Low surface brightness wide–field imaging with CFHT

(a 4–m class legacy telescope)

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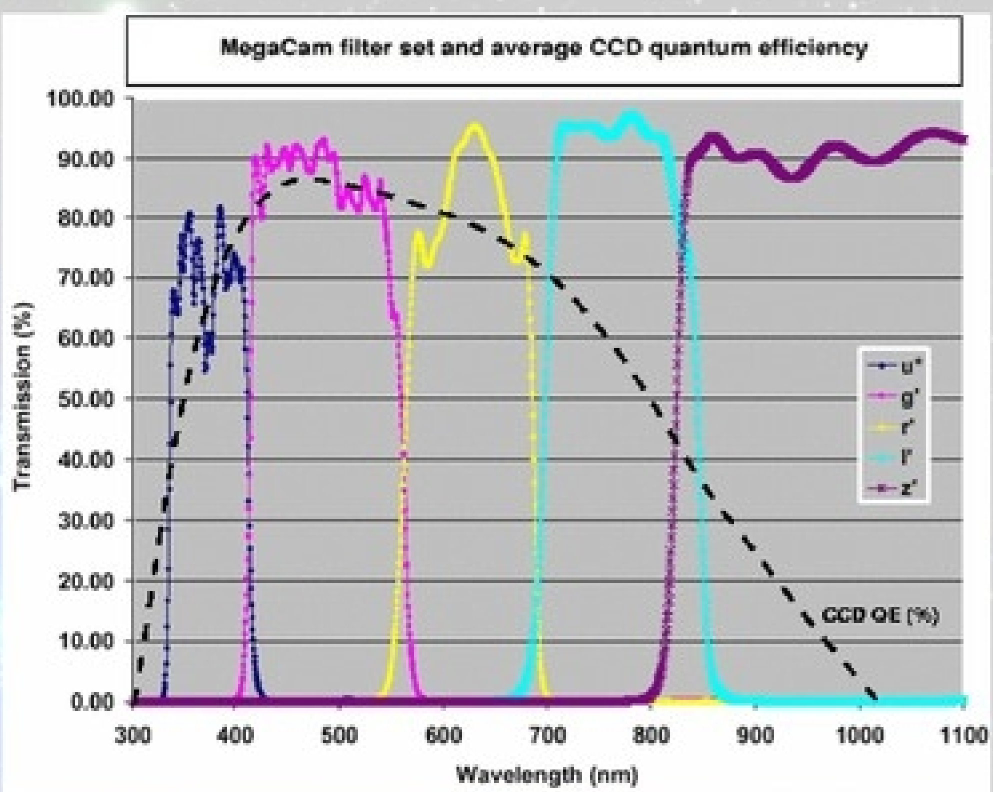
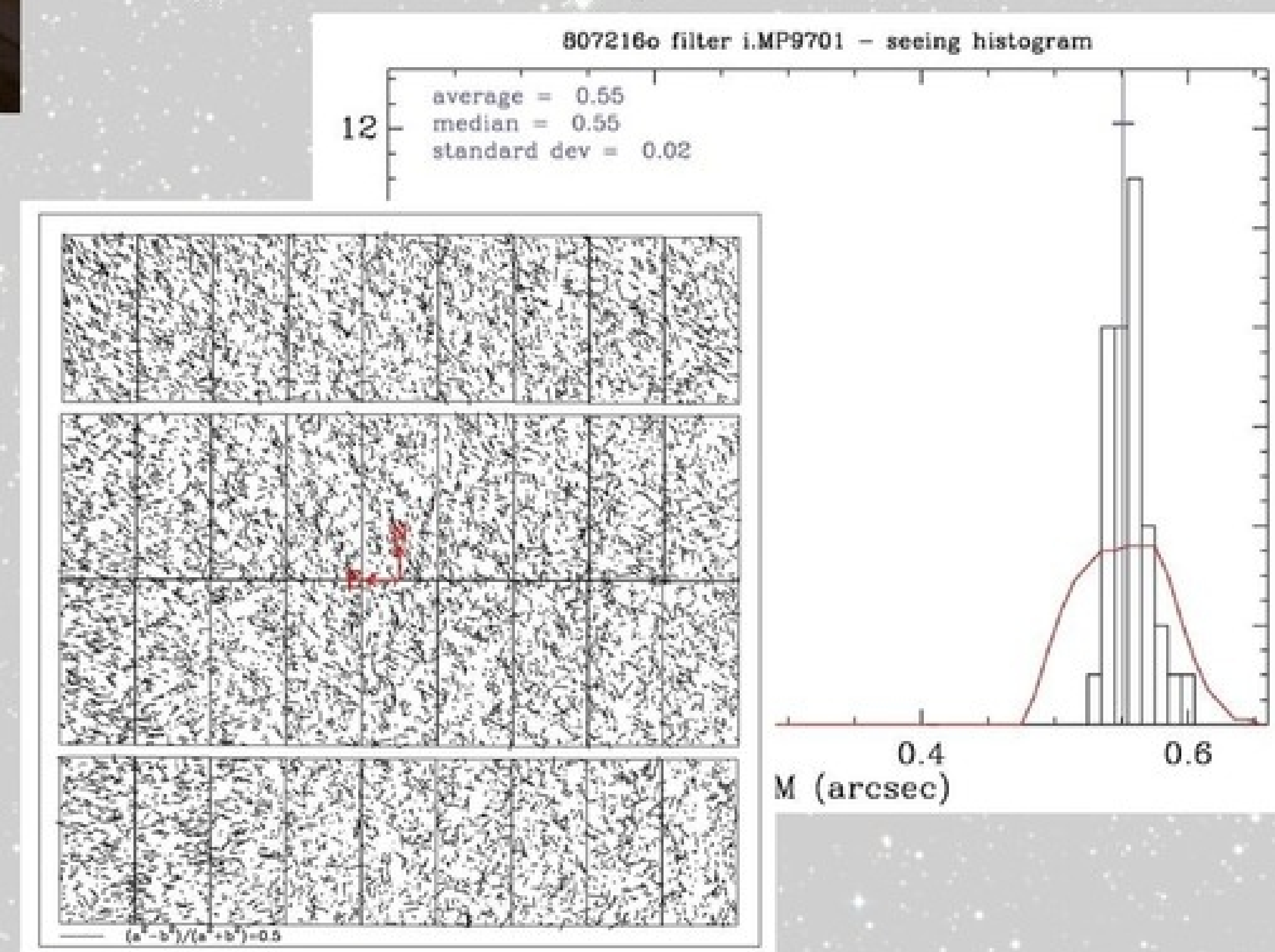
The instrument : MegaPrime/MegaCam on CFHT atop Mauna Kea

MegaPrime on CFHT

MegaCam : 340 megapixels CCD mosaic

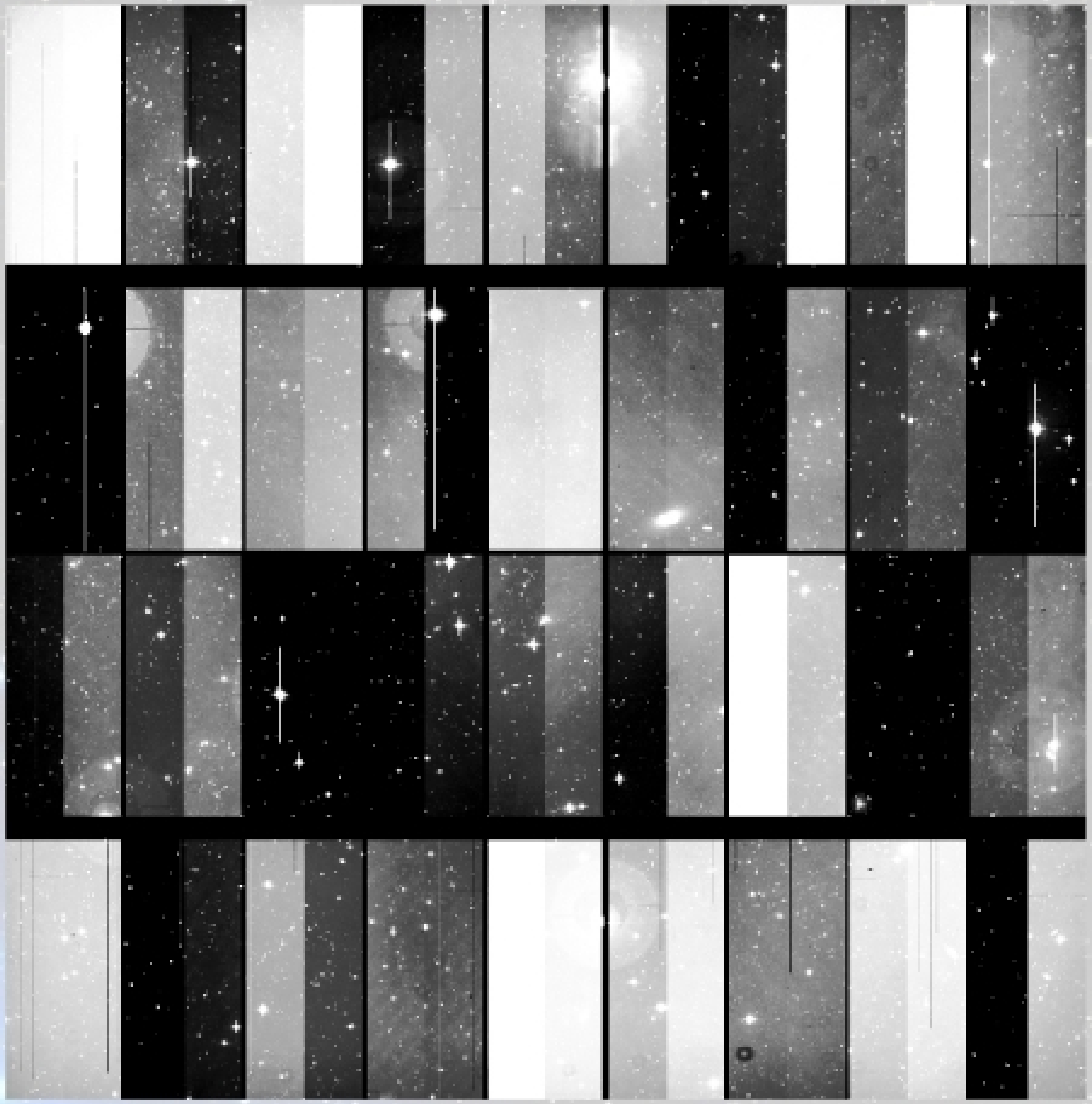


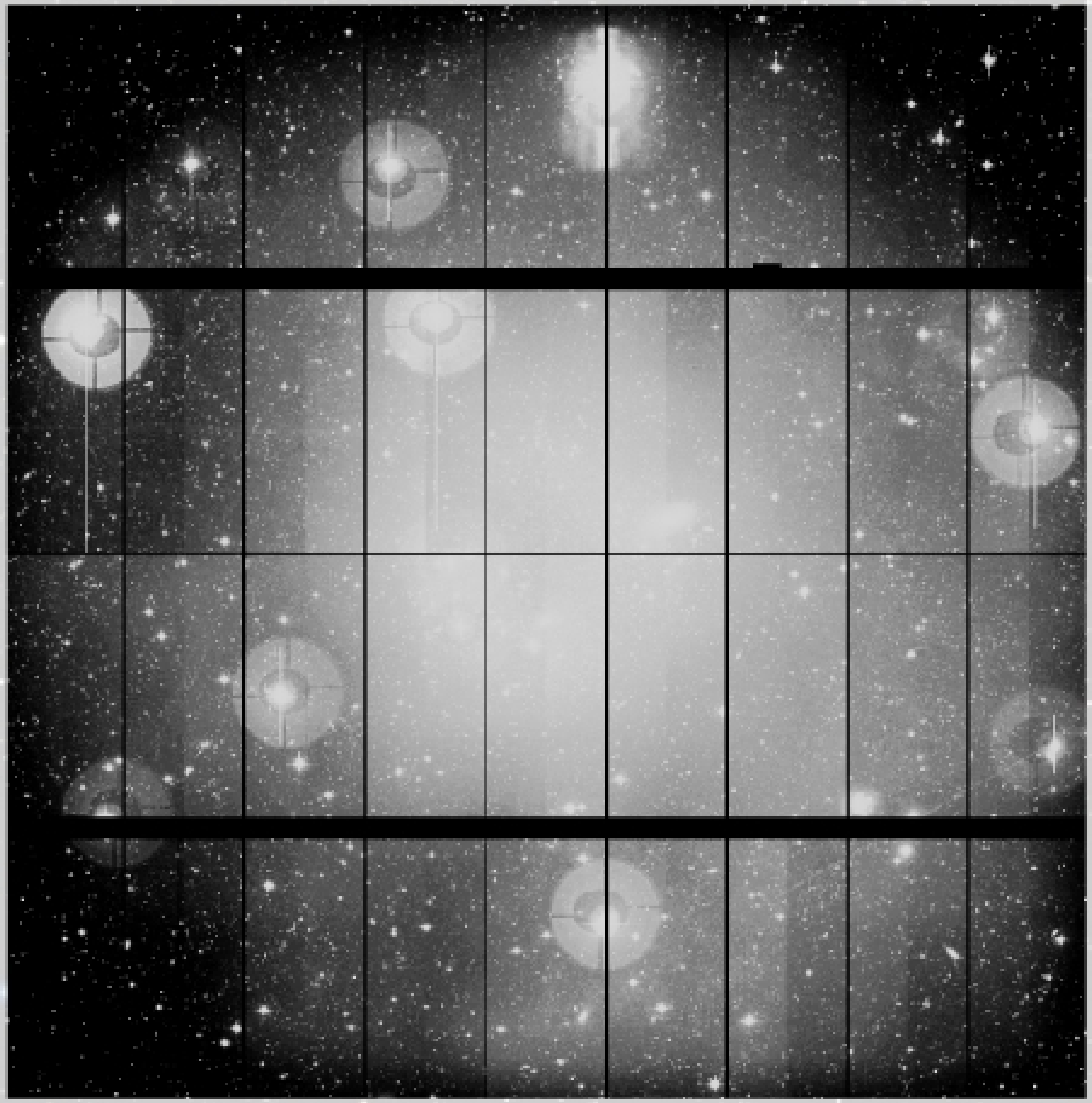
Wavelength coverage: from u to z



Excellent image quality (uniformity)

Raw and Elixir detrended data

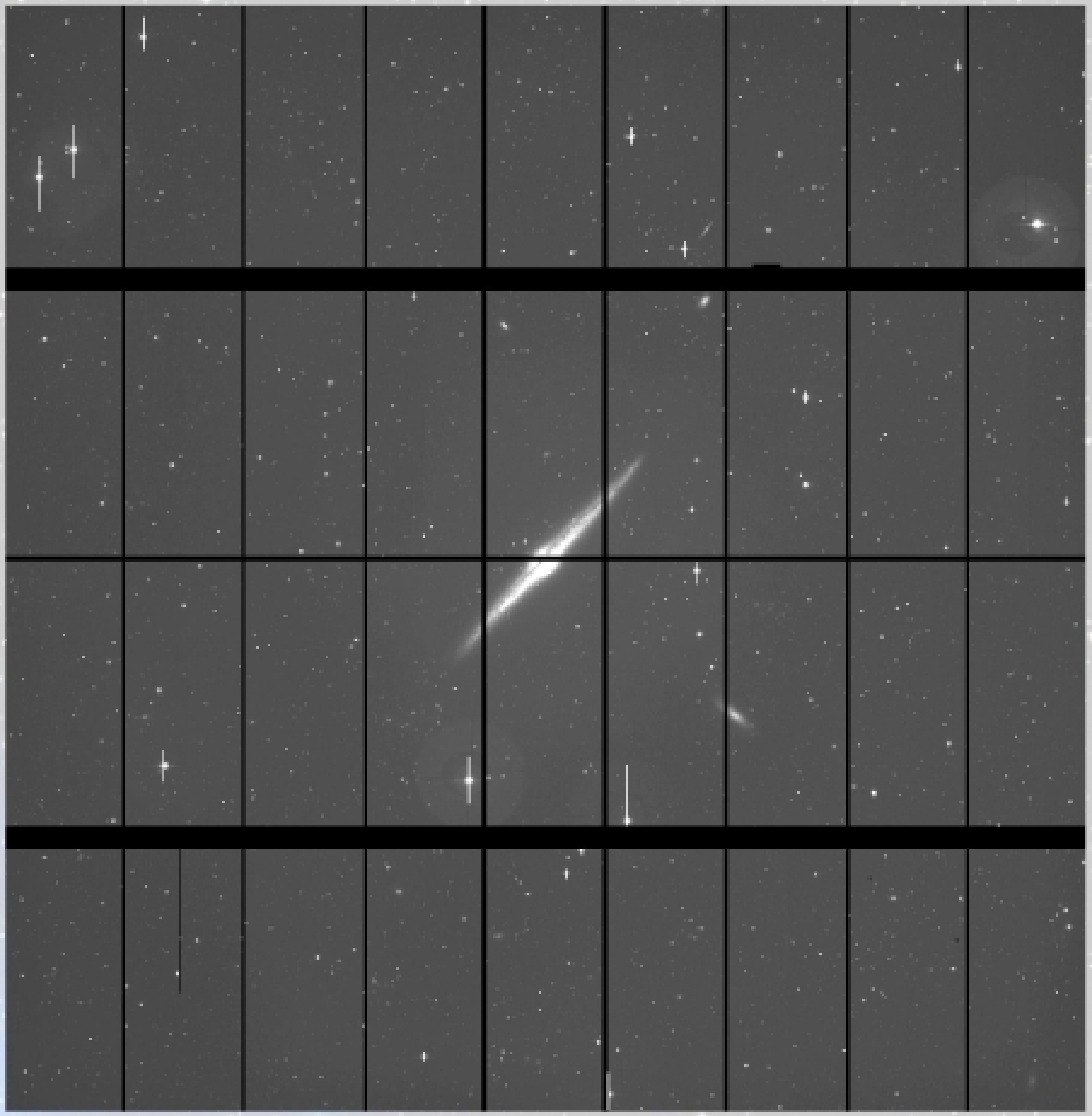




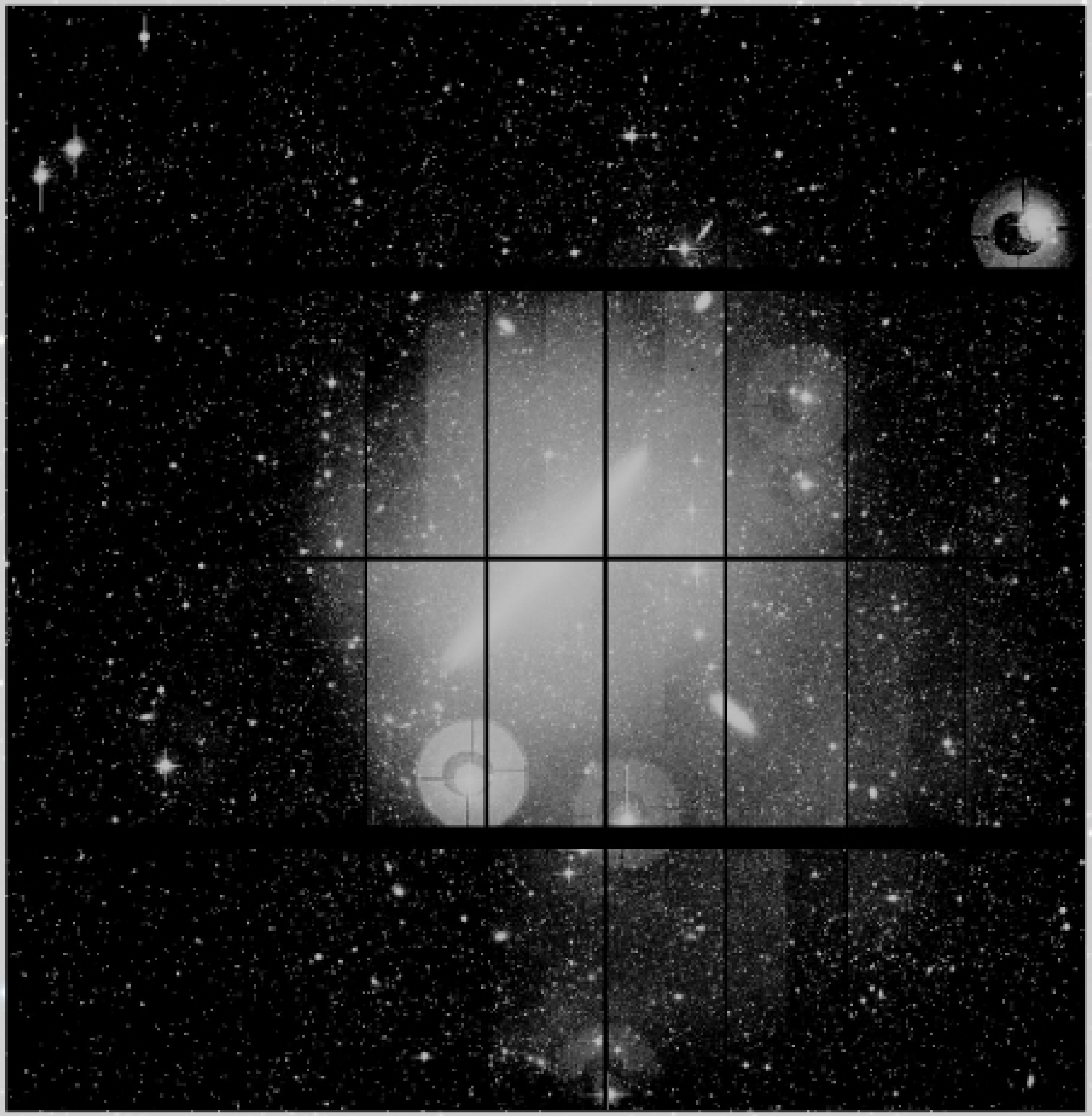
Detrending: 2D overscan + bias + normalized flat−field + masking

Elixir–LSB needed for faint extended sources

Surface brightness 2 or more magnitudes fainter than sky background *and* angular size greater than 2 arcminutes

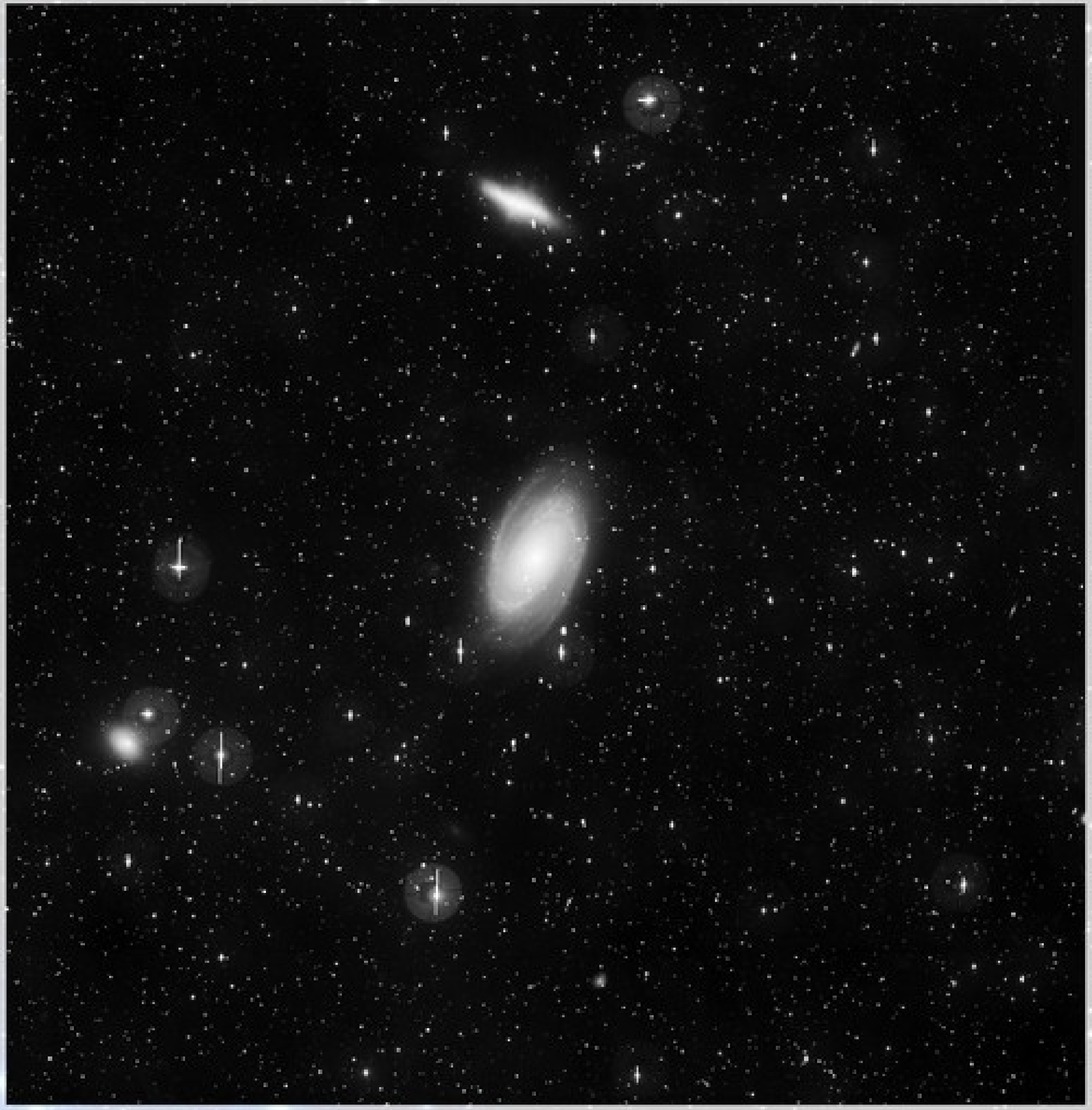


NGC 4565 field – high cuts

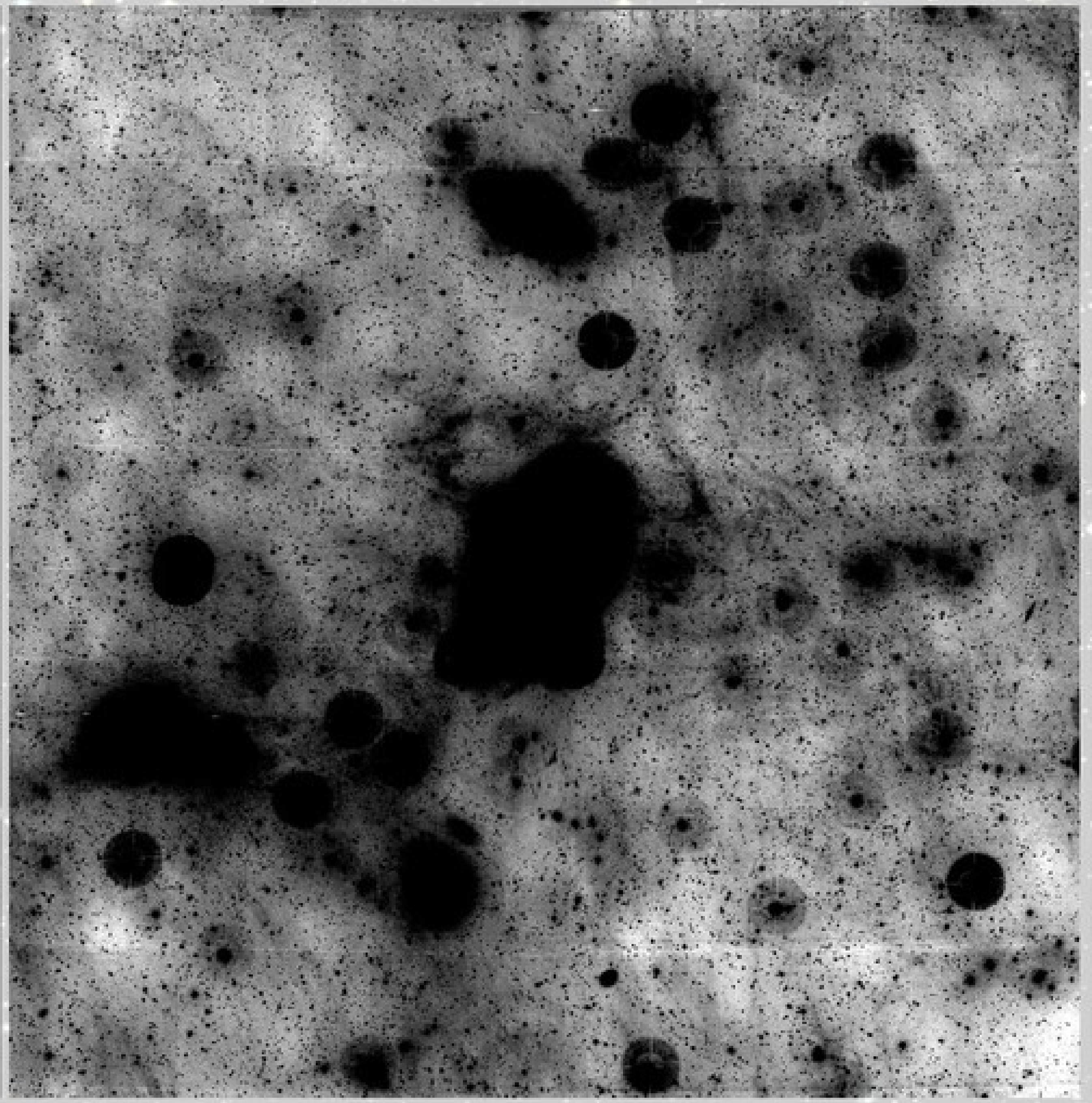


NGC 4565 field – low cuts

Elixir–LSB origins : M81 group (MegaCam, 2005)



High Cuts r' band

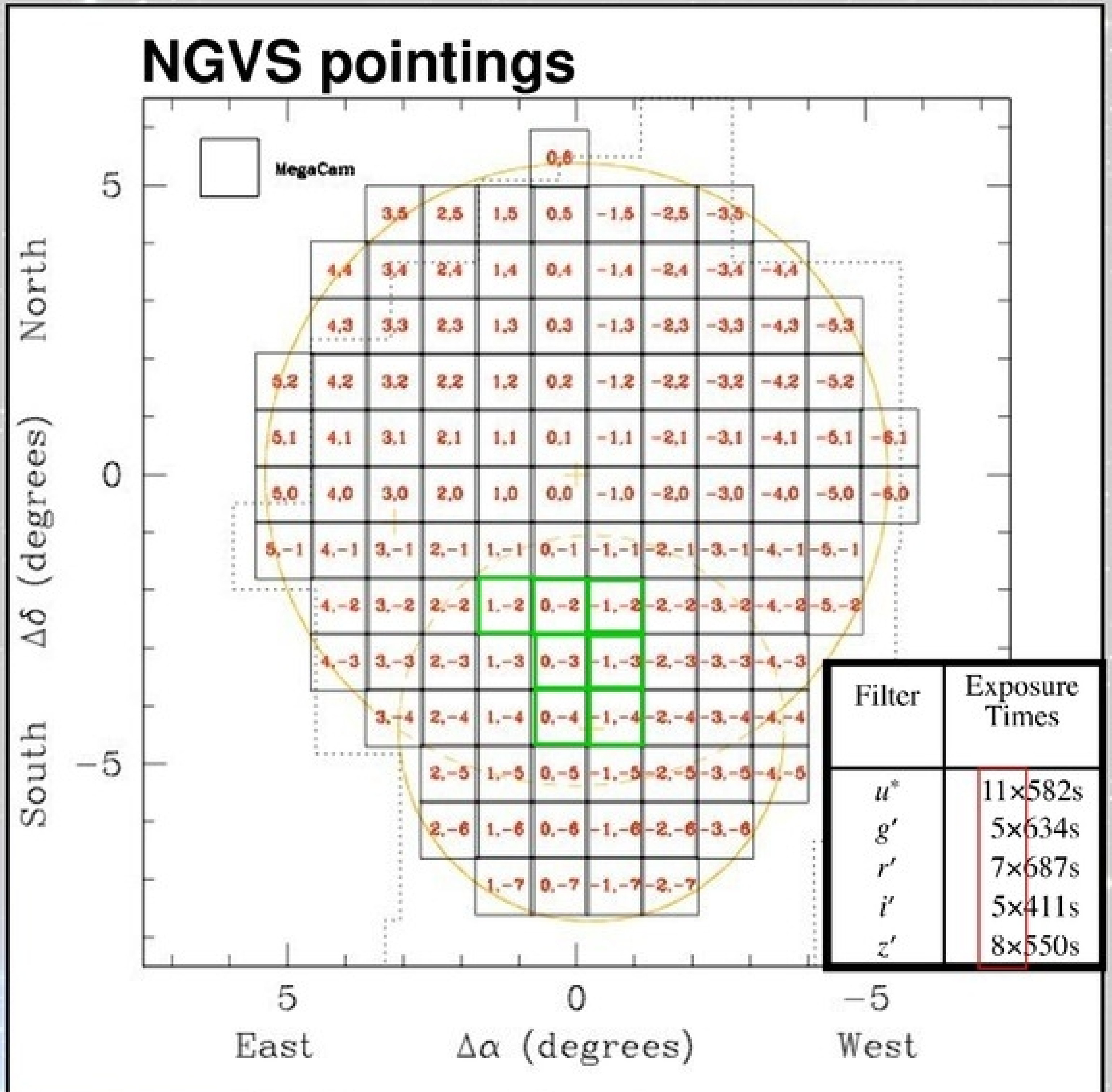


Low Cuts r' band

Demonstrated that MegaCam on CFHT can reach ultra faint surface brightness (28/29th mag.) with the right observing and data processing strategy

The Next Generation Virgo Cluster Survey

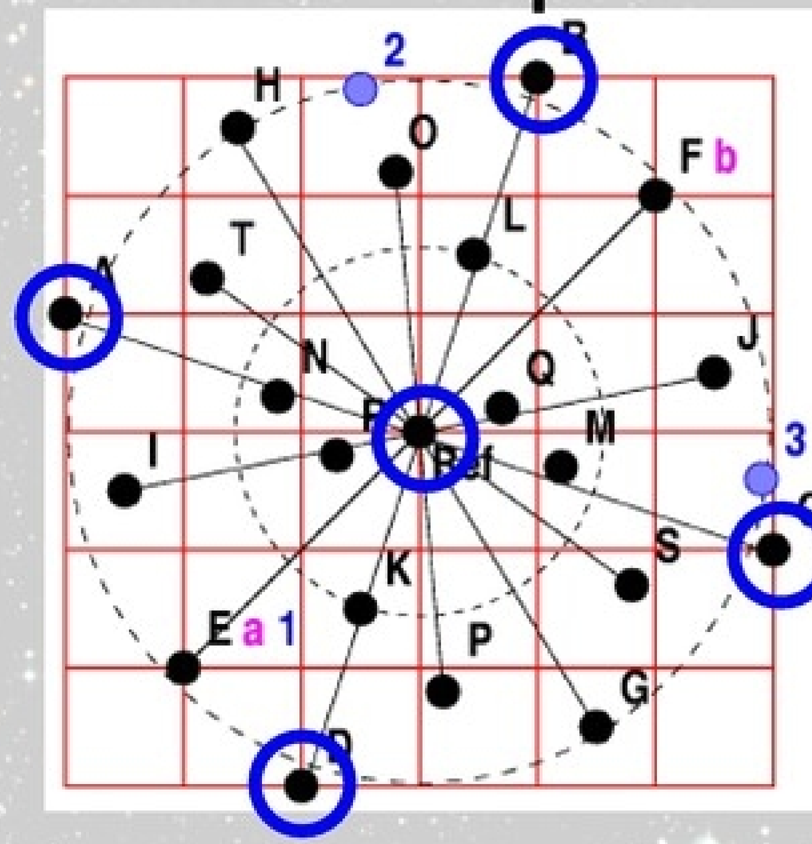
Elixir–LSB observing strategy: incremental dithering



Filter	Exposure Times
u^*	11×582s
g'	5×634s
r'	7×687s
i'	5×411s
z'	8×550s

Example: group of 7 fields requiring 5 exposures each

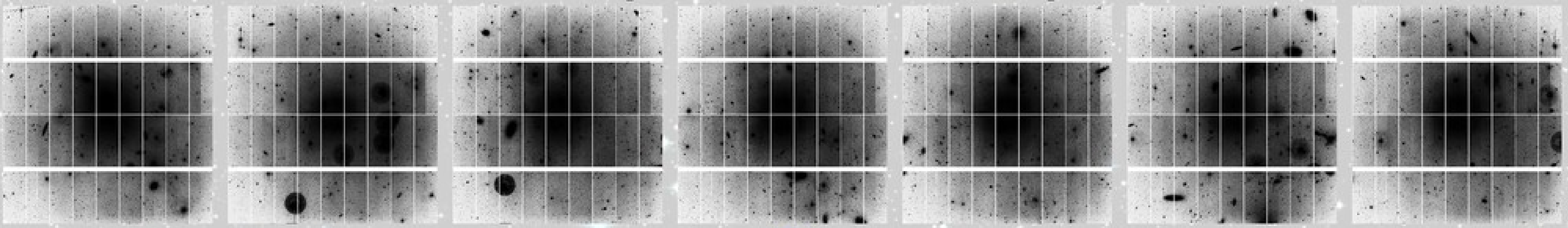
MegaCam dithering 30"x180" ellipse



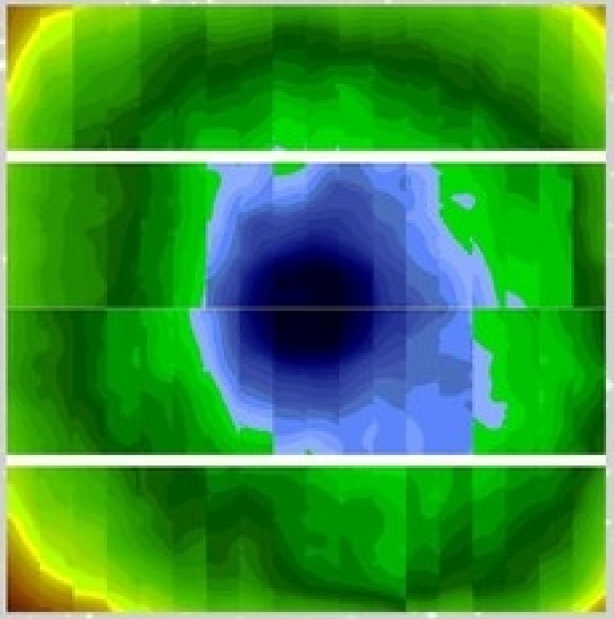
- √ ***Constrain: requires at least 5 exposures to build median sky (7 is better)***
- √ ***Constrain: a sequence (all pointings) must fit within ~1 hour (Mauna Kea)***
- √ ***Constrain: not too close to twilights, no thin cirrus with Moon***
- √ ***Constrain: complete OG if IQ degrades if more than ~50% completed***

Elixir−LSB sky maker : scaling, stacking, & filtering

Set of 7 sequential (in time) exposures



Elixir−LSB makesky



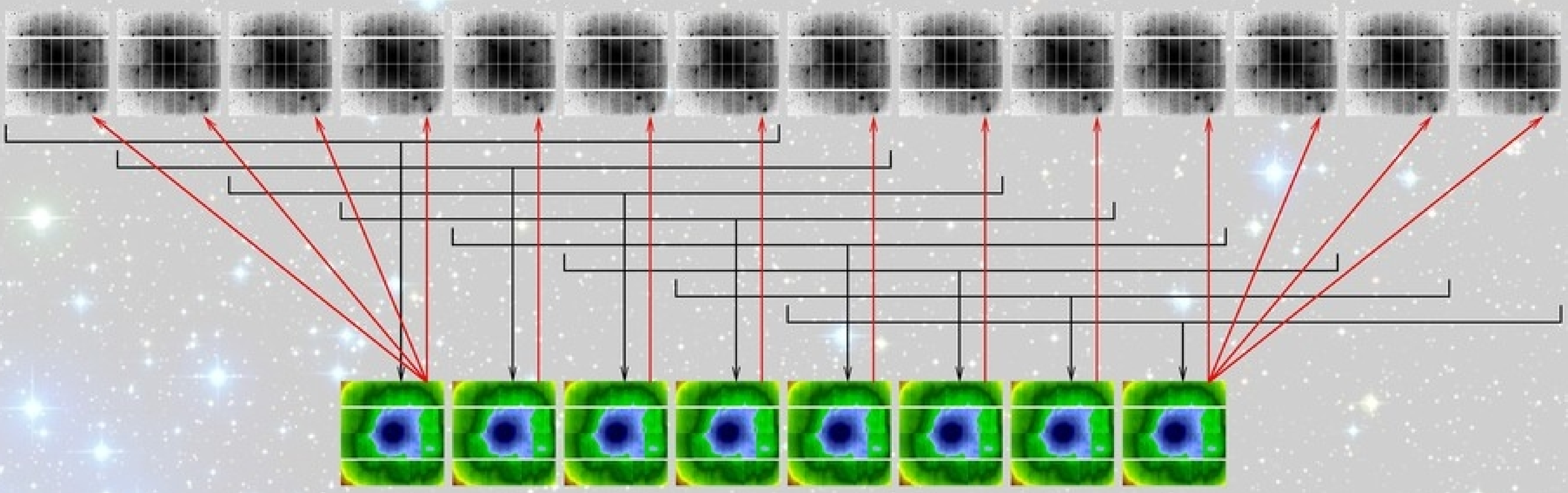
Unique sky for the central exposure (or whole set if single OG)

√ ***Step 1 : build statistics, derive scaling factor per frame based on sky level***
√ ***Step 2 : scale & stack frames using a sigma clipping opt. for low numbers***
√ ***Step 3 : median filter and gaussian smoothing at the amplifier scale***
√ ***Step 4 : build statistics and previews of the sky***

Elixir−LSB sky maker : optimizing the time window

Uses 7 sequential (in time) exposures

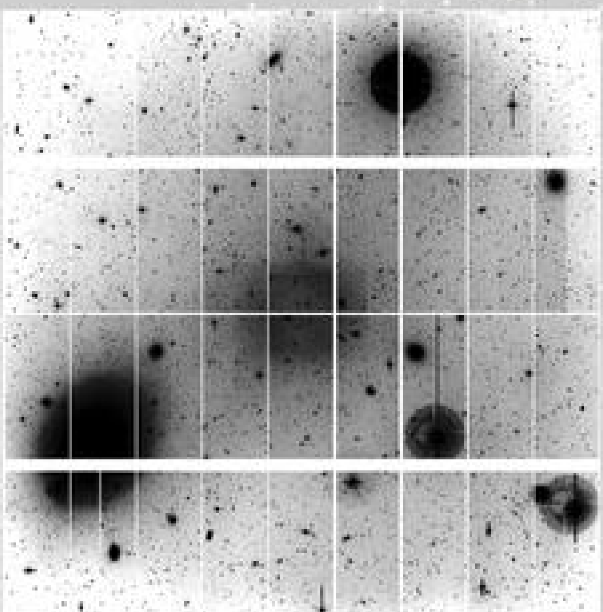
7 sequential exposures (= min = 1 OG) ► 1 sky
14 sequential exposures (2 OGs) ► 8 skies
"n" sequential exposures a x OGs + 1/b x OG ► "n – 6" skies



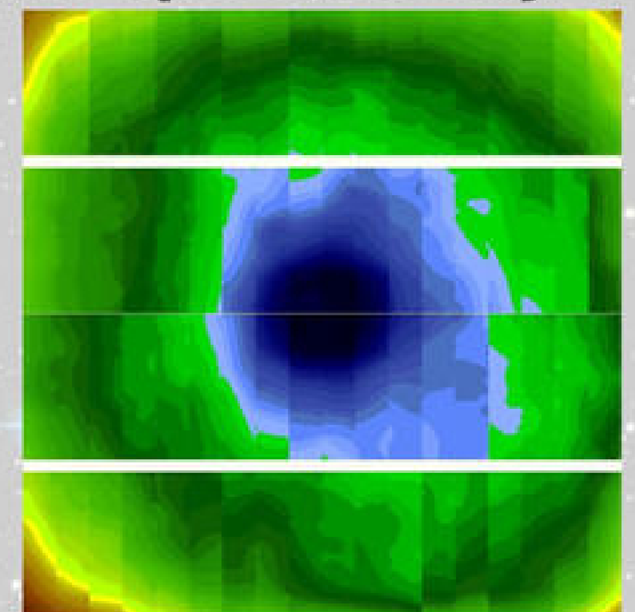
- √ *Width of the sliding window constrained by number of pointings in the OG*
- √ *7 pointings per OG is superior to 6 at the expense of possible sky variations*
- √ *Marginal conditions (cirrus) have led to sets of 5 exposures: redux needed*
- √ *Use of the full set per run or semester causes ~4% residuals*
- √ *Current strategy based on past experience and tests is optimal*
- √ *Along IQ & sky level rejection, this steps defines the "official" NGVS data set*

Elixir–LSB sky corrector : scaling and subtracting

Use of the specific sky for each single exposure

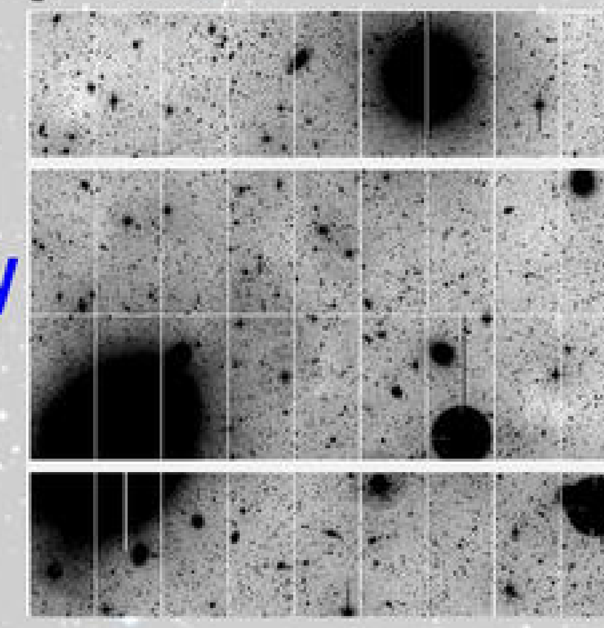


Elixir frame



Elixir–LSB sky

Elixir–LSB sub sky ►

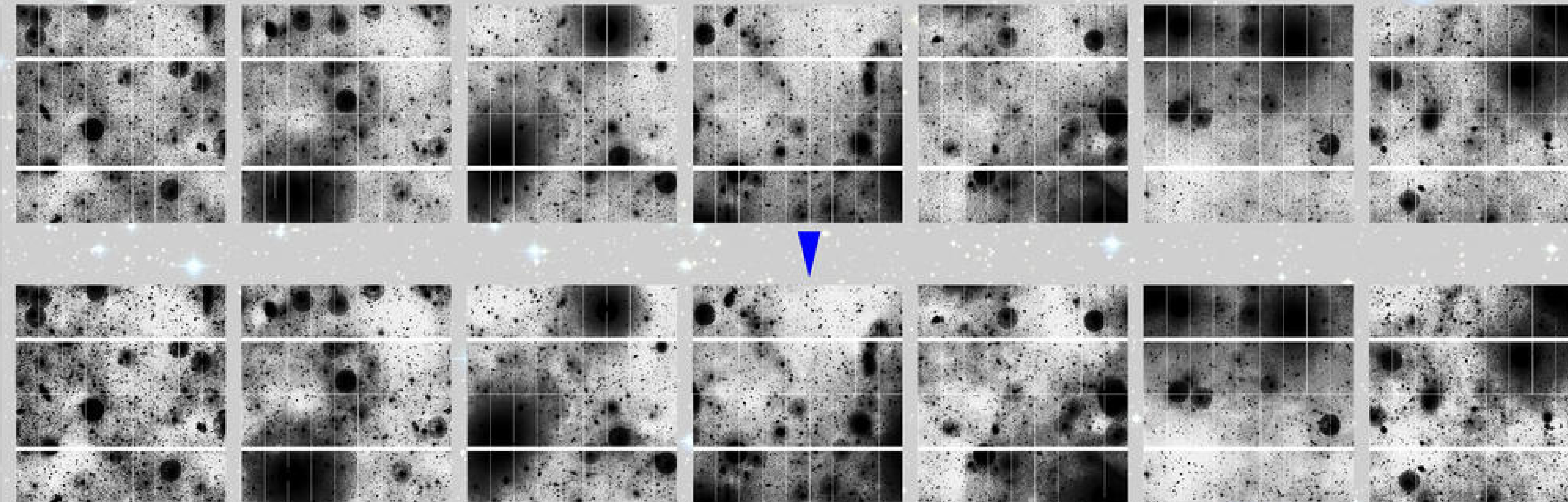


1st pass Elixir–LSB frame

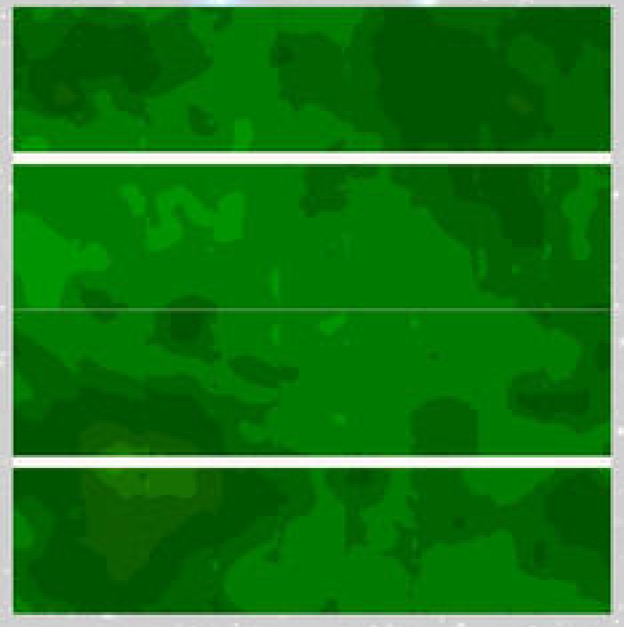
√ ***Step 1 : build statistics and derive the scaling factor based on sky levels***
√ ***Step 2 : scale the sky only and subtract it and compensate with a constant***
√ ***Step 3 : build statistics and generate previews***

- Original flux of astronomical objects not altered in the process
- 1st pass: worse residuals are 2% (tiny areas of the image)
- 1st pass typical residuals are 0.7% of the image (all bands) for typical sky levels (ADUs): u*~250, g'~1100, i'~2000, z'~2500
- 1st pass residuals caused by
  + Low statistics (5/6/7 measures)
  + Crowding of extended objects & low sky
  + Non constant sky during sequence

Elixir–LSB 2nd pass : pre–filtering 1st pass images



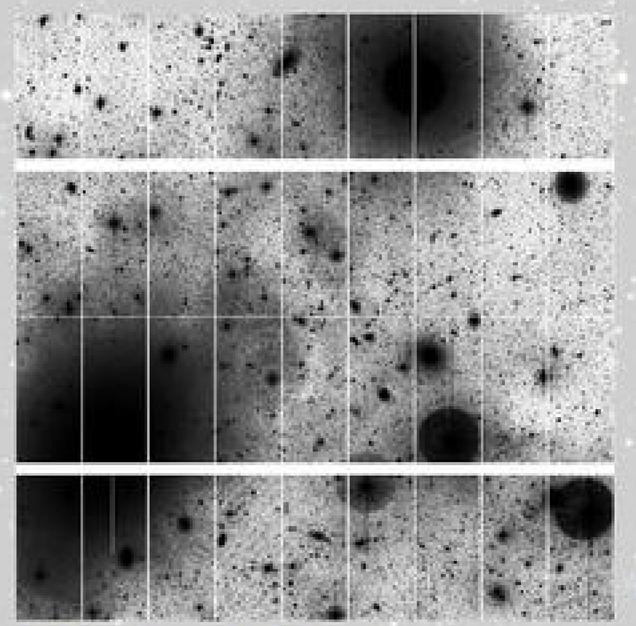
Elixir–LSB makesky



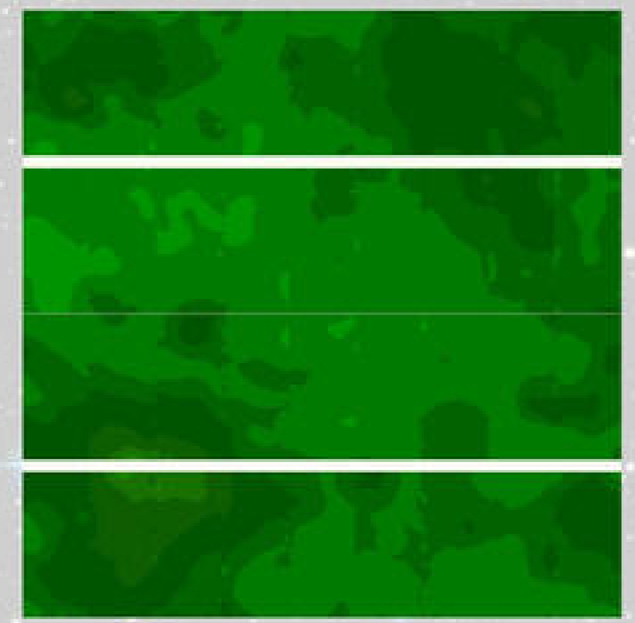
- √ *Step 1 : filter all input frames (~10" scale)*
- √ *Step 2 : build statistics, derive scaling factor per frame based on sky level*
- √ *Step 3 : scale & stack frames using a sigma clipping opt. for low numbers*
- √ *Step 4 : median filter and gaussian smoothing at the CCD scale*
- √ *Step 5 : build statistics and previews of the sky*

Current optimized Elixir–LSB sky corrector

Use of the specific sky for each single exposure

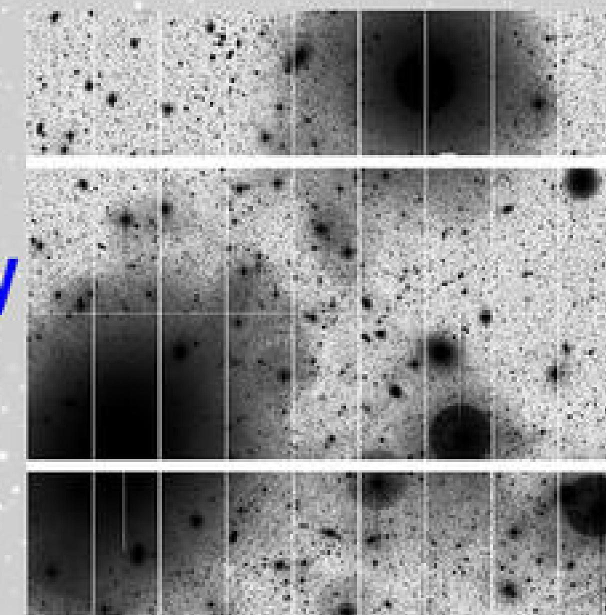


Elixir–LSB 1st pass



Sky 2nd pass

Elixir–LSB sub sky ►



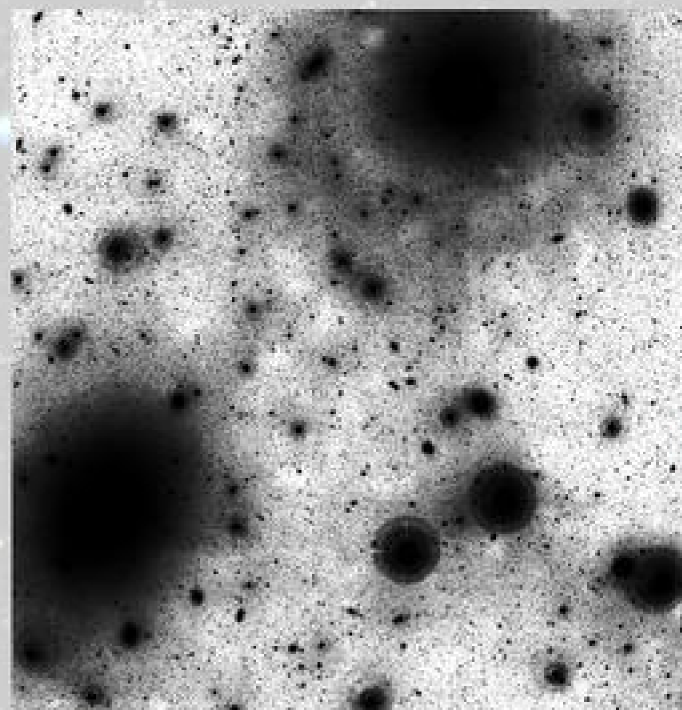
Elixir–LSB 2nd pass

√ ***Step 1 : build statistics and derive the scaling factor based on sky levels***
√ ***Step 2 : scale the sky only and subtract it and compensate with a constant***
√ ***Step 3 : build statistics and generate previews***

- Original flux of astronomical objects not altered in the process
- 2nd pass: worse residuals are 1% (tiny areas of the image)
- 2nd pass typical residuals are 0.2% of the sky background : x 3 gain leading to 6 to 7 mag. fainter than sky background, e.g. 29th in g’
- 2nd pass residuals caused by
  + Low statistics but clear gain over pass#1
  + Crowding of extended objects & low sky
  + Non constant sky during sequence

Elixir−LSB performance today (spring 2010)

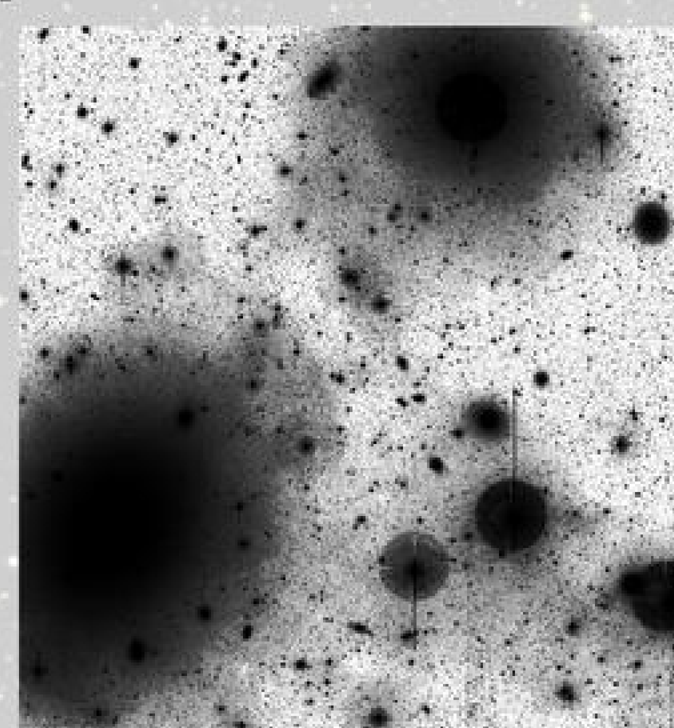
Elixir−LSB now delivers data in specs with the NGVS requirements



u*

Res=0.2%
Sky=22.6 mag.
Lim=29.3 mag.

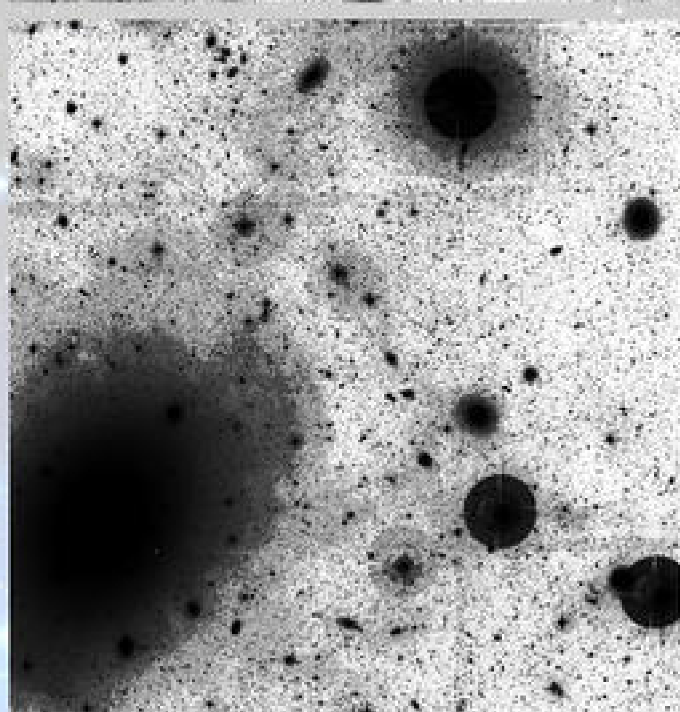
Max=0.5%



g'

Res=0.2%
Sky=22.2 mag.
Lim=29.0 mag.

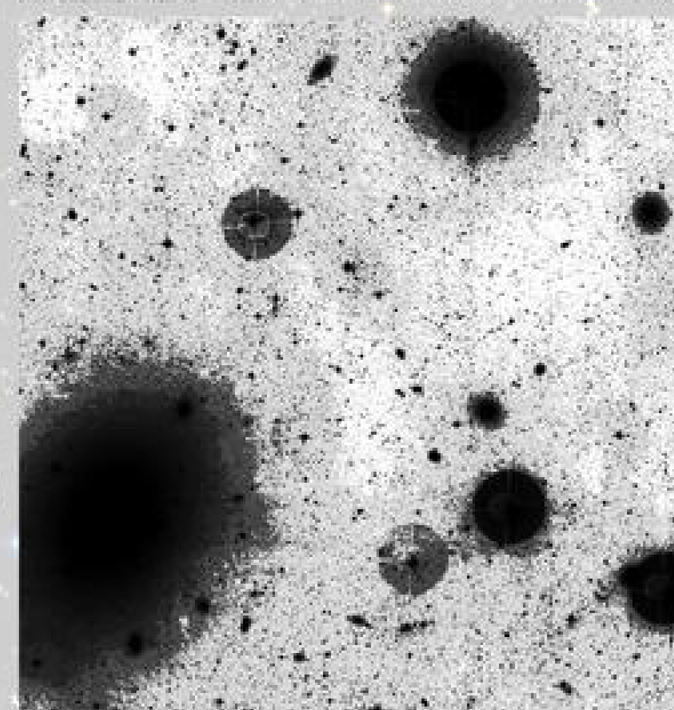
Max=0.5% rare



i'

Res=0.2%
Sky=20.7 mag.
Lim=27.4 mag.

Max=0.5% rare



z'

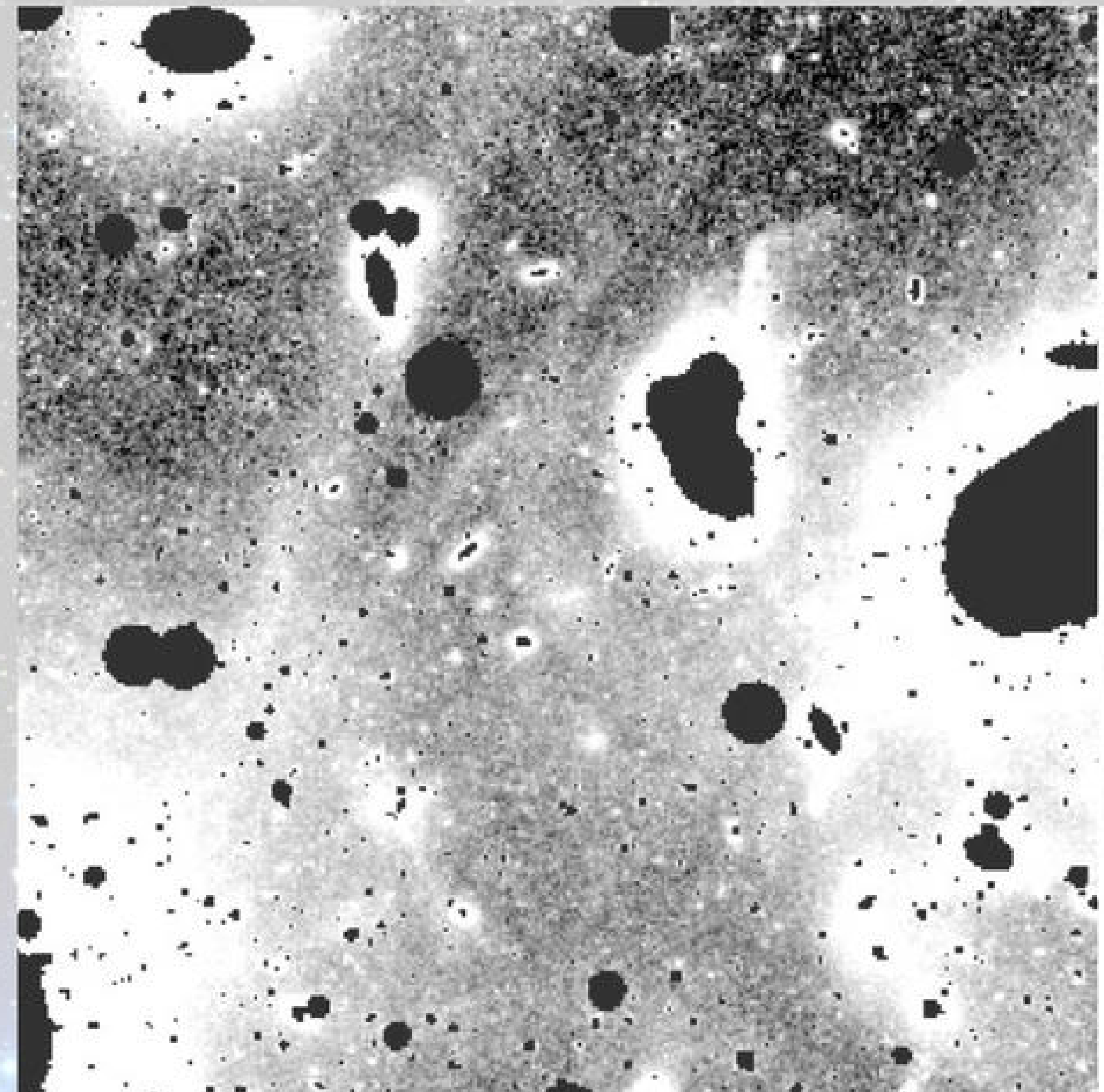
Res=0.2%
Sky=19.3 mag.
Lim=26.0 mag.

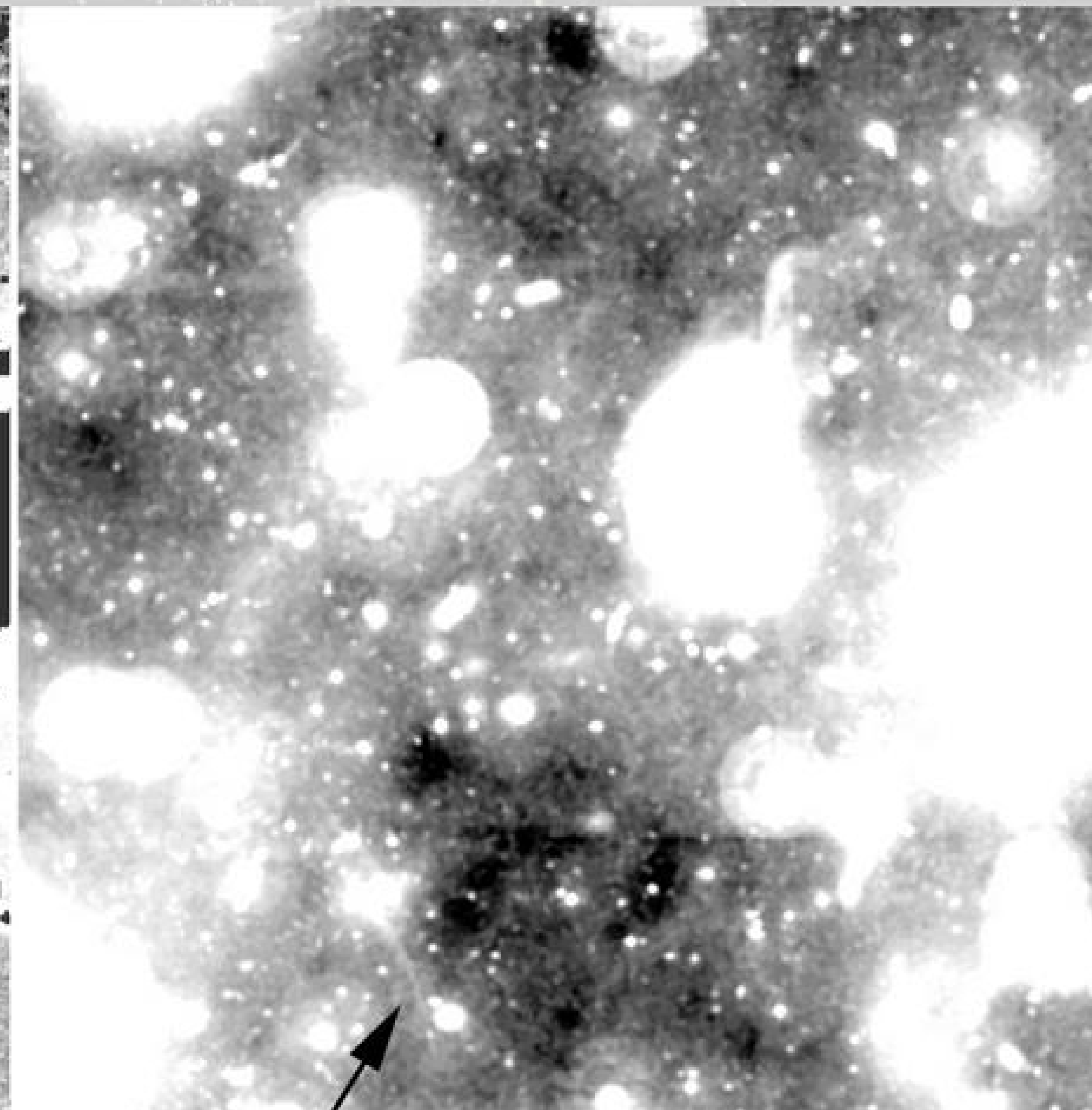
Max=0.5%

NGVS−1−4 (Messier 49)

Elixir–LSB performance today (spring 2010)

Comparison with C. Milhos et al. study with a Schmidt telescope





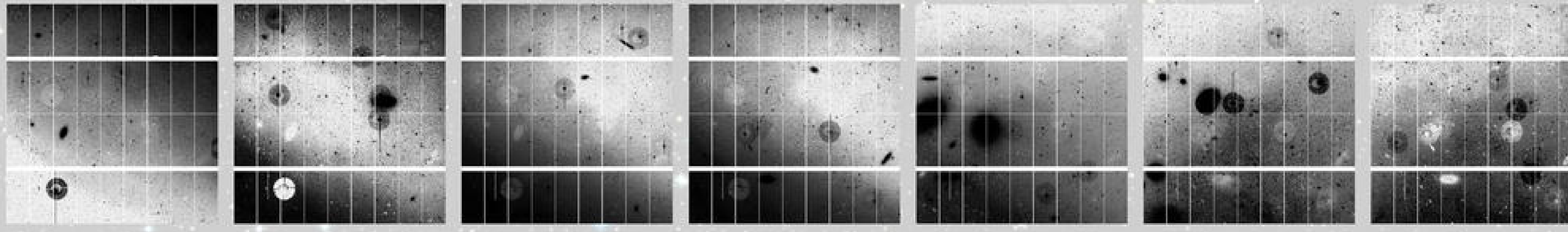
Milhos et al.

g’ = 28.5 mag. arcsec^2

NGVSs–1–1 (Messier 87) – D99 Snapshot

Coping with the near–infrared sky : i' and z' data

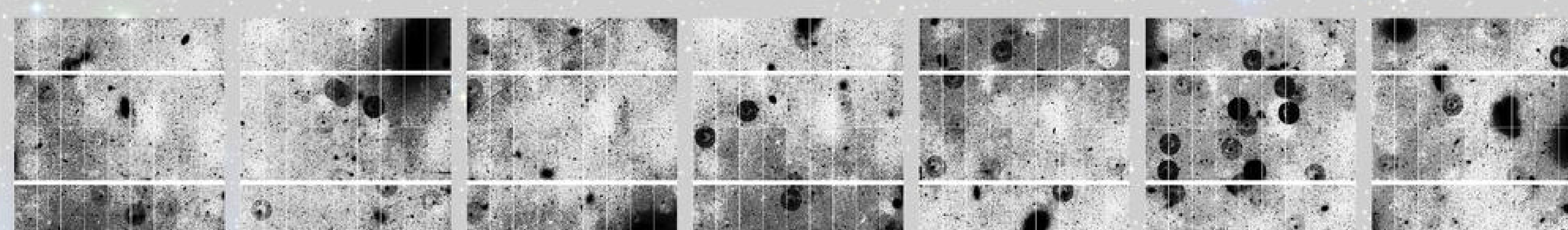
Example of an night impossible to process (10/20% gradients) :



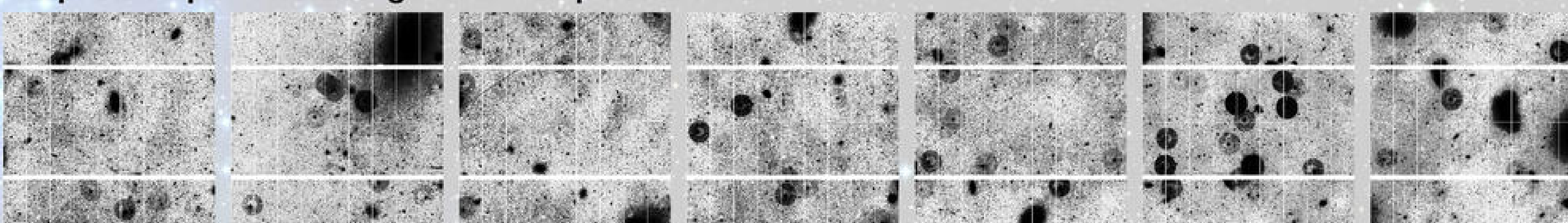
→ represents a rare case for a NGVS global rejection requiring a whole repeat

Only solution : subtract a large scale (15') map from 1st pass images

→ thus far excludes fields with extended objects (e.g. Messier 49)



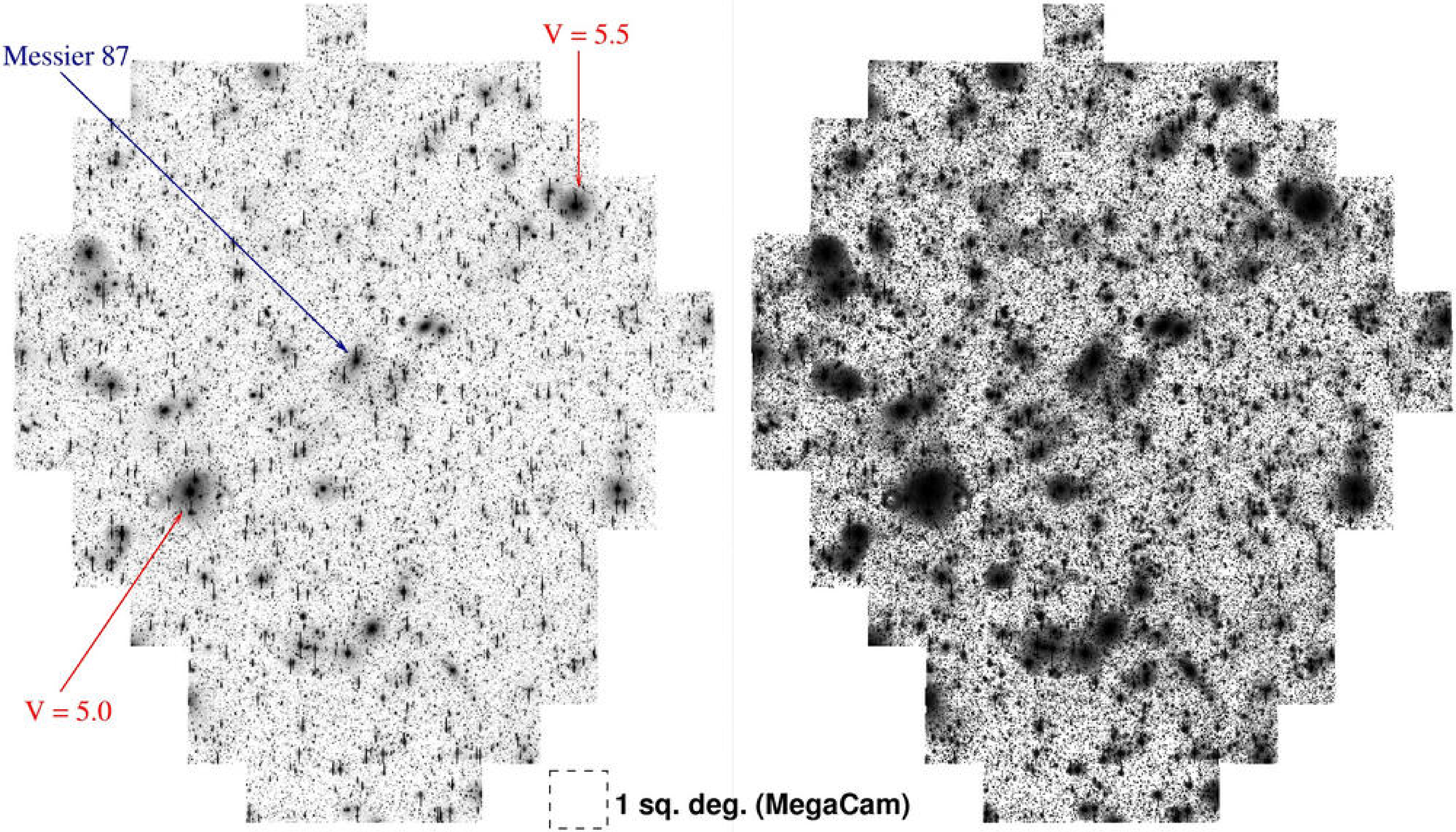
1st pass output before large–scale map subtraction



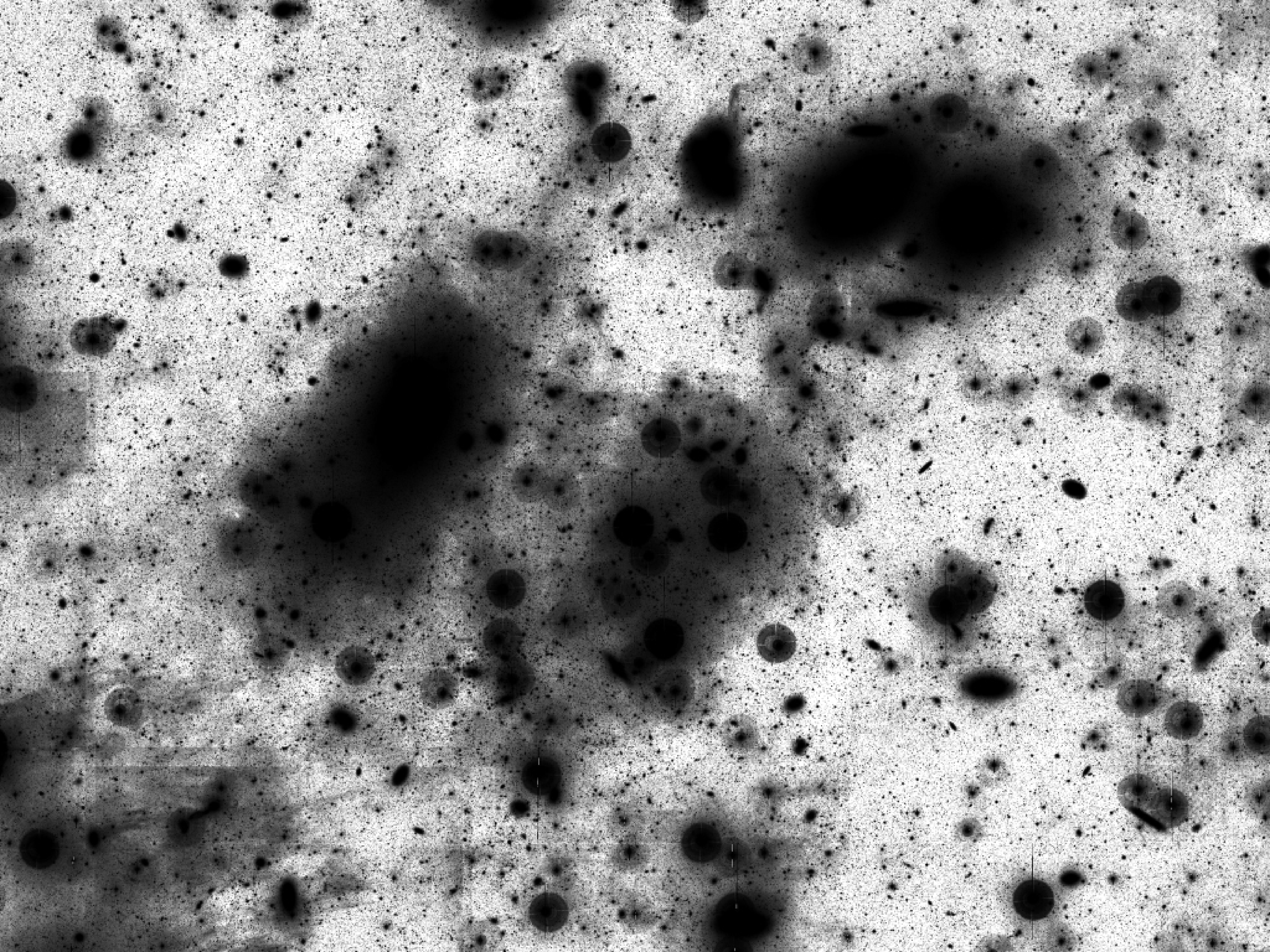
2nd pass output with a large–scale map subtraction : significant improvement in most cases

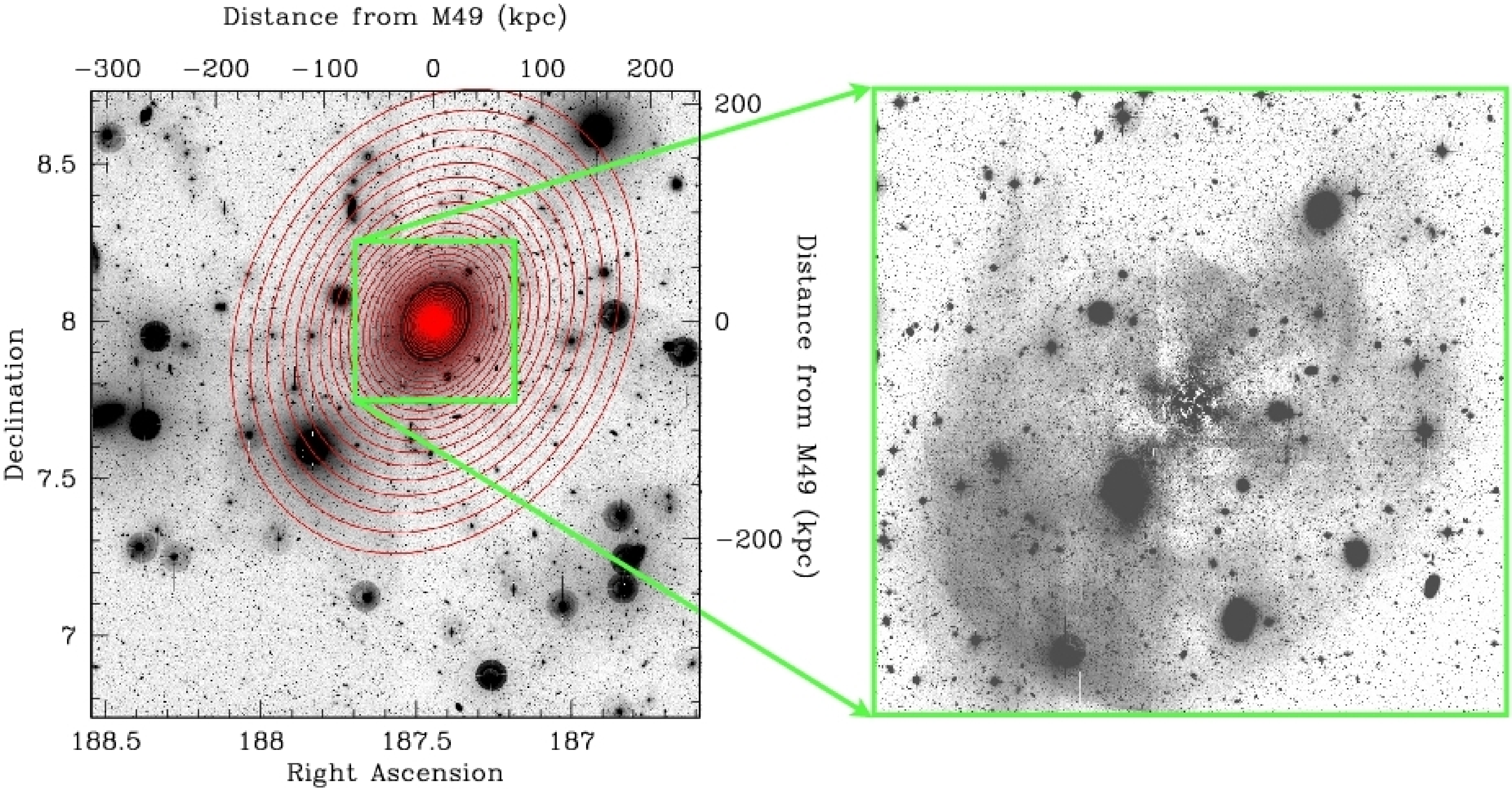
Mosaicing Elixir–LSB pointings : full NGVS footprint

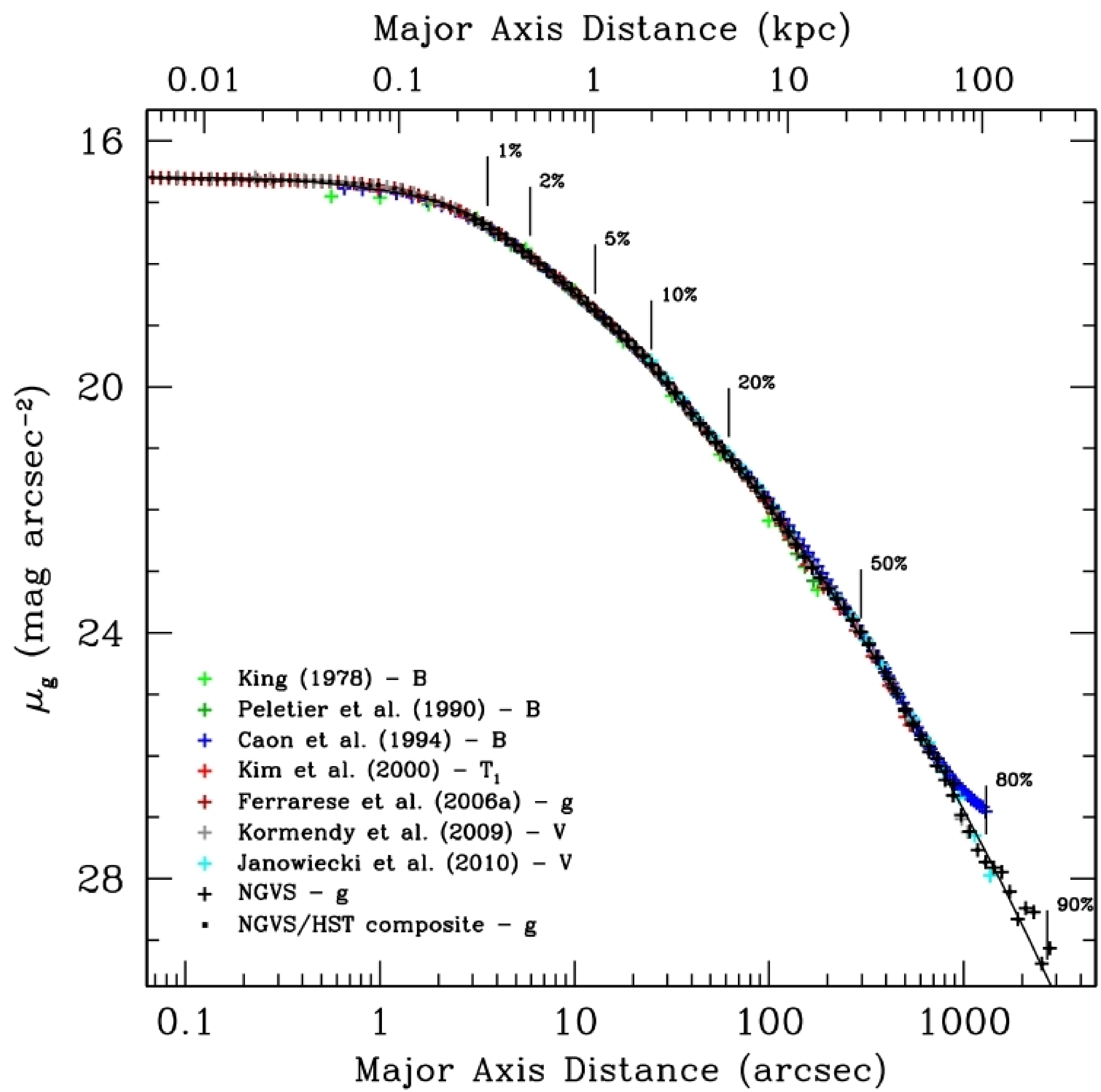
117 sq. deg. ; g' band ; IQ ~ 0.8'' ; 52 min. integration



Residuals gradients of 1% common near bright sources (stars, large galaxies) that are causing sky contamination due to the low number of "sky" frames

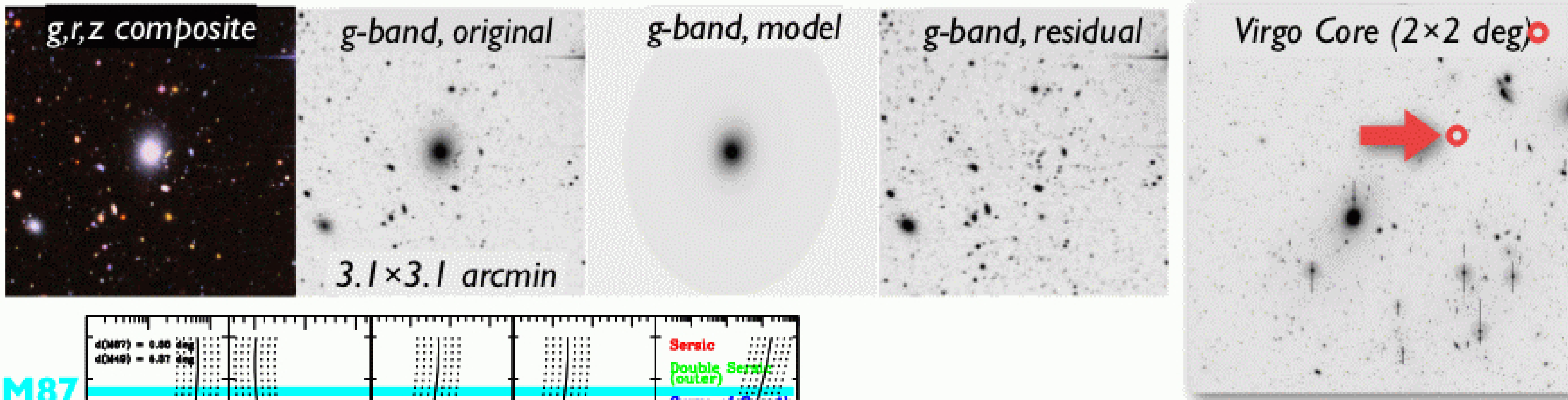


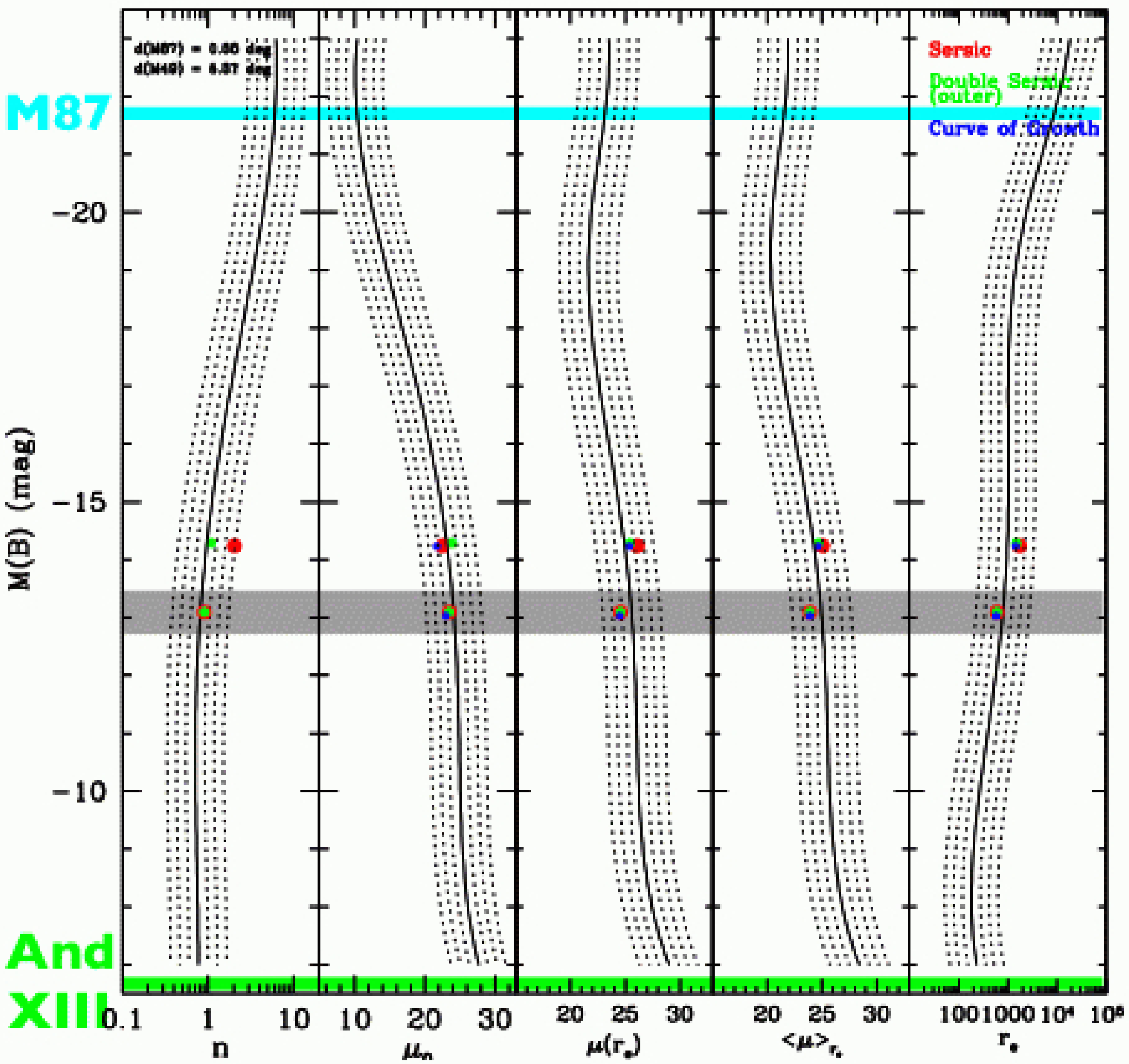

Distance from M49 (kpc)
−300
−200
−100
0
100
200
8.5
8
7.5
7
Declination
200
0
−200
Distance from M49 (kpc)
188.5
188
187.5
187
Right Ascension

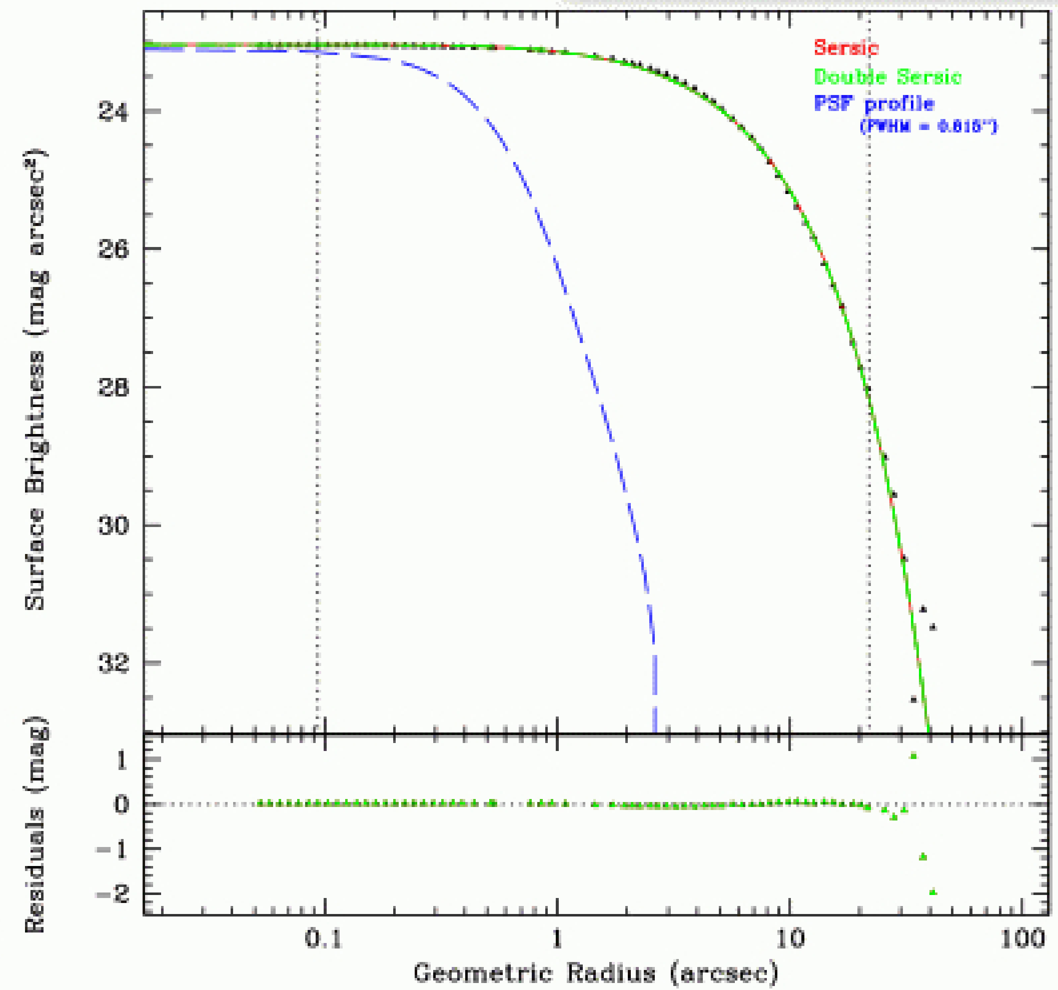


Major Axis Distance (kpc)
0.01
0.1
1
10
100
16
20
24
28
μ_g (mag arcsec^{-2})
1%
2%
5%
10%
20%
50%
80%
90%
King (1978) – B
Peletier et al. (1990) – B
Caon et al. (1994) – B
Kim et al. (2000) – T_1
Ferrarese et al. (2006a) – g
Kormendy et al. (2009) – V
Janowiecki et al. (2010) – V
NGVS – g
NGVS/HST composite – g
0.1
1
10
100
1000
Major Axis Distance (arcsec)

NGVS12:28:44.894+12:48:33.35   VCC1129   M(g) = −13.49 mag

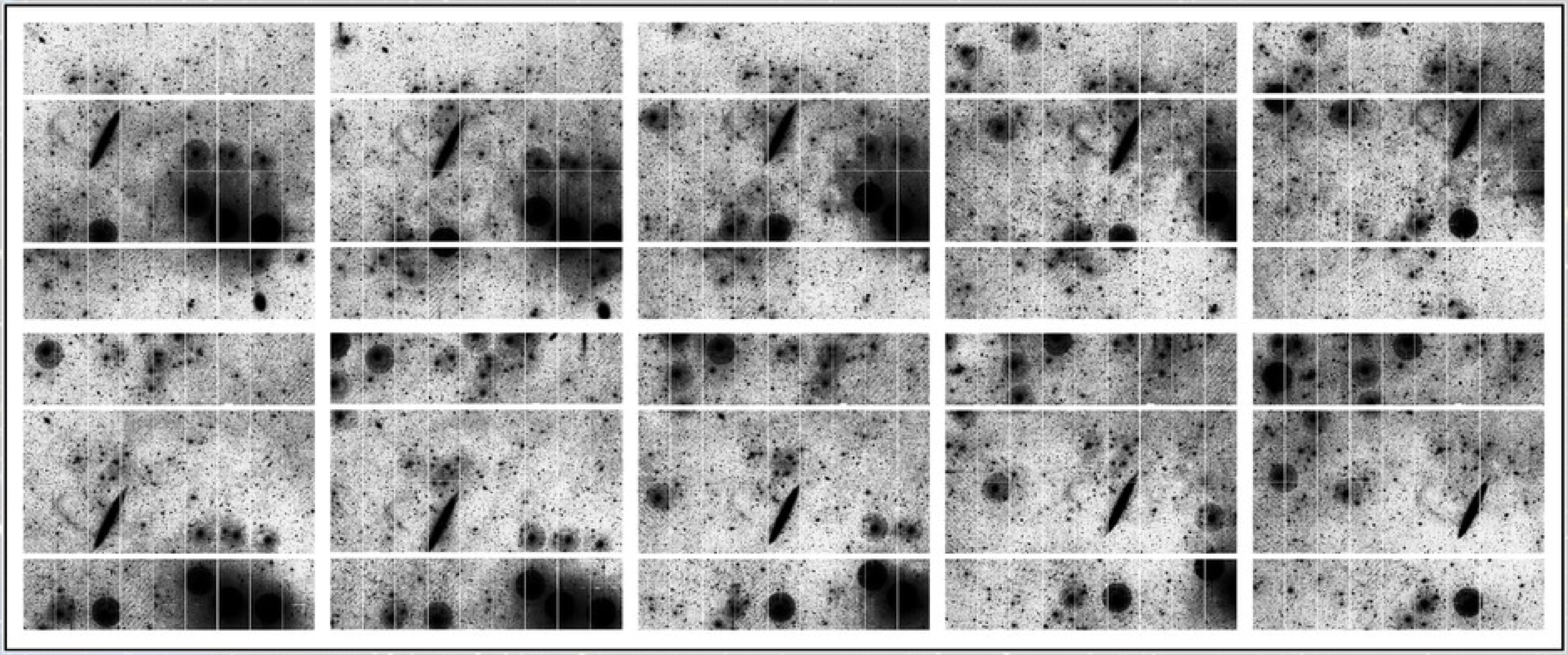






Elixir–LSB for small objects (<10’)

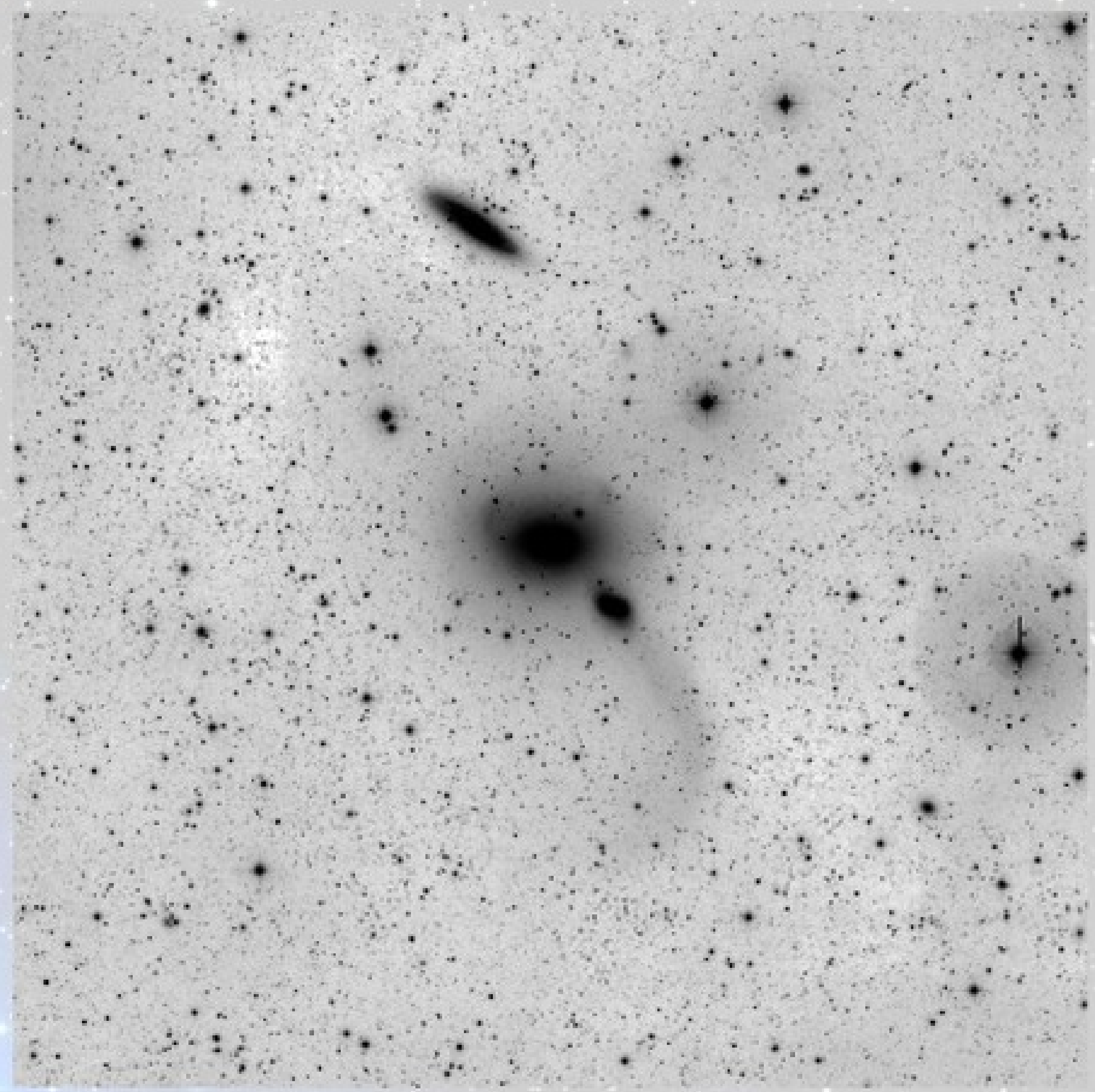
Simultaneous integration of the science field & sky fields
Allows for optimization based on target and surrounding



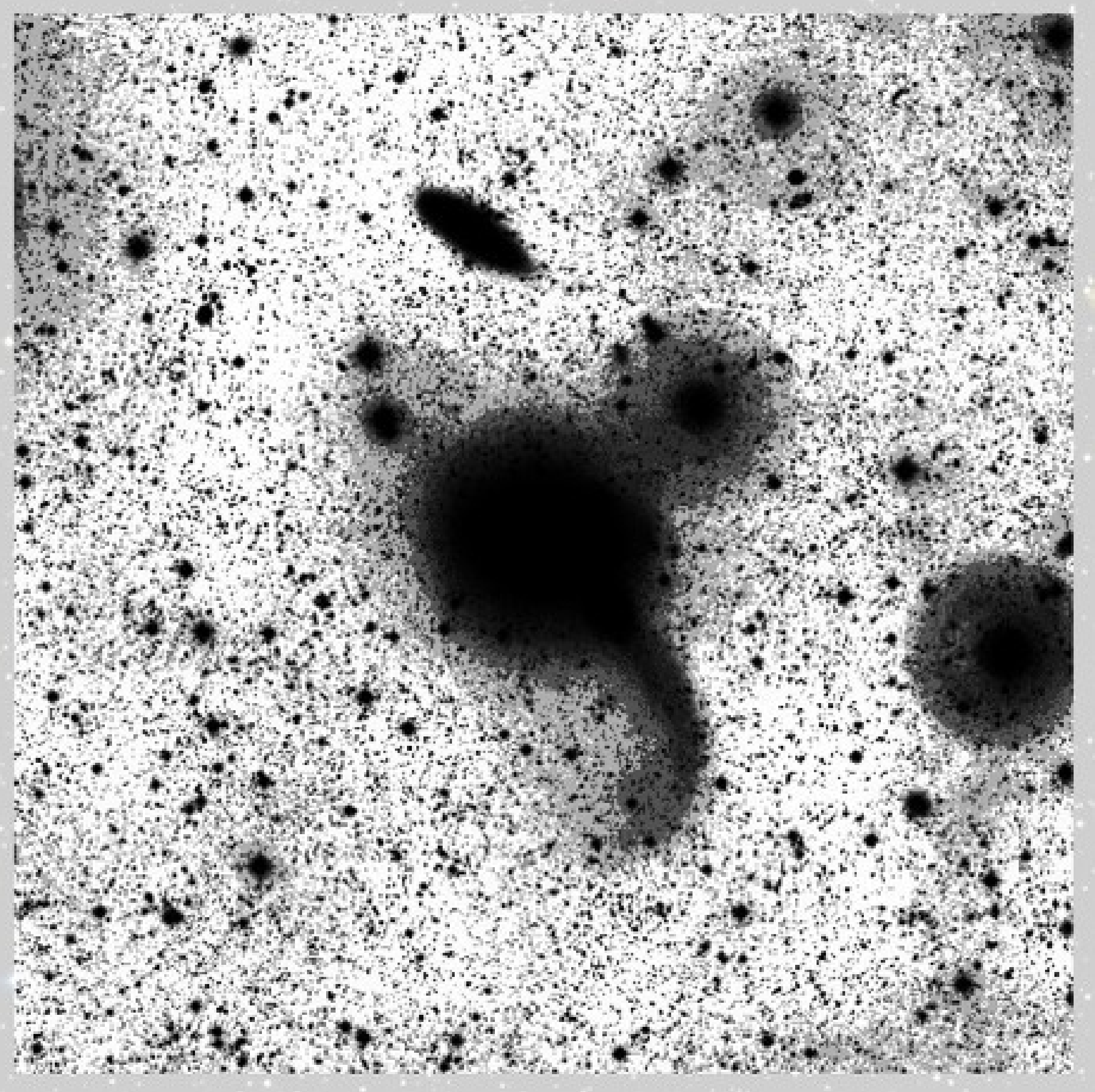
Ultra large dithering pattern on the NGC 5907 field

Mass Assembly of Early Type Galaxies (Duc et al.)

Optical counterpart of the Atlas−3D HI survey



NGC 5574 – high cuts



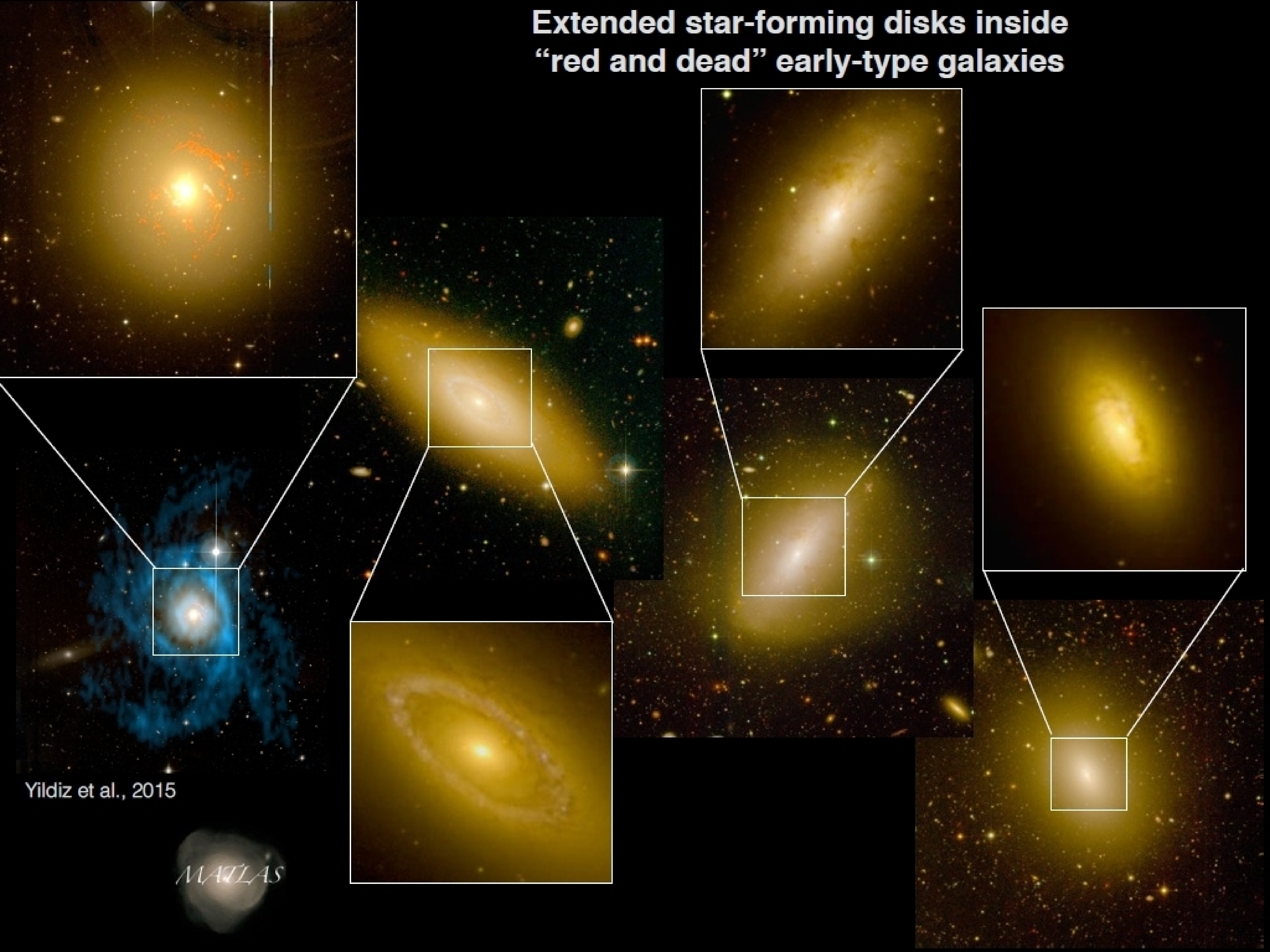
NGC 5574 – low cuts

Star-forming disks around “red and dead” early-type galaxies

Duc et al., 2015

MATLAS

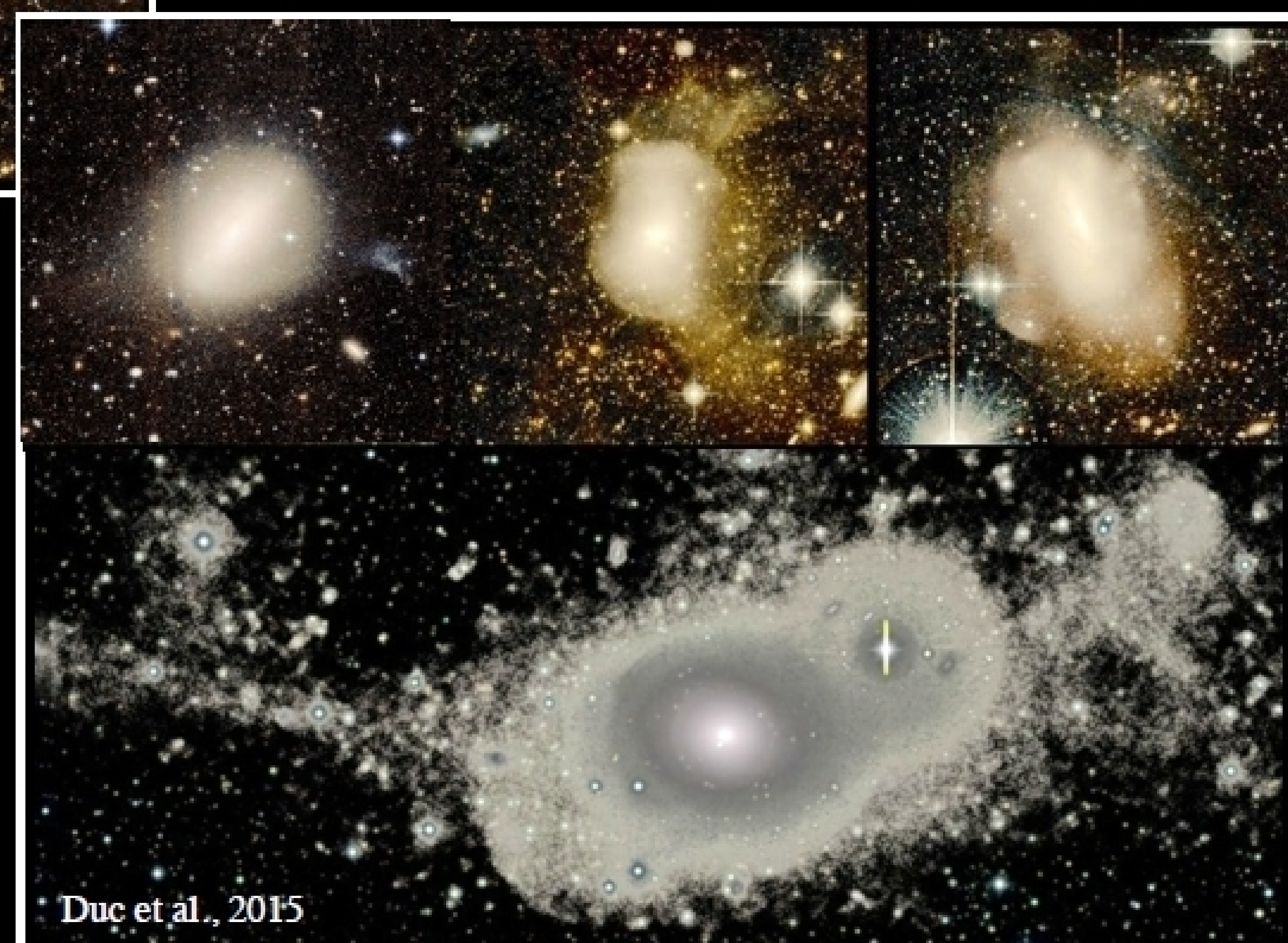
Extended star-forming disks inside "red and dead" early-type galaxies



Passive red halos around lathe-type galaxies

Deep imaging and the detection of fine structures

- ✓ Diffuse tidal plumes … … revealing on going tidal interactions



- ✓ Perturbed isolated central body and gas rich tidal tails … revealing past wet major mergers

MATLAS

Deep imaging and the detection of fine structures

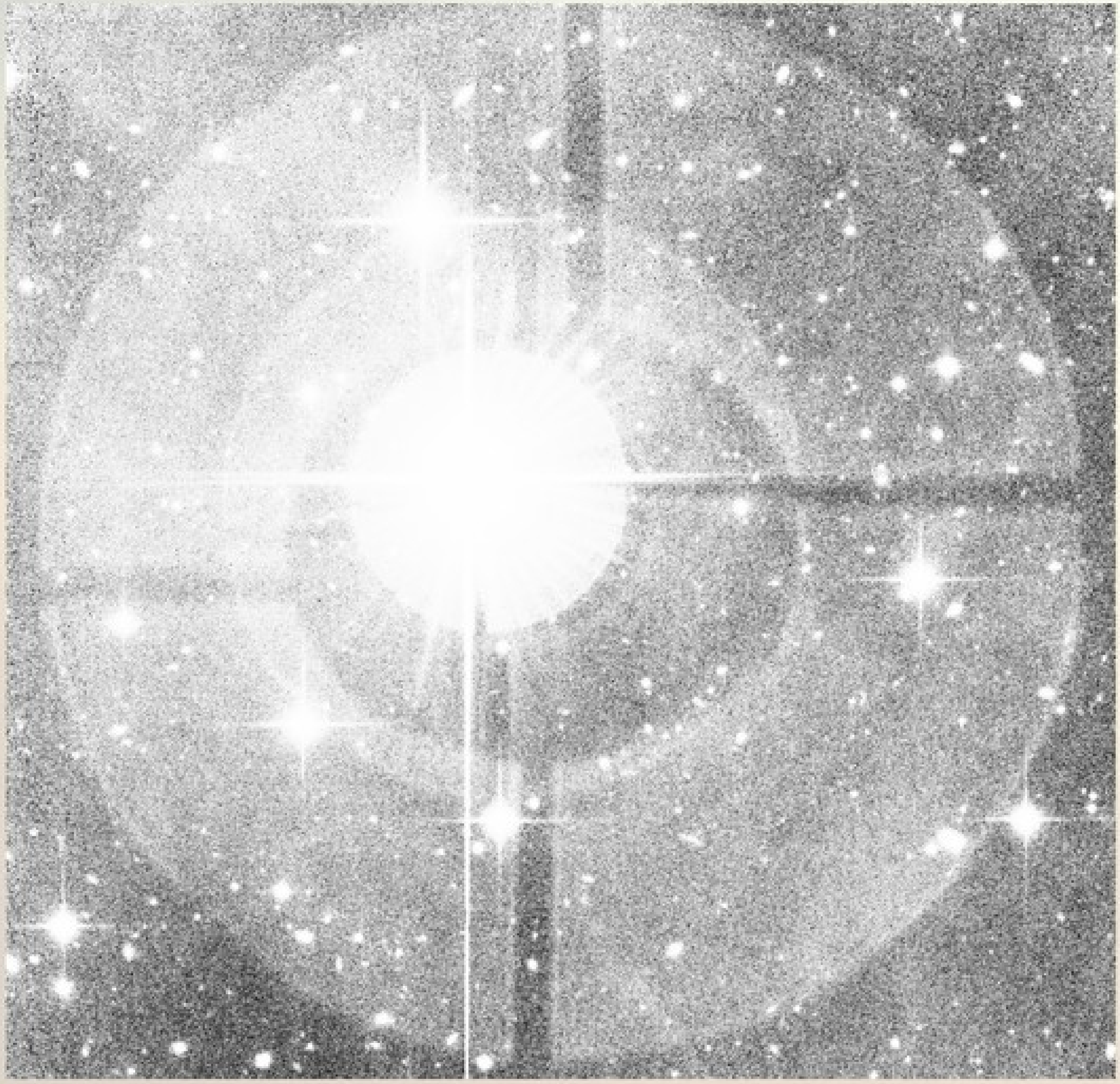
✓ Narrow stellar streams … …
revealing on going / past gas-poor minor mergers

✓ Sharp-edge shells……
revealing past intermediate mass mergers

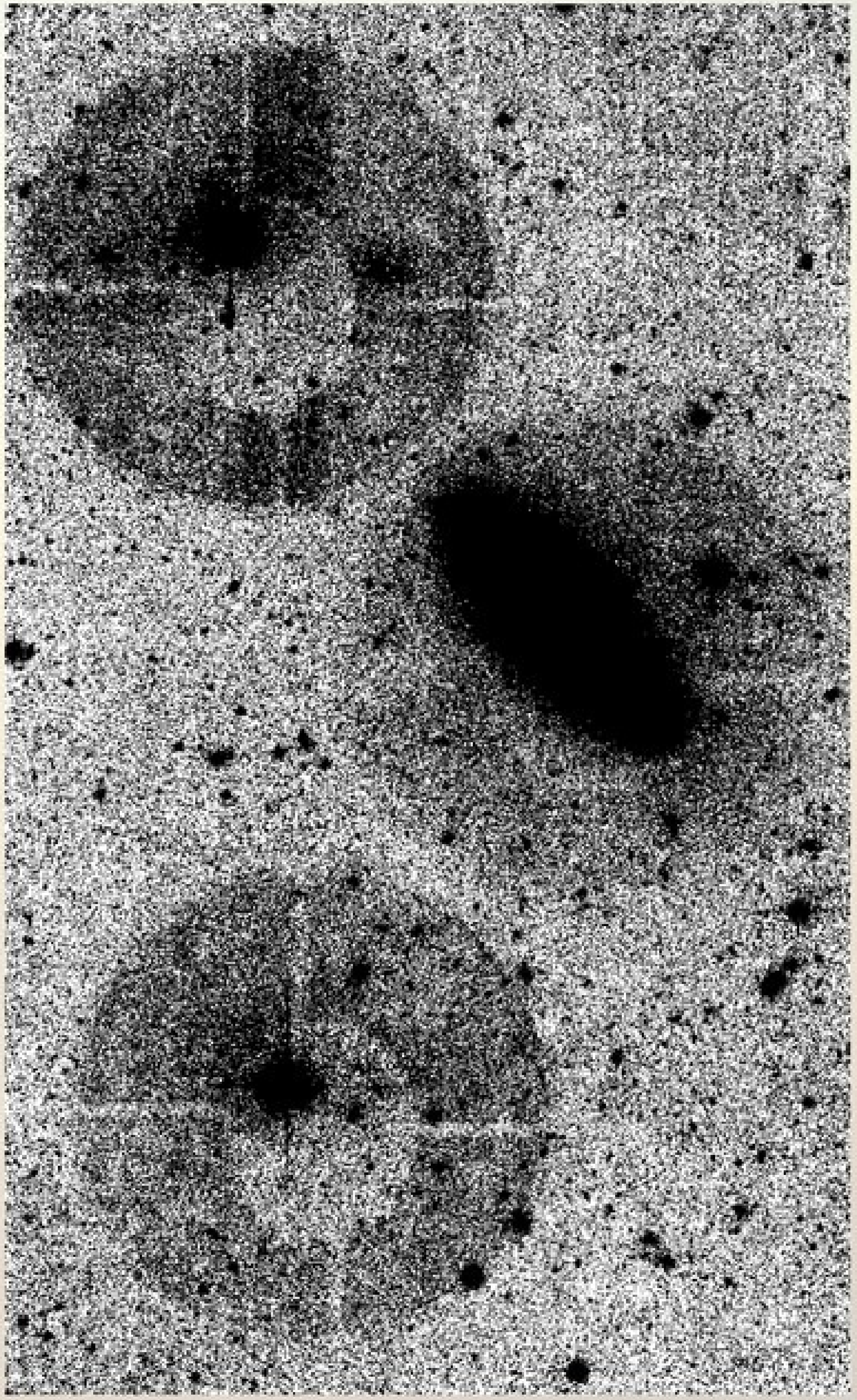
MATLAS

NGVS

MegaCam reflection halos : the main data contaminant

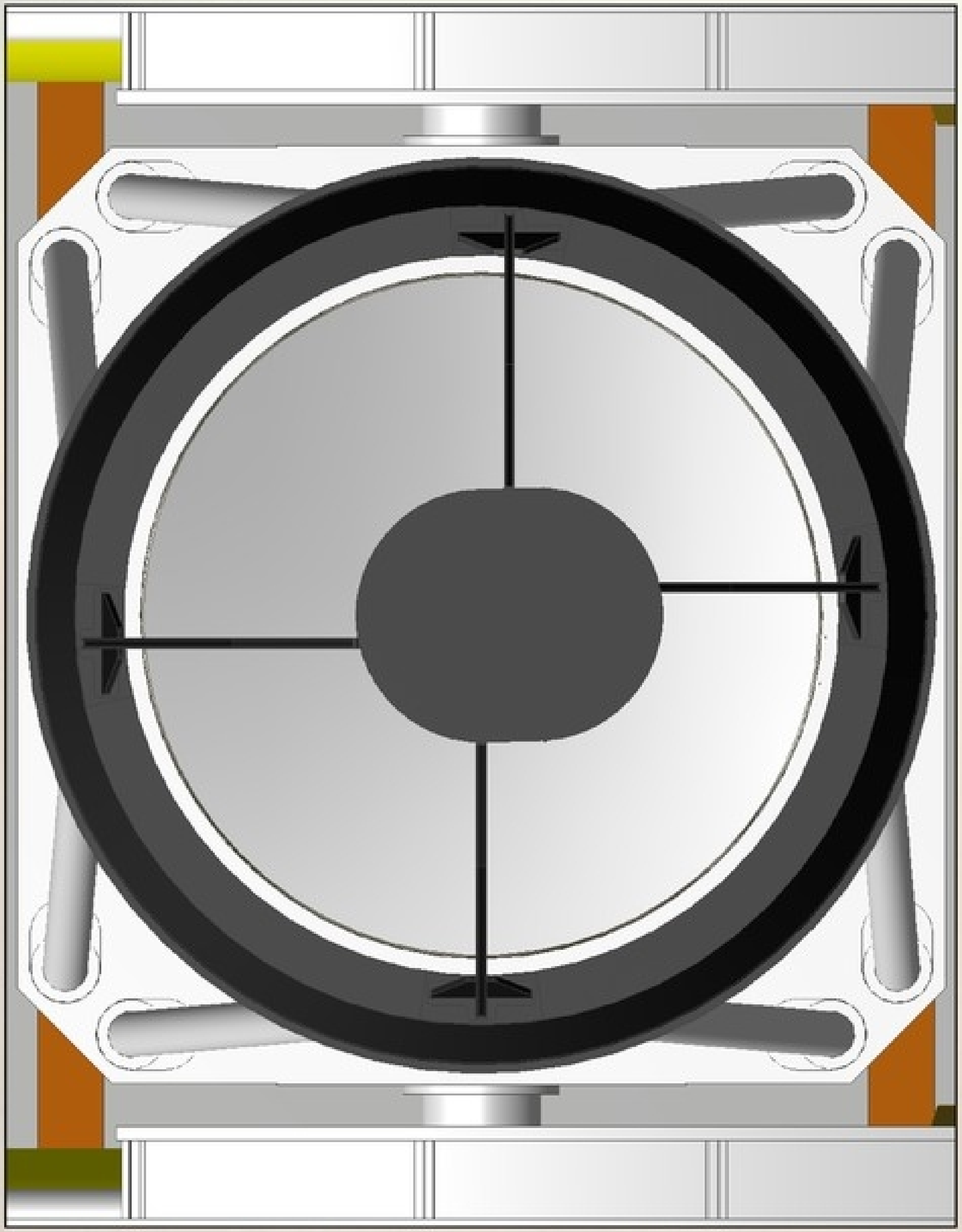


Commonly seen extended structures (diameter 7')

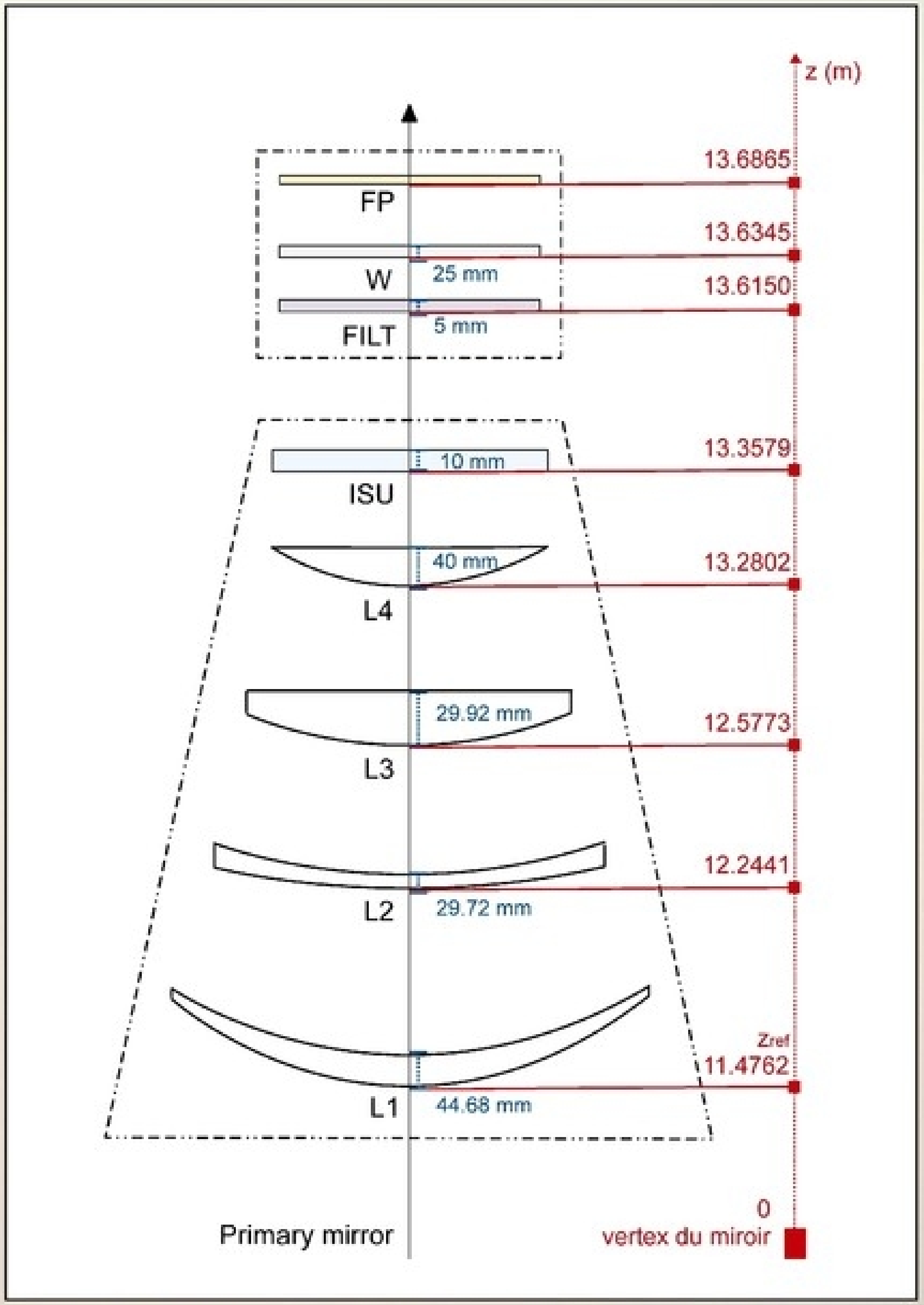


CCD to window halo (diameter 2')

MegaCam and MegaPrime optics : geometry



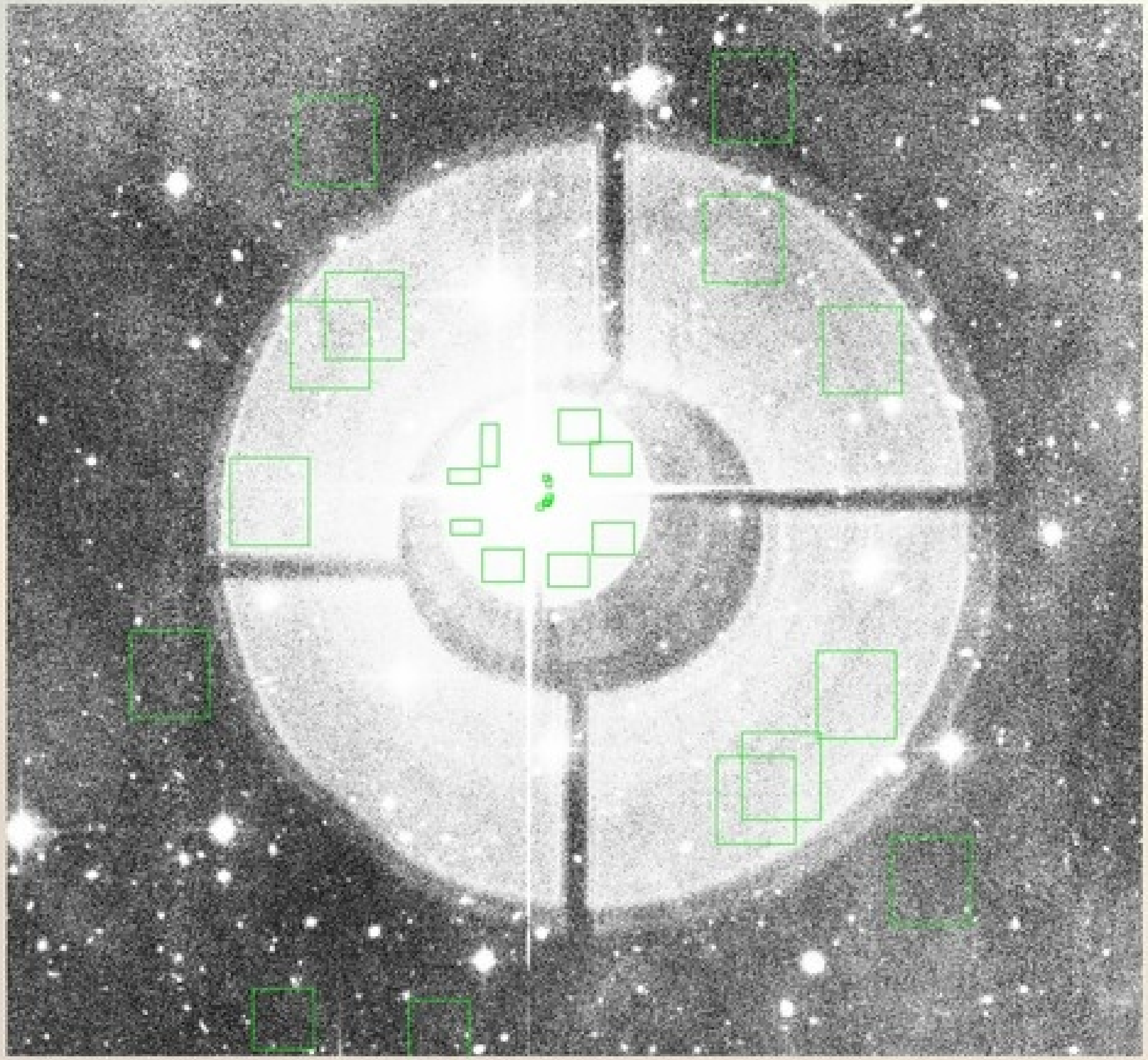
MegaPrime enclosure & support structure



MegaPrime+MegaCam optics: 7+CCDs

Total reflections = [2x7+1]x[2x7] = 210!

Measuring the main optical surfaces reflectivity



Picking reflection halos surface brightness

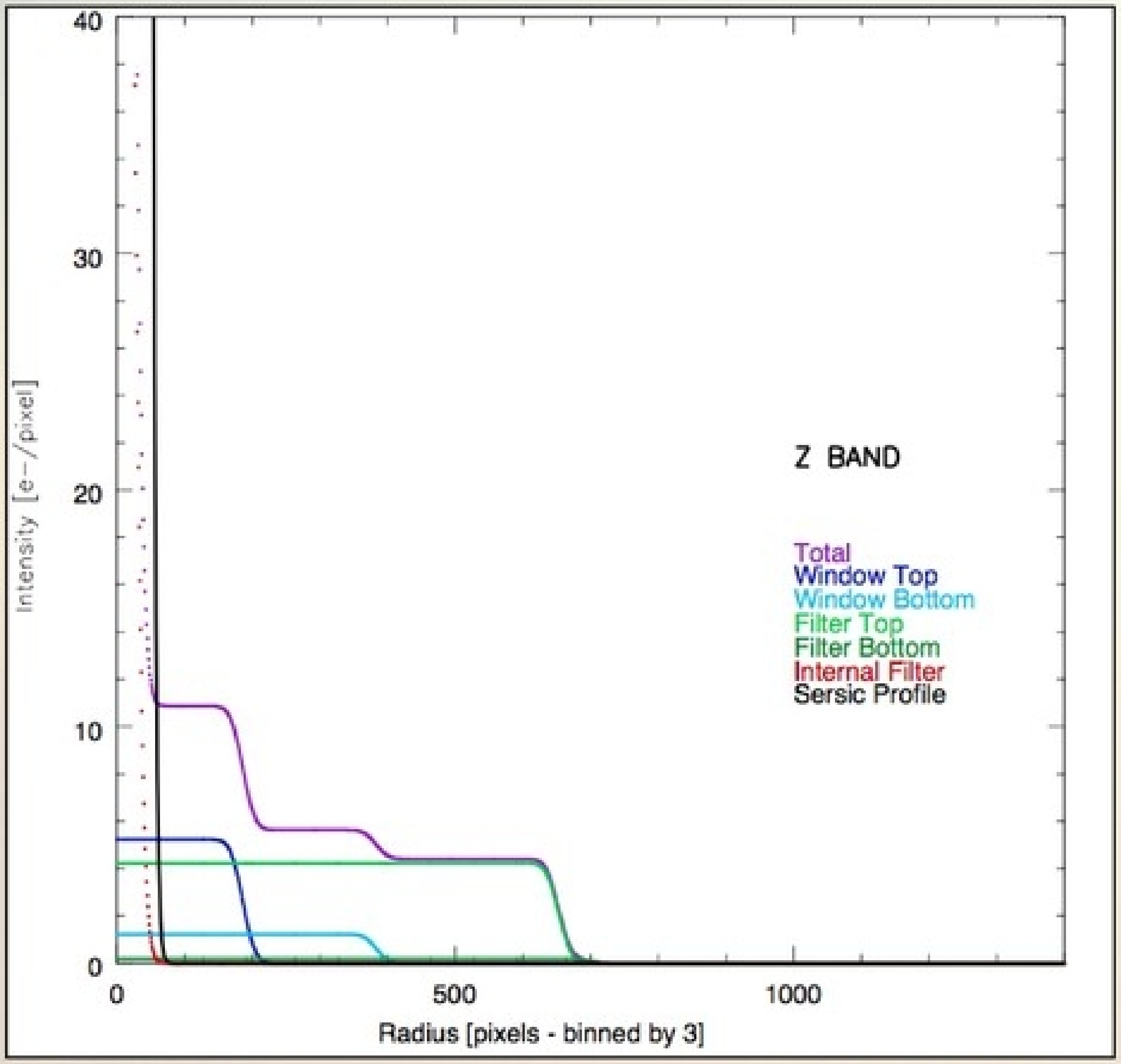
All optics have extra internal reflections

Total reflections ~ 2n^3 (2700!)

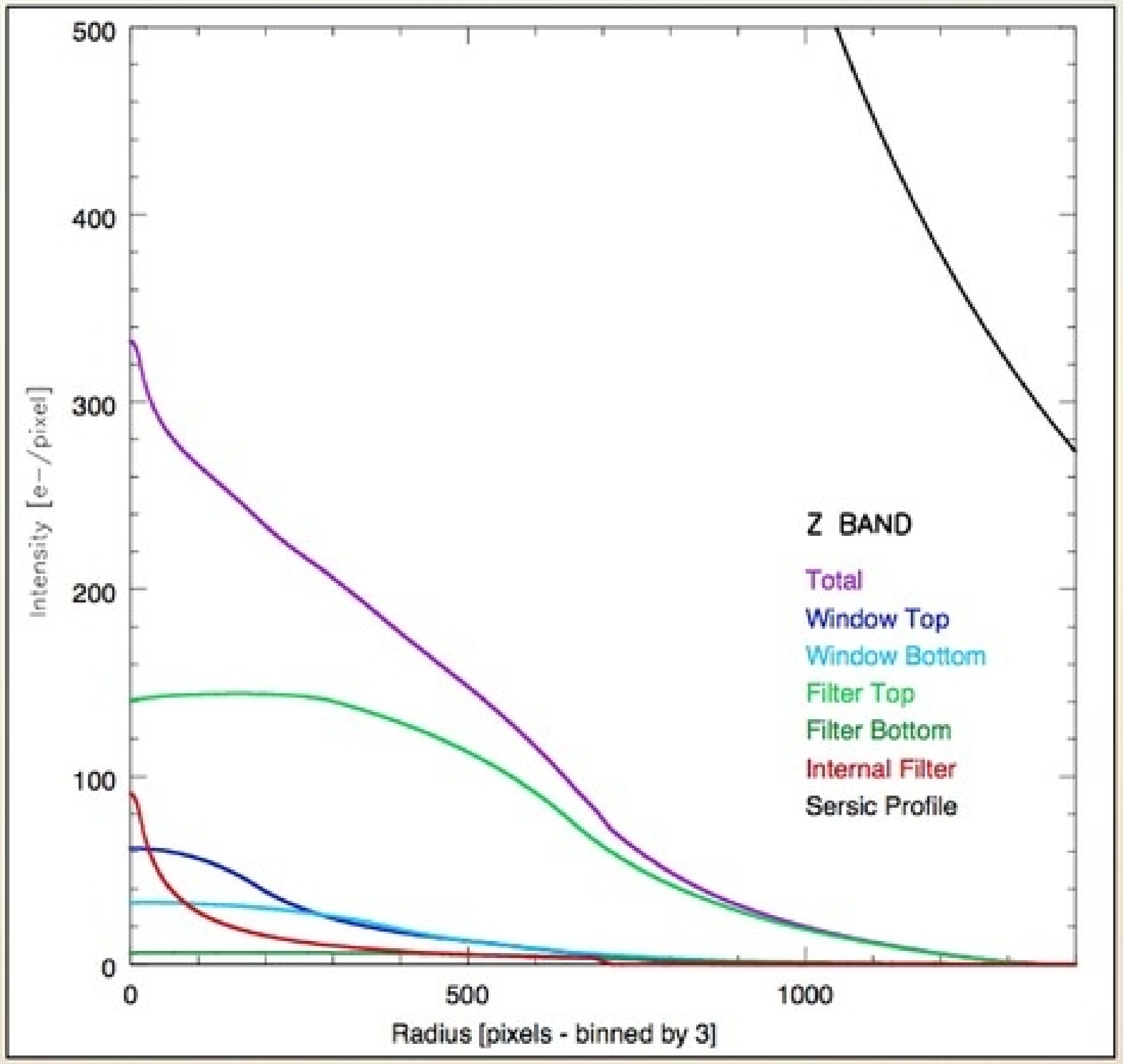
Band	CCD Ref. [%]	Window Ref. [%]	Filter Top Ref. [%]	Filter Bottom Ref. [%]
g	1.4	1.4	2.0	1.5
r	15.0	0.6	2.5	1.5
i	20.0	0.7	2.0	1.5
z	22.0	2.8	2.8	1.5

Derived reflectivities for the CCDs and the main optical interfaces (cryostat window & filter)

Estimation of the total flux integrated in the reflection halos



Star profile: compact core + extended halos

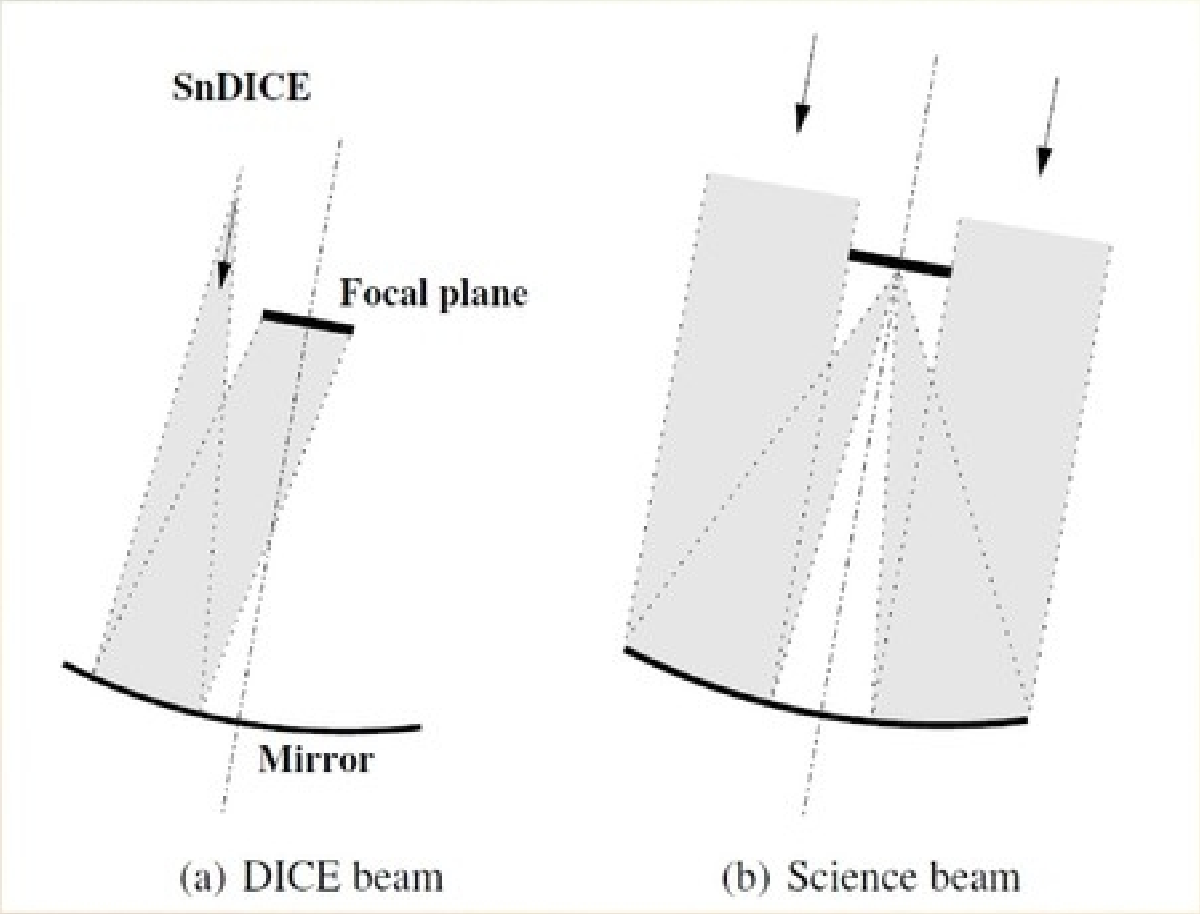


Extended galaxy profile: integrated halos

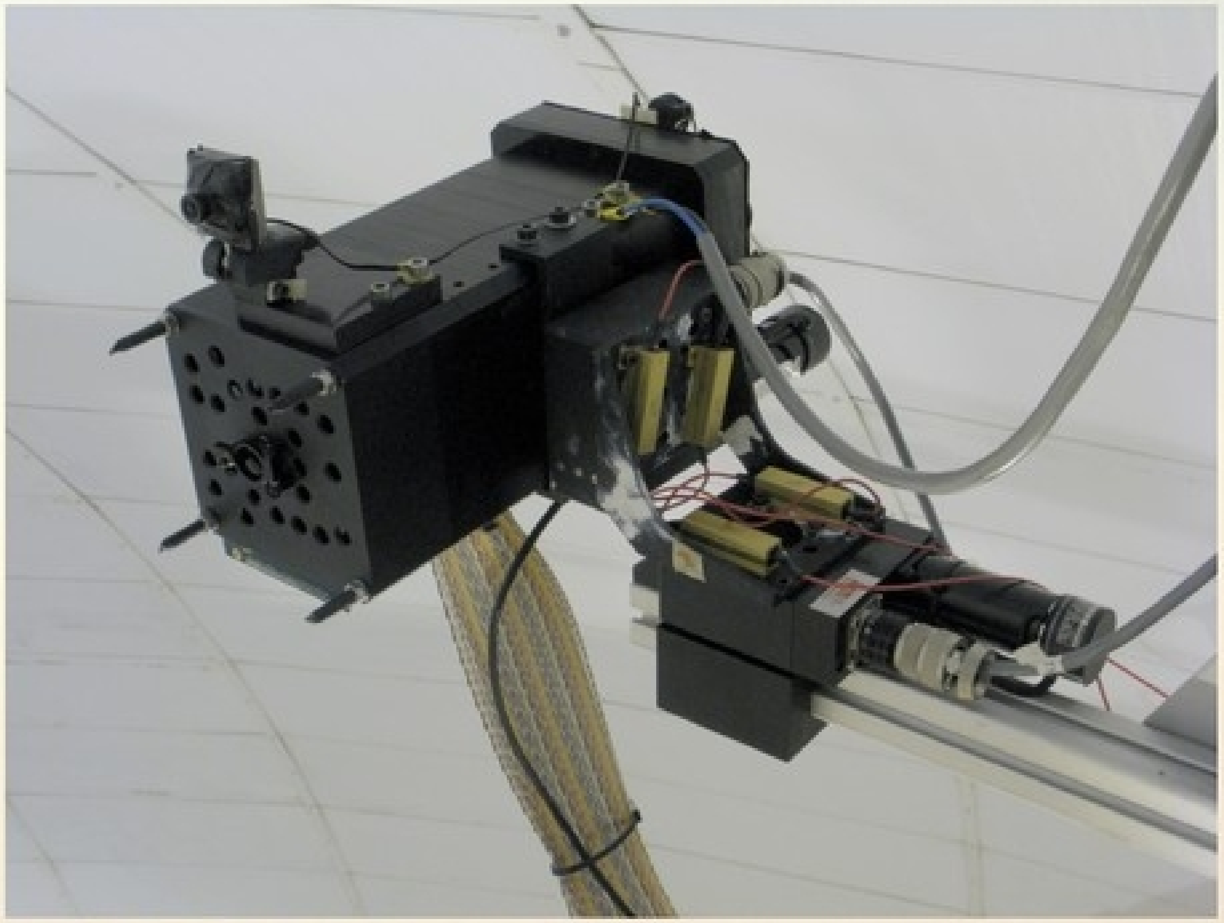
Band	Star Total Max. [%]	Star Total Min. [%]	Est. Galaxy Total[%]
g(fixed)	0.54	0.44	0.89
g(adjusted)	0.18	0.1	0.25
r	1.64	0.63	1.01
i	1.3	0.54	0.95
z	2.74	2.74	4.46

Flux in halos is low compared to the total flux (less than 1% for ugri)

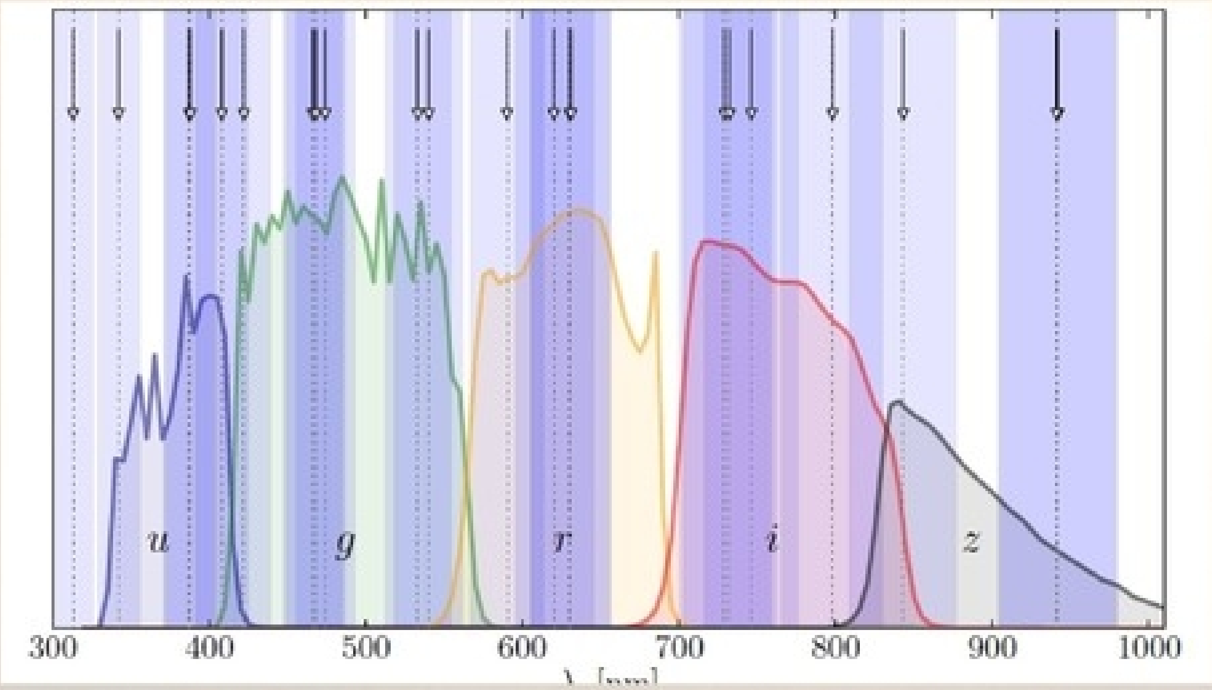
SnDICE by the LPNHE (IN2P3) : imaging calibration system



Calibration beam covers 3% of the mirror

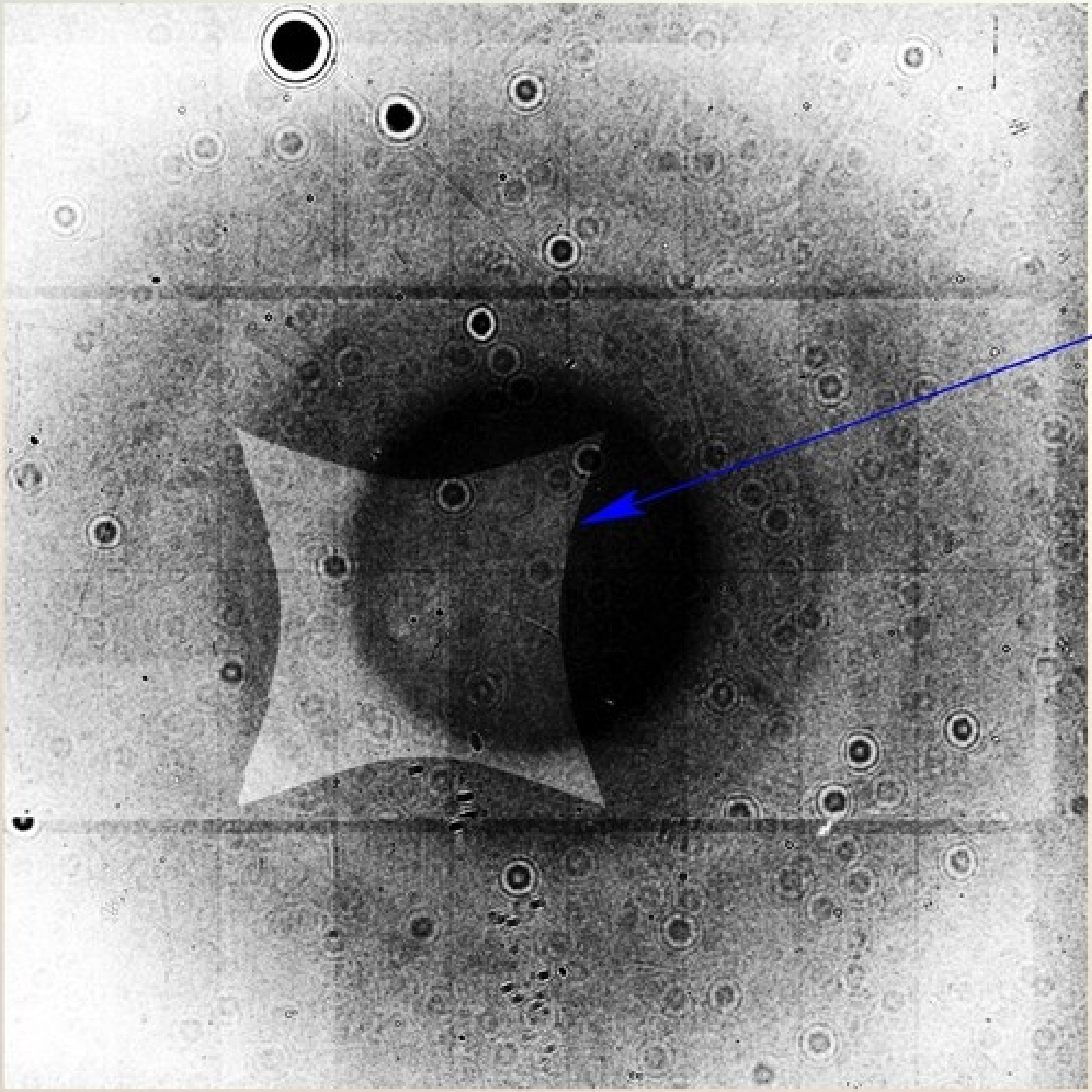


SnDICE in CFHT dome

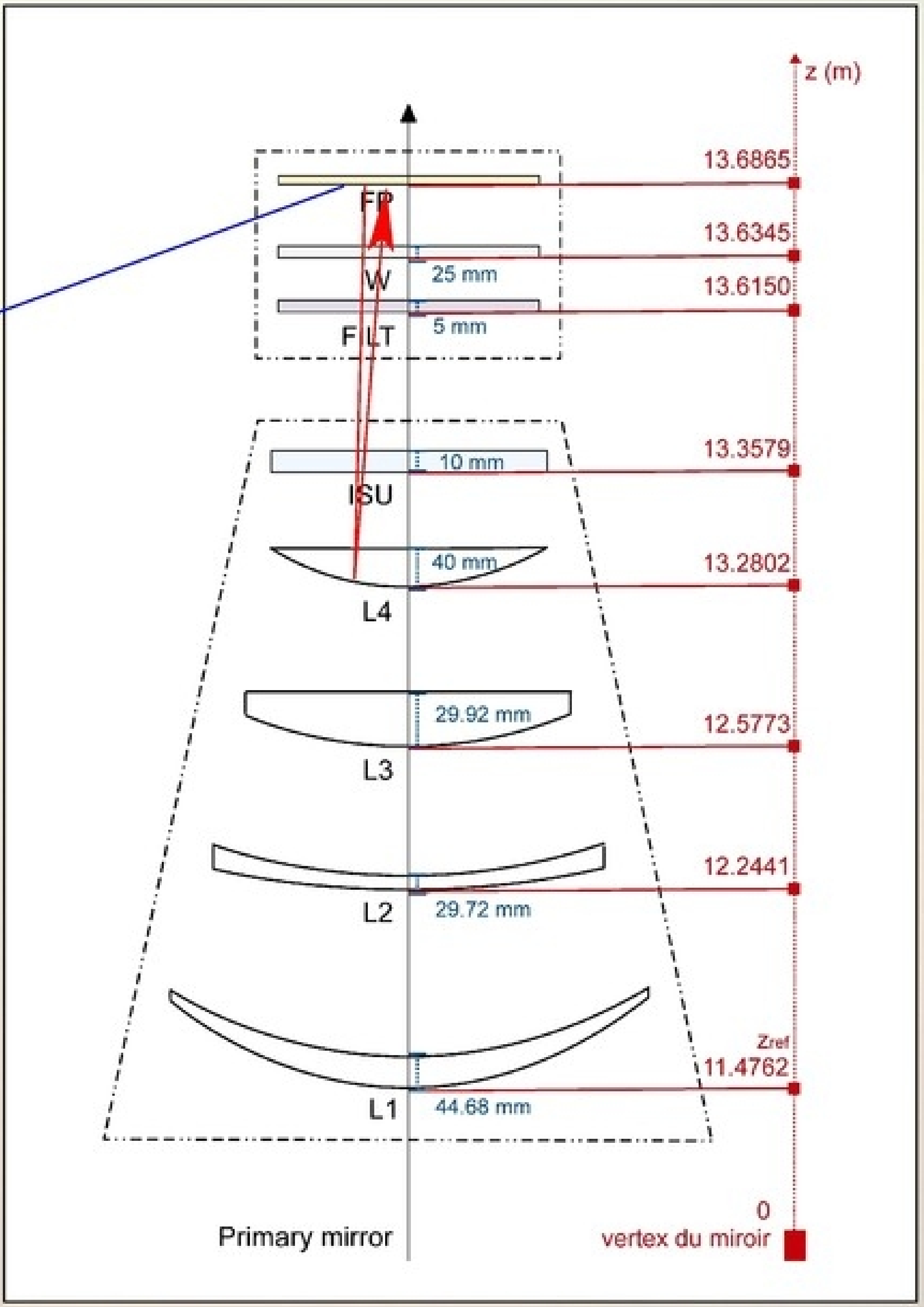


SnDICE LEDs range & MegaCam bands

SnDICE images revealed the prominance of optical reflections

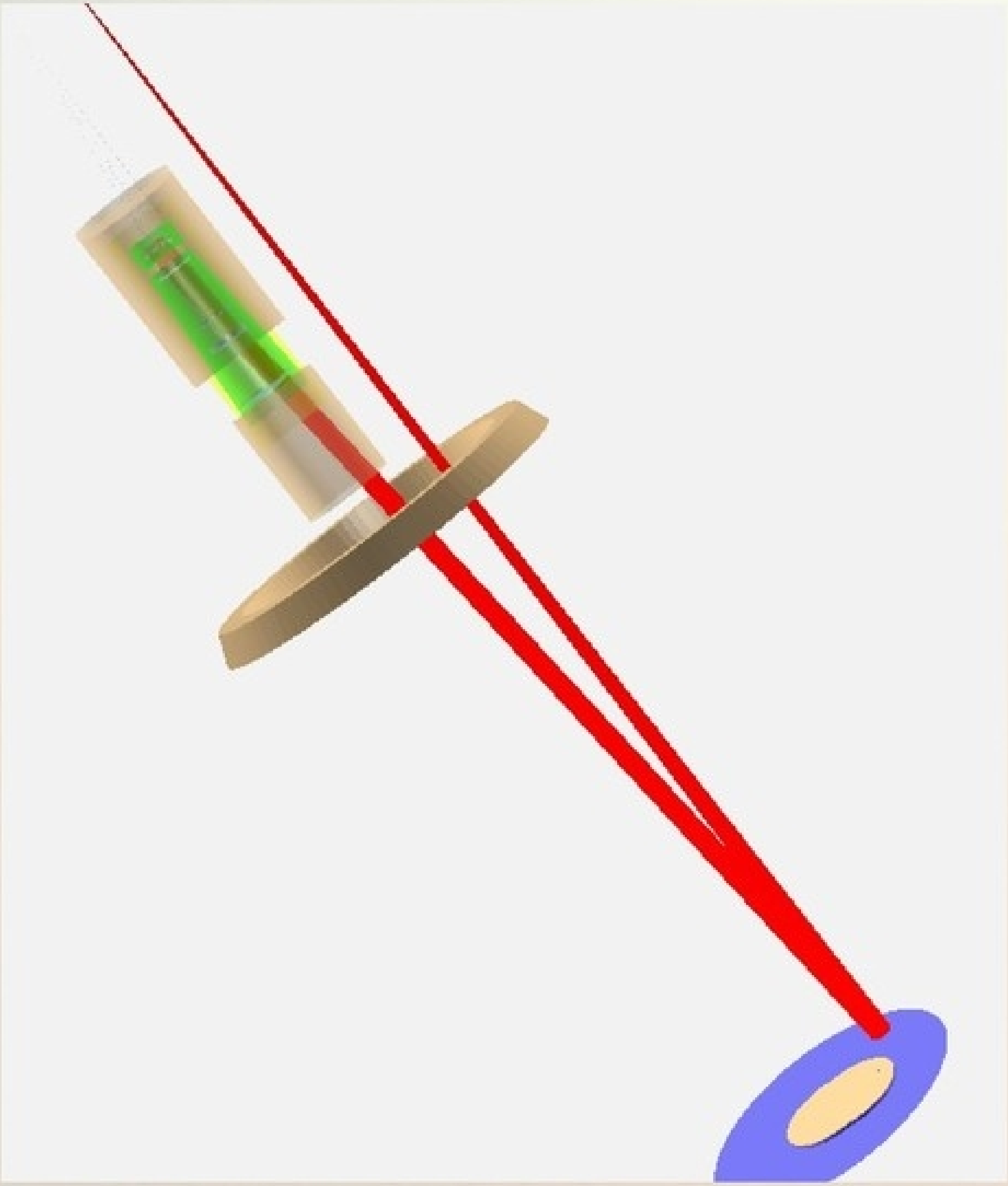


A SnDICE MegaCam frame: L4 effect & more
(a reflection of the entire square focal plane)

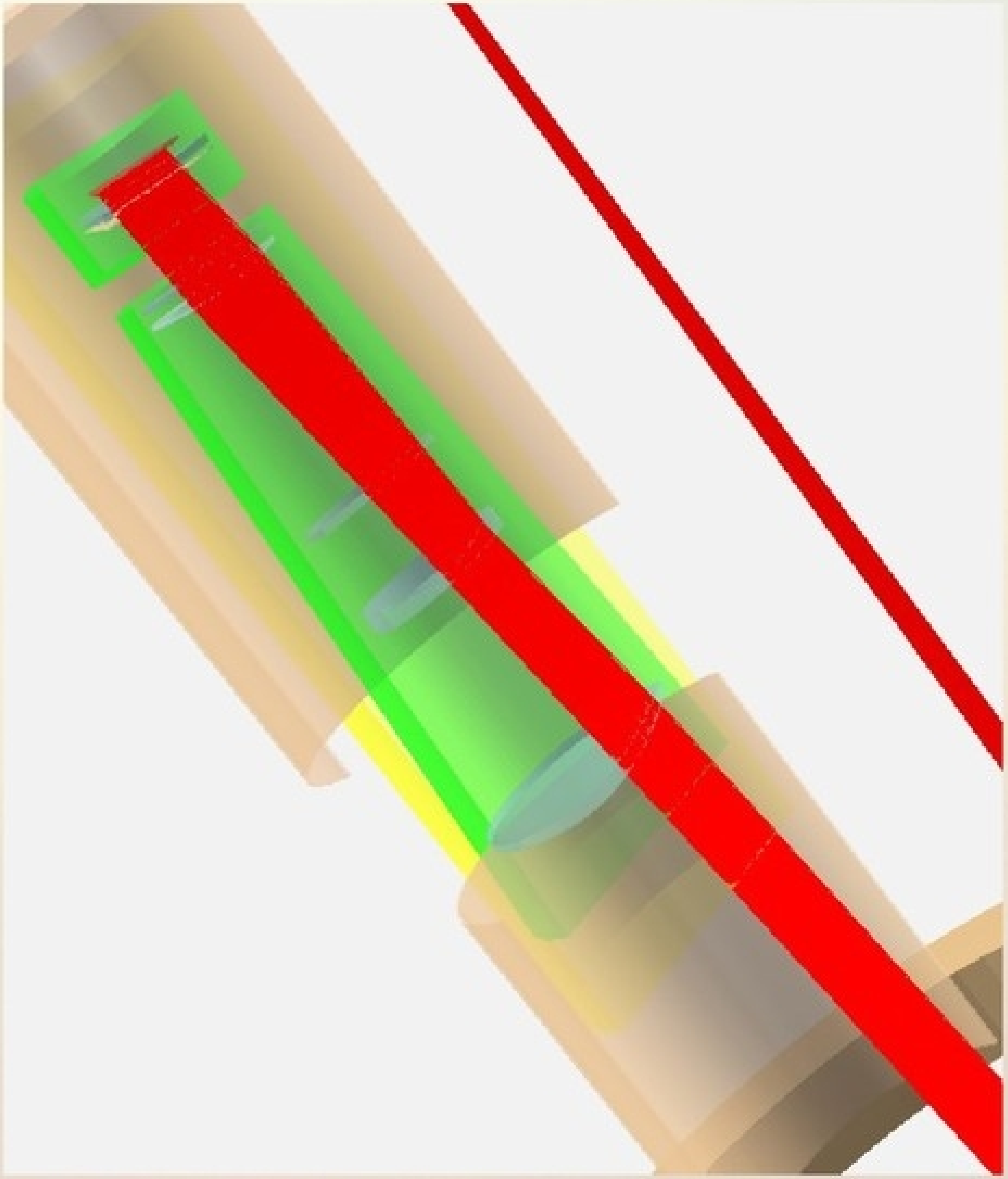


MegaPrime+MegaCam optics: 7+CCDs

Need for a SnDICE ray tracing simulator to model all effects

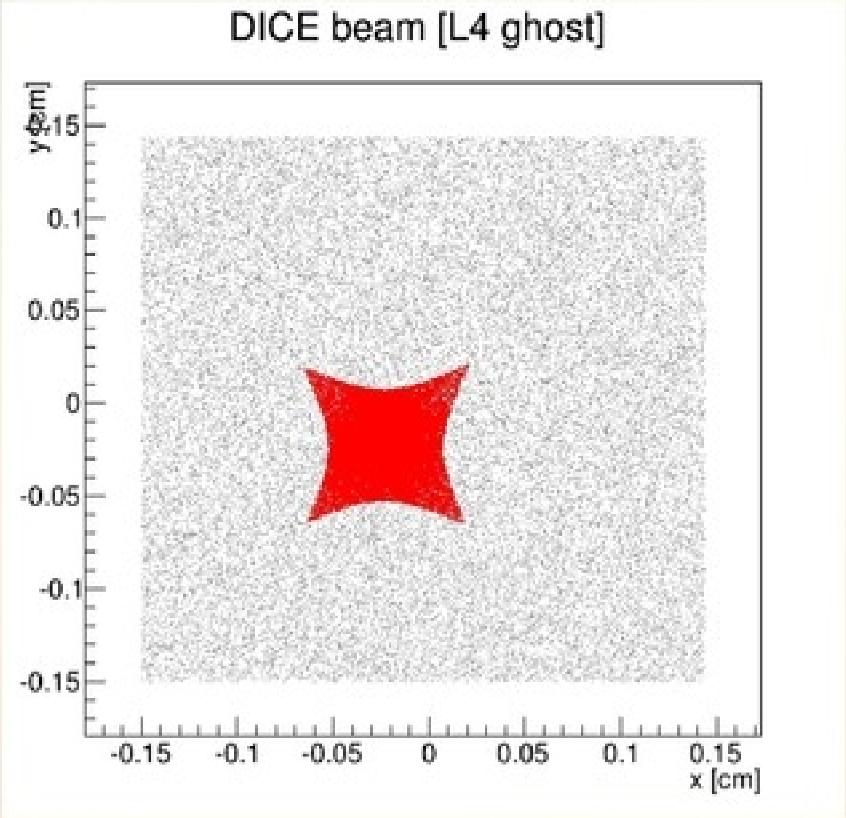


SnDICE beam for one telescope position



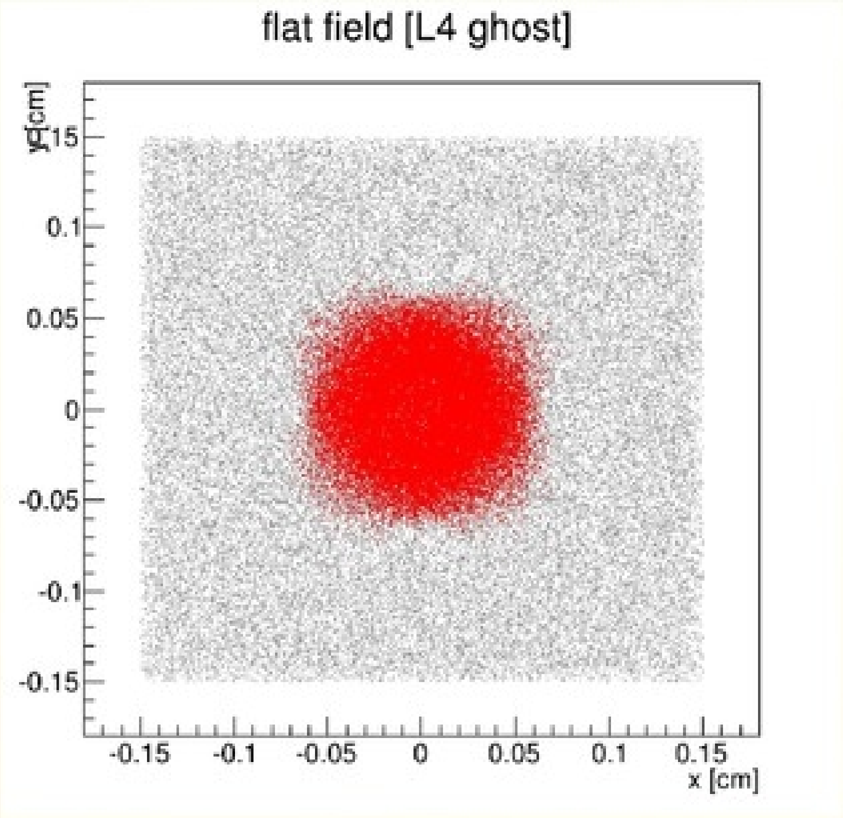
Optics geometry (tilt, distance) + reflectivity

SnDICE flat−field signature simulator : tracing known features

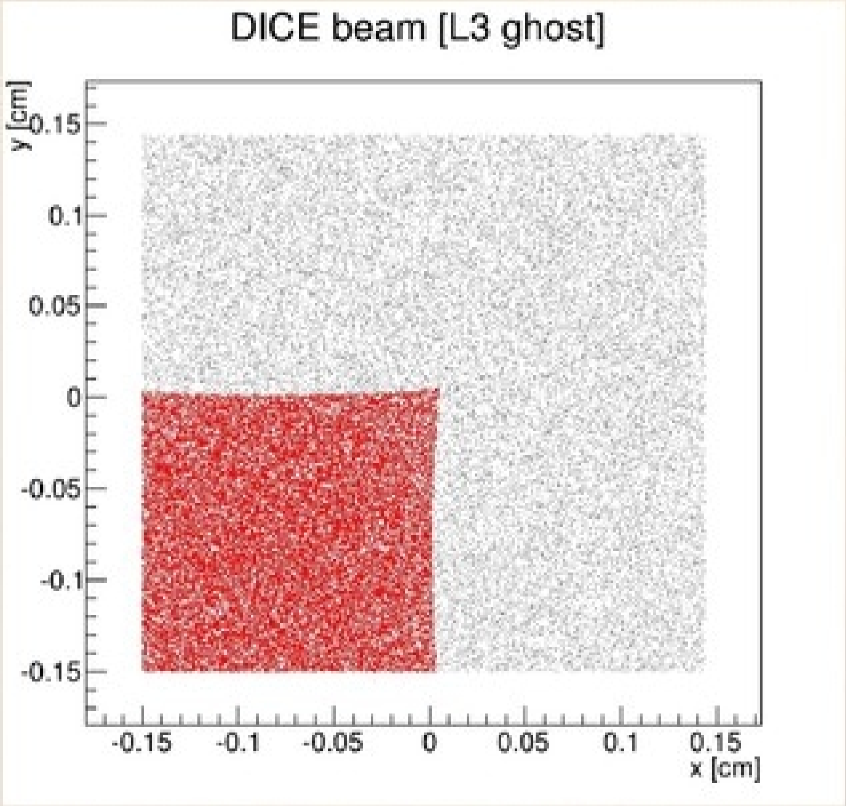


SnDICE L4 beam @ 1 telescope position

Sum over the whole mirror

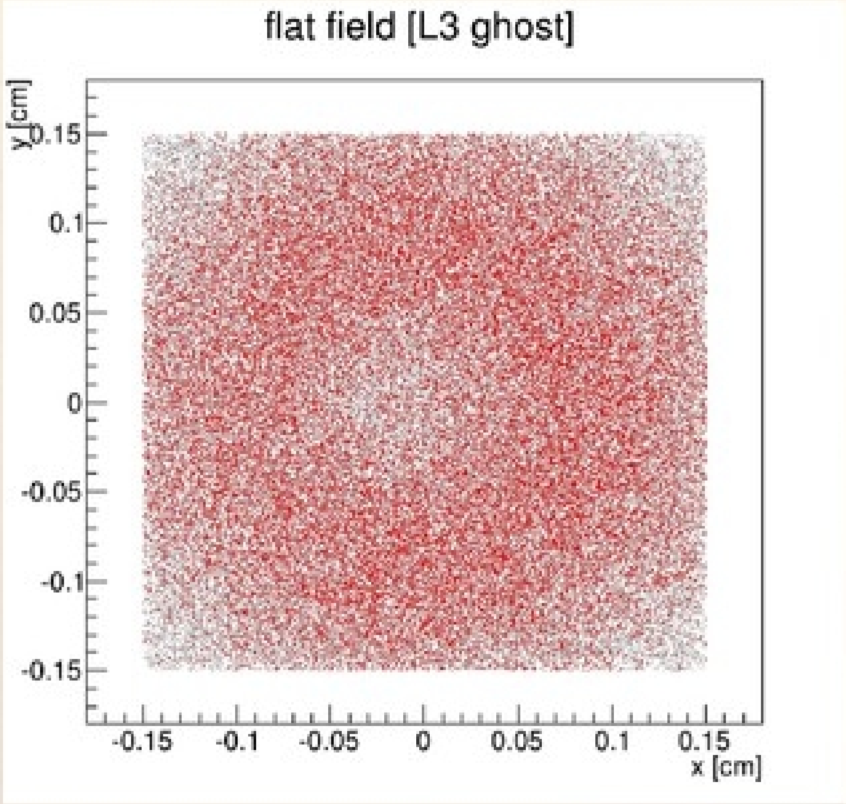


L4 signature in the flat−field



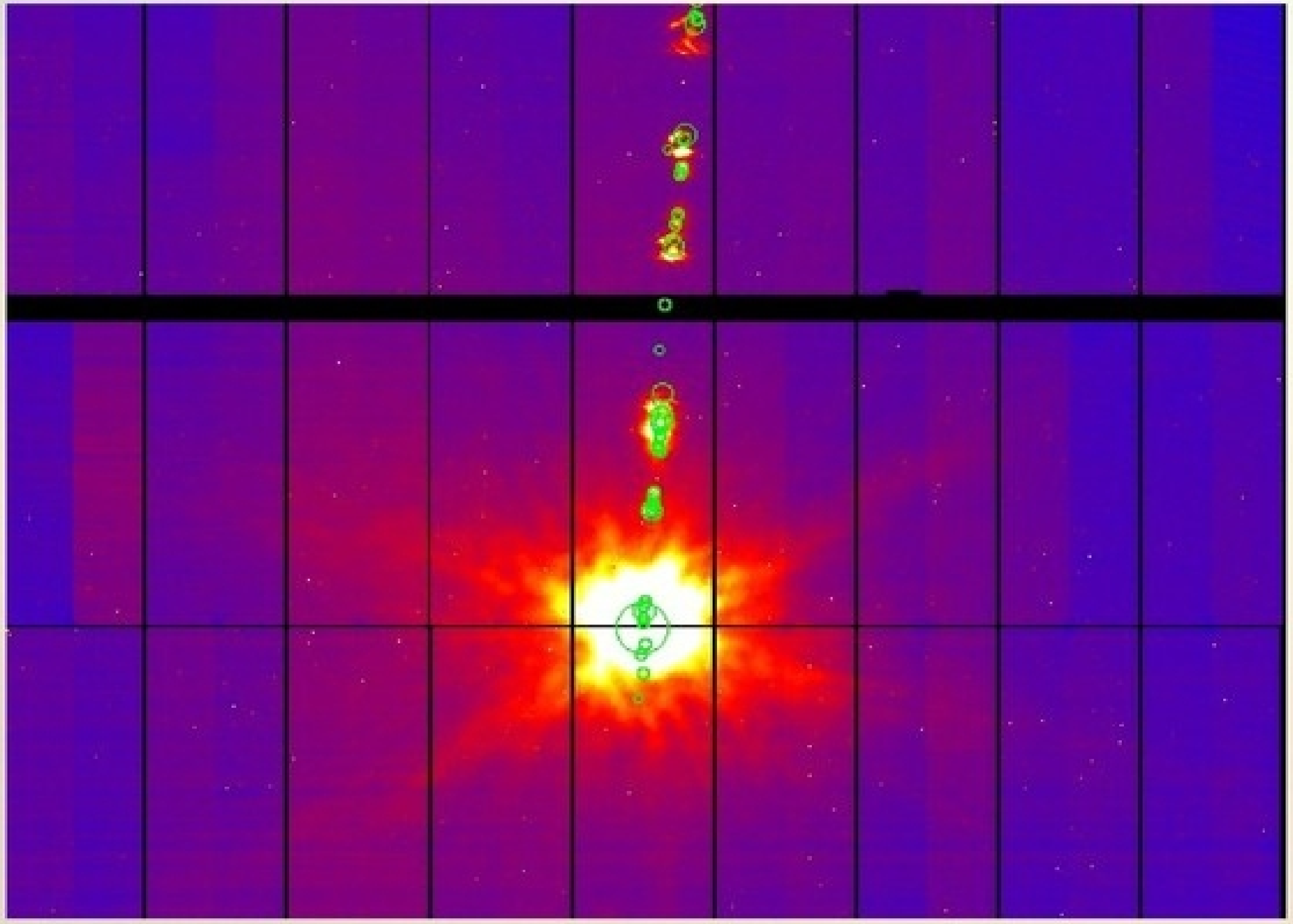
SnDICE L3 beam @ 1 telescope position

Sum over the whole mirror

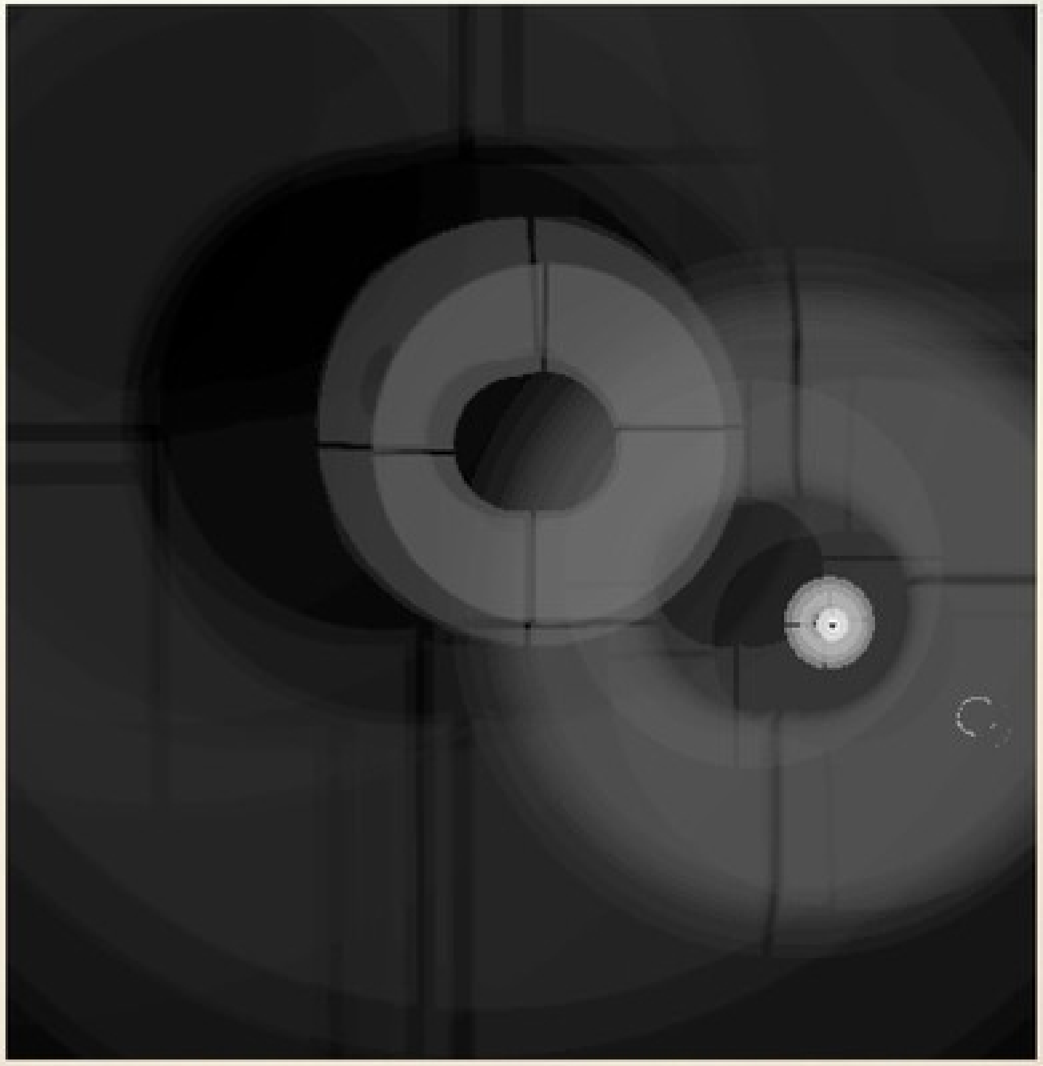


L3 signature in the flat−field

SnDICE pointing model validation : alignement exposures



SnDICE star MegaCam data @ 1 telescope position

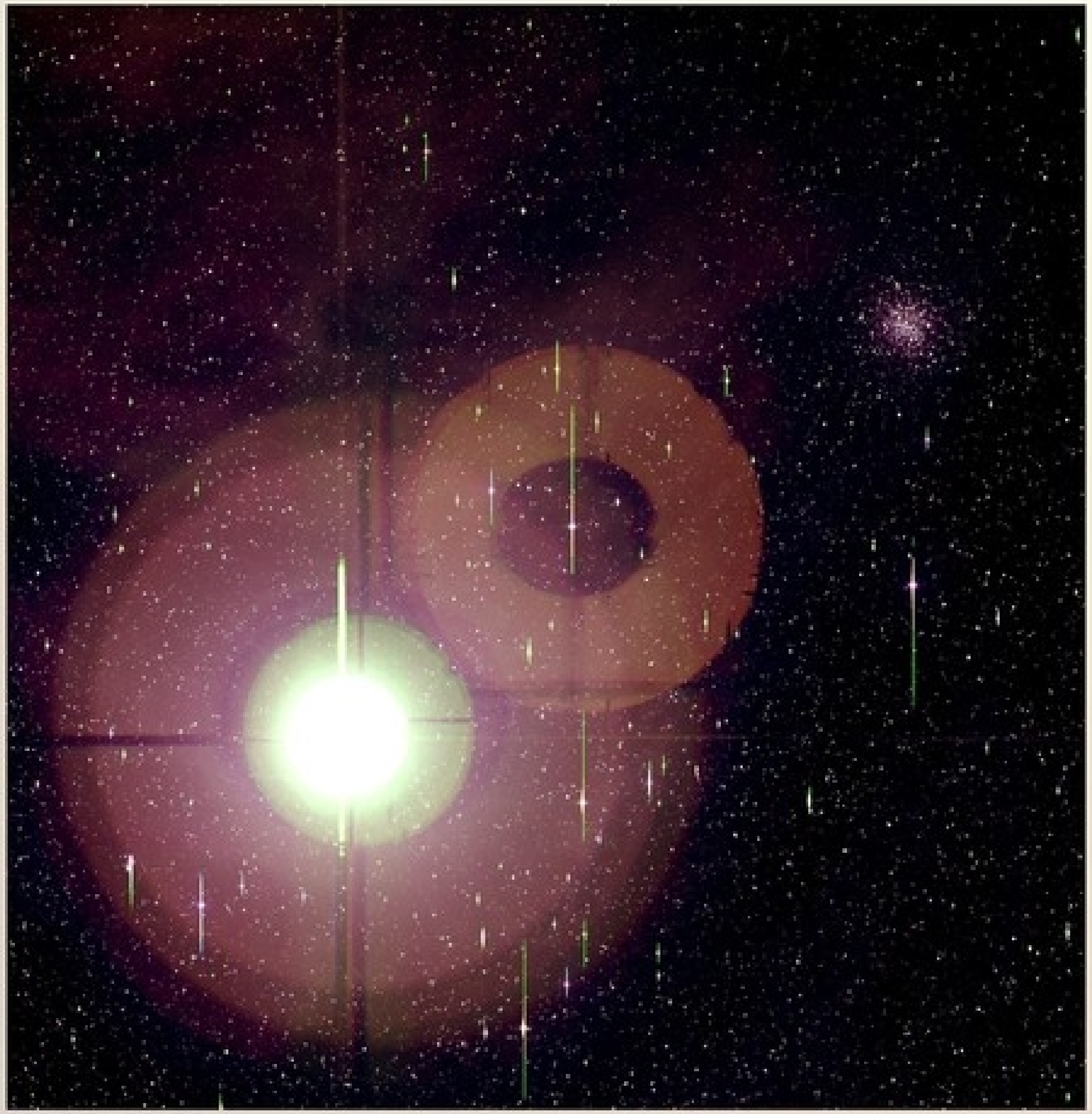


SnDICE simulator over the full mirror
[this shows the entire MegaCam FOV]

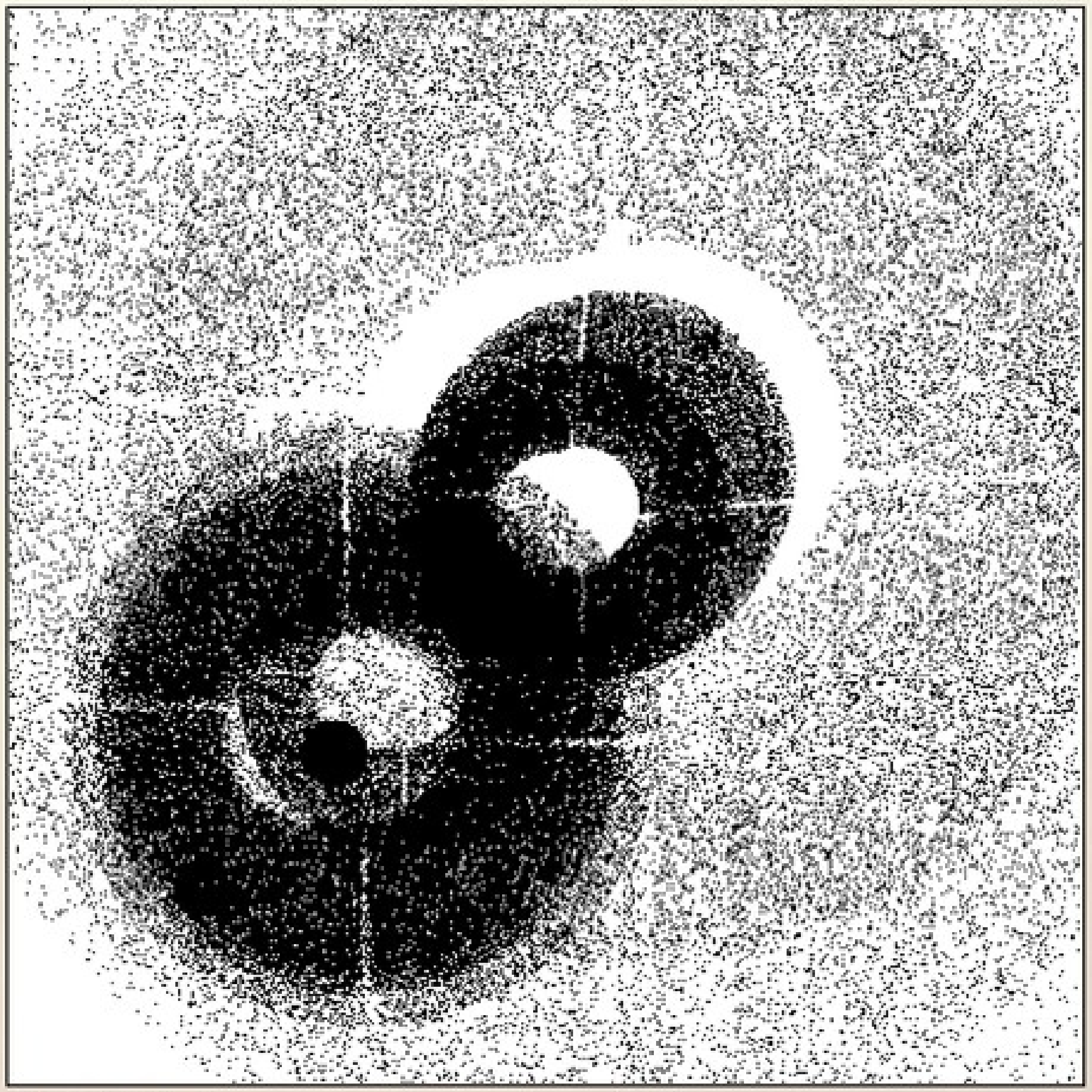
The SnDICE star ghosts contain needed information on optics geometry (distances, tilts)

The SnDICE simulator naturally becomes a star reflections simulator of interest to Elixir−LSB

SnDICE star reflections simulator vs real data : Antares

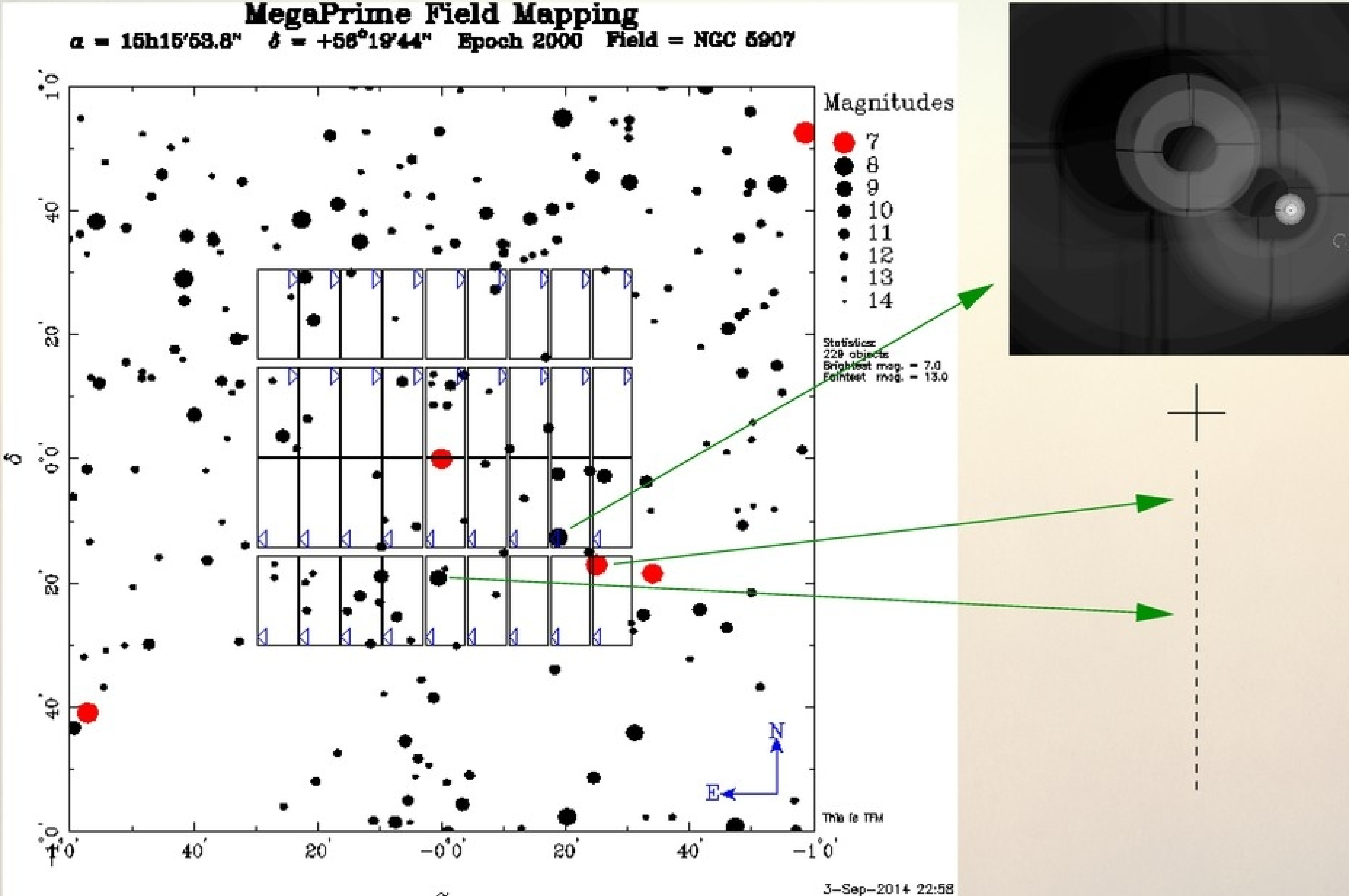


MegaCam ugr image (NGC 6144 field)



SnDICE ray tracing simulation

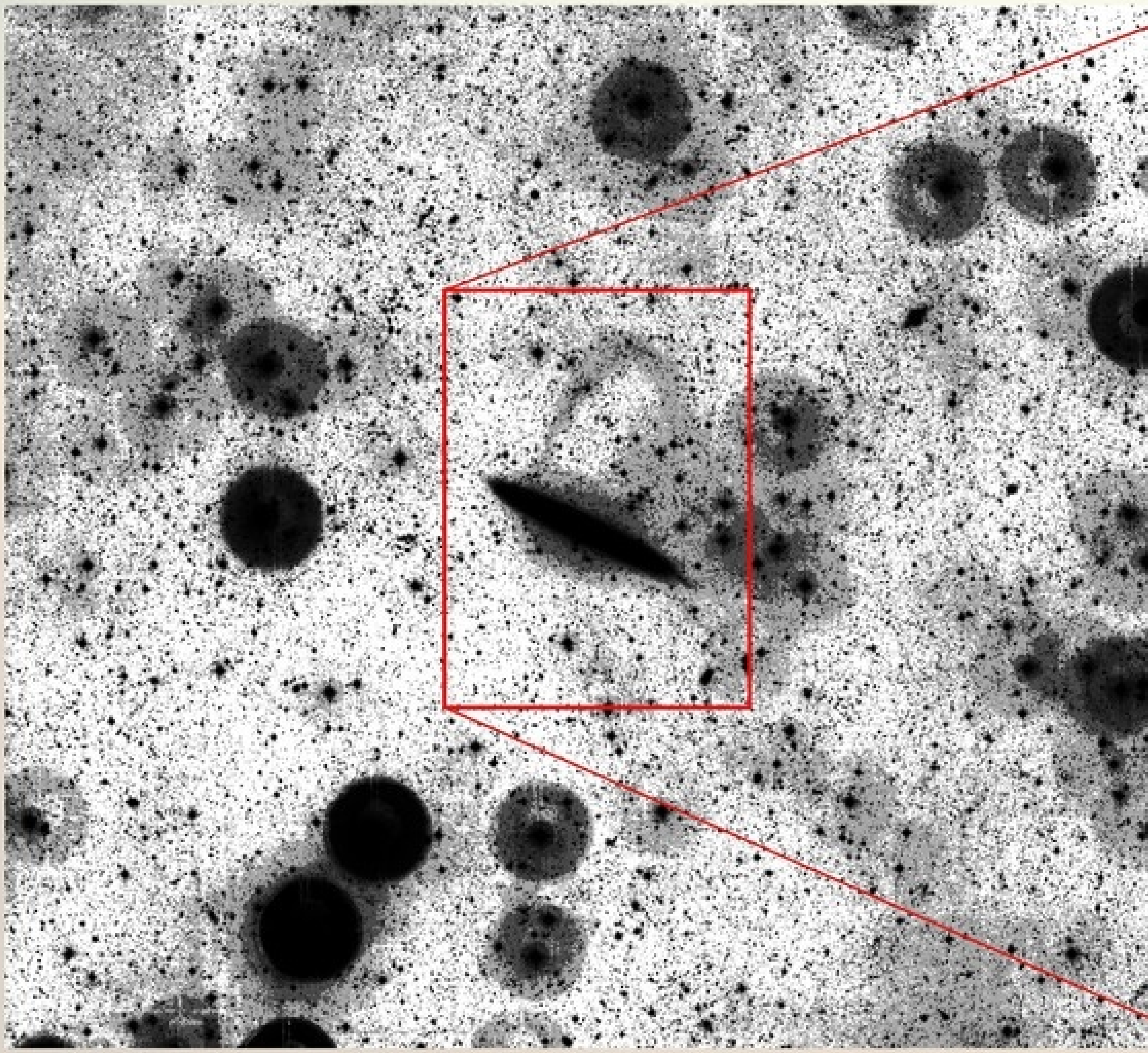
Understanding Elixir−LSB limitation : "reflection background"



Integration of the reflections for all stars in the MegaCam FOV

Can the 7 magnitude limit below sky background be broken?

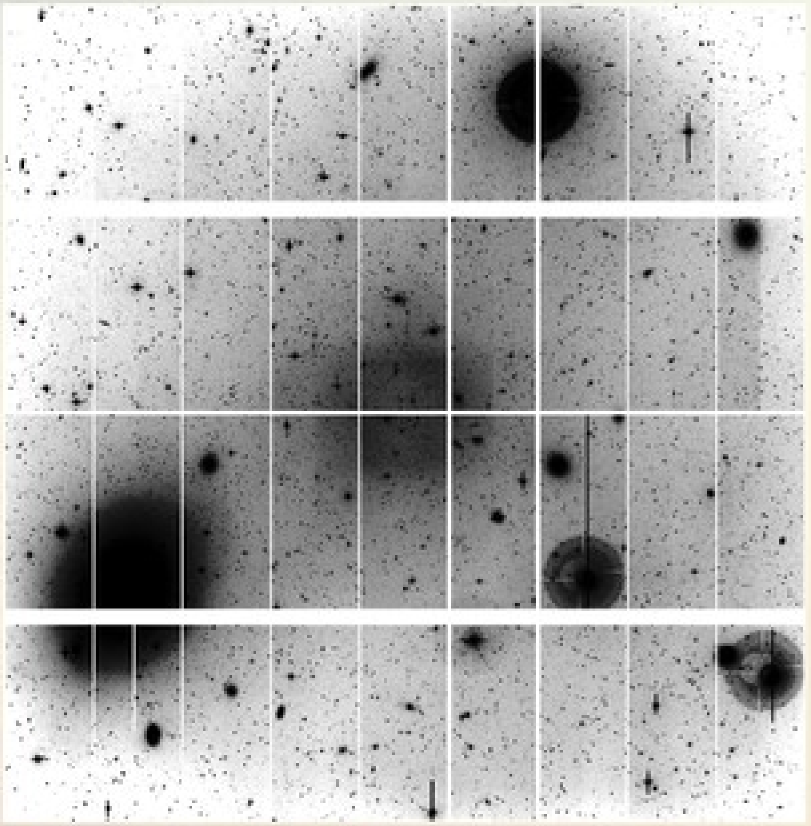
Pushing Elixir−LSB into a new regime: +1 magnitude, more?



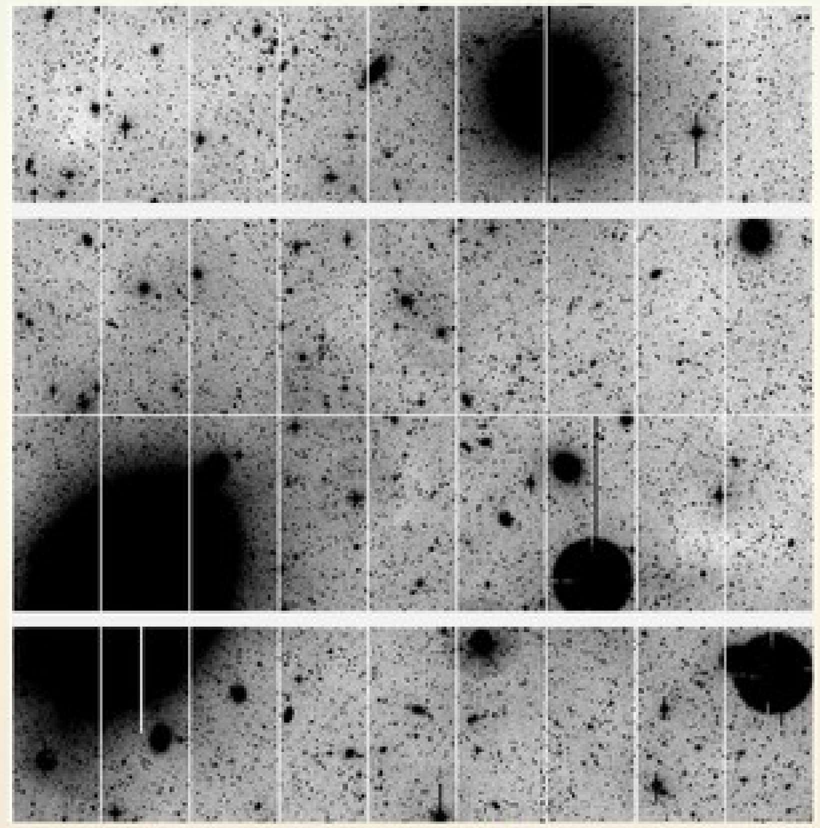
NGC 5907 Elixir−LSB: 3h integration in the r−band

NGC 5907 (Martínez−Delgado et al.)

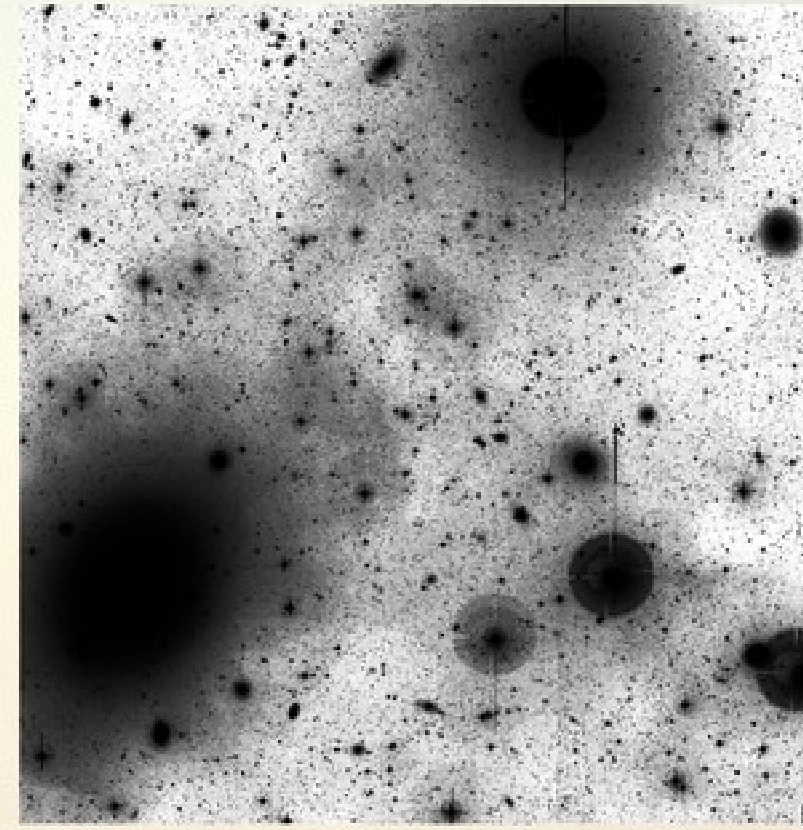
Planned approach for halo correction between Elixir&Elixir−LSB



Elixir frame

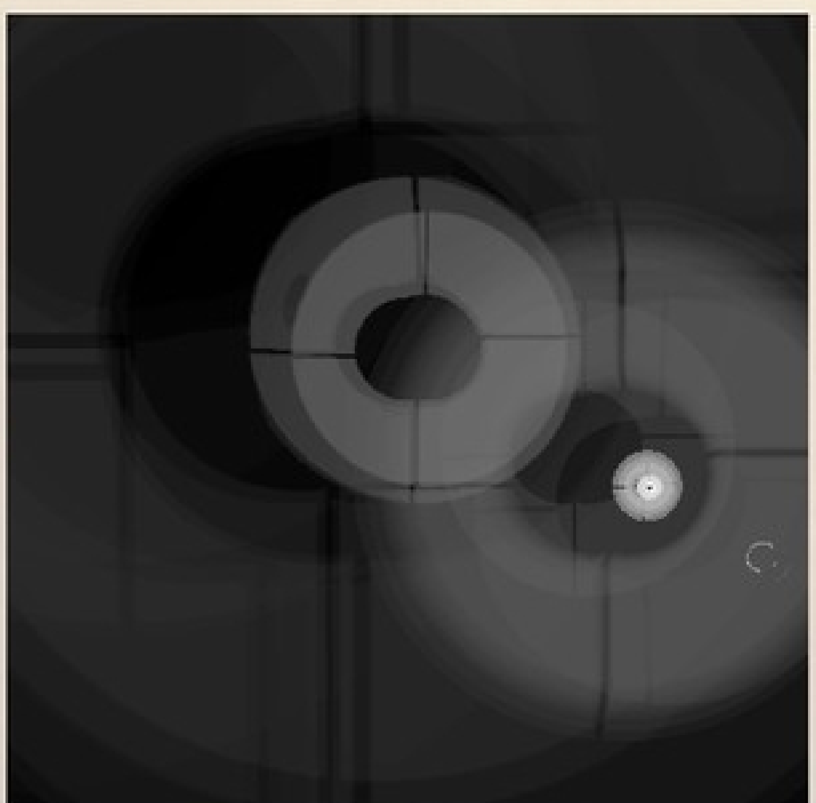


Elixir−LSB frame



Elixir−LSB stack

Halo map



Halo map correction

Bright stars: PS1 3Pi catalog + NGVS mapping