Syllabus

I. Basics Concepts in Observational Astronomy:

- Telescopes
- coordinate systems
- Image Quality

II. Signal and Sources of Noise

- Detectors
- Poisson statistics
- shot noise
- sky
- Read noise
- dark current

III. Observing Strategies

& Planning your observing night

IV. Basics of Data Reduction

- Bias, Flats, Darks
- What, Why, When, How long and How many

V. Data Reduction

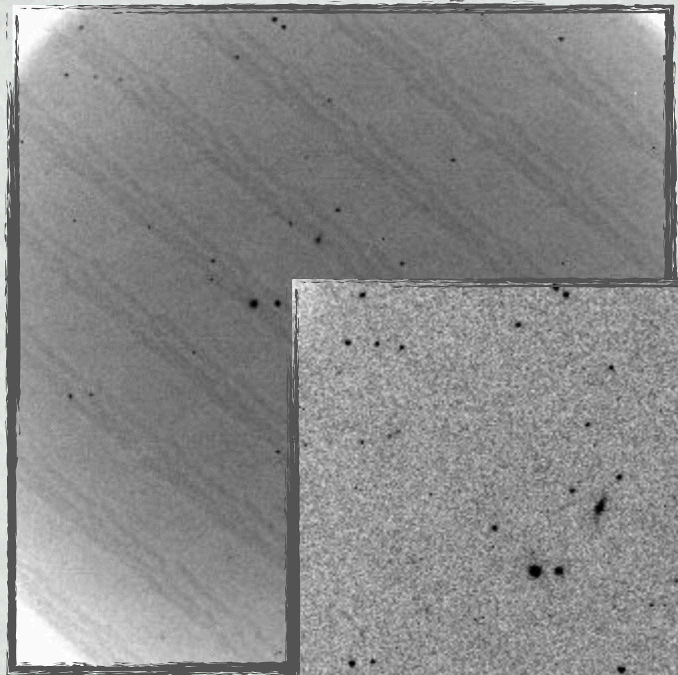
- Simple arithmetics!
- Bringing in the computer tools*
- Using basic IRAF routines or Python

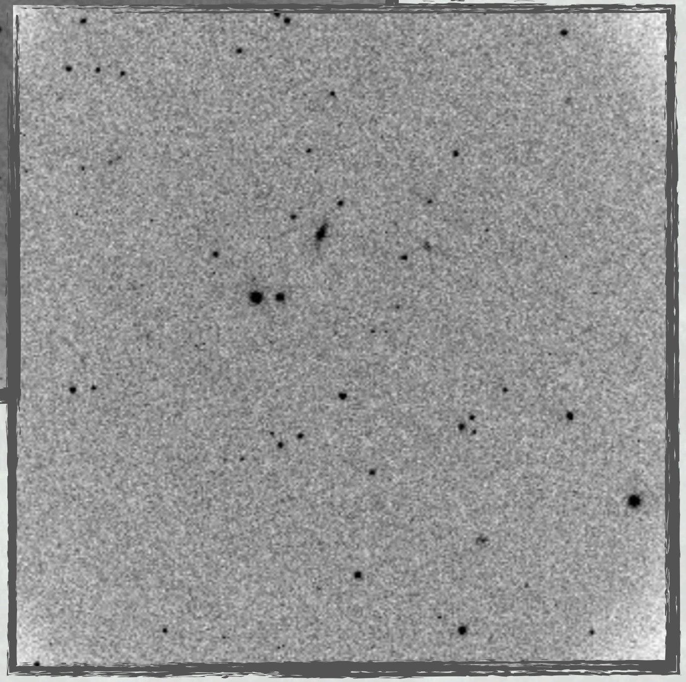
VI. Basic Aperture Photometry

Observational Astronomy & Data Reduction

Lecture 4:
Basics of Data Reduction

https://tinyurl.com/ISYA2018-ObservationalAstro





Karín Menéndez-Delmestre
Observatório do Valongo

A beautiful night at OPD

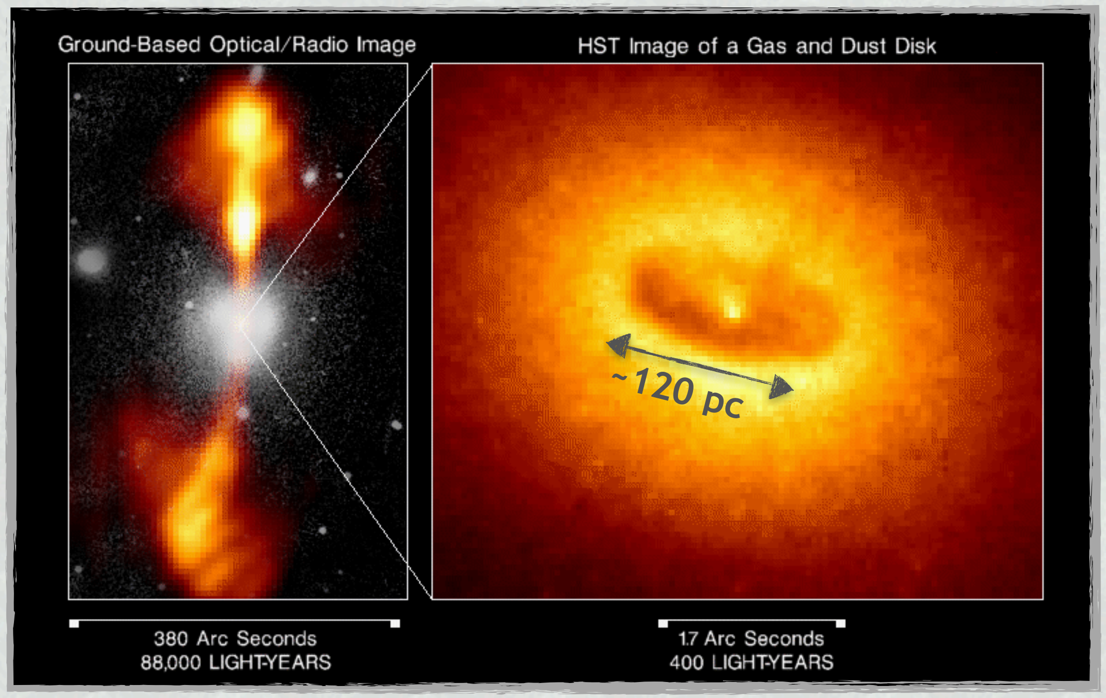
Câmera All Sky

http://lnapadrao.lna.br/videos/videos-home/camera-allsky-do-opd

Science: *Probing for variability in AGNs*

Science Background

- Dimensions of structure surrounding supermassive black holes (SMBHs) — too small to probe with direct imaging!



NGC4261

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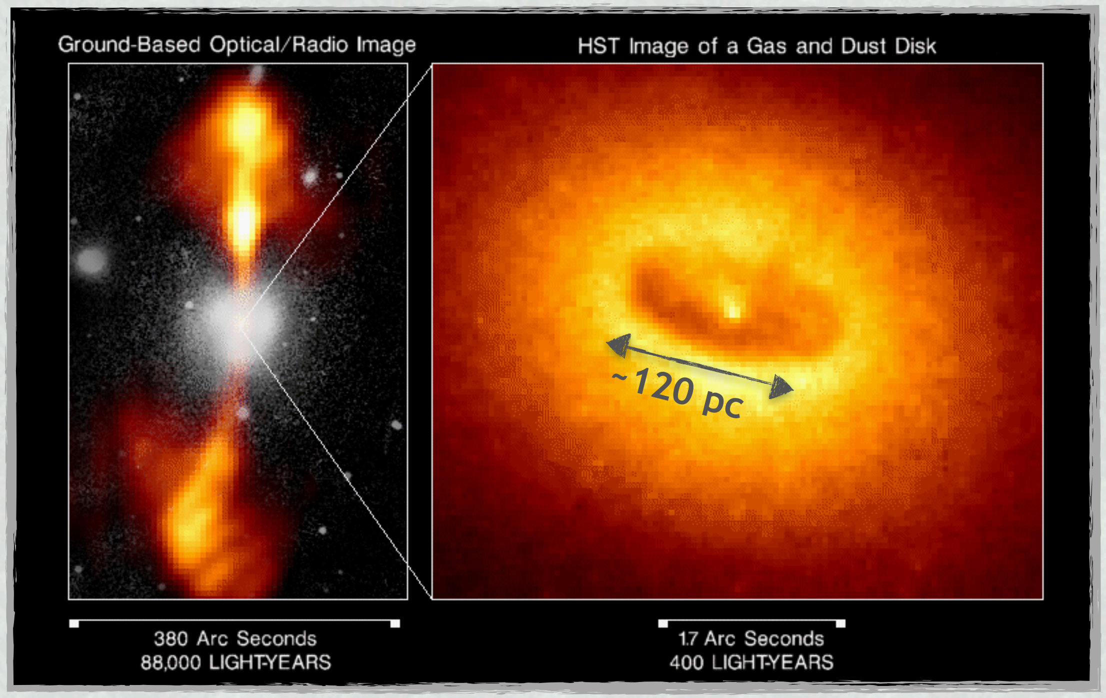
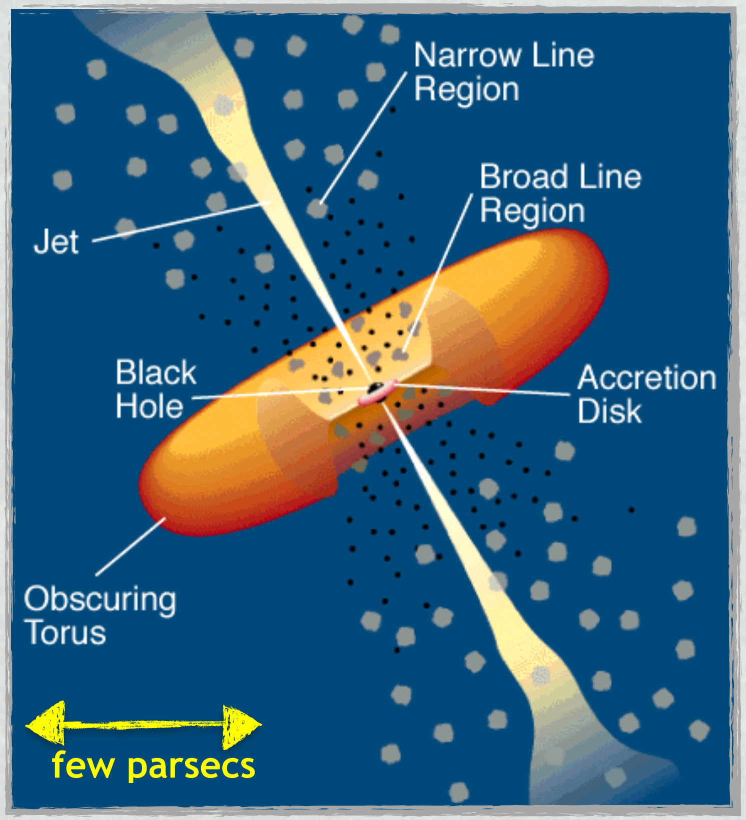


NGC4261



Urry & Padovani 1995

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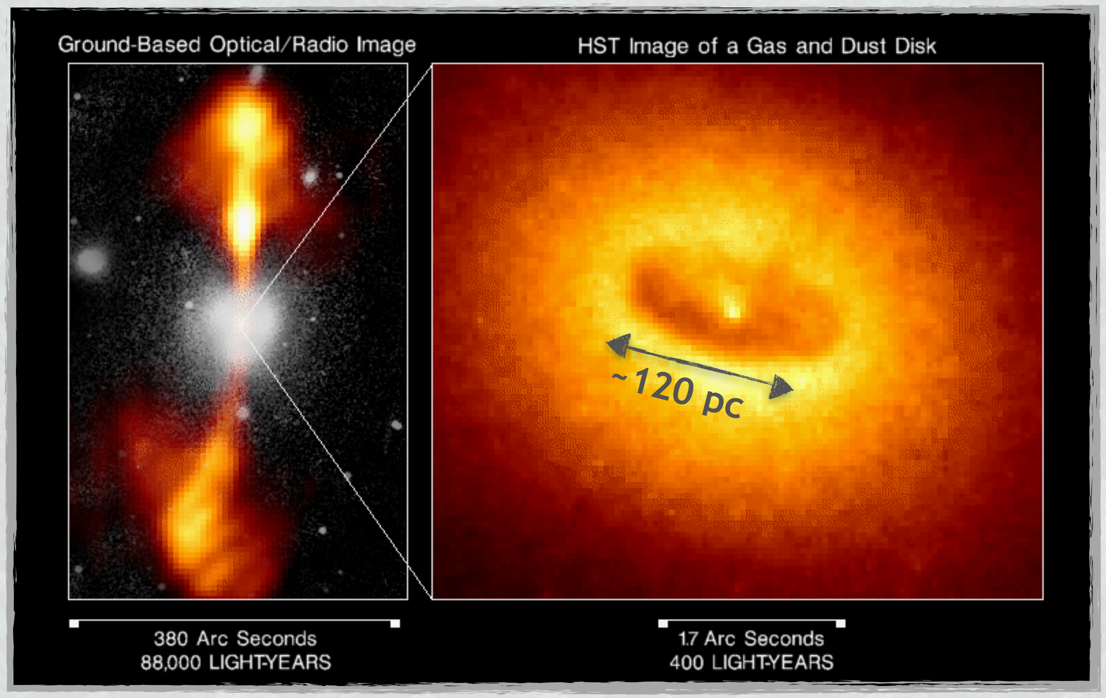
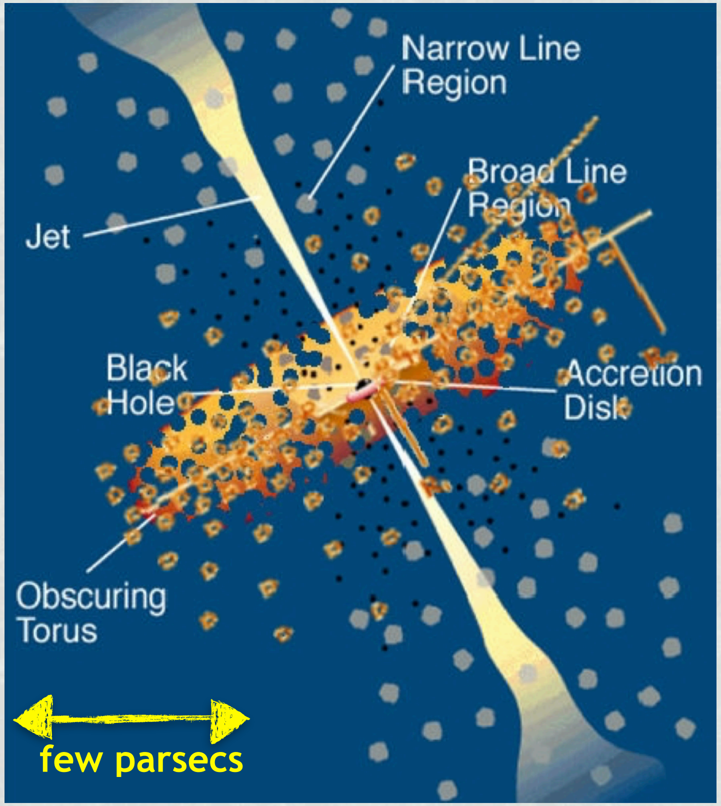


NGC4261



Urry & Padovani 1995
(adapted — taken from
Takuma Izumi's talk @ ALMA Long Baseline Workshop in Kyoto, 2017:
https://alma-intweb.mtk.nao.ac.jp/~diono/

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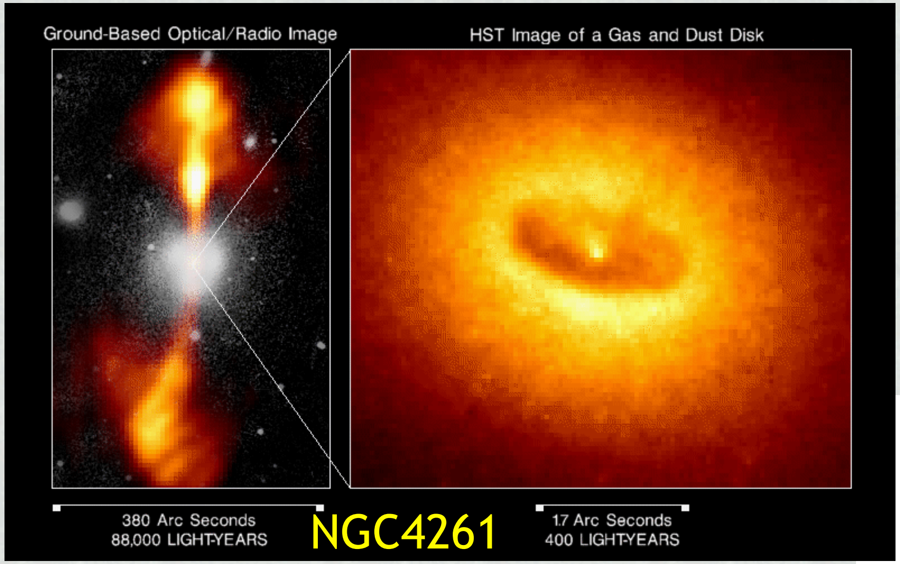
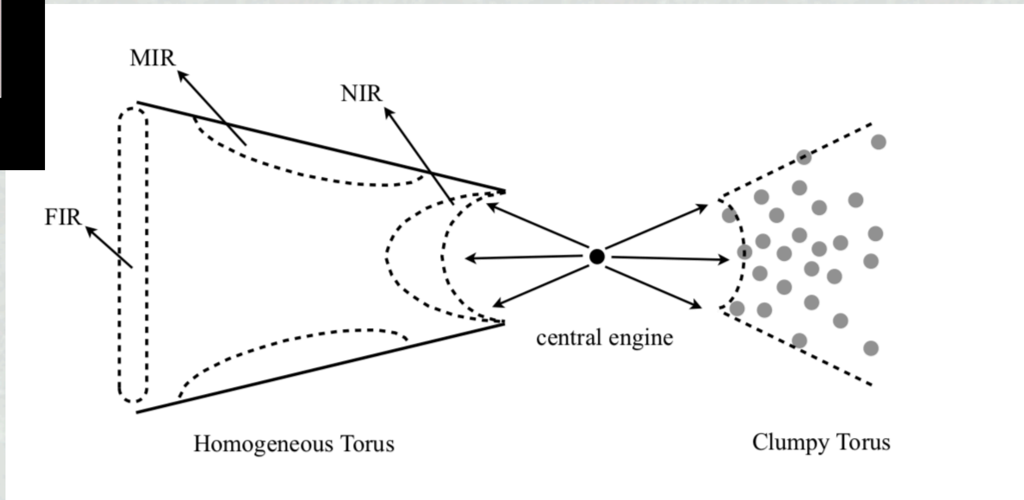


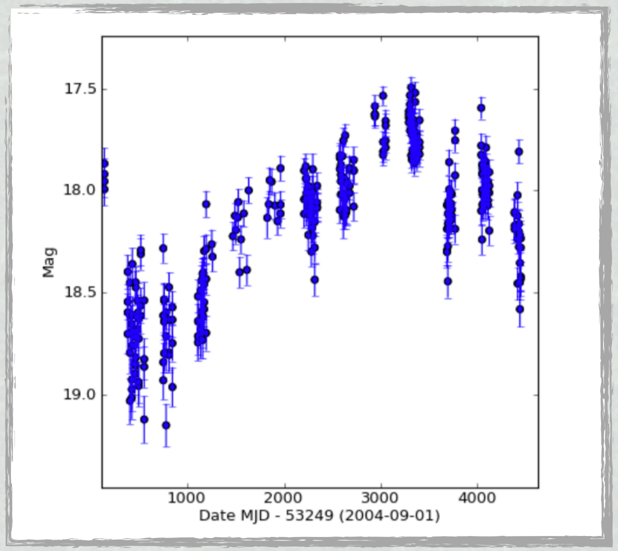


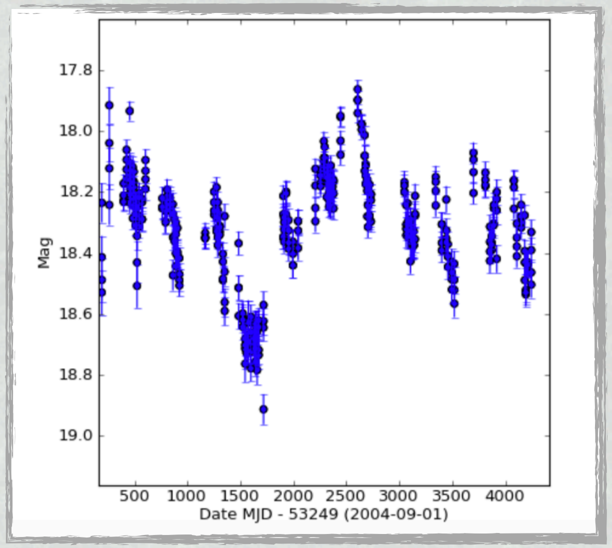
Lopez-Rodriguez+13

Science: *Probing for variability in AGNs*

Proposal

- Probe for variability in AGNs. Repeat photometry measurements for a handful of sources and (in time!) build lightcurves for individual AGNs.

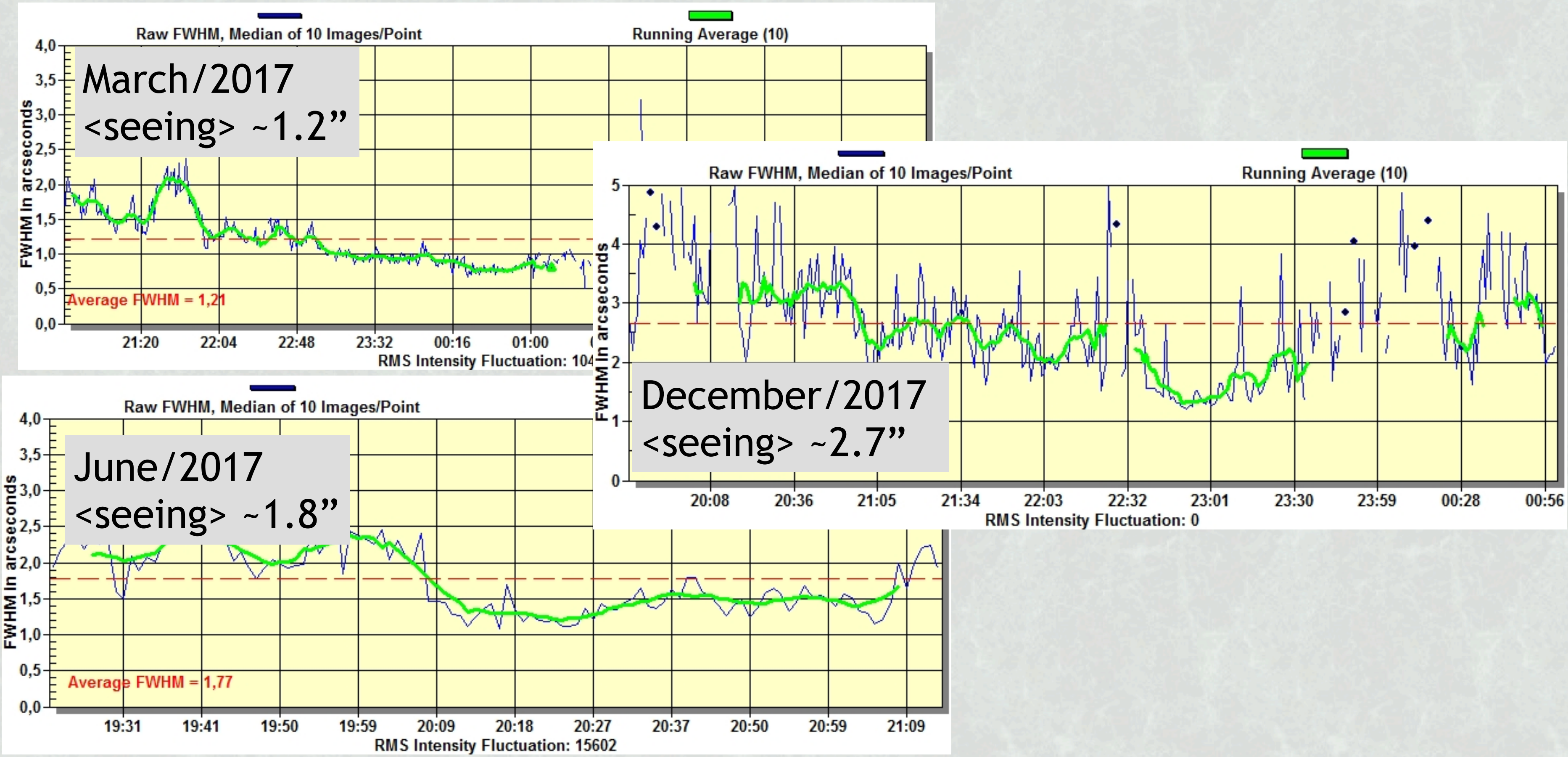




Science: *Probing for variability in AGNs*

<u>Why OPD?</u>

- To test for variability, we only need point-source photometry — no need for spatial resolution! Good compromise between student training at OPD and science return.



Science: *Probing for variability in AGNs*

Sample

- For starters, we need to test the adequacy of OPD for this kind of science. Hence, going after known micro-variable AGNs (Romero+99) as well as non-variable AGNs to have a control sample.

Table 1. Observed AGNs

Object	$\alpha_{1950.0}$	$\delta_{1950.0}$	z	m_V	Type
0537 − 441	05 37 21.1	−44 06 45.0	0.894	16.48	RBL
0637 − 752	06 37 23.25	−75 13 38.2	0.651	15.75	RLQ
1034 − 293	10 34 55.9	−29 18 27.0	0.312	16.46	RLQ
1101 − 232	11 01 11.1	−23 13 20.0	0.186	16.55	XBL
1120 − 272	11 20 34.2	−27 13 35.0	0.389	16.80	RQQ
1125 − 305	11 25 04.0	−30 28 14.0	0.673	16.30	RQQ
1127 − 145	11 27 35.6	−14 32 54.0	1.187	16.90	RLQ
1144 − 379	11 44 30.9	−37 55 31.0	1.048	16.20	RBL
1157 − 299	11 57 10.0	−29 55 10.0	0.207	16.40	RQQ
1244 − 255	12 44 06.7	−25 31 25.0	0.638	17.41	RLQ
1256 − 229	12 56 27.6	−22 54 28.0	?	17.30	RBL
1349 − 439	13 49 52.5	−43 57 55.0	?	16.37	RBL
1510 − 089	15 10 08.9	−08 54 48.0	0.360	16.54	RLQ
1519 − 273	15 19 37.3	−27 19 30.0	?	17.70	RBL
2005 − 489	20 05 46.6	−48 58 43.0	0.071	13.40	RBL
2155 − 304	21 55 58.3	−30 27 54.0	0.116	13.09	XBL
2200 − 181	22 00 27.0	−18 16 14.0	1.160	15.30	RQQ
2254 − 204	22 54 00.5	−20 27 43.0	?	16.60	RBL
2316 − 423	23 16 20.9	−42 23 14.0	0.055	16.00	XBL
2340 − 469	23 40 34.2	−46 56 42.0	1.970	16.40	RQQ
2341 − 444	23 41 08.2	−44 23 58.0	1.900	16.50	RQQ
2344 − 465	23 44 02.3	−46 29 10.0	1.890	16.40	RQQ
2347 − 437	23 47 57.5	−43 42 31.0	2.900	16.30	RQQ

Read-out noise — no way to escape it!

- A consequence of how CCDs are read:
  - Electrons are moved around —> creates a current —> adds an additional noise to the signal
  - The read-out noise depends on the CCD; it's characteristic of the chip

- Within an aperture of radius *r*, the read-out noise will be:

$$\sigma_{\mathrm{RN}} = \sqrt{\pi r^2\,\mathrm{RN}^2} = \sqrt{n_{\mathrm{pix}}\,\mathrm{RN}^2}$$

where RN^2 = quantity of electrons read per read-out, per pixel

  - For *n exposures*:

$$\sigma_{\mathrm{RN}} = \sqrt{n_{\mathrm{exp}} \times n_{\mathrm{pix}}\,\mathrm{RN}^2}$$

→ **S/N decreases by $\sqrt{n_{\mathrm{exp}}}$**

Read-out noise — no way to escape it!

- In certain cases, it may be a good idea to minimize the read-out noise by **binning pixels at the time when the image is generated**
  - i.e., redefine a grid of "coarser" pixels:
    - 2×2 pixels in original grid → 1 pixel on the new grid
- **Pros:**
  - Read-out noise is reduced
  - Faster read-out! —> we gain time during the observations —> more time for science!
- **Cons:**
  - Spatial resolution may be reduced (depending on what the size of the pixel is compared to the PSF… more on this later!)

—> Need to balance these pros and cons

Read-out noise — strategy to get rid of it

- The value of RN may be estimated based on an extremely short dark exposure — a zero-exposure image = *bias frame*
  - CCD is read without being exposed to any light
  - The result shows the electronic noise of the camera, the noise generated when any image is produced.

- It's important to consider that the **read-out noise varies from pixel to pixel and from read-out to read-out.**
  - hence, a set of bias frames is necessary to create a "master" bias (from median-combining all individual bias frames) representative of the read-out noise

- The **"master bias" frame is thus subtracted from ALL images taken through the night** (as well as calibration images taken in the afternoon) to effectively remove the read-out noise.

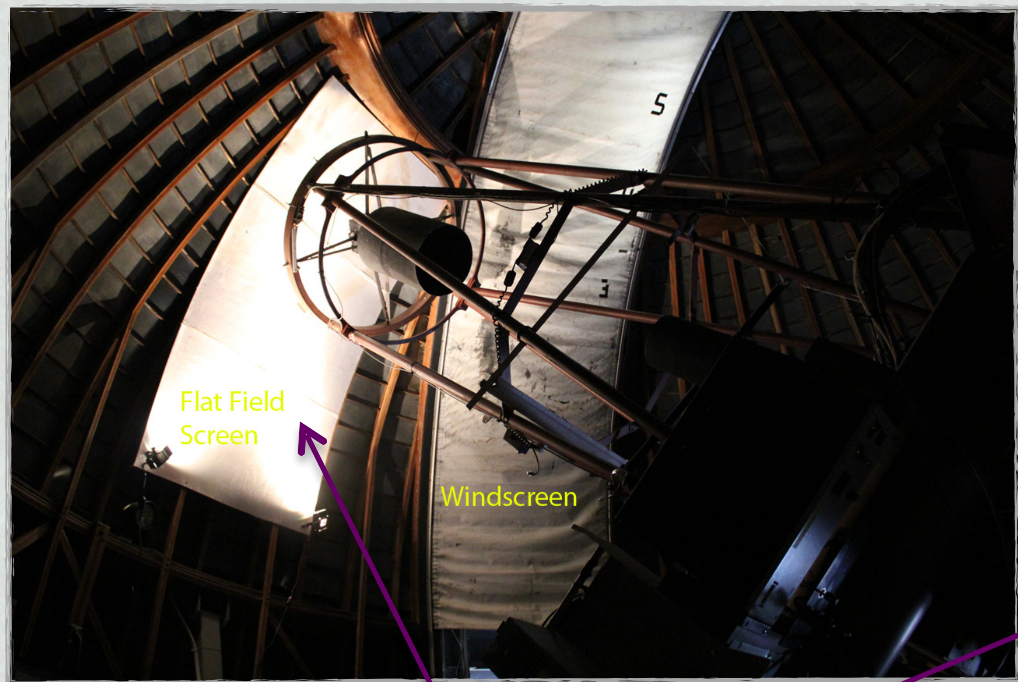
Flat field – CCDs are not homogeneously sensitive

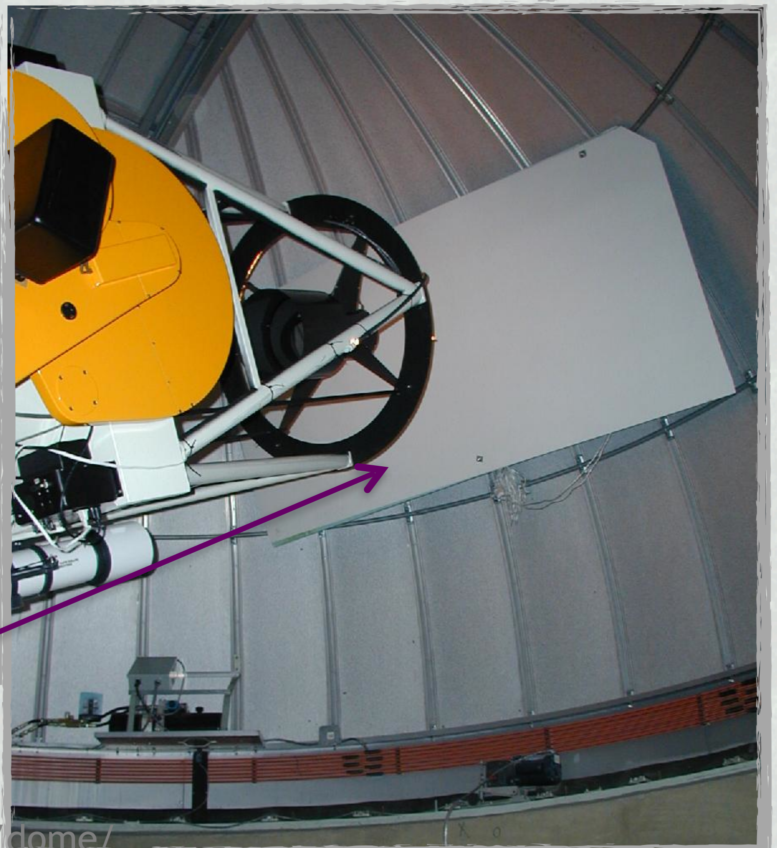
- Some errors may be introduced due to the **non-homogeneity in pixel sensitivity**
  - The pixel-to-pixel response in a CCD may vary
    - Each pixel may have a slightly different response
    - Difficult to measure precisely!
  - This can negatively affect your results

- Flat-fields = reference images to correct for this effect
  - Need to be made with the same filters used for the science images

Flat field – different ways of obtaining them

- There are many "types" of flat-fields that can be taken as part of an observing program:
  - "**dome flats**": obtained by exposing the CCD to a blank screen (within the dome) uniformly illuminated by a lamp





Screen for "dome flat field"

http://mthamilton.ucolick.org/techdocs/telescopes/Nickel/dome/

http://www.jca.umbc.edu/telescope/UsersGuides/TakingFlats.html

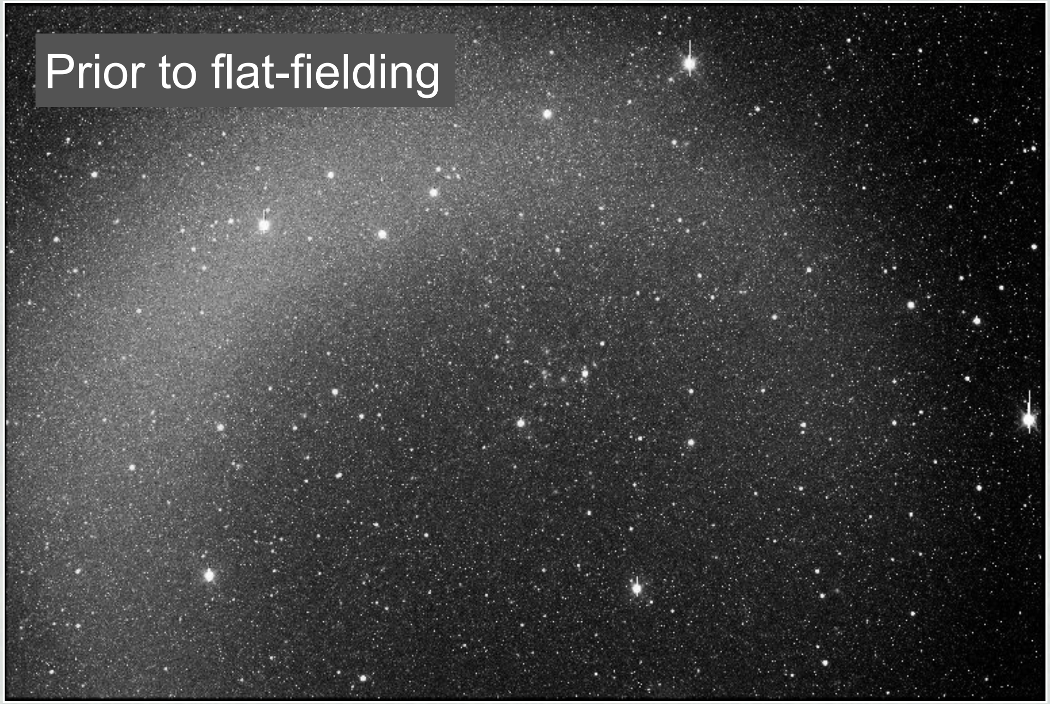
Flat field – different ways of obtaining them

- There are many “types” of flat-fields that can be taken as part of an observing program:
  - “dome flats”
  - “**twighlight flats**”: pointing to the sky immediately after the sunset (or just before the Sun rises, at the end of the night), during twighlight
    - The sky is still too bright for stars to appear, so it presents a nice naturally-illuminated wide screen!
    - Particularly useful when using blue filters, since quartz lamps for dome flats are rather red

Flat field — different ways of obtaining them

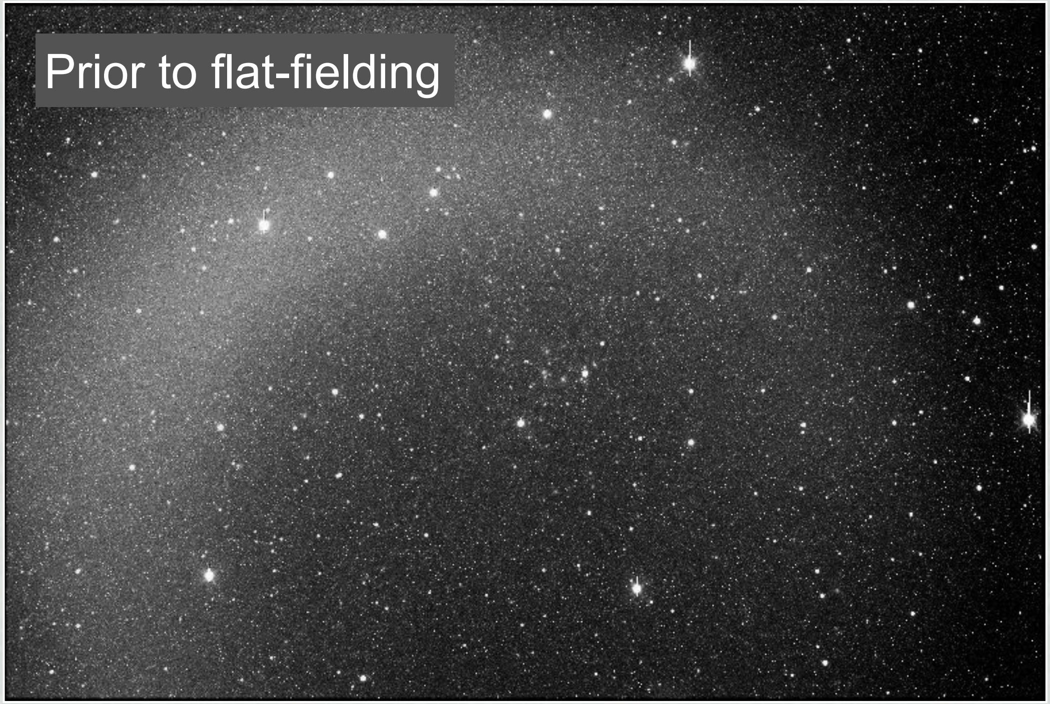
- There are many "types" of flat-fields that can be taken as part of an observing program:
  - "dome flats"
  - "twighlight flats"
  - "**sky flats**":
    - Created by median-combining many science images (with different pointings and few bright stars) taken with one same filter.
      - If field stars are present within individual frames, they will be removed by median-combining with other images that do not include these stars.

Flat field – subtraction

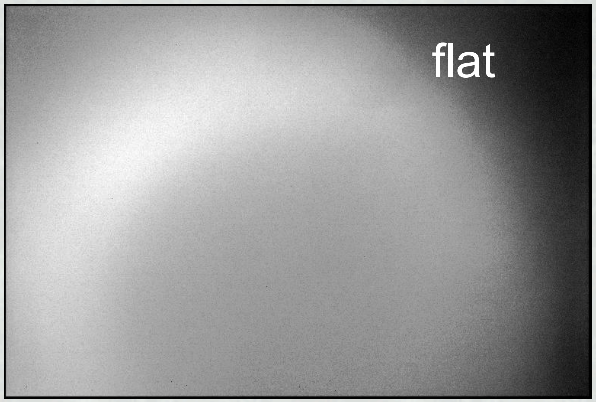


http://www.astro.uni-bonn.de/~mischa/datareduction/superflat.html

Flat field – subtraction



Similarly to other calibration images, a set of flats should be taken to create a “master” flat (for each filter).



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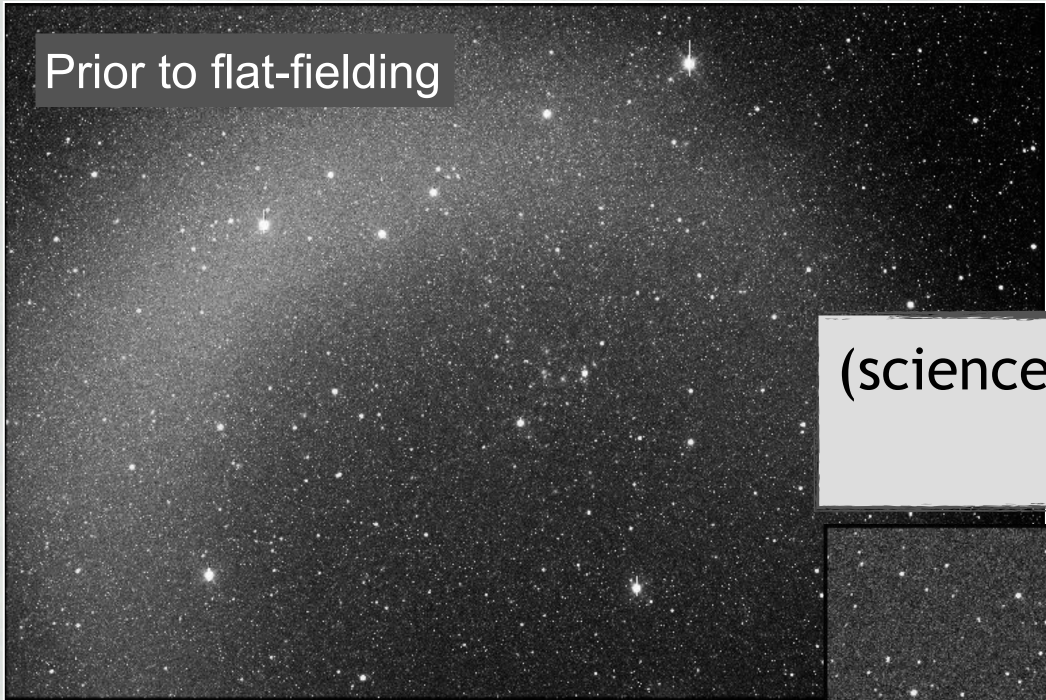
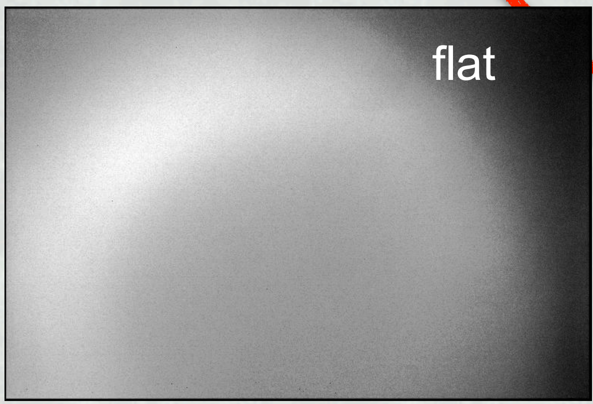
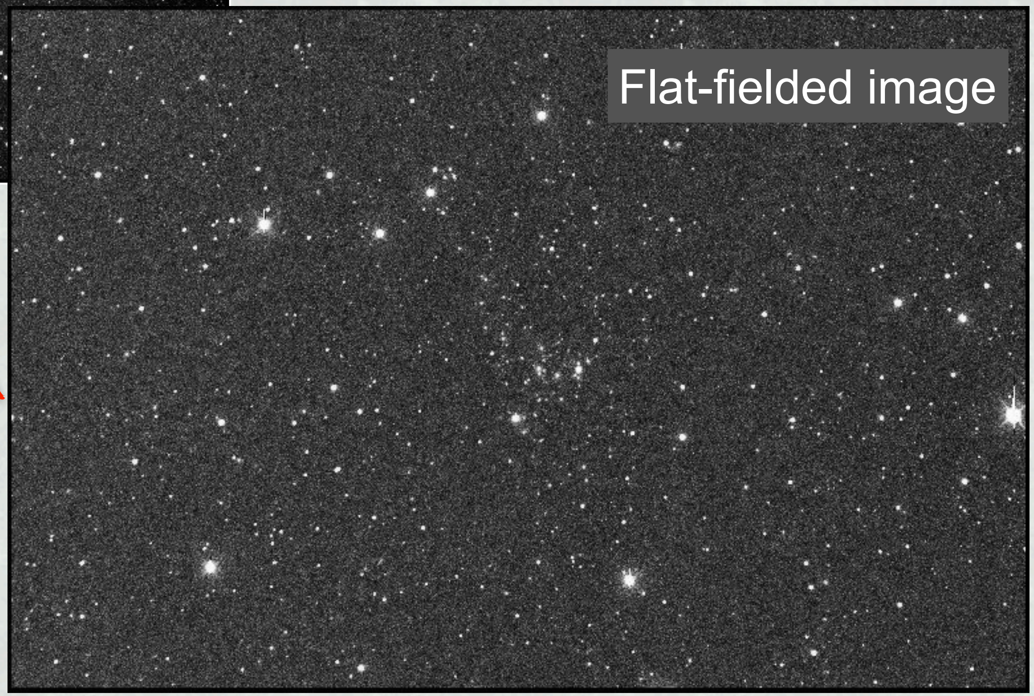
Flat field – subtraction

Similarly to other calibration images, a set of flats should be taken to create a "master" flat (for each filter).

(science frame) – ("master" flat) =
flat-fielded science frame







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Signal-to-Noise – adding different sources of noise

- Signal/Noise (S/N)
  - Where N = total of noises
- Considering the independent sources of noise:

→ $N^2 = (N_{shot})^2 + (N_{sky})^2 + (N_{read\text{-}out})^2 + (N_{dark})^2$

→ $N = \sqrt{[(\sigma_{shot})^2 + (\sigma_{sky})^2 + (\sigma_{read\text{-}out})^2 + (\sigma_{dark})^2]}$

- The resulting S/N is give by:

$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n_{pix}(N_S + N_D + N_R^2)}}$$

shot noise (Poisson)

Sky noise within target's aperture (Poisson)

Dark current

Read-out noise

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- Considering time dependence:

$$S/R = \frac{R_* t}{\left[R_* t + R_{sky} t n_{pix} + n_{pix} RN^2 + D t n_{pix}\right]^{1/2}}$$

shot noise (Poisson)

Sky noise within target's aperture (Poisson)

Read-out noise

Dark current

R* = rate of target's photons

R_{sky} = rate of sky photons

Signal-to-Noise — combining multiple exposures

- We frequently choose to combine multiple exposures (*stacking*) rather than doing one long integration.
- What's the effect in the S/N?
  - Consider ***M*** exposures, with a total exposure of:

$$T_{total} = t_{exp} \times M$$

where t_{exp} = integration time for an individual exposure

<u>For an individual exposure, the S/N is given by:</u>

$$S/R = \frac{R_* T_{\mathrm{total}} / \mathrm{M}}{\left[\frac{R_* \times T_{\mathrm{total}}}{\mathrm{M}} + \frac{R_{sky} \times T_{\mathrm{total}} \times n_{\mathrm{pix}}}{\mathrm{M}} + n_{\mathrm{pix}} RN^2 + \frac{D \times T_{\mathrm{total}} \times n_{\mathrm{pix}}}{\mathrm{M}} \right]^{1/2}}$$

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For stacking multiple images:

$$\text{Signal} = \frac{R_* T_{\text{total}}}{\text{M}} \times \text{M} = S_{\text{Exp\_Indv}} \times \text{M}$$

$$\text{Noise} = \left[\frac{R_* \times T_{\text{total}}}{\text{M}} \times \text{M} + \frac{R_{sky} \times T_{\text{total}} \times n_{\text{pix}}}{\text{M}} \times \text{M} + n_{\text{pix}} RN^2 \times \text{M} + \frac{D \times T_{\text{total}} \times n_{\text{pix}}}{\text{M}} \times \text{M} \right]^{1/2}$$

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$$R = \left[\boxed{R_* \times T_{\text{total}} + R_{sky} \times T_{\text{total}} \times n_{\text{pix}}} + n_{\text{pix}} RN^2 \times M + \boxed{D \times T_{\text{total}} \times n_{\text{pix}}} \right]^{1/2}$$

→ The contributions from the shot noise and the sky noise are the same as those for a single long exposure

Signal-to-Noise – combining multiple exposures

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$$R = \left[R_* \times T_{\text{total}} + R_{sky} \times T_{\text{total}} \times n_{\text{pix}} + n_{\text{pix}} RN^2 \times \text{M} + D \times T_{\text{total}} \times n_{\text{pix}} \right]^{1/2}$$

→ The contributions from the shot noise and the sky noise are the same as those for a single long exposure, but the contribution from the readout noise increases by a factor of M (i.e., the number of exposures)

Signal-to-Noise — Limiting cases

- If we consider the ideal case of an excellent CCD, the total noise is generally well represented by the shot noise and the sky noise:

$$\text{Noise} \approx \sqrt{[(\sigma_{\text{shot}})^2 + (\sigma_{\text{sky}})^2]}$$

- This allows us to simplify the expression for S/N:

$$S/R \approx \frac{R_* t}{\left[R_* t + R_{sky}\, t\, n_{\text{pix}} \right]^{1/2}} \approx \frac{R_*}{\left[R_* + R_{sky}\, n_{\text{pix}} \right]^{1/2}} \times t^{1/2}$$

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- Faint sources:
  – Broad band imaging is usually limited by the brightness of the sky:

$$S/R \cong \frac{R_* t}{\sqrt{n_{\text{pix}} R_{\text{sky}} t}} \propto t^{1/2}$$

- Bright sources:
  – Limited by the shot noise:

$$S/R \cong \sqrt{R_* t} \propto t^{1/2}$$

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- Faint sources:
  - Broad band imaging is usually limited by the brightness of the sky:

$$S/R \cong \frac{R_* t}{\sqrt{n_{pix} R_{sky} t}} \propto t^{1/2}$$

- Bright sources:
  - Limited by the shot noise:

$$S/R \cong \sqrt{R_* t} \propto t^{1/2}$$

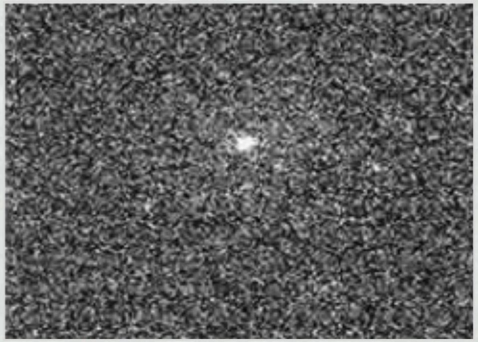
→ To increase the S/N by a factor of 2, we need to increase the observing time by 4!

$$S/R \propto t^{1/2}$$

Signal-to-Noise — Read-out dominated cases

- In the case when the read-out noise dominates, the S/N can be written as:

$$S/R \approx \frac{R_* t}{\left[n_{\mathrm{pix}} RN^2 \right]^{1/2}} \propto (n_{\mathrm{pix}} RN^2)^{-1/2}$$



M100 1s

Short exposure, dominated by read-out noise… need longer exposures!

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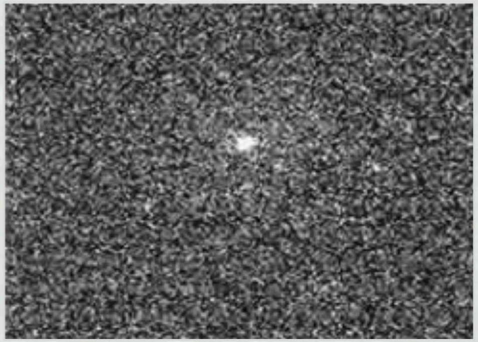


M100 1s

Short exposure, dominated by read-out noise… need longer exposures!

10s

1000s

Applications:

- Narrow-band imaging
  - Few photons within a thin λ range
  - Typical exposures can be up to ~1h
- Echelle Spectroscopy

Signal-to-Noise — Read-out dominated cases

- In the case when the read-out noise dominates, the S/N can be written as:

$$S/R \approx \frac{R_* t}{\left[n_{\rm pix} RN^2\right]^{1/2}} \propto (n_{\rm pix} RN^2)^{-1/2}$$

(1) Noise goes as $(n_{pix})^{-1/2}$

→ **Possible to alter the "binning"** and reduce the noise introduced.

- By going to a 2x2 binning, the noise is reduced by $(2\times2\text{pix})^{-1/2}$ → a gain in S/N of a factor of 2!
- Price to pay? Resolution
  - In case of imaging: spatial resolution
    - » Make sure to keep binning so that at least 2-3 "final" pixels cover the PSF
  - in case of spectroscopy: spectral resolution
    - » At least 2-3 "final" pixels across a spectral lines of interest

Signal-to-Noise — Read-out dominated cases

- In the case when the read-out noise dominates, the S/N can be written as:

$$S/R \approx \frac{R_* t}{\left[n_{\text{pix}} RN^2 \right]^{1/2}} \propto (n_{\text{pix}} RN^2)^{-1/2}$$

(2) Noise in this case is independent of time

→ Good idea to increase integration time of each individual image to minimize the number of exposures (and, hence, the read-out noise).

- Limit?

Signal-to-Noise — Read-out dominated cases

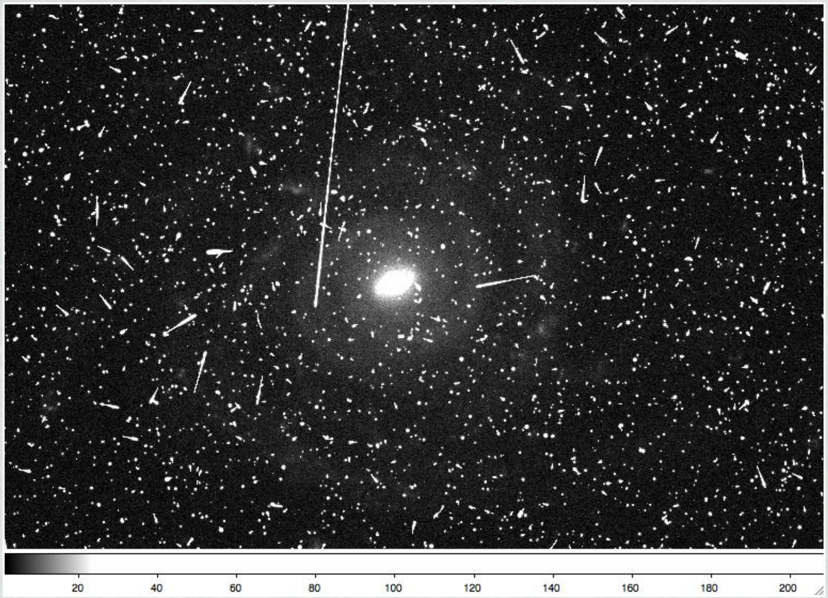
- In the case when the read-out noise dominates, the S/N can be written as:

$$S/R \approx \frac{R_* t}{\left[n_{\mathrm{pix}} RN^2 \right]^{1/2}} \propto (n_{\mathrm{pix}} RN^2)^{-1/2}$$

(2) Noise in this case is independent of time

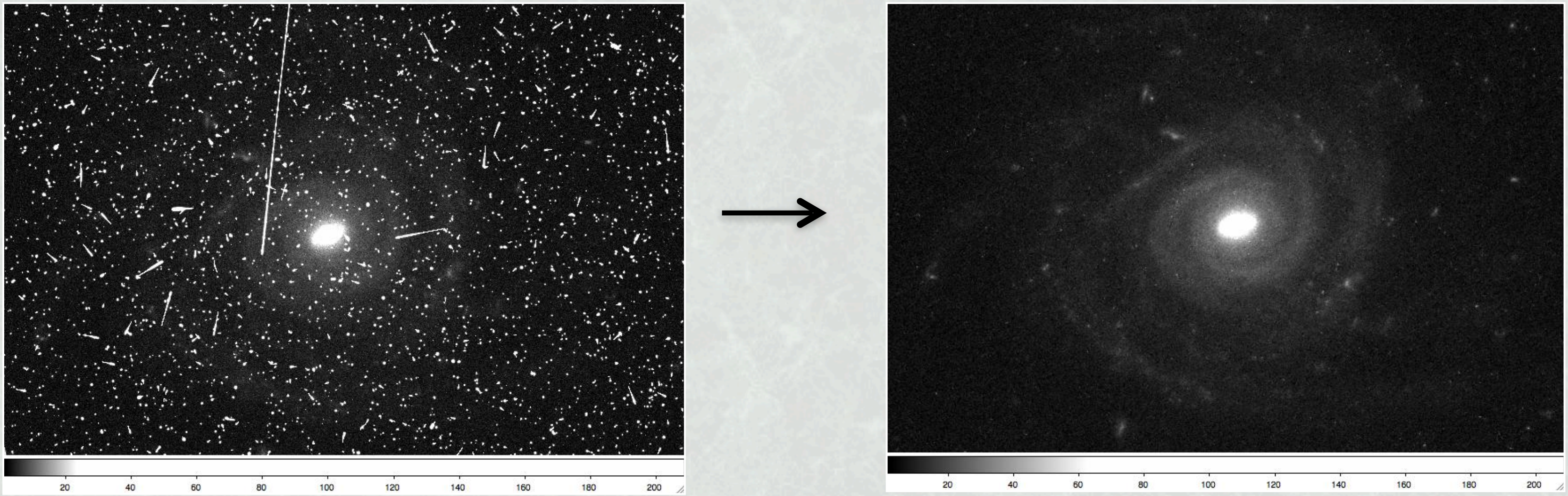
→ Good idea to increase integration time of each individual image to minimize the number of exposures (and, hence, the read-out noise).

- Limit? Cosmic rays!



Cosmic Rays

- Cosmic rays interact with the CCD array
  - Leave traces or dots in the image (their position always varies!)
- Multiple exposures and combine!
  - *sigma clip* algorithms that evaluate all values for each pixel and exclude those values from individual exposures that go beyond ~3σ from the distribution.



http://blog.galaxyzoo.org/2010/04/12/how-to-handle-hubble-images/

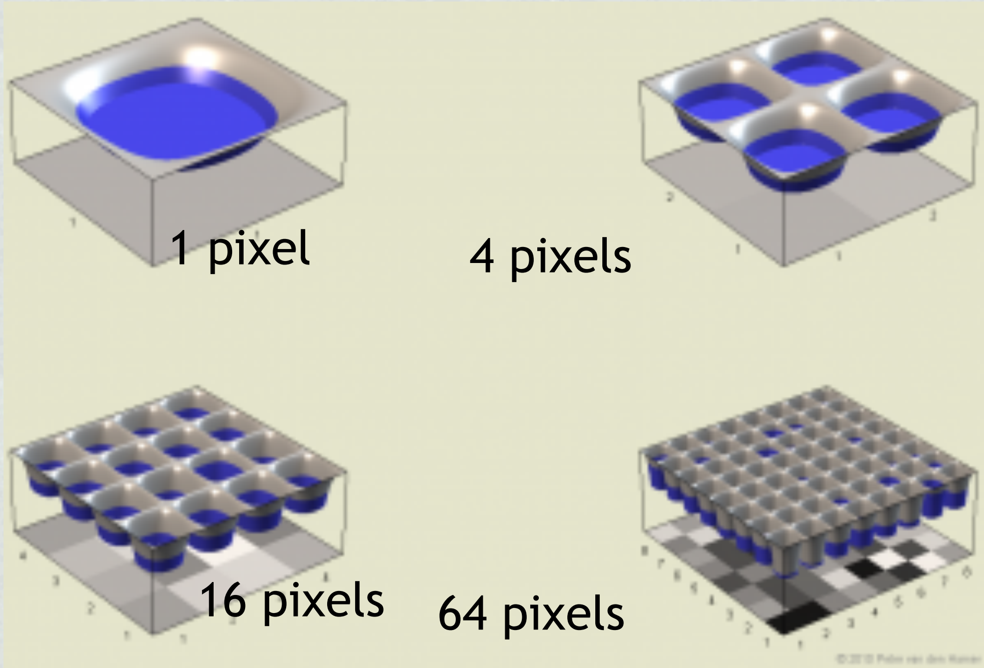
Signal-to-Noise – Surface brightness

- In the case where you are not dealing with a point source, need to consider the spatial extension of your source.
- If the science goal is to study spatial details:
  - Higher spatial resolution is great
  - However... is higher resolution always better?

Signal-to-Noise — Surface brightness

- In the case where you are not dealing with a point source, need to consider the spatial extension of your source.
- If the science goal is to study spatial details:
  - Higher spatial resolution is great
  - However... is higher resolution always better? Not always!
- Consider an extended source observed with different pixel scales:

– The finer the pixel grid, the finer the detail
  - But S/N per pixel is lower!



http://www.tikodata.com/uncategorized/image-sensor-pixel-s

Observing strategy – planning!

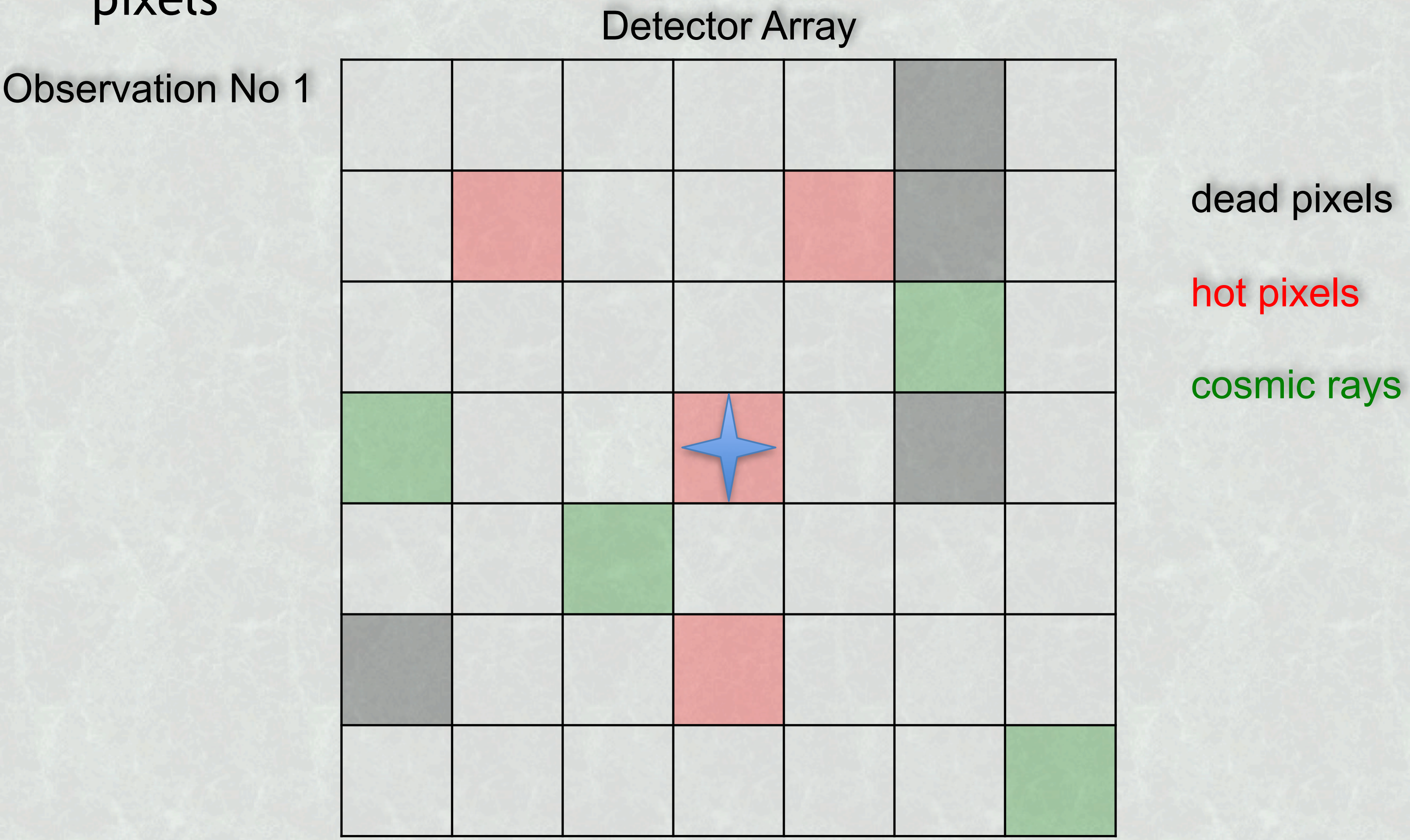
- How much integration to reach the desired S/N?
- Decisions:
  - Split into how many exposures? Integration time for each individual exposure?
  - Dithering pattern
- Considerations:
  - Will the noise be dominated by the shot noise? The sky? read-out?
  - Need to avoid saturation!
    - Either the science target itself, or other sources in the vicinity that may affect the analysis
  - Cosmic rays – how badly. Can they affect your science?
    - Better not to let them accumulate for too long! They can hit precisely your region of interest!

Dithering

- Consists of varying the telescope pointing between one exposure and the next
  - Offsets are usually small (a few arcseconds) and do not require the intervention of the telescope operator
  - In the case of large telescopes:
    - the observer only manipulates the instrument and can implement these small offsets

Dithering – sample your target with different regions from your CCD

- What's the motivation?
  - Minimize the impact of: cosmic rais, "dead" pixels, "hot" pixels



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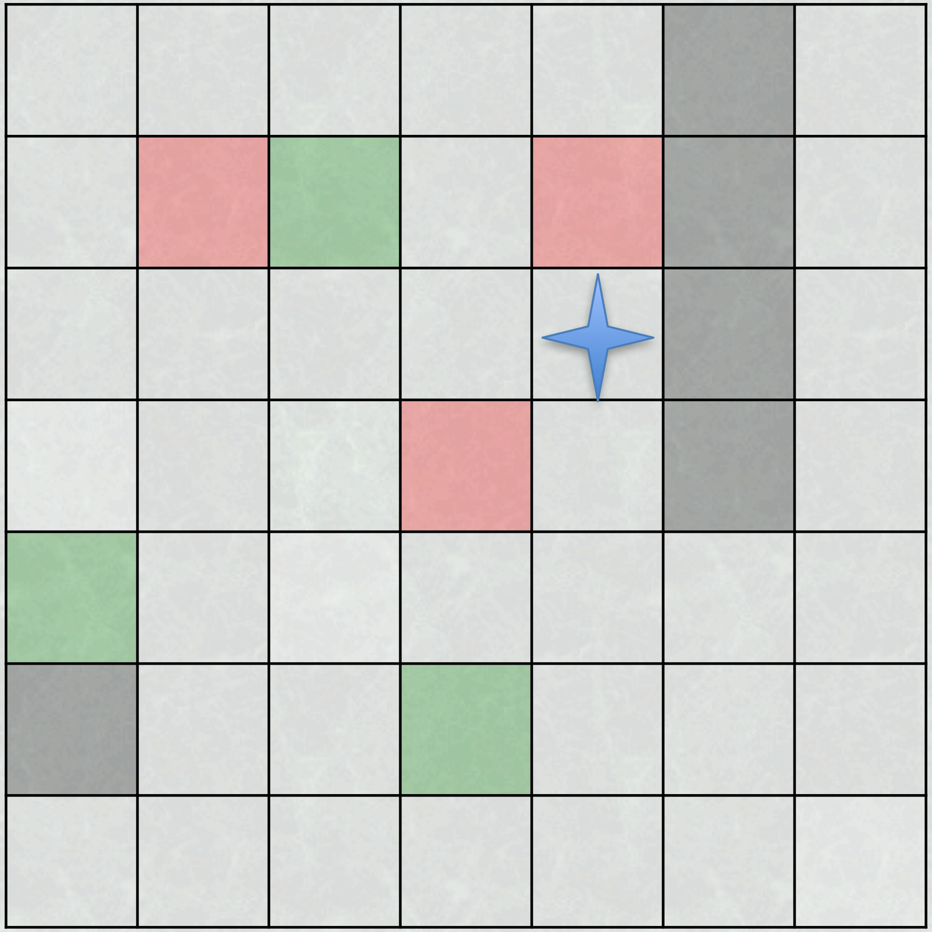
Detector Array

Observation No 2



dead pixels

hot pixels

cosmic rays

Dithering – sample your target with different regions from your CCD

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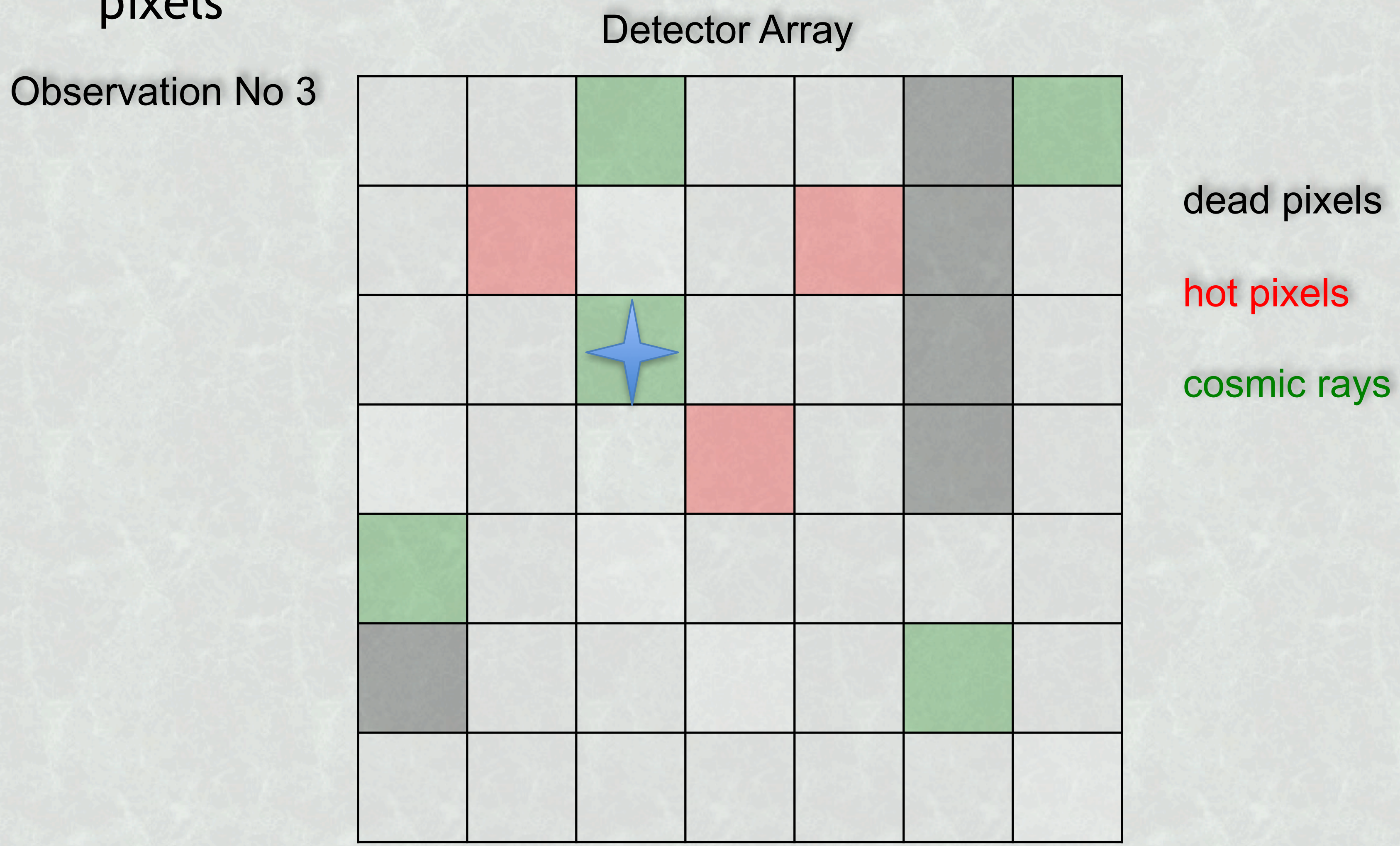

cosmos.physast.uga.edu/iSong/sites/default/files/Lecture9_0.pptx

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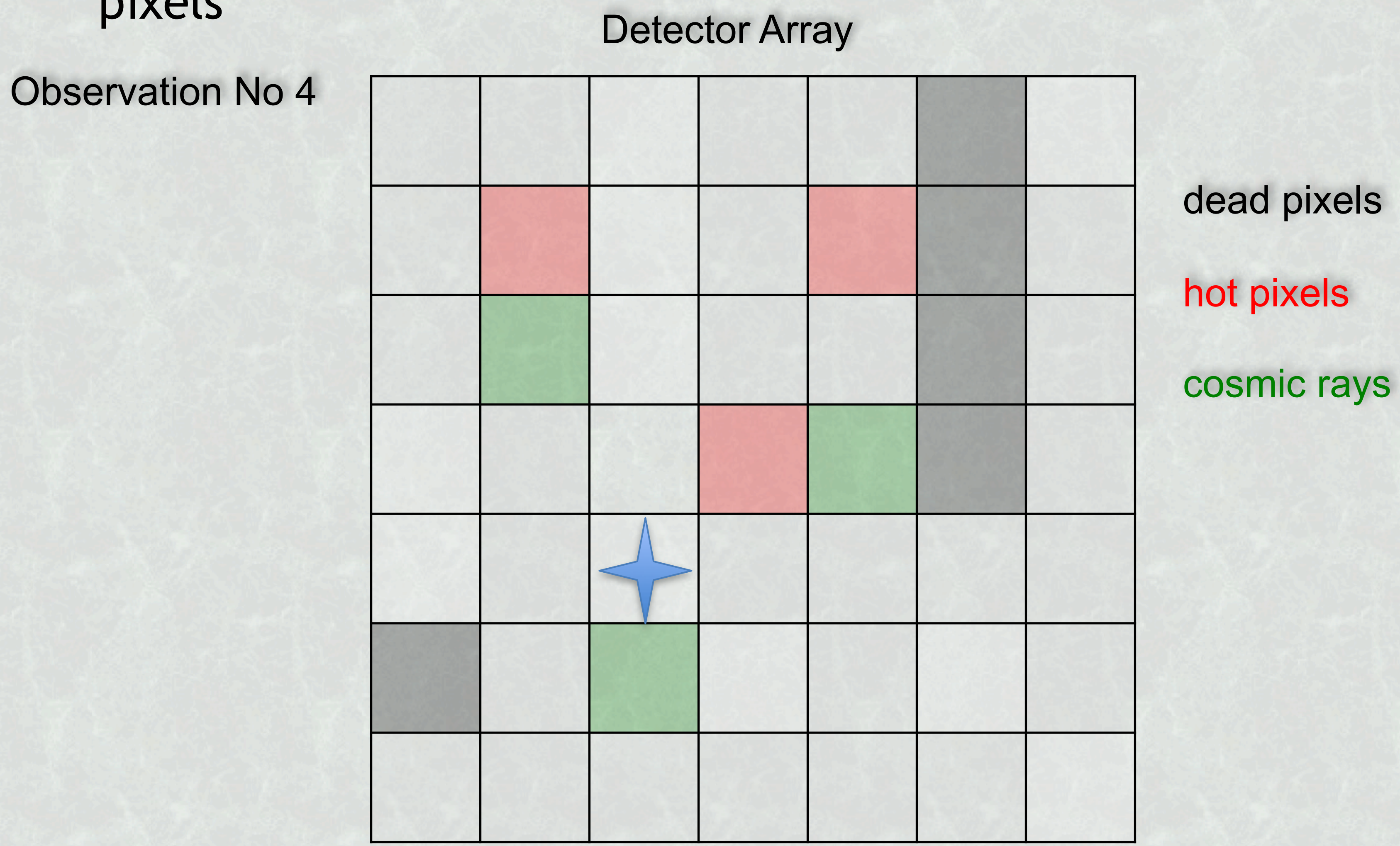

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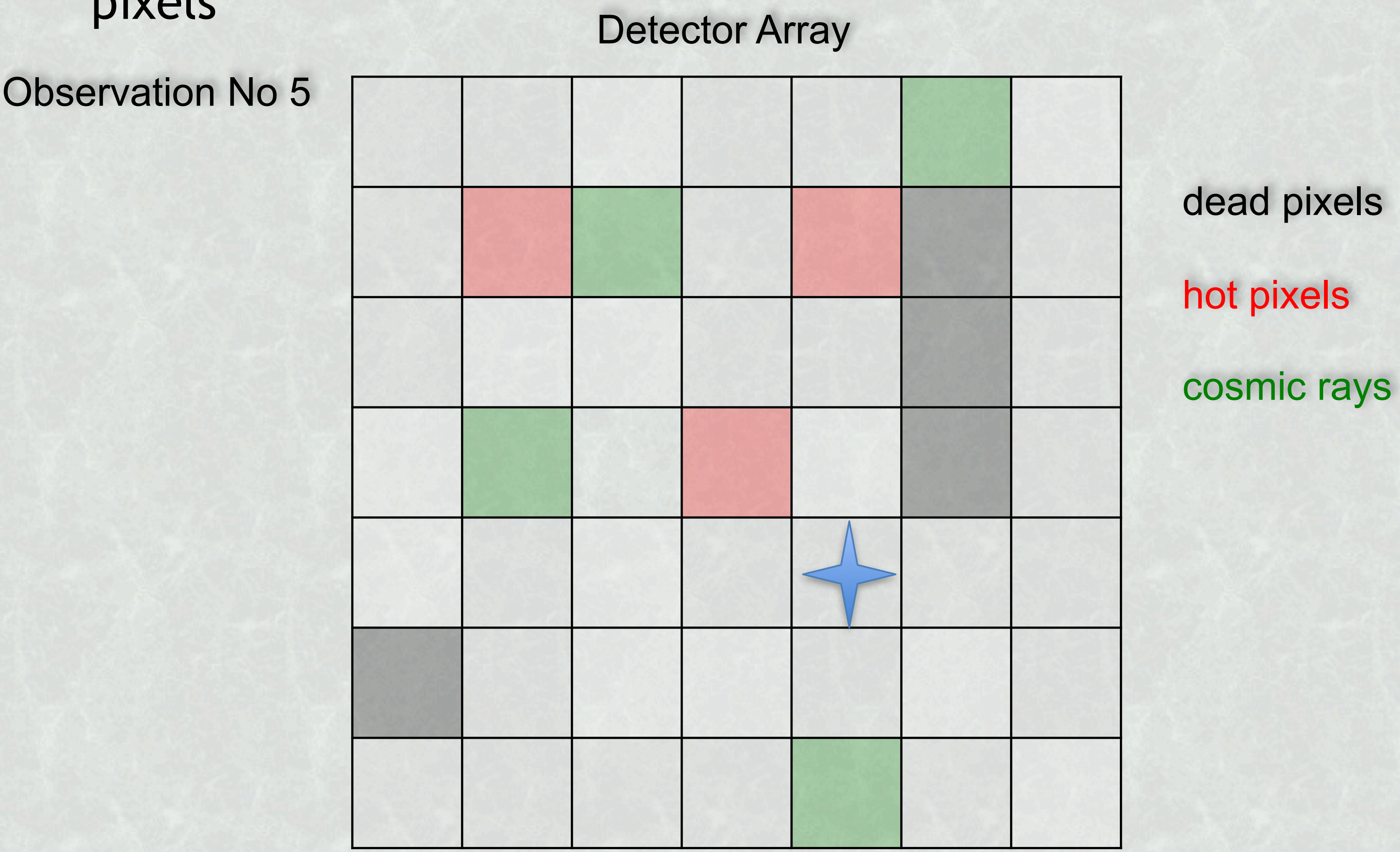

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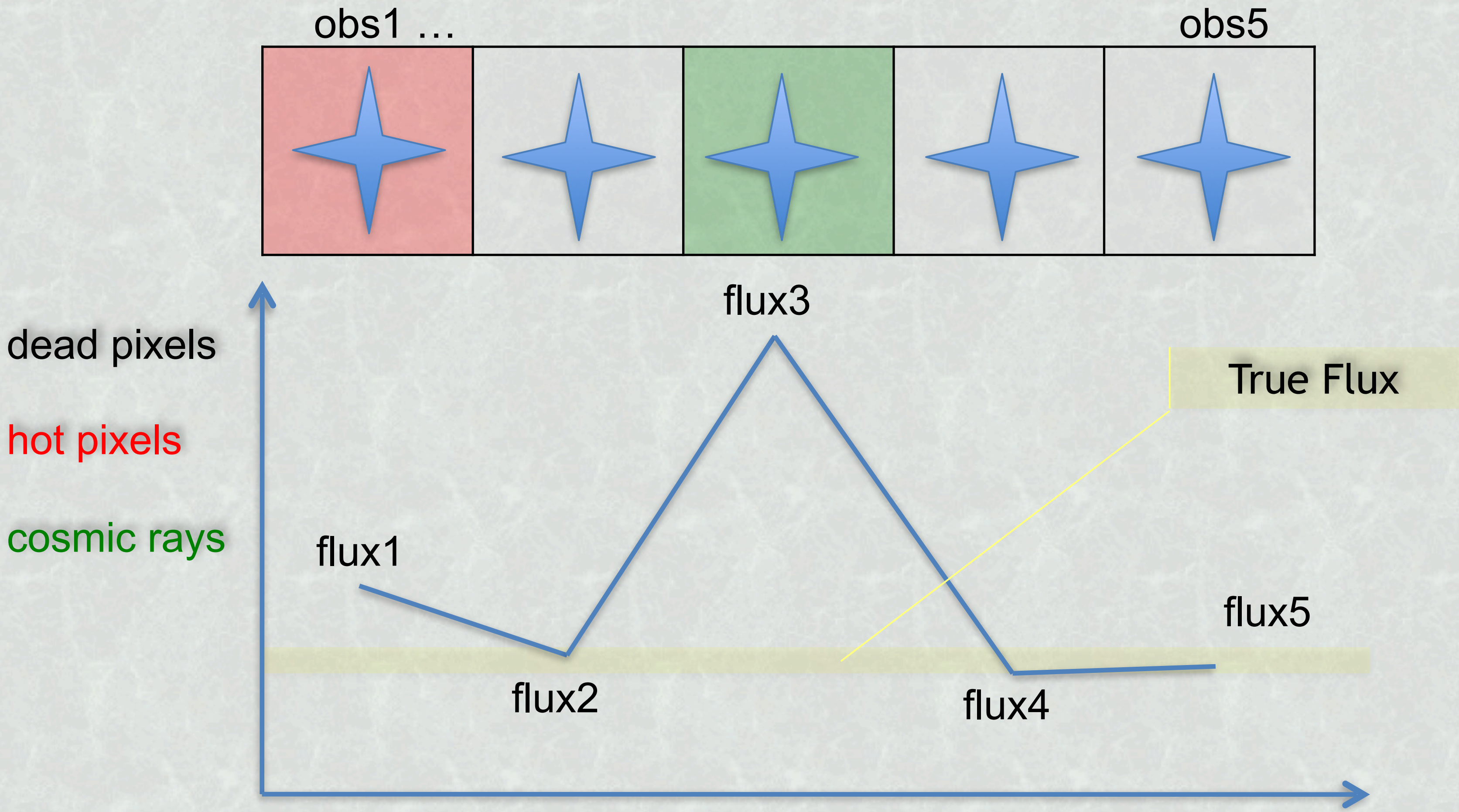
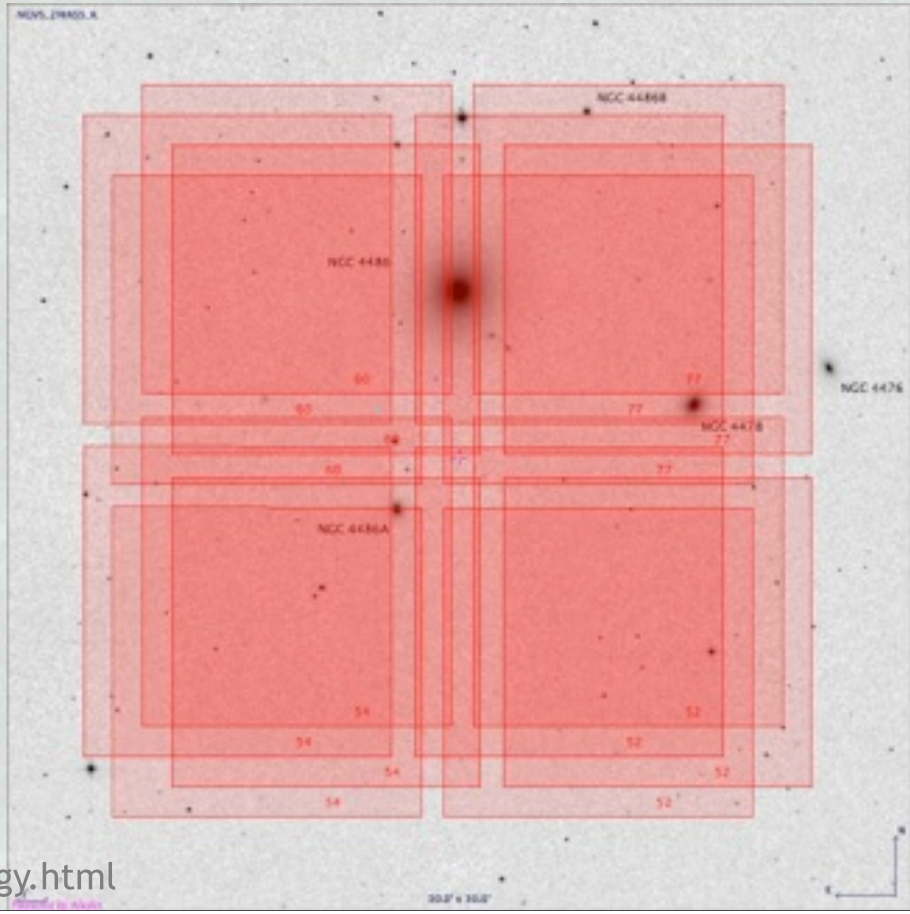


cosmos.physast.uga.edu/iSong/sites/default/files/Lecture9_0.pptx

Dithering – cover a wider field

- What's the motivation?
  - Minimize the impact of: cosmic rais, "dead" pixels, "hot" pixels
  - Fill the gap between multiple CCDs



http://www.astro.puc.cl/~tpuzia/PUC/Observing_Strategy.html

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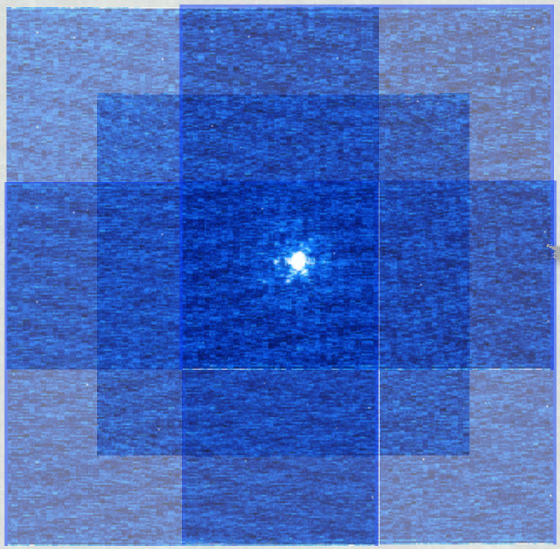
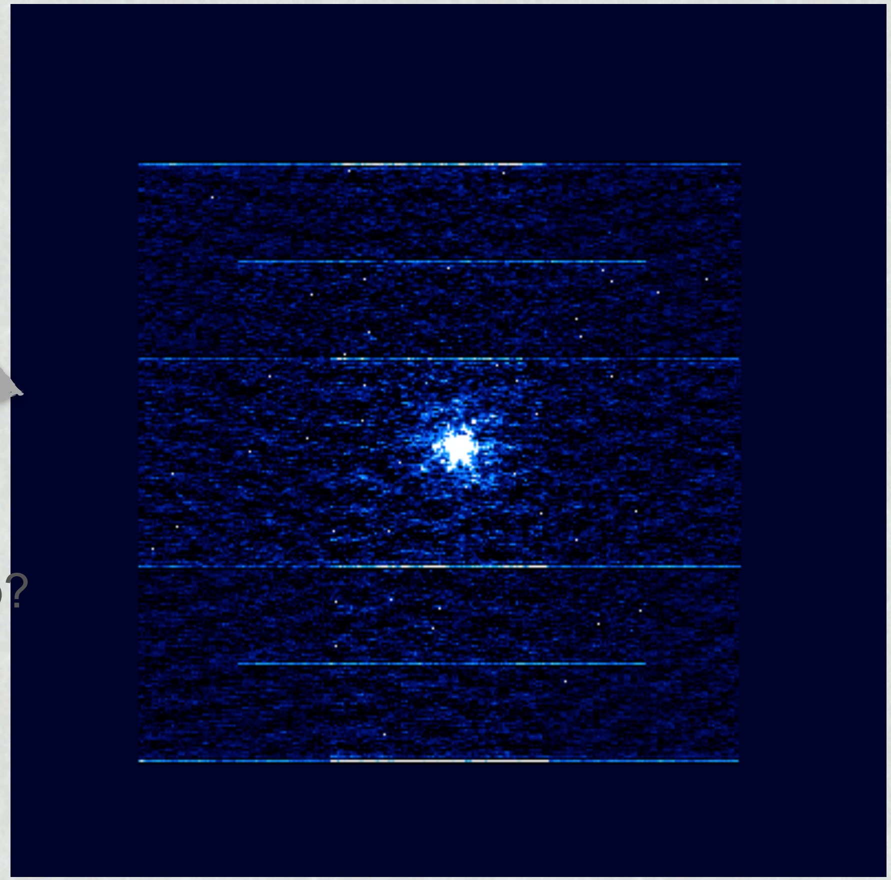


Offset and simply sum up?
No!



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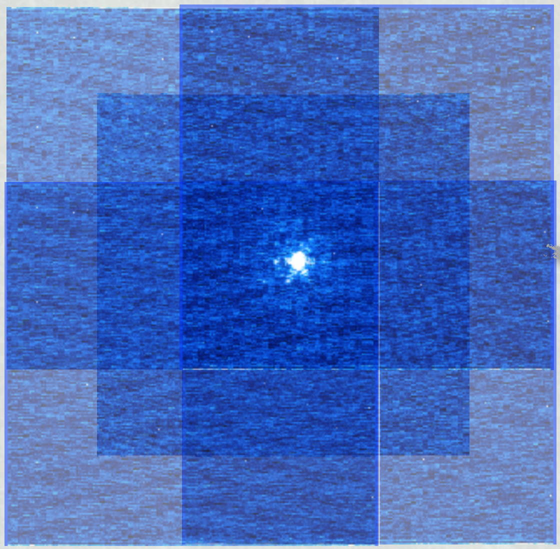
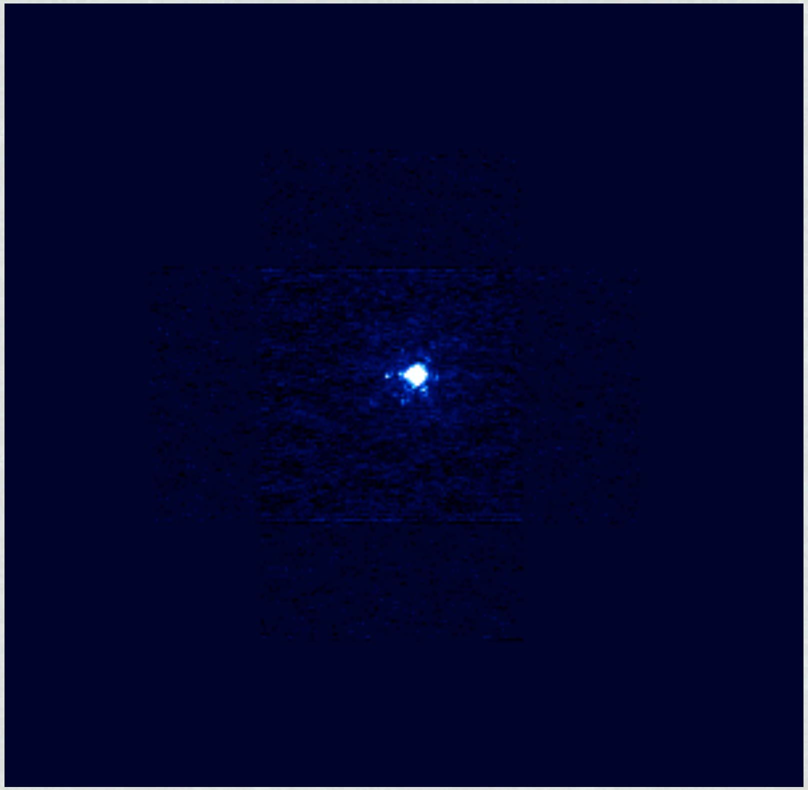


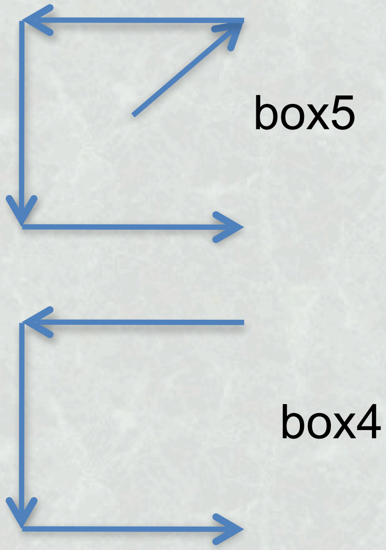
Median combine provides much better results!

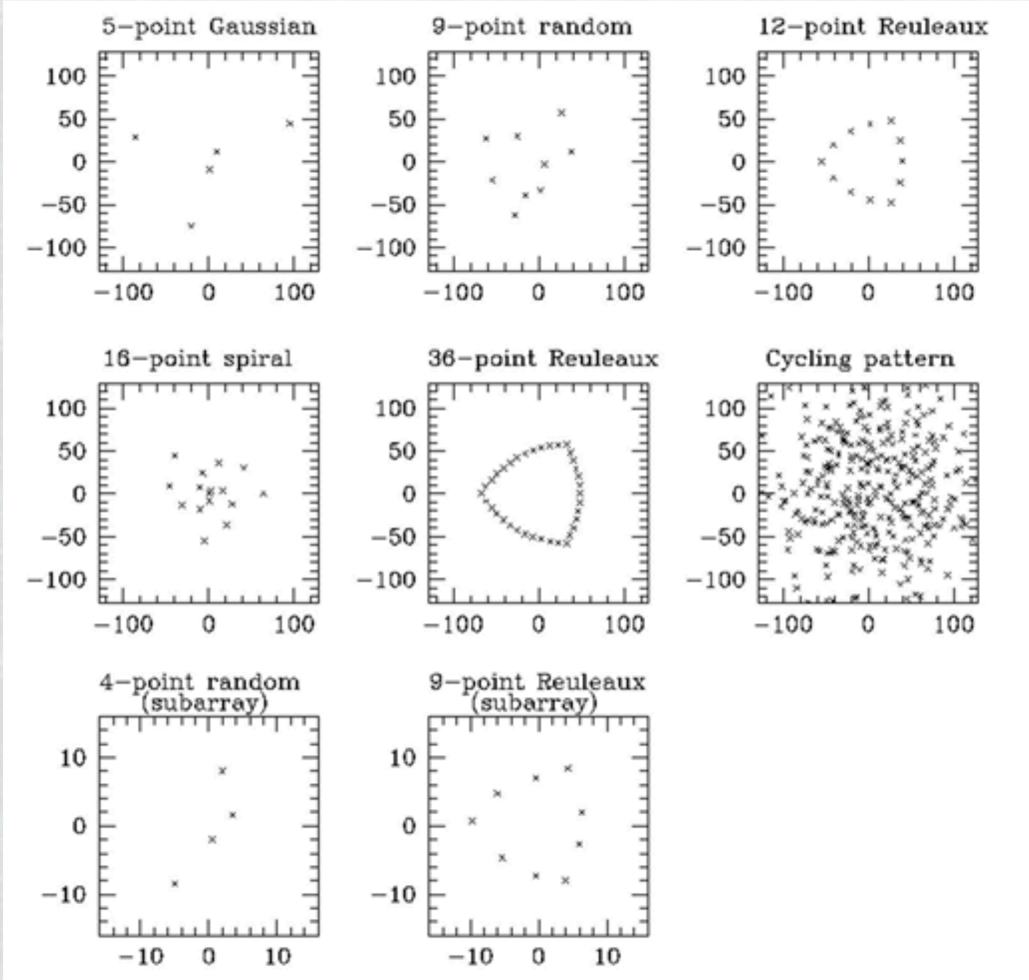
Offset and simply sum up? **No!**



Dithering – sample your target with different regions from your CCD

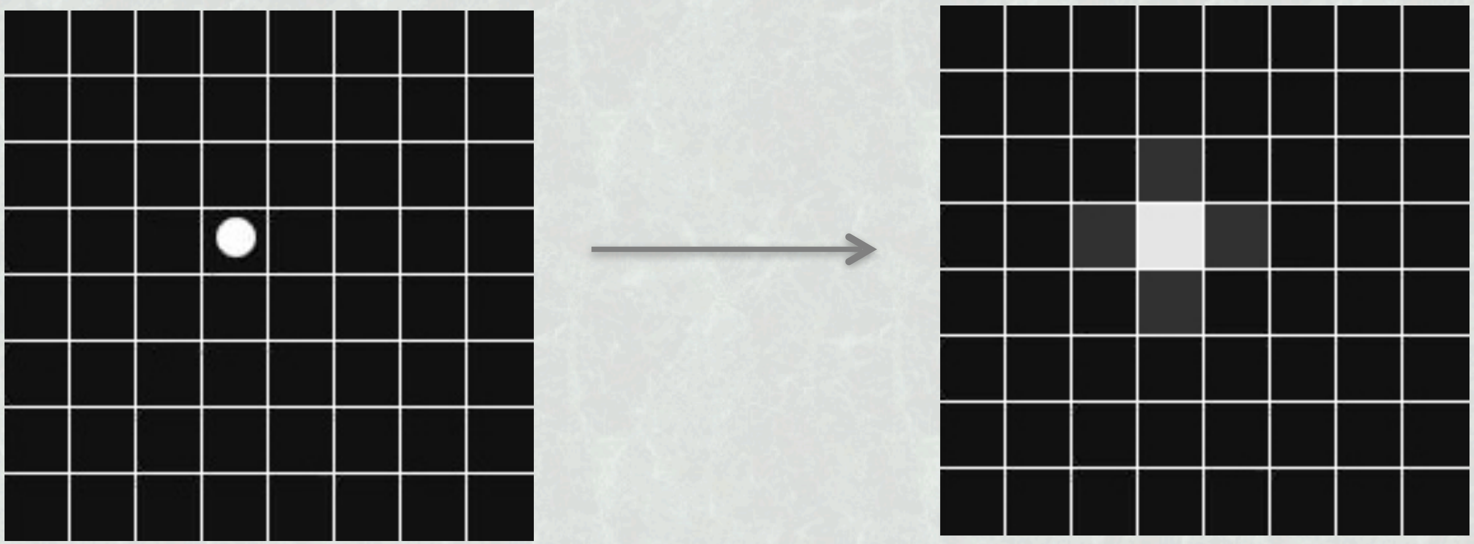
- What's the motivation?
- Multiple options of dithering patterns





Sampling – consider the PSF!

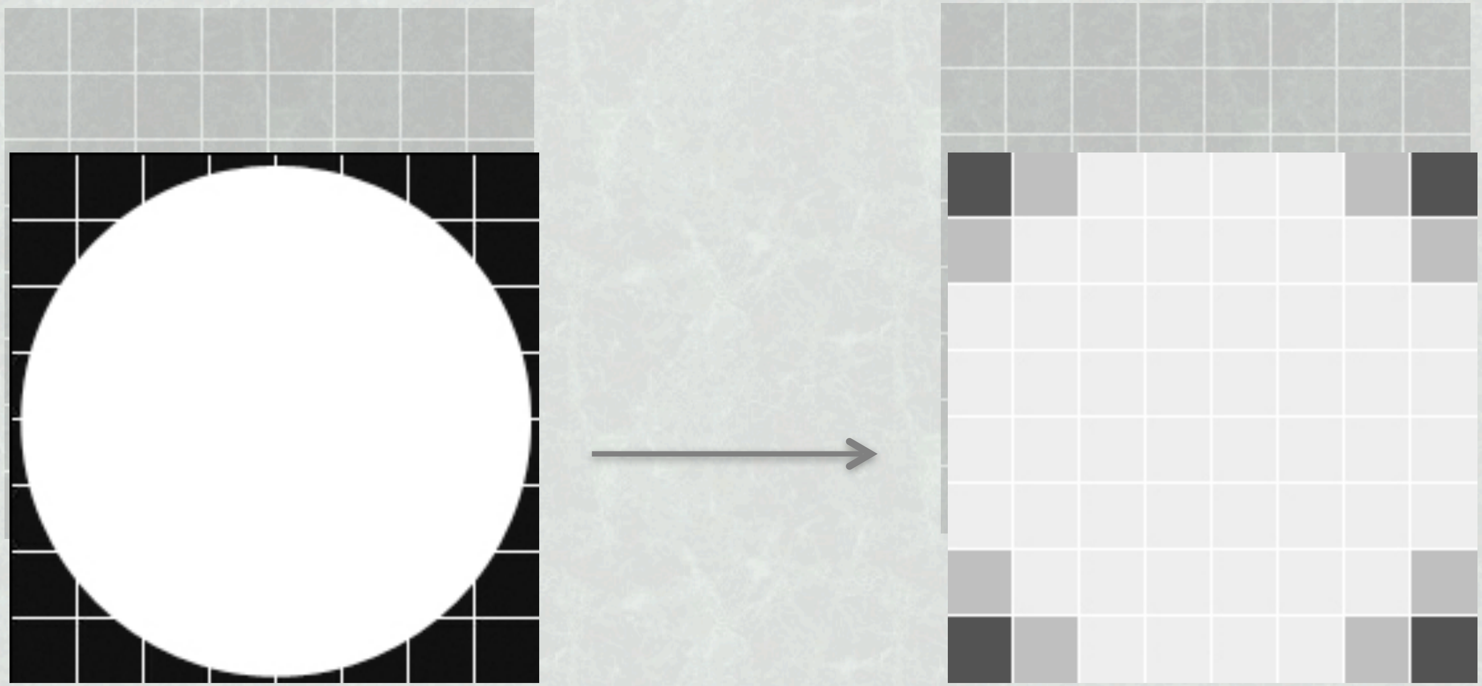
- **Under-sampling**, over-sampling and Nyquist sampling



http://www.frankbrandl.com/htm/webcam.htm

Sampling – consider the PSF!

- Under-sampling, **over-sampling** and Nyquist sampling



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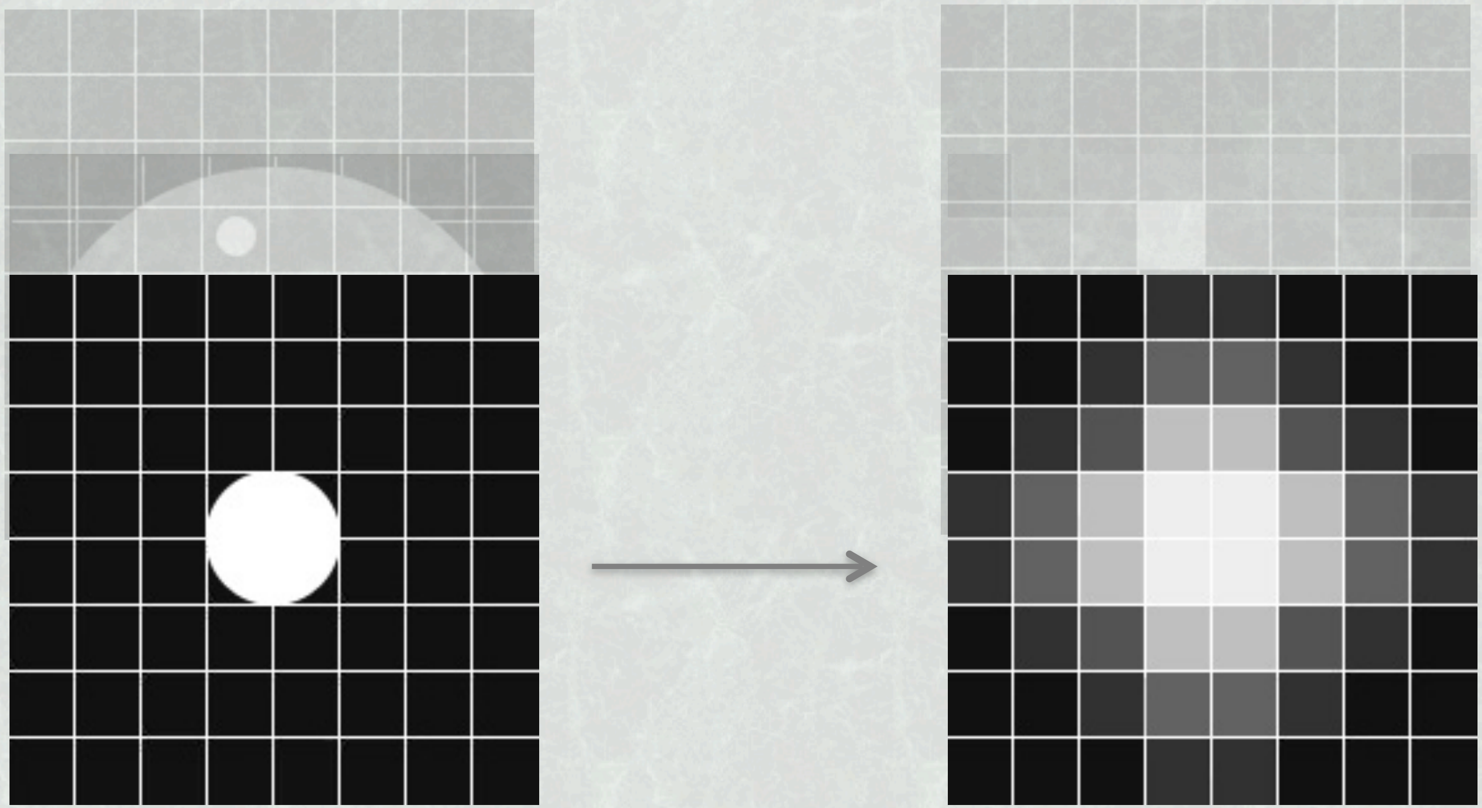

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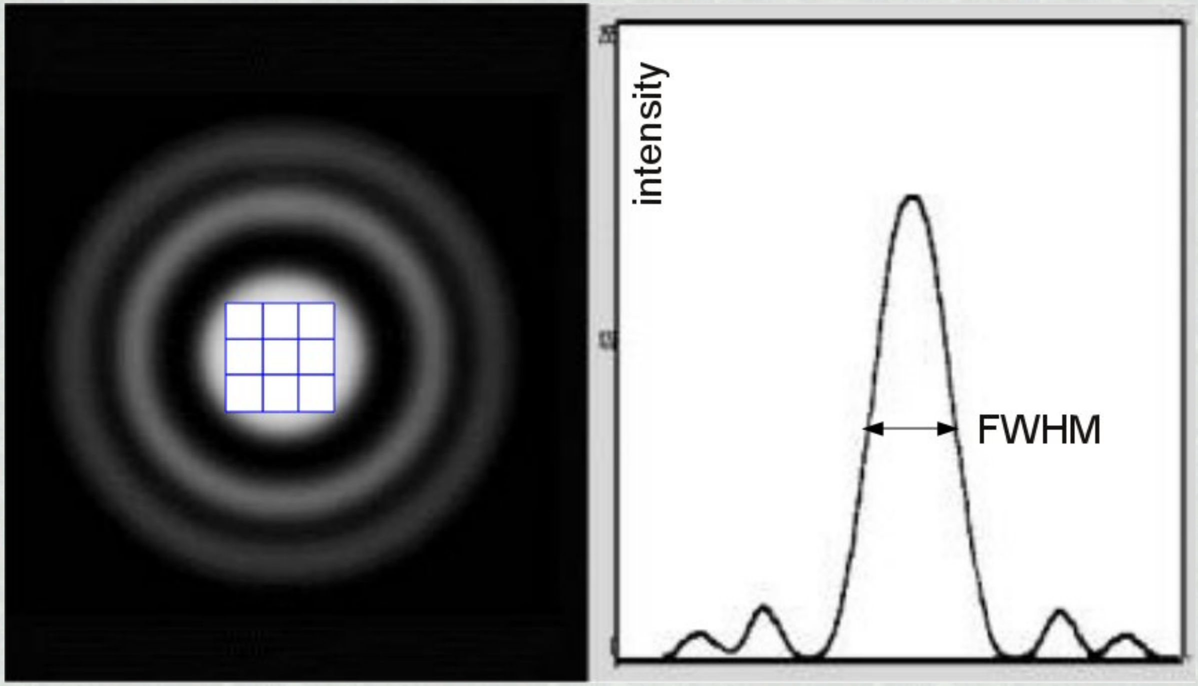
Sampling — consider the PSF!

- Nyquist criterium (for "Nyquist sampling"):
  - Ideally the PSF should be covered by ~2-3 pixels
    [in spectroscopy: ~2-3 spaxels]



http://herschel.esac.esa.int/hcss-doc-13.0/load/pacs_spec/html/PdrgS.Chp.4d.pointVSraster.html

Sampling – consider the PSF!

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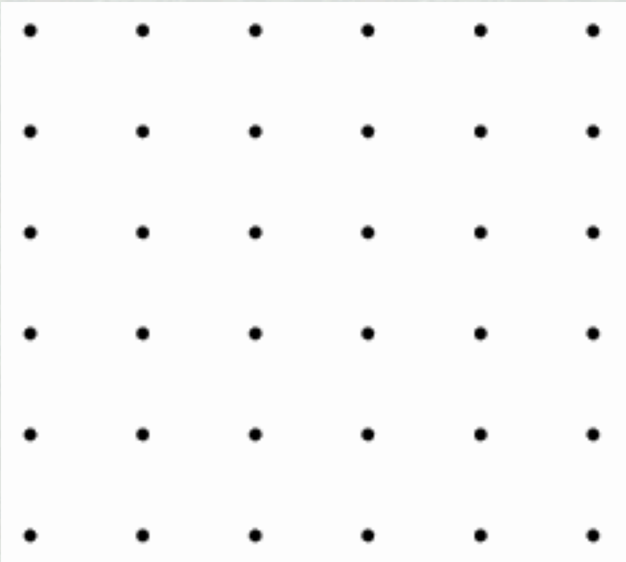
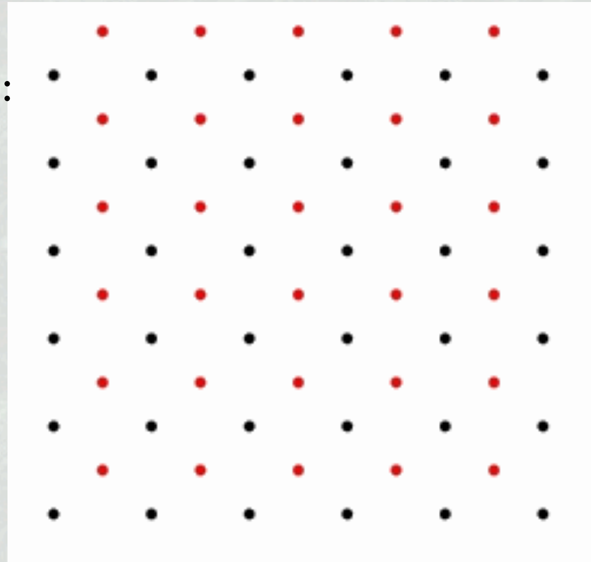
  - If detector pixels are larger (or comparable) to the PSF size, may opt for dithering with non-integer pixel offsets to attain Nyquist sampling.



Offsets entre imagens:
(n+1/2, m+1/2)



http://www.stsci.edu/hst/HST_overview/documents/multidrizzle/ch26.html

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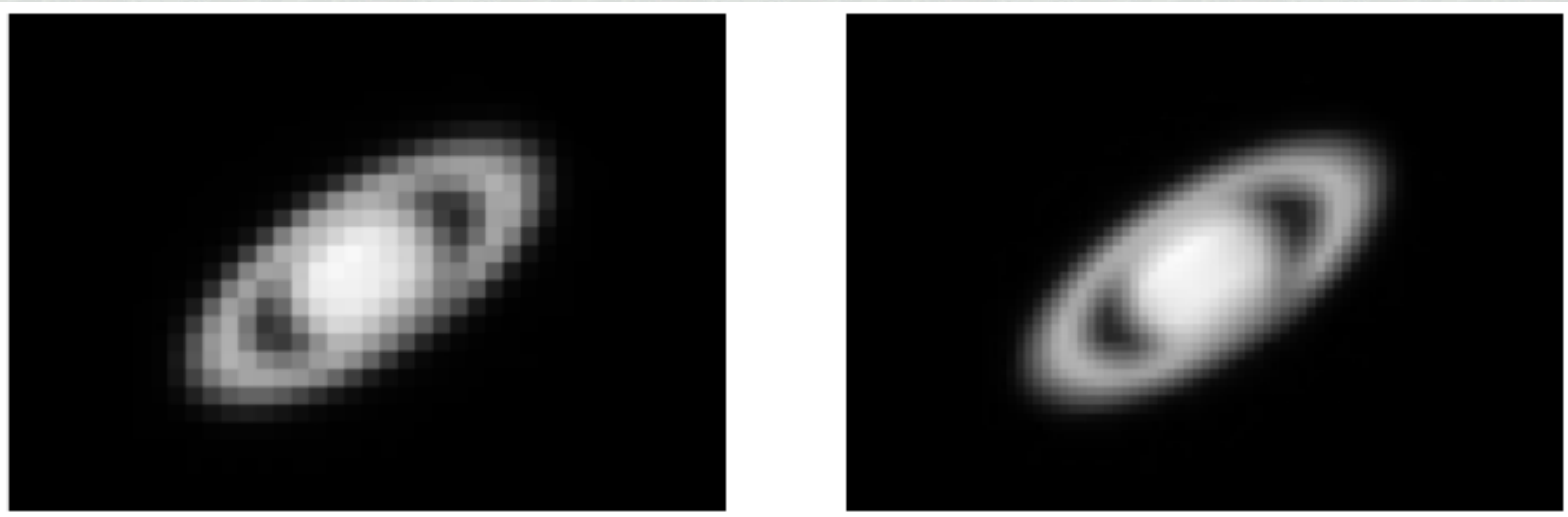

http://www.stsci.edu/hst/HST_overview/documents/multidrizzle/ch26.html

IRAF & ds9 – the very basics

- Here in Socorro:
  - Open a terminal and go to /home/isya/IRAF
  - Open ds9 from the terminal (i.e., type "ds9 &")
  - On the terminal's command line, type "ecl"
    - You're in the IRAF environment!
      - Note: Little hiccup: we'll have to open images directly using the pull-down menus from ds9

IRAF & ds9 — the very basics

- Once on IRAF, common routines you'll use (also on remote computer!)
  - *imstat* <file> —> Get basic statistic on the image/region
  - *display* <file> <frame>
  - *imexamine* <file> —> quickly check source profiles (<r>, <s>, <j>)
  - *imheader* <file> —> View image header
    - Also *dfits*
      - *e.g., for multiple headers in one go: dfits d*.fits l+ | grep EXPTIME*
  - *imarith* <file1> <file2> <operation> <output_file>
  - *imcombine*
- To use IRAF routines:
  - directly on *iraf* command line by inputing the routine name and main input parameters
  - Explicitly open the parameter list by typing "epar <routine>" on the *iraf* command line.

<u>Note:</u> for help in any iraf routine, type "help <routine>" on iraf command line

Data Reduction — getting ready

- Each group will create their own sub-directory under */home/isya/ObservationalAstronomy/Group_<number>*

- Create a subdirectory called "rawdata" and copy the night's data onto this directory, as well as the log sheet. This will be your local go-to folder if you (by mistake) erase an important file.
  - "LOG_OPD160_13julho2018_ISYA2018_original" (Excel)

- Consider the different types of images taken through the night of remote observations and, within the group's directory, create subdirectories for the different types of images taken

- Use the header routines as well as the log sheet to verify that the files are well allocated to the different directories
  - What additional subdivision should be made in the flats and darks subdirectories?

Data Reduction – let's start!

- Create all relevant *master* images
  - Master bias
  - Master flat (each filter)
  - Master dark (each exposure time)

- Consider how should each of the following "corrections" should be executed:
  - Correcting for readout noise
  - Correcting for the accumulation of dark current
  - Correcting for the non-homogeneity in sensitivity of the CCDs pixels

- Which mathematical operations need to be implemented?

- Go for it!