Tracing the Ingredients for a Habitable Earth from Interstellar Space Through Planet Formation

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The Ingredients for a Habitable World

at right distance from star

liquid water

volatile elements (CHON)

How can we make connections from astronomy to planets/ exoplanets?

Tracing Chemical Origins

- For terrestrial worlds and giant planets: difficult to determine what was provided when and in what form.
- For C and N carriers it is easier to concentrate on BULK composition (if possible).
  - i.e. not worrying about a particular organic needed to make RNA
- Oxygen is an important outlier in this regard as we know it was provided as H_2O + silicates.

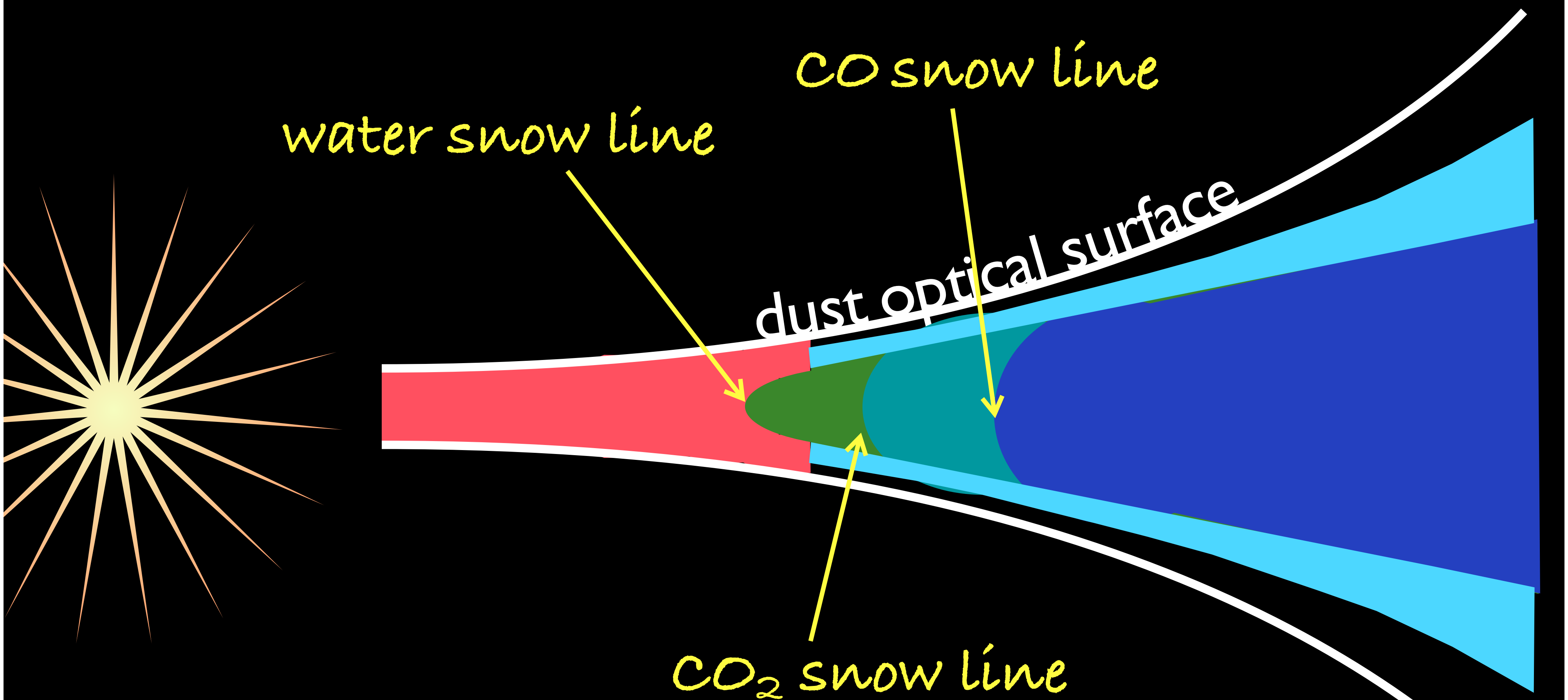
Planetary Synthesis Modeling

- e.g. Mordasini; Rubie; Bond; Mulders; Cridland; …
- Assume some initial chemical composition of disk that is implanted into planetesimals.
  - ➡ Could use chemical equilibrium; solar system constraints; or kinetic chemical models.
- Composition is fixed (no loss) as planetesimals grow.
- Dynamical model is imprinted (where are giant planets and do they move); build giant and terrestrial planets via N-body simulations.

Tracing Chemical Origins: Giant Planets

- Strong focus on atmospheric C/O ratios motivated by Öberg, Murray-Clay, & Bergin 2011.
- Basic idea:
  - ➡ core-accretion model of giant planet formation
  - ➡ rocks/ices go to core (assume it does not mix)
  - ➡ atmosphere accreted from nebular gas
  - ➡ location of planet formation can change C/O ratio based on snowlines.

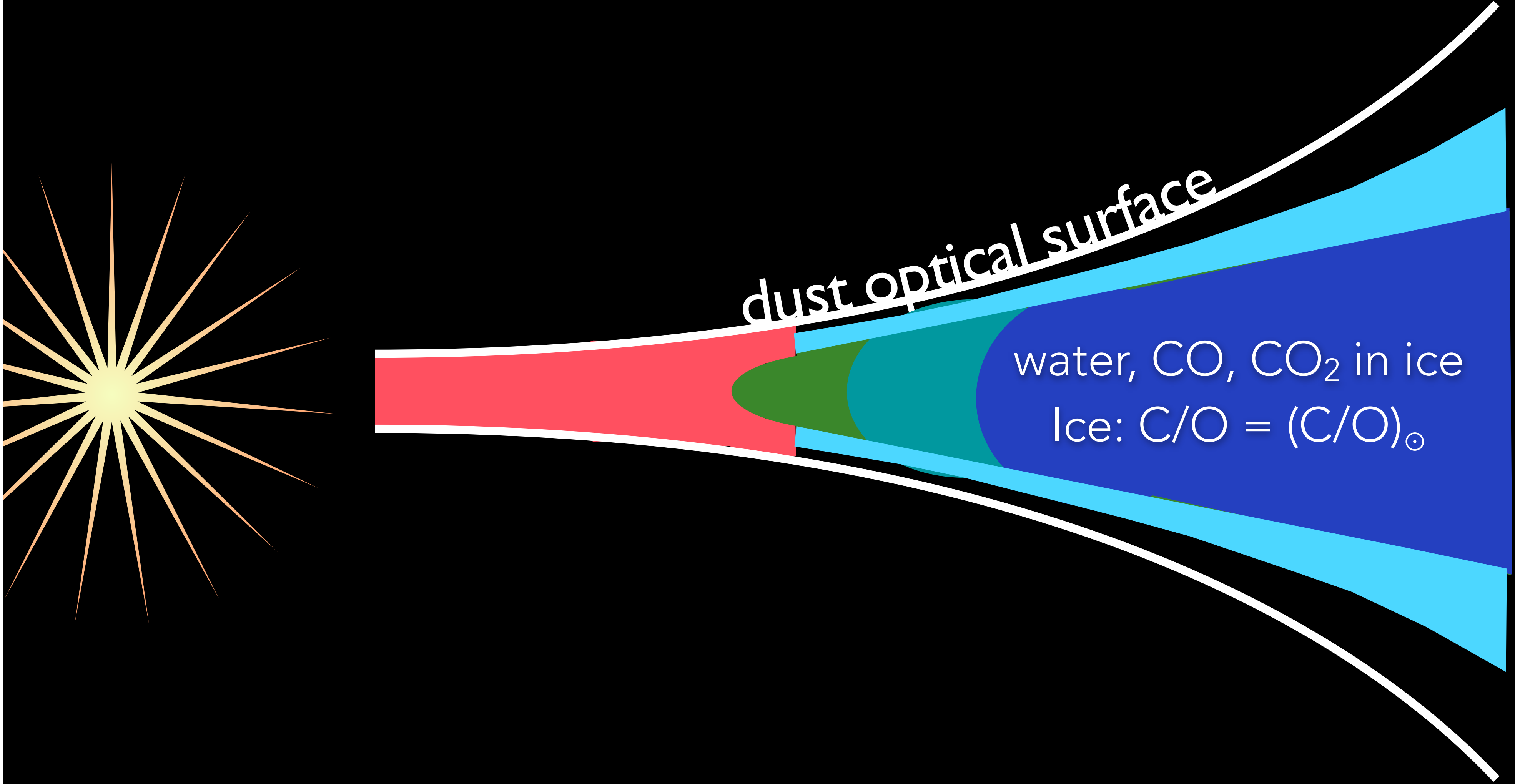
C/O Ratio



Caveat: assuming some O in silicates but does not include organics (C-rich + O) and additional unidentified oxygen component

Öberg, Murray-Clay, & Bergin 2011

C/O Ratio



Öberg, Murray-Clay, & Bergin 2011

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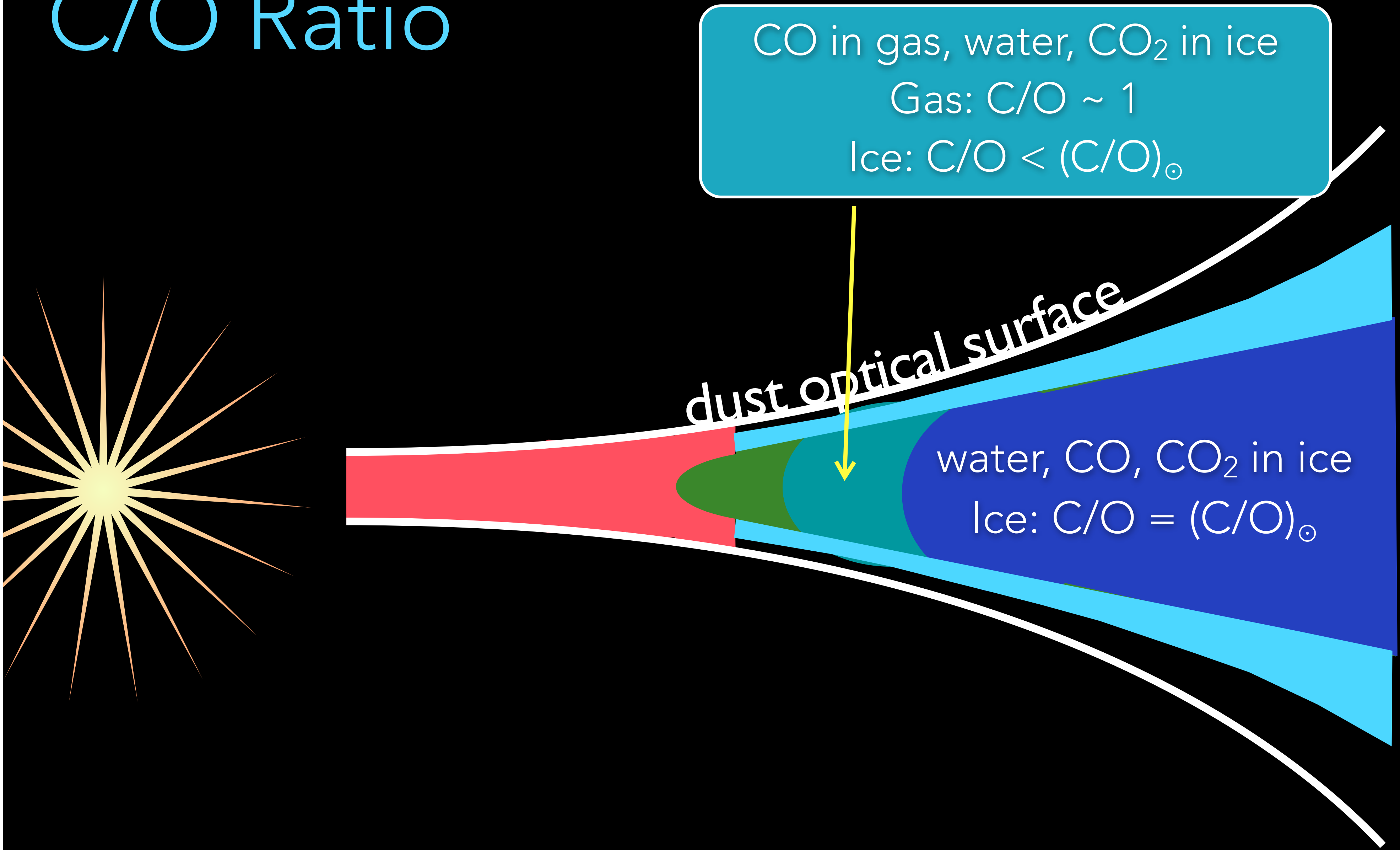

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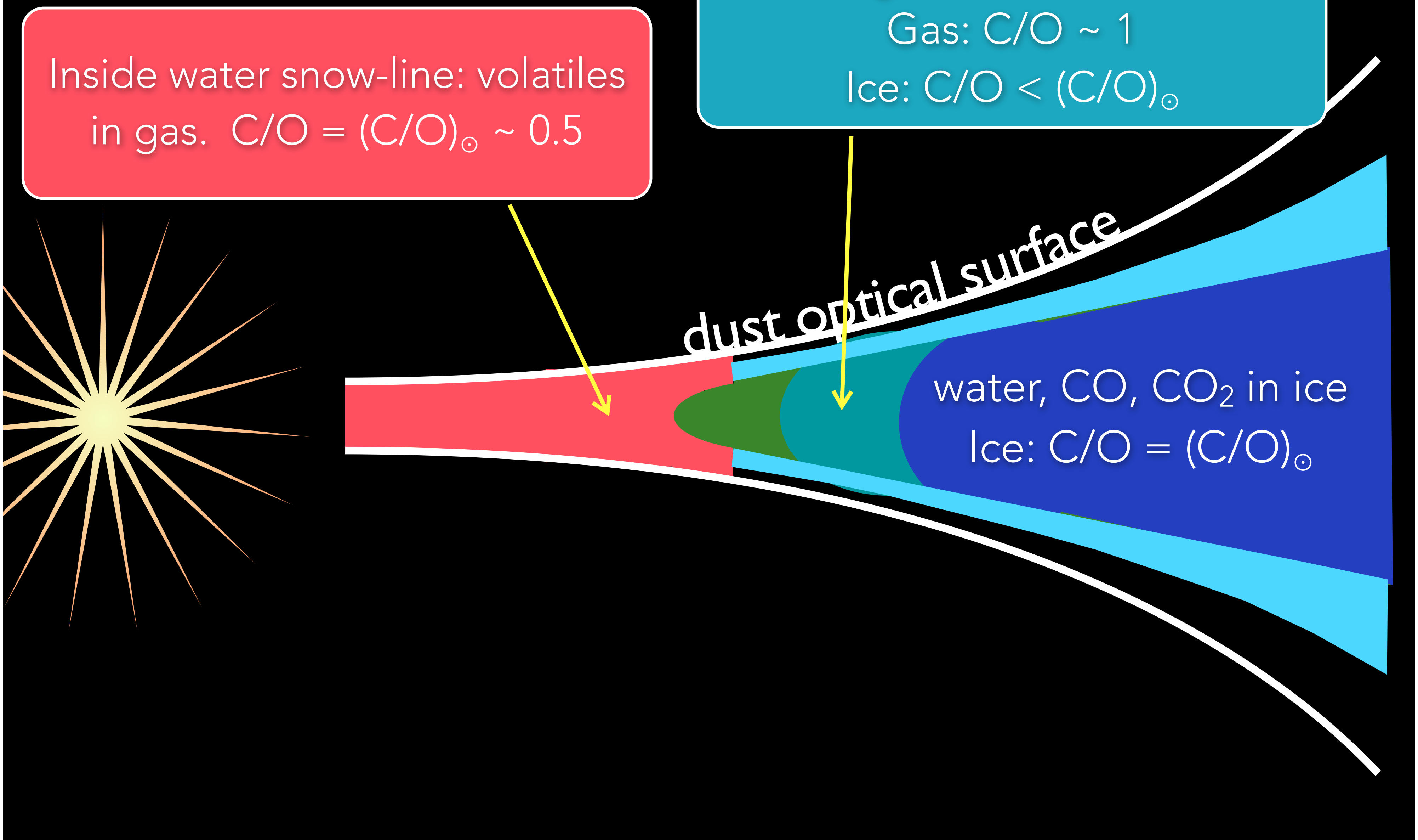

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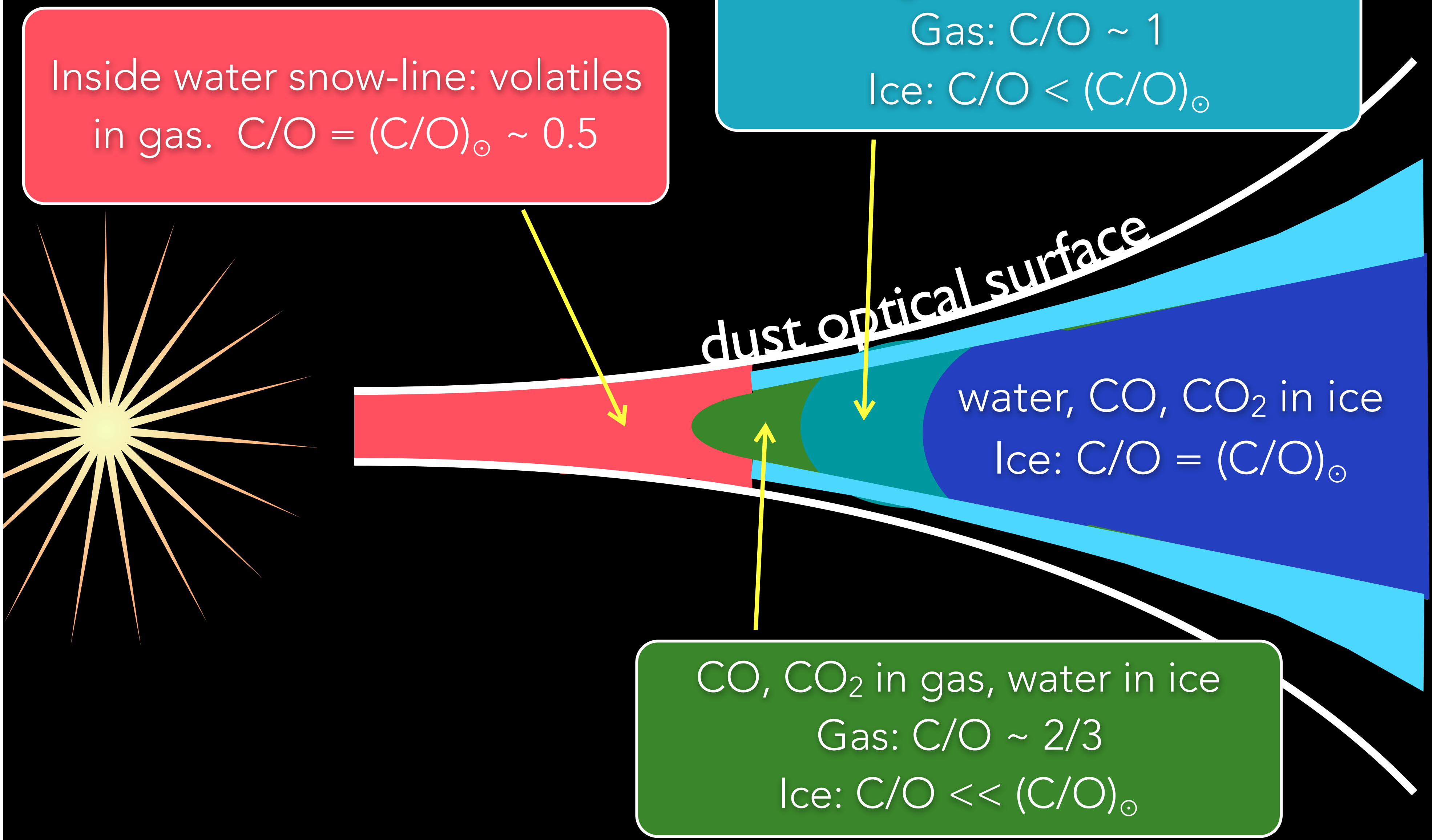
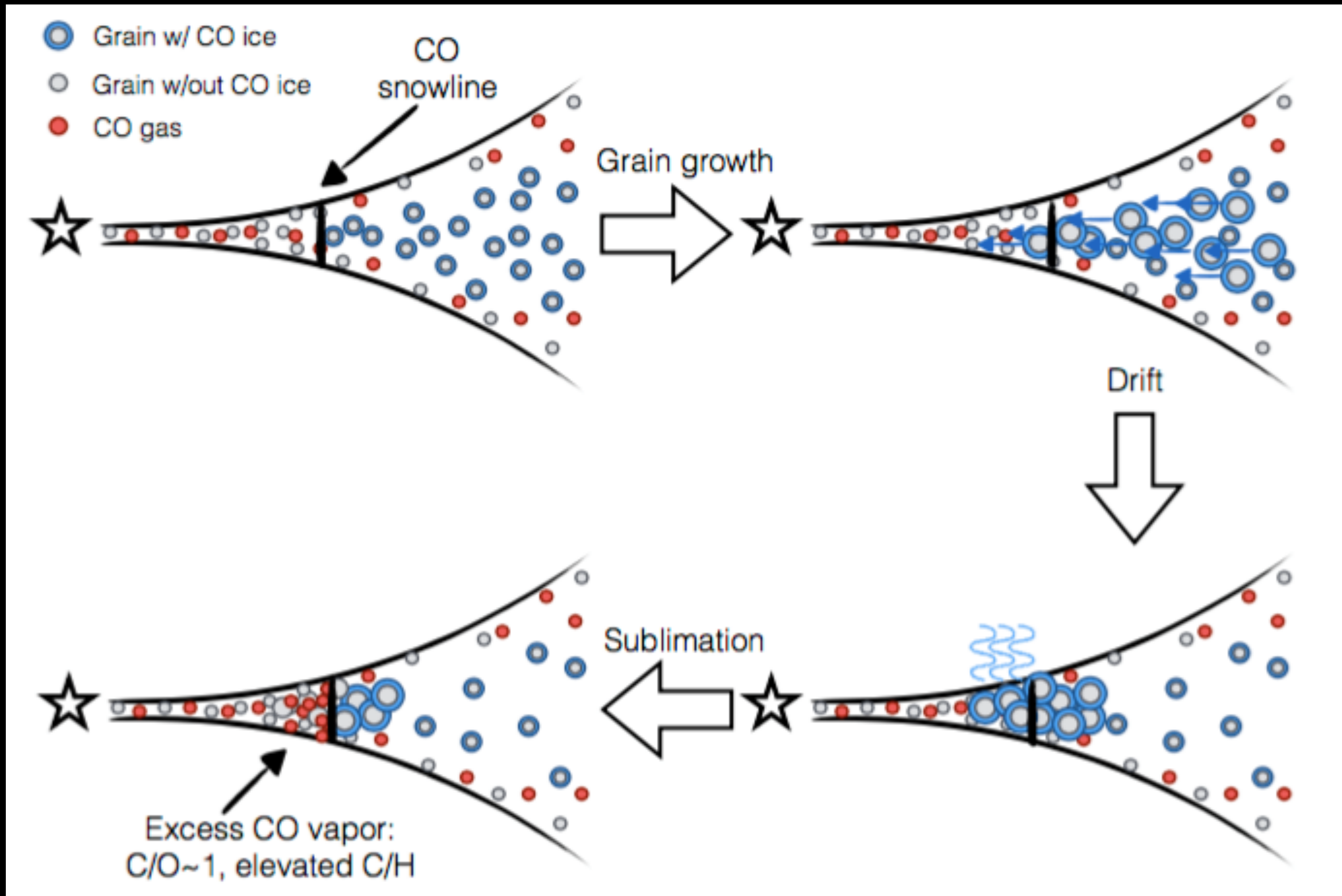


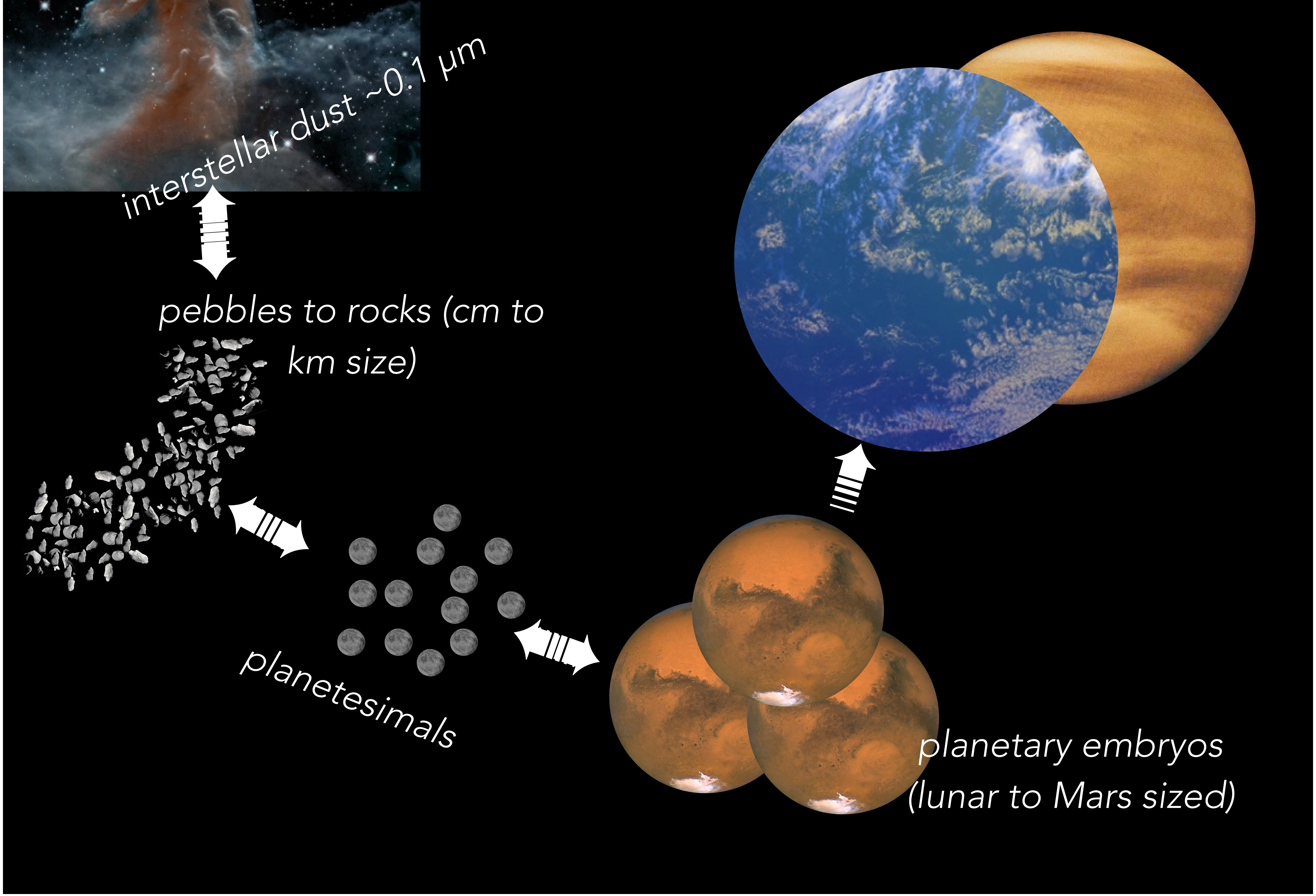
Öberg, Murray-Clay, & Bergin 2011

C/O Ratio & Elevated C/H

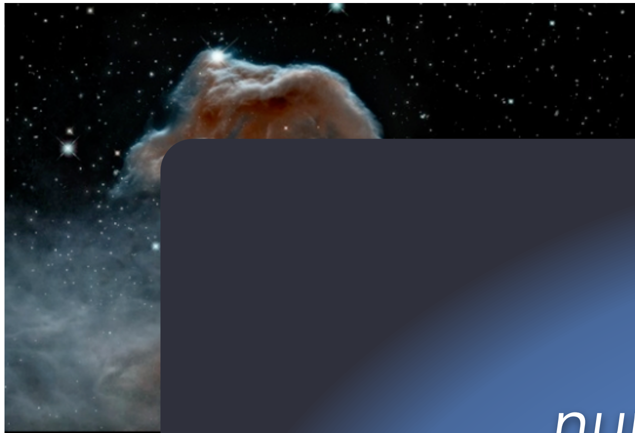


Öberg & Bergin 2016

Making a terrestrial world



Making a terrestrial world



numerous potential loss terms -
drift/evaporation;
internal heatings in planetesimals;
collisions; core formation

NEED to understand key processes first!!!
talk to experts who have studied
our planet

Tracing Origins of the Earth

Tracers of Bulk Composition in Starting Materials

- *Interstellar medium:* initial chemical/physical conditions
- *Comets:*
  - ➡ *Halley* - studied in situ
  - ➡ *Sun-grazing*

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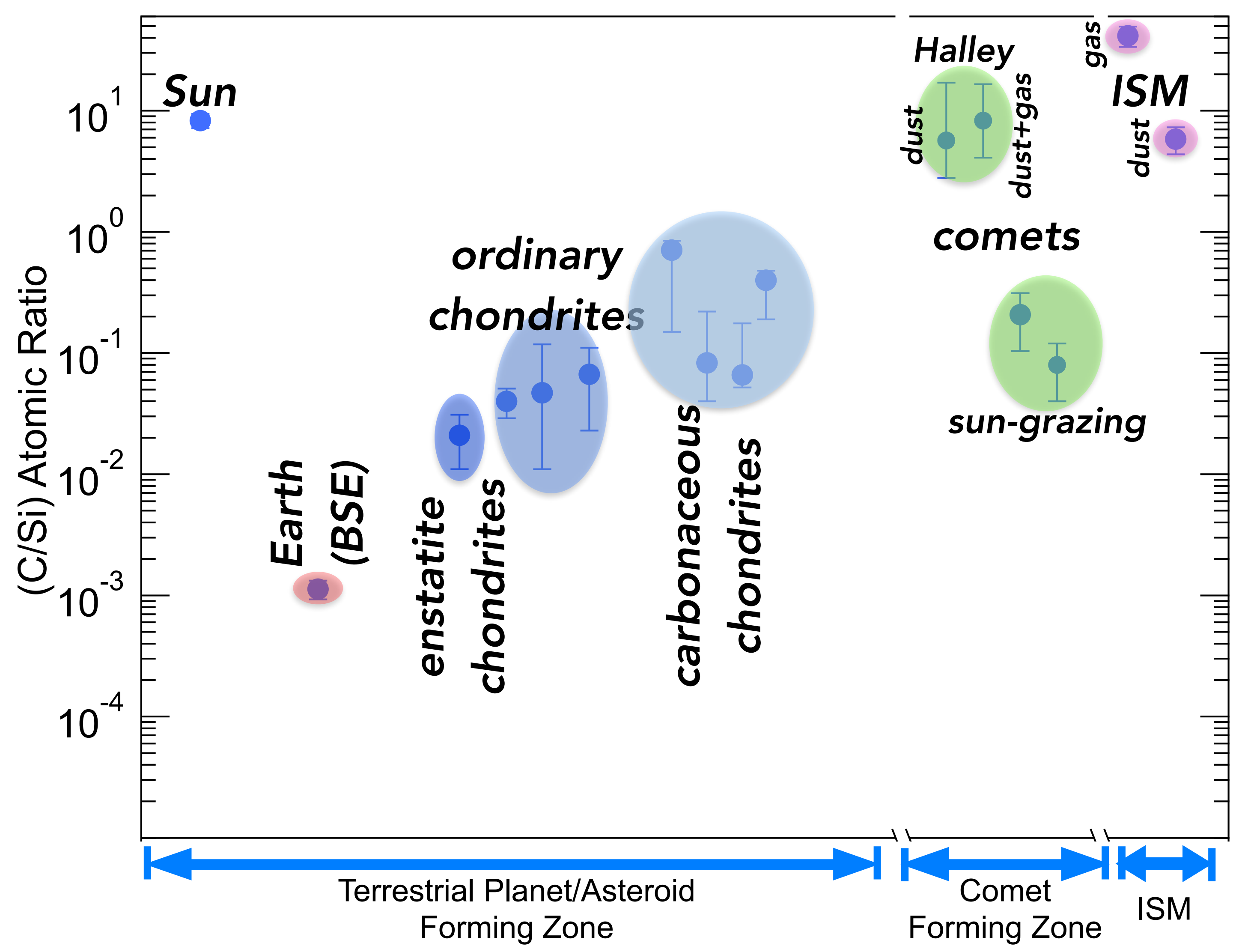
Tracers of Bulk Composition in Starting Materials

- *Meteorites:* sample asteroid belt
  - ➡ *Carbonaceous chondrites:* rare primitive meteorites
  - ➡ *Ordinary chondrites:* common, most have evidence for metamorphism ($T > 800$ K in parent body)
  - ➡ *Enstatite chondrites:* rare, low oxygen
- *Bulk Silicate Earth:* entire Earth (including atm./oceans) minus the core

Carbon



(C/Si) Atomic Ratio
10^1
10^0
10^-1
10^-2
10^-3
10^-4
Sun
Earth (BSE)
enstatite chondrites
ordinary chondrites
carbonaceous chondrites
Halley
dust
dust+gas
comets
sun-grazing
gas
ISM
dust
Terrestrial Planet/Asteroid Forming Zone
Comet Forming Zone
ISM

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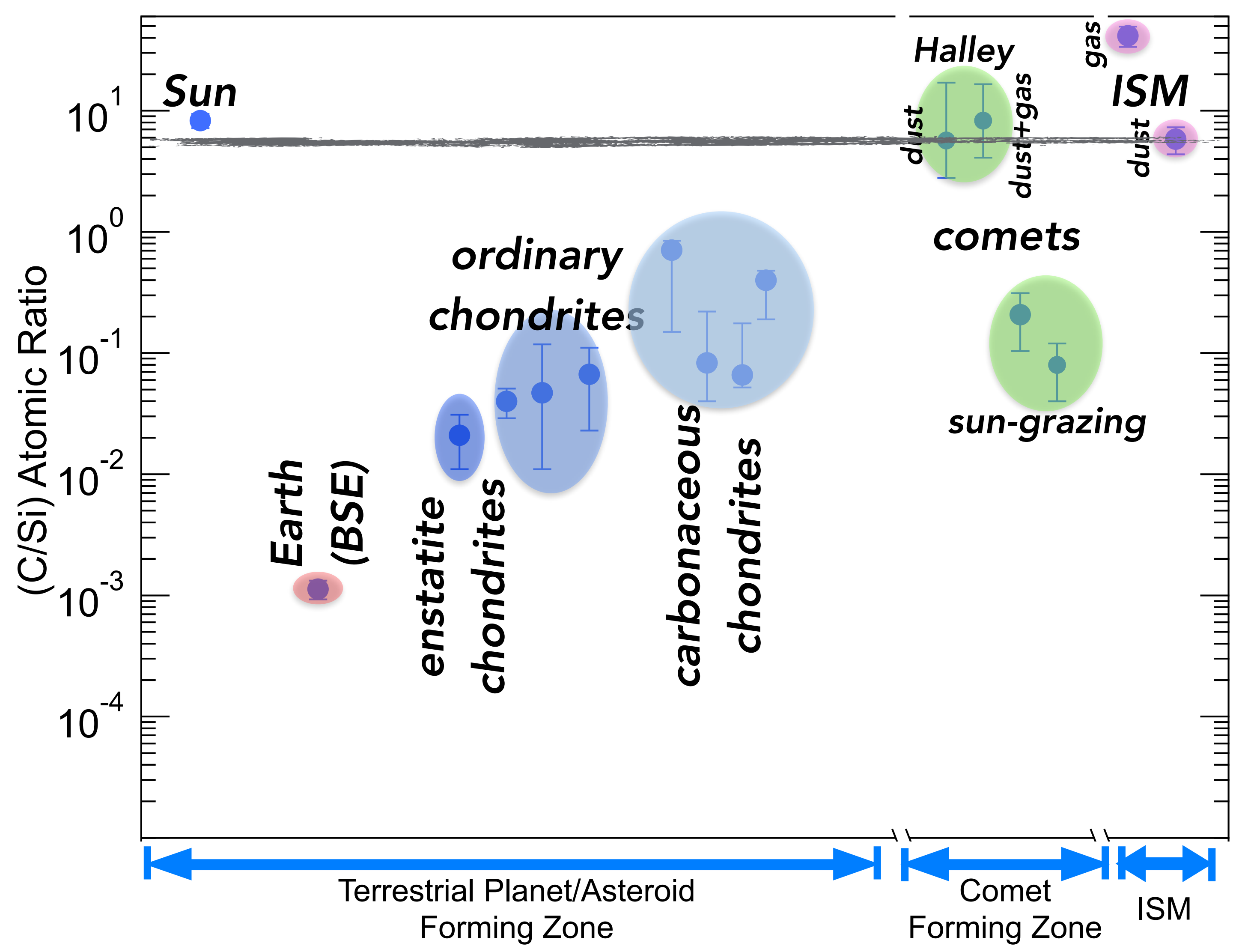

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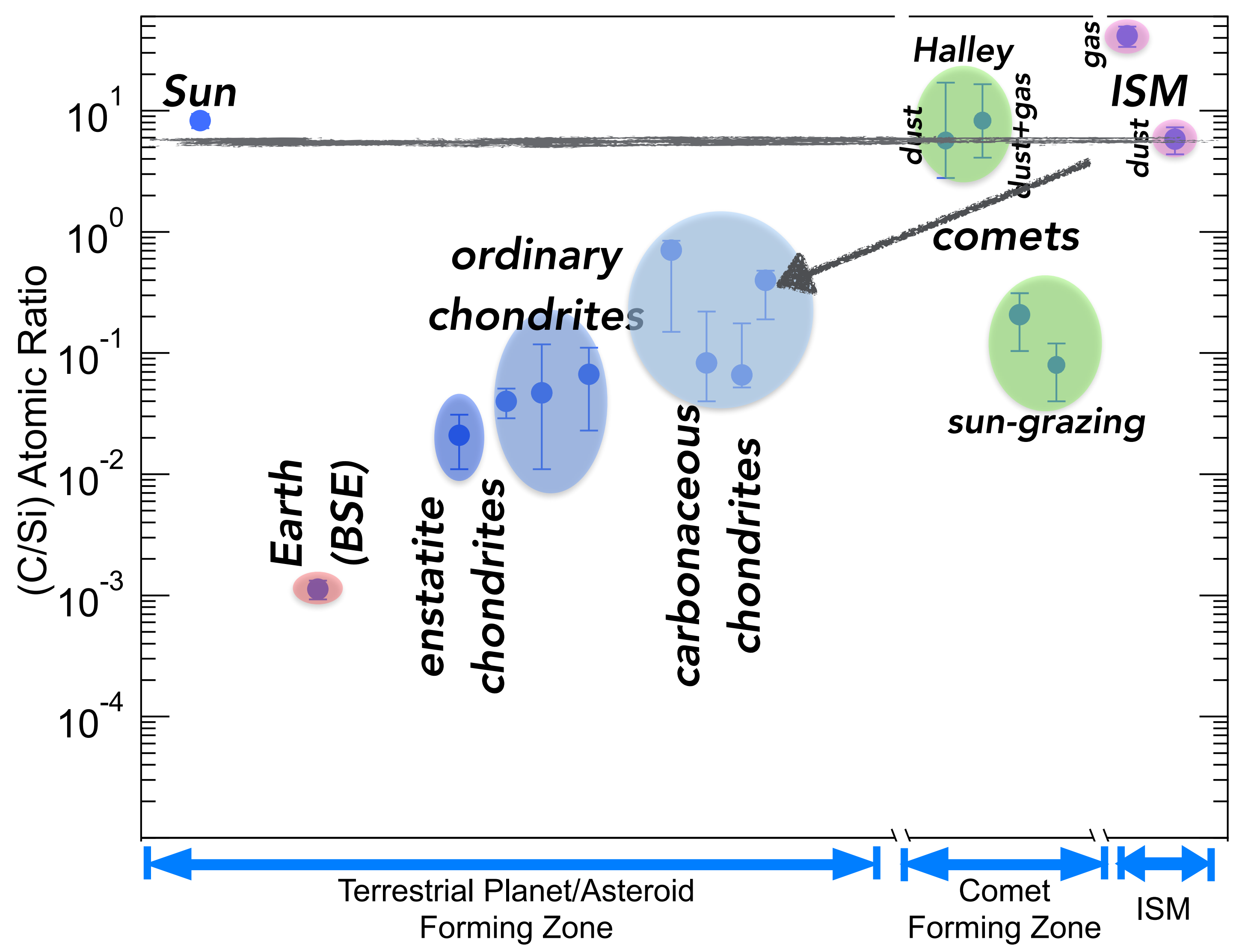

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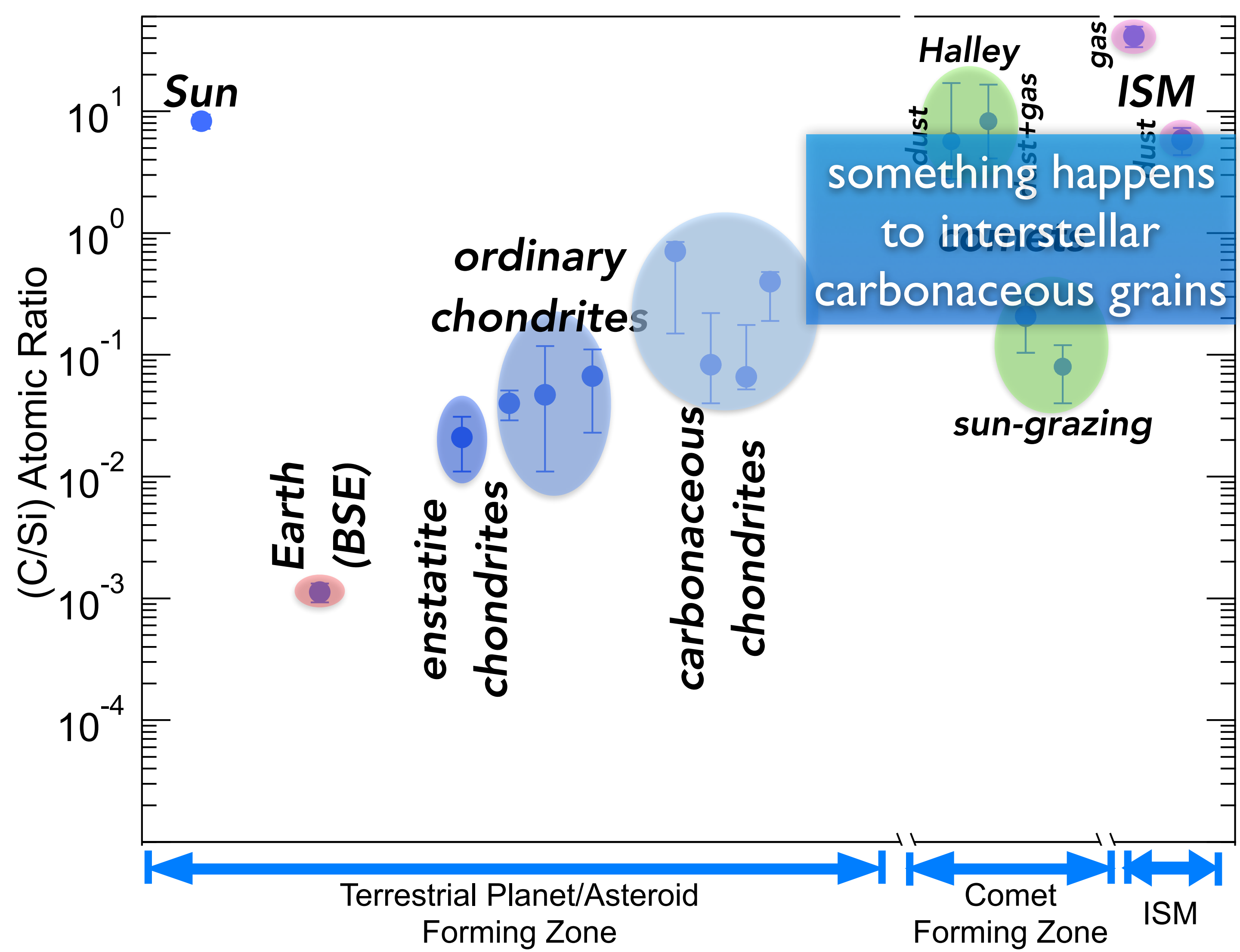
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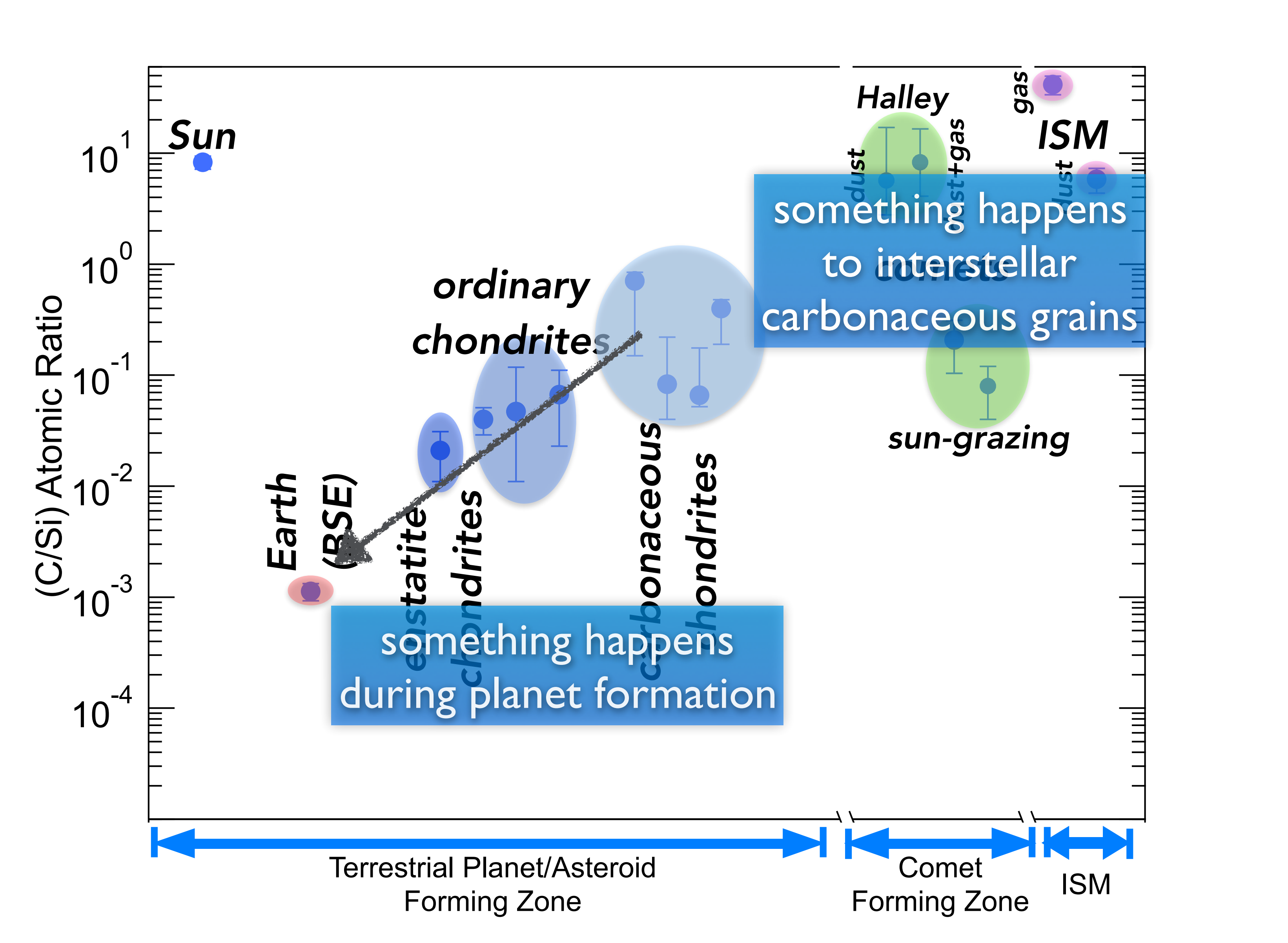
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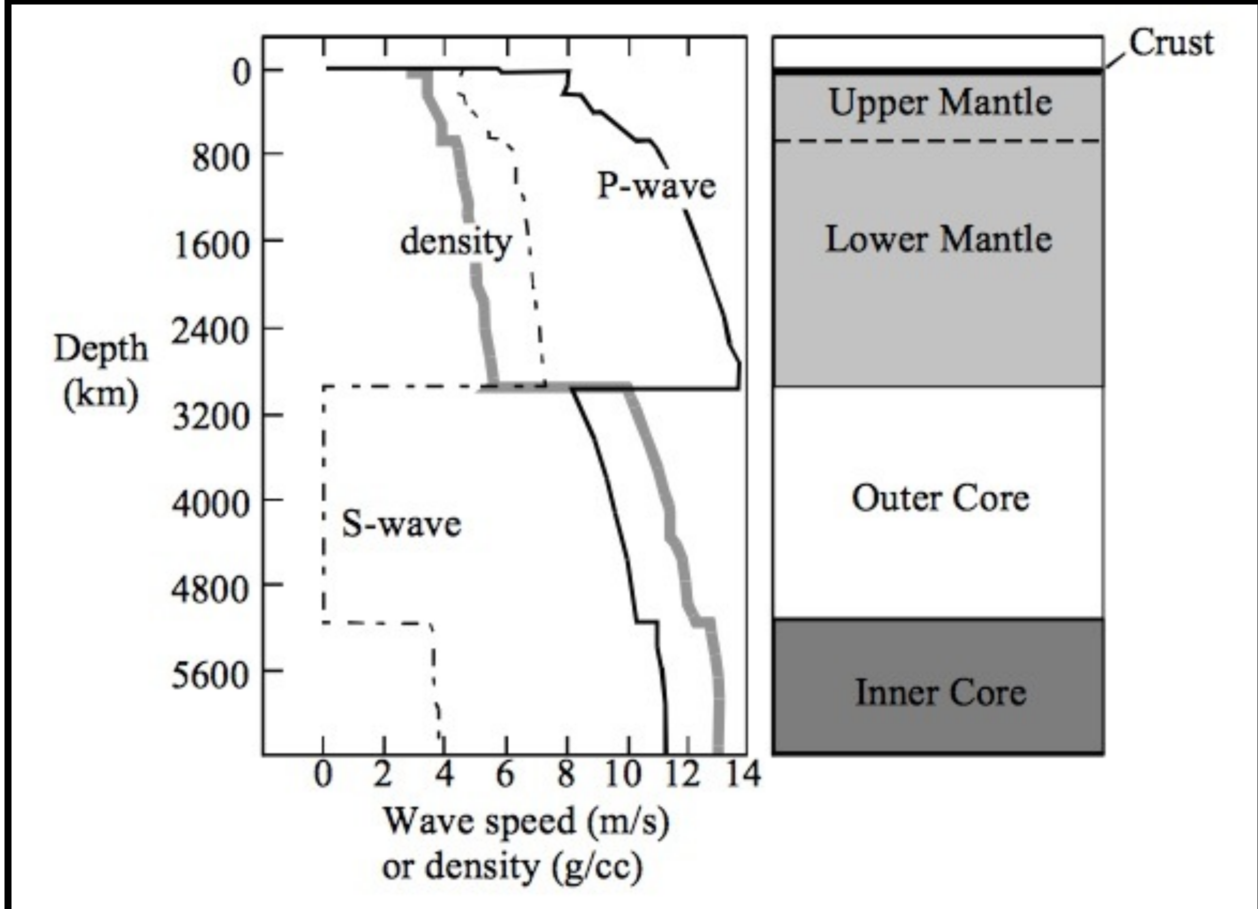
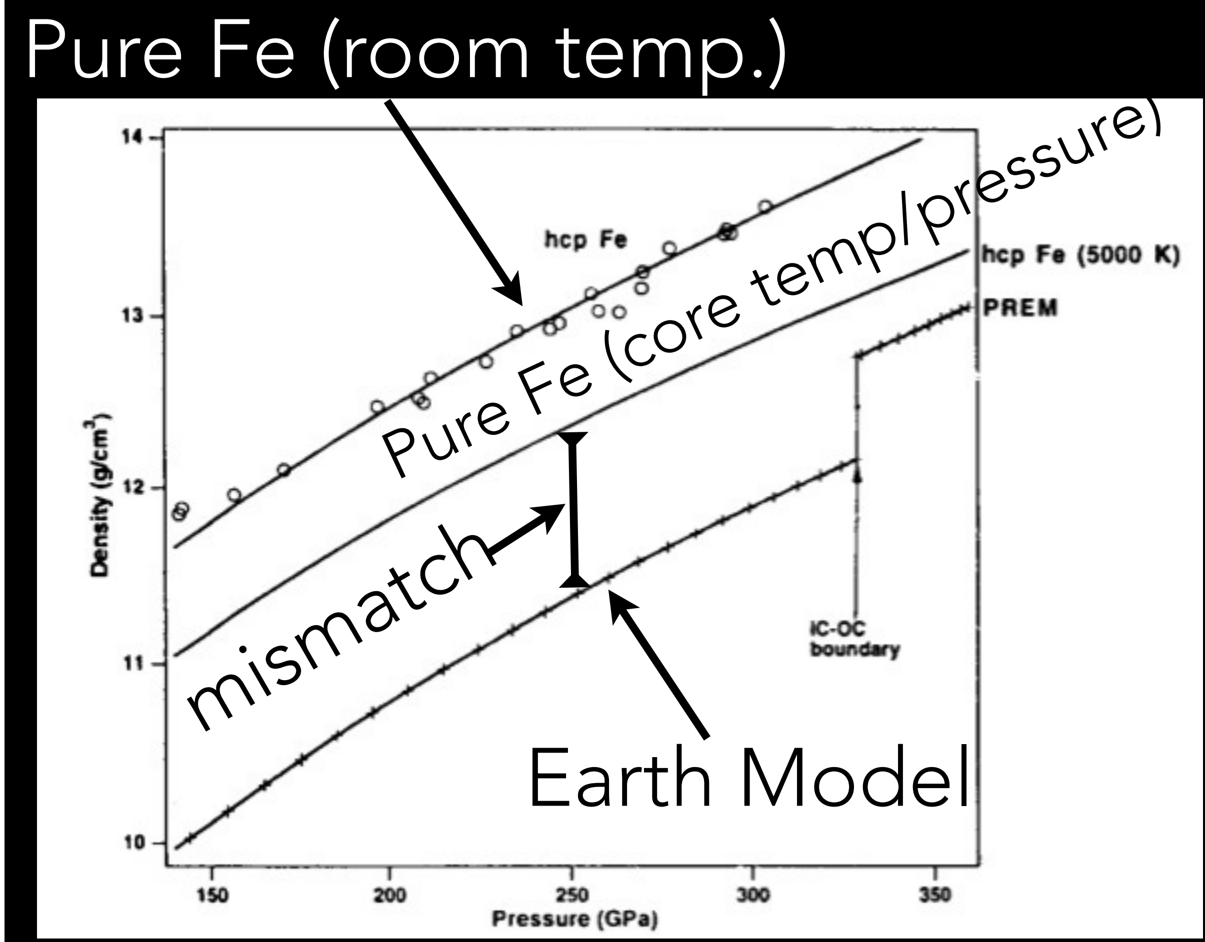
Light Elements in Earth's Core



McDonough 1999

- ➡ can measure the density of Earth's interior via propagation of seismic waves

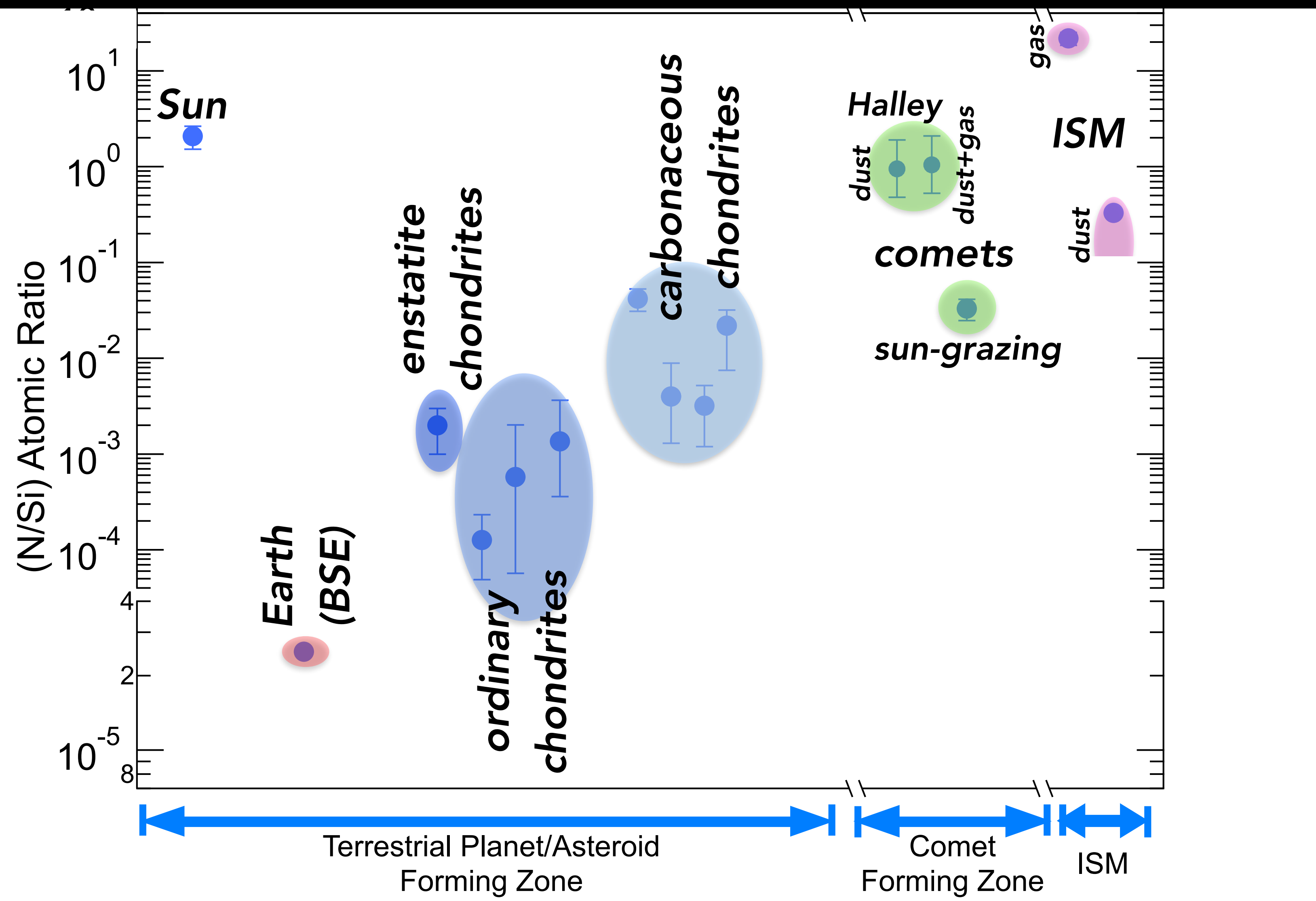
Light Elements in Earth's Core



Poirier 1994; Birsch 1952

- ➡ lower than expected density (than Fe) based on seismic wave propagation
- ➡ potential elements: H, C, O, Si, S, N

Nitrogen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10^1
10^0
10^-1
10^-2
10^-3
10^-4
4
2
10^-5
8
Sun
Earth
(BSE)
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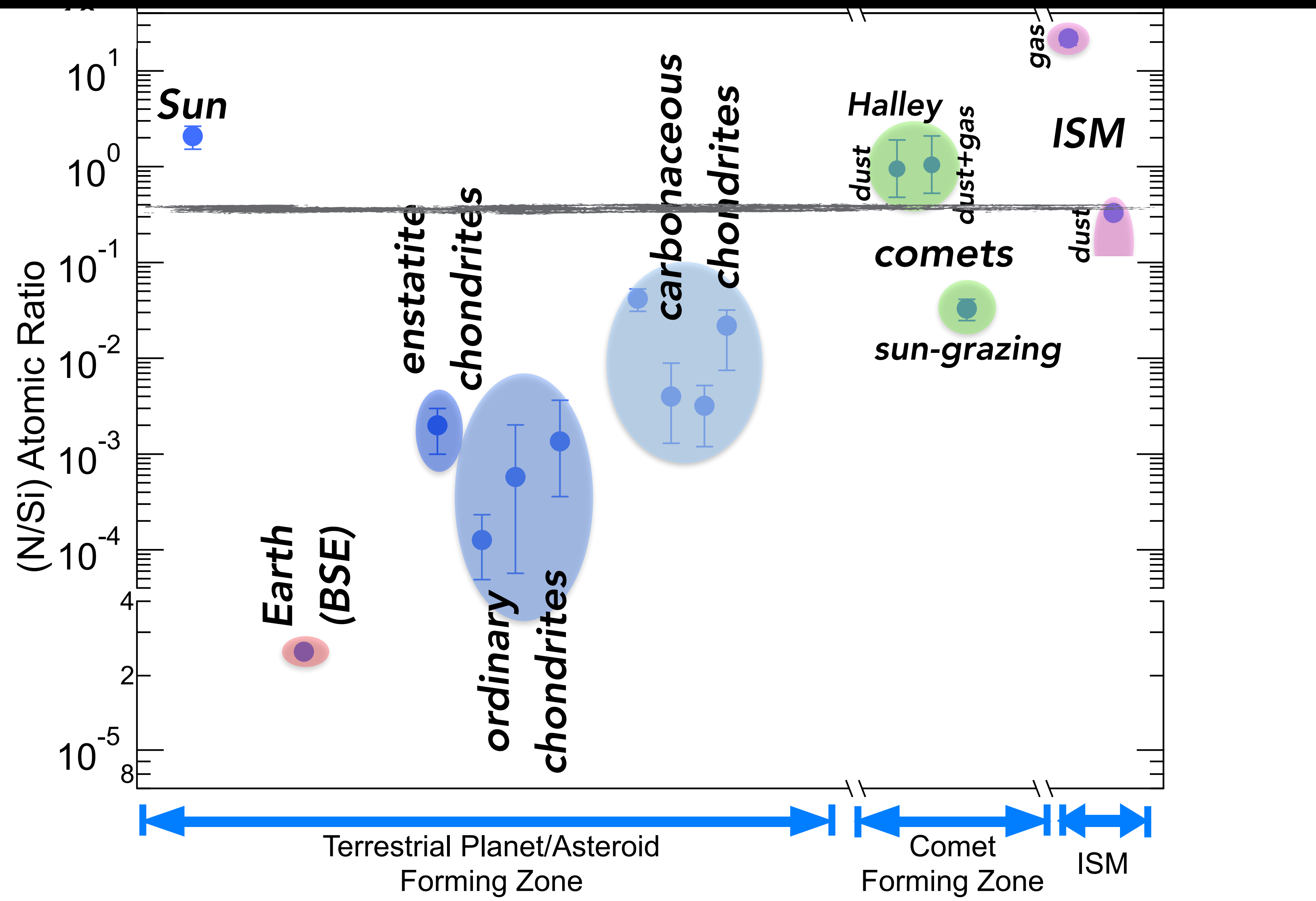

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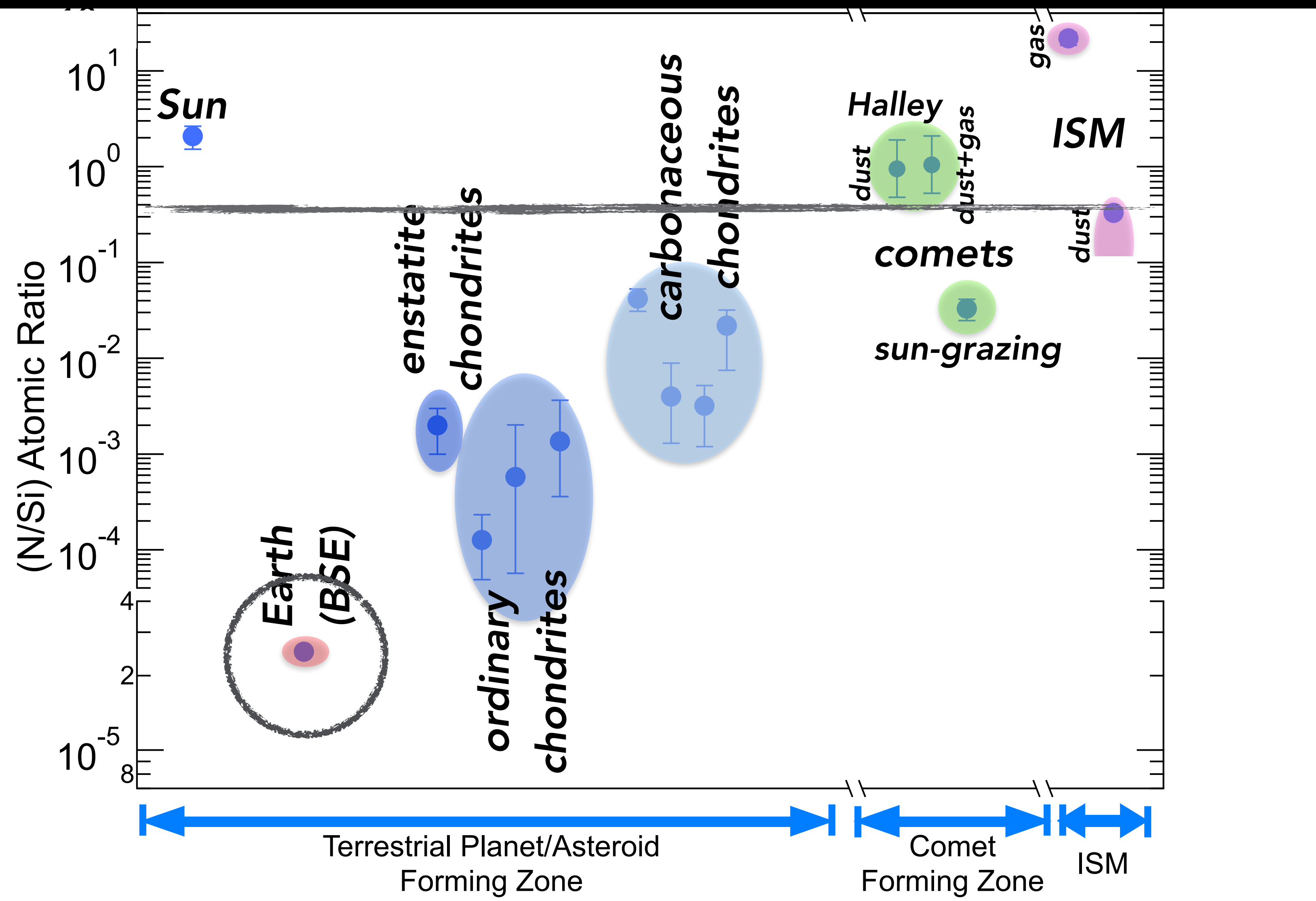

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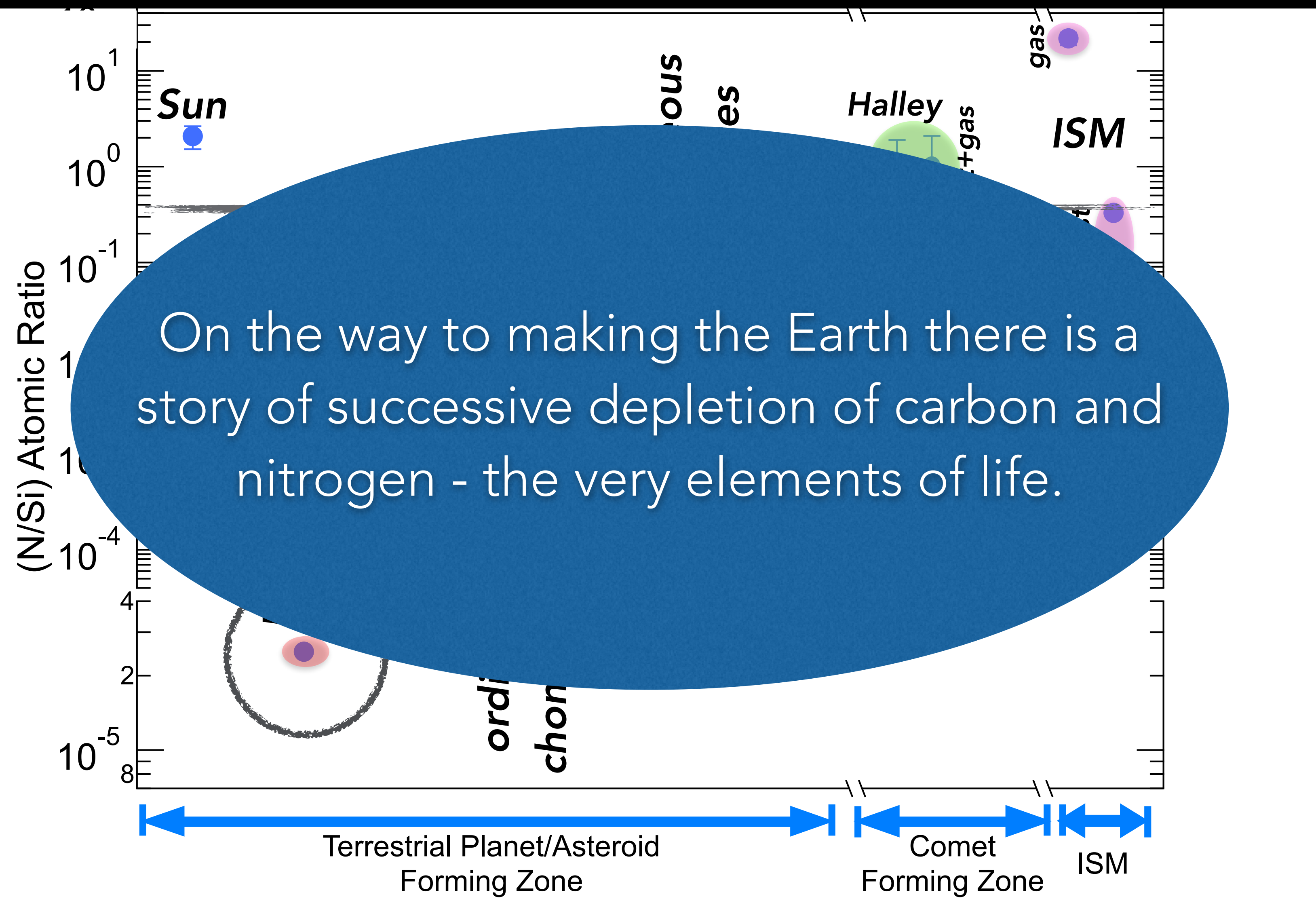
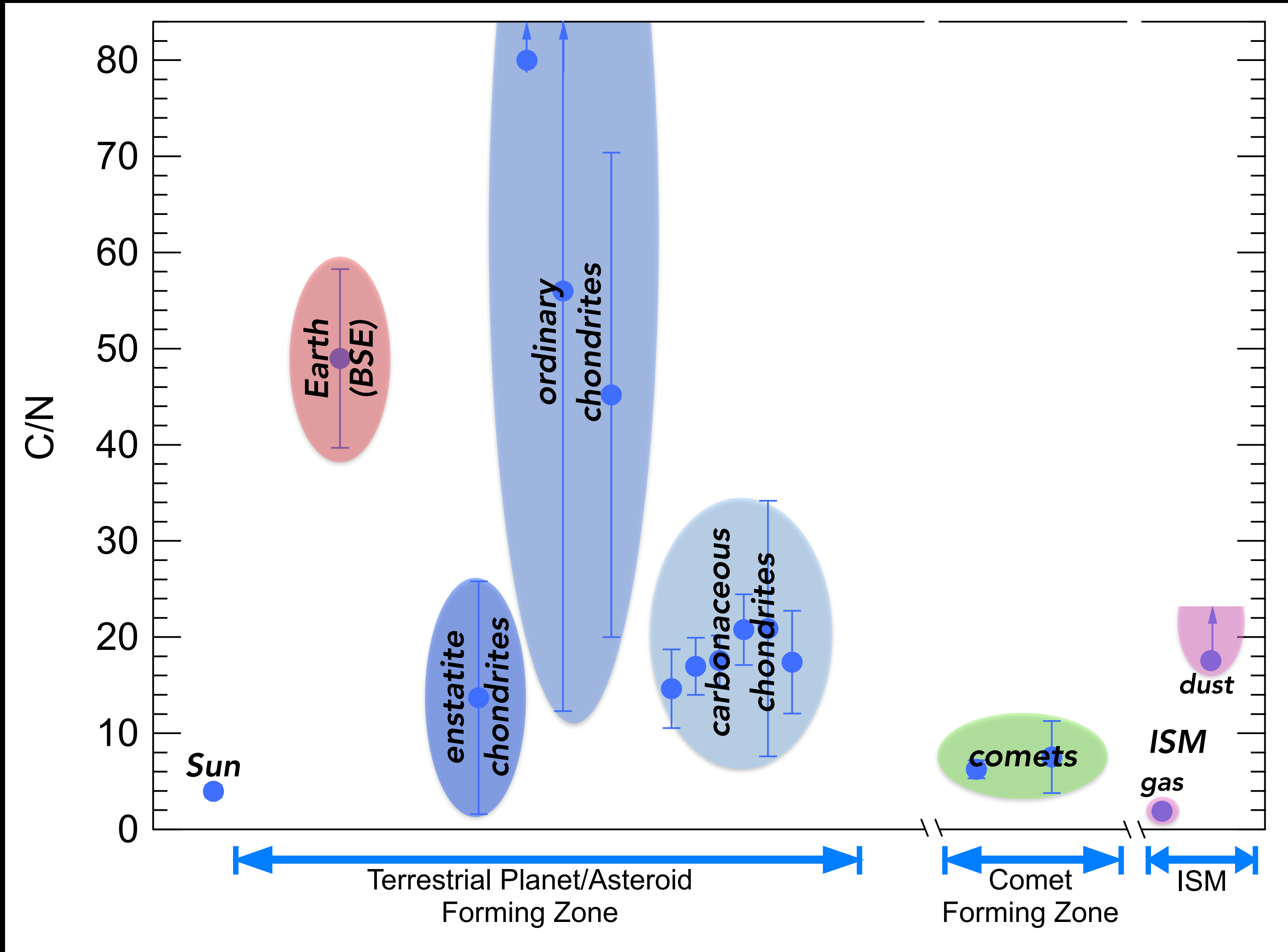


On the way to making the Earth there is a story of successive depletion of carbon and nitrogen - the very elements of life.

C/N as a Tracer of Process



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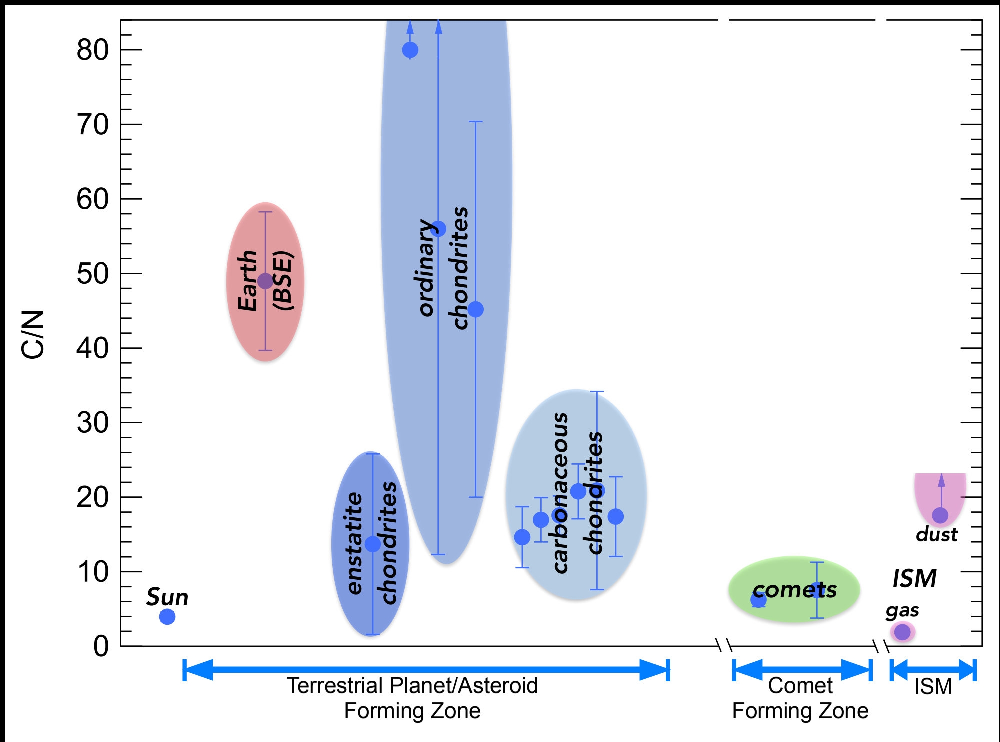

1) Except for Ordinary Chondrites, Earth C/N ≠ potential starting materials

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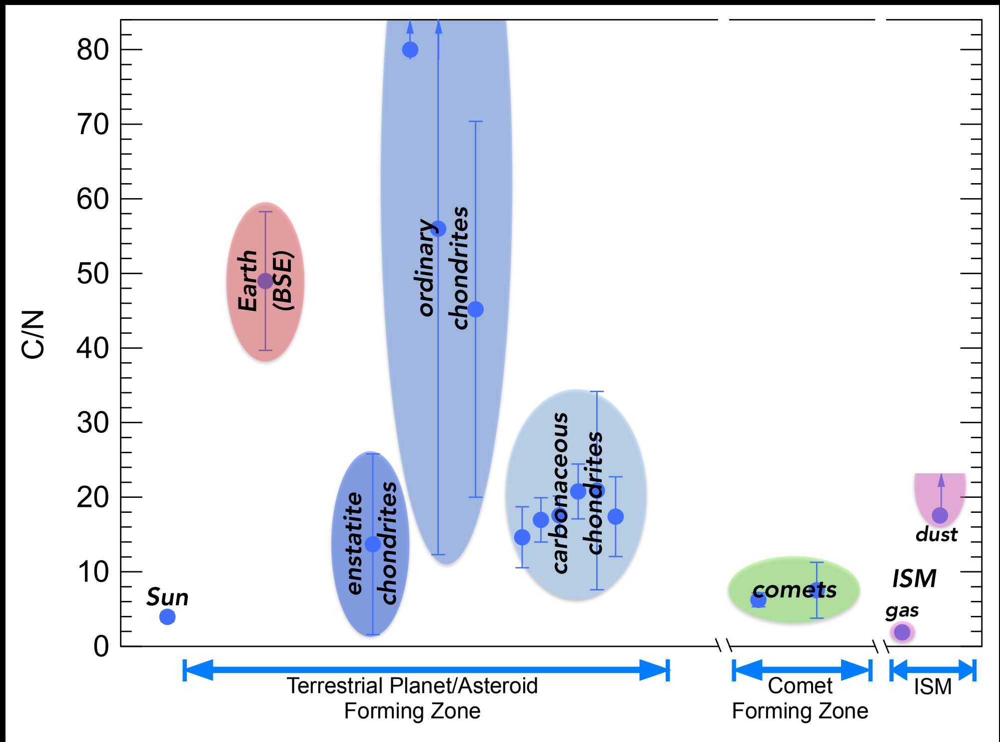

2) Isotopic evidence rules out ordinary chondrites as progenitor material

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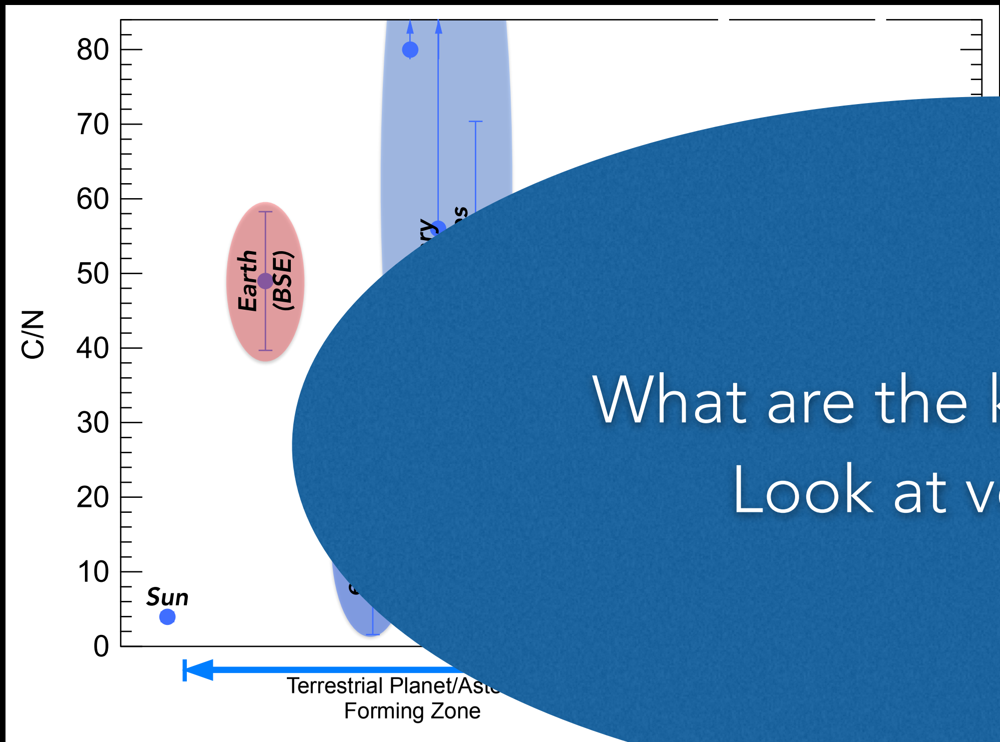
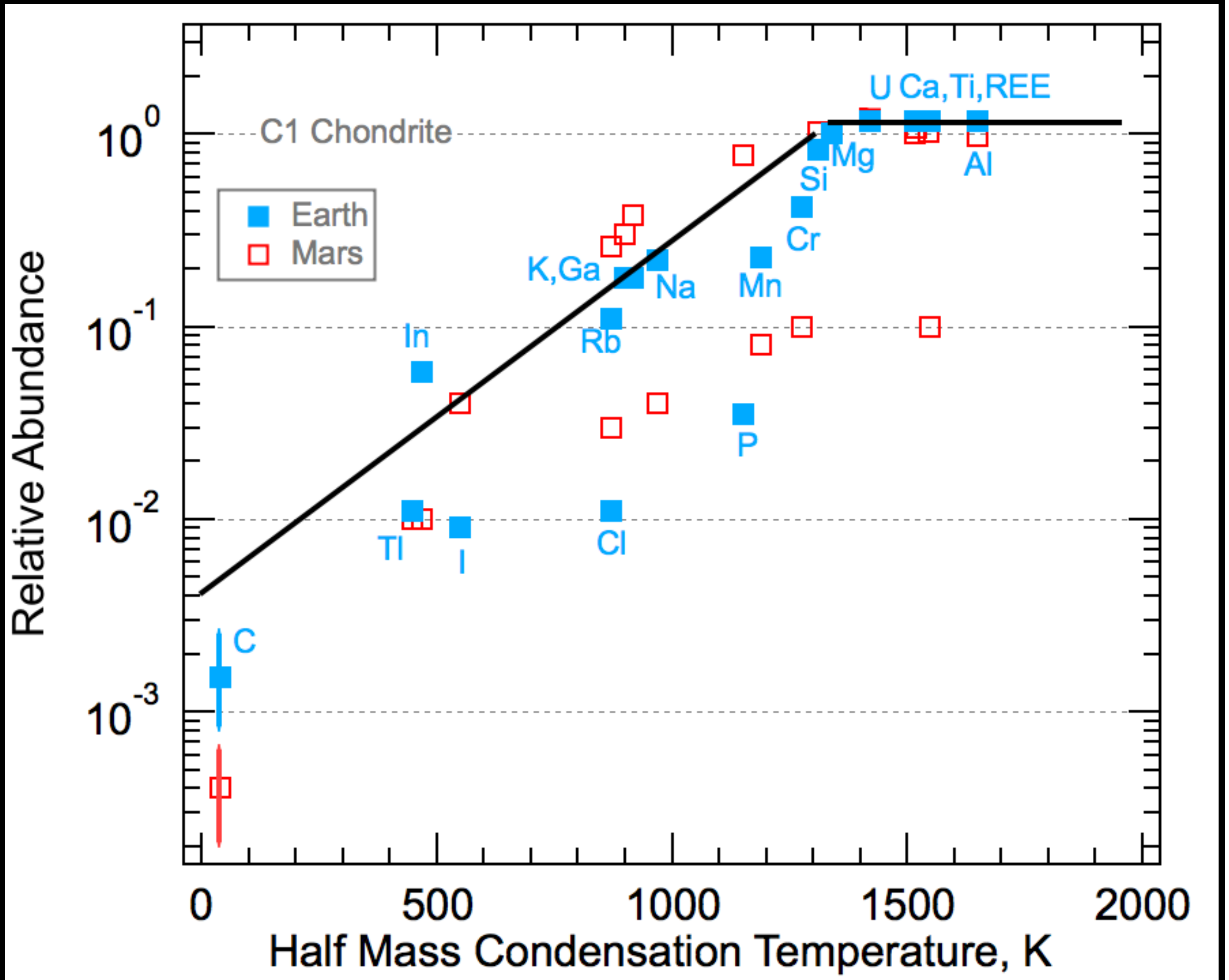


What are the key processes?
Look at volatility….

2) Isotopic evidence rules out ordinary chondrites as progenitor material

Volatility and Planet Composition

- generic idea: planets started hot and cooled down
- minerals form in condensation sequence

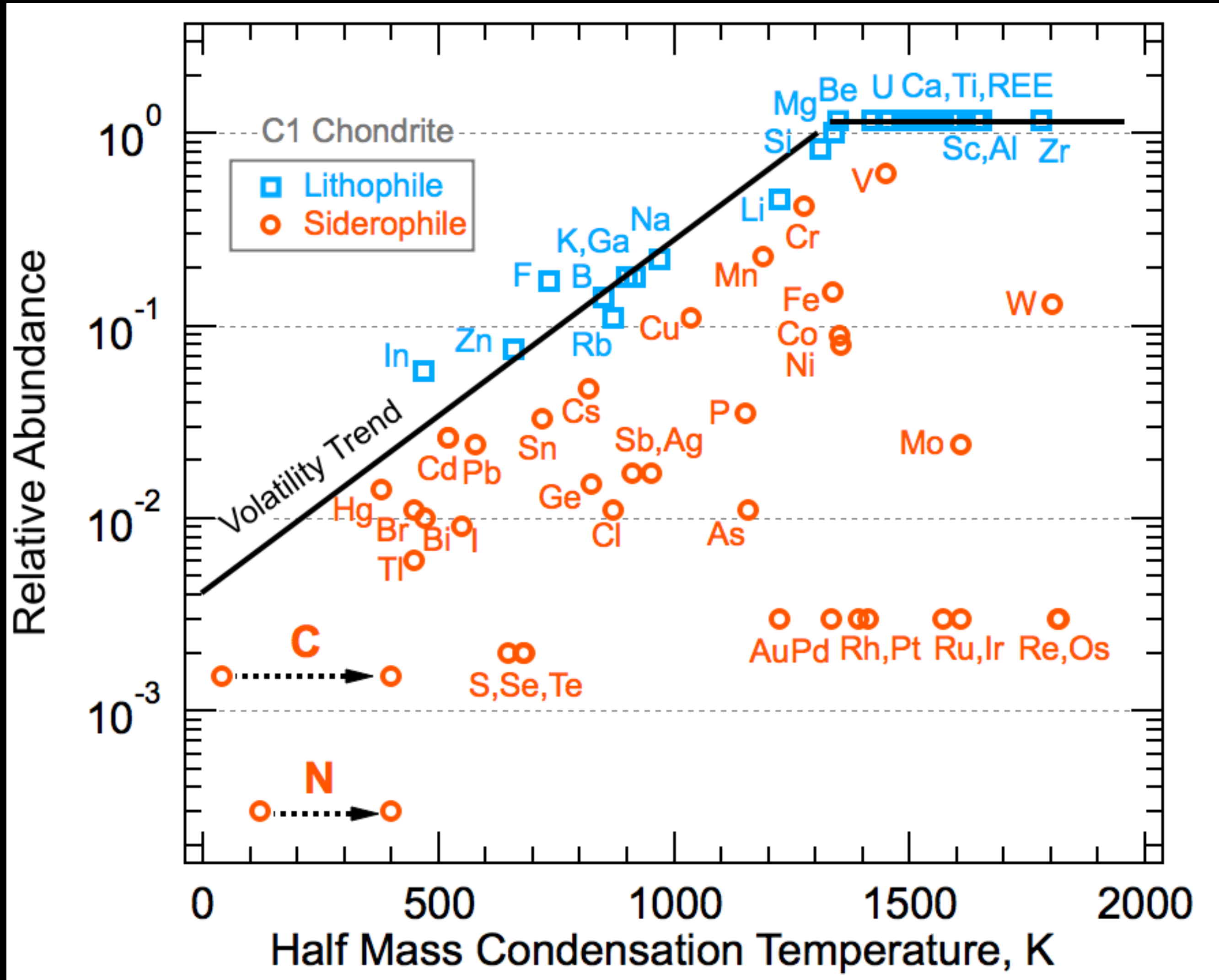


Li et al., in prep.; after McDonough & Sun 1995

Volatility and Planet Composition

From ISM

- 1/2 carbon in refractory form (T_{sub} > 400 K)
- 1/2 carbon in CO gas (T_{sub} ~ 20 K)



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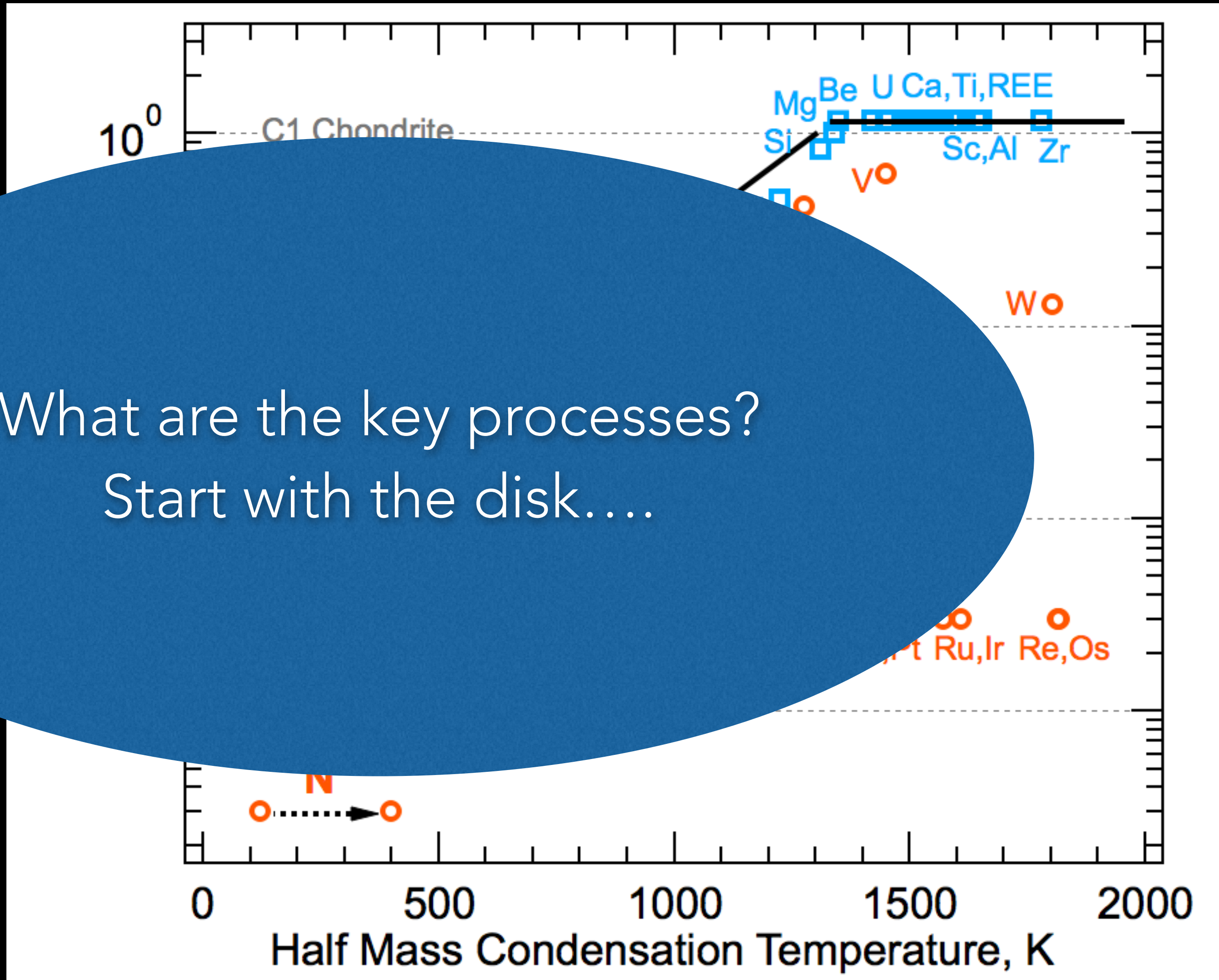
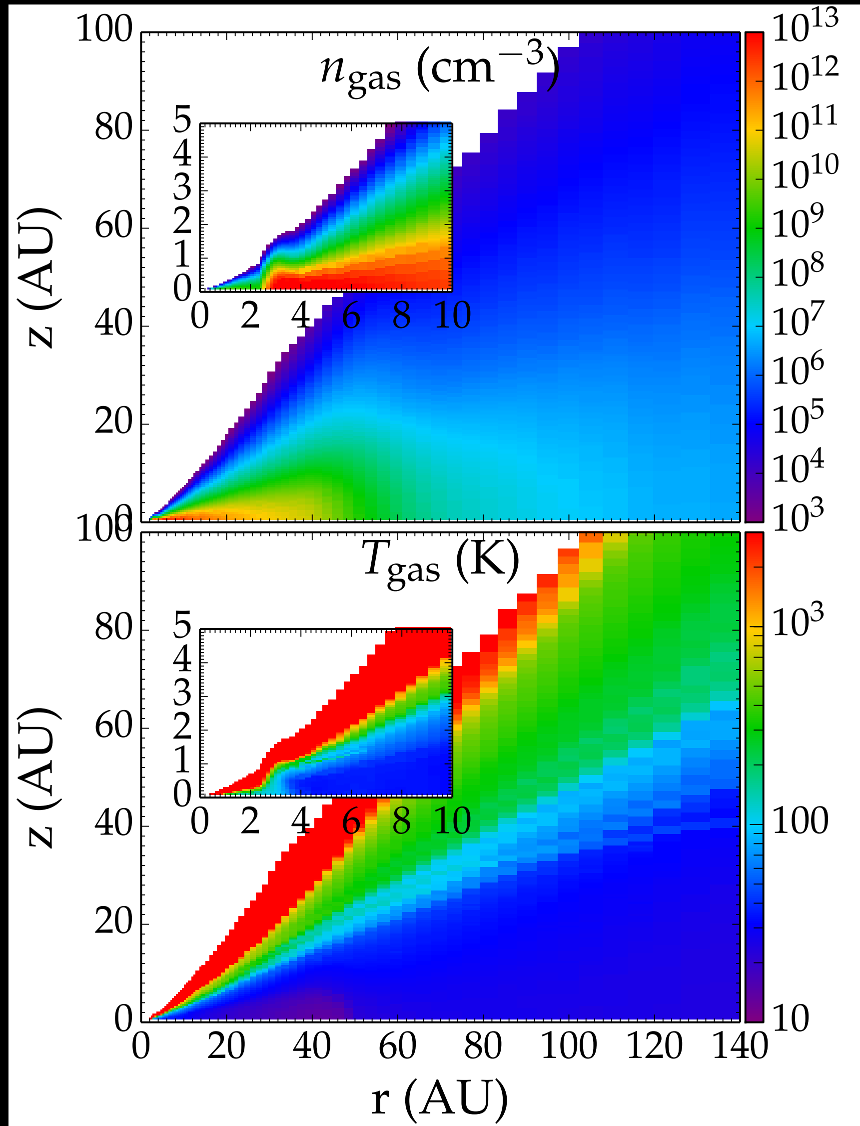


What are the key processes?
Start with the disk….

Li et al., in prep.; after McDonough & Sun 1995

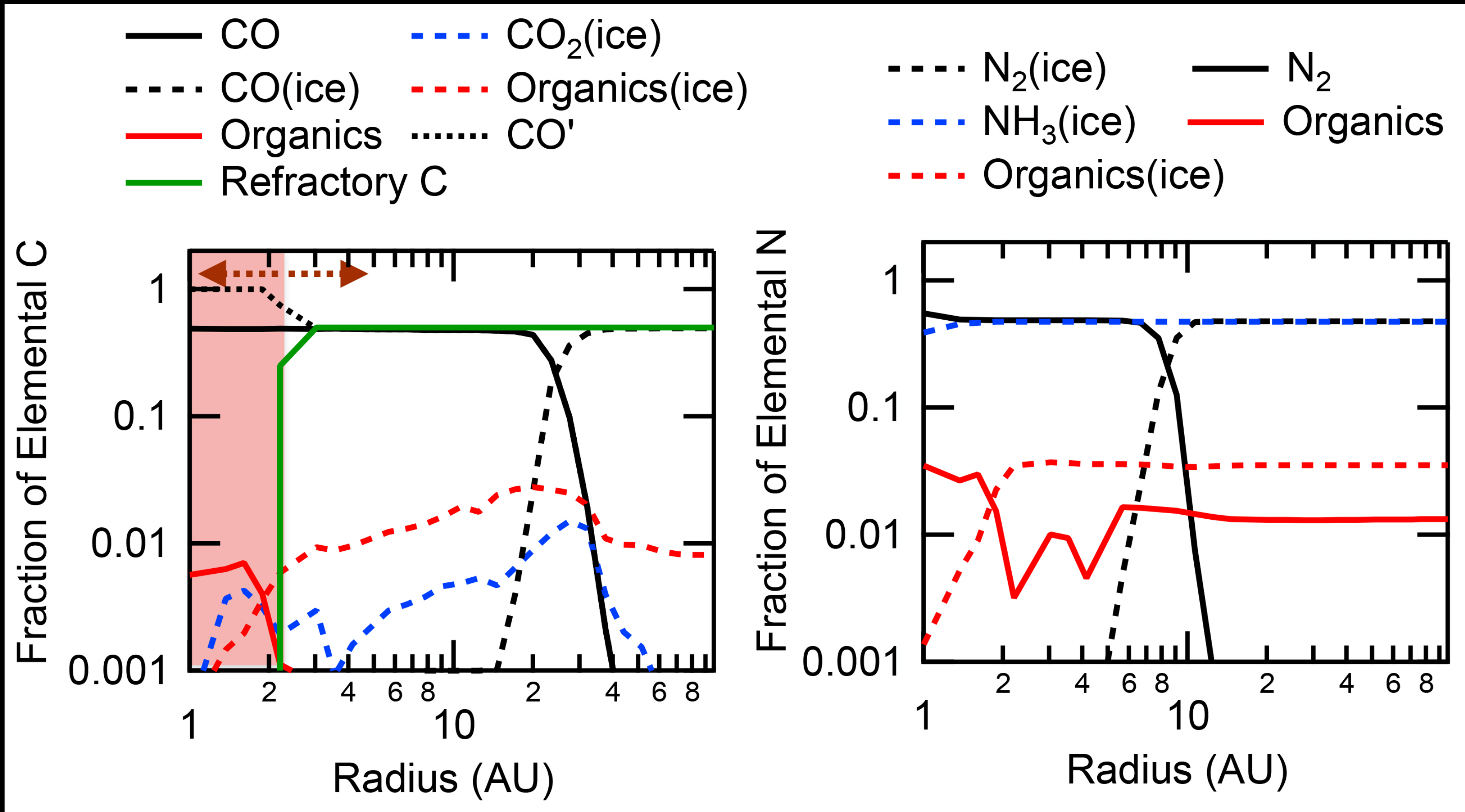
Protoplanetary Disk

- Use dust spectral energy distribution to determine: n(r,z), T(r,z) for dust
- Molecular lines to constrain gas parameters
- Detailed chemical models (Fogel+ 11, Cleeves+ 13, Schwarz+ 14, Du+ 15) to model chemistry



Du et al. 2015, ApJ, subm.

Kinetic Chemical Model



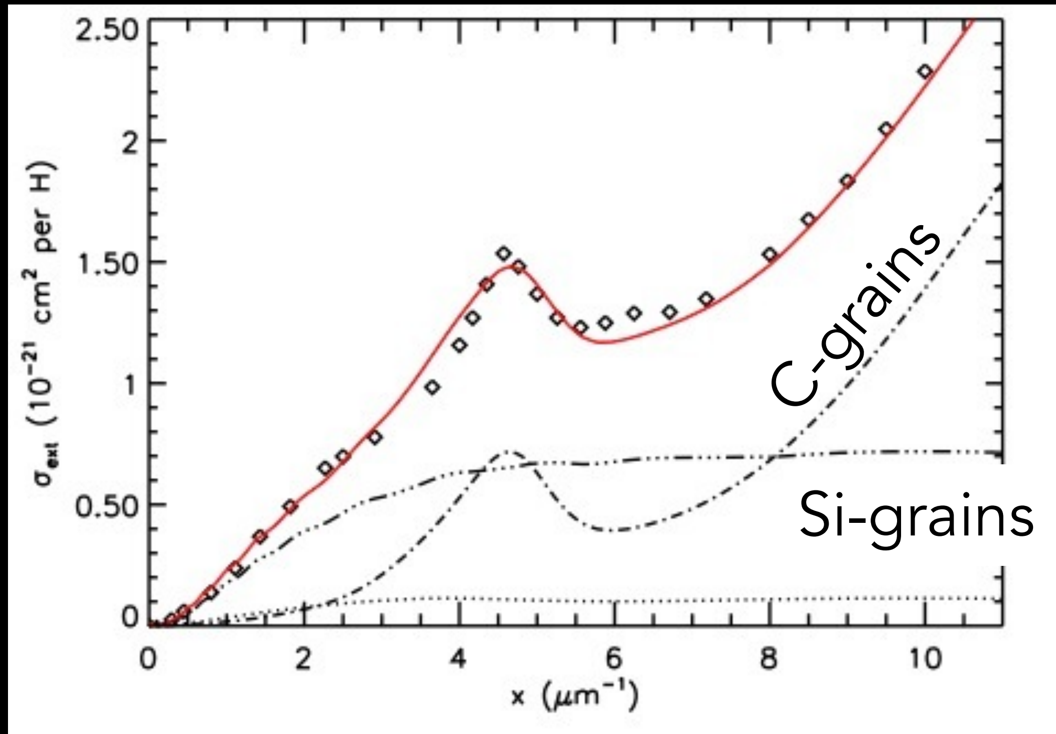
Main C carriers: Refractory grains, CO, CO_2, organics

Main N carriers: N_2, NH_3, organics

Interstellar Refractory Carbon

50% of C in interstellar space is in refractory form.

- ➡ interstellar dust extinction
- ➡ confirmed by absorption line spectroscopy
- ➡ in Solar System: Halley and anhydrous IDPs (C/Si ~ 2) have this carbon



Jones et al. 2013

Interstellar Carbonaceous Grains

➡ For carbonaceous meteorites - $C/Si < 1$

- must destroy ISM carbon grains
- sublimation temperature > 400 K

➡ Four (?) potential mechanisms

1. Photoablation
2. Oxidation (reactions with atomic O, OH)
3. Destruction via reactions with frozen, but free, oxygen (Shi et al. 2015)
4. Parent body processing

Interstellar Carbonaceous Grains

➡ For carbonaceous meteorites - C/Si < 1

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small grains (< 1 μm; early?)

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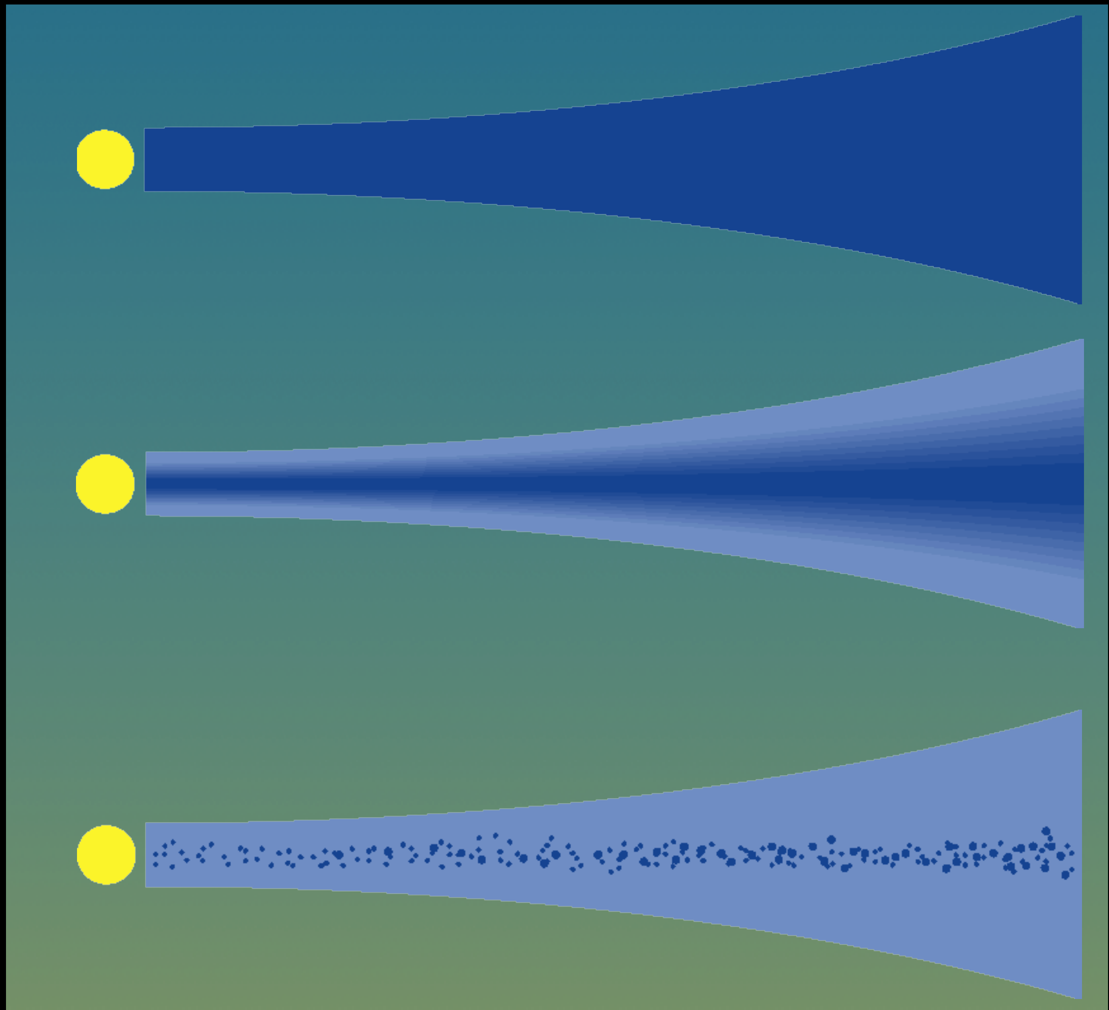
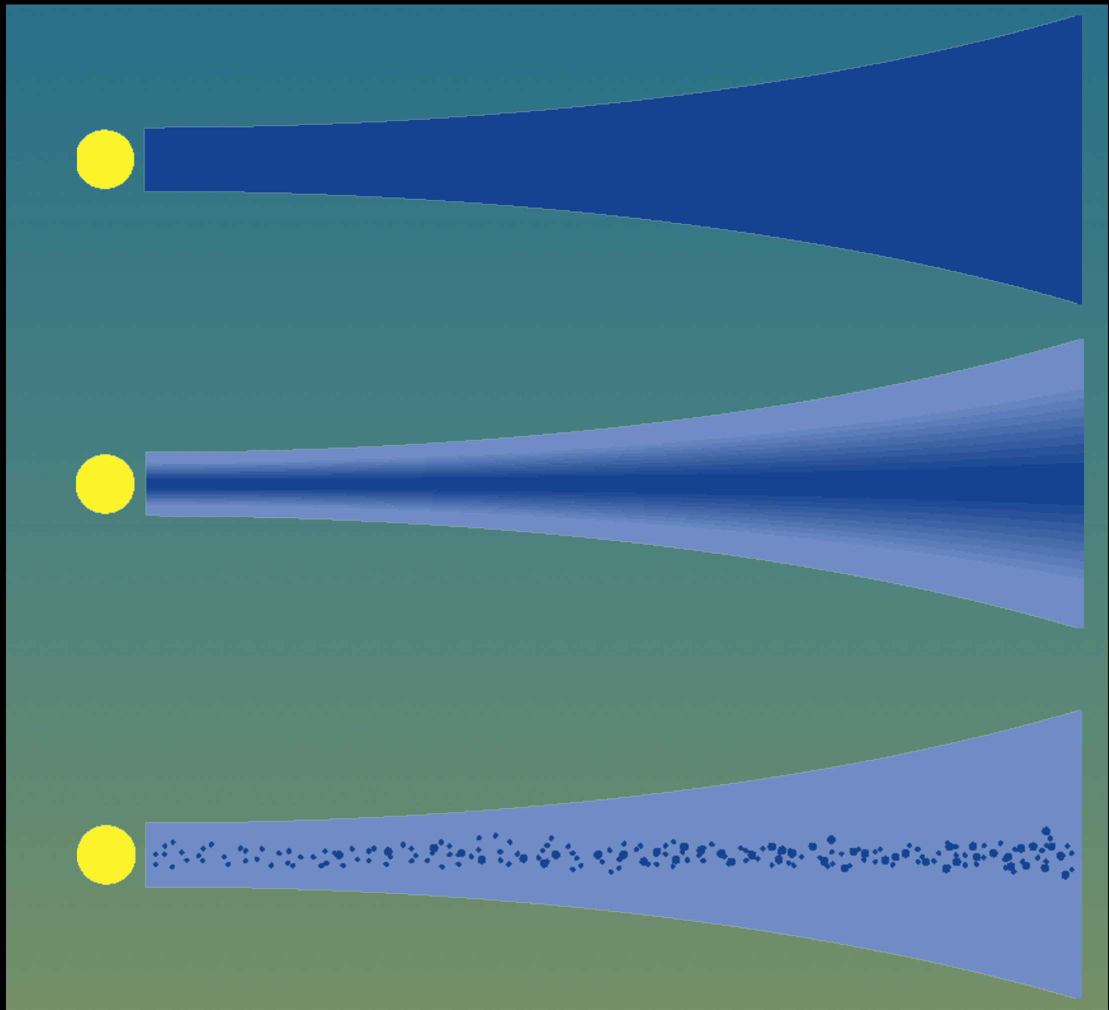
Paradigm of Terrestrial Planet Formation



Start: disk with well mixed gas and dust

Paradigm of Terrestrial Planet Formation



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Due to gas drag and pressure gradients grains accumulate where the gas pressure maximizes: settle to the midplane

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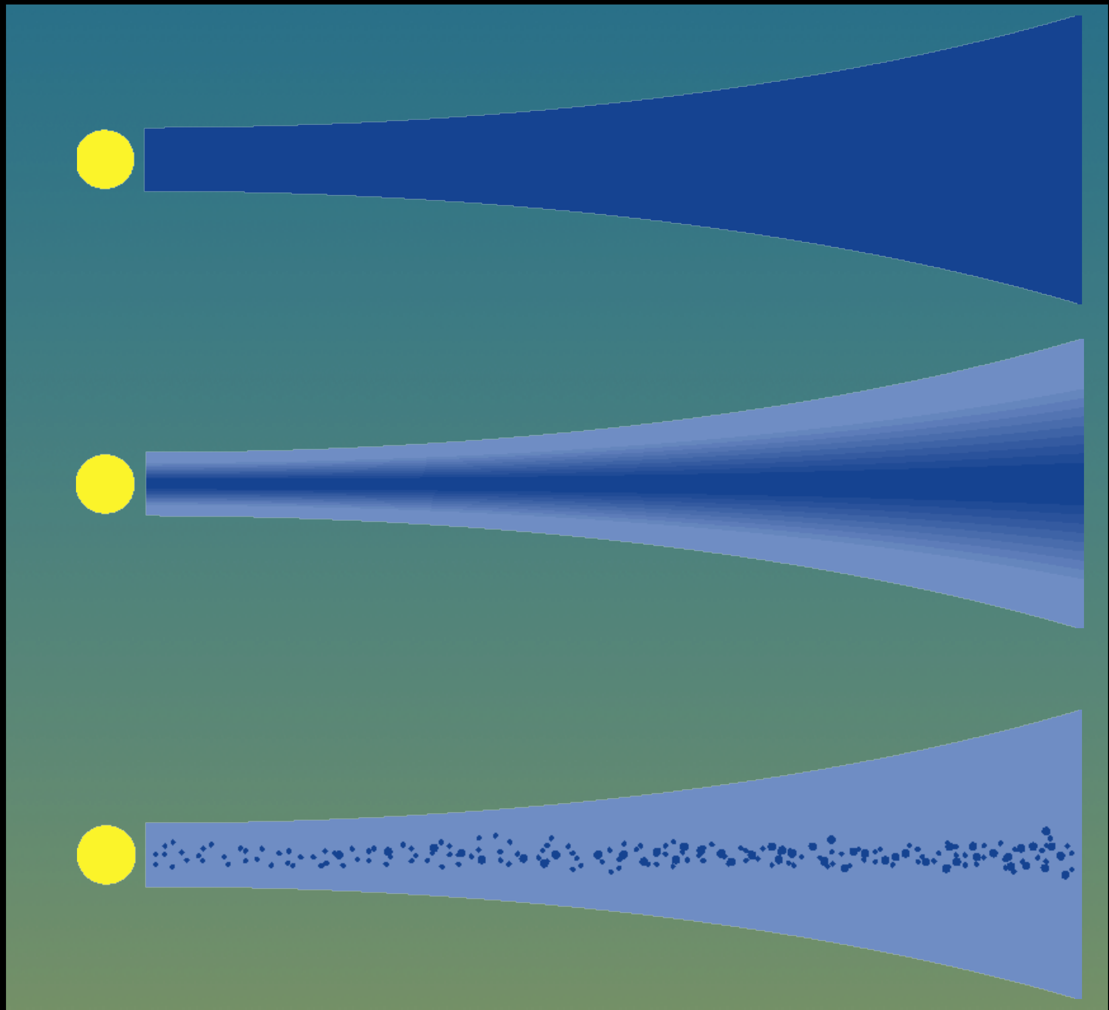

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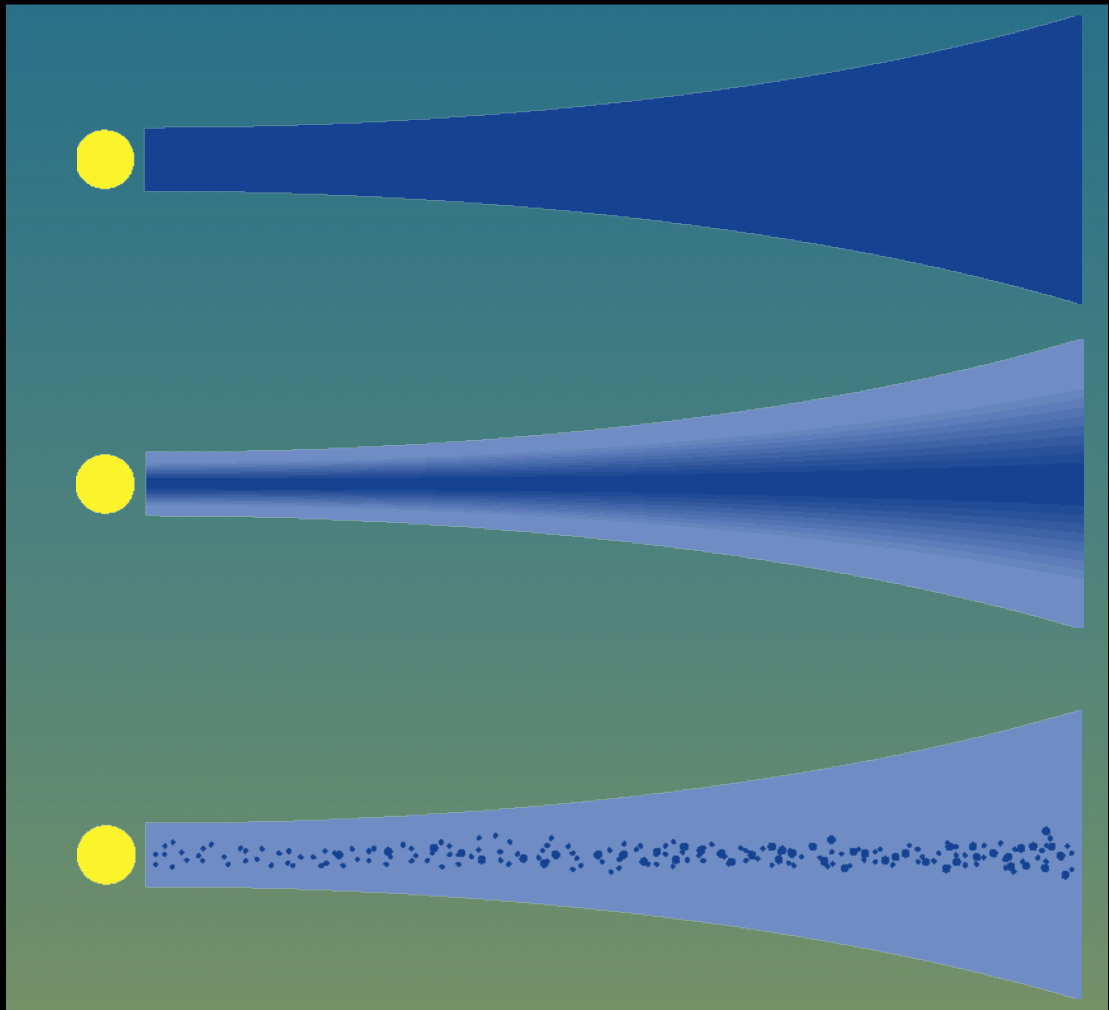
Grains grow into rocks in dust-rich midplane

Paradigm of Terrestrial Planet Formation



Start: disk with well mixed gas and dust

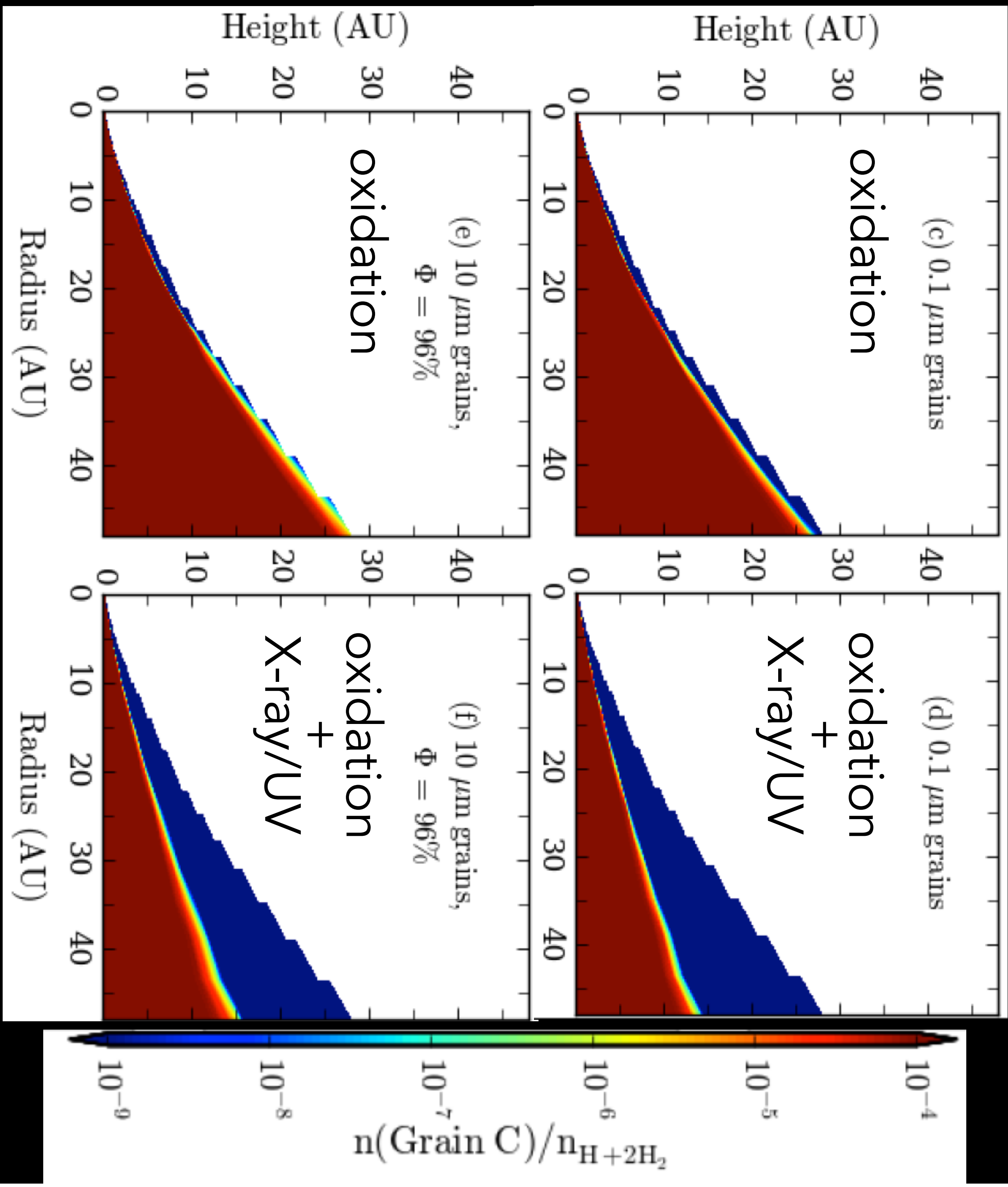
Due to gas drag and pressure gradients grains accumulate where the gas pressure maximizes: settle to the midplane

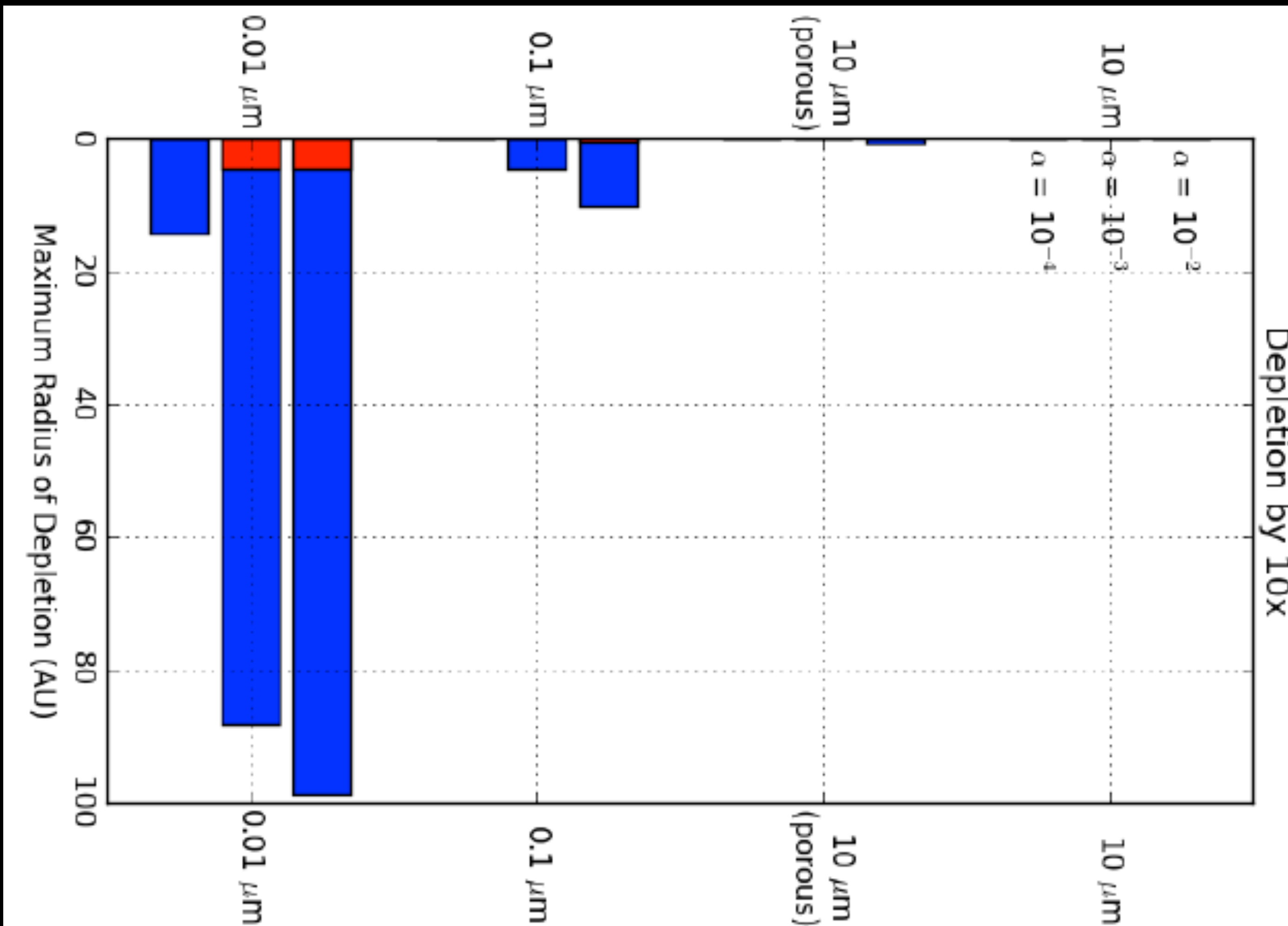
Grains grow into rocks in dust-rich midplane

Turbulence in the disk acts against dust settling (Weidenshilling 1984)

Lee, Bergin, and Nomura 2010

Anderson et al. 2016, ApJ, submitted





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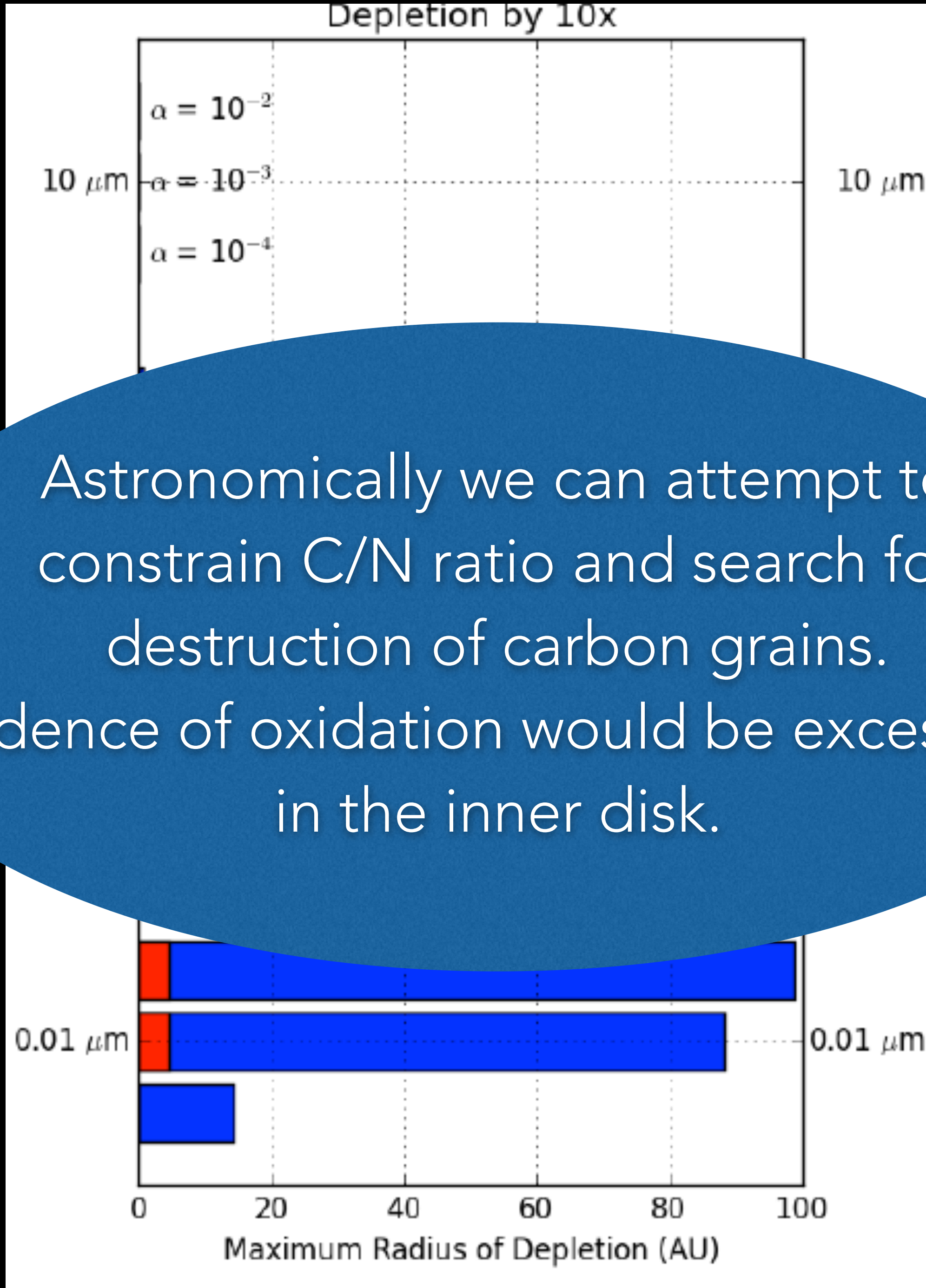
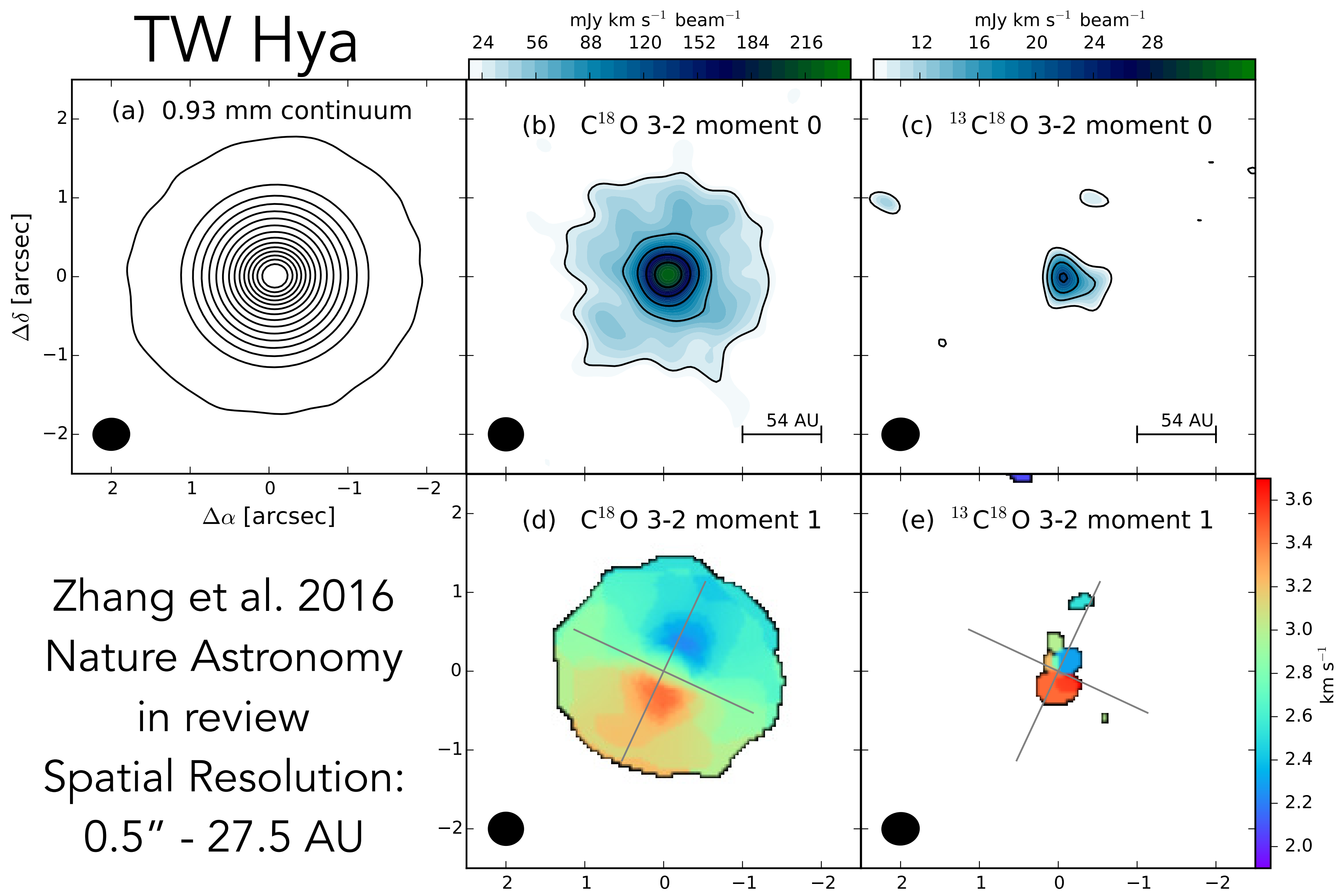


Astronomically we can attempt to constrain C/N ratio and search for destruction of carbon grains.
Evidence of oxidation would be excess CO in the inner disk.

Anderson et a… , submitted

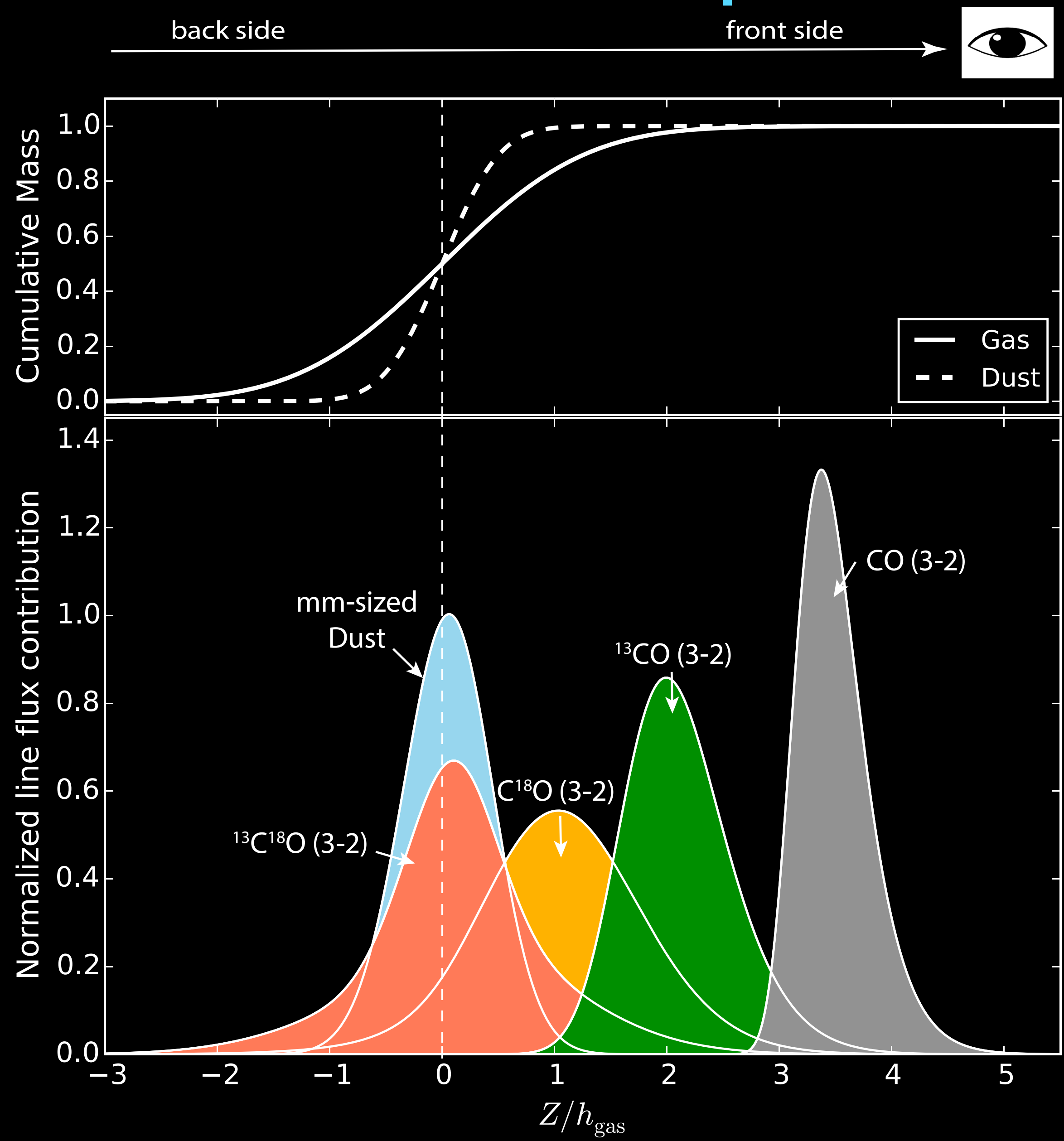
Peering into the midplane



Zhang et al. 2016
Nature Astronomy
in review
Spatial Resolution:
0.5″ - 27.5 AU

Peering into the midplane

- ➡ Concurrent modeling of all data including high resolution (1 AU) dust continuum from Andrews et al. 2016:
- ➡ $^{13}C^{18}O$ AND submm. dust emission is optically thin -> column
- ➡ $C^{18}O$ is optically thick -> temperature



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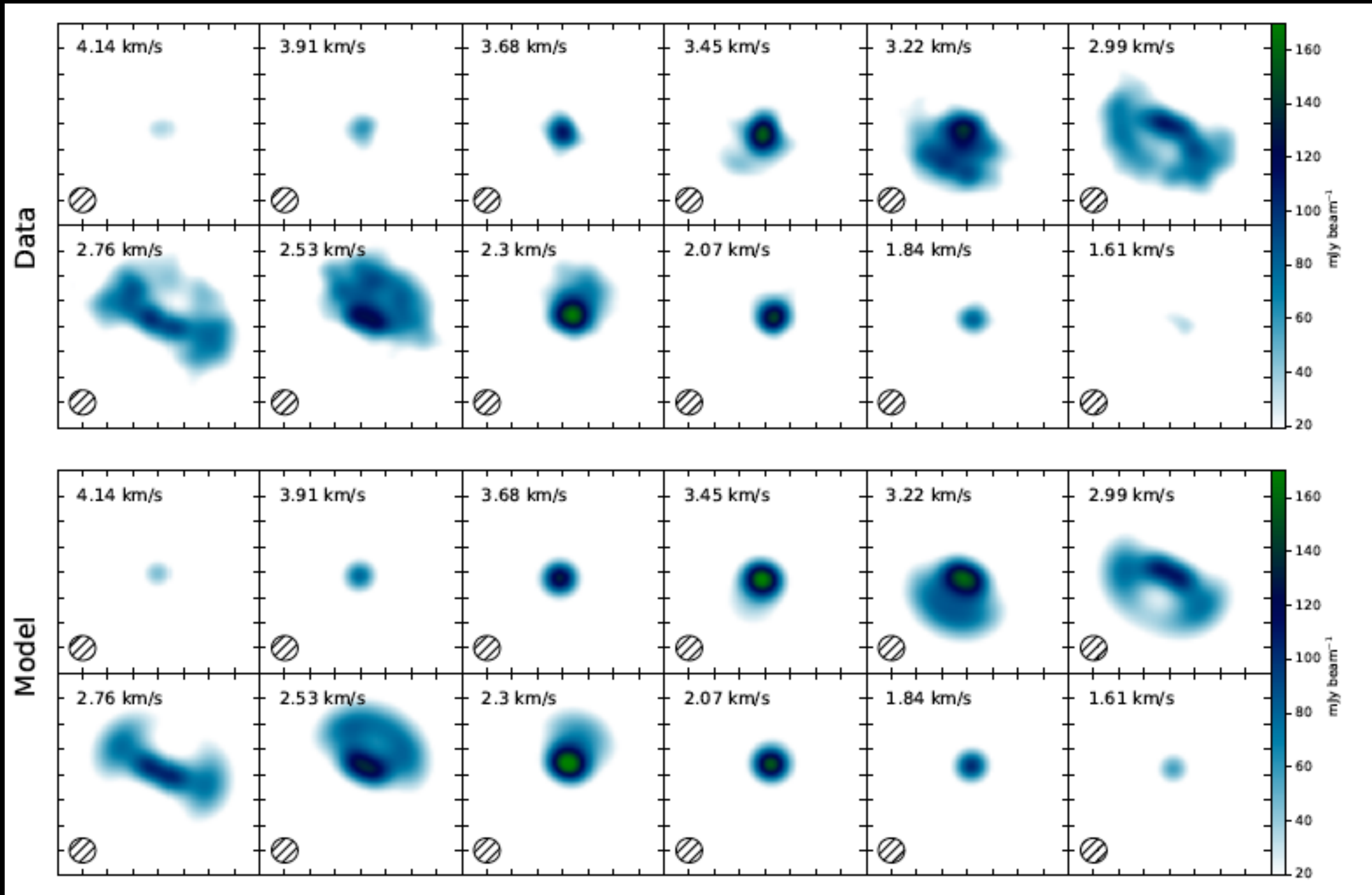

Zhang et al. 2016, Nat. Astro., in review

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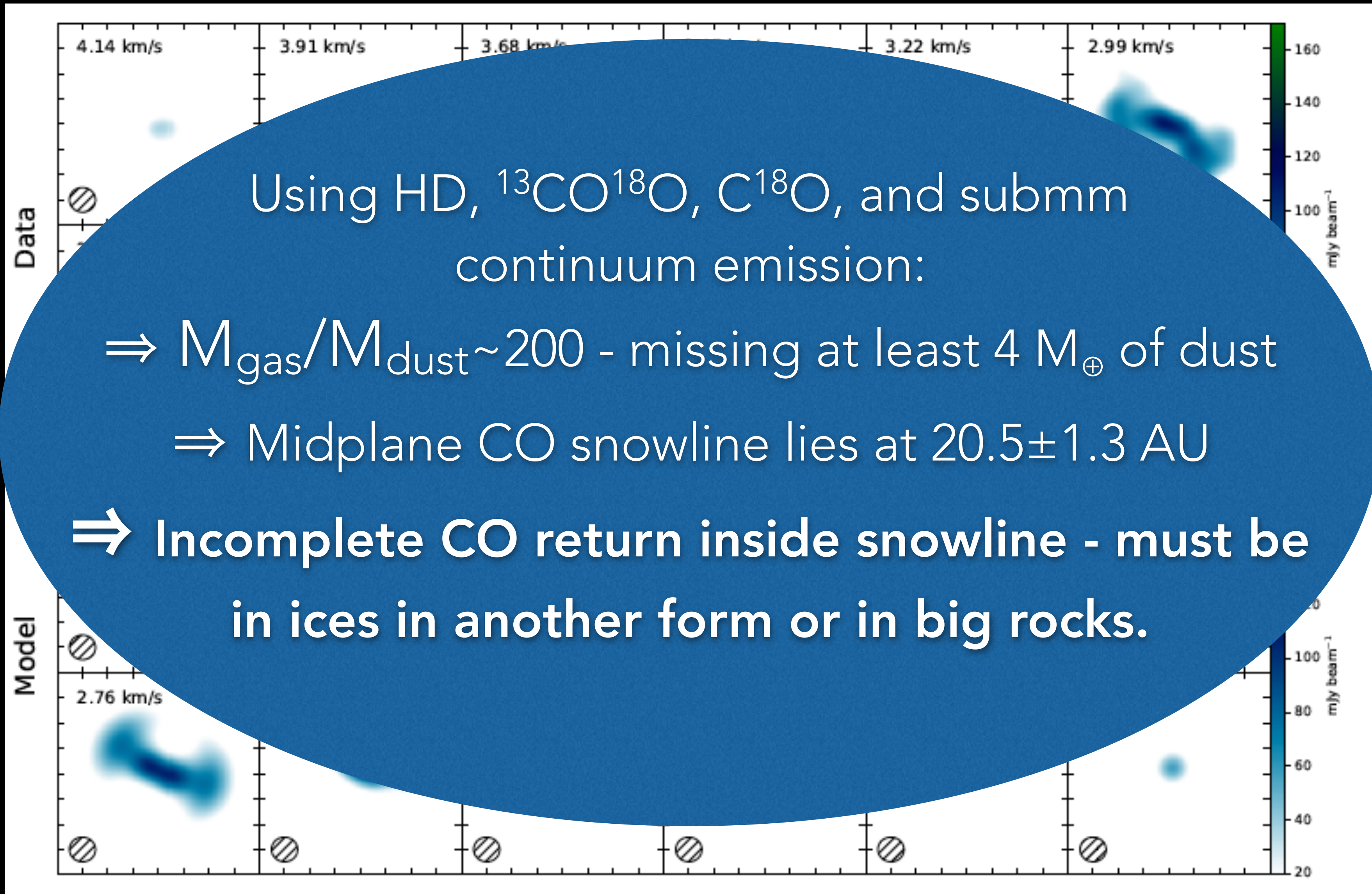


Using HD, $^{13}C^{18}O$, $C^{18}O$, and submm continuum emission:

⇒ M_{gas}/M_{dust}~200 - missing at least 4 $M_{\oplus}$ of dust

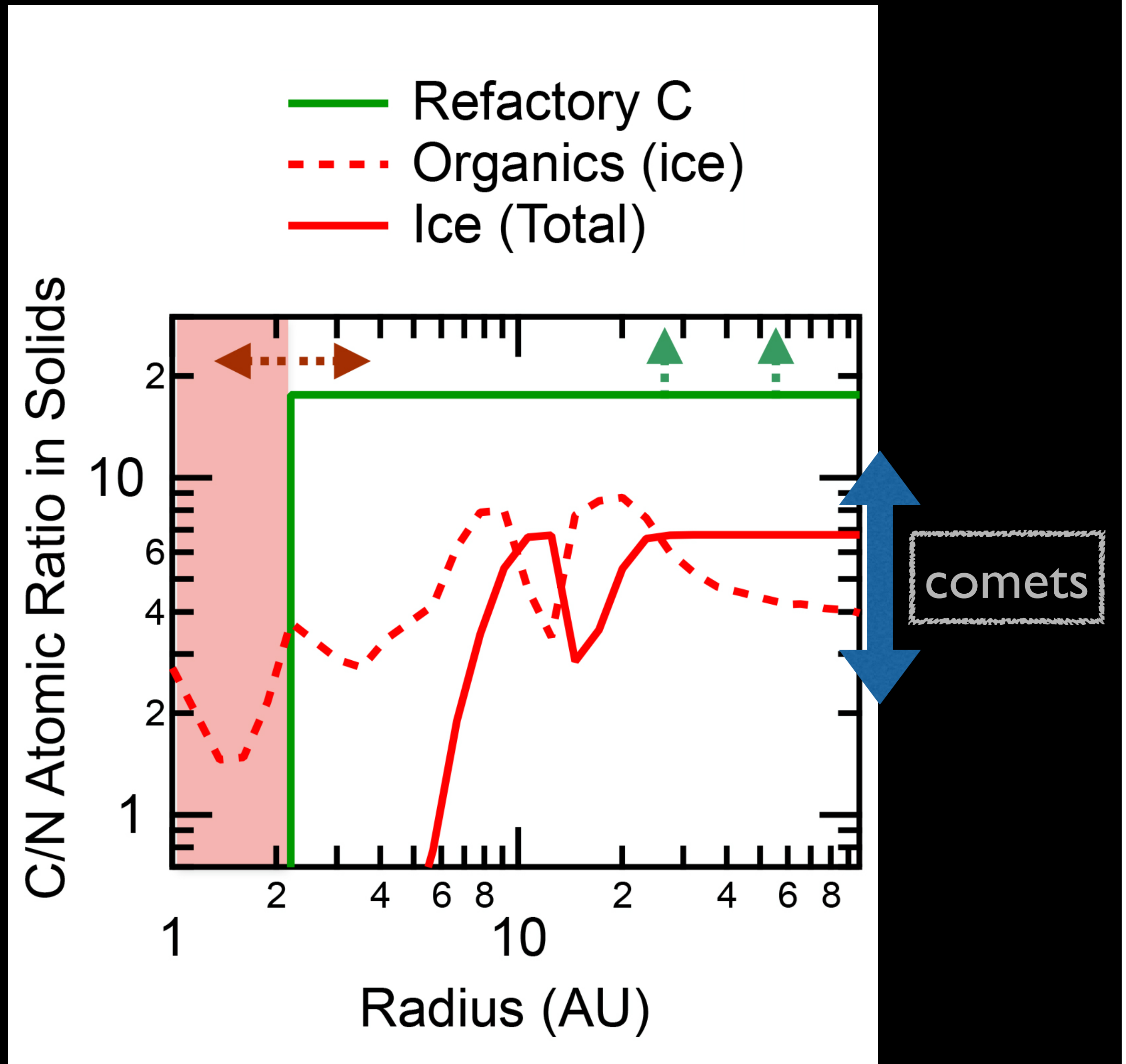
⇒ Midplane CO snowline lies at 20.5±1.3 AU

⇒ **Incomplete CO return inside snowline - must be in ices in another form or in big rocks.**

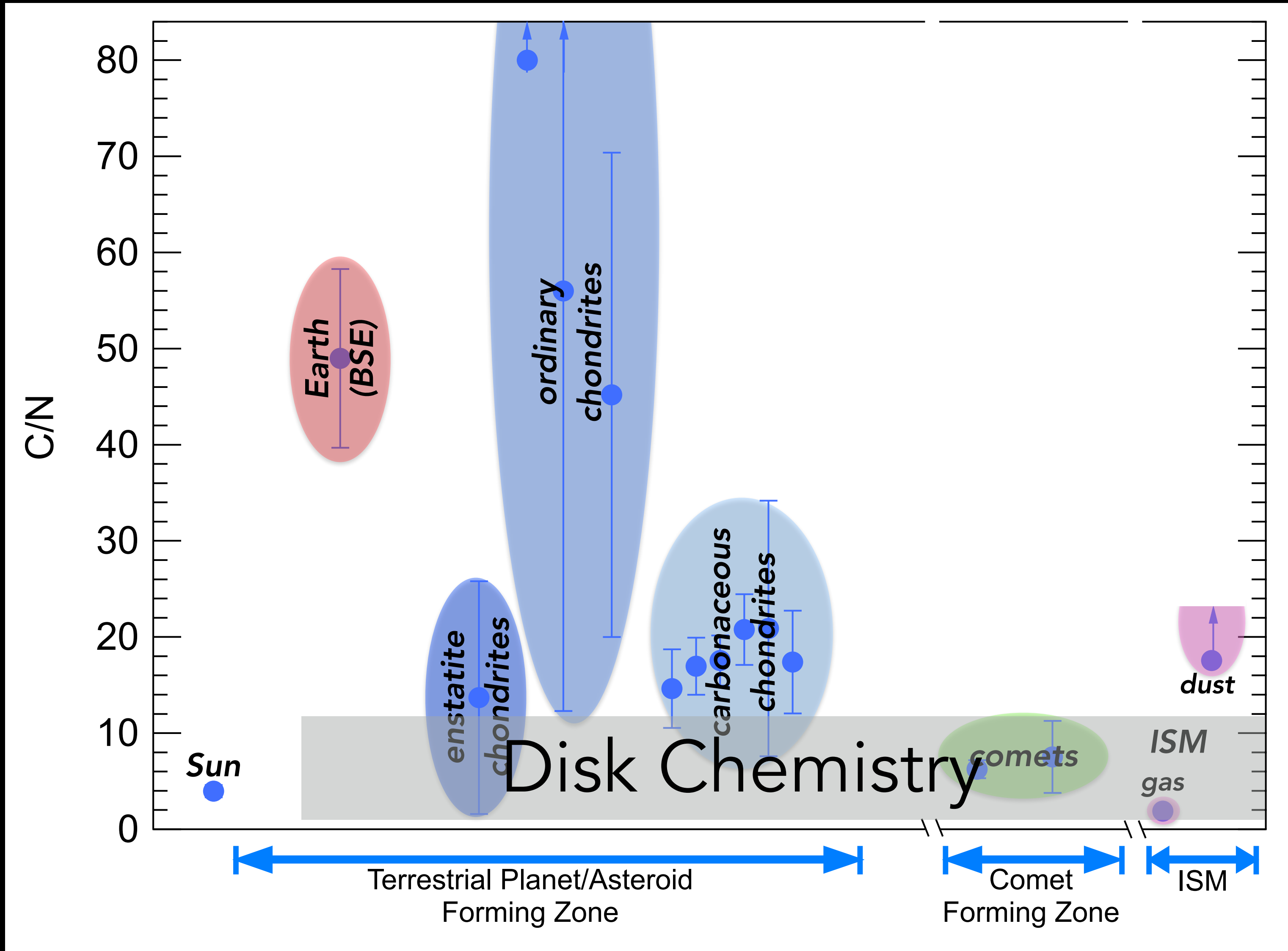
Zhang et al. 2016, Nat. Astro., in review

Kinetic Chemical Model

- Organics/carbon grains most likely carriers
- Halley has ISM carbon content; C/N(max) = 12
- Disk chemistry produces C/N ~ 1-12

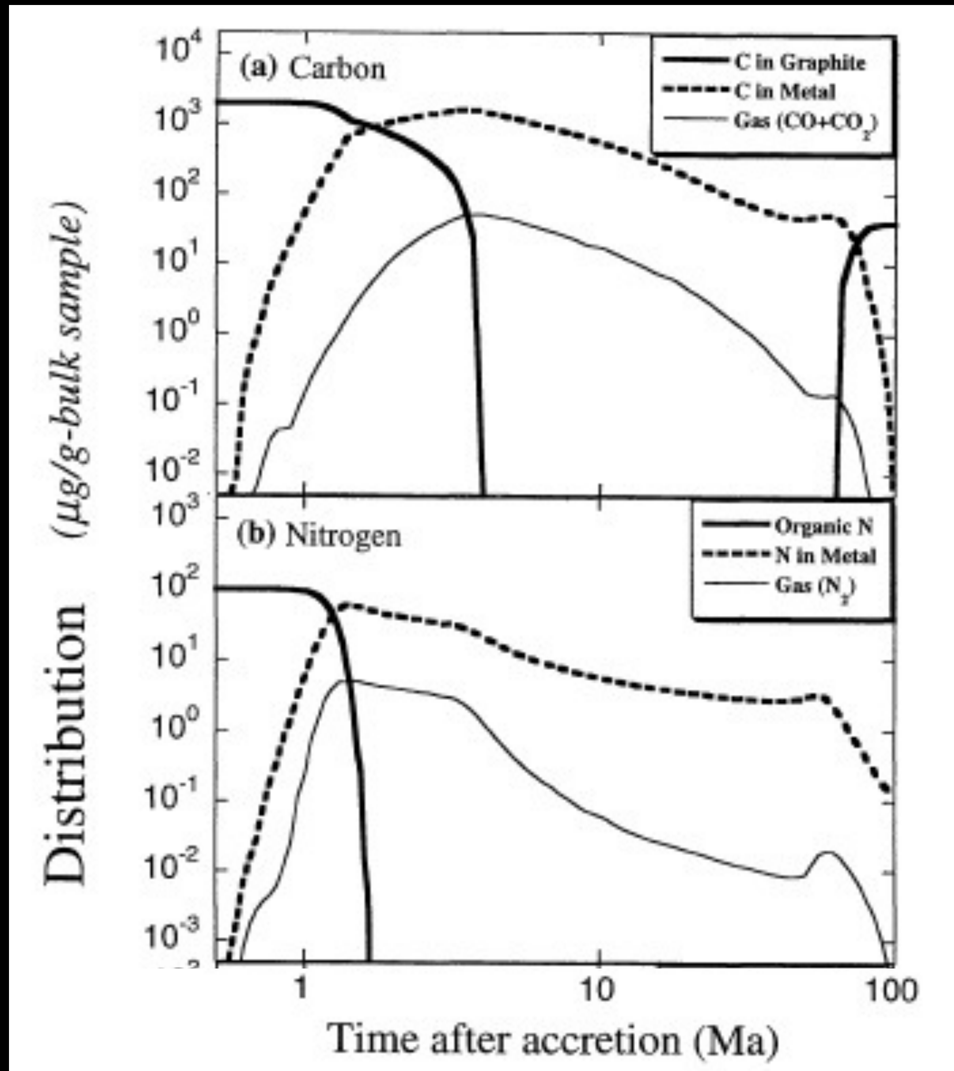


C/N as a Tracer of Process



Parent Body Processing

- ➡ ordinary chondrites: exposed to vary degrees of thermal metamorphism
- ➡ T can reach 1300 K in center of 40 km sized body
- ➡ depending on oxidation state can decompose organics and devolatilize C and N



Hashizume & Sugiura 1998

Parent Body Processing

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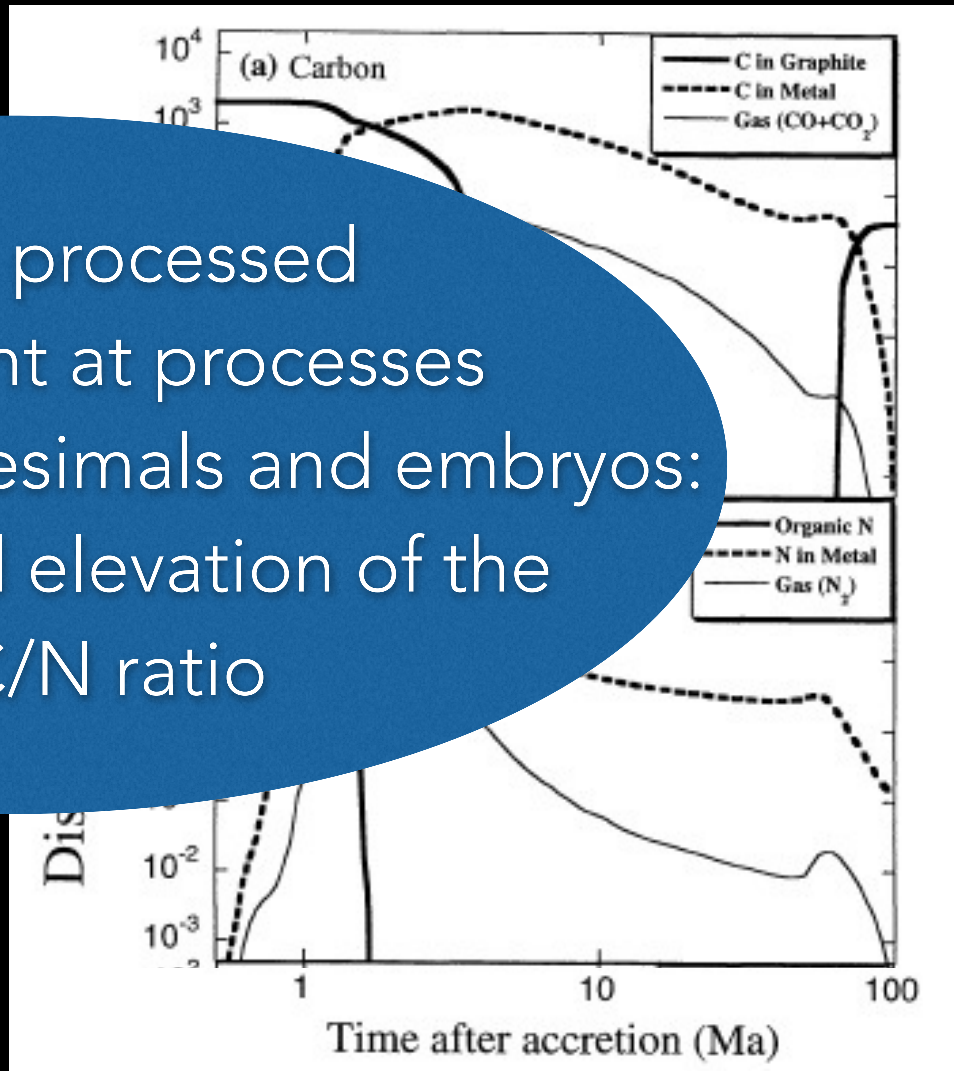
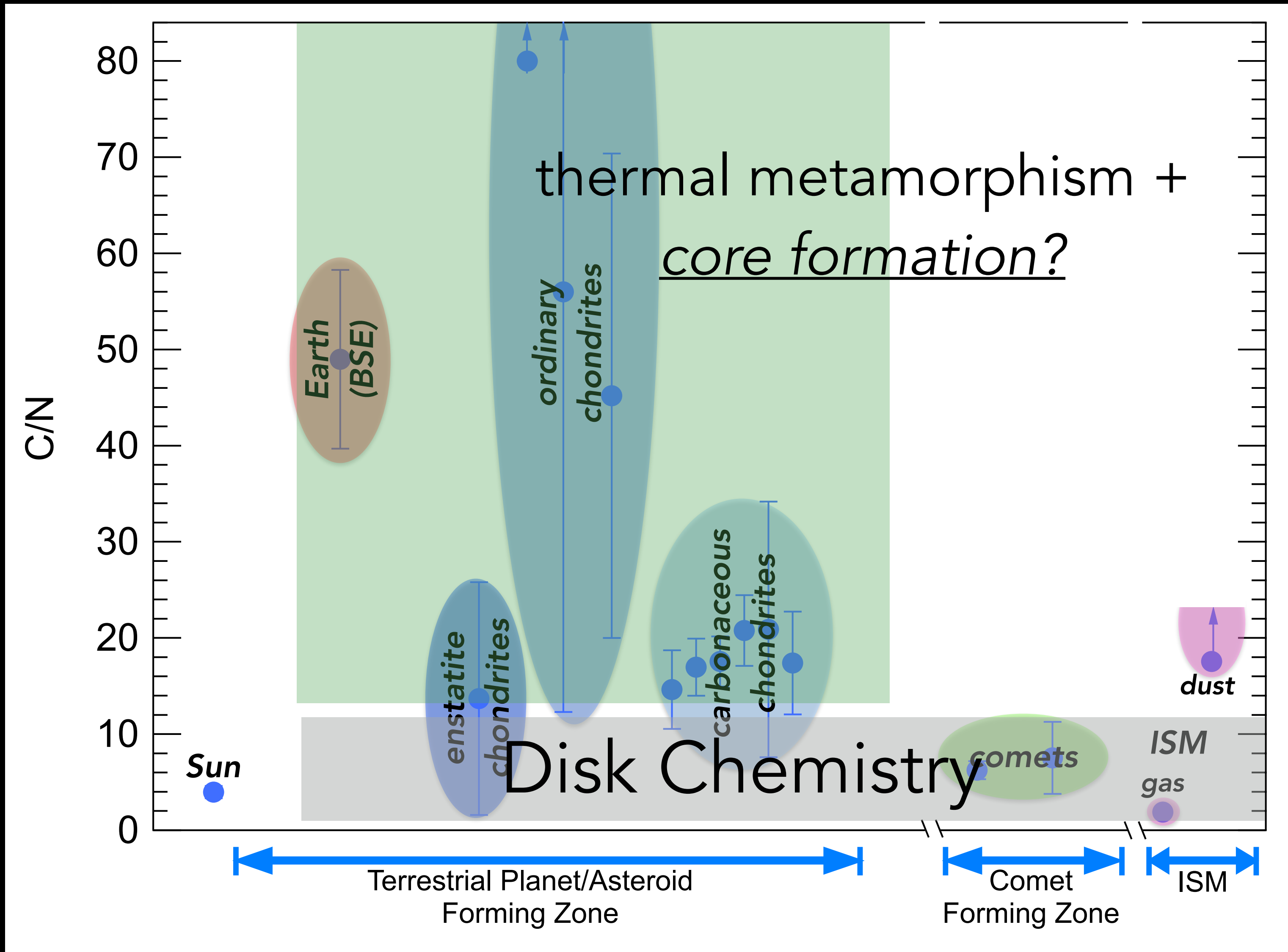
- depending on oxidation state can decompose organics and devolatilize C and N

Thermally processed meteorites hint at processes occurring on planetesimals and embryos: volatile loss and elevation of the initial C/N ratio

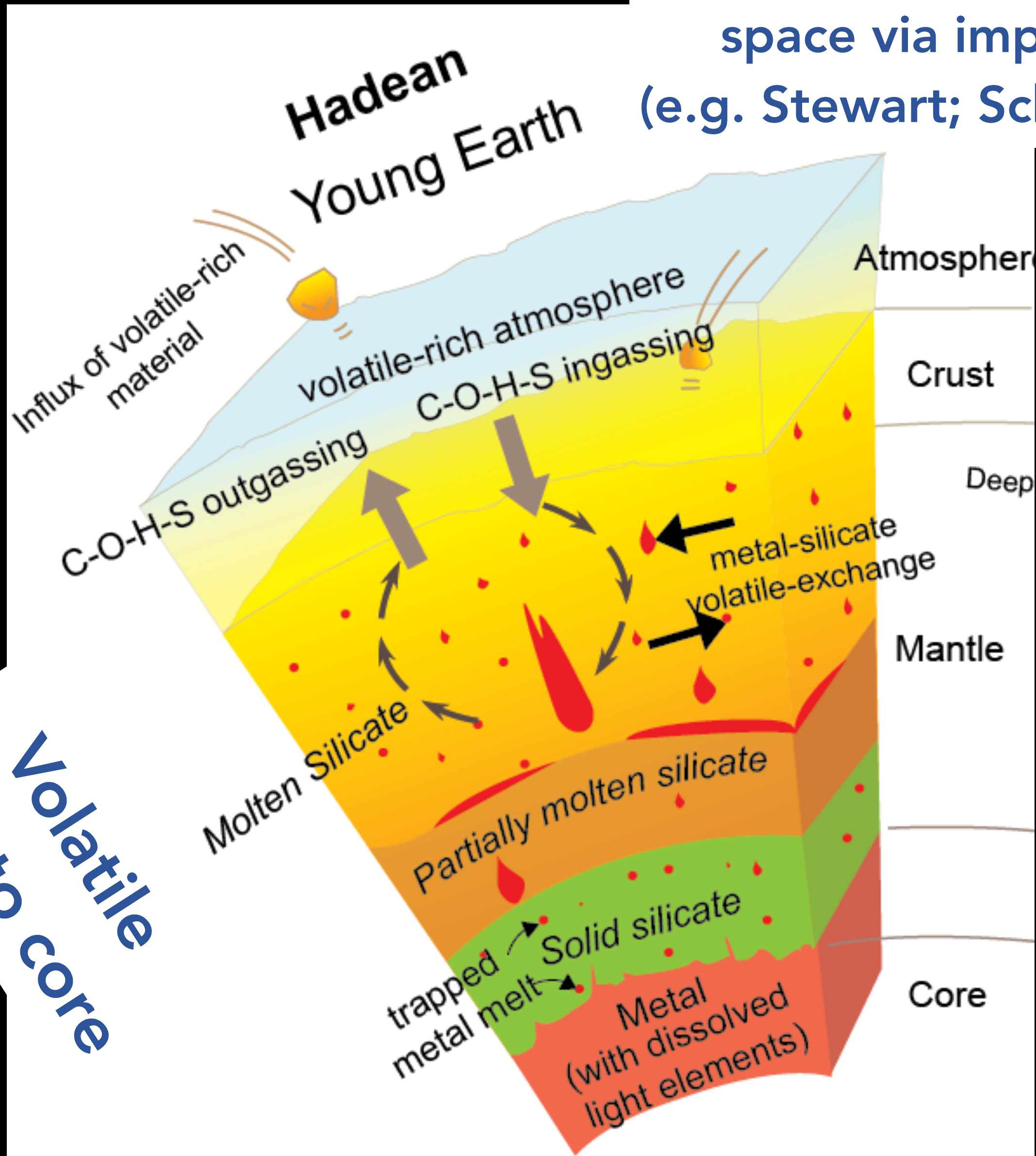


Hashizume & Sugiura 1998

C/N as a Tracer of Process



Planet Formation



Atmosphere loss to space via impacts (e.g. Stewart; Schlicting)

Volatile loss to core

Dasgupta 2013

Key Factors: C/N & Core Formation

- Solubility in silicate melt
  - ➡ C more soluble than N - oxidizing conditions
  - ➡ N more soluble than C - reducing conditions

Oxidized vs Reduced

- Standard definition - loss (oxidized) or gain (reduced) of an electron.
- H is a reducing agent, O is a oxidizing agent
- Scenarios:
  - ➡ Planetary embryos potentially existed as early as 2 Myr after CAI's (Dauphas and Pourmand 2011).
  - ➡ Gas-rich nebula was present.
  - ➡ Early H_2 atmosphere in equilibrium with magma ocean would be highly reducing.

Oxidized vs Reduced

- Standard definition - loss (oxidized) or gain (reduced) of an electron.
- H is a reducing agent, O is a oxidizing agent
- Scenarios:
  - Earth's core formed at least 30 Myr after CAI's (e.g. Nimmo & Kleine 2015).
  - H_2 nebula dissipated; initial H_2 rich atmosphere ablated.
  - Oxidation state driven by presence/absence of water - or previous presence of water forming FeO
  - Earth form's from material primary interior to the snowline presents a moderately reducing proto-Earth

Oxidized vs Reduced

- Standard definition - loss (oxidized) or gain (reduced) of an electron.
- H is a reducing agent, O is a oxidizing agent
- Scenarios:
  - Earth's core formed at least 30 Myr after CAI's (e.g. Nimmo & Kleine 2015).
  - H^2 nebula dissipated; initial H^2 rich atmosphere ablated.
  - Oxidation state driven by presence/absence of water.
  - Earth forms from material with contributions beyond nebular snowline (during magma ocean phase).
  - Current consensus model and is much more oxidizing.

Key Factors: C/N & Core Formation

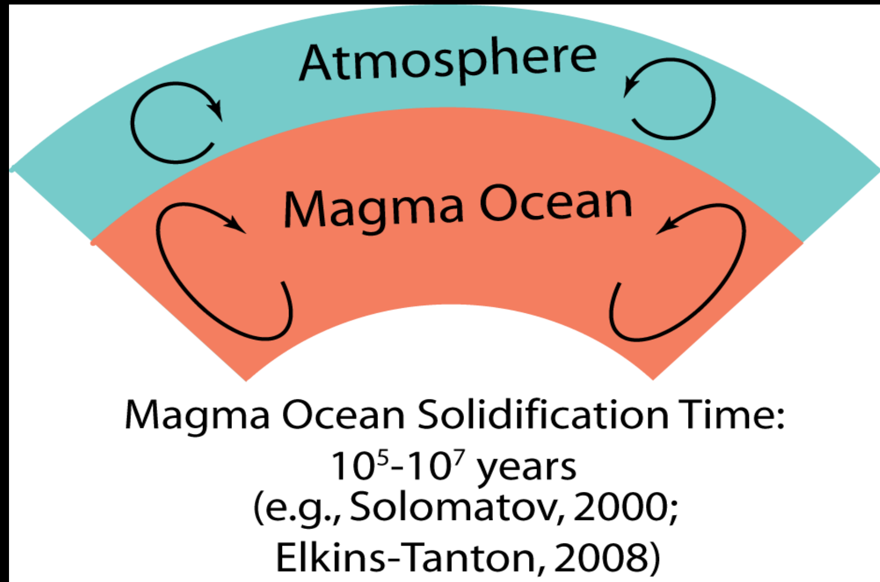
- Solubility in silicate melt
  - ➡ C more soluble than N - oxidizing conditions
  - ➡ N more soluble than C - reducing conditions
- Affinity for Fe-rich metal
  - ➡ C partitions more strongly than N (factors of 100 - 10^4)
- Timing (before, during, after core formation)

Model

1. C/N(initial) = 25
2. Chemical equilibrium with variable fraction of Fe/Silicate mixture

➡ Forms metal/volatile rich silicate mixture

➡ overlying atmosphere

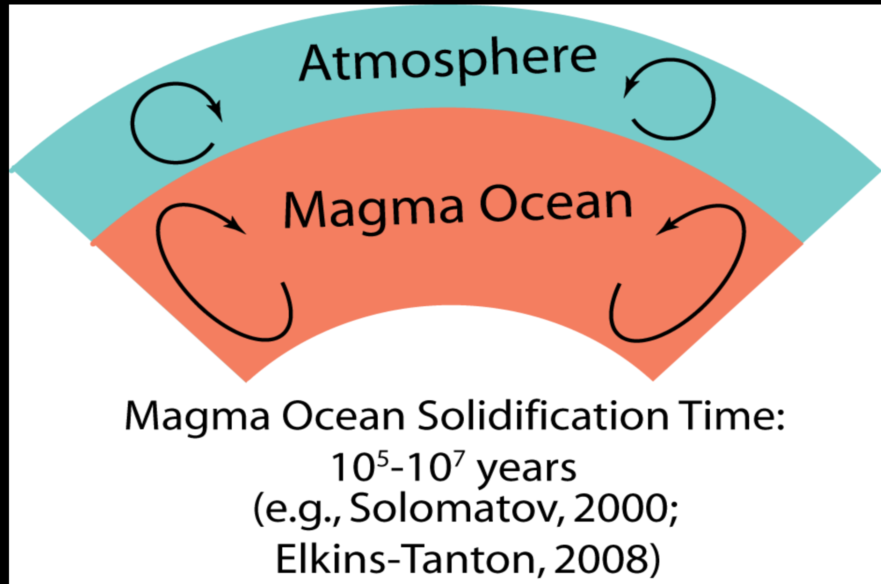


Model

3. Segregation and isolation of core

   ➡ mantle with C and N that do not go to core

   ➡ overlying atmosphere based on initial equilibrium

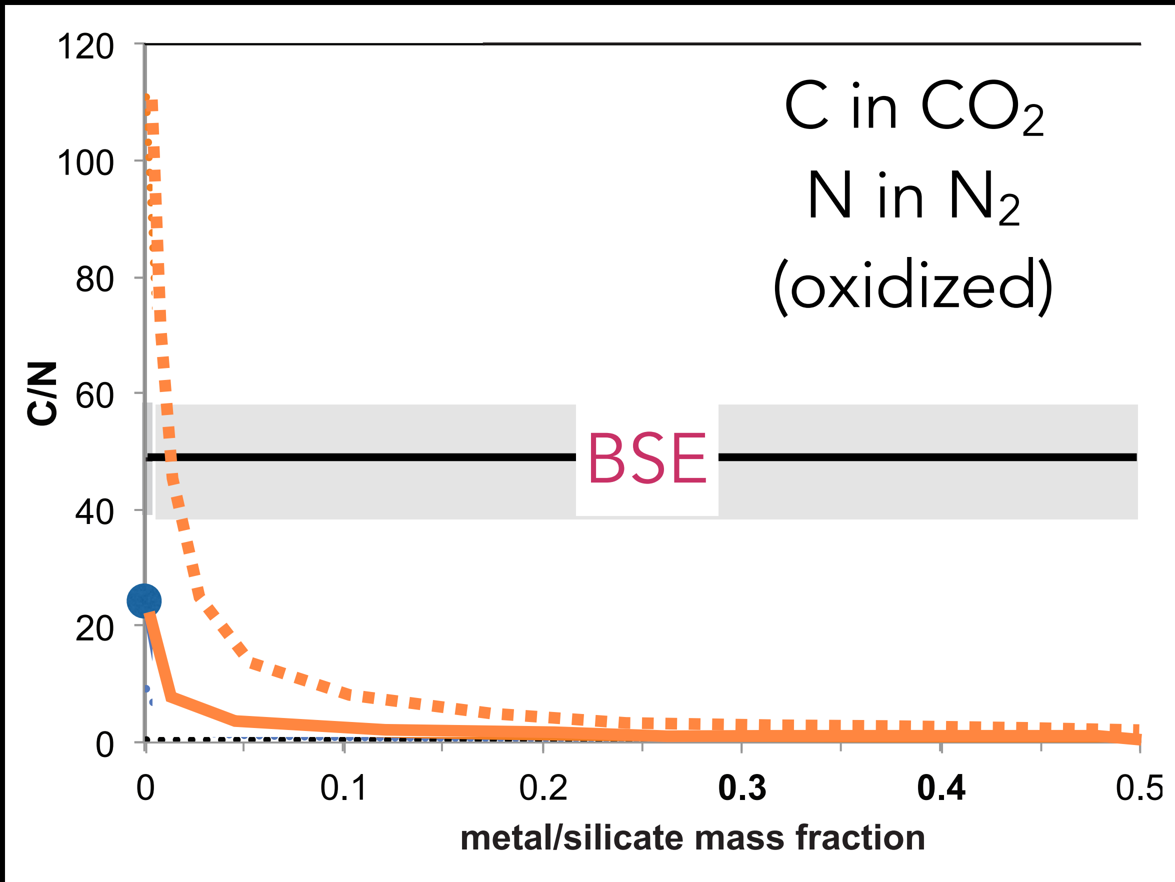


We consider two cases:

A - atmosphere returns to mantle to form BSE

B - atmosphere lost to space, mantle is BSE

Making a Habitable Planet



depletion of metal to core (time)

primordial atm. retained

- C segregates to core
- most N in atm.

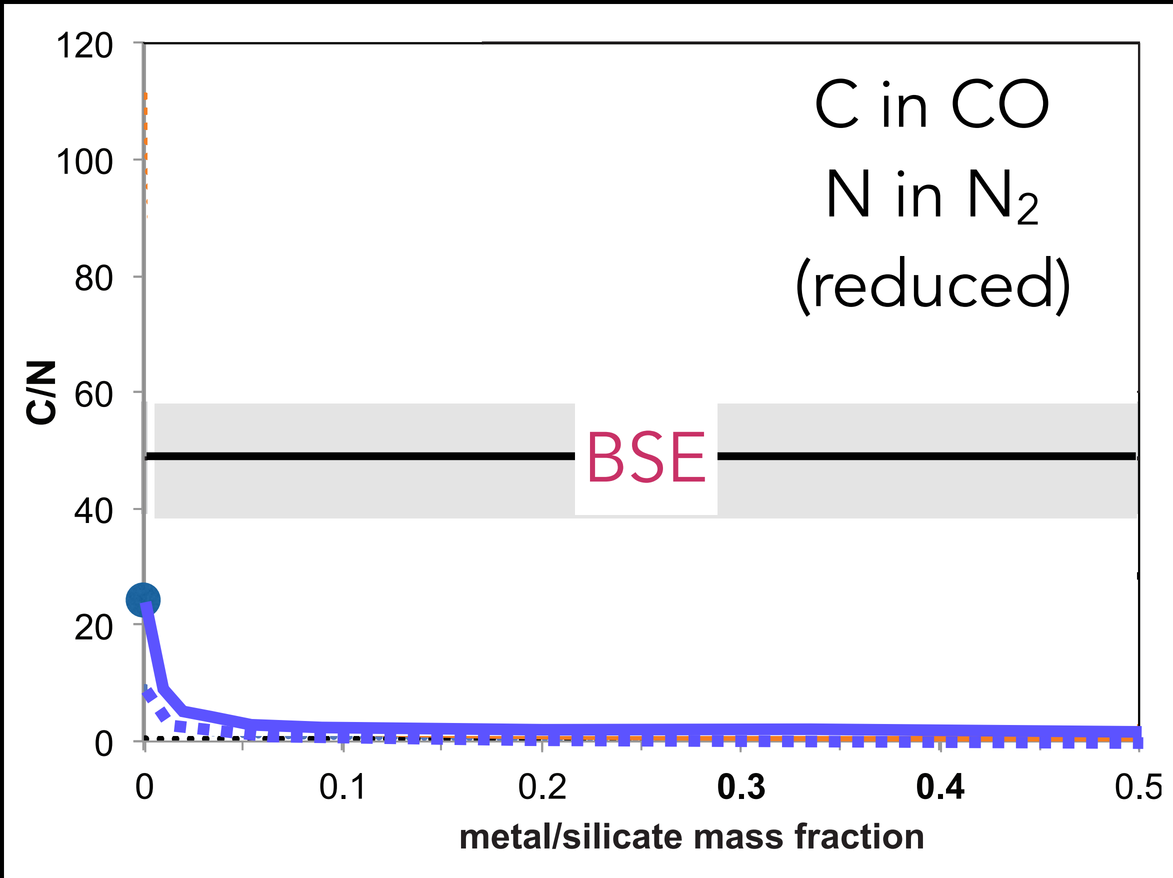
➡ $C/N < (C/N)_{BSE}$

primordial atm. lost to space

- C segregates to core
- N in atm. lost

➡ $C/N < (C/N)_{BSE}$ except metal/silicate < 0.05

Making a Habitable Planet



primordial atm. retained

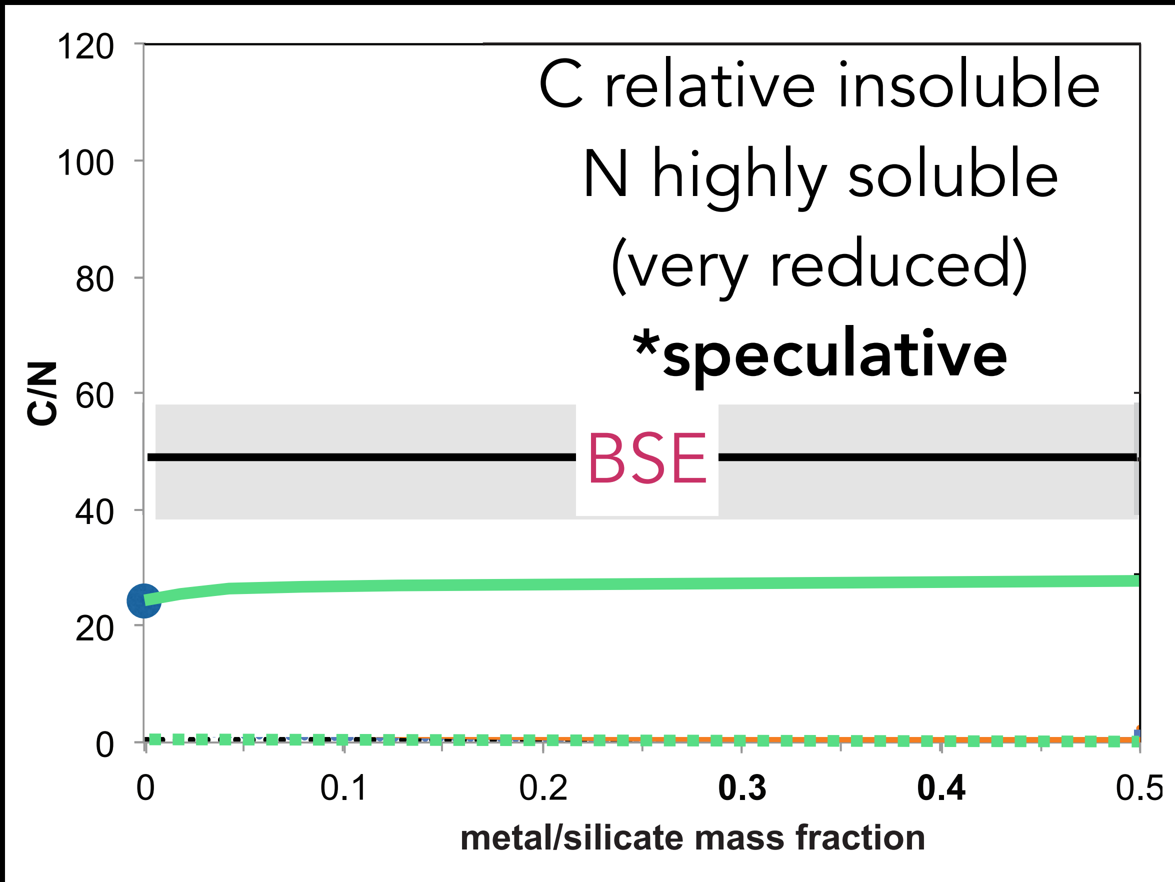
- Similar to last case

primordial atm. lost to space

- C less soluble
- C is lost along with N in atm. for low metal/Si

depletion of metal to core (time)

Making a Habitable Planet



depletion of metal to core (time)

primordial atm. retained

- Some N to core
- C in Atmosphere
- Retain initial C/N

primordial atm. lost to space

- C in atmosphere lost to space
- $C/N \ll (C/N)_{BSE}$

Making a Habitable Planet

- Earth's C and N likely supplied by materials that were a mixture of our cases - so at least reduced, if not oxidized
- magma-ocean related core formation (under most likely conditions) provides
  - ➡ low C in mantle, high N in atmosphere — need loss of primordial atmosphere to account for high C/N ratio

Assembling a Habitable World

- Most likely carriers of C and N are organics and carbonaceous grains
- In large (many km sized planetesimals) C/N fractionates further; between and within bodies.
- Core formation should drastically reduce the C/N ratio of forming planet, requiring substantial loss of N-rich primordial atmosphere - but need improved geochemical constraints.
- Hints at variable supply and retention of key ingredients of habitable worlds