NanoSpace

Funded by the European Union

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Observations
future perspectives

Maryvonne Gerin

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

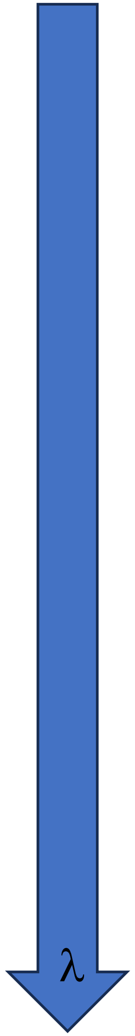
DAN Dutch Astrochemistry Network III

NWO

LERMA Observatoire de Paris | PSL

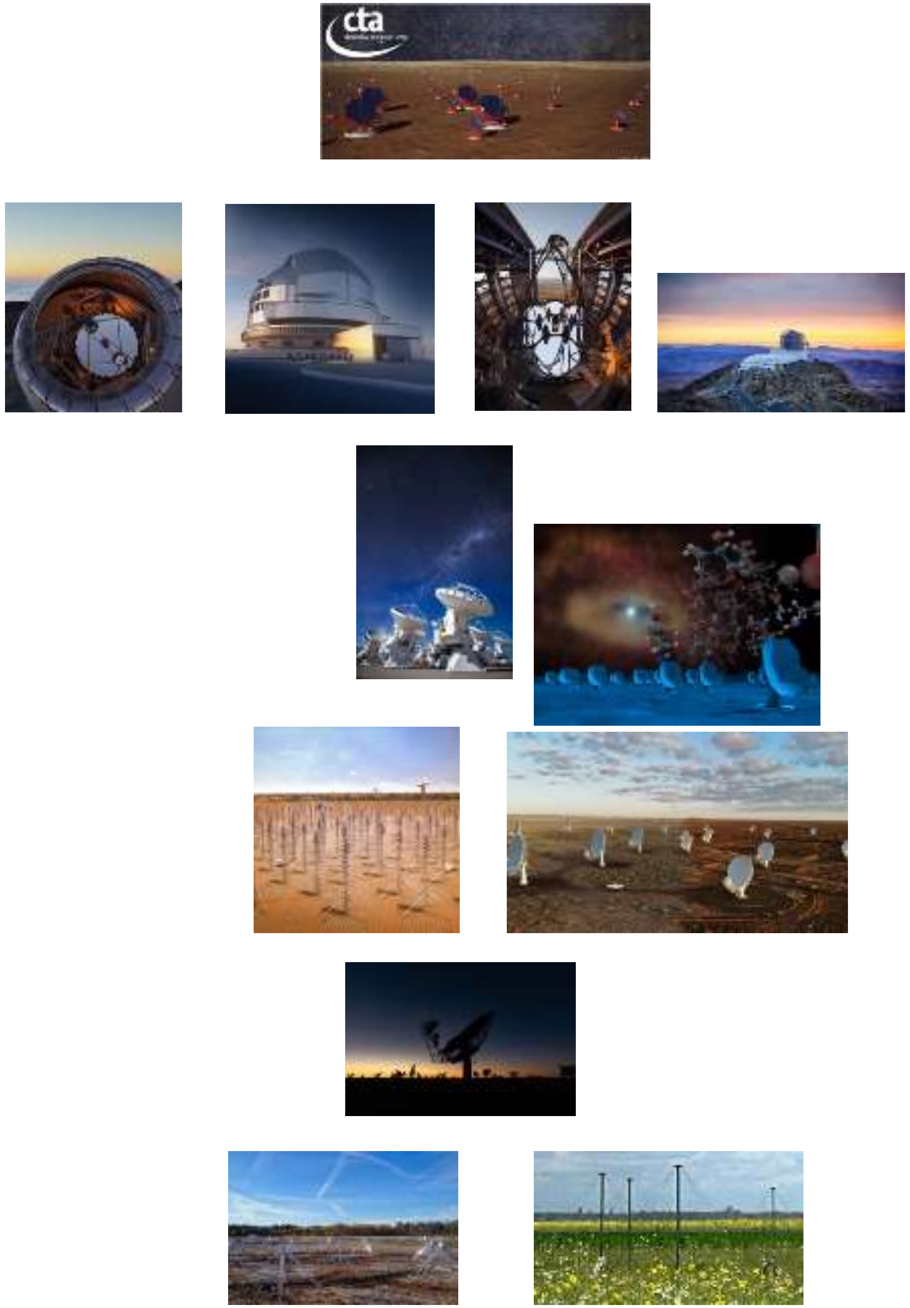
cnrs

Future capabilities



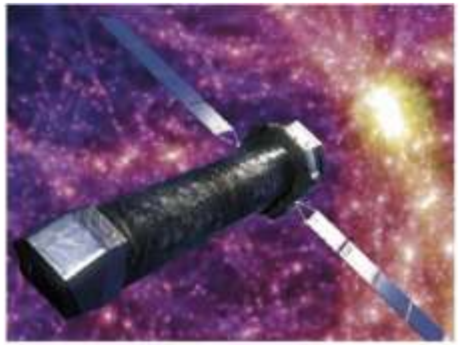
- Planned ground based telescopes :
  - CTA Cerenkov Telescope Array (gamma ray facility with broad energy sensitivity : 1 GeV – 300 TeV)

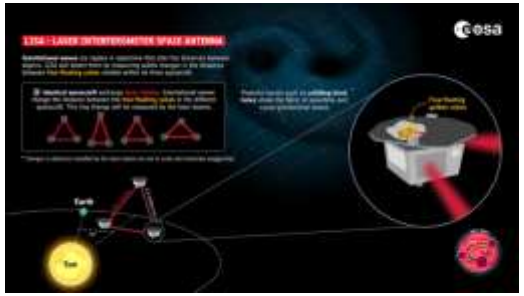
  2 sites Canary islands + ESO-Chile
  - ESO ELT (Extremely Large Telescope)
  - TMT (Thirty Meter Telescope) and GMT (Giant Magellan Telescope)
  - Vera C. Rubin Observatory (for Fast sky survey)
  - ALMA 2030 upgrade (30 – 900 GHz)
  - ngVLA (Next Generation Very Large Array) Arizona 1.2 – 50.5 GHz & 70 – 116 GHz
  - SKA (Square Kilometer Array) 2 sites Australia (SKA-LOW) & South Africa (SKA-MID) (0.05 – 15 GHz)
  - MeerKAT (South Africa) (0.58 – 3.5 GHz)
  - LOFAR (Low Frequency Array, NL & Europe) (0.01 - 0.3 GHz)
  - NenUFAR (France) (0.01 – 0.085 GHz)



Future capabilities
In space

- Solar system exploration : Jupiter system, Venus, …
- Toward sample return missions : asteroids, Mars ? Moon ?
- Nancy Grace Roman Telescope (NASA). Wide field Camera (300 Mpx, 0.48 – 2.3 µm) + low res spectroscopy (R~200) + coronograph
- NewAthena for X rays (0.2 – 12 keV, 2 instruments for imaging & spectroscopy down to 3.5eV resolution, FoV 40’ 9” resolution)
- LISA (Laser Interferometry Space Antenna) for Gravitational waves
- Far infrared mission ? Under discussion





Future capabilities : instruments

New telescopes
→ Improving the instrument concepts and performances
→ Improving the access to data : archives
→ High data flow , new data processing methods

- Some capabilities
    - Extreme Adaptive optics
    - Multi Object/integral field spectroscopy
    - Time monitoring
    - Polarization of dust continuum and line emission for magnetic field information
    - Interferometry : longer baselines, high uv plane coverage, dual frequency operations …
    - Heterodyne cameras : toward large field of view spectral images

ESO future plans

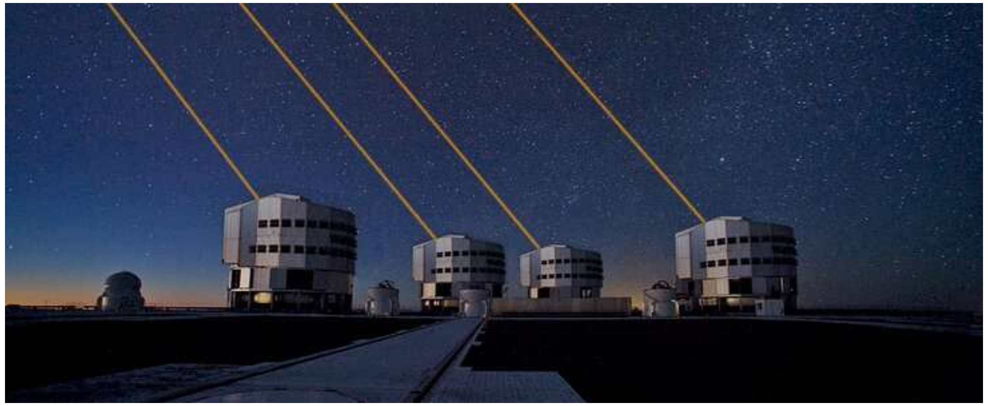
- VLT spectrometers
  - UV spectra with CUBES (local to high z)
  - Infrared spectroscopy MOONS, CRIRES+
- VLTI upgrade
  - GRAVITY+ (IR interferometry with Adaptive optics) 3.5mas, R = 22, 500, 4500
- ELT (https://elt.eso.org/instrument/)
  - HARMONI, MICADO, METIS, … , ANDES & MOSAIC

2026 2027 2028 2029

Dome & Structure

Mirrors

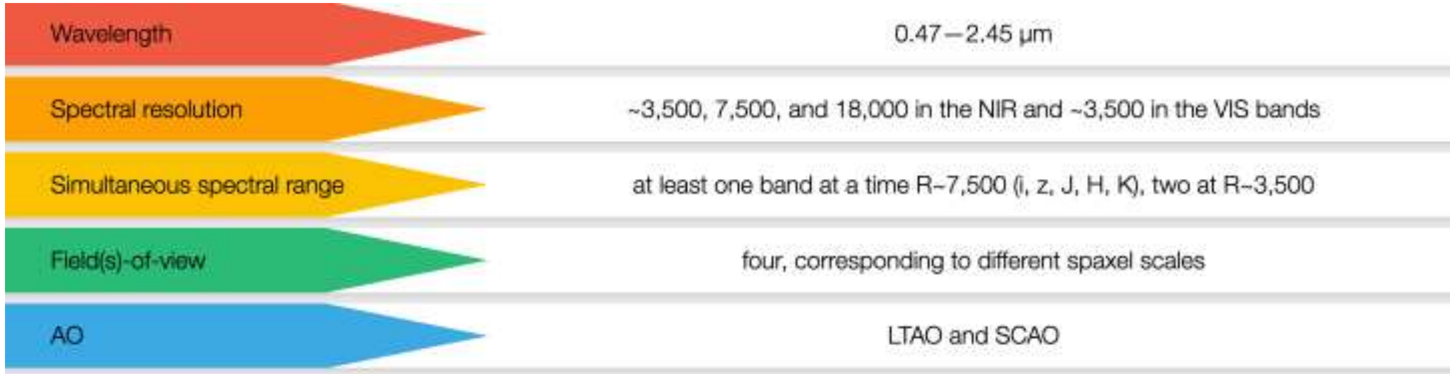
1st light & Science Verification



ELT first light instruments

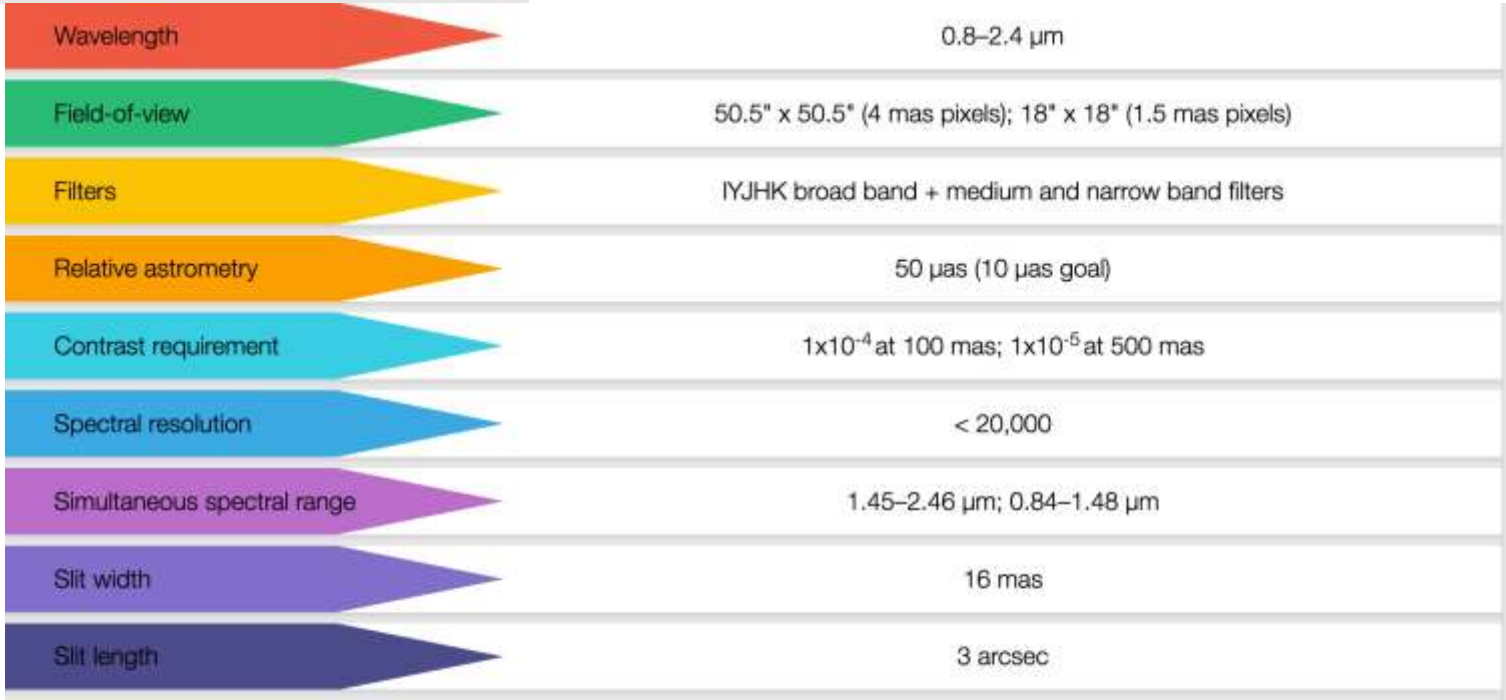
(https://elt.eso.org/instrument/)

- HARMONI (High Angular Resolution Monolithic Optical and Near-infrared Intgeral field spectrometer)



Wavelength	0.47 – 2.45 µm
Spectral resolution	~3,500, 7,500, and 18,000 in the NIR and ~3,500 in the VIS bands
Simultaneous spectral range	at least one band at a time R~7,500 (i, z, J, H, K), two at R~3,500
Field(s)-of-view	four, corresponding to different spaxel scales
AO	LTAO and SCAO

- MICADO (Multi-AO Imaging Camera for Deep Observations)

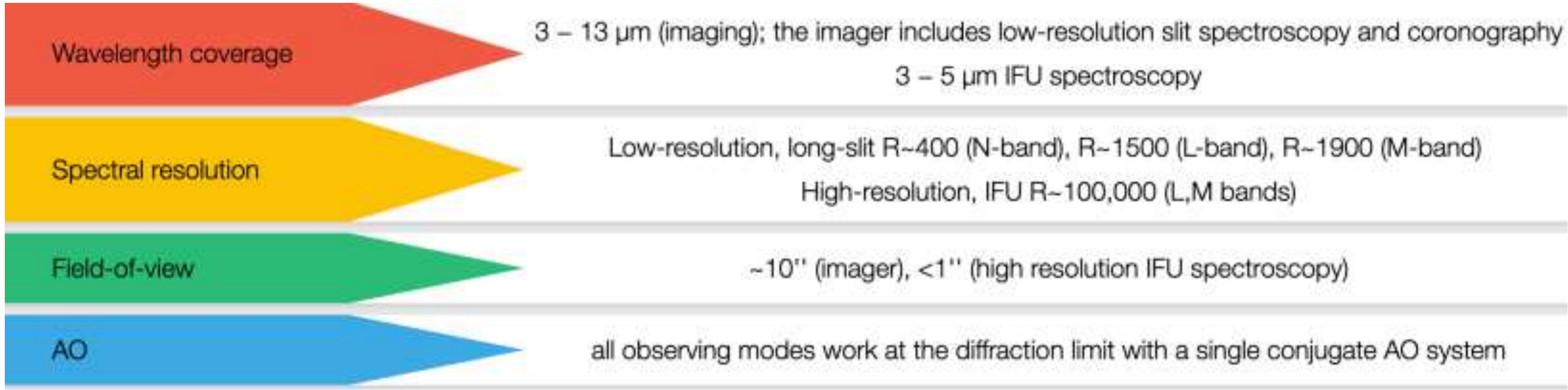


Wavelength	0.8–2.4 µm
Field-of-view	50.5" x 50.5" (4 mas pixels); 18" x 18" (1.5 mas pixels)
Filters	IYJHK broad band + medium and narrow band filters
Relative astrometry	50 µas (10 µas goal)
Contrast requirement	1×10^{-4} at 100 mas; 1×10^{-5} at 500 mas
Spectral resolution	< 20,000
Simultaneous spectral range	1.45–2.46 µm; 0.84–1.48 µm
Slit width	16 mas
Slit length	3 arcsec

ELT first light instruments

- MORFEO (Multi-conjugate adaptive Optics Relay For ELT Observations)

- METIS (Mid-Infrared ELT Imager and Spectrograph)



Wavelength coverage	3 – 13 µm (imaging); the imager includes low-resolution slit spectroscopy and coronography 3 – 5 µm IFU spectroscopy
Spectral resolution	Low-resolution, long-slit R~400 (N-band), R~1500 (L-band), R~1900 (M-band) High-resolution, IFU R~100,000 (L,M bands)
Field-of-view	~10'' (imager), <1'' (high resolution IFU spectroscopy)
AO	all observing modes work at the diffraction limit with a single conjugate AO system

A complete set of imaging and spectroscopy

ALMA-2030 : Wide band Sensitivity Upgrade)

Broader instantaneous frequency coverage

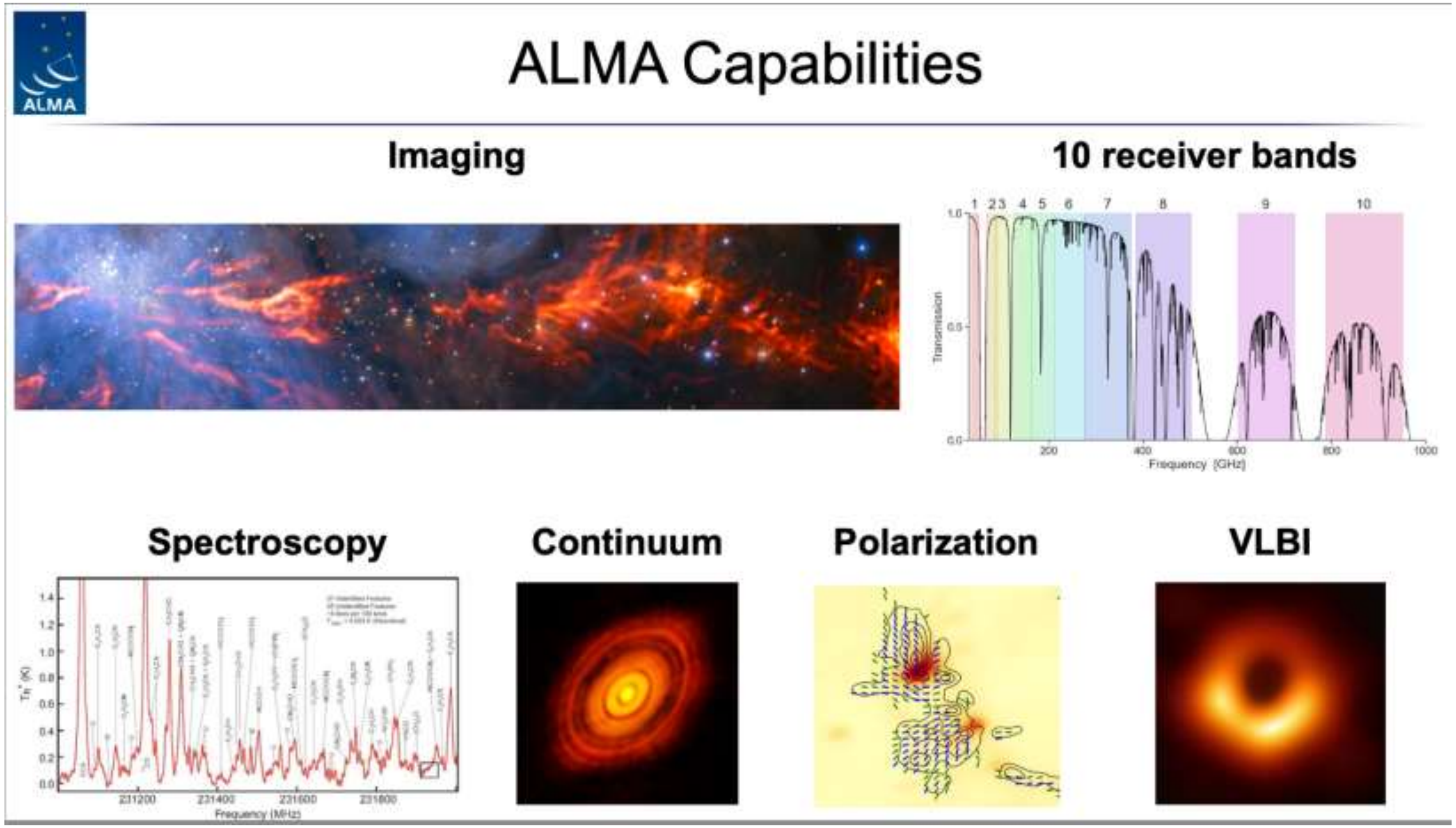
- Broader bands (x2 to 8 GHz up to x4 at 16 GHz)
- Increased sensitivity & flexibility

ALMA Memo 621 and arXiv 2211.00195

Continuous Operations combined with step by step upgrades

Slides from J. Carpenter(ALMA at 10yrs conference) https://zenodo.org/records/10251486

[10.5281/zenodo.10251486](https://doi.org/10.5281/zenodo.10251486)



ALMA Capabilities

Imaging

10 receiver bands

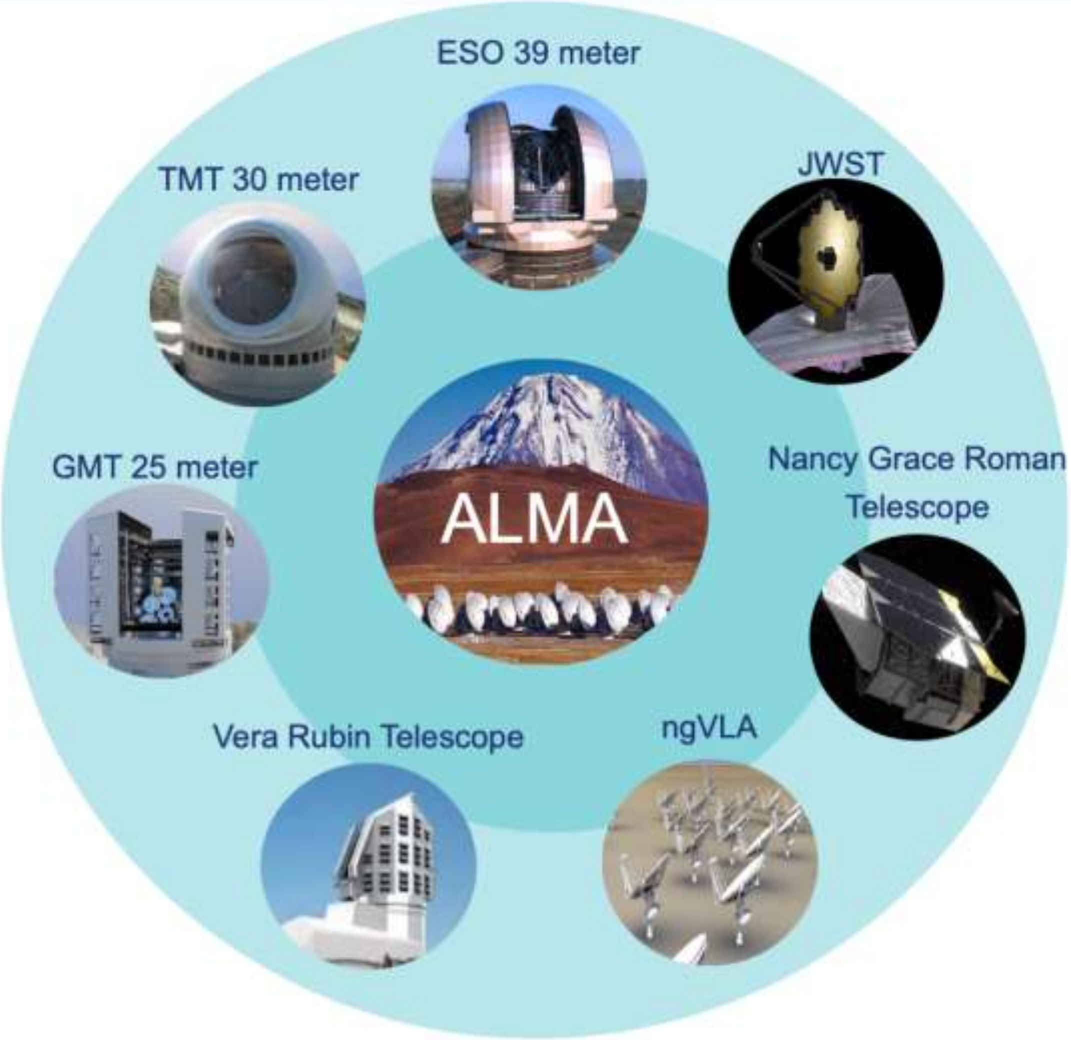
Spectroscopy

Continuum

Polarization

VLBI

New facilities in the next decade



ESO 39 meter

TMT 30 meter

JWST

GMT 25 meter

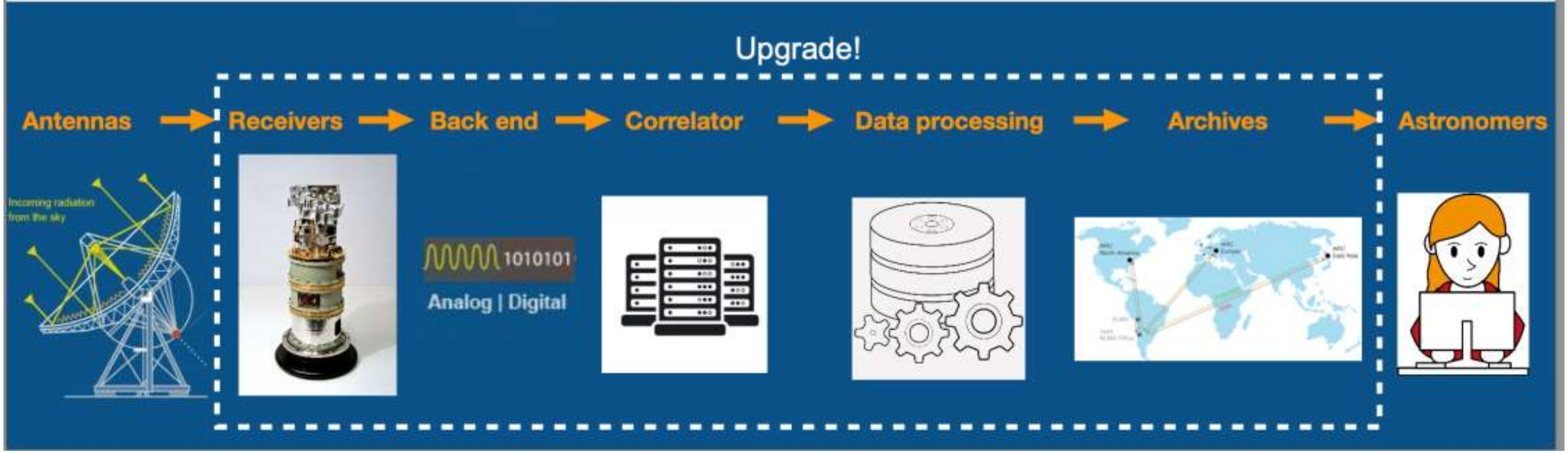
Nancy Grace Roman Telescope

Vera Rubin Telescope

ngVLA

Wideband Sensitivity Upgrade (WSU): Top Priority of the ALMA2030 Roadmap

- Upgrade of the bandwidth and throughput of the ALMA system
  - upgraded receivers with increased bandwidth and improved receiver temperatures
  - more powerful correlator
  - increased data reduction capacity

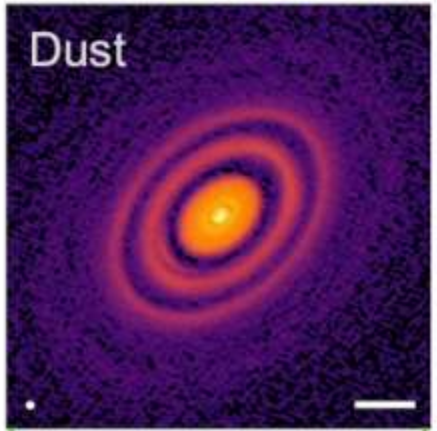


Upgrade!

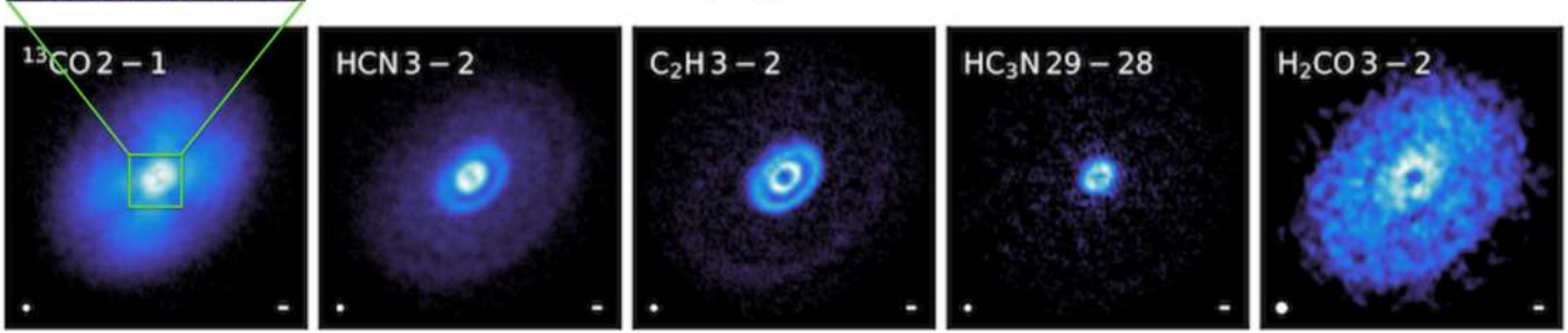
Antennas → Receivers → Back end → Correlator → Data processing → Archives → Astronomers

The power of molecular spectroscopy in disks

HD 163296

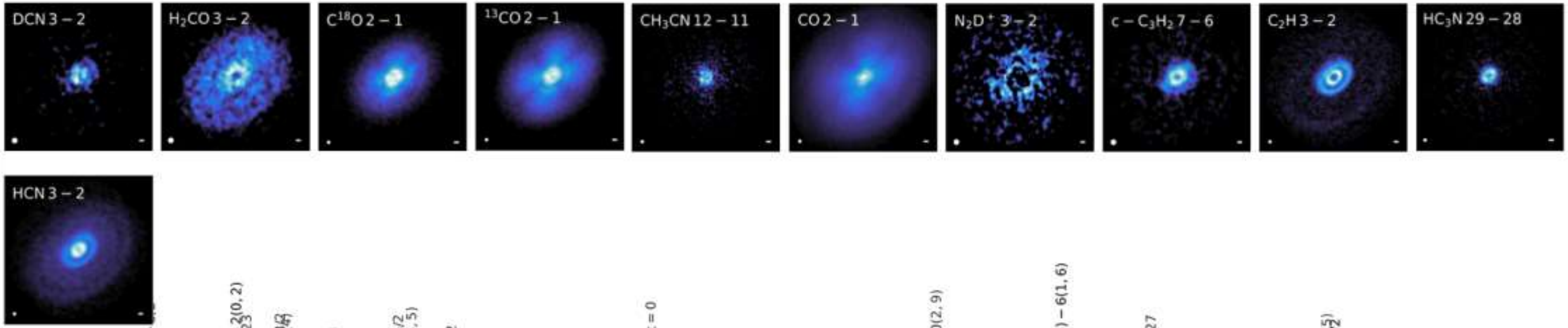


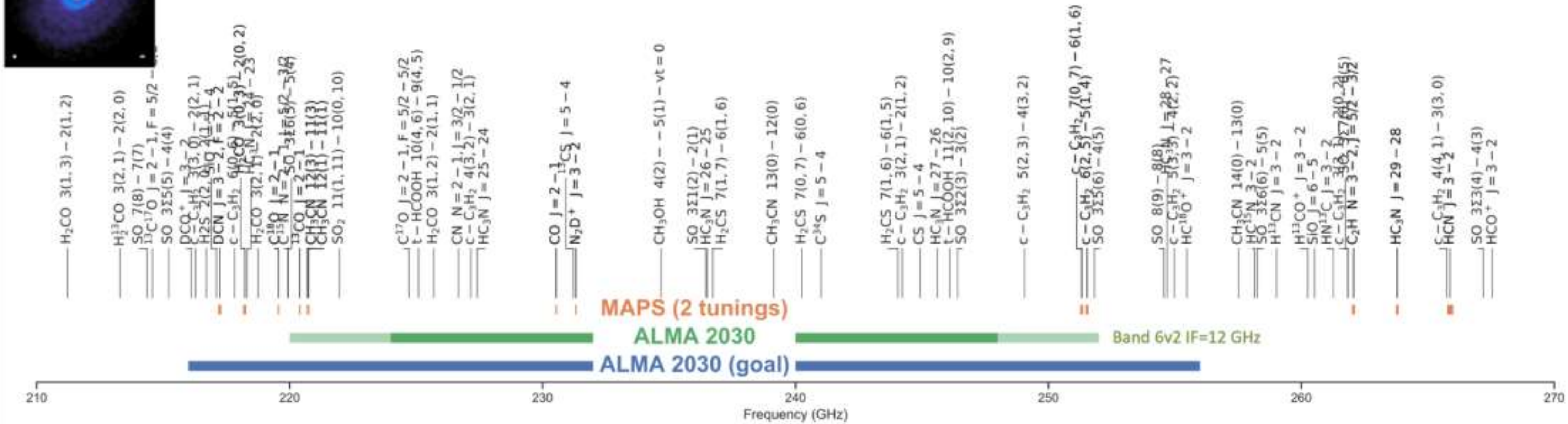
- Gas mass
  - dust traces only ~ 1% of the total disk mass
  - use molecules to trace the dominant disk component (H_2)
- Chemistry and the chemical compositions of planets
- 3D velocity and temperature structure of disks
- Detect embedded planets through velocity distortions
- **With vastly improved spectral grasp and improved line (and continuum!) sensitivity, the Wideband Sensitivity Upgrade will be a tremendous advance for disk studies.**



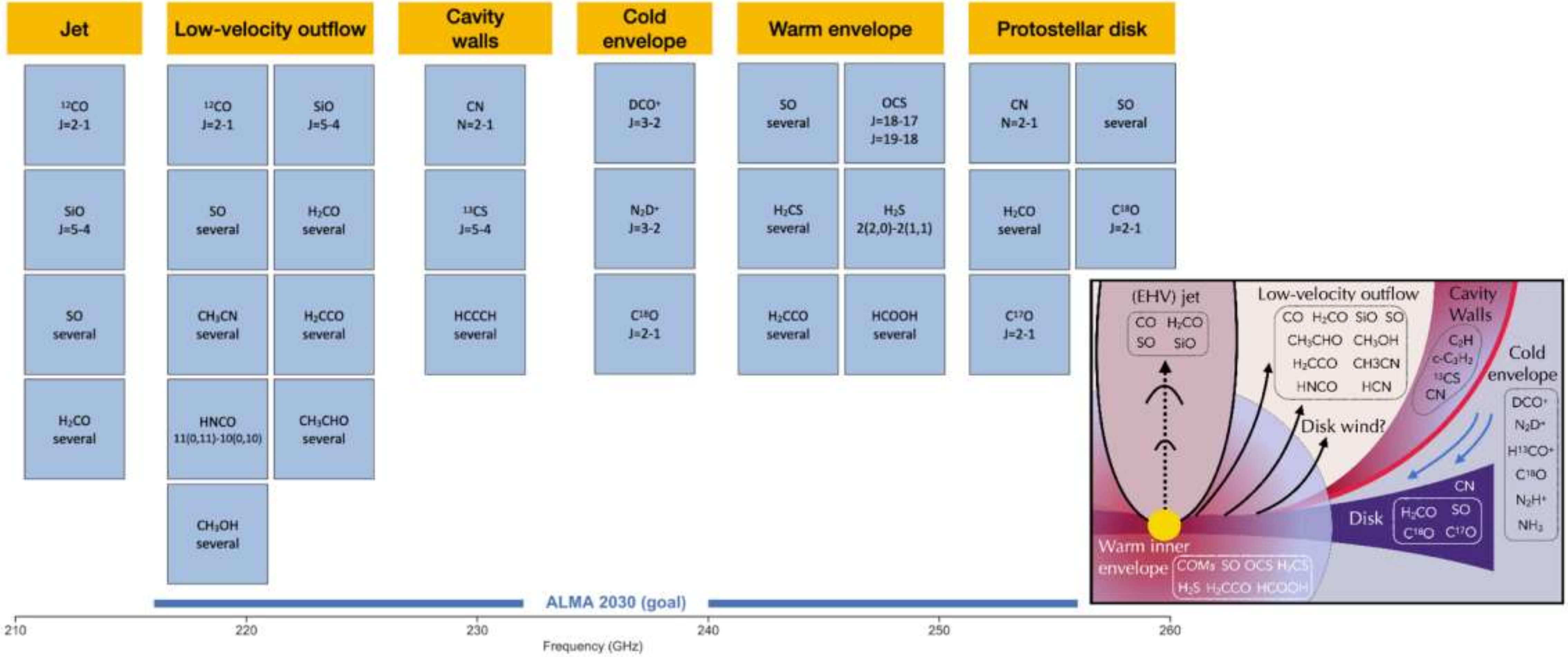
Öberg et al. (2021)

The WSU Advantage





Molecular probes of star formation with ALMA 2030



Jet
- ^{12}CO J=2-1
- SiO J=5-4
- SO several
- H_2CO several

Low-velocity outflow
- ^{12}CO J=2-1
- SiO J=5-4
- SO several
- H_2CO several
- CH_3CN several
- H_2CCO several
- HNCO 11(0,11)-10(0,10)
- CH_3CHO several
- CH_3OH several

Cavity walls
- CN N=2-1
- ^{13}CS J=5-4
- HCCCH several

Cold envelope
- DCO^+ J=3-2
- N_2D^+ J=3-2
- $C^{18}O$ J=2-1

Warm envelope
- SO several
- OCS J=18-17 J=19-18
- H_2CS several
- H_2S 2(2,0)-2(1,1)
- H_2CCO several
- HCOOH several

Protostellar disk
- CN N=2-1
- SO several
- H_2CO several
- $C^{18}O$ J=2-1
- $C^{17}O$ J=2-1

Tychoniec et al. (2021)

Challenges for the future

- High data rate
  - Increased sensitivity, camera field of view and spectrometer bandpass
  - Large number of objects surveys

  →Change the data processing method to manage the data rate
- Higher measurement accuracy
  - Improve absolute and relative calibration
  - Characterize systematic effects and bias
  - Multi wavelength and multi time analysis of objects

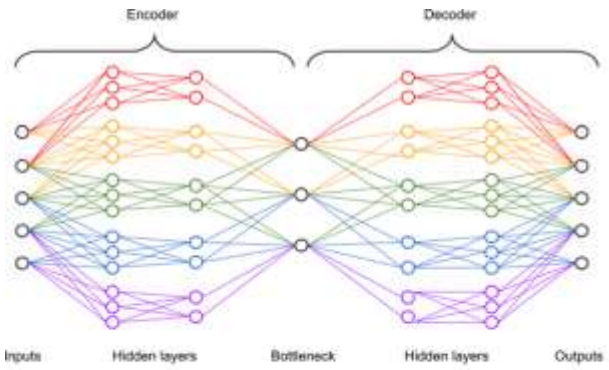
New Data processing methods, with help from AI

- Image (data cube) processing : noise filtering, source extraction, structure decomposition (e.g. filaments, cores)
- Interferometric image computation
- Fourier plane analysis
- Automatic spectral line fitting : determination of physical conditions (density, temperature, velocity field) .. along the line of sight
- Automatic (PDR, shock, …) model fitting
- Spectral line survey processing :
  - Line finding
  - Line stacking & Match filtering for molecule detection
  - New molecule identification

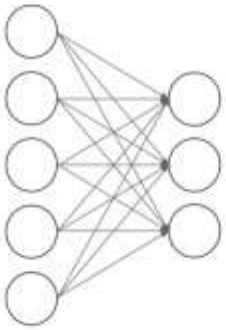
→ Collaboration with data scientists is essential

Advanced data analysis & interpretation

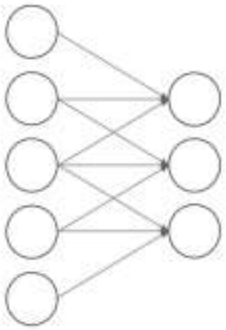
- Large data volumes : automated analysis, and construction of statistical diagnostics
- Limited integration time and optimal use of telescope time : denoise the data using statistical information on the noise and signal properties
  - Simple denoising : multiple gaussian line fit
  - Using neural network (auto-encoder)



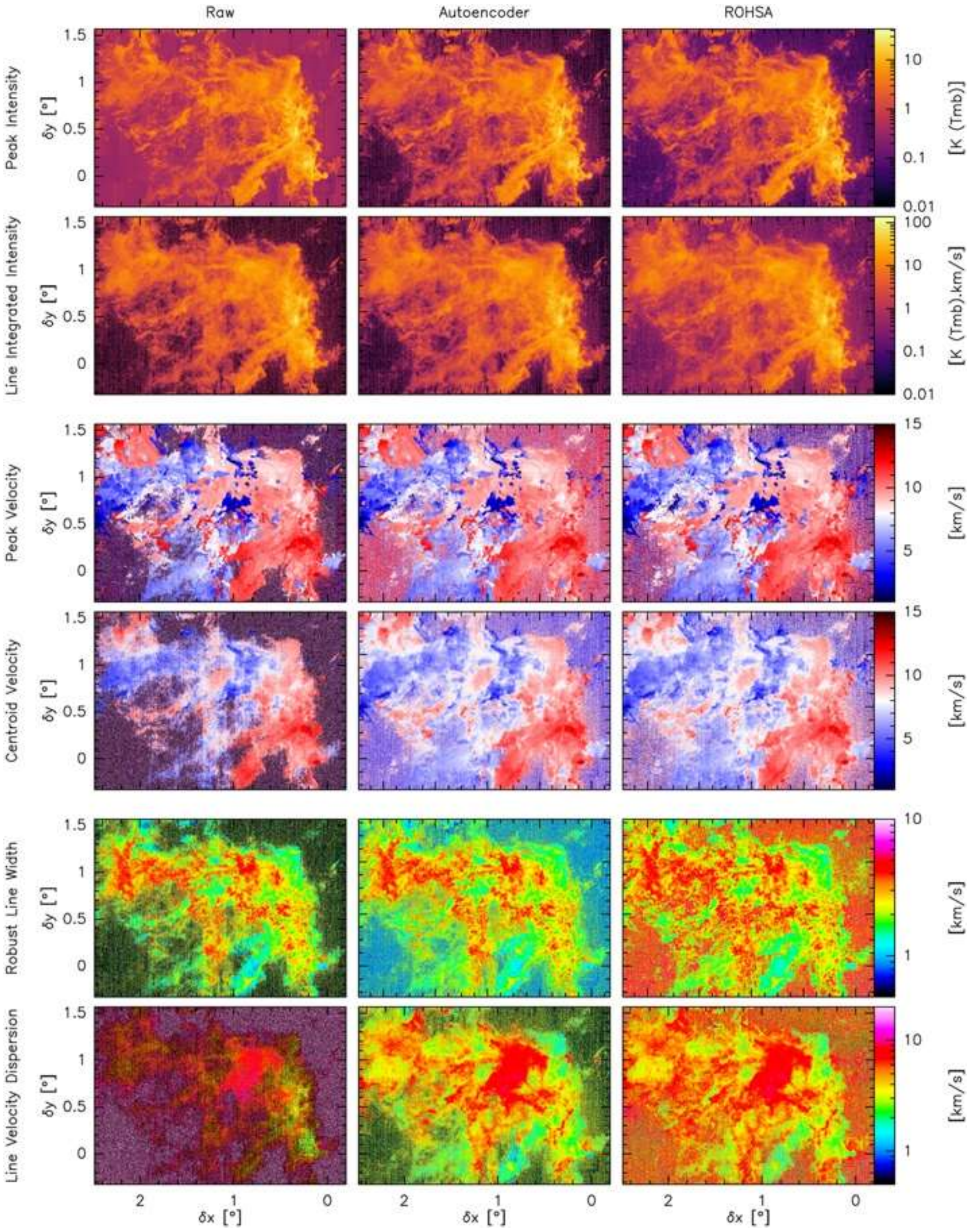
(a) Optimized Autoencoder



(b) Fully connected layer

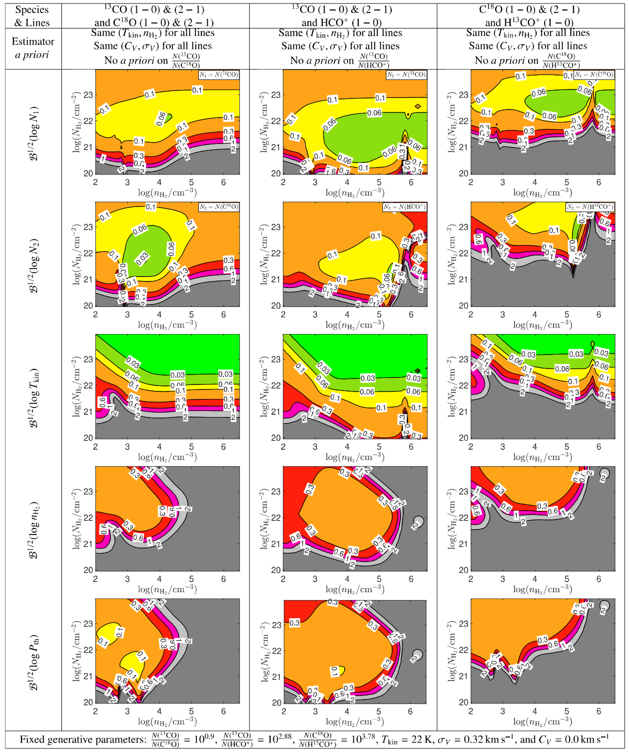


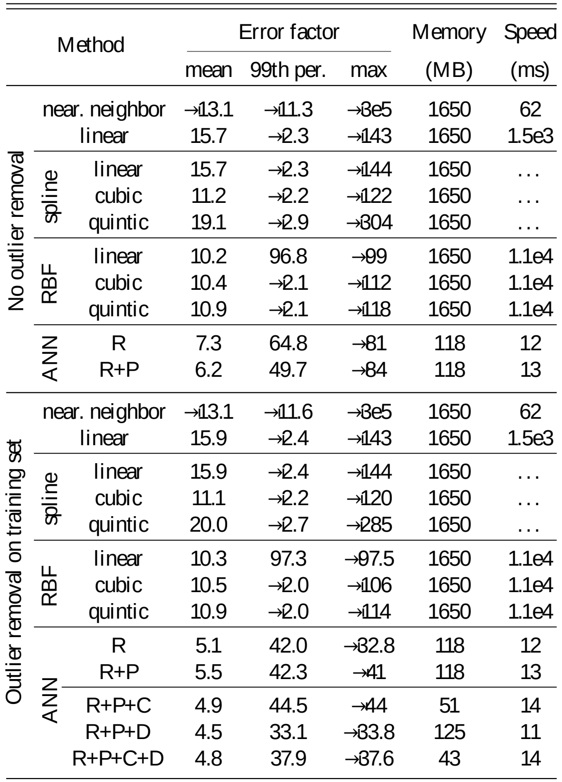
(c) Locally connected layer



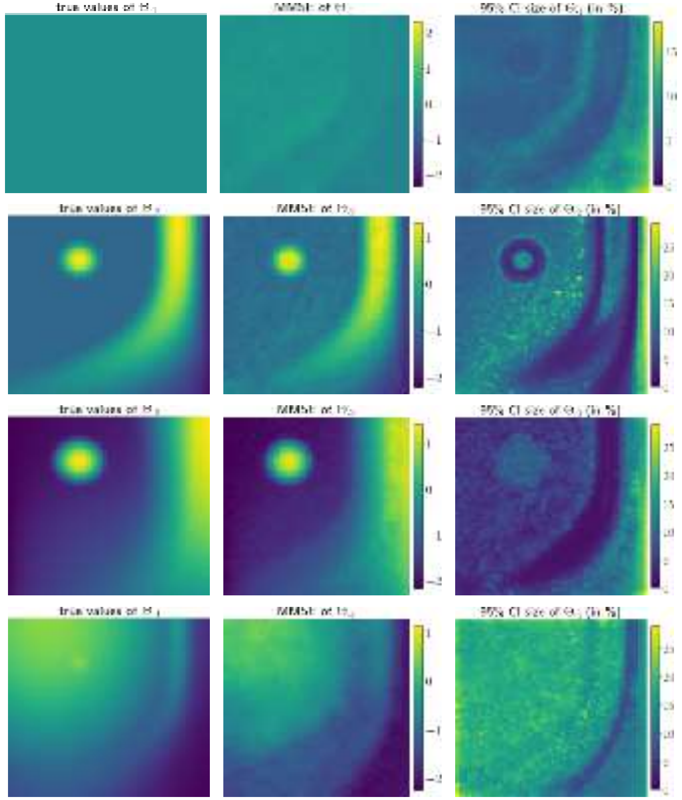
Einig+2023,

Advanced data analysis & interpretation





		Method	Error factor			Memory	Speed
			mean	99th per.	max	(MB)	(ms)
No outlier removal		near. neighbor	→13.1	→11.3	→3e5	1650	62
		linear	15.7	→2.3	→143	1650	1.5e3
	spline	linear	15.7	→2.3	→144	1650	. . .
		cubic	11.2	→2.2	→122	1650	. . .
		quintic	19.1	→2.9	→304	1650	. . .
	RBF	linear	10.2	96.8	→99	1650	1.1e4
		cubic	10.4	→2.1	→112	1650	1.1e4
		quintic	10.9	→2.1	→118	1650	1.1e4
	ANN	R	7.3	64.8	→81	118	12
		R+P	6.2	49.7	→84	118	13
Outlier removal on training set		near. neighbor	→13.1	→11.6	→3e5	1650	62
		linear	15.9	→2.4	→143	1650	1.5e3
	spline	linear	15.9	→2.4	→144	1650	. . .
		cubic	11.1	→2.2	→120	1650	. . .
		quintic	20.0	→2.7	→285	1650	. . .
	RBF	linear	10.3	97.3	→97.5	1650	1.1e4
		cubic	10.5	→2.0	→106	1650	1.1e4
		quintic	10.9	→2.0	→114	1650	1.1e4
	ANN	R	5.1	42.0	→32.8	118	12
		R+P	5.5	42.3	→41	118	13
		R+P+C	4.9	44.5	→44	51	14
		R+P+D	4.5	33.1	→33.8	125	11
		R+P+C+D	4.8	37.9	→37.6	43	14



- Improve the accuracy : study the Precision, bias and degeneracies of the molecular line fits using radiative transfer models
- PDR model fits : Emulation of the PDR model with a neural network for fast calculations and Bayesian fitting

Palud+,2023,Roueff+2021,2024

Learning from the data for the determination of $N(H_2)$

$N(H_2)$ derived from fitting the dust thermal emission between far IR and submm, assuming a dust model and a dust to gas ratio

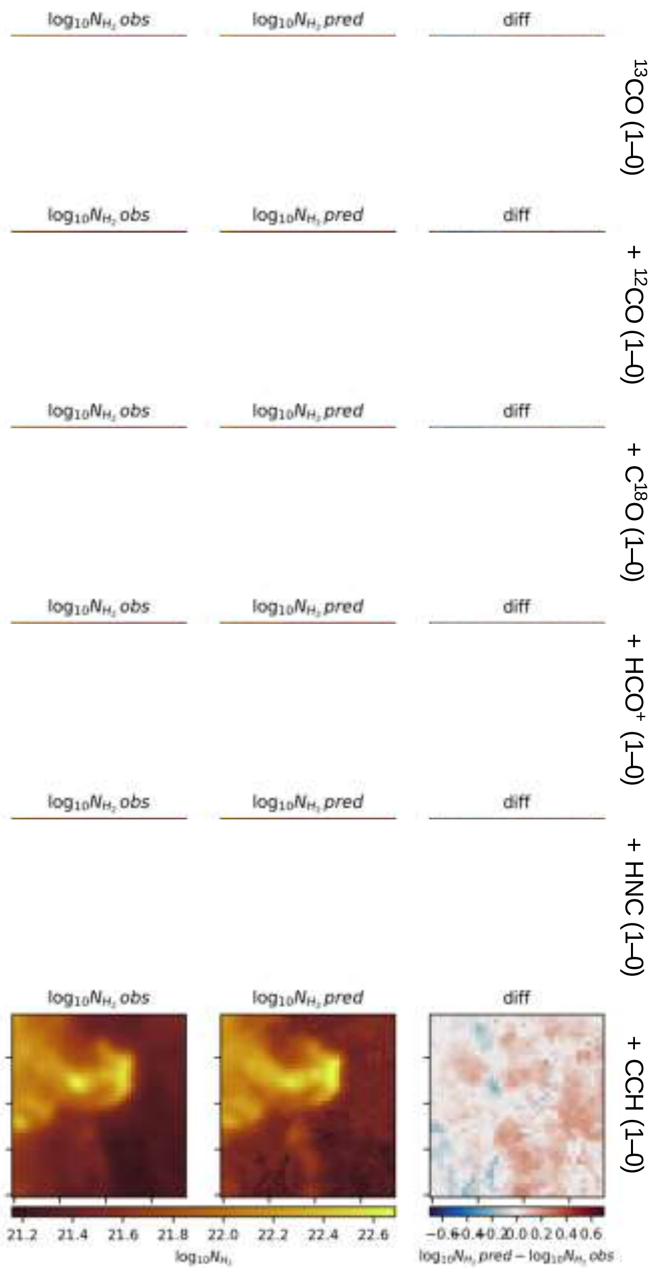
Or

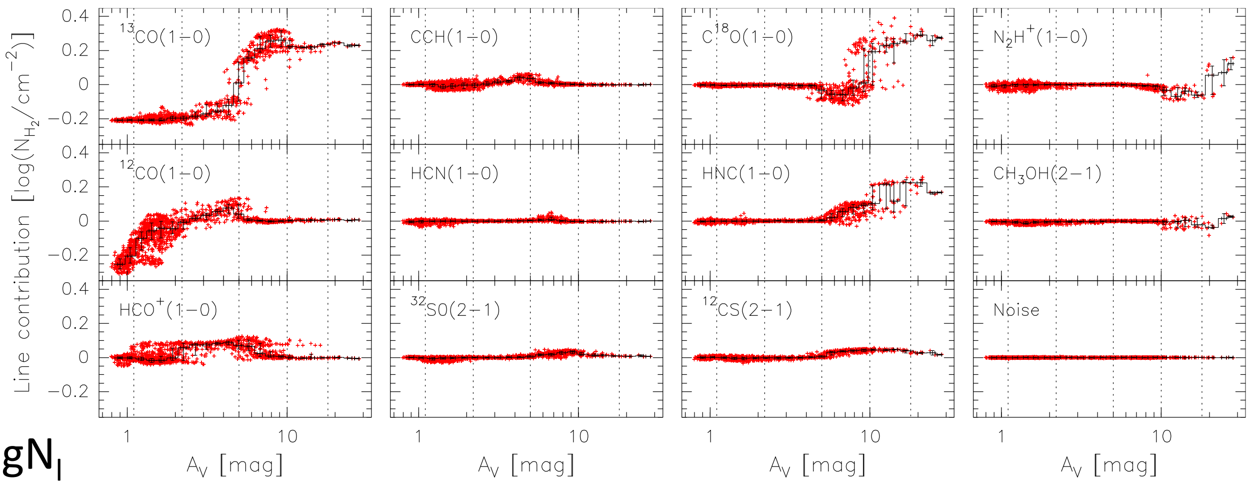
$N(H_2)$ derived from molecular line maps assuming constant emissivity or a fixed and known relative abundances

Learning from the data using four lines : ^{12}CO, ^{13}CO, C^{18}O, HCO^{+} (1-0)

For each pixel, the four lines provide information on the column density, with different relative contributions for different values of $N(H_2)$

⇒ Insight into the physics and chemistry





$\log N = \log N_0 + \Sigma_{l=1,L} \log N_l$

Gratier+2021

Line survey analysis : matched filtering

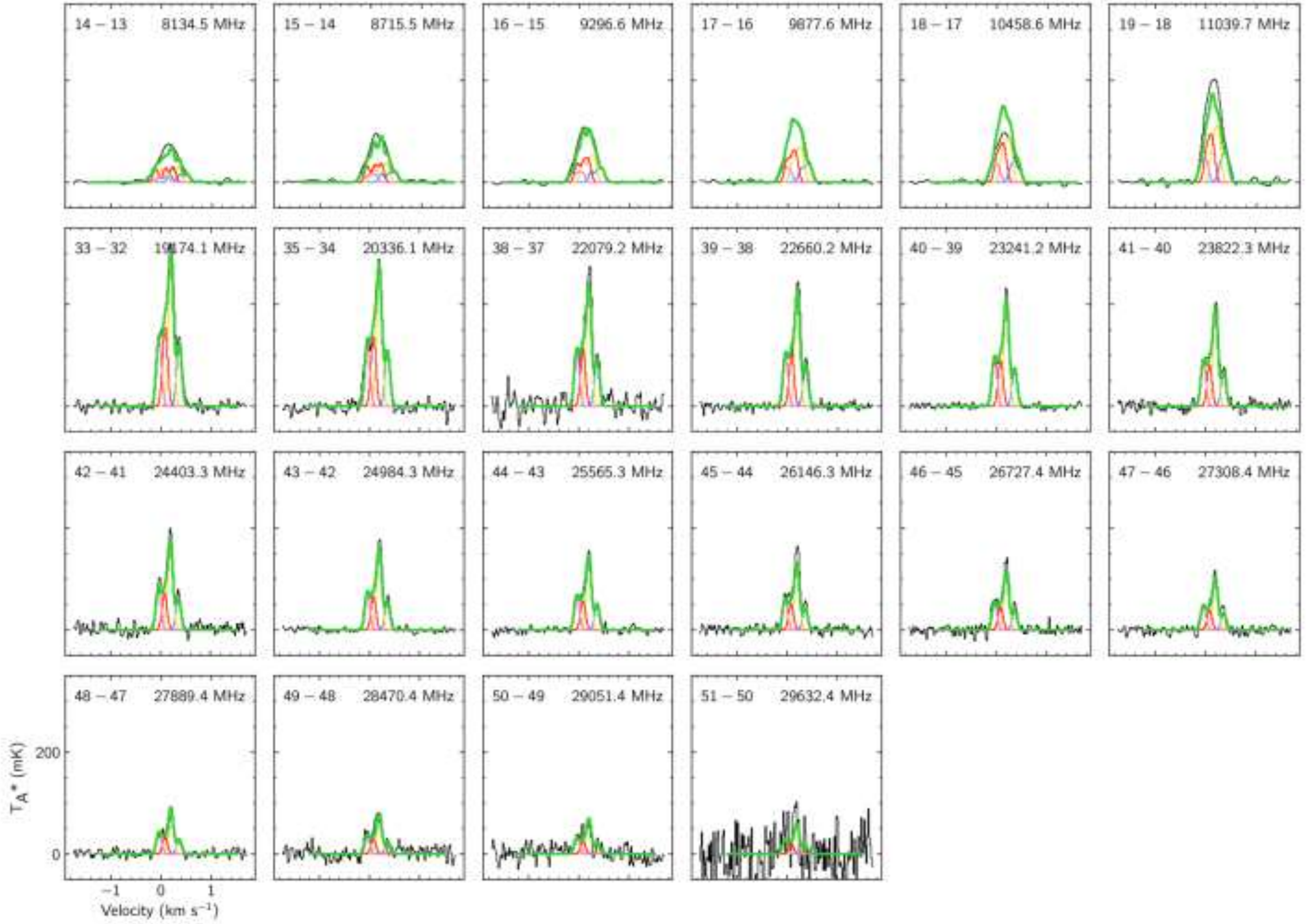
- Known line profile (from theory or from observations of strong spectral lines) and source properties (size, temperature, …)
- Known and accurate molecule spectroscopic parameters
- Known telescope and instrument performances

→Simulation of expected signal

→ Convolution of the observed data with the expected signal

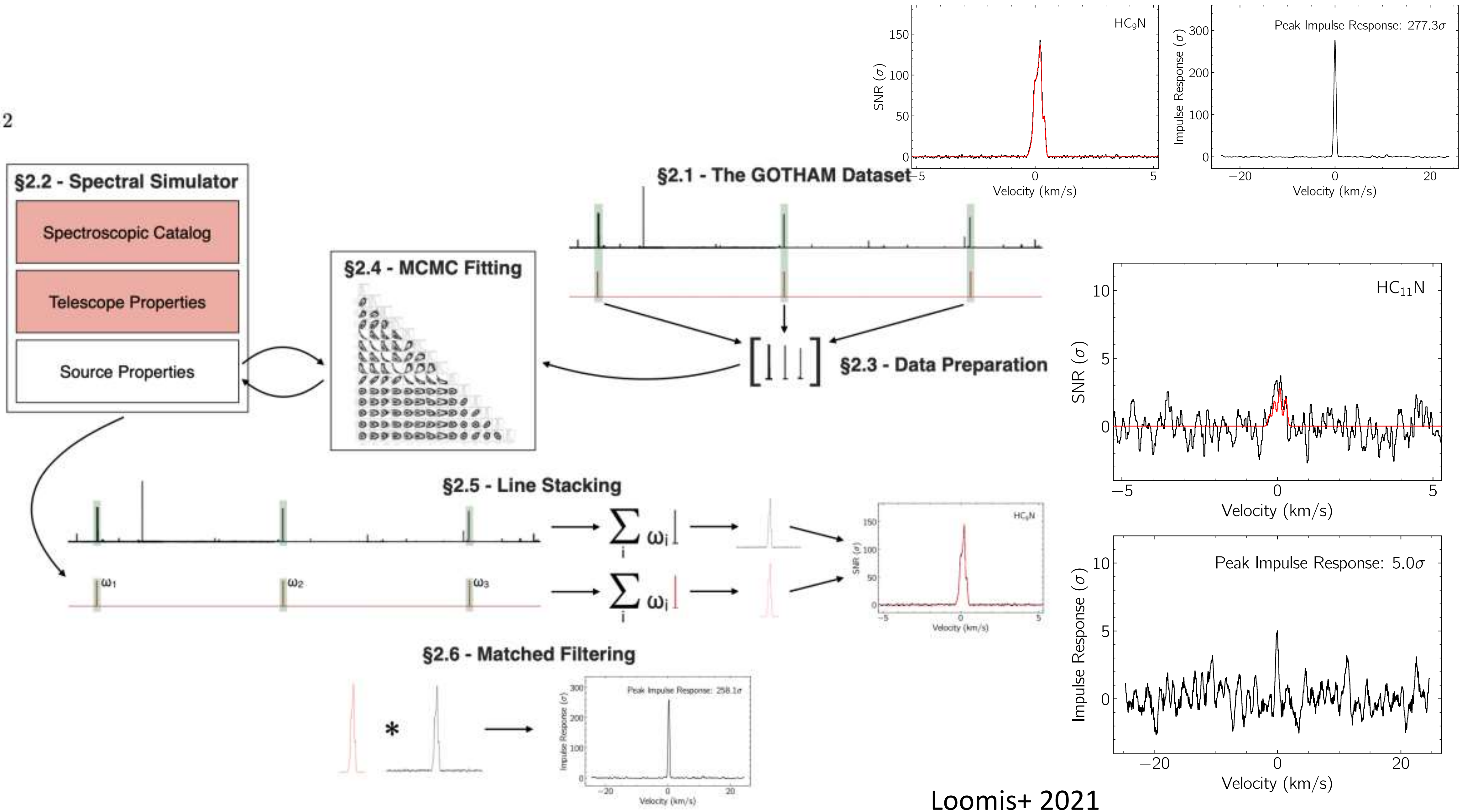
- Allows stacking of different lines

- Confirmation of a detection with detection of individual lines (HC_9N)



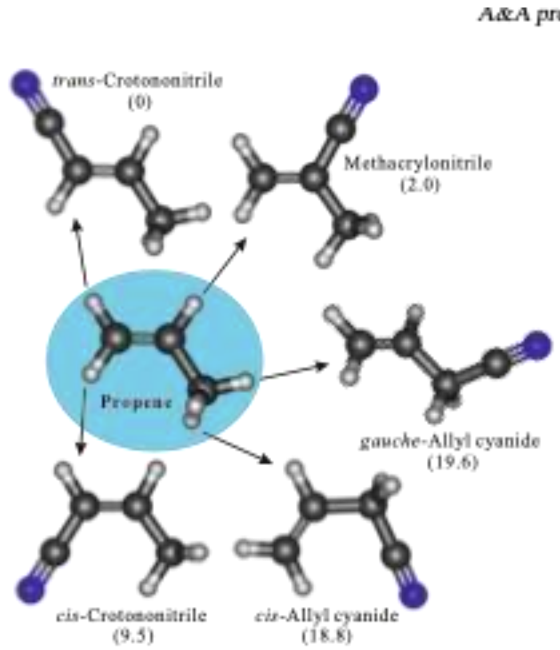
Loomis+ 2021

2

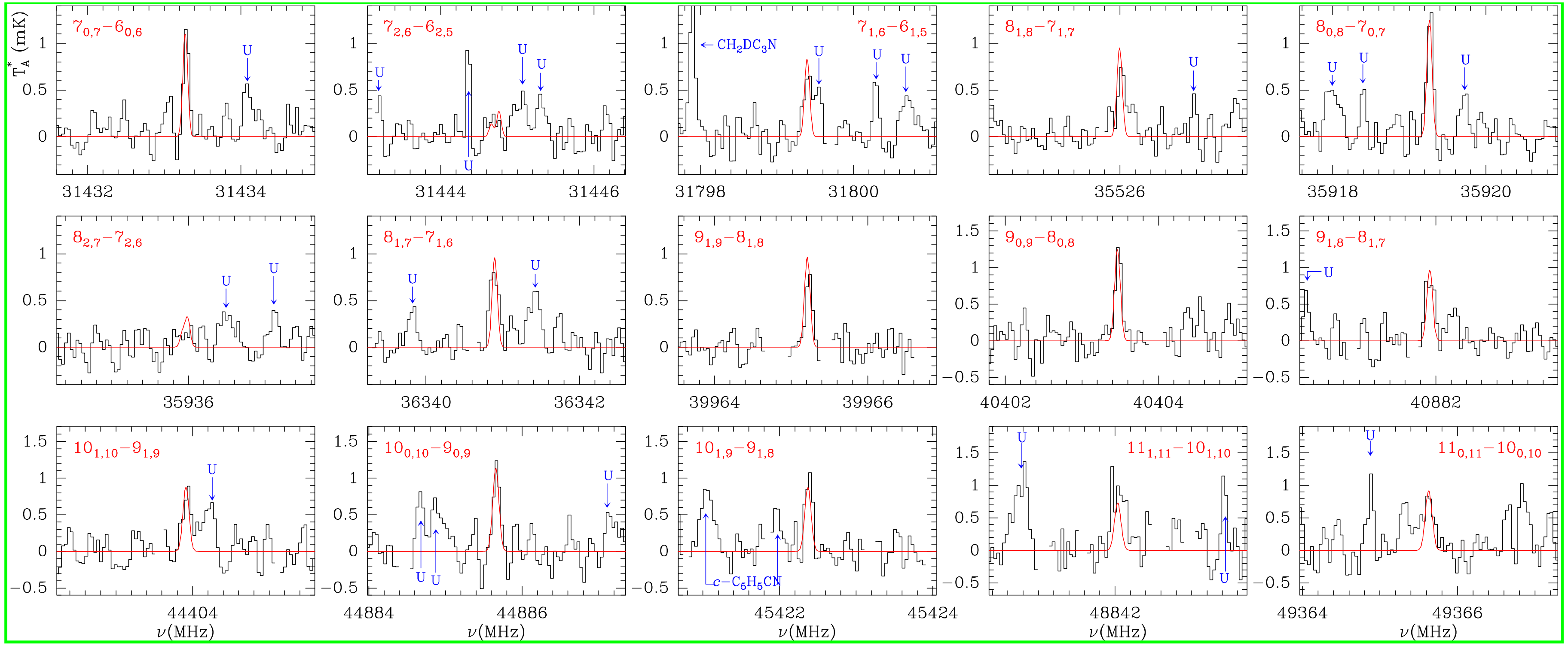


Loomis+ 2021

Line survey analysis



t-$CH_3CHCHCN$

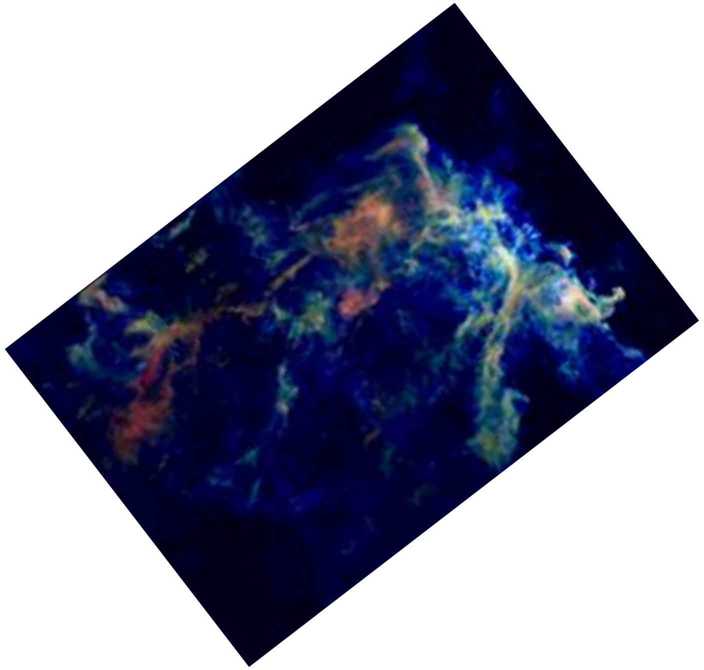


Five cyano derivatives of propene (CH_3CHCH_2) detected

- Deep integrations over a broad frequency range
- Line by line detections and stacking

Cernicharo+2022

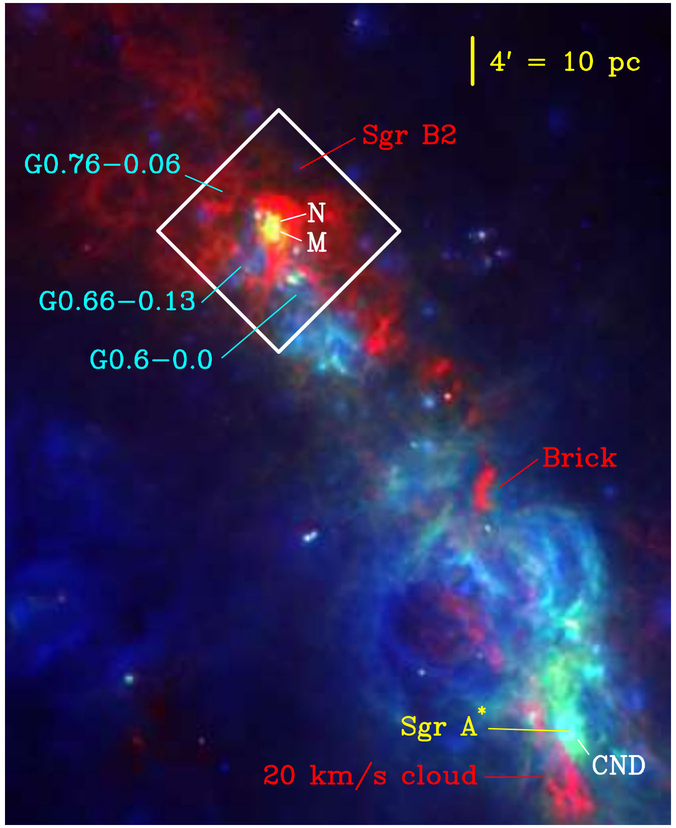
The benefit of large scale maps

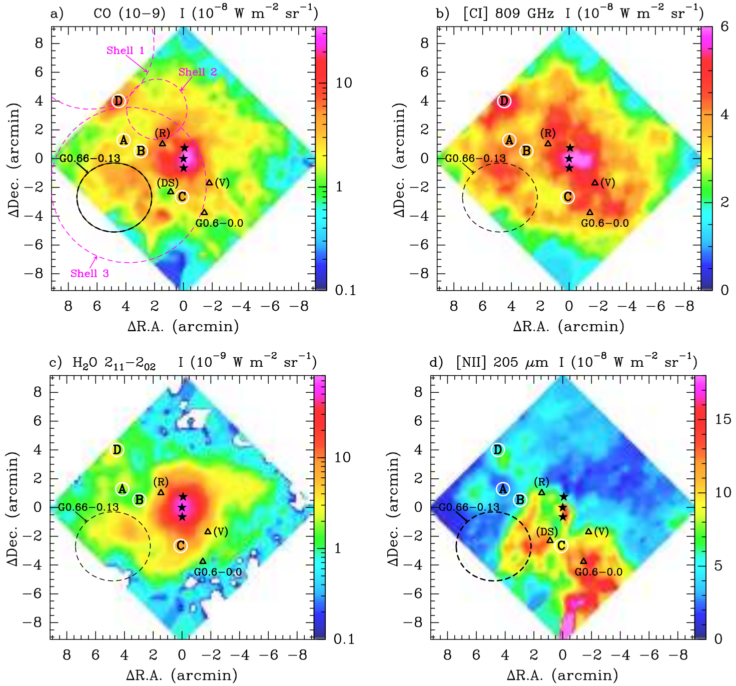


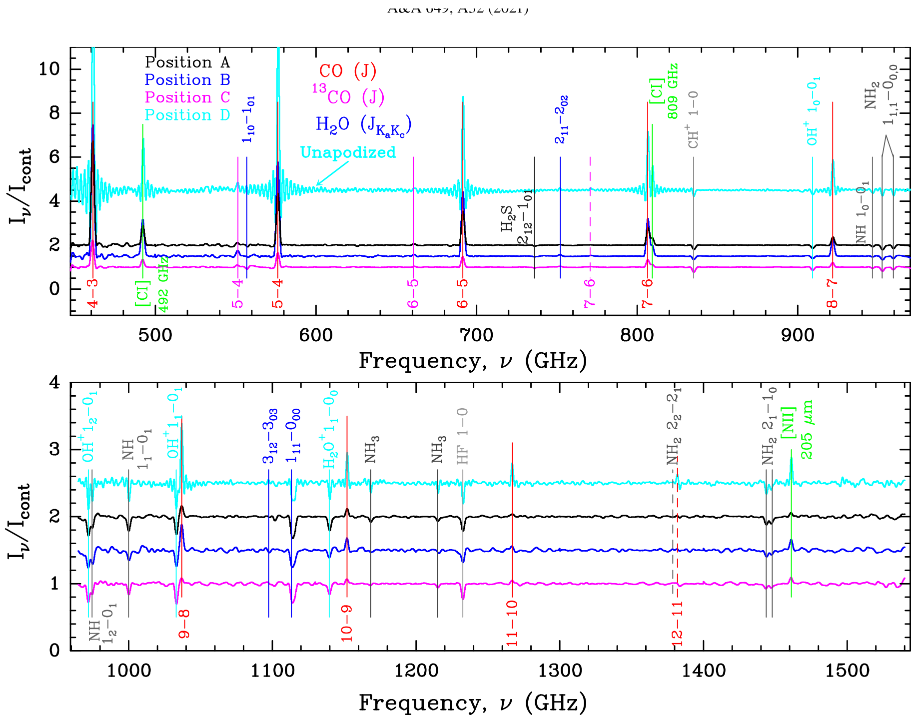
Orion B Herschel vs IRAM-30m

- Large dynamical range of spatial scales
- Large variety of environments
- Relation between star forming regions and their environment
- Unbiased selection of lines : mini line surveys for molecular clouds
- Spectral line maps are smaller than photometry but bring complementary information

The benefic of large scale maps





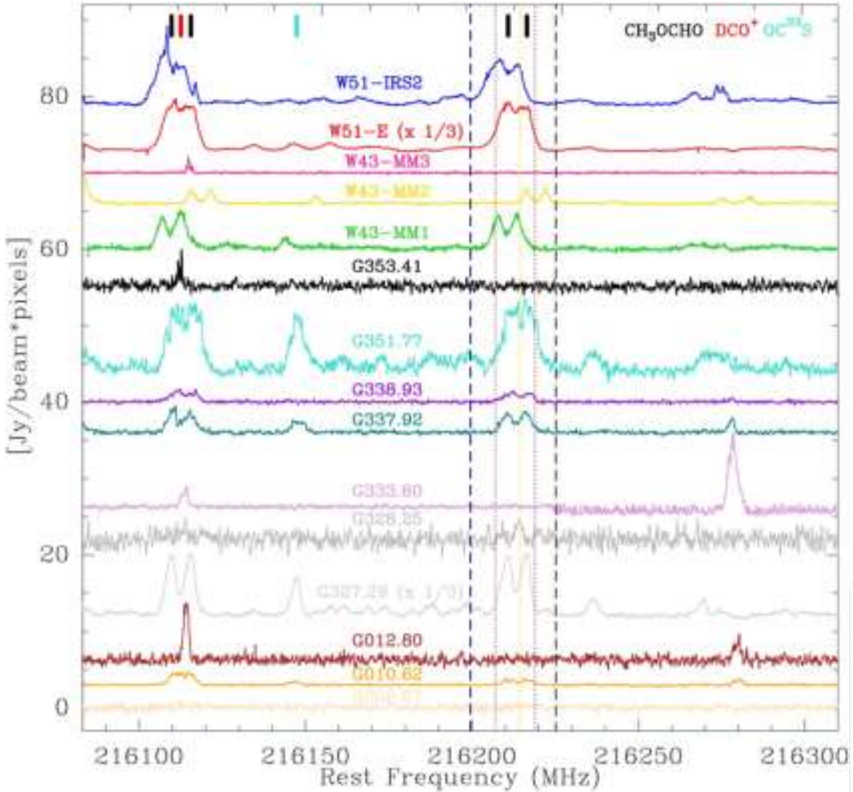


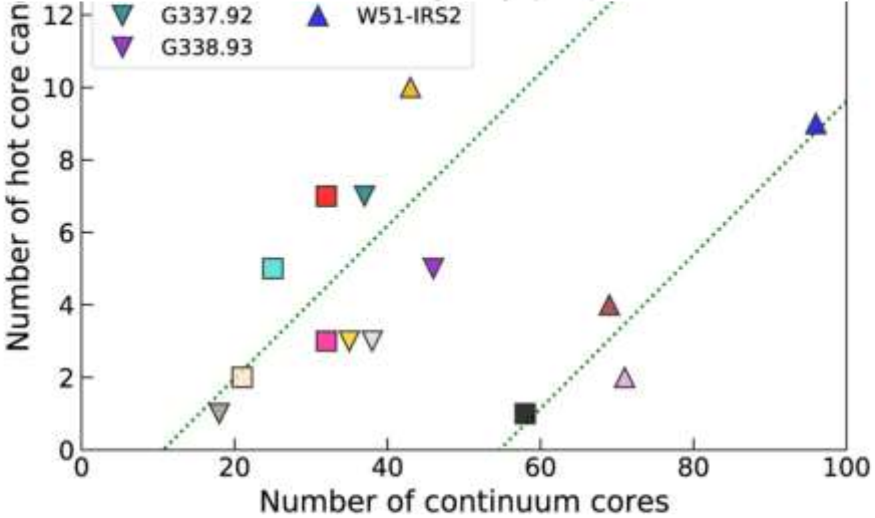
- SgrB2 : an example for molecular cloud associated to super star cluster, as in starbursts
- Combination of spectral diagnostics for the different phases

SgrB2, Santa-Maria+2021

Statistical samples

- Statistical view of ISM and star forming regions : from few (template) sources to unbiased samples
- Large programs, e.g. ALMA-IMF, selection of hot core candidates with CH3OCHO lines
- Hot cores are associated with deeply embedded massive protostars
- Hot core lifetime ~ protostar lifetime few 10^5 yrs

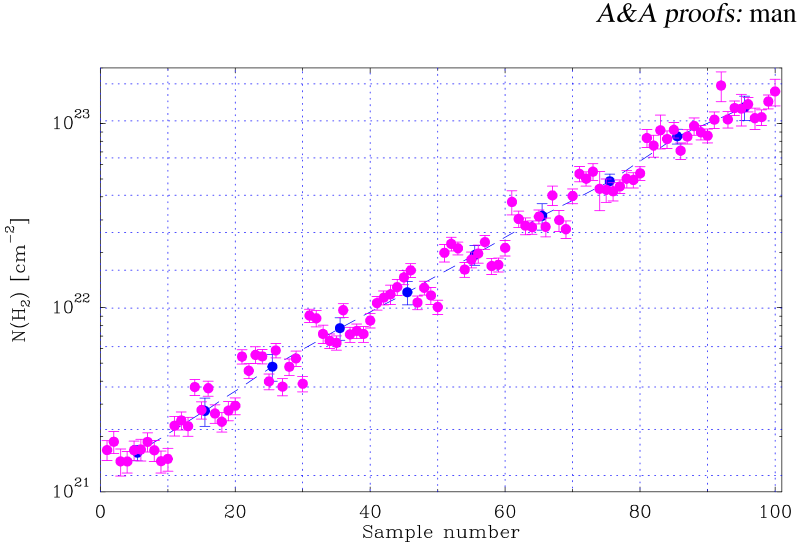




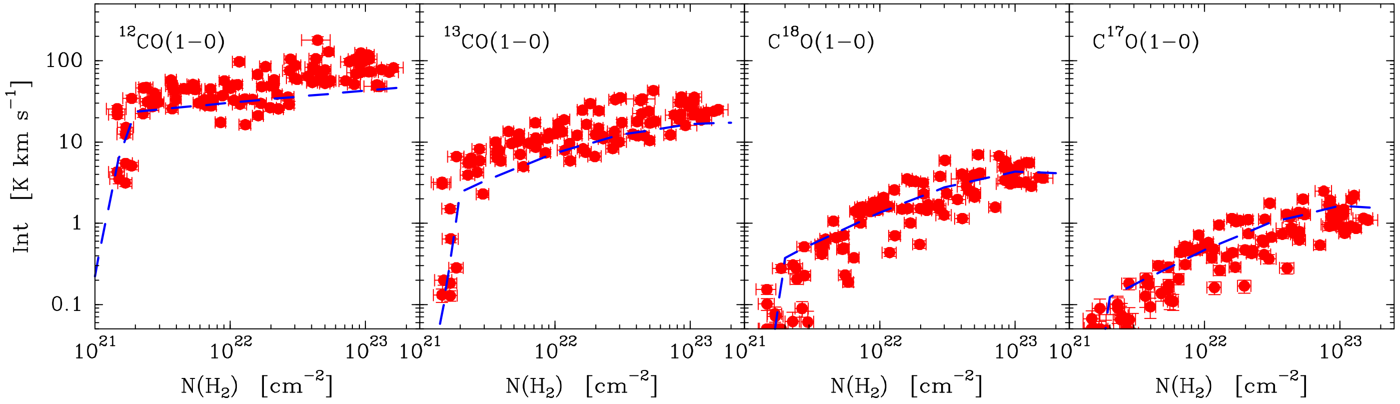
Bonfand+2024

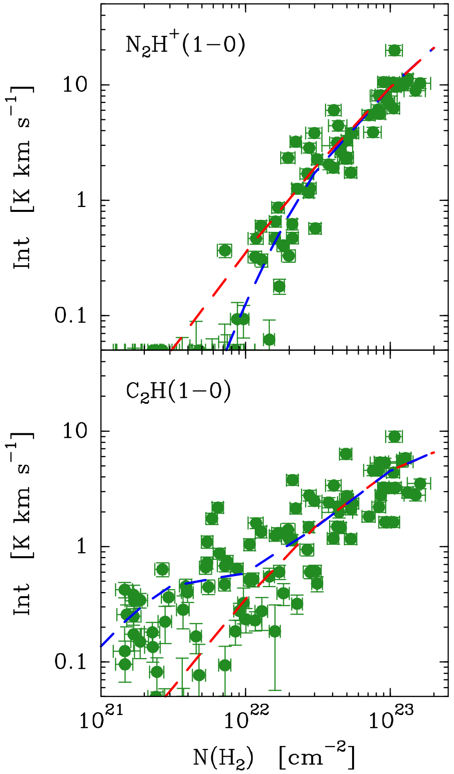
Sampling clouds

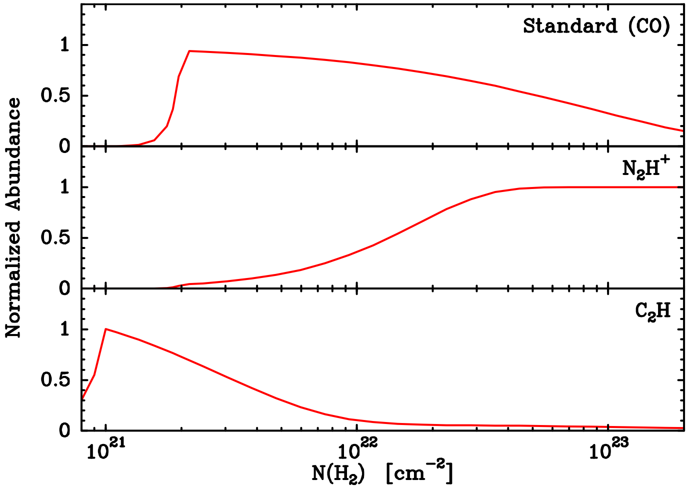
- Random sampling of nearby molecular clouds by selecting positions in different intervals of $N(H_2)$
- Building trends of line emission vs $N(H_2)$
- Fit trends with simple cloud and abundance model including photodissociation at cloud edge and Freezing at high extinction :



Tafalla+2021, 2023







$n(H_2) = 2x10^4\ cm^{-3}\ (N(H^2)/10^{22}\ cm^{-2})^{0.75}$

$\Delta V = 1kms^{-1}\ (N(H_2)/10^{22}\ cm^{-2})^{0.15}$

$X(N(H2)) = X0\ f_{out}(N(H_2))\ f_{in}(N(H_2))$

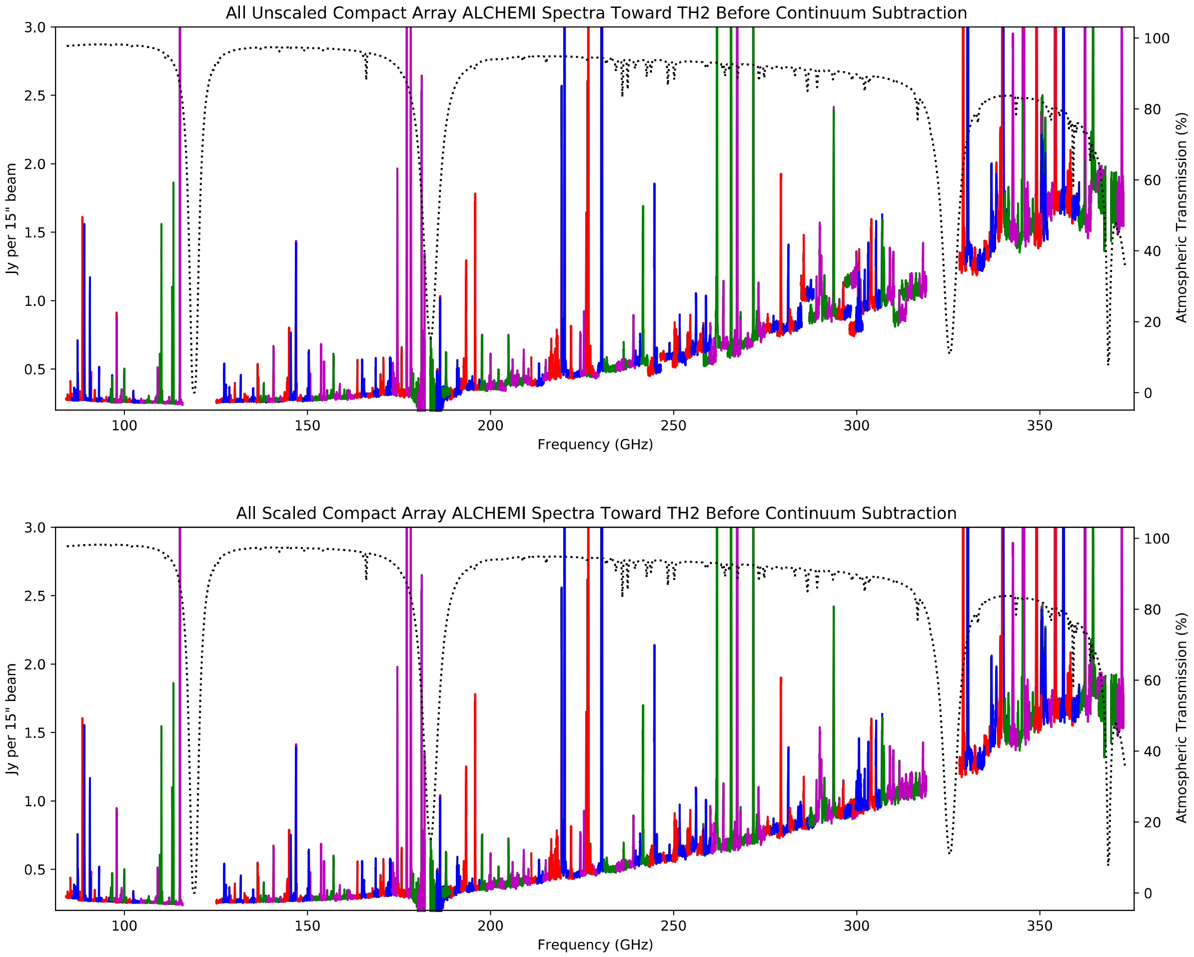
What’s next ? Star and planet forming material

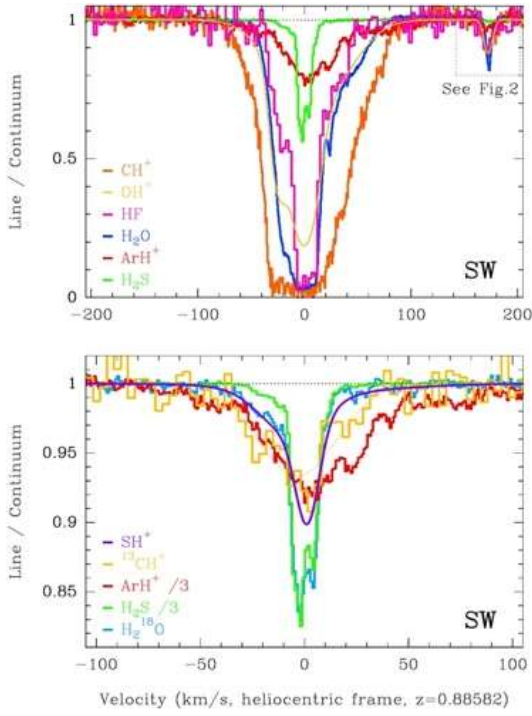
- Far infrared spectroscopy of planet forming disks : HD, H_2O, OI, as in the FIR probe projects
  - Total gas content, depletions, position of the snow line, tomography from the line profiles, evolutionary effects
  - High spectral resolution is key for line profile and line/continuum separation
- IR imaging spectroscopy with JWST
- Ground based interferometers GRAVITY+, NOEMA, ALMA Wide Sensitivity Upgrade (2030+) with 2x (8 – 16 GHz) at high spectral resolution, ngVLA, MeerKat, SKA

What’s next : Astrochemistry at low and high redshift

- From the solar system to high z : variation of elemental abundances, metallicities, dust properties, radiation field, cosmic ray flux, ..
- Dust evolution : dust content and dust composition
- Variation of some fundamental constants with time ?

ALCHEMI NGC253 with ALMA



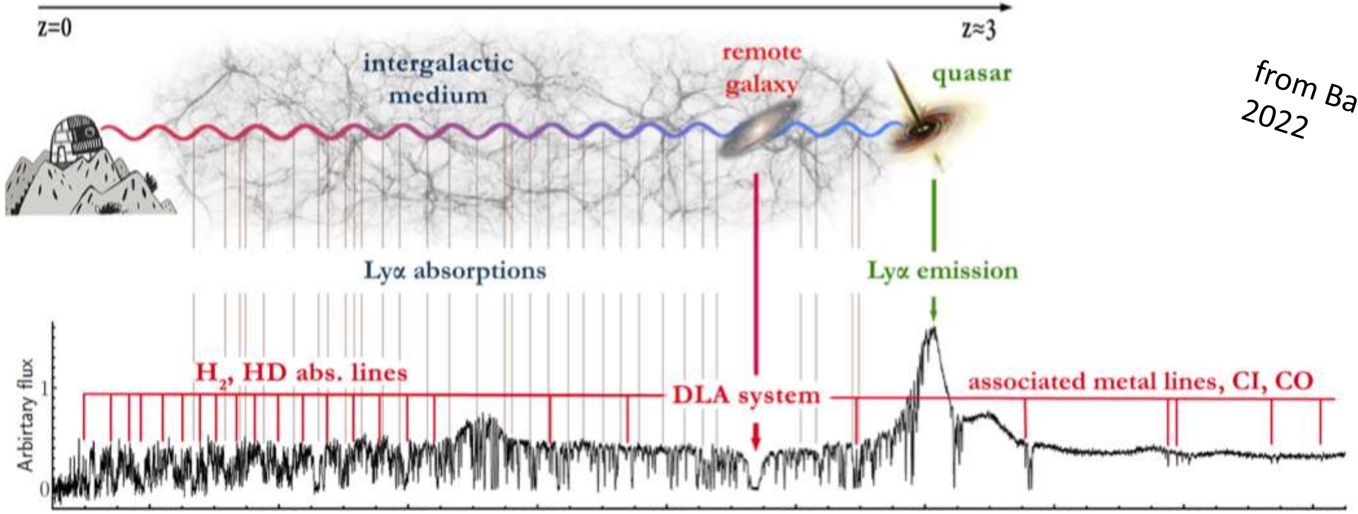


Martin+2021, Müller+2017

H_2, C^+,C , CO .. observations at high redshift

Electronic spectrum of H_2 in the far UV

redshifted ➥ *visible absorption towards extragalactic sources*



from Balashev & Noterdaeme 2022

➥ *test of variation of fundamental constants at high z;* $d\alpha/\alpha \le 10^{-6}$*;*
coupling of high spectral resolution spectra and theoretical computations to derive the K-factors (Ubachs +2019)