# Submm Astronomy and Technology

# Evolution and Future Perspectives


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# Outline of Presentation

1. Introduction: Characteristics FIR/Submm Region for Astronomy and Astrophysics

2. A) Past IR/submm/mm observing facilities and some associated highlights: space missions in evolution
   B) Astrochemistry coming of age

3. Submm/mm Technology and Astronomy
   a cybernetic unity in the early development phase

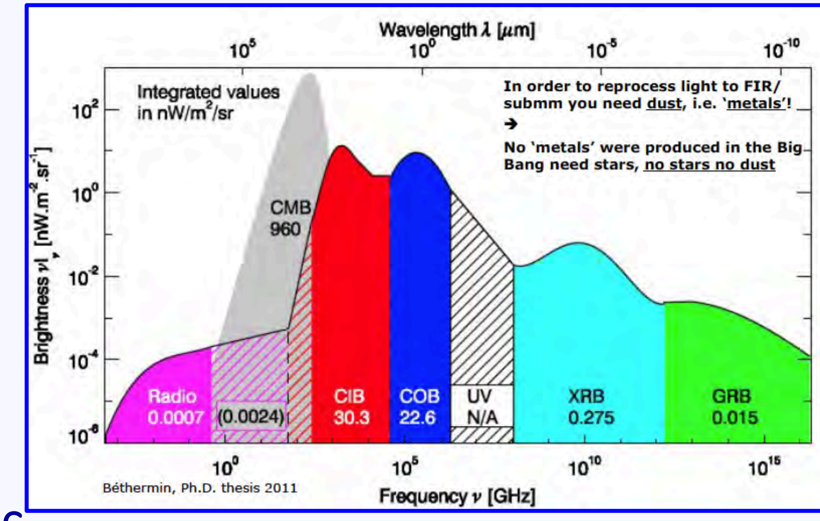
4. Past IR/submm/mm observing facilities and some associated highlights: space and ground-based

5. Desired technical requirements for next submm projects/missions

6. Potential future projects/space missions

8. Summary

# Astronomy in the Mm/Submm Range: the Cool Universe

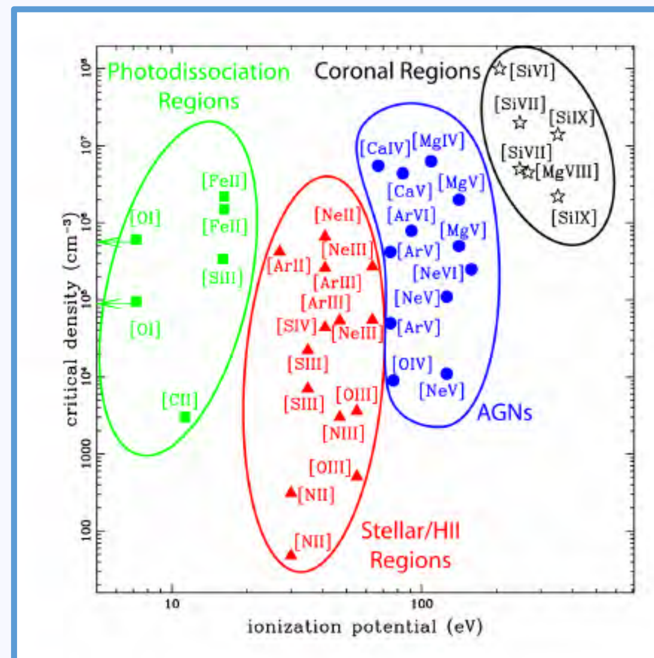



## Spectral coverage for:

- Black-bodies 5-100 K
  continuum radiation from dust grains (re-radiating)
- Gaseous clouds excitation 10-few100 K
  - Atomic/ionic lines
  - Molecular Universe a.o. $H_2$ ,CO, $H_2O$, CII, etc
- IR gal & ISM SED peaks, out to high Z and Cosmic Background

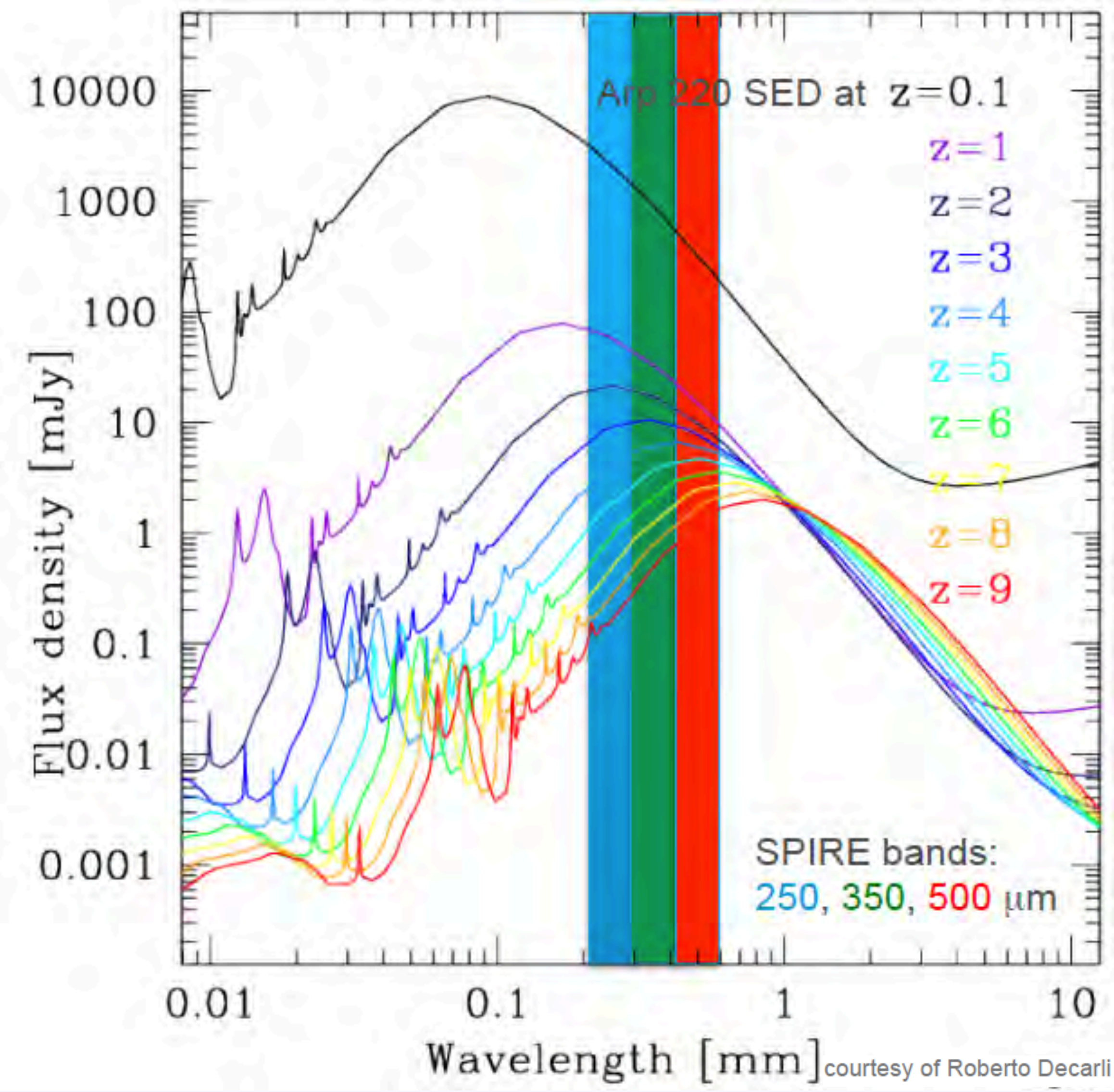
## Anno 20xx: key questions for (F)IR missions:

- First Stars/First Galaxies and Evolution of Galaxies over Cosmic Time
  **"How the Universe started and works"**
- Evolution and Processing (Lifecycle) of Inter-Stellar Matter
  **"Other solar systems, characterization/how many"**
- Understanding Planetary Systems: Disks and Habitable Worlds
  **"Ingredients for habitable exoplanets/ Are we alone?"**




FIR toolbox

# The 1 mm window at the early Universe




courtesy of Roberto Decarli

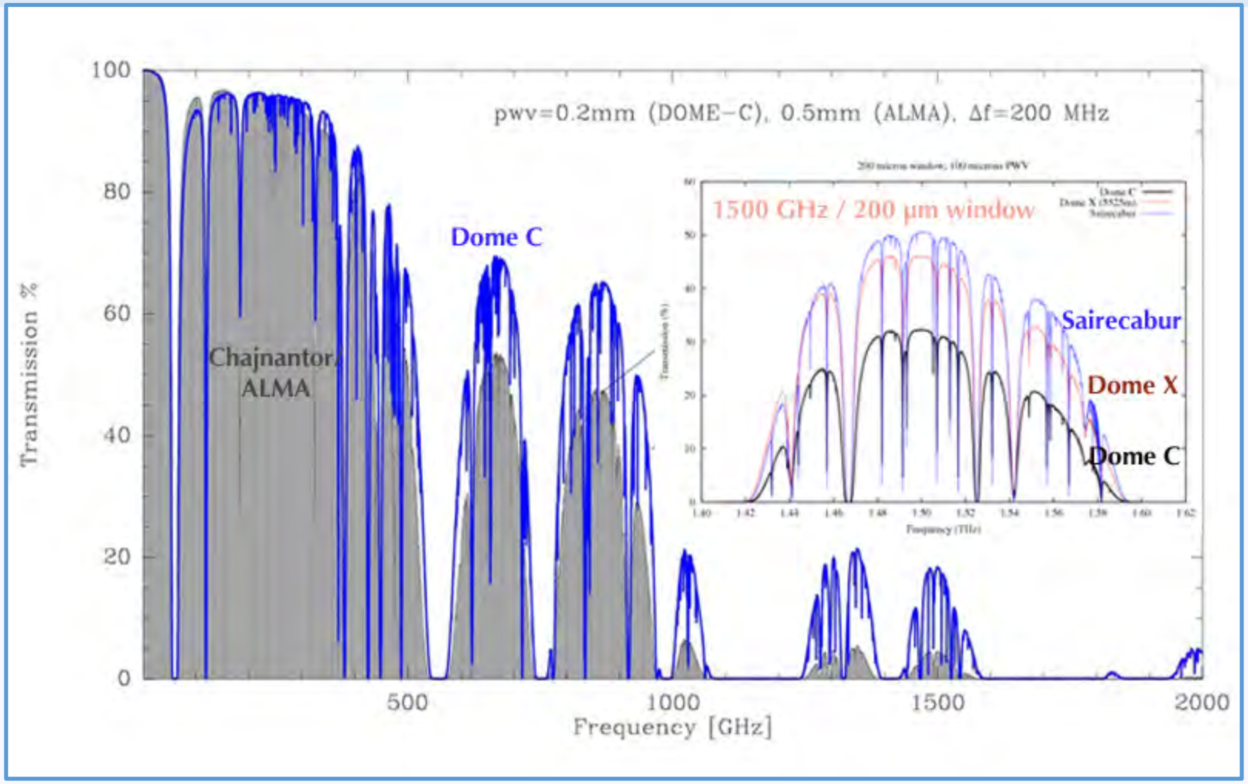
# !! The Birth of ASTRO-CHEMISTRY !!

## More than 200 different molecules identified in the ISM/CMS (not including isotopologues)(credit CMDS)

| 2 atoms | | 3 atoms | | 4 atoms | 5 atoms | 6 atoms | 7 atoms | 8 atoms | 9 atoms | ≥ 10 atoms |
|---|---|---|---|---|---|---|---|---|---|---|
| $H_2$ | HD | $C_3$ | AlNC | $c\text{-}C_3H$ | C5 | $C_5H$ | $C_6H$ | $CH_3C_3N$ | $CH_3C_4H$ | $CH_3C_5N$ |
| AlF | FeO ? | $C_2H$ | SiNC | $l\text{-}C_3H$ | $C_4H$ | $l\text{-}H_2C_4$ | $CH_2CHCN$ | $HCOOCH_3$ | $CH_3CH_2CN$ | $(CH_3)_2CO$ |
| AlCl | $O_2$ | $C_2O$ | HCP | $C_3N$ | $C_4Si$ | [illegible] | $CH_3C_2H$ | $CH_3COOH$ | $(CH_3)_2O$ | $(CH_2OH)_2$ |
| $C_2$ | $CF^+$ | $C_2S$ | CCP | $C_3O$ | $l\text{-}C_3H_2$ | $CH_3CN$ | $HC_5N$ | $C_7H$ | $CH_3CH_2OH$ | $CH_3CH_2CHO$ |
| CH | [illegible] | $CH_2$ | AlOH | $C_3S$ | $c\text{-}C_3H_2$ | $CH_3NC$ | $CH_3CHO$ | [illegible] | $HC_7N$ | $HC_9N$ |
| $CH^+$ | [illegible] | HCN | $H_2O^+$ | $C_2H_2$ | $H_2CCN$ | $CH_3OH$ | $CH_3NH_2$ | $CH_2CCHCHO$ | $C_8H$ | $CH_3C_6H$ |
| CN | AlO | HCO | $H_2Cl^+$ | $NH_3$ | $CH_4$ | $CH_3SH$ | $c\text{-}C_2H_4O$ | $HC_6H$ | $CH_3CONH_2$ | $C_2H_5OCHO$ |
| CO | $OH^+$ | $HCO^+$ | KCN | HCCN | $HC_3N$ | $HC_3NH^+$ | [illegible] | $CH_2CHCHO$ ? | $C_8H^-$ | $CH_3OCOCH_3$ |
| $CO^+$ | $CN^-$ | $HCS^+$ | FeCN | $HCNH^+$ | $HC_2NC$ | $HC_2CHO$ | $C_6H^-$ | $CH_2CCHCN$ | $C_3H_6$ | $c\text{-}C_6H_6$ |
| CP | $SH^+$ | $HOC^+$ | $O_2H$ | HNCO | HCOOH | $NH_2CHO$ | | $H_2NCH_2CN$ | $CH_3CH_2SH$ | $n\text{-}C_3H_7CN$ |
| SiC | SH | $H_2O$ | $TiO_2$ | HNCS | $H_2CNH$ | $C_5N$ | | $CH_3CHNH$ | | $i\text{-}C_3H_7CN$ |
| HCl | $HCl^+$ | $H_2S$ | $C_2N$ | $HOCO^+$ | $H_2C_2O$ | $l\text{-}HC_4H$ | | | | $HC_{11}N$ |
| KCl | TiO | HNC | $Si_2C$ | $H_2CO$ | $H_2NCN$ | $l\text{-}HC_4N$ | | | | $C_{60}$ |
| NH | $ArH^+$ | HNO | | $H_2CN$ | $HNC_3$ | $c\text{-}H_2C_3O$ | | | | $C_{70}$ |
| NO | $NO^+$ ? | MgCN | | $H_2CS$ | $SiH_4$ | $H_2CCNH$ ? | | | | |
| NS | | MgNC | | $H_3O^+$ | $H_2COH^+$ | $C_5N^-$ | | | | |
| NaCl | | $N_2H^+$ | | $c\text{-}SiC_3$ | $C_4H^-$ | HNCHCN | | | | |
| OH | | $N_2O$ | | $CH_3$ | HCOCN | | | | | |
| PN | | NaCN | | $C_3N^-$ | HNCNH | | | | | |
| SO | | OCS | | $PH_3$ | $CH_3O$ | | | | | |
| $SO^+$ | | $SO_2$ | | HCNO | $NH_4^+$ | | | | | |
| SiN | | $c\text{-}SiC_2$ | | HSCN | $H_2NCO^+$ ? | | | | | |
| SiO | | $CO_2$ | | $H_2O_2$ | $HCCNH^+$ | | | | | |
| SiS | | $NH_2$ | | $C_3H^+$ | | | | | | |
| CS | | $H_3^+$ | | HMgNC | | | | | | |
| HF | | SiCN | | HCCO | | | | | | |

- ✶ Cations (positively-charged)
- ✶ Anions (negatively-charged)
- ✶ Radicals (unpaired electrons)
- ✶ Unsaturated carbon chains
- ✶ Structural isomers
- ✶ Complex organic molecules (e.g., ethanol, acetone, ethylene glycol)
- ✶ > 180 and counting ...

# Atmospheric transmission in Submm Range:
# ! **Ground and Space observatories needed!**




Submm technology development had continues verification of concept
Submm Astronomy discoveries pushed further development

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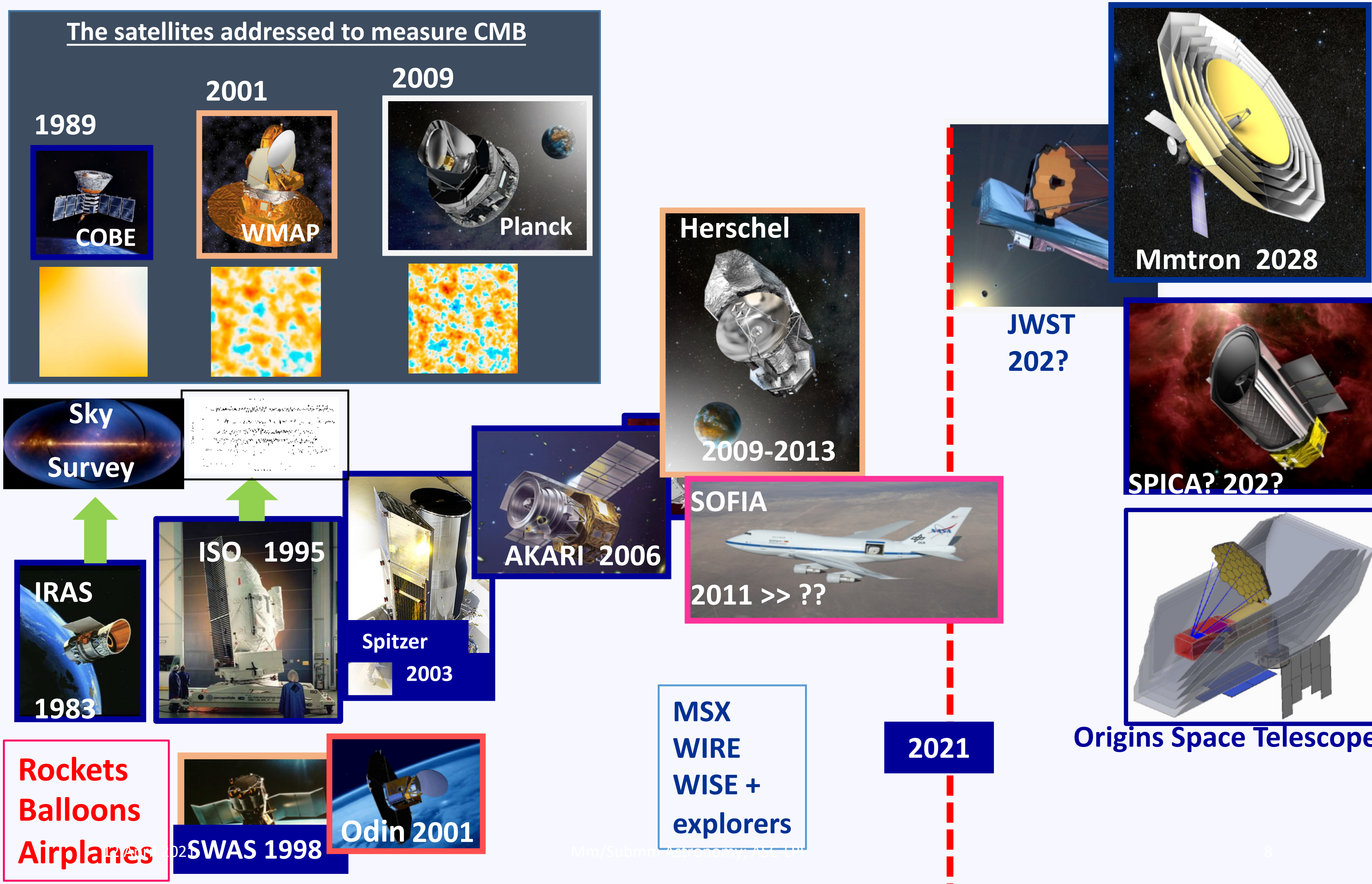
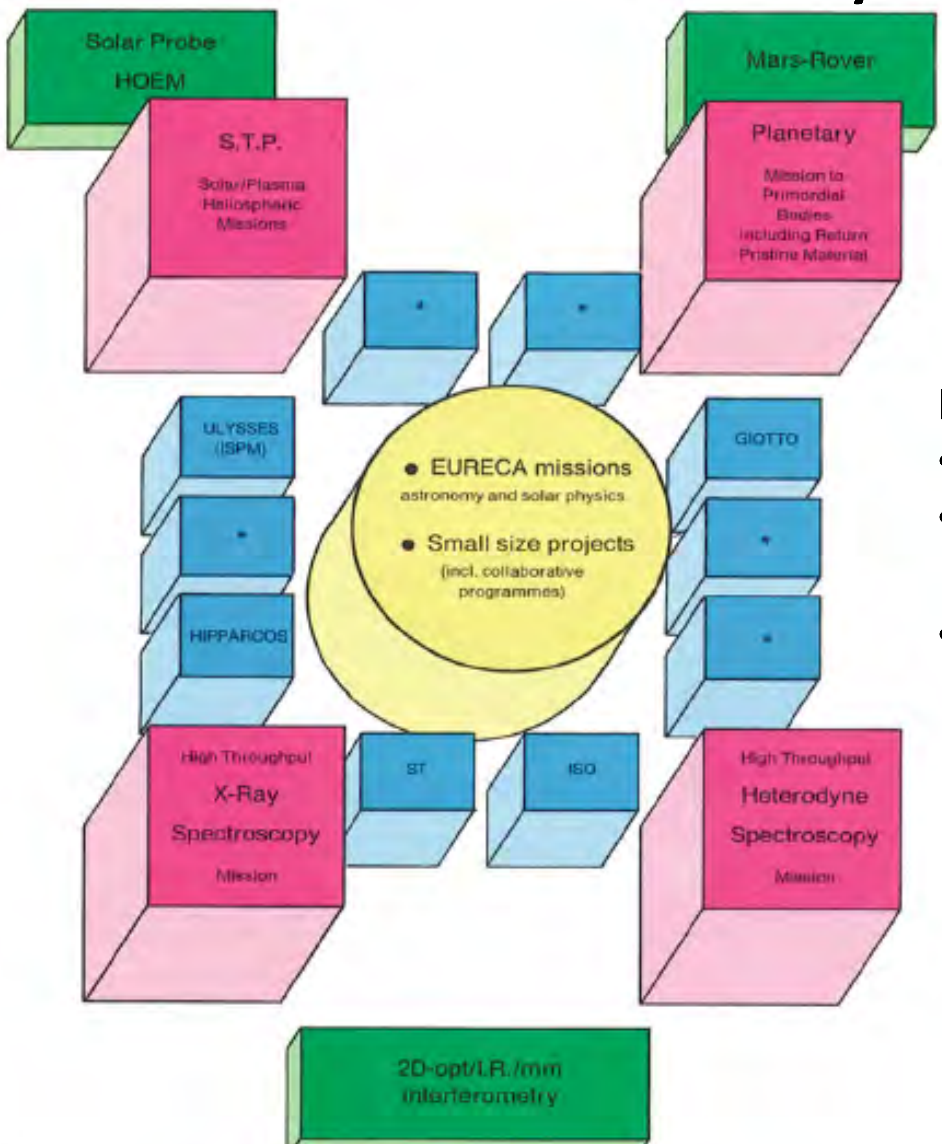
# FIR/Submm/Mm Space Projects for Cosmology and Astrophysics; an evolution of capabilities!



# Horizon 2000, the ESA long-term program: conceived in the years 1982-1984




*The European Long Term Programme*

In ESA program selection processes:

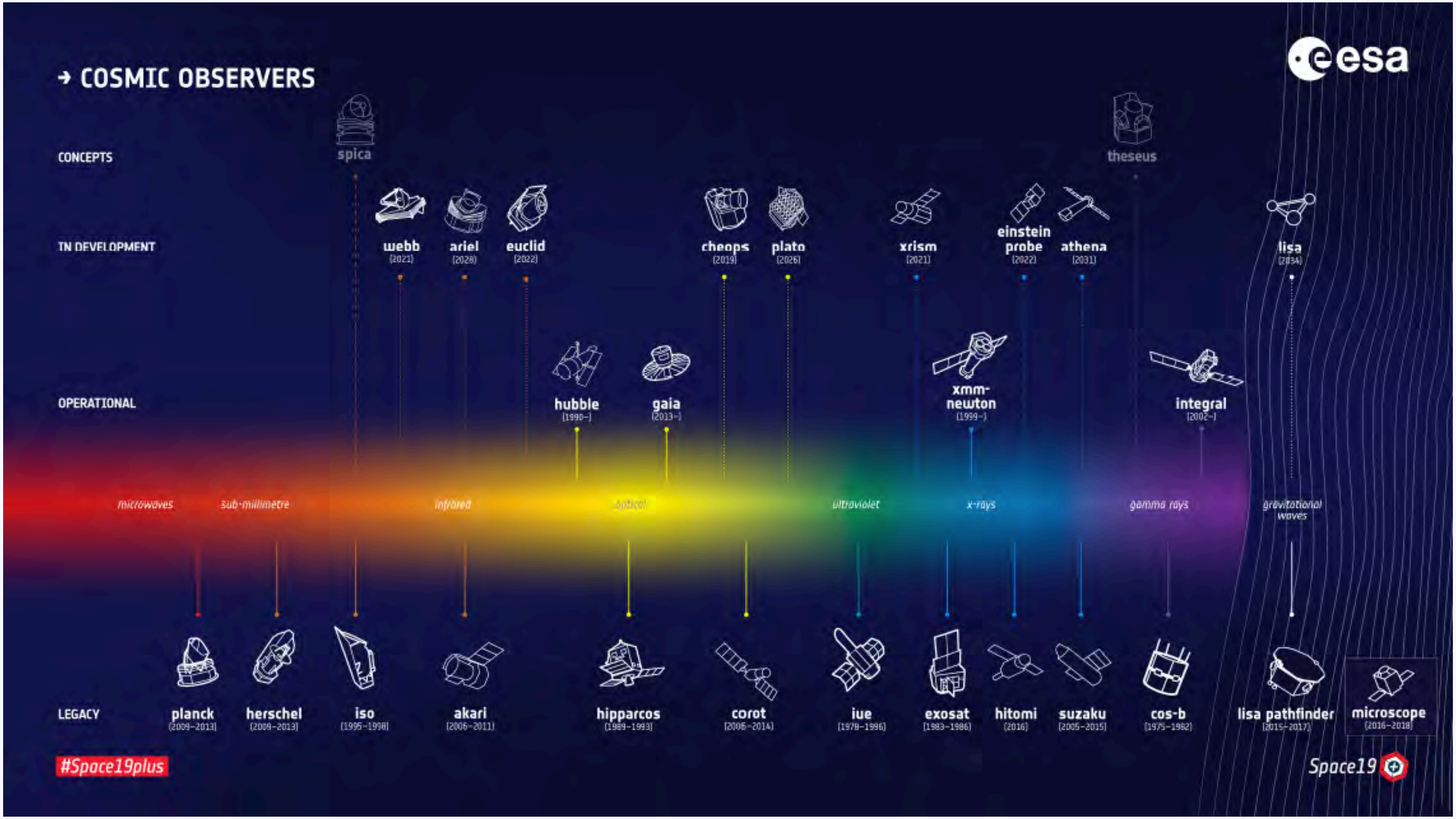
**Science is the most important parameter!!**

H2000 made with:

- Extensive science community consultation
- Science community representatives in selection/decision process
- Scientists strong involvement in
  - instrumentation selection and
  - design and implementation
  - to keep science focus

Projects are not engineering toys

# ESA's Fleet of Cosmic Observers



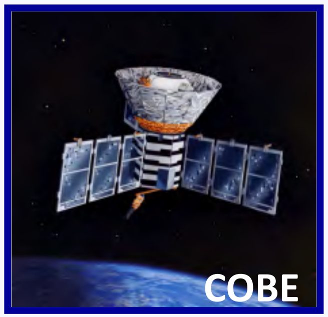
# Early History:
# Rocket Balloon Aircraft



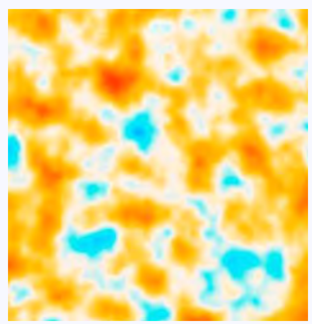
Figure 18. The HI STAR payload being mated to the Aerobee 170 before being mounted on the Nike booster in the tower. Note the plastic bagging around the payload for contamination control.

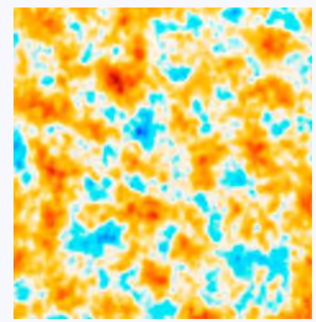


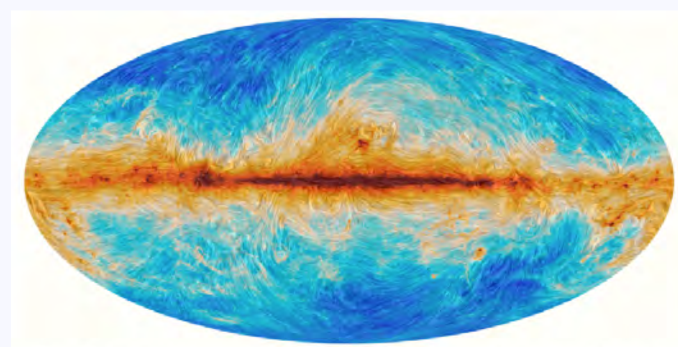
# Space Cosmic Background Missions
# $10^{-7}$ K relative accuracy, thanks to redundant observations





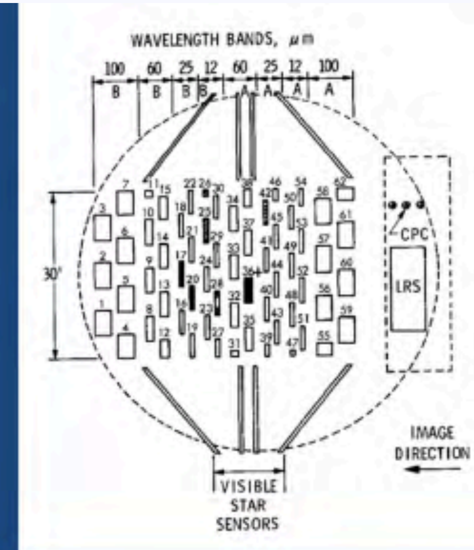



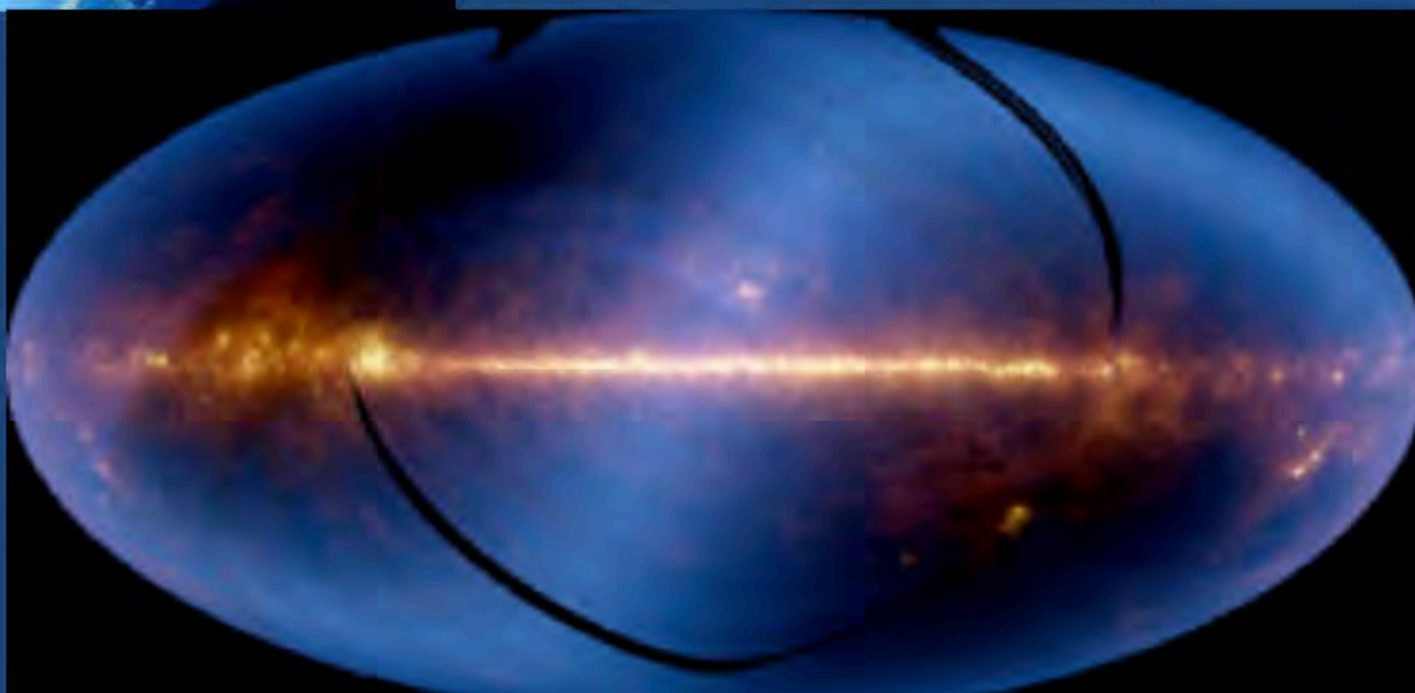



The Galactic magnetic field as revealed by Planck

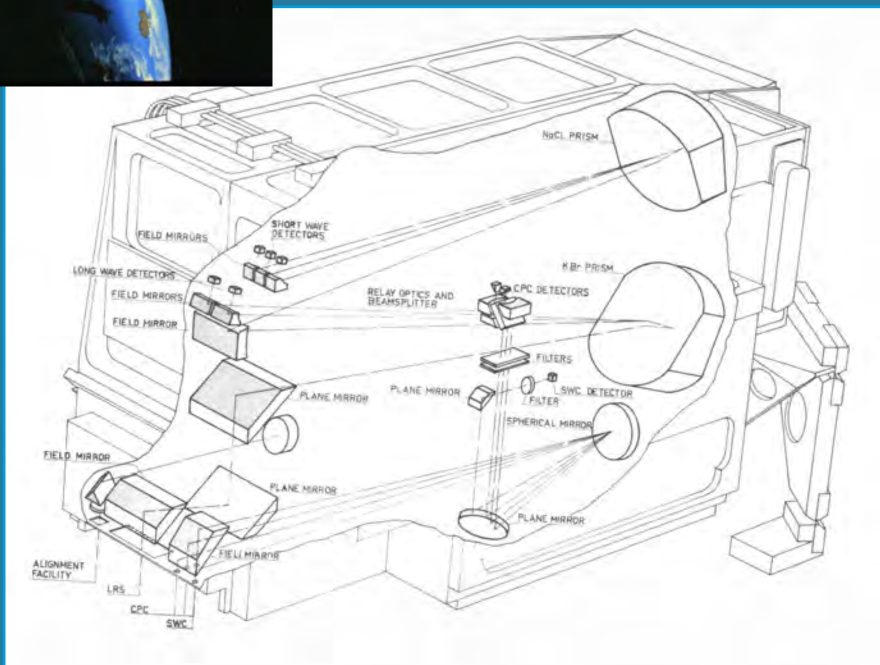
# IRAS 1983

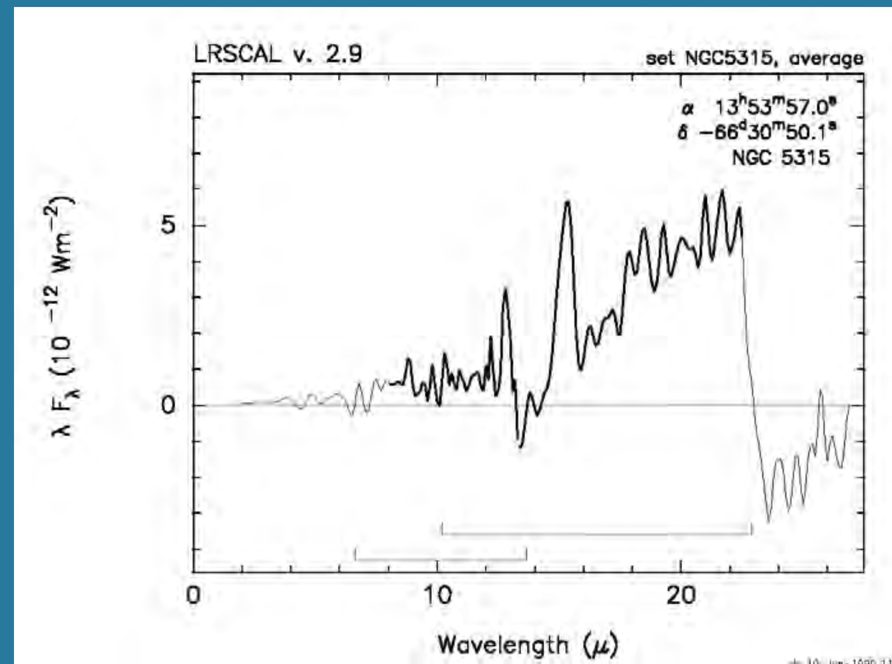
ALL SKY:
12,25,60,100 microns;
LRS and CPC



# – Low Resolution Spectrometer (LRS) results: the ISO spectroscopy stimulus



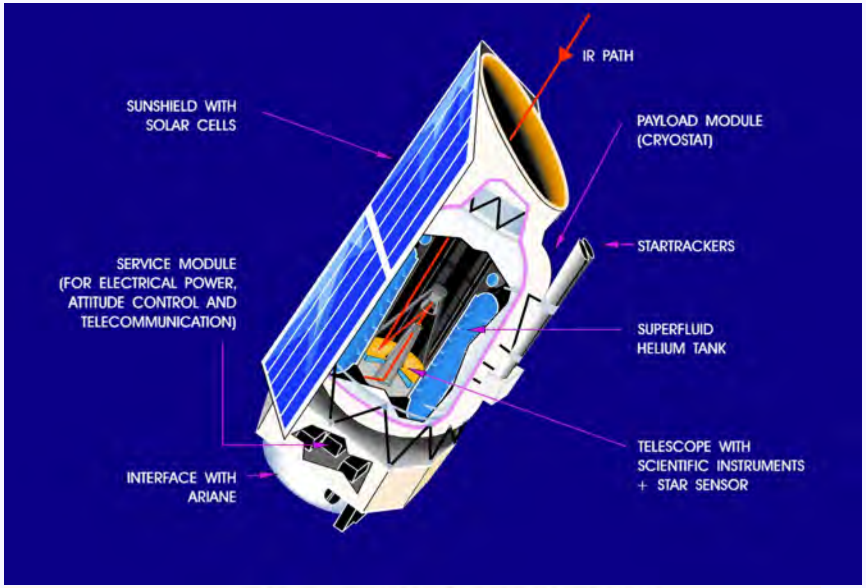



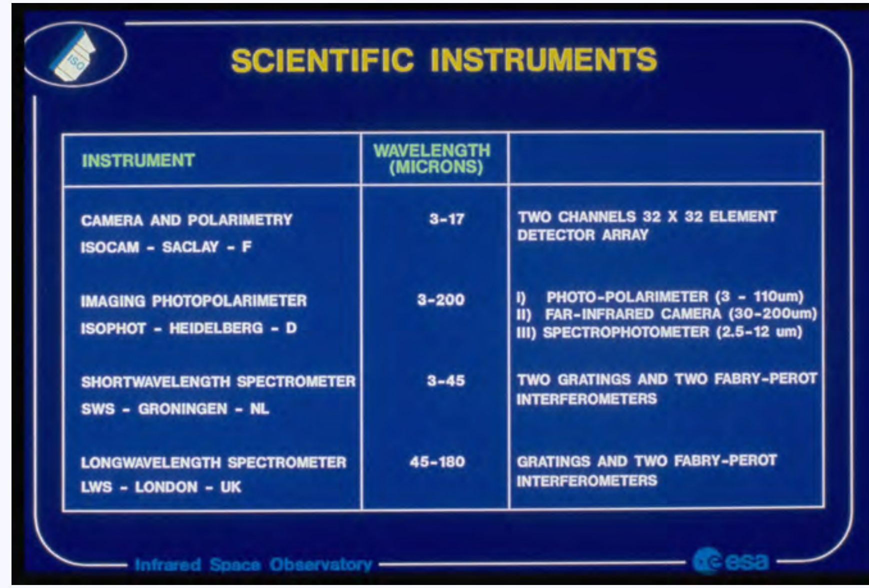

**IRAS-LRS: slit-less prism spectrometer,**

**Spectrum build-up by sky scanning**

**Wavelength range: 8-24 micron; Resolution: ~20-40**

# ISO satellite and its instruments

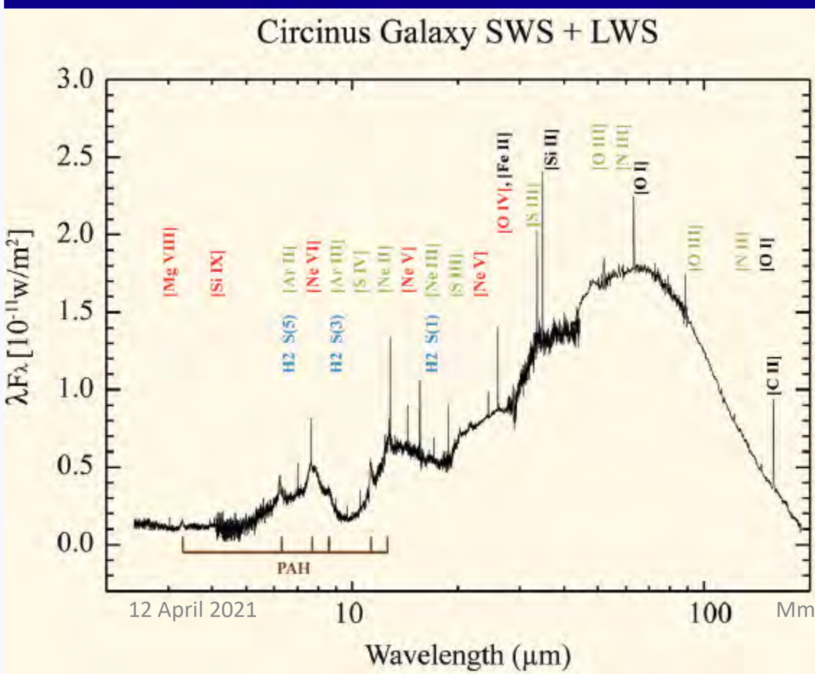


SCIENTIFIC INSTRUMENTS

| INSTRUMENT | WAVELENGTH (MICRONS) | |
|---|---|---|
| CAMERA AND POLARIMETRY ISOCAM - SACLAY - F | 3-17 | TWO CHANNELS 32 X 32 ELEMENT DETECTOR ARRAY |
| IMAGING PHOTOPOLARIMETER ISOPHOT - HEIDELBERG - D | 3-200 | I) PHOTO-POLARIMETER (3 - 110um) II) FAR-INFRARED CAMERA (30-200um) III) SPECTROPHOTOMETER (2.5-12 um) |
| SHORTWAVELENGTH SPECTROMETER SWS - GRONINGEN - NL | 3-45 | TWO GRATINGS AND TWO FABRY-PEROT INTERFEROMETERS |
| LONGWAVELENGTH SPECTROMETER LWS - LONDON - UK | 45-180 | GRATINGS AND TWO FABRY-PEROT INTERFEROMETERS |

Infrared Space Observatory — esa

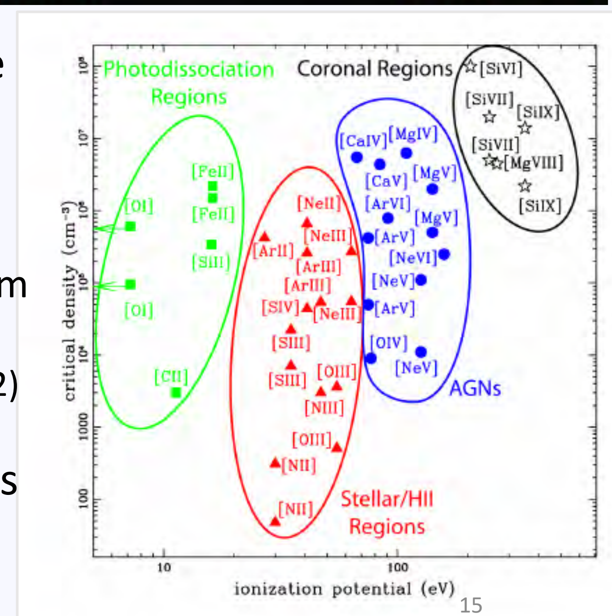



ISO demonstrated the power of the “Far-IR diagnostic toolbox”

Note: most AGN diagnostic lines in 2-40µm band.

(Spinoglio and Malkan, 1992)

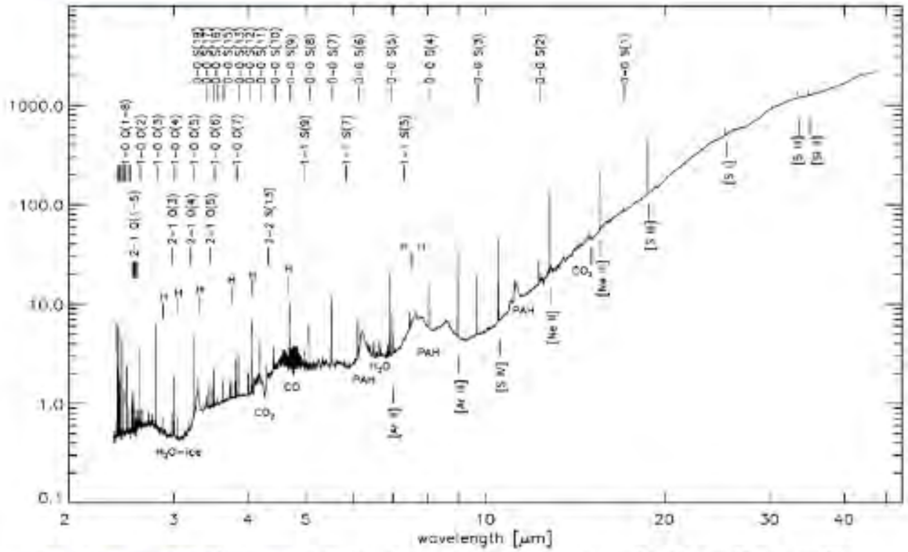
Also with PAH features



# ISO unveiled the molecular Universe

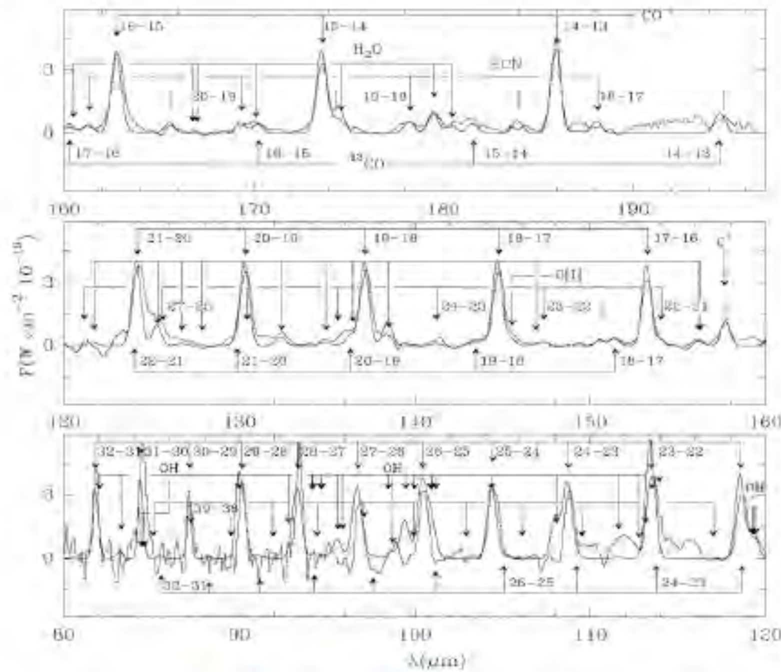
**Molecular Lines**

- **Electronic state**: visible, UV (ISM is generally not energetic enough to excite the electronic states of molecules. Observed in absorption in the line of sight of hot stars: $H_2$, OH, NH, CH, $CH^+$, CN, CO, $C_2$, $C_3$, ...)
- **Rotational state**: radio and millimeter-wave
- **Vibrational state**: infrared (stretching mode, bending mode; Low-energy bending modes of molecules: Far-IR; Ro-vibrational, High-energy rotational transitions: Far-IR ~ sub-mm)




2 - 40 μm (*ISO*) Rosenthal+ 2000 (Orion) : **mainly $H_2$ collisionally excited rotational lines at T~200-800K; and fine structure lines.**

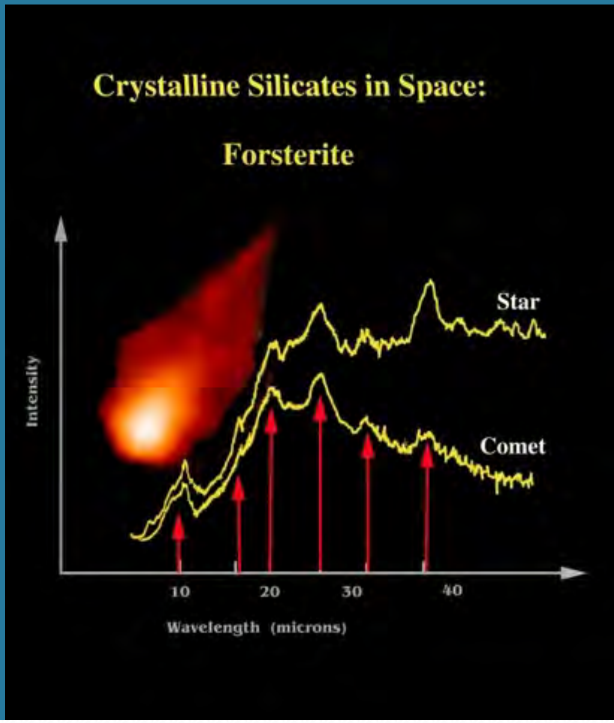
**Many molecular lines, and also many C-H, C-C stretching bending mode emission of PAH in mid-IR.**



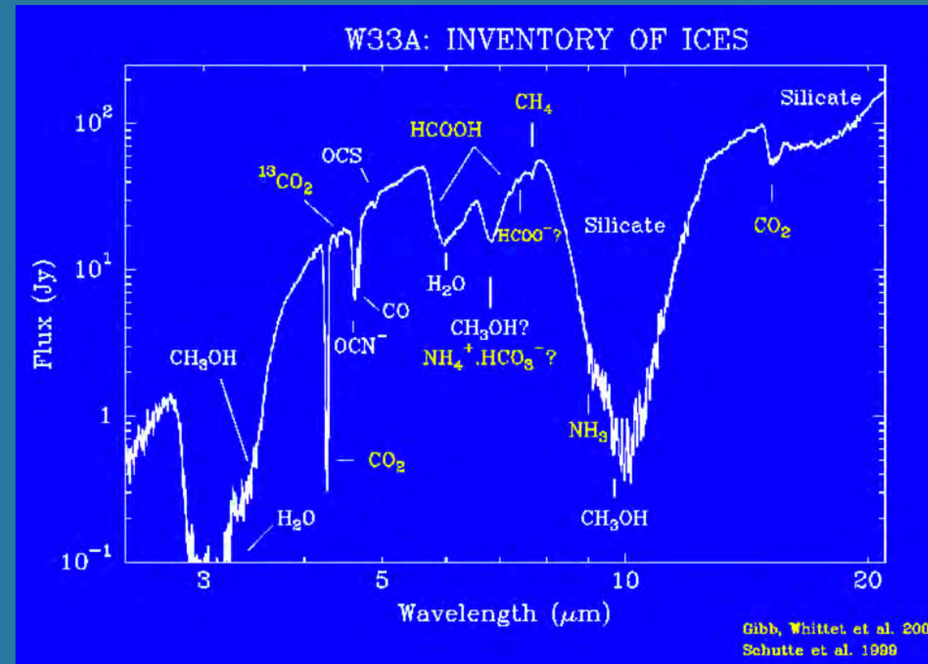

80 - 200 μm (*ISO*): Herpin+ 2000 (AFGL 618)

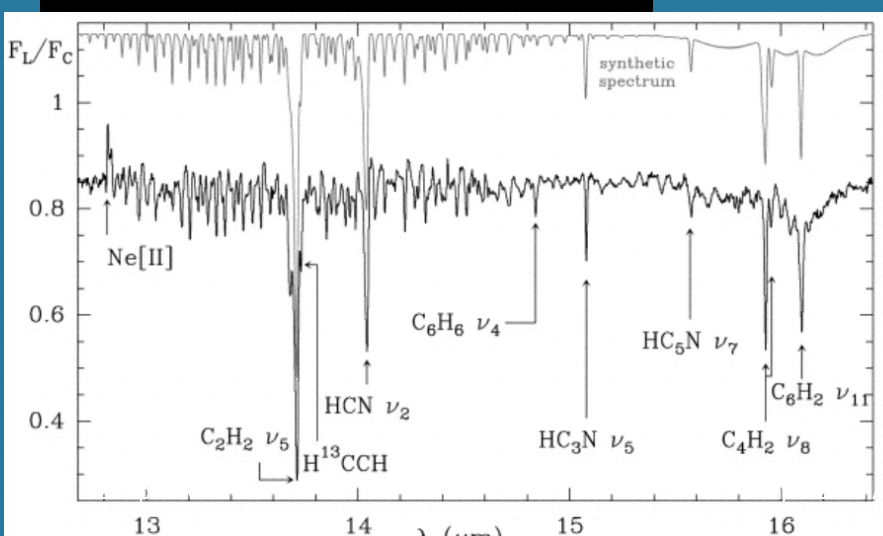
# ISO: iconic results

## Silicate "Revolution"




## Ices "Revolution"

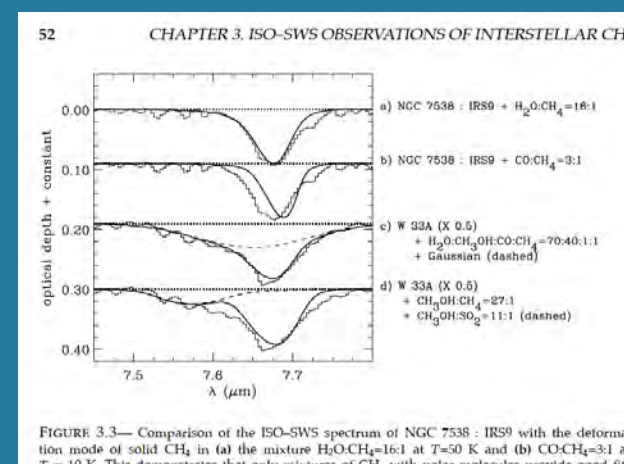


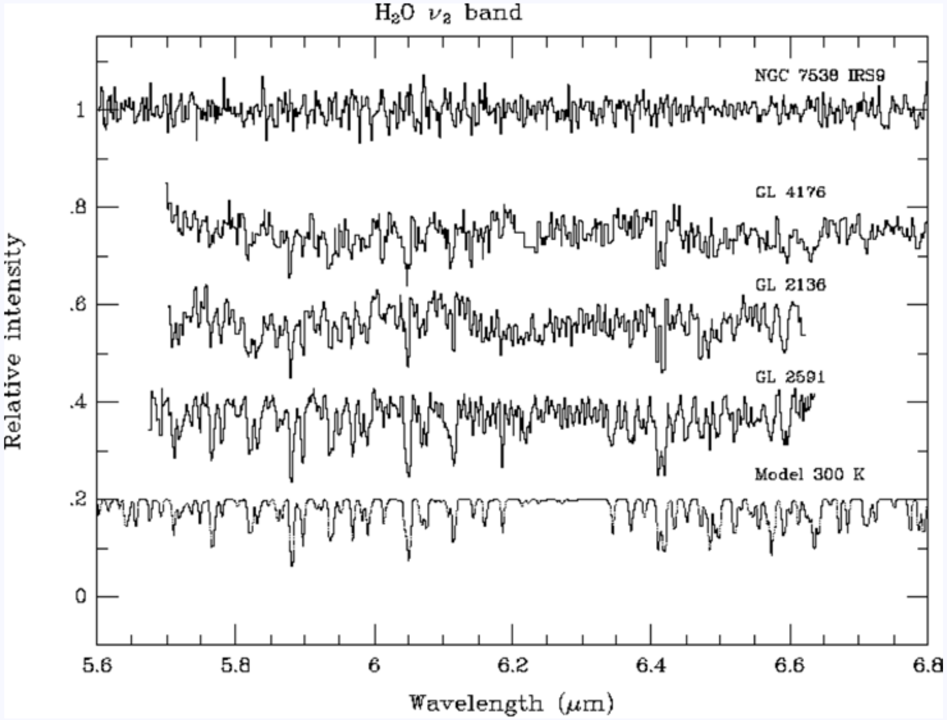

**Power of Modeling/ Experiments**

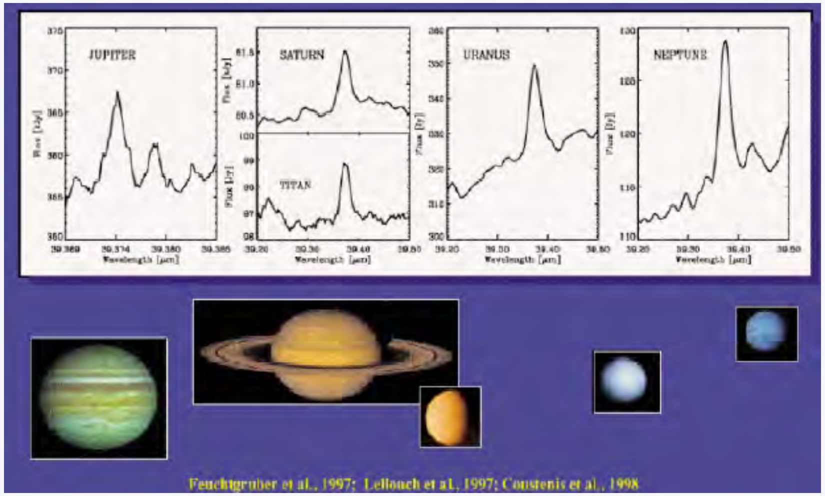
Pepe C.

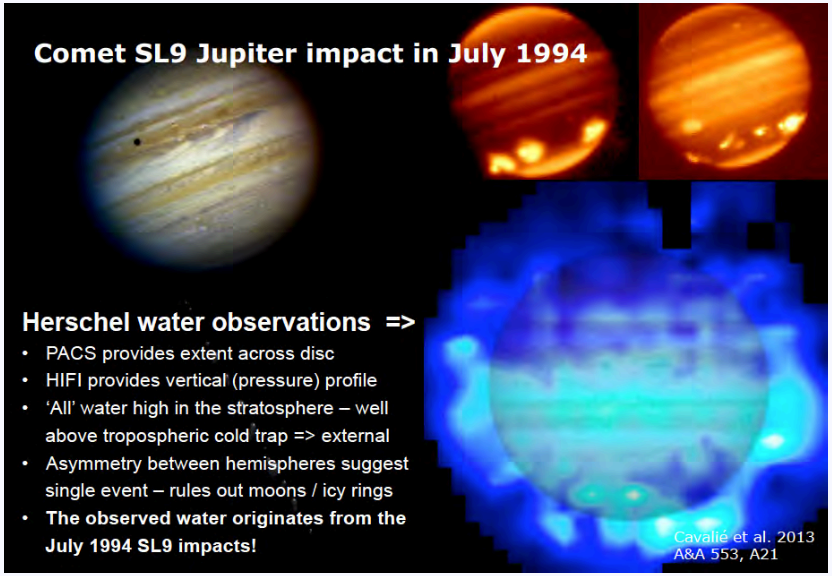
Adwin B.



# ISO: water, & water in the solar system




Herschel water Observations

# The rise of Astrochemistry? (Dalgarno’s definition)

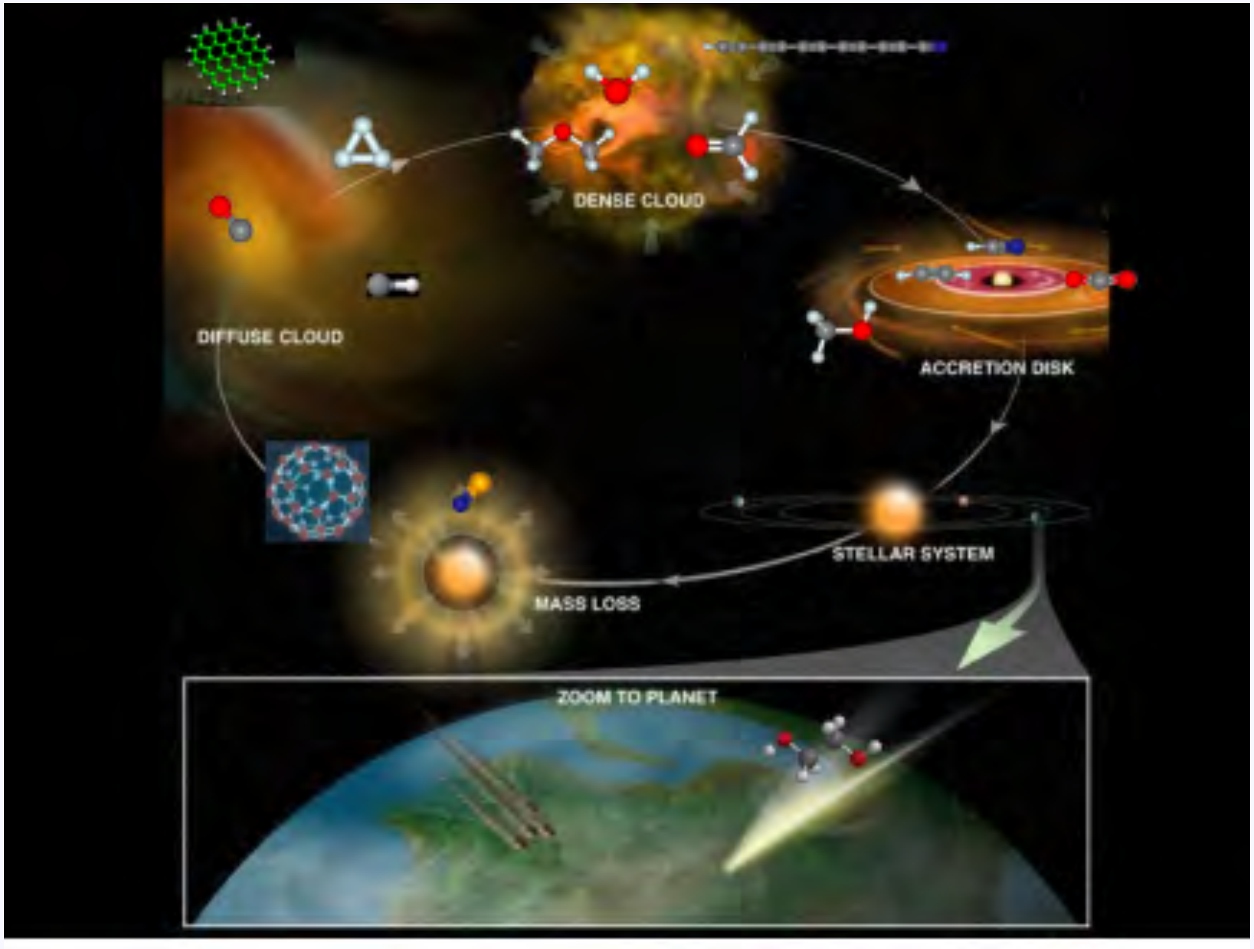
- ‘the study of the formation, destruction and excitation of molecules in astronomical environments and their influence on the structure, dynamics and evolution of astronomical objects’
- It requires experts
    - in theoretical and lab molecular spectroscopy;
    - in molecule formation an destruction;
    - In chemical (molecular)-physical models of ISM sites;
    - laboratory space-simulations;
    - In excitation and radiation processes, with parameters as collisional crosssections, excitation processes and rates,

# Study of Molecular Universe=Lifecycle of gas and dust in interstellar space

From submm observations to publication not simple

see: www.astrochymist.org

**Multi-Discipline Effort: Astro -Chemistry**

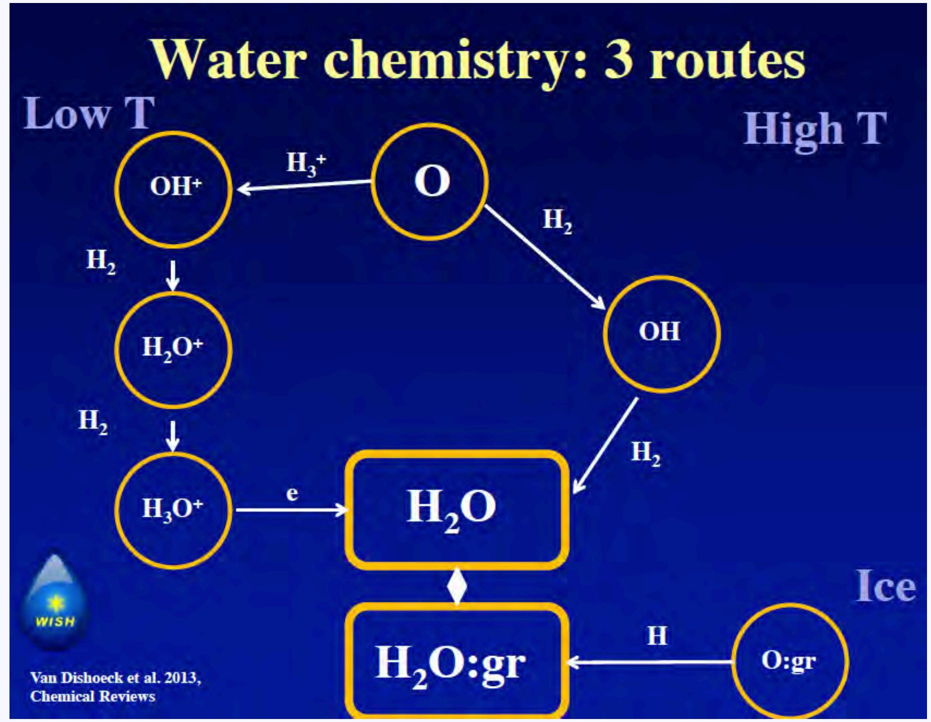



Kavli price 2018 for Astrophysics for Ewine van Dishoeck

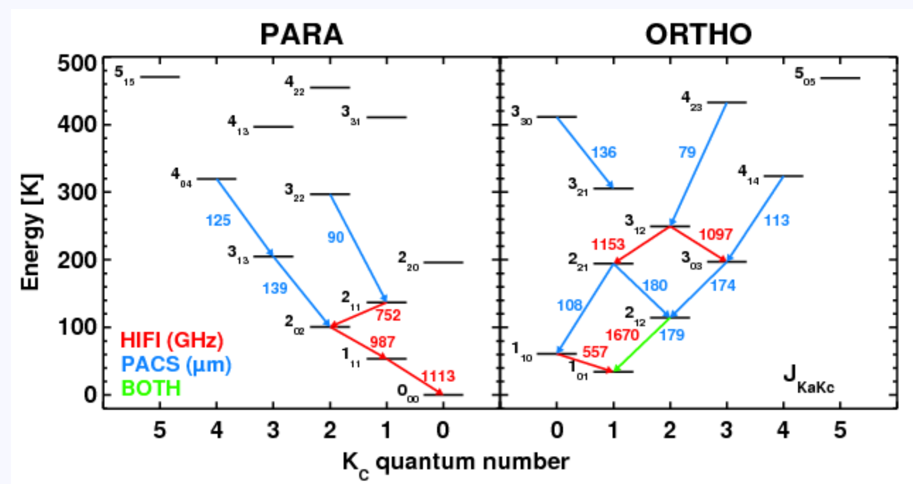
Bill Saxton

# The case of Water

**Summary of the main gas-phase and solid-state chemicalreactions leading to the formation and destruction of H2O:**
Three different chemical regimes can be distinguished:
(1) ion-molecule chemistry, which dominates
(2) gas-phase chemistry at low **T**;
2) high-temperature neutral-neutral chemistry; and
(3) solid-state chemistry.
The latter chemical scheme is based on the latest laboratory data by Ioppolo et al. (2010);

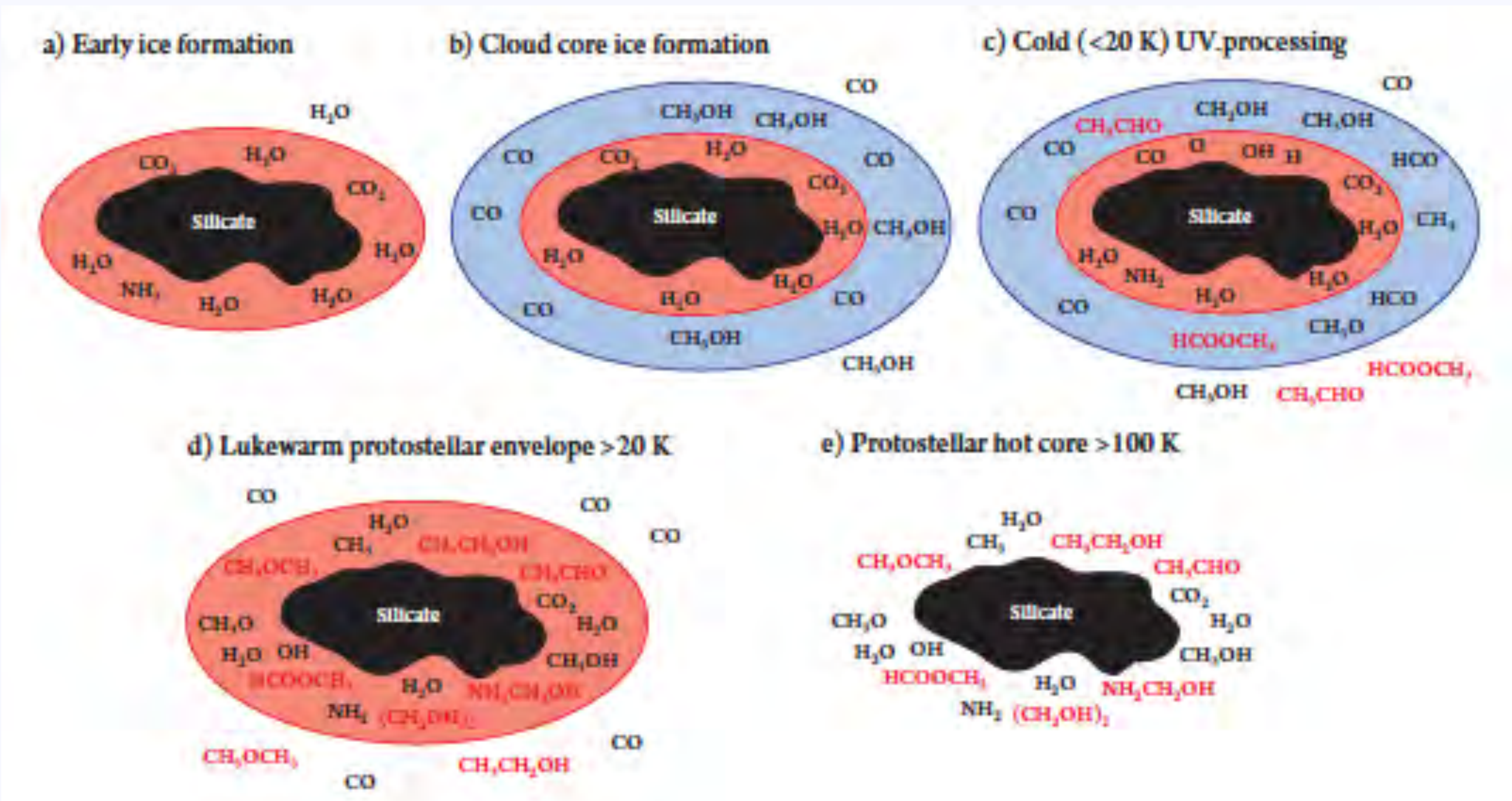



**Energy levels of ortho- and para-H2O**, with HIFI transitions (in gigahertz) and PACS transitions (in microns) observed.



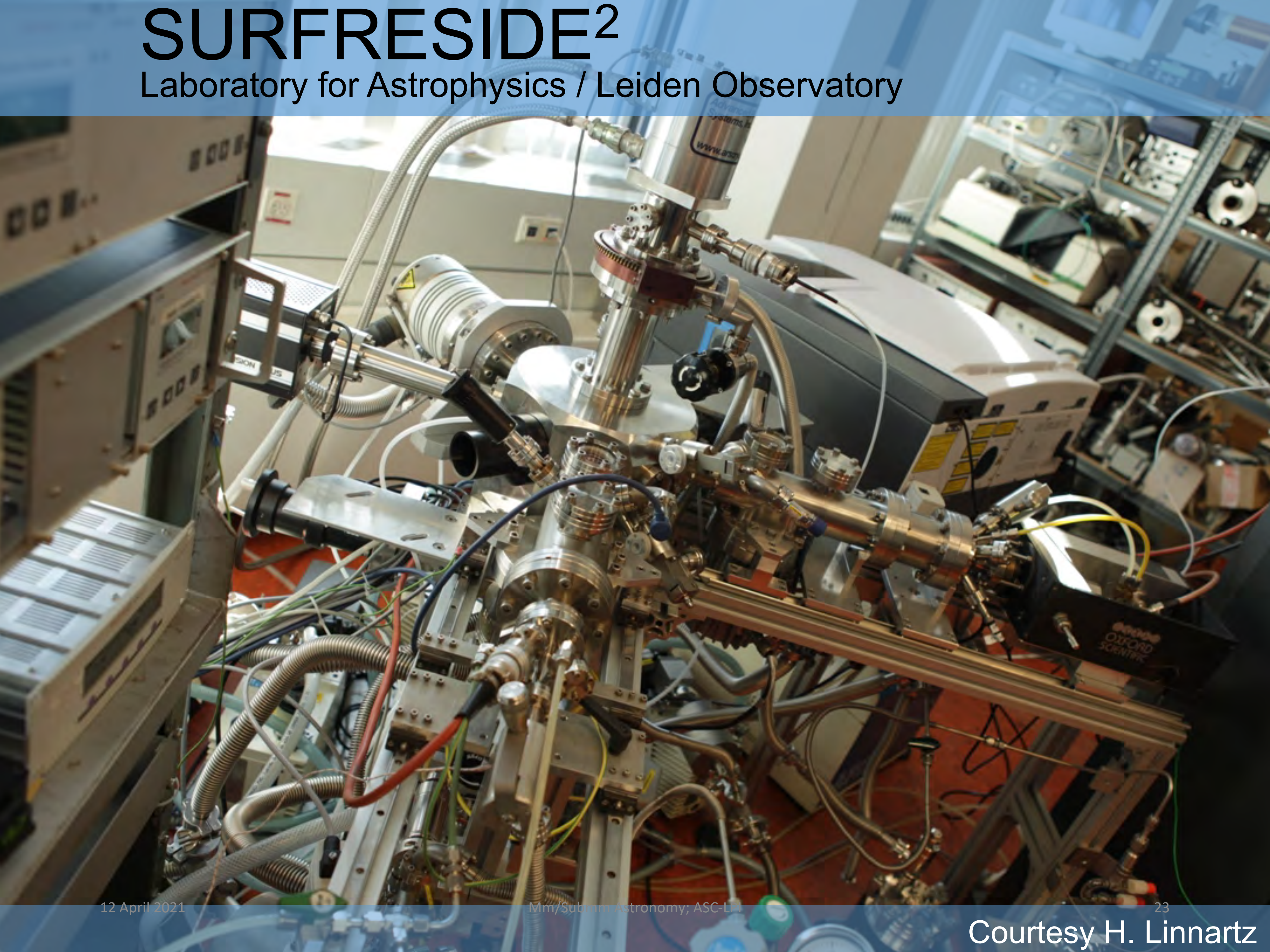
# Proposed evolution of ices during star formation and formation of complex molecules

Ewine F. van Dishoeck, Faraday Discussions 2014, 168, 9

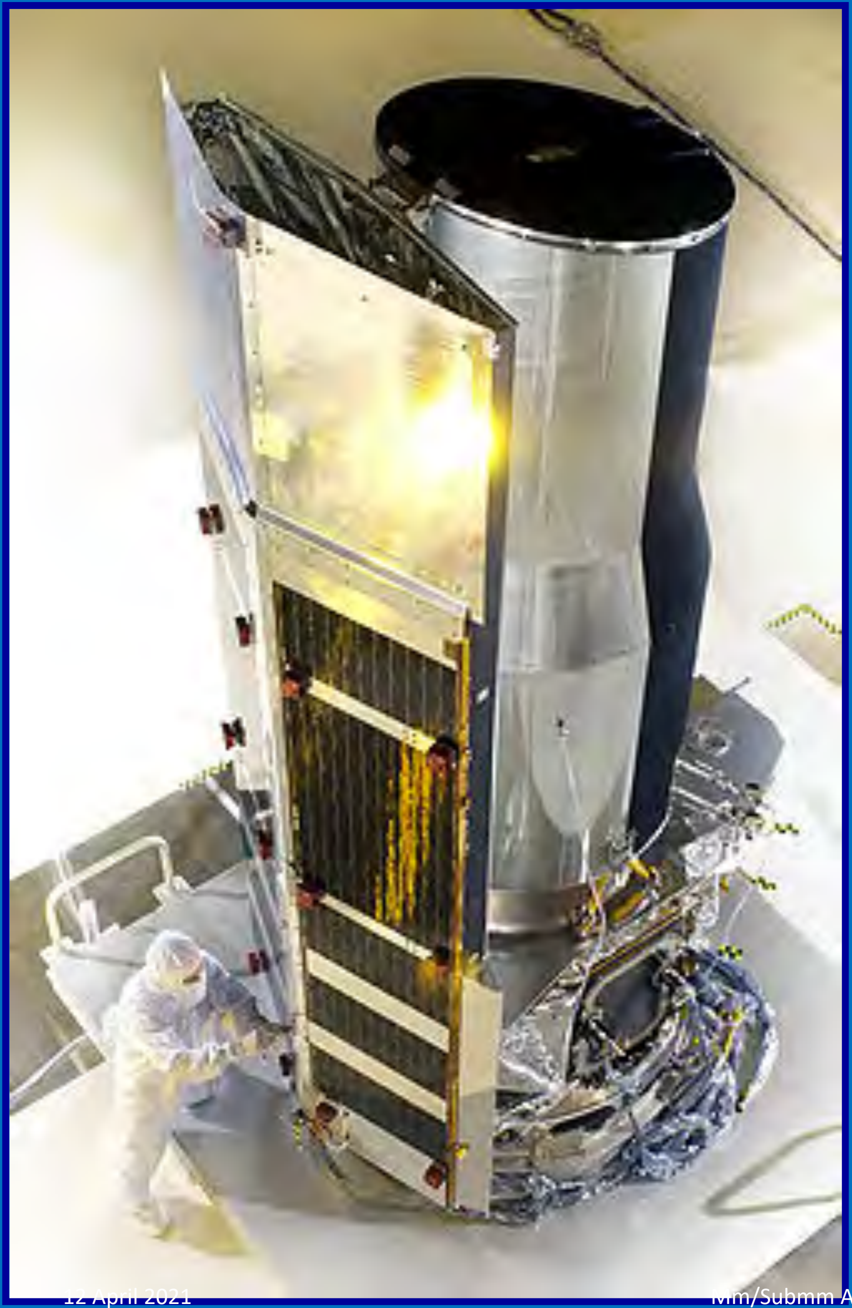


# SURFRESIDE$^2$

Laboratory for Astrophysics / Leiden Observatory



Courtesy H. Linnartz



# SPITZER

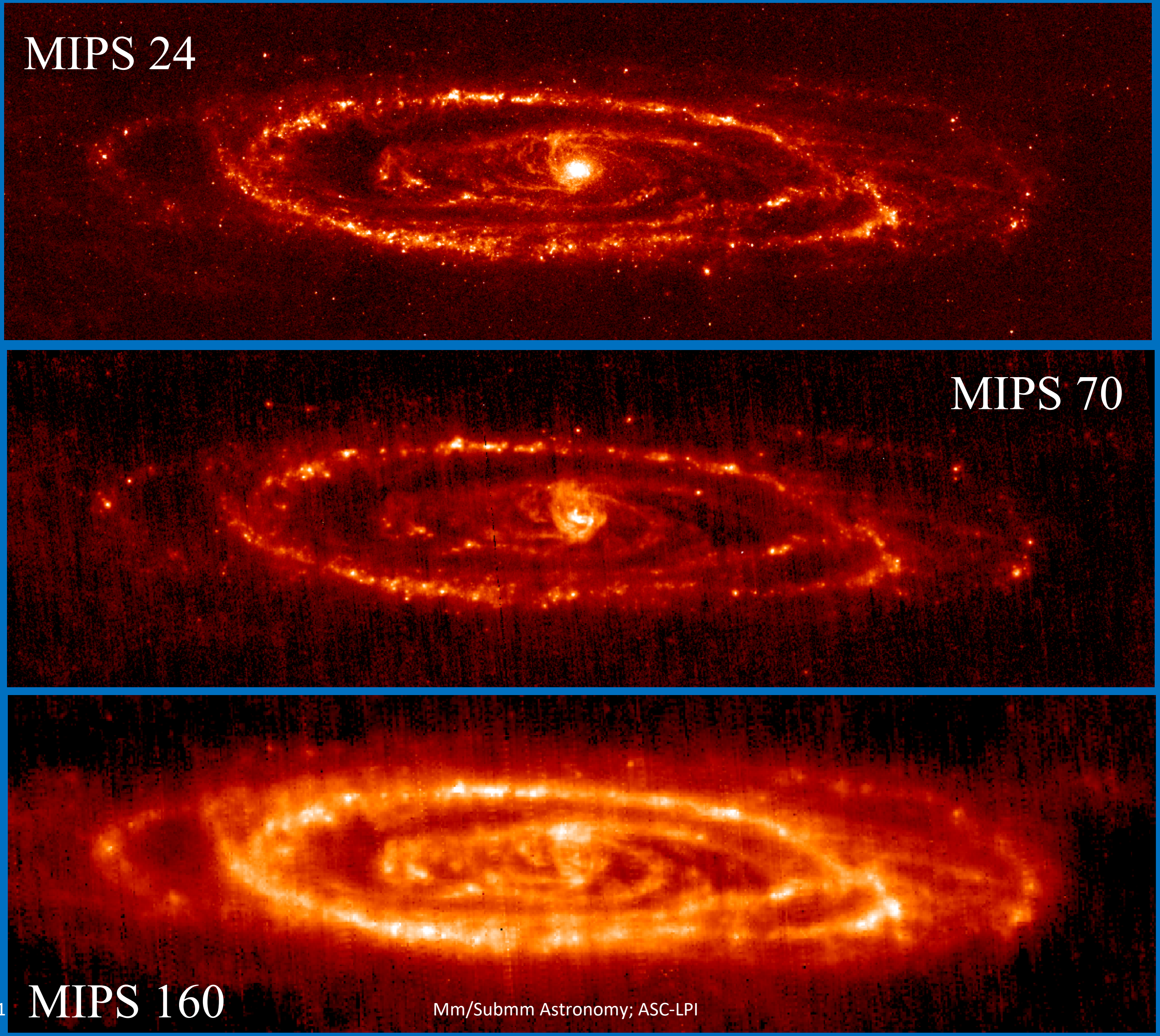
Wavelength Coverage:
3 - 180 microns

Telescope:
85 cm diameter
cooled to less 5.5 K

Diffraction Limit:
6.5 microns

# M31 - The Andromeda Galaxy

Size = 0.83 x 2.83 degrees



# Herschel (2009-2013) in a nutshell

**Large telescope**

- **Large (3.5 m) diameter aperture**
- **collecting area and resolution**

**‘New’ spectral window**

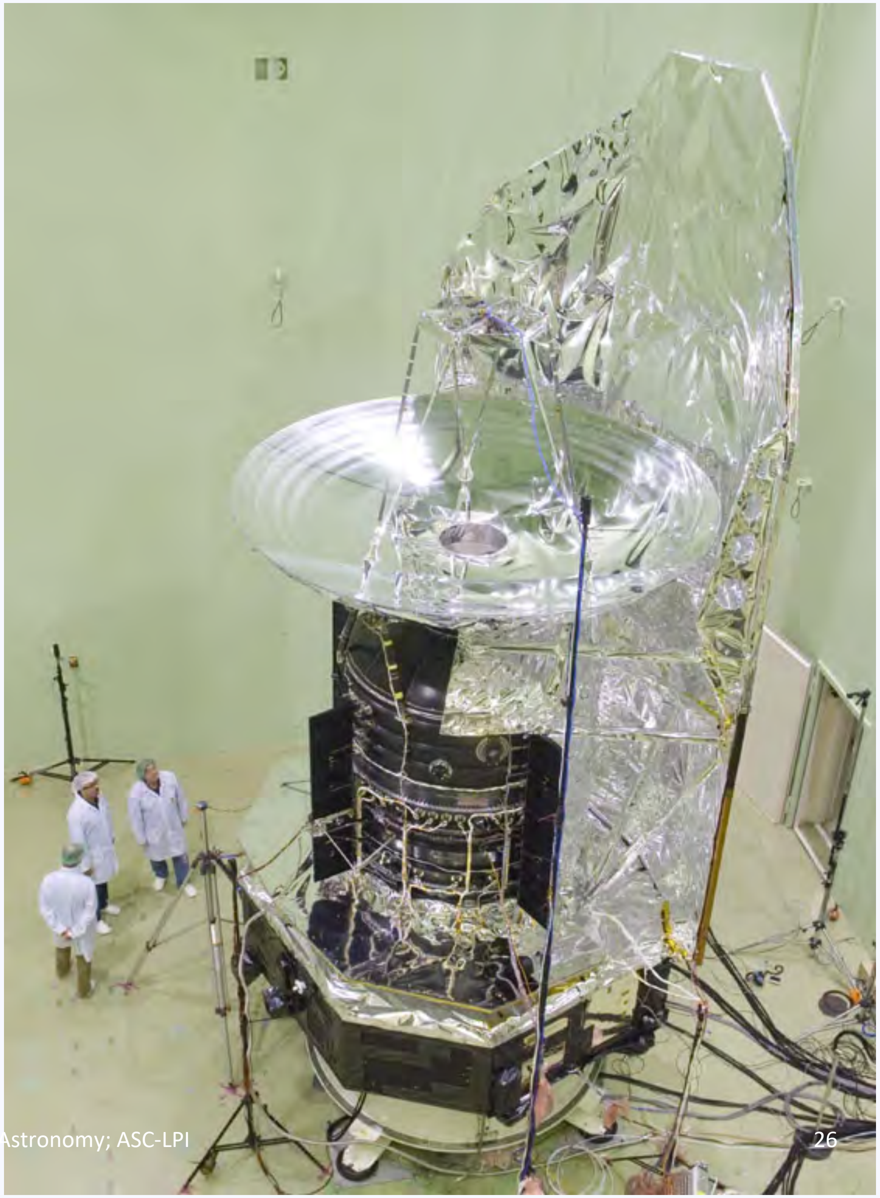
- **55-671 mm – bridging the far infrared & submillimetre – the ‘cool’ universe**

**3 Novel instruments**

- **wide area mapping in 6 ‘colours’**
- **imaging spectroscopy**
- **very high resolution heterodyne spectroscopy**

**Herschel science objectives**

- **star formation & evolution near & far**
- **galaxy evolution over cosmic time**
- **ISM physics/chemistry**
- **our own solar system & IR excess**
- **provide 3 years of routine observing**



# Herschel – the science instruments

3-band camera

250 + 350 + 500 μm
4 x 8 arcmin FOV

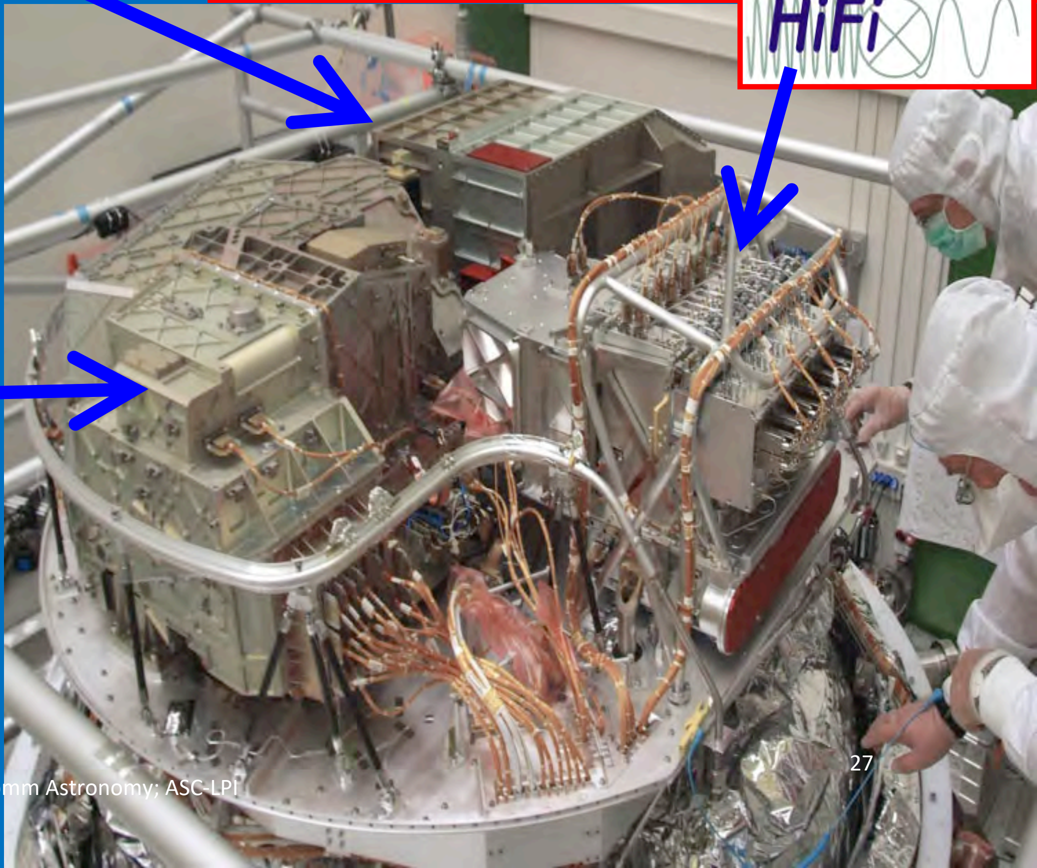
Imaging FT spectrometer
194 - 671 μm (simultaneously)
$\lambda/\Delta\lambda$ = 1300 – 370 (high-res)
= 60 – 20 (low-res)

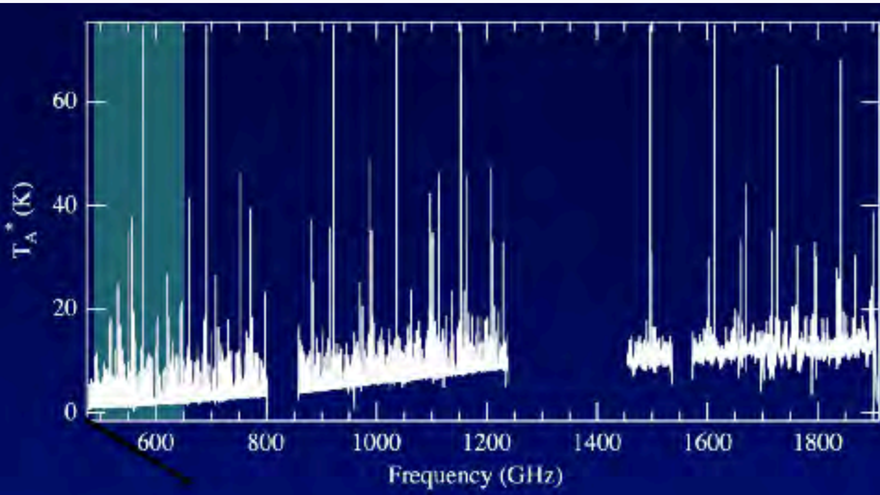
7-channel heterodyne receiver
480 - 1250 GHz (625 - 240 μm)

1410 - 1910 GHz (212 - 157 μm)
$\lambda/\Delta\lambda = 10^5$-$10^6$ w. BW = 4 GHz


3-band camera
70 or 100 + 160 μm
1.75 x 3.5 arcmin FOV

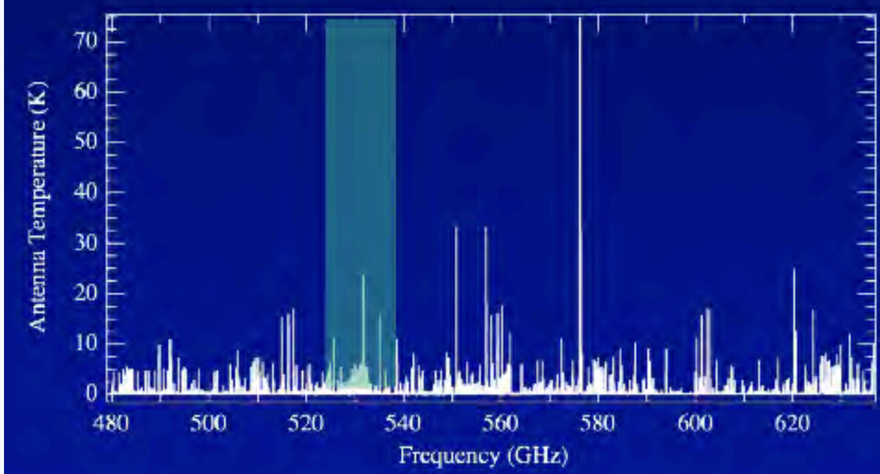
Imaging grating spectrometer
55 - 210 μm (3 orders)
$\lambda/\Delta\lambda$ = 1000 – 4000

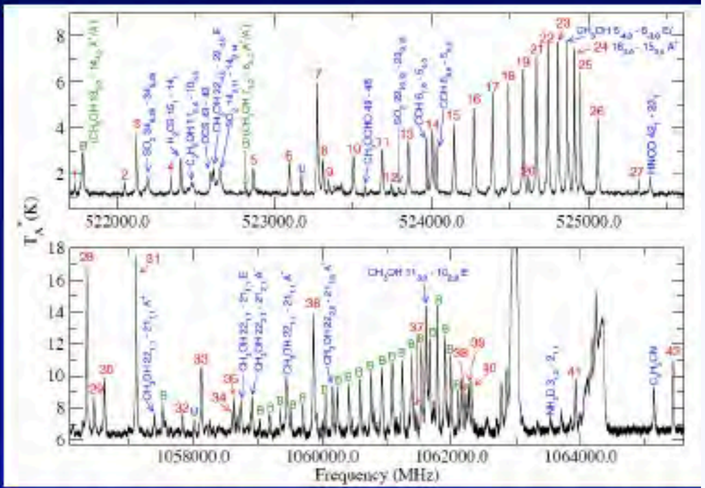





# Line surveys

## Orion-KL
## Herschel-HIFI



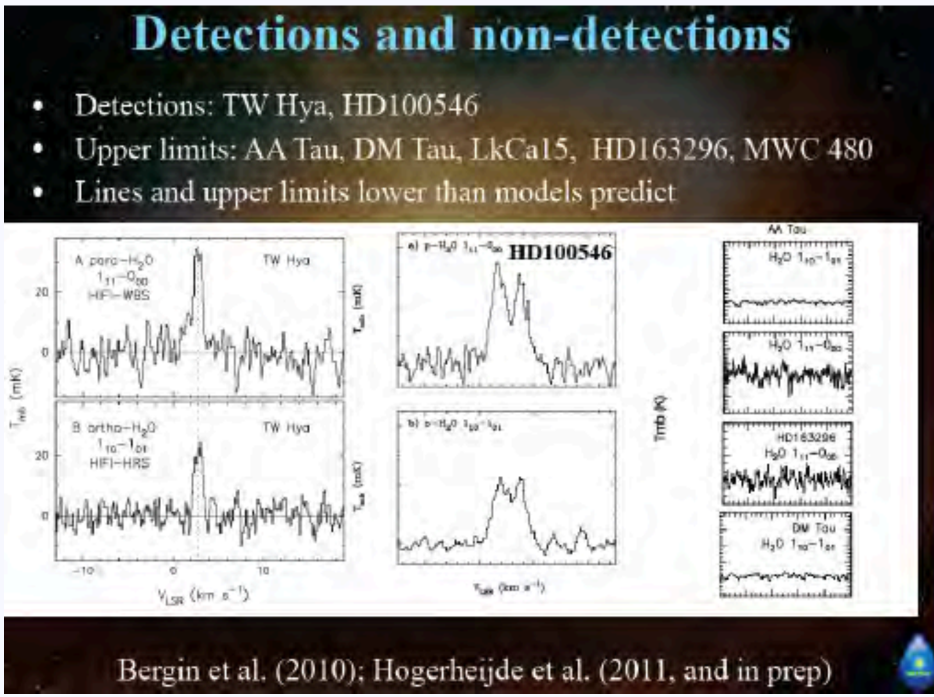

Bergin et al. 2010, Crockett et al. 2014

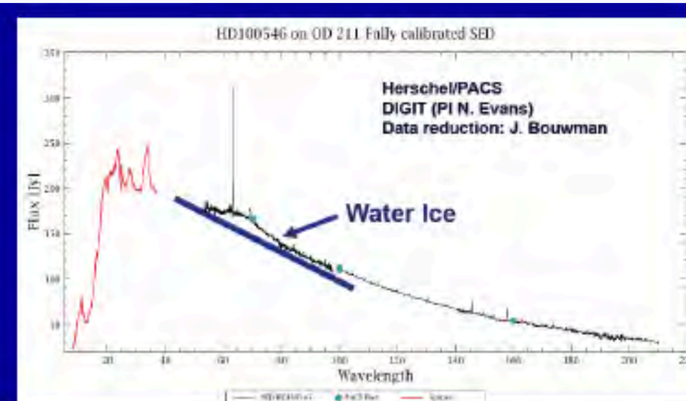
- Wide frequency range → $E_u$ up to 3000 K
- 6-12% of channels unidentified

# The *water trail*: from *Proto-planetary disks*;,comets/asteroids to Oceans: $H_2O$ in gas and ices, HD, etc

Gaseous Water

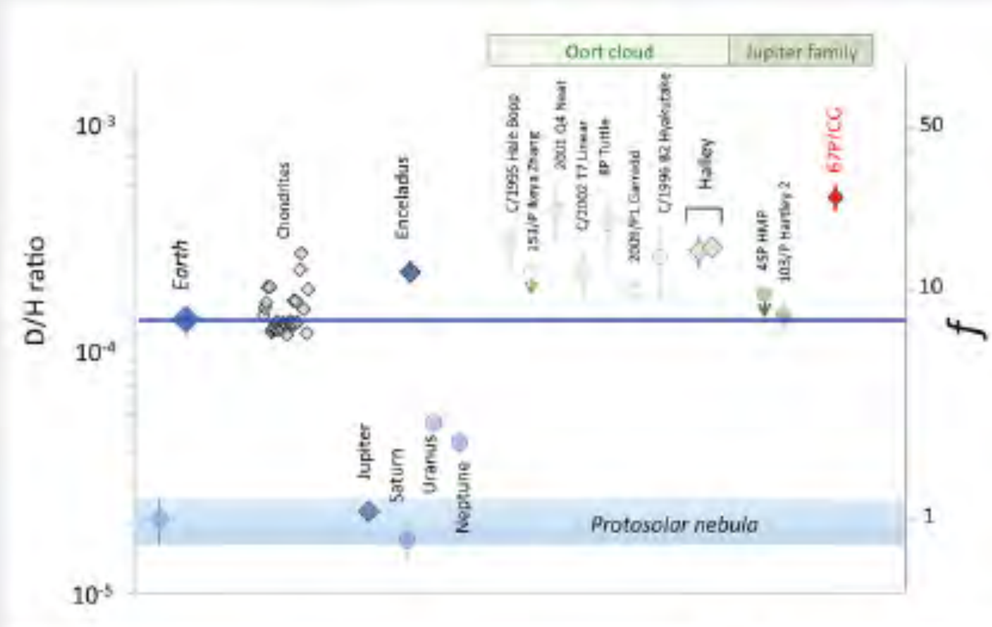
Water Ices



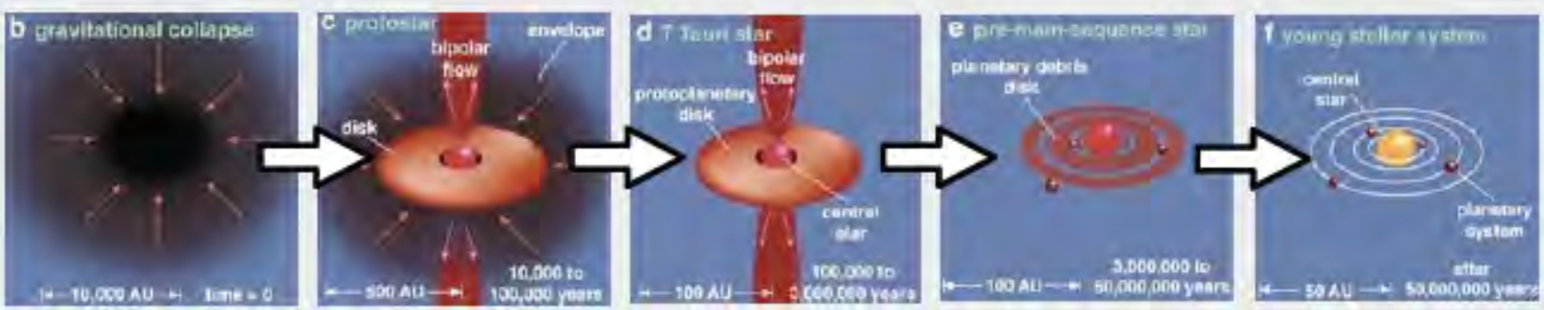
# *Origin of terrestrial water*

**Delivery of water on Earth by comets and/or asteroids through impacts**



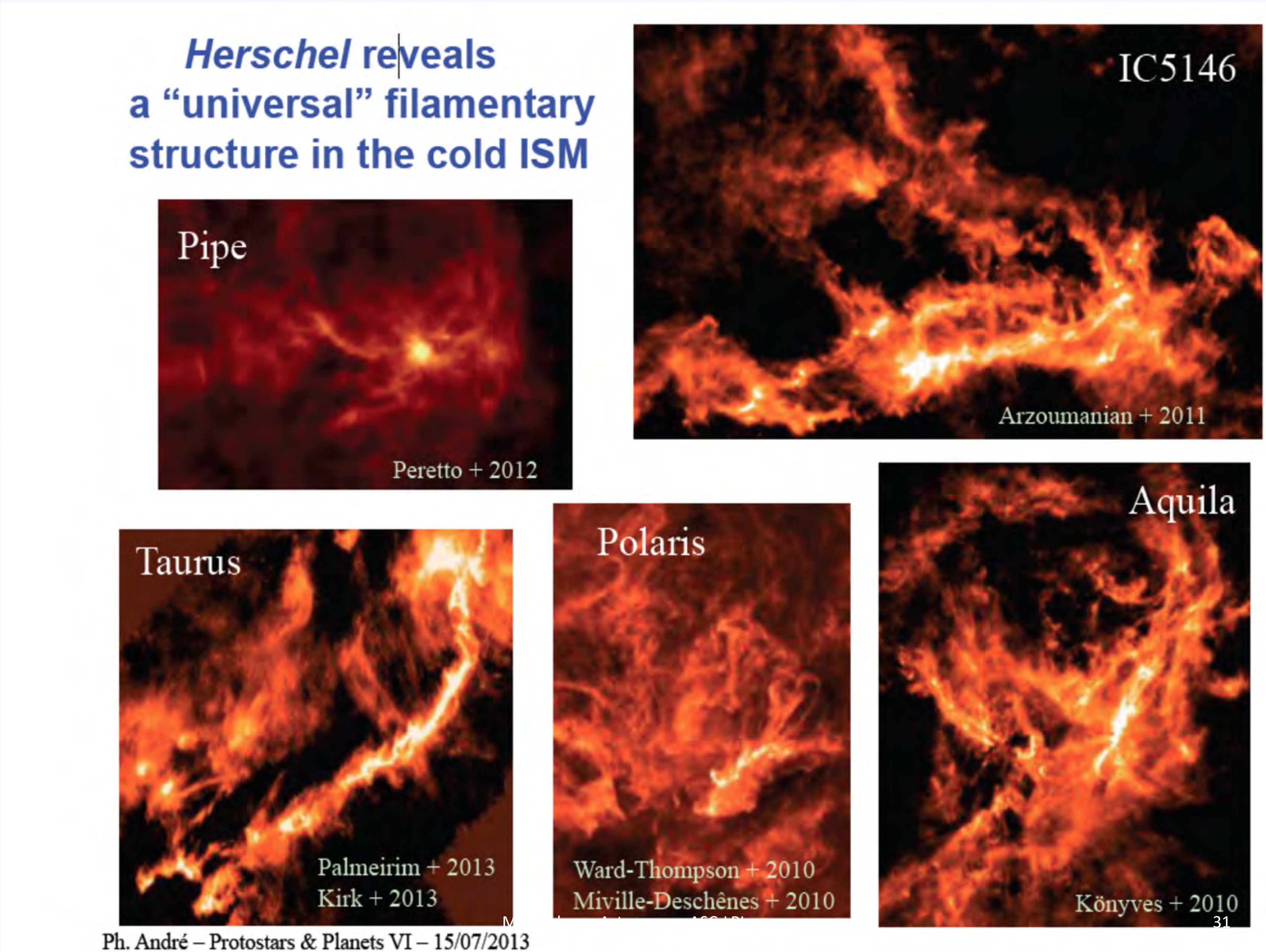

Altwegg et al. 2015

- Where does the water contained in comets and asteroids come from?
- How and when did this water form?

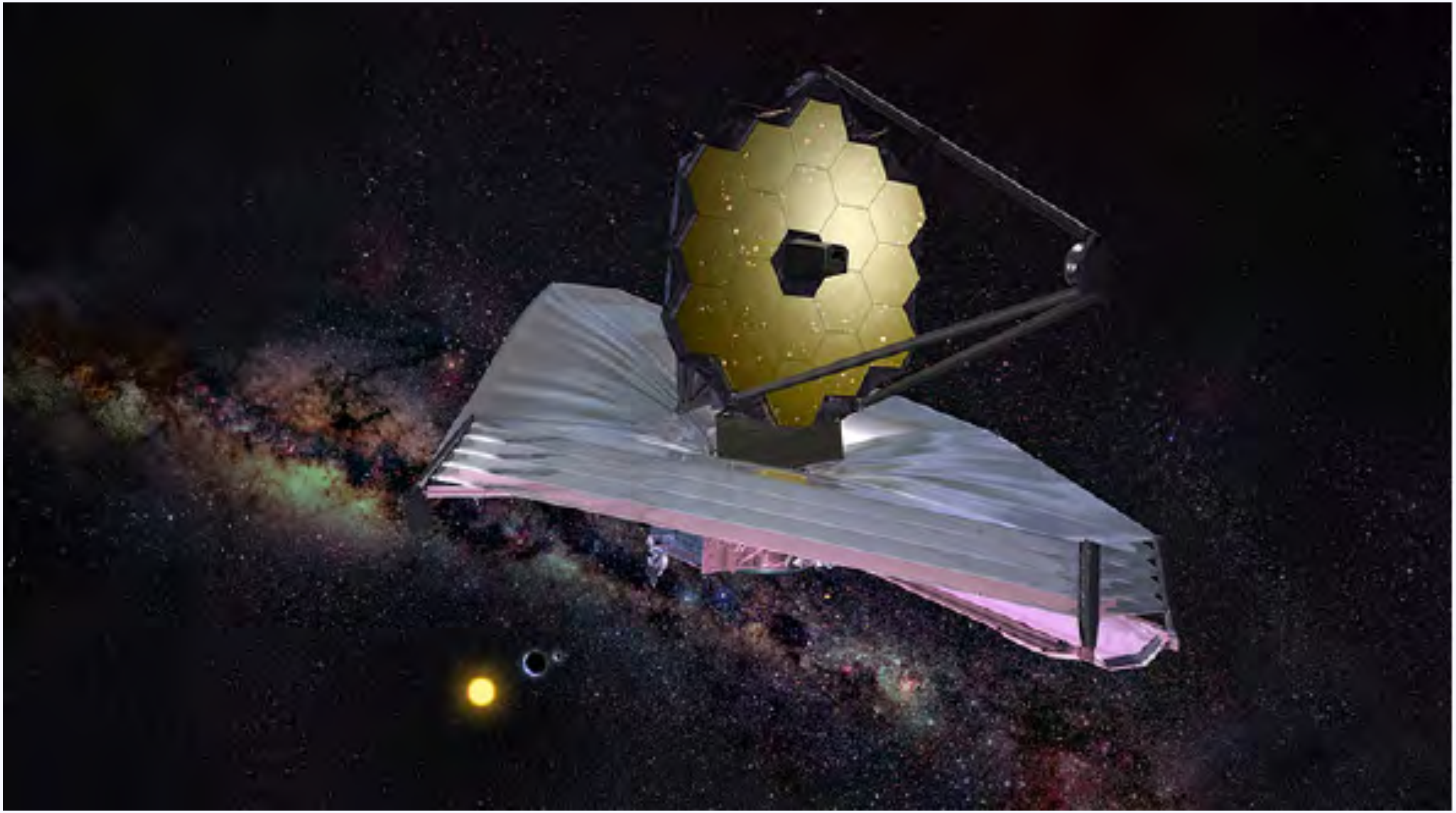


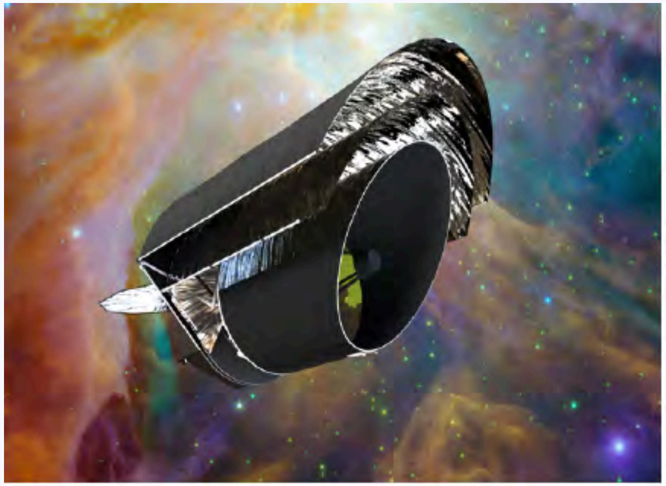

Spitzer Science Center IR Compendium

# Herschel: filaments everywhere and stars form in filaments…



# JWST with MIRI spectrometer till 28 micron





# ORIGINS SPACE TELESCOPE

***From First Light to Life***

**Table 3: *Origins* observatory-level parameters**

| Mission Parameter | Value |
|---|---|
| Telescope: Aperture Diameter/Area | 5.9 m/25 $m^2$ |
| Telescope Temperature | 4.5 K |
| Wavelength Coverage | 2.8—588 μm |
| Maximum Scanning Speed | 60″ per second |
| Mass: Dry/Wet (with margin) | 12000 kg/13000 kg |
| Power (with margin) | 4800 W |
| Launch Year | 2035 |
| Launch Vehicle | SLS Block IB or Space-X BFR |
| Orbit | Sun-Earth L2 |
| Propellant ifetime | 10 years, serviceable, limied by station-keeping propellant |

1. Introduction: Characteristics FIR/Submm Region for Astronomy and Astrophysics

2. A) Past IR/submm/mm observing facilities and some associated highlights: space missions in evolution

   B) Astrochemistry coming of age

3. **Submm/mm Technology and Astronomy**

   **a cybernetic unity in the early development phase**

4. Past IR/submm/mm observing facilities and some associated highlights: space and ground-based

5. Desired technical requirements for next submm projects/missions

6. Potential future projects/space missions

7. Summary

# Submm/mm Technology and Astronomy

in the early development phase a cybernetic unity

- Strong interaction between receiver developments and observational results:
- detection of water (Cheung, Townes et al.)
- detection of CO followed by more molecules
- Looking for lab frequency measurements ( Frank Lovas)
- Too few antennas available
- Mm astronomy was not embraced by many radio observatories
- THE 12 Meter played an important catalyzing role

# Submm/mm Technology and Astronomy

**1960 +++**

Available Budget was small as:

- No military application like the mid-IR, X-ray, CCD's
- No commercial medical applications at that time ( 25 years ago)
- No mass consumers applications

Funded mainly by science programs like astronomy, aeronomy and plasma physics (diagnostics)

Thus became a cybernetic  relationship between submm astronomy and submm technology development
Success for both was required.

# IR/sub-mm technology innovation:

## The Herschel case , from the beginning to end; study on innovation in a Space Mission: Herschel


- **Technical** Instrumentation
  - Detector arrays and mixers
  - Telescope technology
  - Cryogenics

- **Innovation in Management and Organisation of large instrument and satellite consortia**
  - Cooperation and competition: Coopetition
  - Managing different cultures and interfaces
  - Change of ESA Science directors

- **In Horizon 2000 plan with huge financial crises**
  - SOHO/Cluster launch failure
  - Herschel + Planck budget= Corner Stone -10%
  - Impact on Herschel and Planck programs
    - Merger and shared launcher
    - Staying within original budget

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7 Summary

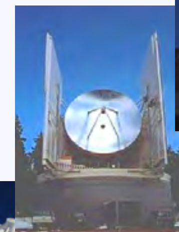
# *Single Dish Ground Based Submm/mm Observatories 1970 ------------2020*

**LMT**

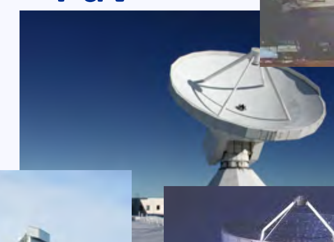
**SPT**

**APEX**

**HH**



**PdV**



**SEST**

**JCMT**

**CSO**

**KP**

GREEN BANK OBSERVATORY

**PM: NANTEN, ASTE,**
**PM: SUFFA, LLAMA, AMT,**
**EMST, Etc..**

# Evolution in Submm/mm Interferometres; before 2011

IRAM PdB (NOEMA)
6 **(12)** antennas,
each 15 m in diameter

| **Square Meters** | |
|---|---|
| **SMA:** | **220** |
| **ATCA:** | **2200** |
| **IRAM:** | **2200** |
| **ALMA:** | **6500** |

ATCA : 6 antennas each 22 m in diameter

SMA
8 antennas each 6 meters in diameter

CARMA
- 6 Antennas each 10.4 m. in diameter. (OVRO)
- 9 Antennas each 6.1 m. (Hat Creek)
- 8 Antennas each 3.5 m. in diameter. (SZA)

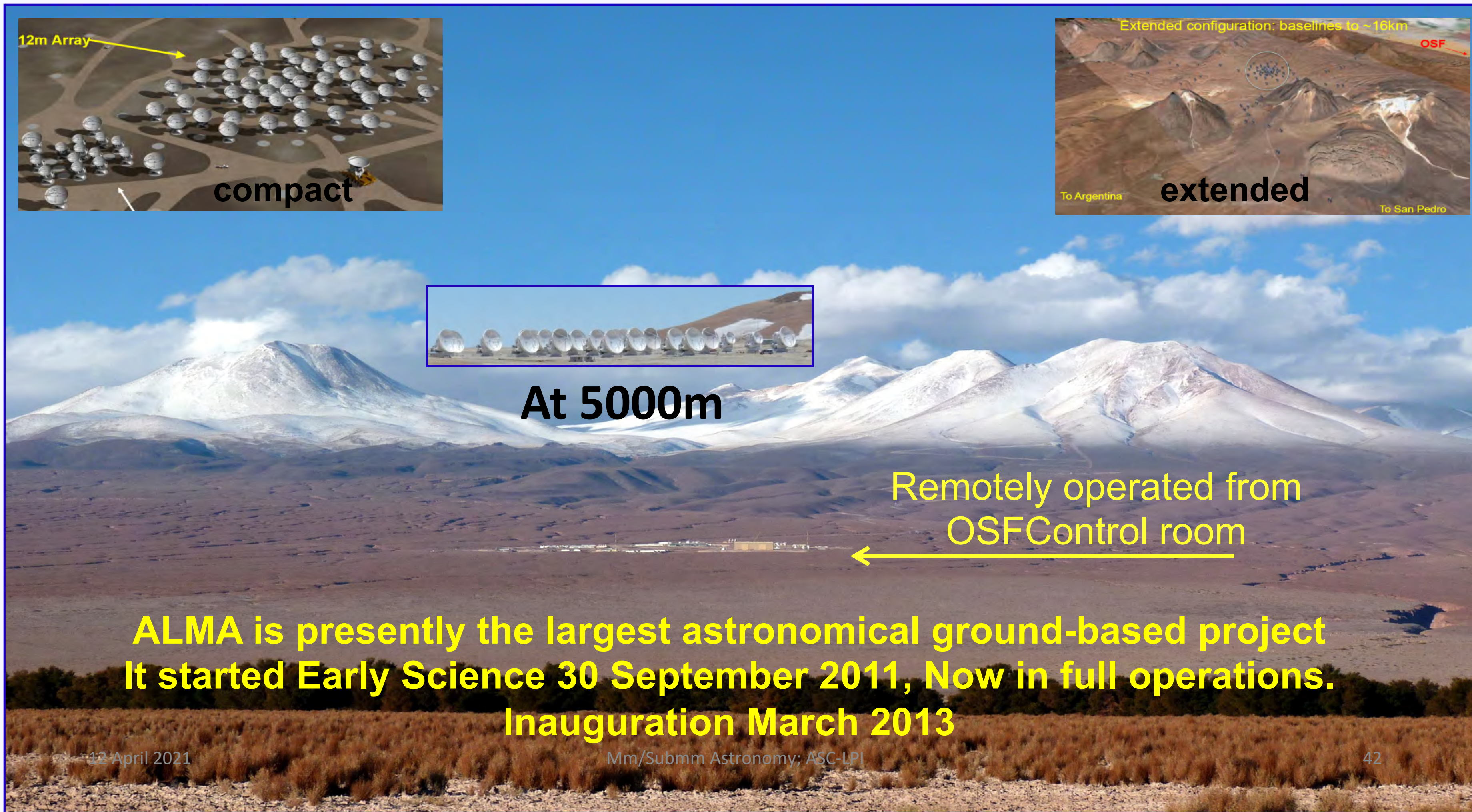
NRO: 6 antennas each 10 metres in diameter

# NOEMA: 10/12 antennas

# ALMA:

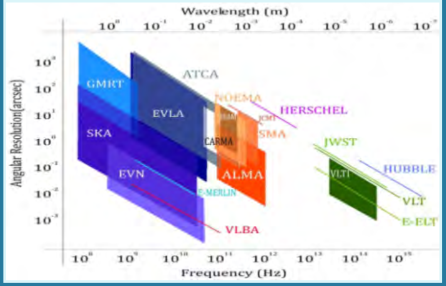
A partnership among Europe, North America and East Asia
(in cooperation with the Republic of Chile) to build and operate:

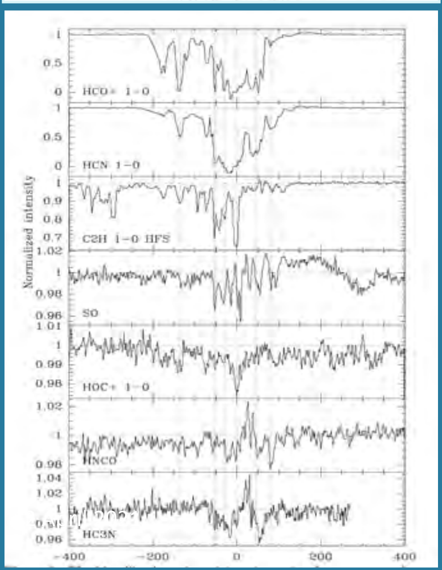
An array of **66 antennas, in *aperture synthesis*** *,as a* “zoom telescope”




**ALMA is presently the largest astronomical ground-based project**
**It started Early Science 30 September 2011, Now in full operations.**
**Inauguration March 2013**

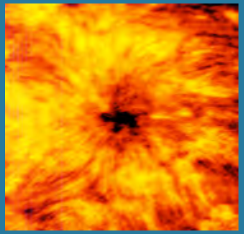
# ALMA Science Capabilities:
## Images in spectral lines!!; Covers complete (sub)mm range



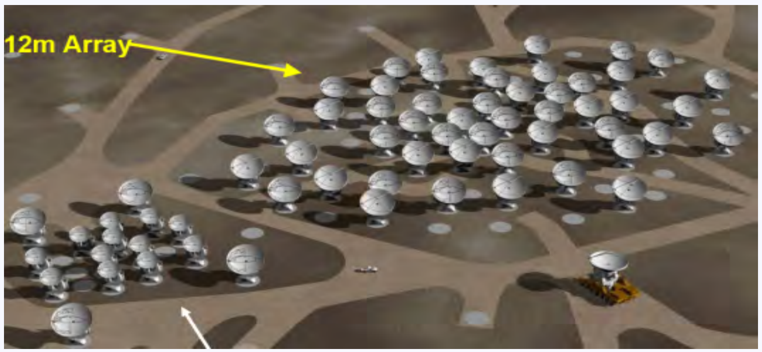




*Angular Resolution*:

- ~8 times better that Hubble ST
- ~10-100 times better than earlier mm interferometers
- *Spectral resolution:* sub-Km/s with heterodyne techniques
- *Sensitivity (Speed)*
- : large increase surface: 10 -100 times
  - 6500m$^2$ collecting area; receivers
  - 6 *μ Jy/beam in 1 hour;*
  - *1.1 m Jy/beam in10 hours. Spectral*
- *Excellent "suitable" and accesable site is of vital importance*

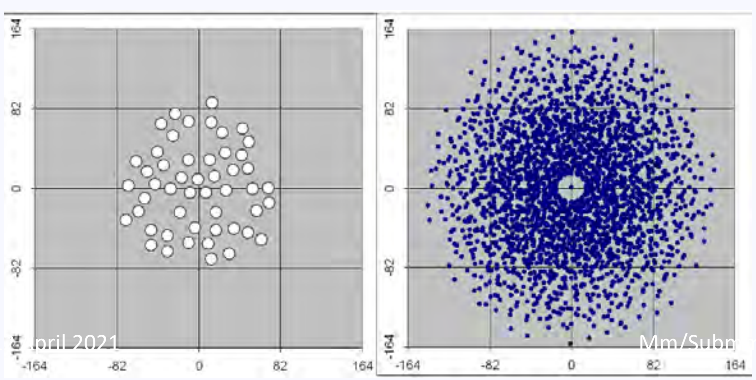


# ALMA: some characteristics
# Speed and Configurations




ACA

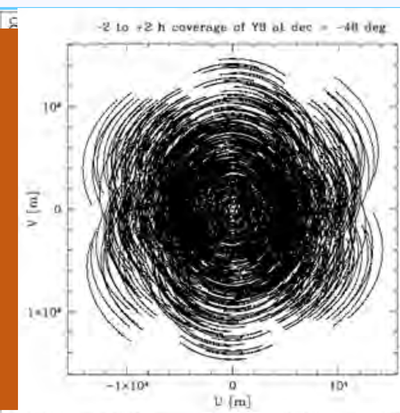
Most compact configuration –
Left: Antennas,
Right: snapshot UV coverage



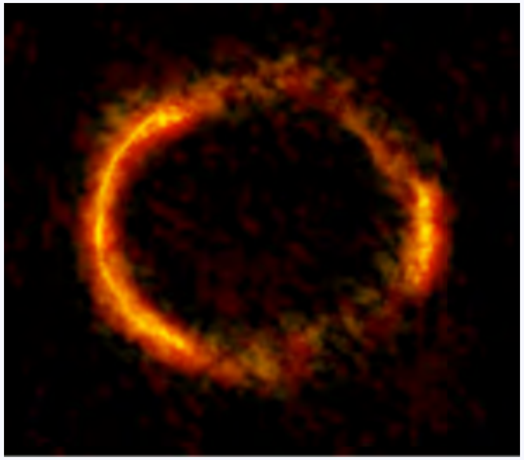


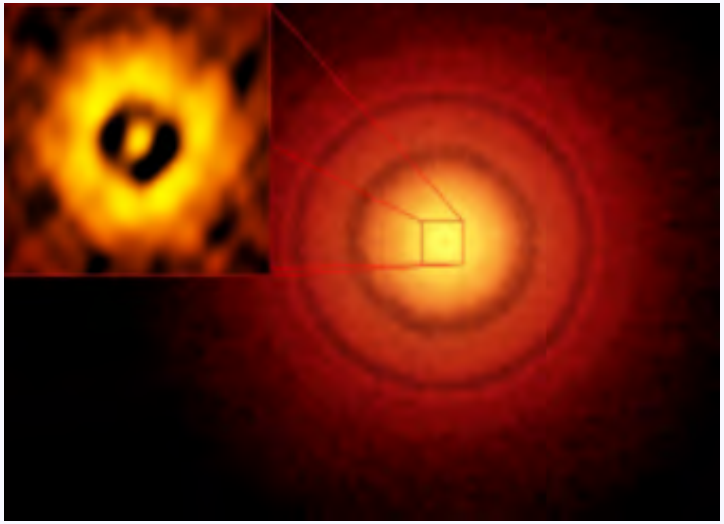
Most extended configuration –
Note that scale is 100 x larger than on previous slide

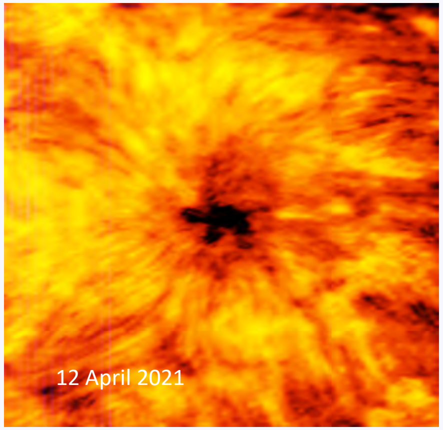
UV coverage of most extended configuration, <u>including</u> earth rotation: 4 hours of observation



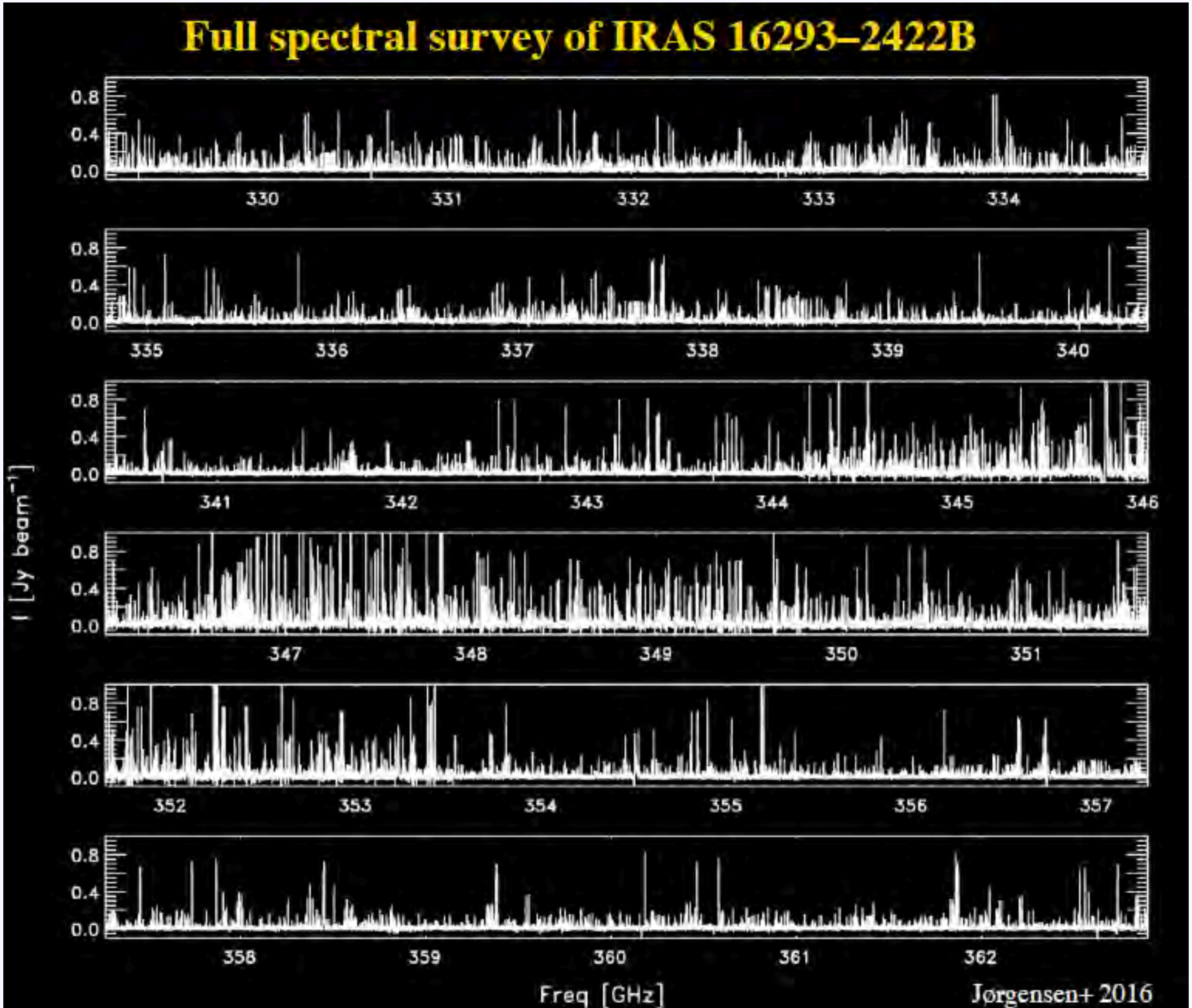
# ALMA: from solar observations, and planetary disks to gravitationally lensed galaxies in the early Universe.!



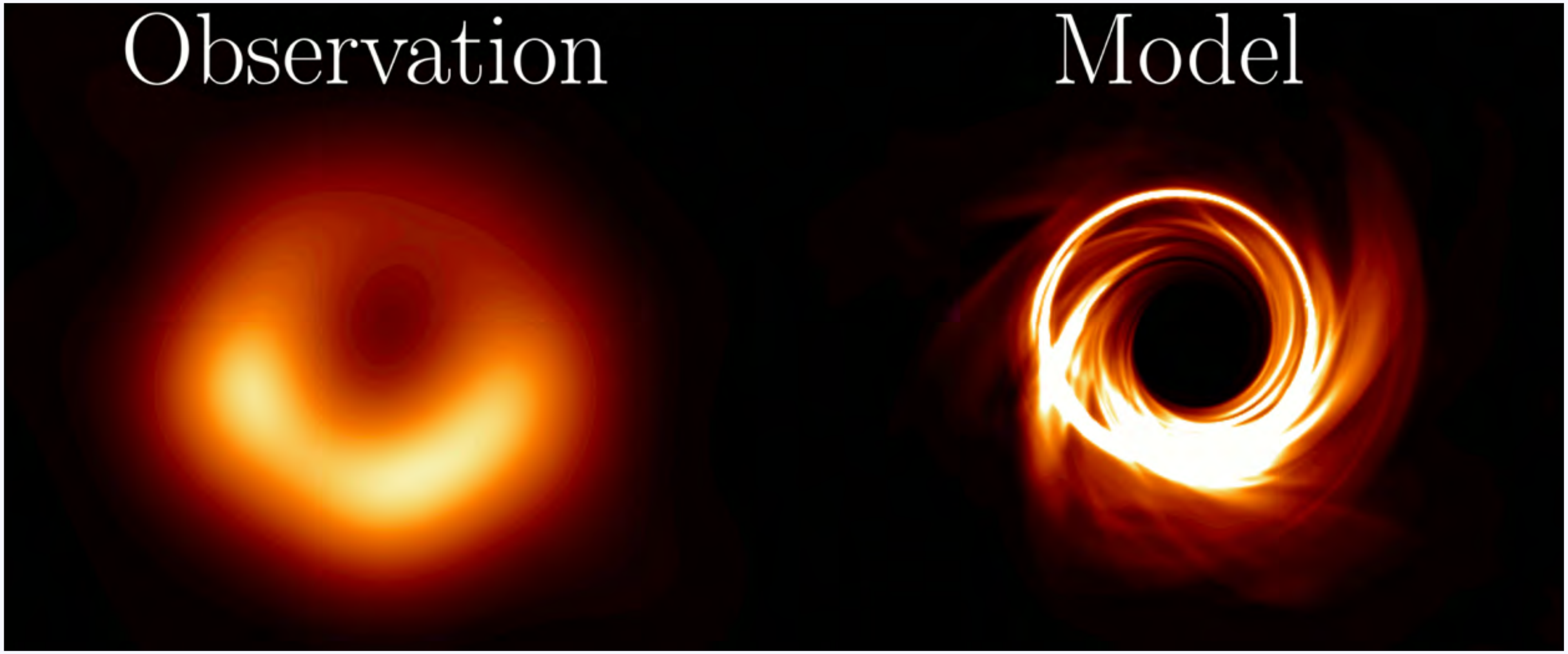




# ALMA results



# EHT results and Models: Space link needed




Animation: S. Issaoun, F. Roelofs, M. Moscibrodzka

Note: EHT observations are made once a year, in April.
Important to take into account for site selection and mission planning.

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# Technical requirements/improvements for the future for Galactic and X-Galactic research:

**Higher angular resolution for imaging**

- Larger dish (10m>) or Interferometer
- X-Galactic: eliminate confusion
- Galactic:

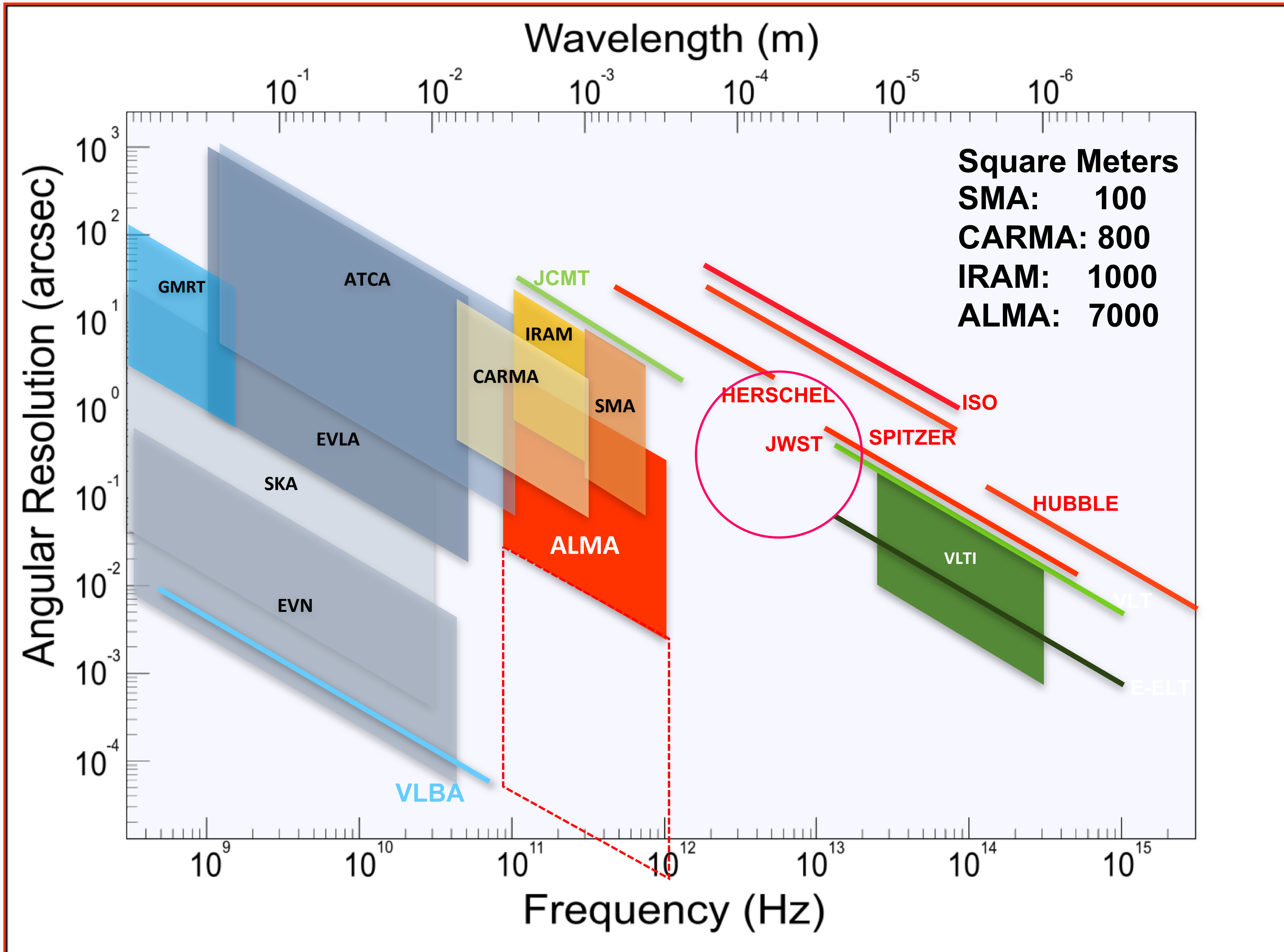
**Spectroscopy: with larger collecting area**

- Galactic research (Lifecycle ISM, protoplanetary disks, etc..):
  - Gaseous components need **heterodyne spectral resolution**; this requires large dish (need more photons)
  - Solids can do with resolution R=300-500
- X-Galactic:
  - Can do with resolution R=500 or more

**Sensitivity: improved mixers and bolometers**

- Mixer noise and IF bandwidth; heterodyne arrays; BE spectrometer
- Cooled Telescope for lower noise
- Bolometer arrays low-noise and more pixels for large fields (faster imaging)

# Filling the FIR/Submm angular resolution gap



# Future submm space facilities:

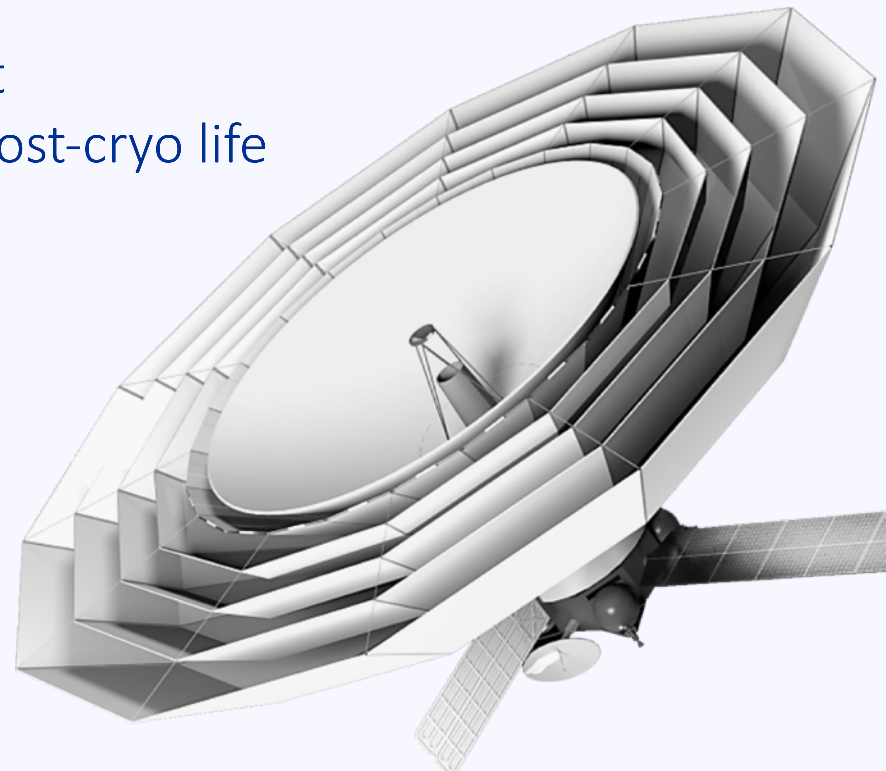
- **Millimetron** (ROSCOSMOS)
  **ALMA – EHT** combination and extension
- **Origins Space Telescope (OST)** (US decadal review)
- ~~SPICA (ESA M5 mission, with Japan 2032 (**Deleted**)~~
- possible CMB mission (PRISMA+; LiteBird, Japan; .)
- Space FIR Interferometer (EHI, FIRI, ESPRIT)

ASC LPI

# Millimetron in a Nutshell

## The first 10-m cooled space telescope

- ✓ for the FIR, submm and mm range (diffraction limited 50μm)
- ✓ for cosmology and astrophysics
- ✓ deployable and adjustable on orbit
- ✓ mechanically cooled (<10K) with post-cryo life
- ✓ orbit around L2 Lagrange point
- ✓ lifetime: 10 years; at cryo >3 years
- ✓ dual operation modes:
- ✓ S-E VLBI for 0.8 – 17 mm
- ✓ Single dish for 60 μm – 5mm



**Spacecraft in Phase-B**
**Science payload in Phase-A**
**Launch date : 2028**

**Mission has been approved by ROSCOSMOS;**
**Budget for spacecraft/antenna/VLBI receivers**

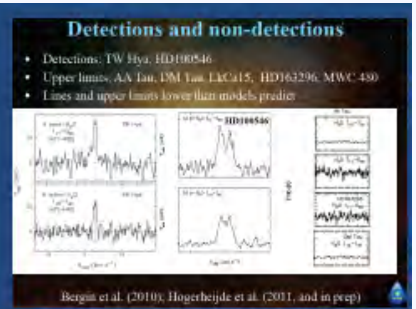
# Instrument wishes; Herschel style complement

(need scrutinizing)

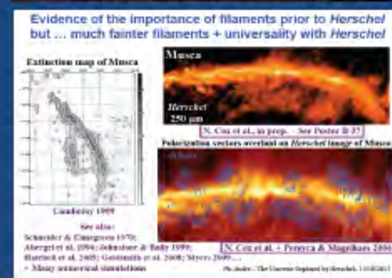
- Space-Ground VLBI receivers (heterodyne)
  - Bands 18-26, 33-50, 84-116, 211-275 GHz
- High Resolution Spectrometer (heterodyne)
  - 557-3000 GHz in 5 bands covering main lines of interest
  - 557-2100 GHz continuous coverage
  - Post cryo 500-700 GHz schottky receiver
- Long Wave array Spectrometer/Imager (KIDs +FTS)
  - Pendulum differential FTS,
  - 100-200, 200-350, 350-700, 700-1000 GHz bands
  - R=100..700
  - 6..36 spatial pixels
- Short wave array spectrometer/Imager (KIDs, Grating)
  - 0.7..6 THz divided into 4 bands, 300..8000 pixels
  - R=500..1000
  - Photometric capability
  - Detector NEP < 10-19 W/√Hz required

# Some key future objectives:

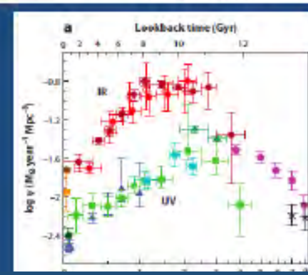
- Water in circumstellar disks



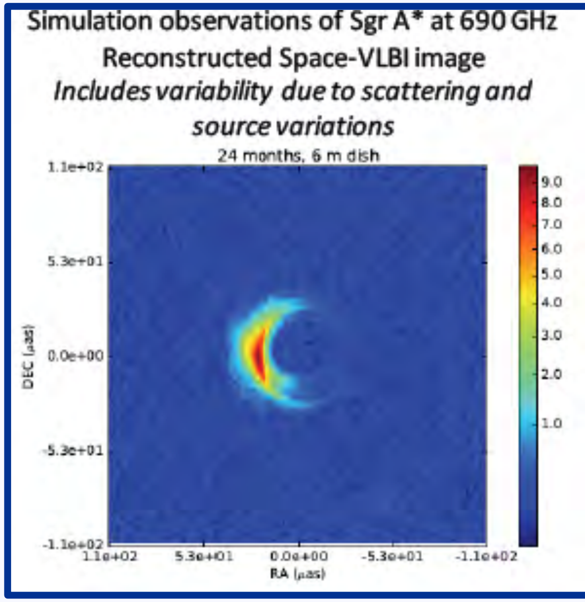

- Study of filaments and magnetic fields



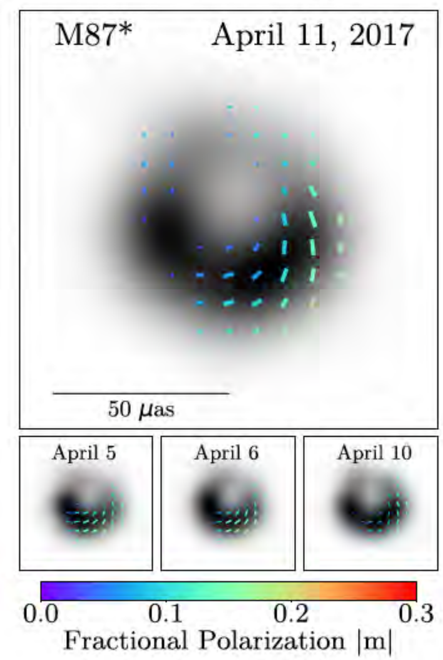

- Star formation in early Universe




SgrA* /M87 observations to image shadow black hole; to observe polarisation




THE ASTROPHYSICAL JOURNAL LETTERS, 910:L13 (43pp), 2021 March 20



# Summary/Recommendations

- Science must be central in all plans and projects
- Involvement of scientists is crucial for state-of-the-art goals;
  must be co-leading
- Observatories only at sites compatible with science goals: not less!!
- Detailing of project plans must include operations plan

# Thank You