Sub-millimetre astronomy

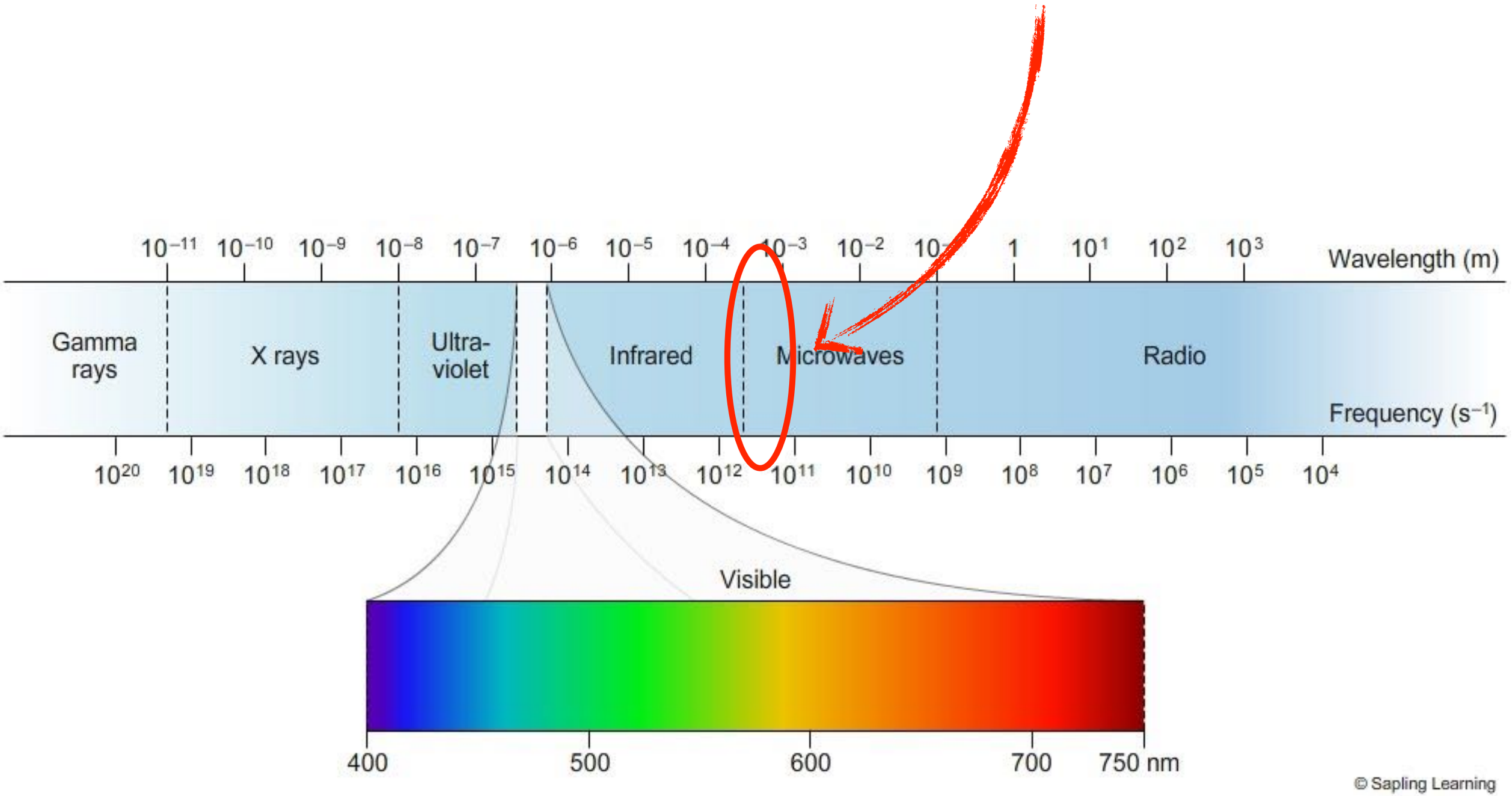
Between radio and IR

Matt Bothwell

Why sub-mm astronomy?

- The regime between the radio and IR is a ‘new frontier’: until ~20 years ago, almost totally unexplored!
- On the boundary between coherent (radio) and incoherent (optical) regimes
- Wavelengths ~1mm

‘Sub-millimetre’ wavelengths



Black-body radiation

Black-body radiation is emitted by all bodies with temperature >0 K

Spectrum of emitted radiation has a characteristic continuous form, which *depends on the temperature of the emitting body*

Black-body radiation

$$\lambda T = 2.898 \times 10^{-3} m.K$$

Peak wavelength depends only on temperature

Example: wood fire is ~1500 K, and so spectrum peaks at 2000nm
This is in the IR — so campfires are warm, but a poor light source

Example: cold dust in the ISM of galaxies T~30K, spectrum peaks at 90 microns — in the IR

Why sub-mm astronomy?

What does the sub-mm band observe?

$$\lambda T = 2.898 \times 10^{-3} m.K$$

Thermal radiation from VERY COLD objects — just a handful of K

The cold Universe: very cold dust, cold gas (i.e., things in formation), and molecules

Why sub-mm astronomy?

- Coherent and incoherent light
- A brief history of sub-mm astronomy
- Sub-mm detectors
- What is in the sub-mm sky?

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Spanning the divide

Coherent regime

- Phase of waves preserved
- Radio astronomy

Incoherent regime

- Phase of waves NOT preserved
- Optical, IR, UV astronomy

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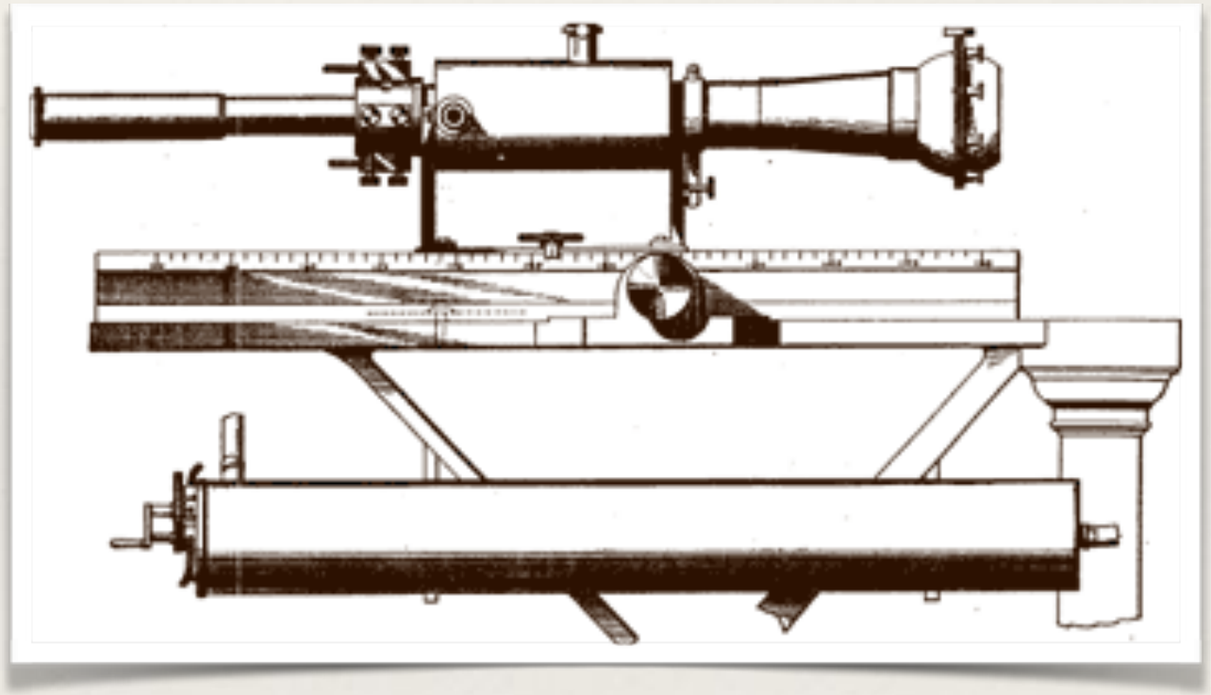
Millimetre and sub-millimetre waves fall in between these categories

Bolometers

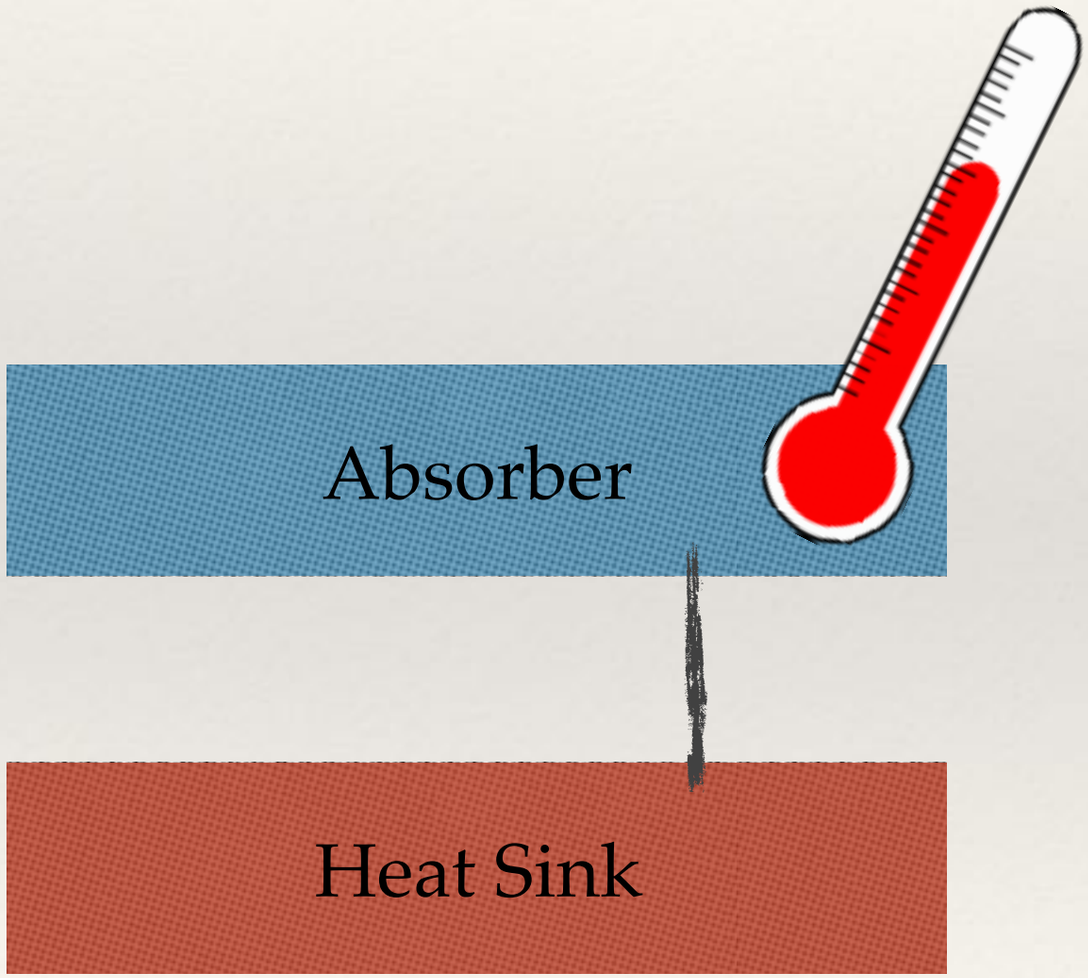
- Means ‘measurer of known things’ (!)
- Invented in 1878 by Samuel Pierpont Langley (astronomer)
- Two strips of platinum in a circuit: **electrical resistivity is a function of temperature**
- First observation: detected a cow (thermal radiation, at a distance of ~400m)



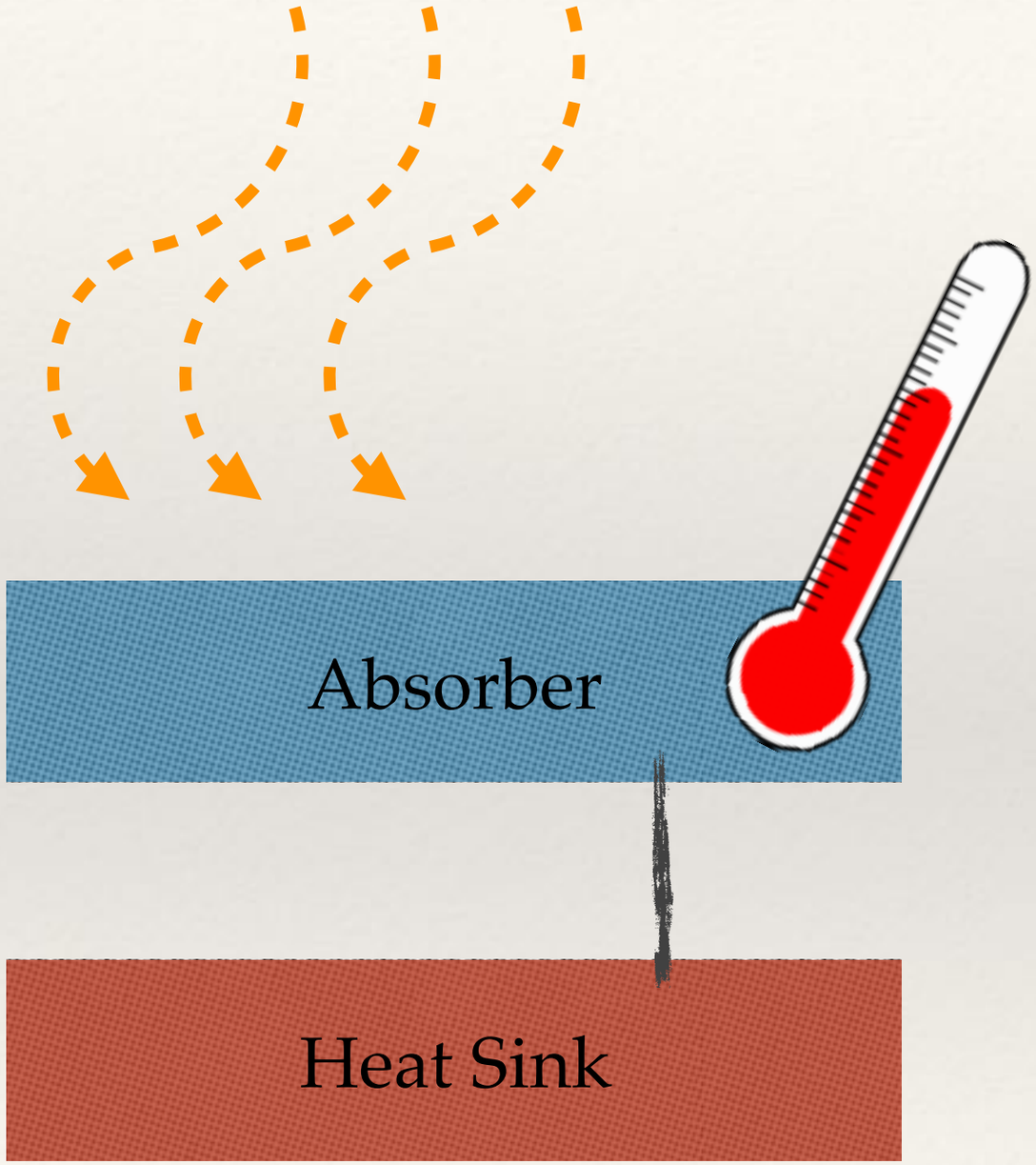
Bolometers

- In the 20th century, improvements were made by cooling the bolometers to very low temperatures (~4K)
- Modern cryogenic bolometers operate at mK temperatures
- This reduced the background radiation due to blackbody thermal emission

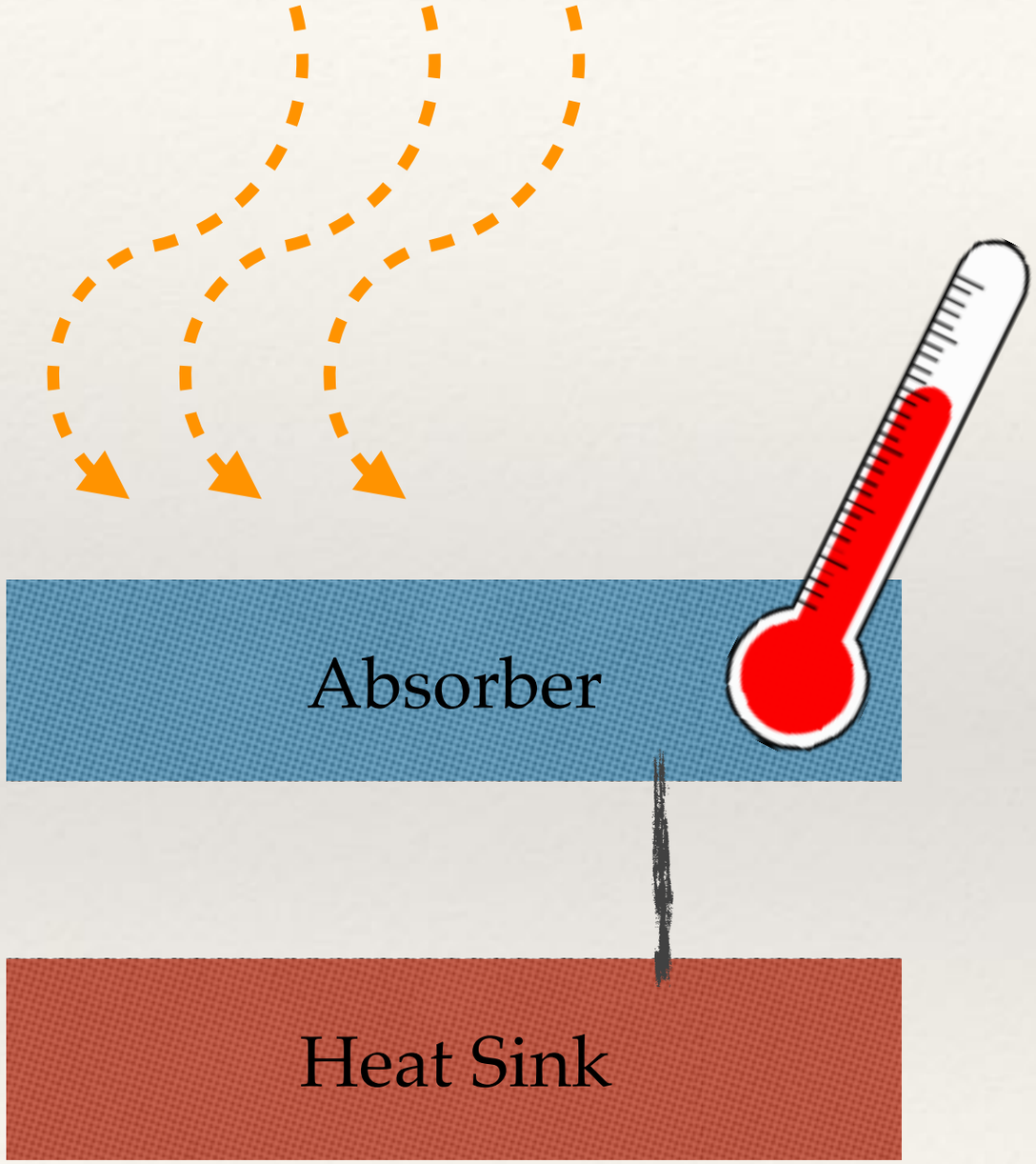
Bolometers



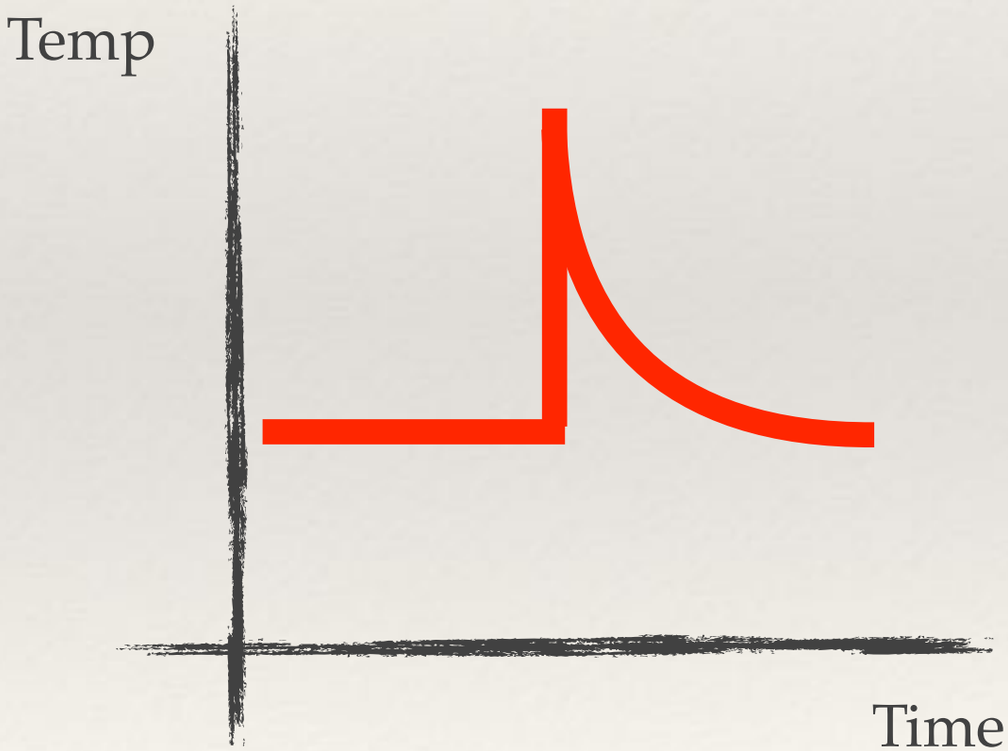
Bolometers



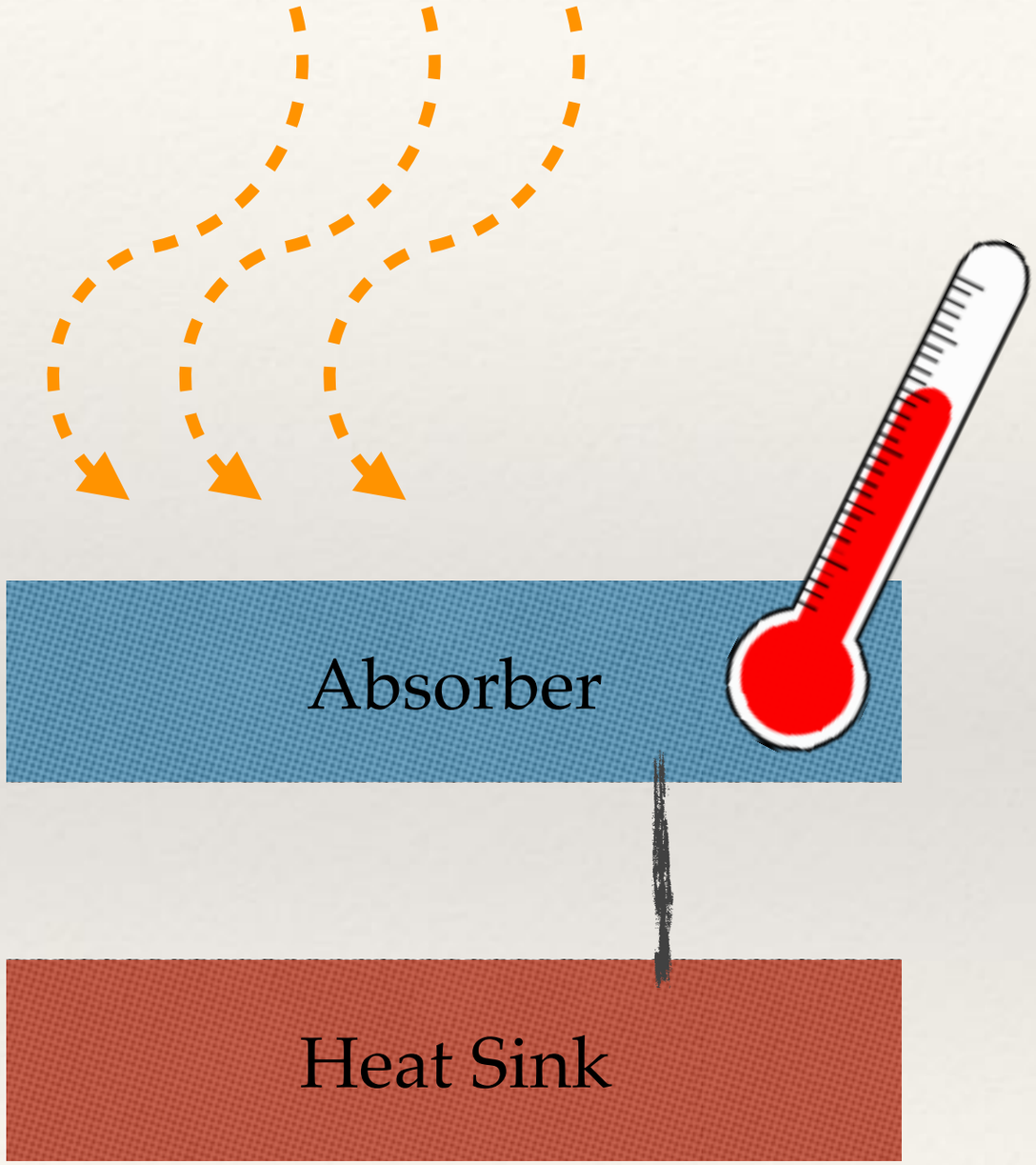
Bolometers



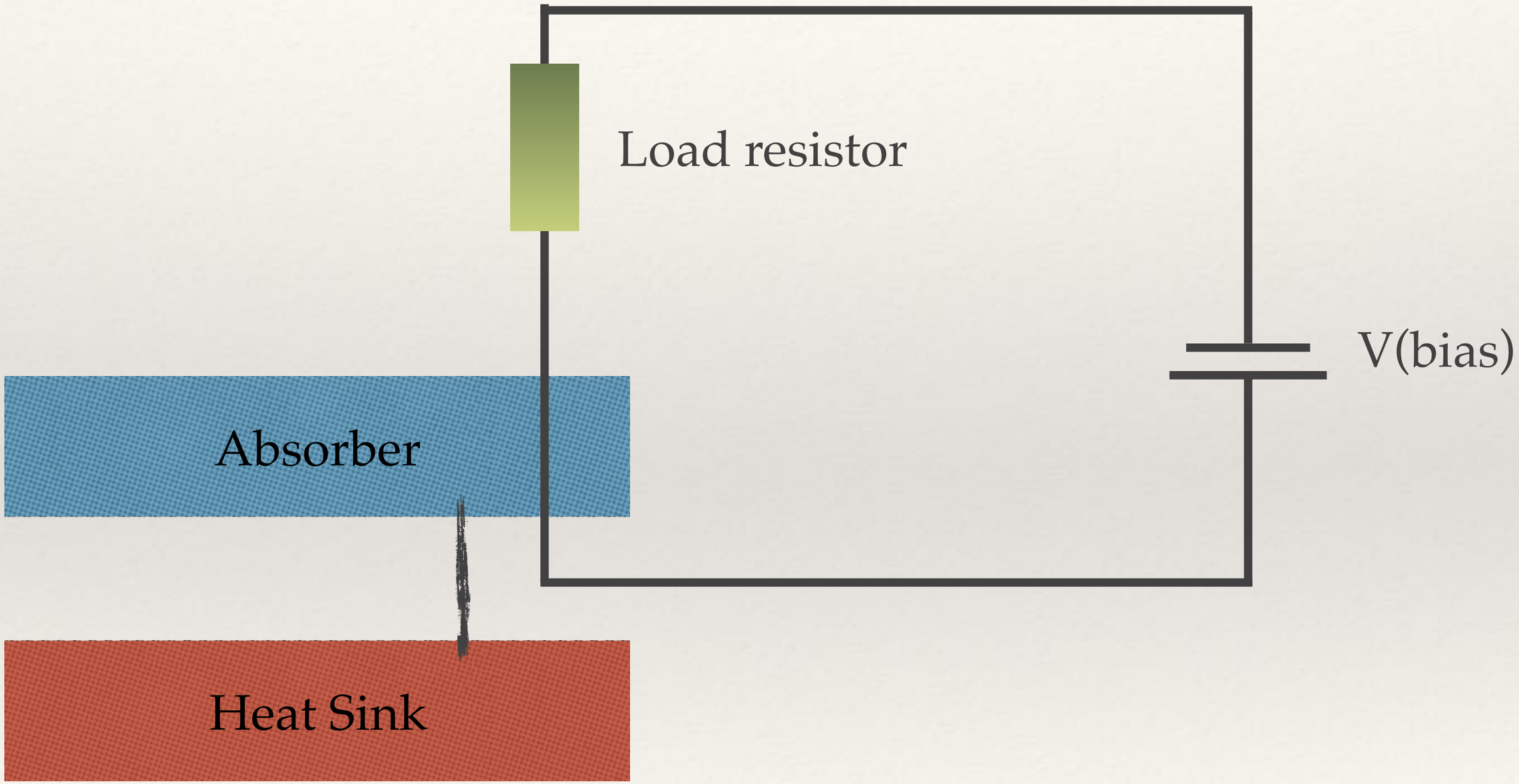
Temperature rise is
proportional
to incoming energy



Bolometers



Bolometers



Bolometers

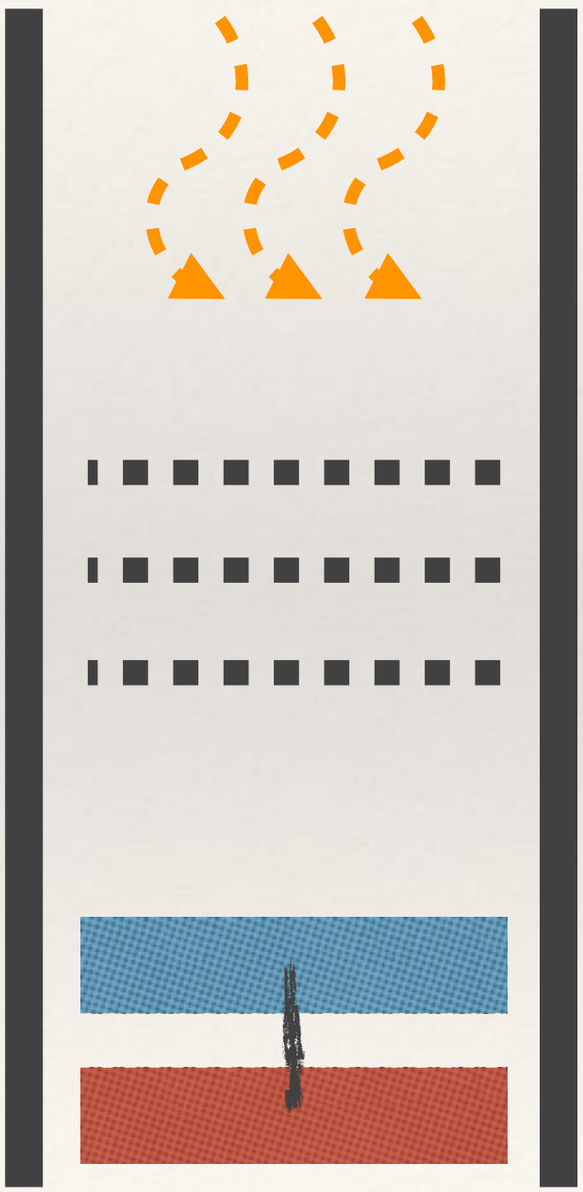
Bolometers are BROAD BAND receiving devices:

They absorb all radiation, and are therefore sensitive to all wavelengths!

(Problematic, if you want to know anything about the radiation you're receiving)

Bolometers

Solution: filters!



Metal mesh filters, with precisely-defined bandpasses

Superconducting bolometers

Very modern, efficient way to build a bolometer:

use a superconductor

Superconductivity

- Superconductivity is a phenomenon where the electrical resistance inside a material drops to ZERO
- Discovered in 1911, and not fully understood until 1950s (Bardeen, Cooper, and Schrieffer won the Nobel for explaining it)
- Quantum phenomenon

Superconductivity

Superconductivity

Superconductivity

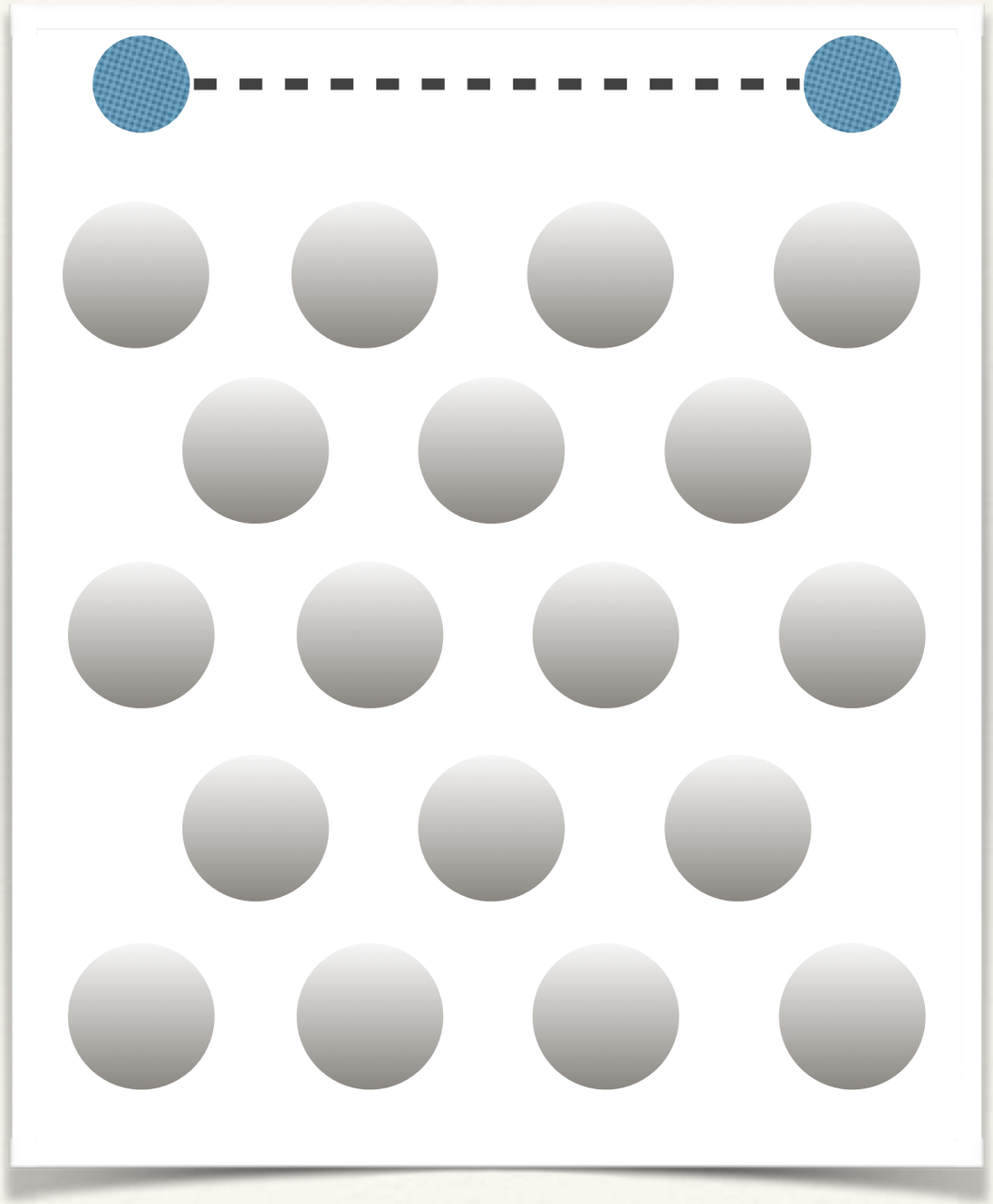
Collisions between ELECTRON and LATTICE
(i.e., substance it's moving through)
produce heat, and waste kinetic energy.

This is what we interpret as electronic
RESISTANCE

Superconductivity

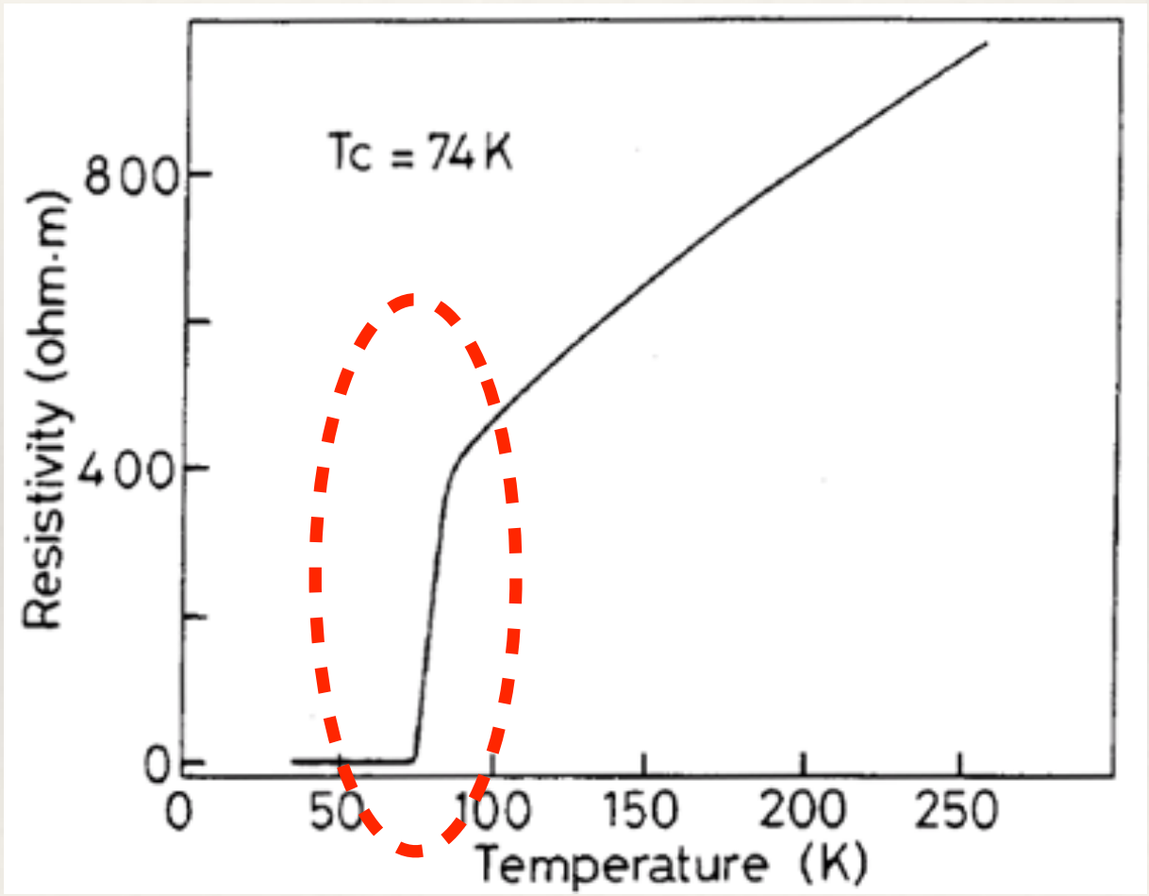
Superconductivity

- Cooper pairs can form a ‘superfluid’, and pass through lattice unimpeded



Superconductivity

- For normal materials, resistance goes down gradually as temperature falls
- For superconductors, if temperature is low enough resistance drops to zero
- This isn't a gradual process — if temperature drops below a critical value, the material starts superconducting



Superconducting Bolometers

Most modern bolometers are built using superconductors in this way

Advantages:

Low noise levels

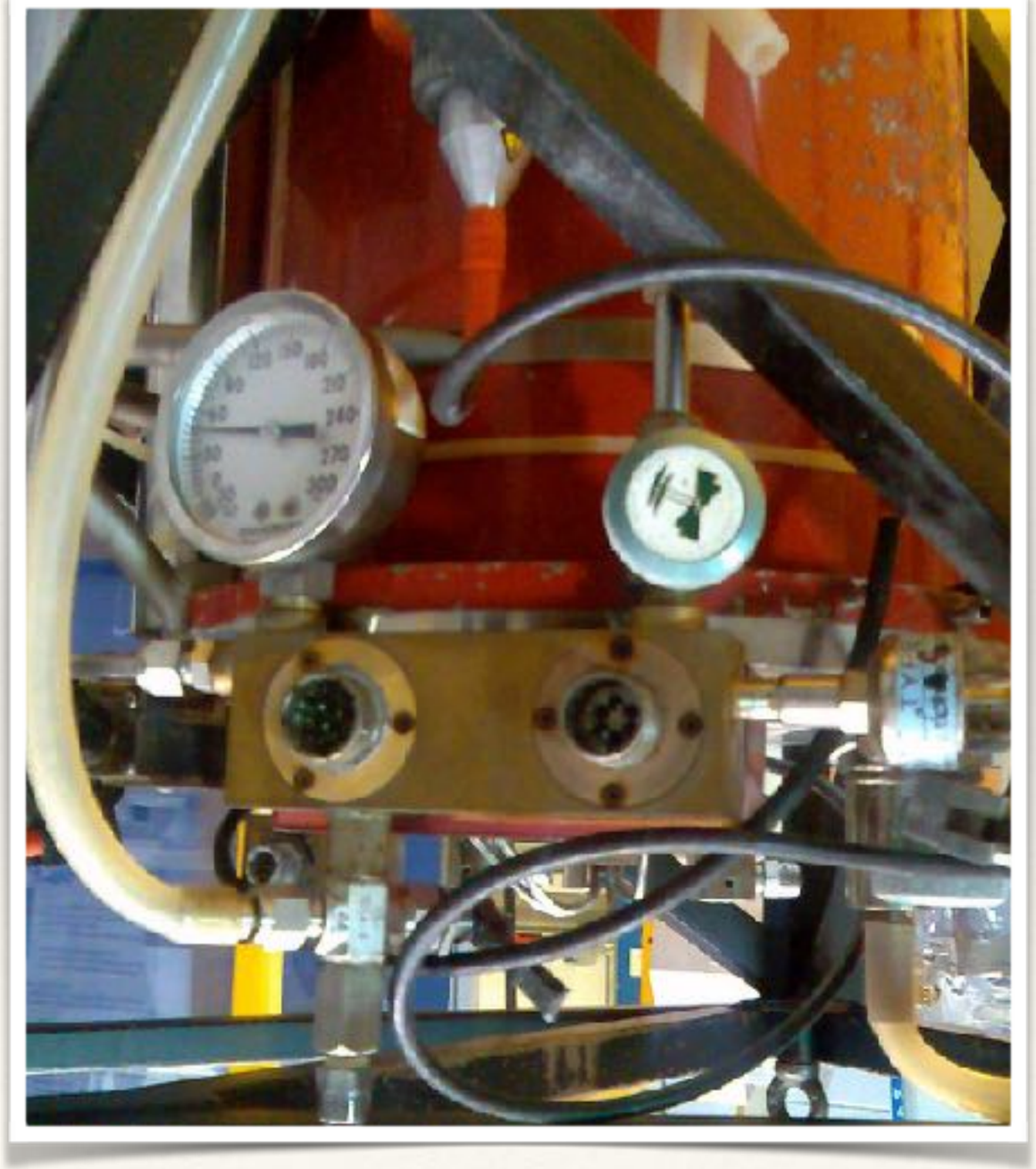
Low power requirements

Easy to multiplex (resistance is always exactly zero!)

Disadvantage: expensive…

Bolometer arrays

- Until mid-1990s, bolometer instruments were single-pixel devices
- Mapping regions of sky was SLOW
- Sensitivity was detector-noise limited



Bolometer arrays

- Breakthrough came with the creation of bolometer ARRAYS
- These had multiple bolometer pixels, and could be used for imaging
- First widely successful example is SCUBA (Sub-millimetre Common User Bolometer Array). This transformed astronomy

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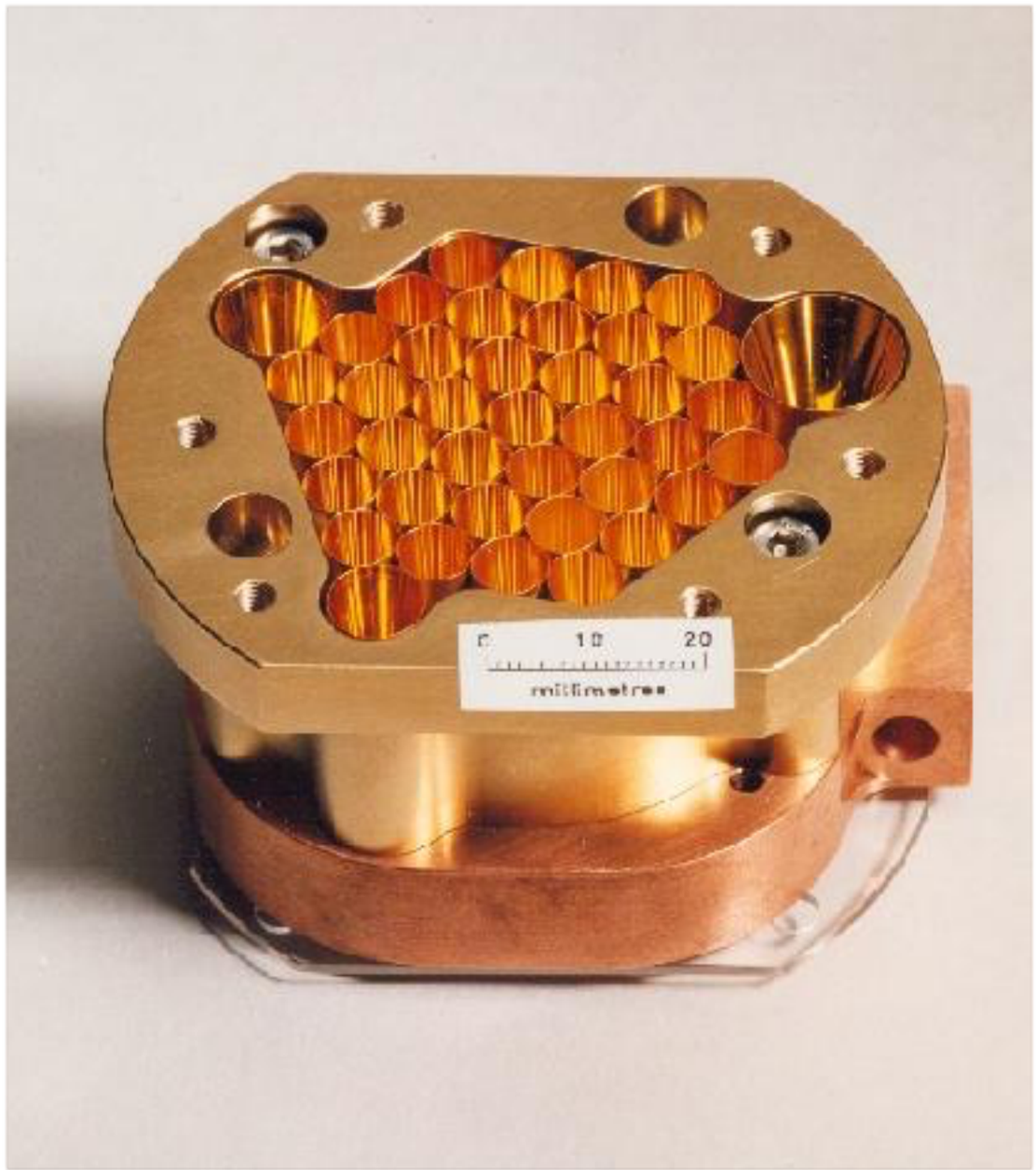
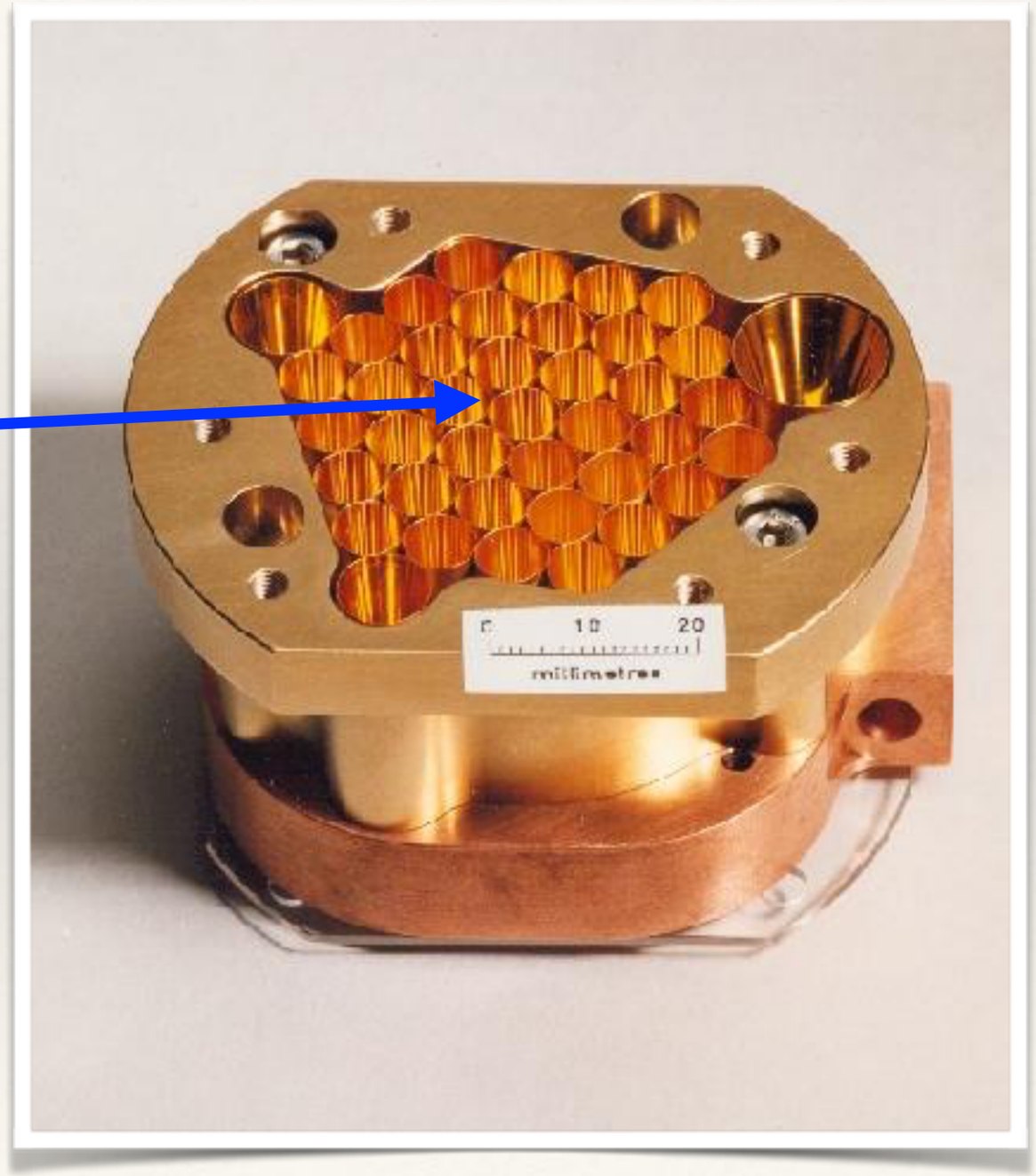
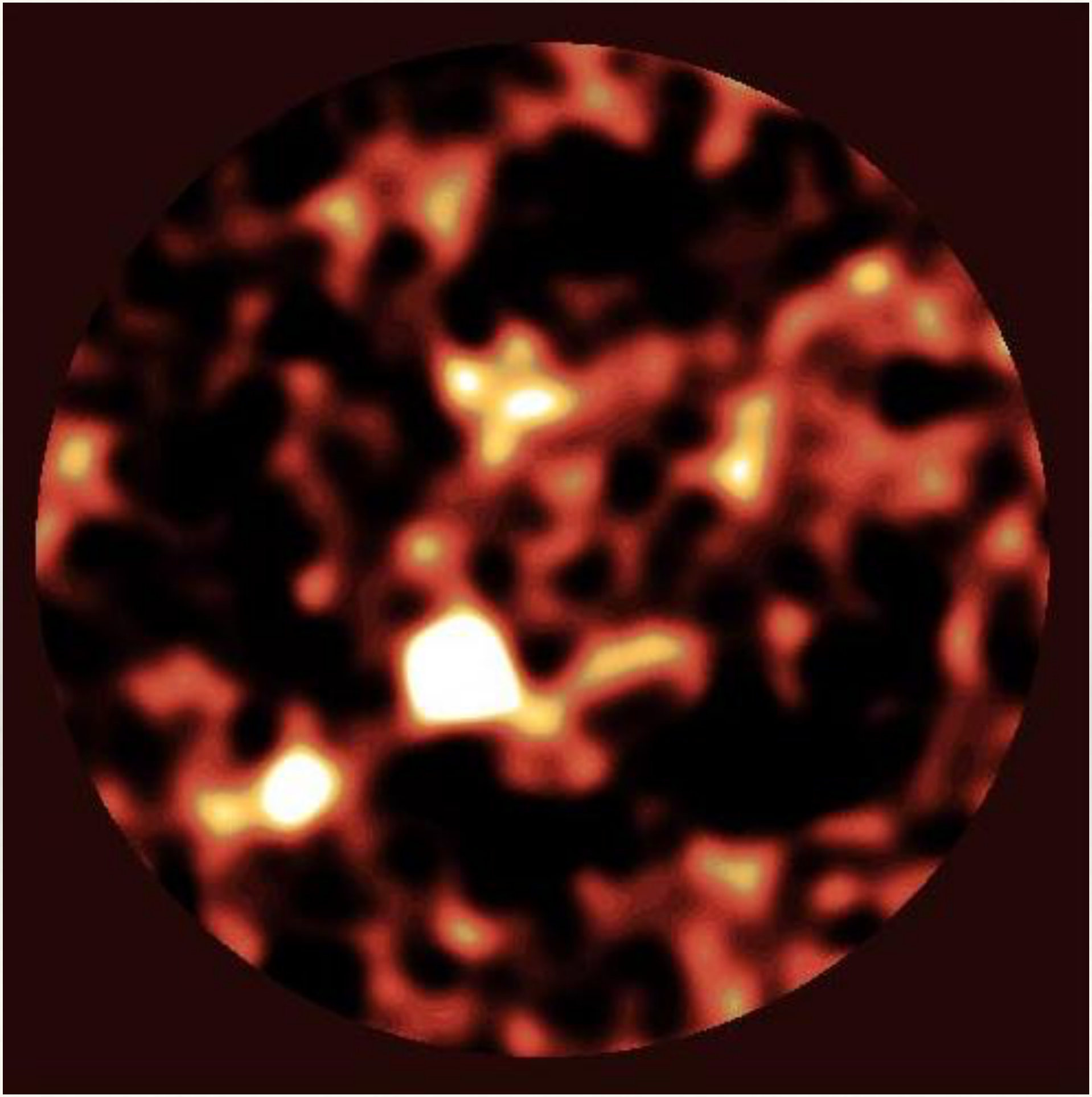


Bolometer arrays

37 bolometers — all linked together

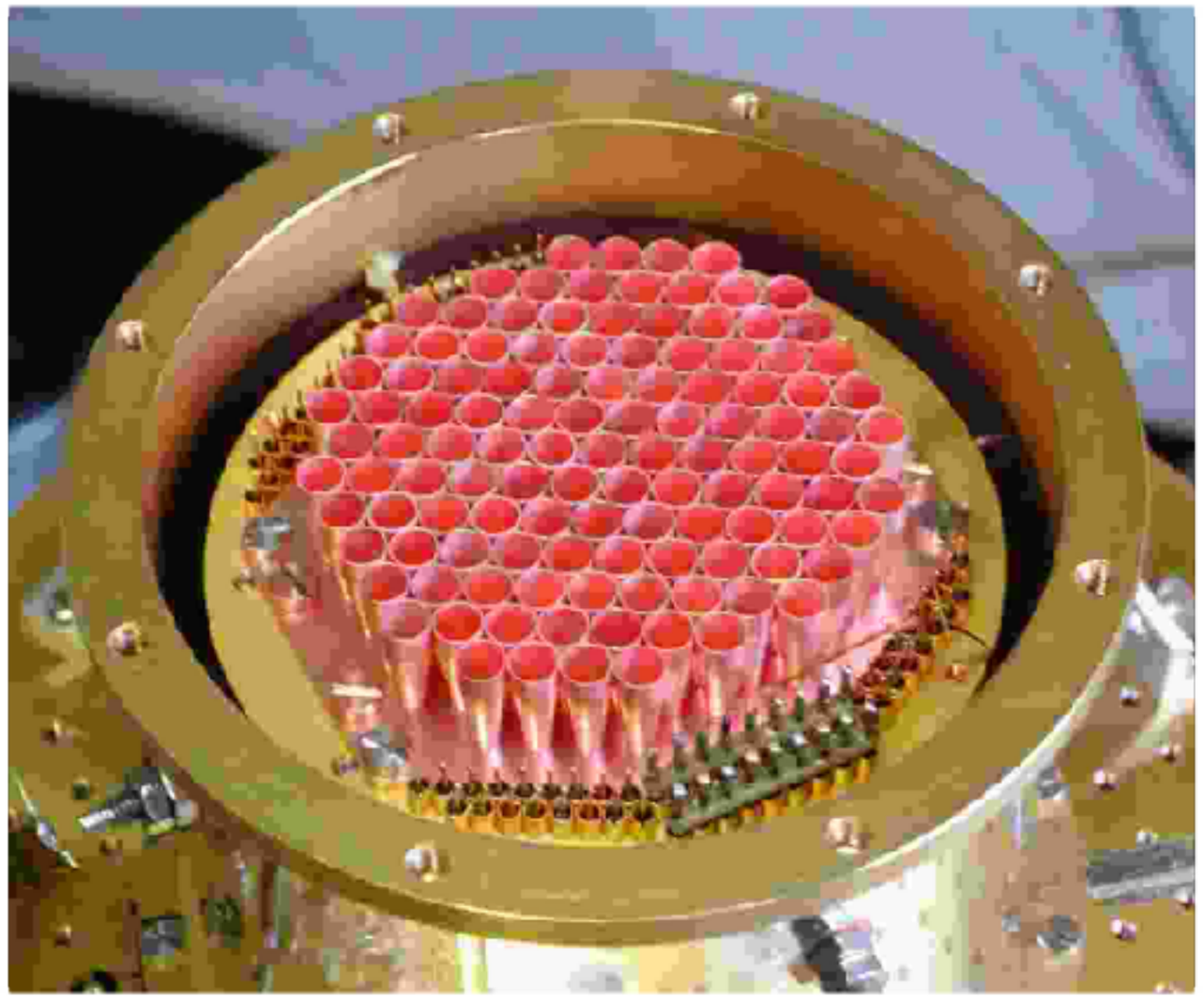
Can provide imaging at mm wavelengths





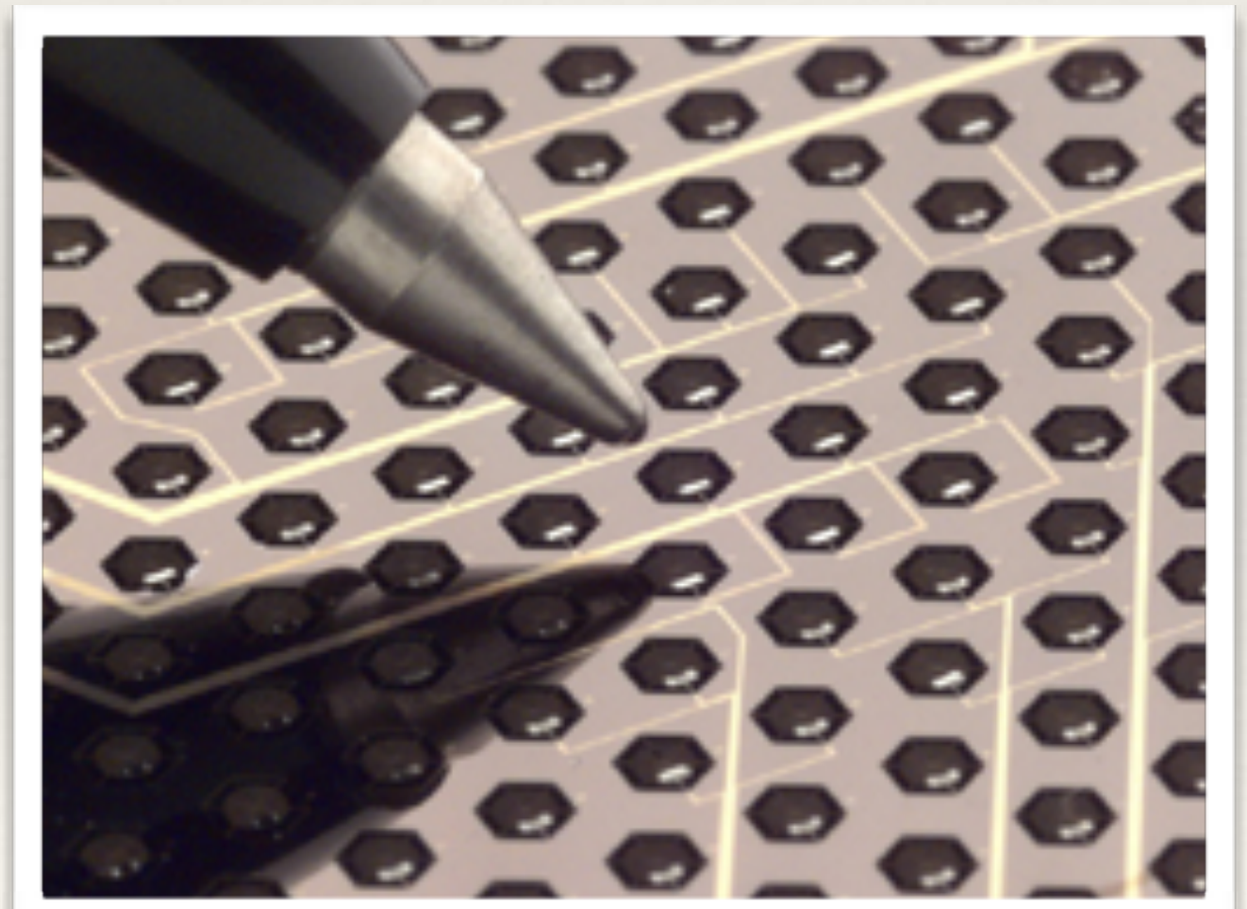
Bolometer arrays

MAMBO:
117 pixels



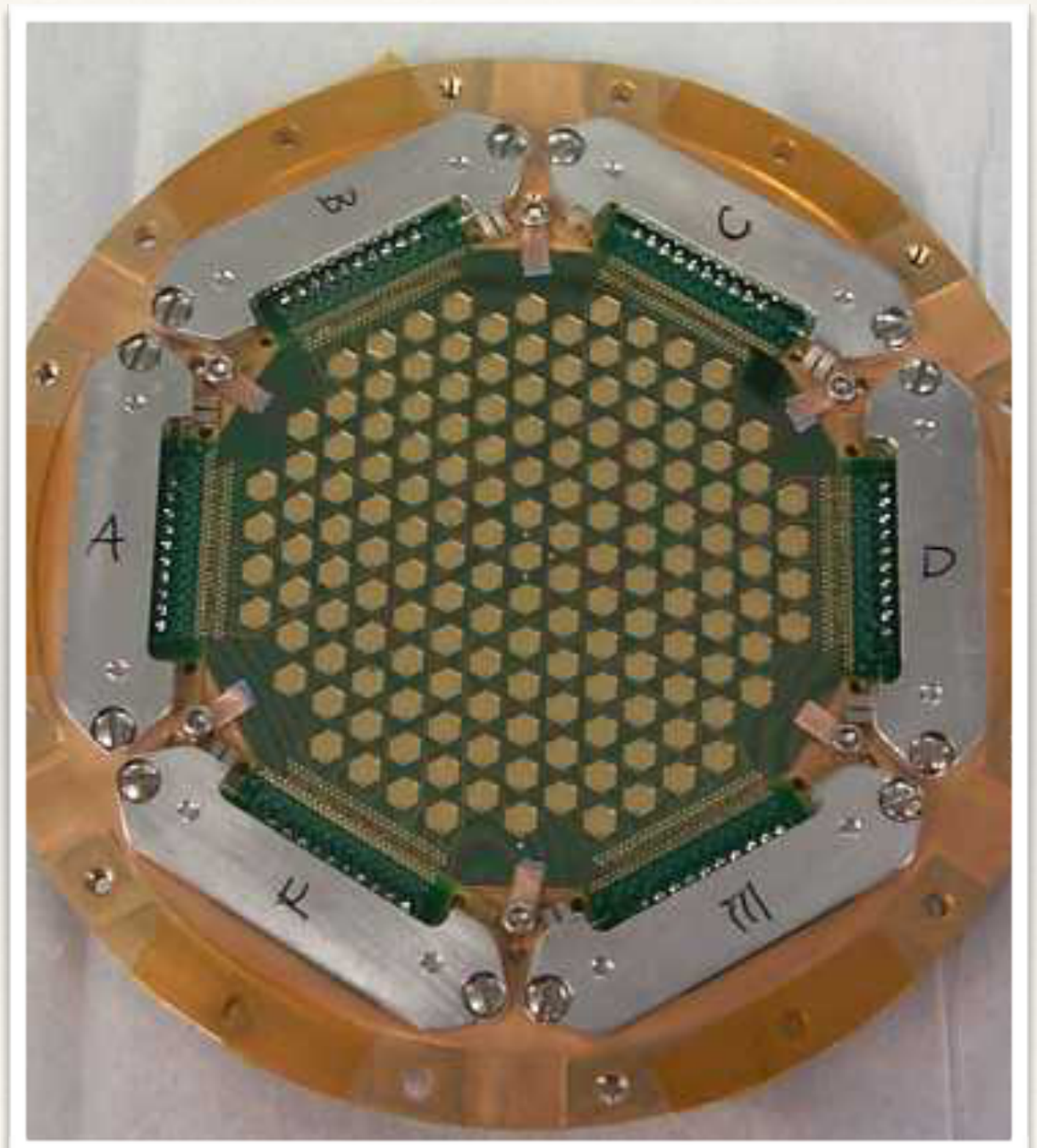
Bolometer arrays

Most modern bolometers are built by micro-machining semi-conductors (which will superconduct) onto silicon wafers…



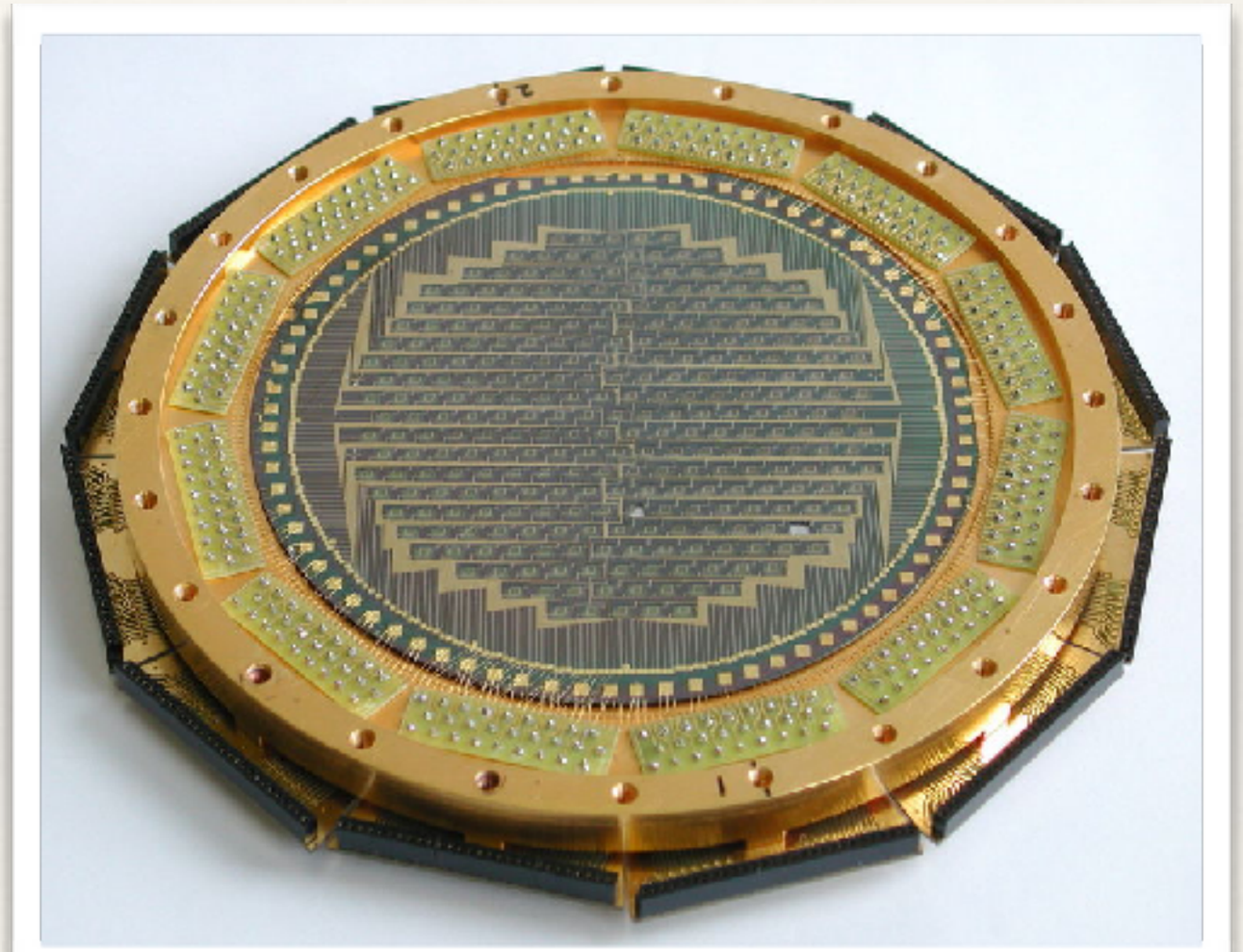
Bolometer arrays

AzTEC
144 pixels



Bolometer arrays

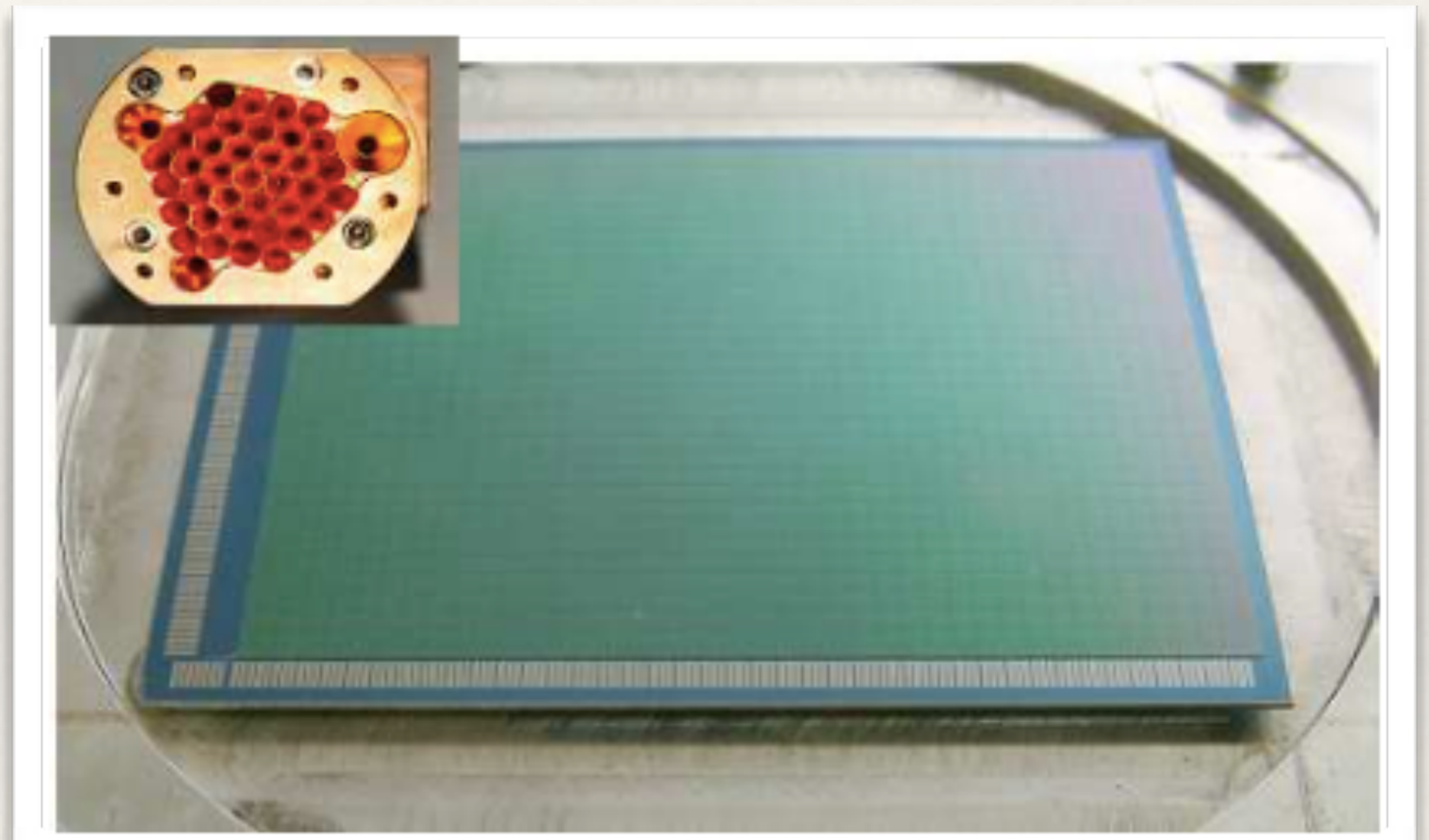
LABOCA
295 pixels



Bolometer arrays

Real state-of-the-art:
SCUBA-2

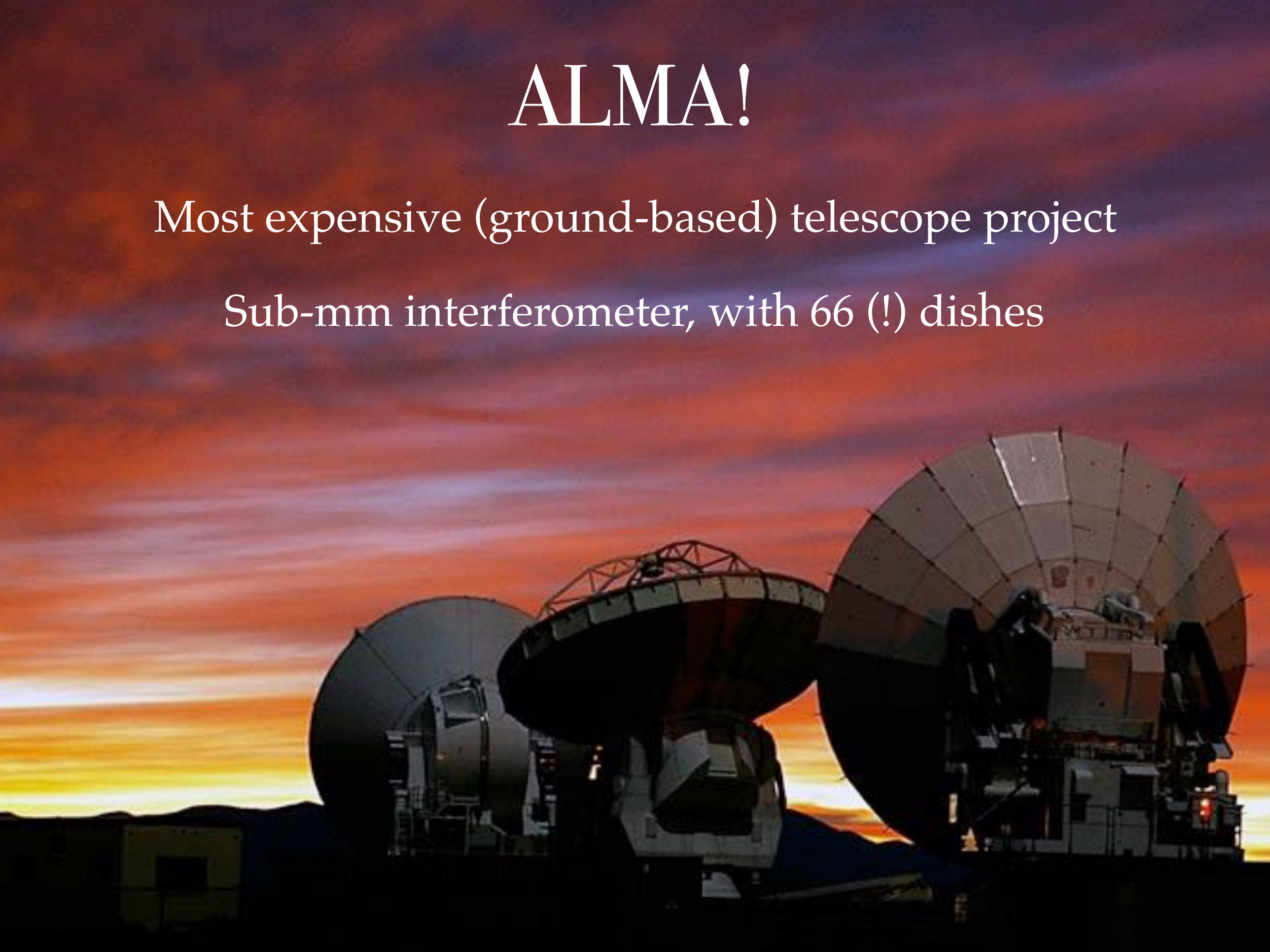
1280 pixels (x 8)
= **10,240 pixels**



ALMA!

Most expensive (ground-based) telescope project

Sub-mm interferometer, with 66 (!) dishes



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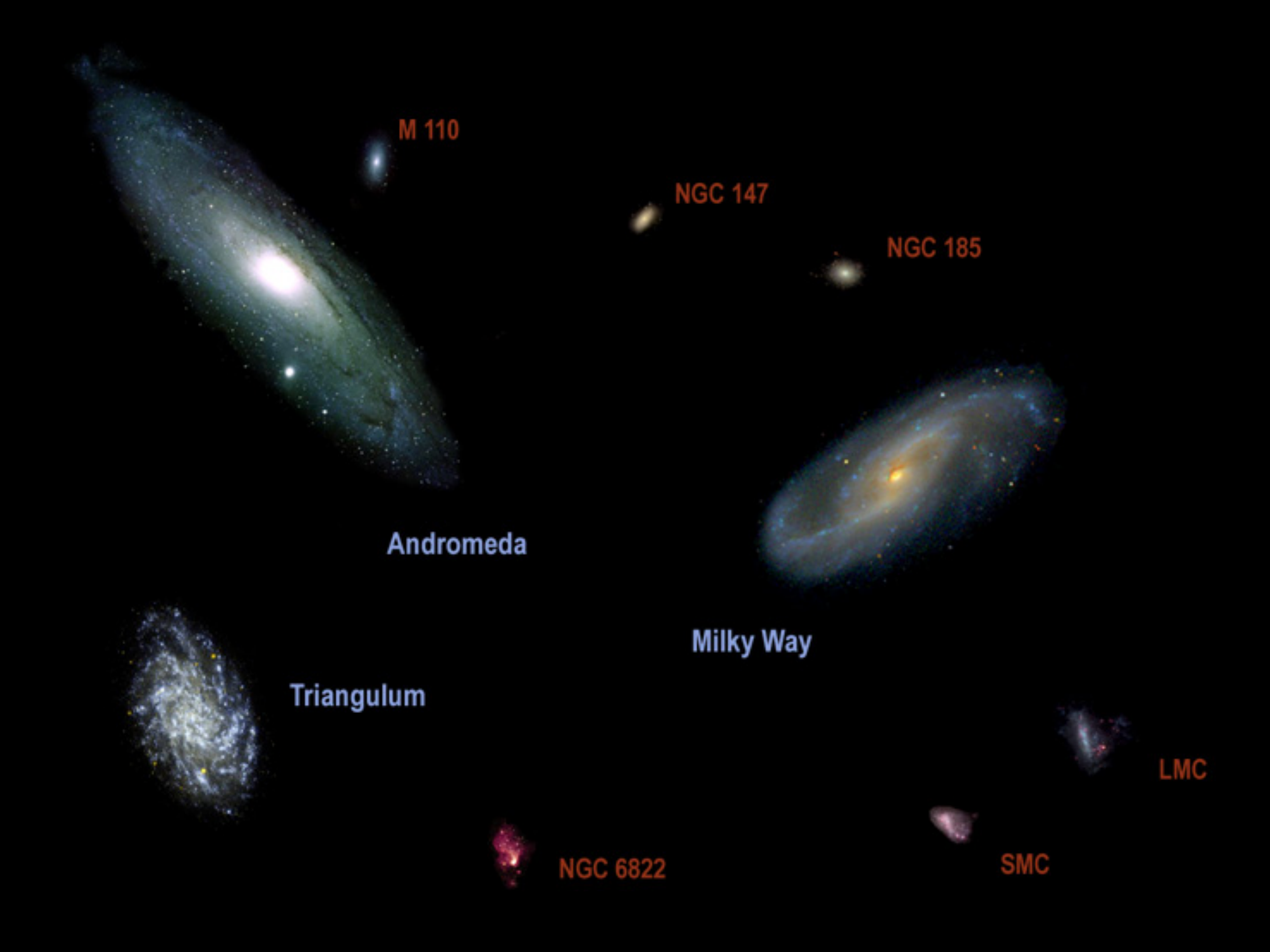
Andromeda


M 110
NGC 147
NGC 185
Andromeda
Milky Way
Triangulum
LMC
NGC 6822
SMC

M87

IC 1101

IC 1101

6,000,000 ly

M87

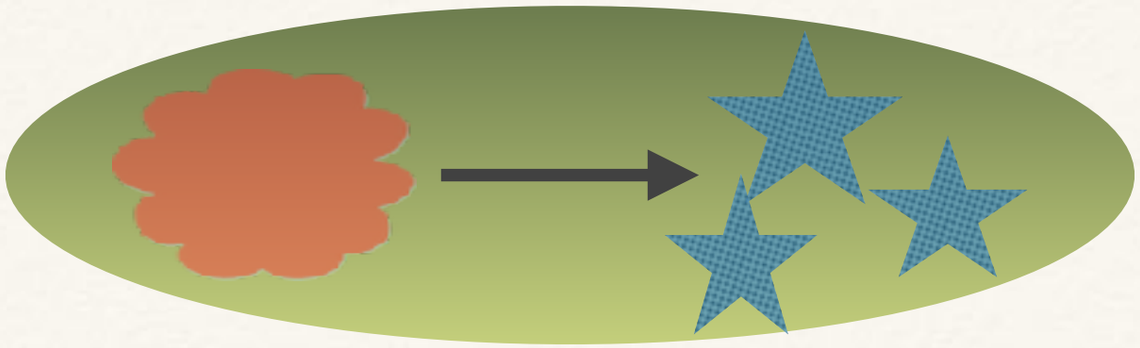
Milky Way

Andromeda

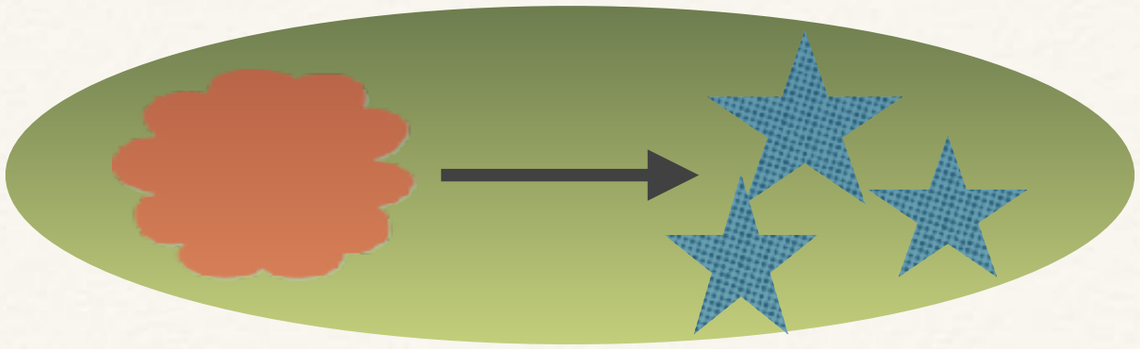
100,000 light-years

200,000 light-years

1,000,000 light-years



A normal galaxy is constantly forming stars



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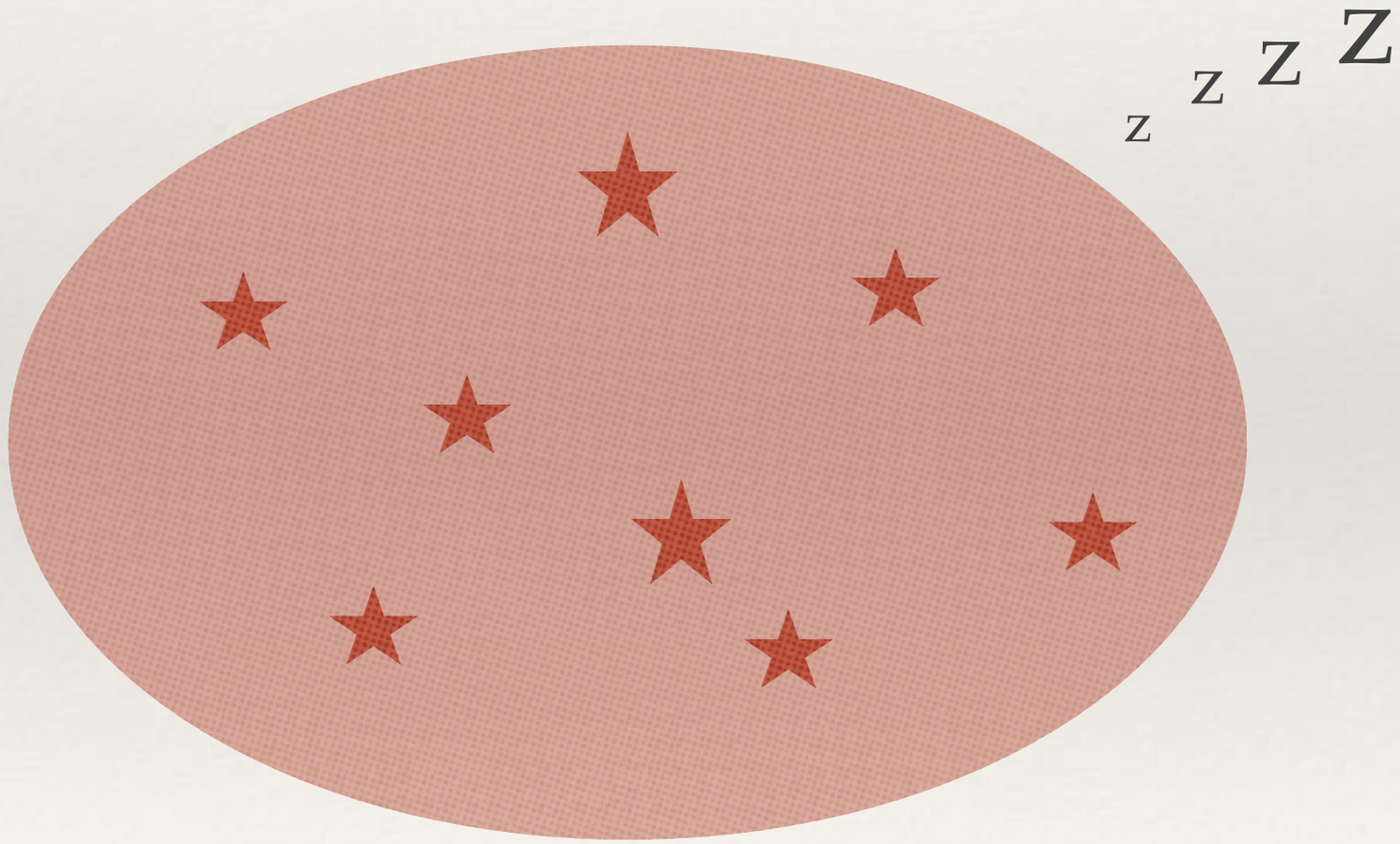
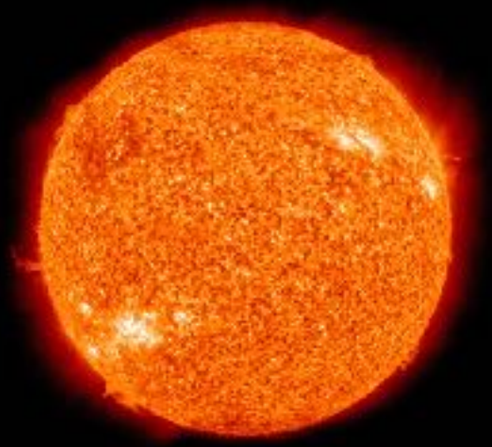
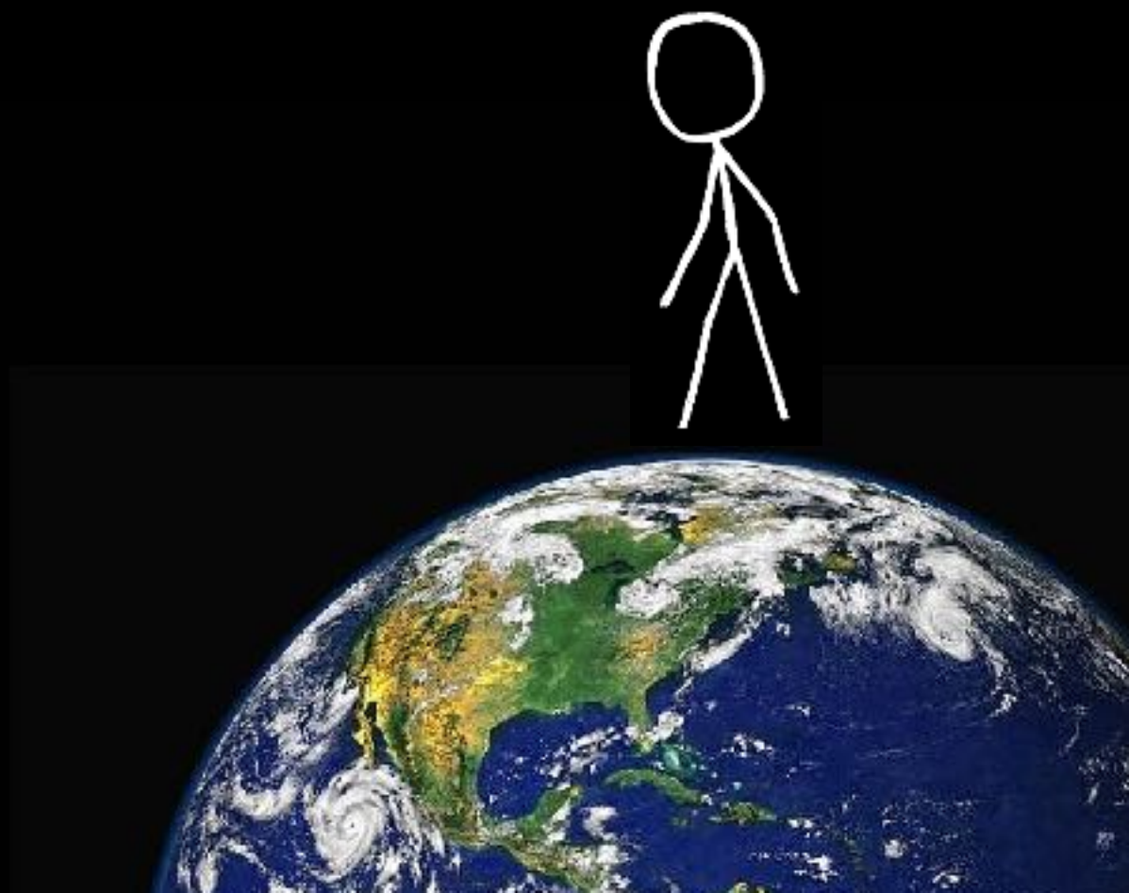
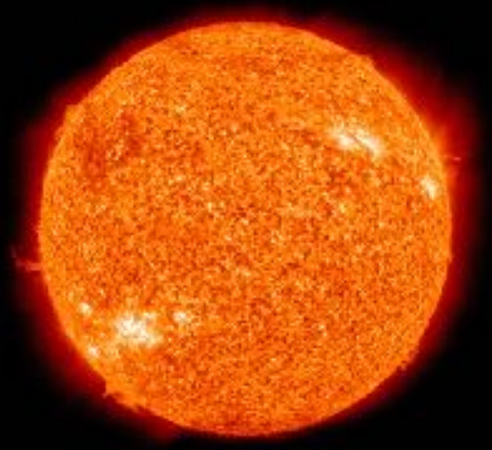


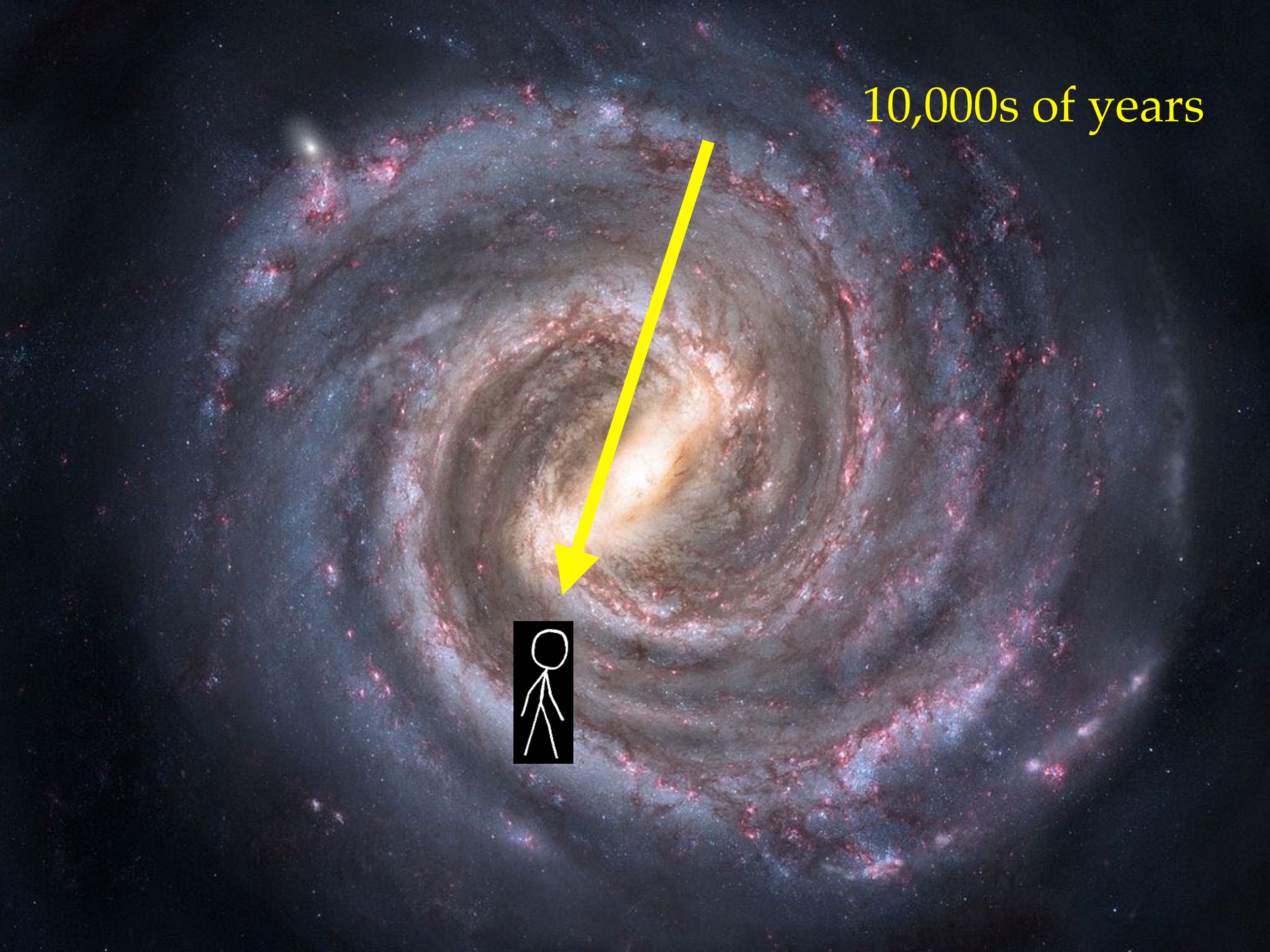
A ‘red and dead’ galaxy isn’t doing much at all…

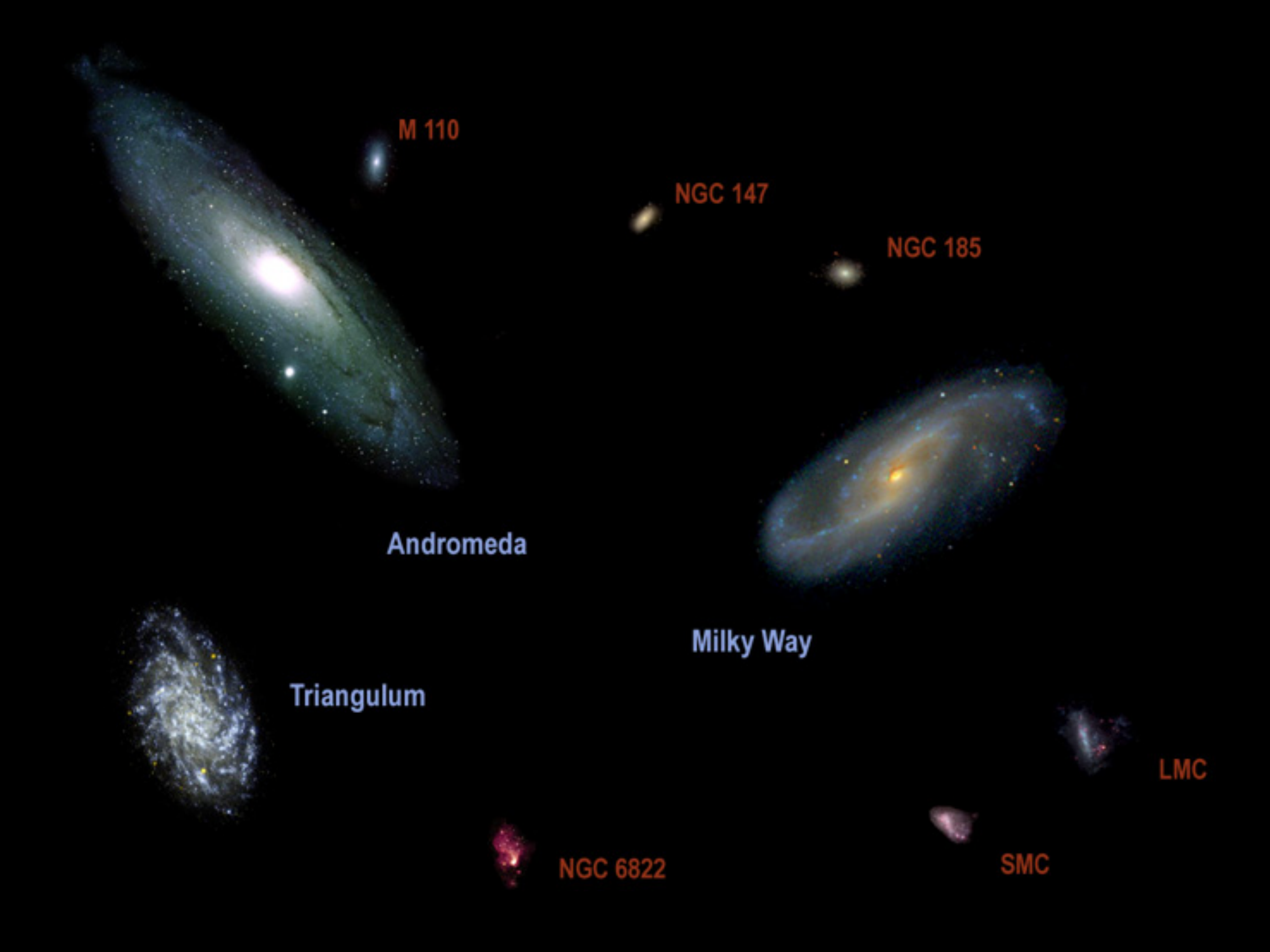






~8 minutes


10,000s of years


M 110
NGC 147
NGC 185
Andromeda
Milky Way
Triangulum
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SMC

Millions of years

M 110

NGC 147

NGC 185

Andromeda

Milky Way

Triangulum

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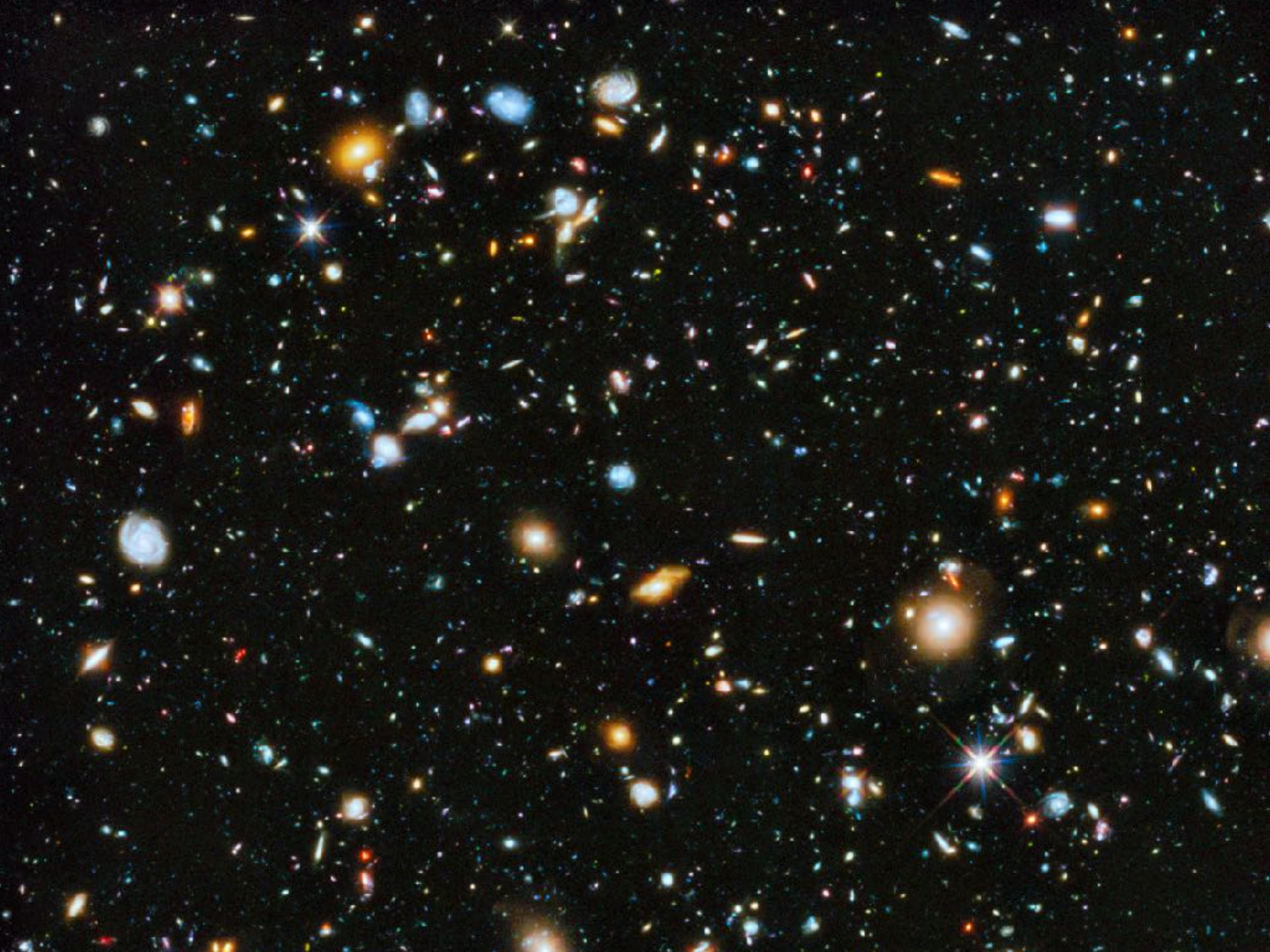
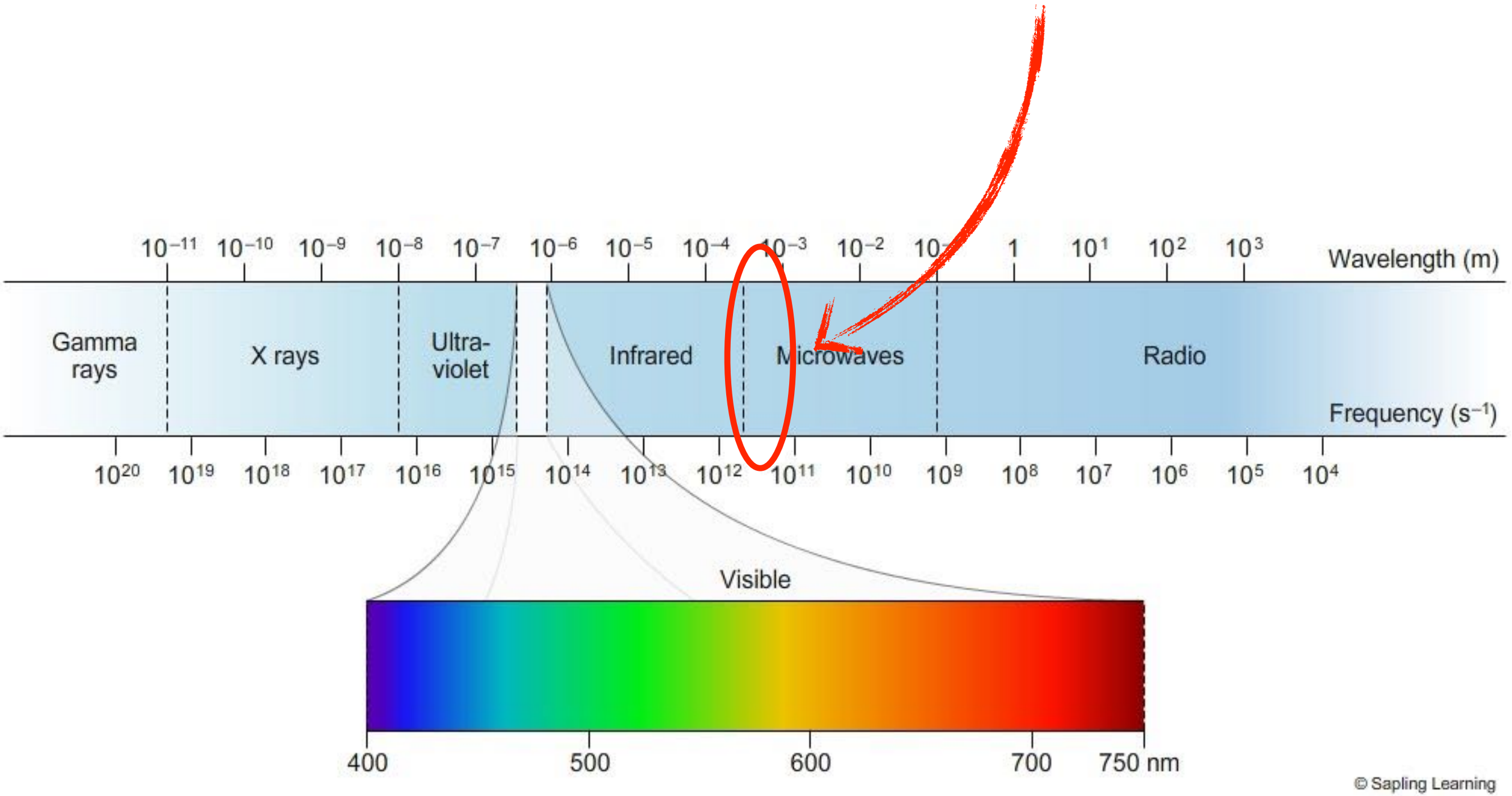
THE `HUBBLE DEEP FIELD'



So… looking at the Universe using optical light doesn't answer our question.

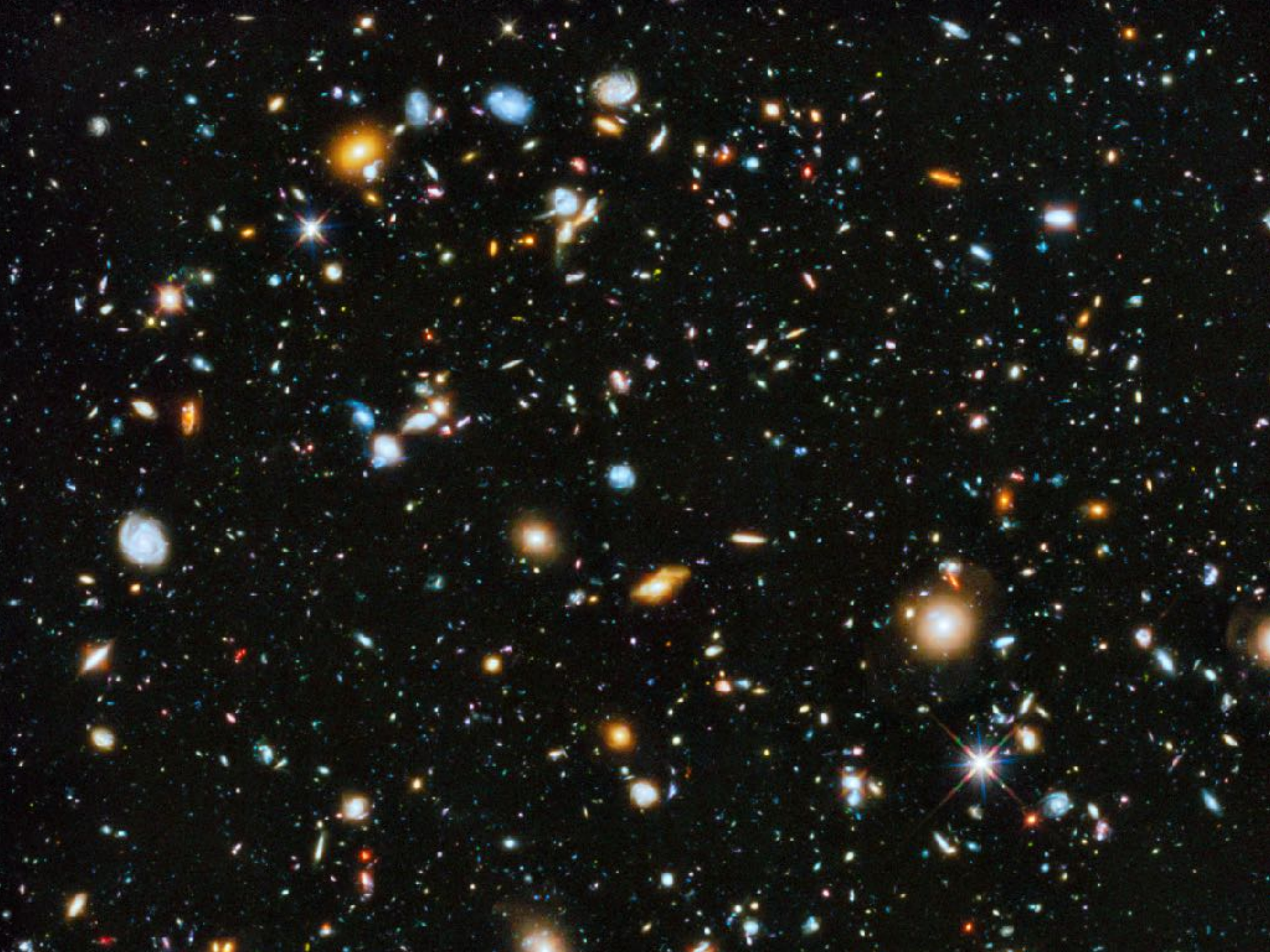
What about other wavelengths? Can we use different wavelengths of light, to find these 'hidden' galaxies?

‘Sub-millimetre’ wavelengths

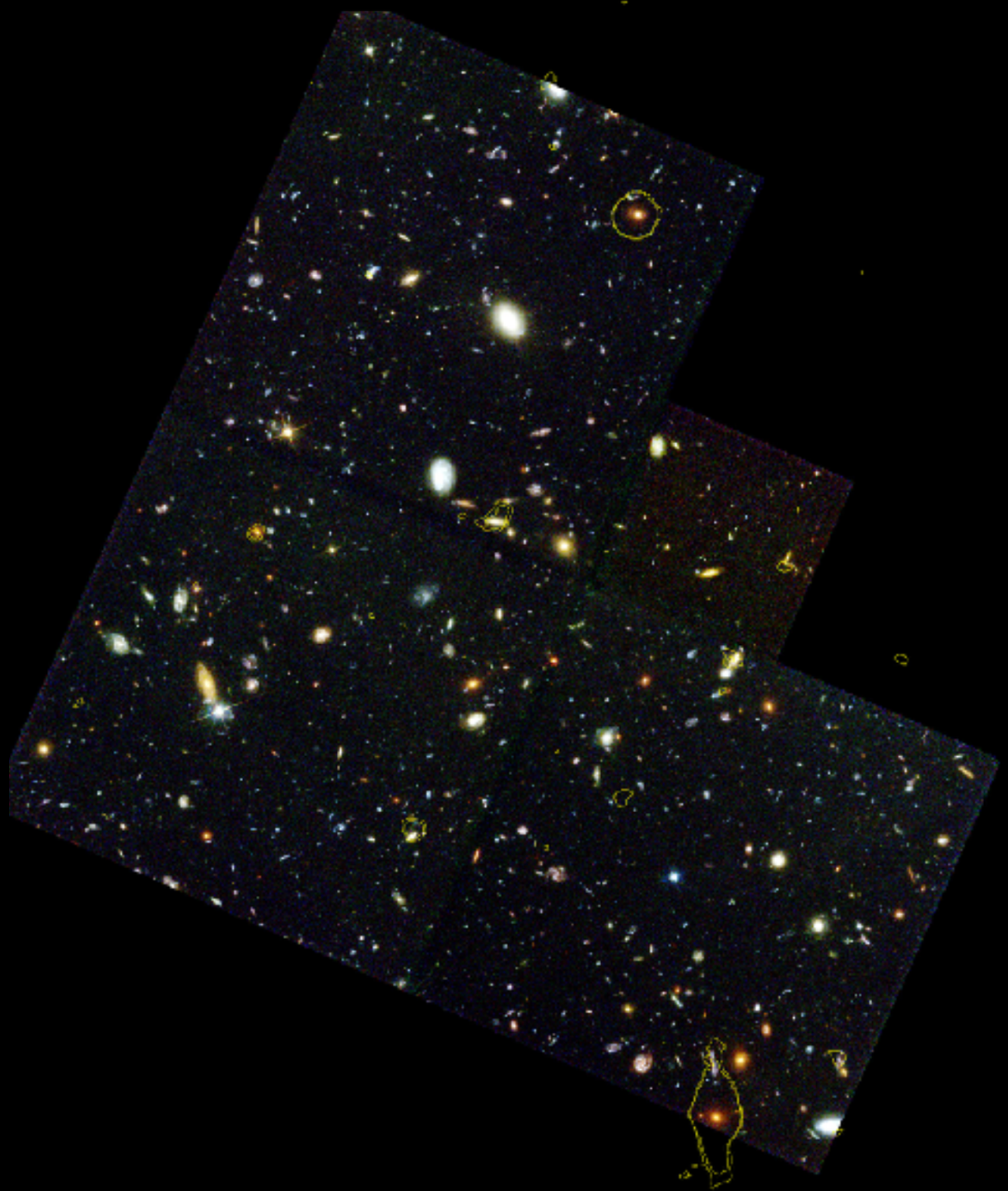


Looking at long wavelength light

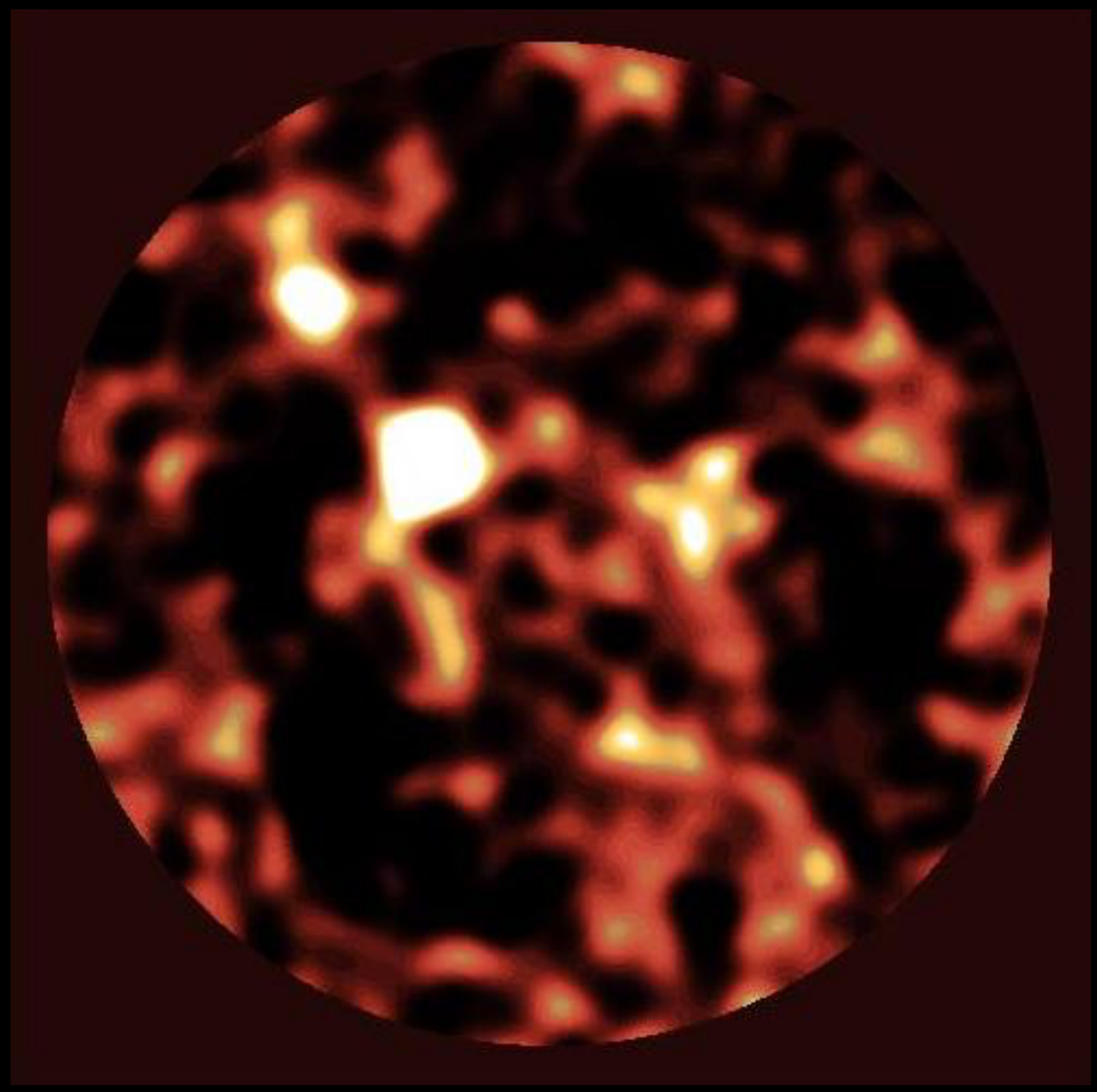
The best kind of ultra-long wavelength detector is a BOLOMETER

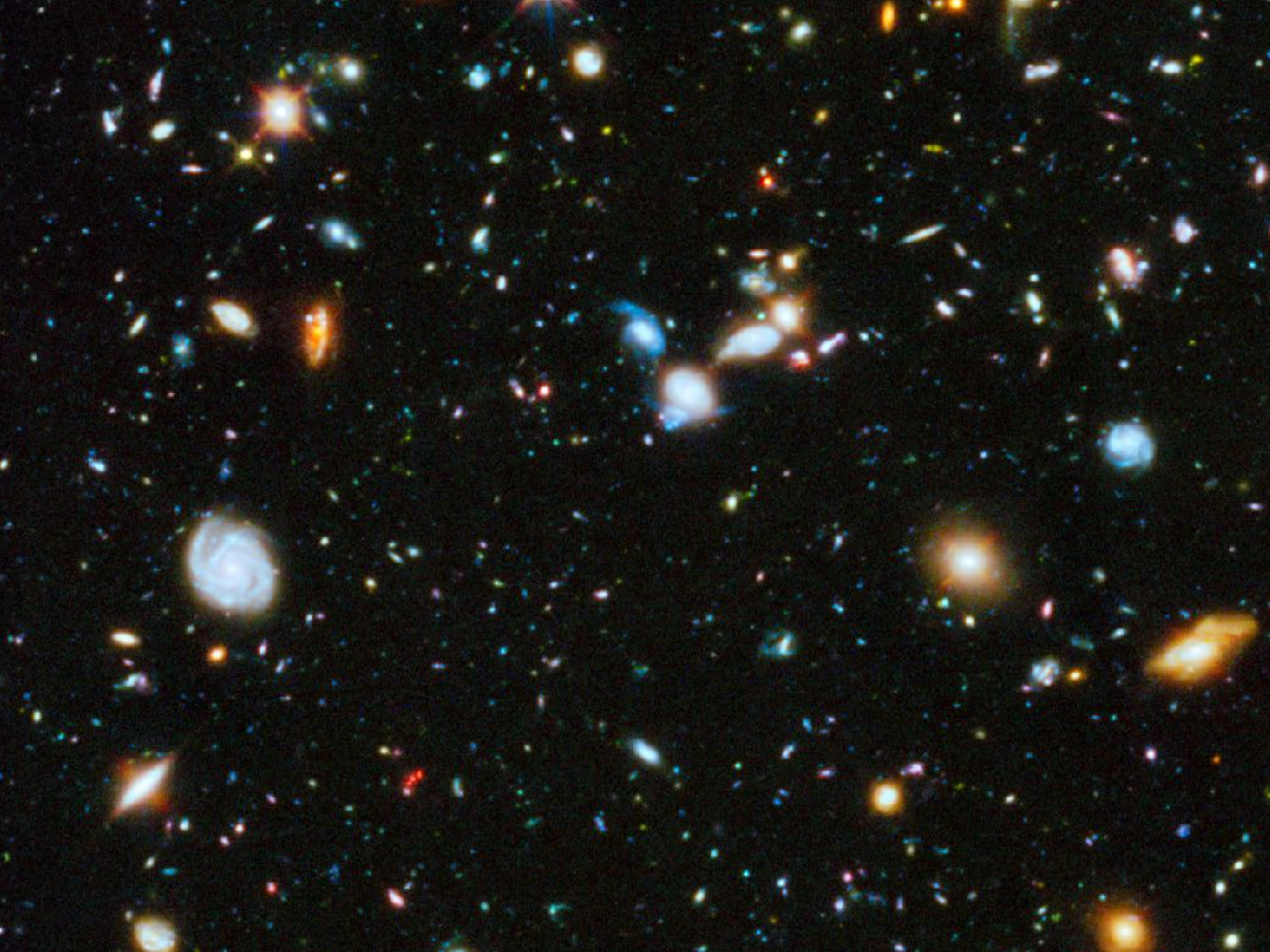


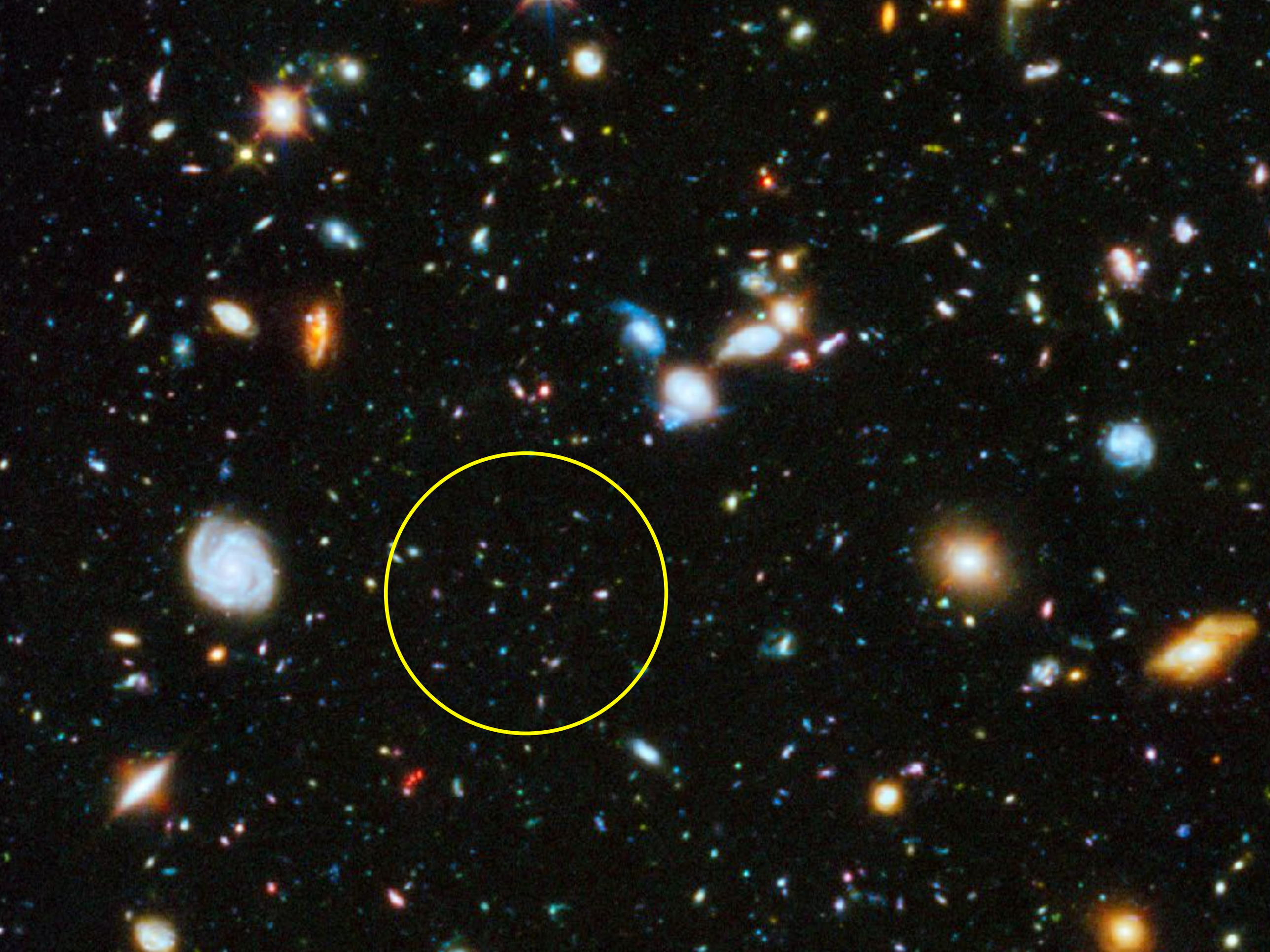
Optical light



‘sub-millimetre’ (very long) wavelength light

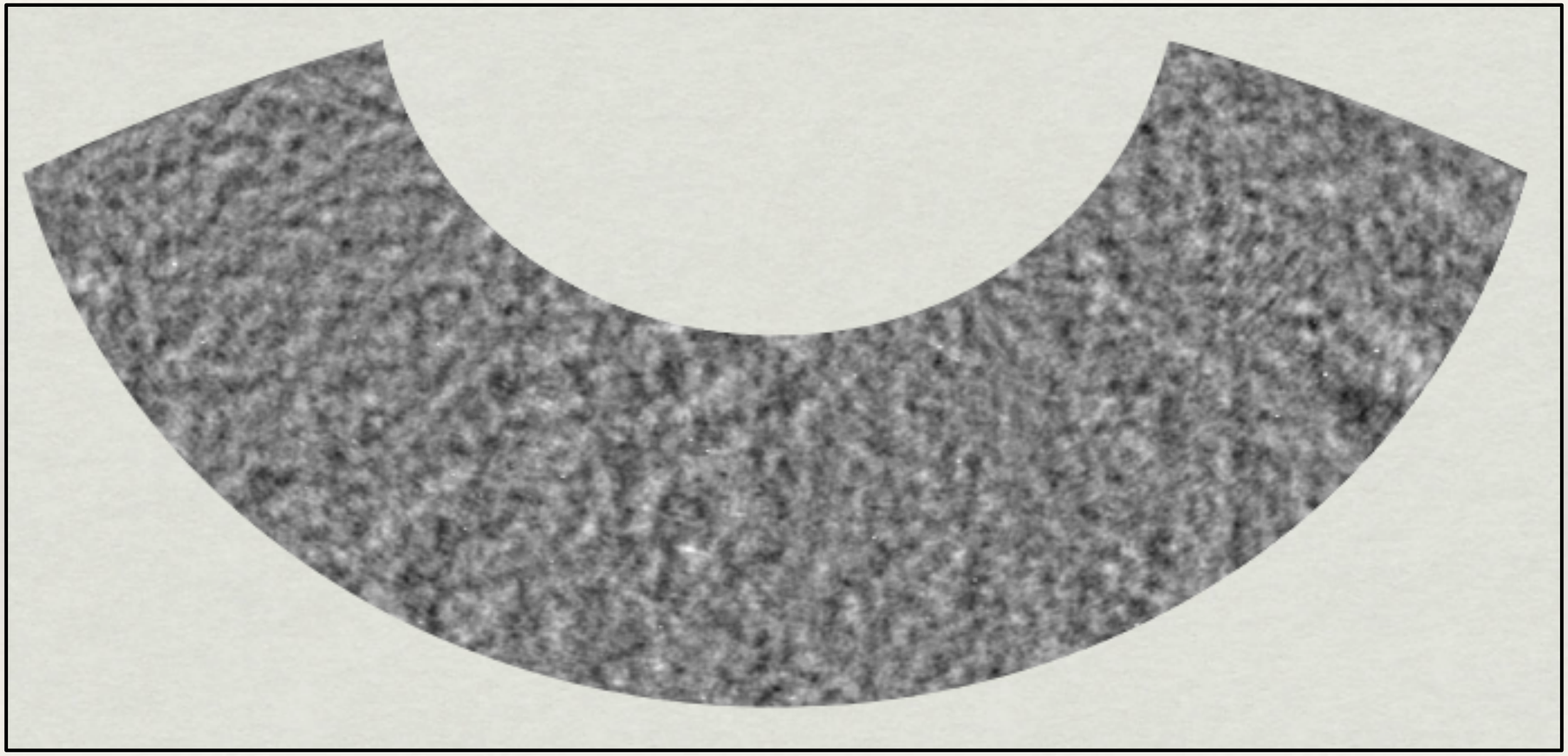


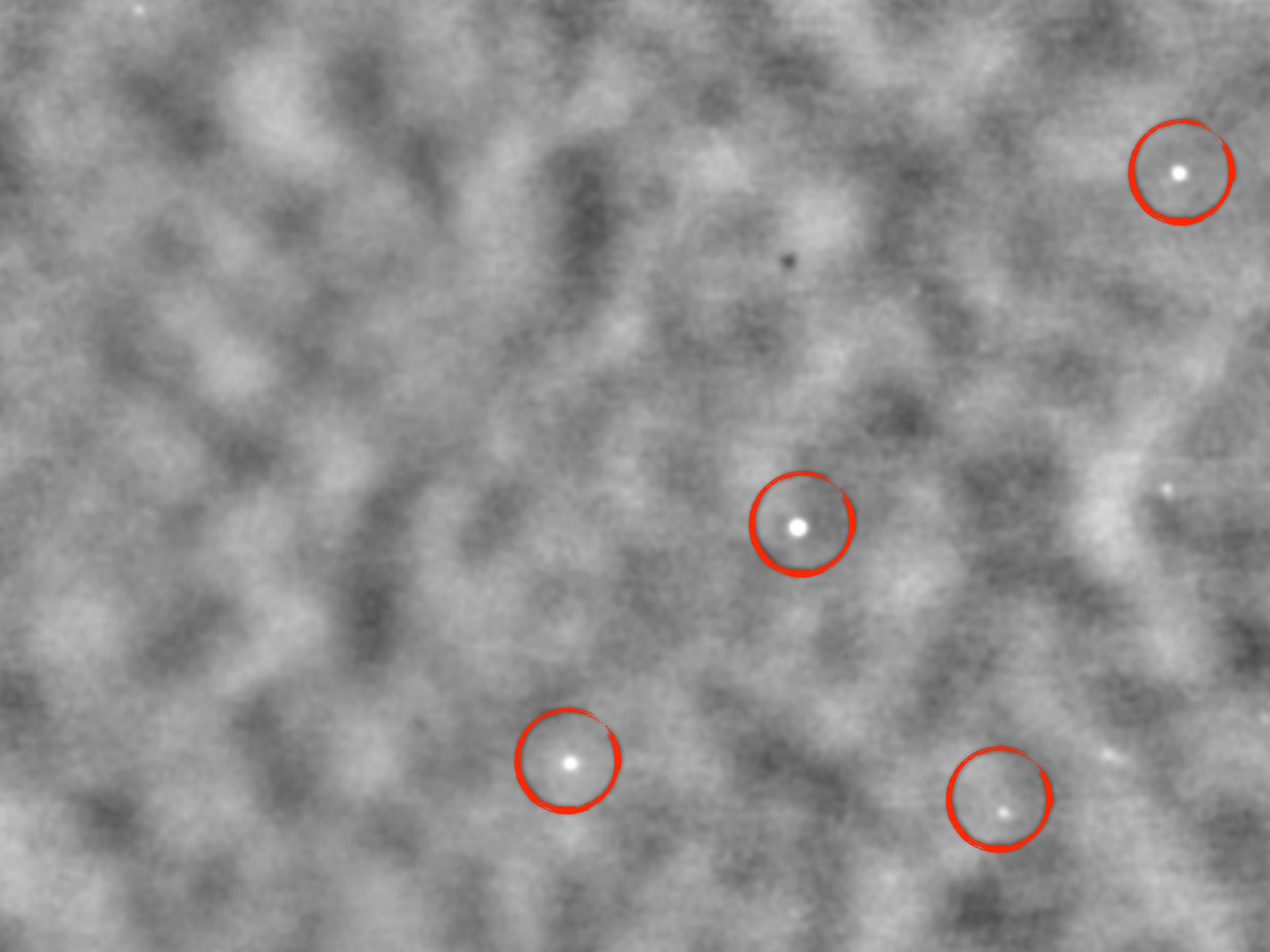


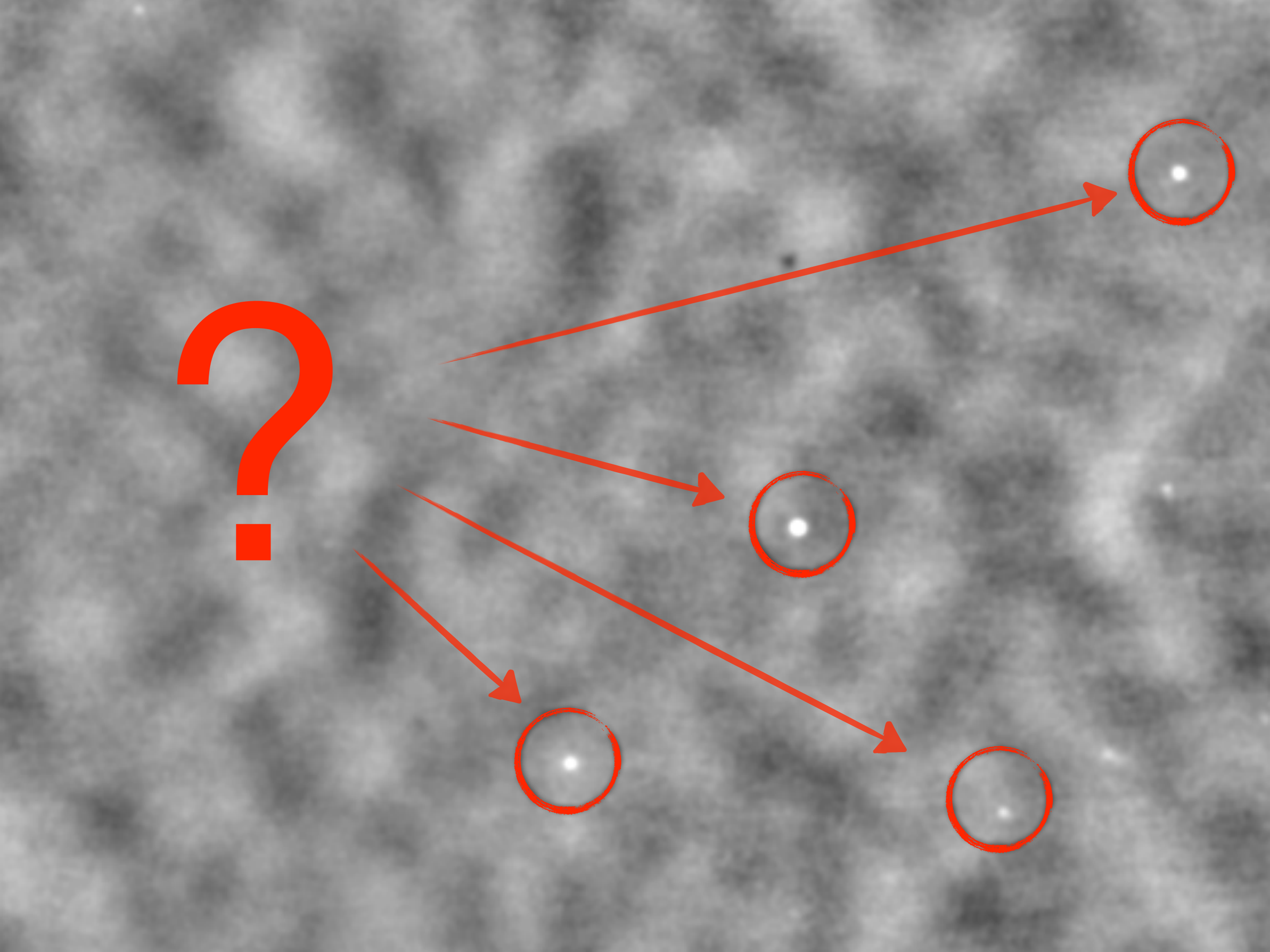


The South Pole Telescope

SPT 2500 deg^2 survey







So, what are these things?

Some galaxies are emitting lots of long-wavelength light…

And, they aren't showing up in optical images

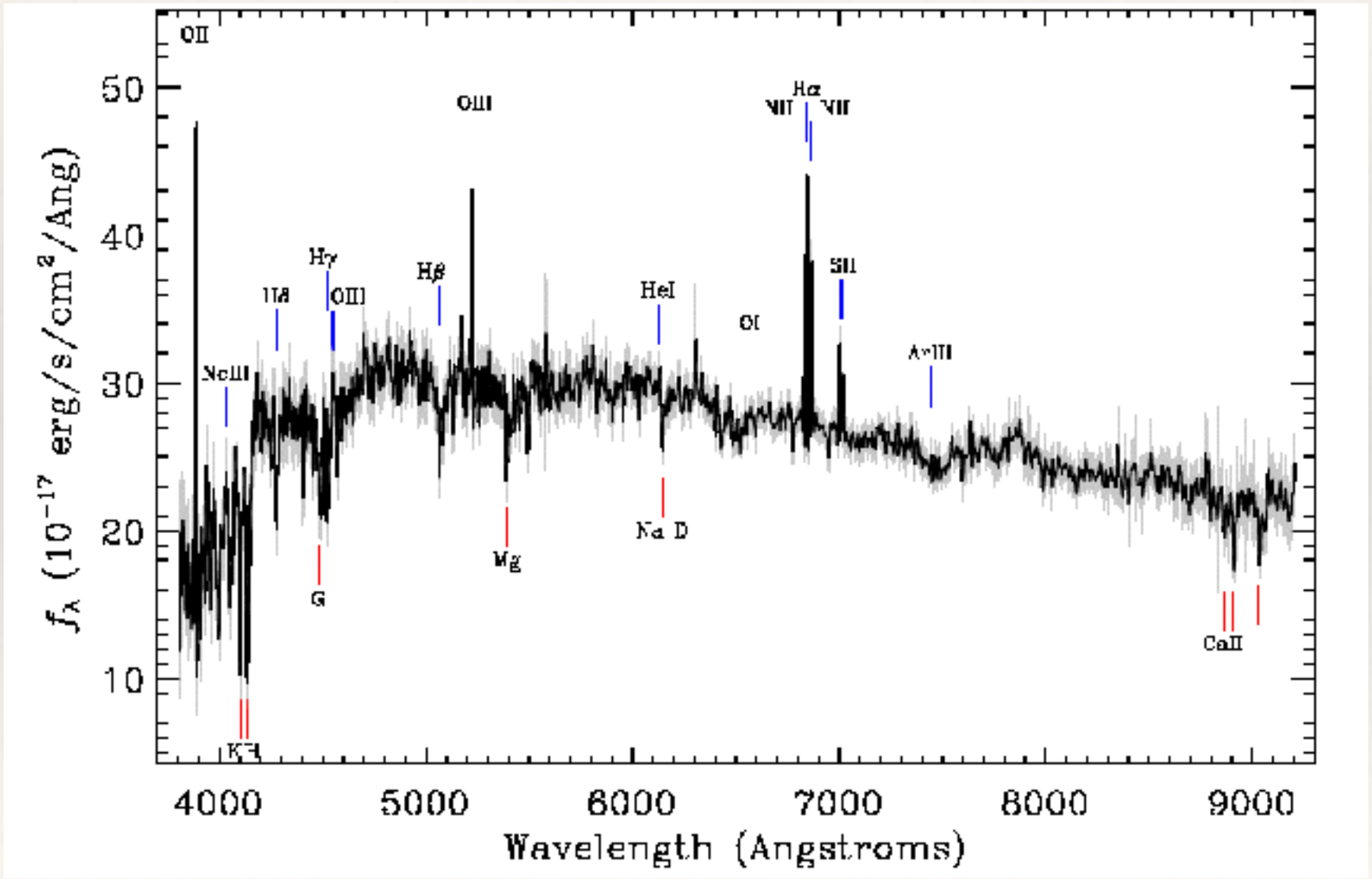
How far away are they?

Sub-millimetre ‘magic’

- Galaxies observed in the sub-millimetre do not obey the normal brightness/distance relationship
- They stay exactly the same brightness across a HUGE range of distances
- … HOW???

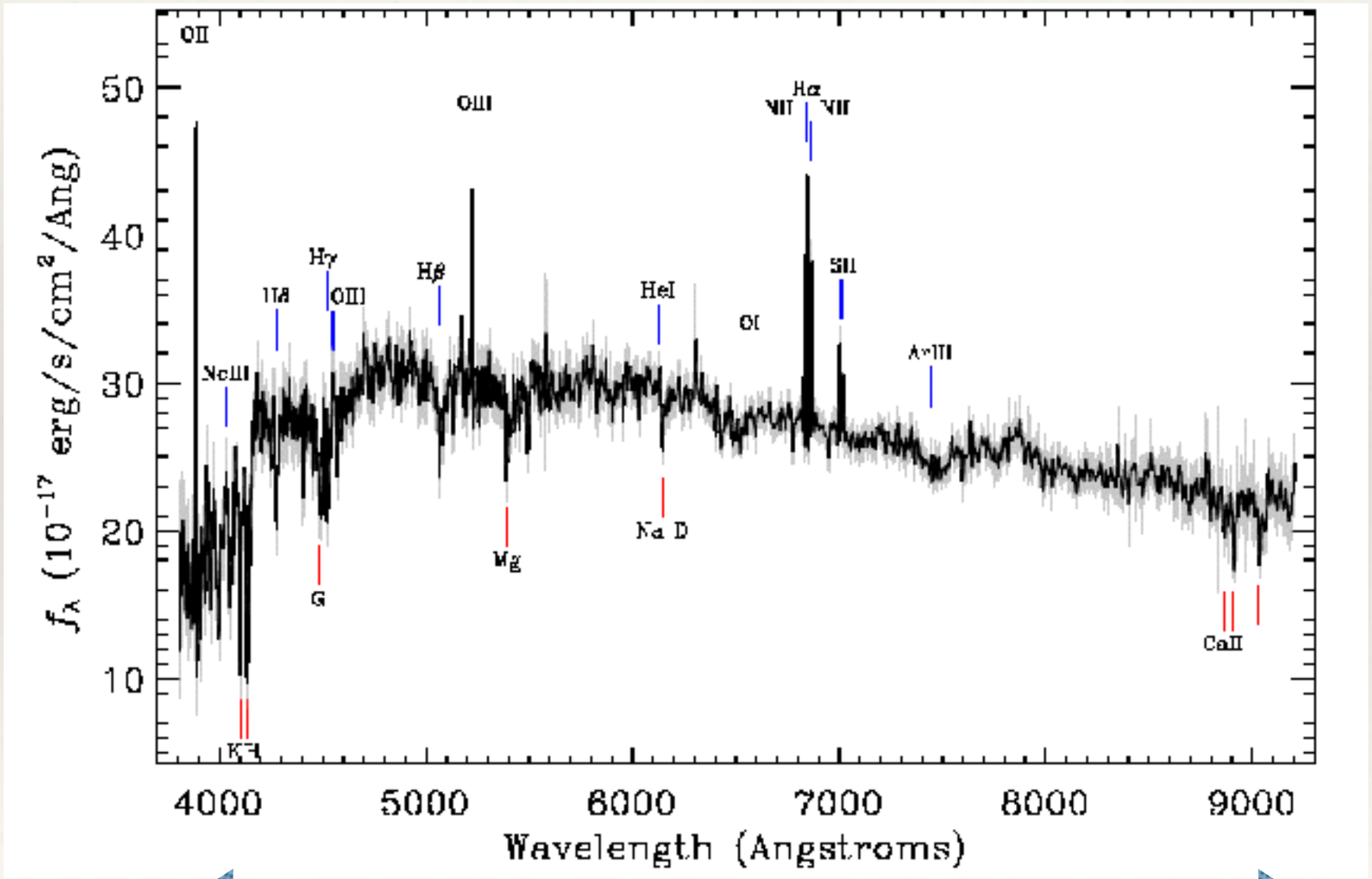
Sub-millimetre ‘magic’

A spectrum from a galaxy…



Sub-millimetre ‘magic’

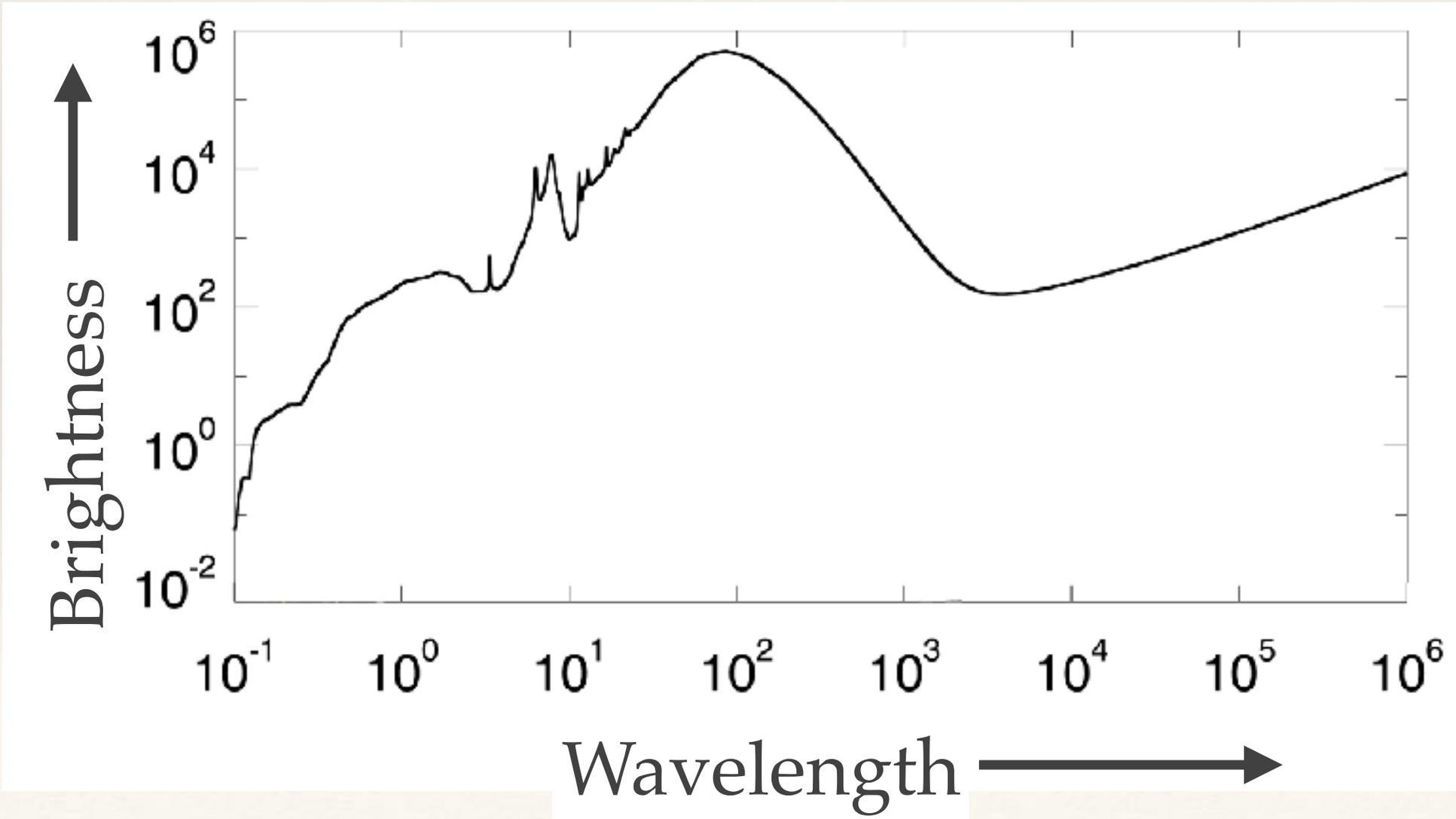
A spectrum from a galaxy…



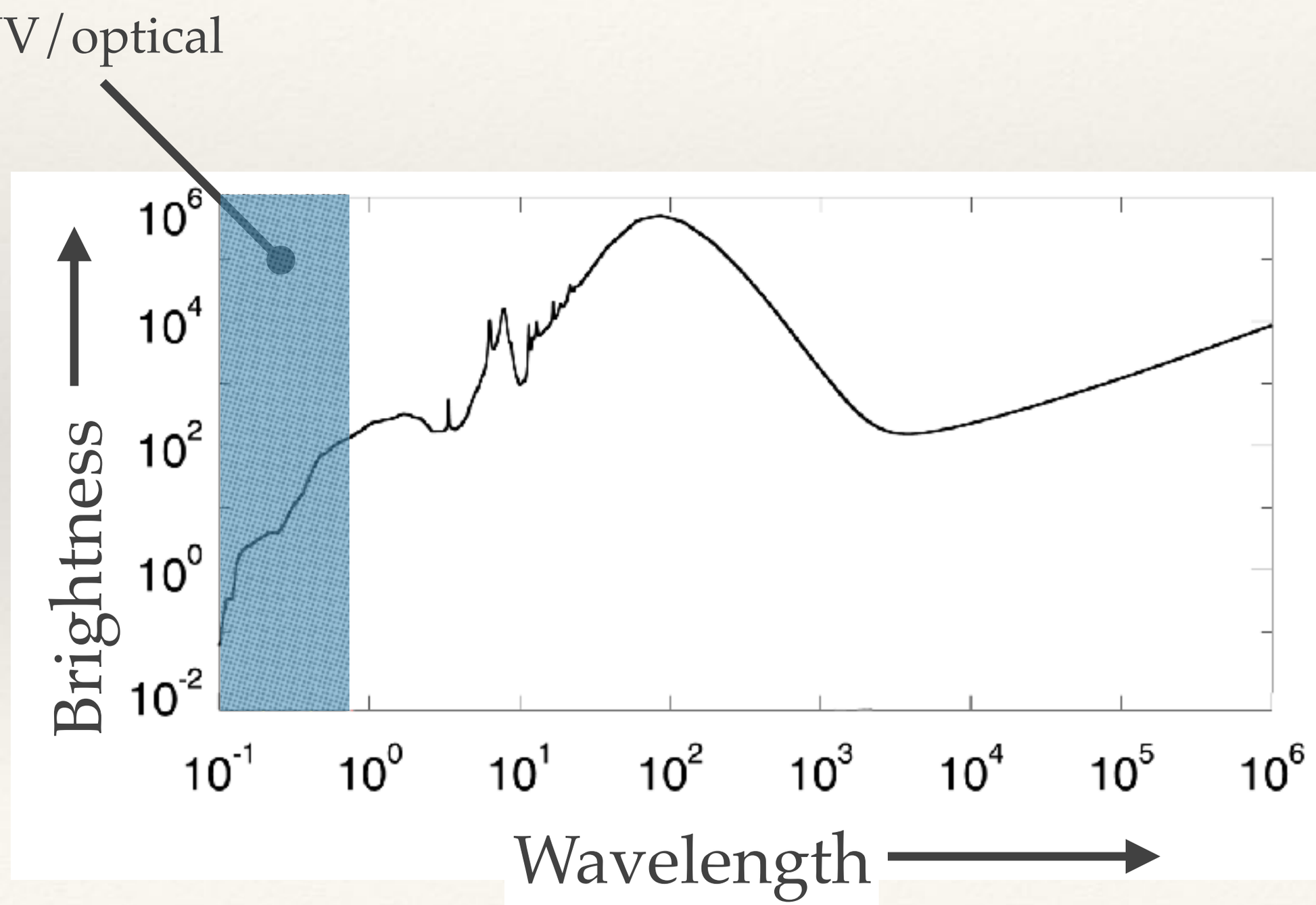
Sub-millimetre ‘magic’

A spectrum covering the full emission (UV -> radio)

‘spectral energy distribution’ (SED)



Sub-millimetre ‘magic’



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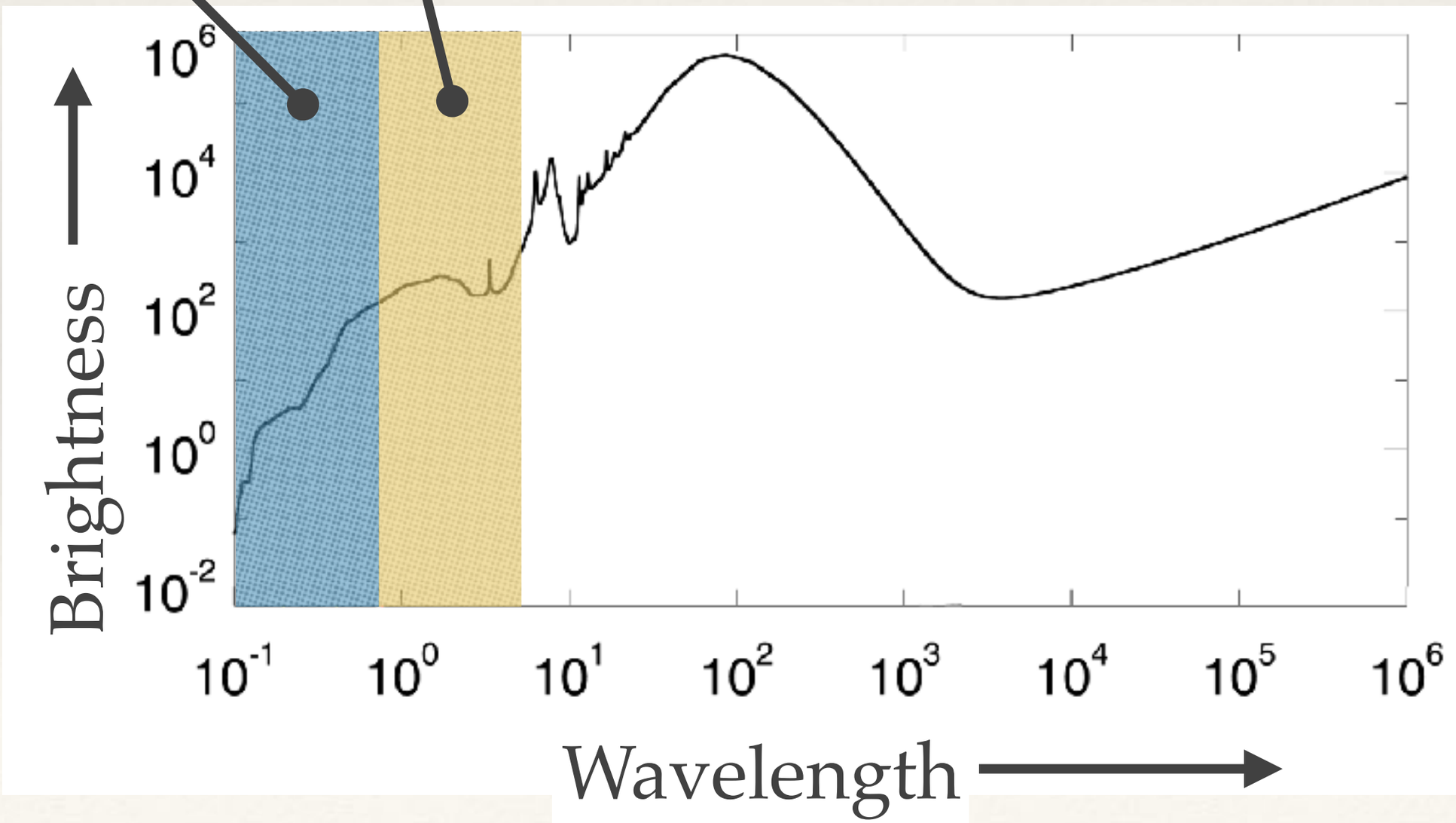

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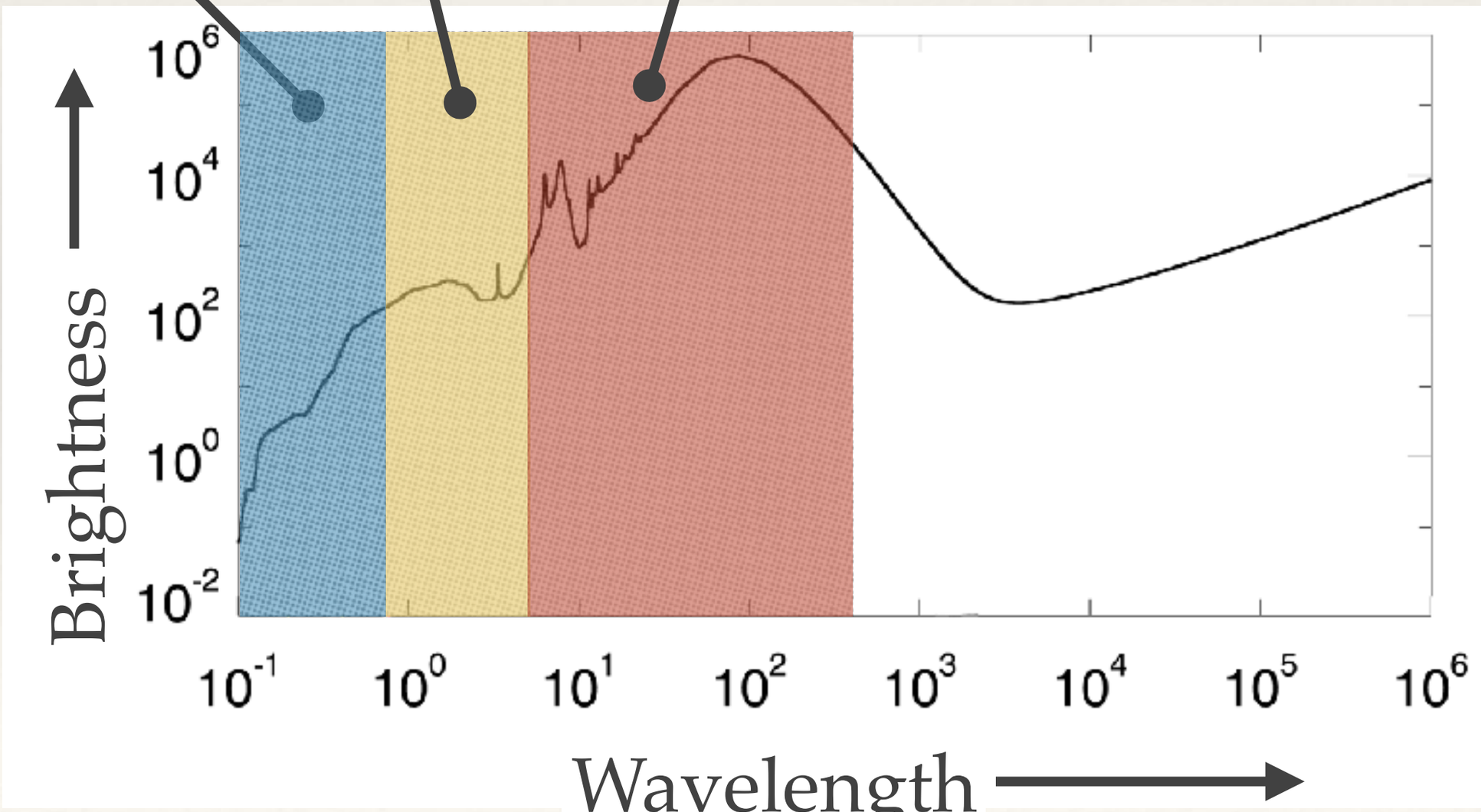

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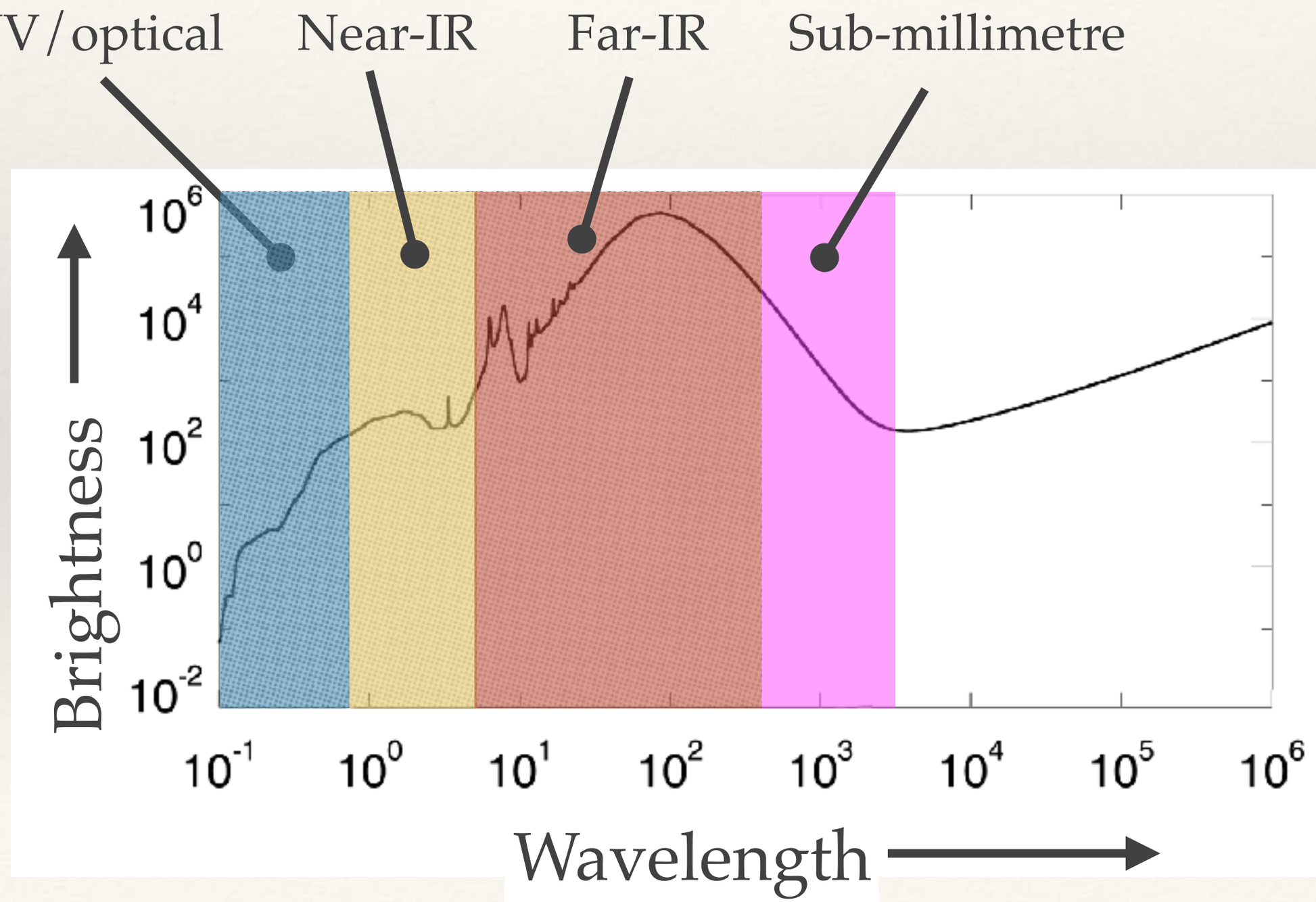
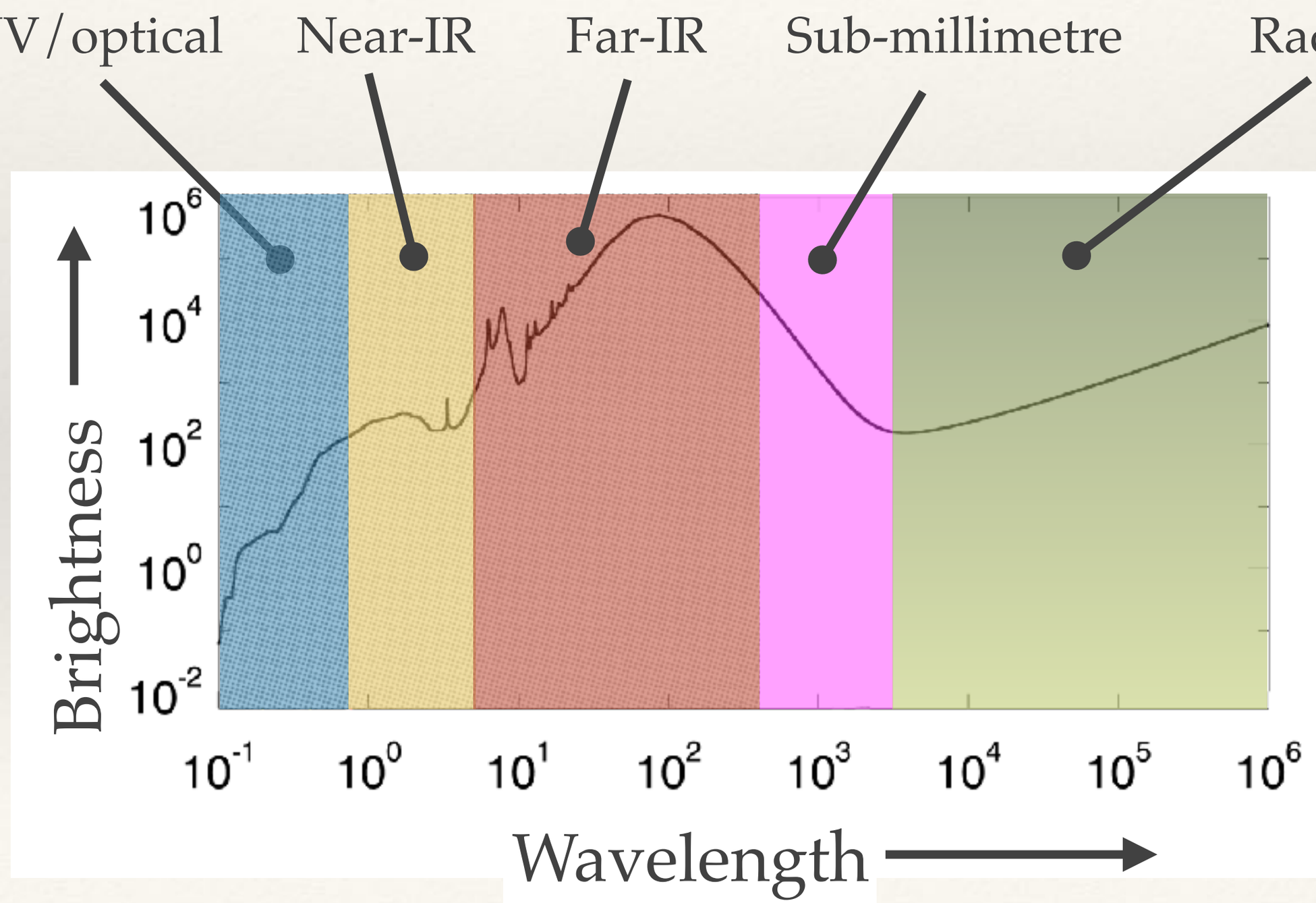
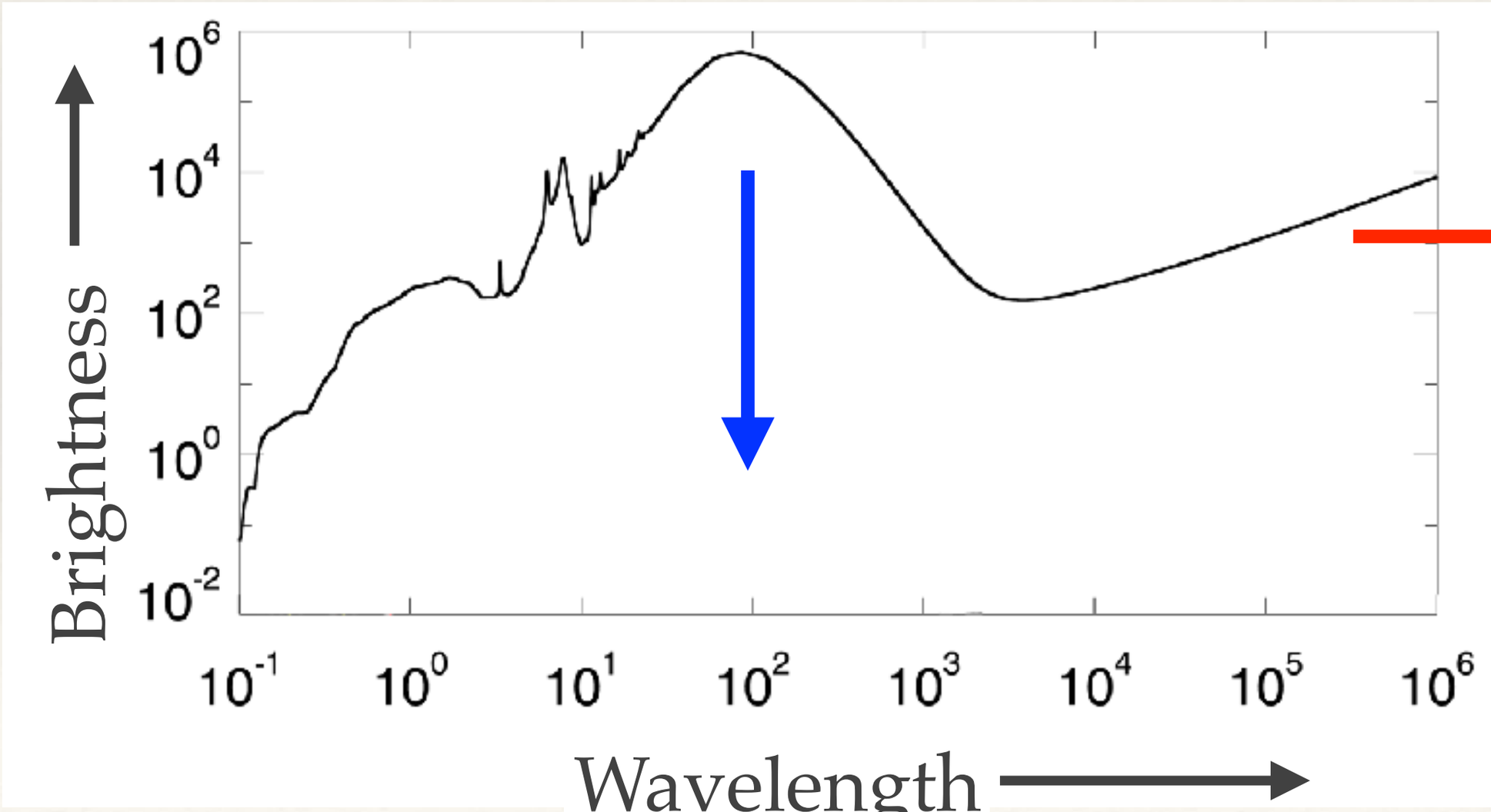


Sub-millimetre ‘magic’



Sub-millimetre ‘magic’

What happens when an object gets ‘moved’ farther away?



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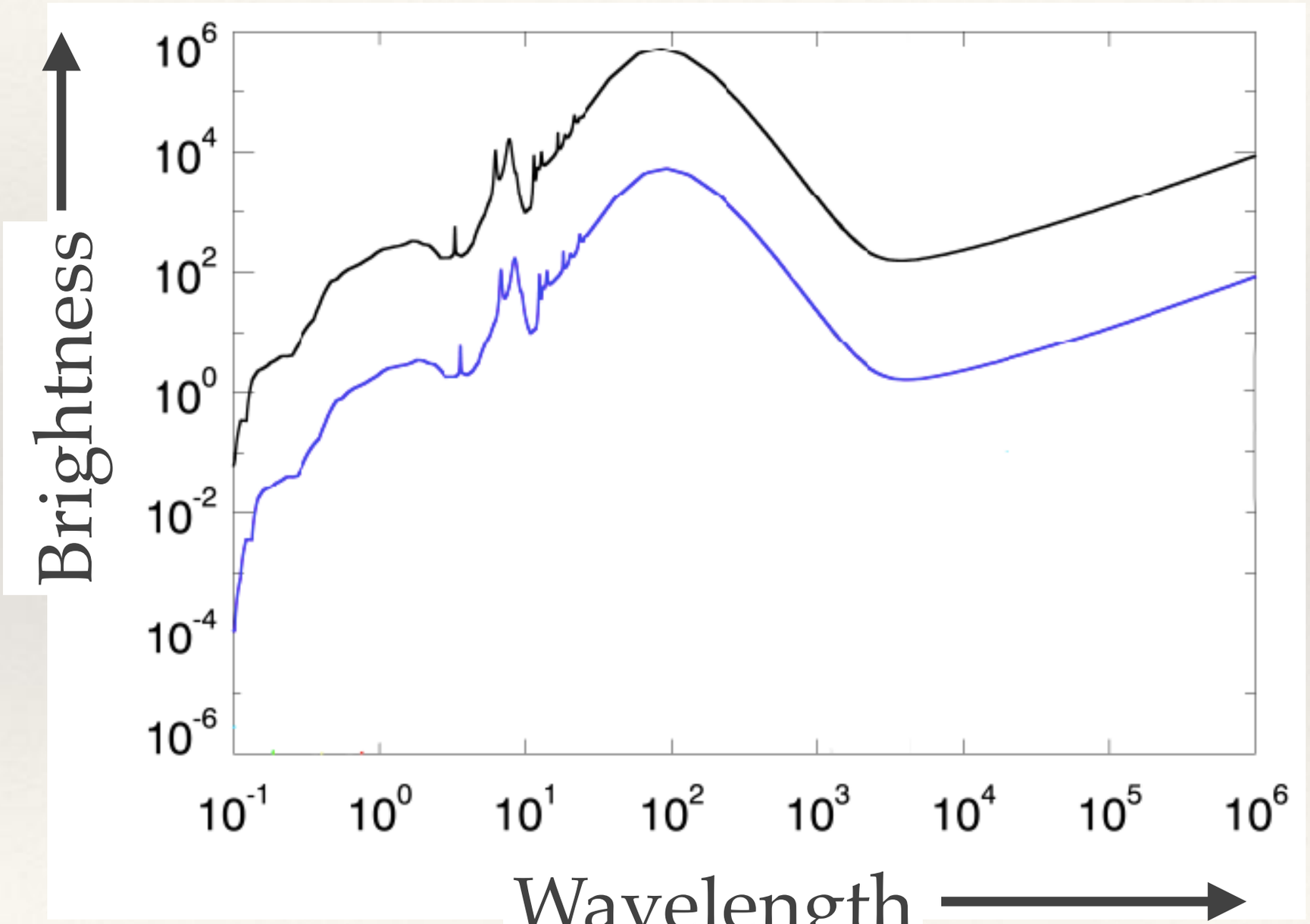
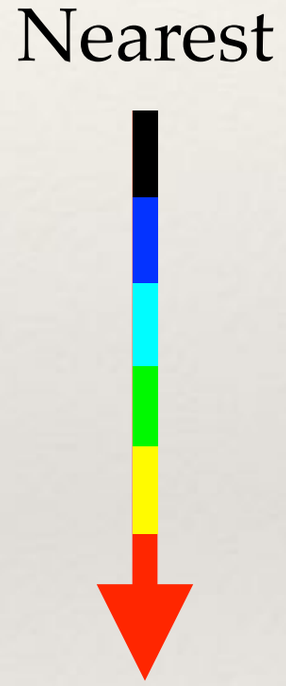
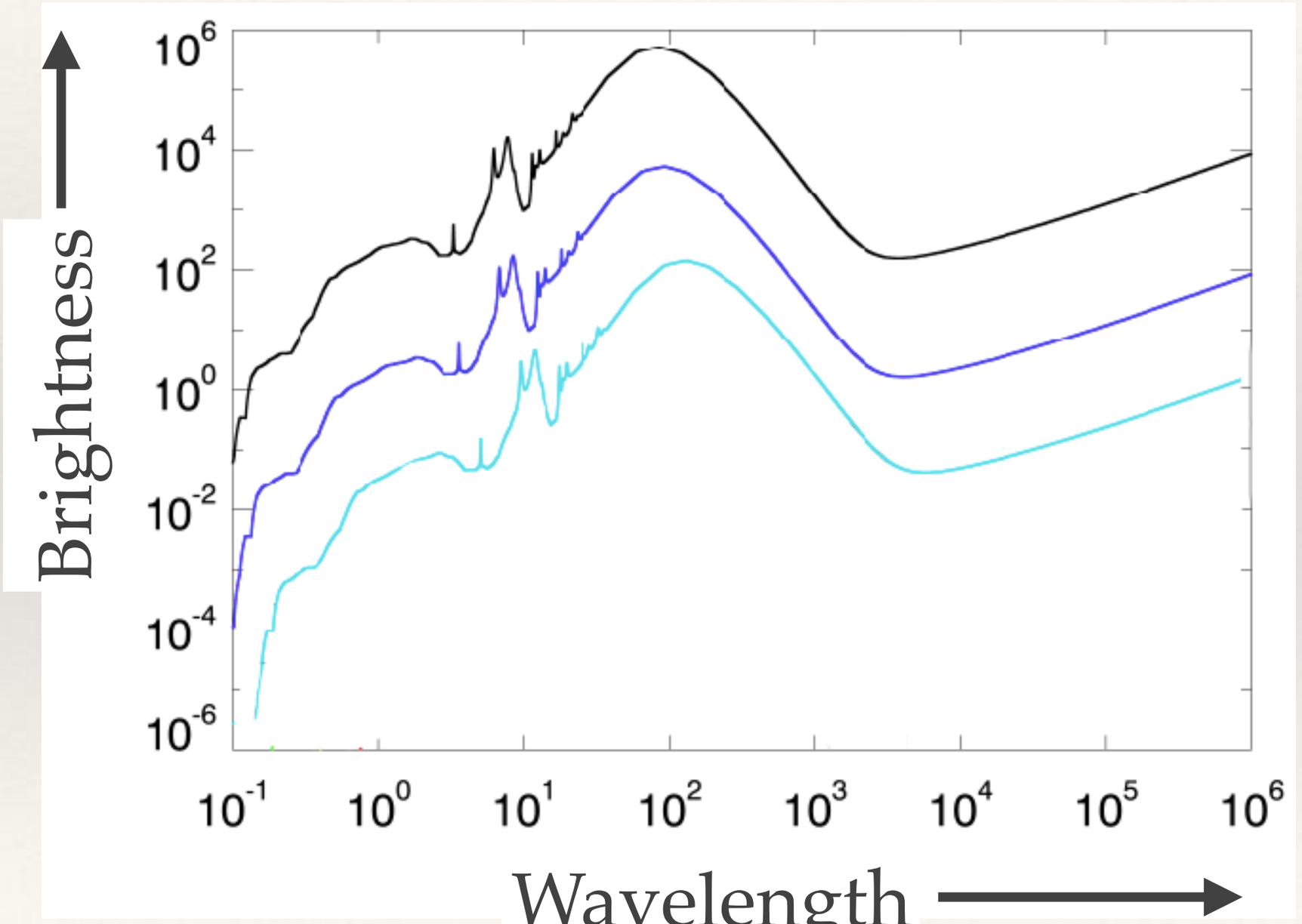
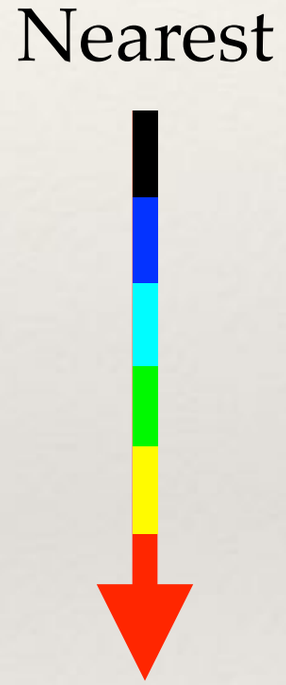




Sub-millimetre ‘magic’





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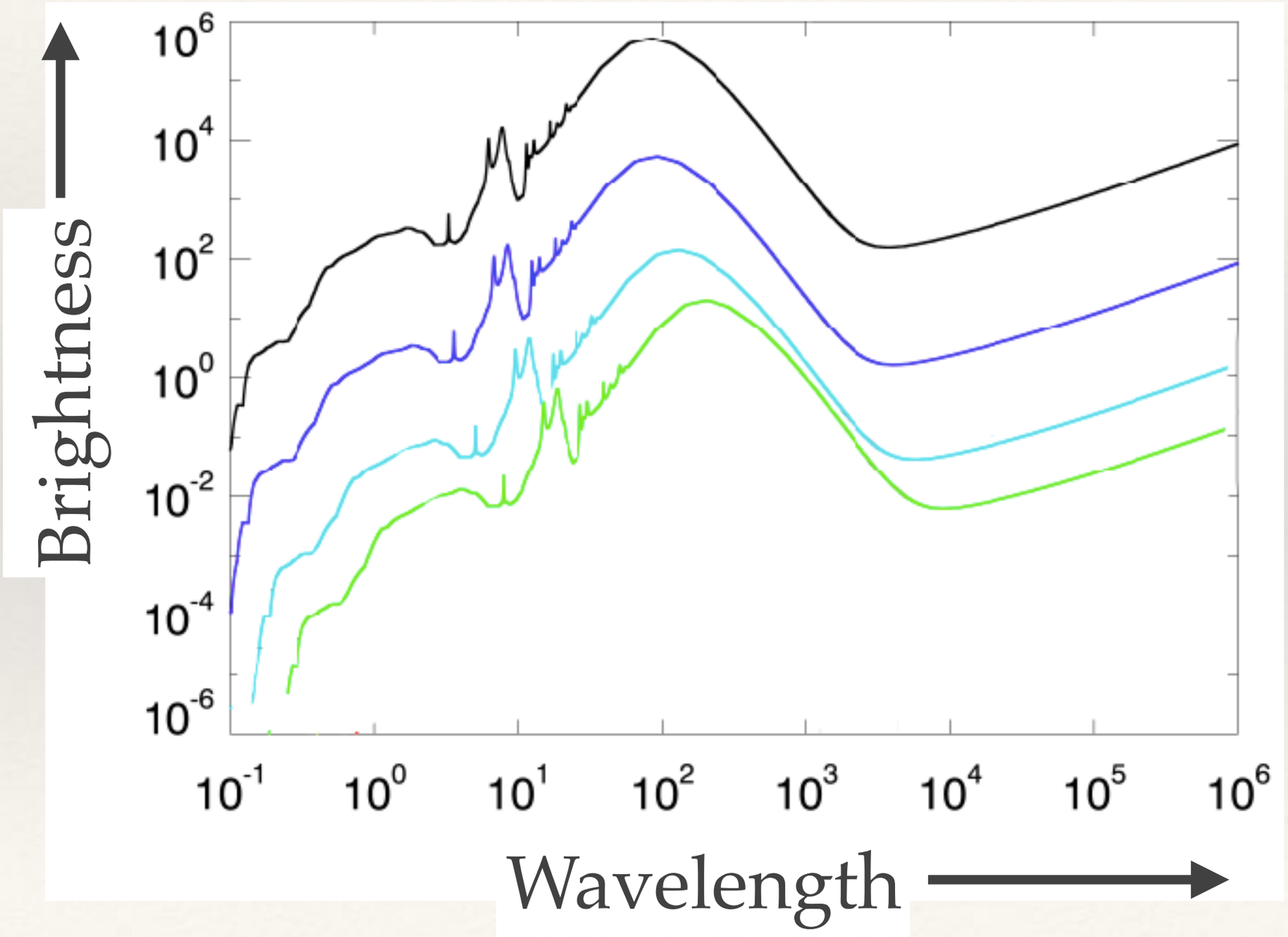

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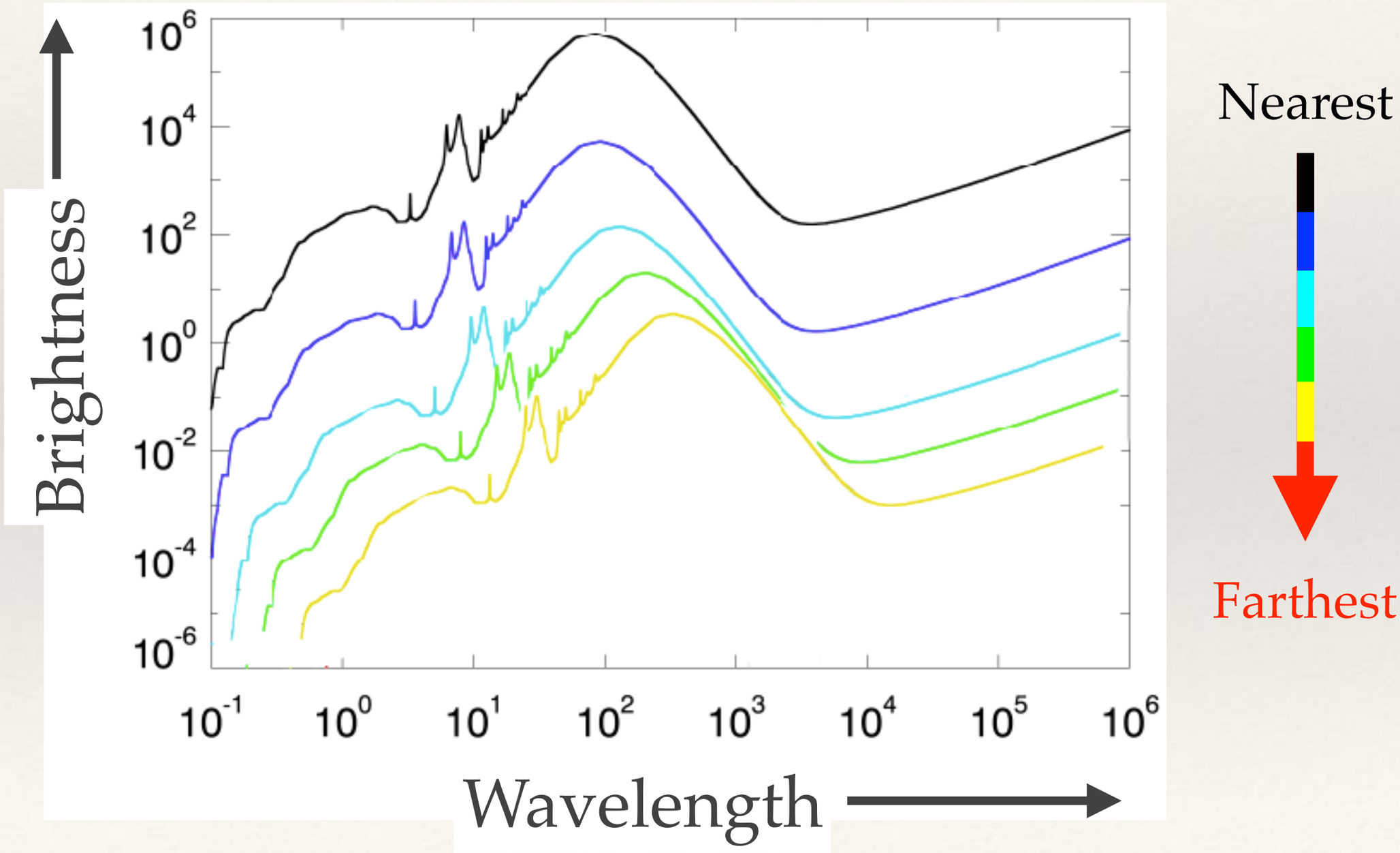

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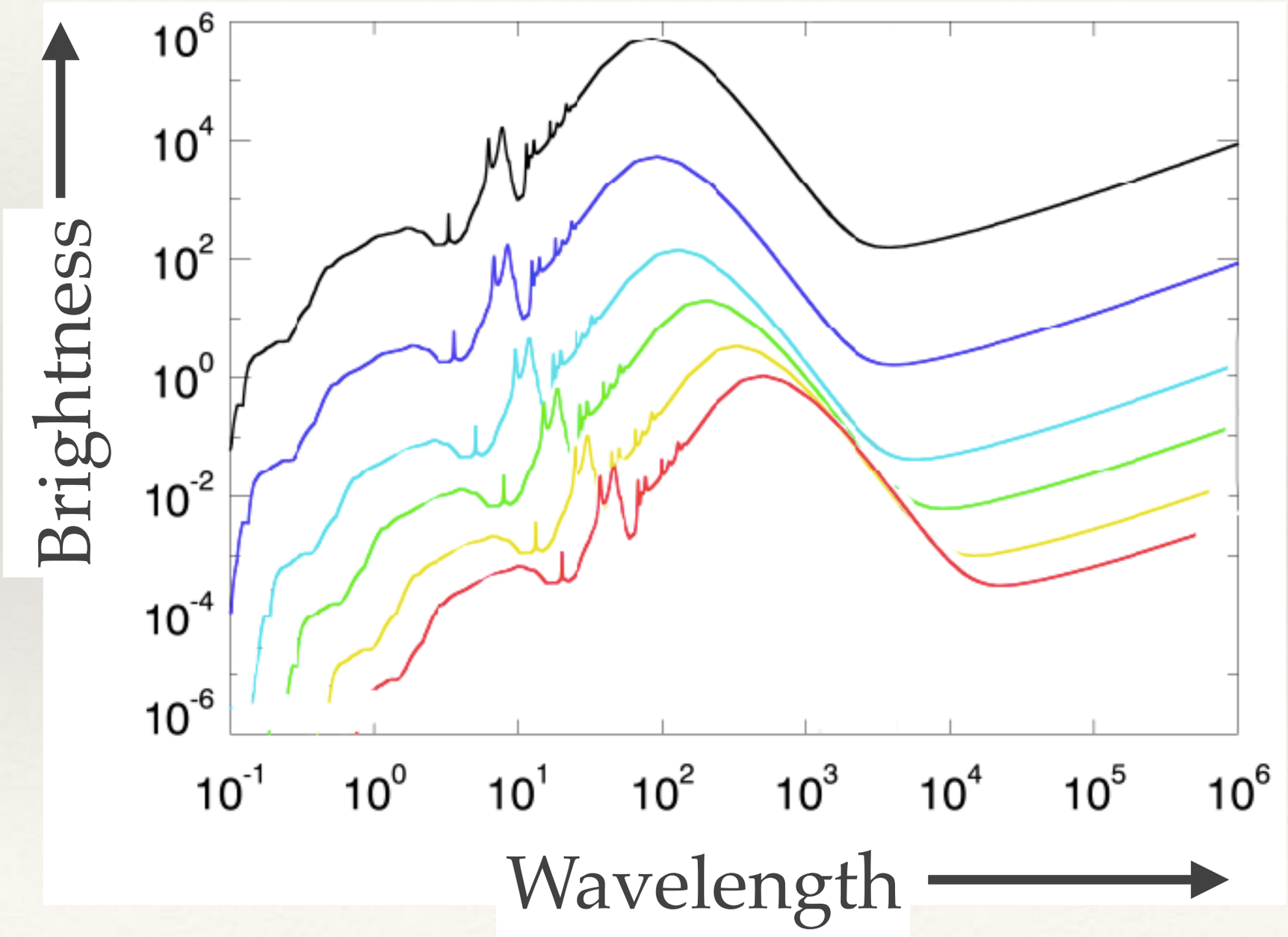

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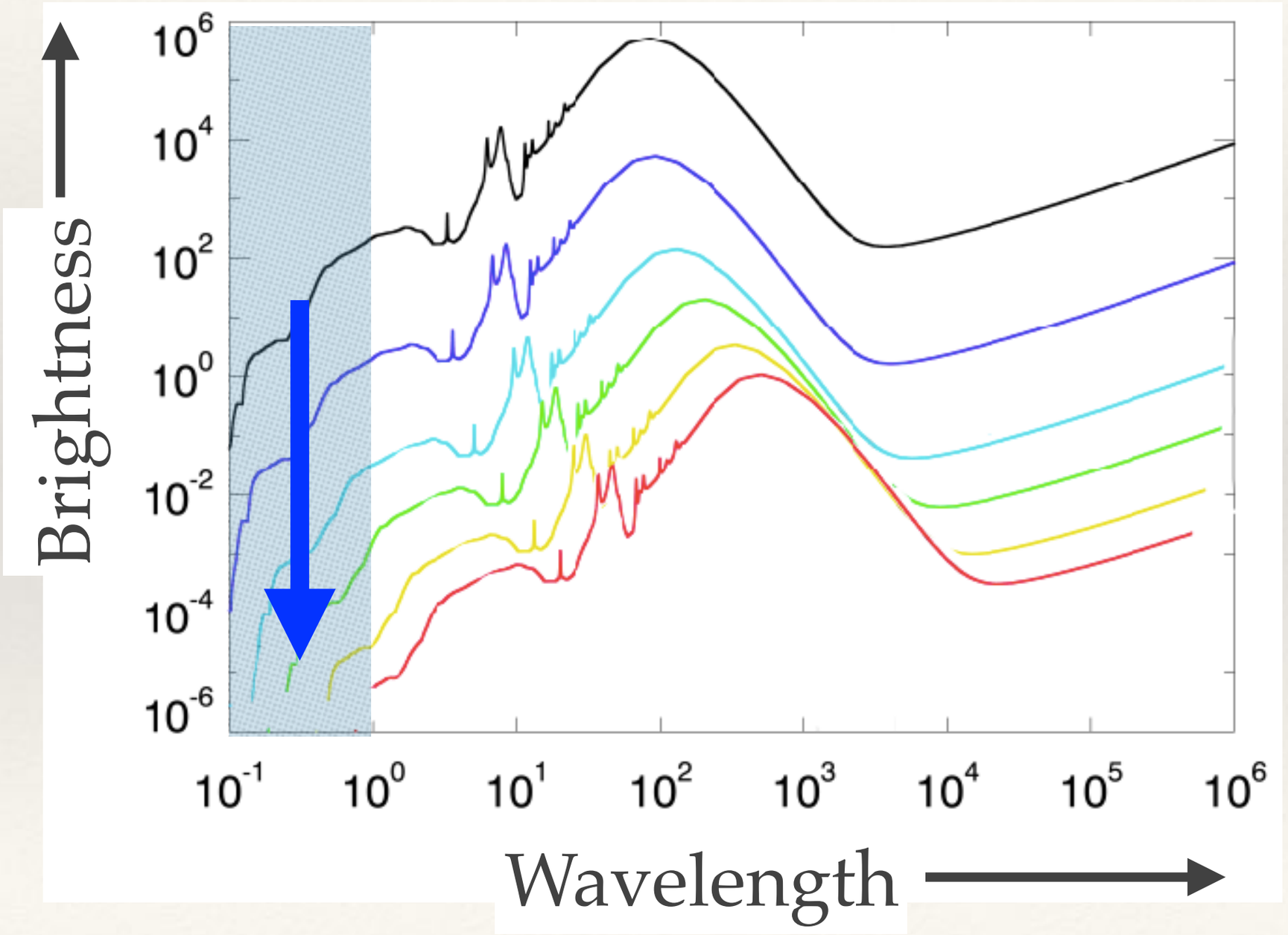

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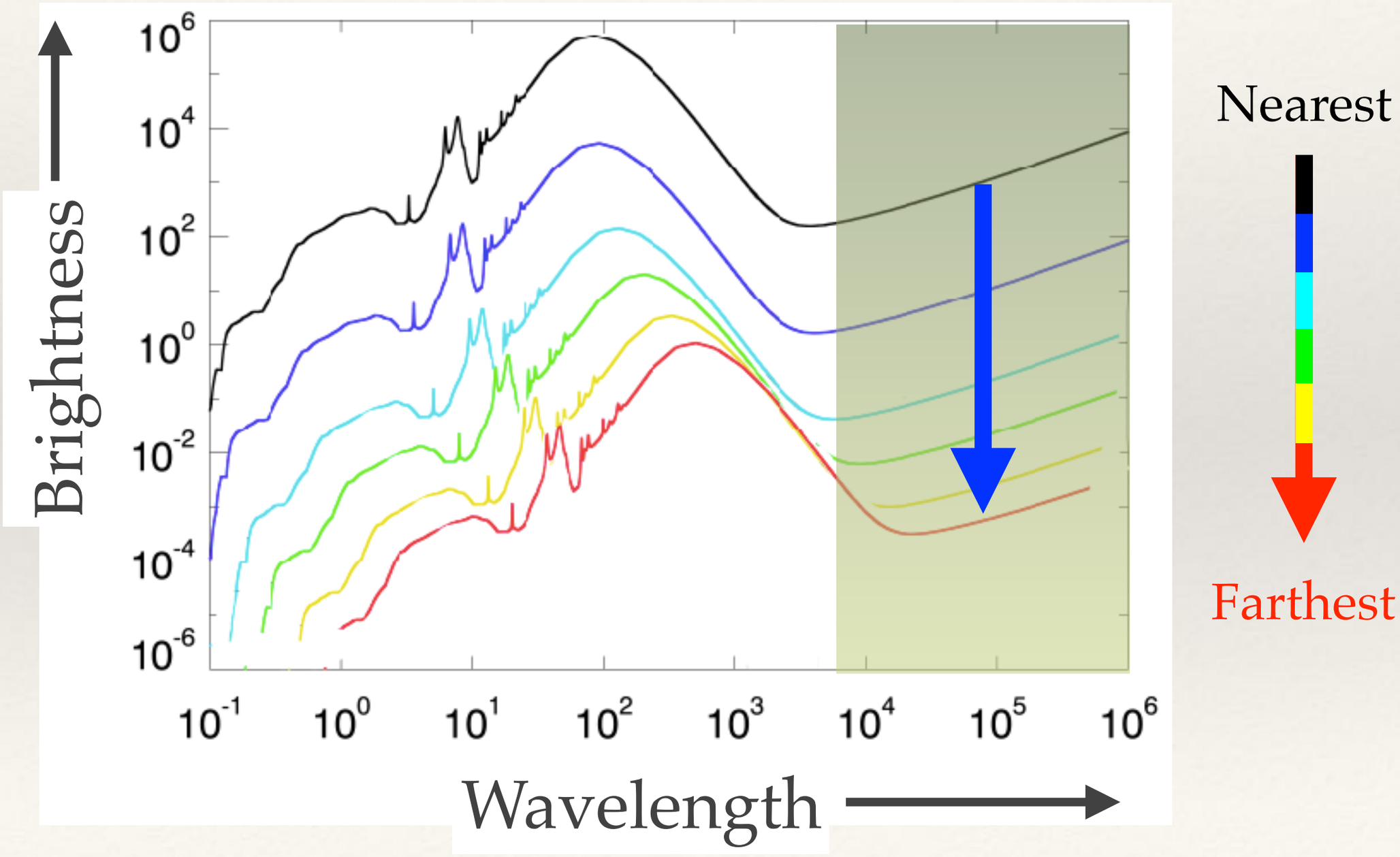
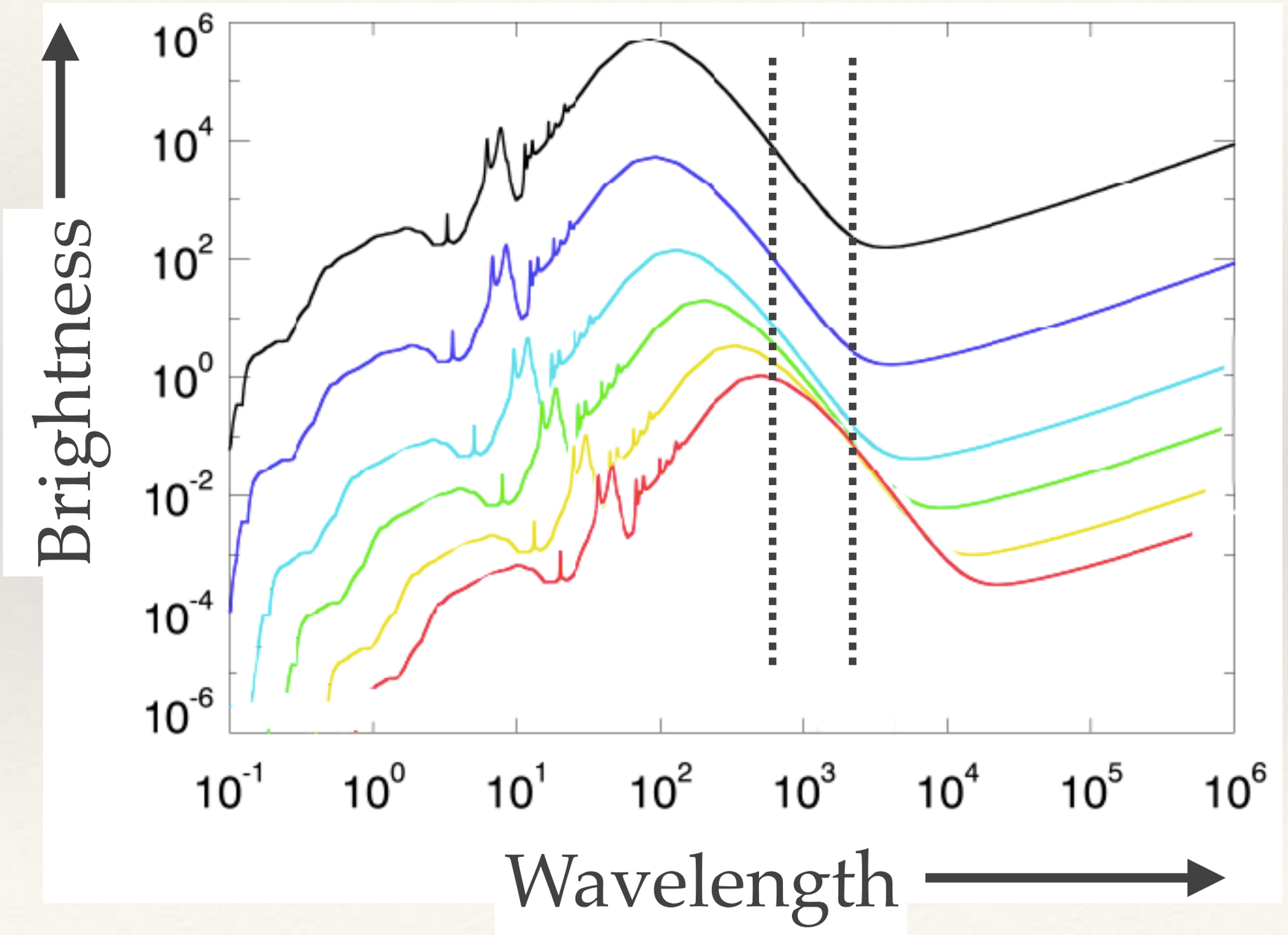
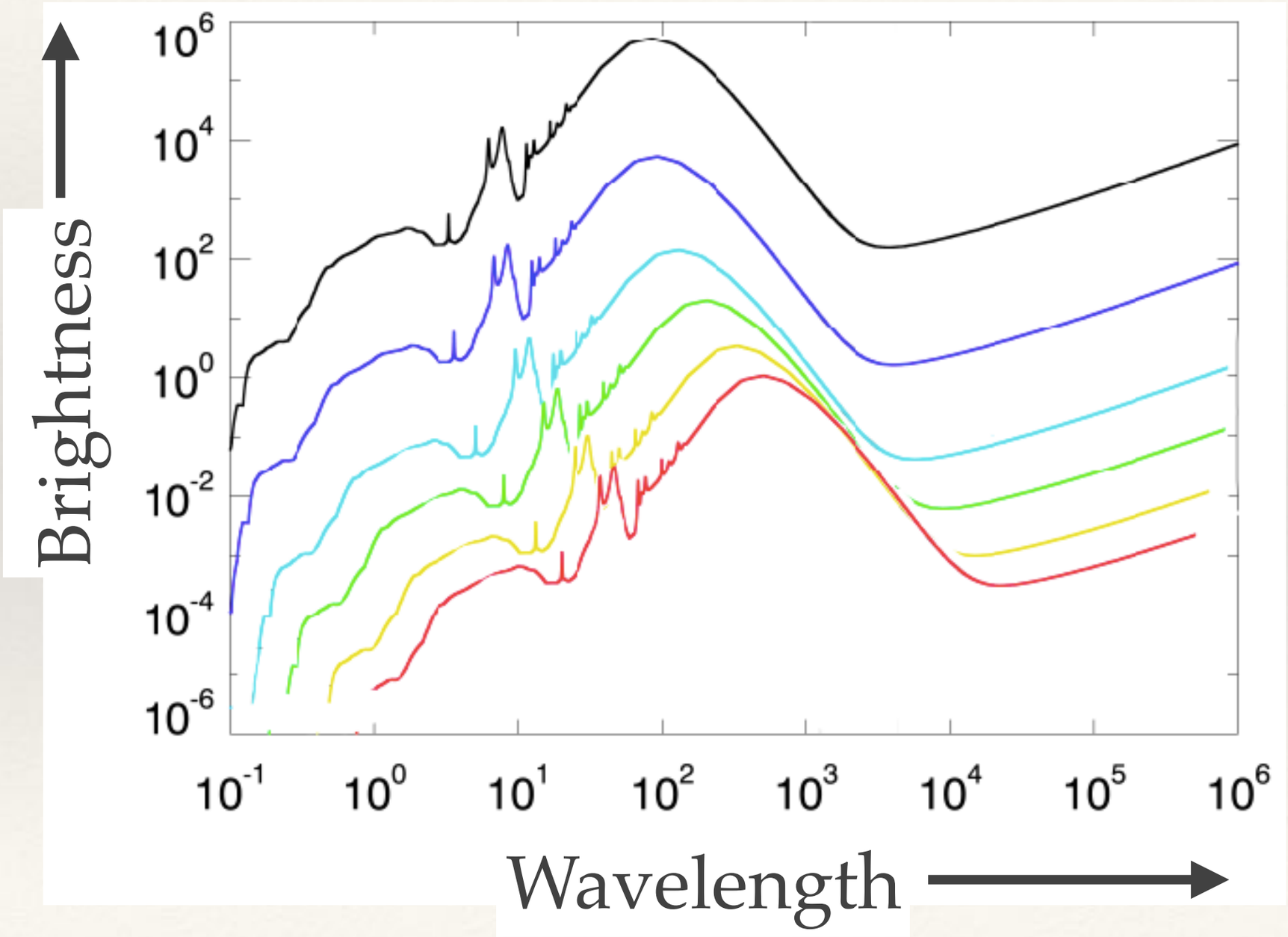


Sub-millimetre ‘magic’

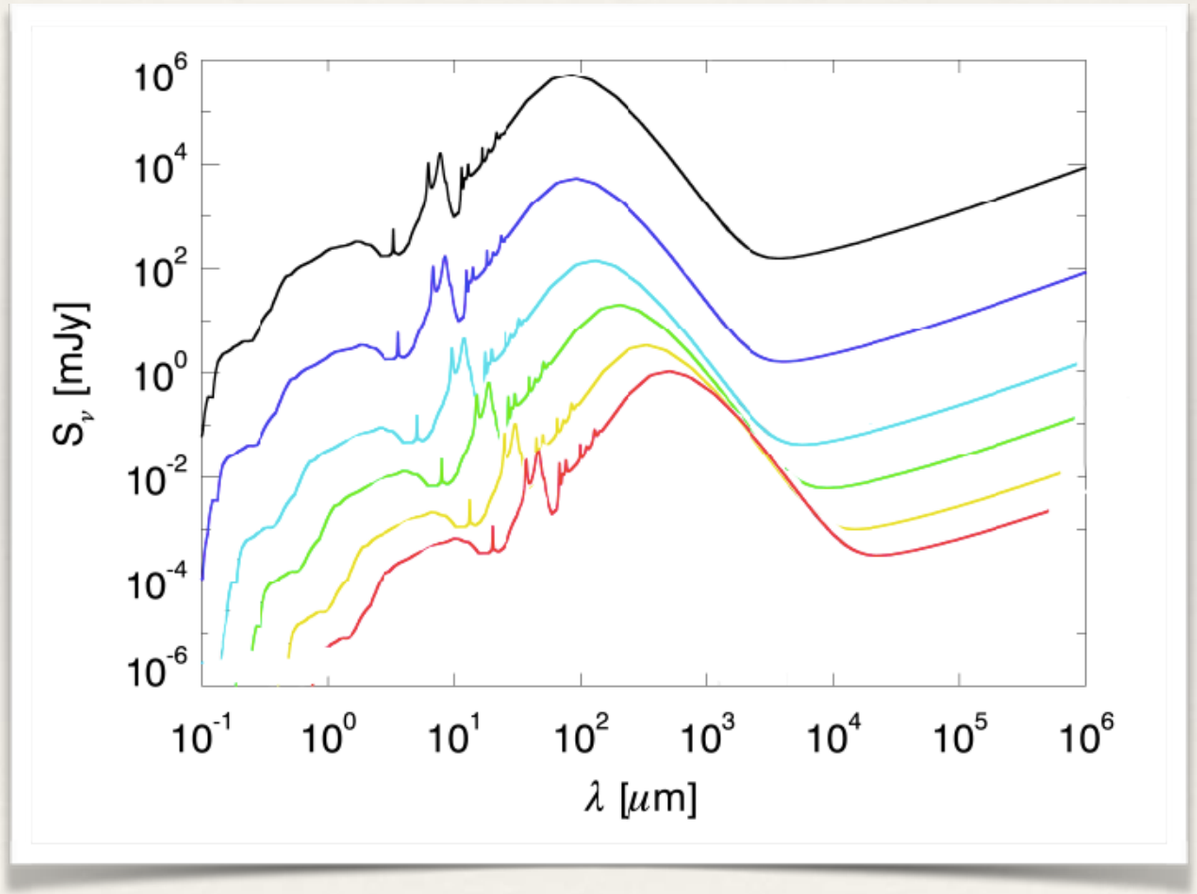


Sub-millimetre ‘magic’



Sub-millimetre ‘magic’

- Object gets dimmer with distance (of course)
- BUT, redshift moves brighter parts of the spectrum into the sub-mm band
- These two effects cancel out!



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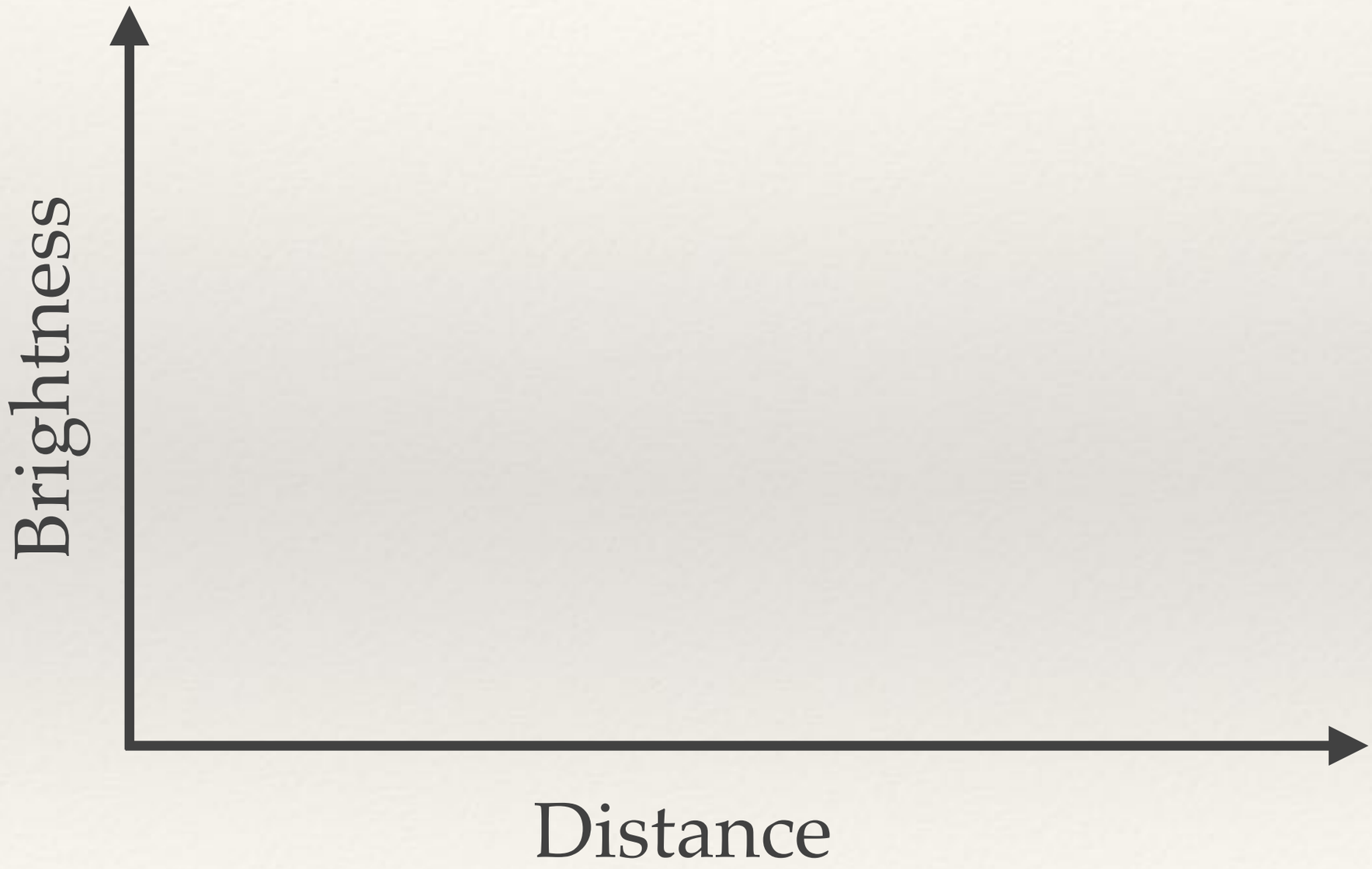

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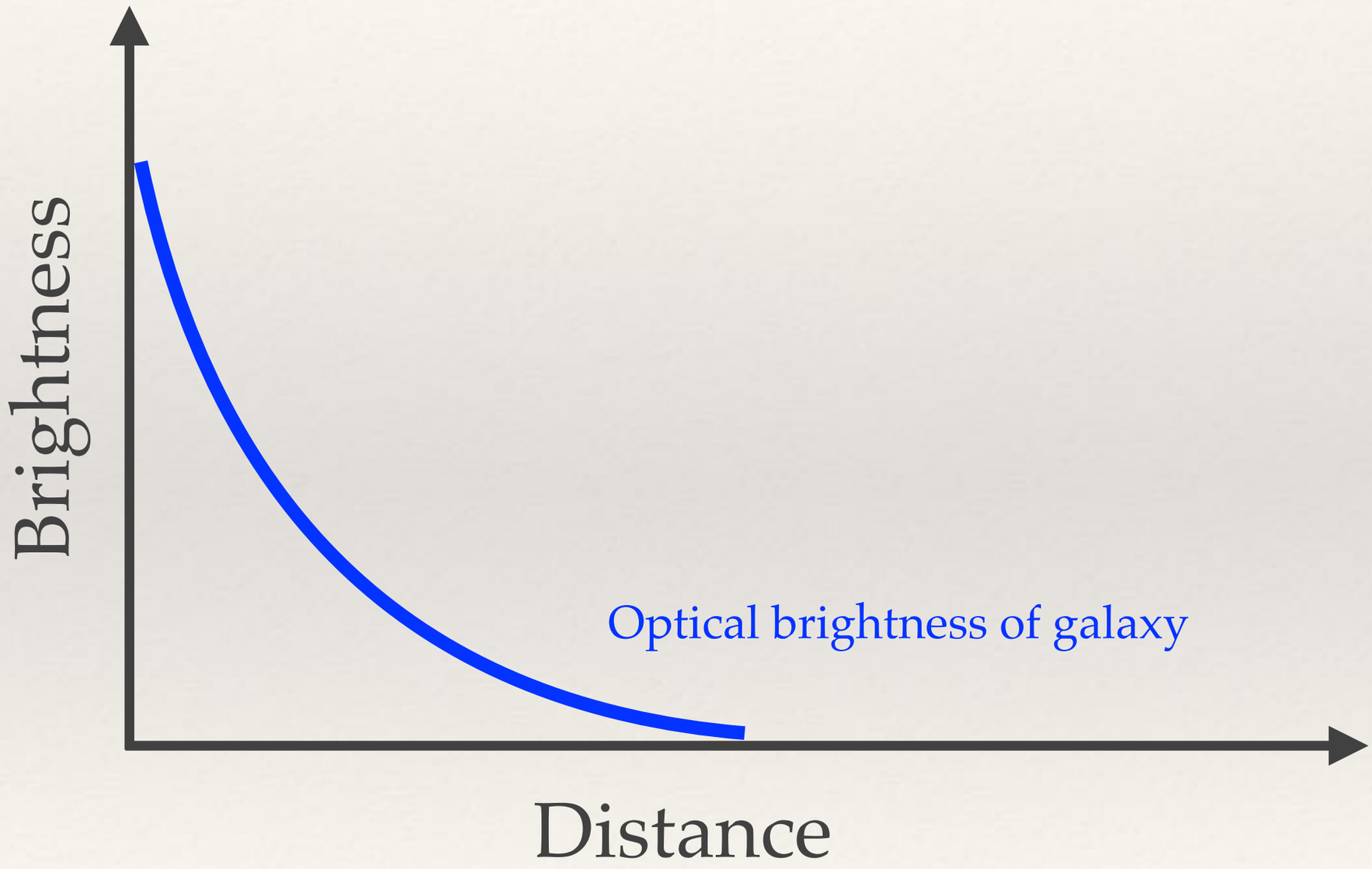

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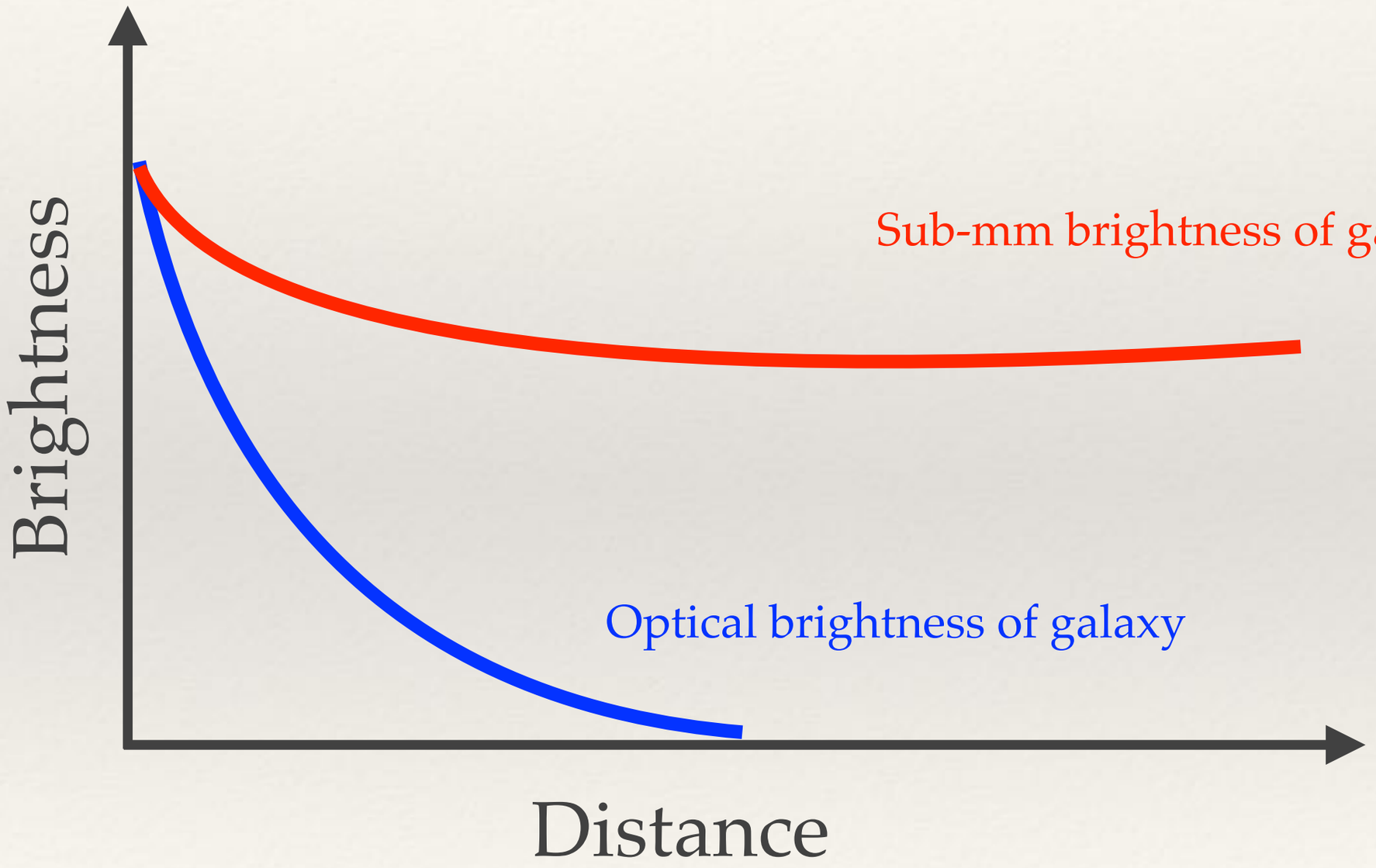
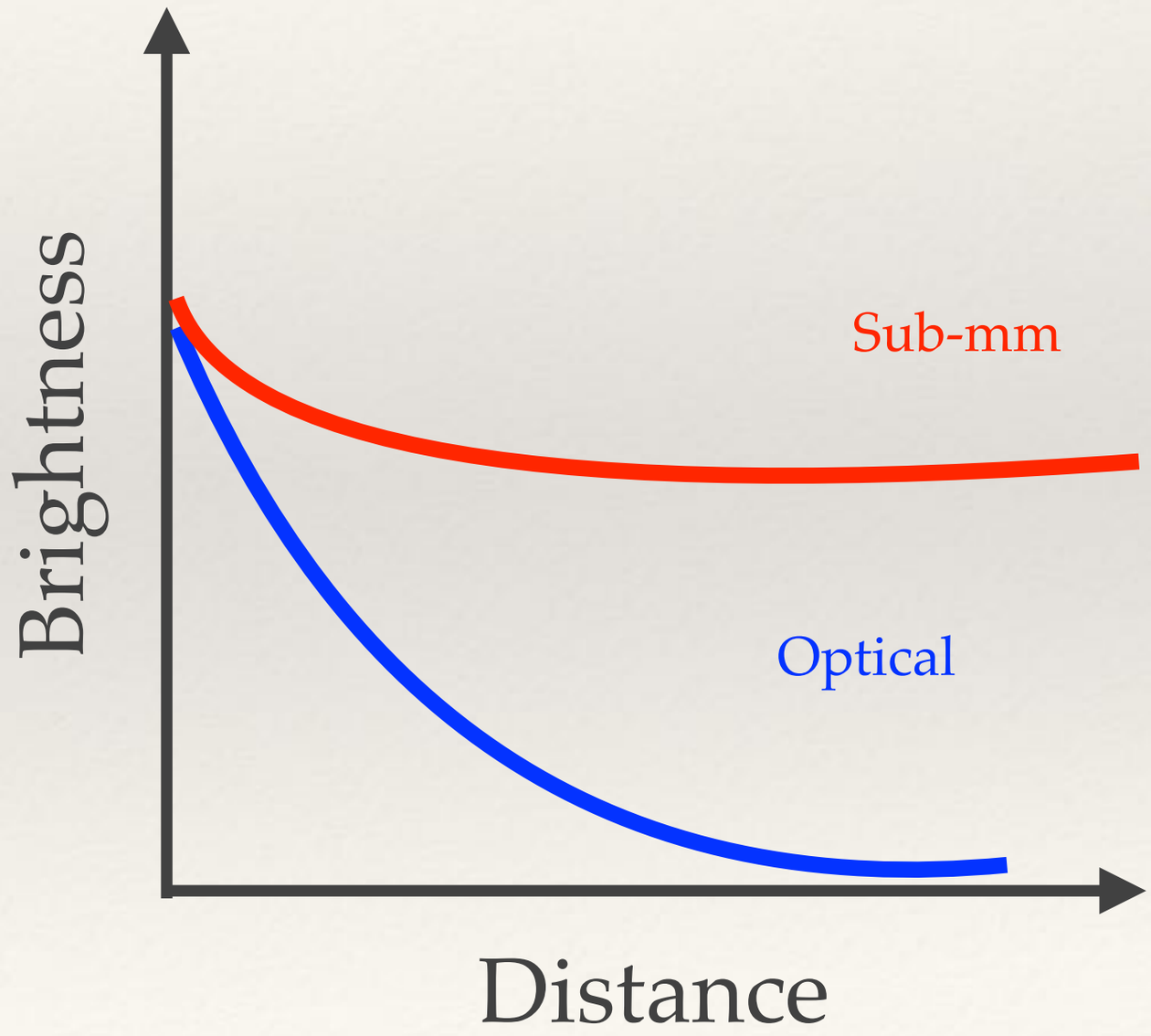


Sub-millimetre ‘magic’

- But, there’s a downside here…
- Brightness being independent of distance means we can detect galaxies out to the very early Universe
- BUT, there’s no way to tell what the distance actually is! (Sub-mm light holds no distance information)



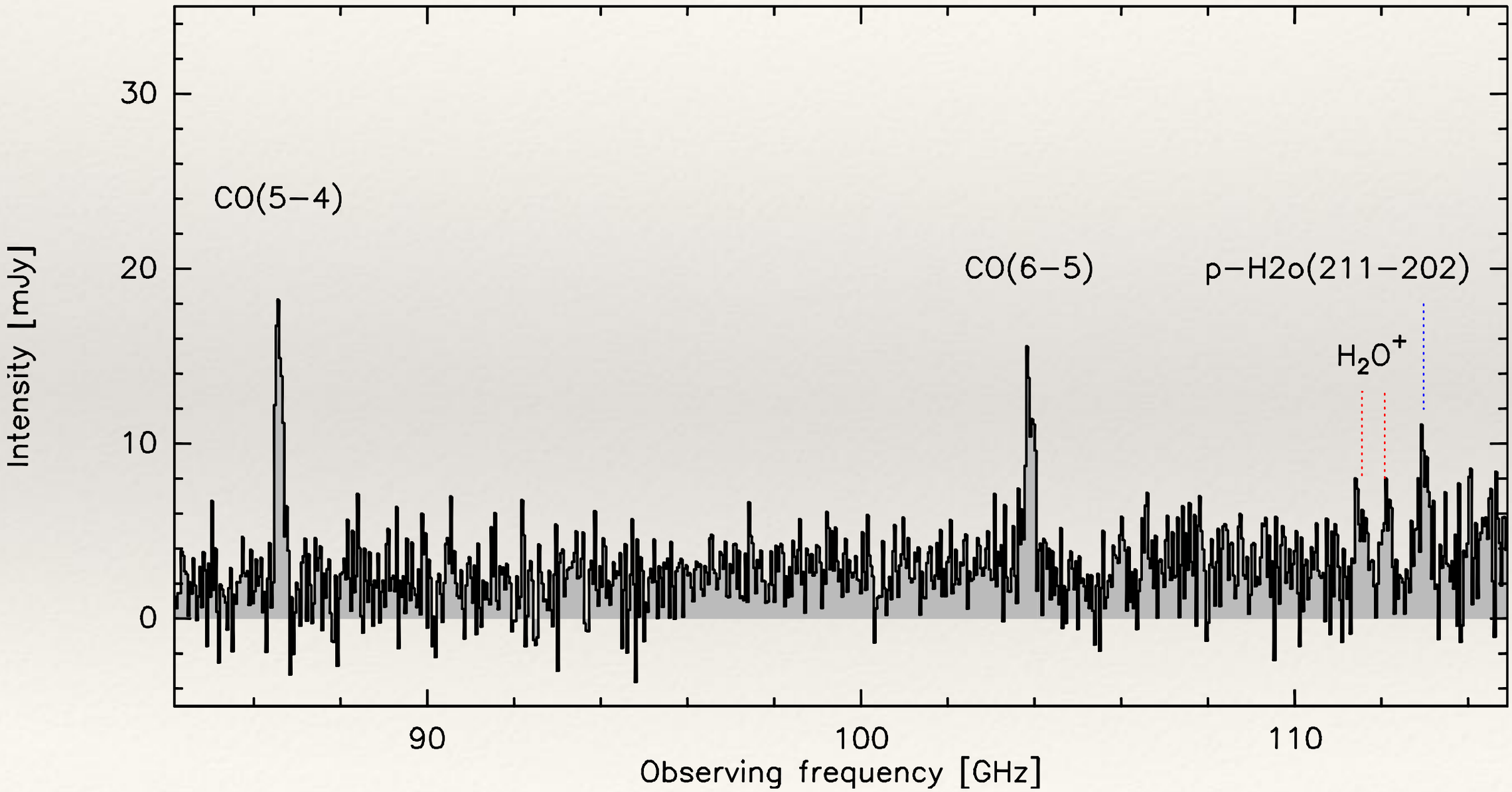
Sub-millimetre galaxies

Point ALMA at bright
sub-mm blob

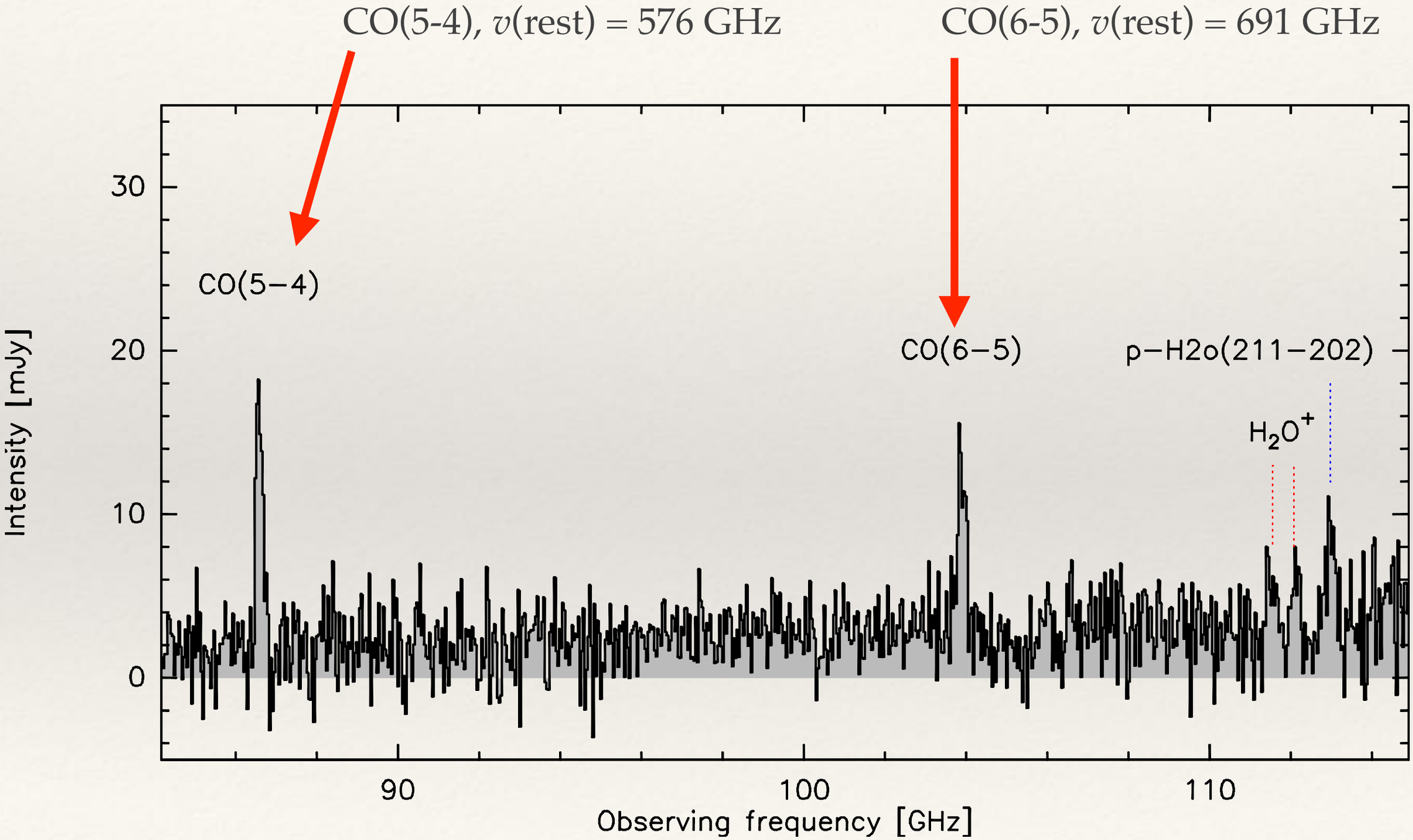
ALMA observes emission lines from molecules (like water, carbon monoxide, etc)

By measuring the frequencies of these lines, you can work out the distance

Sub-millimetre galaxies



Sub-millimetre galaxies

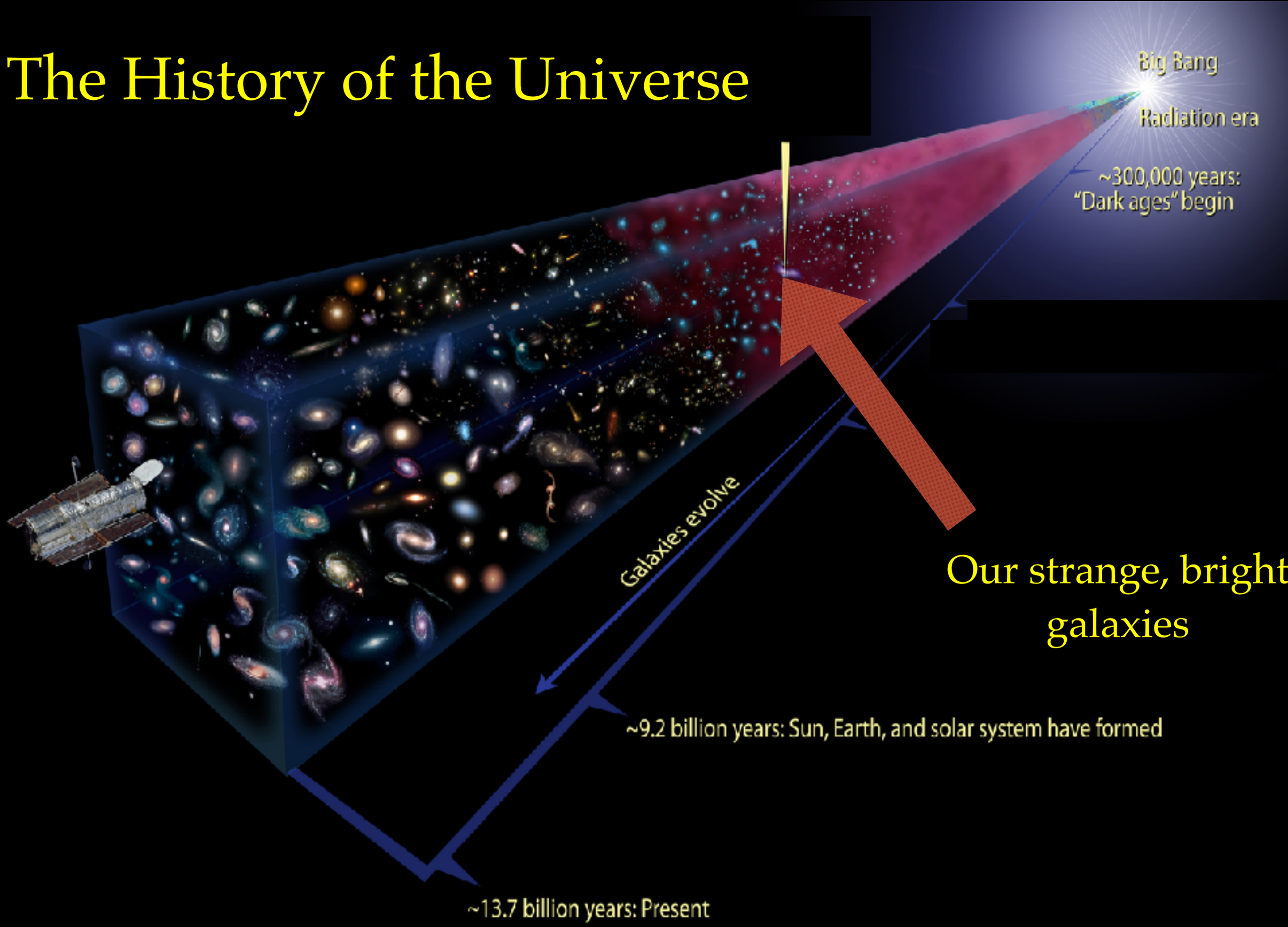


Sub-millimetre ‘magic’

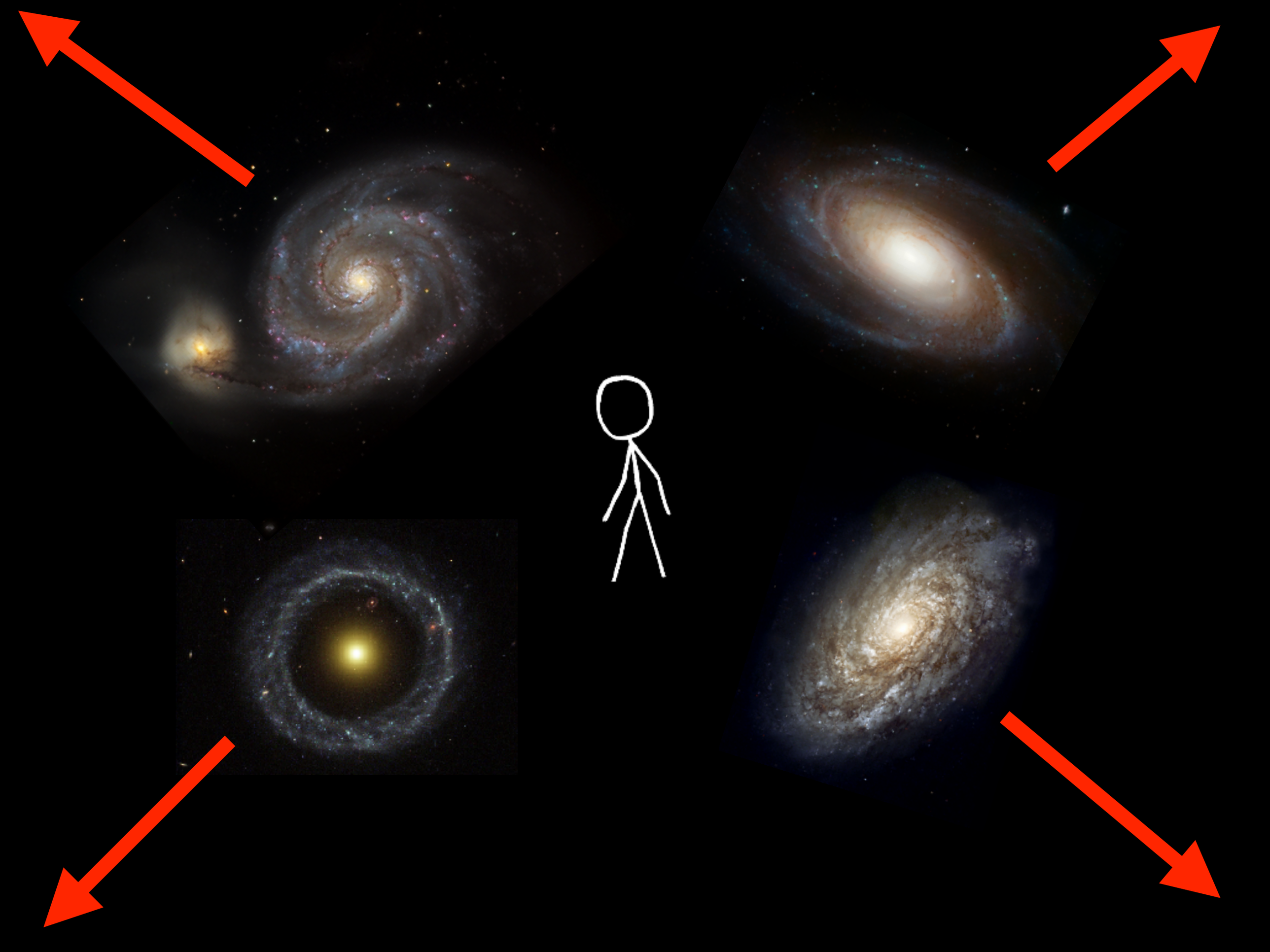
Conclusion:

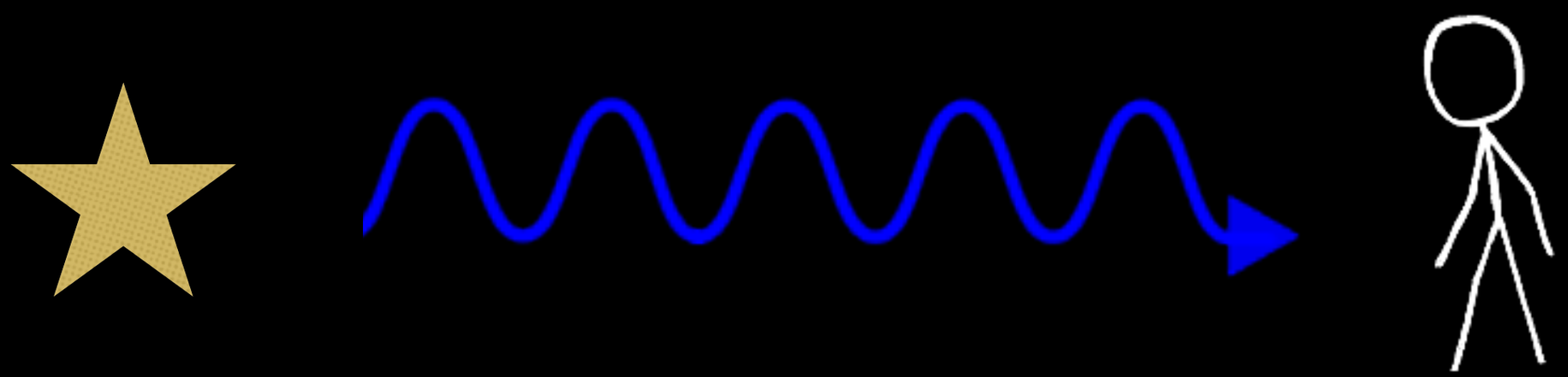
Observing at sub-mm wavelengths is a great way to discover very, very distant galaxies. They are just as bright at extreme distances as they are when `nearby’

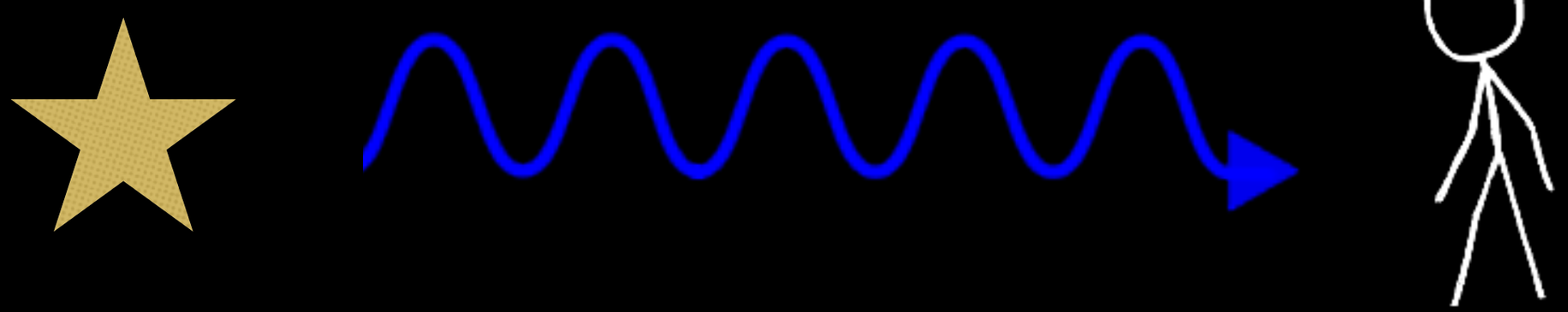
The History of the Universe

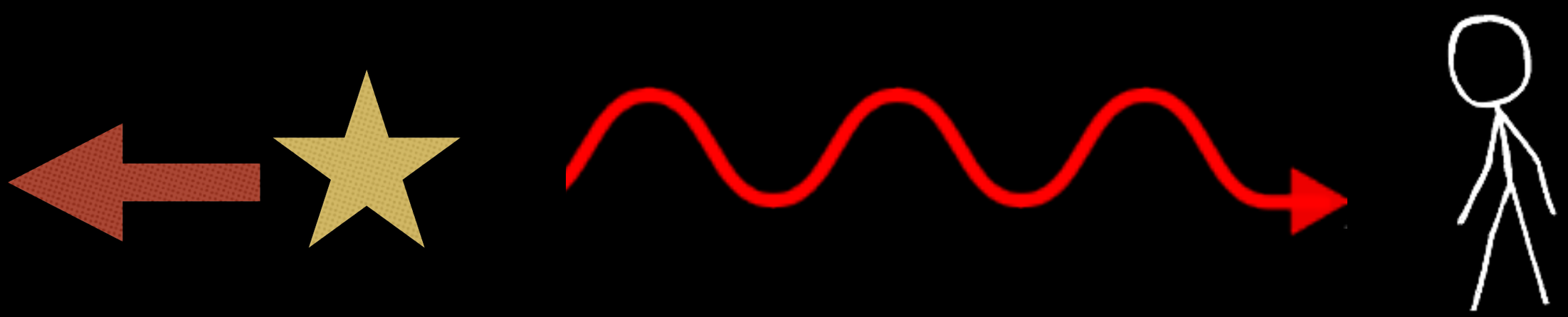


Our strange, bright galaxies









The History of the Universe

Big Bang

Today

(14 billion
years ago)

The History of the Universe

Big Bang

Earth formed

Today

(14 billion years ago)

(5 billion years ago)

The History of the Universe

Big Bang

Our ‘hidden’ galaxies

Earth formed

Today

(14 billion years ago)

(5 billion years ago)

So, what are these things?

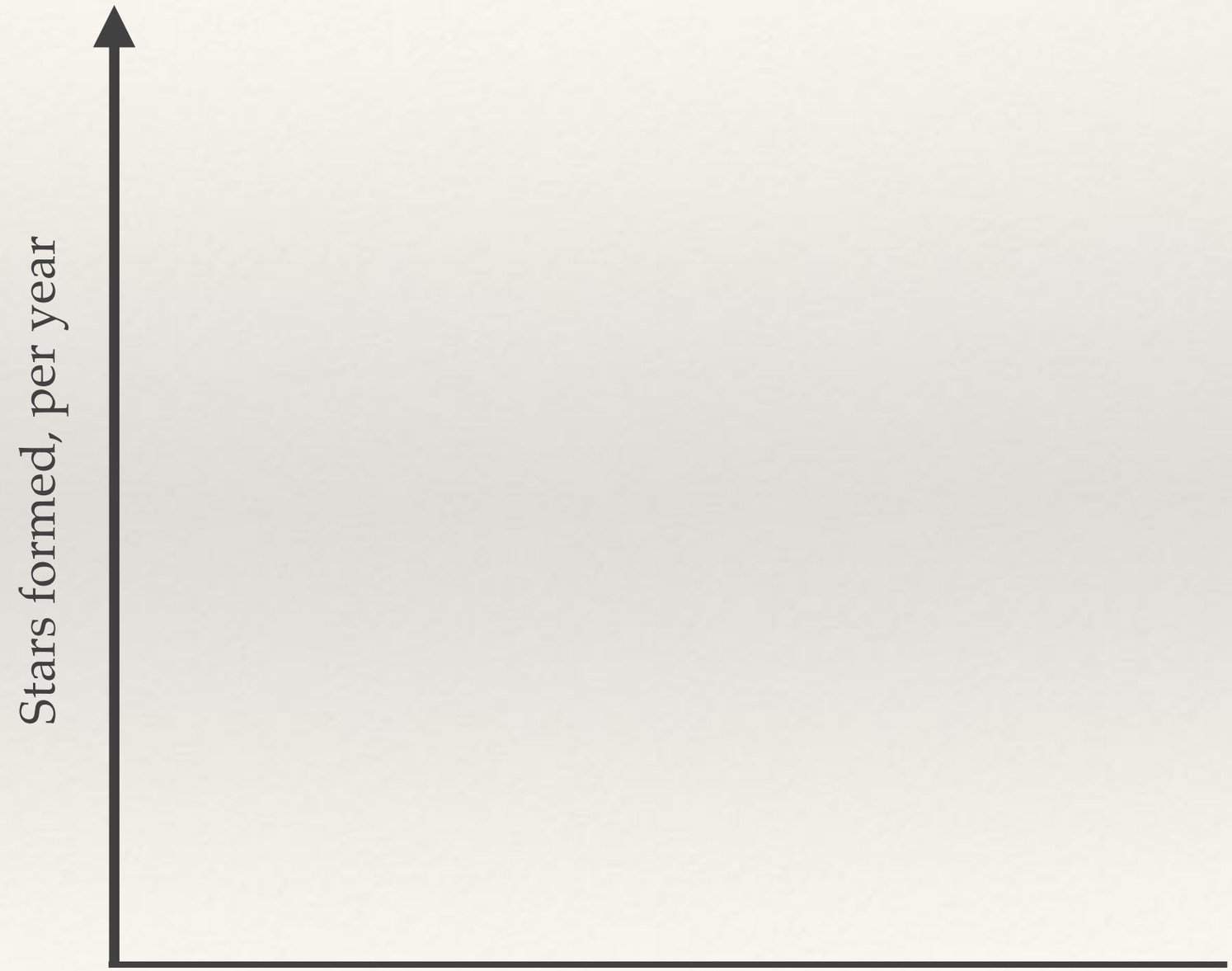
Some galaxies are emitting lots of long-wavelength light…

They are VERY distant, VERY energetic, and live only in the early Universe

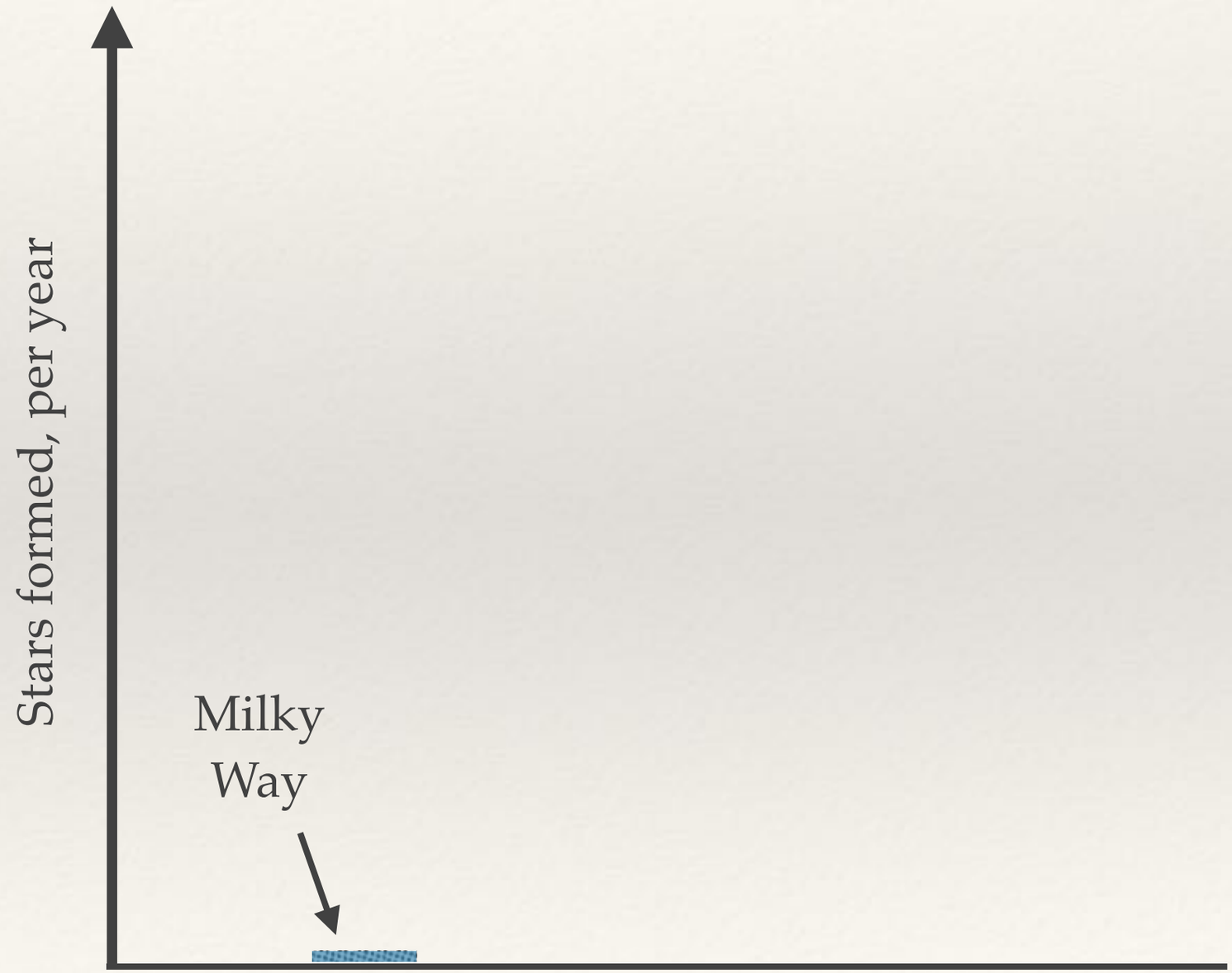
They have to be the ancestors of the massive, dead galaxies we see in today's Universe!

‘Sub-millimetre’ galaxies

How fast are SMGs growing?



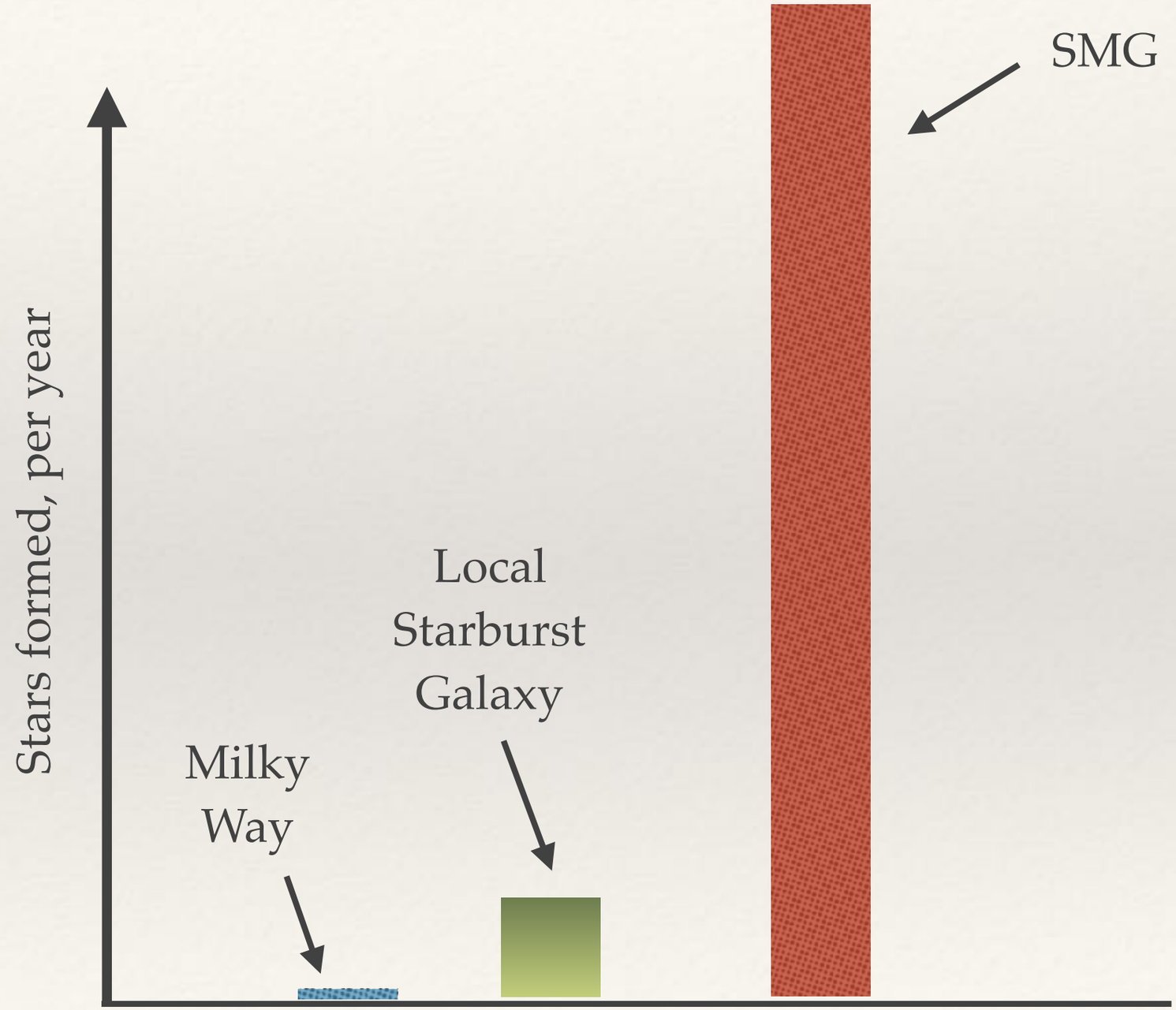
How fast are SMGs growing?



How fast are SMGs growing?

How fast are SMGs growing?

- SMGs form stars at a rate of THOUSANDS every year
- Biggest growth spurt in the Universe!



SMGs are a problem for astronomers

- The existence of SMGs causes a real problem for galaxy formation theories.
- **How do you get a galaxy to form stars that fast?!**

Fuelling extreme star formation

A really high star formation rate must mean LOTS of gas (fuel for stars forming)

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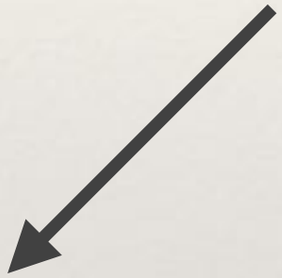
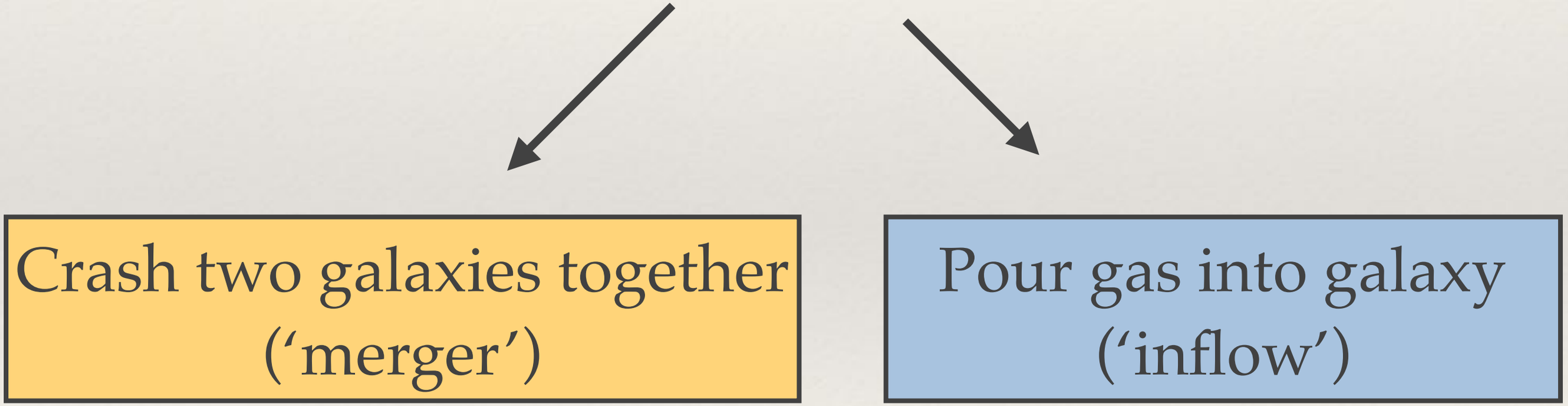


Crash two galaxies together (‘merger’)

Fuelling extreme star formation

A really high star formation rate must mean LOTS of gas (fuel for stars forming)



Fuelling extreme star formation

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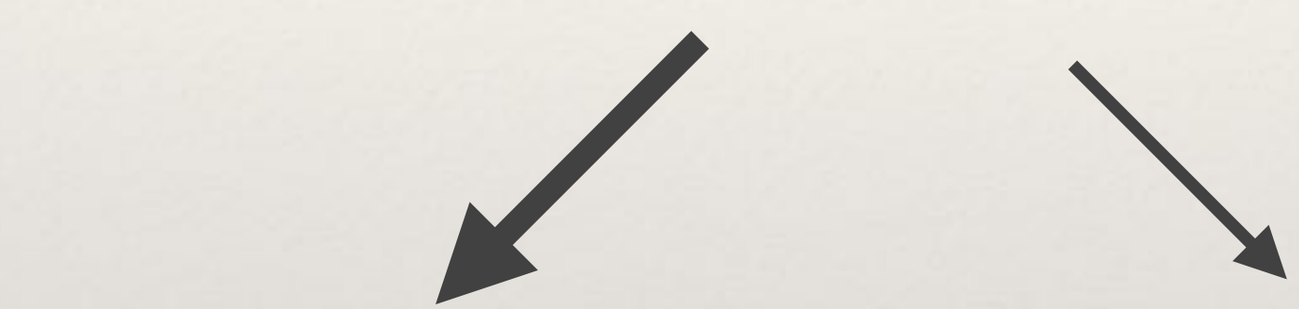
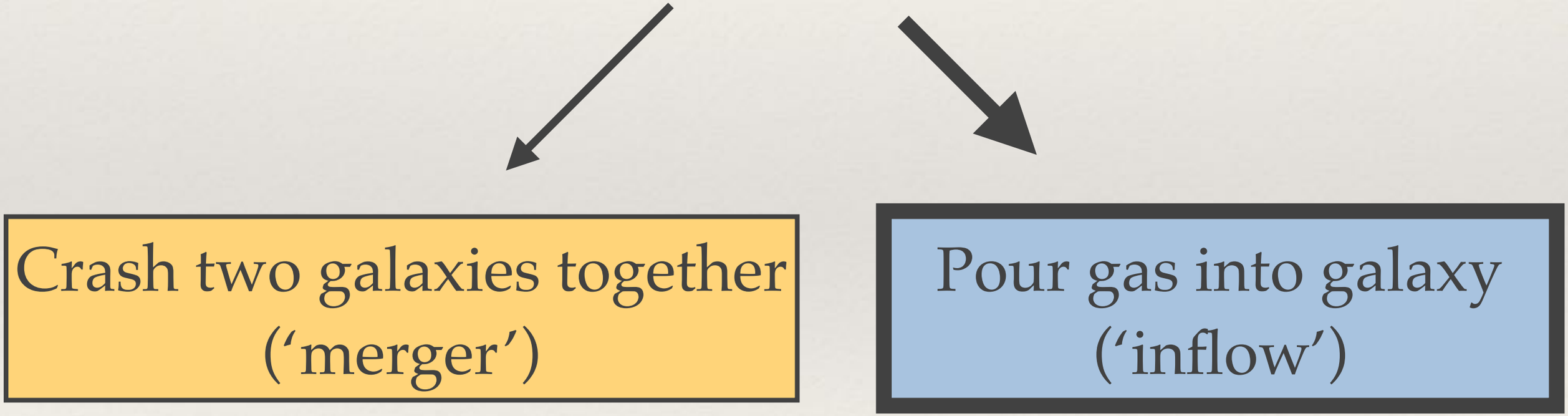


Crash two galaxies together ('merger')

Pour gas into galaxy ('inflow')

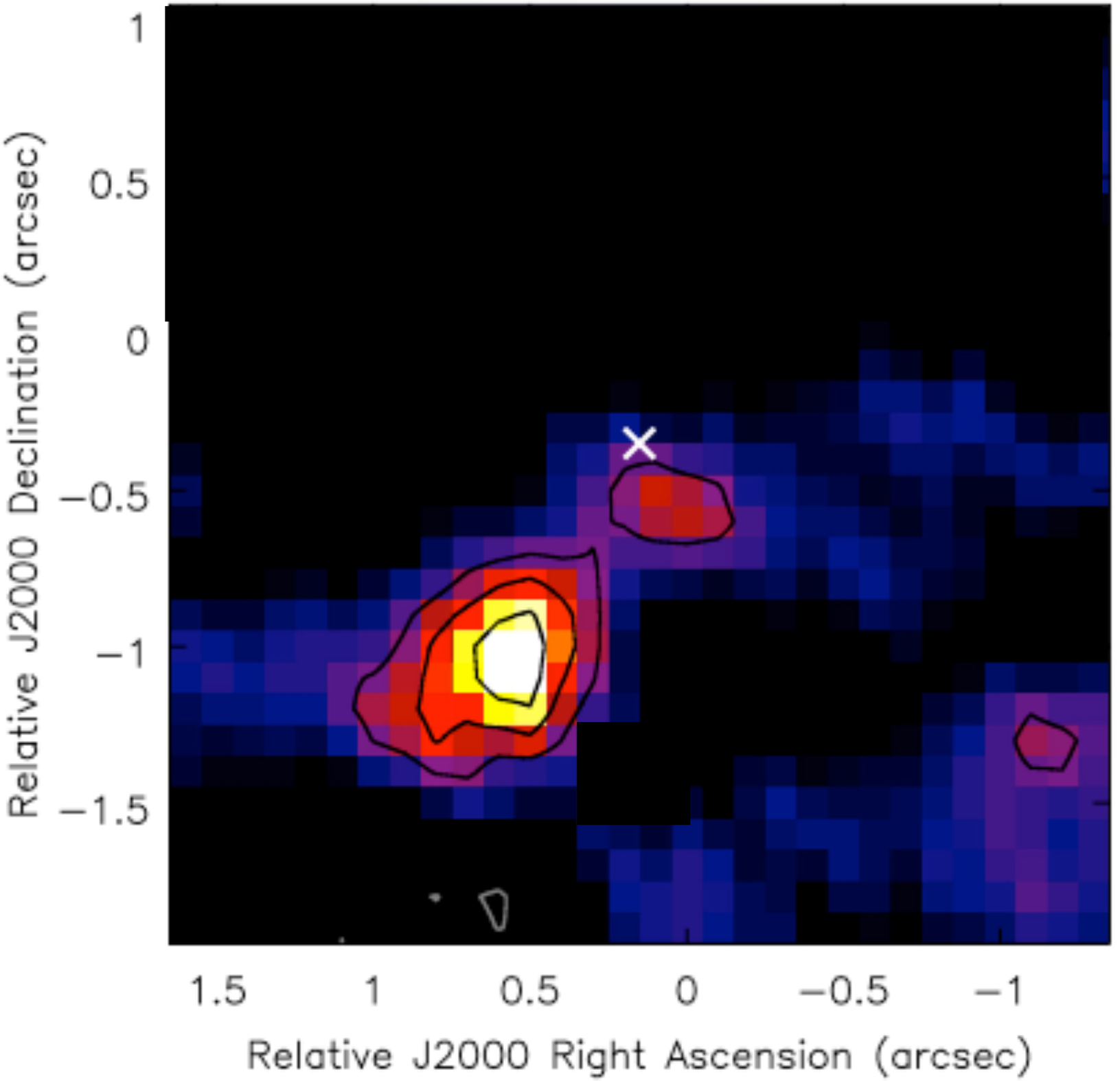
Fuelling extreme star formation

A really high star formation rate must mean LOTS of gas (fuel for stars forming)



SMGs are a problem for astronomers

- The existence of SMGs causes a real problem for galaxy formation theories.
- **How do you get a galaxy to form stars that fast?!**
- The problem is caused by how hard it is to see SMGs. Currently our best actual image of an SMG looks a bit like this…


1
0.5
0
−0.5
−1
−1.5
Relative J2000 Declination (arcsec)
1.5
1
0.5
0
−0.5
−1
Relative J2000 Right Ascension (arcsec)

Molecules in the Universe

Many molecules have emit lines in the sub-millimetre…

This allows us to trace *molecular gas*

Atomic hydrogen (HI), traced via the 21cm line is fuel for FUTURE star formation…

Molecular hydrogen, observed in the sub-millimetre, is the gas that is CURRENTLY forming stars

Observing molecules

- Molecular hydrogen (H2) is the medium in which stars form
- But, H2 is a symmetric molecule… it has no electric dipole moment
- So, how do we observe molecular hydrogen??

Observing molecules

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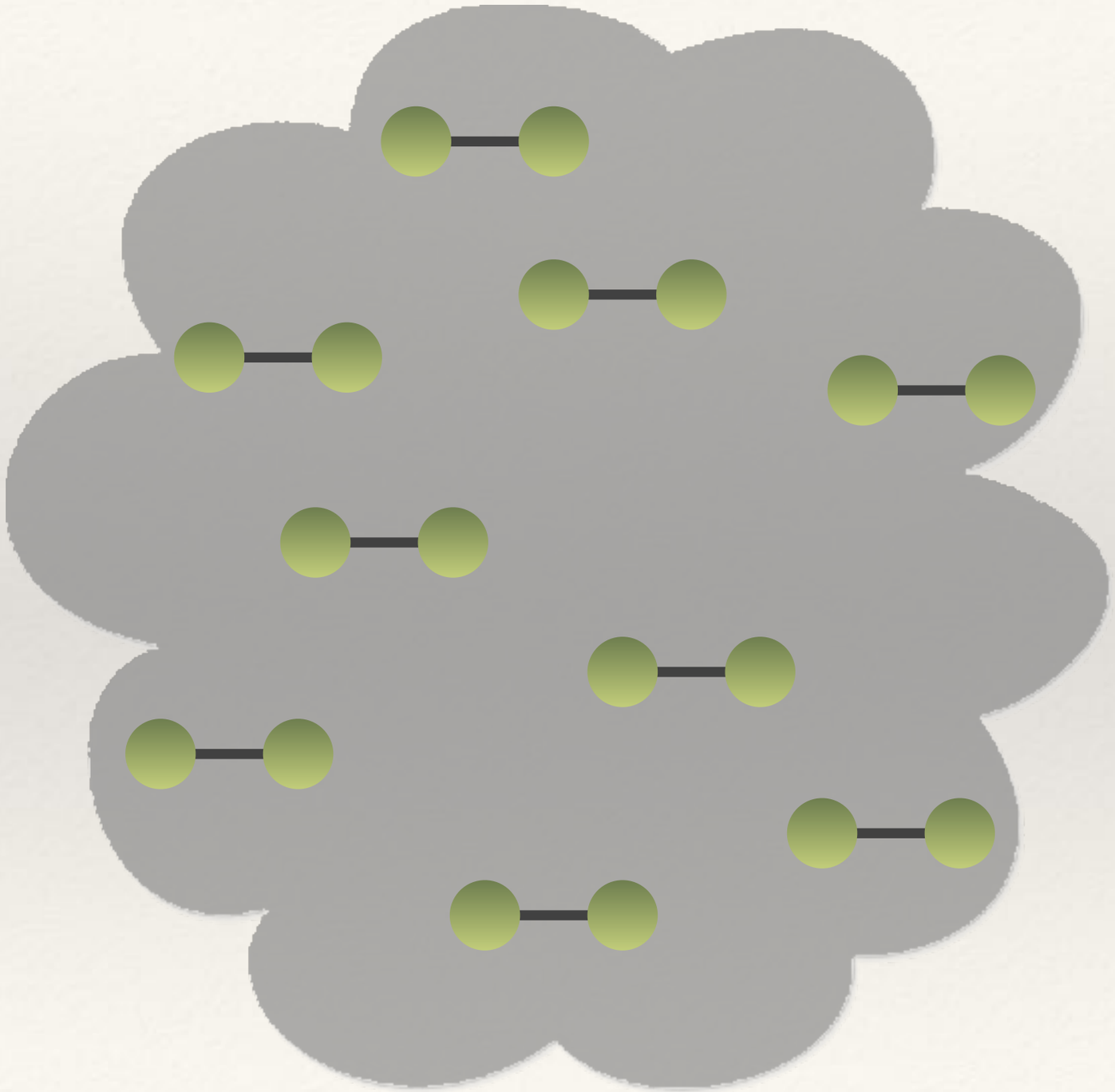
- But, H2 is a symmetric molecule… it has no electric dipole moment
- So, how do we observe molecular hydrogen??

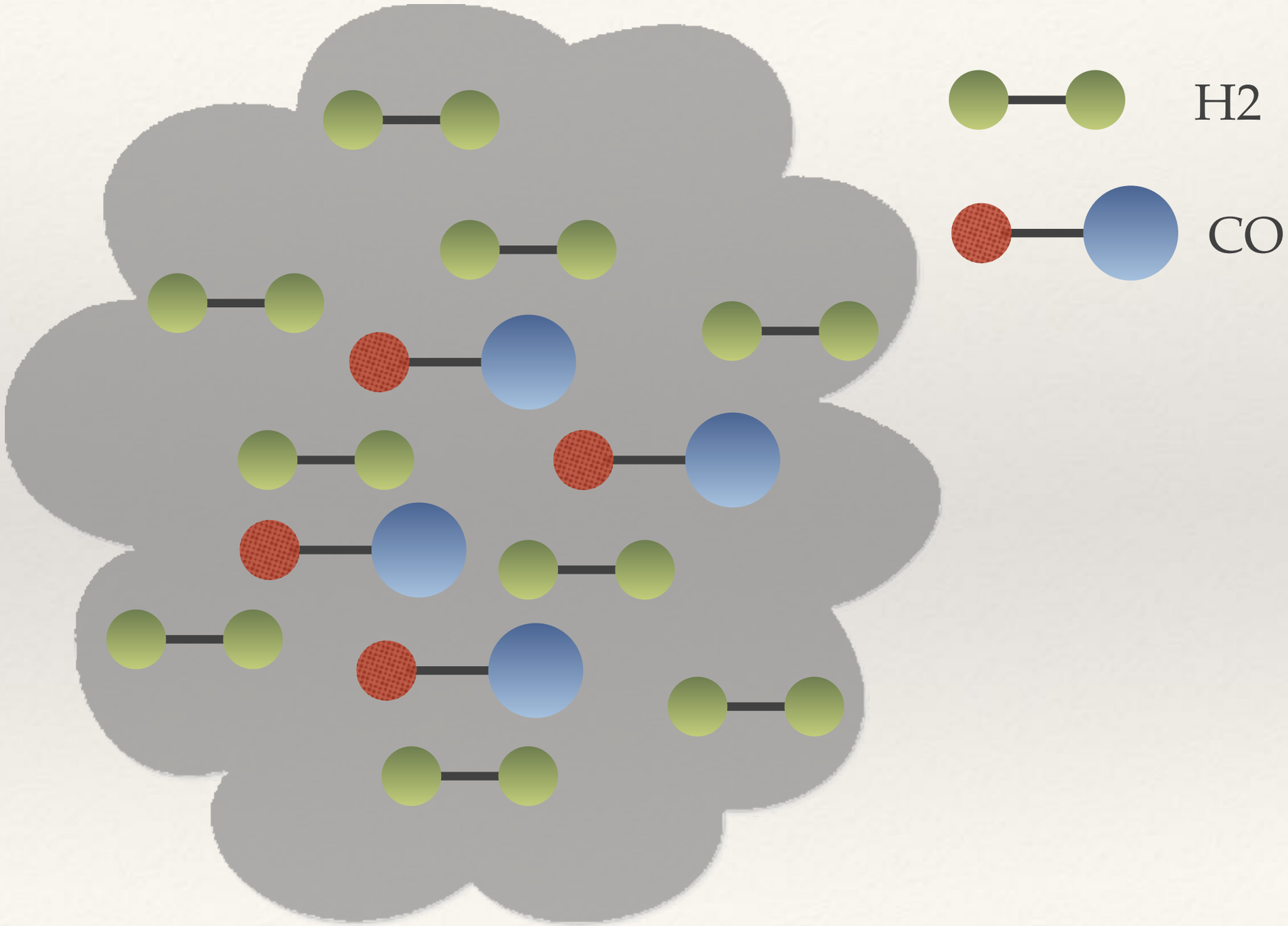
Answer: use a visible ‘tracer’ molecule.

Observing molecules

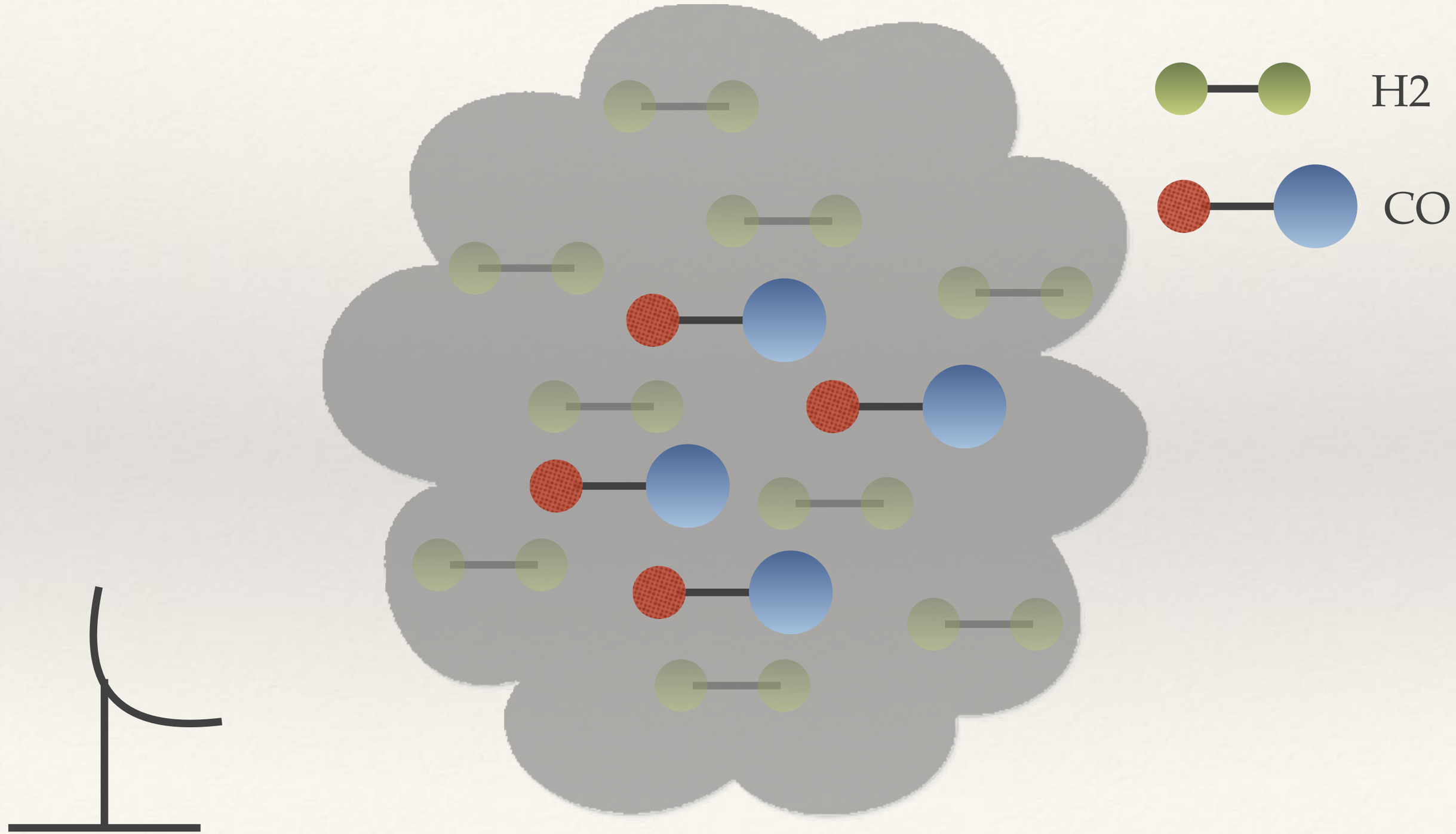


H2

Observing molecules



Observing molecules



Observing molecules

- CO is the most abundant molecule in the Universe
- CO emits emission lines at multiples of 115 GHz (i.e., 115 GHz, 230 GHz, 345 GHz)
- These are right in the ‘sub’-millimetre band (~3mm, ~2mm, ~1mm)