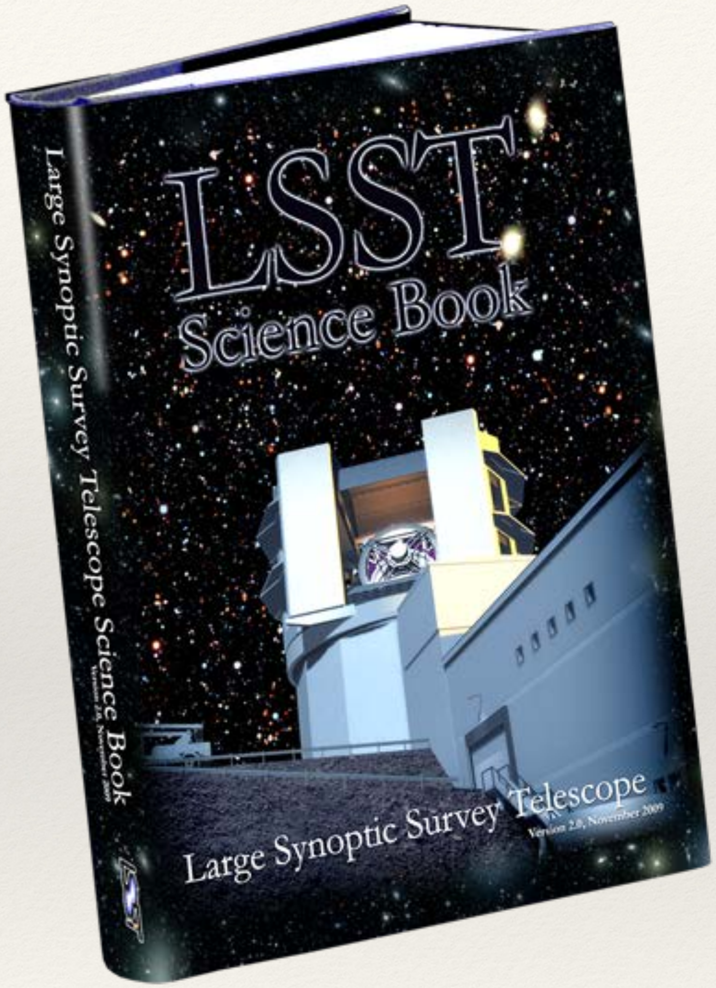
TMT Instruments 101

$$\cancel{\frac{A\,\Omega\,\eta}{d\Omega}}$$

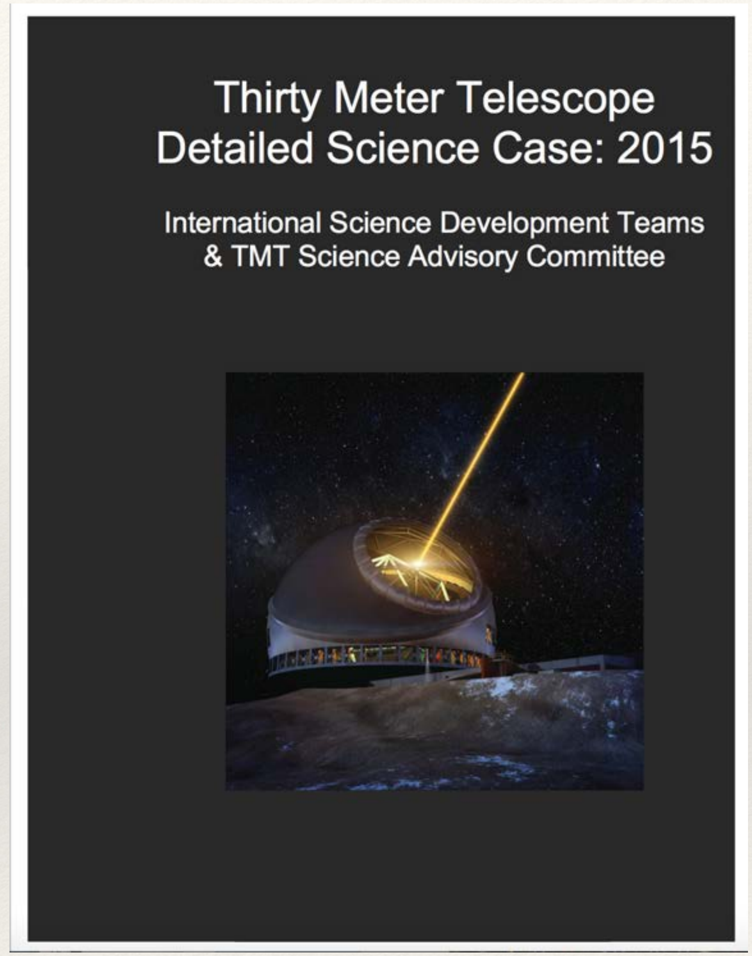
Roberto Abraham (University of Toronto)

600+ pages



http://www.lsst.org/scientists/scibook

203 pages



http://www.tmt.org/sites/default/files/documents/application/pdf/tmt-dsc-2015-release-2015apr29-s2.pdf

Example science requirements for IRIS

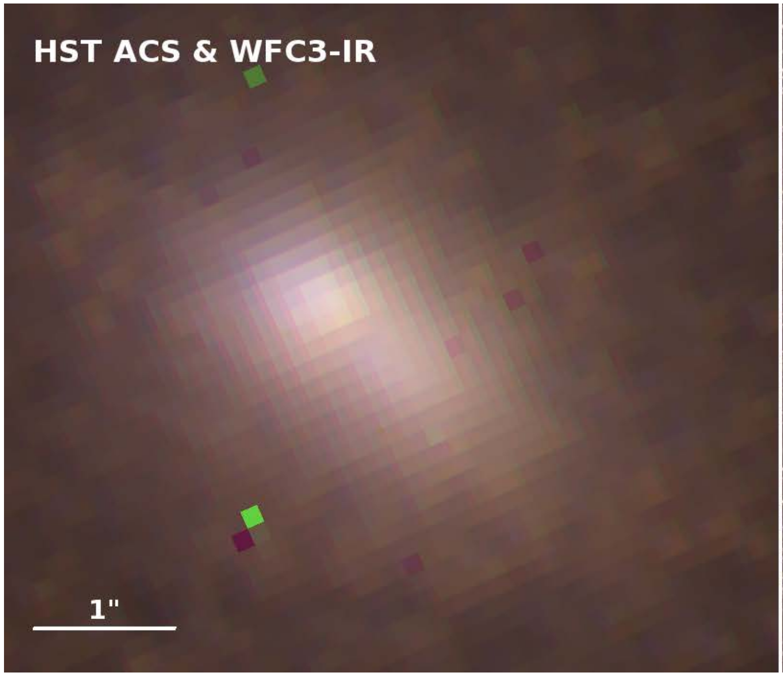
- IRIS is diffraction-limited near-infrared imager and integral field spectrograph designed for first light for TMT

	Requirement	Example Limiting Science Drivers
1. Wave-length Range	**[REQ-2-IRIS-0700]**: Wavelength coverage of 0.84-2.4 μm.	Blue limit: Ca triplet for black hole masses Red limit: full K-band for maximum sensitivity at the highest Strehls (e.g., Galactic Center, stellar IMF and photometry)
2. Image Quality (Imager)	**[REQ-2-IRIS-0710]**: Wavefront error less than 30 nm (may degrade more for coarser scales). **[REQ-2-IRIS-1310]**: Distortion correctable to 50 μas. **[REQ-2-IRIS-1315]**: For a given magnitude (m) star observed in the imager field of view, ghost images should be fainter than m+X magnitudes.	Galactic Center, to enable tests of General Relativity. Stellar photometry to enable probes of the IMF in different environments. Crowded field photometry and astronometry in the Galactic Center and Star formation cases requires limited ghost images, as does the High Contrast exoplanet case.

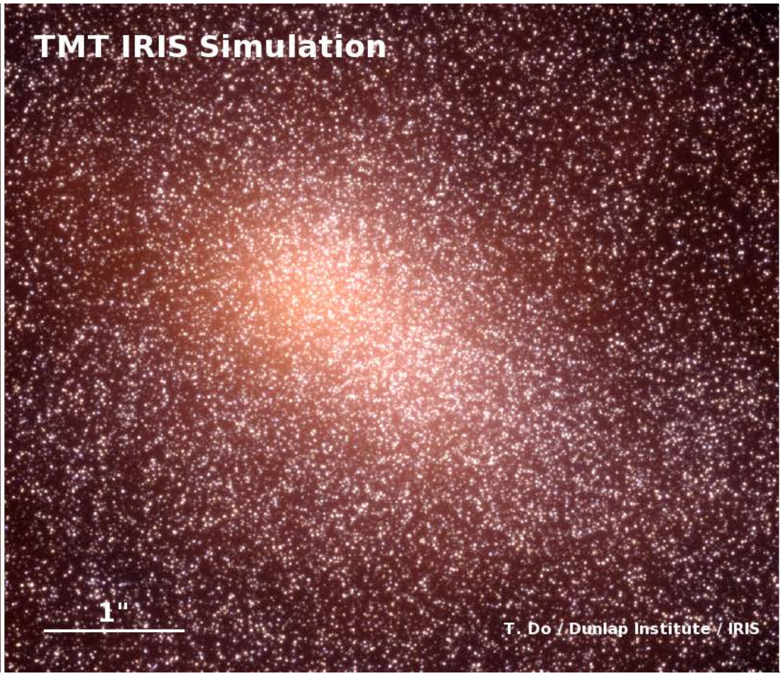
Example science requirements for IRIS

- IRIS is diffraction-limited near-infrared imager and integral field spectrograph designed for first light for TMT

Andromeda M31 Nucleus



HST (2.5m)



TMT (30m)

Discovering the Unexpected in Astronomical Survey Data (Norris 2016)

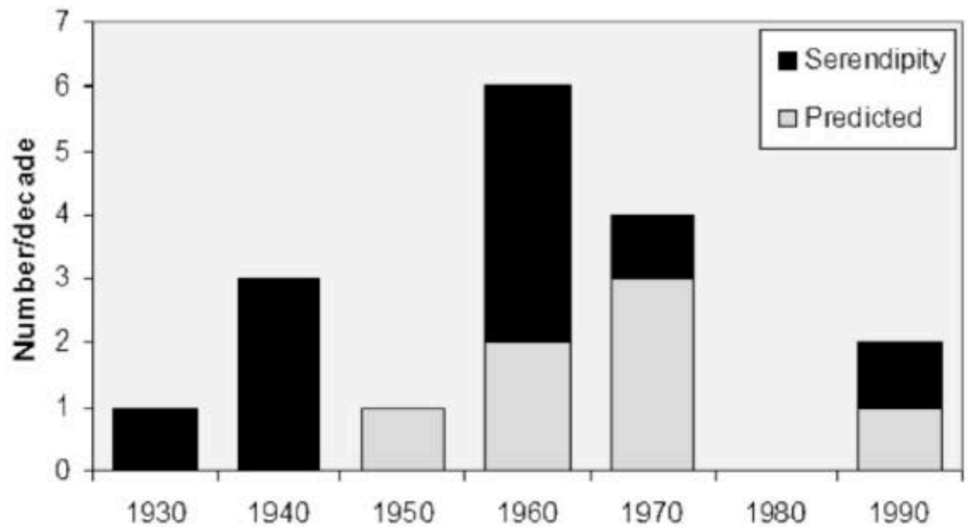


Figure 1 A plot of recent major astronomical discoveries, taken from (Ekers 2009), of which seven were "known-unknowns" (i.e. discoveries made by testing a prediction) and ten were "unknown-unknowns" (ie. a serendipitous result found by chance while performing an experiment with different goals). The data in this plot are taken from Wilkinson et al. (2004).

2.4 The value of Science Goals

New telescopes or surveys are usually justified by their science goals. For example, the EMU project (Norris et al. 2011) is justified by 16 key science projects with goals such as measuring the star formation rate density over cosmic time, studying AGN evolution and the role of AGN feedback, and making independent measurements of fundamental cosmological parameters. However, as demonstrated above in the case of the HST, the major discoveries made with a new telescope or survey are not usually represented by such science goals.

However, science goals are still important for two reasons. First, they represent use cases. If a telescope is built that is able to address challenging science goals, then it is likely to be a high-performing telescope. Second, much of astronomy advances not by spectacular major discoveries, but by the incremental science that is usually encapsulated in science goals. Such incremental advance is also very important, and, unlike serendipitous discoveries, represents a predictable outcome from a new telescope.

nomical object. As a result, she discovered pulsars. She describes the process in detail in Bell-Burnell (2009).

The following critical elements were essential for this discovery.

- she explored a new area of observational parameter space
- she knew the instrument well enough to distinguish interference from signal
- she examined all the data by eye
- she was observant enough to recognise something unexpected
- she was open minded, and prepared for discovery
- she was within a supportive environment (i.e. one that was accustomed to making new discoveries).
- she was persistent

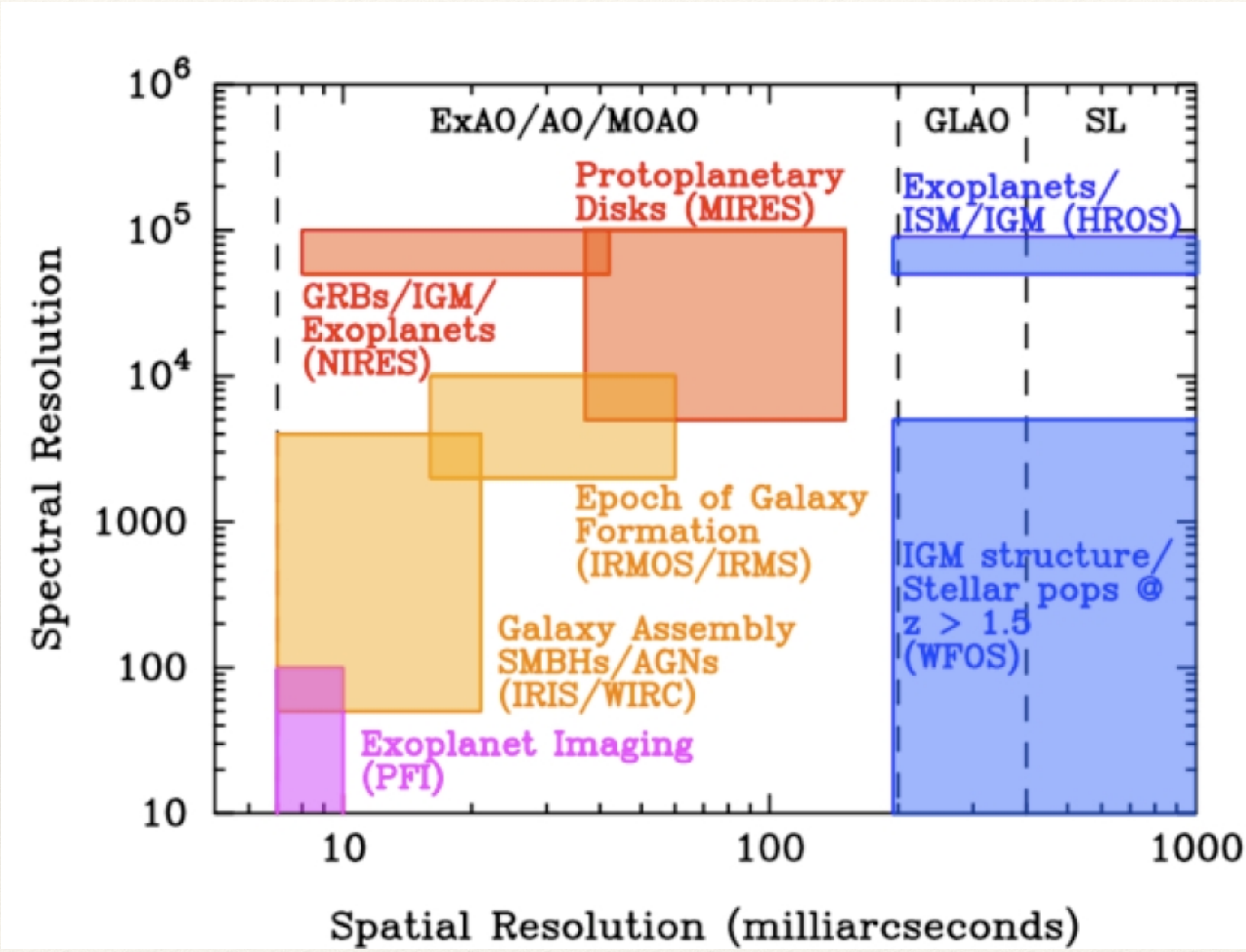
Discovering the Unexpected in Astronomical Survey Data
(Norris 2016)

'Central planning' doesn't have a great track record.
'Careful planning' by individuals in the community does.

Table 1 Major discoveries made by the Hubble Space Telescope (*HST*). Of the *HST*'s "top ten" discoveries (as ranked by National Geographic magazine), only one was a key project used in the *HST* funding proposal (Lallo 2012). A further four projects were planned in advance by individual scientists but not listed as key projects in the *HST* proposal. Half the "top ten" *HST* discoveries were unplanned, including two of the three most cited discoveries, and including the only *HST* discovery (Dark Energy) to win a Nobel prize. This Table was previously published by Norris et al. (2015).

Project	Key Project?	Planned?	Nat Geo top ten?	Highly cited?	Nobel Prize?
Use cepheids to improve value of H_0	✓	✓	✓	✓	
UV spectroscopy of ig medium	✓	✓			
Medium-deep survey	✓	✓			
Image quasar host galaxies		✓	✓		
Measure SMBH masses		✓	✓		
Exoplanet atmospheres		✓	✓		
Planetary Nebulae		✓	✓		
Discover Dark Energy			✓	✓	✓
Comet Shoemaker-Levy			✓		
Deep fields (HDF, HDFS, GOODS, FF, etc)			✓	✓	
Proplyds in Orion			✓		
GRB Hosts			✓		

An alternative approach, based on open parameter space and on some principles.



This is a principle I like. On the next slide, I'll show you one I don't.

$$\frac{A\,\Omega\,\eta}{d\Omega}$$

Replace mirror area A ~D^2, where D is the aperture of the mirror (forget about factors of 2 and pi). Then in natural seeing this thing will scale as:

$$\boxed{\frac{D^2\,\Omega\,\eta}{d\Omega}}$$

But what if we're working at the diffraction limit? Then…

$$d\Omega \sim \left(\frac{\lambda}{D}\right)^2$$

Substituting into the equation at top right gives us…

$$\boxed{\frac{D^4\,\Omega\,\eta}{\lambda}}$$

This "D to the Fourth Advantage" is why people love Adaptive Optics and space telescopes!

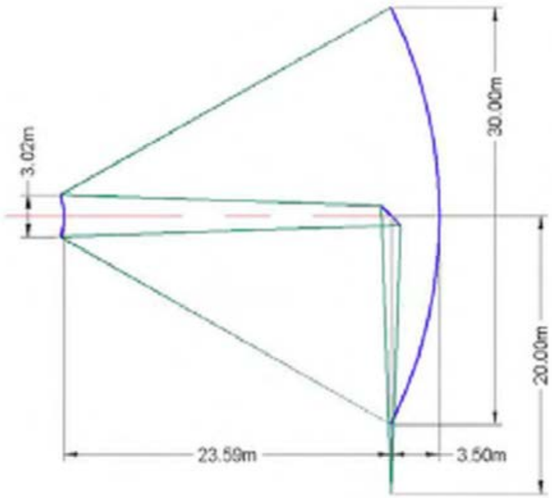


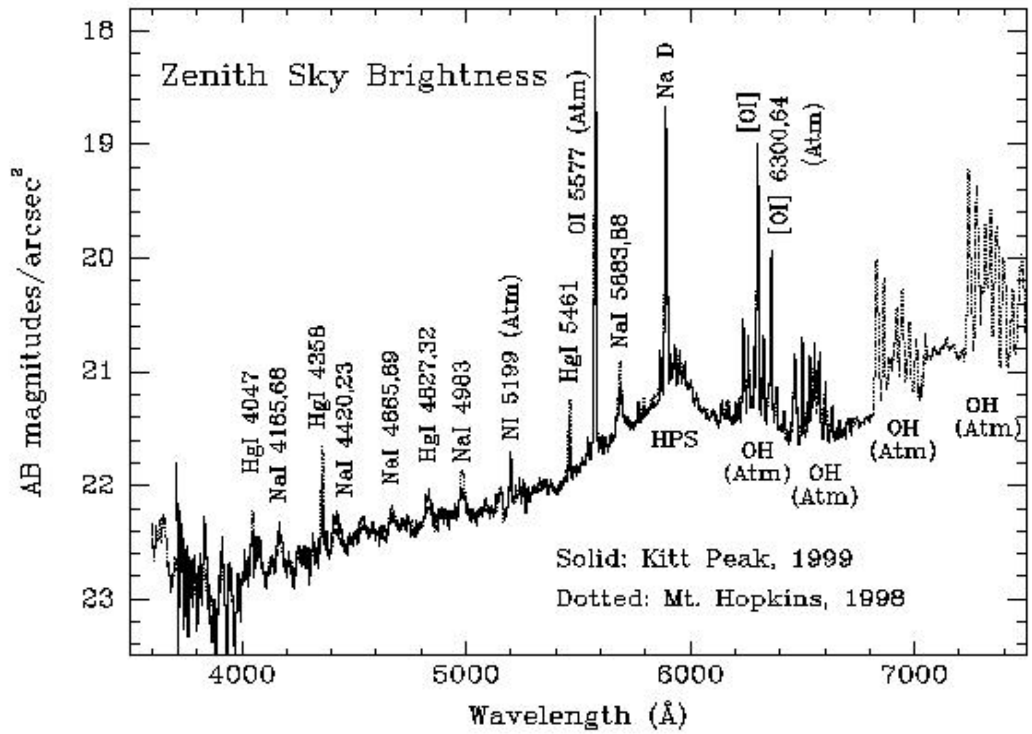
Figure 2. Optical layout of the TMT [6]. The optical prescription is a Richey-Chretien design that eliminates third-order spherical aberration and coma.

This whole approach makes me uncomfortable

- A figure-of-merit/information-theory based view of things, seems far too crude. Contrast the Shannon information content in a 1D spectrum and a 2D image… you learn different things.
- A frequently-noted "benefit" of track-2 instruments (AO-based) is they tend to be fairly small. But the instruments are not small because of fundamental laws of optics, they're small because of a compromised field of view. That is totally fine if you don't need the field of view, but let's make sure it's a science-driven choice, not an engineering-driven choice.
- This whole line of thinking totally ignores the surface brightness of the night sky and a while host of other things.

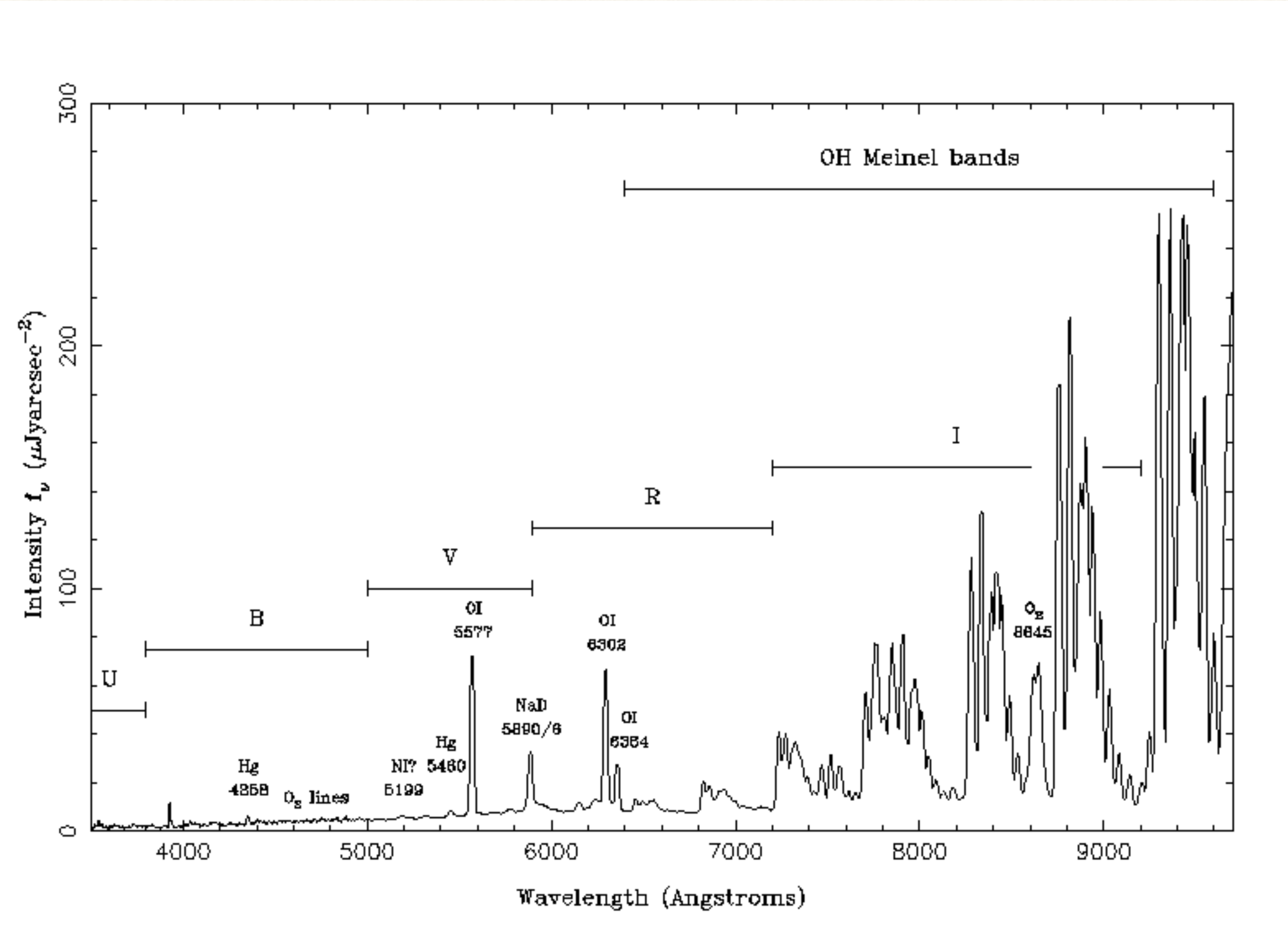
The whole approach makes me uncomfortable

- It’s way too crude
- It encourages people to think more about engineering then science.
- It leaves important stuff out.



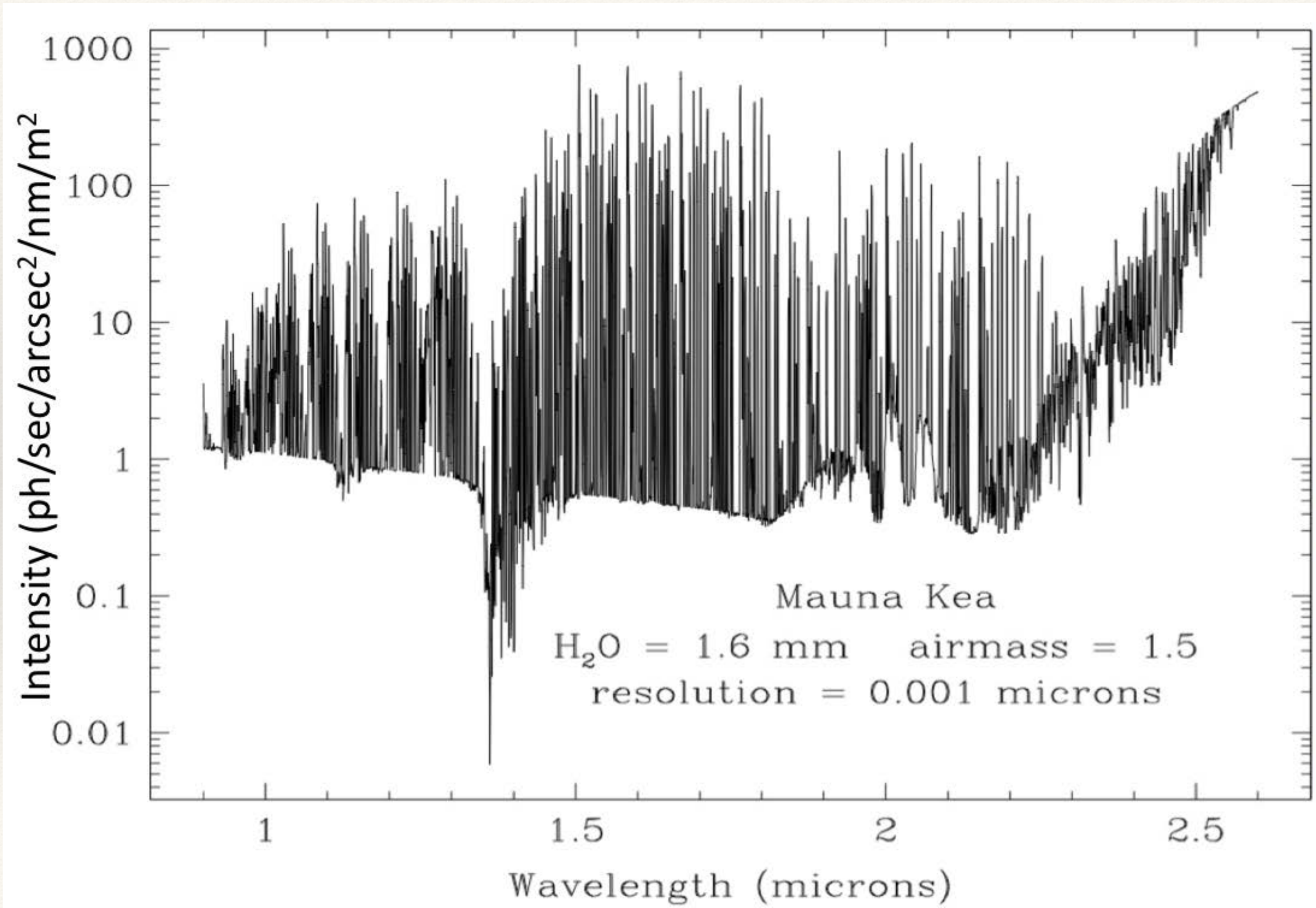
• For extragalactic astronomy the sky is typically way brighter than the objects you're looking at.
• For background limited observations going 1 mag deeper means 2.5x2.5=6.25x longer integration.
• Also goes for making the sky brighter. A 2 mag difference in sky brightness means you need to integrate for 40x longer.

Go redder…



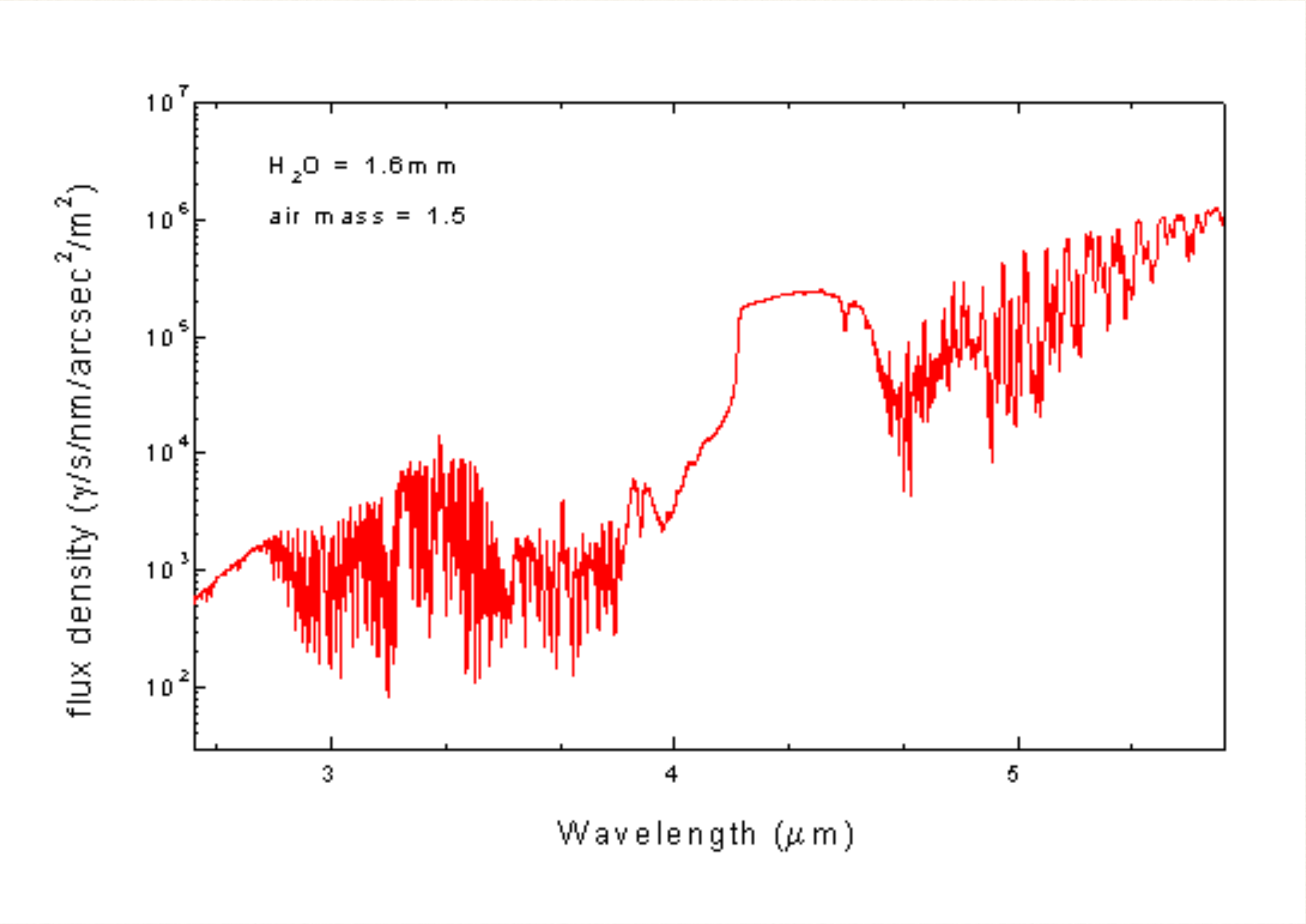
OH Meinel bands
U
B
V
R
I
Hg 4358
O_2 lines
NI? 5199
Hg 5460
OI 5577
NaD 5890/6
OI 6302
OI 6364
O_2 8645
Intensity f_ν (μJy arcsec^{-2})
Wavelength (Angstroms)
0
100
200
300
4000
5000
6000
7000
8000
9000

… and redder…

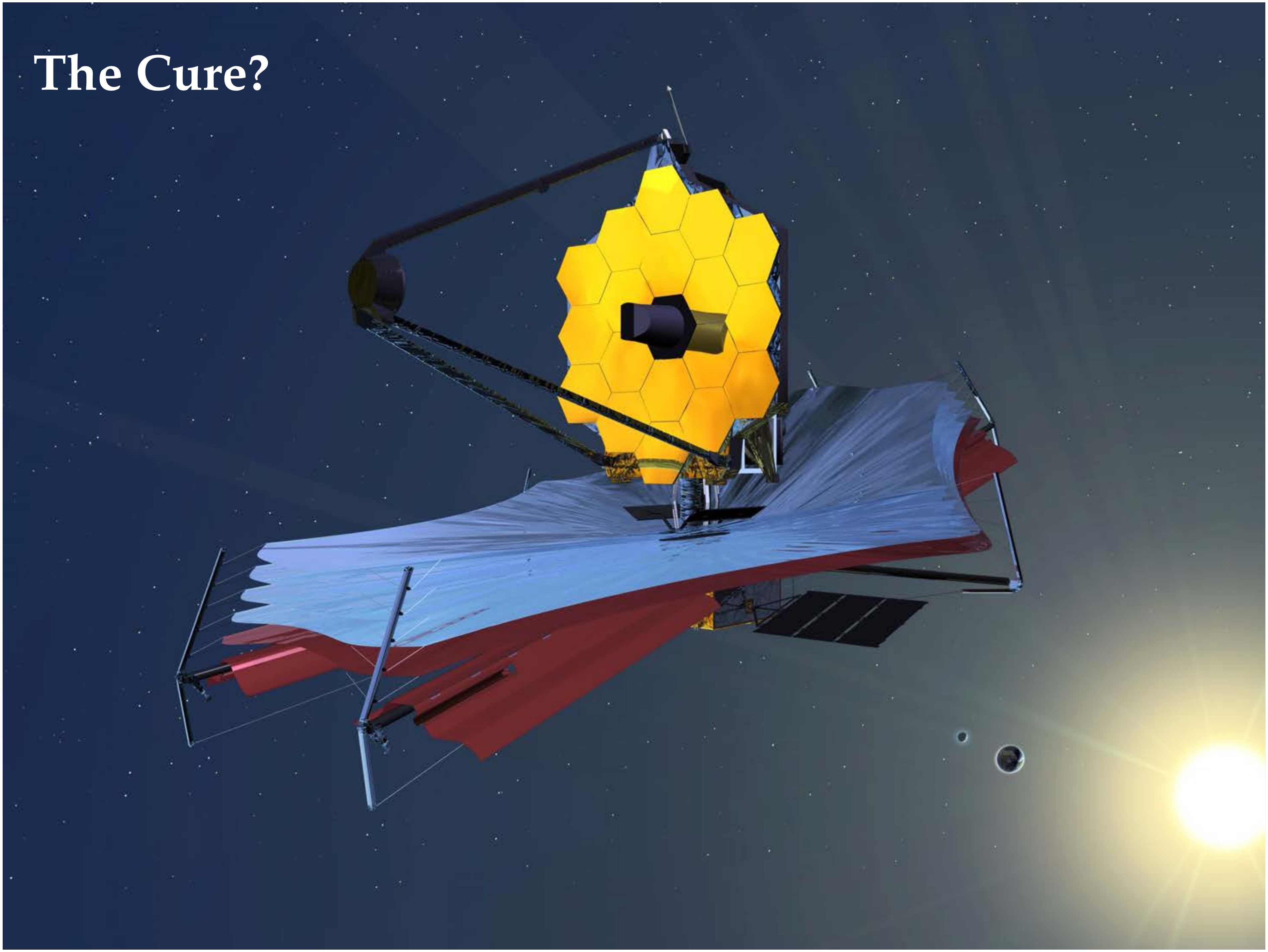


Intensity (ph/sec/arcsec^2/nm/m^2)
1000
100
10
1
0.1
0.01
1
1.5
2
2.5
Wavelength (microns)
Mauna Kea
H_2O = 1.6 mm airmass = 1.5
resolution = 0.001 microns

… it gets ridiculously bad.



The Cure?



Guiding Principles

- It's an Ecosystem, Dummy
- Open up Parameter Space.
- Give The People What they Want
- Experience Matters!
- Respect the Laws of Optics
- Eat Your Own Dog Food
- Make Miracles Happen One at a Time

XKCD comic teaches us some physics

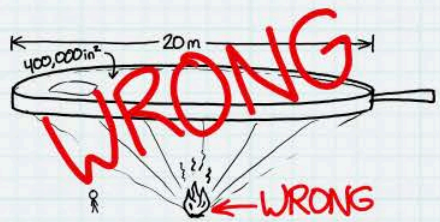
Fire From Moonlight

Can you use a magnifying glass and moonlight to light a fire?

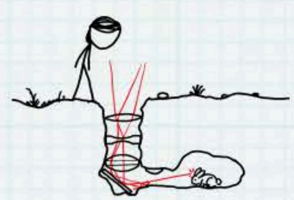
—Rogier Spoor

At first, this sounds like a pretty easy question.

A magnifying glass concentrates light on a small spot. As many mischevious kids can tell you, a magnifying glass as small as a square inch in size can collect enough light to start a fire. A little **Googling** will tell you that the Sun is 400,000 times brighter than the Moon, so all we need is a 400,000-square-inch magnifying glass. Right?

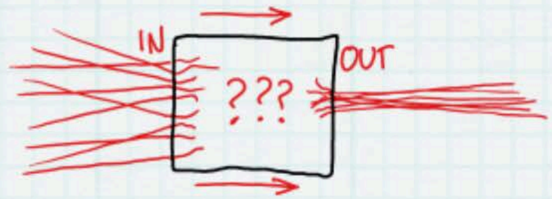


Wrong. Here's the real answer: **You can't start a fire with moonlight**[1] no matter *how* big your magnifying glass is. The reason is kind of subtle. It involves a lot of arguments that sound wrong but aren't, and generally takes you down a rabbit hole of optics.



First, here's a general rule of thumb: **You can't use lenses and mirrors to make something hotter than the surface of the light source itself.** In other words, you can't use sunlight to make something hotter than the surface of the Sun.

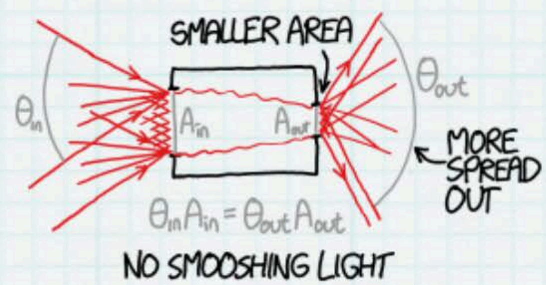
of them side-by-side? Then you could gather lots of smooshed beams and aim them at a target from slightly differ angles.



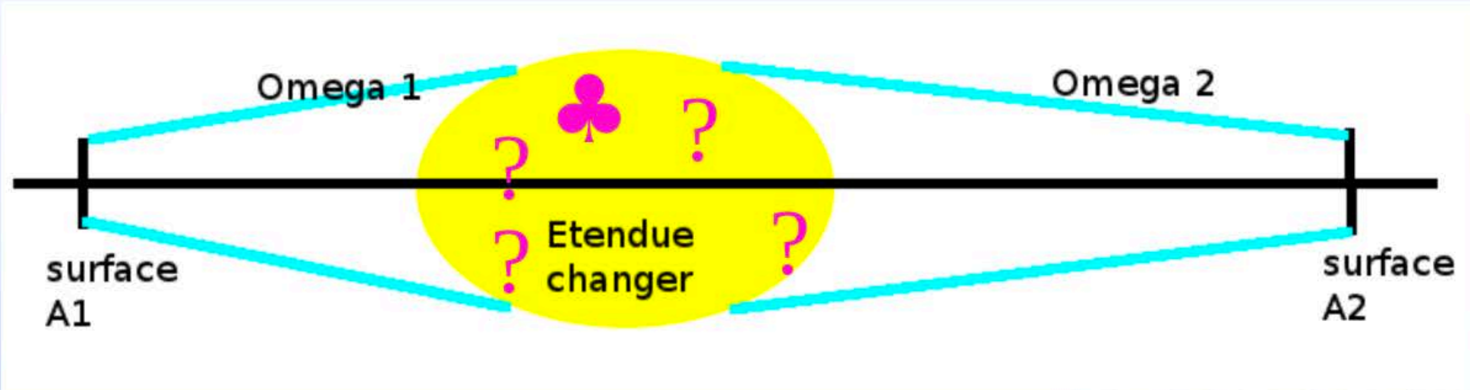
Nope, you can't do this. [5]

It turns out that any optical system follows a law called *conservation of étendue*. This law says that if you have ligh coming into a system from a bunch of different angles *and* over a large "input" area, then the input area times the input angle [6] equals the output area times the output angle. If your light is concentrated to a smaller output area, then it must be "spread out" over a larger output angle.

When you compress a beam you must also magnify.



Can we break $A * \Omega$ = constant? "Gedankenexperiment" Practical application of an Etendue-changer



radiative equilibrium between A1 and A2

$$A_1 \, \Omega_1 \, \sigma \, T_1^4 = A_2 \, \Omega_2 \, \sigma \, T_2^4$$

- Etendue changer: $A_1 \, \Omega_1 > A_2 \, \Omega_2$
- => for equilibrium $T_2 > T_1$
  i.e. heat could flow 'upstream'
- in combination with a steam engine a perpetuum mobile

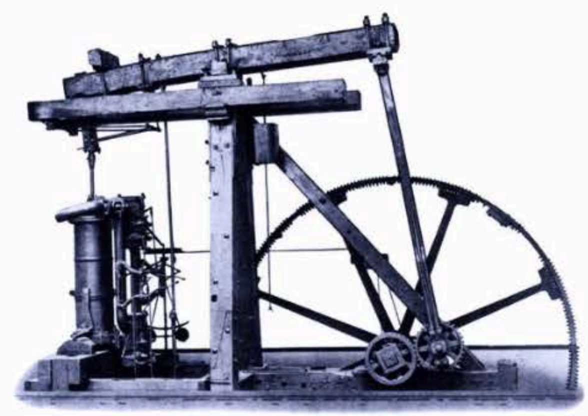


PLATE XII. THE "LAP" ENGINE, 1788
Courtesy of the Science Museum

$f/0.5$

Implication: instruments for large telescopes will themselves be large. Why is anybody surprised?

Etendue conservation says things scale in proportion.

Small instruments will be *specialized* instruments. Some will be be super exciting – all will have small fields of view (AO fed, in many case). Some will be relatively cheap but that doesn't have to follow.

THE COPY OF FORS 1 &2 @ E-ELT, the E-ELFOSC?!?

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

For a straight copy Etendue conservation entails that all dimensions would scale with 39m/8m, or the volume and mass with $(39/8)^3 \sim 115$

- E-ELFOSC would
  - be a >100 tonne class instrument
  - have a length of 15m
- optics would need to be 40-120 cm diameter
- beyond 50cm transmitting optics is difficult to manufacture and keep in shape

so then let us try to design, with bright ideas, a new instrument, having the same promise as EFOSC/FORS, but smarter …

This is a big philosophical difference between the E-ELT project and the TMT project.

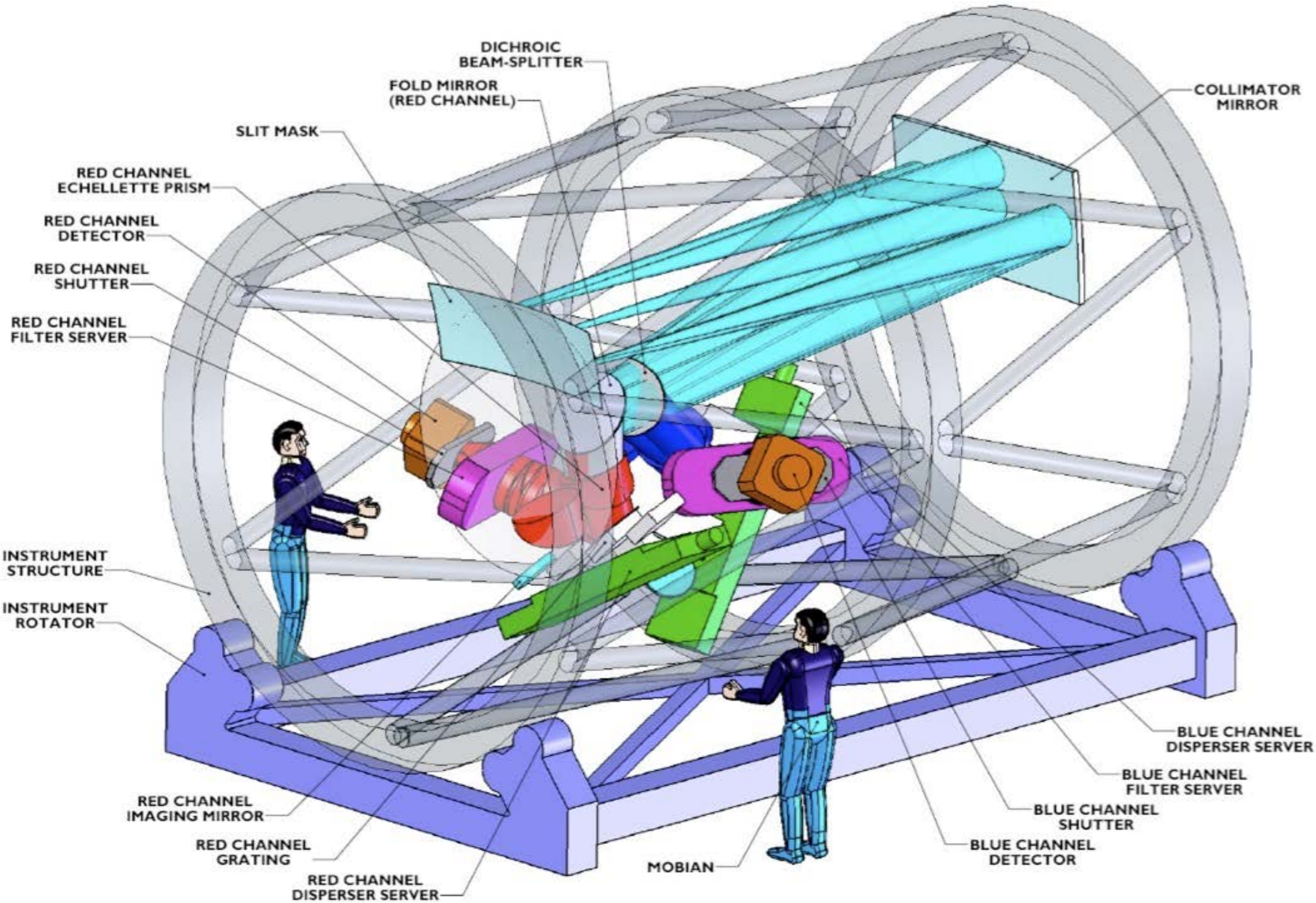
TMT is the maximum size telescope that Jerry Nelson figured he knew how to build that could handle these issues in an open-loop kind of way.

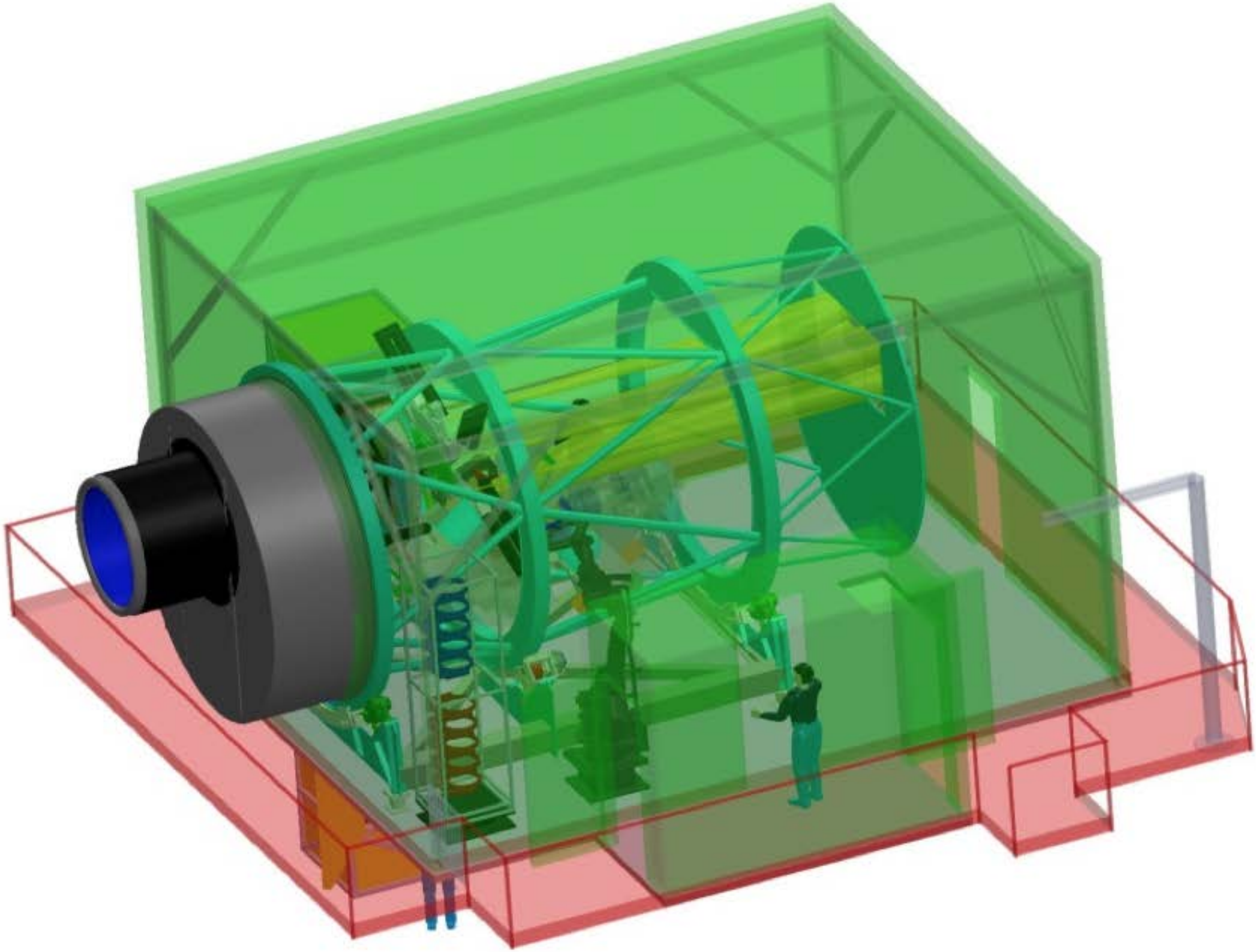
(BTW, this is why I love it so)

- matching 1'' seeing (α_1) yields D_1 = 16m
  => beyond 16m telescope diameter it becomes challenging, or better next to impossible, to match CCDs: 8k x 8k devices would become effectively 512 x 512 detectors or worse
- similar considerations hold for all optical elements as they have to scale strictly with the telescope diameter as well

=> seeing limited instrumentation hard to sell at E-ELTs

WFOS: Big? Yes. Doable? Yes. Unique capabilities in the ELT era? YES.





Because of the philosophical differences in the ELTs, IMHO it's easier for the TMT community to make plans.

Two things I'd like you to do

- 1. Think of what you're doing **now** and figure out the pain points. Imagine how TMT will let you move forward (without wild extrapolation of any kind regarding where the subject will be moving in 10 years time). You'll see how we can move forward in practical ways.
- 2. Get freaking totally excited about the golden age of sensors that we're about to embark upon, and think about what the implications are for doing really radical things in the **future**.

www.tmt.org/page/information-for-tmt-observers#science-capabilities

TMT International Observatory

Information for TMT Observers

Science Capabilities

SCIENCE INSTRUMENTS

- Overview of Instruments capabilities
- WFOS (1st generation instrument)
- IRIS (1st generation instrument)
- Second Generation instruments

TELESCOPE SYSTEMS

- Optics
- Adaptive Optics (AO)
- Controls

SITE

- Overview
- Site Characteristics Full Report

Science Operations

OBSERVING WITH TMT

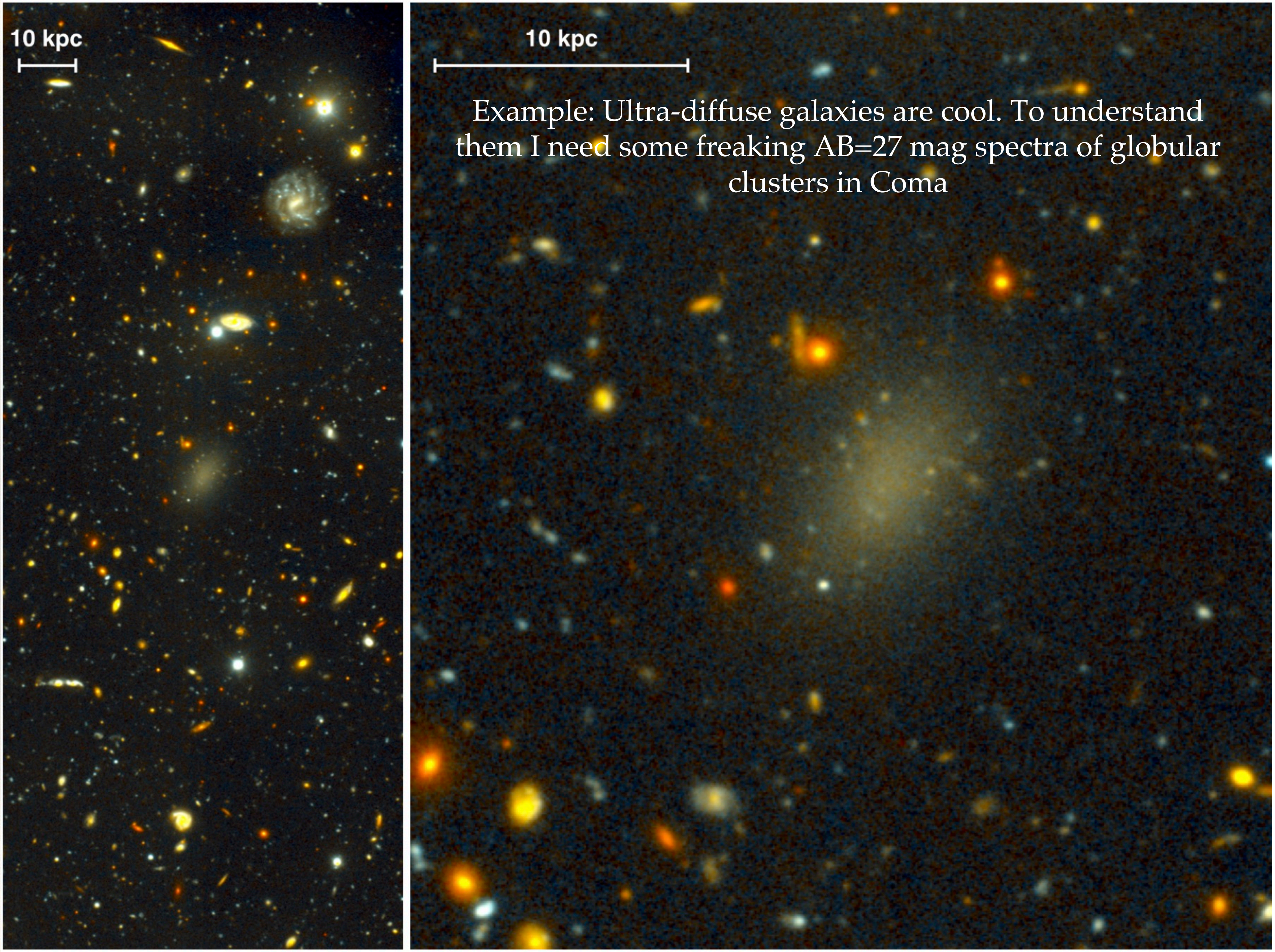
- Observing Modes and Time Allocation
- Observation Planning Tools
- IRIS Exposure Time Calculator
- TMT Infrared AO Guide Star Catalog
- Data Archives and Data Reduction

TIMELINE

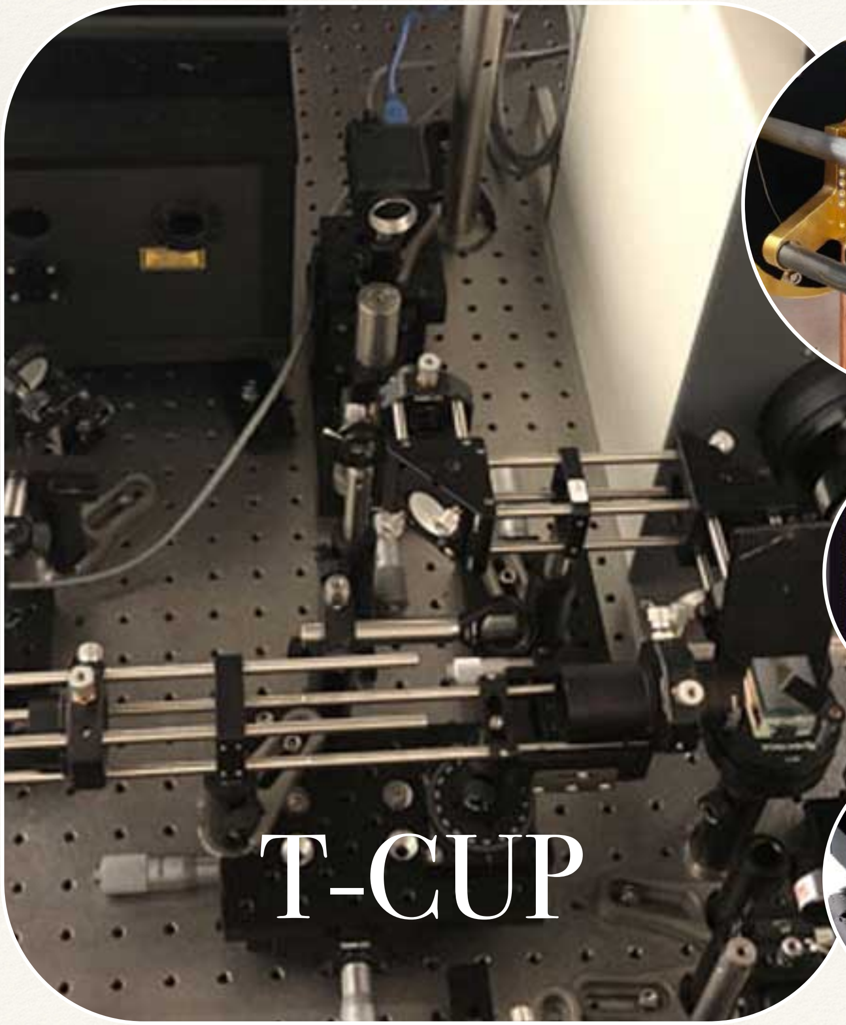
- Full Project Timeline
- Construction Milestones
- Science Milestones

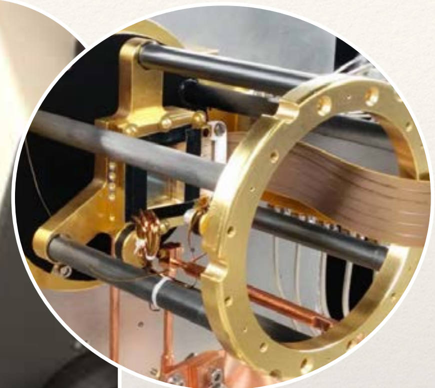
MORE

- 2015 TMT Detailed Science Case
- Science Case Development Tool
- Science Themes
- International Science Development Teams
- Employment Opportunities
- Exploration of Polarimetric Capabilities

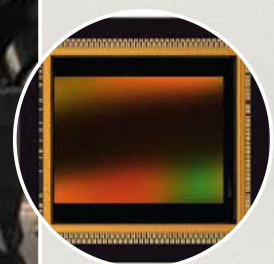

10 kpc
10 kpc
Example: Ultra-diffuse galaxies are cool. To understand them I need some freaking AB=27 mag spectra of globular clusters in Coma

Look for revolutions here: Sensors and Cameras





MKID-IFS

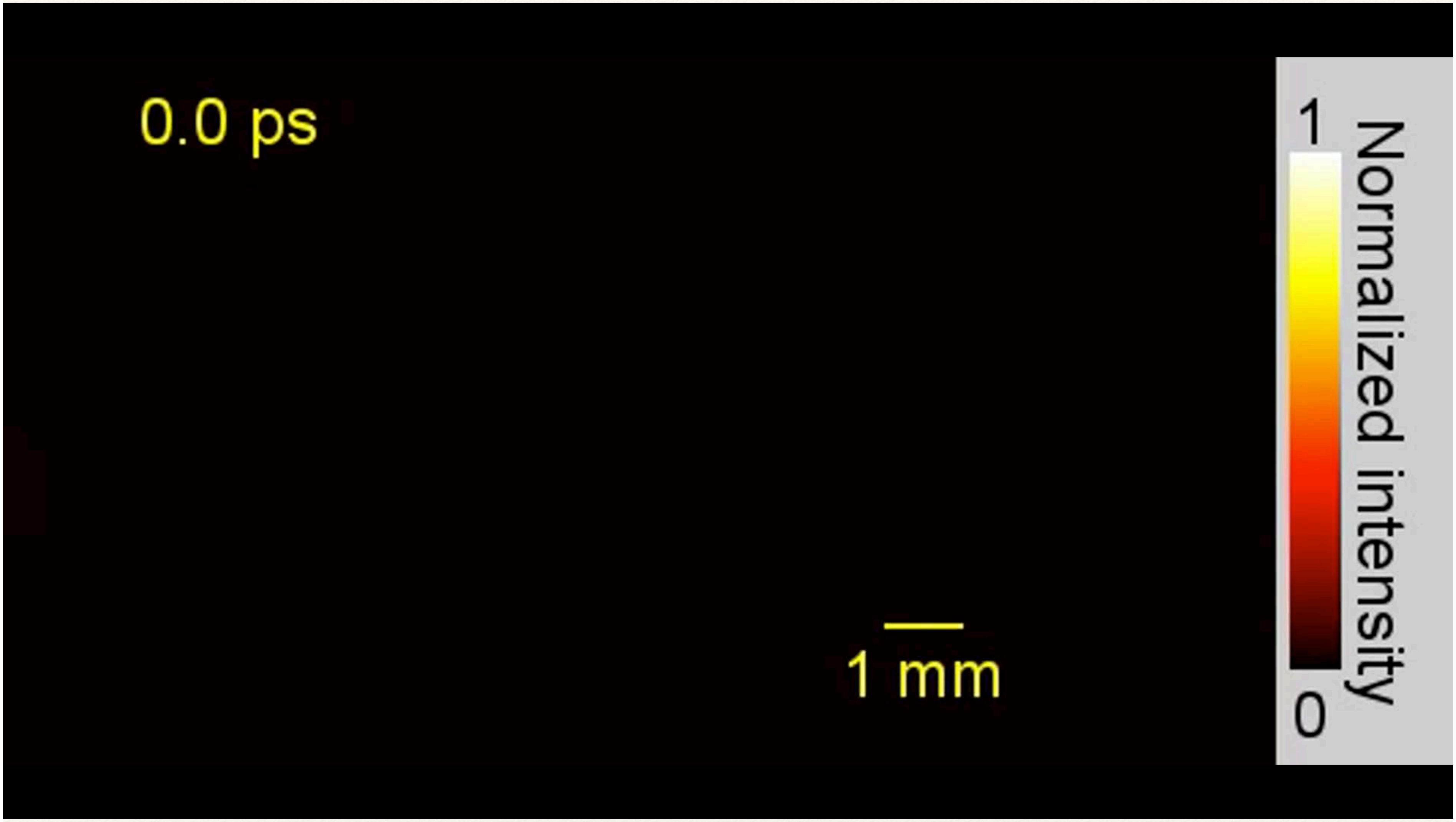


CMOS

EMCCD

As readout noise disappears, and sensors become cheap, these sorts of concepts begin to make a lot of sense. A 3D problem becomes a 2D problem.

Opening up the time domain will open up huge new physics opportunities. Exploiting this in an astronomical context will require the huge light blast of next generation telescopes.



0.0 ps
1 mm
1
0
Normalized intensity

CONCLUSIONS

- The planned ELTs are not all equivalent. There are some fundamental differences aside from hemispheres. These design choices impact instrument choices.
- Natural seeing instruments are going to be big and expensive unless they're specialized or compromised. We know know to build them though… and they will be awesome.
- Half of big discoveries will be totally serendipitous and driven by people as much as hardware. The other half will be planned well in advance, so doing things like working on science case documents is not pointless.
- There's plenty of room for innovation in instruments. On small scales, look to new types of sensors and to photonics for big advances.