巨大惑星の解剖学：
内部構造・熱進化から起源へ (第2部)

堀　安範

国立天文台 理論研究部

© JUNO, NASA

© Cassini, NASA

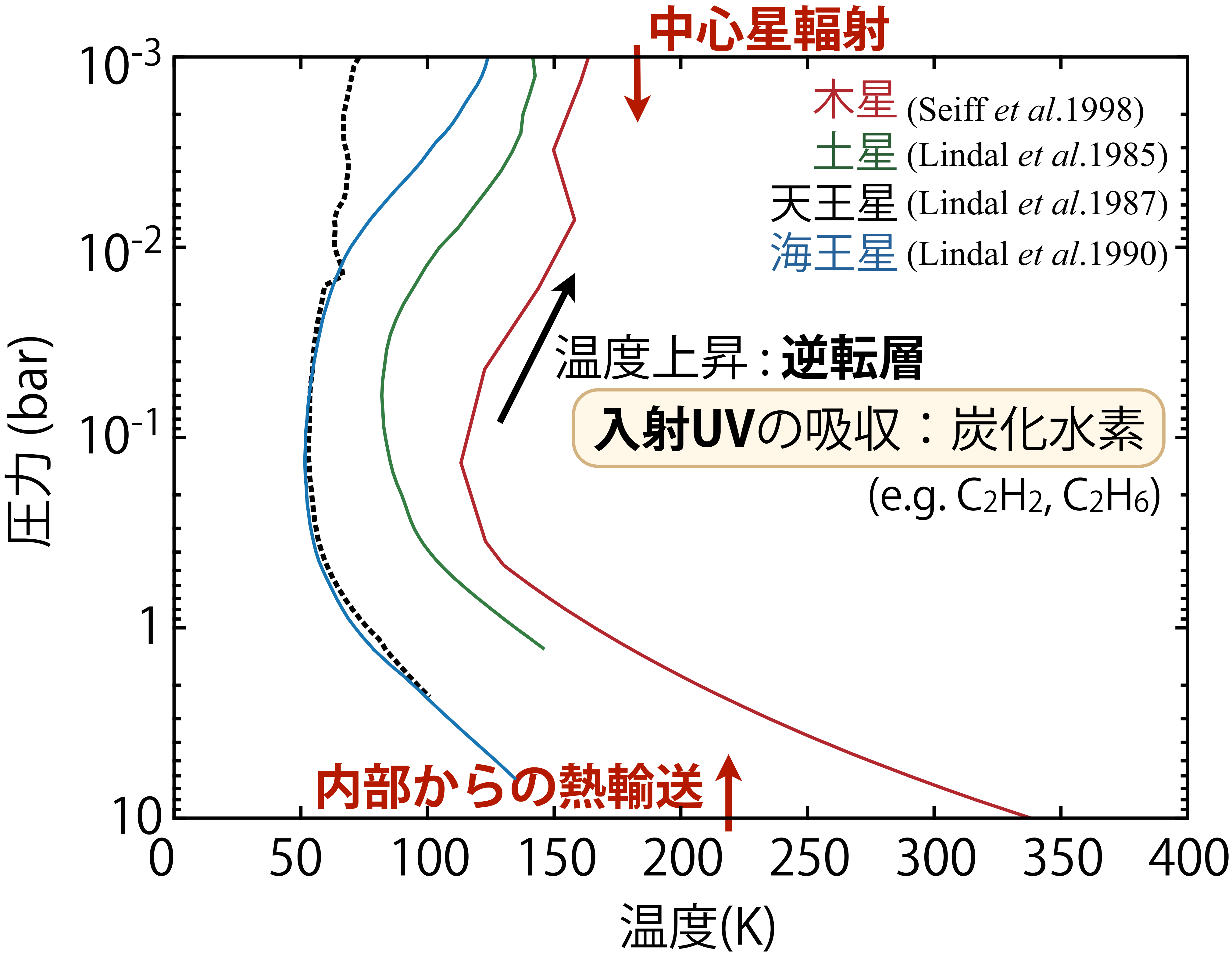
森羅万象学校
The School of the Universe

第13回 森羅万象学校

『木星を解剖する – 巨大ガス惑星の腹のうちと誕生の謎』

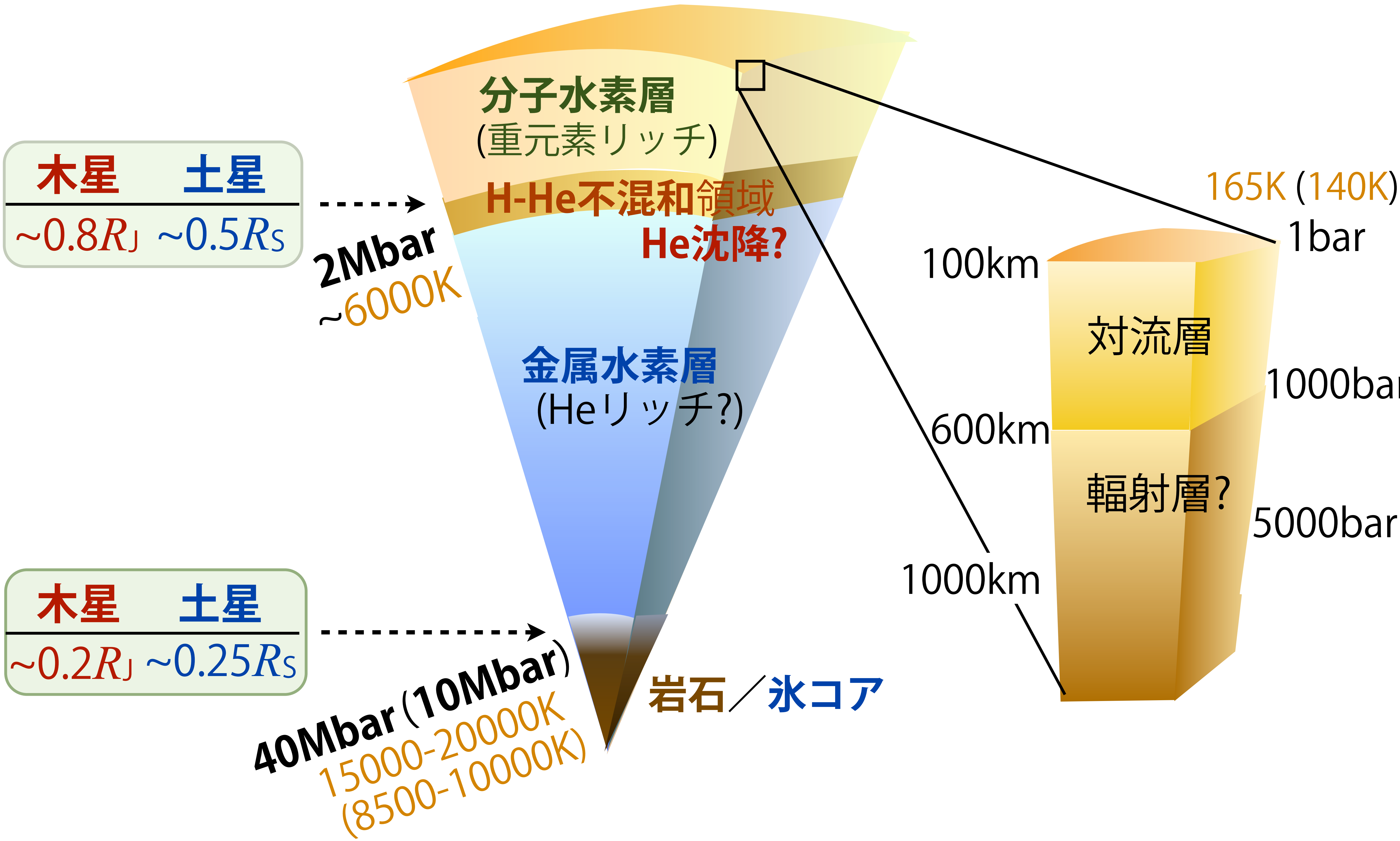
2013年 3月26日-28日＠北海道 支笏湖

1.3 太陽系の巨大惑星の大気構造



※ 木星(Galileo probeによる大気突入)
土星 (Voyager1,2)・天王星・海王星(Voyager 2)：電波掩蔽実験

太陽系のガス惑星の内部構造：最近の描像



※ 1bar = 10kPa ~ 1気圧

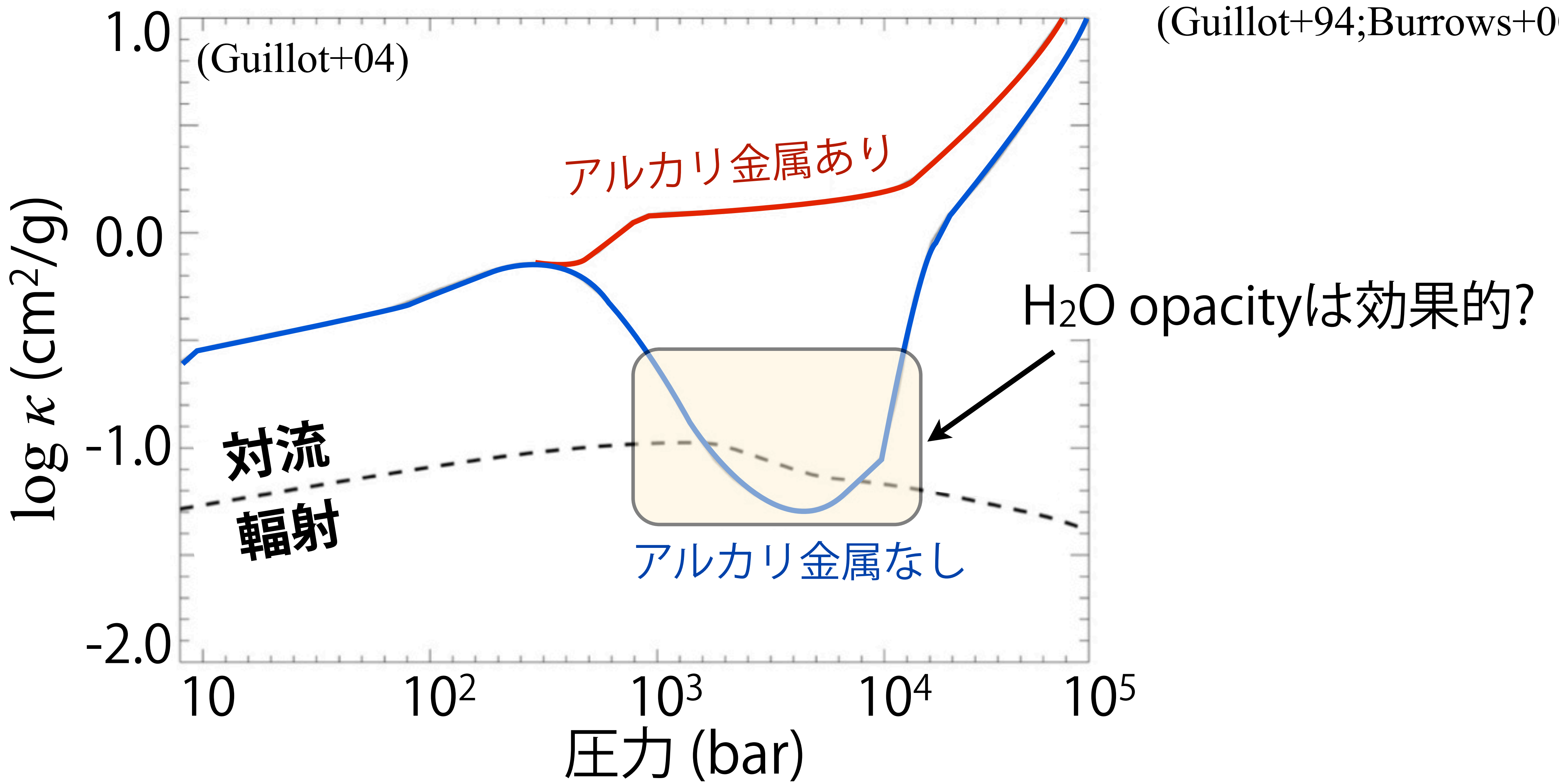
木星・土星の大気：熱輸送

木星・**土星**内部 --- (ほぼ)**全対流**　※ P, Tともに急激なopacity↑

(Q) 木星・土星の大気は？

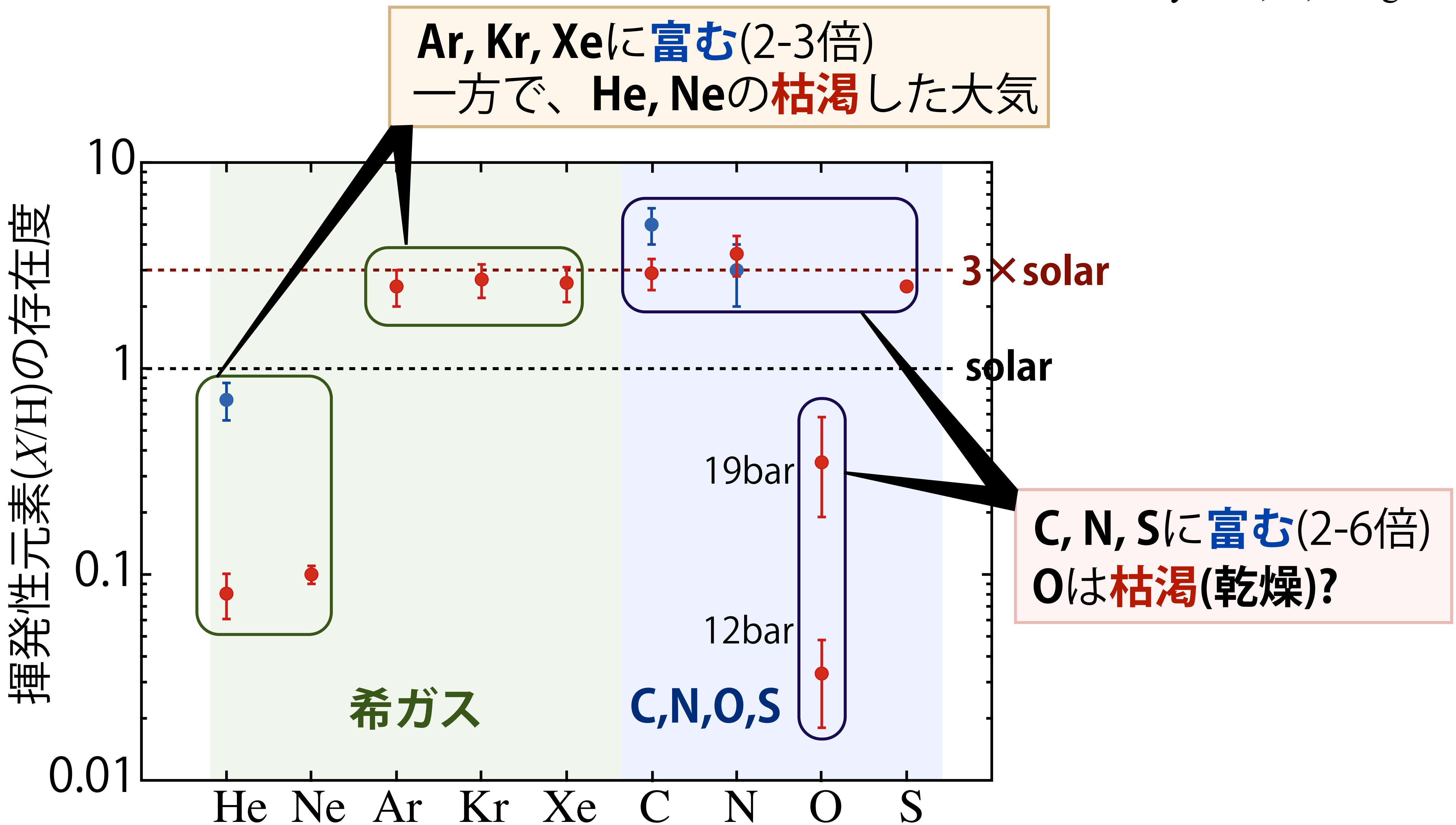
主たる**opacity源** --- H_2-H_2 CIA, **H_2O**, **CH_4** ($T <$ 1000K)
アルカリ金属 (Na, K ...) (T~1200-1500K)
H_2^-, H^-, TiO ($CaTiO_3$) (T ~1500-2000K)

(Guillot+94;Burrows+00)



木星・土星の大気組成：揮発性元素

木星：Voyager, Galileo, Cassiniによる分光観測
土星：IR・電波の地上観測+Cassini (Niemann+98;Mahaffy+00; Atreya+99,03;Wong+04)

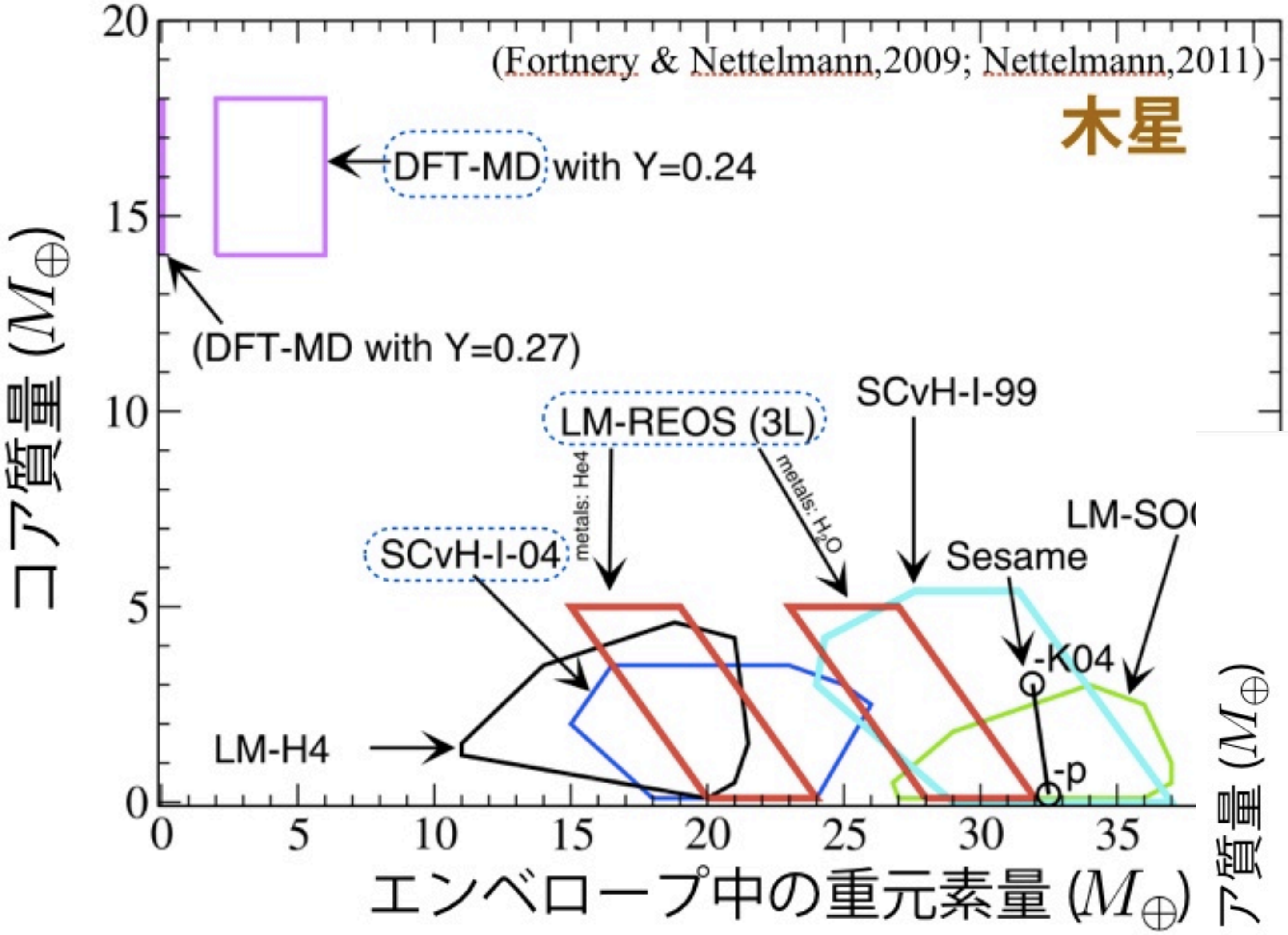


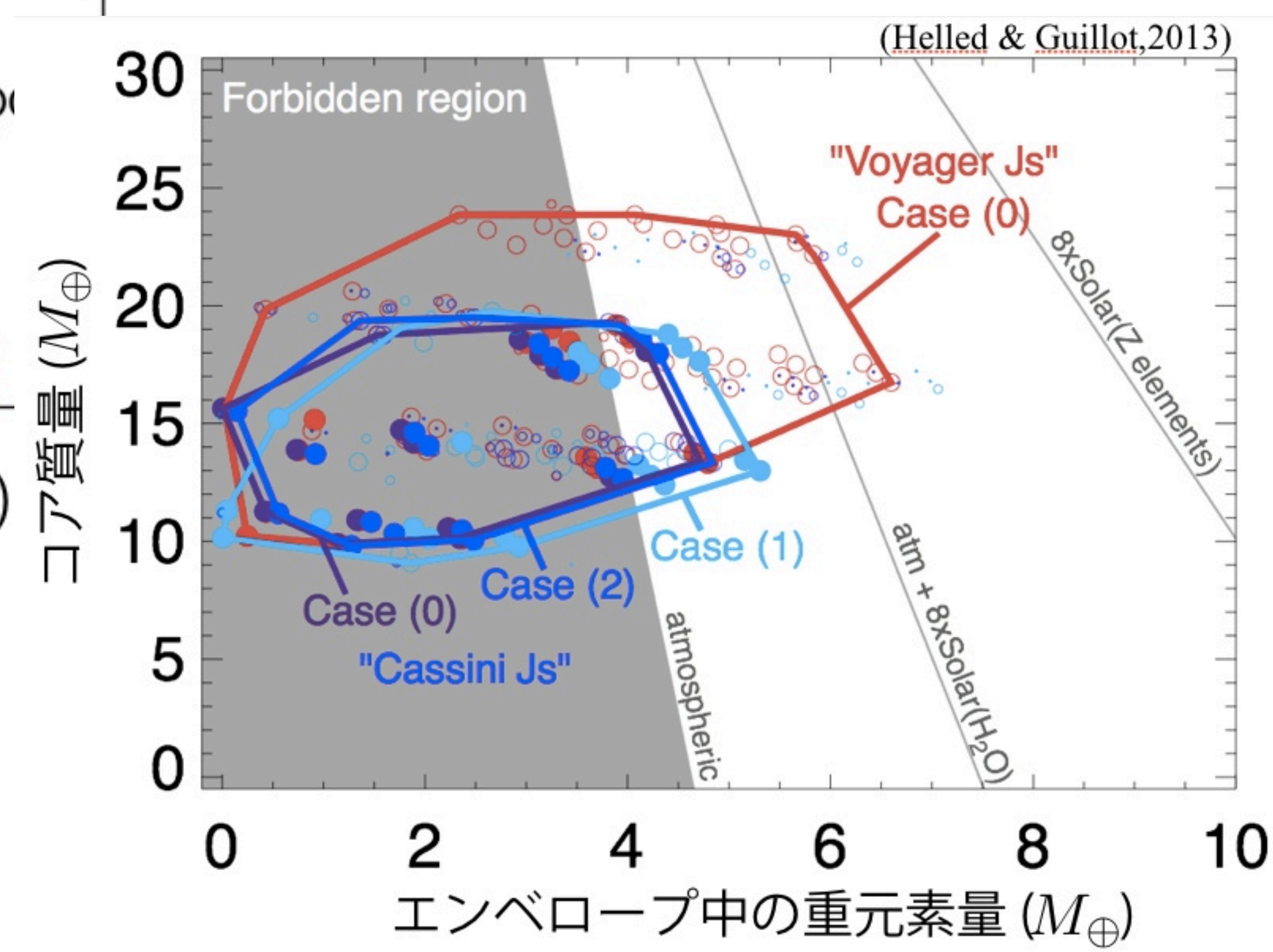
(cf) solar abundances from Anders & Grevese (1989)

木星・土星の揮発性元素に富む大気

エンベロープ全体に含まれる**重元素 (H,He以外**の元素) 量

■ **内部構造モデル** → **エンベロープ**全体で**重元素**に富む



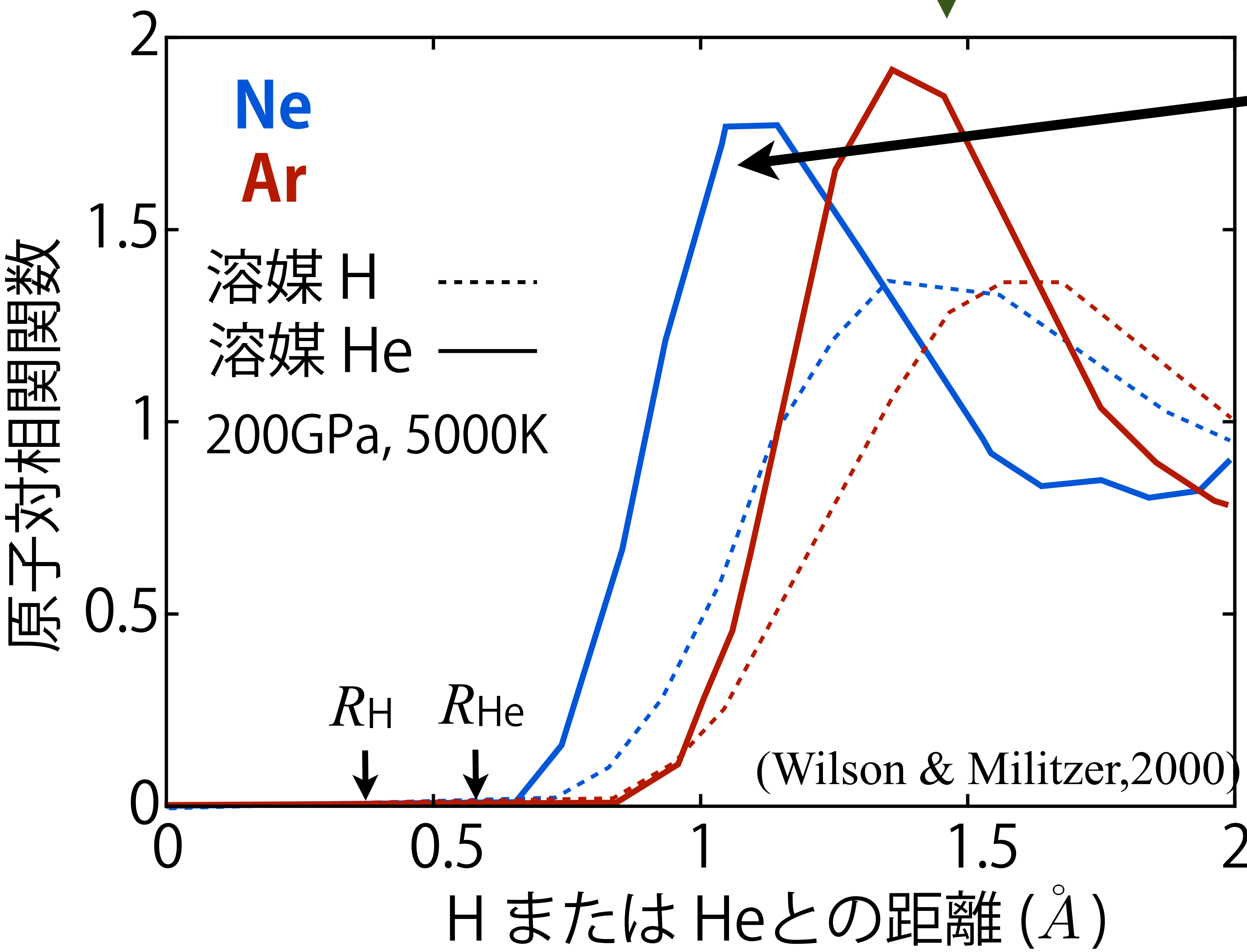


木星・土星の大気組成：He, Neの枯渇

Neの**枯渇**：**H-He分離**の間接的証拠

→ 沈降する**He液滴**に**Ne**が選択的に溶解 (Roulston& Stevenson,1995)

第一原理計算：**H-He不混和**領域でのH, Heに対する**Ne, Ar**の溶解度



Ne-He pair
近接距離に多く存在

＋

$$\Delta G = G(\mathrm{Ne/Ar+He}) + G(\mathrm{H}) - G(\mathrm{Ne/Ar+H}) - G(\mathrm{He})$$

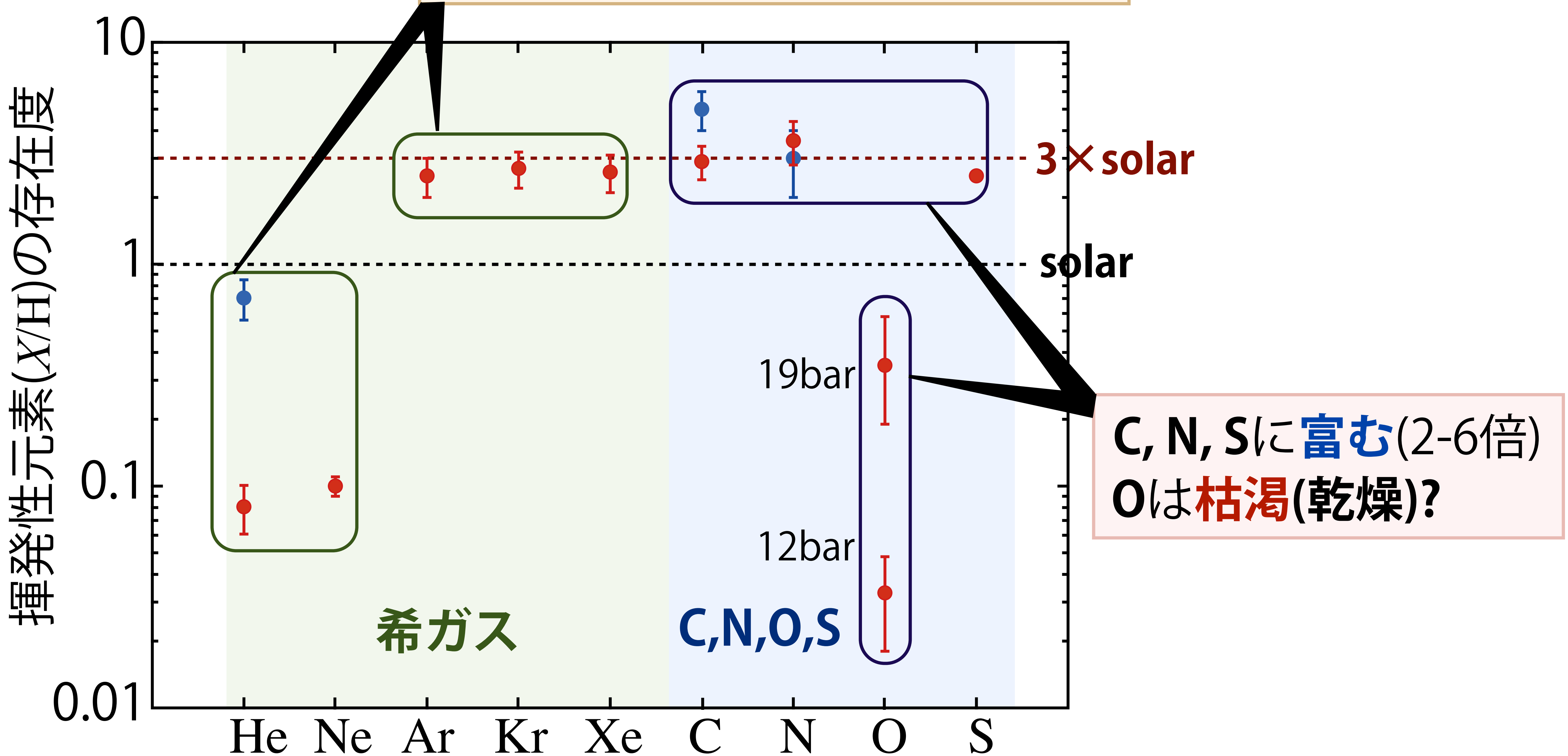
Ne：$\Delta G < 0$ (He相側)

Ar：$\Delta G > 0$ (H相側)

木星・土星の大気組成：揮発性元素

木星：Voyager, Galileo, Cassiniによる分光観測
土星：IR・電波の地上観測+Cassini (Niemann+98;Mahaffy+00; Atreya+99,03;Wong+04)

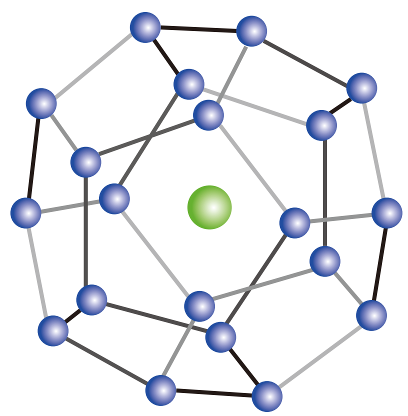
Ar, Kr, Xeに**富む**(2-3倍)
一方で、**He, Ne**の**枯渇**した大気



(cf) solar abundances from Anders & Grevese (1989)

木星・土星の揮発性元素に富む大気

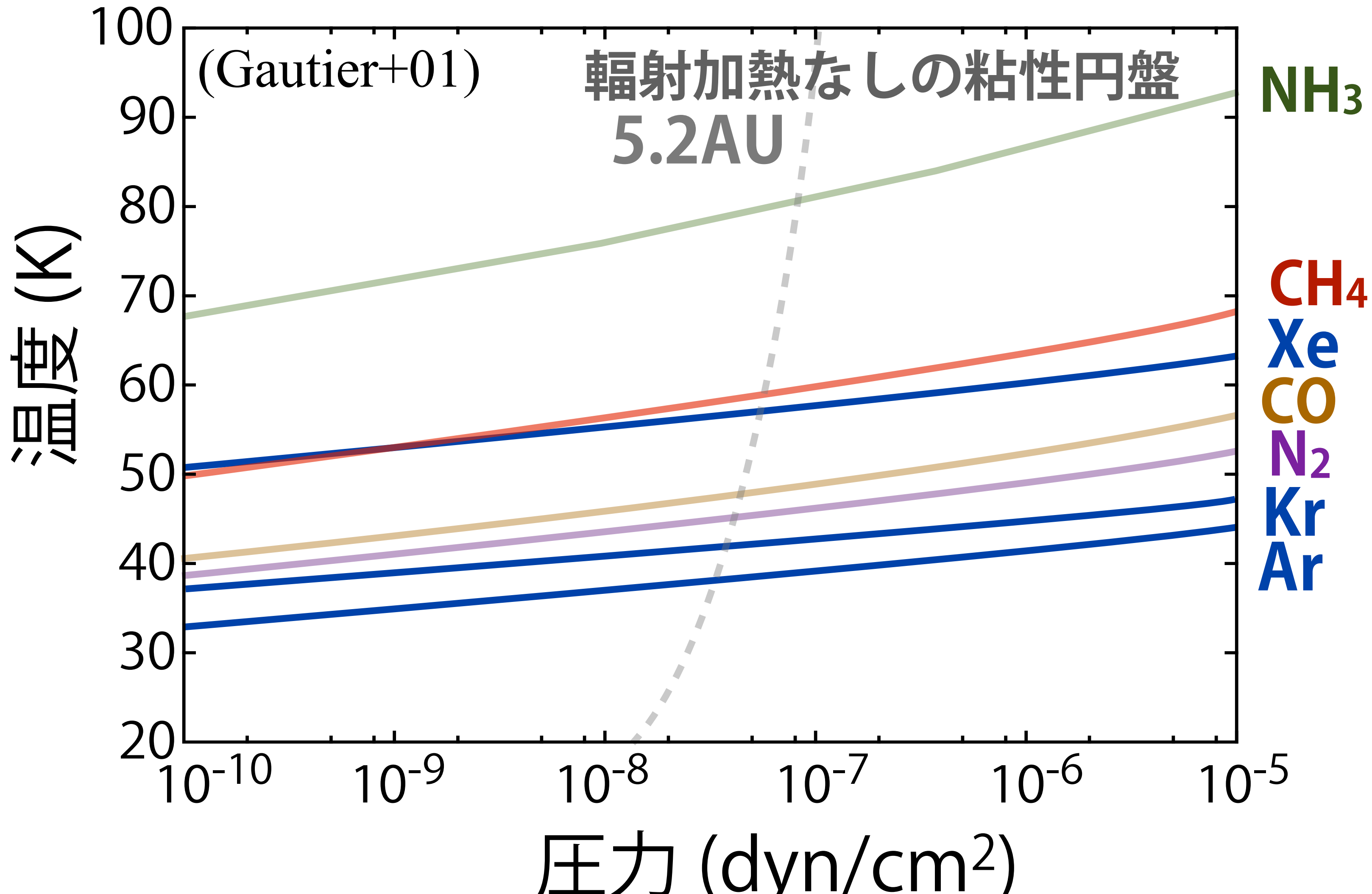
(1) **氷微惑星**が起源：非晶質氷上に凝縮 (Owen *et al*.1999)
結晶質氷によるクラスレート (Gautier+01;Hersant+04)



氷クラスレート・ハイドレートによる
希ガス／**揮発性元素**から成る**気体**の捕獲

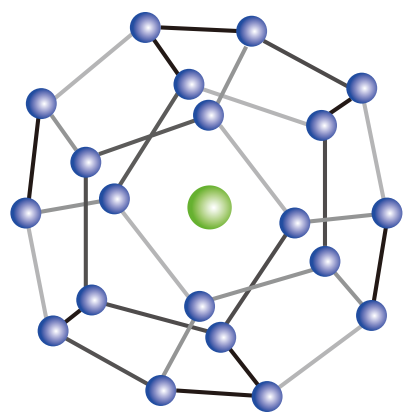
↕

【条件】**低温(< 30K)環境**で生成



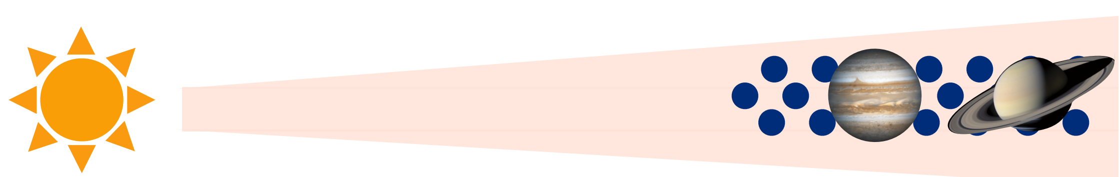
木星・土星の揮発性元素に富む大気

(1) **氷微惑星**が起源：非晶質氷上に凝縮 (Owen *et al*.1999)
結晶質氷によるクラスレート (Gautier+01;Hersant+04)

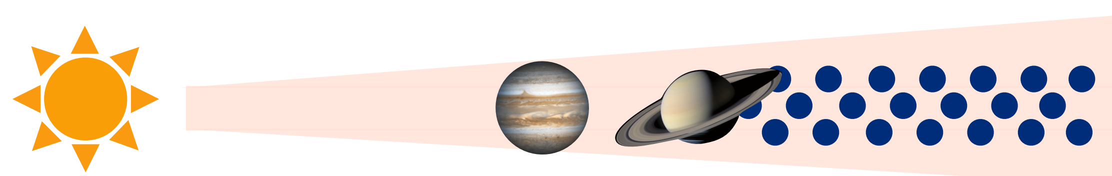


氷クラスレート・ハイドレートによる
希ガス／**揮発性元素**から成る**気体**の捕獲
↕
【条件】**低温(< 30K)環境**で生成

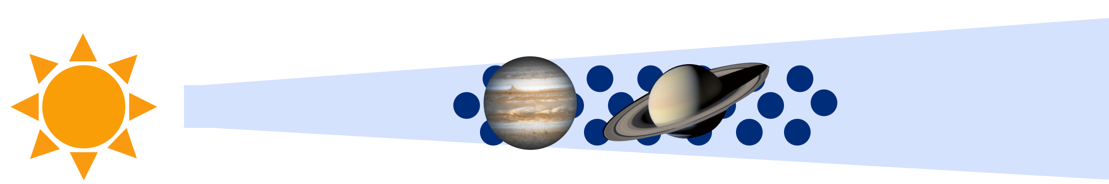
(a) 木星、土星は現在より遠方の低温領域(>30AU)で形成＋内側移動
(Alibert *et al*.2005)



(b) 低温領域で形成された**氷微惑星**の内側輸送＋捕獲

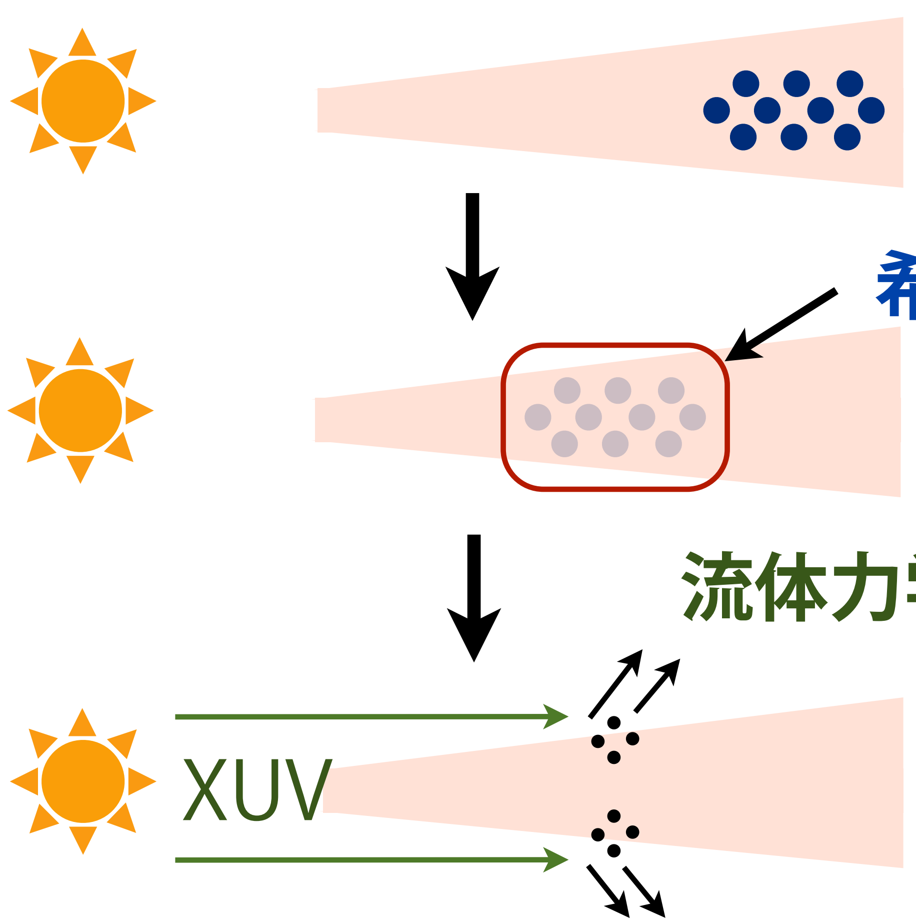


(c) 木星・土星形成時はより低温な原始惑星系円盤



木星・土星の希ガスに富む大気

(b) **光蒸発する円盤**下での大気捕獲 (Guillot & Hueso,2006)



grain上に**希ガス凝縮**

希ガスに富むガス

流体力学的散逸 $(\lambda < H_{\rm p})$

水素の散逸

→ **衝突**で**重い元素／分子**を**引きずる**

→ **質量分別** (--- crossover mass)

■ 木星-土星領域

水素の散逸率

$$\frac{m_{\rm c}}{m_{\rm H}} = 3.0 \times 10^3 - 10^4 \longleftarrow m_{\rm c} = m_{\rm H}\left(1 + \boxed{\frac{kT}{X_{\rm H} m_{\rm H} g}}\,\frac{\boxed{F_{\rm H}}}{b}\right)$$

scale height

$m_{\rm A} < m_{\rm c}$の時、流体力学的散逸

$$F_{\rm A} = \frac{\boxed{X_{\rm A}}}{X_{\rm H}} F_{\rm H}\left(\frac{m_{\rm c} - \boxed{m_{\rm A}}}{m_{\rm c} - m_{\rm H}}\right)$$

→ 拡散・圧力勾配で決まる

(Hunten+87)

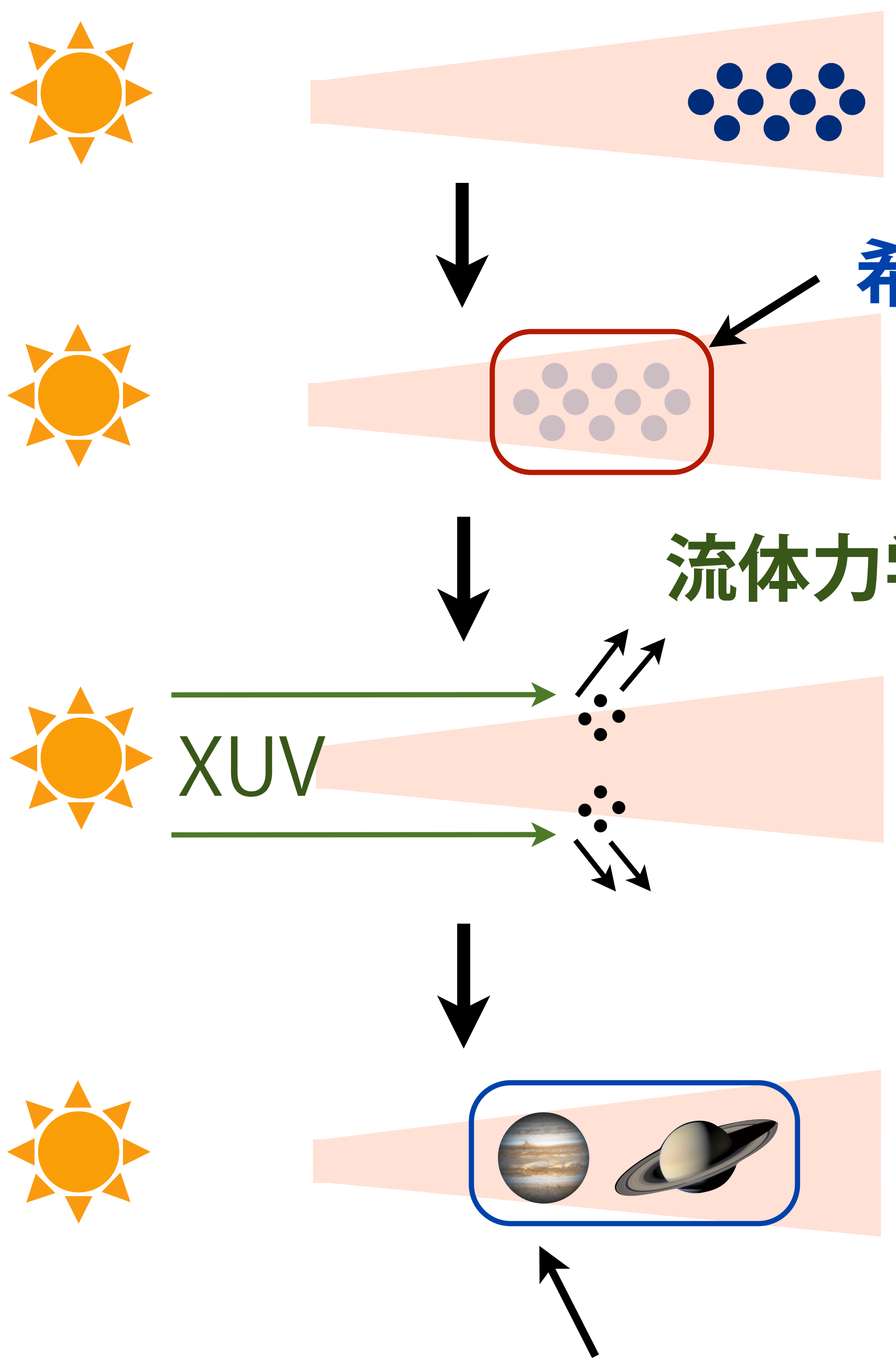
木星・土星の希ガスに富む大気

(b) 光蒸発する円盤下での大気捕獲 (Guillot & Hueso,2006)

grain上に希ガス凝縮

希ガスに富むガス

流体力学的散逸 ($\lambda < H_\mathrm{p}$)



水素の散逸

→ 衝突で重い元素／分子を引きずる

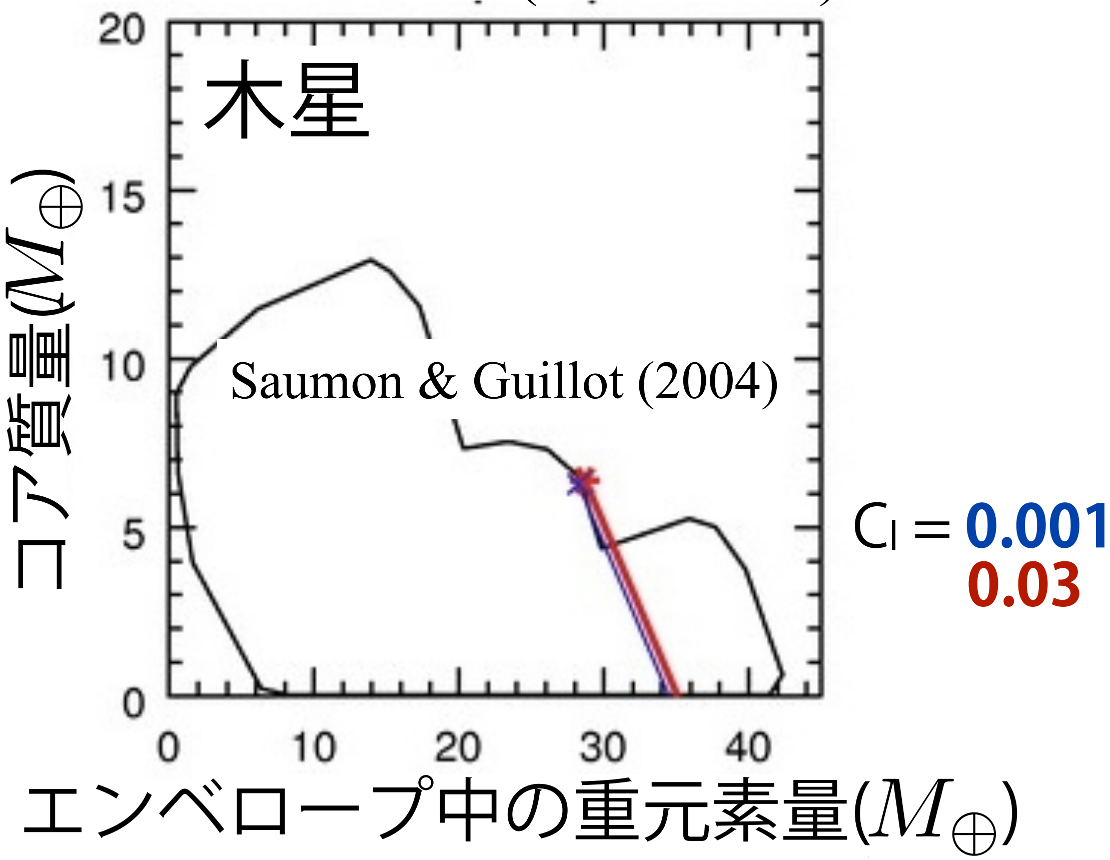
→ 質量分別 (--- crossover mass)

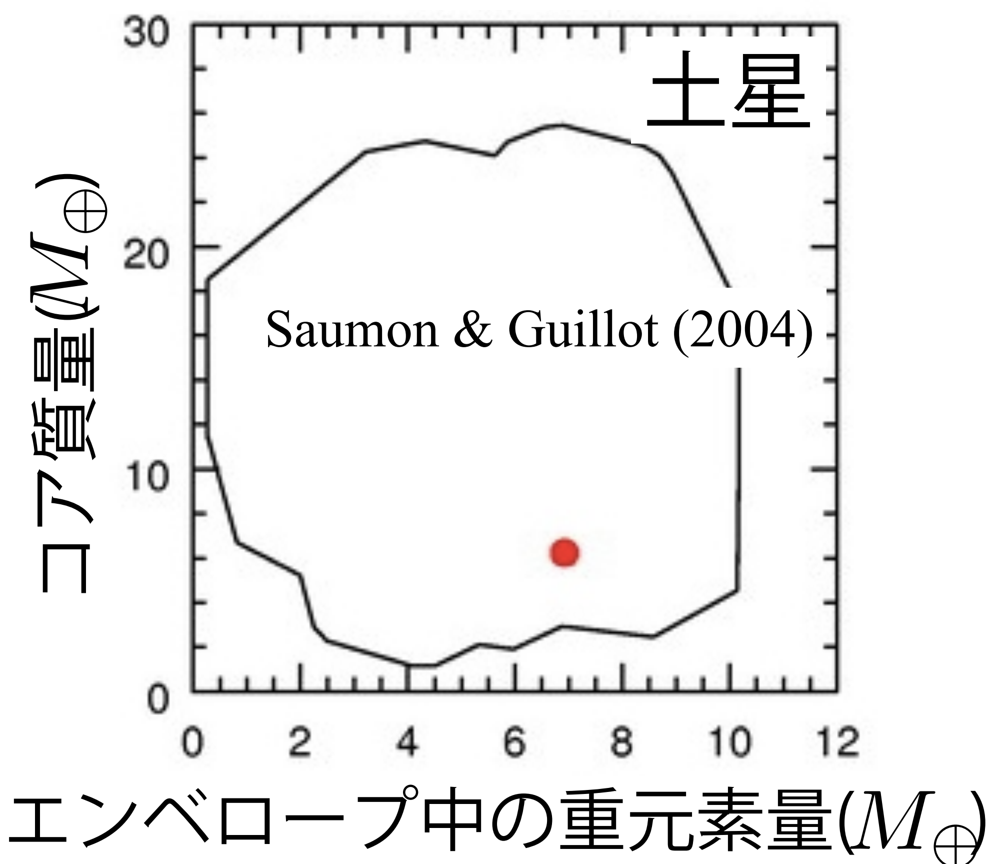
質量分別した希ガスに富む大気を獲得

(= 進化した円盤中でガス惑星形成)

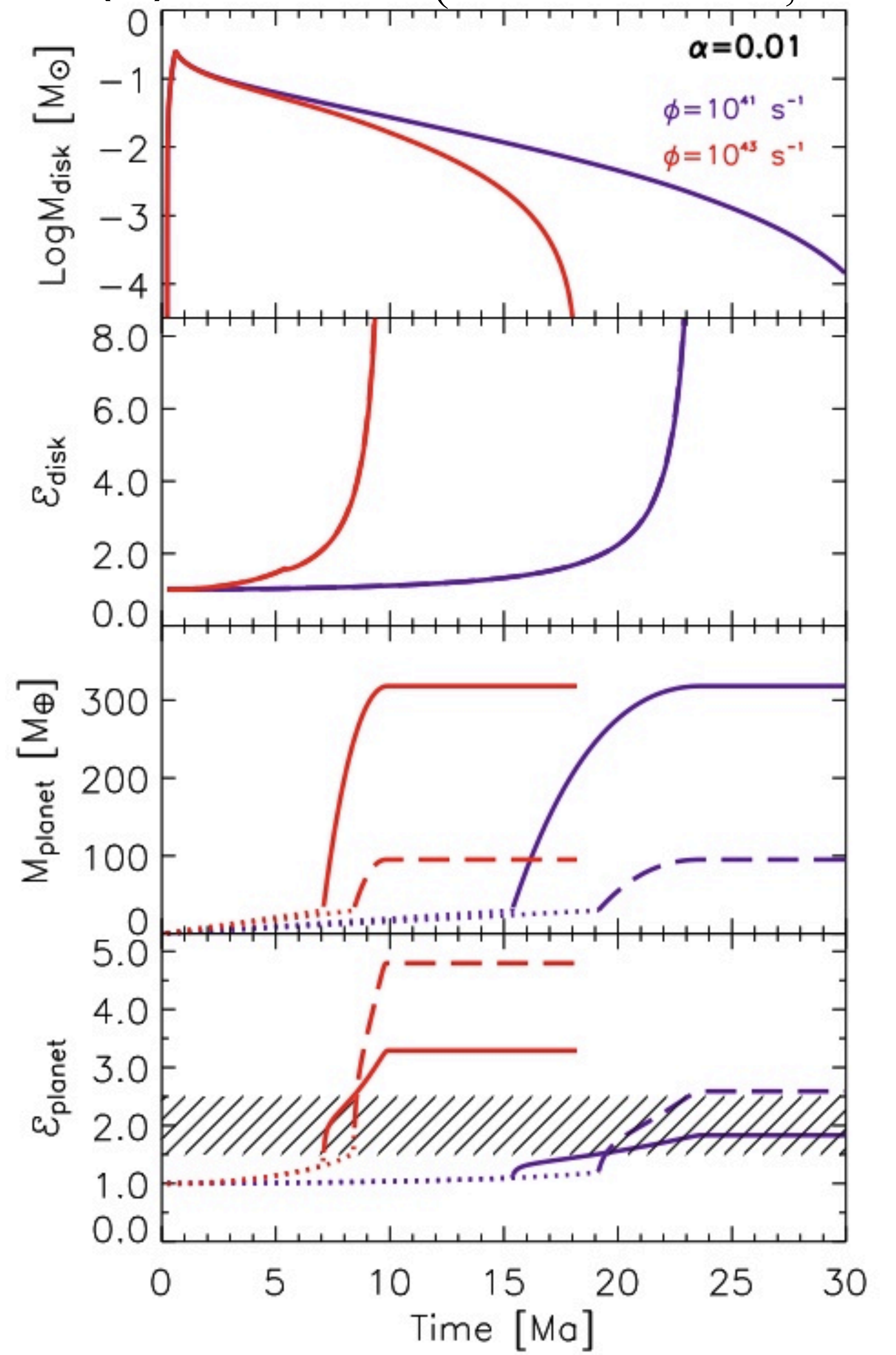
木星・土星の希ガスに富む大気

(a) 氷微惑星 (Alibert+05)





(b) 光蒸発 (Guillot & Hueso,2006)



木星・土星の揮発性元素：同位体比

■ **希ガス**(Ar, Kr, Xe)の**濃縮度合**

(現在) 木星大気 : Ar ~ Kr ~ Xe

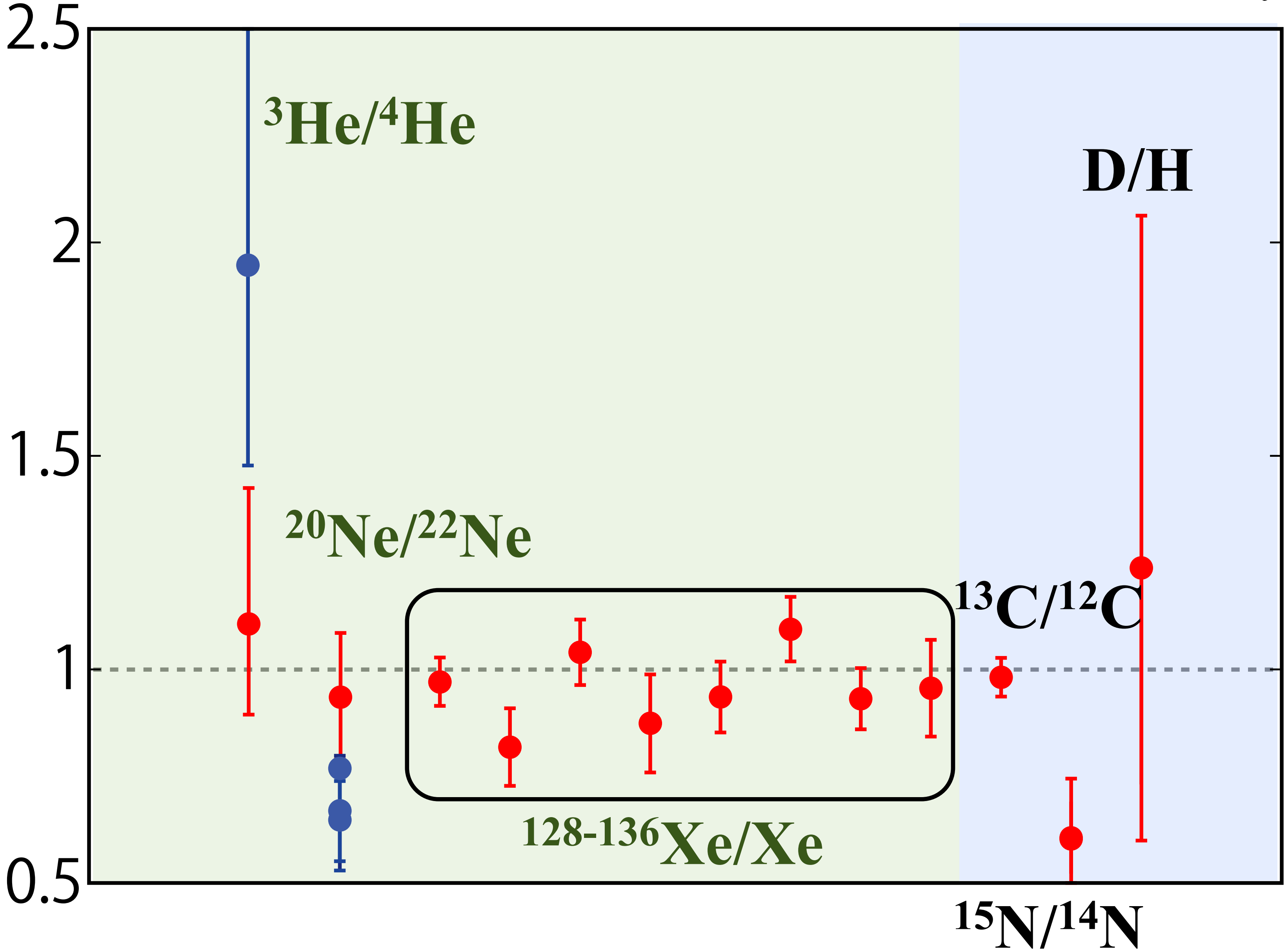
- 氷微惑星 → Ar > Kr > Xe (蒸発温度の違いのため) ?
- 光蒸発による質量分別 → Ar ~ Kr ~ Xeも可能(?)

↓

『**希ガス**の起源 --- **ガス惑星形成の制約**』

木星の揮発性元素：同位体比

■ **希ガス**(He, Ne, Ar, Xe)の**同位体比** (Mahaffy+98,00;Pepin+99;Lellouch+01; Atreya+03;Abbas+04;Fouchet+04;Marty+08)



木星大気／太陽組成(太陽風)

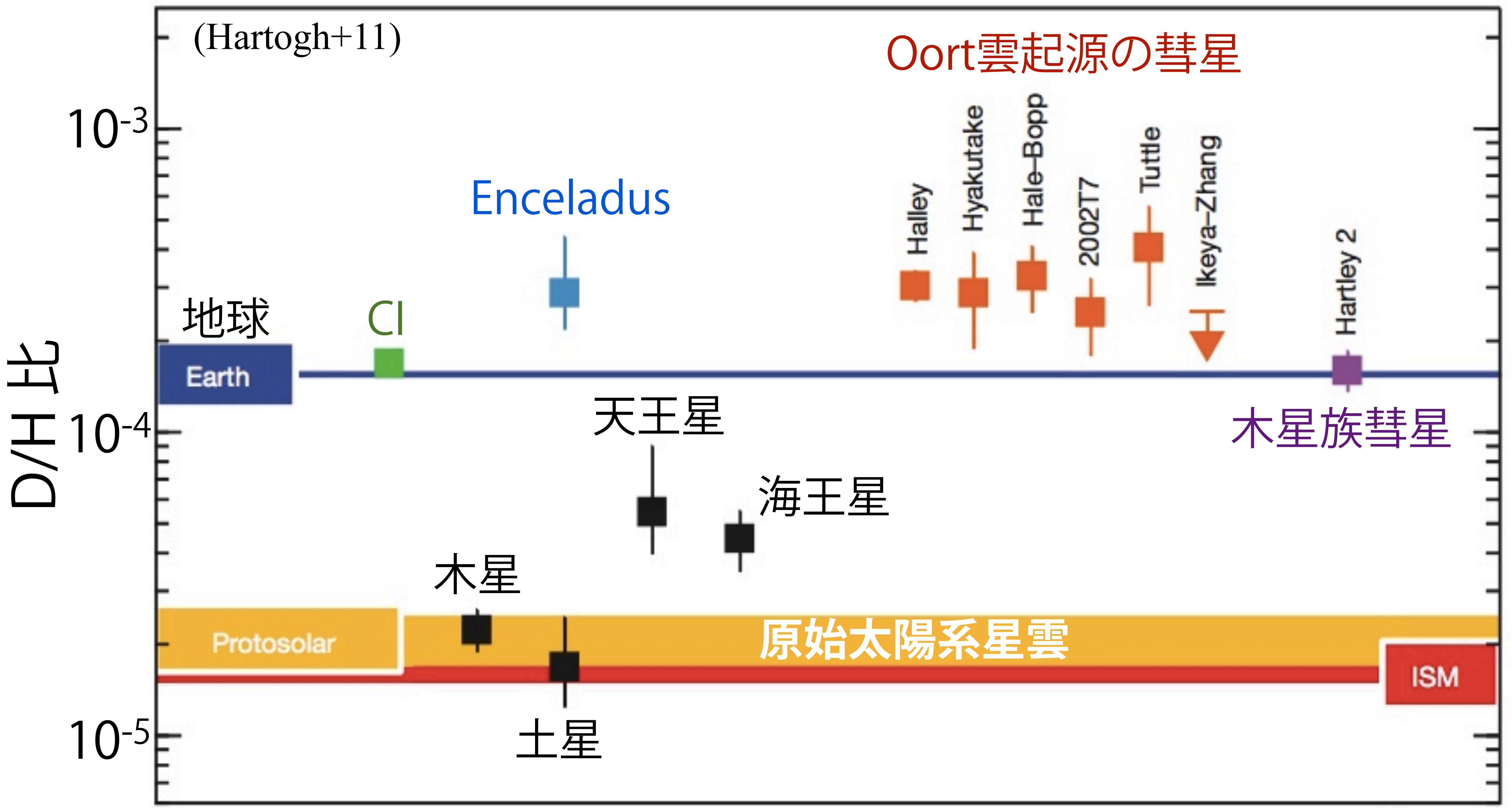
- 木星
- 81P/Wild2彗星 (Stardust計画)

※ ^{3}He/^{4}He : 木星／CI chondrite
^{15}N/^{14}N : 木星／terrestrial値

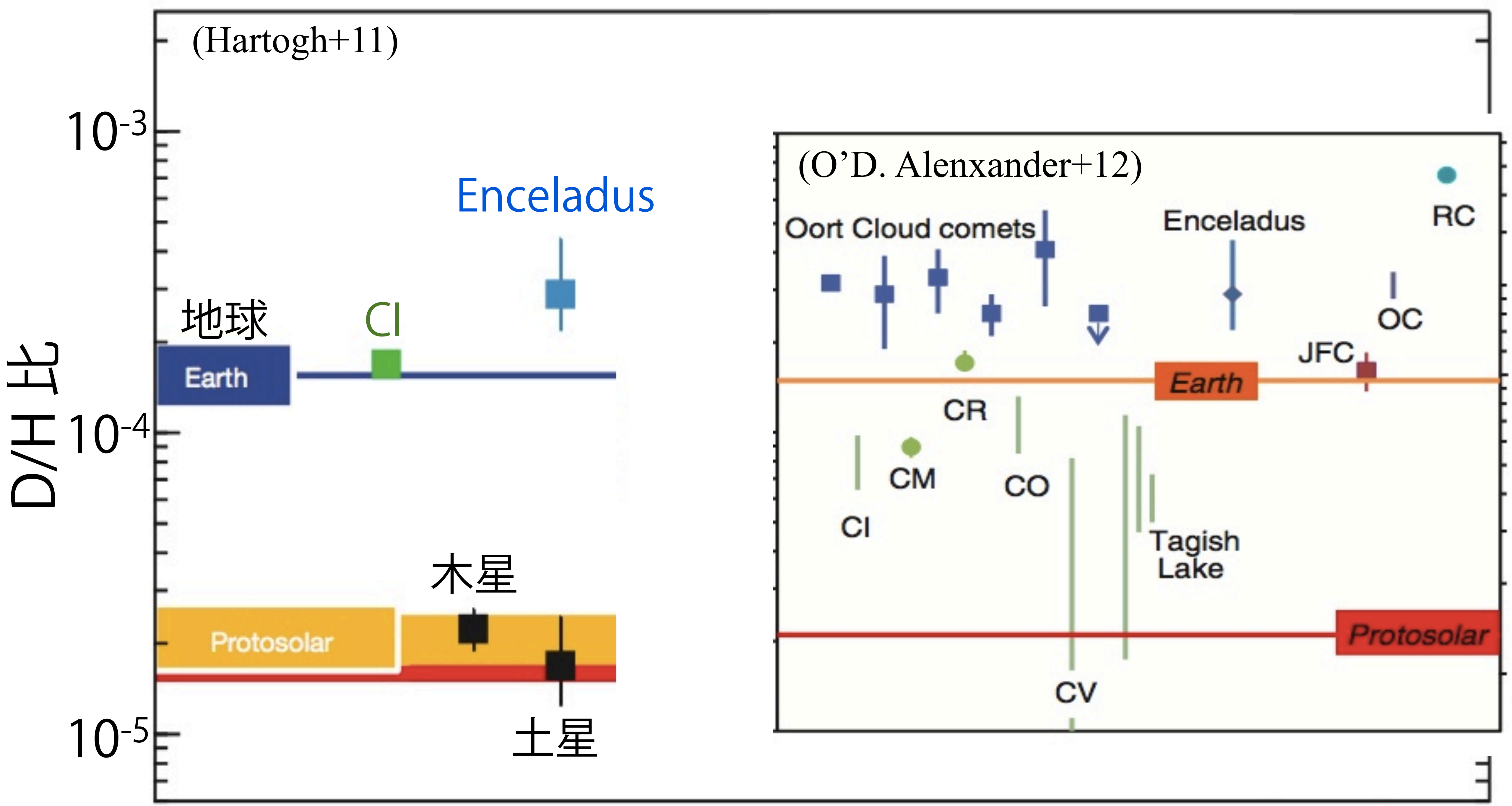
※ Krの同位体比 --- 未決定

- **木星大気**の**Ne, Ar, Xe**の同位体比 ~ **太陽組成**
- **81P/Wild2(短周期)彗星** --- ^{20}Ne/^{22}Ne ≠ 木星大気
  --- ^{3}He/^{4}He **~2×**木星大気

木星・土星のD/H比：protosolar 値



木星・土星のD/H比：protosolar 値

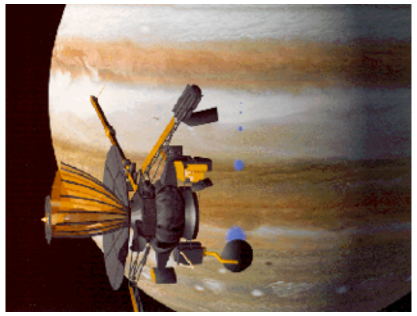


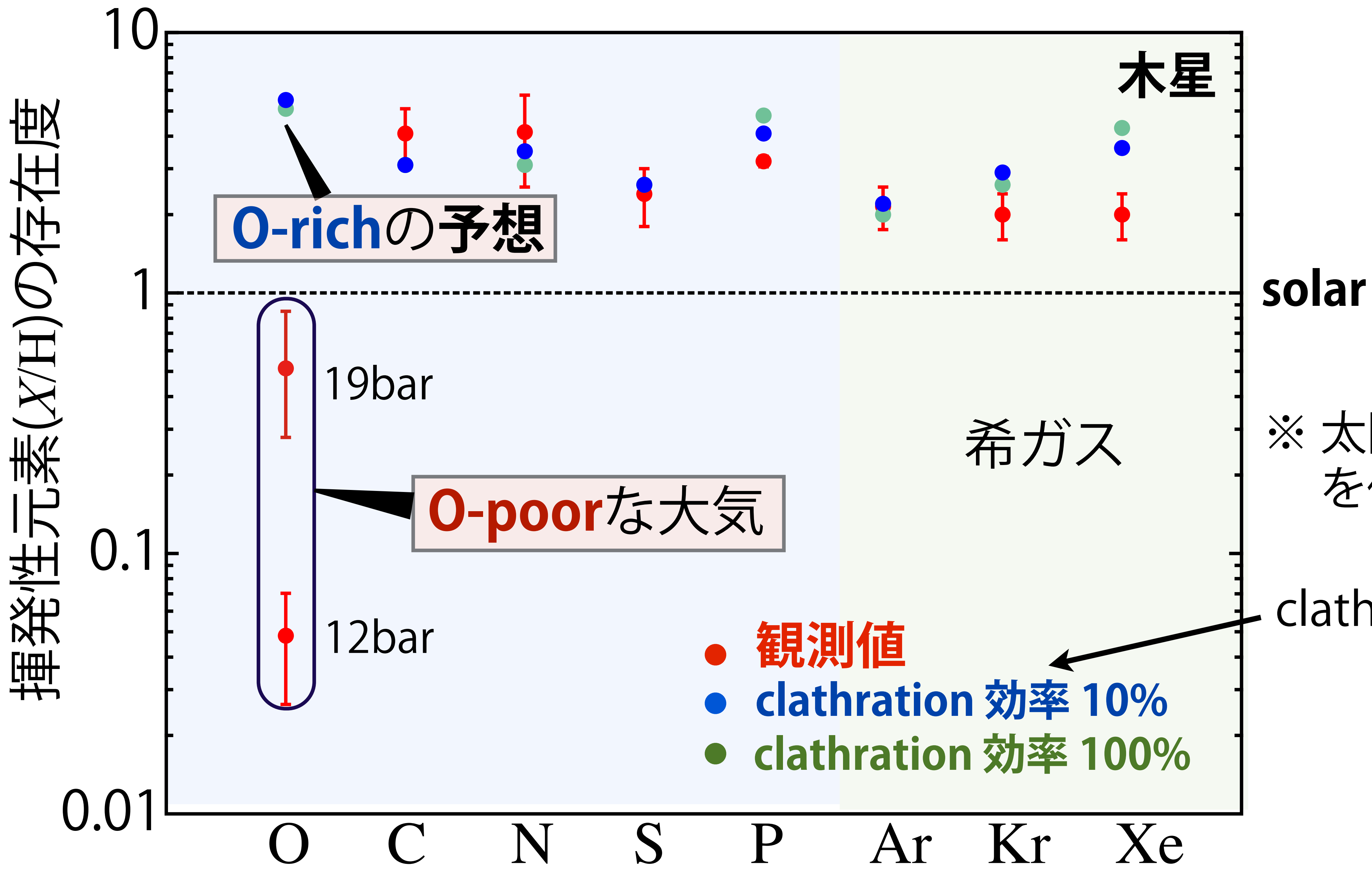
木星大気の酸素存在度

■ 乾燥した木星大気？

Galileo probe : 木星大気は太陽組成よりも**酸素欠乏**(?)

←→ **氷微惑星**起源の描像と**矛盾**? (Mousis+09)





※ 太陽組成の円盤ガスを仮定

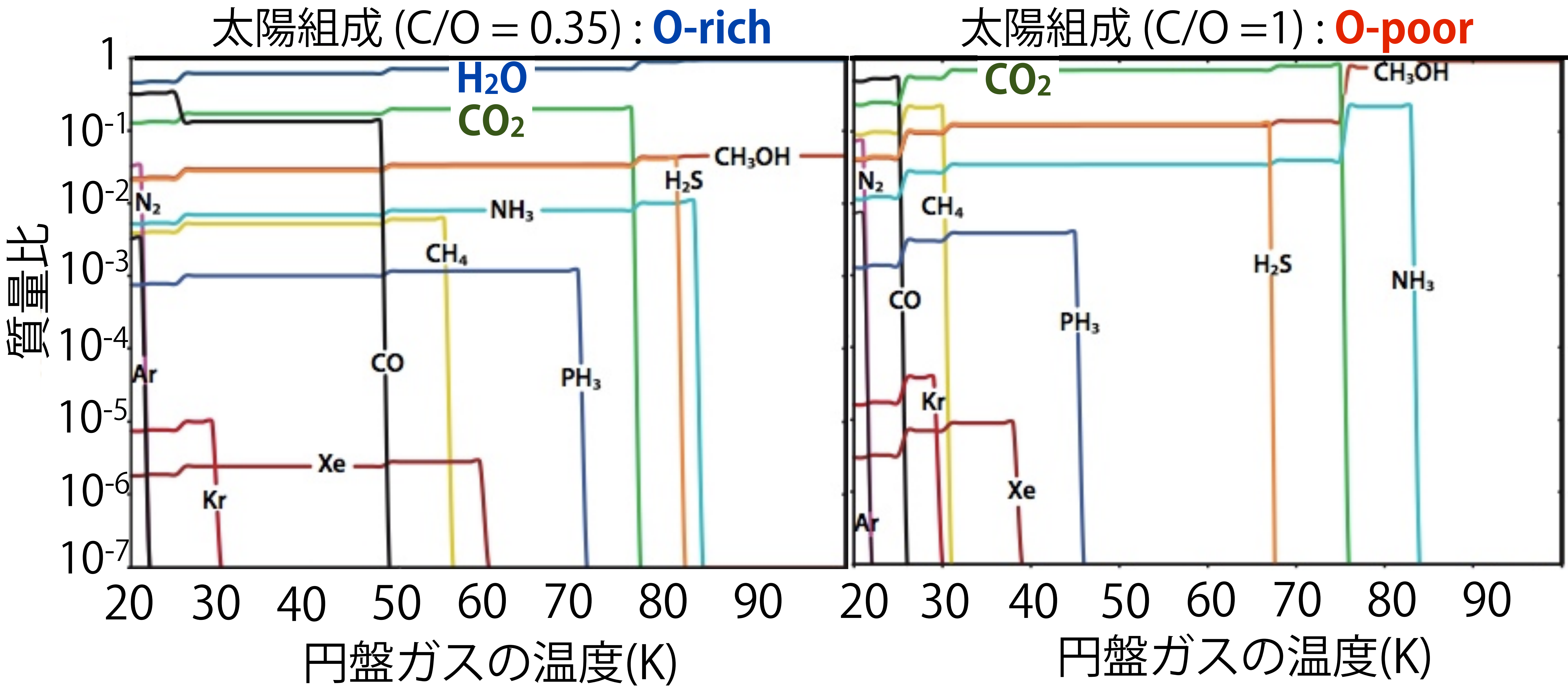
(cf) solar abundances from Lodders (2003)

木星大気の酸素存在度

■ **乾燥**した木星大気？

→ **C/O ~1 (O-poor)**な環境下で木星形成？

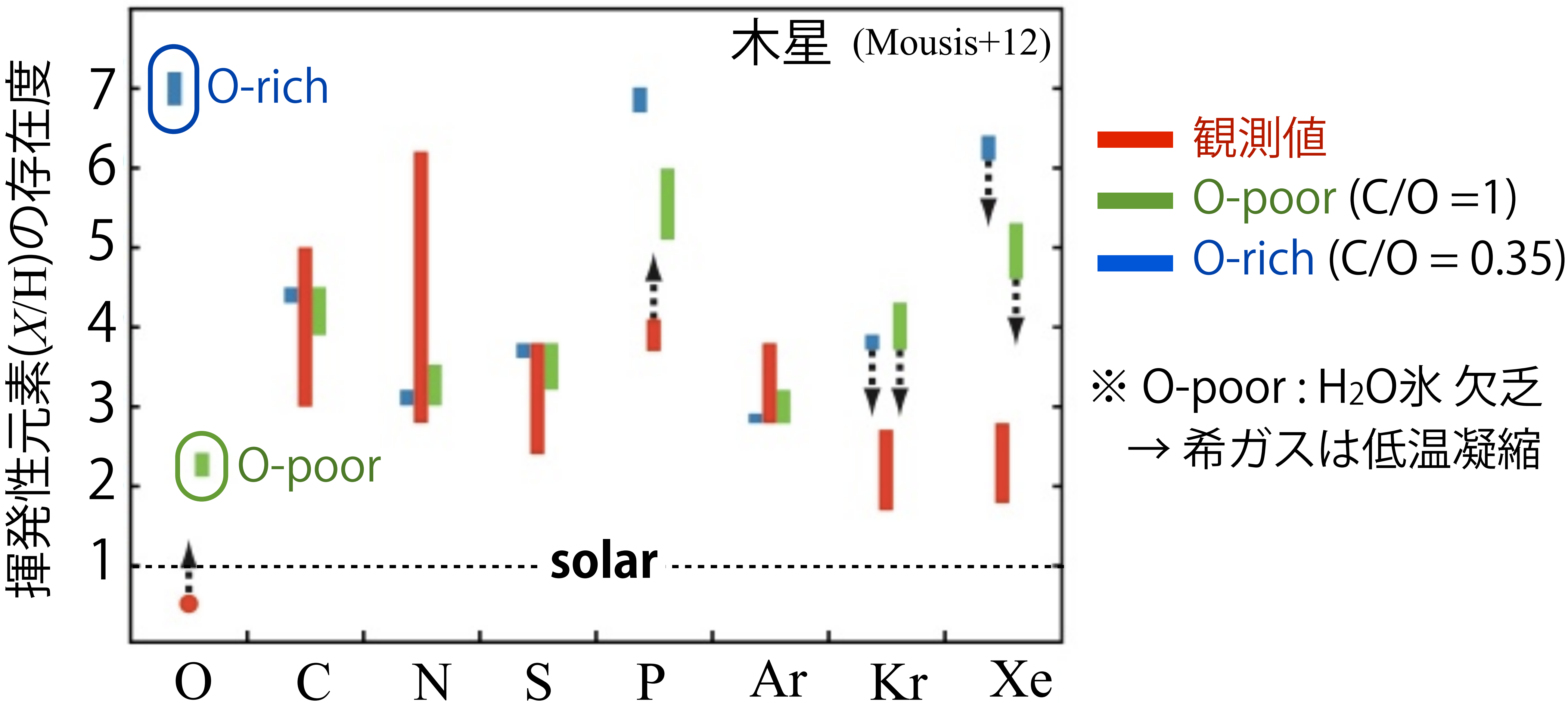
【**O-poor**な環境下での平衡凝縮計算】(Mousis+12)



木星大気の酸素存在度

■ **乾燥**した木星大気？

→ **C/O ~1 (O-poor)**な環境下で木星形成？



※ O-poor : H_2O氷 欠乏
→ 希ガスは低温凝縮

※ **C/O ~1** : H_2O - COのsnow line位置の違い？ (Öberg + 11)

JUNO missionへの期待

NASA 木星探査機 Juno : 2011/8/5 打ち上げ
2016年7月から木星の周回極軌道 (33周)
(1年間 → 木星へ衝突)

(e.g.Bolton+10)

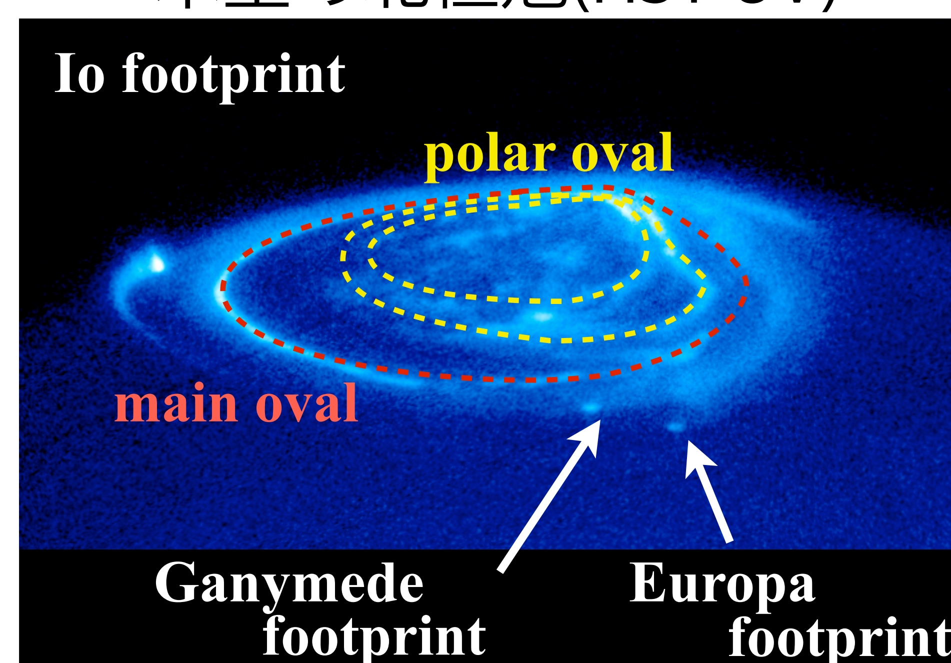
■ 重力場の高精度測定

- 木星のコアサイズ
- 木星内部の回転パターン
- 木星の内部組成

■ 大気深部(深さ数100km)のマイクロ波放射測定

- 大気組成, 大気の運動 (~100bar)
- H_2Oの存在度 (3D map)

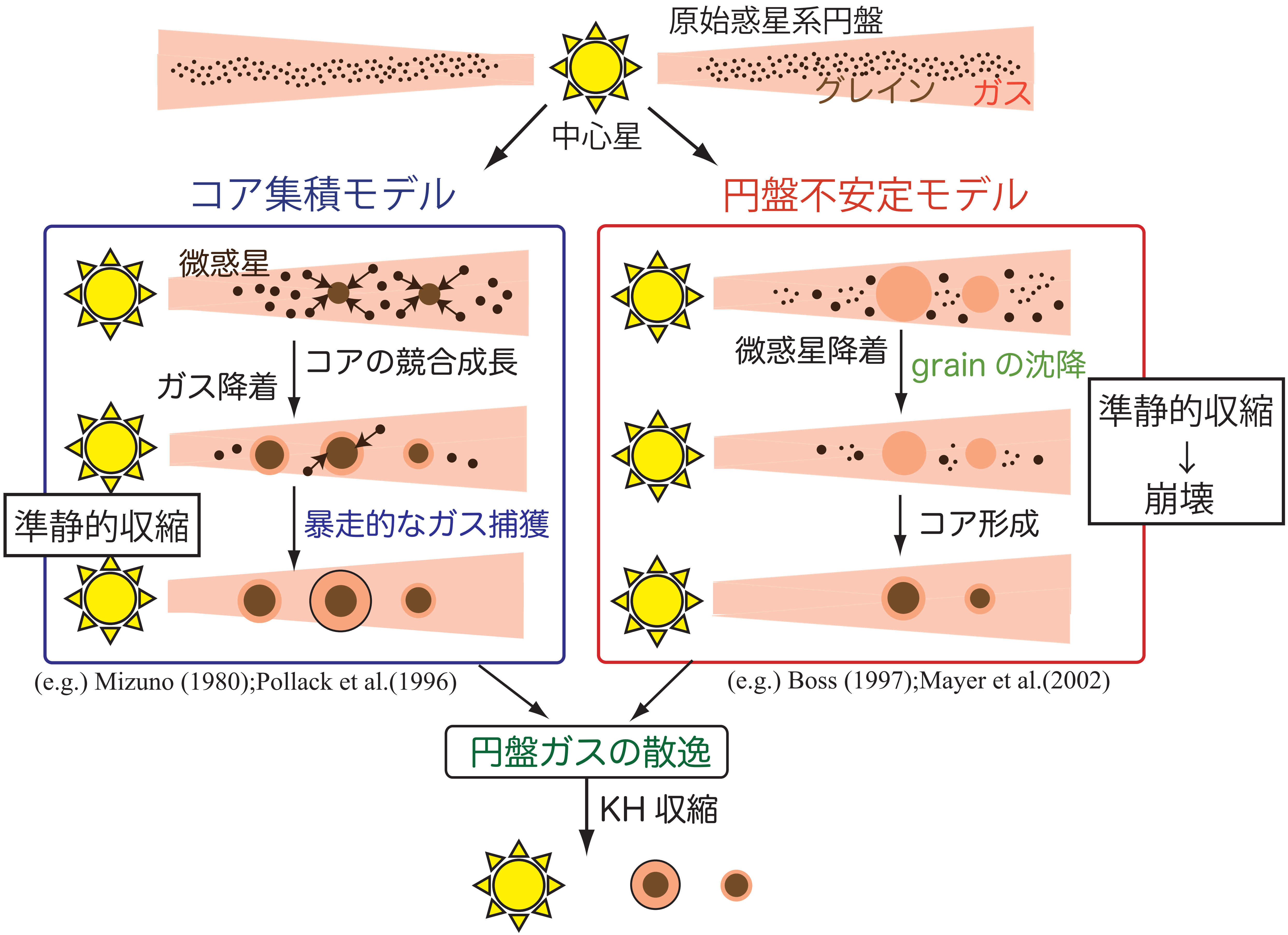
木星の北極冠(HST UV)



■ 磁気圏(磁力計, NIR・UV分光計, 可視撮像)

- 磁場のパターンとダイナモ
- 極域磁気圏の粒子計測 (オーロラ)

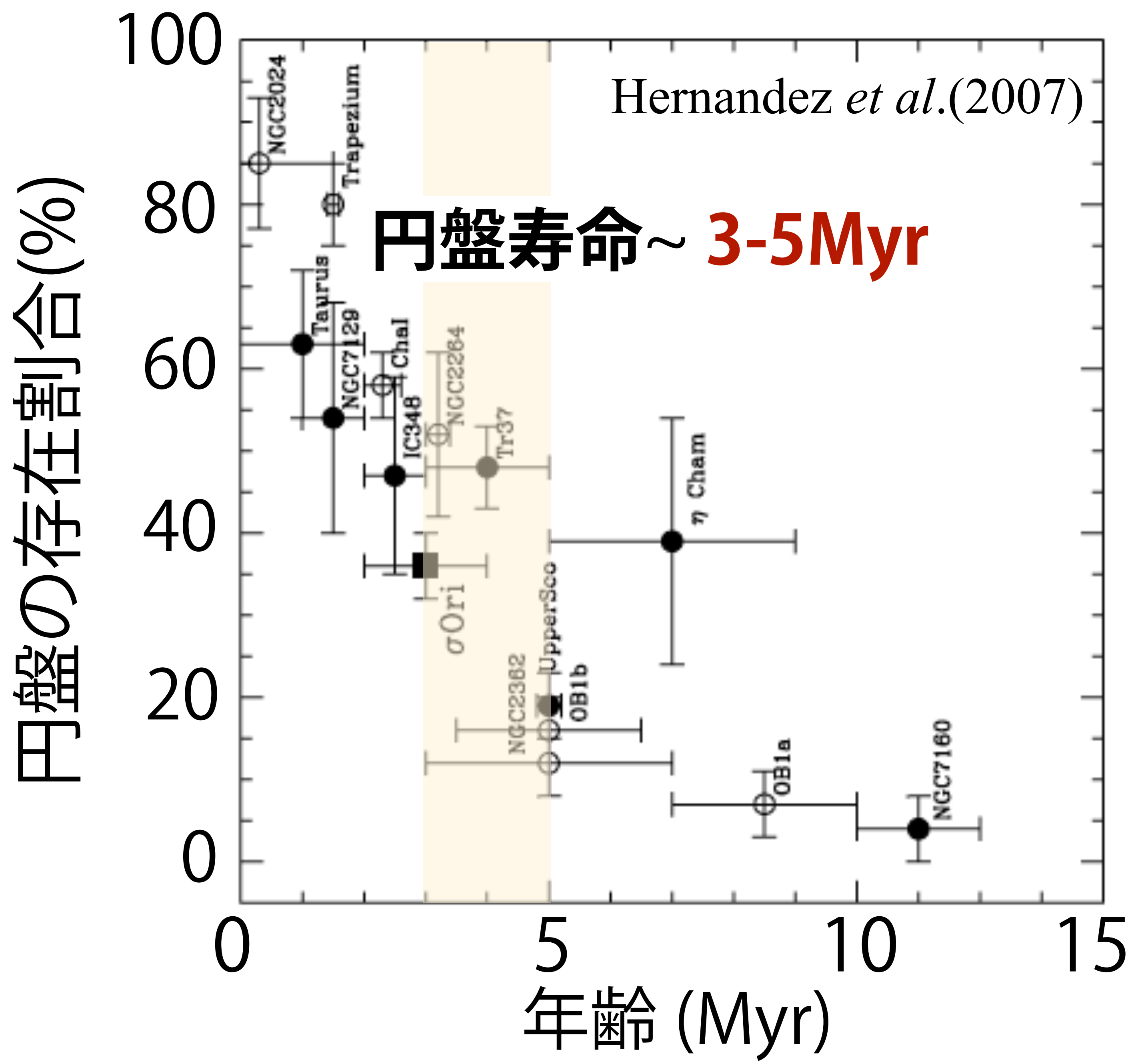
1.4 ガス惑星の内部構造から起源へ



惑星形成の時間的制約

■ 原始惑星系円盤ガスの寿命

cold dust (outer part)からのsub-mm波 (Andrews & Williams,2005)
warm dust (inner part)からの赤外放射 (Haisch+01;Hernandez+07)

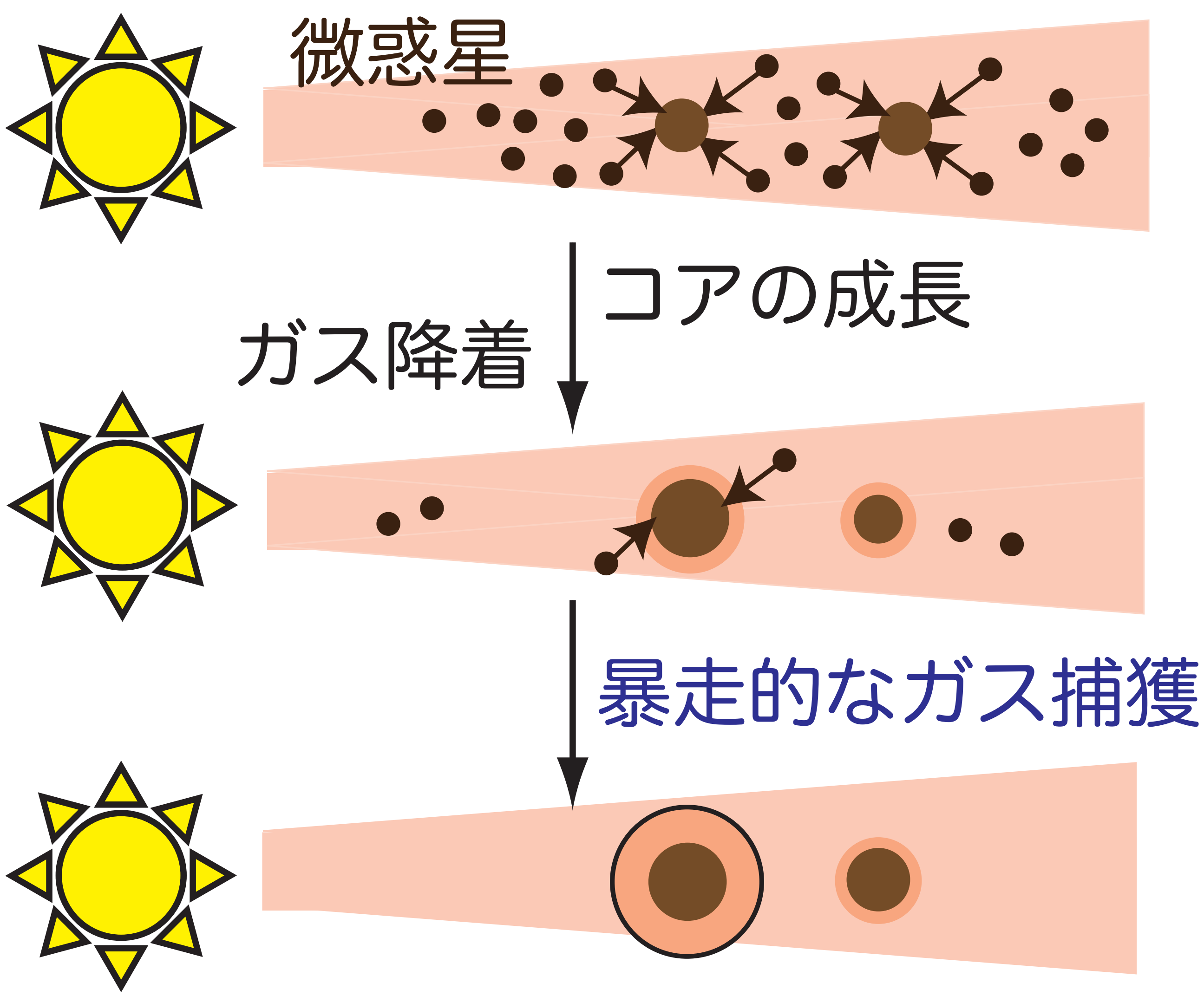


【若い散開星団】

$$\frac{\text{赤外超過(JHKL)ありの恒星数}}{\text{星団内の恒星数}} \times 100$$

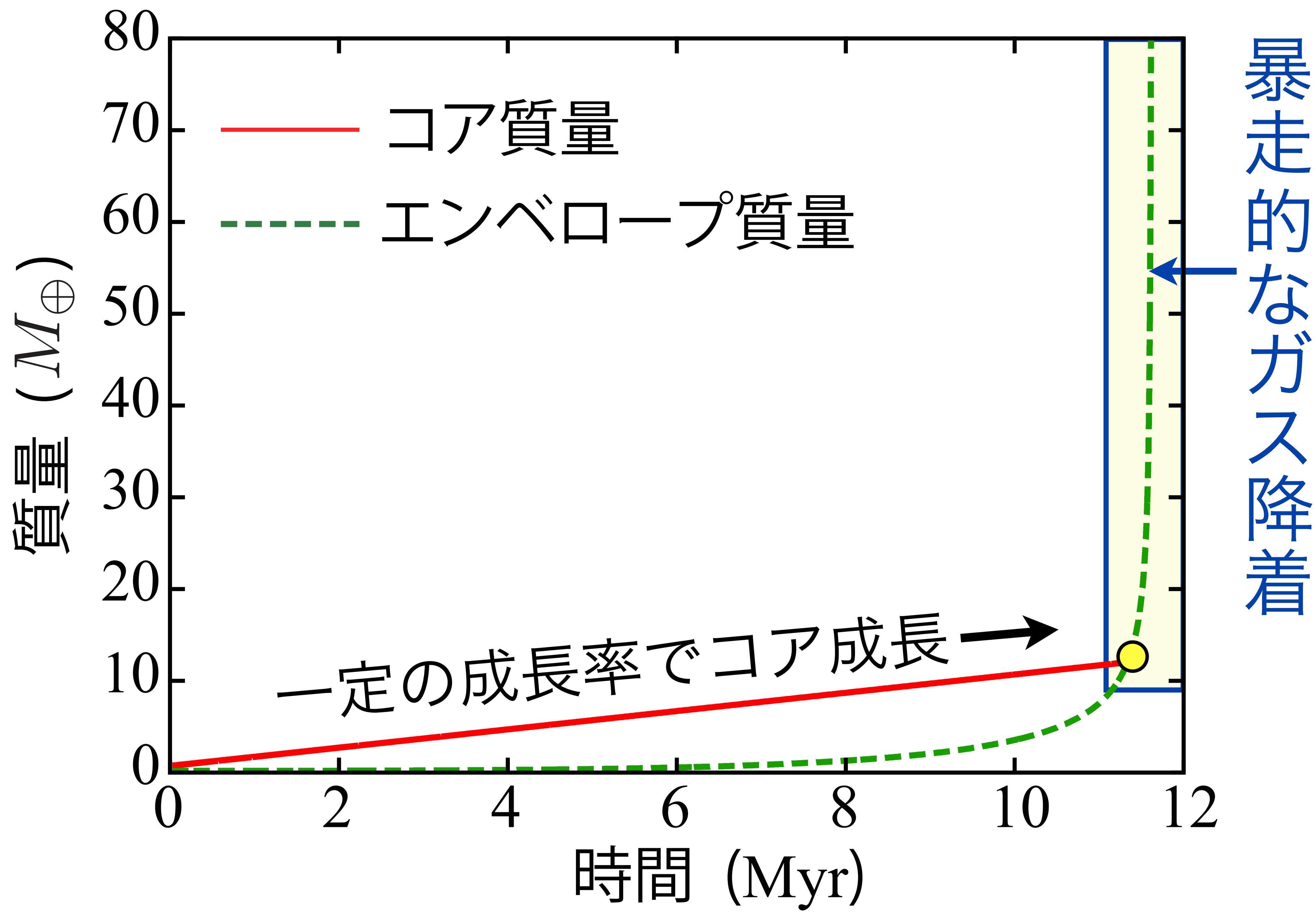
= 円盤の存在割合(%)

ガス惑星形成：コア集積モデル

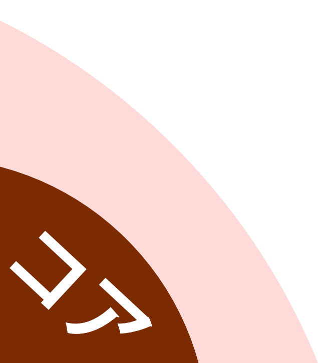


(e.g., Bodenheimer & Pollack,1986; Pollack *et al*.1996)

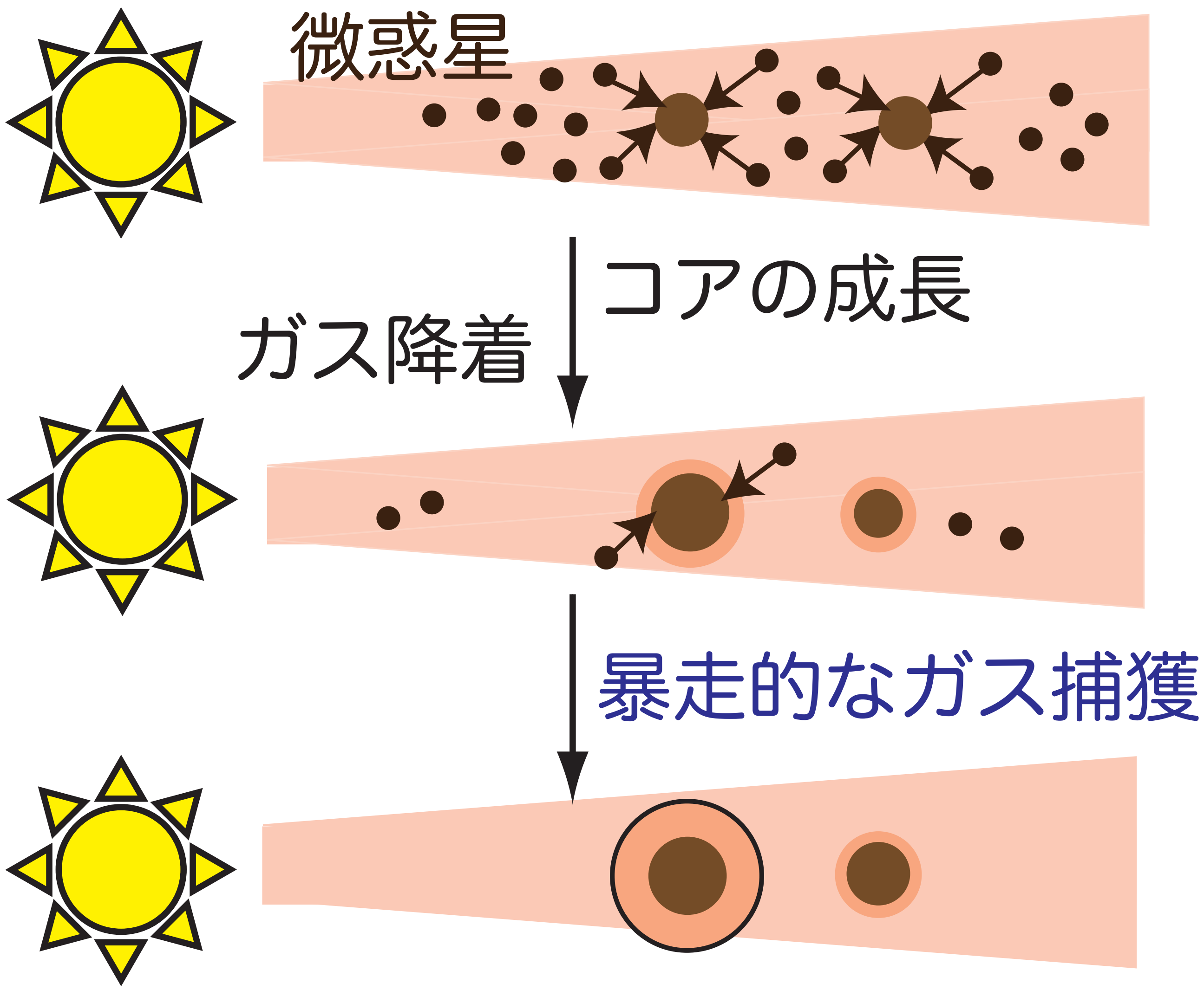
臨界コア質量と暴走ガス捕獲



コアがある質量(**臨界コア質量**)以上
→ **暴走的に円盤ガス**を**捕獲**



ガス惑星形成：コア集積モデル



(e.g., Bodenheimer & Pollack,1986; Pollack+96)

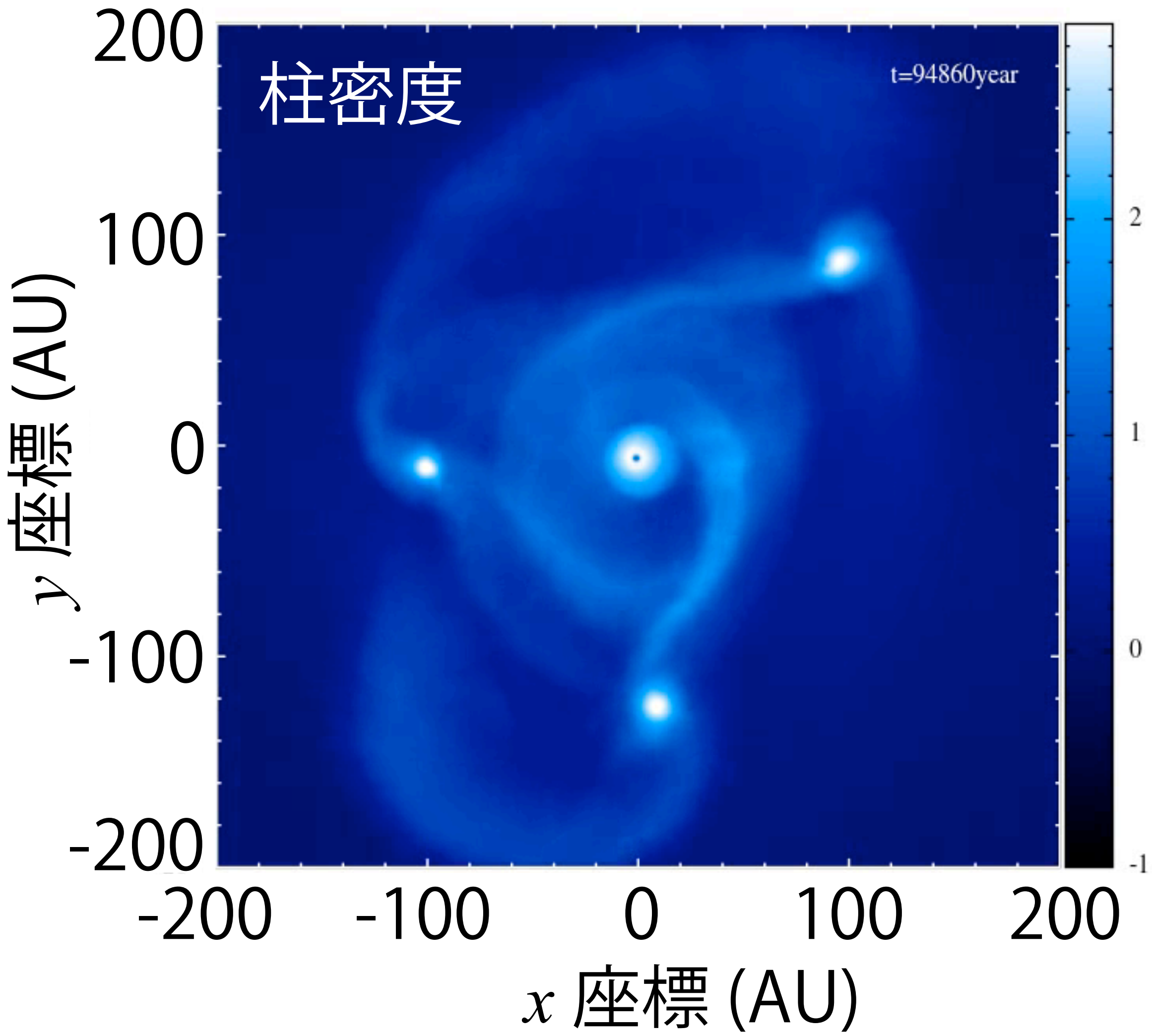
臨界コア質量

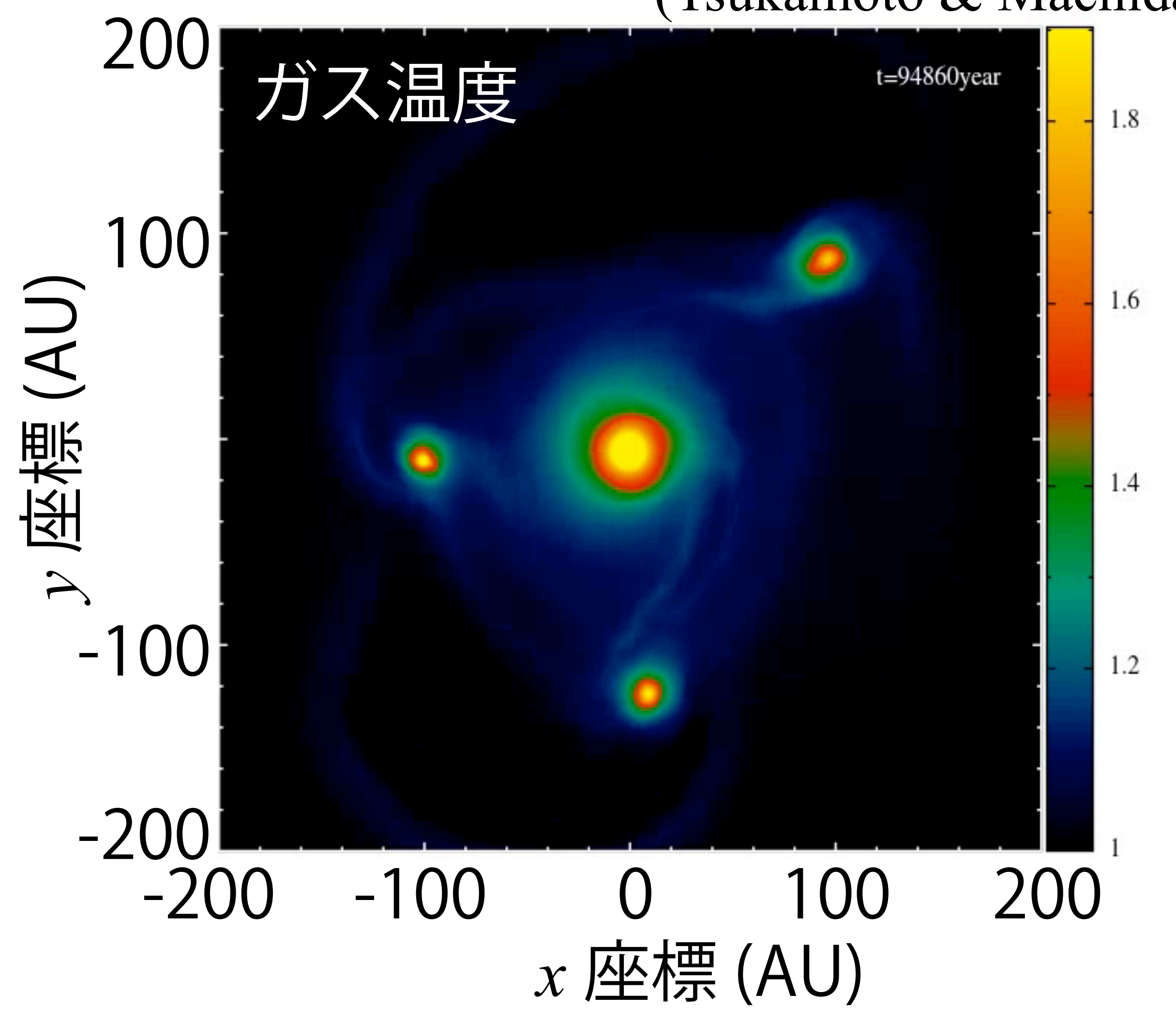
コアが臨界質量に
到達すると

(Mizuno,1980; Ikoma+00)

円盤不安定モデル：再帰的なガス惑星形成

(Tsukamoto & Machida,2012)





不安定条件 (Toomre Q)(Toomre,1964)

$$Q \equiv \frac{c_s \kappa}{\pi G \Sigma} \boxed{\left(\sim \frac{c_s^2 \Sigma}{G\Sigma^2 H^2/H}\right)} \leq 1$$

円盤ガスの**エンタルピー** / 円盤ガスの**自己重力**ポテンシャル

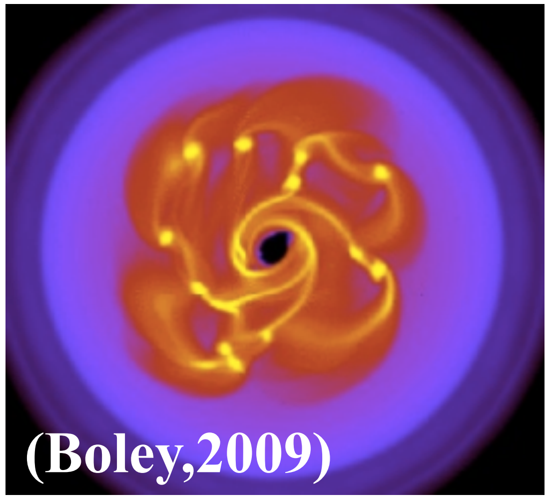
→「**重い**円盤且つ**外側の低温**領域」

※ 局所的：ガスの冷却時間 ($t_{\rm cool}$) < 力学的時間($1/\Omega_K$) (Gammie,2001)

木星・土星と2つの形成シナリオ

■ 円盤不安定モデルの視点

(Q) 円盤不安定は起きるには？



(1) **[Fe/H], ダストopacity**

相関なし(Boss,2002)　　　low [Fe/H]が良い (Cai+06)

(2) **中心星からの距離**

数10AUより内側は起きにくく、r > 100AUで起きる (Boss,2007;Mayer+07)
数10AUより内側は起き、100~200 AU では起きない(Boley+07;Boley,2009)

(3) **熱力学量、エネルギー輸送**

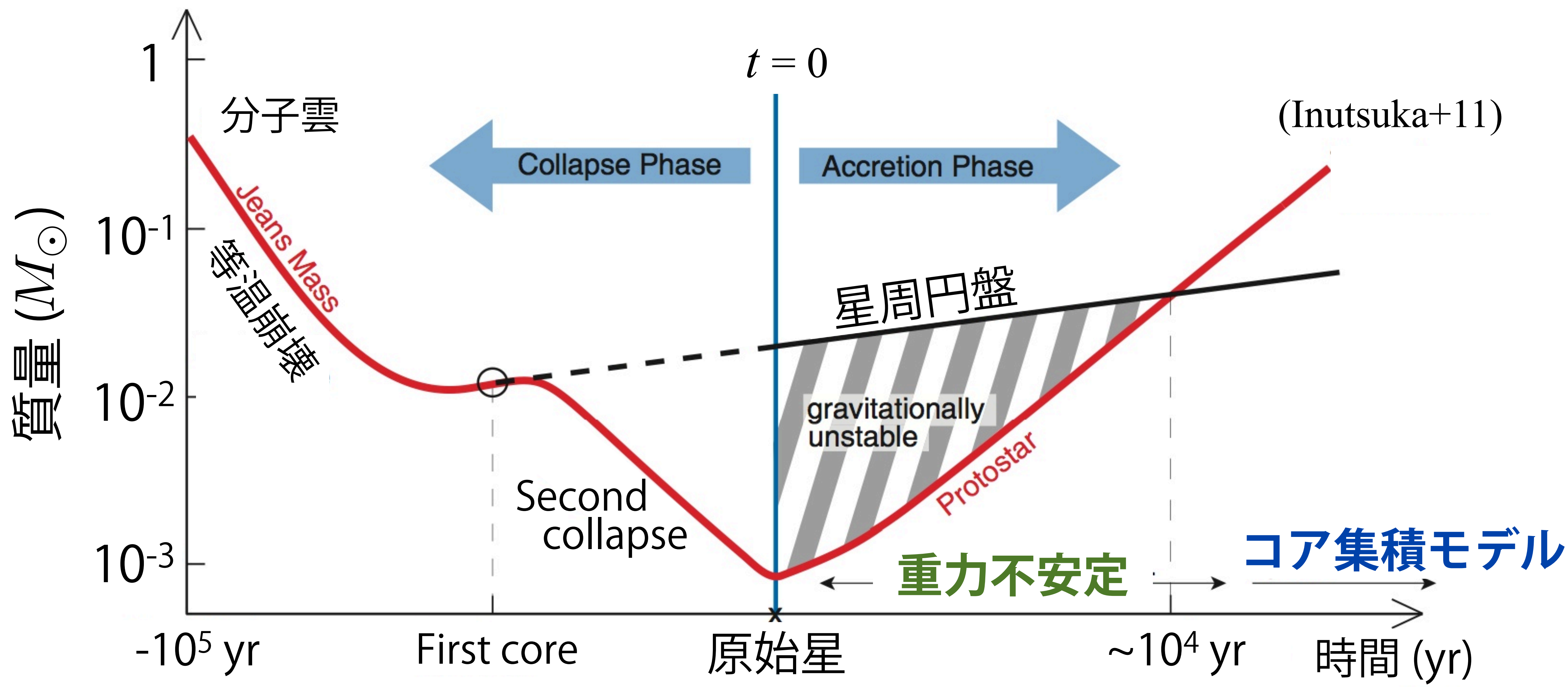
H_2分子の断熱指数(ortho/para比) (Boley+07)
平均分子量(高)と起きやすい (Mayer+08)
中心星輻射は分裂の抑制へ (Mejia,2004)

(4) **円盤質量・円盤への質量降着率** (Mayer+02; Boley, 2009)

(5) **輻射輸送のスキーム・resolution** (Boss,2007; Cai+10)

木星・土星と2つの形成シナリオ

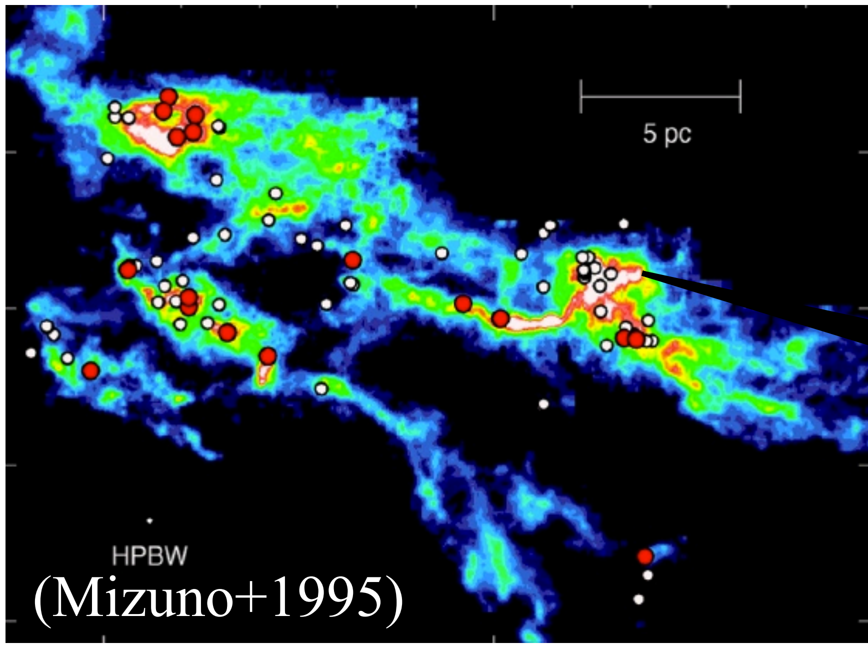
■ **円盤不安定モデル**の視点



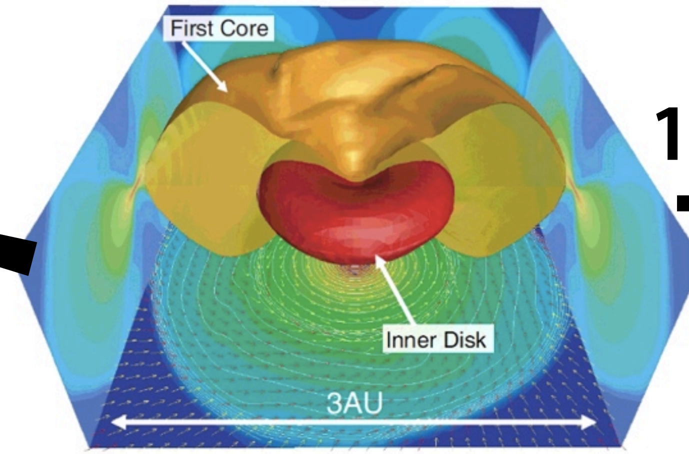
分子雲から星の誕生

おうし座分子雲(^{13}CO : J=1-0)

(Machida+2010;2011;Tomida+2012)

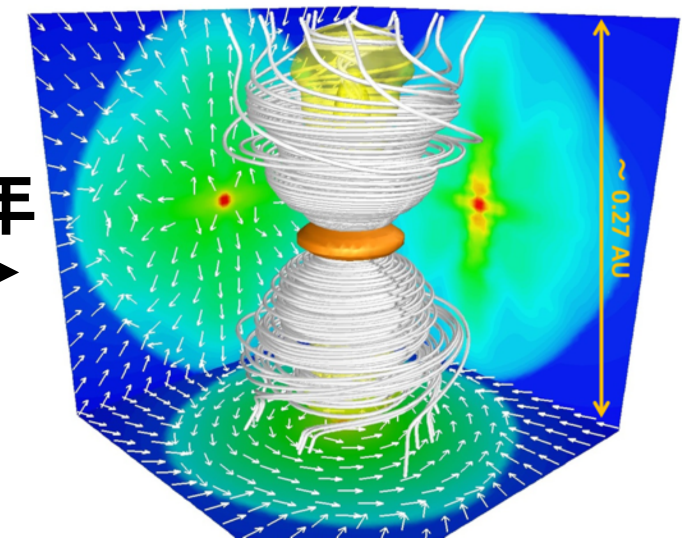


~10Kのガス

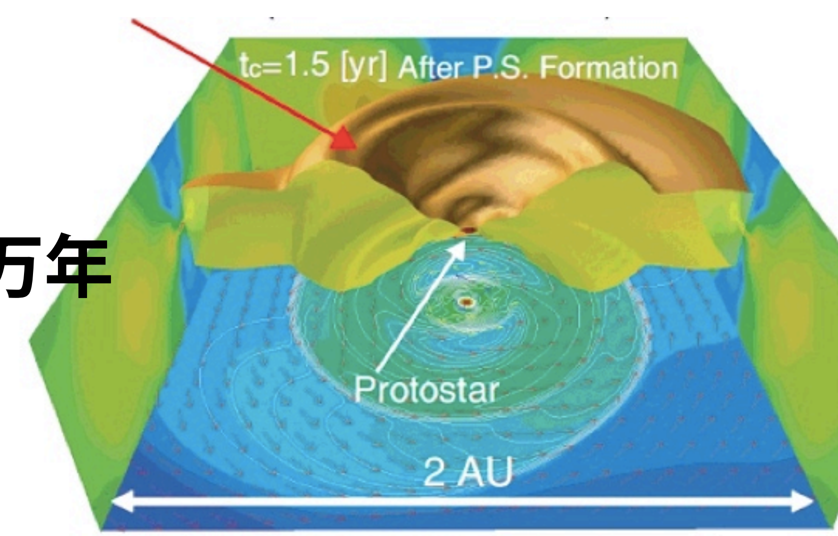


10-100万AU

1-100万年



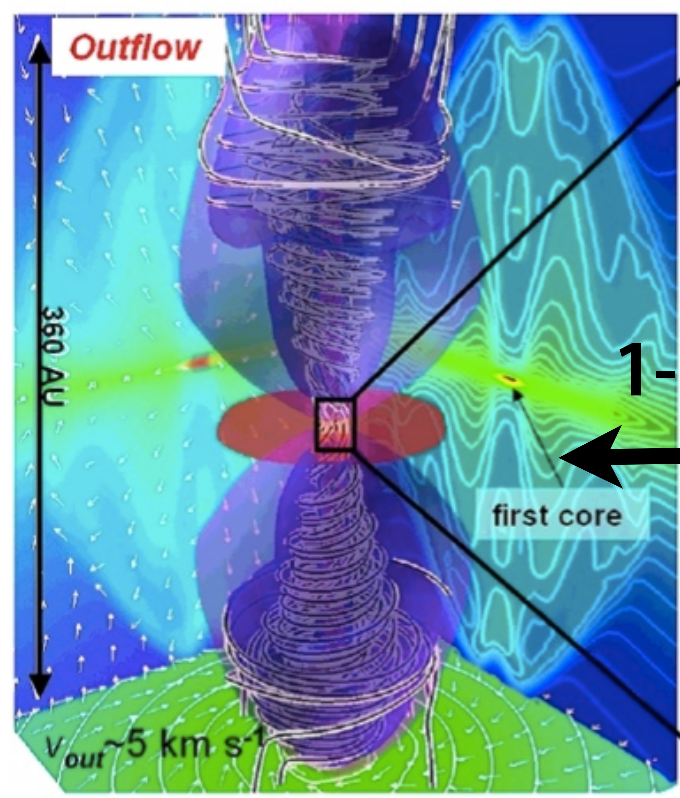
10-1000年



原始星の誕生

~0.01AU

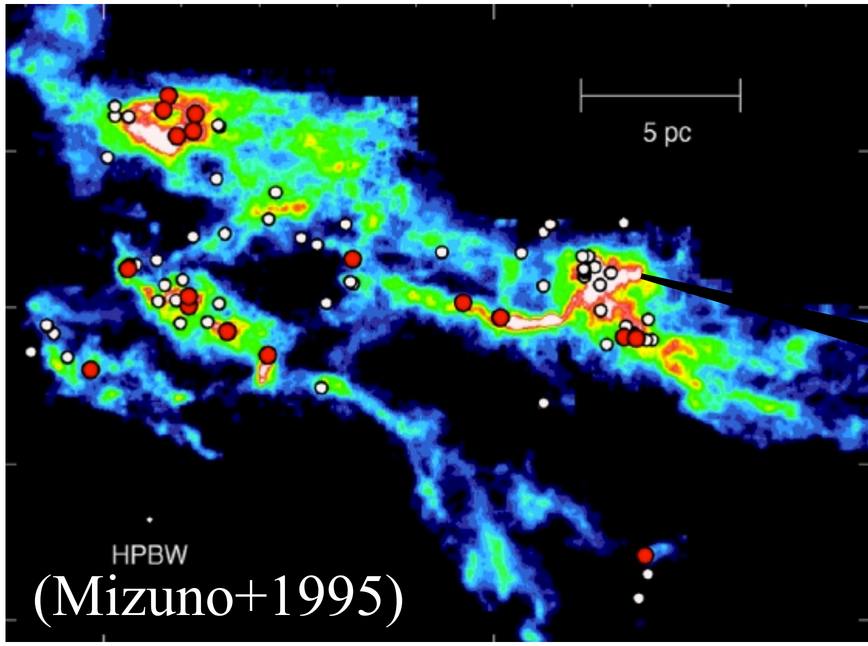
1-100万年

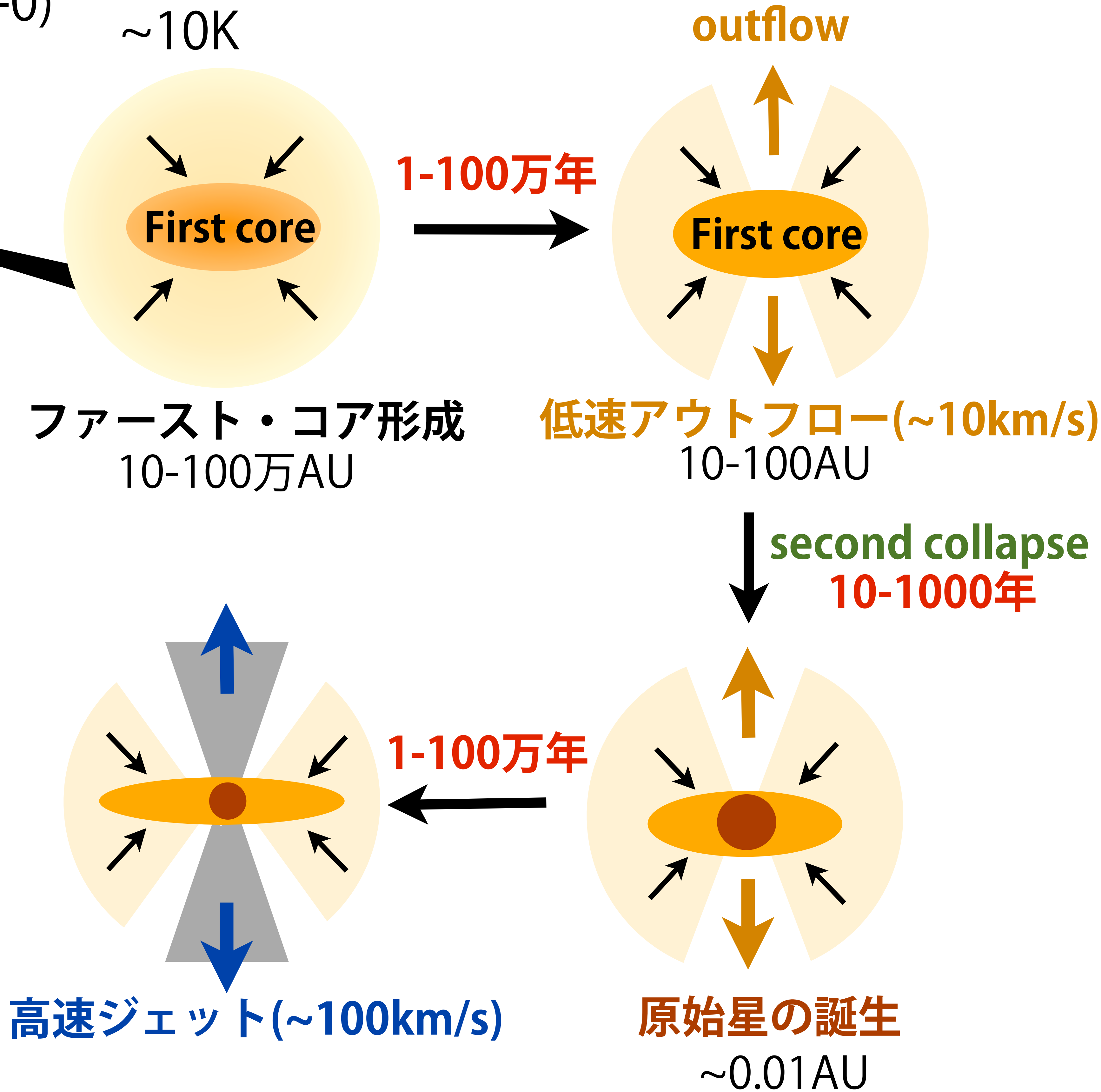


星の周りに円盤が形成

分子雲コアから原始星誕生

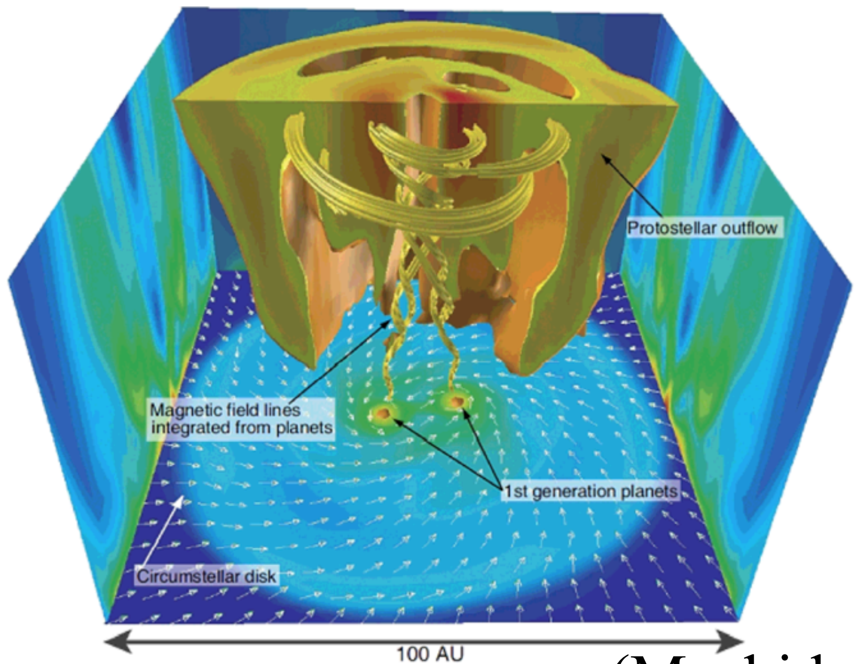
おうし座分子雲(^{13}CO : J=1-0)

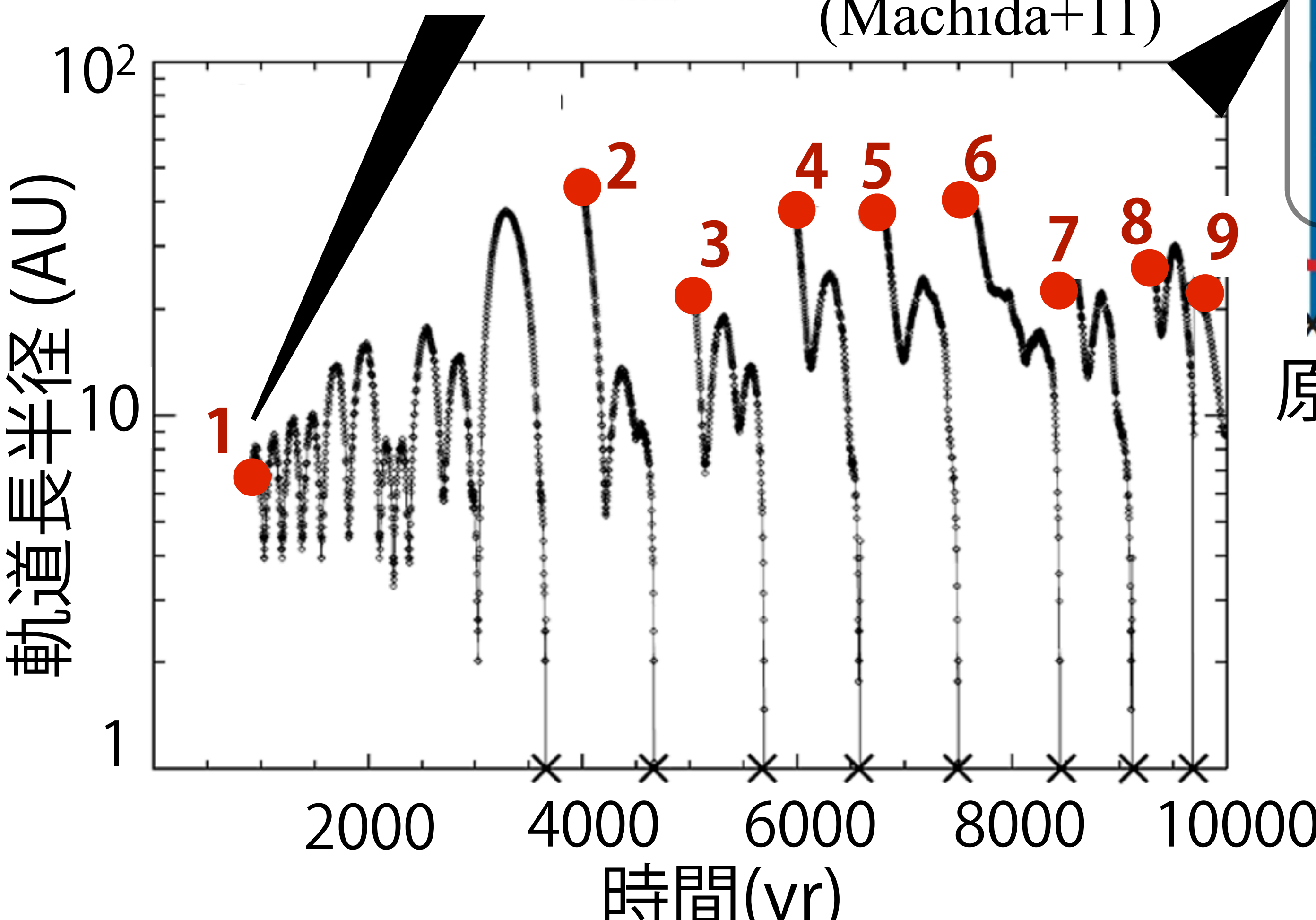


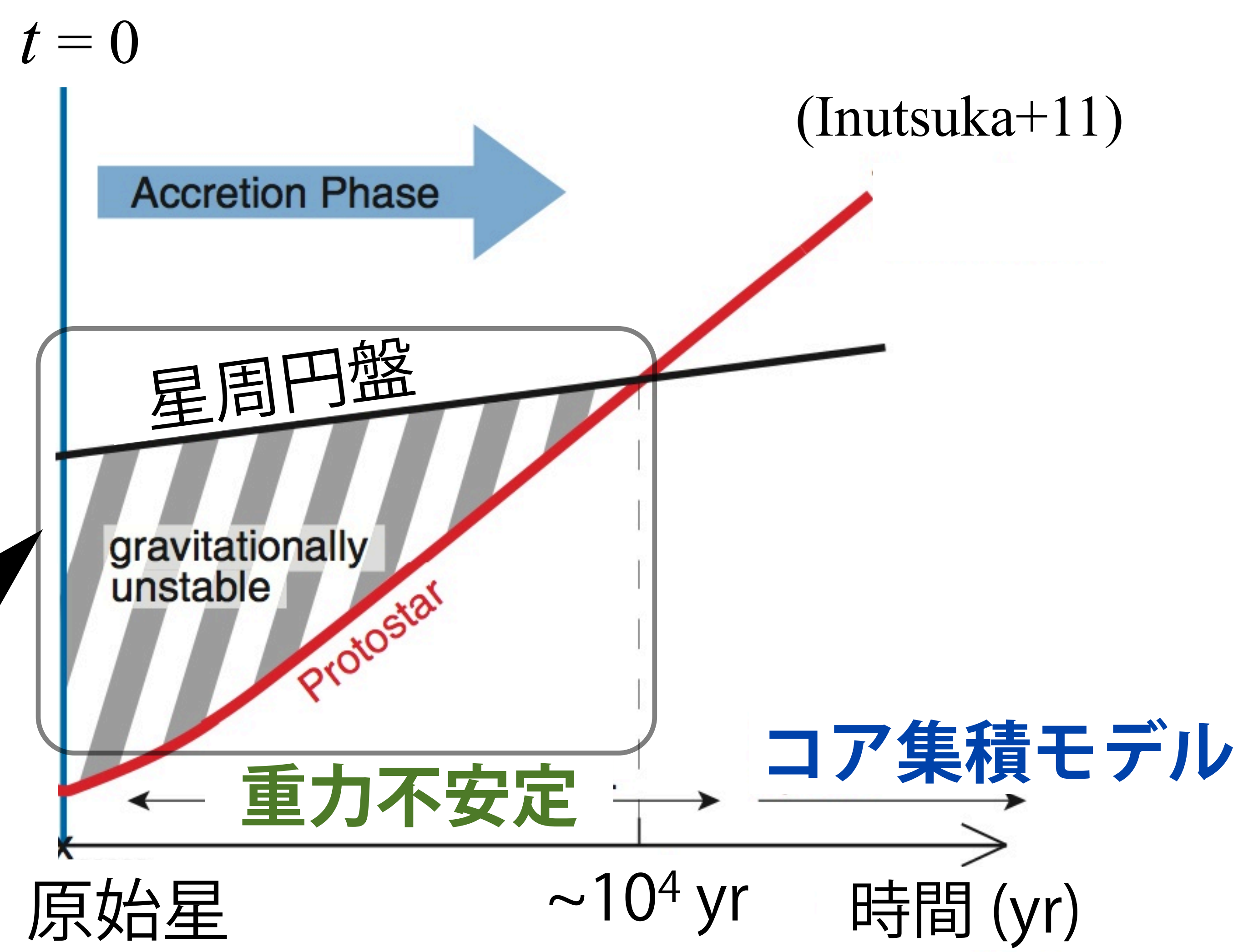


ガス惑星形成の Hybrid model

■ 円盤不安定モデルの視点





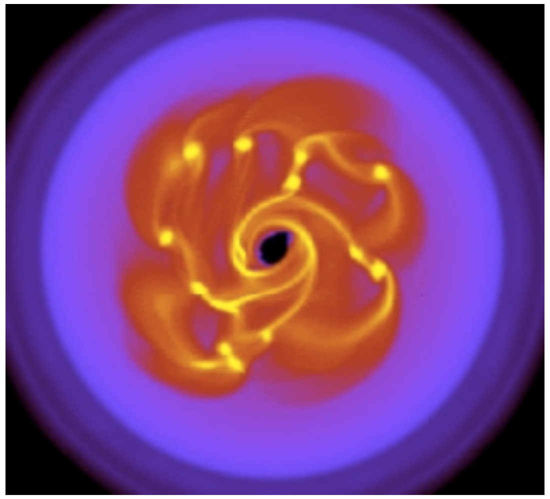


再帰的な**ガス惑星**形成
→ **生き残った**ガス惑星(1,2個)
(+ **コア集積モデル**)

円盤不安定起源のガス惑星のコア

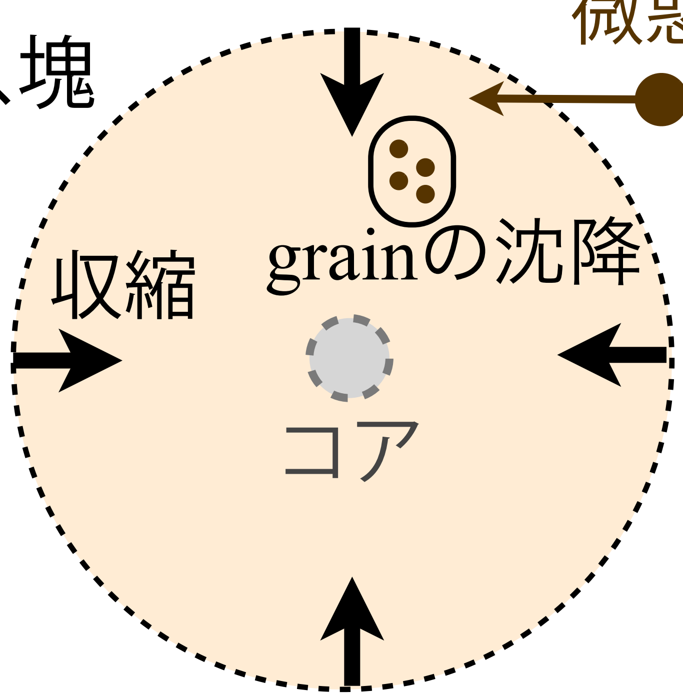
■ 円盤不安定モデルの視点

(1) (再帰的に)**短期間**(10^3-10^4年)の形成
(2) **外側領域**で分裂が起きやすい



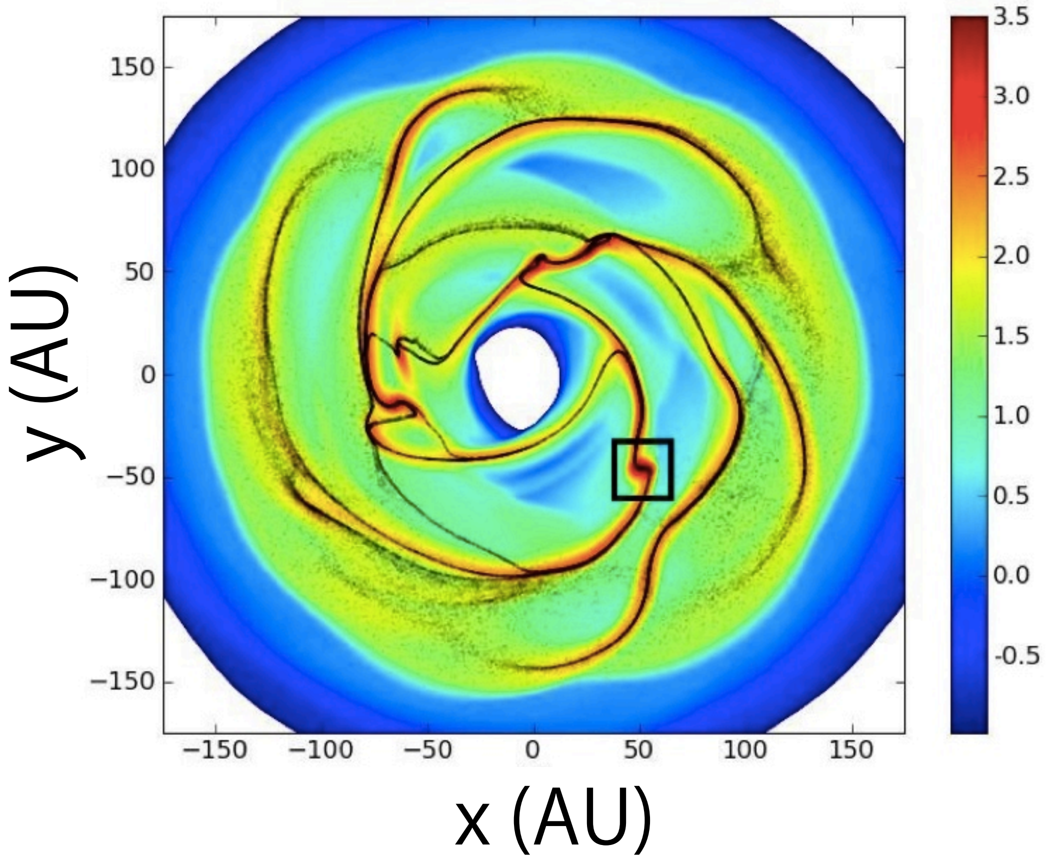
(Q) ガス惑星コアの形成は？

(1) 収縮段階の**微惑星降着**
(e.g. Helled+06,08; Helled & Schubert,2008)



※ 重いガス塊ほど、小さいコア
※ first core → second collapseと類似

(2) **渦状腕**による掃き集め
(Boley+11)



※ ガス面密度分布 (• 固体粒子)

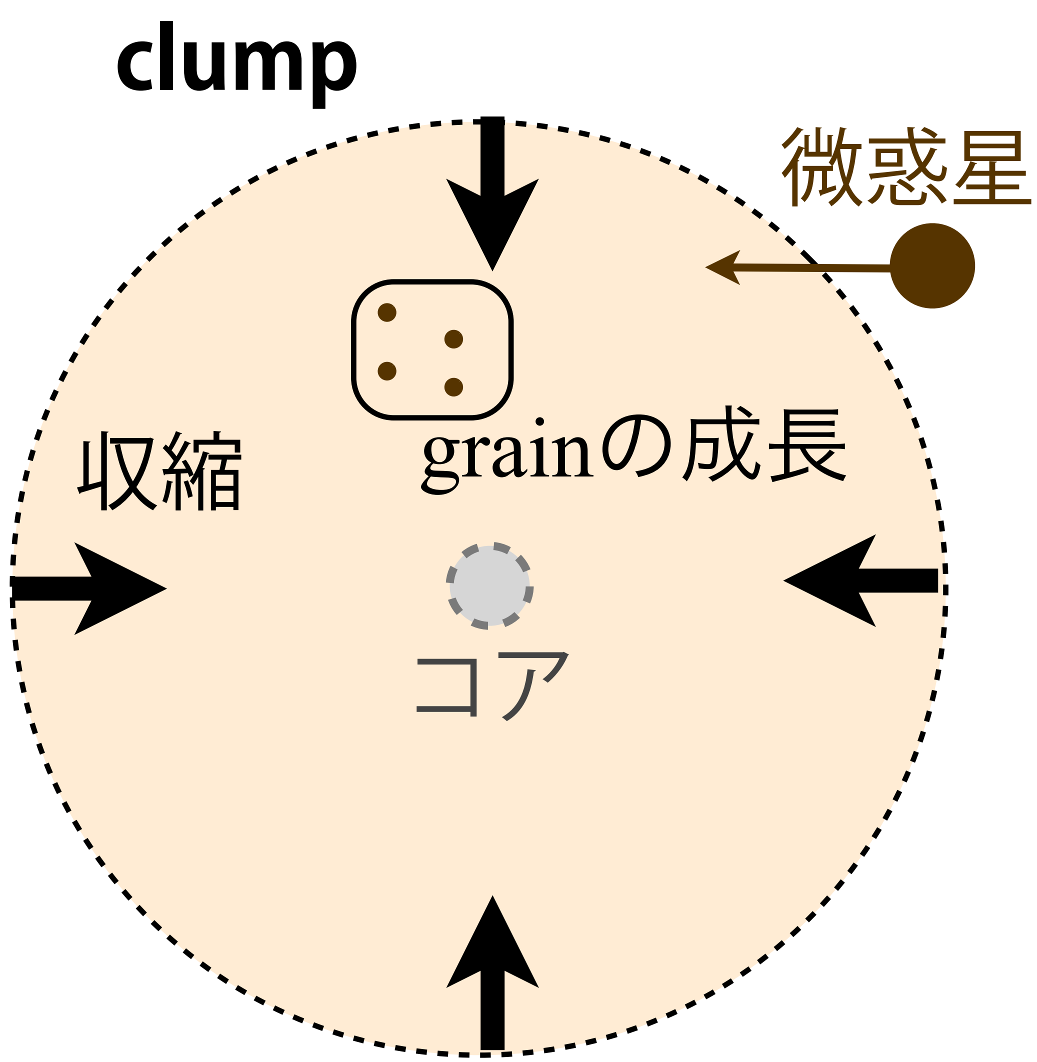
円盤不安定モデルとコア形成・重元素量

■ clumpの収縮段階 (Helled *et al*.2008; Helled & Schubert,2008)

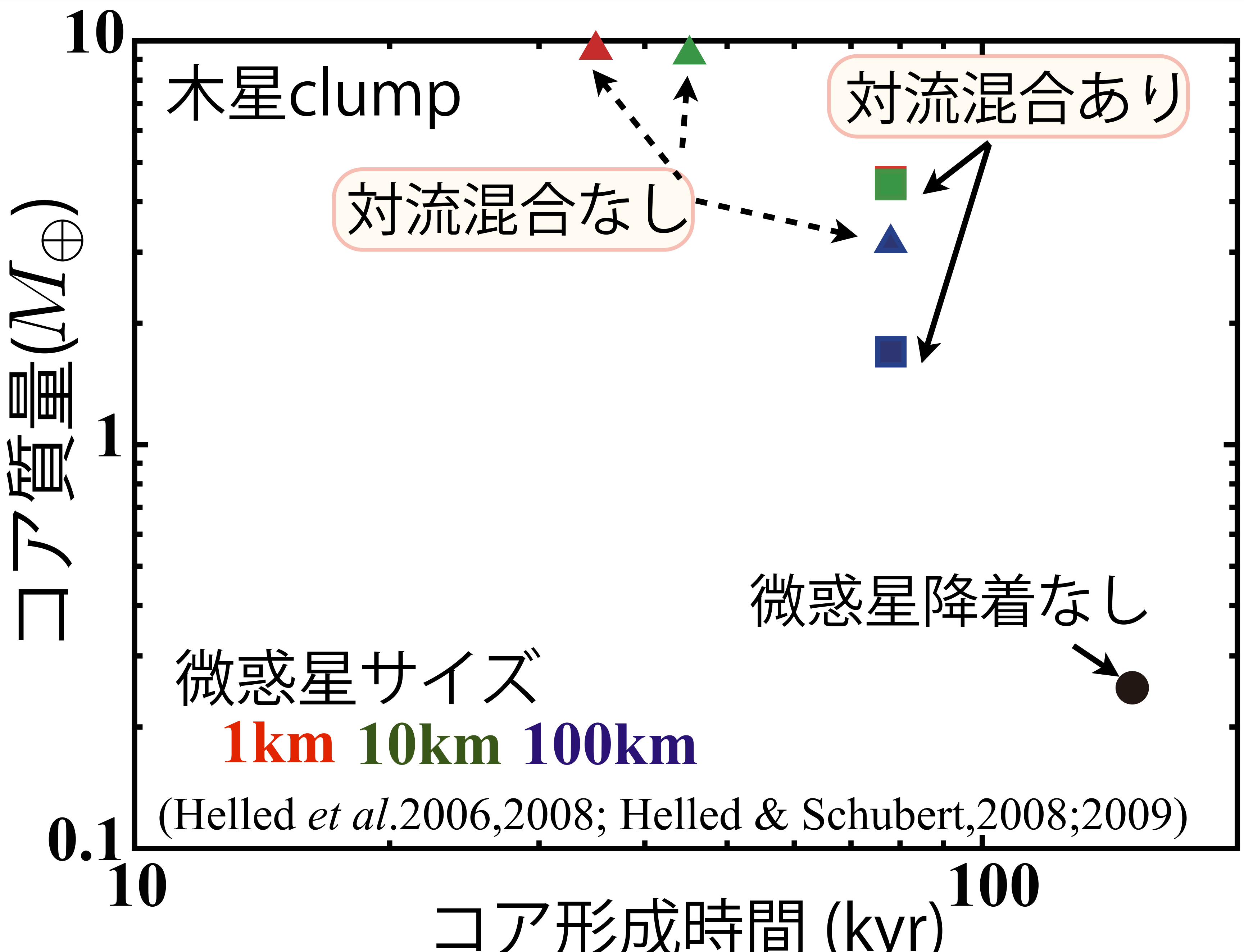
微惑星降着と grainの成長(**10cm**までの成長時間)・沈殿
VS
対流と内部温度(**~2000K**)

【初期条件】
重力不安定でclump 形成後
(e.g. Boss,1997)

- 微惑星の運動や蒸発 (Podolak *et al*.1987)
- grainの沈殿や成長 (Smoluchowsi方程式)
- 微惑星降着率 (Helled *et al*.2006)



円盤不安定モデルとコア形成・重元素量



※ **5 M_J 以上**のclumpはコアを形成出来ない

grainの初期size (0.1cm)

→ 結果を変えない

※ 対流なしの場合
grain(小) → 形成時間(大)

■ コアの組成

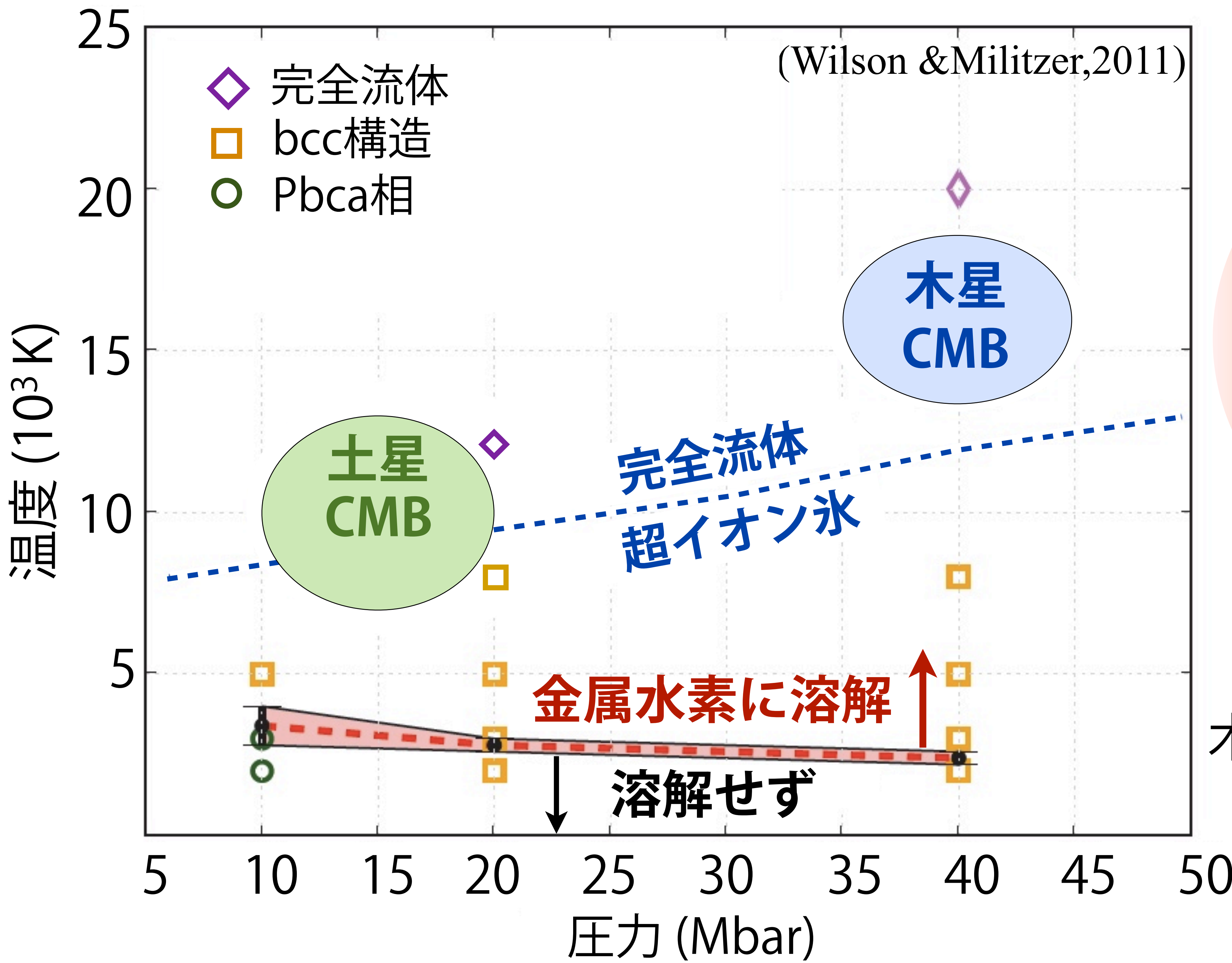
ほぼ**難揮発性物質**
(シリケイト)
※ water ice やCHONの
寄与は小さい

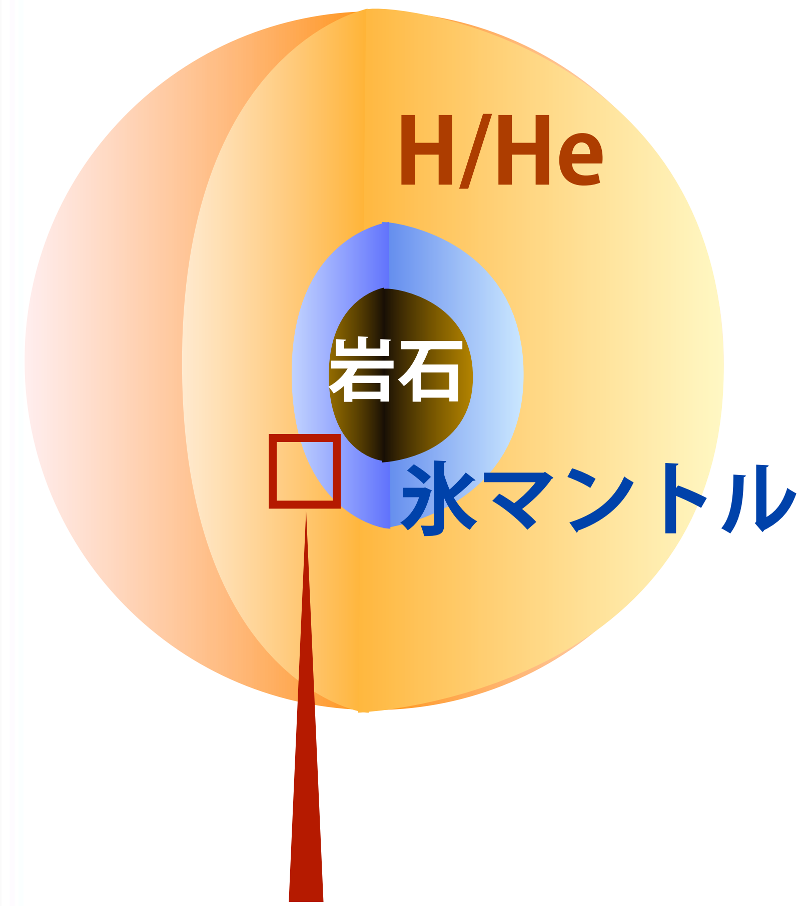
但し、残された課題も多数...

微惑星サイズ分布と降着率, grain沈降の重力ポテンシャル解放
中心星輻射の影響 etc.

ガス惑星の水氷コアの浸食

水氷のHへの飽和溶解線 (H_2O : H = 1 : 125)



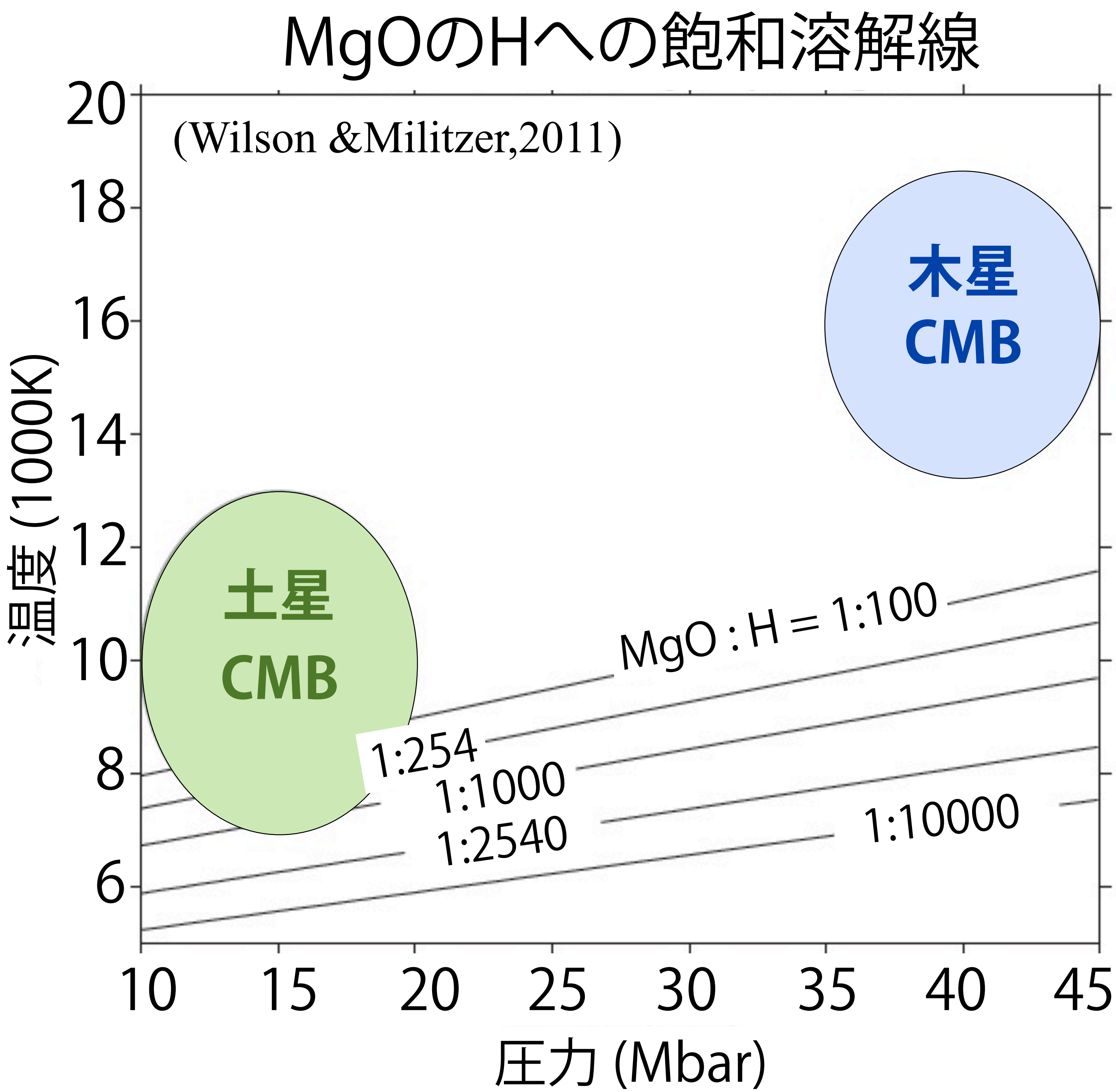


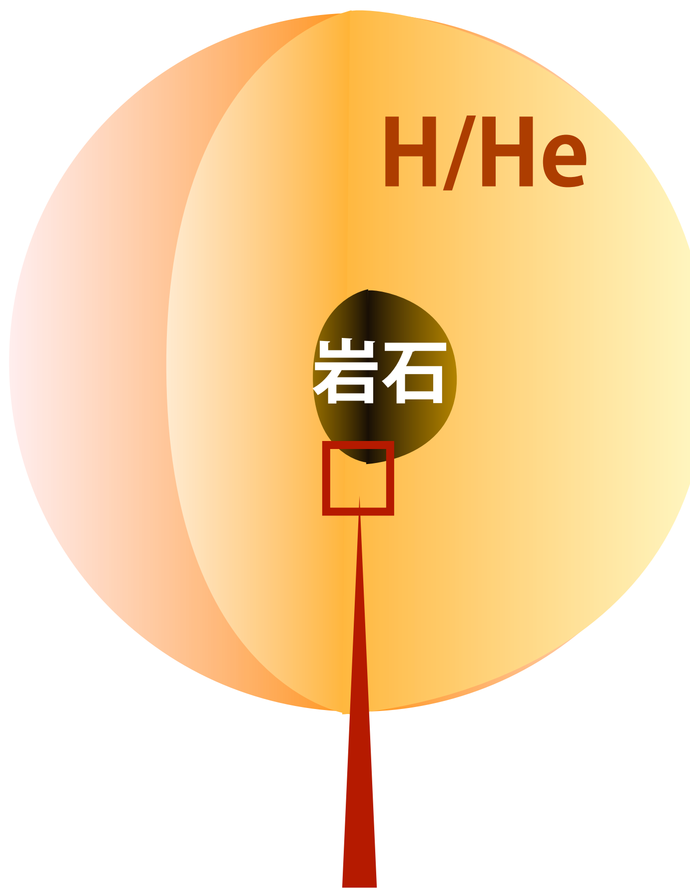
木星・土星の**氷コア**は
金属水素に溶解

↓

コアは浸食を経験

ガス惑星の岩石コアの浸食





木星・土星の**岩石コア**も**金属水素**に溶解

↓

コアは浸食を経験

10000K以上の高温下では、MgOは Hと**混合**

参考文献

- Anders and Grevese, Abundances of the elements - Meteoritic and solar, Geochimica et Cosmochimica Acta (ISSN 0016-7037), vol. 53, Jan. 1989, p. 197-214. 1989.
- Andrews, M., S., Williams, P., J., 2005: Circumstellar Dust Disks in Taurus-Auriga: The Submillimeter Perspective, ApJ, 631, 1134
- Atreya et al., A comparison of the atmospheres of Jupiter and Saturn: deep atmospheric composition, cloud structure, vertical mixing, and origin, Planetary and Space Science, Volume 47, Issue 10-11, p. 1243-1262, 1999.
- Atreya et al., Composition and origin of the atmosphere of Jupiter-an update, and implications for the extrasolar giant planets, Planetary and Space Science, Volume 51, Issue 2, p. 105-112, 2003.
- Bodenheimer, P., Pollack, J. B. 1986; Calculations of the accretion and evolution of giant planets: The effects of solid cores, Icarus, 67, 391
- Boley, A. C., Hartquist, T. W., Durisen, R. H., Michael, S., 2007; The Internal Energy for Molecular Hydrogen in Gravitationally Unstable Protoplanetary Disks, ApJ, 656, L89
- Boley, C., A., 2009; The Two Modes of Gas Giant Planet Formation, ApJ, 695, L53
- Boss, A. P. et al. 2007, Trans. Int. Astron. Union, Ser. A, 26, 183
- Burrows et al., The Near-Infrared and Optical Spectra of Methane Dwarfs and Brown Dwarfs, The Astrophysical Journal, Volume 531, Issue 1, pp. 438-446, 2000.
- Cai, K., Durisen, R. H., Michael, S., Boley, A. C., Mejía, A. C., Pickett, M. K., & D'Alessio, P., 2006; The Effects of Metallicity and Grain Size on Gravitational Instabilities in Protoplanetary Disks, ApJ, 636, L149

参考文献

- Gammie, C. F., 2001; Nonlinear Outcome of Gravitational Instability in Cooling, Gaseous Disks, ApJ, 553, 174
- Gautier et al., Erratum: Enrichments in Volatiles in Jupiter: A New Interpretation of the Galileo Measurements, The Astrophysical Journal, Volume 559, Issue 2, pp. L183-L183, 2001.
- Guillot and Hueso, The composition of Jupiter: sign of a (relatively) late formation in a chemically evolved protosolar disc, Monthly Notices of the Royal Astronomical Society: Letters, Volume 367, Issue 1, pp. L47-L51, 2006.
- Guillot et al., Are the giant planets fully convective?, Icarus (ISSN 0019-1035), vol. 112, no. 2, p. 337-353, 1994.
- Haisch Jr., K.E., Lada, E.A., Pina, R.K., Telesco, C.M., Lada, C.J., 2001: A Mid-Infrared Study of the Young Stellar Population in the NGC 2024 Cluster, ApJ, 121, 1512.
- Helled and Guillot, Interior Models of Saturn: Including the Uncertainties in Shape and Rotation, eprint arXiv:1302.6690, 2013.
- Helled, R., Podolak, M., Kovetz, A. 2006; Grain sedimentation in a giant gaseous protoplanet, Icarus, 195, 863
- Helled, R., Podolak, M., Kovetz, A. 2006; Planetesimal capture in the disk instability model, Icarus, 185, 64
- Helled, R., Schubert, G., & Anderson, J. D. 2009;Empirical models of pressure and density in Saturn's interior: Implications for the helium concentration, its depth dependence, and Saturn's precession rate, Icarus, 199, 368

参考文献

- Hernandez, I., Hill, F., Lindsey, C., 2007: Calibration of Seismic Signatures of Active Regions on the Far Side of the Sun, The Astrophys.J, 669, 2, 1382-1389
- Hersant et al., Enrichment in volatiles in the giant planets of the Solar System, Planetary and Space Science, Volume 52, Issue 7, p. 623-641, 2004.
- Ikoma, M., Nakazawa, K., Emori, H. 2000; Formation of Giant Planets: Dependences on Core Accretion Rate and Grain Opacity, ApJ, 537, 1013
- Inutsuka, S., Machida, M. N., Matsumoto, T., 2010; Emergence of Protoplanetary Disks and Successive Formation of Gaseous Planets by Gravitational Instability, ApJ, 718, L58-L62.
- Lindal et al., The Atmosphere of Neptune: Results of Radio Occultation Measurements with Voyager 2, Bulletin of the American Astronomical Society, Vol. 22, p.1106, 1990.
- Lindal et al., The atmosphere of Saturn - an analysis of the Voyager radio occultation measurements, Astronomical Journal (ISSN 0004-6256), vol. 90, June 1985, p. 1136-1146. NASA-supported research., 1985.
- Machida, M. N., Inutsuka, S., Matsumoto, T., 2011; Recurrent Planet Formation and Intermittent Protostellar Outflows Induced by Episodic Mass Accretion, ApJ, 729, 42-59
- Machida, M. N., Inutsuka, S., and Matsumoto, T., 2010; Formation Process of the Circumstellar Disk: Long-term Simulations in the Main Accretion Phase of Star Formation, ApJ, 724, 1006-1020.
- Mahaffy et al., Galileo Probe Measurements of D/H and 3He/4He in Jupiter's Atmosphere, Space Science Reviews, v. 84, Issue 1/2, p. 251-263, 1998.
- Mahaffy et al., Noble gas abundance and isotope ratios in the atmosphere of Jupiter from the Galileo Probe Mass Spectrometer, Journal of Geophysical Research, Volume 105, Issue E6, p. 15061-15072, 2000.

参考文献

- Hernandez, I., Hill, F., Lindsey, C., 2007: Calibration of Seismic Signatures of Active Regions on the Far Side of the Sun, The Astrophys.J, 669, 2, 1382-1389
- Hersant et al., Enrichment in volatiles in the giant planets of the Solar System, Planetary and Space Science, Volume 52, Issue 7, p. 623-641, 2004.
- Ikoma, M., Nakazawa, K., Emori, H. 2000; Formation of Giant Planets: Dependences on Core Accretion Rate and Grain Opacity, ApJ, 537, 1013
- Inutsuka, S., Machida, M. N., Matsumoto, T., 2010; Emergence of Protoplanetary Disks and Successive Formation of Gaseous Planets by Gravitational Instability, ApJ, 718, L58-L62.
- Lindal et al., The Atmosphere of Neptune: Results of Radio Occultation Measurements with Voyager 2, Bulletin of the American Astronomical Society, Vol. 22, p.1106, 1990.
- Lindal et al., The atmosphere of Saturn - an analysis of the Voyager radio occultation measurements, Astronomical Journal (ISSN 0004-6256), vol. 90, June 1985, p. 1136-1146. NASA-supported research., 1985.
- Machida, M. N., Inutsuka, S., Matsumoto, T., 2011; Recurrent Planet Formation and Intermittent Protostellar Outflows Induced by Episodic Mass Accretion, ApJ, 729, 42-59
- Machida, M. N., Inutsuka, S., and Matsumoto, T., 2010; Formation Process of the Circumstellar Disk: Long-term Simulations in the Main Accretion Phase of Star Formation, ApJ, 724, 1006-1020.
- Mahaffy et al., Galileo Probe Measurements of D/H and 3He/4He in Jupiter's Atmosphere, Space Science Reviews, v. 84, Issue 1/2, p. 251-263, 1998.
- Mahaffy et al., Noble gas abundance and isotope ratios in the atmosphere of Jupiter from the Galileo Probe Mass Spectrometer, Journal of Geophysical Research, Volume 105, Issue E6, p. 15061-15072, 2000.

参考文献

- Mayer, K.U., Frind, E.O., Blowes, D.W., 2002: Multicomponent reactive transport modeling in variably saturated porous media using a generalized formulation for kinetically controlled reactions. Water Resour. Res., 38, 9
- Mayer, L., Lufkin, G., Quinn, T., Wadsley, J., 2007; Fragmentation of Gravitationally Unstable Gaseous Protoplanetary Disks with Radiative Transfer, ApJ, 661, L77
- Mayer, L., Quinn, T., Wadsley, J., Stadel, J., 2002. Formation of giant planets by fragmentation
- Mayor M., Bonfils X., Forveille T., Delfosse X., Udry S., Bertaux J.-L., Beust H., Bouchy F., Lovis C., Pepe F., Perrier C., Queloz D., Santos N.C, 2009; The HARPS search for southern extra-solar planets.
- Mejia, A., 2004, PhD Thesis, Indiana University
- Mizuno, A., Onishi, T., Yonekura, Y., Nagahama, T., Ogawa, H., Fukui, Y.,1995 :Overall distribution of dense molecular gas and star formation in the the Taurus cloud complex, ApJ, 445, L161
- Mizuno, H., 1980: Formation of the giant planets. Prog. Theor. Phys., 64, 544–57.
- Mousis, O., Jonathan I. Lunine, I., J., Madhusudhan, N., Johnson4, V., T., 2012 :NEBULAR WATER DEPLETION AS THE CAUSE OF JUPITER'S LOW OXYGEN ABUNDANCE, ApJL, 751, L7
- Nettelmann, Predictions on the core mass of Jupiter and of giant planets in general, Astrophysics and Space Science, Volume 336, Issue 1, pp.47-51 , 2011.

参考文献

- Niemann et al., The composition of the Jovian atmosphere as determined by the Galileo probe mass spectrometer, Journal of Geophysical Research, Volume 103, Issue E10, p. 22831-22846, 1998.
- Owen et al., Low temperature condensates brought heavy elements to Jupiter, Bulletin of the Astronomical Society, Vol. 31, No. 4, p. 1131, #36.09, 1999.
- Pepin et al., Evidence for a Dominant Component of Solar-Energetic-Particle (SEP) Helium and Neon in a Suite of Interplanetary Dust Particles, 30th Annual Lunar and Planetary Science Conference, March 15-29, 1999, Houston, TX, abstract no. 1864, 1999.
- Podolak, M., J. B. Pollack, R. T. Reynolds, 1987; The interaction of planetesimals with protoplanetary atmospheres. Icarus 73, 163-179
- Pollack, J. B., Hubickyi, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., Greenzwieg, Y., 1996:Formation of the Giant Planets by Concurrent Accretion of Solids and Gas, Icarus, 124, 62-85
- Saumon and Guillot, Shock Compression of Deuterium and the Interiors of Jupiter and Saturn, The Astrophysical Journal, Volume 609, Issue 2, pp. 1170-1180, 2004.
- Seiff et al., Thermal structure of Jupiter's atmosphere near the edge of a 5-μm hot spot in the north equatorial belt, Journal of Geophysical Research, Volume 103, Issue E10, p. 22857-22890, 1998.
- Tomida, K., Tomisaka, K., Matsumoto, T., Hori, Y., Okuzumi, S., Machida, M., N., Saigo, K., 2012; Radiation Magnetohydrodynamic Simulations of Protostellar Core Formation, Astrophys.J., 714, L58-L63
- Toomre, A. 1964; On the gravitational stability of a disk of stars, ApJ, 139, 1217

参考文献

- Tsukamoto, Y., Machida, M., 2013; Formation and early evolution of circumstellar discs in turbulent molecular cloud cores, Monthly Notices of the Royal Astronomical Society, 428, 2, 1321-1334
- Wilson, H., F., Militzer, B., 2012; Rocky Core Solubility in Jupiter and Giant Exoplanets, Phys. Rev. Lett., 108, 11, 111101
- Wong et al., Updated Galileo probe mass spectrometer measurements of carbon, oxygen, nitrogen, and sulfur on Jupiter, Icarus, Volume 171, Issue 1, p. 153-170, 2004.
- XVIII. An Earth-mass planet in the GJ 581 planetary system, astro-ph.EP, 507, 1, 487-494
- Öberg, K.I., Boogert, A.C.A., Pontoppidan, K.M., van den Broek, S., van Dishoeck, E.F., Bottinelli, S., Blake, G.A., and Evans II, N.J., 2011:The Spitzer Ice Legacy: Ice Evolution from Cores to Protostar, ApJ, 740,109-124