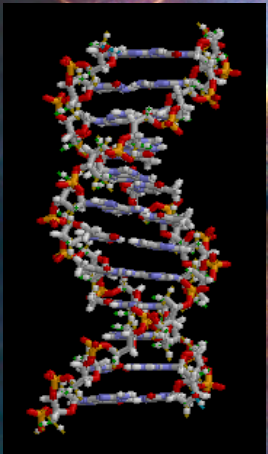
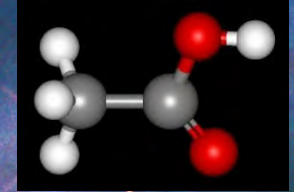
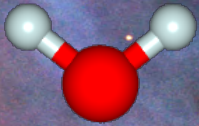


Op zoek naar de bouwstenen van planeten en leven tussen de sterren



Ewine F. van Dishoeck
Sterrewacht Leiden



NGL lezing, Leiden, 18 oktober 2018

Oorsprong van sterren en planeten fascineert de mensheid

Starry night
Van Gogh

Stars
Kandinsky

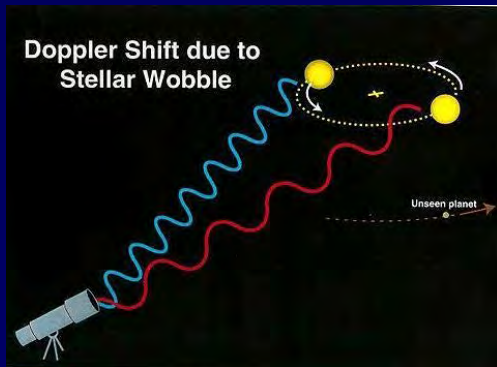
Raven stealing Sun
Pacific Northwest art

Milky Way dreaming
Australia aboriginal art

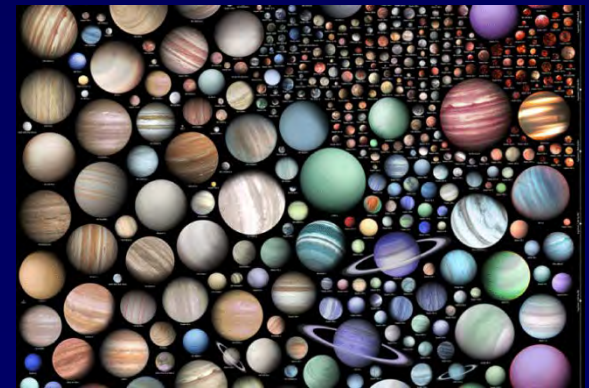
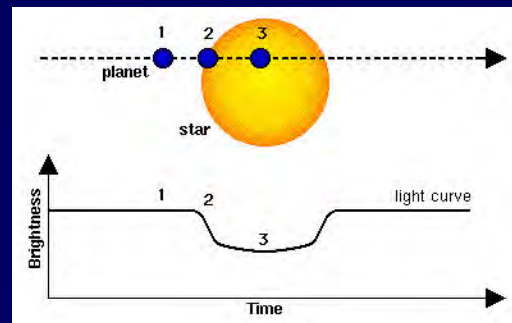
‘Waar komen we vandaan?’
‘Wat is onze plaats in het universum?’

Ontdekking van exo-planeten maakt eeuwenoude vragen actueel

- Waar worden sterren en planeten gevormd?
- Hoe uniek is ons zonnestelsel?
- Welke planeten zouden bewoonbaar kunnen zijn?

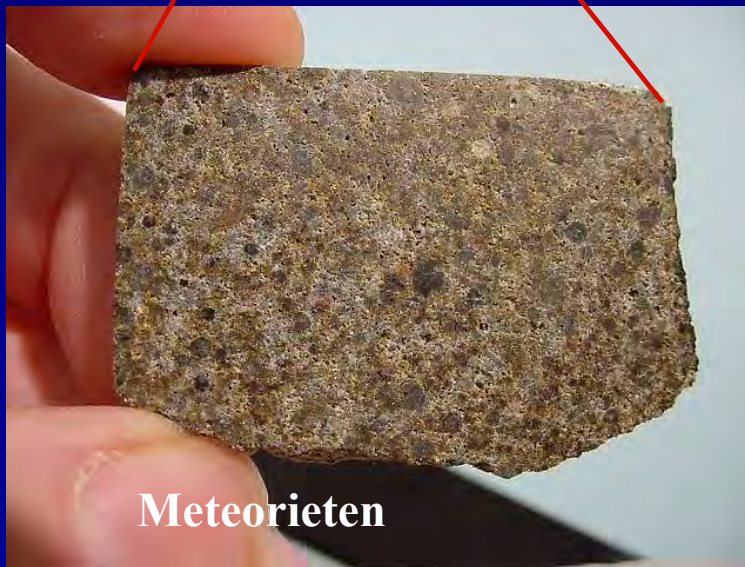
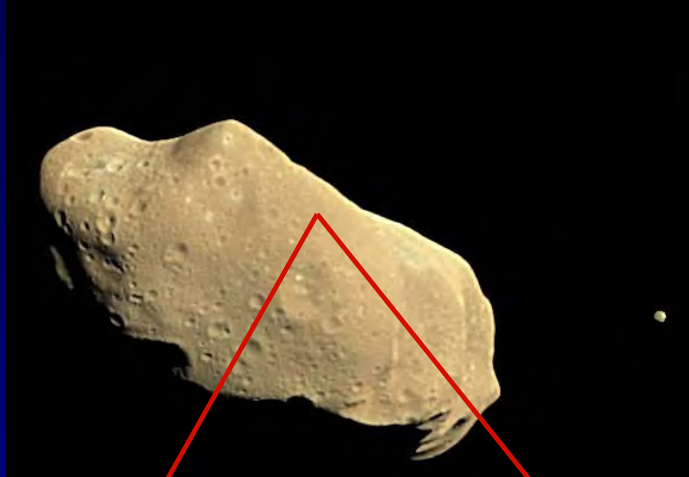


Exoplanet.org



Kepler

Kernvraag: hoe zijn 'wij' 4.5 miljard jaar geleden gevormd?



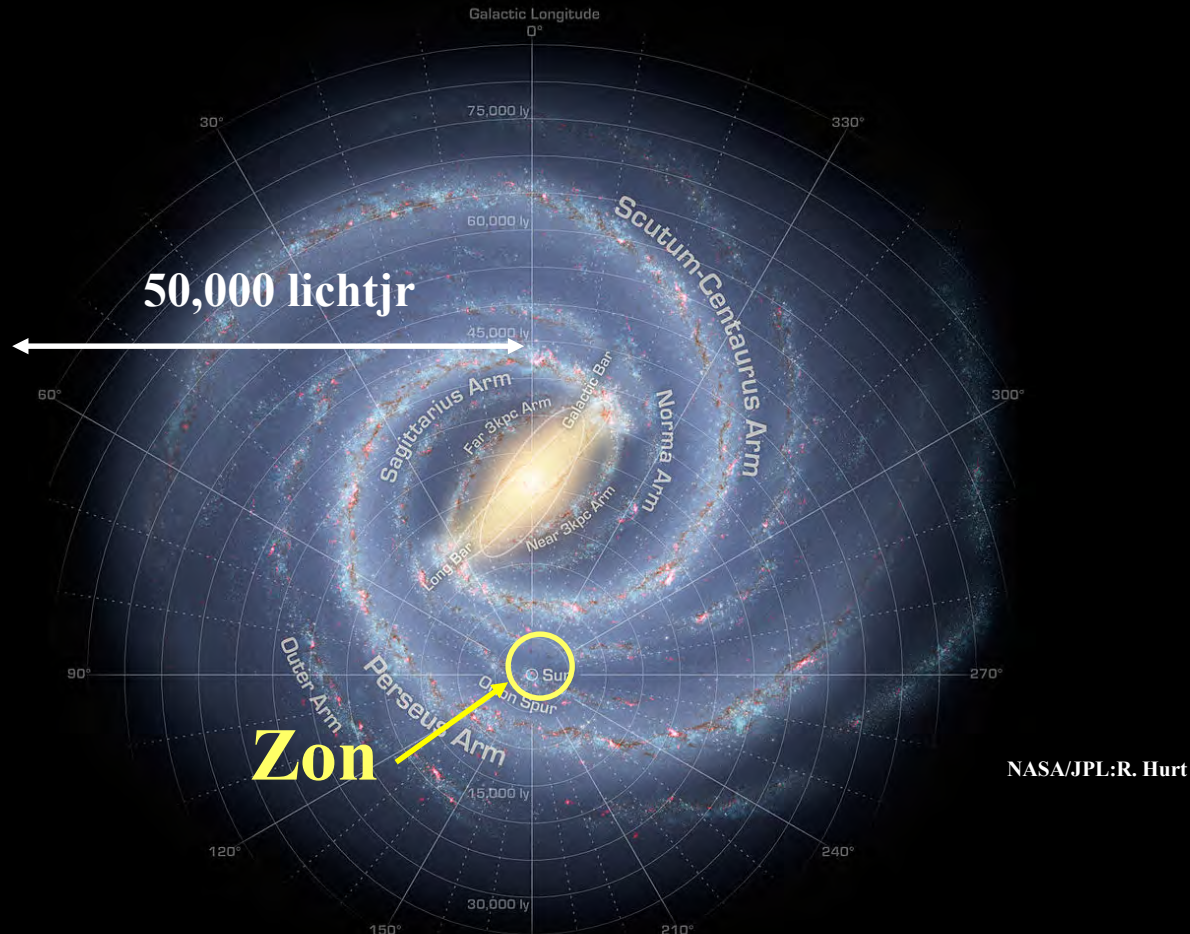
Meteorieten en kometen zijn bodes uit het vroege zonnestelsel

Kraamkamers van sterren:

Interstellaire wolken

- **Ruimte tussen de sterren is niet leeg, maar is gevuld met heel ijl gas**
- **Sterren worden geboren in de dichtere concentraties van het gas (=wolken)**

Onze Melkweg



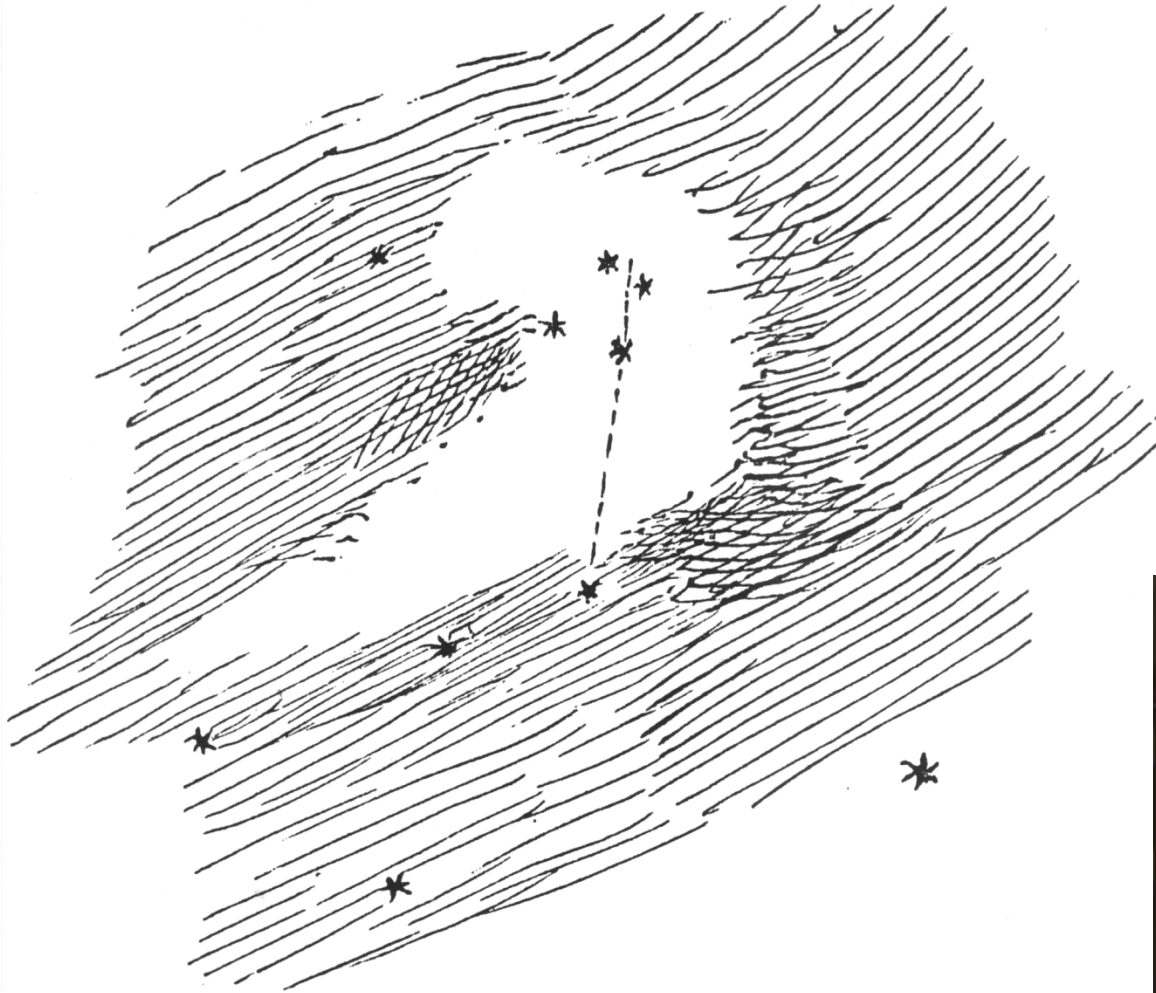
Onze zon is 1 van de honderden miljarden sterren in de Melkweg

Wij wonen op een kleine rotsblok die rond een doodgewone ster cirkelt ergens in de buitenwijken van 1 van de honderden miljarden sterrenstelsels



AAT

Orion Nevel



Christiaan Huygens (1694)



Orion nevel:

Duizenden jonge sterren



ESO-VLT ISAAC
McCaughrean et al. 2001

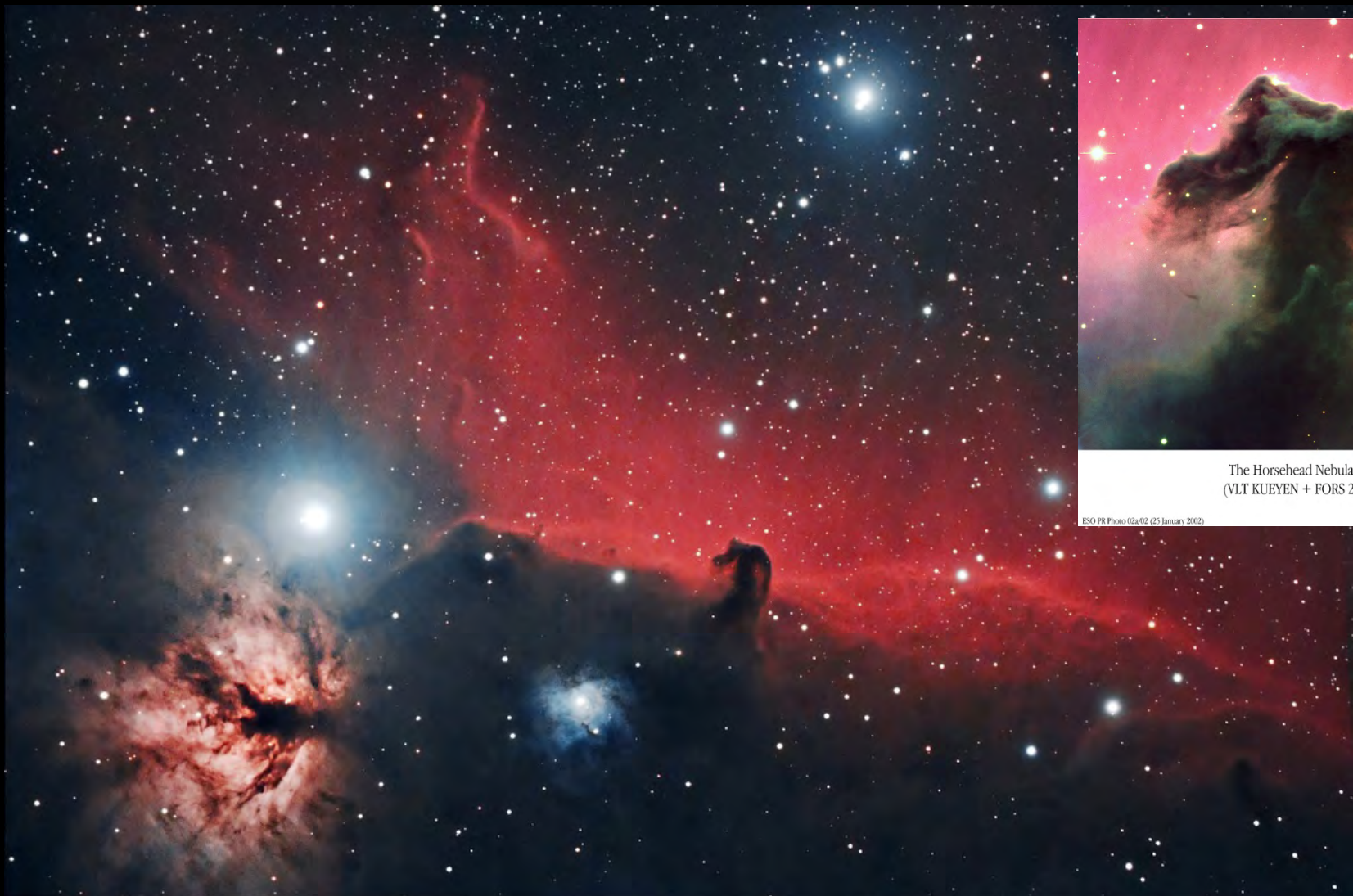
'The chaotic material of future Suns'

W.Herschel (1789)

Orion nevel met de Hubble Space Telescope



Paardekop nevel



The Horsehead Nebula
(VLT KUEYEN + FORS 2)

ESO PR Photo 02a/02 (25 January 2002)

© European Southern Observatory



Moleculaire wolken



- **Sterren worden gevormd in de koude, dichte concentraties van het gas**
- **Wolken hebben voldoende massa om 10^5 sterren te vormen (efficiëntie paar %)**

Donkere wolken: 'kolenzakken'



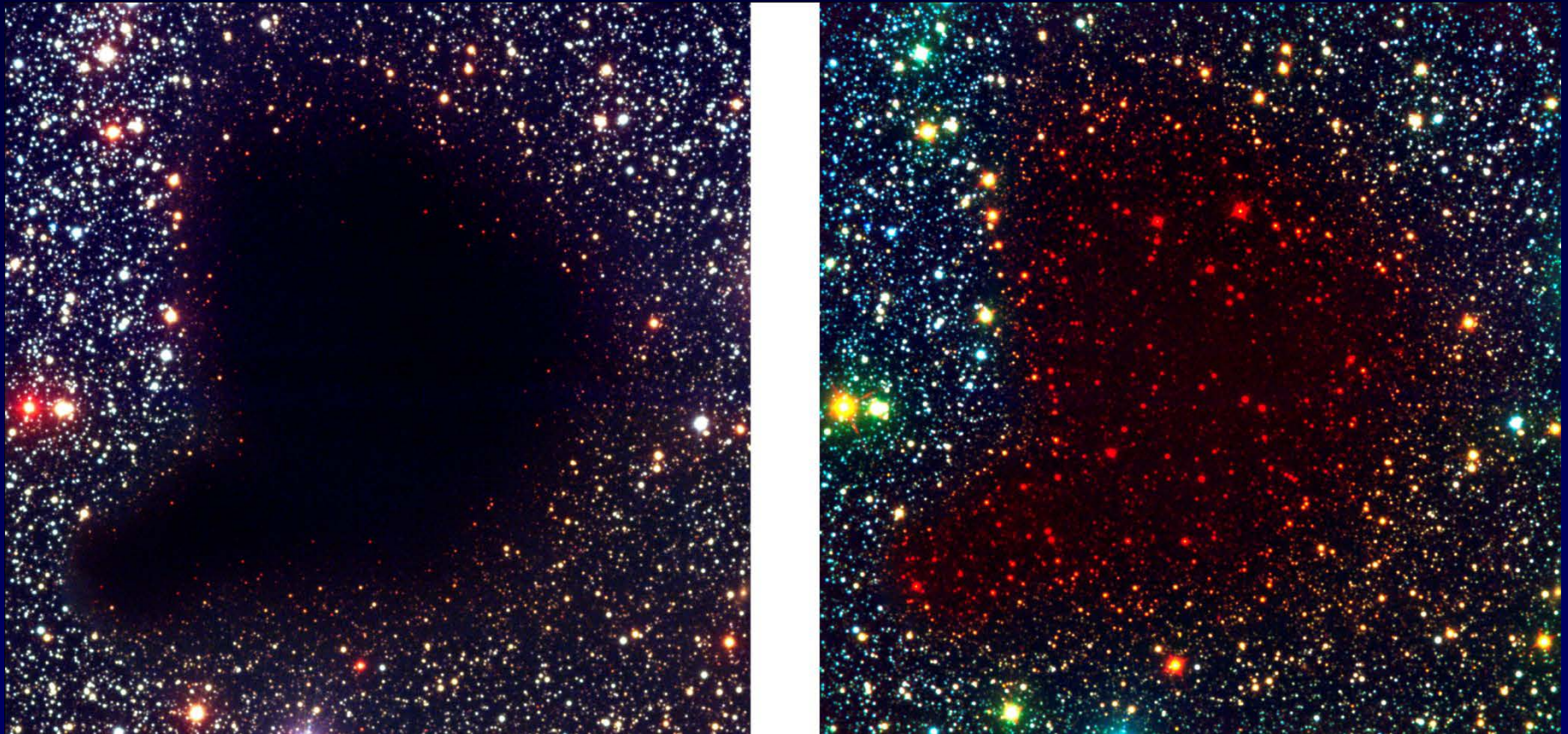
- 99% gas (H_2)
1% stof (0.1 micron silicaten 'zand')
- Temperatuur: ~ 10 K (-263° C)
- Dichtheid: ~ 10000 deeltjes per kubieke cm (miljoen keer minder dan in lab)

→ *Uniek chemisch laboratorium!*

Hoe onderzoeken we wat er in die wolk gebeurt?

Optisch

Infrarood



ESO/VLT; Alves et al.



Langere golflengten!

Van zichtbaar naar infrarood licht

HH 46 protoster

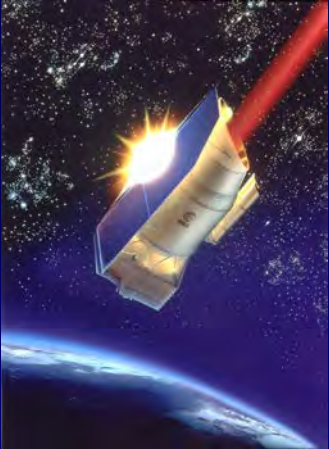


Spitzer/NASA
Noriega-Crespo et al. 2004

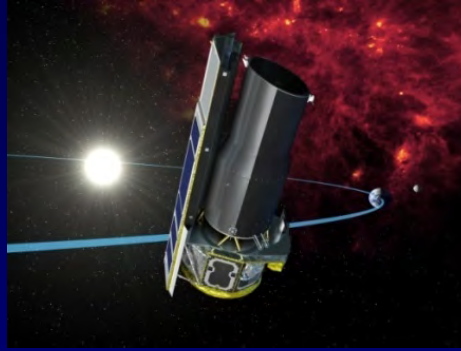


Jonge ster is alleen zichtbaar in infrarood

Fantastische telescopen bij IR en mm golflengten



ISO
SRON: SWS



Spitzer



Herschel
SRON HIFI: water!



JCMT



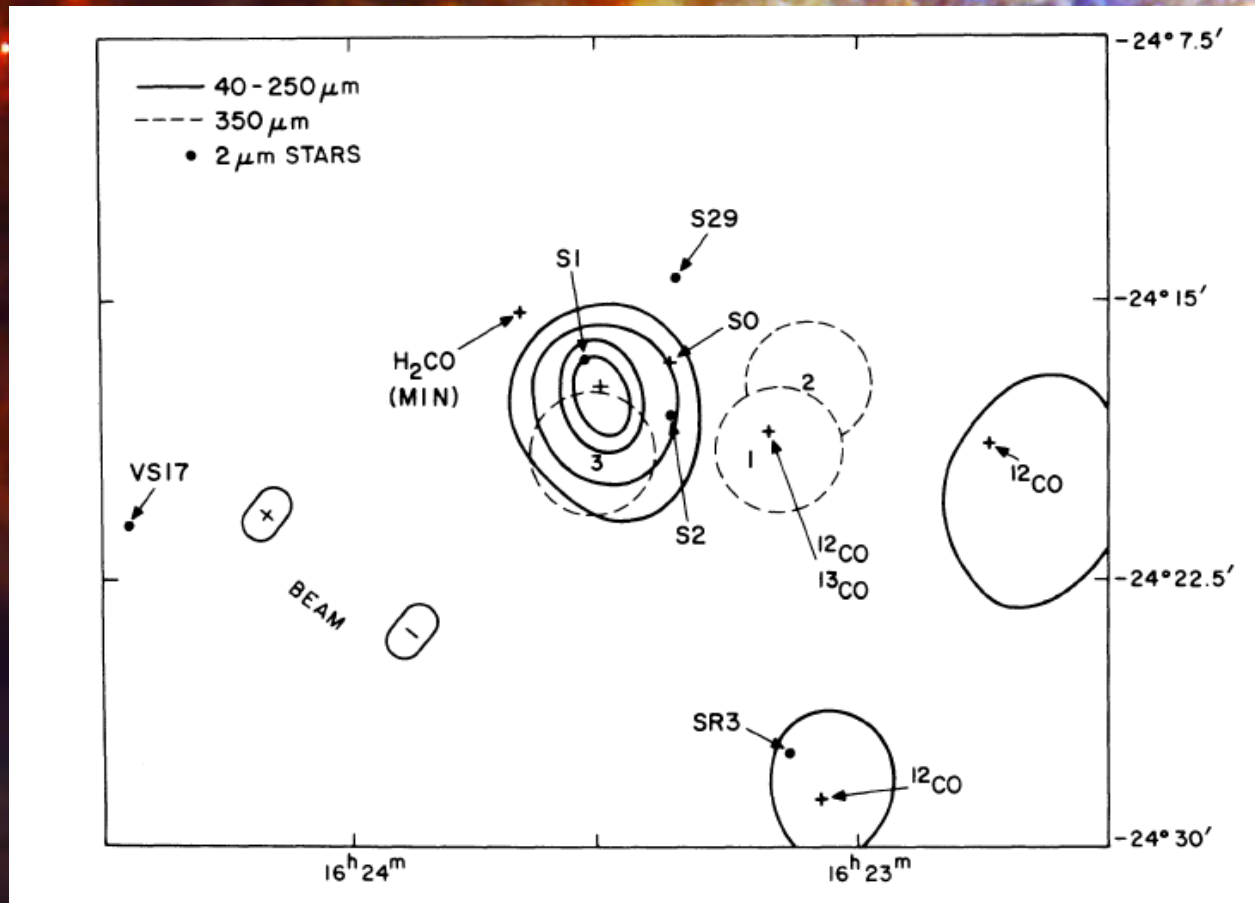
ESO-VLT



ALMA

→ JWST,
E-ELT

Enorme technologische ontwikkeling



100 μm map of the ρ -Oph star forming cloud: Fazio et al. 1976

Rosette molecular cloud

Herschel 70-350 μm Motte et al.

2010

Atacama Large Millimeter Array (ALMA)

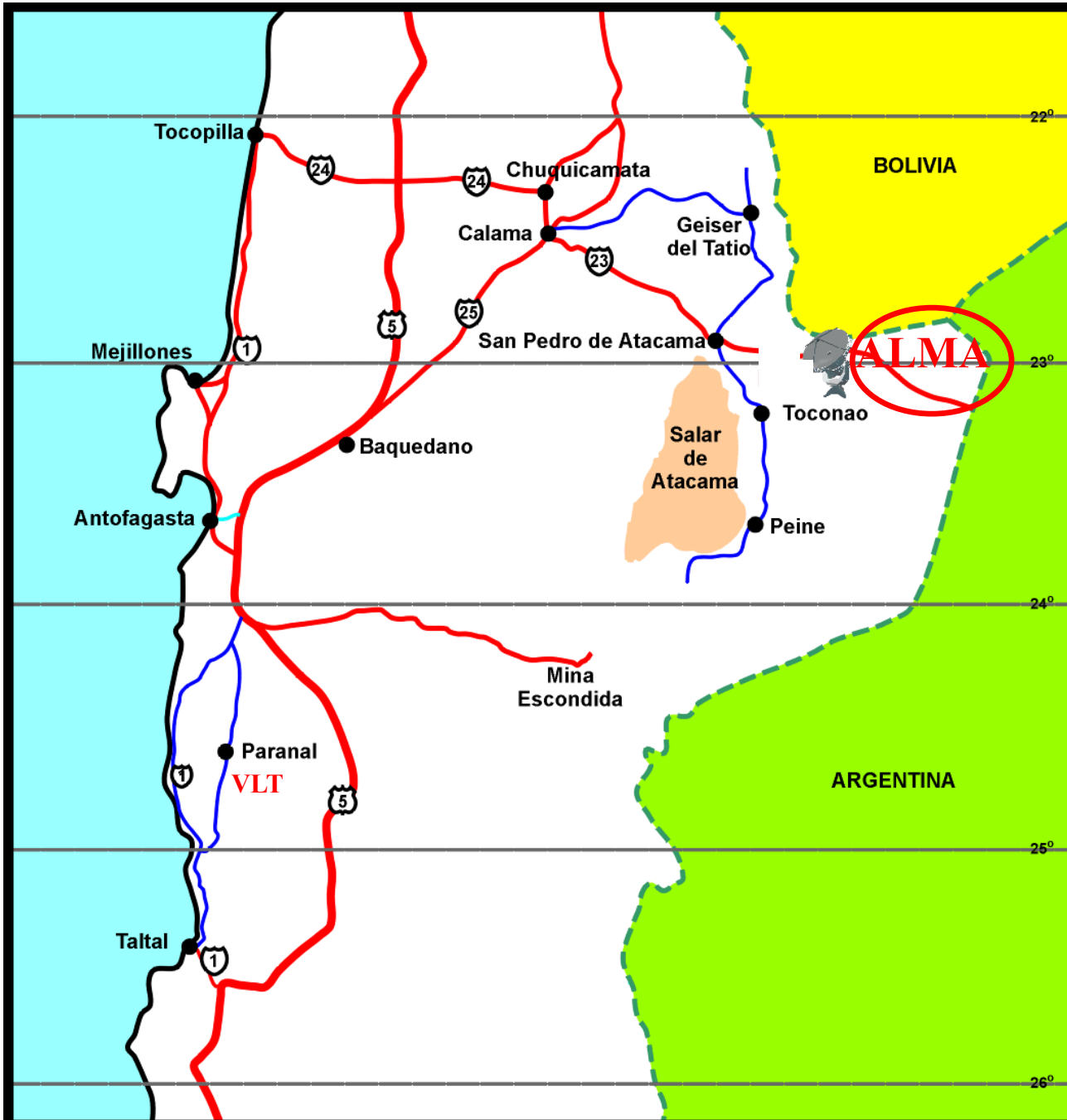


54x12 m + 12x7 m antennas



Inauguratie 13 maart 2013, constructie compleet begin 2014

ALMA Locatie



Operations +
Assembly: OSF
(~3000 m)

Array: high site
(~5000 m)

Atacama Large Millimeter Array



Receiver Cartridges



Band 3
HIA

Band 6
NRAO

Band 7
IRAM

Band 9
NOVA –
SRON

Band 4
NAOJ

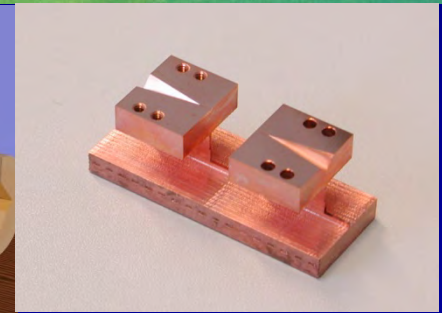
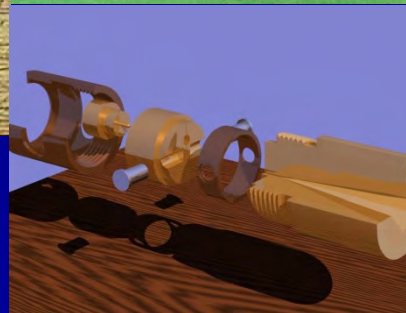
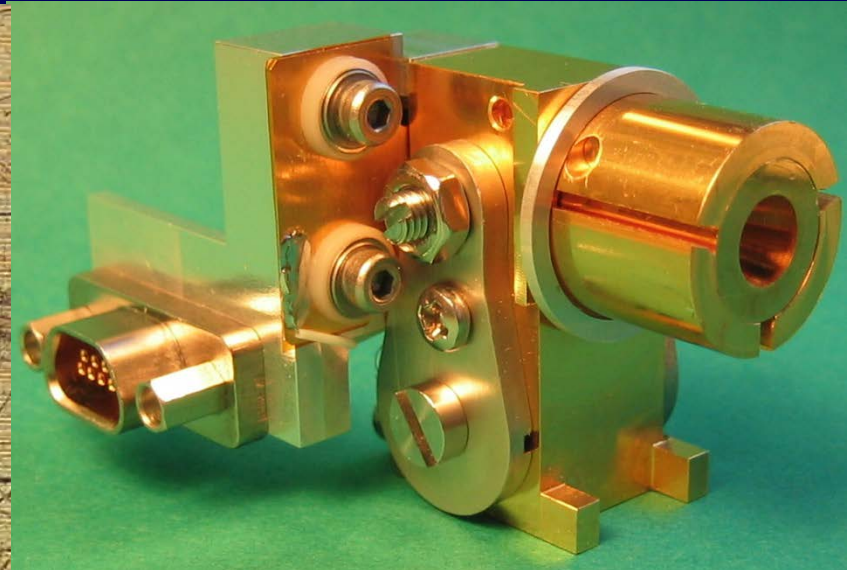
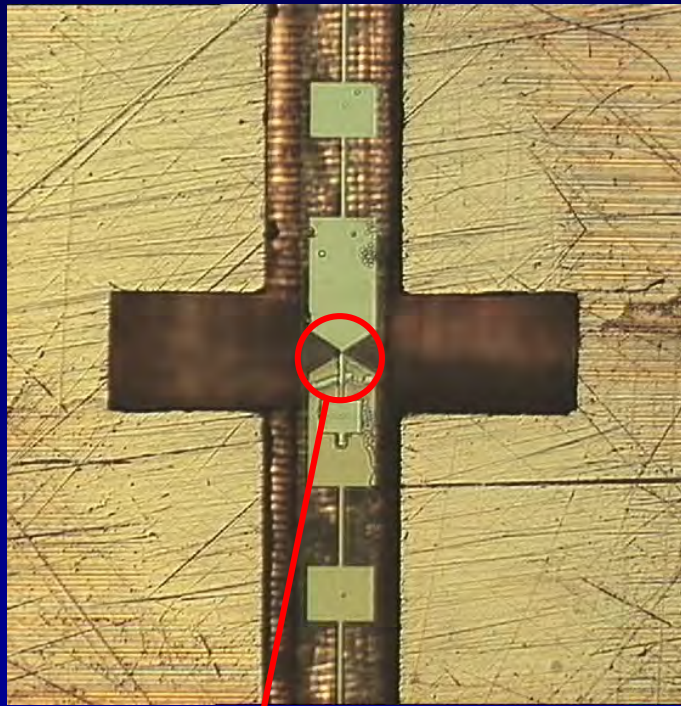
Band 8
NAOJ

Band 10
NAOJ

Band 9: 650 GHz SIS Mixer



Groningen/Delft collaboration



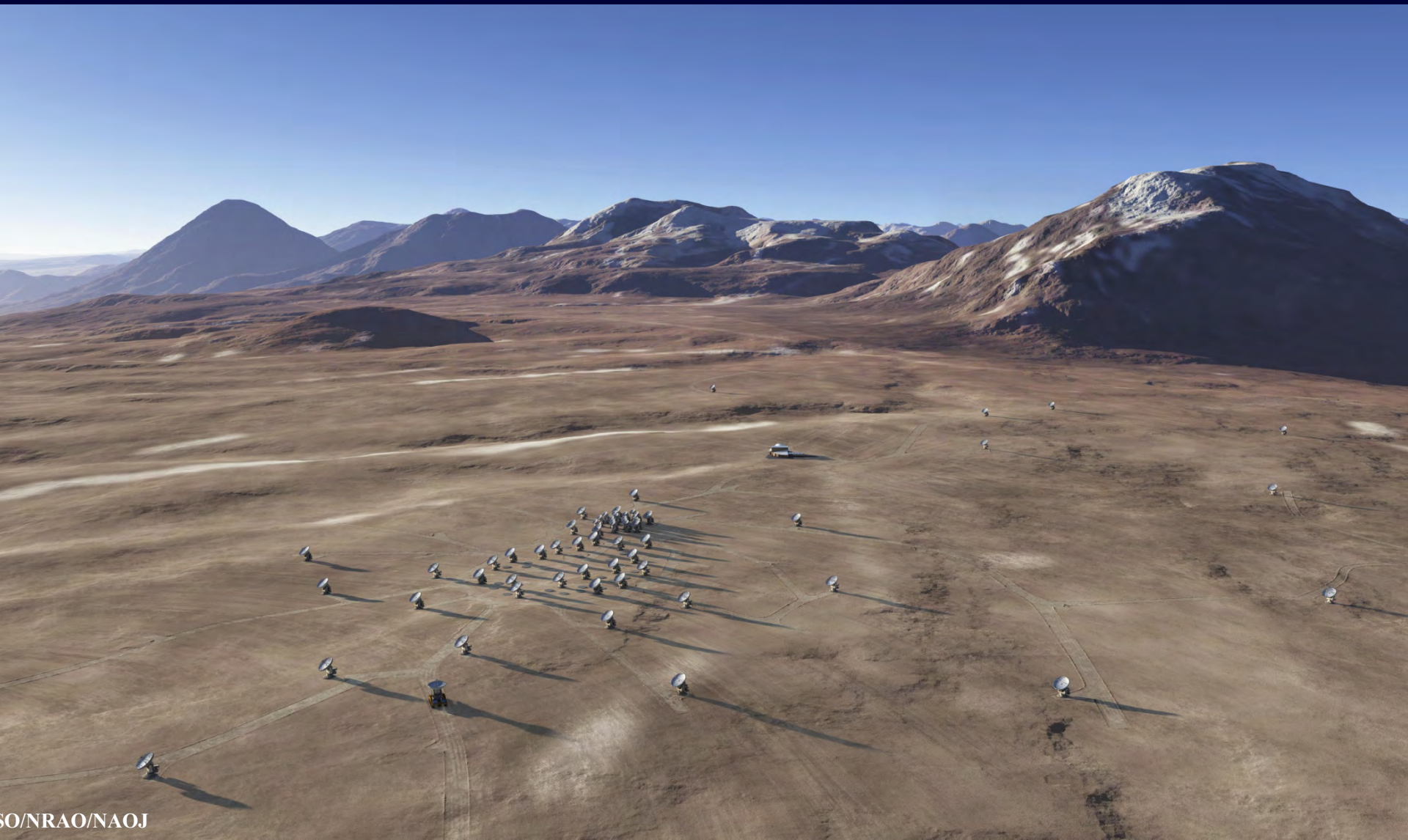
SIS detector element ($\sim 1 \mu\text{m}^2$)

- Receivers designed and built at RuG/SRON under ESO-NOVA contract
- SIS junctions made by Klapwijk at Kavli institute for nanoscience TUD

ALMA in 2018

Een adembenemende ervaring!

~5000 m
www.almaobservatory.org

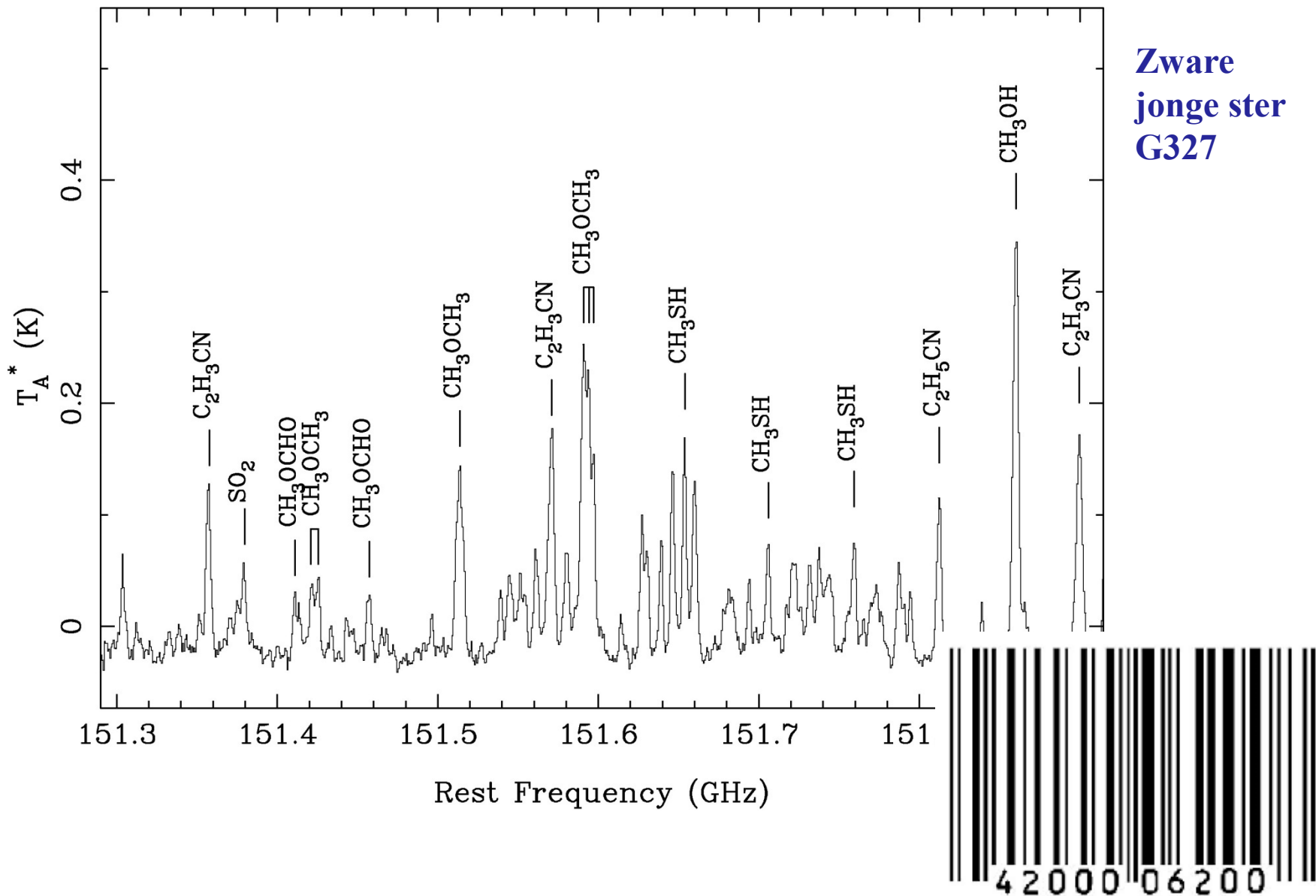


~200 interstellaire moleculen

N=2		N=3		N=4	N=5	N=6	N=7	N=8	N=9	N=10
H ₂	AlCl	CH ₂	C ₂ S	NH ₃	CH ₄	CH ₃ OH	CH ₃ NH ₂	HCOOCH ₃	(CH ₃) ₂ O	(CH ₃) ₂ CO
CH	PN	H ₂ S	OCS	H ₂ CO	SiH ₄	CH ₃ SH	CH ₃ CCH	CH ₃ C ₂ CN	C ₂ H ₅ OH	CH ₃ C ₄ CN
NH	SiN	NH ₂	MgCN	H ₂ CS	CH ₂ NH	C ₂ H ₄	CH ₃ CHO	HC ₆ H	C ₂ H ₅ CN	CH ₃ CH ₂ CHO
OH	SiO	H ₂ O	MgNC	H ₂ CN	C ₅	H ₂ C ₄	c-CH ₂ OCH ₂	C ₇ H	CH ₃ C ₄ H	(CH ₂ OH) ₂
O ₂ (?)	SiS	HNO	NaCN	<i>l</i> -C ₃ H	<i>l</i> -C ₃ H ₂	CH ₃ CN	CH ₂ CHCN	HOCH ₂ CHO	C ₈ H	
HF	PO	C ₂ H	SO ₂	c-C ₃ H	c-C ₃ H ₂	CH ₃ NC	HC ₄ CN	CH ₃ COOH	HC ₆ CN	
C ₂	SH	HCN	N ₂ O	HCCH	H ₂ CCN	NH ₂ CHO	C ₆ H	H ₂ CCCHCN	CH ₃ CONH ₂	N = 11
CN	AlF	HNC	SiCN	HNCO	H ₂ NCN	H ₂ CCHO	H ₂ CCHOH	H ₂ C ₆	CH ₂ CHCH ₃	HC ₈ CN
CO	FeO	HCO	SiNC	HNCS	CH ₂ CO	C ₅ H		CH ₂ CHCHO		CH ₃ C ₆ H
CS	SiC	c-SiC ₂		HCCN	HCOOH	C ₅ N		C ₂ H ₆		
CP		MgCN		C ₂ CN	C ₄ H	HC ₄ N				
NO		MgNC		C ₃ O	HC ₂ CN	C ₅ S(?)				N = 12
NS		AlNC		C ₃ S	HC ₂ NC	HC ₄ H				C ₆ H ₆
SO		HCP	H ₃ ⁺	c-SiC ₃	C ₄ Si	CH ₂ CNH				
HCl	CH ⁺	C ₃	HCO ⁺	C ₃ N ⁻	HNCCC	HC ₂ CHO				
NaCl	CO ⁺	C ₂ O	HOC ⁺	H ₃ O ⁺		c-C ₃ H ₂ O				N = 13
KCl	SO ⁺	CO ₂	N ₂ H ⁺	HCNH ⁺	H ₂ COH ⁺					HC ₁₀ CN
N ₂ (?)	CF ⁺		HCS ⁺	HOCO ⁺	C ₄ H ⁻	HC ₃ NH ⁺	C ₆ H ⁻		C ₅ H ⁻	

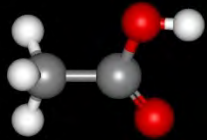
E. Herbst.

Vingerafdrukken van moleculen

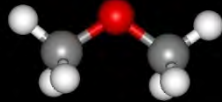


Complexe organische moleculen

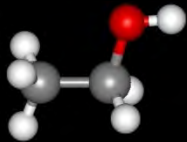
Gedetecteerd



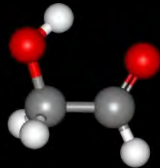
Azijnzuur



Di-methyl ether



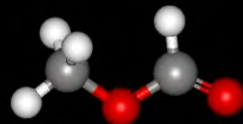
Ethanol



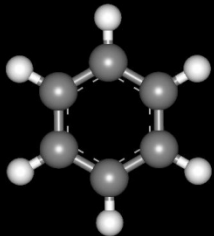
'Suiker'



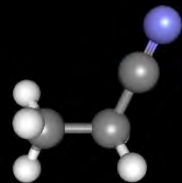
Methyl cyanide



Methyl formaat

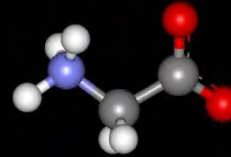


Benzeen

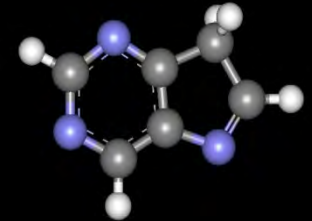


Ethyl cyanide

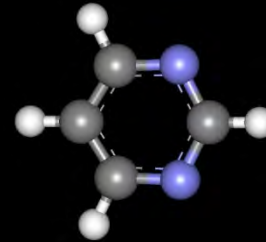
(Nog) niet gedetecteerd



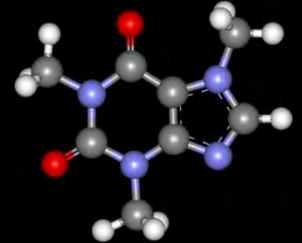
Glycine



Purine

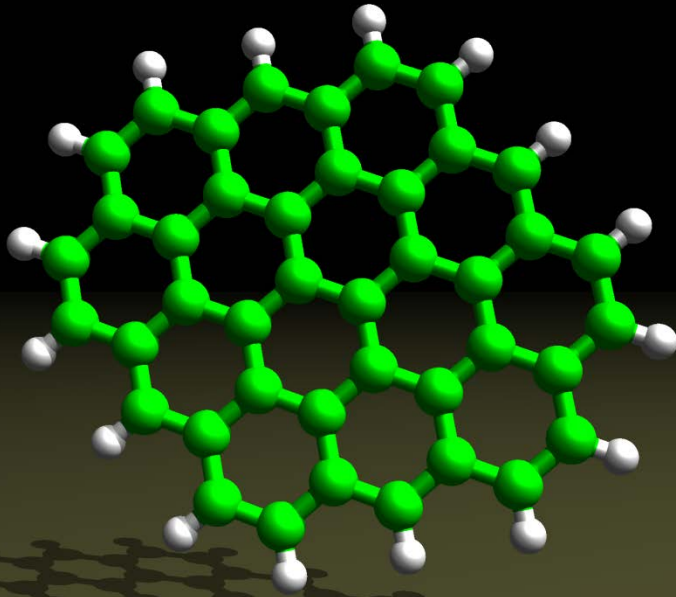


Pyrimidine

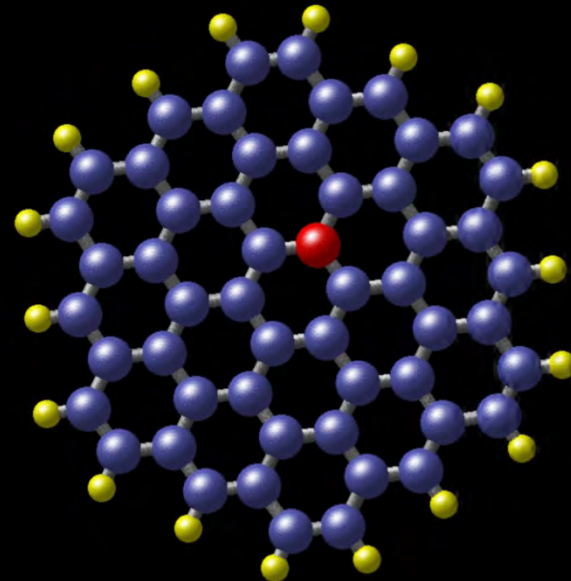


Caffeine

Polycyclische Aromatische Koolwaterstoffen



R. Ruiterkamp



NASA/D. Hudgins

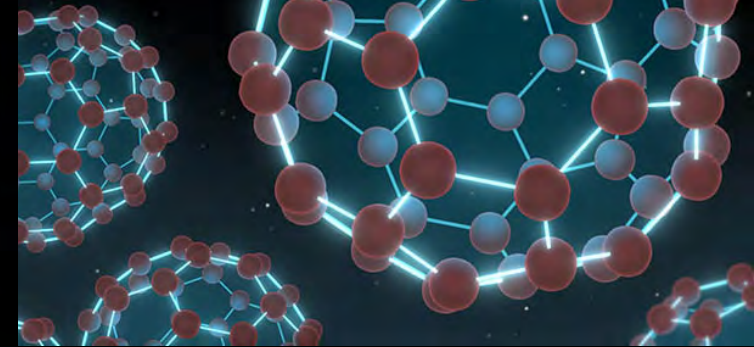
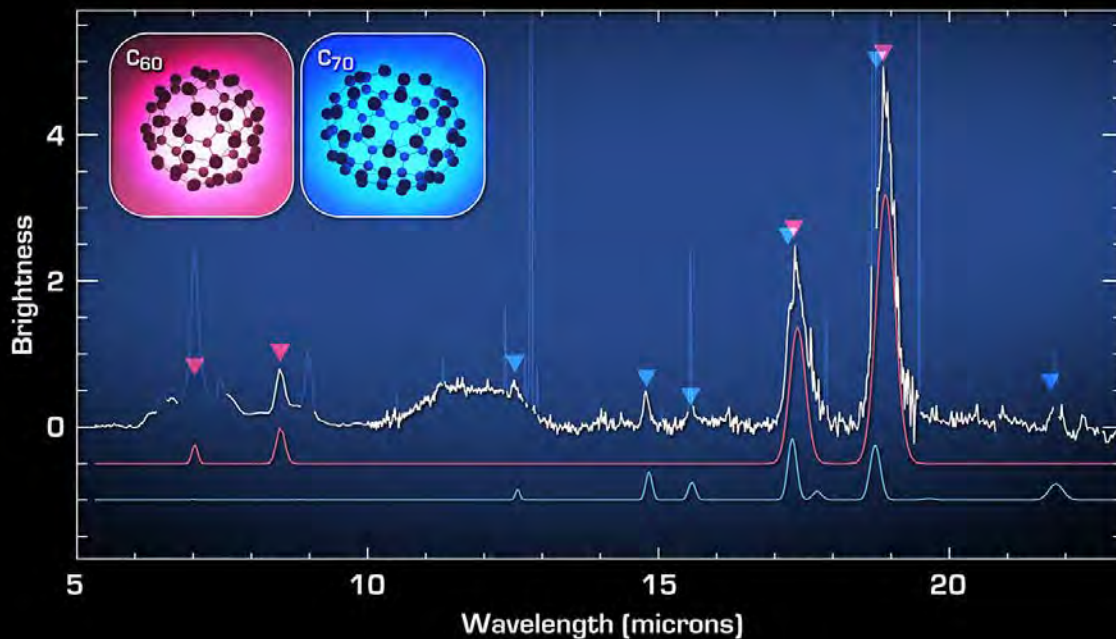
PAHN: PAHs met N

Ontdekking van interstellaire buckyballs

Buckminsterfullerene



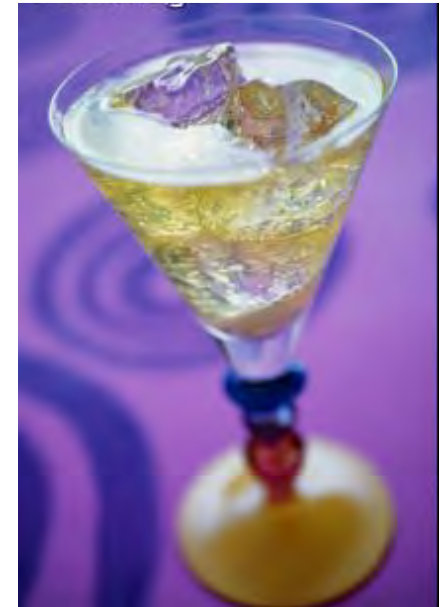
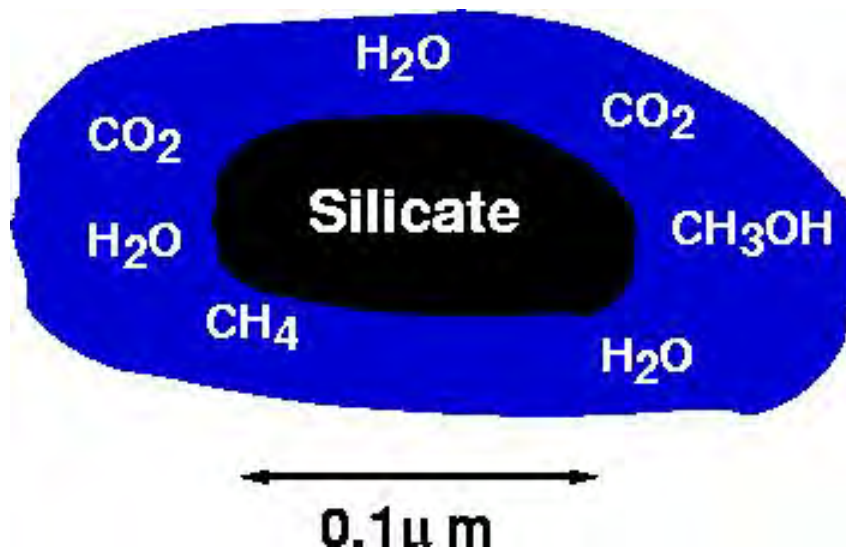
Cami et al. 2010, NASA/Spitzer



Voorspeld door Harry Kroto
toen hij aan interstellaire lange
koolstofketens werkte
1980's

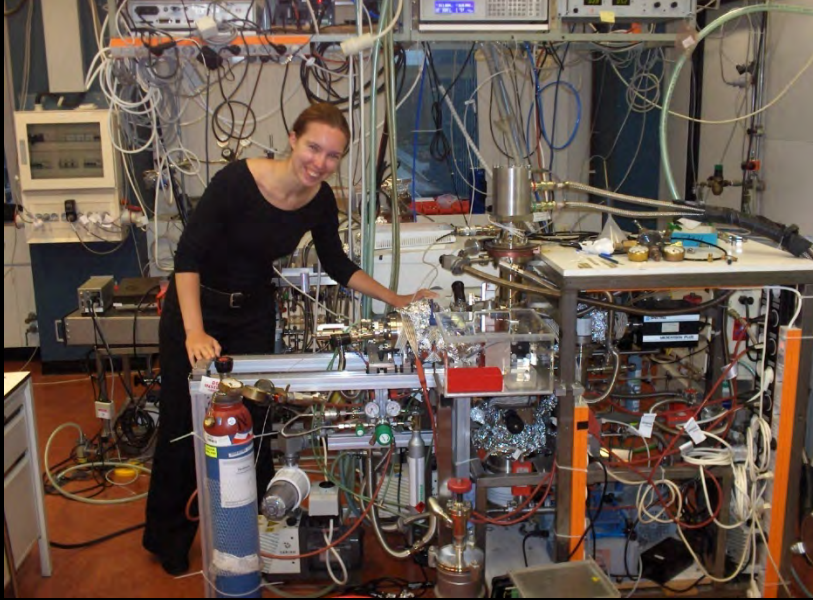
De interstellaire ijscocktail

Moleculen bevroren op koude stofdeeltjes =>
hydrogenatie, b.v. $\text{O} \rightarrow \text{H}_2\text{O}$

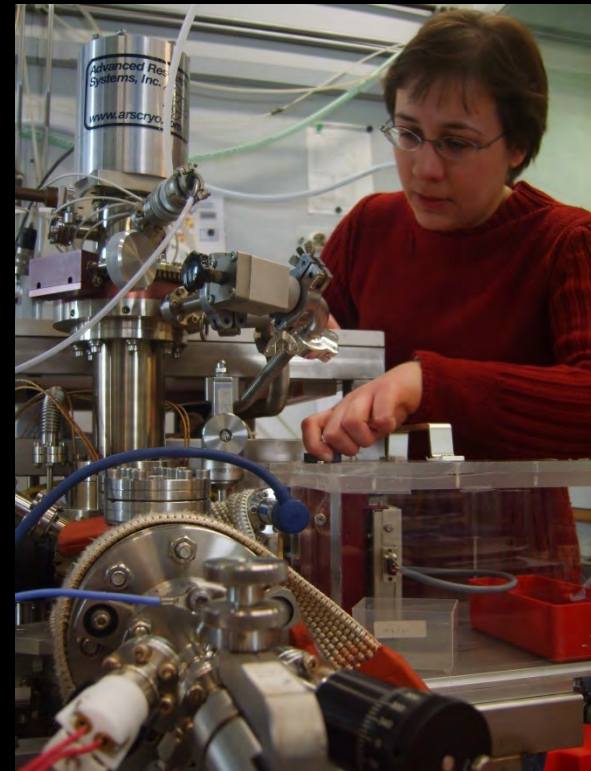


'Alcohol on the rocks'

Sackler laboratory for astrophysics Sterrewacht Leiden



‘Simulating 1 cm⁻³
of interstellar space’



H. Linnartz

Vorming van water op stofdeeltjes



Water is in grote hoeveelheden aanwezig bij vormende sterren
‘Water is ouder dan de Zon’

Water reservoir in schijf



ESA/NASA
Herschel-HIFI

Hogerheijde et al.
2011, Science



~6000 oceanen ijs

Samenvatting tot nu toe

- **Interstellaire wolken hebben een rijke chemische compositie ondanks de koude en ijle condities**
- **Complexe organische moleculen en water worden rond bijna alle vormende sterren gevonden, door de hele Melkweg**

⇒ Bouwstenen voor prebiotisch material zijn wijdverspreid

Hoe wordt een nieuwe ster gevormd?

Ineenstorting wolk



20000 AU

Factor 400
kleiner



50 AU

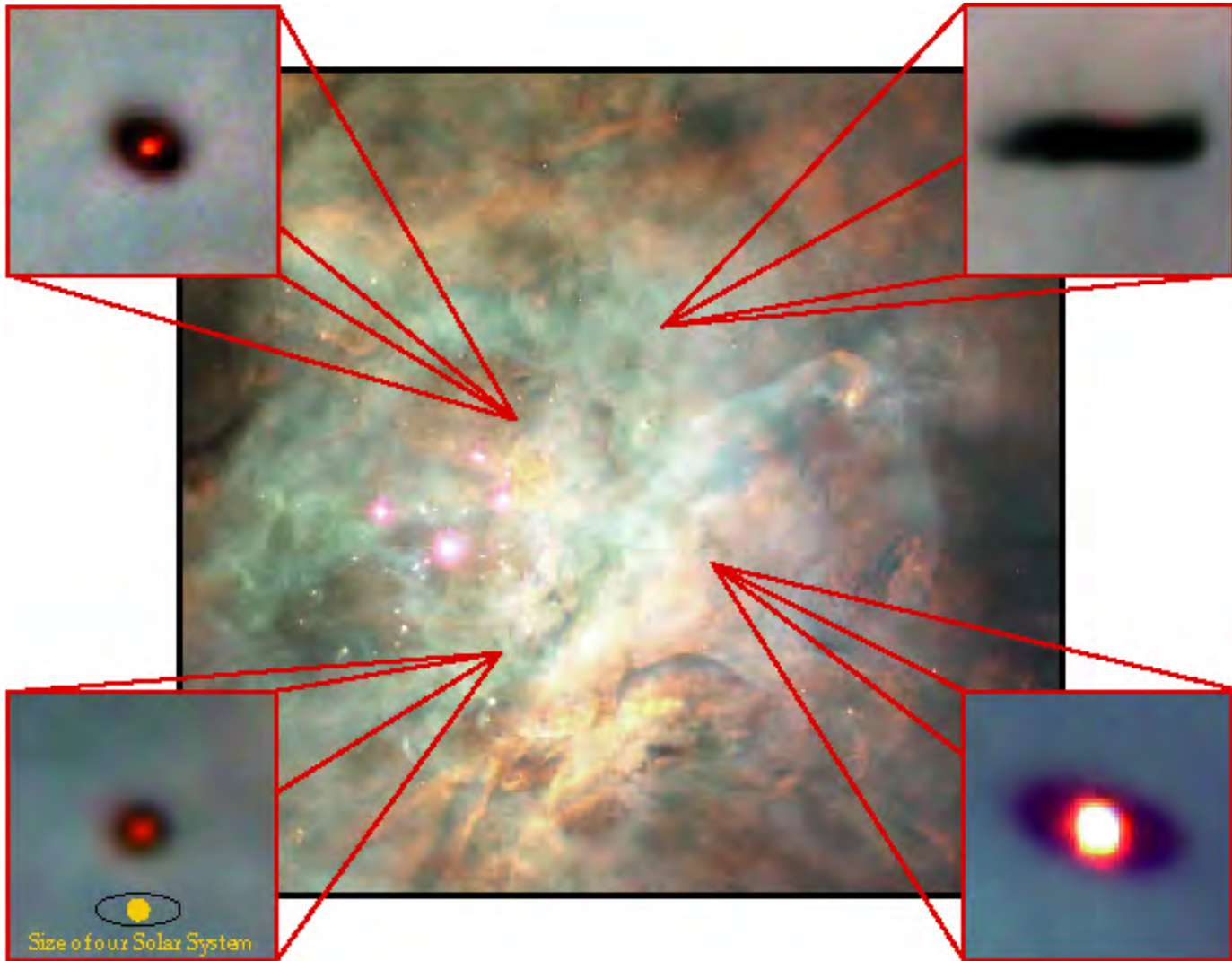
Stervorming in Orion



C.R. O'Dell

AMNH/SDSC

Protoplanetaire schijven

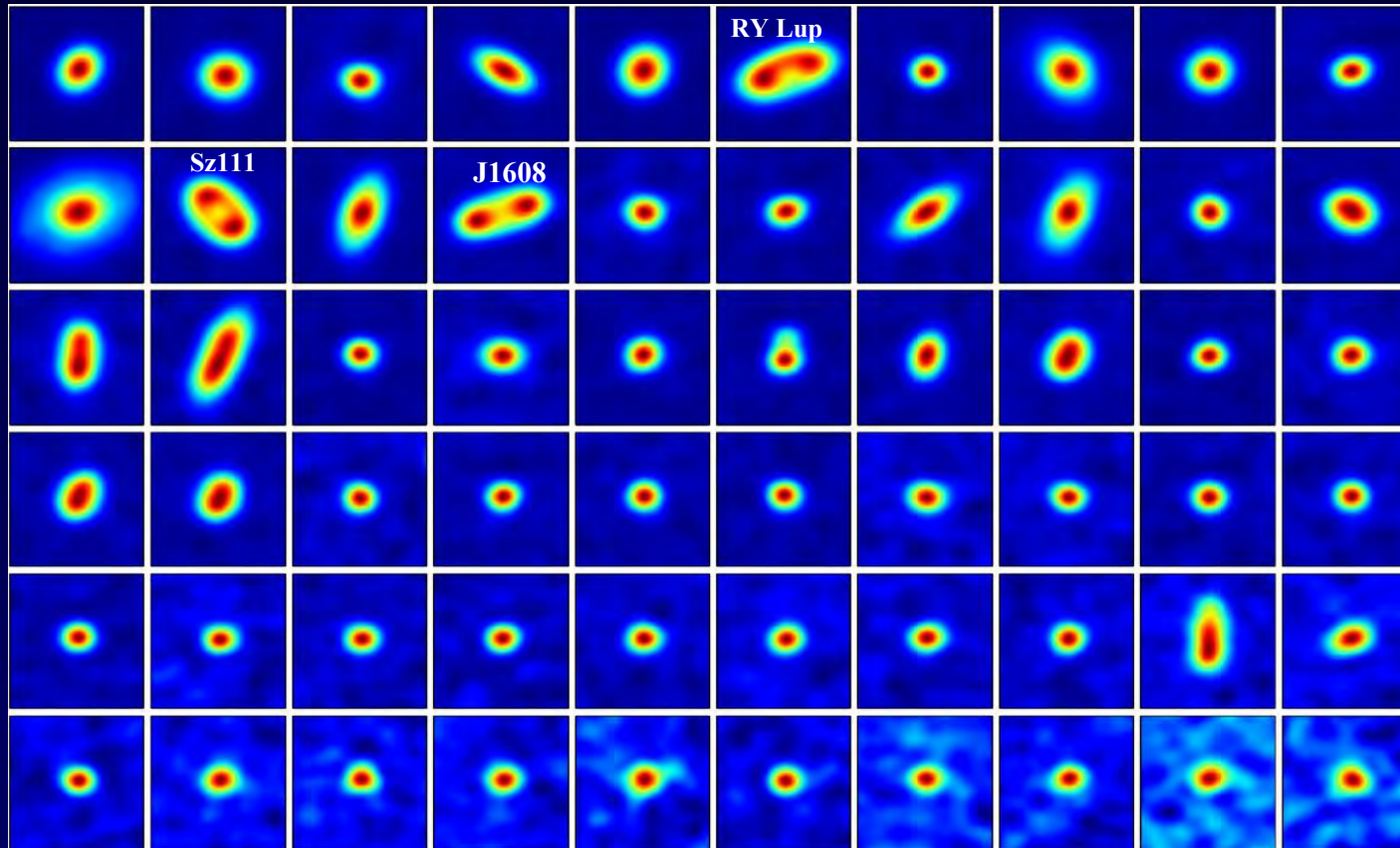


Grootte
 $\sim 10^{10}$ km =
2xZon-Pluto

HST/NASA/ESA
O'Dell et al. 1995

ALMA survey van schijven

2"x2"



0.35''
(20 AE straal)

1-2 minuten
per bron!

0.8 mm
continuum

Andsell, Willians
et al. 2016

Survey van alle jonge sterren in Lupus wolk, 70% gedetecteerd

Protoplanetaire schijven

- Vrijwel alle jonge sterren omringd door schijf
- Grootte van schijven vergelijkbaar met ons zonnestelsel
- Massa van sommige schijven voldoende om zonnestelsel te vormen
 - 1% van massa Zon, 10x massa van Jupiter
- Andere schijven voldoende massa voor aardachtige planet(en)

=> Ingredienten voor vorming planeten zijn overal

Schijven zijn klein



Carina nebula
HST

Wolk: 10^{18} cm

Protoster: 10^{17} cm

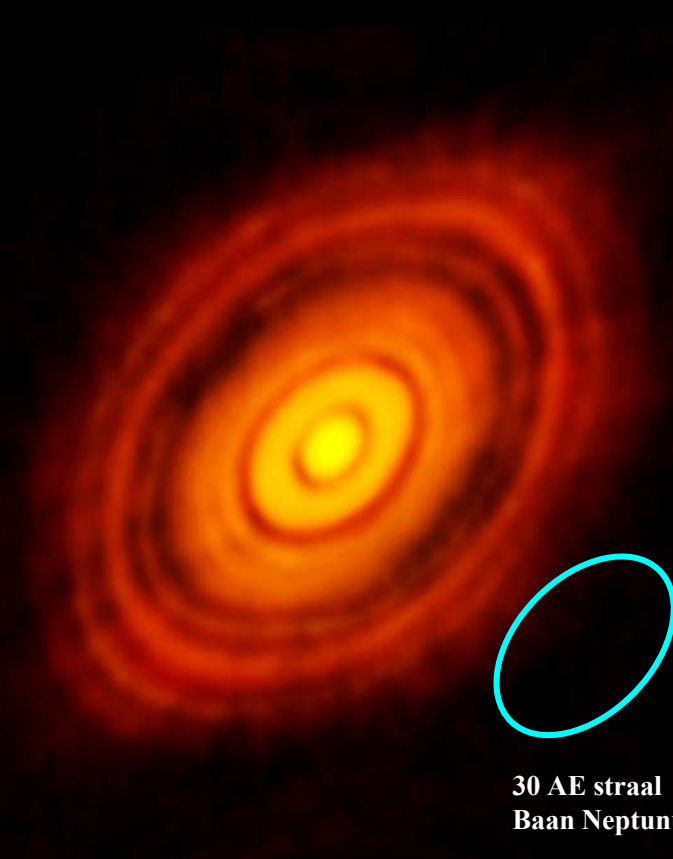
Schijf 10^{15} cm (100 AE; 1 AE = afstand Zon-Aarde)

Hoge resolutie ALMA is nodig om in te zoomen op planeetvorming

Planeetvorming in schijven in kaart gebracht met ALMA

HL Tau

20 milli-arcsec
resolutie
~3 AE



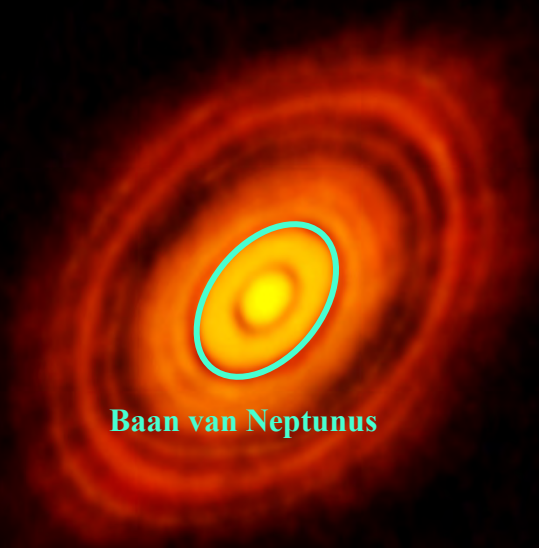
30 AE straal
Baan Neptunus

ALMA Partnership+ 2015
www.almaobservatory.org



Animatie
NASA/Spitzer/R. Hurt

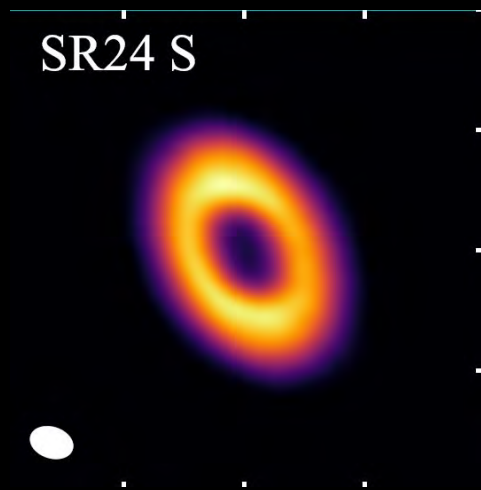
Nieuw tijdperk: planeetvorming in actie!?



Baan van Neptunus

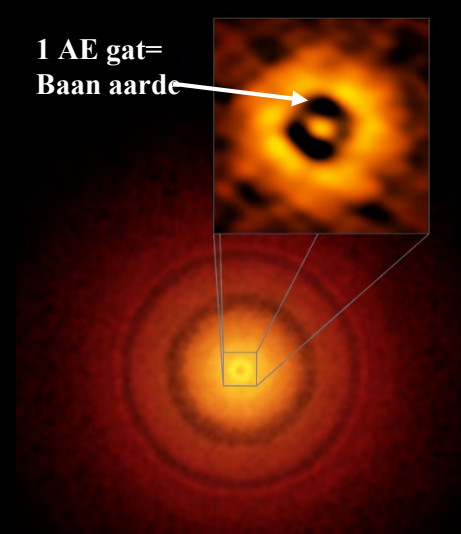
HL Tau jonge schijf

ALMA partnership
et al. 2015



SR24 S

ALMA: Pinilla et al. 2017



1 AE gat=
Baan aarde

ALMA TW Hya

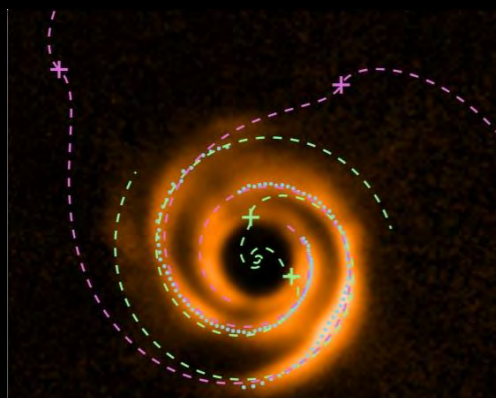
Andrews et al. 2016

IRS48



B9

ALMA: van der Marel et al. 2013, 2016

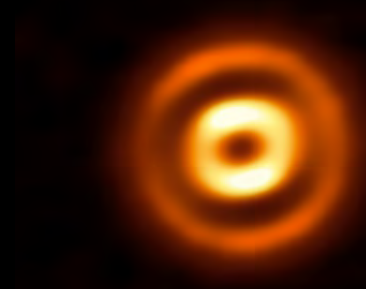


Best-fit inner planets
HD135344B

Surface brightness maxima

VLT-Sphere

Stolker et al. 2016



HD169142

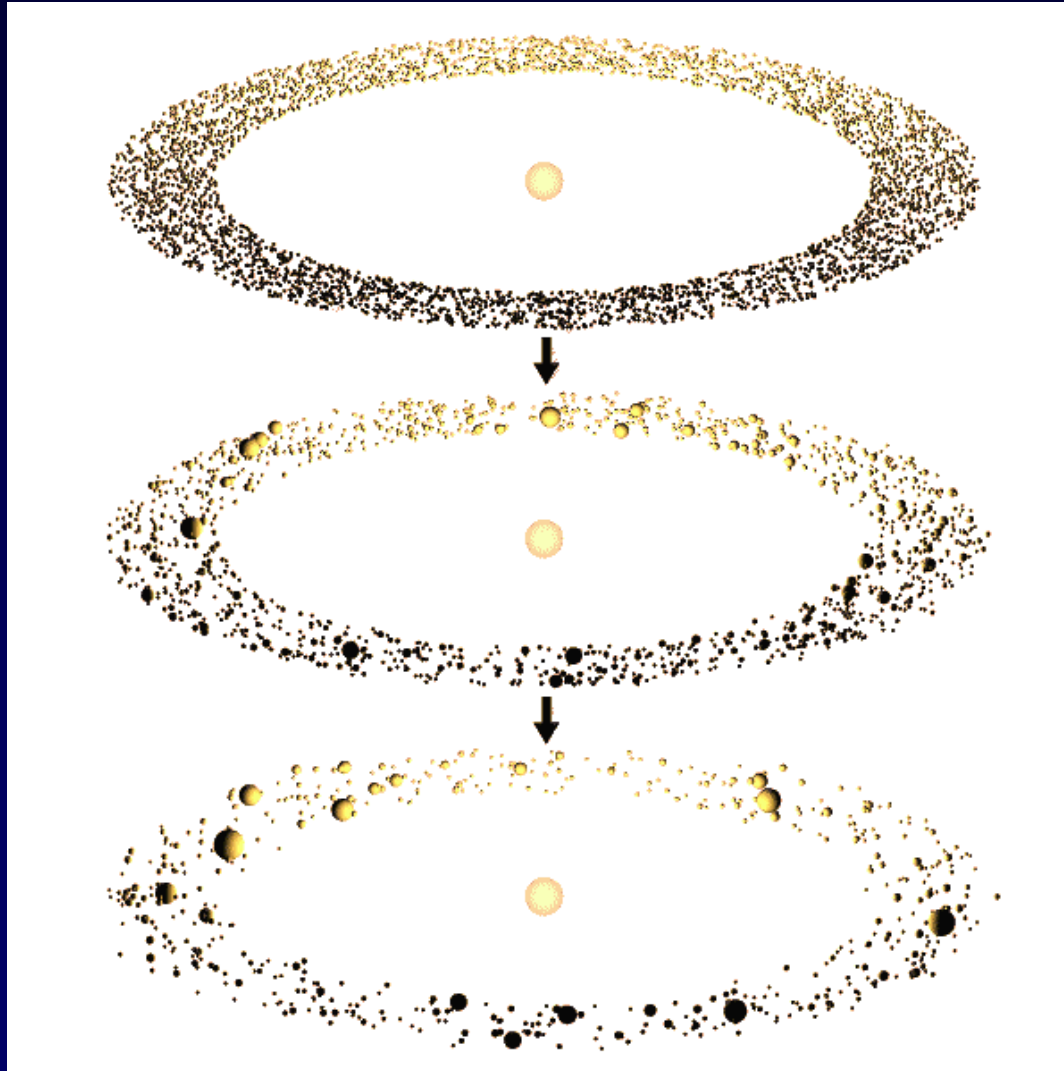
ALMA:
Fedele et al. 2017

Vorming planetesimalen in schijven



www.eso.org

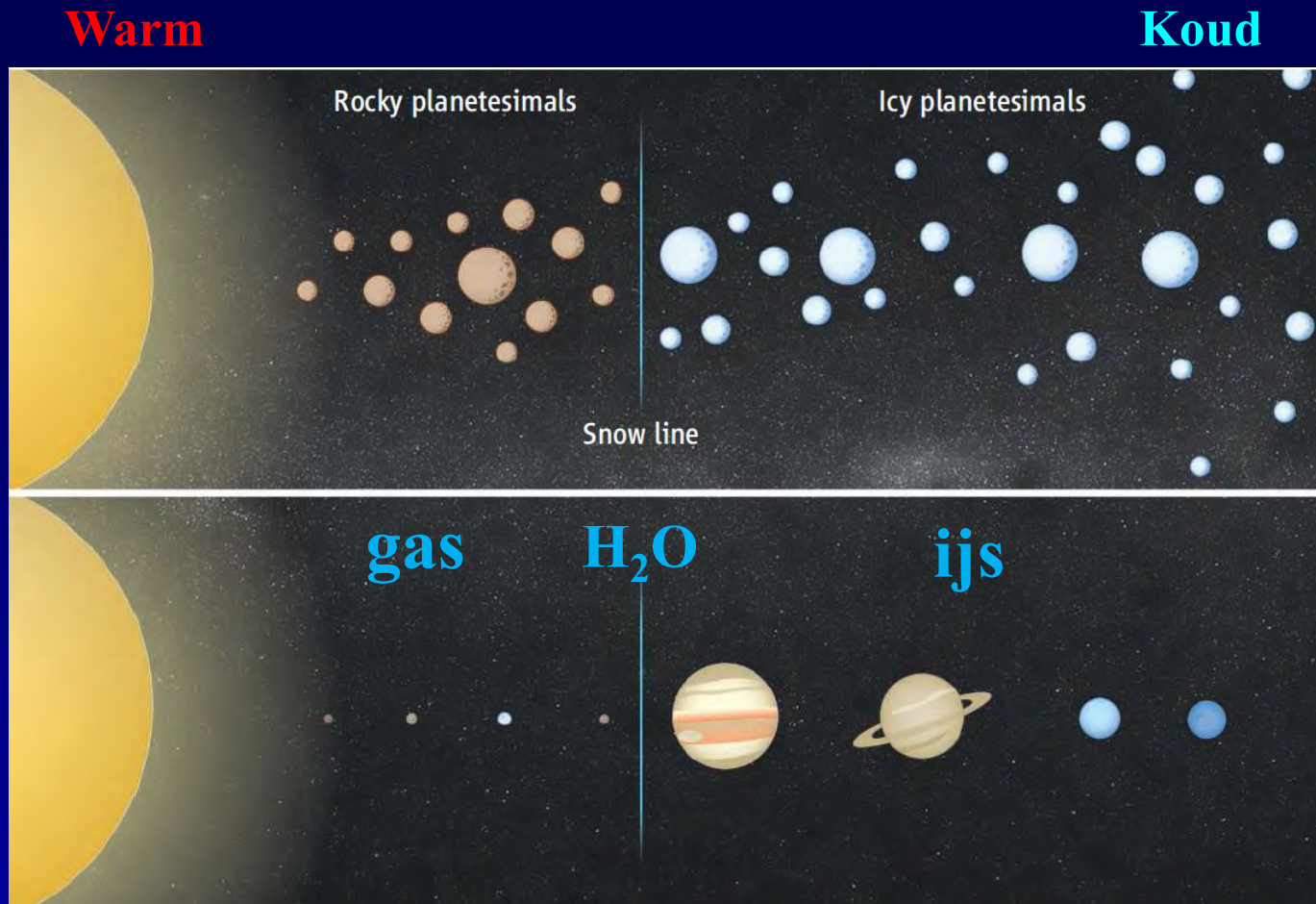
Eerste stap in planeetvorming: Stofdeeltjes klitten aan elkaar tot grotere deeltjes



Sneeuwlijn



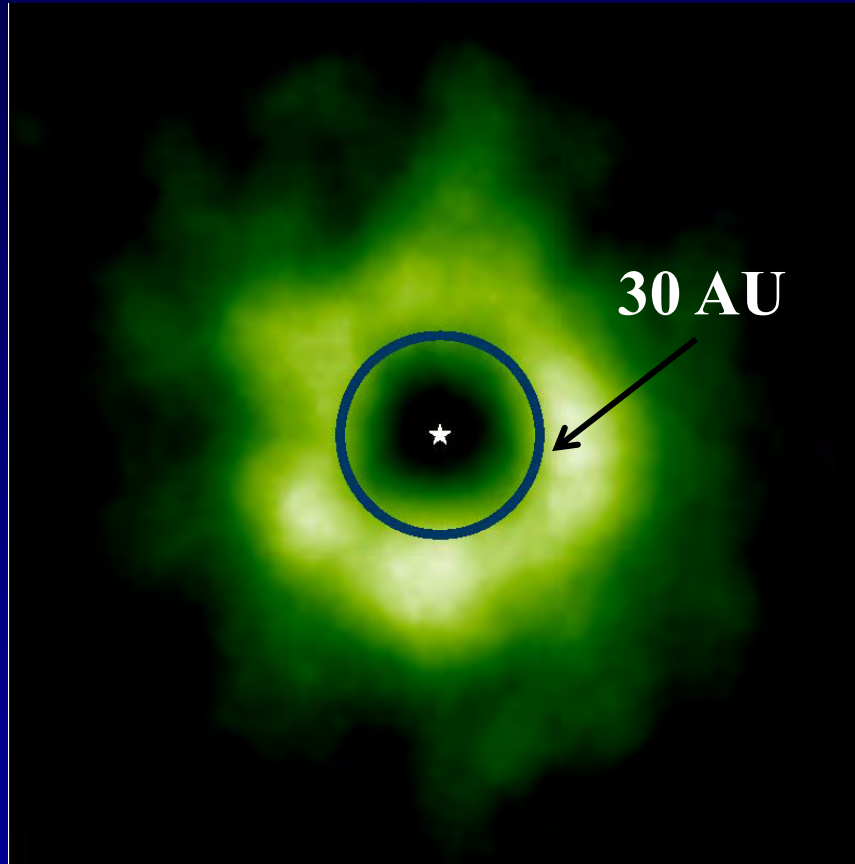
Belang van de water ijslijn



Akeson 2011

Waterijs versnelt vorming van (reuze) planeten

CO sneeuwlijn met ALMA

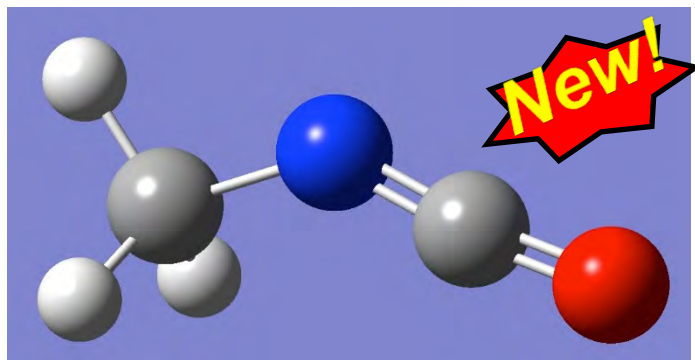


TW Hya
d=68 pc

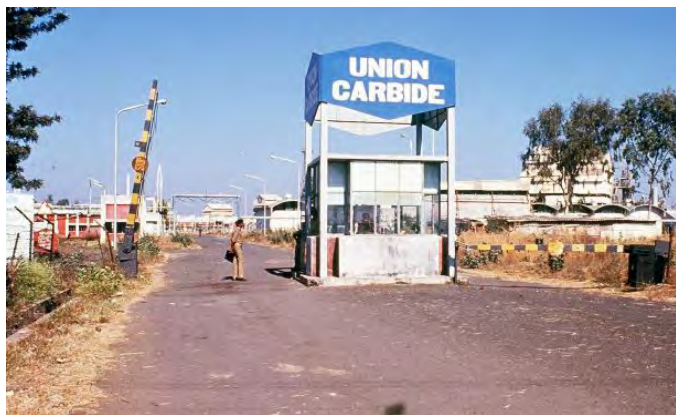
N_2H^+ 4-3

Qi, Öberg et al. 2013

Complexe organische moleculen in jonge schijven



Methyl isocyanate
'Prebiotisch' molecuul



Ligterink et al. 2017, Mariin-Domenéch et al. 2017

Acetone

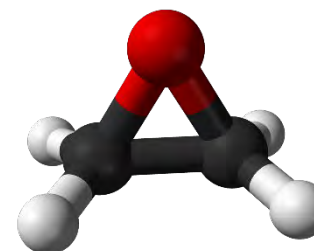
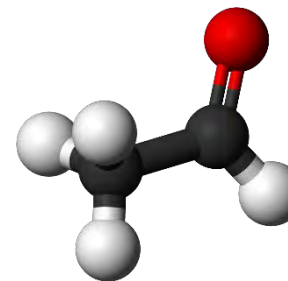
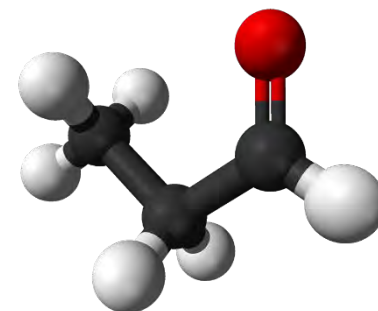
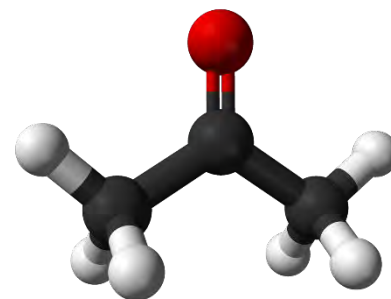


Propanal



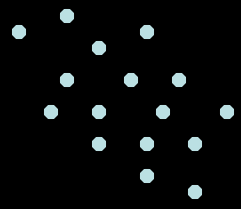
Acetaldehyde

Ethylene oxide

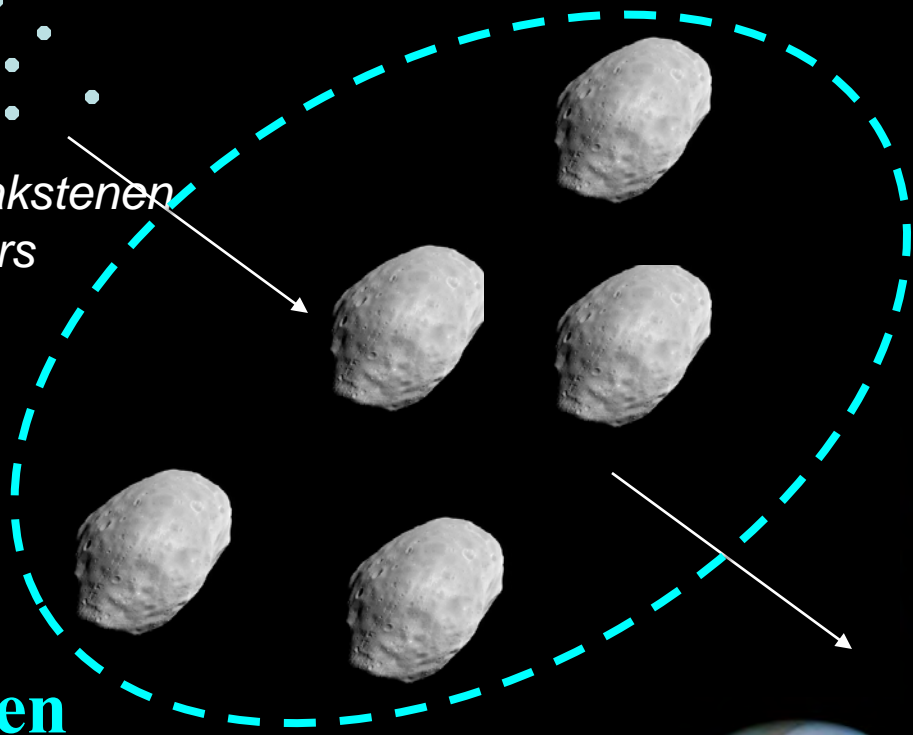


Lykke et al. 2017

Van stofdeeltjes tot planetesimalen tot embryos tot planeten



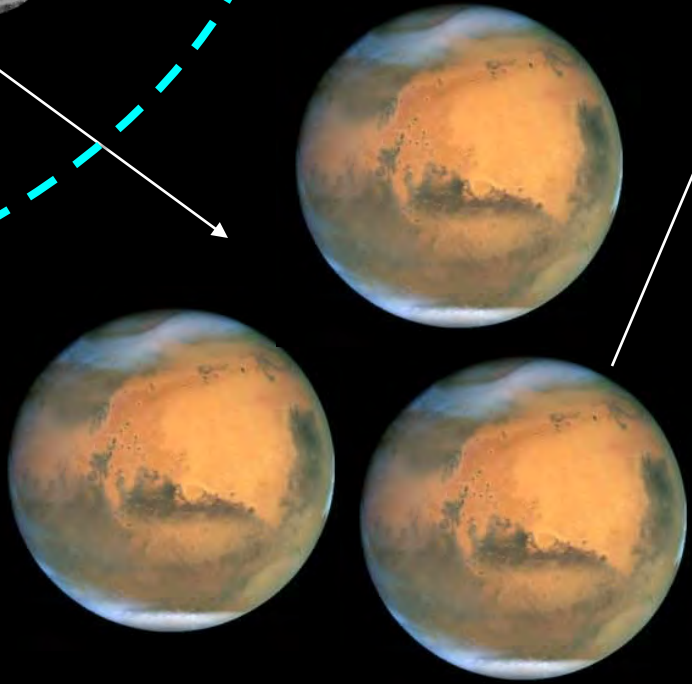
stof, bakstenen
< meters



kometen

Planetesimalen
kilometers

Water ijs versnelt coagulatie



Planeet embryos
Maan (1 AU)-to-Mars (2 AU) grootte



Komeet Hale-Bopp



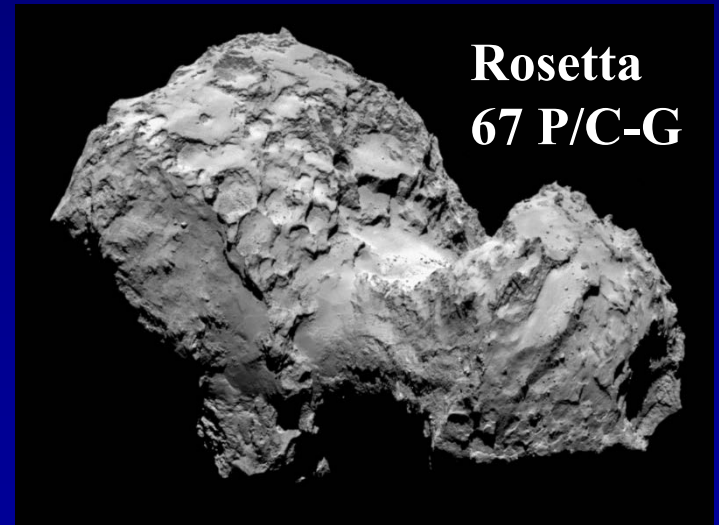
Chemische samenstelling vergelijkbaar met interstellaire ijzen

Schijf – komeet vergelijking

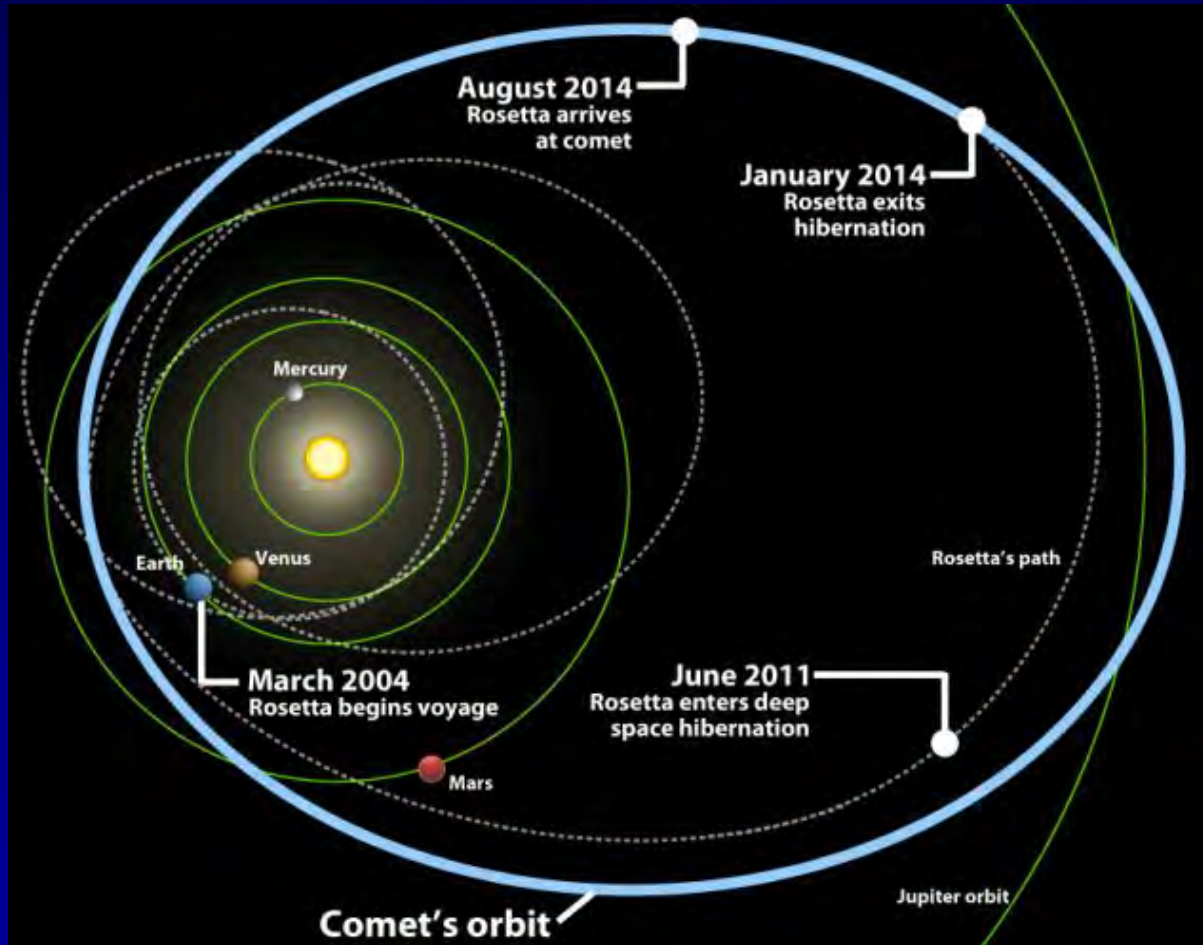
- **Schijf:** moleculen die net sublimeren
- **Komeet:** moleculen *in situ*



NASA/Caltech/SSC R. Hurt animation

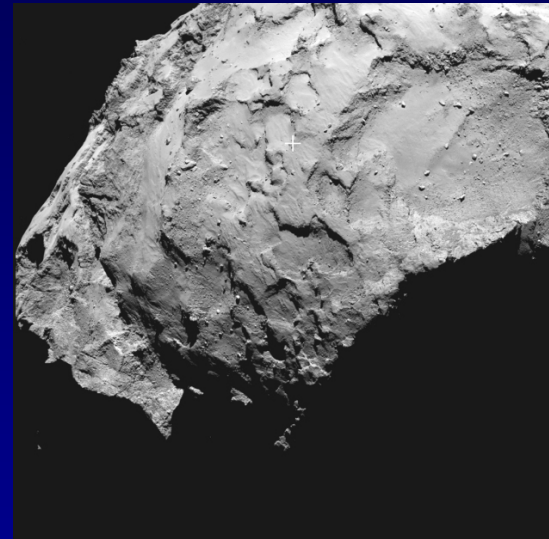


Rosetta missie naar komeet 67P/C-G



12 jaar reizen door zonnestelsel

Komeet 67 p/C-G 'De Eend'

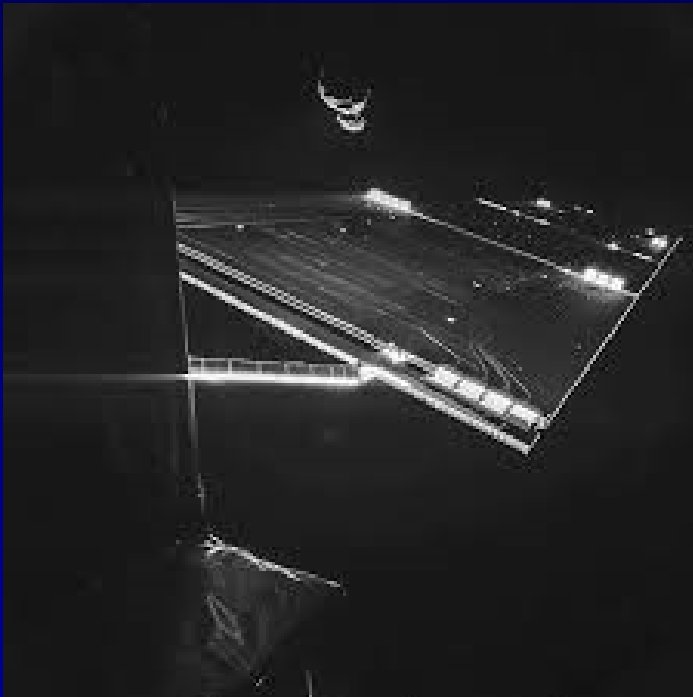


ESA

12 november 2014 landing

Komeet 67 P/C-G

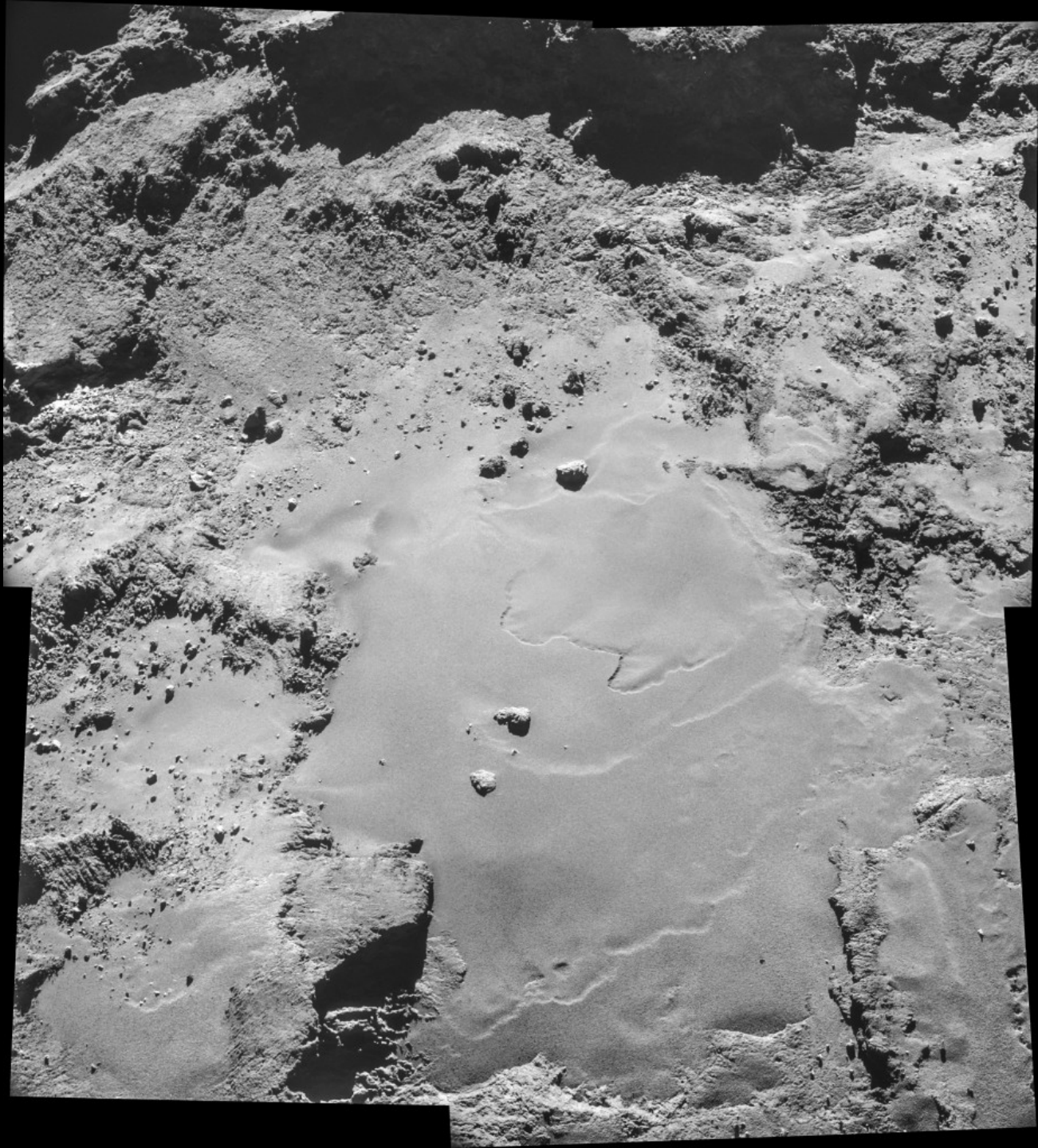
Rosetta 'Selfie'



Jets



Typisch 2 glazen water per seconde
Max 5 liter water per seconde



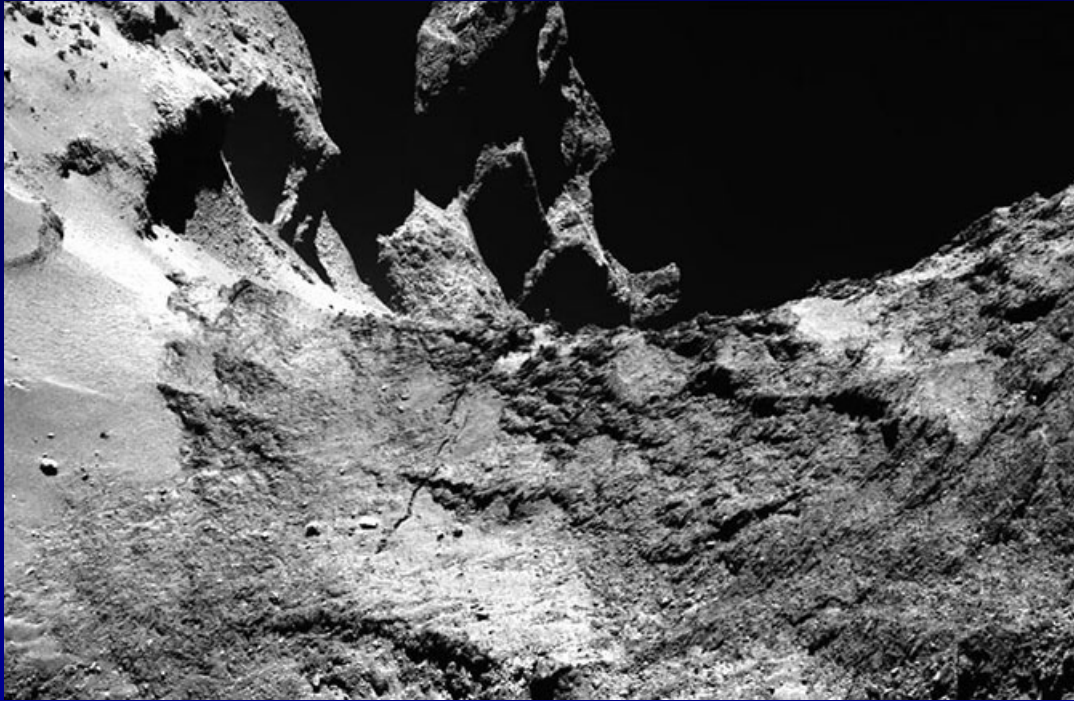
**Blow-up
Landing
site**

**~1 km
diameter**

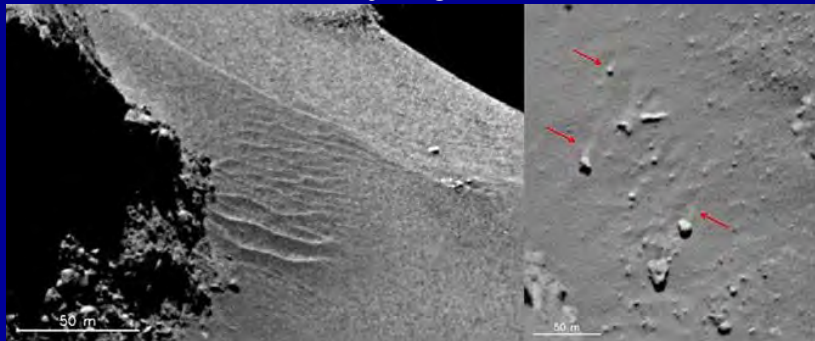
Rosetta landing



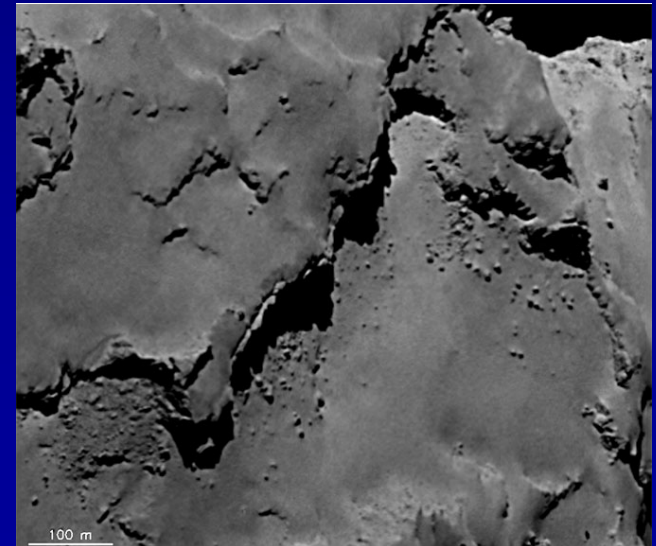
Fascinerende structuren



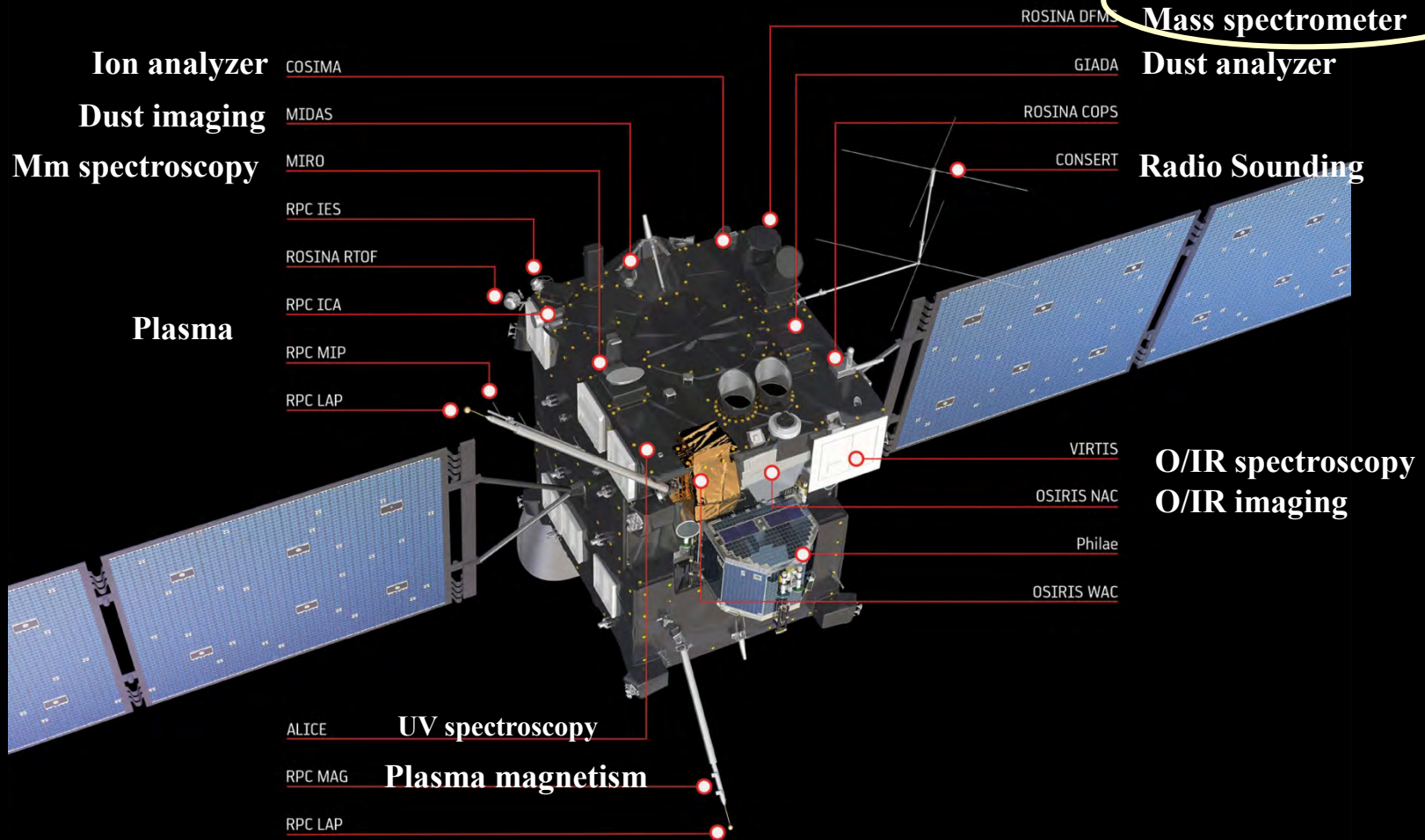
Duinen



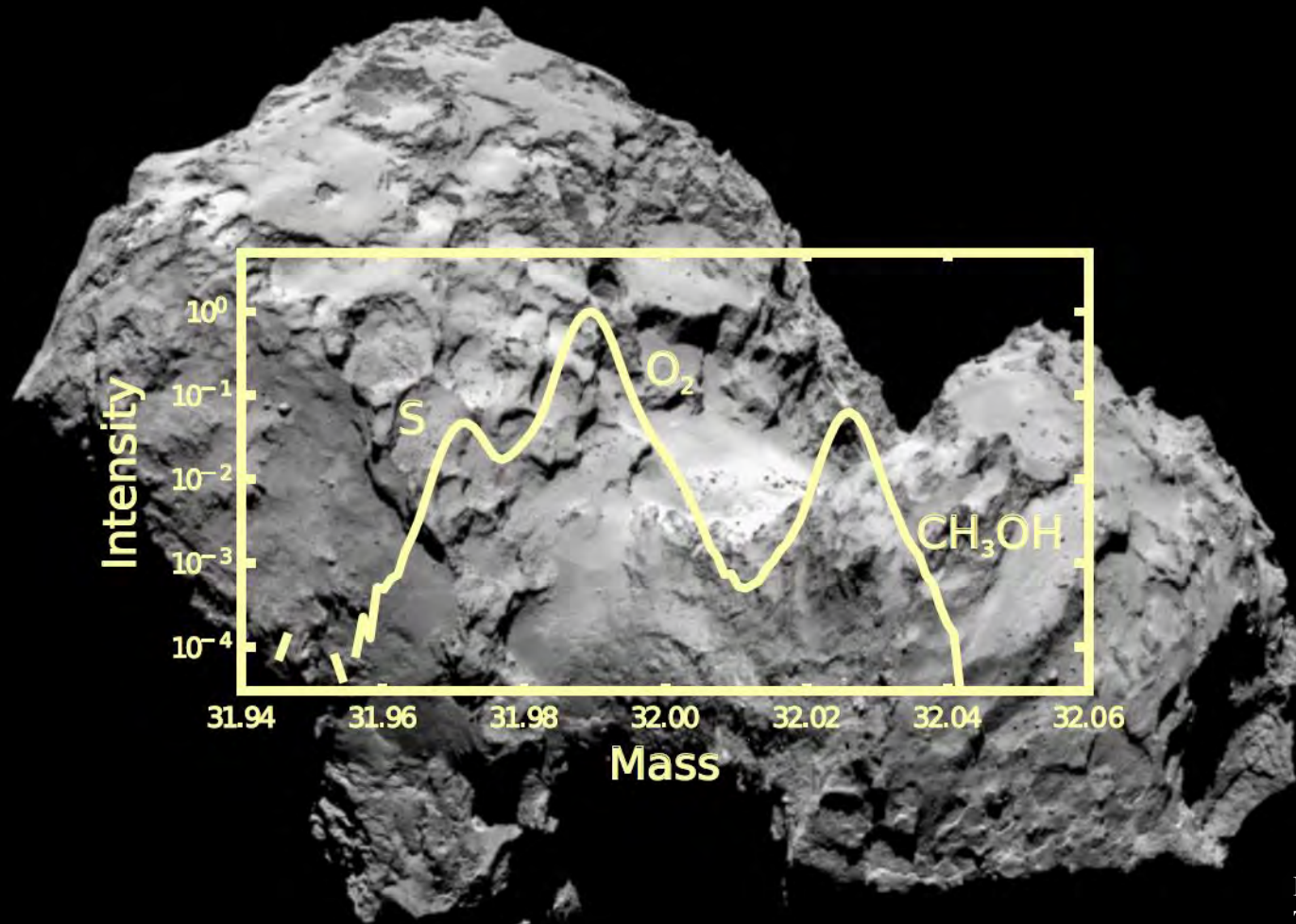
Klif



Instrumenten op orbiter



Komeet bevat veel zuurstof!



$O_2/H_2O \sim 4\%$

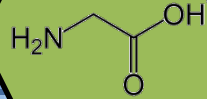
Bieler et al. 2015
Taquet et al. 2016

Is ons zonnestelsel gevormd in een warmere wolk? (20-30 K vs 10 K)

ROSINA Z



Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane



Glycine
(Aminoacid)



HF
HCl
HBr
P



Ammonia
Methylamine
Ethylamine



Formic acid
Acetic acid
Acetaldehyde
Acetonitrile
Ethylenglycol
Propylenglycol
Butanamide



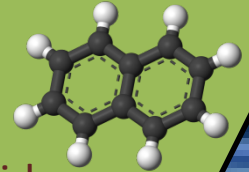
Acetylene
HCN
CH₃CN
Formaldehyde



Methanol
Ethanol
Propanol
Butanol
Pentanol



Benzene
Toluene
Xylene
Benzoic acid
Naphthalene



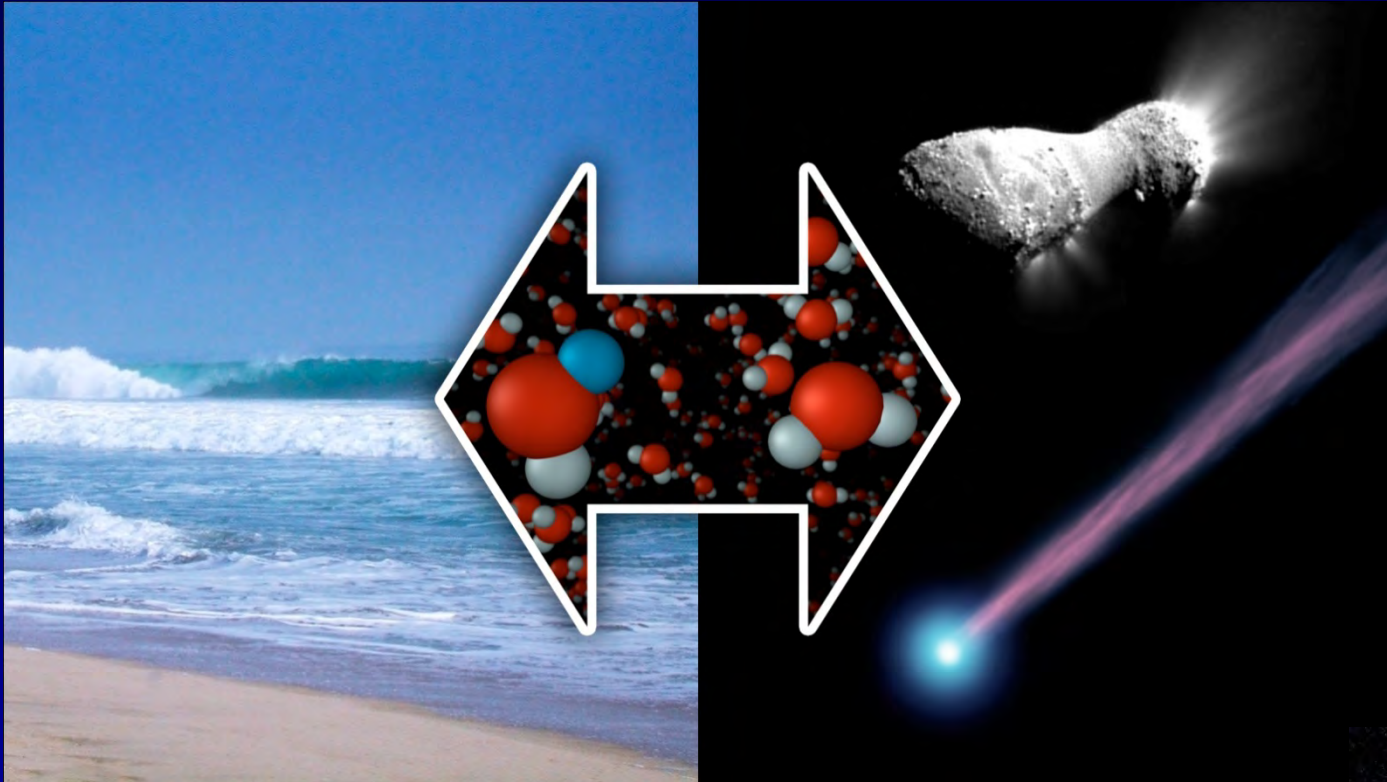
Hydrogensulfide
Carbonylsulfide
Sulfurdioxyde
Carbon disulphide
Thioformaldehyde



Nitrogen
Oxygen
Argon
Hydrogenperoxide
Carbon monoxide
Carbon dioxide



Oorsprong water op aarde?



ESA/NASA
Herschel-HIFI
Hartogh et al.

Zelfde verhouding: $\text{HDO}/\text{H}_2\text{O} = 1.5 \cdot 10^{-4}$



Mogelijke stappen in oorsprong van leven

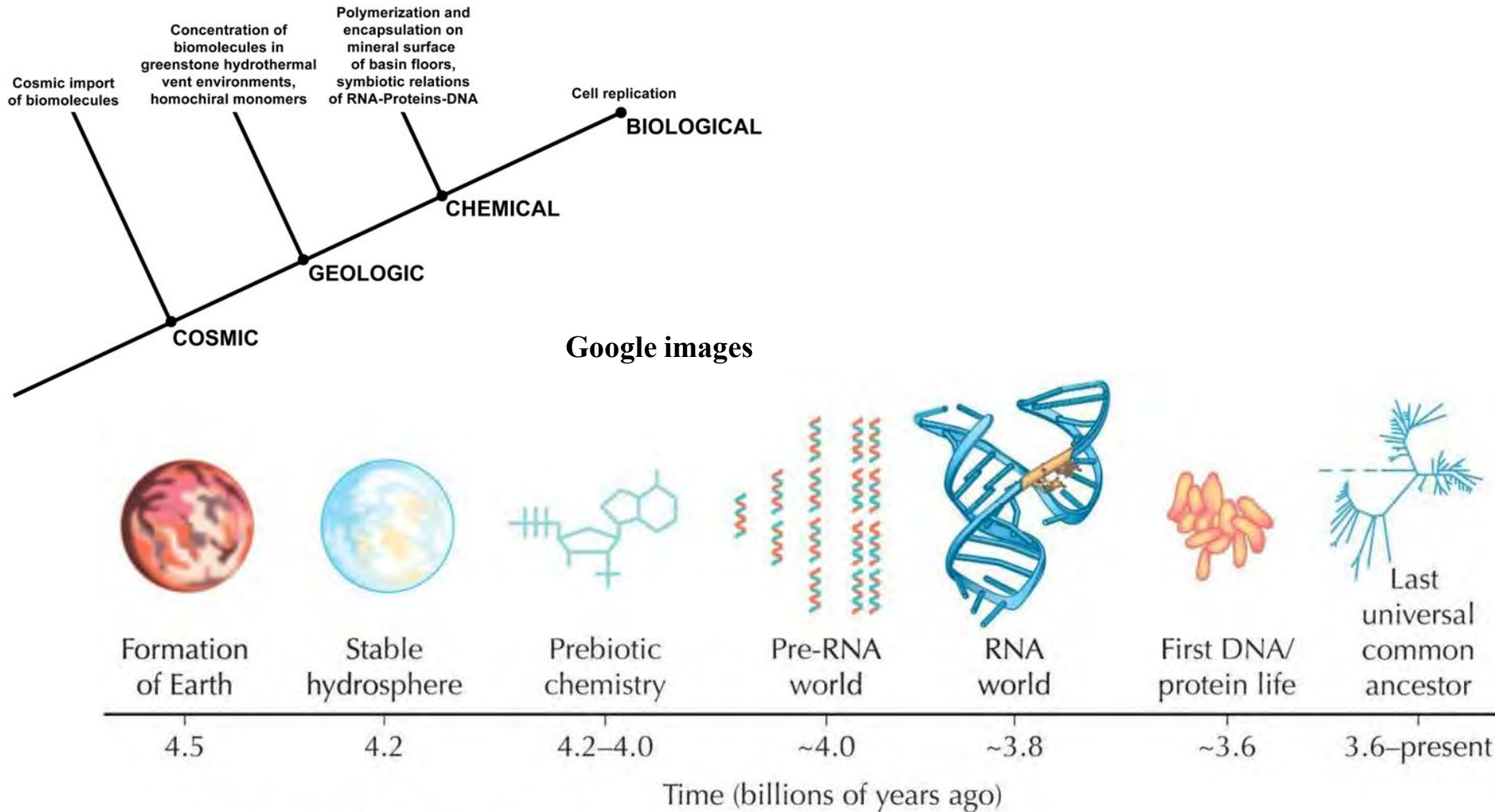
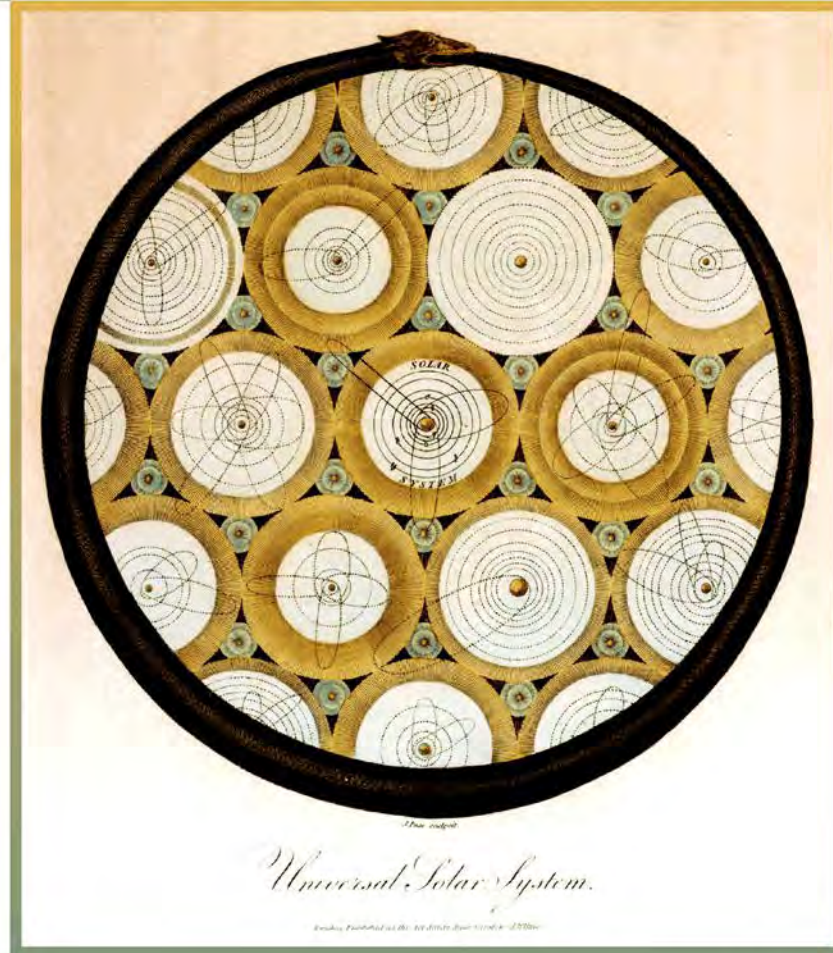


FIGURE 4.4. Steps in the origin of life.

Diversiteit planetenstelsels

APRIL
2004

PHYSICS TODAY

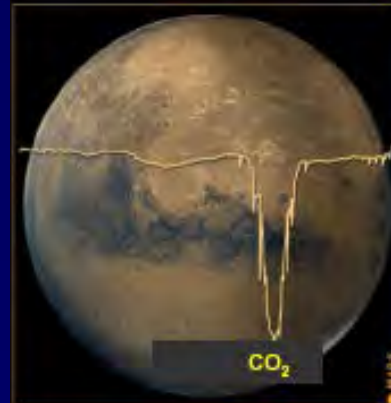
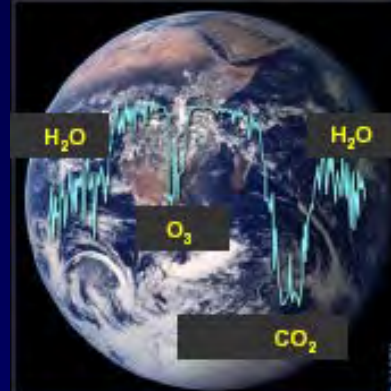
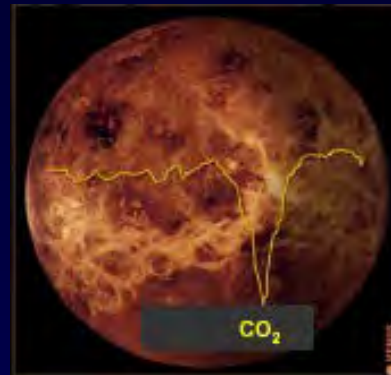
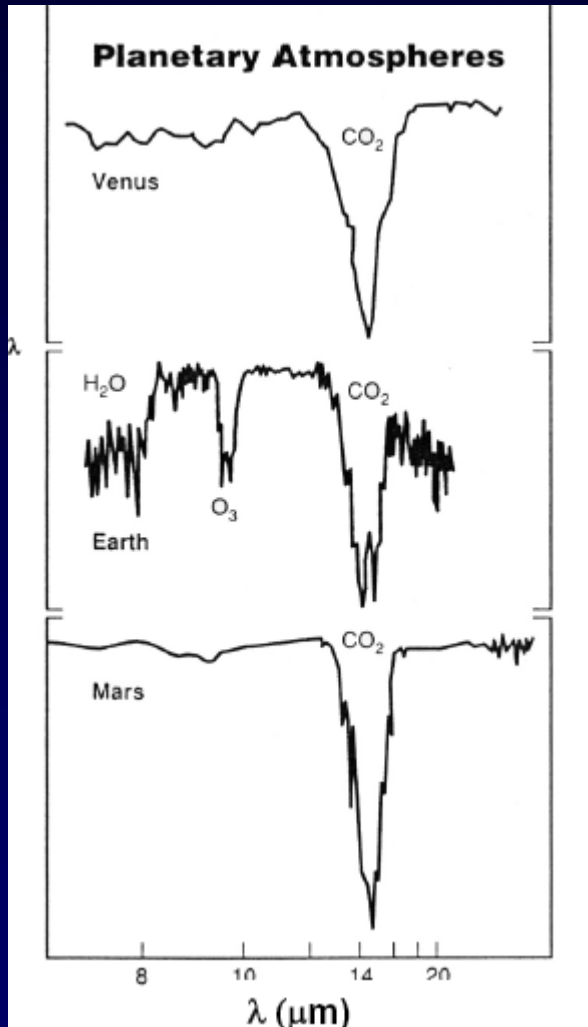


Engelse gravure
1798

Collectie EvD+TdZ

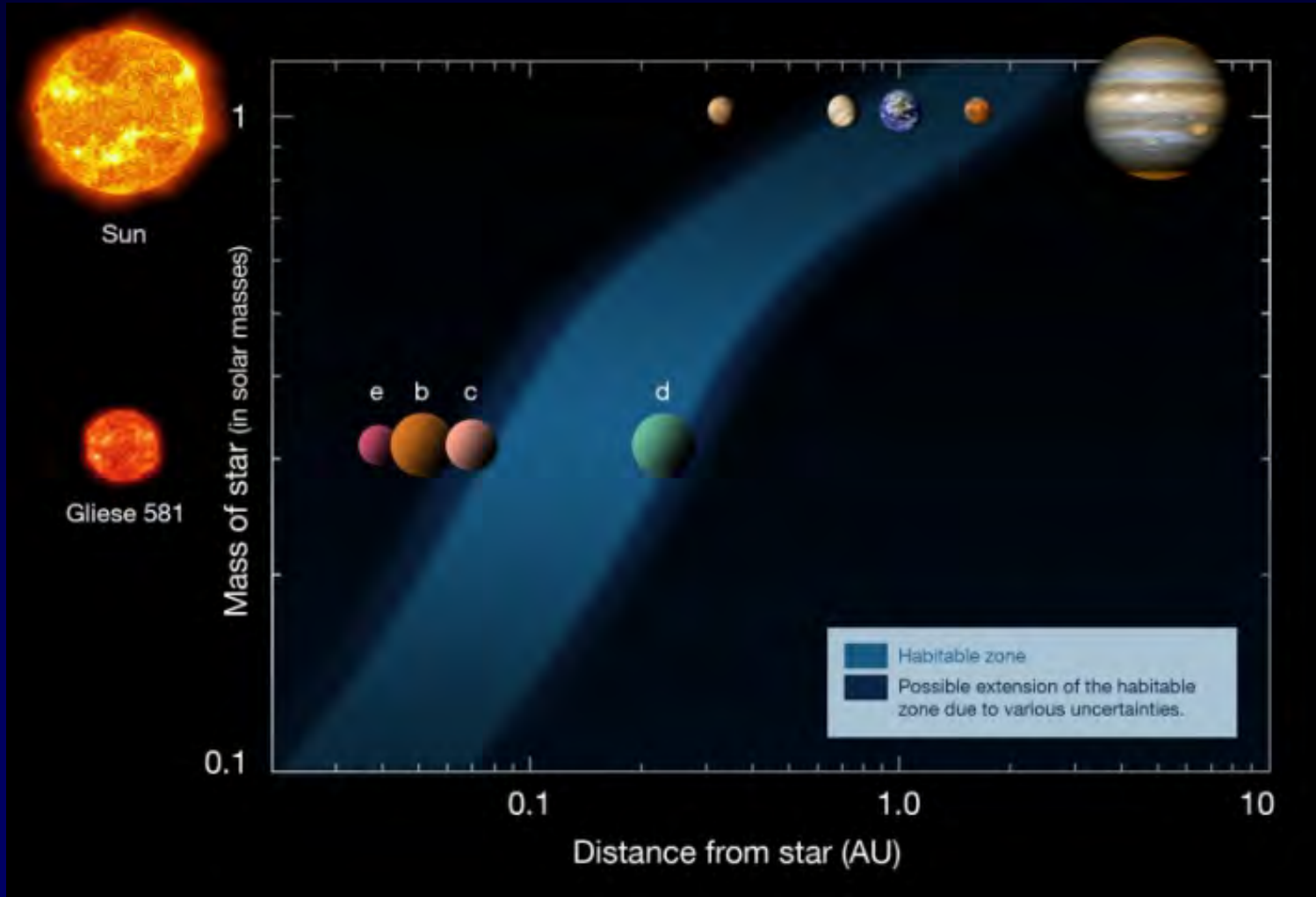
Special issue:
Planetary diversity

Kunnen andere planeten bewoonbaar zijn?



Aarde ligt in de 'bewoonbare zone' met temperaturen waarbij water vloeibaar is

Bewoonbare zone



Water in vloeibare vorm

Leven op de dichtsbijzijnde planeet?

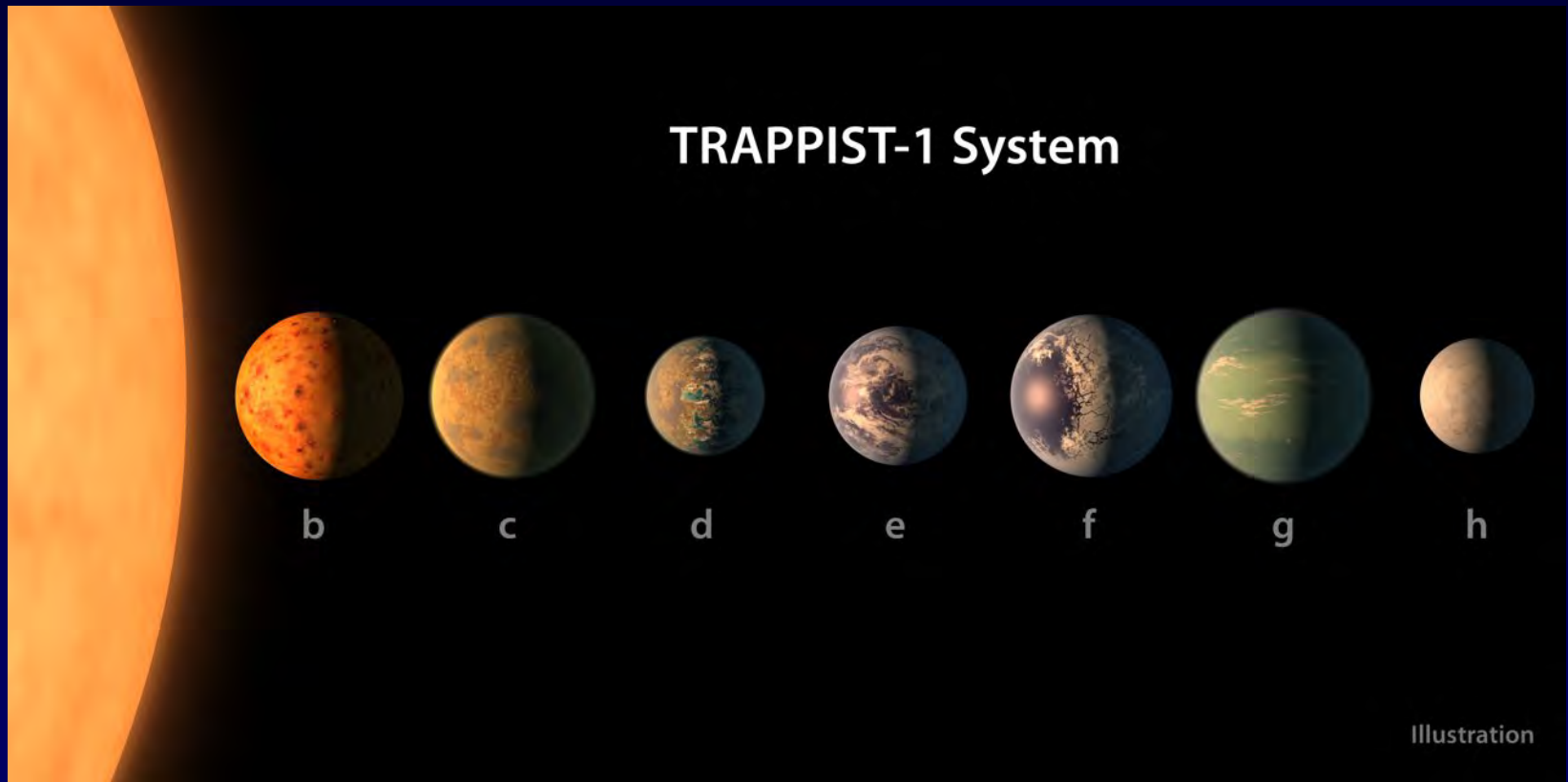


Anglada-Escudé et al. 2016

Met de ELT kunnen we de vraag: ‘Zijn wij alleen?’ beantwoorden



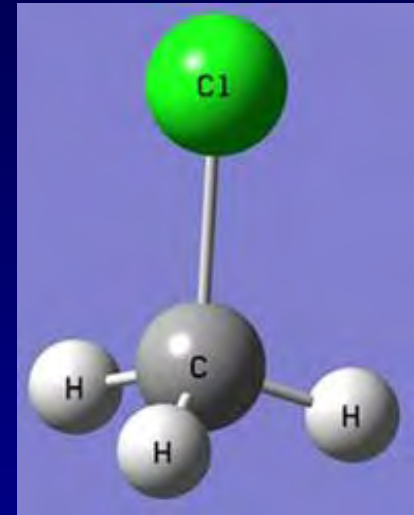
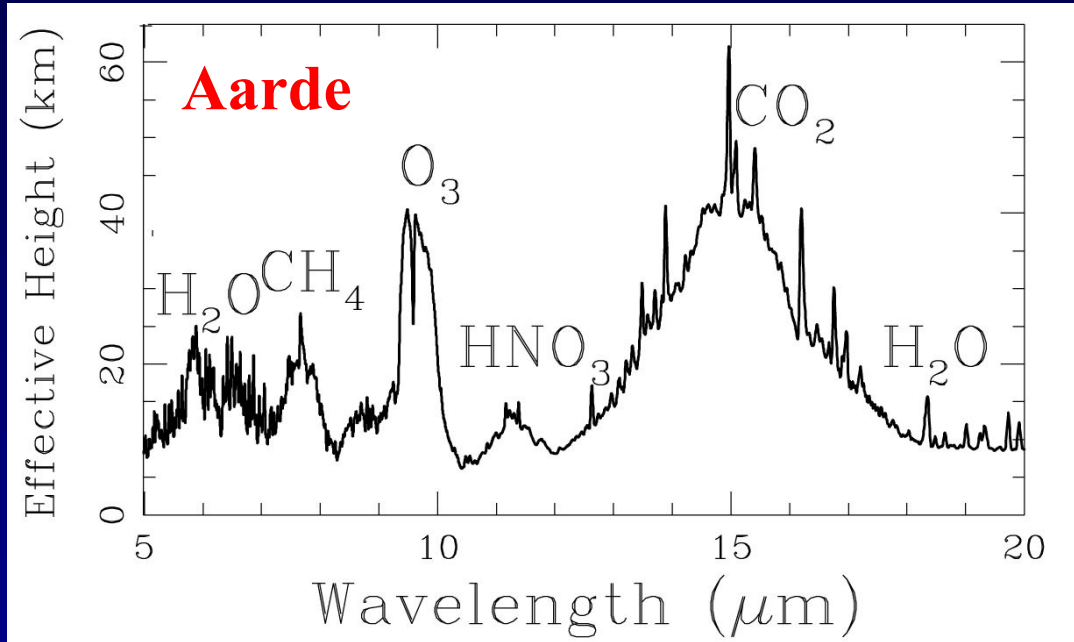
En op een Trappist 1 planeet?



Gillon et al, 2017

7 aardachtige planeten
3 in bewoonbare zone

Biomarkers

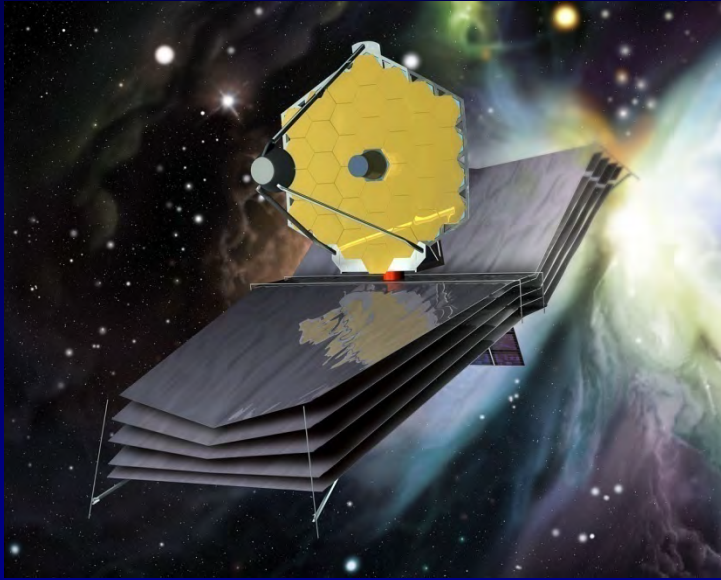


Kaltenegger 2017, ARAA

CH_3Cl 'The biomarker that isn't'
Fayolle et al. Nature Astronomy 2 okt 2017
P ILS + ROSINA \rightarrow abiotische productie

O_2 , O_3 , CH_4 , N_2O , CH_3Cl , ...
Detectie 1 biomarker niet genoeg

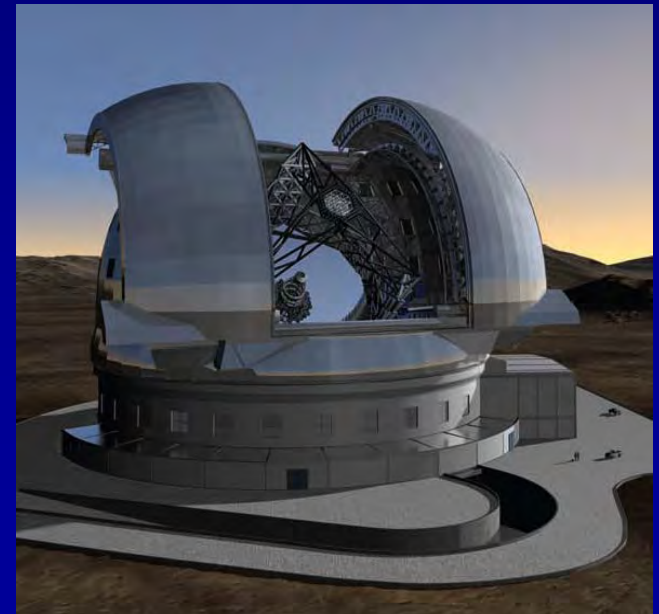
Toekomstige telescopen



**James Webb
Space Telescope**
~6 m diameter
2021
MIRI instrument

**European Southern
Observatory (ESO)**

**European Extremely
Large Telescope**
~39m diameter
~ 2025



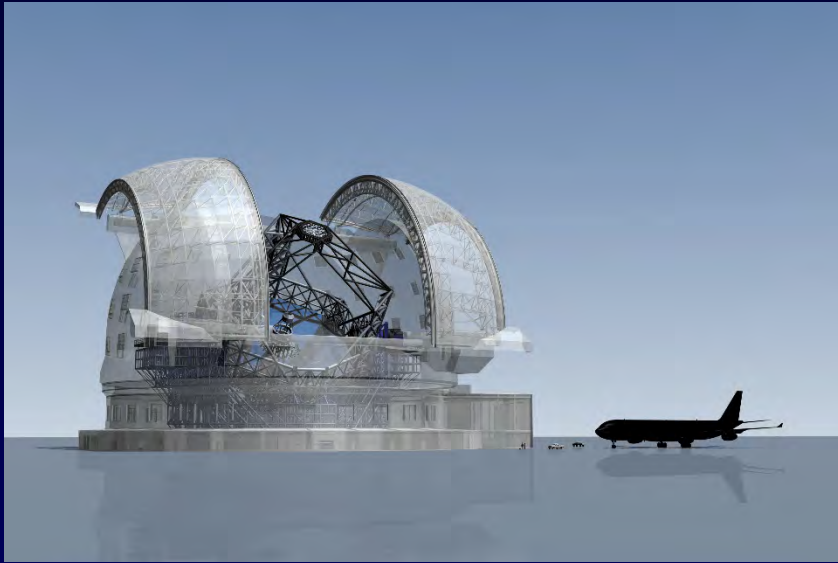
European Extremely Large Telescope



The Next BIG Thing!

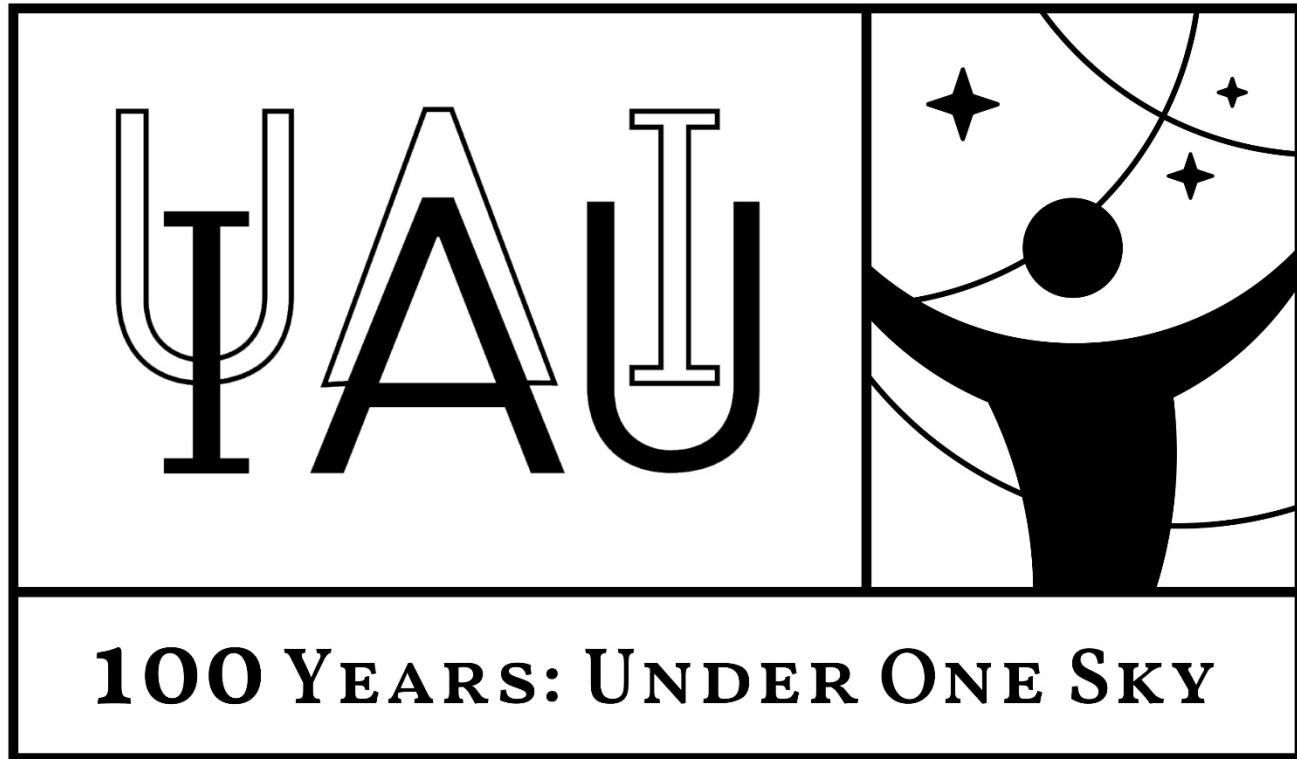
39m spiegel
~2025 gereed

Hoe groot is groot???



International Astronomical Union

1919 - 2019



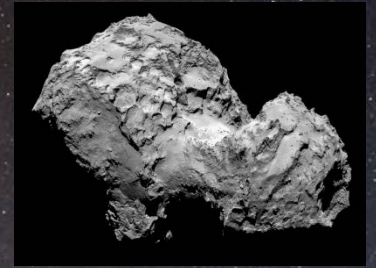
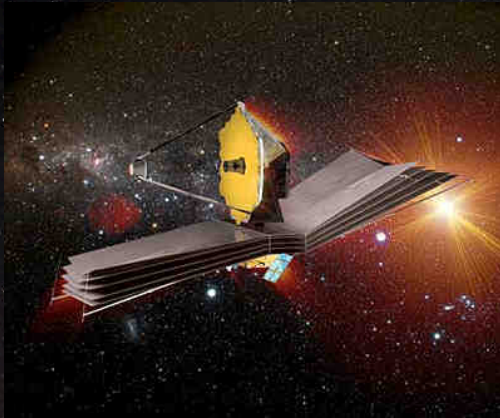
www.iau-100.org #IAU100

Activiteiten door het hele jaar!

Samenvatting

- **Water en organische moleculen zijn overal in de donkere wolken**
- **Wolken storten ineem om nieuwe sterren en planeten te vormen**
 - **Meeste jonge sterren hebben voldoende materiaal om planetenstelsel te vormen**
- **Moleculen kunnen door inslagen van kometen en asteroiden op nieuwe planeet worden gebracht**
- **Met nieuwe krachtige telescopen kunnen we naar het tweelingzusje van onze Aarde zoeken**

Dank voor de aandacht!



Acknowledgments

- **Figuren en filmpjes van:**
 - **European Southern Observatory**
www.eso.org
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hubblesite.org
 - **NASA/Spitzer Space Telescope**
www.spitzer.caltech.edu
 - **ESA/Herschel Space Observatory**
herschel.esac.esa.int
 - **Atacama Large Millimeter array**
 - www.almaobservatory.org
 - **ESA Rosetta mission to comet**
sci.esa.int/rosetta/