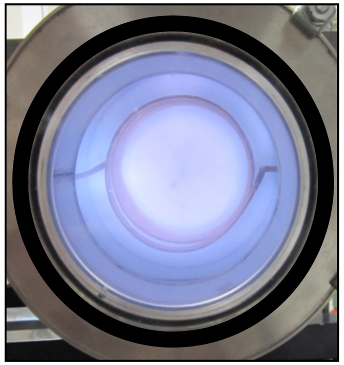
LOW TEMPERATURE PLASMAS FOR LABORATORY ASTROPHYSICS

Isabel Tanarro

i.tanarro@csic.es,
IEM-CSIC, Spain

*C. Bermúdez, C. Cabezas, J. Cernicharo,
J. L. Doménech, V. J. Herrero, R. J. Peláez,
K. Lauwaet, G. Santoro, J. A. Martín-Gago,
F. Beltrán, J. M. Hernández, P. de Vicente, J. D. Gallego
and the Team of Yebes Observatory*



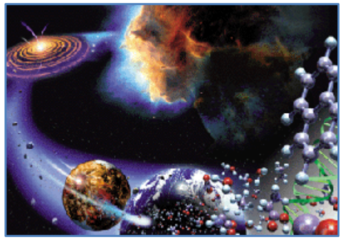
Funding: EU Synergy Grant ERC-2013-Syg 610256 "**NANOCOSMOS**"
Spanish Grants CSD2009-00038 "**ASTROMOL**" & FIS2016-77726-C3-1-P

physics @veldhoven 21-22 January 2020

22 January 2020

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

MOTIVATION



- **Molecules** play a key role in **Interstellar Molecular Clouds** for the formation of stars, and participate in a rich chemistry in those regions.
- Since the original discovery of CH and CN radicals (1940) **more than 200 Molecular Species** have been found in the interstellar medium by **Spectroscopic Methods** (containing up to 70 atoms).
- http://www.astrochymist.org/astrochymist_mole.html

- **Laboratory Data are crucial** for their spectral identification and to clarify their generation and destruction mechanisms.
- Many of them are **Unstable Species** (Ions, Radicals). **Cold Plasmas** are useful to generate them and to characterize their spectral signatures and behavior.

~ **80%** of these species have been detected by **RADIO ASTRONOMY**, from their **Pure Rotational Emissions (ν ≈ GHz, λ ≈ mm, ΔE ≈ meV)**.

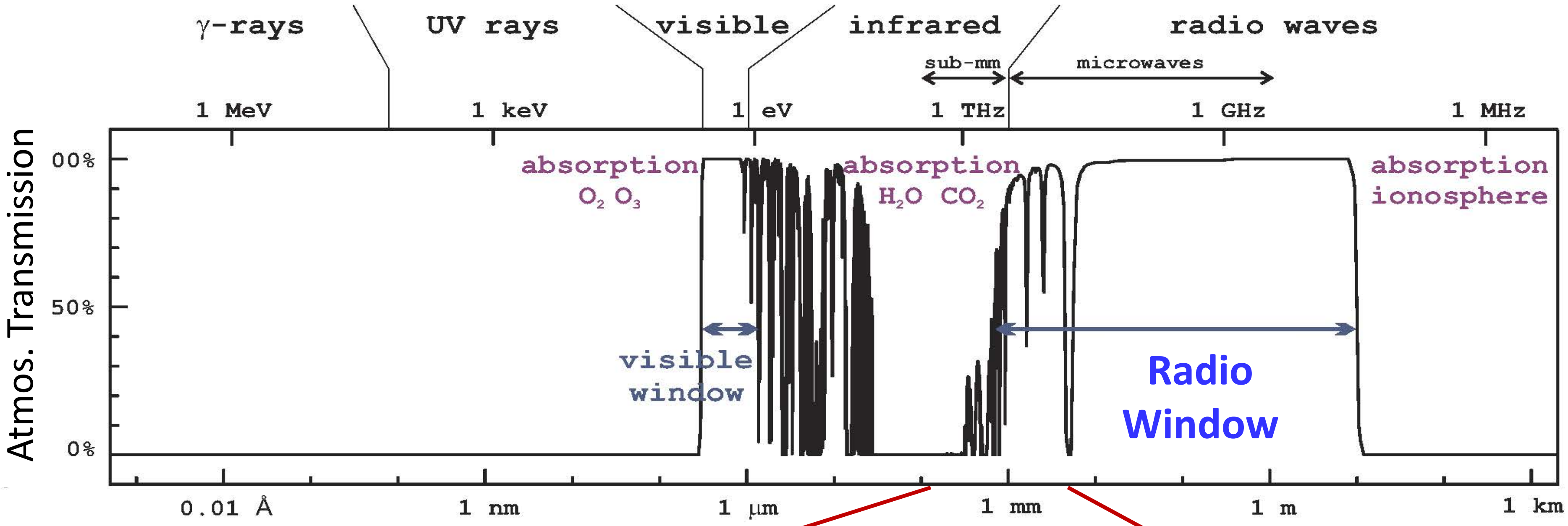
- ***Radio Astronomy*** is crucial to characterize very cold interstellar regions, where only low molecular levels, close to the ground state, are populated.
- ***Radio Astronomy*** provides Broadband Range and High Spectral Resolution.
- ***Radio emissions*** reach Earth observatories better than ***IR, Visible & UV***, due to the different opacities of the media to be crossed by radiation.

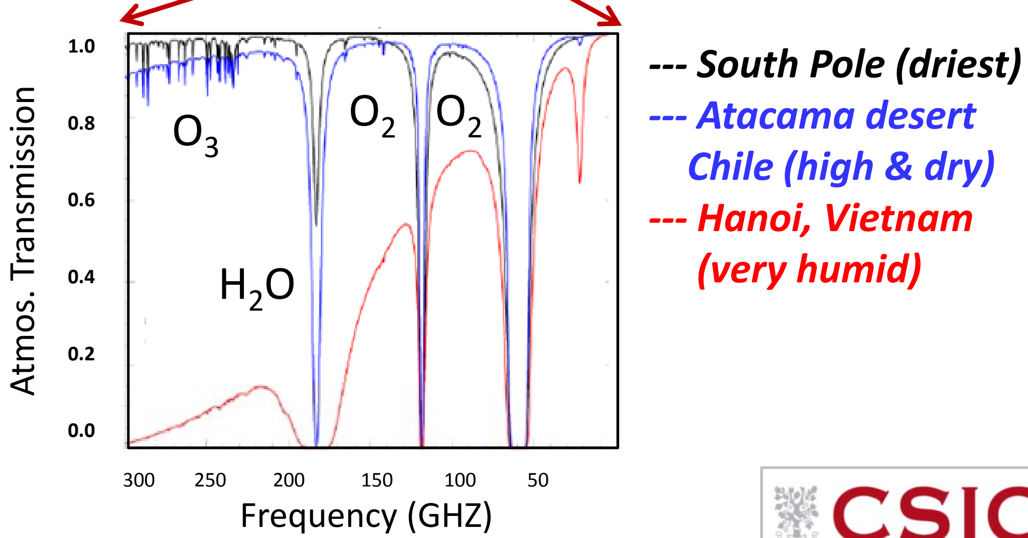
HOW ARE THESE MEDIA?

HOW DO THEY HINDER RADIATION?

EARTH'S ATMOSPHERE

High Transmittance for Radio Waves, especially at high altitude and dryness

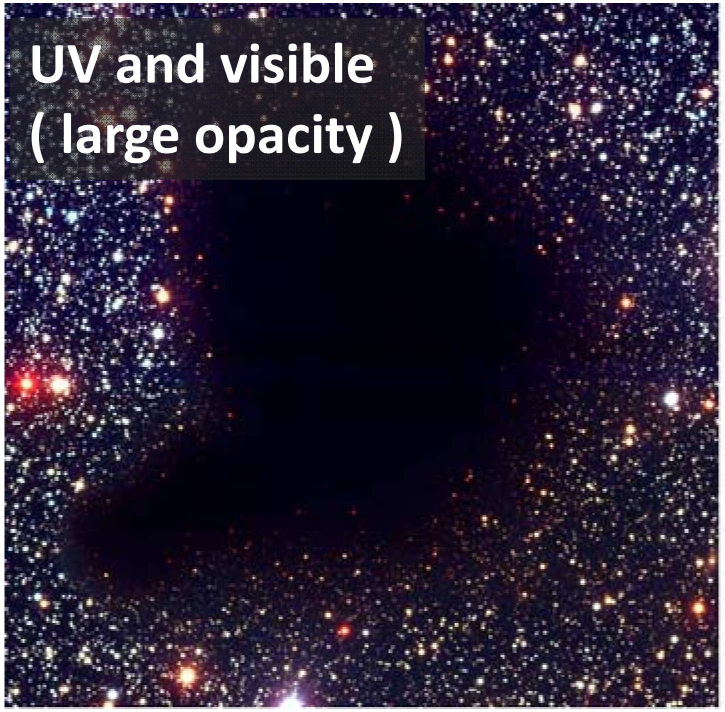




DARK MOLECULAR CLOUDS

Composed mainly of **H_2** and **Dust** (~15% mass of galaxies)

Unlike UV and visible light, scattered or absorbed by interstellar dust, longer wavelengths can pass through the microscopic particles.

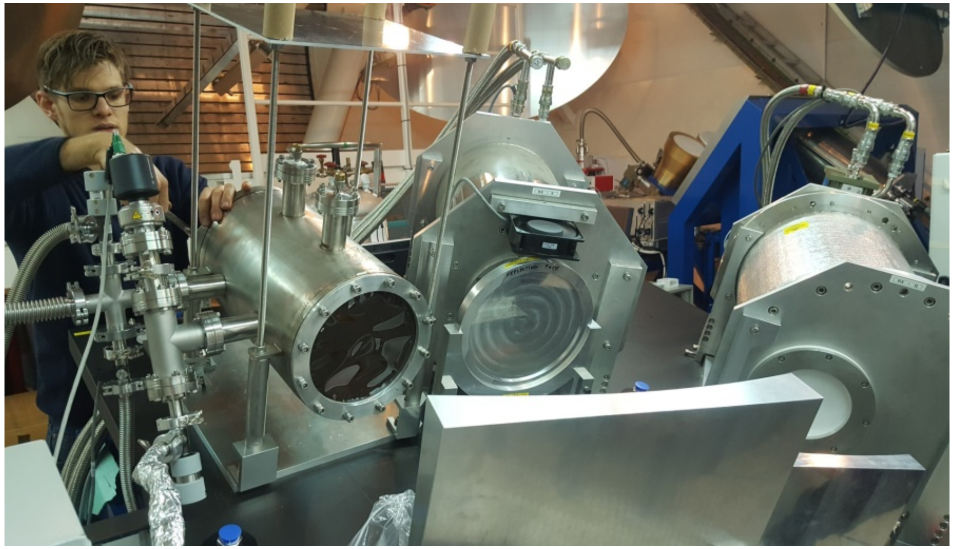


Dark molecular cloud Barnard 68 , T ≈ 16 K

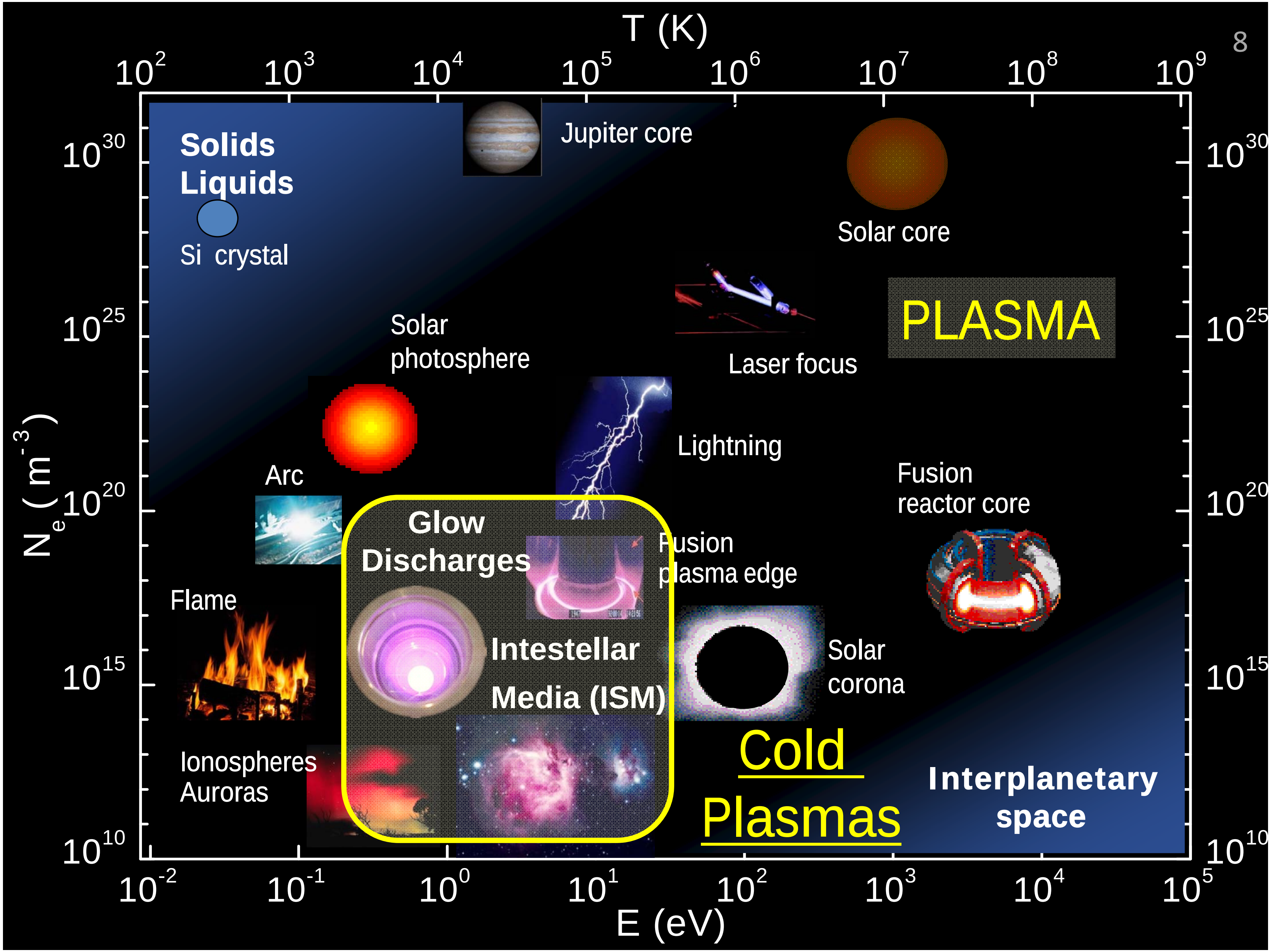
Nowadays, the most recent generation of Radio-Telescopes, like ALMA, provides more sensitivity and angular resolution than all the previous ones to search molecules in space!

ALMA (Atacama Large Mm/sub-mm Array)
Atacama Desert (Chile), ~2400 m altitude

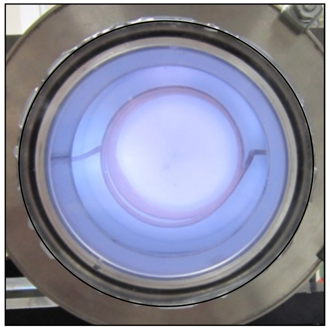
PRESENT WORK: USE FOR THE FIRST TIME OF RADIO-ASTRONOMY TECHNIQUES TO DETECT MOLECULAR EMISSIONS IN LABORATORY COLD PLASMAS



40 m Radio Telescope of Yebes Observatory, Guadalajara, Spain


T (K)
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Solids
Liquids
Si crystal
Jupiter core
Solar core
PLASMA
Laser focus
Solar
photosphere
Lightning
Arc
Fusion
reactor core
Glow
Discharges
Fusion
plasma edge
Flame
Intestellar
Media (ISM)
Solar
corona
Ionospheres
Auroras
Cold
Plasmas
Interplanetary
space
Ne (m-3)
10^30
10^25
10^20
10^15
10^10
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
E (eV)

FUNDAMENTAL MAGNITUDES: THE PROOF OF CONCEPT



Molecular Clouds

Length ~ 10^{19} cm
Density ~ 10^4-10^5 cm^{-3}
⇓
Column density in line of sight
H_2 ~ 10^{22} cm^{-2} , CO ~ 10^{18} cm^{-2}
HCN, HCO^+, C_2H, CN, CS ~10^{14} cm^{-2}

Glow Discharge Reactors

Length ~ 100 cm
Density ~ 2.5 x 10^{15} cm^{-3} (0.1 mbar)
⇓
Column density in line of sight:
Stable species ~ 10^{17} cm^{-2}
Ions and Radicals ~ 10^{13} - 10^{15} cm^{-2}

Observations reasonably expected for times of minutes - hours

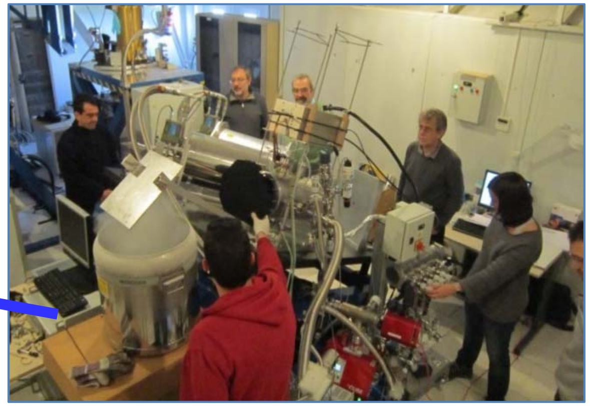
TWO CAMPAIGNS OF EXPERIMENTS

TWO INDEPENDENT EQUIPMENTS

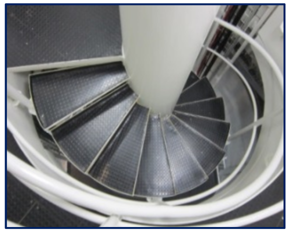
1.- **Proof of Concept in the 40 m Radio-Telescope of Yebes Observatory (Spain).** *Tanarro et al, A&A 609, A15 (2018)*

2.- **New Astrophysics Laboratory in Yebes' Observatory location.** *Cernicharo et al, A&A 626, A34 (2019)*

1. PROOF OF CONCEPT IN THE 40 m RADIO-TELESCOPE



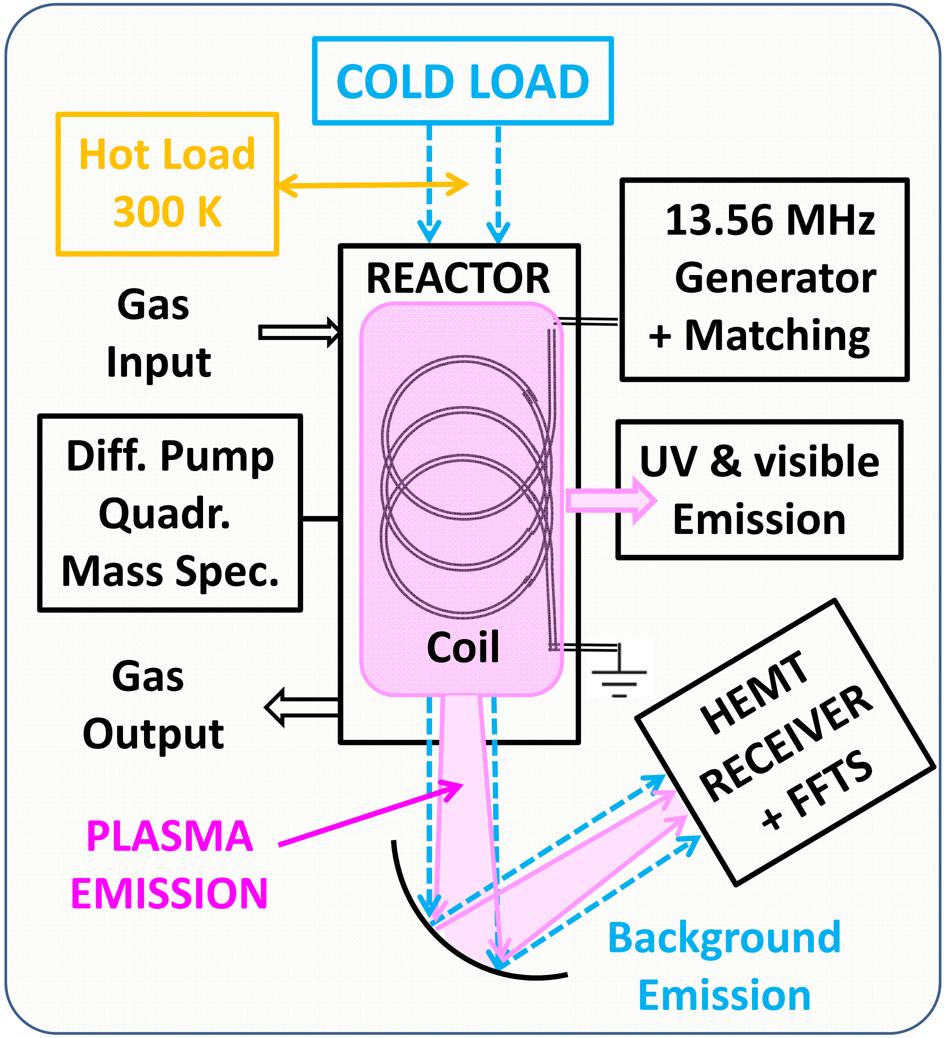
Several short campaigns (2016-2017) in the receptors' room, subjected to the time schedule of the astronomers.



100 steps, no room enough,
no heating, no coffee machine …
but a very funny experience!

BASIC EXPERIMENTAL SCHEME

- **REACTOR** devoted to study **Gases** and **Cold Plasmas** in glow discharges.
- **HETERODINE RECEIVERS** for broad band, high resolution, rotational emission spectroscopy.
- **COLD LOAD** at the backend to minimize mm background radiation (+ movable HOT LOAD for calibration).



Additional equipment:

- Quadrupole Mass Spectrometry
- Visible Emission Spectroscopy

Very weak signal

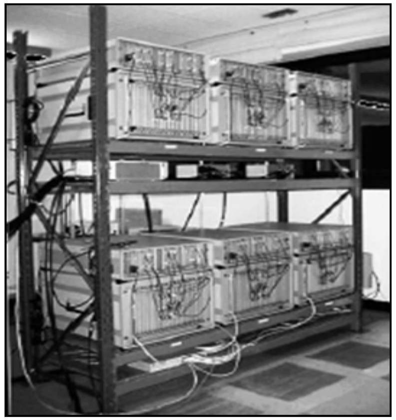
~ 10^{-15} W, ~ 30-300 GHz

Heterodyne Detection

Amplification

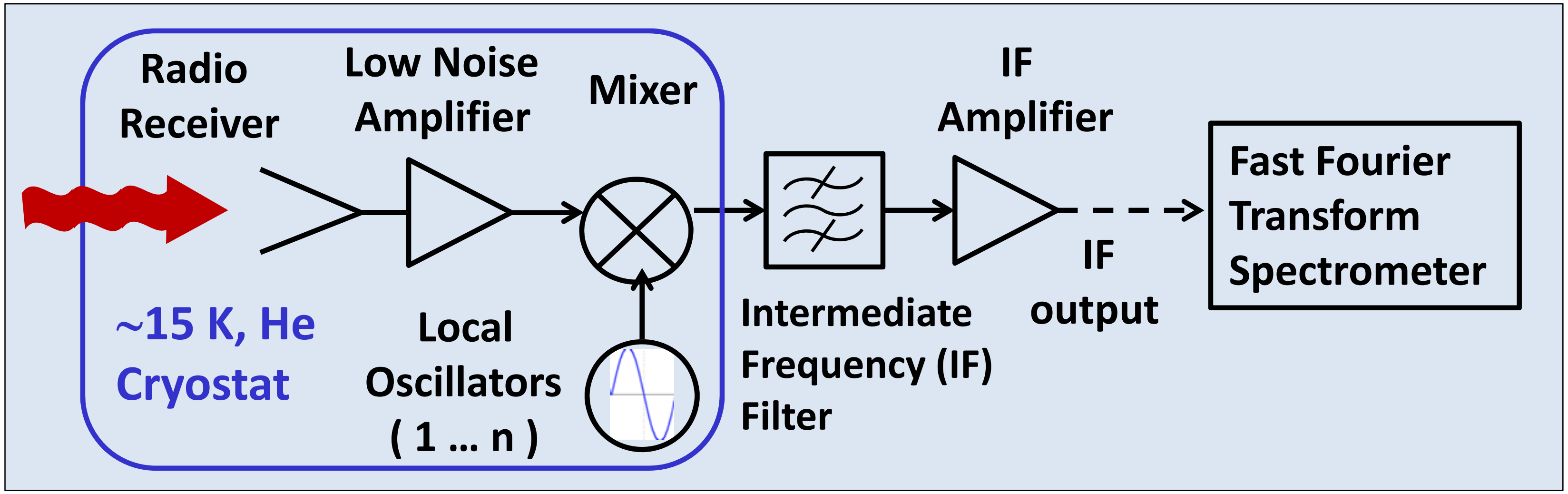
Frequency Down Conversion

Processing by FFTS



Gain ~ 120 dB

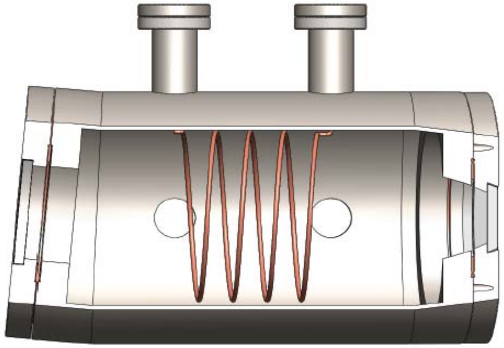
IF ~ 2 GHz

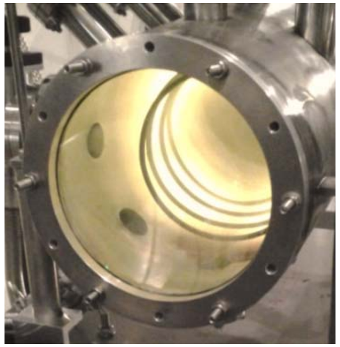


Careful noise reduction is essential

PROTOTYPE REACTOR

- RF inductively coupled discharge: 13.56 MHz, 5-60 W
- Pressures ~ 10^{-2} - 10^{-1} mbar (gas flow or static)
- Stainless steel, 40 cm length x 25 cm diameter, specially designed to be used in the limited space available in the telescope.



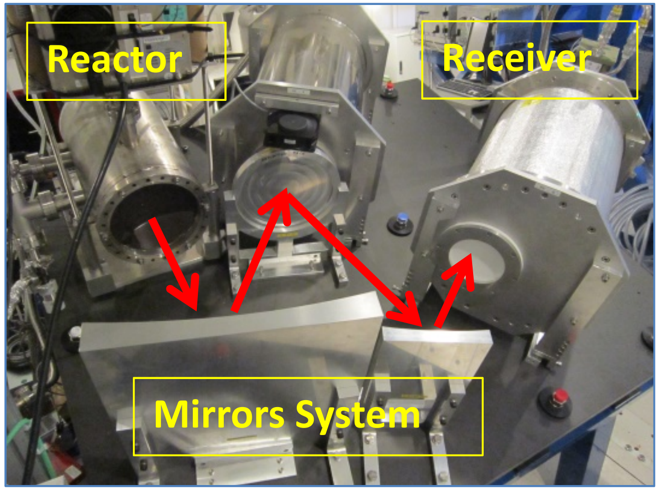


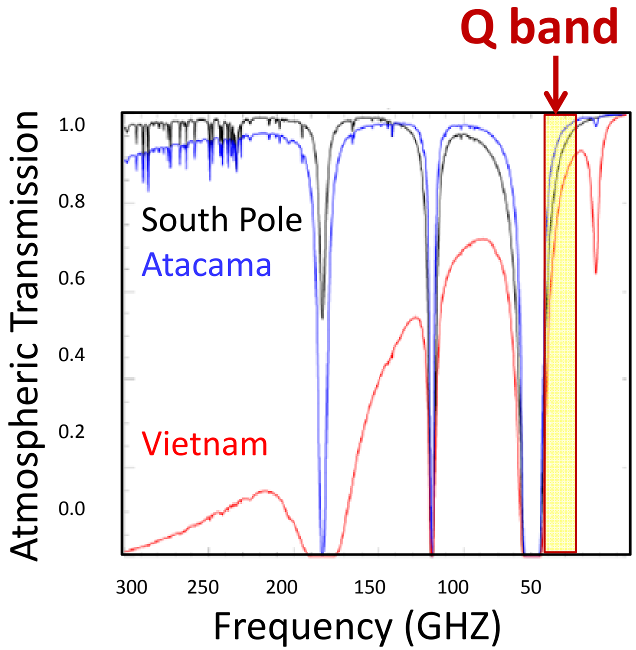
- Windows: 1 cm thickness Fused Silica or a 70 μm yellow polyimide film (Upilex), at different angles to avoid etalon effects.

HETERODINE RECEIVER

The HEMT Q band Receiver of the Radio Telescope

- Spectral Range = 30 - 50 GHz
- Instantaneous Bandwidh = 2 GHz



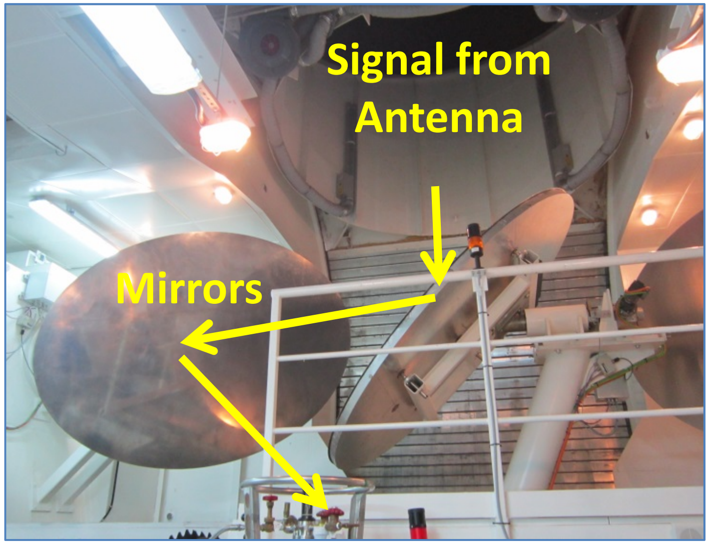


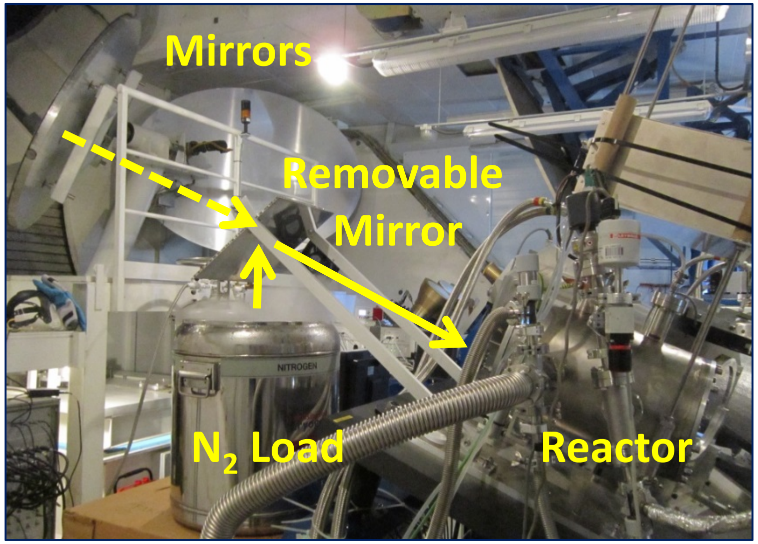
- 2 Fast Fourier Transform Spectrometers (65536 channels/u)

$\Rightarrow$ 38 kHz Spectral Resolution

COLD LOAD

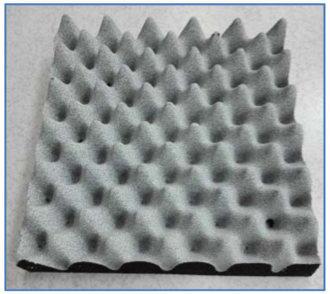
- 40 m Antenna towards the Zenith ⇒ 42 K (45 GHz)
- Load of liquid N_2 (cloudy or rainy weather) ⇒ 77 K





Hot Load

Corrugated foam rubber

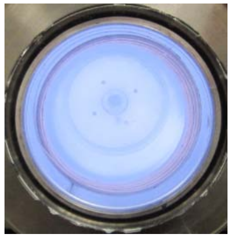


PRELIMINARY TESTS (a)

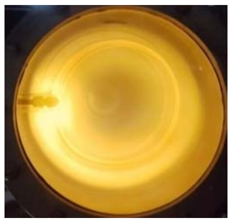
Radiation reflected between both sides of the 1 cm silica windows rose unacceptably the background signal (etalon effect)

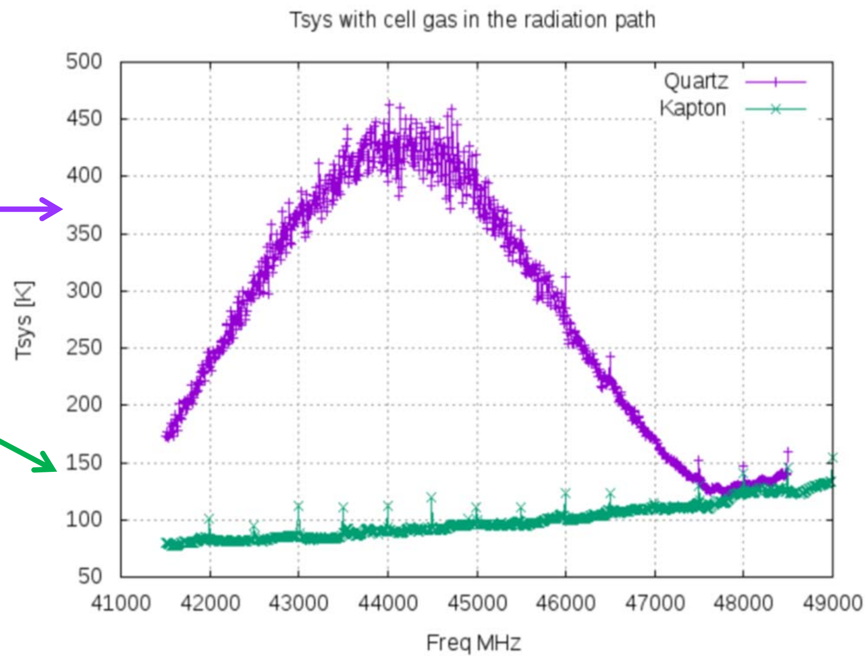
- 1 cm Fused Silica: similar thickness to Q band wavelengths (6-9 mm)

1 cm Fused Silica



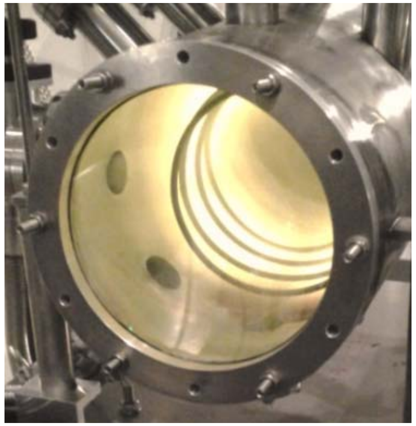
70 μm Polyimide

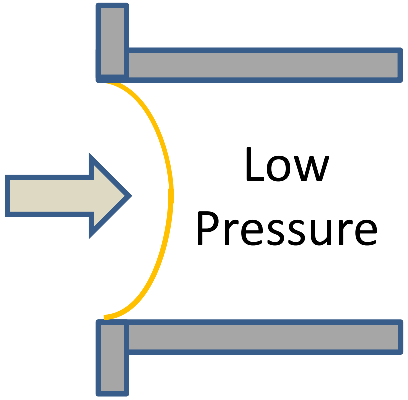




- 70 μm Polyimide Film: much lower interferences.

70 μm Polyimide Film: Low Noise, but Dangerous for warping at vacuum and giving rise to very loud implosions



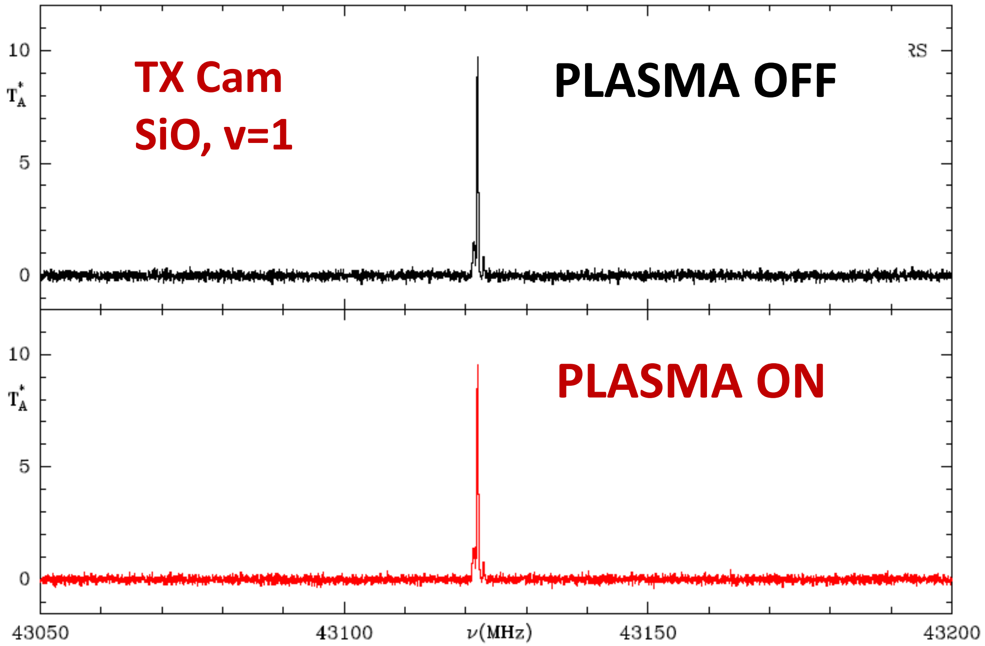


Two Sampling Modes for Noise Reduction

- Sample in/Sample out: the common ON/OFF technique in Astronomy. But too slow for us, by the need to evacuate and fill the reactor.
- Frequency Switching (±24 MHz), much more convenient.

Could electrical noise of the RF discharge affect the RF receivers?

Astronomical observation of a SiO maser signal from TX Cam star through the reactor showed identical results with PLASMA ON/OFF.



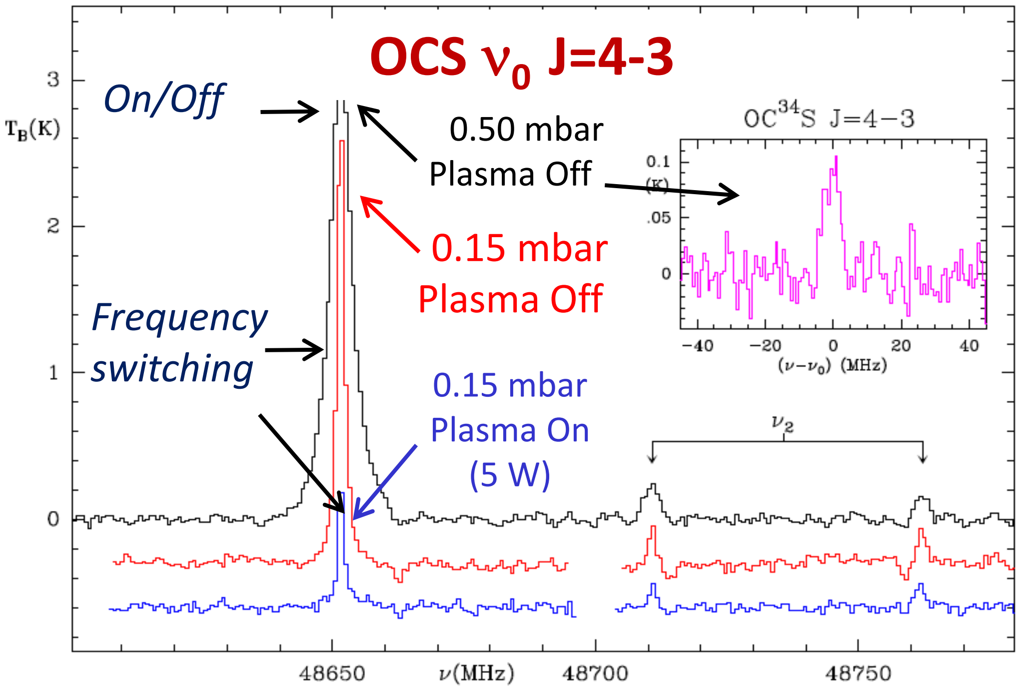
EXPERIMENTAL RESULTS

~ 80% of molecular species discovered in the interstellar medium contain at least one carbon atom ⇒ Study focused on different carbon containing molecules of astrophysical interest.

Particular showcases:

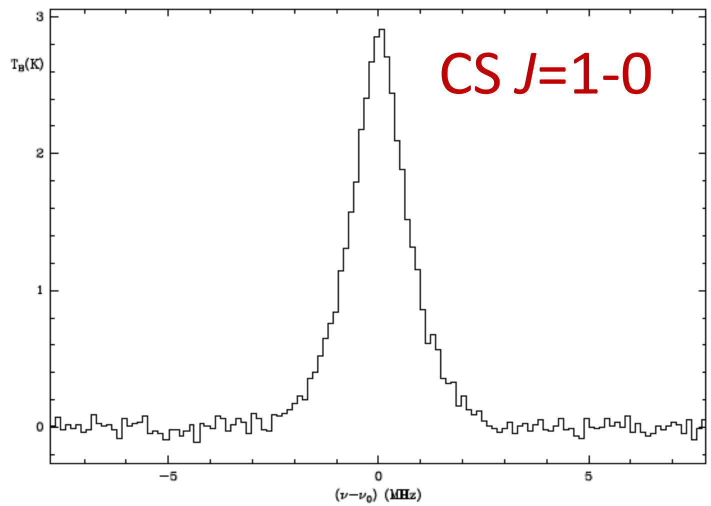
- Carbonile Sulphide (**OCS**) and its plasma products.
- **O_2** plasmas reacting with wall deposits (cleaning effect).

Species are identified and concentrations estimated with MADEX *(Molecular and Atomic Database and Excitation Code, Cernicharo 2012) with* **molecular data of > 6000 species** *including isotopologues.*
https://nanocosmos.iff.csic.es/madex/



OCS Gas (0.15 - 0.5 mbar)

- Higher resolution at lower pressures, with not so large intensity loss.
- OC^{34}S detected (≈ 25 μbar)
- ν_2 J=4-3 doublet detected.

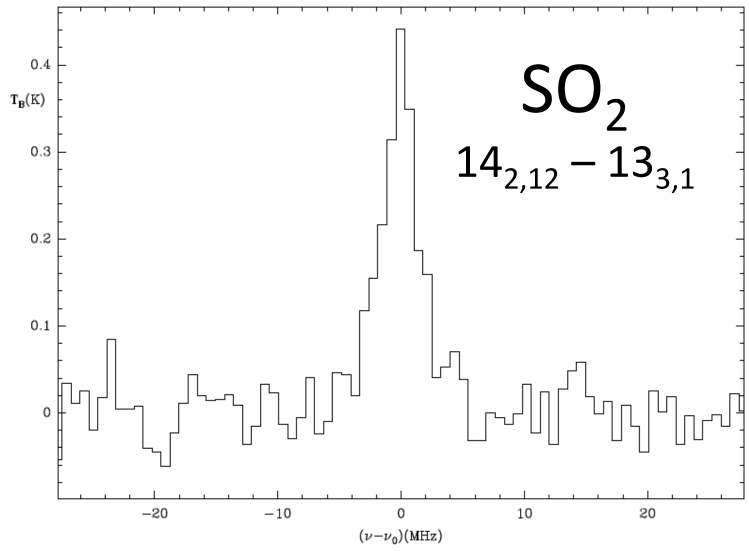


OCS plasma (0.15 mbar, 5 W)

- OCS dissociation ~ 70%
- ν_2/ν_0 intensities ⇒ Temp. change plasma Off / On = 300 K / 450 K
- Production of reactive CS was observed

O_2 discharge (0.1 mbar, 60 W) after deposition of Sulphur & Carbon on the walls by the former OCS plasma

- SO_2 (40 μbar) was produced by surface reactions.
- CO (non active in the Q band) was detected by mass spectrometry.



47913.427 MHz

Proof of concept successful !!!

A&A 609, A15 (2018)
DOI: 10.1051/0004-6361/201730969

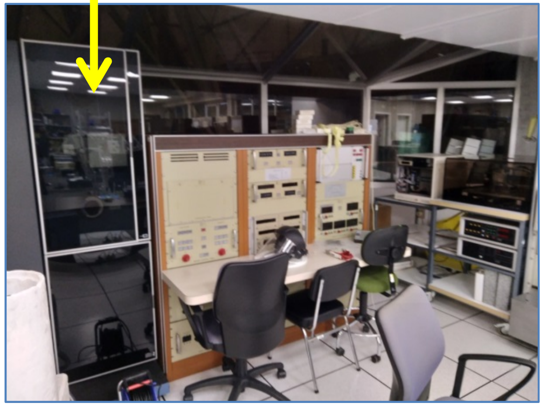
Astronomy & Astrophysics

Using radio astronomical receivers for molecular spectroscopic characterization in astrochemical laboratory simulations: A proof of concept★

I. Tanarro[1], B. Alemán[2], P. de Vicente[3], J. D. Gallego[3], J. R. Pardo[2], G. Santoro[4], K. Lauwaet[4], F. Tercero[3], A. Díaz-Pulido[3], E. Moreno[2], M. Agúndez[2], J. R. Goicoechea[2], J. M. Sobrado[5], J. A. López[3], L. Martínez[4], J. L. Doménech[1], V. J. Herrero[1], J. M. Hernández[3], R. J. Peláez[1], J. A. López-Pérez[3], J. Gómez-González[3], J. L. Alonso[6], E. Jiménez[7], D. Teyssier[8], K. Makasheva[9], M. Castellanos[2], C. Joblin[10,11], J. A. Martín-Gago[4], and J. Cernicharo[2]

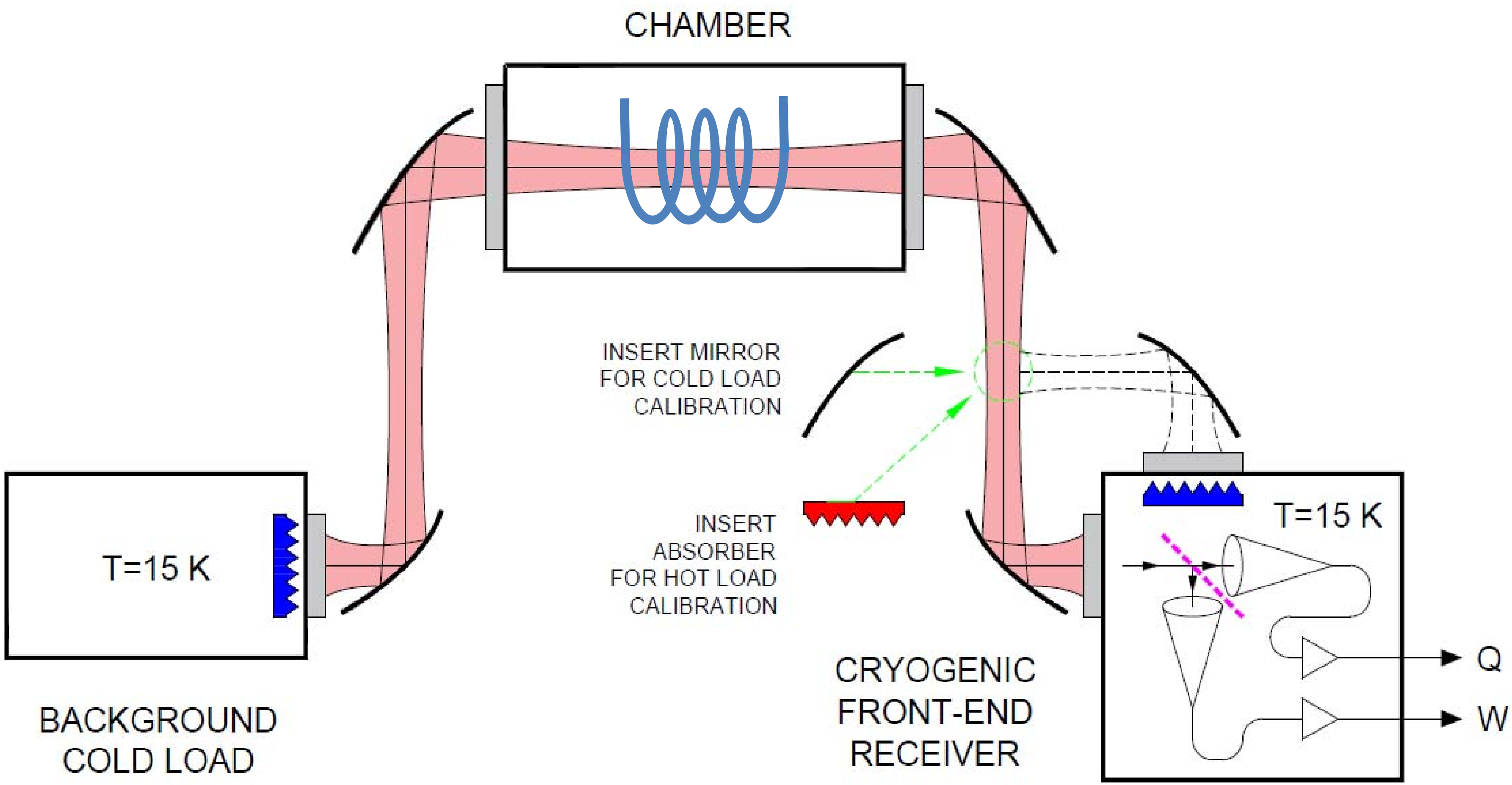
The design and construction of a completely new laboratory, not subject to the unavoidable restrictions of the telescope, was addressed.

2.- NEW SET-UP FOR LABORATORY ASTROPHYSICS



Control room of 13.5 m old telescope (~1980's) covered with spherical dome

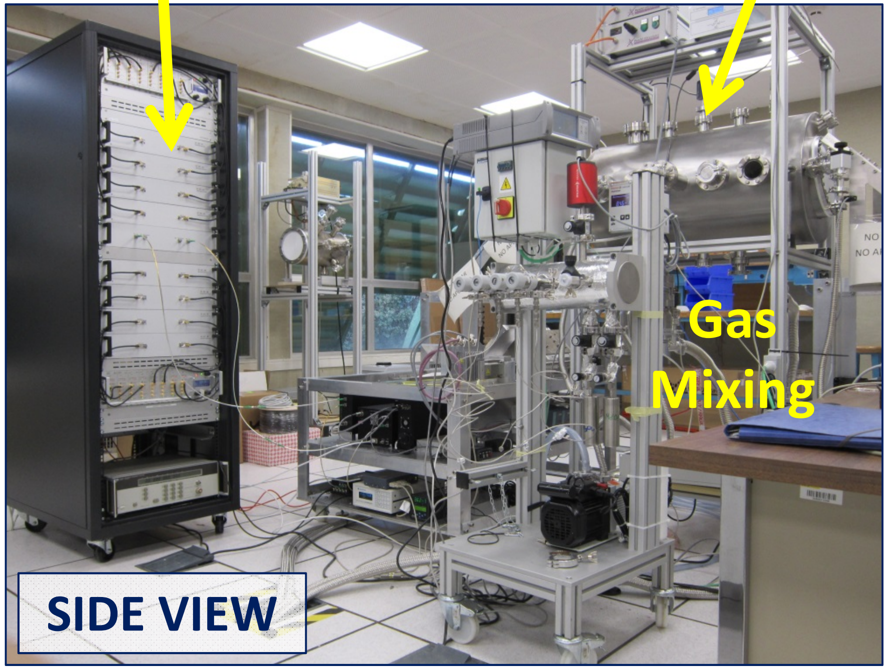
NEW Q AND W BAND RECEIVERS, 16 FFTS, A LARGER REACTOR AND CRYOGENIC COLD LOADS

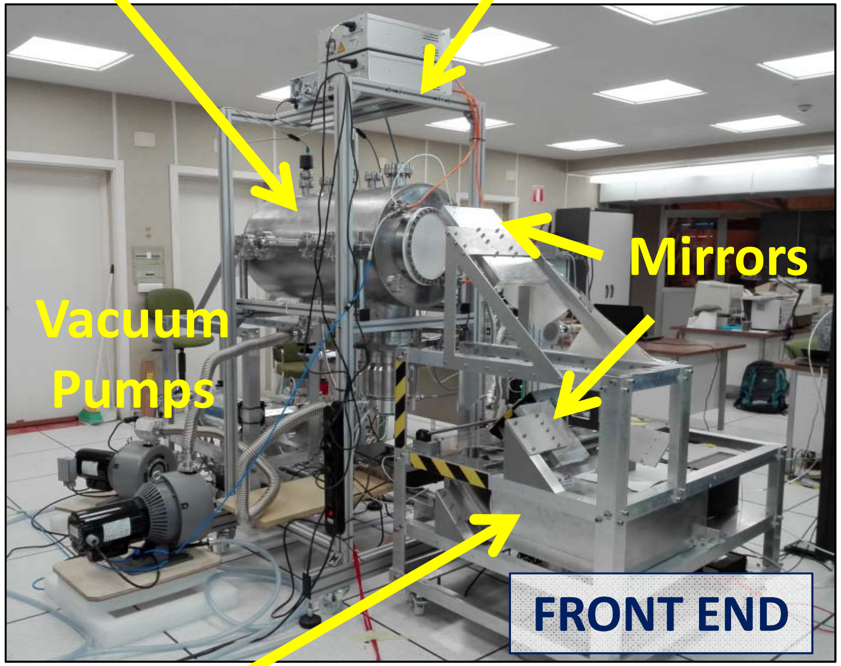


16 FFTS

New Reactor (1 m x 0.6 m)

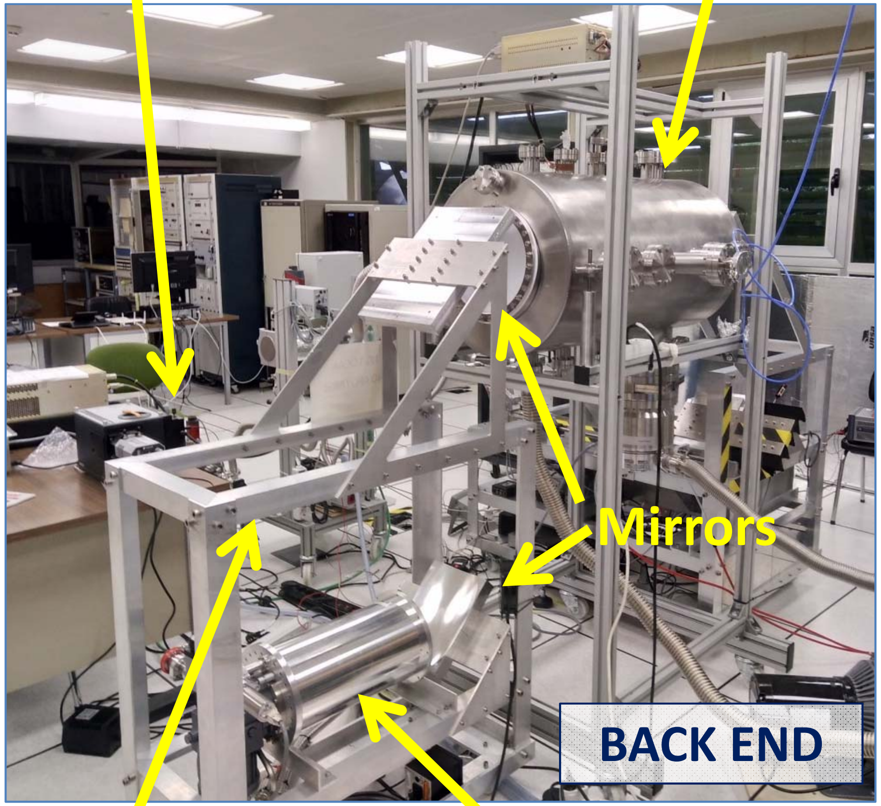
RF Source & Matching





Q & W band Radio-Receivers in a single housing

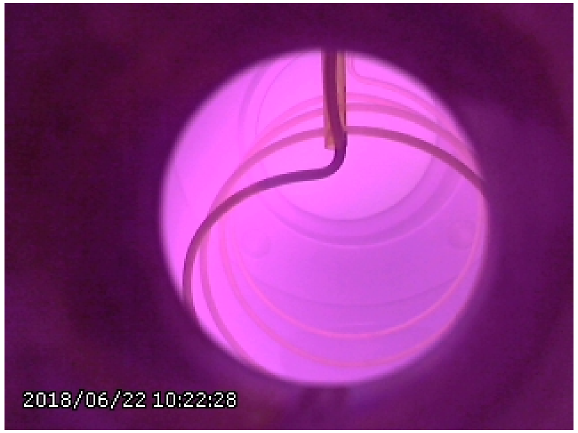
Visible Spectrometer **New Reactor**



Mass Spectrometer

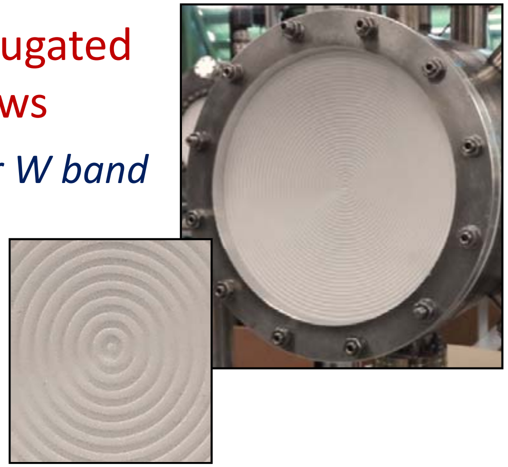
Cold Load: Helium Cryostat (17 K)

Plasma



Teflon corrugated windows

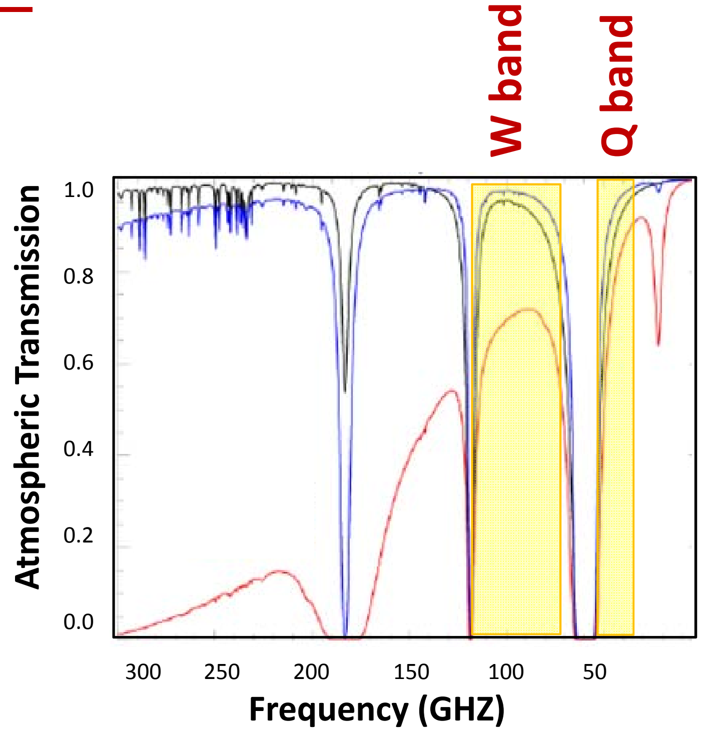
optimized for W band



RECEIVERS

- **Two receivers in a single cryostat:**

  Q band = 32-50 GHz
  W band = 72-116 GHz
  Divided in three sub-bands



- Each one connected to 8 FFTS
  of 2.5 GHz, 1.5 x 10^6 channels $\Rightarrow$

- **Instantaneous Bandwidth = 18 GHz**
  Resolution = 38 kHz

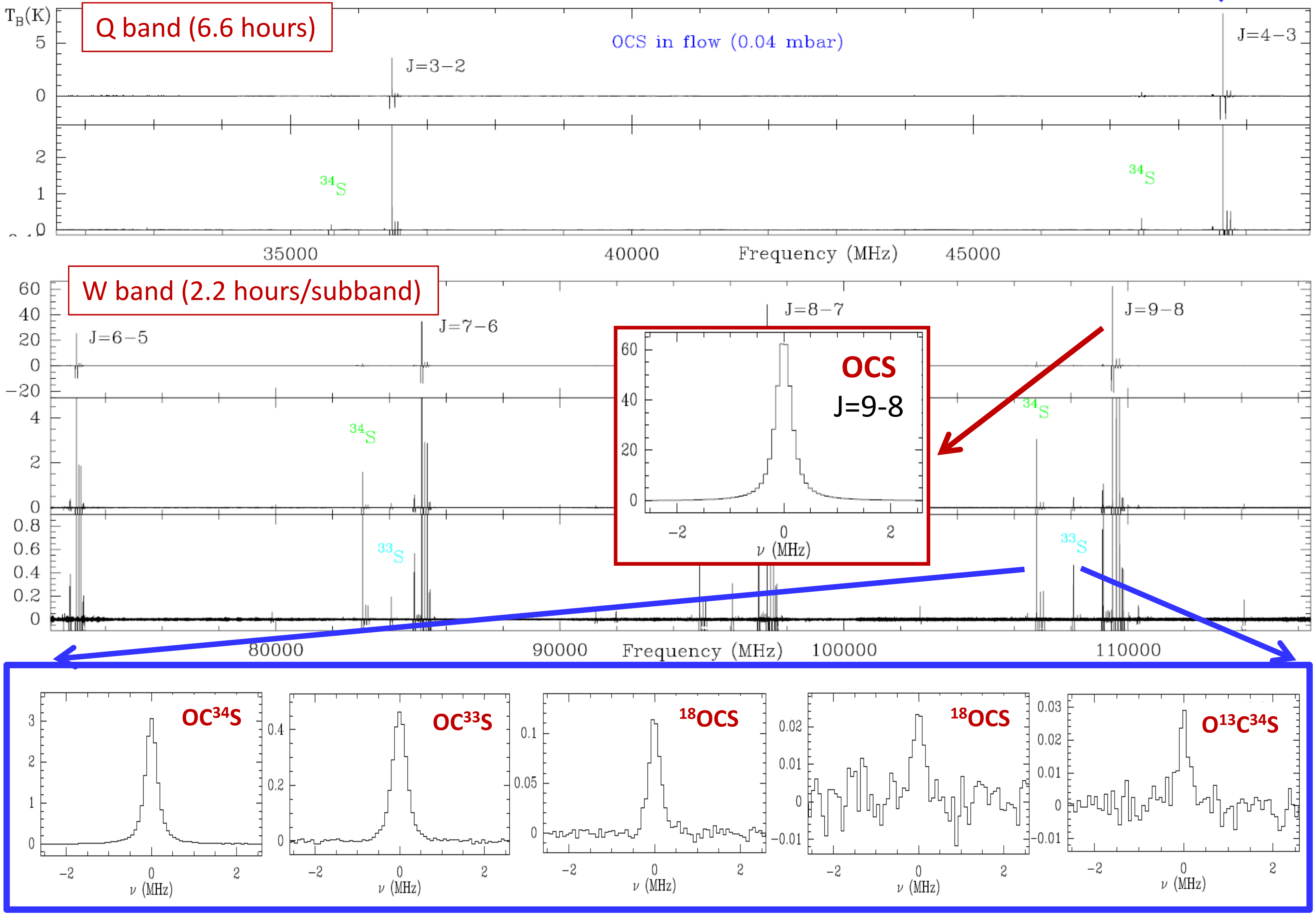
EXPERIMENTAL RESULTS

Particular showcases:

- **OCS**
- **O_2 plasma reacting with wall deposits**
- **$CH_4 + N_2$ plasma**

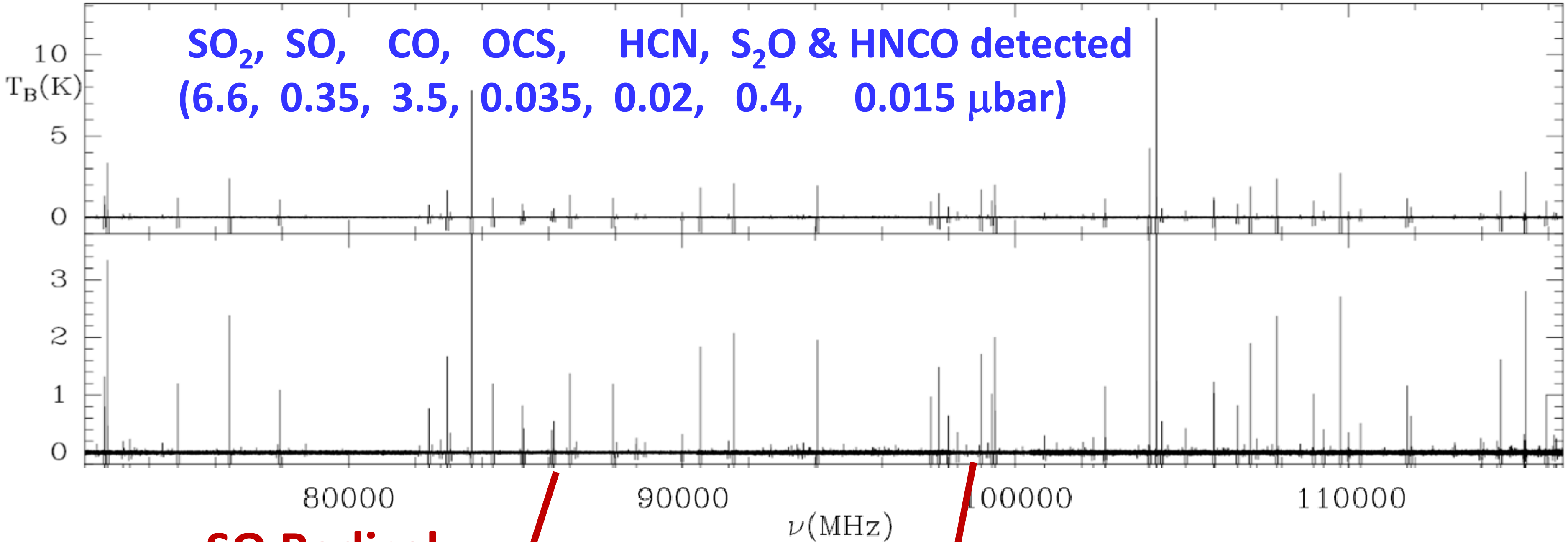
Very low pressures (≈ tens of μbar) could be used at stable plasma conditions, reducing line-widths and improving signal detection.

OCS, 40 μbar, without discharge

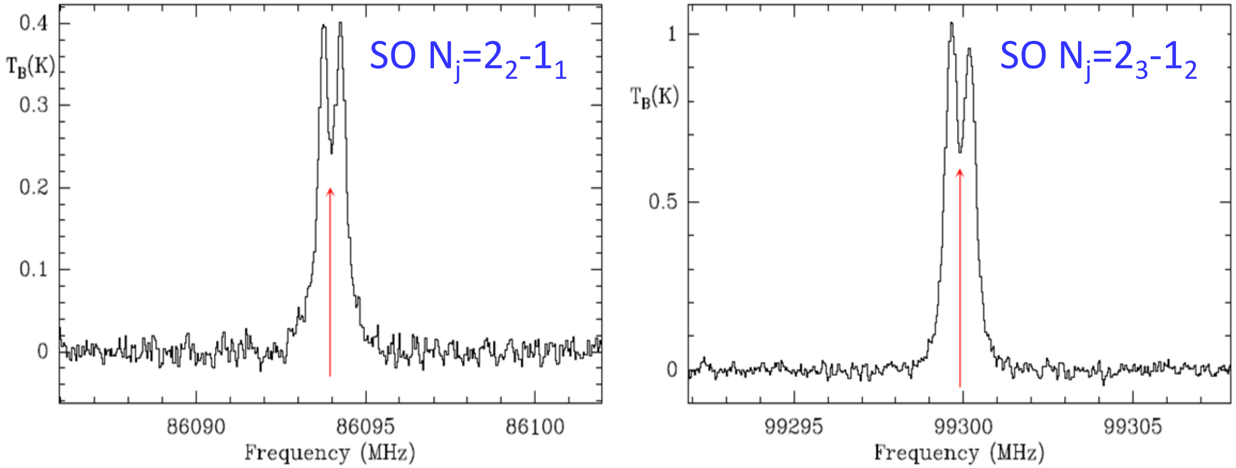


O_2 plasma (20 μbar) after OCS discharge

SO_2, SO, CO, OCS, HCN, S_2O & HNCO detected
(6.6, 0.35, 3.5, 0.035, 0.02, 0.4, 0.015 μbar)



SO Radical



The lines of SO($^3\Sigma$) are Zeeman splitted by the Earth magnetic field (~ 45 μT)

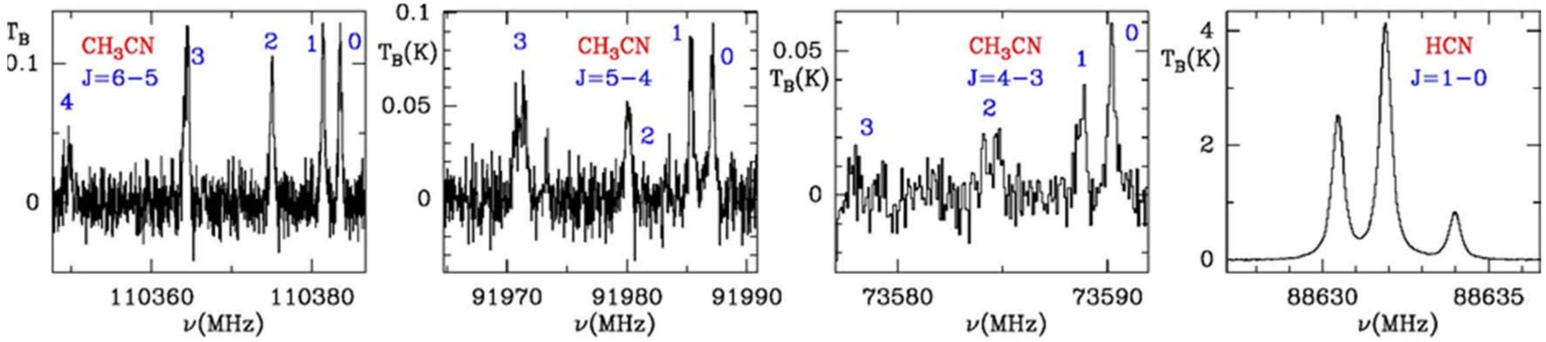
Plasma of 13 μbar CH_4 + 19 μbar N_2 , 20 W (40 min)

Main component of Titan atmosphere

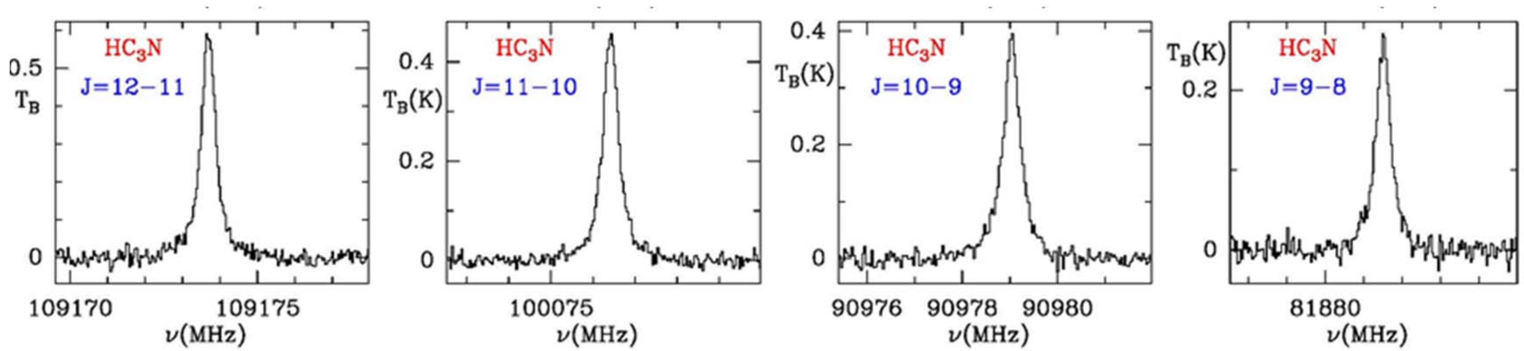
CH_3CN, HCN and HC_3N produced in the discharge were detected.

CH_3CN (0.01 μbar)

HCN (0.4 μbar)



HC_3N (0.015 μbar)



New laboratory successfully working !!!

A&A 626, A34 (2019)
https://doi.org/10.1051/0004-6361/201935197

Astronomy & Astrophysics

Broad-band high-resolution rotational spectroscopy for laboratory astrophysics★

J. Cernicharo[1], J. D. Gallego[2], J. A. López-Pérez[2], F. Tercero[2], I. Tanarro[3], F. Beltrán[2], P. de Vicente[2], K. Lauwaet[4,5], B. Alemán[4,6], E. Moreno[1], V. J. Herrero[3], J. L. Doménech[3], S. I. Ramírez[1,7], C. Bermúdez[1], R. J. Peláez[3], M. Patino-Esteban[2], I. López-Fernández[2], S. García-Álvaro[2], P. García-Carreño[2], C. Cabezas[1], I. Malo[2], R. Amils[2], J. Sobrado[8], C. Diez-González[2], J. M. Hernandéz[2], B. Tercero[2], G. Santoro[4], L. Martínez[4], M. Castellanos[1], B. Vaquero Jiménez[2], J. R. Pardo[1], L. Barbas[2], J. A. López-Fernández[2], B. Aja[9], A. Leuther[10], and J. A. Martín-Gago[4]

Conclusions

1. Technique very useful to detect molecular species with great **sensitivity** and measure their spectral frequencies with high **accuracy**, allowing to derive their rotational constants with large **precision**.

2.- It allows to detect **unstable products of astronomical interest** in **cold plasmas** with complex precursor mixtures, and contribute to the identification of their kinetic processes.

3.- These experiments open new and very encouraging opportunities to laboratory astrophysics and to possible **collaborations between astronomers and plasma specialists**.

Work in progress

1. Laboratory spectra and astronomical search of gases and vapors not previously studied. *Cabezas et al, A&A 629, A35 (2019)*

2.- DC hollow cathode discharges (instead RF) to favor the study of ions.

3.- Photo-chemistry experiments with VUV lamps.

4.- Surface chemistry on ices of astrophysical interest.

Thank you very much for your attention!