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Observational techniques

Maryvonne Gerin



LERMA



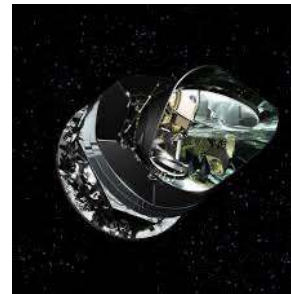
Observatoire
de Paris

PSL



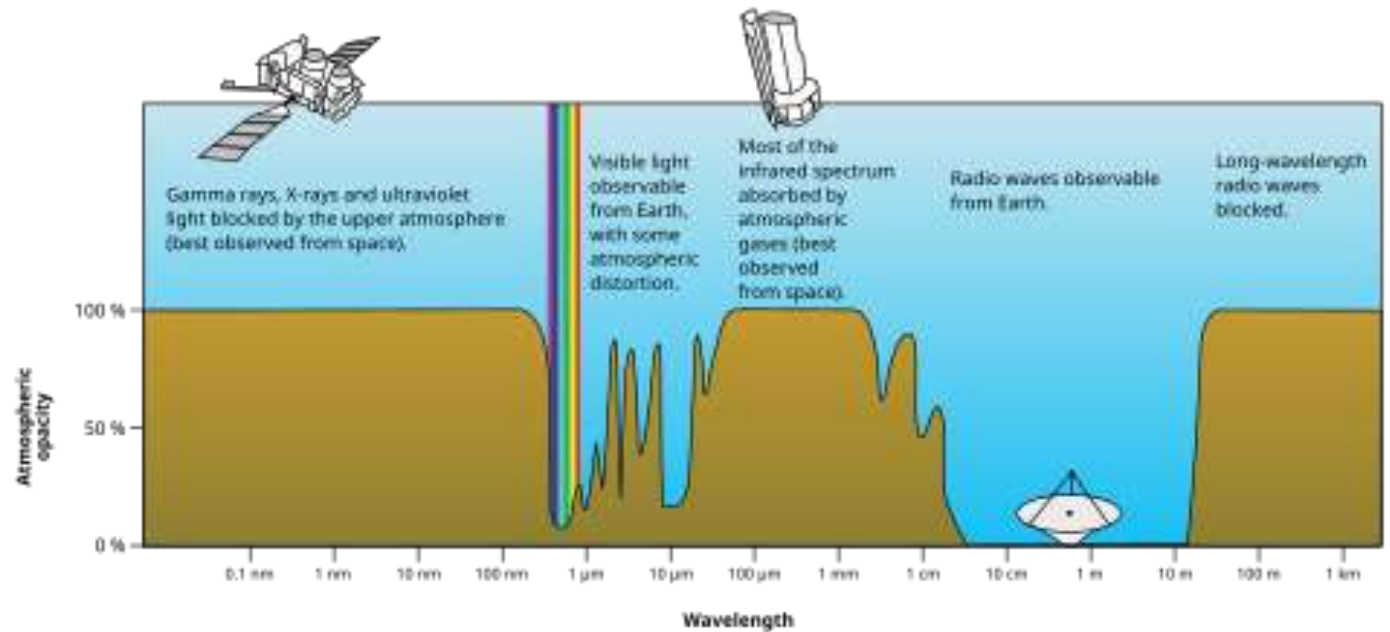
Telescopes and instruments

- Astronomy : Access to most of the electromagnetic spectrum
- Multi-messenger astronomy : photons + particules (cosmic rays, neutrinos) + gravitational waves
- Either from the ground or from space
- Direct exploration (solar system)
Direct exploration for the solar system : sample analysis in situ or on Earth
- Various techniques : Imaging, Spectroscopy, 3D = images+spectra, Polarimetry, Monitoring, ...
- Open archives



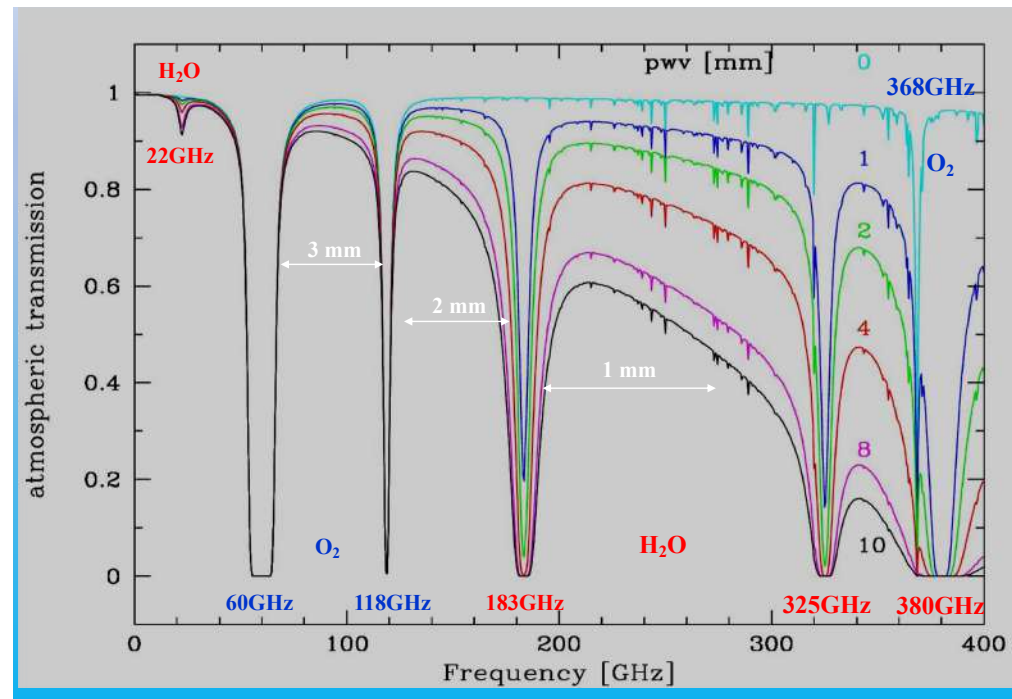
The Earth's atmosphere transmission

- Astronomers try to detect photons at all frequencies : from the gamma rays to radio domain
- Space missions for wavelength not accessible from the ground in most cases



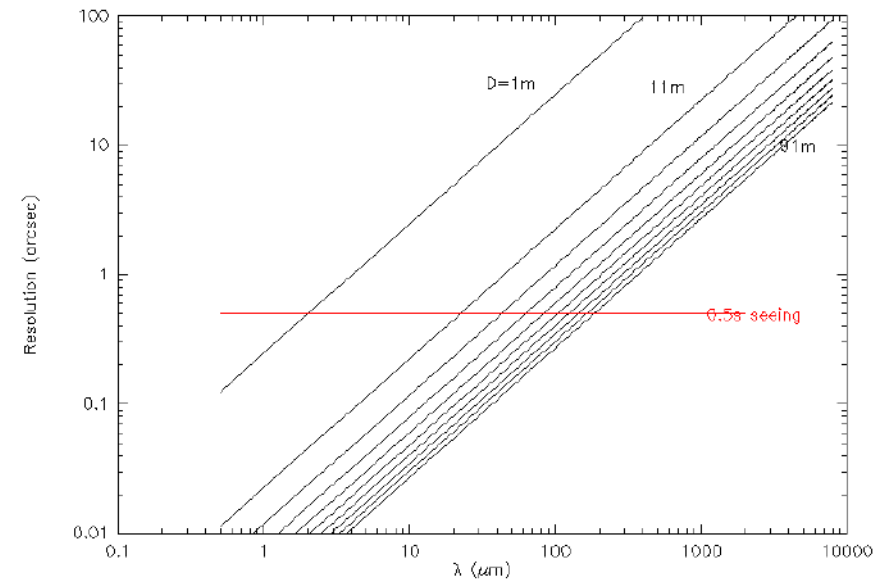
The Earth's atmosphere transmission

- Absorption from molecules (O_2 , O_3 , H_2O , CO_2 ...)
- Absorption from clouds
- Turbulence and winds \rightarrow change of the light path and induce perturbations of the images of the images (seeing)



Specifications for Telescopes and Instruments

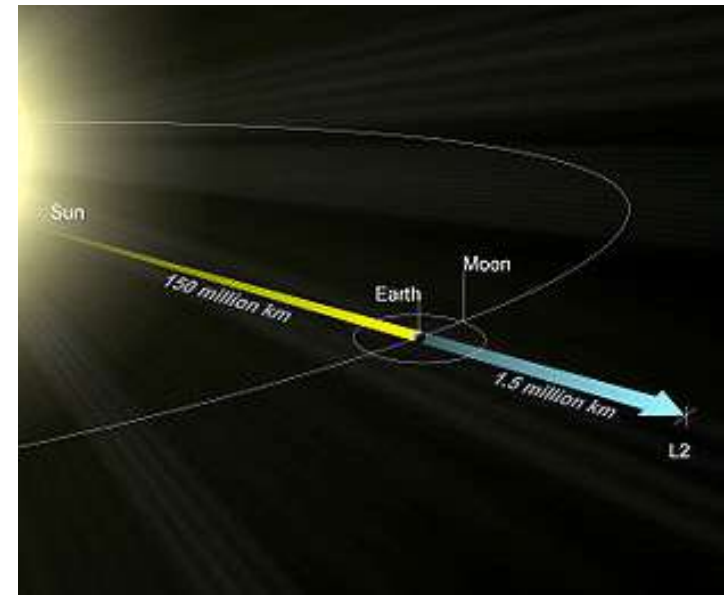
- The telescope and detector technologies depend on the wavelength range
 - Visible : single (up to ~8m diameter) or segmented mirror (glass + thin metal)
 - Radio : parabolic antenna , metallic surface up to ~100m
 - Interferometer f
 - Telescope size → theoretical angular resolution without the atmosphere $\sim 1.2 \lambda/D$
 - Adaptive optics to remove atmospheric image distortion
 - Interferometer to reach the finest angular resolution
- Observatory site
 - atmospheric transmission (H_2O content is the most critical : high altitude site and dry conditions)
 - image quality : stable weather pattern, moderate wind, low turbulence, ...
- Satellite
 - Orbit
 - Stability of environment : e.g. Lagrange point vs Low Earth orbit like HST
 - Instantaneous access to the sky
 - Sky visibility : Sun (+ Earth) avoidance
 - Pointing mode
 - Sky survey (Planck ...)
 - Pointed observations (JWST, HST)



Satellite orbits

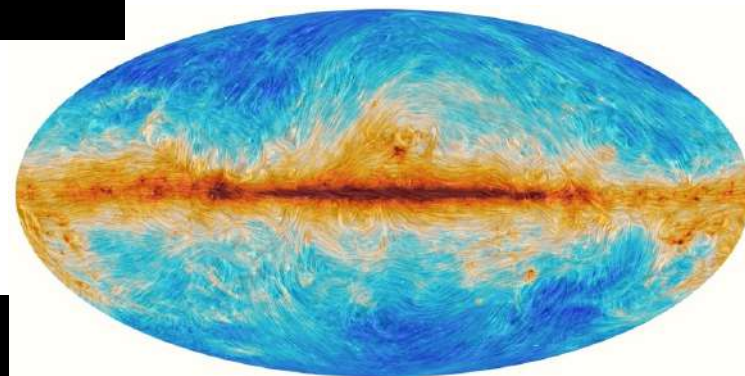
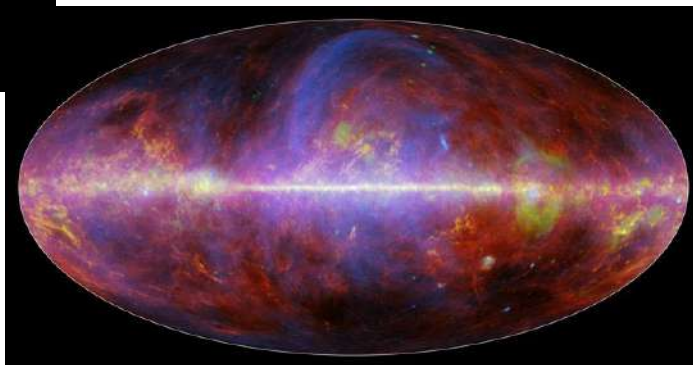
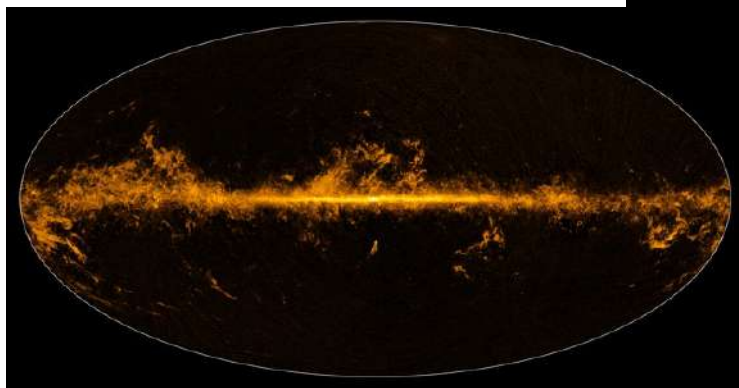
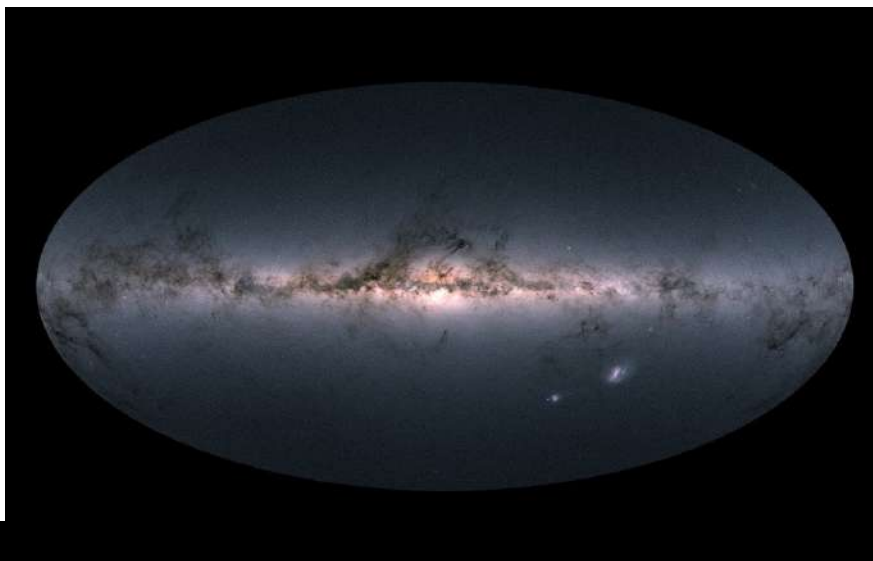


Hubble Space Telescope ~ 570 km



James Webb Space Telescope $\sim 1.5 \cdot 10^6$ km

The benefit of space missions (e.g. GAIA, Planck) : full sky coverage and homogeneous calibration



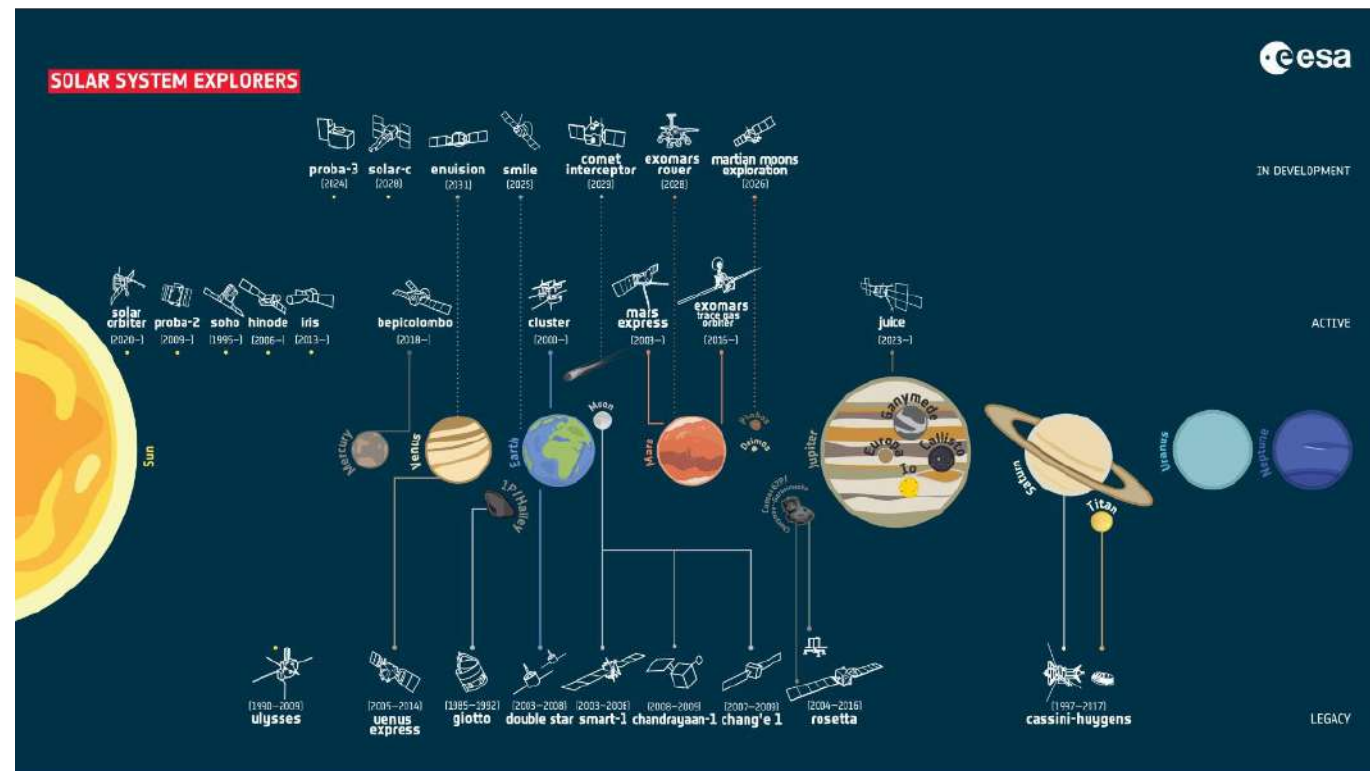
Airplanes & balloons

- Astronomy from airplanes (KAO and SOFIA)
- Few atmosphere left at the tropopause
- Stratospheric balloons operate at ~40km
- More extensively used for atmospheric work than for astronomy
- Main limitations : telescope size and flight time (10 hours ... 2 months)

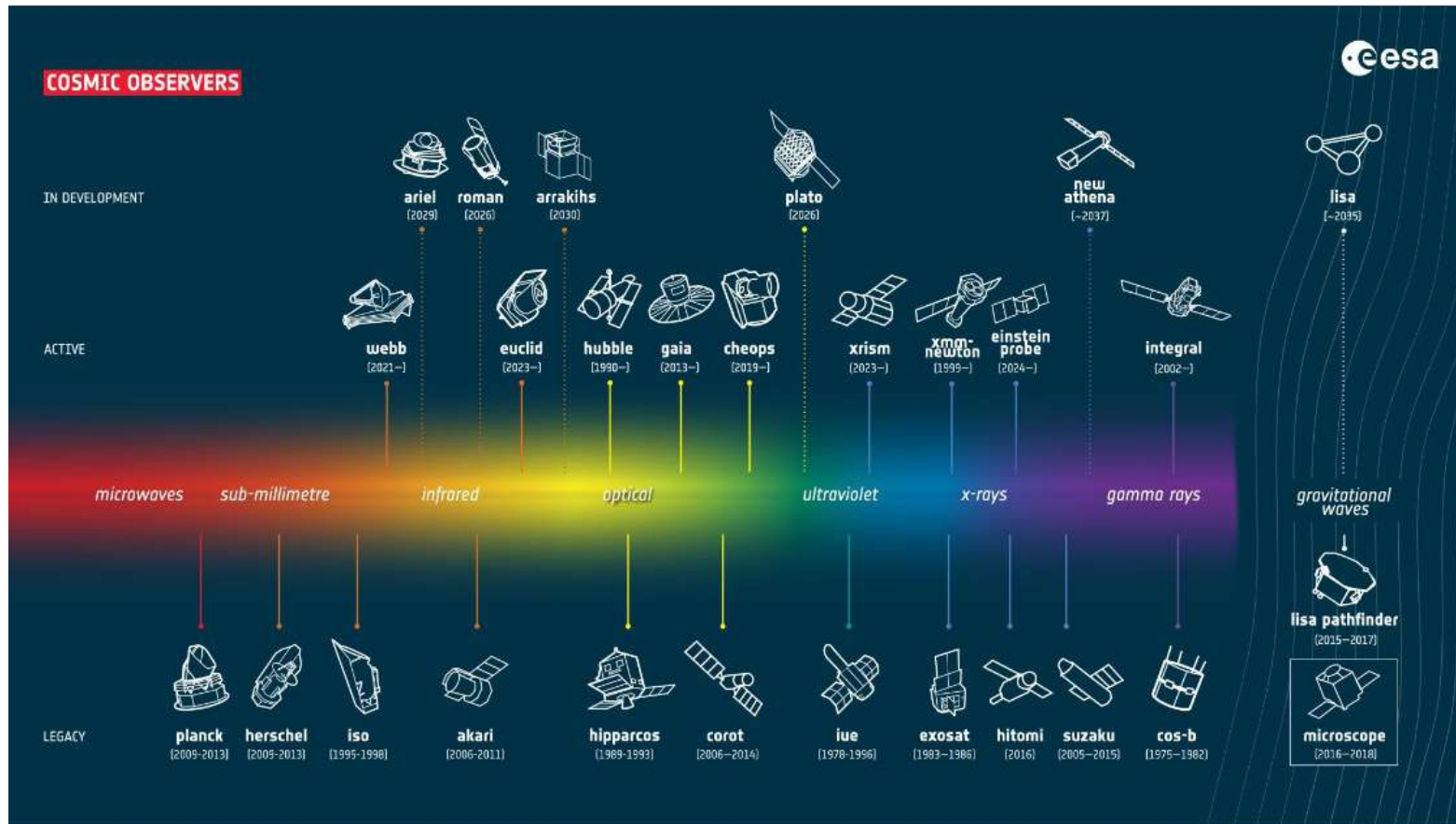


Solar system exploration

- On Earth, extraterrestrial material from meteorites, micro-meteorites and interplanetary dust particles
- Solar system probes allow detailed investigations of solar system bodies surface & atmosphere : images, spectra, in situ measurements, in situ analyses (e.g. Rosetta , Mars rovers)
- Sample collection and return on Earth for further analysis (e.g. NASA/OSIRIS-REX)



Astronomy satellites (ESA view)



Infrared astronomy from Space

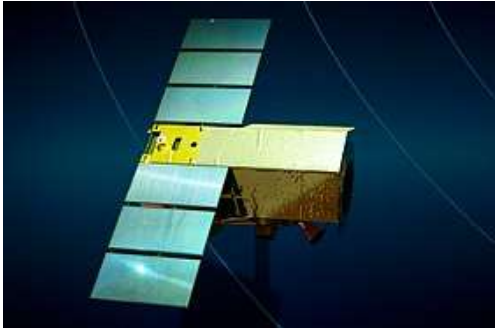
IRAS-1983



MSX-1996



Akari-2006



WISE-2009



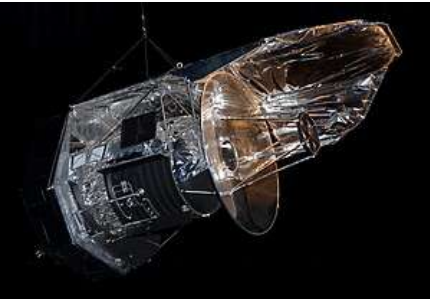
ISO-1995



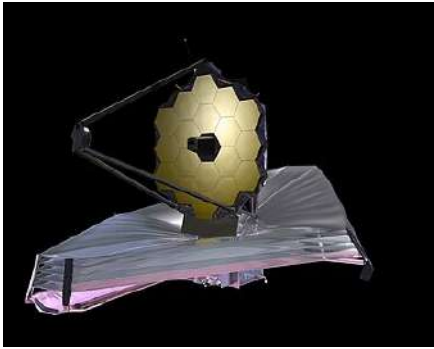
Spitzer-2003



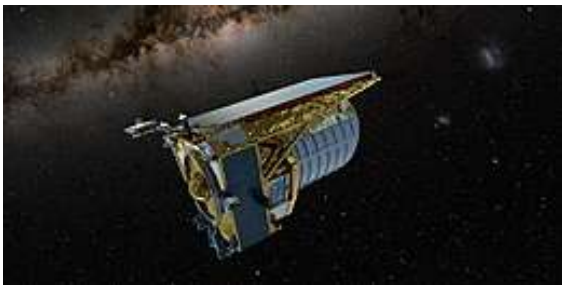
Herschel-2009



JWST-2022



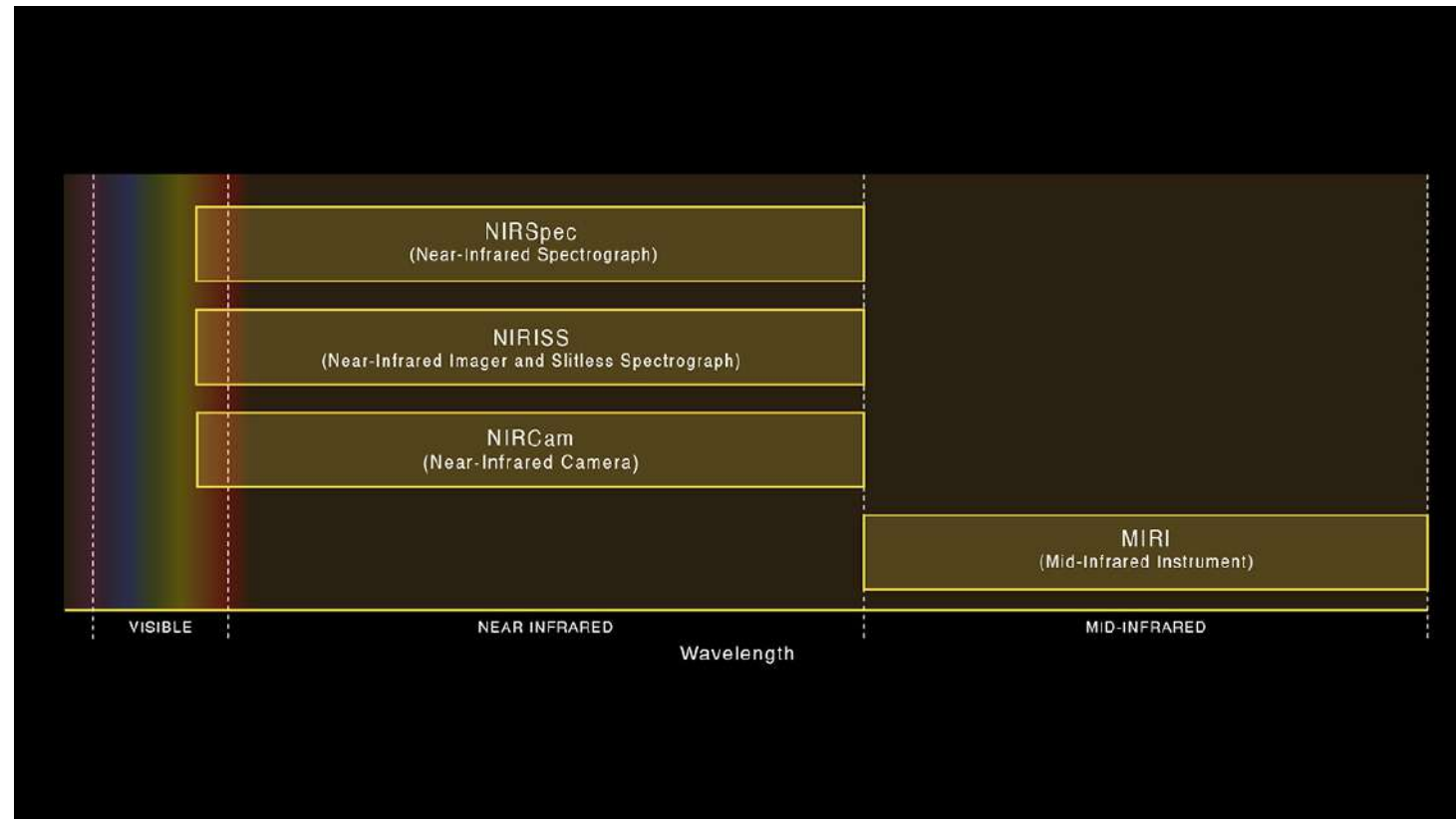
UV satellites



https://en.wikipedia.org/wiki/List_of_space_telescopes#Ultraviolet

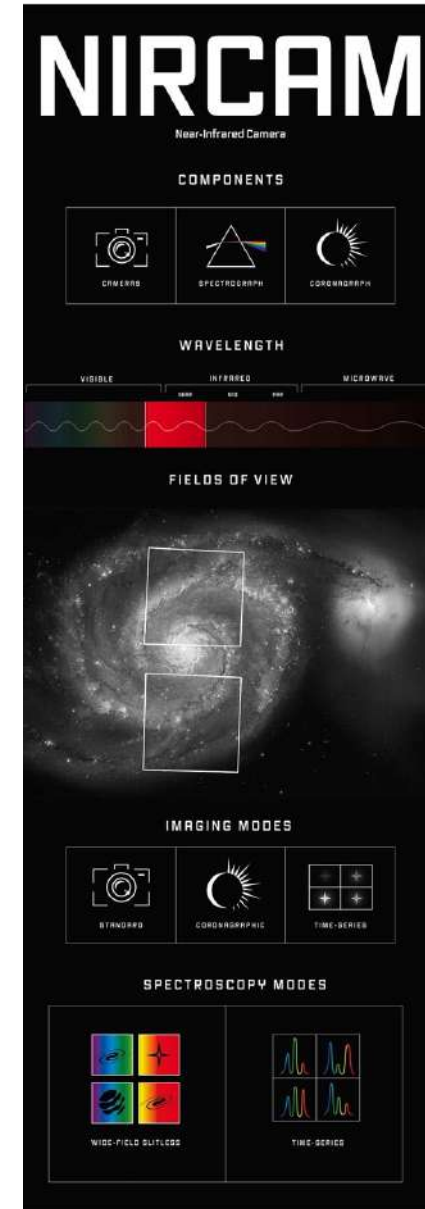
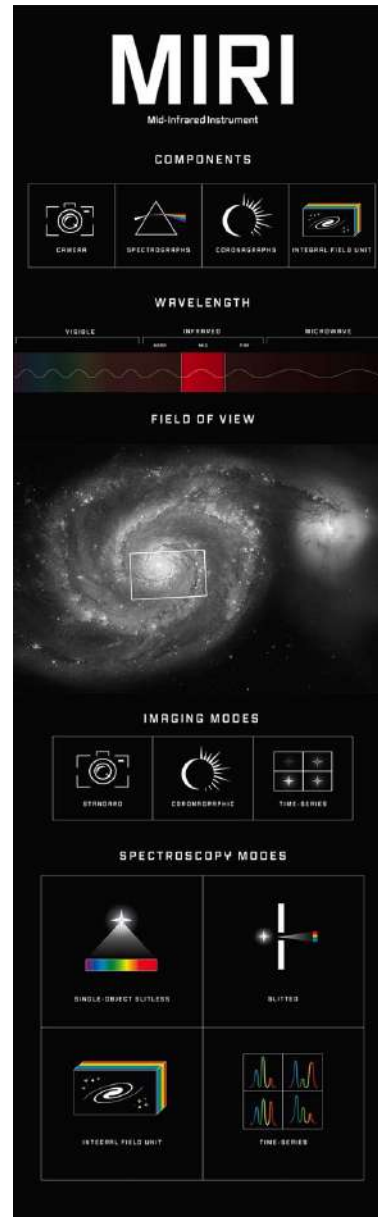
JWST (<https://webbtelescope.org/quick-facts>)

- NASA +ESA and CSA
- 6.5m deployable mirror
- Mid-Infrared Instrument (MIRI) 4.9 – 27.9 μ m
- Near-Infrared Camera (NIRCam) (0.6 – 5 μ m)
- Near-Infrared Spectrograph (NIRSpec) (0.6 – 5.3 μ m)
- Near-Infrared Imager and Slitless Spectrograph/Fine Guidance Sensor (NIRISS/FGS)



JWST Instruments

Optimized combination of imaging and spectroscopic capabilities
Detector choice depends on Wavelength and operation mode



JWST Instruments

NIRSPEC

Near-Infrared Spectrograph

COMPONENTS

- SPECTROGRAPHS
- MICROSHUTTER ARRAY
- INTEGRAL FIELD UNIT

WAVELENGTH

VISIBLE INFRARED MICROWAVE

FIELD OF VIEW

SPECTROSCOPY MODES

- SLITTED
- MULTI-OBJECT
- INTEGRAL FIELD UNIT
- TIME-SERIES

The NIRSPEC infographic features a black background with white text and icons. At the top, the title 'NIRSPEC' is in large white letters, with the subtitle 'Near-Infrared Spectrograph' below it. The 'COMPONENTS' section shows three icons: a spectrograph, a microshutter array, and an integral field unit. The 'WAVELENGTH' section shows a spectrum bar with 'VISIBLE', 'INFRARED', and 'MICROWAVE' labels, and a red box highlighting the instrument's range. The 'FIELD OF VIEW' section shows a spiral galaxy with four white boxes indicating the instrument's field of view. The 'SPECTROSCOPY MODES' section is a 2x2 grid of icons: a slit, a multi-object field, an integral field unit, and a time-series plot.

NIRISS

Near-Infrared Imager and Slitless Spectrograph

COMPONENTS

- CAMERA
- SPECTROGRAPH
- APERTURE MASK

WAVELENGTH

VISIBLE INFRARED MICROWAVE

FIELD OF VIEW

IMAGING MODES

- STANDARD
- APERTURE MASK INTERFEROMETRY

SPECTROSCOPY MODES

- WIDE-FIELD SLITLESS
- SINGLE-OBJECT SLITLESS

The NIRISS infographic features a black background with white text and icons. At the top, the title 'NIRISS' is in large white letters, with the subtitle 'Near-Infrared Imager and Slitless Spectrograph' below it. The 'COMPONENTS' section shows three icons: a camera, a spectrograph, and an aperture mask. The 'WAVELENGTH' section shows a spectrum bar with 'VISIBLE', 'INFRARED', and 'MICROWAVE' labels, and a red box highlighting the instrument's range. The 'FIELD OF VIEW' section shows a spiral galaxy with a single white box indicating the instrument's field of view. The 'IMAGING MODES' section shows two icons: a camera and an aperture mask interferometry mask. The 'SPECTROSCOPY MODES' section shows two icons: a wide-field slitless spectrograph and a single-object slitless spectrograph.

Some ground based telescopes

- Visible (+ near IR) :
 - European Southern Observatory (Chile)
 - Keck telescope, Gemini, Subaru, ... Mauna Kea (Hawaii)
 - Grantecan (Canary Island)
- Gamma rays (from the light produced by interaction of energetic photons and particles with the Earth atmosphere) Cerenkov effect
 - HESS (Namibia)
 - CTA : under construction : 2 sites: Canary Island & Chile
- Radio
 - From meter (LOFAR) to centimeter (JVLA, MeerKAT) to (sub)millimeter wavelengths (ALMA, APEX, JCMT, IRAM-30m, NOEMA, ...)

European Southern Observatory

- <https://www.eso.org/public>
- <https://www.eso.org/public/teles-instr/>
- <https://www.eso.org/public/teles-instr/lasilla>
- <https://www.eso.org/public/teles-instr/paranal-observatory/vlt>
- <https://elt.eso.org>



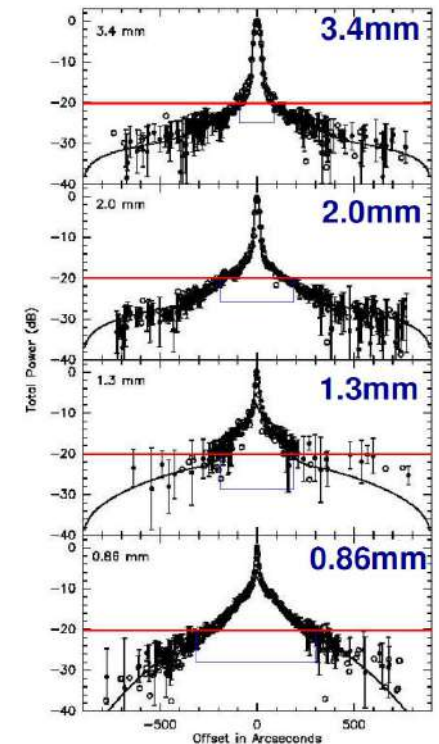
IRAM (Institut de Radioastronomie Millimétrique)

- <https://iram-institute.org/about/resources-outreach>
- <https://iram-institute.org/virtual-tour/30m>
- <https://iram-institute.org/virtual-tour/noema>

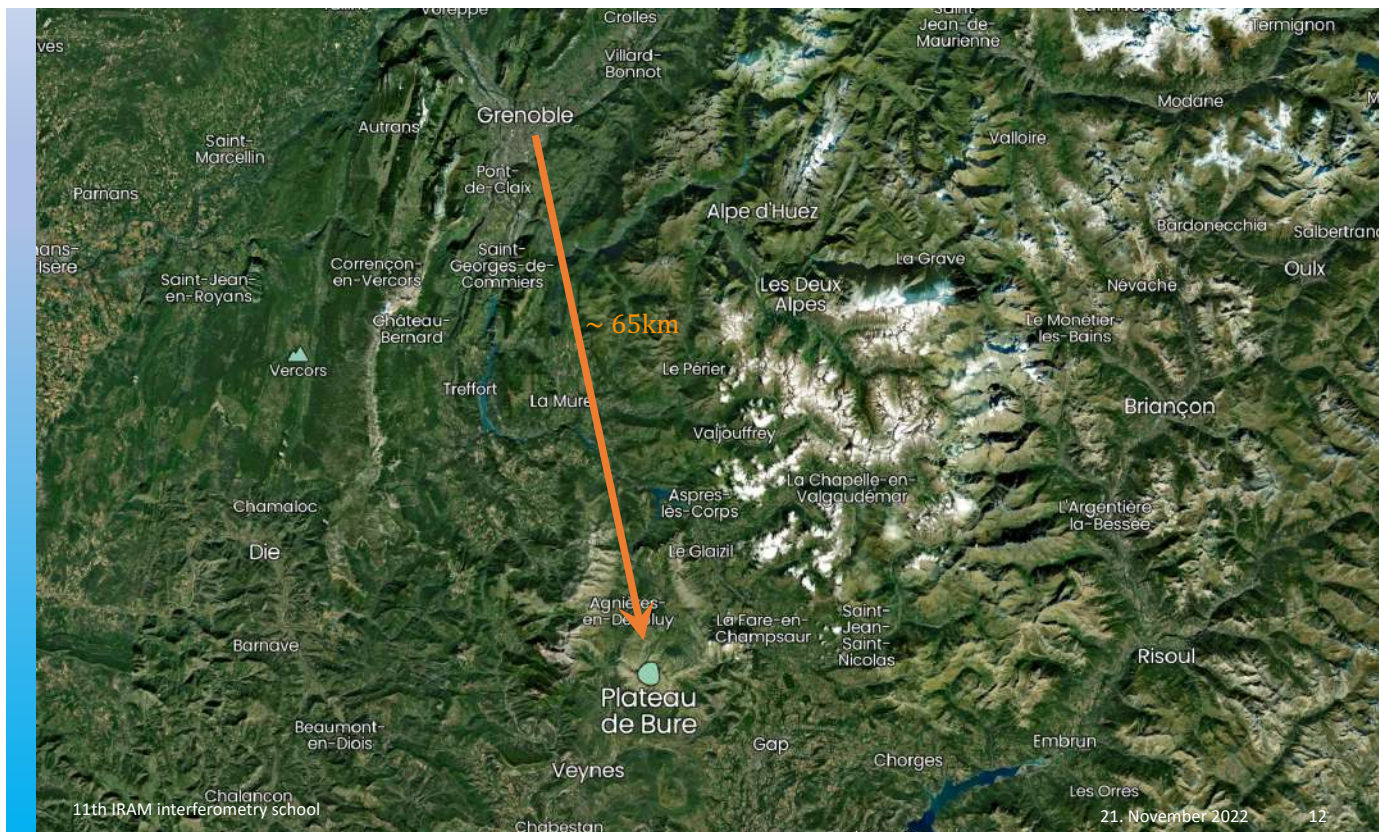


A single dish millimeter telescope : IRAM-30m

- Camera : NIKA2
 - 2 wavelengths : 2mm and 1.2mm
 - Polarization capabilities
 - 2900 detectors in three arrays (616 Pixels at 2mm and 2x1140 at 1.2mm)
 - FoV 6.5'
- Heterodyne receivers : EMIR
 - Single pixel , double polarization
 - 4 frequency bands (72-116 GHz, 120-175 GHz, 200-270 GHz, 260-250 GHz) 16 GHz per frequency band
 - Large scale maps require scanning the sky with the telescope beam : On the Fly observations
 - Telescope beam pattern : theoretical angular resolution (main beam) + secondary lobes



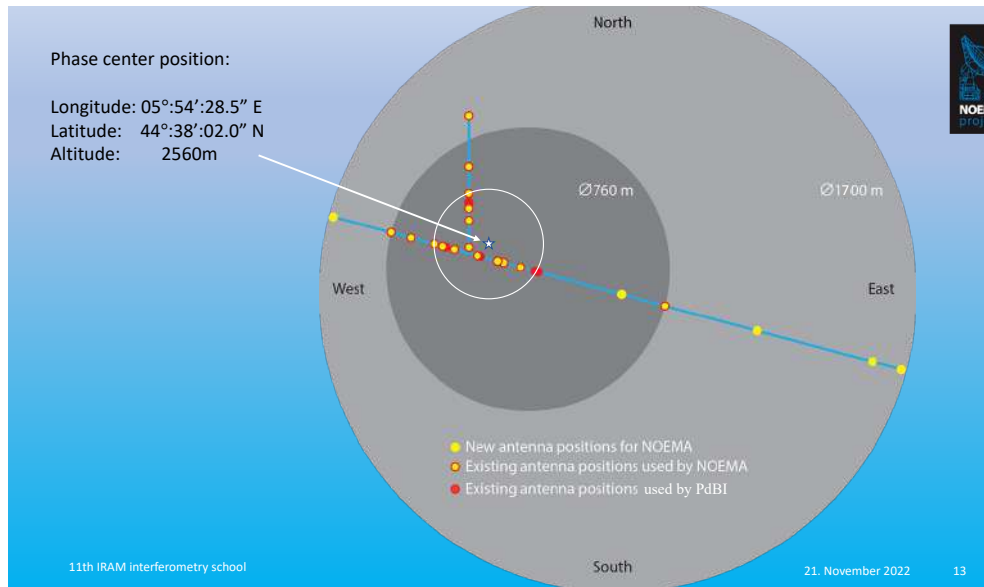
The NOEMA interferometer



Radio interferometer : the NOEMA example

Increase the angular resolution by using several antennas together : the resolution is determined by the distance between the antennas, not by their sizes

Optical/near infrared interferometry at ESO (VLTI) for extremely fine angular resolution



Antennas (I)



Antennas (II)



Diameter: 15 m
Collecting area: 176.7 m²
No. of panels: 176 adjustable aluminum panels
Surface accuracy: 35 μm

A submillimeter interferometer ALMA

Atacama Large (sub)Millimeter Array

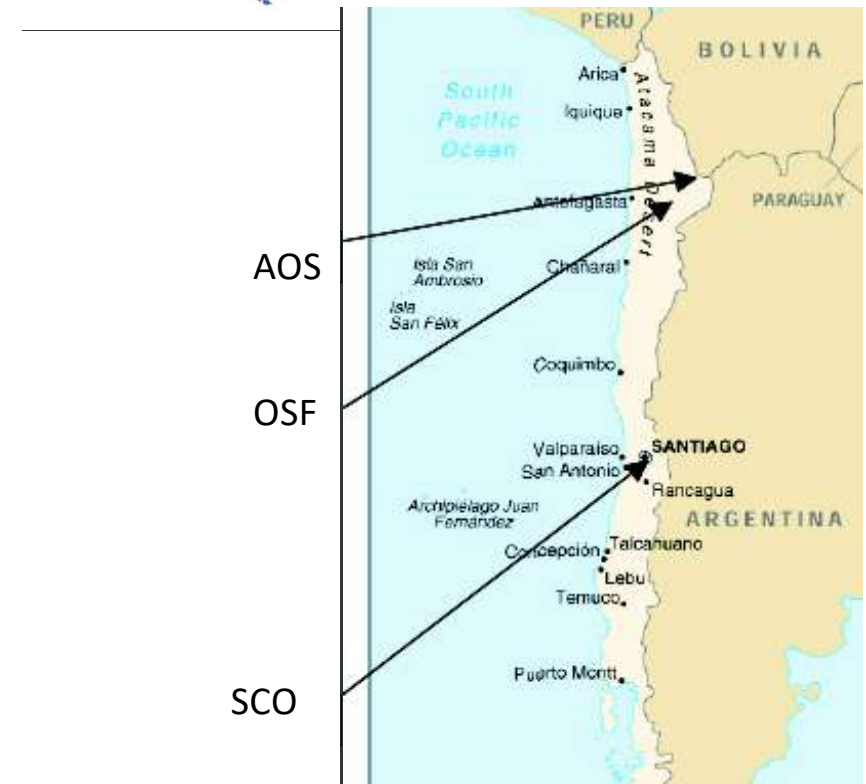
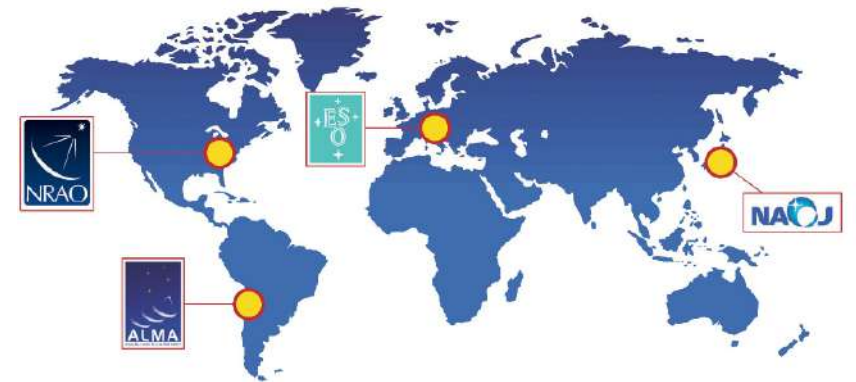
- <https://almascience.eso.org/>
- Main array : 50 x 12m diameter antennas
- Morita (Compact) array : 12x7 m diameter antennas
- 4 single dish telescopes
- 10 frequency bands from 35 to 850 GHz (one at a time)
- 10 main array configurations : baselines up to 16km
- Various observing modes
 - Single pointing
 - Mosaic
 - Spectral survey
 - Full Stokes parameters
 - Solar
 - VLBI



From E. Chapillon's presentation, IRAM interferometry school

ALMA

- World Wide collaboration :
 - Europe (ESO)
 - North America (NRAO, USA, Canada)
 - East Asia (Japan, South Korea, Taiwan)
 - Chile
- A complex organization
 - Main site (AOS), Atacama plateau
 - JAO = Main operations = AOS+OSF+SCO
 - ARC nodes : interfaces with users
- Fully open science archive
- 1 call for observations /year



Specifications for Observations

- One size does not fit all !
 - Compromise between angular resolution (fine details) and Field of View (global view)
 - Compromise between spectral resolution (high for line profile information) and spectral coverage (low to moderate R give a broader coverage)
 - Compromise between complexity of observing modes and easy scheduling survey with standard setups)
- Different detector and spectrometer technologies with wavelength domain : these compromises lead to different instrument concepts

Preparing for observations : e.g. ALMA

- Explain your idea and explain which information you wish to collect and how you can derive it from the measurements : Proposal writing
- Use the Observing tool to derive the sensitivity and optimize the observation procedure : ALMA-OT
 - Selection of the target(s)
 - Selection of the observing mode : FoV, angular resolution, polarization, ..
 - Selection of the spectral line, spectral resolution, spectral bandwidth
 - Sensitivity requirements and computation of the observing time !
Compromise between the sensitivity and time

Preparing for observations : the ALMA science portal

The screenshot shows the ALMA Science Portal website. At the top left is the ALMA logo and the text "Atacama Large Millimeter/submillimeter Array" and "In search of our Cosmic Origins". The navigation bar includes "About", "Science", "Proposing", "Observing", "Data", "Processing", "Tools", "Documentation", "Help", and "Internal Documents". The "Proposing" and "Documentation" items are circled in red. In the top right corner, the user name "Edwige Chapillon" is also circled in red. The main content area is divided into three columns: "Science Highlight", "Observatory News", and "ALMA Status".

Science Highlight
Complex Organic Molecules in a Planet-Forming Disk

0.9 mm
CH_{3OH} E_{up} = 72.9 K
CH_{3OH} E_{up} = 332.6 K
CH_{3OCH₃} E_{up} = 303.9 K

Integrated intensity maps of the 0.9 mm continuum emission and emission from several COMs. Brunken et al. (2022, A&A 659, A29) have detected Complex Organic Molecules (COMs) in the highly

Observatory News

- ALMA Science Archive version 1.0 Oct 13, 2022
- Results of the ACA Standalone Cycle 8 2021 Supplemental Call Sep 07, 2022
- ACA Observatory Filler Programs page now available in the Science Portal Aug 05, 2022
- Issue affecting ALMA polarization and VLBI data taken in Cycle 8 Jul 08, 2022

ALMA Status

- Configuration Schedule
- Refereed publications: 2931
- Last observed source: HOPS-138
- Current configuration: C-2

The ALMA Science Portal is a one-stop source for information and tools aimed at the scientific community as a whole, including proposers, archive researchers, ALMA staff, journalists, and funding agencies.

Quick Links

The ALMA observing tool

The screenshot shows the ALMA observing tool interface with several key components highlighted by red-bordered callout boxes:

- Menu:** Located at the top left, containing File, Edit, View, Tool, Search, and Help.
- Toolbar:** Located below the menu, containing various icons for project management and editing.
- Project Structure Pane:** Located on the left side, showing a tree view of the project structure. A callout box indicates it can be used to "Expand/collapse project tree" and "Navigate the project tree".
- Editor Pane:** The main central area for editing project information. A callout box indicates it is used to "Define the Setup".
- Feedback Pane:** Located below the editor pane, showing validation feedback. A callout box indicates it is used for "Validation feedback".
- Overview Pane:** Located at the bottom right, showing a flowchart of the science proposal process. A callout box indicates it is used for "Information only".
- Contextual Help:** Located at the bottom left, providing instructions for creating a new proposal.

The interface also includes a "Project Structure" pane on the left, an "Editors" pane at the top right, and a "Feedback" pane at the bottom right. The "Project Structure" pane shows a tree view with "Project" and "Proposal" nodes. The "Editors" pane shows fields for "Principal Investigator", "Project", "Assigned Priority", and "Project Code". The "Feedback" pane shows a table with columns for "Description" and "Suggestion". The "Contextual Help" pane contains the following text:

Contextual Help

1. Please ensure you and your co-Is are registered with the [ALMA Science Portal](#).
2. Create a new proposal by either:
 - Selecting *File > New Proposal*
 - Clicking on the icon in the toolbar
 - Or clicking on this [link](#).
3. Click on the proposal tree node and complete the relevant fields.

The "Overview Pane" shows a flowchart for "Phase 2: Science Proposal" with steps: "New Science Proposal", "Create Science Goals", "Validate Science Proposal", and "Submit Science Proposal". Below the flowchart are buttons for "Importing And Exporting", "Template Library", "Need More Help?", and "View Phase 2 Steps".



Project Structure

Proposal Program

Unsubmitted Proposal

- Project
 - Proposal
 - Planned Observing
 - ScienceGoal (Science Goal)
 - General
 - Field Setup
 - Spectral Setup**
 - Calibration Setup
 - Control and Performance
 - Technical Justification

Editors

Spectral Spatial Spectral Setup

Spectral Type ? -

Spectral Line

Single Continuum

Spectral Scan

Polarization products desired XX DUAL FULL

Spectral Setup Errors

Spectral Line ? -

Baseband-1 ? -

Fraction	Centre Freq (rest,lsrk)	Centre Freq (sky,bar)	Transition	Bandwidth, Resolution (smoothed)	Spec Avg	Representative Window
1/2	230.53800 G...	230.53822 G...	CO v=0 2-1	117.188 MHz(152 km/s), 122.070 kHz(0.159 km/s)	1	<input checked="" type="radio"/>
1/4	231.22069 G...	231.22091 G...	13CS v=0 5-4	58.594 MHz(76 km/s), 122.070 kHz(0.158 km/s)	1	<input type="radio"/>
1/4	231.32183 G...	231.32205 G...	N2D+ J=3-2	58.594 MHz(76 km/s), 122.070 kHz(0.158 km/s)	1	<input type="radio"/>

Select Lines to Observe in Baseband-1...

Baseband-2

1(Full)	230.00000 G...	230.00022 G...	...Enter Name...	1875.000 MHz(2444 km/s), 31.250 MHz(40.733 km/s)	1	<input type="radio"/>
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Select Lines to Observe in Baseband-2...

Baseband-3

Feedback

Validation Validation History Log

Data Archives

Observatory archives :

ESO <https://archive.eso.org/scienceportal/home>

ALMA <https://almascience.eso.org/aq/>

JWST <https://mast.stsci.edu/search/ui/#/jwst>

Astronomy science portal : Strasbourg Astronomical Data Center (CDS)

<http://cdsportal.u-strasbg.fr/>

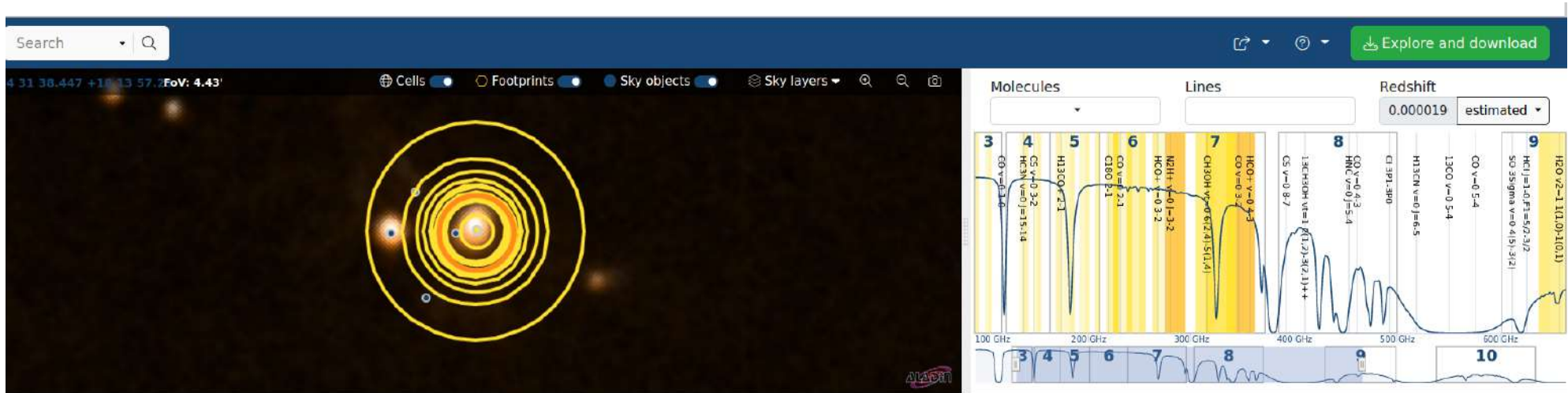
Several tools : ALADIN for Images, VizieR for catalogs, SIMBAD for bibliography, Xmatch for source identification , ...

<https://aladin.cds.unistra.fr/aladin.gml>

ALMA data archive

Search

4 31 38.447 +18 13 57.3 FoV: 4.43' Cells Footprints Sky objects Sky layers



The interface displays a radio continuum image of the HL Tau protoplanetary disk on the left. On the right, a spectral plot shows emission lines from 100 GHz to 600 GHz. The plot is annotated with 10 numbered lines, each corresponding to a specific molecule and transition:

- 3: CO v=2-1
- 4: CS v=1-0 3-2
- 5: H13CO+ v=2-1
- 6: C18O v=2-1
- 7: N2H+ v=0-1 3-2
- 8: HCO+ v=0-1 3-2
- 9: CH3OH v=0-0 6(7,4)-5(1,6)
- 10: H2O v=0-0 1(1,1)-1(0,1)

Below the plot, the redshift is set to 0.000019 (estimated).

Observations (21) | Projects (4069) | Publications (2896)

ALMA source name: HL_Tau

Project code	ALMA source name	RA	Dec	Band	Cont. sens.	Frequency support	Release date	Publications	Ang. res.	Min. vel. res.	Array	Mosaic	Max. reco. scale
		h:m:s	d:m:s		mJy/beam				arcsec	km/s			arcsec
<input type="checkbox"/> <input type="button" value="G"/> <input type="button" value="↔"/> <input type="button" value="~"/> <input type="button" value="📄"/>	<input type="text" value="2011.0.00015.5"/>	HL_Tau	04:31:38.426	+18:13:57.04'	7	0.0357	335.498..351.486 GHz	2016-06-24	27	0.020	26.654	12m	1.719
<input type="checkbox"/> <input type="button" value="G"/> <input type="button" value="↔"/> <input type="button" value="~"/> <input type="button" value="📄"/>	<input type="text" value="2011.0.00015.5"/>	HL_Tau	04:31:38.426	+18:13:57.04'	6	0.0199	223.003..242.99 GHz	2016-06-24	27	0.027	38.555	12m	2.811
<input type="checkbox"/> <input type="button" value="G"/> <input type="button" value="↔"/> <input type="button" value="~"/> <input type="button" value="📄"/>	<input type="text" value="2013.1.00355.5"/>	HL_Tau	04:31:38.427	+18:13:57.03'	7	0.0364	335.493..351.528 GHz	2016-10-29	1	0.112	53.309	12m 7m	7.787
<input checked="" type="checkbox"/> <input type="button" value="G"/> <input type="button" value="↔"/> <input type="button" value="~"/> <input type="button" value="📄"/>	<input type="text" value="2016.1.00961.5"/>	HL_Tau	04:31:38.435	+18:13:56.87'	7	0.0377	276.98..290.734 GHz	2017-12-15	0	0.449	0.131	12m	4.863
<input type="checkbox"/> <input type="button" value="G"/> <input type="button" value="↔"/> <input type="button" value="~"/> <input type="button" value="📄"/>	<input type="text" value="2016.1.00115.5"/>	HL_tau	04:31:38.446	+18:13:57.28'	3	0.0118	89.507..105.475 GHz	2018-01-27	5	0.379	181.016	12m	3.825
<input type="checkbox"/> <input type="button" value="G"/> <input type="button" value="↔"/> <input type="button" value="~"/> <input type="button" value="📄"/>	<input type="text" value="2016.1.00162.5"/>	HL_Tau	04:31:38.447	+18:13:57.28'	7	0.0382	335.526..351.496 GHz	2018-06-23	3	0.340	53.609	12m	3.976

Astronomy portal : Strasbourg astronomical Data center : CDS

A screenshot of the CDS search results page for the object M42. The search bar contains 'M42' and the position '05 35 16.800 -05 23 24.00'. The page is divided into several sections: 'Object (Simbad)' and 'Object (NED)' provide identification details. The 'Images' section shows 375 HiPS images available, with a table of search results. The 'Aladin Lite' section shows a DSS colored image of the object.

Search results for M42 (J2000 position: 05 35 16.800 -05 23 24.00):

- 375 HiPS images
- 1417 VizieR tables
- 4116 bibliographical references

Object (Simbad) details:

- Main ID: M 42
- Object type: HII Region
- z: 0.00009273511836616066
- [More info in Simbad](#)

Object (NED) details:

- Main ID: MESSIER 042
- Object type: HII region
- [More info in NED](#)

Images section:

375 HiPS images available 0.20° around 05 35 16.800 -05 23 24.00 :

Wavelength: Gamma-ray X-ray UV Optical Infrared Radio Gas-line

Resolution: Low Medium High

Show: All HiPS CDS featured My favorites

Filter: [] 16 entries (filtered from 375 total records) continuous update

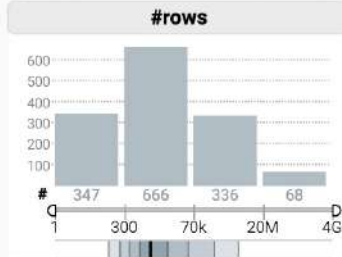
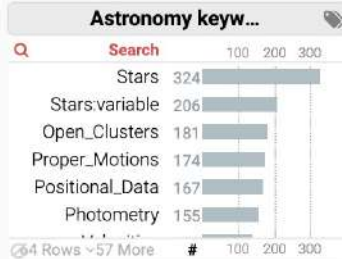
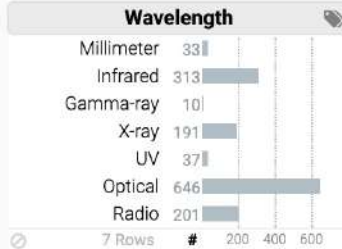
title	wavelength	Sky fraction
★ Fermi Color HEALPix survey	Gamma-ray	100 %

Aladin Lite section:

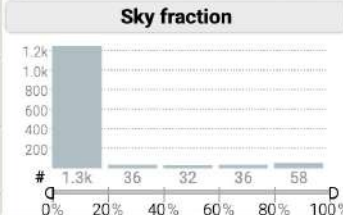
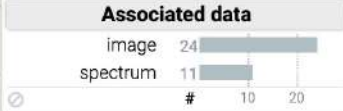
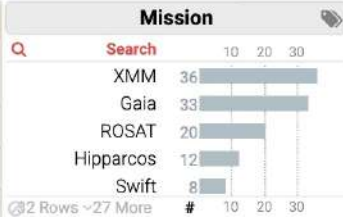
DSS colored image of M42 (J2000 position: 05 35 16.800 -05 23 24.00)

Catalogues

1417 VizieR Catalogs within radius 0.20°

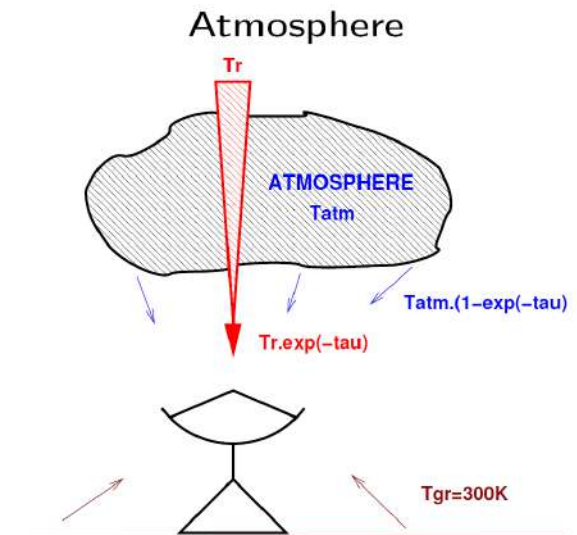


- Popularity Q Search: Title
- ★ Gaia DR3 Part 1. Main source (Gaia Collaboration, 2022) (gaiadr3) [i](#)
 - ★ Gaia EDR3 (Gaia Collaboration, 2020) (comscanl) [i](#)
 - ★ Gaia EDR3 (Gaia Collaboration, 2020) (giaaedr3) [i](#)
 - ★ Gaia EDR3 (Gaia Collaboration, 2020) (tyc2tdsc) [i](#)
 - ★ TESS Input Catalog version 8.2 (TIC v8.2) (Paegert+, 2021) (tic82) [i](#)
 - ★ 2MASS All-Sky Catalog of Point Sources (Cutri+ 2003) [i](#)
 - ★ AllWISE Data Release (Cutri+ 2013) (allwise) [i](#)
 - ★ Gaia DR2 (Gaia Collaboration, 2018) (gaia2) [i](#)
 - ★ Gaia DR2 (Gaia Collaboration, 2018) (lrv) [i](#)
 - ★ Gaia DR2 (Gaia Collaboration, 2018) (rrlyrae) [i](#)
 - ★ Gaia DR2 (Gaia Collaboration, 2018) (varres) [i](#)
 - ★ The Pan-STARRS release 1 (PS1) Survey - DR1 (Chambers+, 2016) (ps1) [i](#)
 - ★ AAVSO Photometric All Sky Survey (APASS) DR9 (Henden+, 2016) (apass9) [i](#)
 - ★ Gaia DR3. Cross-match with known variable objects (Gavras+, 2023) (catalog) [i](#)
 - ★ UCAC4 Catalogue (Zacharias+, 2012) [i](#)



Calibration and data analysis : from instrument units to physical units

- Sophisticated observation procedures : acquisition toward the target, off source, on standards, ..
- Calibration must include
 - a correction of the Earth atmosphere emission and attenuation (ON OFF procedure)
 - Frequency/wavelength Calibration
 - Knowledge of filter bandpass
 - Corrections for instrument drifts (internal, related to observation conditions e.g. telescope temperature or elevation) .. According to the observation procedure
 - Correction of instrument function (telescope PSF, spectral response)
- Calibration makes use of standards
 - Astronomical standards = well known objects with accurate models of their emission (e.g. stars, planets)
 - Internal standards (e.g. hot and cold load in radio telescopes, frequency or wavelength reference)
- The overall accuracy depends on the telescope & instrument ..
 - Absolute flux calibration is at the level of 5/10% ;
 - Relative flux calibration is much better
 - Wavelength and frequency calibrations are excellent



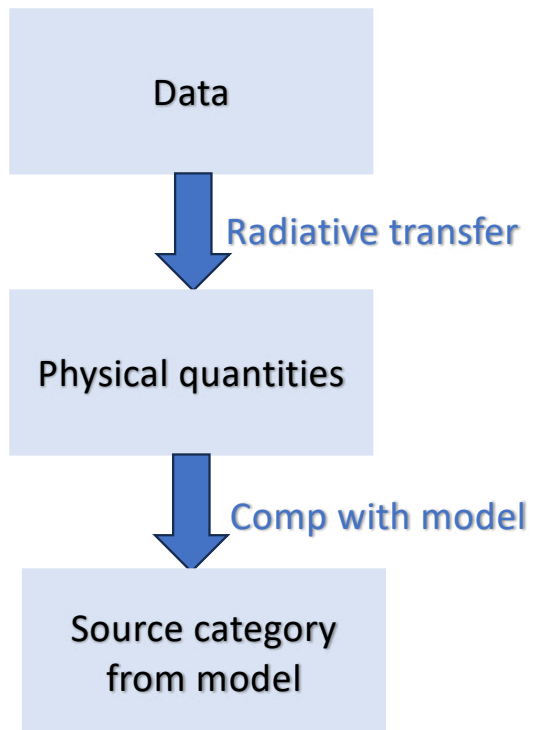
Calibration and data analysis : From physical units to calibrated spectra and images

- Data calibration, and data processing
 - Making images and spectra from raw data :
 - Sampling in frequency / velocity space
 - Gridding and resampling the data acquisitions
 - Correction for telescope & instrument artefacts (beam shape, instrument function, instrument efficiency ...)
 - Computing the physical quantities
 - Each of this step can introduce noise and systematic errors
- The sensitivity calculations in the Observing tools include all steps
- Systematic effects (e.g. a flux calibration error, pointing offset, beam smearing...) can be significant even for high S/N data and are not usually included in the sensitivity calculations

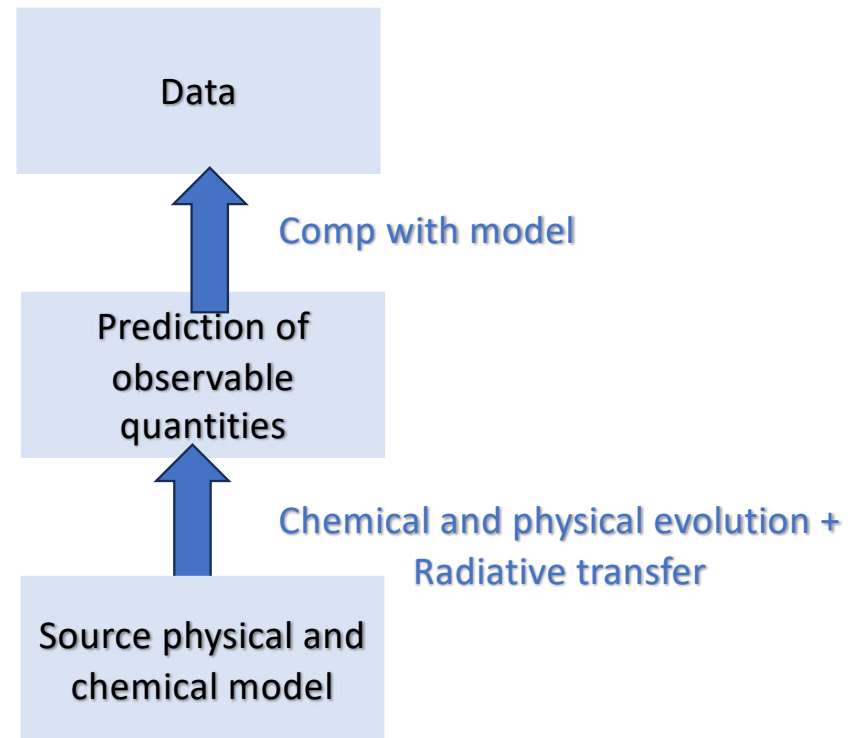
Extracting physical and chemical information

- Use all available information : images, spectra, polarization
- Inversion of the radiative transfer equation
 - Start from the data and use the radiative transfer equations to compute physical quantities (column density, excitation temperature, kinetic temperature, density, etc.)
 - The comparison with models is done using the extracted physical quantities and not the observed data
- Forward Model
 - Run physical and chemical models of the source providing predictions of fluxes of observed line and continuum intensities (e.g. the Meudon PDR model, a shock model, molecular cloud numerical simulation ..)
 - The predictions from the forward model can be compared to the observed data to extract information on the model control parameters (Density, radiation field, time etc.)

Inversion



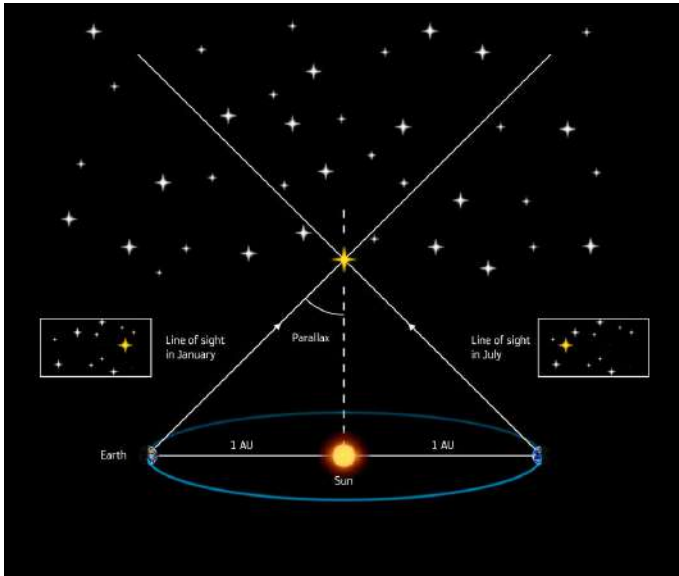
Forward model



Physical and chemical information : structure

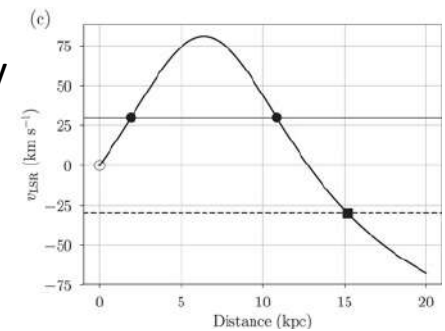
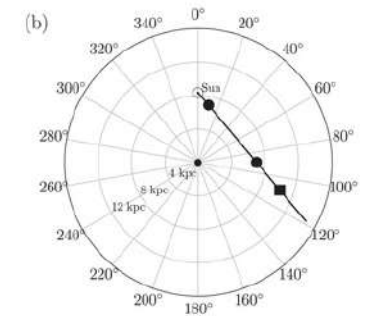
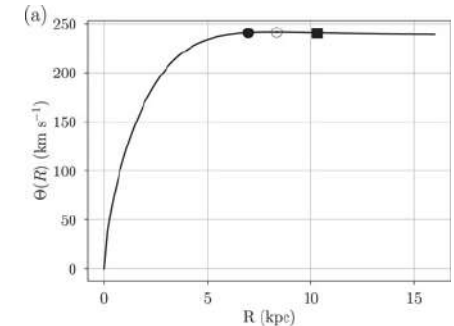
- Source sizes
 - From the angular extent of the source
 - Must know the source distance
- Definition : 1 parsec = the distance from Earth to Sun ($1 \text{ AU} = 1.5 \cdot 10^8 \text{ km}$) is viewed with an angle of $1 \text{ arcsec} = 648000/\pi$ astronomical units
- Angular size of well known objects
 - Moon. $30'$
 - Planet : Jupiter $\sim 32\text{-}50''$; Uranus $\sim 3\text{-}4''$
 - Circumstellar Disk $0.25''$ (100 ua) if in Orion (Distance of 400pc)
 - Star forming core $50''$ (0.1 pc)
 - Nebula/Cloud 1.4° (10pc) if in Orion
 - Galaxy $8.5'$ (10 kpc) for a galaxy in the local group (4 Mpc)
 - High redshift galaxy $\sim 1''$ (not a point source)

Measuring distances



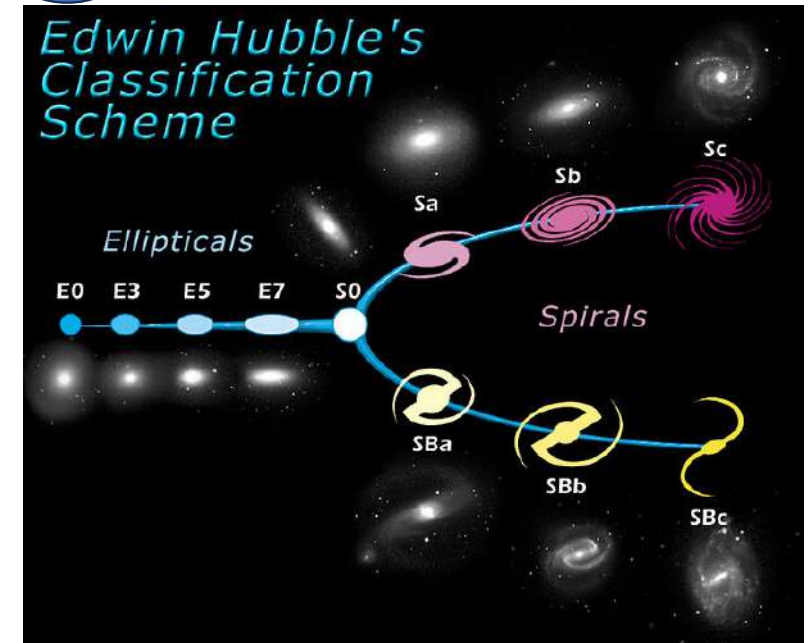
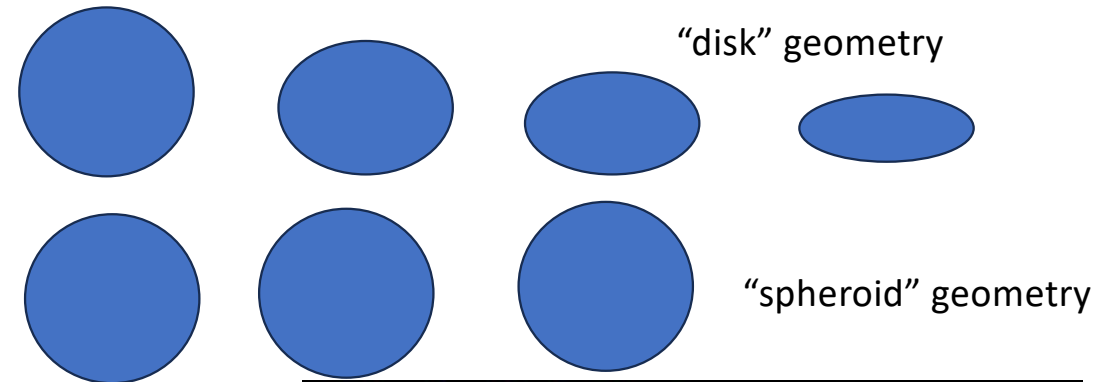
- Parallax = displacement of the source apparent position due to the Earth motion
 - Most accurate distance determination (geometrical effect)
 - The GAIA mission has measured $\gg 10^6$ stellar parallax
 - Maser features (H_2O , SiO) can also provide parallax associated to star forming regions, or stellar envelopes

- The radial velocity provides information on the relative displacement of the source with respect to the observatory
- Using a velocity field model (e.g. Galaxy rotation curve) in the Milky Way, the source distance can be derived



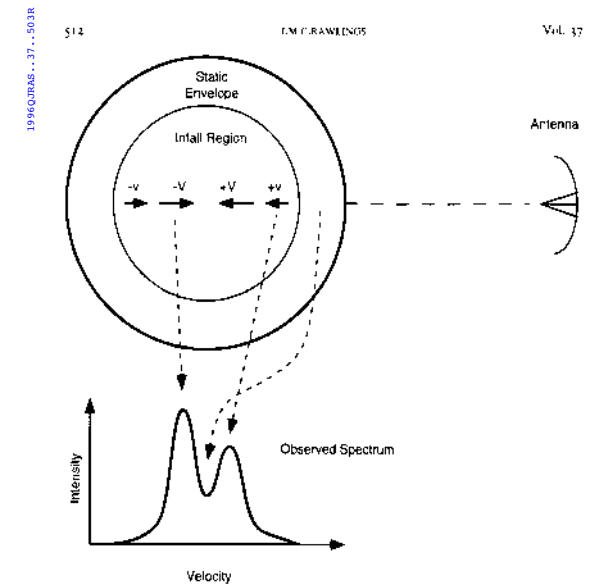
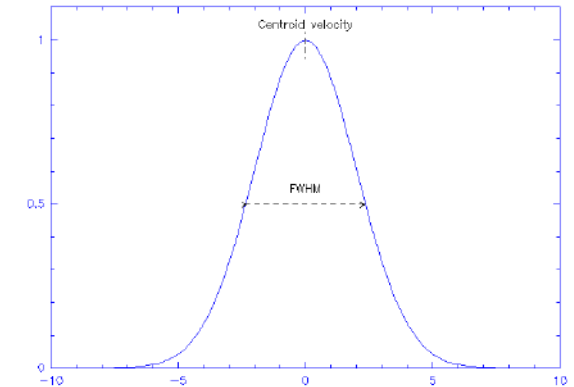
Physical and chemical information : structure

- Images = 2D projections of 3D structures on the plane of the sky.
- Integration along the line of sight → use assumptions to get information on the 3D structure :
 - Statistics : different viewing angles of similar sources
 - Velocity field (e.g. rotation, expansion, infall, outflow, ..)
 - Differential extinction



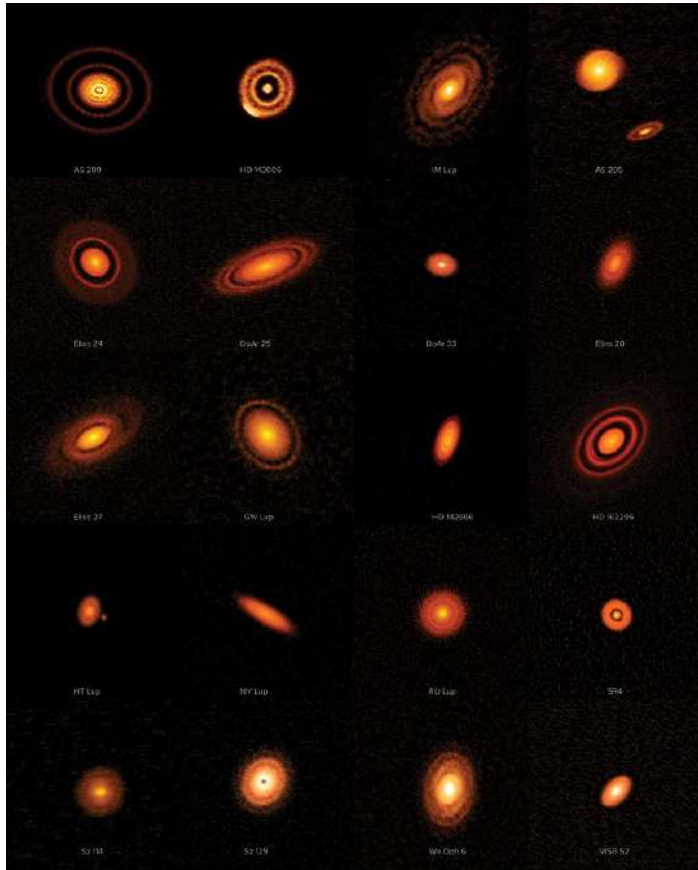
Physical and chemical information : velocity

- Along the line of sight
 - The velocity along the line of sight easily derived from the Doppler effect $\delta v/c \sim \delta \lambda/\lambda \sim \delta v/v$ (positive velocity and redshifted wavelengths for receding objects, negative velocity and blueshifted wavelengths for approaching objects)
 - Spectrally resolved line profile \rightarrow Centroid velocity, velocity dispersion or Full Width at Half Maximum
- Velocity in the plane of the sky ?
 - From proper motions : displacement of the source due to its intrinsic motion
 - Requires accurate positioning and multiple observations spaced in time
 - 100 km/s \rightarrow \sim 0.05 arcsec/yr in Orion

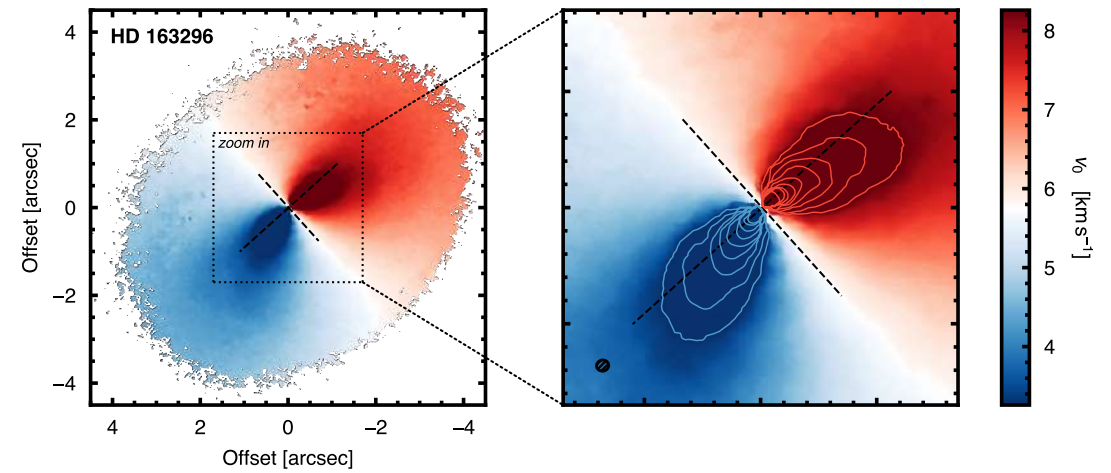
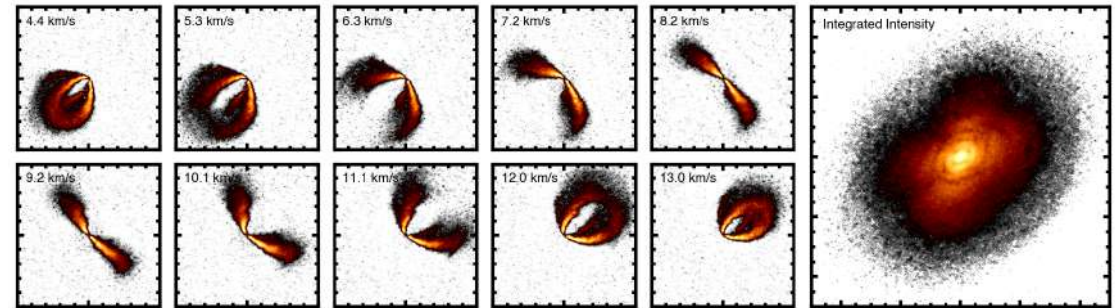


Collapsing core

FIG. 4. Signatures of collapse: the formation of asymmetric, double-peaked, optically thick line profiles in collapsing clouds. See text for description.

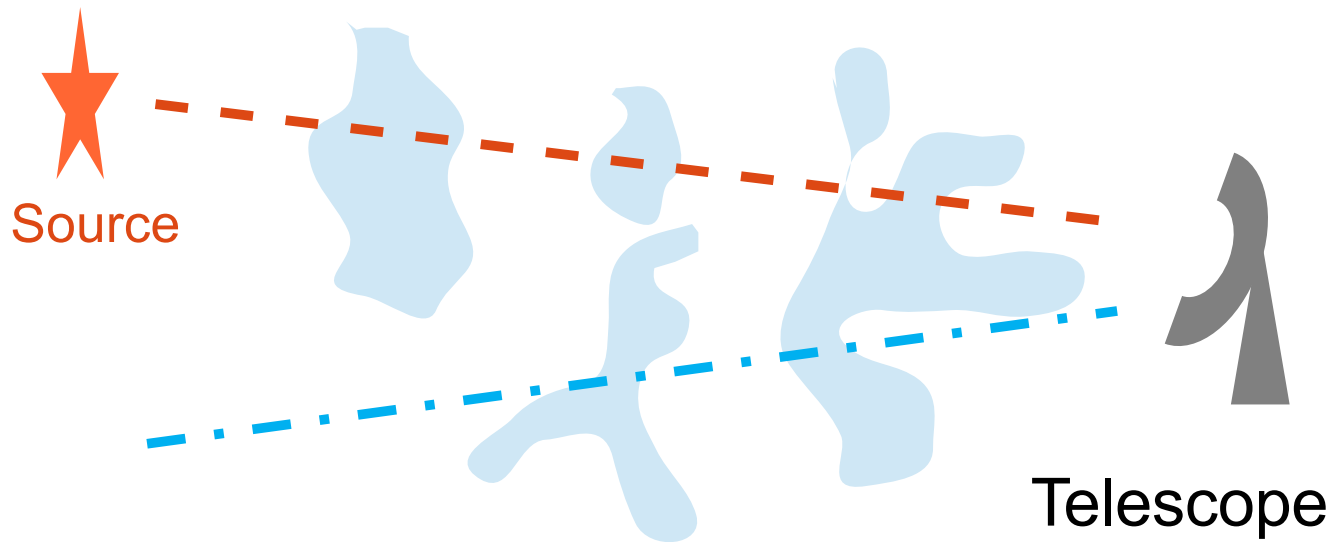


DSHARP , protoplanetary disks with ALMA



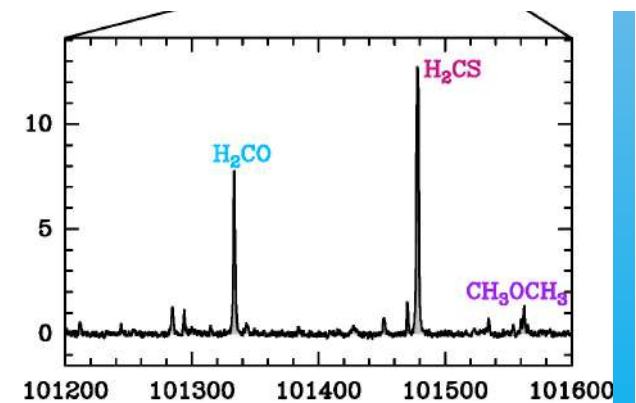
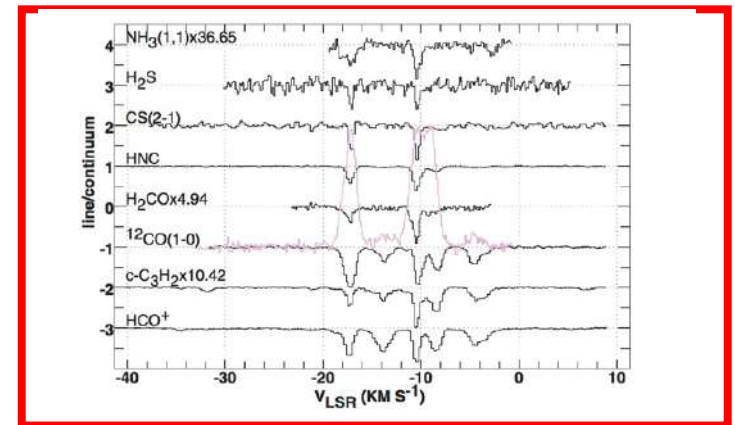
HD 163296 12CO channel ma & velocity field (Armitage+, Isella+)

Line of sight structure : combine emission & absorption

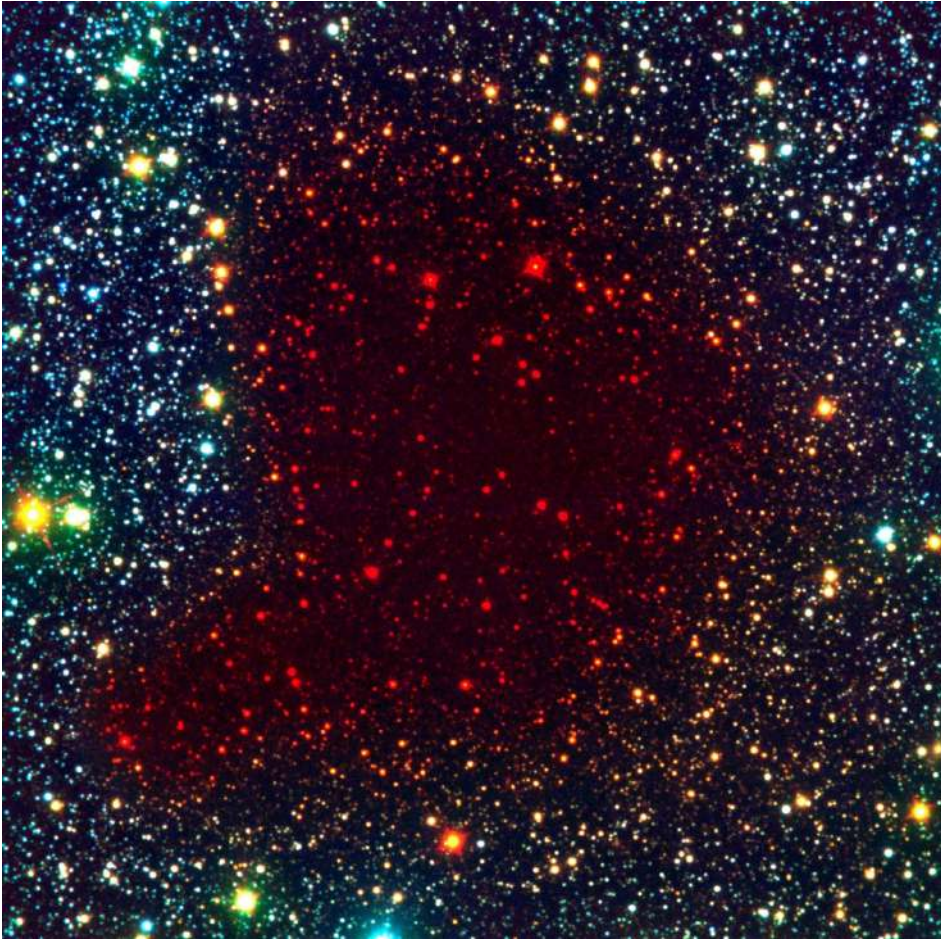


Absorption and emission provide complementary information

This information can be used to locate the object along the line of sight and for extracting the physical conditions

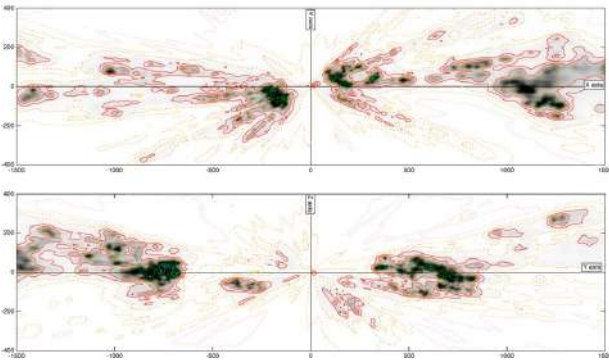
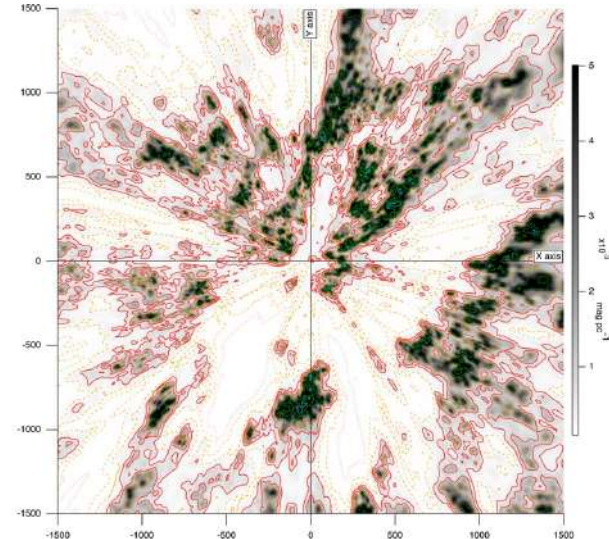


Extinction and reddening

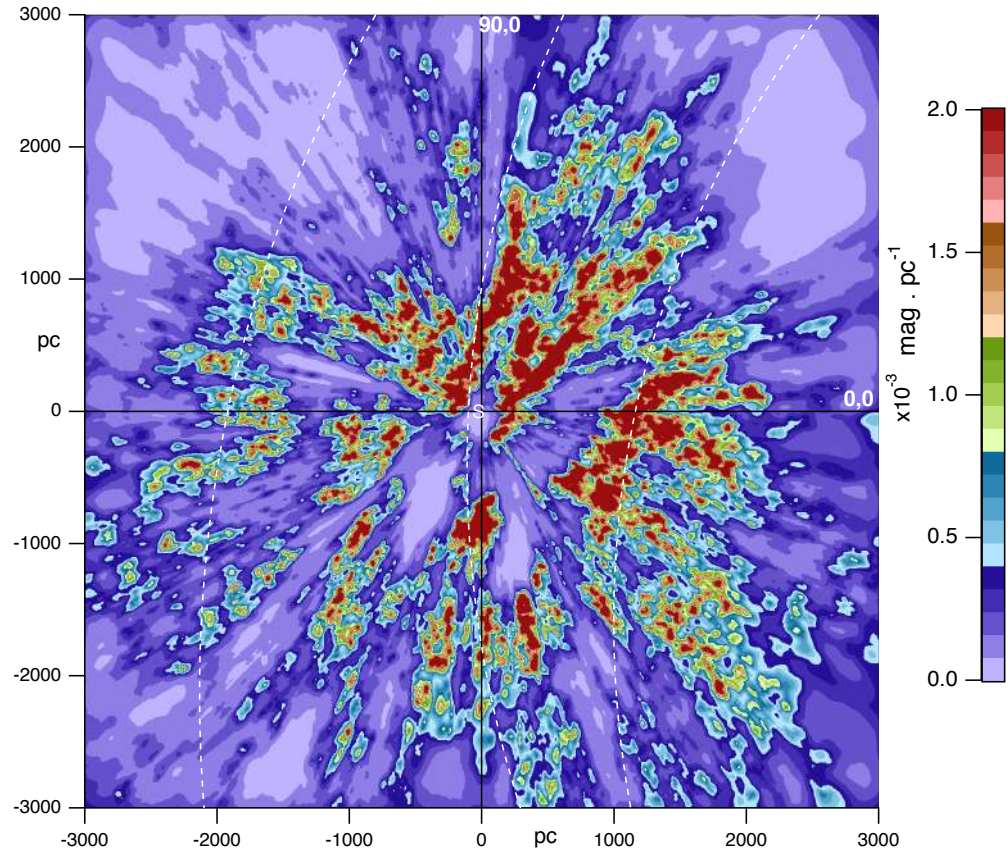


- The light from background stars is absorbed and scattered by dust grains
- The extinction is stronger for short wavelengths → reddening effect
- If the distance to the stars is known (e.g. from GAIA) the differential extinction can be used to locate the dust clouds with respect to the stars

The 3D structure

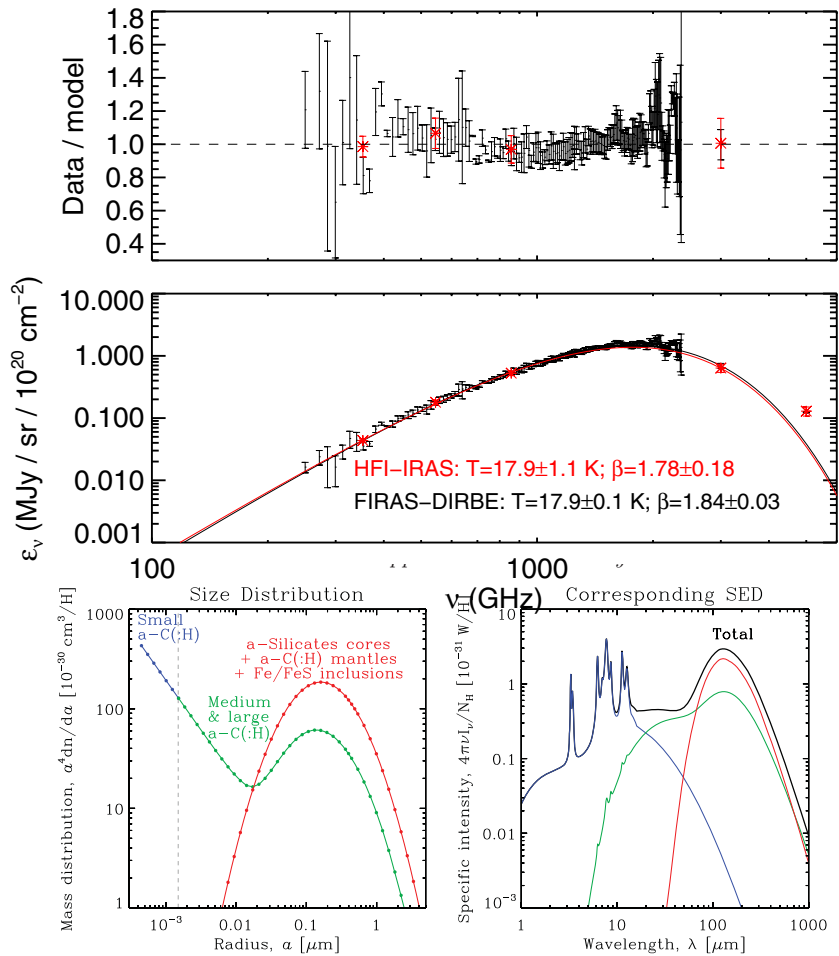


Vergely+2022



- The matter accumulates in “clouds”
- Most of the volume is filled with low density material ($n < 1 \text{ cm}^{-3}$) with little dust
- Limited spatial resolution

Dust emission (simplistic view)



Dust grains are well mixed with gas with a gas/dust ratio of ~100

Dust grains produce a thermal grey body emission that can be modelled as

$$I_\nu \sim M_{\text{grains}} \epsilon(\nu) B_\nu(T_g) \sim N_{\text{gas}} \epsilon(\nu) B_\nu(T_g)$$

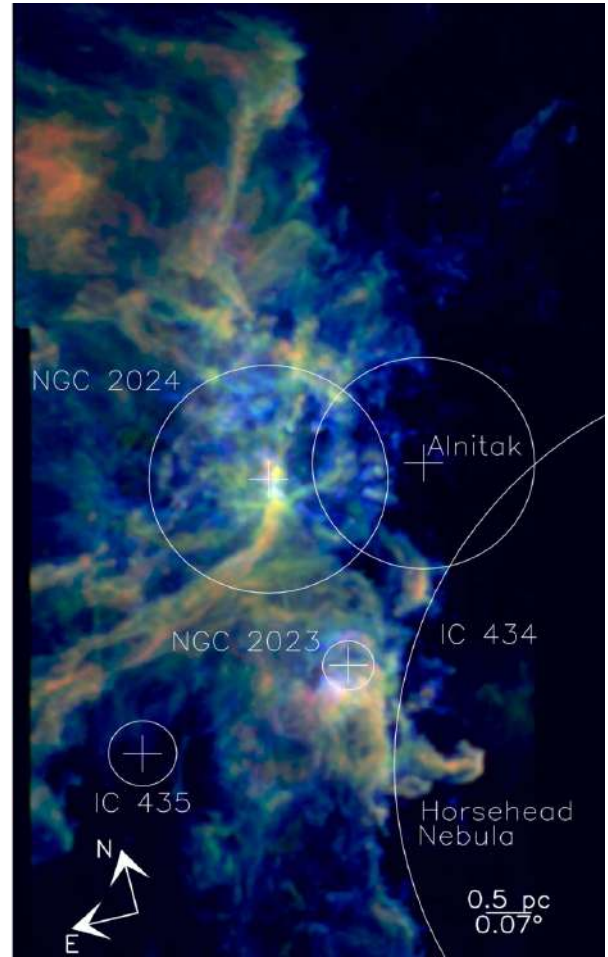
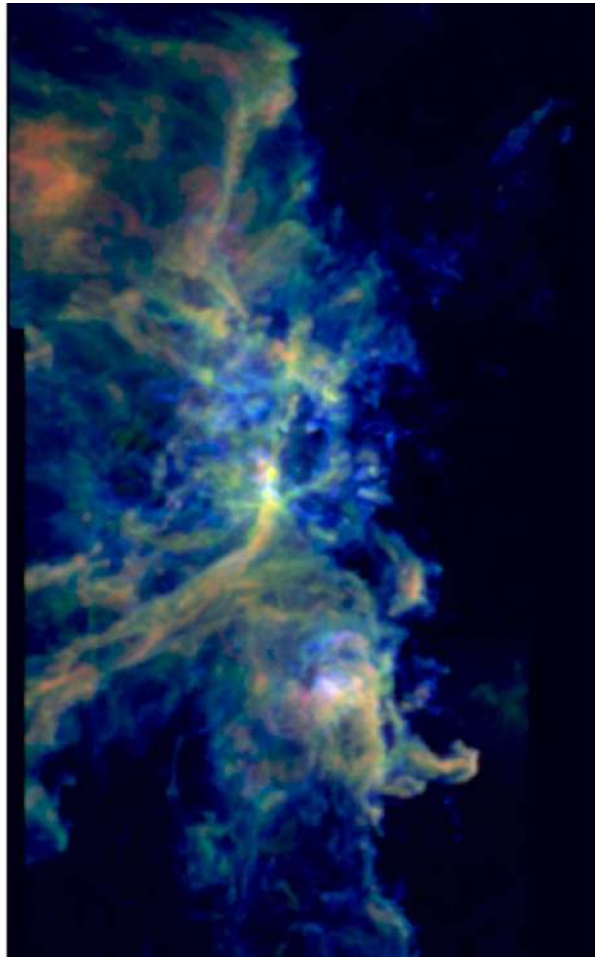
With dust emissivity $\epsilon(\nu)$ scaling as ν^β

With measurements of I_ν in different frequency bands, the Spectral energy distribution (SED) can be built

The SED fit gives the dust temperature T_g , the dust emissivity index β and the gas column density N_{gas} (with assumptions on the dust properties)

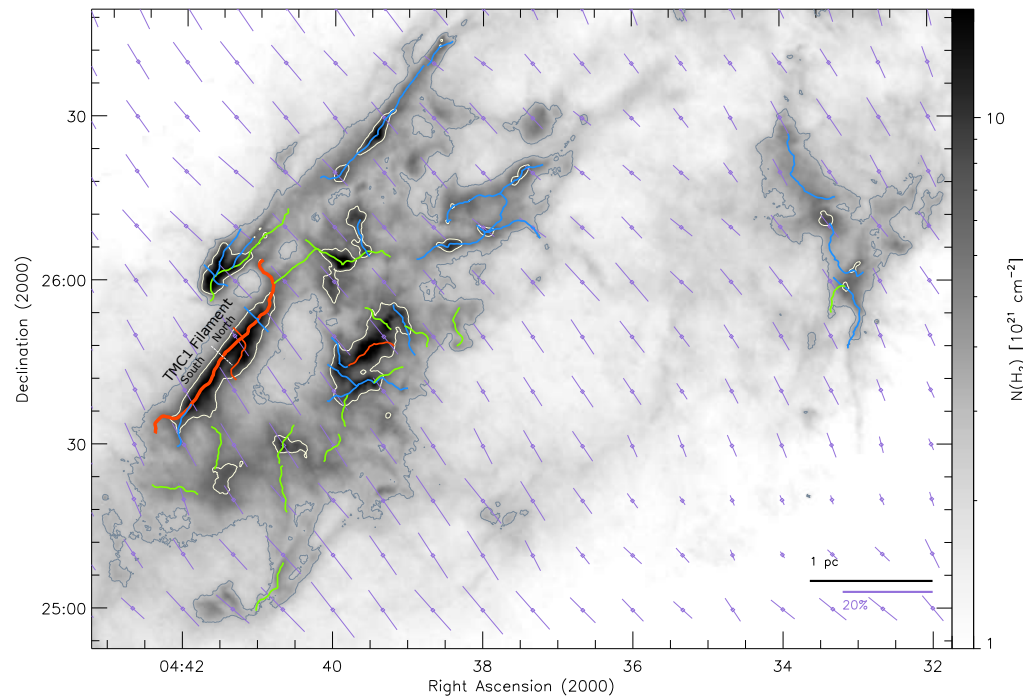
! Not so simple : Mixture of dust grain population & sizes + temperature gradient along the line of sight + variation of emissivity with grain properties ..

Read carefully the assumptions



3D structures in molecular clouds : Filaments

A census of dense cores in TMC1 9



Identification of filaments, measurement of filament width, orientation and linear mass (Kirk+2024)

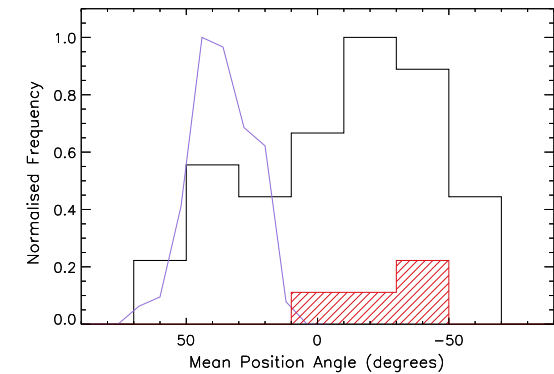
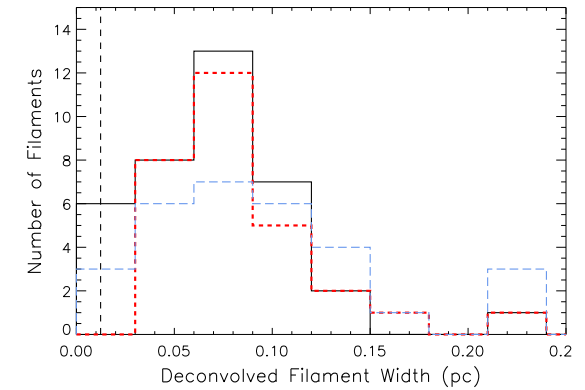


Figure 10. Comparison of filament position angles to the magnetic field direction. The black curve shows the histogram of all robust filaments towards the TMC1 region. The red-shaded histogram shows the orientation of supercritical filaments. The purple curve shows the normalised histogram of the magnetic field direction across the map sampled on a $1'$ scale. Both red and black histograms are normalised to the peak of the black histogram.

Determinations of the gas density, temperature and pressure

- Using the level population of C (fine structure levels) or molecules like CO, C₂, NH₃, etc. (rotational levels)
- Needs an accurate modeling of the excitation processes (collisions with H, He, H₂, e⁻; radiative pumping ...)
- Hypothesis of single structure associated with a given (Gaussian) velocity component with uniform physical conditions (n, T) and simple geometry (sphere, plane-parallel ..)

Kinetic Temperature : NH_3

- Symmetric top molecule
Transitions between rotation/inversion states have similar frequencies
→ can be observed simultaneously with same spectral and angular resolution
- Metastable levels, the relative population depend on T_{kin} for $n \geq 10^4 \text{ cm}^{-3}$
- T_{kin} can be deduced from the relative population of the 2,2 and 1,1 states using radiative transfer calculations based on accurate collision cross sections

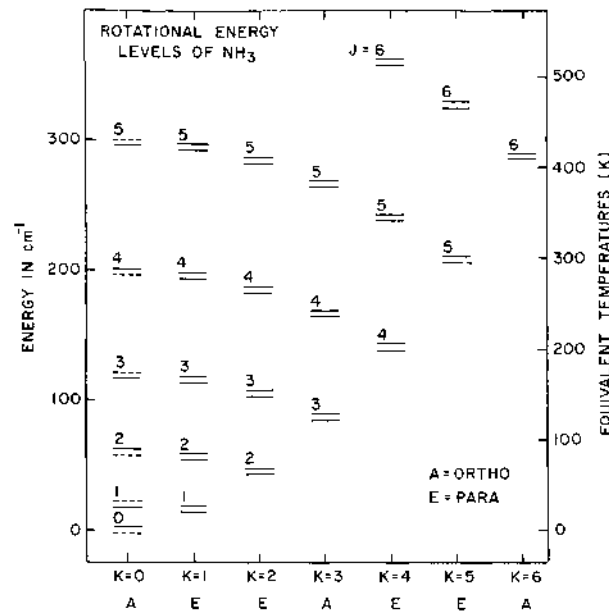
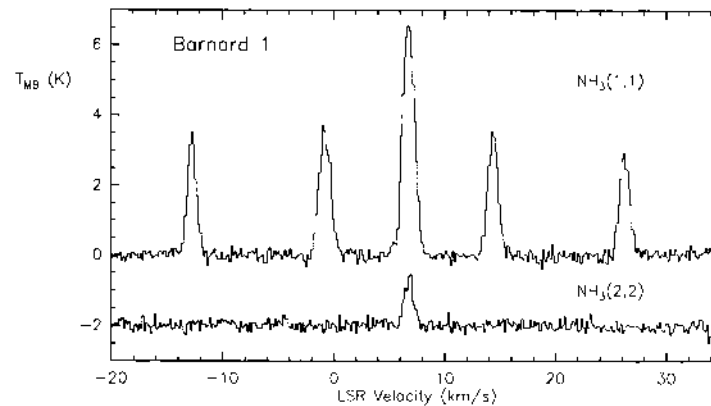
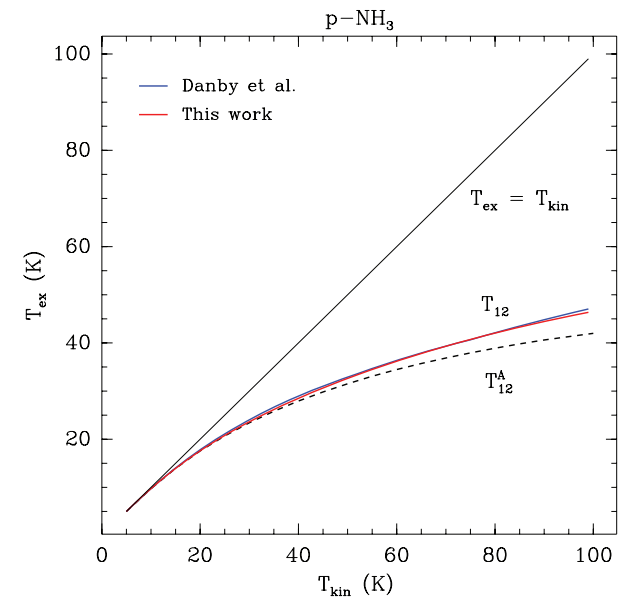


Figure 1 Energy level diagram of rotation-inversion states. J is the total angular-momentum quantum number, and K is the projected angular momentum along the molecular axis.

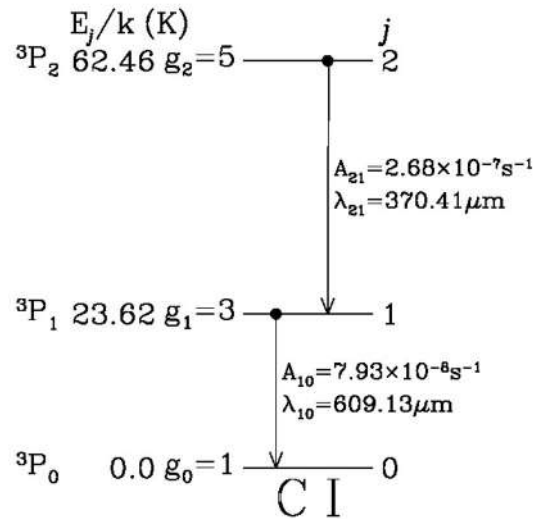


Species	Transition $J_{K,\epsilon} - J'_{K',\epsilon'}$	ν (GHz)	E_{up} (K)	n_{crit} (cm^{-3})
p- NH_3	$1_{1,-} \rightarrow 1_{1,+}$	23.694496	1.1	3.90×10^3
p- NH_3	$2_{2,+} \rightarrow 2_{2,-}$	23.722633	42.3	3.08×10^3
p- NH_3	$2_{1,+} \rightarrow 2_{1,-}$	23.098819	58.3	1.44×10^8
p- NH_3	$3_{2,-} \rightarrow 3_{2,+}$	22.834185	128.1	3.01×10^8
p- NH_3	$3_{1,-} \rightarrow 3_{1,+}$	22.234506	144.0	5.41×10^8
o- NH_3	$3_{3,-} \rightarrow 3_{3,+}$	23.870129	123.6	2.63×10^3
o- NH_3	$1_{1,+} \rightarrow 0_{0,+}$	572.498068	27.5	5.45×10^7



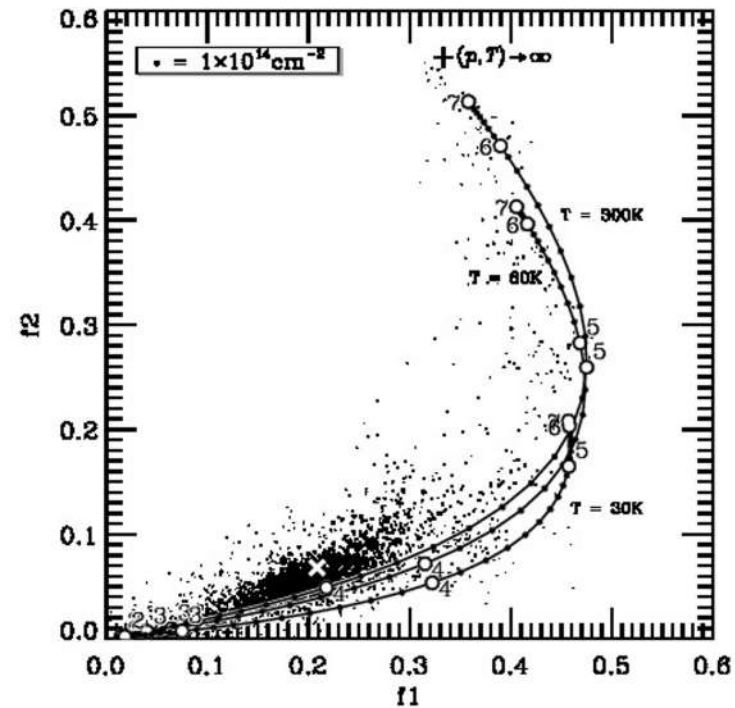
Ho&Townes 1983, Maret+2001

Gas pressures with CI



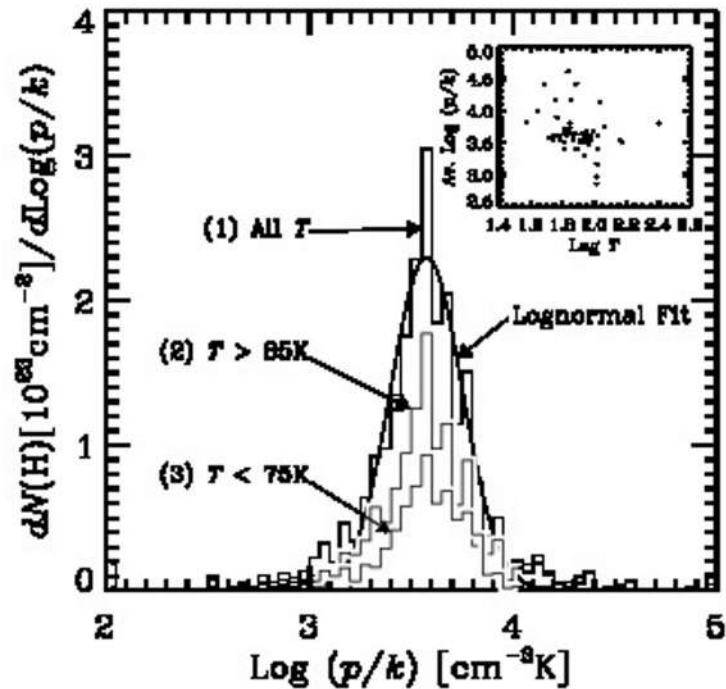
Fraction of C atoms in the 2nd excited level

Jenkins & Tripp (2011)



Fraction of C atoms in the 1st excited level

Pressure distribution



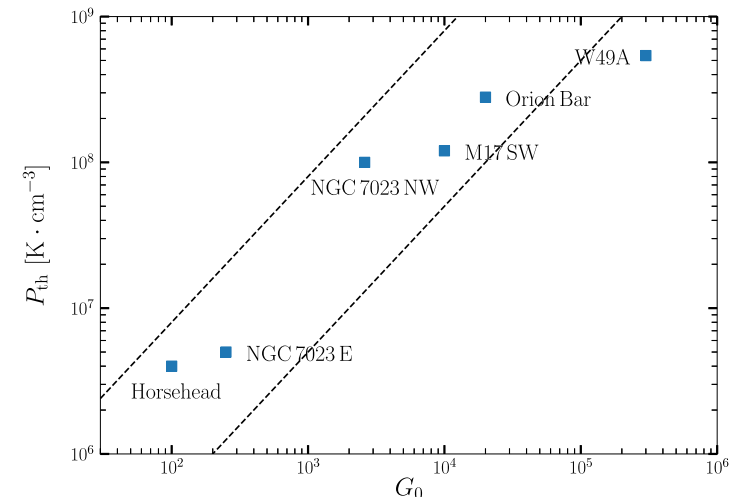
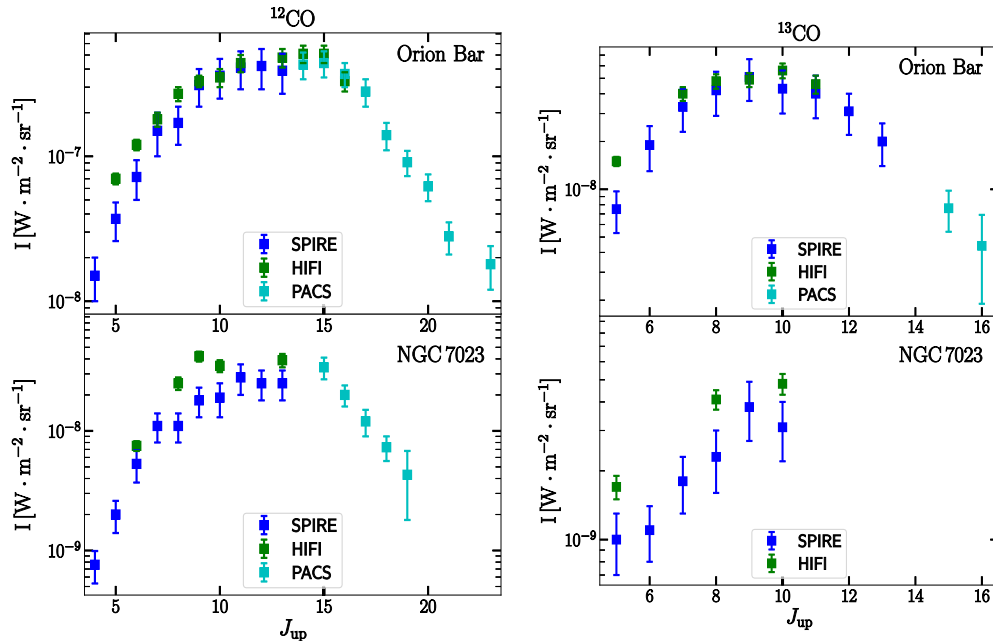
Median pressure

$$\log(p) = 3.58 \pm 0.175$$

$$p \sim nT \sim 3800 \text{ Kcm}^{-3}$$

within a factor 1.5

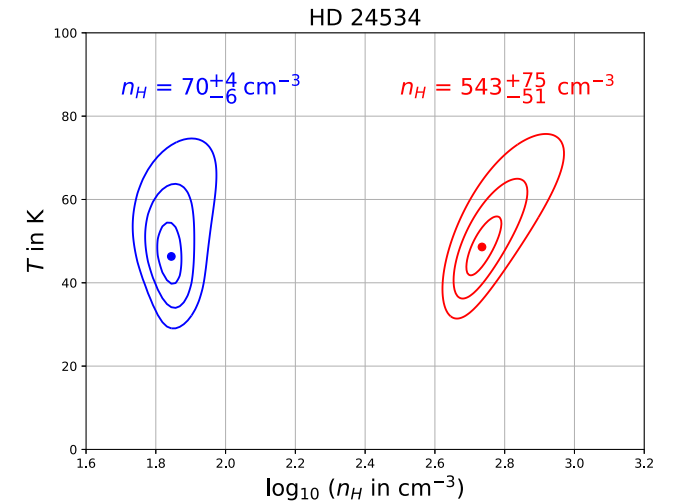
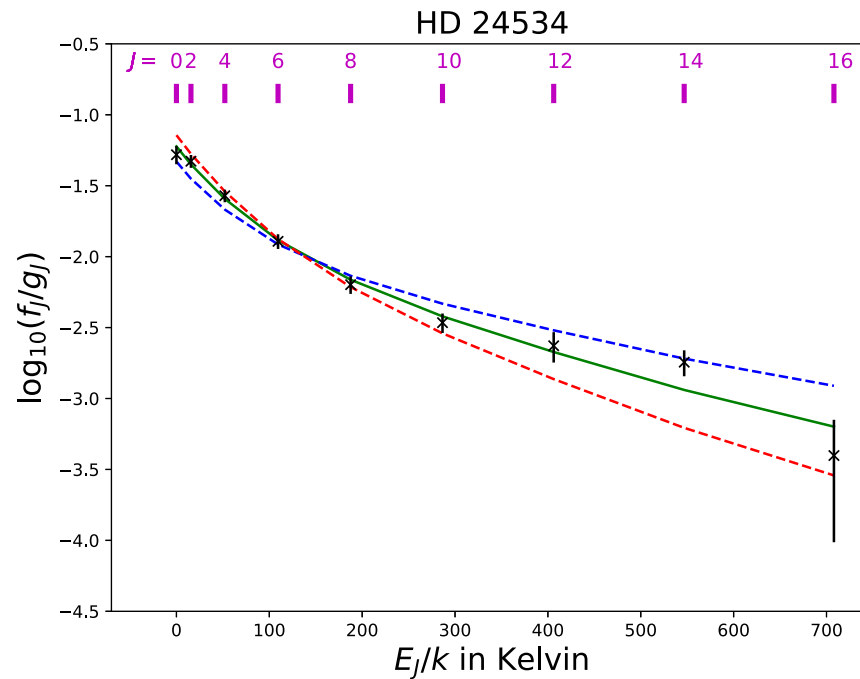
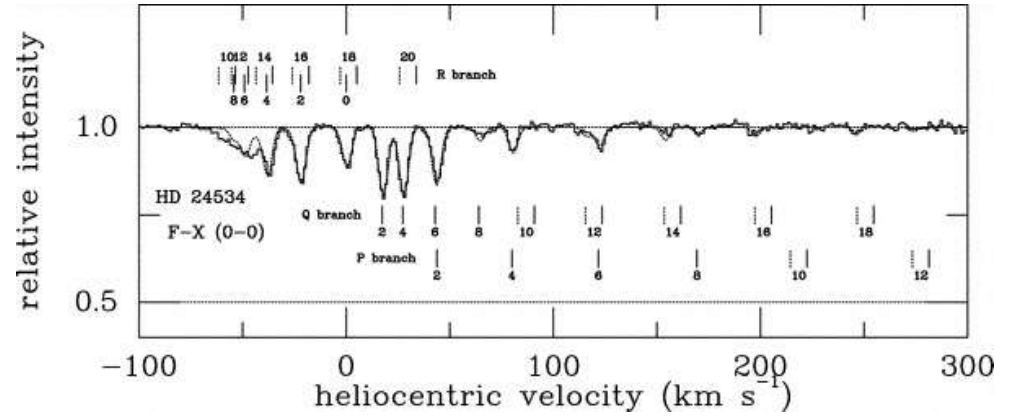
Molecular gas excitation : the CO ladder



- Dense PDRs : Orion Bar and NGC 7023. Detection of CO emission up to $J = 18$!
- Good characterization of the dense gas pressure
- Relation between P_{th} and G_0 : feedback
- Implication for CO emission in active and high z galaxies : small regions can contribute a large fraction of the flux

Gas density : C_2

- Symmetric molecule : the level populations are very sensitive to the density
- More accurate collisional cross sections : revised density determinations



Sonnentrucker+2007, Neufeld+2024

Finding molecules : Spectral surveys

A&A 658, A39 (2022)

- IRC+10216. A template evolved carbon star
- Characteristic double peak line profile
- The line density increases at low brightness level
- Deep integrations (> 100hours)

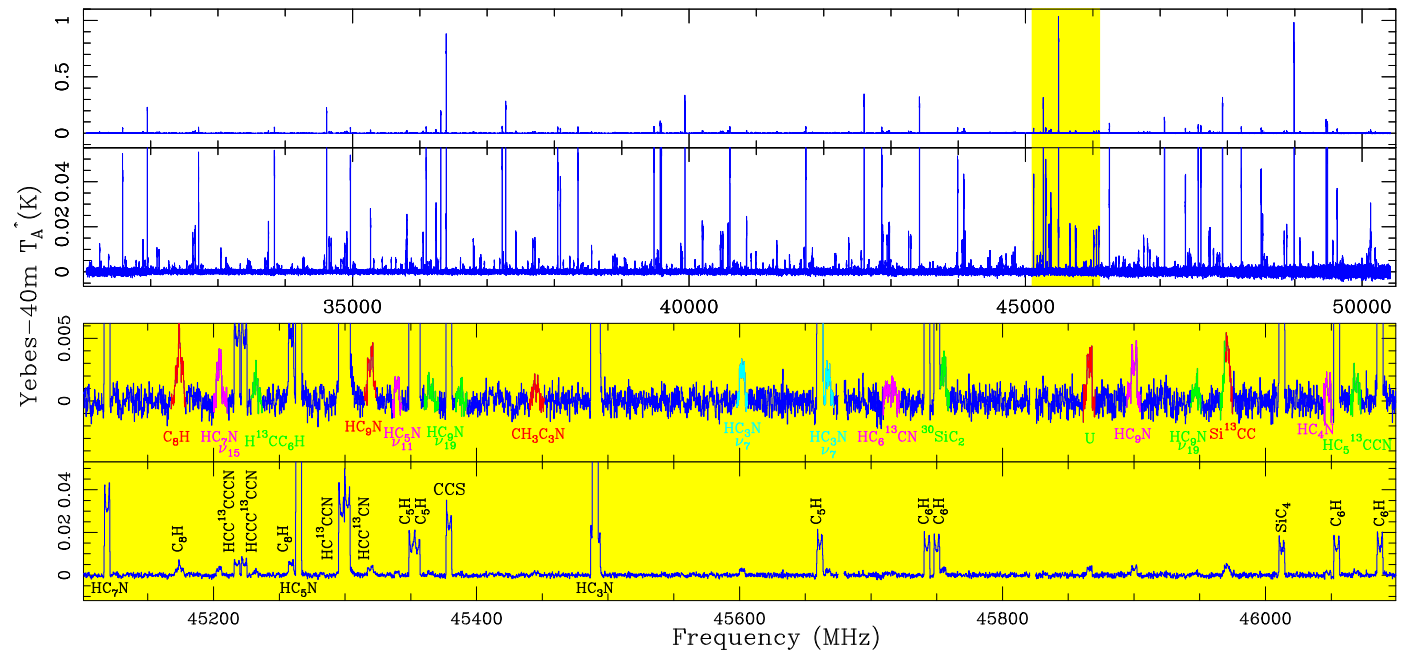
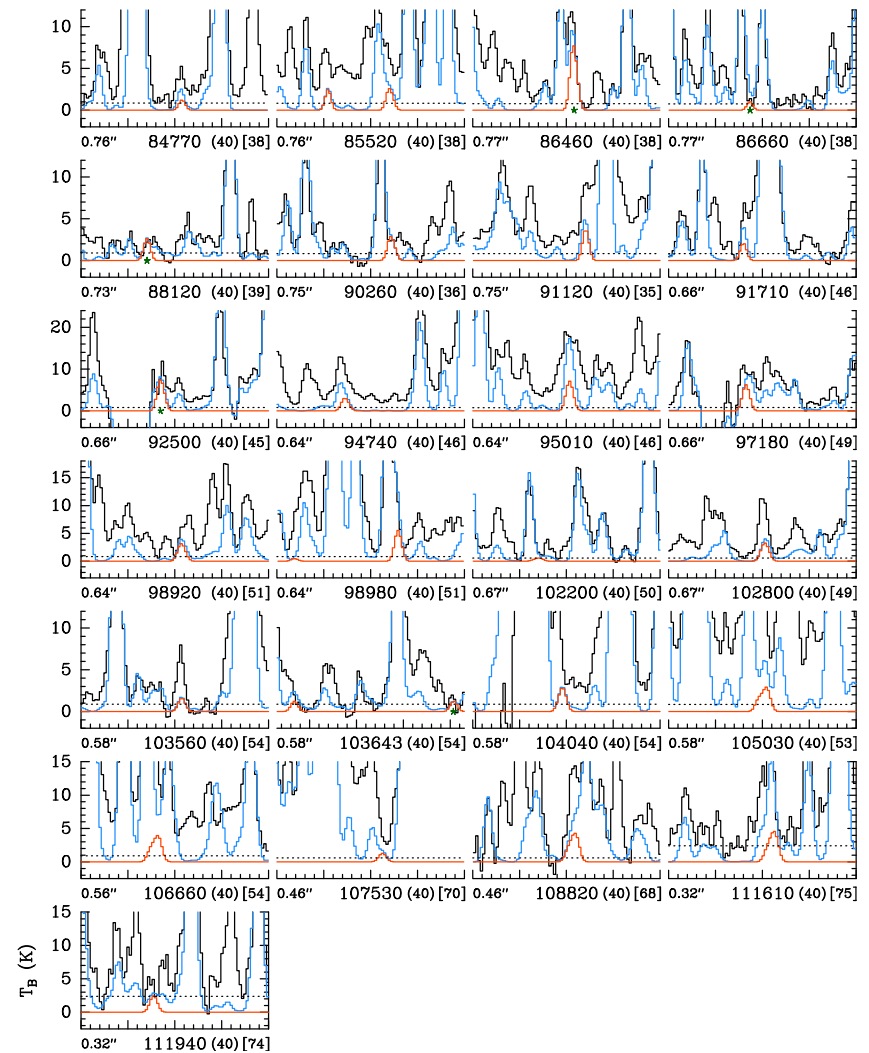


Fig. 2. Overall view of the data with a zoom around 45.6GHz. Several weak spectral features ($\sim 1-3$ mK), revealed in this work, are shown in different colors in one of the panels.

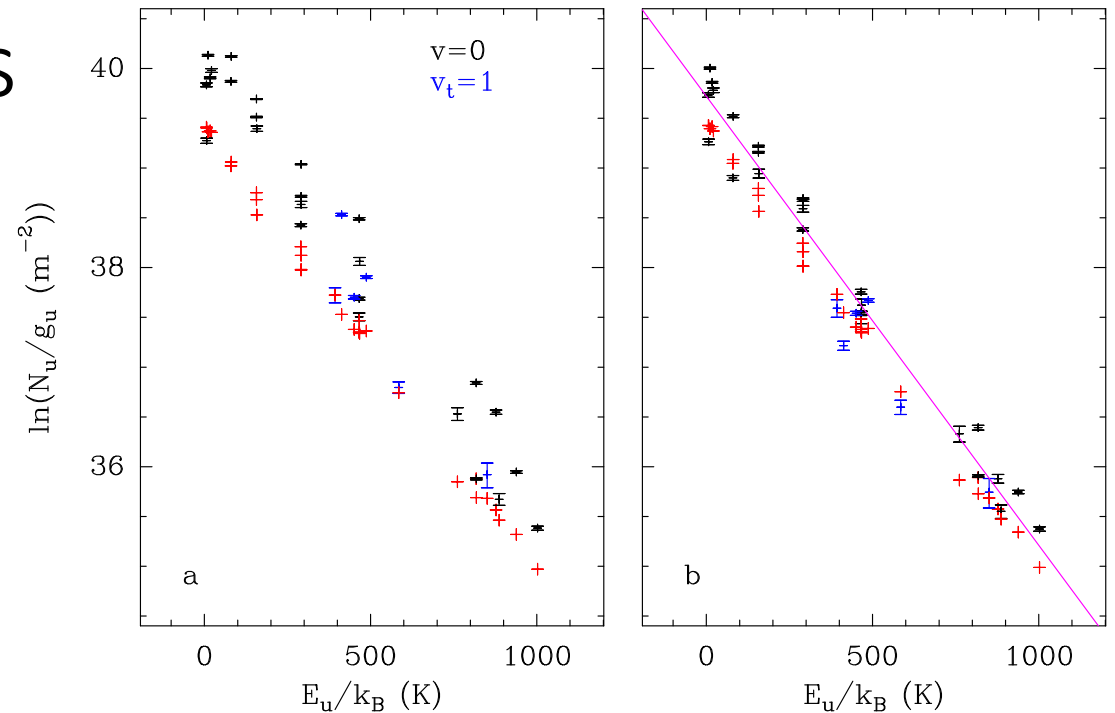
Spectral surveys analysis

- Consistent fit of all accessible lines of known molecules with an emission model (e.g. LTE)
- U lines = unassigned spectral features
- Detection of a molecule if
 - A significant number of not blended U lines is fit
 - All lines stronger than the noise level are detected or blended



Spectral surveys analysis

- Rotation diagram allows to check for the consistency of the identification :
- The slope of $\ln(N_u/g_u)$ vs E_u/k_B is $1/T_{ex}$
- The intercept provides $\ln(N_{tot}/Q_{rot})$
- $\ln(N_u/g_u)$ can be deduced from the line integrated intensity W

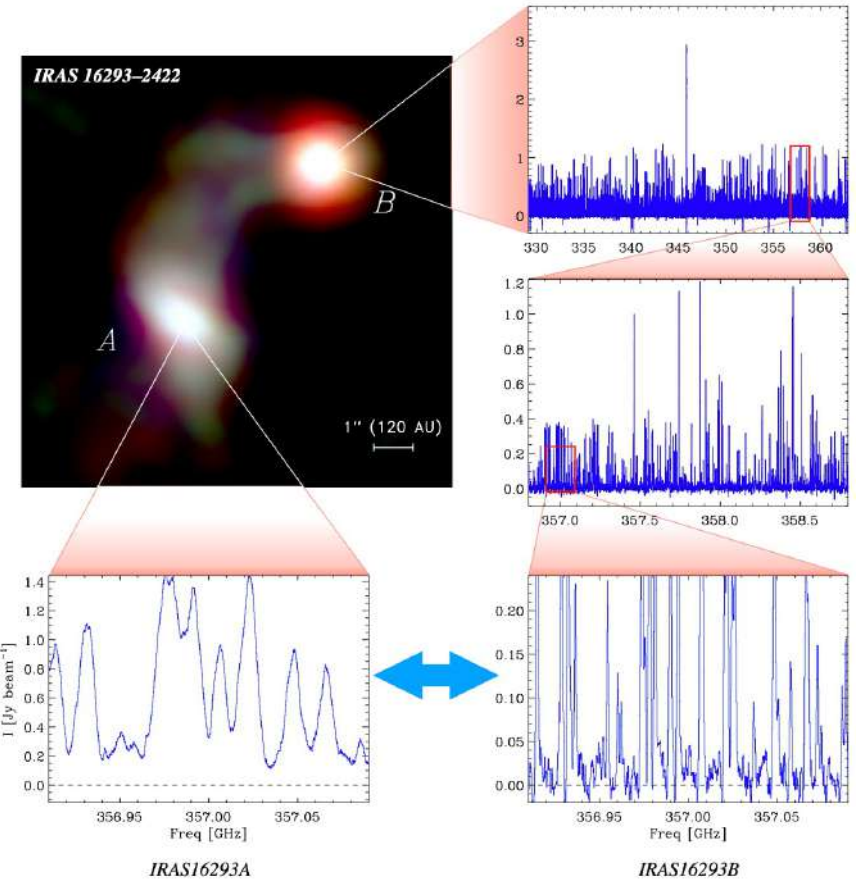
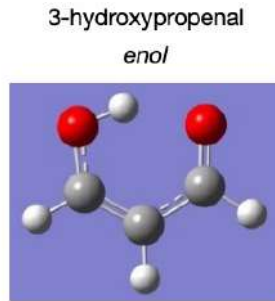
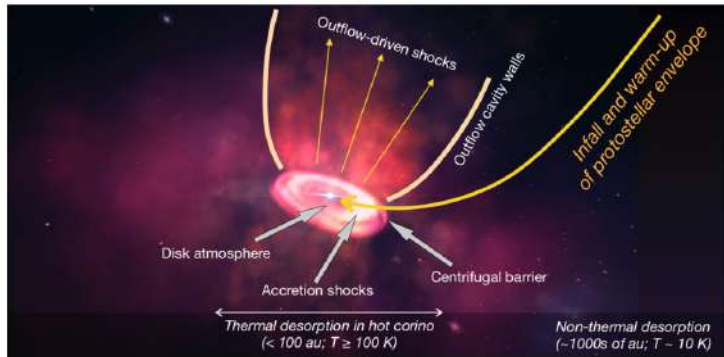


CH_3NH_2 $v_t = 0$ and $v_t=1$

$$N_u/g_u = (8\pi k_B/hc^3) (\nu[\text{GHz}])^2 W [\text{Kkm/s}] / A[s^{-1}]g_u$$

$$\sim 1943 (\nu[\text{GHz}])^2 W [\text{Kkm/s}] / A[s^{-1}]g_u$$

Physical and chemical information : spectral surveys



The structure of a Protostar : collapsing cold core + disk + outflow

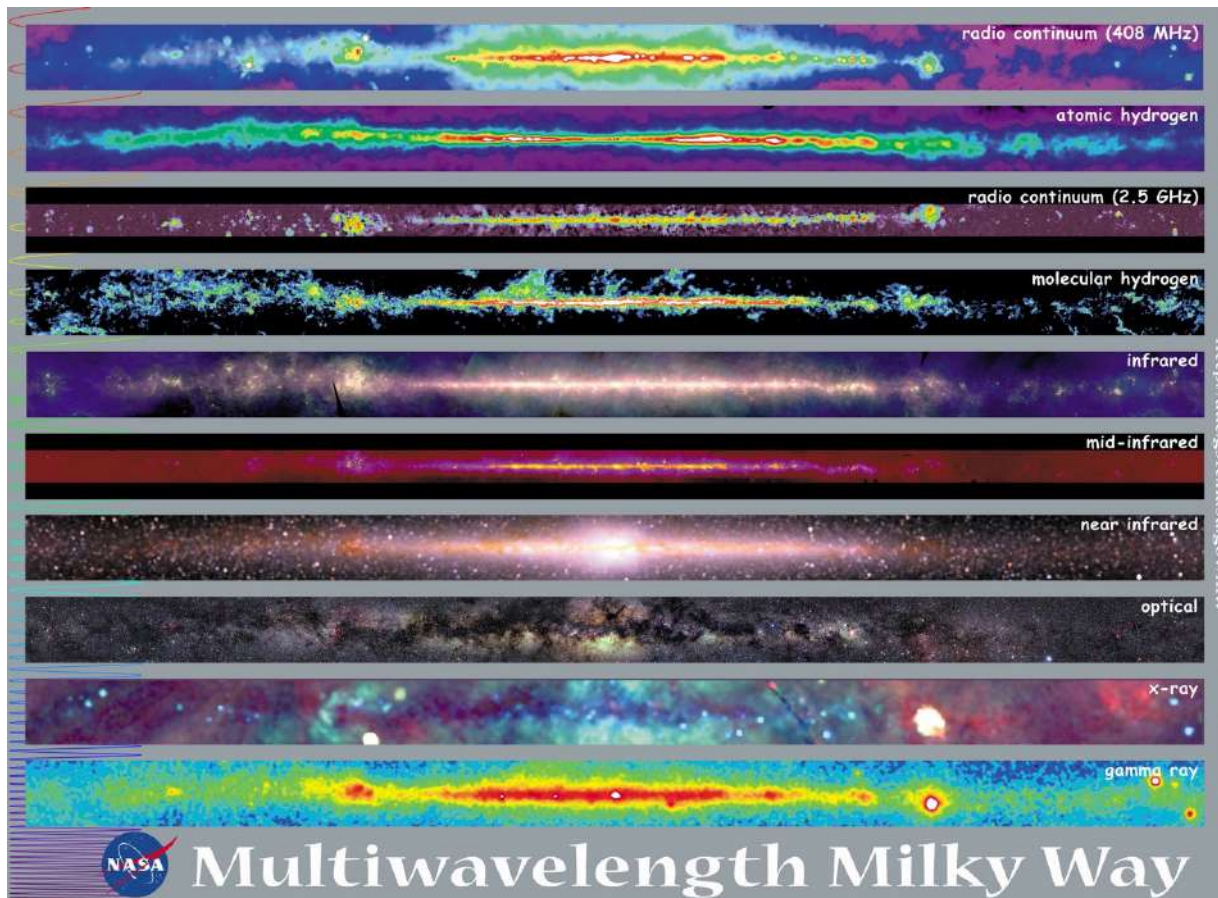
→ Hot corino = hot region zone (> 100K) near the protostar with a rich spectrum displaying a plethora of molecular lines from complex organic molecules (COMP) and their isotopologues (With D, ¹³C, ¹⁸O, ¹⁵N,..)

→ The ALMA PILS survey of IRAS16293-2422, a double protostar with different spectra for A & B :

- Orientation or Evolutionary effect ?
- Transfert of pristine matter from the core & hot corino to the disk ?

Jorgensen+2016,2020, Manigand+2021, Coutens+2020, Sakai+2017

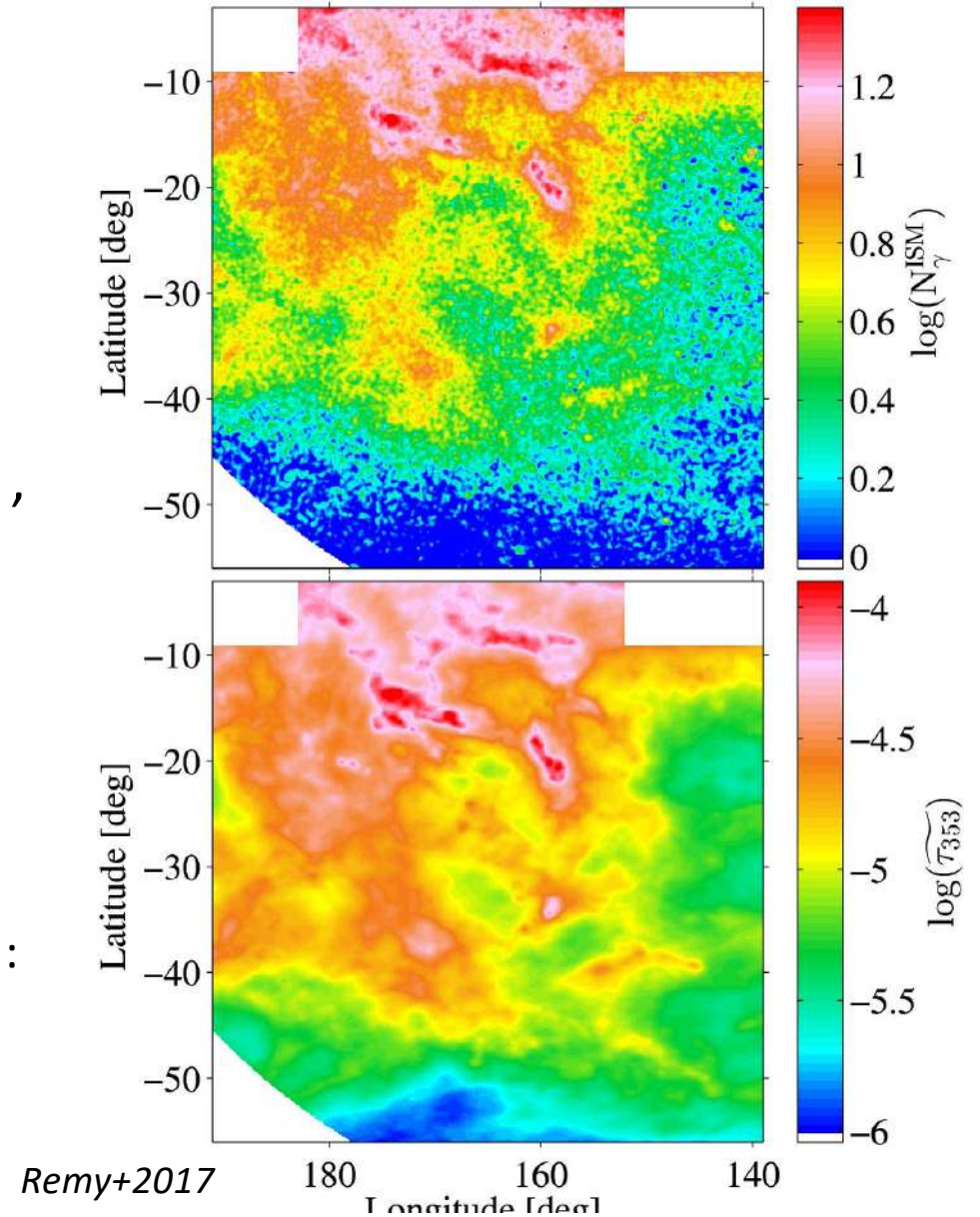
The Milky way at different wavelengths



- Different morphologies depending on the wavelength :
- ➔ Complex ISM structure with multiple phases.
 - ➔ These different ISM phases are accessible through different radiation processes and wavelengths

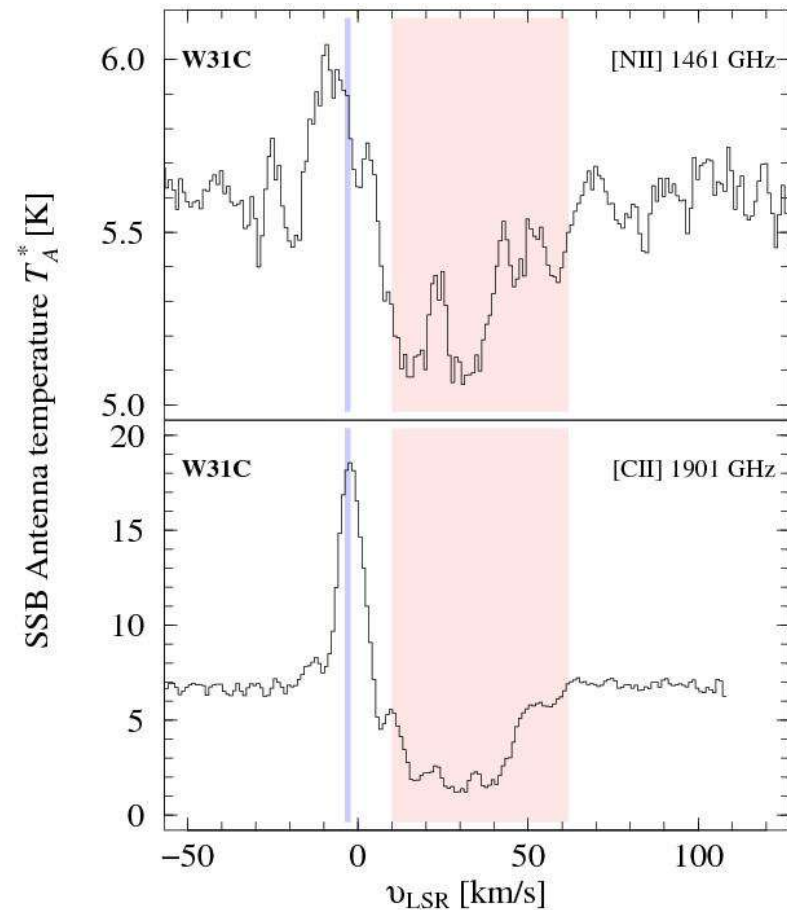
Probing the ISM Phases with observations

- Information on all phases is necessary for the full picture
- What is needed : Structure of the matter + , dynamics and kinematics
- Total gas content
 - From dust : far IR and submm emission, dust extinction
 - from gamma ray (interaction of cosmic rays with the matter)
 - No kinematics
 - Dust properties change with the environment : uncertainty in the gas/dust ratio



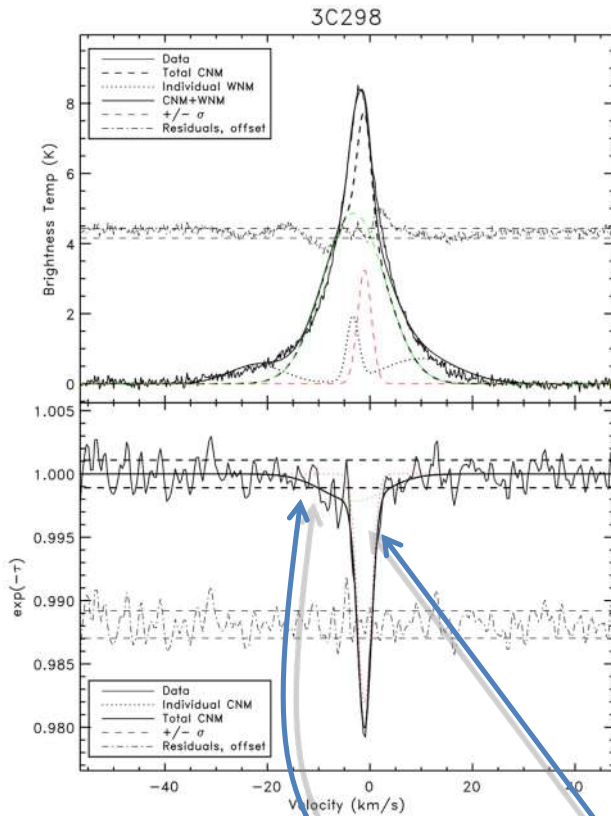
Probing the ISM phases with observations : ionized gas

- Diffuse Warm Ionized gas :
 - Hydrogen Recombination lines $H\alpha$
 - Far infrared fine structure lines including [NII]
- Absorption along the line of sight consistent with the expected WIM properties ($N \sim 1.5 \cdot 10^{17} \text{ cm}^{-2}$, $n \sim 0.1 - 0.3 \text{ cm}^{-3}$, volume filling factor ~ 0.3)
- Waiting for the ASTHROS balloon ?



Persson+2014;Langer+2021

Probing the ISM phases with observations : atomic gas



Neutral atomic gas can exist in 2 phases :
Warm neutral medium with $T_k \geq 4000$ K and
Cold neutral medium with $T_{kin} \leq 200$ K

Emission along a line of sight is a combination of the
2 phases

Absorption is dominated by the cold phase

The combination of emission and absorption HI
21cm data allows to separate the contributions from
the warm and cold media

Gaussian fitting gives:

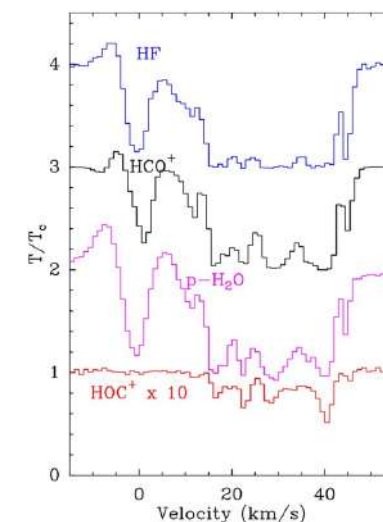
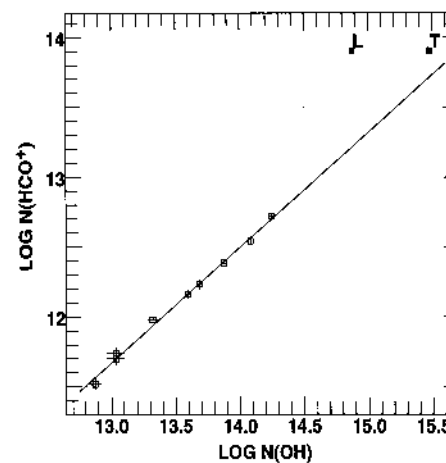
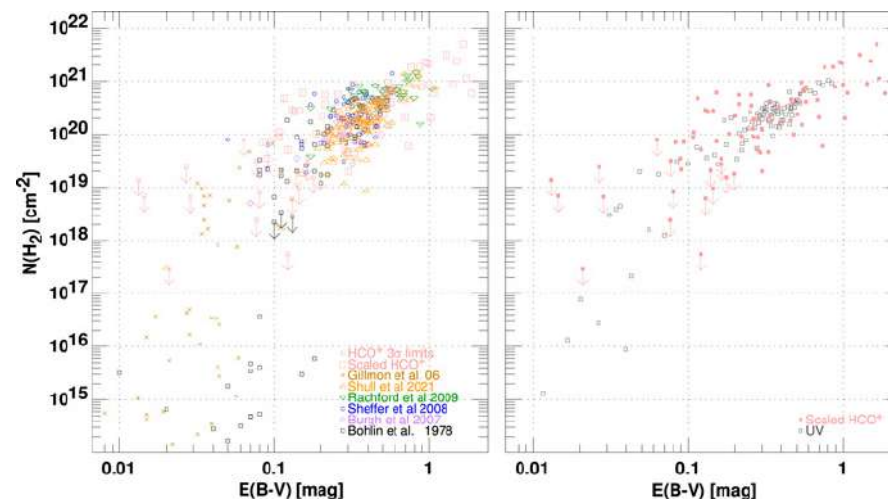
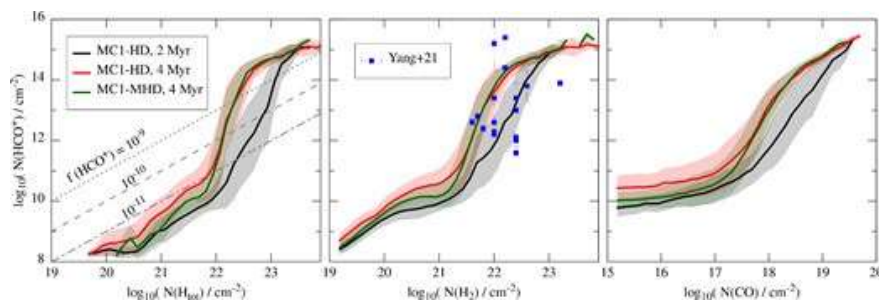
$$T_{sp} = 178 \text{ K}$$

$$T_{sp} = 2280 \text{ K}$$

Murray+2014 with VLA,

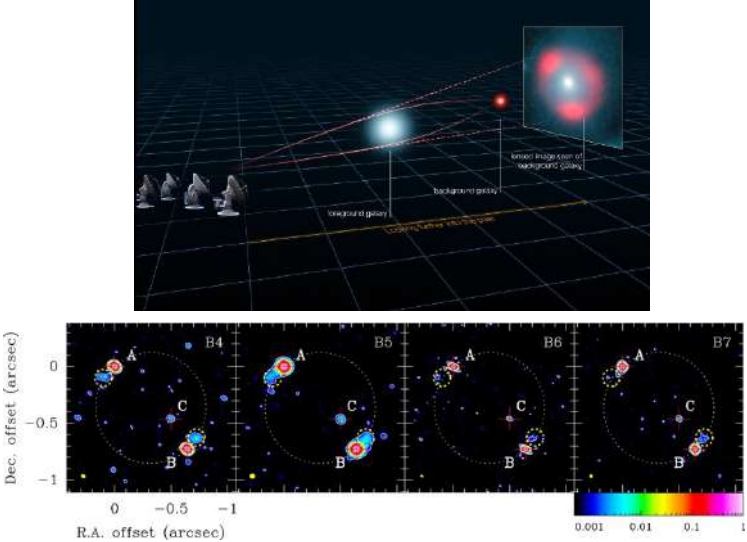
Probing the ISM phases from observations : molecular gas

- Hydrides as proxy for H_2 : HF, CH , OH from theory and direct comparison
- HCO^+ absorption can be used as a proxy for H_2 ($[HCO^+/H_2] = 3 \times 10^{-9}$ within less than a factor of 2)
- Same threshold for HCO^+ or H_2 detection and same variation with $E(B-V)$
- Very weak emission \rightarrow low to moderate densities : $50 - 500 \text{ cm}^{-3}$
- Challenge for chemical models



Lucas & Liszt 1996,
Liszt+2023, Gerin+2019, Panessa+2023

From local systems to high redshifts



$z=0.89$ galaxy along the line of sight to the PKS1830-211 Quasar

Gravitational lens \rightarrow Multiple images \rightarrow 2 sight lines across the lensing galaxy

A unique opportunity to probe the ISM at $z=0.89$

Molecular gas content, density, chemistry, nucleosynthesis, CMB temperature, variation of fundamental constants, etc.

