Astrochemistry: the next 40 years

Xander 1985

Ewine F. van Dishoeck, Leiden Observatory

XT2019, Avignon, September 6 2019

Xander as mentor for Leiden PhD students

PhD Karin Öberg 2009

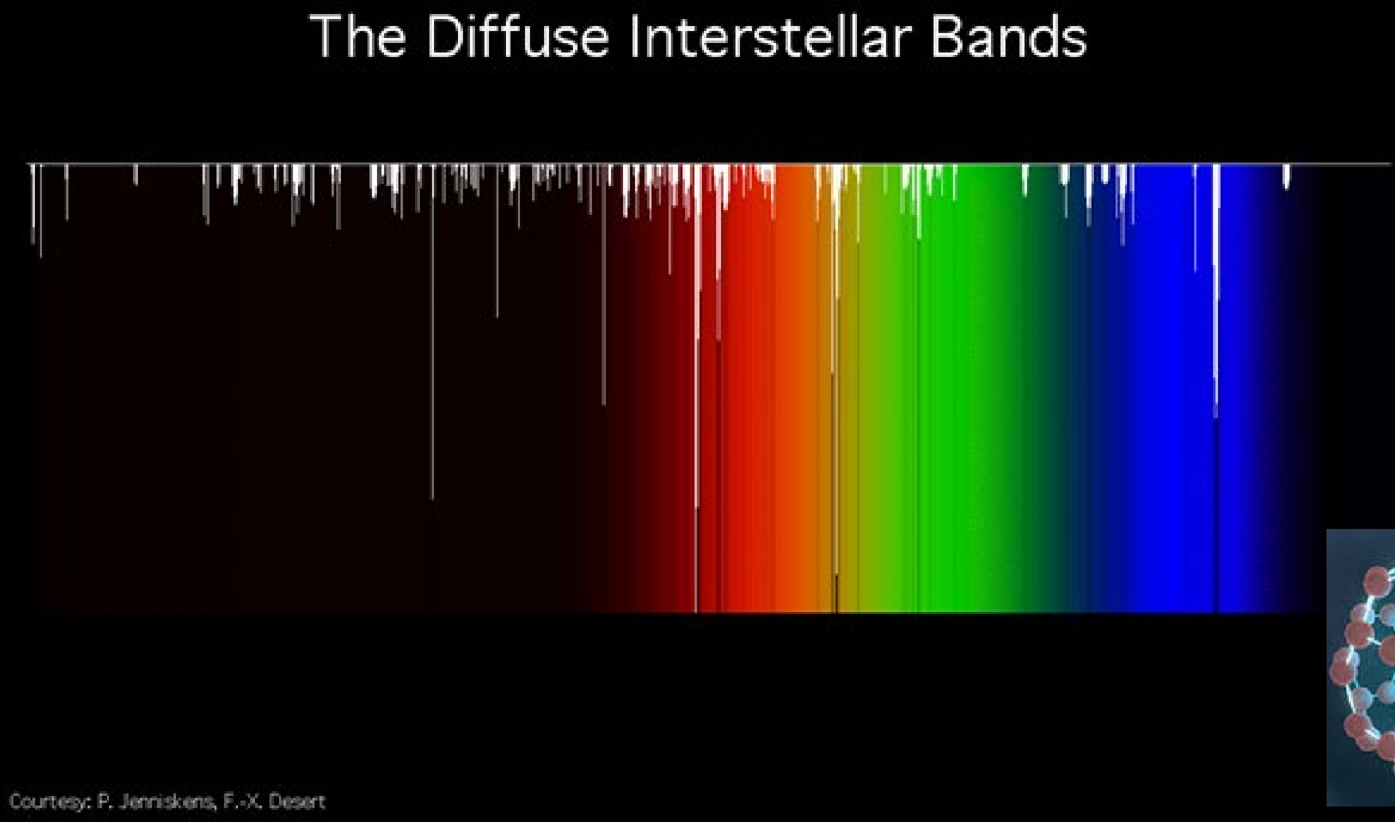
Big thanks from all Leiden PhD students

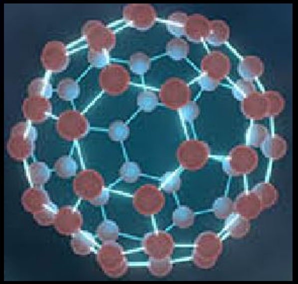
PhD Annemieke Boonman 2003

What did we know 100 years ago?

- Small universe
- One galaxy (the Milky Way)
- Eight planets, all in our Solar System
- Many elements in Periodic Table
  - but no clue how they were formed

Nearly 100 yr of astrochemistry



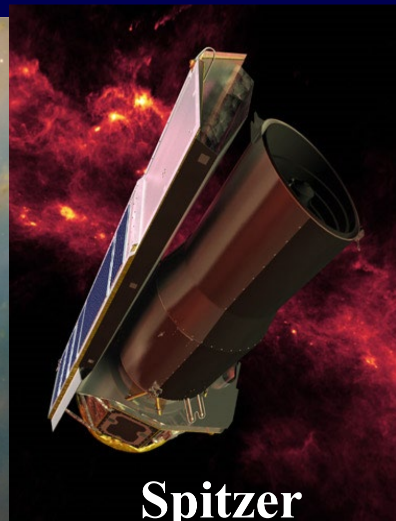


First seen by Heger 1922, latest survey Cox, Cami et al. 2017 (EDIBLES)
>500 lines, still mostly unidentified

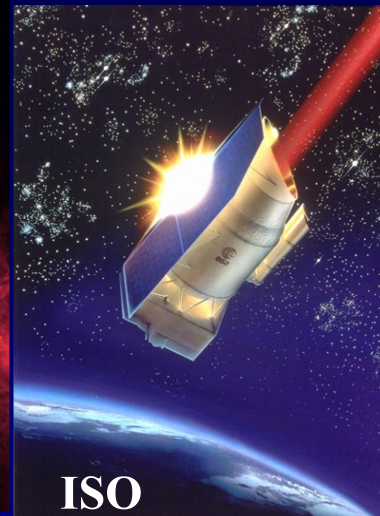
Astronomy driven by new facilities

It has been a rich era for infrared astronomy

Herschel



Spitzer



ISO

SOFIA

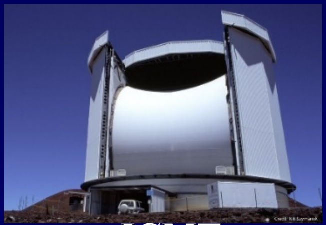
Rosetta
Sample return

Keck, Gemini, Subaru,
IRTF, …

VLT

ALMA: the astrochemistry machine

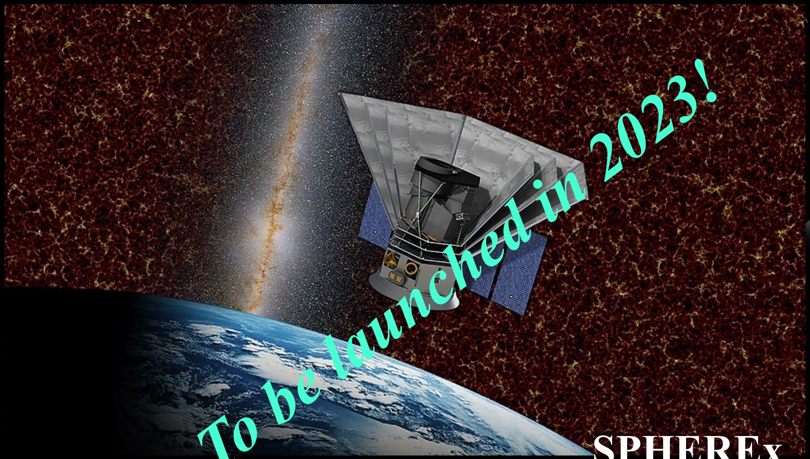
Also NOEMA, SMA with wide-band receivers



JCMT

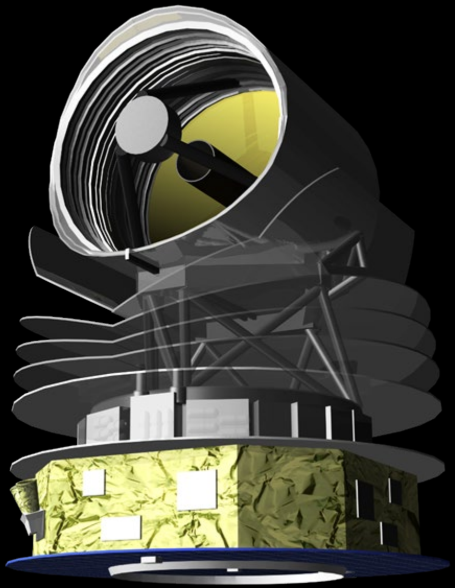
Single-dish data

Upcoming facilities for astrochemistry

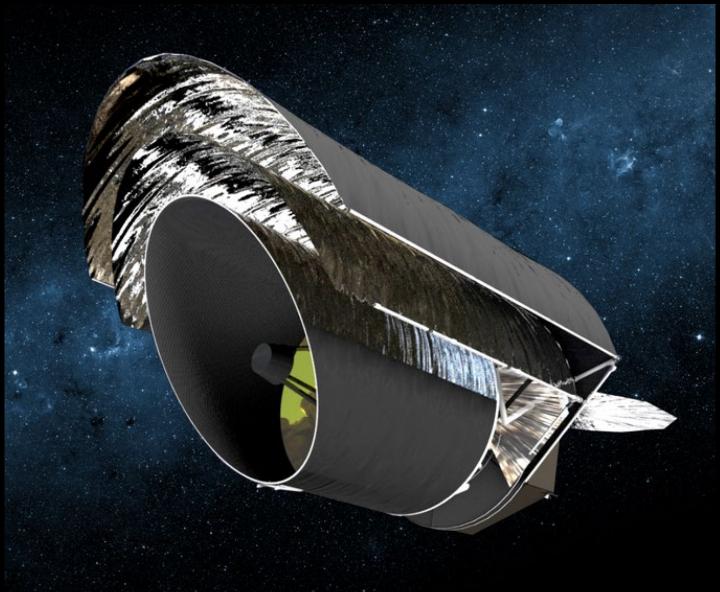


But strong push from other communities for limited resources

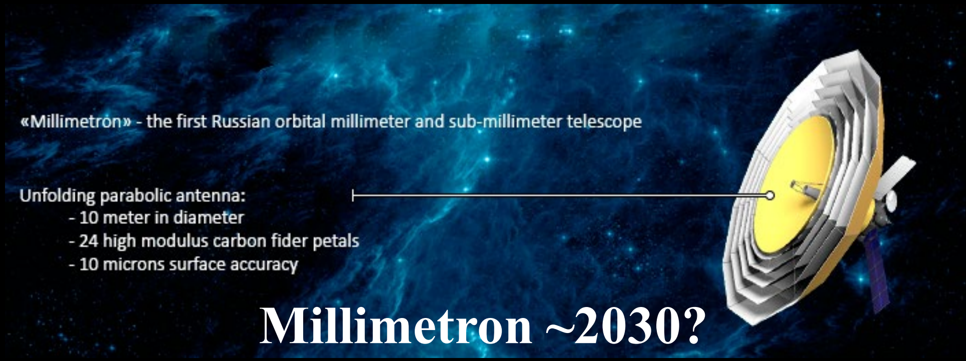
Future of mid-far infrared?



SPICA ~2030?



Origins Space Telescope ~2035-2040?



Millimetron ~2030?

Need to start making case now for flagships to be launched ~2050!

Need for 'laboratory' astrophysics

- **Spectroscopy**
- **Collisional rate coefficients**
- **Ion-molecule, neutral-neutral reactions**
- **Photodissociation, photoionization**
  - **Also branching ratios!**
- **Solid-state, ice chemistry**
- **Dust formation, dust growth**
- **Sample analysis**
- **….**

Keep up the good relations astronomy – chemical physics!

Astrochemical models challenge

- Continued progress in gas-grain models
- Black box vs understanding critical reactions
- Will 'deep learning' / artificial intelligence help or hurt our understanding?

Observations

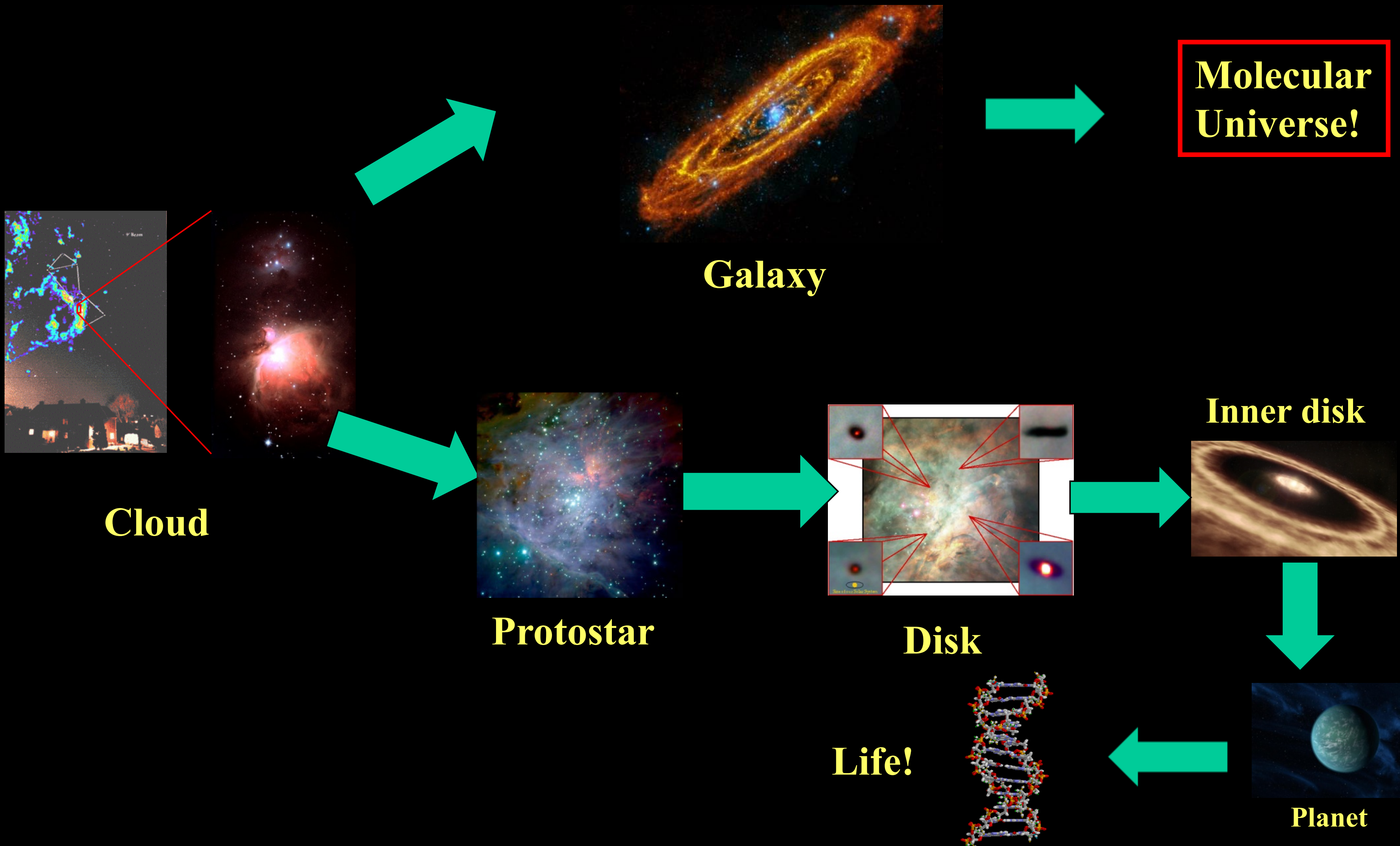
Physical parameters (*n*, *T*, *I*, *ff*, ...), Chemical abundances

Answer only as good as the basic data that go into the model

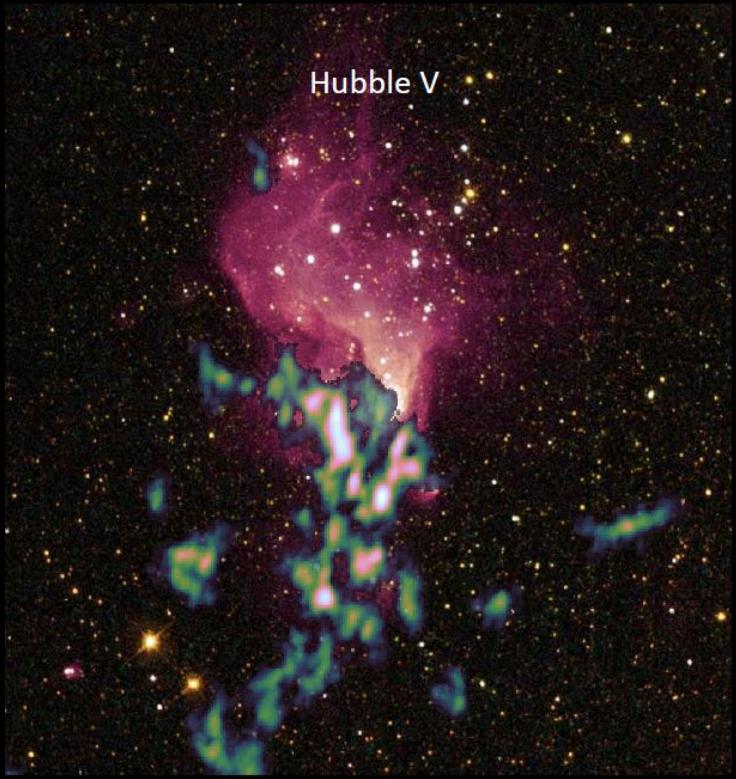
Where Xander's research started

From: CfA Harvard, Millimeter Wave Group

Zooming in and out



Extragalactic clouds at 2 pc resolution

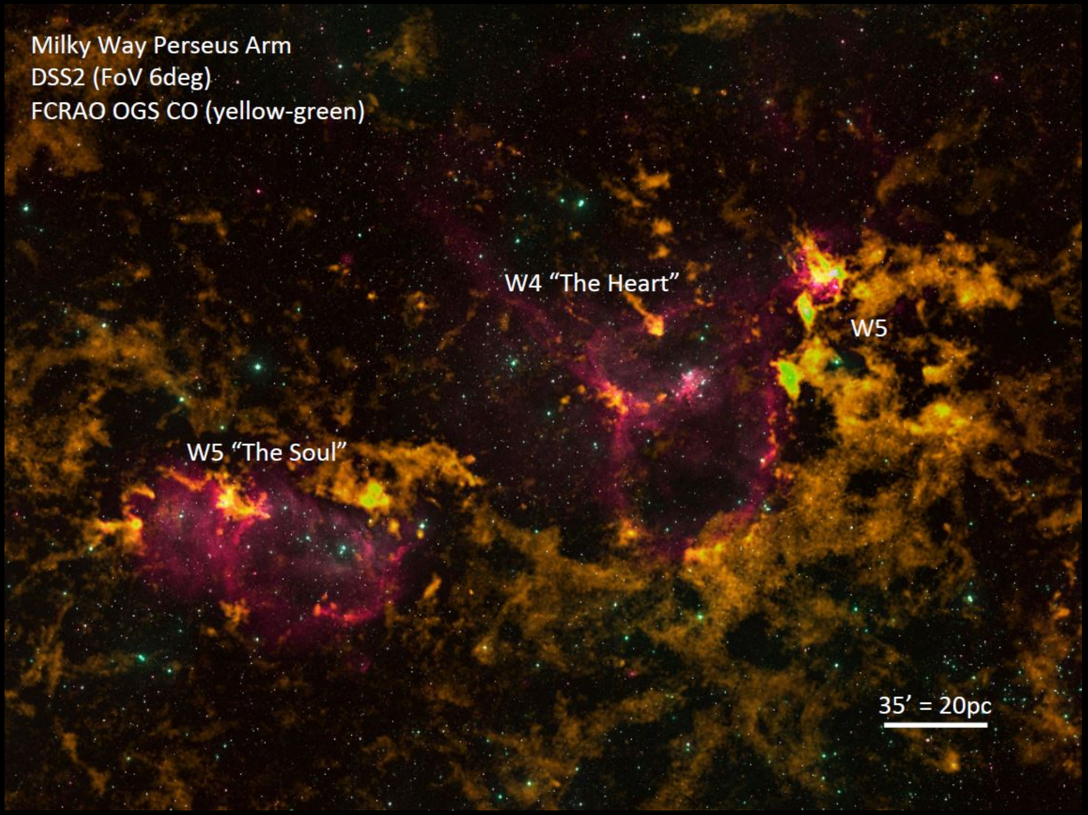


NGC 6822

Low metallicity dwarf galaxy

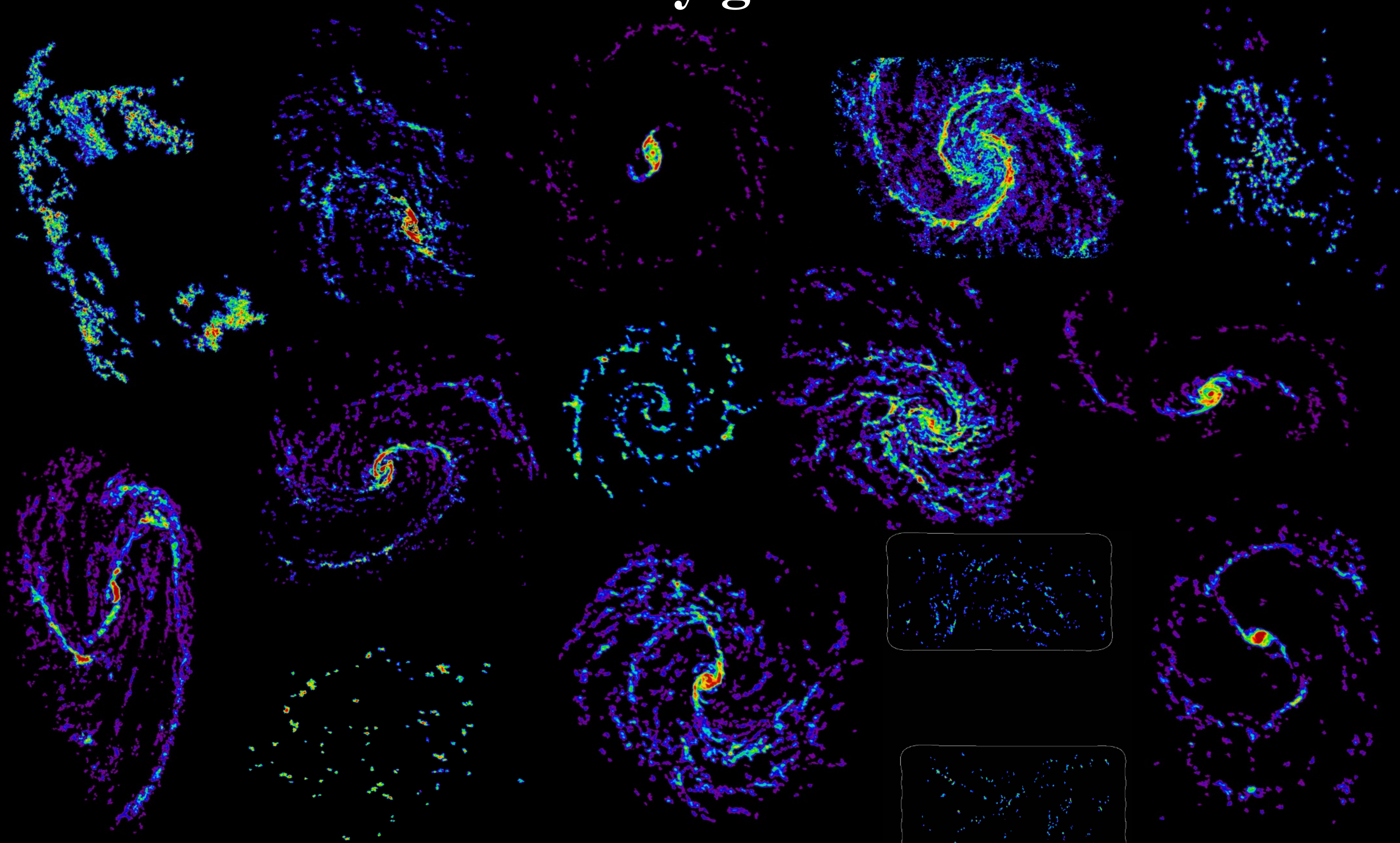
CO clouds limited to only the densest regions

Galactic



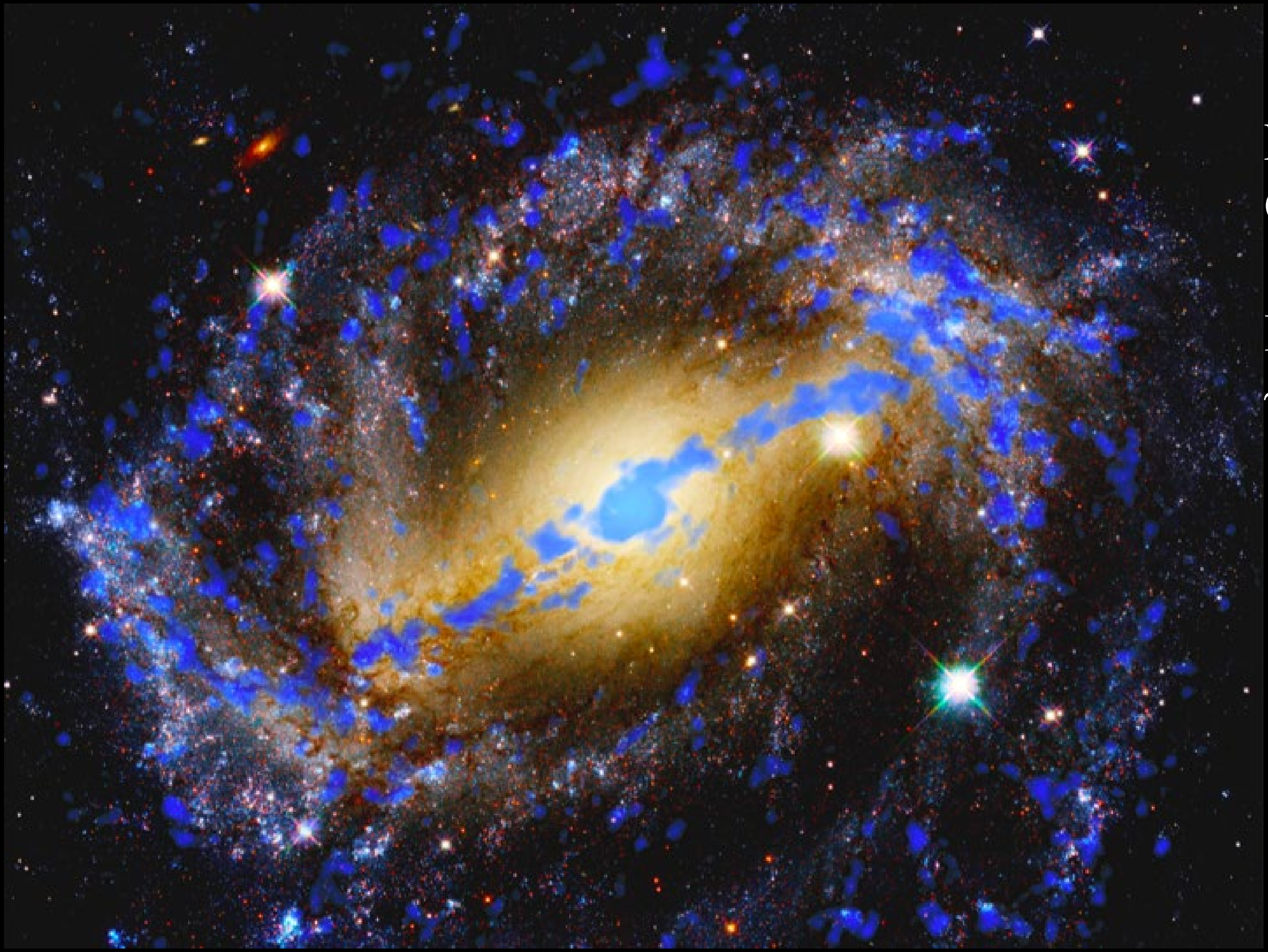
Schruba et al. 2017

Cloud-scale view of the molecular gas in nearby galaxies



‘Star Formation in Nearby Galaxies’ Collaboration

Resolving clouds in galaxies

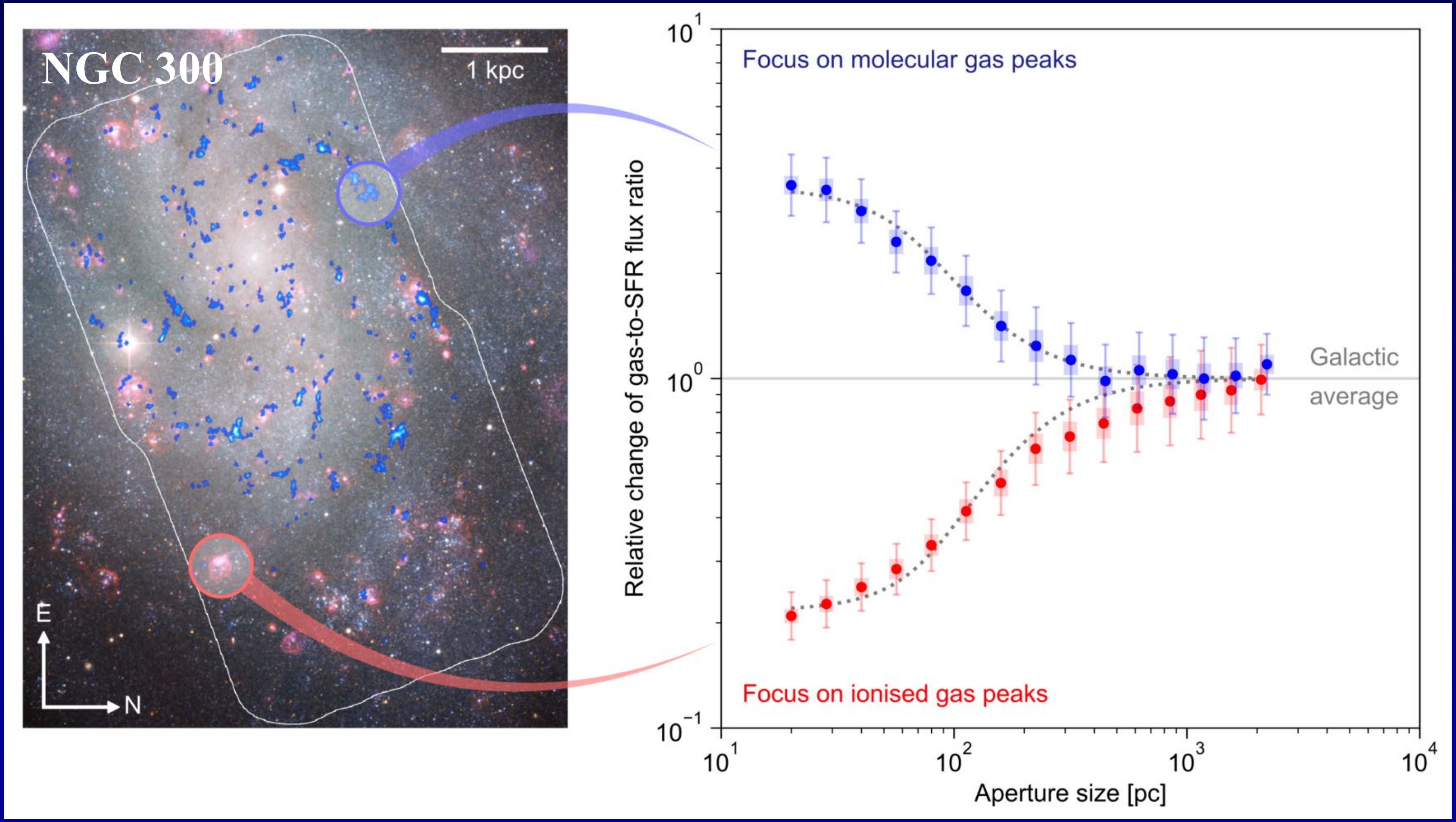


NGC 5643
Opt vs ALMA

PHANGS
~20 pc resolution

Schinnerer et al.

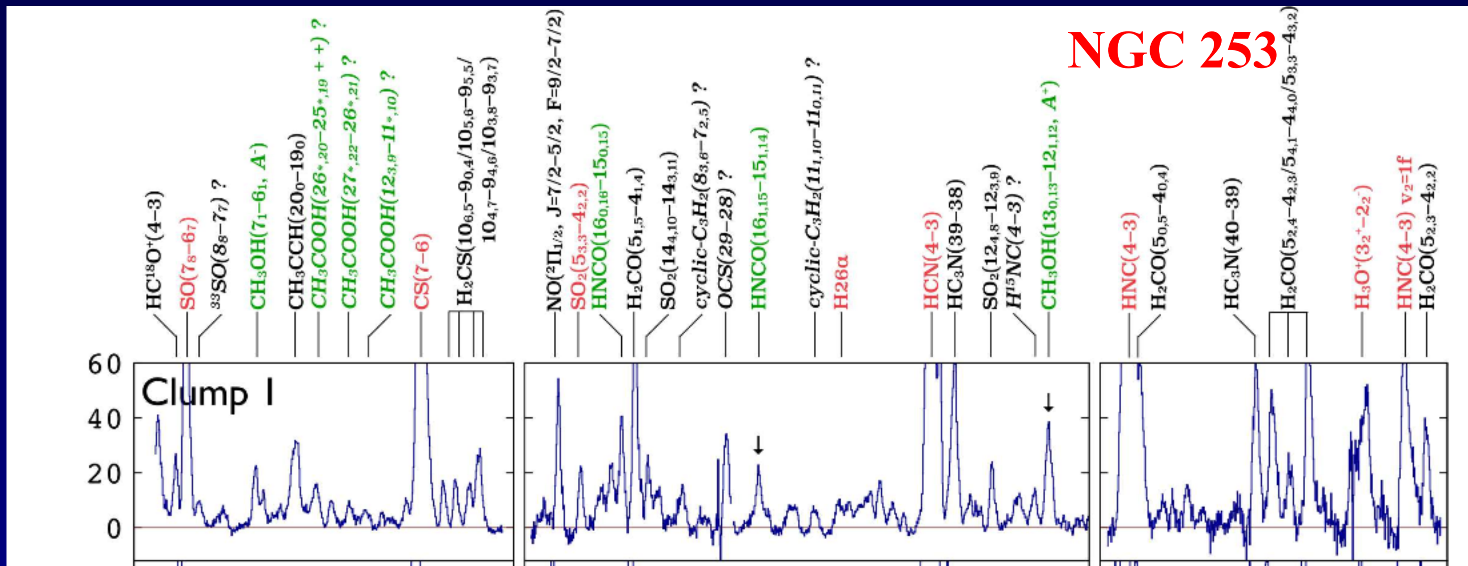
Star formation is fast and inefficient



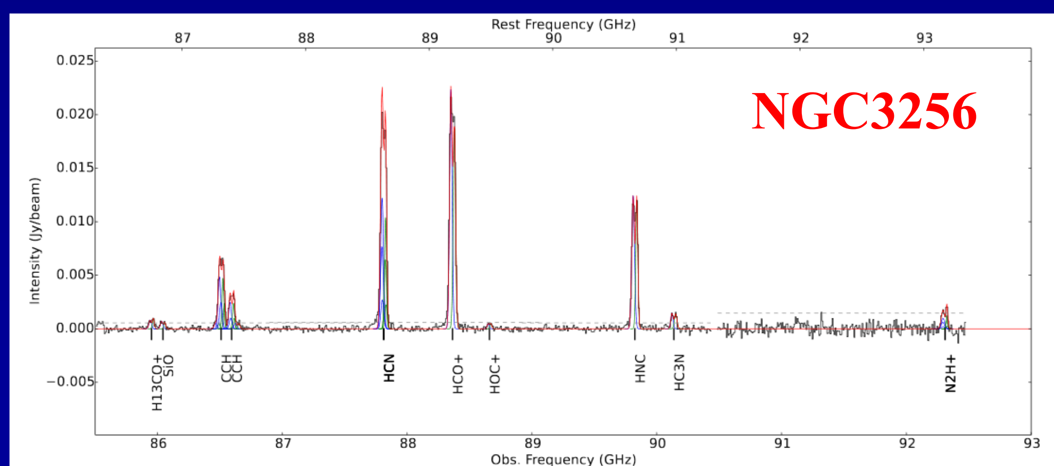
Kruijssen et al. 2019, Nature

Hα and CO peaks offset in high angular resolution ALMA data

Galactic nuclei: like Orion 40 yr ago



Ando et al. 2017



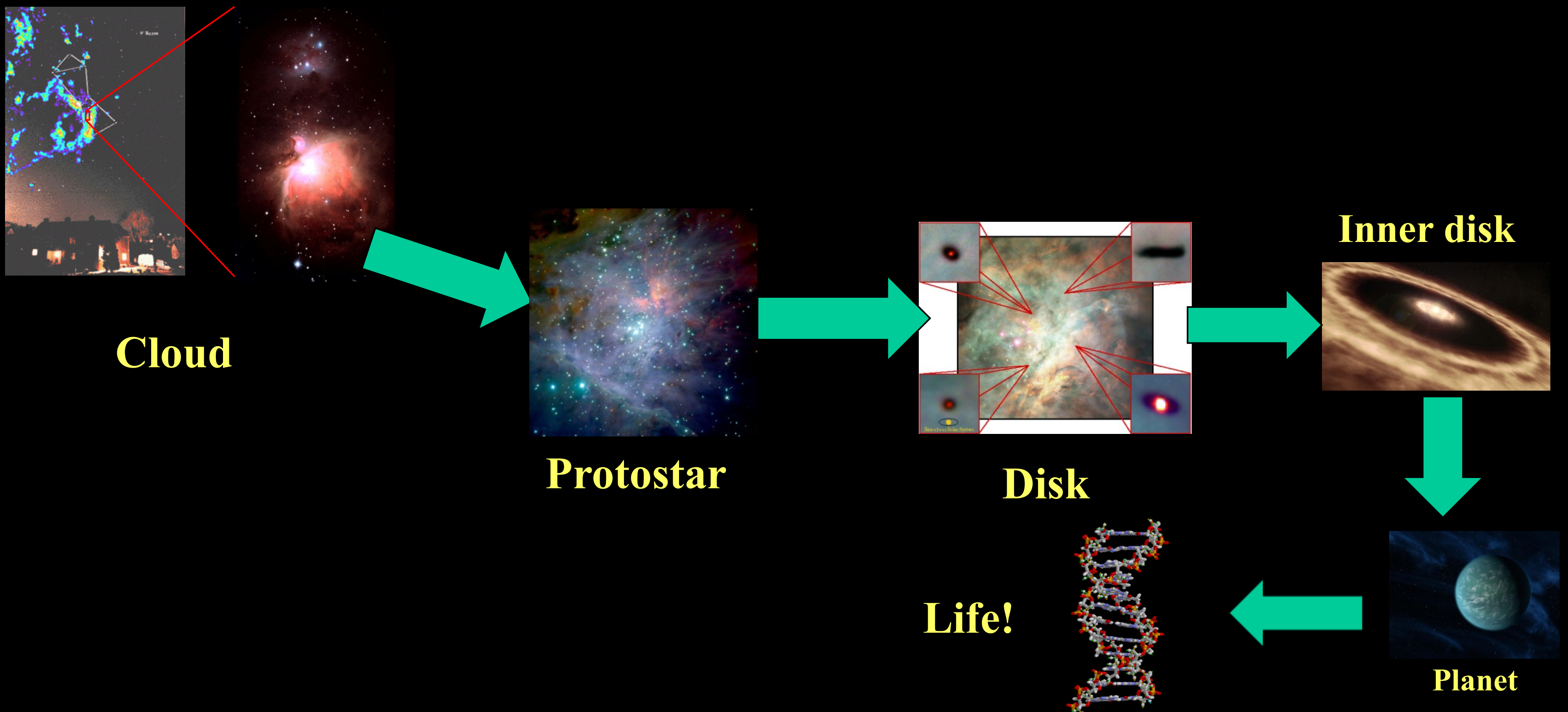
Lots to discover on 1-100 pc scales!

Harada et al. 2018

Xander pondering extragalactic chemistry

Nobel Symposium 2006

Zooming in and out



How far does chemical complexity go?

IRAS16293-2422

Source B 1 L_{Sun}
Face-on disk

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

60 AU

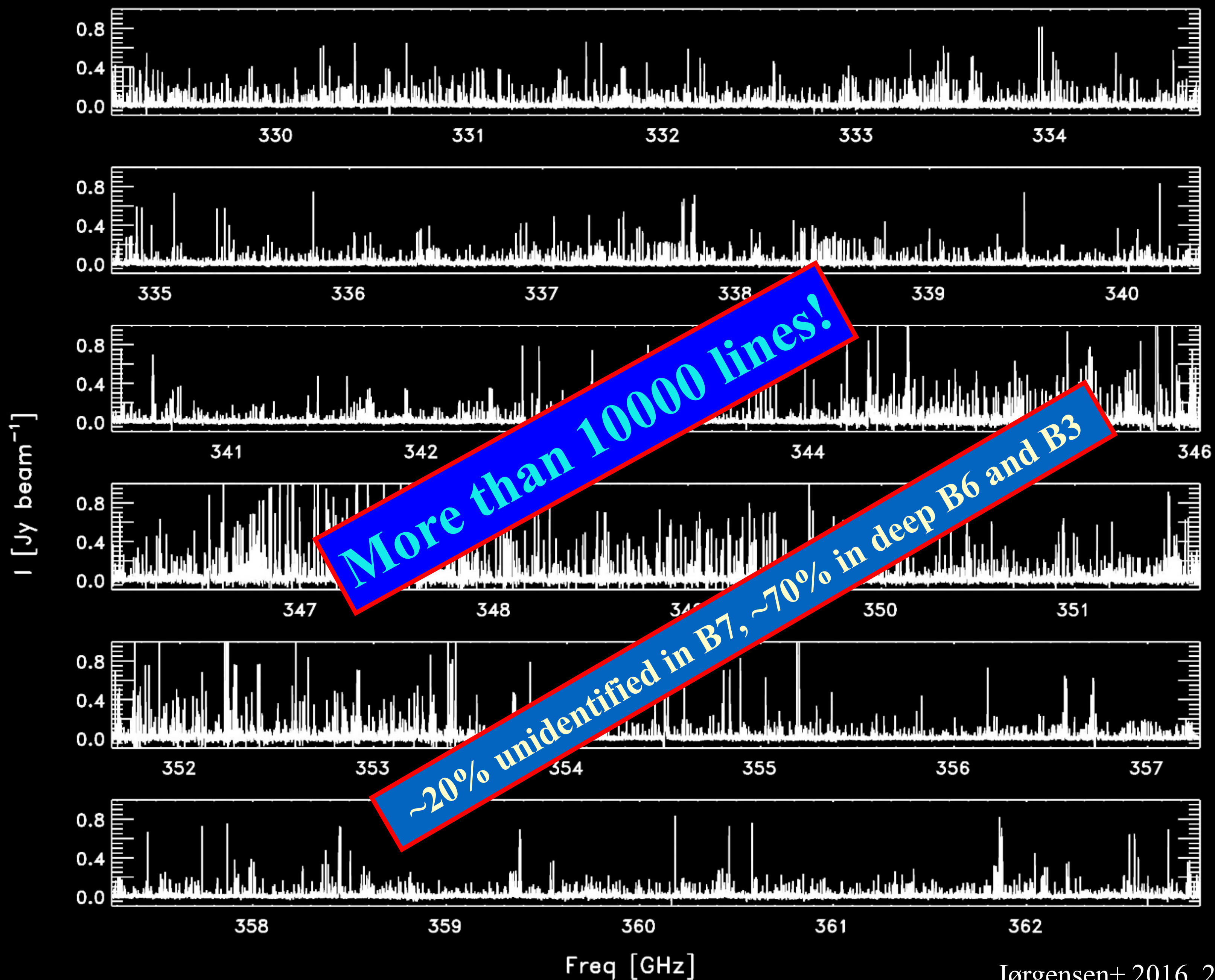
ALMA: 0.4-3 mm continuum

Protostellar Interferometric Line Survey (PILS)

PILS

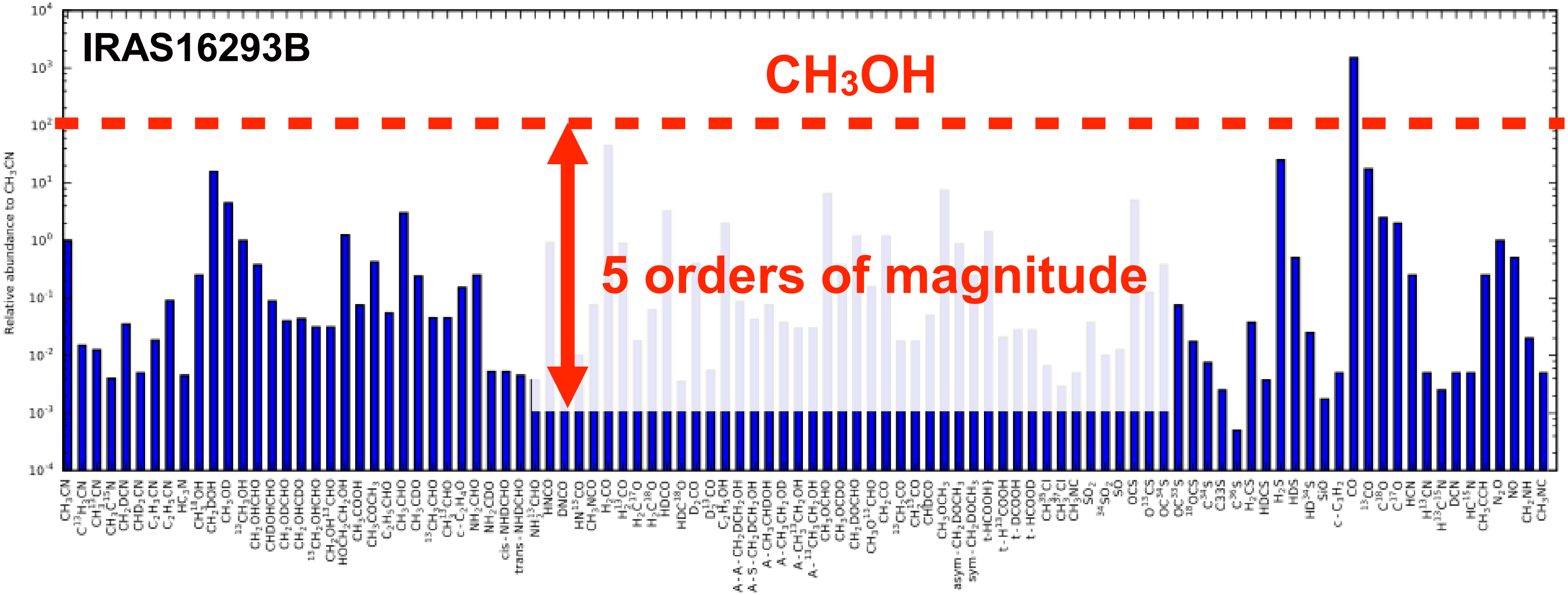
Jes Jørgensen & the PILS team

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



Jørgensen+ 2016, 2018

Protostellar chemical fingerprint on disk scales

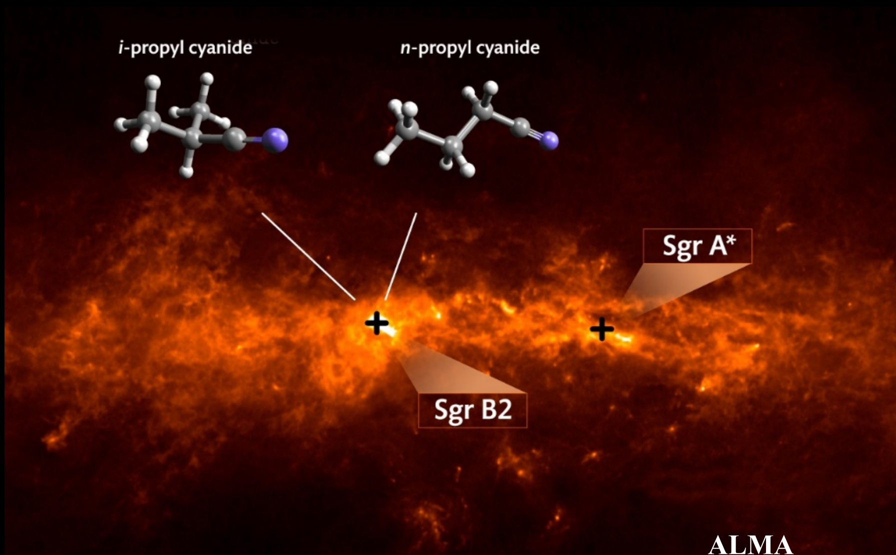


- More than 100 molecular species (including isotopologues)
- 28 new detections toward a low-mass protostars (so far)
- 17 new detections in the interstellar medium overall

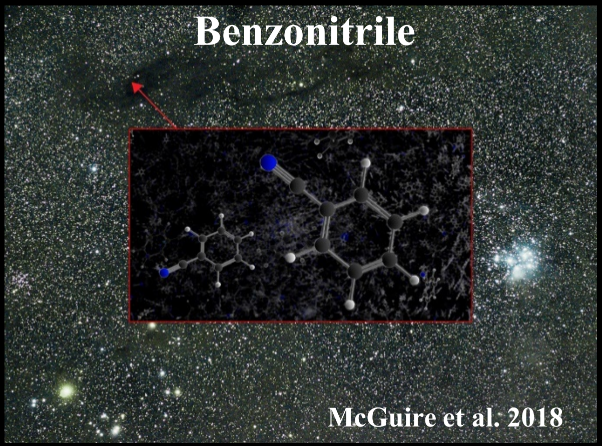
Only young 'disks' reveal chemical complexity for planet formation

Figure credit: Hannah Calcutt & Marit Fiechter

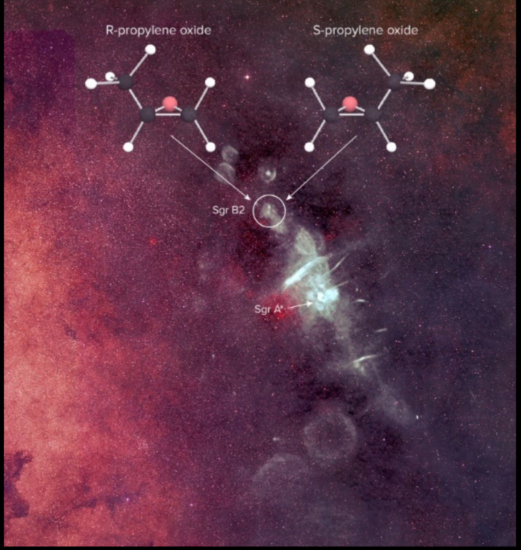
Some recent new detections

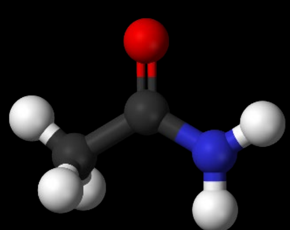


ALMA
Belloche et al. 2014



First chiral molecule





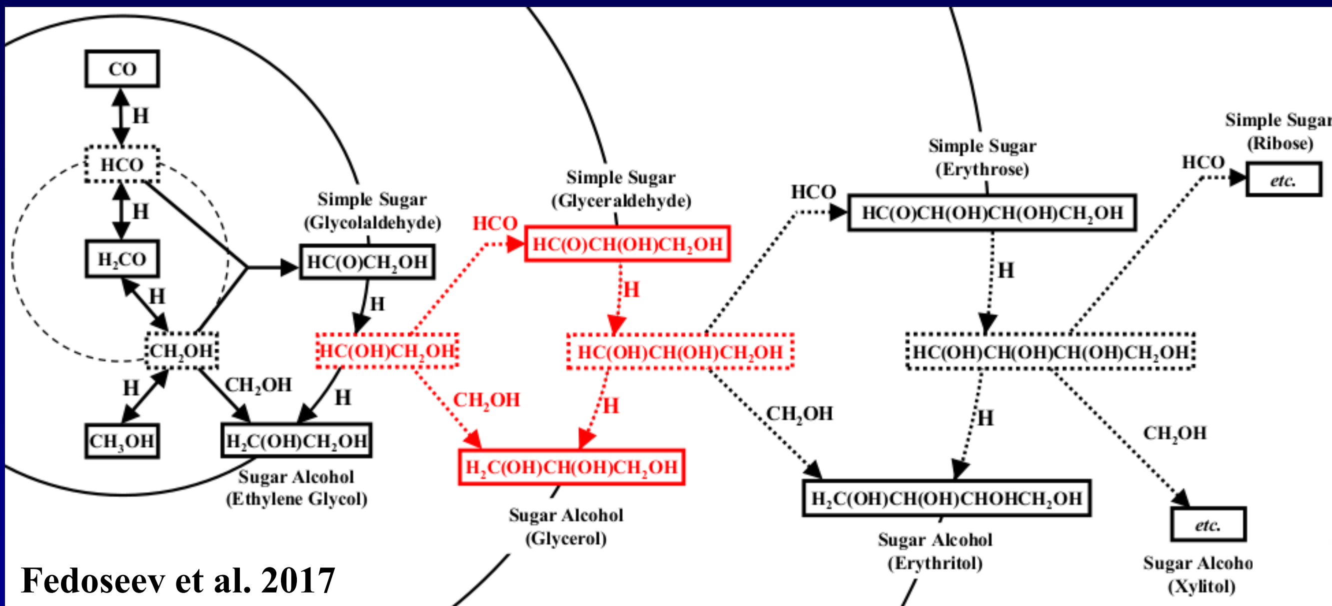
Acetamide

Belloche et al.
Ligterink et al. 2018

McGuire et al. 2016
GBT, ATCA

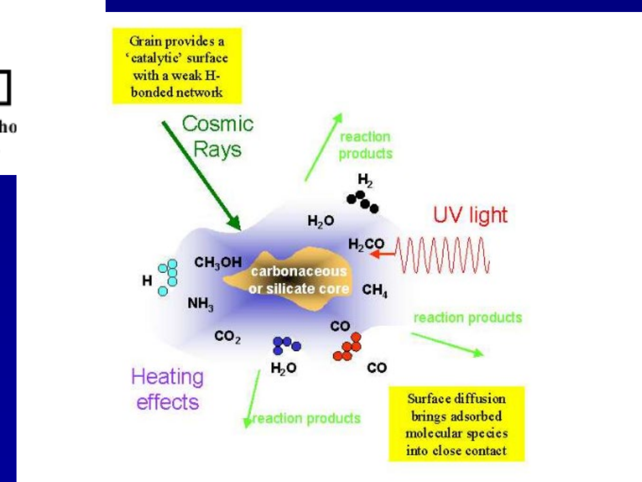
How far can complexity go?

Starting from CO hydrogenation→ Real sugars



Fedoseev et al. 2017

UV or not?



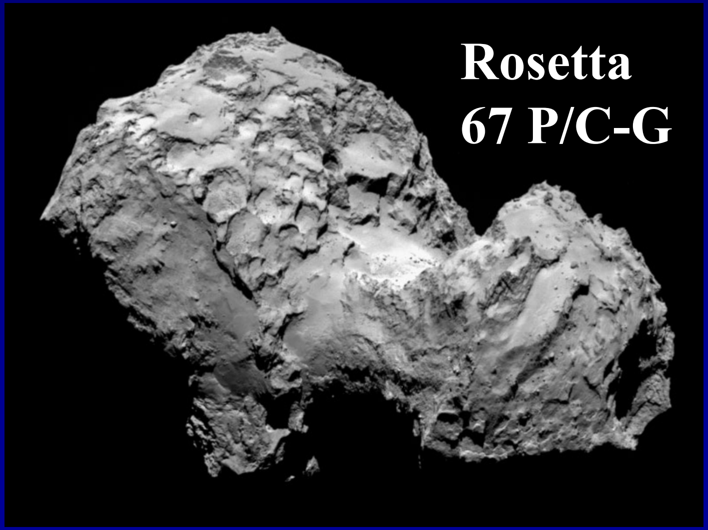
How are we going to test these schemes?
Even 3-carbon organics are hard

Many experiments around the world on UV processing of ices, ion bombardment etc., making amino acids and other complex organics

Young disk – comet comparison

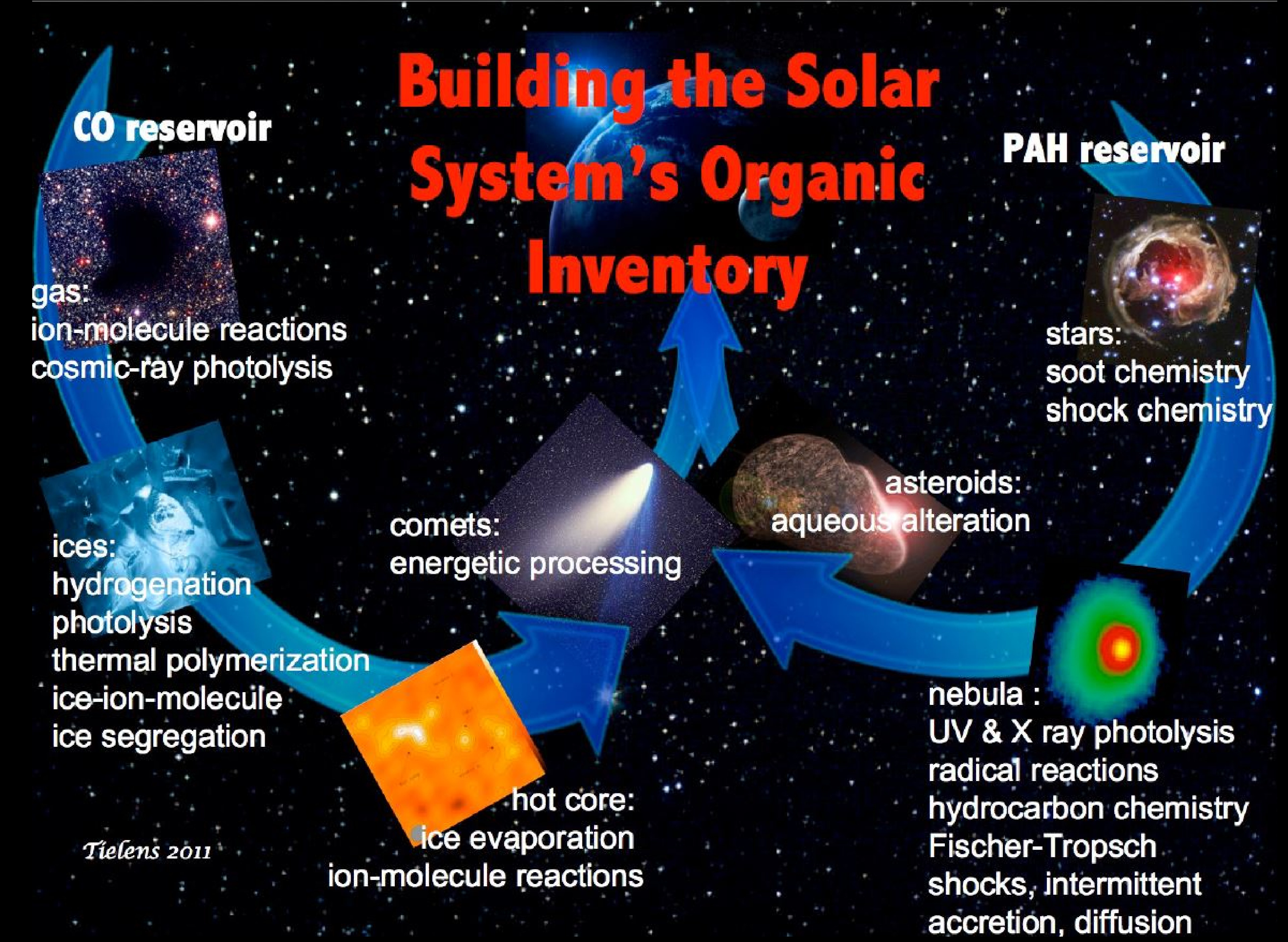
- **Young disk: observe just sublimated ices**
- **Comet: measure coma molecules *in situ***

NASA/Caltech/SSC R. Hurt animation

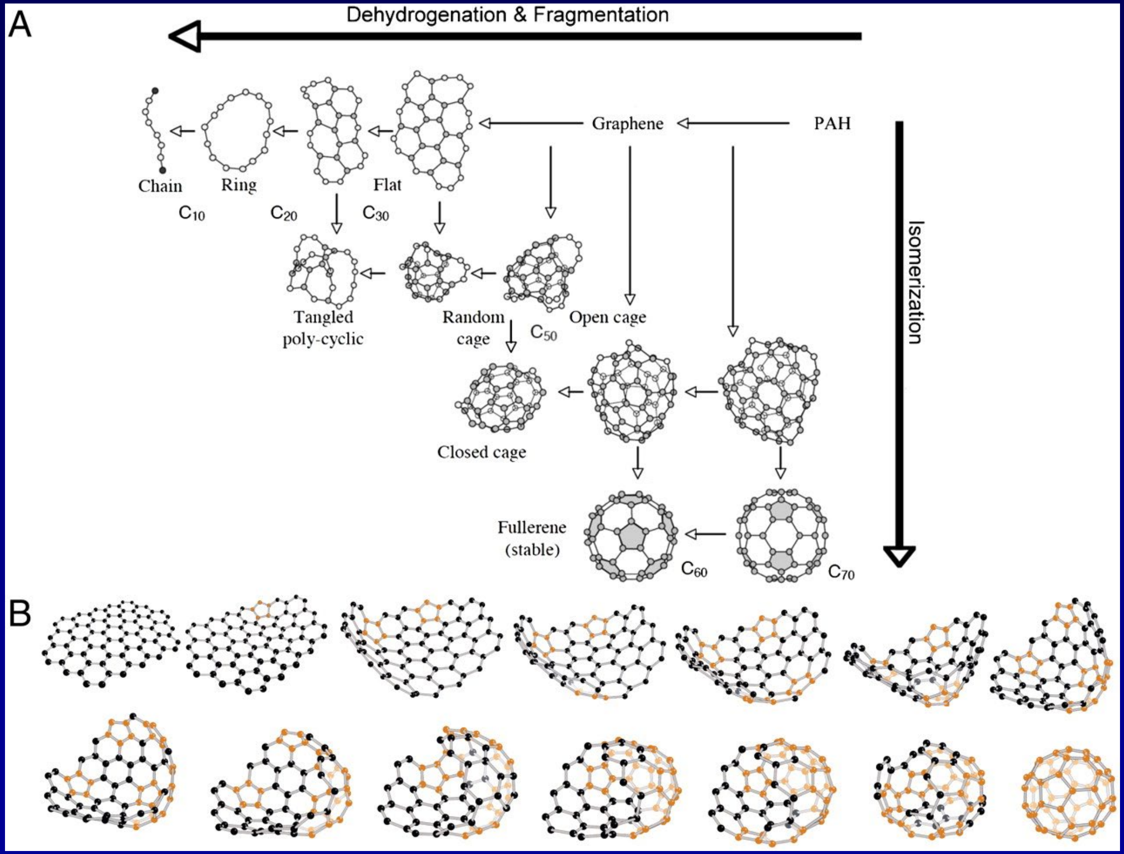


Are ices preserved from cloud to comet? Need many more samples!!

ROSINA Zoo
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
H_2N
OH
O
Glycine
(Aminoacid
S_2
S_3
S_4
Methanethiole (CH3SH)
Ethanethiol (C2H5SH)
Thioformaldehyde
(CH2S)
Ammonia
Methylamine
Ethylamine
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
Argon
Krypton
Xenon
Acetylene
HCN
Acetonitril
Formaldehyde
HF
HCl
HBr
P
CH3Cl
Benzene
Toluene
Xylene
Benzoic acid
Naphthalene
Methanol
Ethanol
Propanol
Butanol
Pentanol
Cyanogen
Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide
N≡N
Nitrogen
Oxygen
Hydrogenperoxyd
Carbon monoxide
Carbon dioxide
Na, K, Si,
Mg
Detected in IRAS16293
Upper limit
Drozdovskaya et al. 2019
Altwegg et al. 2019, ARAA

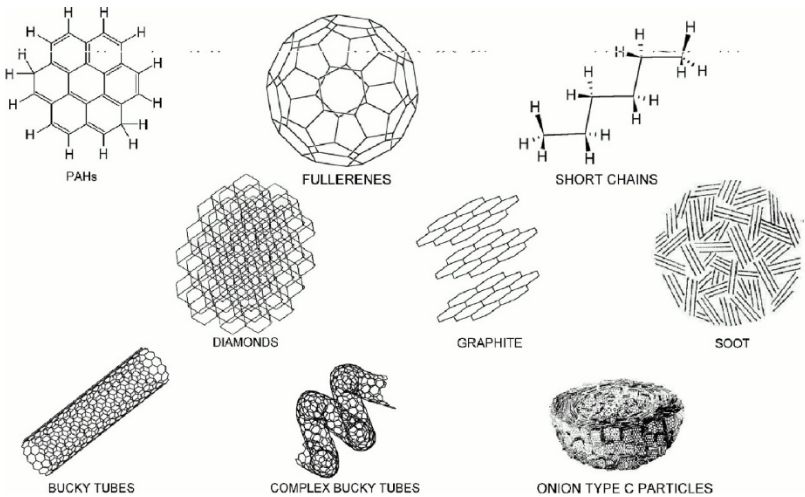

Building the Solar System's Organic Inventory
CO reservoir
PAH reservoir
gas:
ion-molecule reactions
cosmic-ray photolysis
stars:
soot chemistry
shock chemistry
asteroids:
aqueous alteration
comets:
energetic processing
ices:
hydrogenation
photolysis
thermal polymerization
ice-ion-molecule
ice segregation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

Top down formation
From PAHs to C_{60}

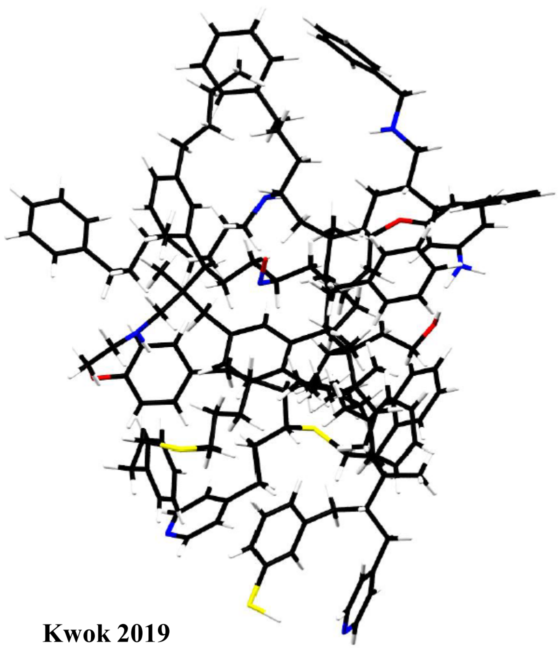


Berné & Tielens 2011
Zhen, Castellanos et al. 2014

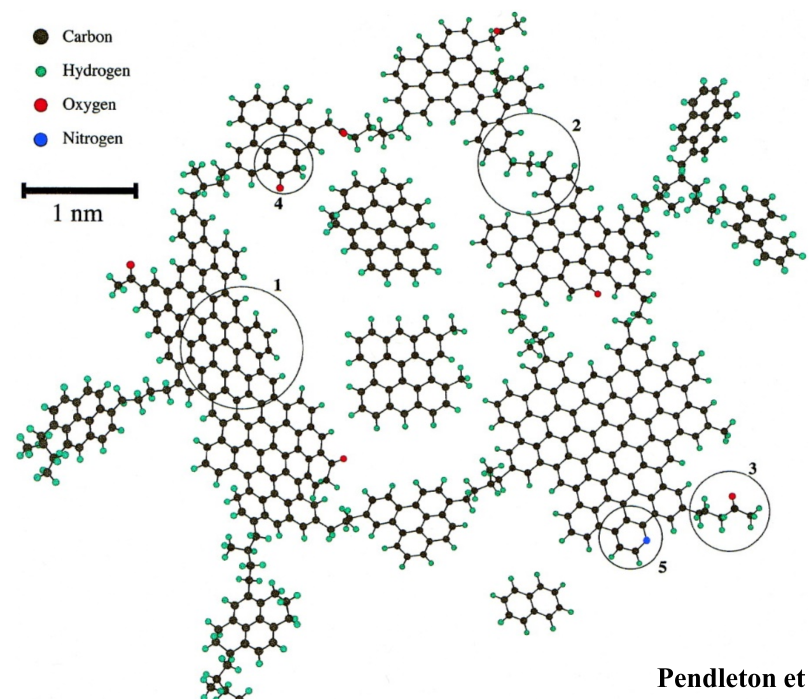
Solid carbonaceous material



Tielens



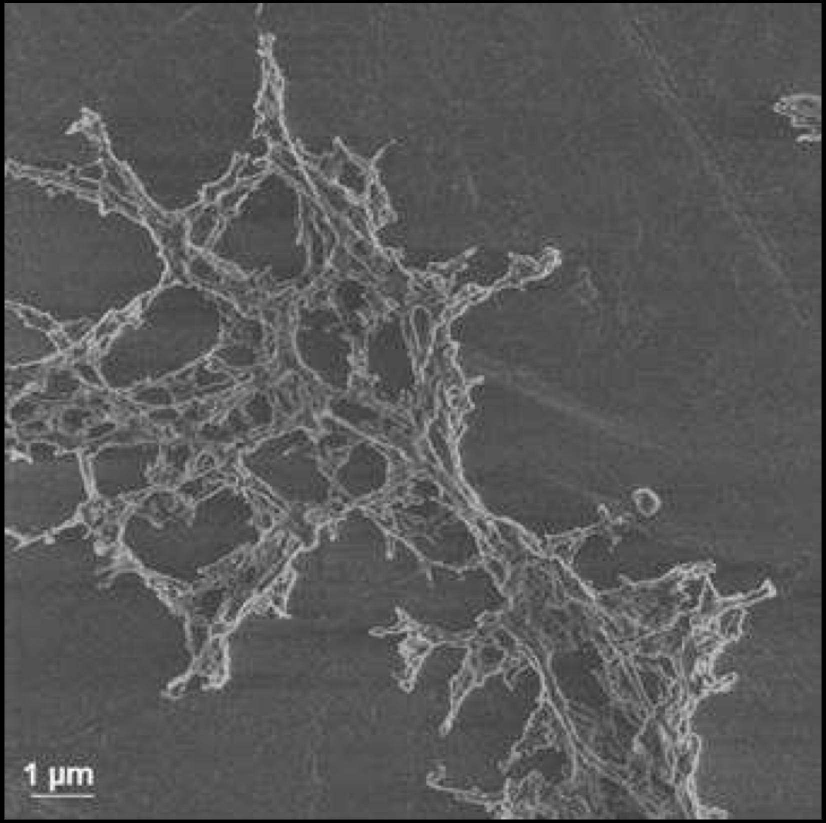
Kwok 2019



Pendleton et al. 1999

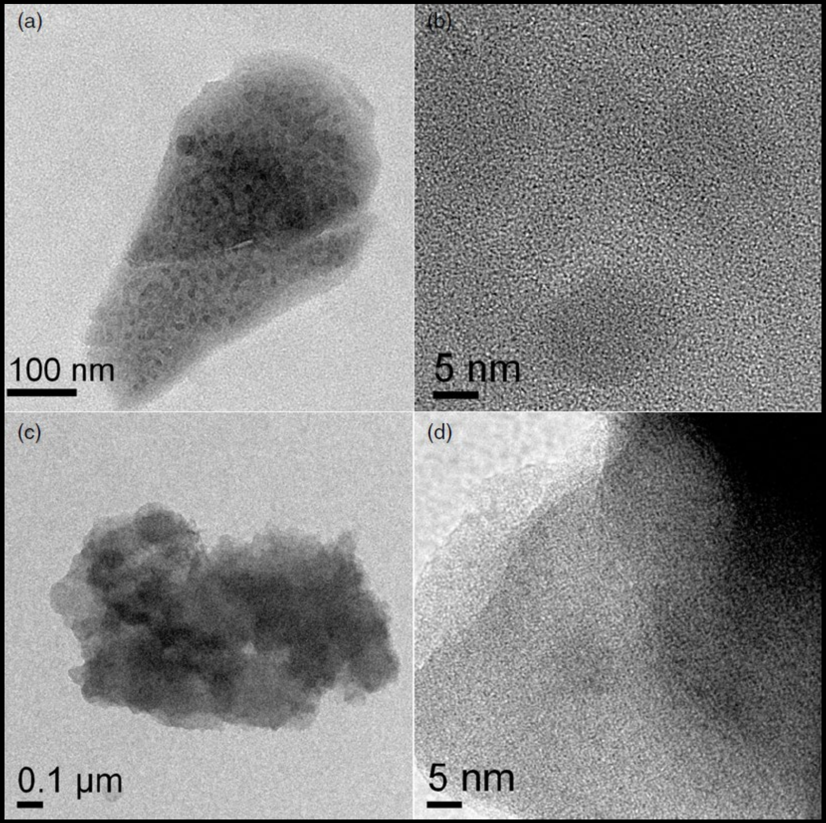
Making grains in the ISM

Carbonaceous grains



Fulvio et al. 2018

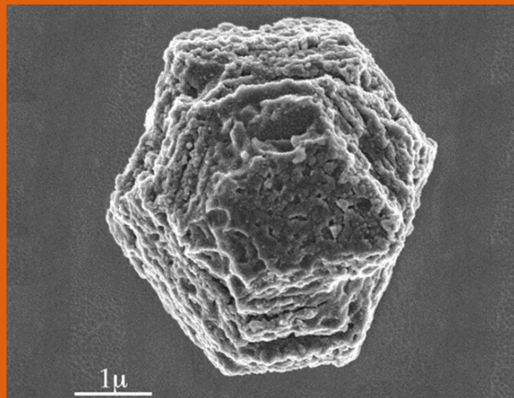
Silicate grains



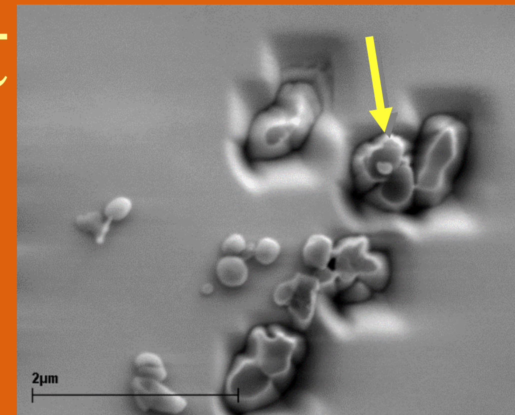
Krasnokutski et al. 2014: SiO polymerization barrierless

Will take many more decades to understand dust formation + destruction

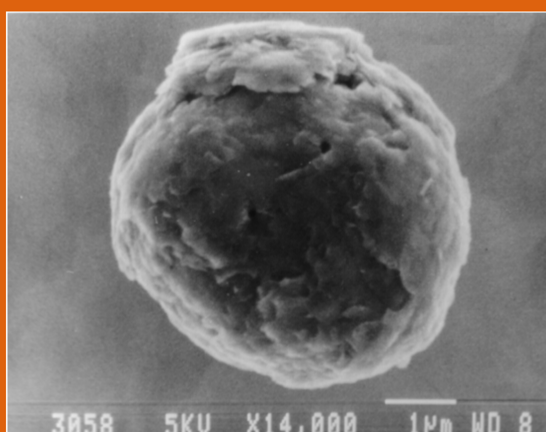
Stardust



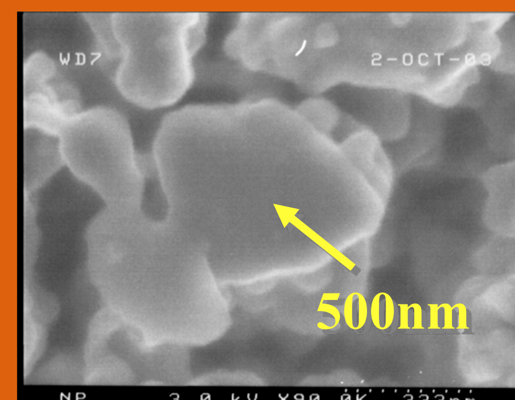
Silicon carbide grains: all are of stellar origin



Spinel grains: only ~2% are of stellar origin



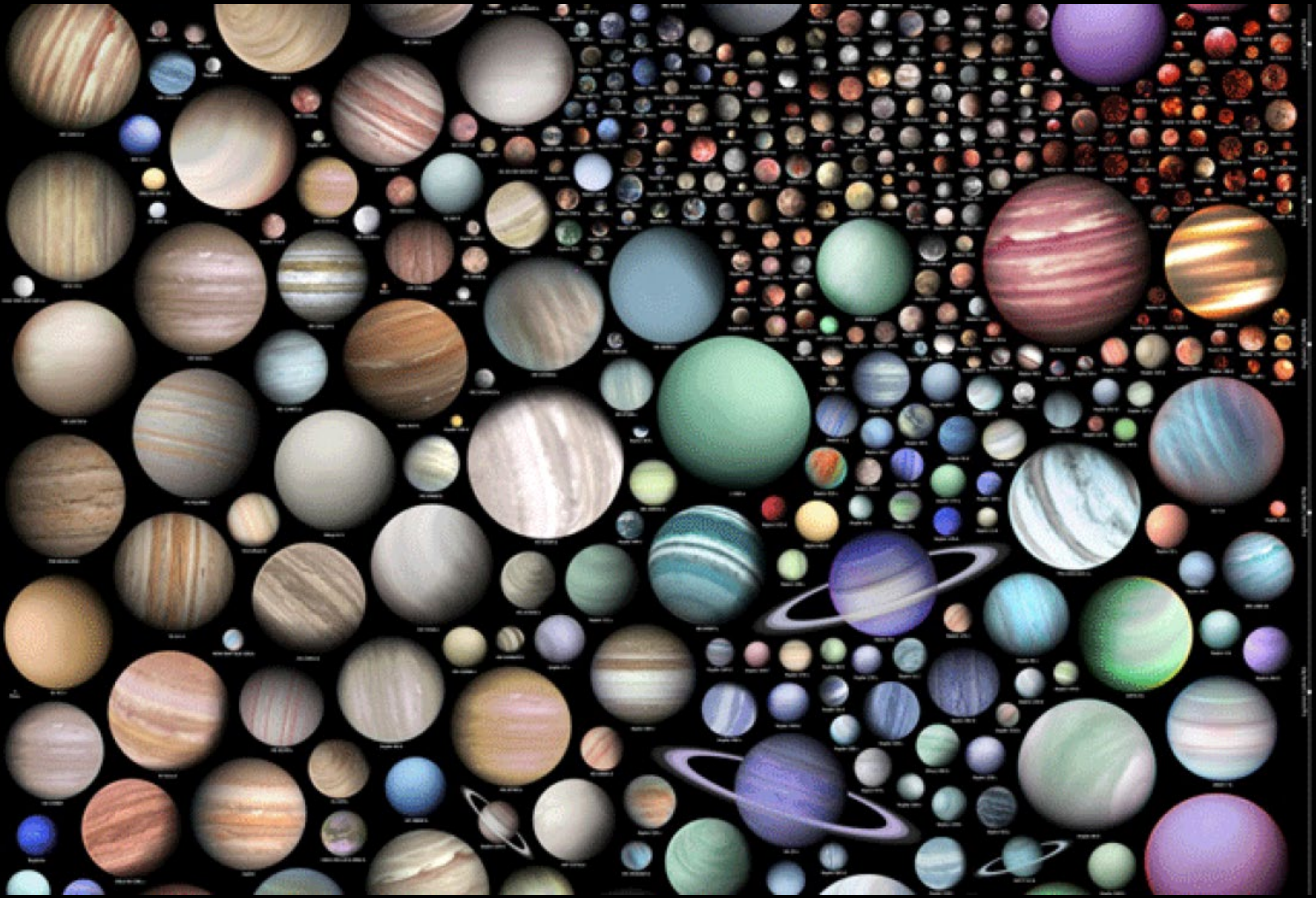
Graphite grains: approximately half of them are of stellar origin



Silicate grains: only 0.001-0.02% are of stellar origin

L. Nittler, E. Zinner

Exoplanet zoo



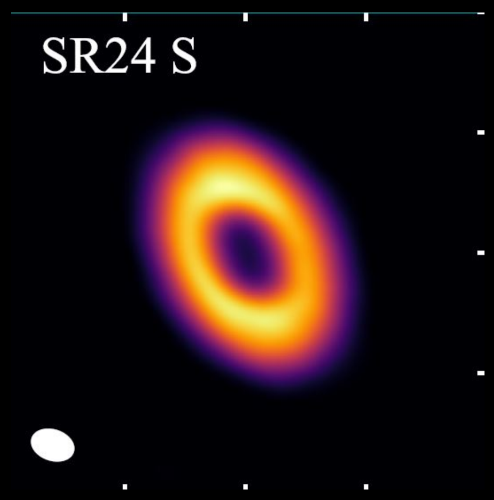
Kepler: Borucki et al. 2011, Batalha et al. 2013

~4000 exoplanets detected; many super-Earths, mini Neptunes. Why?

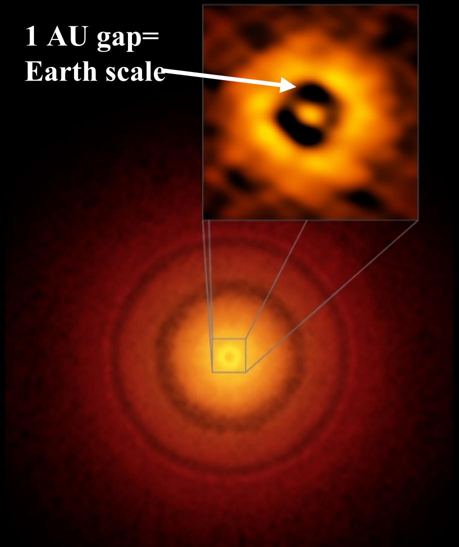
New era of observational planet formation

Next step: gas, chemistry
JWST: inner disk; ALMA: outer disk

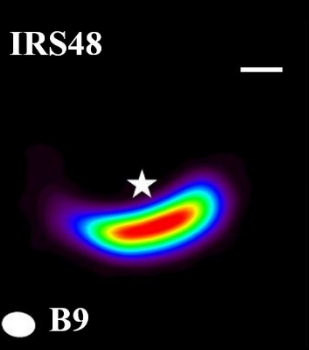
HL Tau young disk
ALMA partnership
et al. 2015



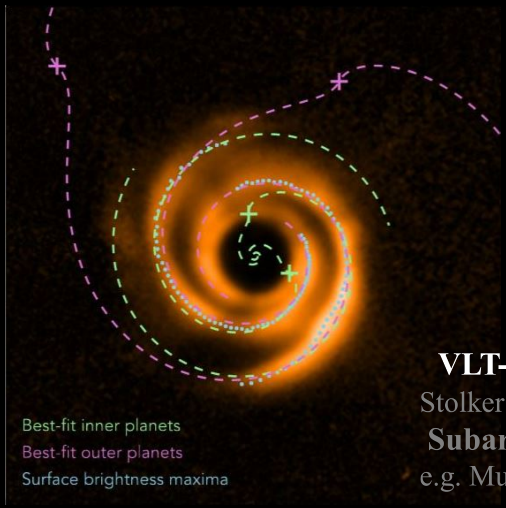
ALMA: Pinilla et al. 2017



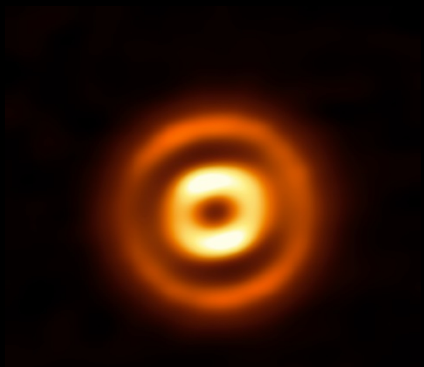
ALMA TW Hya
Andrews et al. 2016



ALMA: van der Marel et al. 2013, 2016

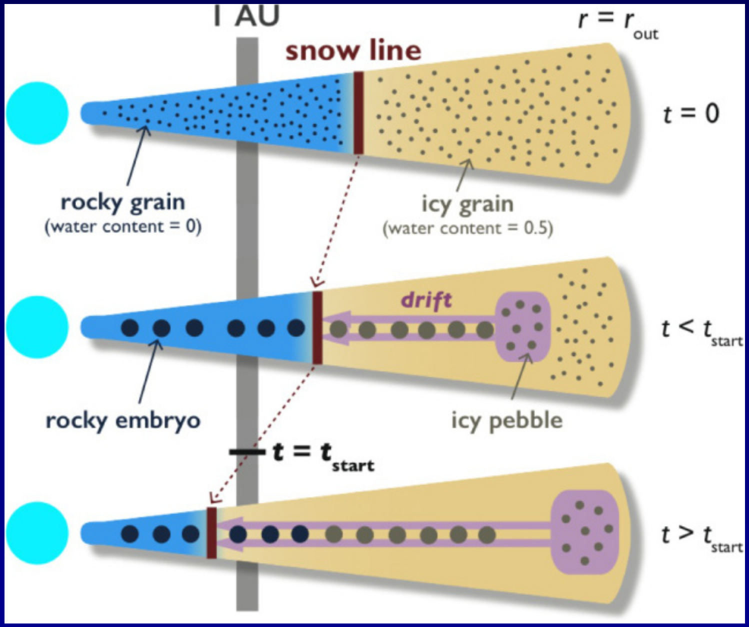


VLT-Sphere
Stolker et al. 2016
Subaru-SEEDS
e.g. Muto et al. 2012



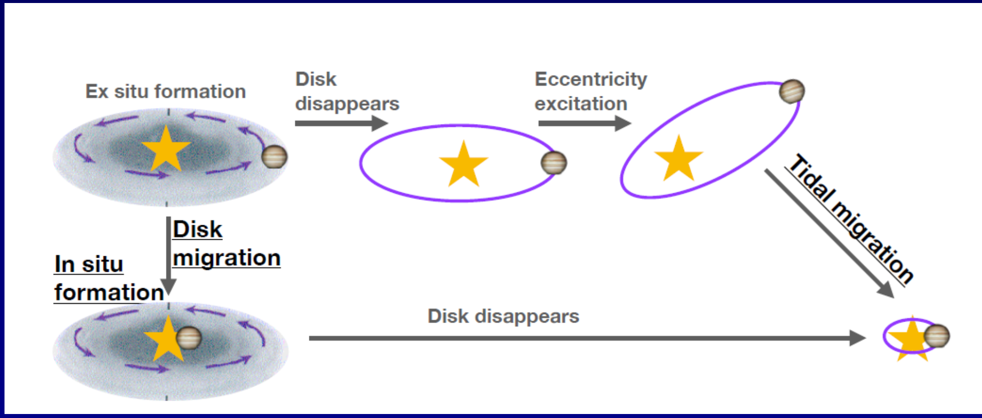
ALMA:
Fedele et al. 2017

Can we link planetary atmosphere composition with its formation location / history?



Sato et al. 2016, Cridland et al. 2019

Origin hot Jupiters

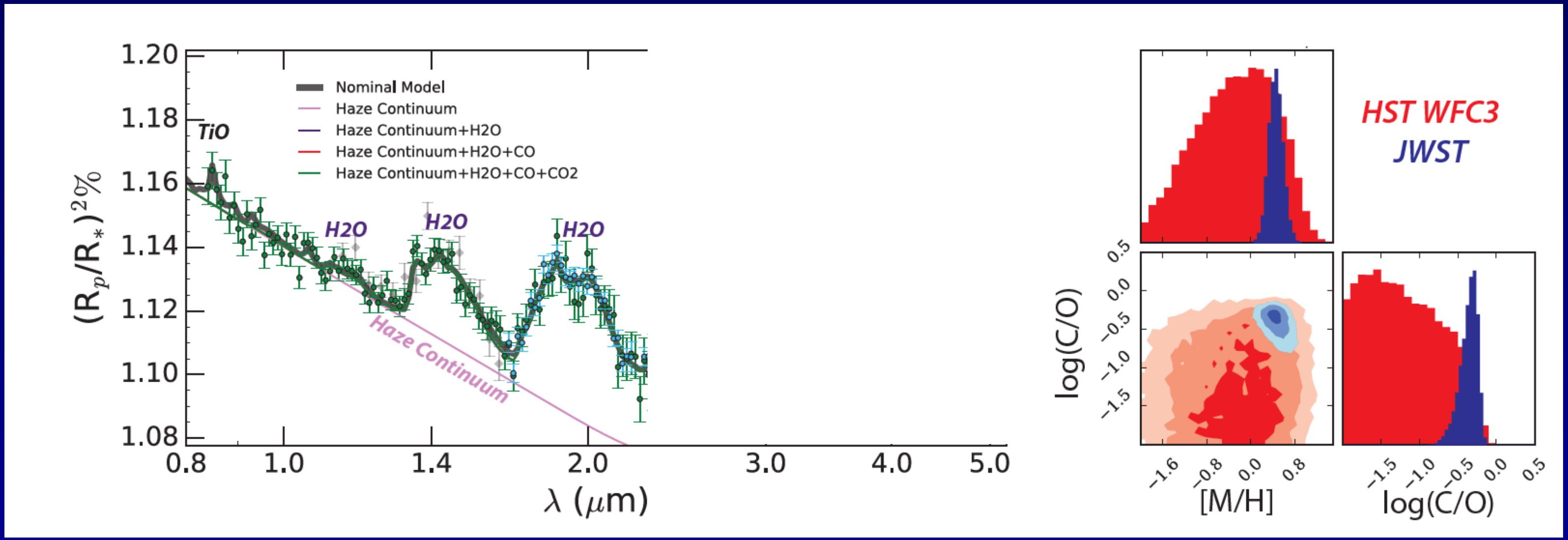


Dawson& Johnson 2018

- Radial drift pebbles, dust traps, diffusive mixing
- Migration planets
- Reset chemistry in inner disk (inside snow lines)
- Reset chemistry in planetary atmospheres→ preserve C/O, C/N, C/H, ….?

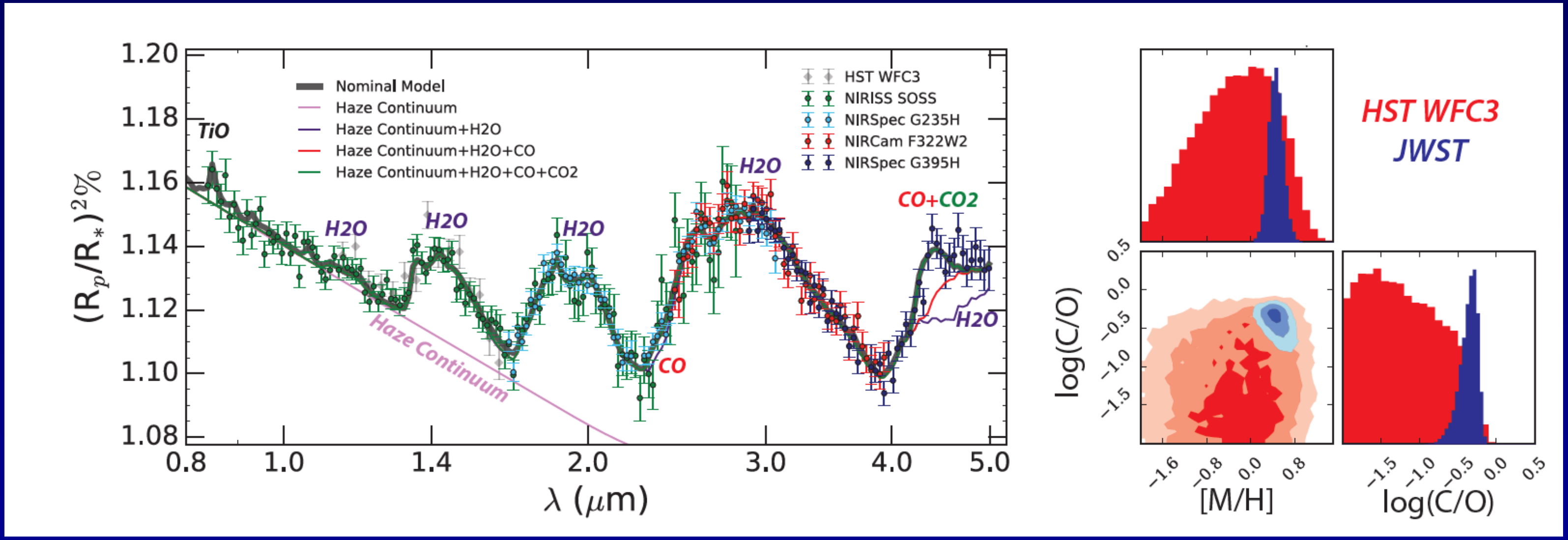
New era of exoplanet atmosphere characterization

Importance of broad wavelength coverage



Bean et al. 2017

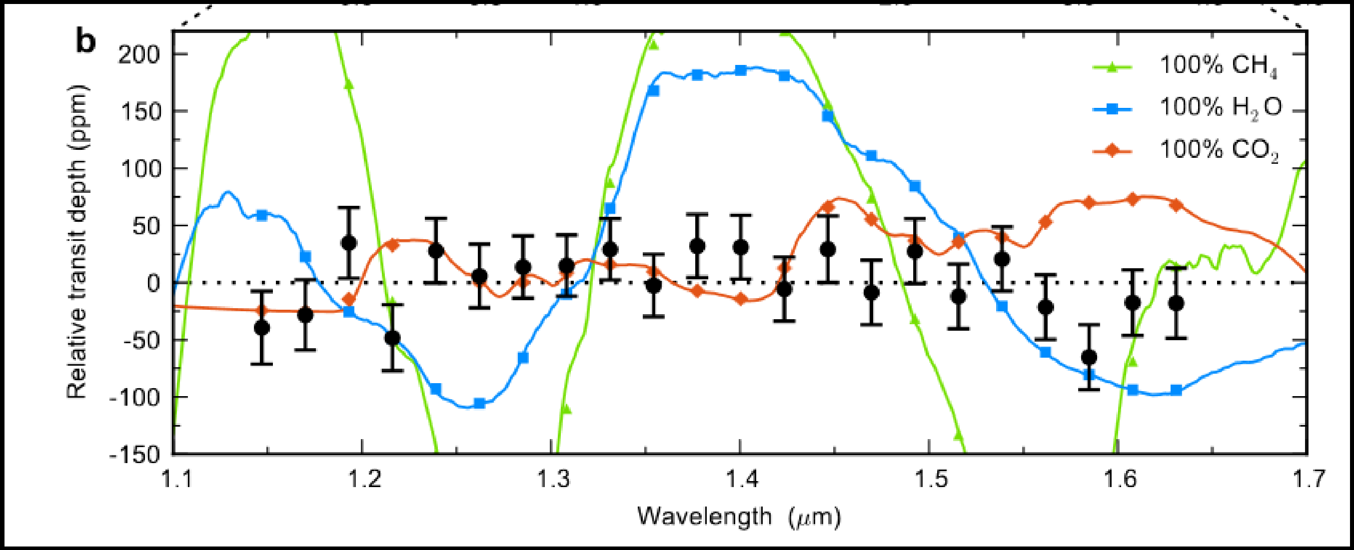
Transmission spectroscopy
Importance of broad wavelength coverage



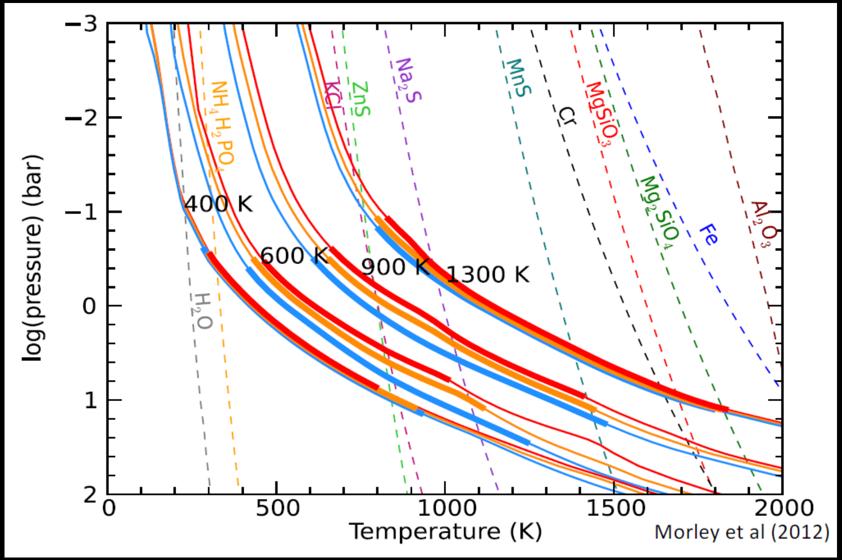
Bean et al. 2017

- Much more accurate retrieval of C/O with JWST

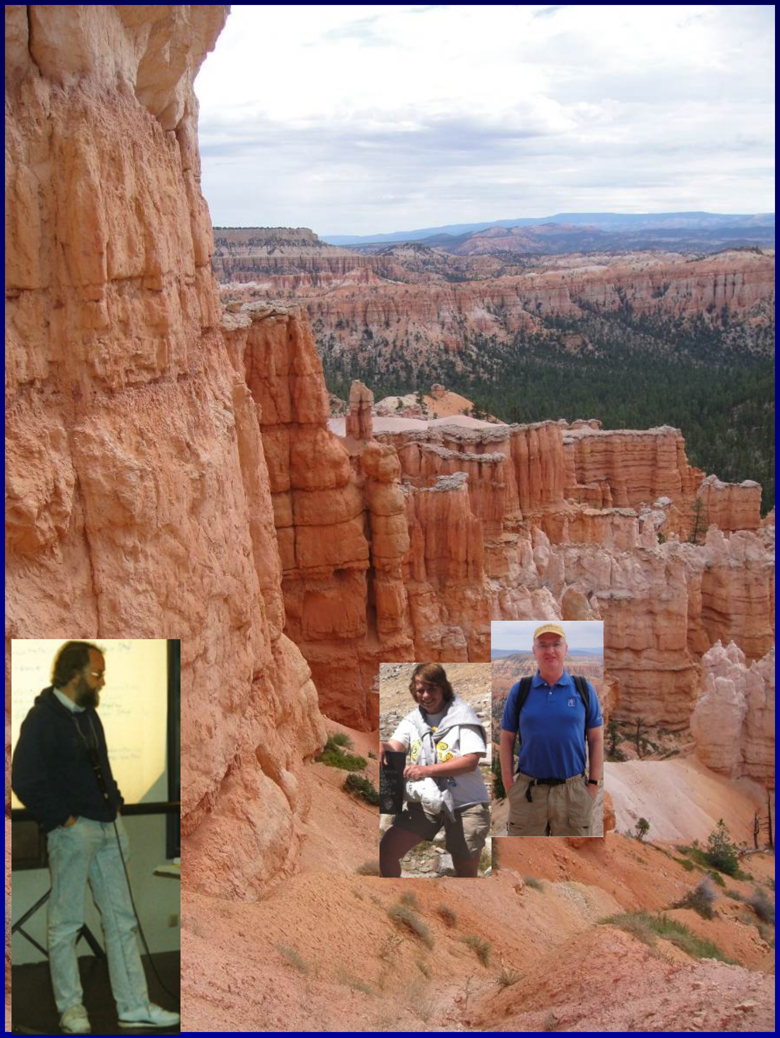
But: clouds and haze



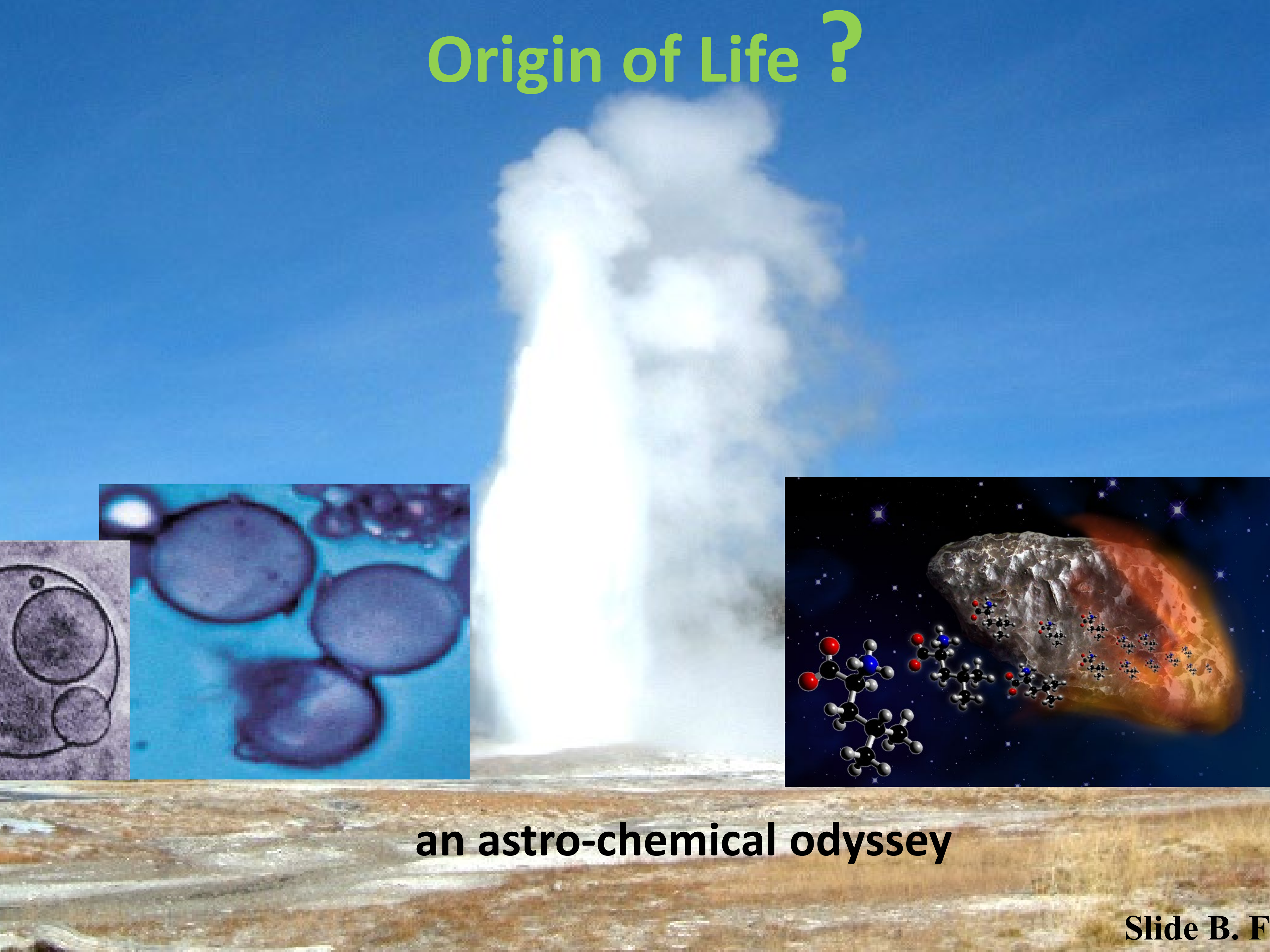
Kreidberg et al. 2014



Enjoying the western US nature



Bryce NP 2012


Origin of Life ?
an astro-chemical odyssey
Slide B. F

A new paradigm!

Two nearby lakes: different evolution

Near Mammoth Lakes

How to make progress: Working together

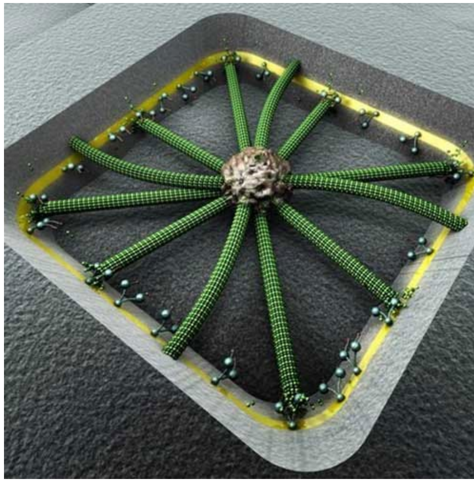
ORIGINS CENTER

Origin and co-evolution of earth-like planets and life

Building and directing life from molecule to biosphere

Disciplines

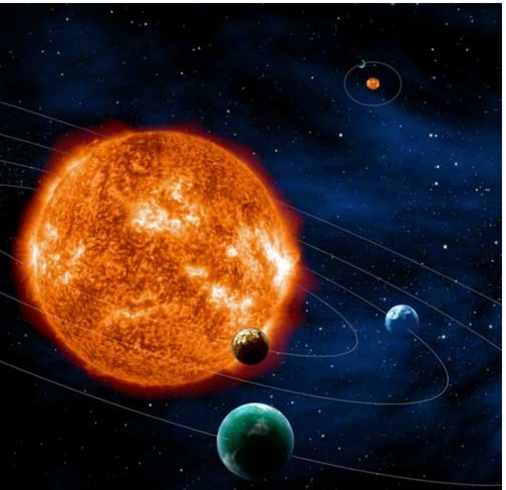
astronomy, biophysics, chemistry, ecology, evolution, mathematics and computational science, molecular biosciences, planetary and geosciences.



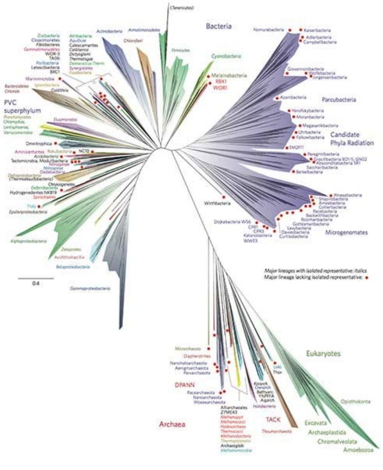
Finding extraterrestrial life

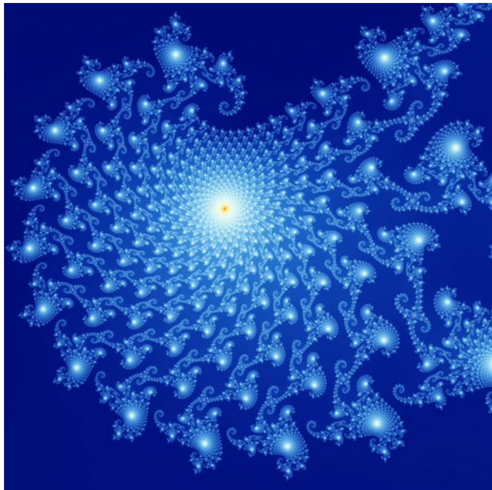
Predicting evolution

Bridging long temporal and spatial scales



Slide B. Feringa





Astrochemistry: the next 40 years

Thanks Xander, for pointing and paving the way,
and shaping the field!