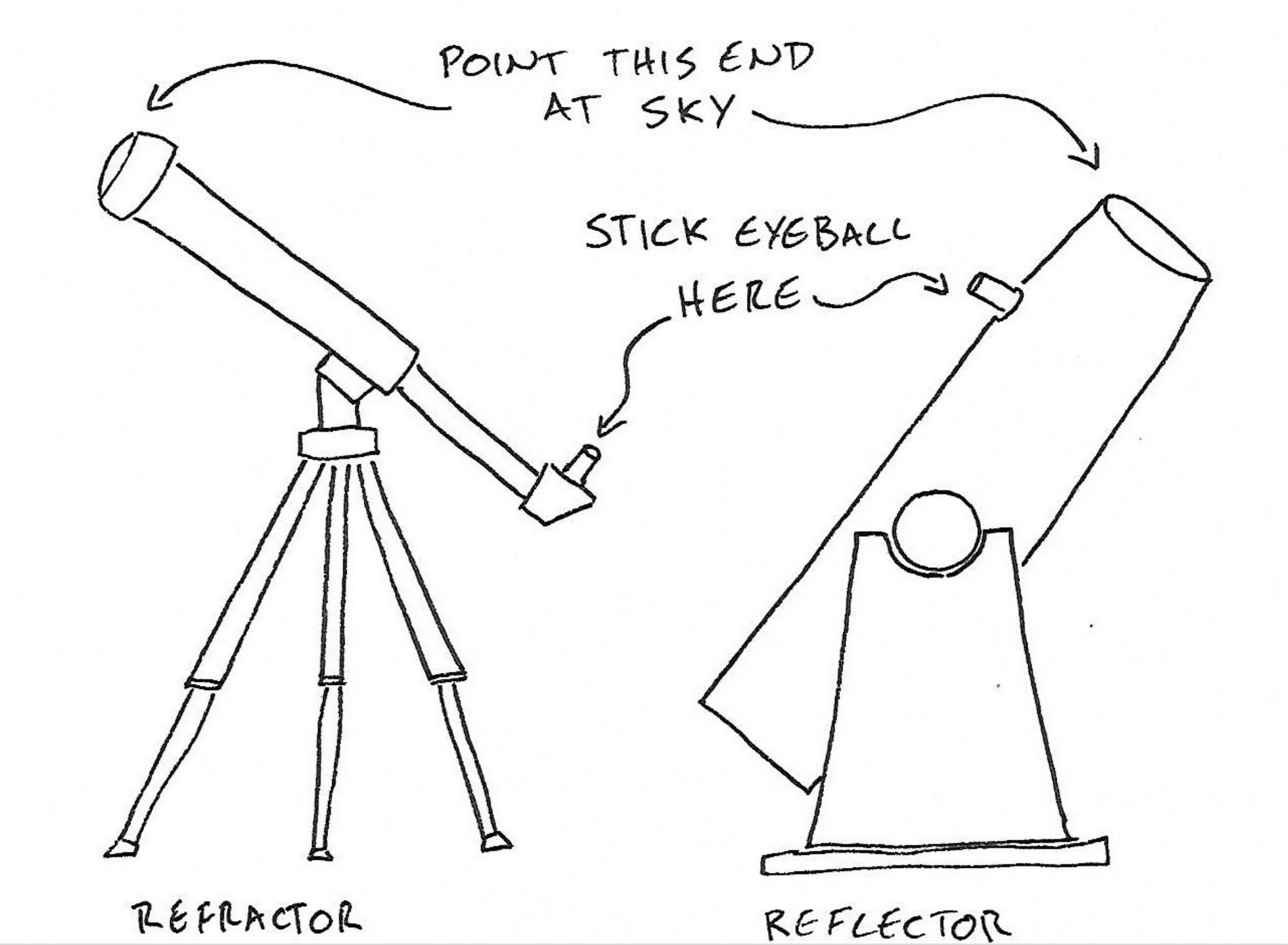
# Telescopes

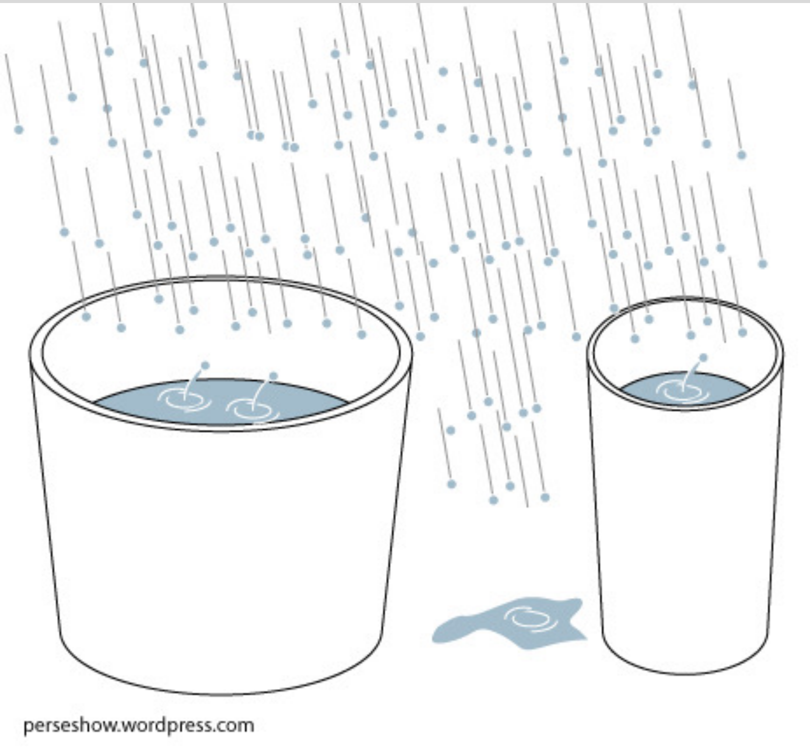



courtesy [Zach Dickeson]

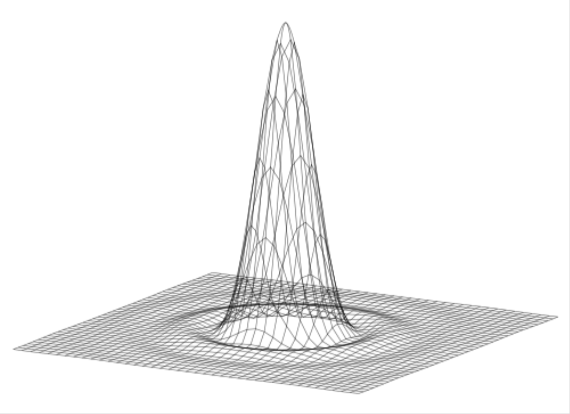
# Telescopes: why so big?

**1. Collecting area:** Telescopes are light buckets.

The amount of light at telescope collects scales as the area of the primary lens or mirror. Bigger telescopes collect more light. When an astronomer talks about the size of a telescope, they almost always are refering to the diameter of the primary.



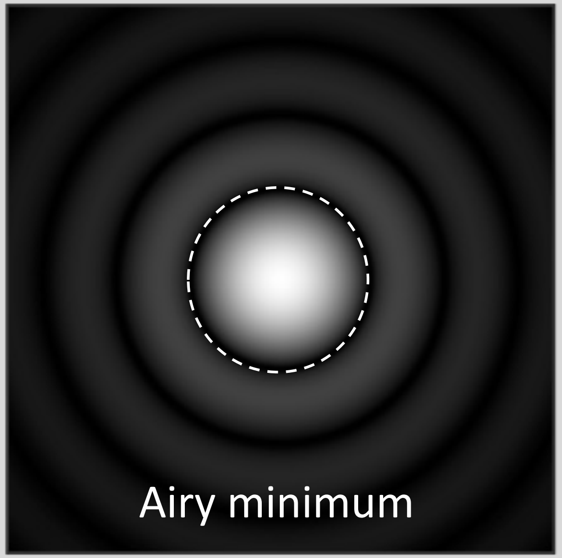
# Telescopes: why so big?



**2. Angular Resolution**: Bigger telescopes can (in principle) produce sharper images.

The interaction of light waves with an aperture leads to interference patterns: diffraction. In the case of a perfect circular aperture (like an unblocked lens or mirror), this leads to a point source (like a star) being imaged as an Airy pattern.

The "Rayleigh limit": once two point sources come closer than the angular size of their first Airy minimum, they are not resolved.

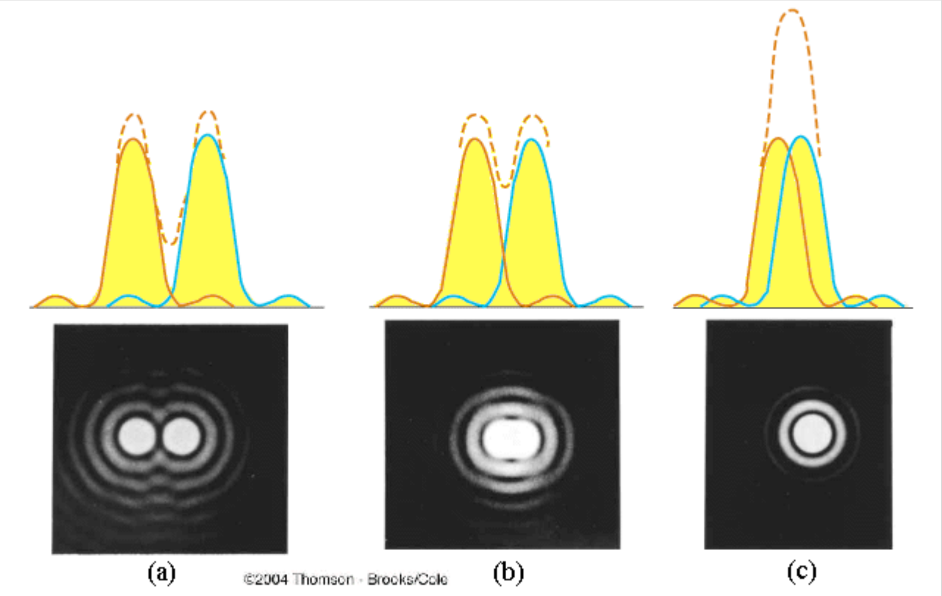



The first minimum of the Airy pattern comes at an angular size:

$$\theta_{min} = 1.22\,\lambda/D$$

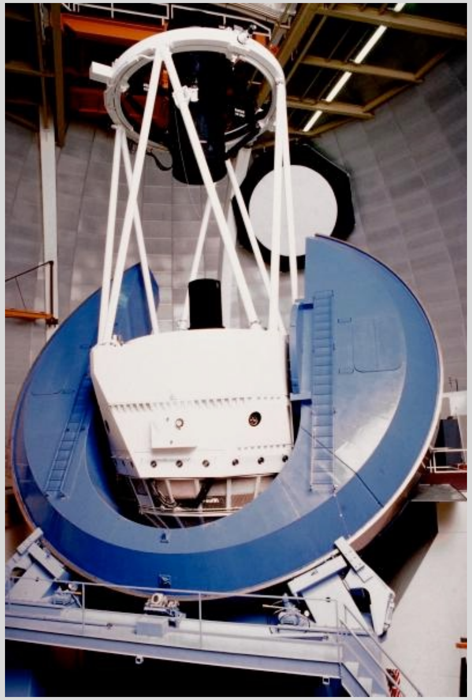
where $\lambda$ is the wavelength of the light and $D$ is the diameter of the telescope.

Big telescope: smaller Airy disk, better resolution, *in principle.*



# Diffraction limit of telescopes

"Diffraction limit" means that the angular resolution of the telescope is set by the Rayleigh criteria for diffraction: $\theta_{min} = 1.22\,\lambda/D$.



λ=5000Å (optical)

- D=10cm ➔ $\theta_{min}$=1.2 arcsec
- D=4m ➔ $\theta_{min}$=0.03 arcsec

λ=21cm (radio)

- D=20m ➔ $\theta_{min}$=35arcmin
- D=100m ➔ $\theta_{min}$ = 7 arcmin

Two important caveats:

- To make a diffraction limited mirror, the surface must be polished to accuracy < λ
- From the ground, atmospheric blurring ("seeing") is typically 1 arcsec or so.


https://twitter.com/fox_ori/status/1659196706079264774

# Telescope Types

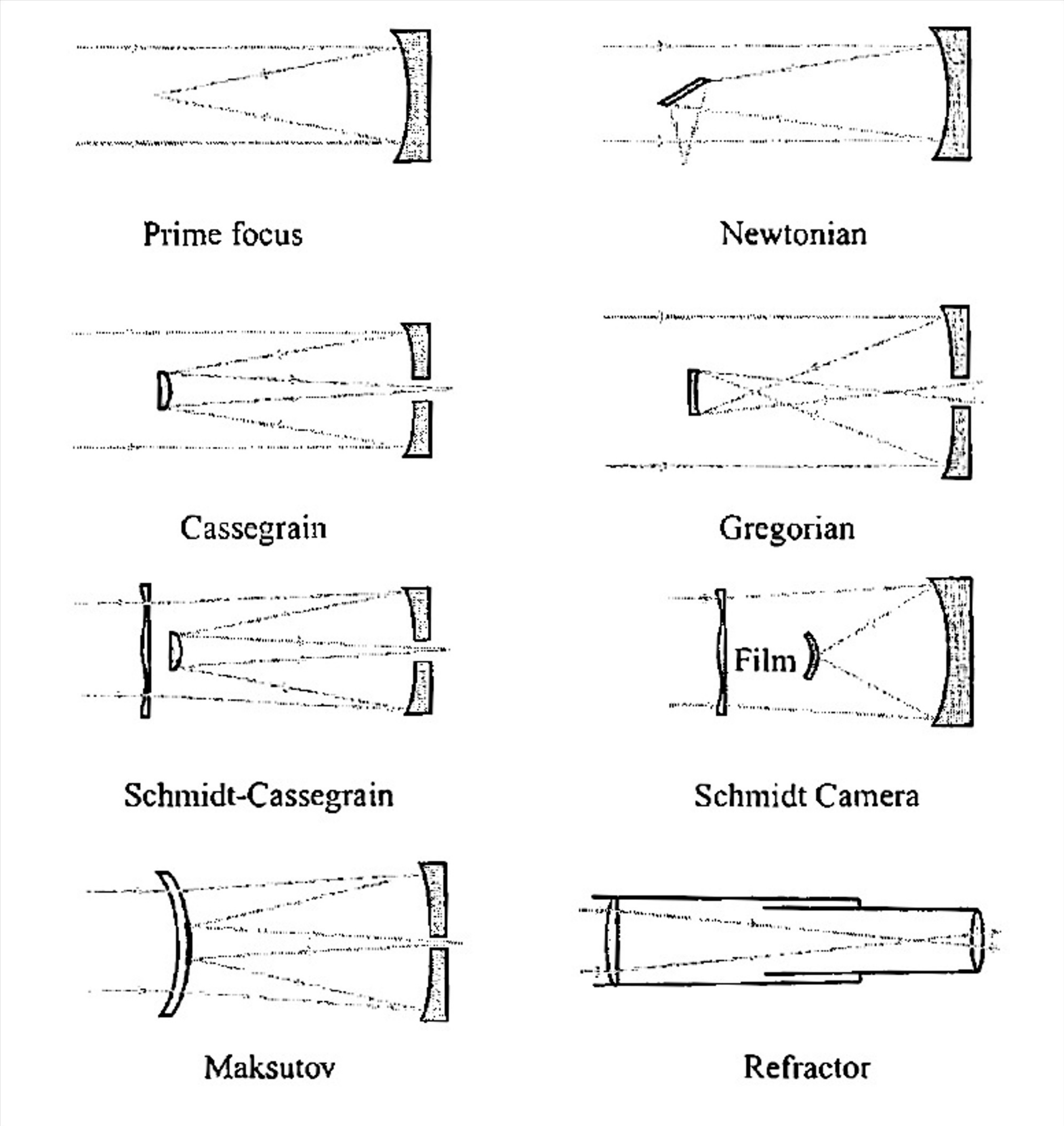
Refractors use lenses, reflectors use mirrors. Easier to construct/support big mirrors than big lenses, so most big telescopes are reflecting telescopes.

“Primary” is the main collector (mirror/lens)
“Secondary” mirrors redirect the light to focus postion

Differences in design due to:

- where to put the focus
- maximize field of view
- minimize field distortions

The full optical properties of a telescope depend on the properties of the primary, the secondary, and all the details of the camera/spectrograph which gets placed at focus.



**The Focal Plane and the Detector**

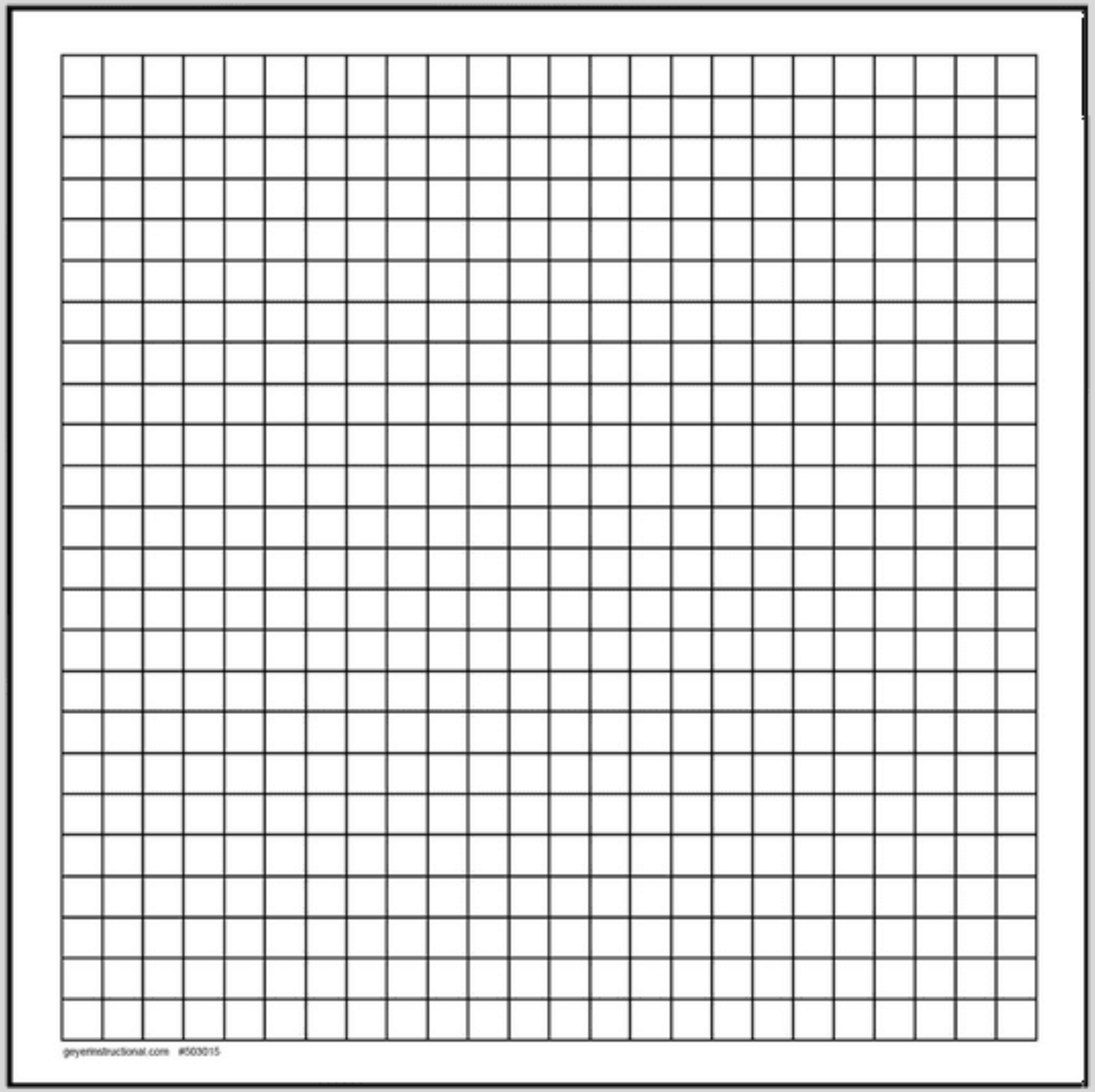
The focal plane is the location along the light path where the incoming light rays come to a focus.

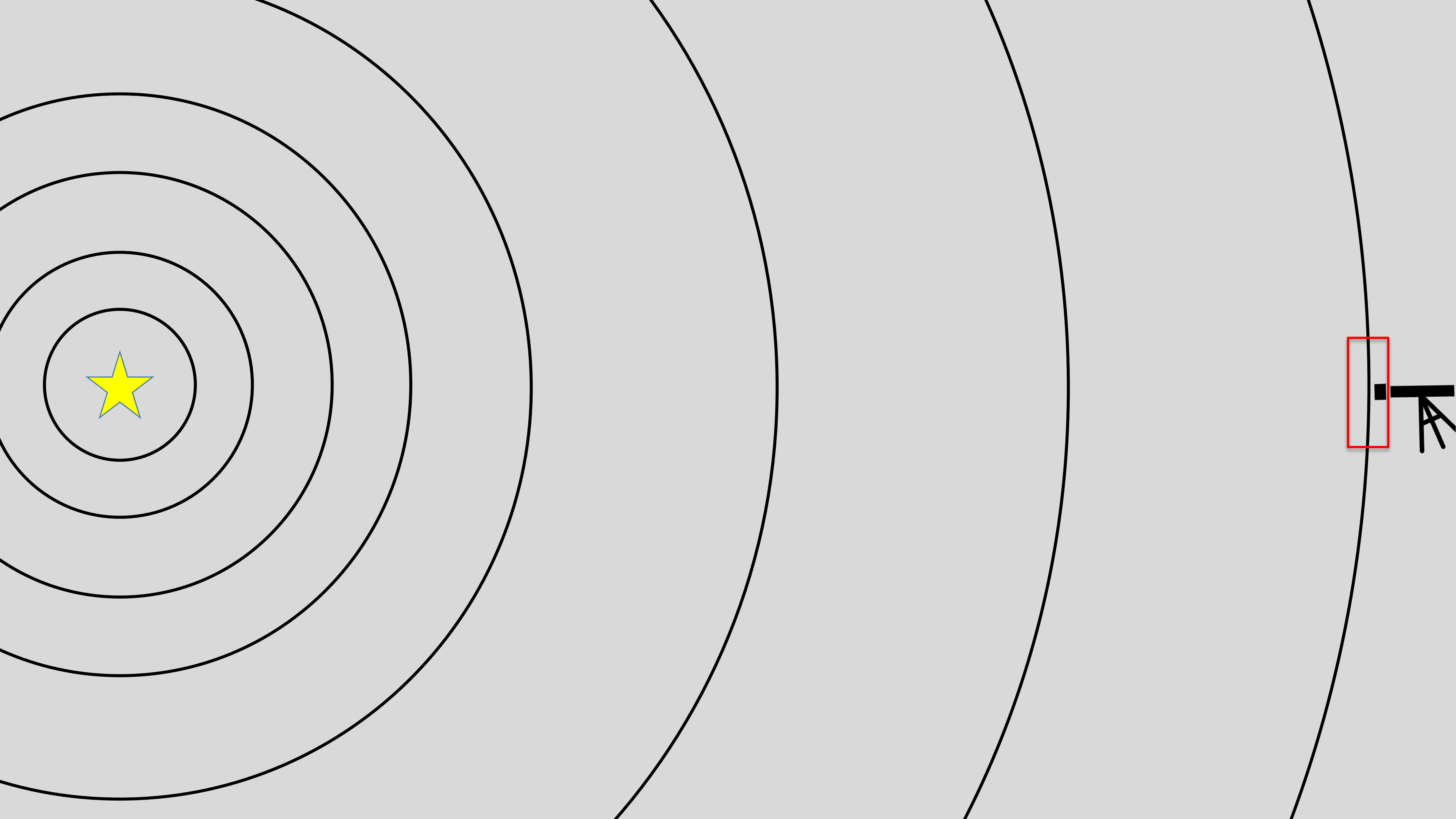
The detector sits at the focal plane and detects the light. Modern detectors are "charge-coupled devices" (CCDs) that have a grid of pixels that count the photons received at each position.

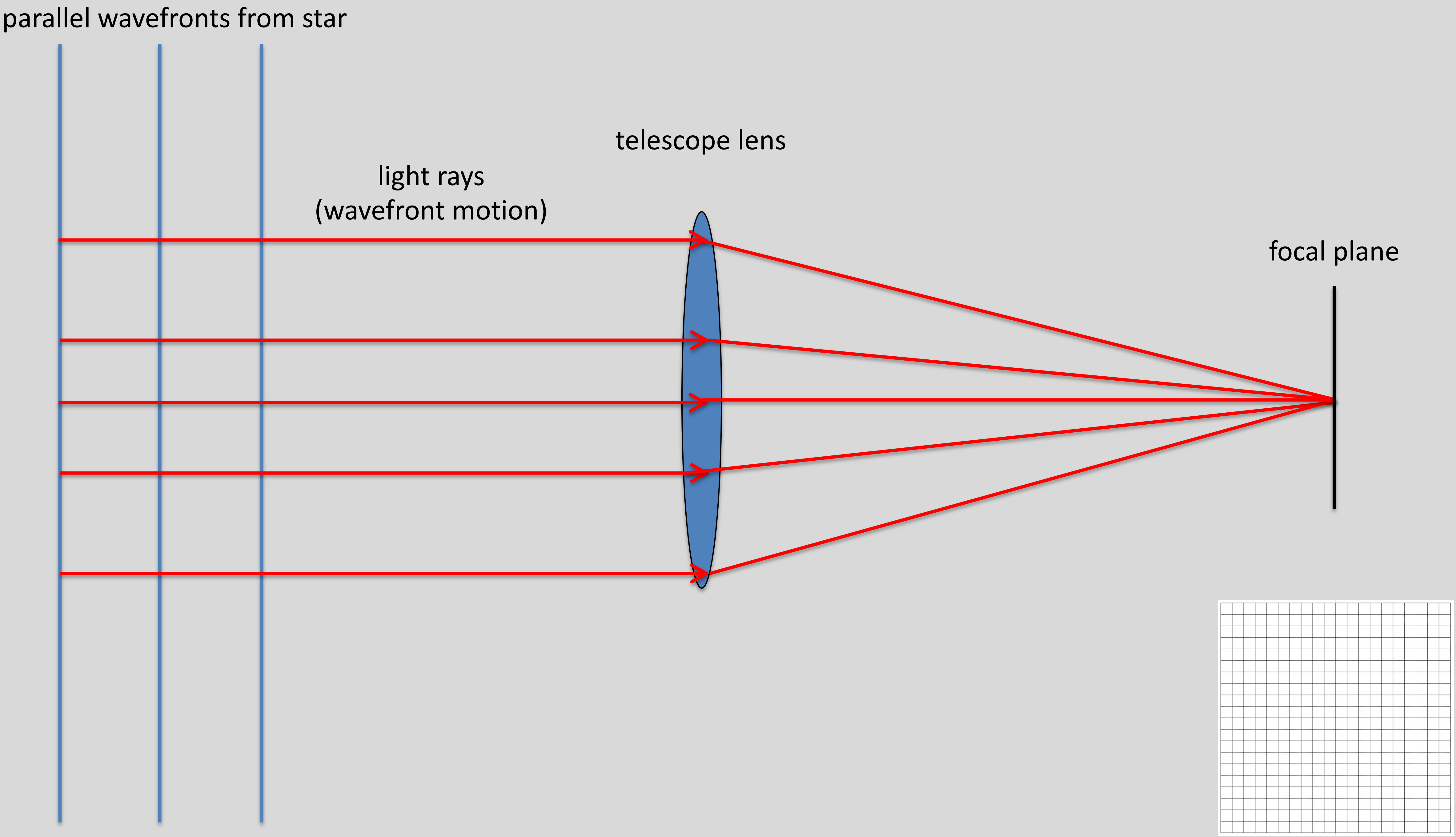
A CCD is a grid of pixels, each with a certain physical size.

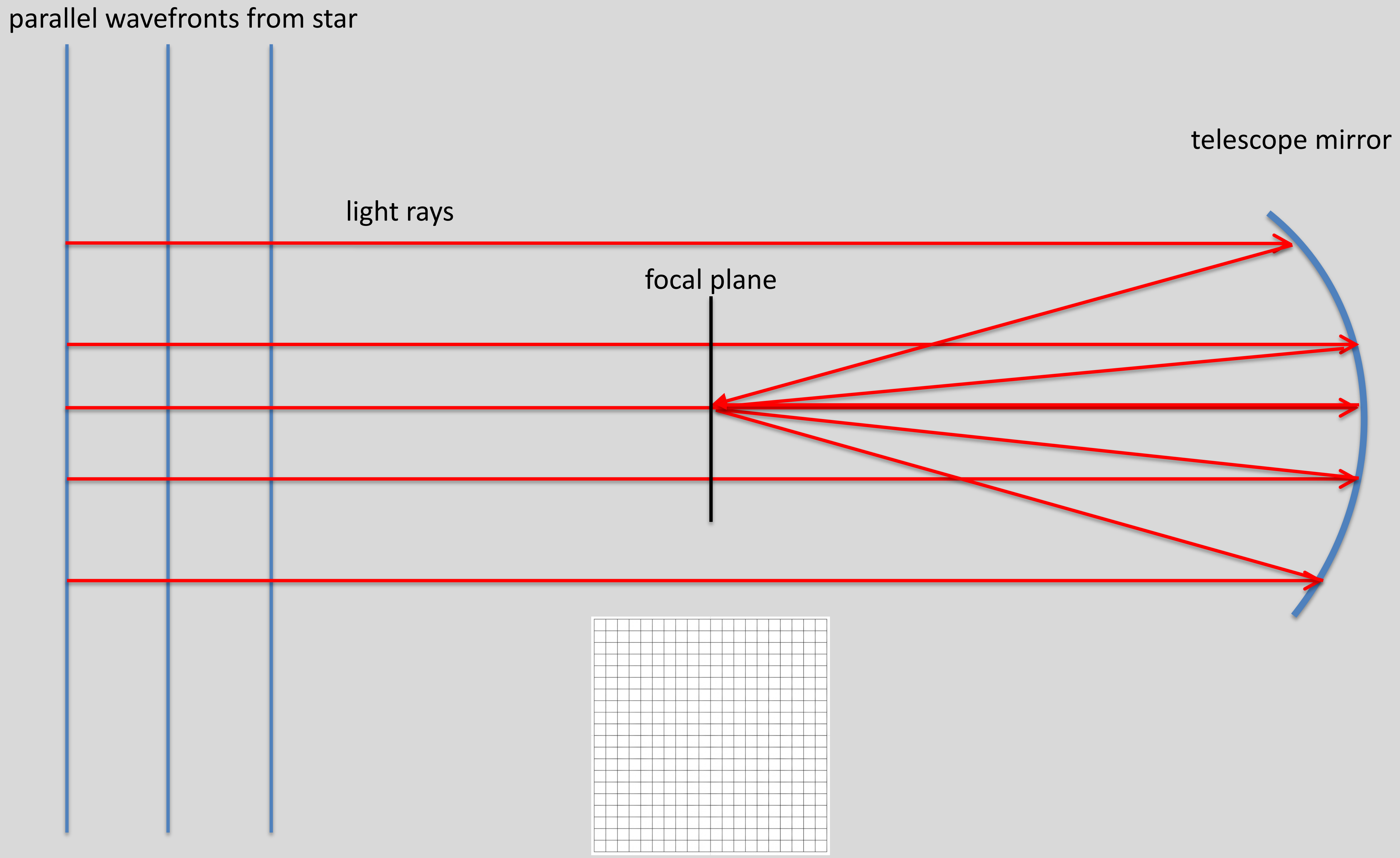
For example, a 2048x2048 CCD with 9 micron pixels.

The telescope focuses an angular area of the sky (say 30x30 arcmin) onto this physical CCD.






parallel wavefronts from star
telescope lens
light rays
(wavefront motion)
focal plane


parallel wavefronts from star
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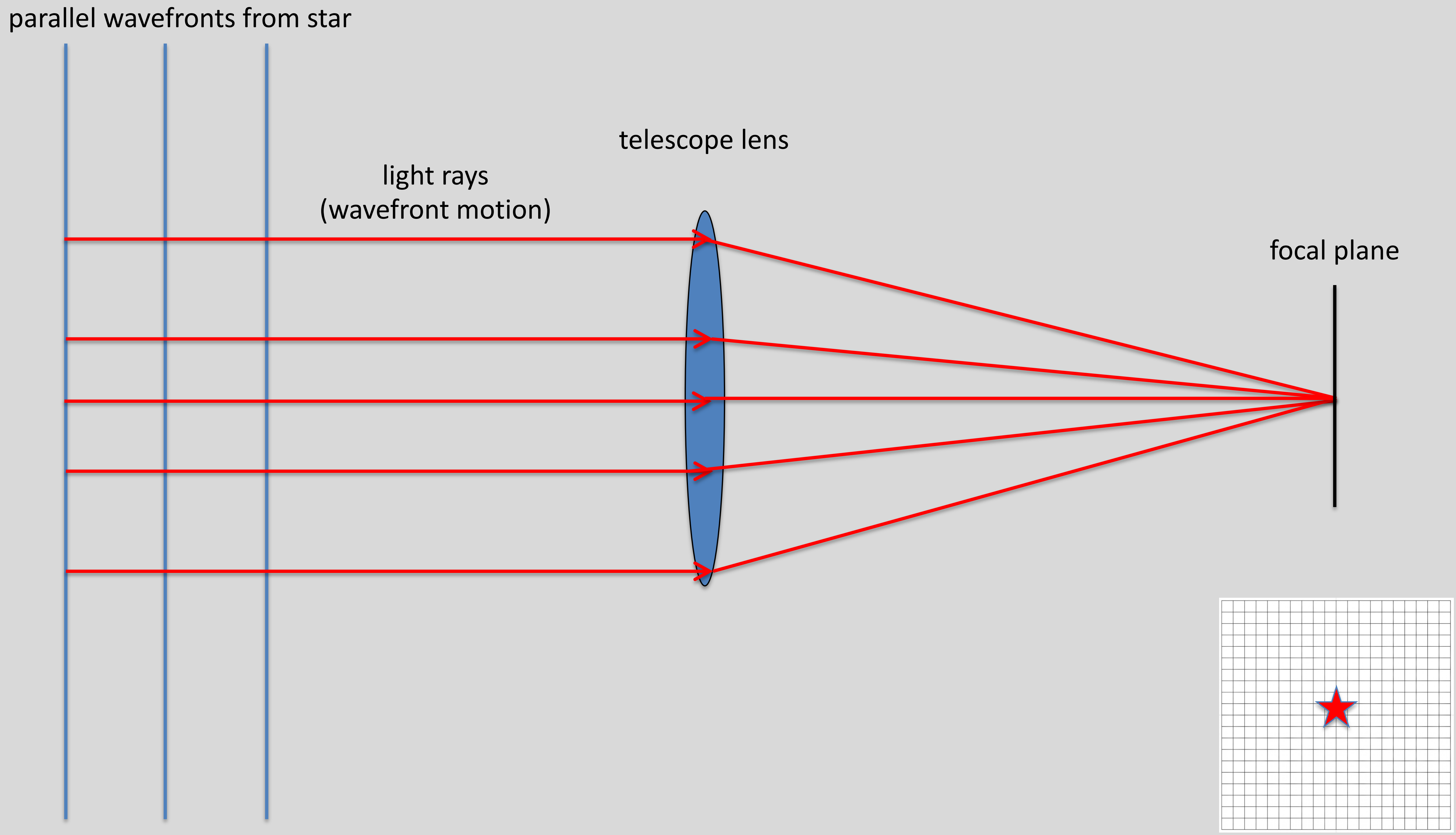
parallel wavefronts from star
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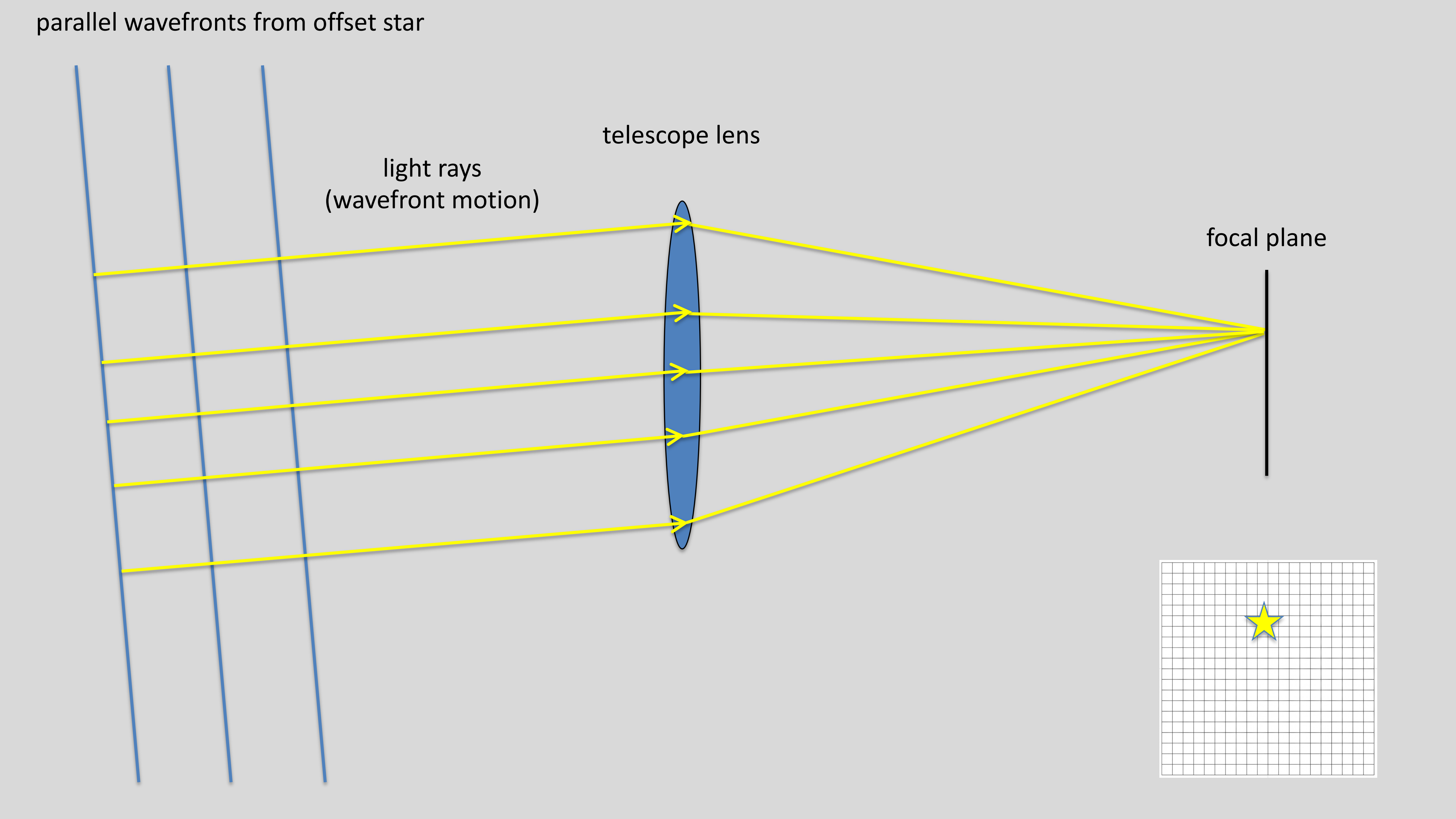
focal plane


parallel wavefronts from offset star
telescope lens
light rays
(wavefront motion)
focal plane

# Image formation and plate scale

If a lens has a focal length $f_L$, a star on the sky positioned at a angle α from the center of the field will be offset by a distance $s$ in the focal plane, where

$$s = f_L \tan \alpha \;\approx\; f_L \alpha$$

using the small angle approximation*

So the image plane has a plate scale $\alpha / s = 1/f_L$. Plate scale converts displacement on the detector to angle in the sky.

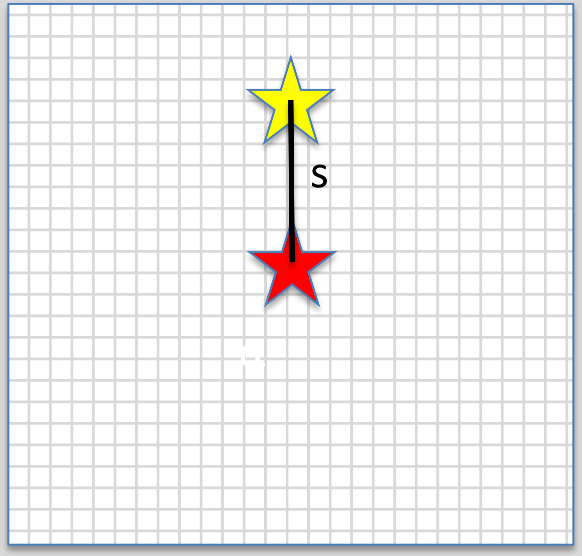
This has units of radians/length, so in practical applications, you'll need to convert to arcsec/mm on the detector.

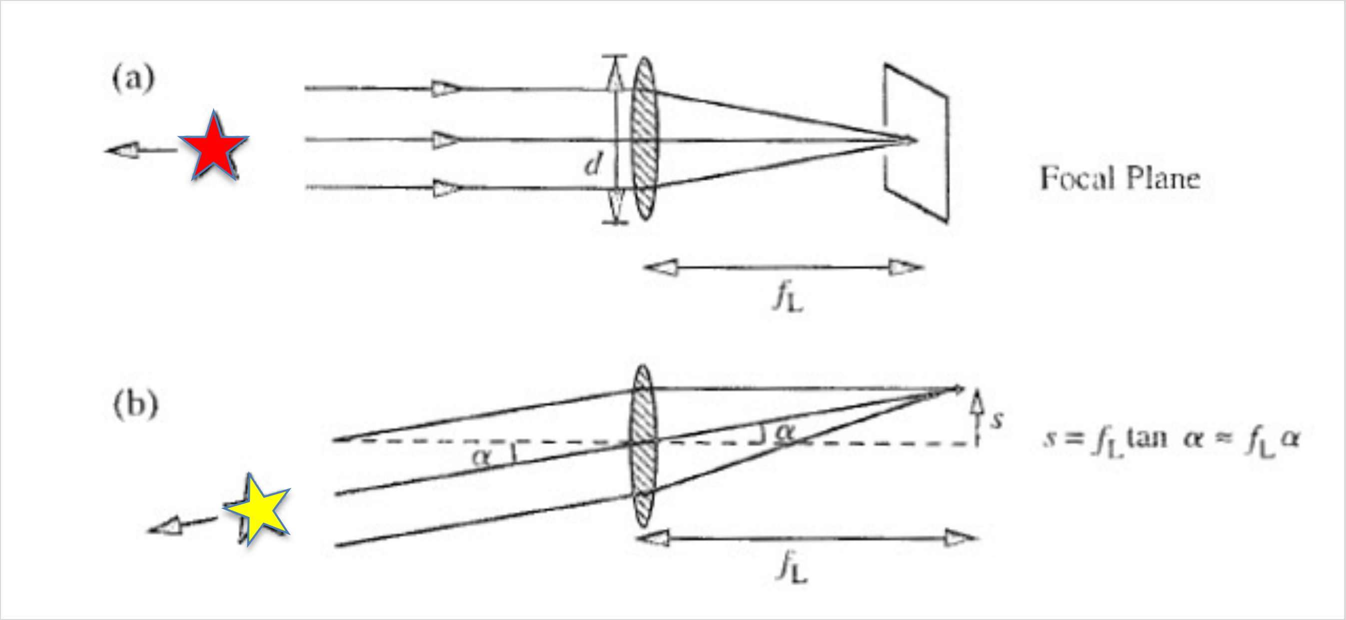
*Example: A telescope with a focal length of 30m has a plate scale of 1/30 = 0.033 rad/m, or 6.88 arcsec/mm.*

* *remember, when you see a bare angle in a formula, it should be measured in radians, not degrees!*

Sky view


Focal Plane



# Telescope/Camera "Speed"

For an **extended** source (galaxy, nebula), the light from the source is deposited over an area that scales as $s^2$ (where s is image size on the detector). So as the plate scale goes up (size on detector gets bigger), the energy ***per pixel*** on your detector drops. So it takes longer to detect an object.

But if the telescope has a big aperture (D), it collects a lot of light. Light collecting scales as $D^2$.

So the total energy collected per pixel scales as:

$$E/pix \sim D^2/s^2 \sim D^2/f_L^2$$

We can define the focal ratio as $R = f_L/D$, so energy per pixel scales as: $E/pix \sim 1/R^2$.

**Telescope "beam speed", written as "f/R"**

f/4 : "Fast beam", since E/pix is large and you can build up signal fast.
f/16 : "Slow beam", since E/pix is small and takes time to image extended sources.

small plate scale;
image is small on detector

large plate scale;
image is spread out more on detector

**The importance of pixel scale**

Pixel scale: like plate scale, but for detector pixels. The size of a pixel **on the sky**, in arcsec.

Big pixels:

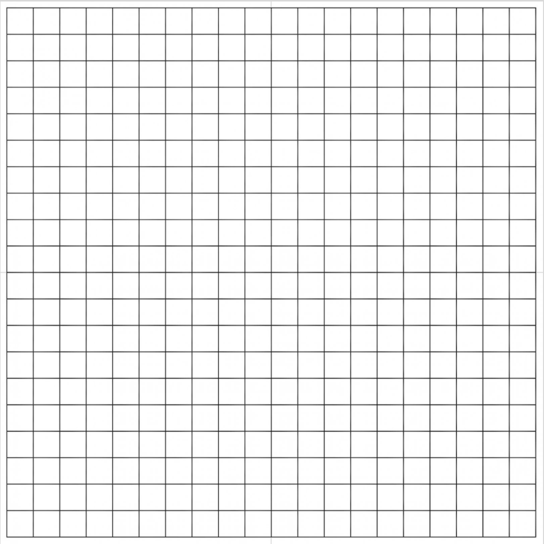
- Good for faint, extended sources: lots of light per pixel.
- Implies large field of view for the detector
- But gives poor spatial resolution

Small pixels:

- Good for stars: finely samples the point spread function of stars, and allows for accurate photometry
- Gives the best spatial resolution.
- But small pixels mean less light per pixel: exposure time goes up.

Always want the best resolution that the telescope and conditions can deliver.

- If the seeing is 1 arcsec, no need for pixels much smaller than 0.3 arcsec or so.
- When do you need smaller? When you can get better spatial resolution.
    - Space based imaging
    - Ground-based adaptive optics



Detector properties:

- 1000x1000 pixels
- pixel size: 24 micron

If the telescope setup gives a plate scale of 6.88 arcsec/mm, a 24 micron pixel covers 0.2” on the sky.

*(remember: the symbol for arcsec is ”)*