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A new perspective of Solar System science with close collaboration with Astronomy

Shogo Tachibana

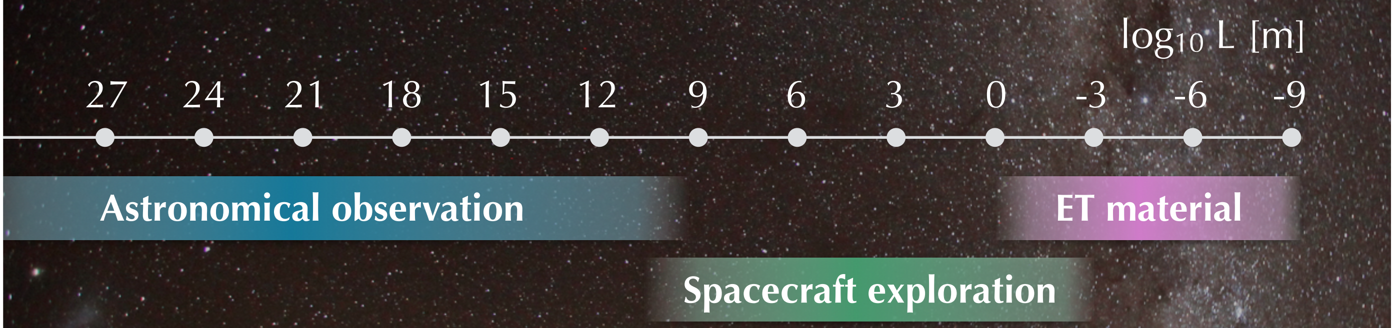
UTOPS, U. Tokyo / ISAS, JAXA

1. **Solar System science explores the formation and evolution of the Solar System** incl. the life on the Earth, which is **a part of the evolution of the Galaxy**

2. Many of celestial bodies in the Solar System are **reachable by spacecraft** that provide geophysical and geochemical information of the bodies and even **samples** for us

3. **Extraterrestrial materials** incl. the samples returned by spacecraft tell what happened in their parent bodies and/or in the Solar System (*in case of meteorites, we even do not what the parent bodies were!*), but do **not tell in detail how the Solar System architecture formed at the beginning**

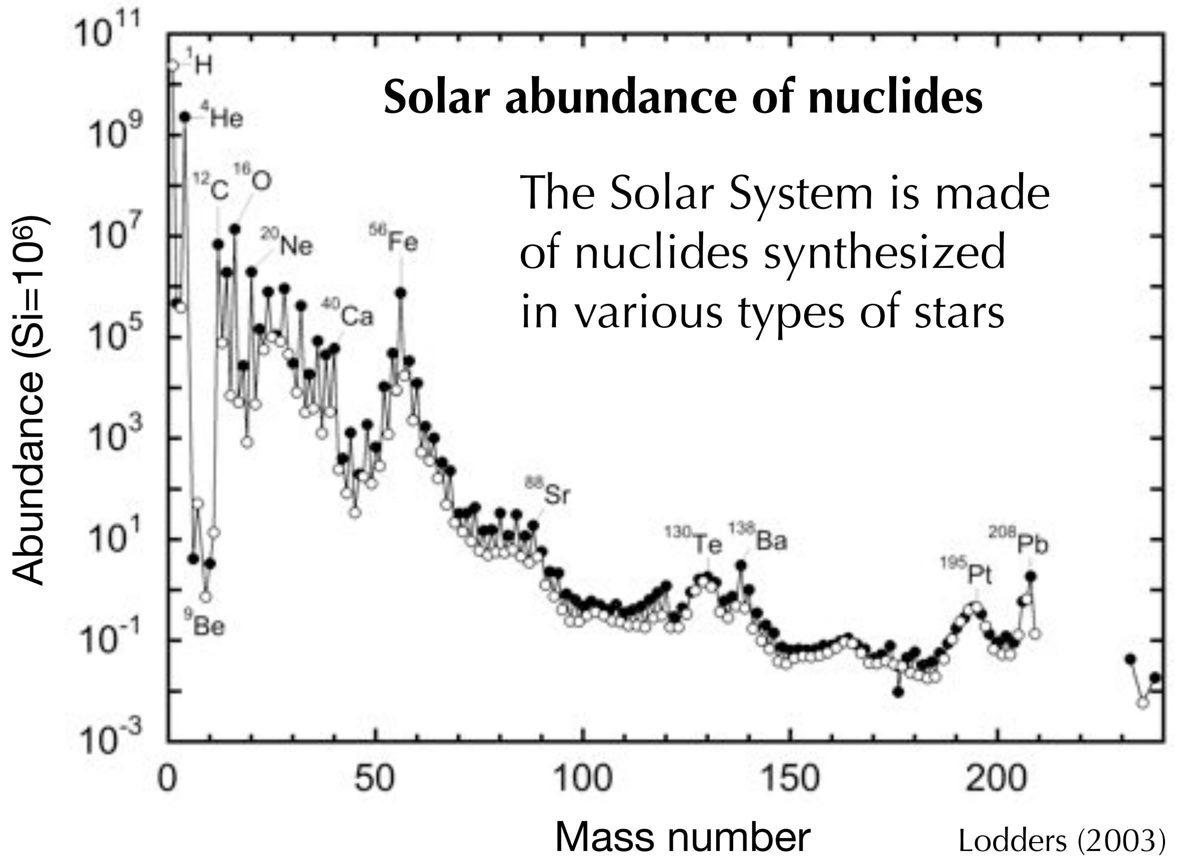
4. **Astronomical observation** should help us to understand how the Solar-System dynamically and chemically evolved to the present state, as a part of the Galactic evolution, by **combining with the extraterrestrial material research**



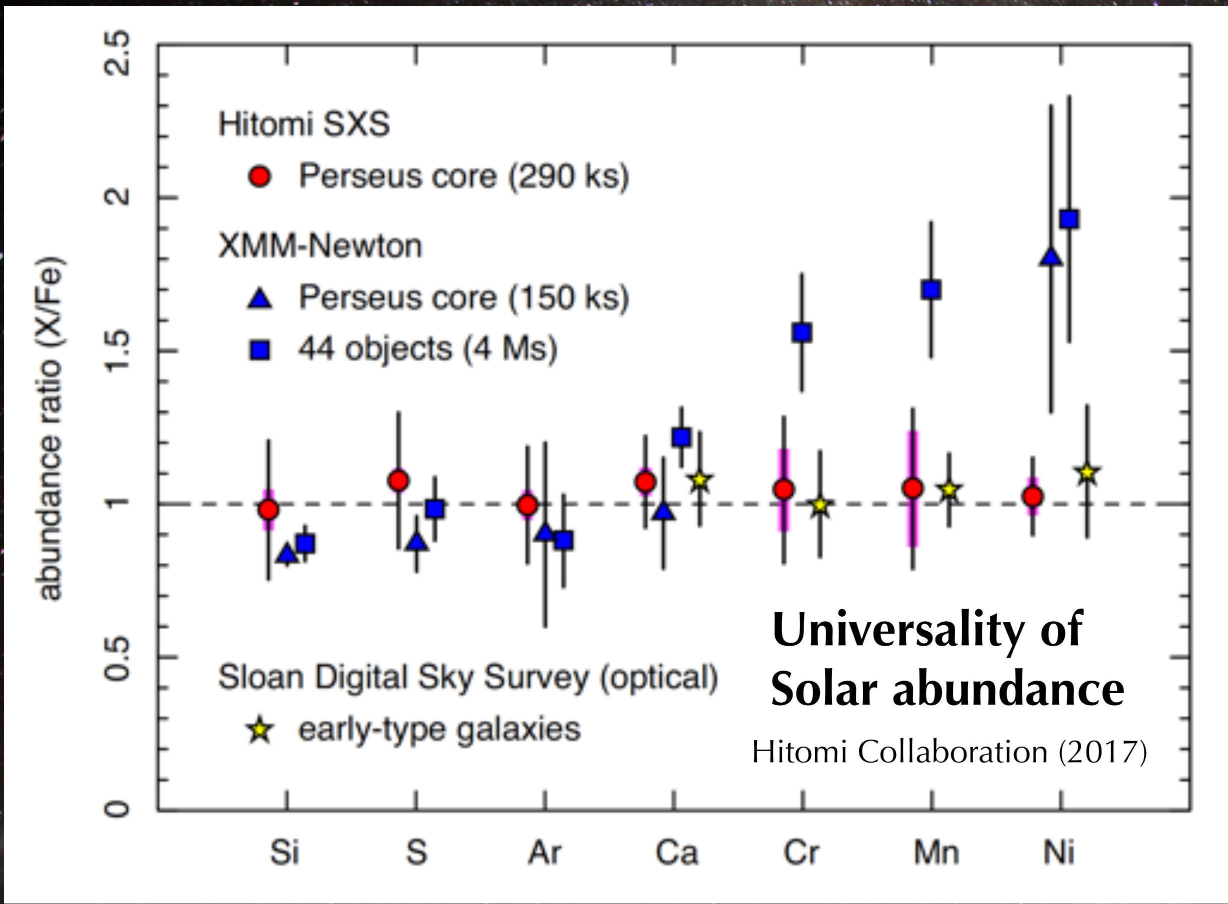
1. **Solar System science explores the formation and evolution of the Solar System** incl. the life on the Earth, which is **a part of the evolution of the Galaxy**

Solar abundance of nuclides

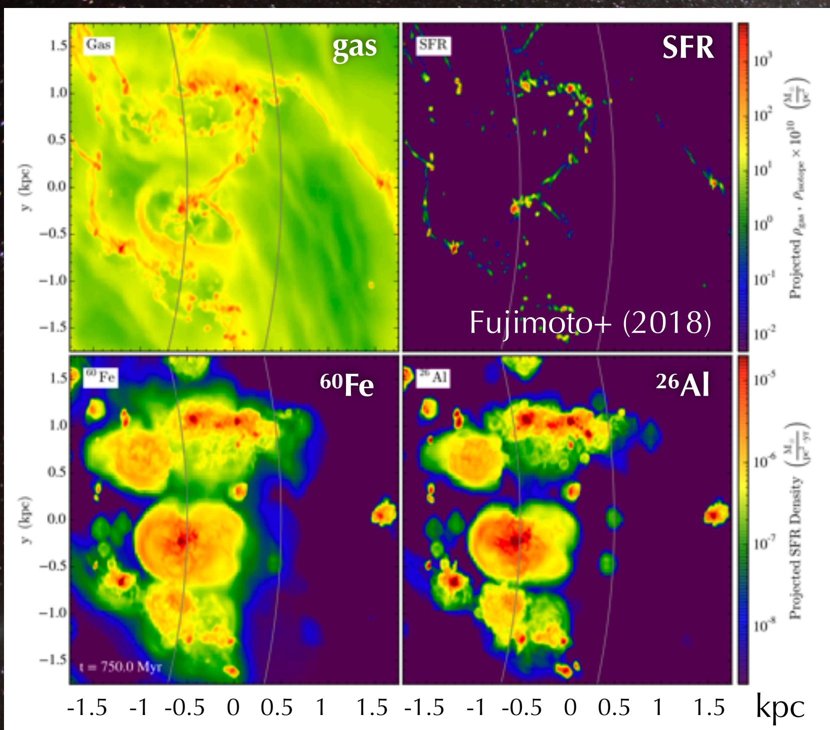
The Solar System is made of nuclides synthesized in various types of stars



Lodders (2003)



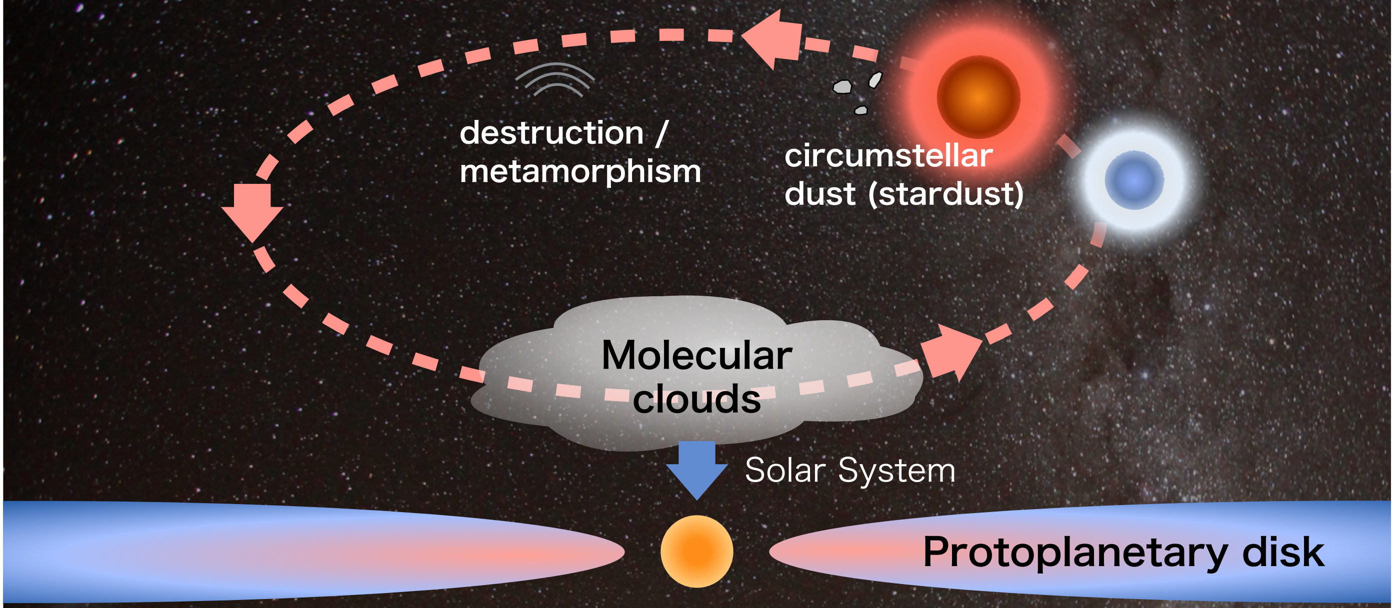
Short- and long-lived radionuclides may record the Solar System forming environment



^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{92}Nb, ^{107}Pd, ^{129}I, ^{182}Hf, ^{244}Pu

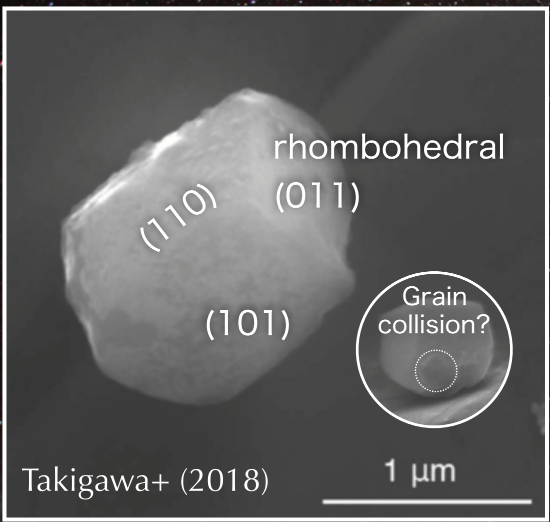
^{232}Th, ^{235}U, ^{238}U

The Solar System is made of nuclides synthesized in various types of stars



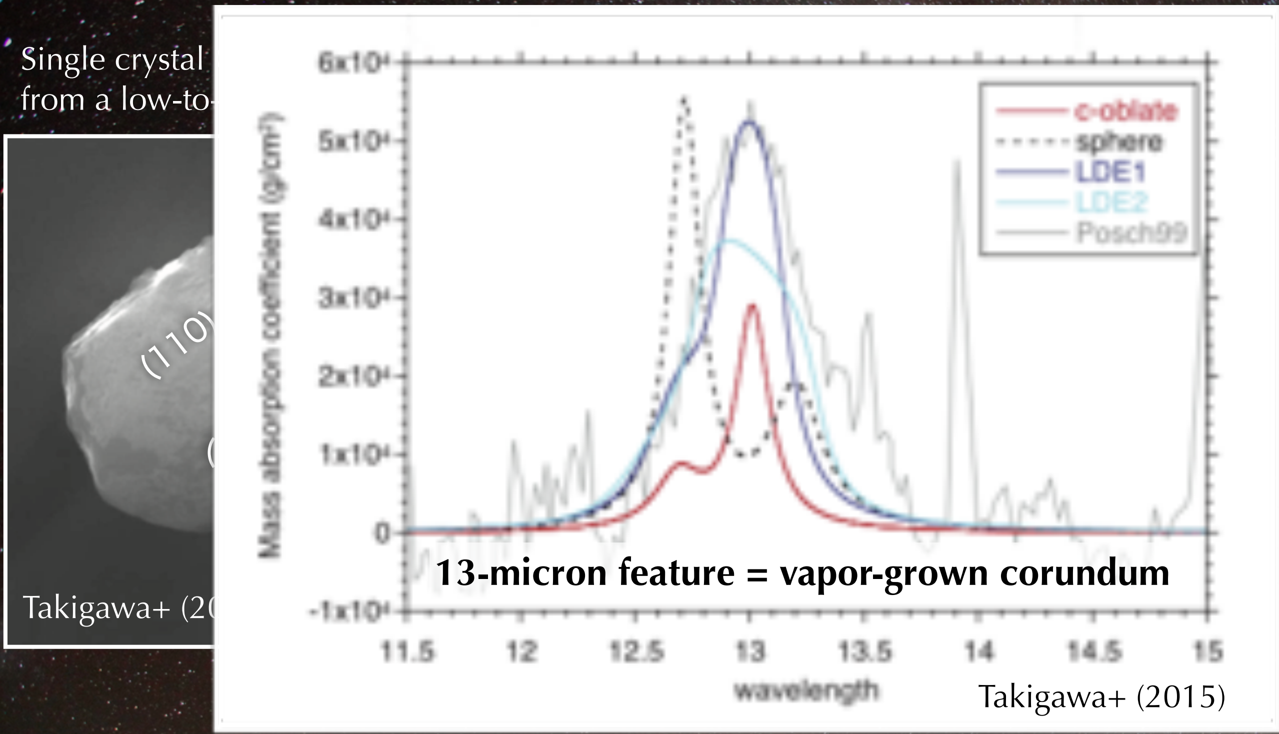
Presolar grains with isotope anomalies are real 'stardust'

Single crystal Corundum (α-Al_2O_3)
from a low-to-intermediate AGB star



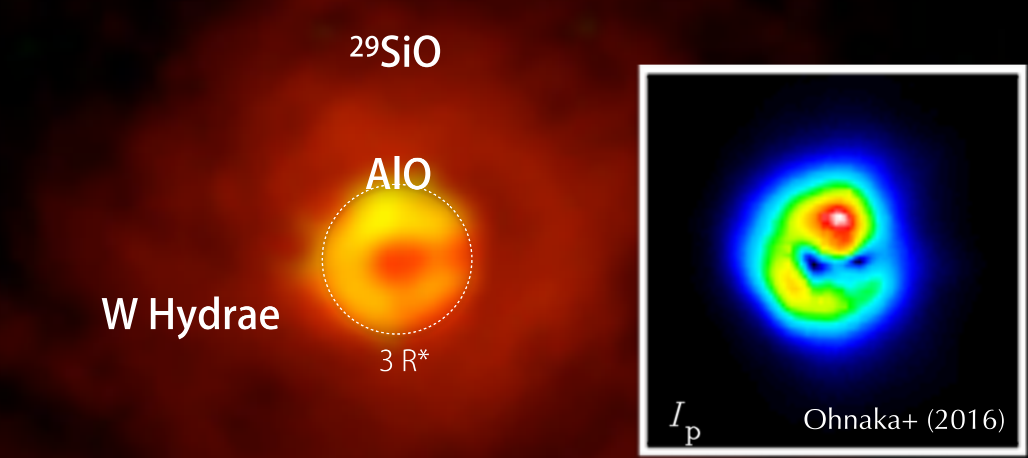
Takigawa+ (2018)

Mineralogy revealed 13-micron feature as vapor grown corundum



ALMA first observed alumina-dust forming region around an O-rich evolved star

Takigawa+ (2017)



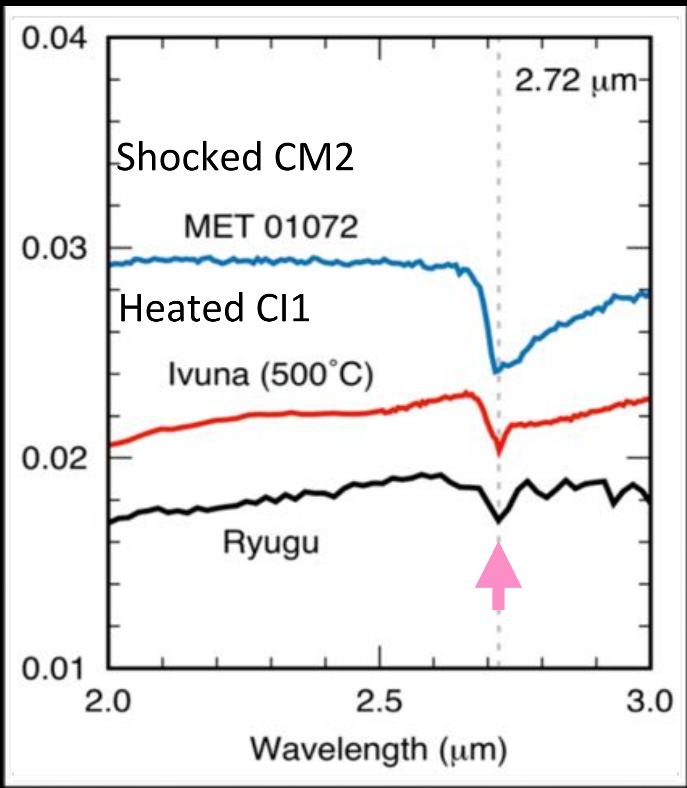
Condensed aluminum oxide dust accelerates the stellar wind and prevents the efficient formation of silicate dust

2. Many of celestial bodies in the Solar System are **reachable by spacecraft** that provide geophysical and geochemical information of the bodies and even **samples** for us

Hayabusa2 visited Ryugu

Watanabe+ (2019), Sugita+ (2019), Kitazato+ (2019)

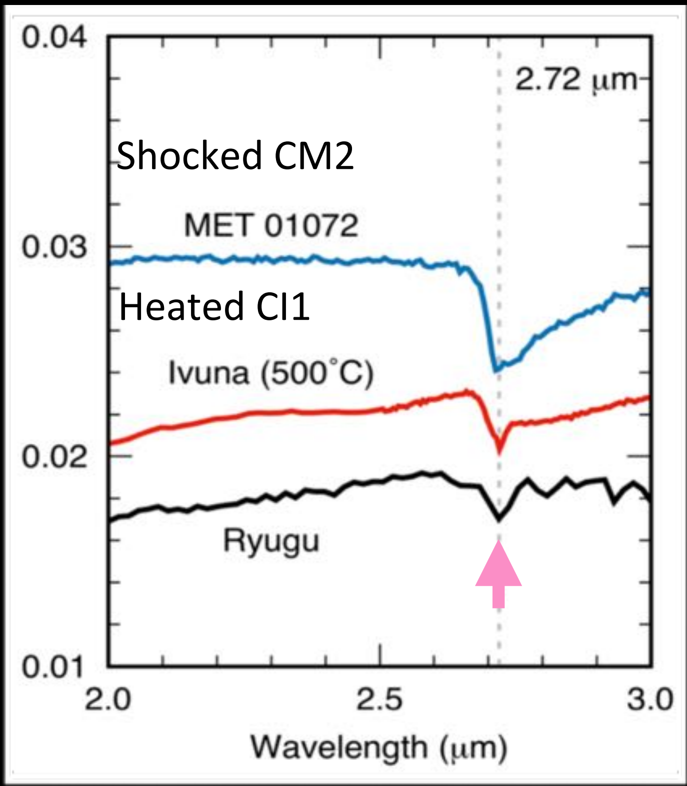
OH signature at 2.7 micron



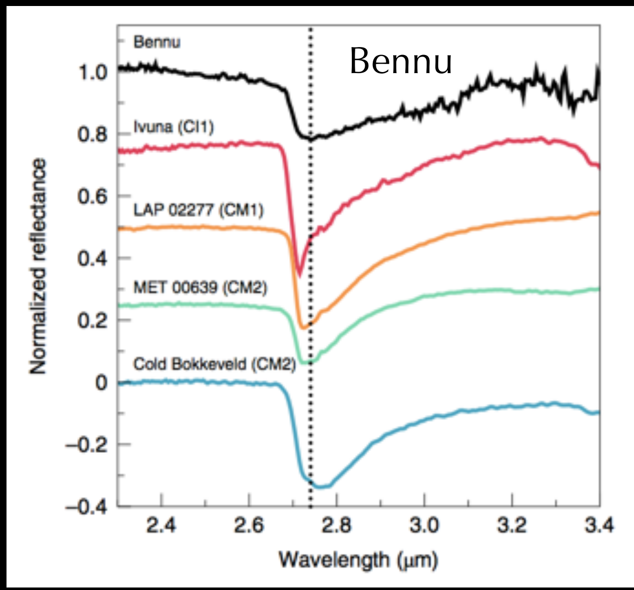
Kitazato+ (2019)

OSIRIS-REx has been investigating Bennu

OH signature at 2.7 micron



Kitasato+ (2019)



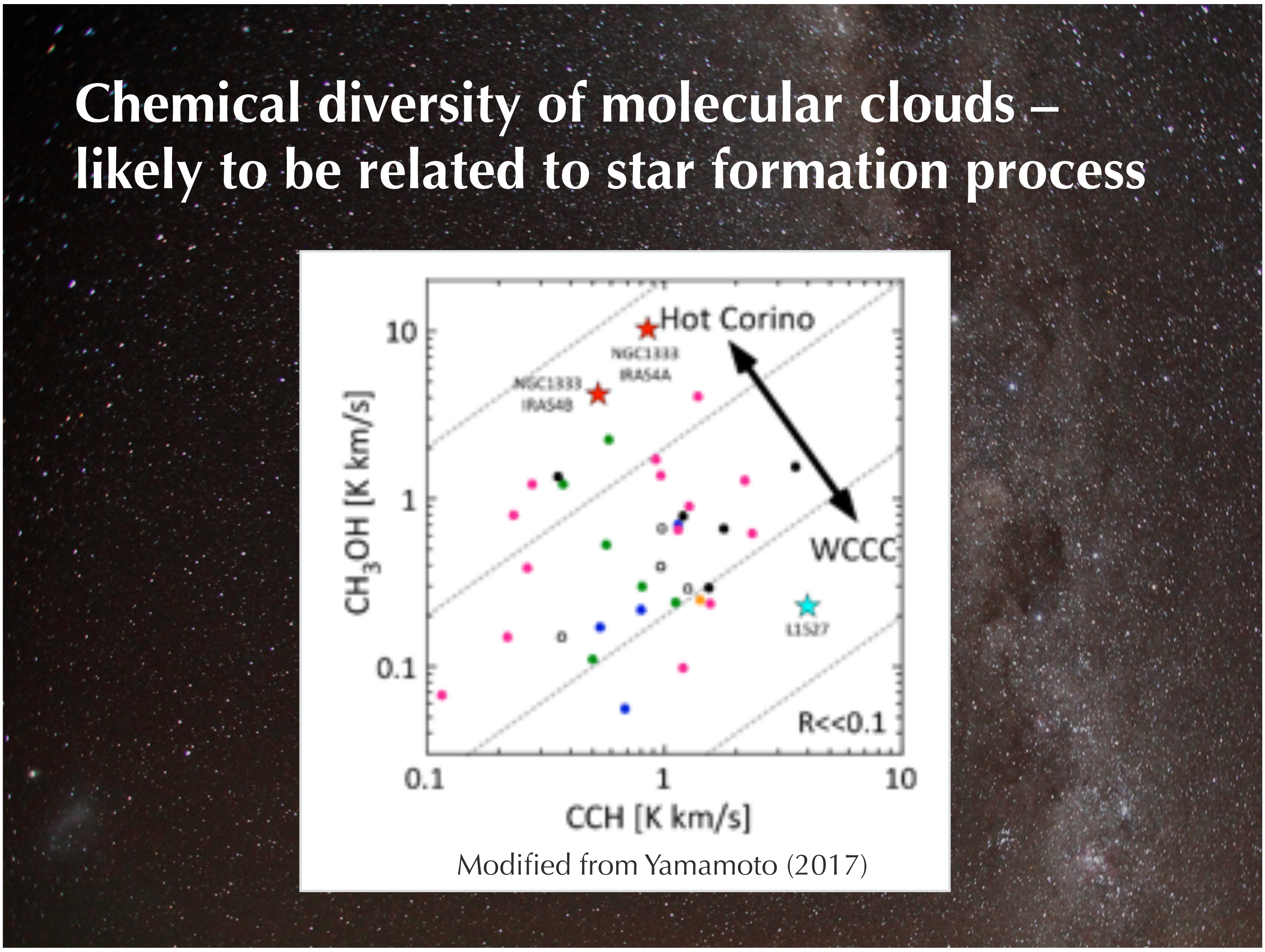
Hamilton+ (2019)

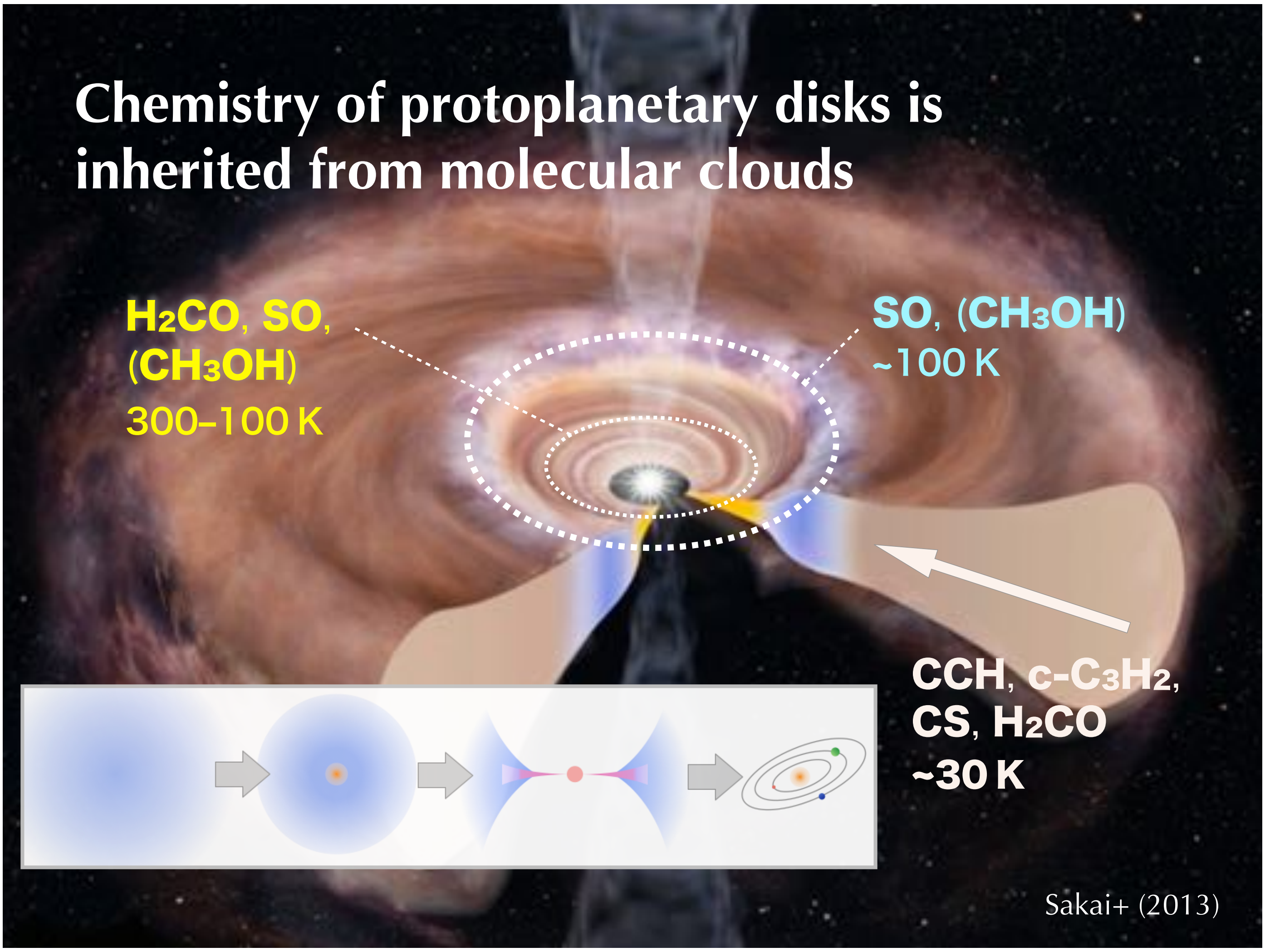
Dehydration?
Weak aqueous alteration?

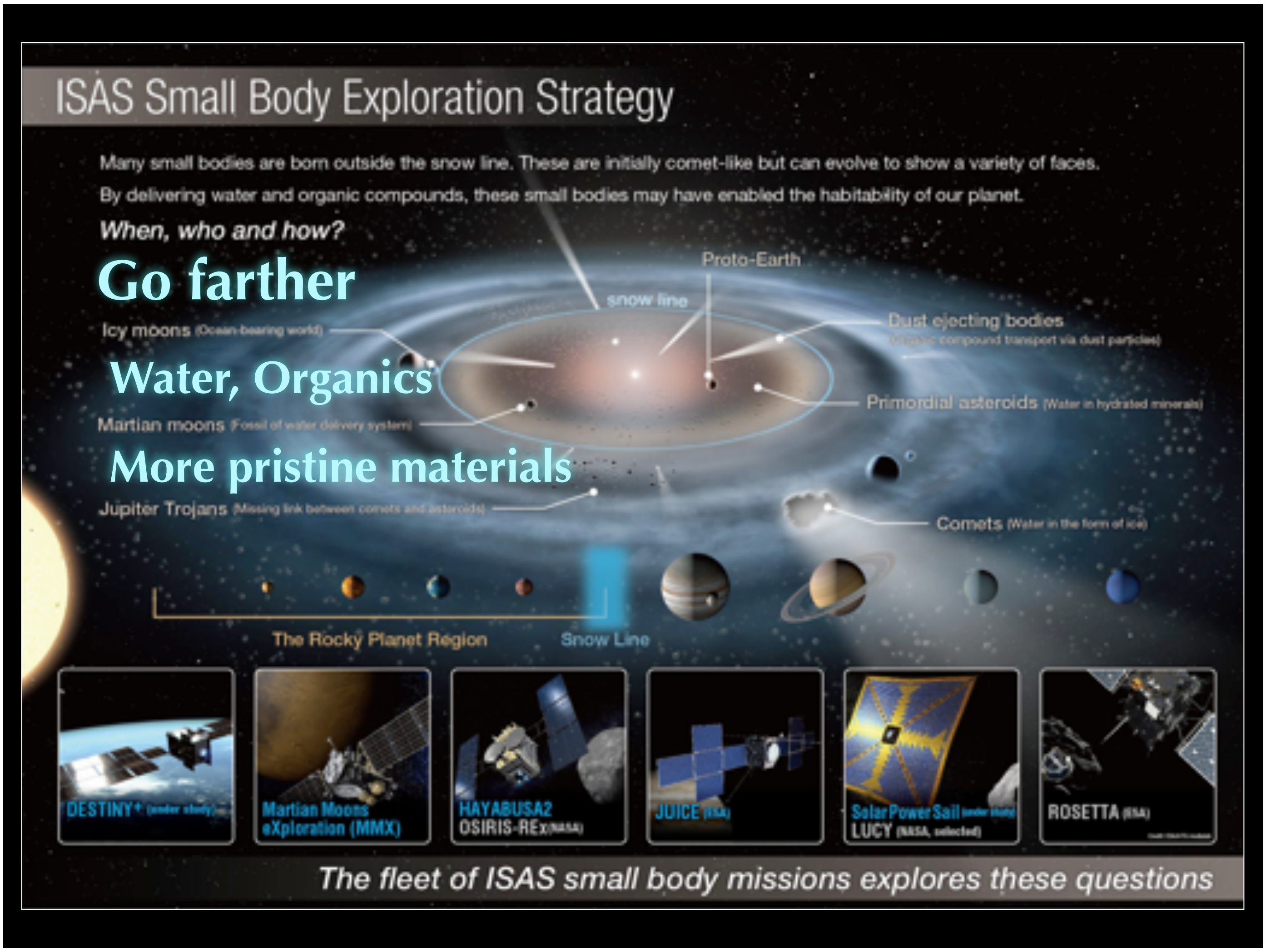
Rosetta sniffed organic molecules from 67P/C-G

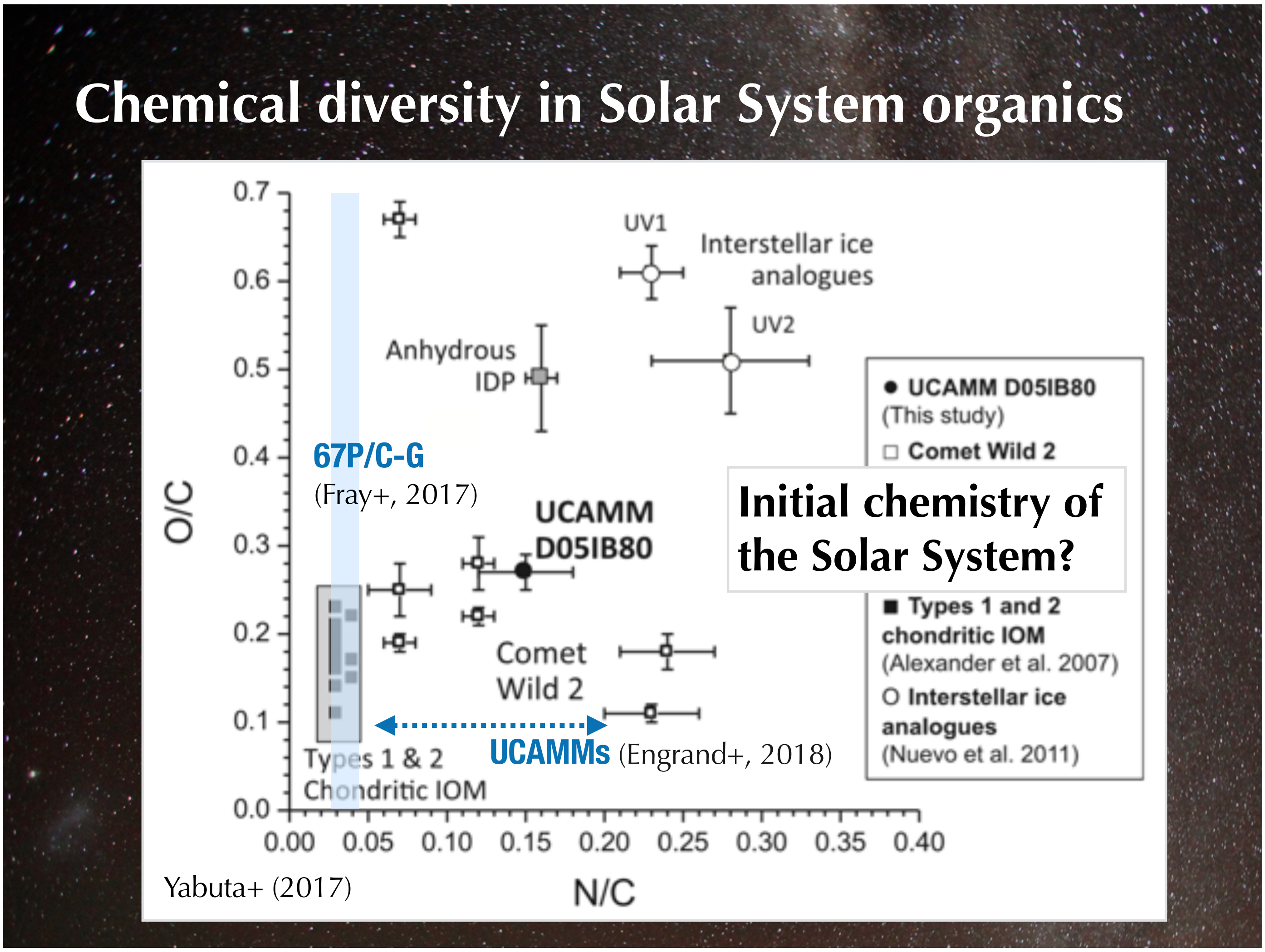
H_2O	80.92 (%)
CH_4	0.70
HCN	1.06
CO	1.09
CH_3NH_2	1.19
CH_3CN	0.55
HNCO	0.47
CH_3CHO	1.01
$HCONH_2$	3.73
$C_2H_5NH_2$	0.72
CH_3NCO	3.13
CH_3COCH_3	1.02
C_2H_5CHO	0.44
CH_3CONH_2	2.20
CH_2OHCHO	0.98
$CH_2(OH)CH_2(OH)$	0.79

Comet
67P/C-G

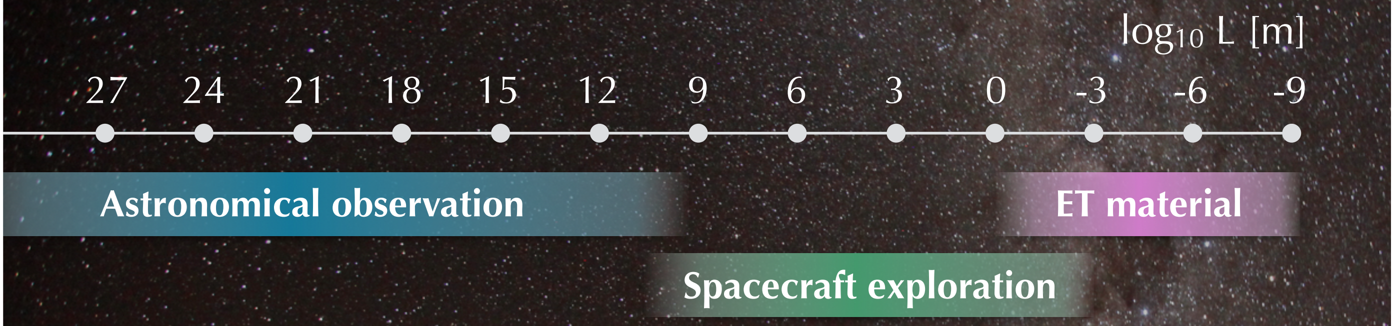

Chemical diversity of molecular clouds –
likely to be related to star formation process
Hot Corino
NGC1333 IRAS4A
NGC1333 IRAS4B
WCCC
L1527
R<<0.1
CH_3OH [K km/s]
10
1
0.1
0.1
1
10
CCH [K km/s]
Modified from Yamamoto (2017)


Chemistry of protoplanetary disks is
inherited from molecular clouds
H_2CO, SO,
(CH_3OH)
300–100 K
SO, (CH_3OH)
~100 K
CCH, c-C_3H_2,
CS, H_2CO
~30 K
Sakai+ (2013)


ISAS Small Body Exploration Strategy
Many small bodies are born outside the snow line. These are initially comet-like but can evolve to show a variety of faces.
By delivering water and organic compounds, these small bodies may have enabled the habitability of our planet.
When, who and how?
Go farther
Icy moons
Water, Organics
Martian moons
More pristine materials
Jupiter Trojans
Proto-Earth
snow line
Dust ejecting bodies
Primordial asteroids
Comets
The Rocky Planet Region
Snow Line
DESTINY+
Martian Moons eXploration (MMX)
HAYABUSA2
OSIRIS-REx
JUICE
Solar Power Sail
LUCY
ROSETTA
The fleet of ISAS small body missions explores these questions

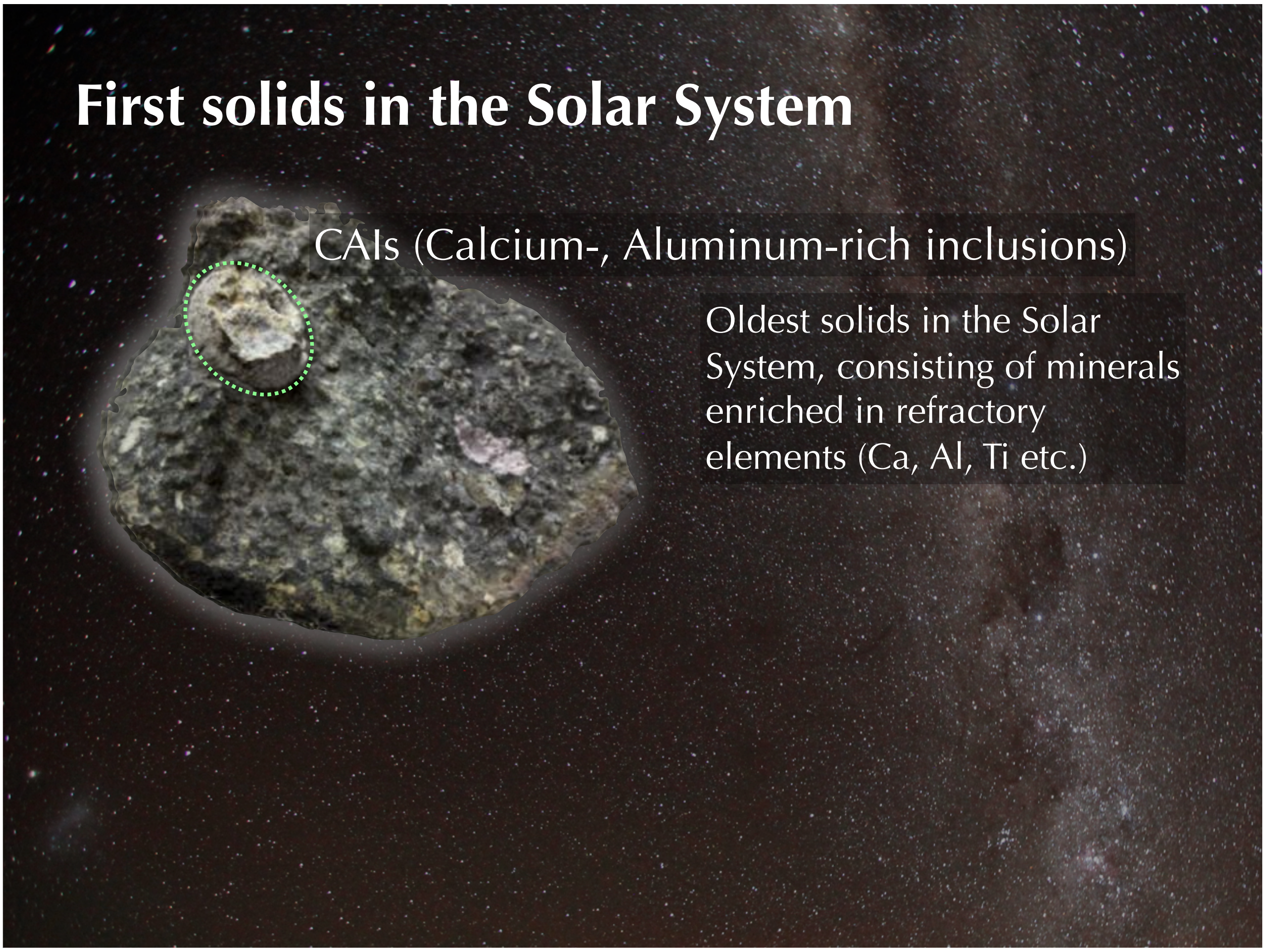

Chemical diversity in Solar System organics
O/C
N/C
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
UV1
Interstellar ice analogues
UV2
Anhydrous IDP
67P/C-G
(Fray+, 2017)
UCAMM D05IB80
Comet Wild 2
Types 1 & 2 Chondritic IOM
UCAMMs (Engrand+, 2018)
● UCAMM D05IB80 (This study)
□ Comet Wild 2
■ Types 1 and 2 chondritic IOM (Alexander et al. 2007)
O Interstellar ice analogues (Nuevo et al. 2011)
Initial chemistry of the Solar System?
Yabuta+ (2017)

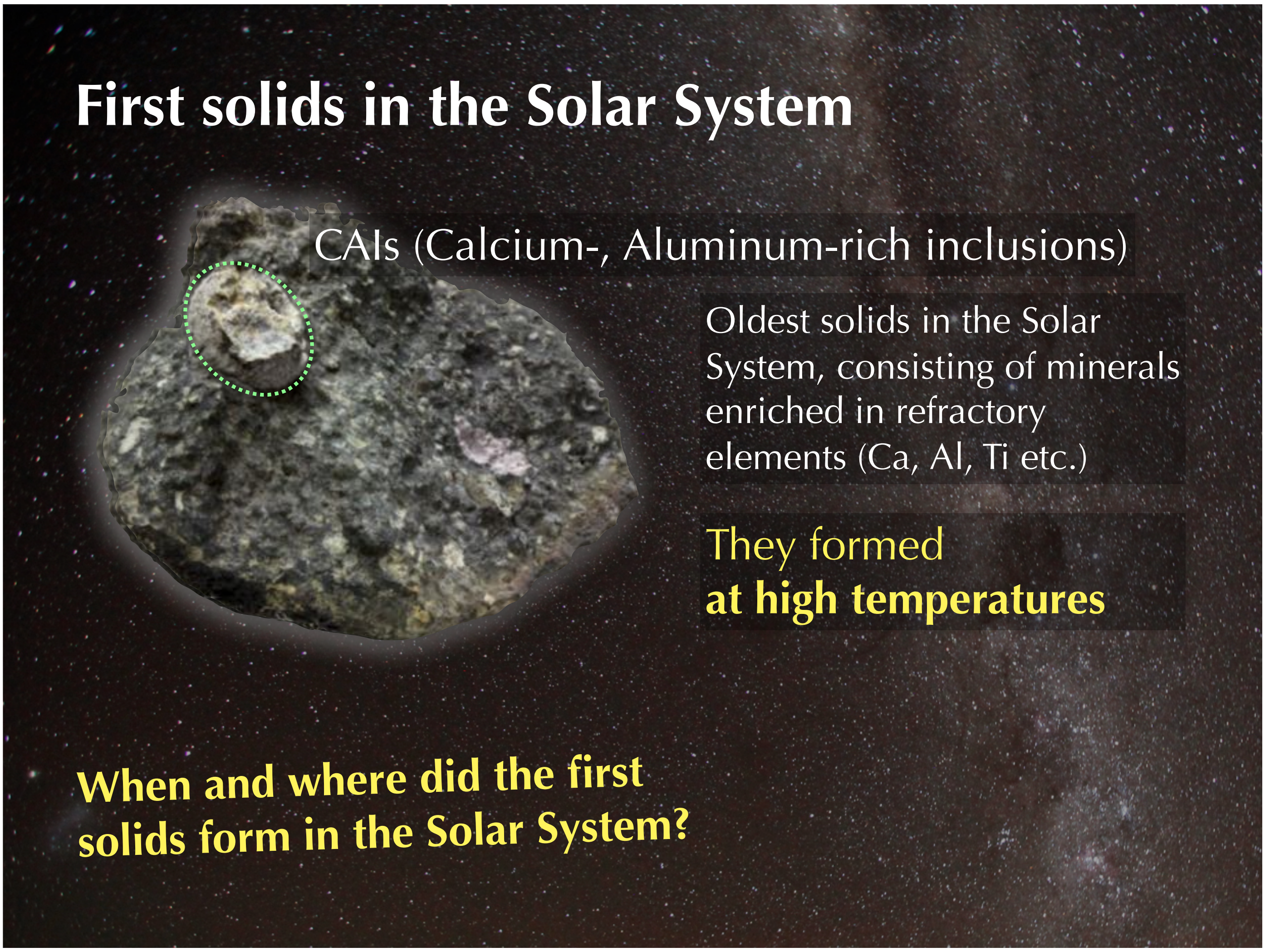
Spacecraft go farther to the scale comparable to astronomical observation

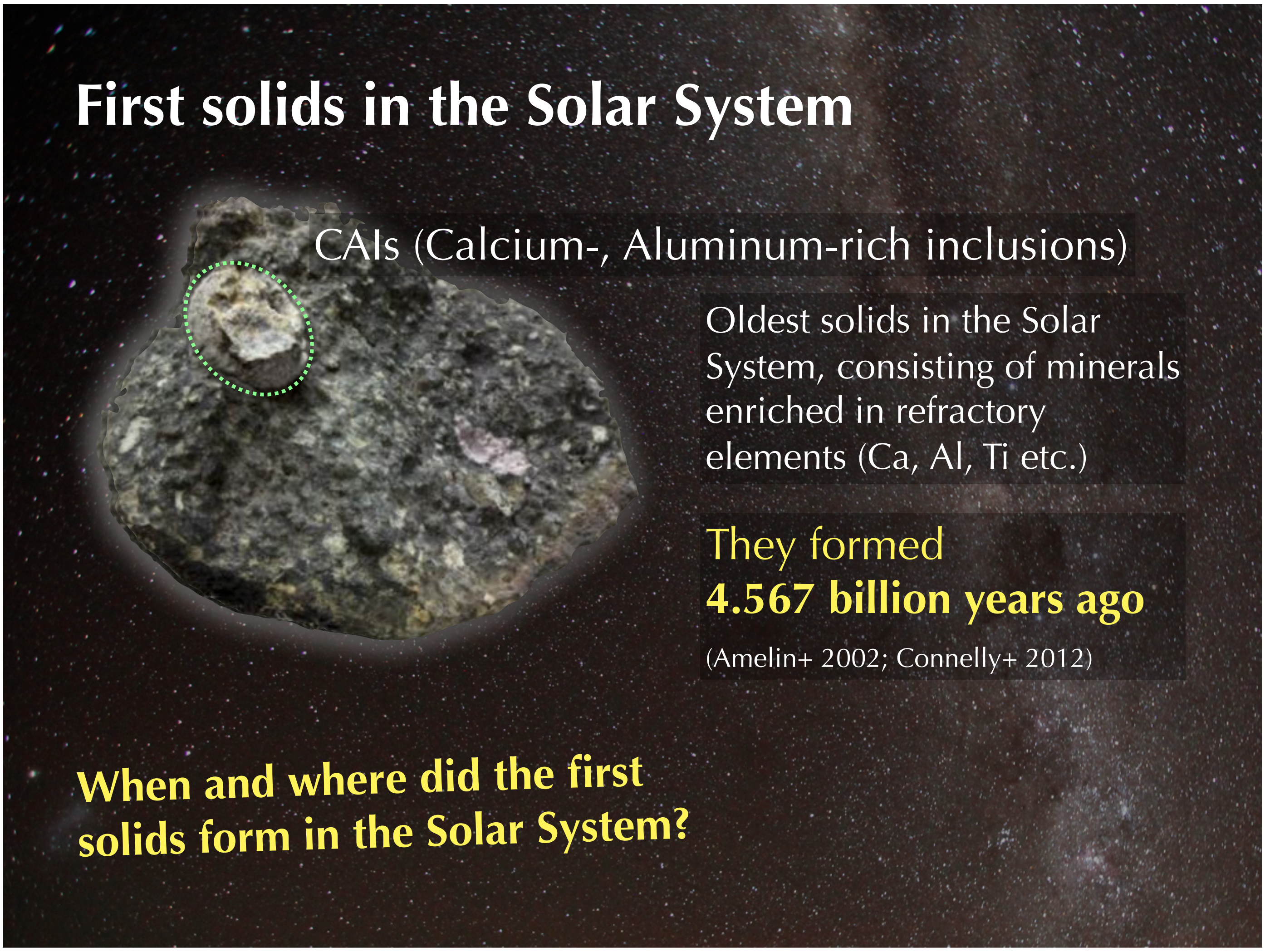


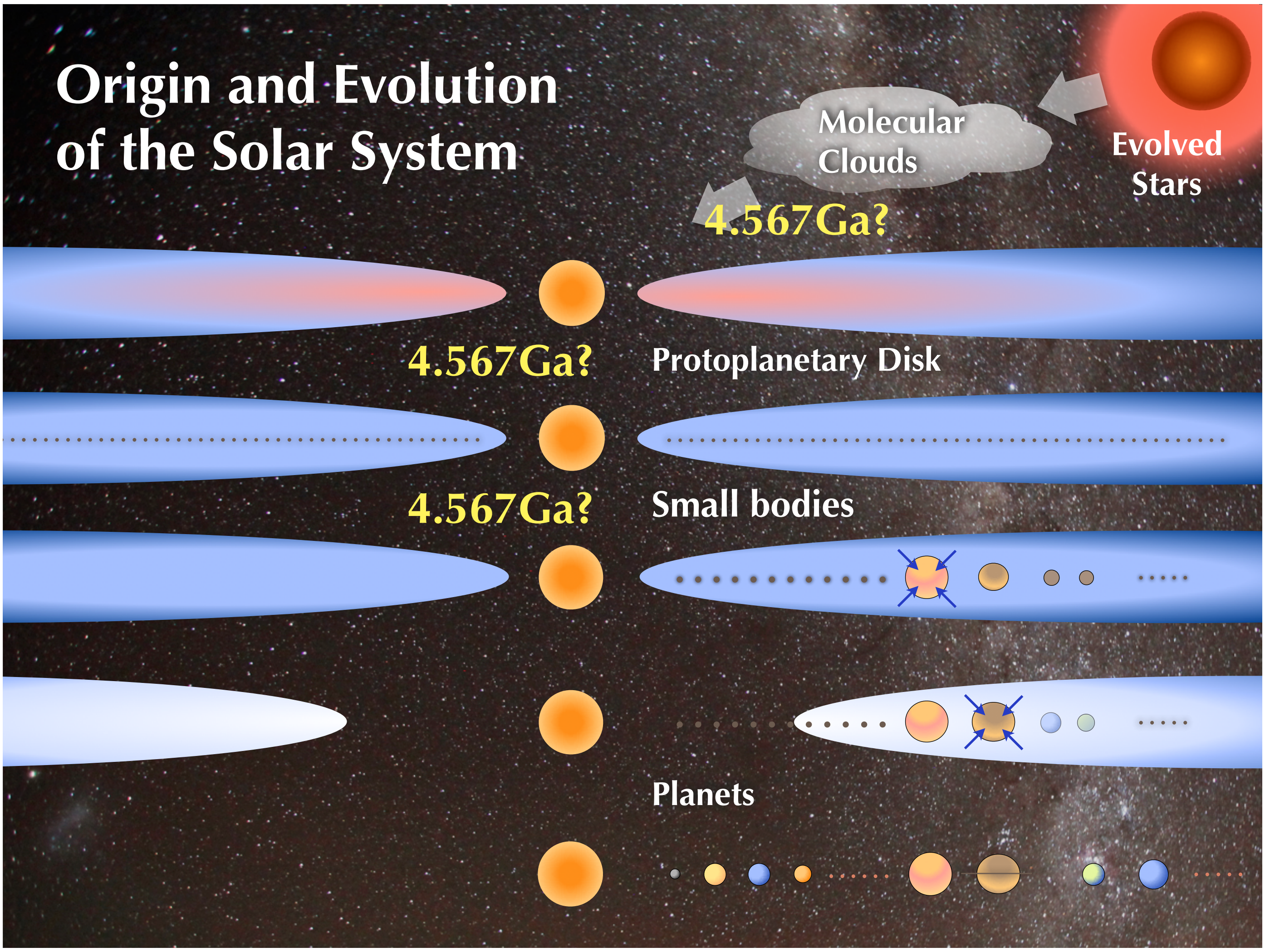
3. **Extraterrestrial materials** incl. the samples returned by spacecraft tell what happened in their parent bodies and/or in the Solar System (*in case of meteorites, we even do not what the parent bodies were!*), but do **not tell in detail how the Solar System architecture formed at the beginning**

- **When and where did the first solids form in the Solar System?**
- **What is the Earth made of?**

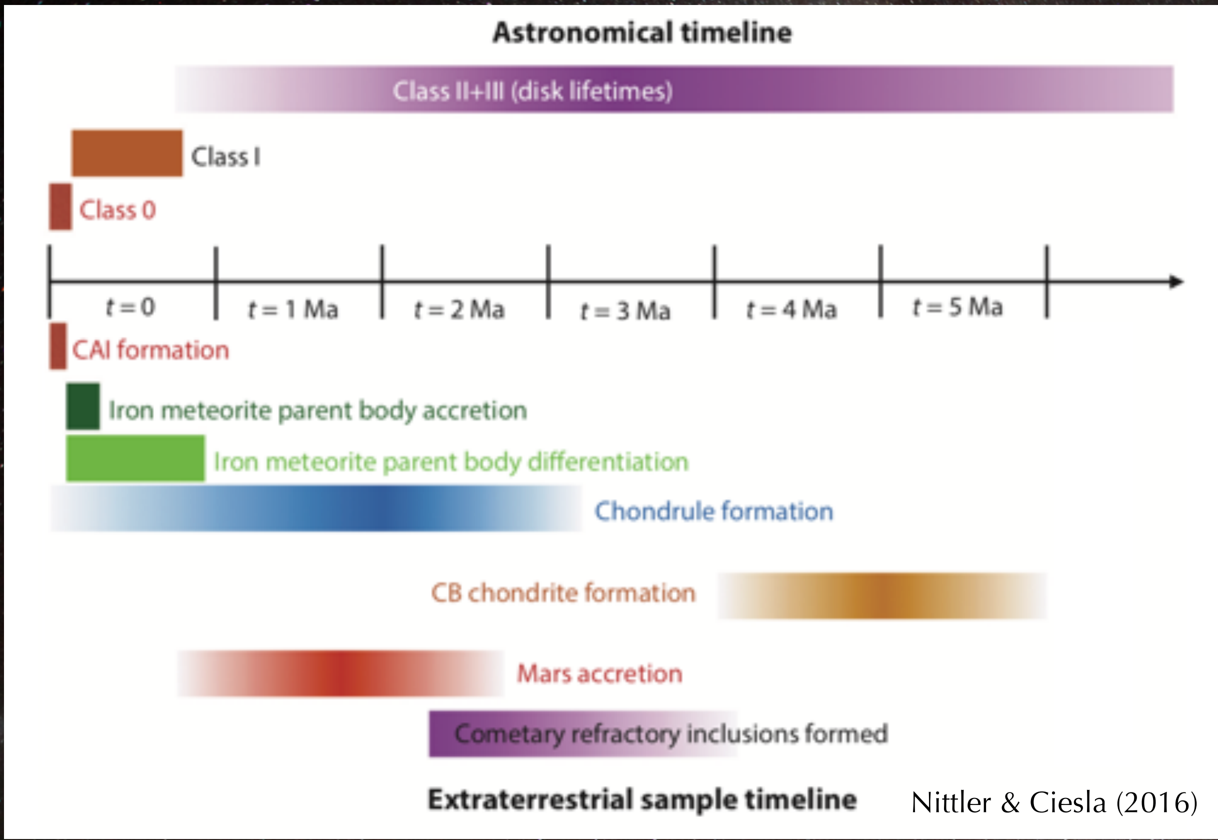

First solids in the Solar System
CAIs (Calcium-, Aluminum-rich inclusions)
Oldest solids in the Solar System, consisting of minerals enriched in refractory elements (Ca, Al, Ti etc.)


First solids in the Solar System
CAIs (Calcium-, Aluminum-rich inclusions)
Oldest solids in the Solar System, consisting of minerals enriched in refractory elements (Ca, Al, Ti etc.)
They formed at high temperatures
When and where did the first solids form in the Solar System?


First solids in the Solar System
CAIs (Calcium-, Aluminum-rich inclusions)
Oldest solids in the Solar System, consisting of minerals enriched in refractory elements (Ca, Al, Ti etc.)
They formed
4.567 billion years ago
(Amelin+ 2002; Connelly+ 2012)
When and where did the first solids form in the Solar System?

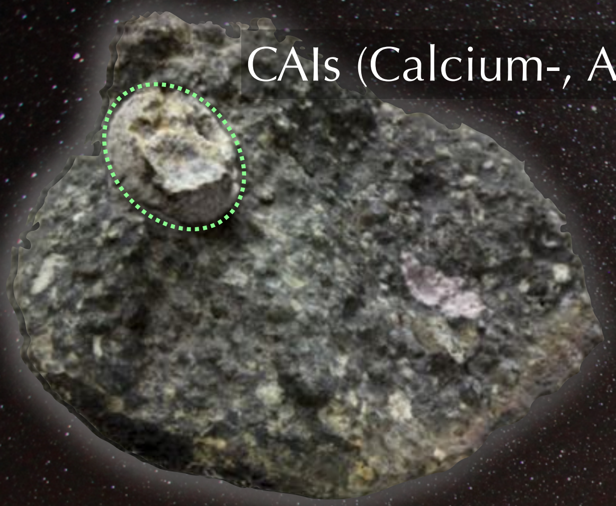

Origin and Evolution of the Solar System
Molecular Clouds
Evolved Stars
4.567Ga?
4.567Ga?
Protoplanetary Disk
4.567Ga?
Small bodies
Planets

Astronomical & Cosmochemical timelines



Nittler & Ciesla (2016)

First solids in the Solar System



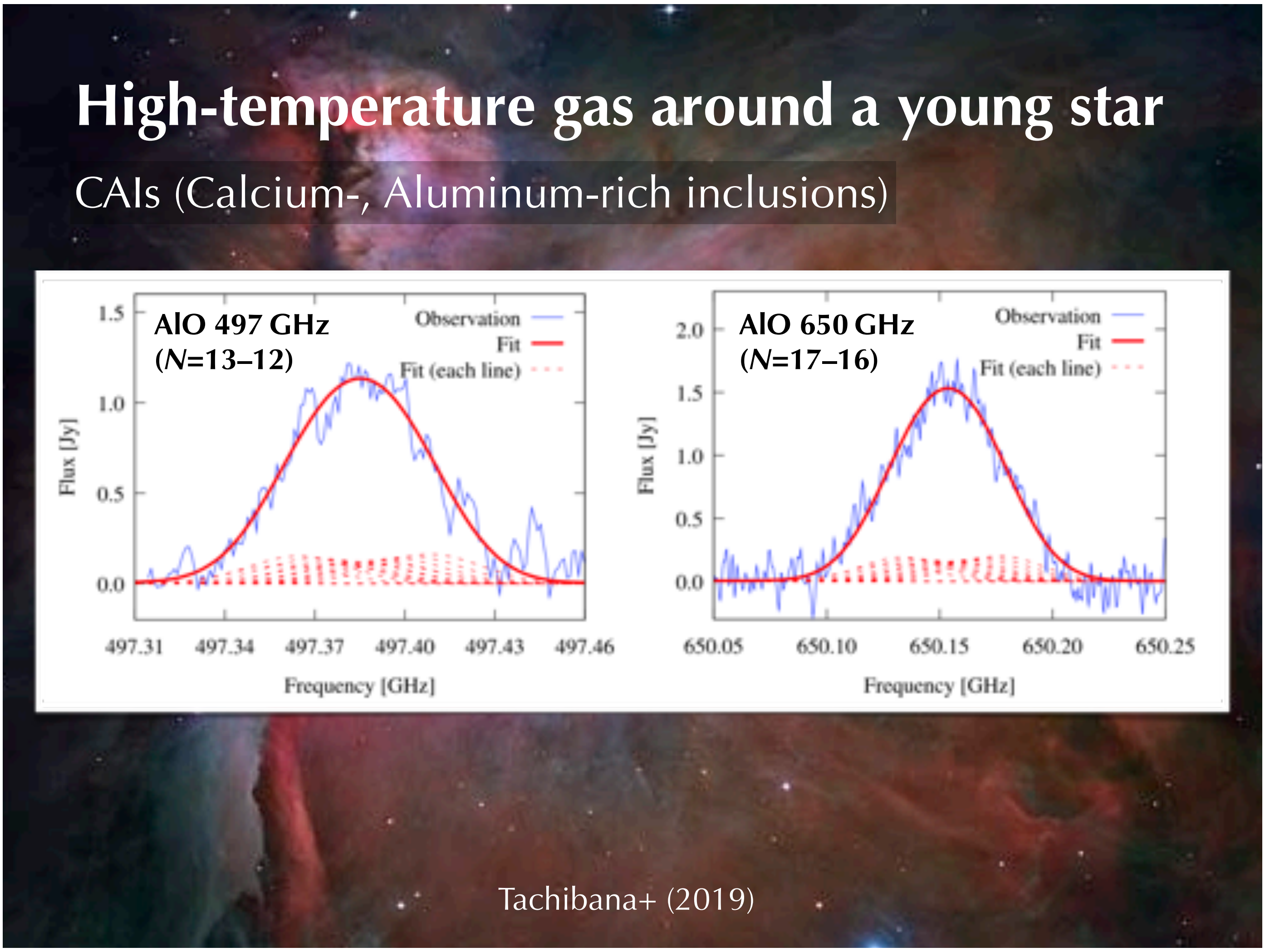
CAIs (Calcium-, Aluminum-rich inclusions)

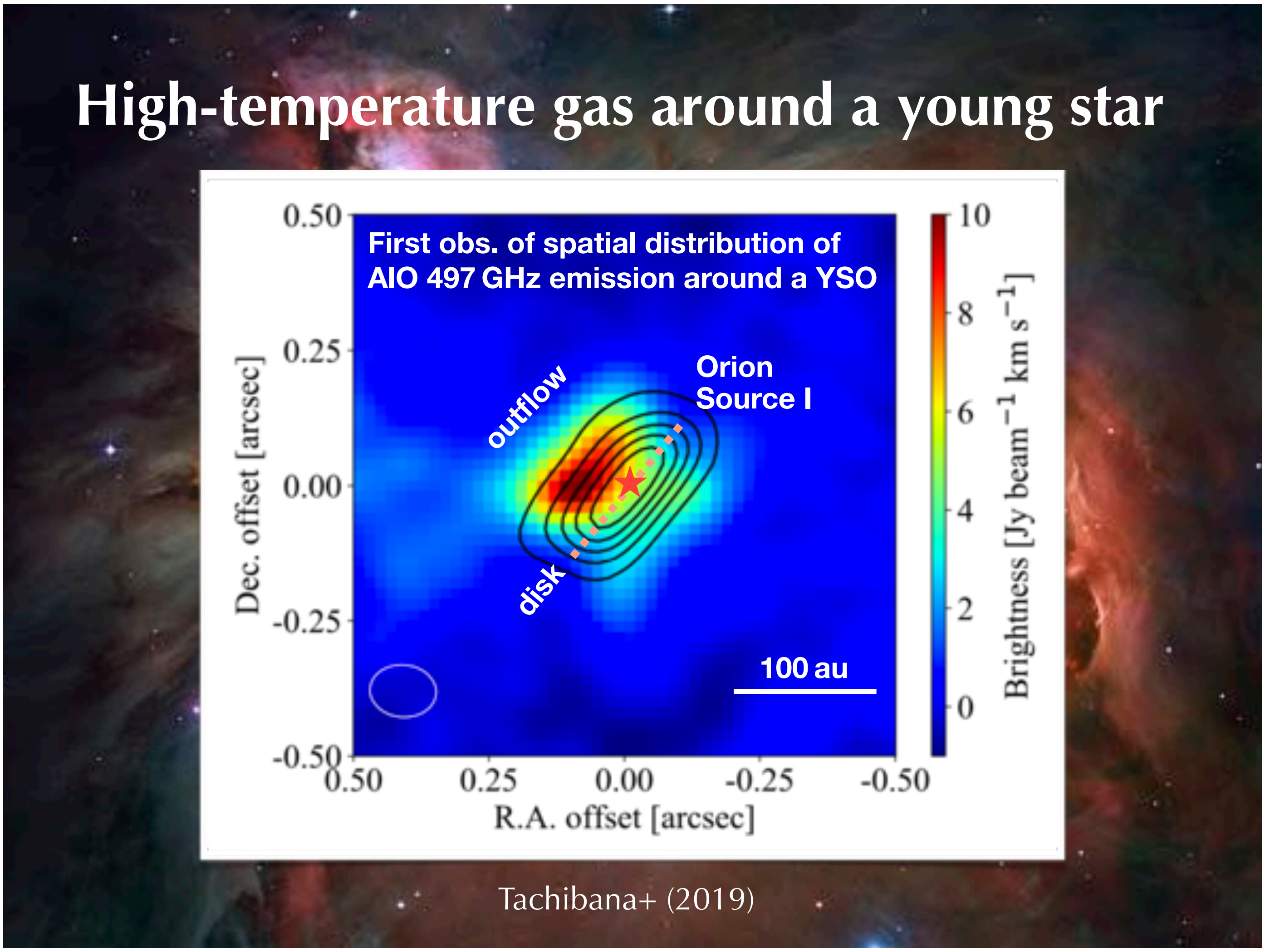
Oldest solids in the Solar System, consisting of minerals enriched in refractory elements (Ca, Al, Ti etc.)

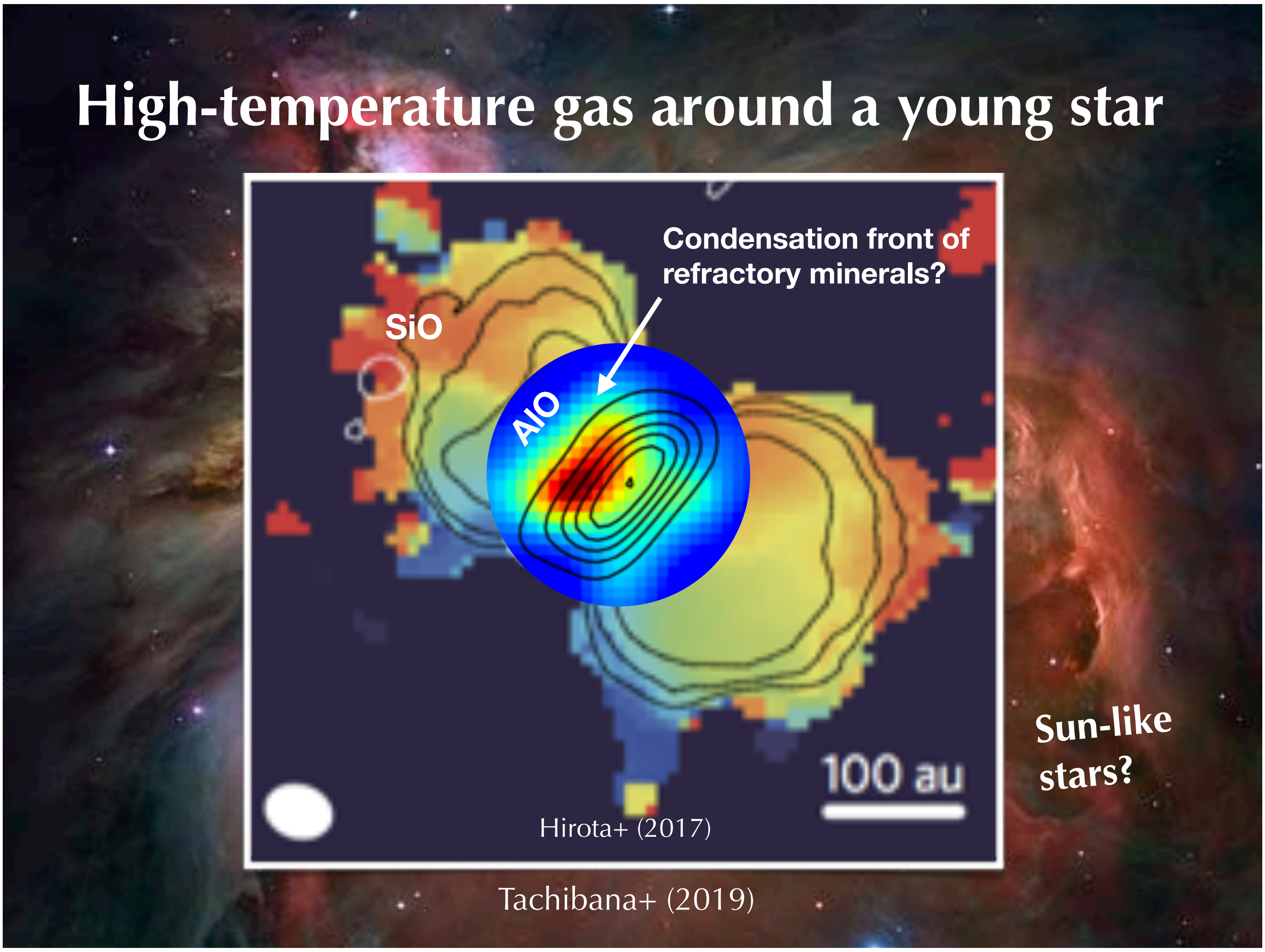
Let us look at other systems!

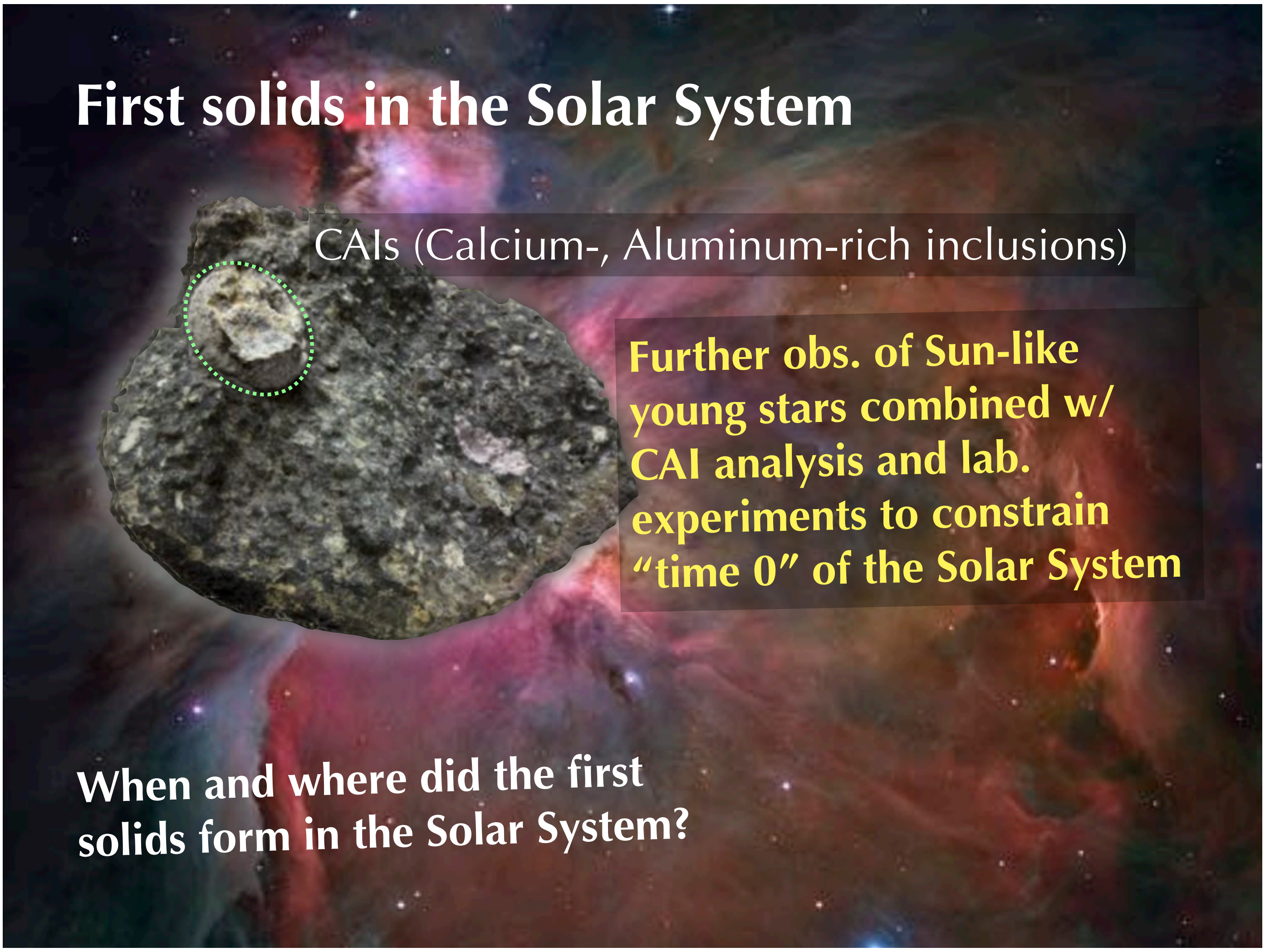
When and where did the first solids form in the Solar System?

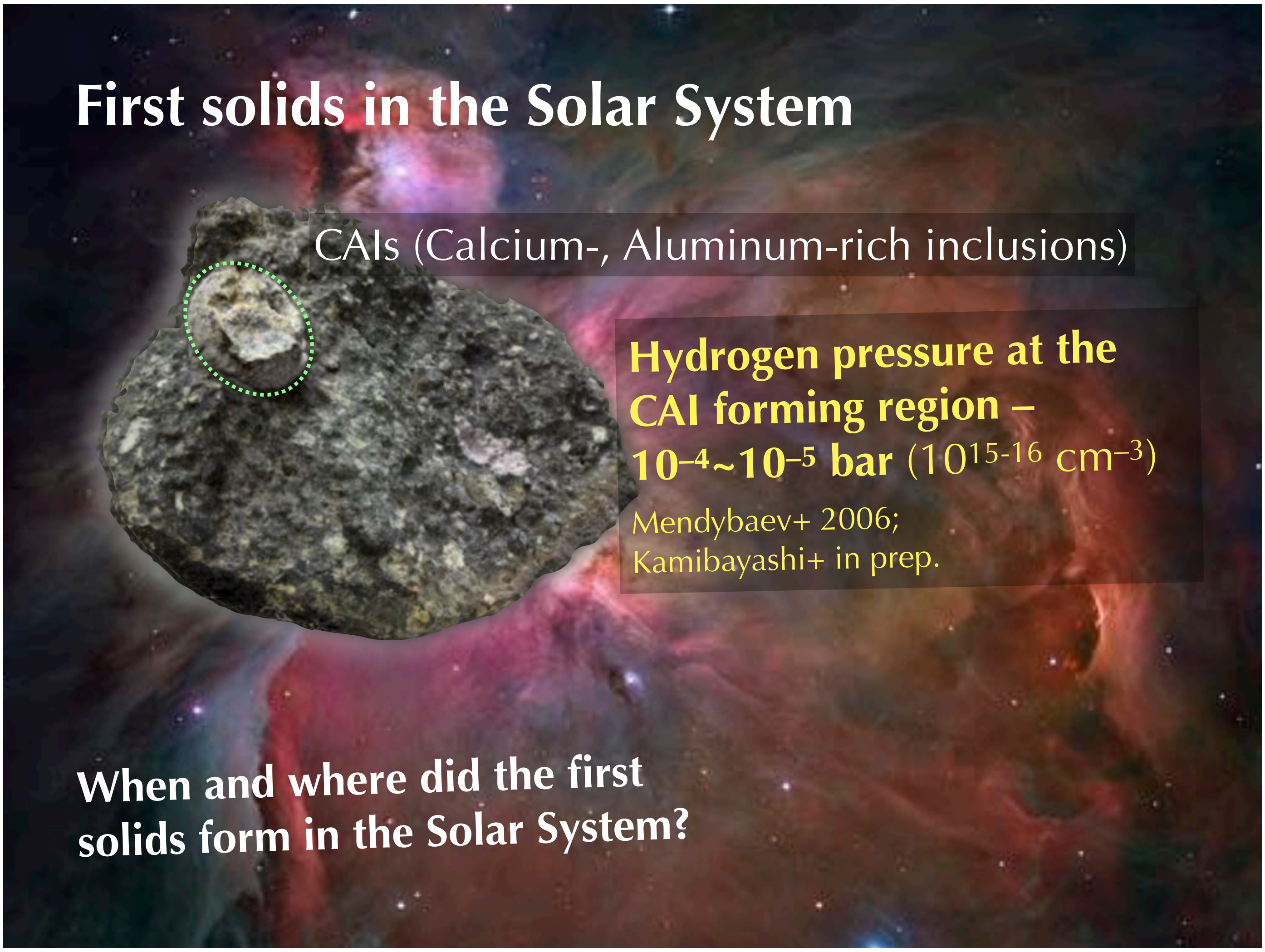

High-temperature gas around a young star
Orion Source I
A massive young star candidate
(5–7 MSUN: Plambeck & Wright 2016;
15 MSUN: Ginsburg+ 2018)


High-temperature gas around a young star
CAIs (Calcium-, Aluminum-rich inclusions)
AlO 497 GHz
(N=13–12)
Observation
Fit
Fit (each line)
Flux [Jy]
1.5
1.0
0.5
0.0
497.31
497.34
497.37
497.40
497.43
497.46
Frequency [GHz]
AlO 650 GHz
(N=17–16)
Observation
Fit
Fit (each line)
Flux [Jy]
2.0
1.5
1.0
0.5
0.0
650.05
650.10
650.15
650.20
650.25
Frequency [GHz]
Tachibana+ (2019)

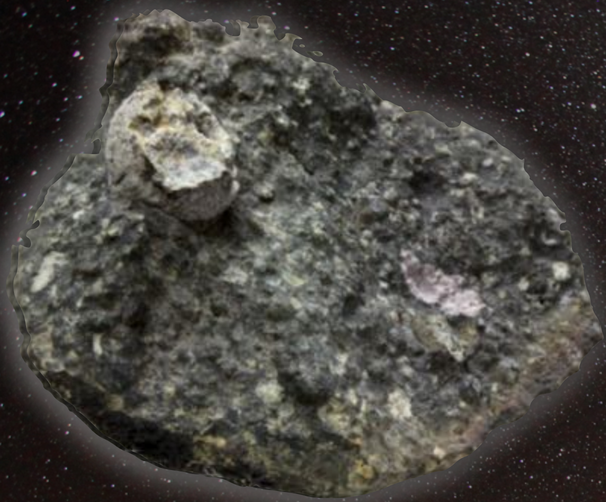

High-temperature gas around a young star
First obs. of spatial distribution of
AlO 497 GHz emission around a YSO
outflow
Orion
Source I
disk
100 au
Dec. offset [arcsec]
0.50
0.25
0.00
-0.25
-0.50
R.A. offset [arcsec]
0.50
0.25
0.00
-0.25
-0.50
Brightness [Jy beam^{-1} km s^{-1}]
10
8
6
4
2
0
Tachibana+ (2019)


High-temperature gas around a young star
Condensation front of
refractory minerals?
SiO
AlO
100 au
Hirota+ (2017)
Sun-like
stars?
Tachibana+ (2019)


First solids in the Solar System
CAIs (Calcium-, Aluminum-rich inclusions)
Further obs. of Sun-like young stars combined w/ CAI analysis and lab. experiments to constrain "time 0" of the Solar System
When and where did the first solids form in the Solar System?


First solids in the Solar System
CAIs (Calcium-, Aluminum-rich inclusions)
Hydrogen pressure at the CAI forming region – 10^{-4}~10^{-5} bar ($10^{15\text{-}16}$ cm^{-3})
Mendybaev+ 2006; Kamibayashi+ in prep.
When and where did the first solids form in the Solar System?

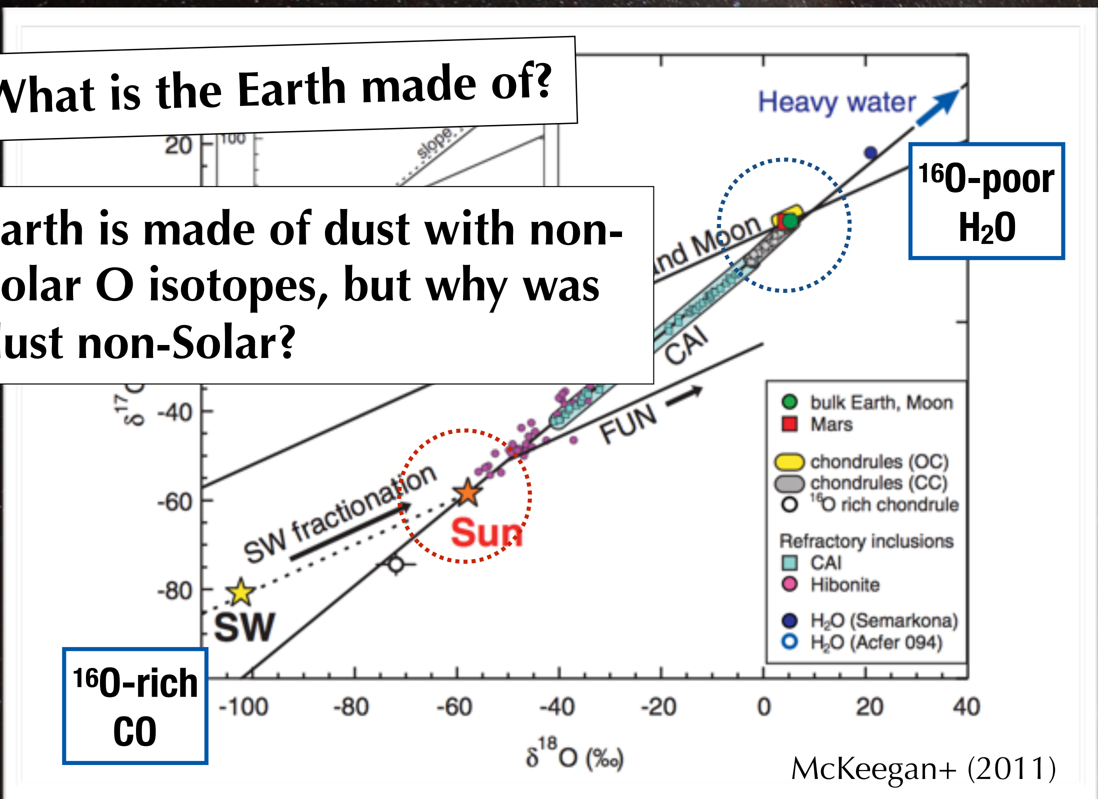
Oxygen isotope evolution



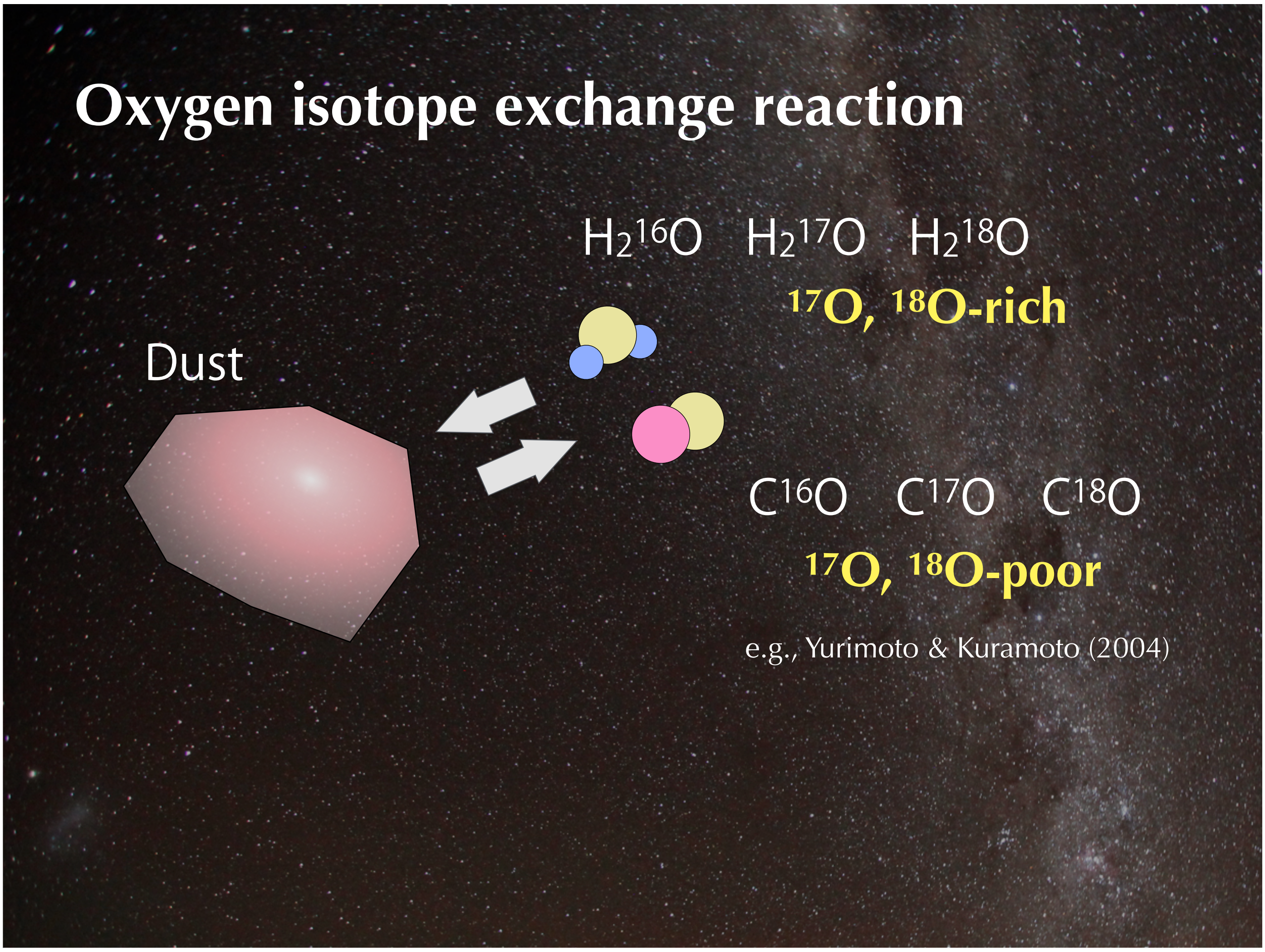
Three isotopes:

^{16}O, ^{17}O, ^{18}O

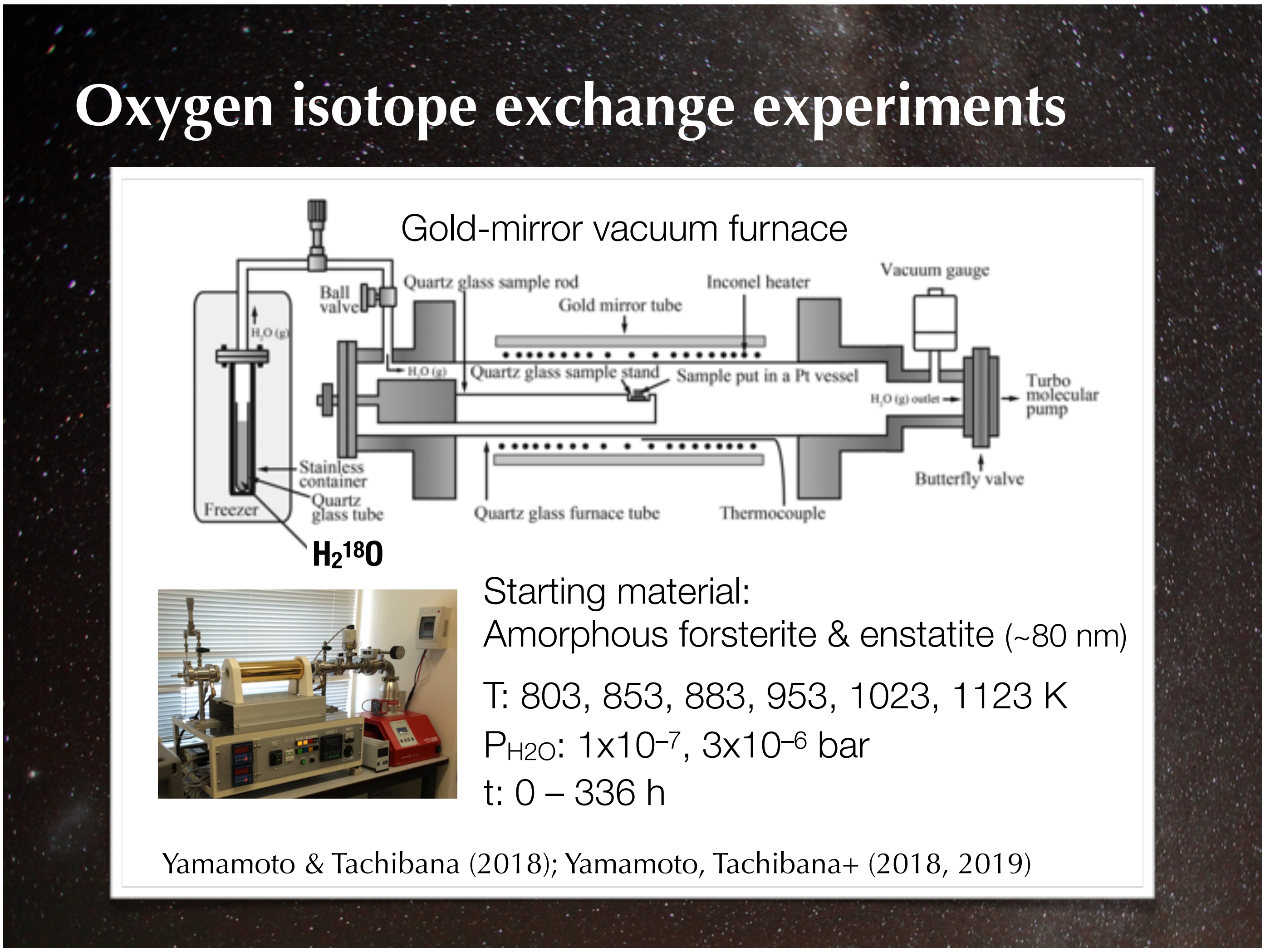
Oxygen isotope evolution



McKeegan+ (2011)



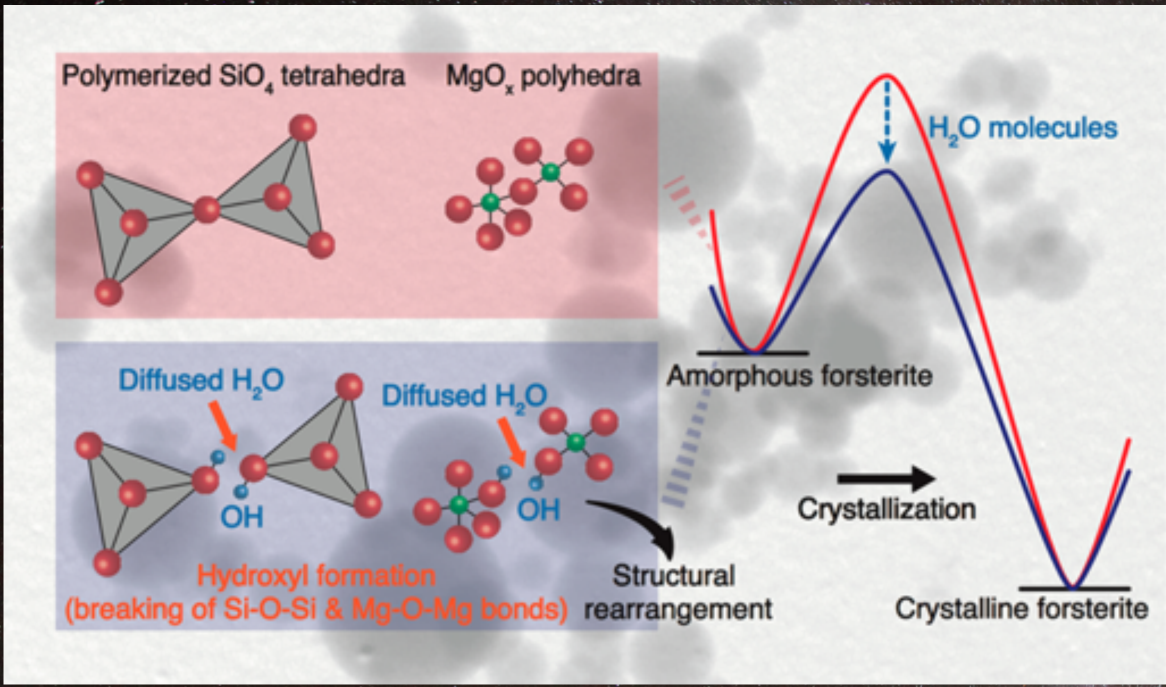
Oxygen isotope exchange reaction
H2 16O H2 17O H2 18O
17O, 18O-rich
Dust
C16O C17O C18O
17O, 18O-poor
e.g., Yurimoto & Kuramoto (2004)



Oxygen isotope exchange experiments
Gold-mirror vacuum furnace
Ball valve
Quartz glass sample rod
Gold mirror tube
Inconel heater
Vacuum gauge
H2O (g)
Quartz glass sample stand
Sample put in a Pt vessel
H2O (g) outlet
Turbo molecular pump
Stainless container
Quartz glass tube
Freezer
Quartz glass furnace tube
Thermocouple
Butterfly valve
H2 18O
Starting material:
Amorphous forsterite & enstatite (~80 nm)
T: 803, 853, 883, 953, 1023, 1123 K
PH2O: 1x10-7, 3x10-6 bar
t: 0 – 336 h
Yamamoto & Tachibana (2018); Yamamoto, Tachibana+ (2018, 2019)

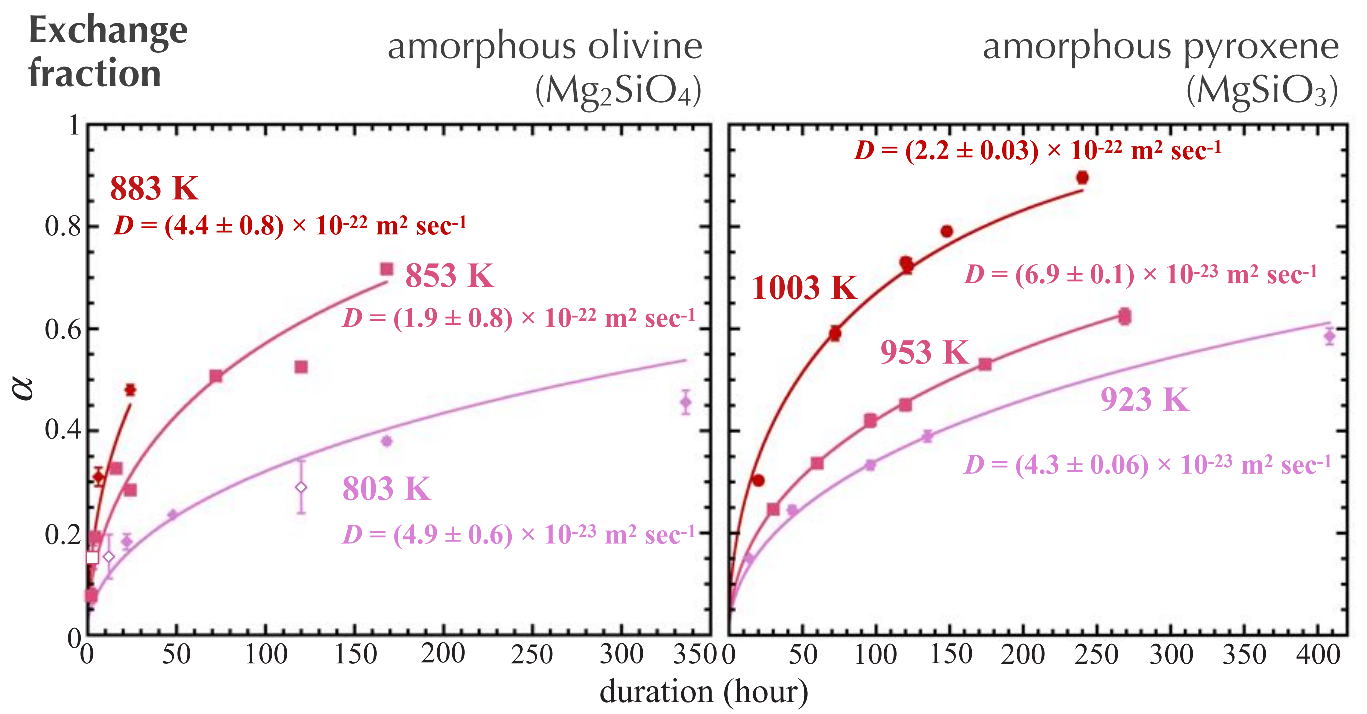
O isotope exchange b/w amorphous silicate & H_2O

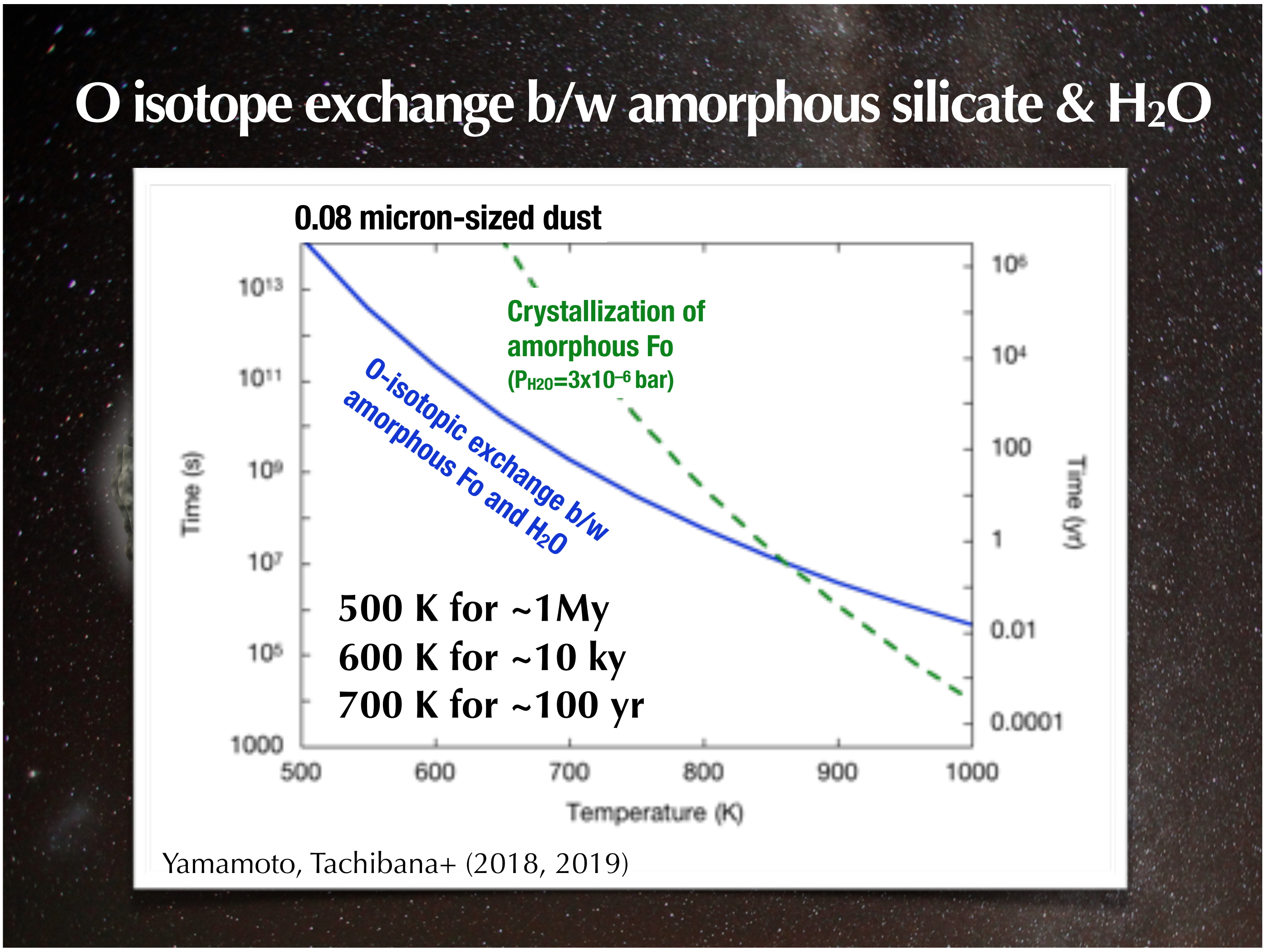
structural O + $H_2{}^*O$ ⇆ *OH + OH ⇆ structural *O + H_2O

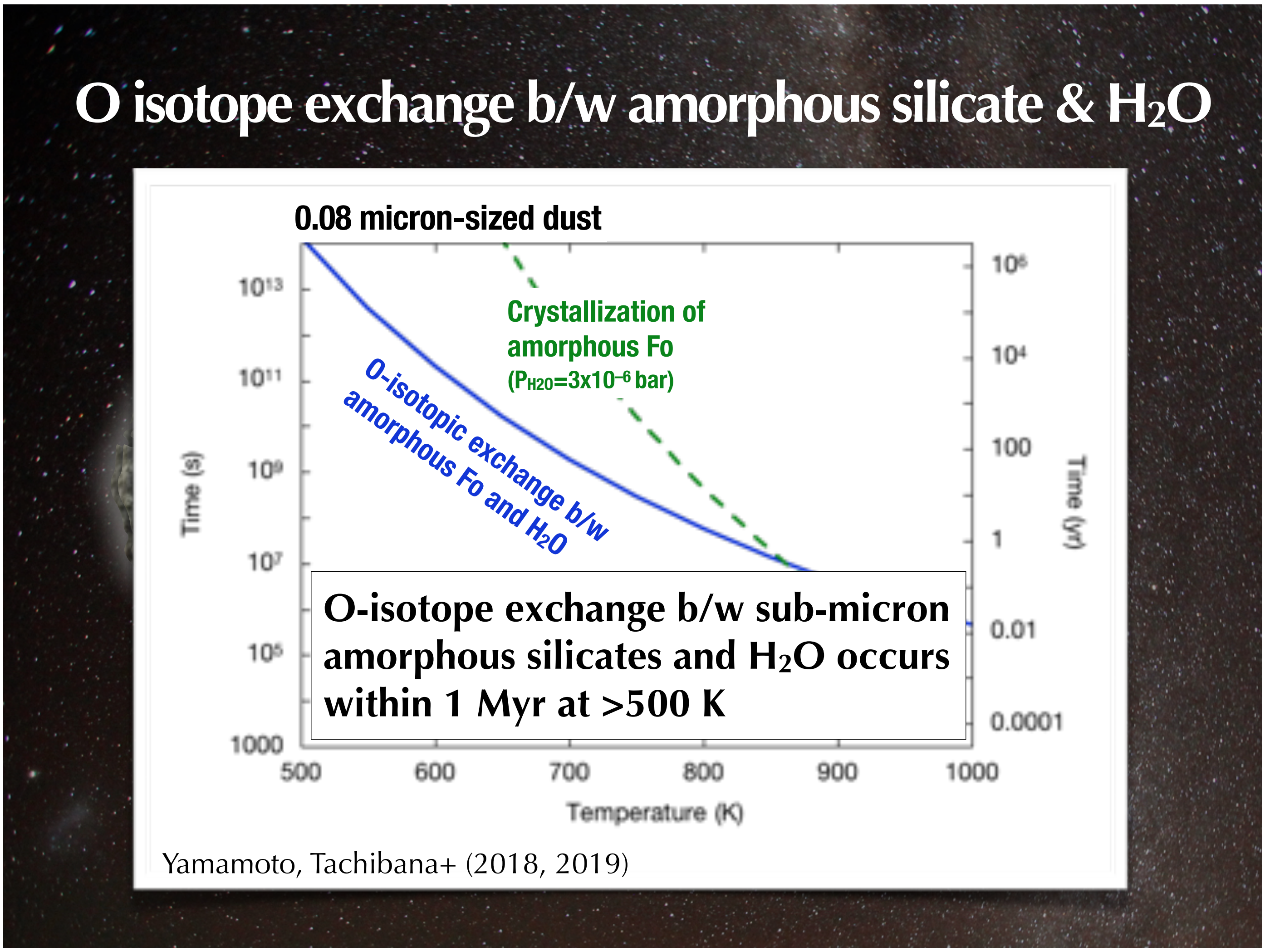


Yamamoto & Tachibana (2018); Kuroda, Tachibana+ (2018);

O isotope exchange b/w amorphous silicate & H_2O



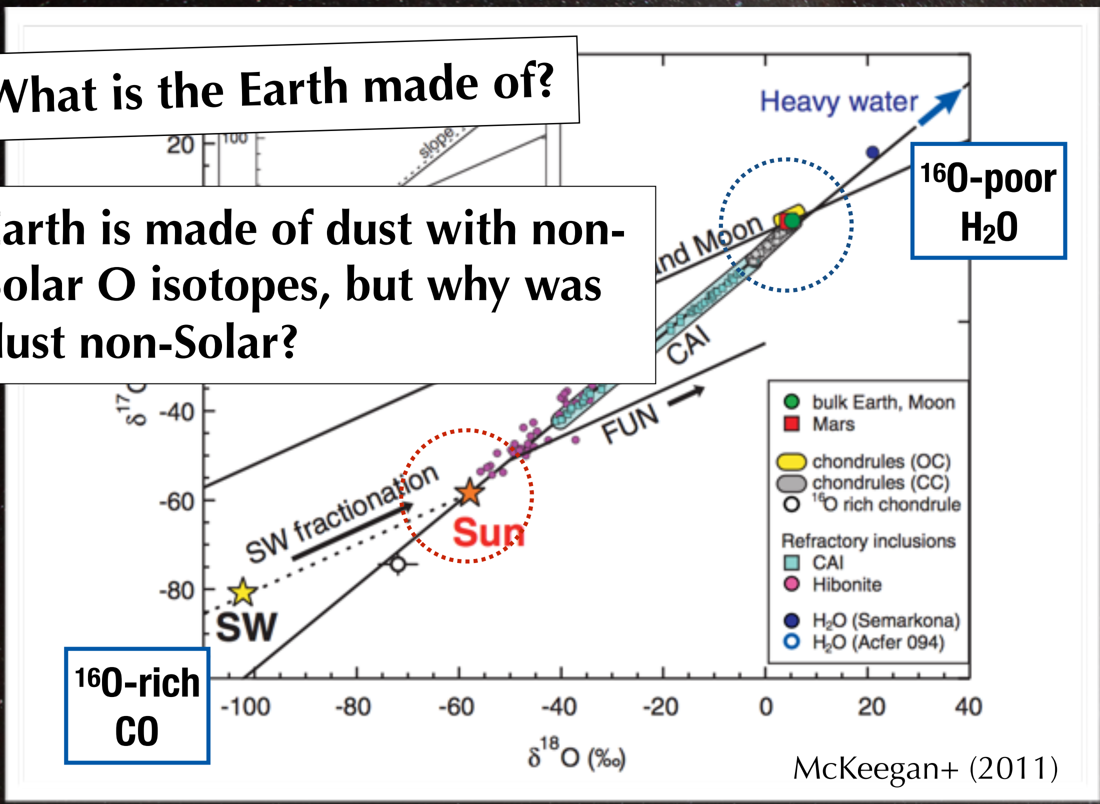

O isotope exchange b/w amorphous silicate & H_2O
0.08 micron-sized dust
Crystallization of
amorphous Fo
(P_{H2O}=3x10^{-6} bar)
O-isotopic exchange b/w
amorphous Fo and H_2O
500 K for ~1My
600 K for ~10 ky
700 K for ~100 yr
Time (s)
10^{13}
10^{11}
10^{9}
10^{7}
10^{5}
1000
Time (yr)
10^{6}
10^{4}
100
1
0.01
0.0001
500
600
700
800
900
1000
Temperature (K)
Yamamoto, Tachibana+ (2018, 2019)


O isotope exchange b/w amorphous silicate & H_2O
0.08 micron-sized dust
Crystallization of
amorphous Fo
(P_{H2O}=3x10^{-6} bar)
O-isotopic exchange b/w
amorphous Fo and H_2O
O-isotope exchange b/w sub-micron amorphous silicates and H_2O occurs within 1 Myr at >500 K
Time (s)
10^{13}
10^{11}
10^{9}
10^{7}
10^{5}
1000
Time (yr)
10^{6}
10^{4}
100
1
0.01
0.0001
500
600
700
800
900
1000
Temperature (K)
Yamamoto, Tachibana+ (2018, 2019)

Oxygen isotope evolution

What is the Earth made of?

Earth is made of dust with non-Solar O isotopes, but why was dust non-Solar?



Oxygen isotope evolution

What is the Earth made of?

Earth is made of dust with non-Solar O isotopes, but why was dust non-Solar?

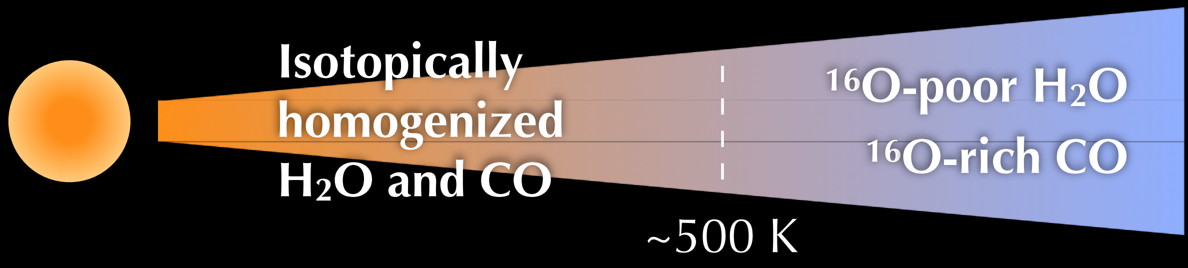
Oxygen isotope exchange reaction

Did all the dust experience heating at above 500 K?

Are there any residual ^{16}O-rich pristine dust anywhere in the Solar System?

Ryugu? Another comet sample return?

Oxygen isotope evolution



Oxygen isotope homogenization-line?

4. **Astronomical observation** should help us to understand how the Solar-System dynamically and chemically evolved to the present state, as a part of the Galactic evolution, by **combining with the extraterrestrial material research**