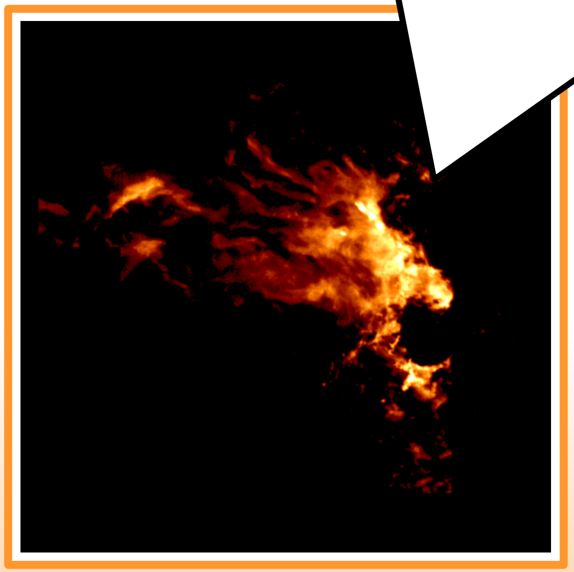
English translation of:



The multiscale interstellar medium

from massive molecular clouds to cold cores

Emma Mannfors
Lectio Praecursoria
30.1.2026

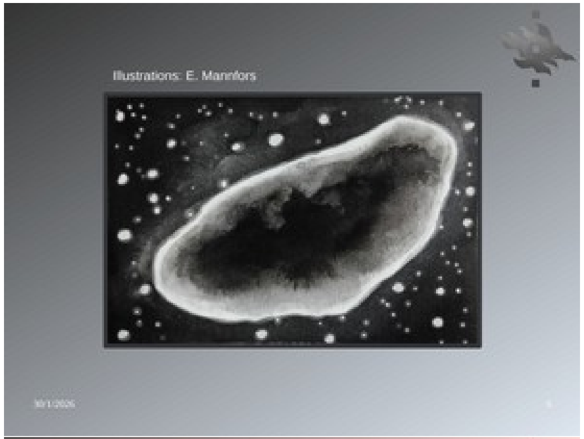
Units

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

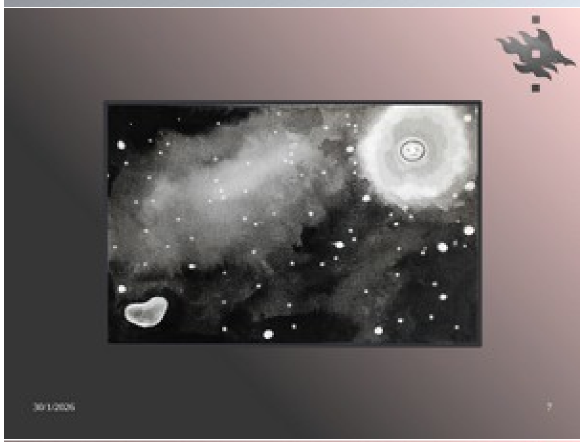
- A few common units I may use in this lektio. A parsec is a measure of length. It is about 3.26 lightyears, or well over a billion kilometers
- Kelvin are used in science to describe temperature. At zero Kelvin, atoms should theoretically stop all movement. This is equal to about -273 Celsius.

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

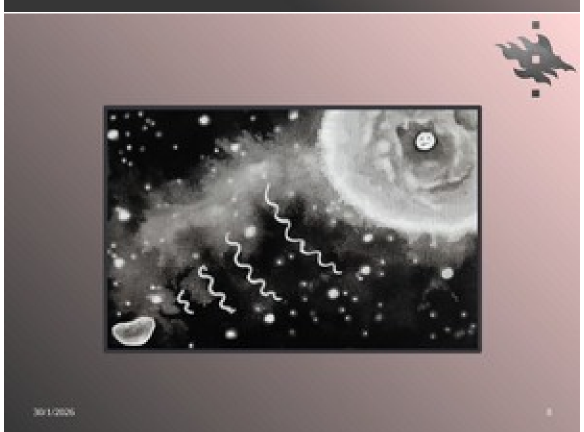
- I will try to avoid using acronyms in this lektio. However, I will likely use the term ISM, which stands for the interstellar medium. The ISM includes all the baryonic matter inside galaxies, which are not in stars or solid bodies.



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...

30/1/2026 12

- ….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.

30/1/2026 13

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

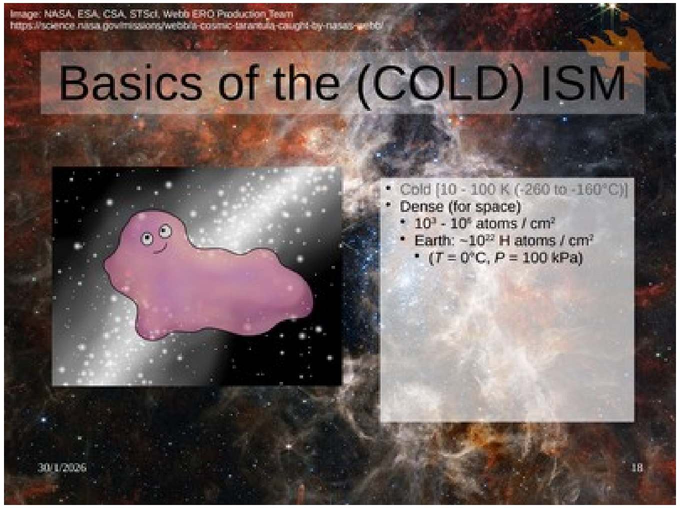
- Many years later, the cloud had begun fading away. In its place, were a hundred young stars and many tiny solar systems.

- 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).

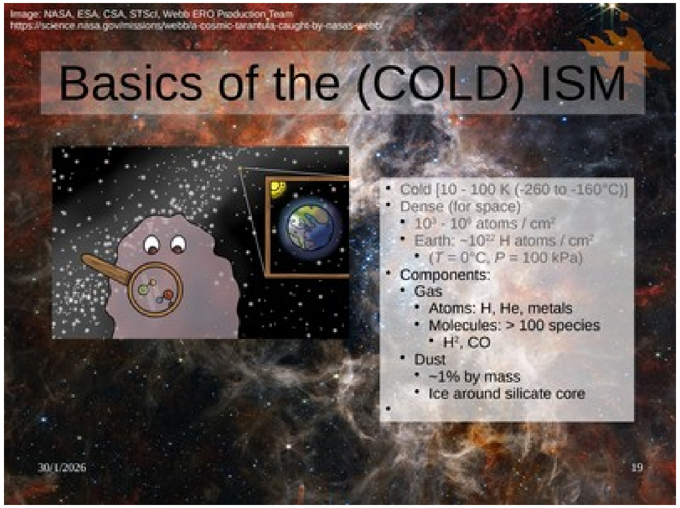
- So what exactly are clouds in space? ISM comes in many forms, but I focus on the *cold* ISM.

- The cold ISM is cold(*), as low as 10 K.

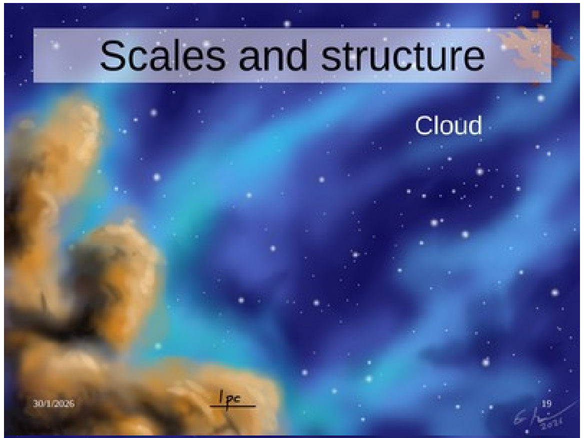
(*) Spoiler alert



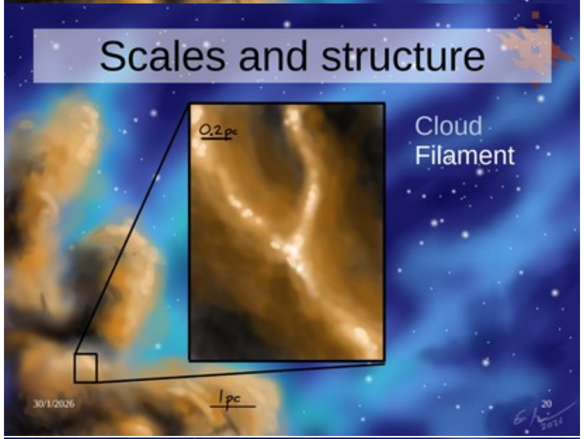
- It is also dense, when compared to the rest of space. However, compared to the Earth’s atmosphere this matter is very diffuse.
- There is a lot of radiation in space. This radiation heats up and dissociates (=breaks up) atoms and molecules.
- Therefore, this cold gas can only exist if the surrounding medium is dense enough to protect it from this radiation.



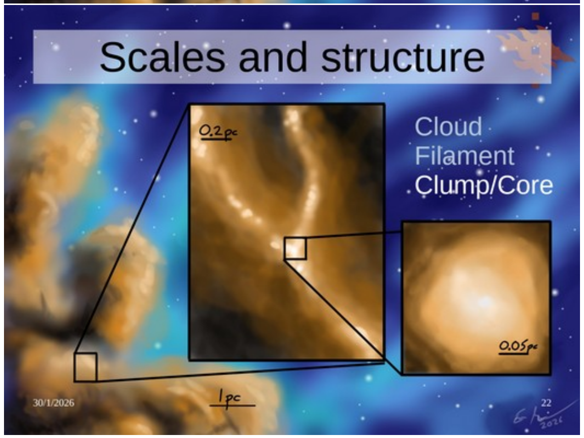
- Because of this dense gas, molecules and larger icy particles known as dust can exist in the cold ISM.
- Even molecules which are the basis of life on Earth have been found in the ISM; however the most common are molecular hydrogen and carbon monoxide.



- The ISM forms structure on many scales.
- Matter forms large, cloudy structures. This matter is not distributed evenly throughout the clouds.

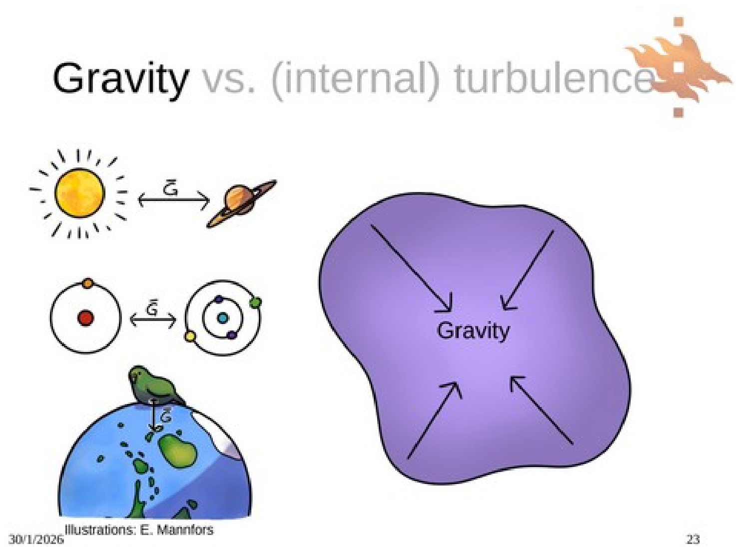


- Instead, matter forms filamentary structures. A filament is a long, thin structure. Filaments can also have complex shapes, and can collide.

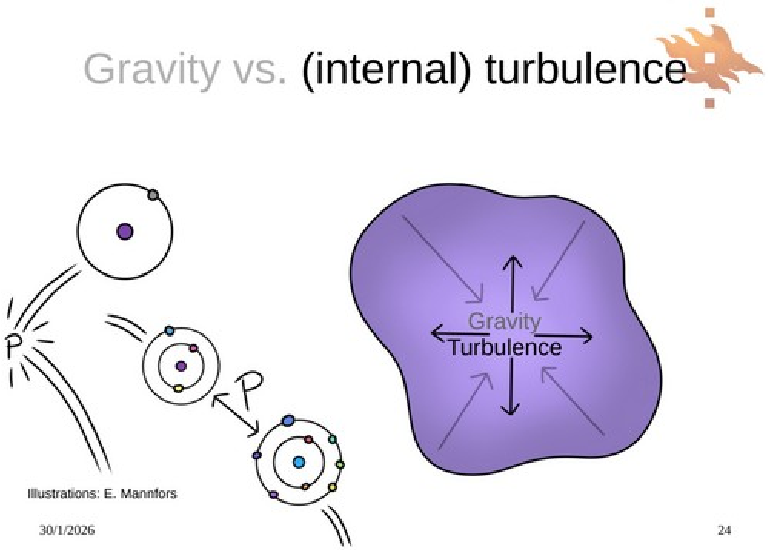


- Within filaments, (especially where filaments collide) are small overdensities, clumps and cores. Within the clumps and cores, one or more stars can be formed.

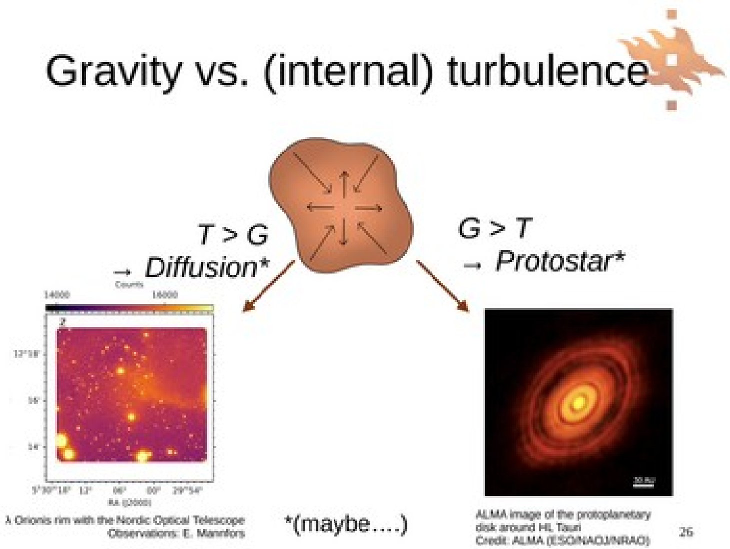
- These structures form and evolve due to complicated processes.



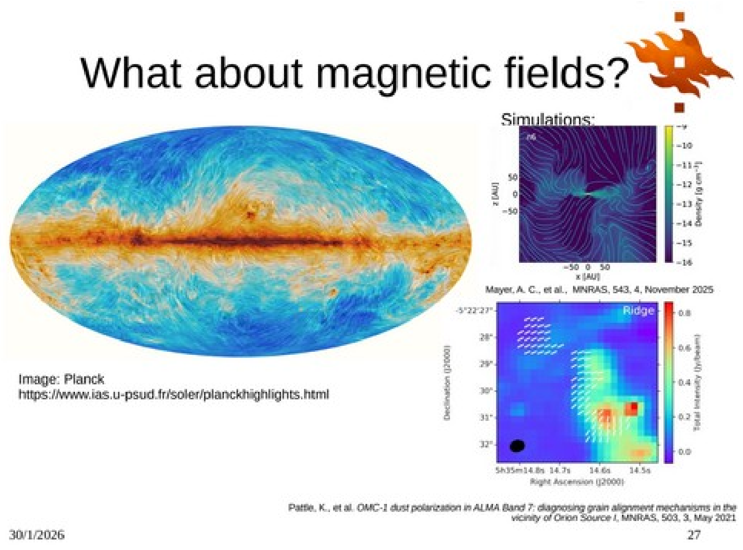
- The stability of a cloud, filament, or clump is a battle between gravity and internal pressure.
- Matter, from atoms to stars, attracts matter due to gravity.
- The gravitational energy of a cloud depends on the mass and physical size (~radius) of the object.



- Internal pressure is born from the motions of the particles inside the cloud, known as turbulence.
- When particles collide, they create pressure inside the cloud.
(- This same process creates pressure outside the cloud as well.)

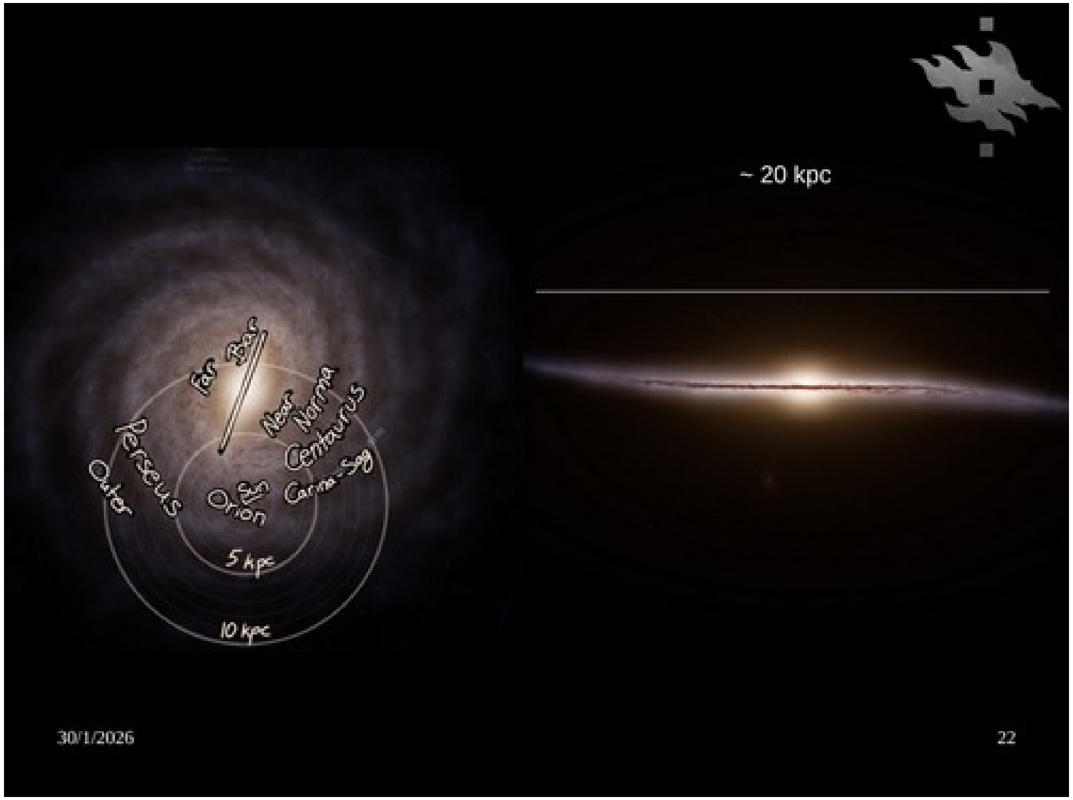


- With a large enough mass, gravity takes over and the object can begin to collapse, forming new stars.
- If the mass is too low, turbulence dominates and the cloud diffuses into the wider ISM.

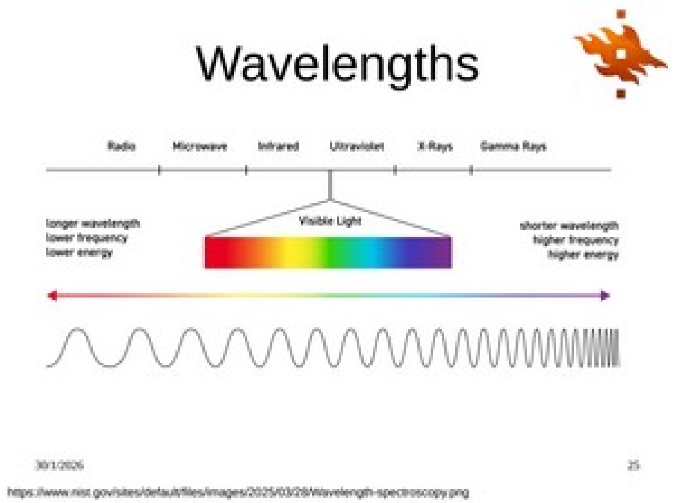


- Magnetic fields are a further complicating factor.
- Our galaxy has both large-scale galactic magnetic fields (left picture) as well as clump-scale fields (right pictures).
- Magnetic fields and gas can be connected. A strong magnetic field can direct gas onto the surface of a dense clump.
- On the other hand, a magnetic field can prevent the collapse of an object.

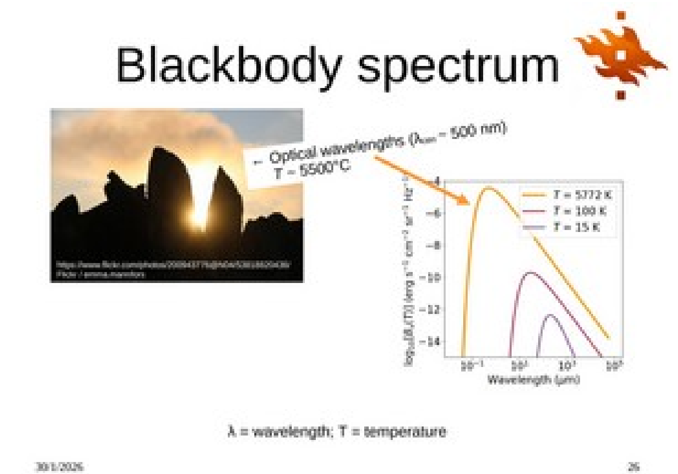
- The interplay of these processes drives ISM evolution in our galaxy.



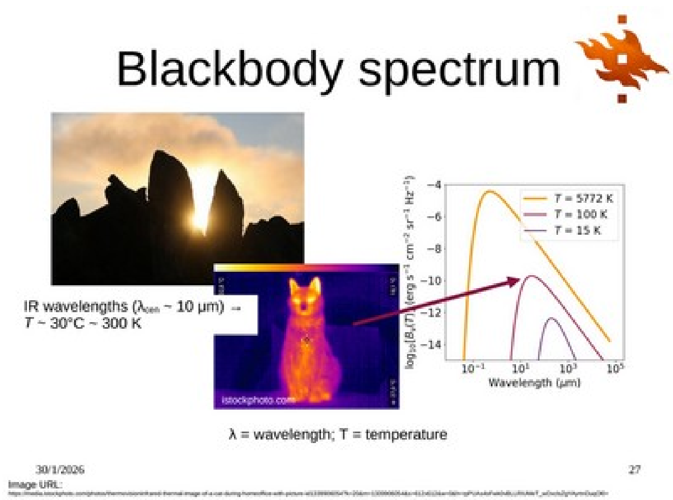
- We live in the Milky Way galaxy, a massive spiral galaxy. As you can see by this image, it is quite pancake-shaped.
- The Milky Way consists of stars, a central black hole, but also a large amount of cold molecular gas shown by the dark lines on the right-hand figure. The cold gas and young stars are 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.



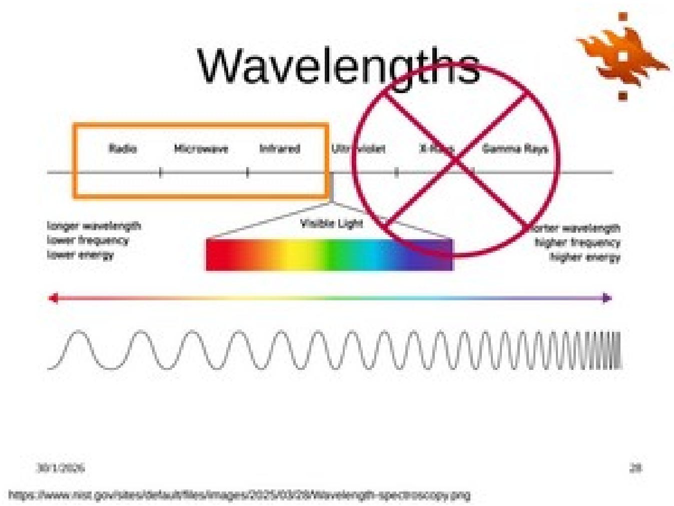
- Light can be described as a wave. The only difference between x-rays, radio waves, or visible light is the wavelength. This wavelength correlates with energy; x-rays have more energy than radio waves.



- Objects radiate a certain amount of light. A *spectrum* describes the amount of radiation as a function of wavelength.
- Sometimes we can assume 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.

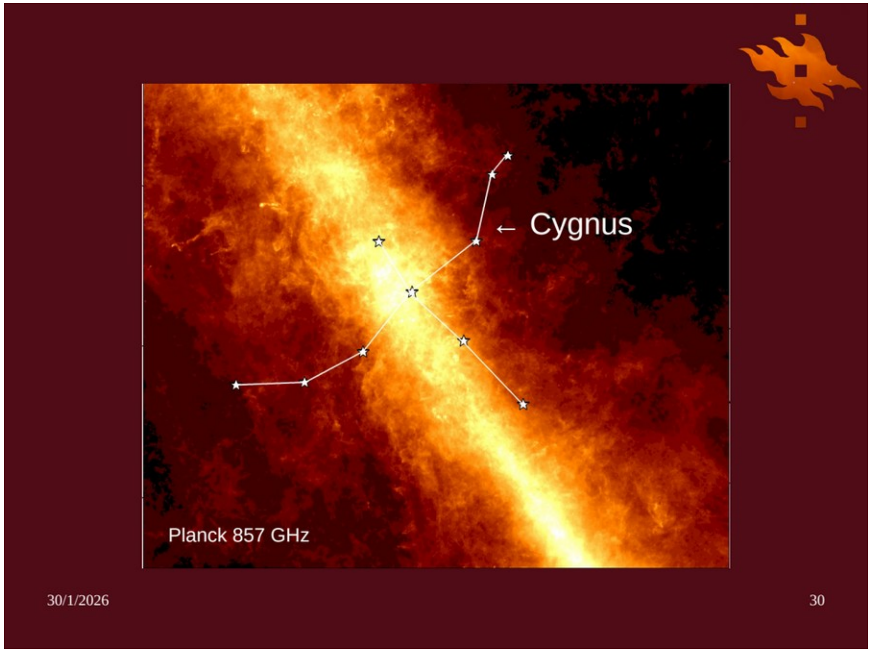


- In contrast, the radiation of a cooler object peaks in longer wavelengths. For example, a body at 30-40 Celsius radiates in the infrared. This is why thermal cameras are used to find missing people.
- You can also see how a cooler temperature leads to a lower level of radiation overall.
- Now if we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



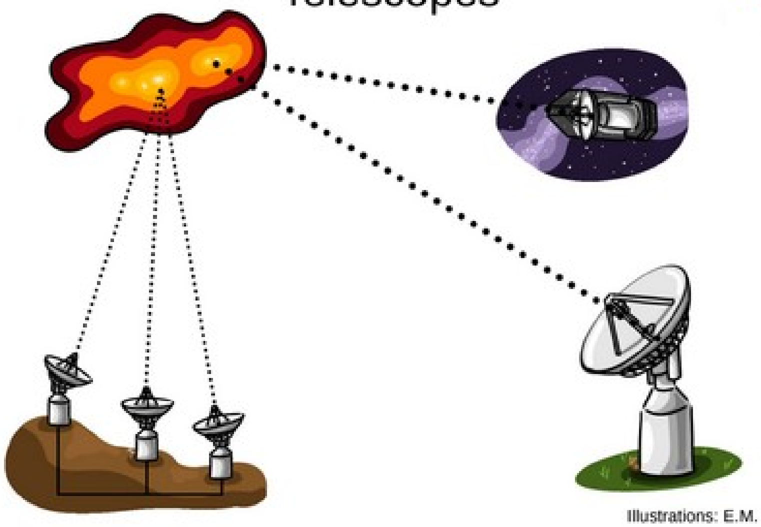
- … we can see that the ISM radiates in infrared and longer wavelengths.
- Shorter wavelengths can also be used to study the ISM. However, this thesis focuses on longer wavelengths.

- The sky would look very different if we saw in the infrared. This is illustrated by the following picture, which I took in Svalbard a few years ago. I have marked a few visible constellations on the image.
- The swan (Cygnus) flies along the plane of the Milky Way galaxy so the plane of our galaxy crosses this image.

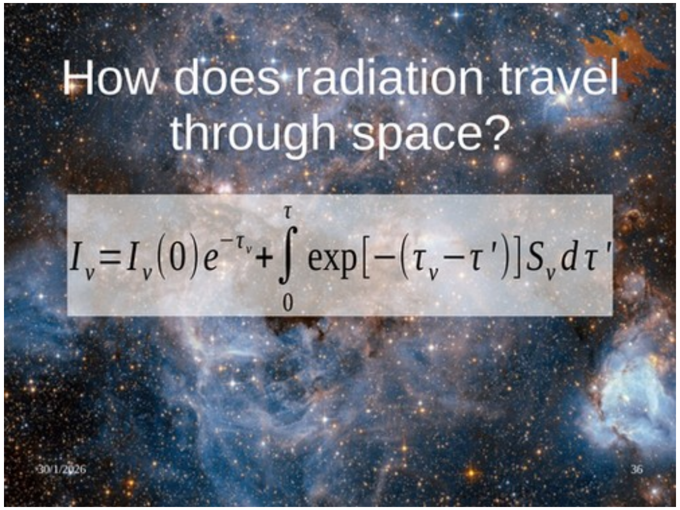


- If we were able to observe the same view in the infrared, the picture would be very different.
- The cold gas of the Milky Way is vibrant in this Planck 300 um picture. Meanwhile the swan is not visible at all.

Telescopes



- Because we can’t see in the infrared, we use telescopes.
- We can roughly divide the telescopes we use into three categories: space telescopes, Earth-based single-dish telescopes, and interferometers.
- The Earth’s atmosphere creates a lot of noise in out observations. On the other hand, launching a telescope into space is expensive and more dangerous.
- Then again, for example large-scale filamentary clouds are best viewed from space.
- Signals from multiple single-dish telescopes can be combined using a technique known as interferometry. With this technique we can create a telescope with a very high resolution.



- Now we know how to observe radiation, but how does it get here in the first place?

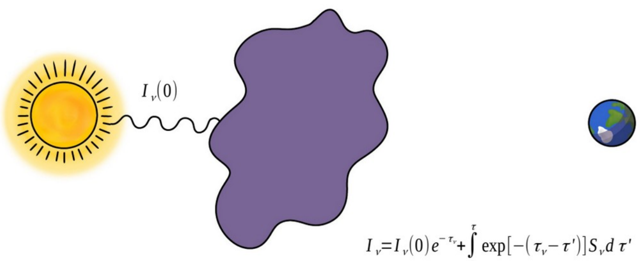
Radiative transfer

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

Illustrations: E.M.

- 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



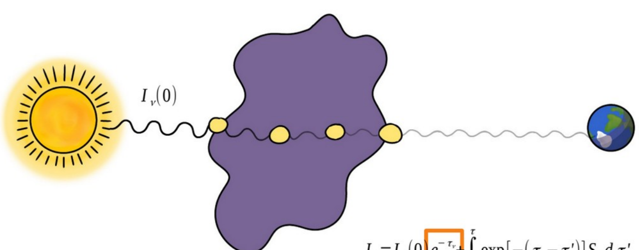
$$I_\nu = I_\nu(0) e^{-\tau_\nu} + \int_0^{\tau} \exp[-(\tau_\nu - \tau')] S_\nu d\tau'$$

Illustrations: E.M.

30/1/2026 38

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

Radiative transfer



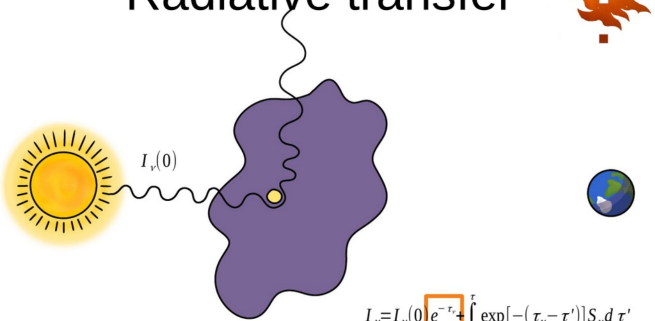
$$I_\nu = I_\nu(0) \boxed{e^{-\tau_\nu}} + \int_0^{\tau} \exp[-(\tau_\nu - \tau')] S_\nu d\tau'$$

Illustrations: E.M.

30/1/2026 39

- 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



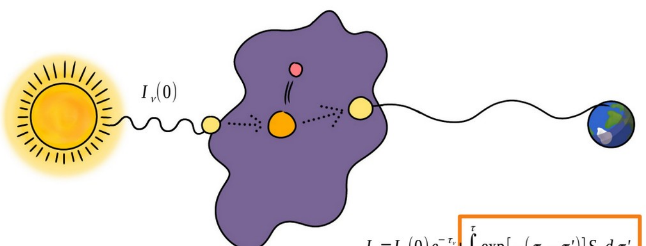
$$I_\nu = I_\nu(0)\boxed{e^{-\tau_\nu}} + \int_0^{\tau} \exp[-(\tau_\nu - \tau')] S_\nu \, d\tau'$$

Illustrations: E.M.

30/1/2026 40

- 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



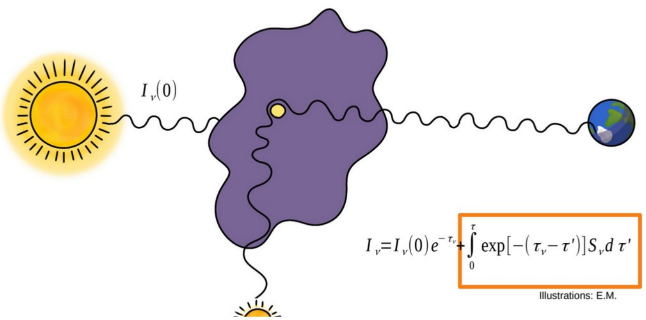
$$I_\nu = I_\nu(0) e^{-\tau_\nu} + \boxed{\int_0^{\tau} \exp[-(\tau_\nu - \tau')] S_\nu \, d\tau'}$$

Illustrations: E.M.

30/1/2026 41

- 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

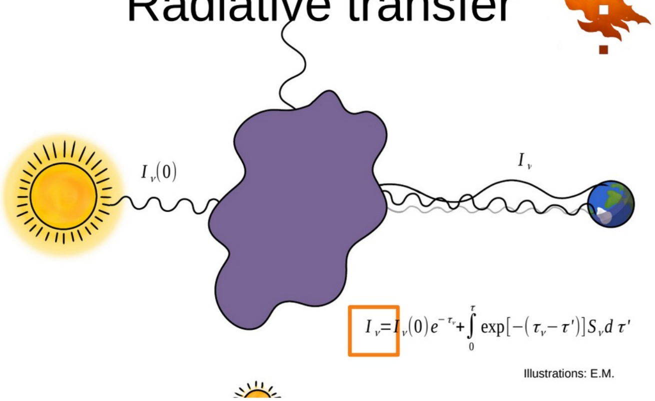


$$I_\nu = I_\nu(0)e^{-\tau_\nu} + \boxed{\int_0^{\tau} \exp[-(\tau_\nu - \tau')] S_\nu d\tau'}$$

Illustrations: E.M.

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

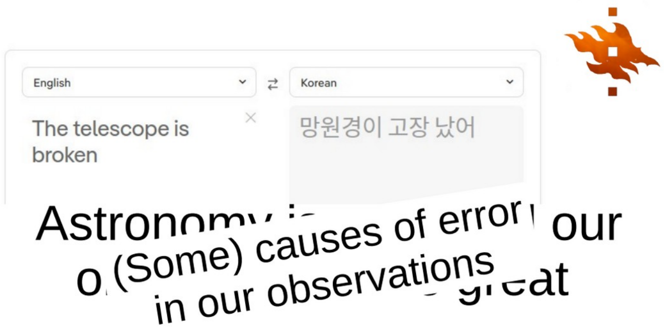
Radiative transfer



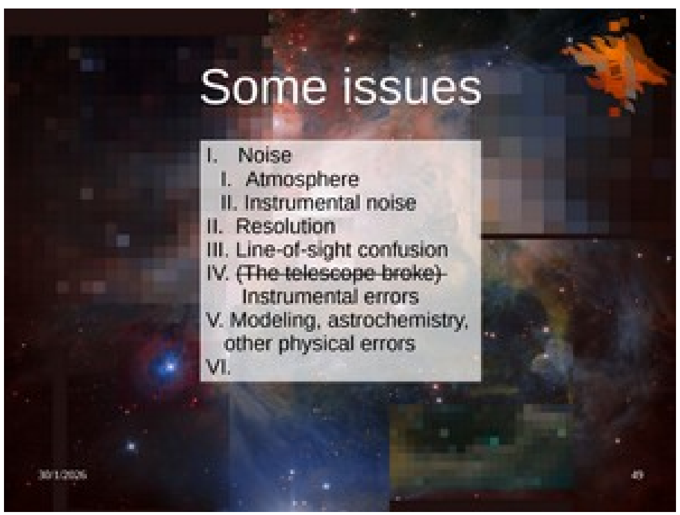
$$\boxed{I_\nu} = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau} \exp[-(\tau_\nu - \tau')] S_\nu d\tau'$$

Illustrations: E.M.

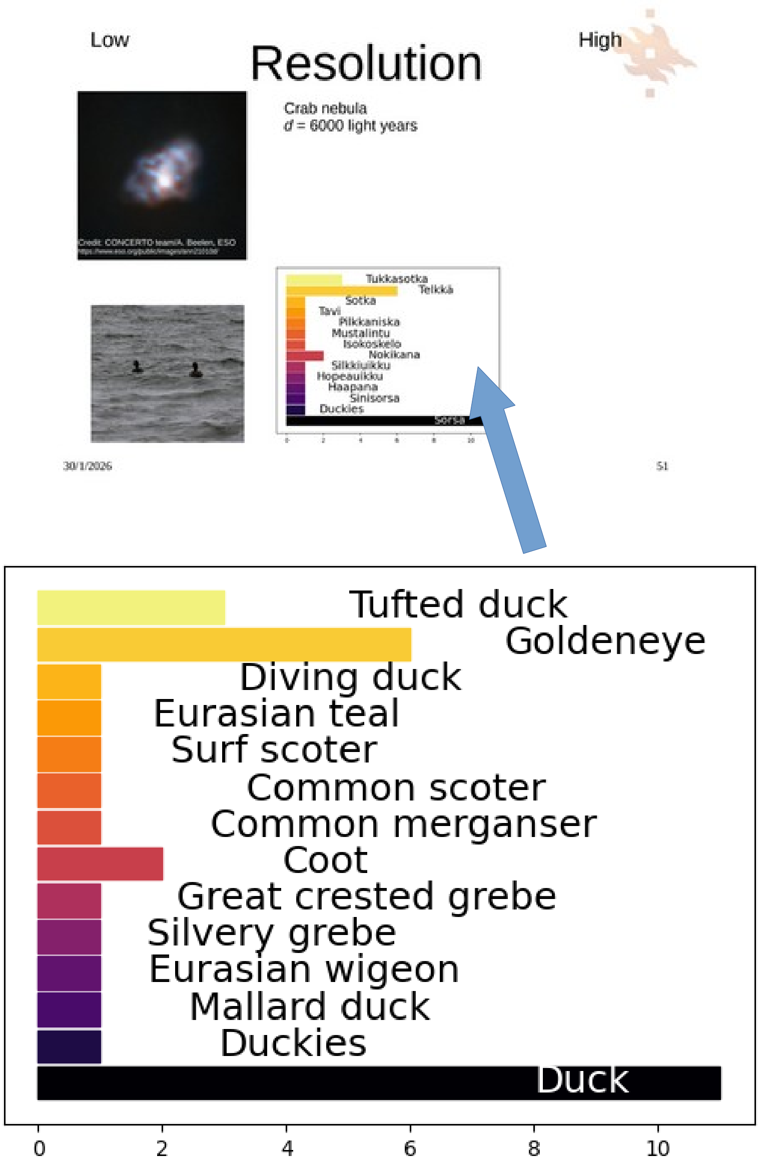
- Thus, the radiation we detect is a combination of many physical processes.
- For example, scattered and absorbed light can be studied together to observe differing processes within a cloud.



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

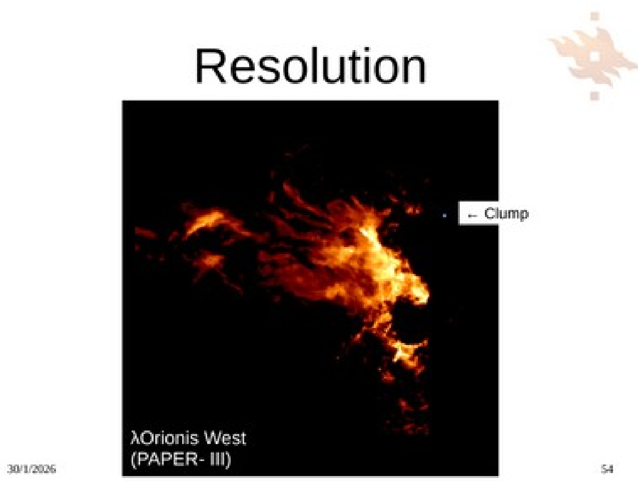


- Unfortunately, reality is rarely simple.
- There are many causes of error or uncertainty in observations.
- The atmosphere causes noise , but also electronic noise is present even in space-based observations.
- In addition, there are also uncertainties in modeling and the underlying physics.
- Assumptions are necessary in science. Therefore it is crucial to understand the effect these assumptions have on our conclusions.
- Further sources of error come from e.g. the limited resolution of telescopes.

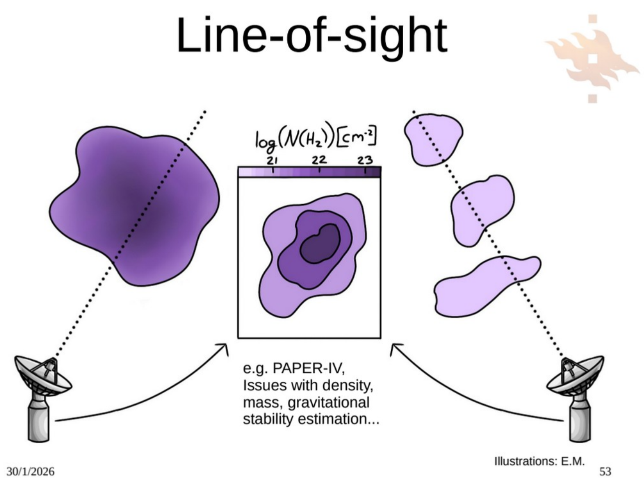


- A lower resolution means we are able to see less detail. However, to achieve a higher resolution is more difficult: it requires a larger telescope, better observing conditions, and often longer exposure times.
- Up top we can see this image of the Crab Nebula, a supernova remnant. From this image, 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.
- However, for some questions a higher resolution is necessary.

- 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. If we want to study the structure of these inner filaments, we need the higher resolution data.

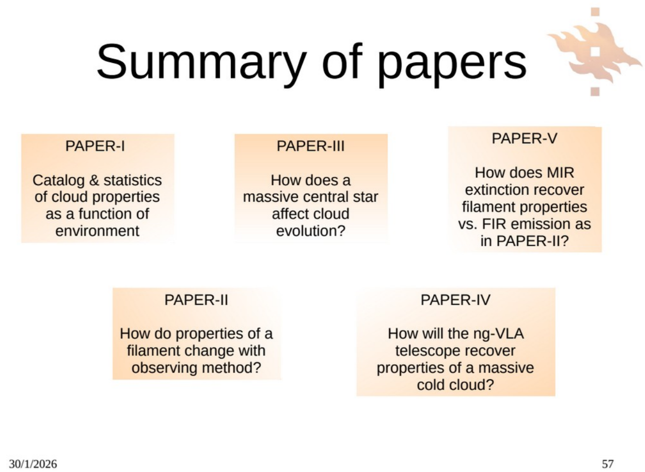


- In the same vein, the large-scale, large-extent data of PAPER-III would not be useful if one wanted to study dense cores in Lambda Orionis.
- On the other hand, this dataset is excellent in for studying the large-scale motions and structure of the gas.



- 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.
- Molecular line observations can help with this issue, but do not solve the issue.

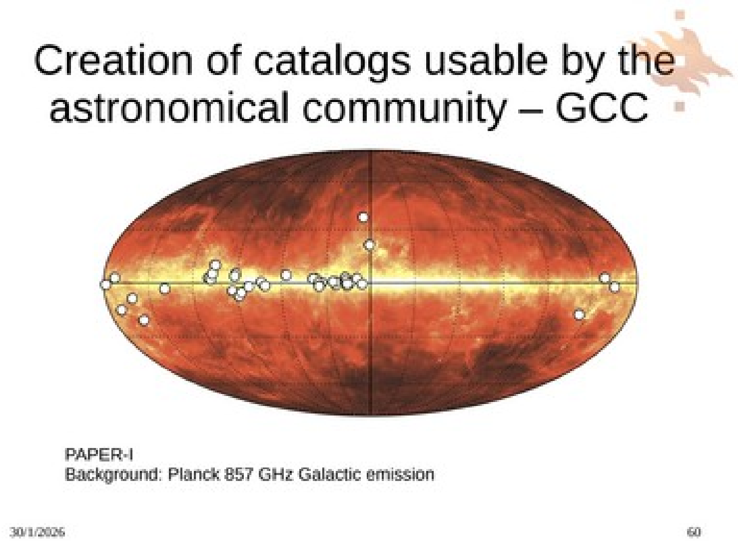
- This thesis covers five quite broad papers.



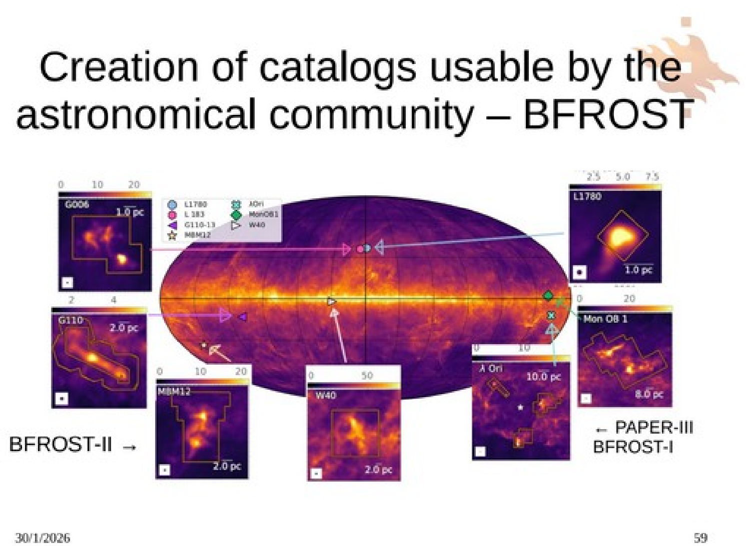
- In Paper 1 we observed dense cores and analyzed their properties e.g. as a function of location and star-formation status.
- In Papers 2 and 5 we determined the properties of the OMC-3 filament and studied how these properties change depending on the observing method.
- In Paper 3 we analyze how a cloud around a bright star is developing.
- Paper 4 determines how the ngVLA-interferometer would observe a dense interstellar dark cloud.

- I present some main results of my thesis work.

- 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.

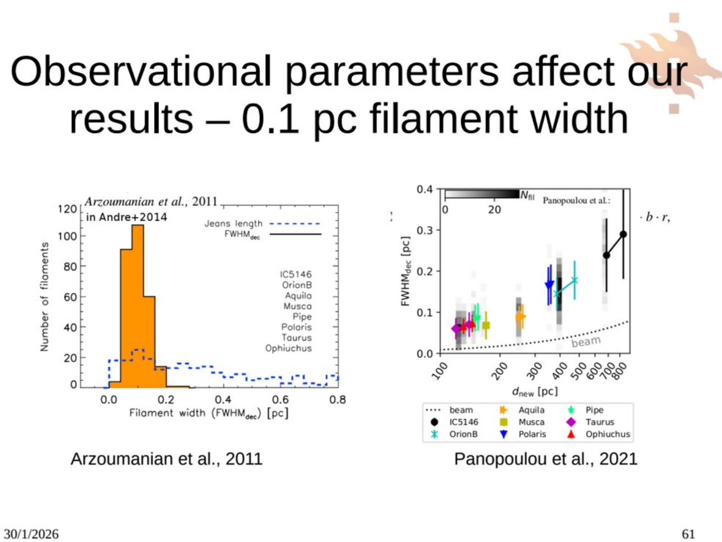


- In PAPER-I, I analyzed hundreds of dense clumps and cores (circles on the plot).
- I created a catalog of properties (mass, temperature, presence of protostars, and so on) for these clumps. This can be compared internally and combined with other data for a more full picture of galactic star formation.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



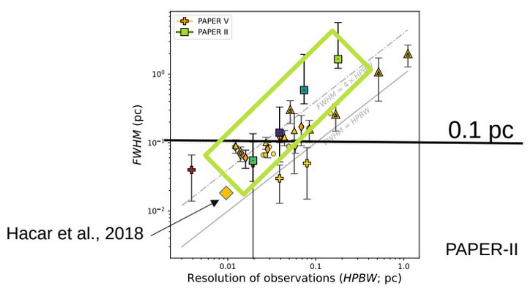
- I have participated in observations for the B-FROST survey, which has observed 9 clouds in 7 regions at large scales. As the data have been observed in a consistent way, they are able to be compared.
- PAPER-III has analyzed the high-energy Lambda Orionis ring, shown here.

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



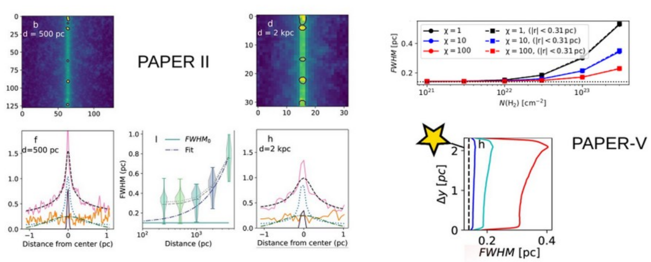
- Over a decade ago, Arzoumanian et al., 2001 and Adre et al., 2014 detected how almost all filaments in the Gould Belt survey seemed to have a uniform width of around 0.1 pc (orange histogram).
- Physically, the widths of these filaments should have had a much higher range (blue histogram).
- They came to the conclusion that some important physical change is occurring at scales of 0.1 pc. Perhaps the change of turbulence from super- to subsonic.
- Later studies, notable Panopoulou et al., have called this universal width into question.

Observational parameters affect our results – 0.1 pc filament width



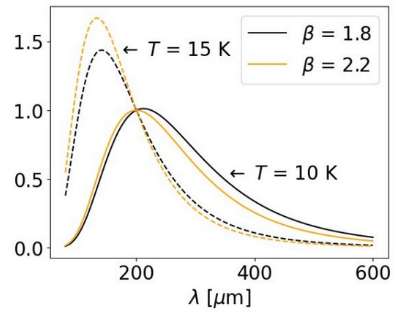
- In PAPER-II, we have found a strong dependence of filament width on resolution of the observations. These four squares show the mean of the data observed in the paper.
- The data from PAPER-V are also shown with crosses.
- Plotting results from various recent publications, including Hacar et al, 2018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

Observational parameters affect our results – 0.1 pc filament width



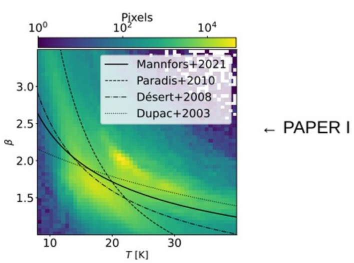
- In both Papers II and V, we have performed simulations which also quantify how loss of resolution due to e.g. distance, filament central column density, and the presence of a bright star change observed widths.
- (This finding was very controversial)

Observational parameters affect our results – T-β anticorrelation



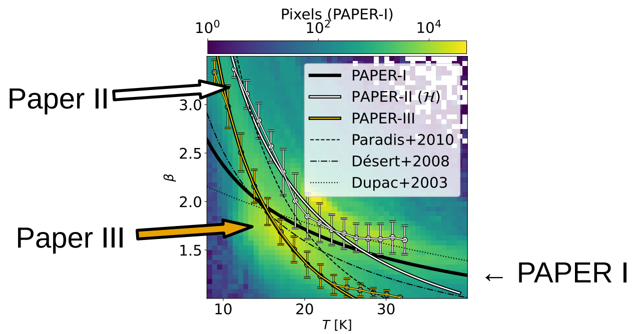
- The observed spectra of interstellar clouds depends on temperature and the beta-parameter. Temperature affects the peak of the spectrum. Beta affects the slope.

Observational parameters affect our results – T-β anticorrelation



- In Paper 1, we detected a very strong anticorrelation between temperature and beta.
- We also performed statistical testing, concluding that all of this anticorrelation is likely not due to instrumental noise.

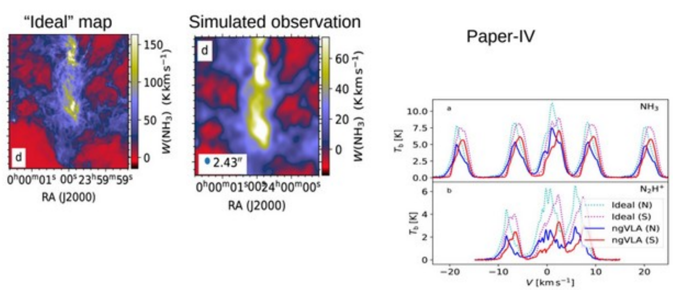
Observational parameters affect our results – T-β anticorrelation



30/1/2026 63

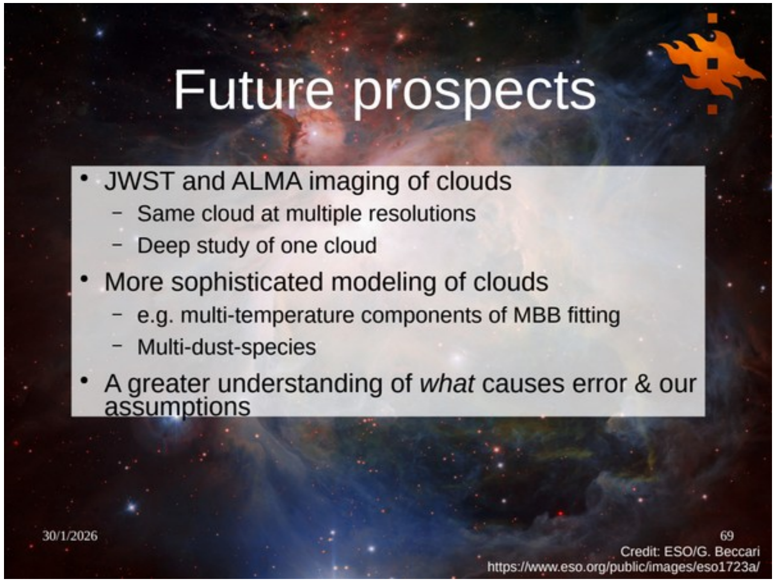
- The Herschel data from Papers 2 and 3 also show the same anticorrelation.

Observational parameters affect our results – ngVLA study



30/1/2026 68

- In PAPER-IV, using simulations we have studied how this proposed telescope would detect a dense filament extracted from a simulated cloud.
- (On the left) I show an ideal map, and the same data observed with the telescope.
- We can see how the resolution is lower, and some emission is not seen (plot on the right).
- Nevertheless, ngVLA is excellent for observing small-scale clumps and cores, but to observe the large-scale cloud single-dish observations are needed.



- Unfortunately I have not solved all of astronomy.
- The new JWST and ALMA observatories give the opportunity to observe sources with excellent resolution.
- For example, the question of the 0.1 pc filament width could be understood by observing the same region at multiple resolutions.
- This would also give the possibility of understanding and connecting physics at large and small scales.
- Also the refinement of models can clarify observations. For example, better dust modeling can clarify what is happening inside clouds.