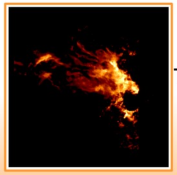

The multiscale interstellar medium
from massive molecular clouds to cold cores

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Lectio Praecursoria
30.1.2026

-

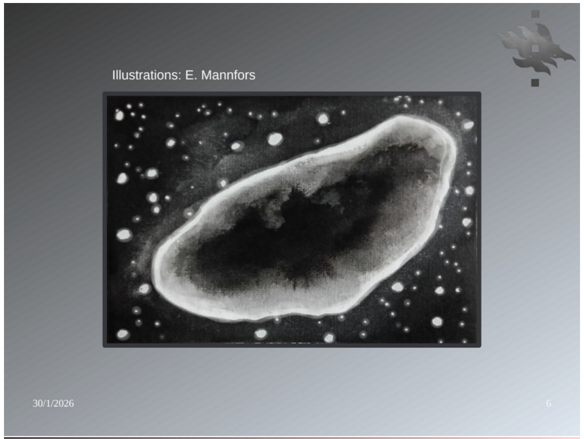
Units

- 1 parsec (pc)
  = 3.26 lightyears
  = 3.09 x 10^{16} m
  (1 billion = 10^{9})
- 0 K = -273.15 °C

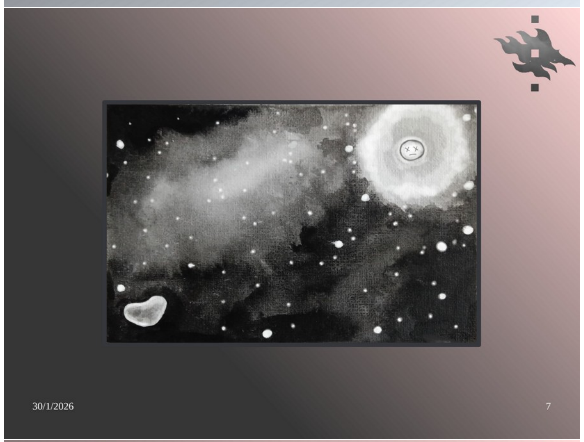
- A few common units I may use in this lektio. A parsec is a measure of length. It is about 3.26 lightyears, or well over a billion kilometers
- Kelvin are used in science to describe temperature. At zero Kelvin, atoms should theoretically stop all movement. This is equal to about -273 Celsius.

ISM = Interstellar medium
= Tähtienvälinen aine
(= space clouds)

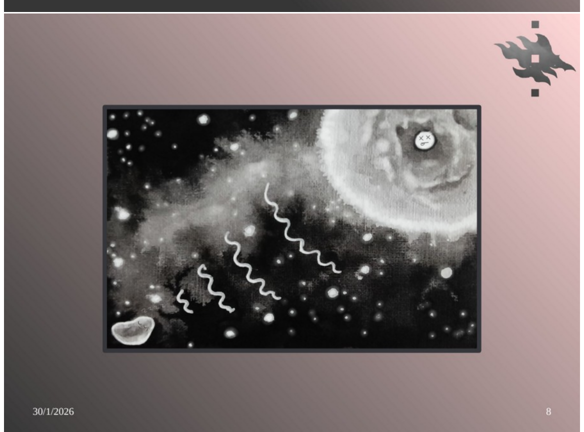
- I will try to avoid using acronyms in this lektio. However, I will likely use the term ISM, which stands for the interstellar medium. A.k.a. all the baryonic matter inside galaxies, which are not in stars or solid bodies.



I will begin with a short story.
- Once upon a time there was a lonely space cloud.

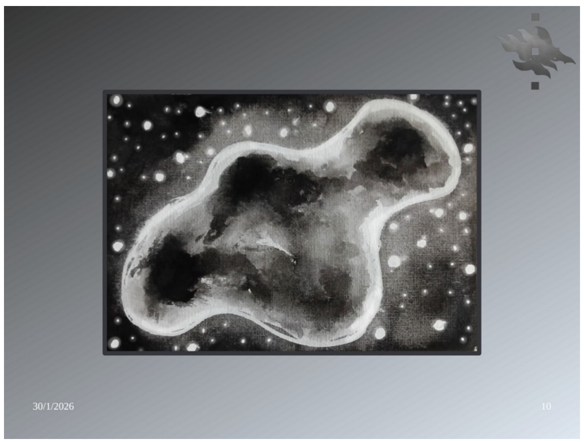


- One day, a nearby supernova said “let there be turbulence.”

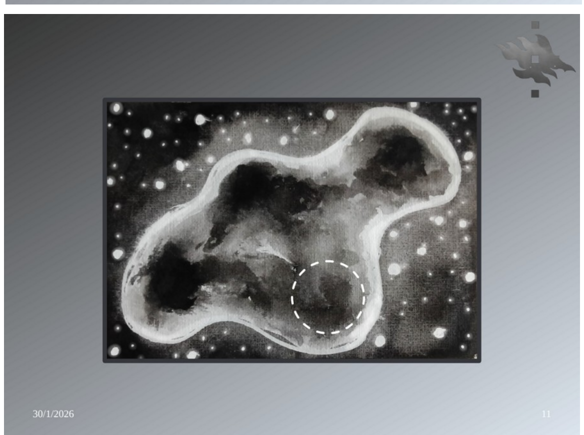


- And there was. The shock waves traveled through space….

- ...finally reaching the cloud. The atoms inside the cloud began to tumble around.

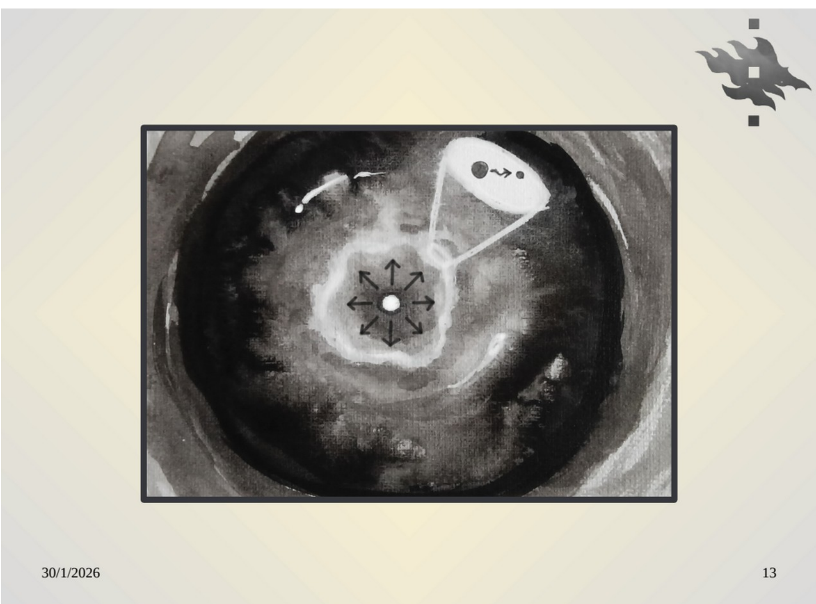


- The cloud began fragmenting, forming small, dense clumps.



- Inside one of these clumps...

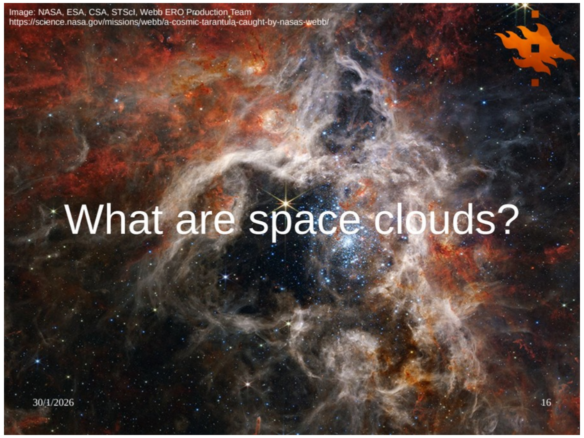
- ….a star began to form. Matter from the surrounding cloud flowed onto the region. The core became thicker and hotter until eventually, a star was born.



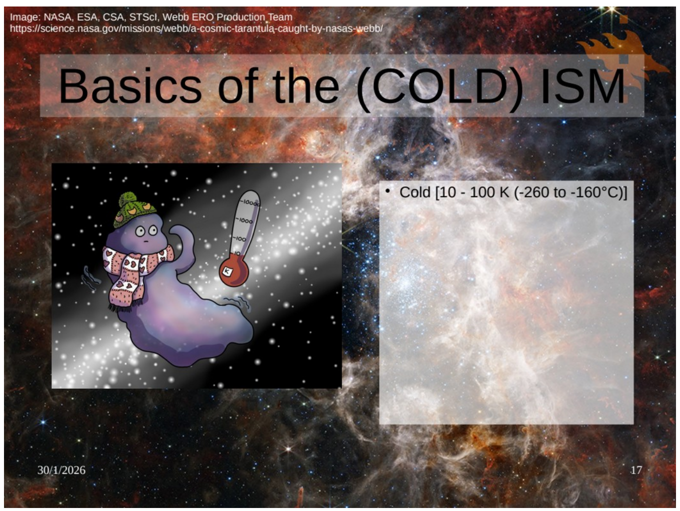
- The star began to blow away the gas surrounding it. In a disk around the star, baby planets were forming….

- Many years later, the cloud had begun fading away. In its place, were a hundred young stars.

- This story presented a very oversimplified picture of star formation. While every phase is connected, my thesis focuses more on core scales and larger, and on the earlier stages of star formation (i.e. the first three pictures).

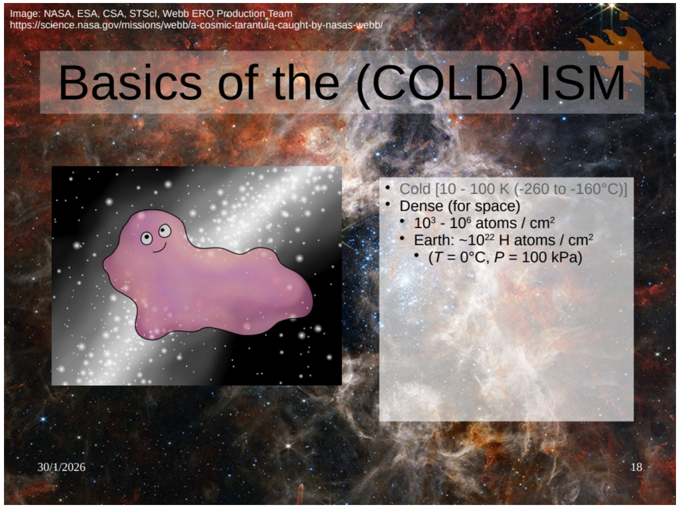


- So what exactly are clouds in space? Out galaxy (and the universe) are filled with gas in many forms, from extremely hot, ionized gas to the topic of my thesis, the cold ISM.

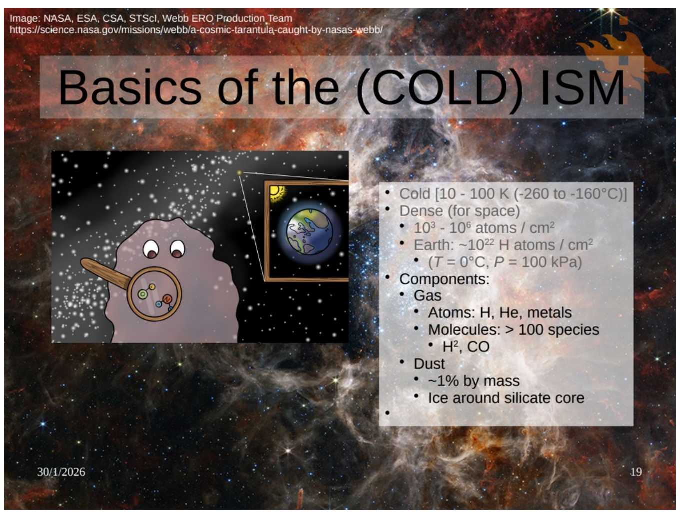


- The cold ISM is cold(*), around 10-100 K.

(*) Spoiler alert

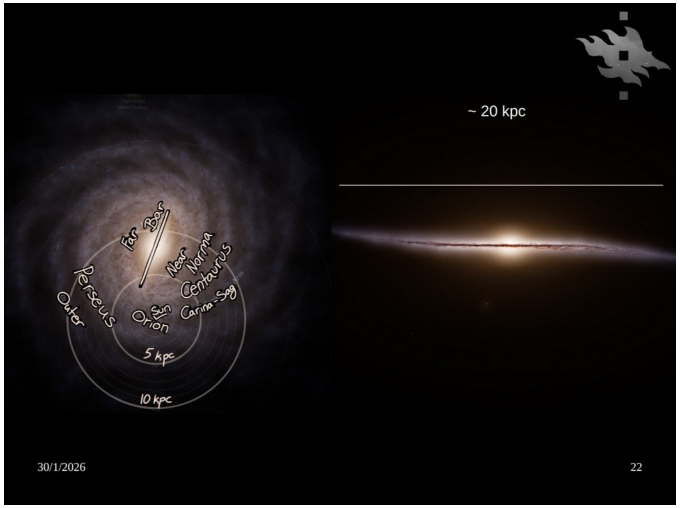


- It is also dense, when compared to the rest of space. Interstellar radiation heats matter. Thus, a higher density is needed for cold gas since the gas protects itself from this heating radiation.

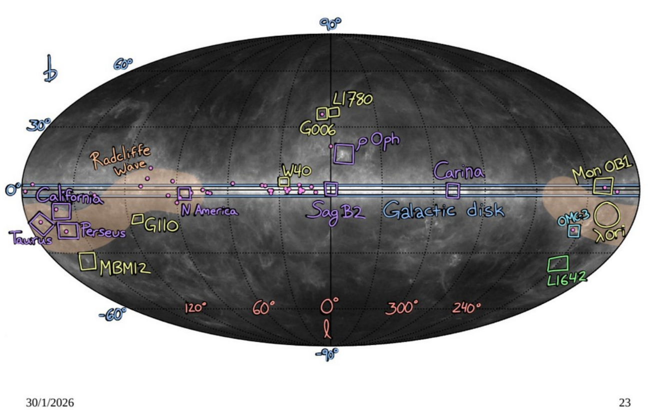


- Molecules and atoms can split up when exposed to radiation. Gas in most of the galaxy is ionized or atomic, and only in the densest gas can molecules form. Hundreds of large molecules have been observed in the cold ISM.
- Around 1% of the cold ISM is made of dust, which are composed of ice around a silicate core.

- Scales page :D

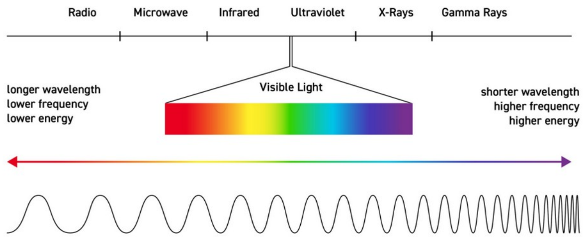


- We live in the Milky Way galaxy. As you can see by this image, it is quite pancake-shaped.
- The Milky Way consists of stars, a central black hole, but also a large amount of cold molecular gas shown by the dark lines on the right-hand figure. While older stars are located around the galaxy, the cold gas and young stars are mostly located within the galaxy’s spiral arms.
- The Sun is here. Most of the regions studied in this thesis are within 1 kpc of the Sun, i.e. within this circle.



- This image shows the plane-of-the-sky locations of the fields studied in this thesis. We can see that most of the clouds are located in the Galactic plane.

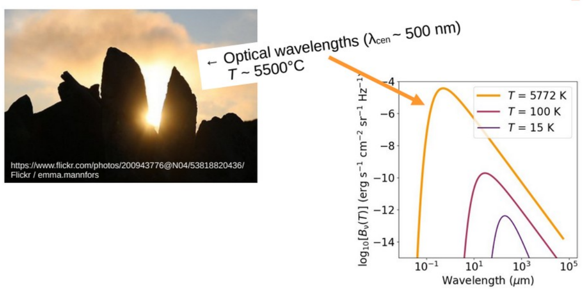
Wavelengths



https://www.nist.gov/sites/default/files/images/2025/03/28/Wavelength-spectroscopy.png

- Light can be described as a wave. The only difference between x-rays, radio waves, or visible light is the wavelength.

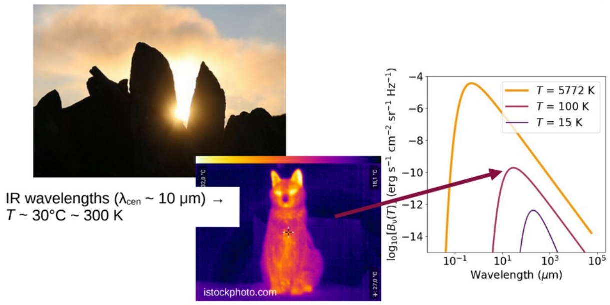
Blackbody spectrum



λ = wavelength; T = temperature

- There is a concept of blackbody radiation. Very simplified, it states that an object’s radiation is described only by its temperature.
– The Sun, at around 5500 Celsius, has a peak in radiation at around 500 nm (i.e. green light).
- Fun fact: the human eye is most sensitive to light at around 500 nm.

Blackbody spectrum



λ = wavelength; T = temperature

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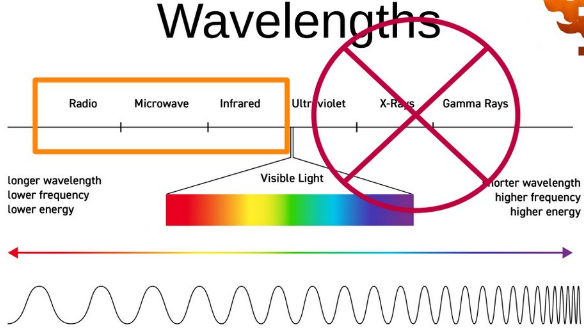
- In contrast, the radiation of a cooler object peaks in longer wavelengths. For example, a body at 30-40 Celsius radiates in the infrared. This is why thermal cameras are used to find missing people.
- You can also see how a cooler temperature leads to a lower level of radiation overall.
- Now if we remember that the temperature of the cold ISM is below 100 K….

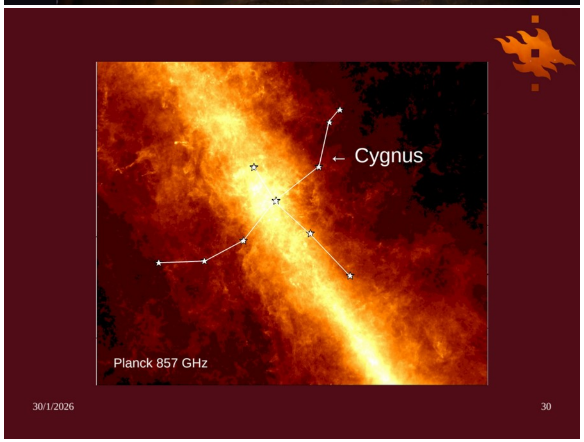
Wavelengths



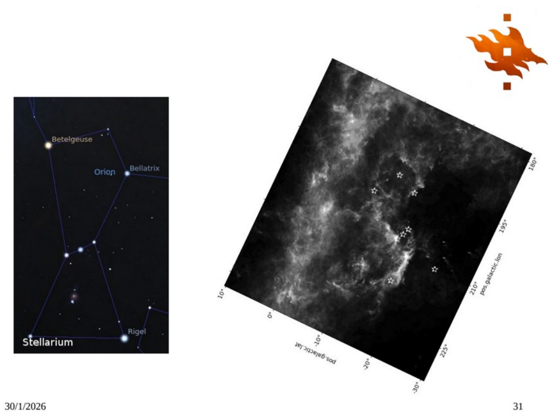
https://www.nist.gov/sites/default/files/images/2025/03/28/Wavelength-spectroscopy.png

- … we can see that the ISM radiates in infrared and longer wavelengths.
- Shorter wavelengths *can* be used to study the ISM, and hot young stars emit x-rays and UV radiation as well. However, this thesis focuses on radio wavelengths.

- This is illustrated by the following picture, which I took in Svalbard a few years ago.
- You can see a few stars (as well as the SunRiseSet).
- I have marked the constellations of the Swan, who flies along the Milky Way galactic plane.



- If we were able to observe the same view in the infrared, the picture would be very different.
- The cold gas of the Milky Way is vibrant in this Planck 300 um picture.



- A similar phenomenon can be seen in Orion.

Telescopes

Resolution → $\theta = \frac{\lambda}{D}$ ← $\frac{\text{Wavelength}}{\text{Diameter of dish}}$

Longer wavelength
=> lower resolution

Larger dish
=> higher resolution

Illustrations: E.M.

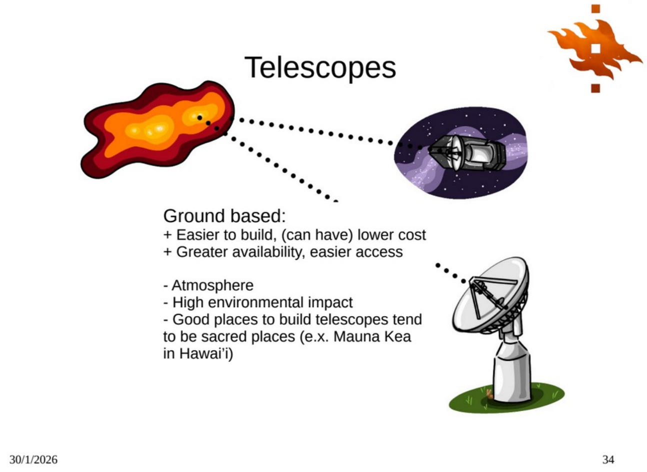
Telescopes

Space based:
+ No atmosphere
+ Less light pollution

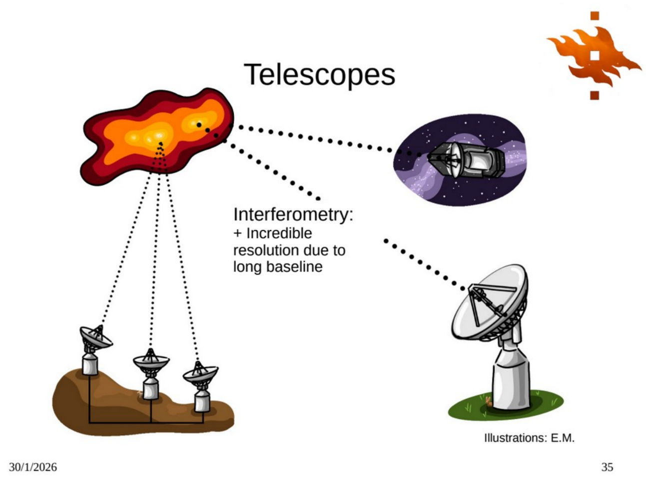
- Expensive
- High-risk & difficult or impossible repairs
- High environmental impact of launches
- Space weather, micrometeorites, etc.
- Size limit

- We use telescopes to observe the night (or day) sky.
- One important factor of a telescope is its resolution: the smallest details that can be resolved with the instrument.
- The resolution is dependent on the wavelength of the light being observed, as well as on the size of the telescope dish.
- A telescope of the same size has a better resolution in visible light than in infrared.
- Likewise, a larger dish is needed to increase resolution.

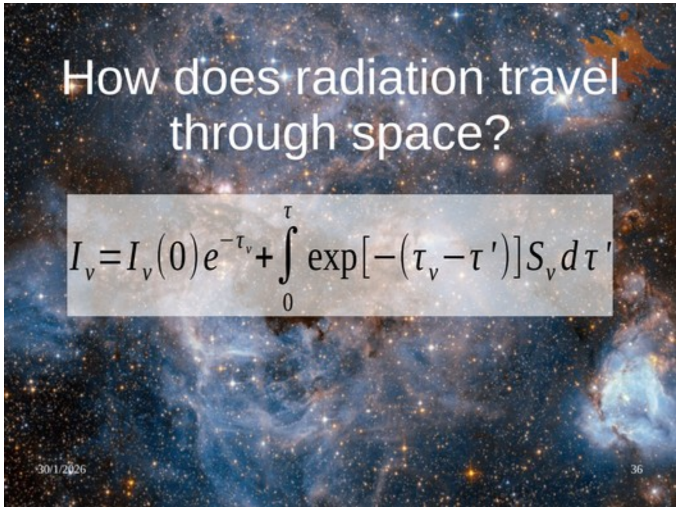
- There are many types of telescopes.
- Space telescopes are ideal as the atmosphere is a major cause of error in observations.
- However, space telescope launches are risky, with repairs difficult or impossible.
- If the JWST had an issue, it would have been unusable.



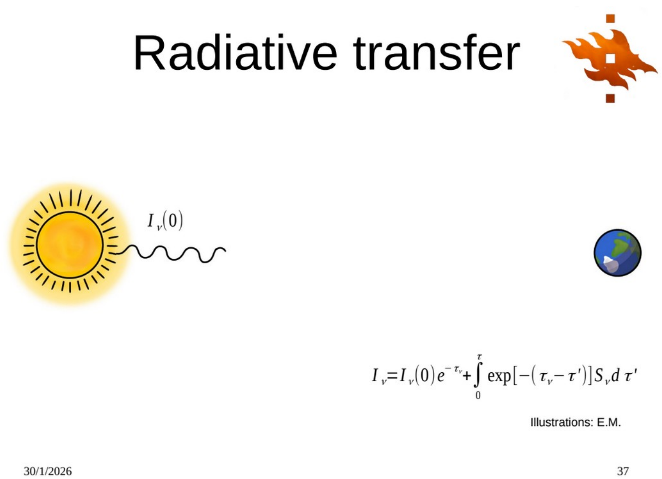
- Gound-based single-dish telescopes are the easiest to build and upkeep. They are the most accessible.
- To mitigate the atmosphere, telescopes are usually built at high latitude.
- Weather, light pollution, satellites, etc. also interfere with telescopes. Cellphone signals are thousands of times stronger than the faint radio signals from space.



- Signals from multiple single-dish telescopes can be correlated in a method called interferometry.
- The distance between the two furthest antennae is the diameter of the interferometric antenna. This leads to very high resolution.

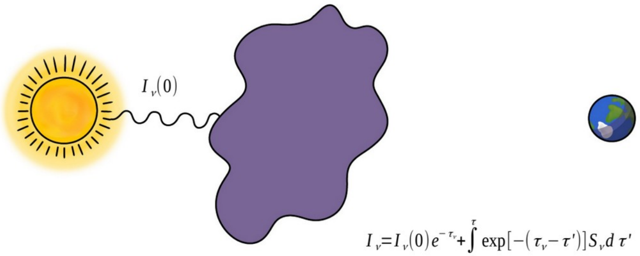


- Now we know how to observe radiation, but how does it get here in the first place?
- This can be explained using the radiative transfer equation, shown here (don’t worry, I will explain it with pictures).



- Some body, often a star, emits radiation at some intensity I.
- If there were no matter in space, we would then detect this light at the same intensity and wavelength (if ignoring relativistic effects).
- The atmosphere introduces similar effects.

Radiative transfer

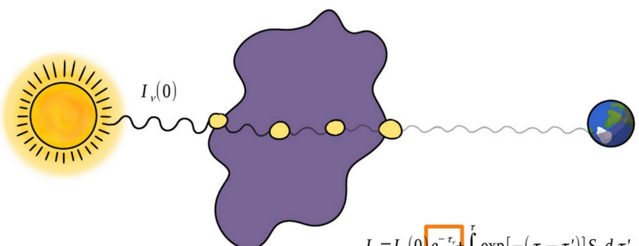


$$I_\nu = I_\nu(0)e^{-\tau_\nu} + \int_0^\tau \exp[-(\tau_\nu - \tau')] S_\nu d\tau'$$

Illustrations: E.M.

- However, when there is something, such as a cloud, in the way, the light changes.

Radiative transfer

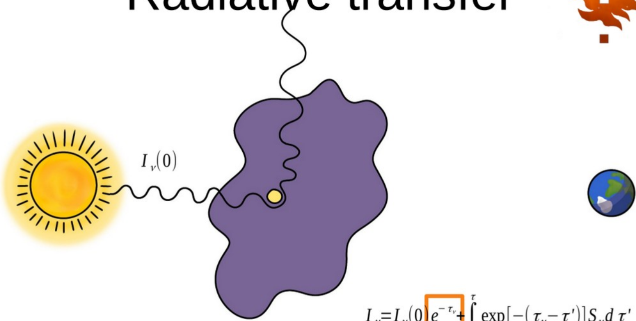


$$I_\nu = I_\nu(0)\boxed{e^{-\tau_\nu}} + \int_0^\tau \exp[-(\tau_\nu - \tau')] S_\nu d\tau'$$

Illustrations: E.M.

- First, can be absorbed by the atoms in the cloud. This is explained by this term (circled in orange).
- For a real-world example, think of how the Sun disappears in November.

Radiative transfer

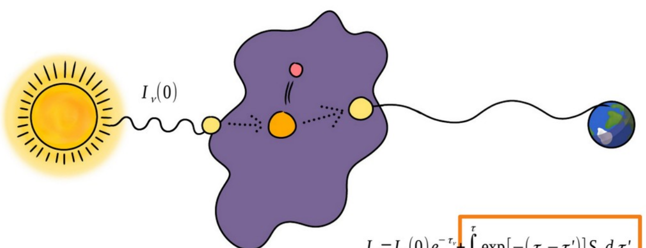


$$I_\nu = I_\nu(0)\boxed{e^{-\tau_\nu}} + \int_0^{\tau} \exp[-(\tau_\nu - \tau')] S_\nu d\tau'$$

Illustrations: E.M.

- In addition to being absorbed, light can also be scattered.
- A photon will change its direction through interactions with particles in the cloud.
- This also causes the total amount of radiation to decrease.

Radiative transfer

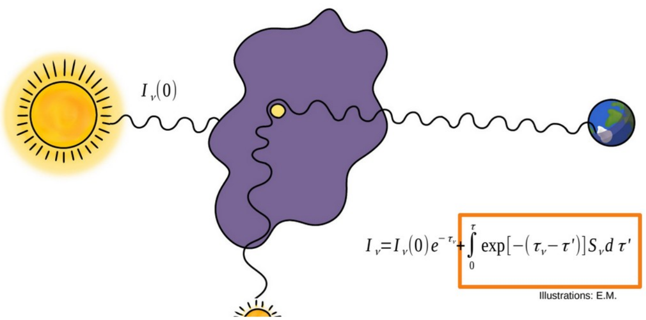


$$I_\nu = I_\nu(0)e^{-\tau_\nu} + \boxed{\int_0^{\tau} \exp[-(\tau_\nu - \tau')] S_\nu d\tau'}$$

Illustrations: E.M.

- Light that has been absorbed by an atom/molecule can be re-emitted.
- The emission of the cloud itself is described by this term (orange circled region).
- This self-emitted light can also be scattered and absorbed again.

Radiative transfer



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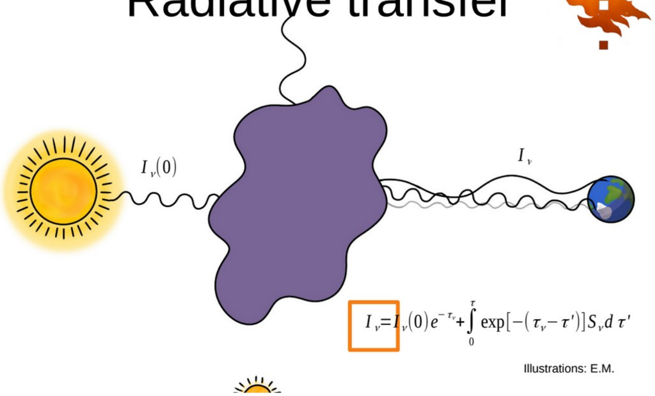
- Light from other stars can be scattered *toward* the viewer, seemingly increasing the light detected.

Radiative transfer



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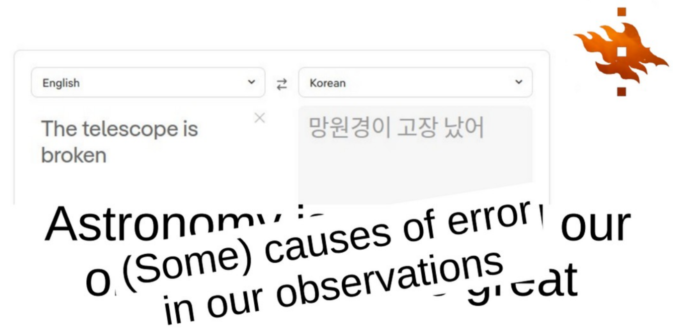
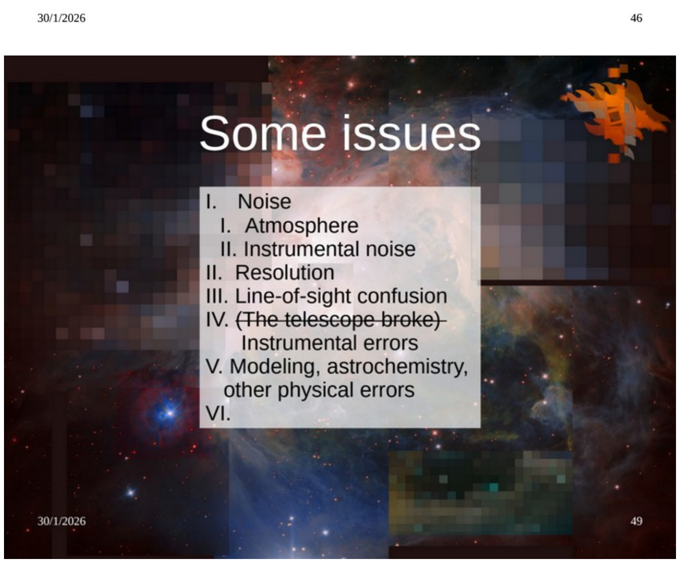
- Thus, the radiation we detect is a combination of many physical processes.
- For example, scattered and absorbed light can be studied together to observe differing processes within a cloud.



- Now that we know everything about star formation and the ISM, we can go have cake….

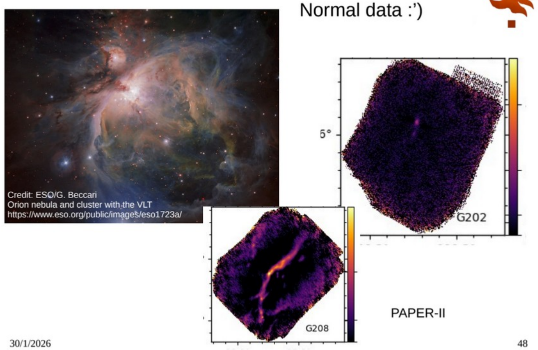


- Unfortunately, reality is rarely simple.
- There are many causes of error or uncertainty in observations.
- In addition to the ones I will discuss in more depth, there are always uncertainties in our analysis of data: what dust composition and chemistry, physical processes, and models we assume.
- This is why it is crucial to understand where error comes from.

Publication image

- We are used to seeing beautiful, high-quality published images in the media. But these images represent the best data which has gone through rigorous reduction.

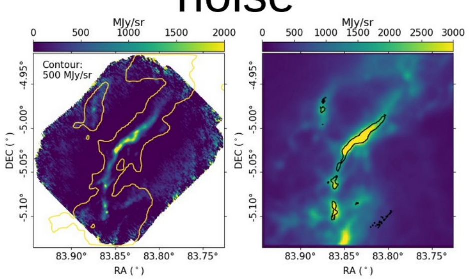
Normal data :')



PAPER-II

- In reality, astronomical data is rarely quite so beautiful…
- On the right we see two observations from PAPER-II. Of the four fields observed for this paper, only one (G208, shown here) was usable.

Removal of atmospheric noise



especially PAPER-II, PAPER-V

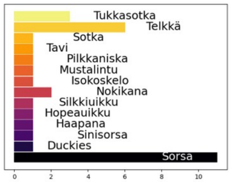
- In Earth-based observations, the atmosphere causes noise. This effect must be factored out of our observations. Unfortunately, with extended sources such as clouds, this also causes loss of large-scale structure.
- On the left, we have the OMC-3 cloud observed from the ground. On the right, from space. You can clearly see how the visible extent of the cloud is much larger in the space-based image.
- The contours show the extent (at the same level) of the cloud.

Low

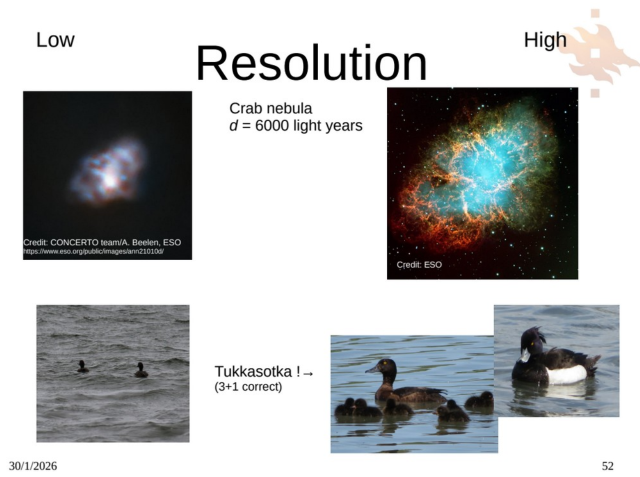
Resolution

High

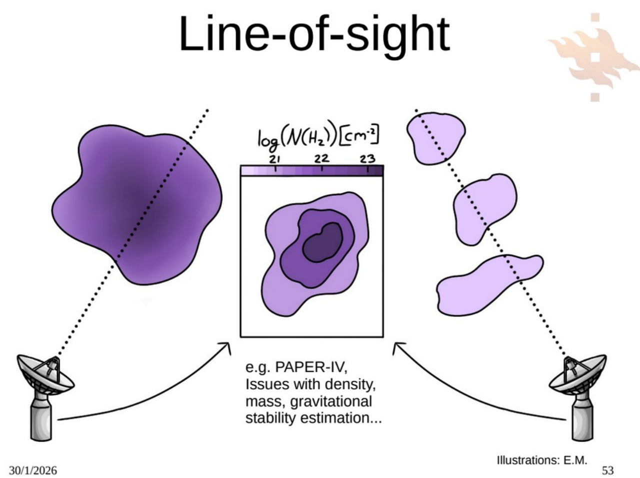
Crab nebula
d = 6000 light years



- Another issue is the limiting power of resolution.
- To achieve a higher resolution is more difficult: it requires a larger telescope, better observing conditions, and so on.
- Up top we can see this image of the Crab Nebula, a recent supernova remnant. From this image, we can see it is an oval-shaped cloud with a brighter center and some structure.
- I illustrate this with a real-world example: I have provided the photo below, with no context, and asked people (many avid birdwatchers) to guess the species of bird. We see that all were able to guess water birds, but there is a lot of scatter in the results.
- For some purposes, lower resolution would be sufficient. For example, to understand the radial extent of the crab nebula (or count the number of ducks), these images would be sufficient.



- At high resolution, many more details become apparent.
- For example, it is now easy to identify the birds!
- (Tufted duck, *Aythia fuligula,* a type of diving duck)
- In the crab nebula, we can now see that this is a shell around a more empty center, with filamentary structures extending toward the center.



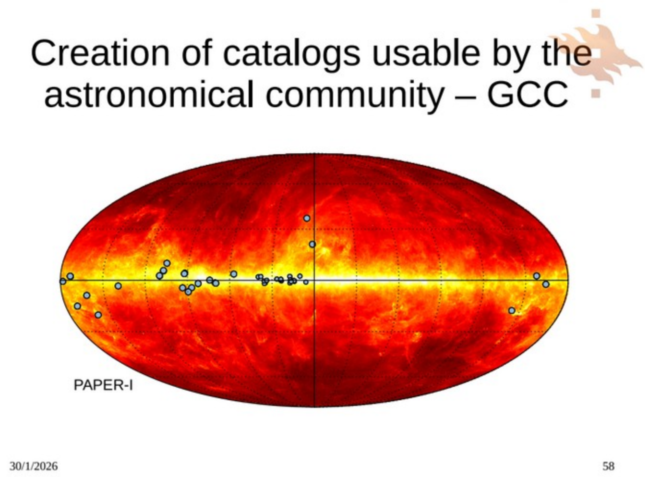
- Issues also arise from line-of-sight (LOS) confusion.
- We observe the 3D universe in 2 dimensions. That means we often have little idea about the true shape of interstellar clouds.
- A dense cloud along a LOS can look very similar to multiple more diffuse clouds along the same LOS.
- This can cause difficulty in estimating volume densities, masses, and thus gravitational stability.

Summary of papers

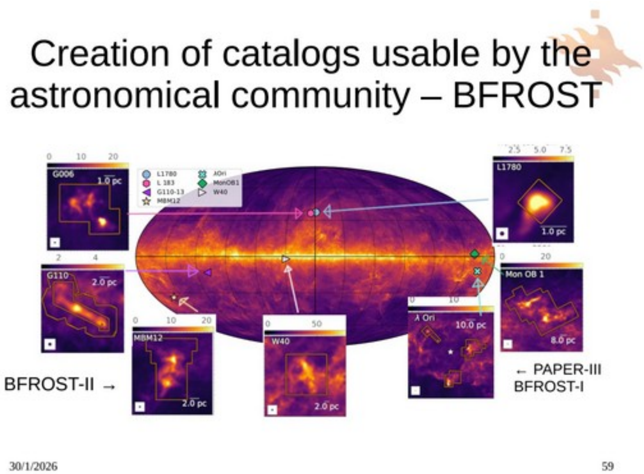
PAPER-I	PAPER-II	PAPER-III	PAPER-IV	PAPER-V
- Catalog of cores in 52 dense MCs - Do properties show correlation with e.g. SF status, location in the Galaxy, etc?	- Study of the main filament in OMC-3 with *Herschel* and ArTeMiS - Determine properties of this filament. - Do the properties change based on observing method?	- Three dense clouds in the LOri bubble observed in 12CO & 13CO - How does the cloud evolve in a high-feedback environment?	- Simulated observations of high-mass filament - How does the proposed ngVLA telescope recover properties of the filament?	- Dense filament segments in OMC-3, including MIR Spitzer data. - How do properties of this filament change based on observing method?

- Due to the large variety in interstellar clouds and the environments in which they reside, it is often difficult to draw universal conclusions from a single source.

- Through this thesis I have participated in the creation of catalogs and datasets which can be used by the community.



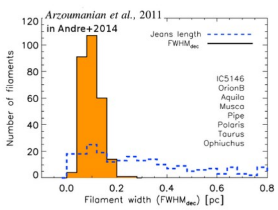
- In PAPER-I, I analyzed hundreds of dense clumps and cores in over 50 galactic fields (circles on the plot).
- I created a catalog of properties (mass, temperature, presence of protostars, and so on) for these clumps. This can be compared internally and combined with other data for a more full picture of galactic star formation.
- We found some correlation between location in the Galaxy, SF status, temperature, and so on.



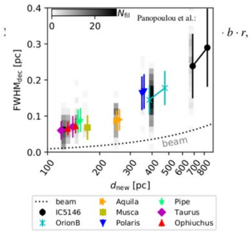
- I have participated in observations for the B-FROST survey, which has observed 9 clouds in 7 regions at large scales. We plan to make some of the data available to the community.
- PAPER-III has analyzed the high-energy Lambda Orionis ring, finding evidence of compression from the hot central star.
- As the data have been observed in a consistent way, they are able to be compared.

- One of the major findings have been clarification and confirmation of the effect observational parameters have on detected results.

Observational parameters affect our results – 0.1 pc filament width



Arzoumanian et al., 2011



Panopoulou et al., 2021

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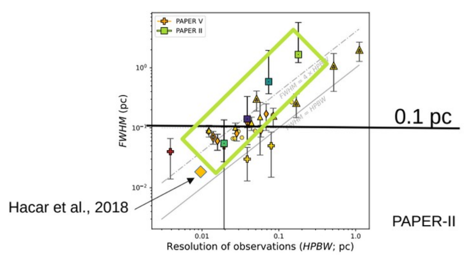
- Over a decade ago, Arzoumanian et al., 2001 detected how almost all filaments in the Gould Belt survey seemed to have a uniform width of around 0.1 pc (orange histogram).
- Physically, the widths of these filaments should have had a much higher range (blue histogram).
- Later studies, notable Panopoulou et al., have called this universal width into question.

Observational parameters affect our results – 0.1 pc filament width



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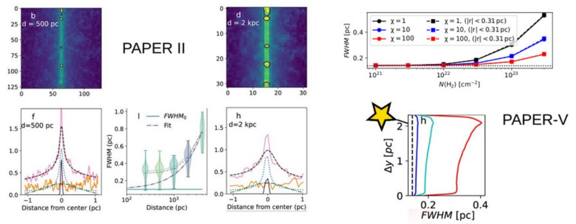
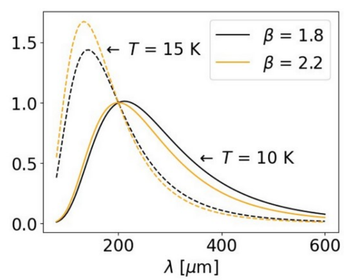
- In PAPER-II, we have found a strong dependence of filament width on resolution of the observations. These four squares show the mean of the data observed in the paper.
- The data from PAPER-V are also shown with crosses.
- Plotting results from various recent publications, including Hacar et al, 2018 in Orion, shows a similar trend.

Observational parameters affect our results – 0.1 pc filament width



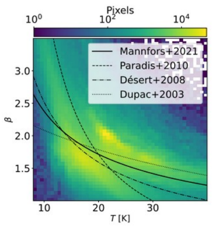
- In both Papers II and V, we have performed simulations which also quantify how loss of resolution due to e.g. distance, filament central column density, and the presence of a bright star change observed widths.
- We conclude that while 0.1 pc may be *an* important width, it is certainly not universal.
- (This finding was very controversial)

Observational parameters affect our results – T-β anticorrelation



- In PAPER-I, we studied how temperature and beta relate to each other.
- Both parameters affect the shape of a spectrum. Temperature increases emission and moves the peak of radiation to shorter wavelengths, whereas beta affects the shape of the spectrum.

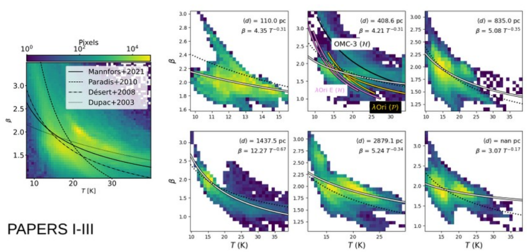
Observational parameters affect our results – T-β anticorrelation



← PAPER I

- We detected a very strong anticorrelation between temperature and beta.
- We also performed statistical testing, concluding that all of this anticorrelation is not due to instrumental noise.

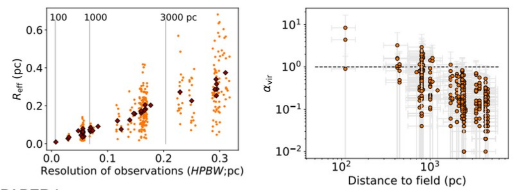
Observational parameters affect our results – T-β anticorrelation



PAPERS I-III

- When writing this lektio, I also decided to use the data from Papers II and III to estimate the anticorrelation. As can be seen by this frame (center, top), there is also an anticorrelation in the data for Lambda Orionis East and OMC-3.
- I did not find any correlation between distance and this relation using the data from PAPER-I.

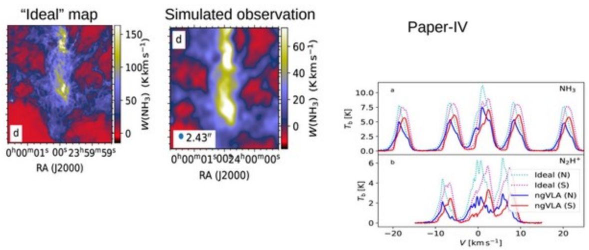
Observational parameters affect our results – Distance dependence



PAPER I

- We also detected strong dependence between distance and clump size and gravitational stability.
- As in the case with filament widths, we interpret this to be more due to lower physical resolution at large distances.

Observational parameters affect our results – ngVLA study



- In PAPER-IV, using simulations we have studied how this proposed telescope would detect a dense filament.
- A few examples are shown on this page.

Future prospects

- JWST and ALMA imaging of clouds
  - Same cloud at multiple resolutions
  - Deep study of one cloud
- More sophisticated modeling of clouds
  - e.g. multi-temperature components of MBB fitting
  - Multi-dust-species
- A greater understanding of *what* causes error & our assumptions

Credit: ESO/G. Beccari
https://www.eso.org/public/images/eso1723a/