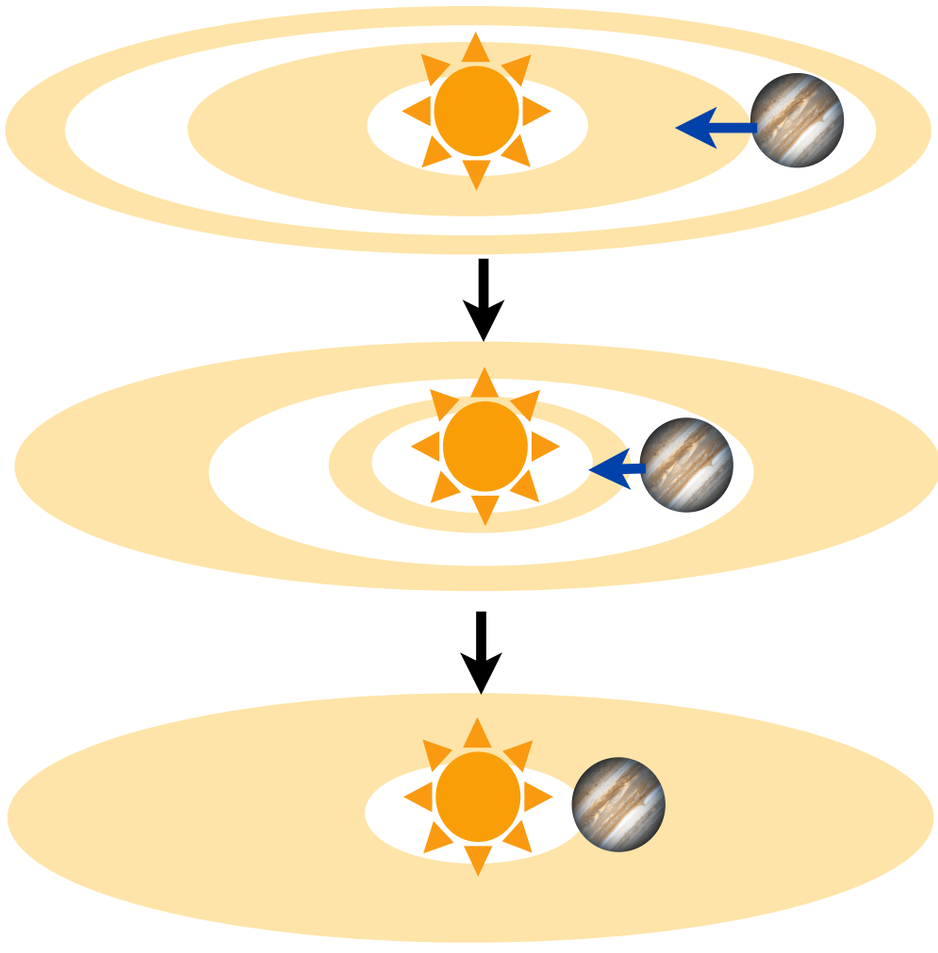
太陽系：in situ 形成 とNice モデル

(Q) 木星・土星は**現在の位置**で**形成**されたのか？

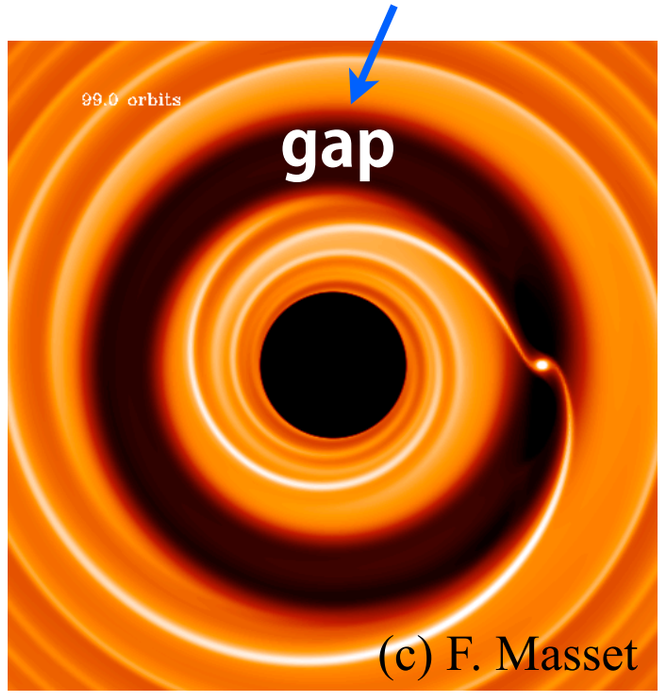
木星：**5.2**AU, 土星：**9.5**AU

■ Type II 移動 (Lin & Papaloizou,1986;Ward,1997)



惑星重力による跳ね飛ばし

> 圧力勾配, 粘性拡散によるガス流入



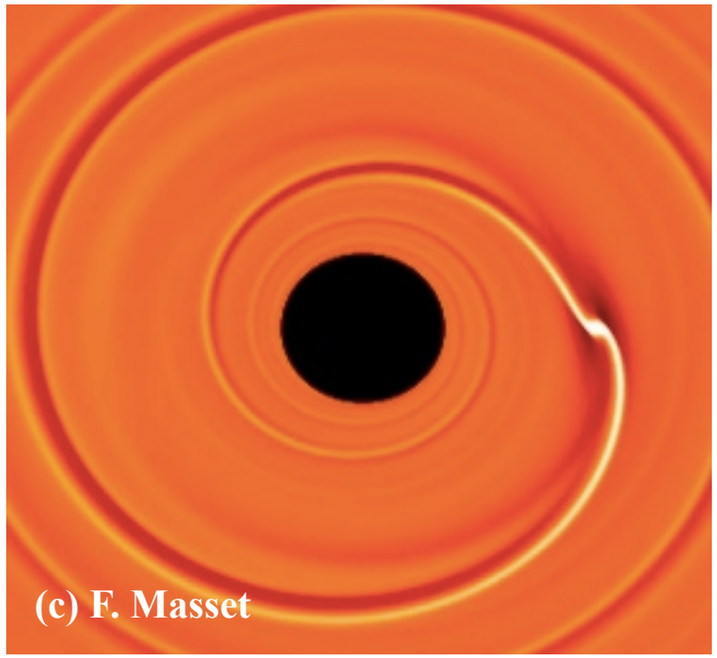
※ 重い円盤(Q = 1-10)＋土星サイズの惑星

→ 部分的なgap形成 : **Type III**移動 (Masset & Papaloizou,2003)

※ 重力不安定下では惑星移動は速い(Type I的)? (Baruteau+11;Michael+11)

What is Type I Migration ?

(e.g. Tanaka+02;Muto+09)



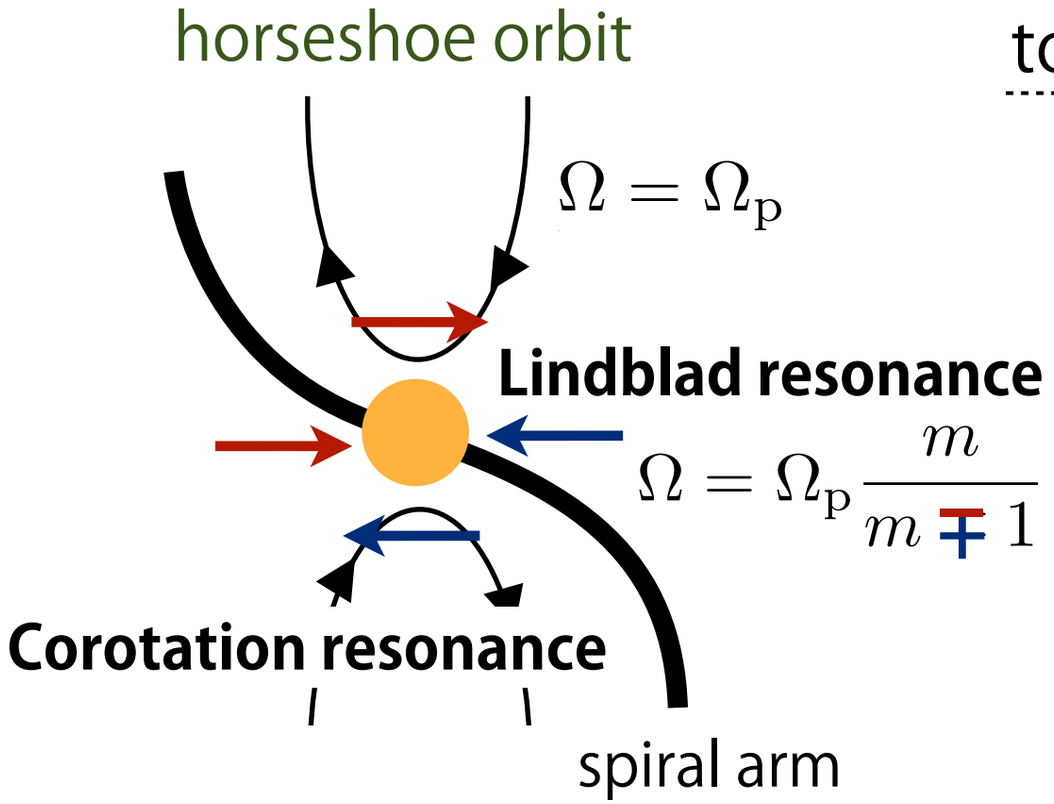
wave excitation (~**sonic point**)

$$\frac{3}{2} r_{\rm s} \Omega_{\rm p} = c_{\rm s} \longrightarrow r_{\rm s} = \frac{2}{3} \frac{c_{\rm s}}{\Omega_{\rm p}} \sim H_{\rm p}$$

Kepler shear

$$c_{\rm s}^2 \frac{\delta\Sigma}{\Sigma_0} \sim \frac{G M_{\rm p}}{H_{\rm p}}$$

energy fluctuation of the disk gas ~ gravitational potential of a planet



torque from a **density wave**

$$T \sim a_{\rm p} \frac{G M_{\rm p} \delta\Sigma H_{\rm p}^2}{H_{\rm p}^2} \left(\frac{H_{\rm p}}{a_{\rm p}} \right) \sim \frac{d}{dt} \left(M_{\rm p} a_{\rm p}^2 \Omega_{\rm p} \right)$$

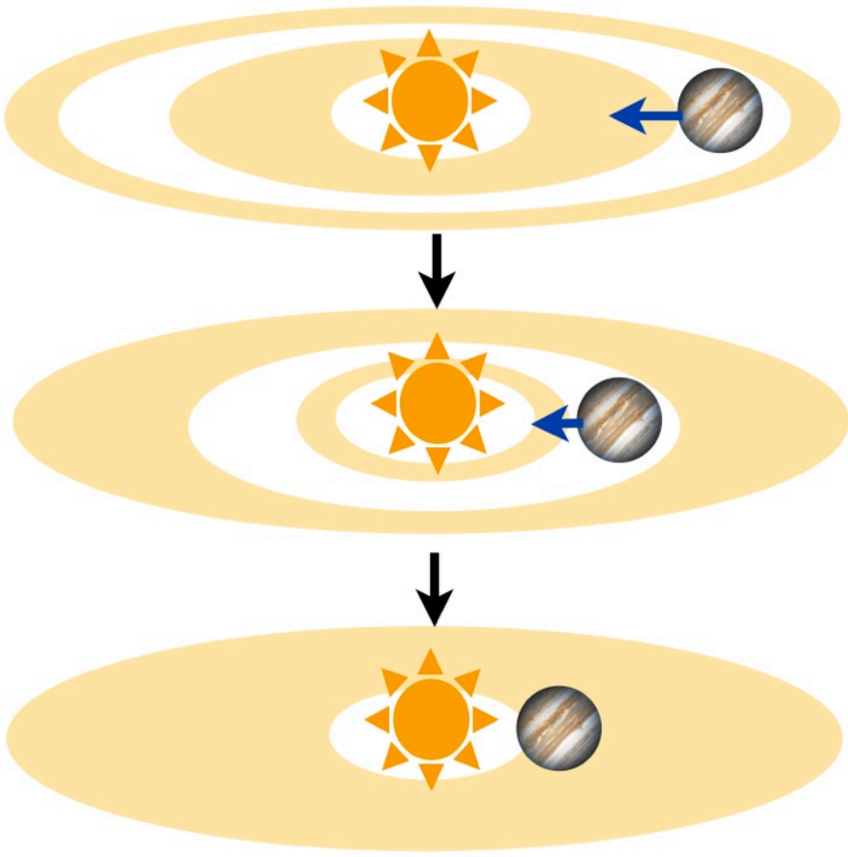
Force · curvature · angular momentum

$$\tau_{\rm mig} \left(= \frac{a_{\rm p}}{\dot{a}_{\rm p}} \right) \sim \left(\frac{M_\star}{M_{\rm p}} \right) \left(\frac{M_\star}{a_{\rm p}^2 \Sigma_0} \right) \left(\frac{H_{\rm p}}{a_{\rm p}} \right)^2 \Omega_{\rm p}^{-1}$$

planetary mass · aspect ratio

What is Type II Migration ?

(Lin & Papaloizou,1986;Ward,1997)



pressure gradient

$$r_{\rm H} \geq 1.5 H_{\rm P}$$

viscous diffusion

$$M_{\rm p} > \frac{40\nu}{a_{\rm p}^2 \Omega} M_\star$$

gravitational scattering
by a gas giant

Gap-opening (Type II migration)

■ Transport of angular momentum (J)

(1) **viscous diffusion**

$$\frac{dJ}{dt} \sim a_{\rm p} \cdot \frac{3}{2} a_{\rm p}\Omega \cdot \frac{\nu}{a_{\rm p}} \cdot a_{\rm p}\Sigma_{\rm gas}$$

Kepler shear　mass accretion

$$\tau_{\rm mig} \left(= \frac{a_{\rm p}}{\dot{a}_{\rm p}} \right) \propto \frac{a_{\rm p}^2}{\nu} \cdot \frac{M_{\rm p}}{a_{\rm p}^2 \Sigma_{\rm gas}}$$

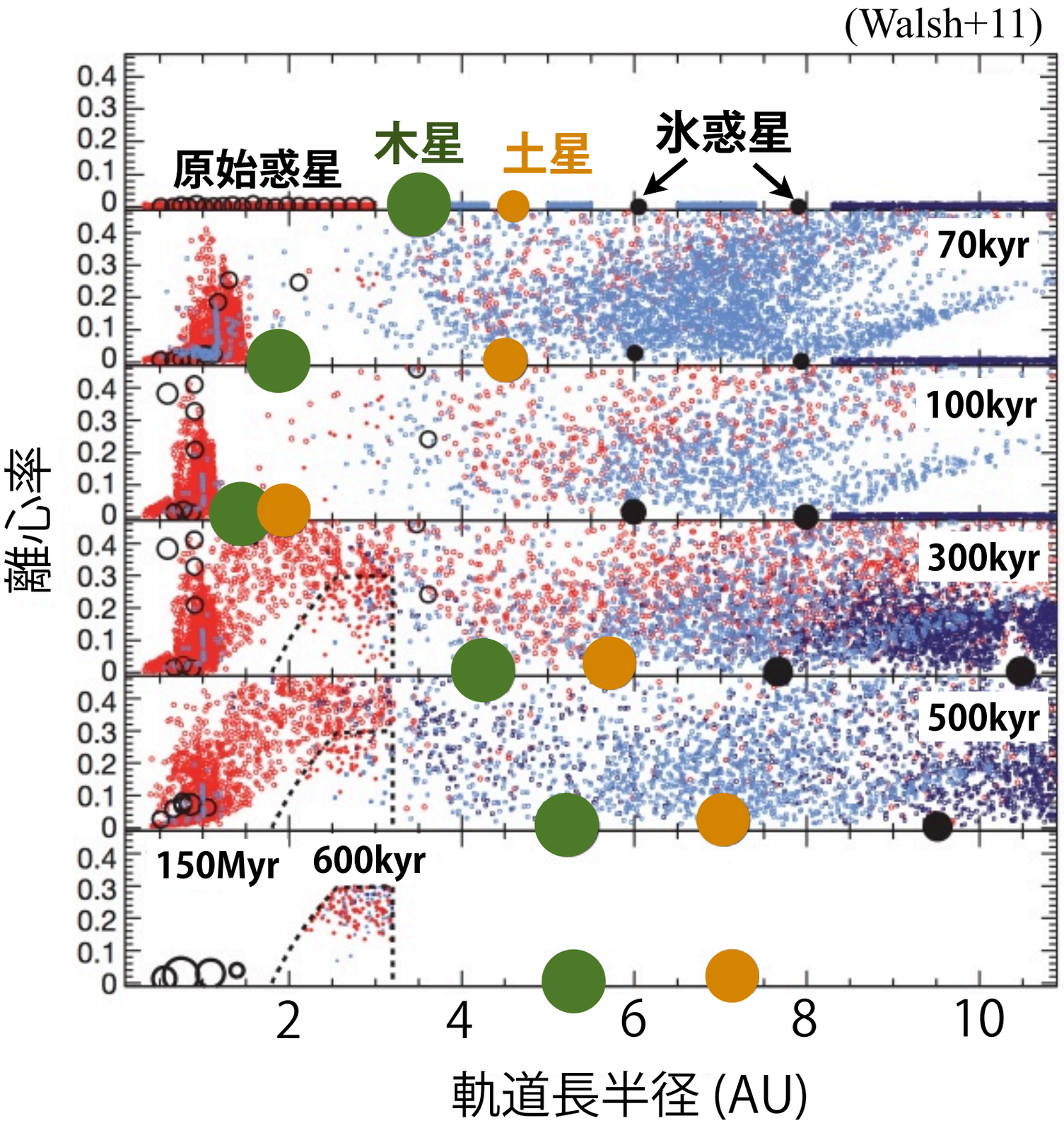
(2) **orbital migration**

$$\frac{dJ}{dt} = \frac{d}{dt}\left(M_{\rm p} a_{\rm p}^2 \Omega\right)$$

(cf) Jupiter@5.2AU

$\tau_{\rm mig}$ ~ **0.1-1Myr**

木星・土星の大移動 (Grand Tack仮説)

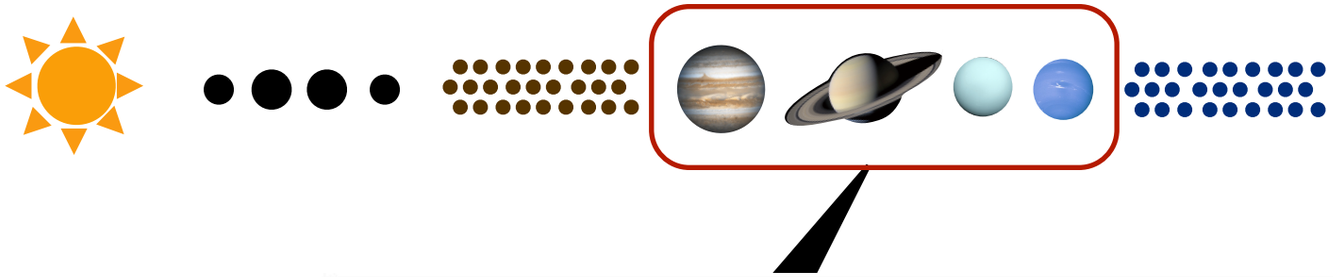


木星(3.5AU) : **内側移動**を開始
土星コア($30M_\oplus$@~4.5AU)

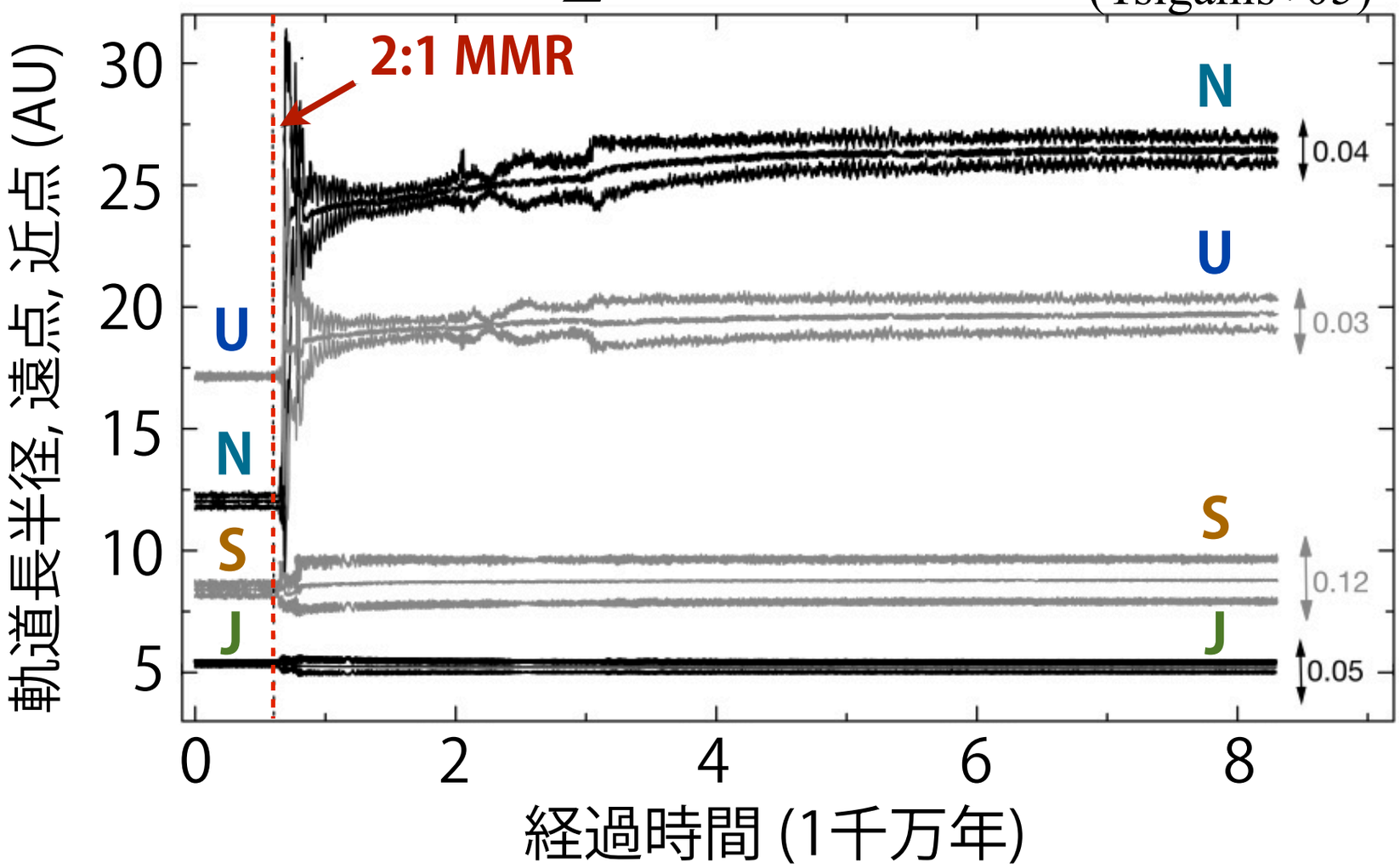
土星が木星(~1.5AU)を捕獲
(**3:2 平均運動共鳴**)

木星・土星ペアの外向き移動
(Masset & Snellgrove,2001;
Morbidelli & Crida,2007;
D'Angelo & Marzari,2012)

Niceモデル：軌道不安定と後期重爆撃



(Tsiganis+05)

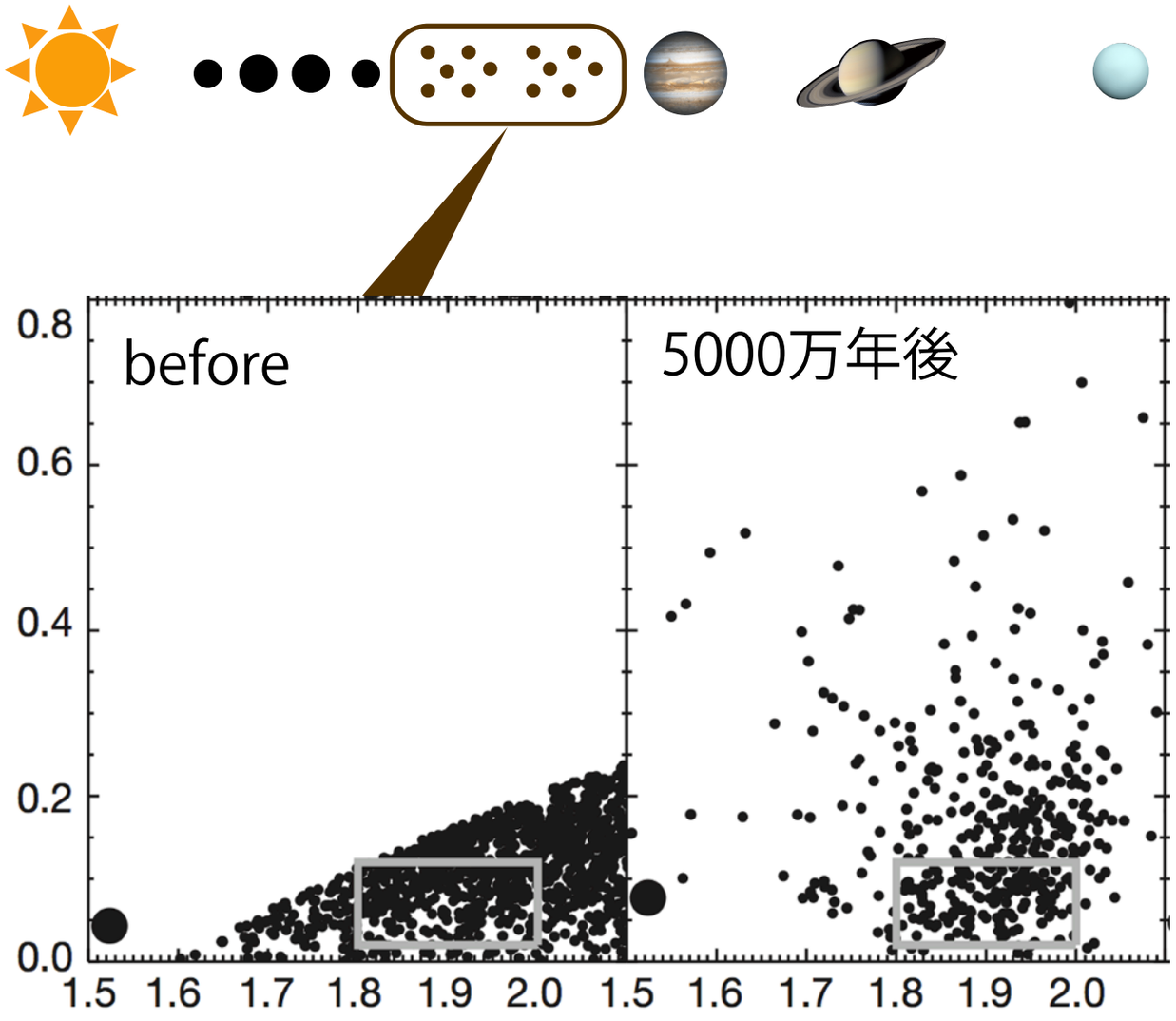


木星と**土星**が **2:1 平均運動共鳴(MMR)**を経験(通過)

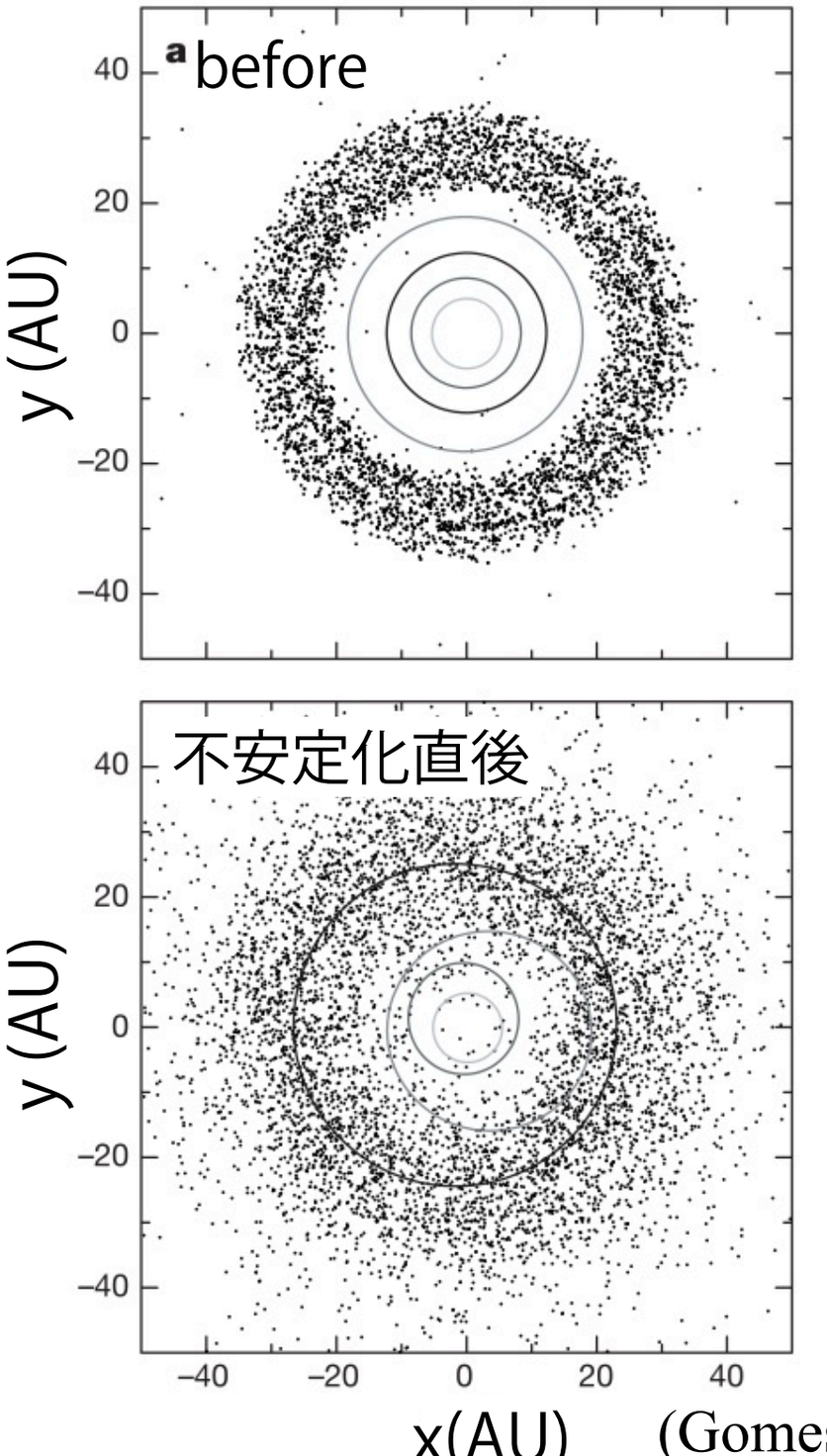
→ **木星**と土星 : eccentricな軌道

→ 4巨大惑星系の**軌道不安定**を誘発

Niceモデル：軌道不安定と後期重爆撃



(Bottke+12)



(Gomes+05)

【コンパクトな巨大惑星系の軌道不安定】

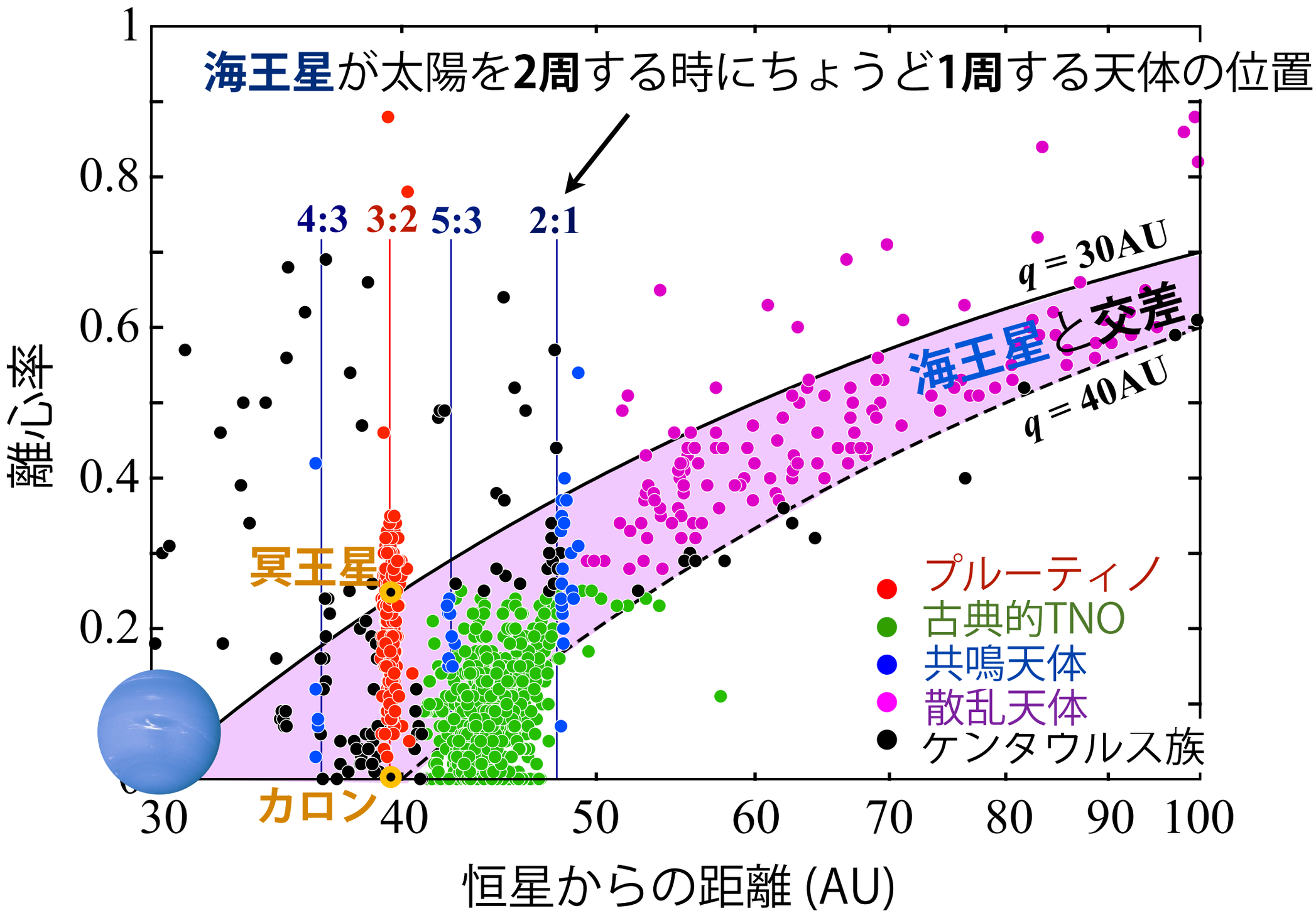
→ 小惑星帯／TNOs領域の天体をかき乱す

→ 数億年の期間、後期重爆撃

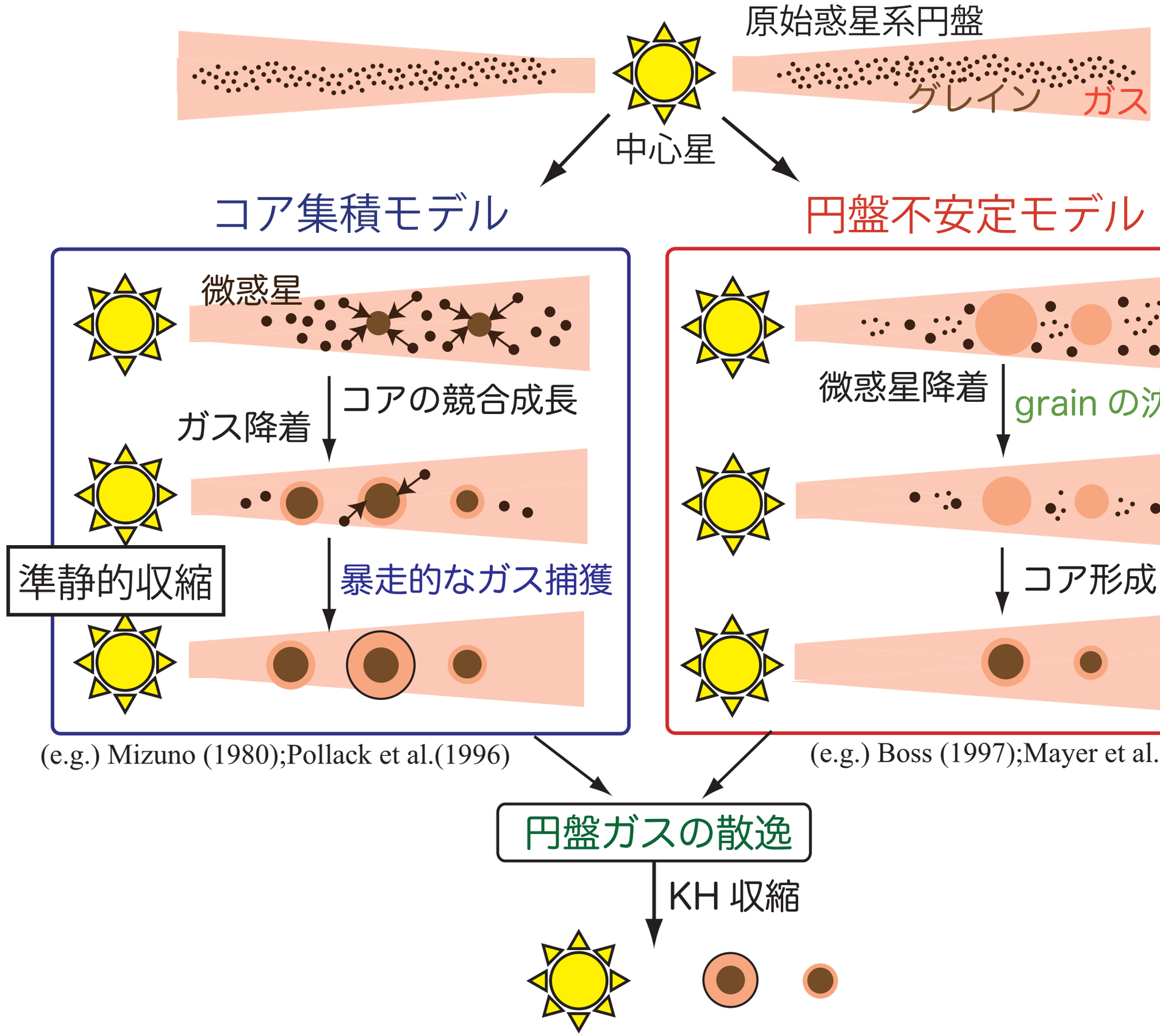
海王星の移動

海王星以遠天体(Trans-Neptunian Object : TNO)

--- 軌道が**楕円型**や**平均運動共鳴**にある



まとめ：ガス惑星の内部構造から起源



太陽系のガス惑星から
太陽系外のガス惑星へ (第3部)



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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

Uranus, Neptuneの形成シナリオ

【時間的制約】コア成長

■ in situ形成

$$t_{\rm growth} \propto \frac{M_{\rm p}^{1/3}}{\Sigma_{\rm d}\Omega_{\rm K}} \rightarrow$$ 天王星, 海王星：10^8 -10^9年(以上)

■ 様々なアイデア

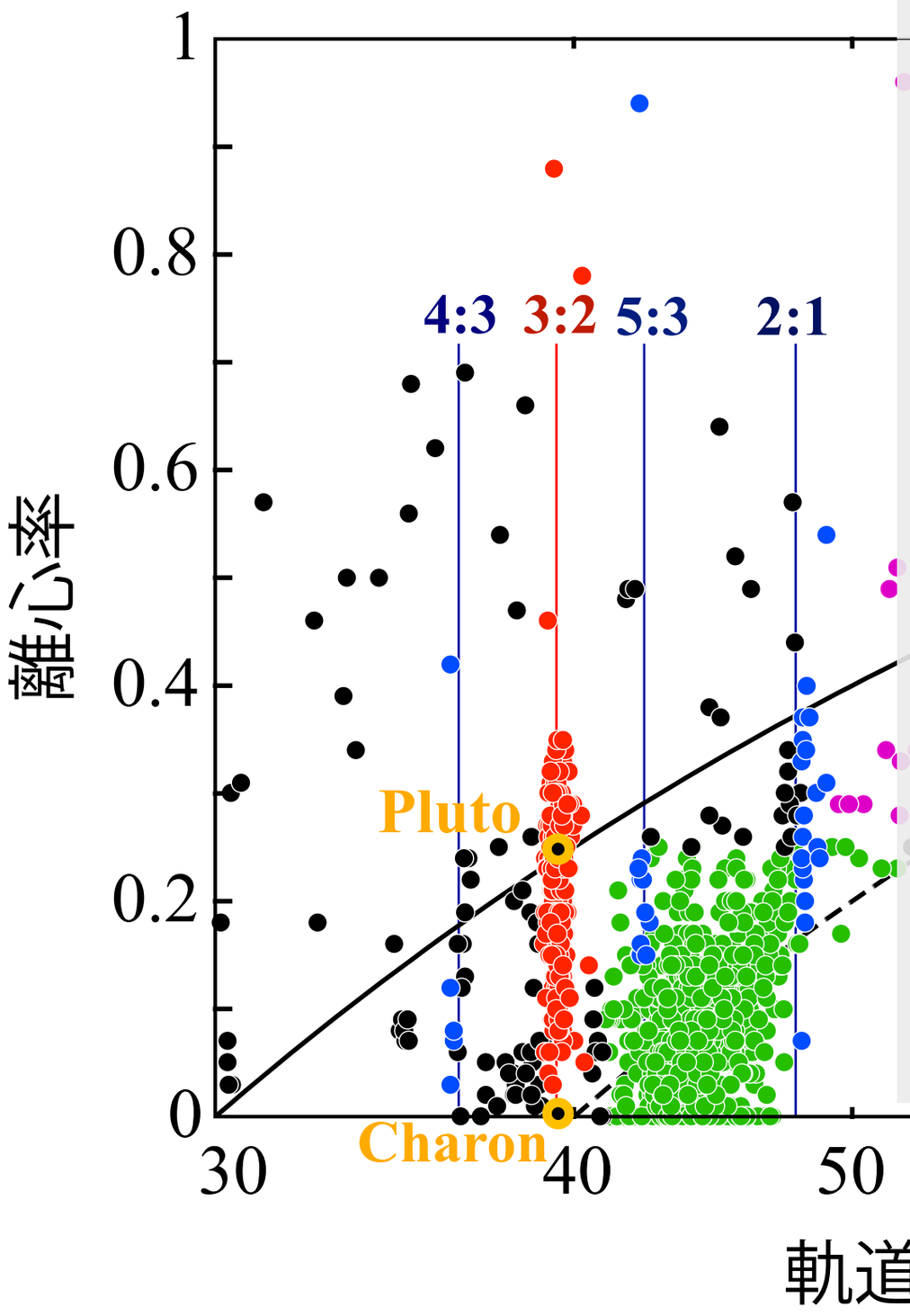
in situ形成＋ **小さな**微惑星(1km-size) (Pollack *et al*.1996)
高い固体面密度 (e.g. Dodson-Robinson *et al*.2009)

現在の位置よりも**内側で形成** → **外側移動**

・木星–土星間で成長＋重力散乱 (Thommes *et al*.2002)
・巨大惑星による微惑星のgravitational stirring
(Fernandez & Ip, 1984; Brunini & Fernandez,1999)
・外側移動に伴い、feeding zone内へ微惑星供給
(Bryden *et al*. 2000)
・微惑星**サイズ**分布 (Benvenuto *et al*.2010)

Neptune形成に対する制限：TNOs

【TNOsの軌道要素＋Pluto-Charon系】--- **Neptuneの外側移動**



(1) Plutoのe 励起

→ **sweeping共鳴** (Malhotra,1993)

($\Delta a > 5$AU+$\Delta t > 0.1$Myr)

(2) Plutinoのe, i 励起

→ **ν_{18} 永年共鳴＋Kozai共鳴**

(Malhotra,1998;Gomes,2000)

(3) 3:2 > 2:1 resonant TNOs

→ **遅い外側移動** (1-10Myr)

(Ida *et al*,2000)

(4) TNOsの枯渇 (MMSNの2桁)

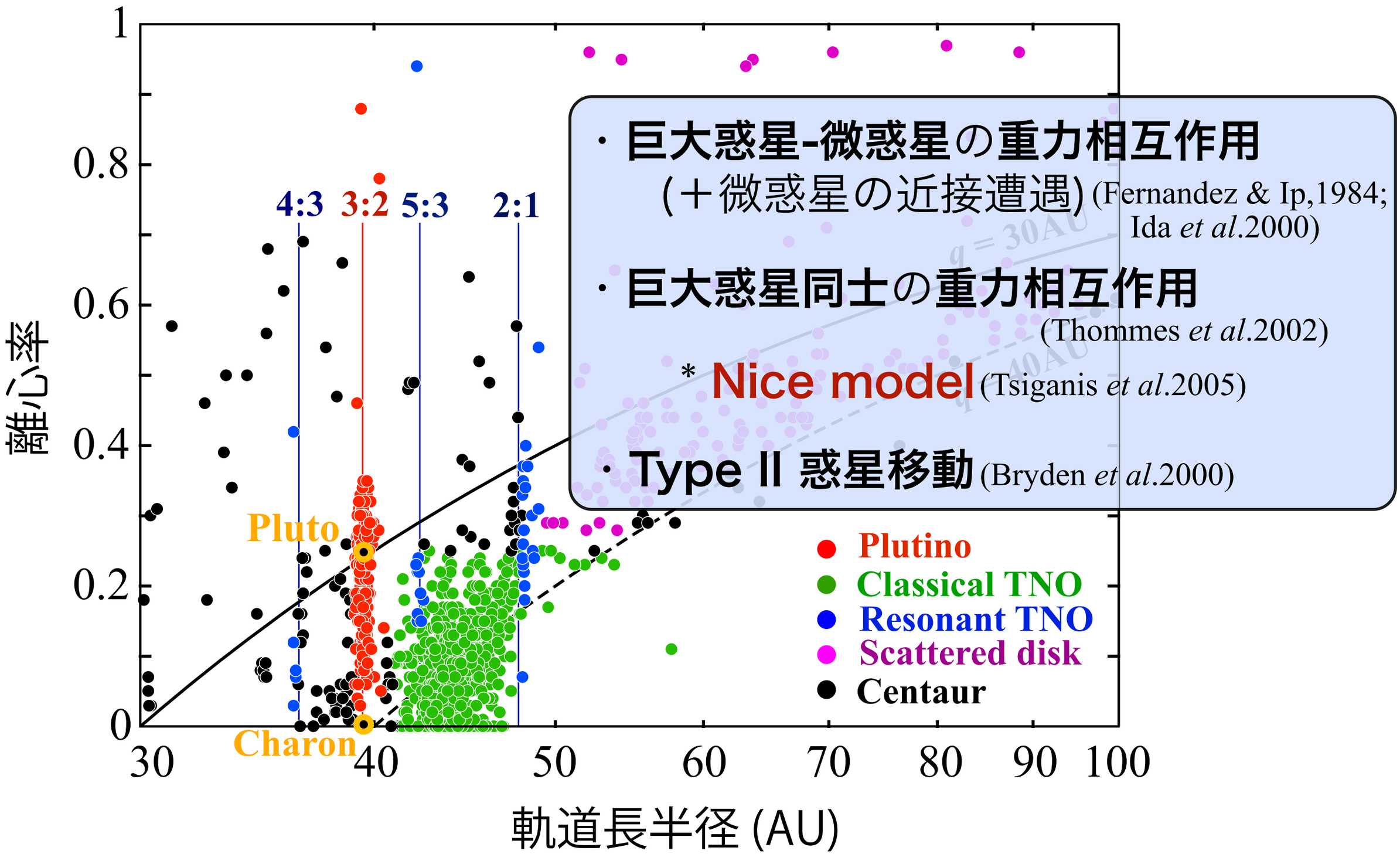
→ **diskのtruncation**

or **散乱された大きな微惑星**

(Petit *et al*.1999; Levison *et al*.2008)

Neptune形成に対する示唆：外側移動

【TNOsの軌道要素＋Pluto-Charon系】--- **Neptuneの外側移動**



巨大惑星の解剖学：
内部構造・熱進化から起源へ (第3部)

堀　安範

国立天文台　理論研究部



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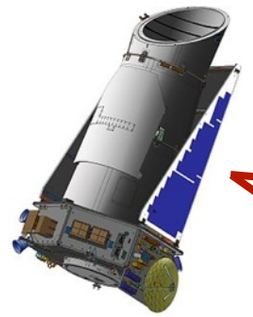
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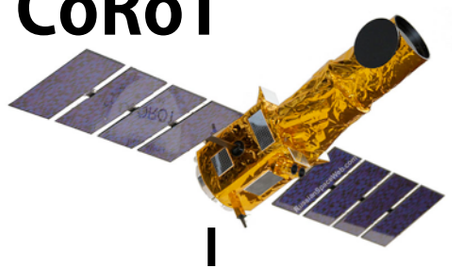
過去18年で発見された太陽系外惑星

~**3,540**個 (2013年3月現在)



Kepler

CoRoT



最初の super-Earth

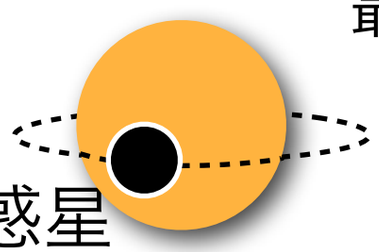
Gl 876d

51Peg. b



惑星

HD209458b



個数

4000
3500
3000
2500
2000
1500
1000
500
0

1 7 7 14 25 44 56 85 112 143 176 204 265 327 409 523

2326 674
2326 727
2800 737

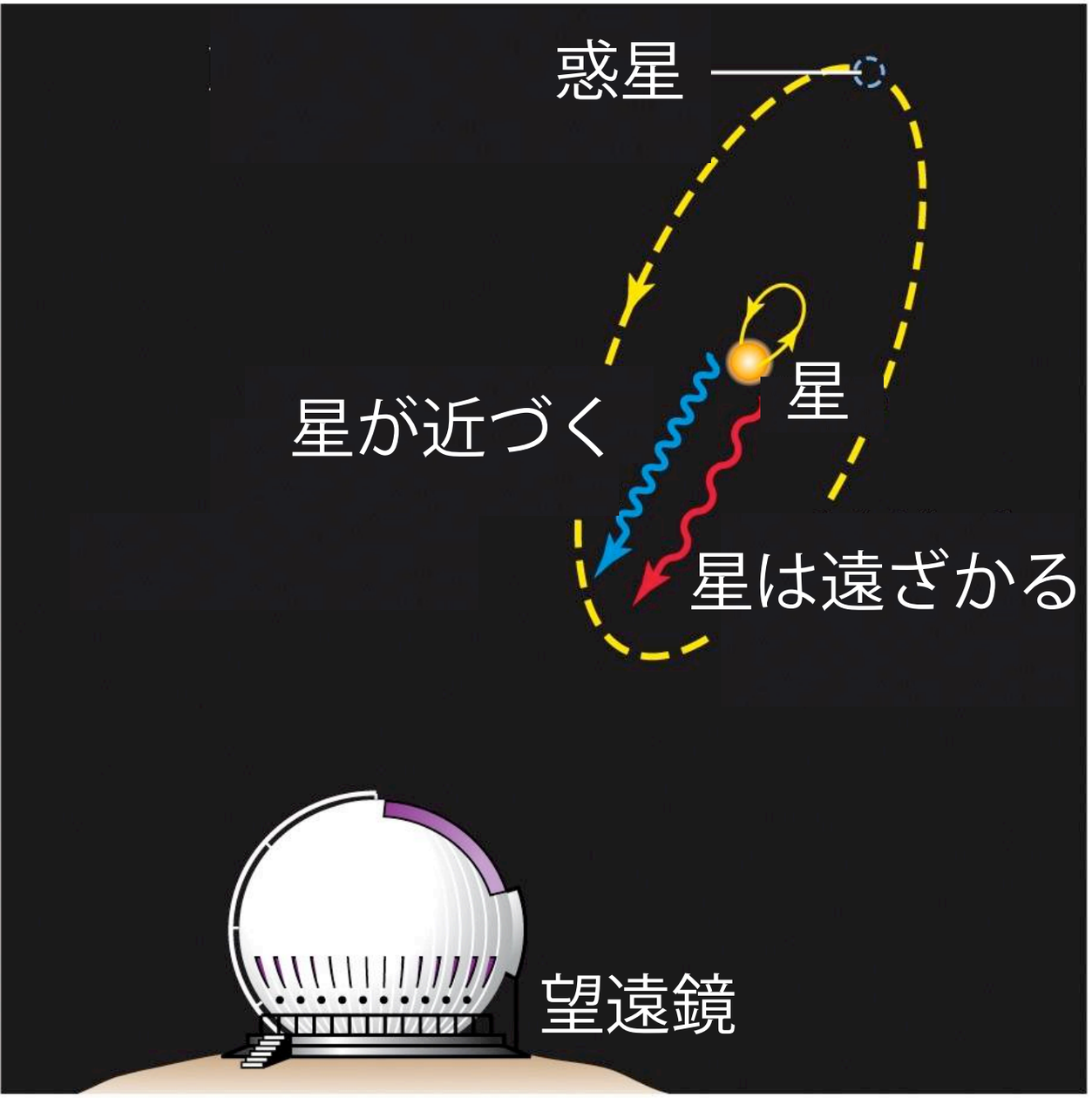
1995 1996 1998 2000 2002 2004 2006 2008 2011 2012 2013

時系列

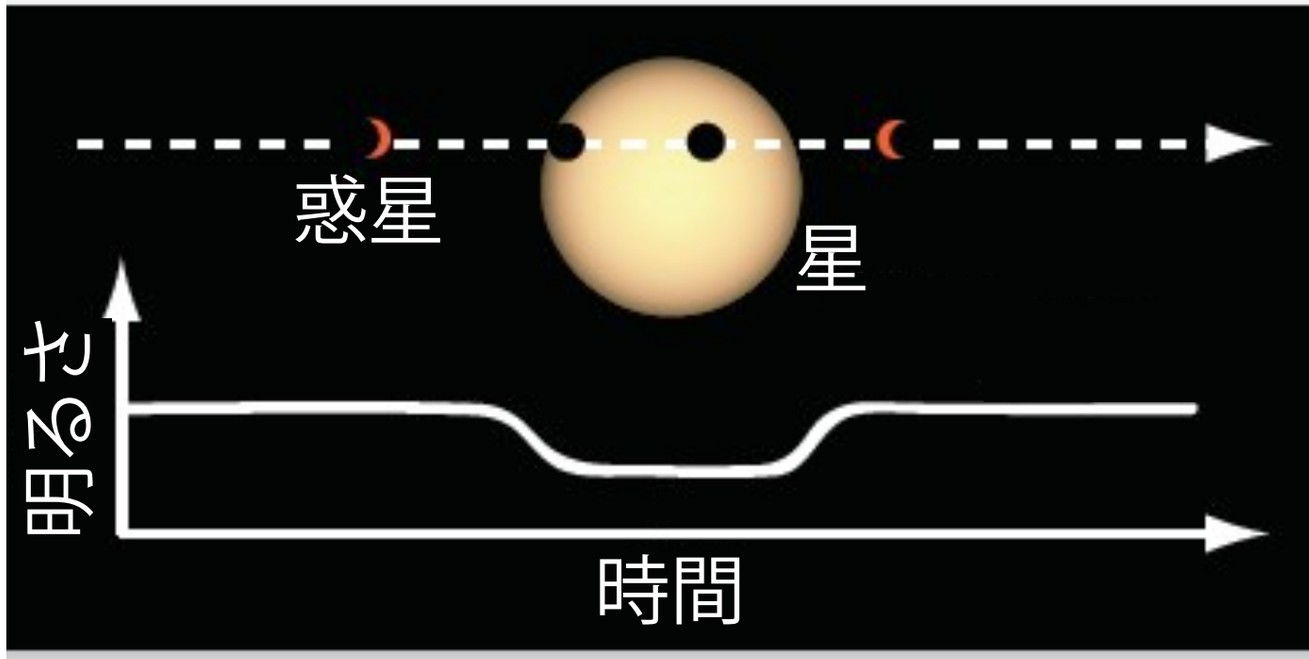
© ESA(CoRoT), NASA(Kepler)

太陽系外惑星を探す

■ 視線速度法 (Doppler 法)



■ Transit 法

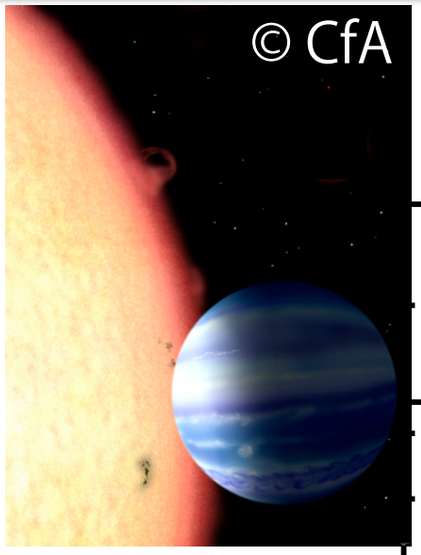




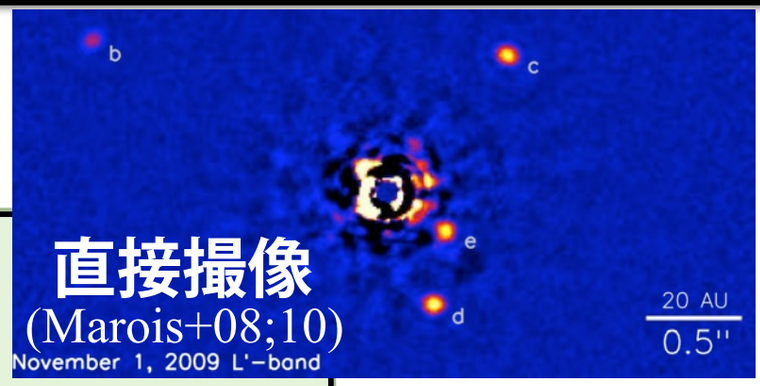


c

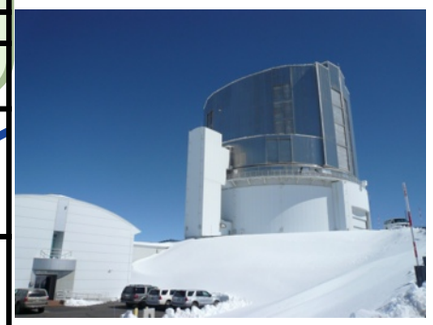
太陽系外惑星の軌道分布



hot Jupiter



直接撮像
(Marois+08;10)
November 1, 2009 L'-band



惑星質量 ($M_\oplus$)

100

10

1

木星

土星

海王星

天王星

金星

地球

視線速度 1m/s

視線速度 10cm/s

周期15年

α Centauri Bb

0.01

0.1

1

10

100

1000

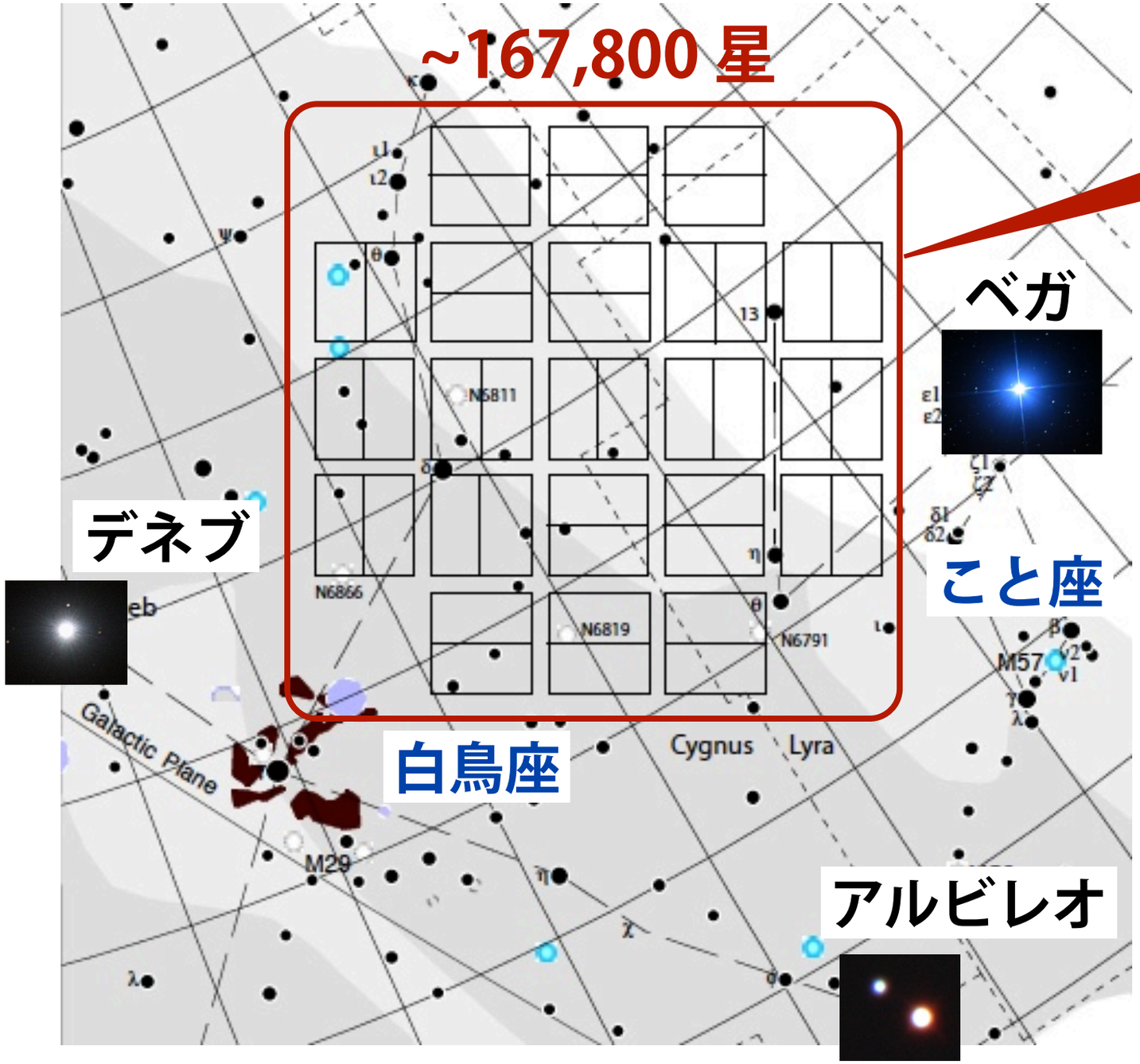
軌道長半径 (AU)

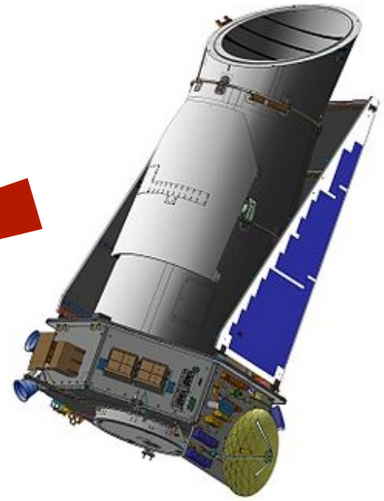


Super-Earth

Kepler宇宙望遠鏡

Kepler宇宙望遠鏡 --- NASA は2009年5月6日に打ち上げ





- 太陽周回軌道 (地球を追尾)
- 視野

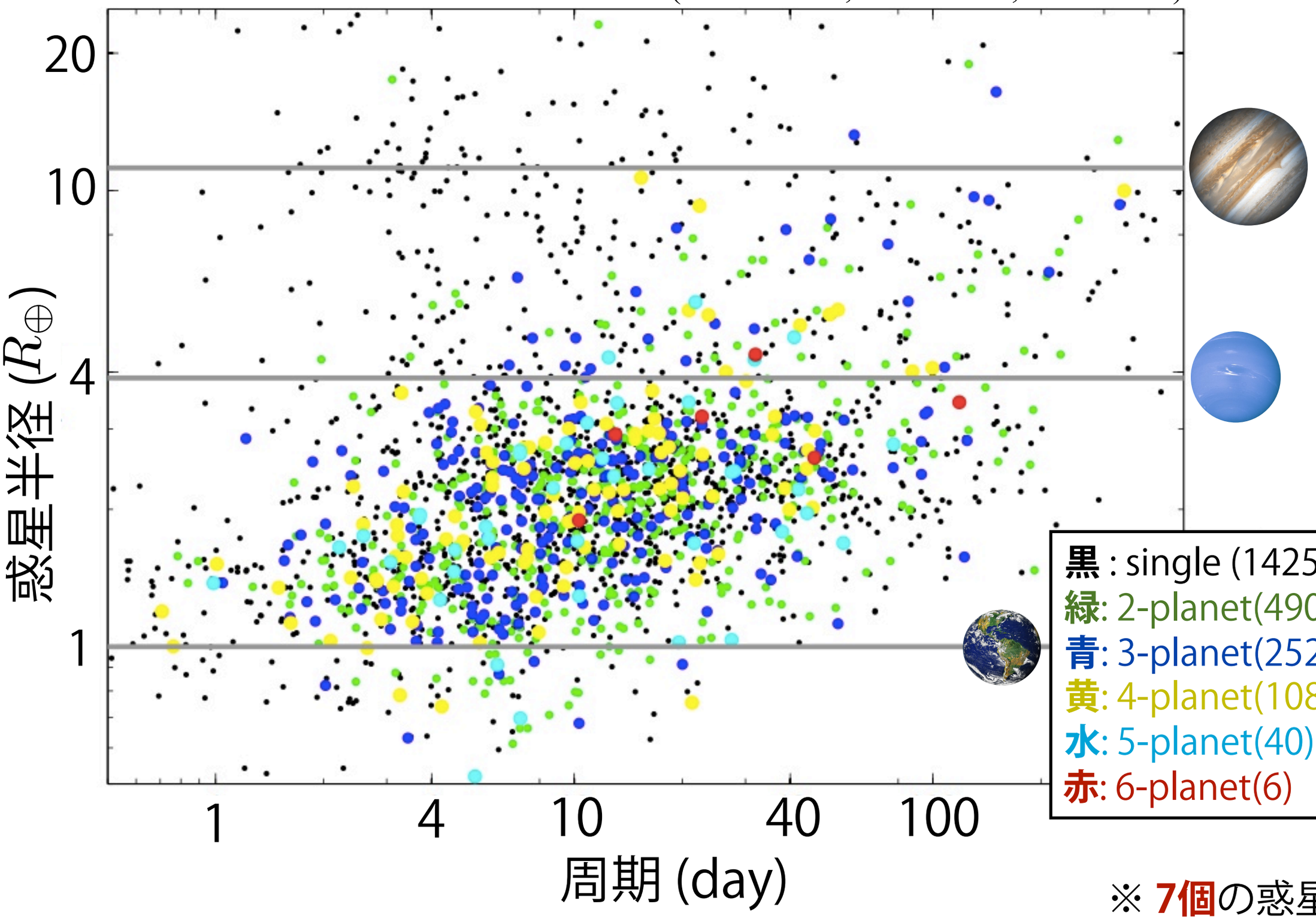
(i) **太陽** を避ける
　黄道面から > 55°
　＋太陽から十分遠い
(→ 小惑星の食を排除するため)

(ii) **恒星の数**
　銀河面を避けつつ、銀河の腕

Kepler惑星候補天体と系の惑星数

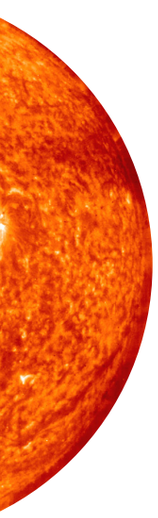
Kepler惑星候補天体2321個 (※ 2013年現在、2800個)

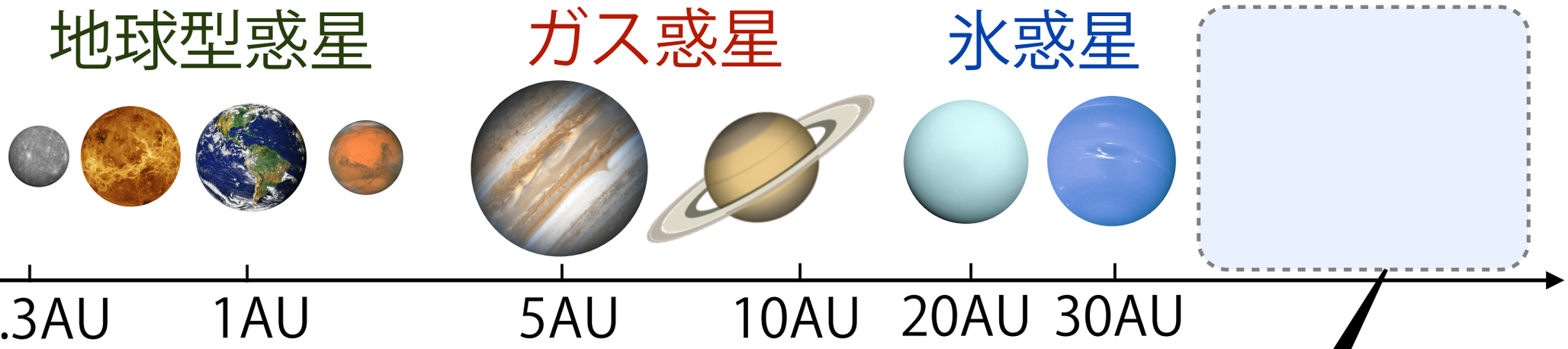
(Lissauer+11;Borucki+11;Batalha+12)



※ **7個**の惑星系も発見

太陽系と太陽系外の惑星系







super-Earth
(巨大な地球型惑星)



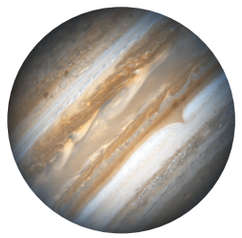
hot Neptune
(灼熱氷惑星)



hot Jupiter
(灼熱ガス惑星)

~0.1AU以内

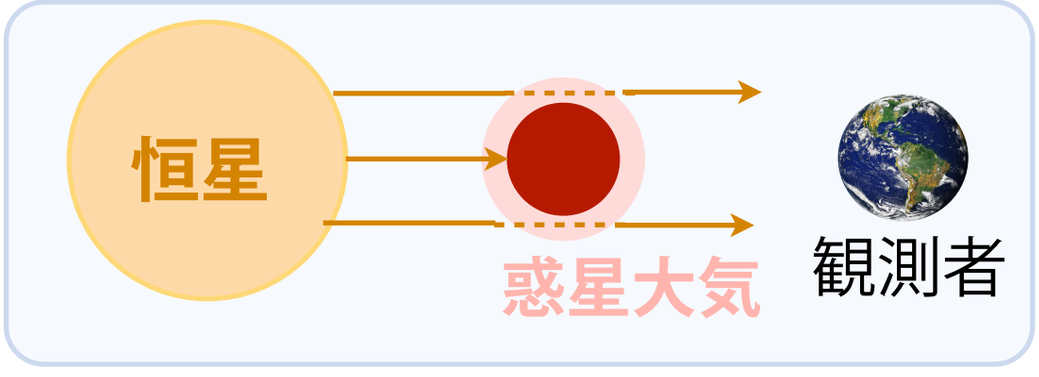
遠方ガス惑星



数10~数100AU

惑星大気・表層を知る3つの光

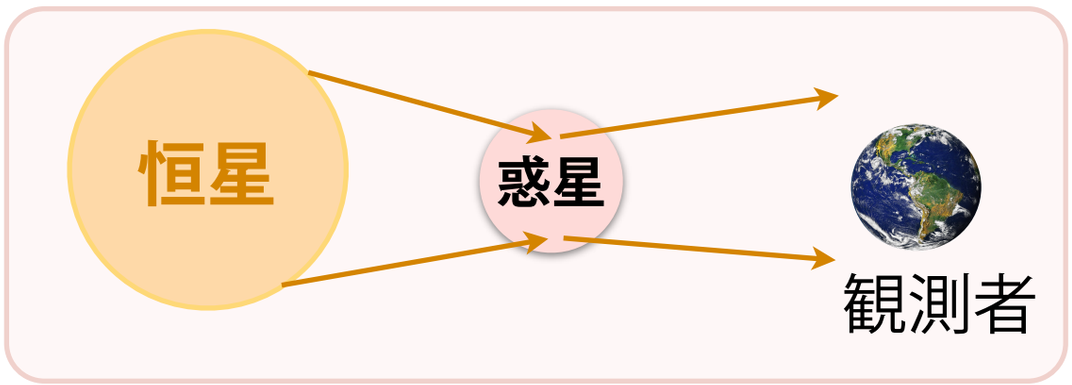
(1) 惑星大気の**透過光**



Fluxの強度(比) @波長 λ

$$\frac{F_{\rm p}}{F_\star} \approx \frac{2R_{\rm p}H}{R_\star^2} \sim 3\times10^{-7}\left(\frac{R_{\rm p}}{R_\oplus}\right)\left(\frac{R_\star}{R_\odot}\right)^{-2}\left(\frac{H}{10{\rm km}}\right)$$

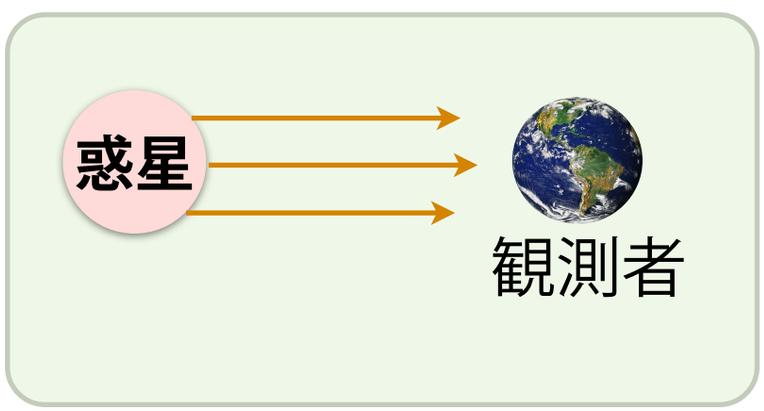
(2) 惑星の**反射光**



Fluxの強度(比) @波長 λ

$$\frac{F_{\rm p}}{F_\star} = A_\lambda\left(\frac{R_{\rm p}}{a_{\rm p}}\right)^2 \sim 10^{-17}\left(\frac{A_\lambda}{0.4}\right)\left(\frac{R_{\rm p}}{R_\oplus}\right)^2\left(\frac{a_{\rm p}}{1{\rm AU}}\right)^{-2}$$

(3) 惑星自身の**熱放射**



Fluxの強度(比) @波長 λ

$$\frac{F_{\rm p}}{F_\star} \sim \frac{T_{\rm eq}^p}{T_{\rm eff}^\star}\left(\frac{R_{\rm p}}{R_\star}\right)^2 \sim 4\times10^{-6}\left(\frac{T_{\rm eq}^p}{300{\rm K}}\right)\left(\frac{T_{\rm eff}^\star}{6000{\rm K}}\right)^{-1}\left(\frac{R_{\rm p}}{R_\oplus}\right)^2\left(\frac{R_\star}{R_\odot}\right)^{-2}$$

Transit観測から見る惑星の姿

恒星

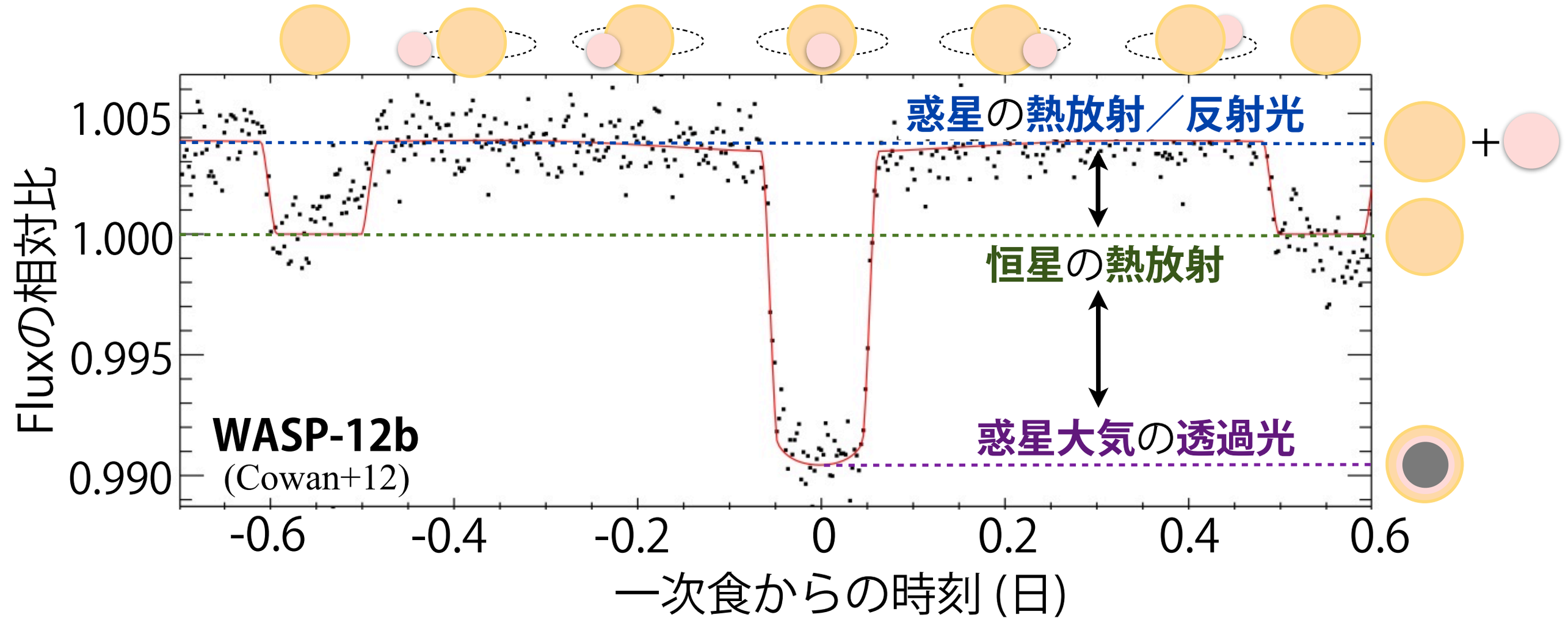
惑星

二次食
(secondary eclipse)

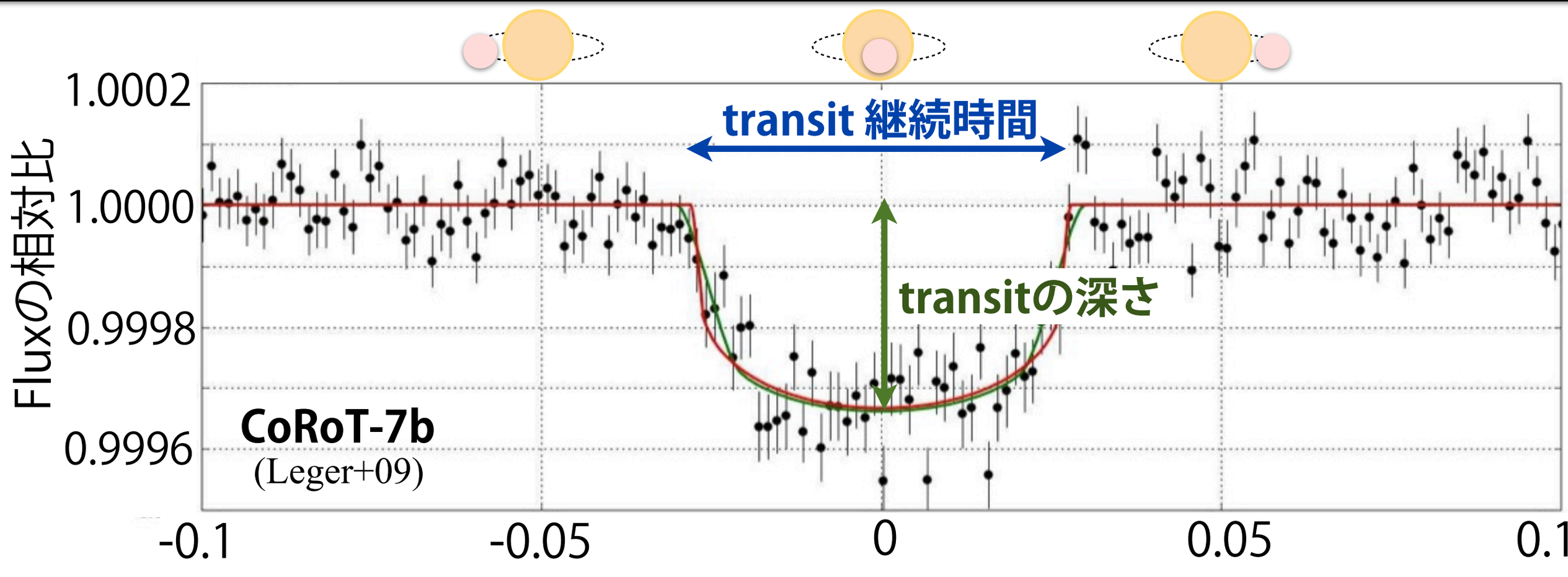
惑星大気の**温度構造**
惑星大気の**反射率**・熱輸送効率
惑星の**離心率**

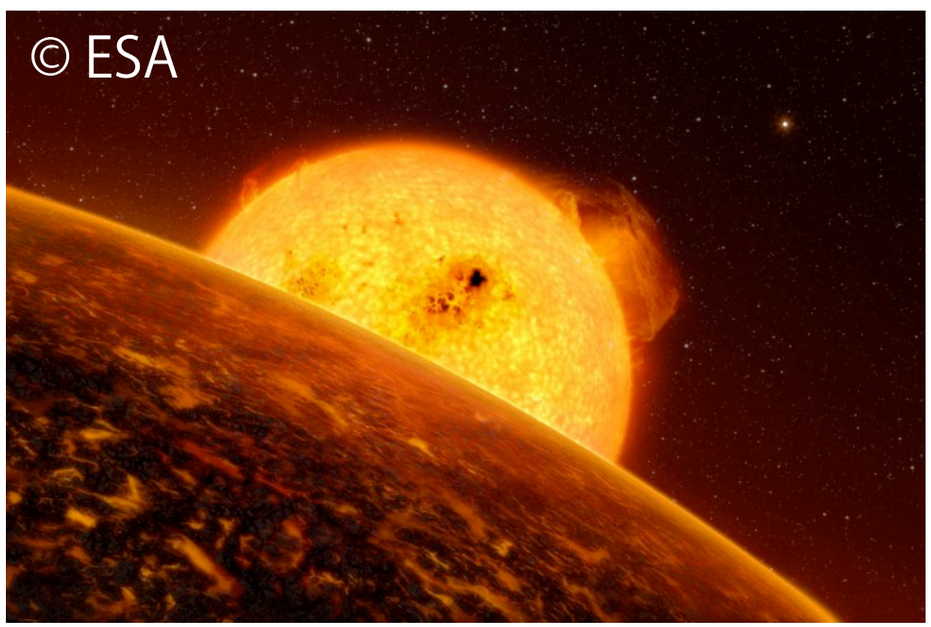
一次食
(primary eclipse)

惑星半径 (公転周期)
惑星の**大気組成**
惑星大気の**散逸**



Transit観測が出来る／出来ない惑星

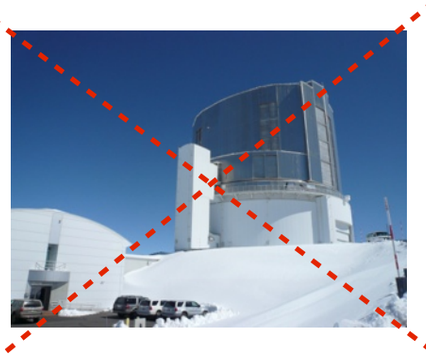




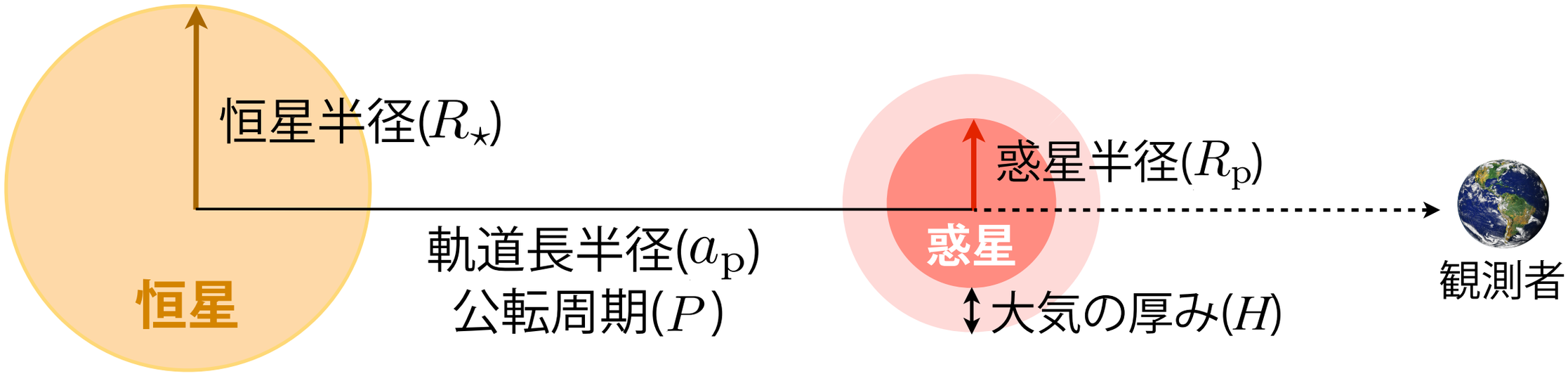
■ CoRoT-7b

周期 ~ 20hr (0.0172AU)
半径 ~ **1.68**倍の地球半径
質量 ~ **4.8**倍の地球質量

(恒星) K型星 : $0.87R_{\odot}$
V等級 = 11.7 (150pc)



Transit観測の3つの基本量



transit 確率 $\sim \dfrac{R_\star}{a_\mathrm{p}} \sim 5 \left(\dfrac{R_\star}{R_\odot}\right) \left(\dfrac{a_\mathrm{p}}{0.1\mathrm{AU}}\right)^{-1}$ (%)

---

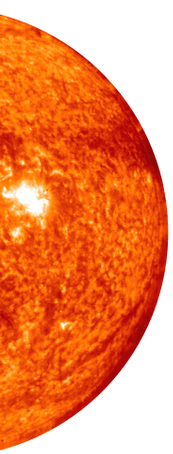
transitの深さ $\sim \left(\dfrac{R_\mathrm{p}}{R_\star}\right)^2 \sim 0.01 \left(\dfrac{R_\mathrm{p}}{R_\oplus}\right)^2 \left(\dfrac{R_\star}{R_\odot}\right)^{-2}$ (%)

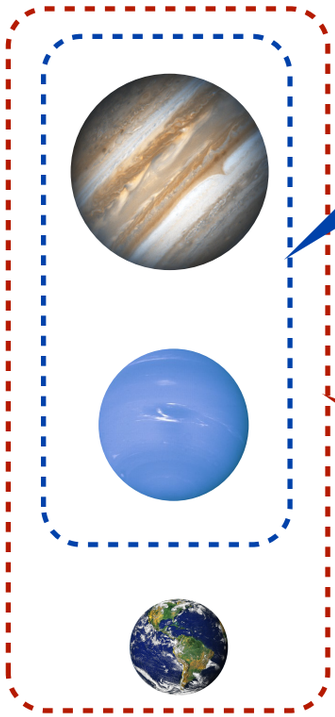
---

transitの継続時間 $\sim \dfrac{P}{\pi}\left(\dfrac{R_\star}{a_\mathrm{p}}\right) \sim 20 \left(\dfrac{R_\star}{R_\odot}\right) \left(\dfrac{a_\mathrm{p}}{0.1\mathrm{AU}}\right)^{-1} \left(\dfrac{P}{1\mathrm{day}}\right)$ (分)

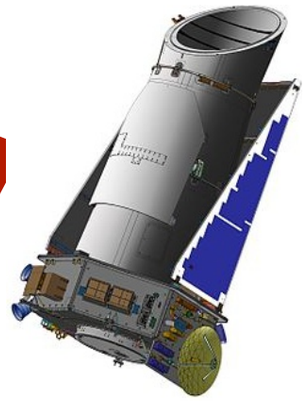
Transit観測の(現在の)精度

	小さな恒星	大きな惑星	恒星近傍
透過光の強度比	◎	◎	—
熱放射の強度比	◎	◎	◎
transitの**深さ**	◎	◎	—
transitの**継続時間**	×	—	×
transit **確率**	×	—	×









Subaru望遠鏡 (8.2m)

(深さ) 1mmag (~0.1%)

(継続時間) ~数10秒

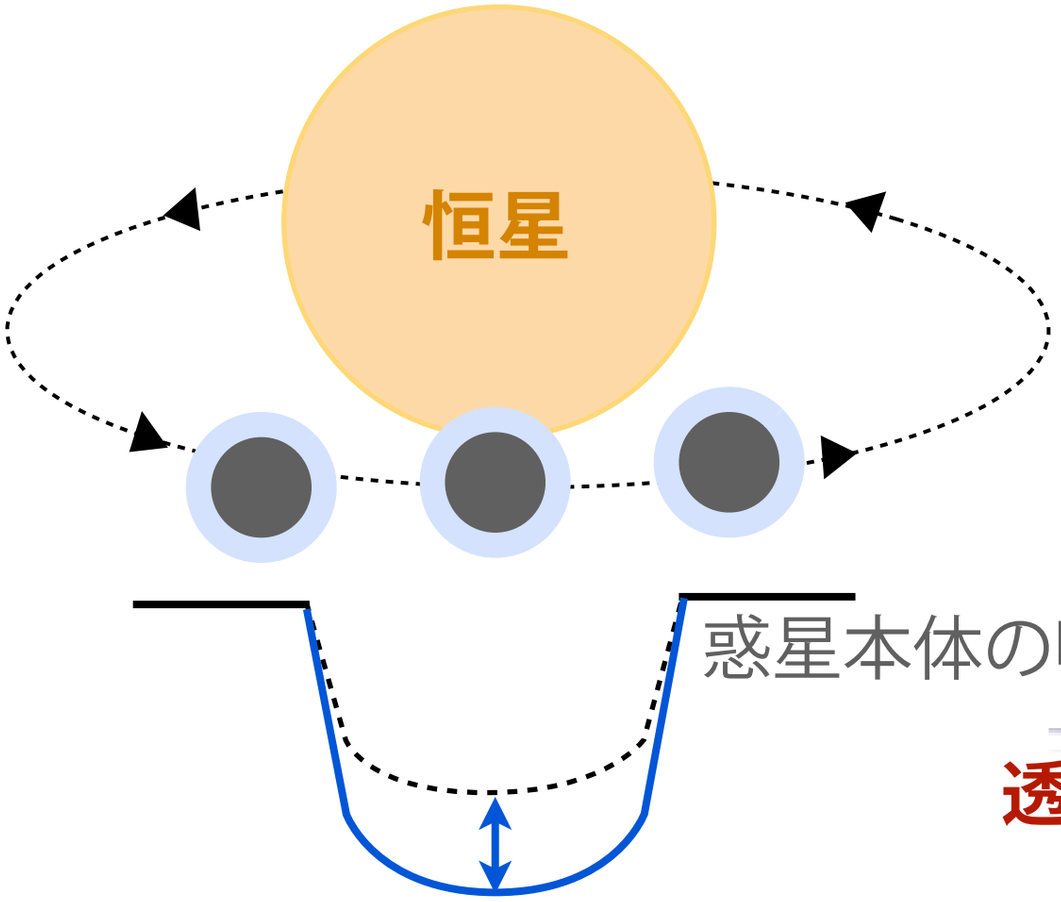
Kepler宇宙望遠鏡

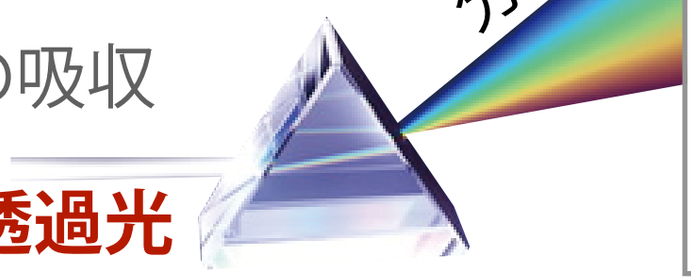
(深さ) 0.1mmag (~0.01%)

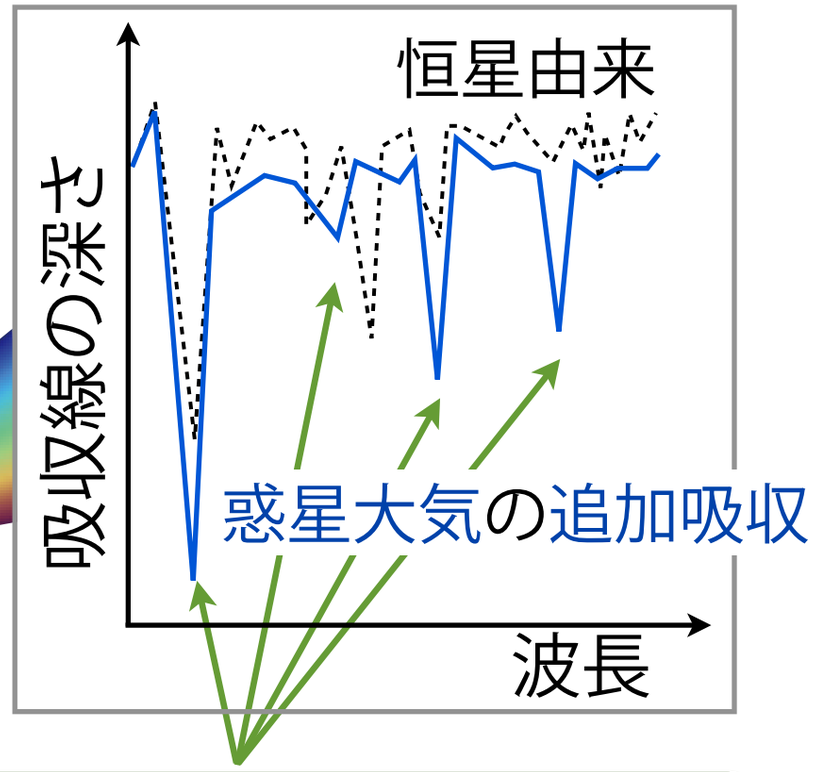
(継続時間) ~秒

※ 原理的には、地球@1AUも可能だが、
transit 確率(継続時間)的に×

Primary Eclipseから惑星大気の組成

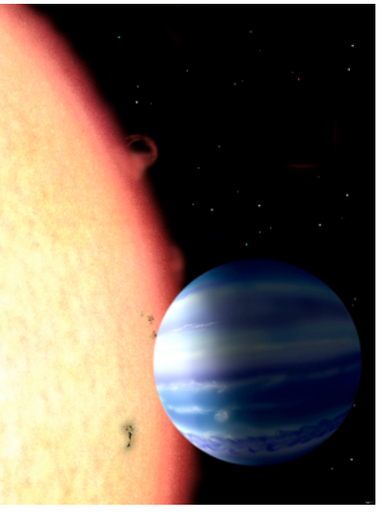






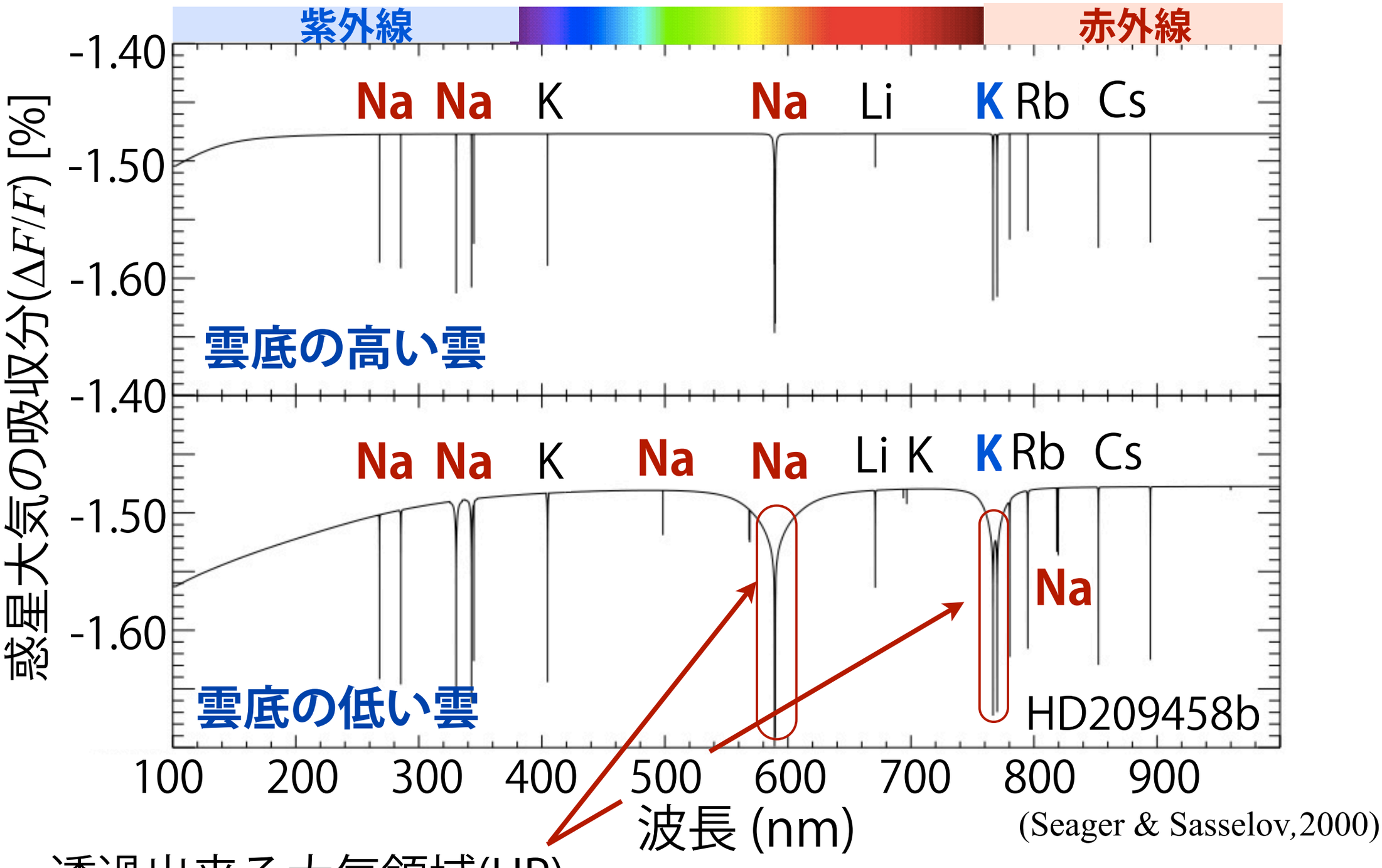
惑星大気中にある**原子・分子**の存在を検出

hot Jupiter大気中に**アルカリ金属**の検出 (Na D線 : 589, 589.6nm)



HD209458b	Na (HST/地上)	(e.g. Charbonneau+02;Snellen+08)
HD189733b	Na (地上)	(Redfield+08)
WASP-17b	Na (地上)	(Wood+11;Zhou+12)
WASP-12b	Na (HST)	(Fossati+10) ※ 他にMgII等(?)
XO-2b	Na, K (地上)	(Sing+11;12)

Hot Jupiter 大気中のアルカリ金属と雲の存在



(1) より**深い吸収線**
(2) 高密度領域でのRayleigh散乱 → **圧力broadening**

木星からHot Jupiterの大気上層

縞模様
(**白色**) 雲
(**有色**)リン化合物
硫黄分子etc.

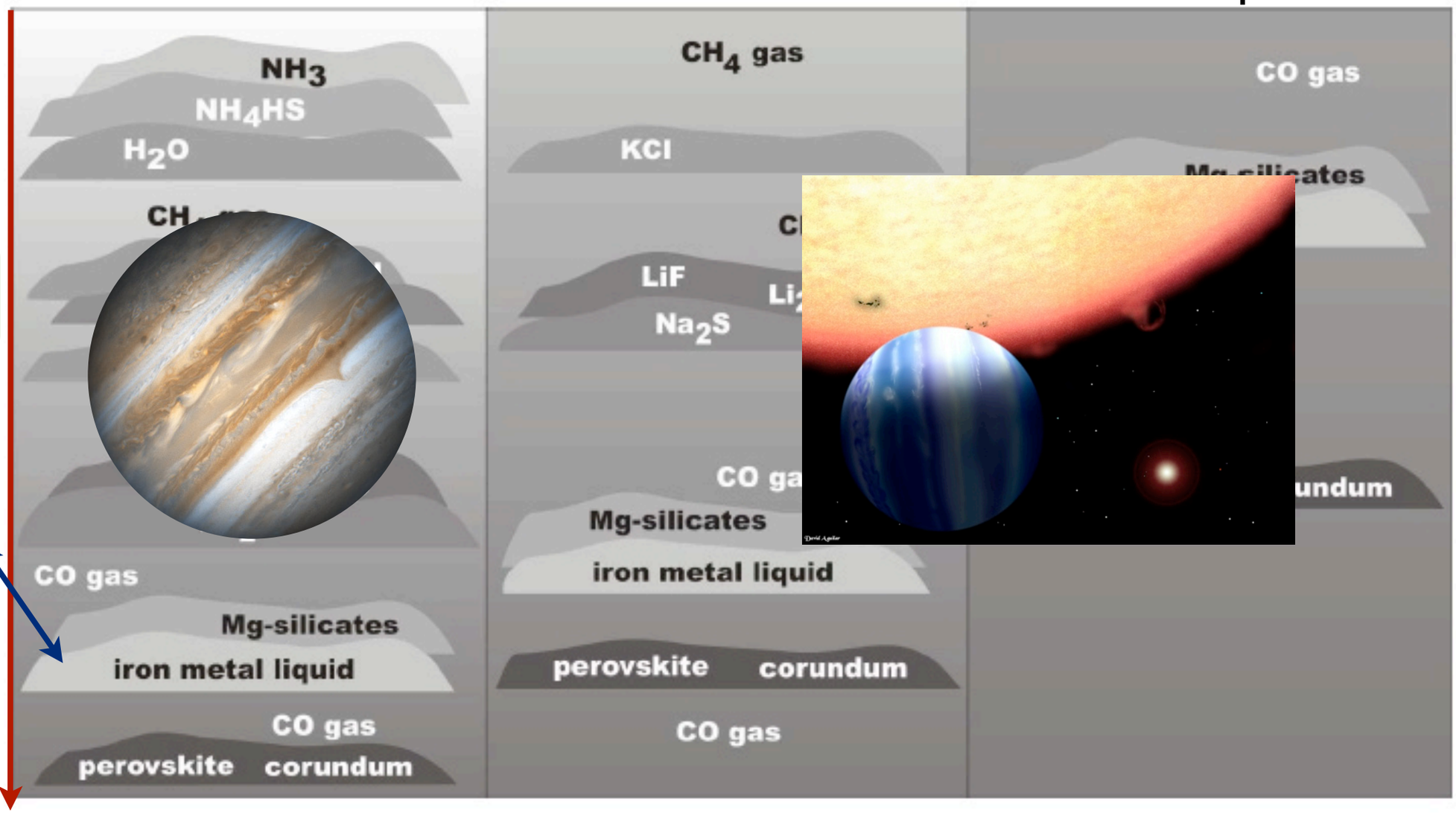
アルカリ金属
の凝縮 ~600K

H_2Sの検出

TiO, VO
の凝縮

~2000K

温度



(Lodders,2004;Marley,2008)

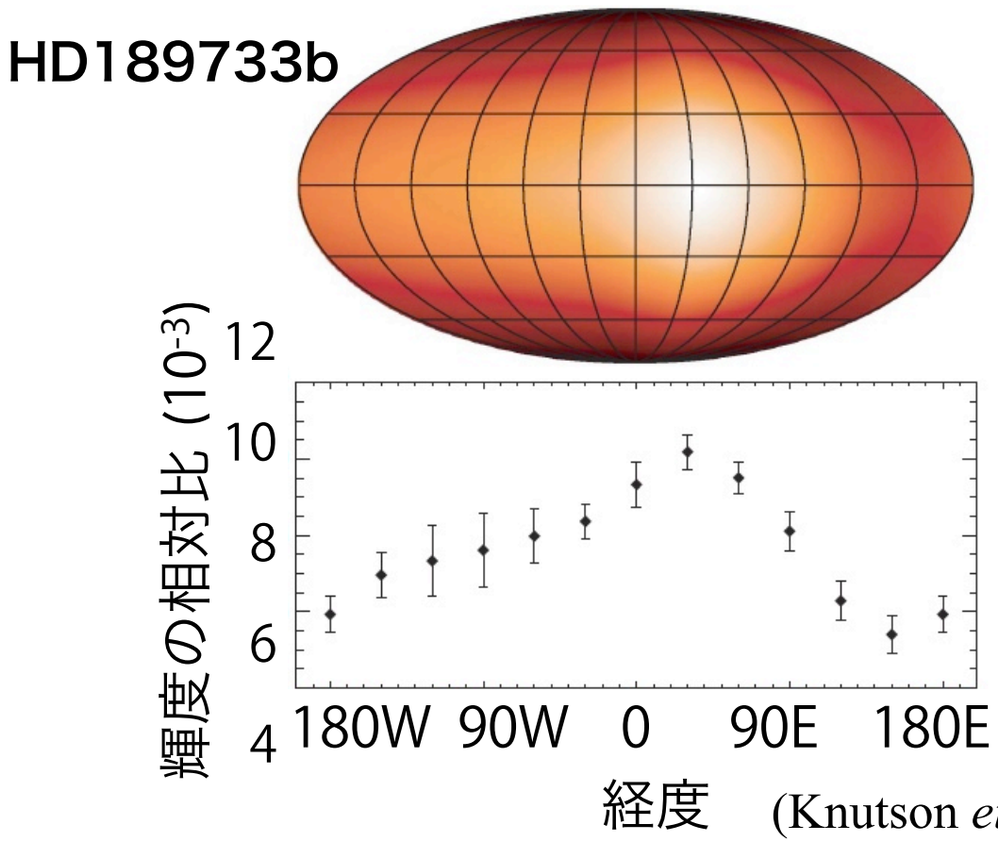
■ 中心星UV ---

(1) **haze(→雲)**生成 : (H_2S)→ S, 炭化水素 (e.g C_2H_2)
(2) **大気散逸**

Secondary EclipseからHot Jupiterの大気構造

多バンド測光観測(Spitzer : 3.6, 4.5, 5.8, 8.0μm 他)
→ 惑星からの熱放射

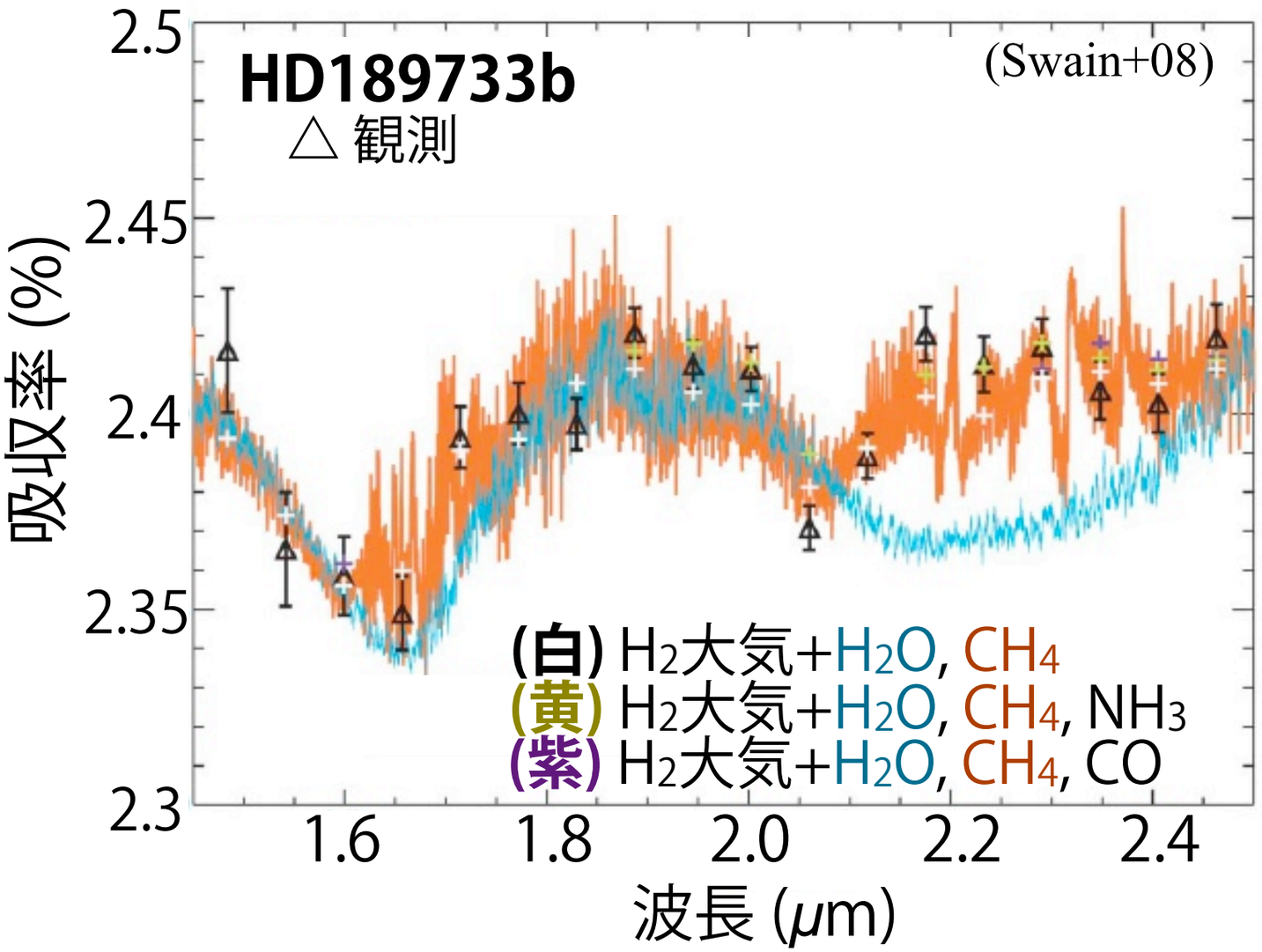
- **H_2Oなど分子種**の存在, 混合比率
- 温度の**逆転層**の有無 (温度分布)
- **平衡温度(~1000-2000K)**, **Bond アルベド**(< 0.3と低い?)
- 昼側→夜側への**熱の再分配**：非効率?(~10%, 30%, 60%?)
- 全球の温度マップ



(Knutson *et al*.2007)

(例) WASP-12b, WASP-33b, WASP-19b(?)
WASP-18b, HAT-P-1b, CoRoT-1b,2b
HAT-P-7b, HD189733b, WASP-4b,
TrES-2, TrES-3, WASP-3b, HAT-P-11b,
OGLE-TR-113b, KELT-1b, Kepler-17b
GJ436b, HD209458b

hot Jupiterの大気組成：揮発性成分, C/O比



■ 大気モデル

T-P分布：line-by-line 輻射輸送
化学組成：化学平衡 or 光化学反応)

※ 光化学なし(=化学平衡)

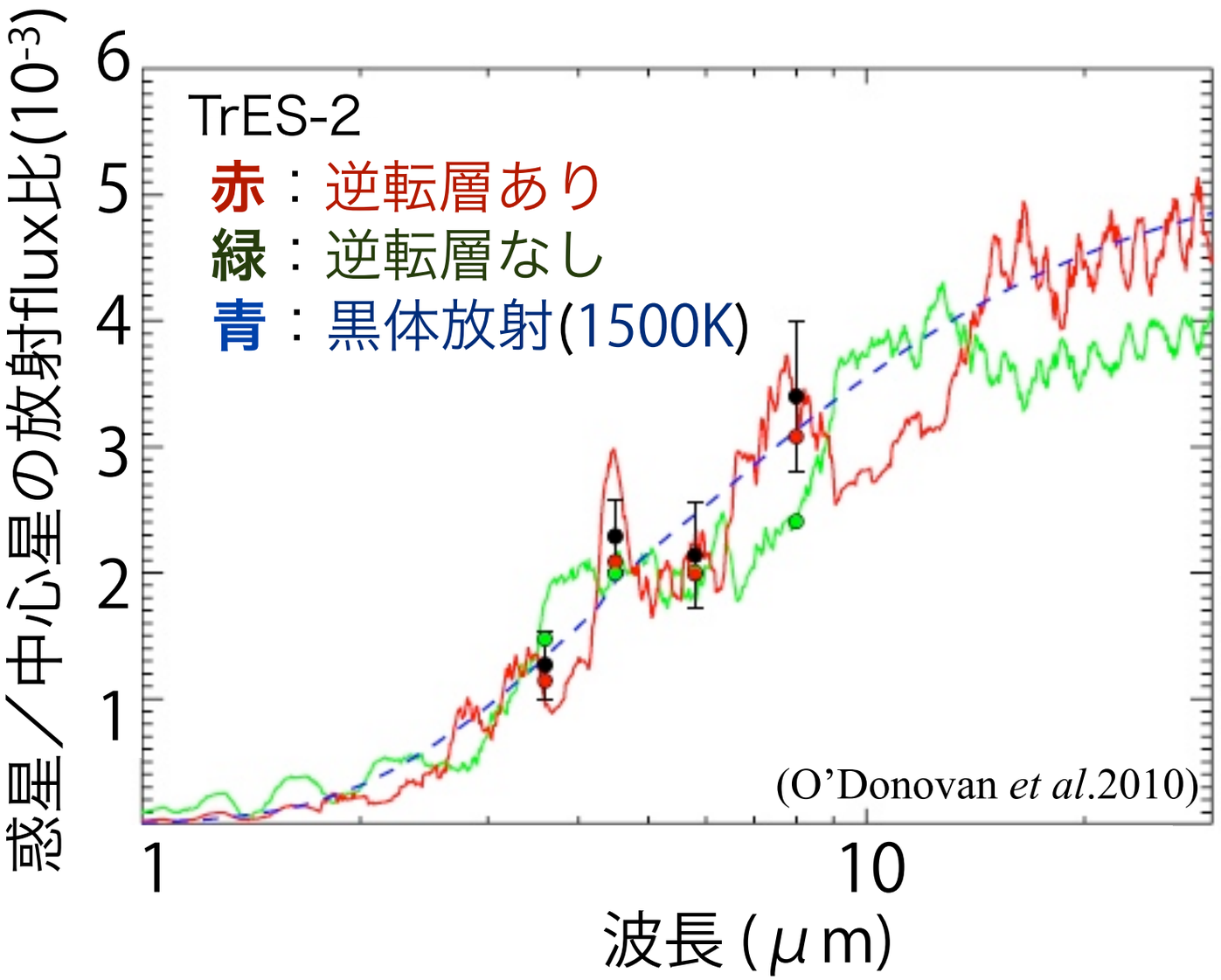
C/O比 < solar : **H_2O豊富**
C/O比 ~ solar : 熱平衡で**CH_4**, **CO**, **H_2O**
C/O比 > solar : **H_2O欠乏**
CO (>1200K), **CH_4** (<800K)

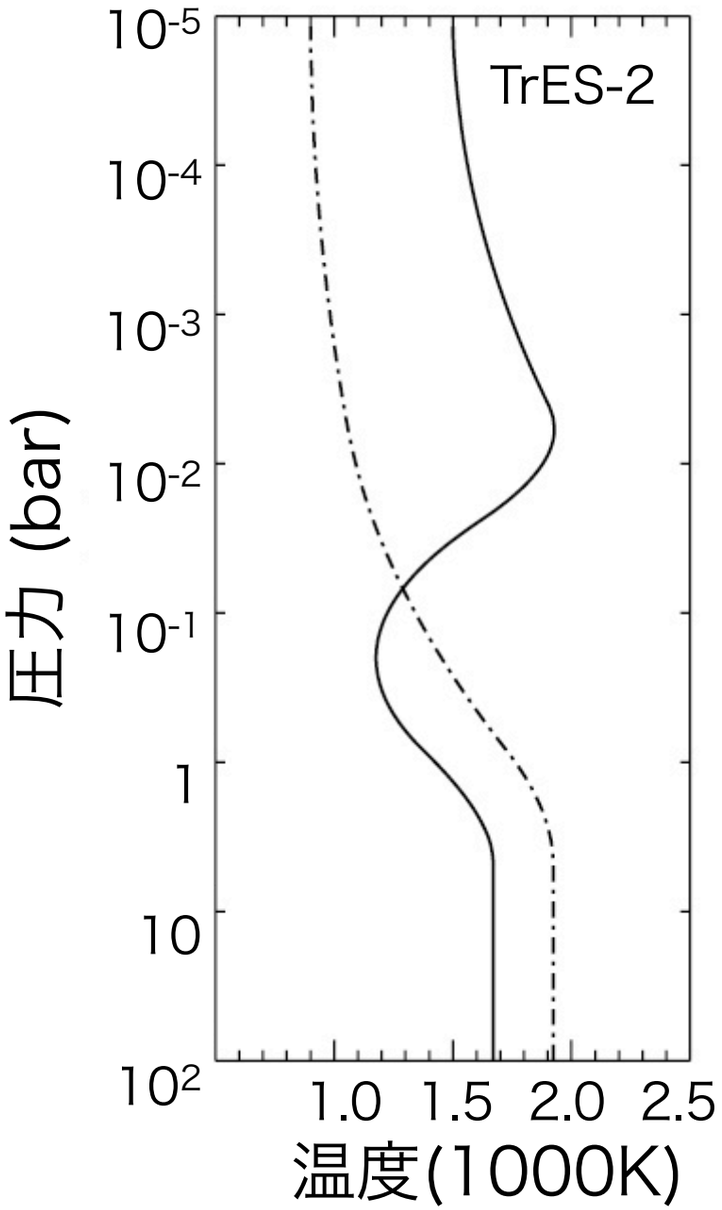
↓

太陽系以外の**C/O比**

(例) **HD209458b**	H_2O (Barman+07;Beaulieu+10) CH_4, CO, CO_2 (Swain+09;Madhusudhan & Seager,2009)
HD189733b	H_2O (Tinetti+07;Beaulieu+08;Swain+09) CH_4, CO, CO_2 (Swain+08;09)
51Peg.b	H_2O, CO (?) (Brogi+13)

hot Jupiter大気の温度構造：逆転層の有無





(○?) HD209458b (e.g. Knutson *et al*. 2008)
TrES-4 (Knutson *et al*. 2009), XO-1b (Machalek *et al*. 2008)
TrES-2 (O'Donovan *et al*. 2010), HAT-P-7b (Christensen *et al*. 2010)

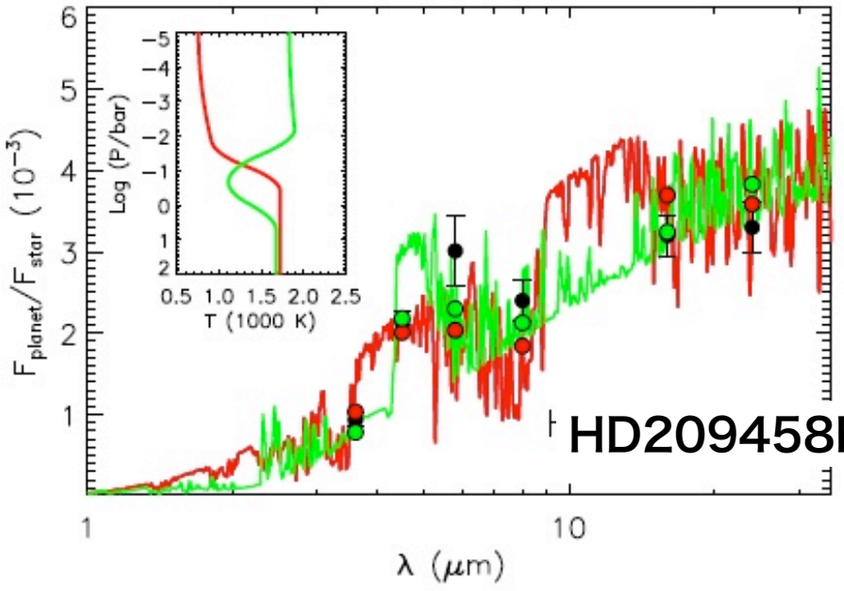
(×?) HD189733b (e.g. Barman, 2008)
TrES-1 (Charbonneau *et al*.2005)

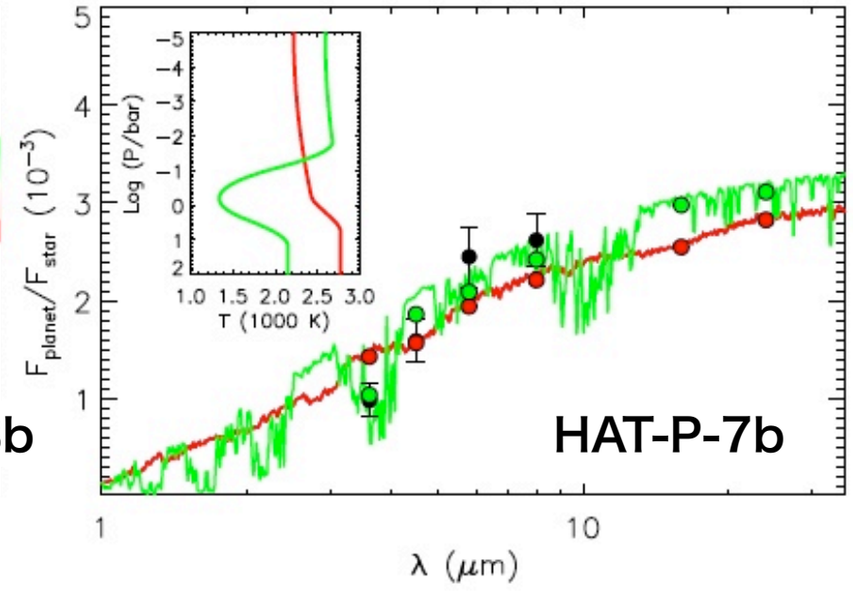
hot Jupiter大気の逆転層とUV

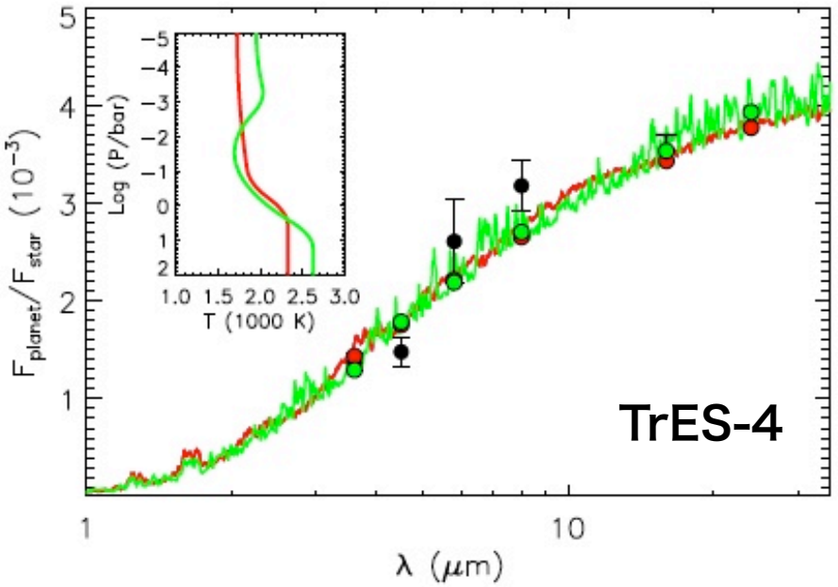
■ 逆転層：UV吸収源 (TiO, VOなど)の影響

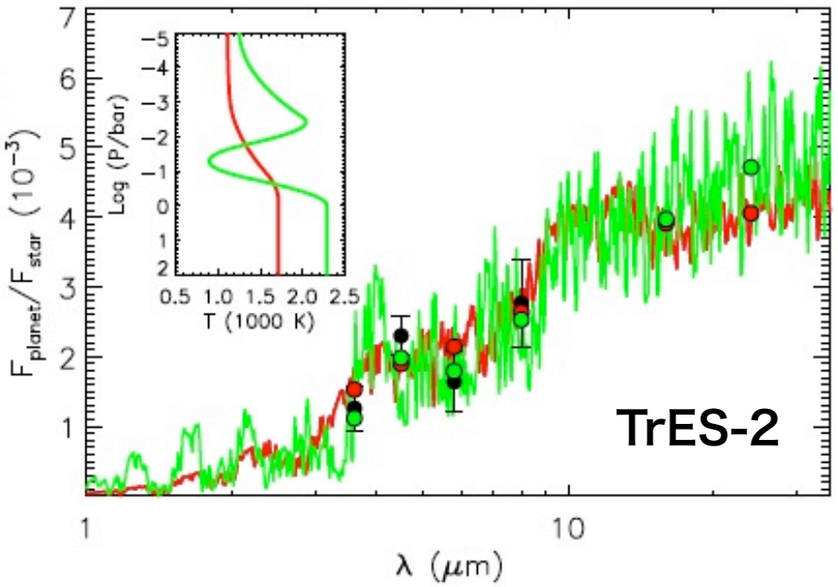
UV照射が強いHD189733b× ←→ UV照射の弱いXO-1b○
→ **UV吸収源の破壊**(UVが強過ぎる)　(Knutson *et al.*2010)

逆転層と大気組成の縮退 (Madhusudhan & Seager, 2010)









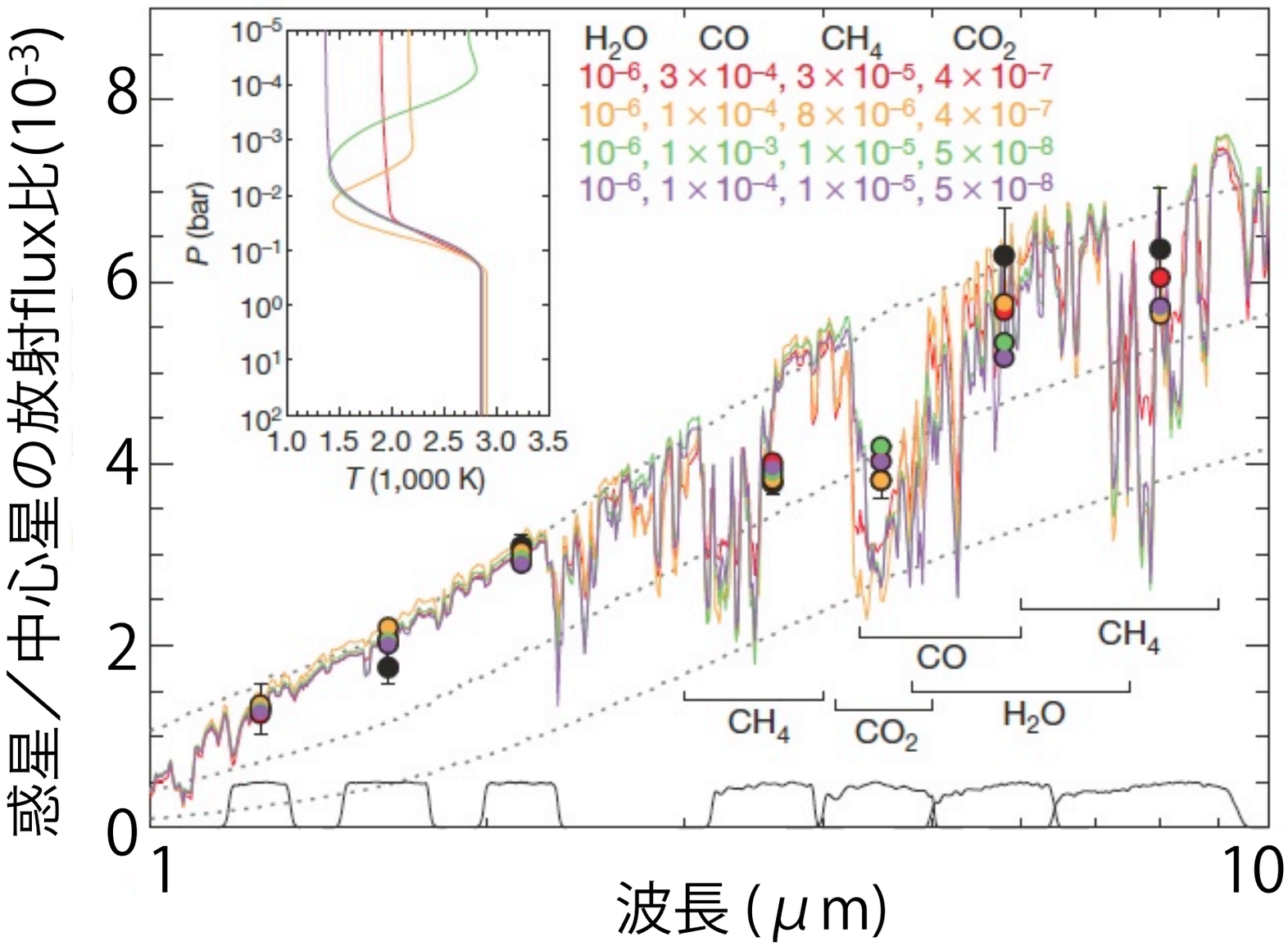
T-P分布, 組成
↑Monte Carlo計算

赤：逆転層なし
緑：逆転層あり
● Spitzer観測

TrES-2, TrES-4
↓
逆転層と組成の縮退

hot Jupiter大気の逆転層と大気組成の縮退

逆転層と大気組成の縮退 (Madhusudhan & Seager, 2010)



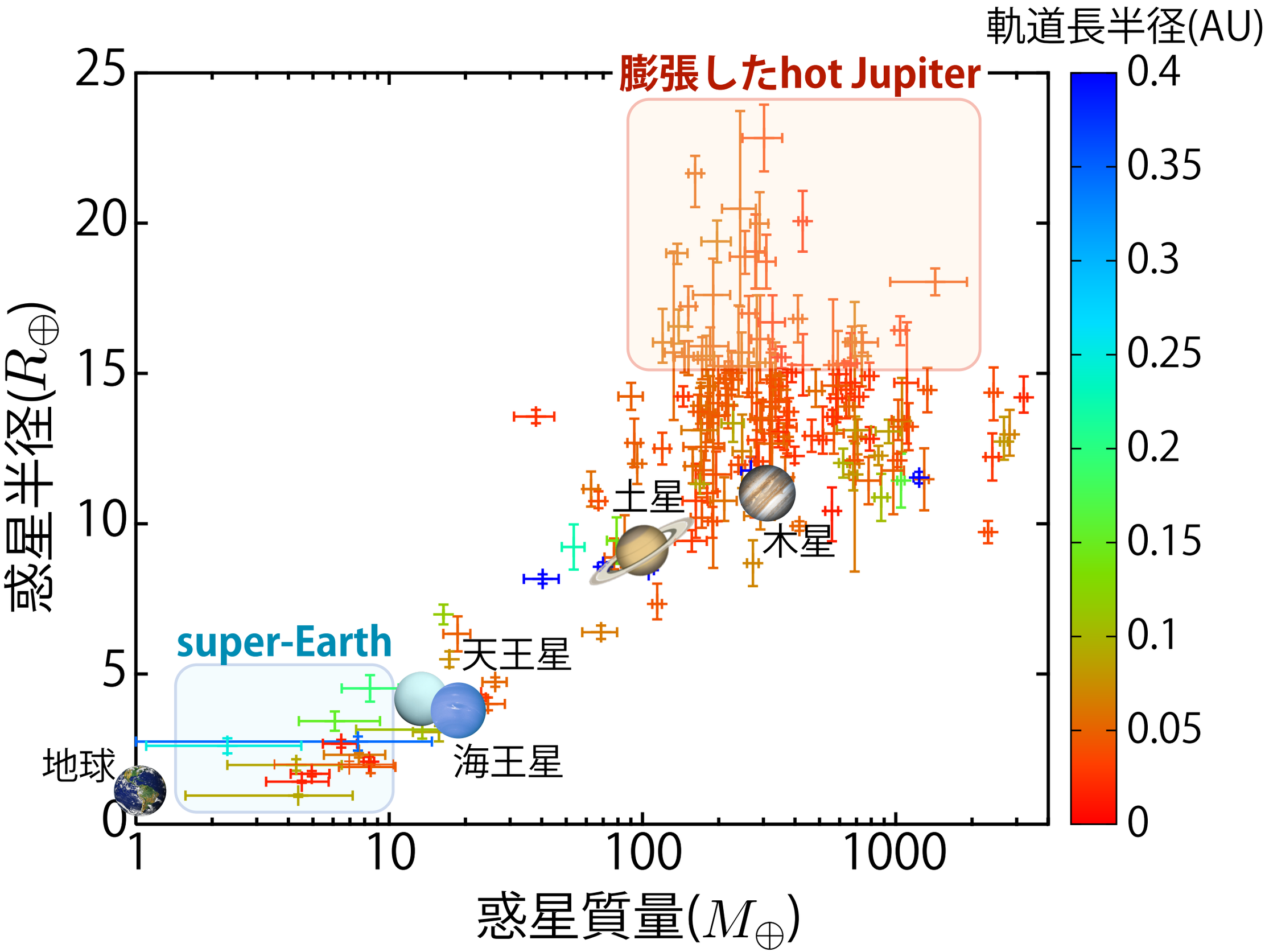
← WASP-12b
(Madhusudhan *et al*. 2011)

● Spitzer観測

高いC/O比

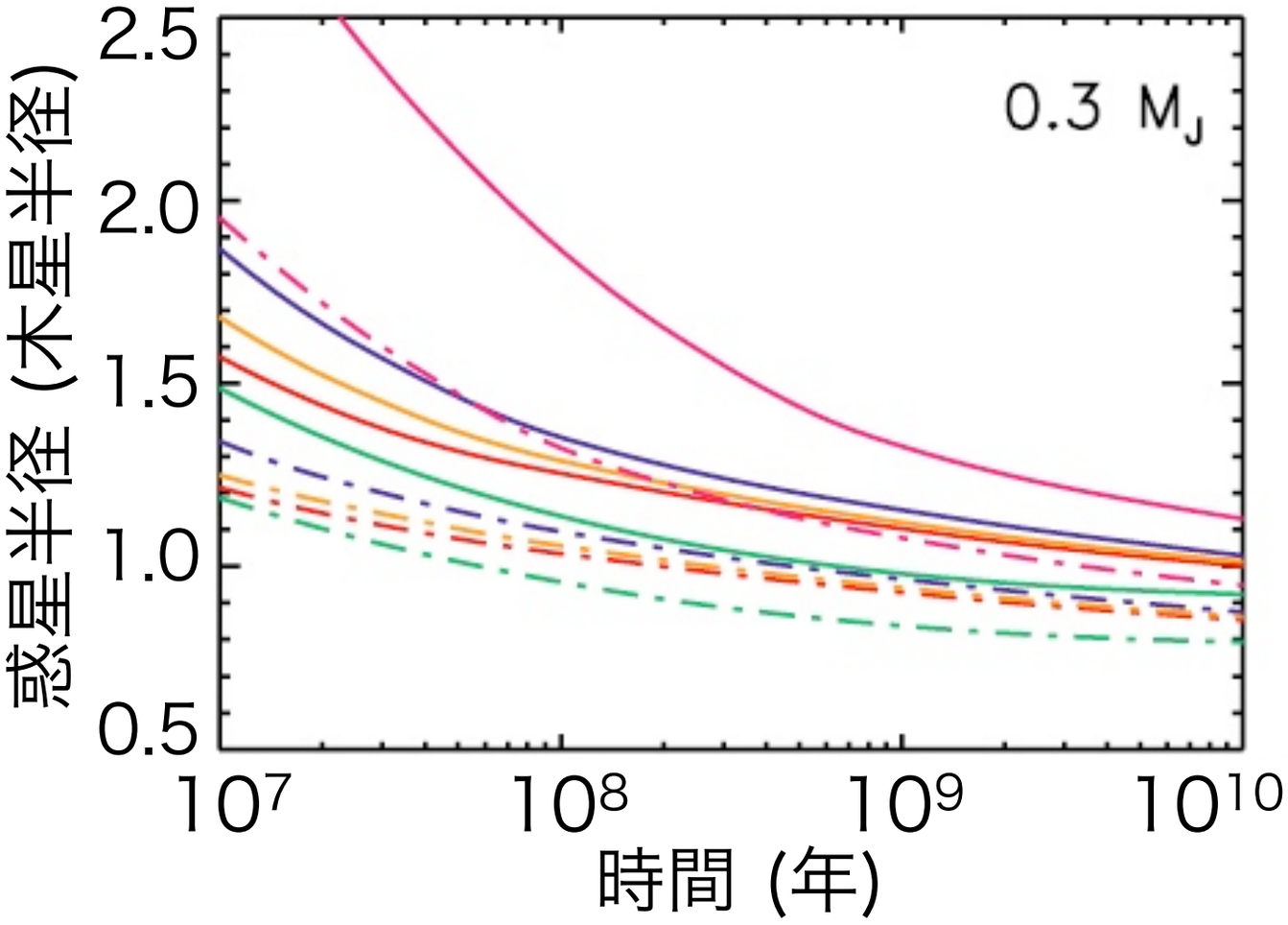
逆転層あり	●
	●
逆転層なし	●
	●

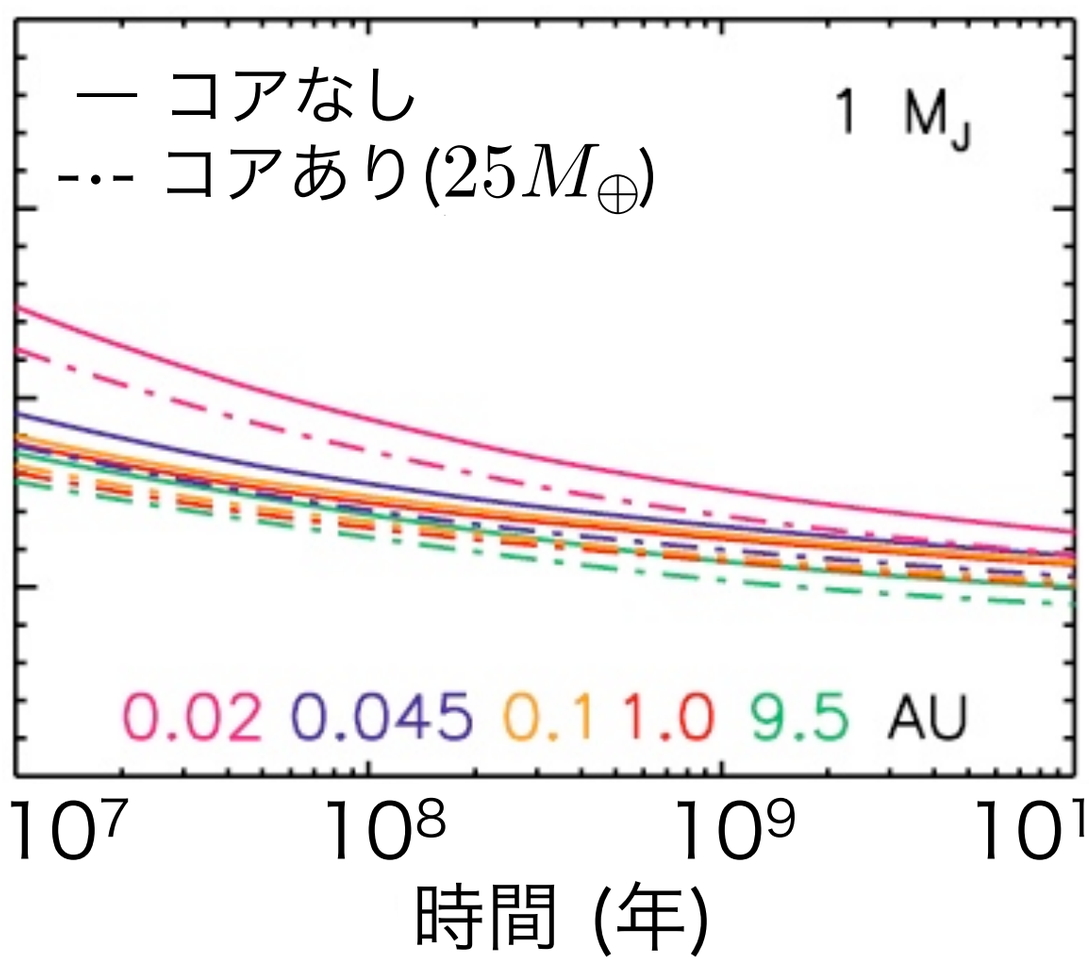
これまでに発見されたTransit惑星



hot Jupiterの熱進化

強烈な中心星輻射を経験するガス惑星 (e.g. Fortney *et al.* 2007)





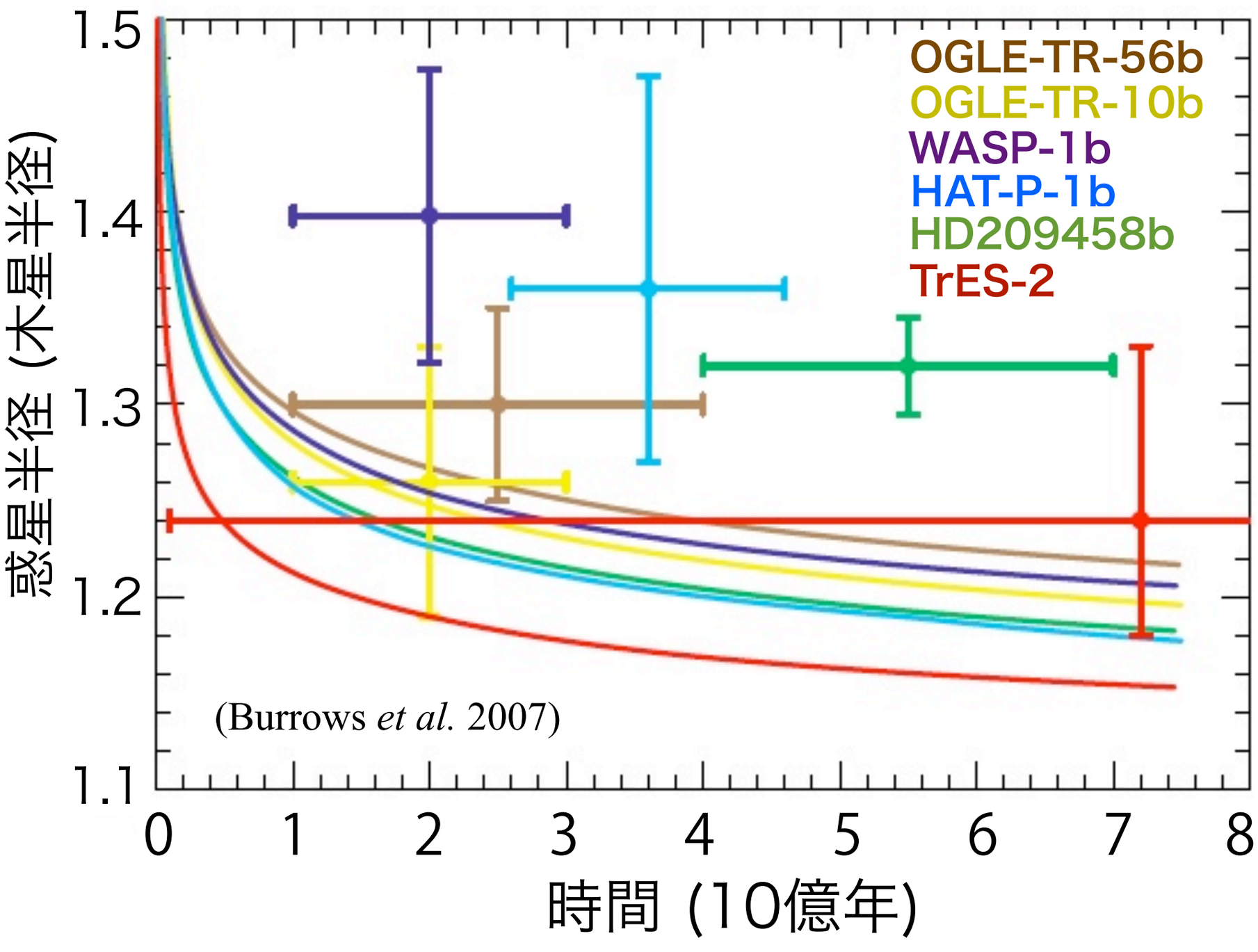
■ 中心星(Fluxや半径)の進化とカップルしたhot Jupiterの熱進化

CoRoT-8b (Borde *et al.* 2010)
CoRoT-13b (Cabrera *et al.* 2010)
CoRoT-2b (Guillot & Havel, 2011)

膨張半径を持つ hot Jupiter

標準的な**(熱)進化モデル** --- 初期は高温状態 → 冷却

「太陽組成ガス＋コアなし(+ extra 熱源なし)」



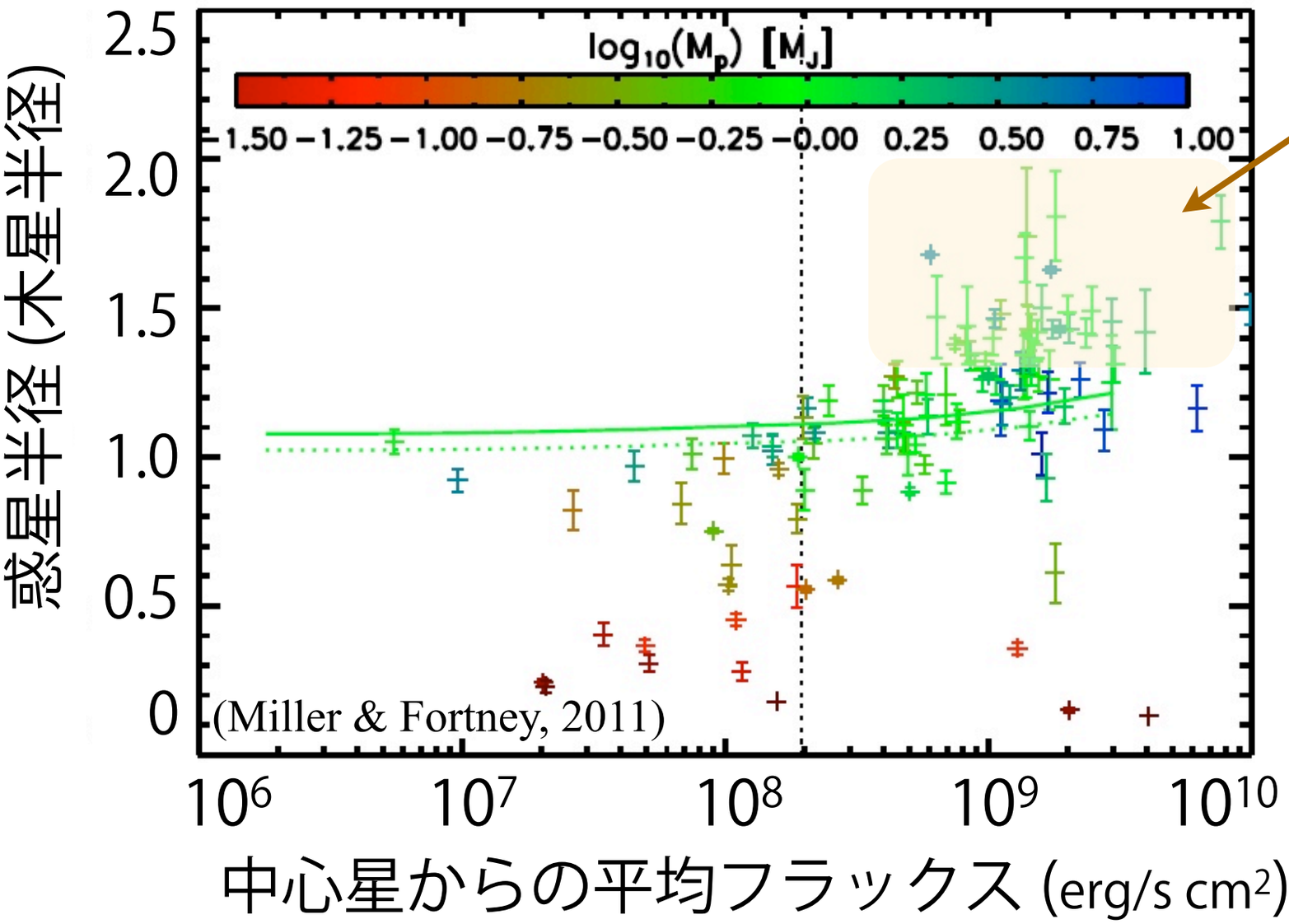
膨張した半径
を持つhot Jupiter

(> 1.2-1.3木星半径)

↓

異常半径問題

hot Jupiter の異常半径と熱源



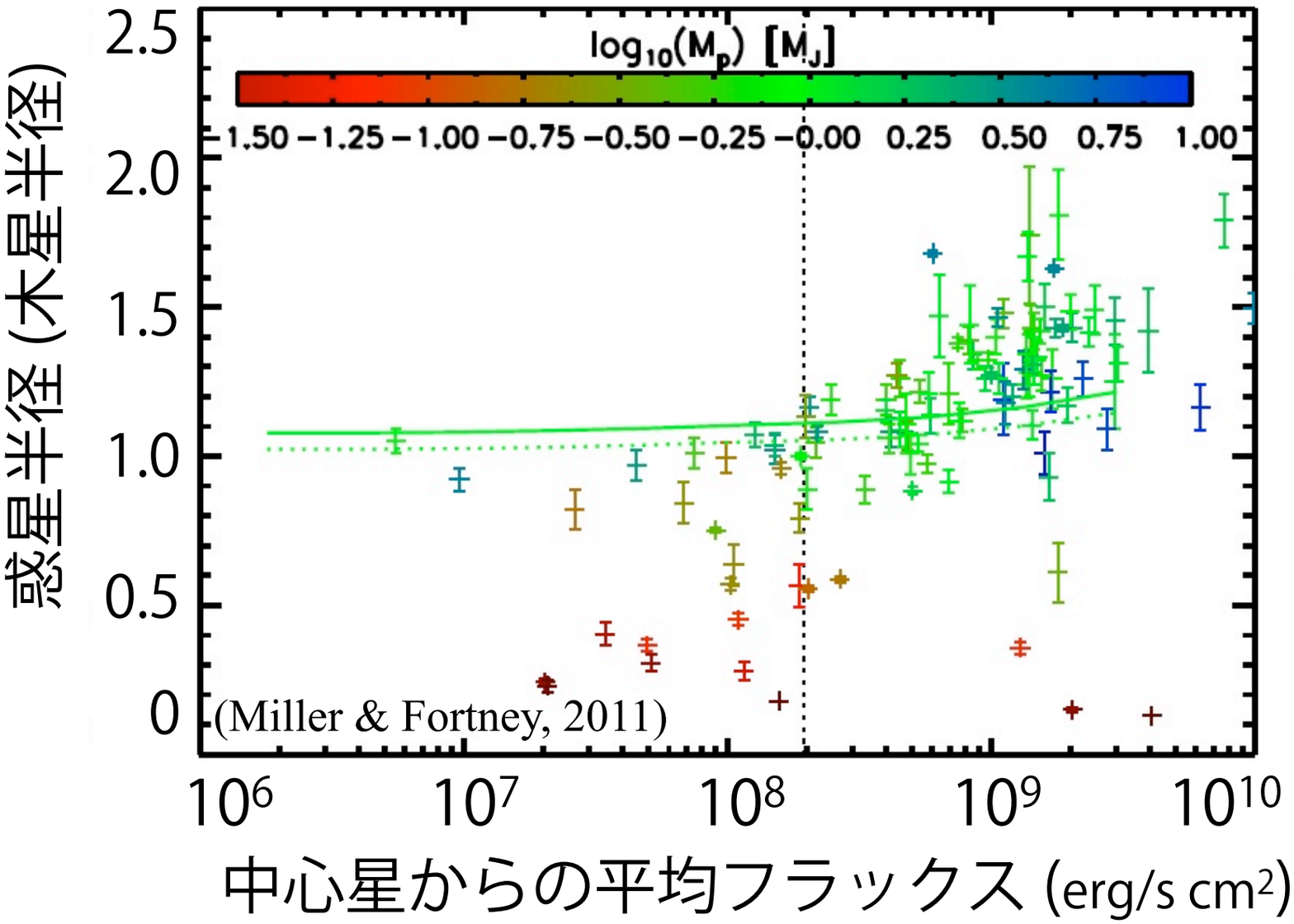
膨張したhot Jupiter(?)

(1) **何らかの熱源**
(2) **大気収縮を遅らせる**

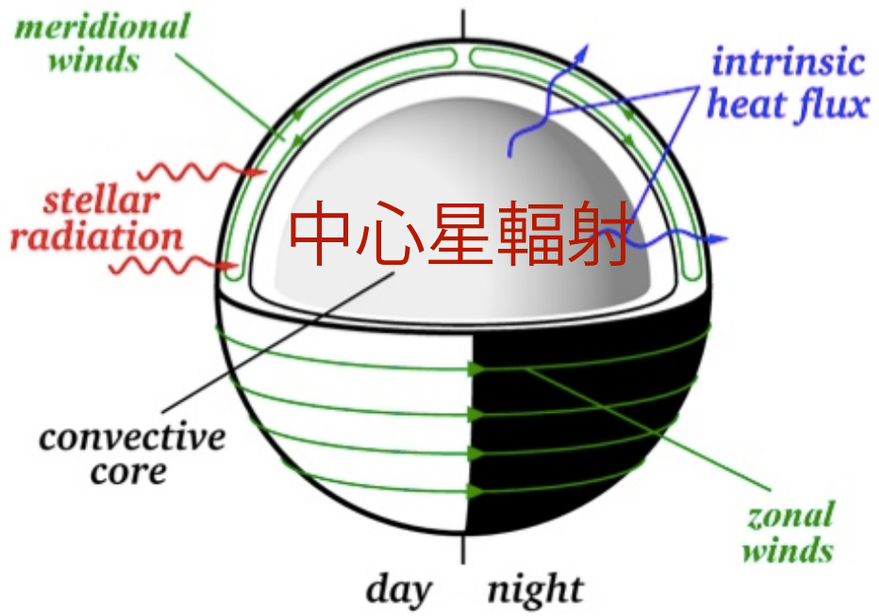
(1)のアイデア：熱潮汐 (Arras & Socrates, 2010), **weather noise** (Guillot & Showman, 2002)
オーム散逸 (Batygin & Stevenson, 2010; Batygin+11;Rauscher & Menou,2010; Perna+10;Wu & Lithwick,2012;Heng,2012)

(2)のアイデア：大気中の高いopacity (e.g. Burrows *et al*.,2007; Guillot,2008)
半対流 (Chabrier & Baraffe, 2007)

hot Jupiter の異常半径と熱源



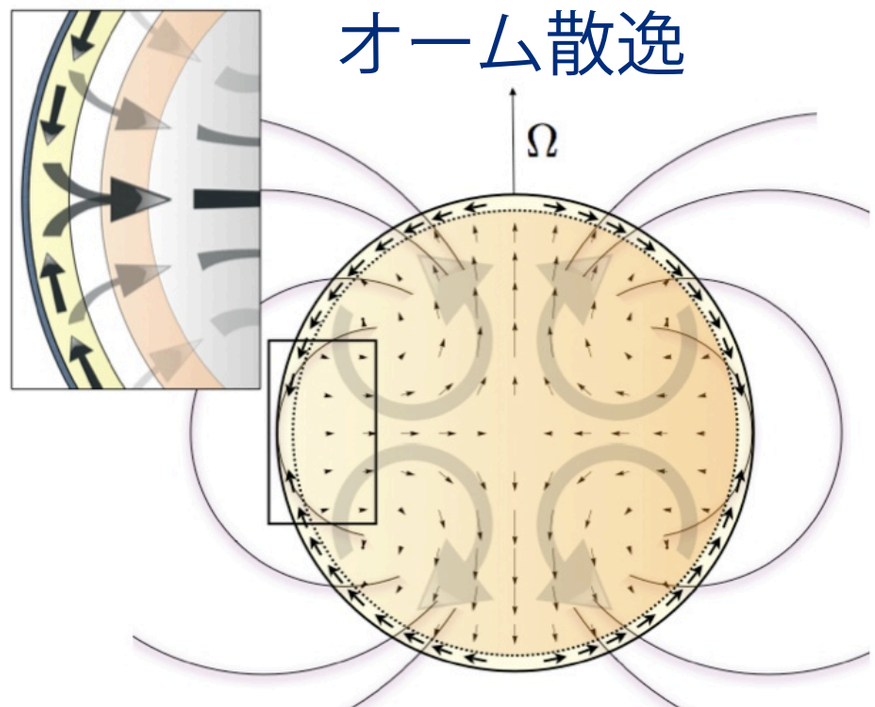
(Guillot & Gautier, 2009)



※ 大気中のオーム散逸

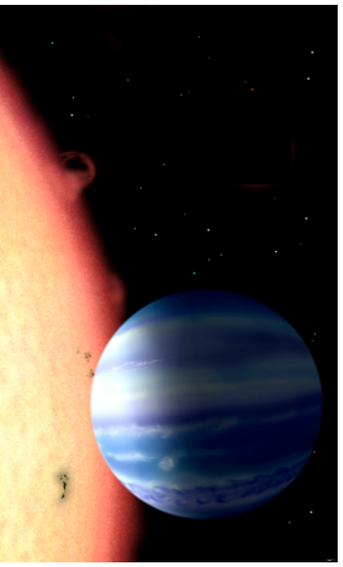
「**アルカリ金属**の**電離**＋**惑星磁場**」

(a) 上層：中性ガス流への磁気抵抗
(b) 内部：誘導電流の貫入
　大気の運動エネルギー → **熱エネルギー**



(Batygin & Stevenson, 2010)

Hot Jupiterの起源 : Type II 惑星移動

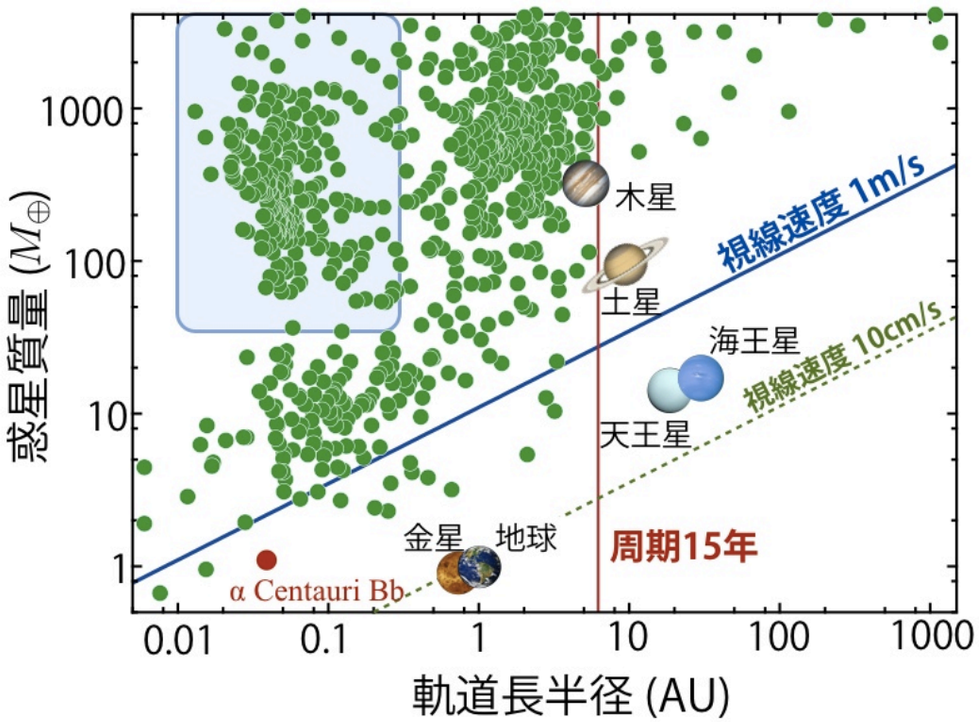


中心星近傍の**ガス惑星**(≦ **0.1AU**)

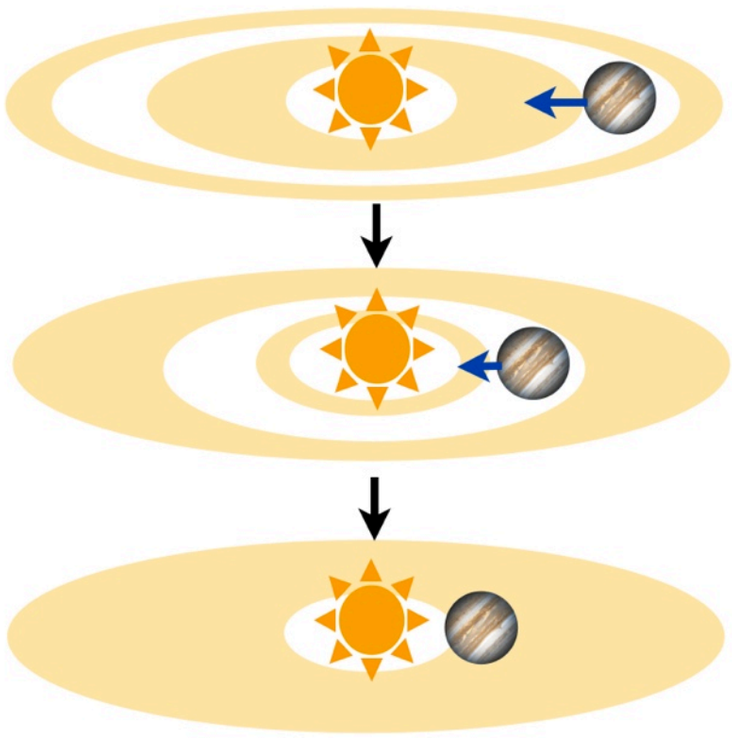
AFGKM型星周りでの**存在頻度**：**数%**

- コア集積モデル
- 円盤不安定モデル

↳ ~~その場形成~~

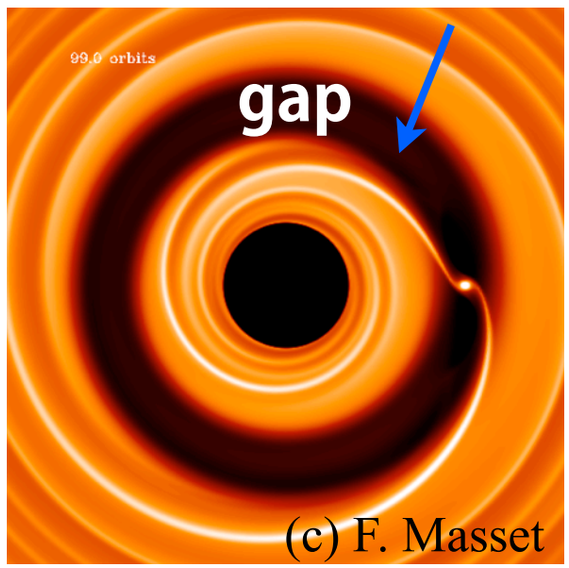


■ Type II 惑星移動 (Lin & Papaloizou,1986;Ward,1997)



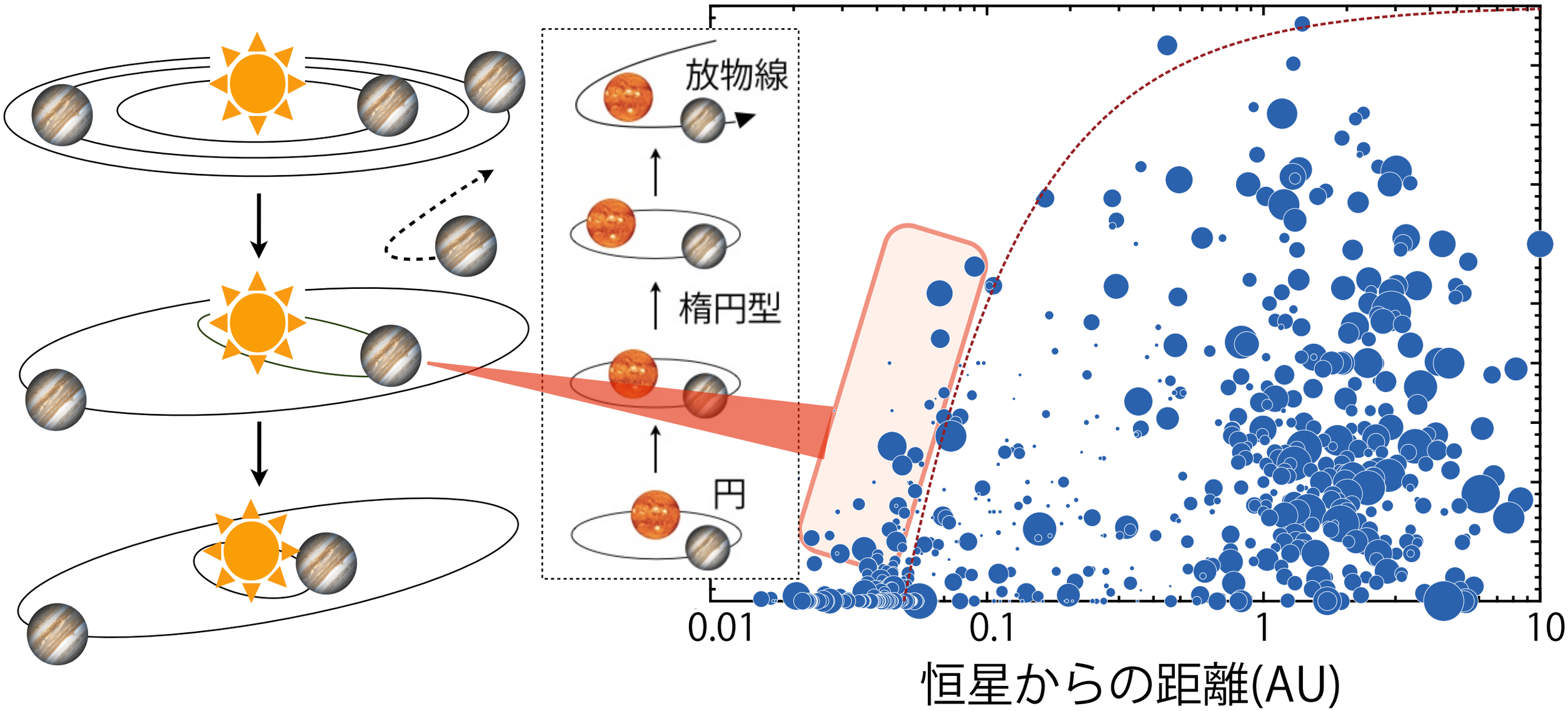
惑星重力による跳ね飛ばし

> 圧力勾配, 粘性拡散によるガス流入



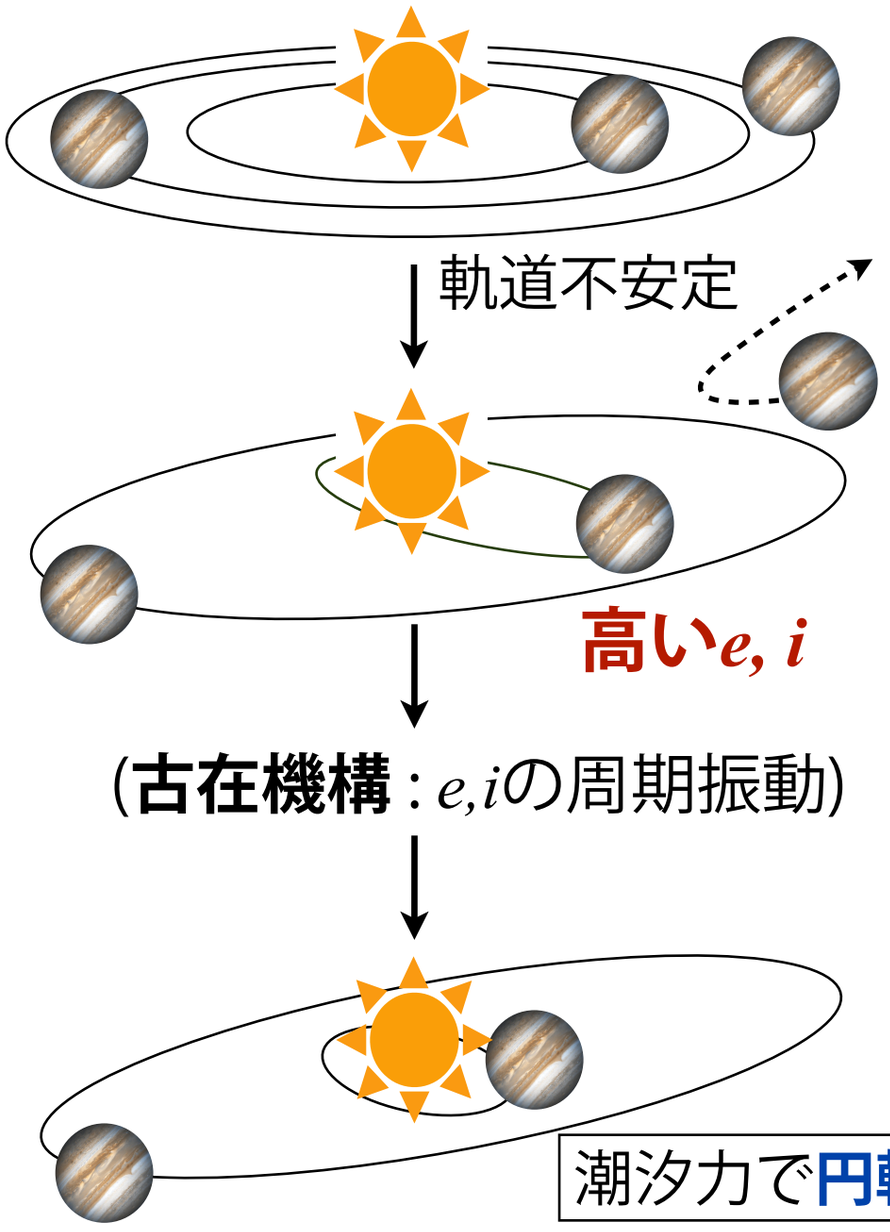
Hot Jupiterの起源：ガス惑星同士の散乱

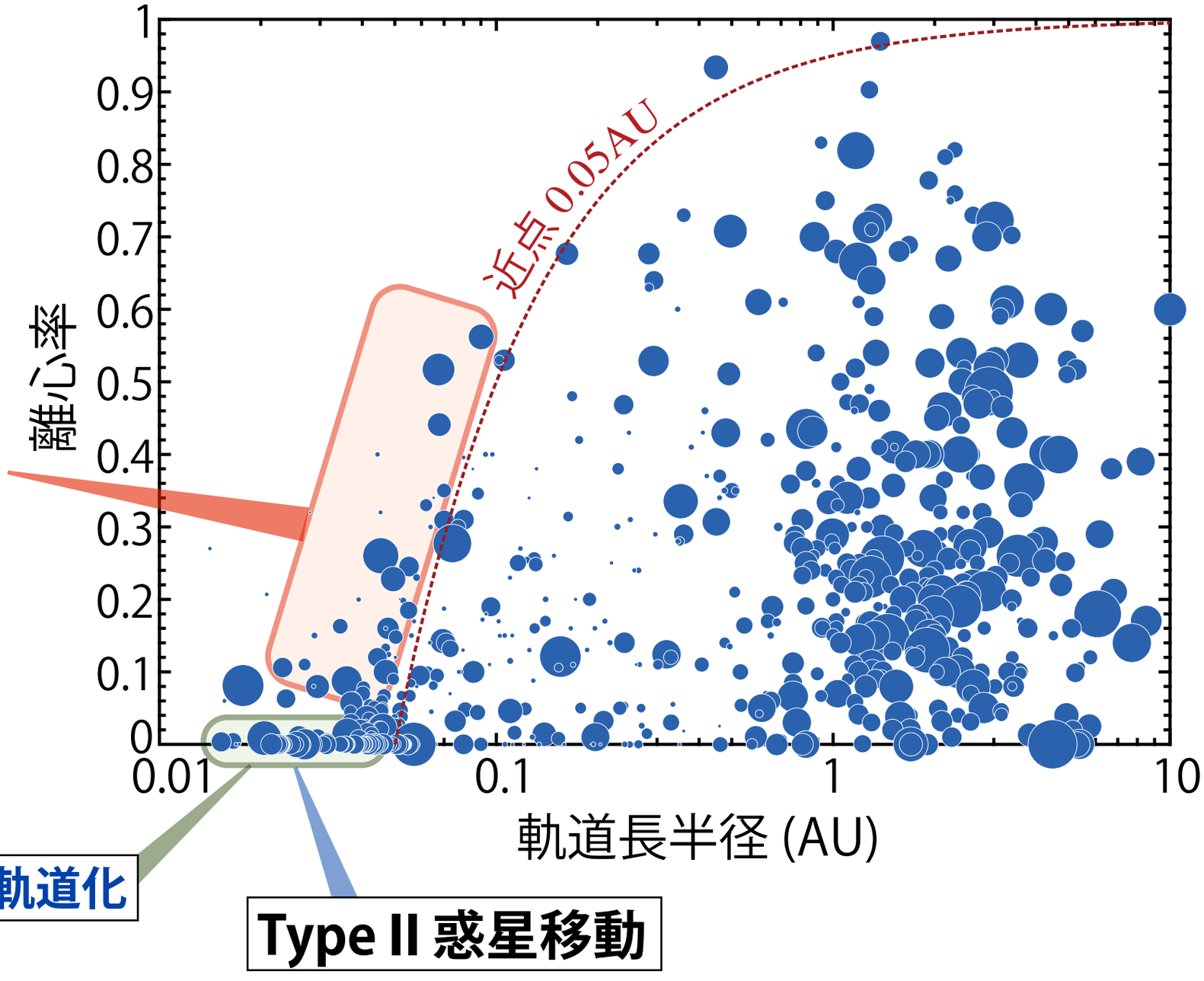
■ 惑星同士の重力散乱 (e.g. Rasio & Ford,1996;Weidenschilling & Marzari,1996; Chatterjee *et al*. 2007;Nagasawa *et al*.2008)



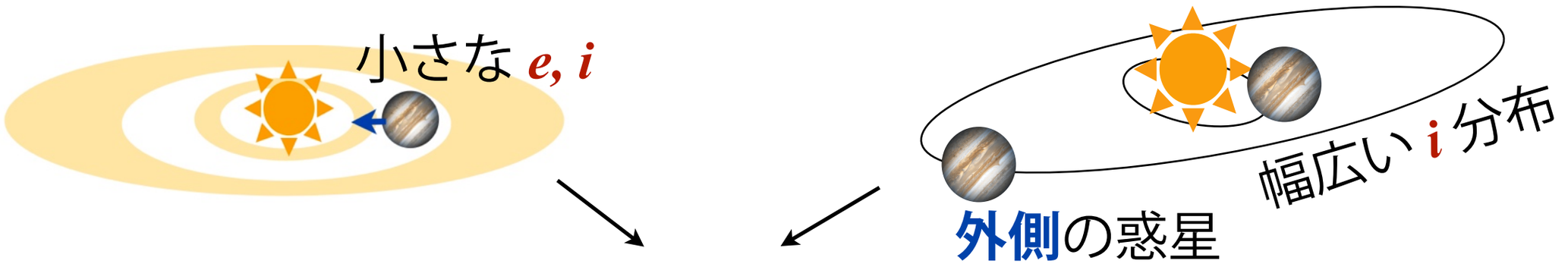
Hot Jupiterの起源：複数ガス惑星の軌道不安定

■ 惑星同士の重力散乱 (e.g. Rasio & Ford,1996;Weidenschilling & Marzari,1996; Chatterjee *et al*. 2007;Nagasawa *et al*.2008)

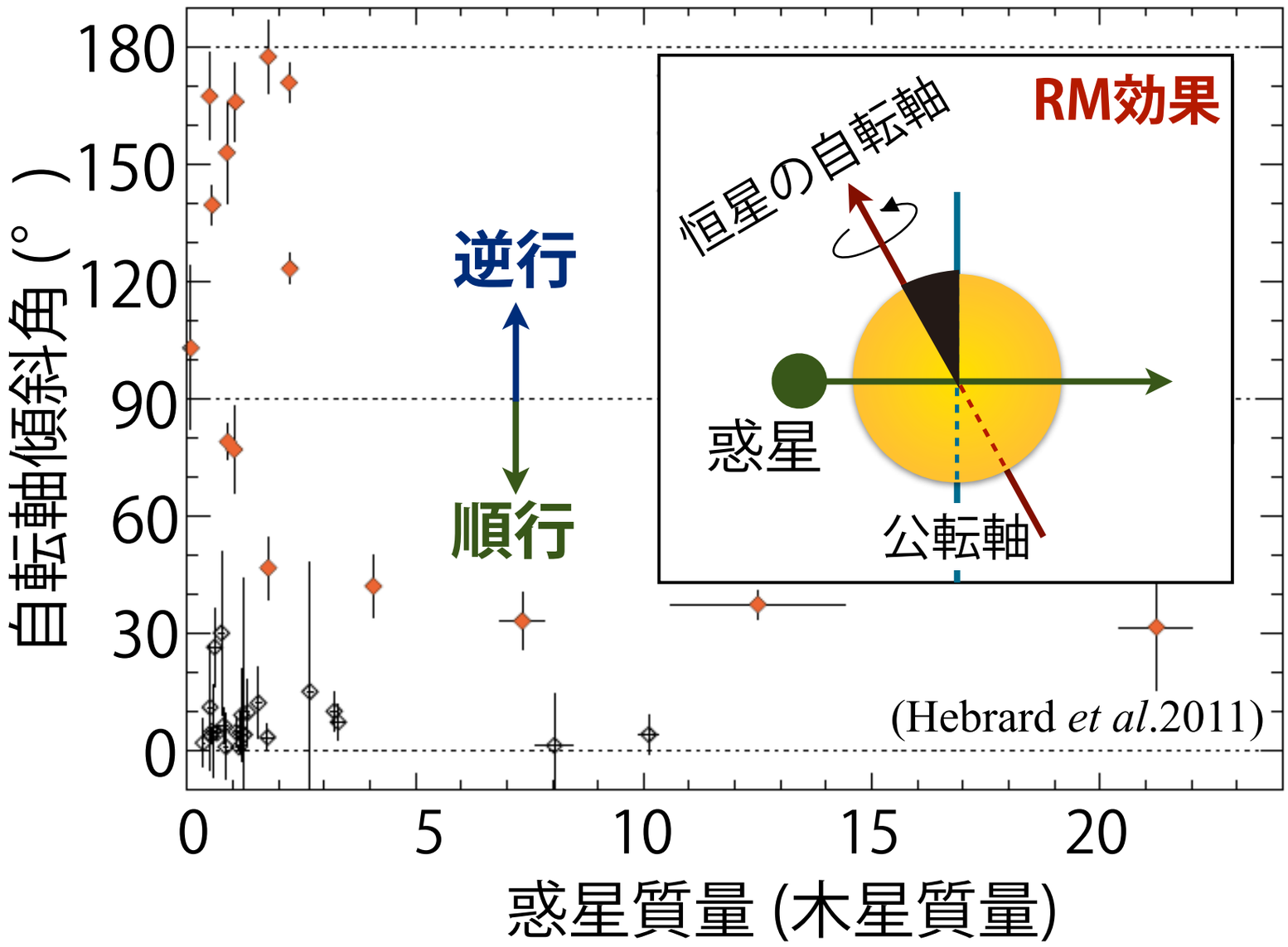




Hot Jupiterの起源：自転軸傾斜角と外側の惑星



hot Jupiterの起源??



(a) **潮汐力**の強さ (Winn.2011)

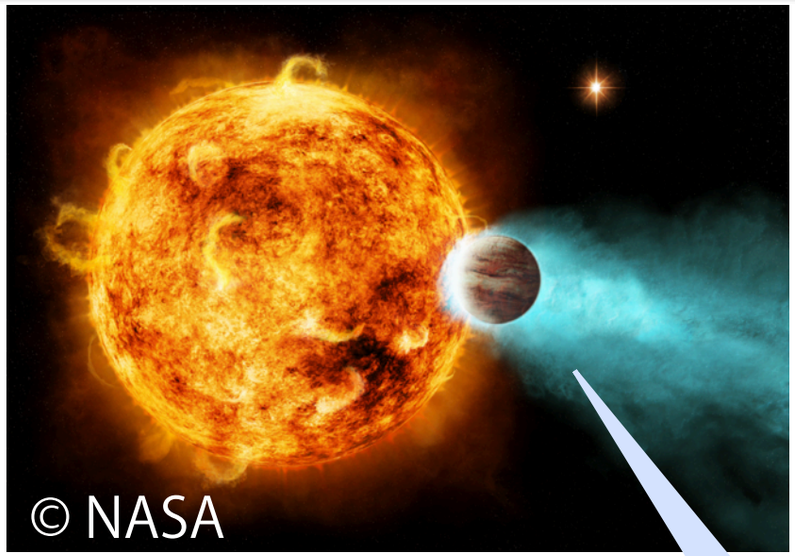
低温星($T_{eff} \leqq 6250$K)ほど傾いていない

(b) **恒星磁場**と**円盤**の相互作用

→ 様々な自転軸傾斜角 (Lai *et al.*2011)

(c) **単独のhot Jupiter**が多い?

恒星からのXUVと系外ガス惑星の大気散逸

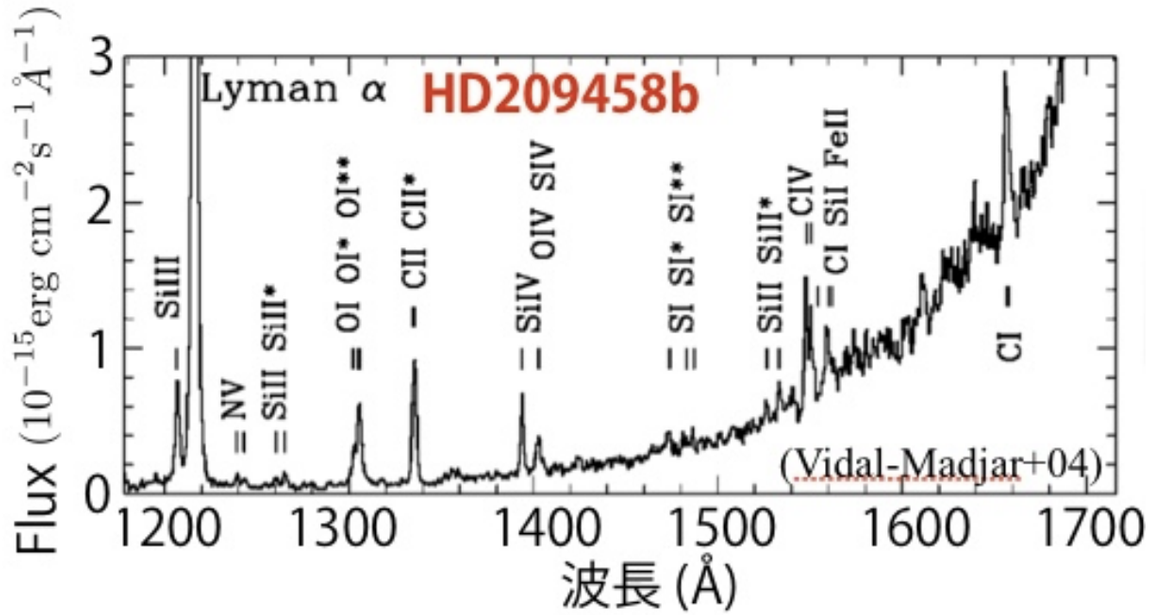


H_2大気の流出
流出した**Hガスの尾**

短周期ガス惑星 (hot Jupiter)

中心星近傍のガス惑星

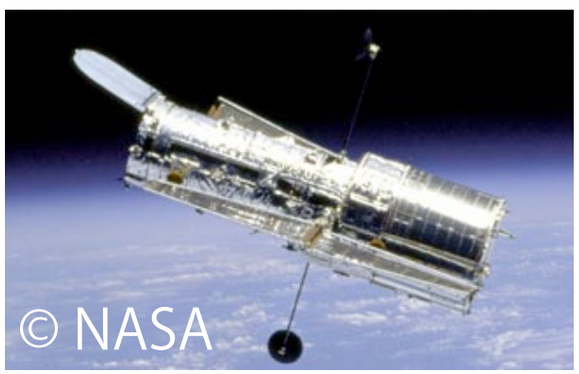
(公転周期~ 数日, a~0.05AU)



【大気散逸するhot Jupiterの間接的証拠】

4例のみ (**すべてUV観測** by HST)　　Hubble宇宙望遠鏡 (HST STIS)

HD209458b	**HI Lyα, OI, CII, Si III** (Vidal-Madjar+03;04;08; Ballester+07;Linsky+10)
HD189733b	**HI Lyα, Si III, N V** (Lecavelier des Estang+10;Bourrier+13)
55 Cnc.b	**HI Lyα** (Ehrenreich+12)
WASP-12b	**Mg II** (NUVA,B,C~2500-2800Å) (Fossati+10)



系外ガス惑星の散逸とEUV観測

(a) 中心星近傍で強烈な**X線, EUV照射**
→ 上層大気の加熱で**流体力学的散逸**
(e.g. Lammer+03;Lecavelier des Etangs+04;Yelle,04;Erkaev+07)

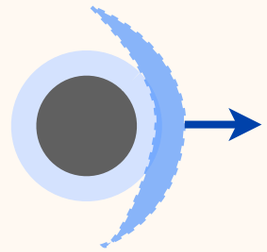
(b) 潮汐固定による遅い自転で**弱い磁場(?)**
→ **恒星風／コロナ質量放出**による**H^+ pick-up**
(Khodachenko *et al.*2007;Lammer *et al.*2009)

① Transit入りのズレ

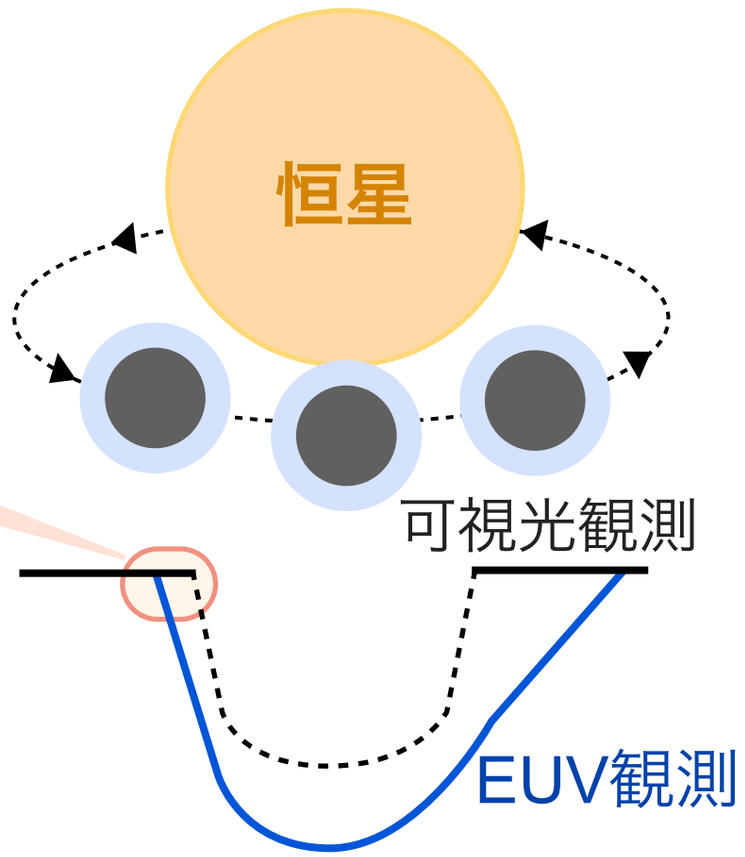
恒星風と**惑星磁場**の相互作用で
惑星の進行方向 前面に
bow shock形成 (Vidotto+10)

↓

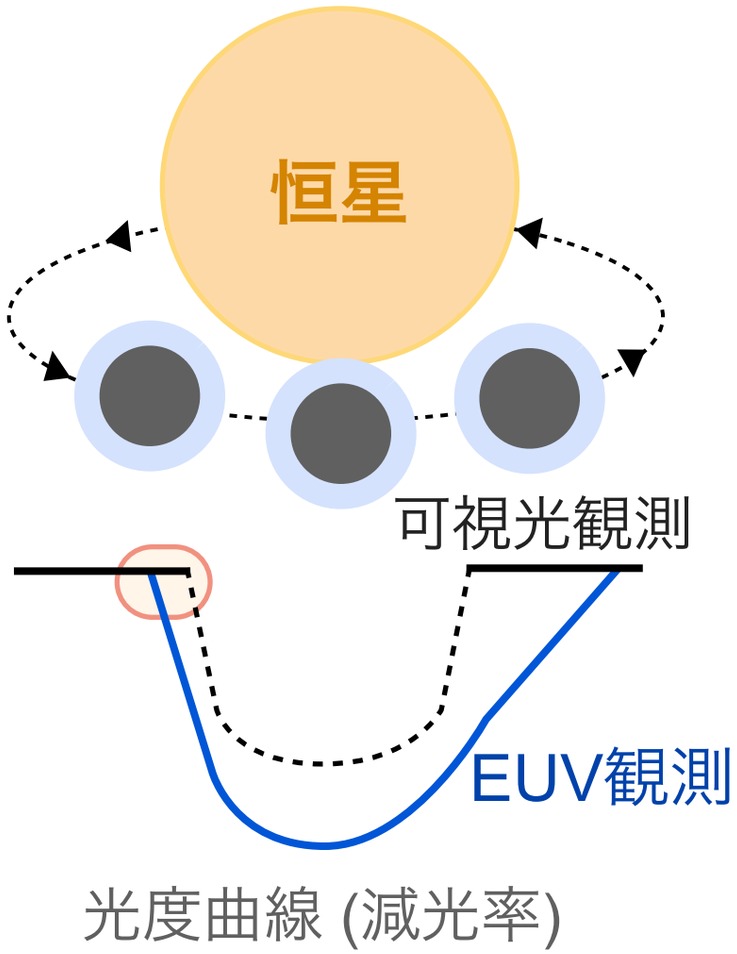
「惑星磁場の情報」



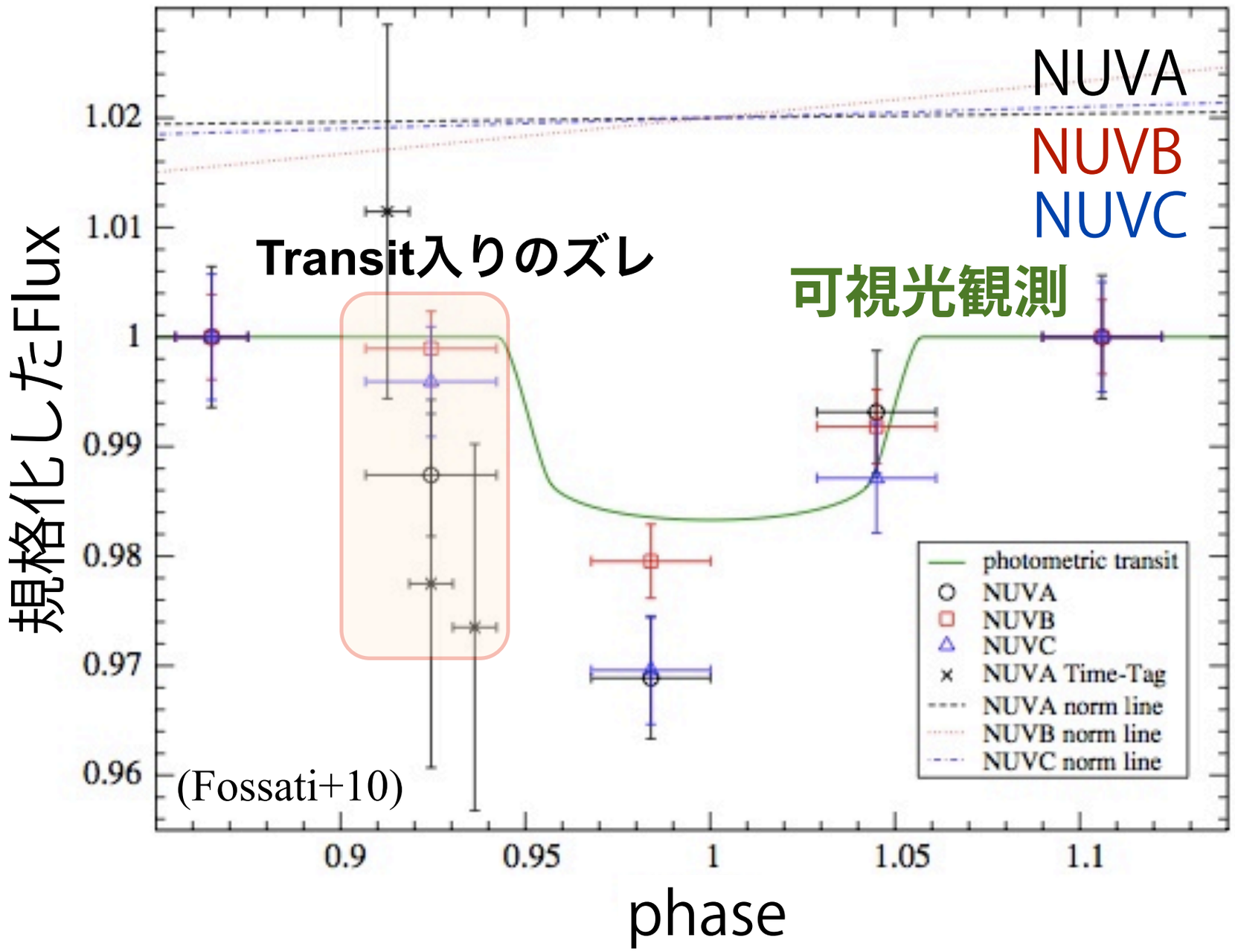
(観測例) **WASP-12b** (Fossati+10)



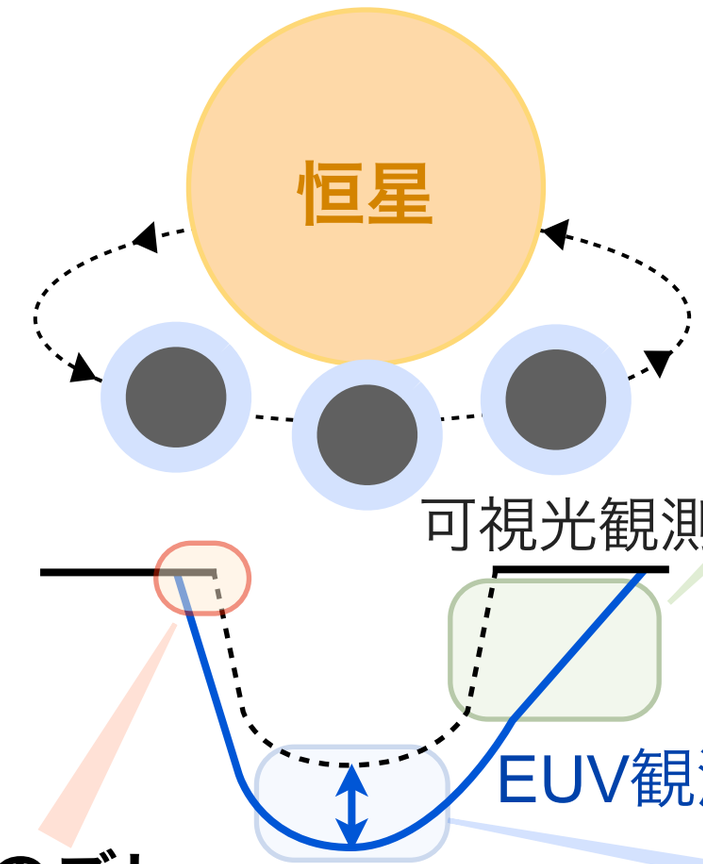
系外ガス惑星の散逸とEUV観測



光度曲線 (減光率)



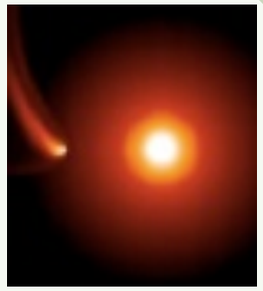
系外ガス惑星の散逸とEUV観測



② 非対称な光度曲線

水素大気の流出

Coriolis力 + 輻射圧



ガス尾 → 大気の散逸率

(e.g. Schneiter+07;Holmstrom+08)

③ 深い減光率

水素大気(Lyα)の**UV吸収分**
(OI, CII, Si IIIでも同様)

R_{UV} > Roche半径

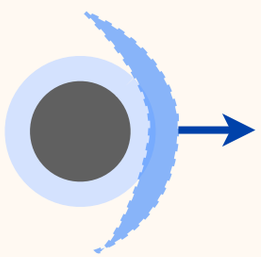
↳ **大気散逸の証拠**
大気の散逸率

(e.g. Vidal-Madjar+03;04)

① Transit入りのズレ

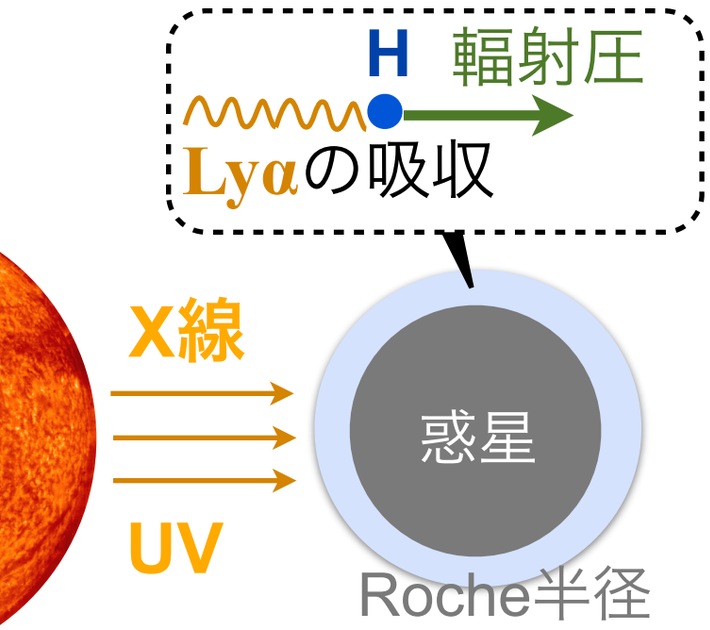
恒星風と**惑星磁場**の相互作用で
惑星の進行方向 前面に
bow shock形成 (Vidotto+10)

「惑星磁場の情報」



(観測例) **WASP-12b** (Fossati+10)

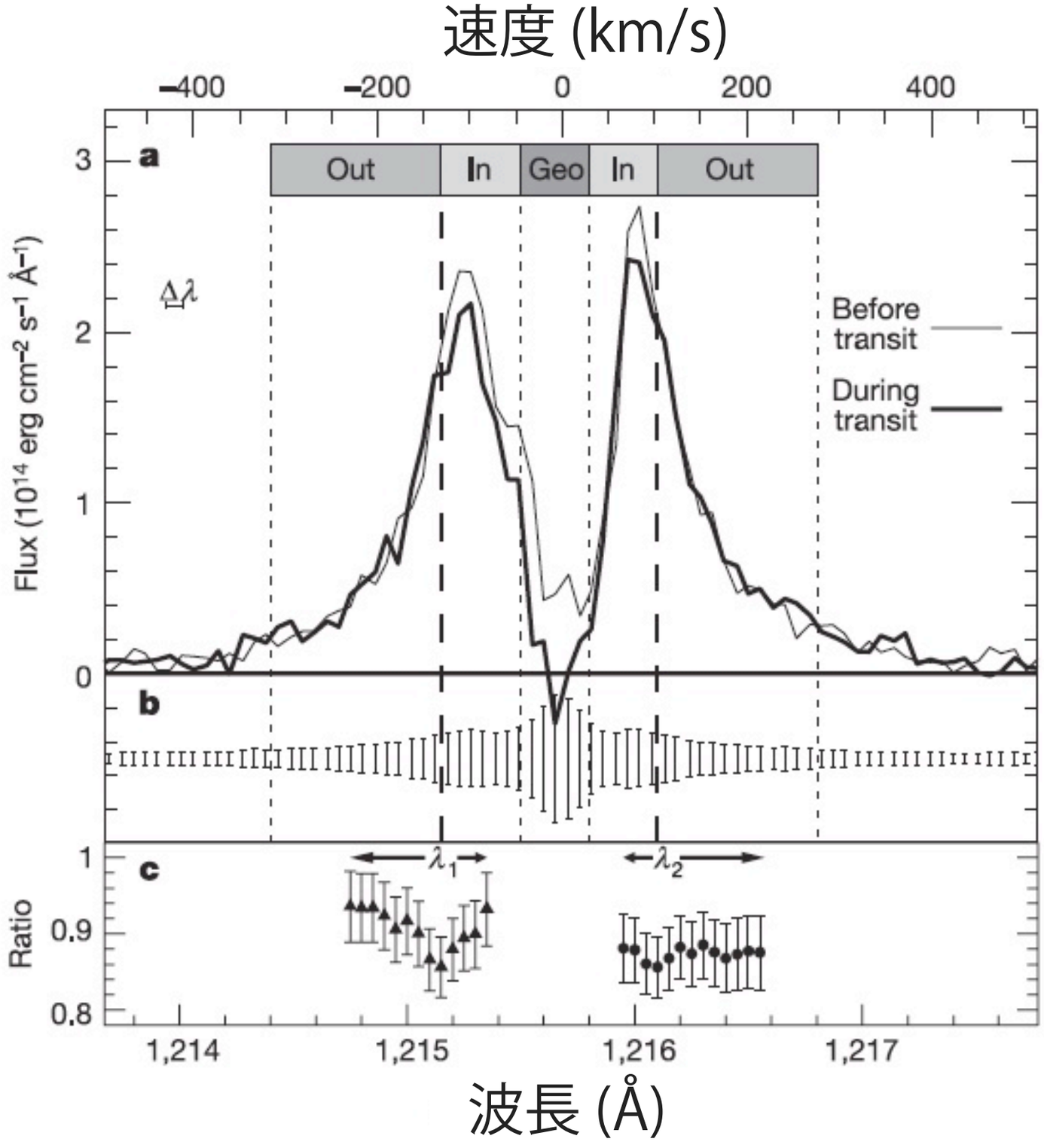
hot Jupiterの大気散逸



④ **Lyα吸収の分光観測**

Lyα 吸収線の**青方偏移**
H原子の速度分布 (> **脱出速度**)
↓
「**大気散逸**の証拠」

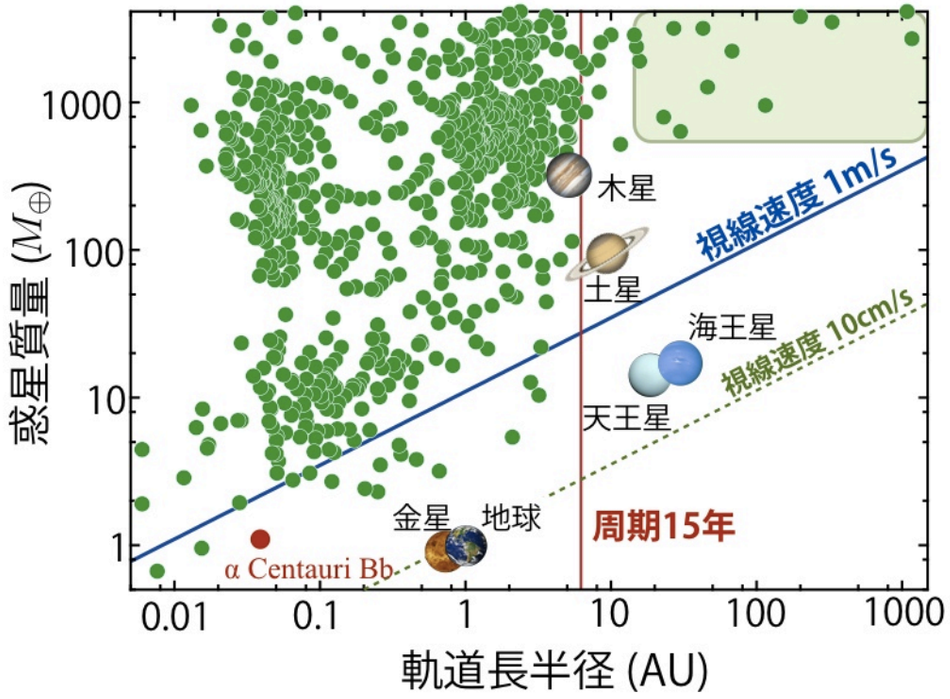
(OI, CII, Si IIIなどの
他の吸収線でも)



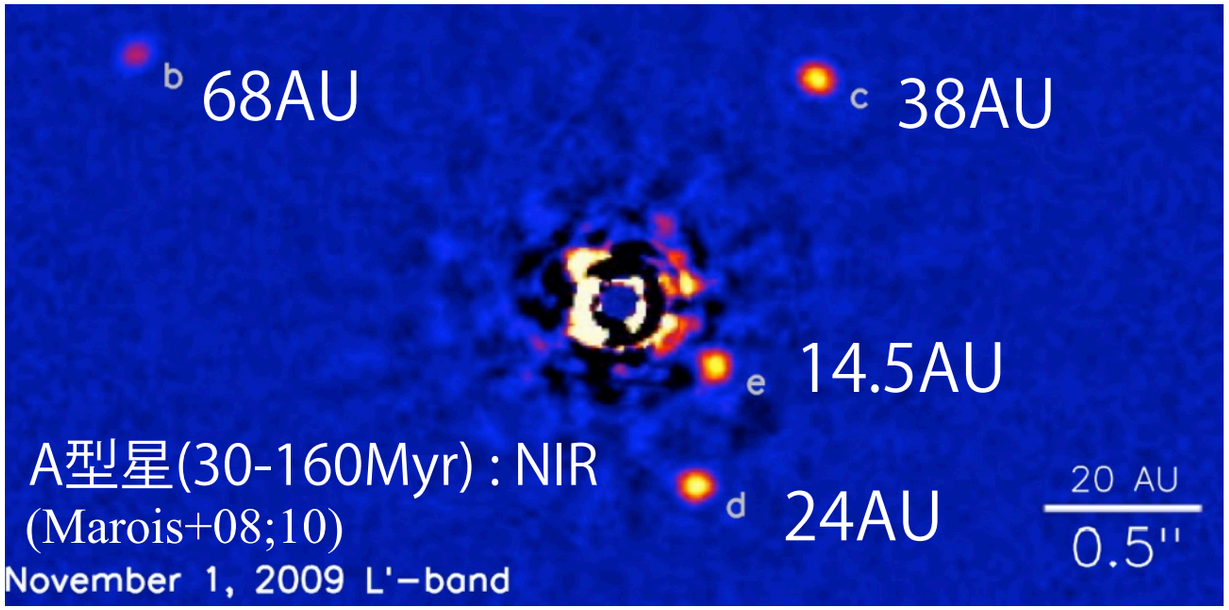
(Vidal-Madjar *et al.*, 2003)

直接撮像：遠方ガス惑星の存在

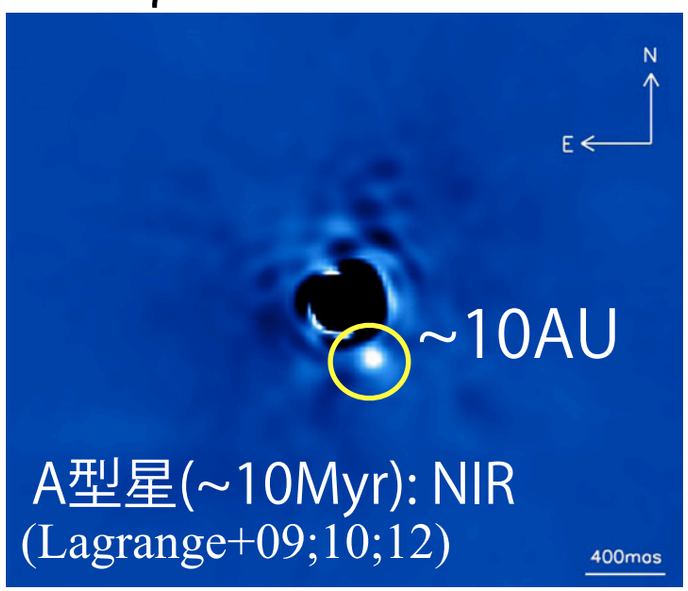
コロナグラフ撮像：約**15個**の惑星候補※
(地球からの距離 ≦ **150pc**)

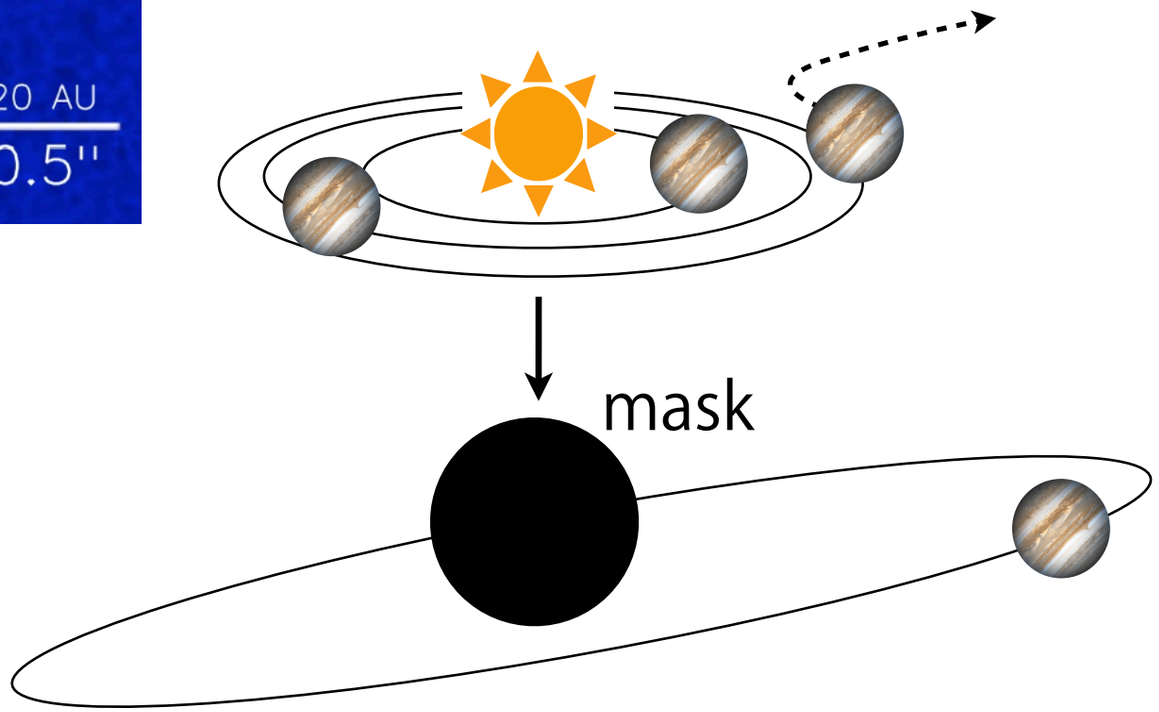


■ HR8799 : 4つのガス惑星(5-10木星質量)



■ がか座β星b : ~10木星質量

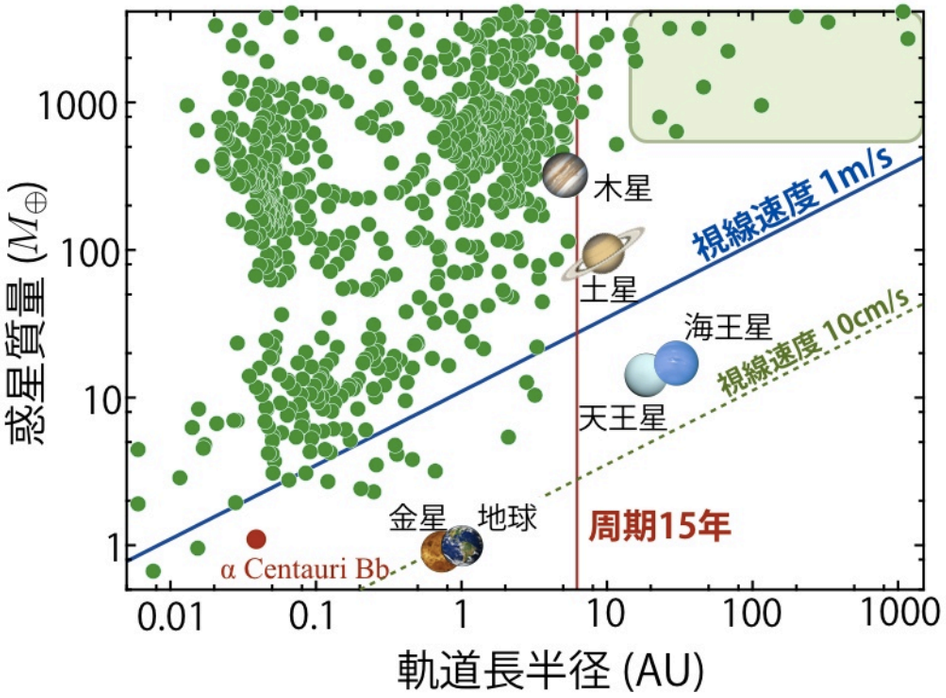




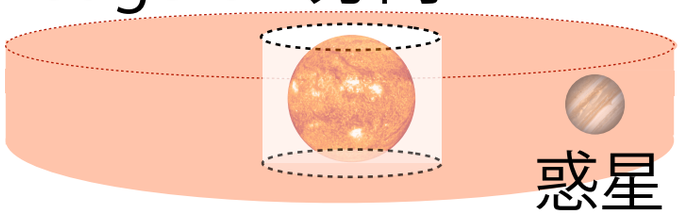
惑星同士の重力散乱?

直接撮像：遠方ガス惑星の存在

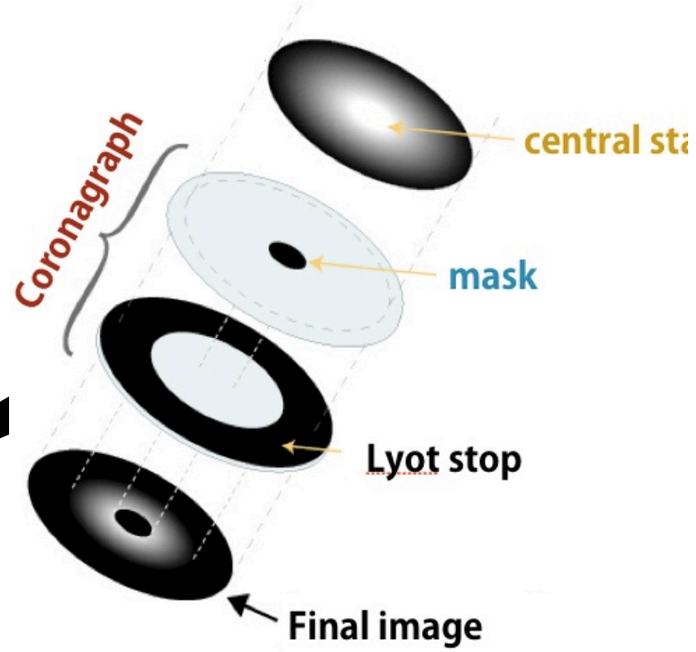
コロナグラフ撮像：約**15個**の惑星候補※
(地球からの距離 ≦ **150pc**)



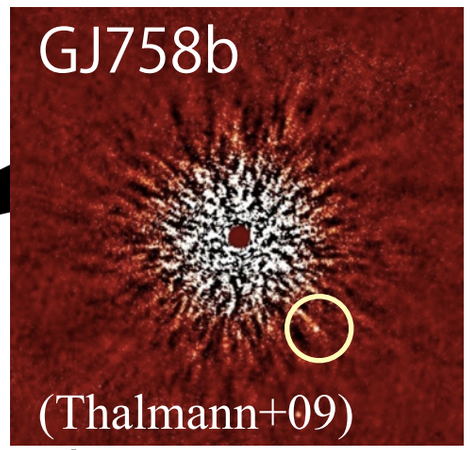
edge-on 方向



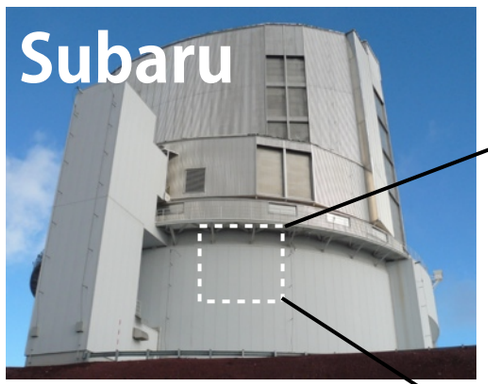
中心星をマスク



Face-on方向



コロナグラフ



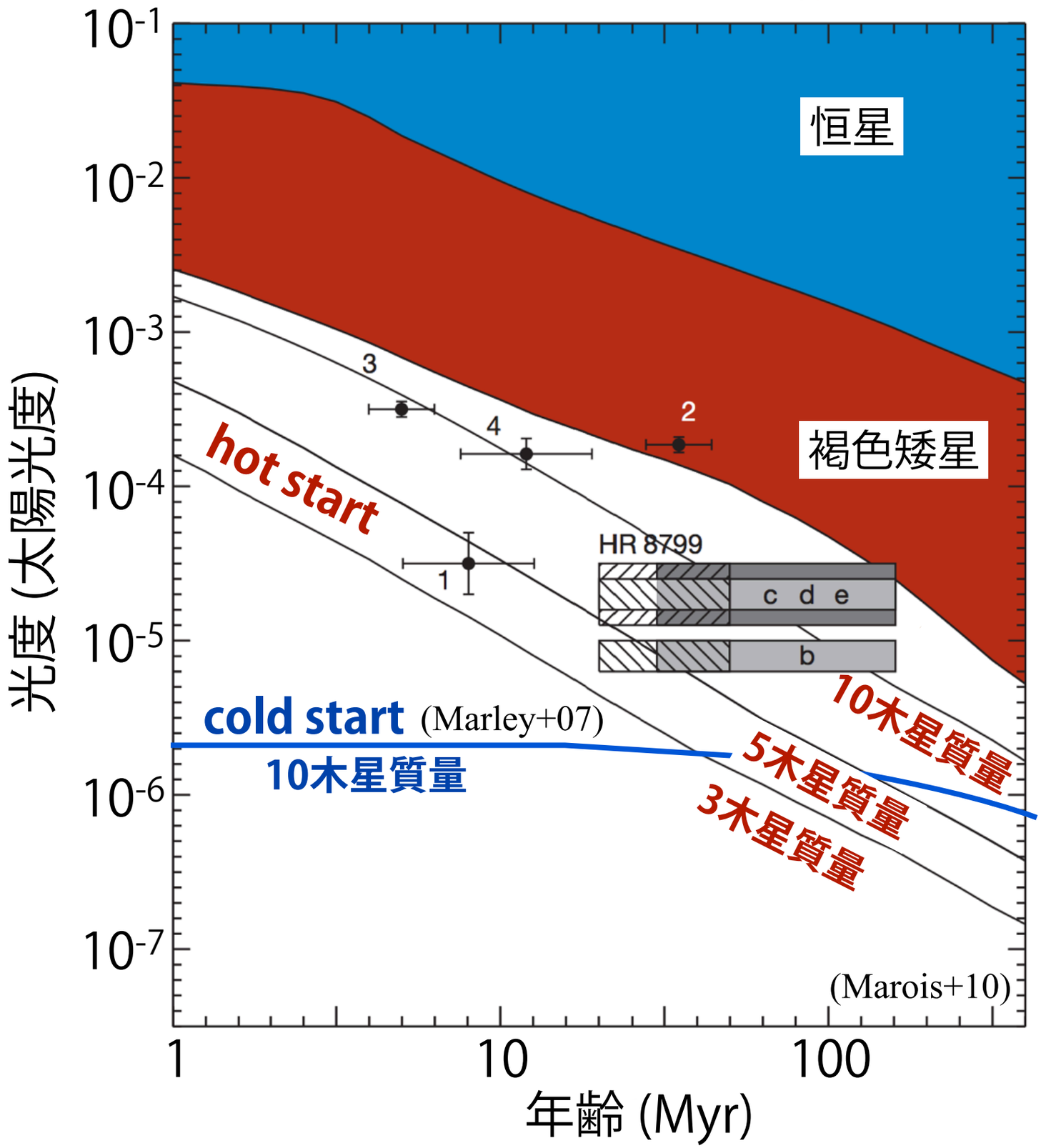


直接撮像：惑星質量の推定

コロナグラフ撮像：約15個
(地球

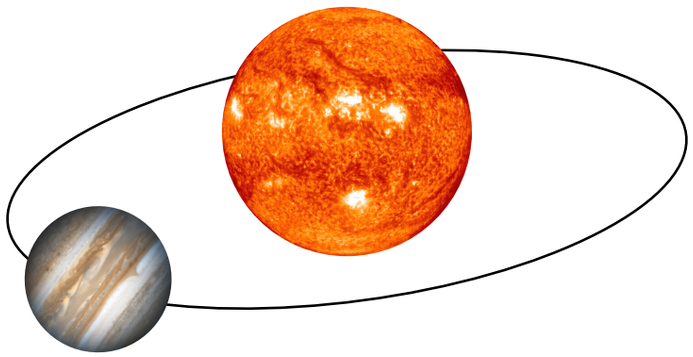
■ HR8799 : 4つのガス惑星(5-1

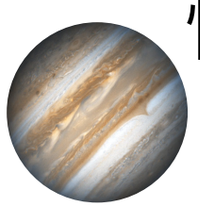
■ がか座β星b : ~10木星質



※ 惑星質量の不確定性：中心星の年齢, 惑星の光度・形成, 進化モデル

宇宙を漂うガス惑星





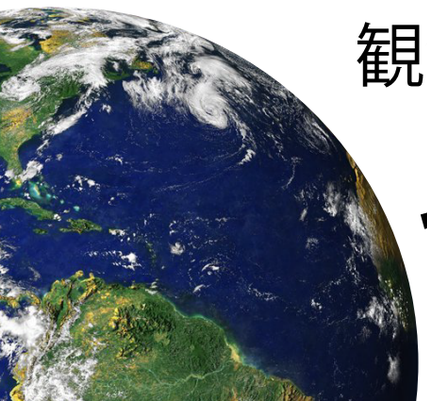
恒星の周りを回っていない惑星
→ **浮遊惑星** (Free-floating planet)

※ 束縛されていない惑星 (Unbound planet)
※ 放浪する惑星 (Rogue planet)

■ 重力マイクロレンズ (一般相対性理論)

- **地球から遠く離れた恒星**を見れる
- 恒星から**遠くにある惑星**も検出可能





観測者

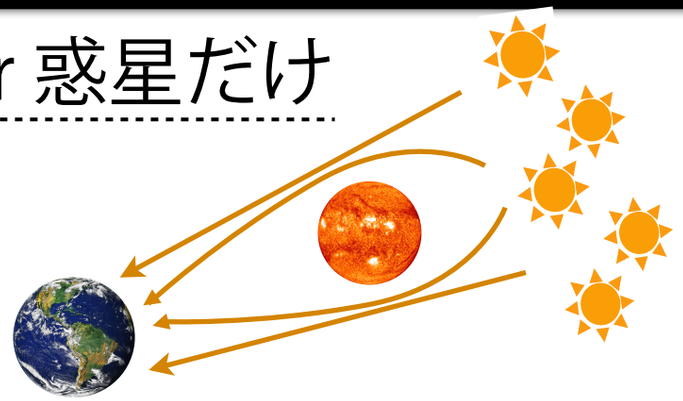
増光した光

レンズの役割



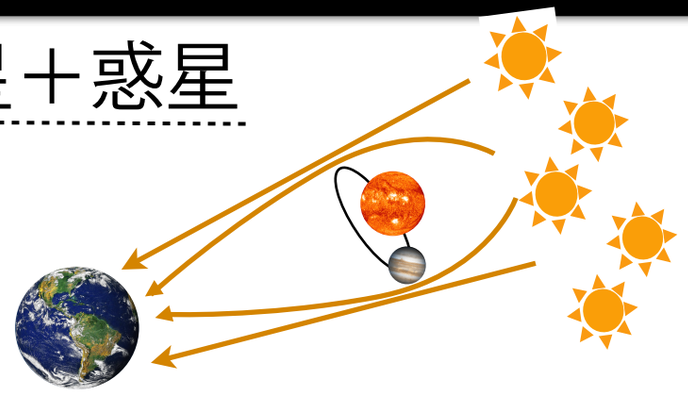
重力マイクロレンズ

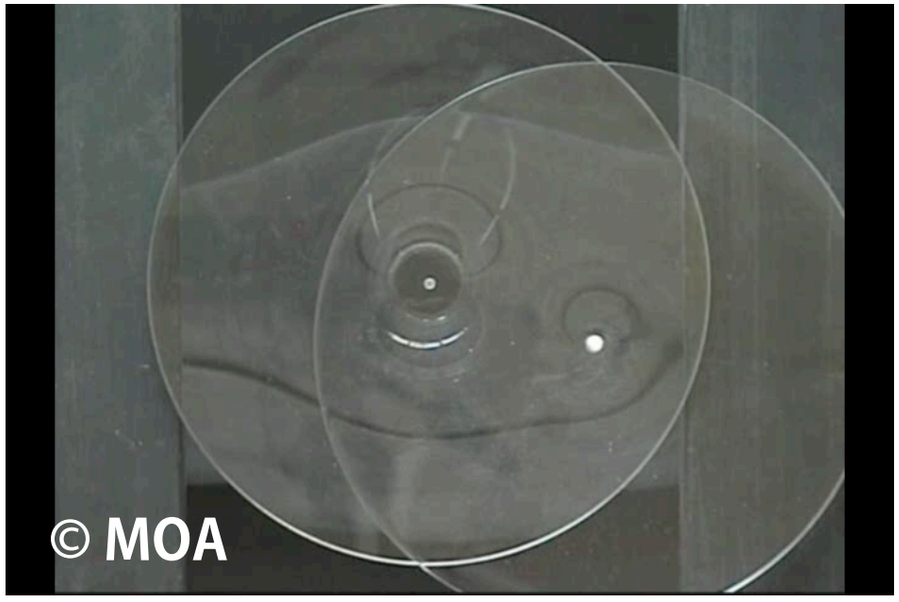
■ 恒星 or 惑星だけ

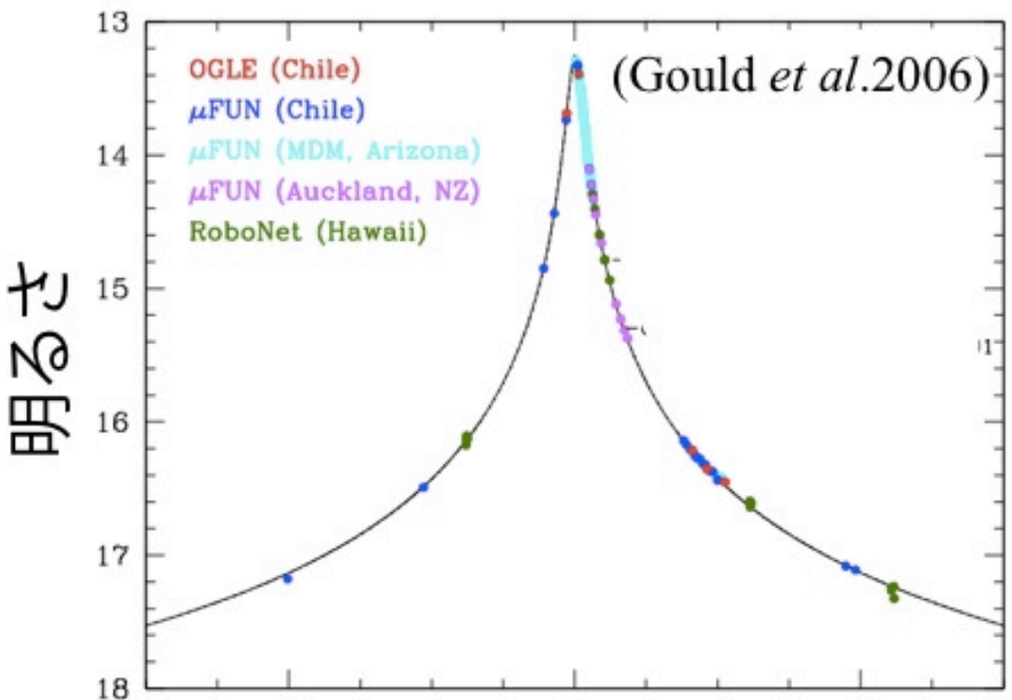


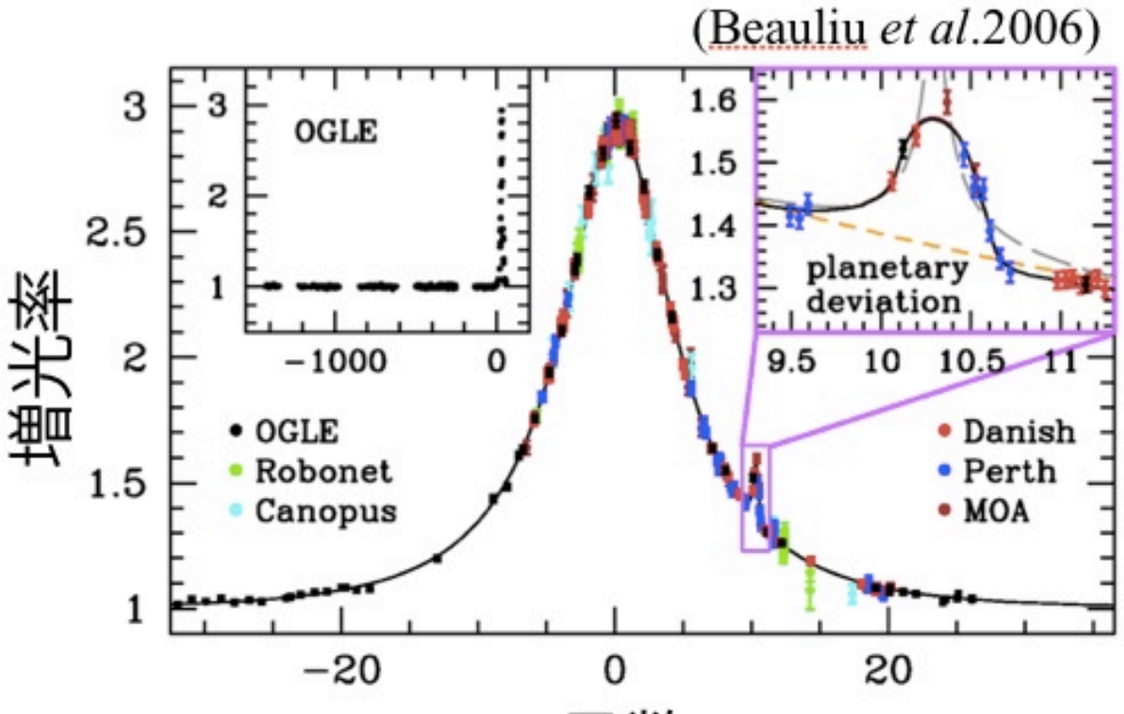


■ 恒星＋惑星



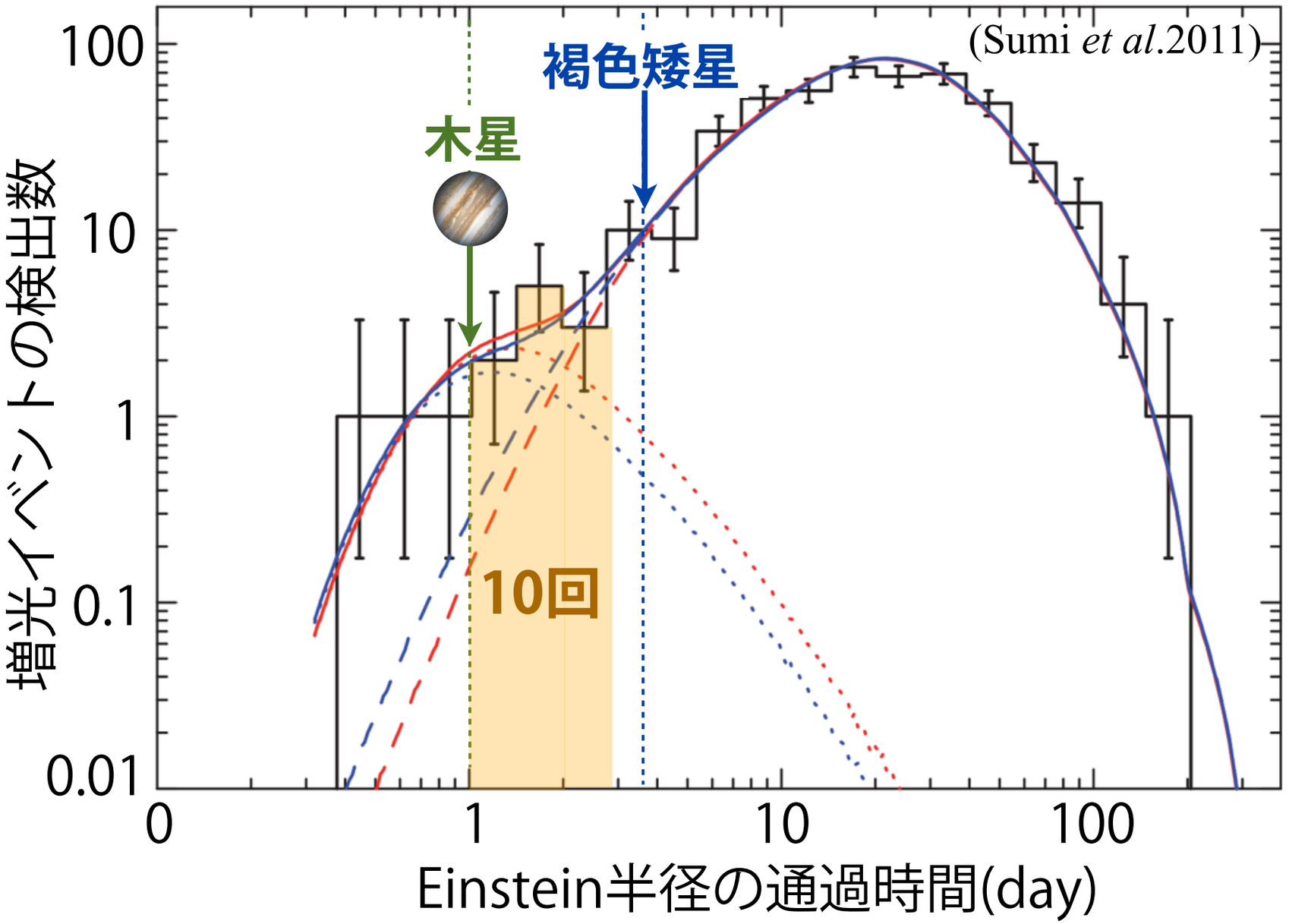


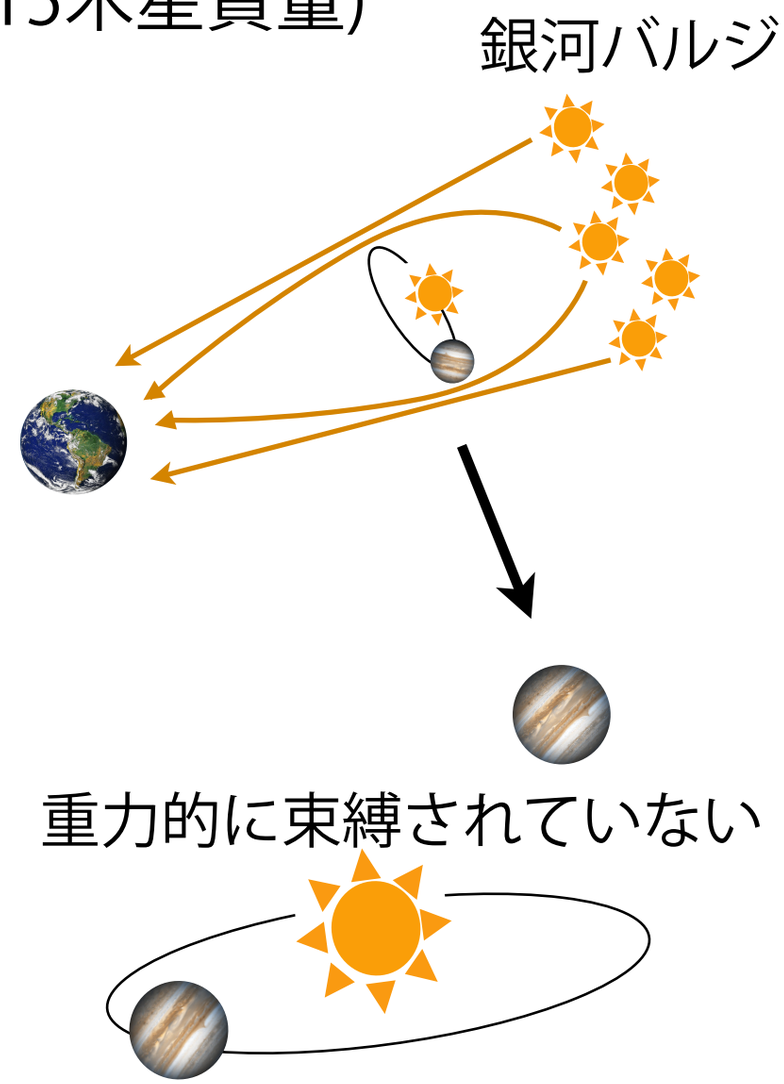




普遍的な浮遊ガス惑星

2年間(2006-2007)で5,000万個の星を**重力μレンズ観測**
→ **474増光**イベント：**10個**の**浮遊ガス惑星**(3-15木星質量)





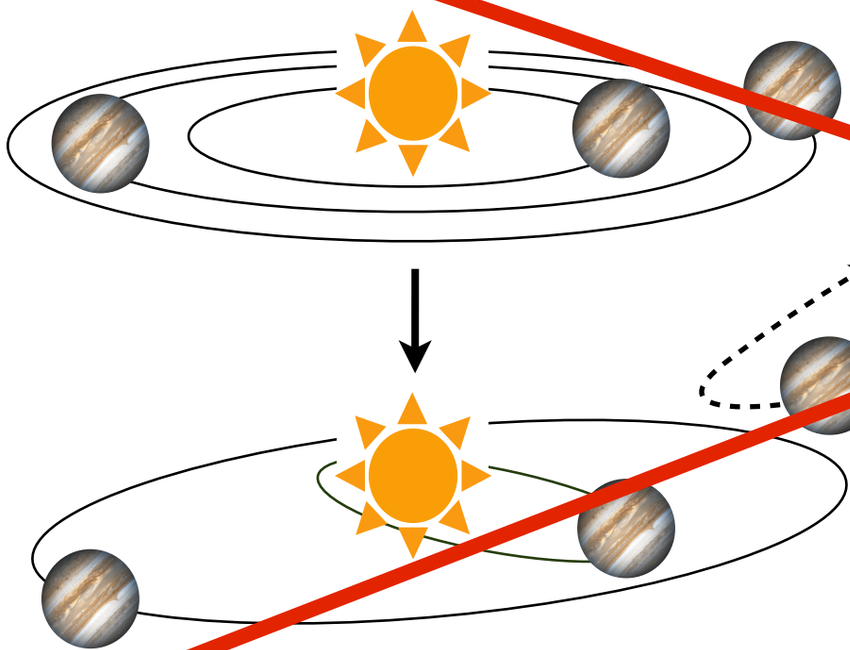
銀河系内の**恒星数**(**主系列星**)の**1.8倍**程度、浮遊ガス惑星がある(?)

宇宙は浮遊ガス惑星で溢れている?

銀河系内の**恒星数**(**主系列星**)の**1.8倍**程度、浮遊ガス惑星がある(?)
(Sumi *et al.*2011)

※ 天の川銀河：約**3000億個**の恒星
→ 約**5400億個**の**浮遊ガス惑星**が存在(?)

(a) 惑星の重力散乱



(b) 分子雲から誕生



崩壊

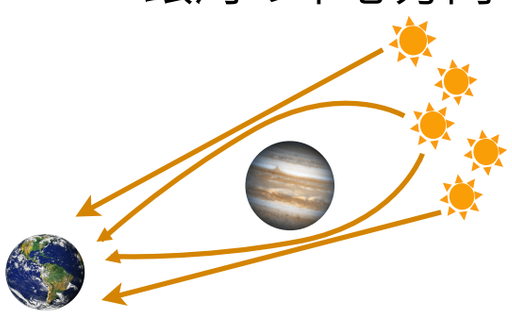
(c) 星の最期(超新星爆発)



吹き飛ばし

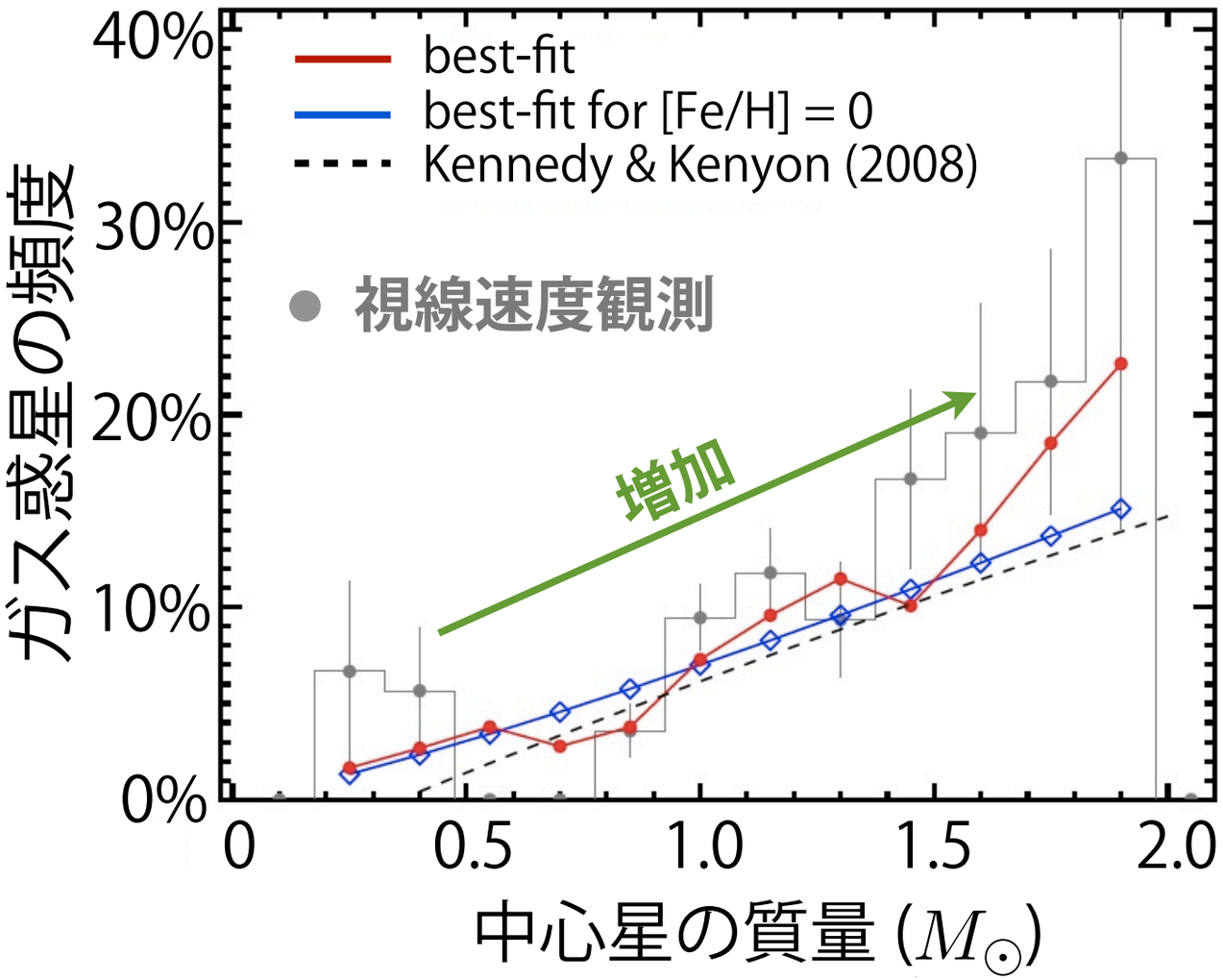
※ 2年間(2006-2007)で5,000万個の星を**重力マイクロレンズ観測**
→ **474増光**イベント：**10個**の**浮遊ガス惑星**(3-15木星質量)

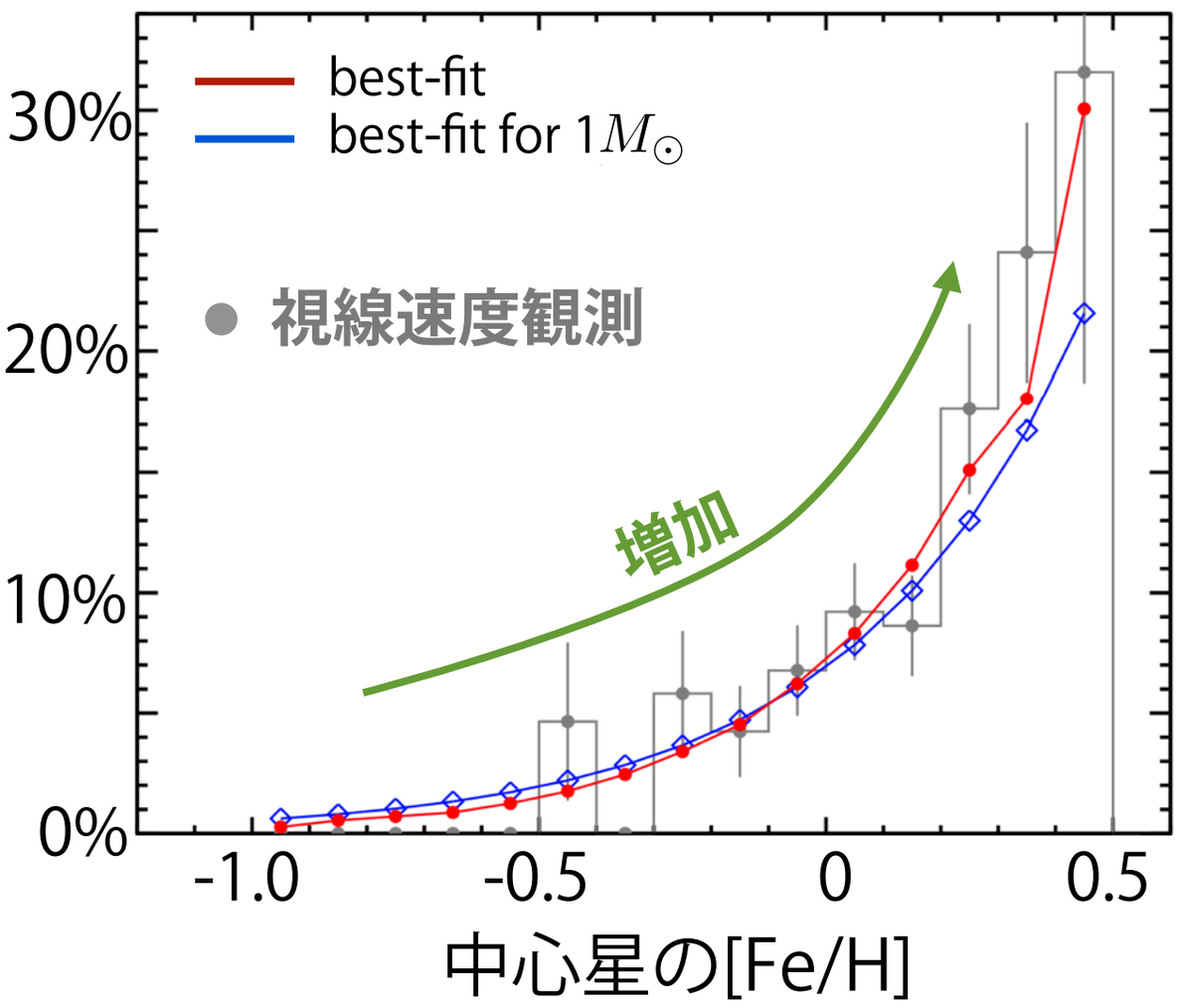
銀河の中心方向



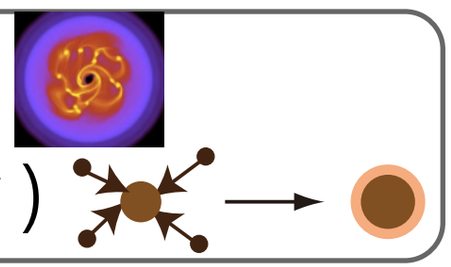
系外ガス惑星と惑星形成論

0.2-1.9$M_\odot$(1266 stars) の視線速度観測の統計(Johnson *et al.* 2010)





- 中心星の**質量**が**大きい** (重い円盤)
- 中心星の**[Fe/H]**が**高い** (固体物質↑)



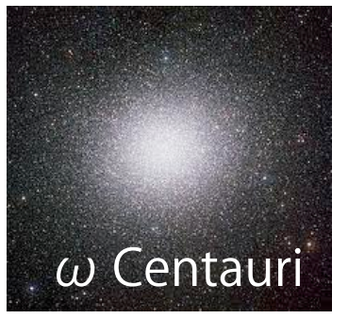
⟶「**ガス惑星の存在割合**(高)」

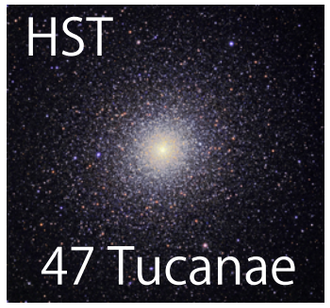
金属欠乏な恒星周りの系外惑星

【金属欠乏な恒星周りの系外惑星】**(-2 < [Fe/H] < -0.4)**

(1) **球状星団**([Fe/H] = -2, -1.7,-0.7) --- **0個**／約70,000星
(Gilliland+00; Weldrake+05;08;Nascimbeni+12)





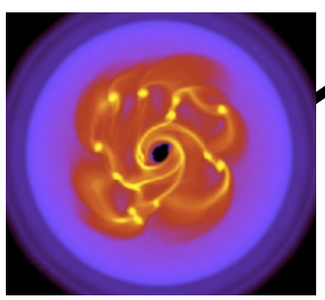


(2) 金属欠乏な恒星 --- **3個**の**ガス惑星**／360星(Sozzetti+06;09;Santos+10)

HD5388b --- 1.96木星質量@1.76AU ※ **[Fe/H] = -0.27**
HD181720b --- 0.37木星質量@1.78AU ※ **[Fe/H] = -0.53**
HD190984b --- 3.1木星質量@5.5AU ※ **[Fe/H] = -0.48**

(3) 銀河ストリーム --- **3個**の**ガス惑星**／96星 (Setiawan+10;12)

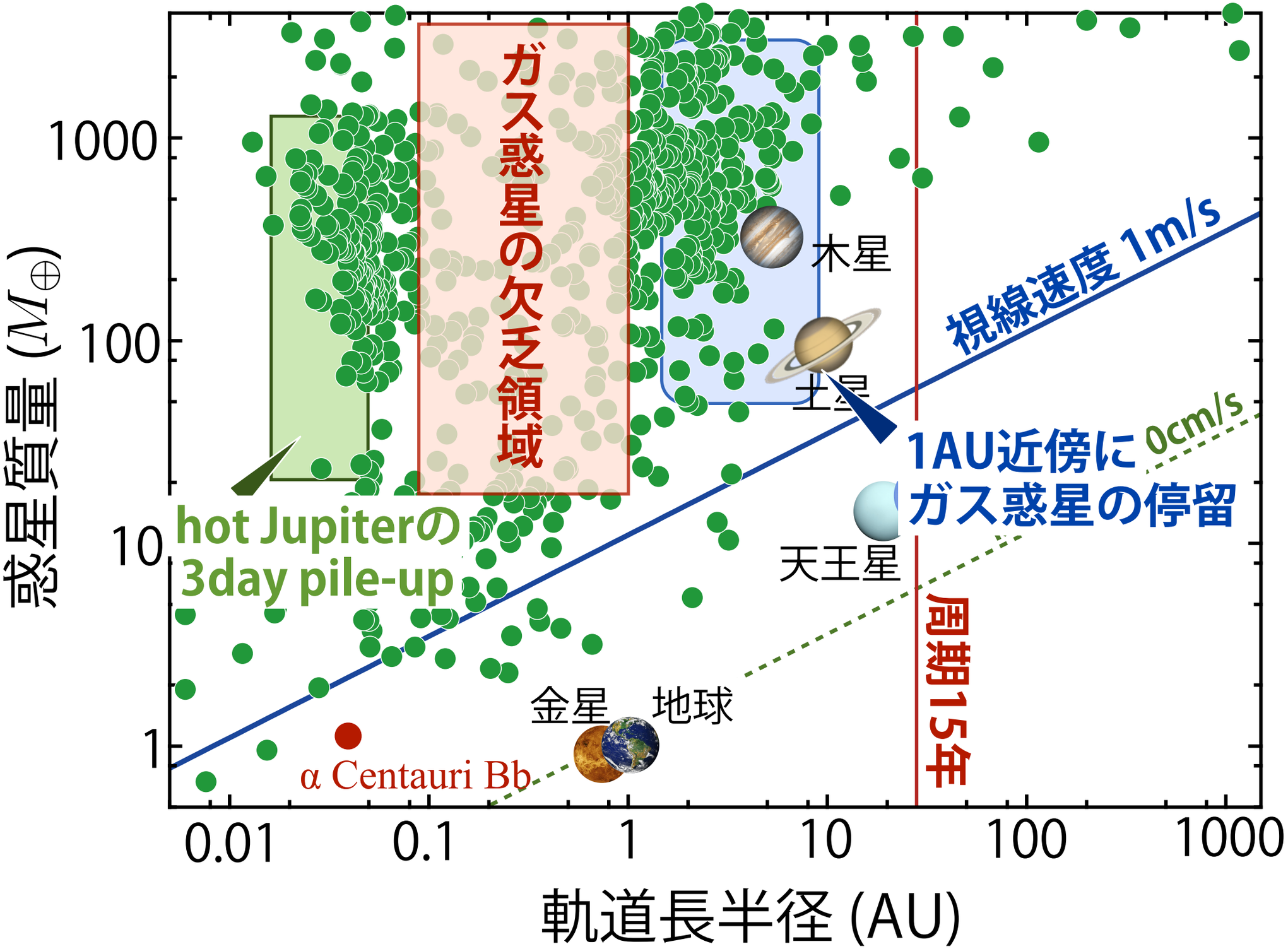
HIP13044b --- 1.25木星質量@0.116AU ※ **[Fe/H] = -2.09**
HIP11952b --- 0.78木星質量@0.07AU ※ **[Fe/H] = -1.9**
c --- 2.93木星質量@0.81AU



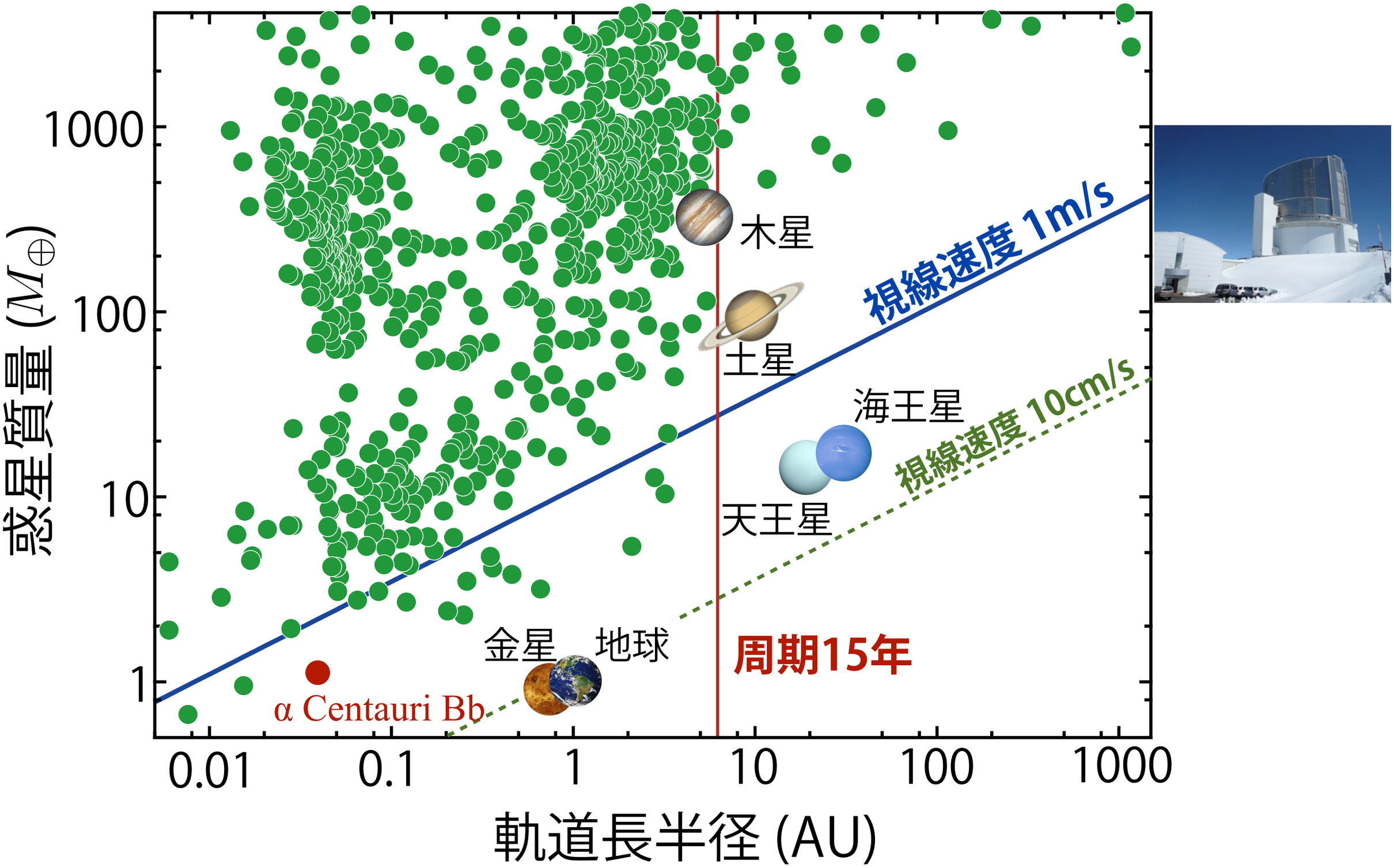
円盤不安定で**形成(?)**

※ コア集積モデル：[Fe/H]~-1.5+log(r/AU) --- dust沈殿 v.s 円盤散逸 (Johnson & Li,2012)

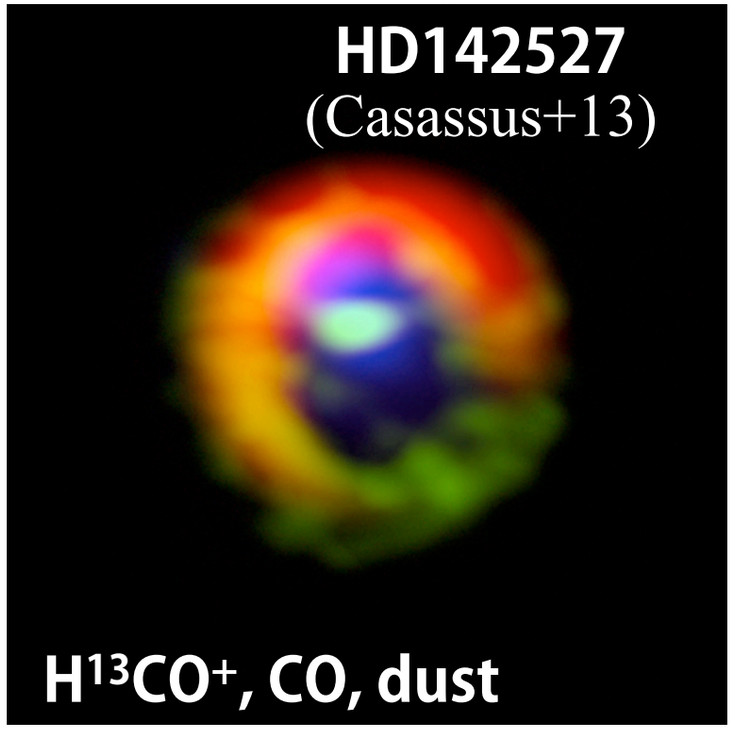
FGK型星周りのガス惑星砂漠 (0.1-1AU)

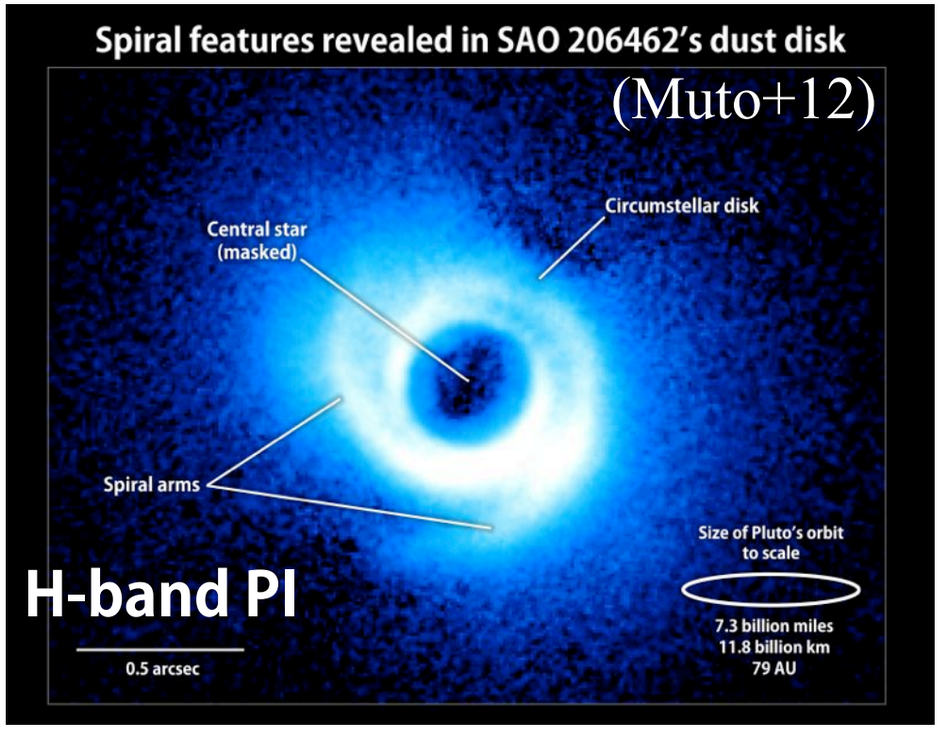


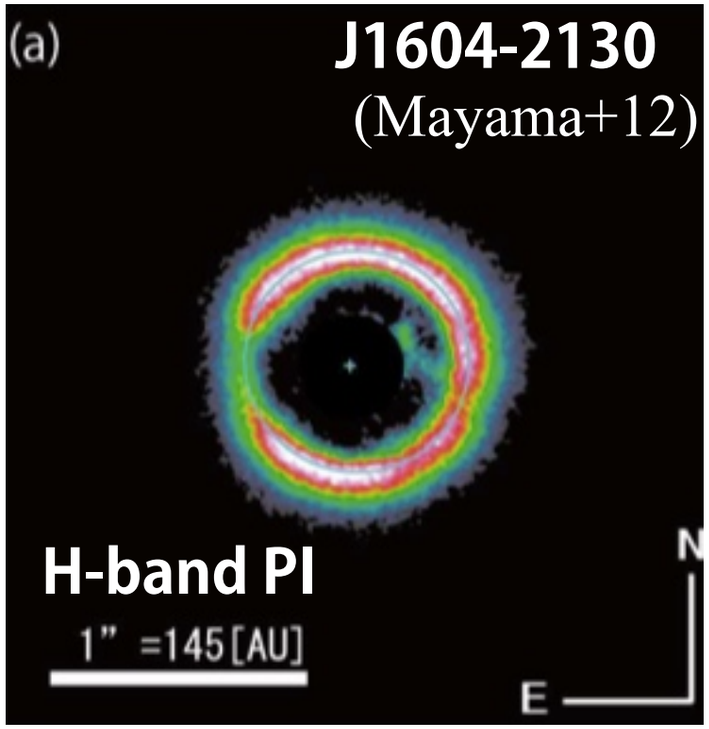
最後に、これからの太陽系外ガス惑星

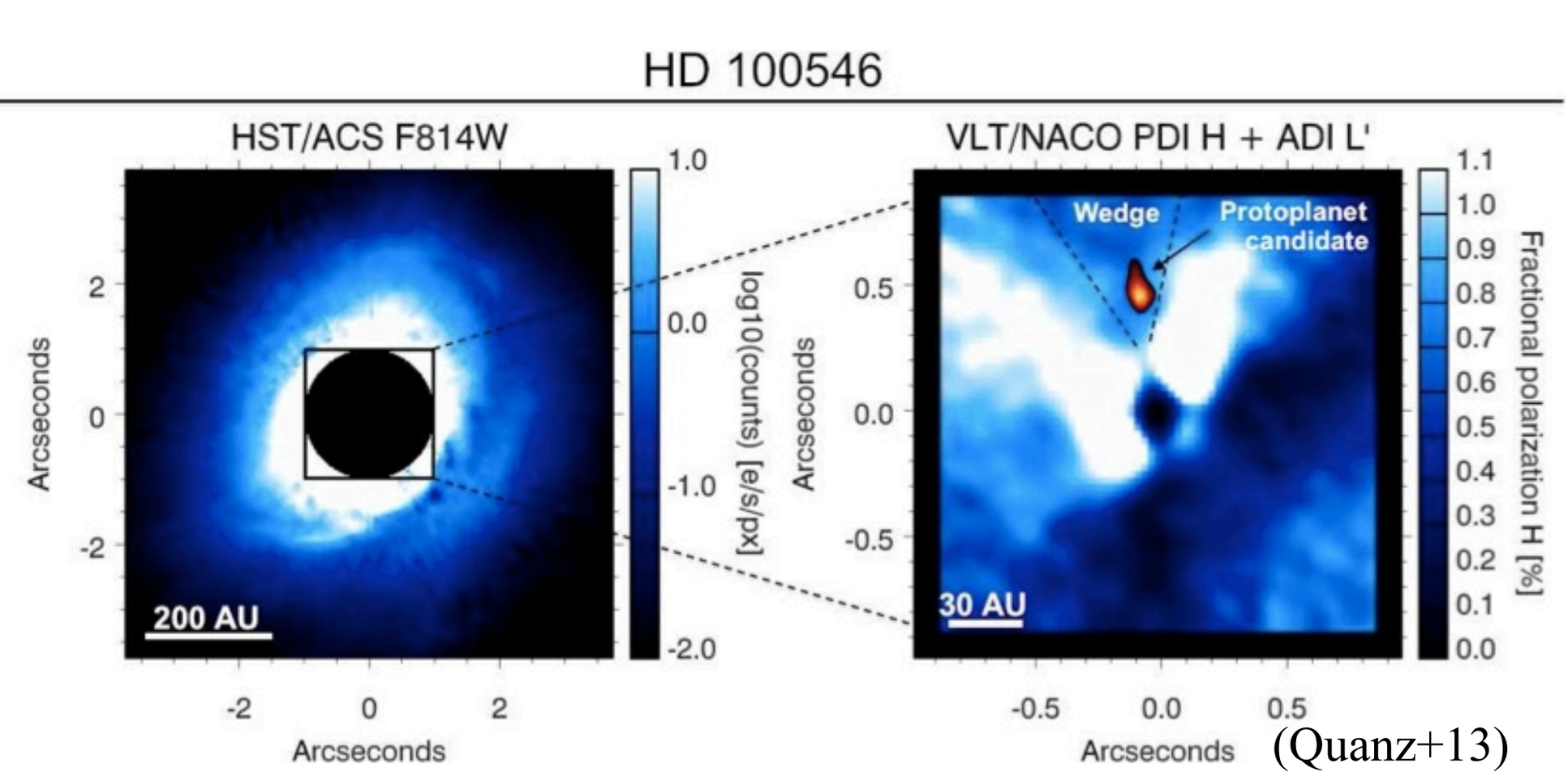


見え始めて来た系外(ガス)惑星 誕生の姿









(Quanz+13)

長らく、ご清聴ありがとうございました

森羅万象学校
The School of the Universe

国立天文台
NAOJ
National Astronomical Observatory of Japan

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