Astronomical site selection 101

Astronomy Site Testing and Training
Workshop, Nairobi, Kenya,
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Your speakers this morning (many years ago)

So, you want to build an astronomical observatory

- You participate in this workshop
  - Yesterday you learned that Earth's atmosphere will be impacting your telescope/observatory performance (btw. only negatively)
  - Let's look at two slides how to bypass all the atmospheric mess (and why it's done only rarely)

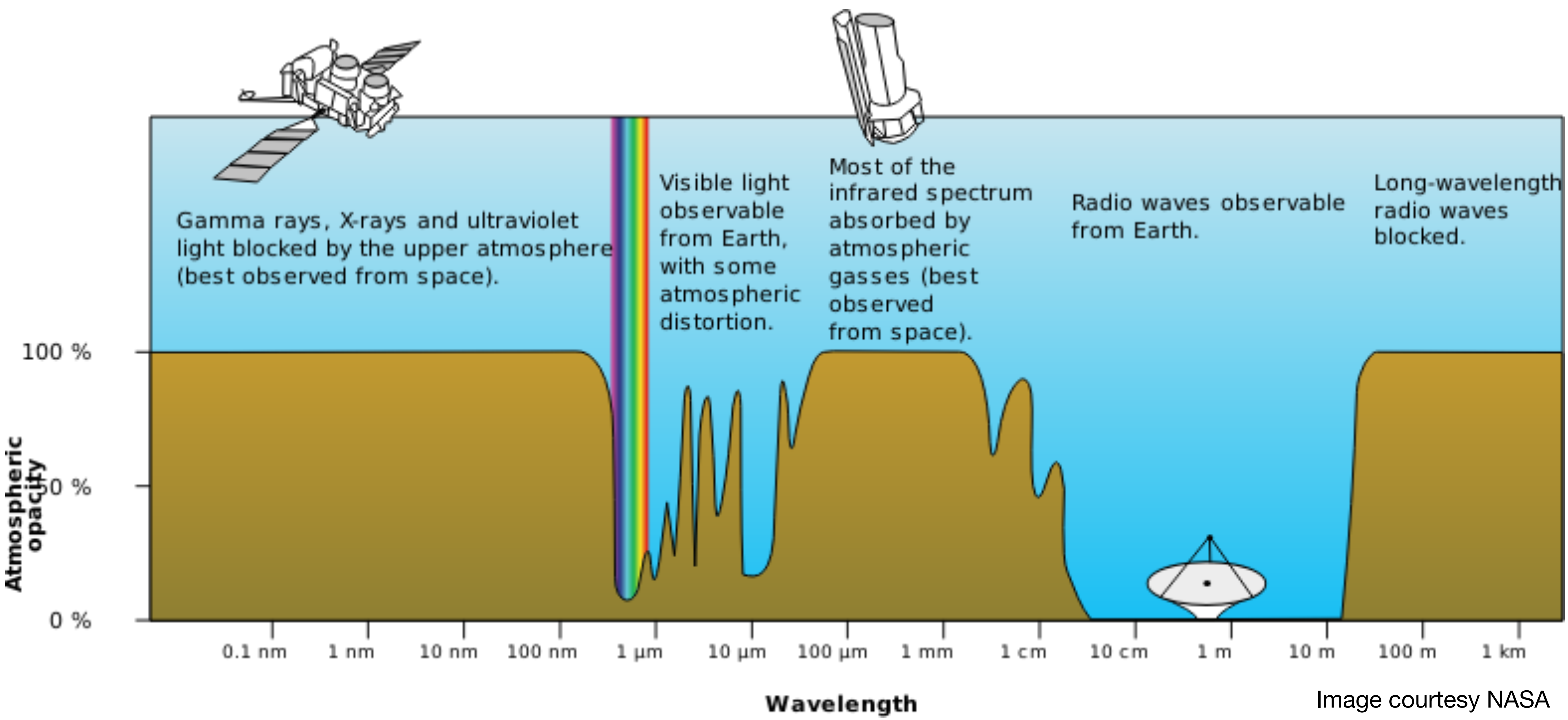
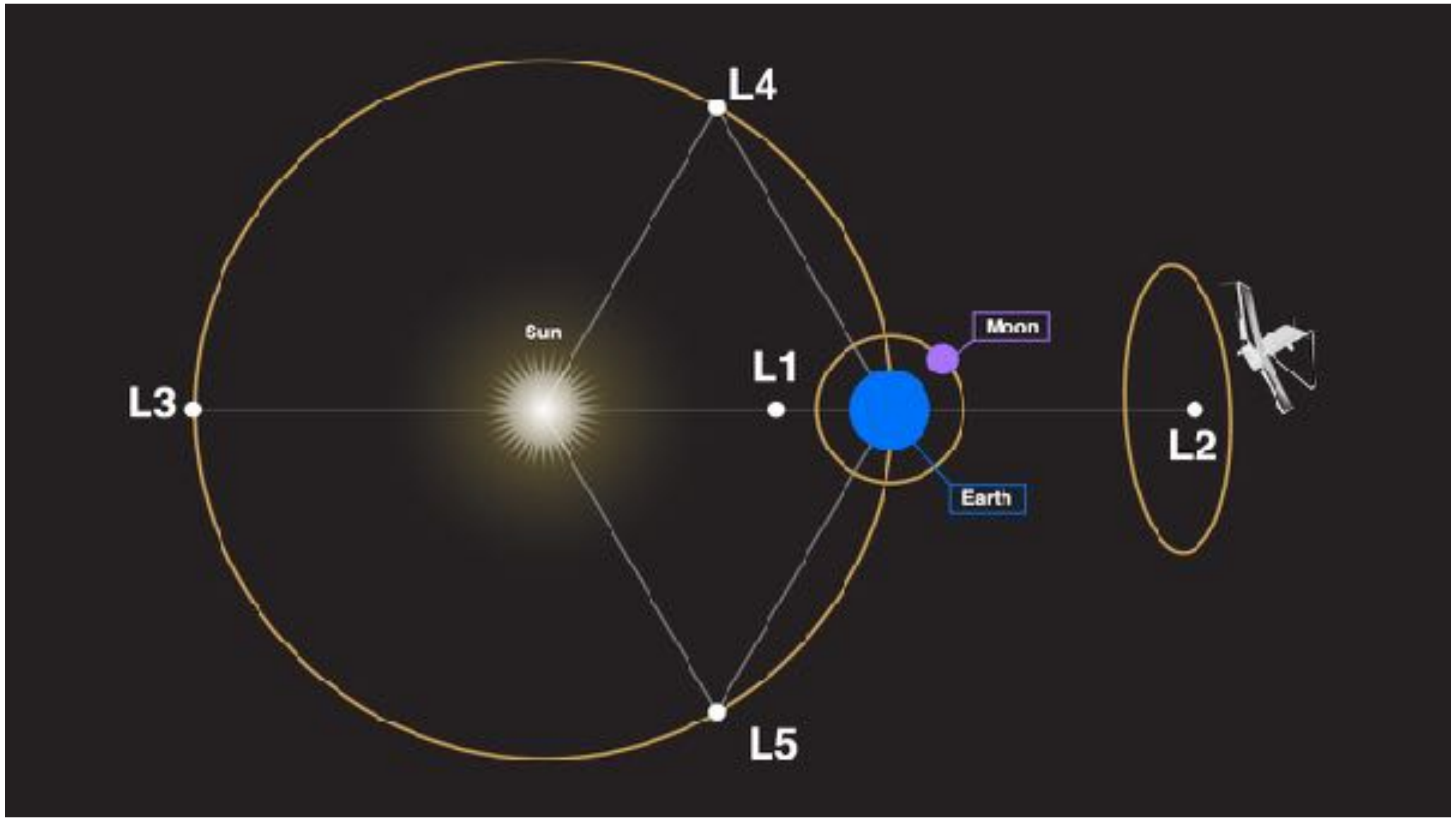


Image courtesy NASA

X/UV/Optical/IR observations are best done from the Langrange points

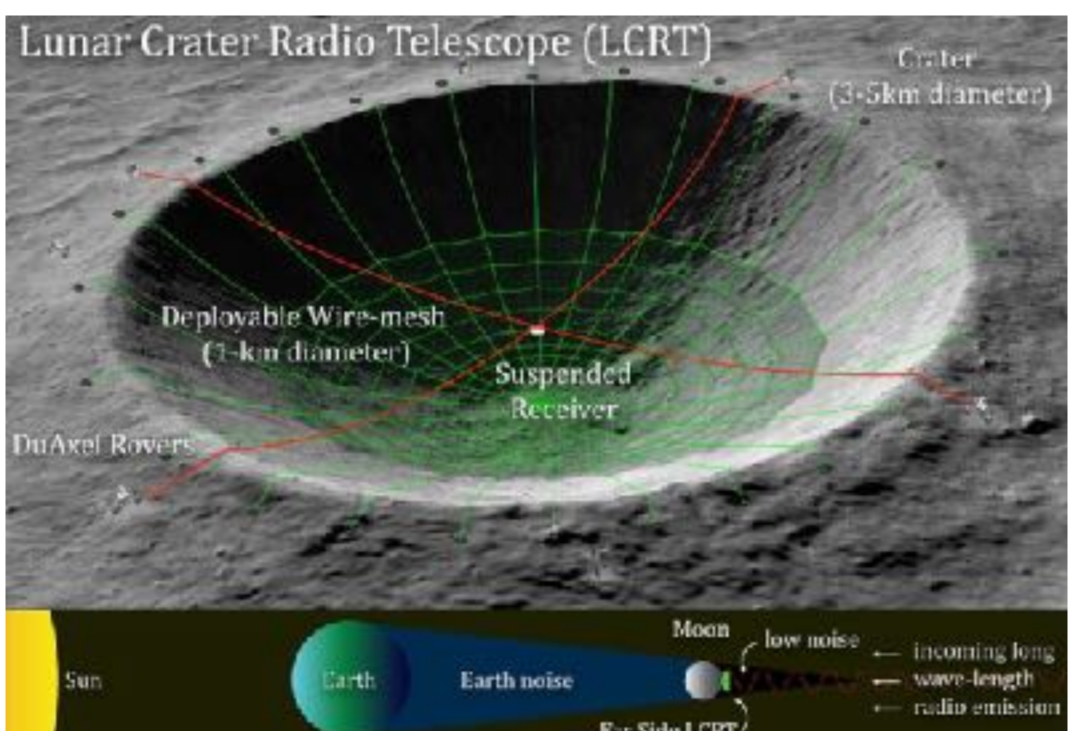
Image courtesy webtelescope.org



- Here you can achieve
  - optical performance from telescope only
  - extreme thermo-mechanical stability

Radio observations are best done from the far side of the Moon

Image courtesy NASA



- Here you can achieve best radio quiescence

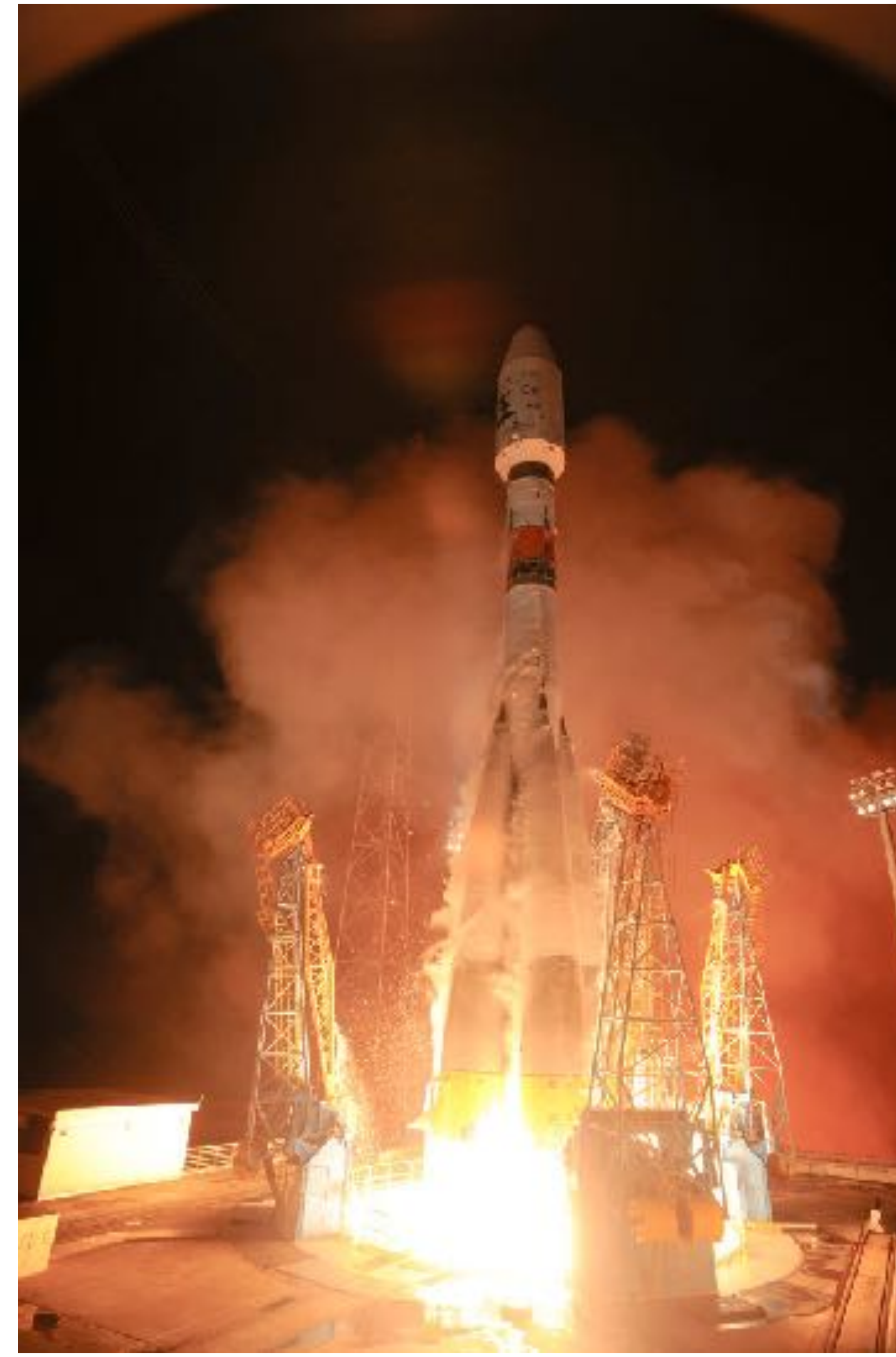
Why is doing astronomy from space done not very often and maybe not the best way to start off your own observatory

Space observatories are

- Technologically very demanding
  ⇒ long time for development
  ⇒ development cost
- The telescope has to be brought into orbit
  ⇒ launch and transfer cost
- Operations time limited
  - fuel
  - bandwidth

  ⇒ cost per observation

Due to their cost and limitations, you have <u>no room for error</u> you have to know <u>*exactly*</u> <u>*what*</u> you want and <u>*how*</u> to achieve it



Launch of Gaia 2013
Image courtesy ESA

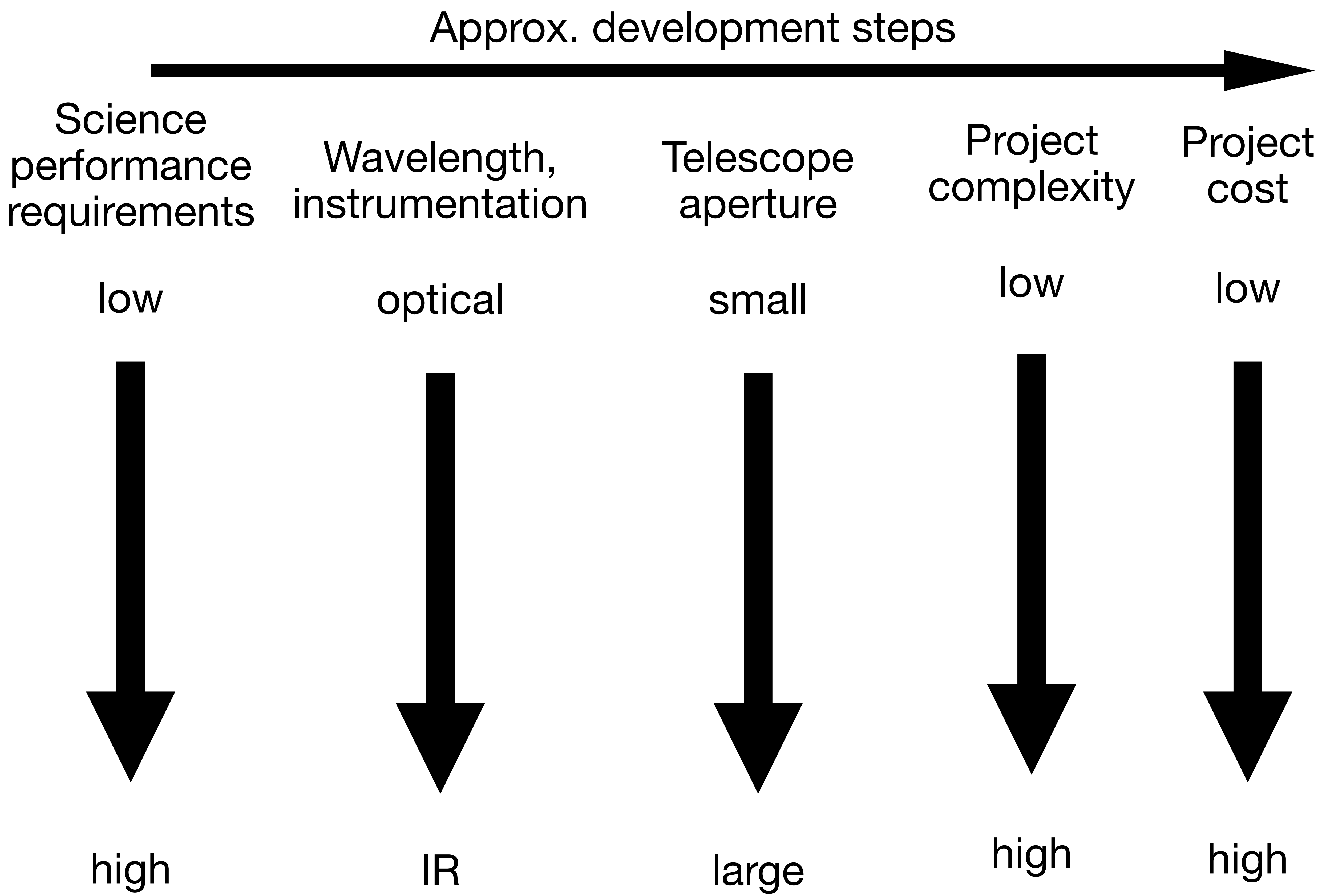
The remainder of this presentation is about ground-based observatories and what you need to take into account to select the location for, and build your observatory

- As described in the presentation by Skidmore you have to prepare the basics to get your observatory project started

  - devise one, better several
    - science cases
    - also more use cases: e.g., education and outreach, or industrial opportunities for your initial stakeholders

  - from these follow initial requirements for
    - the telescope aperture and type
    - first light instrumentation
    - observatory operations and facilities

    $\Rightarrow$ define required site conditions (not only atmospheric ones)


Approx. development steps
Science performance requirements
low
high
Wavelength, instrumentation
optical
IR
Telescope aperture
small
large
Project complexity
low
high
Project cost
low
high

Building a science requirement for a telescope+instrument

- Which *physical process (the case)* you want to investigate and by means of which *observable parameter* ?

- Which method you want to employ to measure that parameter
  → Imaging or Spectroscopy
  → Wavelength range
  → Spatial and spectral resolution

- How bright is the object you want (need) to observe
  → Estimate the signal strength (or signal-to-noise-ratio) you need to achieve in order to measure the observable parameter

- Is the physical process a transient phenomenon and requires fast acquisition
  → Positioinig precision/speed, data acquisition speed, overall measurement time

  ⇒ The resulting values constitute the **science requirements** for the system for that particular science case:
  Wavelength, field of view, spatial resolution, spectral resolution, SNR, pointing, uptime

Deriving the requirements for the telescope+instrument

These values constitute the **science requirements** on the overall system
Wavelength, spatial resolution, spectral resolution, SNR, pointing

From this one derives the individual requirements:

⇒ **Instrument requirements:**
wavelength, field of view, spatial/spectral resolution, throughout,
needed time on target

⇒ **Telescope requirements:**
aperture, optical performance, wavelength, throughout,
pointing precision/speed, uptime

To do this derivation, one follows the light path

Object

↓

Atmospheric impact → Telescope performance → Instrument performance → signal estimation

What is Atmospheric impact - a. transmission/opacity

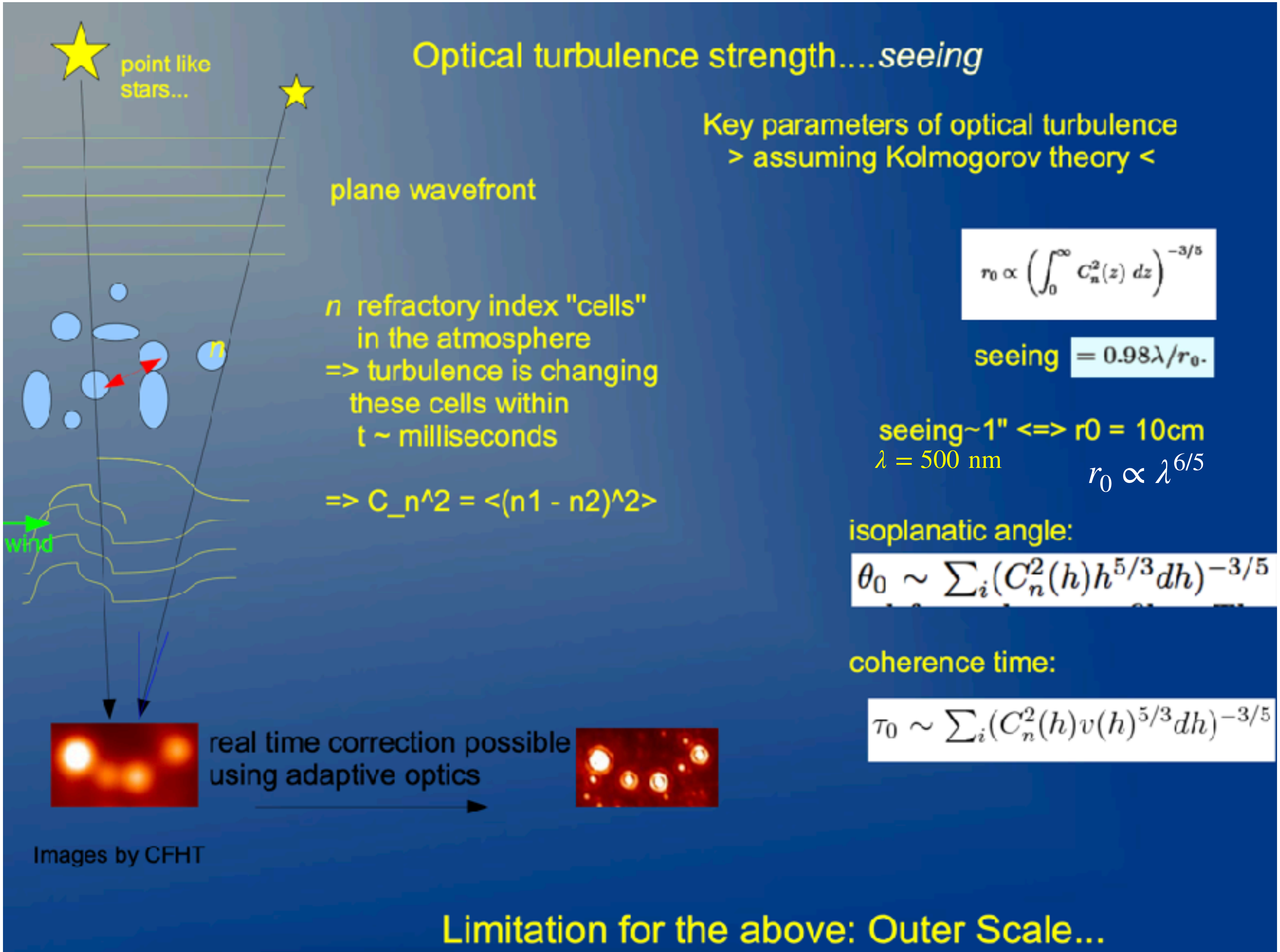
$$f_T = F(\lambda) \cdot A \cdot \eta_T(\lambda) \cdot \eta_A(\lambda)$$

F: flux of object of interest $[Wm^{-2}s^{-1}\lambda^{-1}]$
f_T: flux collected by the telescope and fed to the instrument $[W/(s\lambda)]$
A: telescope aperture area $[m^2]$
η_T: telescope throughpout [0…1]

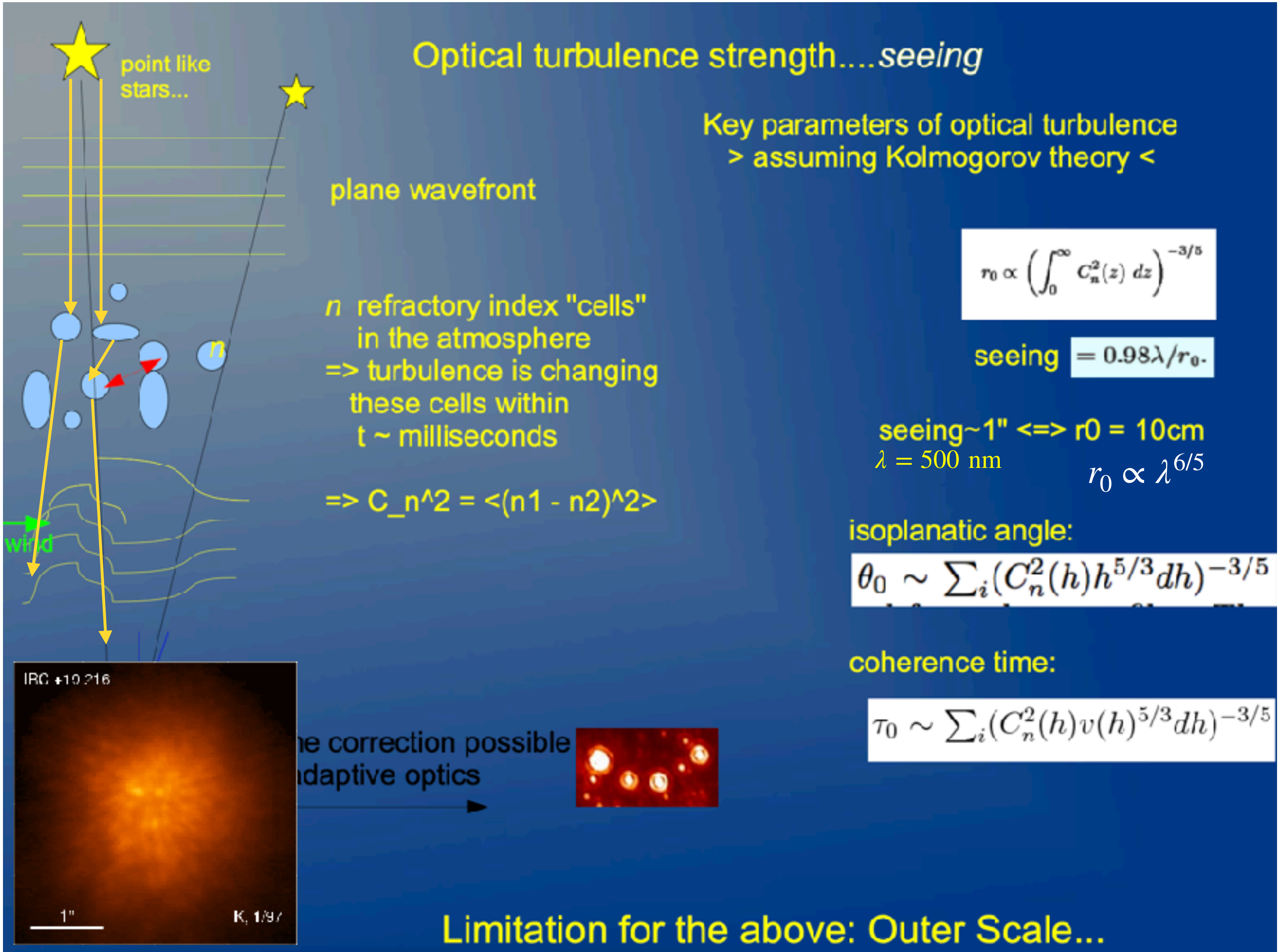
η_A: atmospheric throughput [0…1] - the opacity (see Fig. on slide 2).
Highly variable due to clouds and dust

Note: don't forget the $d\lambda$ in the above discussion

Atmospheric impact - b. image blur/seeing



Atmospheric impact - image blur/seeing



Atmospheric impact - image blur/seeing

The image blur (seeing) reduces the ability to

- resolve smaller spatial structures
- detection of faint objects
- astrometric measurements

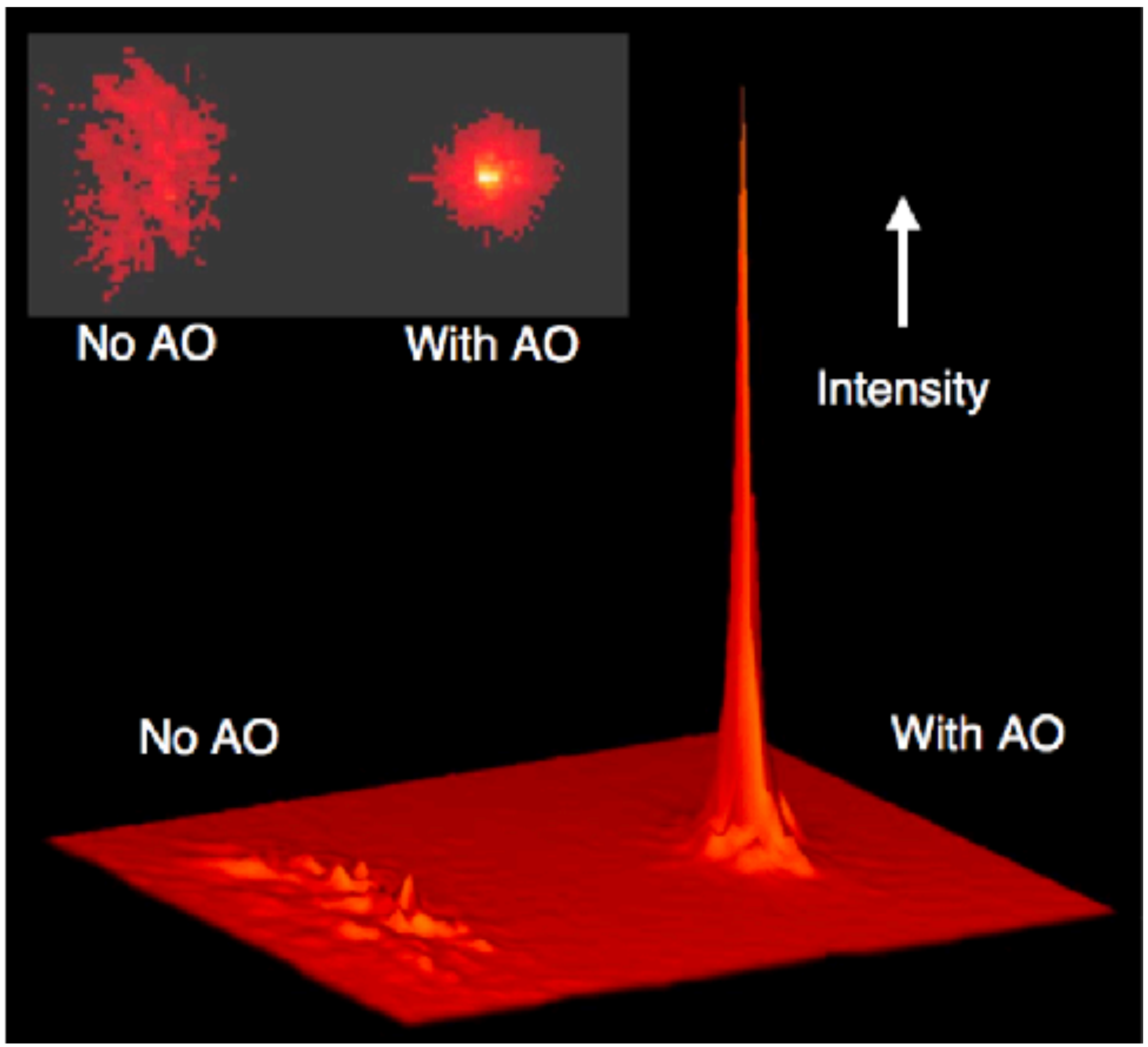


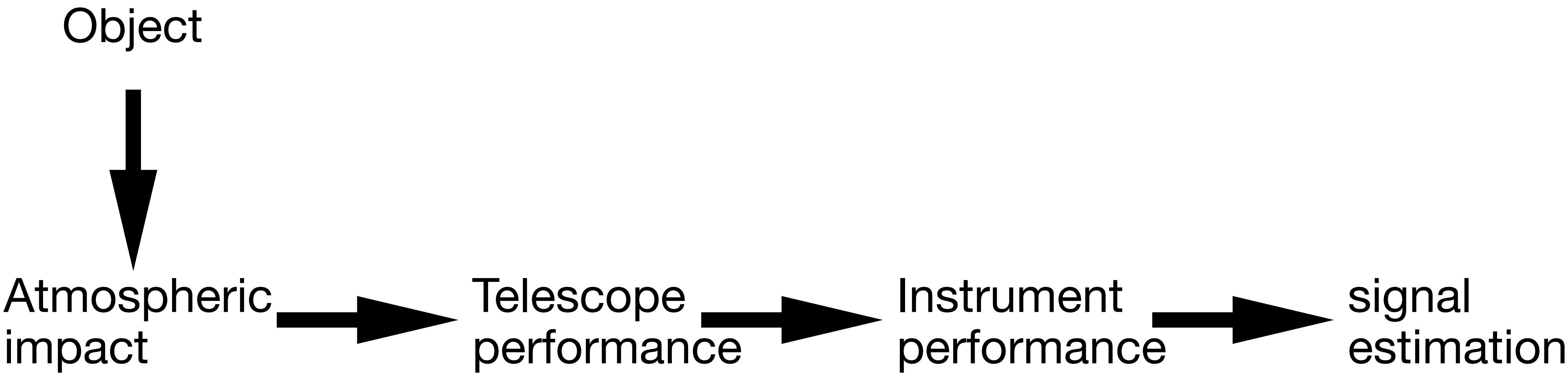
Image by Claire Max

Peak intensity for image with perfect telescope without atmosphere = 100%
in other words: Strehl = 1

Typical peak intensity for telescope in atmopshere $\lesssim 5\,\%$
Strehl $\lesssim 0.05$ (remember this is extra η_A^*)

Adaptive optics corrected image peak intensity for telescope in atmopshere $20...80\,\%$
Strehl $\lesssim 0.2...0.7$
heavily depends on atmospheric conditions and the AO system conditions

Deriving the requirements for the telescope+instrument



Initially, you have to make assumptions on the typical atmospheric conditions to derive at the various system paramters for telescope and instrument.

⇒ Site testing provides you the inputs for the later system design

But the atmosphere is not all which impacts the design, especially when you think about an holistic observatory system

Site testing and selection has to address quite a bit more

What are the conditions which you need to take into account to select a site for an observatory

1. Orography/topography
2. Seismicity
3. Availability
4. Logistics
5. Accessibility
6. Neighbouring activities
7. Geotechnical properties
8. Cloud coverage
9. Light pollution
10. Wind speeds (and direction)
11. Dust content
12. Humidity, pwv
13. Optical turbulence

Approx. area		Consideration type
wide	↓	technical, political
local		science performance

Most of these points are cross-linked !

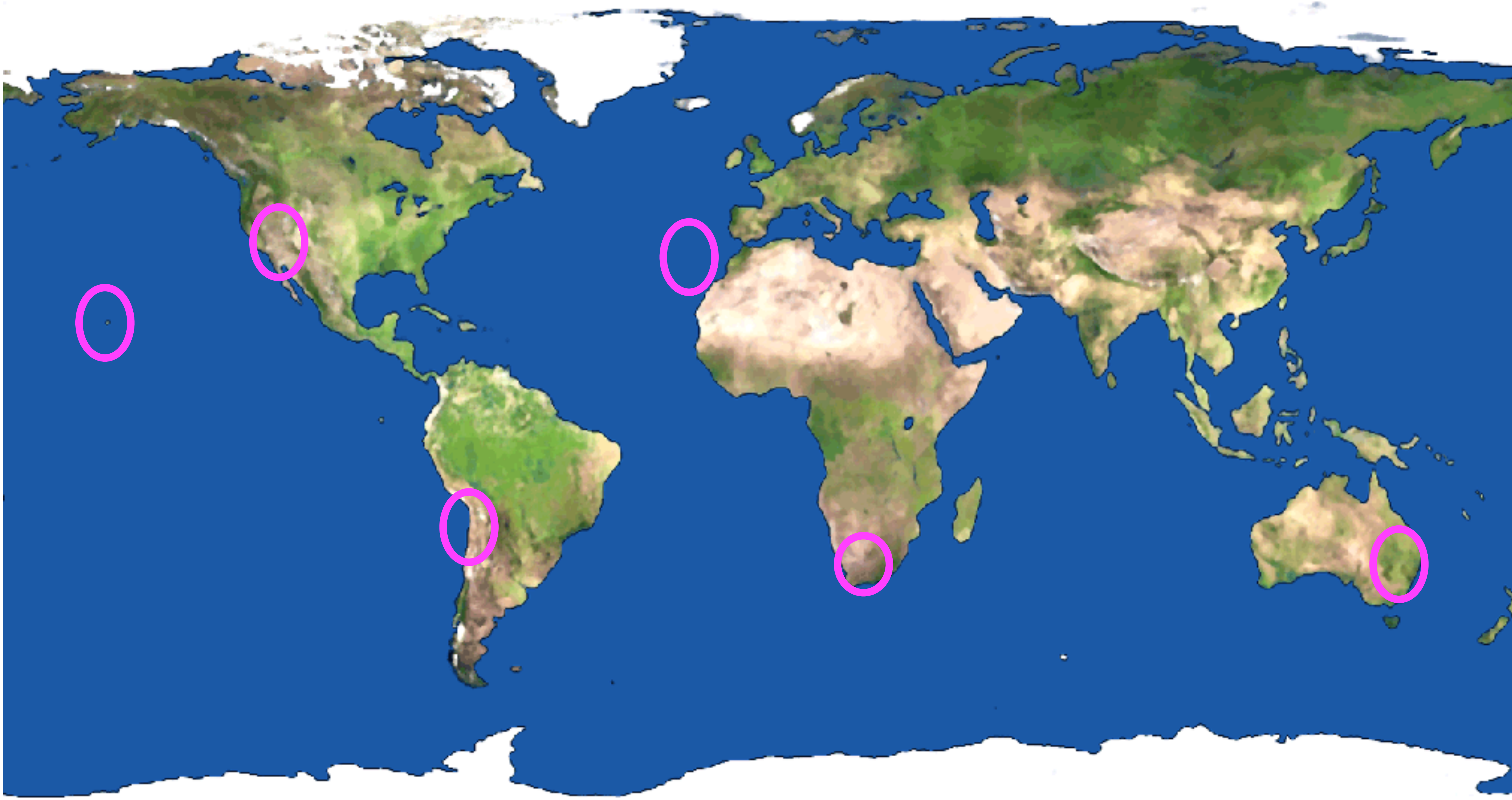
1. Orography/topography

- Local and wider area meteorological conditions
  - Height of inversion layer
  - Prevailing wind direction
- Visibility of light/dust sources in the area
- Hydrology
- Accessibility

High Andes “dry” the Easterly winds.

Atacama desert is a high a high and dry plateau

Cold Humboldt stream of the Pacific ocean pulls down the inversion layer and the cloud layer stops at approx. 1500 m

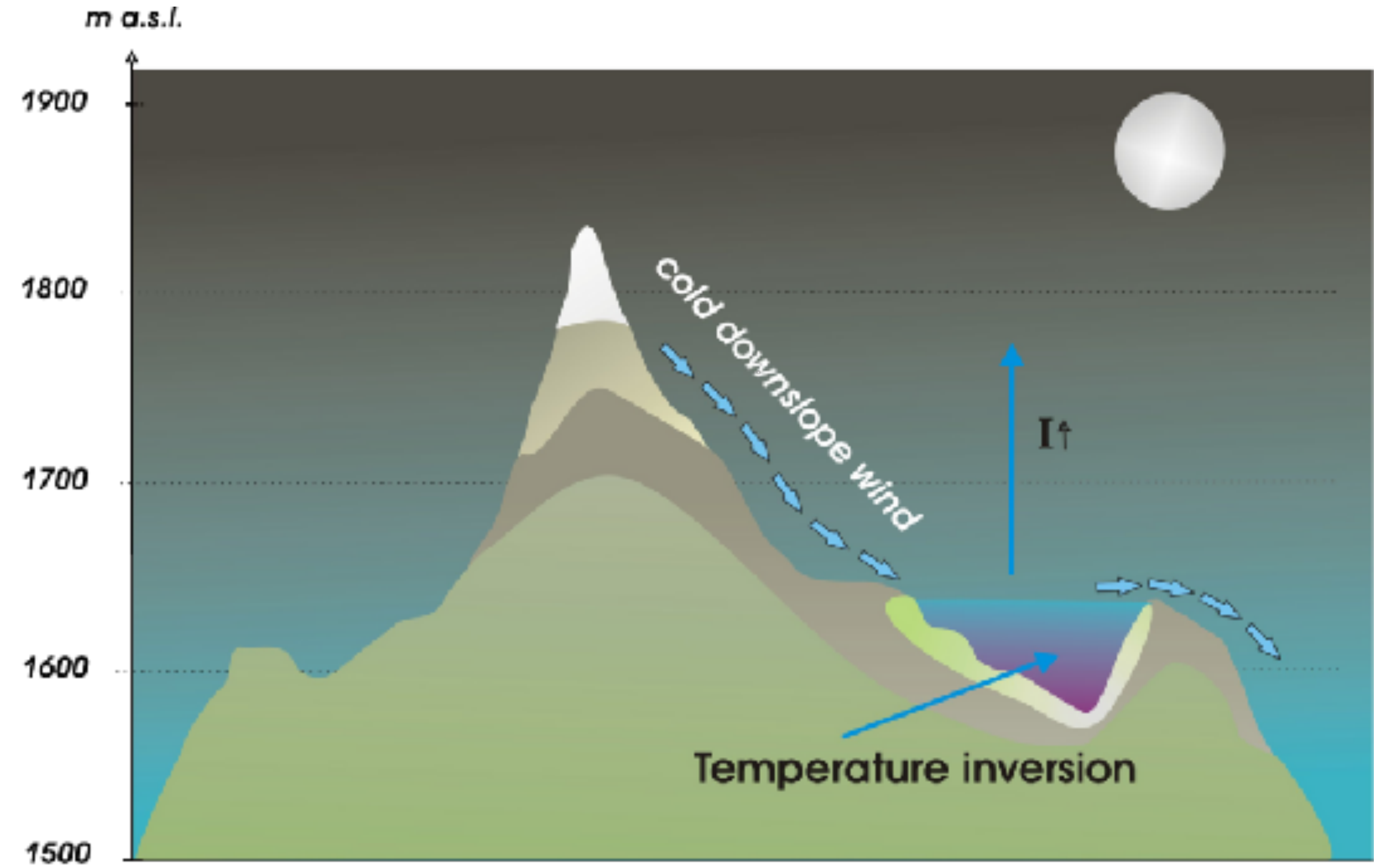


A long known wisdom

- The observatory should be above the height of the inversion layer
  - Not in a valley
  - Not on a plain

O. Heckmann in the Preface to
"Astronomical Site Testing in South Africa"
by U. Mayer (ed.), ESO Publication, 1967
“If the need to make analogous observations should ever reoccur, they would probably have a higher degree of reliability than those submitted here. The main changes would be more effective automation of the difficult optical observations of turbulence, automatic recording of temperature fluctuations and, of great importance, observation posts of greater height (10 metres and more) above the surrounding ground. And most probably somewhat **isolated mountains** only would examined.”

Things are somewhat different for solar observatories !



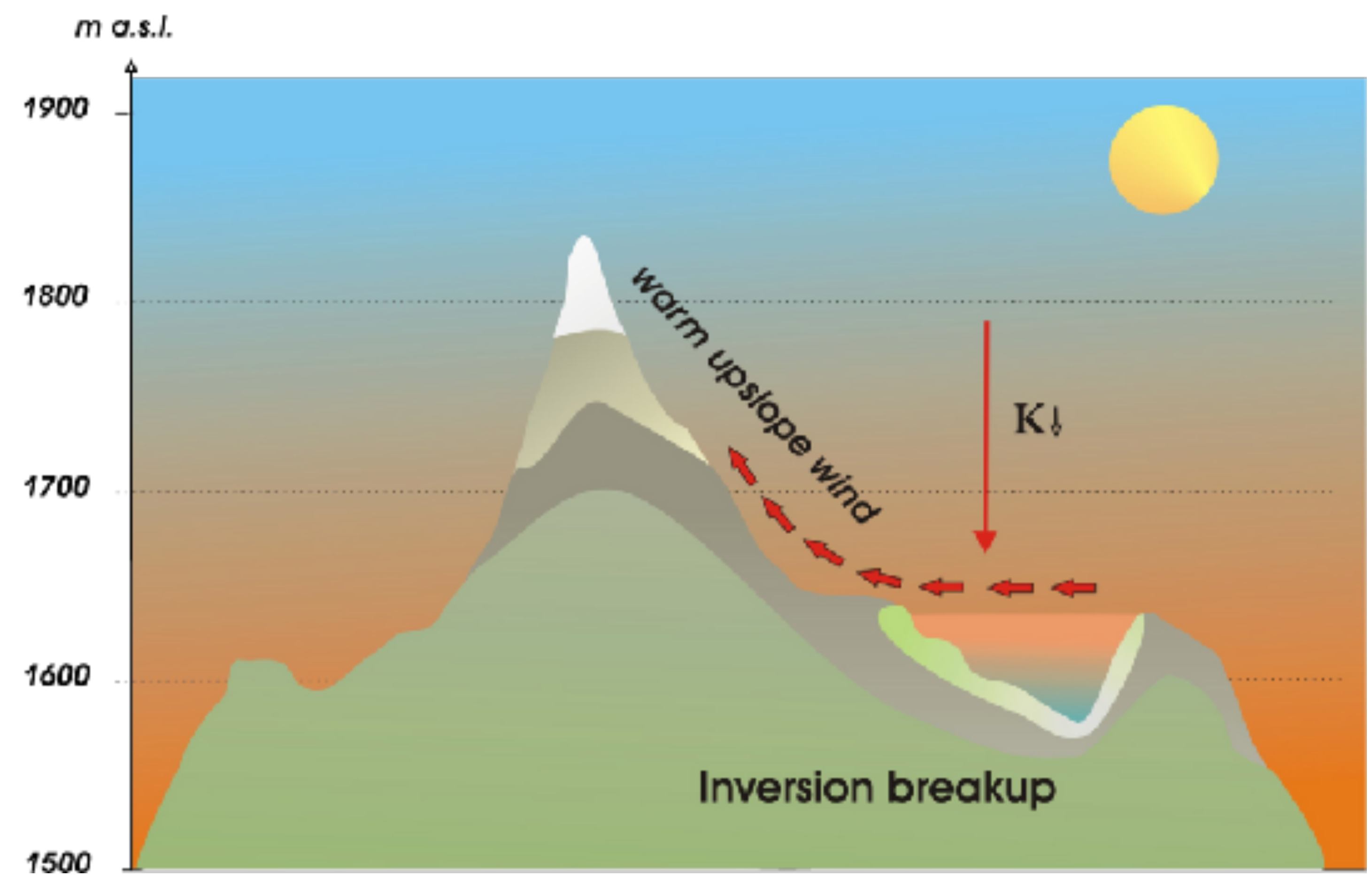


Image source wikipedia

One approximate way to find the minmum height for an observatory in your area - UAE example

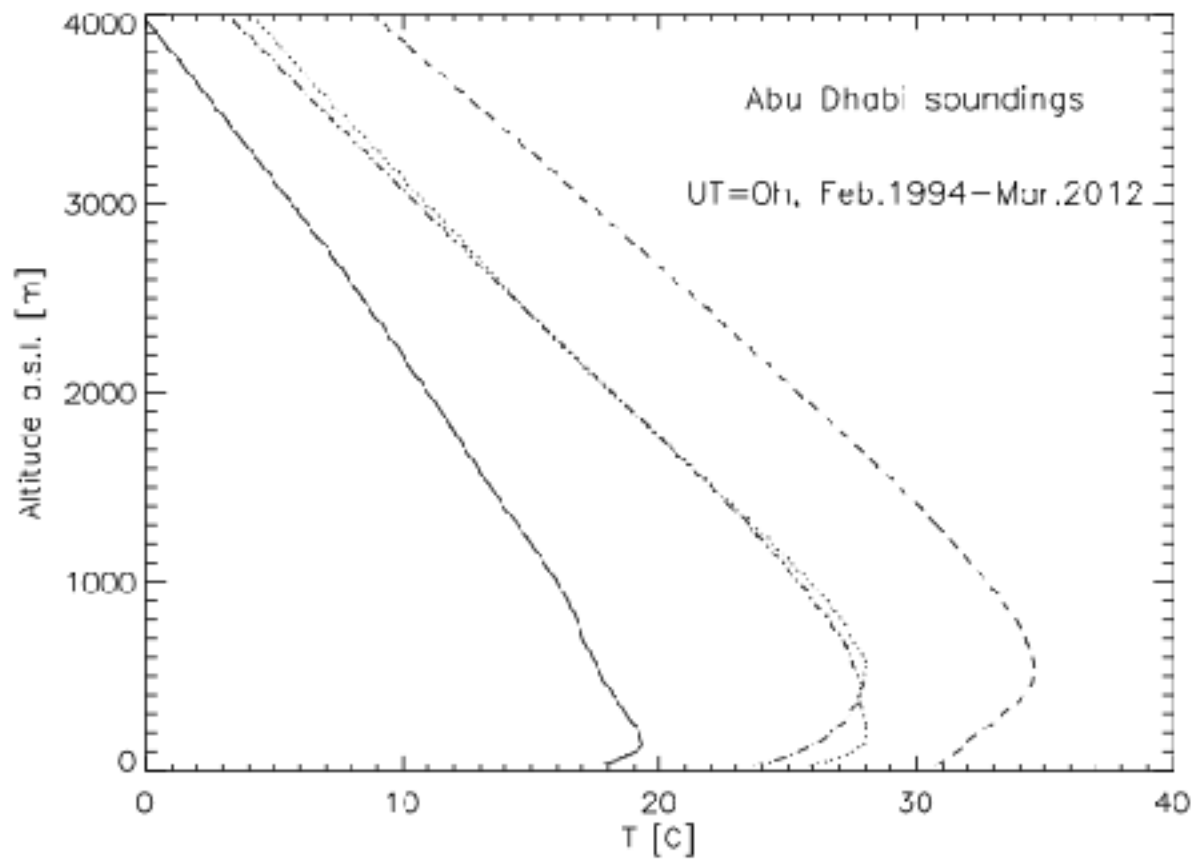


Figure 2. Seasonal median temperature profiles measured by radiosoundings at Abu Dhabi between February 1994 and March 2012 at 0Z. The solid line represents the median of measurements during winter (Dec-Jan-Feb), the dotted line during spring (Mar-Apr-May), the dashed line during summer (Jun, Jul, Aug), and the dashed-dotted line during autumn (Sep, Oct, Nov).

Aim to be above the clouds - for exmple at island sites

2. Seismicity

- Earthquakes might
  - damage or destroy the facility, or its access, or logistics
  - at minimum they will impact the observation at the time they occur
- Need to be taken into account in the civil engineering process
- But: most major observatories are in seismic highly active regions

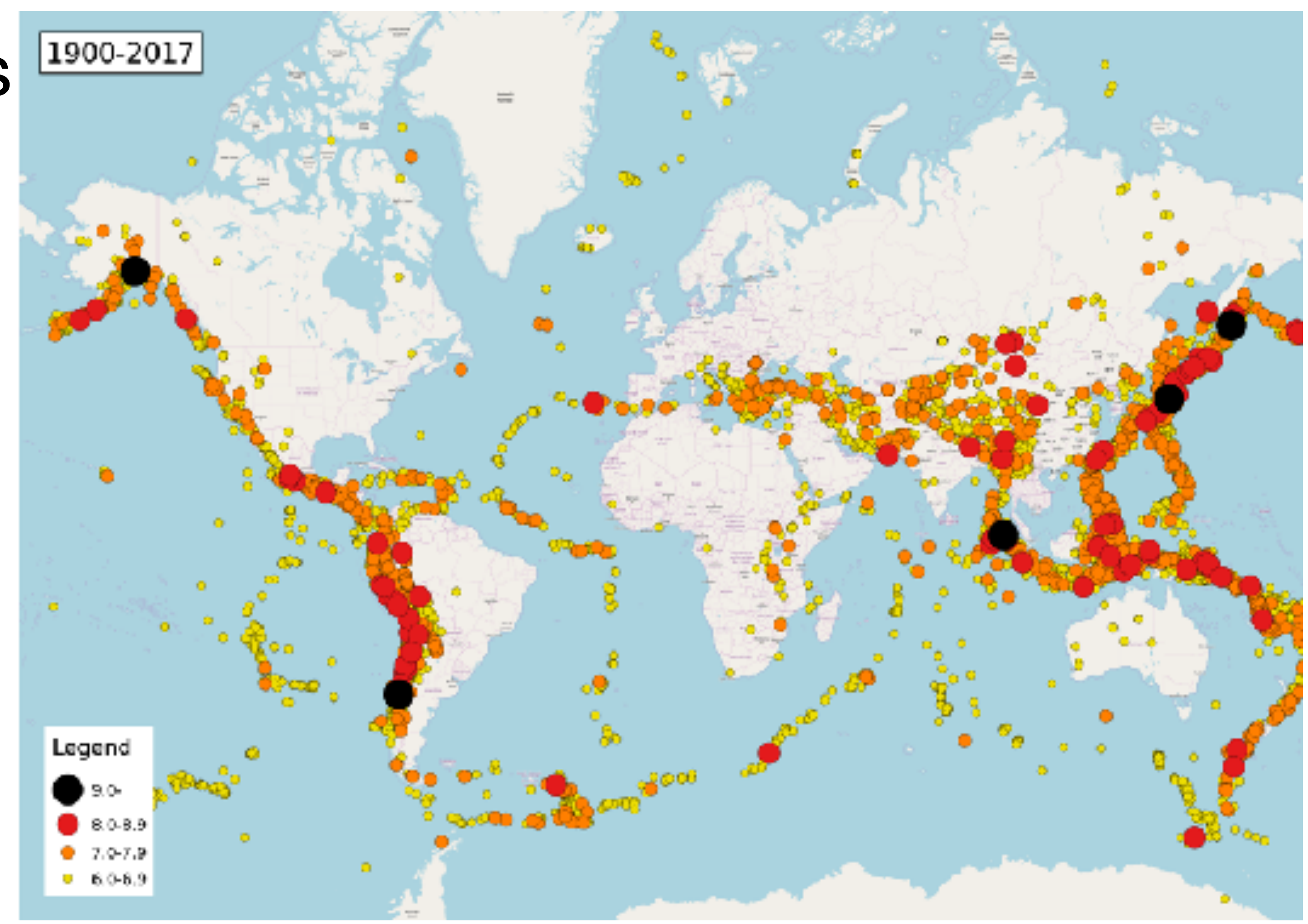


Image source wikipedia

Building an observatory close to a volcano is dangerous

La Palma

Image source canarianweekly.com

Chajnantor

3. Availability

- Ownership of the candidate site - and its surrounding
  - Must be very well understood, also historically
    - Be prepared for surprises
  - Acquire ownership and rights (mining, water, etc.)
    - Be discreet
  - Aim to declare a “science reserve” to prevent future disturbance by light pollution and industrial activities
- Establish positive contact with local communities
  - You will need their support in years/decades to come
  - Assess cultural importance of the site

3. Example - things that almost went wrong, …

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WORLD & NATION

Dispute Threatens Observatory Project in Chile : Astronomy: Legal wrangling imperils plan for the world's most powerful telescope in the Atacama Desert.

By WILLIAM R. LONG

Aug. 6, 1994 12 AM PT

…

"It is not what ESO wants," but "if the impediments continue and we see that we cannot go on in an adequate way, we will have to look for an alternative," Hofstadt said. ESO already is studying an alternative site in Namibia, which also has clear skies ideal for astronomy.

was resolved soon thereafter
and Paranal hosts the VLT

3. -…or might go wrong again (30 years later)

Hydrogen

Big science and climate collide – Chile observatory under threat from proposed hydrogen plant

Jonathan Spencer Jones •
Jan 31, 2025

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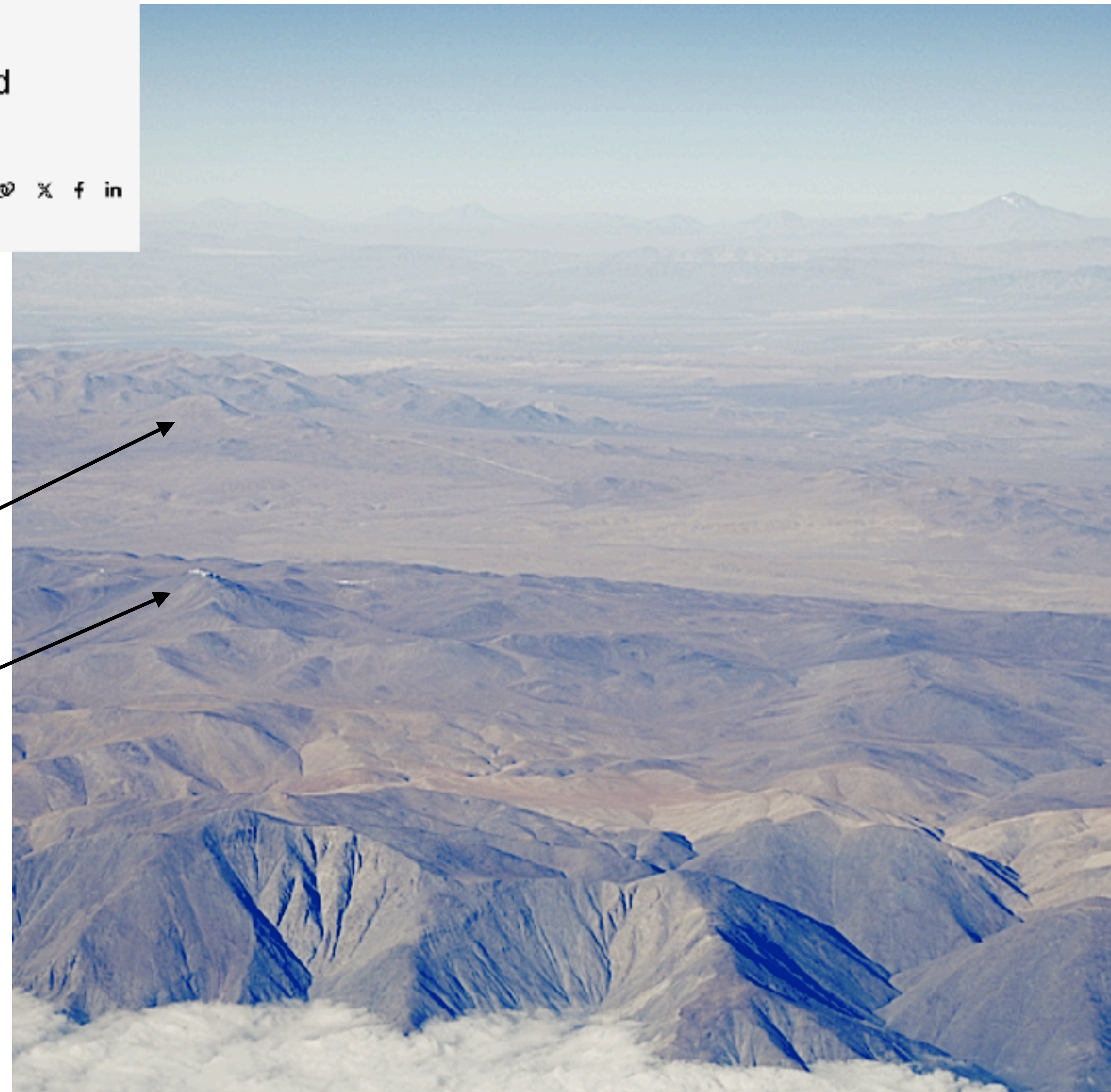


E-ELT

VLT

4. Logistics

- Availability or proximity to
  - electricity line, or gas or diesel pipeline
    - can you connect to it?
    - if not: generators or solar panels
  - surface water or springs
    - if not: drilling or trucking
  - paved road
    - transport of heavy equipment to within reasonable distance of site
  - hospital
    - have 1st aid for serious injuries on-site
  - town
    - staff and observers should not stay weeks on site

4. Example how to organise water supplies

ESO VLT Paranal observatory

several water trucks per week

Image courtesy ESO/Max Alexander

ESO La Silla observatory water pipeline with 3 stations pumping the water from a spring about 1000m below

Image courtesy ESO/C.Madsen

4. Example for having neighbours can be beneficial

Historically, the proximity to mines was desired - for logistical reasons
- electrical power
- water
- workshops
- transportation

Image of the members of the Curtis/Mills expedition in 1911 to the Copiapo region

5. Accessibility

- Is there a road to the site ?
- If not
  - how long is the road which would be needed
  - pavement needed or dirt road ok?
    - small telescope equipment can be trucked in on dirt road, maybe even off-road
  - does your development and operations budget cover
    - cablecar
    - helicopter transport

4. Example:

2.1m Wendelstein observatory (German alpes)

Image courtesy LMU

4. Example:

2.1m Wendelstein observatory (German alpes)

despite the other means of transportation,
dome parts needed to be lifted by helicopter

Image courtesy LMU

6. Neighbourhood

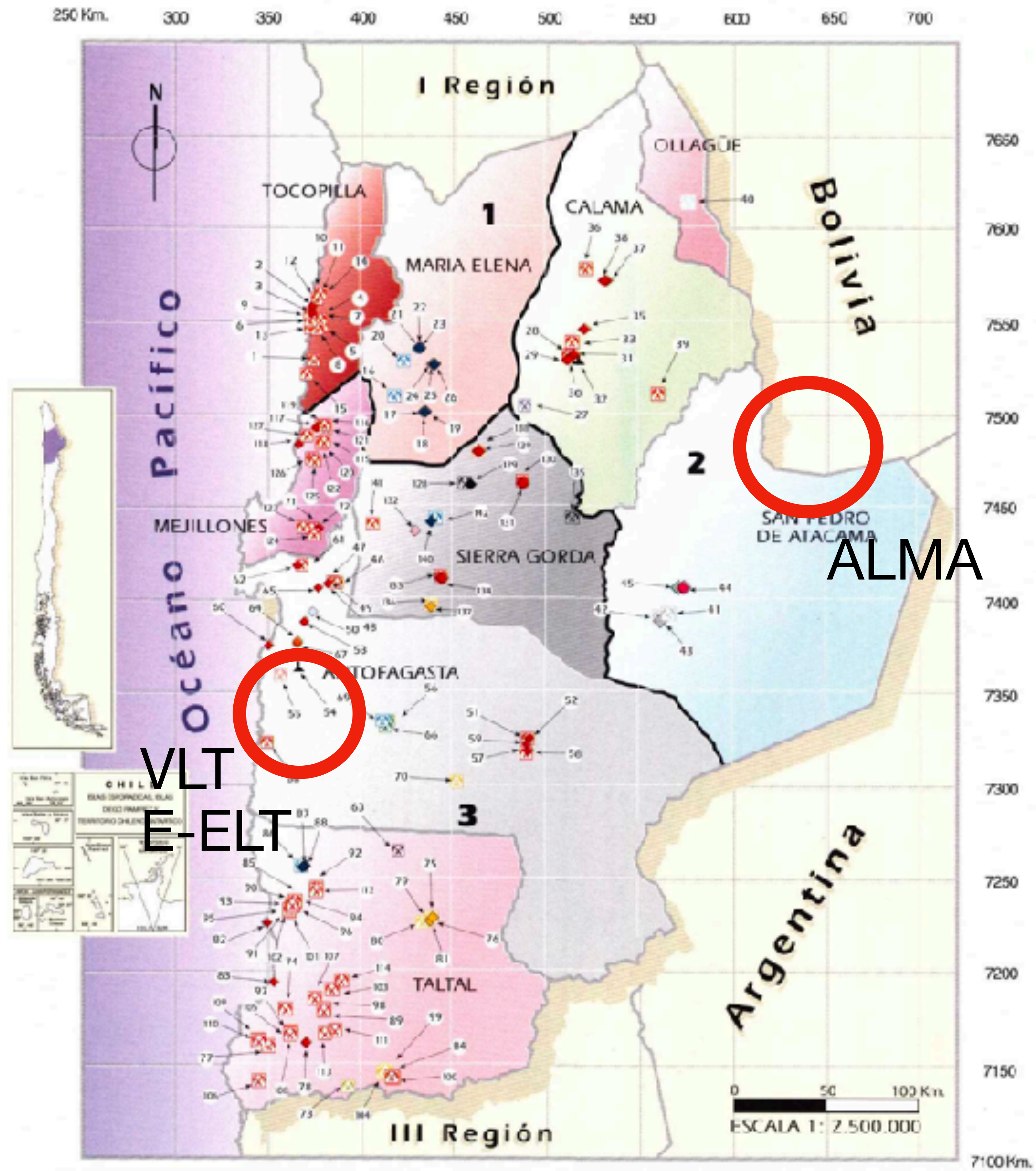
- Are there mining or other major industrial activities in the area
  - Increased dust content in the air
  - Light pollution
- Tourism
  - Light shows, night time illumination
- Power plants
  - increased wake turbulence from aeolic towers
  - change of height of inversion layer due to temperature change of exhaust coolant

⇒ Know your neighbours and assess their potential impact on the observatory
also in the long term (decades)

⇒ Try to also think ahead who could become your neighbour (section 3 earlier)

6. Example

Paranal, Chajnantor observatories wrt. mines

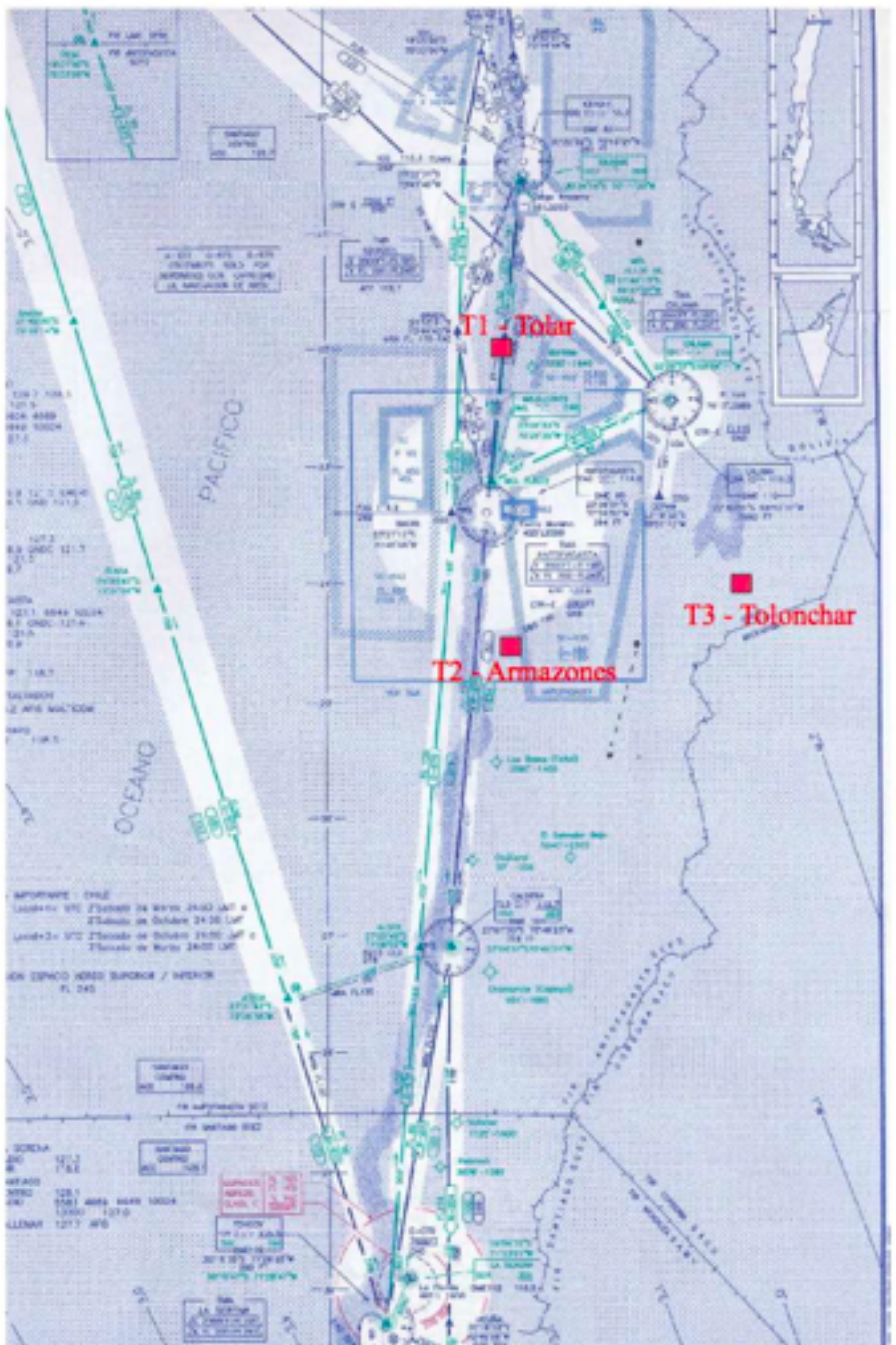


Source: Atlas de faenas mineras (1999)

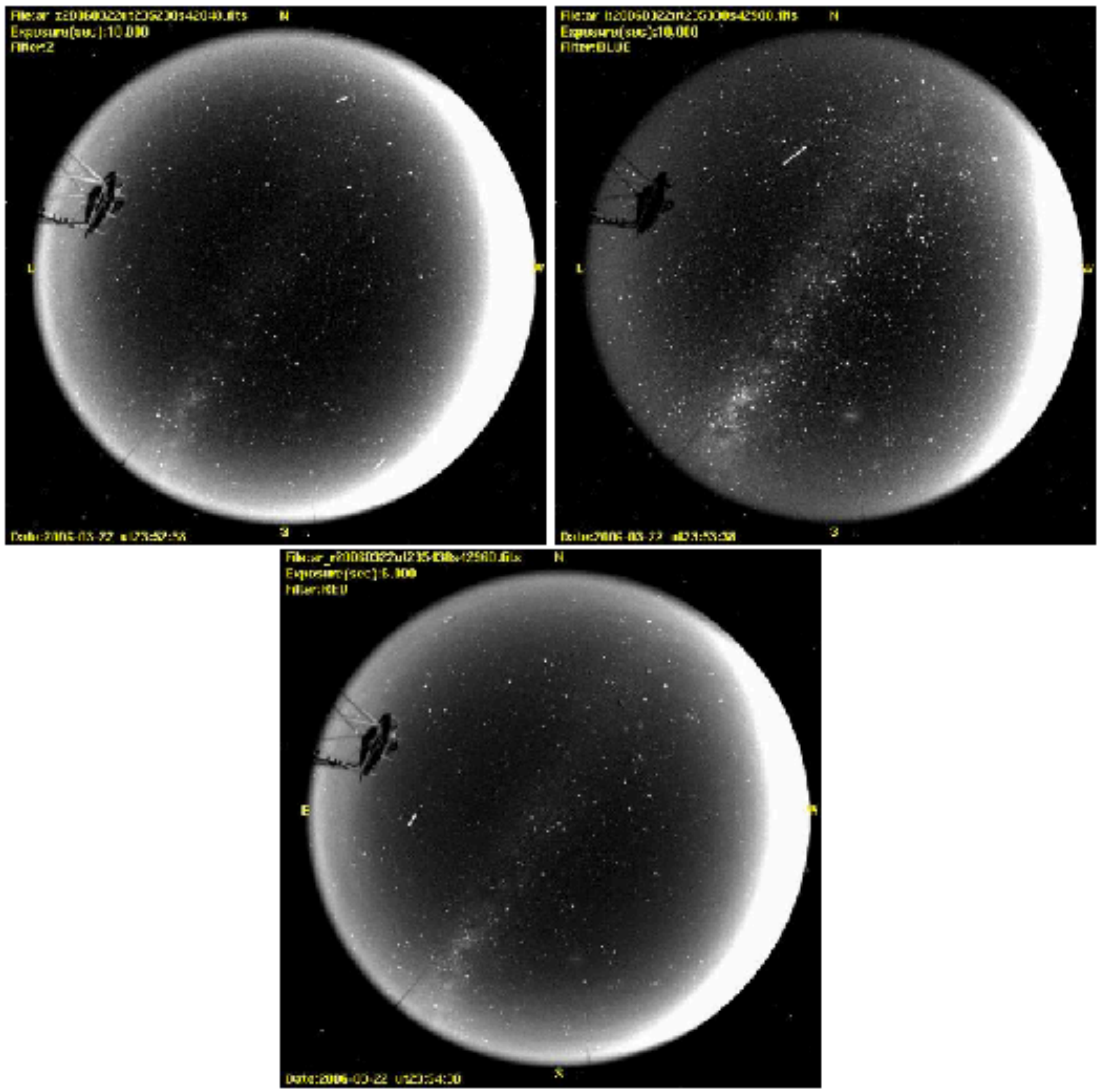
6. Example

Don’t forget the neighbors overhead

map of flight corridors



airplane crossing seen in an all sky camera



7. Geotechnical properties

- Does the site need levelling or major ground works?
- Can the site sustain the expected load of the telescope and its support structures
  - Hidden crevasses
  - Unstable terrain or slopes
  - Hydrology

7. Example for what turns into a more complex geotechnical study

Former candidate site for an observatory which still hosts a communication station
The two original summits were leveled and connected to allow for a helipad

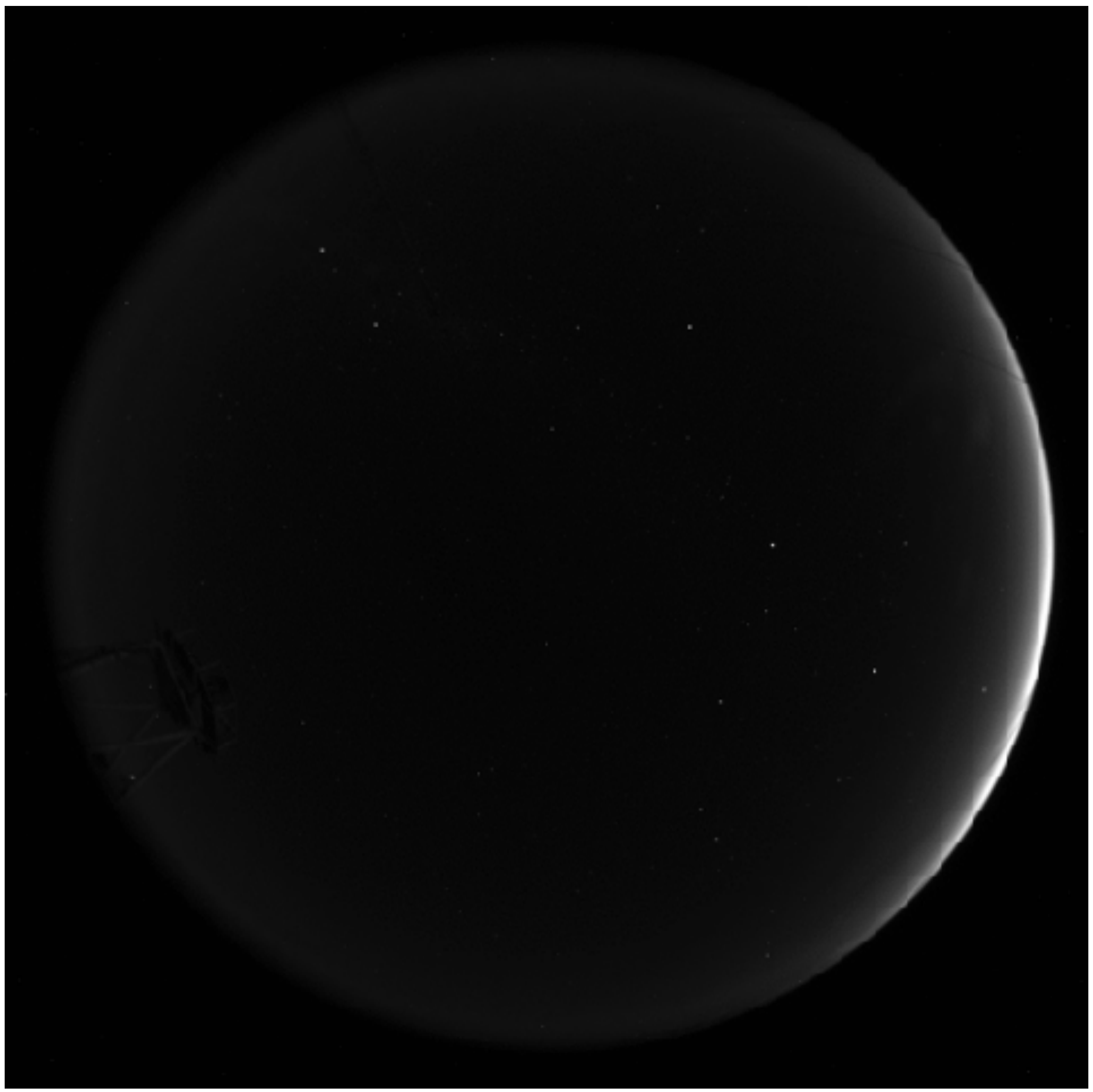
8. Cloud cover

- Photometric studies will be impacted already with few clouds
- Dome closed when overcast
  - If there are clouds there is always the potential danger of precipitation (see humidity)
  - In some regions (observatories) closing the dome is already advised when only few clouds are on the sky
- Monitoring from the site can be used to link with remote sensing data to build up a decade long statistics.

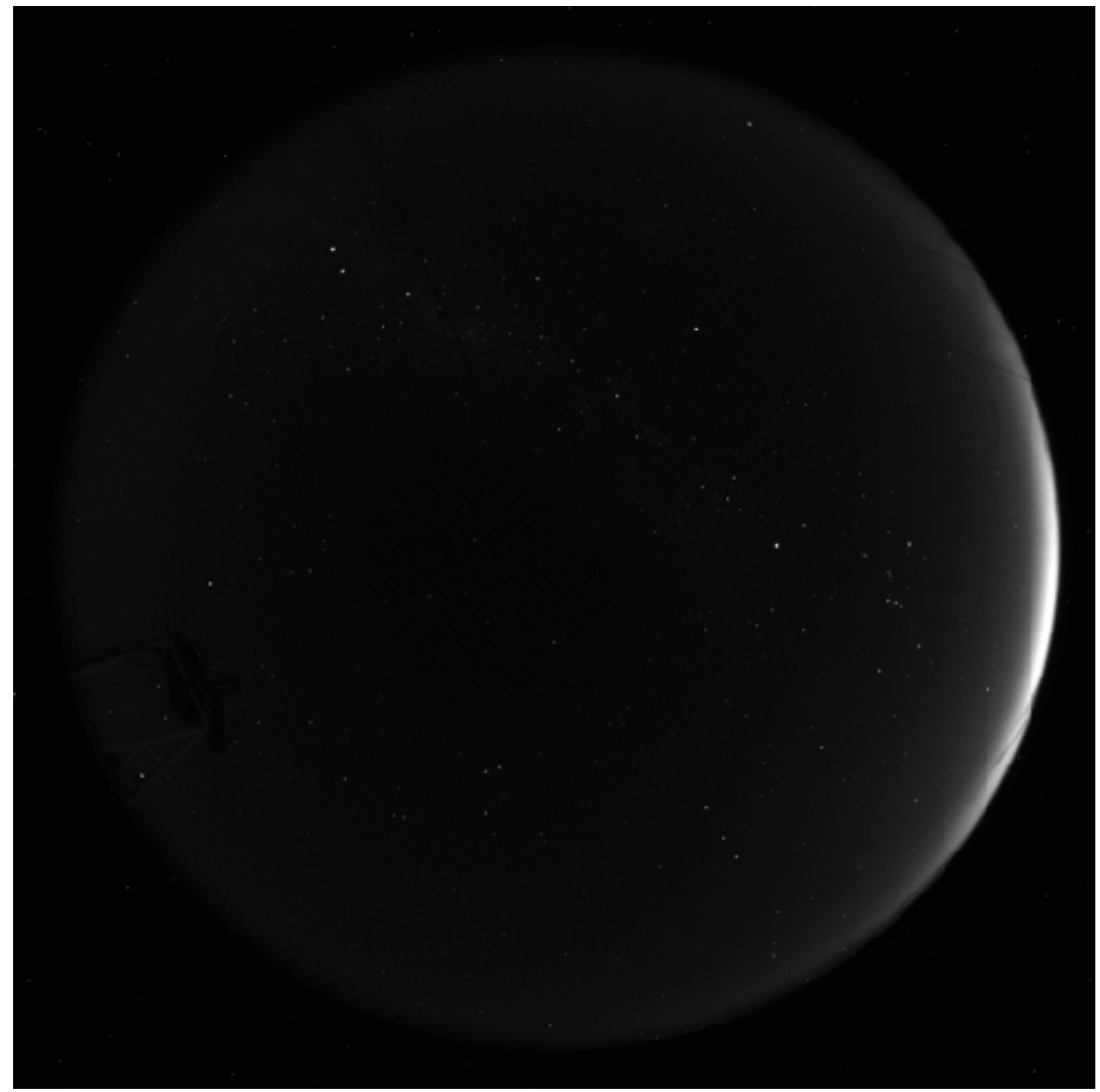
⇒ The best sites on Earth provide a clear-sky fraction of 85-90%.

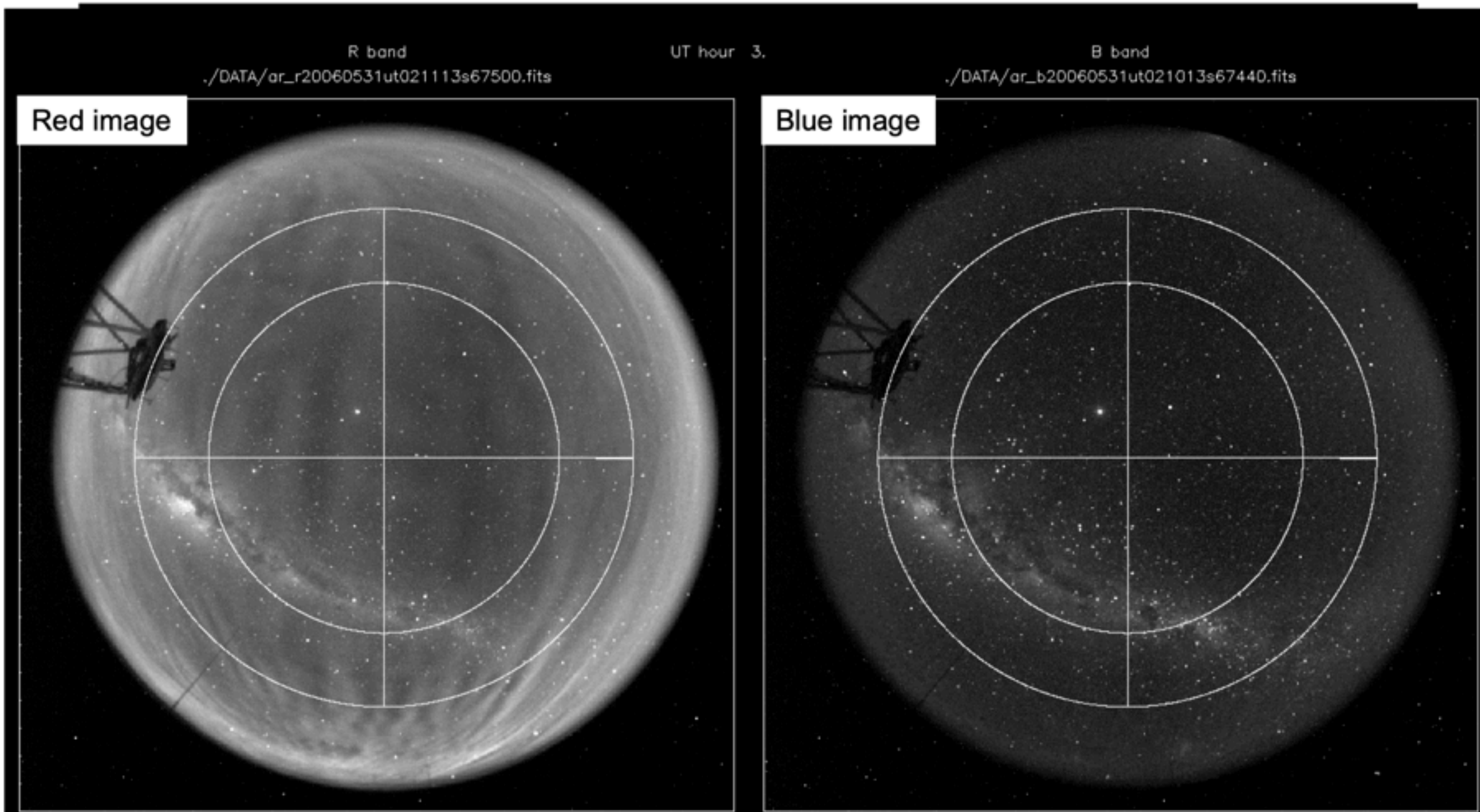
8. All sky camera image of one night

R band



B band



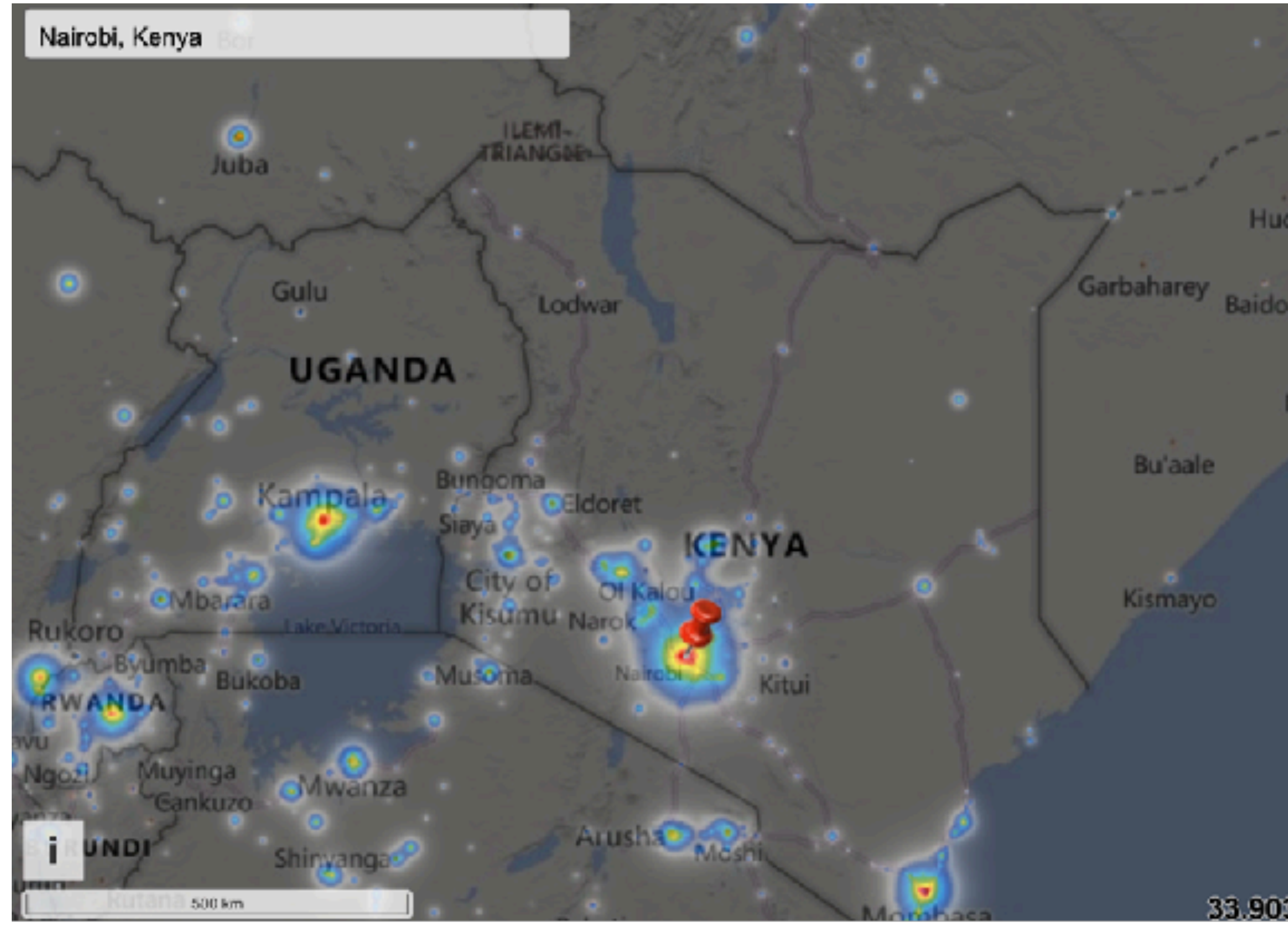


No clouds, just very strong sky glow

9. Light pollution

Atmospheric scattering of light from mostly on-ground light sources

⇒ Swamps the light from celestial objects



from Falchi et al. (2016)
https://doi.org/10.1126/sciadv.1600377

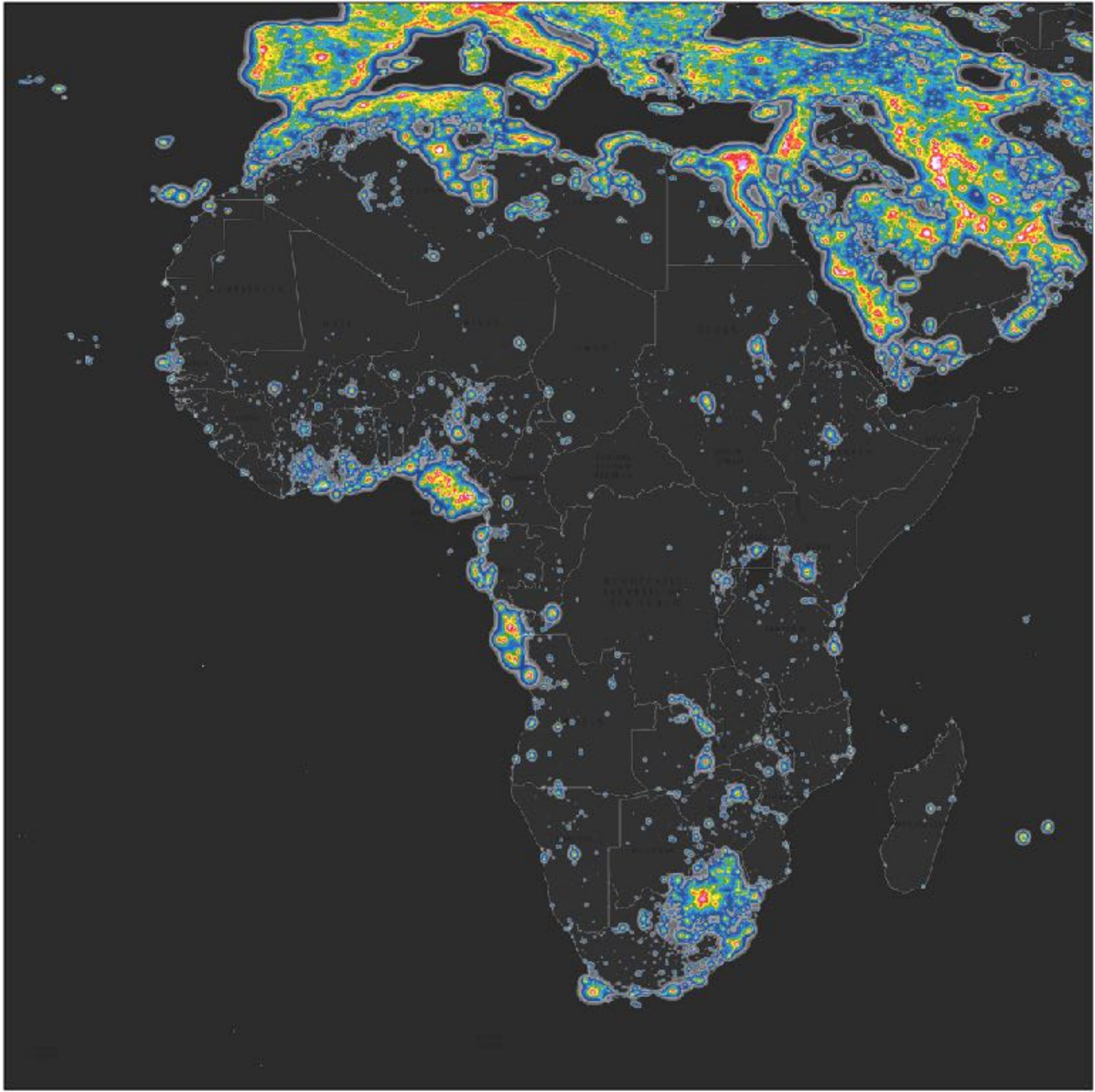
Outreach case
visual observer using 250x

Faintest stars which can be seen by eye at zenith	Limiting magnitude for visual observations using 1.2 m telescope	1 m	0.7 m	0.5 m
6 mag	16.9	16.7	16.2	15.7
5 mag	16.0	15.9	15.5	15.1
4 mag	15.1	15.1	14.8	14.5

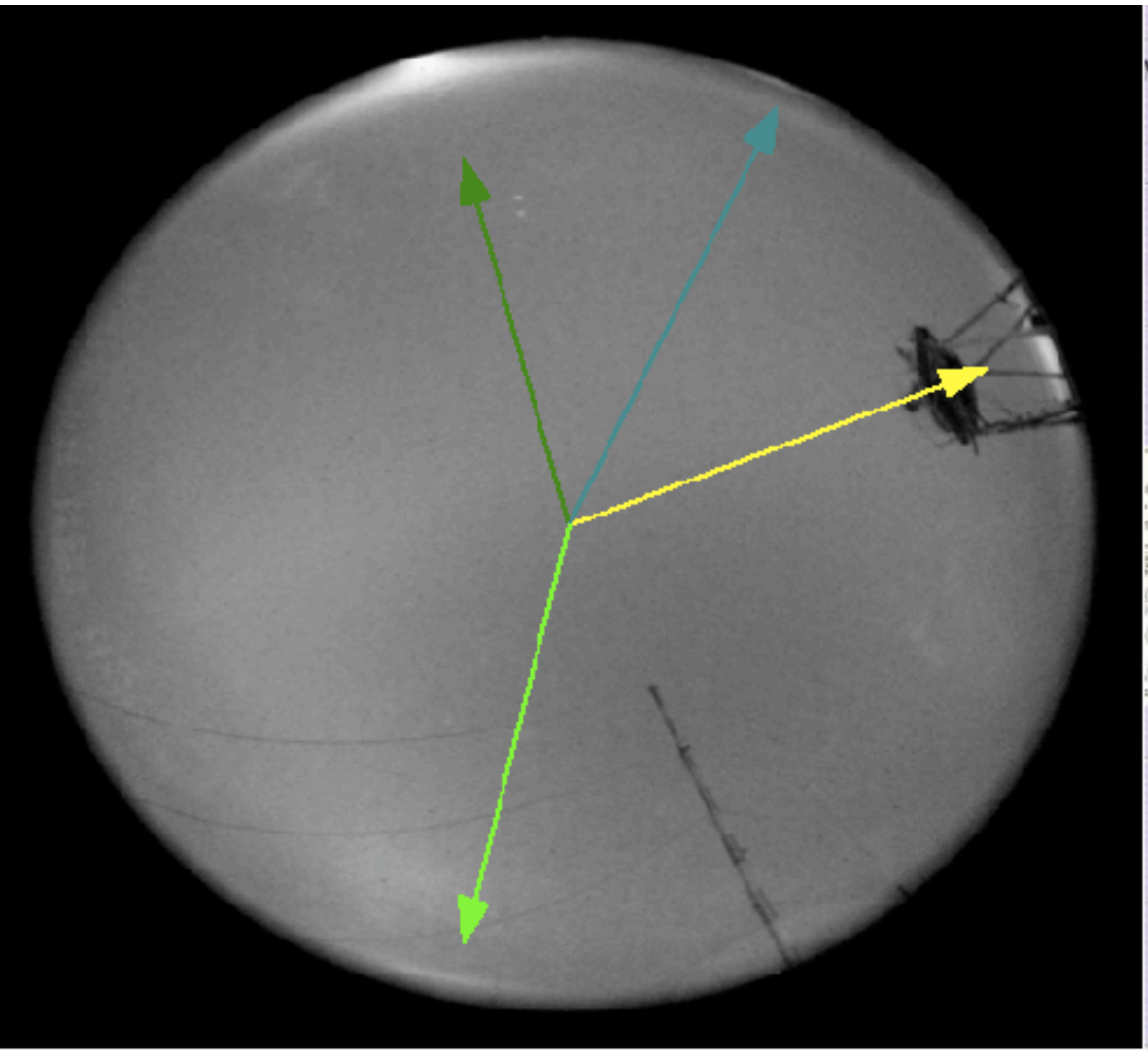
Following Schaefer, (1990) PASP, 102, 212

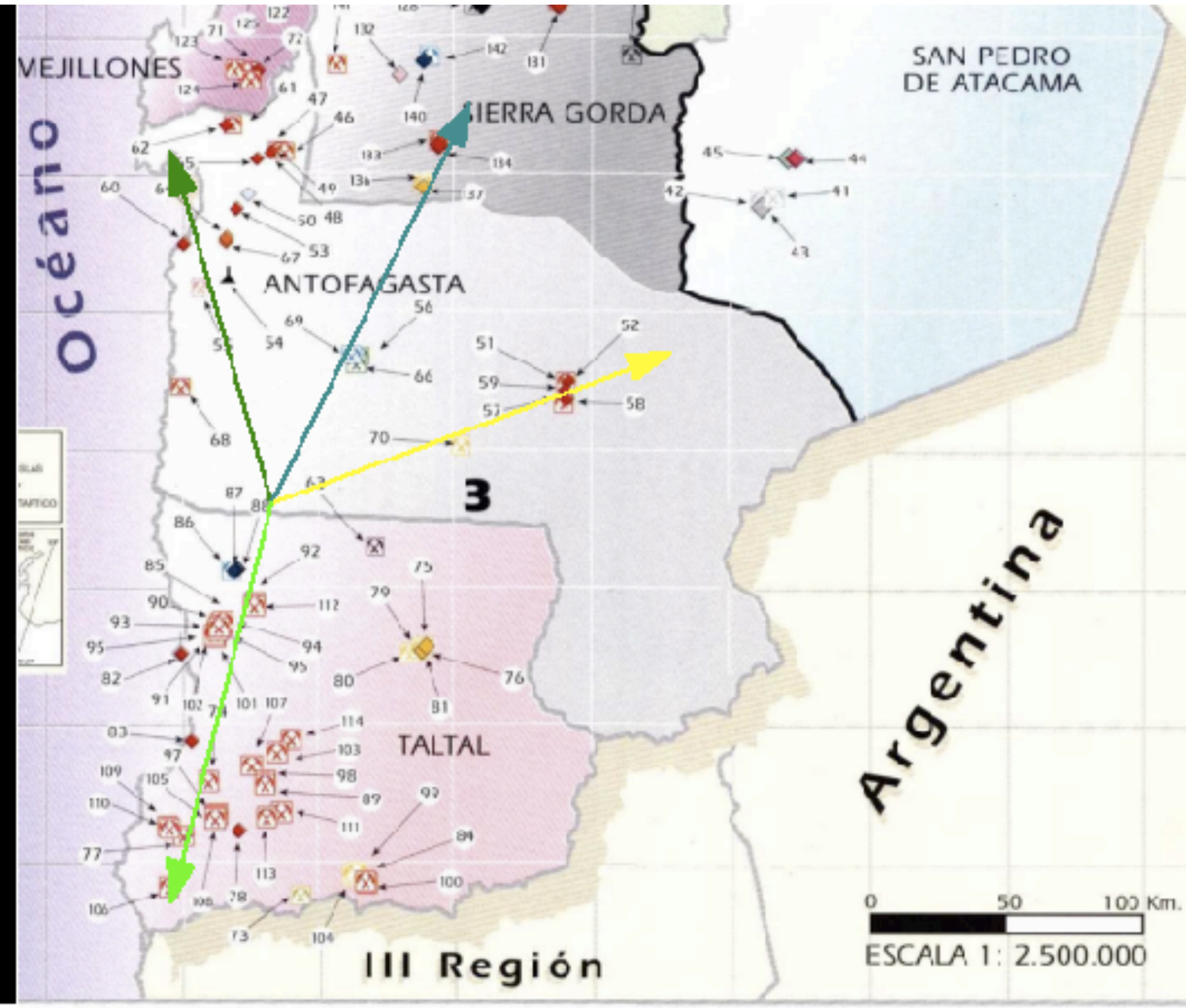
Artificial sky brightness from Falchi et al. (2016)

https://www.arcgis.com/home/webscene/viewer.html?webscene=f80c755f77f24dcbbc9c68db4070c16b&viewpoint=cam:-101.35652637,37.83266155,12622407.685;350.602,0.168



9. Correlation of all sky camera image with map to identify detailed sources of light pollution on your site





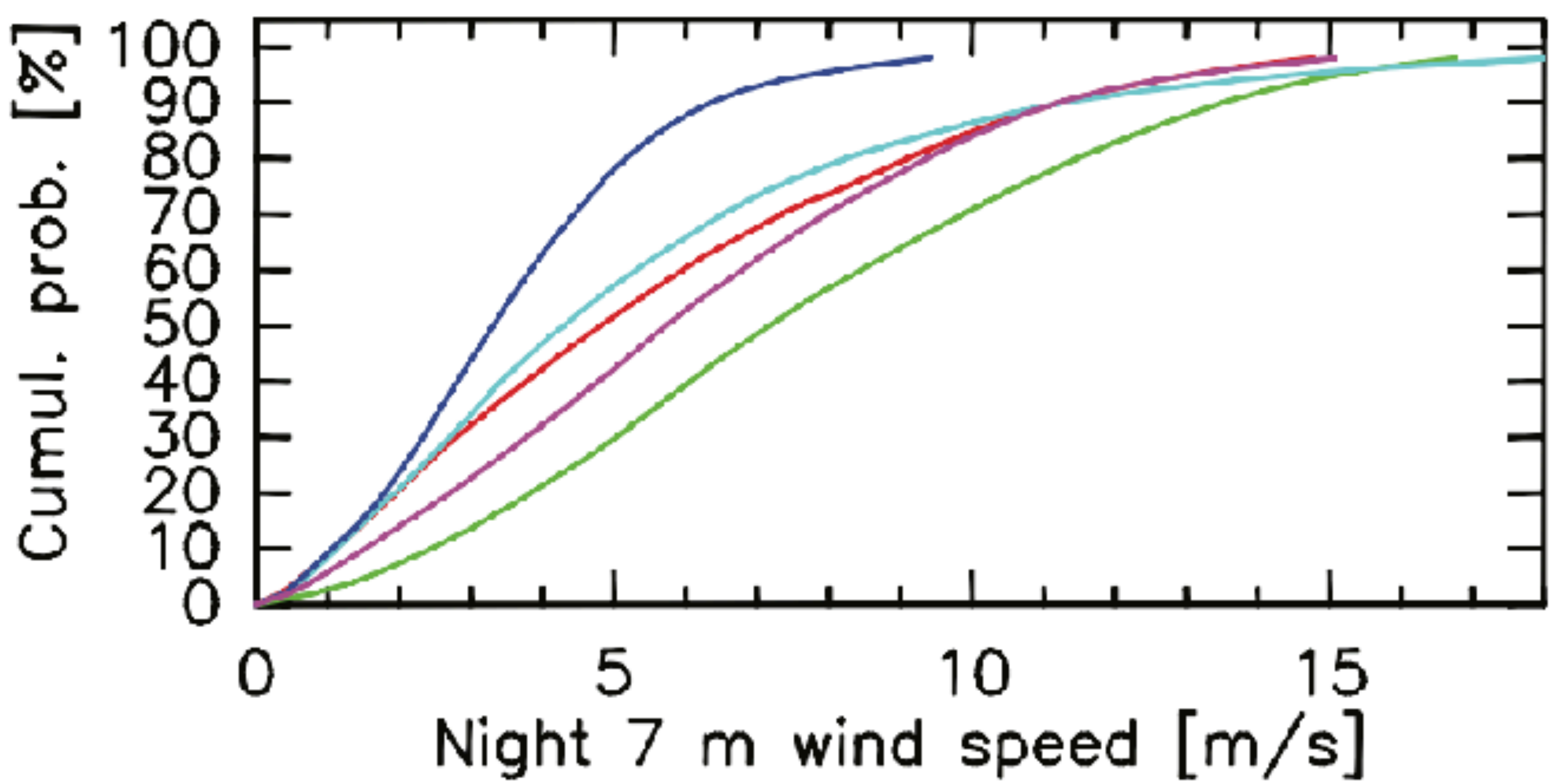
The effect depends on scattering conditions (clouds, aerosols, dust) and will vary with time

10. Wind speed

High wind speeds shake the telescope, thereby

- moving the image during an observation
- put mechanical strain on mechanisms

⇒ Dome only open if wind speed below certain value, typically 12…16 m/s



11. Dust content

- Increases opacity
- Increases light scattering (light pollution)
- Settles on optics, reduces throughput
- Abrasive effect under high winds
- Enters and clogs mechanism
- If dust is composed of organic material (e.g. ashes from wild fires) eventual chemical reaction with optical coatings
- Still a field of investigation
  - no coherent limitations for dust concentrations at observatories
  - sensors are quite expensive

12. Humidity

- Condensation carries dust and aerosols
  - Such dirty condensation on optics will degrade throughput or performance
  - Effect at least temproarily (until next cleaning), but can cause permanant damage
  - Water can damage mechanics
  - Water can damage electronics

⇒ Dome only open if humidity below certain value

$$\text{RH} \leq 90...95\,\%$$

or

$$(T_{air} - T_{dew}) \geq 2^{\circ}\mathrm{C}$$

13. Seeing, optical turbulence, pwv

Finally, you made it here

- it’s night time
- you have a telescope+instrument
- there are few/no clouds
- low wind
- low humidity
- no dust storm or wild fire
- low wind

→ now you can start see *seeing*

→ and if you are observing in the infrared, say at $\lambda \gtrsim 1.65~\mu\mathrm{m}$, then you can also start worrying about *pwv*

will be discussed by others in this workshop and also as part of the pratical session

Putting it all together - which one is your best site

- For the TMT site testing and selection, Schoeck et al. (2010) noted:
  "..site selection will not be based on the exact values of any single parameter at any of the sites. It is based on a careful balancing act of atmospheric, technical, and programmatic parameters in which small changes in one parameter are unlikely to affect the outcome."
  and
  "They *(the data)* also show that not a single site is perfect or is the best (or worst) in all parameters."

My (SE) conclusion:

- If the site with the best atmospheric, technical and logistical conditions is not available (spoiler: it never is) then site selection will be a compromise (spoiler: it always is)

- If a site is *available and the compromise is acceptable*: go for it !

  - This is especially true for apertures $\lesssim$ 1.5m

Example for a good site selected without any prior on-site testing

ESO La Silla observatory selected in the early 1960s

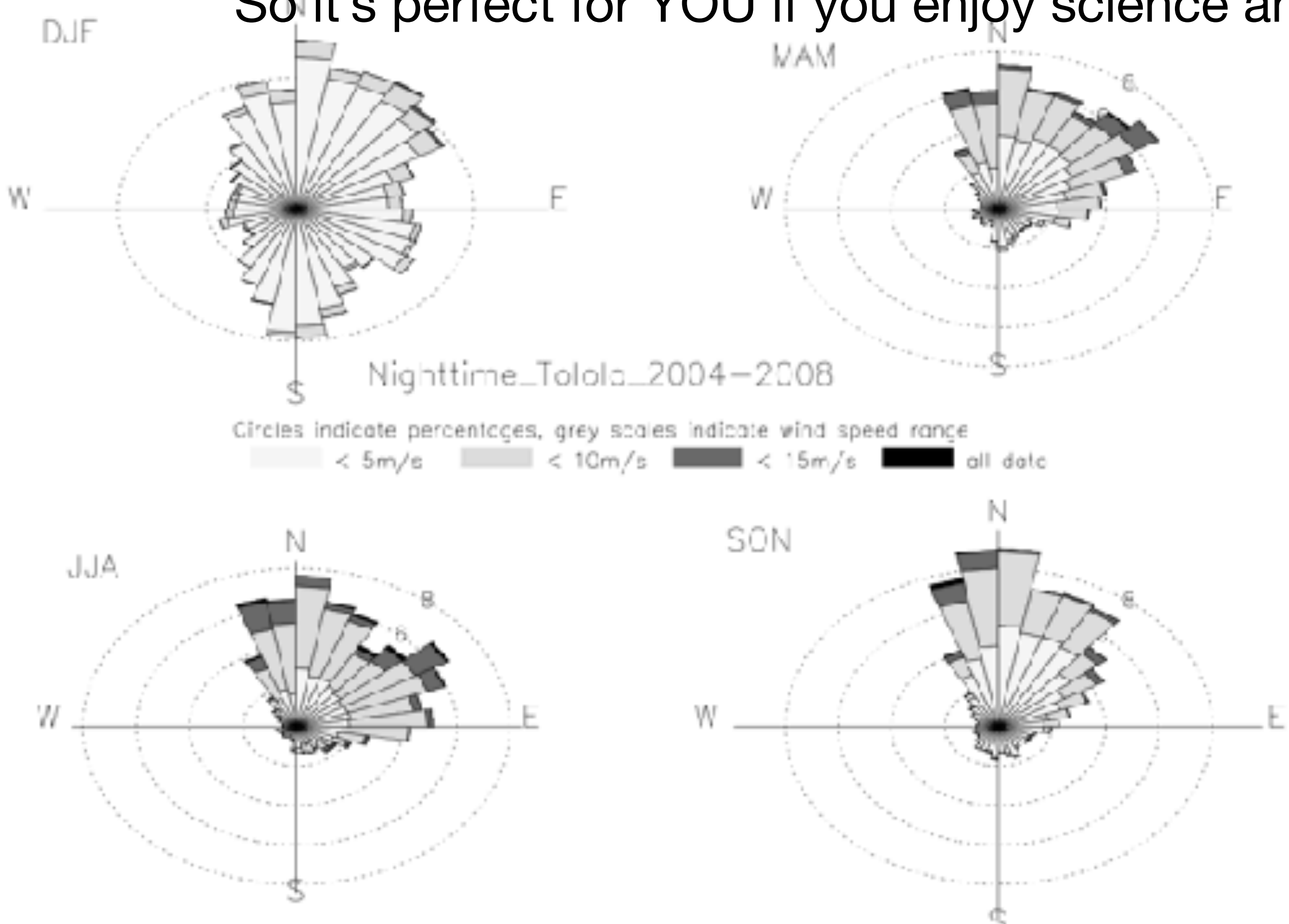
- Conditions were measured prior to selection more than 100 km away
- The government provided a map of available mountains
- After some basic scouting, the then ESO DG decided (note, the board/council was not thrilled at first)

But beware - only do this if you really know what you're doing and if all other conditions are just right

Final notes for site testing

Worry first about the basics

- Install (at least) one weather station on every candidate (or the already selected) site as early as possible
    - Make sure to do proper setup and regularly check the sensor calibration
    - These data will form the main basis for your facility design and planning, as well as providing the empirical basis for detailed meteorological models
    - And - when power available - add an all sky camera
    - Site testing and monitoring is an inter-disciplinary area (optics, meteorology, geology, and civil, electrical, computer engineering).
      So it's perfect for YOU if you enjoy science and fresh air !



Practical session - preparing an observation proposal

Preparing an observation

1. Science case:
   which object
   which parameter(s) to observe

2. How to observe that parameter:
   instrument selection
   instrument settings

3. Estimate observation performance
   how long do you have to use the telescope?
   how much faster is it using the bigger telescope?
   how does the seeing impact the performance?

4. Present 1, 2, 3 to another group to convince them to give you observing time

Investigation type		Energy range	Imaging	Spectroscopy
Brightness		Optical-IR	X	X
Temperature	Atomic	Optical	X	X
	Molecular	IR	X	X
Chemical composition	Atomic	Optical		X
	Molecular	IR		X
Astrometry		Optical-IR	X	
Radial velocity	Atomic	Optical		X
	Molecular	IR		X