系外惑星研究の進展

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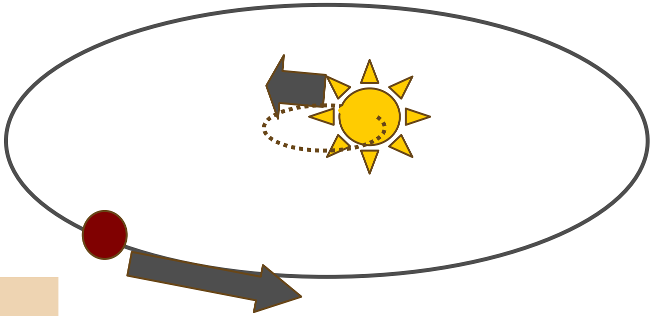
系外惑星系形成の理論モデル

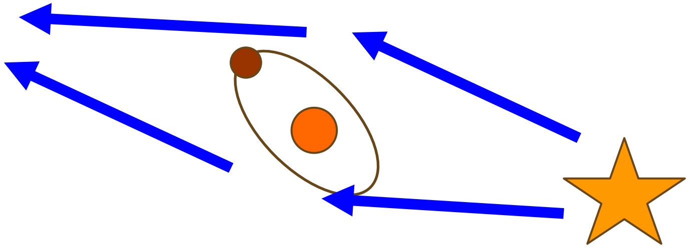
- 京都モデル (太陽系形成モデル) を祖とした多段階過程
- ただし、かなり進化 ← 観測の急進展 (原始惑星系円盤、ダスト・デブリ円盤、系外巨大惑星)
- 円盤観測 (初期状態) つなげる 系外惑星観測 (終状態)
  - 観測データを使って惑星形成の物理をキャリブレーション
  - 多様性の起源: ホット・ジュピター、エキセントリック・プラネット
- 観測の指針を与える
- 現状では観測不可能な惑星の予測
  - e.g. ハビタブル・プラネット (生命惑星) の分布
- 大きな展開
  - e.g. 天文学をハビタビリティ (生命) で再構築する

系外惑星の観測

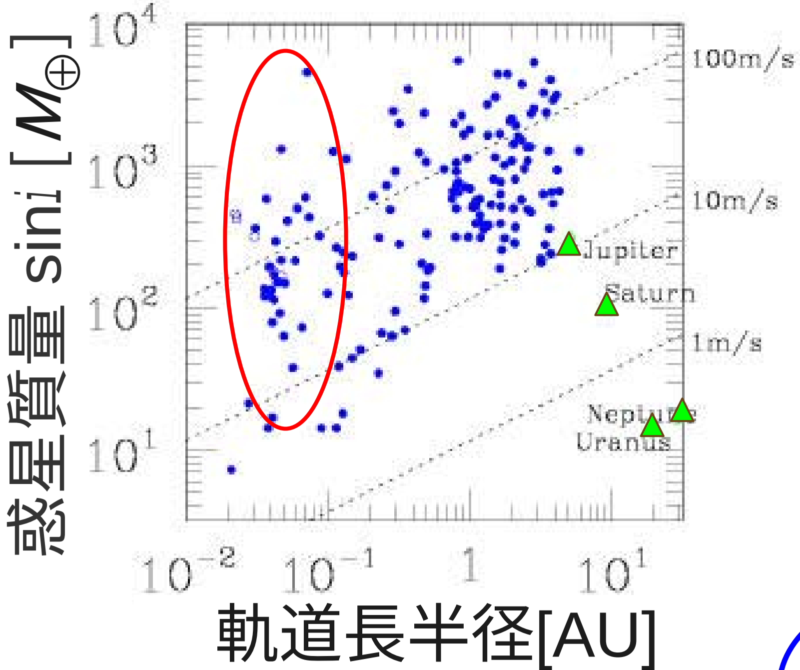
- 視線速度法 153の星, 186個
- トランジット 13個
- 重力レンズ 4個
- 直接撮像?

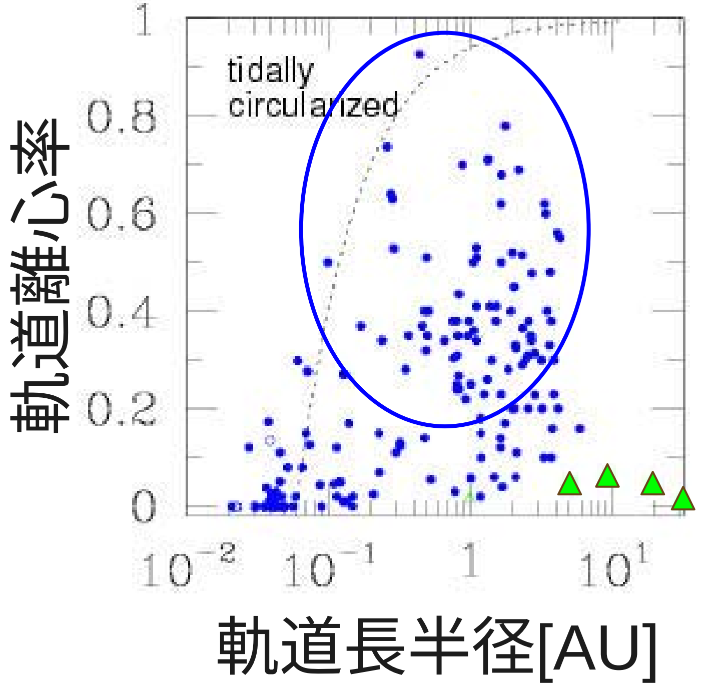


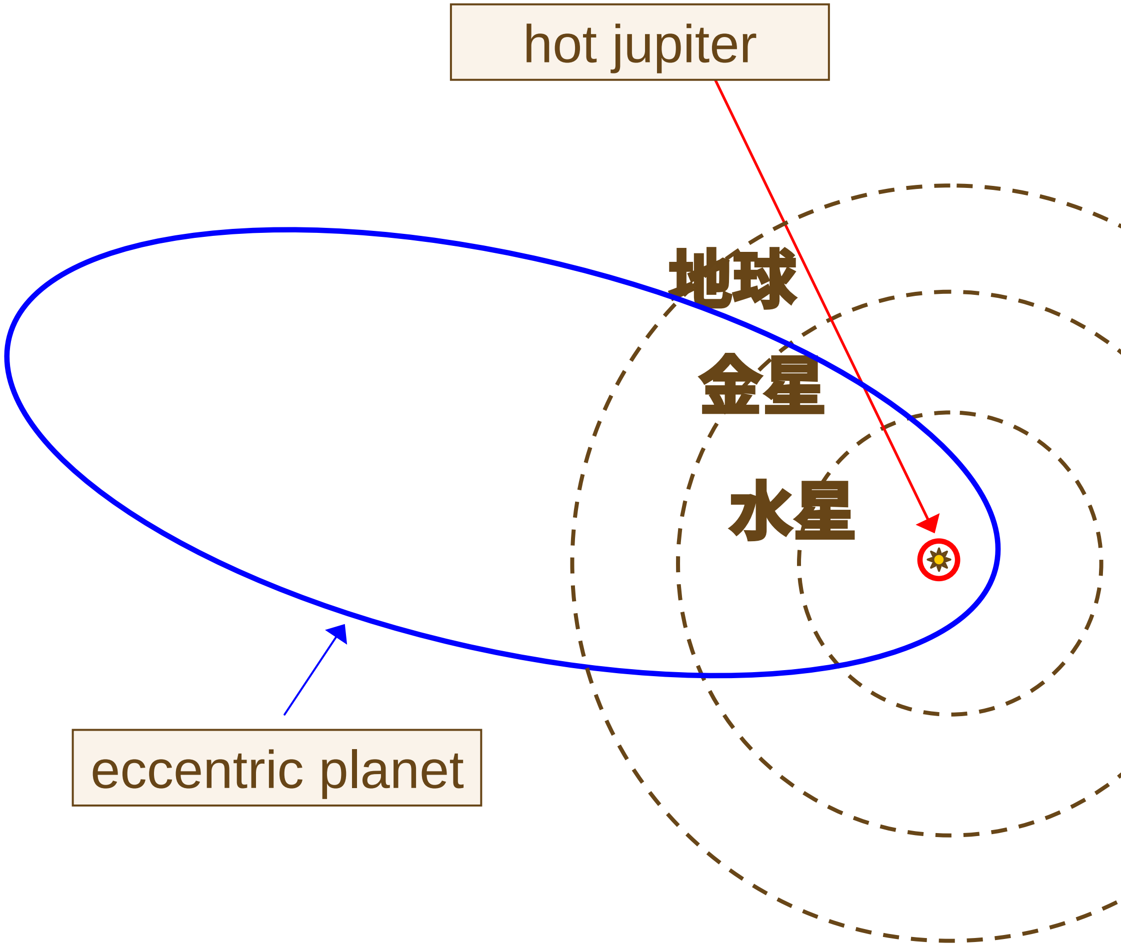
FGK矮星で $\eta_{\mathrm{J}} > 5\%$



観測された惑星：多様な軌道







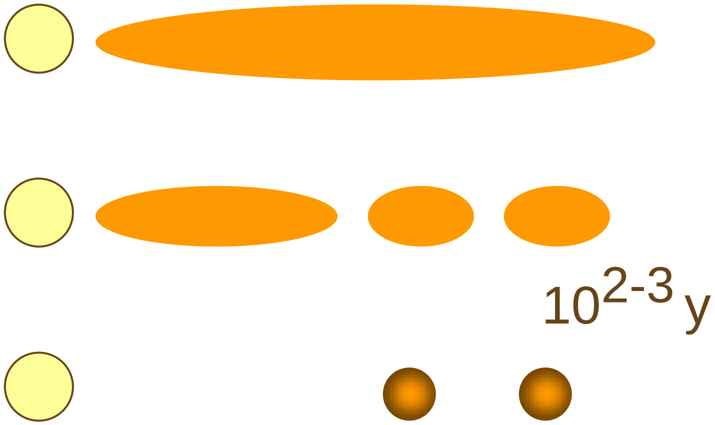
hot jupiter

eccentric planet

惑星形成の基本物理

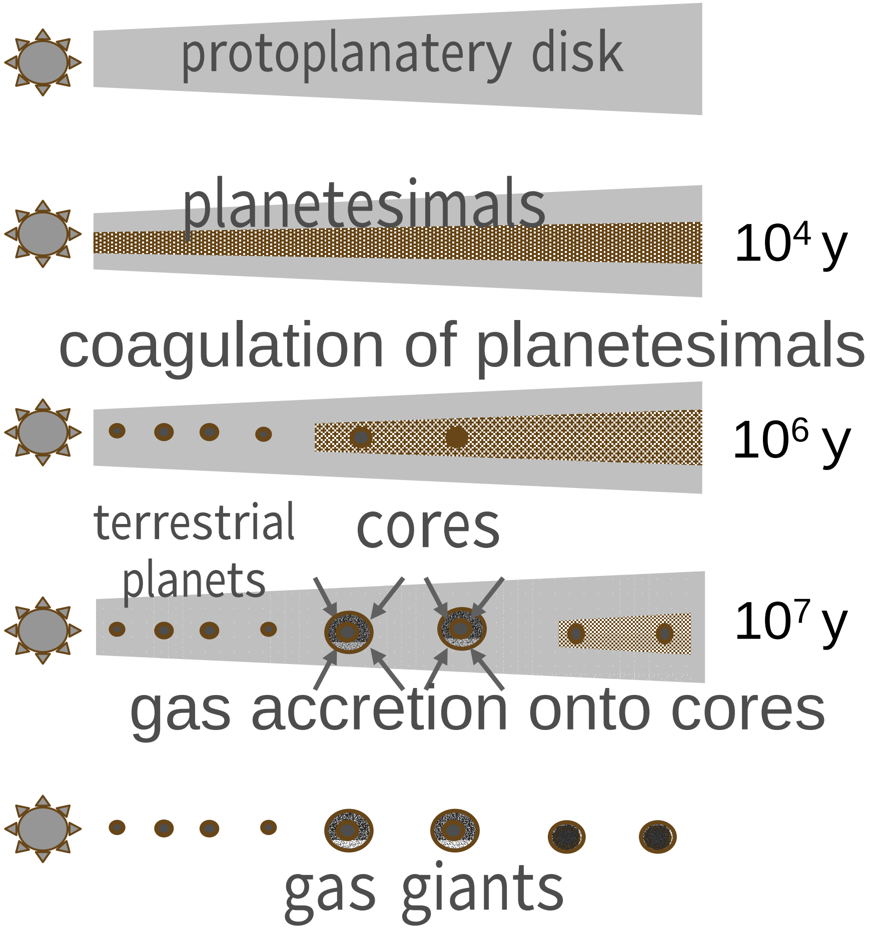
惑星形成モデル

自己重力不安定モデル



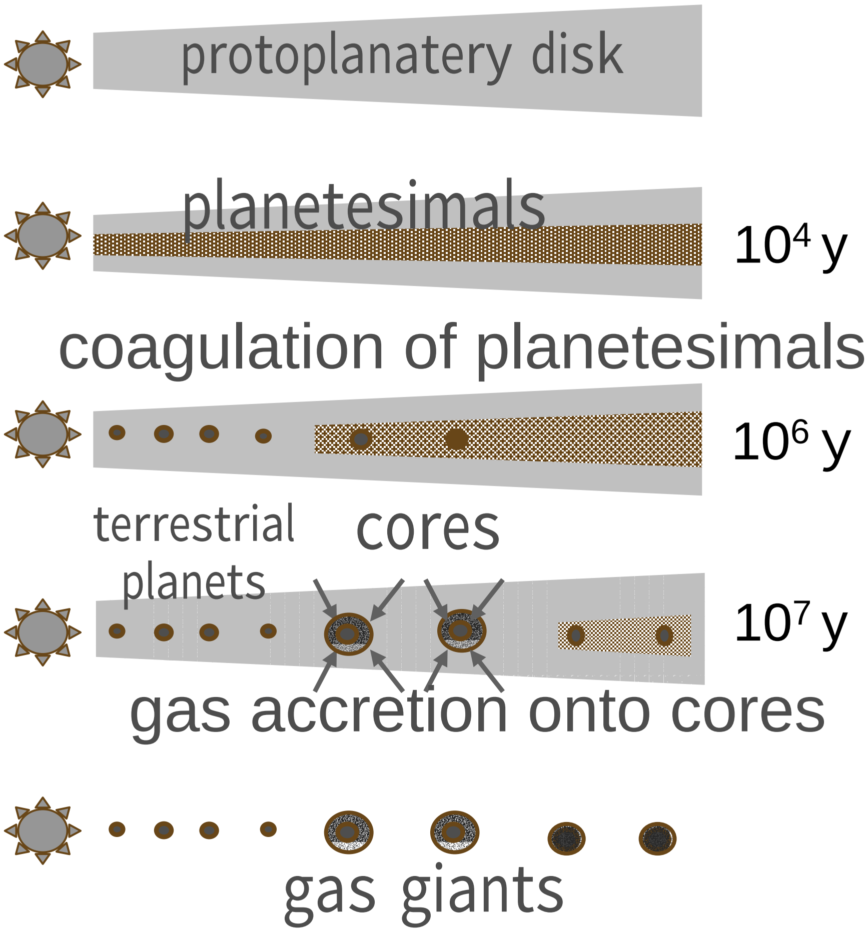
問題点
[Fe/H]依存性
~10$M_\oplus$の惑星多数発見

コア集積モデル(標準モデル)



原始惑星系円盤

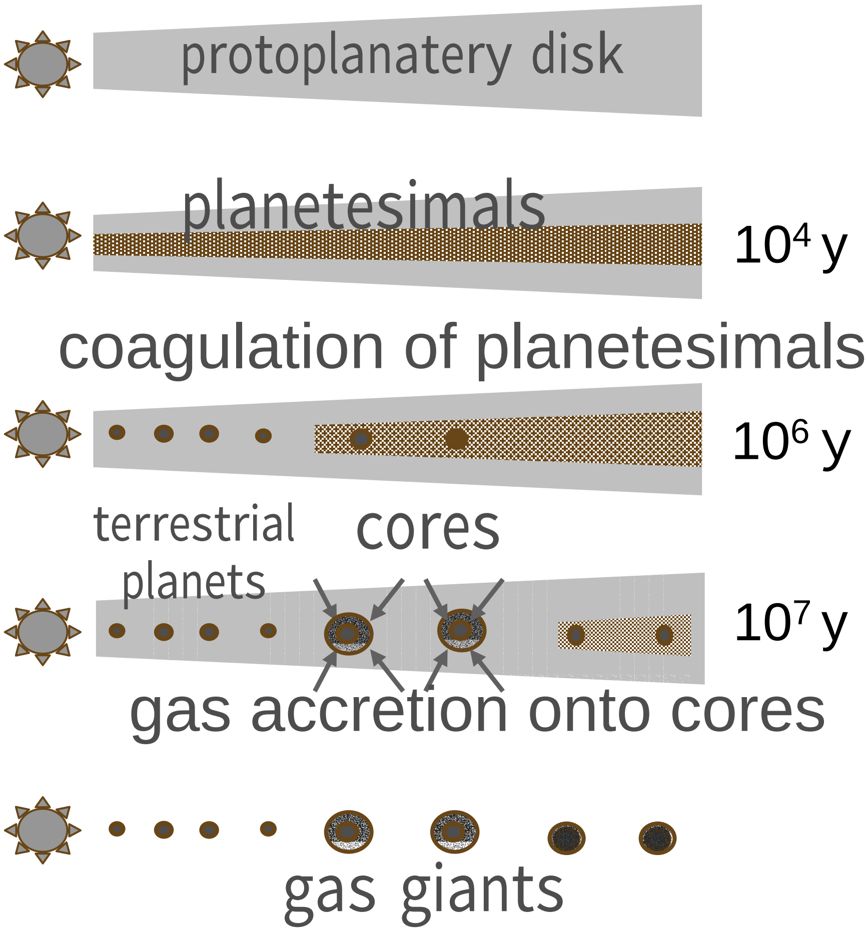
- 進化：MRI乱流の粘性拡散による降着 (+EUVによる蒸発)
  - 惑星系＝星形成の一部が取り残されたもの
- 観測データ
  - $M_{\mathrm{disk,dust}}$：初期条件
  - **lifetime** (ダスト放射)：ガス惑星形成を制約
  - $\mathrm{d}M_*/\mathrm{d}t$ vs t, vs M_*：降着円盤の性質



ダストから微惑星へ

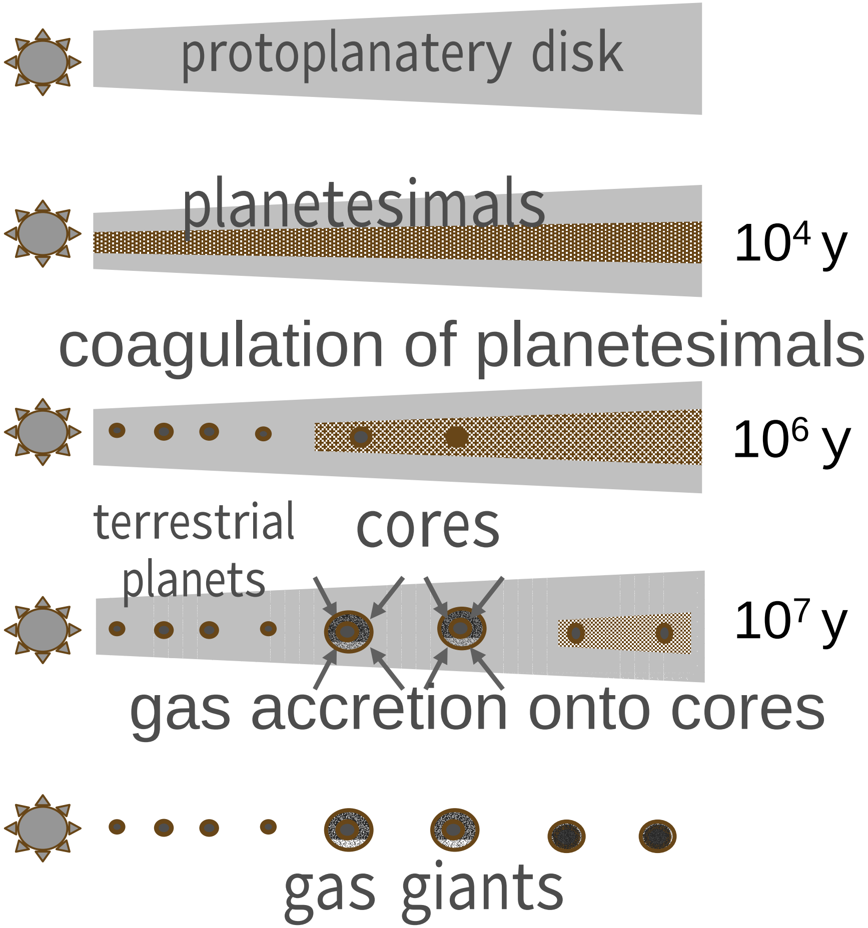
- **ダスト落下問題：**
  mサイズのダストは $10^{2\text{-}3}$年で中心星に落下

- 微惑星
  - > km：落下しない、自己重力で合体 ⇒ 惑星のビルディング・ブロック
  - **形成問題：** ダストの赤道面沈殿、薄い層形成
    ⇒ 自己重力不安定？
    MRI, KH乱流で阻害？
    乱流渦にダストを濃集？

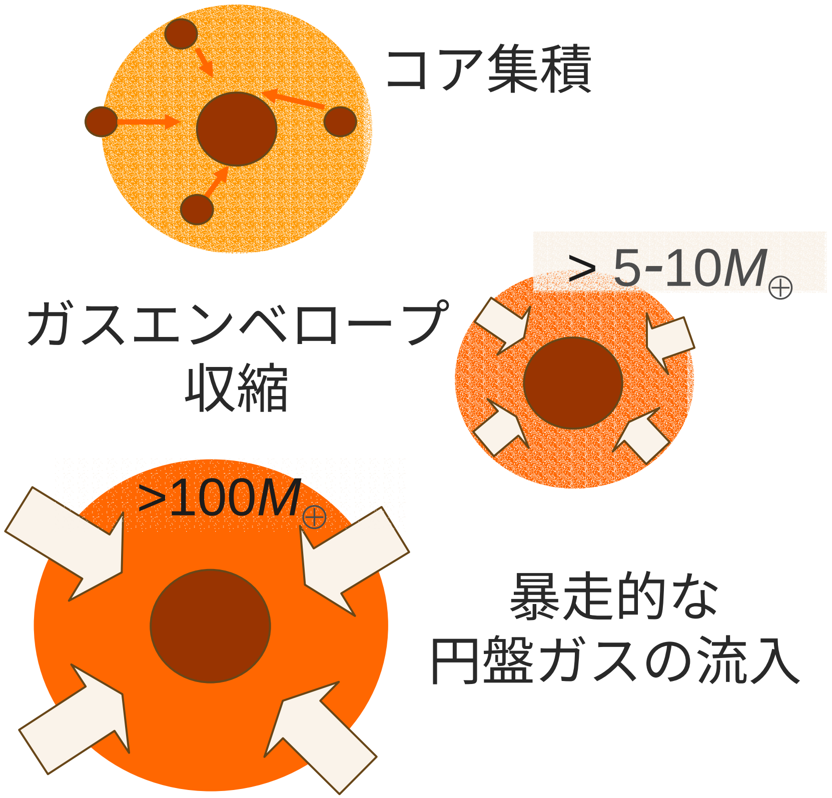


微惑星から原始惑星へ

- 微惑星の集積：よくわかっている（N体、統計的手法）
  - 暴走成長、寡占成長（原始惑星の形成）、原始惑星同士の衝突
- 惑星落下問題
  - 難問！
  - 地球、木星のコアは、１０万年以内に落下



微惑星から原始惑星へ



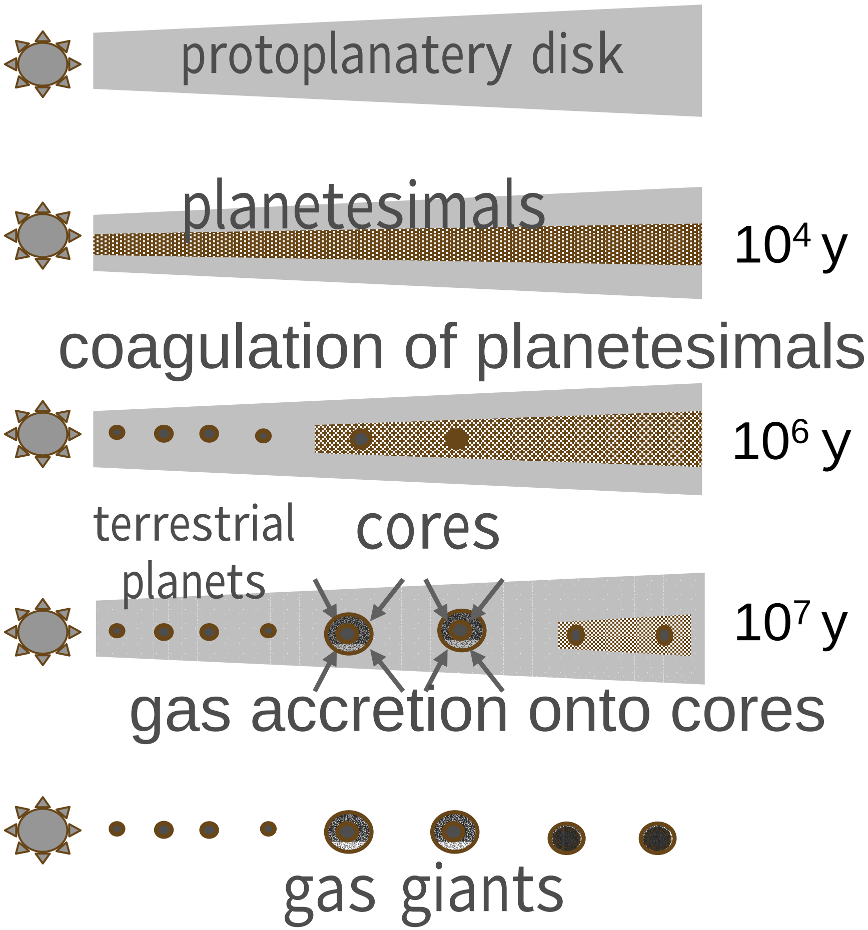
コア集積

ガスエンベロープ
収縮

$> 5\text{-}10 M_\oplus$

$>100 M_\oplus$

暴走的な
円盤ガスの流入



protoplanatery disk

planetesimals

10^4 y

coagulation of planetesimals

10^6 y

terrestrial
planets

cores

10^7 y

gas accretion onto cores

gas giants

外側領域で円軌道で形成

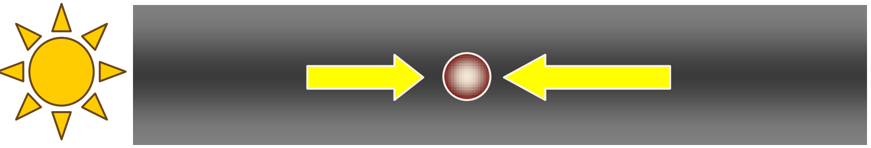
- 特に氷ダスト凝縮領域（＞3 AU for $\sim 1 M_\odot$ 恒星)
- 外過ぎると、コア成長が遅く、だめ

Disk-planet tidal interactions

type-I migration

Goldreich & Tremaine (1979),
Ward (1986, 1997), Tanaka et al. (2002)

$$M \sim (0.1-10)M_{\oplus}$$



disk torque imbalance

$$\tau_{\rm mig,I} \approx 5\times10^{4}\left(\frac{\Sigma_{\rm g}}{\Sigma_{\rm g,MMSN}}\right)^{-1}\left(\frac{M_{\rm p}}{M_{\oplus}}\right)^{-1}\left(\frac{a}{\rm 1AU}\right)^{\frac{3}{2}}\ {\rm yrs}$$

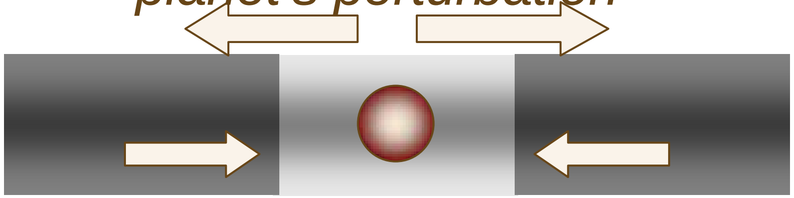
円盤ガスよりもずっと速く落下

type-II migration

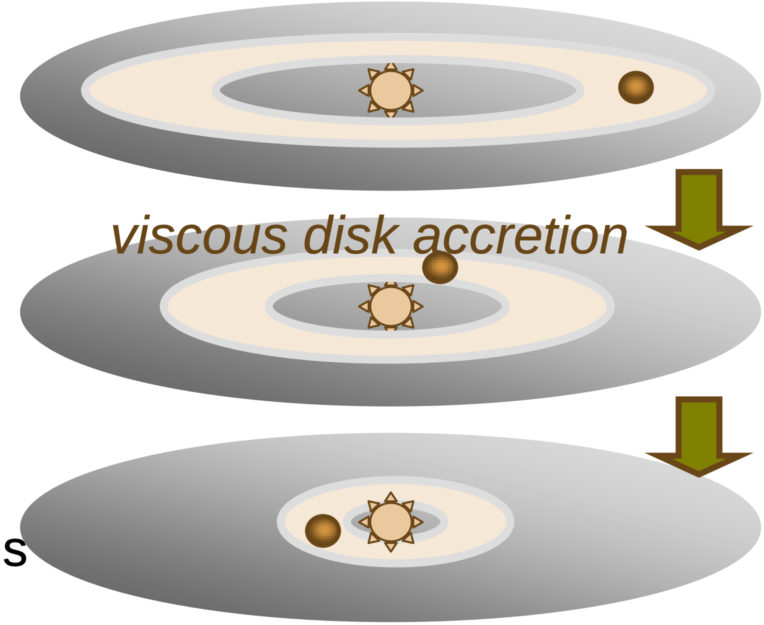
Lin & Papaloizou (1985),....

$$M > (10-100)M_{\oplus}$$

planet's perturbation



viscous diffusion



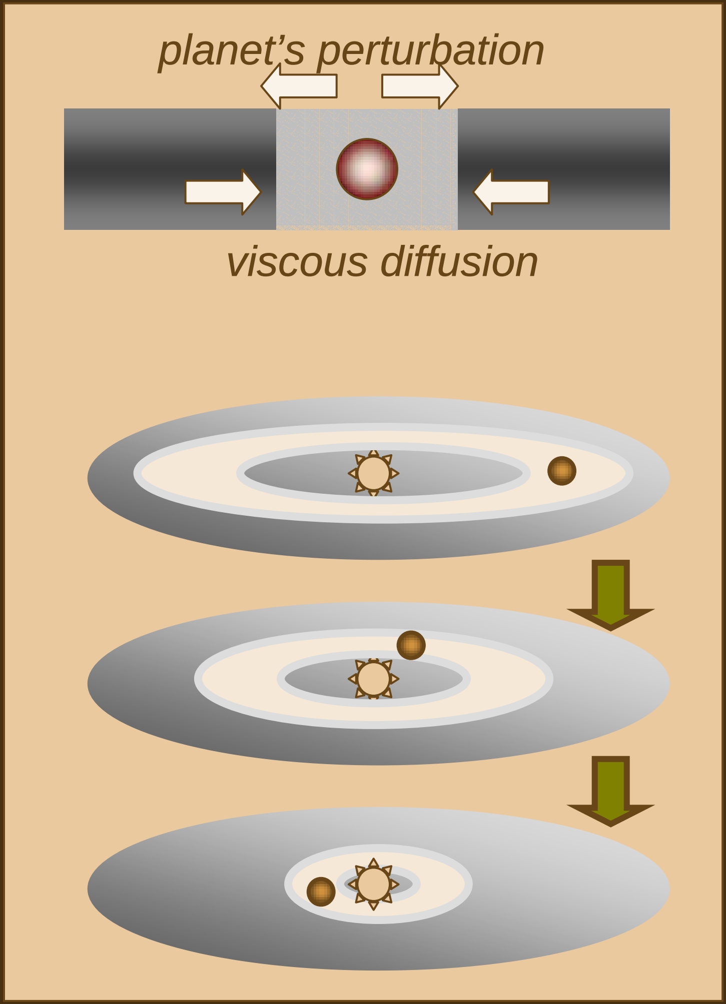
viscous disk accretion

$$\tau_{\rm mig,II} \approx 10^{6}\left(\frac{\Sigma_{\rm g}}{\Sigma_{\rm g,MMSN}}\right)^{-1}\left(\frac{M_{\rm p}}{M_{\rm J}}\right)\left(\frac{\alpha}{10^{-3}}\right)^{-1}\left(\frac{a}{\rm 1AU}\right)^{\frac{1}{2}}\ {\rm yrs}$$

系外惑星の多様性の起源

type II migration → ホット・ジュピターの起源

[もとは惑星非存在論の論拠、あまり注目されていなかった]

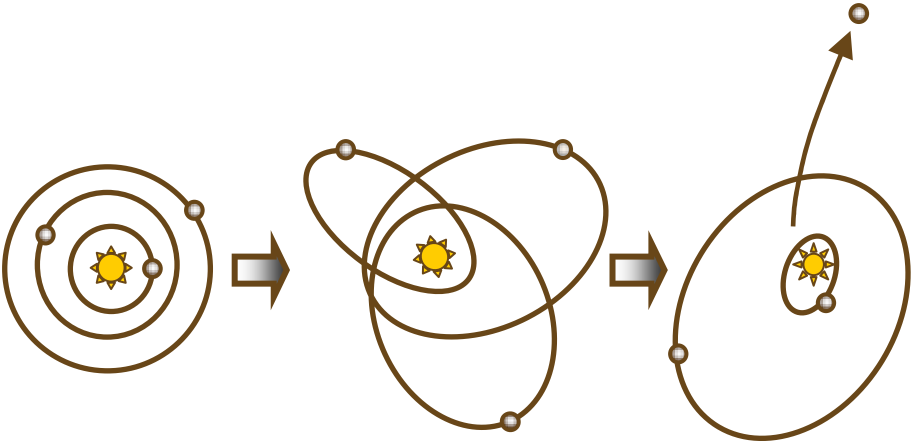


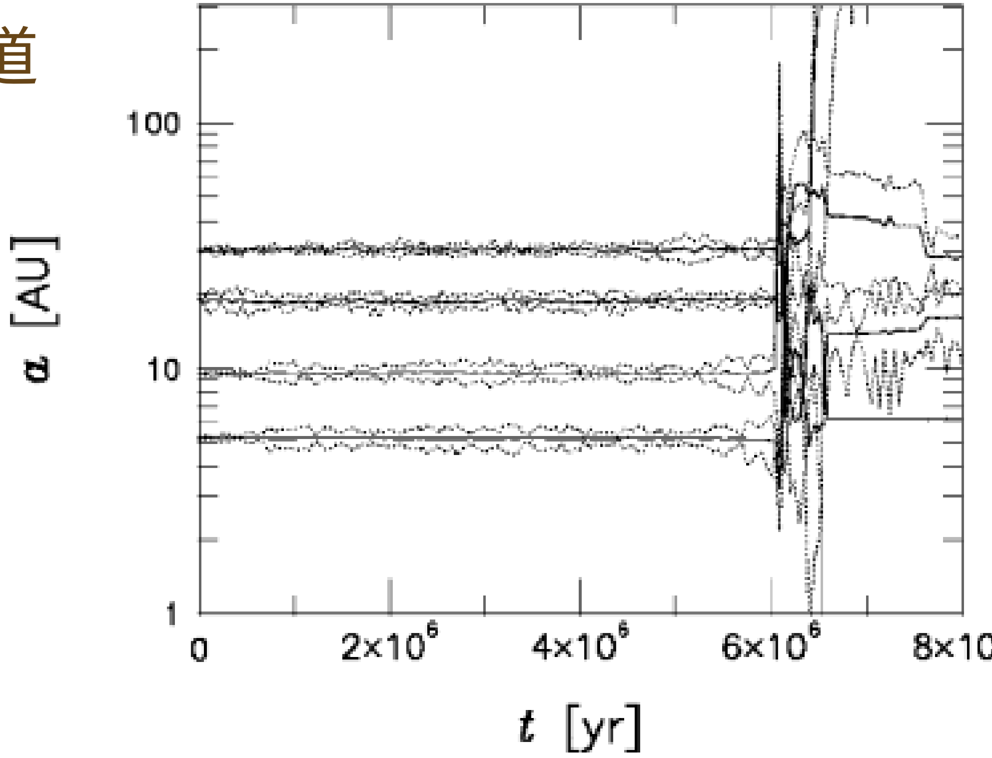
惑星軌道の不安定化→エキセントリック･プラネットの起源

[もとは地球型惑星の巨大衝突の論拠、論文は一旦は rejected]

- 3個以上の巨大惑星（円軌道） [2個では安定]
- 永年摂動で軌道交差開始
- 一つが放出

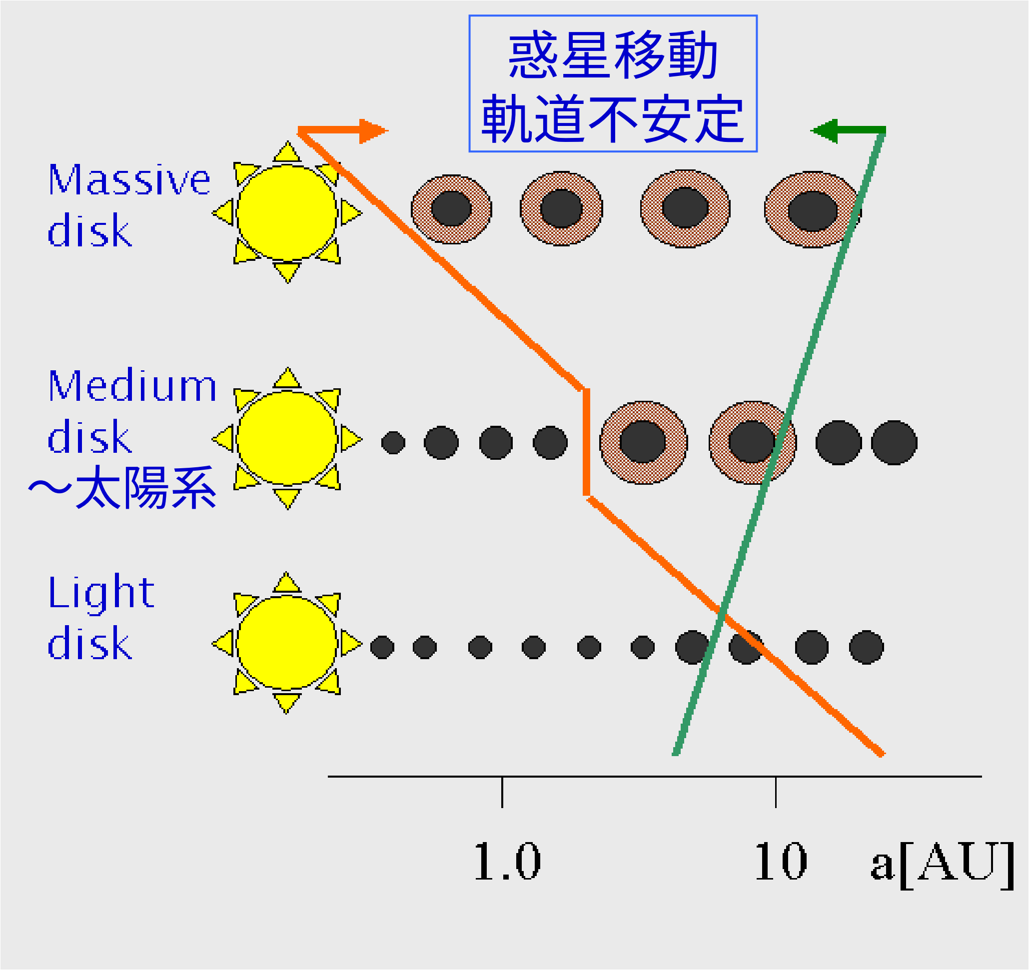
  残りが分離した安定楕円軌道
  - $a_{\mathrm{in,最終}} \sim 0.5a_{\mathrm{in,初期}}$
  - $a_{\mathrm{out,最終}} \sim$ 10-50AU





惑星系の多様性 ← 円盤質量?

Kokubo&Ida(2002), Ida&Lin(2004)



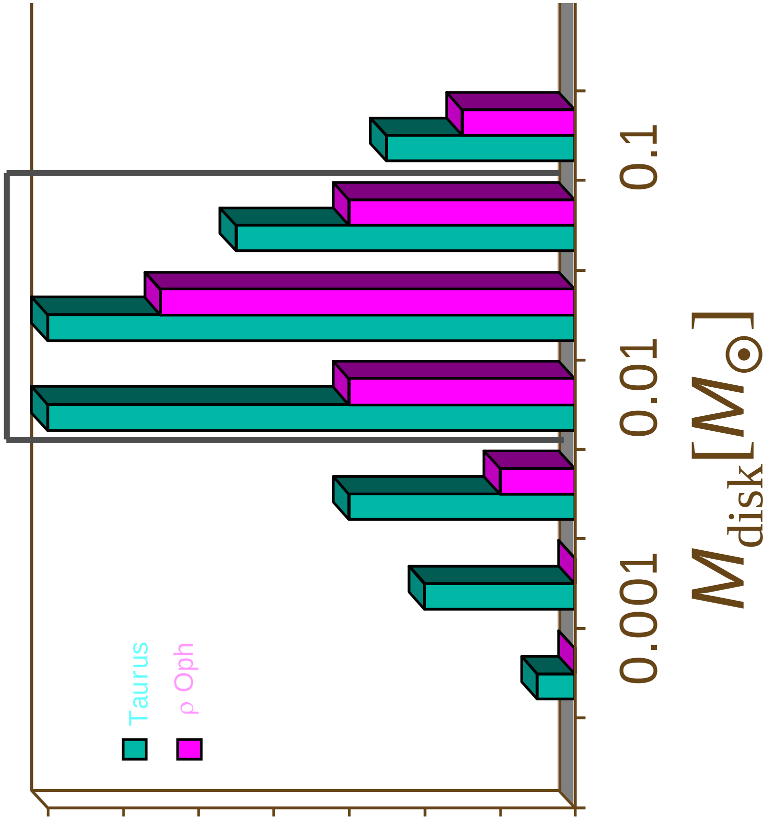
惑星移動
軌道不安定

Massive disk

Medium disk
〜太陽系

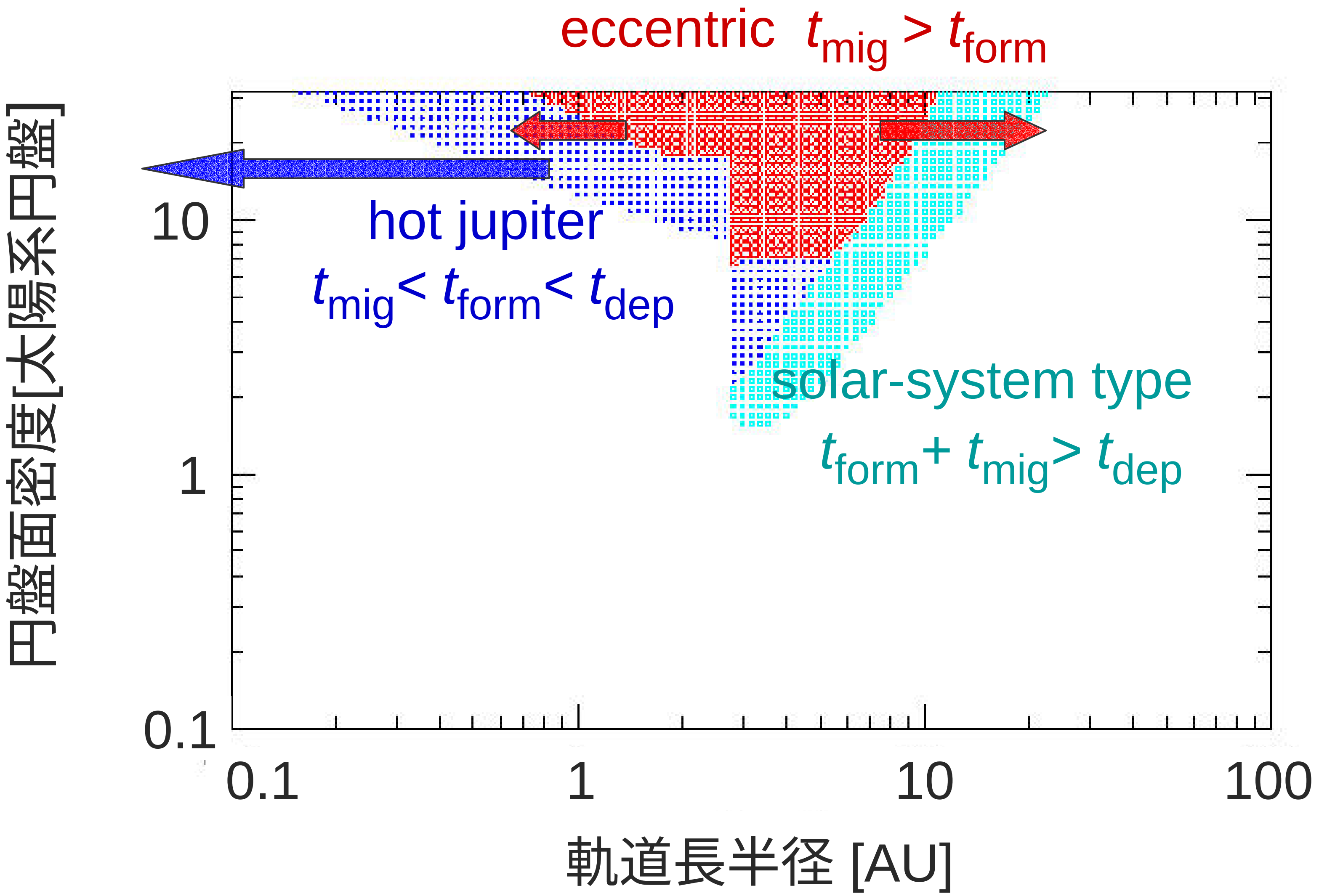
Light disk

Tタウリ星の円盤質量の電波観測
Beckwith & Sargent (1996)

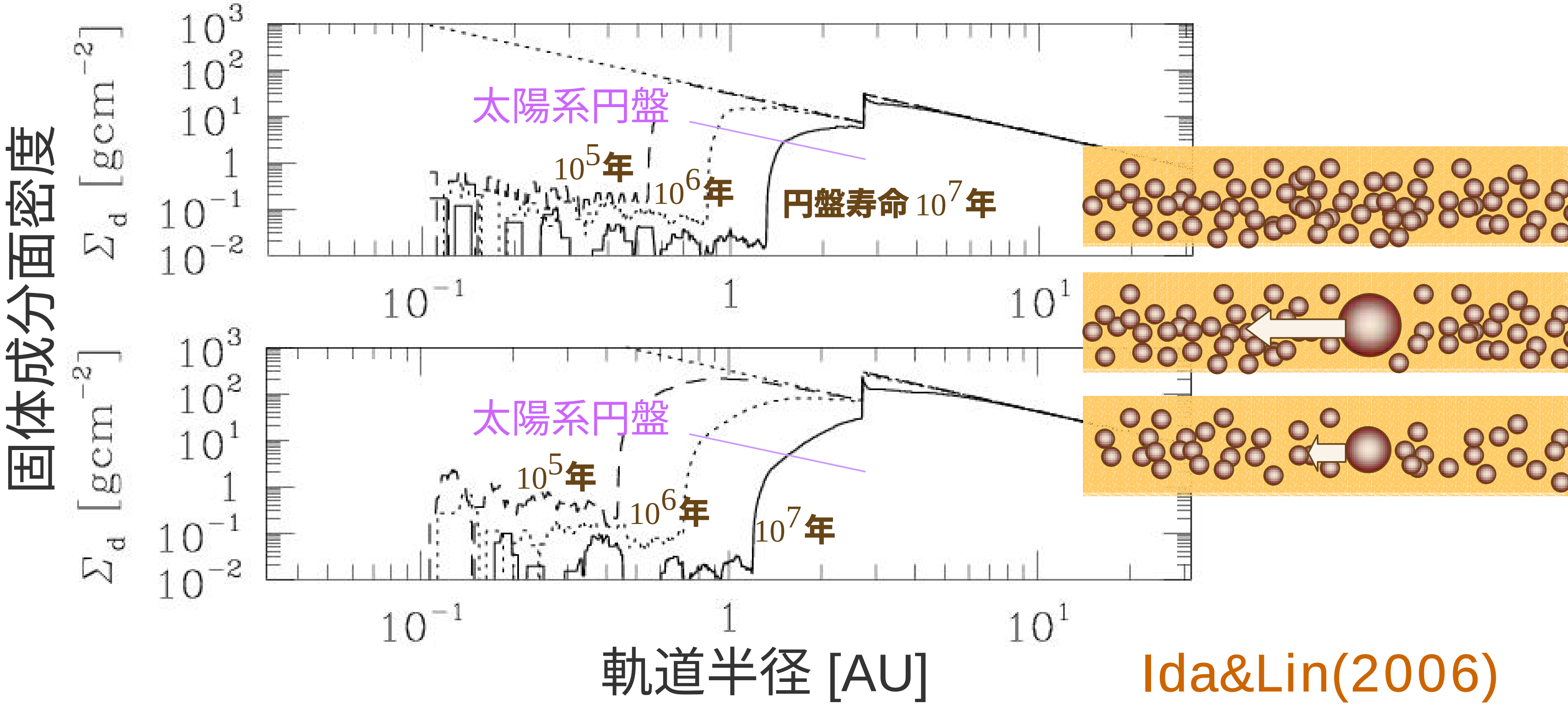


Diversity of gas giant planets

Ida&Lin(2006)



type-I migration



Ida&Lin(2006)

- 円盤寿命10^6-10^7年：1-2AUで火星クラス原始惑星が多数残る。
  円盤ガス散逸後、原始惑星合体で地球サイズ惑星形成。
- self-regulation: 重い円盤での ~1AUでの木星型惑星形成阻止。
- 系外巨大惑星の分布も説明可能 (late formation model)

Monte Carlo simulation

theoretical prediction for *M-a* distribution of exoplanets
with the overall planet formation model
(type-I & II migrations are included)

start from planetesimals

Σ, $a_{\rm ini}$ =(integration on 10^9y)$\Rightarrow$ M_p, $a_{\rm final}$

1) Ida & Lin (2004a, ApJ, 604, 388)
2) Ida & Lin (2004b, ApJ, 616, 567)
3) Ida & Lin (2005, ApJ, 626, 1045)
4) Ida & Lin (2006, ApJ, submitted)

Monte Carlo simulation to predict M_p-a distribution of exoplanets

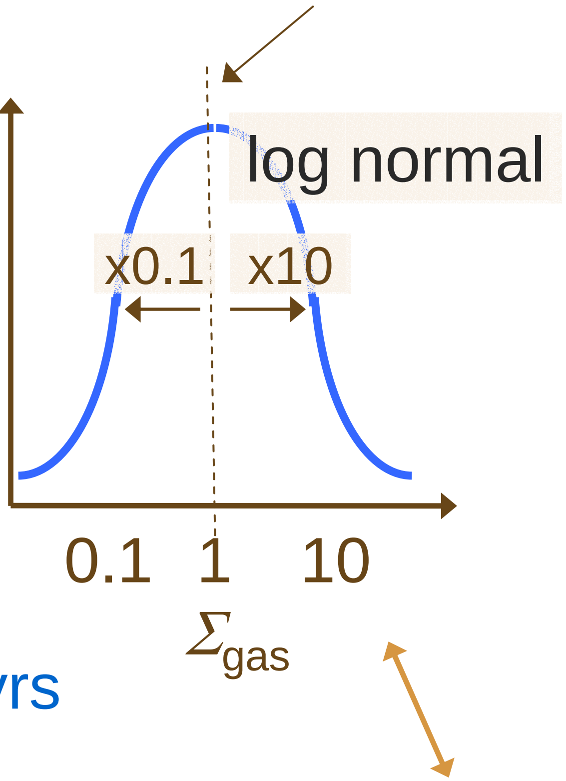
- **disk gas surface density Σ_g :**
  - initial distribution: log normal

    $\Sigma_g(0) = 0.1\text{-}10\,\Sigma_{g,\mathrm{MMSN}} \times (M_*/M_\odot)^2$
  - *a priori* exponential decay

    $\Sigma_g(t) = \Sigma_g(0)\exp(-t/\tau_{\mathrm{dep}})$
- **planetesimal surface density**

  $\Sigma_{pl}(0) \sim 10^{[\mathrm{Fe/H}]} \times 0.01\,\Sigma_g(0)$; [Fe/H]=0.2
- **semimajor axis** : log uniform
- **disk lifetime τ_{dep}** : log uniform 10^6-10^7yrs
- **migration:** artificially stopped at 0.04AU

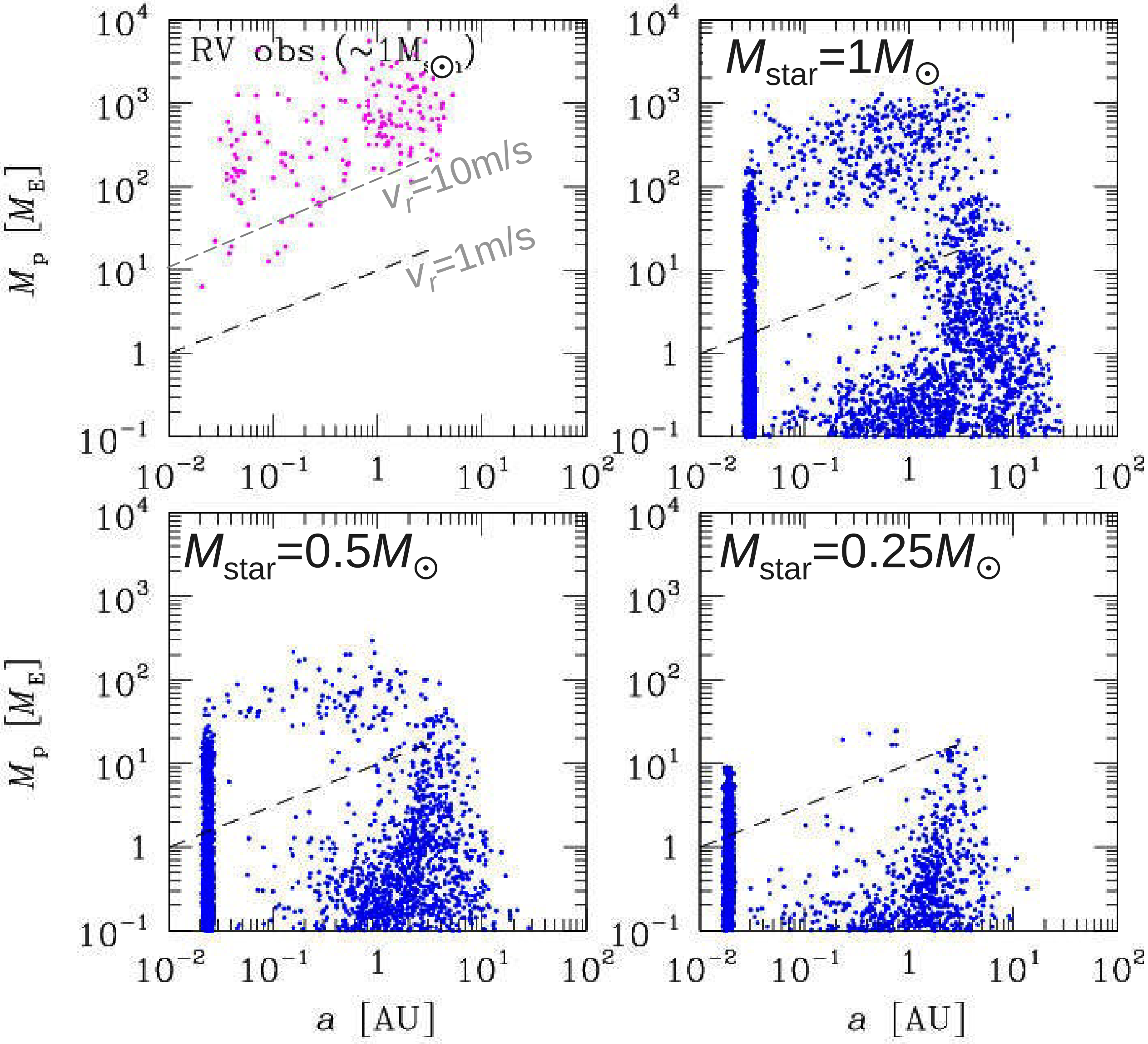
Min. Mass Solar Nebula



radio observation of disks around T-Tauri stars
Beckwith & Sargent (1996)

planets around various mass stars

with type-I migration



with k=8,C_1= 0.1,[Fe/H]=0.2

- gas giants
  - $M_{\rm star}$~1.0$M_\odot$: abundant
  - $M_{\rm star}$~0.5$M_\odot$: marginal
  - $M_{\rm star}$~0.25$M_\odot$: rare

$\Sigma_{\rm pl}$ &T ↘ for $M_{\rm star}$ ↘

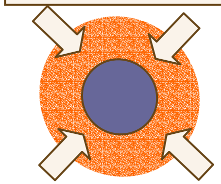
Laughlin et al. 2004
Ida & Lin 2005

consistent with current RV & microlensing surveys

constraints on type-I mig & envelope contraction

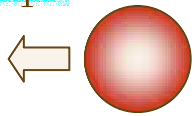
G dwarfs
obs: many gas giants

envelope contraction



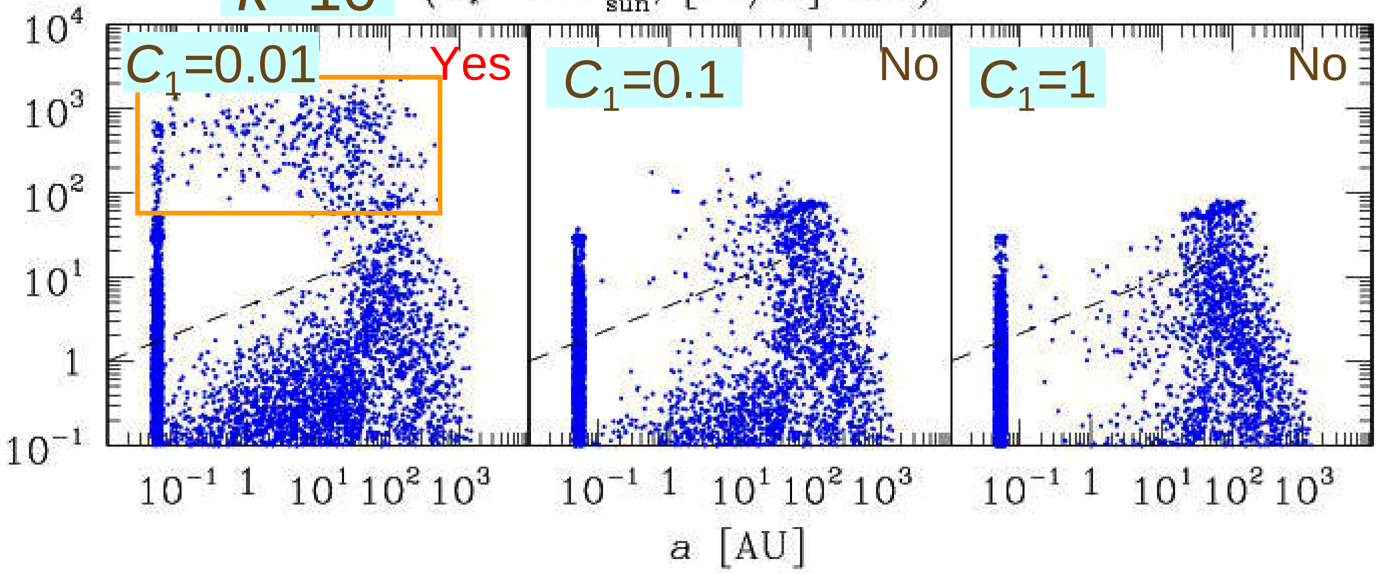
$$\frac{M_p}{\dot{M}_p} \approx 10^{k} \left(\frac{M_p}{M_\oplus} \right)^{-3} \text{ yrs}$$

$$C_1 = \dot{a} / \dot{a}_{\text{linear}}$$



type-I migration

k=10 ($M_* = 1.0 M_{\text{sun}}$, [Fe/H]=0.2)



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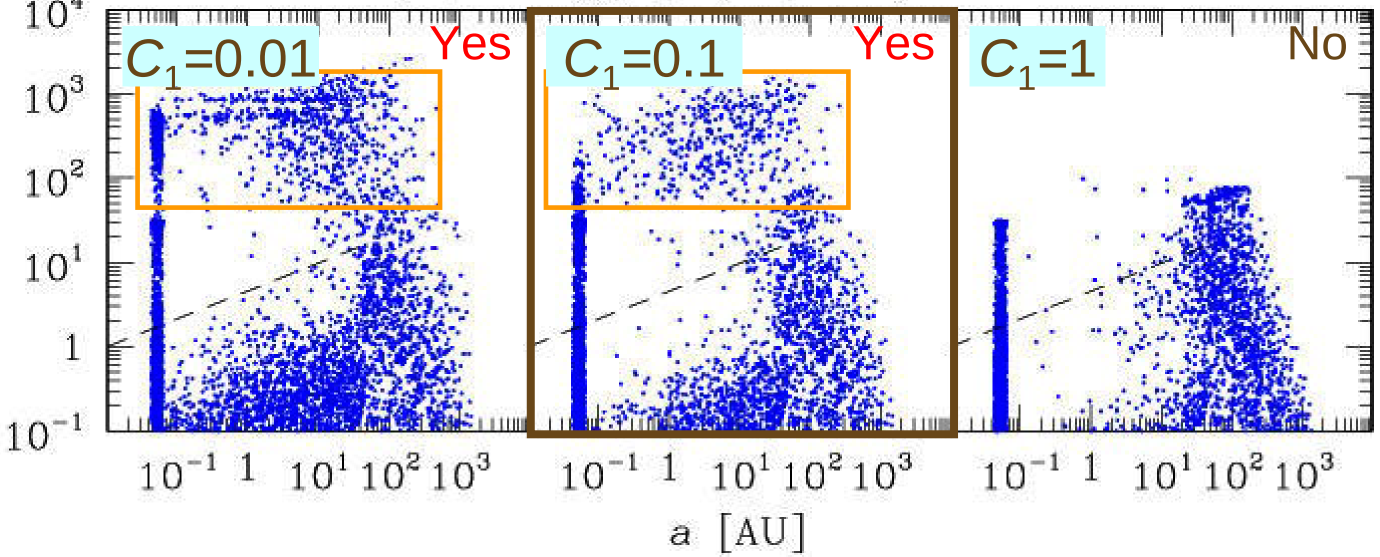
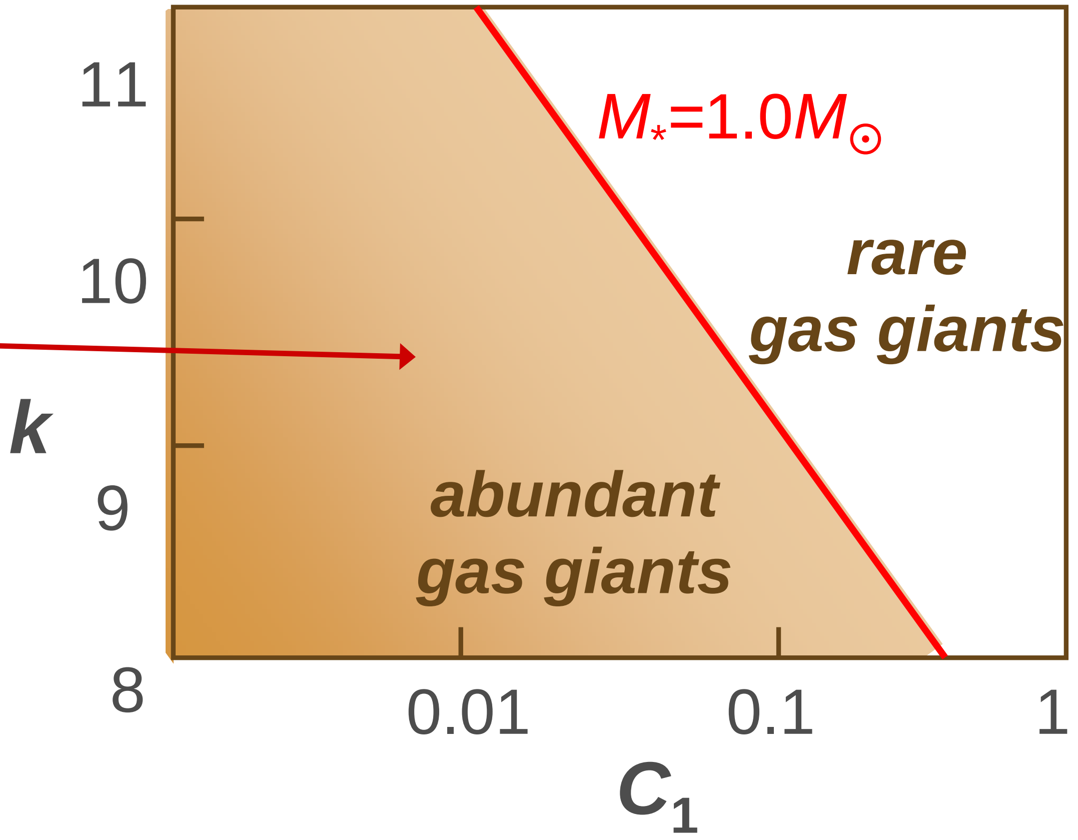


constraints on type-I mig & envelope contraction

- **M_*~1.0$M_\odot$**
  - observed gas giants: abundant
  - C_1 & *k* must be

theoretical results for [Fe/H]=0.2



$$\frac{M_p}{\dot{M}_p} \approx 10^{k} \left(\frac{M_p}{M_\oplus}\right)^{-3} \text{ yrs}$$

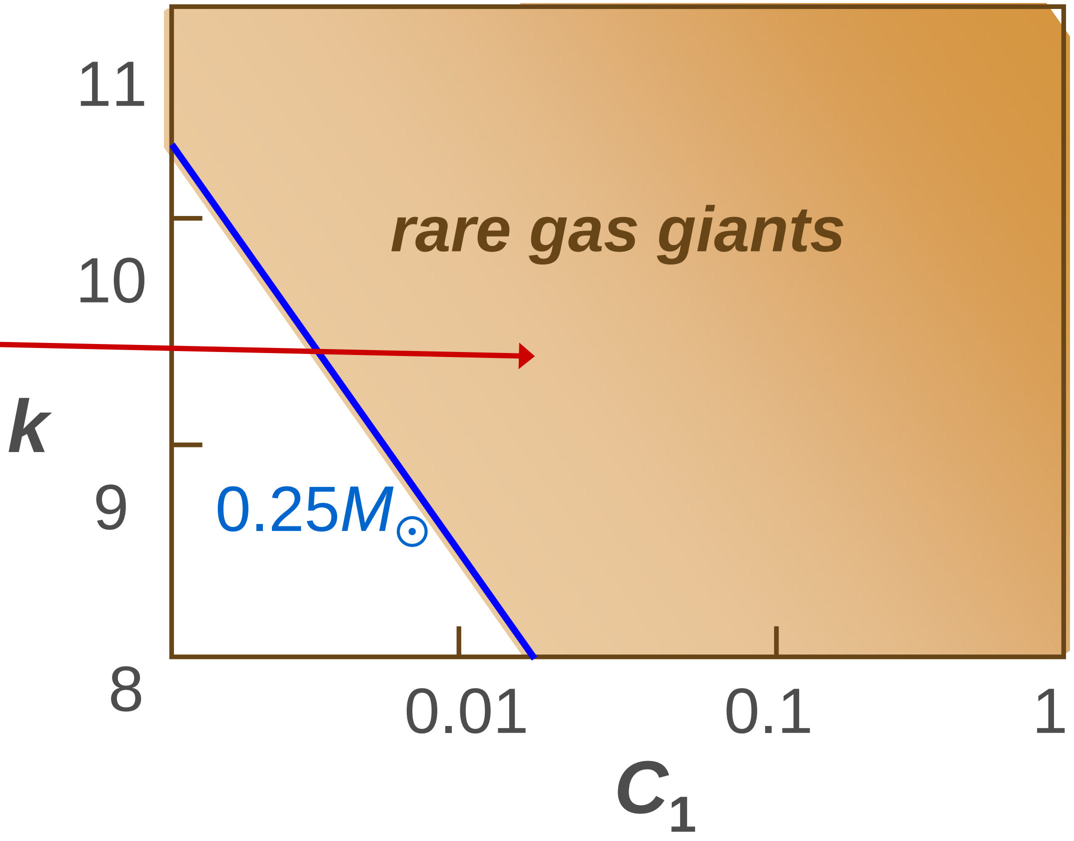
k~11: Pollack et al. with “phase II”
k~10: Pollack et al. for “phase III”
k~8: Ikoma et al. (different opacity table)

$$C_1 = \dot{a} / \dot{a}_{\text{linear}}$$

constraints on type-I mig & envelope contraction

- $M_* \sim 0.25 M_\odot$
  - observed gas giants: rare
  - C_1 & k must be

theoretical results for [Fe/H]=0.2



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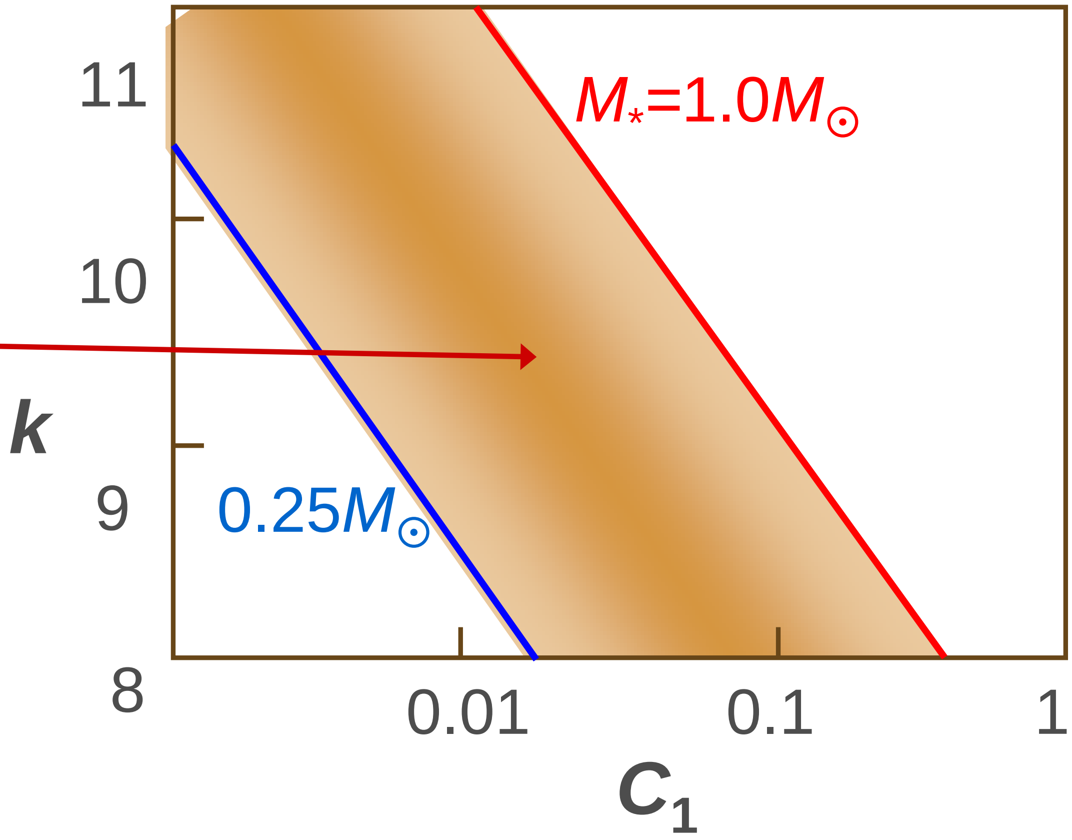
constraints on type-I mig & envelope contraction

- observed gas giants
  - M_*~1.0$M_\odot$: abundant
  - M_*~0.25$M_\odot$: rare

→ C_1 & k must be

theoretical results for [Fe/H]=0.2



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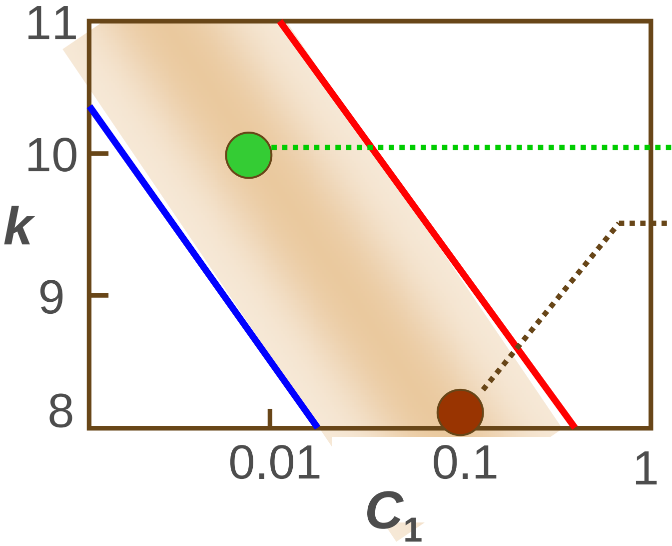

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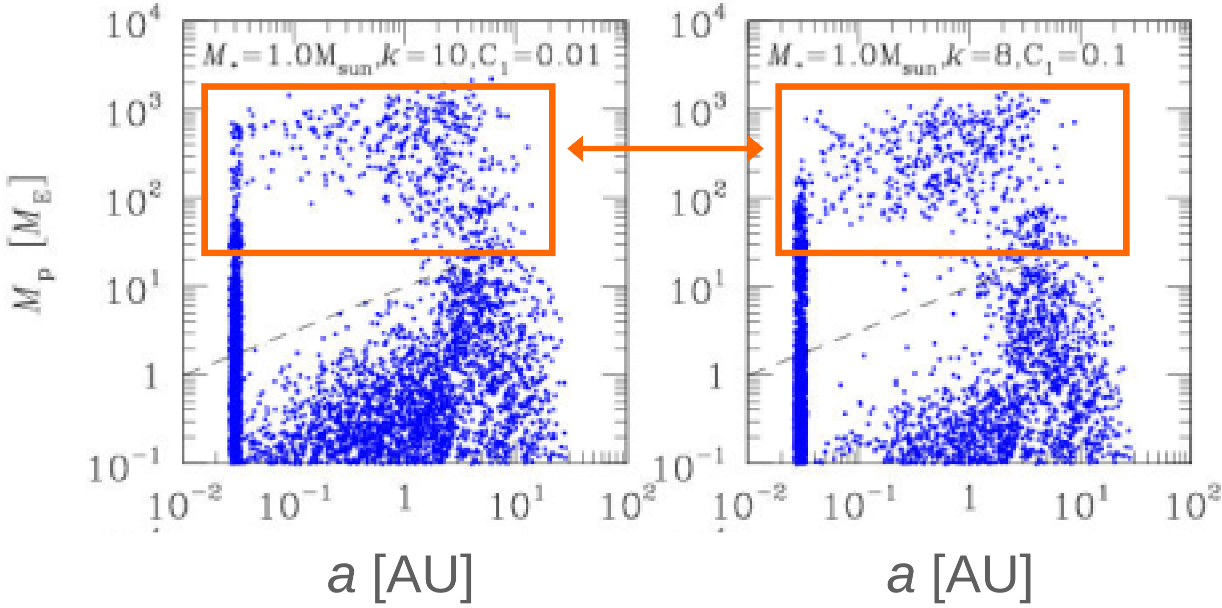
$$C_1 = \dot{a} / \dot{a}_{\text{linear}}$$

theoretical results for [Fe/H]=0.2
$M_* = 1.0 M_\odot$

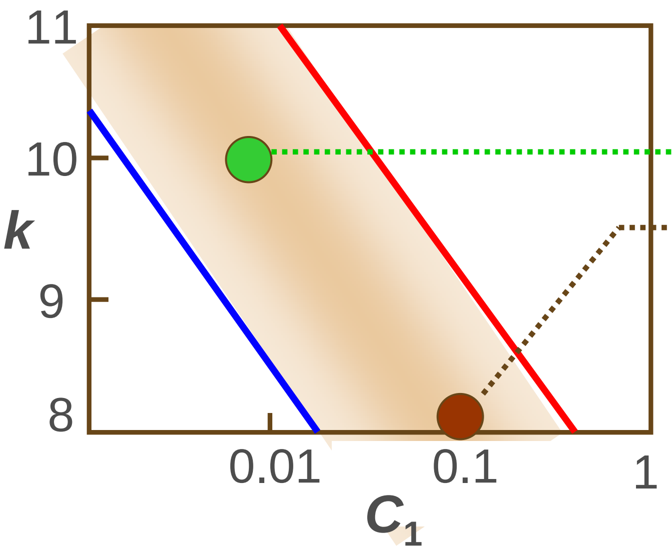
C_1=0.01,k=10

C_1=0.1,k=8



constraints on type-I mig & envelope contraction

theoretical results for [Fe/H]=0.2
$M_*=1.0M_\odot$



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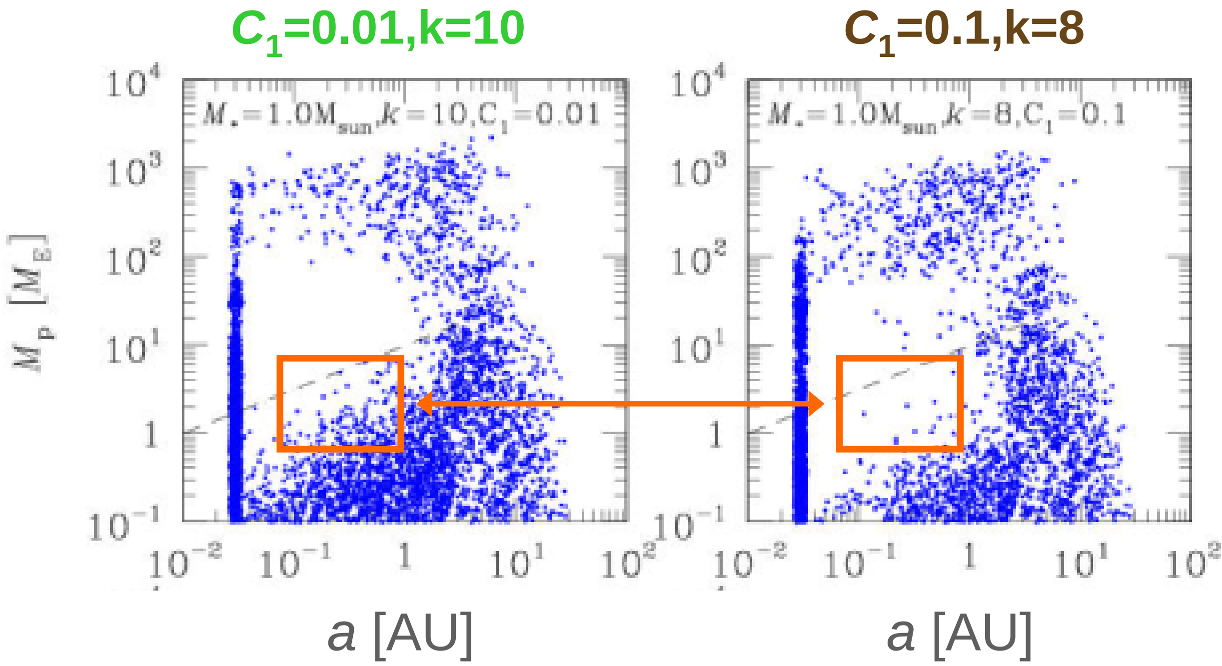
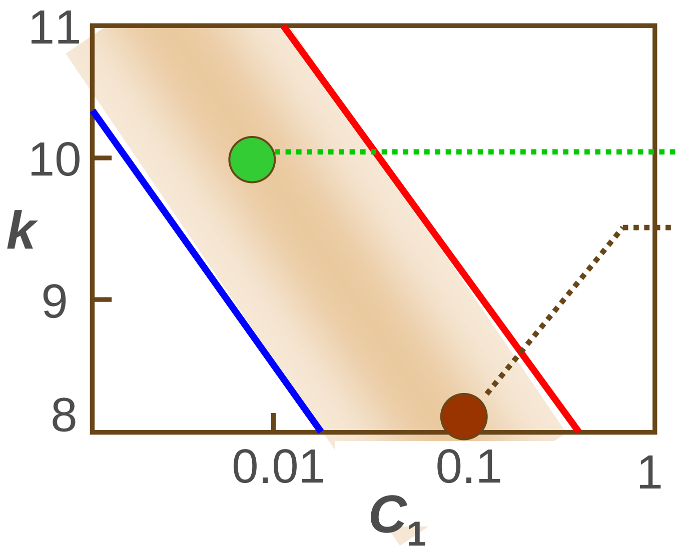


Corot/Kepler will distinguish

constraints on type-I mig & envelope contraction



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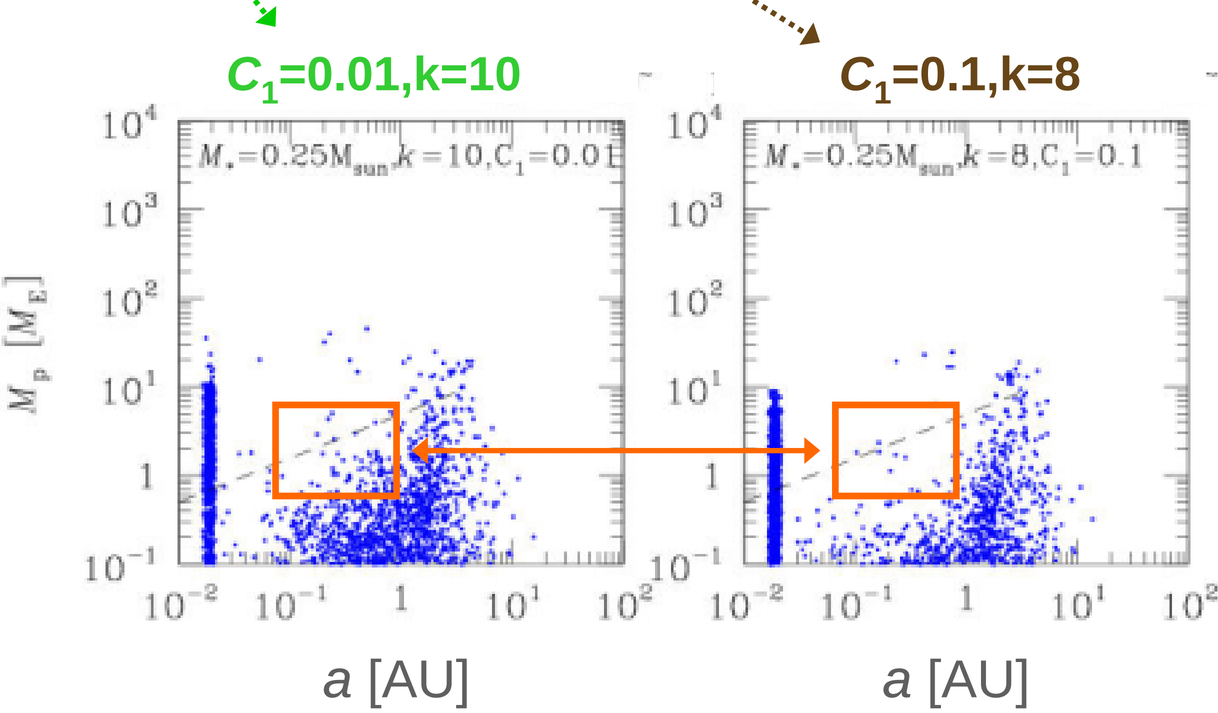
$$C_1 = \dot{a} / \dot{a}_{\text{linear}}$$

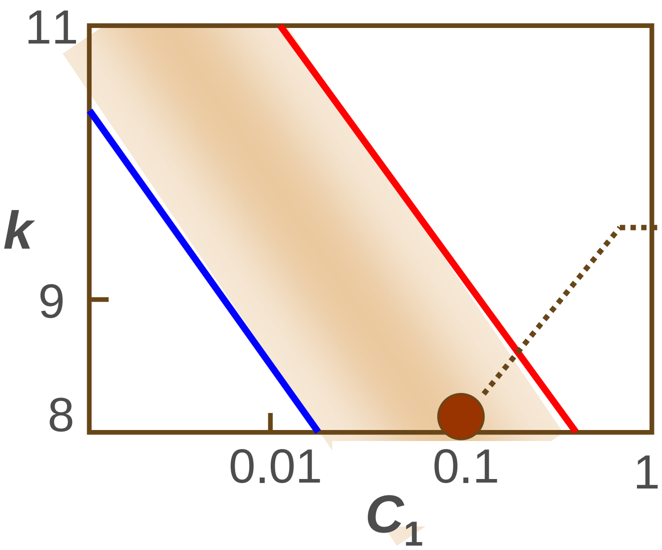
theoretical results for [Fe/H]=0.2

$M_* = 0.25 M_\odot$



*Around **low-mass stars**, distribution is affected only by type-I migration, but not by giant planets' perturbations*

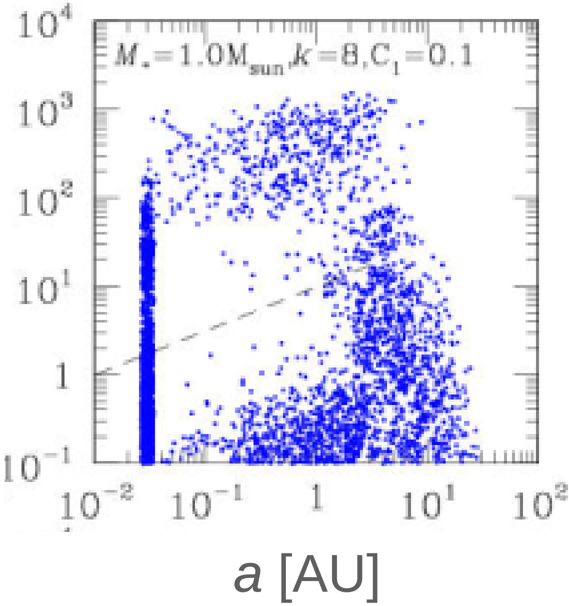
Inference of population of habitable planets (G stars)



theoretical results for [Fe/H]=0.2

$M_*=1.0M_\odot$

C_1=0.1,k=8

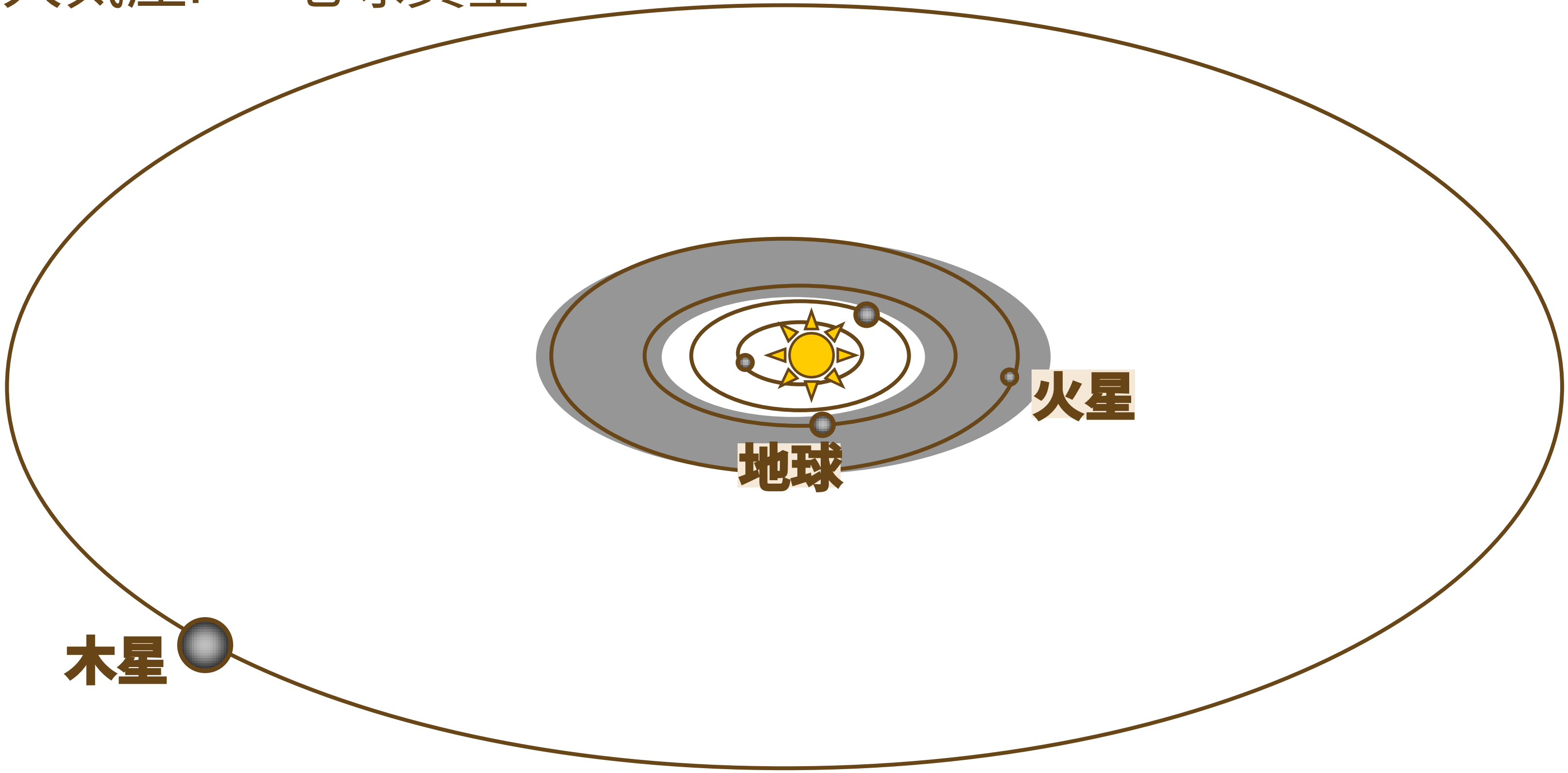


$$\frac{M_p}{\dot{M}_p} \approx 10^{k} \left(\frac{M_p}{M_\oplus}\right)^{-3} \text{yrs}$$

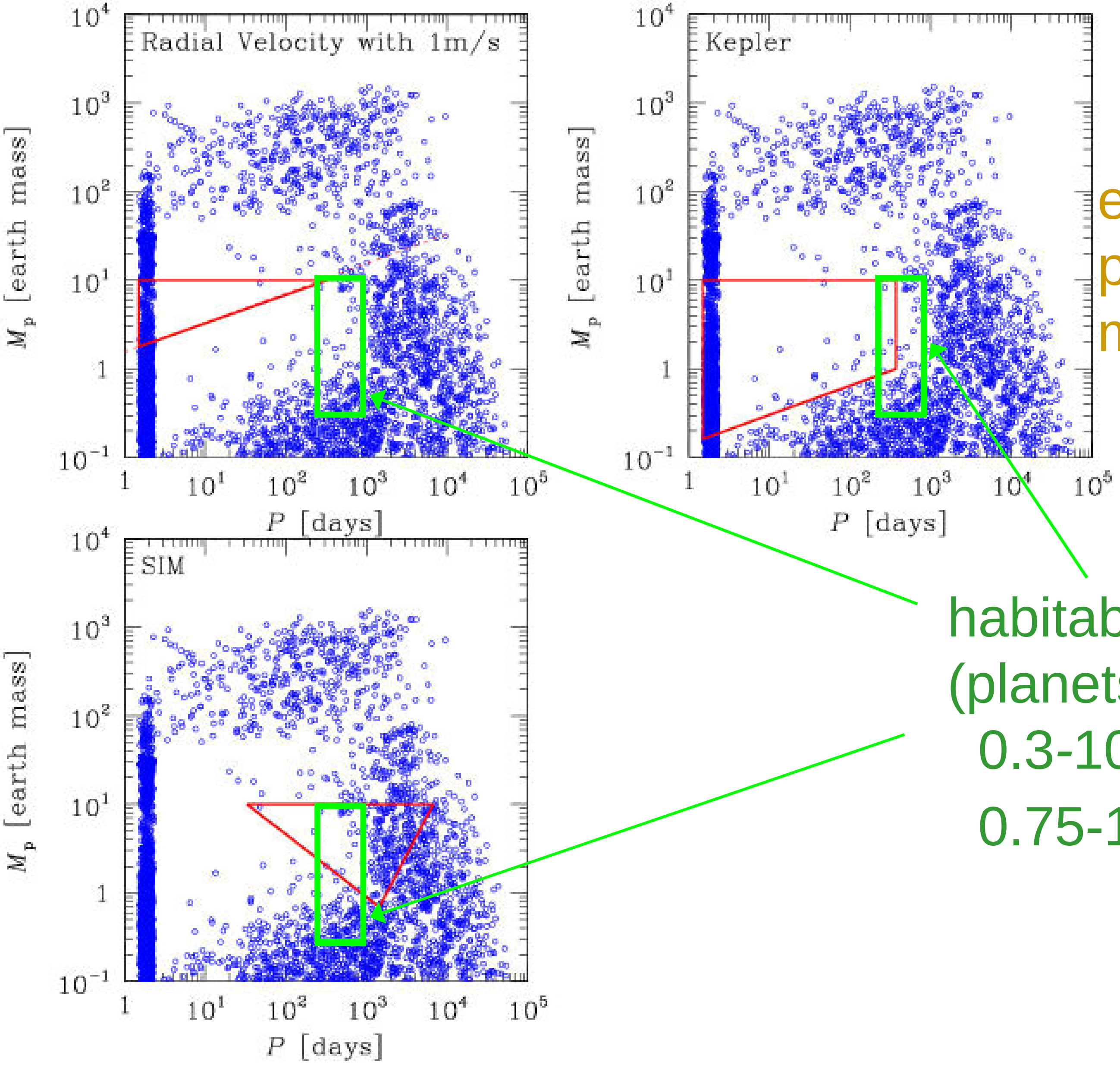
$$C_1 = \dot{a} / \dot{a}_{\rm linear}$$

生命惑星 ⇔ 液相のH_2O (海)

- **生命の起源 ⇔ 化学進化 ⇔ 海＋エネルギー**
- **液相：ある**温度、圧力範囲
  - 表面温度: 中心星からの距離が適当な範囲 ～$(M/M_{\odot})^2$AU
  - 大気圧: ～地球質量



Inference of population of habitable planets (G stars)



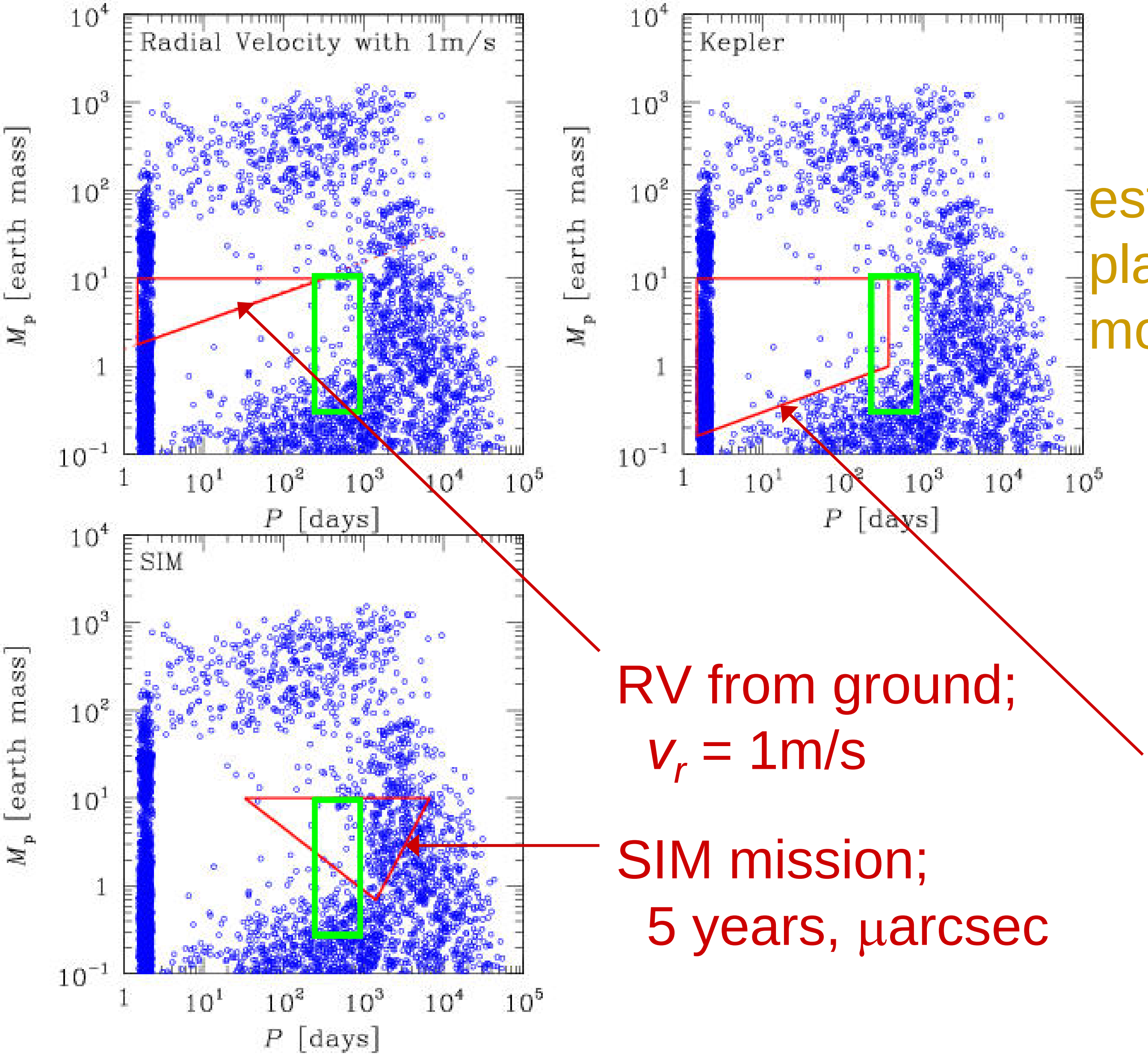
M_*=1.0$M_\odot$ C_1=0.1,k=8

estimation from rocky planets (<10$M_\oplus$): more reliable

habitable planets (planets sustaining ocean):
- 0.3-10$M_\oplus$
- 0.75-1.8AU x $(M_*/M_\odot)^{1.5-2}$

Inference of population of habitable planets (G stars)

$M_* = 1.0 M_\odot$ $C_1 = 0.1, k = 8$



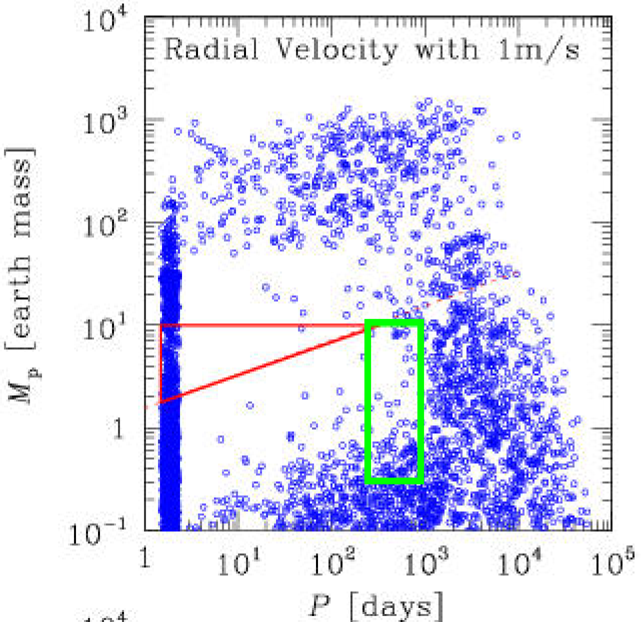
estimation from rocky planets ($<10 M_\oplus$): more reliable

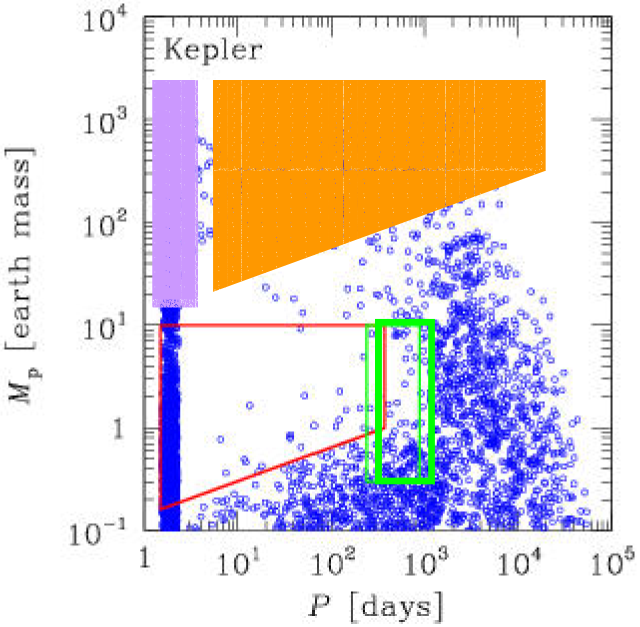
RV from ground;
v_r = 1m/s

Kepler mission;
4 years, V = 12

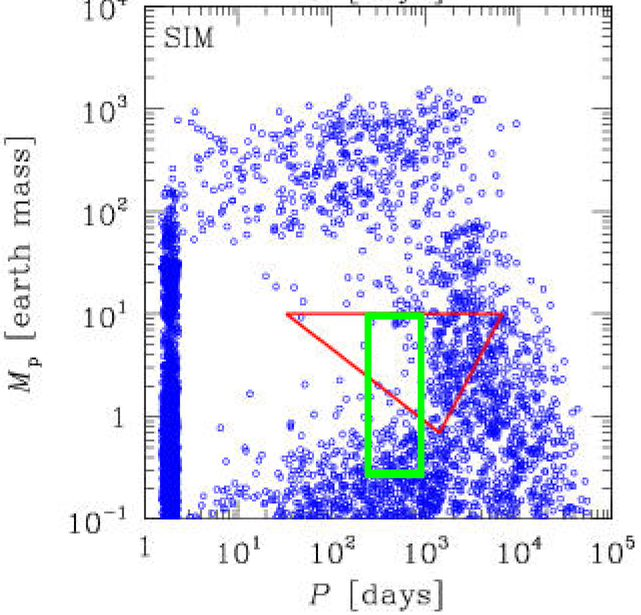
SIM mission;
5 years, μarcsec

Inference of population of habitable planets (G stars)





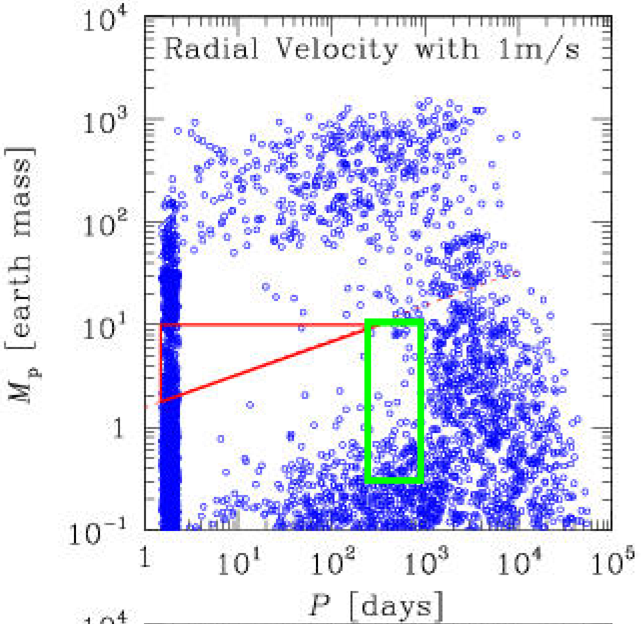
$M_*=1.0M_\odot$ $C_1=0.1$,k=8

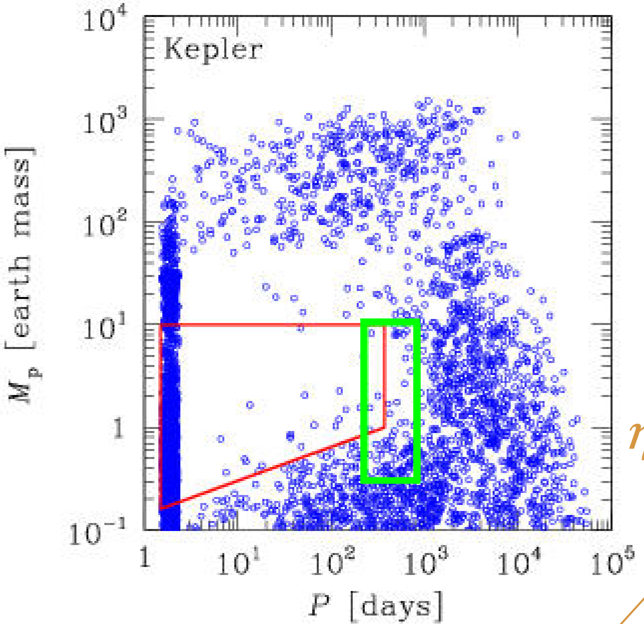


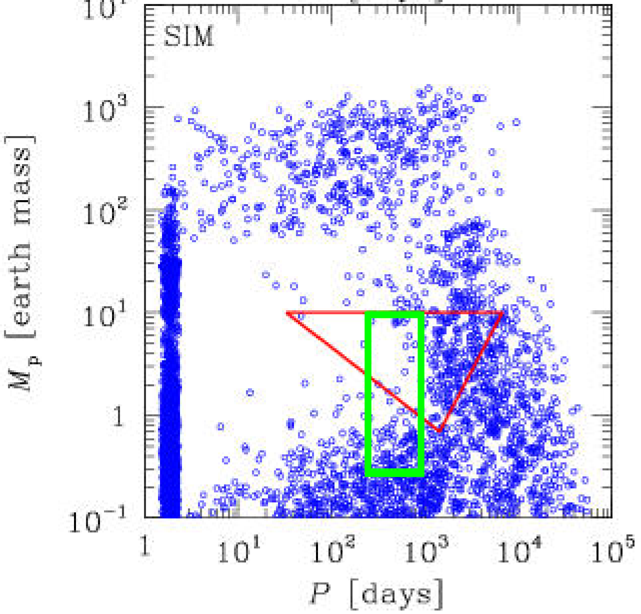
retention rate η of close-in planets is estimated from giant planets detectable by RV survey with >10m/s & < 5 years:

$$\eta \sim \frac{\text{close-in}/\text{distant (RV data)}}{\text{close-in}/\text{distant (theory)}} \sim 0.07$$

Inference of population of habitable planets (G stars)







$M_*=1.0M_\odot$ $C_1=0.1, k=8$

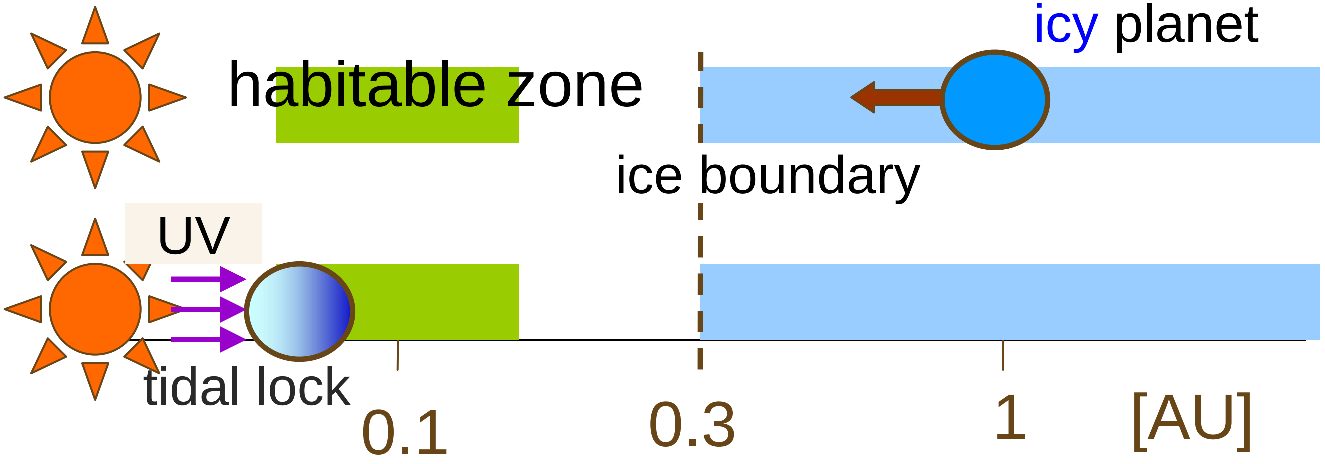
η x #close-in + #distant

$$\frac{\text{\# of habitable planets}}{\text{\# of detectable planets with } <10M_\oplus}$$

RV with v_r=1m/s	0.79
Kepler	0.84
SIM	0.23

habitable “ocean planets”?

- Around M stars, **habitable zone ~ 0.1AU**
  - rocky planets formed in situ: too small to sustain atmosphere
- **close-in neptunes** around M **stars**
  - ***H_2O*** *planets in* ***warm*** *environment*



- **habitable “ocean planets”?** Kuchner(2003),Leger et al. (2004)

  liquid water & energy supply, H_2O atmosphere, tidally locked...
- **marginally observable** at present
- more abundant than Earth-like planets around G stars?

「生命」で天文学を再構築

metallicity
⇔
habitability

高過ぎると木星ばかり

低過ぎると
大気を保持できない
小さい惑星ばかり

重元素比は銀河のタイプに依存
habitable galaxy

重元素比は増加
宇宙 habitable era