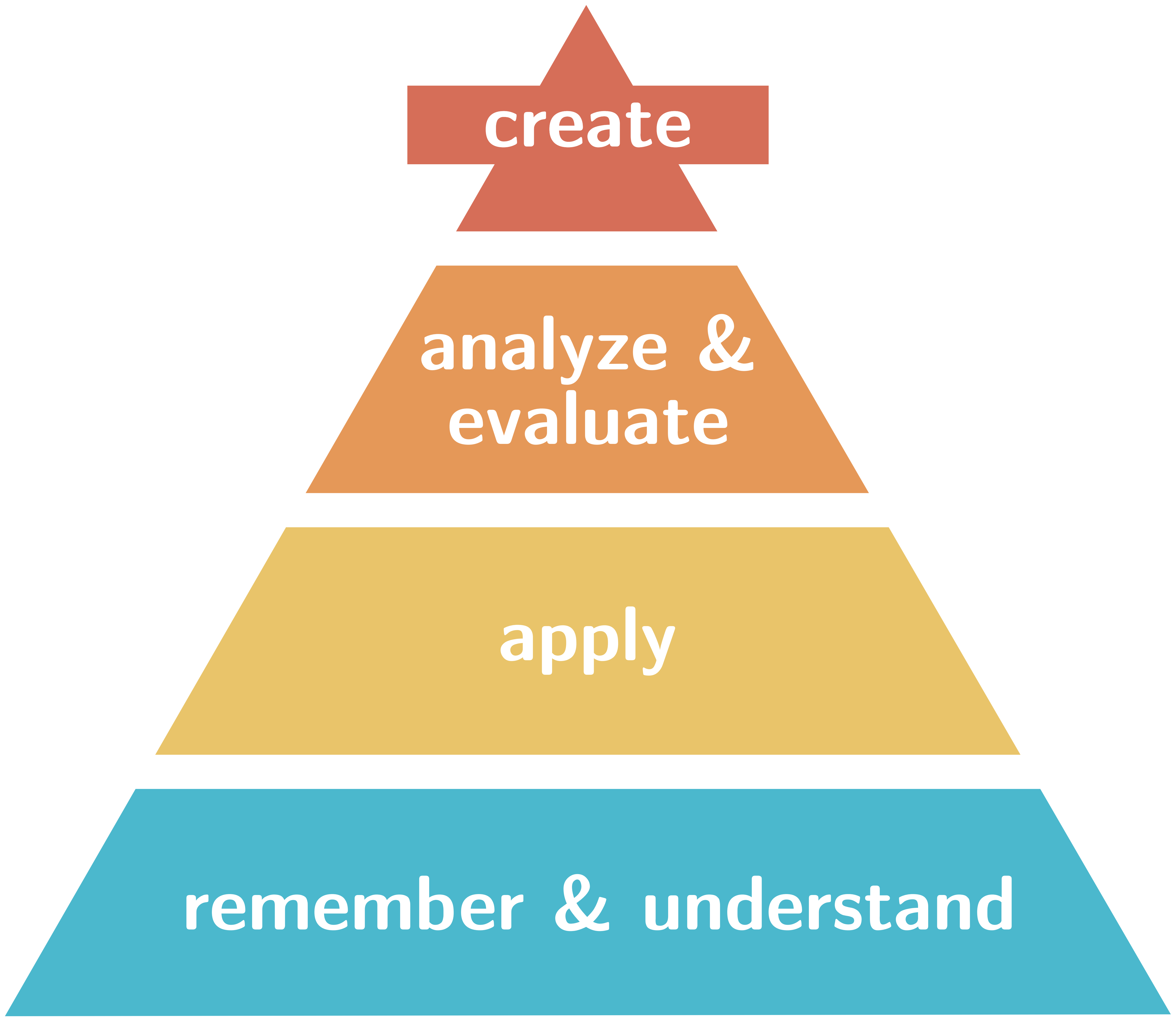
Lecture I:
Tiling, Stacking, & Difference Imaging

LSST Data Science Fellowship Lectures, 2025.09.17

Bloom's Taxonomy … abbreviated



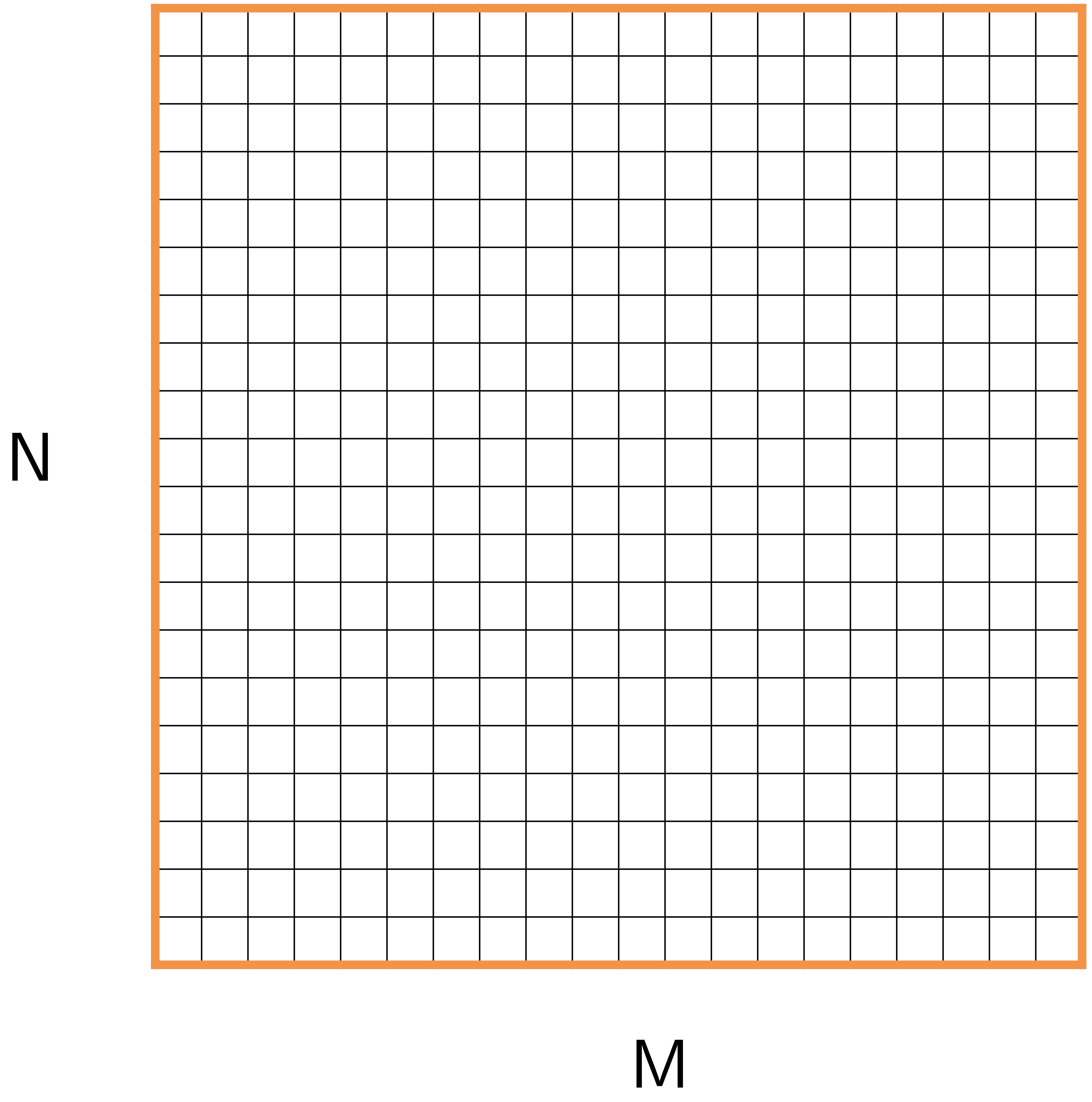
Problem set!

How do we design surveys to optimize for different/diverse science goals?

How are coadds and difference images made with astronomical data?

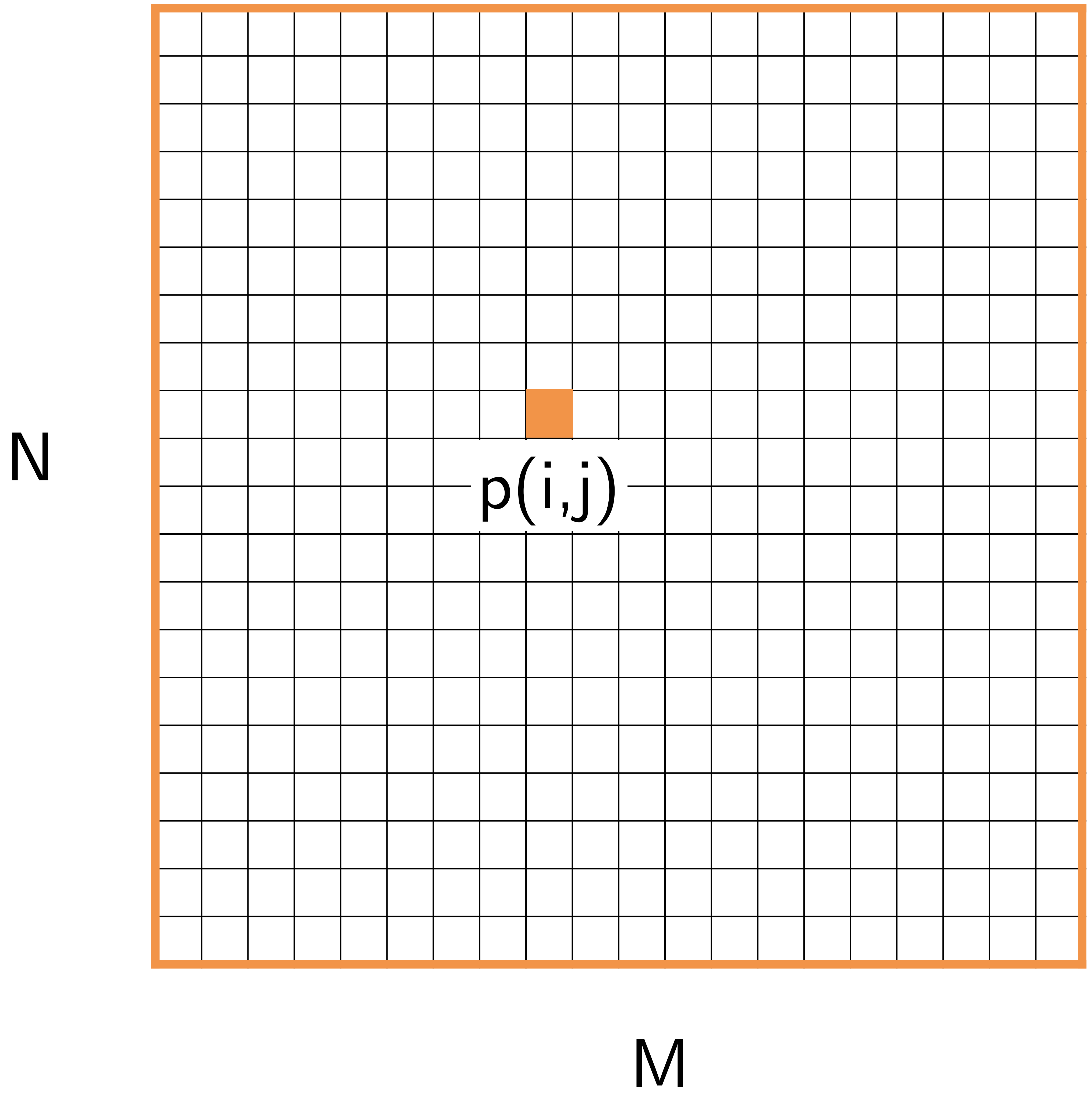
Stacking, tiling, and difference imaging: *what* and *why*?

The anatomy of an exposure



Let us take a **single-frame** exposure of size NxM

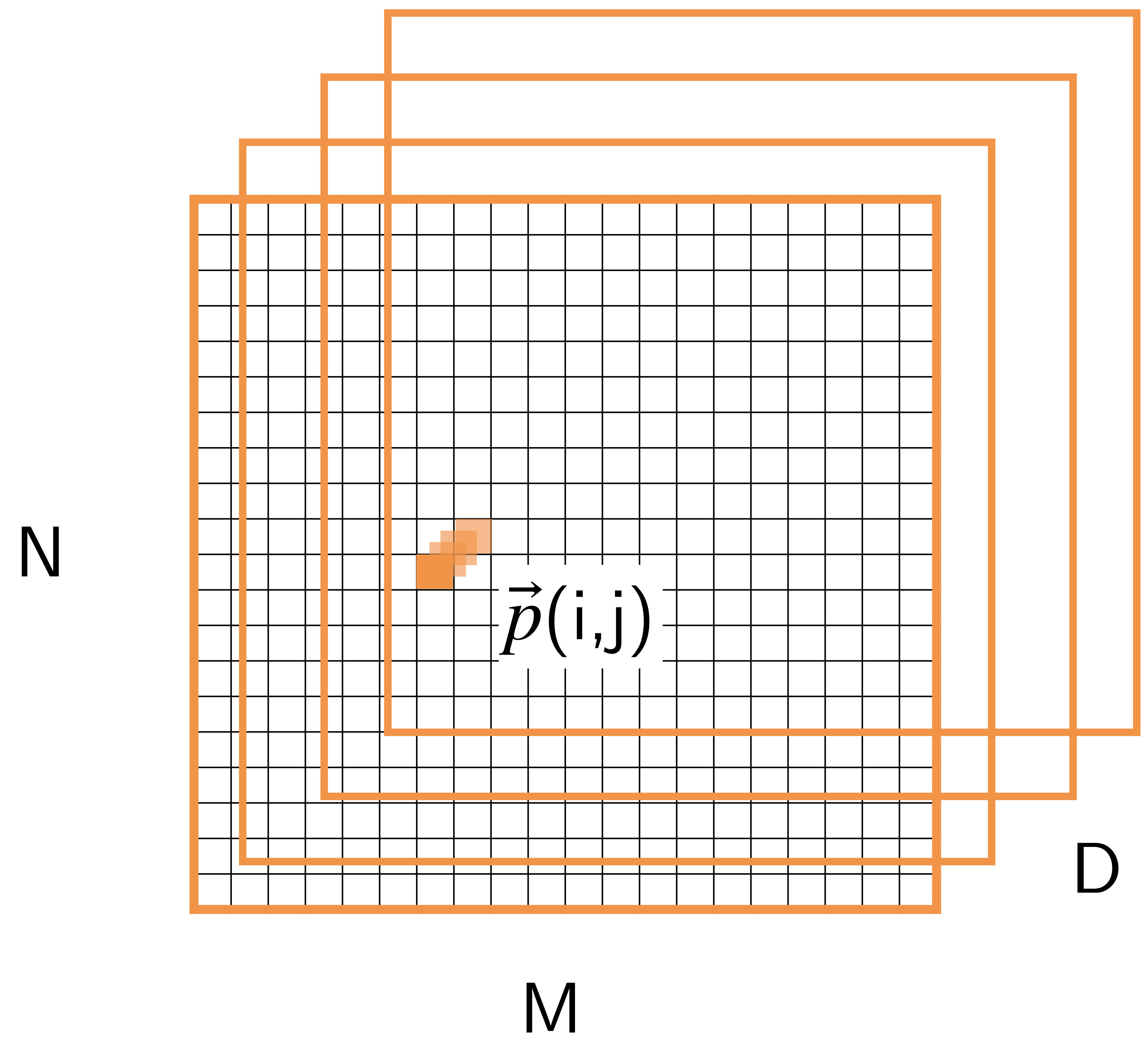
The anatomy of an exposure



Let us take a **single-frame** exposure of size NxM

Each pixel registers a value corresponding to the number of incident photons
(recall Monday's lecture on CCDs!)

The anatomy of an exposure



Let us take a **single-frame** exposure of size NxM

Each pixel registers a value corresponding to the number of incident photons
(recall Monday's lecture on CCDs!)

Now, we'll consider a **stack** of D exposures of shape NxMxD;

each vector of pixels $\vec{p}$(i,j) will now describe the photons seen over the set of exposures at position i,j.

Why not just take longer exposures?

Discuss with your partner:

From what you learned in the earlier lectures, what prevents us from just taking very long exposures?

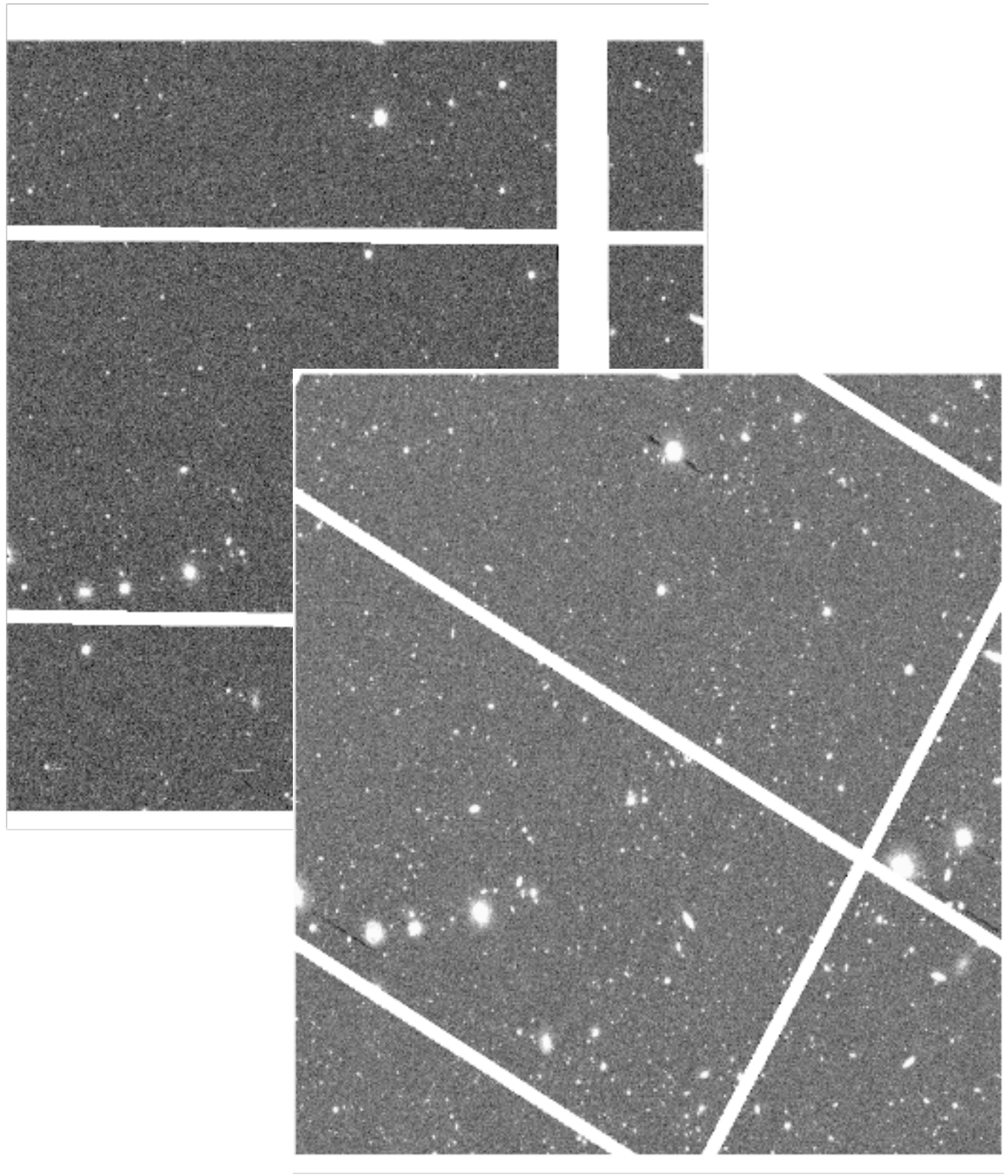
Why not just take longer exposures?

Discuss with your partner:

From what you learned in the earlier lectures, what prevents us from just taking very long exposures?

- CCDs saturate
- System drift
- Transient artifacts (satellites, cosmic rays)
- Changing observational conditions
- Astrophysical variation!

What is a coadd?



HSC-SSP single frame processing

From a stack of exposures, we want to obtain a "**coadded**" image from the single-frame visits.

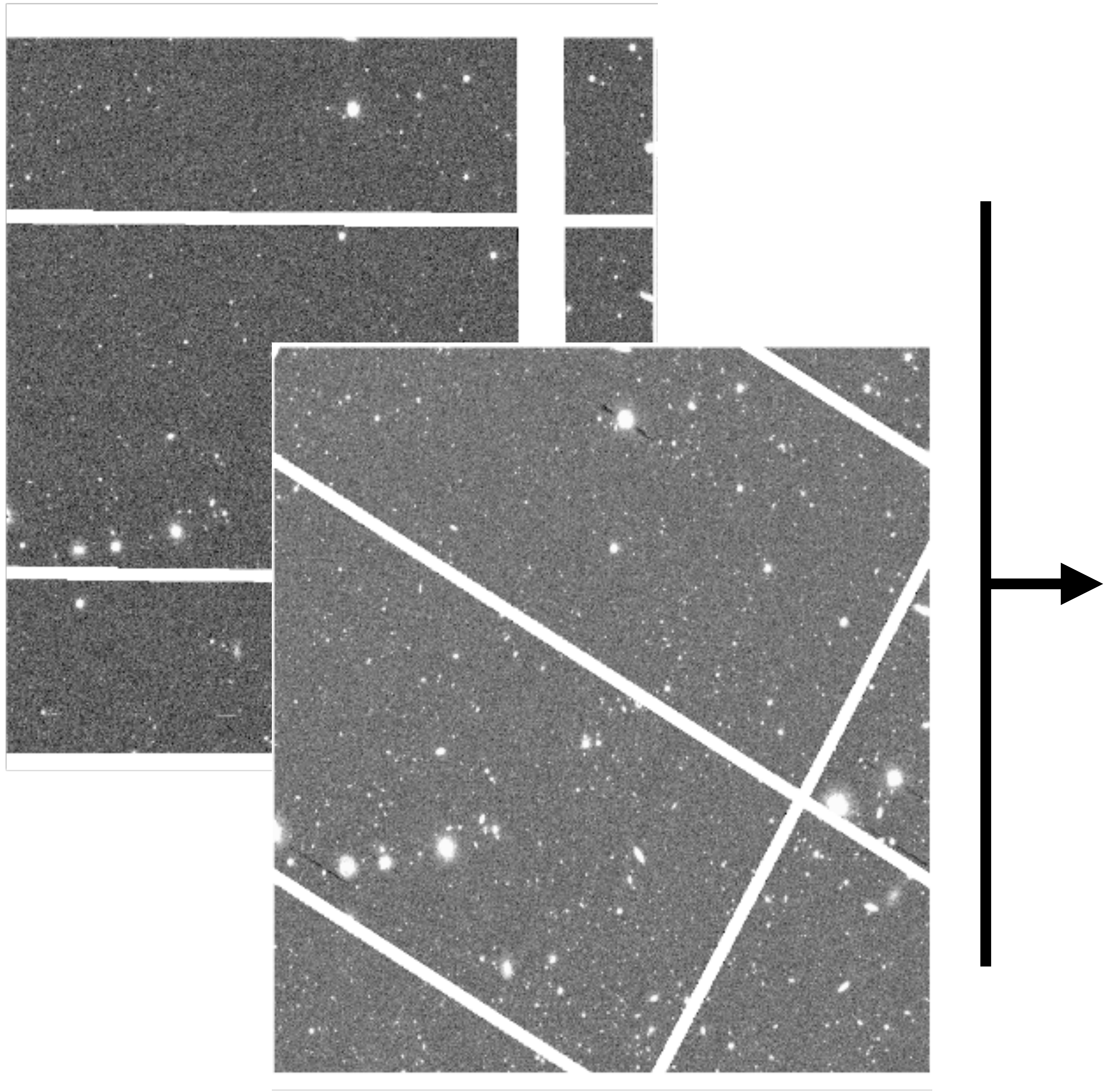
Goals of coaddition:

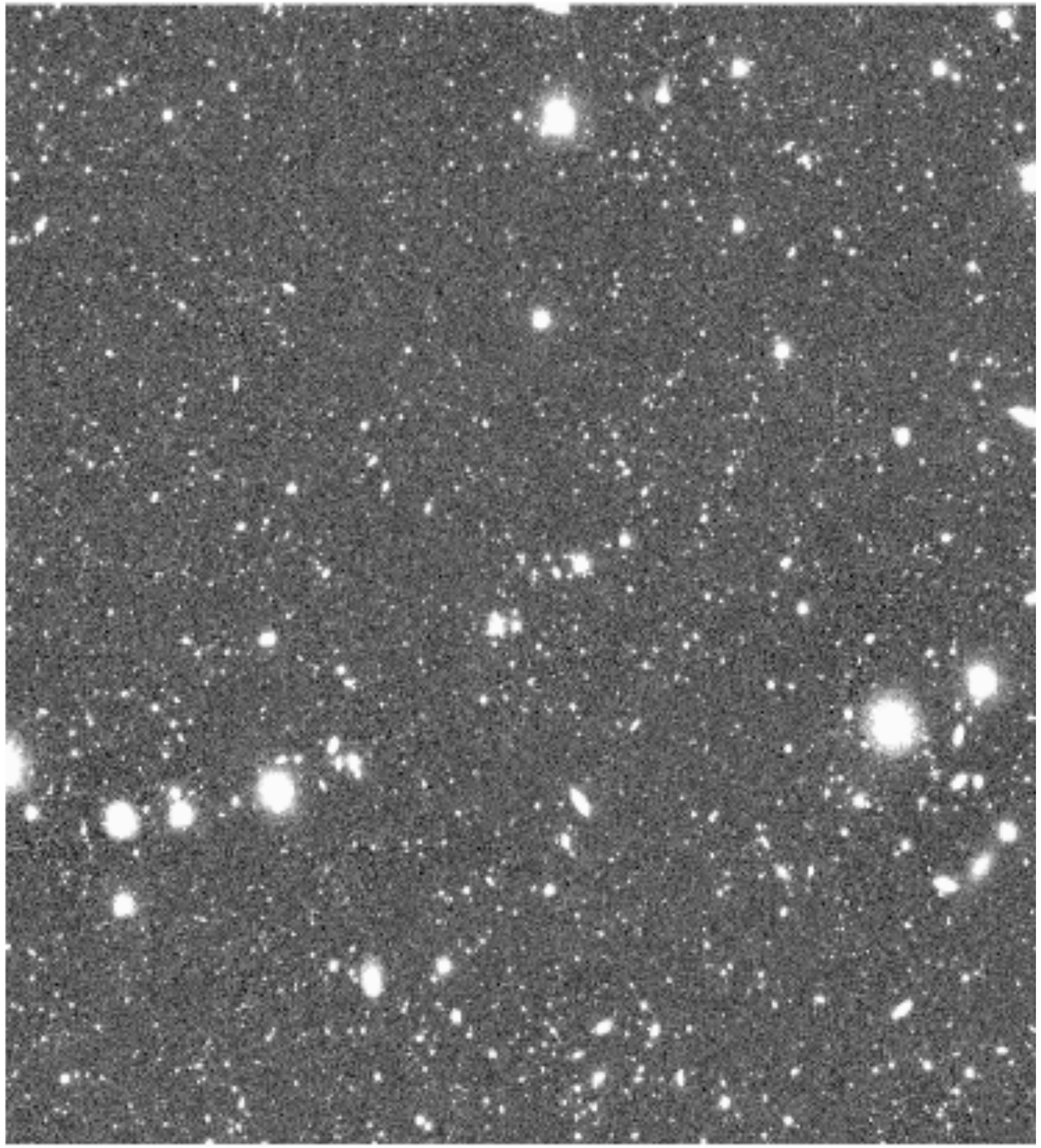
- Maximize image SNR
- Remove/reject imaging artifacts
- Construct contiguous survey imaging

Optimal coaddition method can vary with science case!

Hyper-Suprime Cam
Subaru (8.2m)

What is a coadd?





Hyper-Suprime Cam
Subaru (8.2m)

HSC-SSP single frame processing

A roadmap to coadd generation

- Convert all single-frame images to the same on-sky geometry
- Map all single-frame images to the same flux scale
- Stack images to create coadds
- [Distribute coadds to the scientific public!]

Discuss with your partner:

What are some potential technical hurdles to making coadds?

A roadmap to coadd generation

- Convert all single-frame images to the same on-sky geometry

  The sky frame is not Euclidean; pixel resampling

- Map all single-frame images to the same flux scale

  Images are taken under different conditions; identifying calibrating sources

- Stack images to create coadds

  How to optimize for different-quality images in the stack; time-variable artifacts

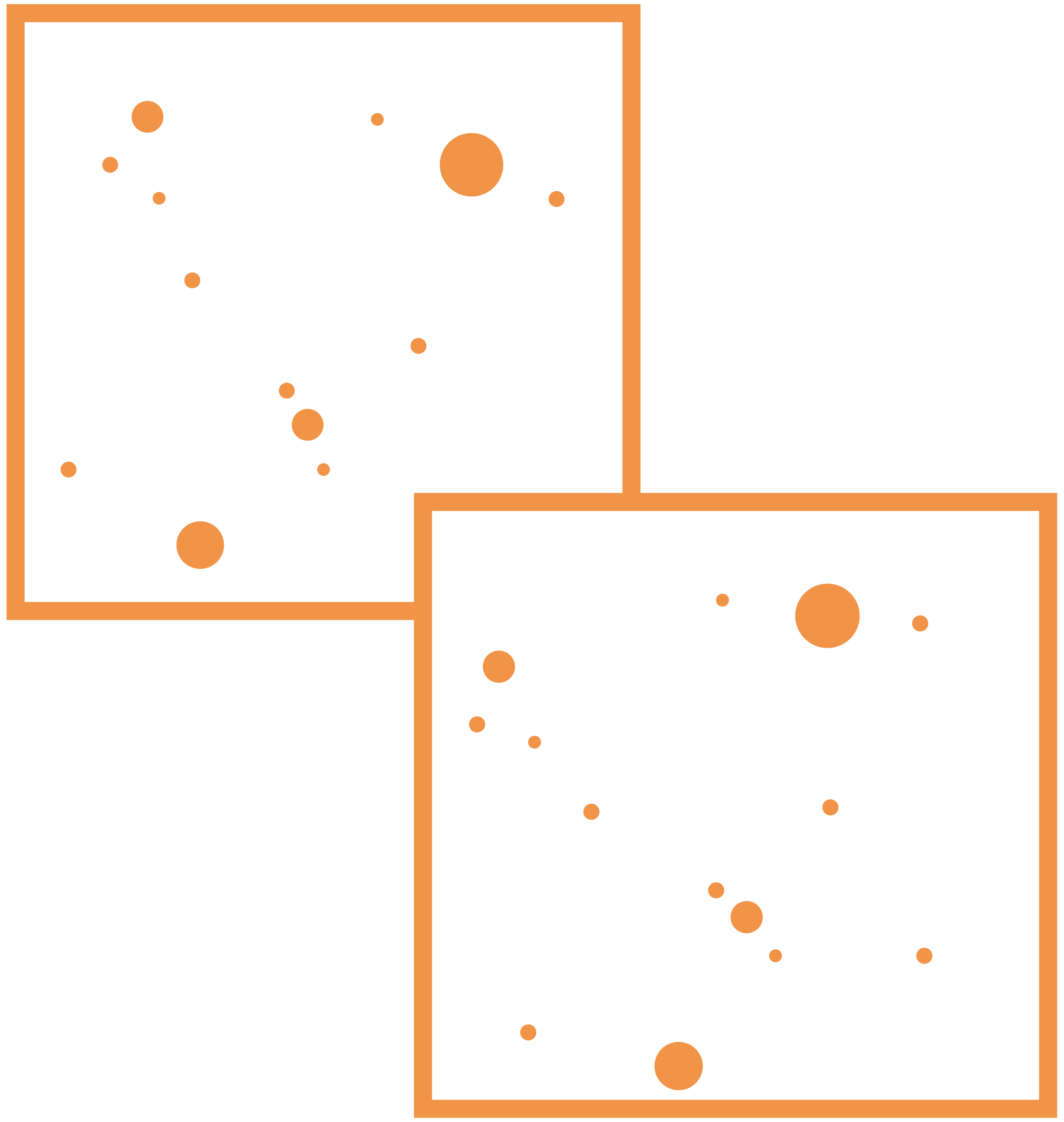
- [Distribute coadds to the scientific public!]

  Accessibility; dataset size

Discuss with your partner:

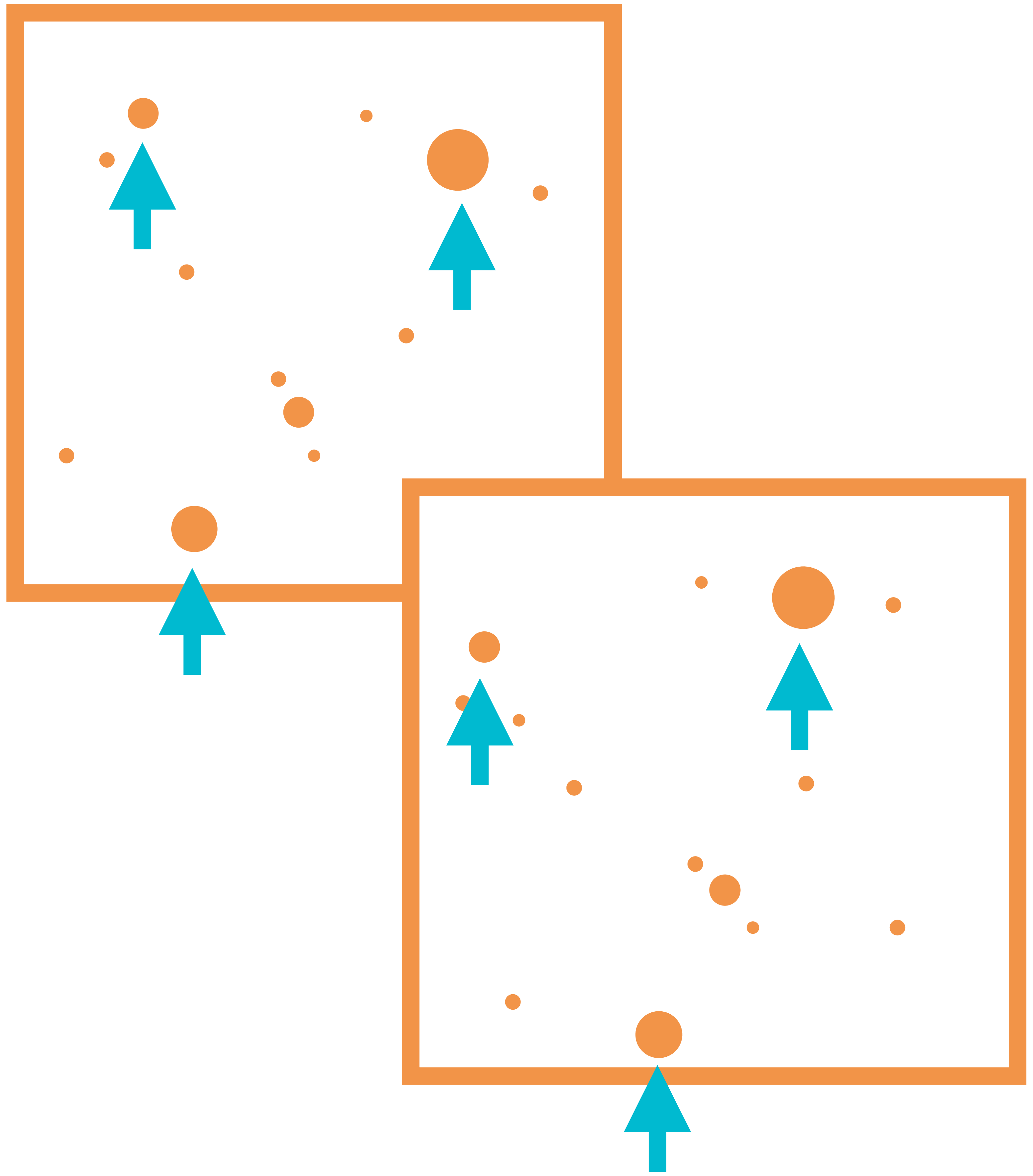
What are some potential technical hurdles to making coadds?

Convert all single-frame images to the same on-sky geometry



Single-frame exposures won't natively have the same mapping between pixel and real-world coordinates.

Convert all single-frame images to the same on-sky geometry

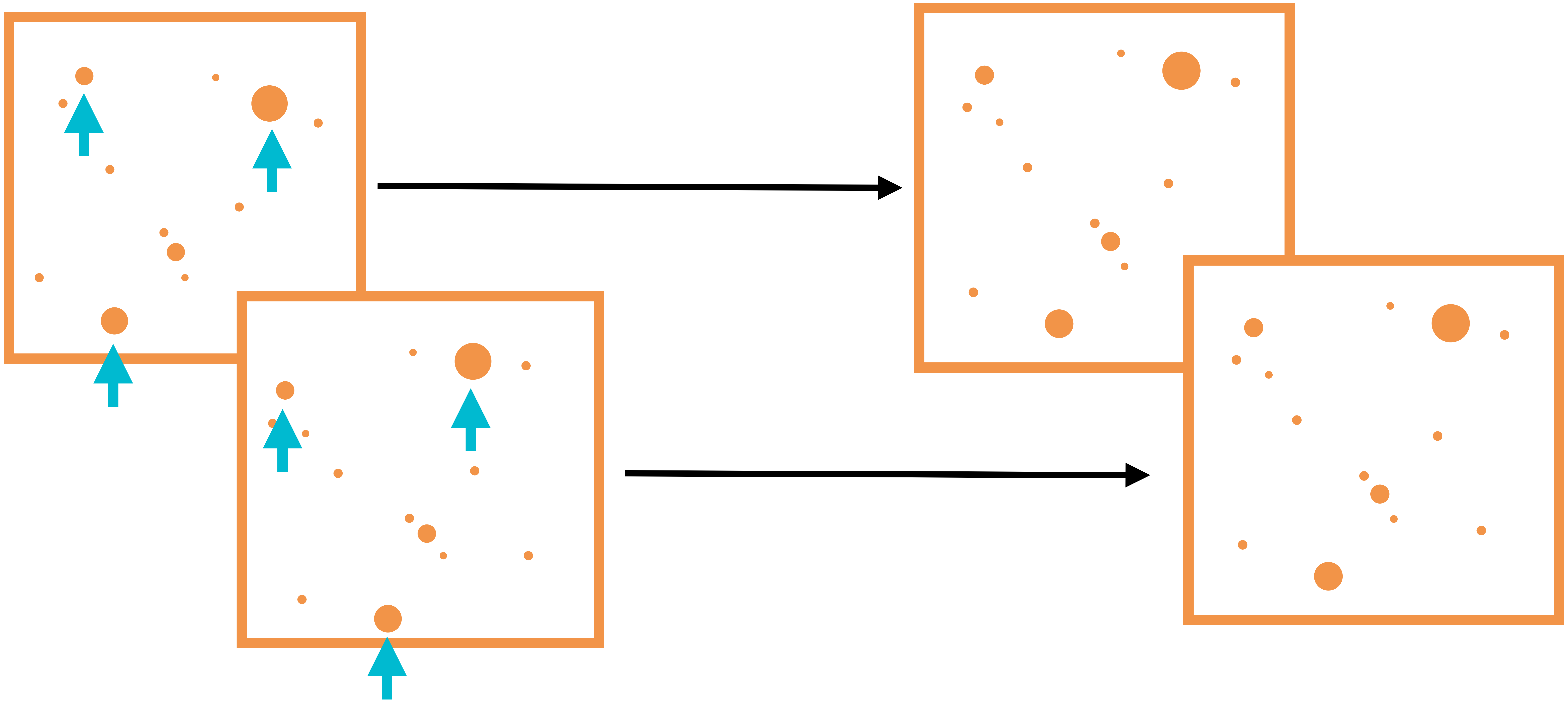


Single-frame exposures won't natively have the same mapping between pixel and real-world coordinates.

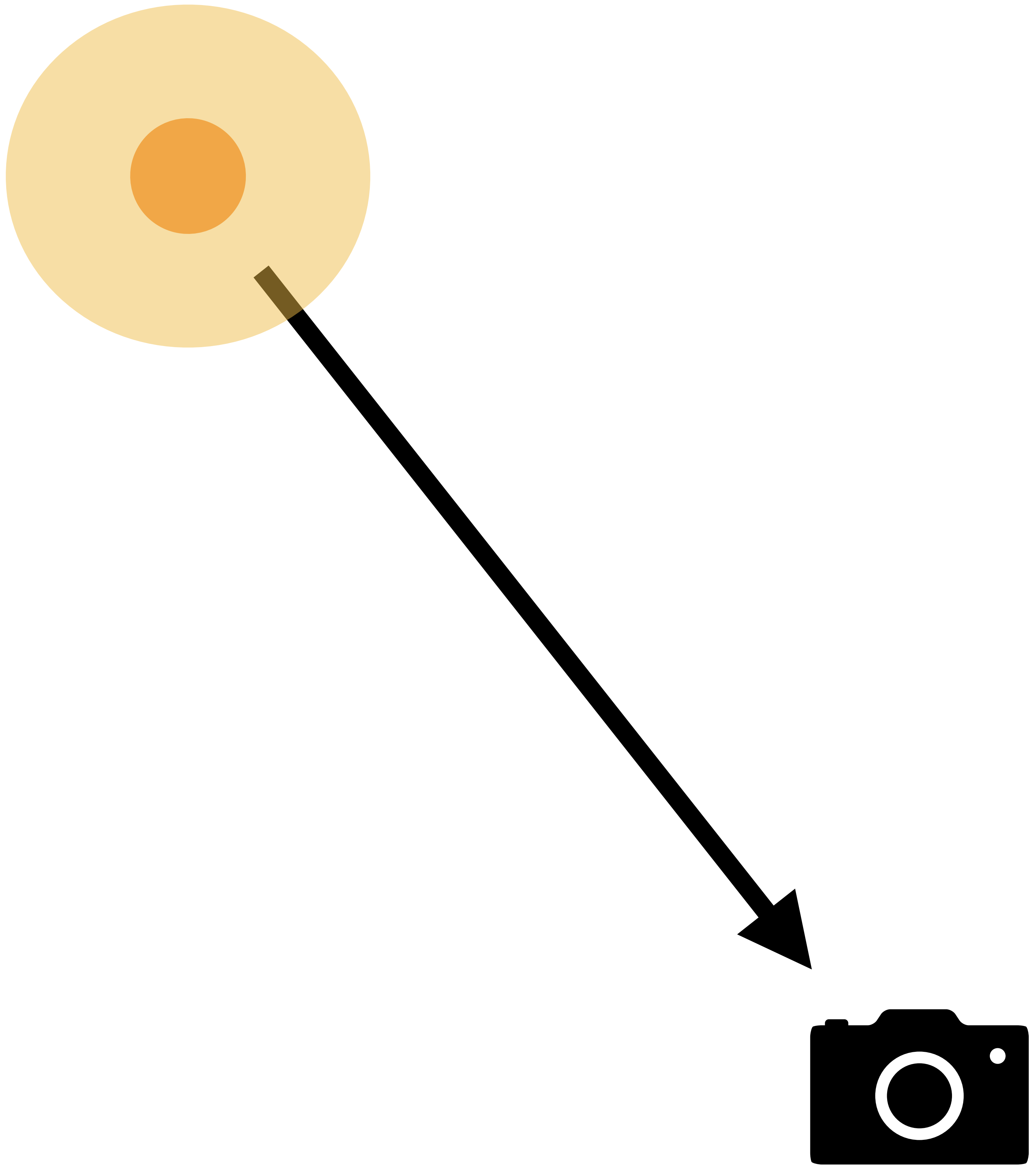
We can use positions of known sources to orient each exposure (recall yesterday's astrometry lecture!)

Then each exposure must be **warped** to a unified pixel coordinate space to create our image stack.

Convert all single-frame images to the same on-sky geometry



Map all single-frame images to the same flux scale

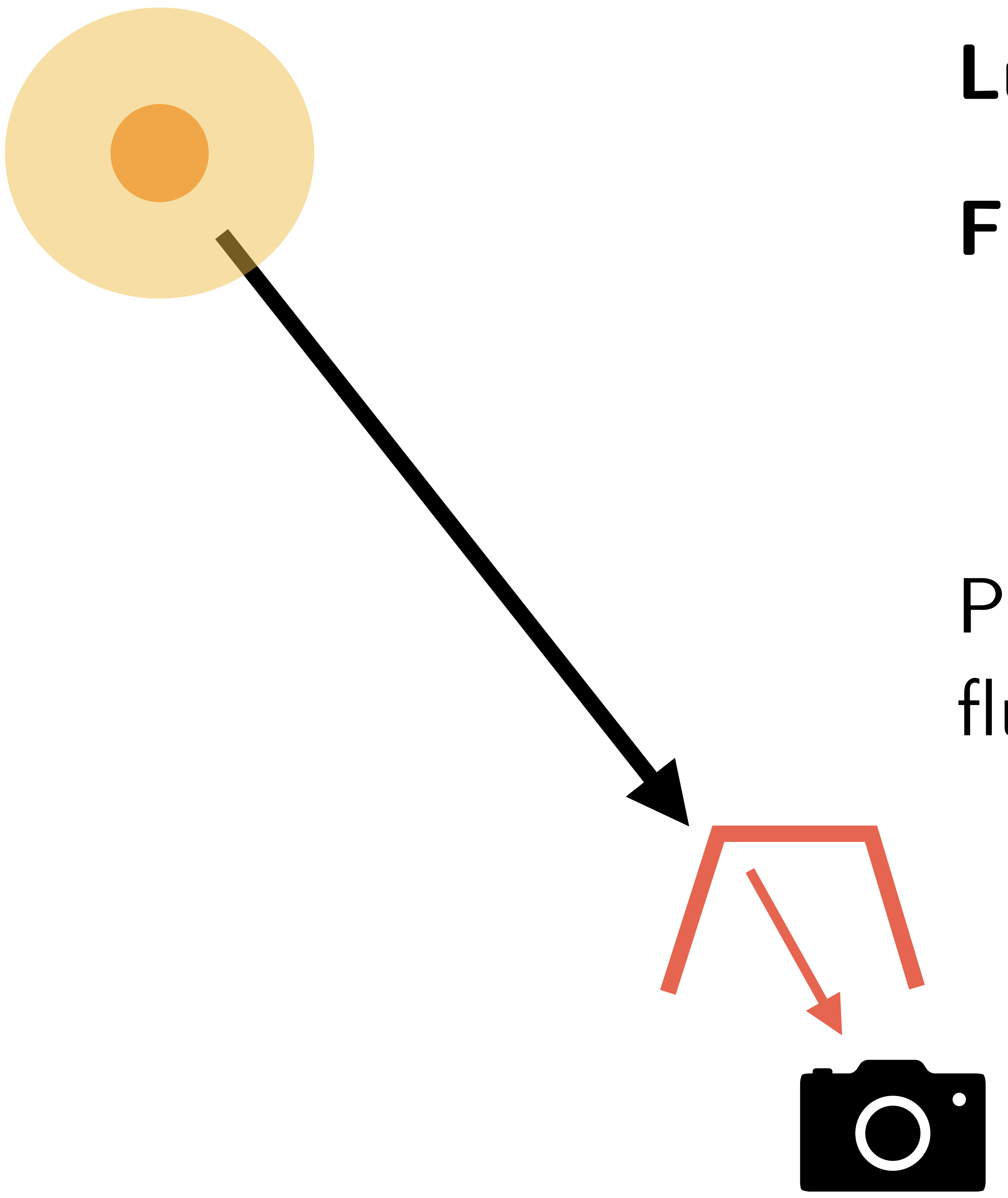


Luminosity: intrinsic source brightness [erg/s]

Flux: observed source brightness at Earth [erg/s/cm^2]

$$F = \frac{L}{4\pi d_L^2}$$

Map all single-frame images to the same flux scale



Luminosity: intrinsic source brightness [erg/s]

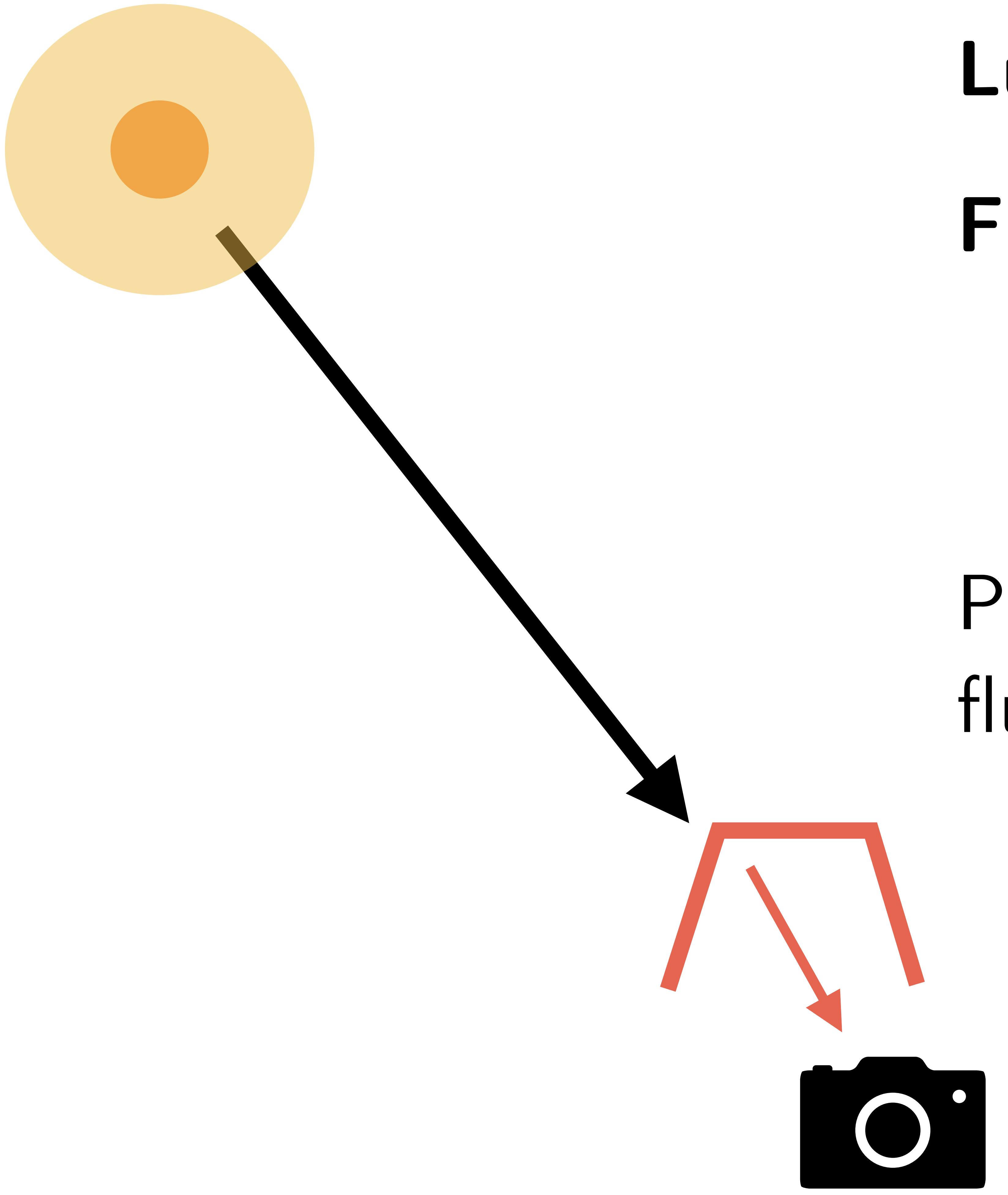
Flux: observed source brightness at Earth [erg/s/cm^2]

$$F = \frac{L}{4\pi d_L^2}$$

Photometric filter allow us to observe **specific spectral** flux averaged over a known bandpass:

$$m_X = -2.5\log_{10}\frac{\int_0^\infty \frac{f_\lambda(\lambda)}{hc/\lambda}T_X(\lambda)d\lambda}{\int_0^\infty \frac{g_{AB}(\lambda)}{hc/\lambda}T_X(\lambda)d\lambda}$$

Map all single-frame images to the same flux scale



Luminosity: intrinsic source brightness [erg/s]

Flux: observed source brightness at Earth [erg/s/cm^2]

$$F = \frac{L}{4\pi d_L^2}$$

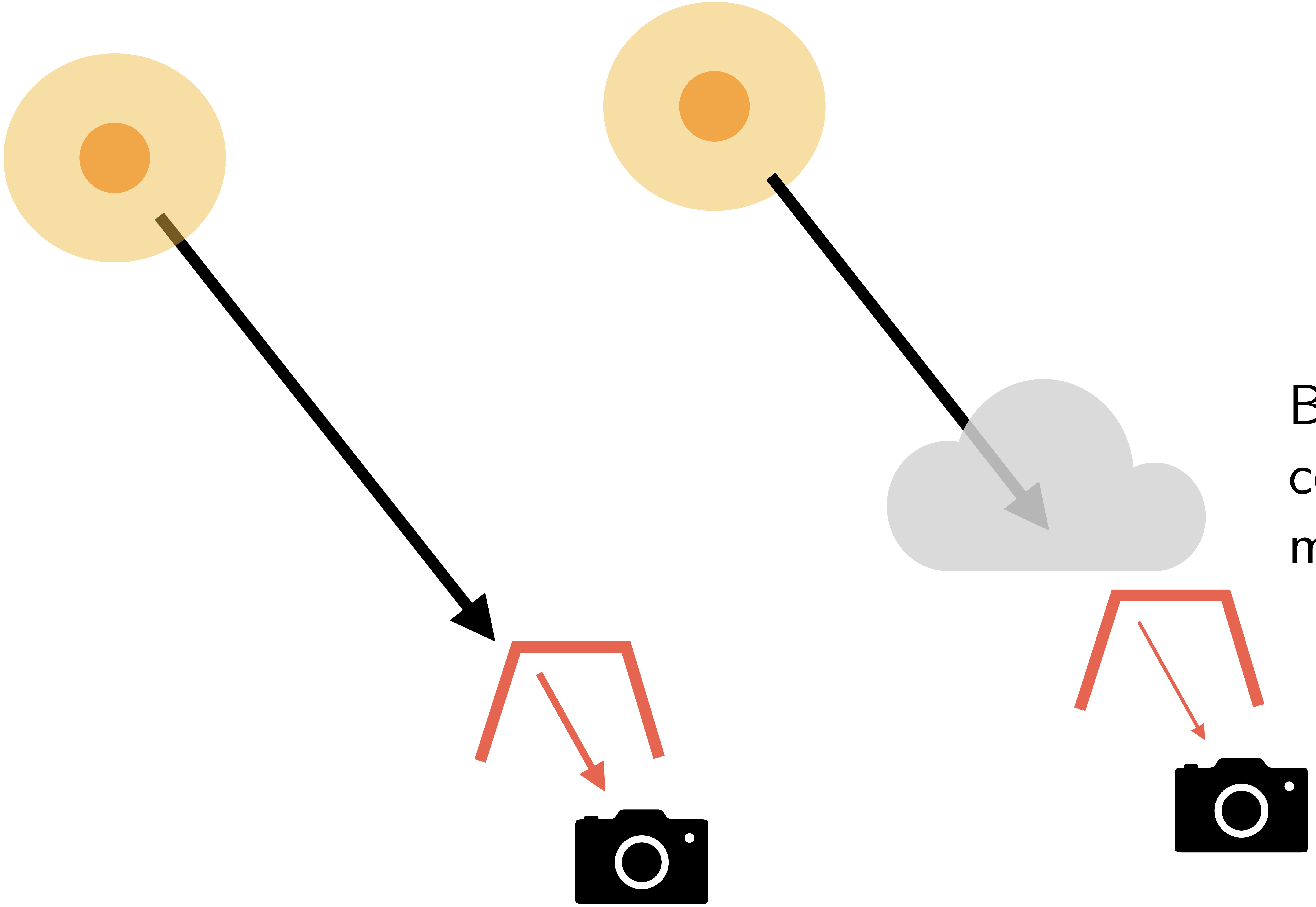
Photometric filter allow us to observe **specific spectral** flux averaged over a known bandpass:

$$f_\lambda(\lambda) = \frac{dF}{d\lambda}$$

$$m_X = -2.5\log_{10}\frac{\int_0^\infty \frac{f_\lambda(\lambda)}{hc/\lambda} T_X(\lambda) d\lambda}{\int_0^\infty \frac{g_{AB}(\lambda)}{hc/\lambda} T_X(\lambda) d\lambda}$$

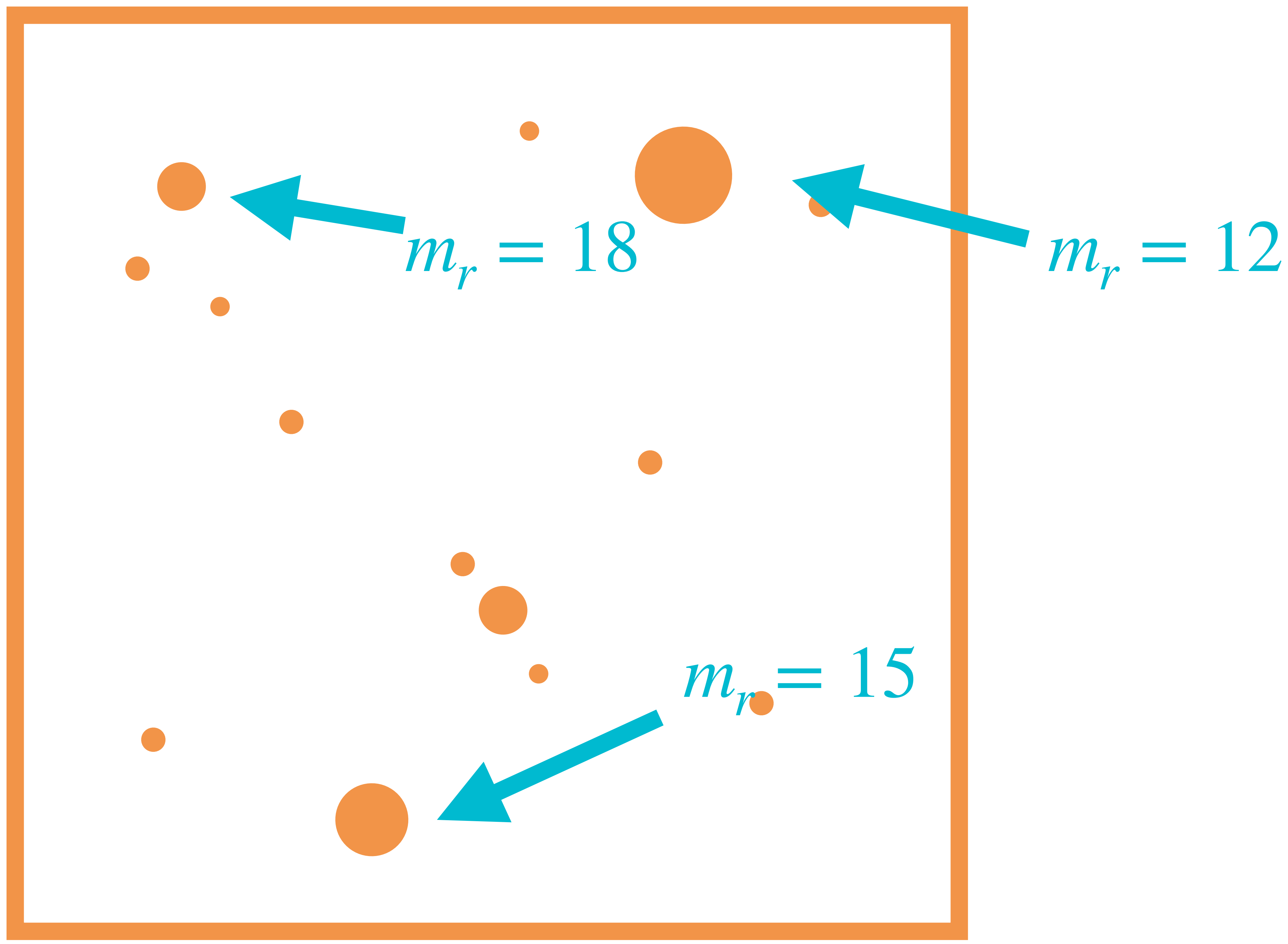
filter transmission

Map all single-frame images to the same flux scale



But, changes in observing conditions can also change how many photons hit the CCD

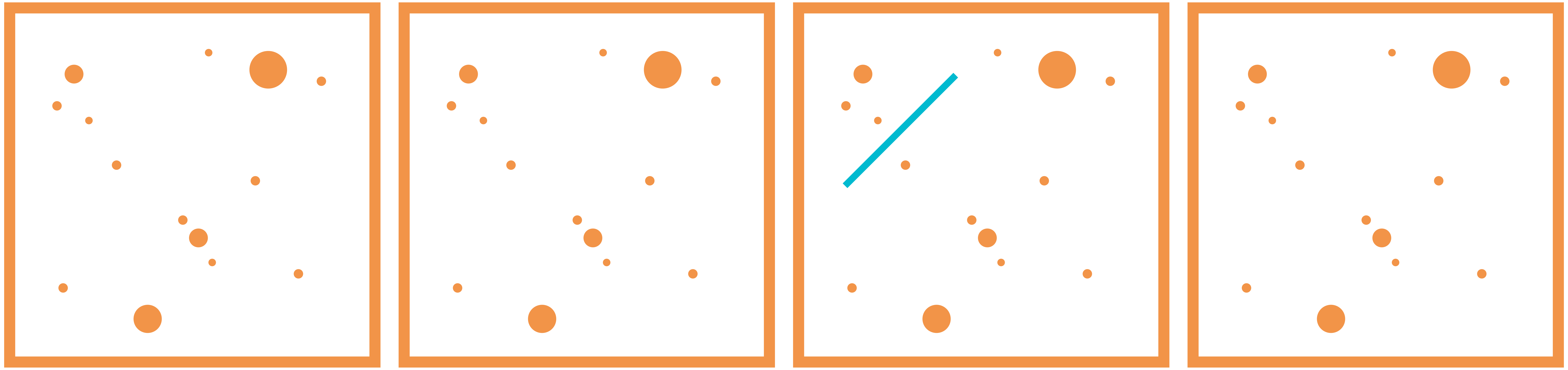
Map all single-frame images to the same flux scale



Observations are taken under different conditions;
detector properties may vary with time.

Use brightnesses of known sources to **flux calibrate** single-frame images.

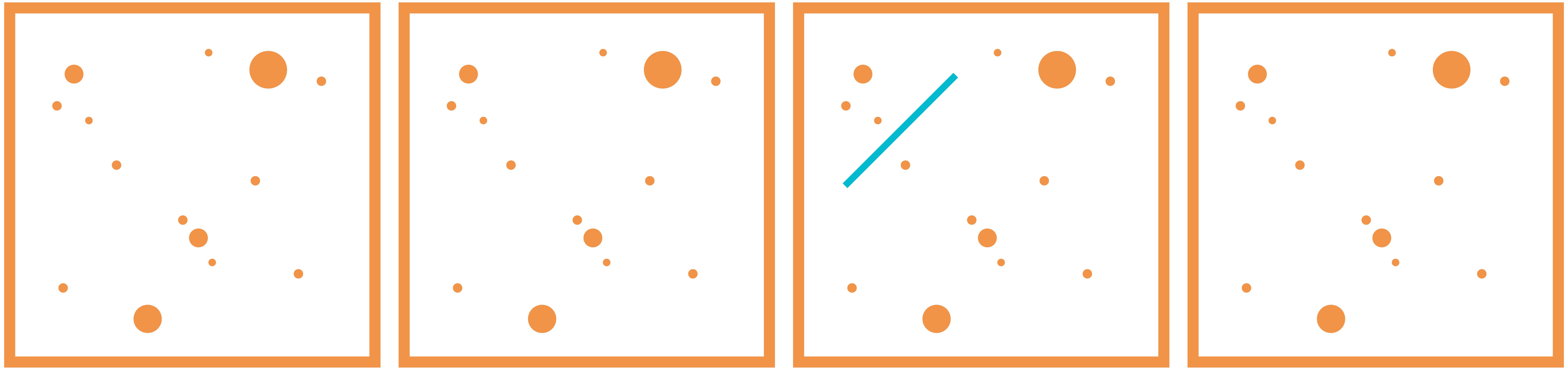
Stack images to create coadds — but first, artifacts



Non-astrophysical artifacts are common phenomena, e.g.:

- satellite trails
- cosmic rays
- optical ghosts

Stack images to create coadds — but first, artifacts

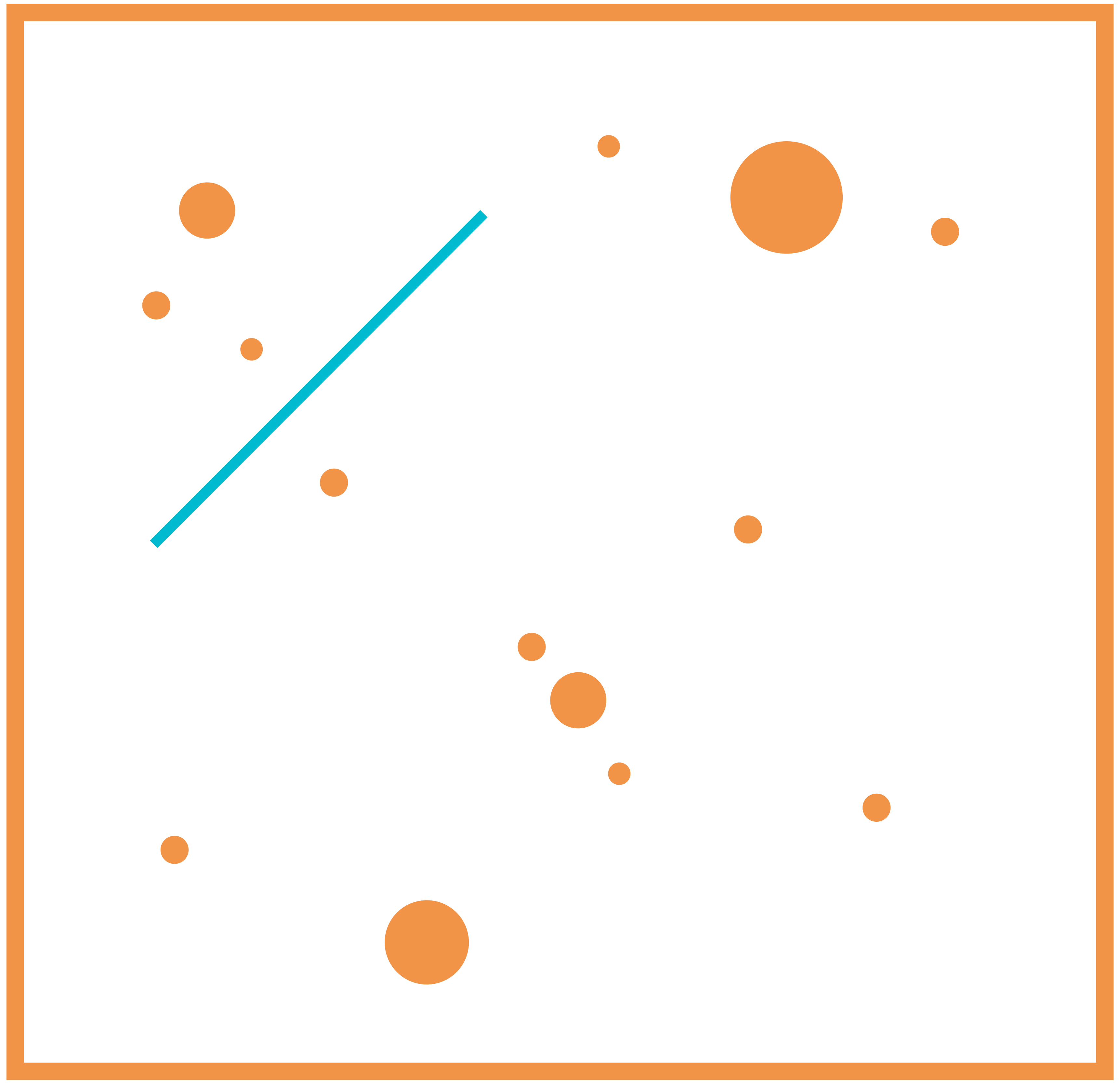


Non-astrophysical artifacts are common phenomena, e.g.:

- satellite trails
- cosmic rays
- optical ghosts

We want to keep all coaddition operations linear to preserve the PSF, but can use "spot the difference" algorithms to remove transient artifacts

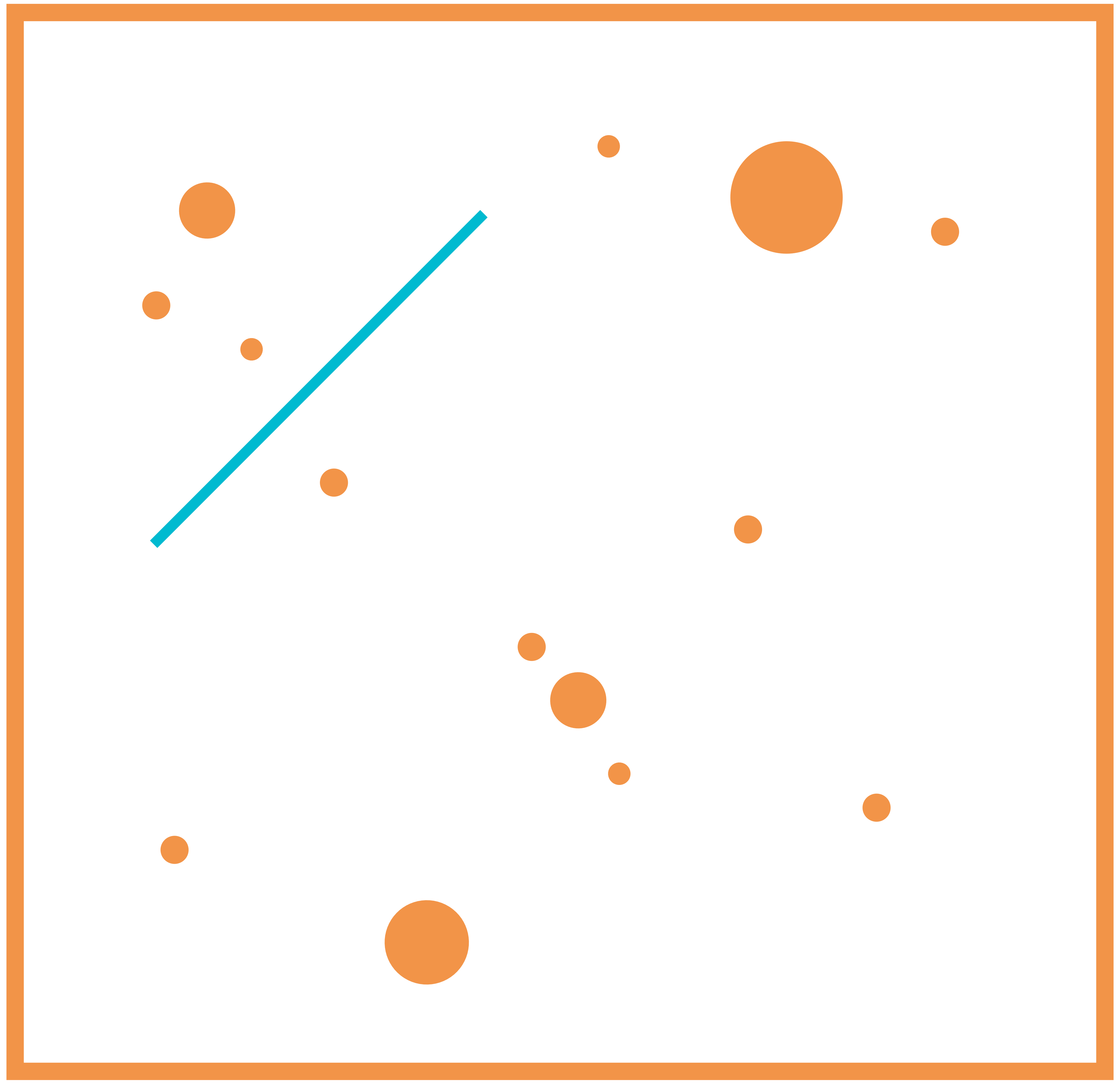
Stack images to create coadds — but first, artifacts



Sometimes you only have a few exposures (or even just one)

We can also use morphology to flag artifacts.

Stack images to create coadds — but first, artifacts



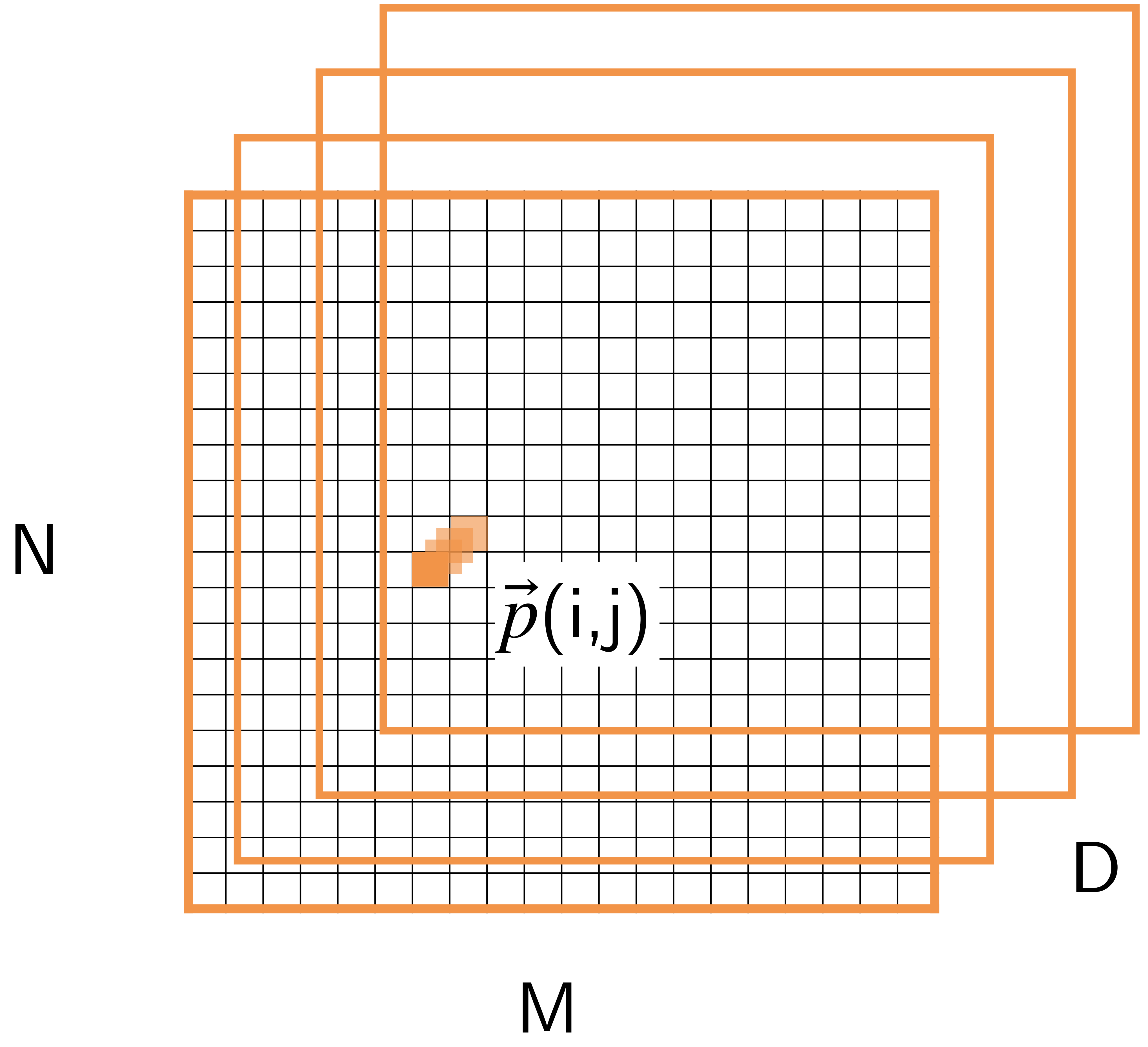
Sometimes you only have a few exposures (or even just one)

We can also use morphology to flag artifacts.

Cosmic rays hit the detector and excite electrons, creating a characteristic thin linear pattern.

We can use the "impossible" thinness of these features to flag them — as you'll see in the problem set.

Stack images to create coadds



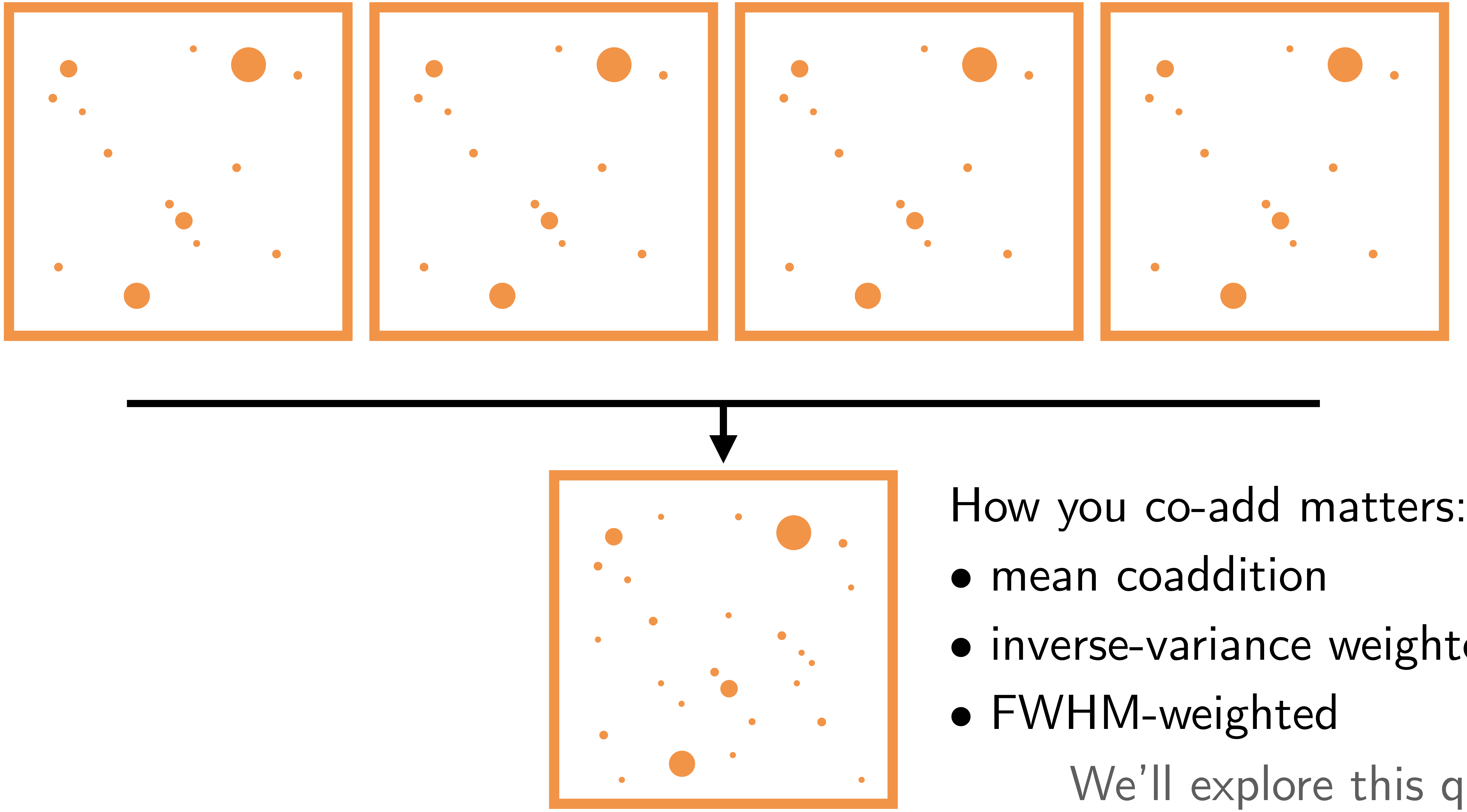
Apply averaging function to go from exposure stack to final coadd:

$$p^{coadd}(i,j) = f(\vec{p}(i,j))$$

In the simplest case (all exposures have the same noise properties), use a mean stack:

$$p^{coadd}(i,j) = \frac{\sum_d^D p_d(i,j))}{D}$$

Stack images to create coadds



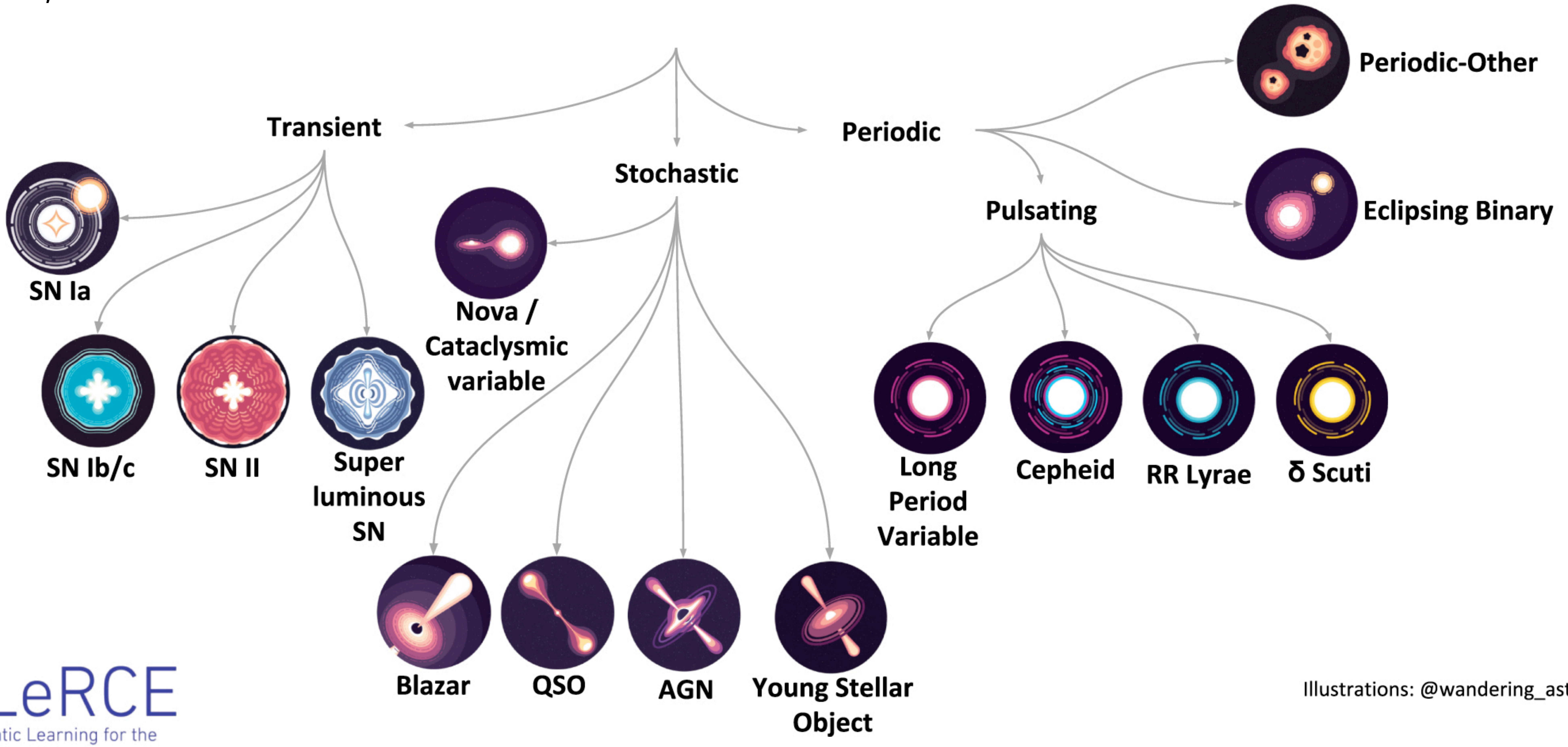
How you co-add matters:

- mean coaddition
- inverse-variance weighted
- FWHM-weighted

We'll explore this quantitatively in the problem set

What is difference imaging?

We often think of astronomy as happening on timescales long compared to human timescales, but!



Illustrations: @wandering_astro

ALeRCE
Automatic Learning for the Rapid Classification of Events

What is difference imaging?

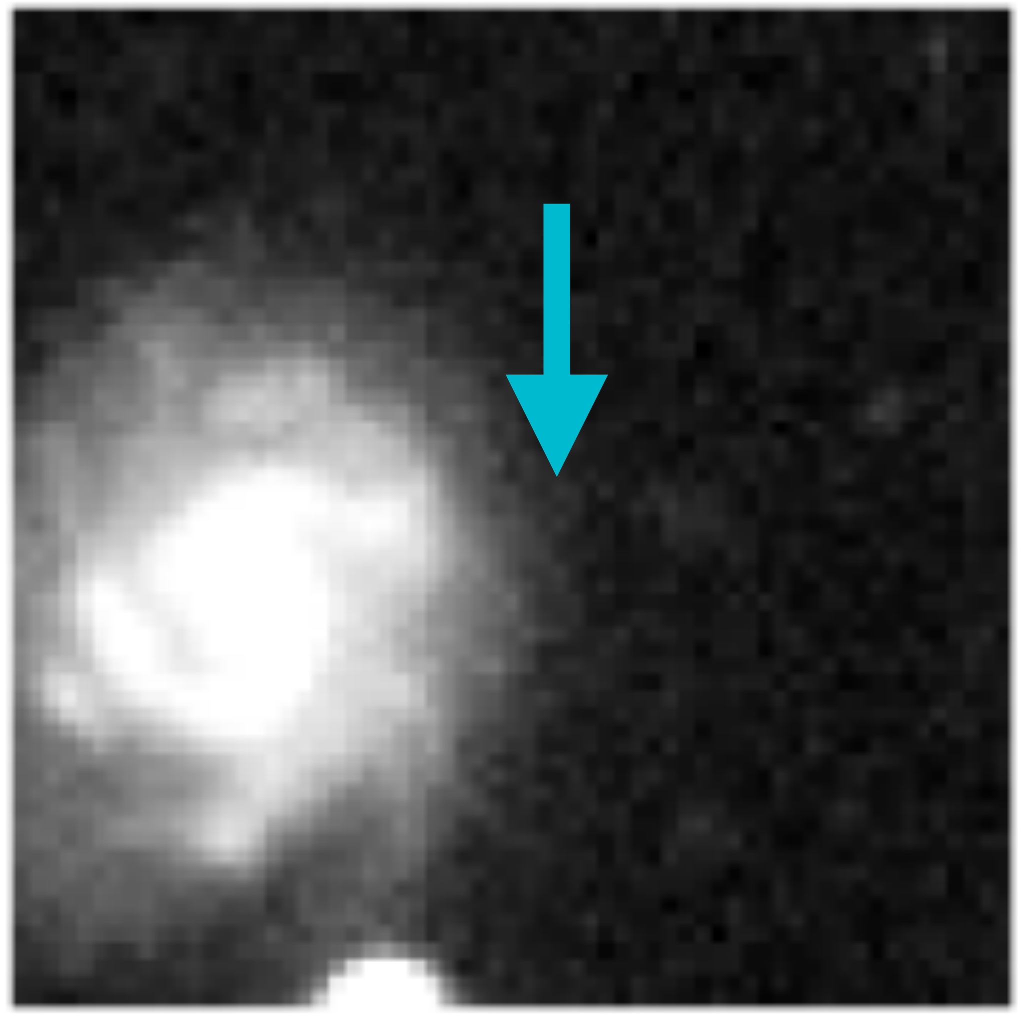
How do we know if something has changed in an image?

science frame

What is difference imaging?

We can compare to a previously constructed **reference image**!

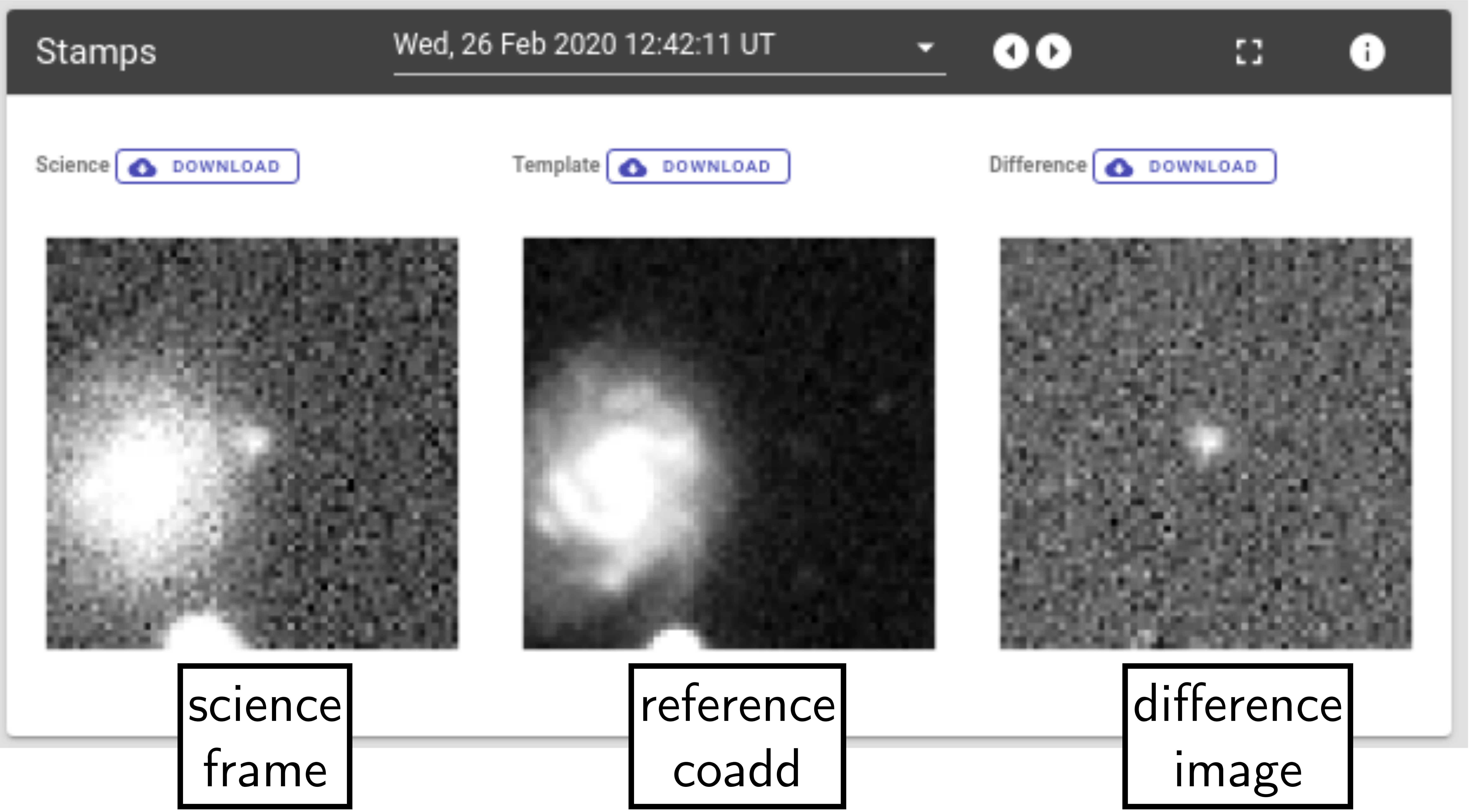
science frame



reference coadd

What is difference imaging?

Doing this quantitatively is called **difference imaging**



A roadmap to difference imaging

- Convert all single-frame images to the same on-sky geometry
- Map all single-frame images to the same flux scale
- Create reference image
- Perform single-epoch photometry against reference image
- [Distribute coadds to the scientific public!]

Discuss with your partner:

How might difference image processing differ from coadditon?

[besides subtraction instead of addition :)]

A roadmap to difference imaging

- Convert all single-frame images to the same on-sky geometry
- Map all single-frame images to the same flux scale
- Create reference image
- Perform single-epoch photometry against reference image
- [Distribute coadds to the scientific public!]

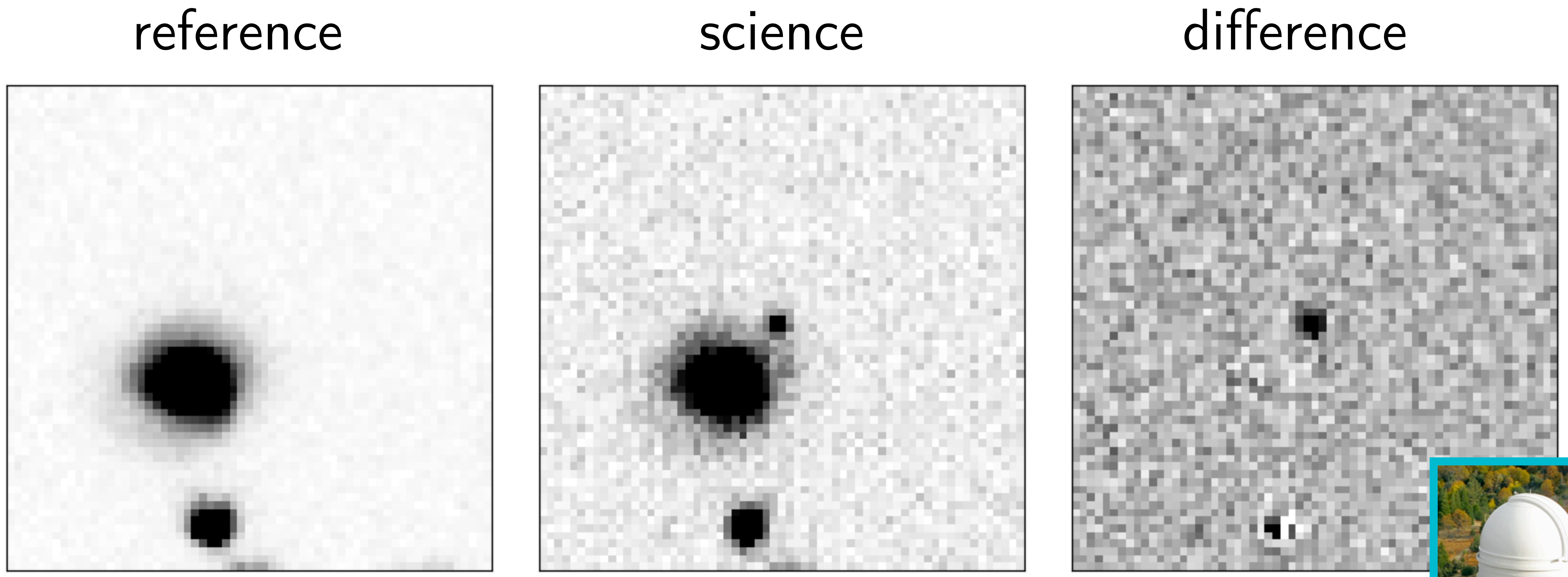
Discuss with your partner:

How might difference image processing differ from coadditon?

[besides subtraction instead of addition :)]

Difference photometry

Difference imaging can be pixel-scale:

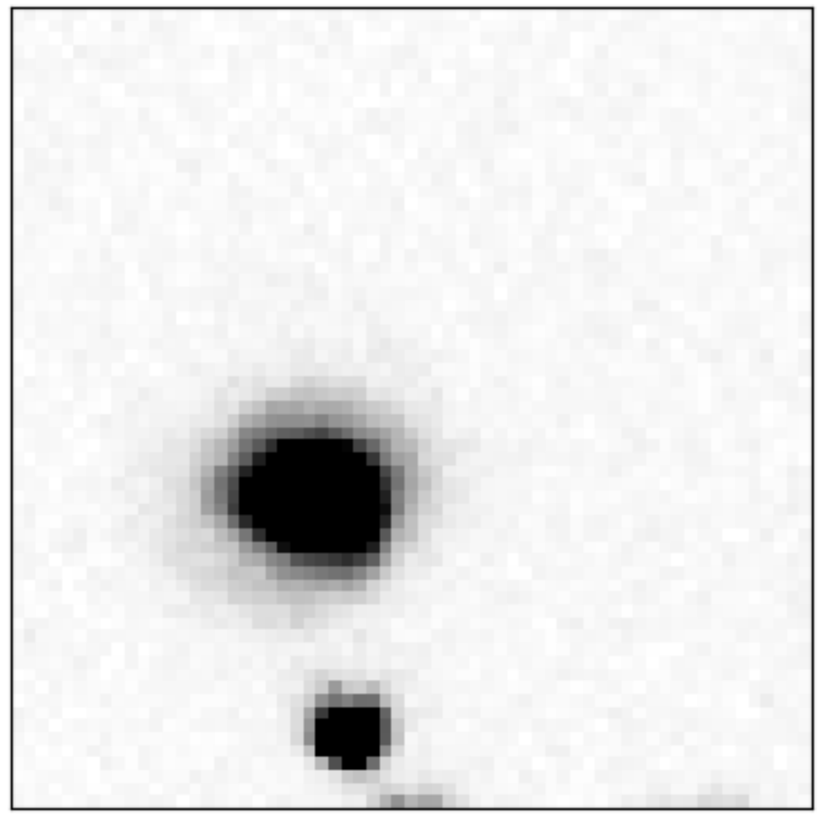


Zwicky Transient Facility
P48 (1.2m) @ Palomar

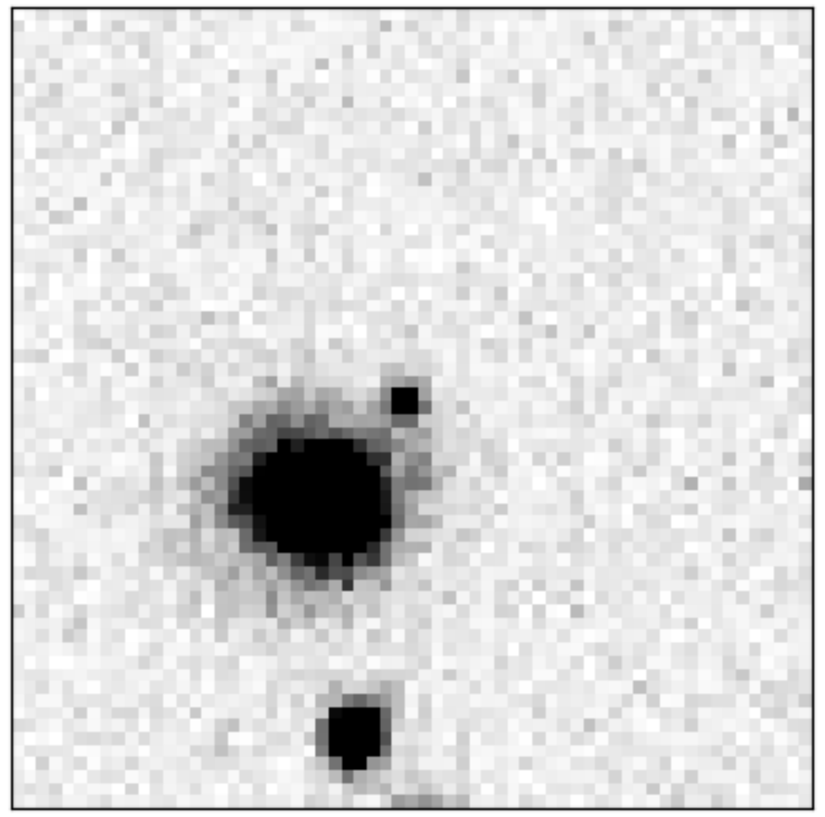
Difference photometry

Difference imaging can be pixel-scale:

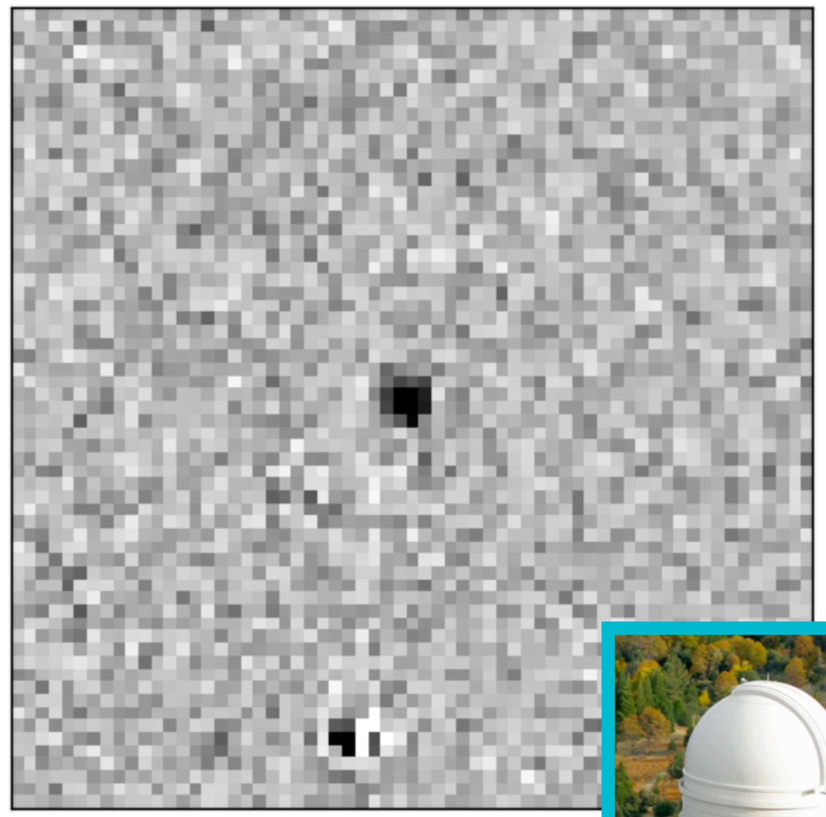
reference



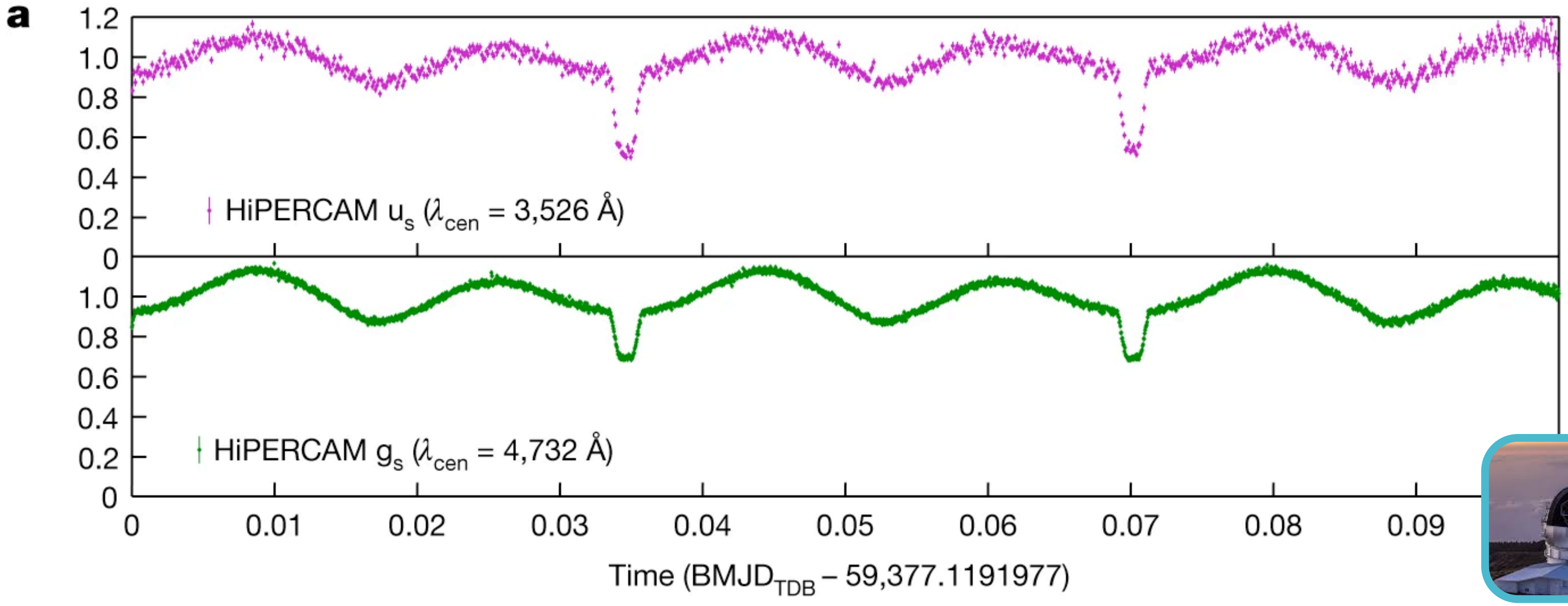
science



difference



Zwicky Transient Facility
P48 (1.2m) @ Palomar

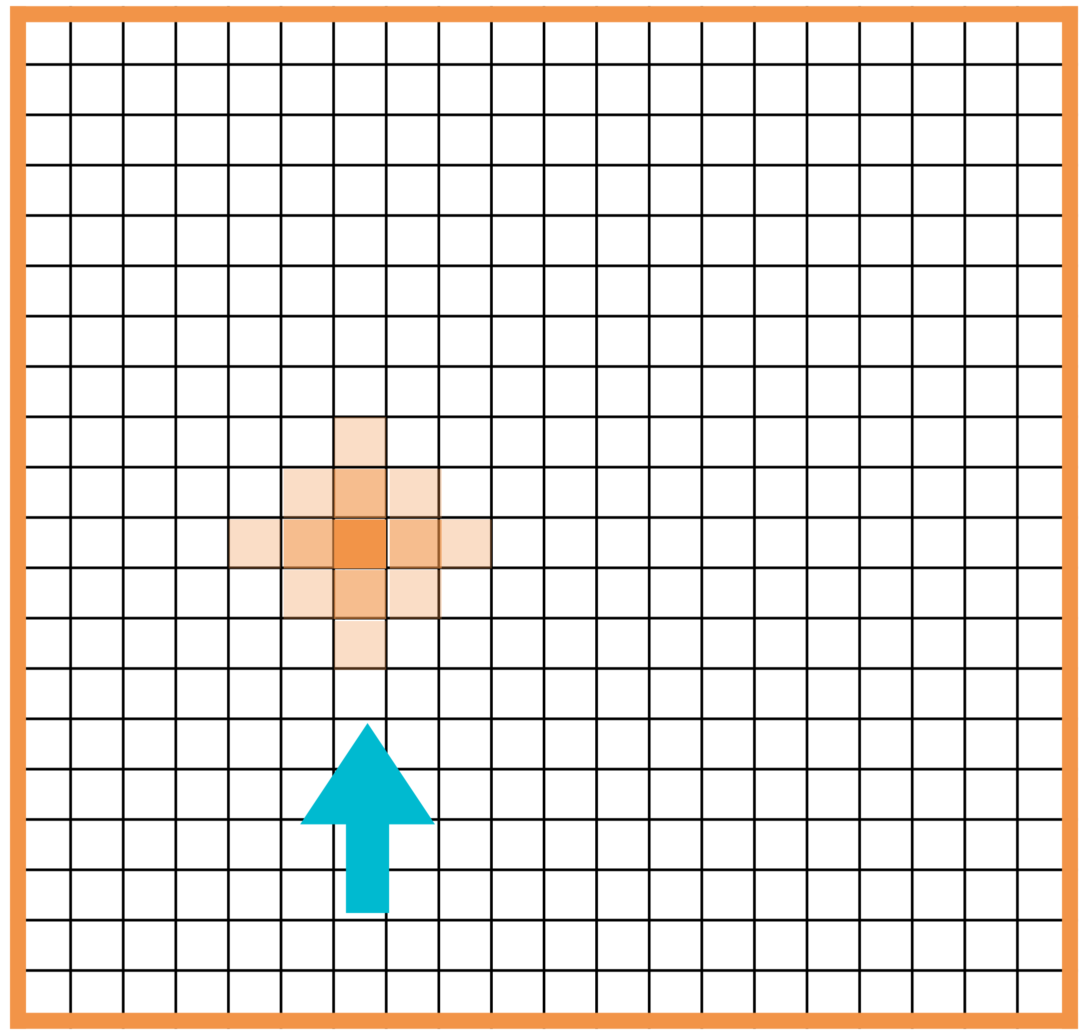


Or done at the source scale

HiPERCAM
Gran Telescopio Canarias (10.4m)

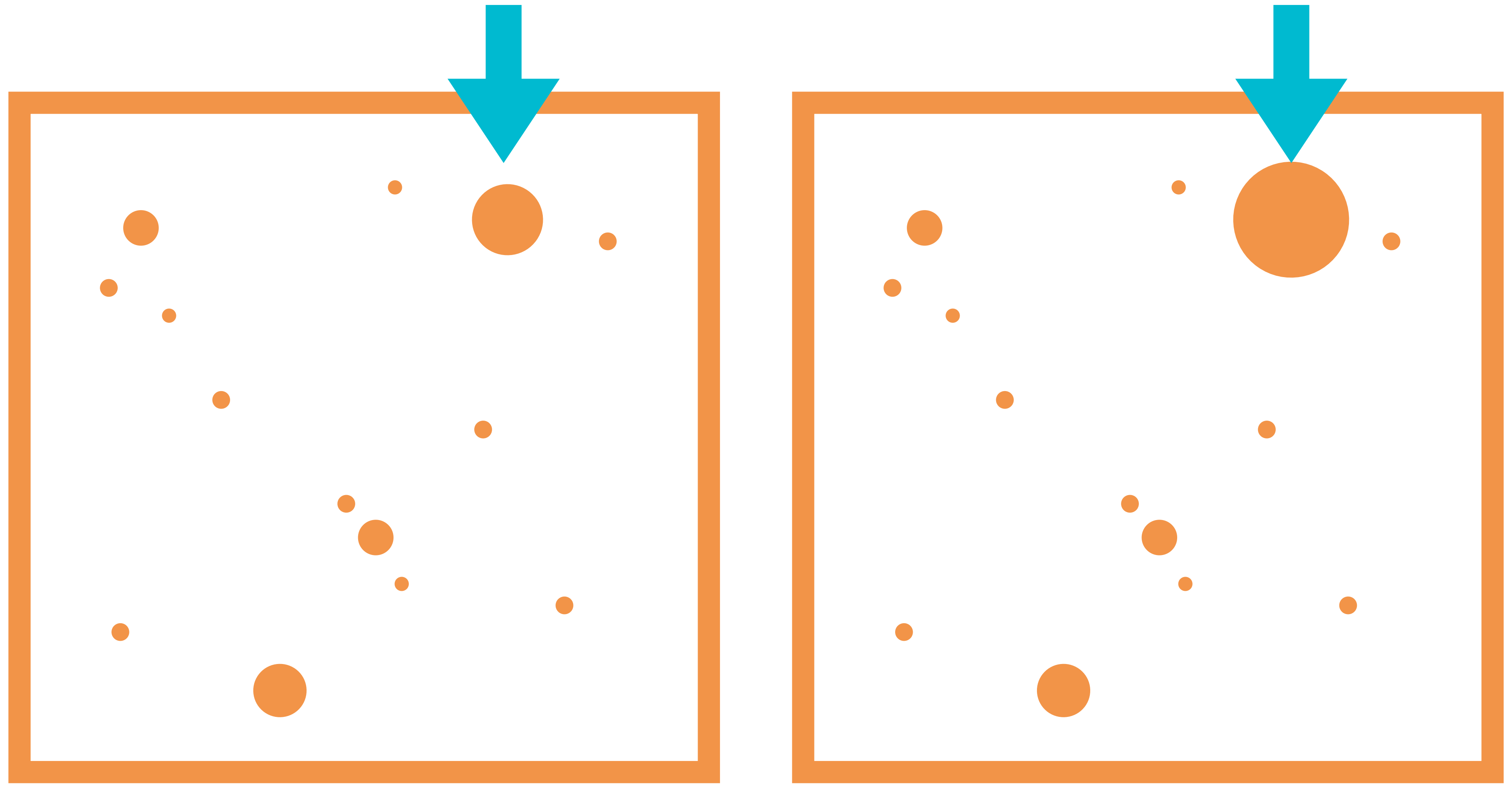
Difference imaging - pixel vs. source scale

difference image



pixel-scale: construct difference image by subtracting reference frame from science frame, look for sources that have changed

$$\Delta m = m_{sci} - m_{ref}$$

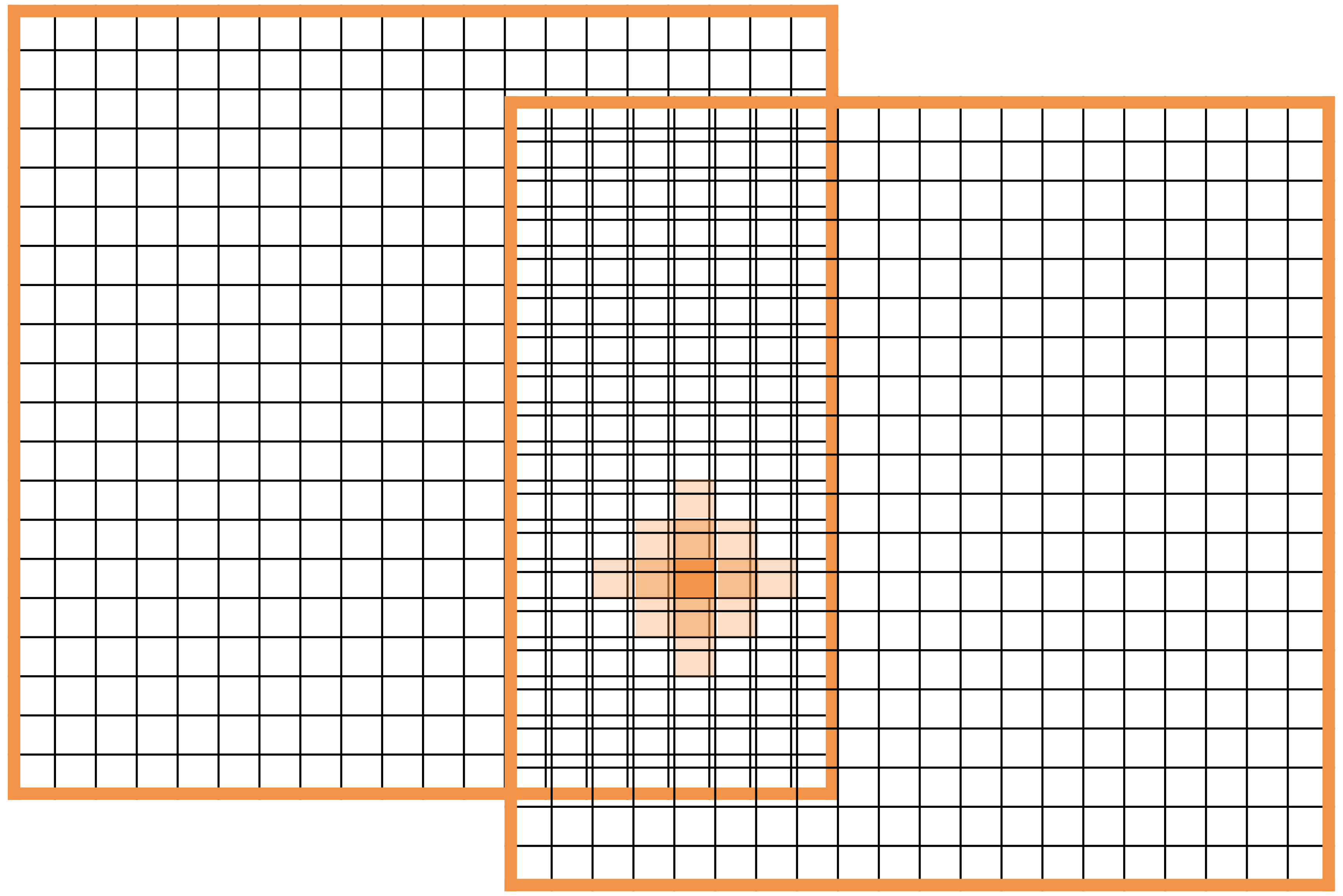


reference

science

source-scale: from a catalog of known sources, perform matched photometry on reference image and science frames

Tiling - what and why?



Tiling refers to the pointing strategy observers use to image contiguous and overlapping areas of the sky.

Why tile?

- Overcome detector non-uniformity (e.g. FOV variation, hot pixels)
- Fill CCD chip gaps
- Provide contiguous imaging

Tiling & Survey Strategy

Imaging surveys are often characterized by the **depth**, **area**, and **resolution** of their resulting coadds,

But as observers, we can't actually control many aspects of exposure quality:

- Not all parts of the sky are visible in any given night
- Imaging quality for a given exposure depend on observing conditions
- Not all parts of the detector are equally sensitive/FOV bandpass variations

How survey strategy relates to image processing

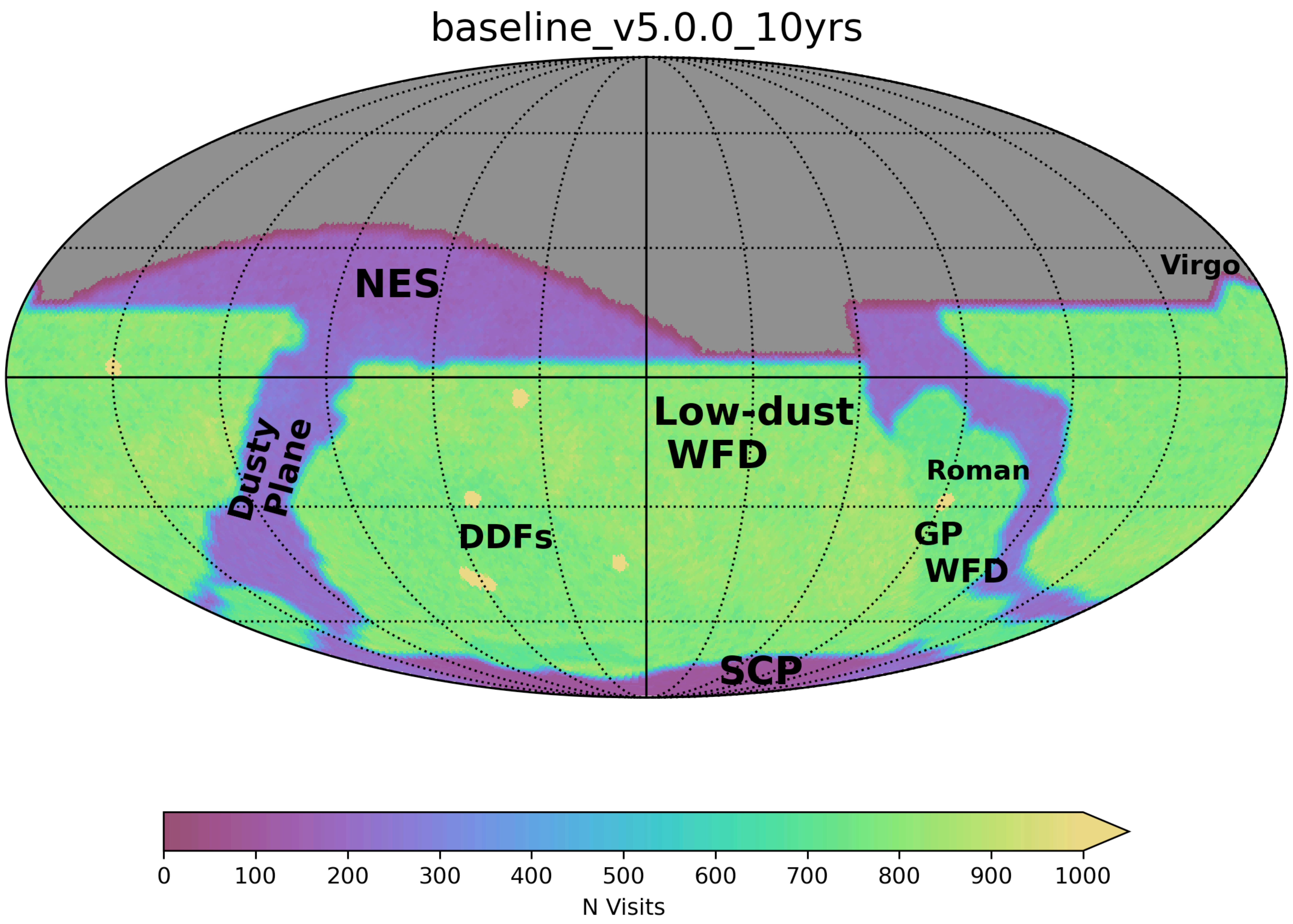
Different science goals can require different observation strategies:

- **Faint galaxy surveys** might want very deep coadds over a relatively small part of the sky
- **Short-period variable surveys** might want high cadence observations for known interesting targets
- **Transient surveys** might want to monitor large areas of the sky to maximize probability of detection

Discuss with your partner:

If you were the sole decider of LSST observations, what cadence/coverage would maximize our science goals? What science might we miss out on with this strategy?

LSST Baseline Strategy



- **Wide Fast Deep** (WFD) survey
- **"Mini"/"Micro"** surveys
- **Deep Drilling Fields** (DDF)
- **Target of Opportunity** (ToOs)