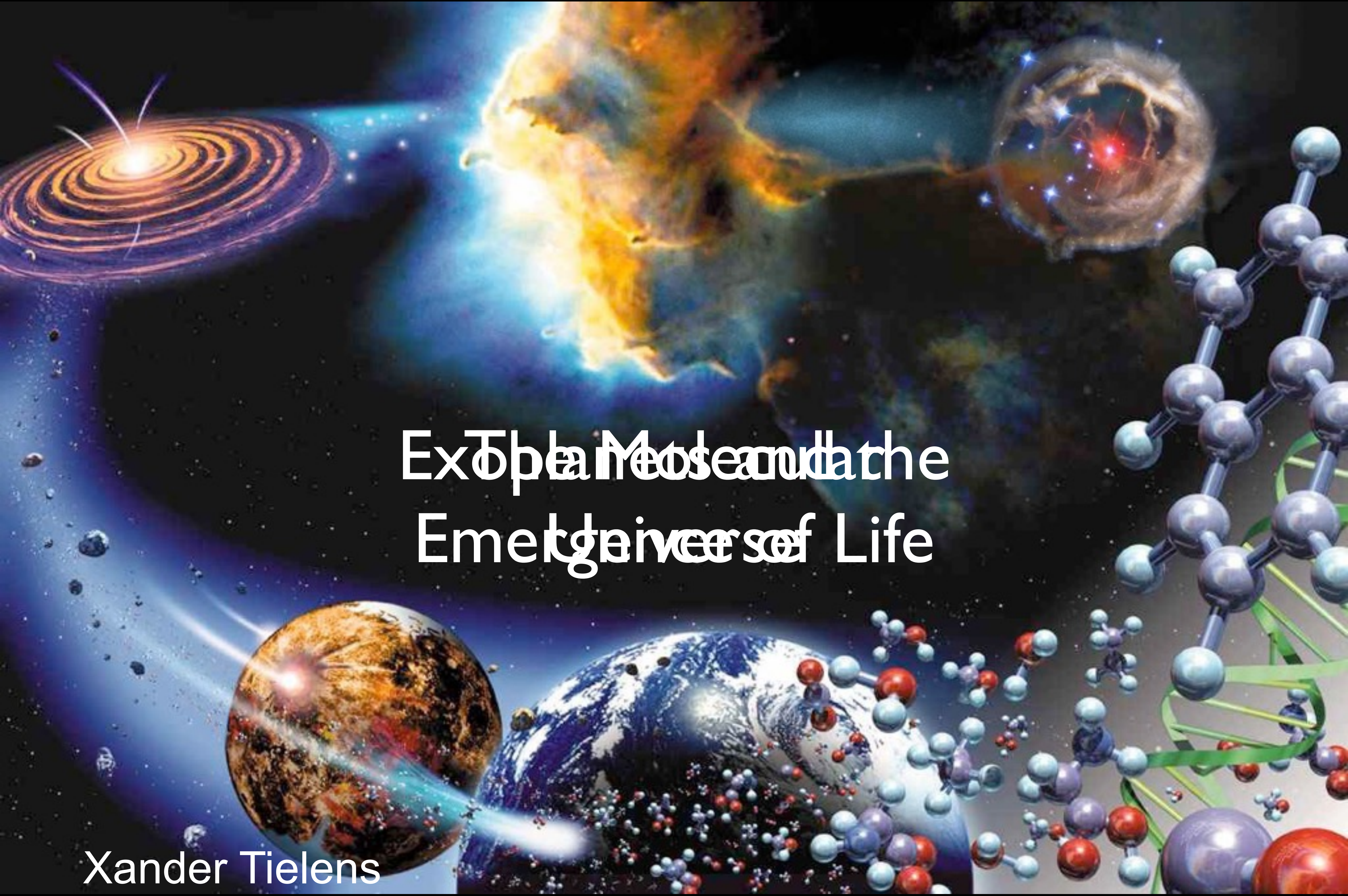
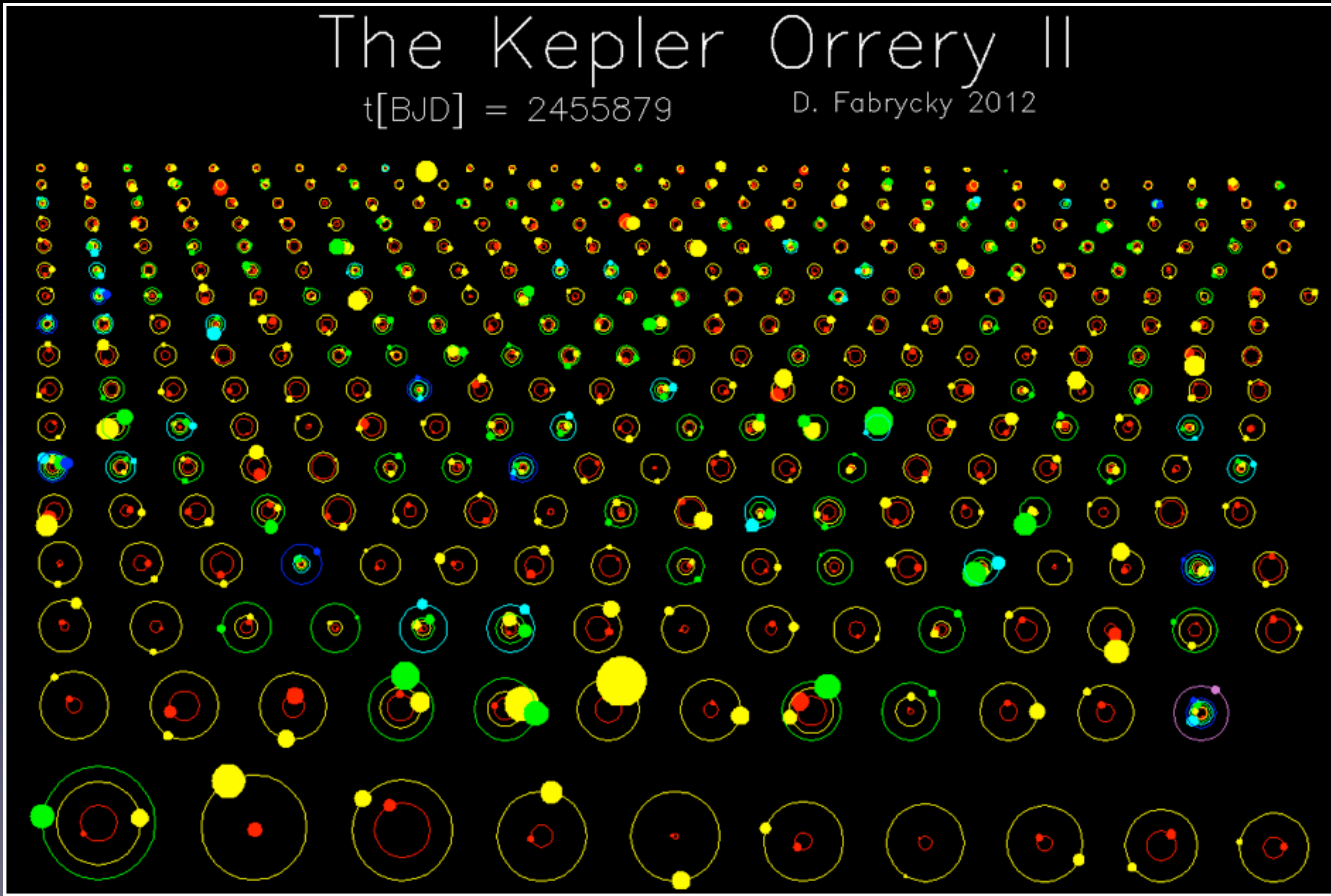


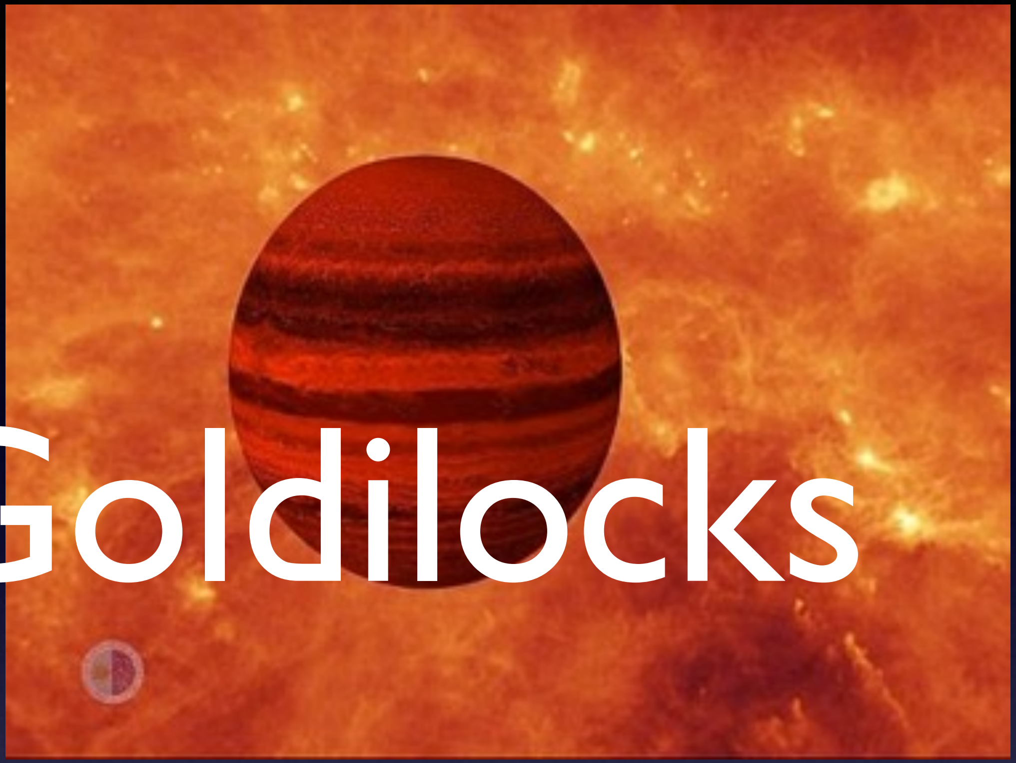
Exoplanets and the Emergence of Life

The Molecular Universe

Xander Tielens
Sterrewacht Leiden

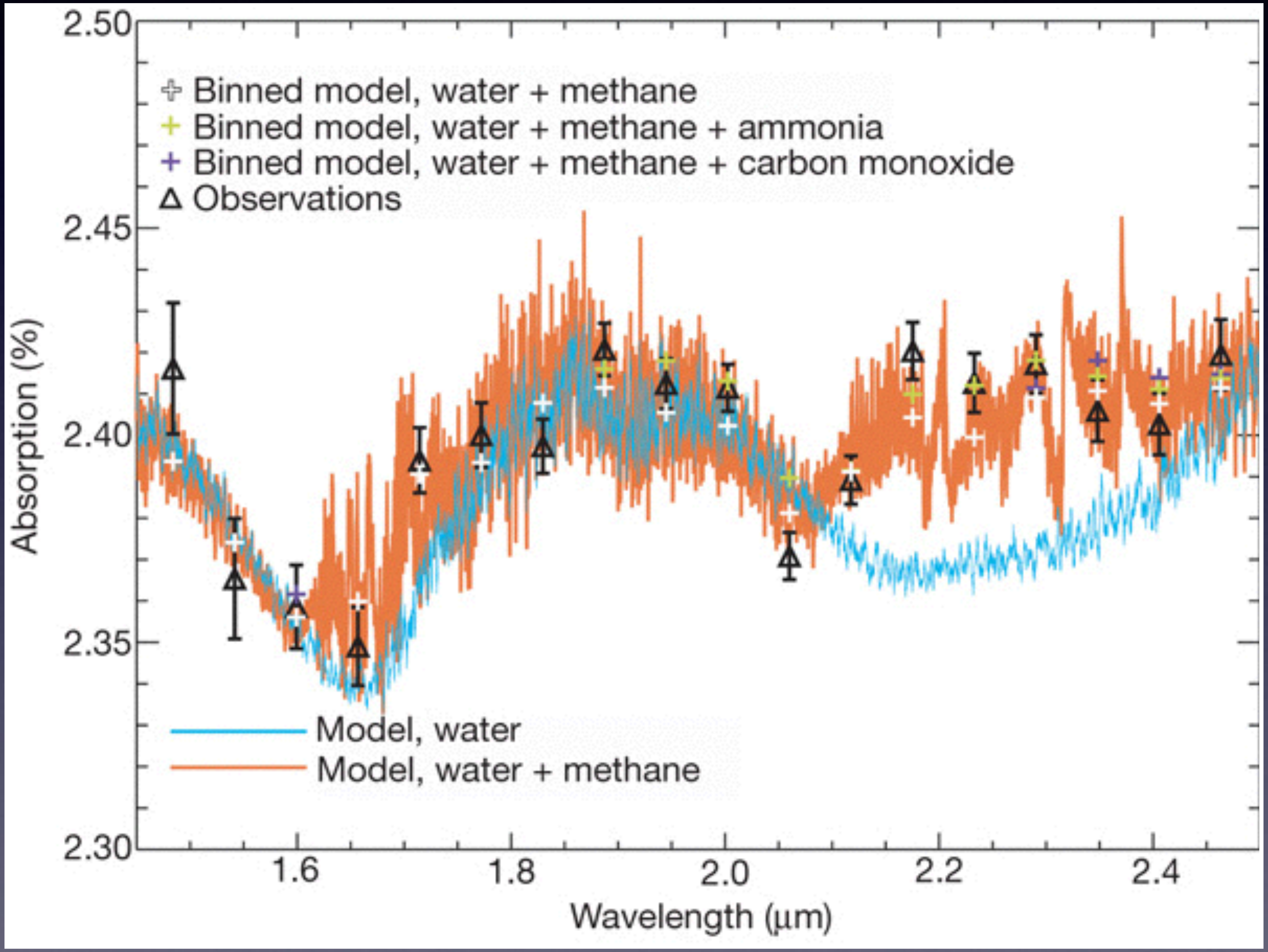

The Kepler Orrery II
t[BJD] = 2455879
D. Fabrycky 2012

Looking for Goldilocks



η(Earth)=1/5, Kepler mission

Exoplanet atmosphere



Swain et al, 2008, Nature, 452, 6823

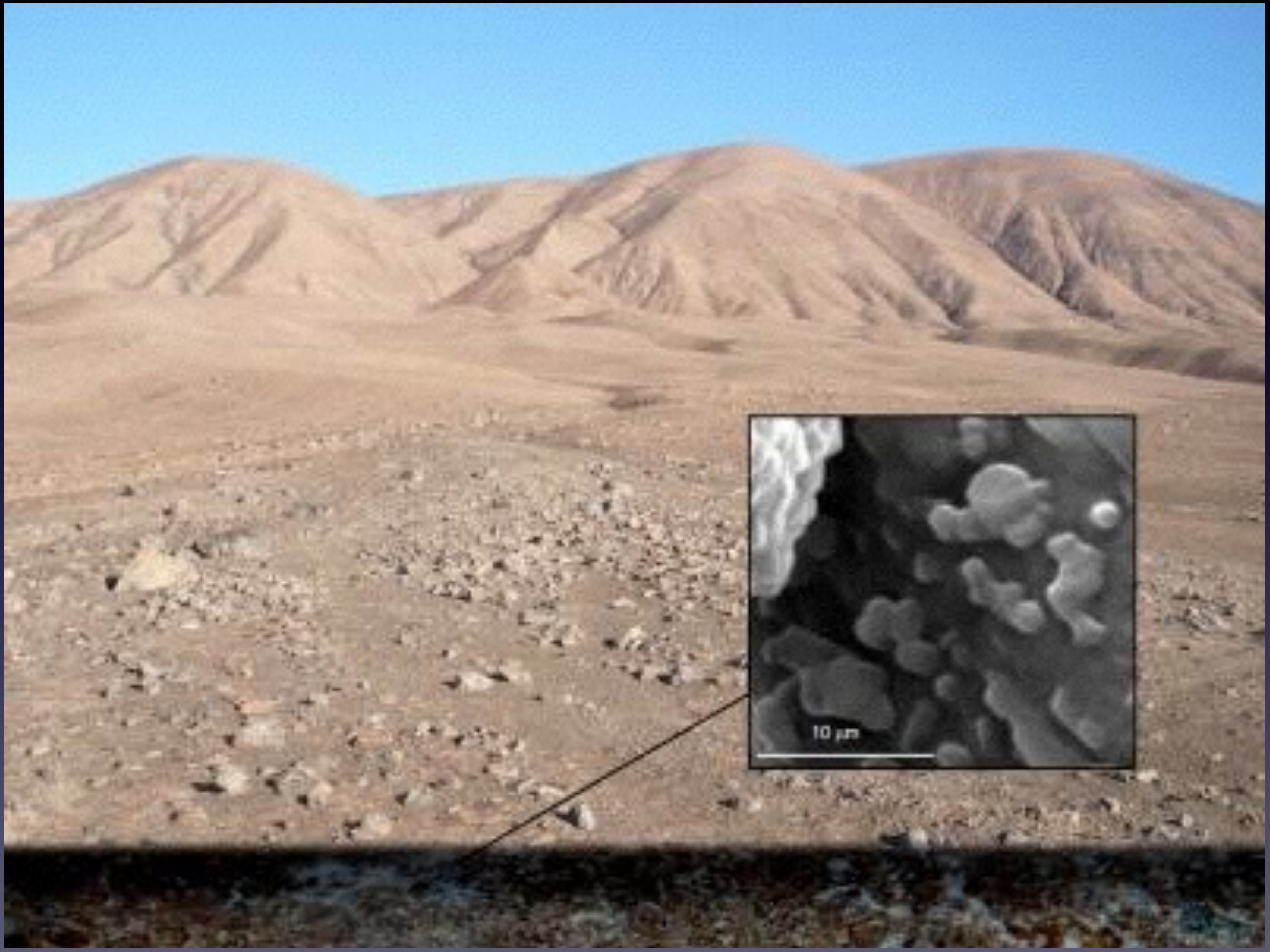
Hell on Earth

Cyano Bacteria in Grand Prismatic Spring Yellowstone

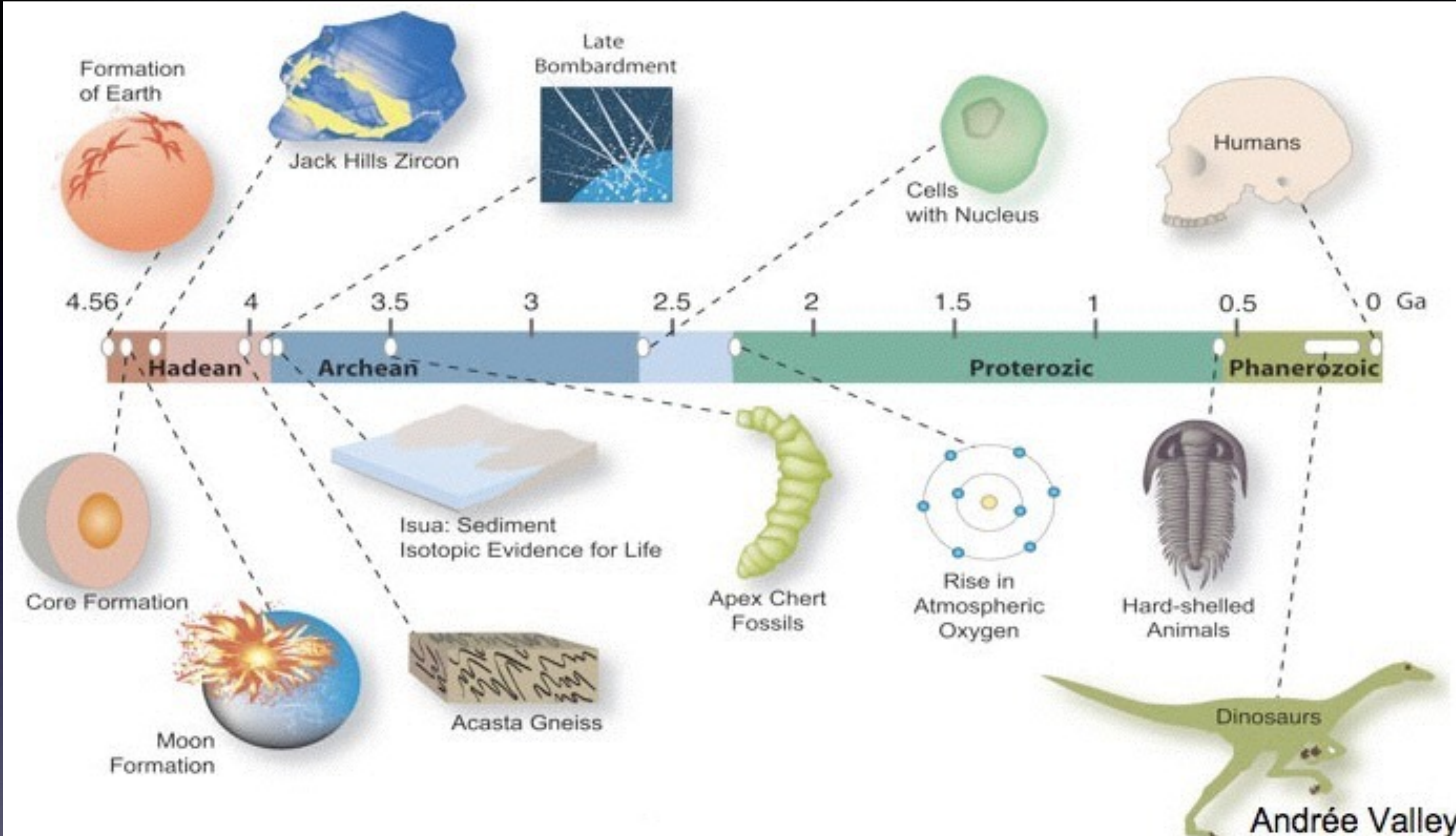
Lakebed Fossils under the Ice

Bacterial colonies in Antartica

Life in the driest spot on Earth



Microbes grow on salt crystals in the Atacama desert

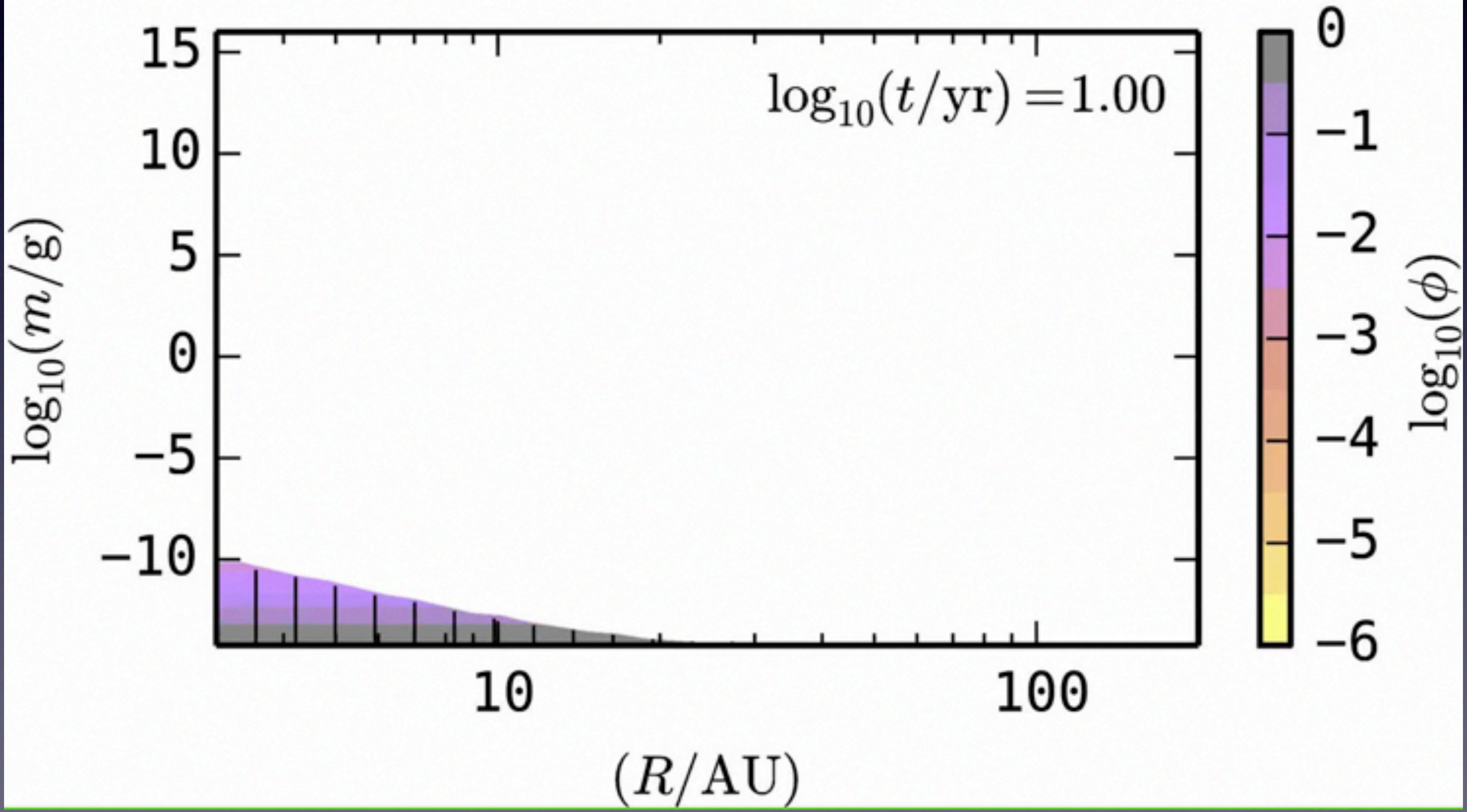


Life quickly evolved once the Solar System was formed

Key Questions

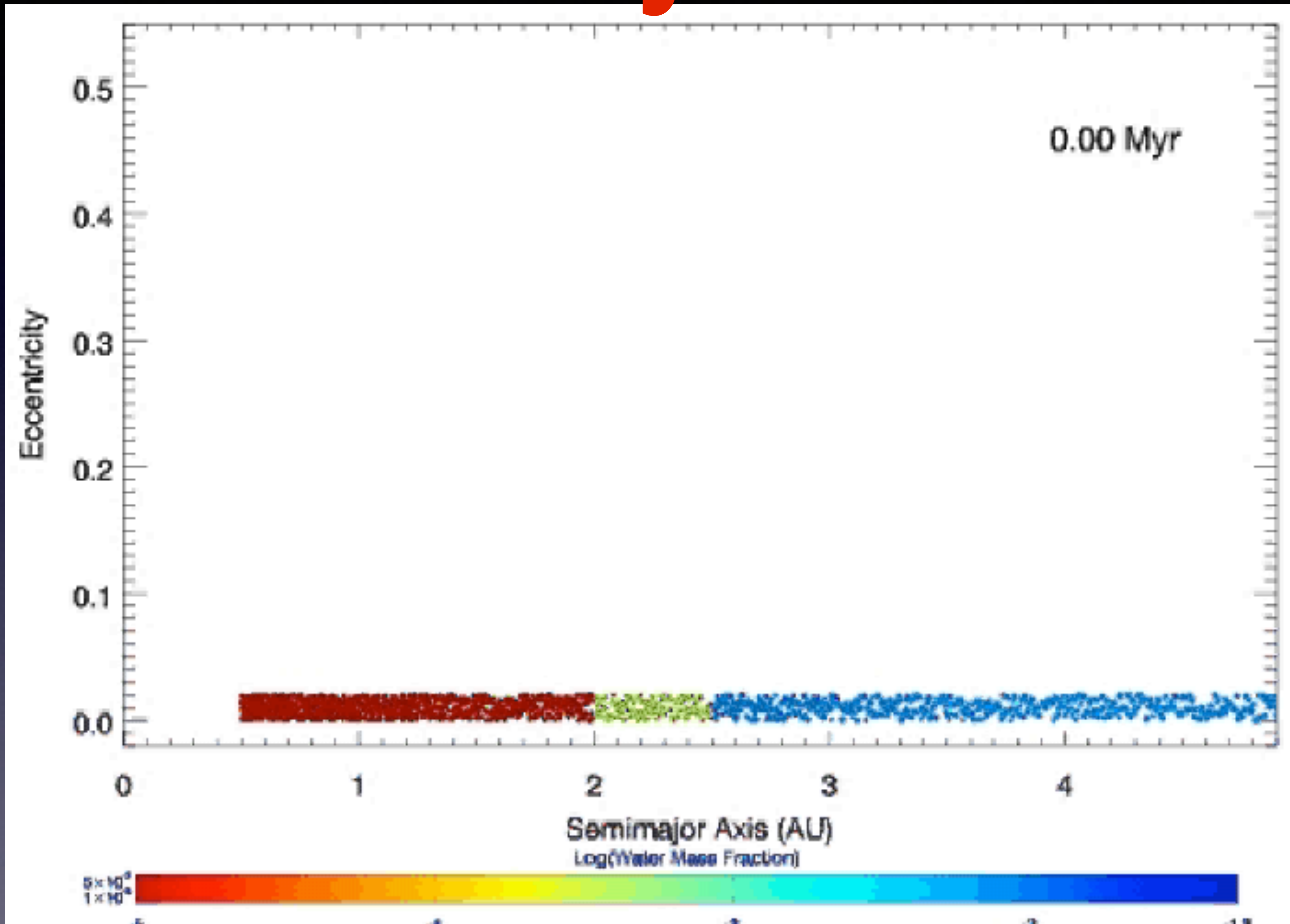
- Building new worlds: What are the key processes in planet formation ? How do they depend on the environment ? What is the inventory of planets, particularly in the habitable zone ?
- Planetary habitats: What are the primordial sources of organics and volatiles and the processes that play a role in their formation and delivery ?
- Setting the stage for life: What are the conditions on the early Earth & newly formed planets and what are the key processes that set the stage for life ?

Building Planetesimals One Grain at a Time



Krijt 2015, PhD thesis

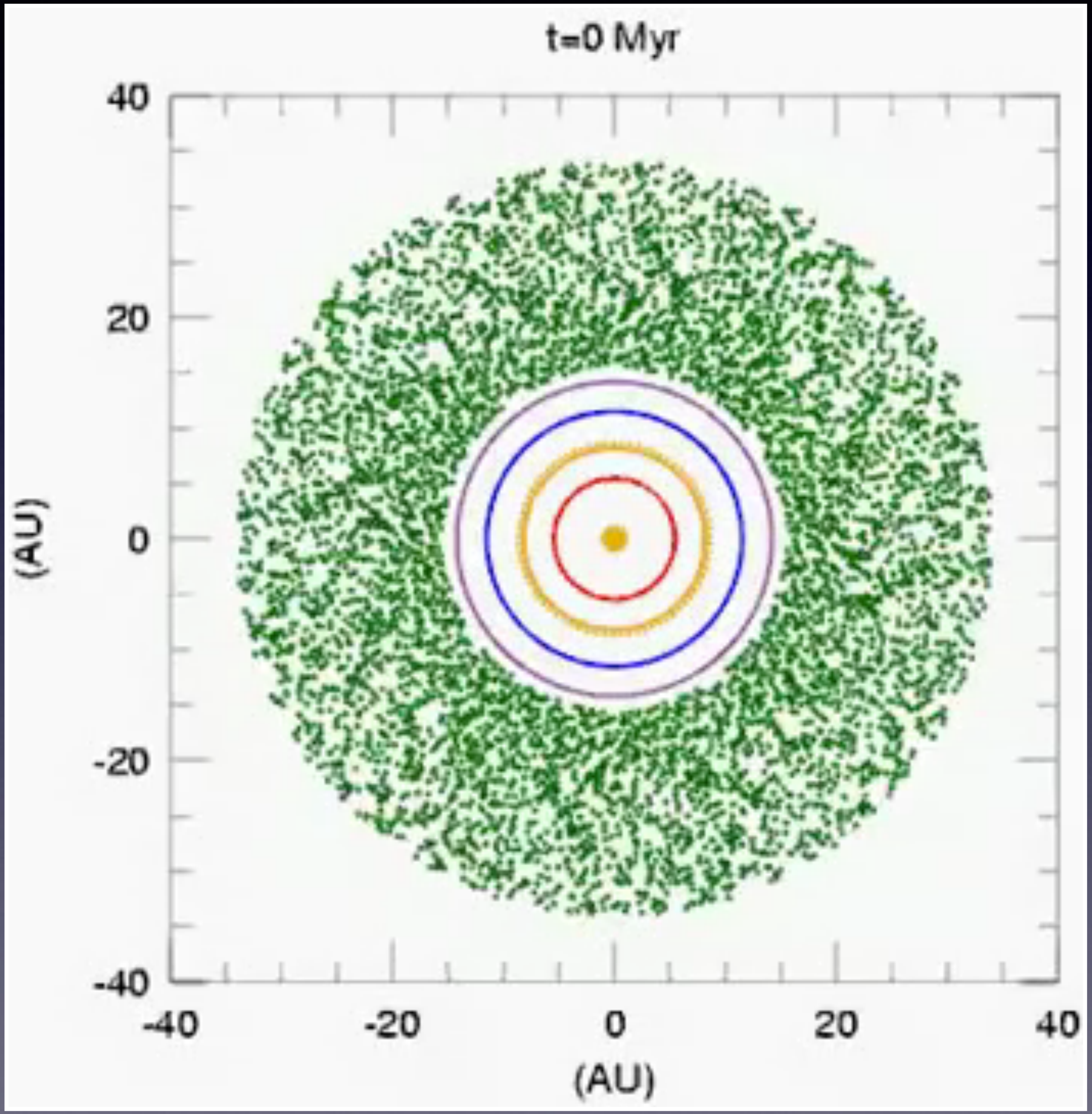
From Embryo to Planet



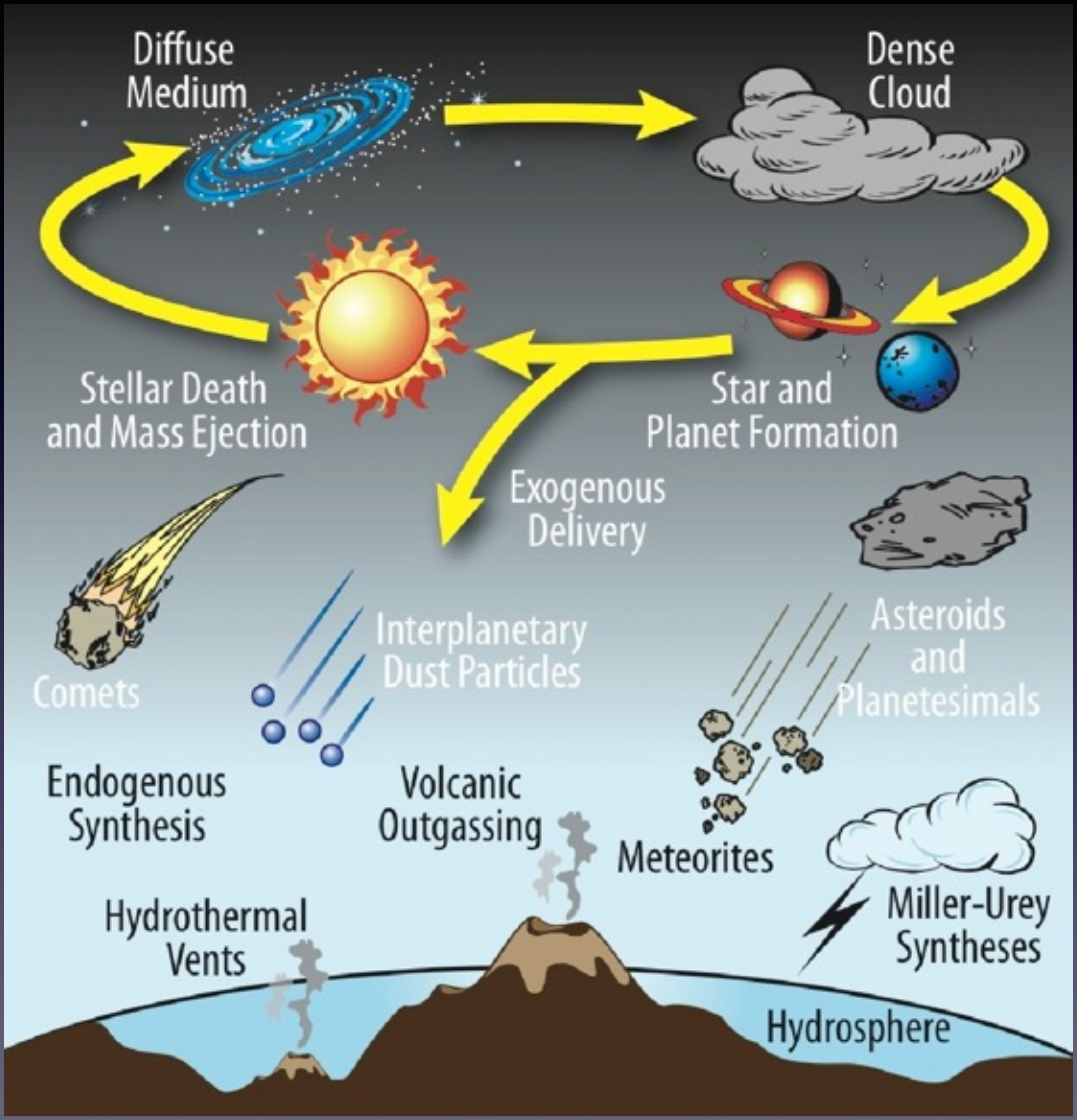
Petit et al, 2001, Icarus, 153, 338
Raymond et al, 2004, Icarus, 168, 1

from embryo's to planets

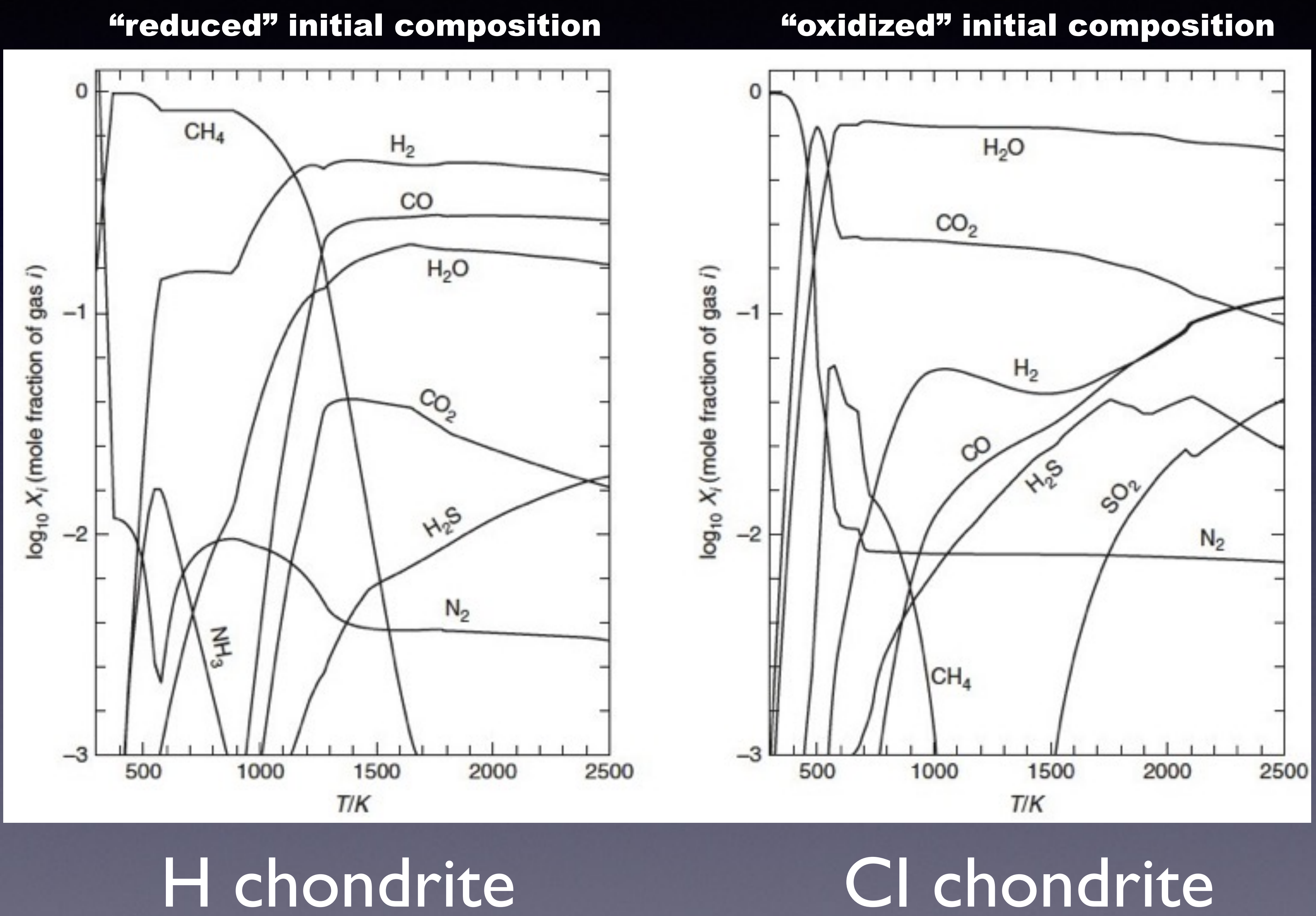
Late Heavy Bombardment



Gomes et al, 2005, Nature, 435, 466


Diffuse
Medium
Dense
Cloud
Stellar Death
and Mass Ejection
Star and
Planet Formation
Exogenous
Delivery
Comets
Interplanetary
Dust Particles
Asteroids
and
Planetesimals
Endogenous
Synthesis
Volcanic
Outgassing
Meteorites
Hydrothermal
Vents
Miller-Urey
Syntheses
Hydrosphere

Heritage Shows



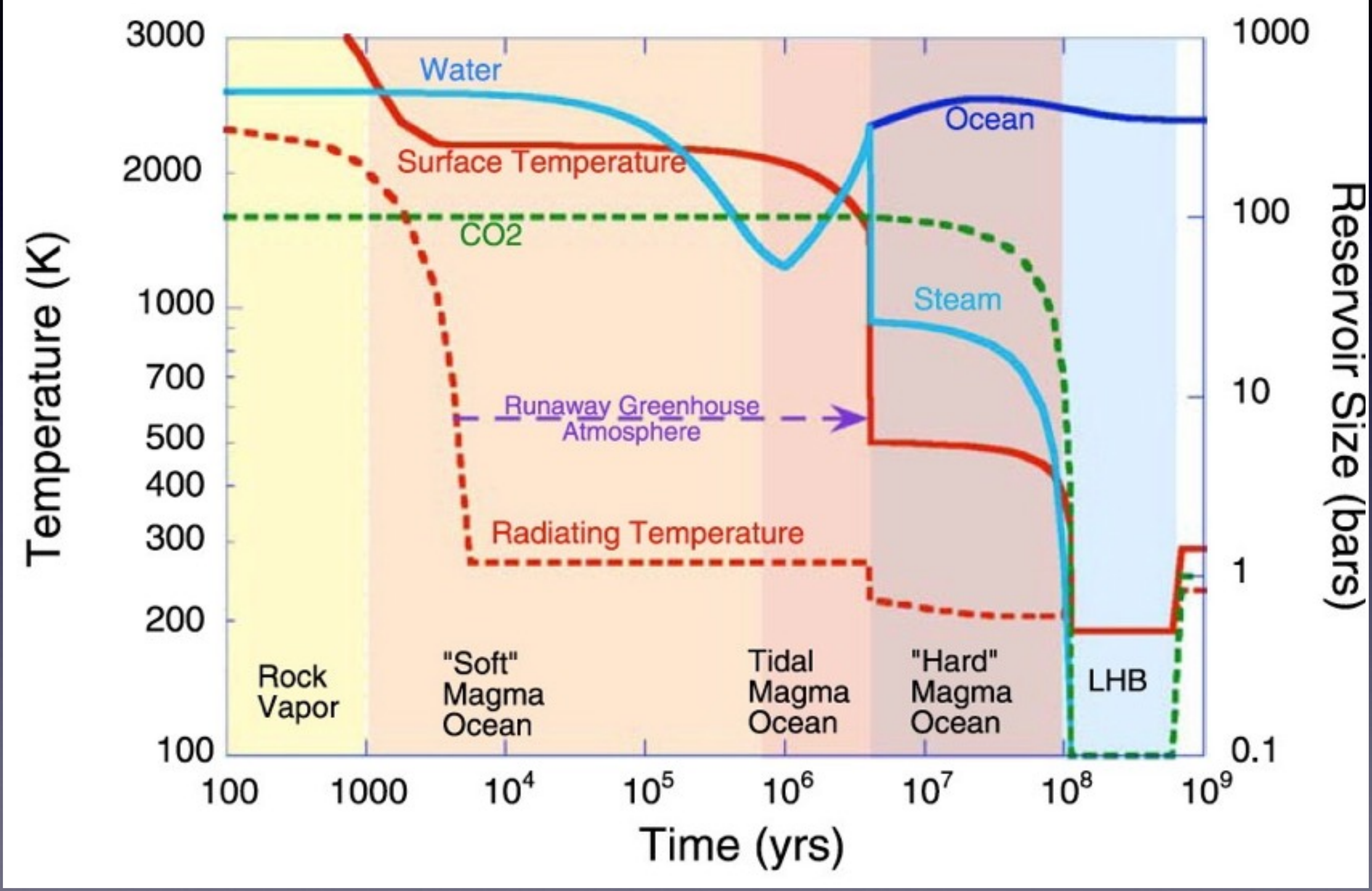
Schaefer & Fegley, 2007, Icarus, 186, 462

The Hadean Period

Moon forming event

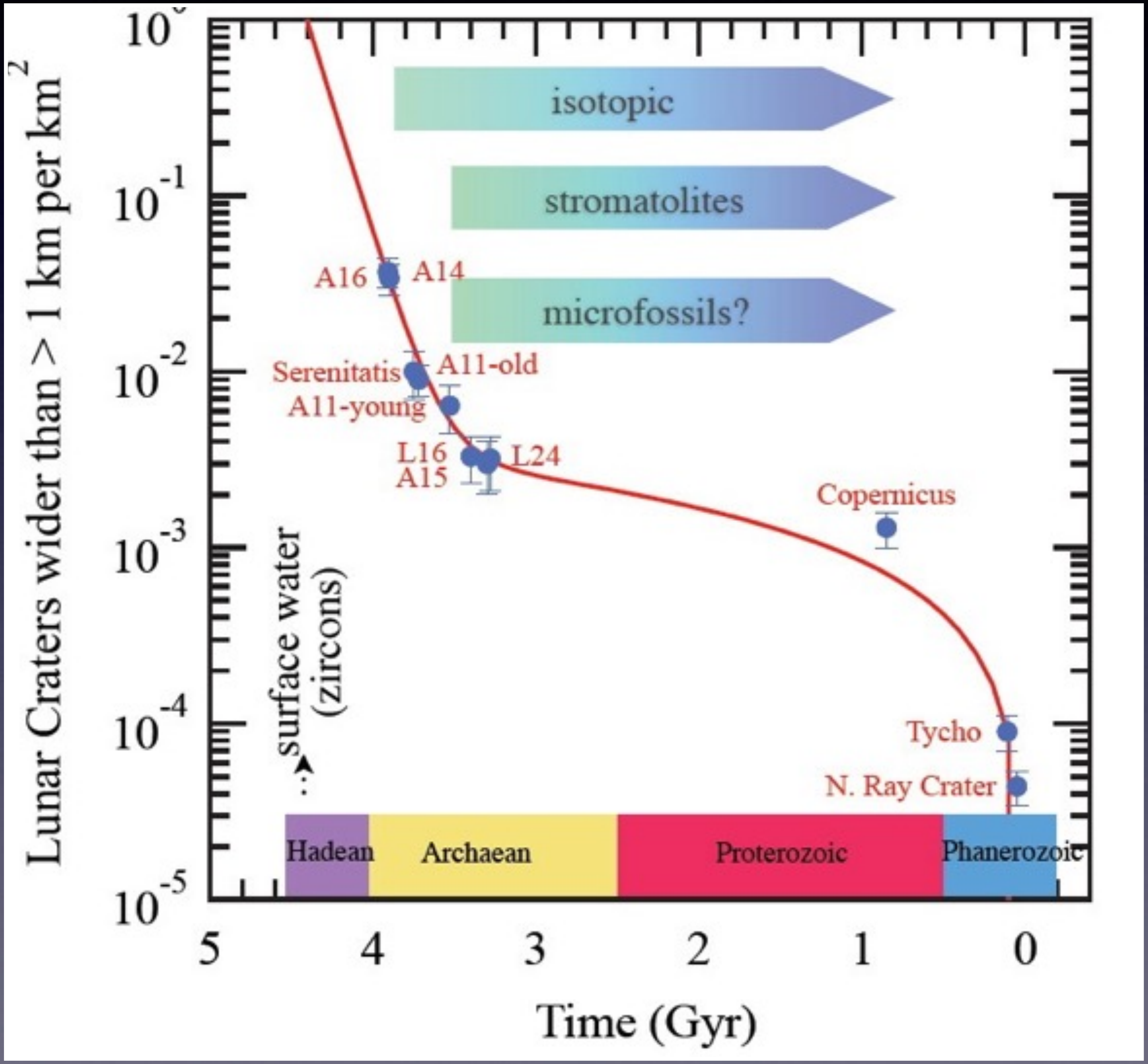
Magma ocean: H_2O & CO_2 degassing

Warm, wet early Earth and subduction of CO_2



Zahnle et al, 2007, Space Sci Rev, 129, 35

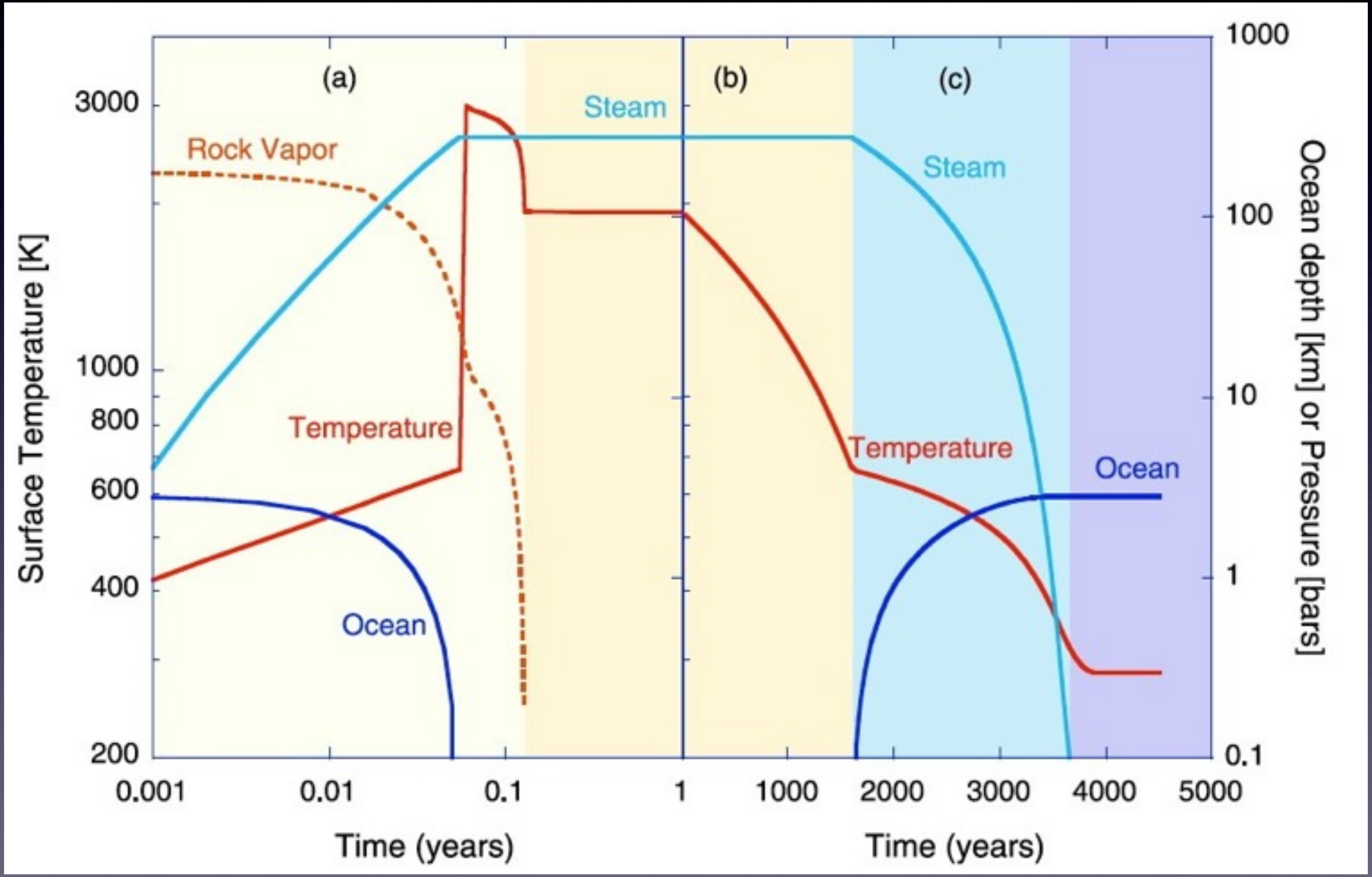
Late Heavy Bombardment



Neukum et al, 2001, Space Sci Rev, 96, 9

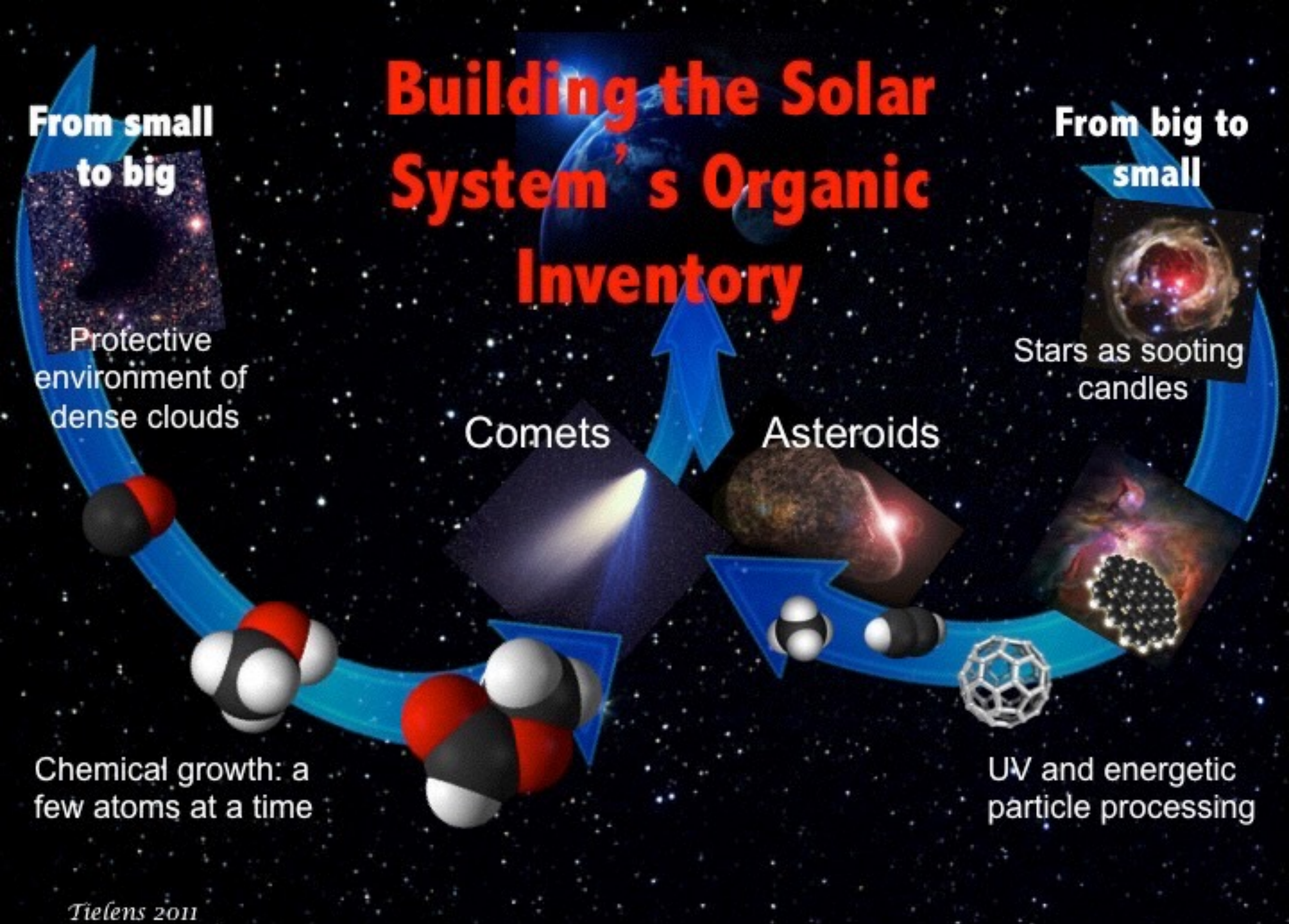
LHB: Ocean Vaporizing Impact

Rock vapor **Cloud layer** **Rain**



Zahnle et al, 2007, Spa Sci Rev, 129, 35


How did the Earth & terrestrial planets get their volatile and organic inventory ?
Does life have an interstellar heritage ?


Building the Solar System's Organic Inventory
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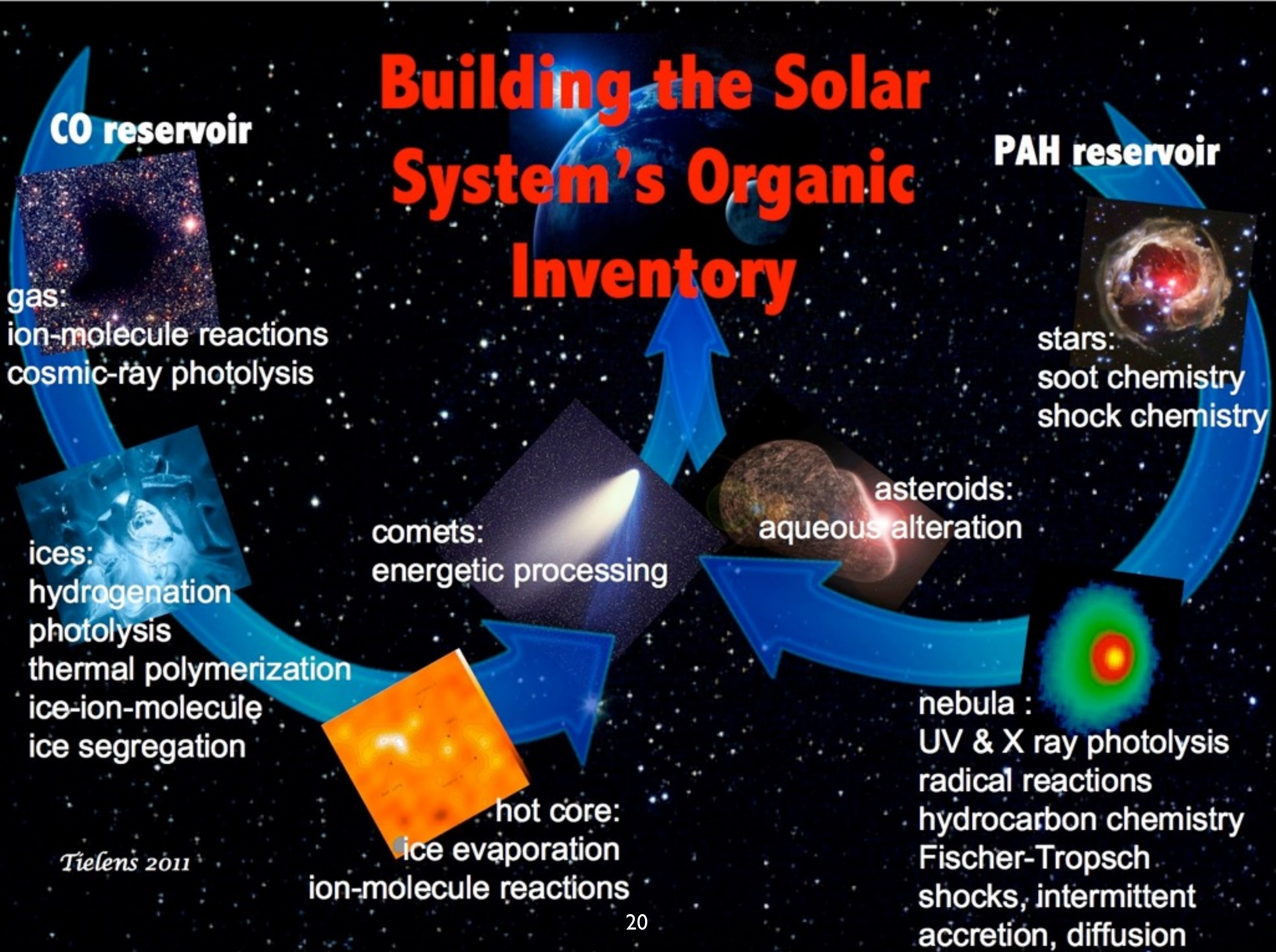
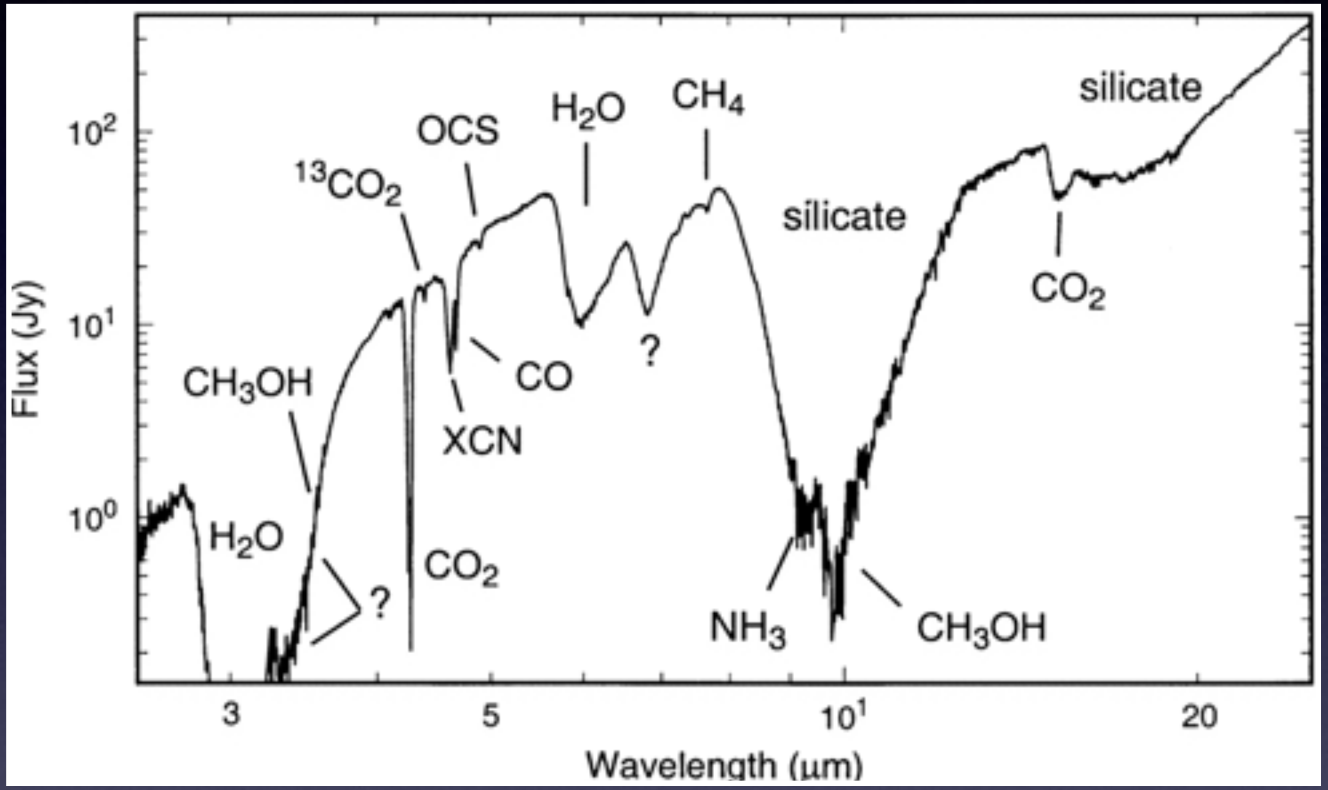
Chemical growth: a few atoms at a time
UV and energetic particle processing
Tielens 2011


Building the Solar System's Organic Inventory
CO reservoir
PAH reservoir
gas:
ion-molecule reactions
cosmic-ray photolysis
stars:
soot chemistry
shock chemistry
ices:
hydrogenation
photolysis
thermal polymerization
ice-ion-molecule
ice segregation
comets:
energetic processing
asteroids:
aqueous alteration
hot core:
ice evaporation
ion-molecule reactions
nebula :
UV & X ray photolysis
radical reactions
hydrocarbon chemistry
Fischer-Tropsch
shocks, intermittent
accretion, diffusion
Tielens 2011

Gas-Grain Interaction

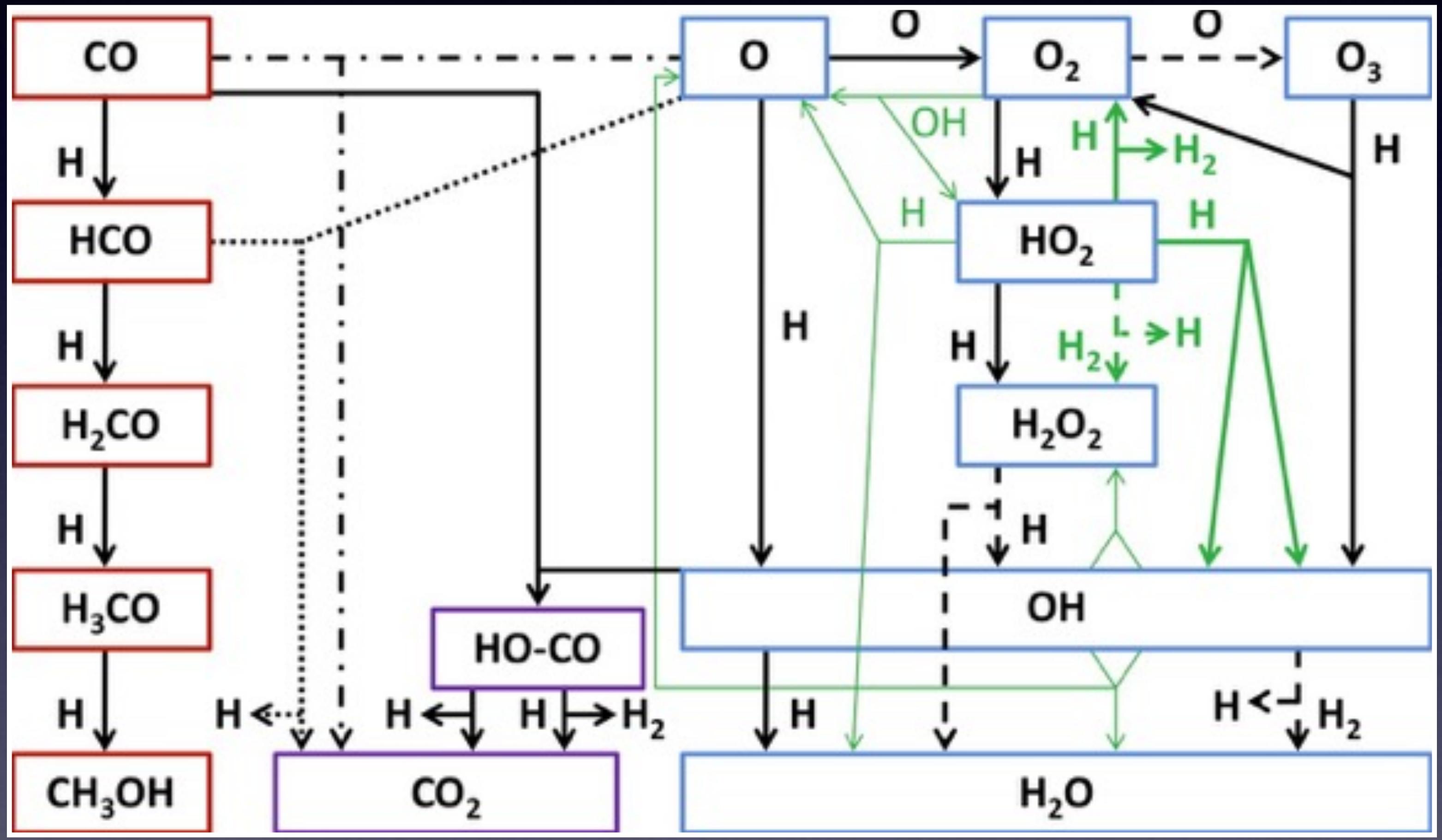
- Depletion in dense cores (i.e., B68)
- Interstellar ice
- Gas phase HO_2 & H_2O_2 (i.e., r Oph)
- High deuterium abundances of CH_3OH/H_2CO in protostellar envelopes
- Hot Core/Corino composition & deuterium fractionation



Caselli et al, 1999, ApJ, 523, L165 & Bergin et al, ApJ, 2001, 570, L101
Gibb et al, 2004, ApJS, 151, 35; Boogert et al 2015, ARAA, 53, 541
Parise et al 2012, A&A, 541, L11
Praise et al, 2006, A&A, 453, 949
Blake et al 1987, ApJ, 315, 621 & Ceccarelli et al, 2007, PPV, 47

Grain Surface Reactions

- Hydrogenation & oxidation
- Tunneling
- Deuteration



H_2CO/CH_3OH

H_2O

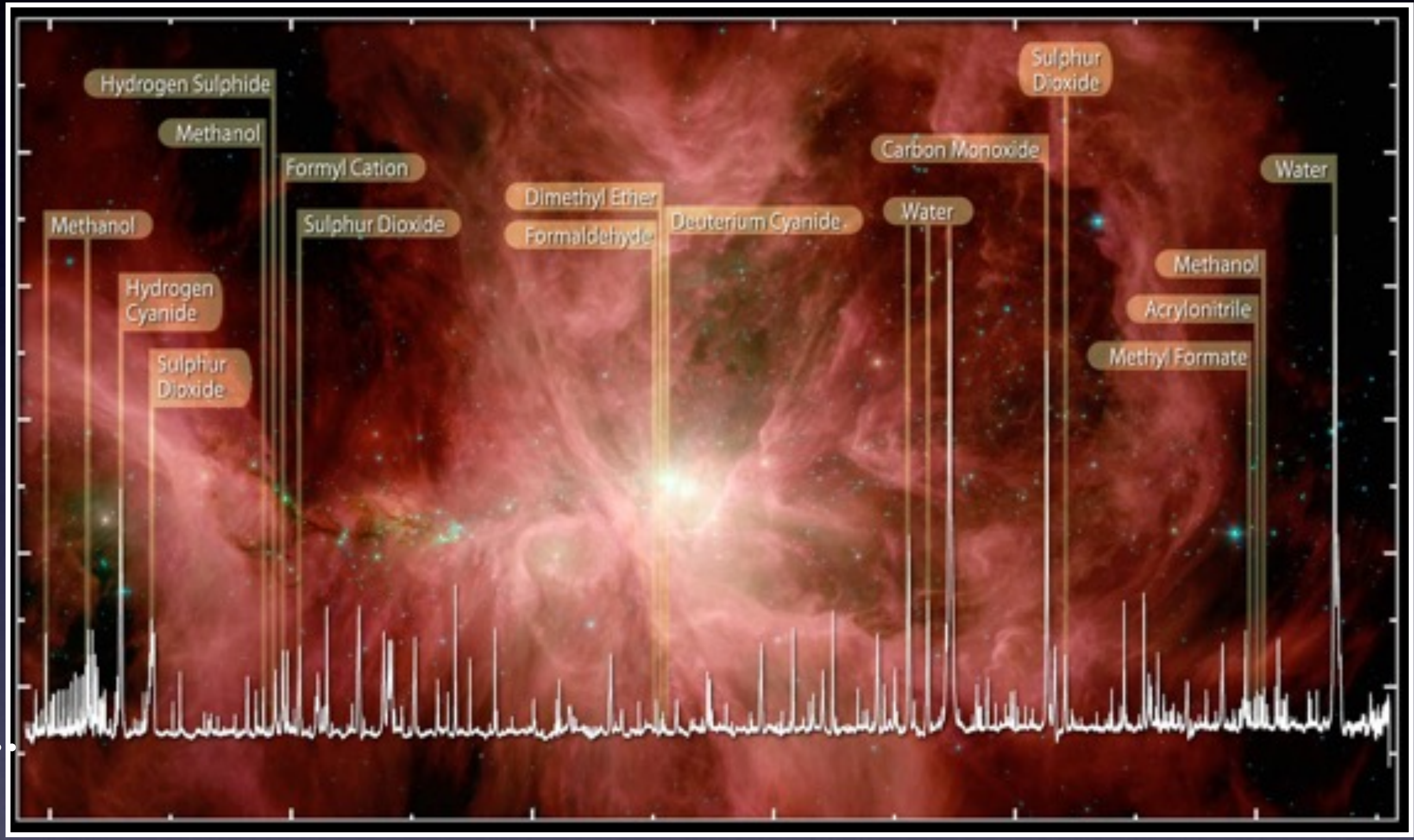
Tielens & Hagen, 1982, A&A, 114, 245

Fuchs et al 2009, A&A, 505, 629; Hidaka et al, 2004, ApJ, 614, 1124; 2009, ApJ, 702, 291; Hiraoka et al 1998, ApJ, 498, 710; Ioppolo et al. , 2008, ApJ, 686, 1474

Ioppolo et al. , 2008, ApJ, 686, 1474; Dulieu et al 2010, A&A, 512, A30; Hiraoka et al 1998, ApJ, 498, 710; Miyauchi et al 2008, Chem Phys Lett, 456, 27; Mokrane et al, 2009, ApJ, 705, L195

Simple Organic Molecules ("SOM")

- Warm dense gas with rich organic inventory: of relatively simple organic molecules
  - CH_3OH, CH_3CH_2OH, CH_3OCH_3, H_2CO, CH_3CHO, $HCOOH$, NH_2CHO, ...
  - HCN, CH_3CN, CH_3CH_2CN, ...
- Large deuterium fractionations
- Driven by evaporation of ice mantles formed in cold phase



Blake et al, 1987, ApJ, 315, 621
Ceccarelli et al, 2007, PPV, 47
Bergin et al 2010, A&A, 521, L20

Origin of "SOM"

Deuterium fractionation implies formed from cold-reservoir-progenitors

- Surface chemistry in cold regions
- Photolysis of ices
- Evaporation followed by gas phase reactions
- Ion molecule chemistry in ices

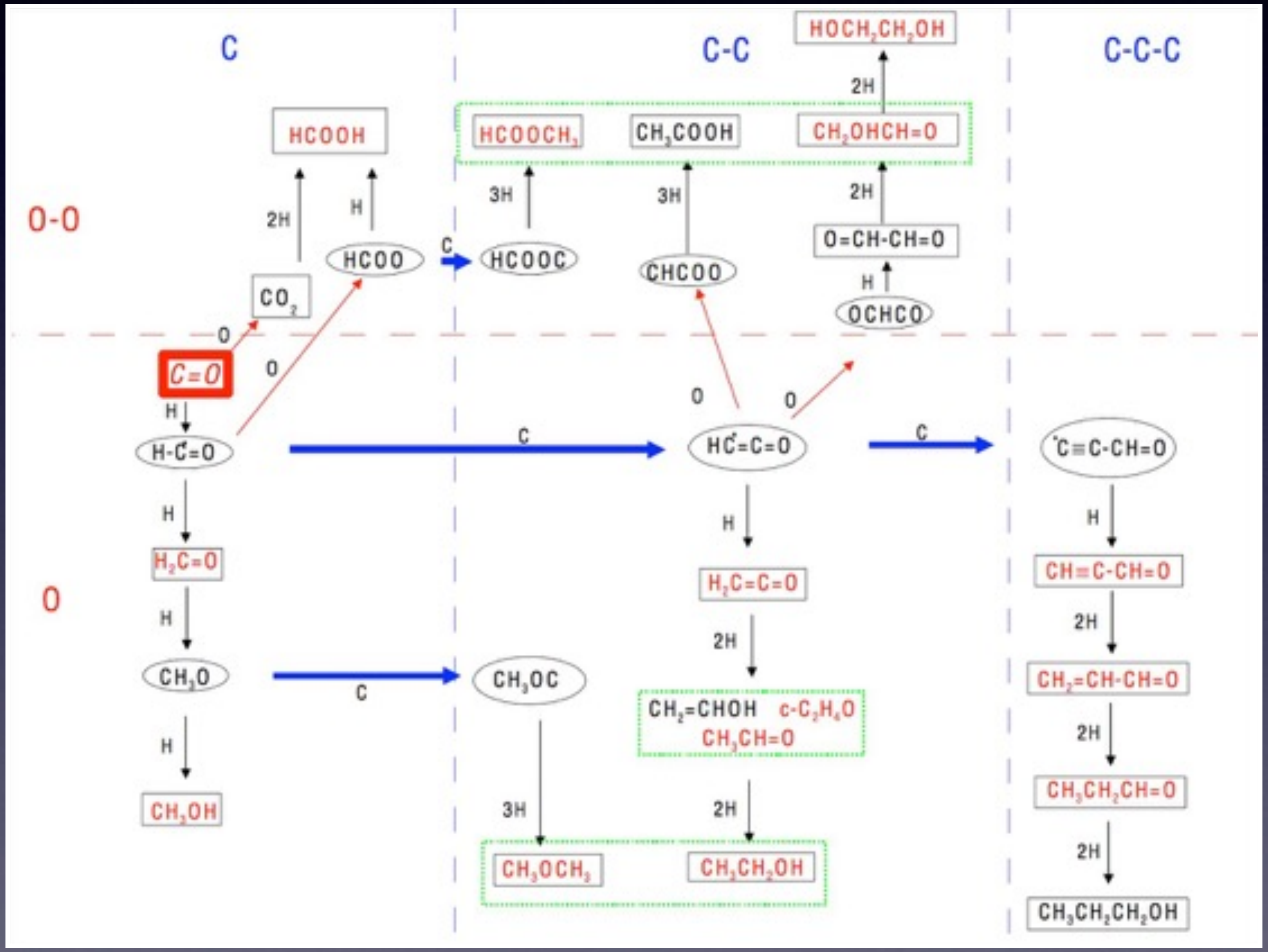
Gas phase chemistry: Charnley et al 1992, ApJ, 399, L71, Caselli et al, 1993, ApJ, 408, 538; Geppert et al, Faraday discussions, 133, 177, Horn et al, 2004, ApJ, 611, 605

Grain surface chemistry: Charnley & Rodgers 2007 Bioastronomy

Charged ices: Bouwman et al, 2011, A&A, 529, 46; Schutte et al, 2003, 398, 1049; Demyk et al, 1998, A&A, 339, 553, Balog et al 2009, Phys Rev Lett, 201, 73003

Photolyzed ices: Garrod et al, 2008, ApJ, 682, 283; Oberg et al, 2010, ApJ, 718, 832

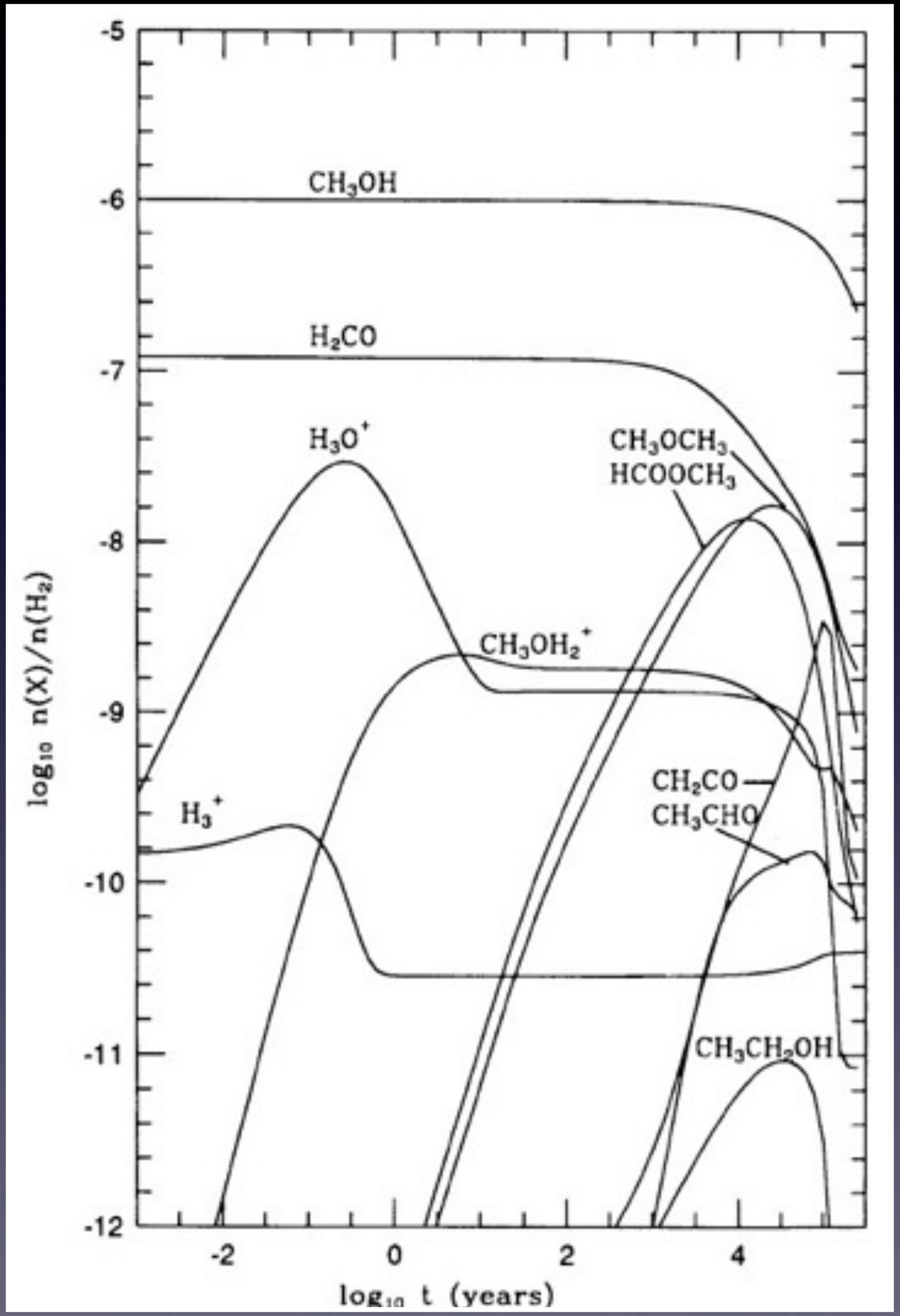
Grain Surface Chemistry



"SOM" molecules require 'free' carbon

Evaporating Ices

- Evaporating ice molecules drive rich chemistry
- Protonated methanol & methyl transfer
- Issues:
  - Experimental studies disagree
    - formation of intermediaries inhibited
    - Recombination leads to fragmentation
    - Role of ammonia as proton scavenger
  - Chemical clock ~$3x10^4$ yr incompatible with hot corinos

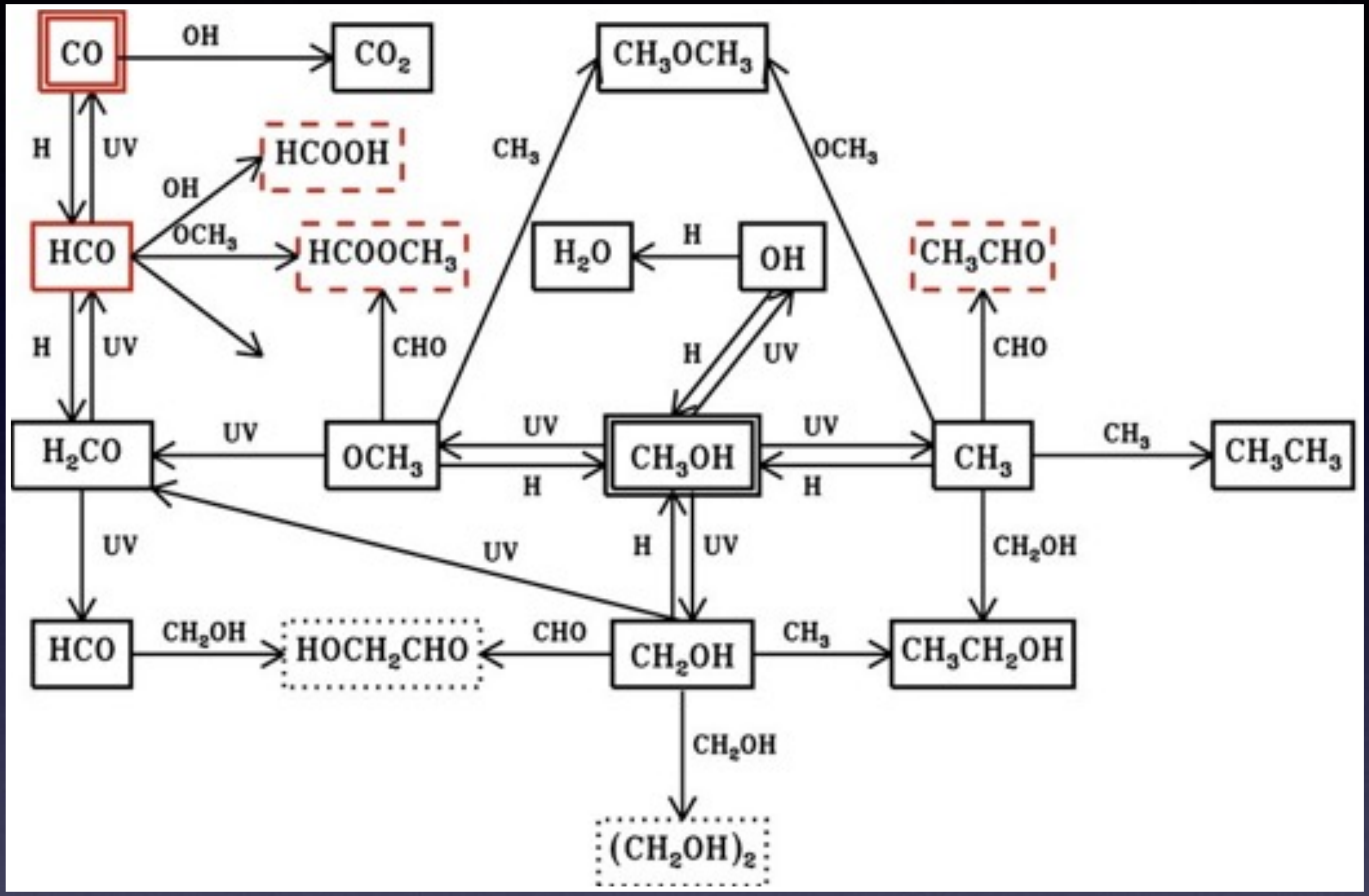


Charnley et al 1992, ApJ, 399, L71
Caselli et al, 1993, ApJ, 408, 538
Geppert et al, Faraday discussions, 133, 177
Horn et al, 2004, ApJ, 611, 605

Photolyzed Ices

UV photolysis/ion bombardment & warm up

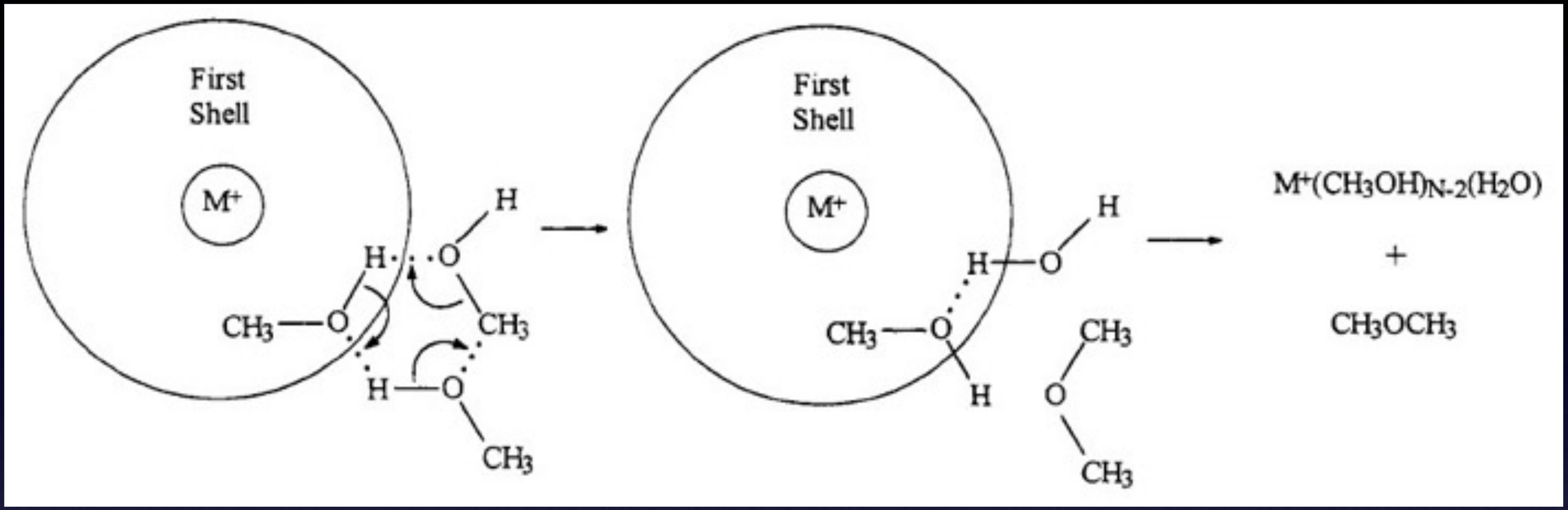
- Radical production (CH_3 & others)
- Recombination



- Issues:
  - Chemical specificity
  - Polymerization

Garrod et al, 2008, ApJ, 682, 283
Oberg et al, 2010, ApJ, 718, 832

Charged Ices



Ion-molecule Chemistry in Ices

- Ices are charged & charges are localized:
  - Na, PAHs
  - OCN^-
  - Polarization charge
- Warm-up leads to segregation
- H-bonding
- Stereochemistry
- Methanol drives chemistry
- Near evaporation, "droplets" may conduce methyl transfer without fragmentation

charged ices: Bouwman et al, 2011, A&A, 529, 46; Schutte et al, 2003, 398, 1049; Demyk et al, 1998, A&A, 339, 553, Balog et al 2009, Phys Rev Lett, 201, 73003

Warm organics in protoplanetary disks

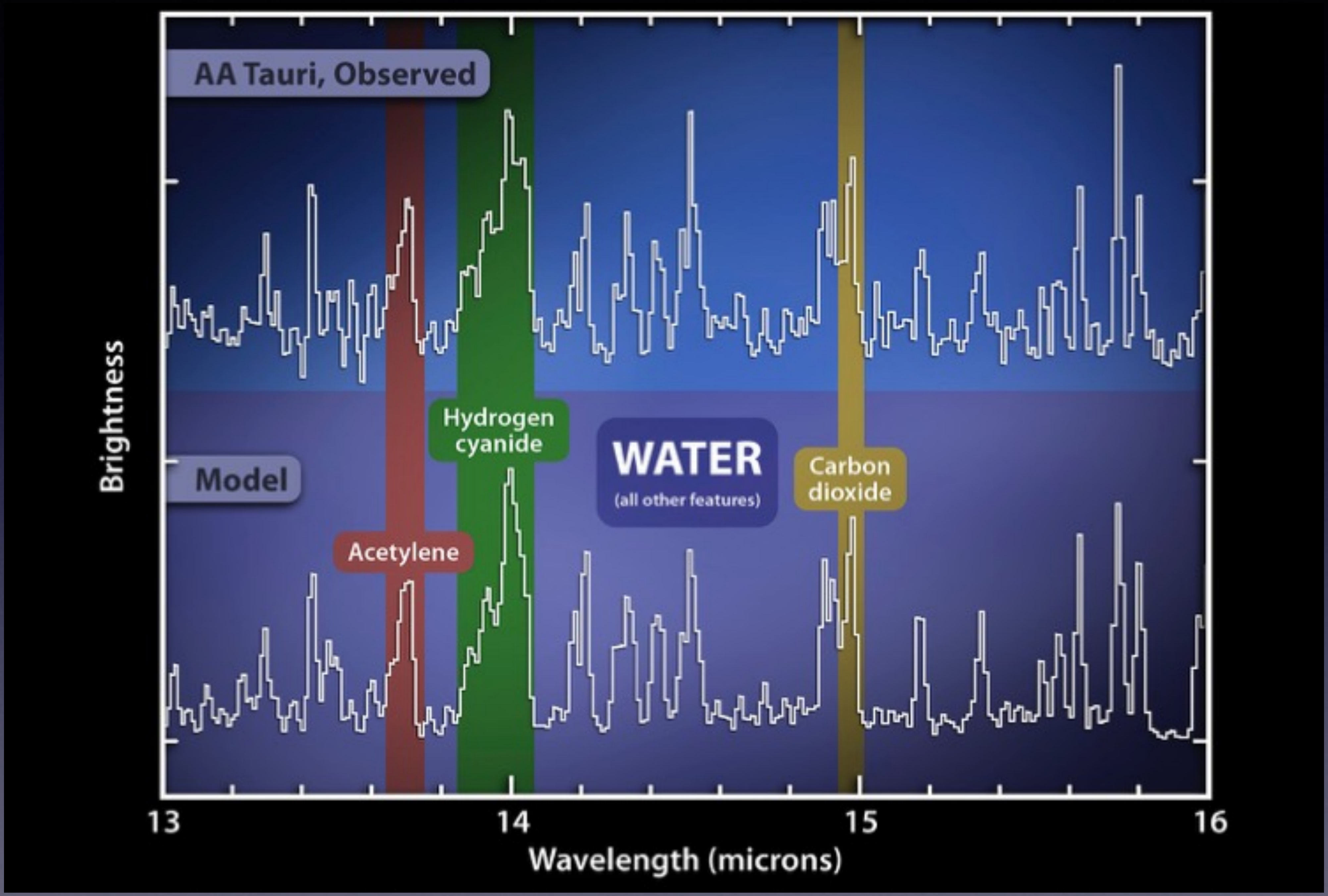
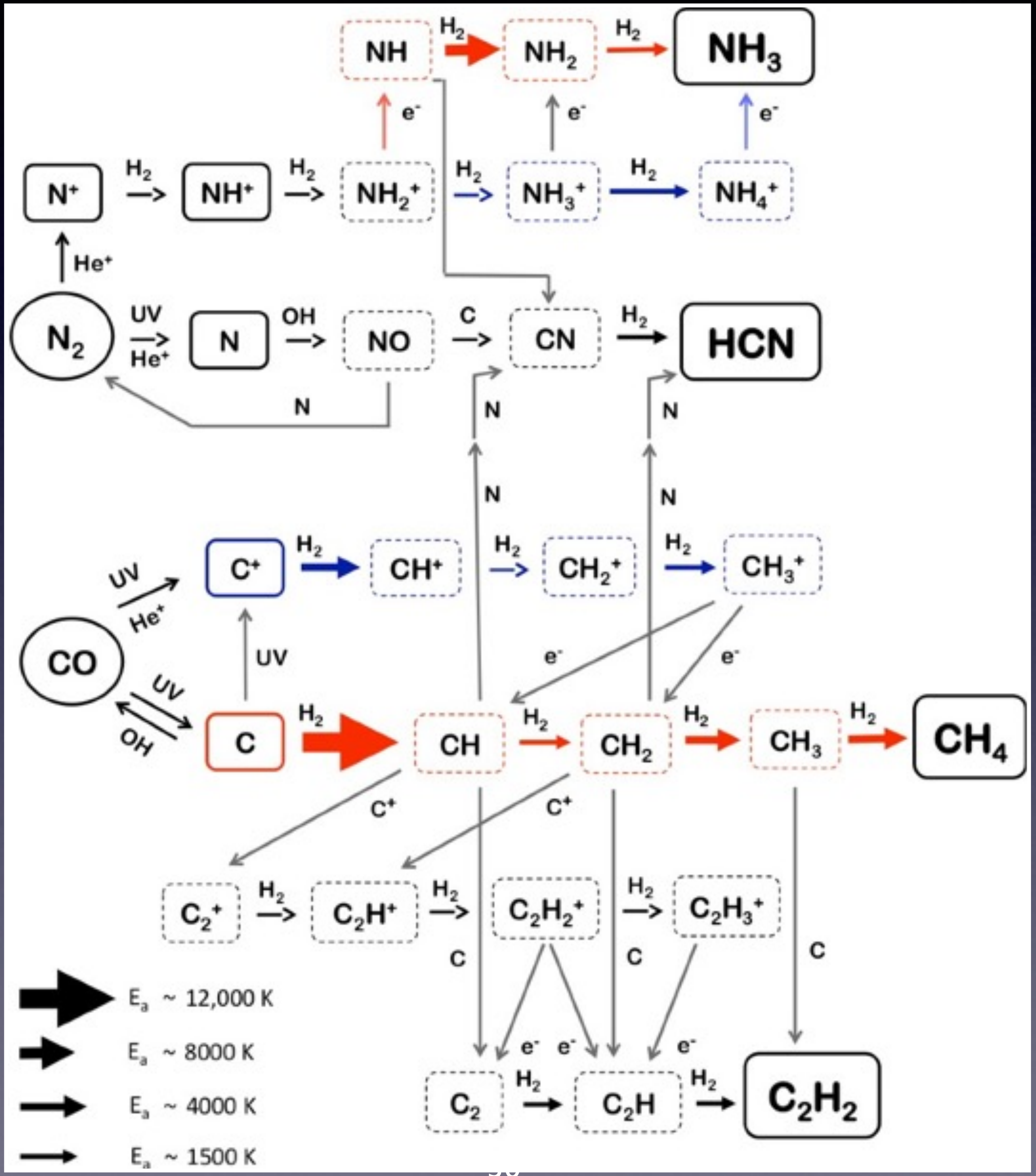


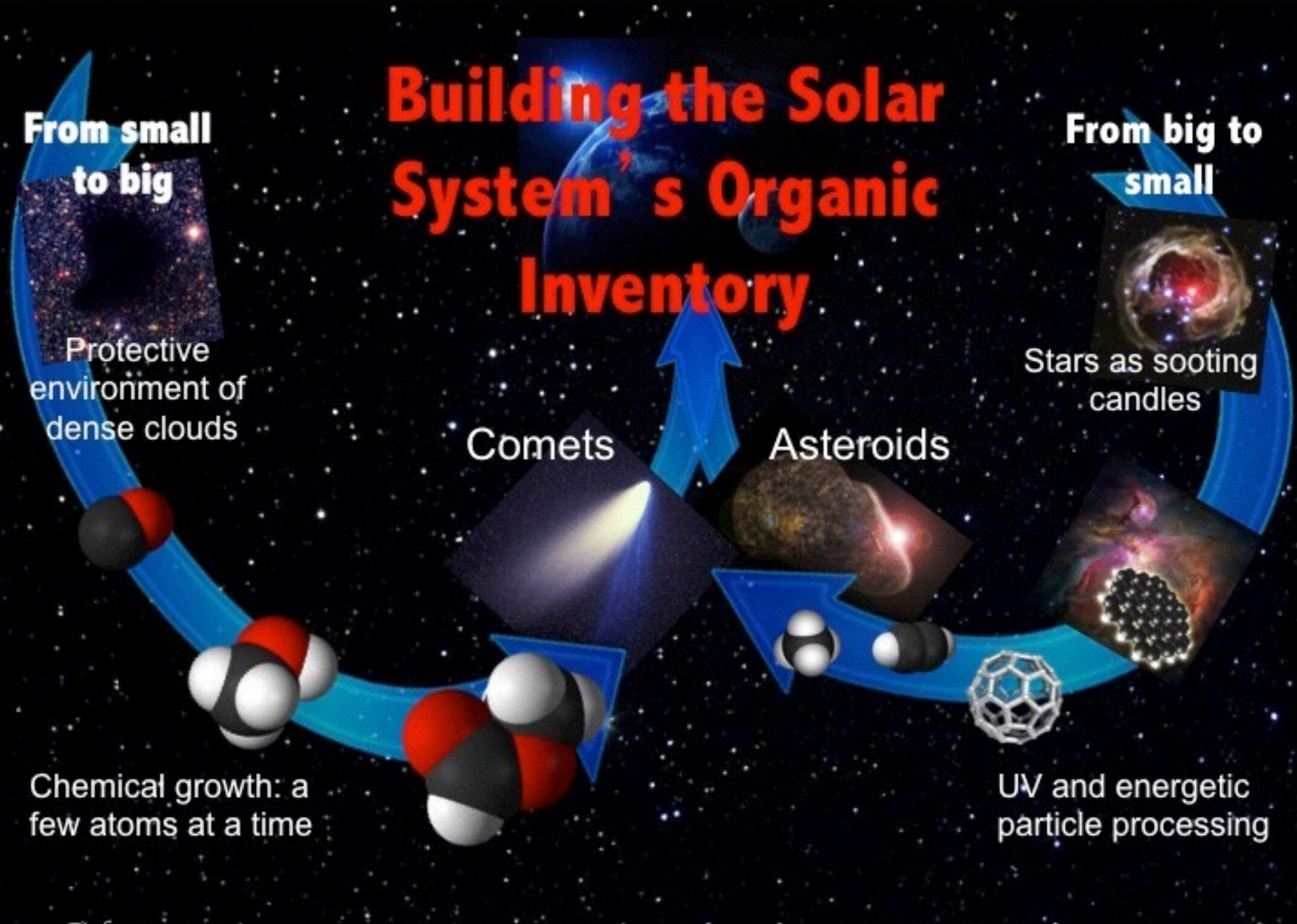
Photo-Chemistry in Warm Surface Layers

Najita et al, 2003, ApJ, 589, 931
Carr & Najita, 2011, ApJ, 733, 102
Lahuis et al, 2006, ApJ, 636, L145
Salyk et al, 2011, ApJ, 731, 130

Chemistry in warm, UV/X-ray irradiated gas



Bast et al, 2012, A&A, 551, A118
and refs therein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UV and energetic particle processing
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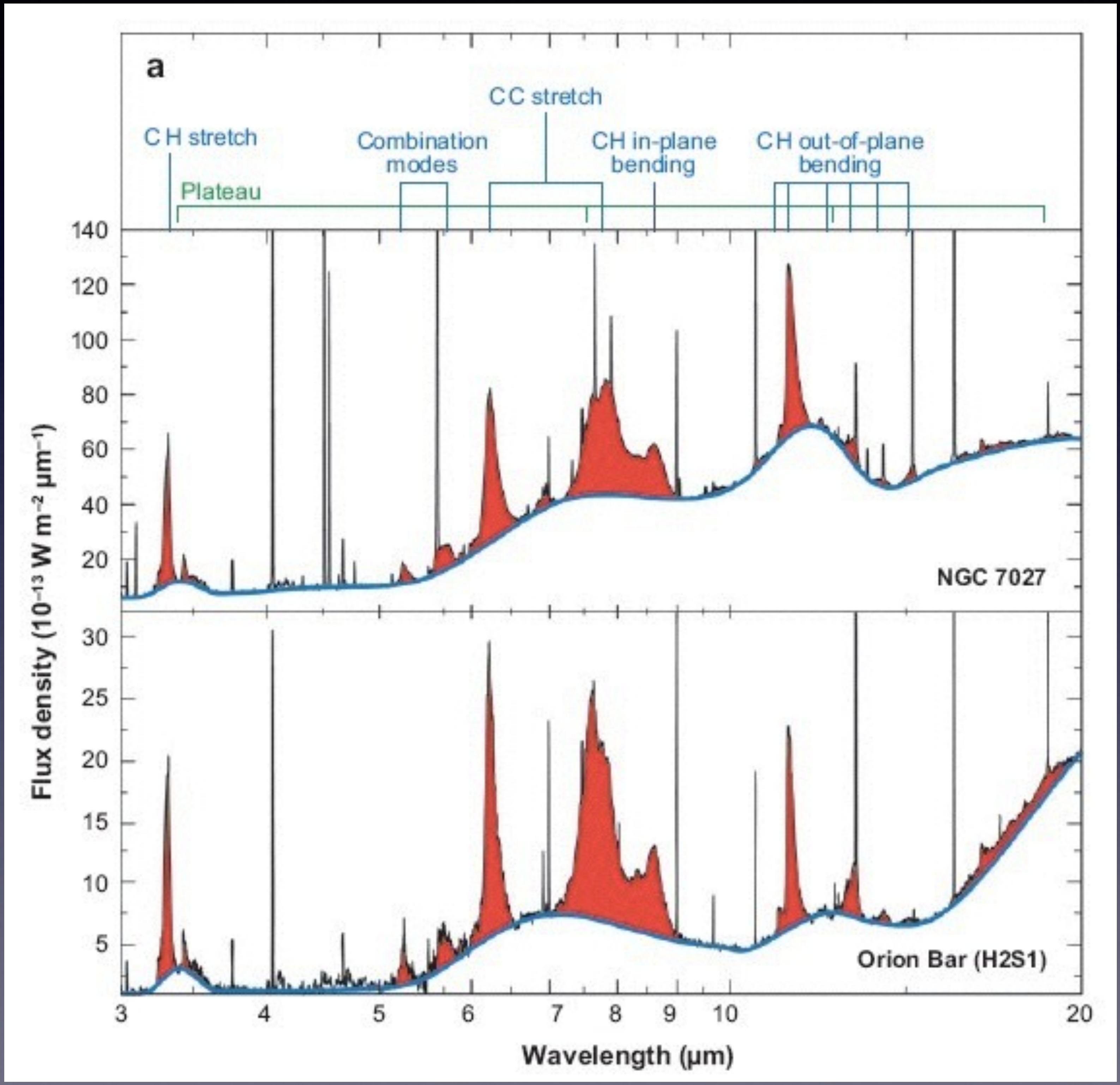
The incredibly rich spectrum of interstellar PAHs



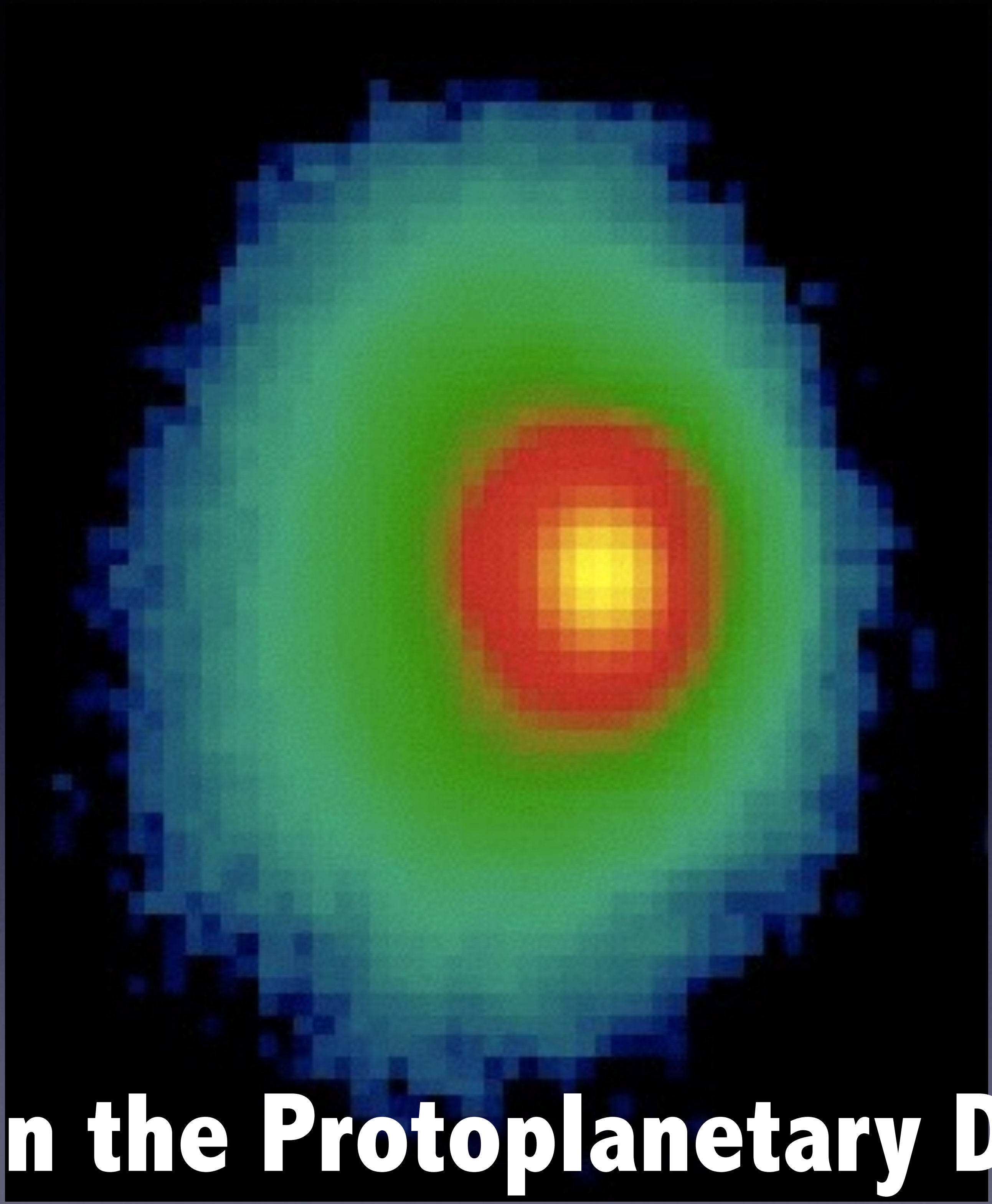
Peeters et al, 2002, A&A,390, 1089

Orion

PAHs in Orion

M51: The Whirlpool Galaxy

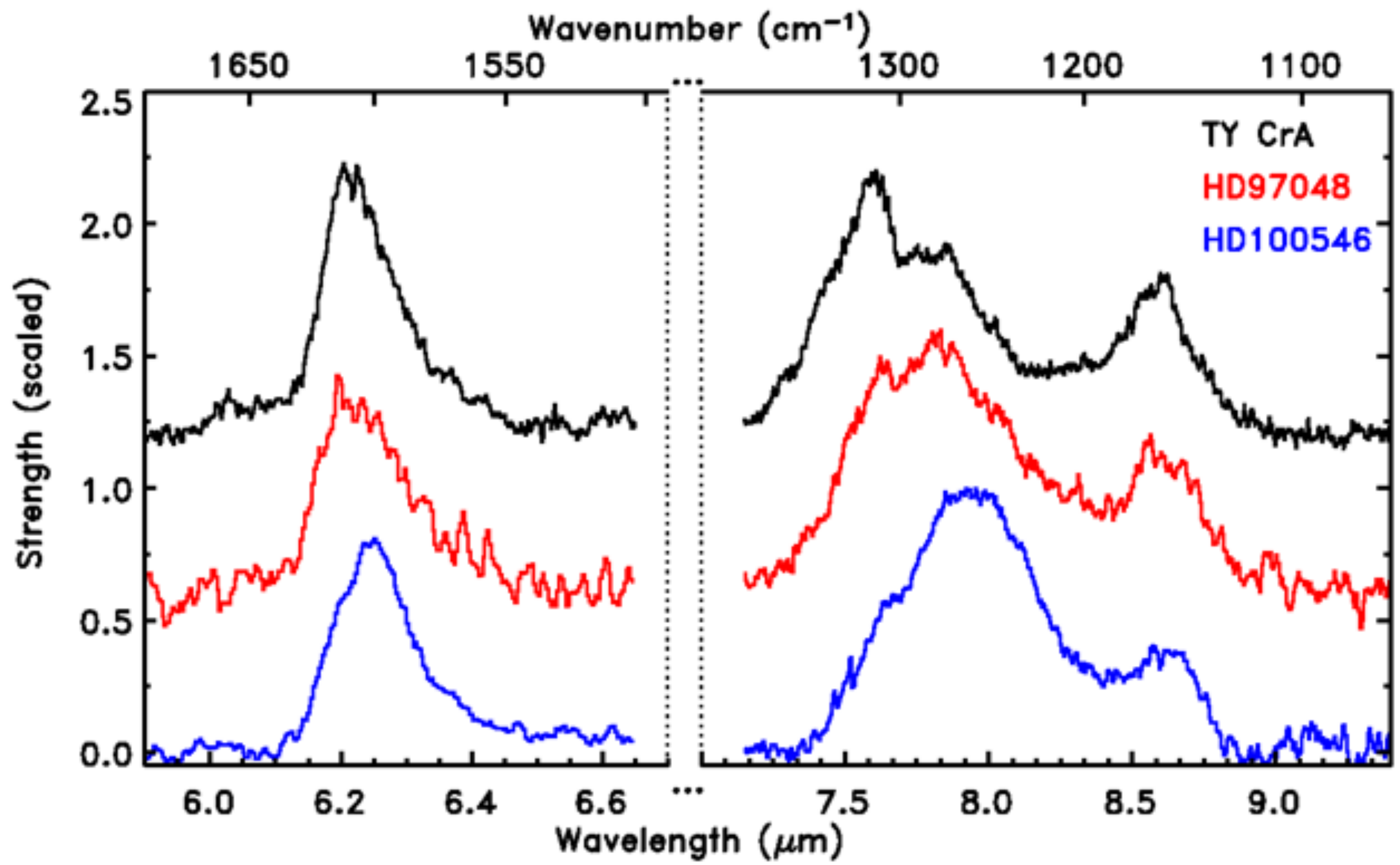
M51: The Whirlpool Galaxy



PAHs in the Protoplanetary Disk of HD 97048

Doucet et al 2007, A&A, 470, 625

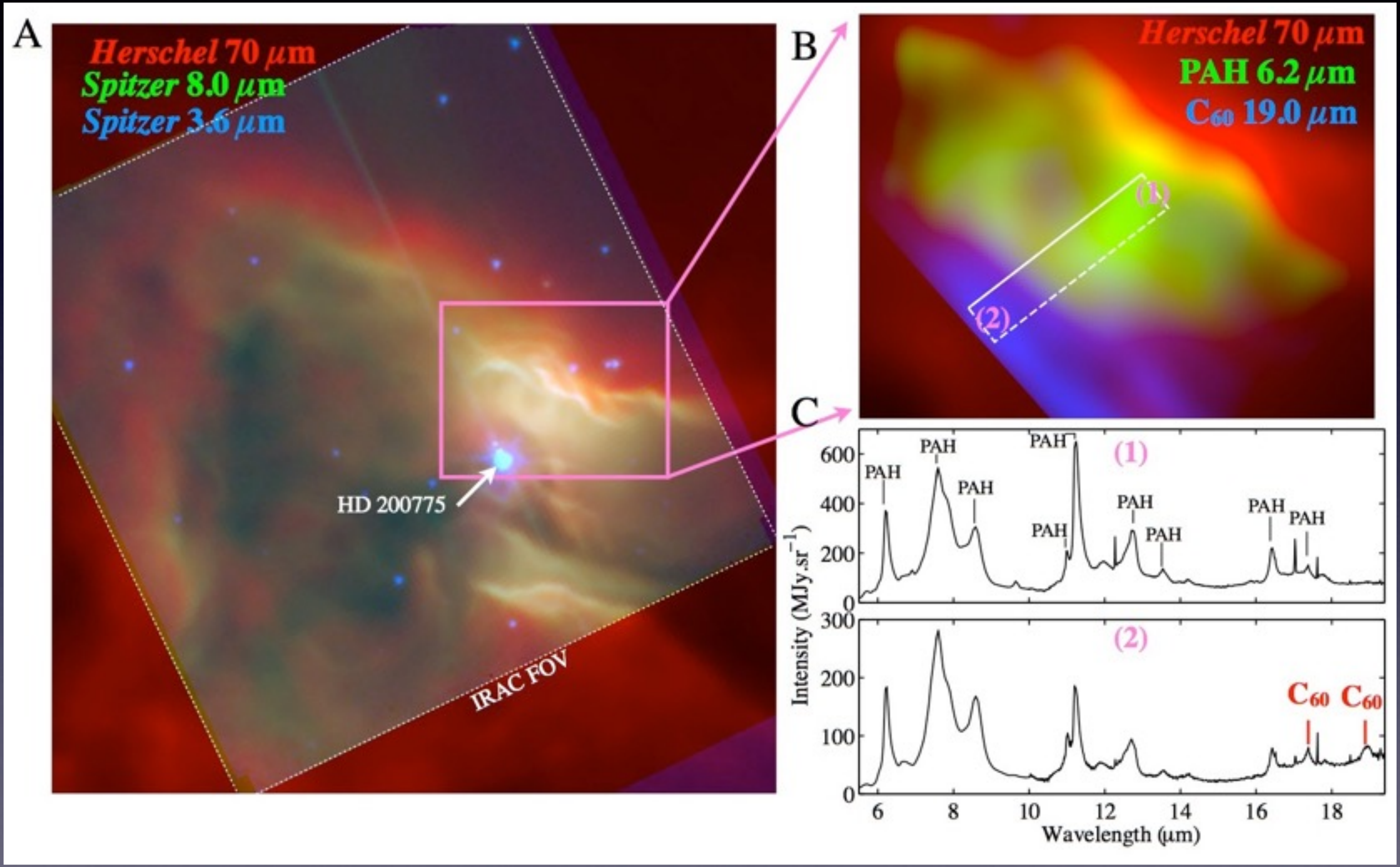
PAHs and Herbig Stars



Source	Sp T	Size	Location
TY Cra	B7-B9	~2000 AU	HAeBe in cloud
HD 97048	B9-A0	~100-1000 AU	HAeBe cloud edge
HD 100546	B9	~150 AU	isolated HAeBe star

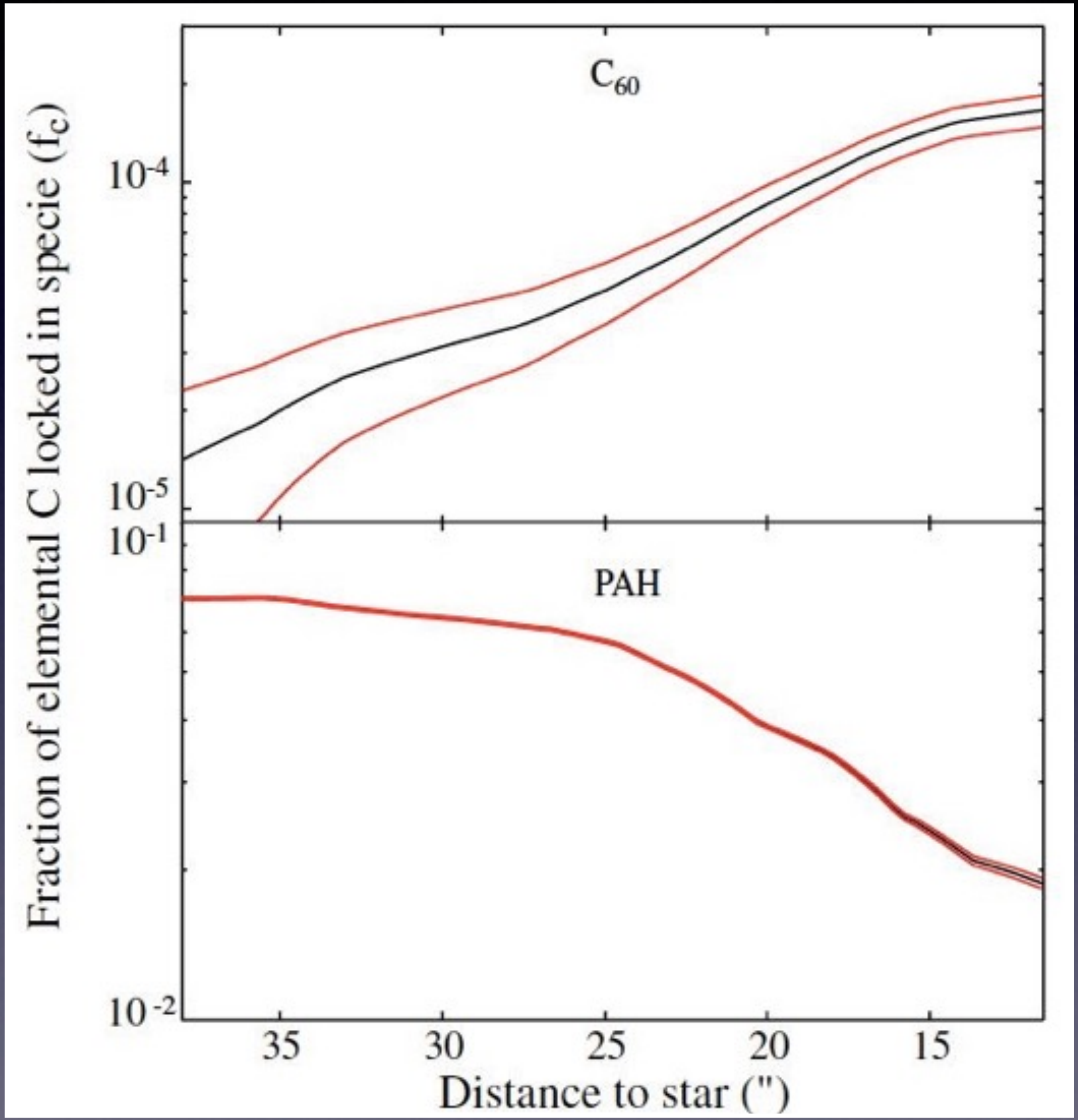
Sloan et al 2007, ApJ, 664, 1144; Keller et al, 2008, ApJ, 684, 411; Boersma et al, 2008, A & A, 484, 241

PAHs & C_{60} in NGC 7023



Berne & Tielens, 2012, PNAS, 109, 401

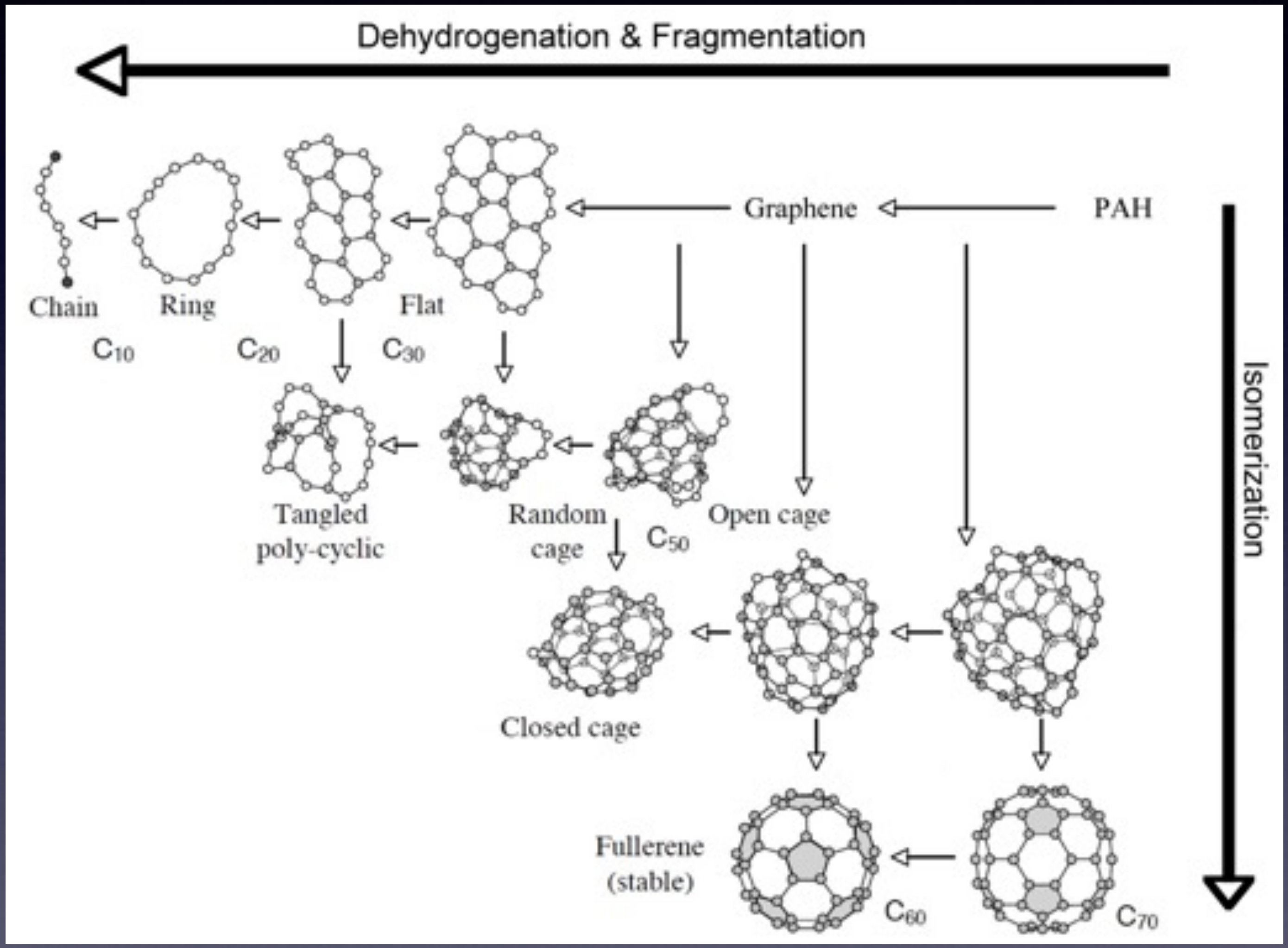
PAHs & C_{60} abundance



Berne & Tielens, 2012, PNAS, 109, 401

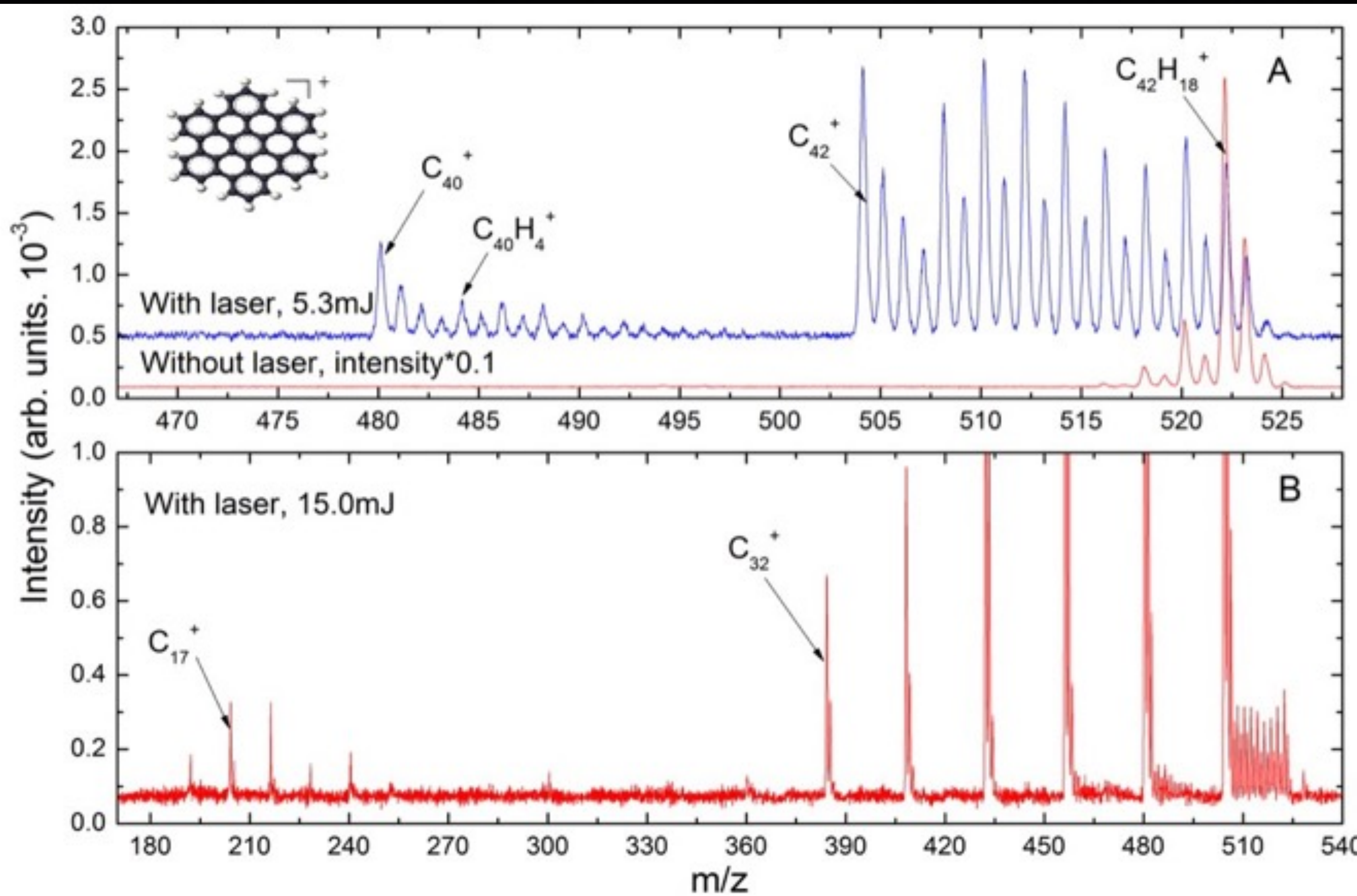
PAH photolysis

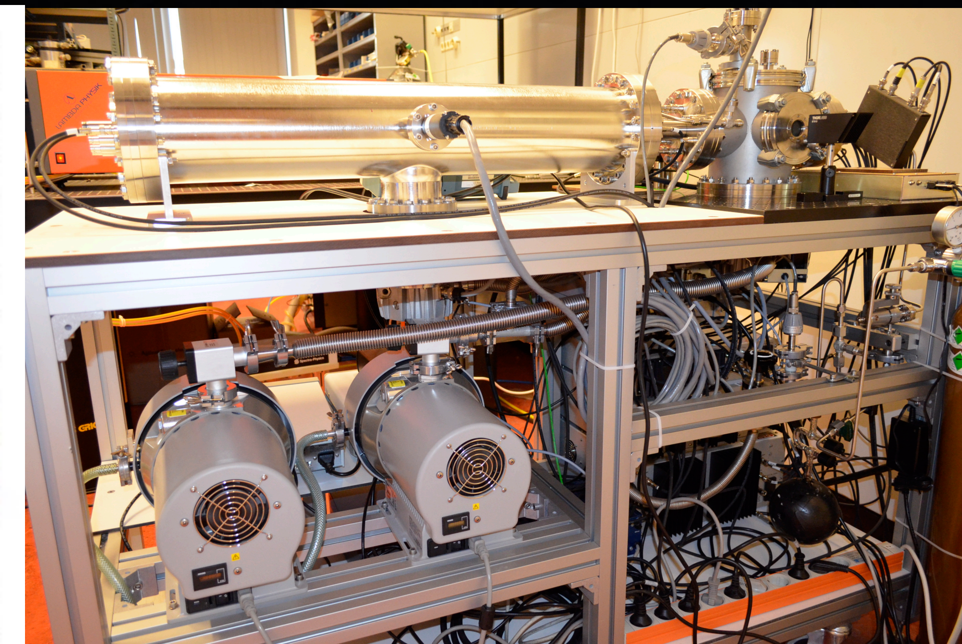
- Dehydrogenation & isomerization
- Stable intermediaries: cages & fullerenes
- Fragmentation products: hydrocarbon chains & radicals



Berne & Tielens, 2012, PNAS, 109, 401
Pety et al, 2005, A&A, 435, 885
Wehres et al, 2010, A&A, 518, 36

PAHs Photolysis



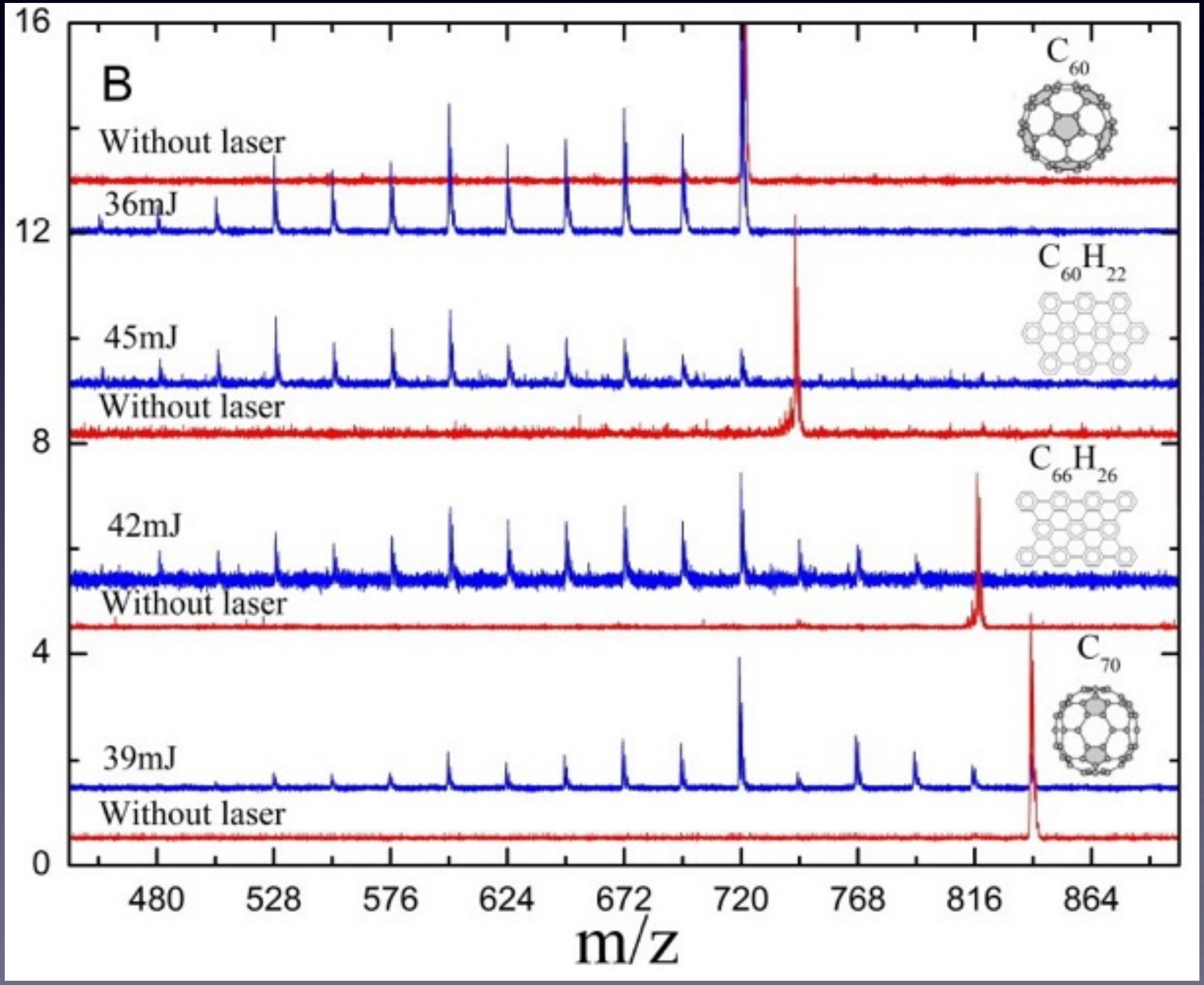


Ekern et al, 1997, ApJ, 488 L39
Joblin et al, 2003, Edp. Sci. Conf. Ser. 175
Zhen et al, 2014, Chem Phys Lett, 592, 211

- Multiphoton absorption leads to fragmentation in a laser pulse
- Many pulses strip the molecule down
- Loss of all H followed by loss of C_2 and C units (magic numbers)

From PAHs to C_{60}

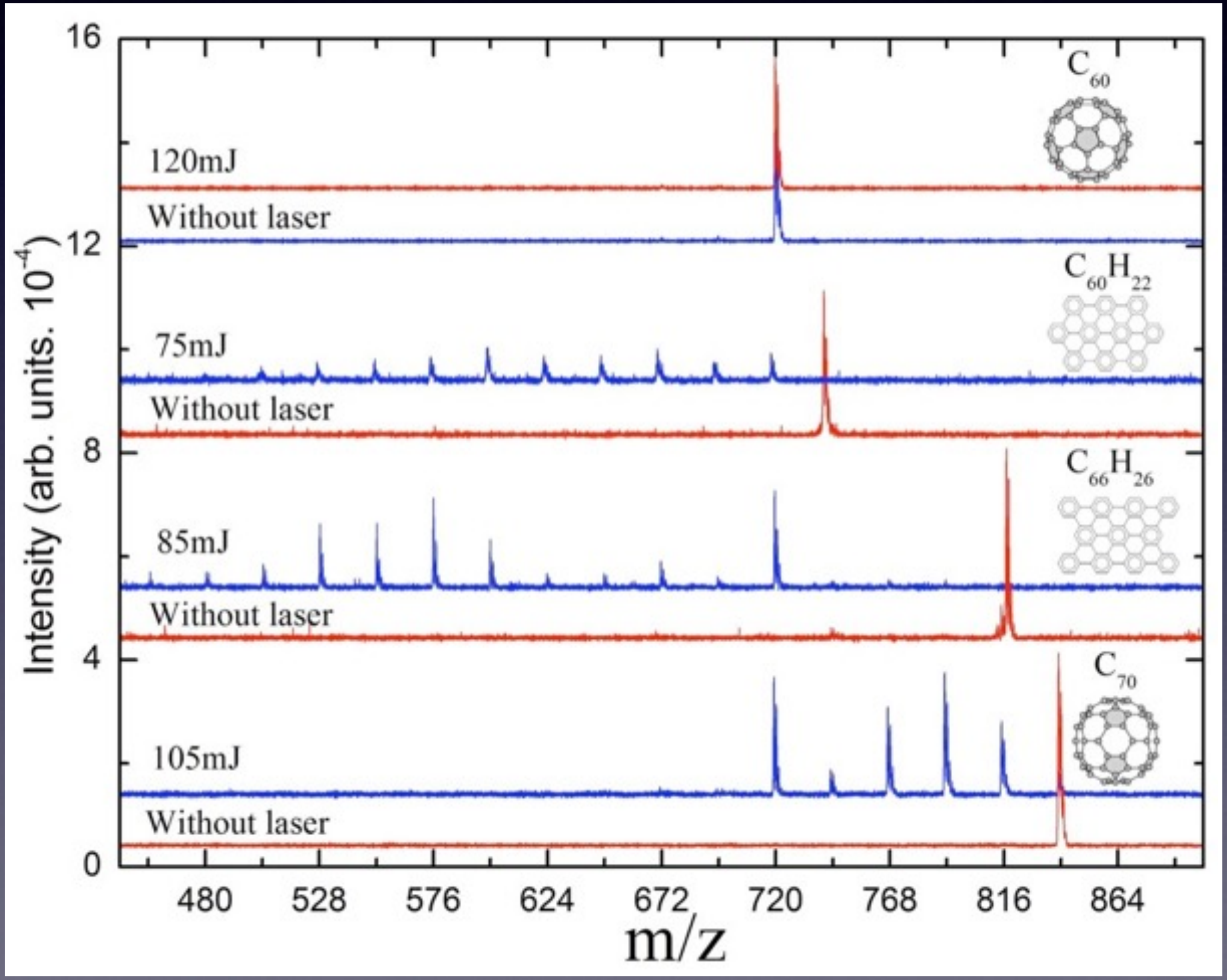
UV photolysis at 355 nm



Zhen et al, 2014, ApJ, 797, L30

From PAHs to C_{60}

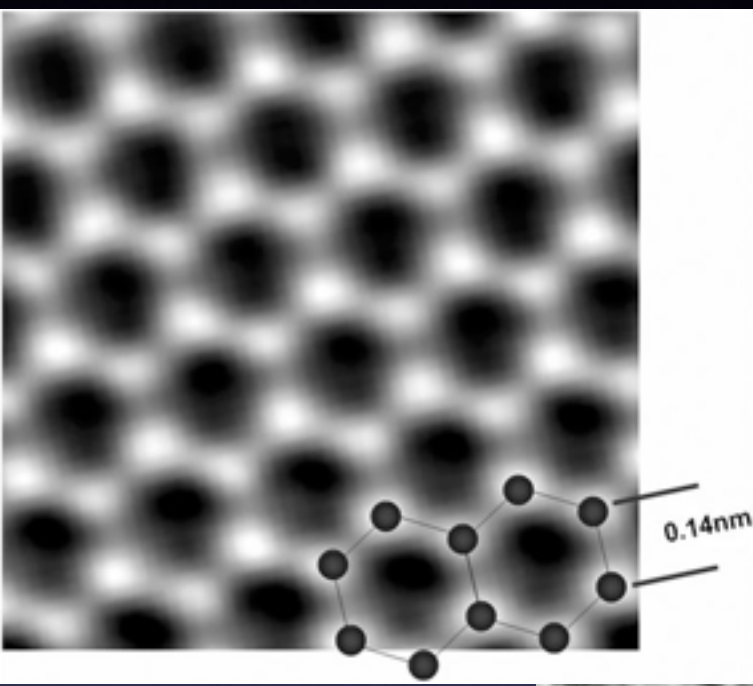
UV photolysis at 532 nm

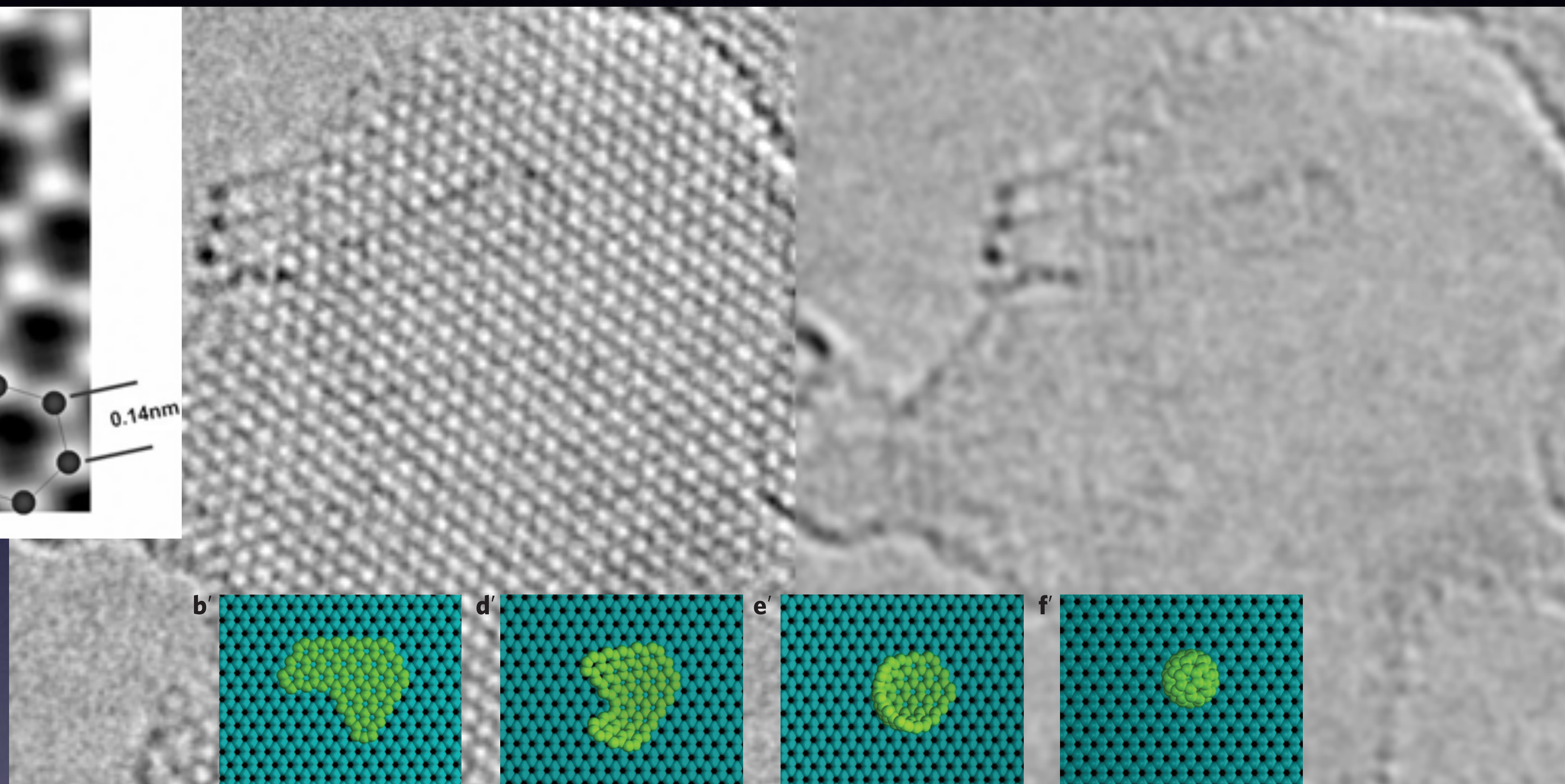


Zhen et al, 2014, ApJ, 797, L30

From Graphene to C_{60}

[National Center for electron microscopy]





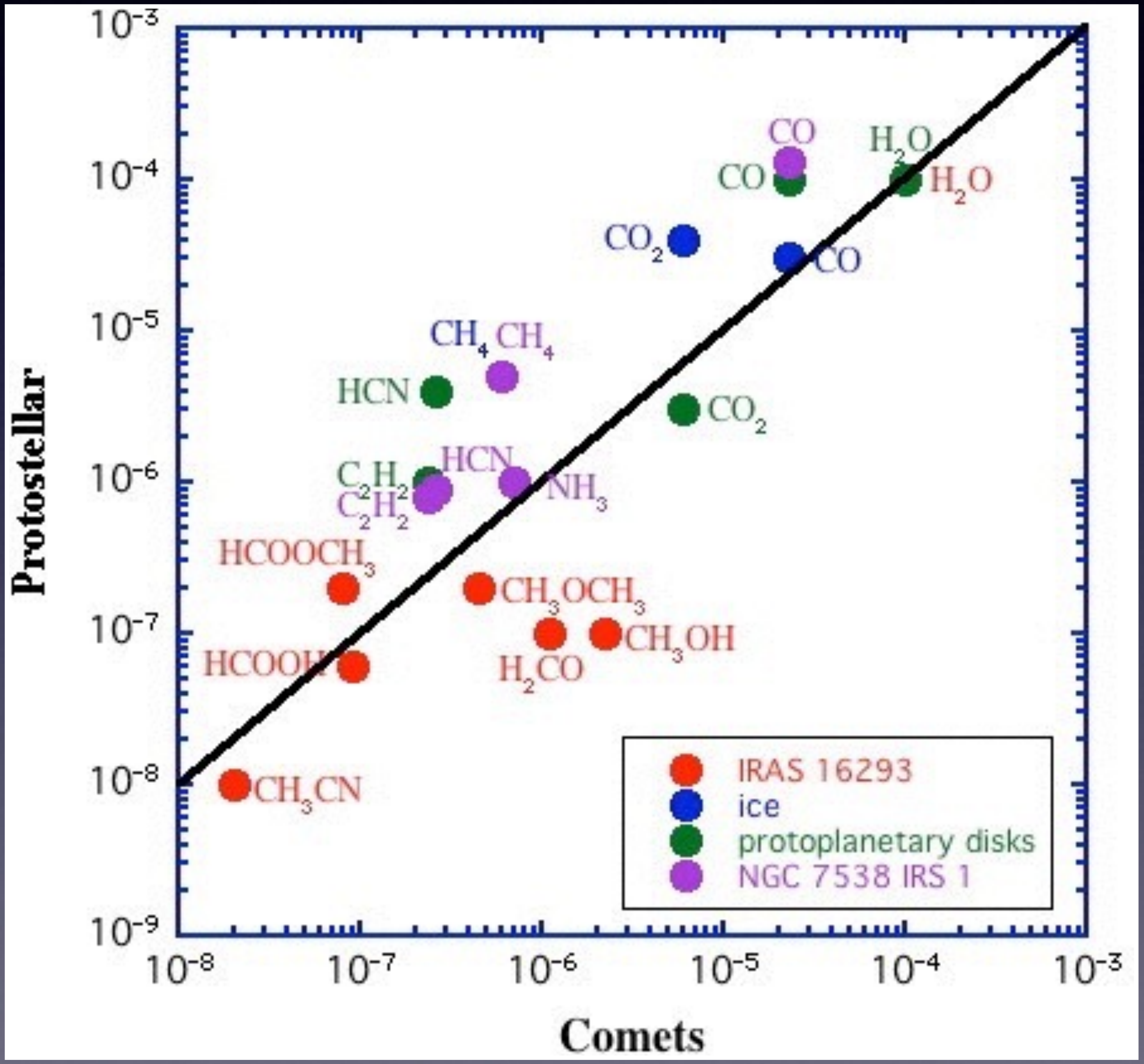
[Chuvilin et al. Nature Chem. 2010]

Transformation of graphene to C_{60}, driven by electron irradiation

Imagine Brazil as Soccer Champions of the molecular Universe !!

The Organic Inventory of Comets

Comets, and hence the Earth, sampled many reservoirs with a diverse chemical history



ice chemistry

Hot Core chemistry

Warm gas photochemistry

PAHs

Tielens, 2013, Rev Mod Phys and refs therein

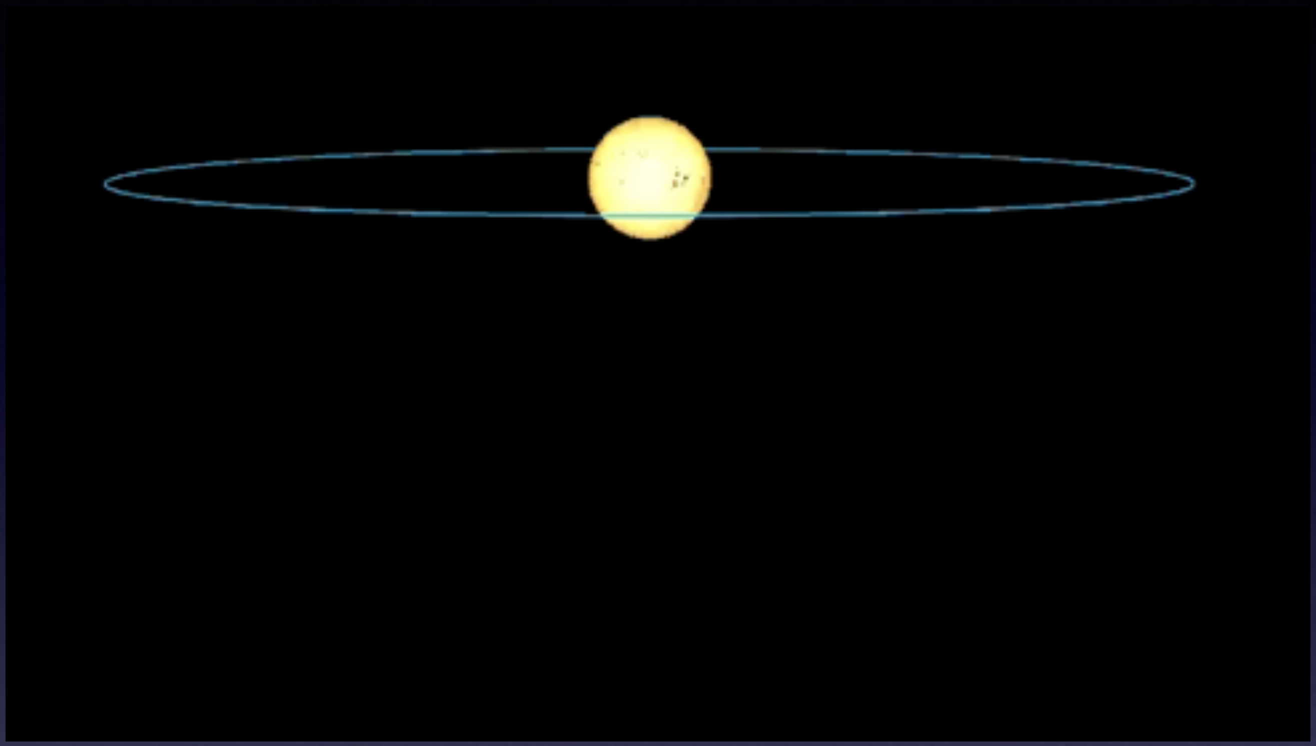
Key Questions

- Building new worlds: What are the key processes in planet formation ? How do they depend on the environment ? What is the inventory of planets, particularly in the habitable zone ?
- Planetary habitats: What are the primordial sources of organics and volatiles and the processes that play a role in their formation and delivery ?
- Setting the stage for life: What are the conditions on the early Earth & newly formed planets and what are the key processes that set the stage for life ?

Future of Astrochemistry

- Paradigms have been developed which provide precise descriptions of the various stages in the formation and early evolution of planetary systems
- Goal for the near future:
  - Review these paradigms & determine how accurate are
  - Predict the composition of terrestrial exoplanets & exomoons
  - Predict biosignatures of exoplanets

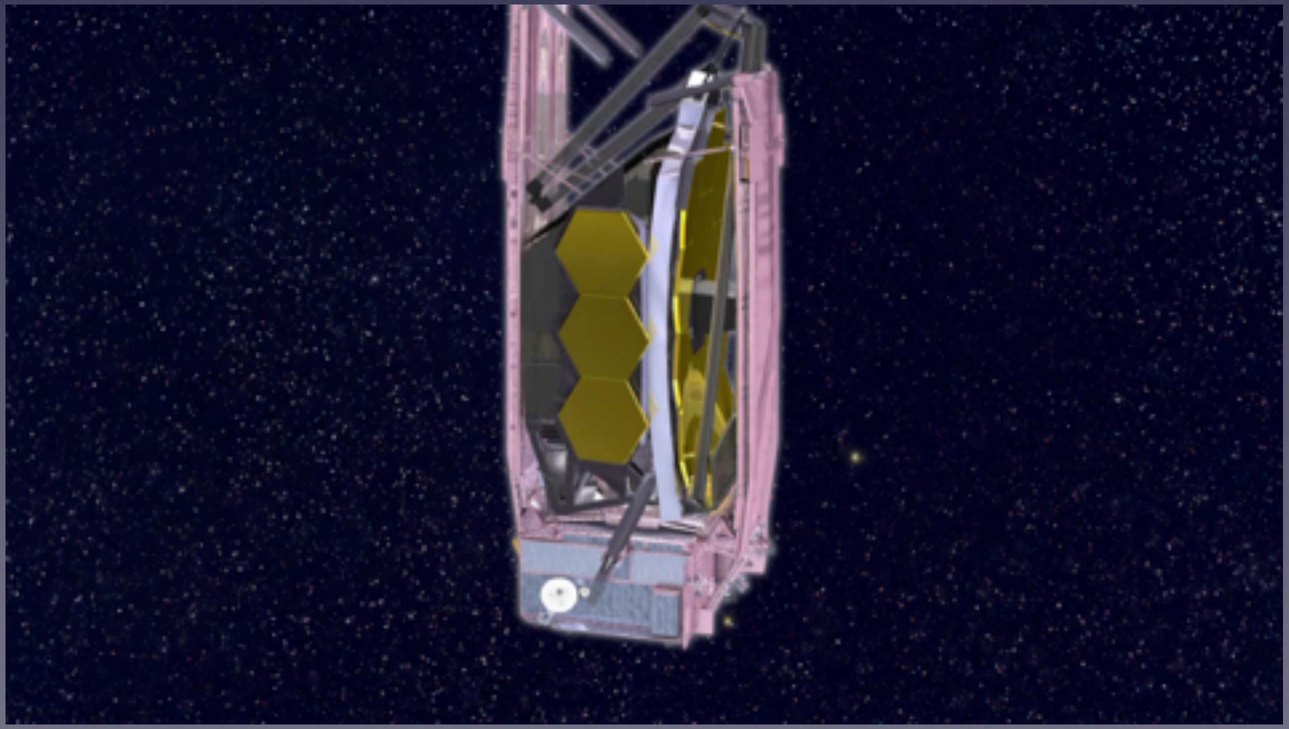
Kepler, TESS & Plato



ALMA

SOFIA

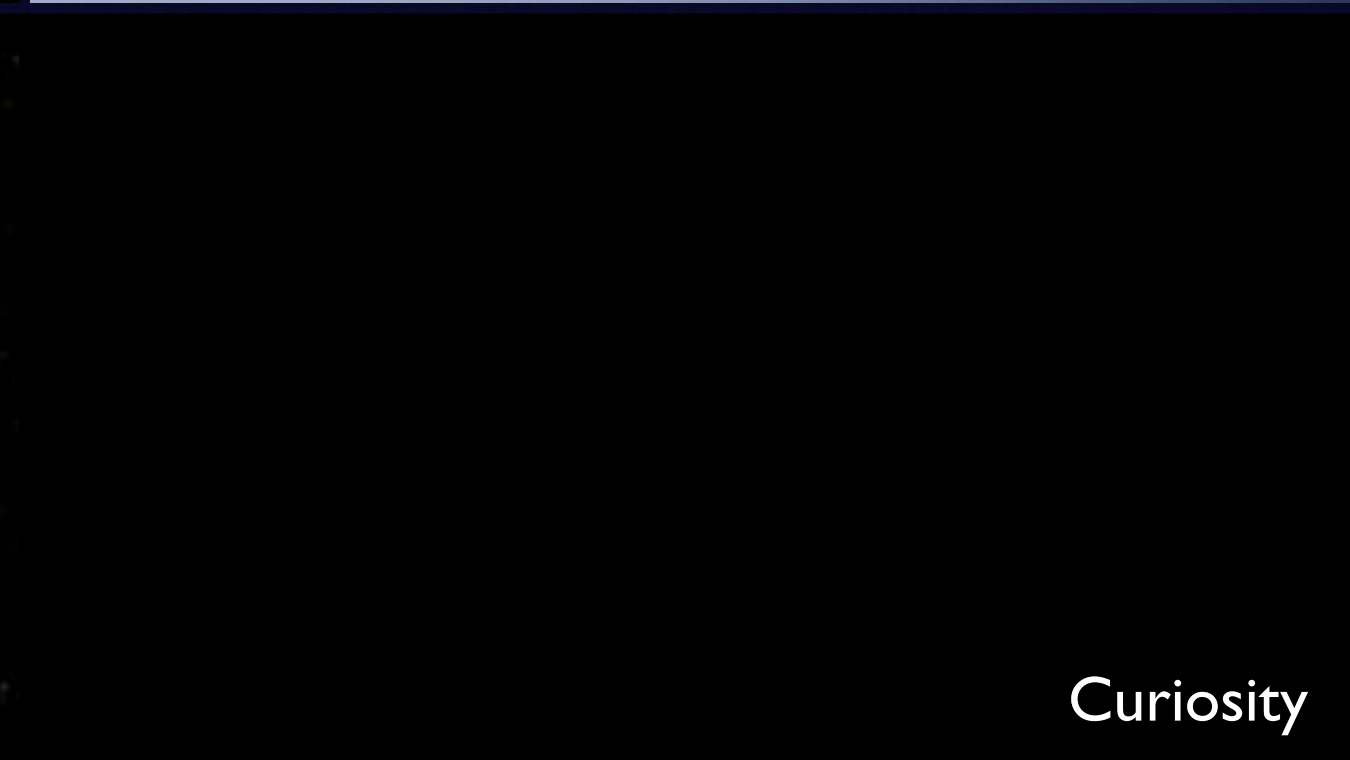
James Webb




Cassini/Huygens

Rosetta


Stardust

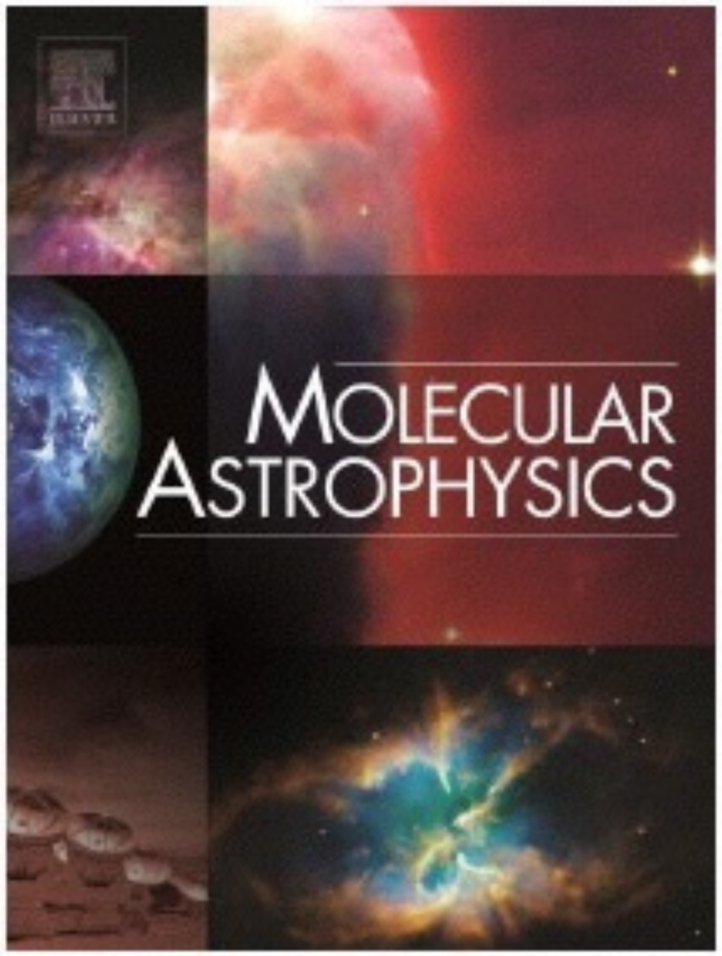

Curiosity


Juice


Space missions cost 1 Billion euro and up !
Grad students: Any study is relevant somewhere in the Universe. Your challenge is to find out where !

Molecular Astrophysics

The journal is welcoming submissions!



NEW JOURNAL

Molecular Astrophysics aims to provide a platform for scientists studying the chemical processes that form and deconstruct molecules, and control chemical abundances in the universe, particularly on Solar System objects such as planets, moons, and comets, and comets, in the atmospheres of exoplanets, as well as in regions of star and planet formation in the Interstellar Medium of galaxies.

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