NanoSpace

Funded by the European Union

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Observational techniques

Maryvonne Gerin

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

DANI Dutch Astrochemistry Network III

NWO

LERMA Observatoire de Paris | PSL

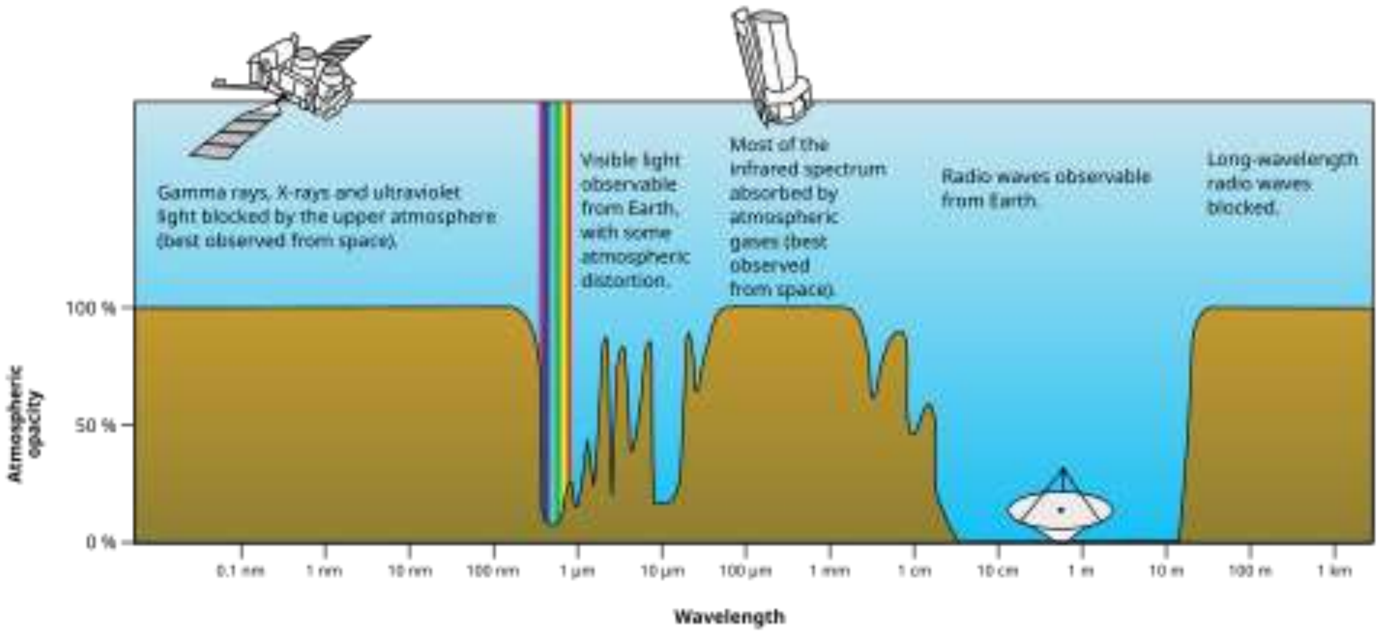
cnrs

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

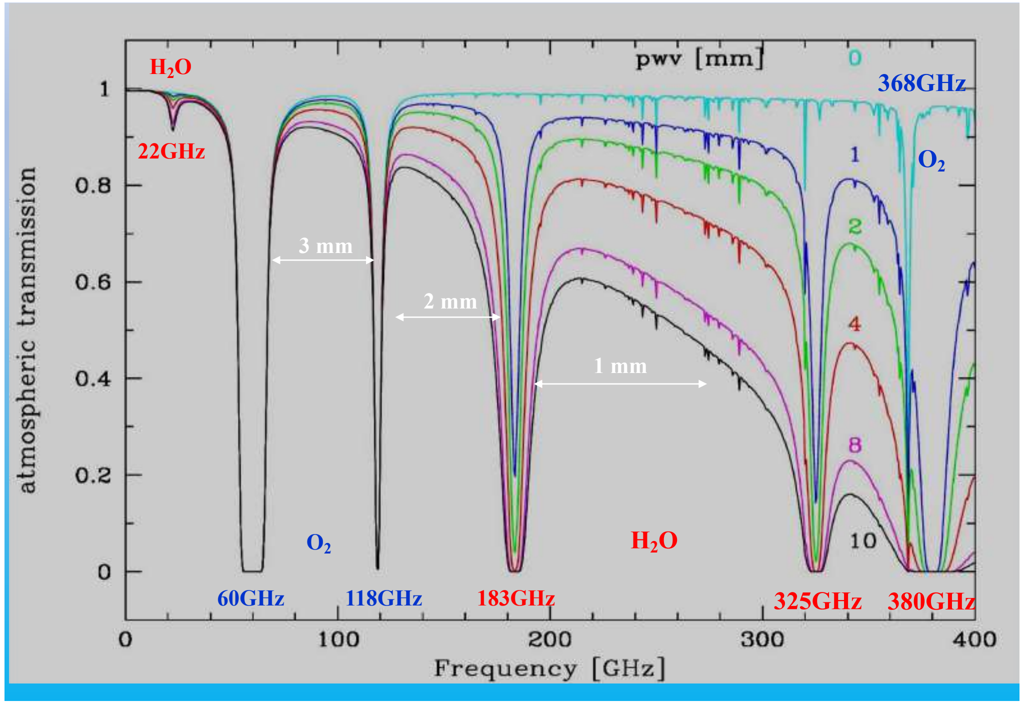
The Earth’s atmosphere transmission

- 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



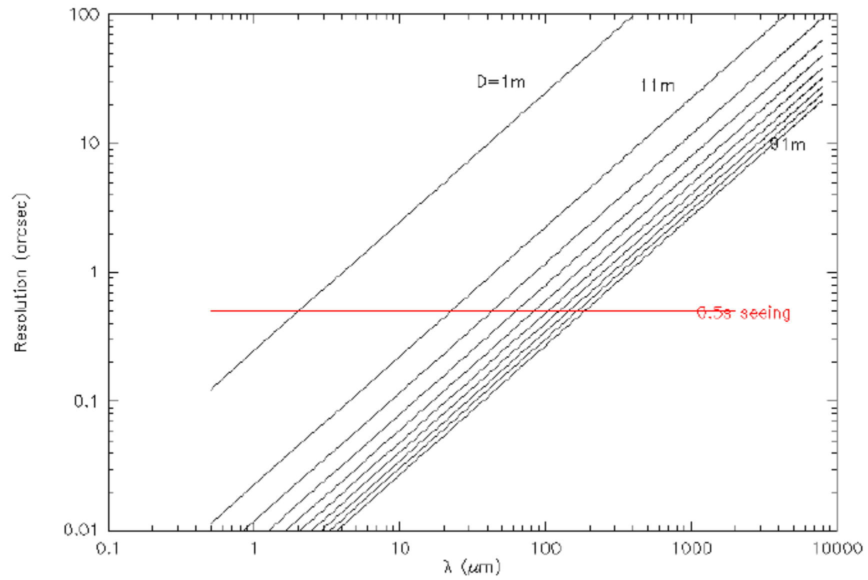
The Earth's atmosphere transmission

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



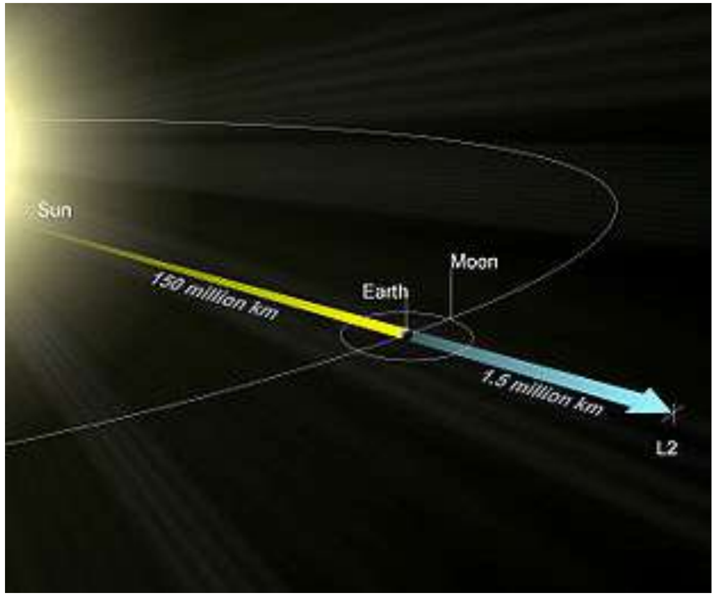
Specifications for Telescopes and Instruments

- 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 ~ 1.2 λ/D
  - Adaptive optics to remove atmospheric image distorsion
  - 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)



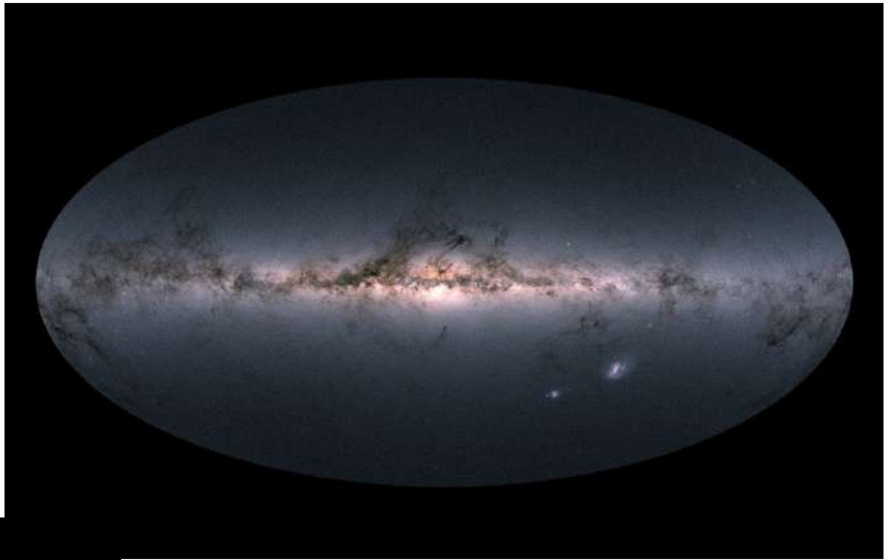
Satellite orbits

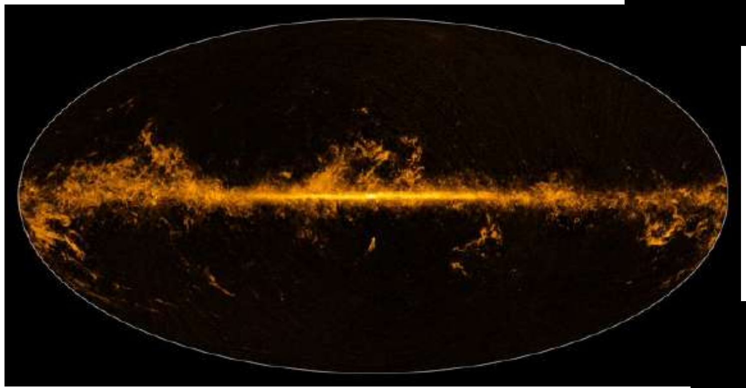
Hubble Space Telescope ~570 km

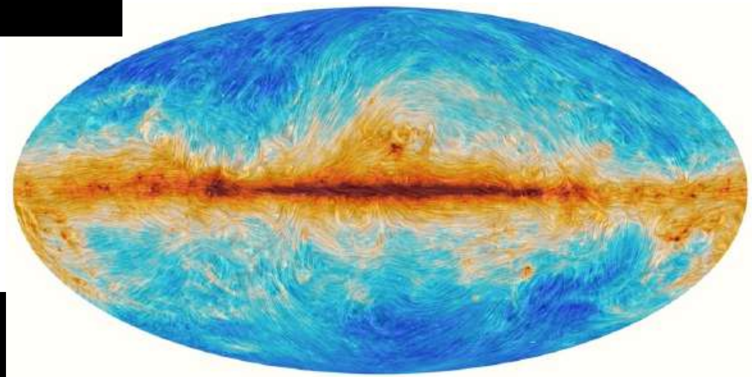


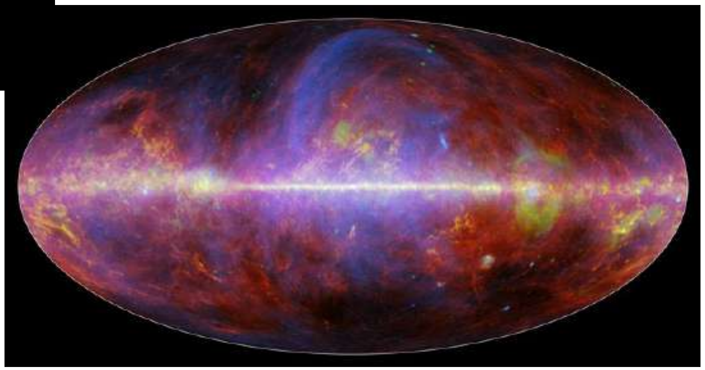
James Webb Space Telescope ~1.5 10^6 km

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







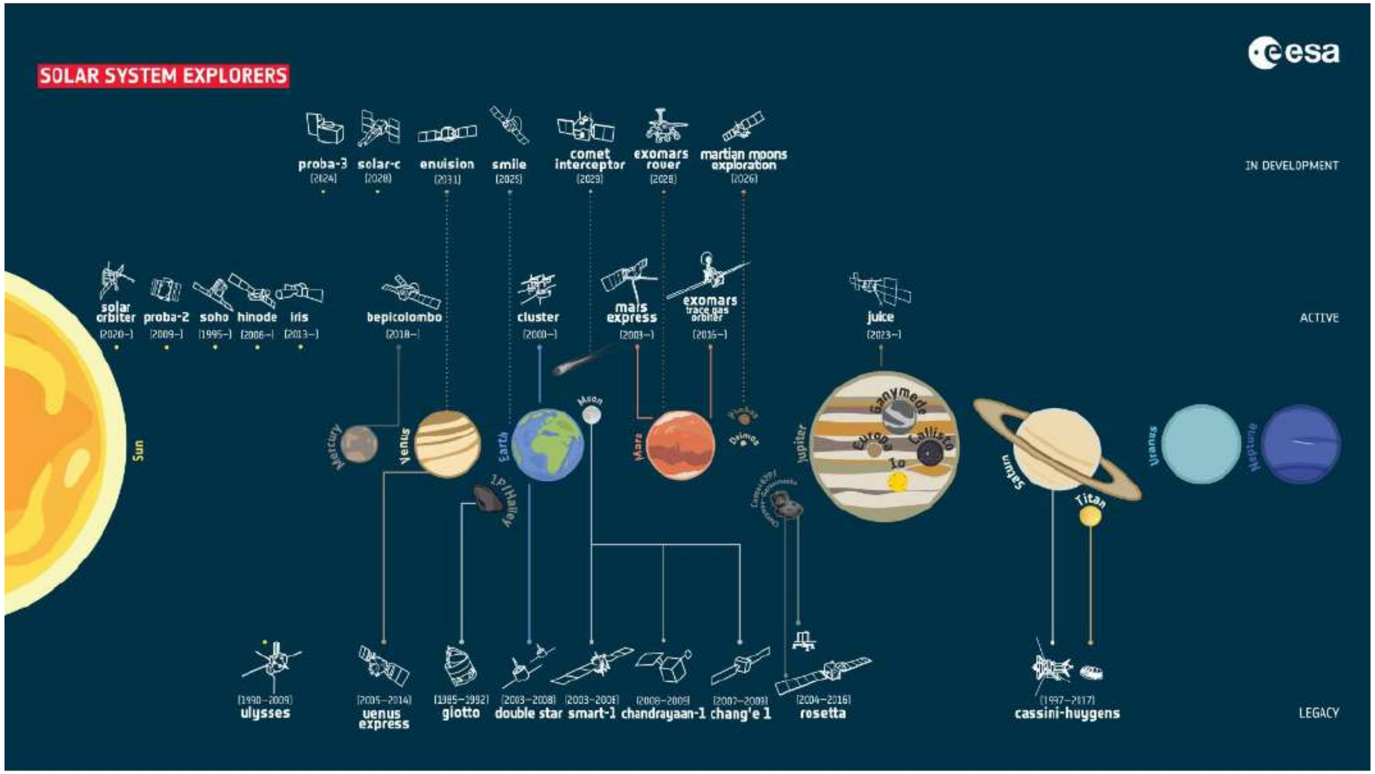


Airplanes & balloons

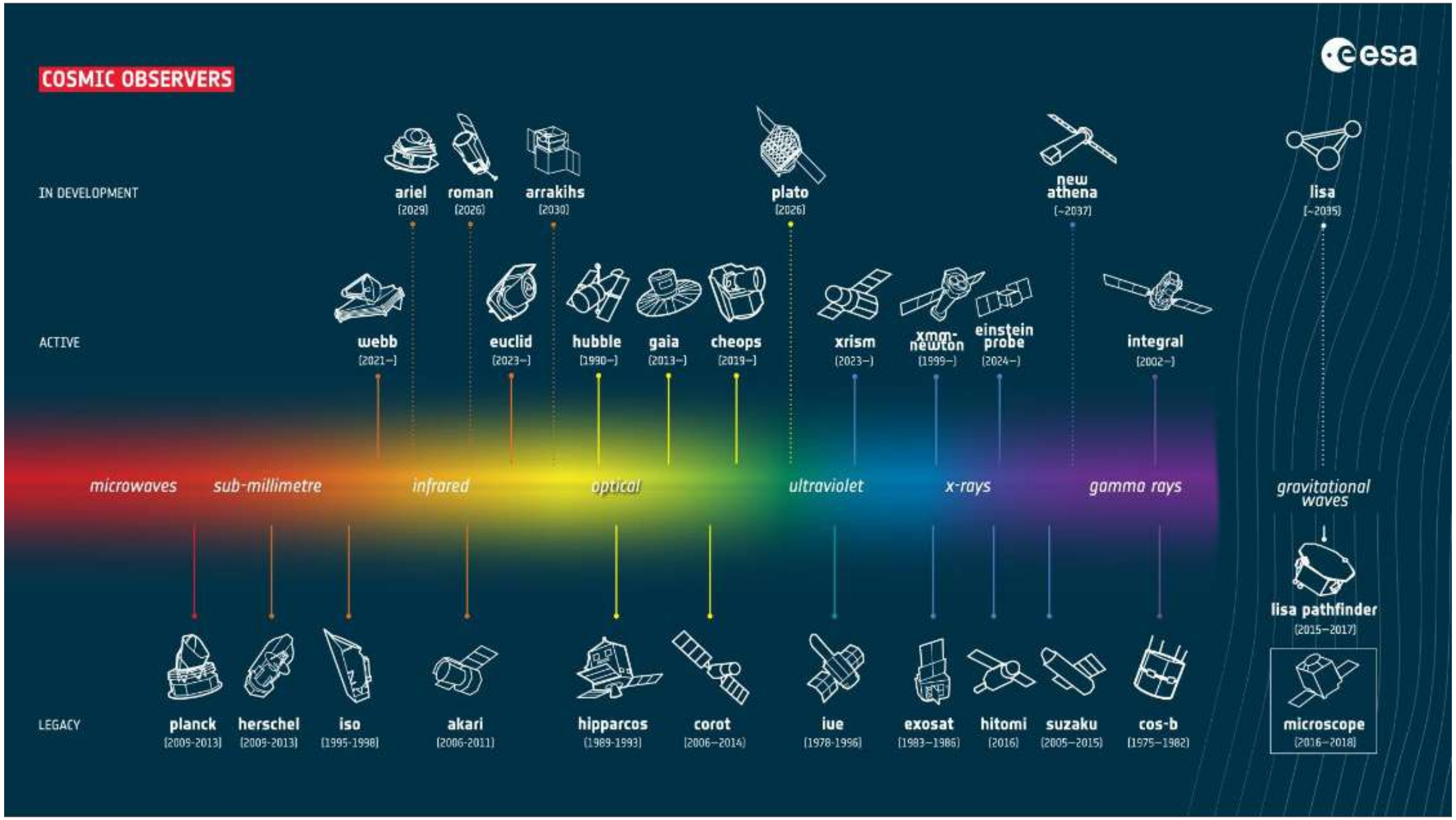
- Astronomy from airplanes (KAO and SOFIA)
- Few atmosphere left at the tropopause
- Stratospheric balloons operate at ~40km
- More extensively used for atmospheric work than for astronomy
- Main limitations : telescope size and flight time (10 hours … 2 months)

Solar system exploration

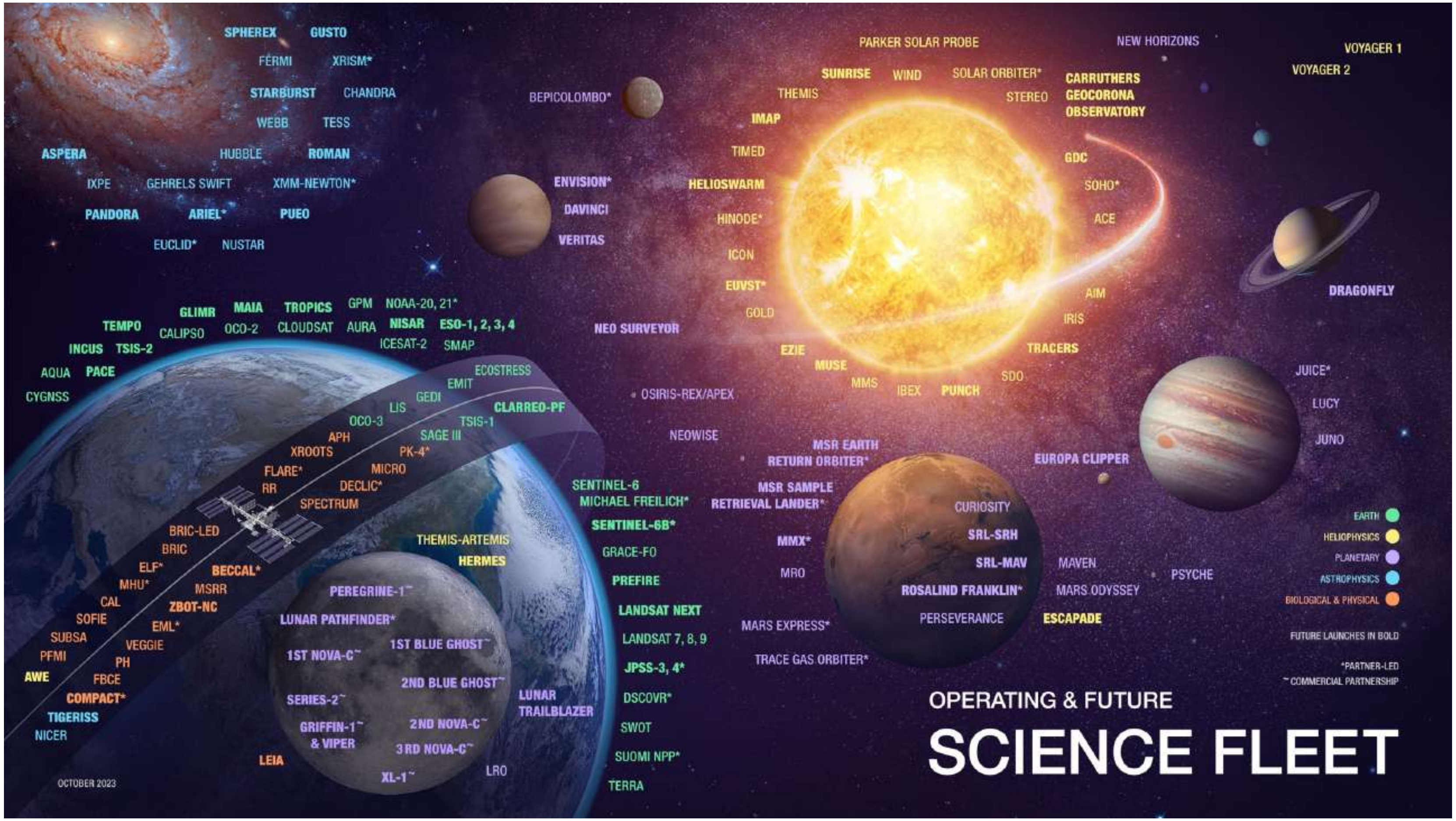
- On Earth, extraterrestrial material from meteorites, micro-meteorites and interplanetary dust particules
- Solar system probes allow detailed investigations of solar system bodies surface & atmosphere : images, spectra, in situ measurements, in situ analyses (e.g. Rosetta , Mars rovers)
- Sample collection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



Astronomy satellites (ESA view)

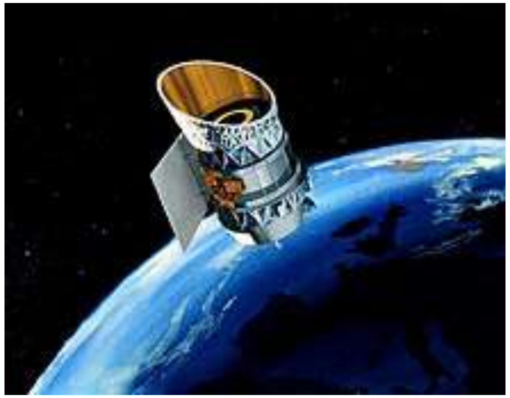


NASA science missions



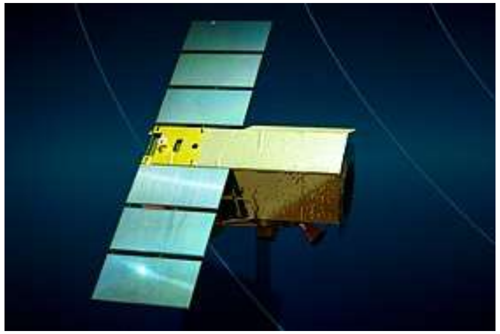
Infrared astronomy from Space

IRAS-1983



MSX-1996

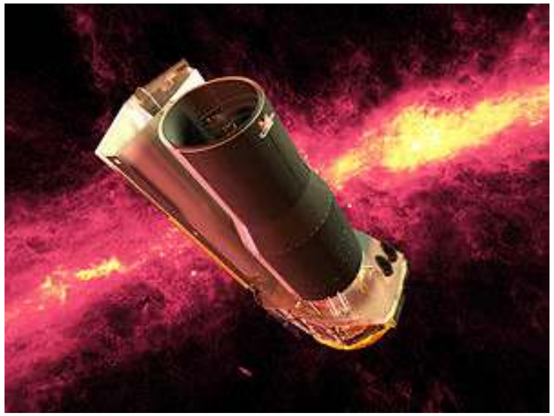
Akari-2006



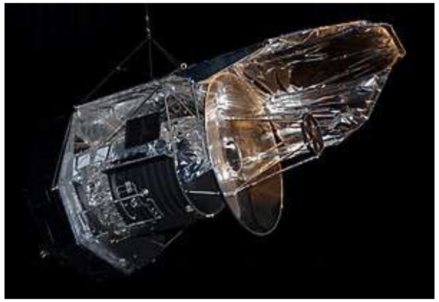
WISE-2009

ISO-1995

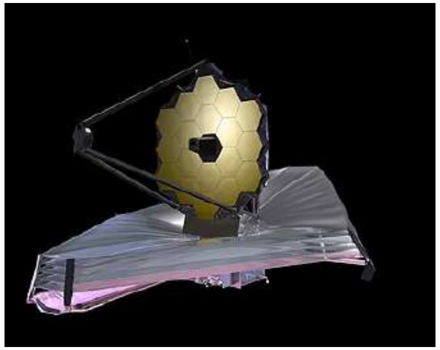
Spitzer-2003



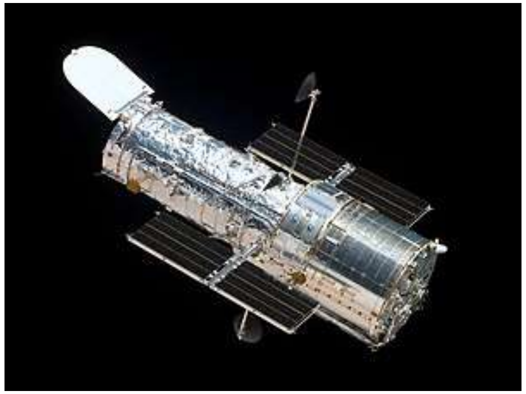
Herschel-2009

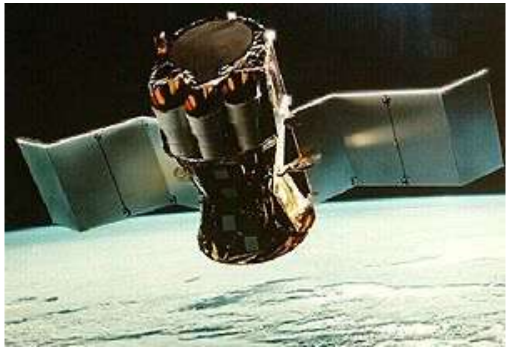


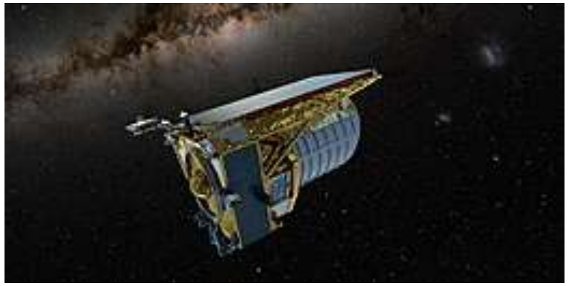
JWST-2022



UV satellites



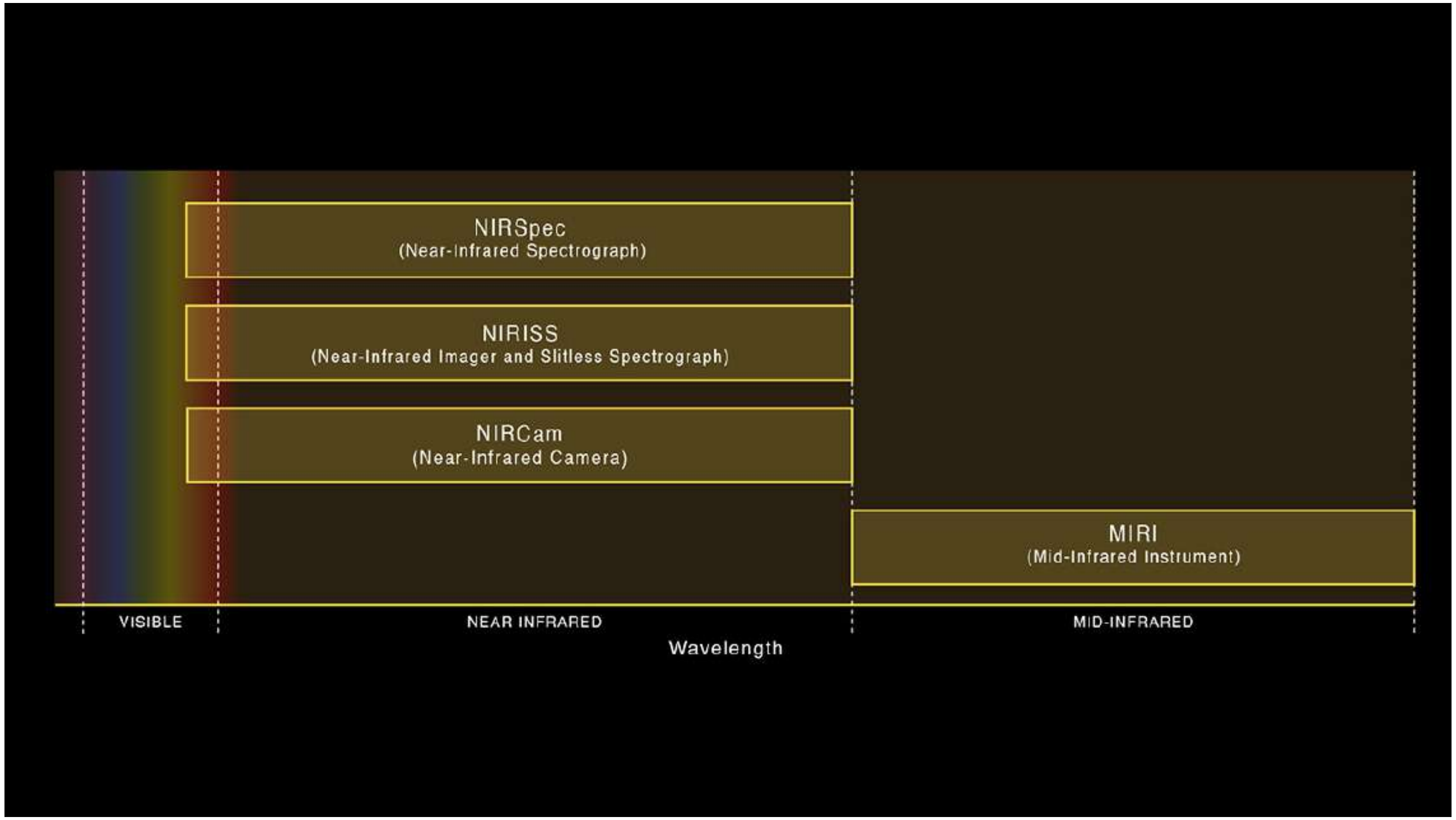




https://en.wikipedia.org/wiki/List_of_space_telescopes#Ultraviolet

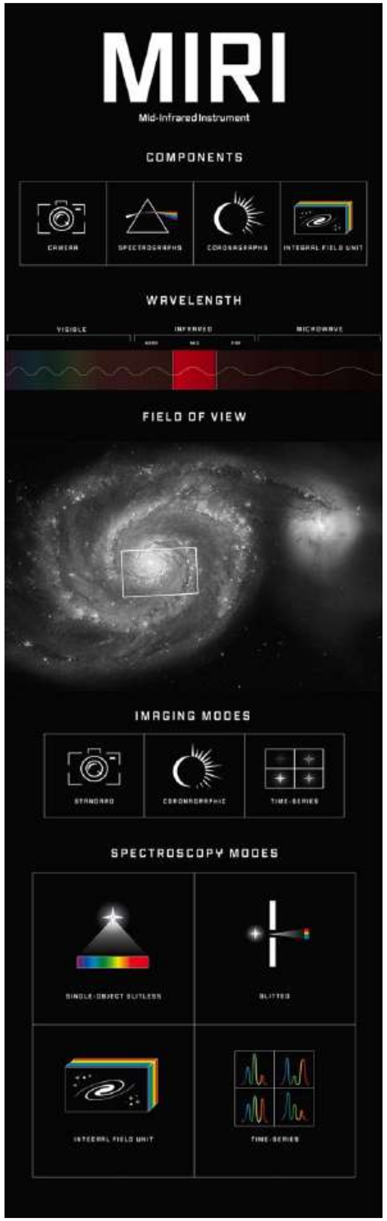
JWST (https://webbtelescope.org/quick-facts)

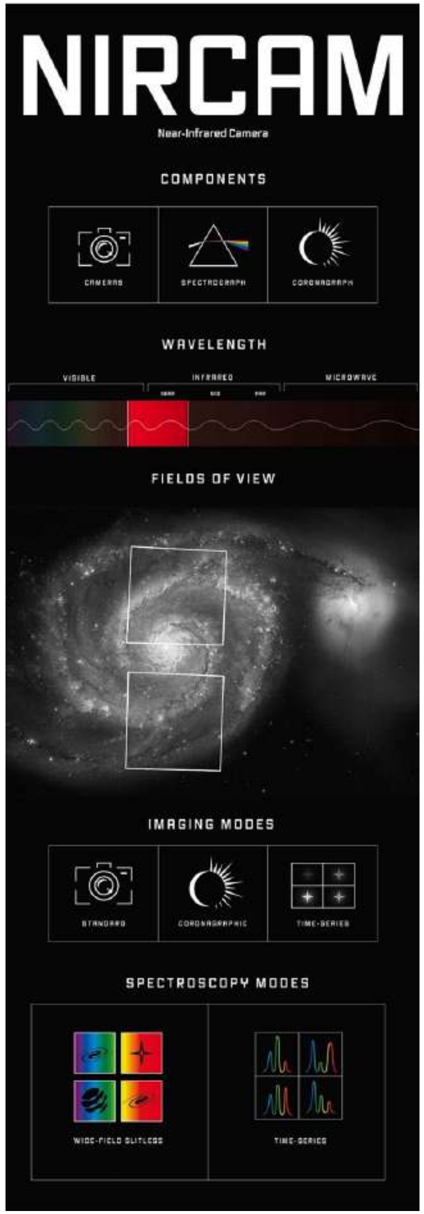
- NASA +ESA and CSA
- 6.5m deployable mirror
- Mid-Infrared Instrument (MIRI) 4.9 – 27.9µm
- Near-Infrared Camera (NIRCam) (0.6 – 5 µm)
- Near-Infrared Spectrograph (NIRSpec) (0.6 – 5.3µm)
- Near-Infrared Imager and Slitless Spectrograph/Fine Guidance Sensor (NIRISS/FGS)



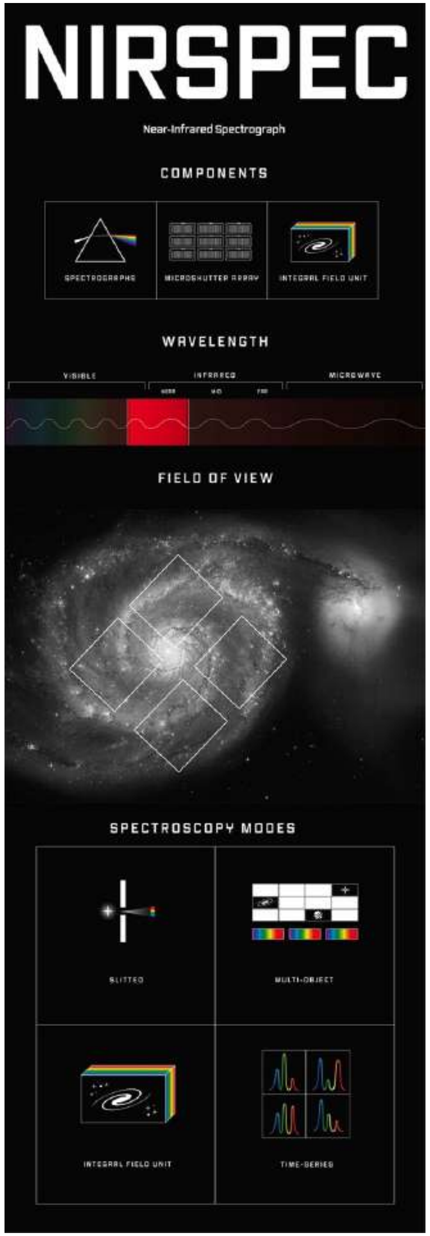
JWST Instruments

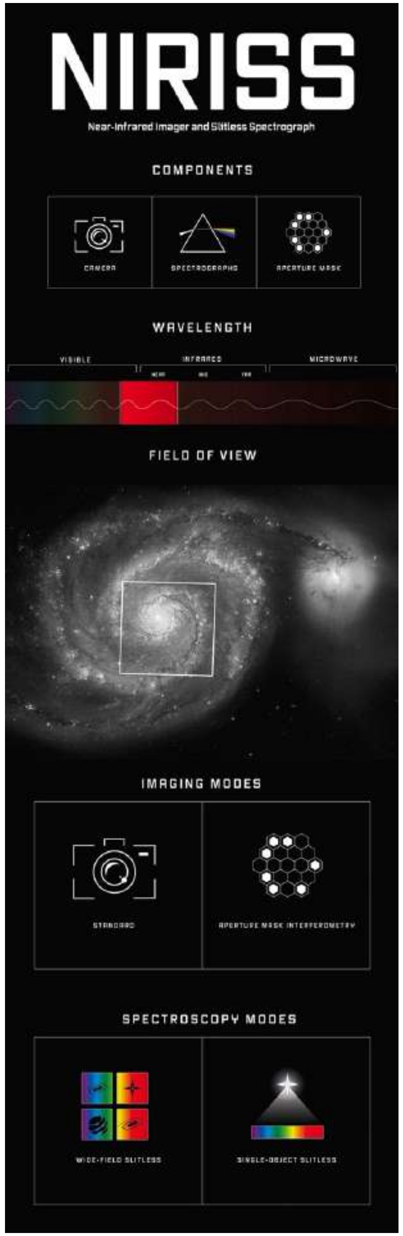
Optimized combination of imaging and spectroscopic capabilities
Detector choice depends on Wavelength and operation mode





JWST Instruments





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

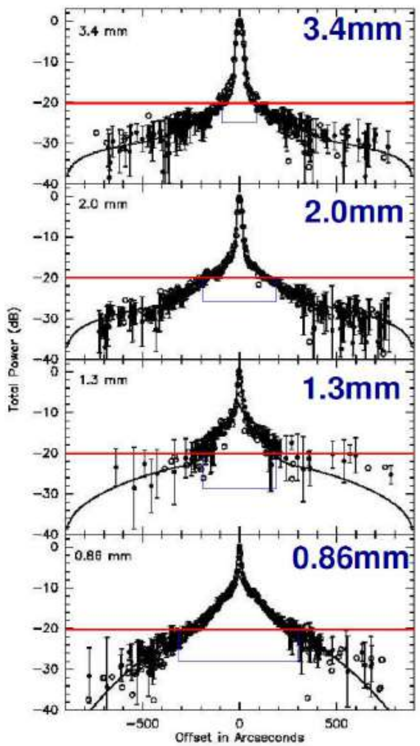
- https://www.eso.org/public
- https://www.eso.org/public/teles-instr/
- https://www.eso.org/public/teles-instr/lasilla
- https://www.eso.org/public/teles-instr/paranal-observatory/vlt
- https://elt.eso.org

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

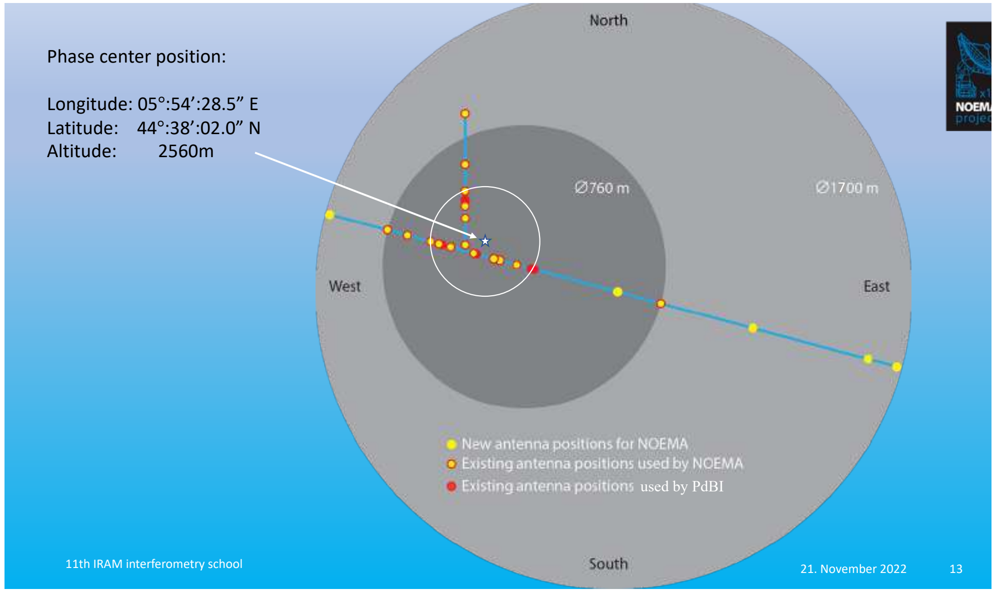
- Camera : NIKA2
  - 2 wavelengths : 2mm and 1.2mm
  - Polarization capabilities
  - 2900 detectors in three arrays (616 Pixels at 2mm and 2x1140 at 1.2mm)
  - FoV 6.5'
- Heterodyne receivers : EMIR
  - Single pixel , double polarization
  - 4 frequency bands (72-116 GHz, 120-175 GHz, 200-270 GHz, 260-250 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)

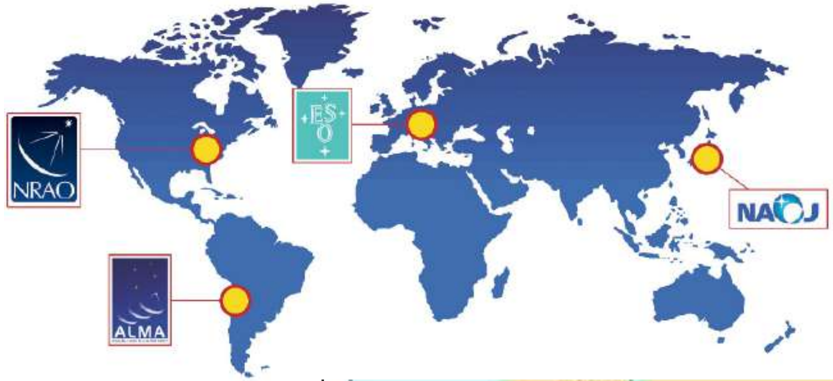
Diameter: 15 m
Collecting area: 176.7 m²
No. of panels: 176 adjustable aluminum panels
Surface accuracy: 35 µm

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

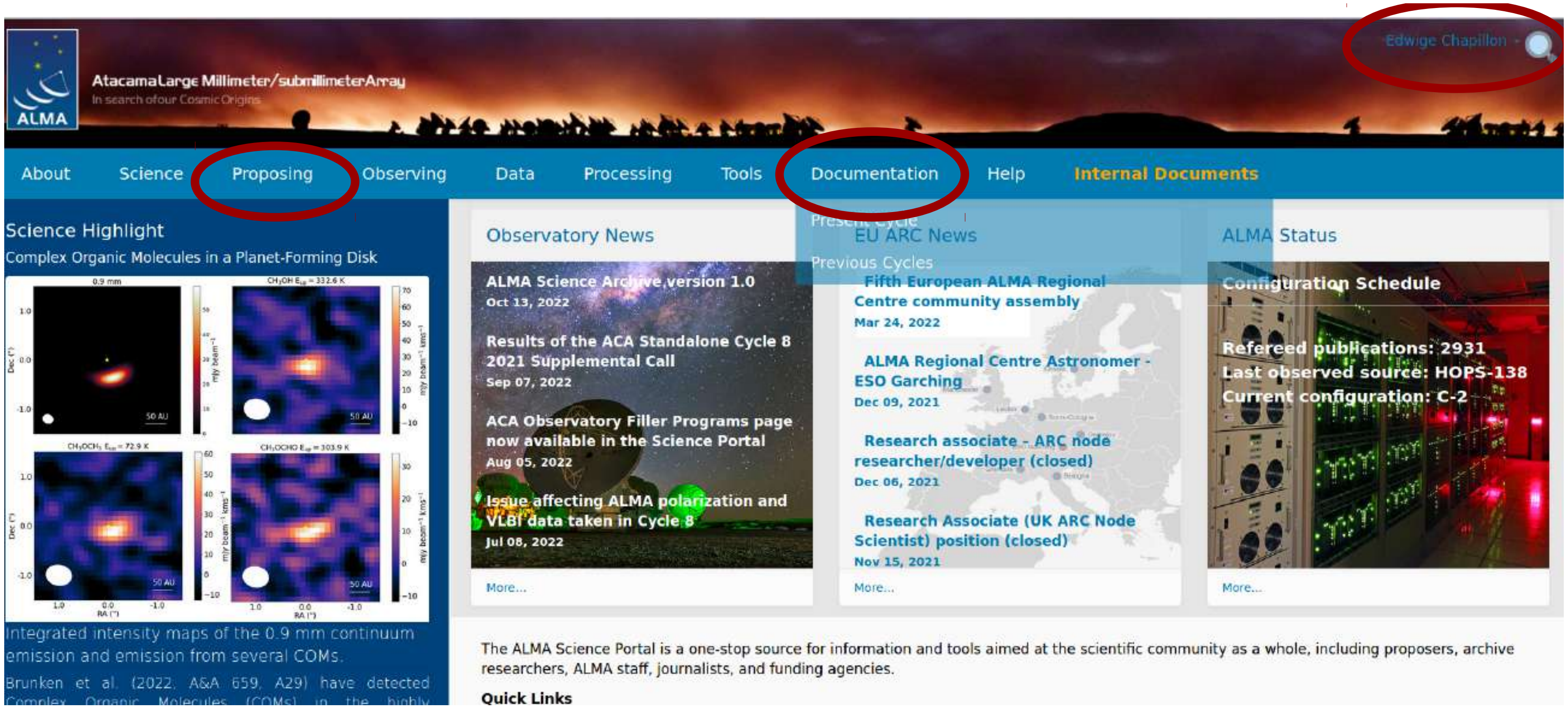
- One size does not fit all !
  - Compromise between angular resolution (fine details) and Field of View (global view)
  - Compromise between spectral resolution (high for line profile information) and spectral coverage (low to moderate R give a broader coverage)
  - Compromise between complexity of observing modes and easy scheduling survey with standard setups)

  - Different detector and spectrometer technologies with wavelength domain : these compromises lead to different instrument concepts

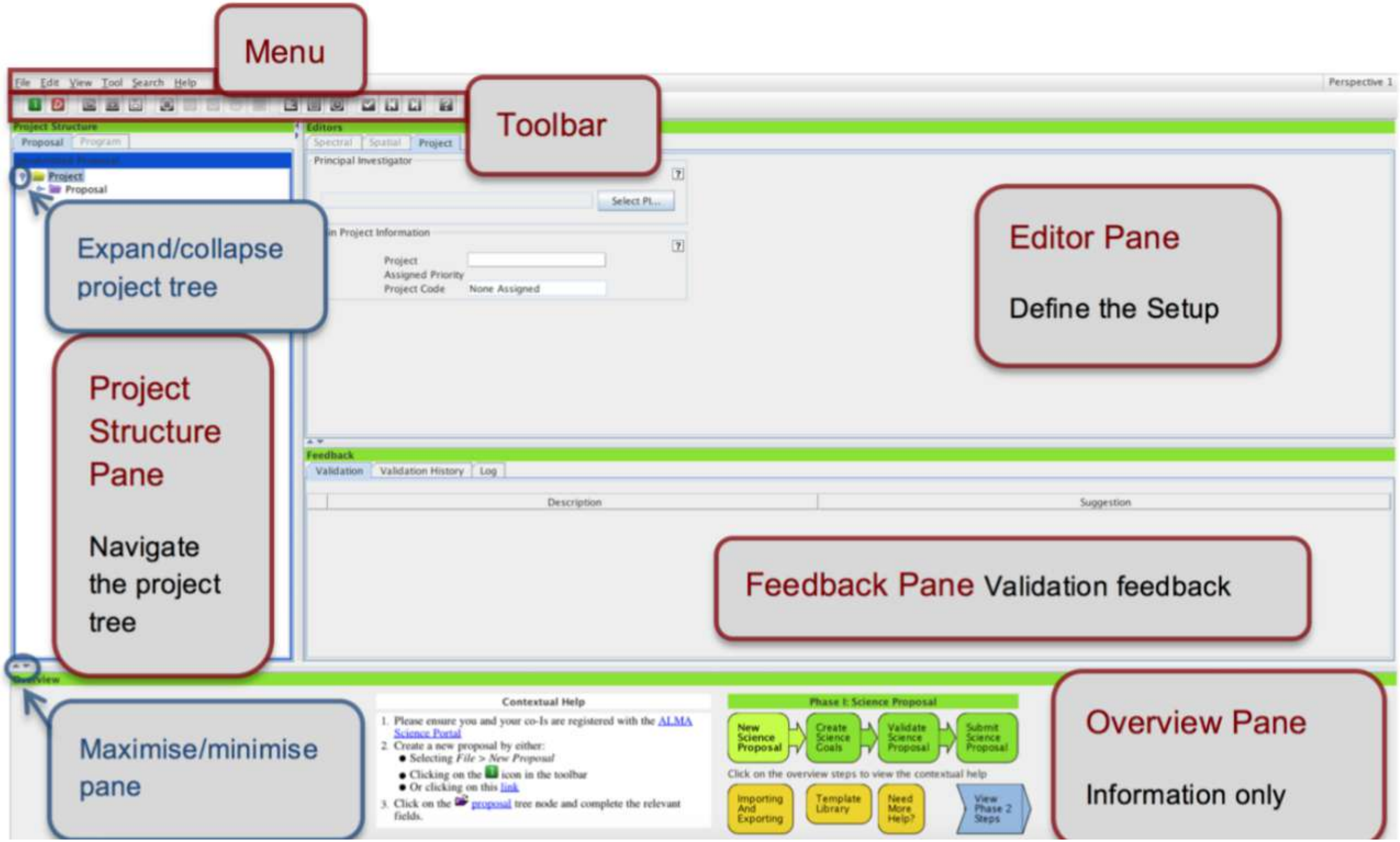
Preparing for observations : e.g. ALMA

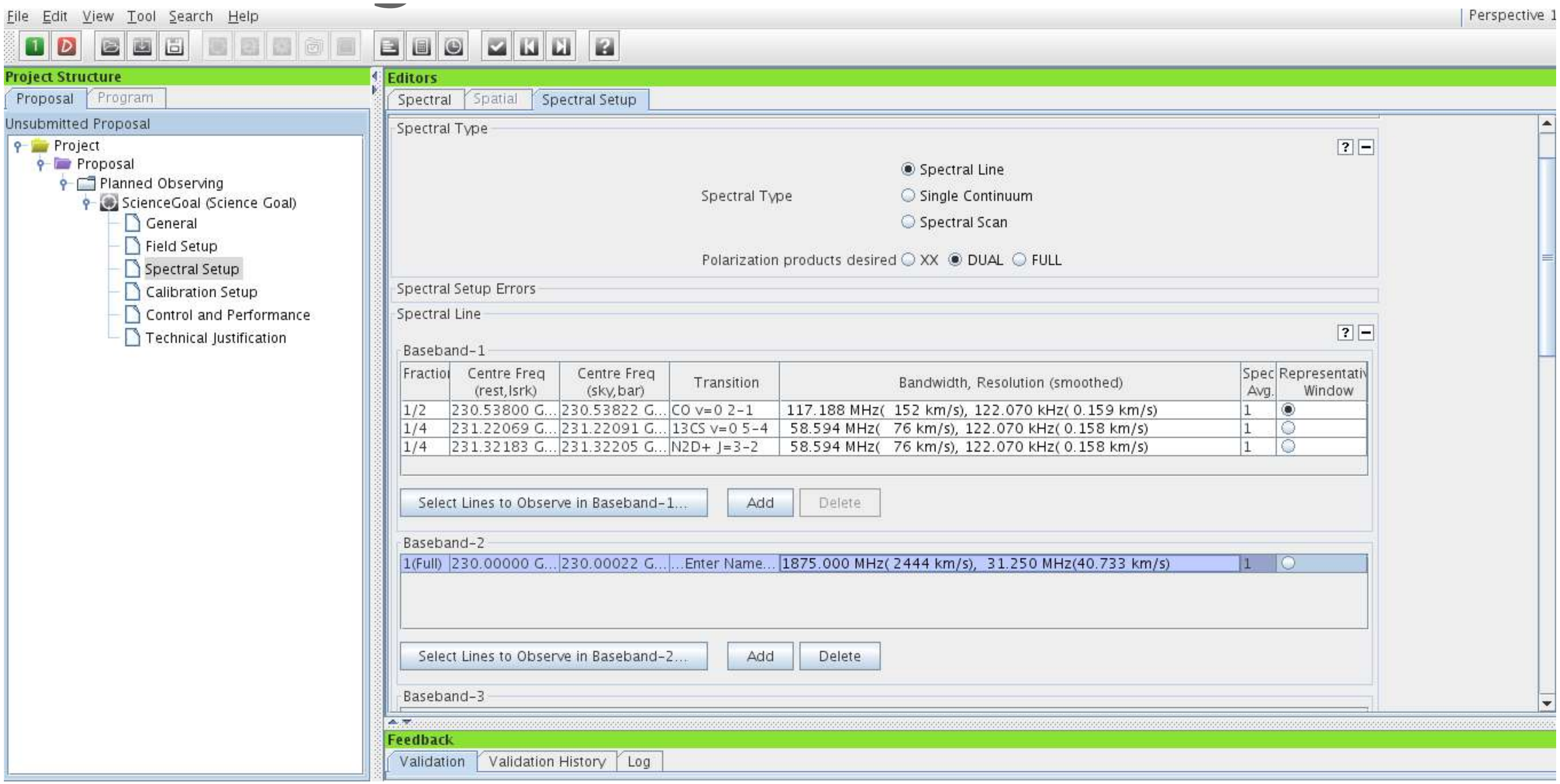
- Explain your idea and explain which information you wish to collect and how you can derive it from the measurements : Proposal writing
- Use the Observing tool to derive the sensitivity and optimize the observation procedure : ALMA-OT
  - Selection of the target(s)
  - Selection of the observing mode : 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 ALMA observing tool




File Edit View Tool Search Help
Perspective 1
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 Type
Spectral Line
Single Continuum
Spectral Scan
Polarization products desired XX DUAL FULL
Spectral Setup Errors
Spectral Line
Baseband-1
Fractioi
Centre Freq (rest,lsrk)
Centre Freq (sky,bar)
Transition
Bandwidth, Resolution (smoothed)
Spec Avg.
Representativ 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
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
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
Select Lines to Observe in Baseband-1...
Add
Delete
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
Select Lines to Observe in Baseband-2...
Add
Delete
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

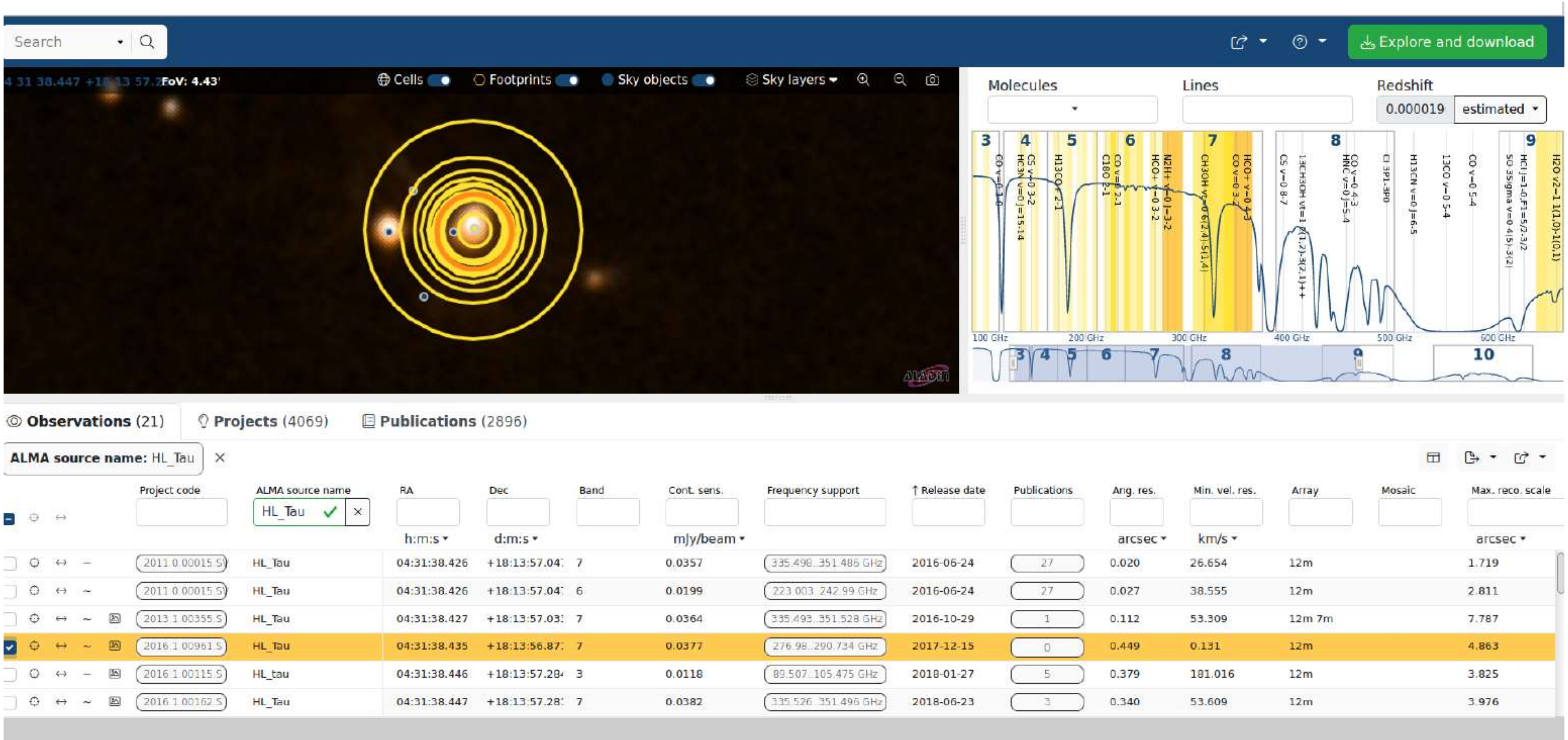
Astronomy science portal : Strasbourg Astronomical Data Center (CDS)

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

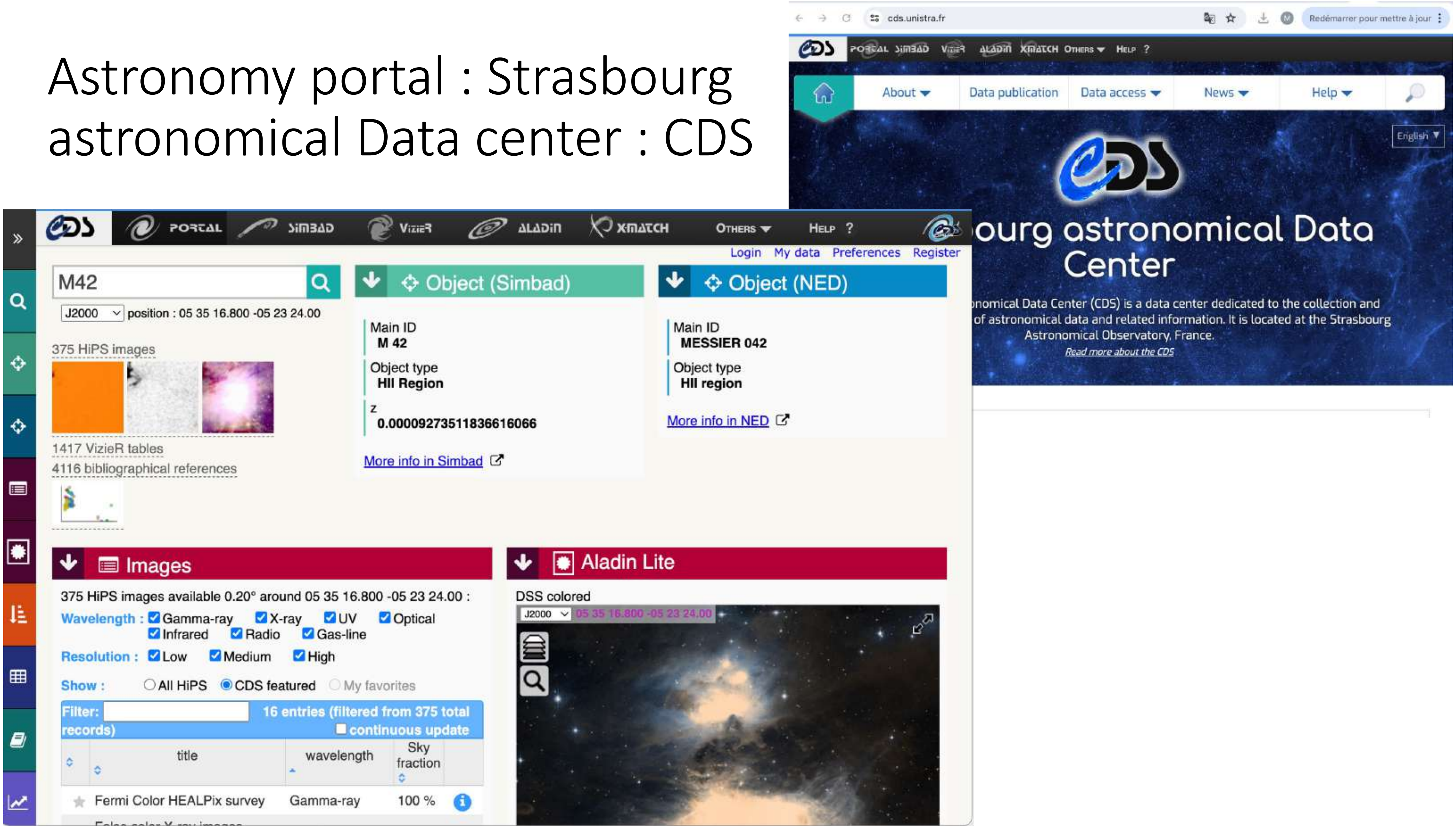
Several tools : ALADIN for Images, VizieR for catalogs, SIMBAD for bibliography, Xmatch for source identification , …

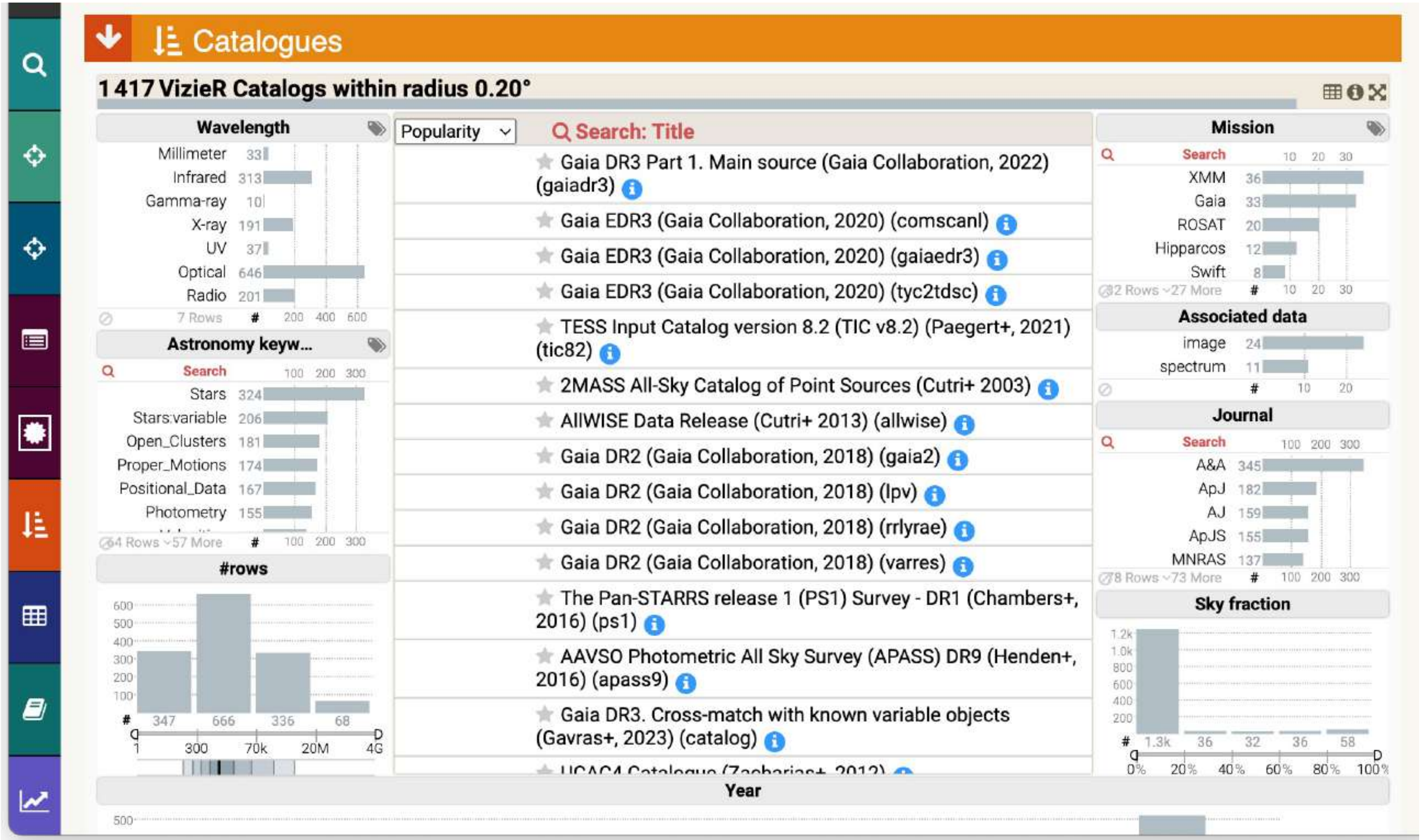
https://aladin.cds.unistra.fr/aladin.gml

ALMA data archive



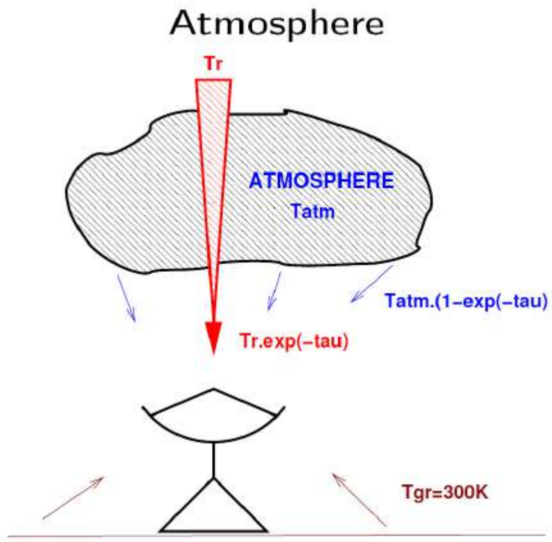
Astronomy portal : Strasbourg astronomical Data center : CDS




Catalogues
1 417 VizieR Catalogs within radius 0.20°
Wavelength
Millimeter 33
Infrared 313
Gamma-ray 10
X-ray 191
UV 37
Optical 646
Radio 201
7 Rows
Astronomy keyw...
Search
Stars 324
Stars:variable 206
Open_Clusters 181
Proper_Motions 174
Positional_Data 167
Photometry 155
64 Rows ~57 More
#rows
347 666 336 68
1 300 70k 20M 4G
Popularity
Search: Title
Gaia DR3 Part 1. Main source (Gaia Collaboration, 2022) (gaiadr3)
Gaia EDR3 (Gaia Collaboration, 2020) (comscanl)
Gaia EDR3 (Gaia Collaboration, 2020) (gaiaedr3)
Gaia EDR3 (Gaia Collaboration, 2020) (tyc2tdsc)
TESS Input Catalog version 8.2 (TIC v8.2) (Paegert+, 2021) (tic82)
2MASS All-Sky Catalog of Point Sources (Cutri+ 2003)
AllWISE Data Release (Cutri+ 2013) (allwise)
Gaia DR2 (Gaia Collaboration, 2018) (gaia2)
Gaia DR2 (Gaia Collaboration, 2018) (lpv)
Gaia DR2 (Gaia Collaboration, 2018) (rrlyrae)
Gaia DR2 (Gaia Collaboration, 2018) (varres)
The Pan-STARRS release 1 (PS1) Survey - DR1 (Chambers+, 2016) (ps1)
AAVSO Photometric All Sky Survey (APASS) DR9 (Henden+, 2016) (apass9)
Gaia DR3. Cross-match with known variable objects (Gavras+, 2023) (catalog)
Mission
Search
XMM 36
Gaia 33
ROSAT 20
Hipparcos 12
Swift 8
32 Rows ~27 More
Associated data
image 24
spectrum 11
Journal
Search
A&A 345
ApJ 182
AJ 159
ApJS 155
MNRAS 137
78 Rows ~73 More
Sky fraction
1.3k 36 32 36 58
0% 20% 40% 60% 80% 100%
Year

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



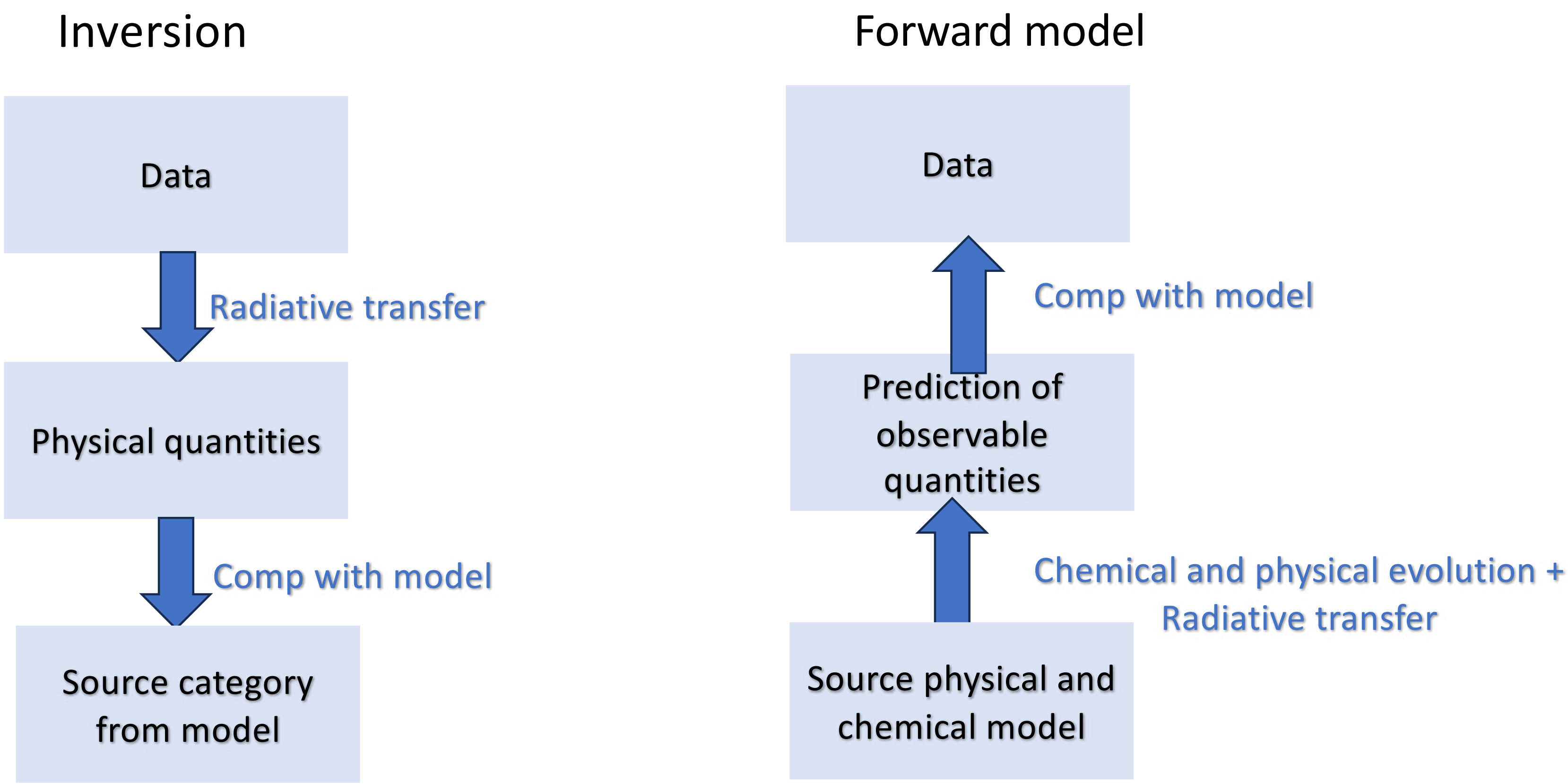
Calibration and data analysis : From physical units to calibrated spectra and images

- 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.)

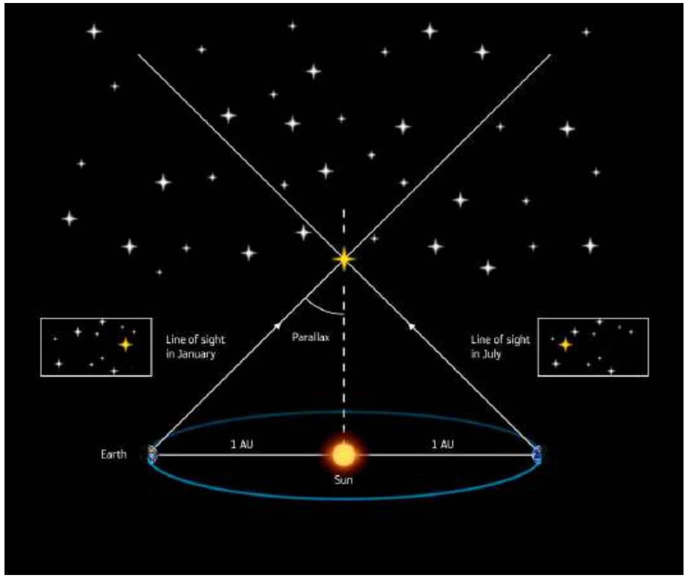

Inversion
Data
Radiative transfer
Physical quantities
Comp with model
Source category from model
Forward model
Data
Comp with model
Prediction of observable quantities
Chemical and physical evolution + Radiative transfer
Source physical and chemical model

Physical and chemical information : structure

- Source sizes
  - From the angular extent of the source
  - Must know the source distance

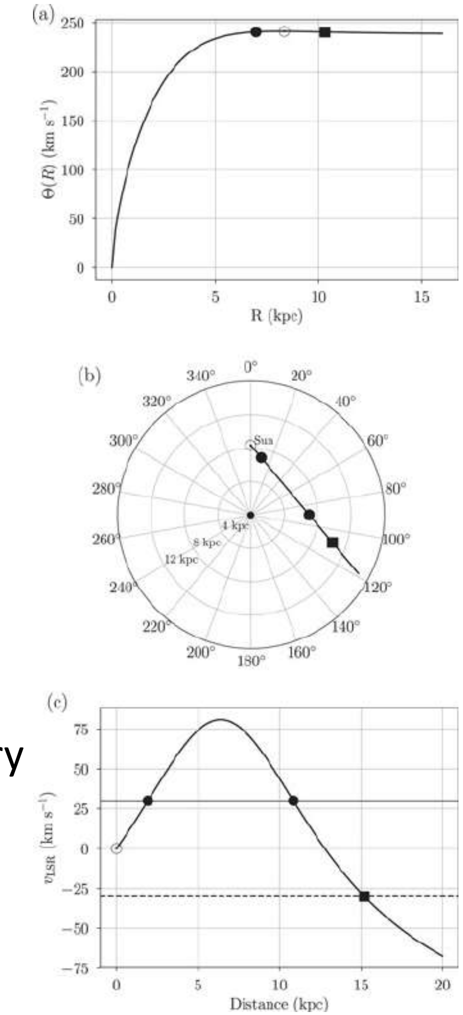
  - Definition : 1 parsec = the distance from Earth to Sun (1 AU = 1.5 10^8 km) is viewed with an angle of 1 arcsec = 648000/Pi astronomical units
  - Angular size of well known objects
    - Moon. 30’
    - Planet : Jupiter ~32-50” ; Uranus ~3-4”
    - Circumstellar Disk 0.25” (100 ua) if in Orion (Distance 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 ~ 1” (not a point source)

Measuring distances

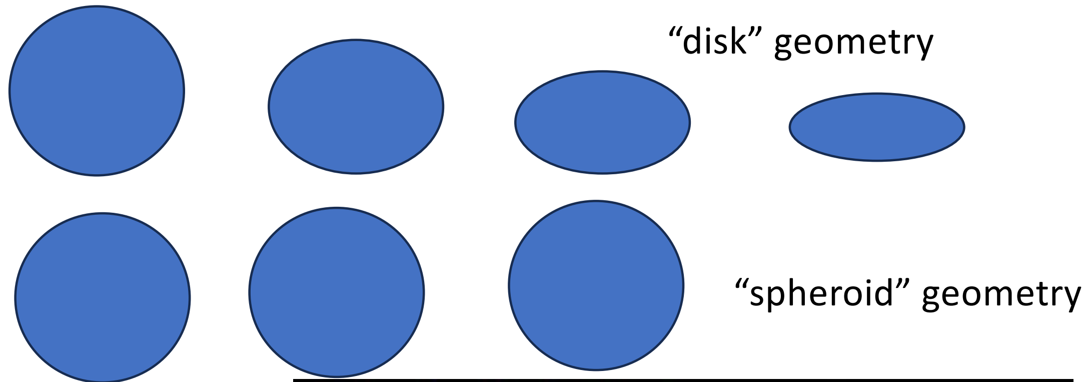


- Parallax = displacement of the source apparent position due to the Earth motion
  - Most accurate distance determination (geometrical effect)
  - The GAIA mission has measured >> 10^6 stellar parallax
  - Maser features (H_2O, SiO) can also provide parallax associated to star forming regions, or stellar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

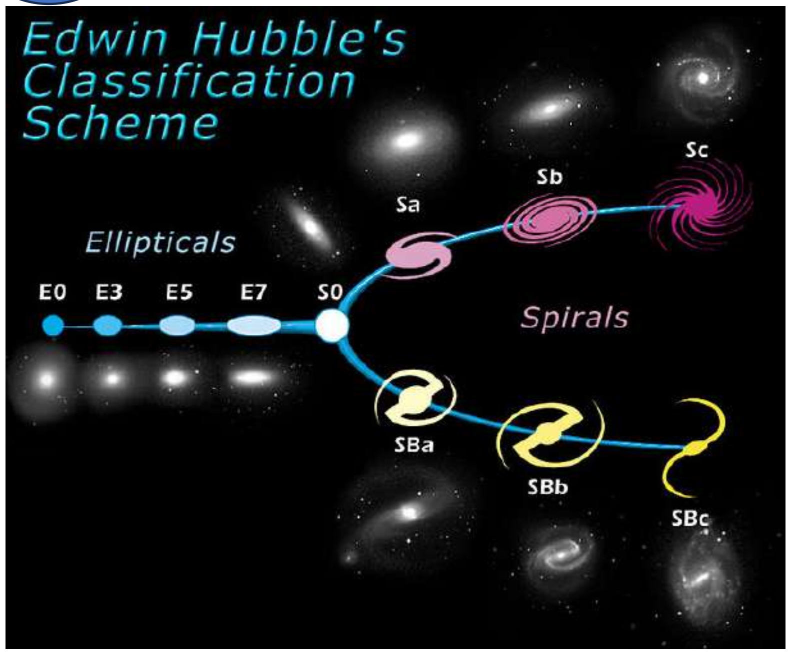
- The radial velocity provides information on the relative displacement of the source with respect to the observatory
- Using a velocity field model (e.g. Galaxy rotation curve) in the Milky Way, the source distance can be derived



Physical and chemical information : structure



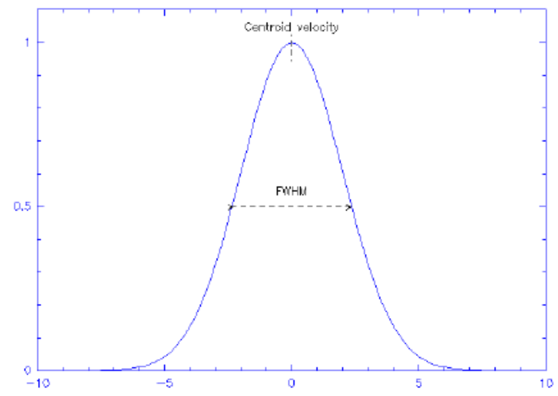
- Images = 2D projections of 3D structures on the plane of the sky.
- Integration along the line of sight → use assumptions to get information on the 3D structure :
  - Statistics : different viewing angles of similar sources
  - Velocity field (e.g. rotation, expansion, infall, outflow, ..)
  - Differential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



Physical and chemical information : velocity

- Along the line of sight
  - The velocity along the line of sight easily derived from the Doppler effect $\delta v/c \sim \delta\lambda/\lambda \sim \delta\nu/\nu$ (positive velocity and redshifted wavelengths for receding objects, negative velocity and blueshifted wavelengths for approaching objects)
  - Spectrally resolved line profile → 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 → ~ 0.05 arcsec/yr in Orion



Collapsing core

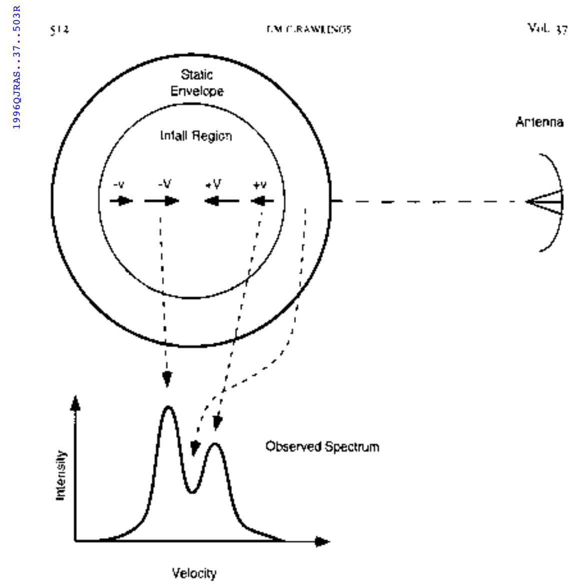
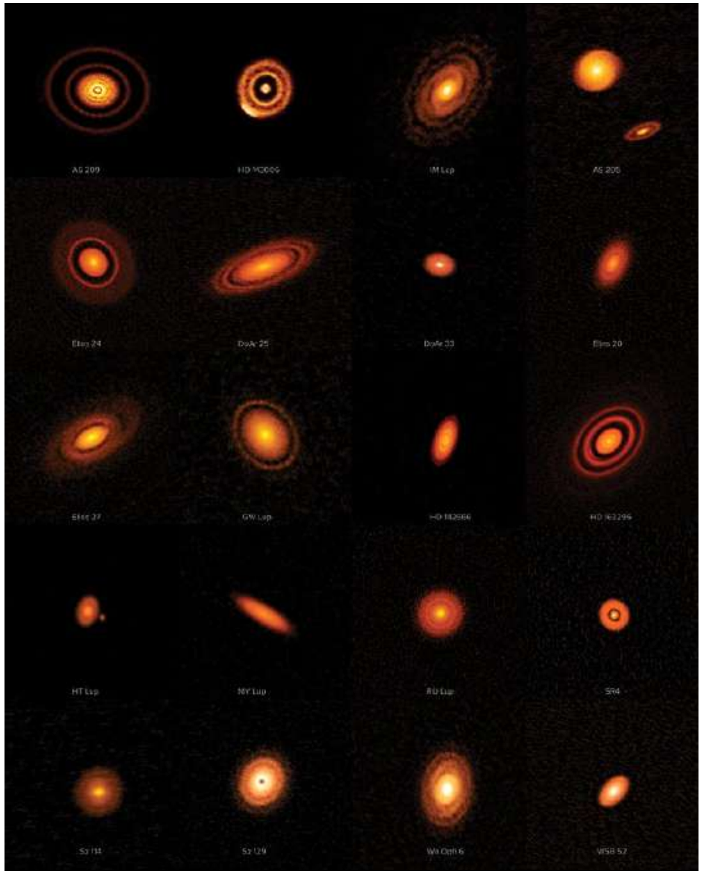
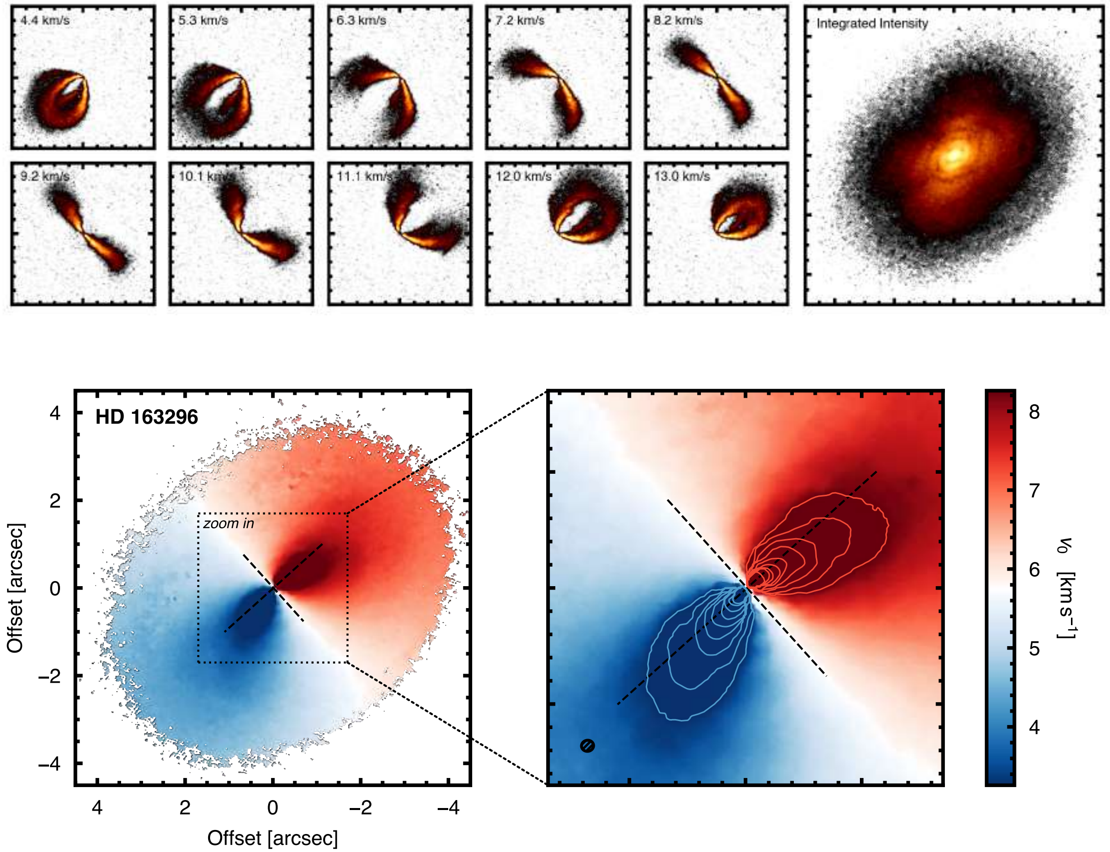


FIG. 4. Signatures of collapse: the formation of asymmetric, double-peaked, optically thick line profiles in collapsing clouds. See text for description.

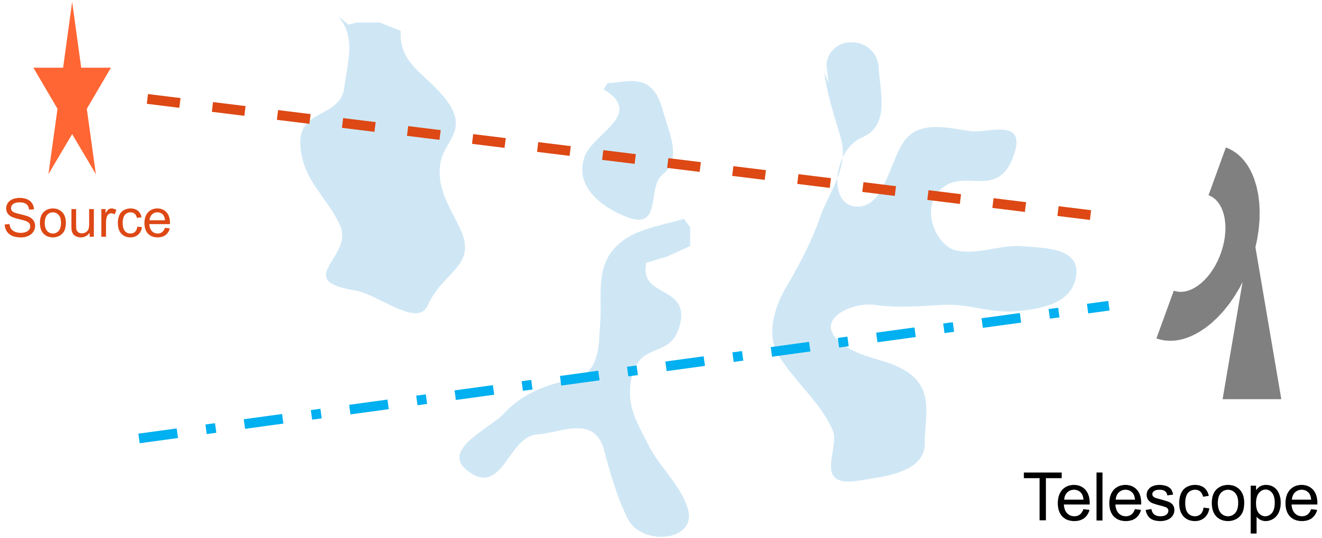


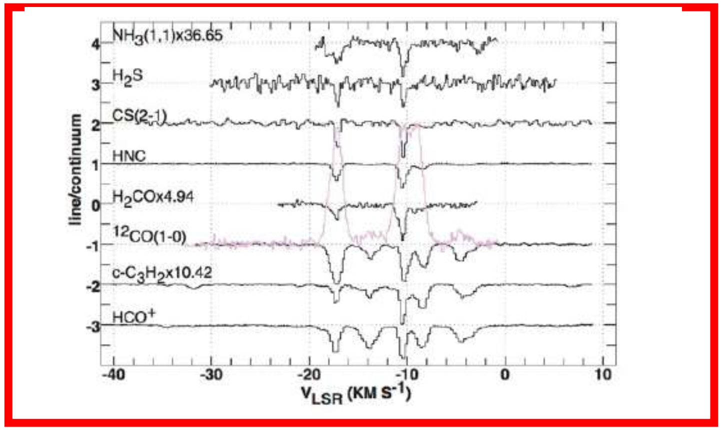
DSHARP , protoplanetary disks with ALMA

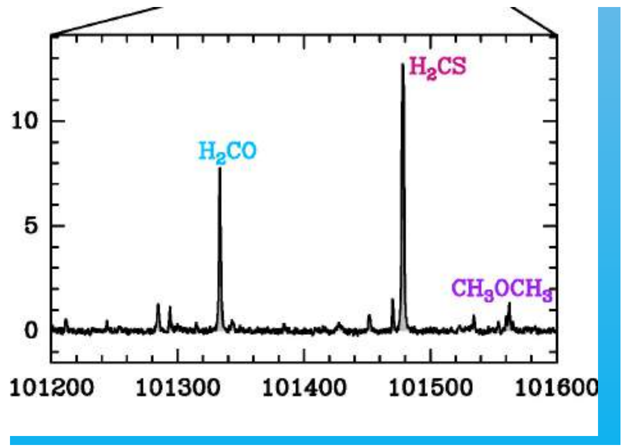


HD 163296 12CO channel ma & velocity field (Armitage+, Isella+)

Line of sight structure : combine emission & absorption



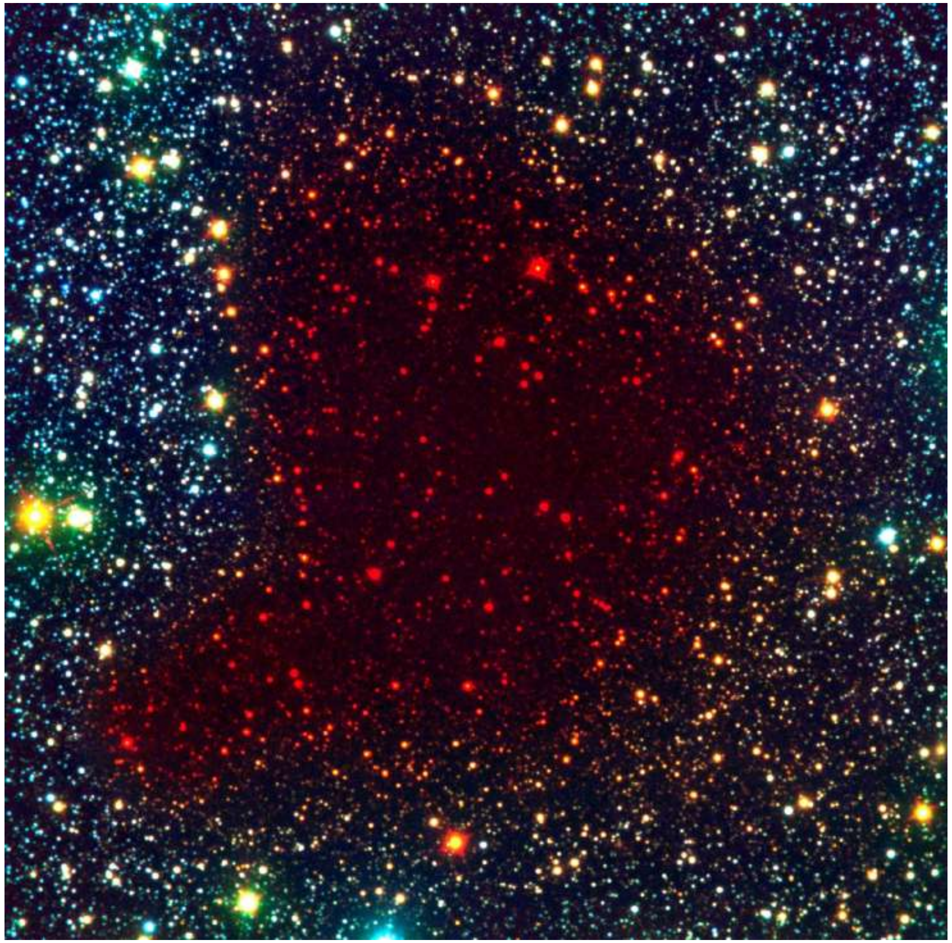




Absorption and emission provide complementary information

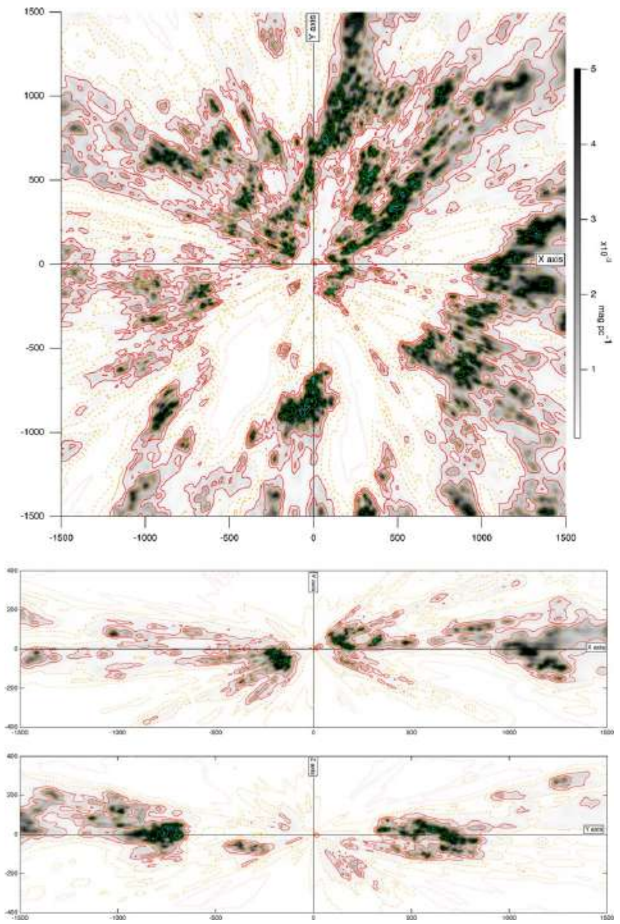
This information can be used to locate the object along the line of sight and for extracting the physical conditions

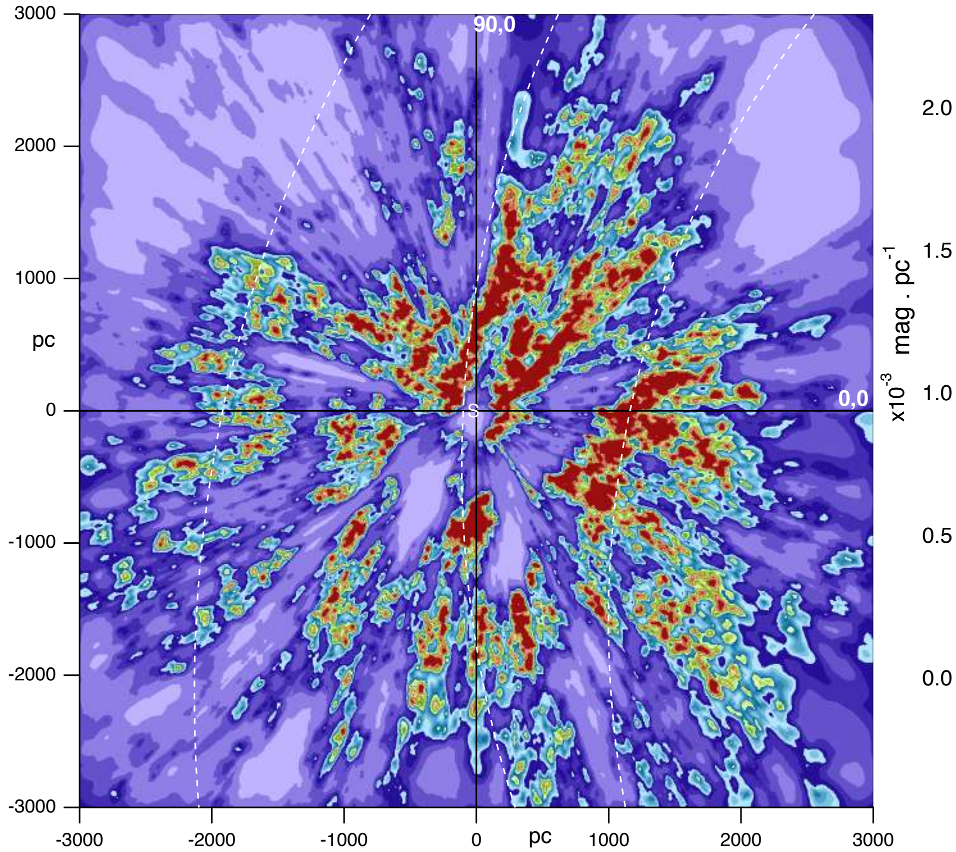
Extinction and reddening



- 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

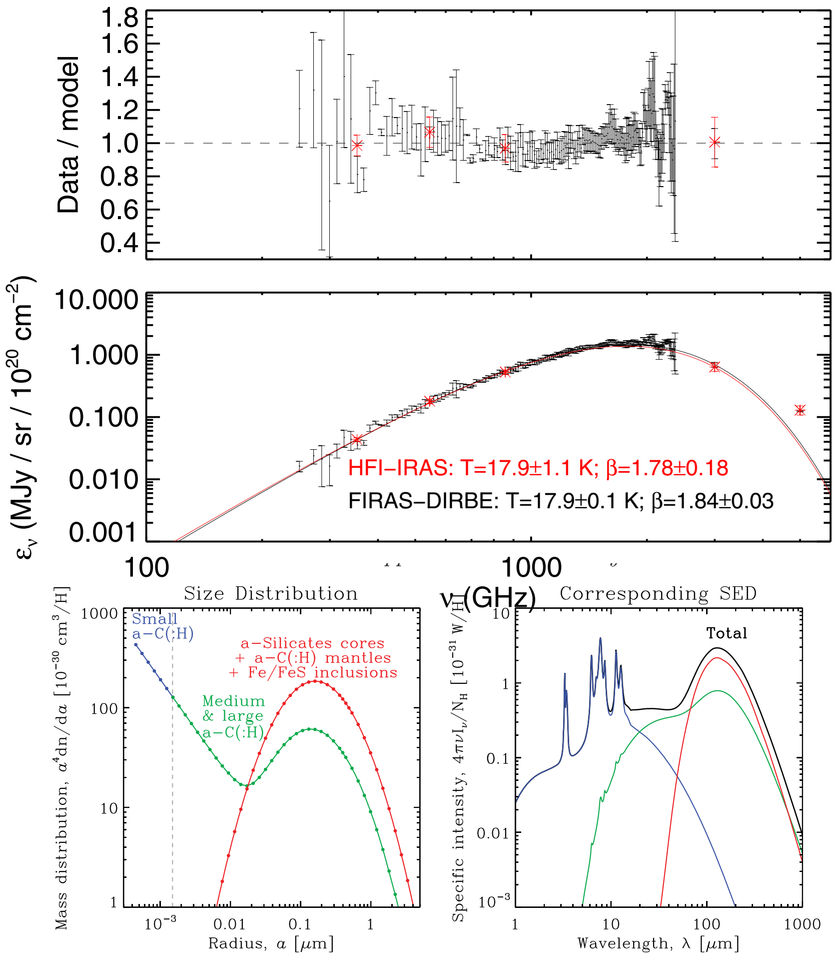




- The matter accumulates in “clouds”
- Mos of the volume is filled with low density material (n < 1 cm^{-3}) with little dust
- Limited spatial resolution

Vergely+2022

Dust emission (simplistic view)



Galliano+2020, Planck XXIV

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

$$I\nu \sim M_{grains}\ \varepsilon(\nu)\ B\nu(T_g) \sim N_{gas}\ \varepsilon(\nu)\ B\nu(T_g)$$

With dust emissivity $\varepsilon(\nu)$ scaling as ν^{β}

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

The SED fit gives the dust temperature Tg, the dust emissivity index β and the gas column density Ngas (with assumptions on the dust properties)

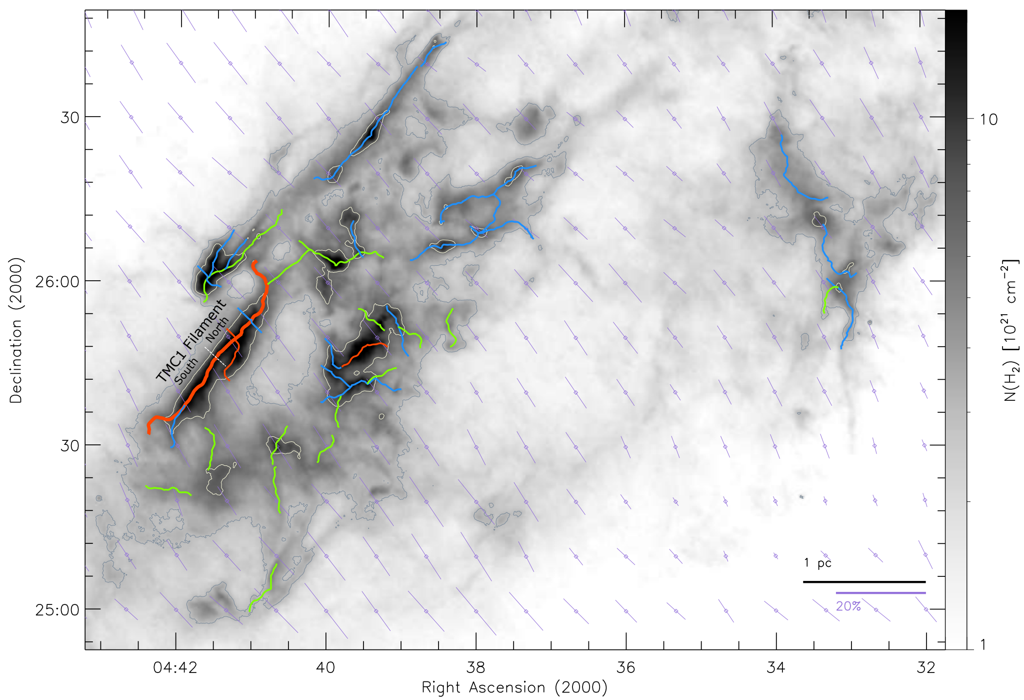
! Not so simple : Mixture of dust grain population & sizes + temperature gradient along the line of sight + variation of emissivity with grain properties ..

Read carefully the assumptions

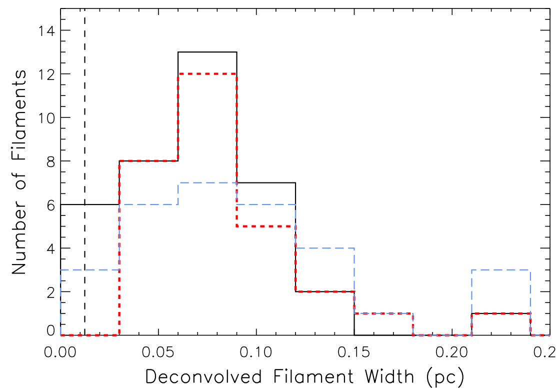
NGC 2024
Alnitak
NGC 2023
IC 434
IC 435
Horsehead
Nebula
N
E
0.5 pc
0.07°

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)



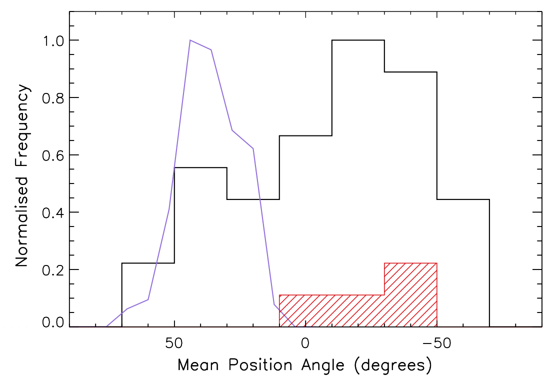


Figure 10. Comparison of filament position angles to the magnetic field direction. The black curve shows the histogram of all robust filaments towards the TMC1 region. The red-shaded histogram shows the orientation of supercritical filaments. The purple curve shows the normalised histogram of the magnetic 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, C_2 , NH_3, etc. (rotational levels)
- Needs an accurate modeling of the excitation processes (collisions with H, He, H_2, 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 Tkin for n ≥ 10^4 cm^{-3}
- Tkin 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

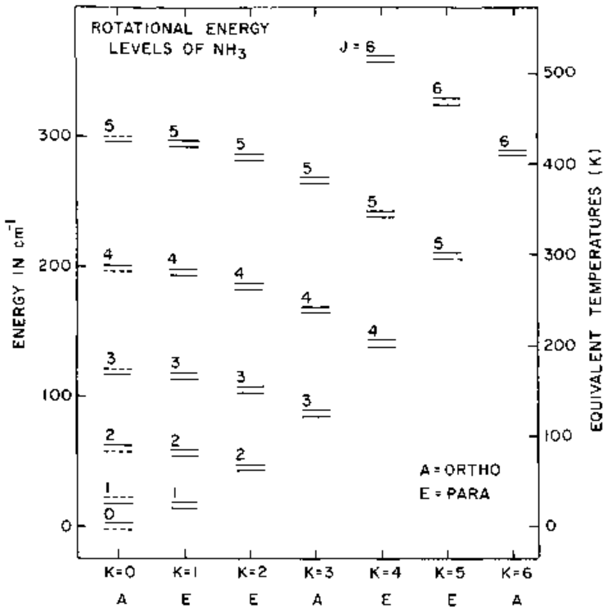
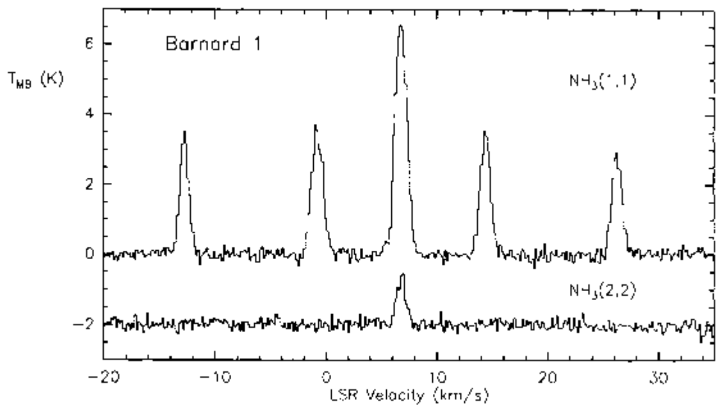
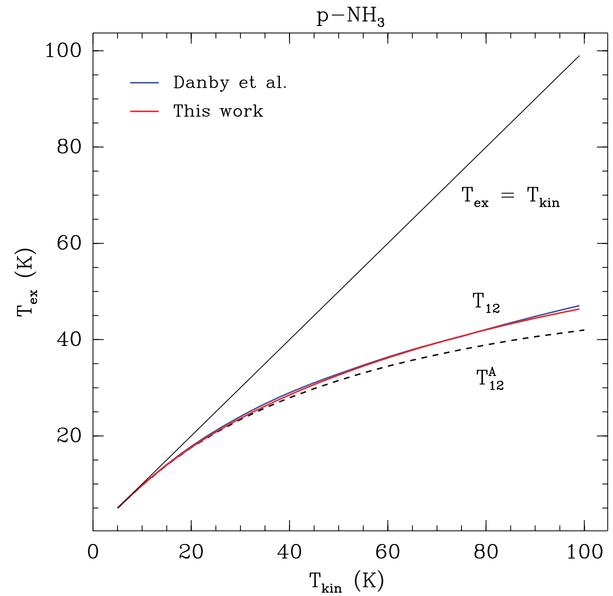


Figure 1 Energy level diagram of rotation-inversion states. J is the total angular-momentum quantum number, and K is the projected angular momentum along the molecular axis.

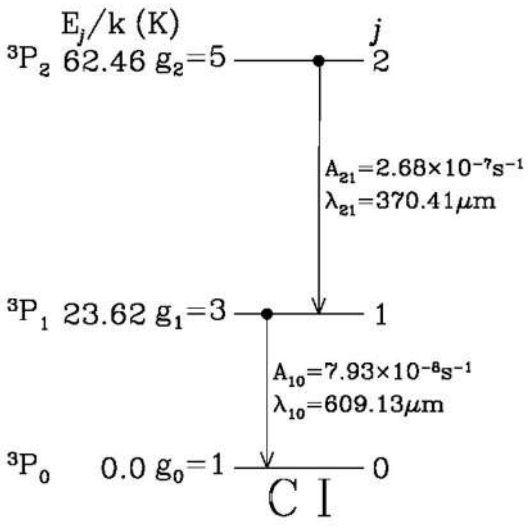


Species	Transition $J_{K,\epsilon} - J'_{K',\epsilon'}$	ν (GHz)	E_{up} (K)	n_{crit} (cm^{-3})
p-NH_3	$1_{1,-} \rightarrow 1_{1,+}$	23.694 496	1.1	3.90×10^3
p-NH_3	$2_{2,+} \rightarrow 2_{2,-}$	23.722 633	42.3	3.08×10^3
p-NH_3	$2_{1,+} \rightarrow 2_{1,-}$	23.098 819	58.3	1.44×10^8
p-NH_3	$3_{2,-} \rightarrow 3_{2,+}$	22.834 185	128.1	3.01×10^8
p-NH_3	$3_{1,-} \rightarrow 3_{1,+}$	22.234 506	144.0	5.41×10^8
o-NH_3	$3_{3,-} \rightarrow 3_{3,+}$	23.870 129	123.6	2.63×10^3
o-NH_3	$1_{1,+} \rightarrow 0_{0,+}$	572.498 068	27.5	5.45×10^7

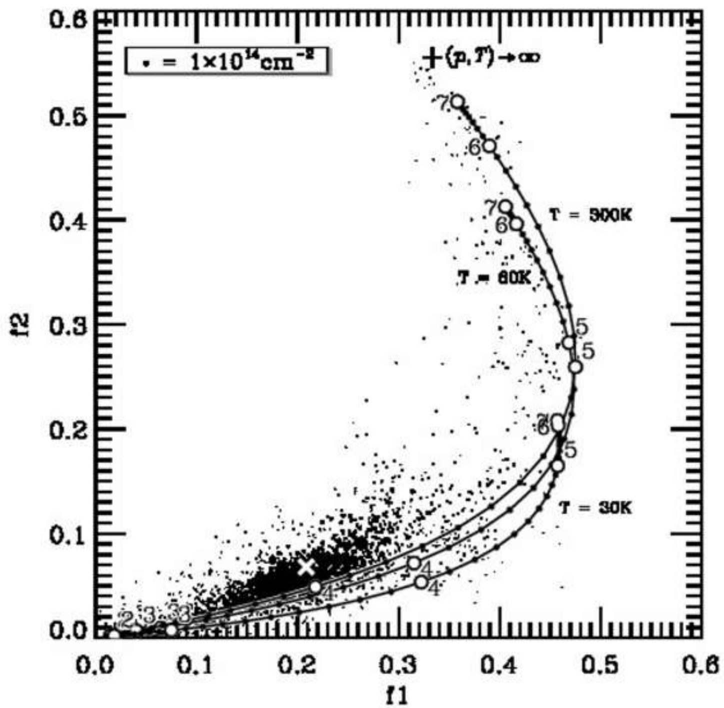


Ho&Townes 1983,Maret+20(

Gas pressures with CI



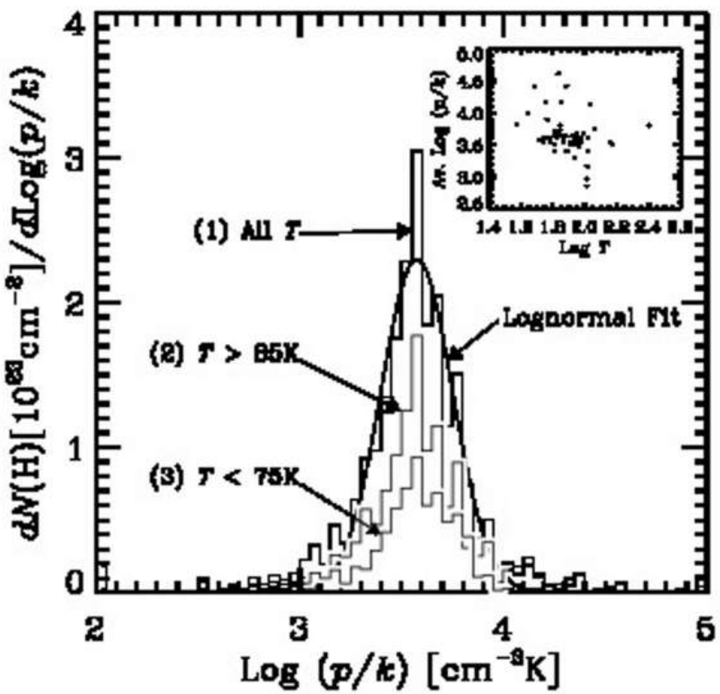
Fraction of C atoms in the 2nd excited level



Fraction of C atoms in the 1st excited level

Jenkins & Tripp (2011)

Pressure distribution



Median pressure

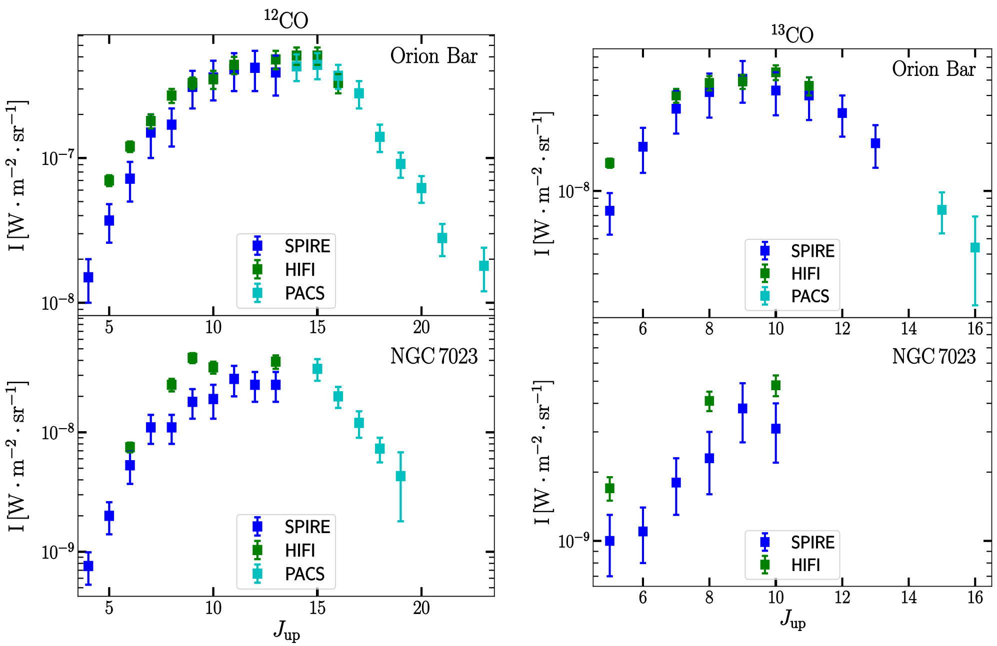
log(p) = 3.58 +/- 0.175

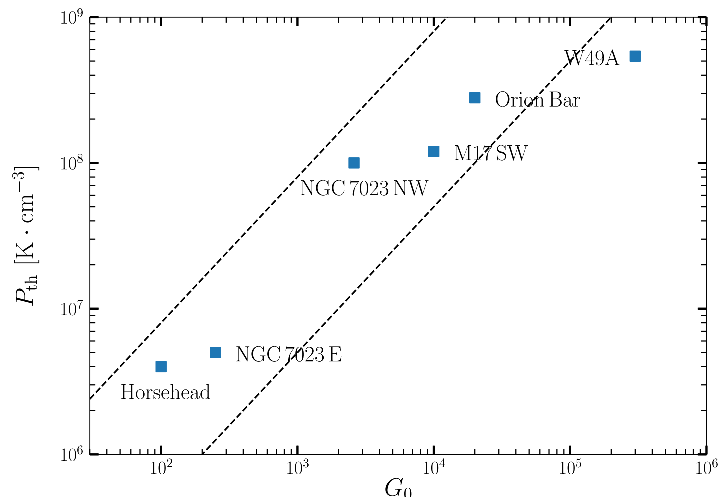
p ~ nT ~ 3800 Kcm^{-3}

within a factor 1.5

Jenkins & Tripp (2011)

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

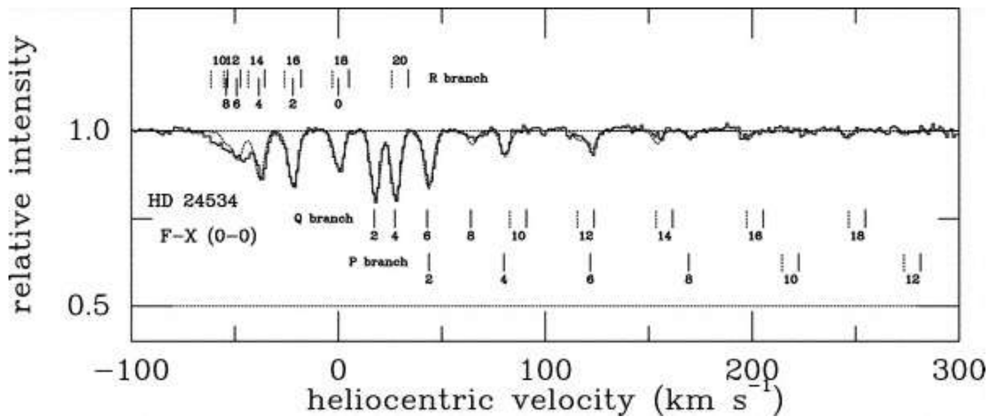
→ Relation between Pth and G0 : feedback

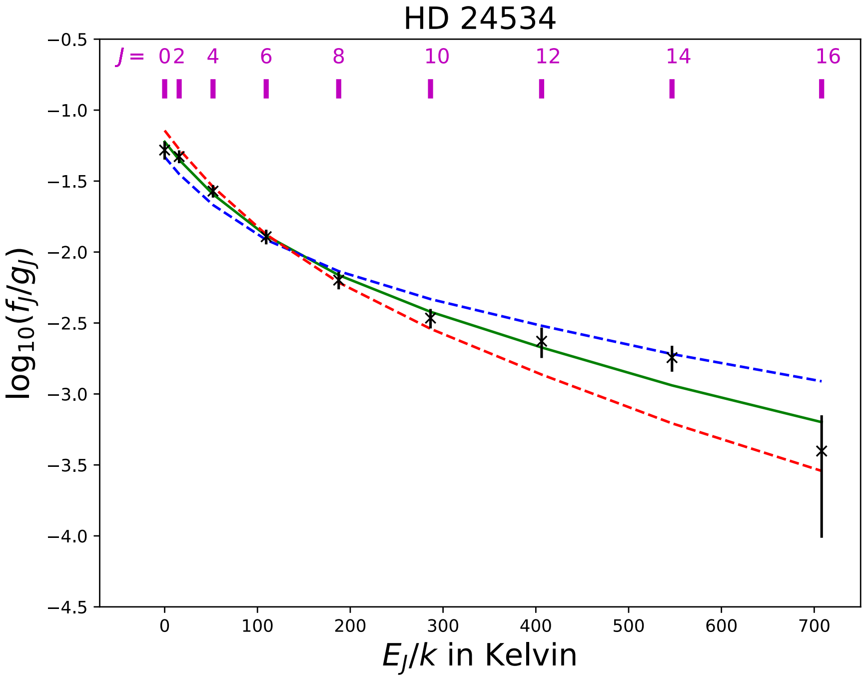
- Implication for CO emission in active and high z galaxies : small regions can contribute a large fraction of the flux

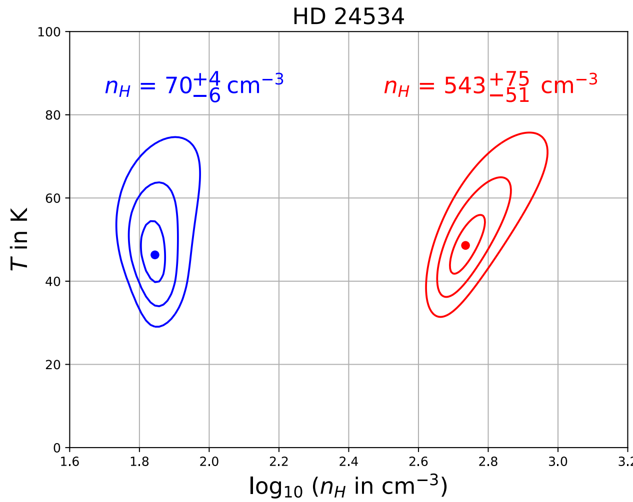
Joblin+2018

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

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

A&A 658, A39 (2022)

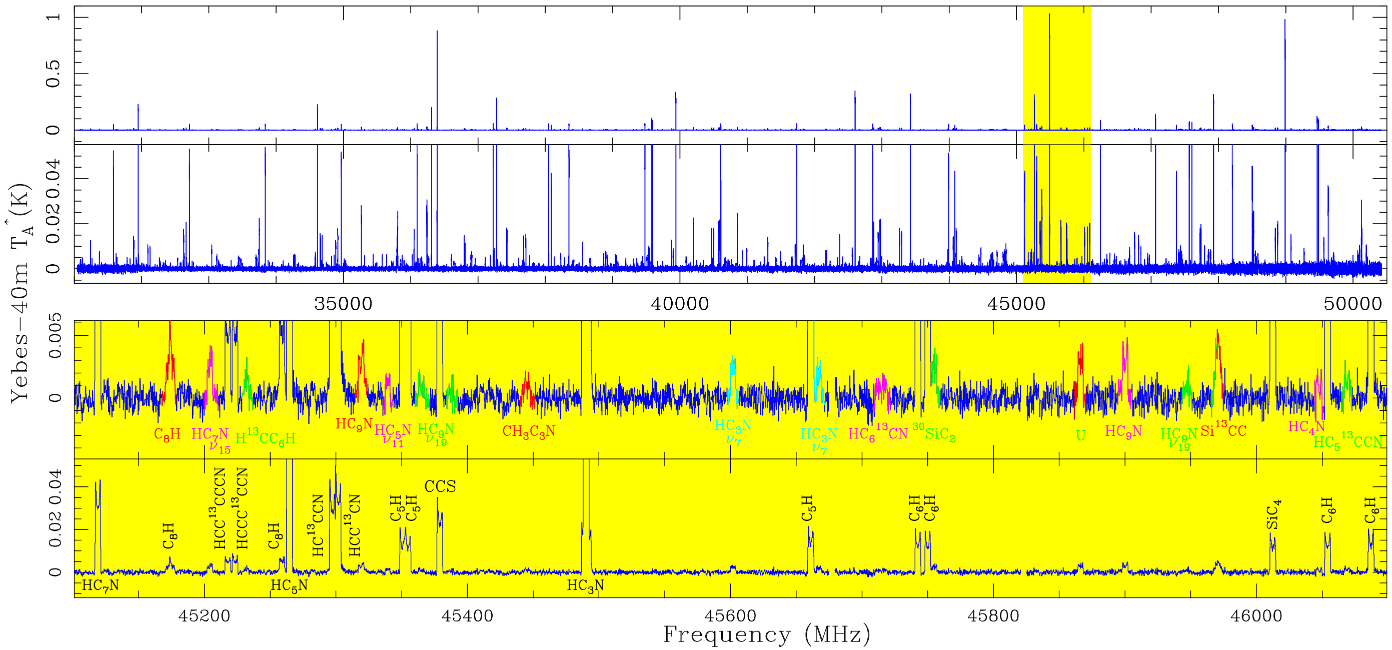


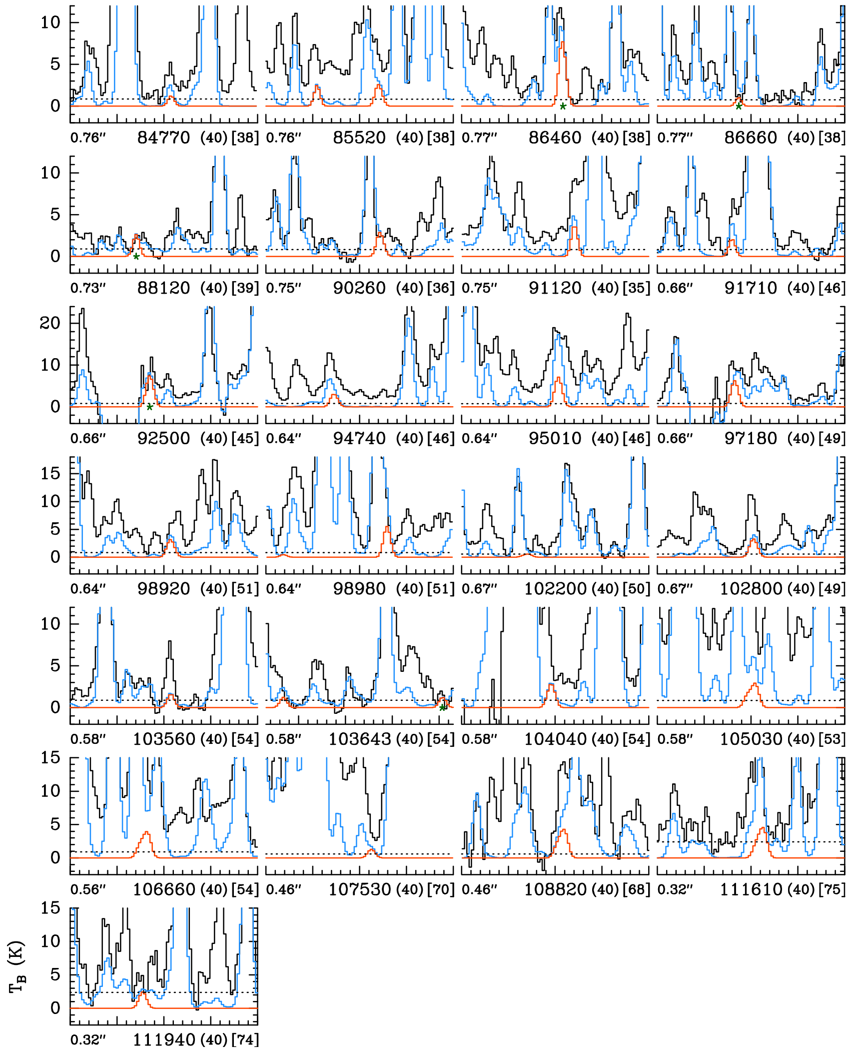
Fig. 2. Overall view of the data with a zoom around 45.6 GHz. Several weak spectral features (∼1−3 mK), revealed in this work, are shown in different colors in one of the panels.

Pardo+2022

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

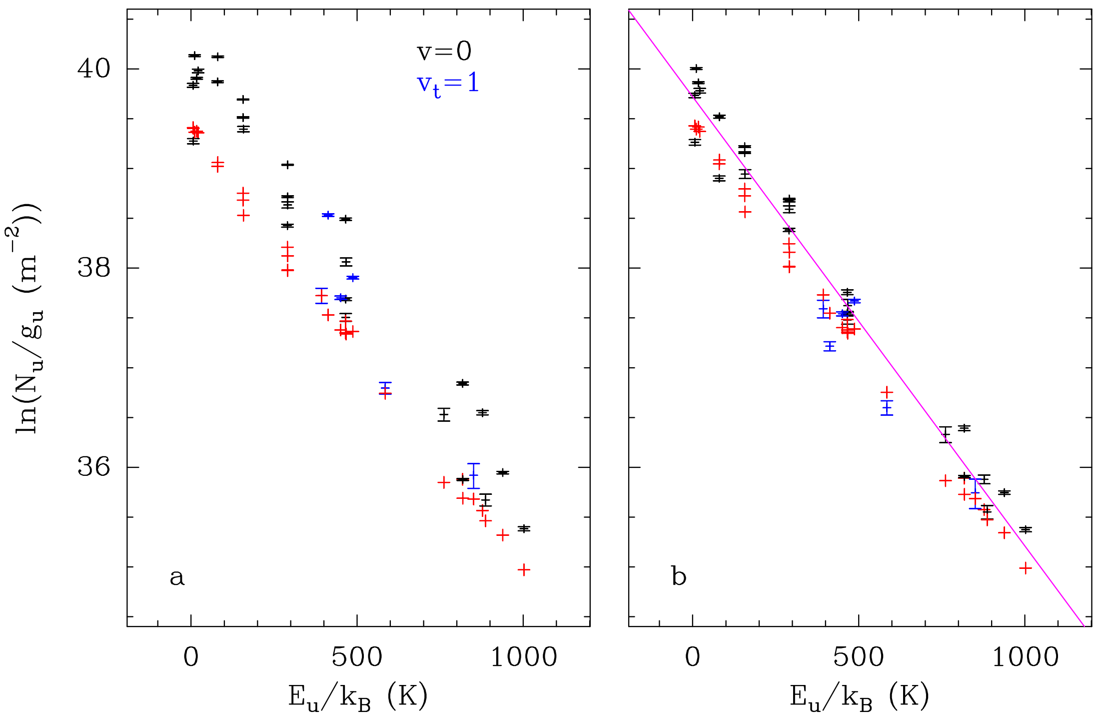
Gyawali, P., et al.: A&A, 677, A65 (2023)



Gyawali+2023

Spectral surveys analysis

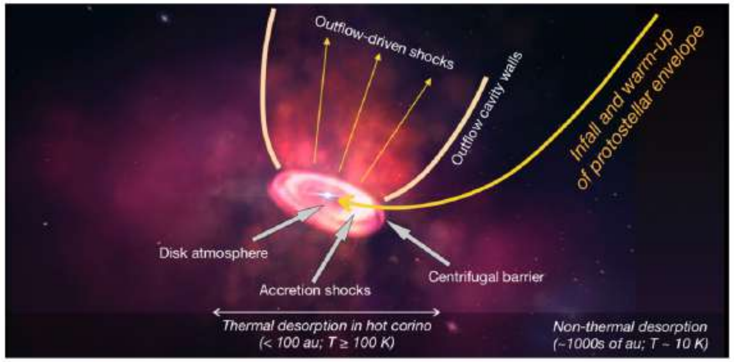
- Rotation diagram allows to check for the consistency of the identification :
- The slope of ln(Nu/gu) vs Eu/k_B is 1/Tex
- The intercept provides ln(Ntot/Qrot)
- ln(Nu/gu) can be deduced from the line integrated intensity W



CH_3NH_2 vt = 0 and vt=1

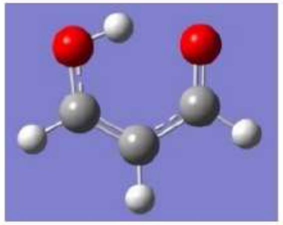
$$Nu/gu = (8\pi k_B/hc^3)\,(\nu[\mathrm{GHz}])^2\ W\ [\mathrm{Kkm/s}]\ /A[s^{-1}]gu$$
$$\sim 1943\ (\nu[\mathrm{GHz}])^2\ W\ [\mathrm{Kkm/s}]\ /A[s^{-1}]gu$$

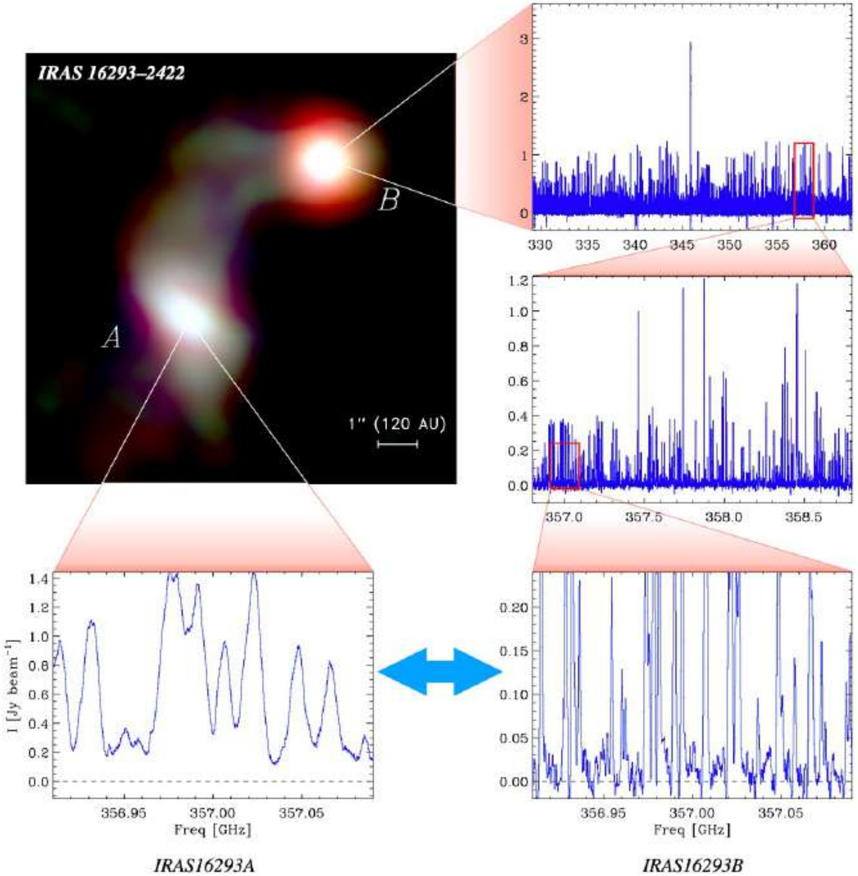
Physical and chemical information : spectral surveys



3-hydroxypropenal

enol





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

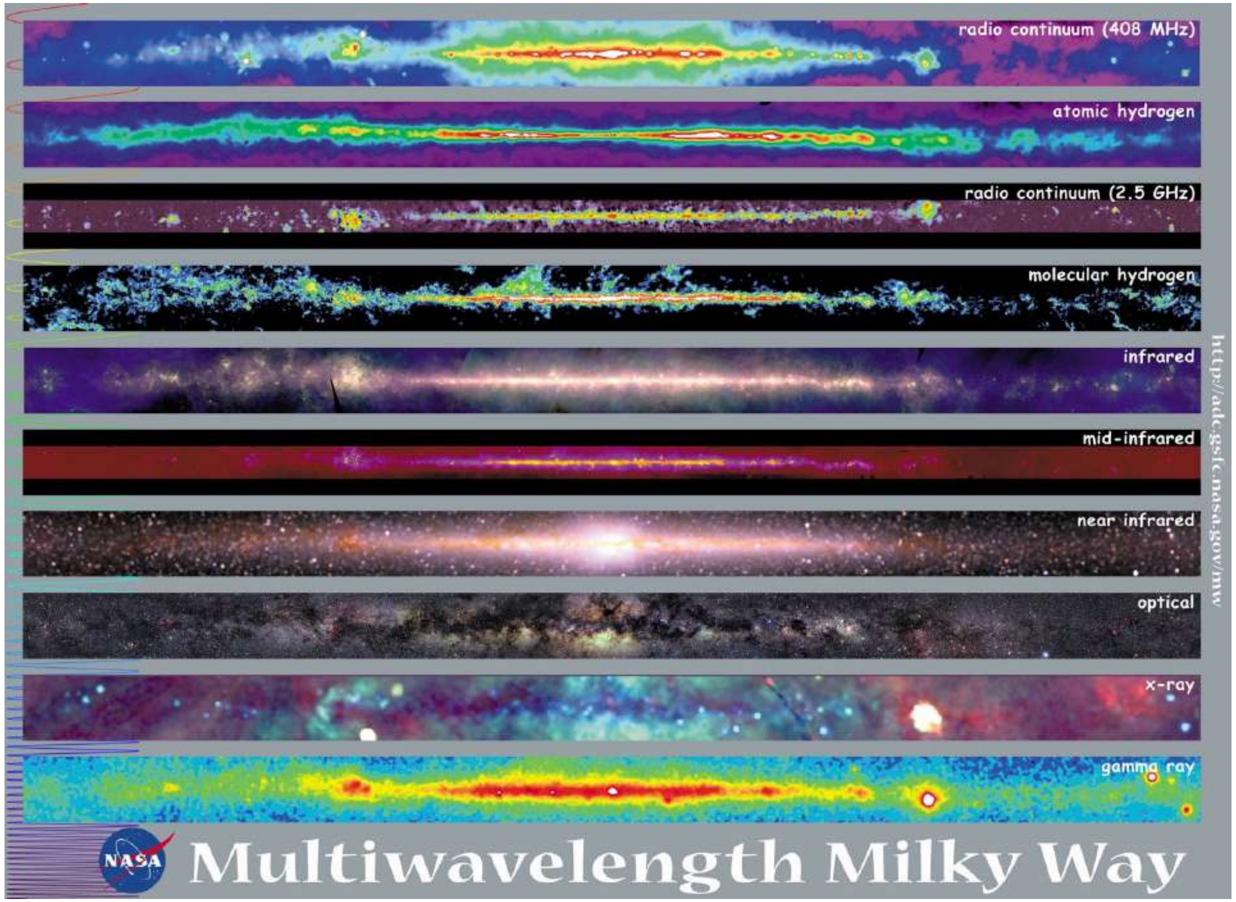
→ Hot corino = hot region zone (> 100K) near the protostar with a rich spectrum displaying a plethora of molecular lines from complex organic molecules (COMP) and their isotopologues (With D, 13C, 18O, 15N,..)

→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.

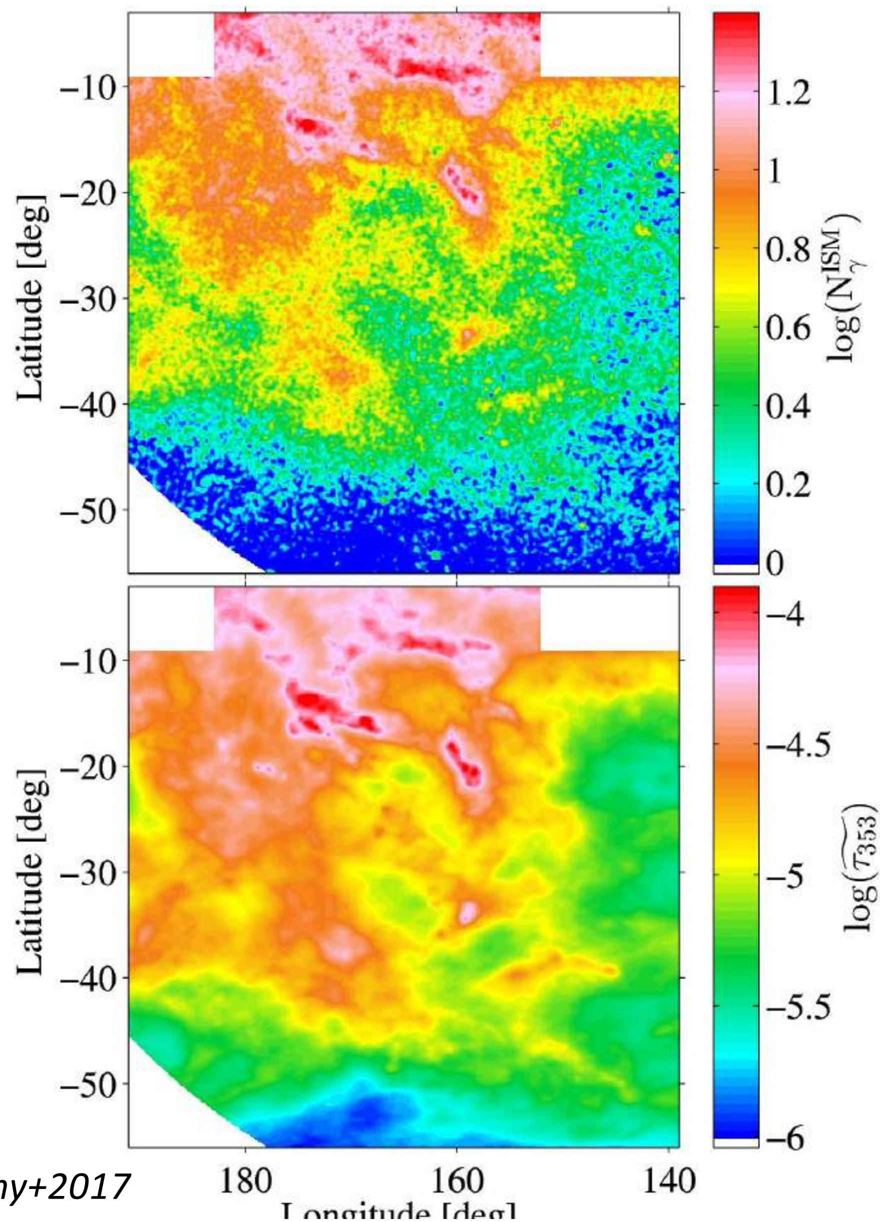
➔ These different ISM phases are accessible through different radiation processes and wavelengths

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



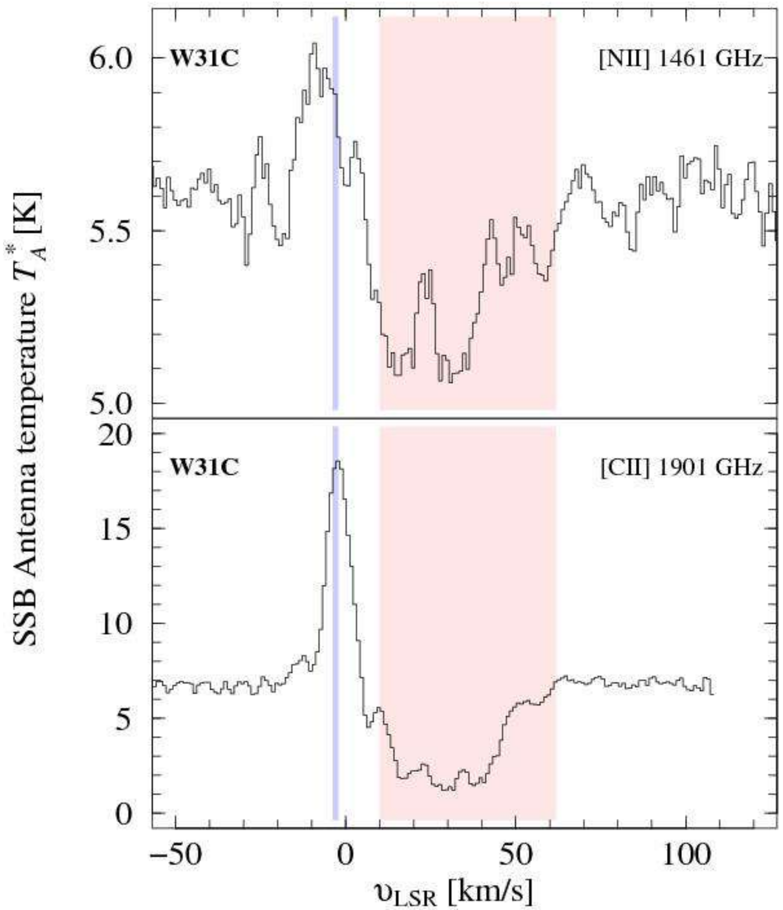
Remy+2017

Probing the ISM phases with observations : ionized gas

- Diffuse Warm Ionized gas :
  - Hydrogen Recombination lines Hα
  - Far infrared fine structure lines including [NII]

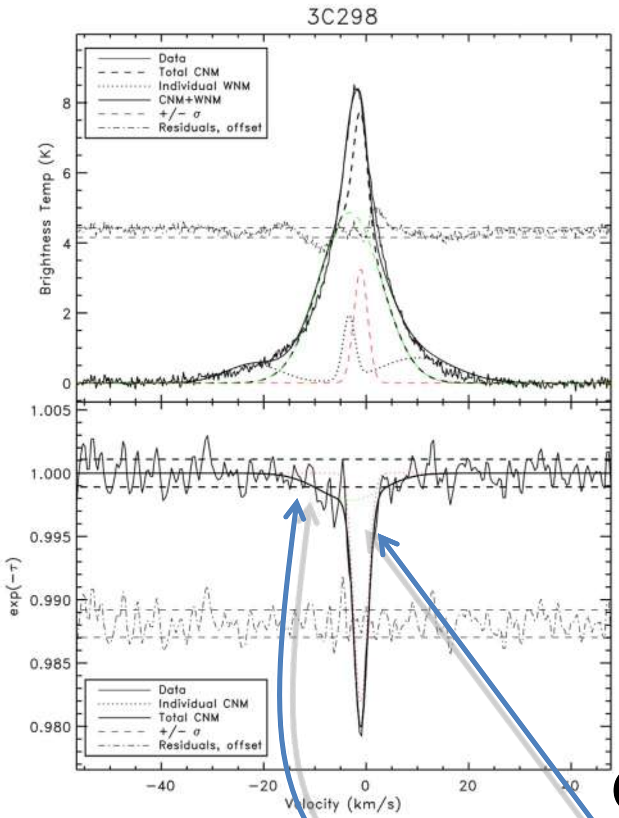
→Absorption along the line of sight consistent with the expected WIM properties (N ~ 1.5 10^{17} cm^{-2}, n ~0.1 – 0.3 cm^{-3}, volume filling factor ~0.3)

→ 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 Tk ≥ 4000 K and
Cold neutral medium with Tkin ≤ 200 K

Emission along a line of sight is a combination of the 2 phases
Absorption is dominated by the cold phase

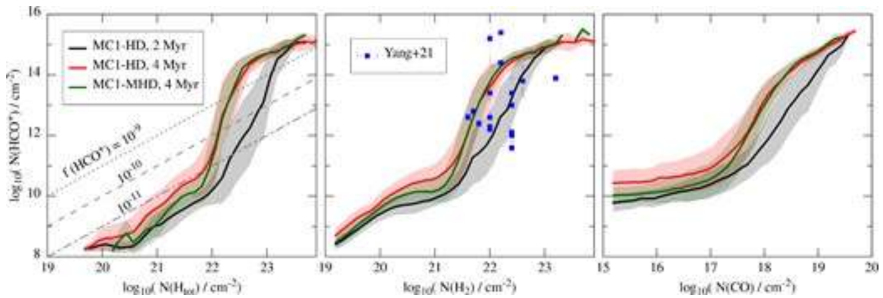
The combination of emission and absorption HI 21cm data allows to separate the contributions from the warm and cold media

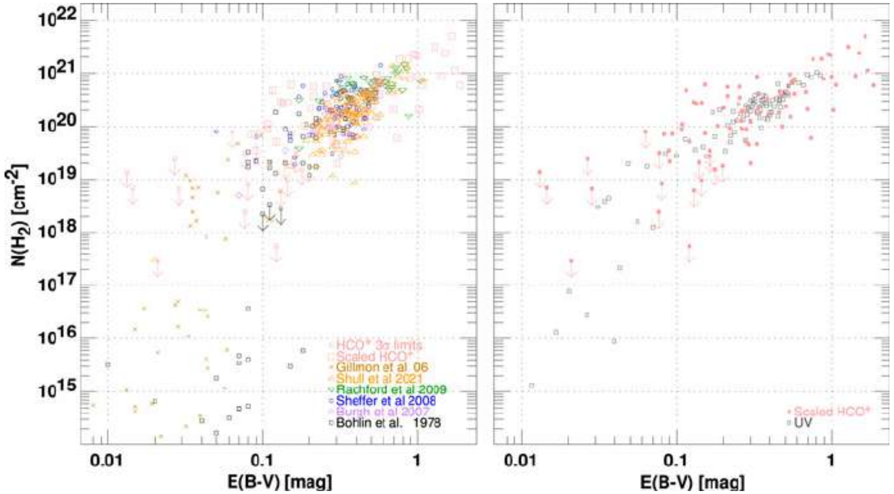
Gaussian fitting gives:
T_{sp} = 178 K
T_{sp} = 2280 K

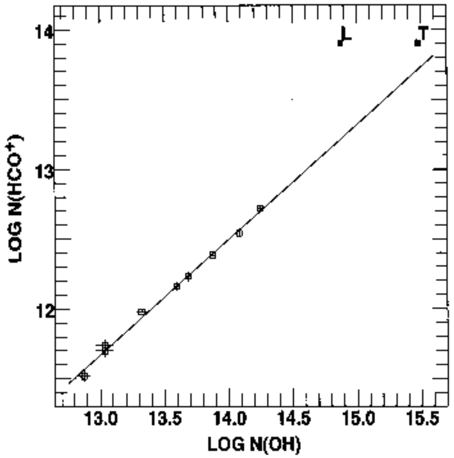
Murray+2014 with VLA,

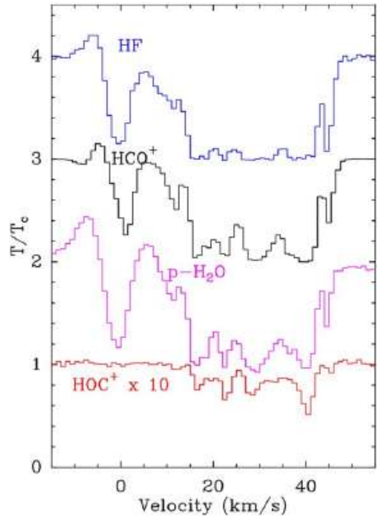
Probing the ISM phases from observations : molecular gas

- 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 ($[HCO^+/H_2] = 3\times10^{-9}$ 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 → low to moderate densities : 50 – 500 cm^{-3}
- Challenge for chemical models



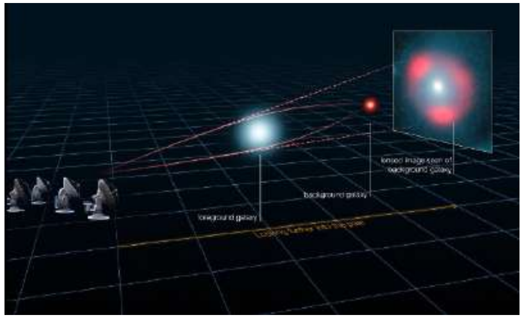


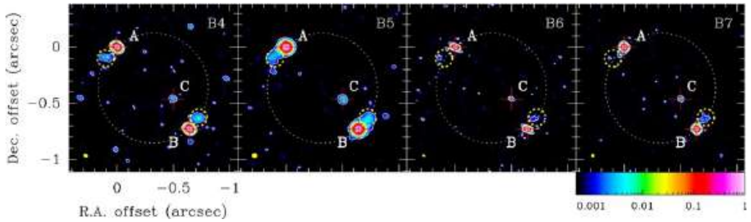




Lucas & Liszt 1996,
Liszt+2023, Gerin+2019, Panessa+2023

From local systems to high redshifts



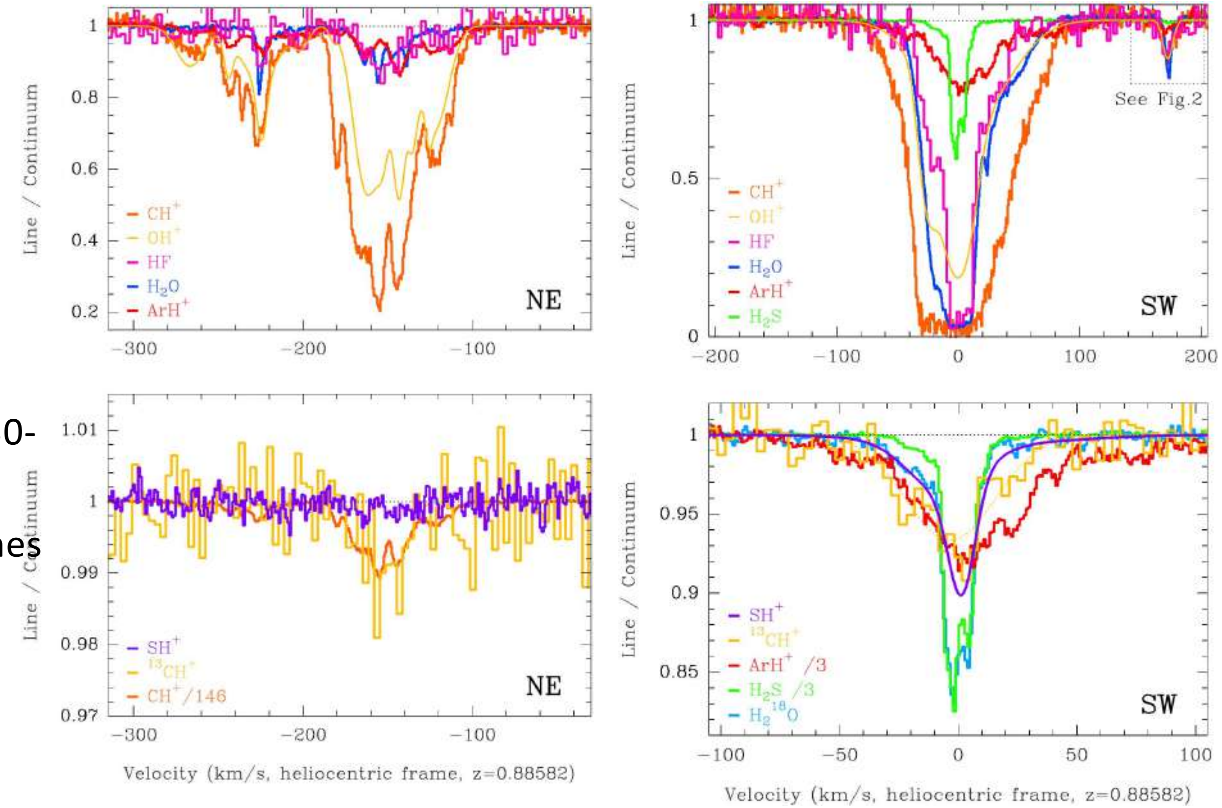


z=0.89 galaxy along the line of sight to the PKS1830-211 Quasar

Gravitational lens → Multiple images → 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.



Muller+2017,2020,2021