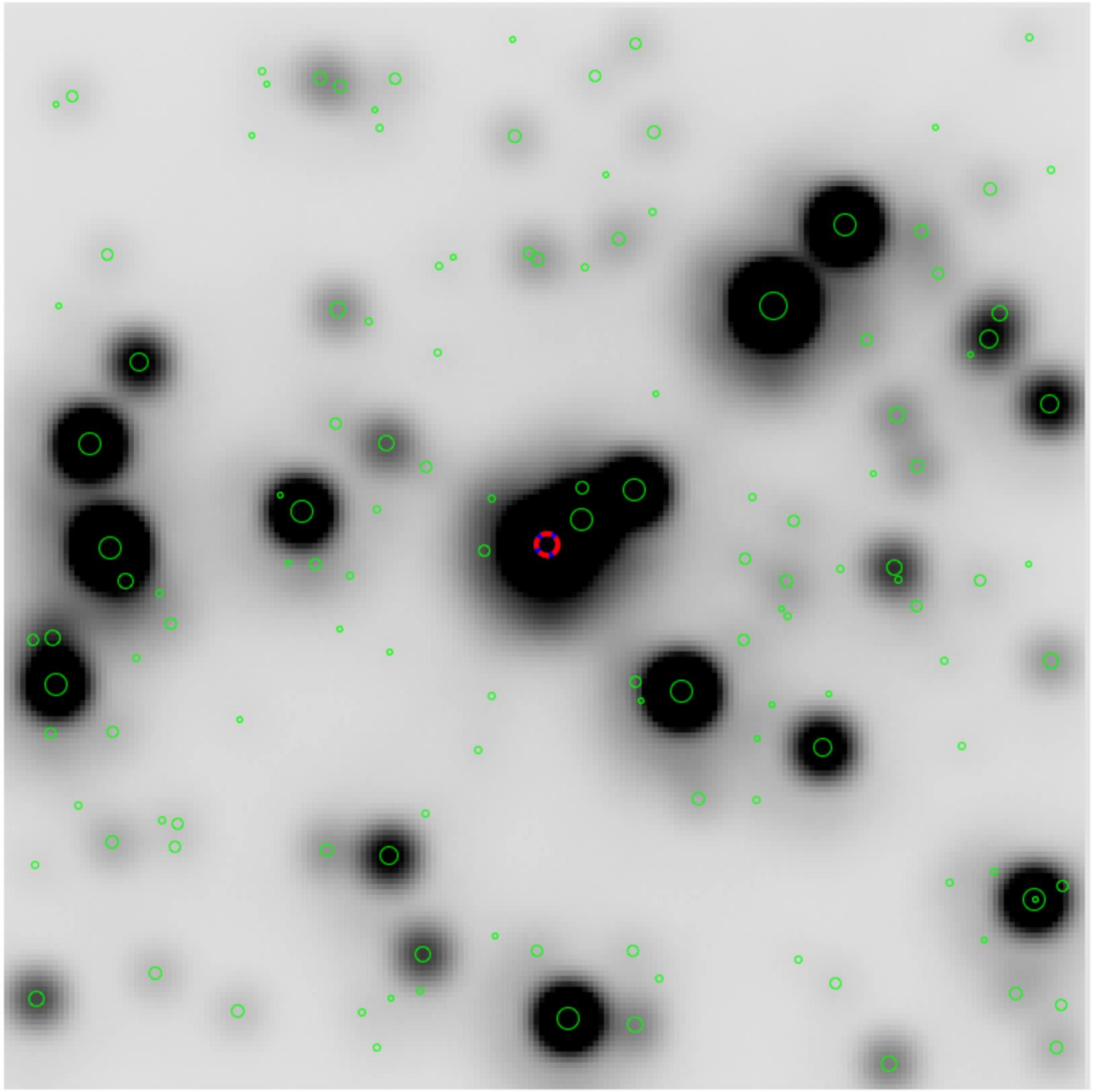
4) A microlensing event in DIs

5) SS Objects in DIs

6) Color Dependence in Roman PSF

7) Fitting stars with undersampled PSFs

All the stars...



It's stars all the way down!

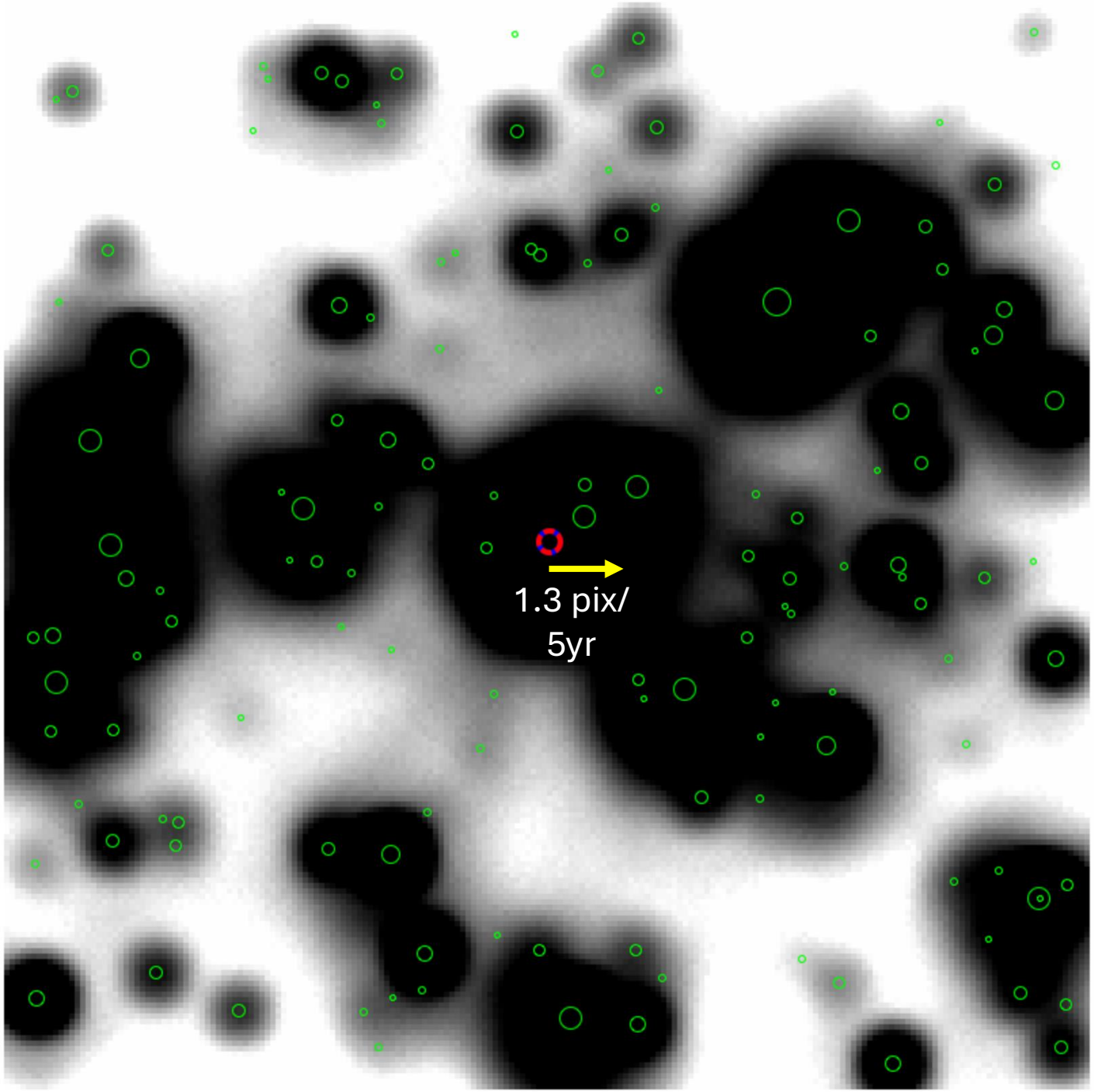
150 stars in
in 25x25 true pixels

625 pixels / 150
→ 4 pixels per star

And…
All the stars are moving!

Proper motions can help and hurt

- lens flux analysis
- churning background
- typical star moves ~0.5 pixel in 5 years



Some Vignettes...

1) Realization of scene with dithers
2) Hal, it's full of stars!
3) **Visualizing DIs...**
4) A microlensing event in DIs
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6) Color Dependence in Roman PSF
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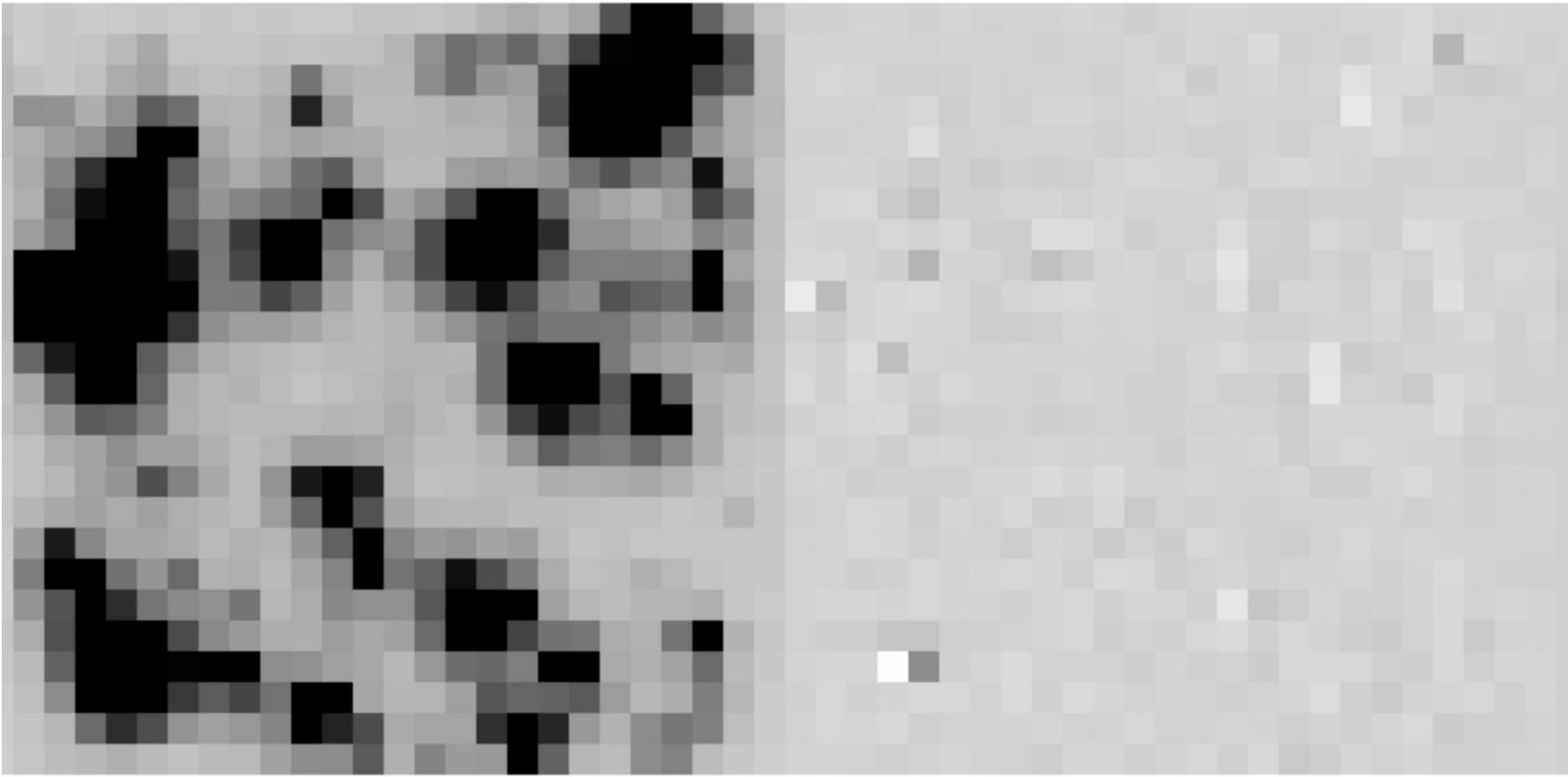
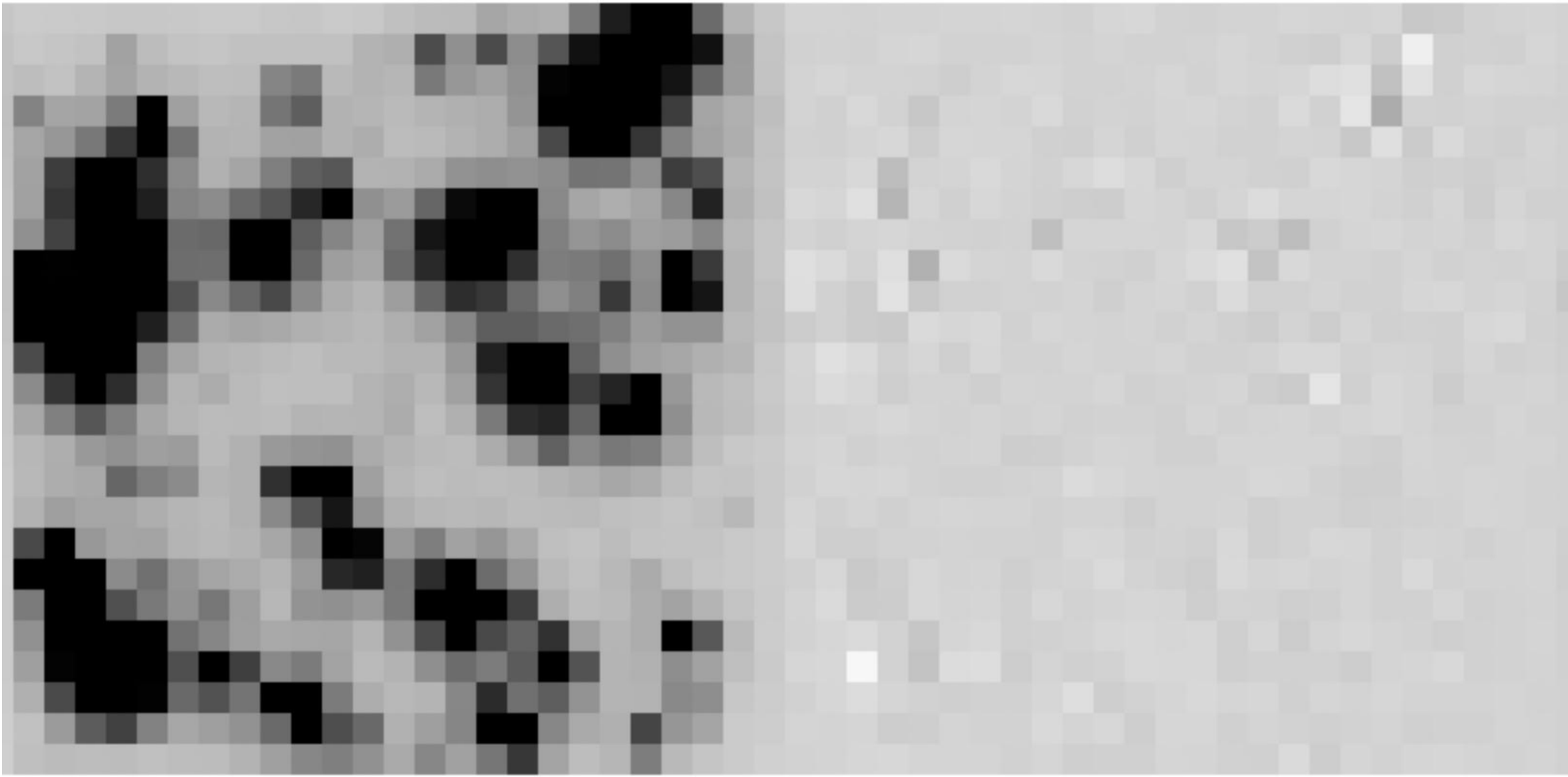
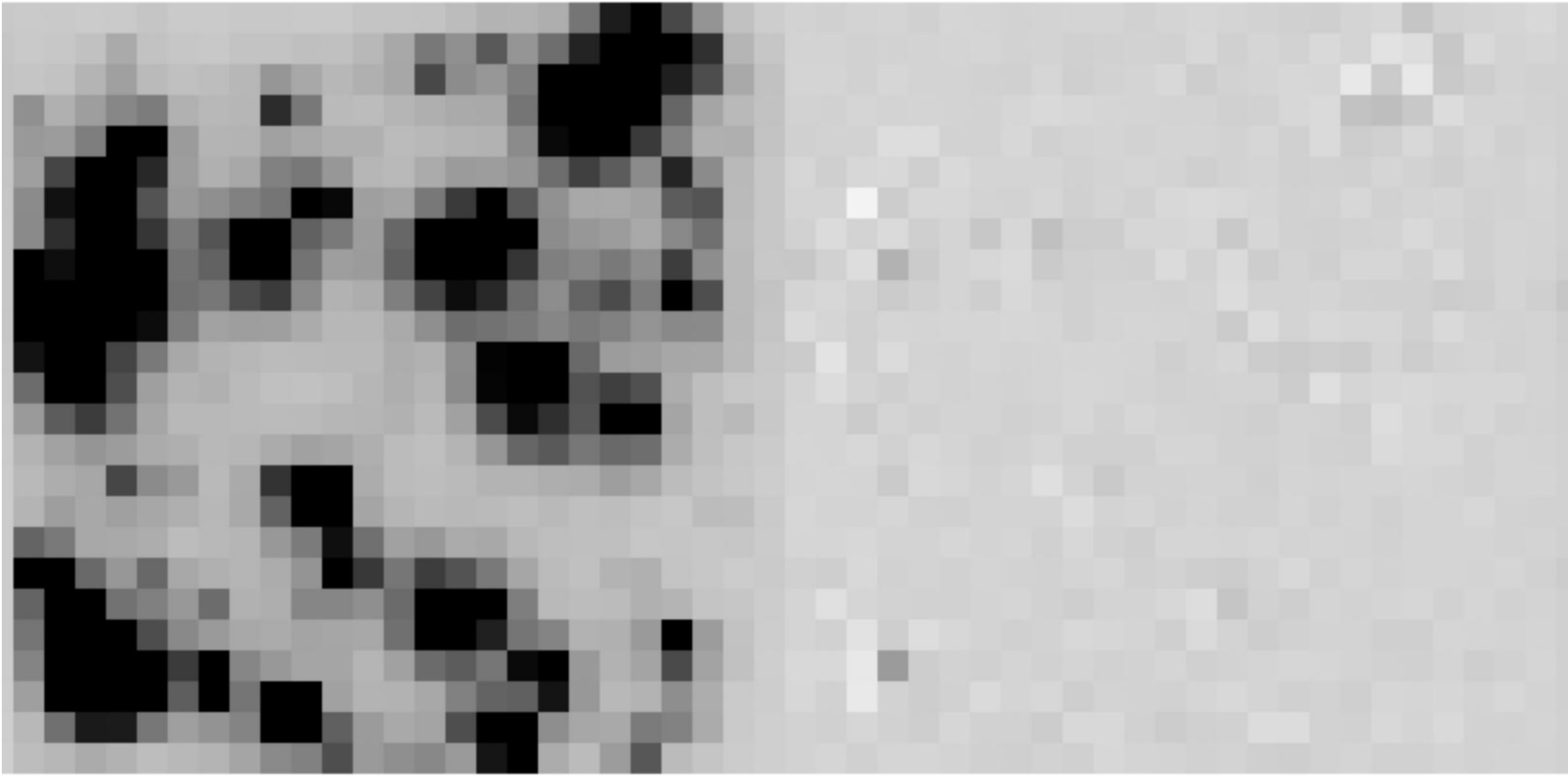
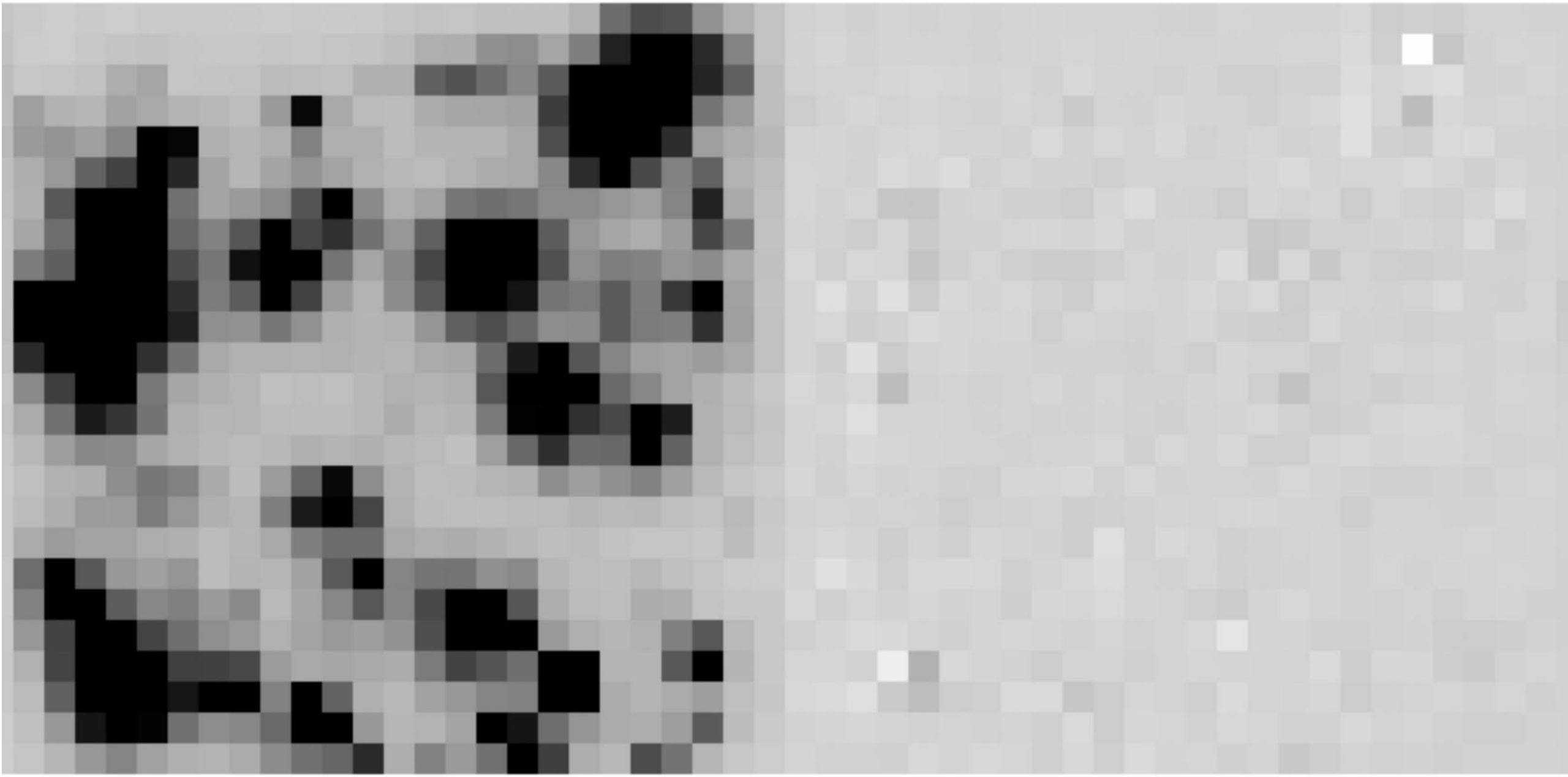
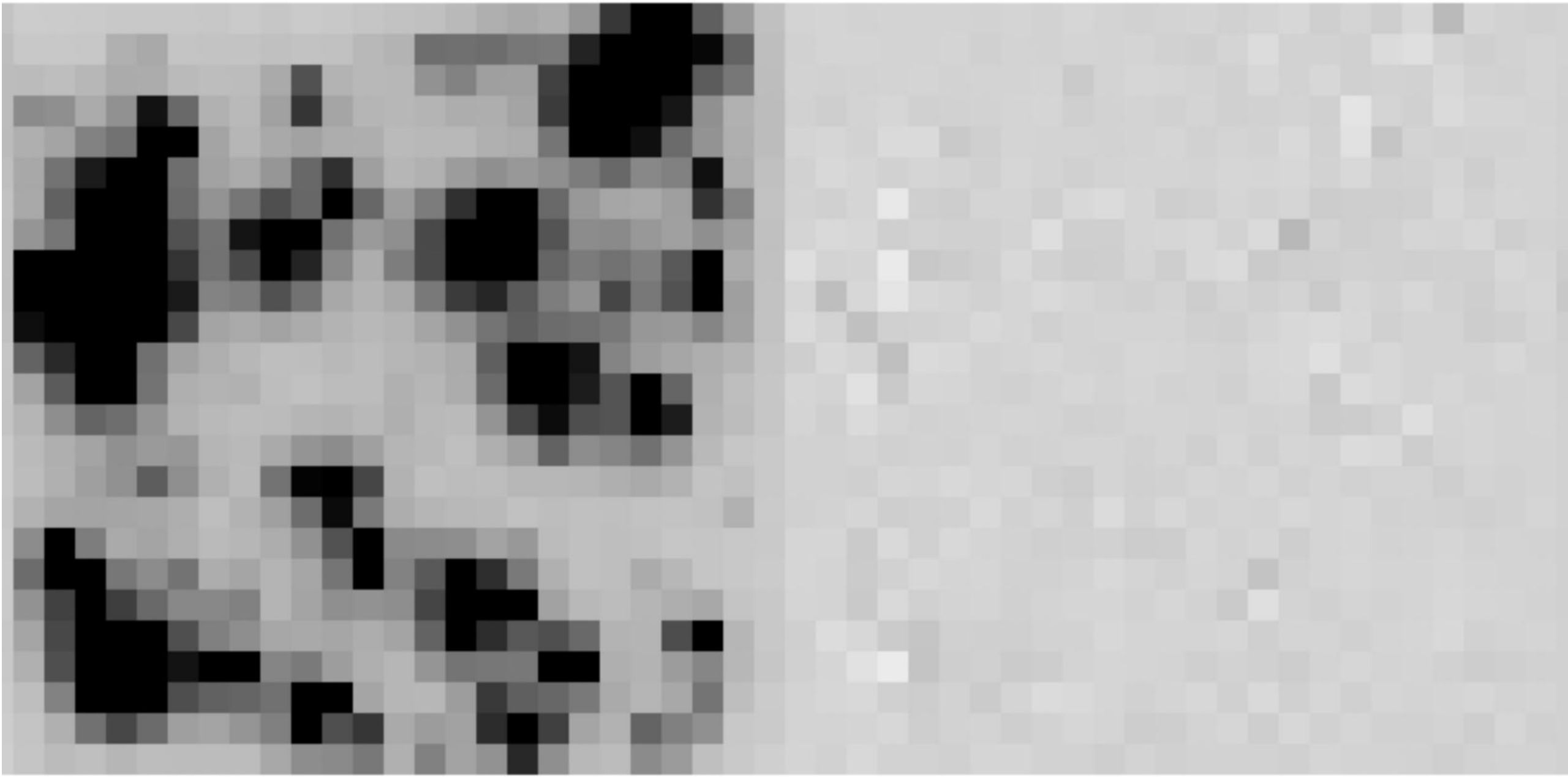
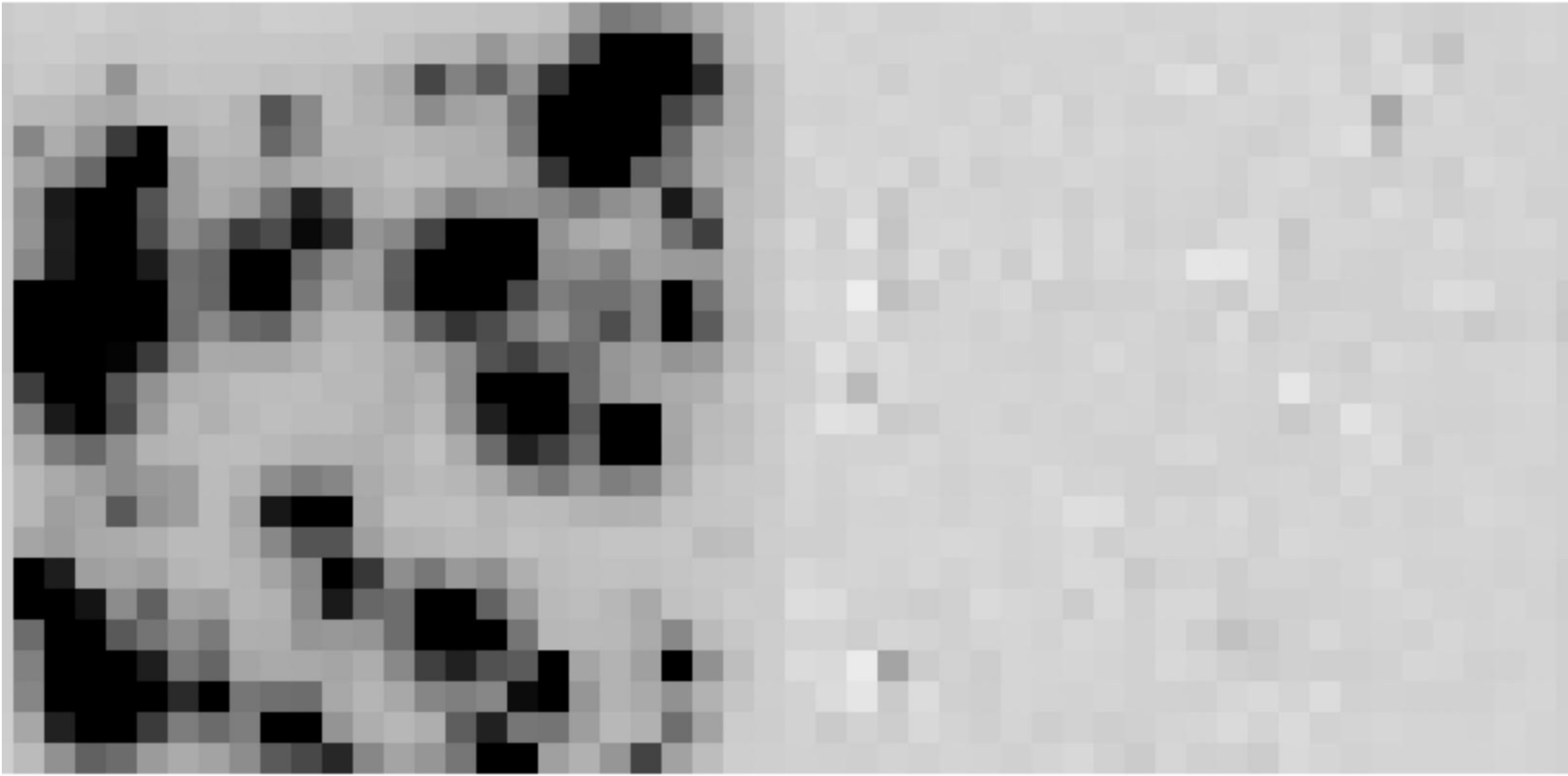


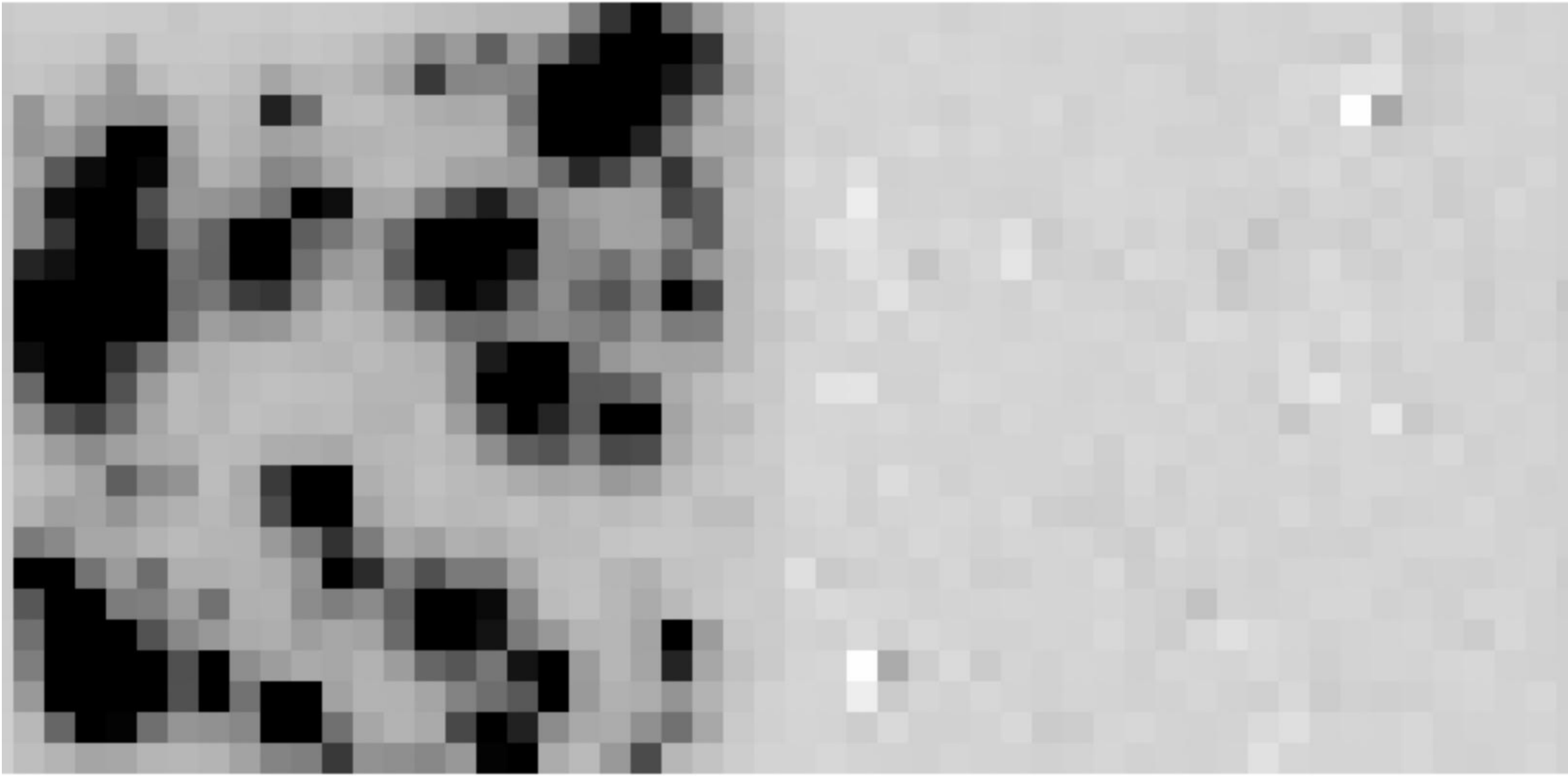


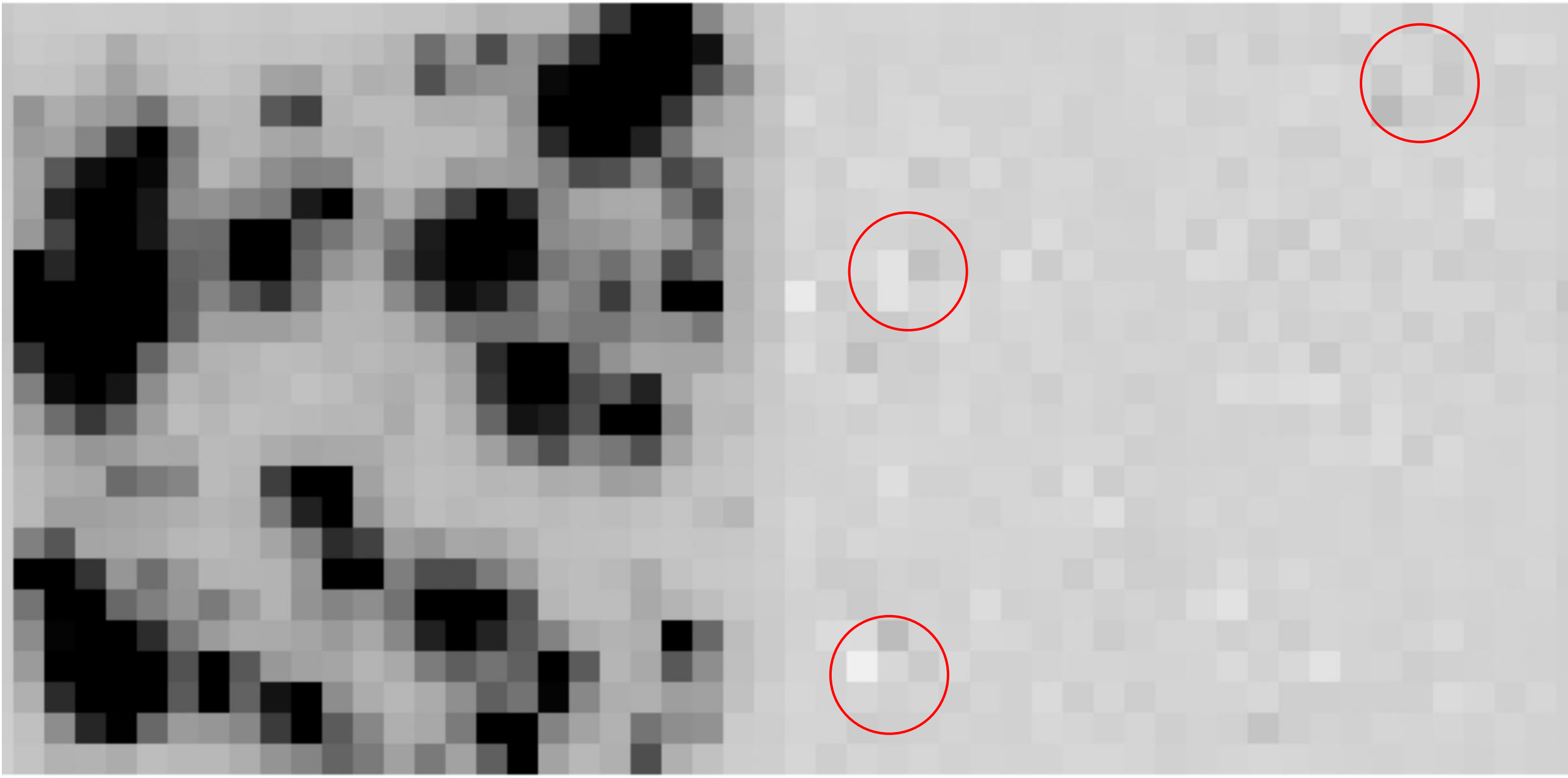








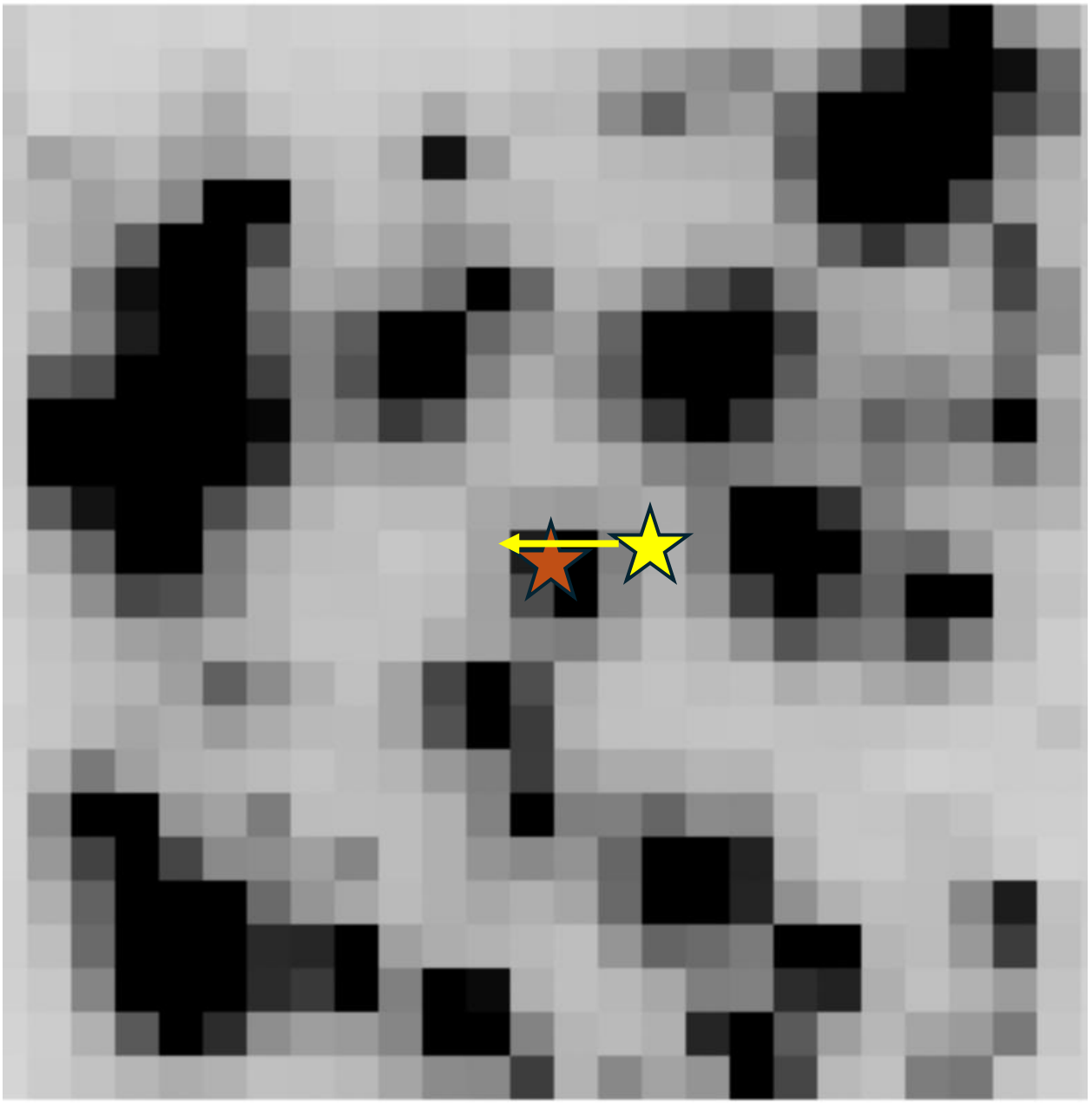




Noisier at the locations of bright stars…

Some Vignettes...

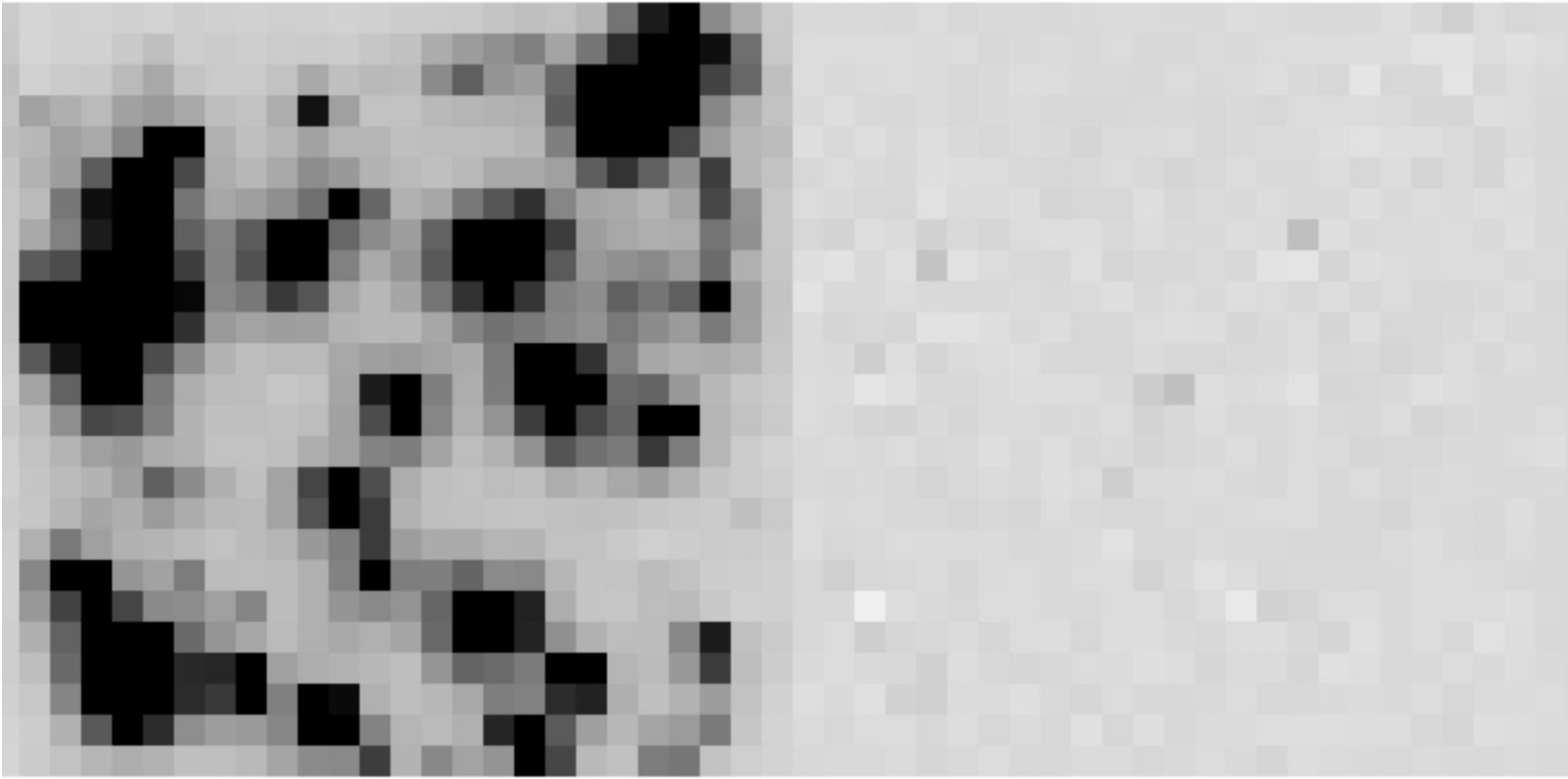
1) Realization of scene with dithers
2) Hal, it's full of stars!
3) Visualizing DIs...
4) A microlensing event in DIs
5) SS Objects in DIs
6) Color Dependence in Roman PSF
7) Fitting stars with undersampled PSFs



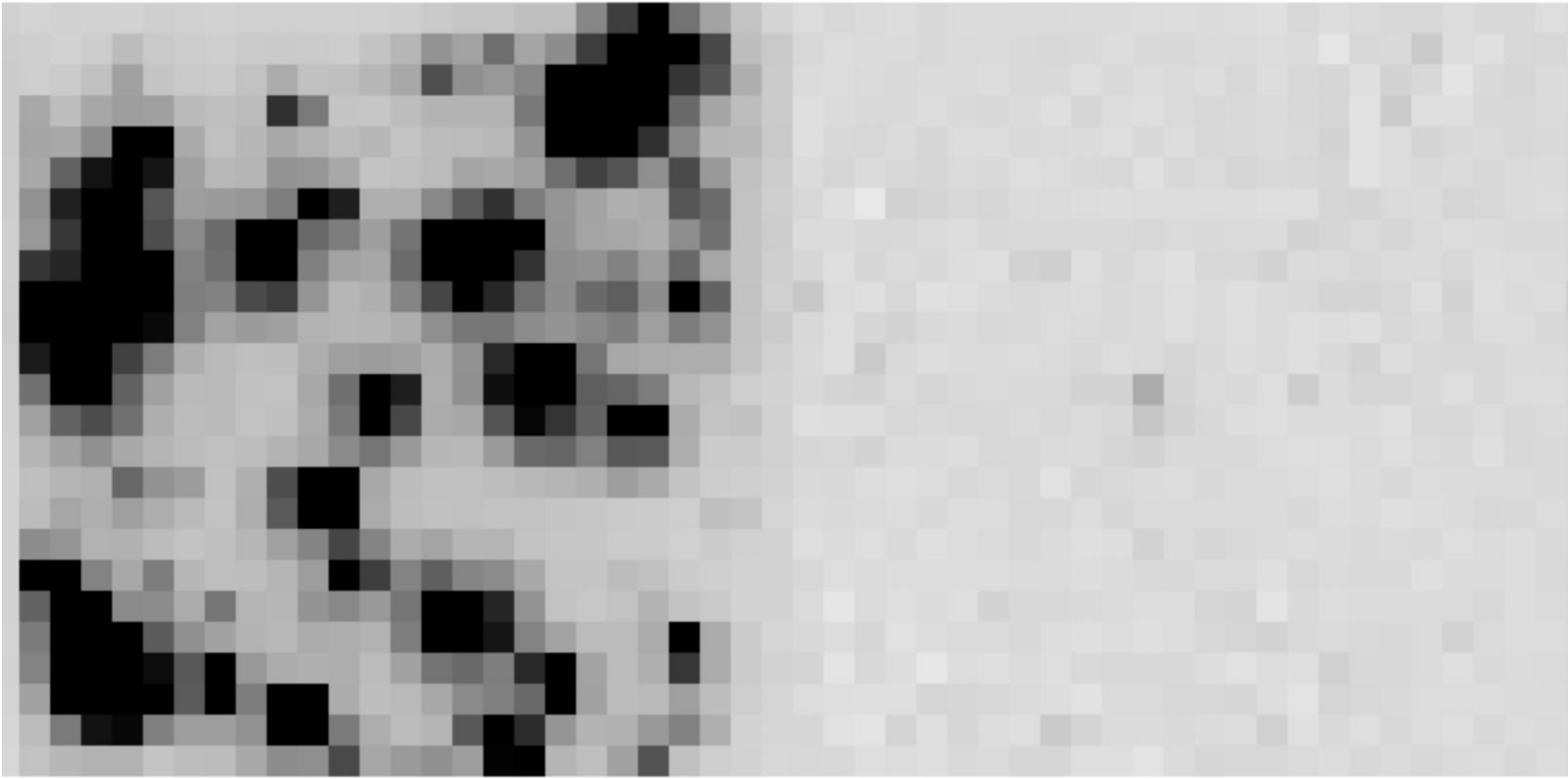
IMPACT PARAMETER: 0.1 R_E

AMPLIFICATION: x10

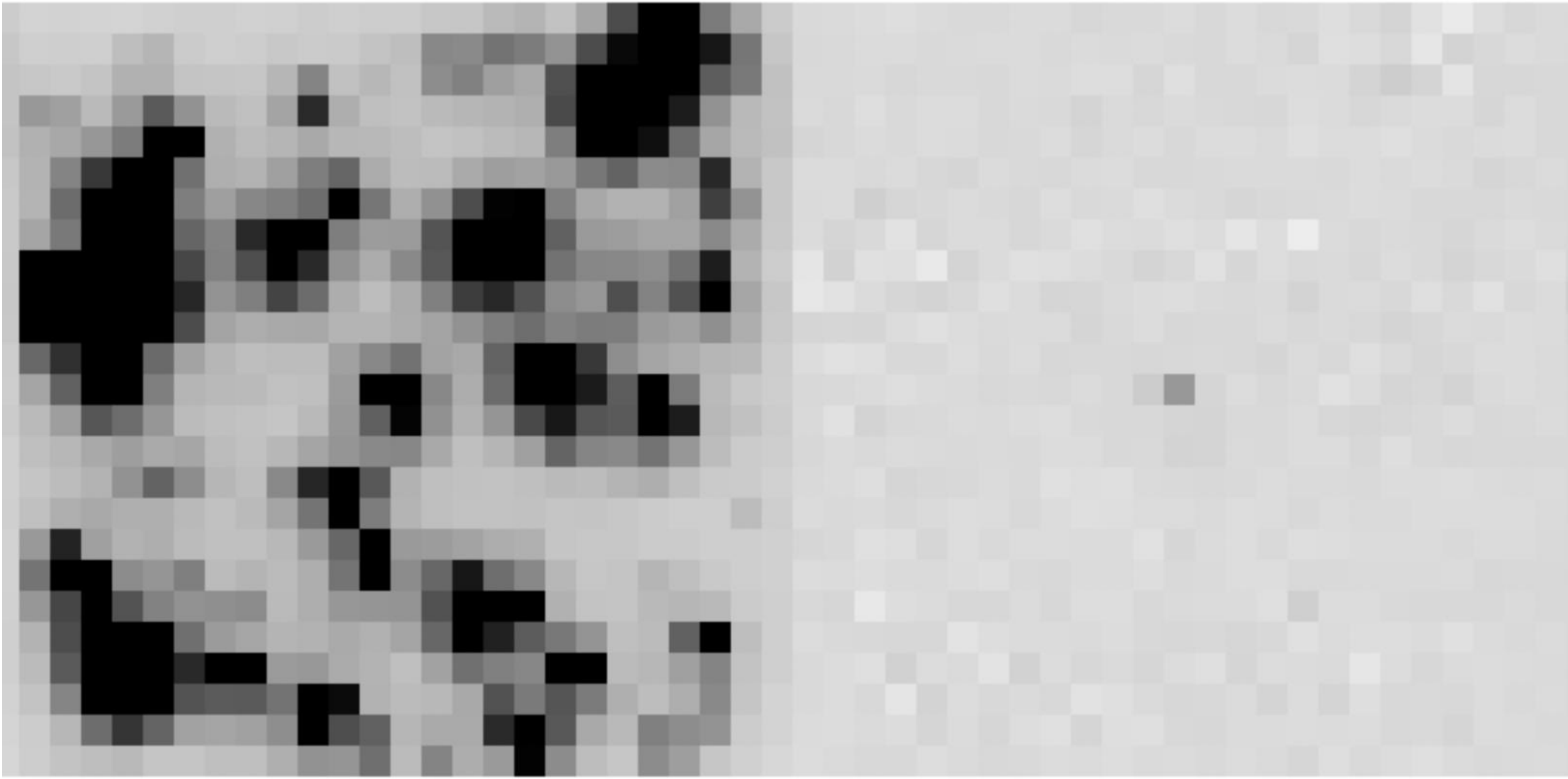
RE = 1.3 AU
= 0.3 mas
= 0.003 pixel



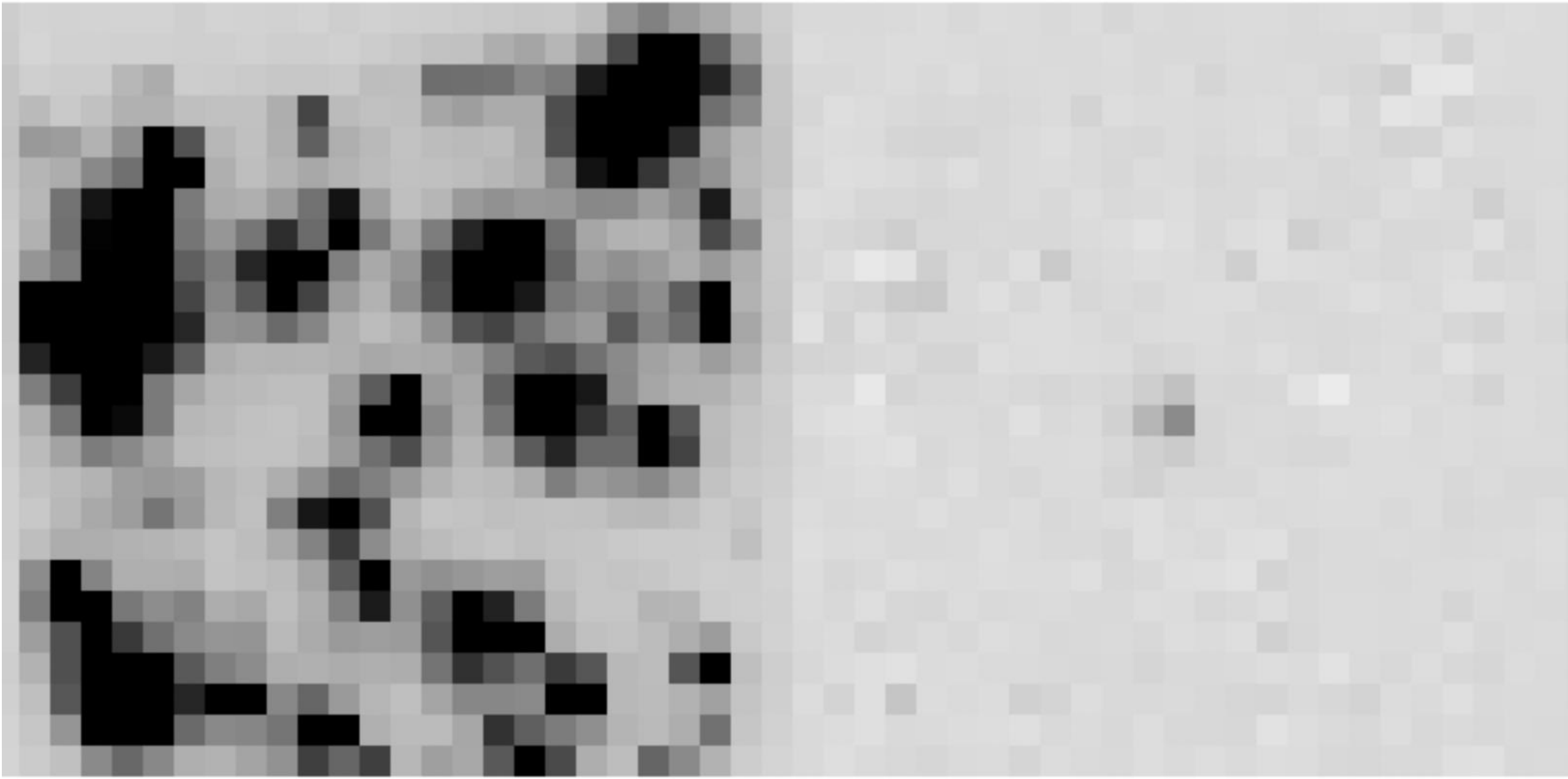
−9 days



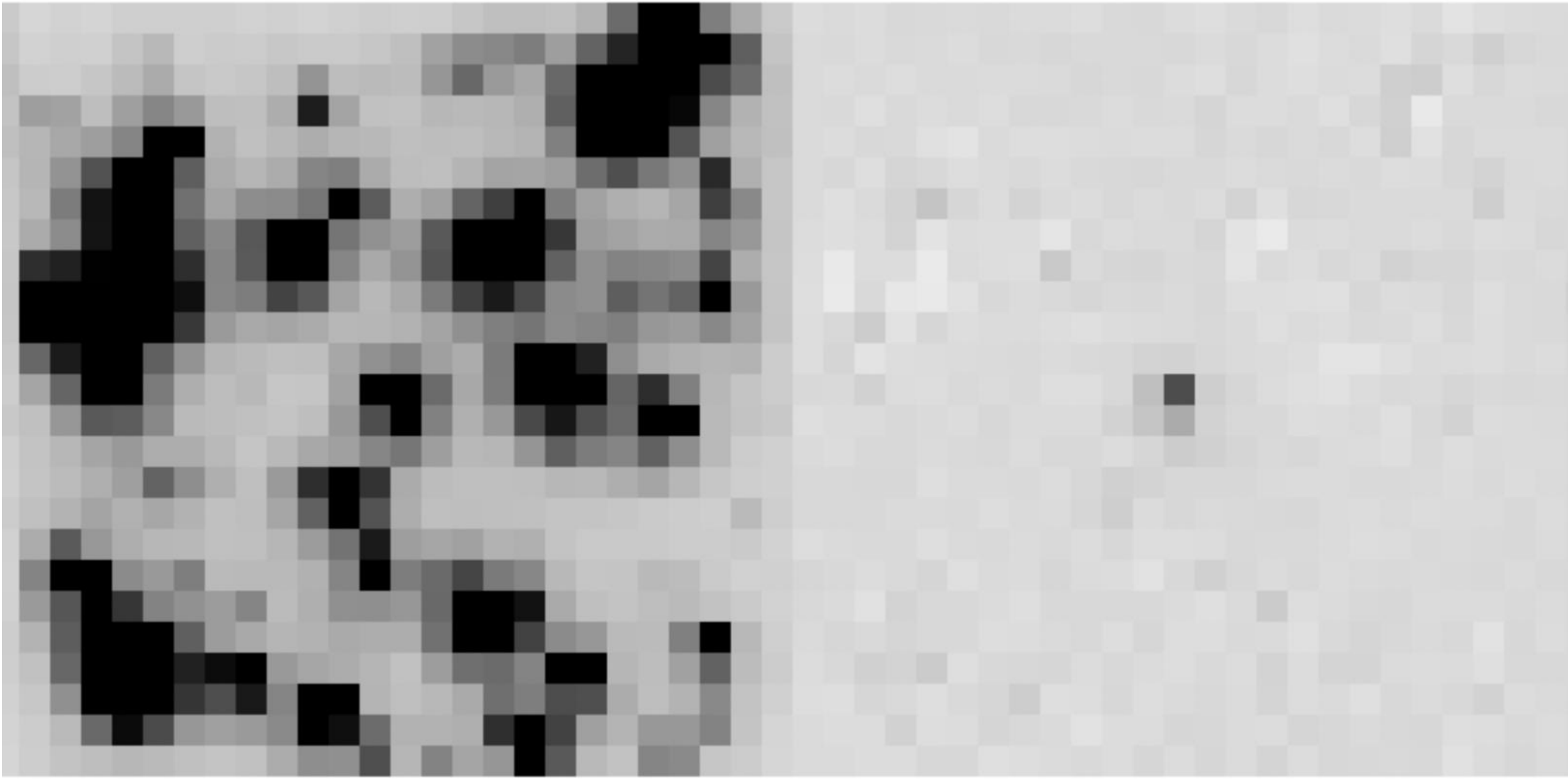
−8 days



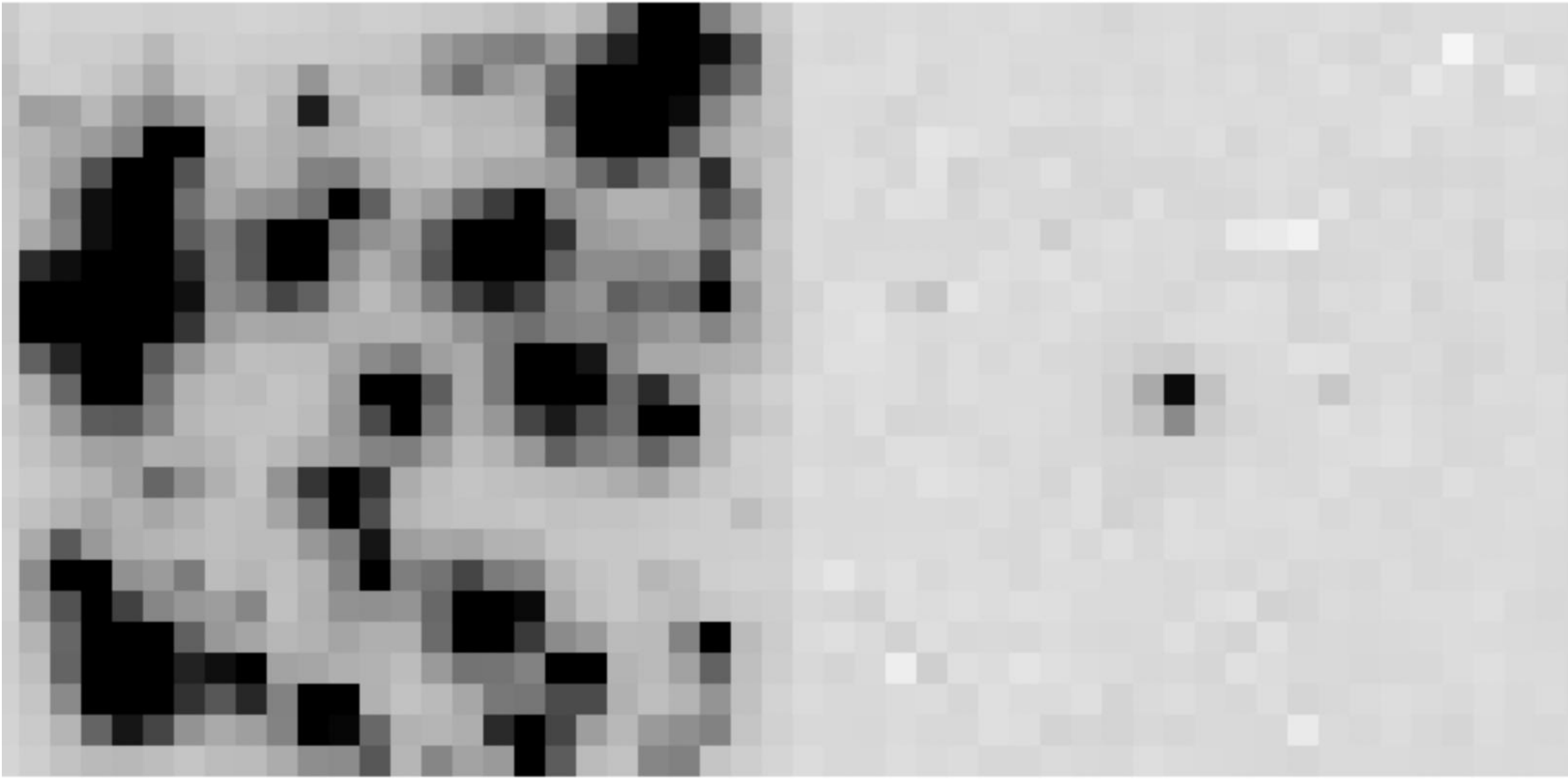
−7 days



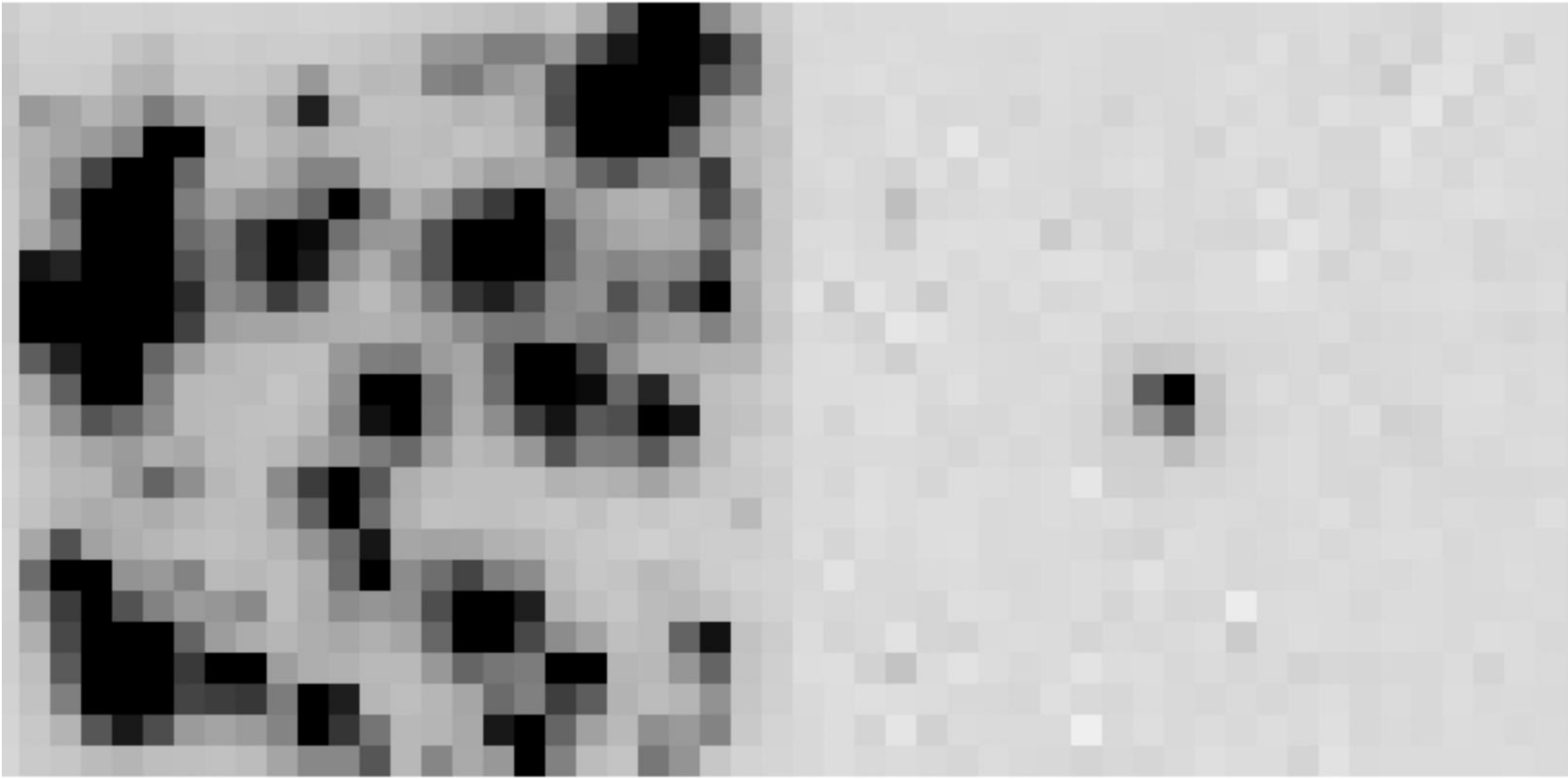
−6 days



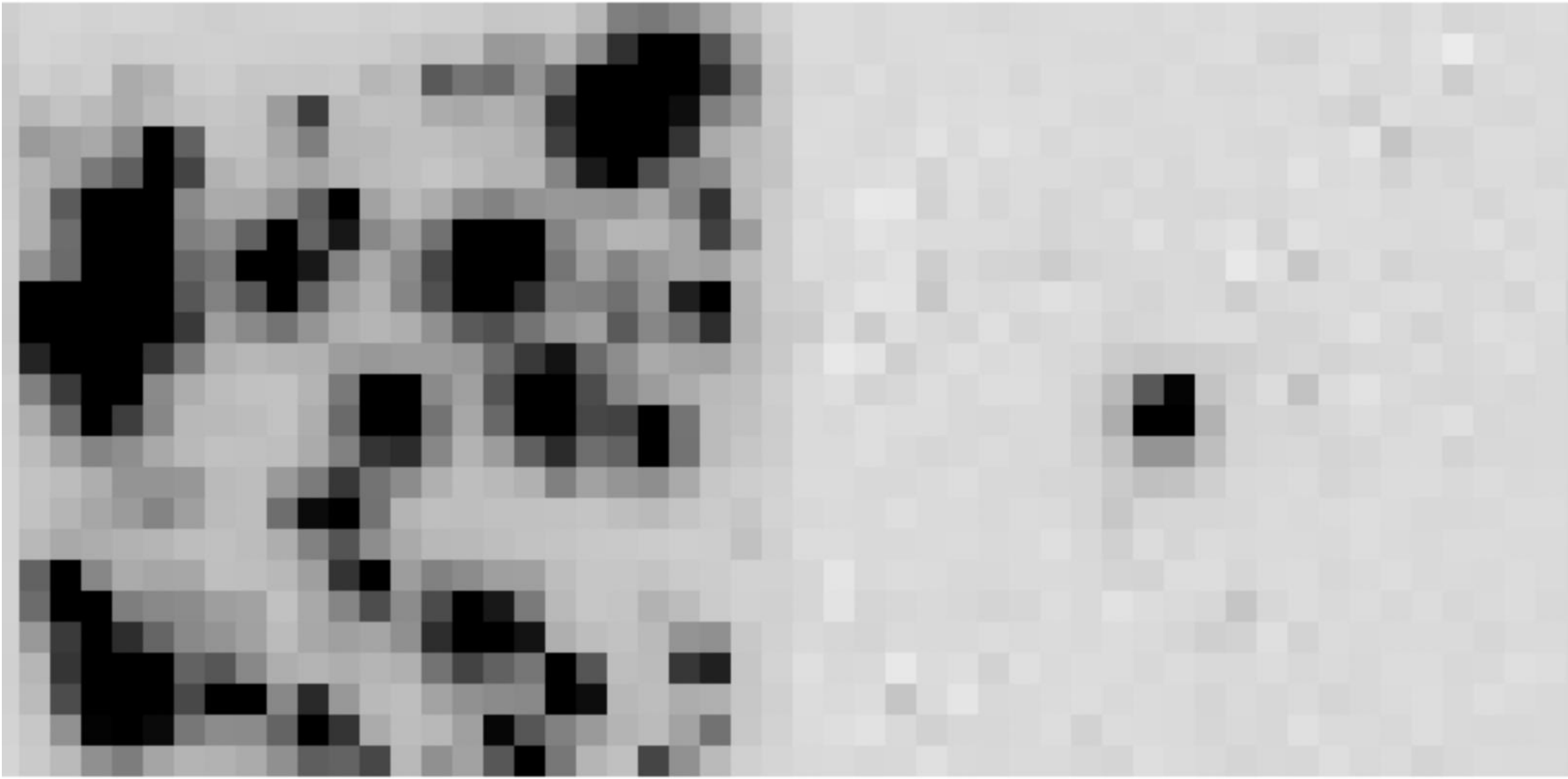
−5 days



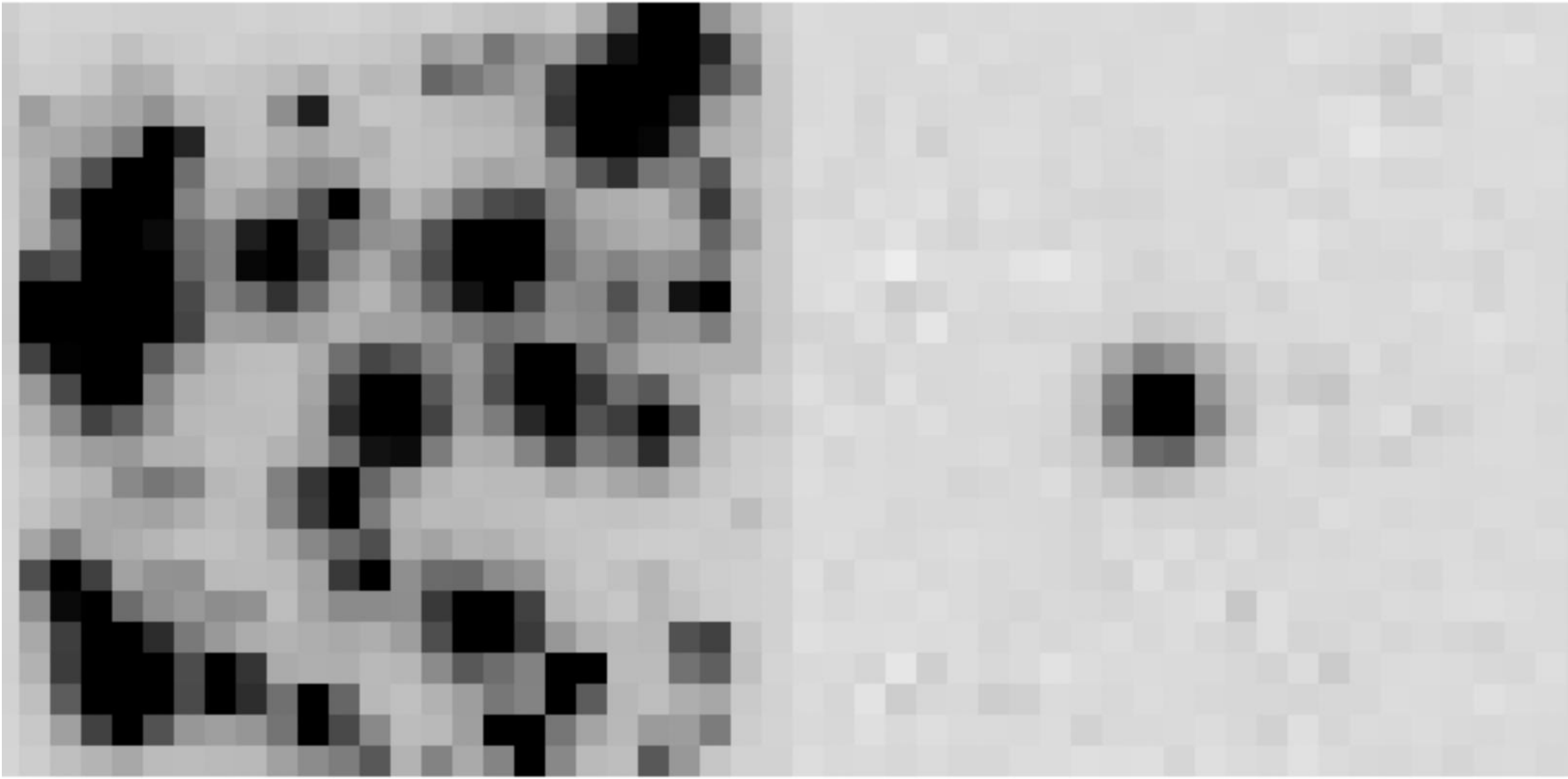
−4 days



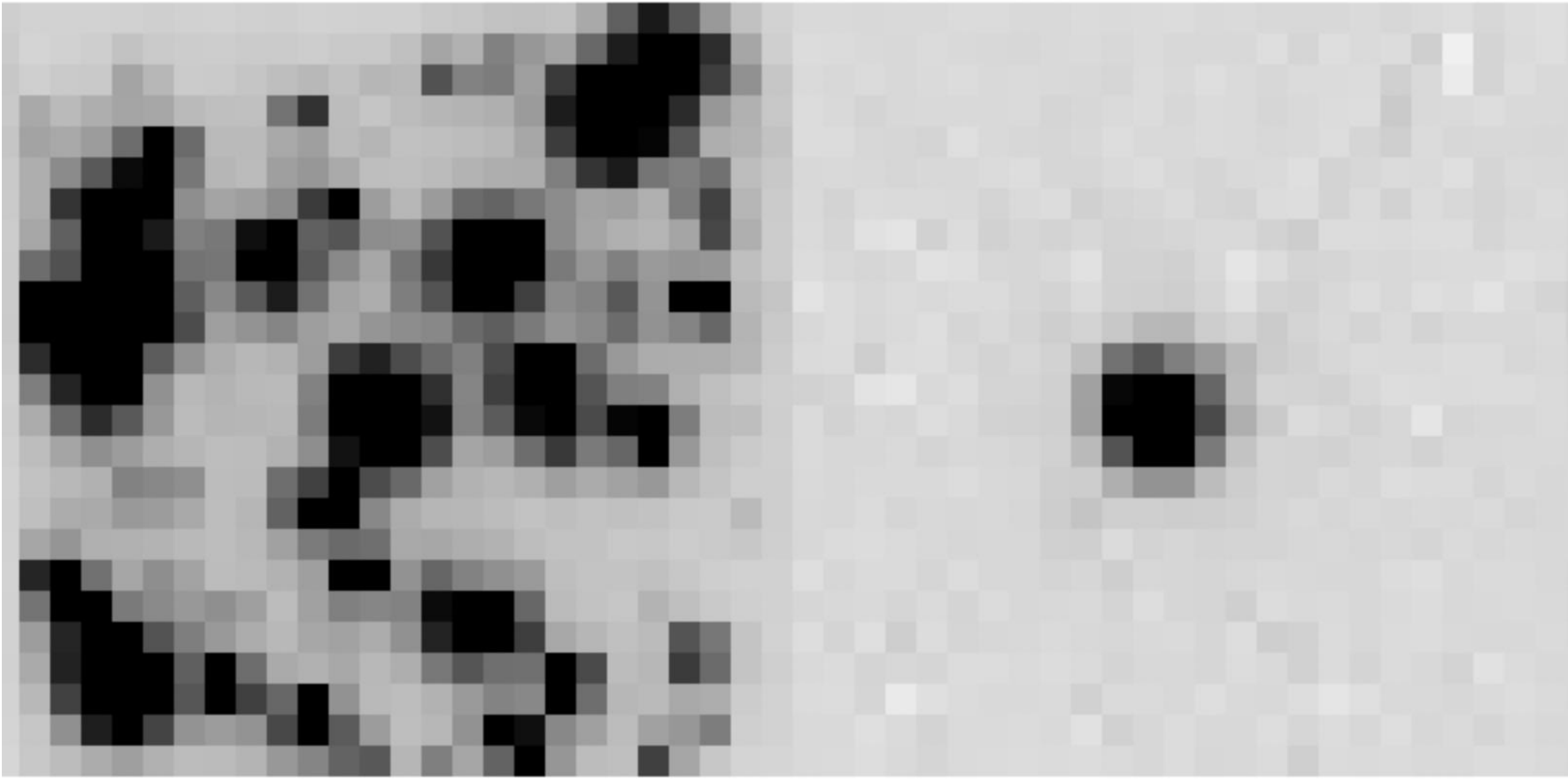
−3 days



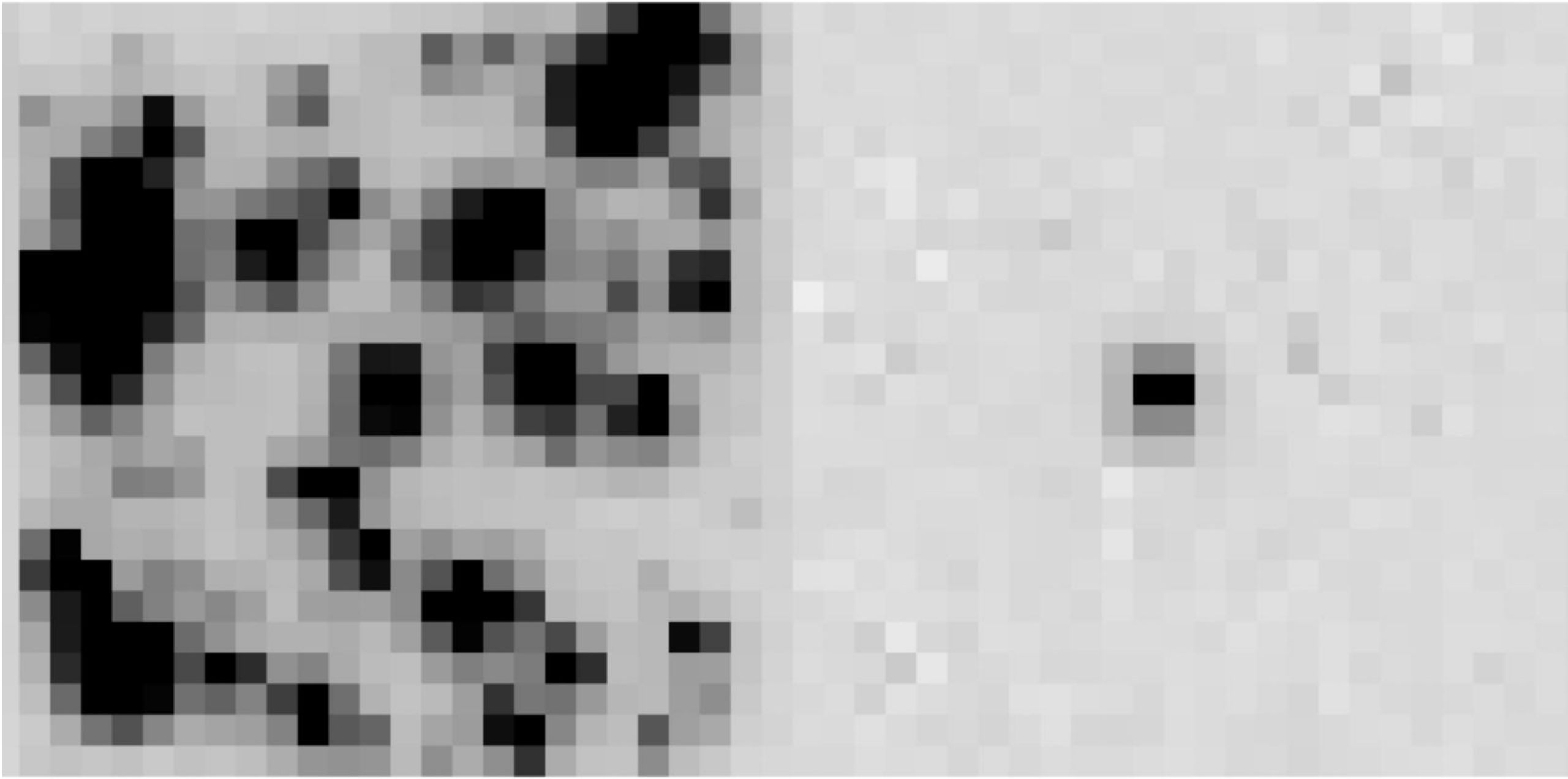
−2 days



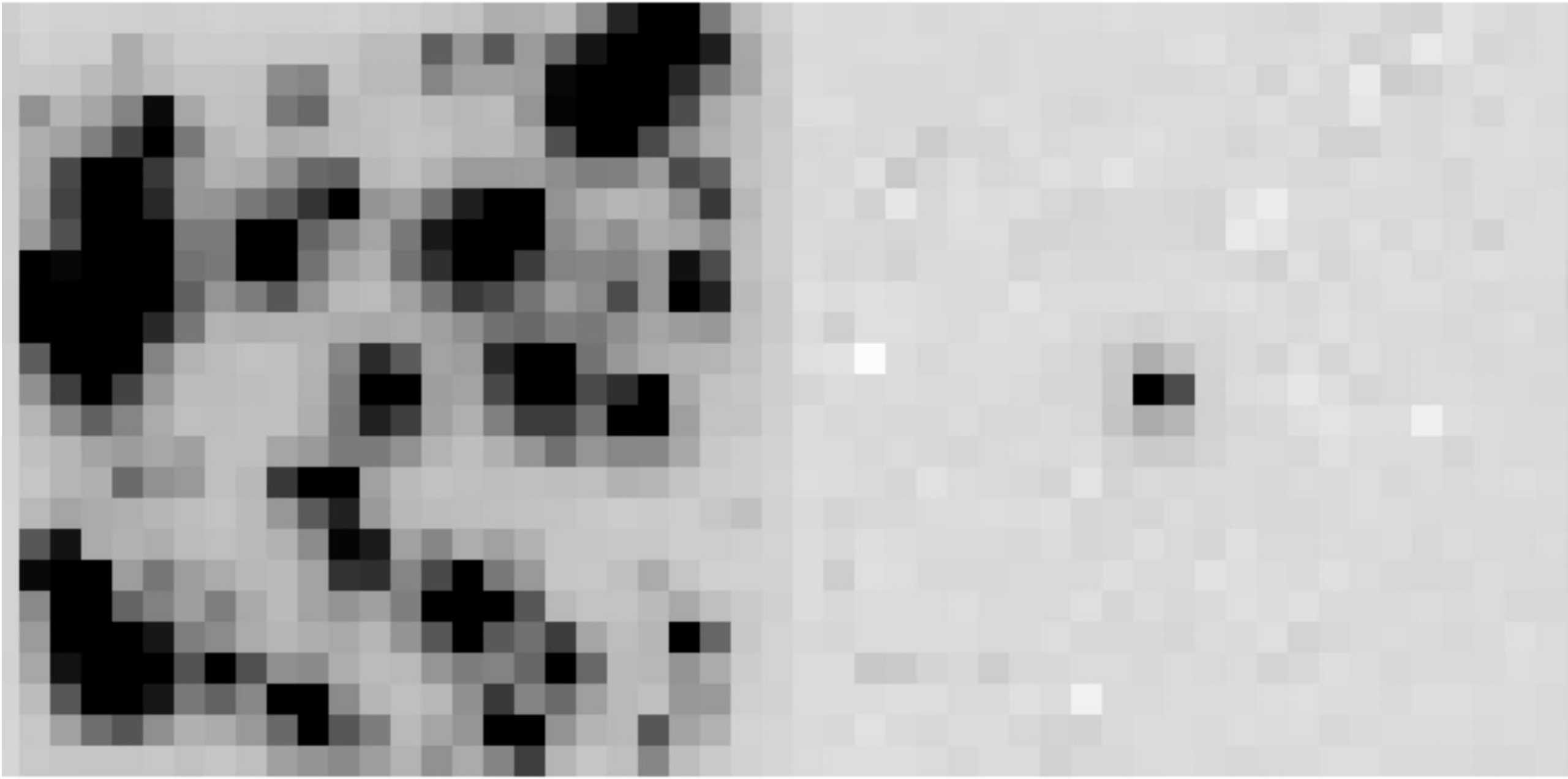
−1 day



PEAK! x10 AMPLIFICATION!



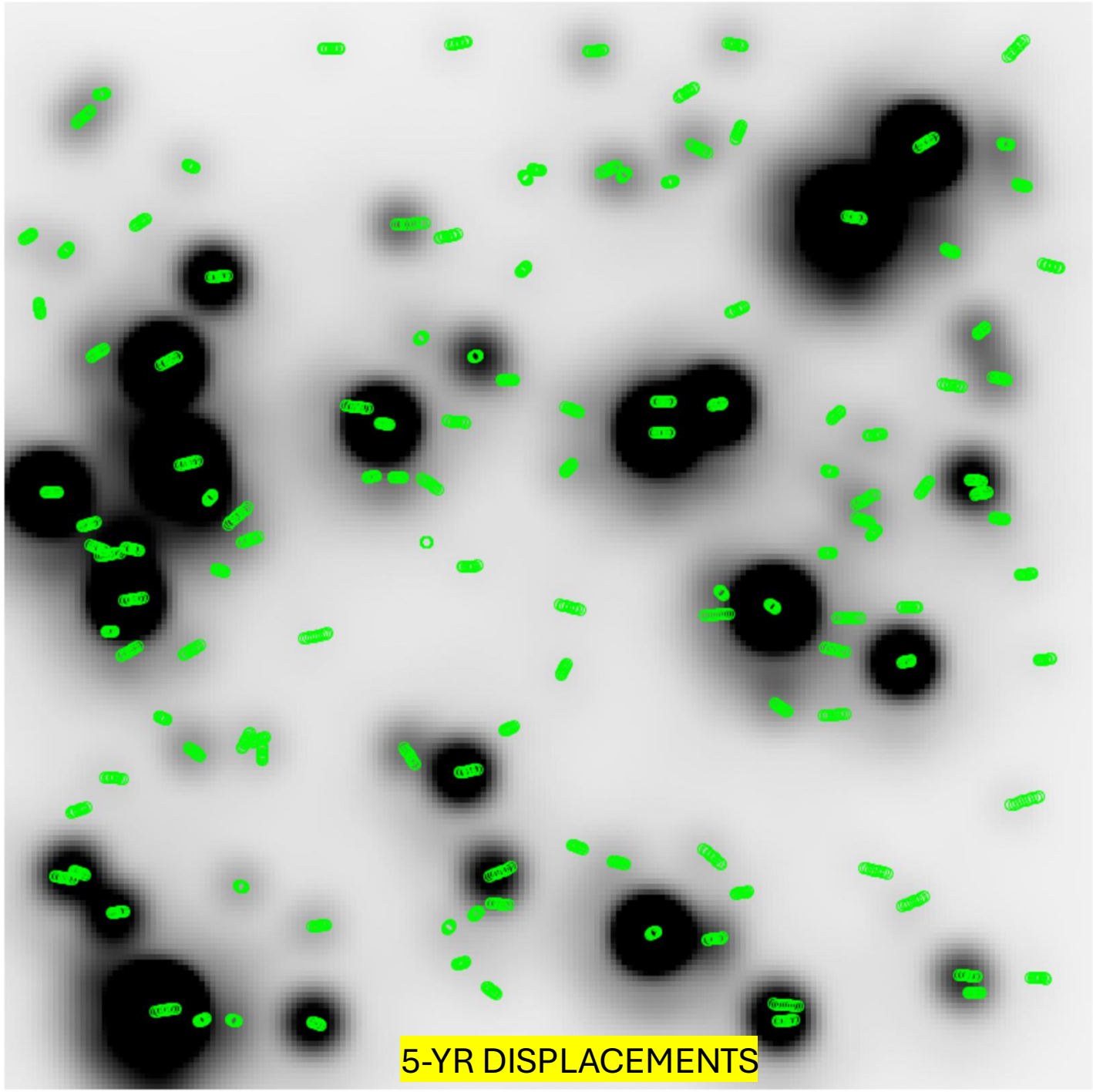
+1 day



+2 days

Some remaining challenges

- DIs good because they remove stars we don't know about!
- Challenges:
  - Cannot make infinite-time stacks (PMs)
  - The event can affect the local stack.



Some Vignettes...

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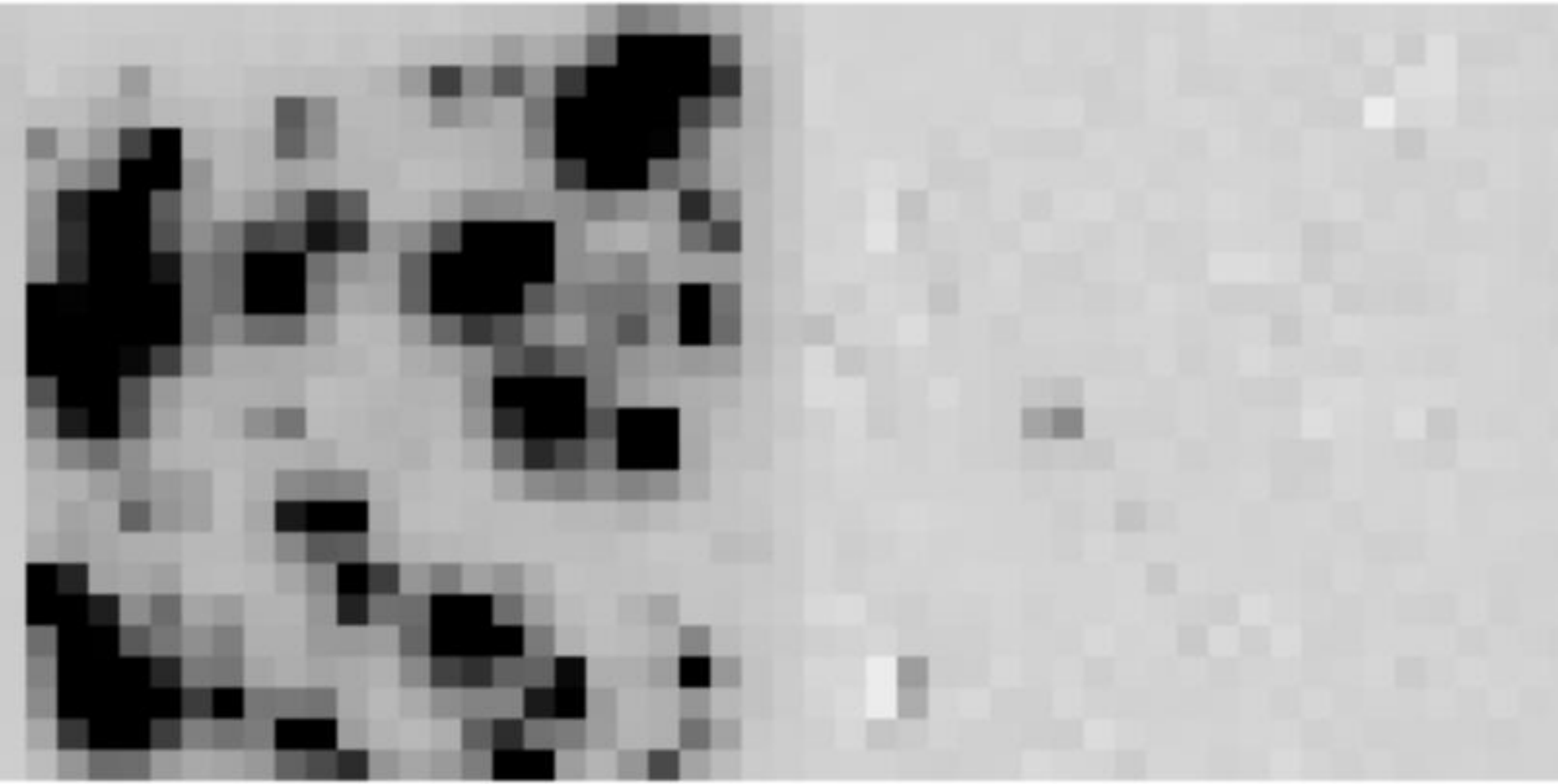
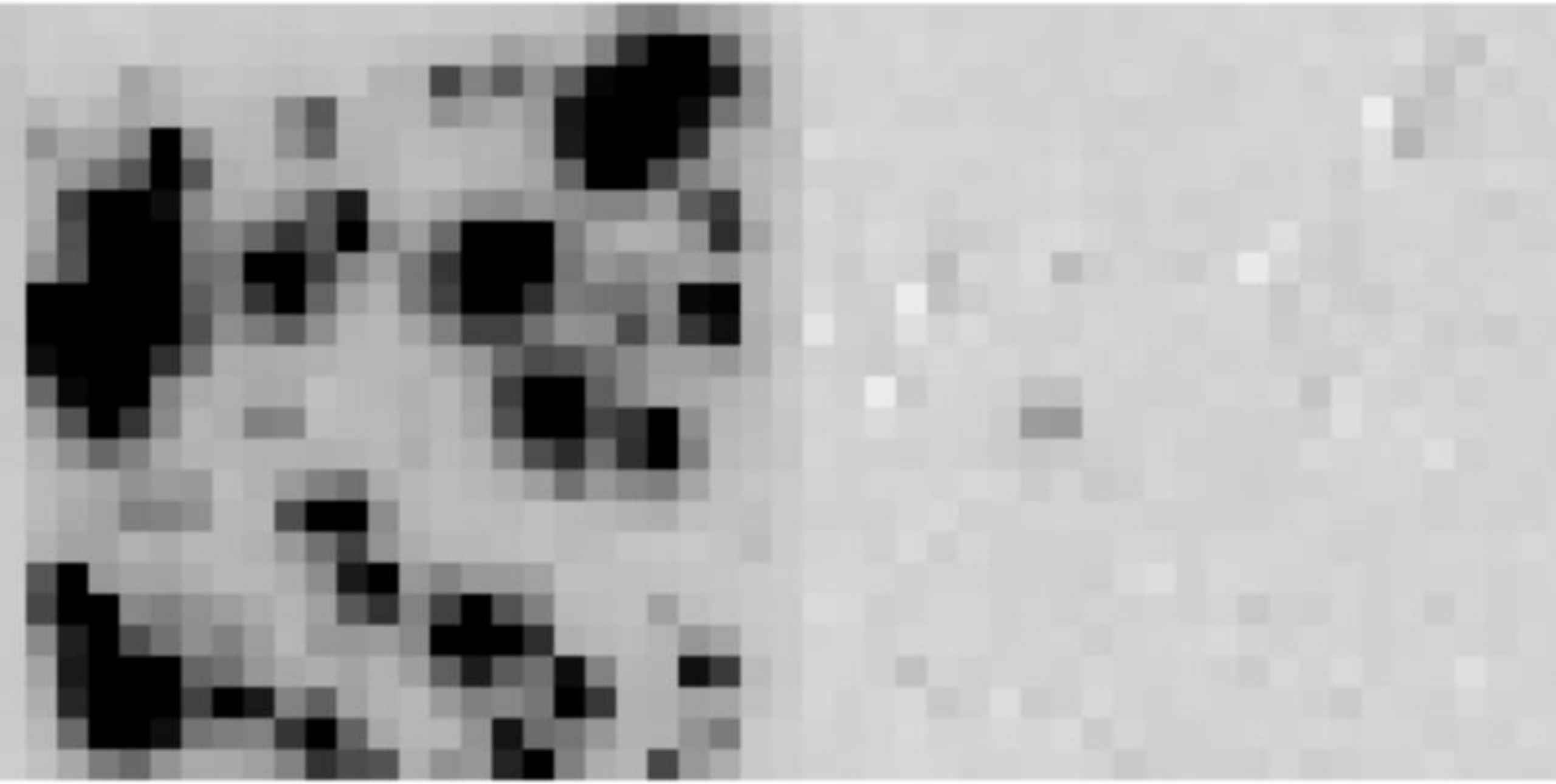
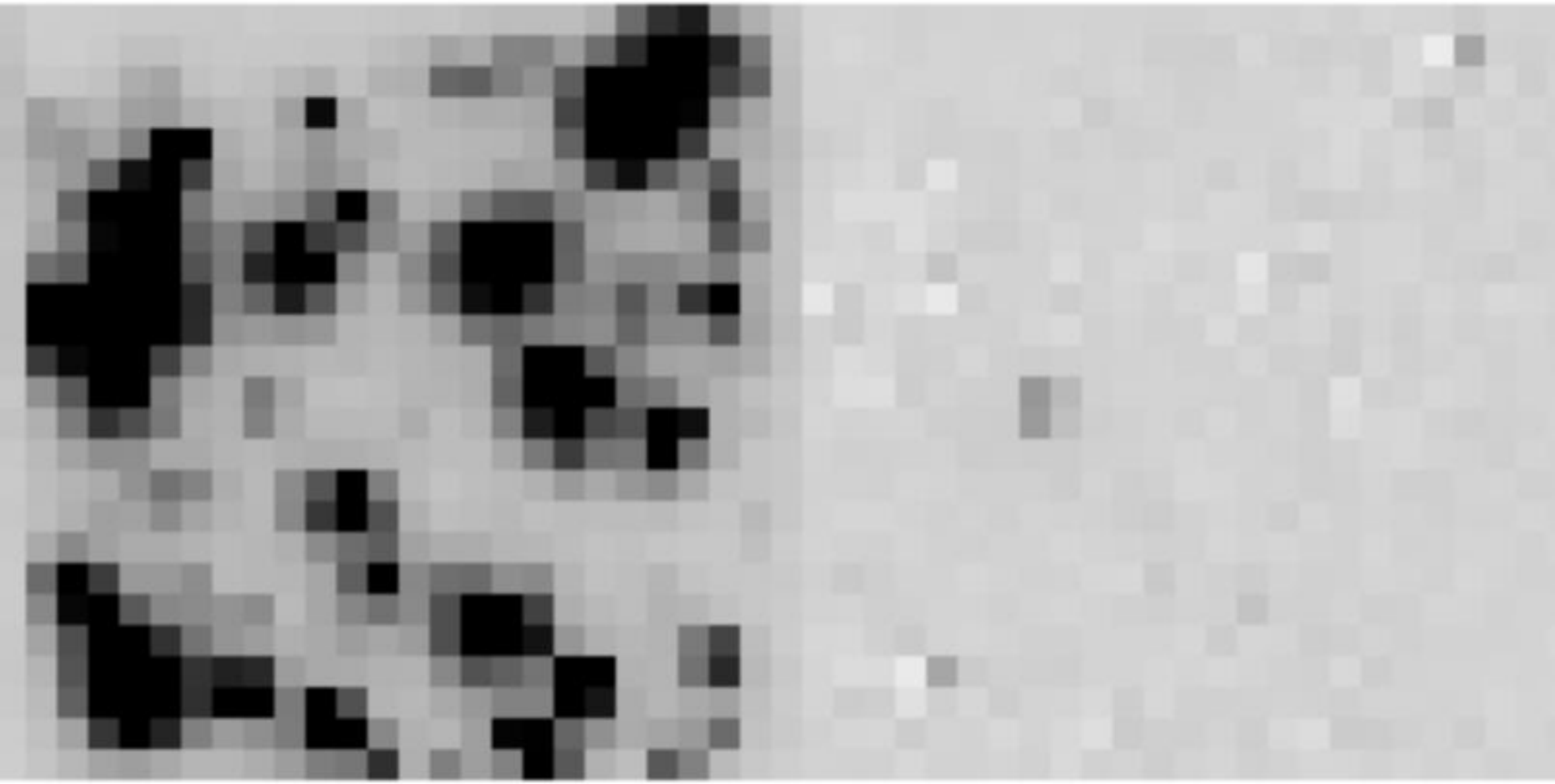
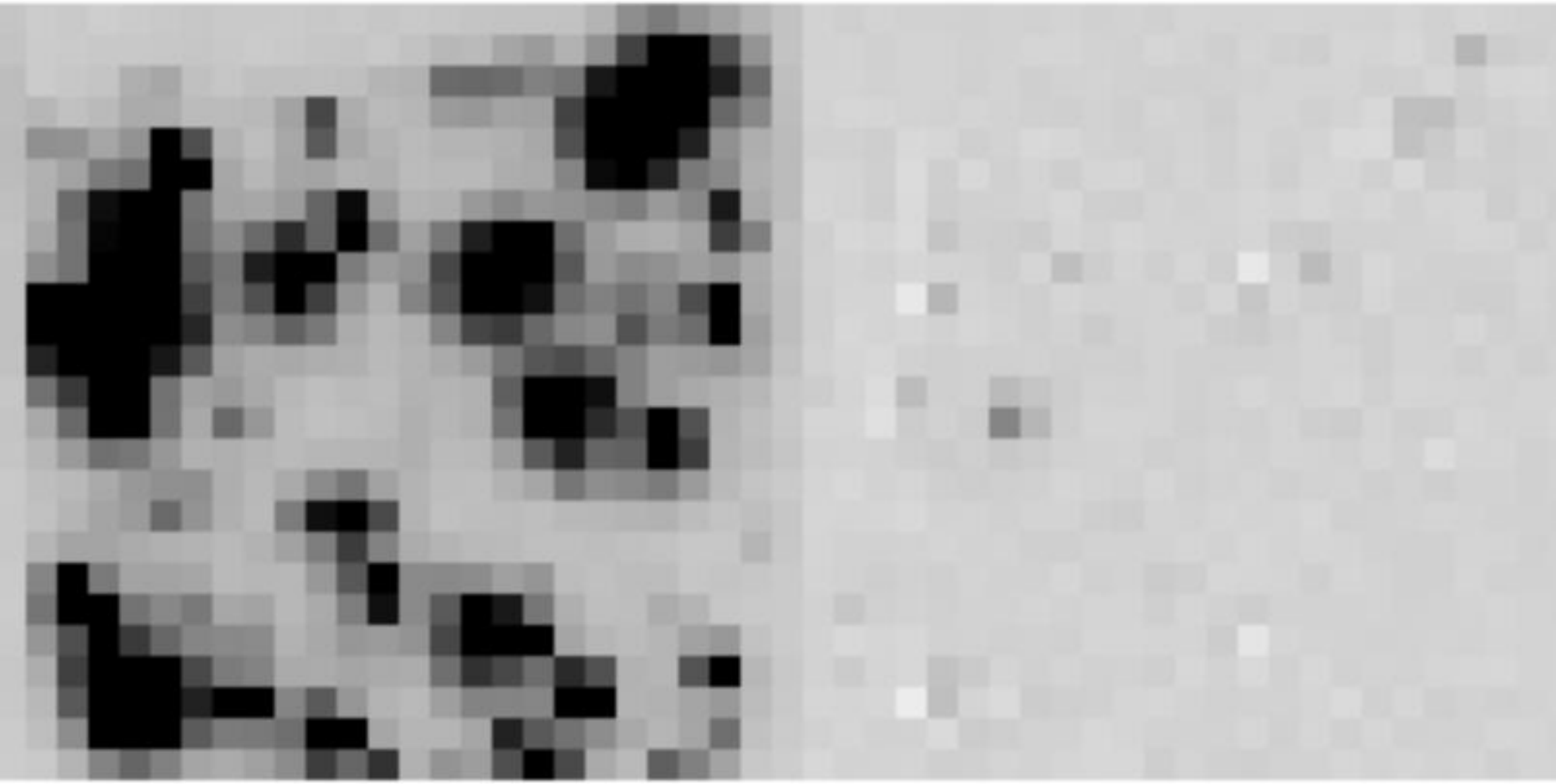
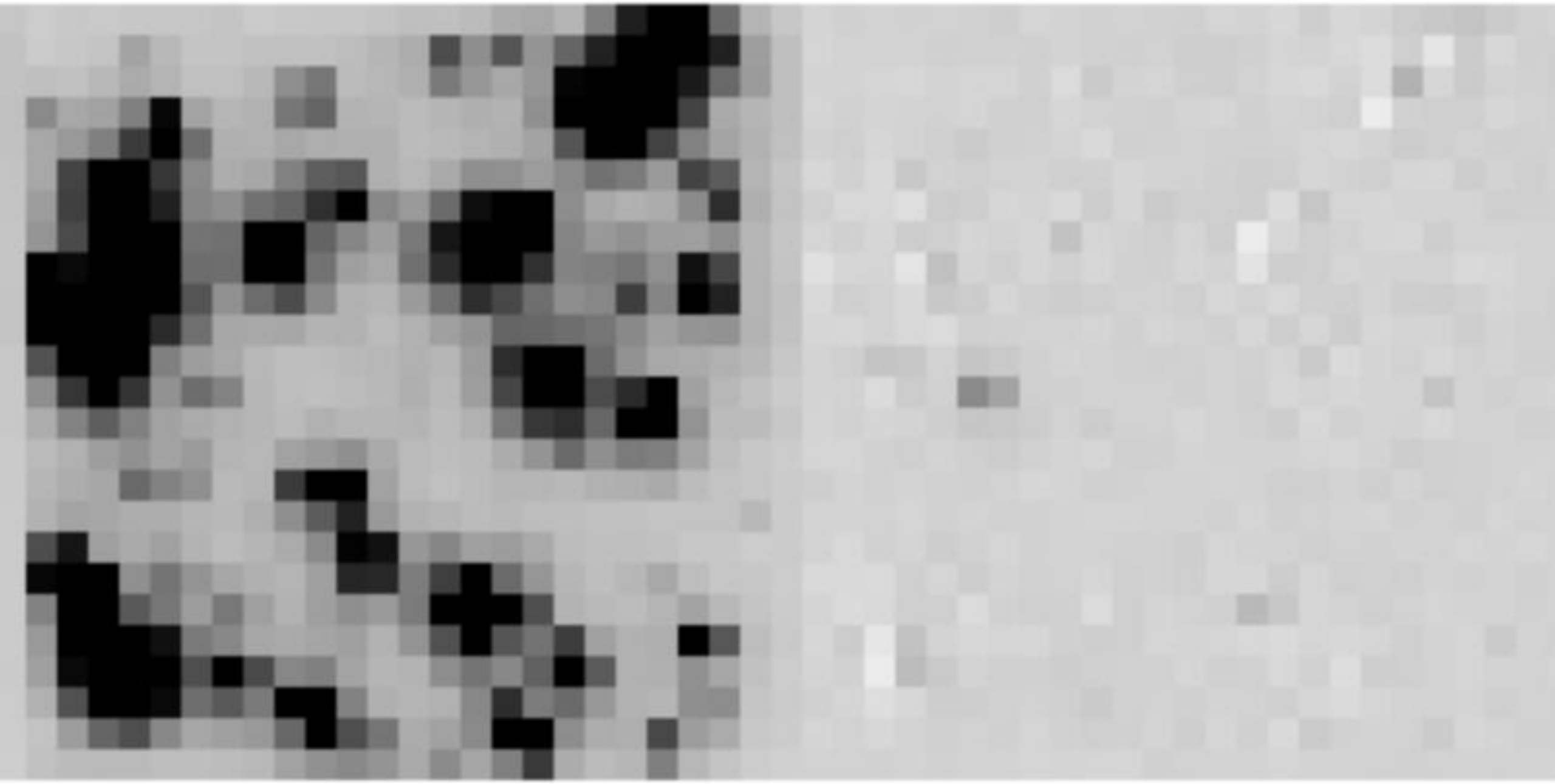
6) Color Dependence in Roman PSF
7) Fitting stars with undersampled PSFs

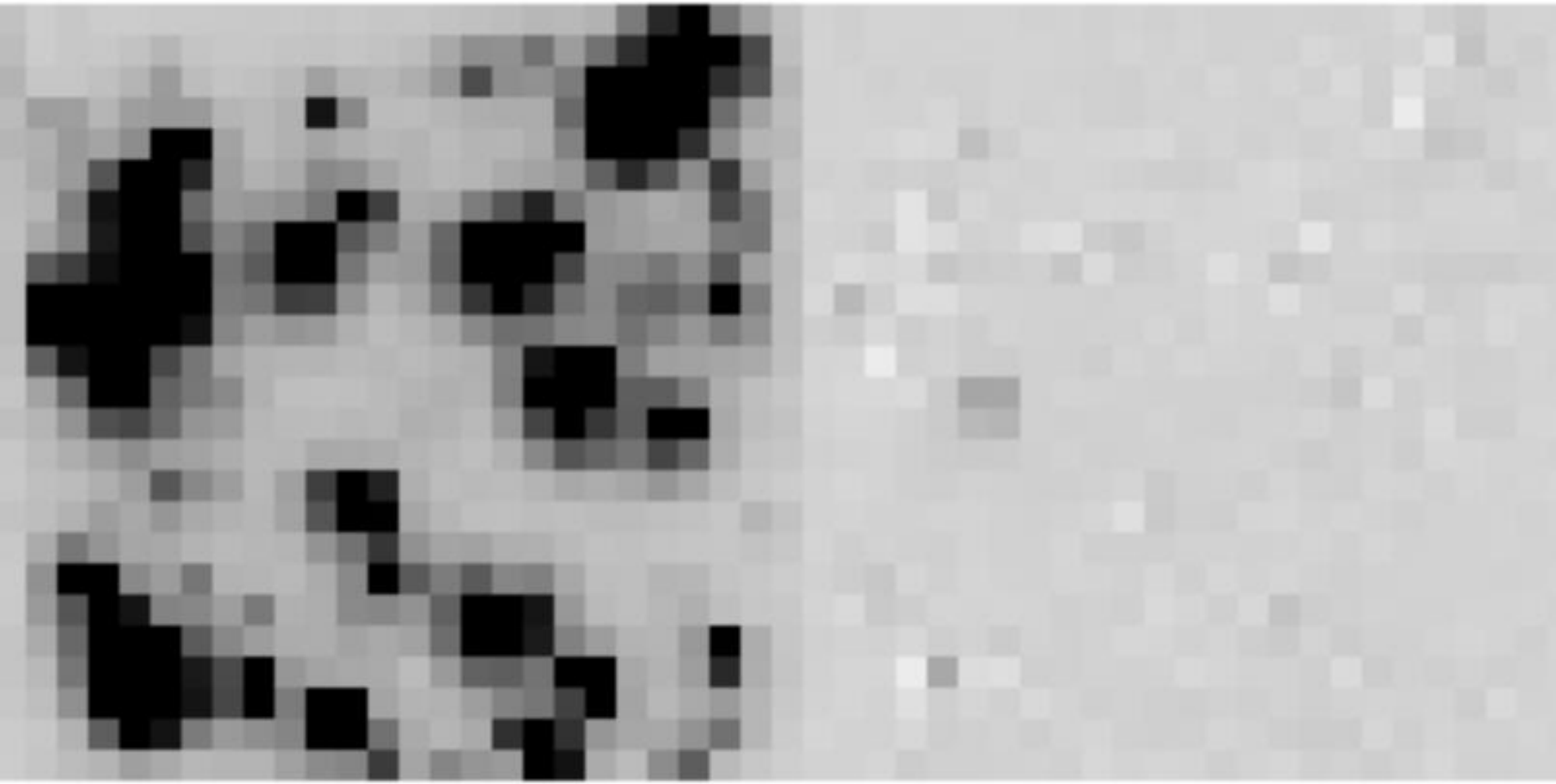


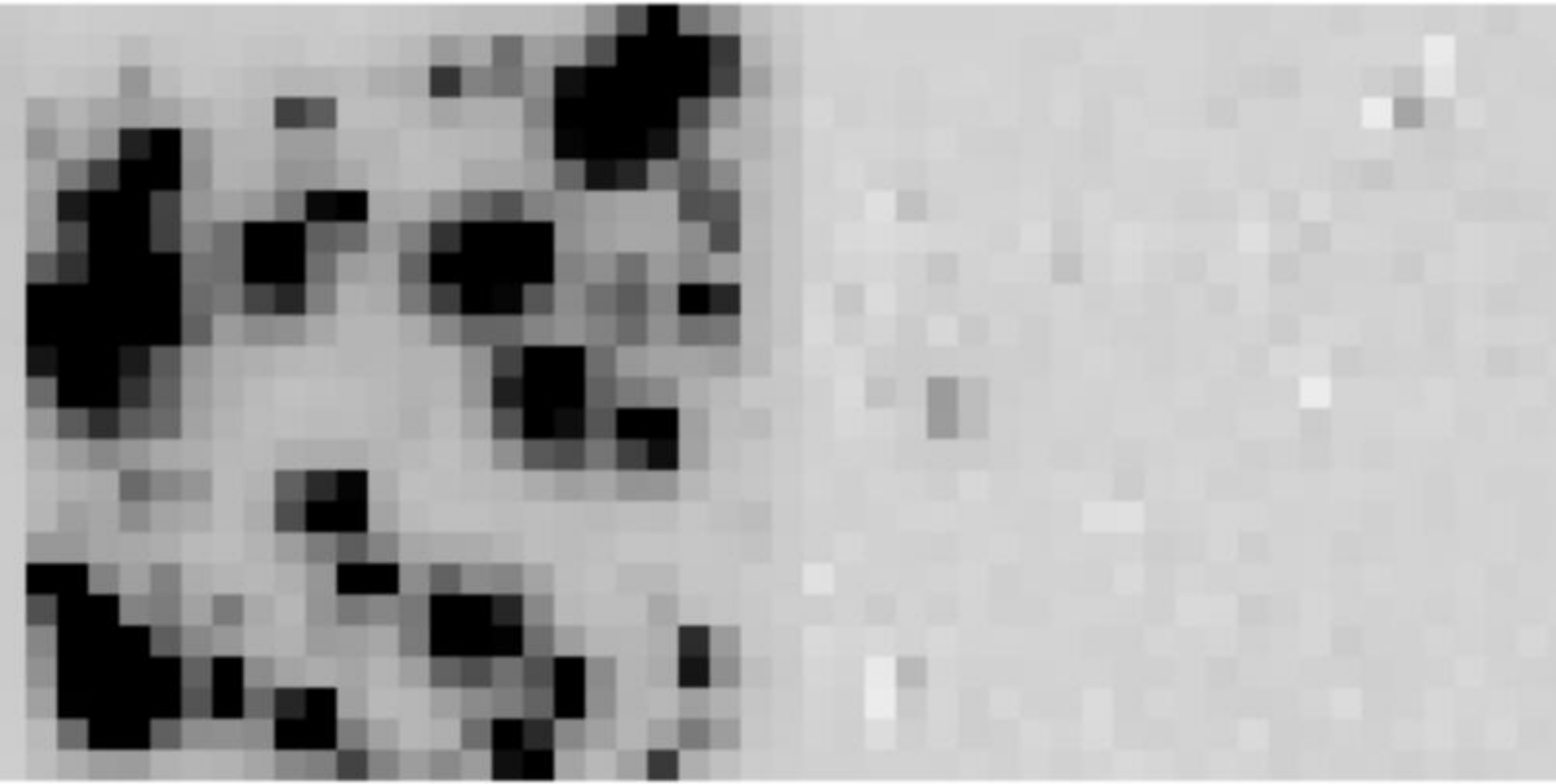


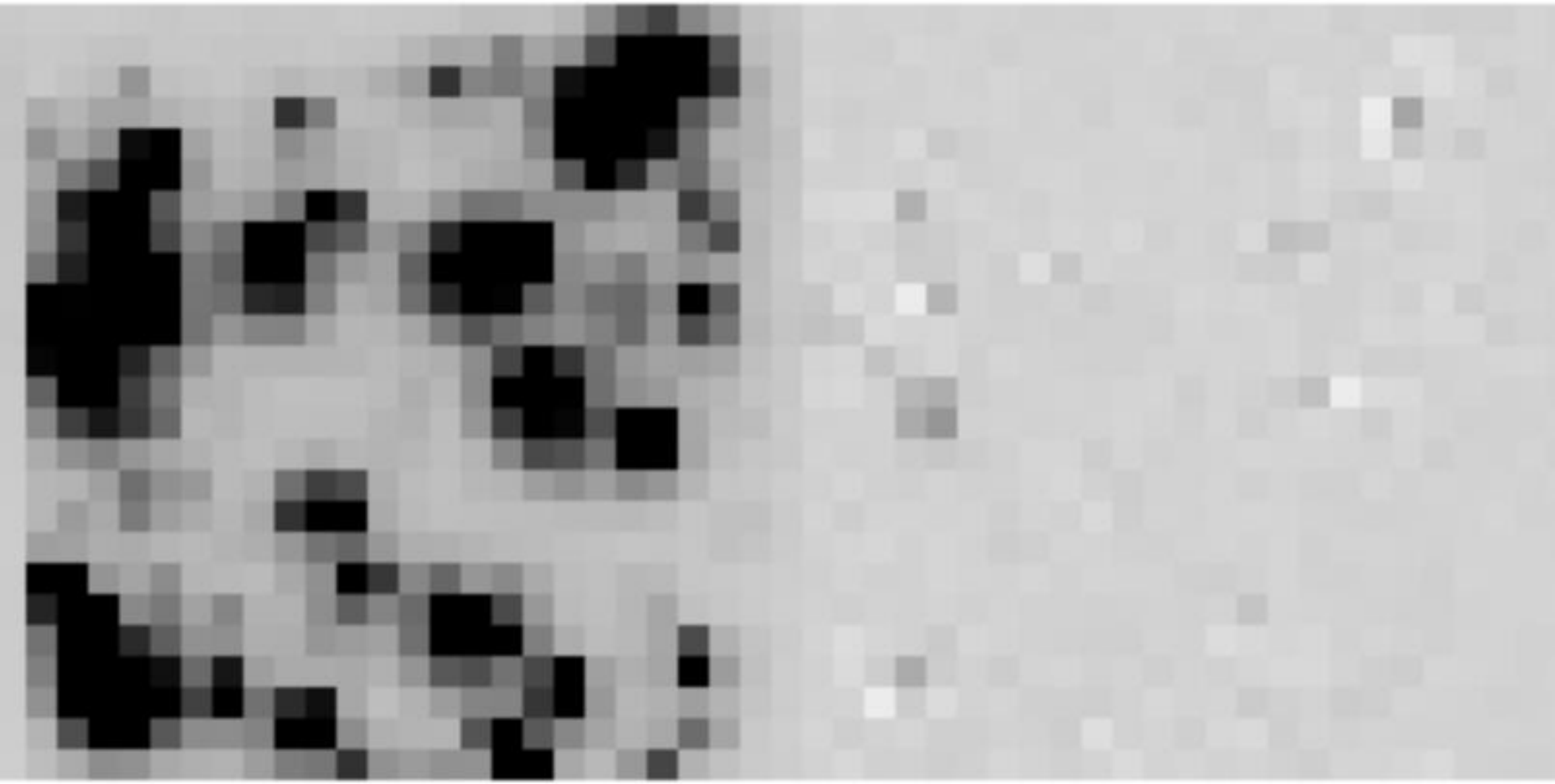


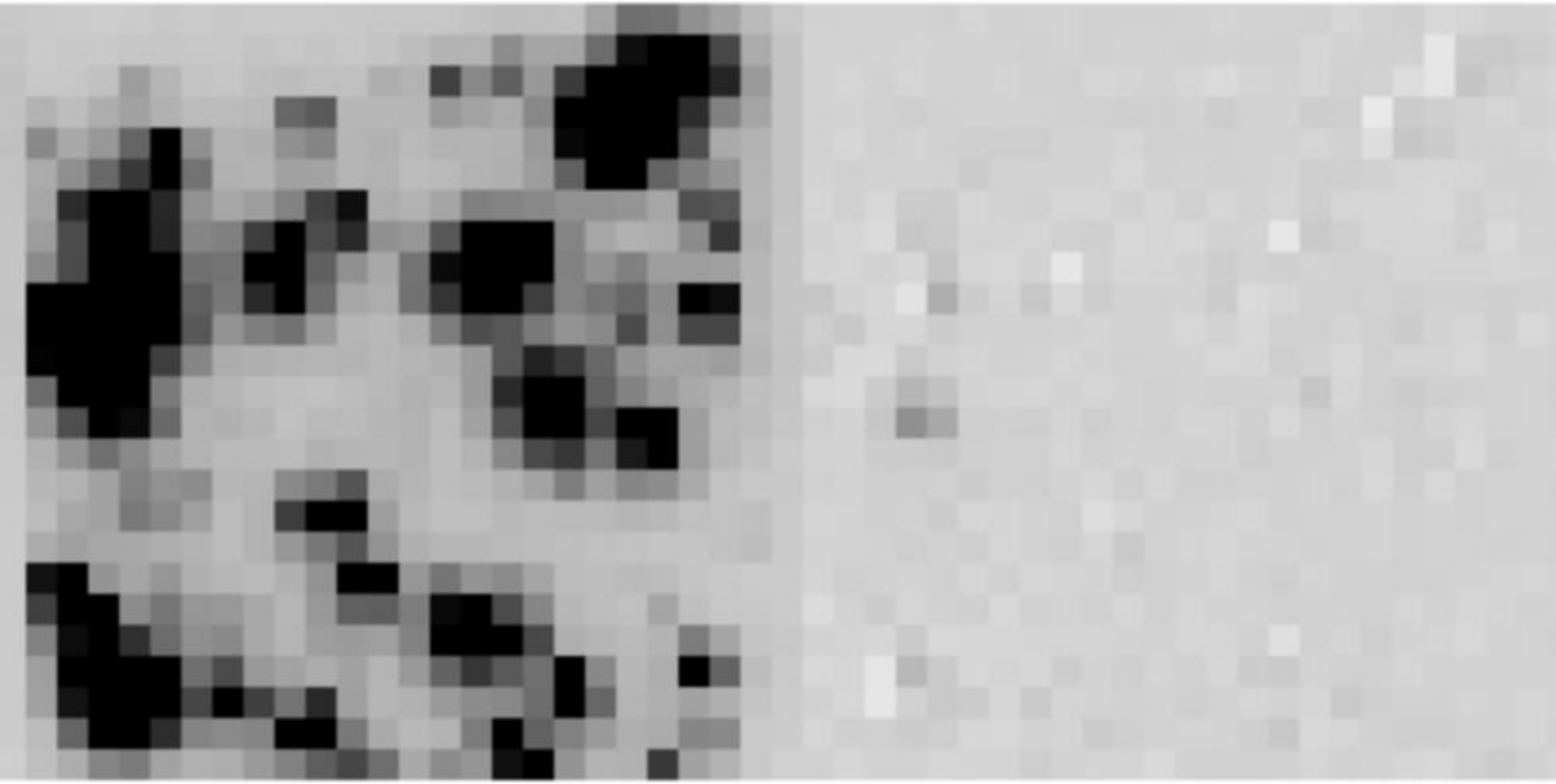


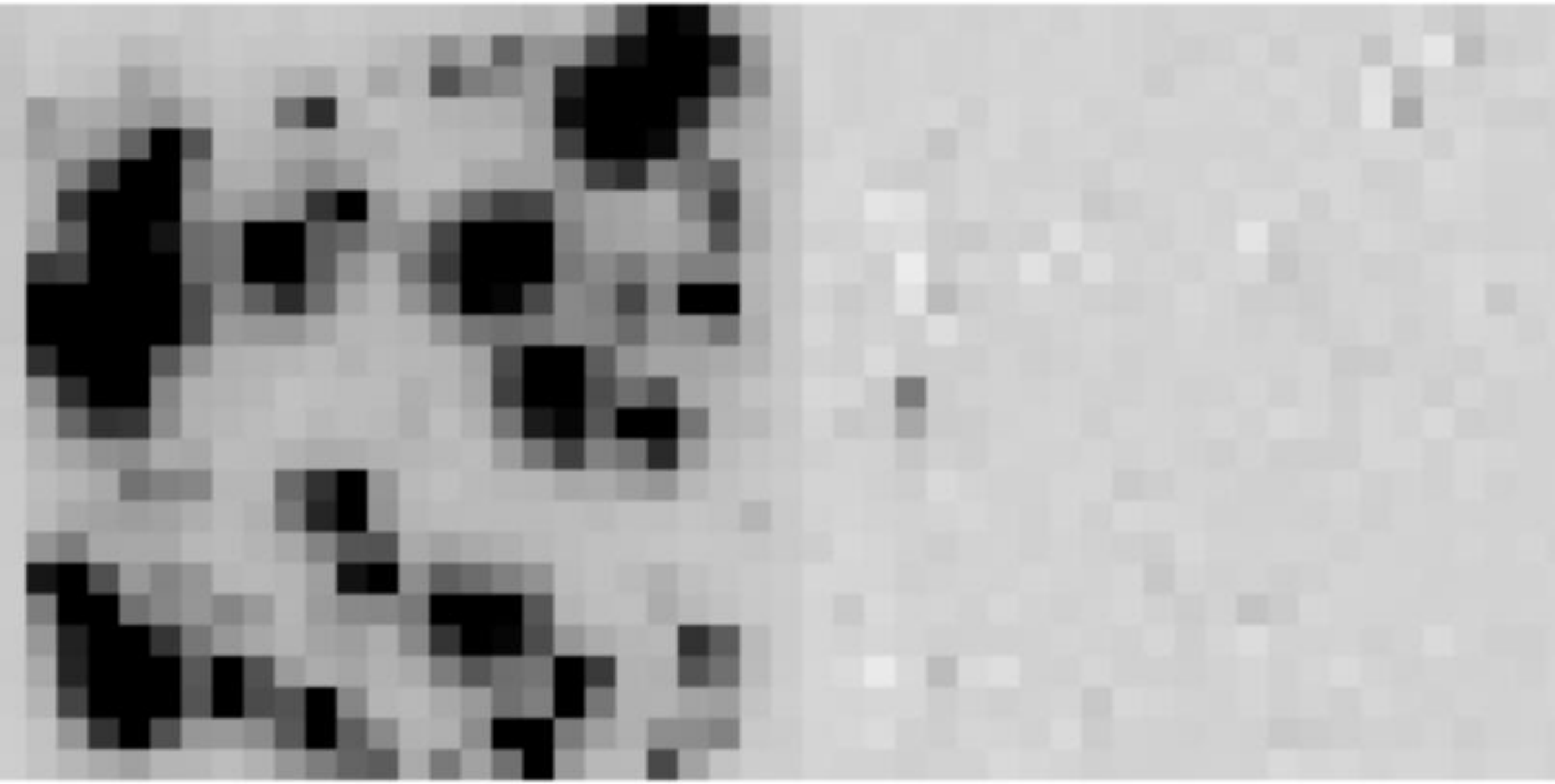


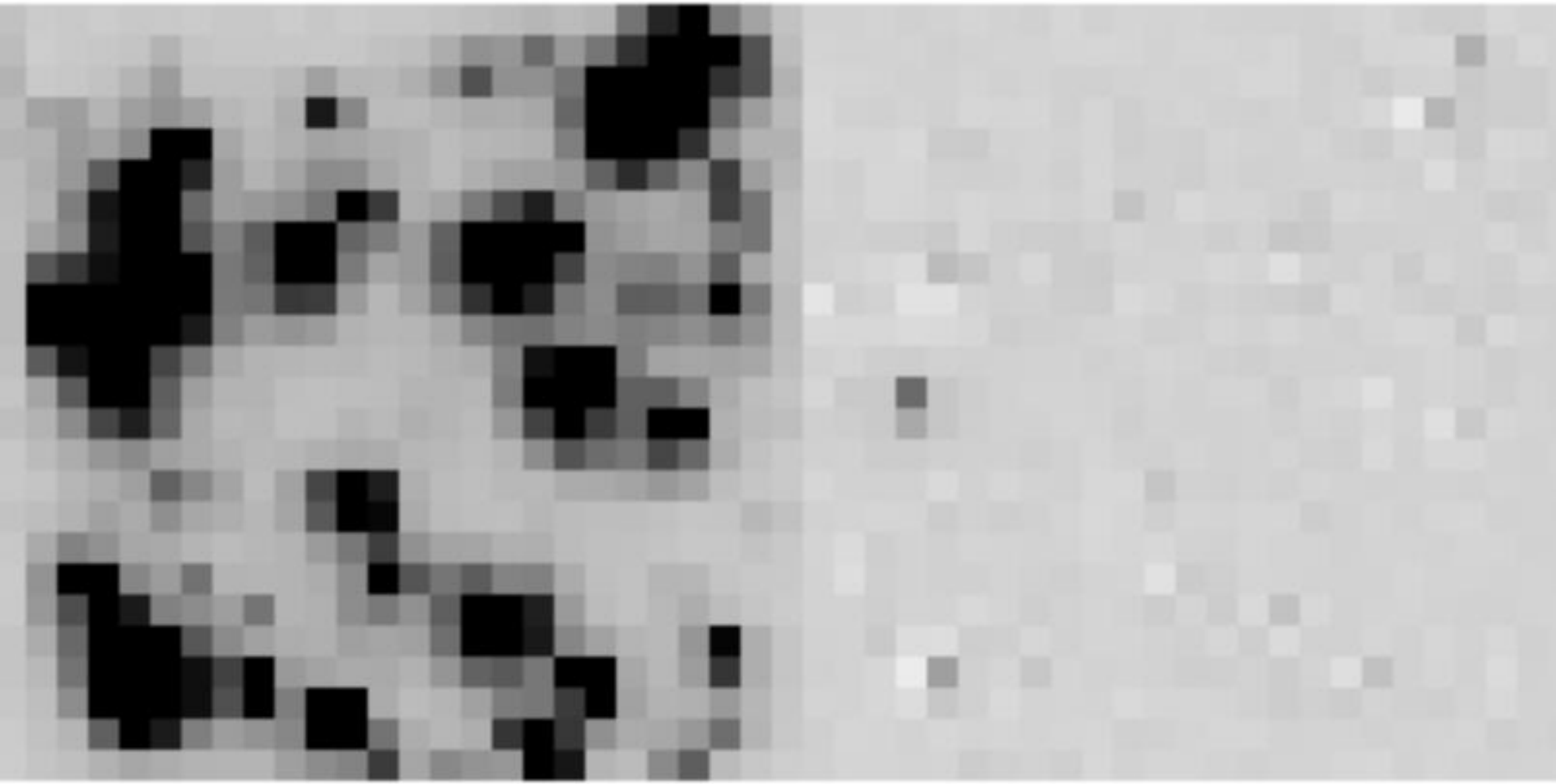


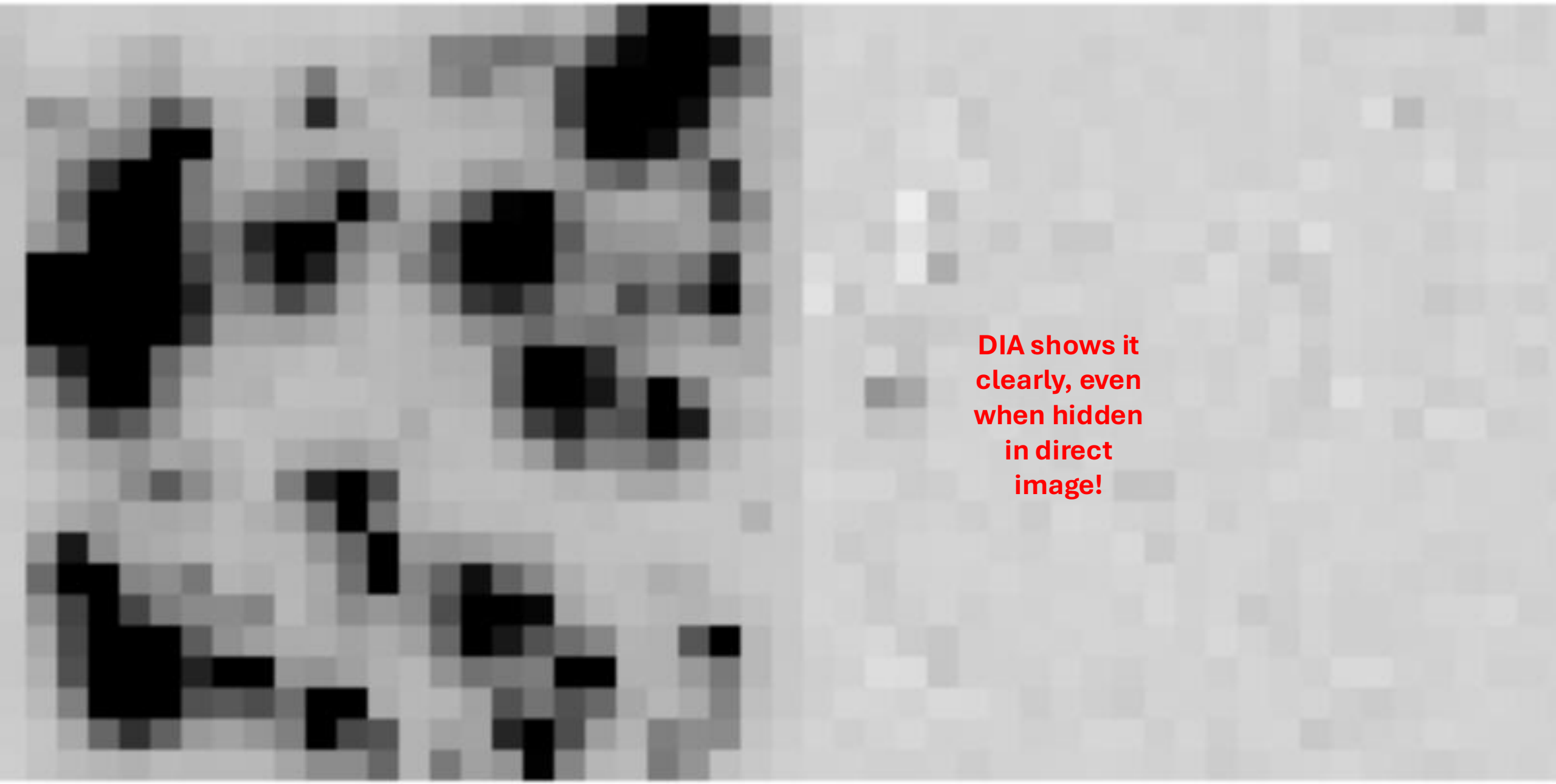











DIA shows it clearly, even when hidden in direct image!

Some Vignettes...

1) Realization of scene with dithers
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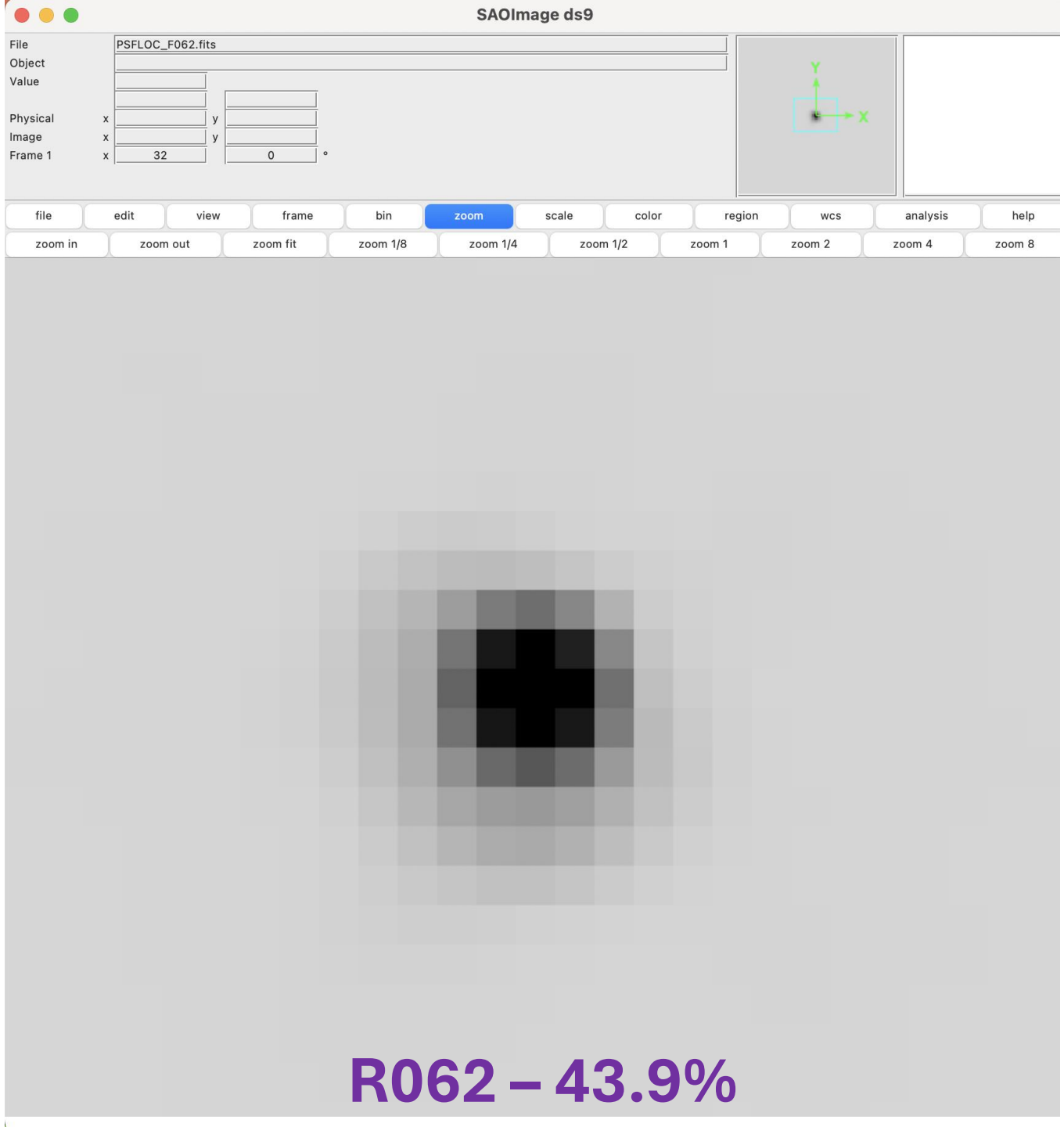
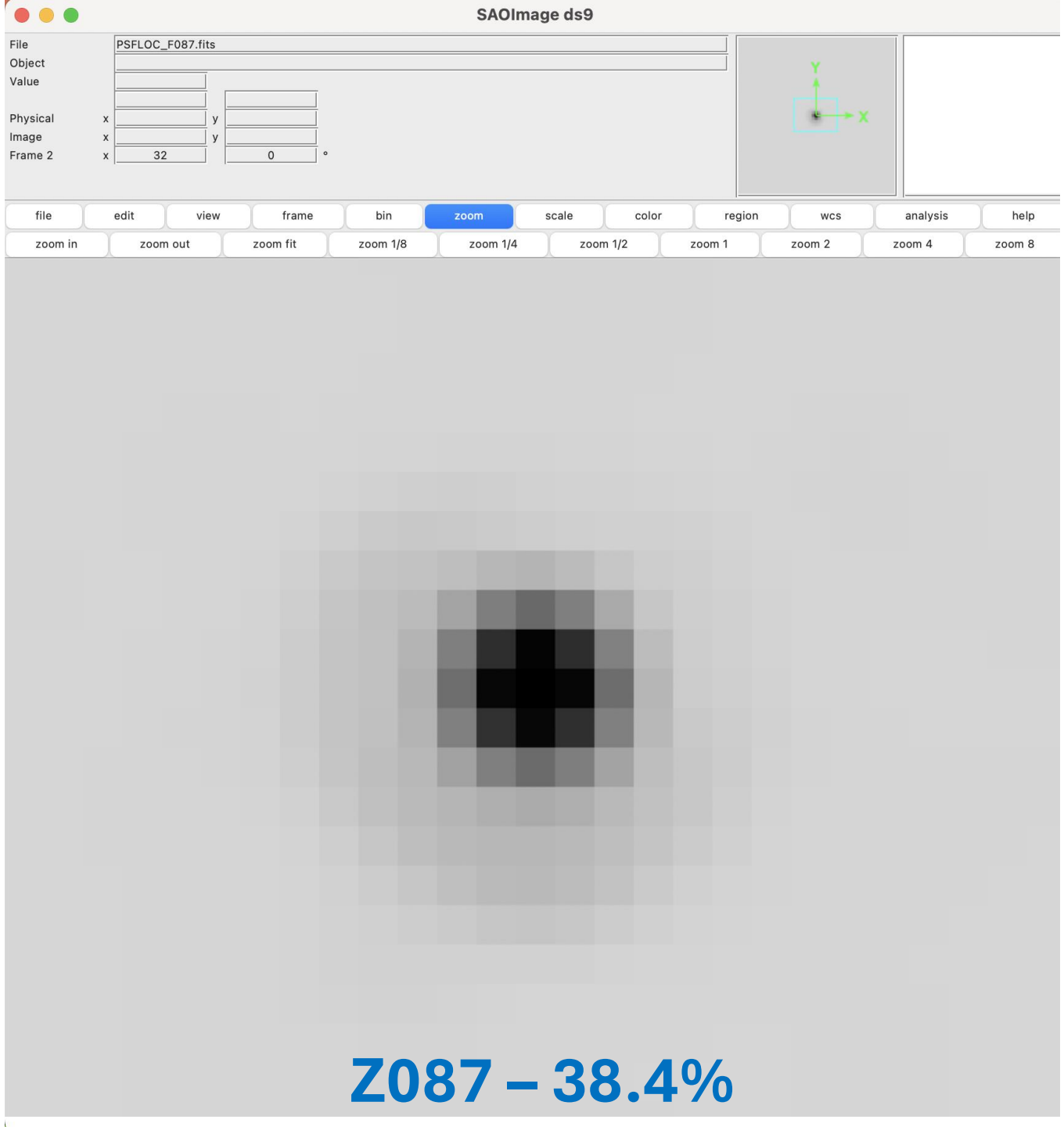
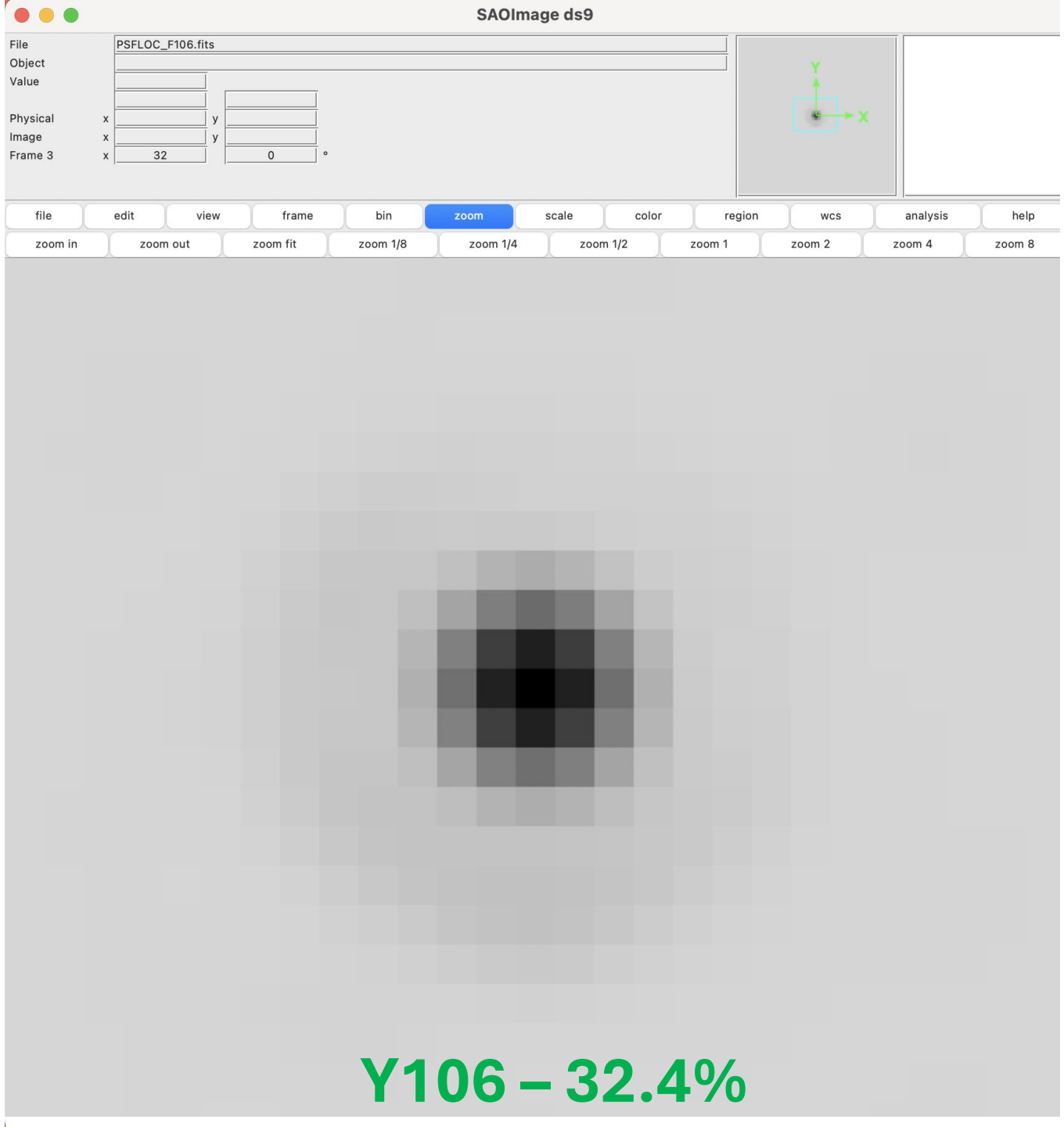
ROMAN PSF BY FILTER



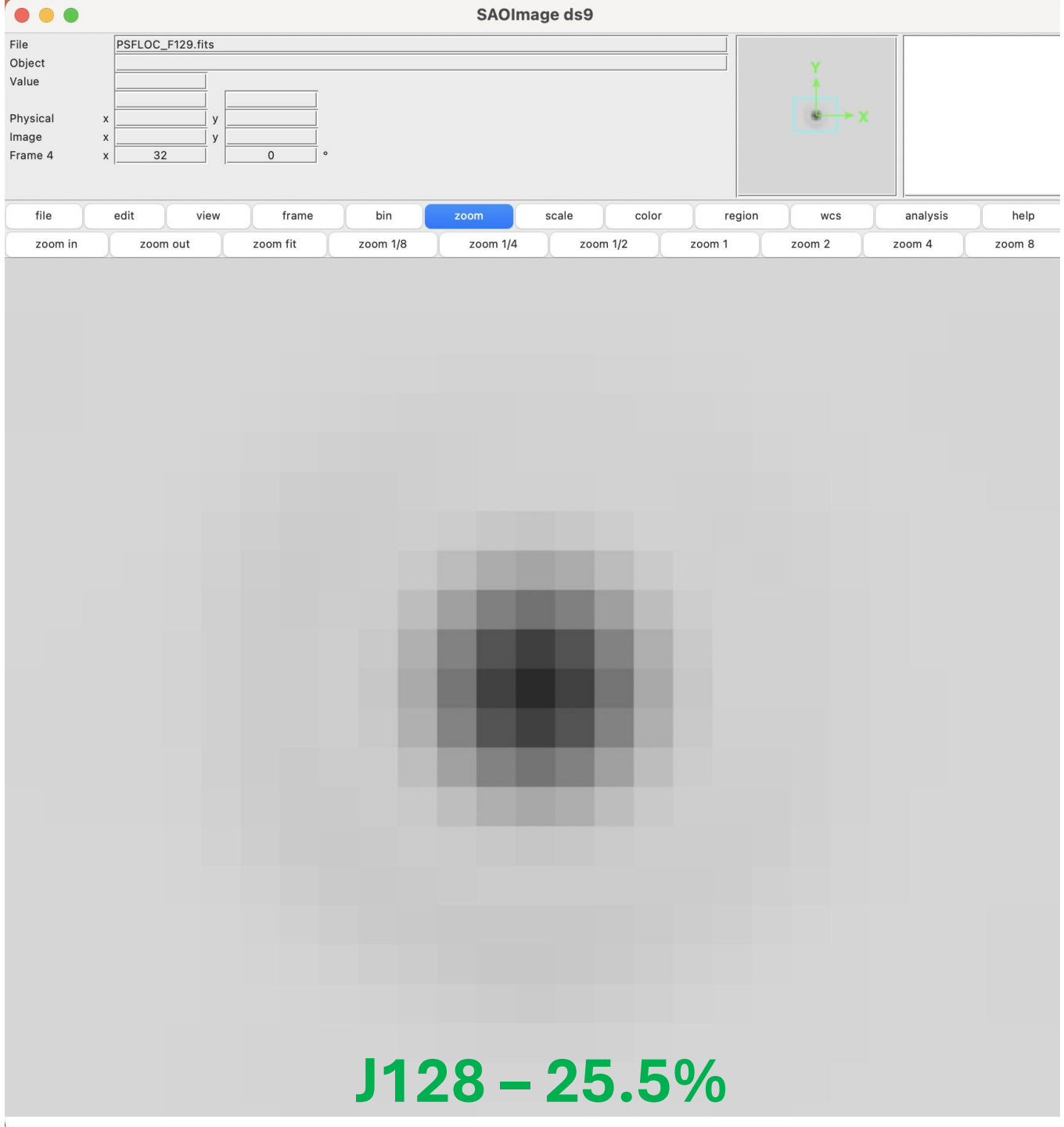
ROMAN PSF BY FILTER



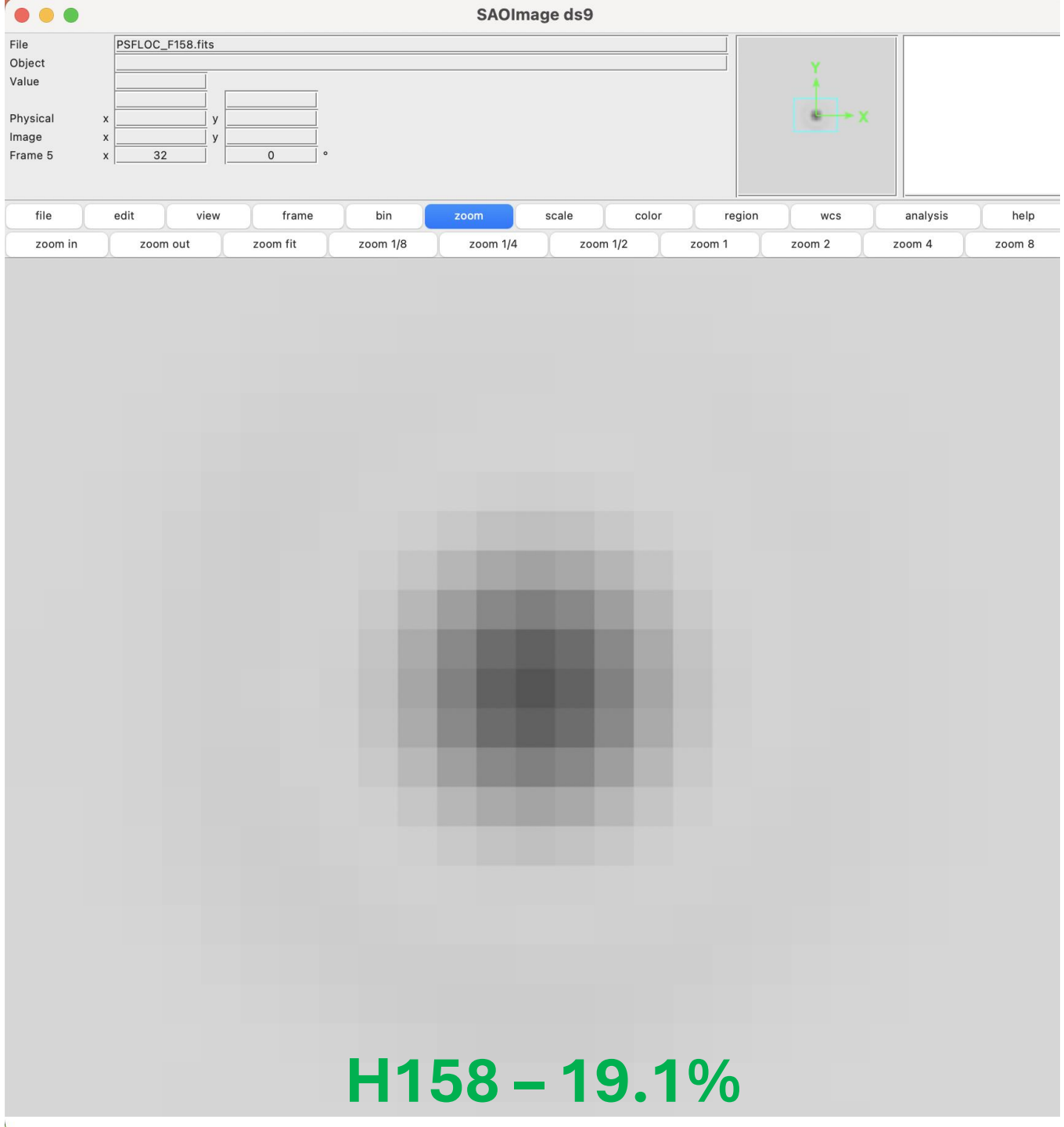
ROMAN PSF BY FILTER



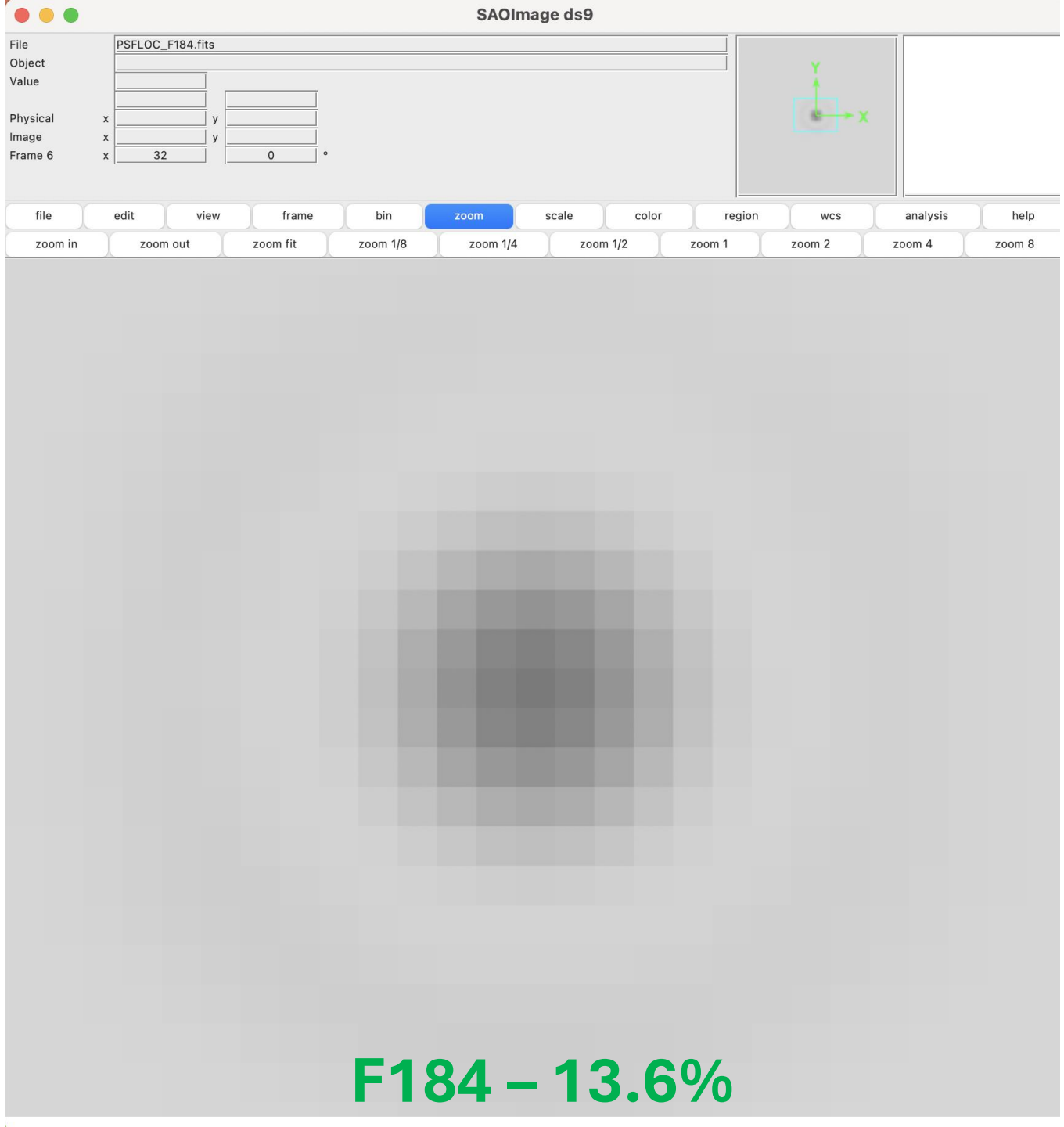
ROMAN PSF BY FILTER



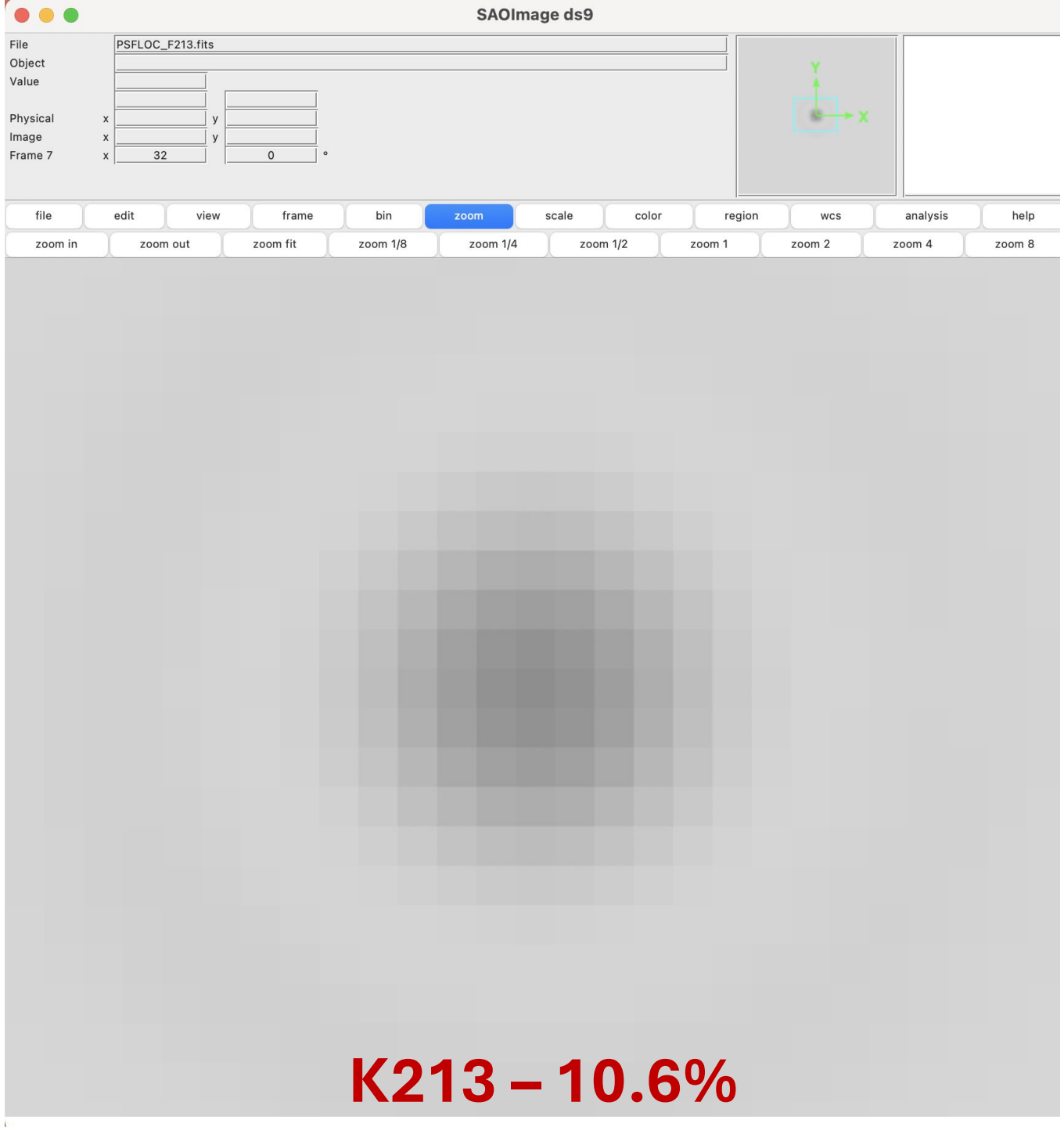
ROMAN PSF BY FILTER



ROMAN PSF BY FILTER



ROMAN PSF BY FILTER



W146

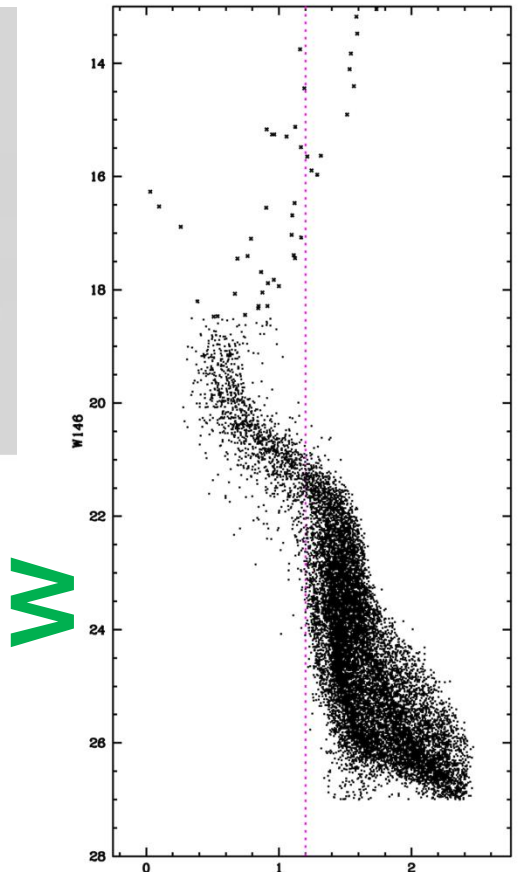
Y106 – 32.4%

J128 – 25.5%

H158 – 19.1%

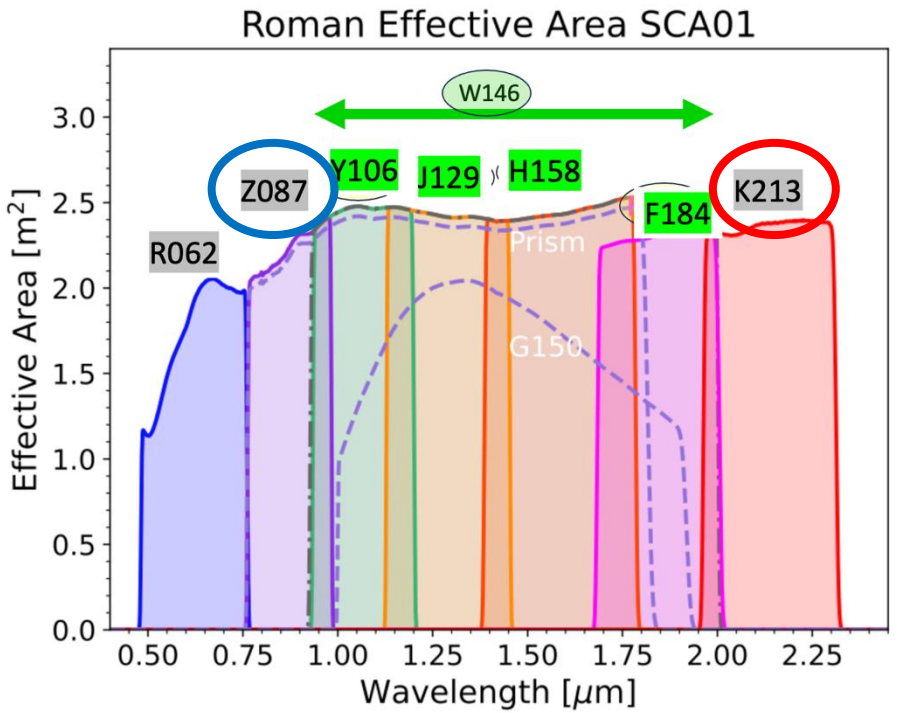
F184 – 13.6%

Z087 – 38.4%

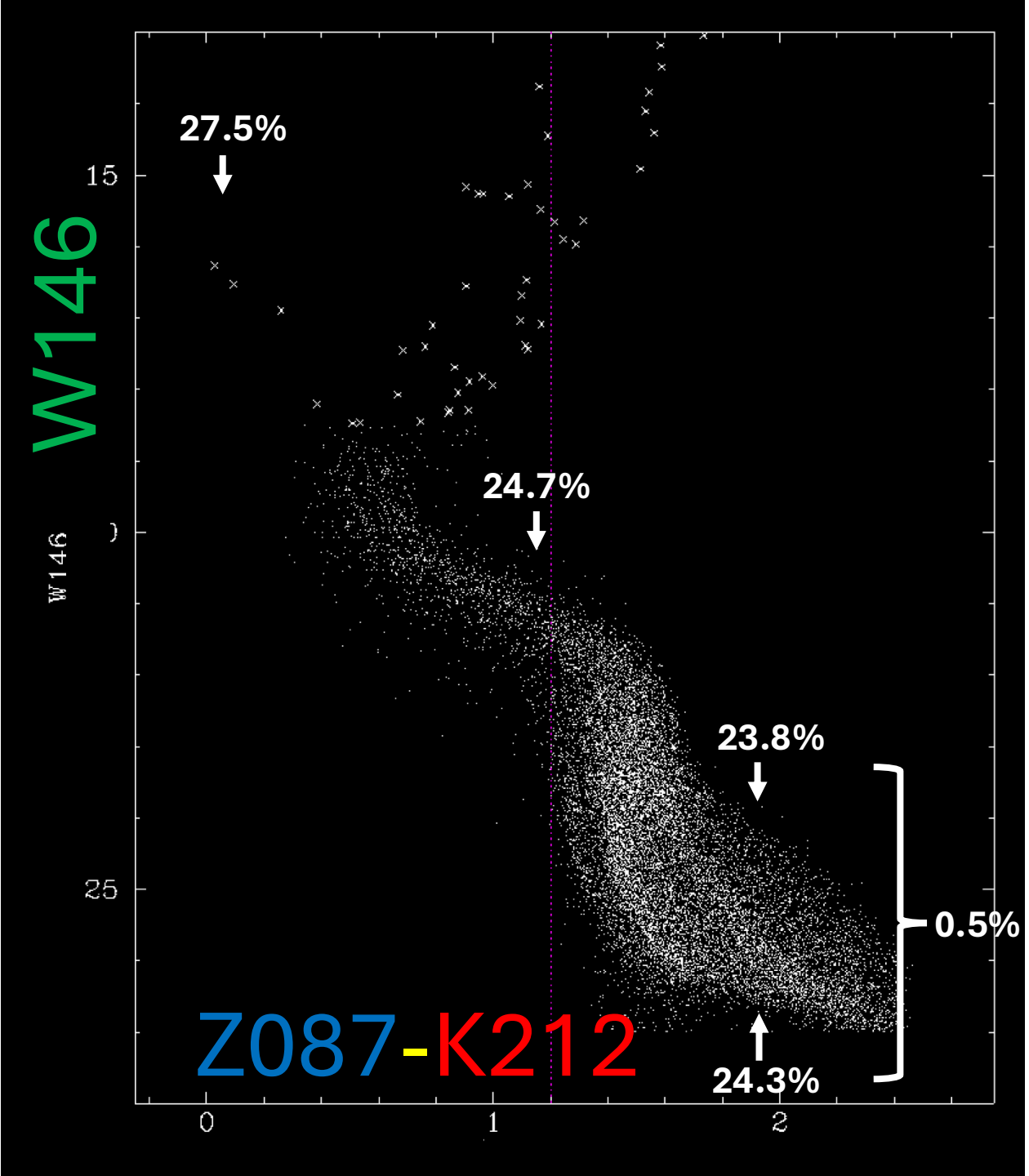


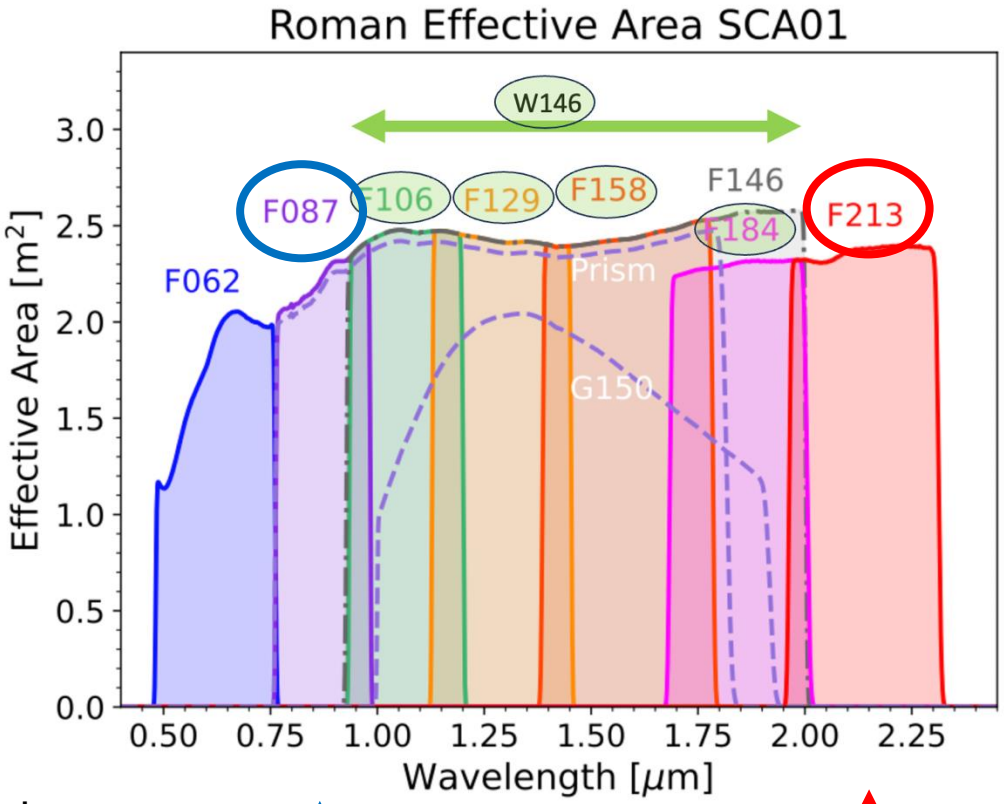
W

Z087 – K213



K213 – 10.6%





Not just
Z-K, but
W-K, too!

Z087 – K212

Some Vignettes...

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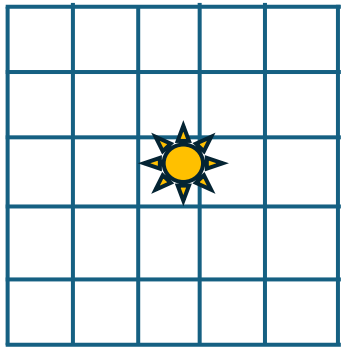
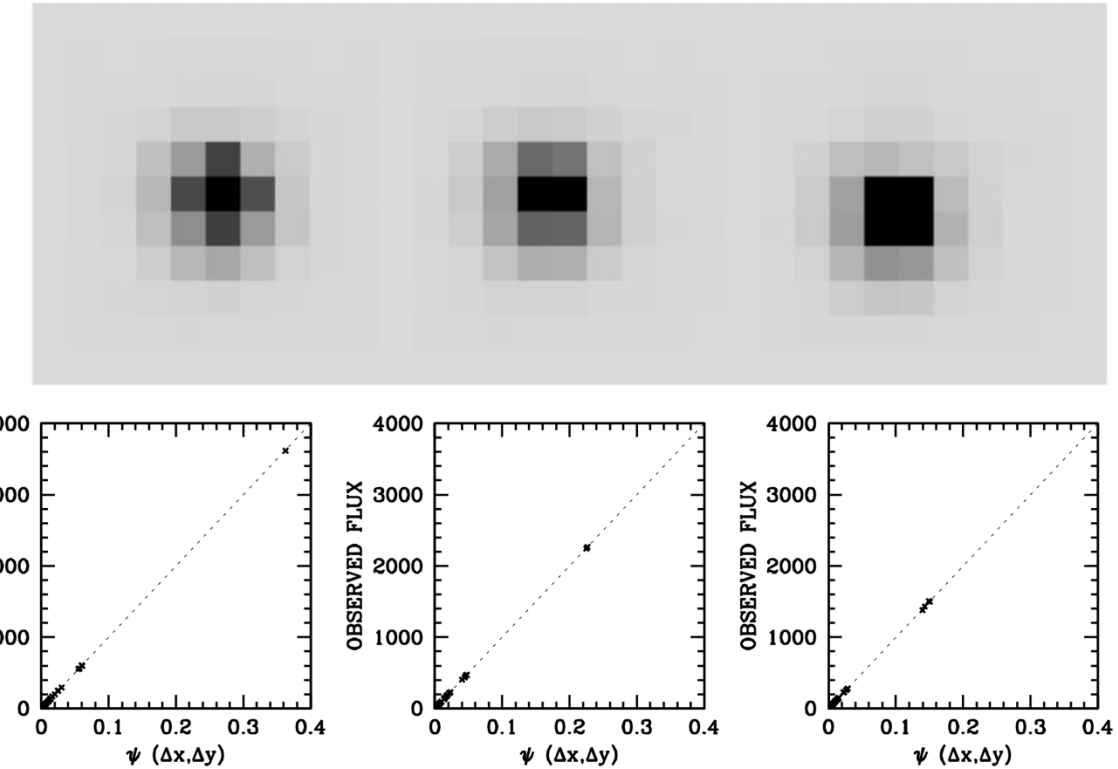
7) **Fitting stars with under-sampled PSFs**

Fitting stars with under-sampled PSFs



- **Three stars:**
  - centered
  - edge
  - corner



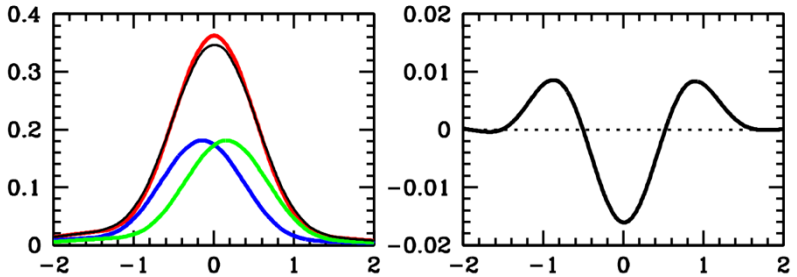
Poisson noise

x,y shift

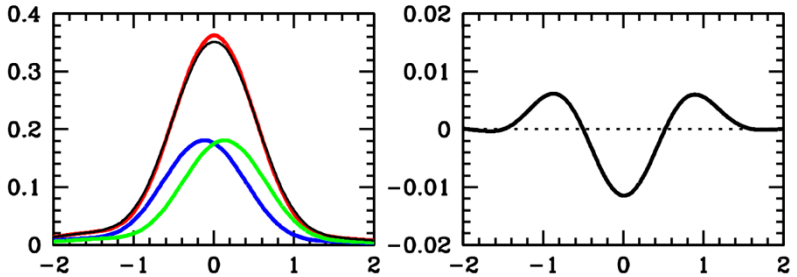
- **Moments:**
  - 0th moment: flux: sum of pixels → forgiving of PSF model
  - 1st moment: position: differences between pixels → need good PSF model
  - 2nd moment: elongation: differences of differences → need v good model

Fitting 2-Star Blends

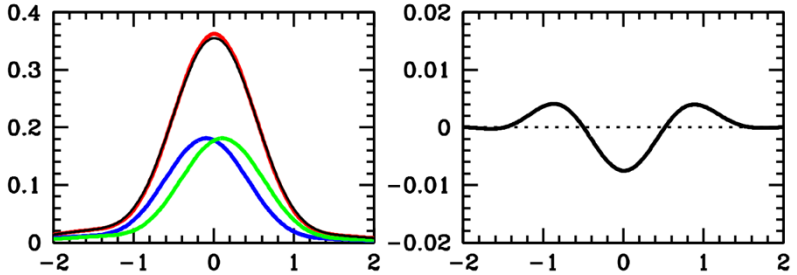
- **Lens-Flux Two-star fits:**
  - 1) Measuring small separations
    - 0.3 pix, 0.25 pix, 0.2 pix, 0.1 pix
    - small offsets go as $(\Delta x)^2$
  - 2) Dithering matters!
  - 3) Degeneracy between Δx / flux ratio
  - 4) Challenges with spoiler stars!
  - 5) Color dependence of W146 PSF!



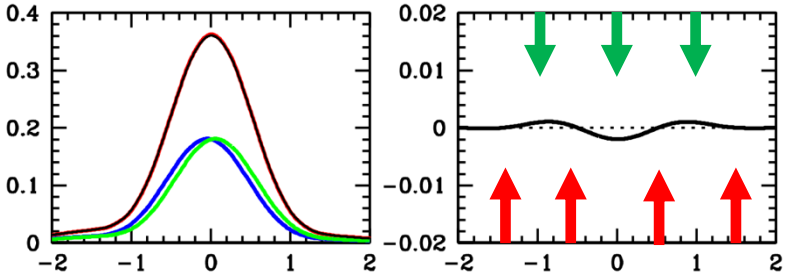
OFFSET = 0.30 pix
0.015 = 4 %



OFFSET = 0.25 pix
0.012 = 3 %

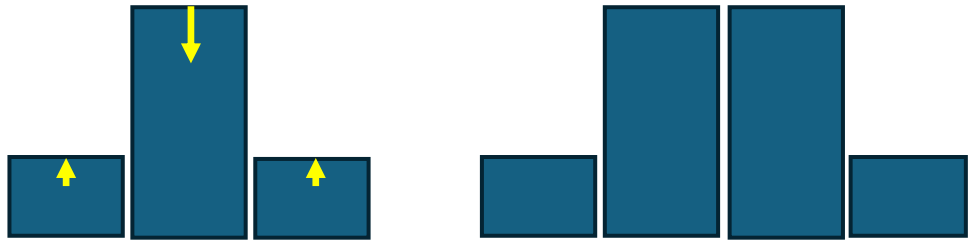


OFFSET = 0.20 pix
0.008 = 2 %

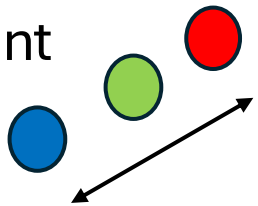


DITHERING MATTERS!!!

OFFSET = 0.10 pix
0.002 = 0.5 %

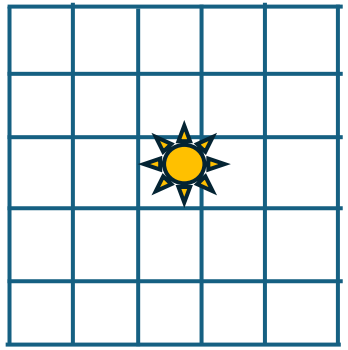


- **LF: Color-dep centroid**
  - 1) Moment#1 direct measurement
  - 2) Linear with time
  - 3) Ref frame should be set
  - 4) Positions to 0.01 pixel per exposure



2) New pipeline, familiar products

- **MSOS is producing the official reduction products**
  - Designed to meet requirements
  - Works out of the box on "enough" events
  - MAST ready to host
- **Produce weekly products**
  - x8 well-sampled ~weekly stacks: good for many things!
  - extracted catalogs from stacks
  - catalog products:
    - stars PSF-fit in individual exposures, fixed/floating positions, many metrics
    - stars PSF-fit in DIs, fixed/floating positions, many metrics
    - most people won't have to ever see the under-sampled pixels!
  - Stacks weekly, products released within 2 days
- **Re-reduce after season(s)**
  - proper motions, parallaxes, etc



PBAP:
PSF-Based
Aperture
Photometry

$$f = \frac{\Sigma_{5x5}(p\text{-}s\text{-}o)}{\Sigma_{5x5}\,\psi}$$

3) Additional analyses needed…

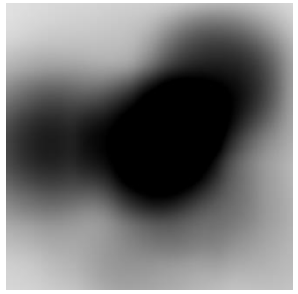
- **Corner cases**
  - binary lenses, complicated planets, careful vetting, more neighbors
- **Remaining DIA**
  - MSOS will not find on DIs
  - DIs not released
  - RAPID team will create DIs for all other surveys, not GBTDS
  - Yet… DIs very useful for other analyses: SS objects, non-catalog events
- **Cutouts**
  - ASDF format makes it cutouts complicated
  - MAST will do, but not sure how easy/fast it will be

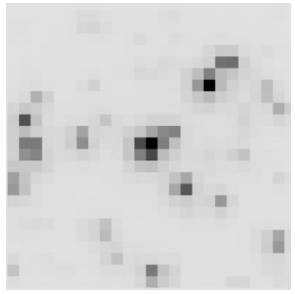
4) Possible additional analyses by PIT

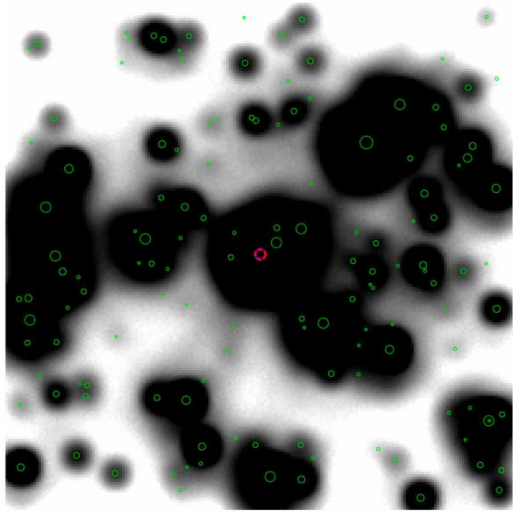
- **Good to have independent check**
  - Everyone else will, plus 30-day hold on MSOS products
- **2-day cadence**
  - full dither block: **216W** + **9K** + **9Z** → **234 images in "block"**
- **Evolving straw plan**
  - Generate quick very limited catalog + light curves
  - Save "lite" difference images (and maybe search them!)
  - 25×25×234-pixel "lite" cutouts for flagged events: "bundles"
    - Solar-system objects
    - Make windowed stacks for DIA
    - Find more neighbors
    - Optimize PSF fitting
    - Analysis Software to come over time
- **Timeframe/scope TBD!**
  - Goal to complement MSOS

Everyone can do black-belt things!

Overview of Talk



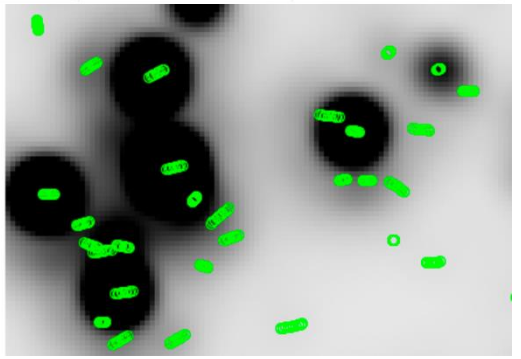




1) Microlensing from space

Improvements from ground, but…

- under-sampling
- never enough sampling
- better PSF, more matters
- proper motions can't be ignored

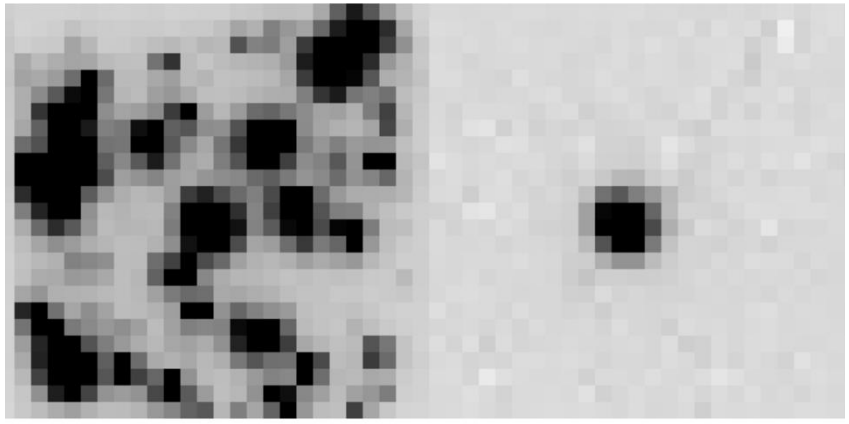


2) New Pipeline, familiar products

- Careful stacking: flux & sampling
- Fluxes + positions several ways

3) Additional products?

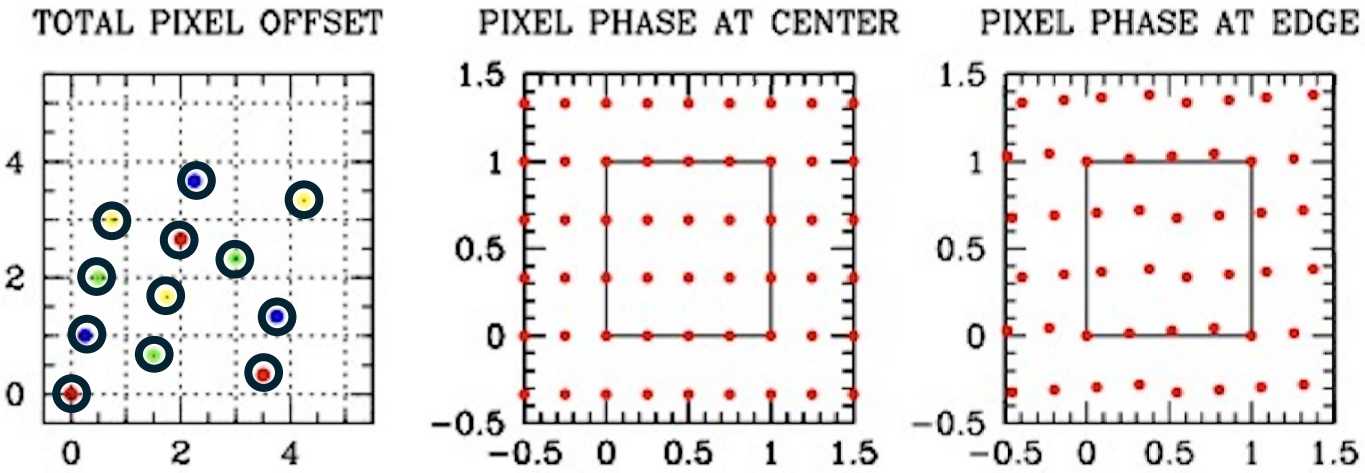
- DIs, finding in DIs
- Cutouts; windowed stacking

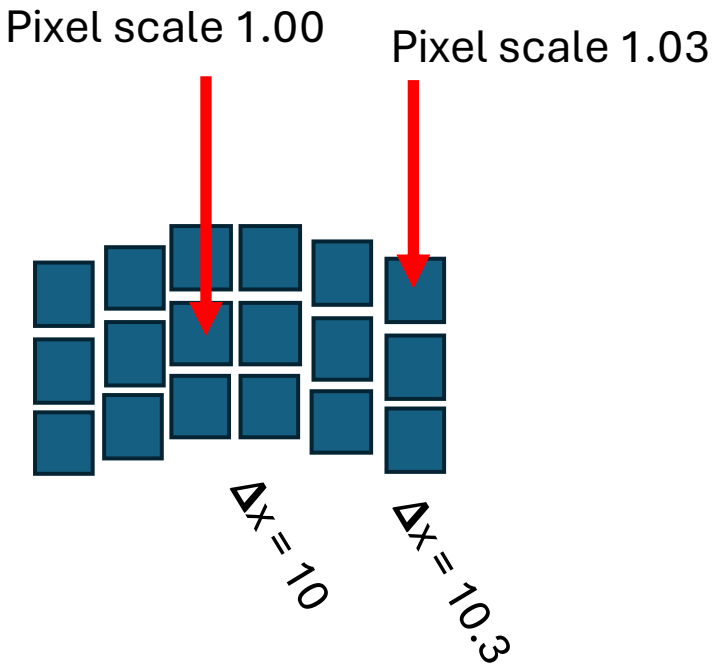


Questions?

Dithering

- **Goals of dithering**
  - Sub-pixel sampling
    - To allow hi-res reconstruction
    - For lens-flux extraction, catalog
  - Whole-pixel dithering
    - Mitigate flat-field errors
    - To allow absolute astrometry/photometry
    - Not too much (for trending)
  - Interplay with distortion
    - Minimize decoherence
  - Want good dither over short/long term
- **APT constraints**
  - 12W-1B-12W-1R blocks
  - Need 3x3 dither of B/R
  - 9 blocks: 216W + 9B + 9R





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