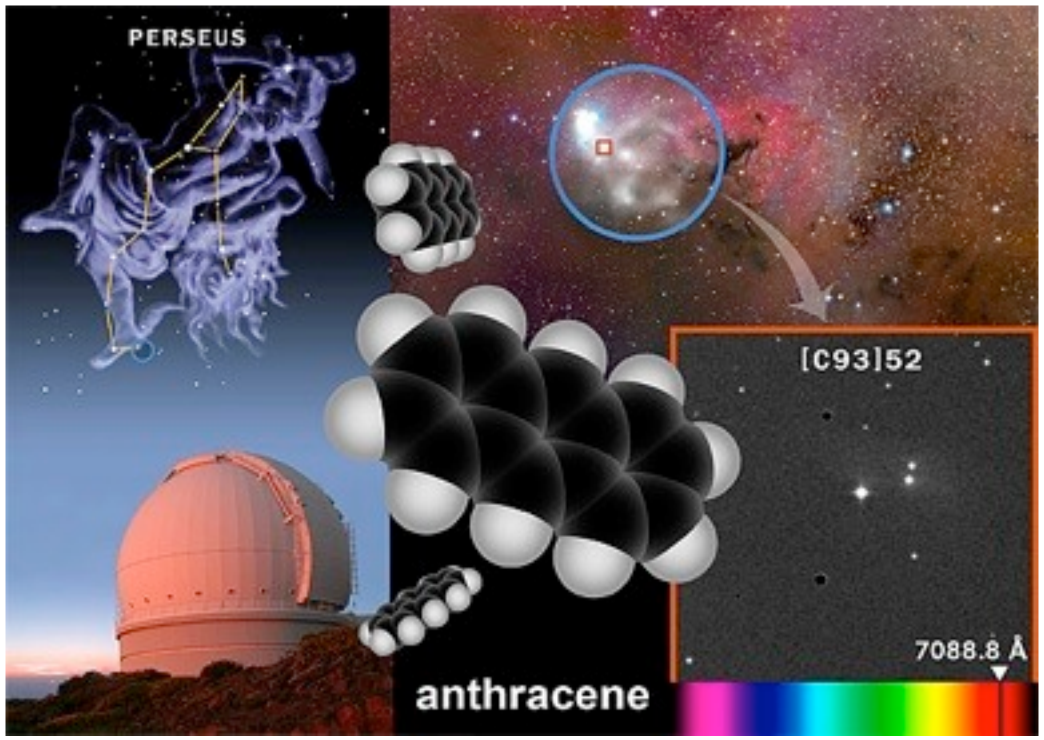
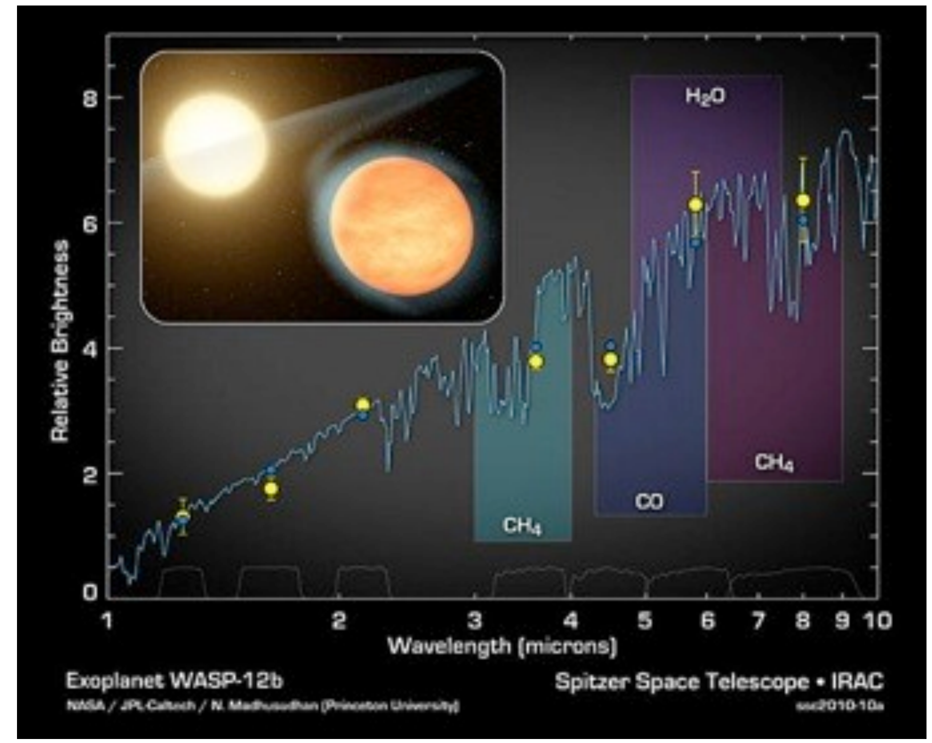
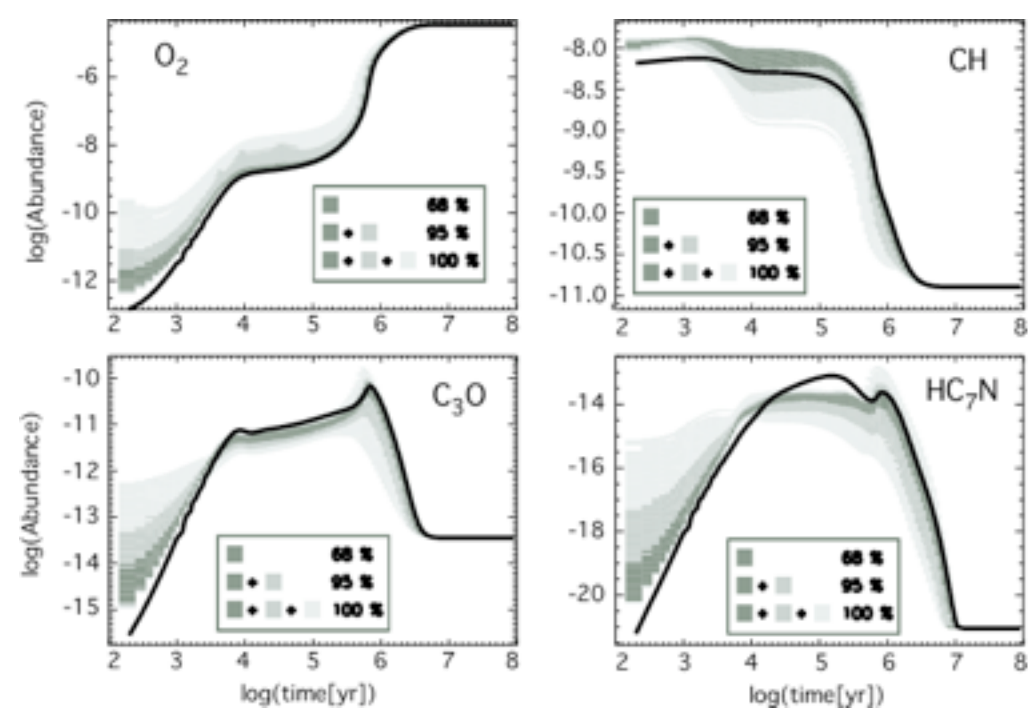
"Molecular Astrophysics: from Lab to Theory to Observations" 2012







Welcome!

- PhD and MSc students from ITA
- ... from Max Planck Institute for Astronomy (MPIA)
- ... from Max Planck Institute of Nuclear Physics (MPIfK)
- ... from Astronomisches Rechen-Institut (ARI)
- ... from HD Uni
- others!

- Lectures will be accessible as PDFs online

Teachers

• Dmitry Semenov, Max Planck Institute for Astronomy (MPIA): theoretical and observational astrochemistry & astrophysics

http://www.mpia-hd.mpg.de/homes/semenov/

• Holger Kreckel, Max Planck Institute of Nuclear Physics (MPIfK): laboratory astrochemistry & physics

http://www.hkreckel.de/

Organization

- **Lectures:**
  - Monday, 11:00-13:00 (10 min break?)
  - April 16 till July 23
  - 15–20 min for discussion of home work

- **Exam:**
  - Final oral exam: Dima, Holger + 1 or 2 professors

- **Prerequisites:**
  - 80% attendance
  - home work
  - general understanding + simple equations

Outline of the course (13 lectures)

- Molecules in space
- Molecular properties and spectroscopy
- Different ways to detect molecules
- The first 20 minutes of the Universe
- Gas-phase molecular processes and the first molecules
- Laboratory astrophysics: gas-phase experiments
- Basics of star formation and stellar nucleosynthesis
- Dust evolution and surface processes
- Laboratory astrophysics: surface and dust experiments
- Physics and chemistry of the diffuse interstellar medium
- Physics and chemistry of the dense interstellar medium
- Physics and chemistry of protoplanetary disks
- Planetary atmospheres, exoplanets, water, and life

Background reading

- Relevant reviews for each lecture

- S. Kwok, "Physics and Chemistry of the Interstellar Medium" (2006)

- A. G.G.M. Tielens, "The Physics and Chemistry of the ISM" (2007)

- Master course in Astrochemistry, Ewine van Dischoek (2011)
http://www.strw.leidenuniv.nl/~sanjose/astrochem

- E. Herbst & E. van Dishoeck, "Complex Organic Interstellar Molecules" (2009), Annual Rev. in Astron. & Astrophys., 47, 427

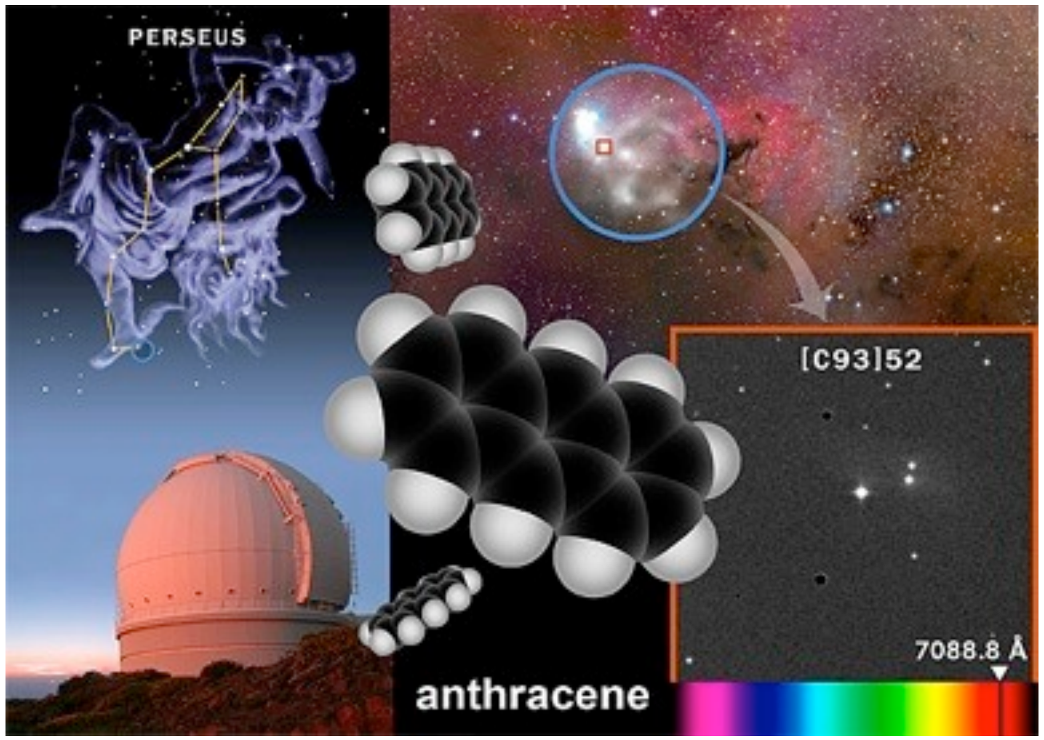
- "Protostars & Planets V" (2007), Part VI, eds. B. Reipurt et al., Univ. Arizona P.

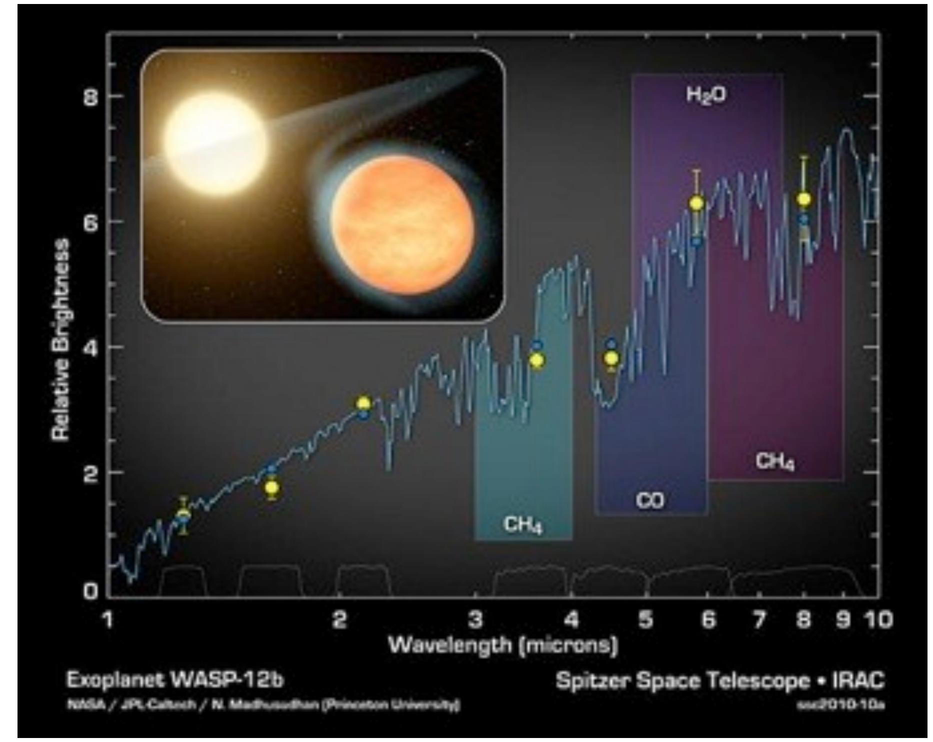
- T. Wilson et al., "Tools of Radioastronomy" (2009), Springer

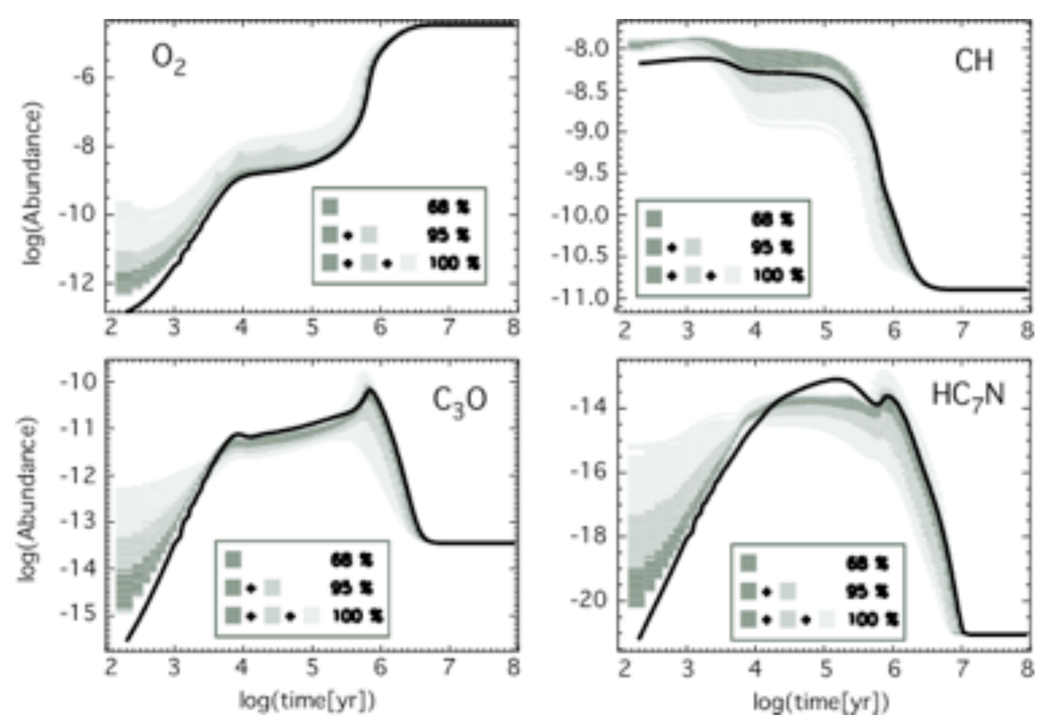
Astronomical units

- 1 pc = parsec = 206,265 AU = 3.086 x 10^{18} cm
- 1 M_{sun} = solar mass = 1.99 x 10^{33} g
- 1 L_{sun} = solar luminosity = 3.90 x 10^{33} erg s^{-1}
- 1 eV = 1.602 x 10^{-12} erg
- 1 Å = 10^{-8} cm
- 1 Jansky = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}
- 1 Debye = 10^{-18} esu cm
- 1 Kcal/mol = 6.947 x 10^{-14} erg $atom^{-1}$
- 1 year = 3.1536 x 10^{7} s
- Proton mass = 1.6726 x 10^{-24} g
- Boltzmann's constant = 1.3807 x 10^{-16} erg K^{-1}
- Planck's constant = 6.6261 x 10^{-27} erg s
- see Tielens' book!

Lecture 1: Molecules in space







What is "molecular astrophysics"?

• Eddington: "Atoms are physics but molecules are chemistry"

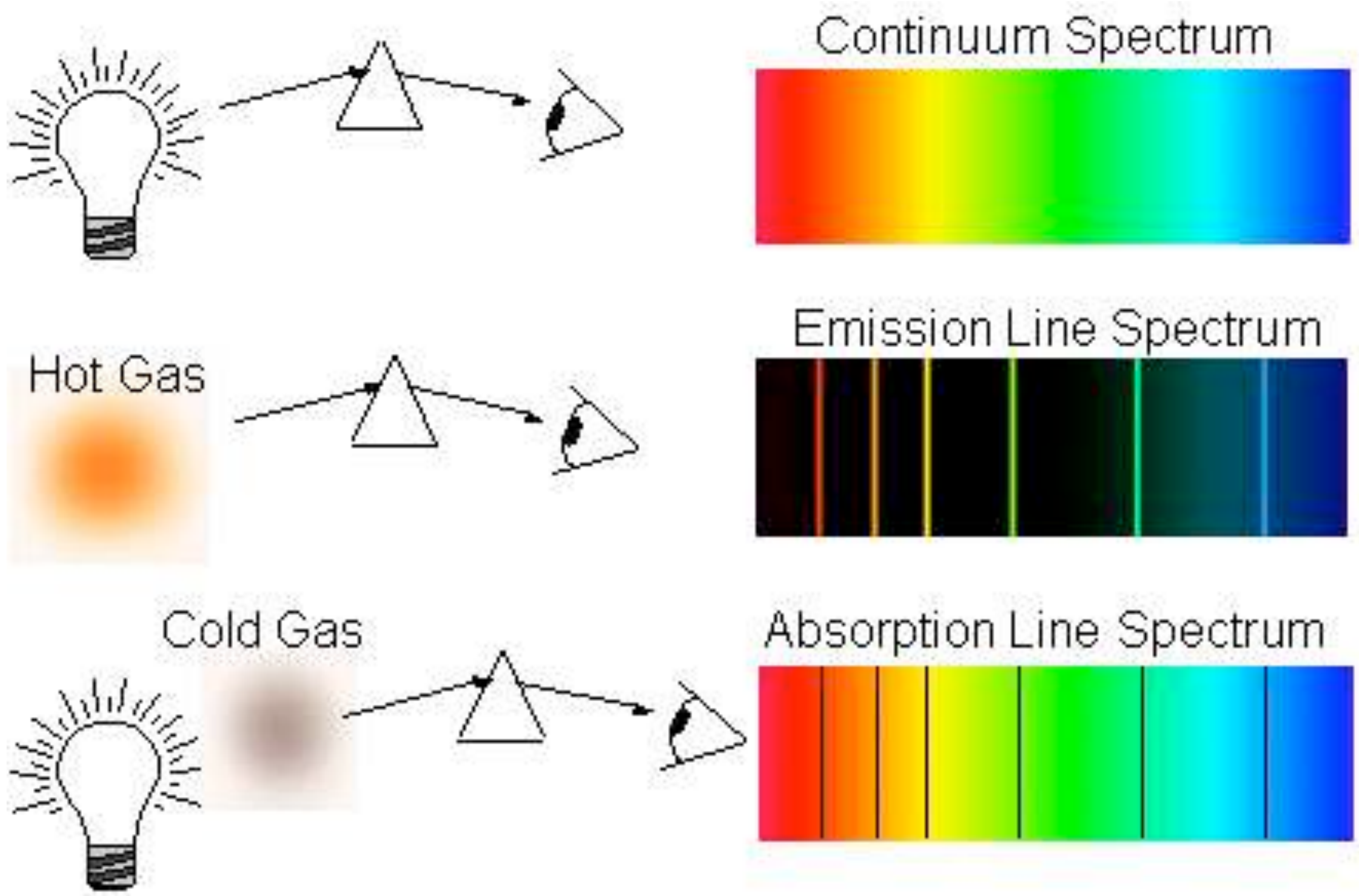
• Molecular astrophysics (or astrochemistry) is the study of formation and destruction of molecules in the Universe, their interaction with radiation, and their feedback on physics of the environments"

• Interdisciplinary field: chemistry + physics + astronomy (+biology?)

• Observations (UV-millimeter), theoretical (astro)physics and chemistry, and laboratory astrochemistry

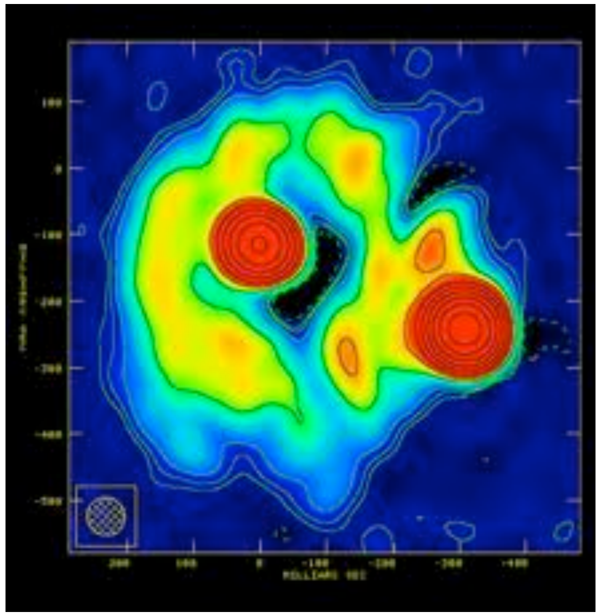
Detecting molecules

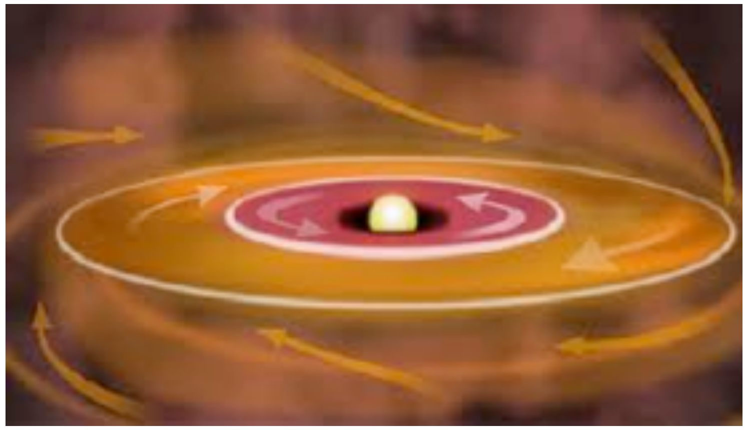
- Absorption: UV, optical, IR
- Emission: (sub-)millimeter
- Gas-phase & ices



Molecules are everywhere!

- Molecules are found everywhere in the Universe:
  - Appeared in the Early Universe, ~ few min after Big Bang
  - High-z quasars and galaxies
  - Milky Way: interstellar and circumstellar medium
  - Solar system: solar photosphere, planetary atmospheres, comets, meteorites



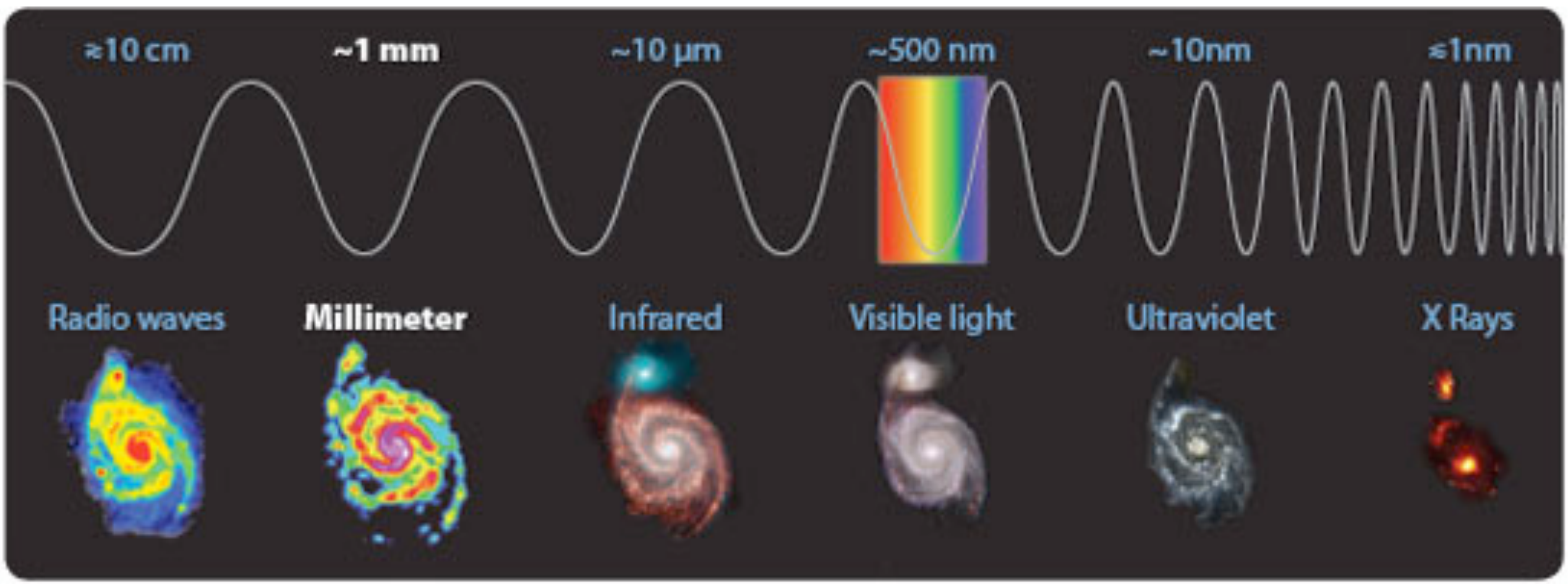


Importance of molecules

- Unique probes of physical conditions:
  - T_{kin}, density
  - Ionization
- Unique probes of kinematics
- Chemical composition and evolution
- Coolants of gas

Detecting molecules

- Molecular lines: (far-)UV–millimeter wavelengths
- Rotational, vibrational, electronic transitions (and their combination)
- Atmosphere transparency windows at IR: blocked by OH, H_2O, etc.



Physical conditions in various astrophysical objects

- Diffuse clouds: T_{kin}~100 K, n ~100 cm^{-3}
- Dense clouds: T_{kin}~10–100 K, n ~10^4–10^8 cm^{-3}
- Hot cores: T_{kin}~100–1000 K, n ~10^6–10^8 cm^{-3}
- Protoplanetary disks: T_{kin}~10–1000 K, n~10^4–10^{13} cm^{-3}
- Circumstellar shells of evolved stars: T_{kin} ~300–3,000 K, n<10^{14} cm^{-3}
- More: HII regions, photo-dissociation regions, supernova remnants, ...

- Earth atmosphere at sea level: T_{kin}~300 K, n~3 10^{19} cm^{-3}

Typical timescales

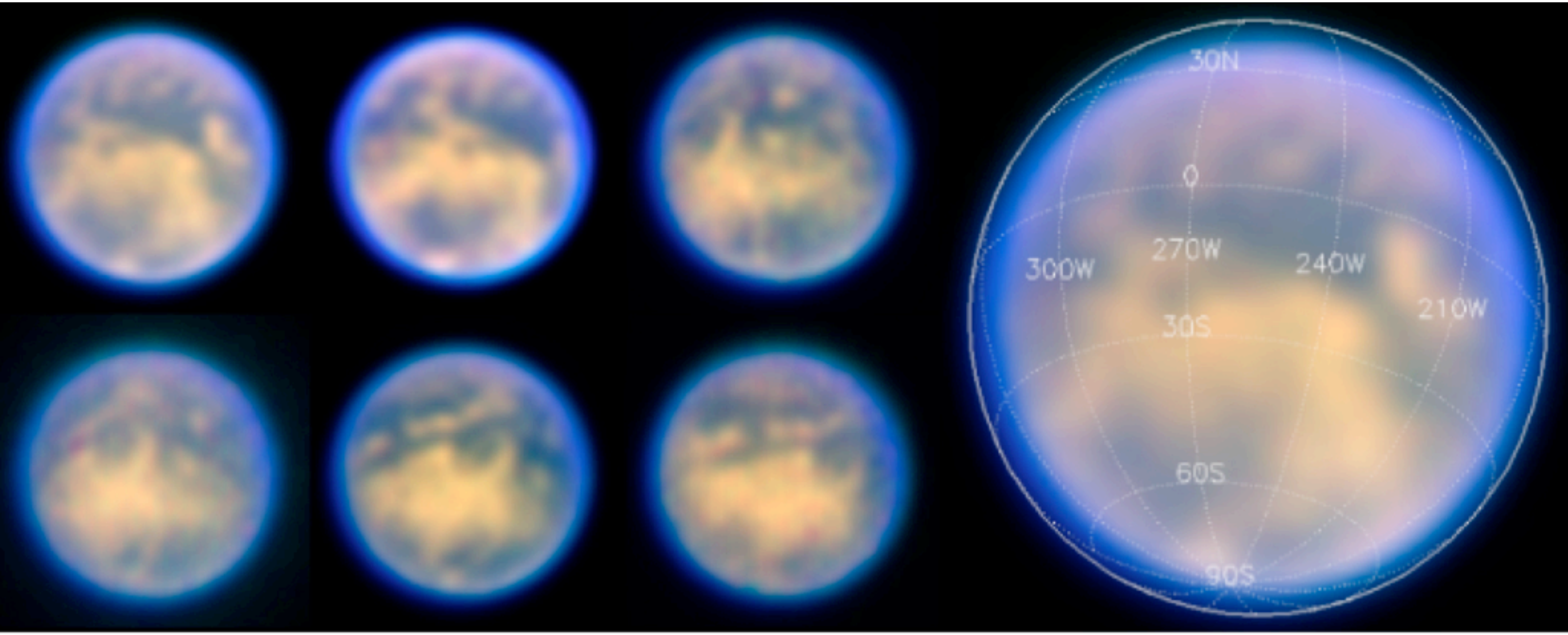
- Collision time: ~1 month at 10 K and 10^4 cm^{-3}
- Chemical time: >10^4–10^5 years (molecular clouds)
- Life-time of a cloud: ~1–10 x 10^6 years
- Low-mass star formation: ~10^6 years

Chemistry is slow yet there are many molecules in the interstellar medium!

Molecularly-rich environments

- Titan, 10 AU
- Taurus molecular complex (TMC): low-mass, 140 pc
- Orion molecular cloud: high-mass, ~450 pc
- AB Aur protoplanetary disk, ~140 pc
- IRC +10216 (CW Leo), evolved C-rich star, ~120–150 pc
- Sagittarius B2: a ring of molecular clouds, Galactic center, ~8.2 kpc
- Andromeda Galaxy (M31), nearest spiral galaxy, ~1 Mpc
- J 1148+5251, quasar at z=6.4 (~6.9 Gpc)

Titan



- Near-IR, NACO at the Very Large Telescope (VLT)

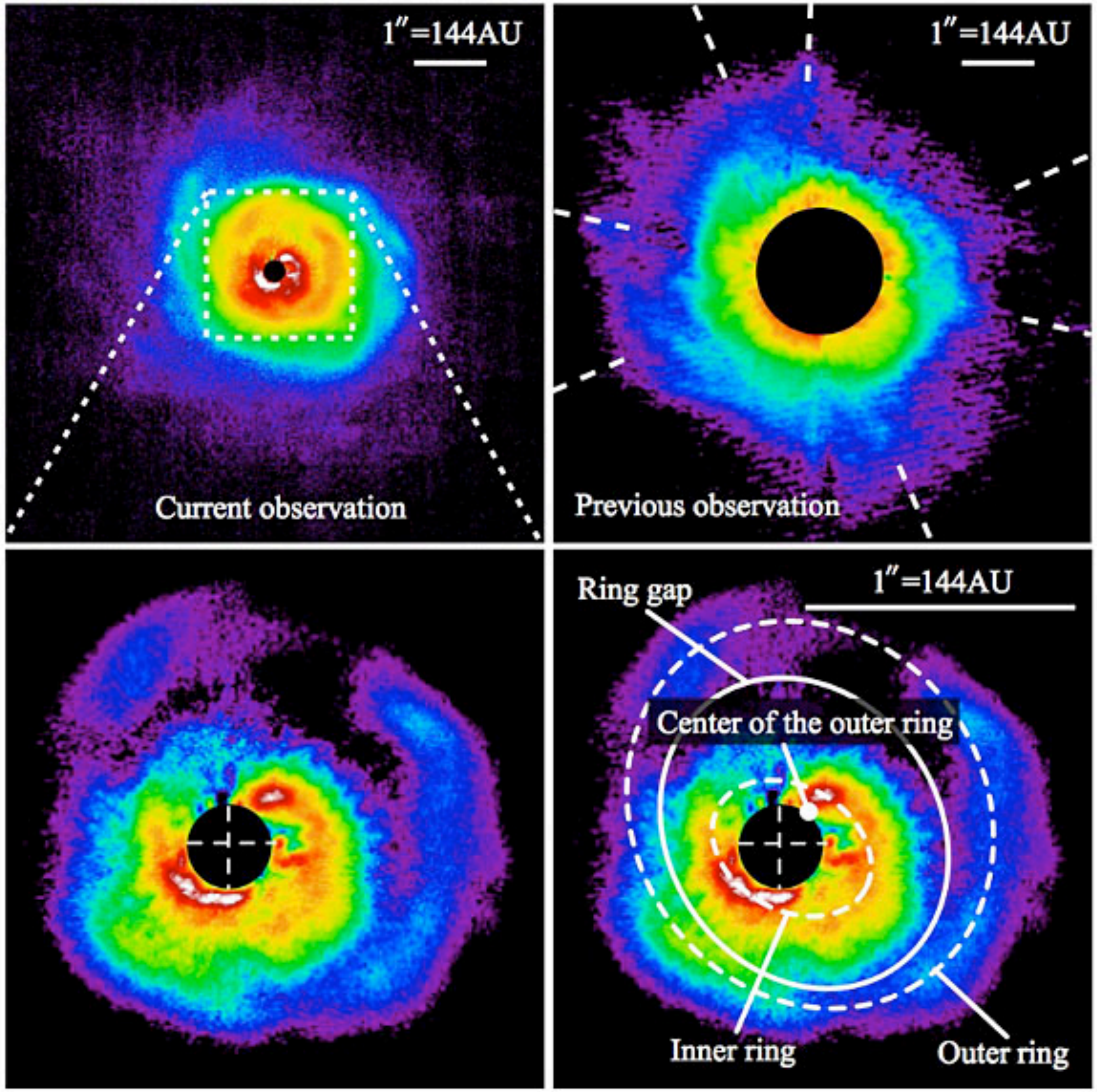
Taurus Molecular Cloud

- Optical + near-IR, Digitized Sky Survey (DSS) 2

Orion Molecular Cloud

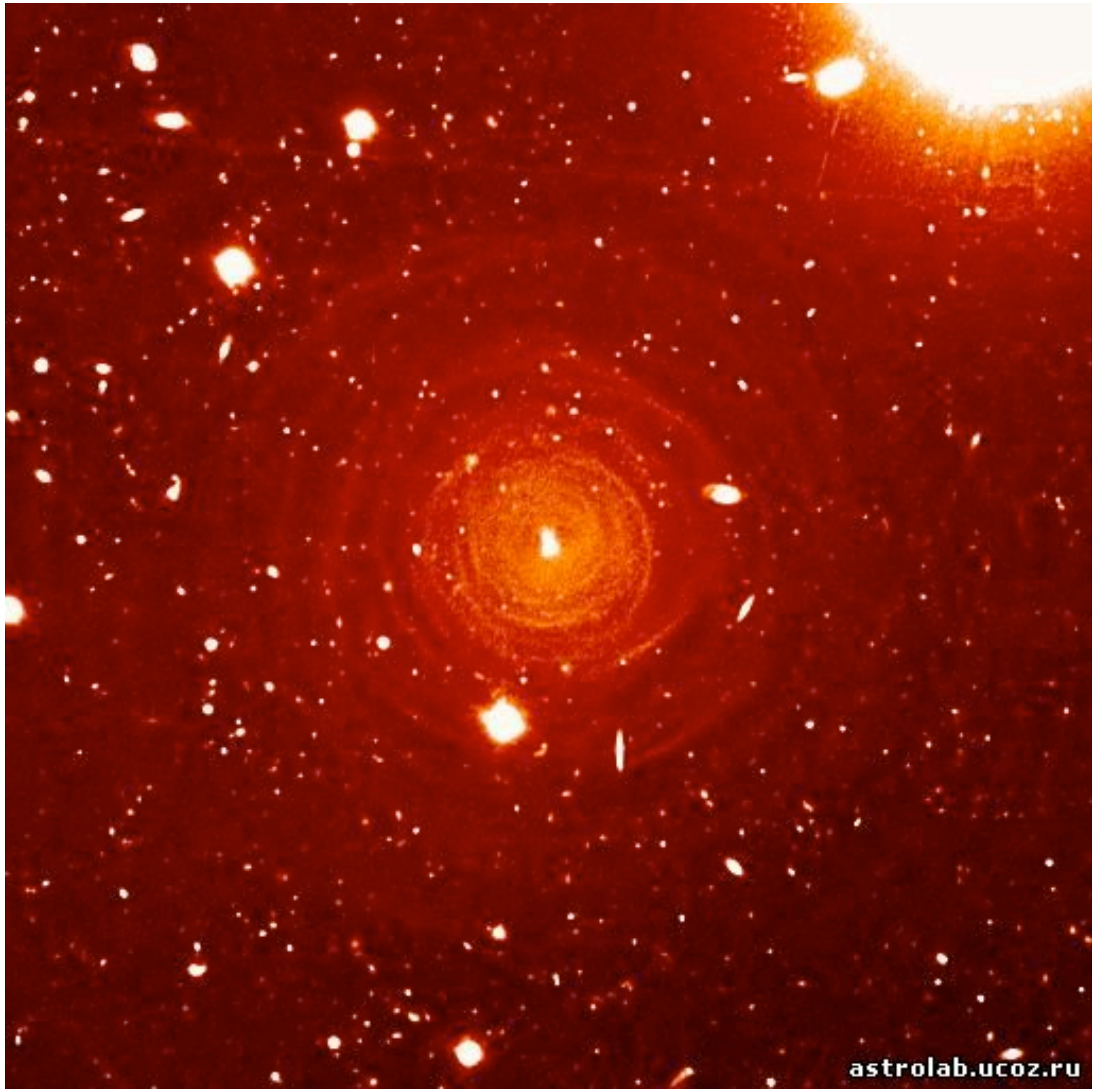
- Optical, Hubble Space Telescope

Protoplanetary disk around AB Aur



- Near-IR, HiCIAO, Subaru

CW Leo (IRC +10216)

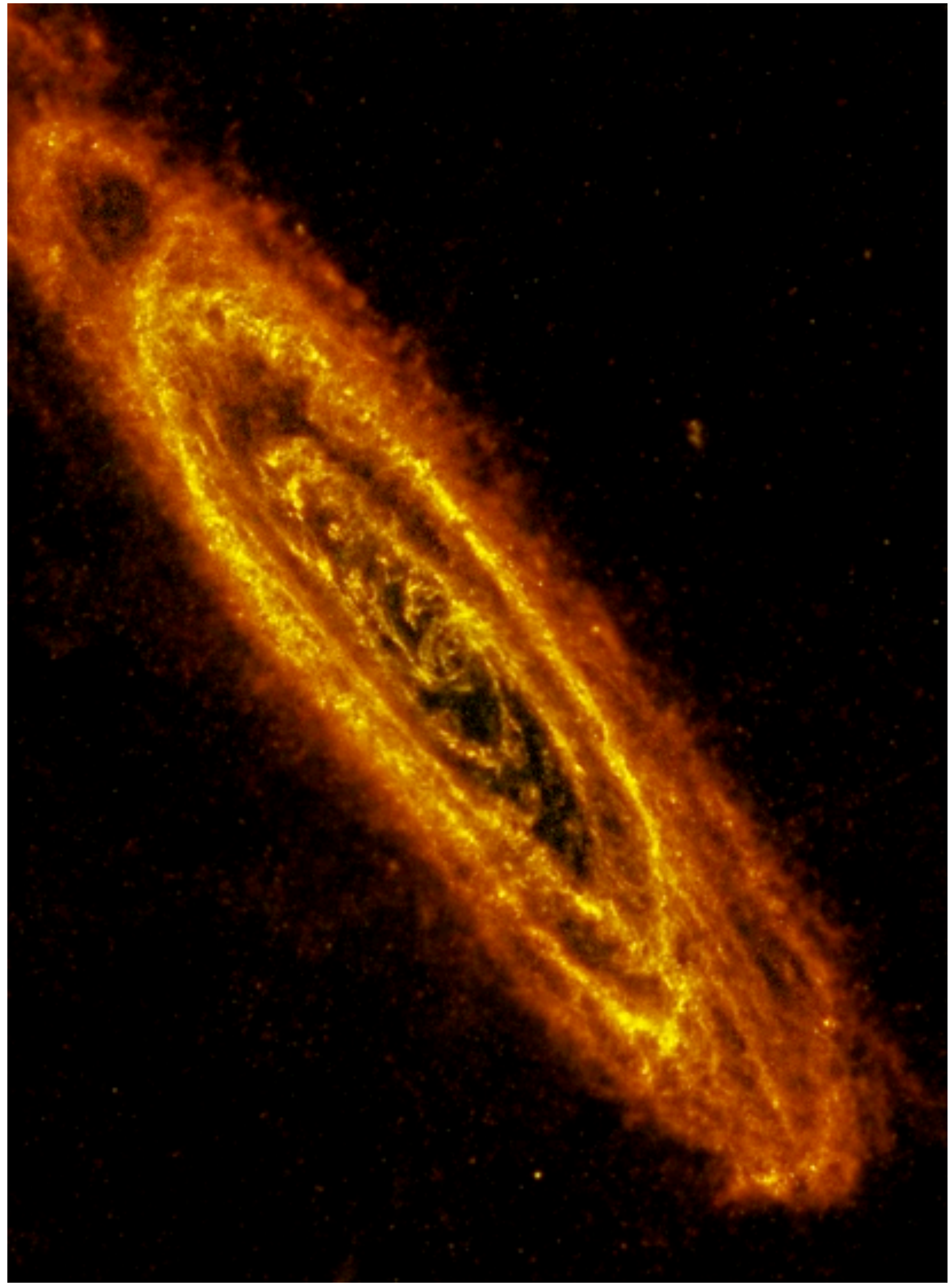


- 50-210 mum (FIR), PACS and SPIRE, Herschel

Sagittarius B2

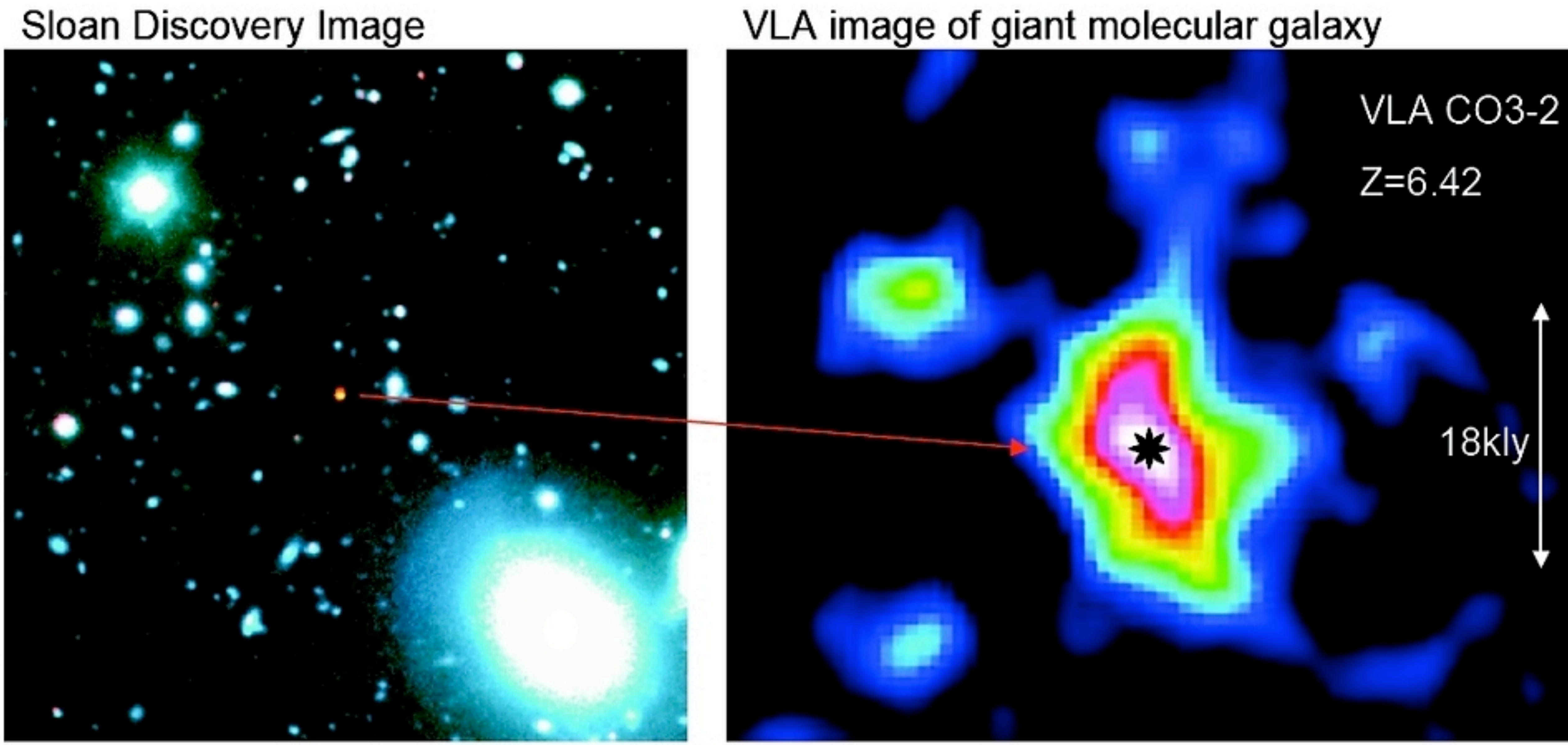
ATLASGAL, submillimeter (red) + Midcourse Space Experiment (MSX), IR (green and blue)

Andromeda Galaxy (M31)



FIR, Spire, Herschel

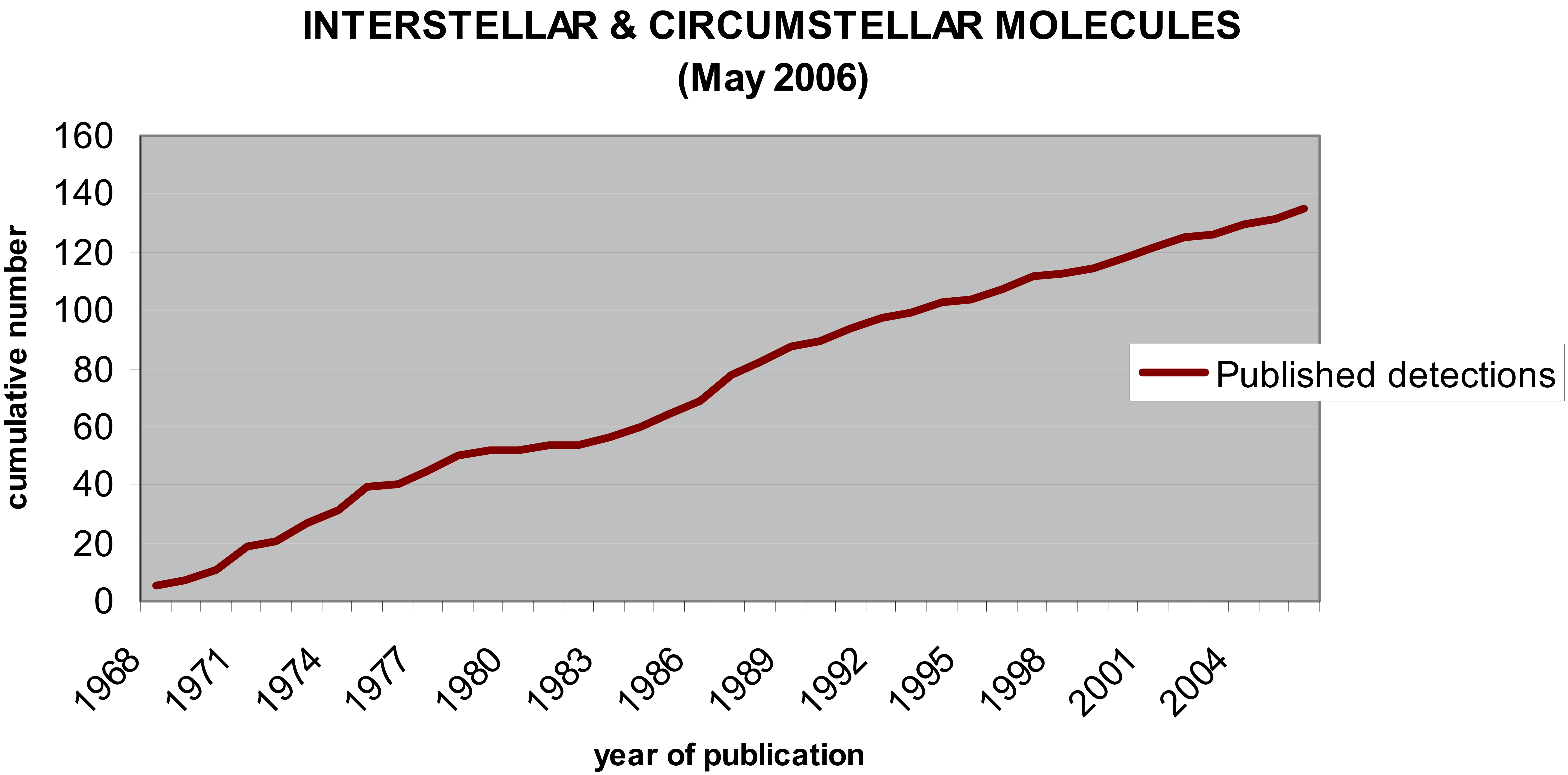
J1148+5251



J1148+5251: Coeval formation of a super massive black hole and giant elliptical galaxy within 870Myr of the Big Bang

Pause

History of molecules in space

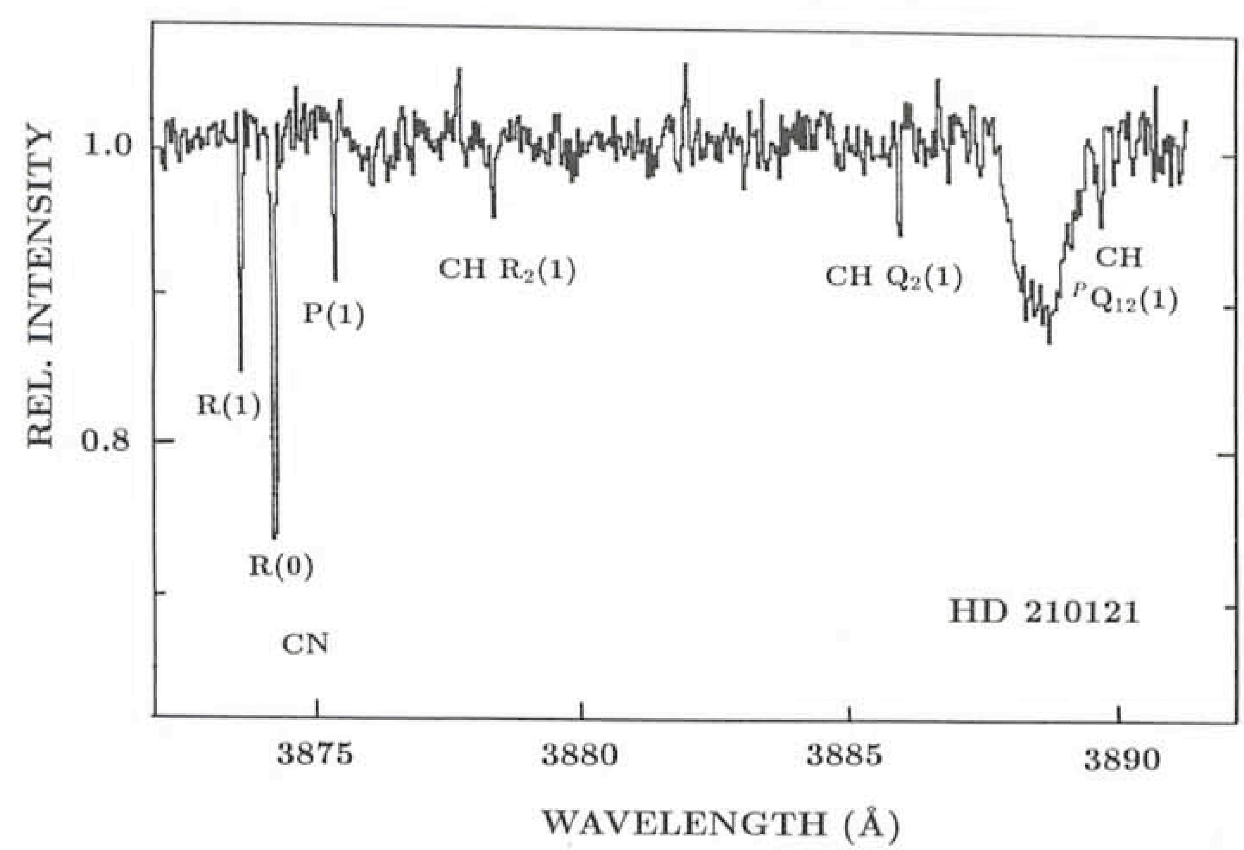


M. Guelin, Nobel Symposium, June 2006

History of molecules in space

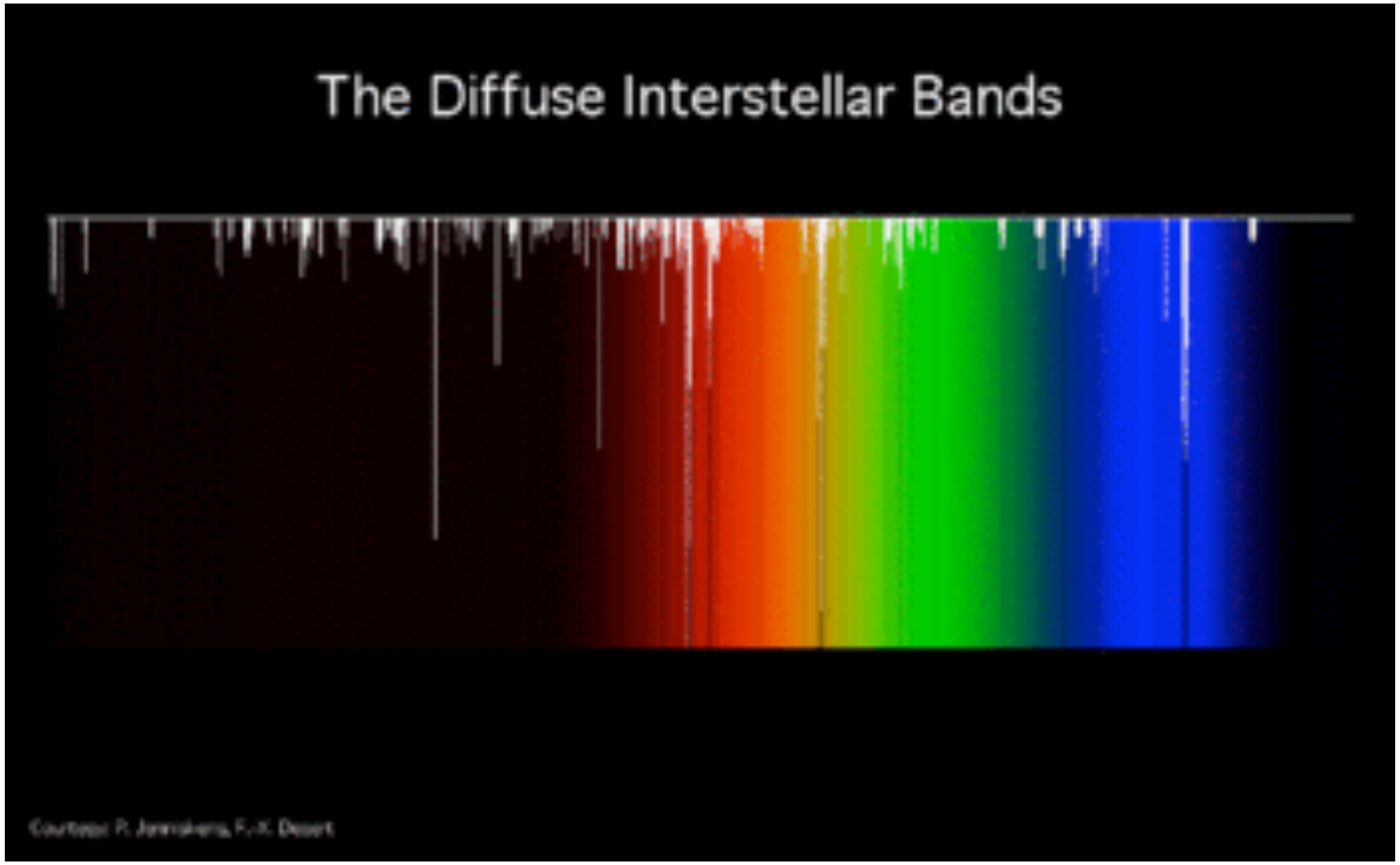
- Diffuse Interstellar Bands (DIBs), optical:
  - Discovered by Heger (1922) and Merill (1934):
  - Remains unidentified till 2012 (polyaromatic hydrocarbons?)

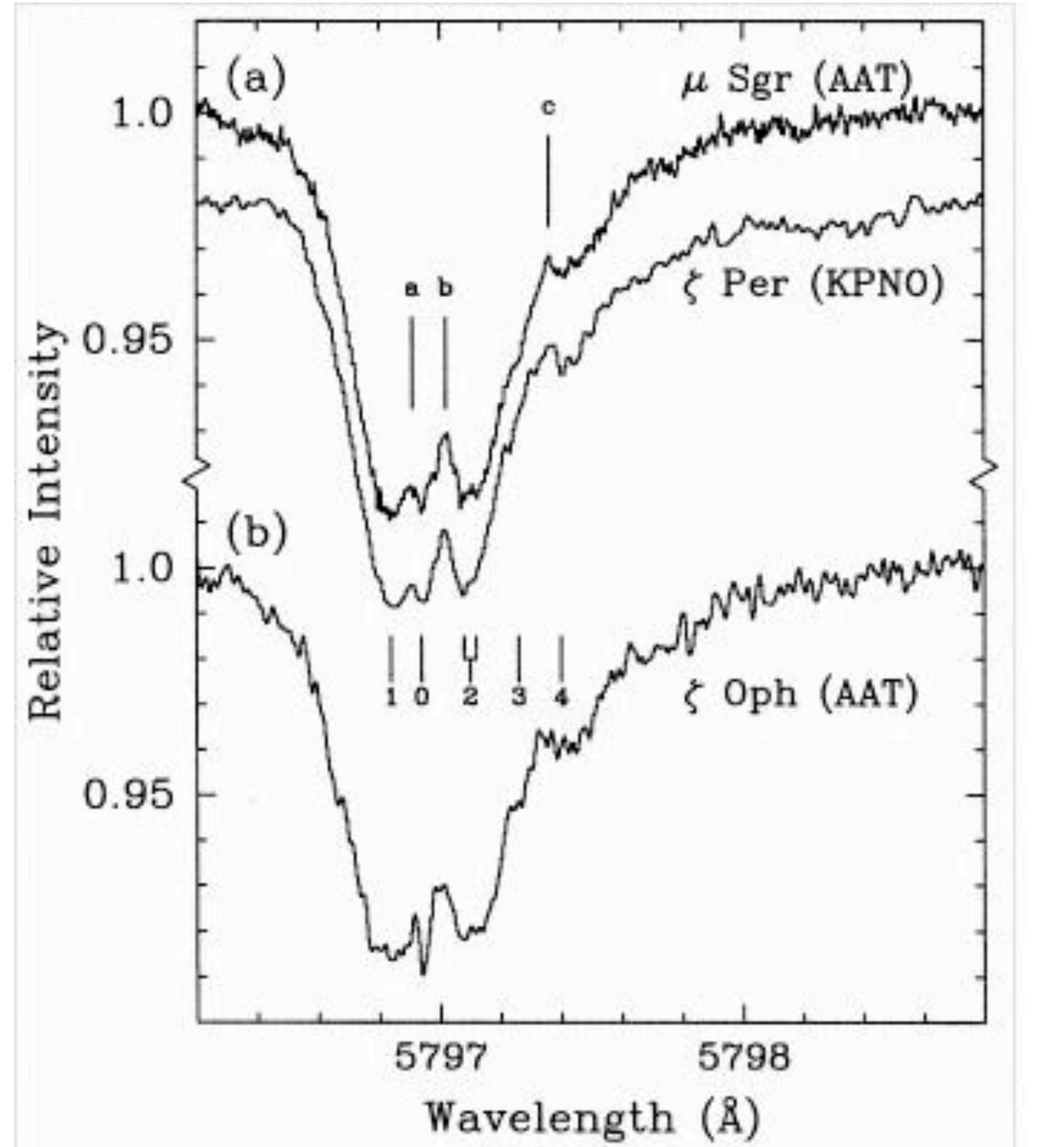
- Sharp absorption bands (optical):
  - CH: Swings & Rosenfeld (1937)
  - CN: McKellar (1940)
  - CH^+: Douglas & Herzberg (1941)



- First theory by Bates and Spitzer (1951), Herbst & Klemperer (1973)

Diffuse Interstellar Bands

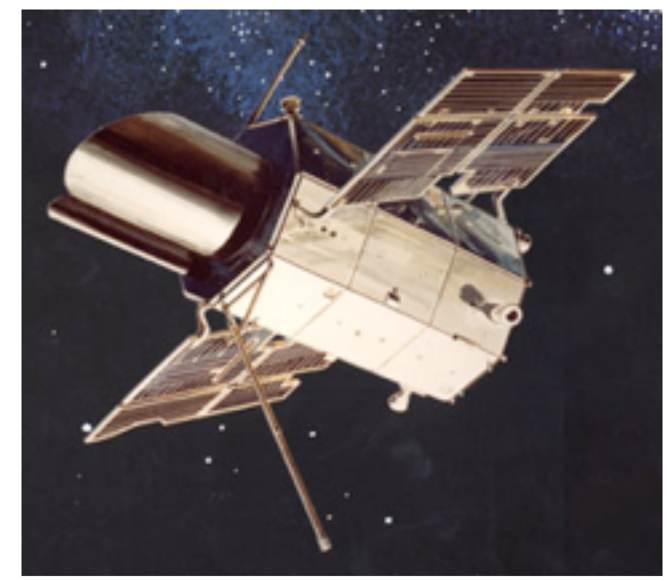




- >400 (UV–near IR), very sharp, <1 nm
- Strengths of DIBs do no correlate
- Present consensus:
  - large gas-phase molecules (PAHs?)
  - likely carbon-based
  - not dust (fine structures in spectra), albeit correlate with A_V

History of molecules in space

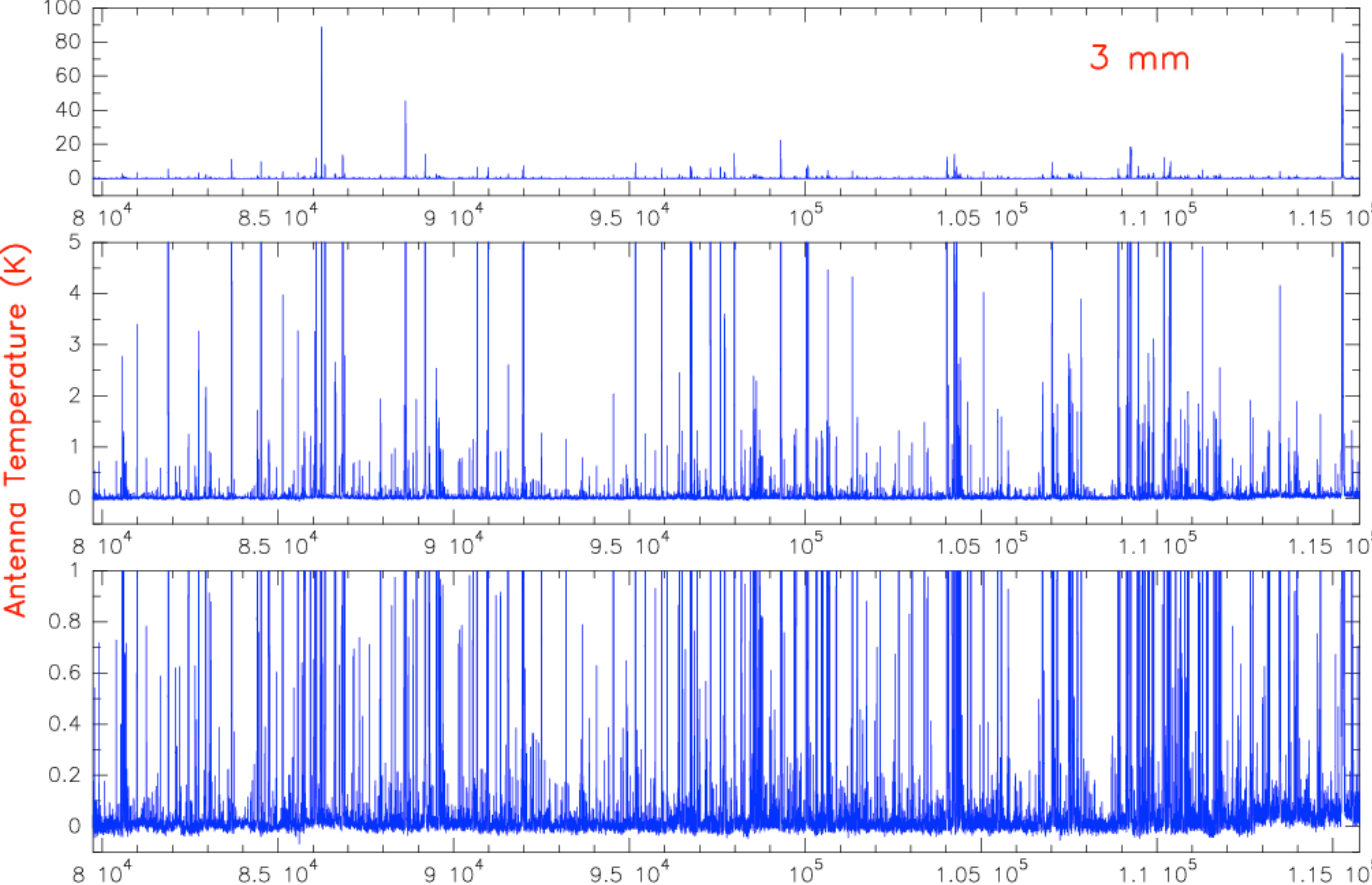
- Radio telescopes:
  - H I 21 cm: Ewen & Purcell (1951)
  - OH 18 cm: Weinreb et al. (1963)
  - NH_3 1 cm: Cheung, Townes et al. (1968)
  - H_2O 1 cm: Cheung et al. (1969)



- UV telescopes: Copernicus (1970): H_2 at ~125nm (1970), later N_2

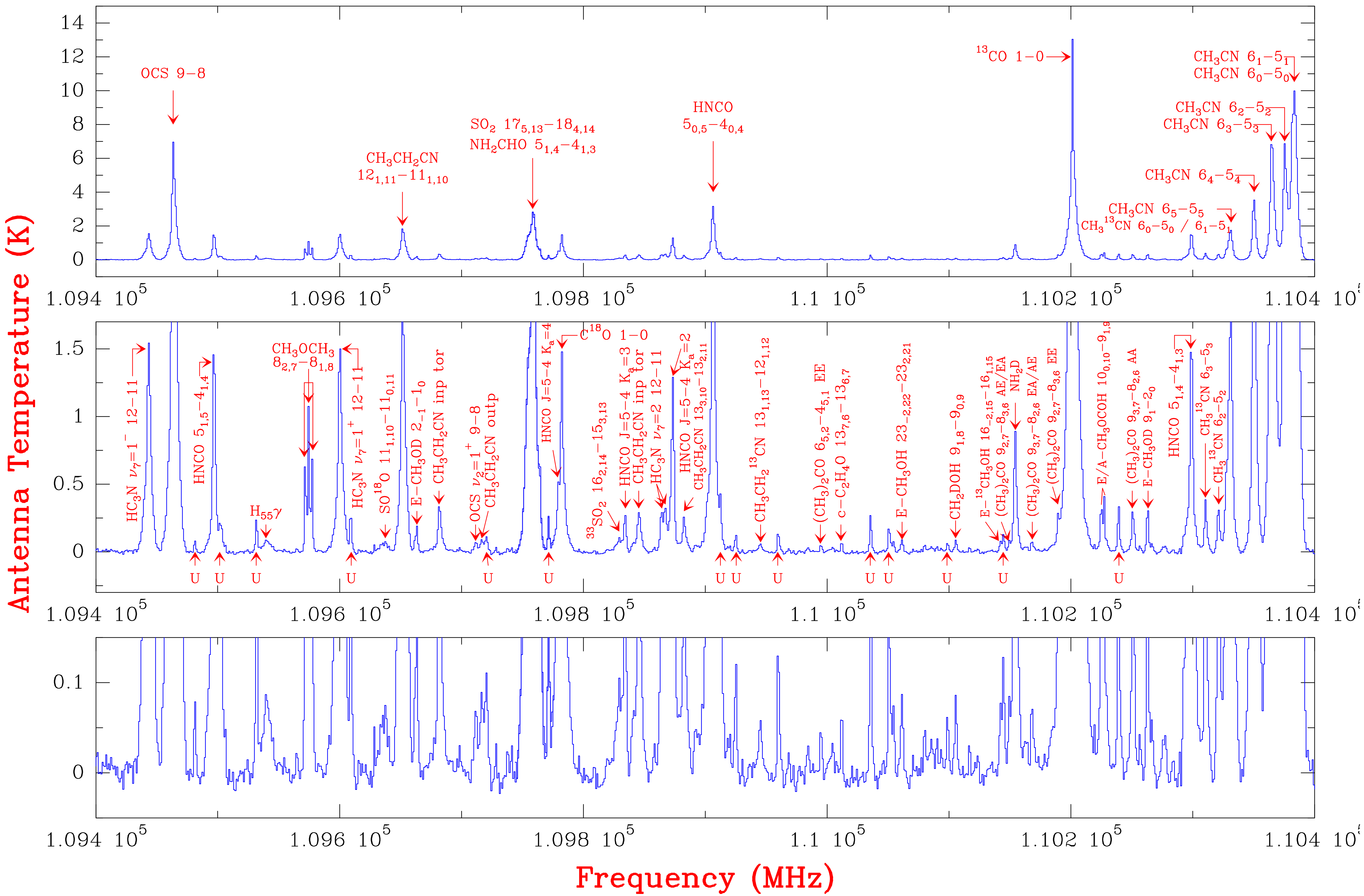
- (Sub-)millimeter telescopes: CO at 115 GHz (1970), H_2CO (1970), and many others

Orion KL Survey, 3 mm, IRAM 30-m



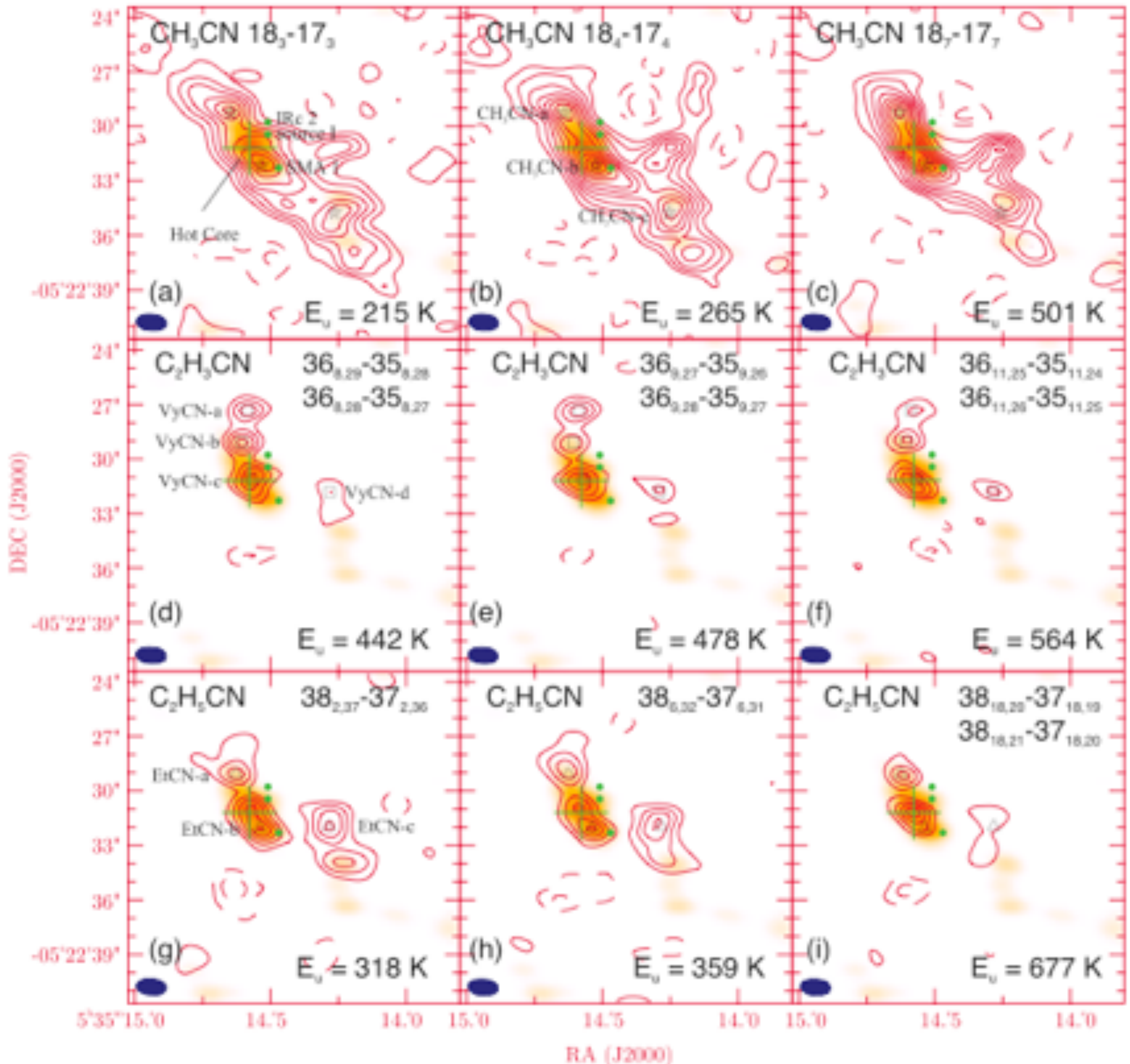
Tercero et al. (2010)

Orion KL Survey, 3 mm, IRAM 30-m



Tercero et al. (2010)

Orion KL map, 1mm, Submillimeter Array



Wang et al. (2008)

History of molecules in space

- IR telescopes:

  - IRAS (1983): 0.6 m, 12–100 μm, first sky survey, dust (β Pictoris disk)

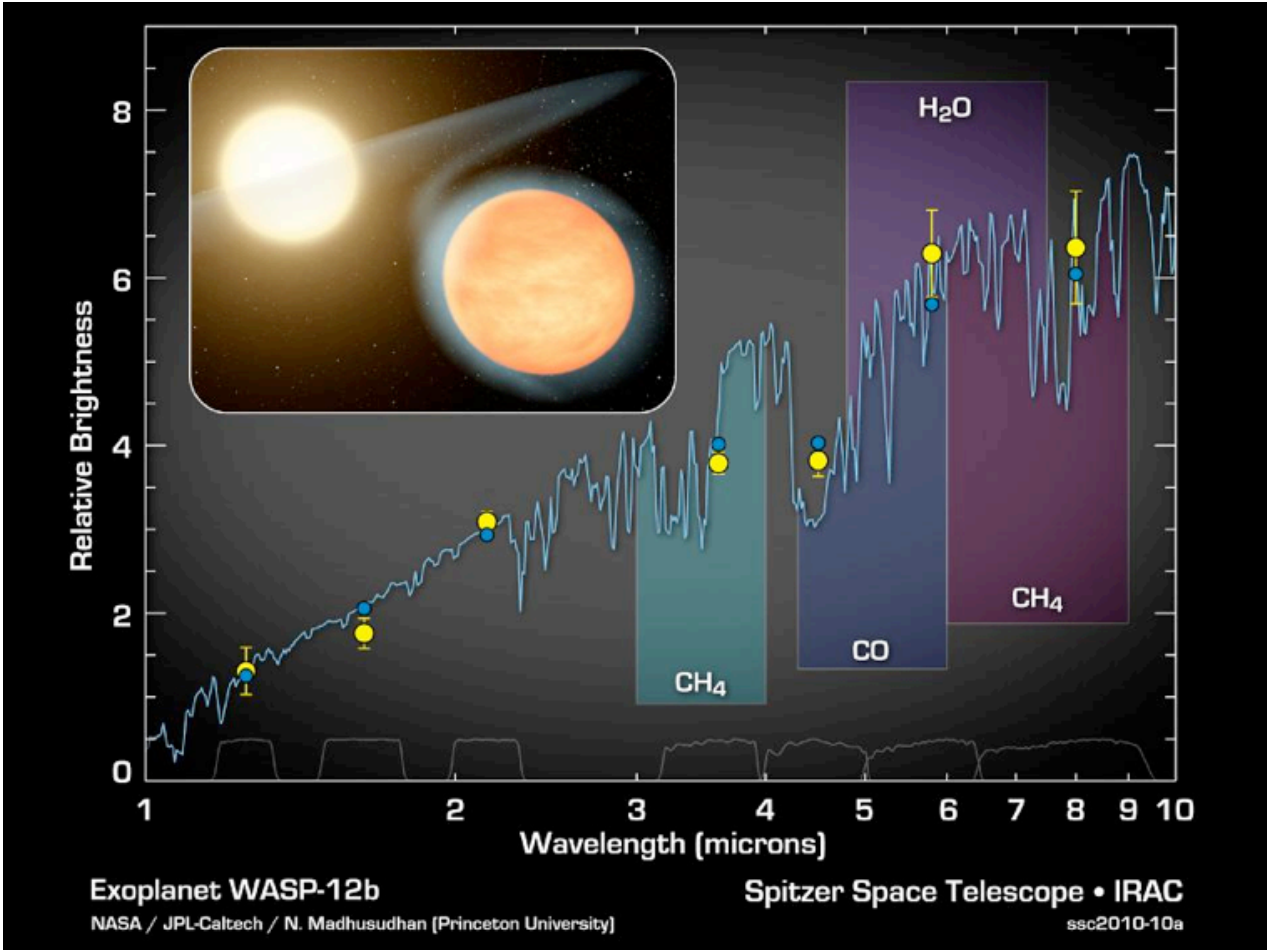
  - Infrared Space Observatory (1995–1998): 0.6 m, 2.5–240 μm, dust & molecules (H_2O, HF, OH, OI, C_6H_6, CH_3, CO_2, ...), infrared cirrus clouds

  - Spitzer Space Telescope (2003–2009): 0.8 m, 3–180 μm, high-sensitivity imaging and mapping, dust & molecules (OH, H_2O, C_2H_2, ...)

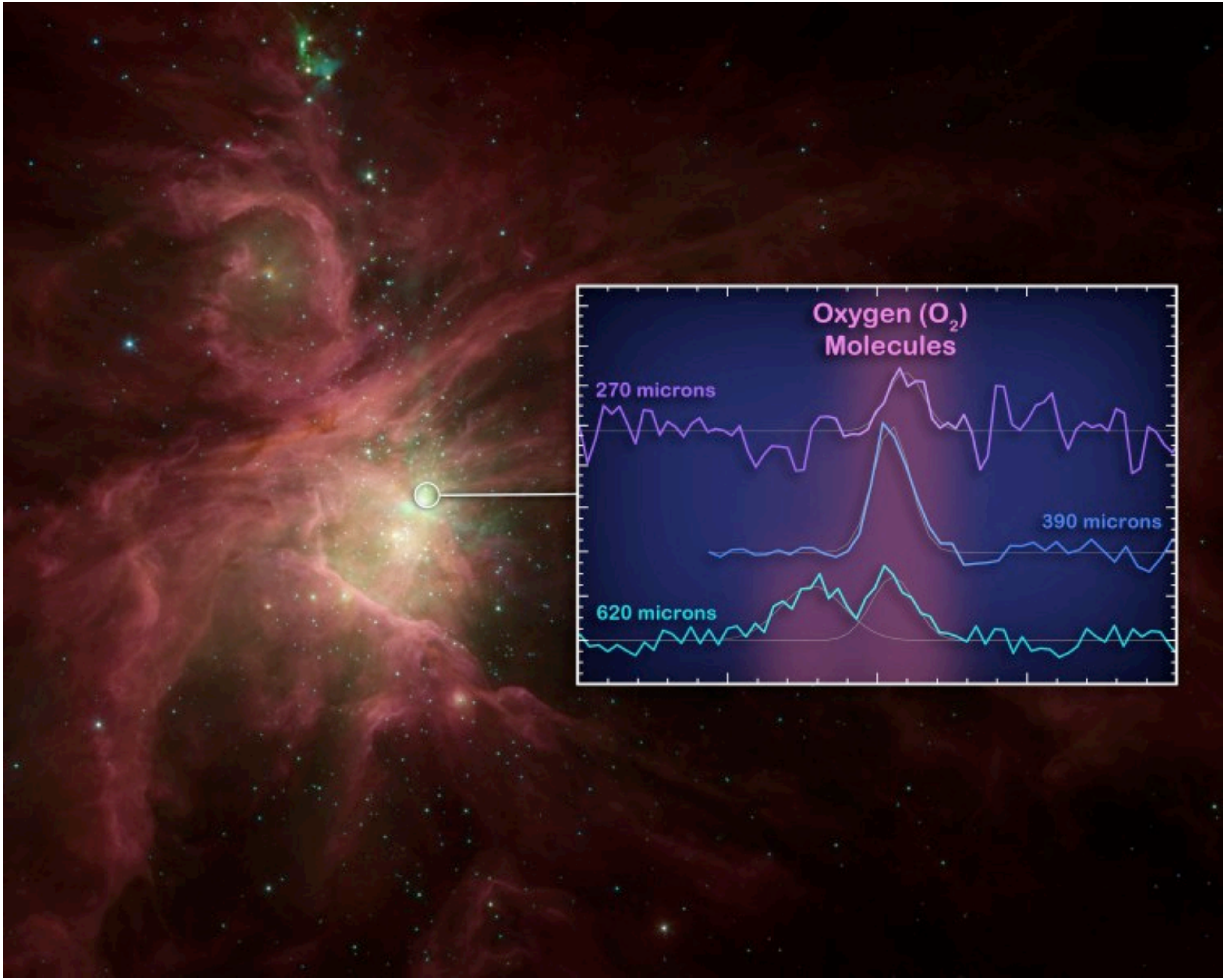
  - Herschel Space Observatory (2009–2012): 2.4 m, 60–670 μm, high-sensitivity imaging and mapping, dust & molecules (CH_3OH, H_2S, HCN, SO_2, H_2CO, H_2O, ...)

  - Ground-based: Keck, VLT, ...

Molecules, exoplanet WASP-12b, Spitzer



O_2 in Orion, 487–1121 GHz, Herschel



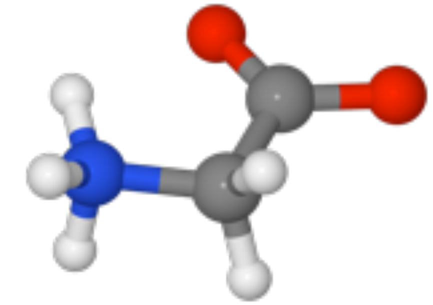
Goldsmith et al. (2011)

Detected molecules (~170)

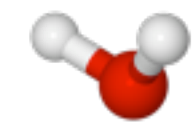
H2	**H3+**	CH3	CH4	CH3OH	CH3NH2	HCOOCH3	(CH3)2O	(CH3)2CO
CO	CH2	NH3	CH2NH	CH3SH	CH3CCH	CH3C3N	C2H5OH	CH3C5N
CS	NH2	**H3O+**	**H2CCC**	C2H4	CH3CHO	HC6H	C2H5CN	CH3CH2CHO
CN	H2O	H2CO	c-C3H2	CH3CN	c-CH2OCH2	**C7H**	CH3C4H	(CH2OH)2
C2	H2S	H2CS	CH2CN	CH3NC	CH2CHCN	HOCH2CHO	**C8H**	HCOOC2H5
CH	**CCH**	c-C3H	NH2CN	CH2CHO	**HC5N**	CH3COOH	**HC7N**	**HC9N**
CH+	**HCN**	**l-C3H**	CH2CO	NH2CHO	**C6H**	H2CCCHCN	CH3CONH2	CH3C6H
HF	HNC	C2H2	HCOOH	HC3NH+	CH2CHOH	**H2C6**	CH3CHCH2	C6H6
CF+	HCO	**HCNH+**	**C4H**	**H2CCCC**	**C6H-**	CH2CHCHO	**C8H-**	C3H7CN
SiO	**HCO+**	H2CN	**HC3N**	**C5H**		NH2CH2CN		**HC11N**
SiS	**HOC+**	HCCN	HCCNC	HC4H				C2H5OCH3
SiC	**N2H+**	HNCO	HNCCC	HC4N				
SiN	HNO	HOCN	**H2COH+**	c-C3H2O				
NH	**HCS+**	HCNO	**C4H-**	CH2CNH				
NO	**C3**	HNCS	SiH4	**C5N-**				
SO	**C2O**	HSCN	**C5**	**C5N**				
SO+	**C2S**	**C3N**	**SiC4**					
CP	SO2	**C3O**	CNCHO					
PO	N2O	**C3S**						
PN	CO2	**C3N-**						
HCl	**H2O+**	**HCO2+**						
KCl	**H2Cl+**	CNCHO						
AlCl	OCS	C-SiC2						
OH	MgNC				AlF	AlNC	AlOH	NaCl
OH+	MgCN				SiNC	CCP	HCP	FeO
SH	NaCN				CO+	O2	N2	
CN-	SiCN							

http://www.astro.uni-koeln.de/cdms/molecules

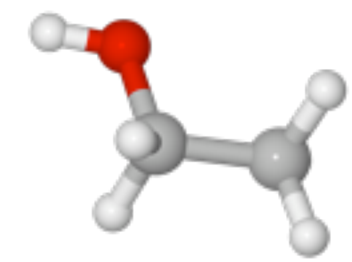
Detected molecules



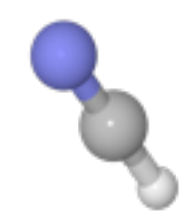
- 170 interstellar & circumstellar molecules
- 41 extragalactic molecules
- Up to 11 atoms (since 2010 => 70)!



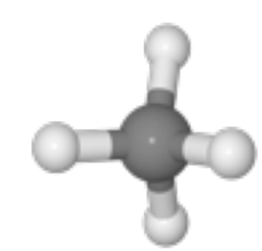
- 20 positive ions (cations)
- 6 negative ions (anions)



- ~30 free radicals
- ~20 isomers
- 6 linear and 6 cyclic species (including simplest PAH, C_6H_6)

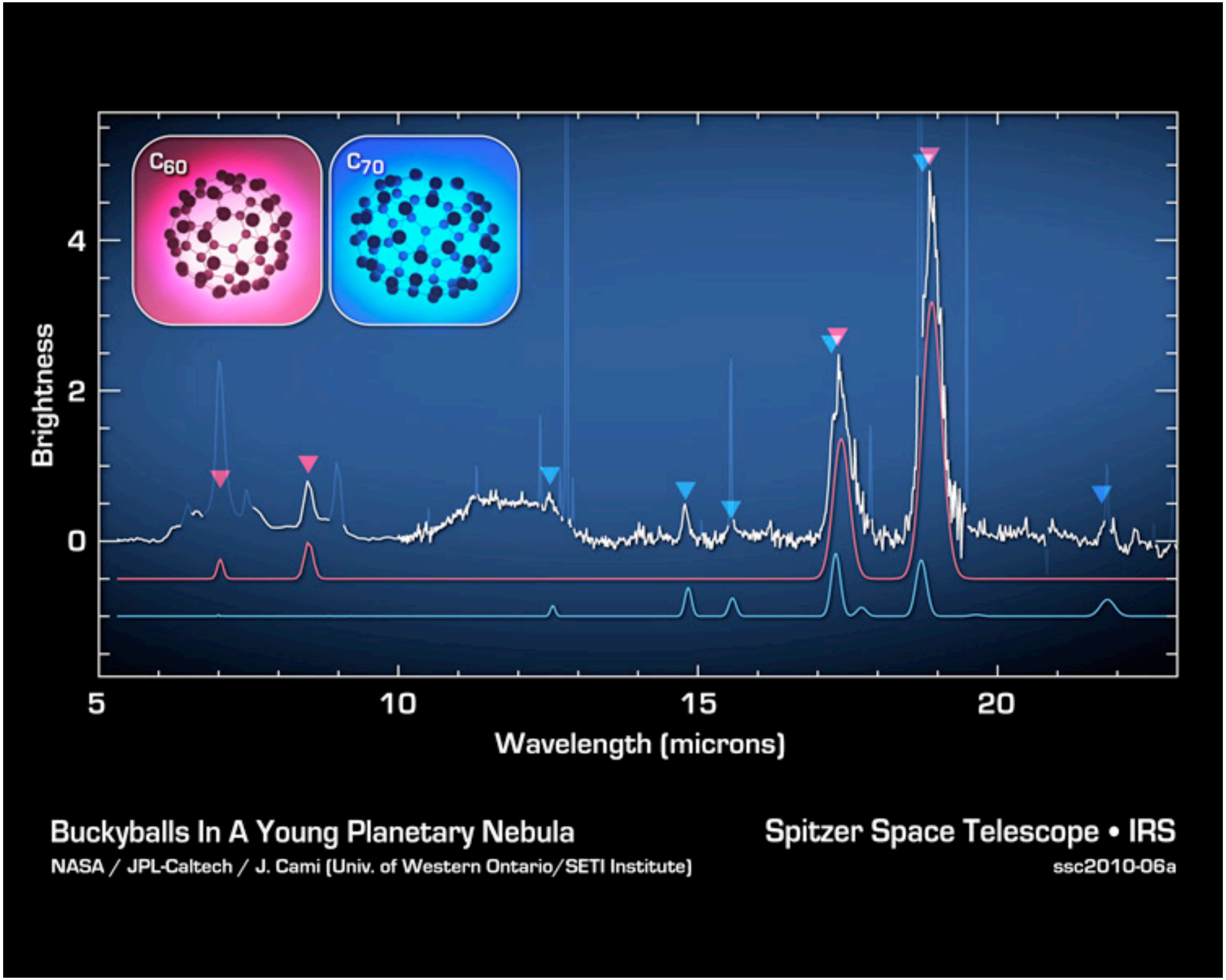


- 11 Si-, 6 P-, and 5 Cl-bearing species
- 11 metal-bearing species
- 10 species with deuterium

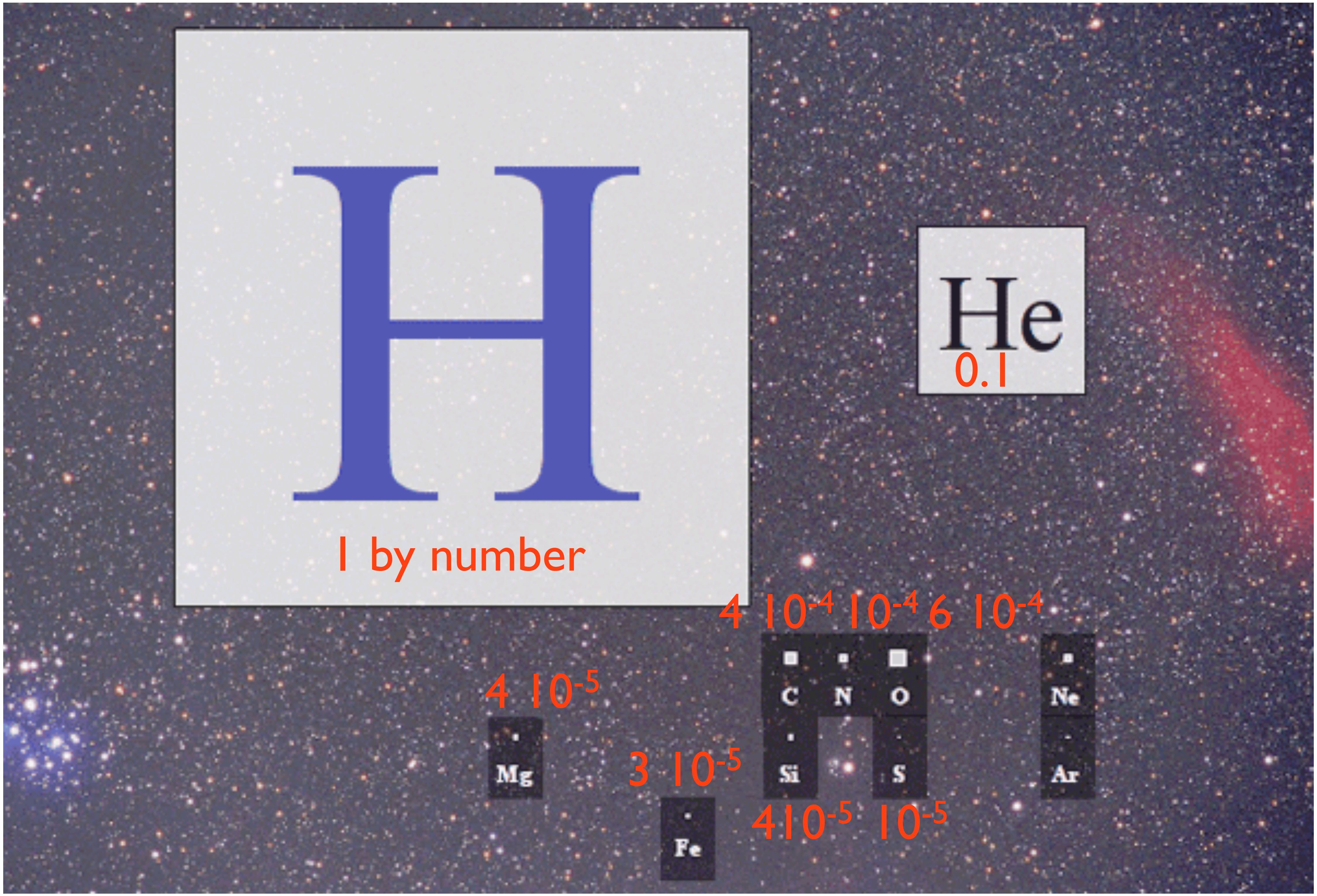


- Organic molecules: ethers, acids, alcohols, aldehydes, ...

Detection of fullerenes (C_{60} & C_{70})



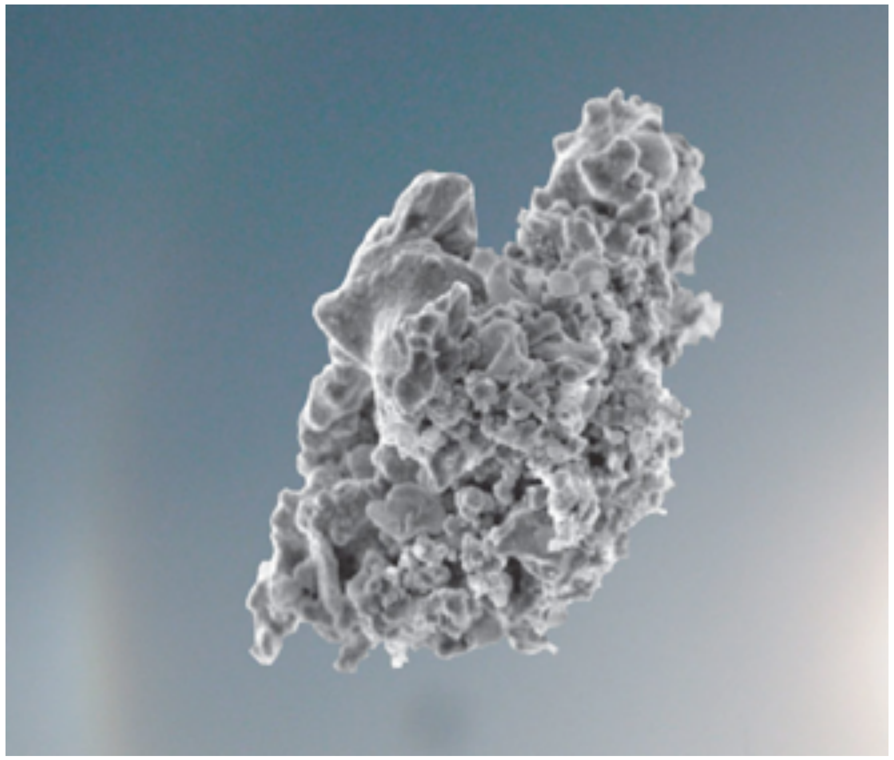
Astronomer's periodic table

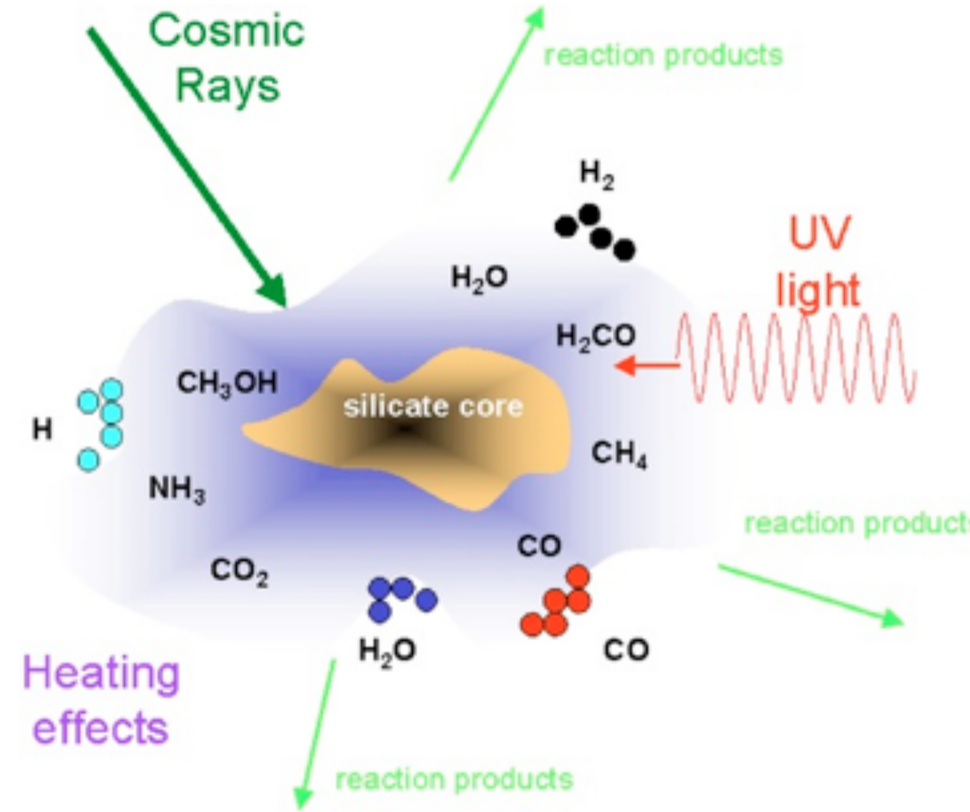


- 99% gas, 1% dust (by mass), depletion of refractory elements

McCall (2001)

Interstellar Dust





- Formed in AGB stars & grow in the ISM/CSM
- Small, ~0.01–1 μm
- Silicate core, with refractory materials (most of Si, Mg, Fe)
- Carbonaceous material (~30% of O, ~60% of C)
- Abundance ~10^{-12} wrt to H_2
- T_{kin} <150 K: condensation of gas => icy mantles

How molecules form, survive, and "shine"?

Next lectures!