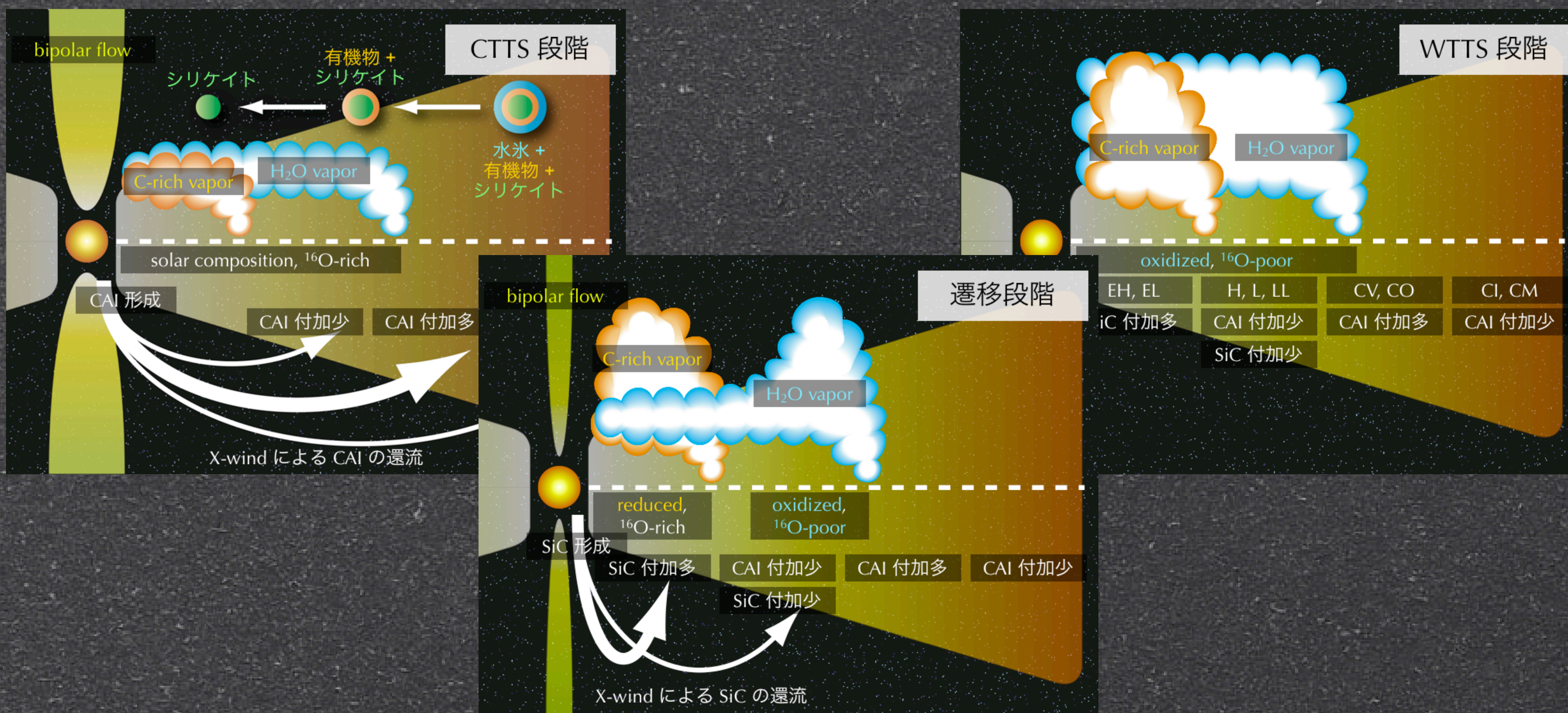
原始太陽系における水と有機物の挙動

—物質科学的惑星系起源論へ向けて—



福井　隆

DM2 Seminar, Nov. 17, 2005

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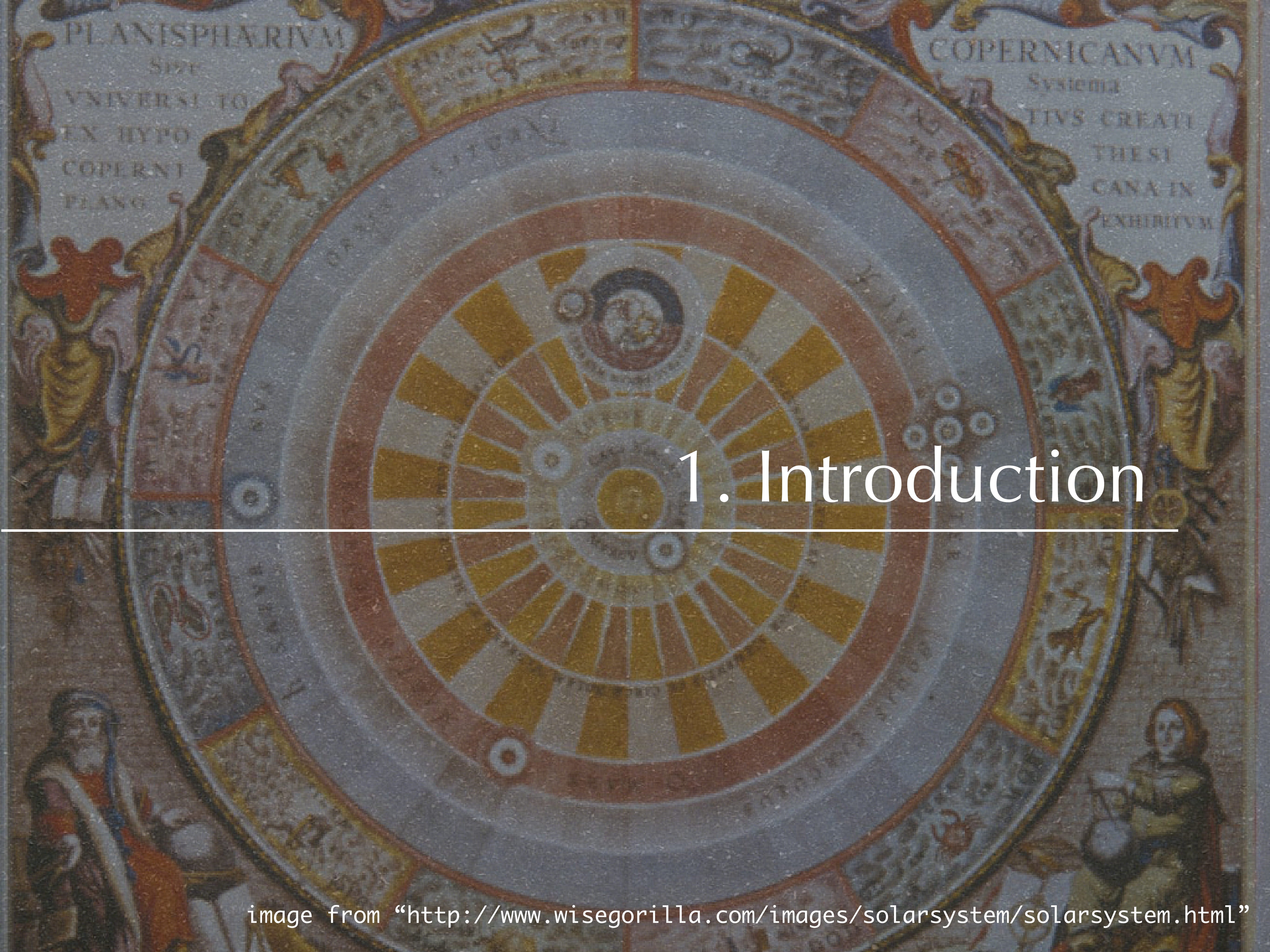
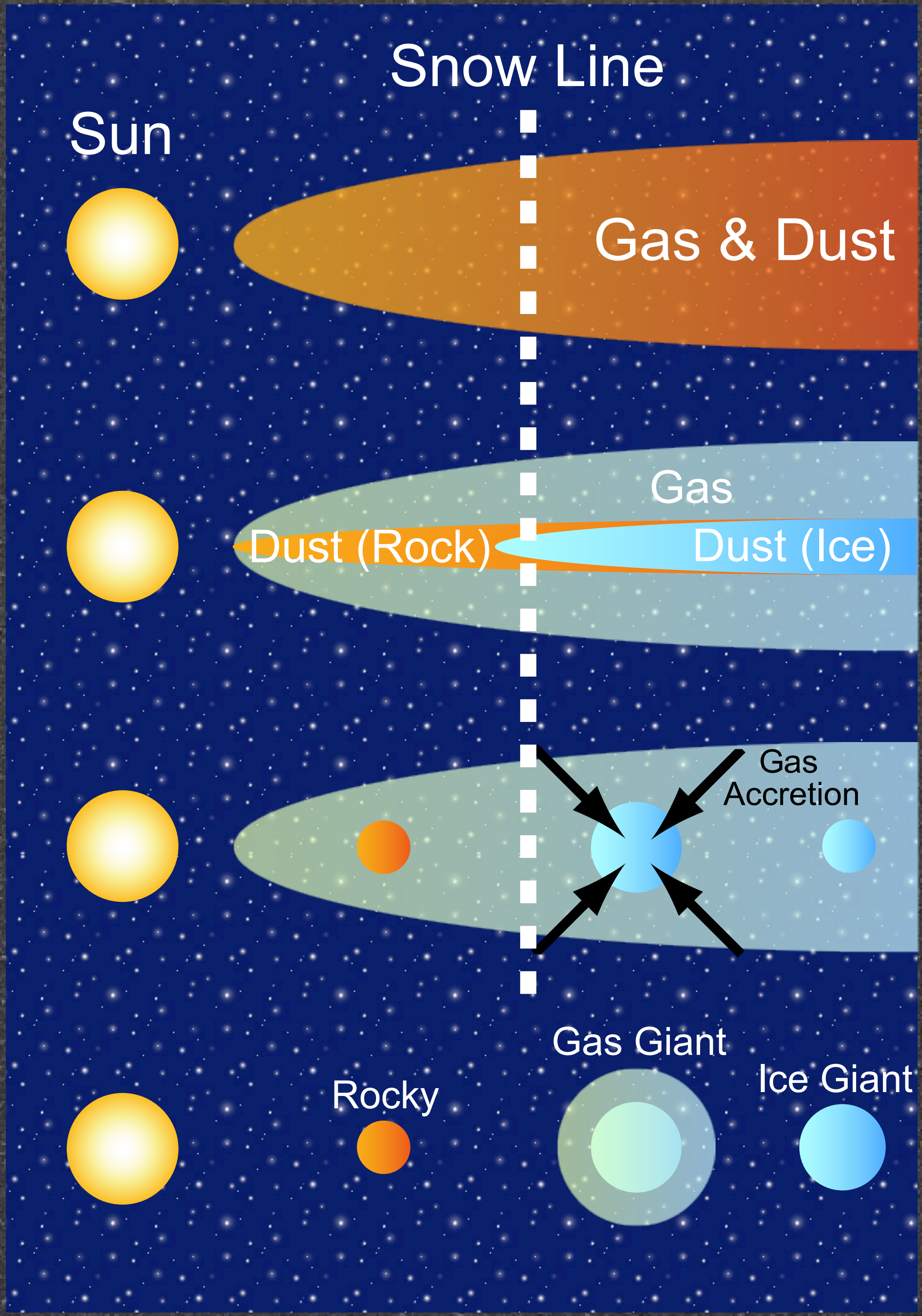


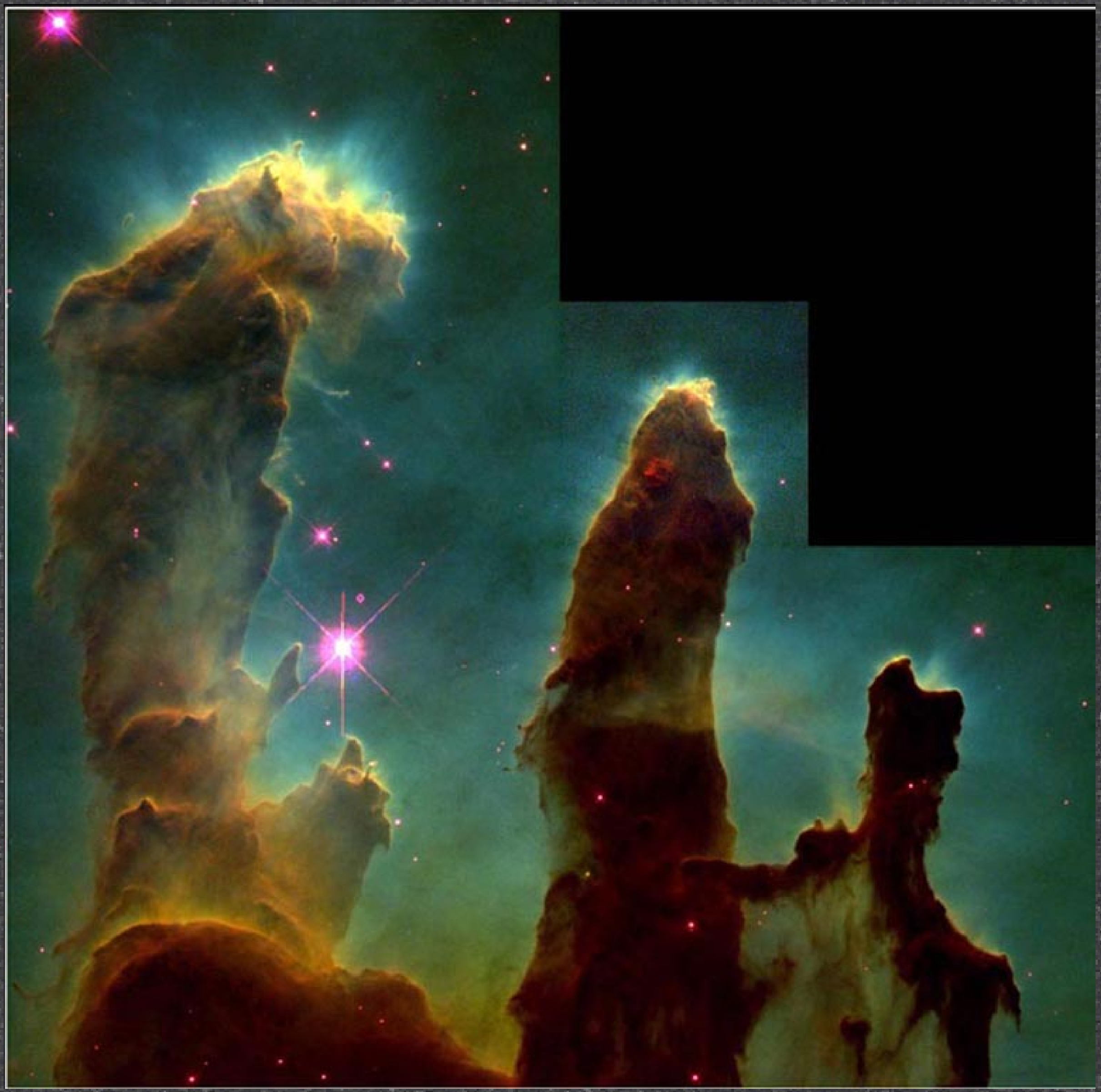
1. Introduction

image from “http://www.wisegorilla.com/images/solarsystem/solarsystem.html”

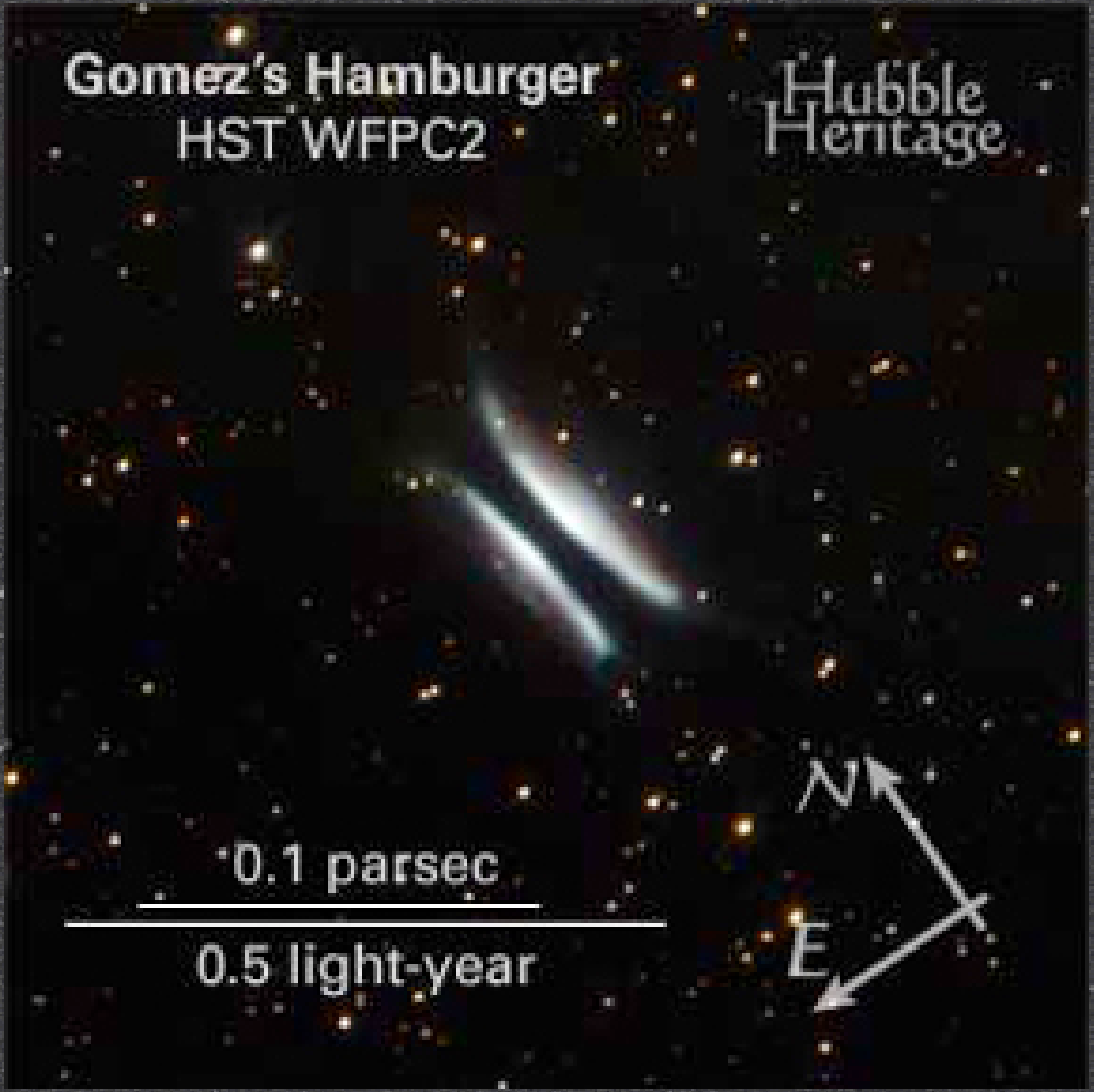
惑星系形成の標準モデル

- Hayashi, C. et al. (1985) 他が 1980 年代に構築.
- 各種惑星の形成, その配置などが説明可能.
- 問題もあるけれど…
  - 星雲モデルの妥当性
  - ダスト落下問題
  - 微惑星形成問題
  - “異形の惑星” 問題
- 大体わかった気になってる





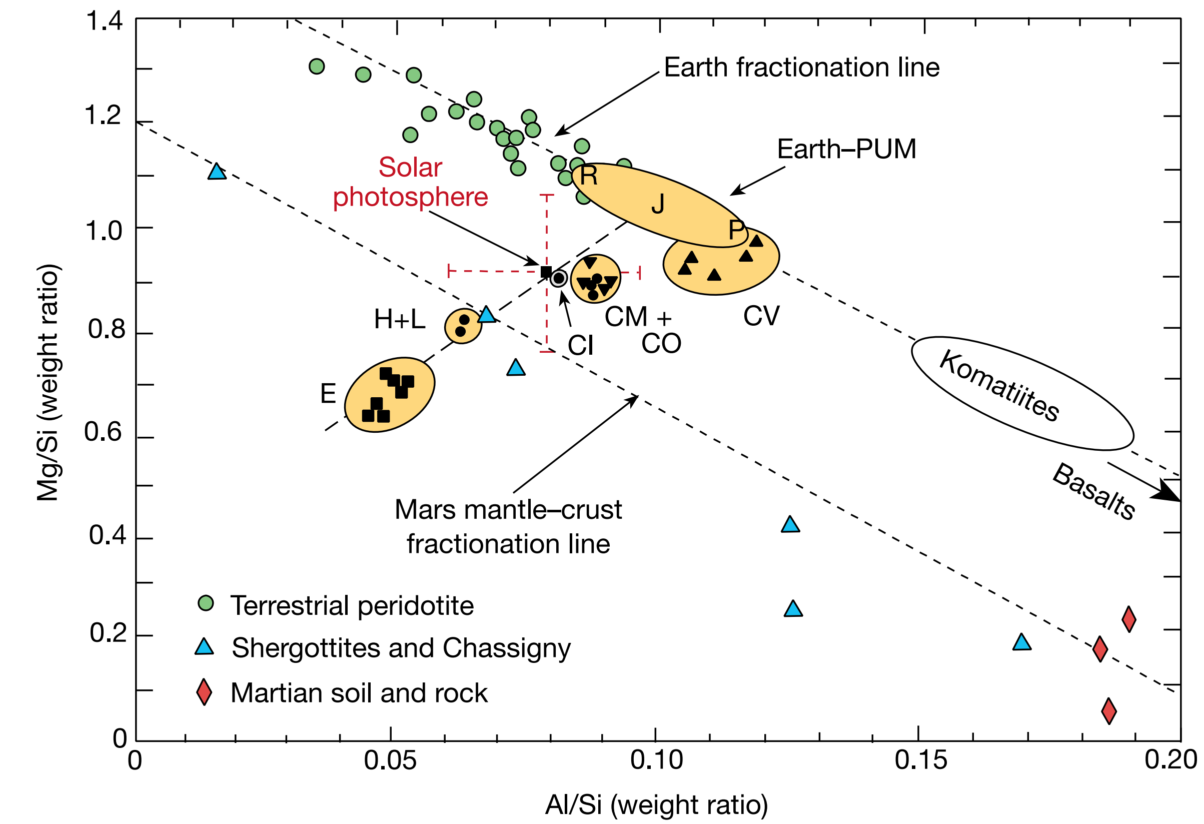
分子雲 (わし星雲)



原始惑星系円盤

物質科学的問題

- 地球の組成とその起源
  - コンドライトと PUM の組成の相違
  - “地球型” 隕石が存在する(した) か？
  - 他の地球型惑星は？
- コンドライトの起源
  - 各グループの成因は？
  - 構成物質の成因は？



Drake & Righter (2002)

2. 隕石学ミニマム

image from “http://mail.dominikanerinnen.at/gaeste/goldi/vmoe/boerse2.html”

隕石の分類

- 成因的分類
  - 未分化な隕石
    … コンドライト
  - 分化した隕石
    … エコンドライト,
    石鉄隕石, 隕鉄
- 分類の根拠
  - 組織的な特徴
  - 太陽組成との類似

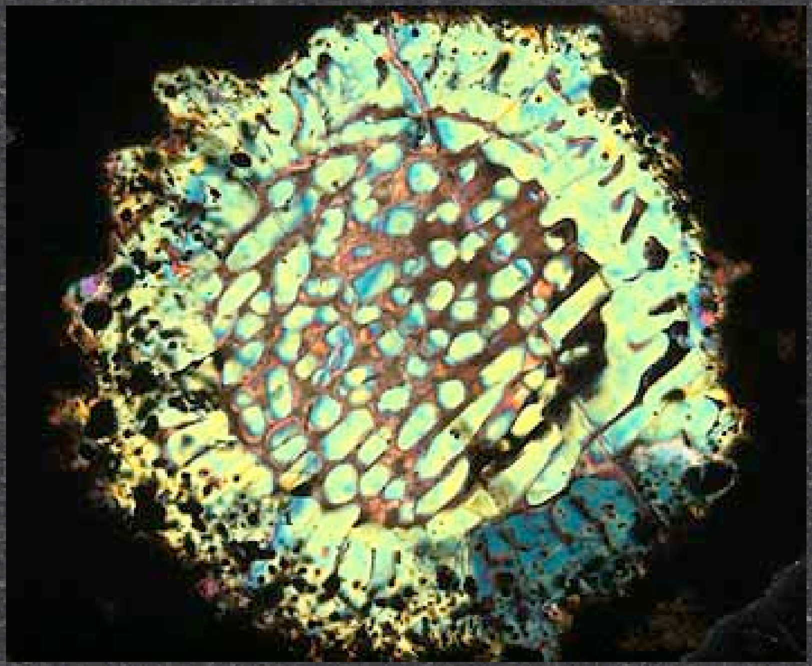
コンドライトの構成物質

- コンドリュール
  - mm サイズの球粒
  - ケイ酸塩鉱物, ガラス
- 難揮発性包有物
  - 1 cm 〜 10 μ m サイズ
  - Al-Ca 酸化物, シリケイト
- マトリックス
  - μ m サイズの微細結晶
  - プレソーラー粒子を含む

http://www.star-bits.com/CV3.htm

コンドリュール

- 球粒の由来
  - 無重力下での融解・再固化
  - 前駆物質はマトリックス
- 形成機構
  - 組織から冷却時間に制限
- 形成年代
  - CAI より数 Myr 若い
  - CAI-bearing chondrule の発見
- 酸素同位体組成
  - CAI に比べ ^{16}O-poor

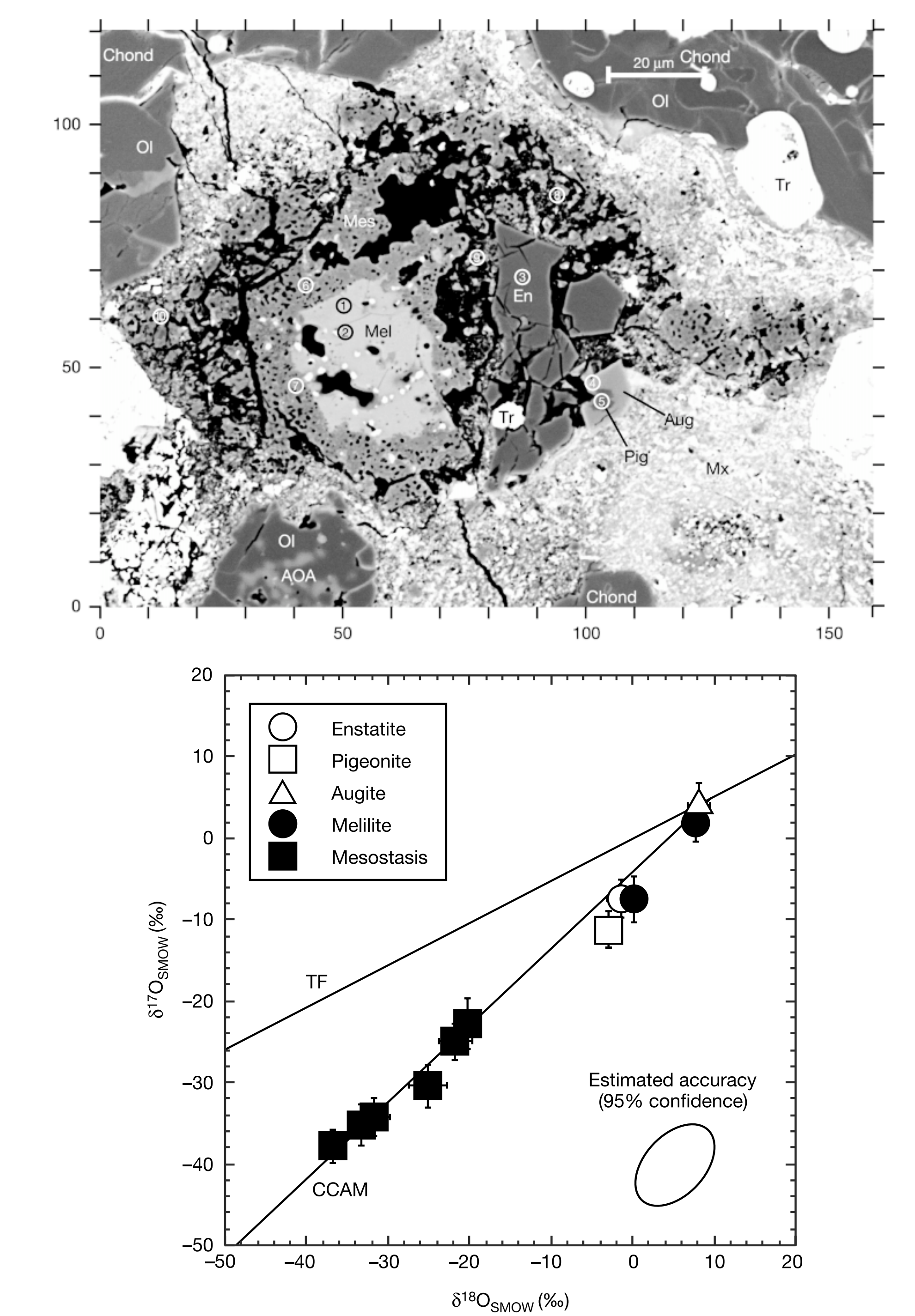


http://www.zeiss.com/

http://rst.gsfc.nasa.gov/Sect19/Sect19_2.html

Ca-Al-rich>Inclusion

- 最も高温で凝縮する物質
  - 太陽系最古の固体物質
  - fine grain (< 50 μ m)
    ... 気相からの凝縮
  - coarse grain (>50 μ m)
    ... 蒸発残渣
- chondrule-bearing CAI
- 酸素同位体組成
  - 地球等に比べ ^{16}O-rich
  - coarse grain は複雑

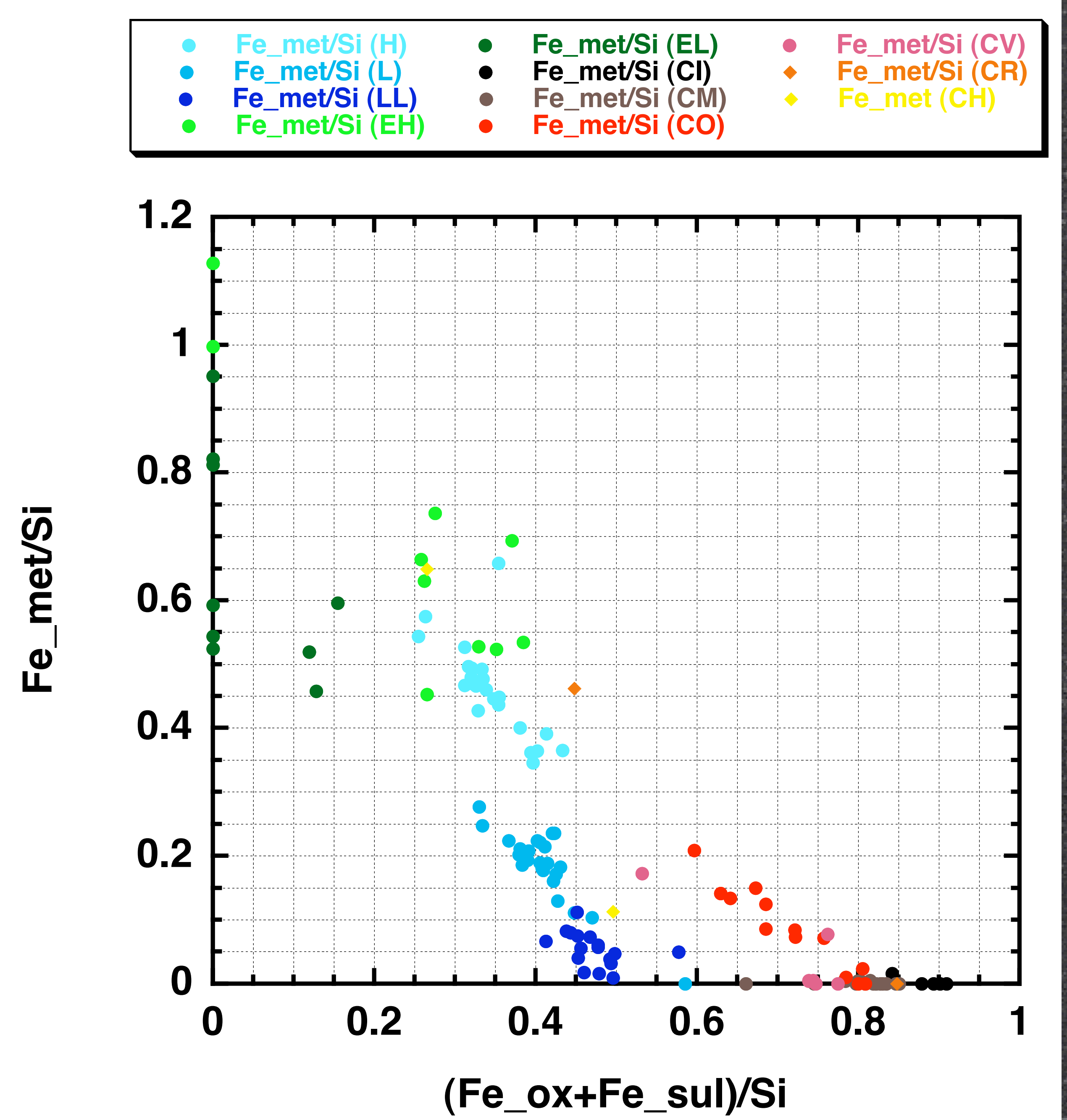


Ito & Yurimoto (2003)

コンドライトの分類

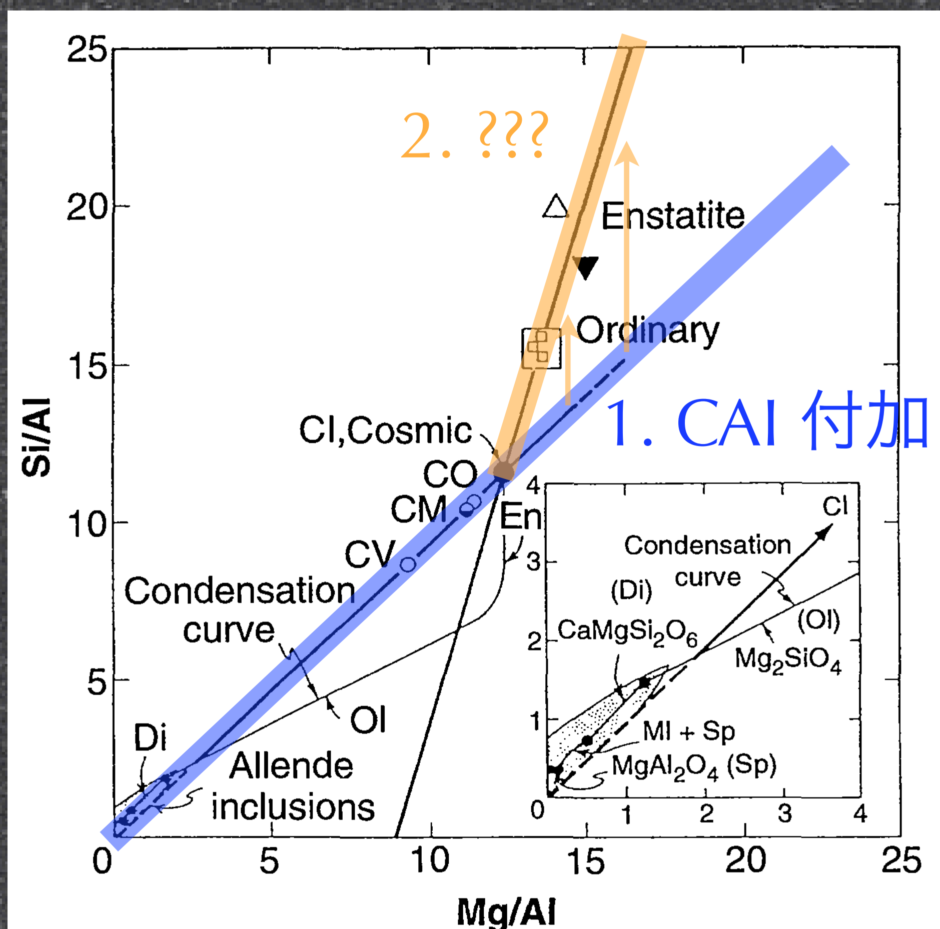
グループ	サブグループ	名前の由来
C (Carbonaceous)	CI	Ivuna, ～ C1
	CM	Mighei, ～C2
	CO	Ornans
	CV	Vigarano
O (Ordinary)	H	Hi-Fe
	L	Low-Fe
	LL	Low-Fe, Low-metal
E (Enstatite)	EH	Hi-Fe
	EL	Low-Fe

- Fe の総量の違い
  - シリケイトとの分別過程の存在を示唆

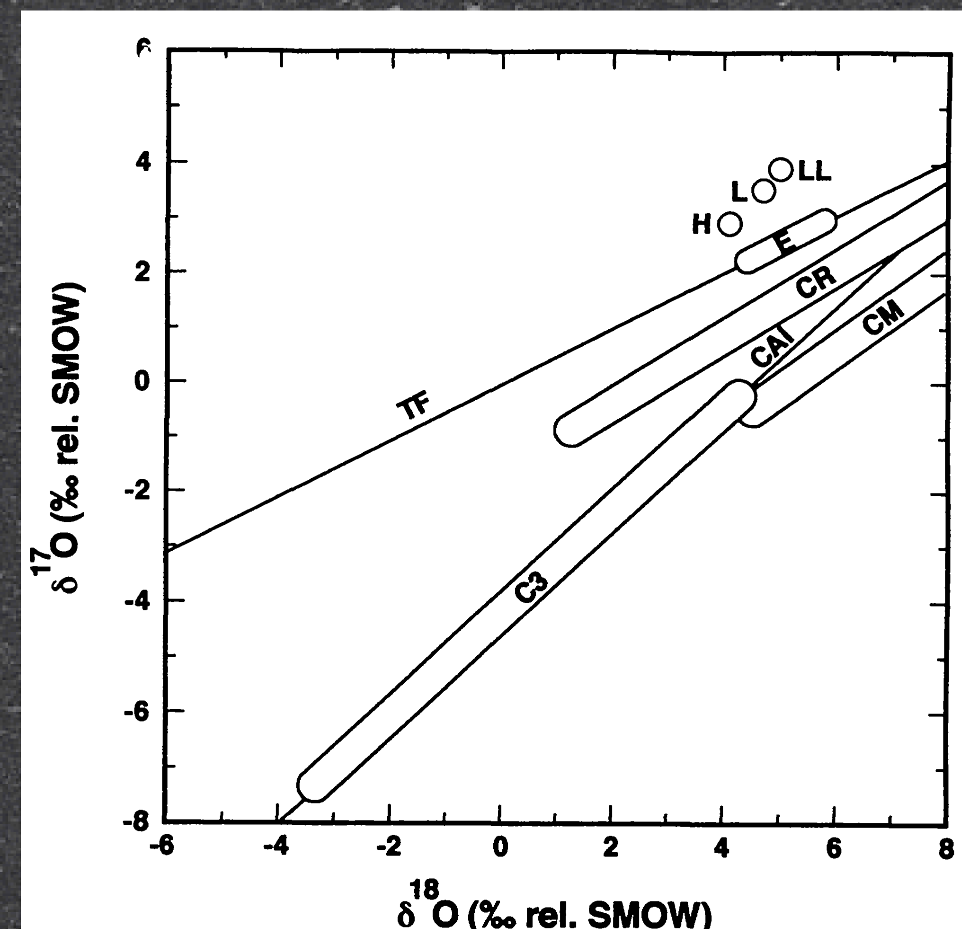


(倉本さん作成)

Si/Al-Mg/Al>比,>酸素同位体組成

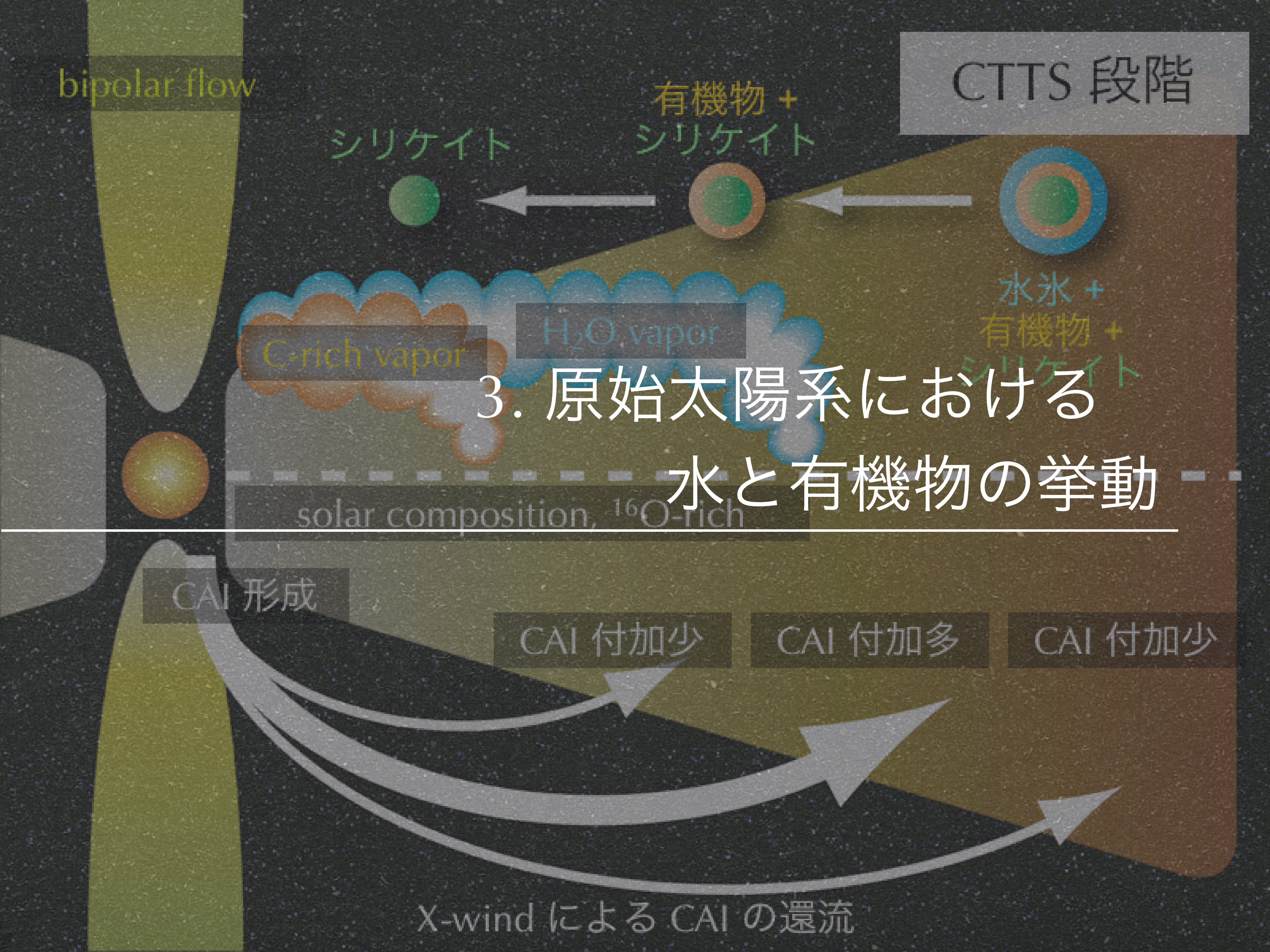


Larimar & Wasson (1988)



R. N. Clayton (1993)

3. 原始太陽系における水と有機物の挙動

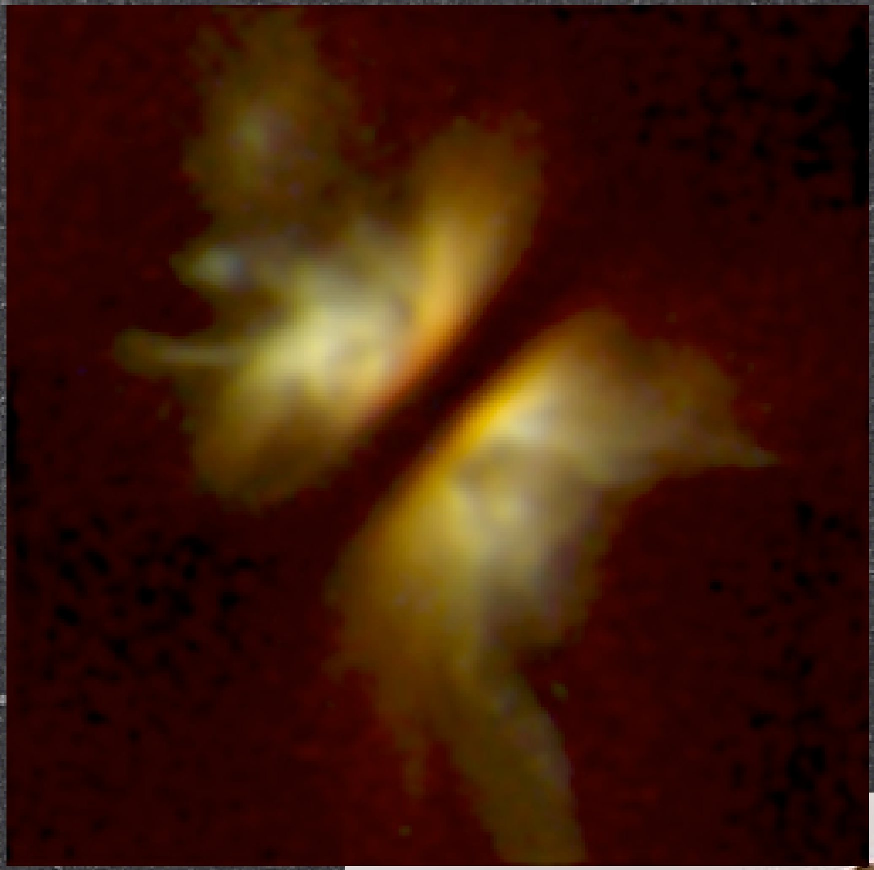


Evolution of Protoplanetary Disk

- Dynamical evolution
  - Disk structure
  - Accretion rate

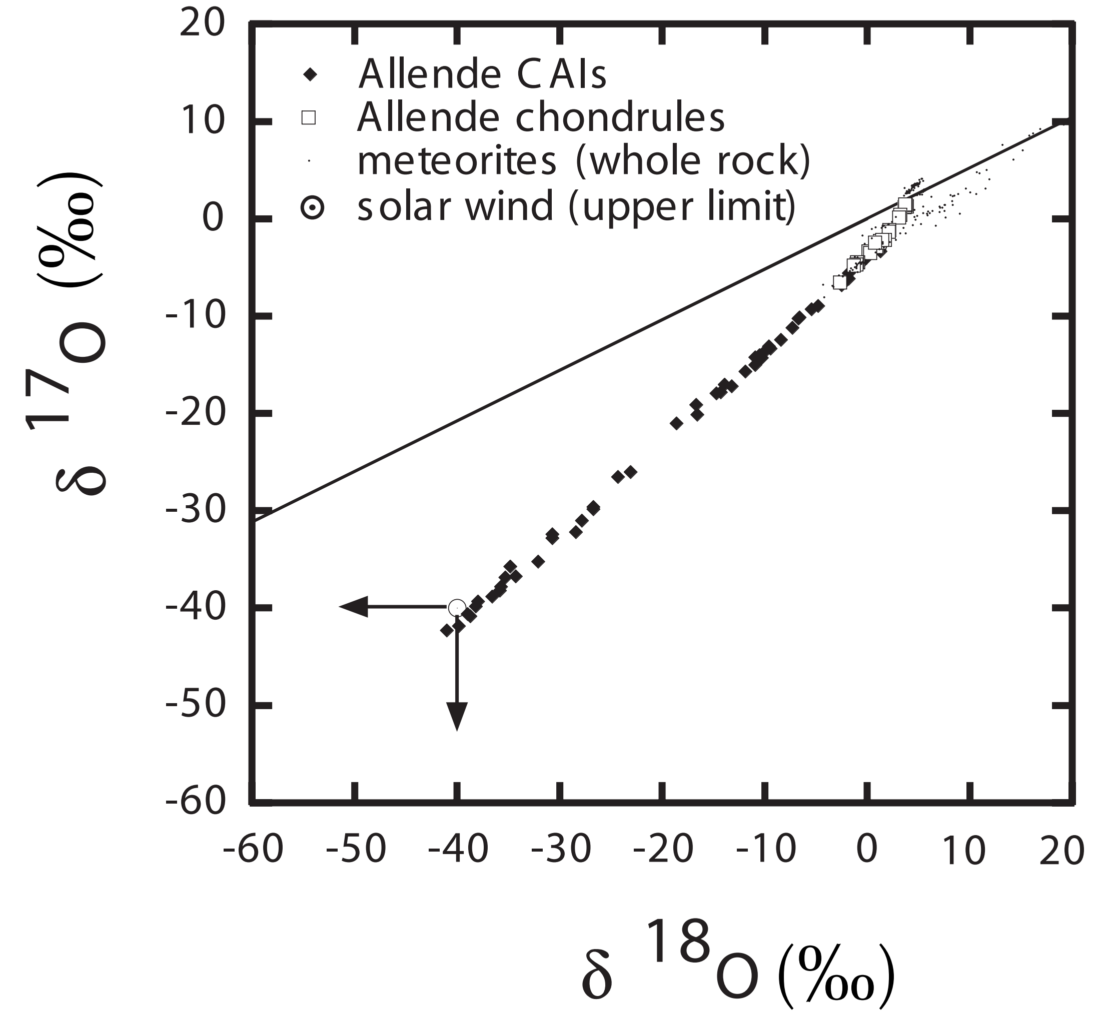
→ recently available
(e.g., Calvet et al. 2000)

- Compositional evolution
  - Chemical composition?
  - Isotopic composition?



Hints from Chondrites: Oxygen Isotopic Composition

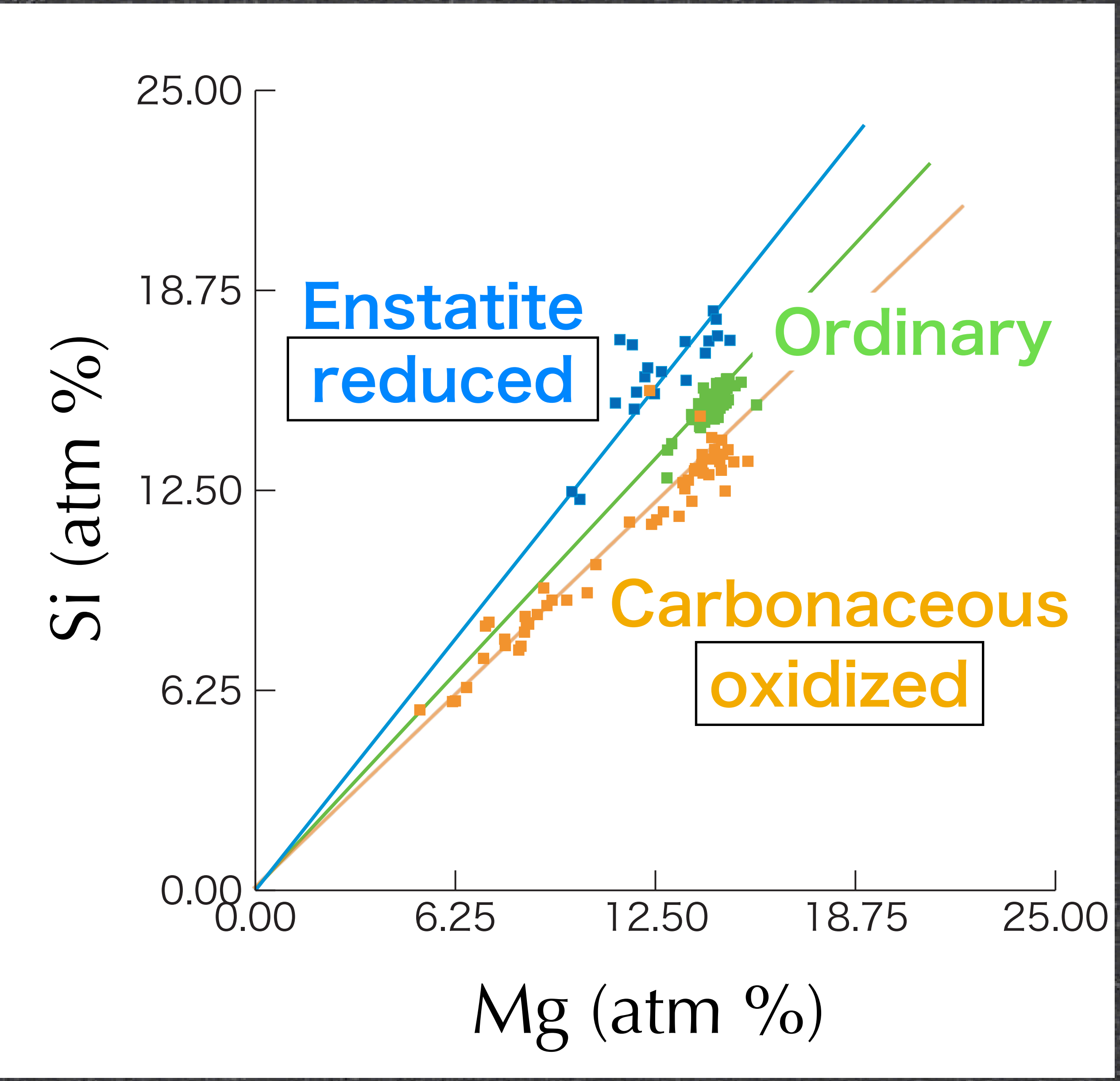
- Mass-independent fractionation
  - ^{16}O-rich ... CAI
  - ^{16}O-poor ... Chondrule
- Implying existence of ^{16}O-rich & -poor reservoirs
- Chronology suggests that oxygen isotopic composition changed during several Myr



Kuramoto & Yutimoto (2005)

Hints from Chondrites: Redox State

- Systematic variations in Si/Mg ratio and redox state
  - More reduced type has higher Si/Mg ratio
  - Heterogeneous addition of SiC and reprocessing possibly produce these variations.
- Formation of SiC requires high C/O ratio (>0.95) relative to original one (0.5).



Early Studies

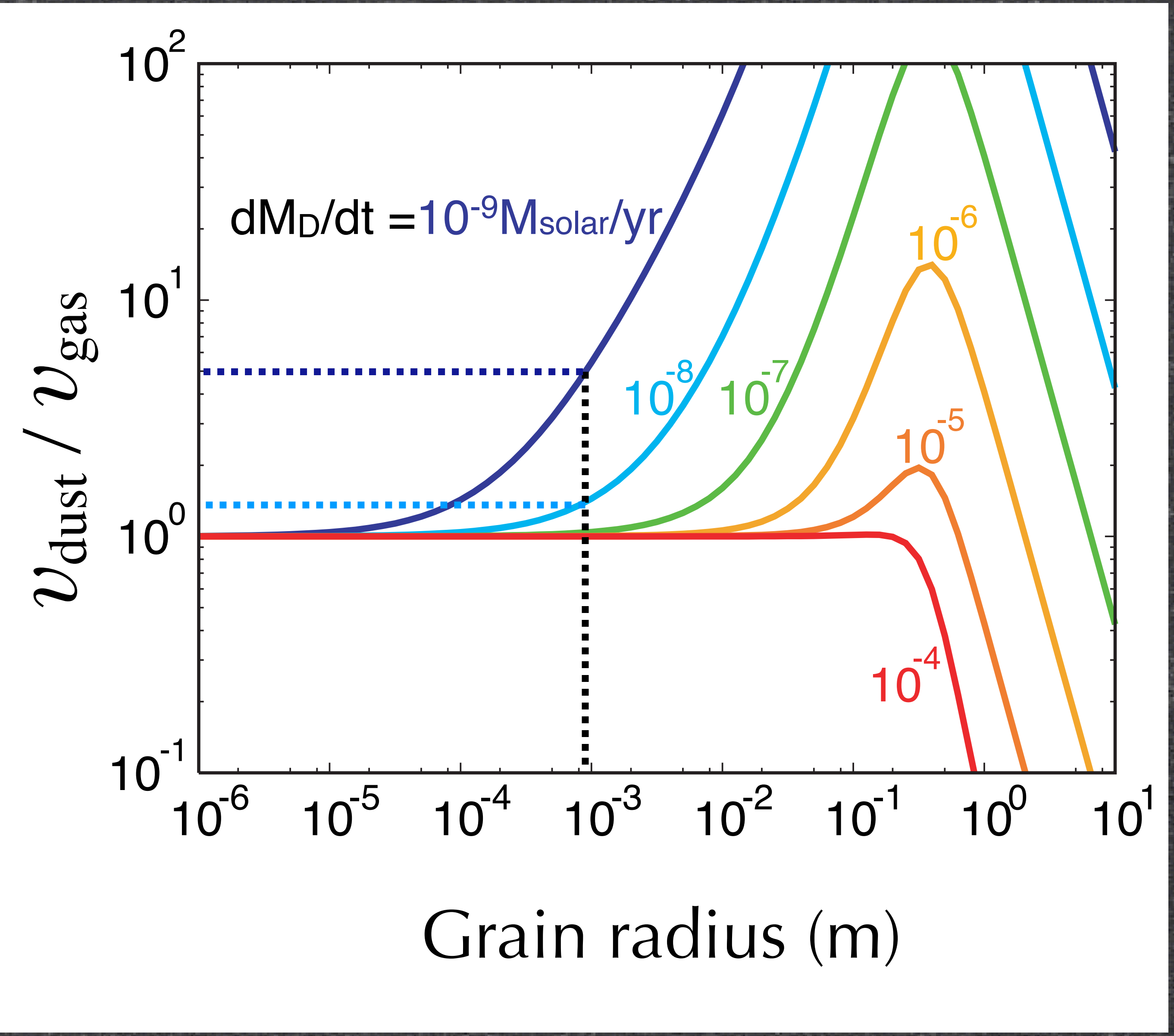
- Cuzzi & Zahnle (2004)
  pointed out that preferential migration of dust particles would enhance vaporized component at inner disk.
- Yurimoto & Kuramoto (2004)
  modeled oxygen isotopic evolution of disk by using same process, but they assumed steady evolution of disk and time scale of the evolution was not fully discussed.
- Nakano et al. (2003)
  suggested that C-bearing vapor (hydrocarbons) from organic materials controlled C/O ratio of disk, but they did not consider the effect of advective diffusion in accretion disk.

In This Study...

- We have performed a numerical calculation for advective diffusion in accretion disk, considering
  - preferential migration of dust particles
  - evaporation of H_2O ice and organic materials
  - rapid decay of gas accretion
- To clarify compositional evolution of disk & its time scale.

Preferential Migration of Dust

- Dust particles radially migrate faster than gas due to gas drag.
- v_{dust} / v_{gas} increases with decay of disk accretion.
- For mm sized particle :
  - 10^{-8} M_{solar} / yr ...
    $v_{dust} / v_{gas} \sim 1$
  - 10^{-9} M_{solar} / yr ...
    $v_{dust} / v_{gas} \sim 5$



Dust evaporants are enhanced in its evaporation area

Advective Diffusion Equation

$$\frac{\partial c_i}{\partial t} + v_r \frac{\partial c_i}{\partial r} - \frac{1}{\Sigma r} \frac{\partial}{\partial r} \left(\Sigma r D \frac{\partial c_i}{\partial r} \right) = \frac{S_i}{\Sigma}$$

c_i : Concentration of species i S_i : Source for species i

r : Distance from disk center v_r : Migration velocity of gas

Σ : Surface density of disk D : Diffusion coefficient

We can rewrite as...

$$v_r = \frac{\dot{M}}{2\pi r \Sigma}, \quad \nu = -\frac{2 r v_r}{3}, \quad D = \nu$$

ν : Turbulent viscosity

Distribution of O&C for Each Carrier

	Silicate	Ice (H_2O)	Organic material	Gas (CO)
O	1	3.5	~ 0	1.5
$\delta\,^{17,18}O_{MC}$ (‰)	0	+100	—	-230
C	0	0	1.5	1.5

- Assuming that half of C is partitioned into CO gas and another half into organic materials.
- $\delta\,^{17,18}O_{MC}$ means deviation from isotopic composition of molecular cloud.

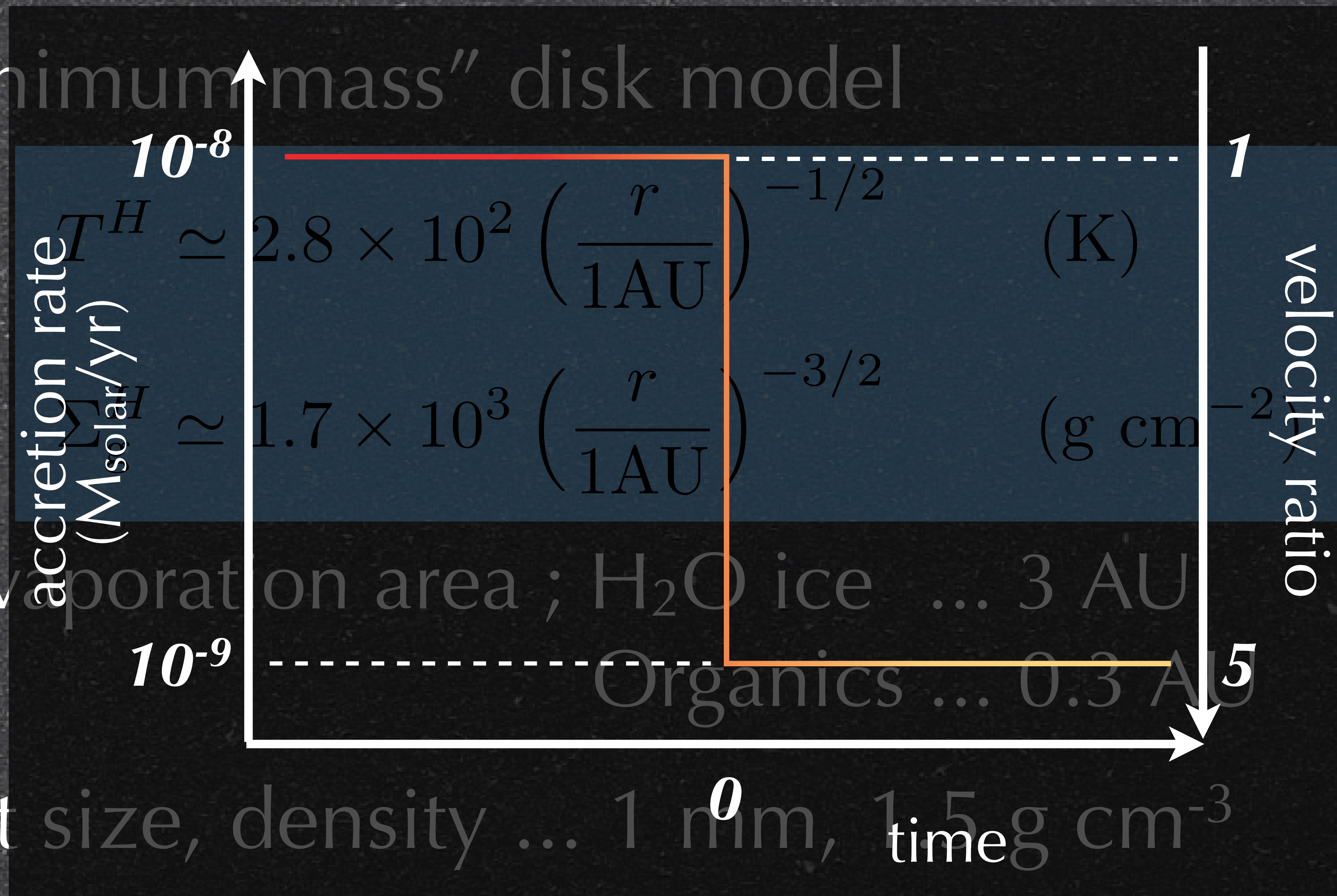
Disk Model & Parameters

- "Minimum mass" disk model

$$T^H \simeq 2.8 \times 10^2 \left(\frac{r}{1\mathrm{AU}}\right)^{-1/2} \quad (\mathrm{K})$$

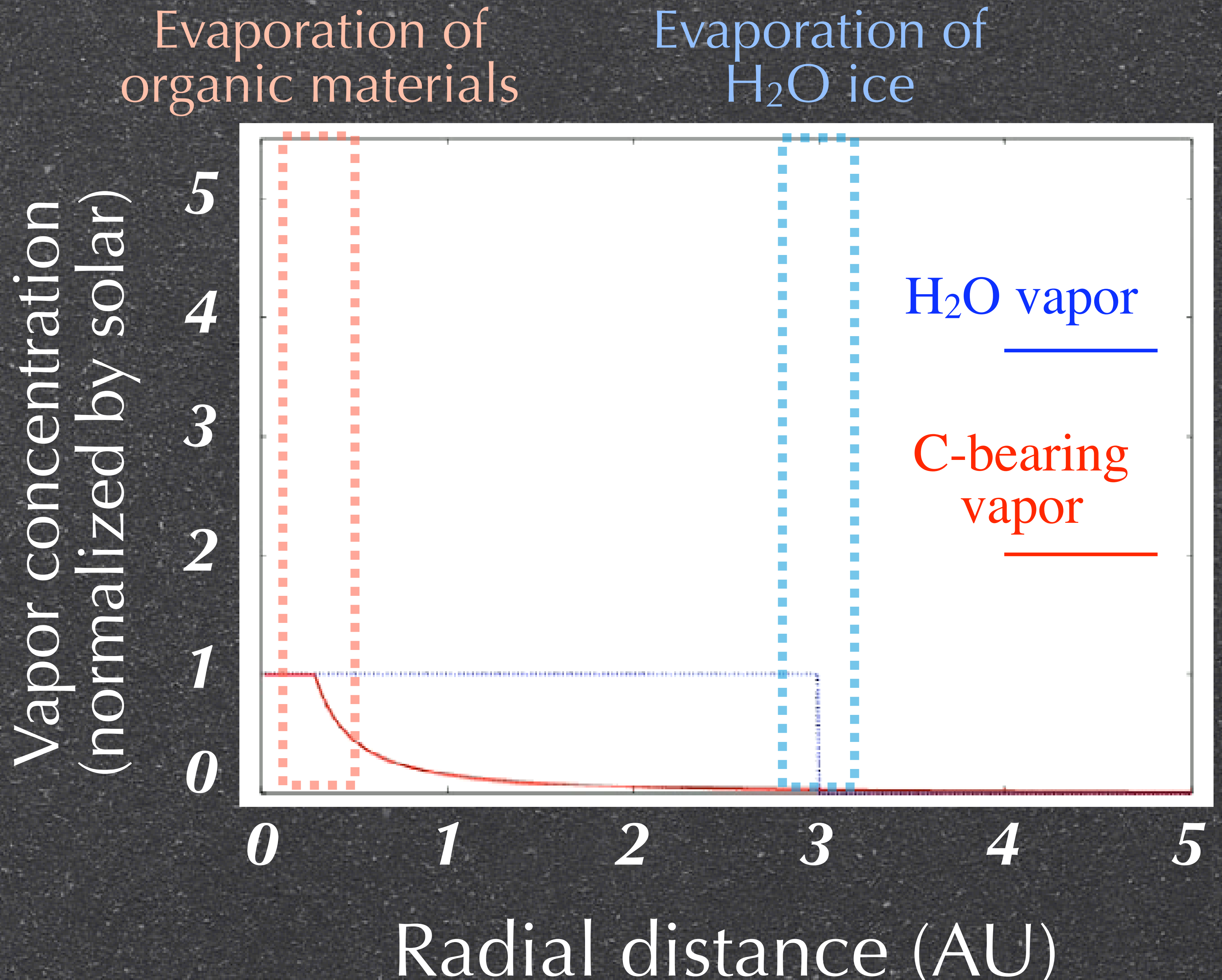
$$\Sigma^H \simeq 1.7 \times 10^3 \left(\frac{r}{1\mathrm{AU}}\right)^{-3/2} \quad (\mathrm{g\ cm^{-2}})$$

  - Evaporation area ; H_2O ice ... 3 AU
    Organics ... 0.3 AU

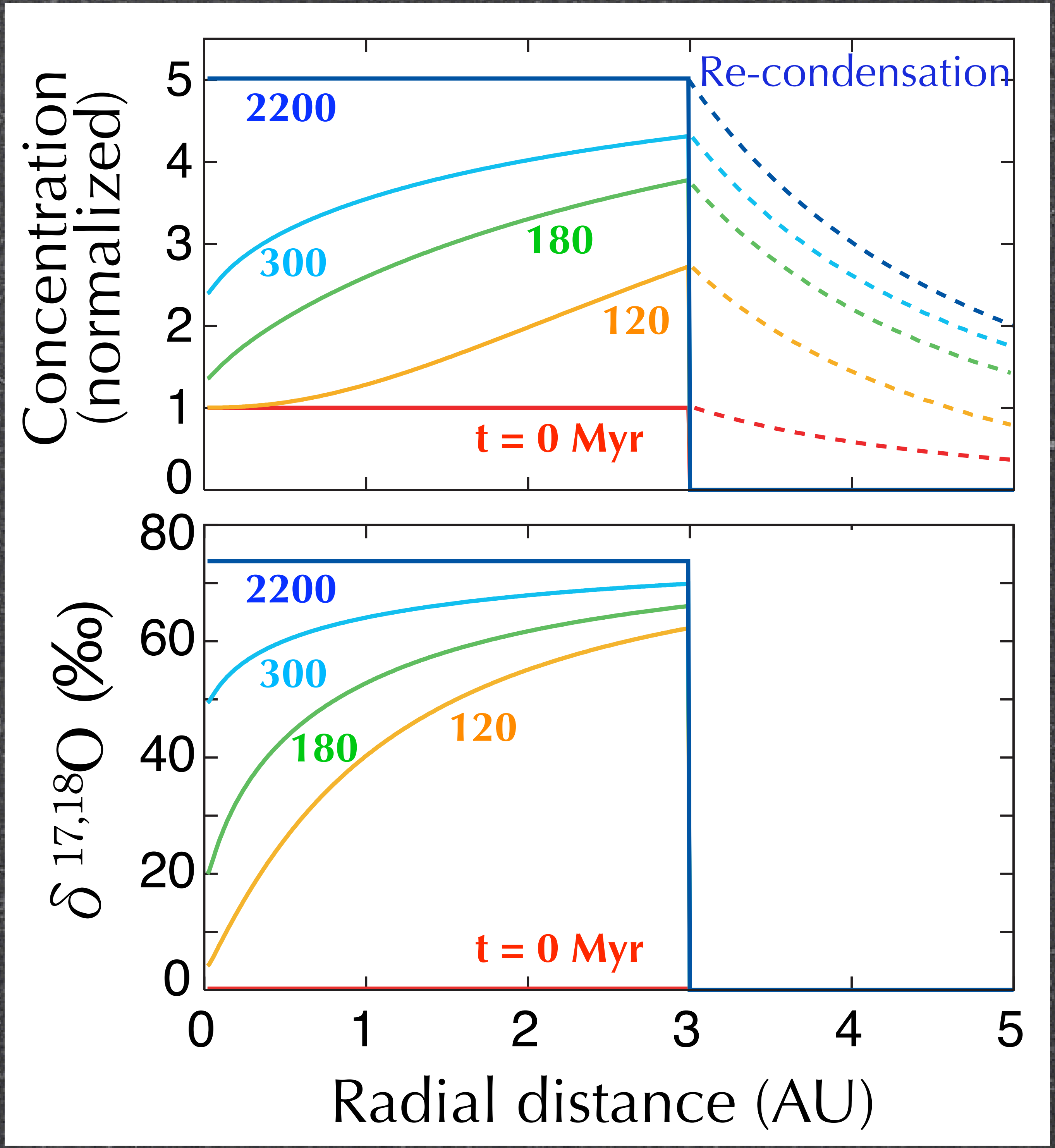


- Dust size, density ... 1 mm, 1.5 g cm^{-3}
- Accretion rate ... 10^{-8} - 10^{-9} M_{solar} /yr
  - correspond to transitional phase from CTTS to WTTS
  - assuming the time scale of decay is very short

Results


Evaporation of organic materials
Evaporation of H_2O ice
H_2O vapor
C-bearing vapor
Vapor concentration (normalized by solar)
0
1
2
3
4
5
Radial distance (AU)

Evolution of Oxygen Isotopic Composition

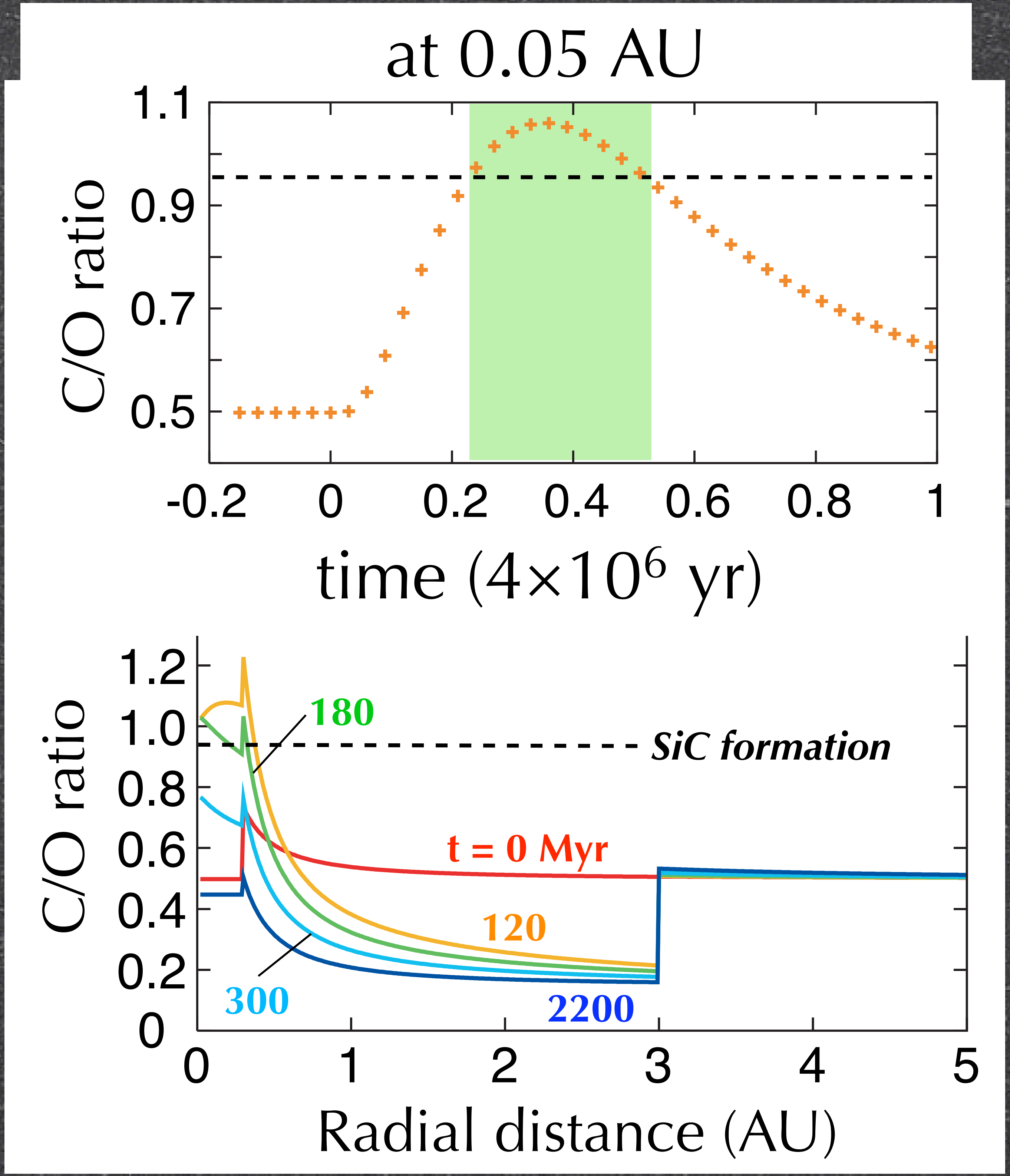


- Compositional evolution time is scaled by residence time t_{res} ~ 4 Myr;

$$t_{\mathrm{res}} = \frac{\text{inner disk mass}}{\text{mass accretion rate}}$$

- This value is consistent with evolution time suggested by chronology (several Myr).
- Locational heterogeneity also exists.

Evolution of C/O ratio



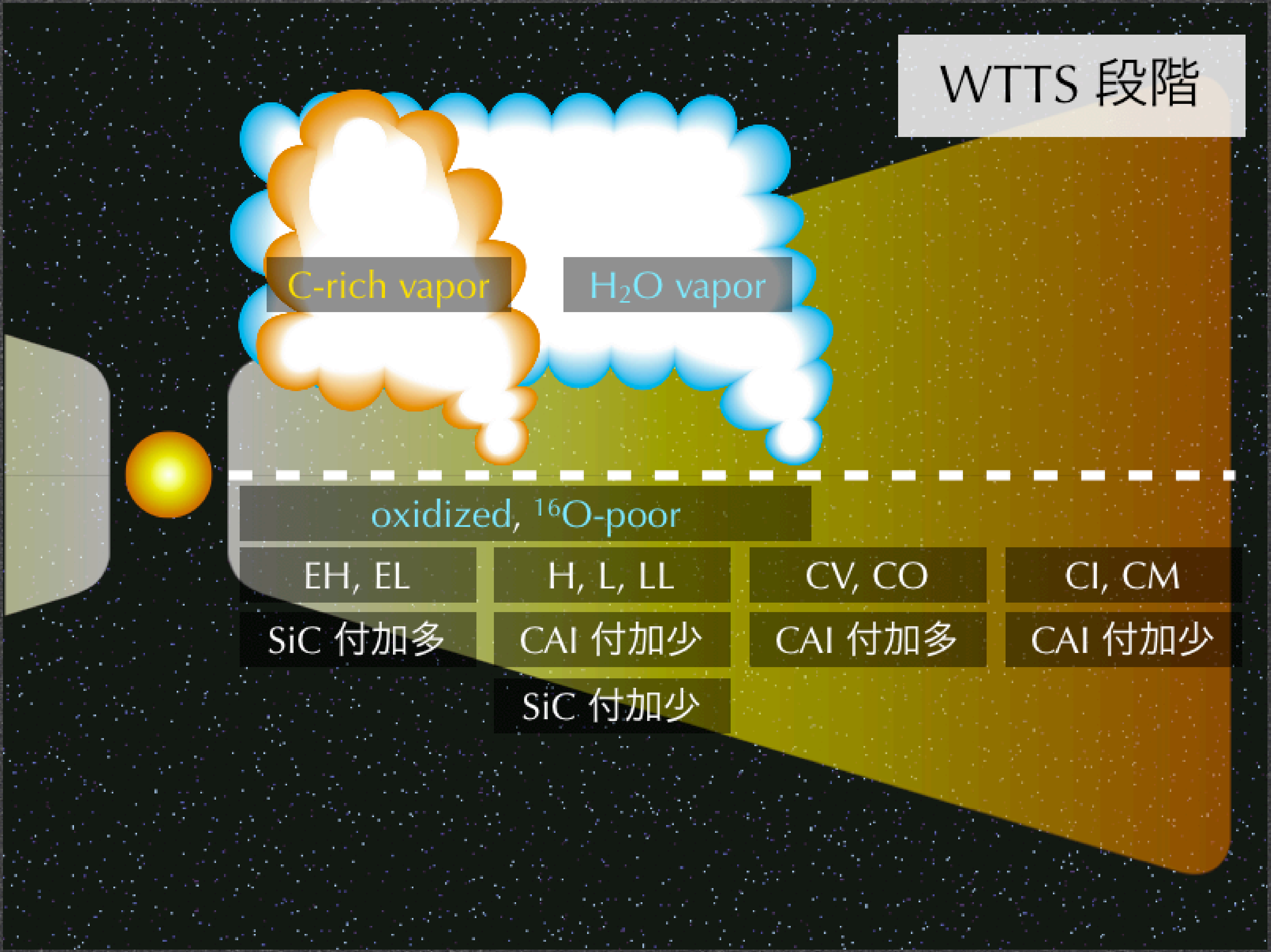
- In case that time scale of accretion decay is sufficiently shorter than t_{res} , a reduced environment would be formed at innermost region of disk.
- t_{res} ~ 4 Myr is longer than the lifetime of CTTS, so this is a presumable assumption.
- At 0.05 AU where X-wind arises, SiC formation would last for 1 Myr.

A Possible Scenario of Material Formation

1. at high accretion rate
   ... oxidized ^{16}O-rich disk,
   CAI formation at the disk center
2. soon after accretion decays
   ... reduced disk center, SiC formation
3. at low accretion rate
   ... oxidized ^{16}O-poor disk, continuous chondrule formation event, reprocess with added SiC

- Large addition of SiC ... reduced chondrule
- Small addition of SiC ... oxidized chondrule

A Possible Scenario of Material Formation

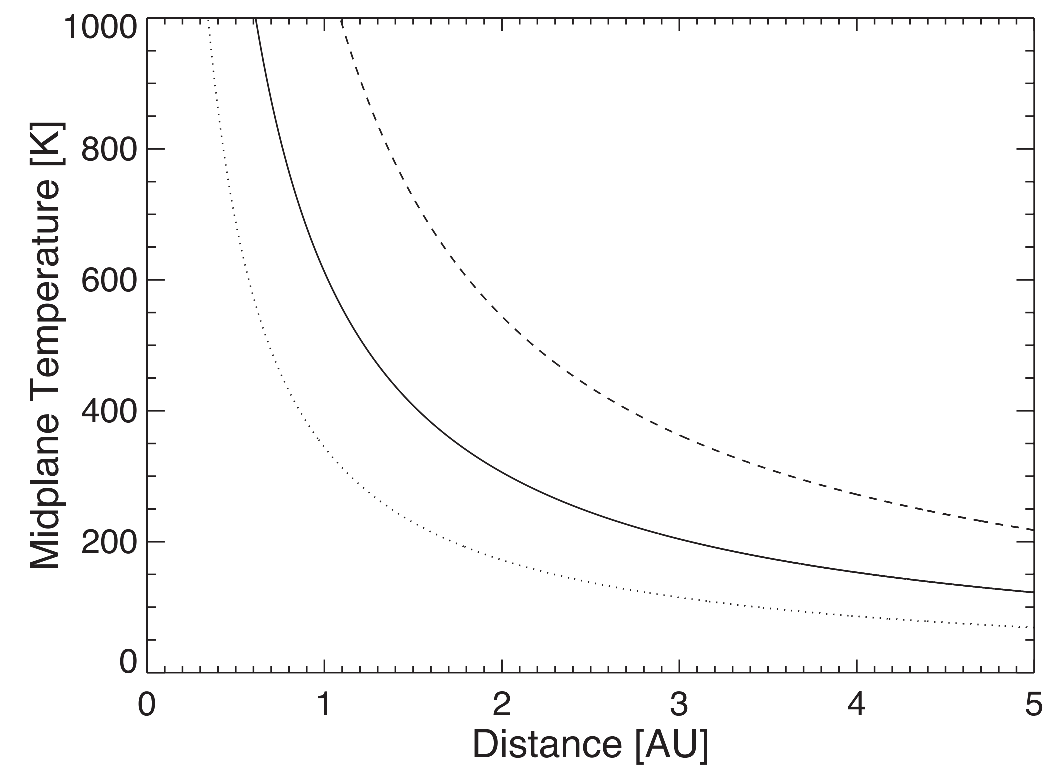


4. 修士論文へ向けて

image from “http://www.ep.sci.hokudai.ac.jp/~chihiro/

円盤モデルの精密化

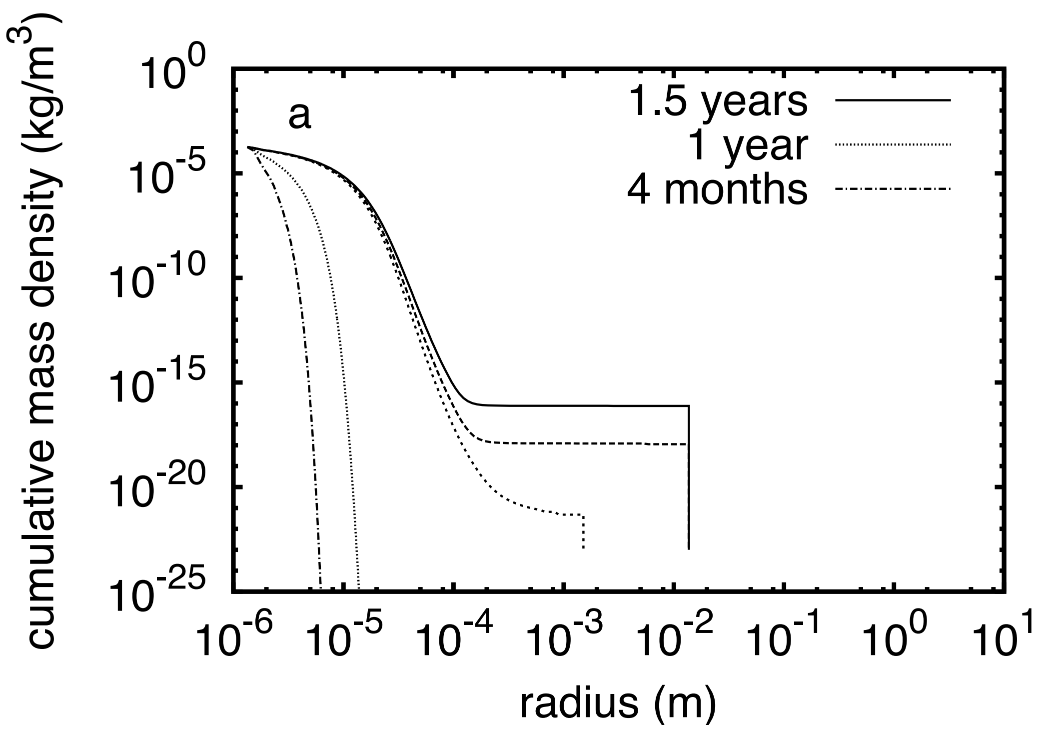
- 円盤温度の進化
  - まずは解析的モデルで
  - ダストサイズ分布と合わせて
- 円盤面密度の進化
  - ダストは枯渇するか？



Ciesla & Lauretta (2005)

ダストの付着成長過程

- 島沢コードの活用
  - サイズ分布の考慮が可能
- ダスト–ガス分別への影響
  - z 方向の分別は？
  - 有機物の付着限界速度大
    - 水との濃集度に差？
- 円盤構造への影響
  - 温度分布 etc.



(木星系 subnebula について)

同位体交換速度の見積り

- コンドリュール
  - ^{16}O-poor
  - 元々は ^{16}O-rich (YK04)
  - 融解時間 : 1 〜 100 hour
- 形成環境への制約
  - ダストディスクの厚さ
  - 他の見積りとの比較

5. 強敵(とも)の動向


Tennessee
North Carolina
State Line
ELEVATION 5048
GREAT SMOKY MOUNTAINS
NATIONAL PARK

F.>J.>Ciesla>さん

- ダスト–ガス分別過程
  - 我々と同じ
- 有機物は考えない
  - H_2O の欠乏で還元的環境
- 計算コード
  - 色々解いているらしい
    - 付着成長過程
    - ダストの動径移動