

Origin of elements and chemistry in outer space



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Leiden University, the Netherlands
President International Astronomical Union

XXI Mendeleev congress, September 10 2019, St Petersburg

Where do we come from?

Starry night
Van Gogh

Milky Way dreaming
Australia aboriginal art

From the Big Bang to supernovae

The periodic table is color-coded by origin:

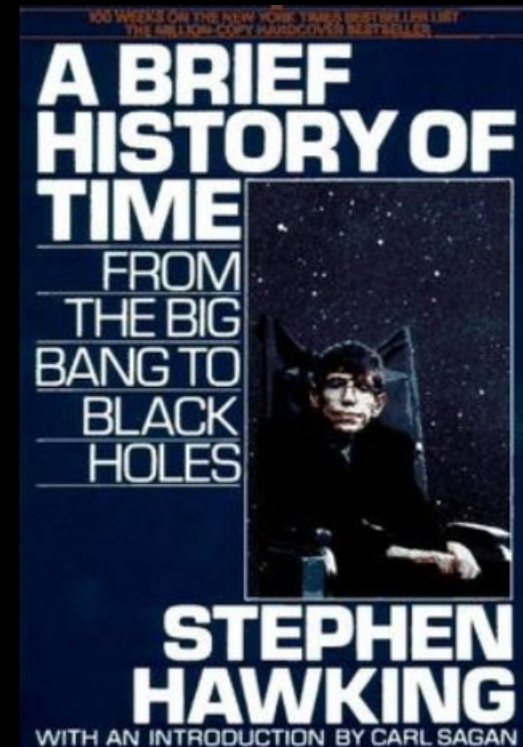
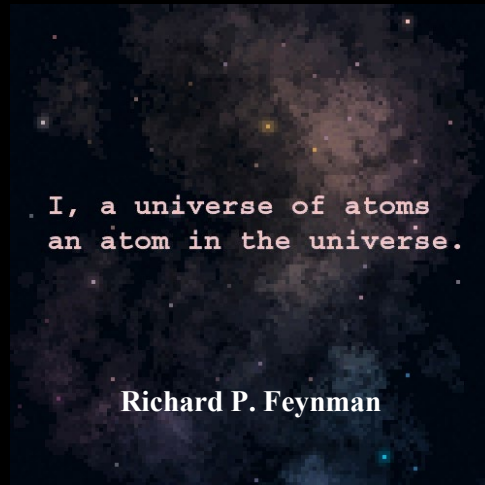
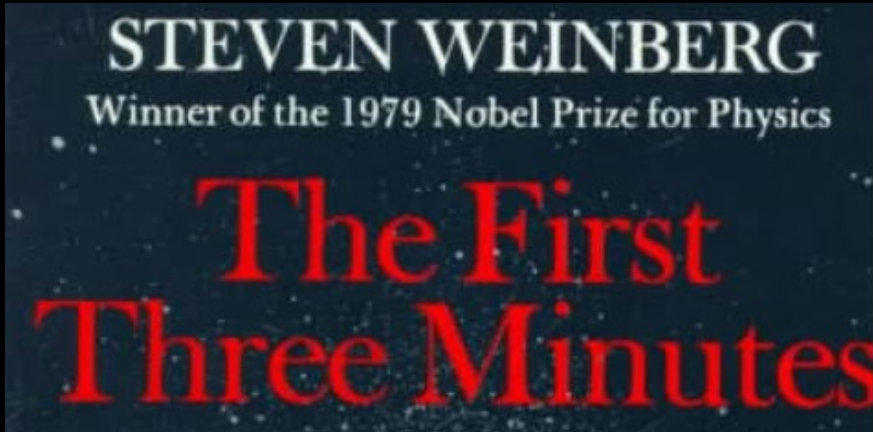
- Big Bang (Purple):** H, He
- Large stars (Green):** Li, Be, B, C, N, O, F, Ne, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr
- Supernovae (Orange):** Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr
- Cosmic rays/BB (Light Blue):** Li, Be, B, C, N, O, F, Ne, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr
- Small stars (Yellow):** Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr
- Man-made (Pink):** Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr

Red dashed circles highlight Hydrogen (H) and Helium (He).

Credit: Wikipedia: Cmglee

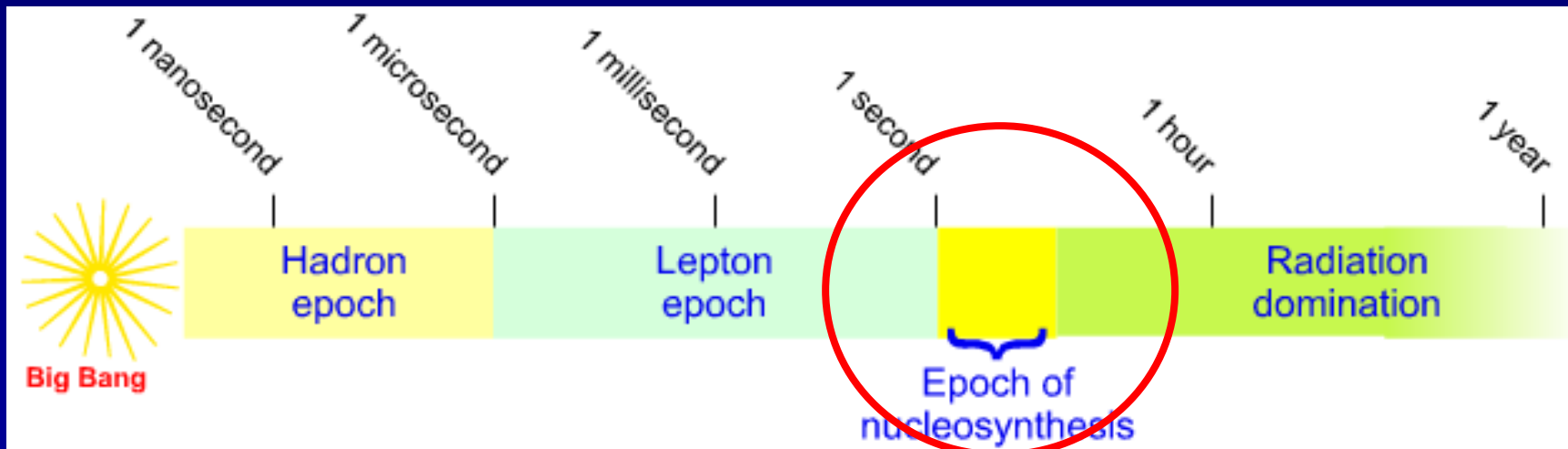
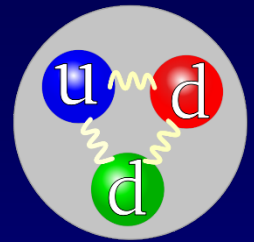
Credit: Wikipedia: Cmglee

In the beginning there was..... Hydrogen



Big Bang production elements

- Expansion Universe => cooling of quark soup so that protons and neutrons can be formed
 - ~1 minute after Big Bang
- Big Bang only produces H, D, He and some Li, Be



wikipedia

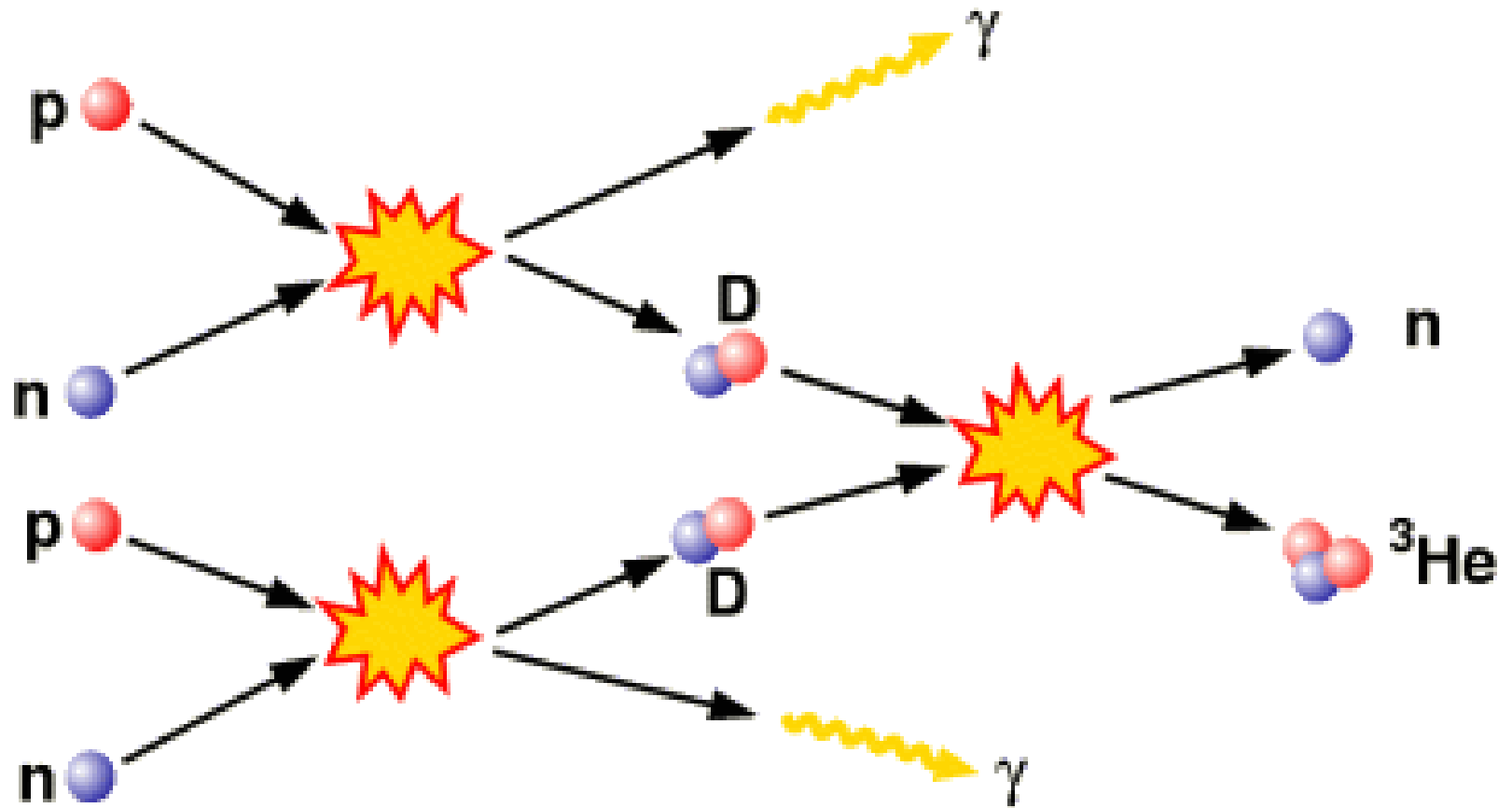


$$p:n \sim 6 : 1$$

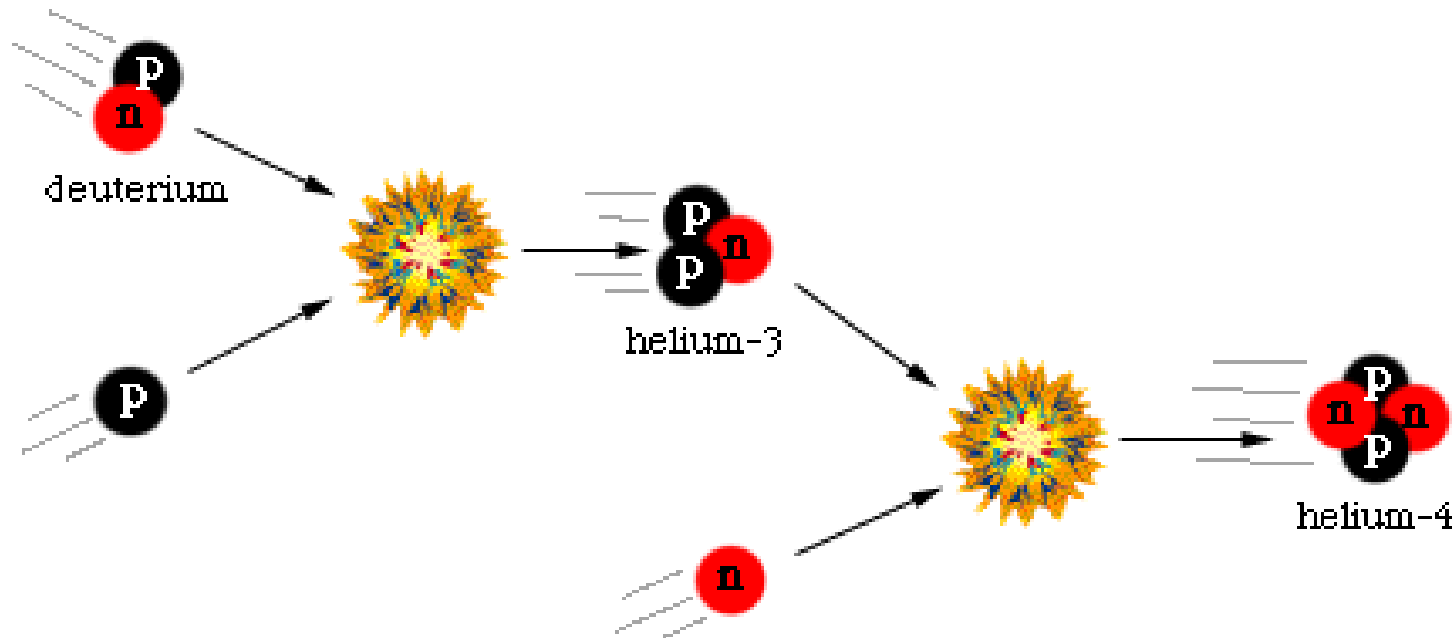
p= proton (H^+)

n=neutron

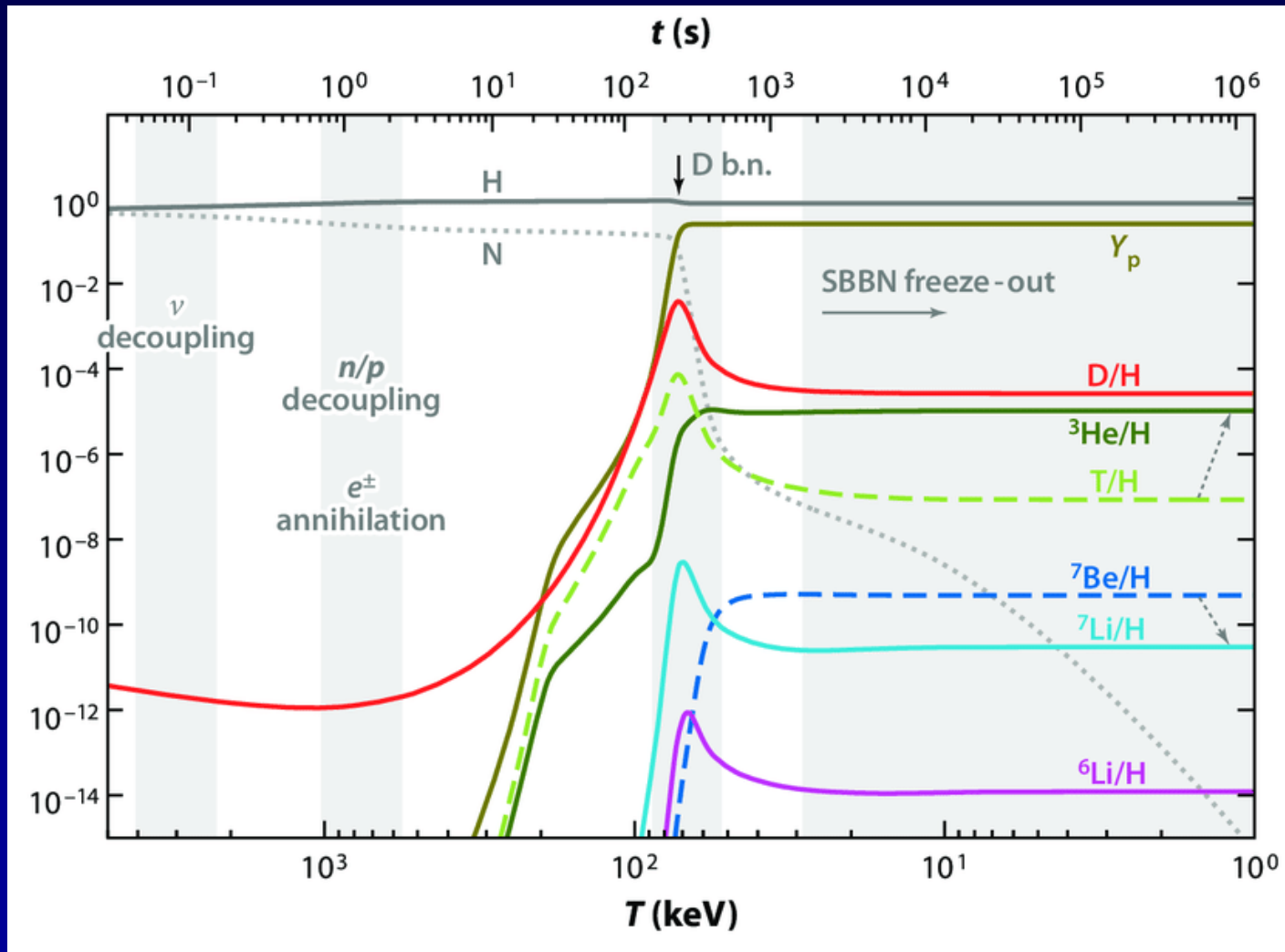
Production D and ^3He



Production ^3He and ^4He

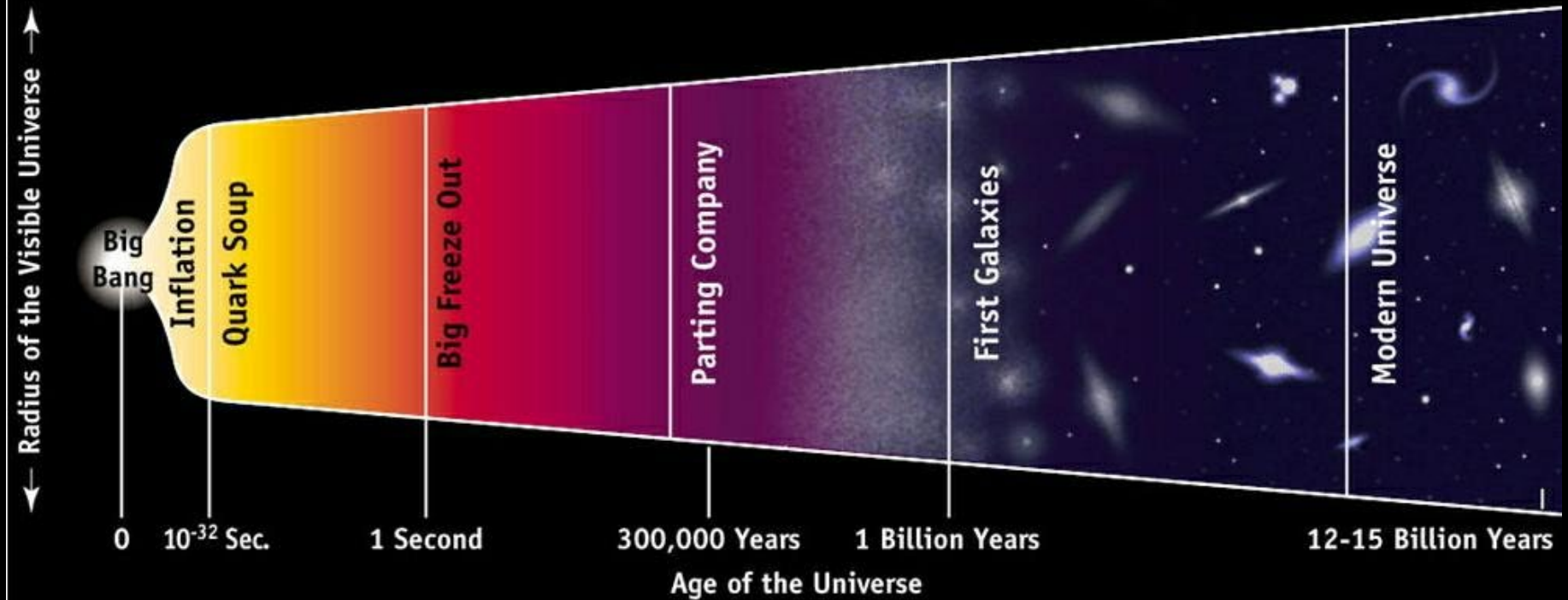


Expansion: Abundances 'frozen in'



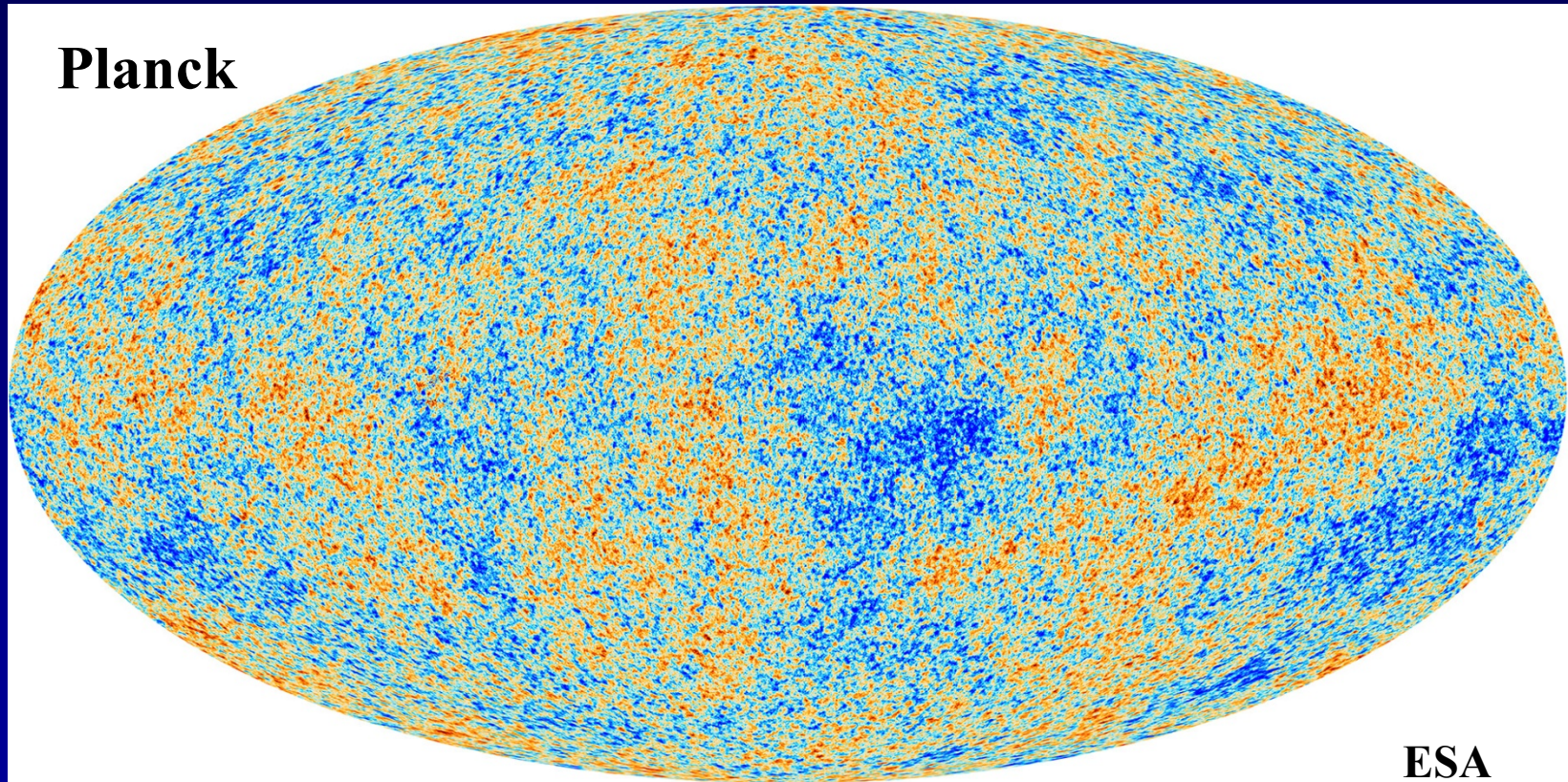
Thereafter.....

Formation first structures in Universe



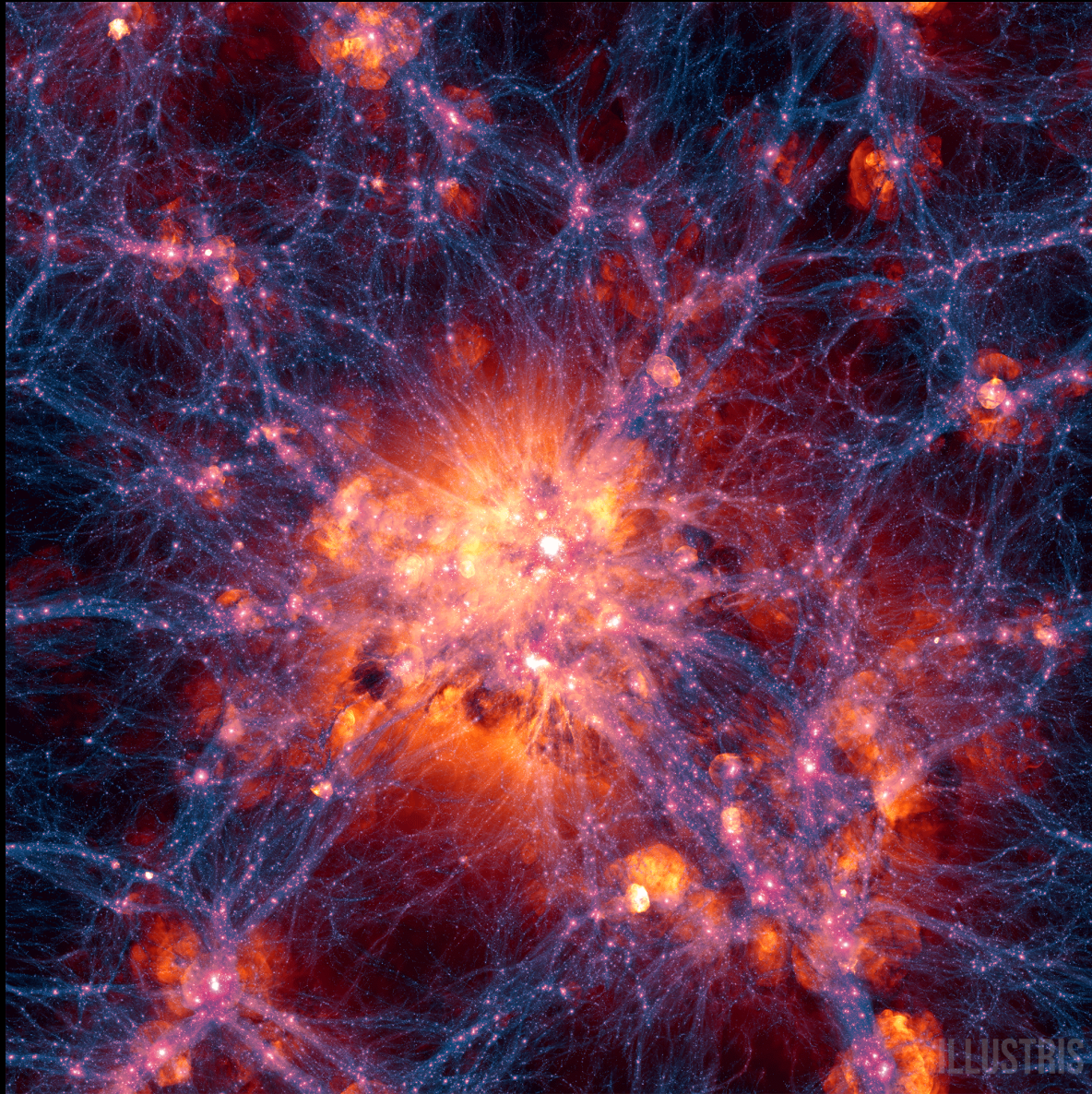
Cosmic microwave background

Tiny fluctuations $\rightarrow$ seeds of future structures



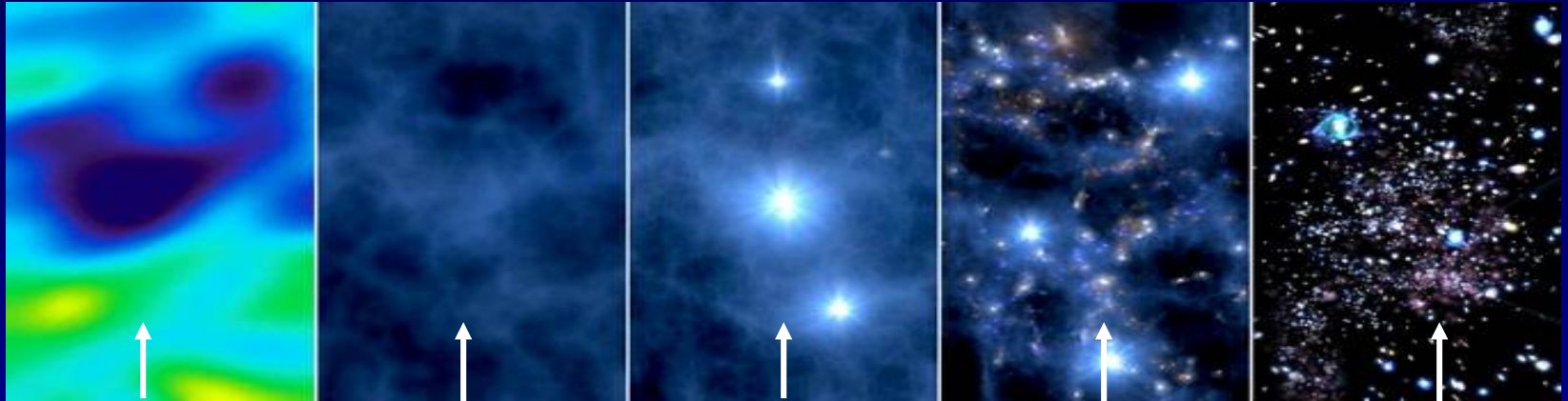
COBE, WMAP and Planck satellites

Formation galaxies and stars



Illustris hydrodynamical cosmological simulation

The first billion years



Fluctuations in
primordial soup

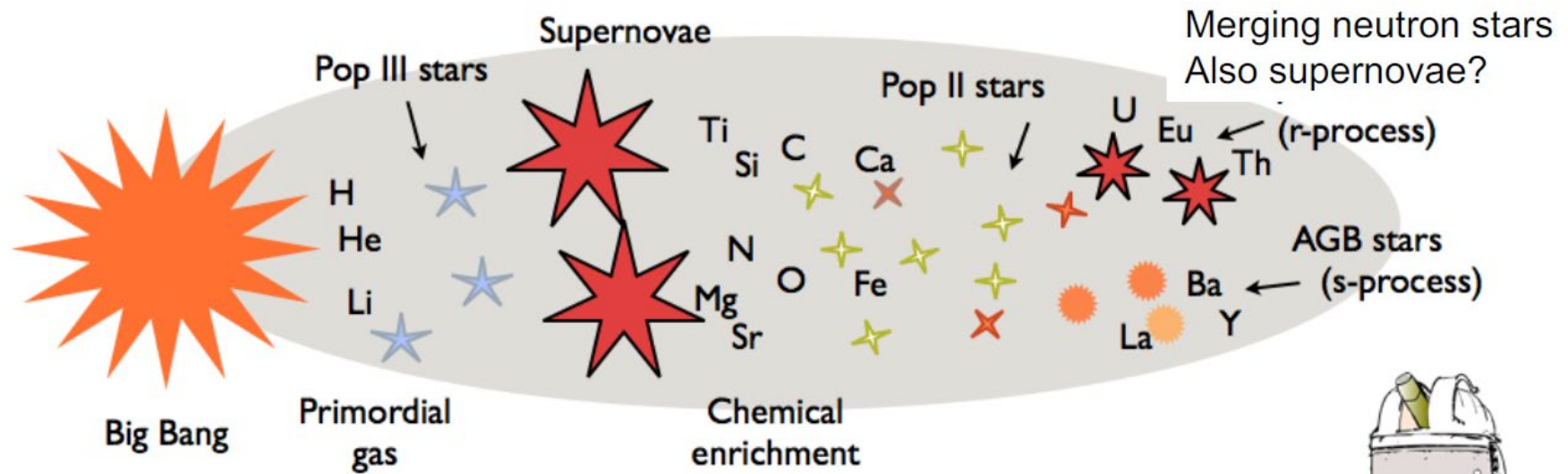
The illumination era
First stars

Today

The dark ages:
Giant H clouds

*Formation of
galaxies*

Nucleosynthesis in stars enriches Universe in heavy elements



H. Jacobson

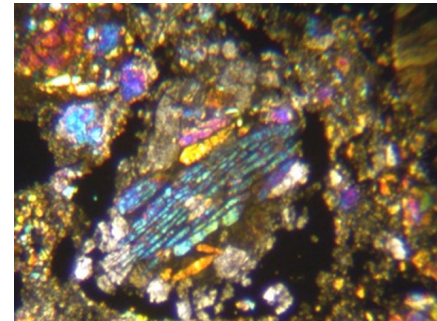
See symposium on 'The Periodic Table through Space and Time'

Analysis of meteorites

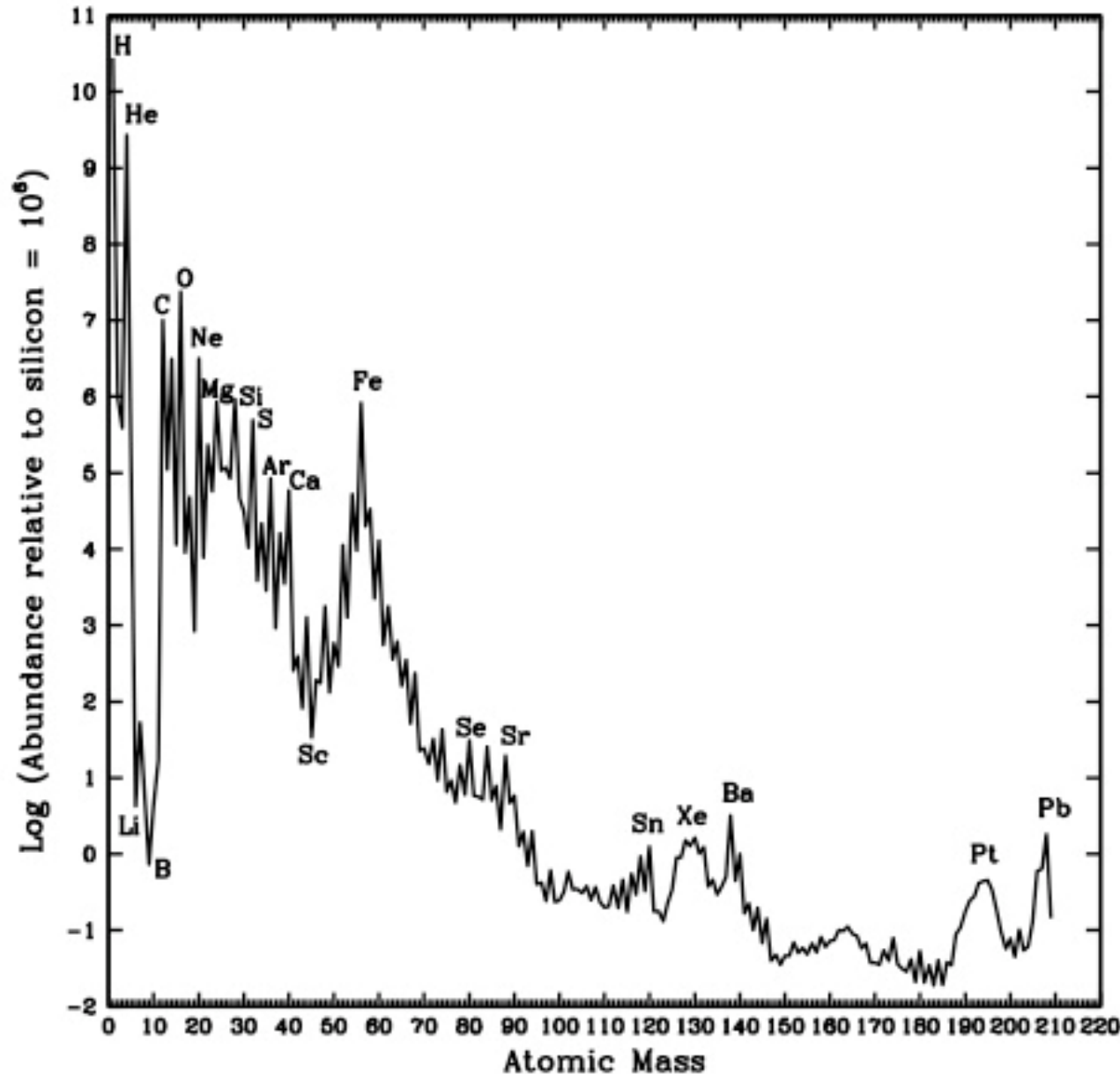
Primitive meteorites that underwent little chemical modification provide the most accurate information on the chemical composition of the Solar System



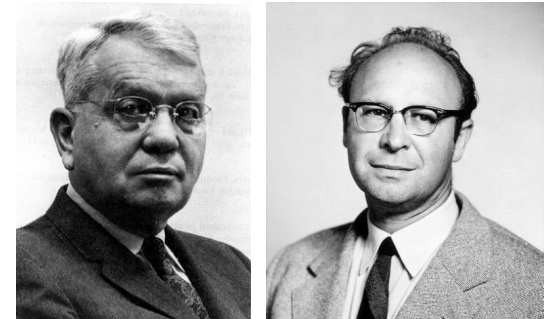
Carbonaceous
chondrites,
such as Allende,
Murchison, Renazzo,
....



Solar System and cosmic abundances

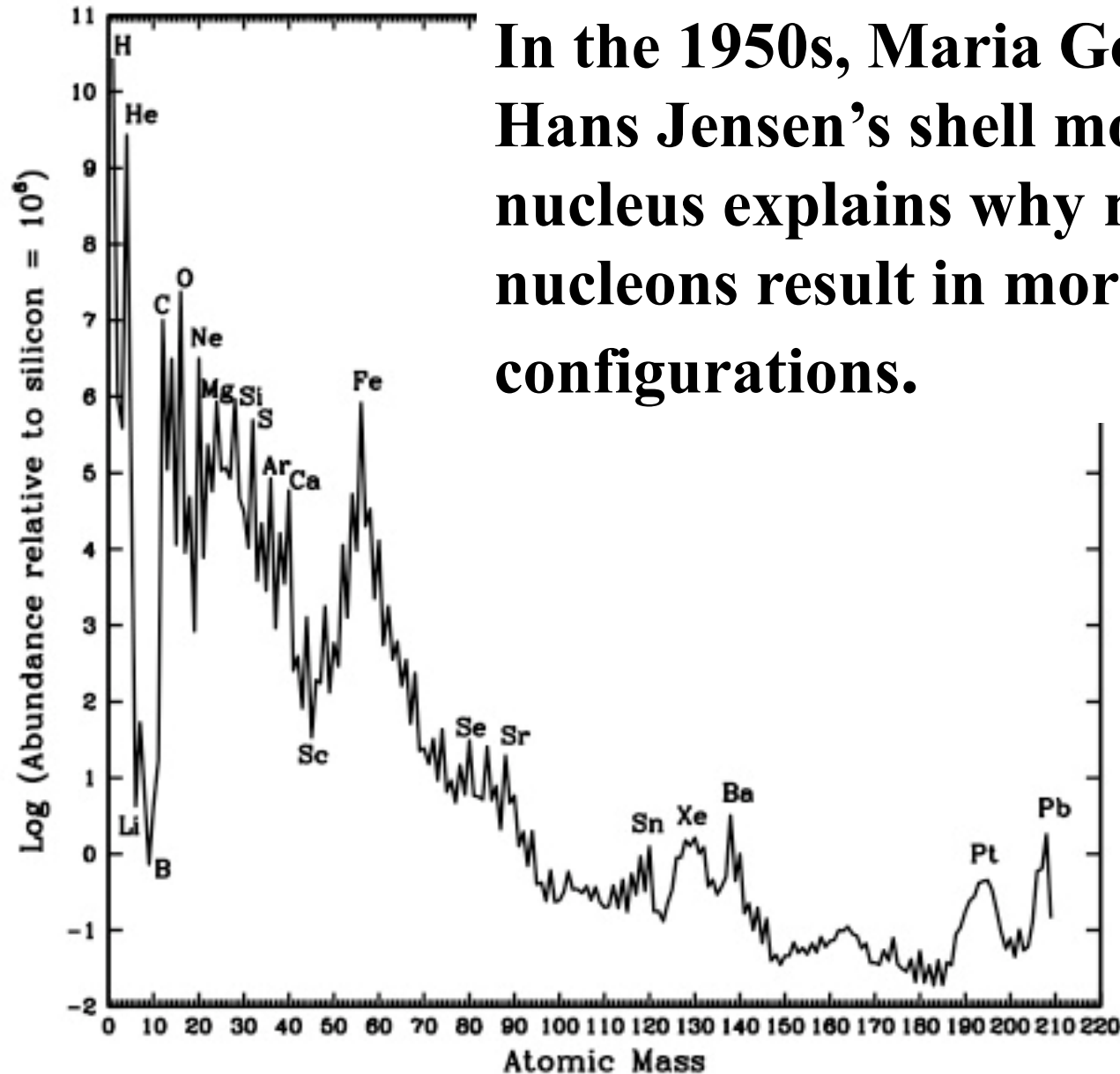


In 1956, Harold Urey and Hans Suess, publish a famous table of *isotopic* cosmic abundances

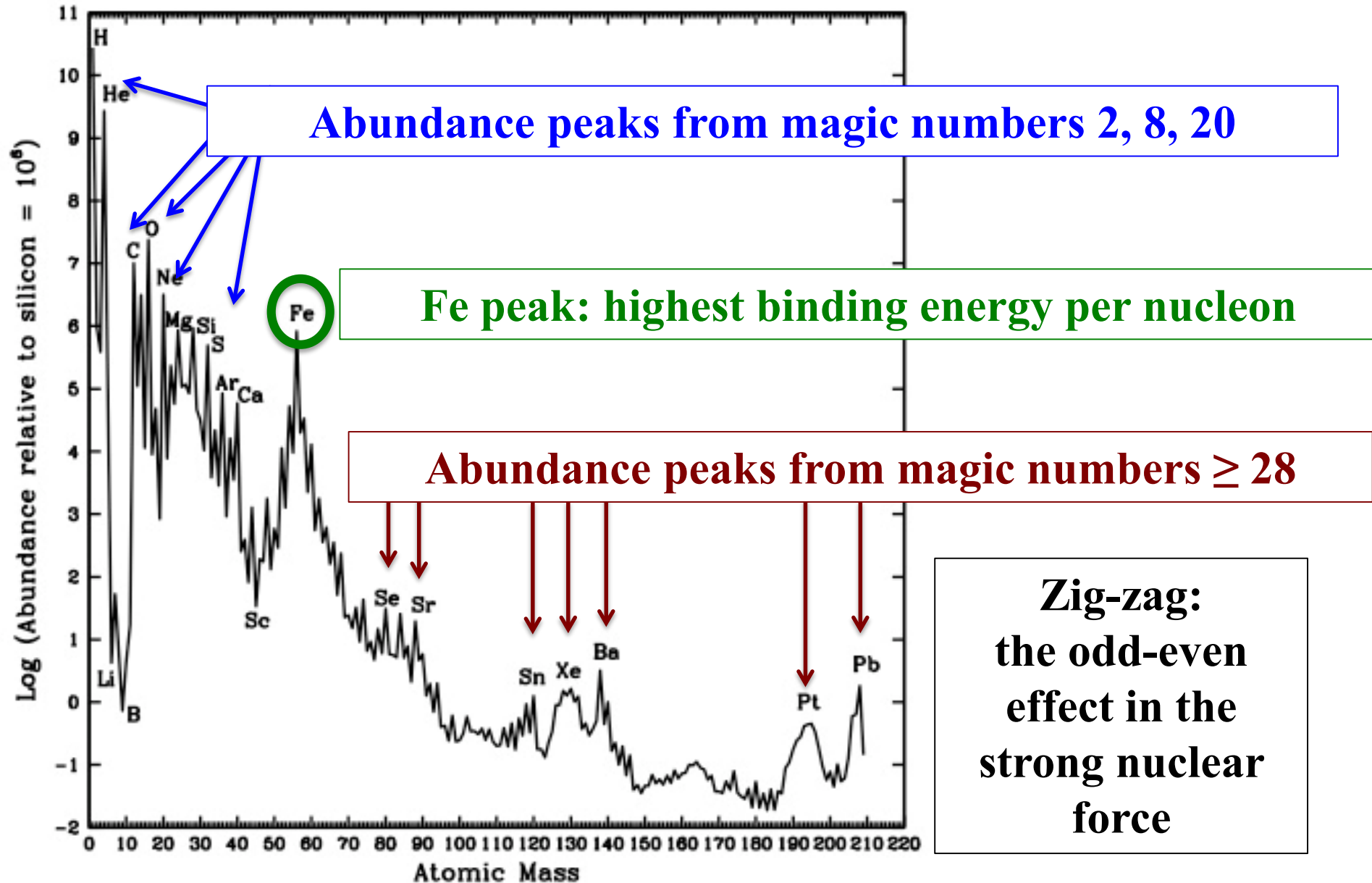


...from meteorites to nuclear physics!

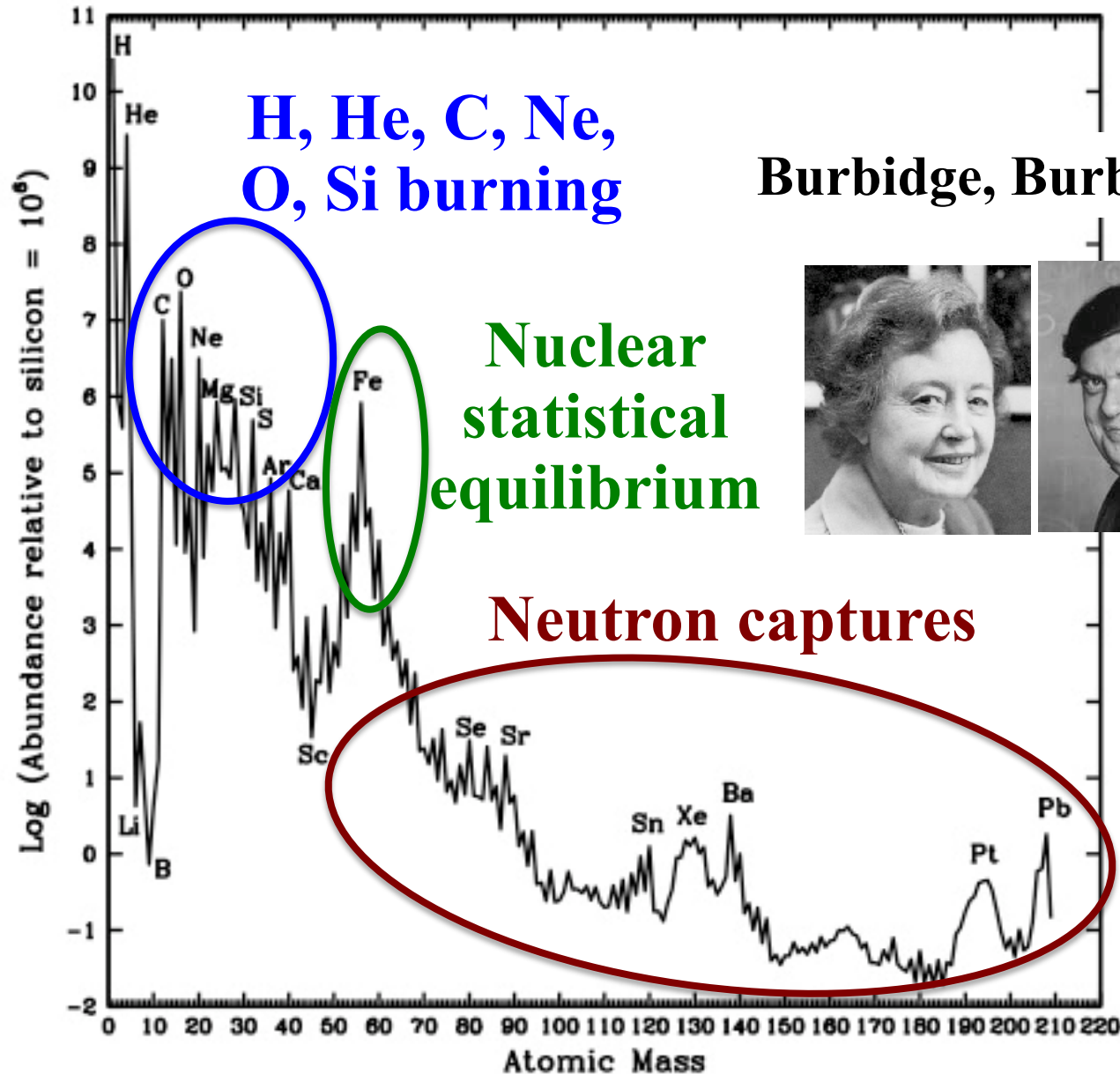
In the 1950s, Maria Goeppert Mayer and Hans Jensen's shell model for the atomic nucleus explains why magic numbers of nucleons result in more stable nuclear configurations.



...from meteorites to nuclear physics!

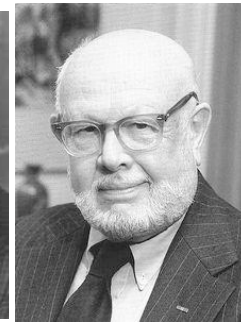
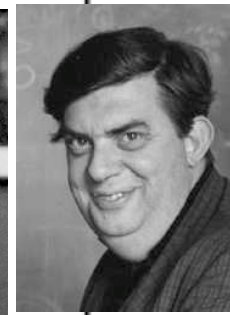


...from meteorites to nucleosynthesis!



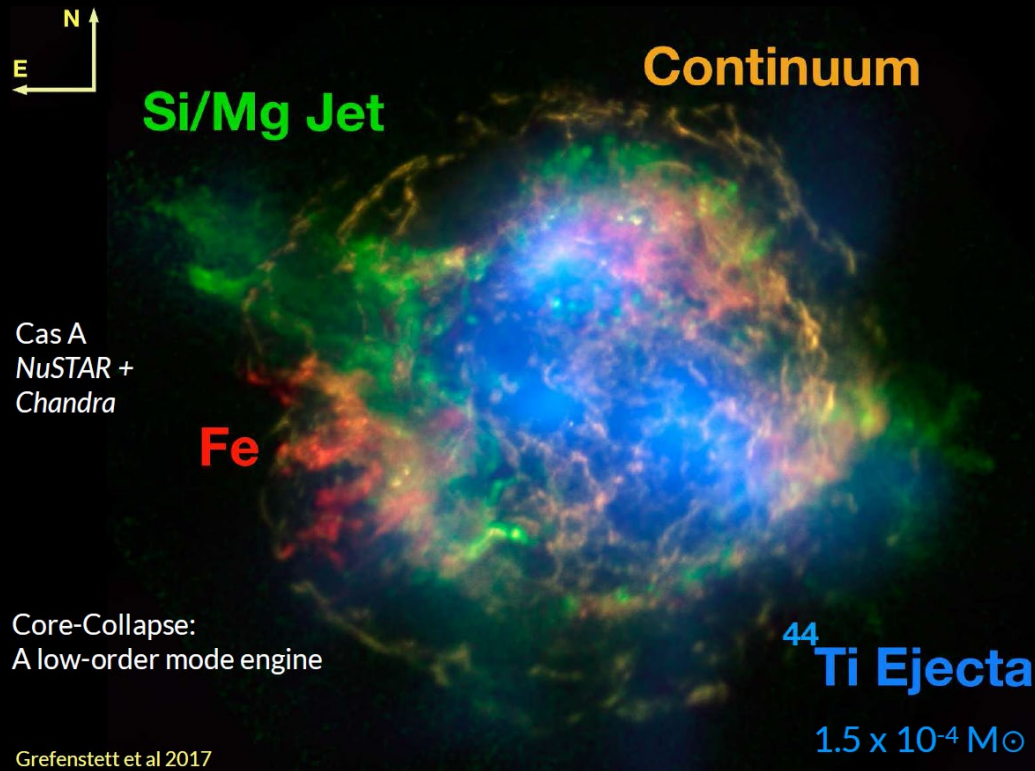
In 1957, B²FH

Burbidge, Burbidge, Fowler & Hoyle

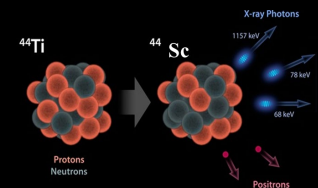


publish the first
classification of
nucleosynthesis
processes in stars

Production of Iron and Titanium



Supernova
Remnant
Cas A



Making Gold in the Universe!



Neutron-neutron star merger
LIGO-VIRGO collaboration 2017

**GW 170817 produced
several oceans of gold**

● H, He, Li

BIG BANG

FIRST STARS

Be, C, N, O

Ti, Co, Fe

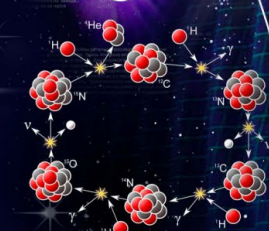
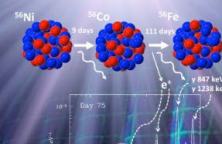
Si, Mg, Ne

Ag, Au, U

NEUTRON
STAR

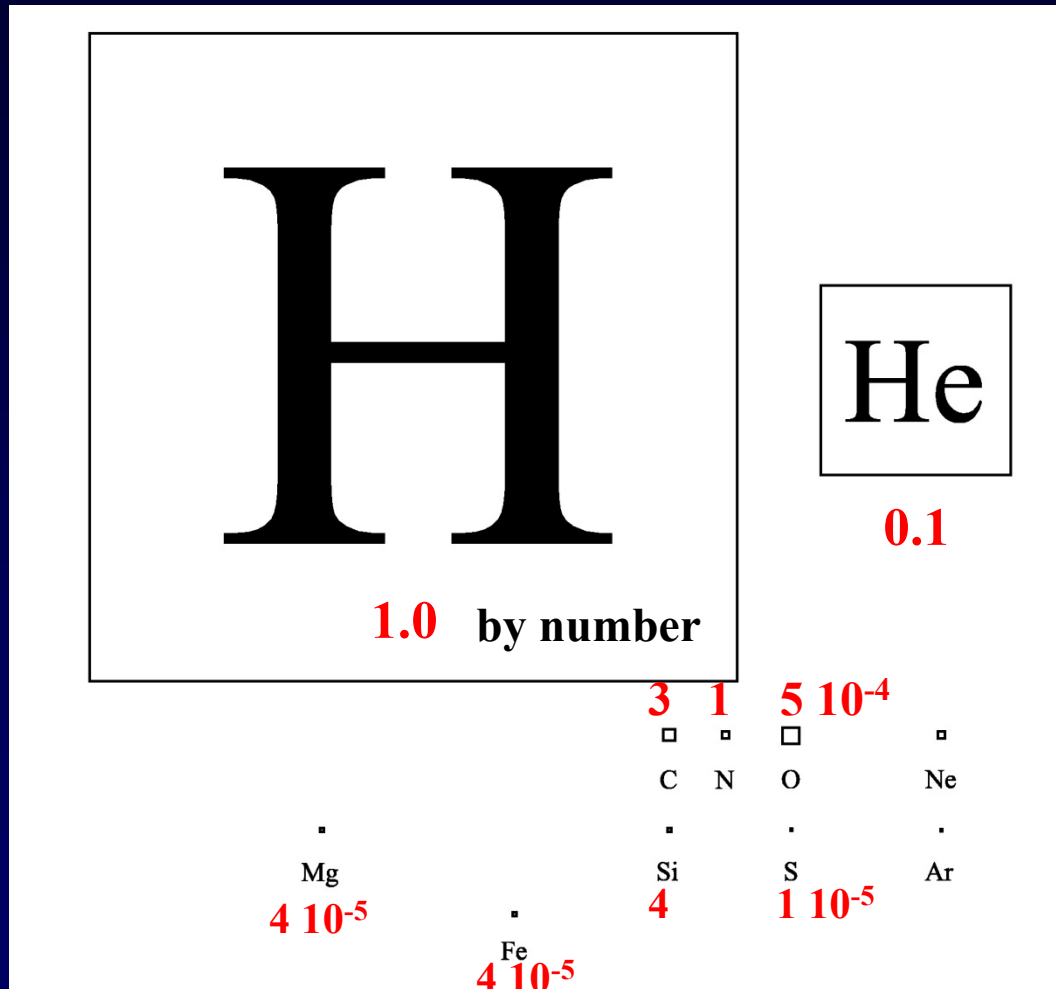
MERGION
OF NEUTRON
STARS

● Proton
● Neutron
● Positron
γ Gamma Ray
ν Neutrino



Chemistry in Space

The Astronomers' Periodic Table



B. McCall 2001

Orion nebula: nursery of thousands of young stars and chemical factory



Red=ionized gas (H^+)
Too hot for molecules

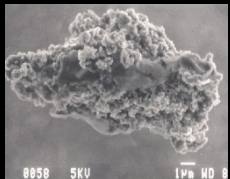
Hubble Space
Telescope NASA/ESA



Stars do not have eternal life: they are born and they die
Victor Ambartsumian (1908-1996)

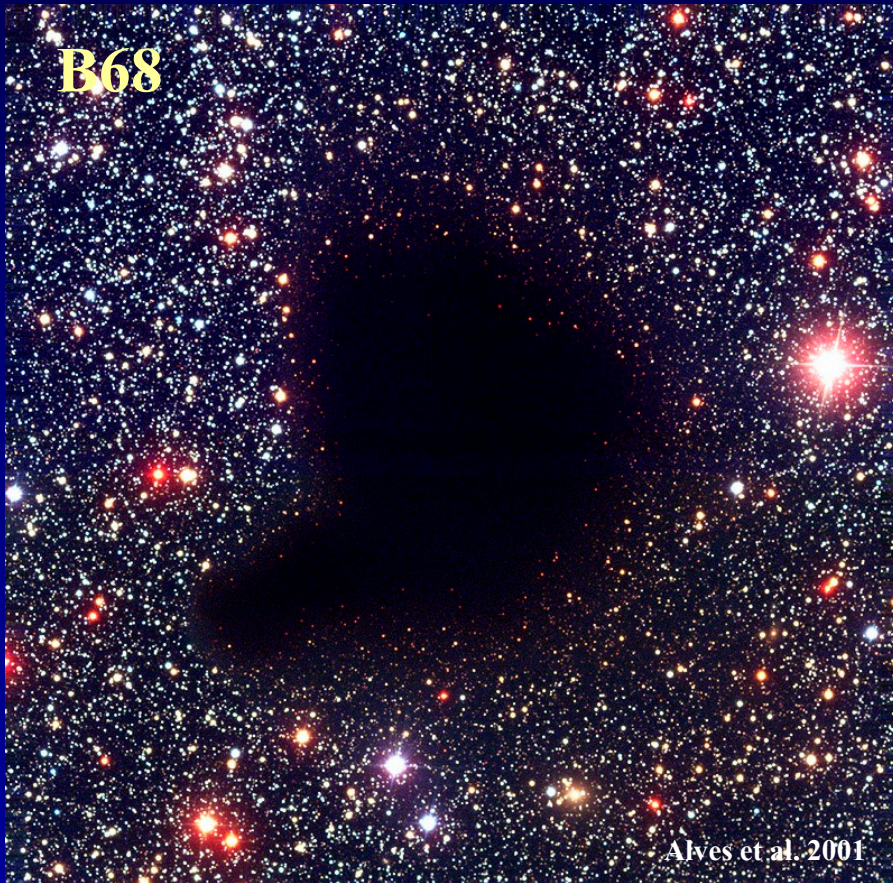
Molecules are formed in dark clouds

HST Carina nebula



Clouds consist of gas and small dust grains ('sand')

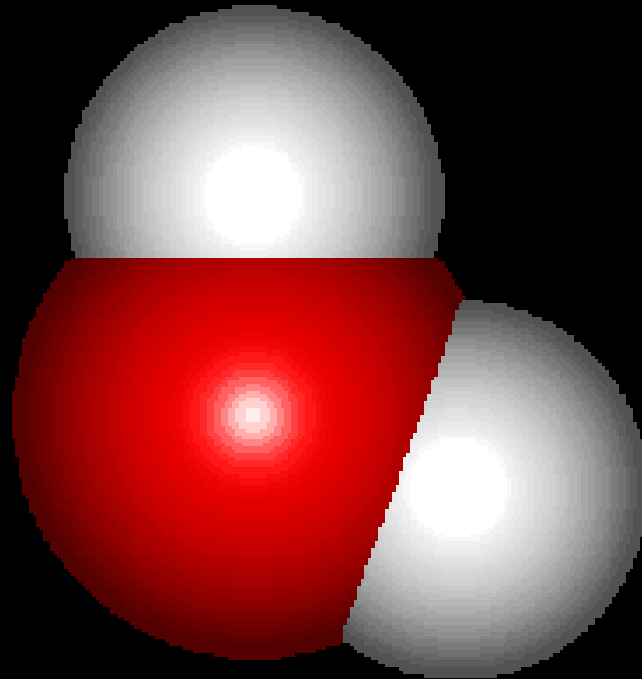
Cold dark clouds



- Mostly H_2
- Dust grains (1% by mass)
 - Silicates, carbonaceous $0.1 \mu\text{m}$
- Temperature: $\sim 10 \text{ K}$
- Density: $\sim 10^4 \text{ cm}^{-3}$
- Ionization fraction $\sim 10^{-7}$
- Collision time: $\sim$ once per month
- Chemical time: $\sim 10^5 \text{ yr}$
- Cosmic rays, UV

————→ *Unique physical and chemical laboratory!*

From elements to molecules: water as example



Formation of water on dust grains

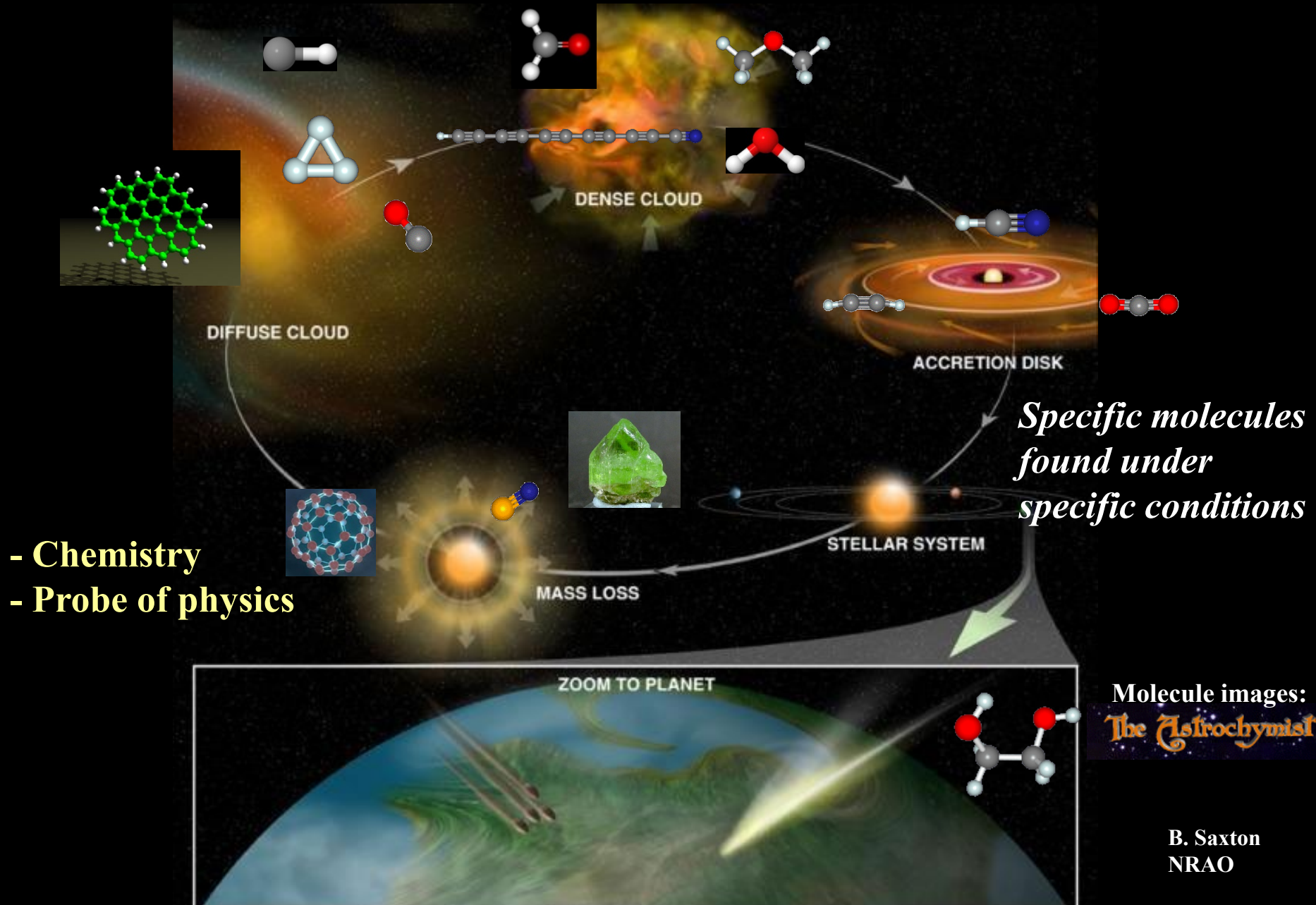


‘Water on Earth is older than the Sun’

I. Cleaves et al.

Based on laboratory experiments
in Leiden, Paris, Japan
Cuppen et al. 2010

Lifecycle of elements and molecules



Atacama Large Millimeter Array (ALMA)



54x12m + 12x7 m antennas

0.3-3 millimeter
84-950 GHz

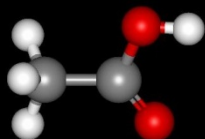


**ALMA observes cold dust (continuum)
and myriad of molecules (pure rotational lines)**

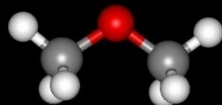
Some complex organic molecules

'Molecular bricks for life'

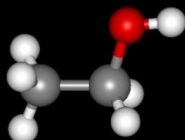
Detected



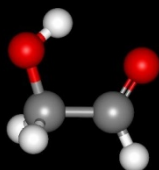
Acetic acid



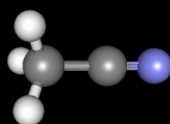
Di-methyl ether



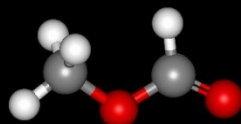
Ethanol



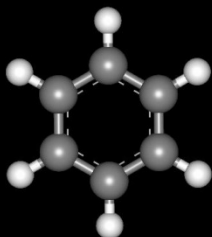
Sugar



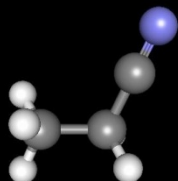
Methyl cyanide



Methyl formate

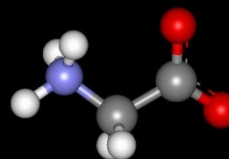


Benzene

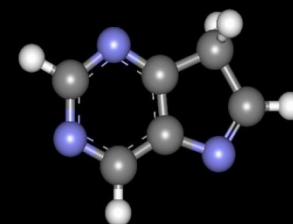


Ethyl cyanide

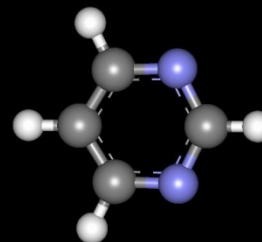
Not (yet) detected



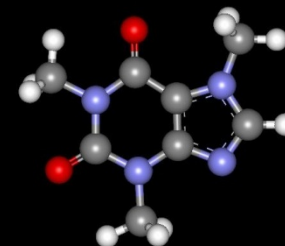
Glycine



Purine



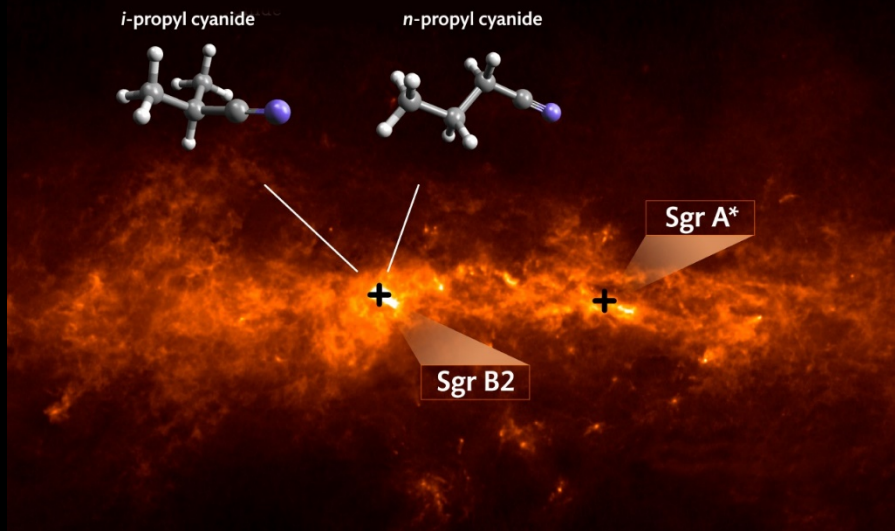
Pyrimidine



Caffeine

ALMA: How far does chemical complexity go?

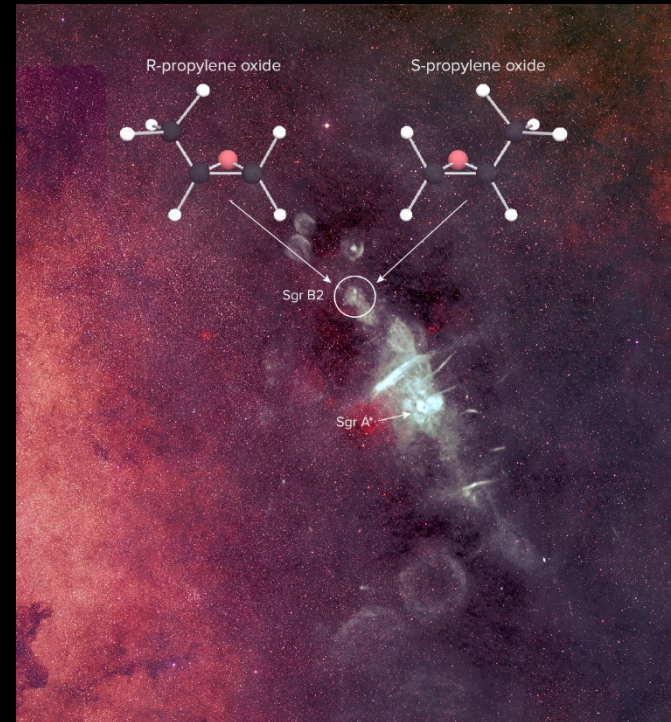
Molecules are branching out



Such side chains are characteristics of amino acids

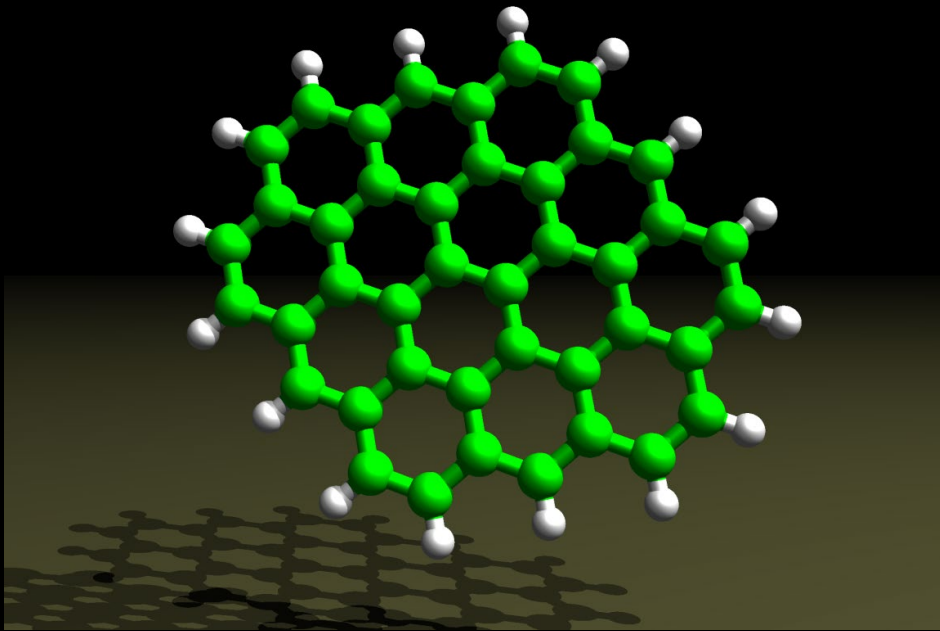
ALMA
Belloche et al. 2014

First chiral molecule

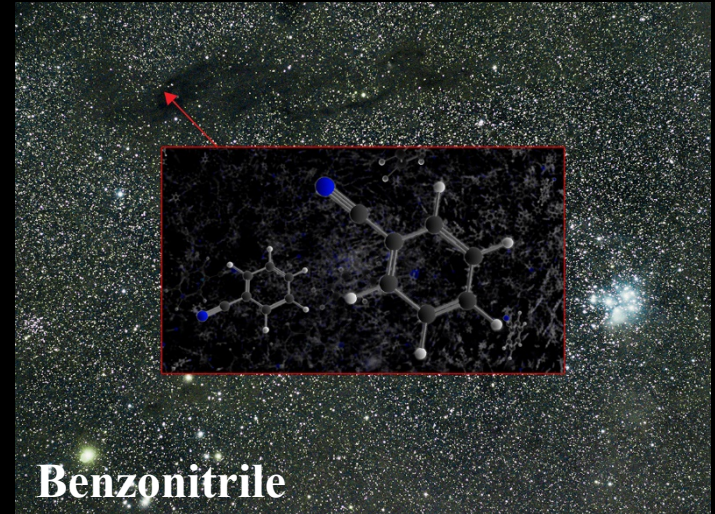


McGuire et al. 2016
GBT, ATCA

Very large carbonaceous molecules

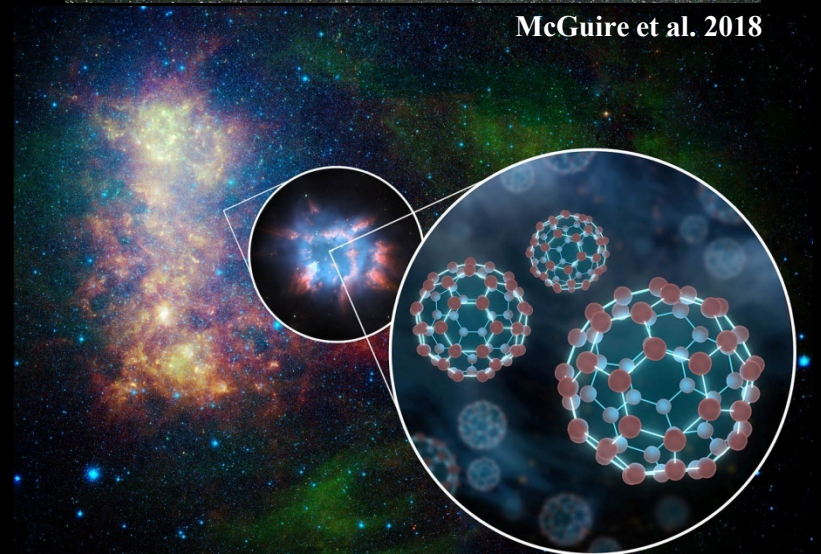


Polycyclic Aromatic Hydrocarbons



Benzonitrile

McGuire et al. 2018



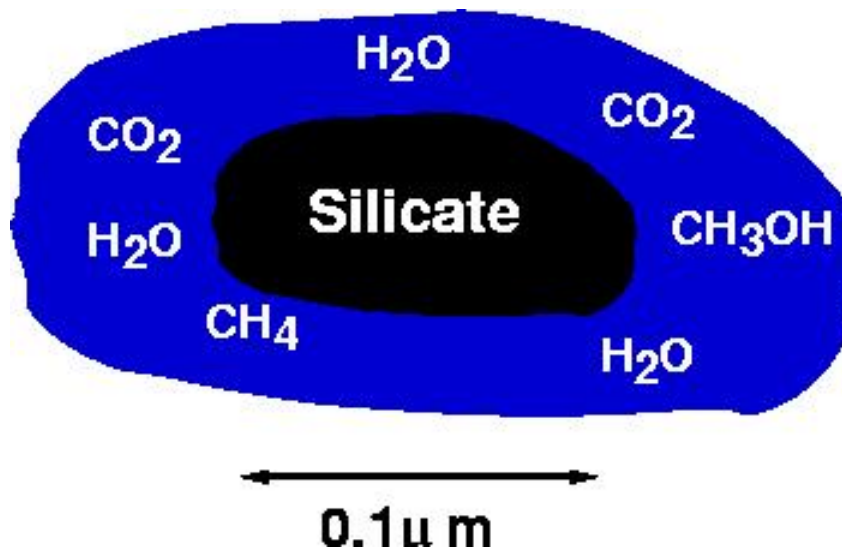
Fullerenes C_{60} , C_{70}

H. Kroto Nobel prize

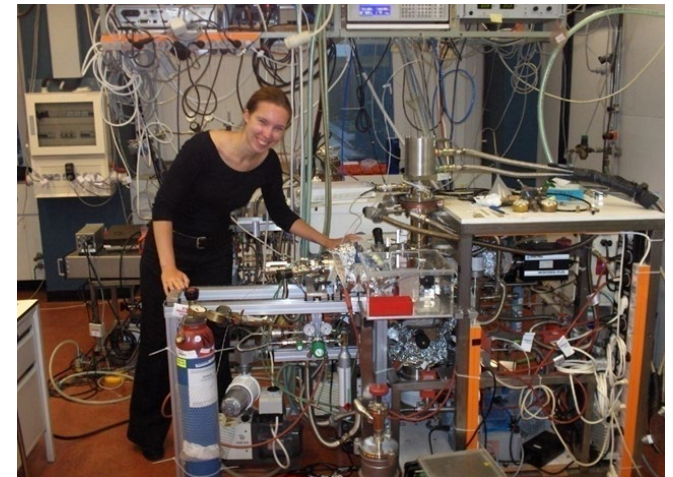
Cami et al. 2010

The interstellar ice cocktail

Atoms and molecules freeze-out onto cold dust grains
 $\Rightarrow$ hydrogenation, e.g. $\text{O} \rightarrow \text{H}_2\text{O}$



Leiden laboratory for
Astrophysics



H. Linnartz

Surface chemistry dominates during star formation

Formation new star and planetary system

Collapse of cloud



20000 AU

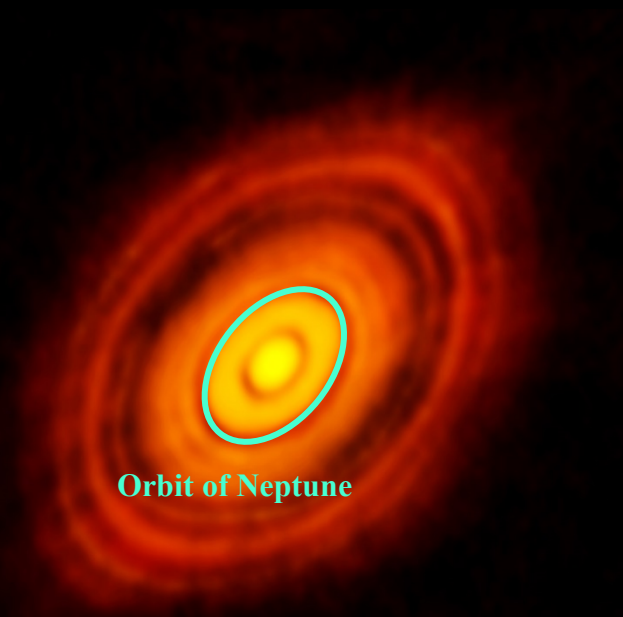
Factor 400
smaller



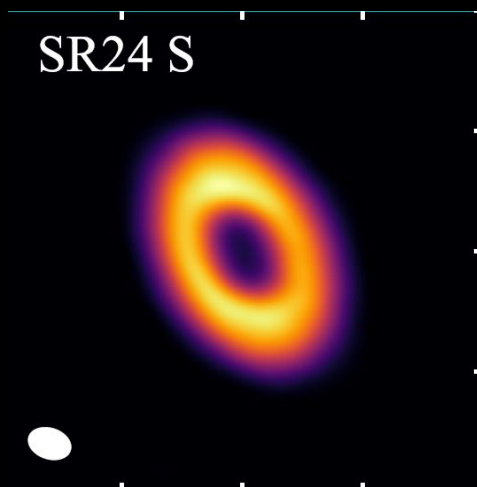
50 AU

Gas and ice from collapsing cloud is transported to disk

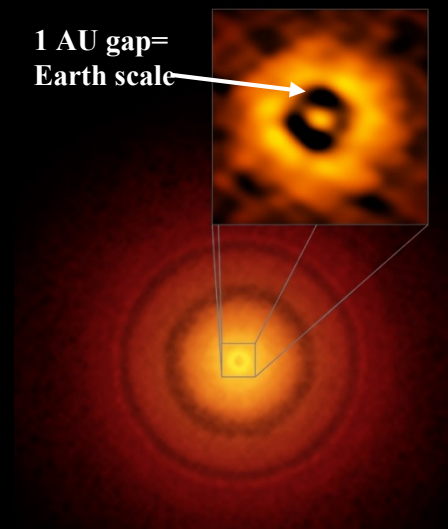
New era of observational planet formation



HL Tau young disk
ALMA partnership
et al. 2015

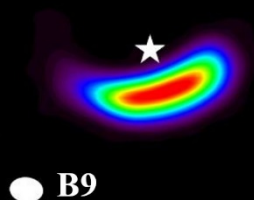


SR24 S
ALMA: Pinilla et al. 2017



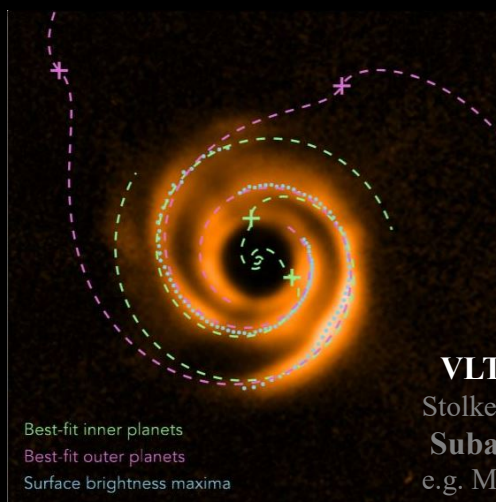
ALMA TW Hya
Andrews et al. 2016

IRS48

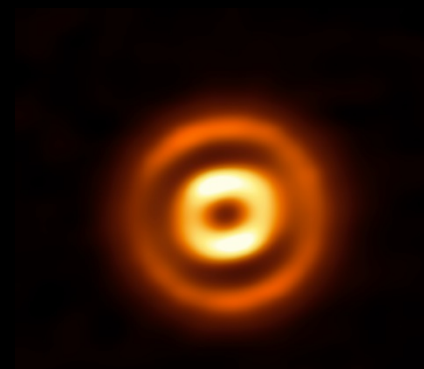


B9

ALMA: van der Marel et al. 2013, 2016



VLT-Sphere
Stolker et al. 2016
Subaru-SEEDS
e.g. Muto et al. 2012



ALMA:
Fedele et al. 2017

Chemical complexity on solar system scales

IRAS16293-2422

Source B $1 L_{\text{Sun}}$
Face-on disk

Source A $18 L_{\text{Sun}}$
Inclined disk
 $d=140 \text{ pc}$

60 AU
↔

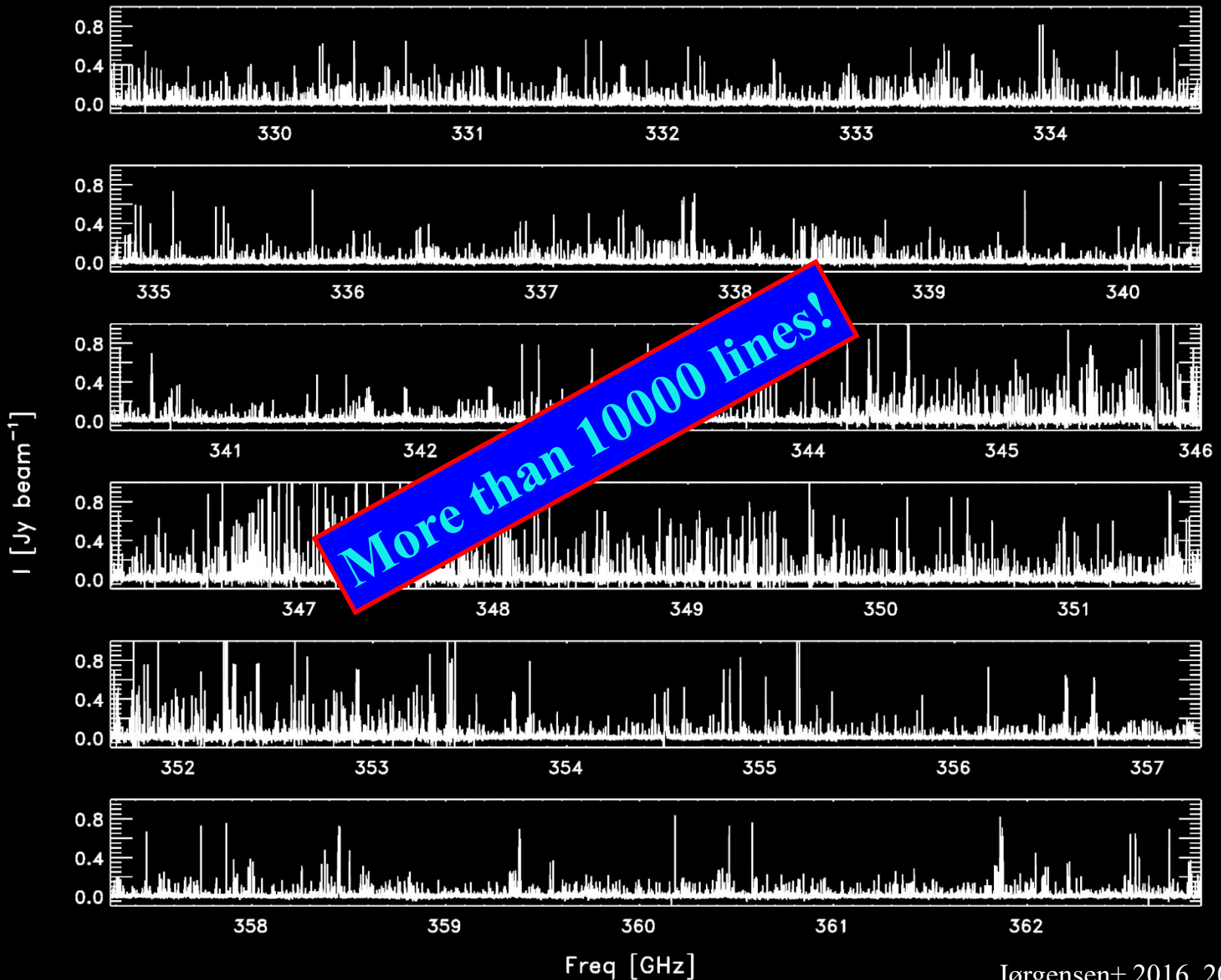
ALMA: 0.4-3 mm continuum

Protostellar Interferometric Line Survey (PILS)

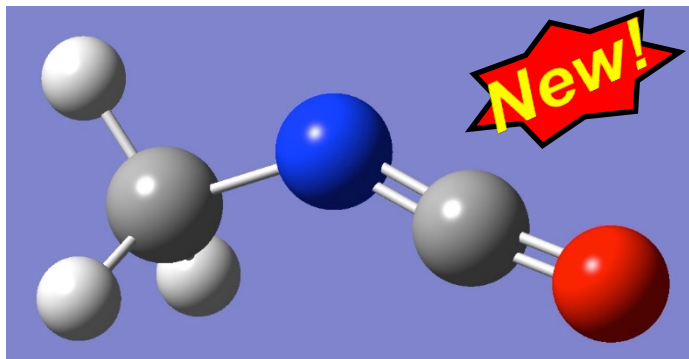


Jes Jørgensen & the PILS team

Full spectral survey of a young disk: IRAS 16293–2422B

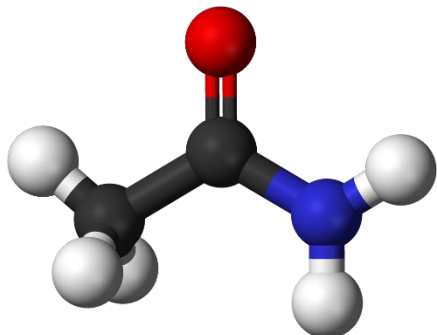


Complex molecules on disk scales



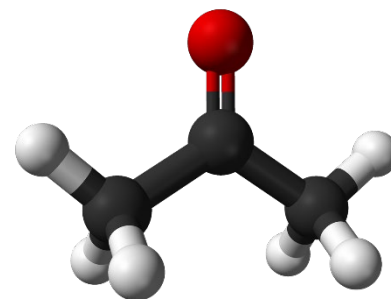
Methyl isocyanate
'Prebiotic' molecule

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

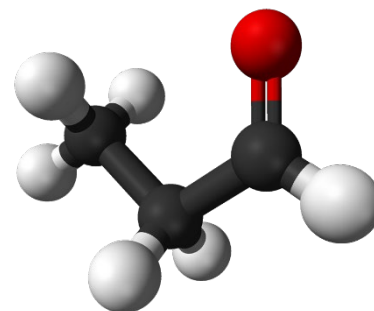


Acetamide (but no glycine yet)

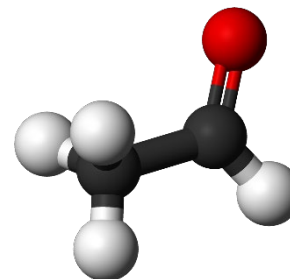
Ligterink et al. 2018



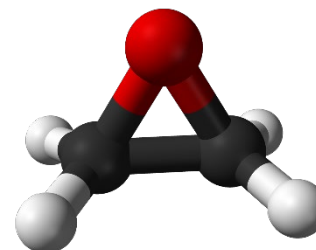
Propanal



Acetaldehyde



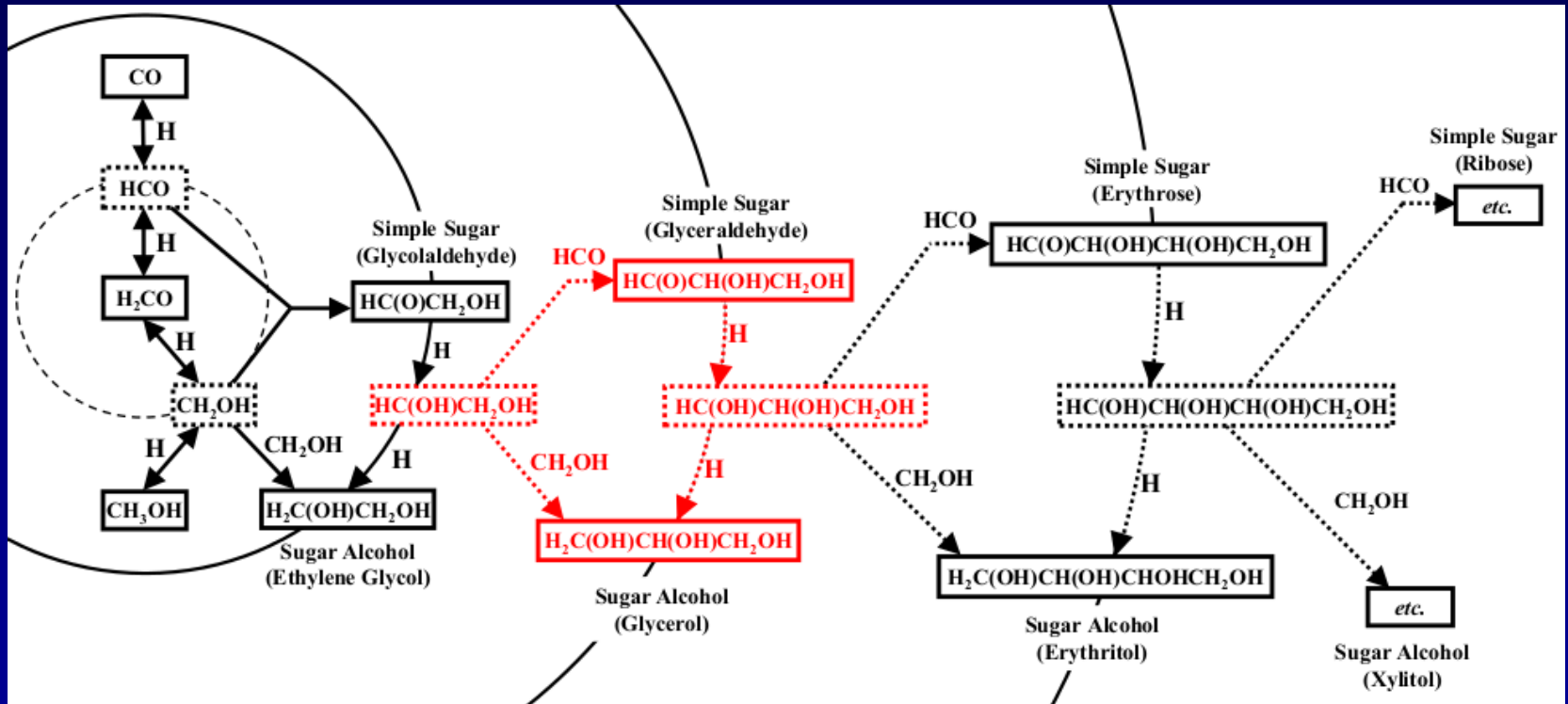
Ethylene oxide



Lykke et al. 2017

How far can complexity go?

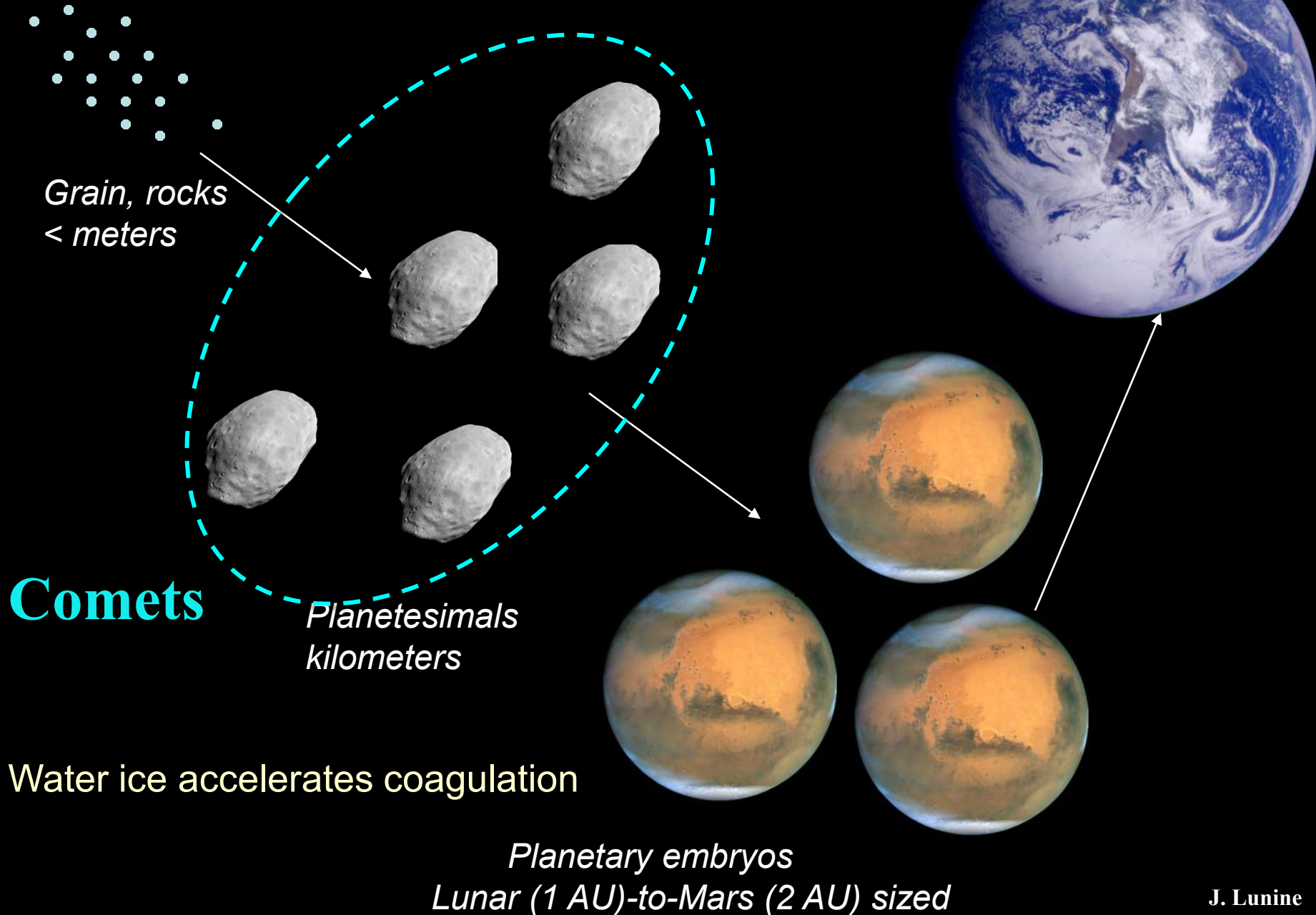
Lab experiments starting from CO hydrogenation



Reactions proceed already at 15 K, without need for heating or UV!

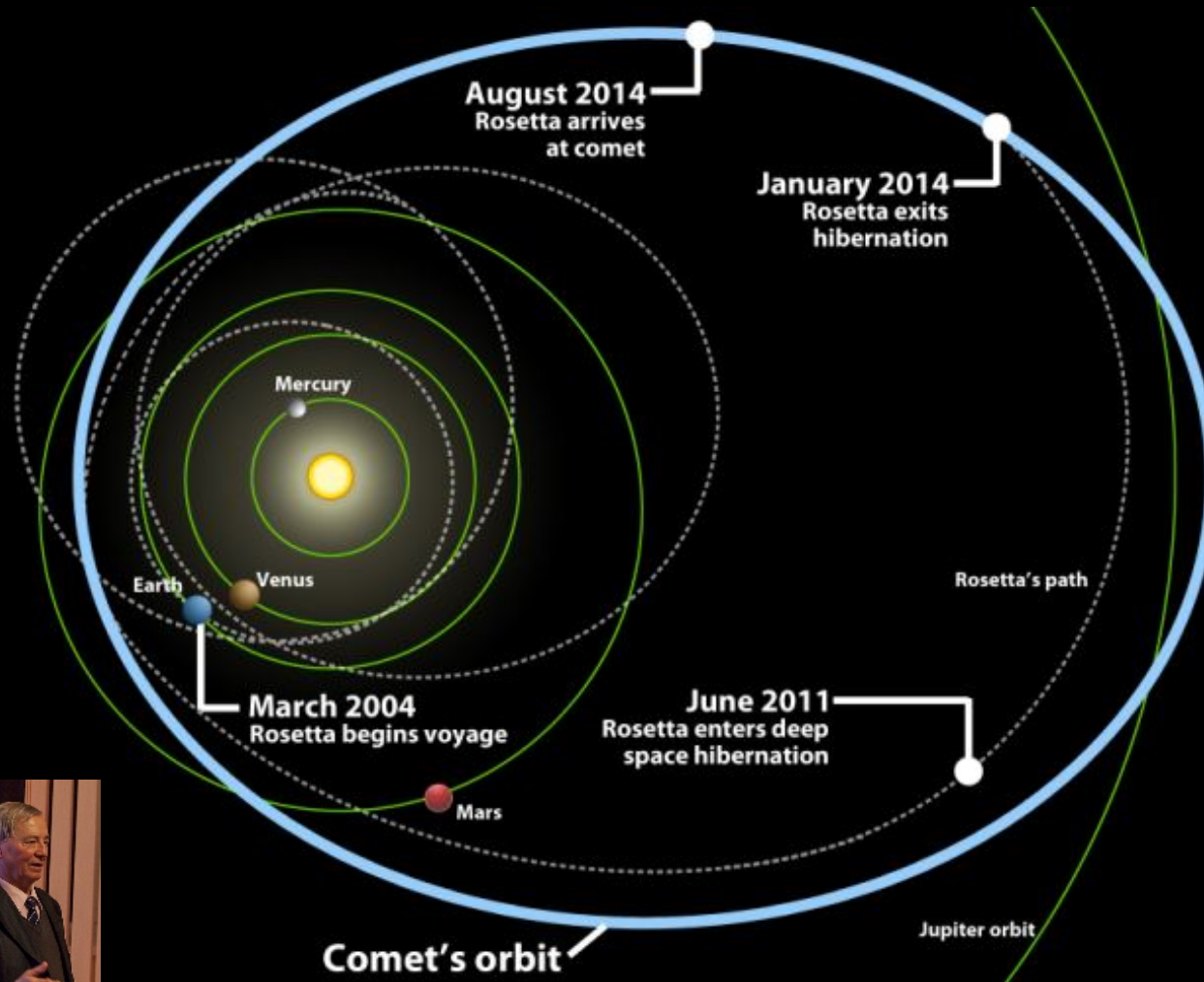
Can even make glycerol and real sugars! (Fedoseev et al. 2017)

From icy grains to planetesimals to embryos to planets



Rosetta mission to comet 67P

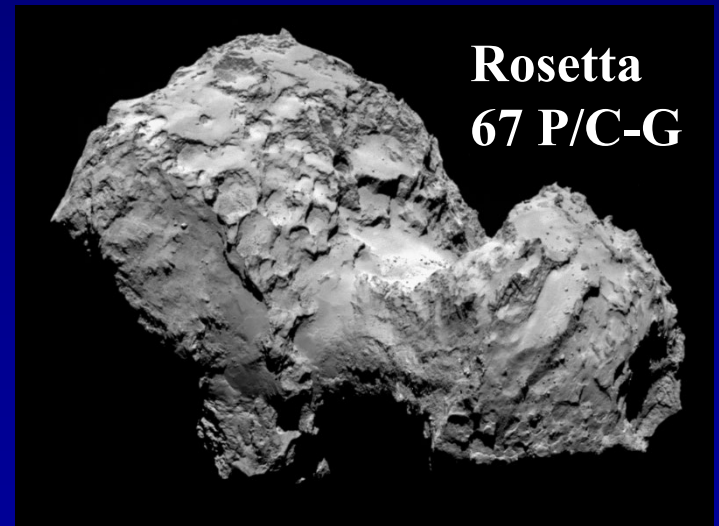
12 year journey through our solar system



Comet 67P/Churyumov-Gerasimenko

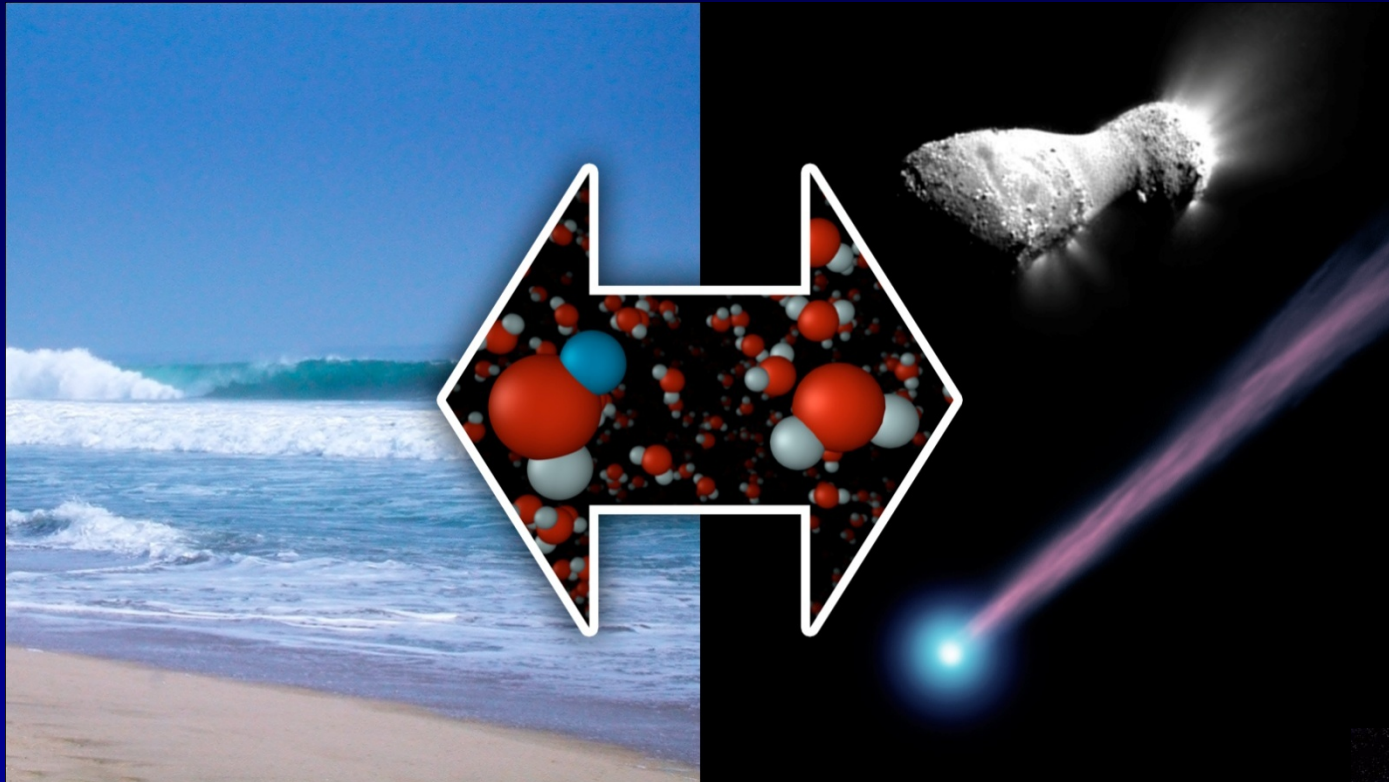
Young disk – comet comparison

- Young disk: observe just sublimated ices
- Comet: measure coma molecules *in situ*



Drozdovskaya et al. 2019
Altwegg et al. 2019

Origin water and organics on Earth?



ESA/NASA
Herschel-HIFI
Hartogh et al.

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

Icy planetesimals delivered water?

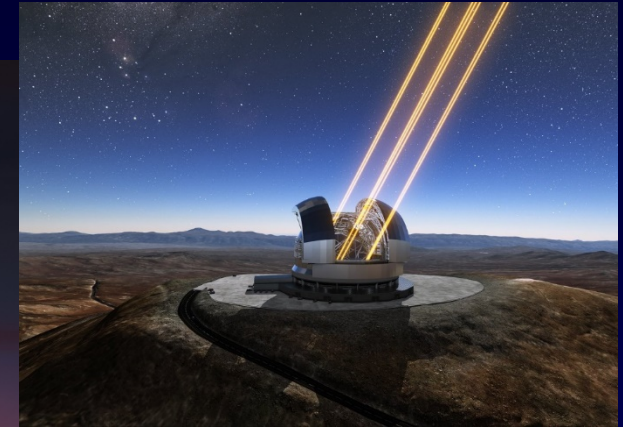


Next frontier: search for life on the nearest planets

Low mass star
with flares

Proxima Centauri

Alpha Centauri AB



Proxima b

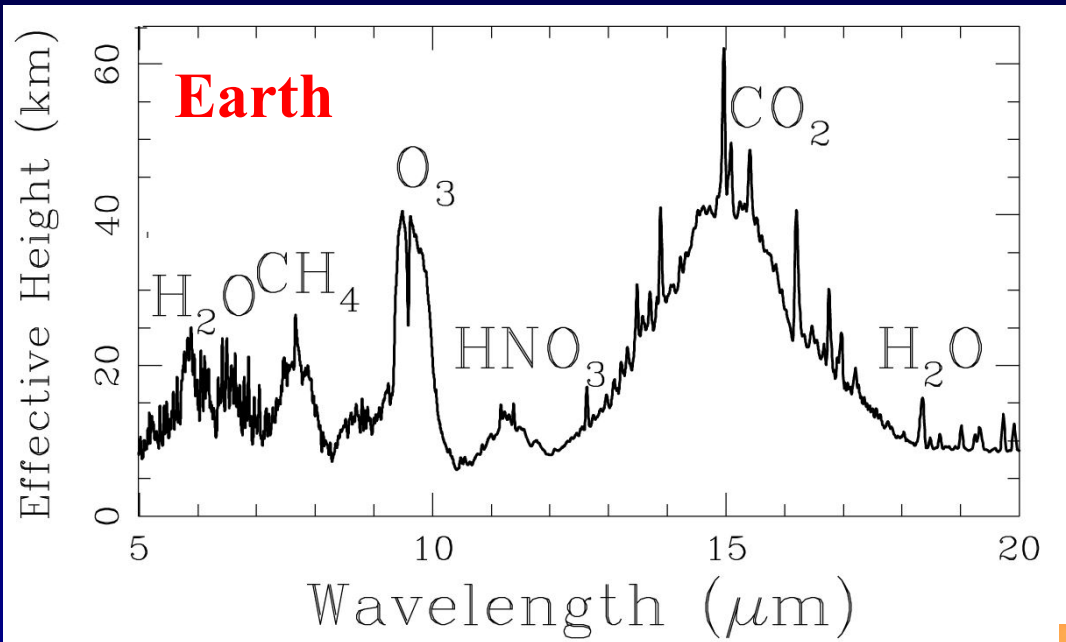
Artist impression

Anglada-Escudé et al. 2016

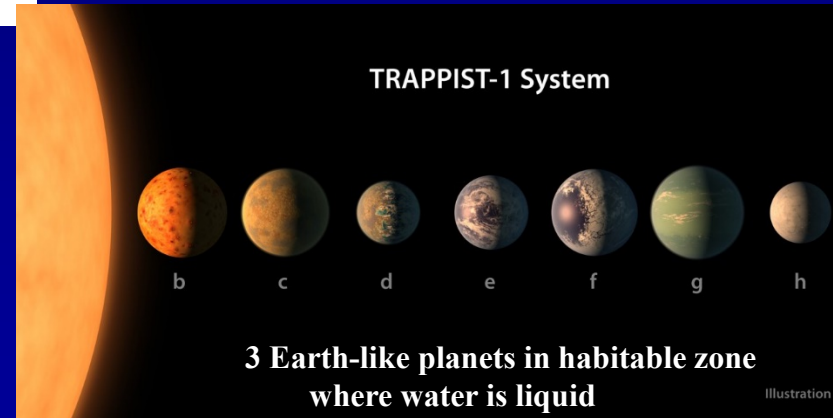
With ELTs we can answer the question: ‘Are we alone?’



Biomarkers



Kaltenegger 2017, ARAA



Gillon et al. 2017

O_2 , O_3 , CH_4 , N_2O , CH_3Cl , ...

Looking back at Earth from beyond Saturn

Pale Blue Dot

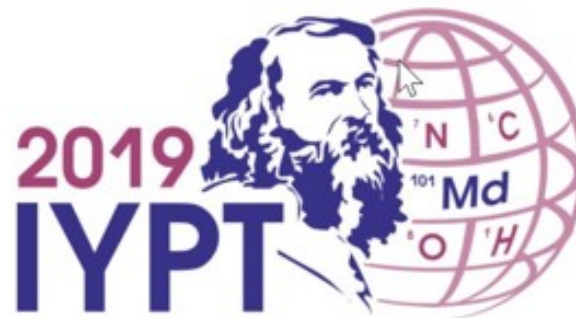


Astronomy provides perspective, modesty, tolerance

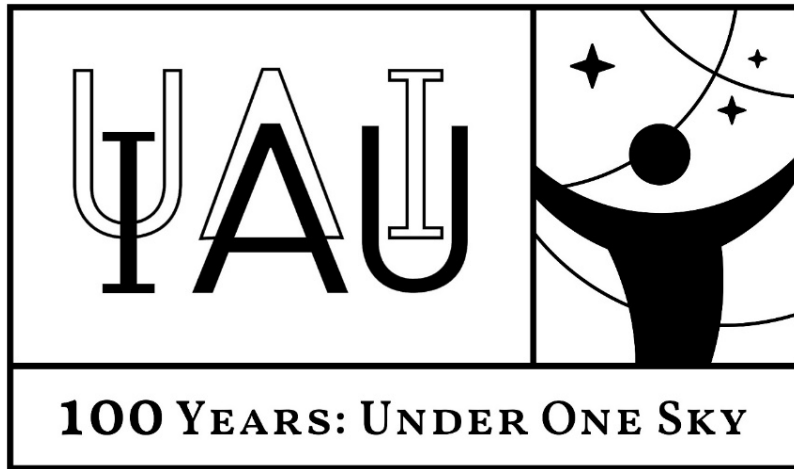
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2019
IYPT
International Year
of the Periodic Table
of Chemical Elements
150 yr Mendeleev



‘We are all world citizens under the same sky’

>4000 events in 100 countries: www.iau-100.org

Celebrate a century of astronomical discoveries, technological progress and cultural impact

Thanks for your attention!



Acknowledgments

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hubblesite.org
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www.spitzer.caltech.edu
 - **ESA/Herschel Space Observatory**
herchel.esac.esa.int
 - **Atacama Large Millimeter array**
www.almaobservatory.org
 - **ESA Rosetta mission to comet**
sci.esa.int/rosetta/