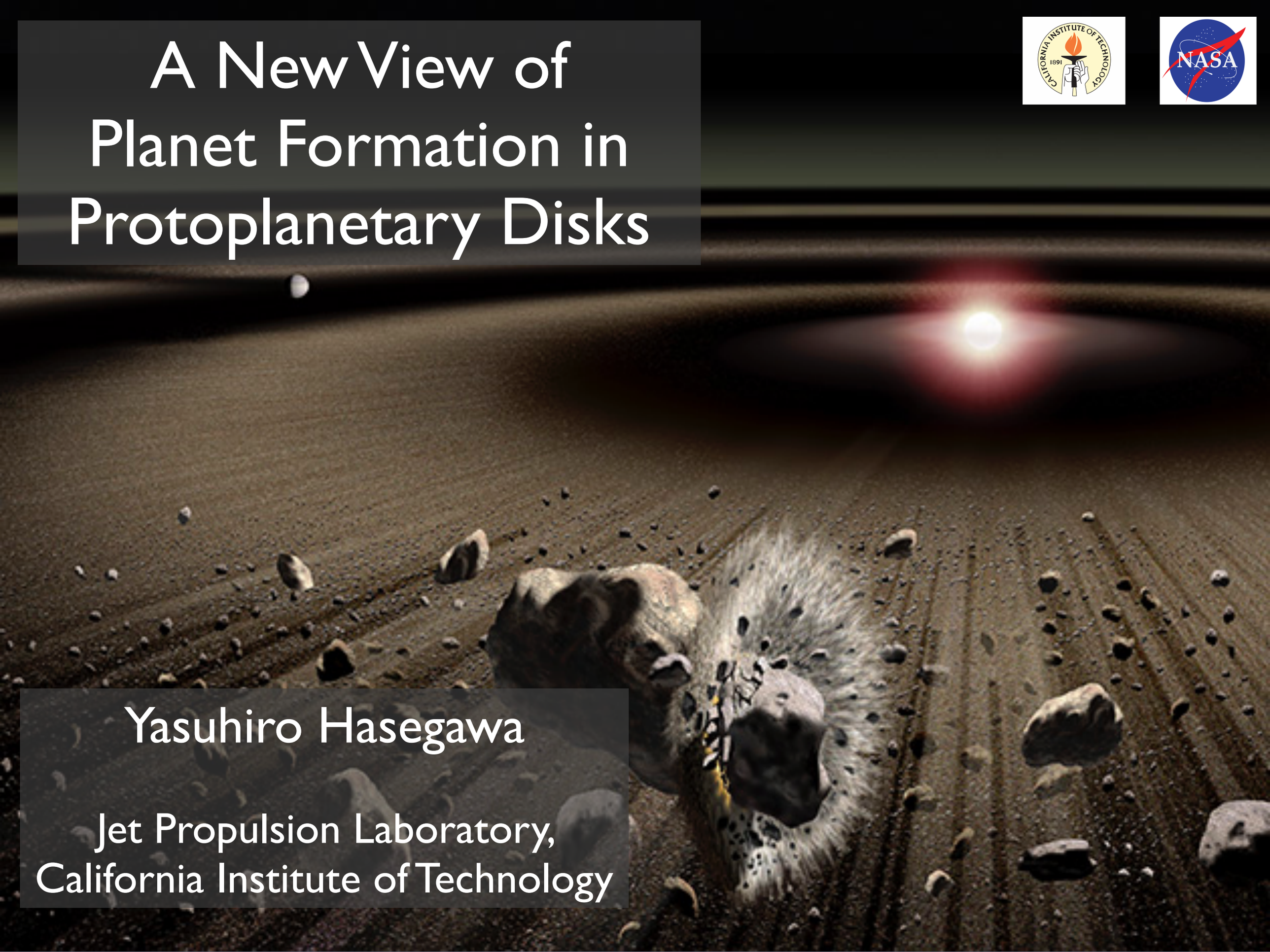
A New View of Planet Formation in Protoplanetary Disks



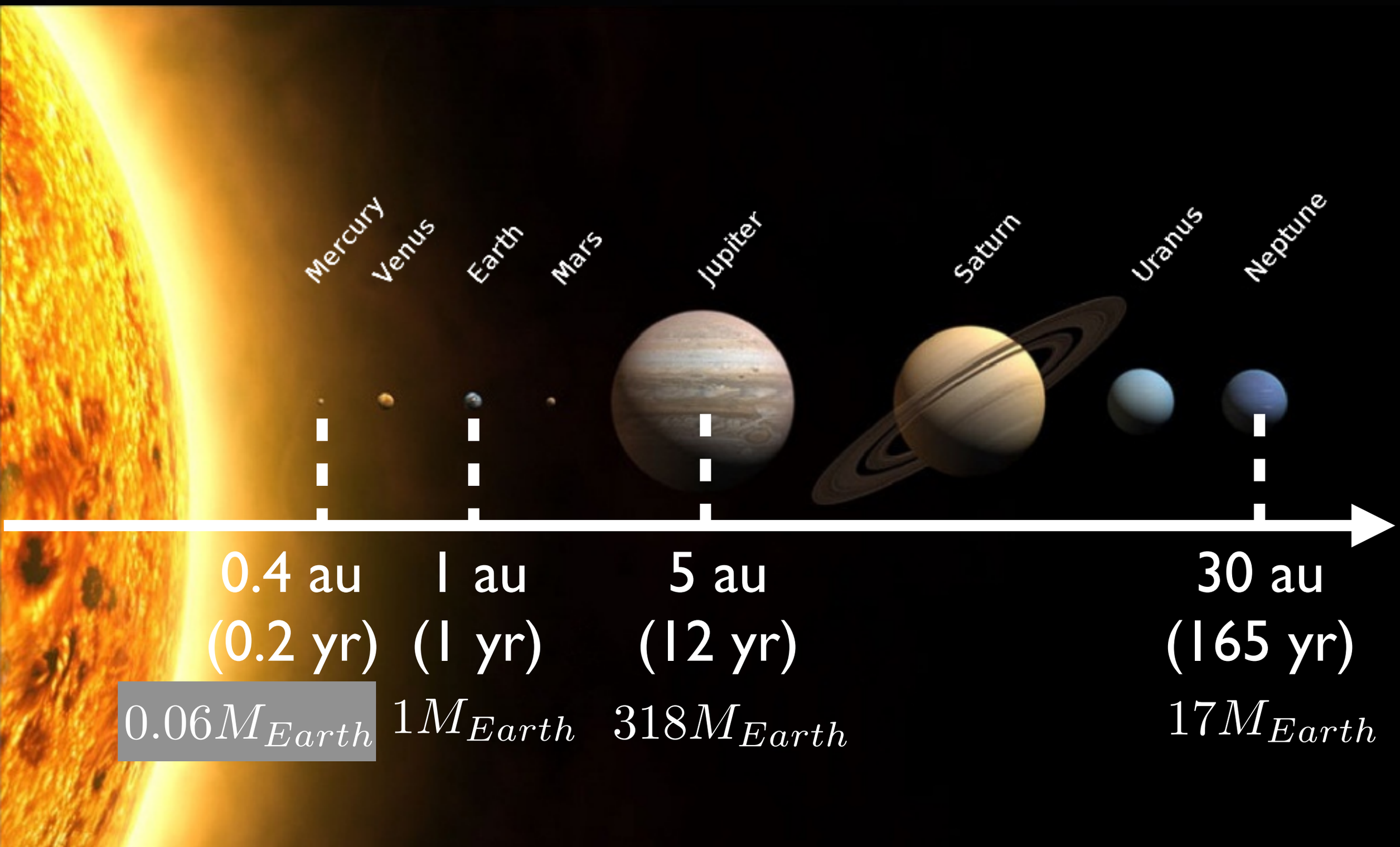
Yasuhiro Hasegawa

Jet Propulsion Laboratory,
California Institute of Technology

Best Example of Planetary Systems

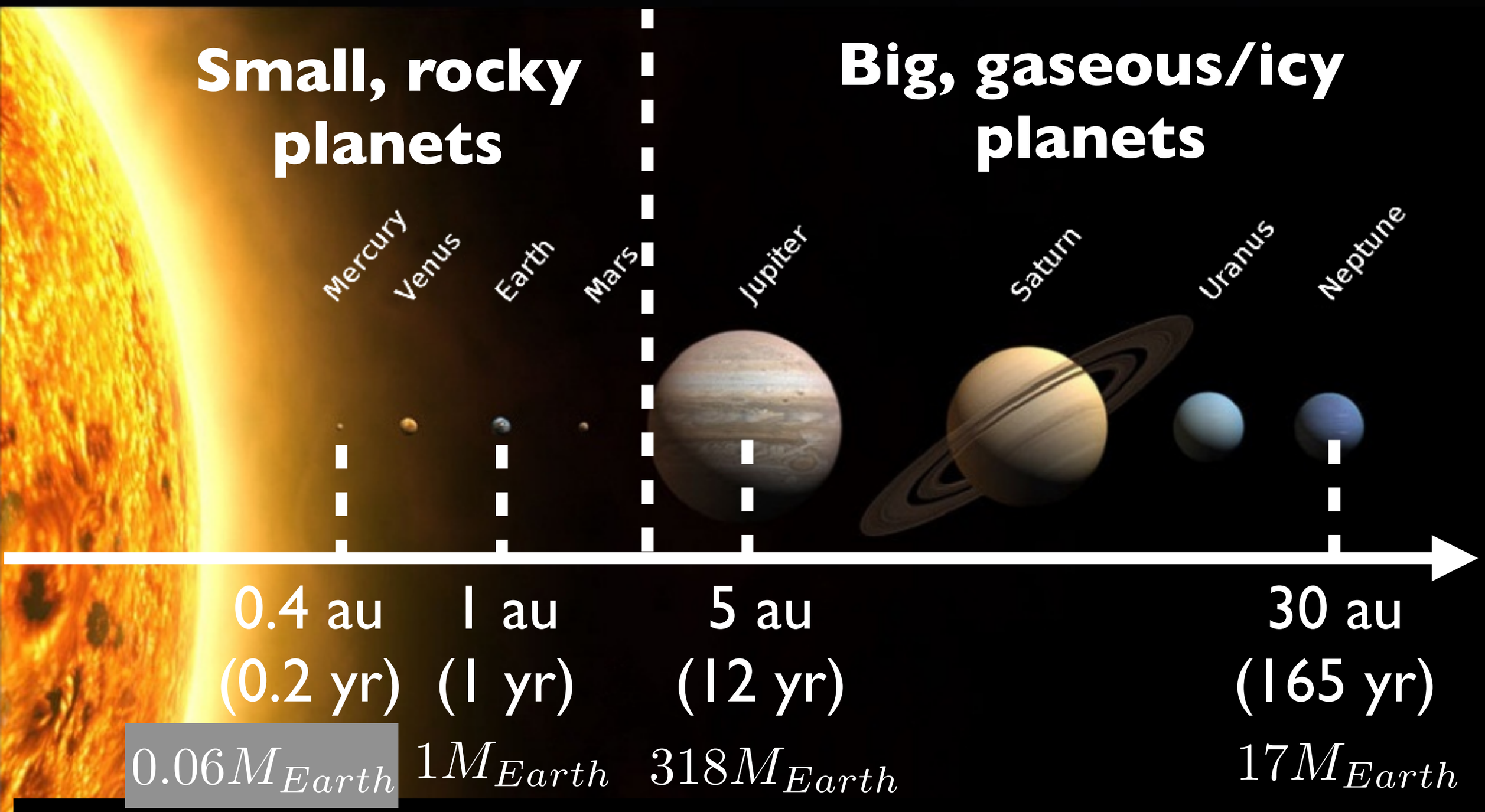
???

Best Example of Planetary Systems



1 au $= 1.47 \times 10^{13} cm$ $\quad$ $1 M_{Earth} = 5.9 \times 10^{27} g$

Best Example of Planetary Systems



All the planets (except Mercury) are in the circular (e < 0.1), coplanar (i ~ 6 degree) orbit

“Classical” Picture

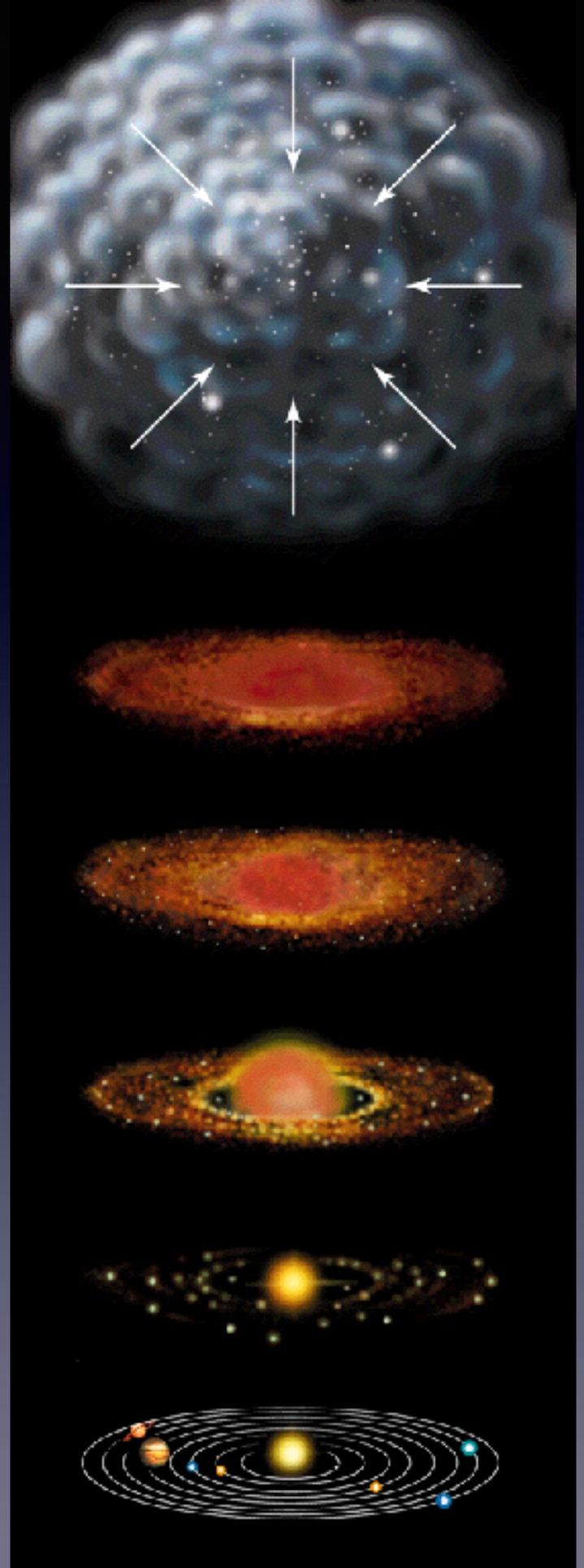
e.g., Hayashi 1981

Natural outcome of star formation

Minimum-mass Solar nebula

In-situ formation

Dynamically inactive



the First Detection of an Extra Solar Planet about 20 years ago

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article

Nature **378**, 355 - 359 (23 November 1995); doi:10.1038/378355a0

A Jupiter-mass companion to a solar-type star

MICHEL MAYOR & DIDIER QUELOZ

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

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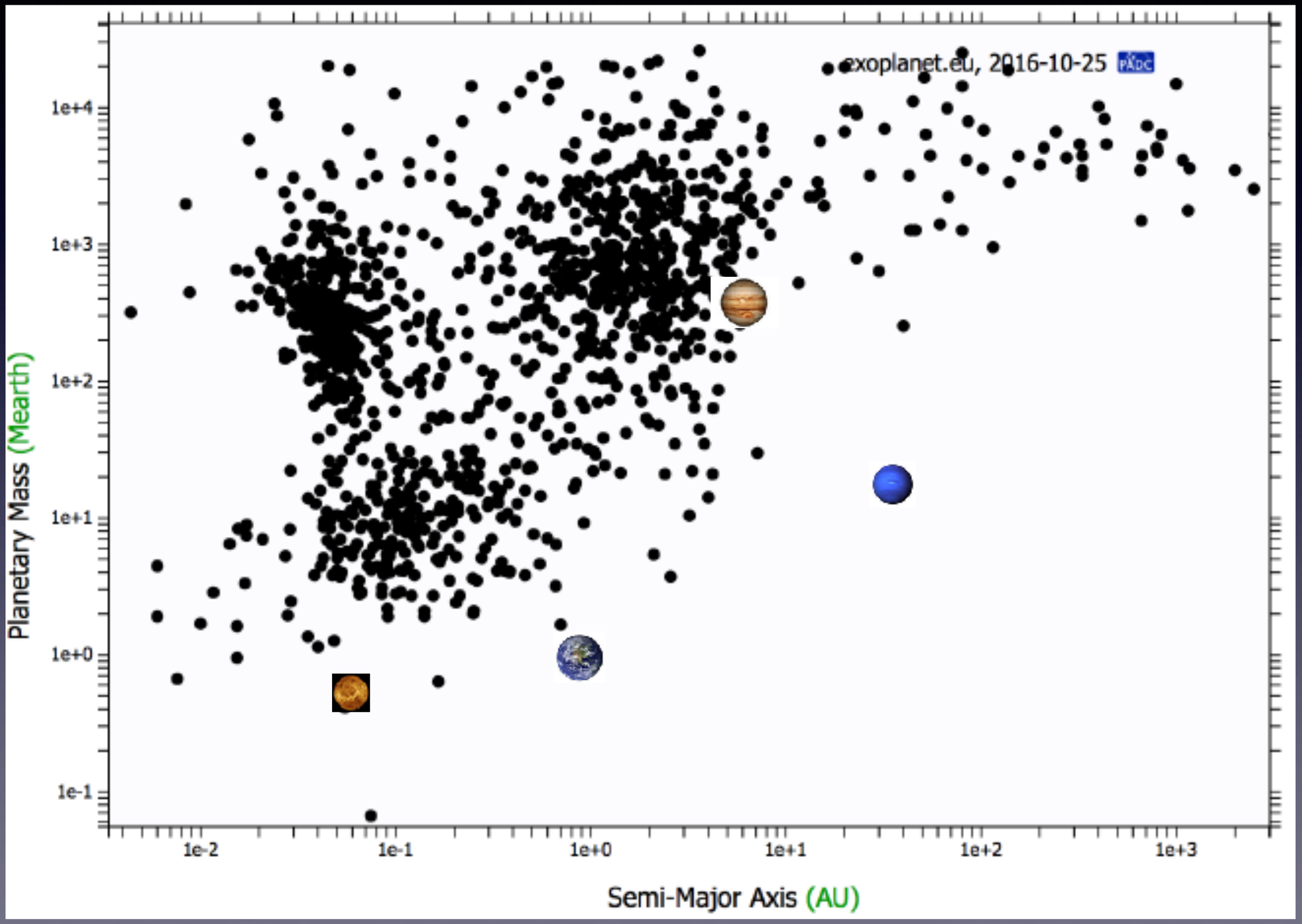
Semimajor axis is 0.05!!! (cf. that of Mercury is 0.4 au)

Exoplanetary Populations

e.g., Winn & Fabrycky 2015 for a review



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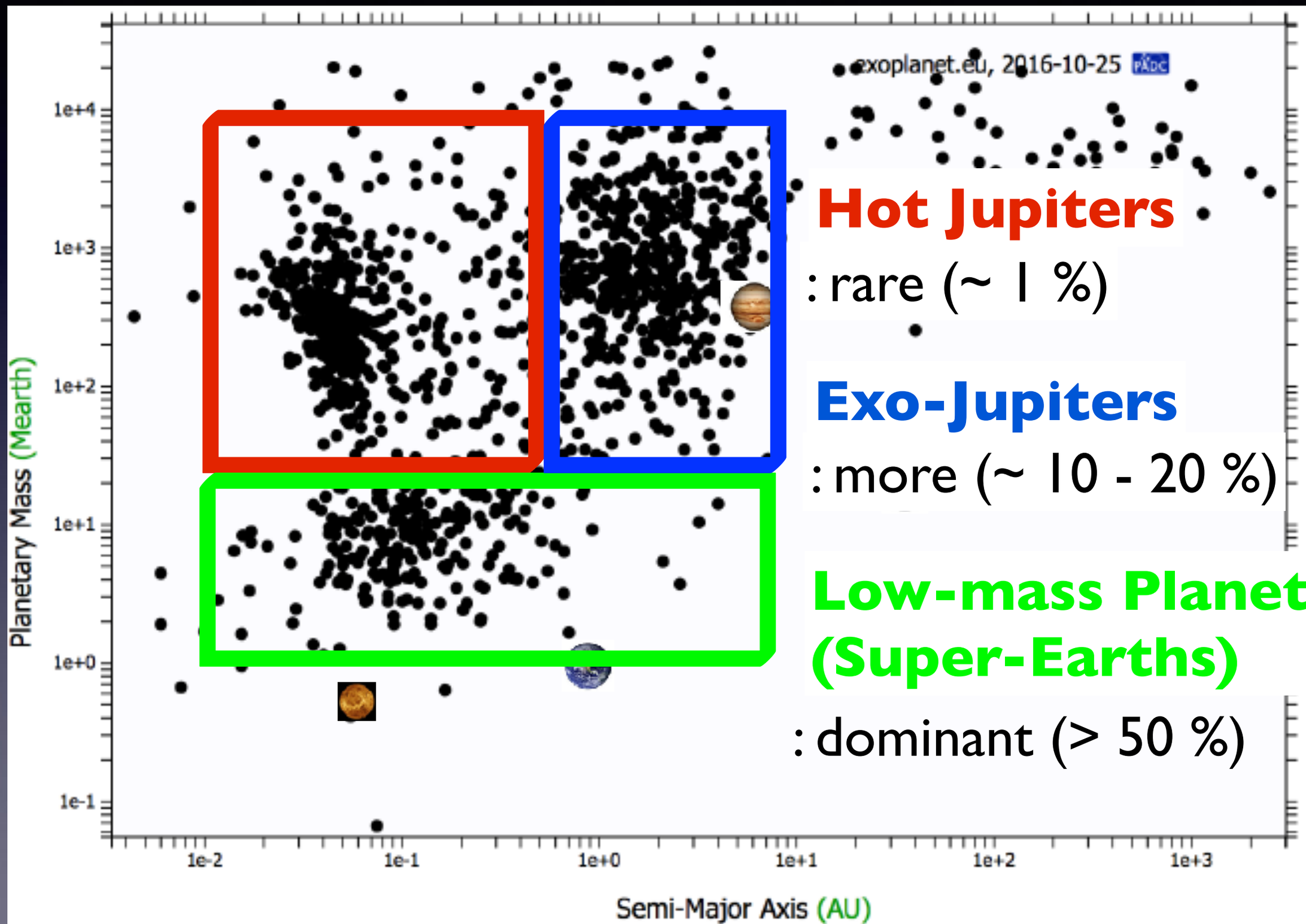

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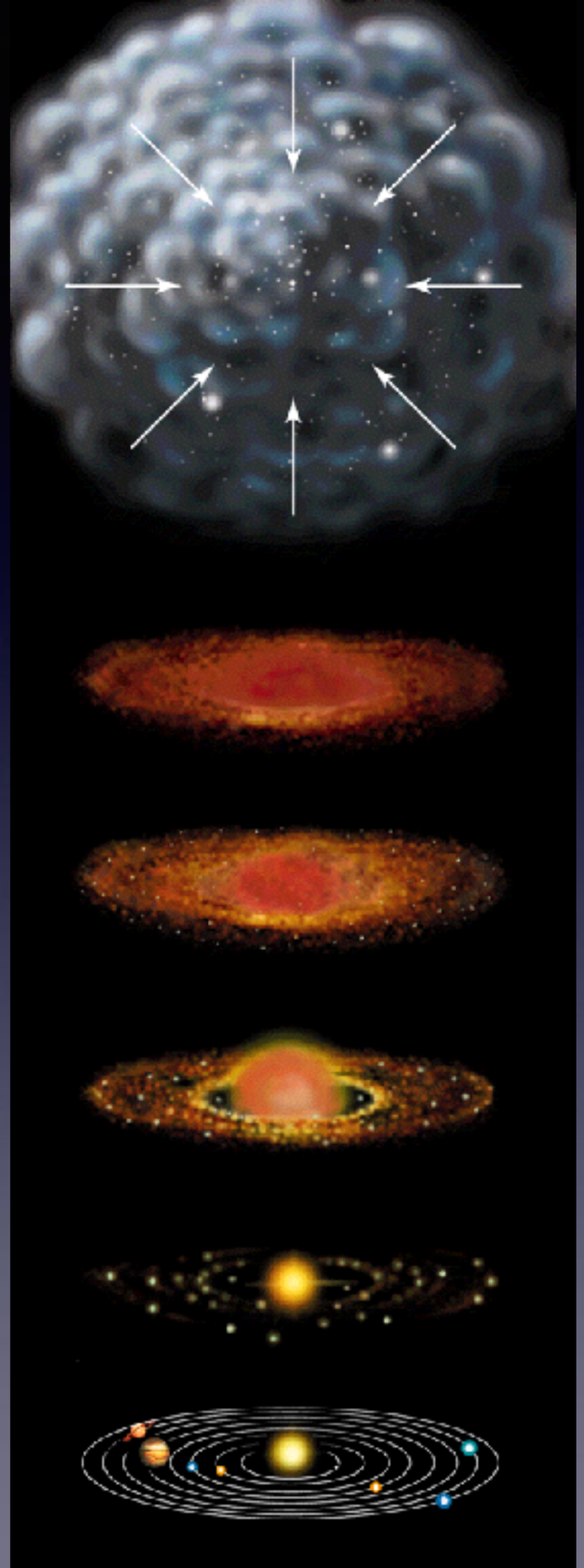

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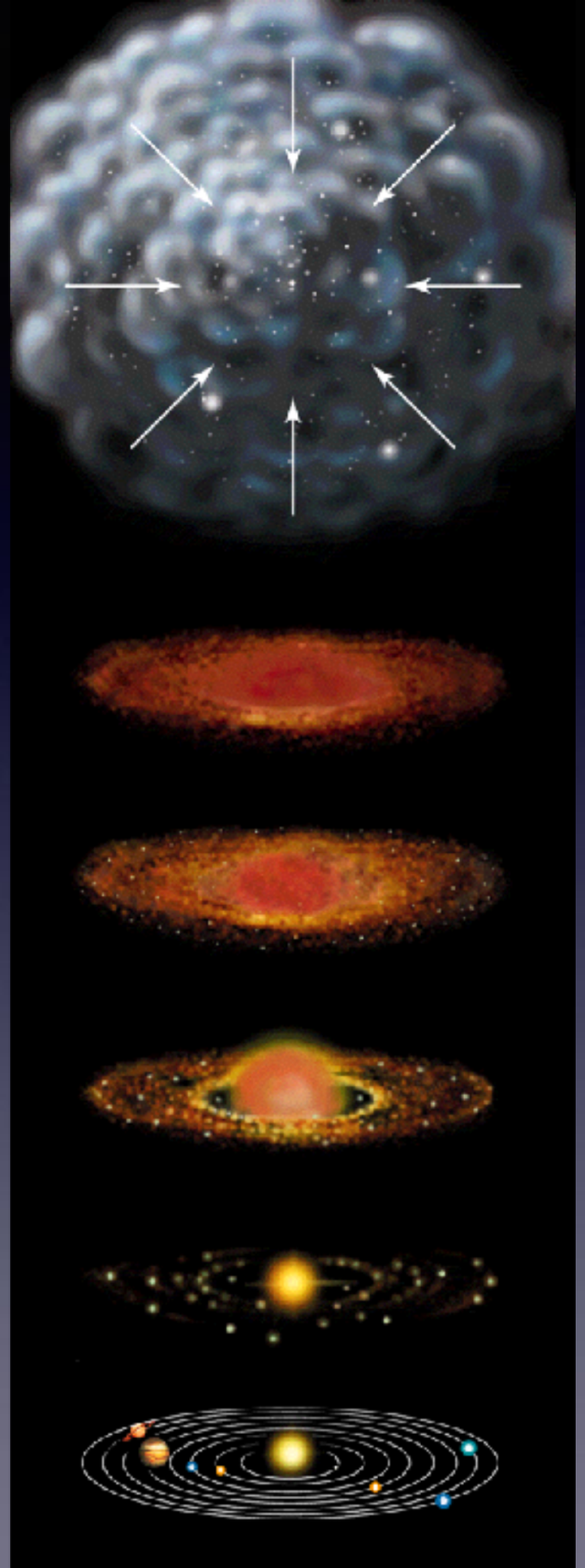


New Picture

New Disk model:

Disk evolution,
Spatial distribution
of gas and dust

New Planet Formation Model:

Solar system planets
vs
Exoplanets

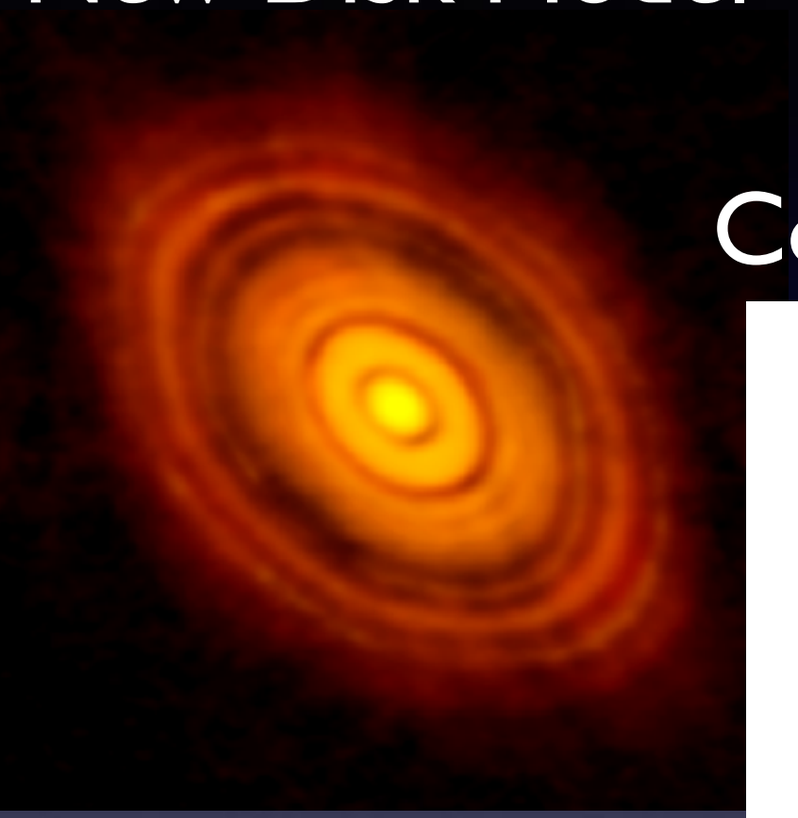
Statistical Approach:

Exoplanet population

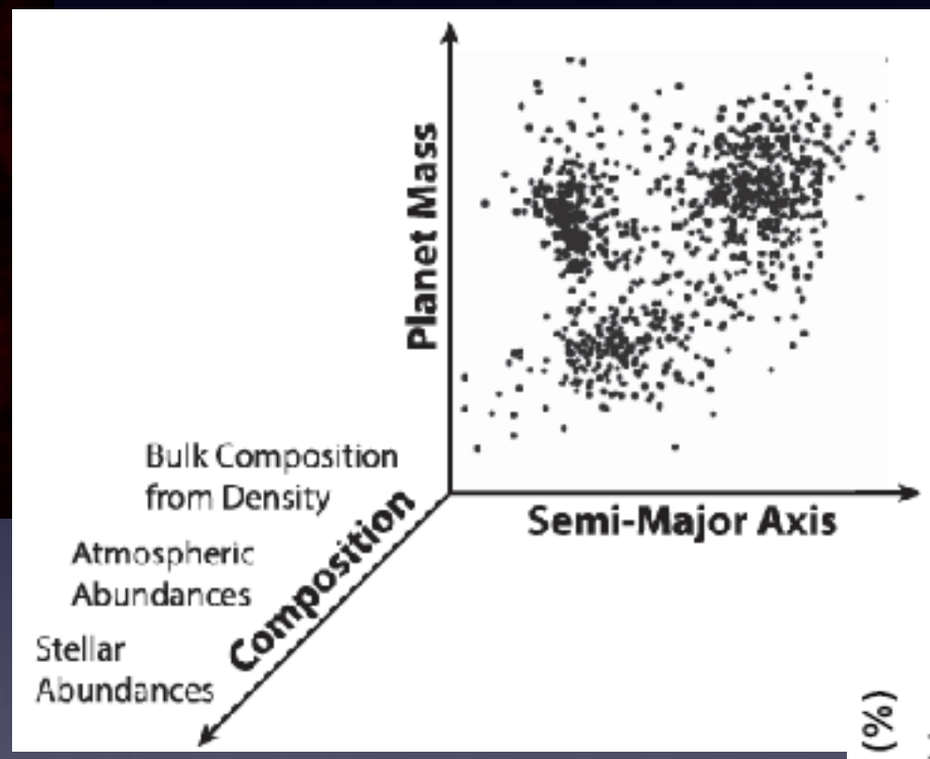
↓

Disk model

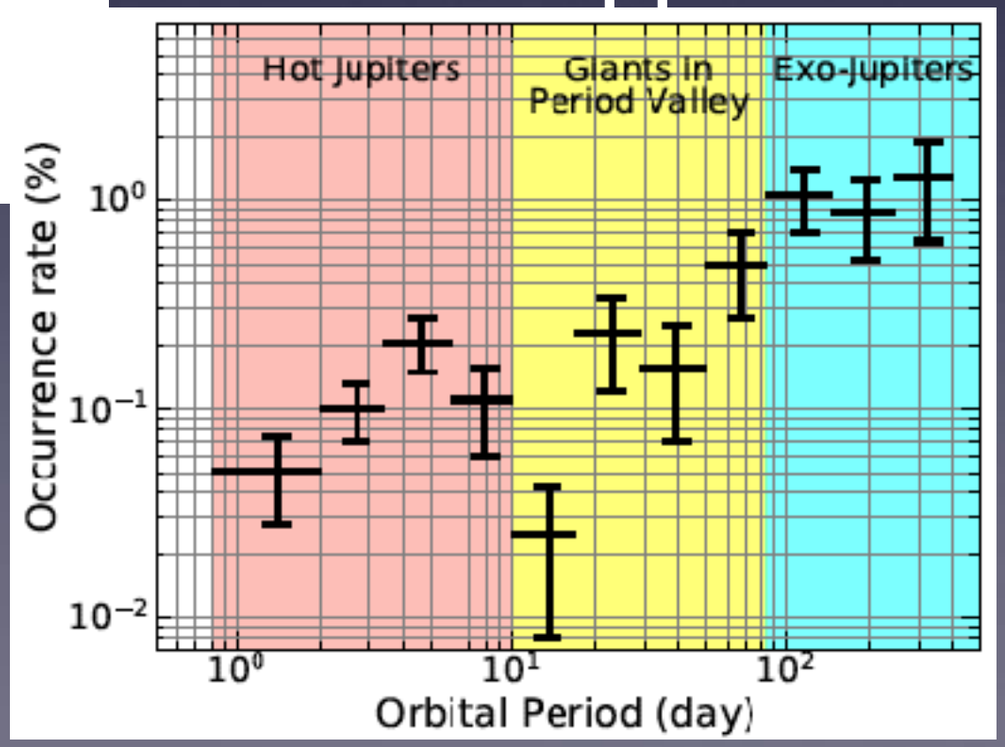
New Disk Model



Composition of planets



Retrieval approach



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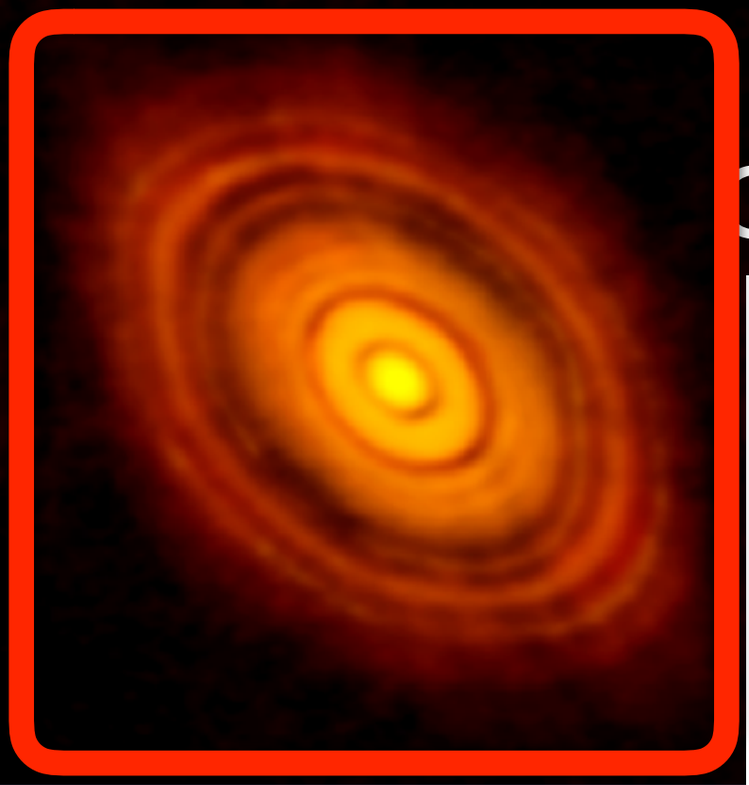

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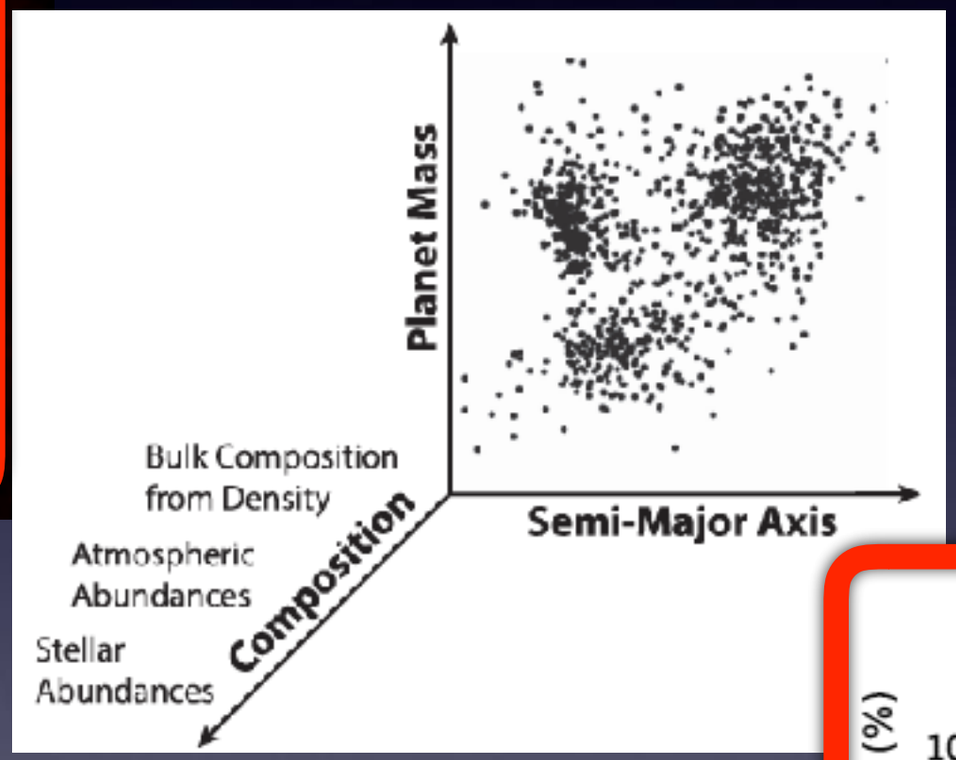

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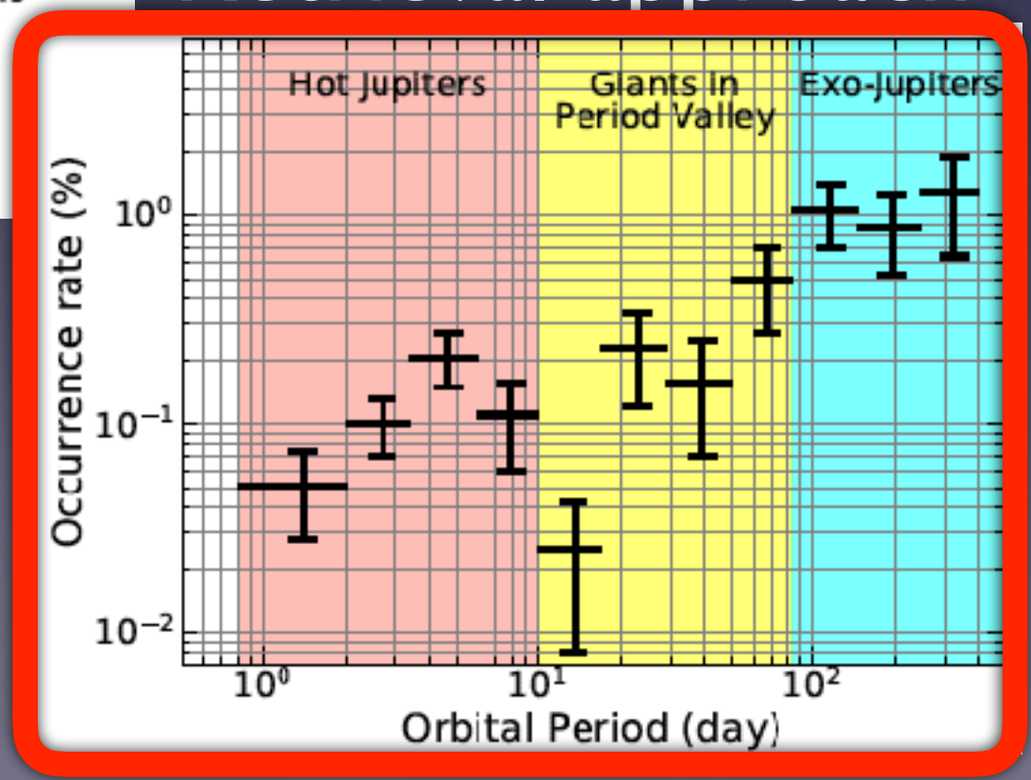
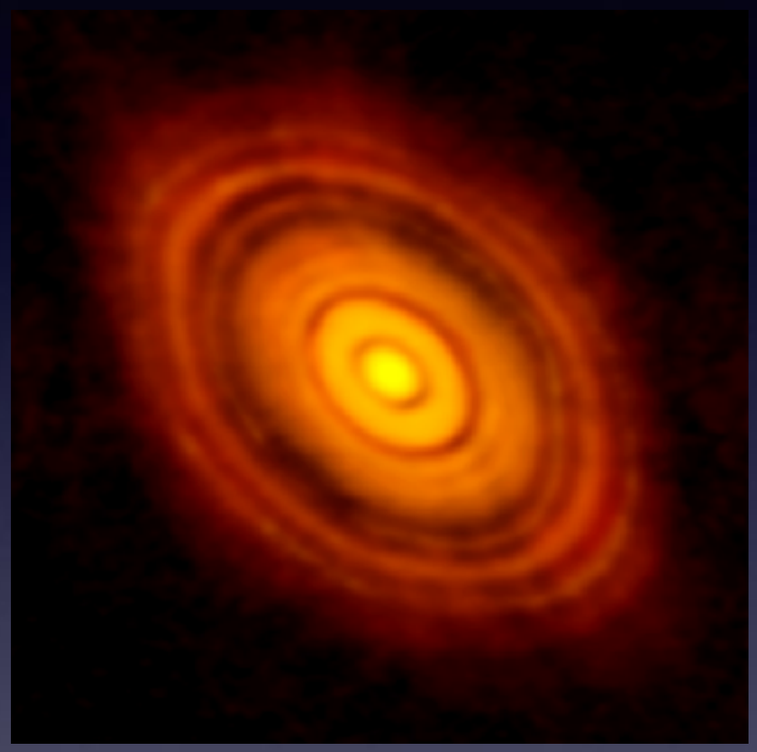
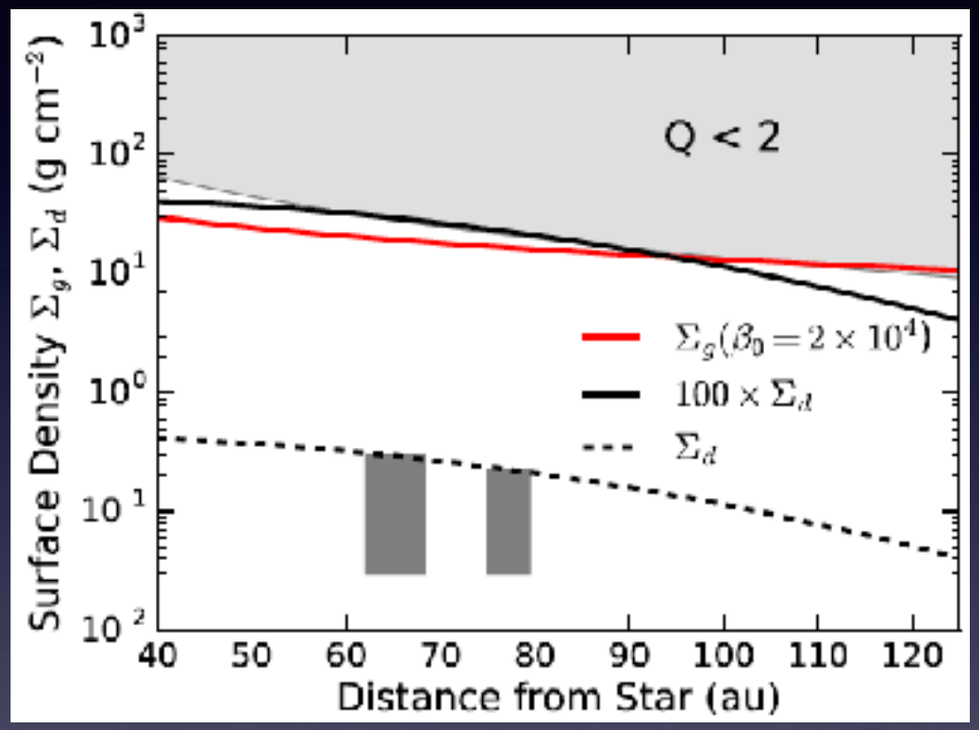


Magnetically Induced Disk Winds and Transport in the HL Tau Disk





in collaboration with
Satoshi Okuzumi (TokyoTech), Mario Flock (MPIA), Neal Turner (JPL)

Canonical View of Protoplanetary Disks

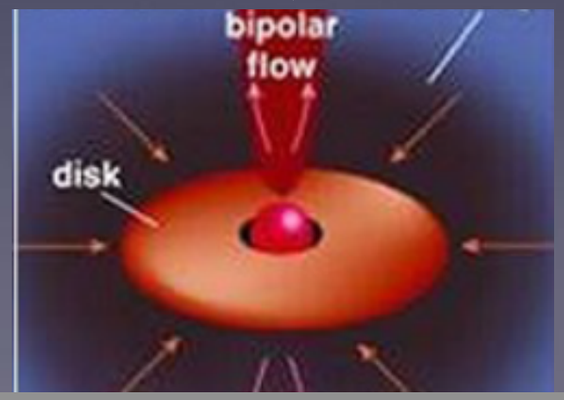
e.g., Hayashi 1981

NIR image of
Hubble Space Telescope

The Eagle Nebula
(d ~ 2000 pc)

Molecular Clouds

Gravitational
collapse

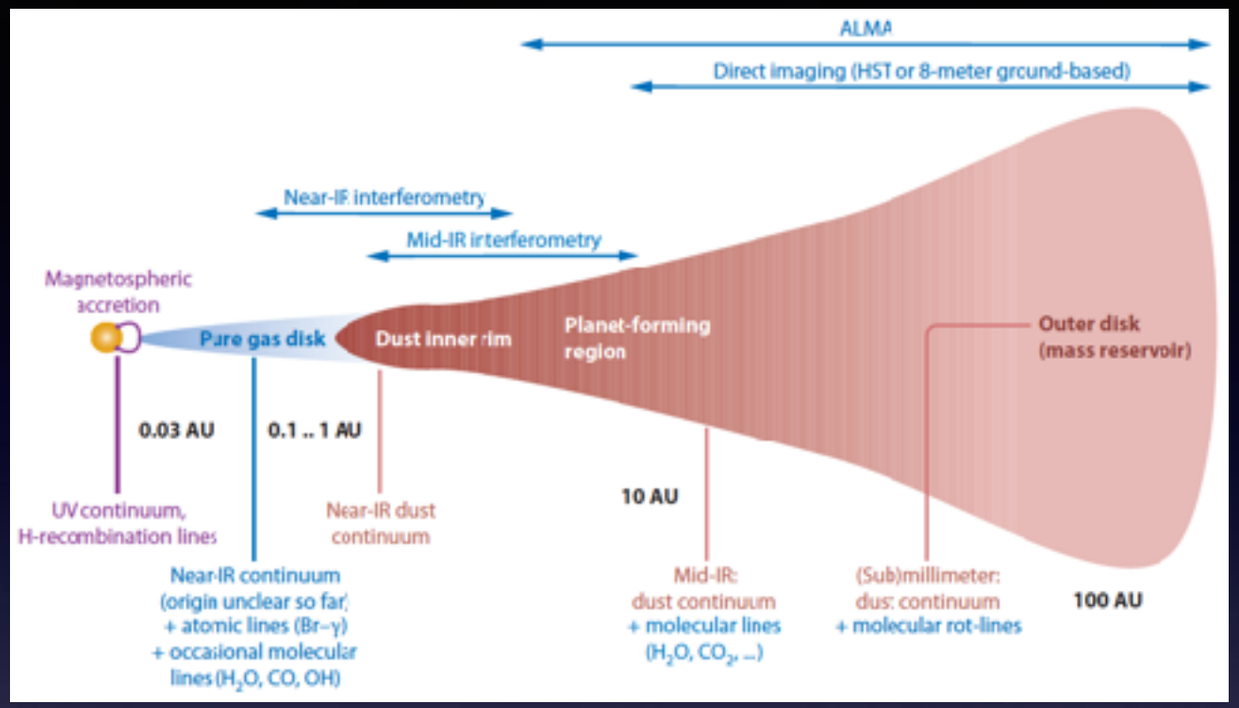


Circumstellar Disks

1 pc $= 3 \times 10^{18} cm$

Canonical View of Protoplanetary Disks

e.g., Hayashi 1981



$$M_{disk} \sim 10^{-2} M_\odot$$

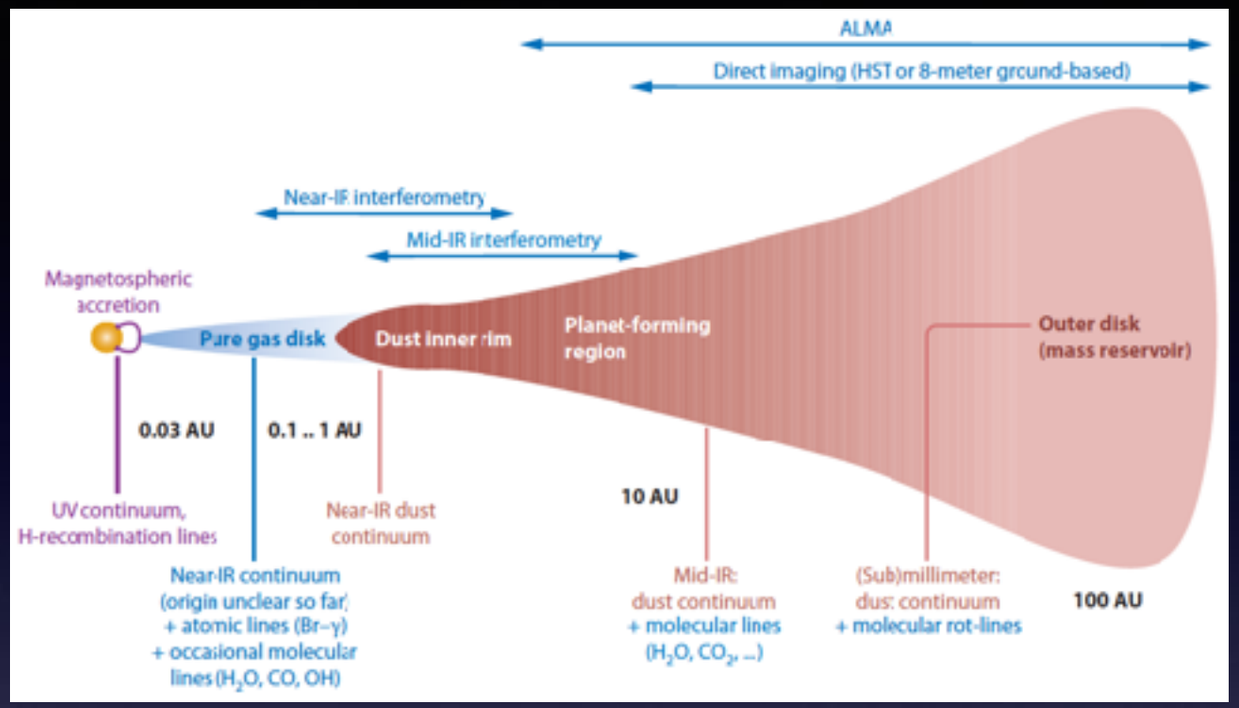
(: ~ 99% of gas and ~ 1% of dust)

$$\tau_{disk} \sim 10^6 - 10^7 yr$$

Disks are **turbulent** possibly by magnetic fields

Canonical View of Protoplanetary Disks

e.g., Hayashi 1981



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Disks are **turbulent** possibly by magnetic fields

At 1 au, $n \sim 10^{14} cm^{-3}$

$T \sim 300K$

cf) the atmosphere of the Earth,

At 1 bar, $n \sim 10^{19} cm^{-3}$

Canonical View of Protoplanetary Disks

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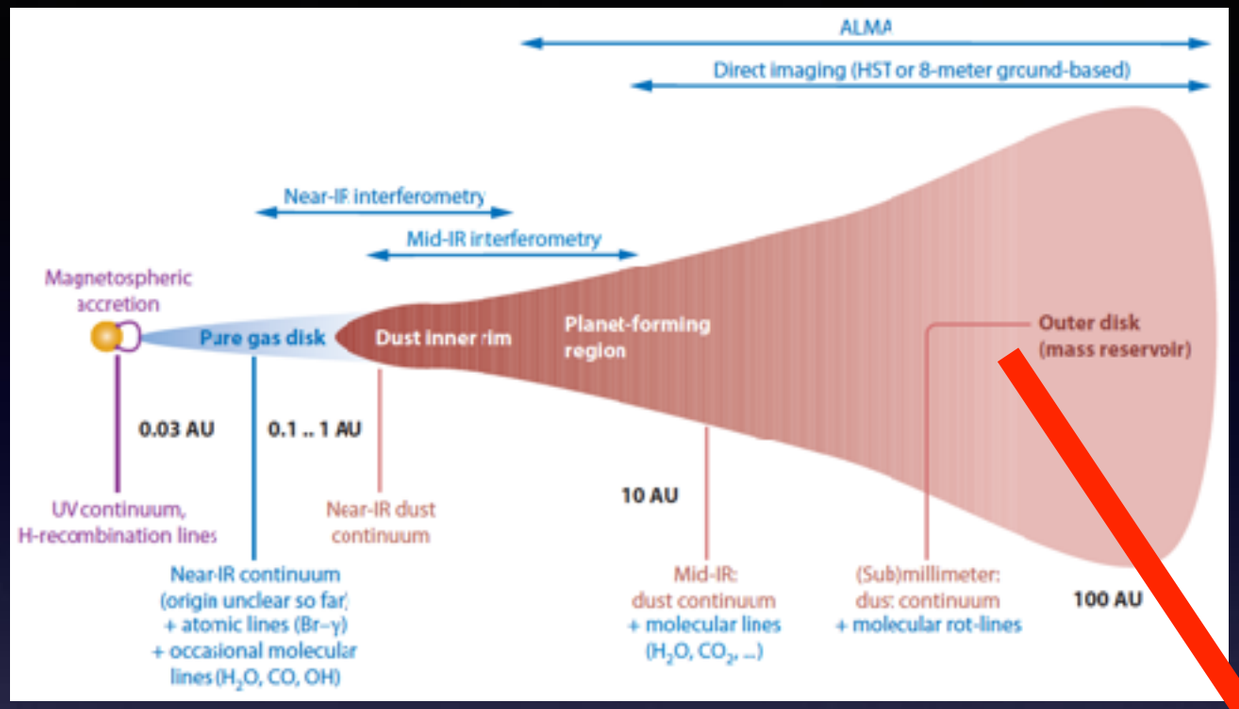

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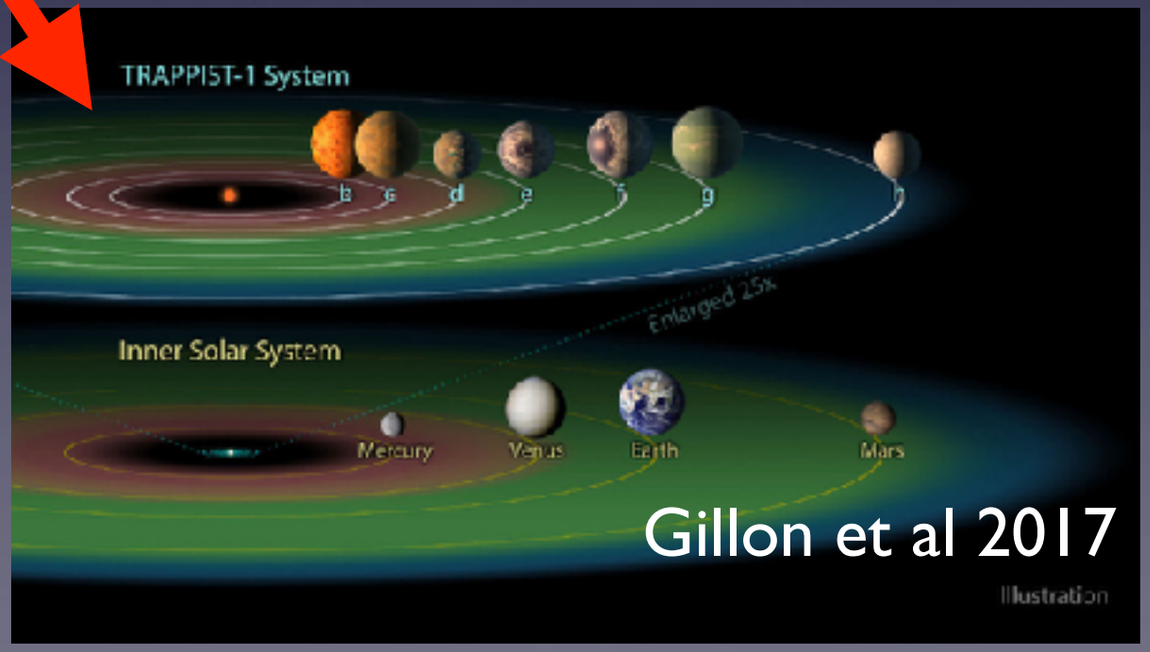
10 -100 Myr



Gillon et al 2017

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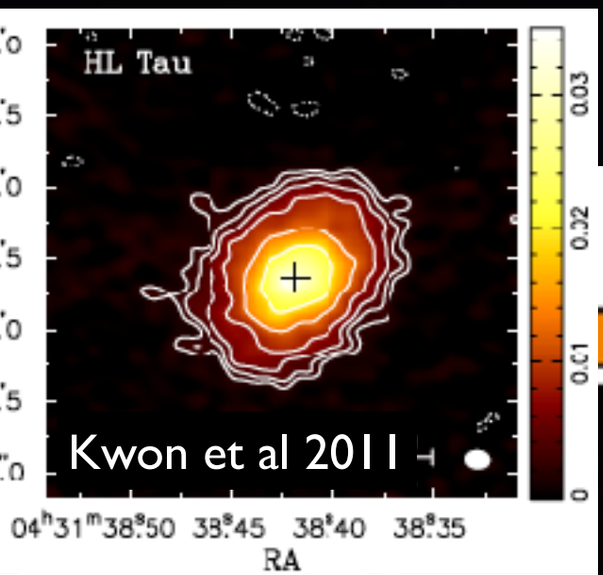
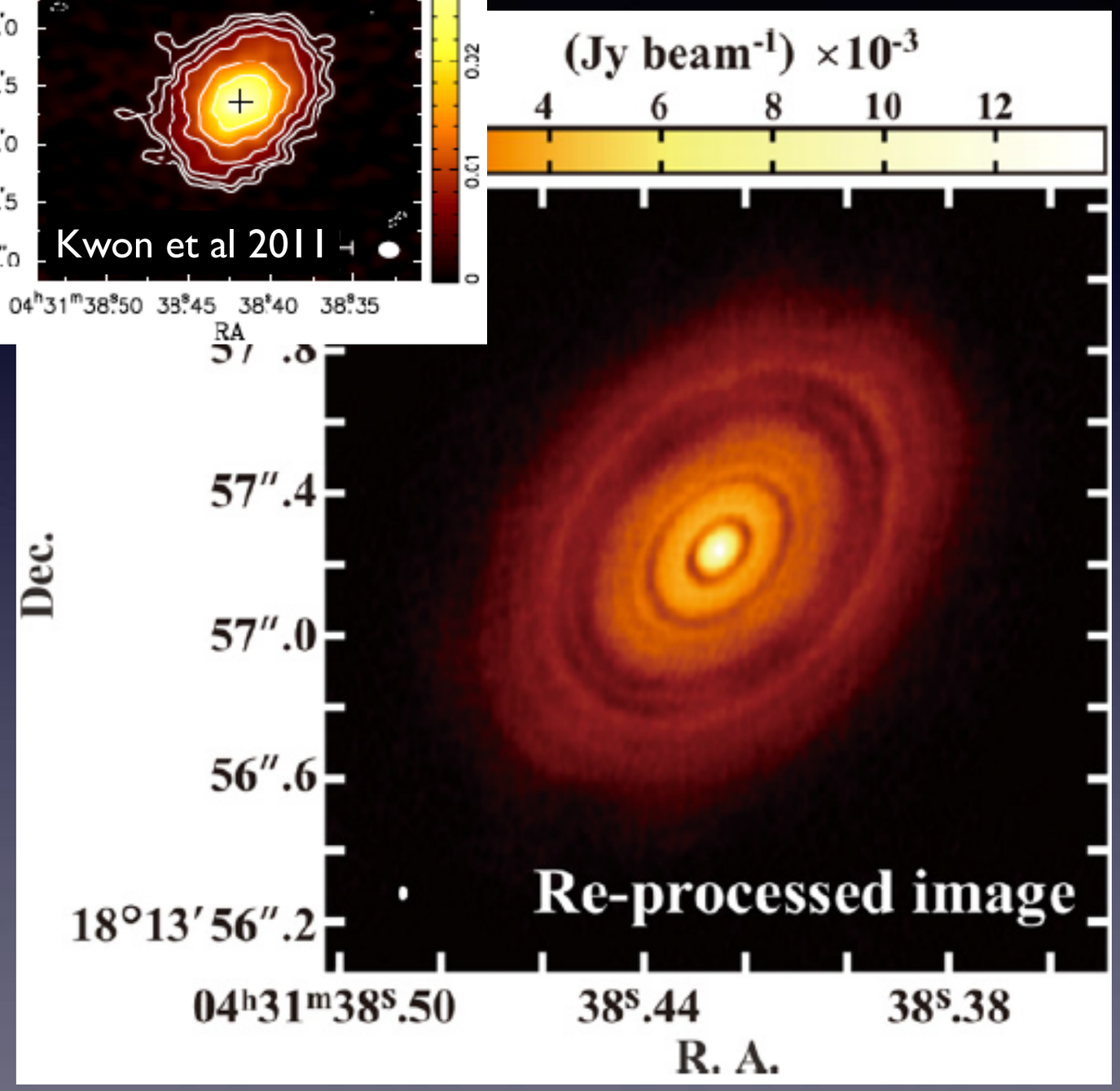
Astonishing ALMA Images of HL Tau

ALMA Partnership et al 2015,
also see Akiyama YH et al 2016





HL Tau : a Class I/II YSO
: ~140 pc (< 1 Myrs)

Nearly concentric
multiple gaps in
the dust thermal emission

Potential signature of
planet formation

The origin of observed gaps is not identified yet!!

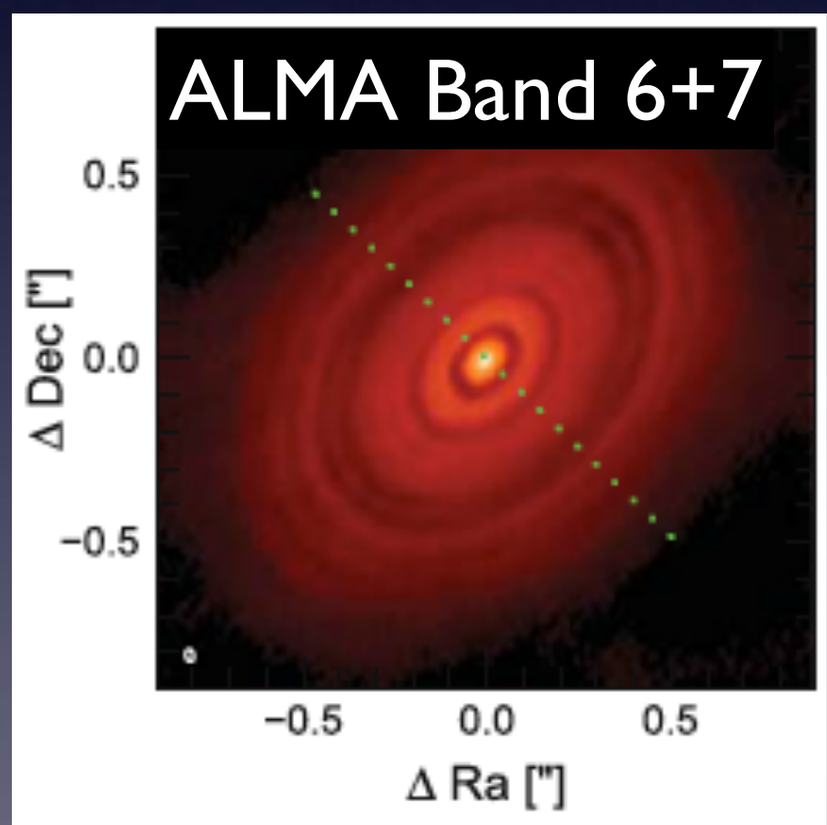
Global Properties of the HL Tau Disk

Disk accretion rate $\simeq 10^{-7} - 10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$

Hayashi et al 1993, Beck et al 2010

Global diffusion coefficient : $\alpha_{\mathrm{GL}} \simeq 10^{-2} - 10^{-1}$

=> can be explained by MRI and MHD turbulence



ALMA Partnership et al 2015
also see Akiyama et al 2016

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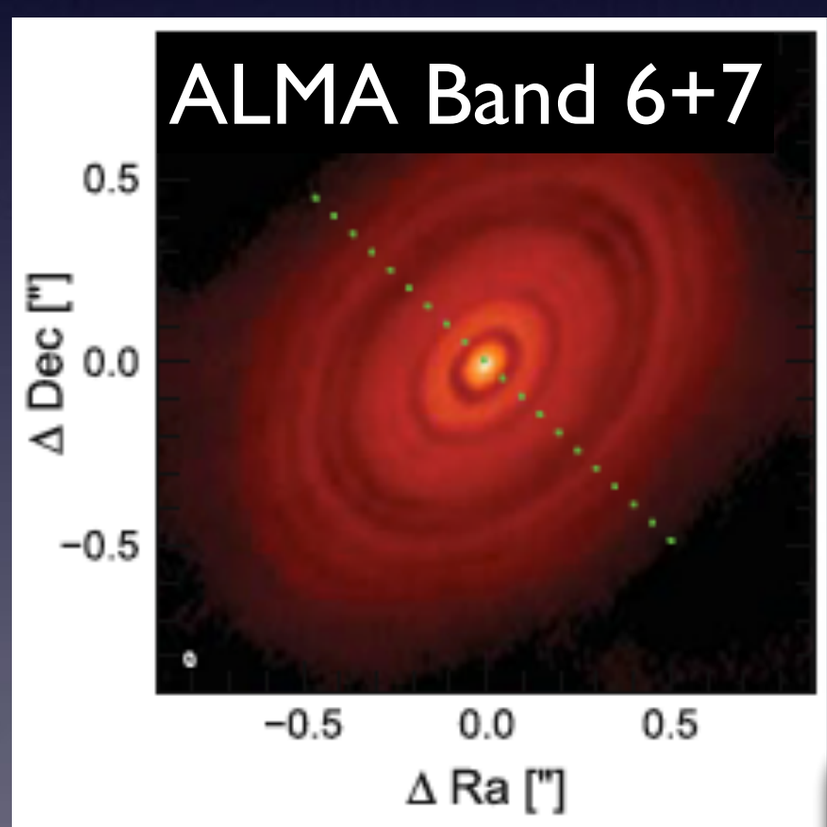

Pinte et al 2016

Vertical dust height: ~1au at r =100 au

Local diffusion coefficient: $\alpha_{\mathrm{LC}} \sim 10^{-4}$

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Hayashi et al 1993, Beck et al 2010

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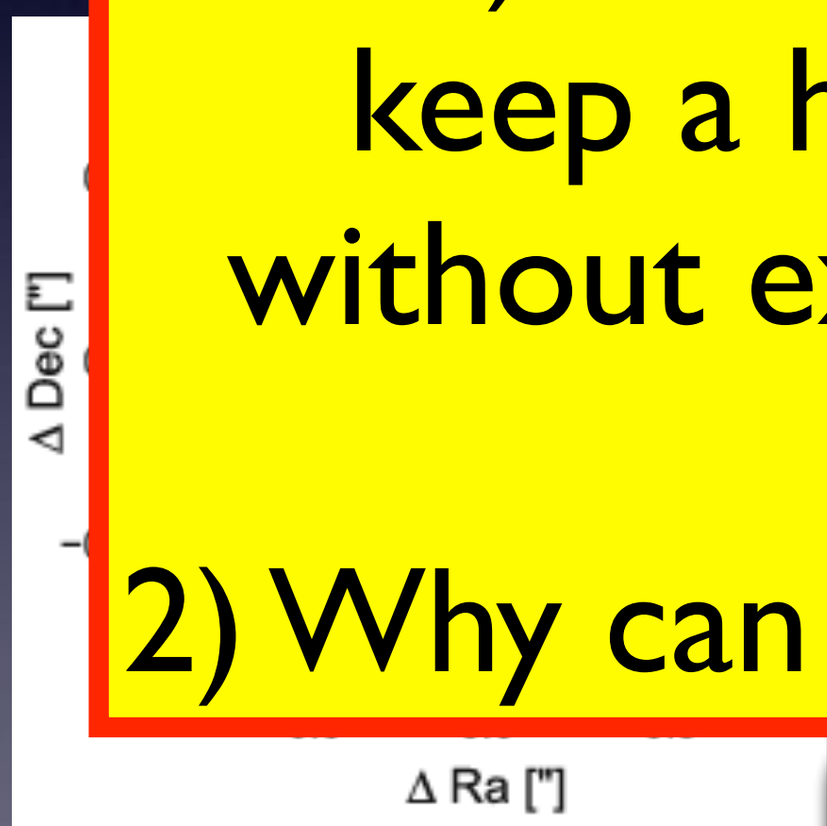
1)How does the HL Tau disk keep a high disk accretion rate without exciting local turbulence??

2) Why can the HL Tau disk avoid GI??



Pinte et al 2016

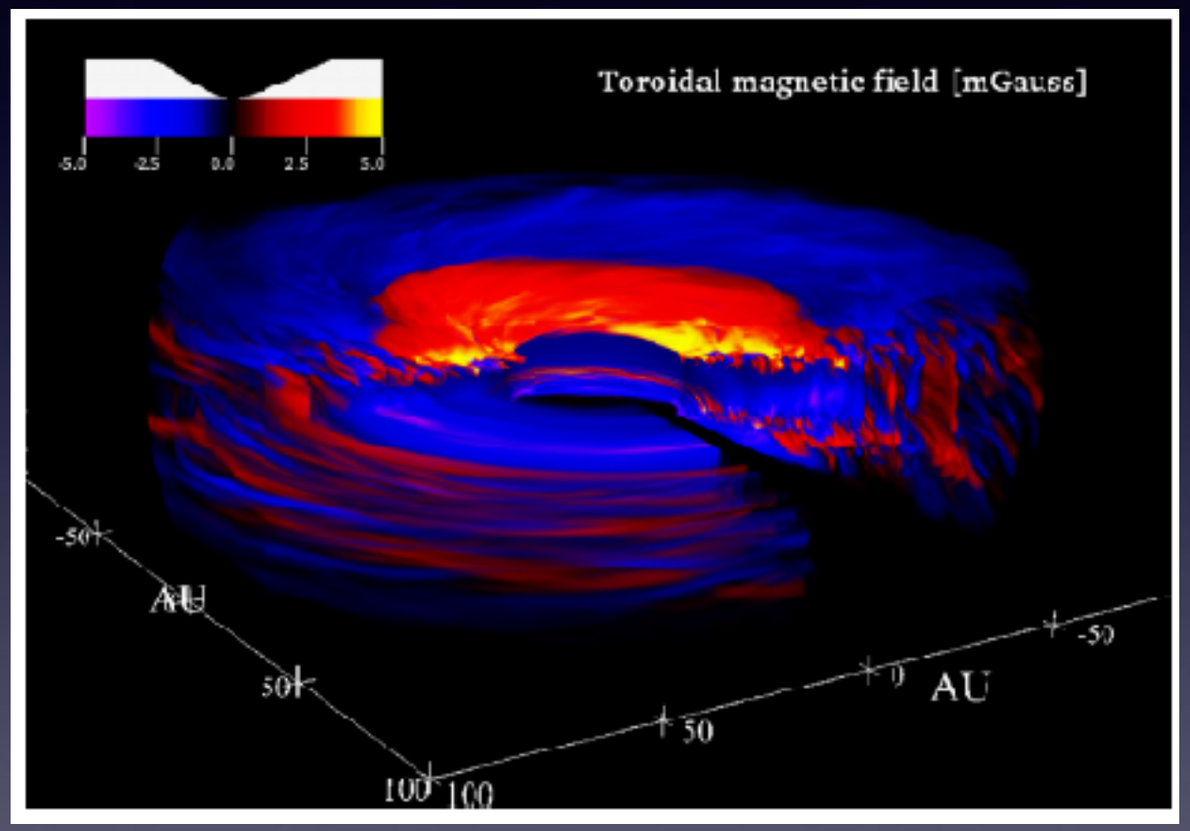
Vertical dust height: ~1au at r =100 au

Local diffusion coefficient: $\alpha_{\mathrm{LC}} \sim 10^{-4}$

Magnetically Driven Disk Accretion

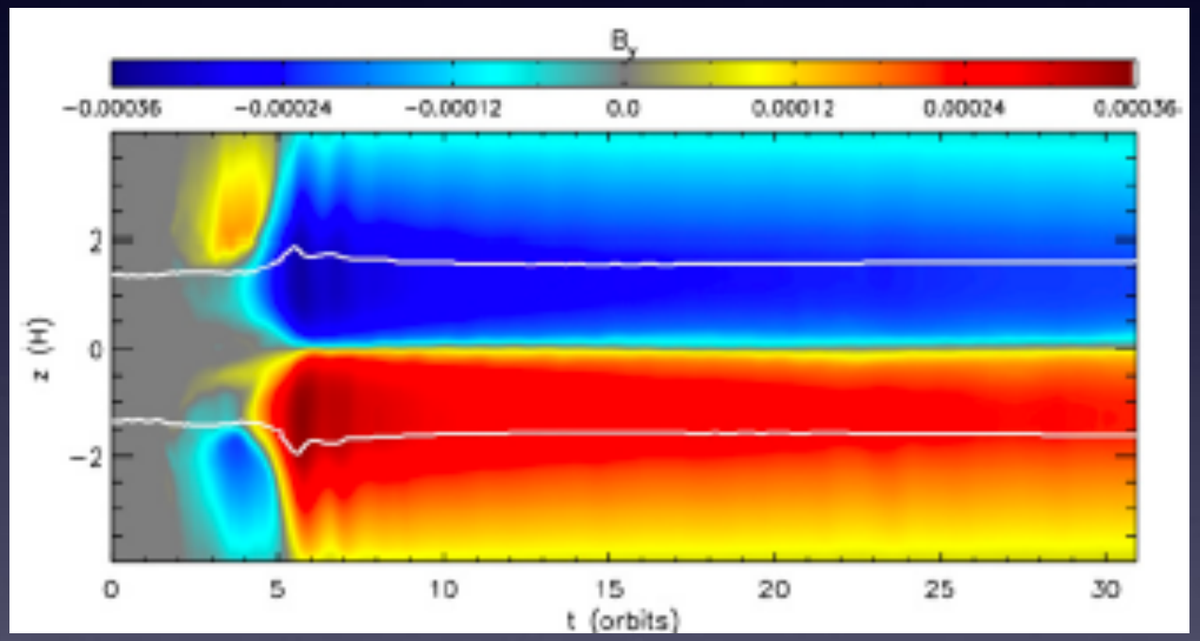
e.g., Armitage et al 2011, Bai & Stone 2013, Turner et al 2014, Suzuki et al 2016

Magnetized Turbulence



Flock et al 2015

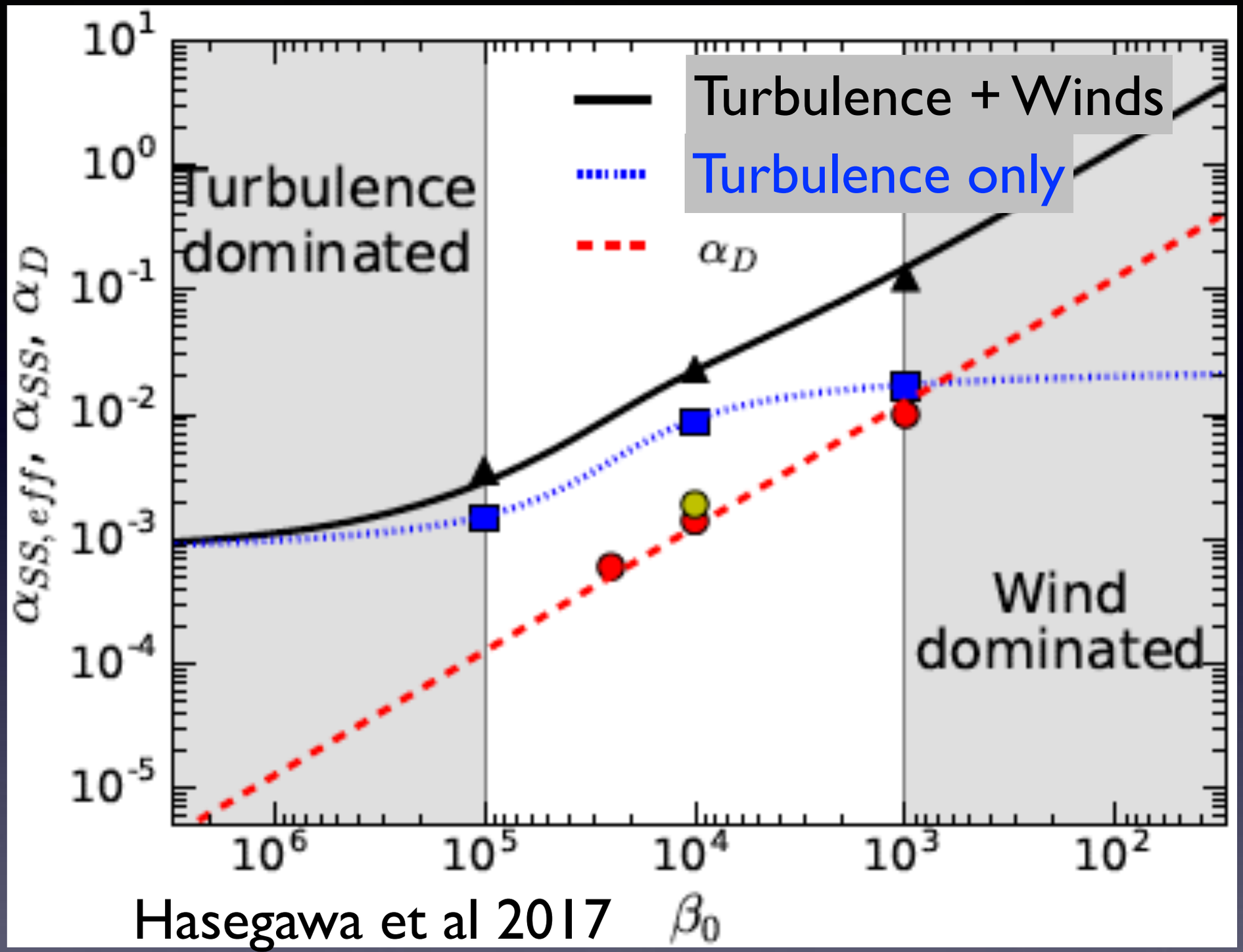
Magnetically Induced Disk Winds



Simon et al 2013

Weak → Strong

B-fields



Hasegawa et al 2017

α_D : vertical mixing of dust

β_0 : the plasma beta

Weak → Strong

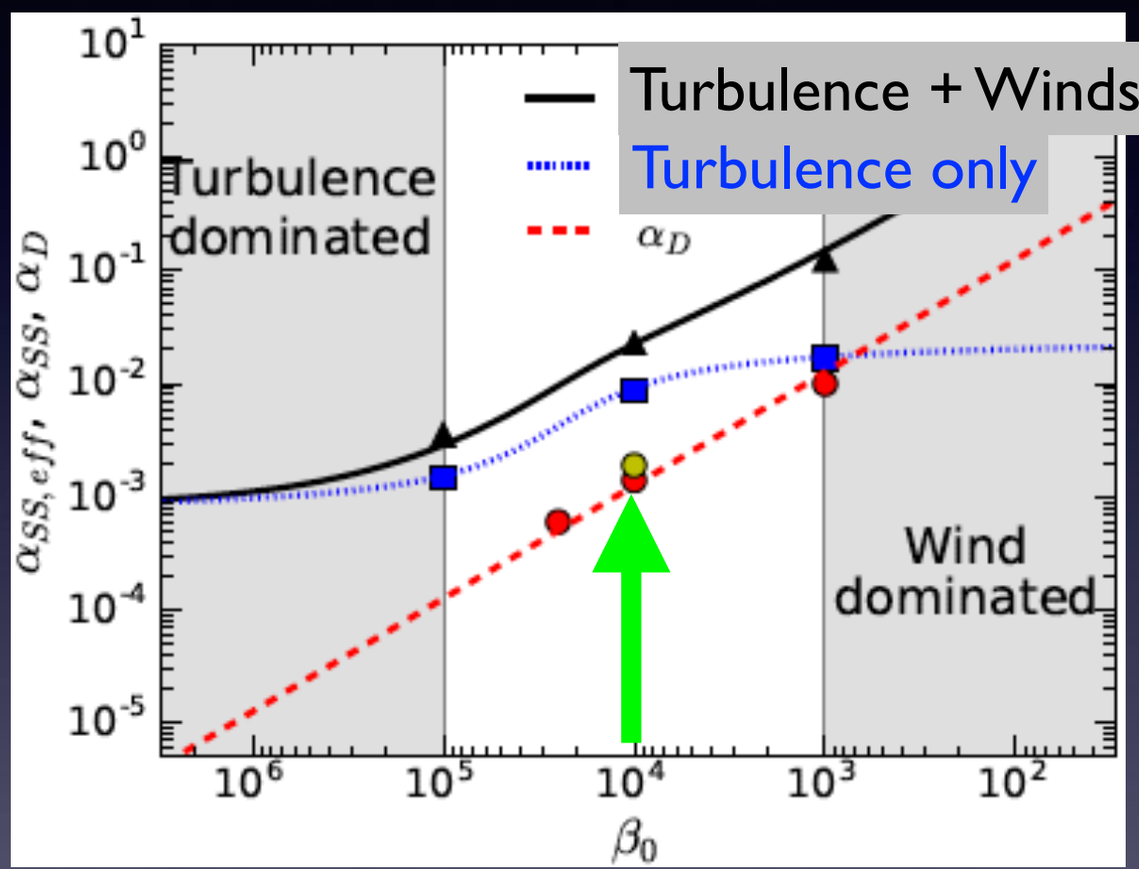
B-fields

Simulation results from Simon et al 2013, Zhu et al 2015 are used

Given that

$$\dot{M}, c_{\rm s}^2(\propto T_d),\ \Omega(\propto \sqrt{M_*})$$

1. Gas surface density

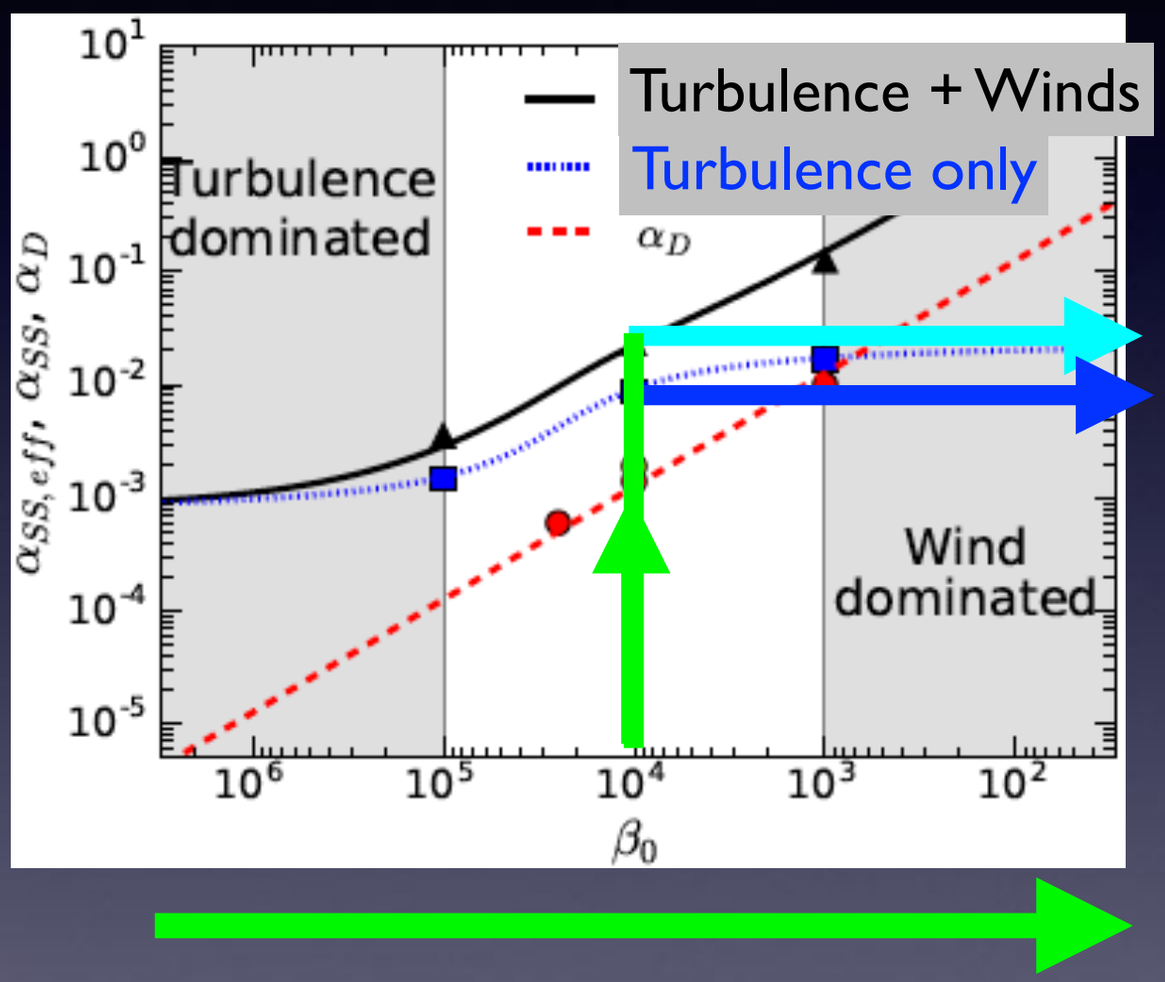


2. Dust height

B-fields

Given that

$$\dot{M}, c_{\rm s}^2(\propto T_d),\ \Omega(\propto \sqrt{M_*})$$



B-fields

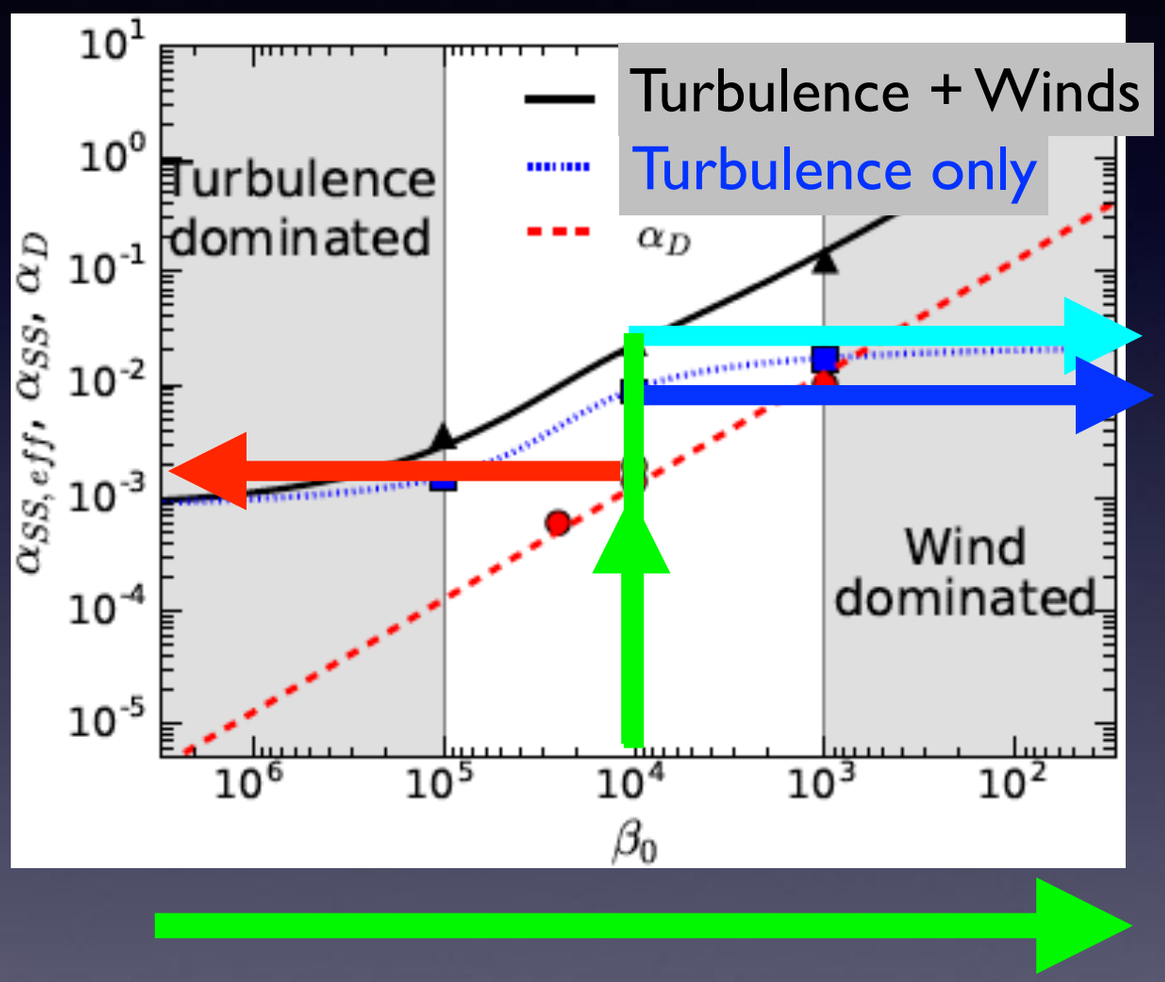
1. Gas surface density

$$\Sigma_{\rm g} = \frac{\dot{M}\Omega}{3\pi\alpha_{\rm GL}c_{\rm s}^2}$$

2. Dust height

Given that

$$\dot{M}, c_{\rm s}^2(\propto T_d),\ \Omega(\propto \sqrt{M_*})$$



B-fields

1. Gas surface density

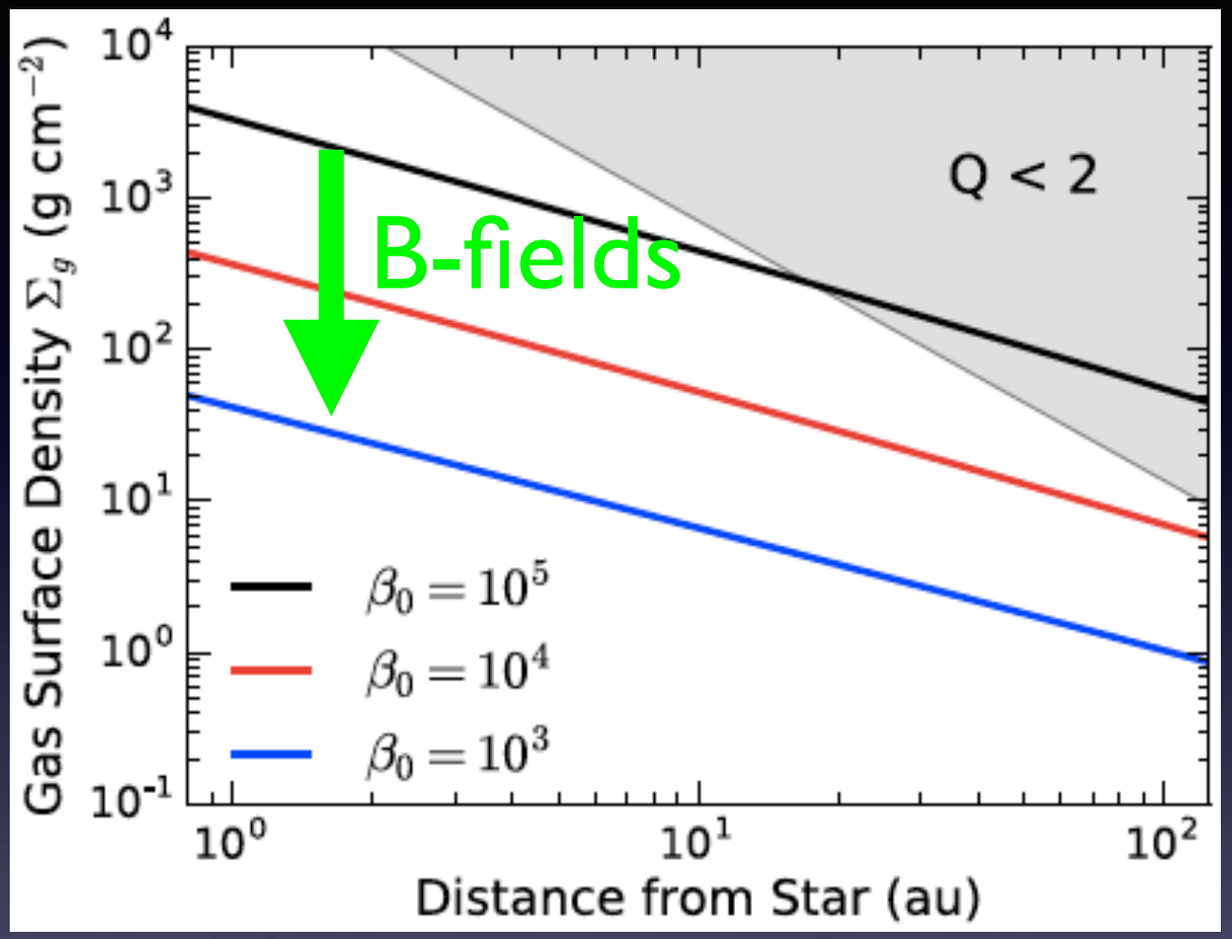
$$\Sigma_{\rm g} = \frac{\dot{M}\Omega}{3\pi\alpha_{\rm GL}c_{\rm s}^2}$$

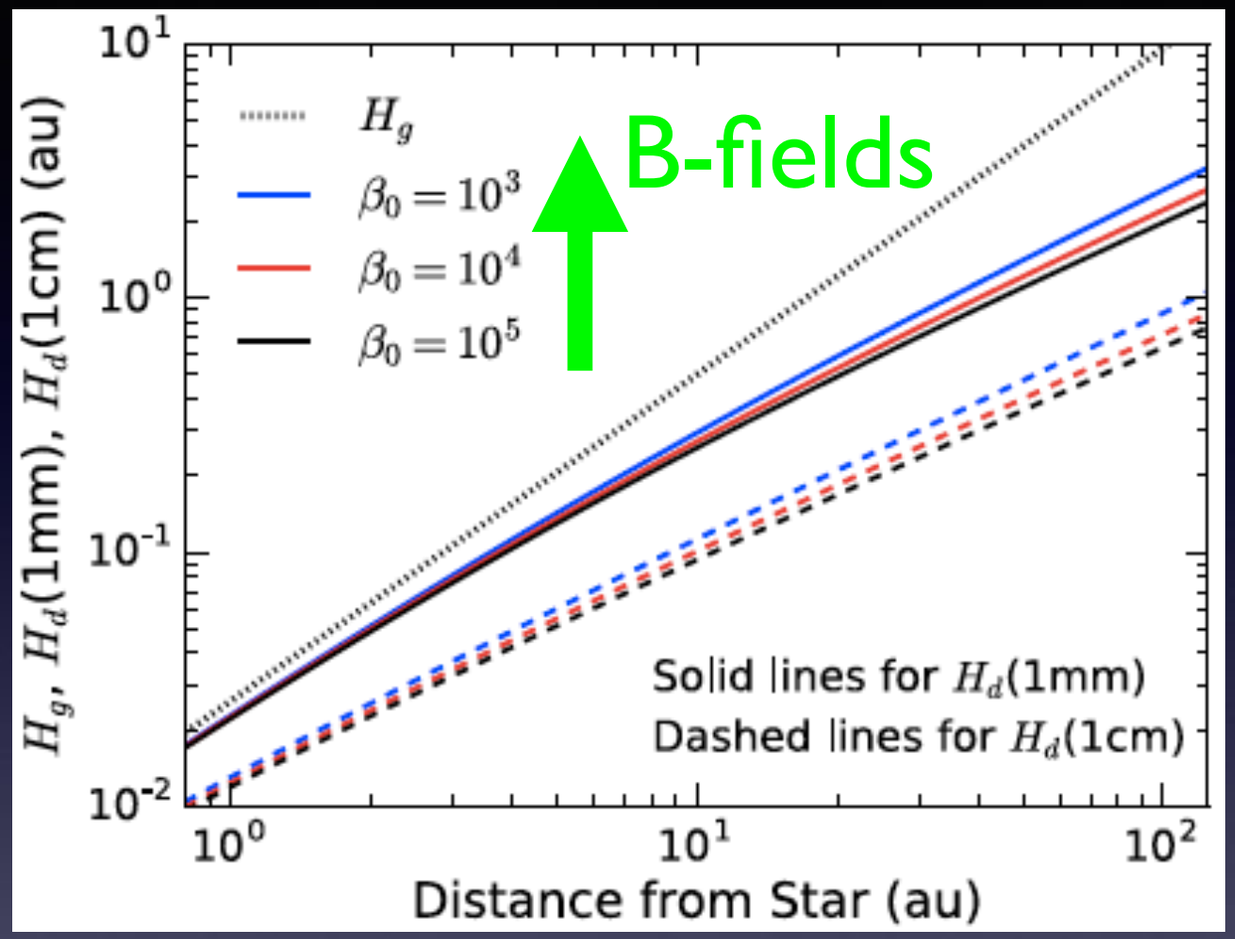
2. Dust height

$$H_{\rm d} = \left(1 + \frac{St}{\alpha_D}\right)^{-1/2} H_{\rm g}$$

$$St \propto \frac{a}{\Sigma_{\rm g}}$$

Ex) Resulting Disk Structures with Disk Winds



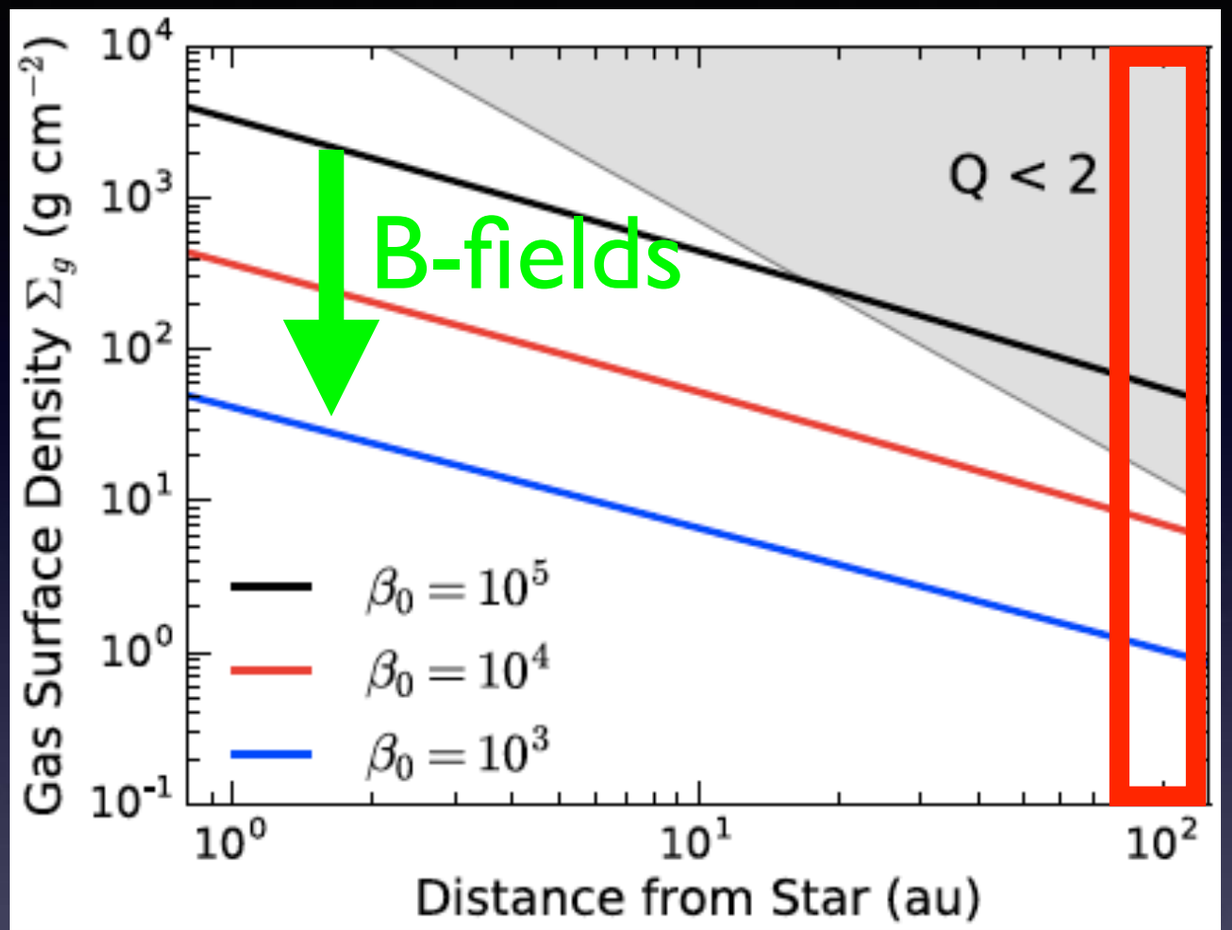


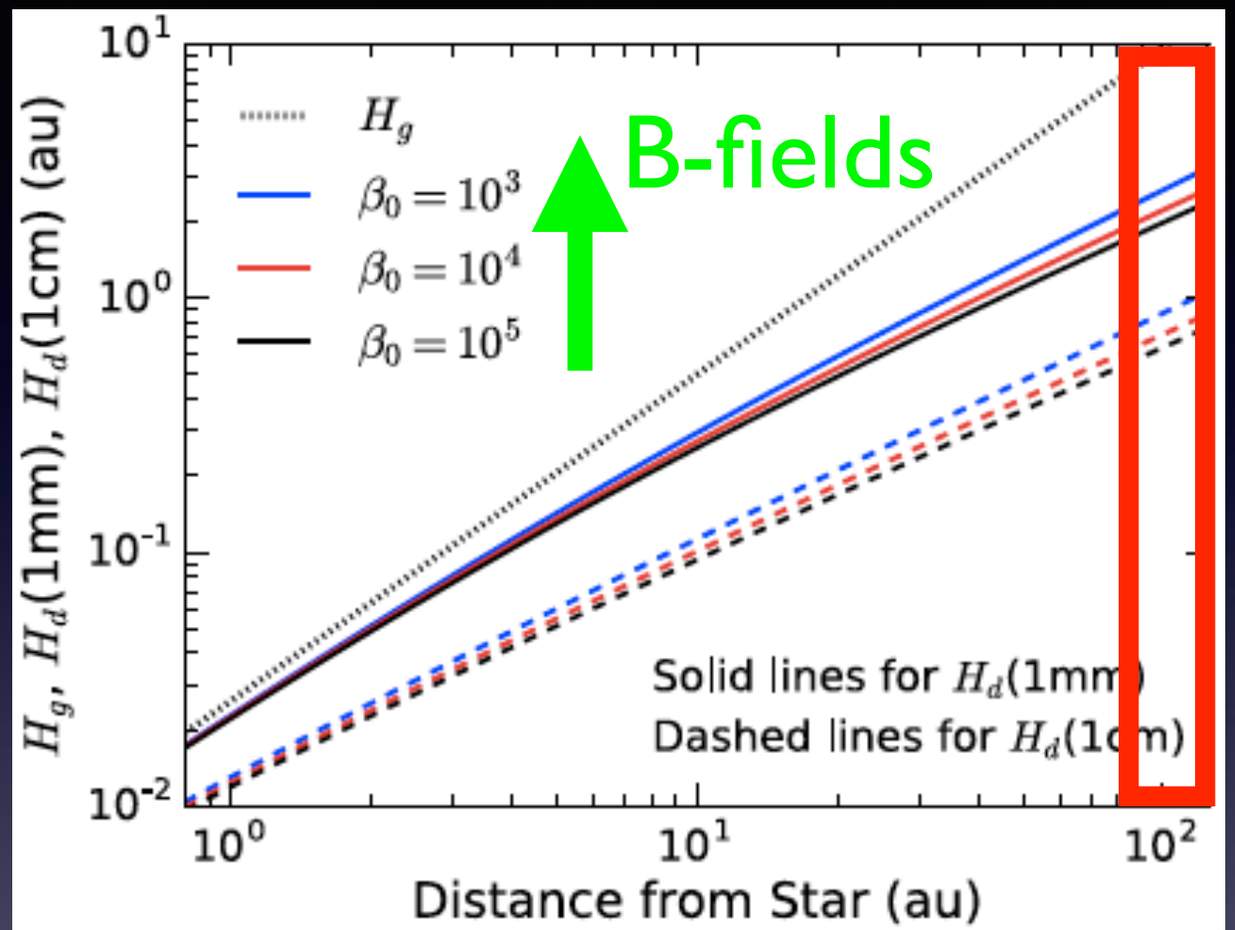
As B-fields are stronger, surface density decreases due to disk winds

Dust scale heights are independent of B-fields

Results are obtained for given values of disk accretion rate, disk temperature

Ex) Resulting Disk Structures with Disk Winds





Focus on the HL Tau disk

Inversely solve the problem

1. Find β_0 with which $\Sigma_{\rm g}$ marginally avoids GI

2. Find β_0 with which the dust size satisfies $H_{\rm d} = 1$ au

Results at r = 100 au

Turbulence only

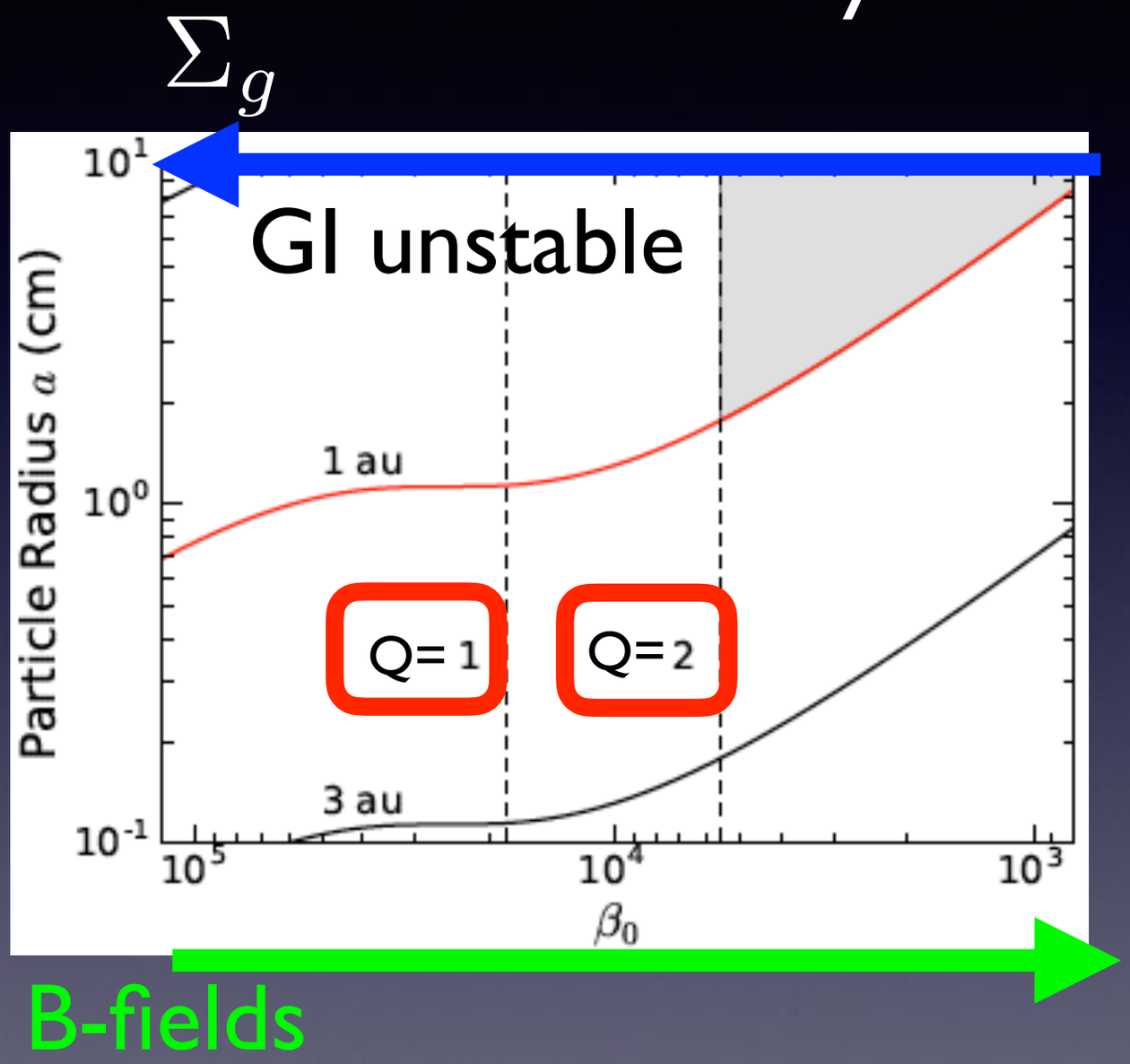
Turbulence + Winds

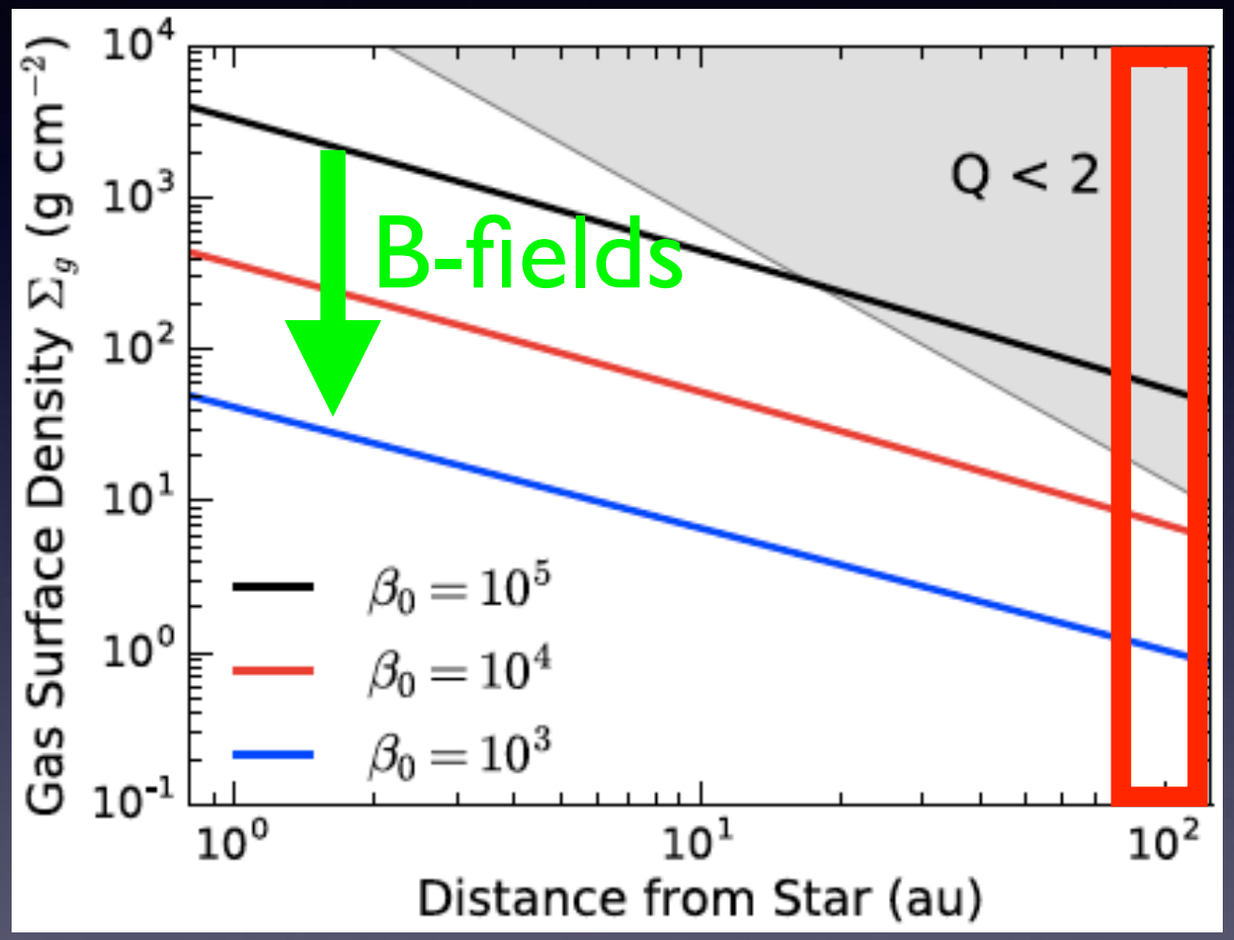
Results are obtained for given values of disk accretion rate, disk temperature

Results at r = 100 au

Turbulence only

Turbulence + Winds





Results are obtained for given values of disk accretion rate, disk temperature

Results at r = 100 au

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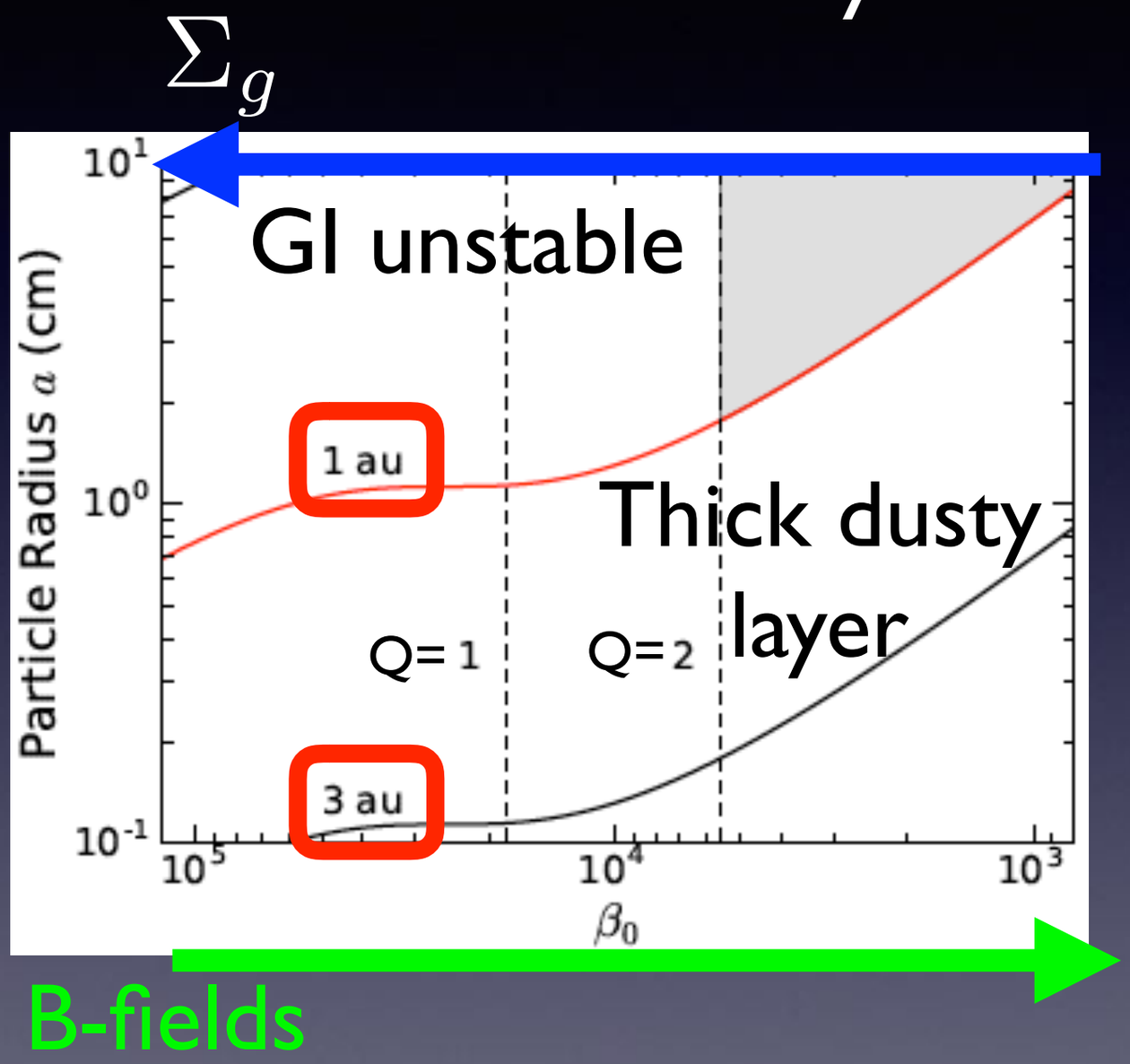
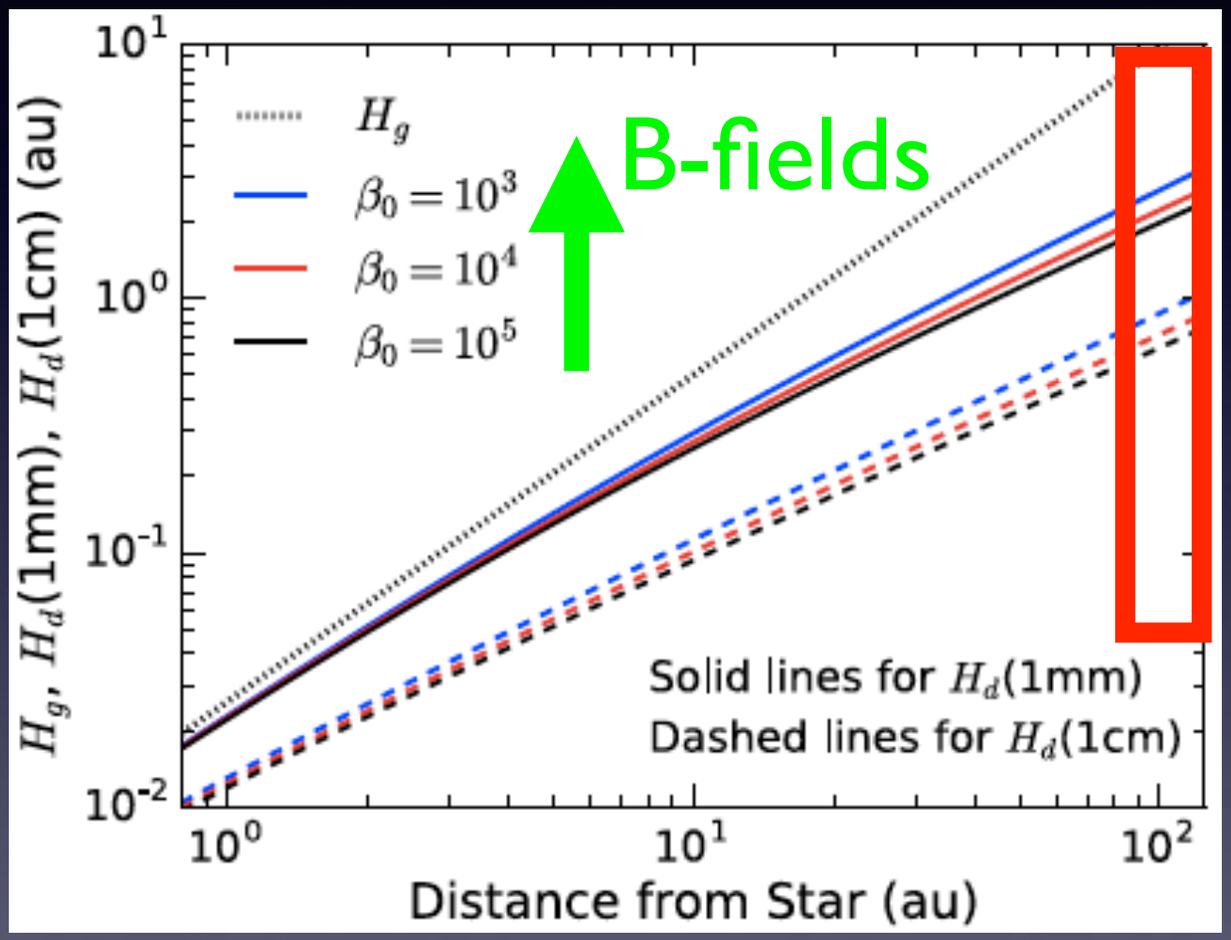
Turbulence + Winds



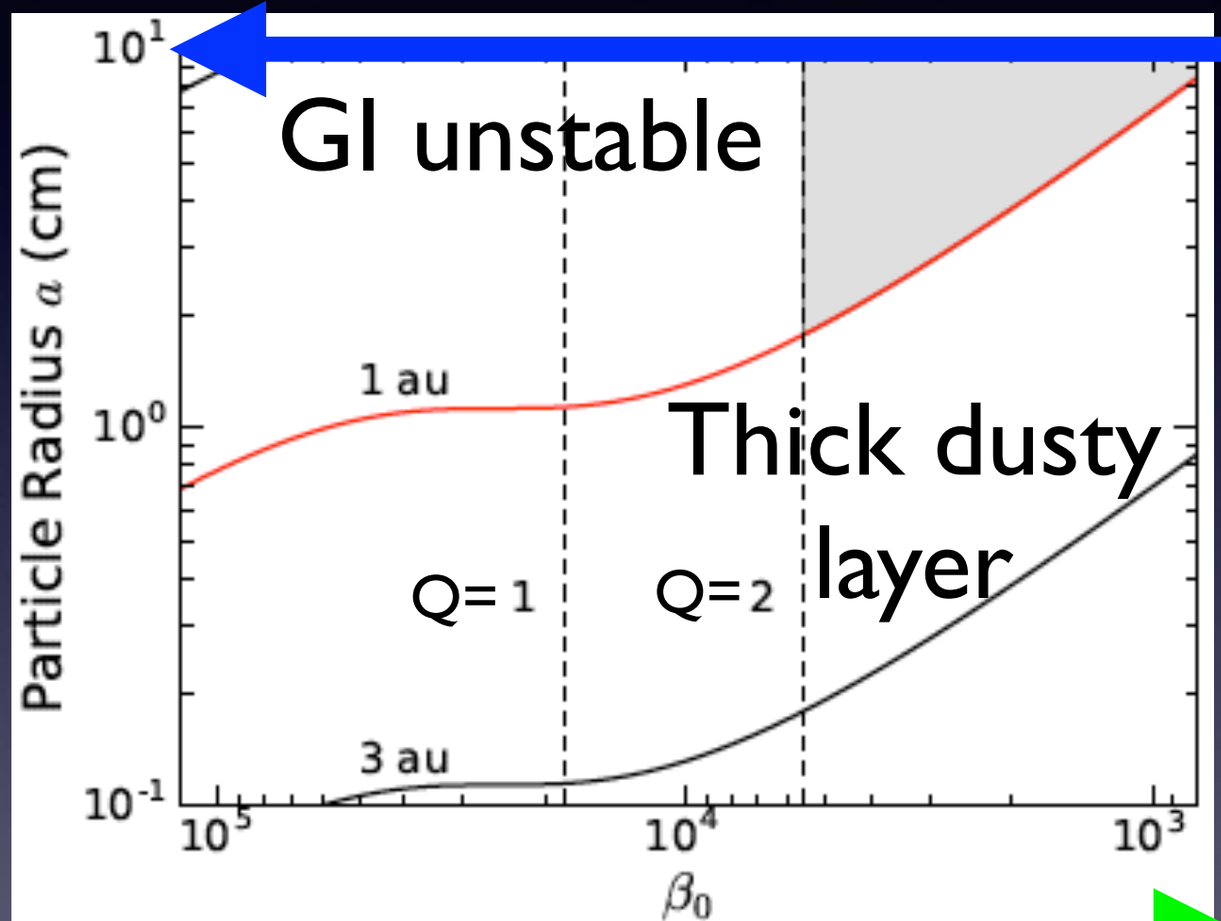


Results are obtained for given values of disk accretion rate, disk temperature

Results at r = 100 au

Turbulence only

Σ_g

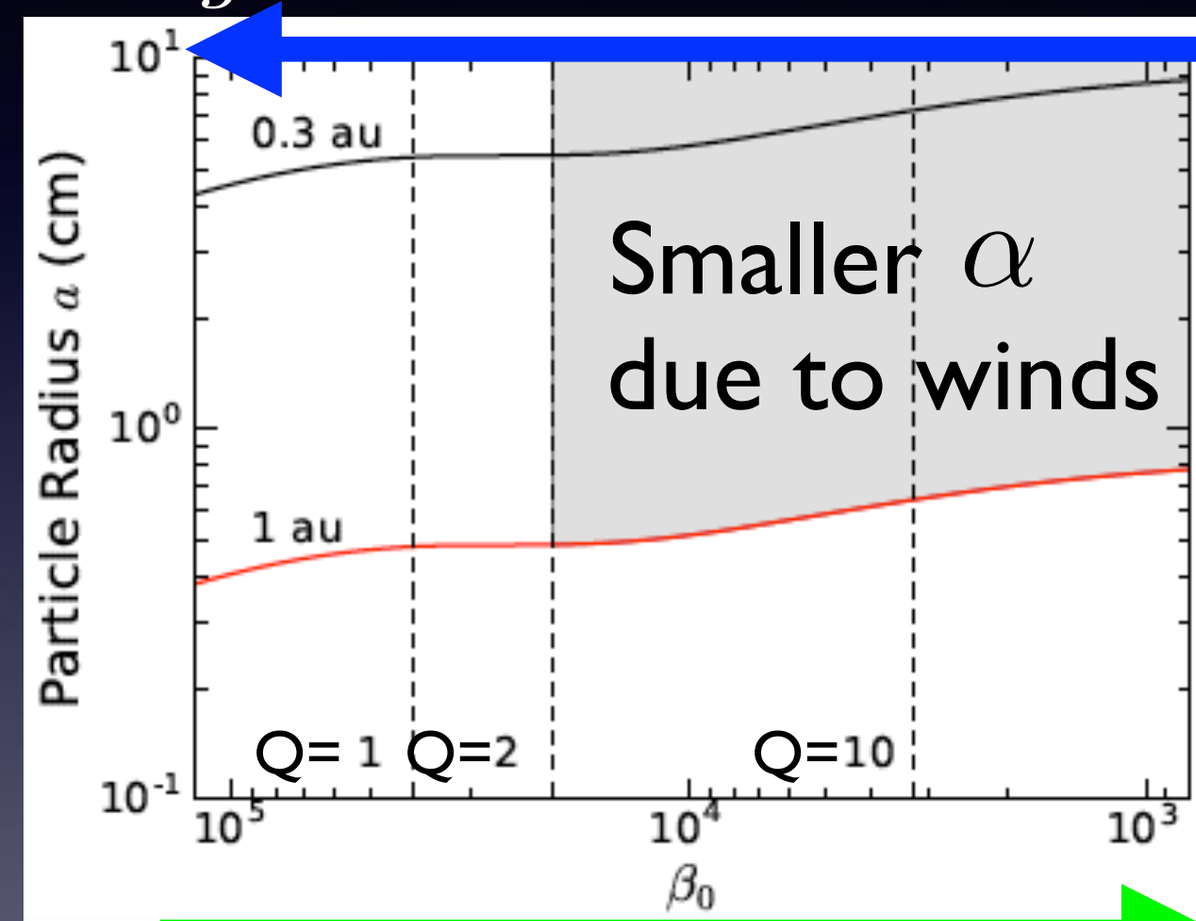


B-fields

20 mm-sized dust is needed to reproduce ALMA image

Turbulence + Winds

Σ_g

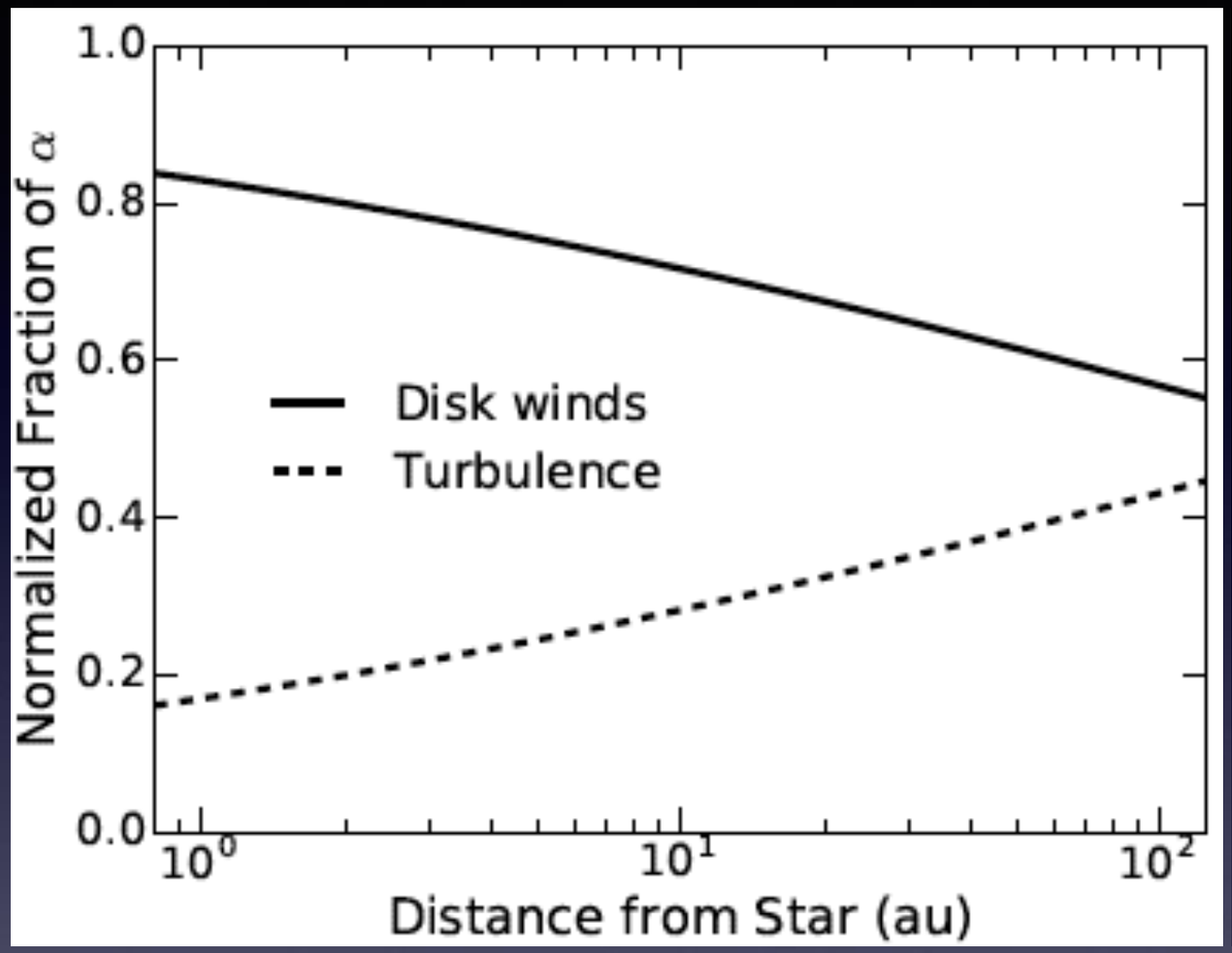


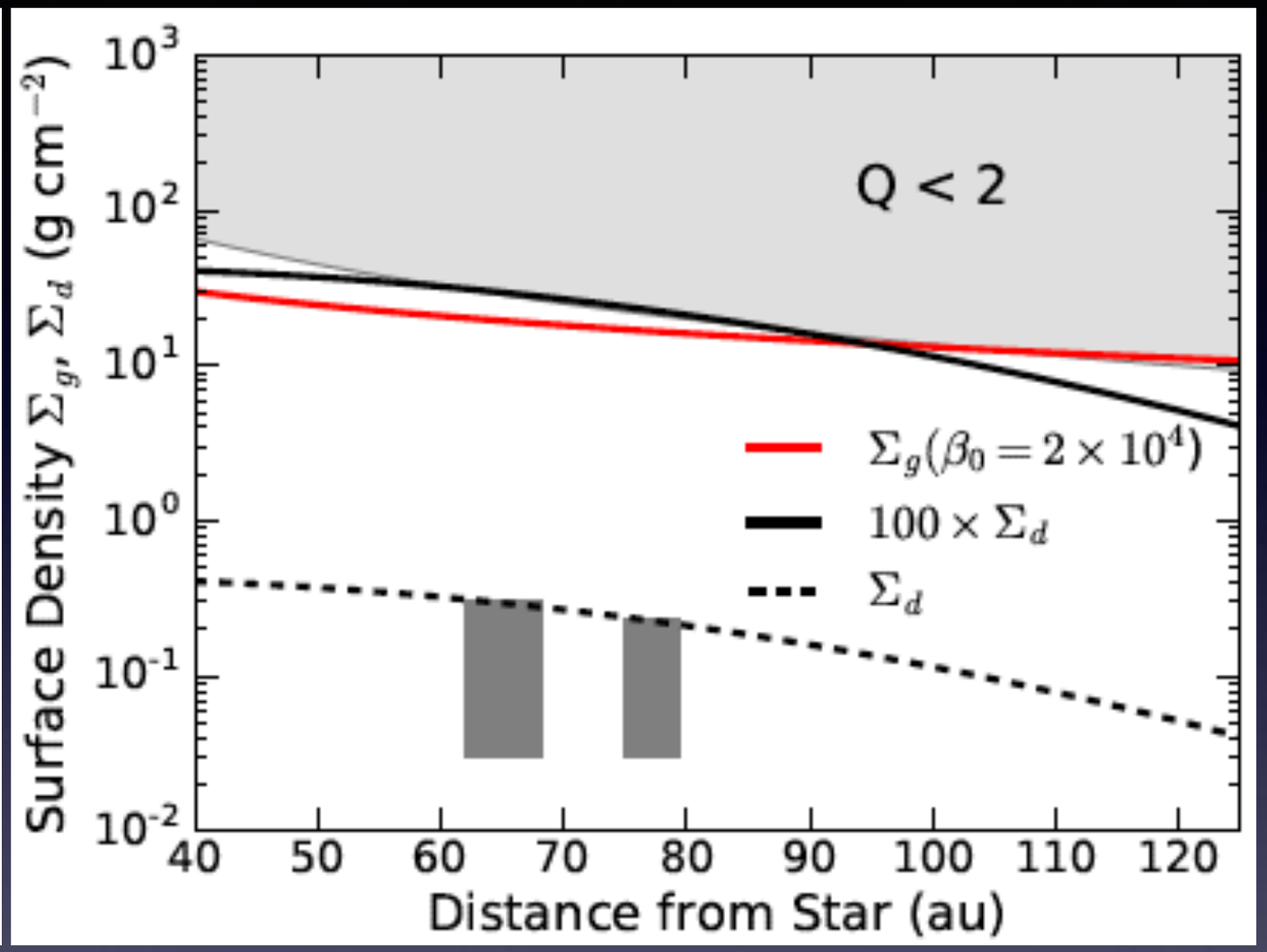
B-fields

4 mm-sized dust is needed to reproduce ALMA image

Results are obtained for given values of disk accretion rate, disk temperature

Resulting Global Structure of the HL Tau Disk

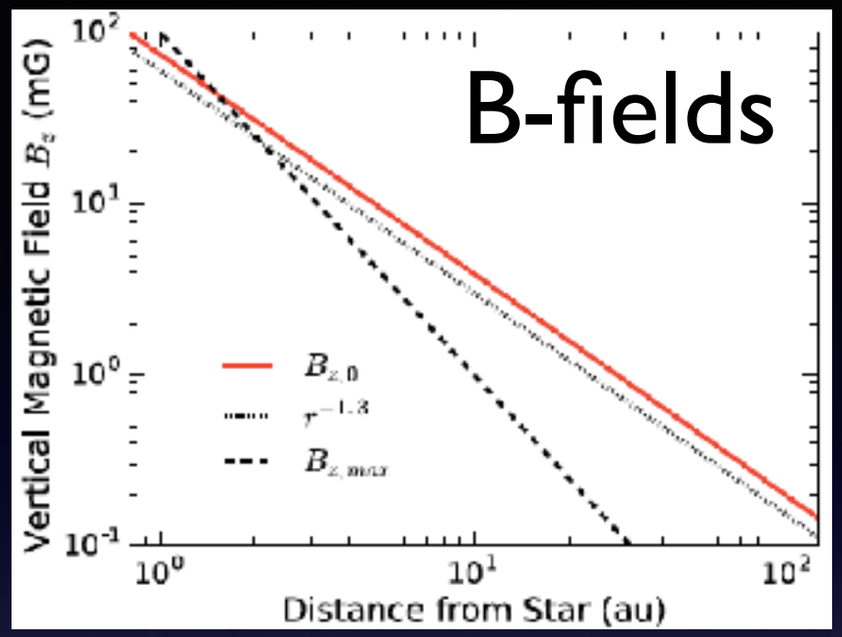


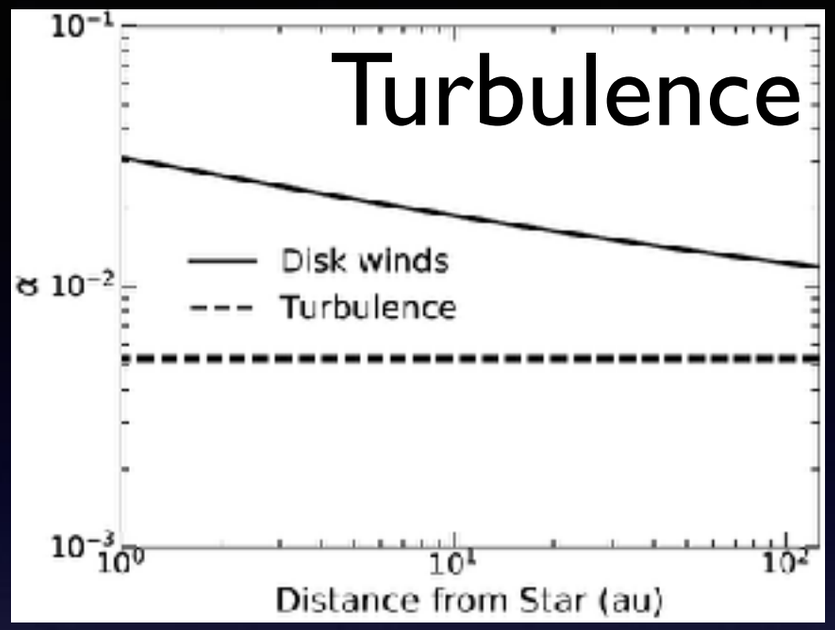


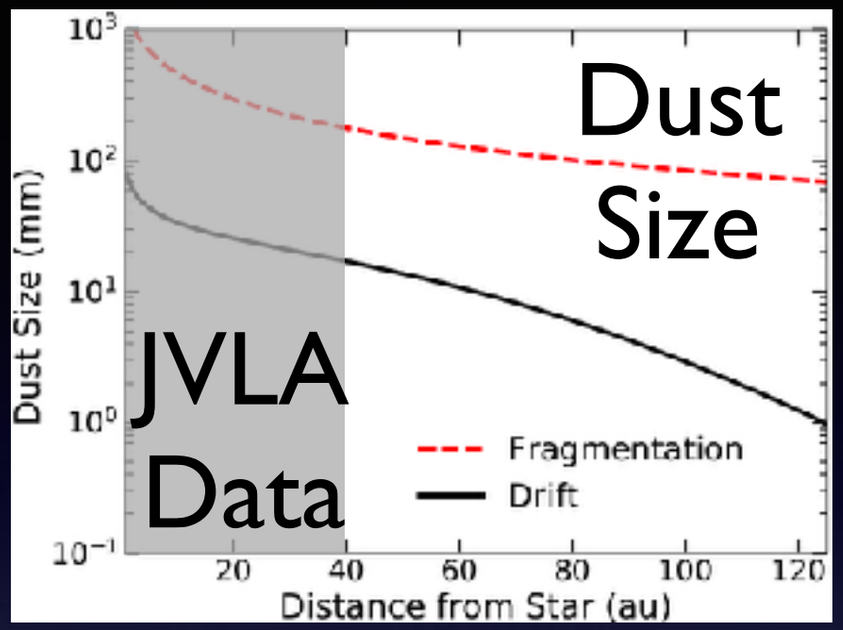
Disk winds transport the most of angular momentum (50-80 %) across the entire region of the disk

The gas-to-dust rate varies along the distance from the star (lower in the inner region & higher in the outer region)

Next Step



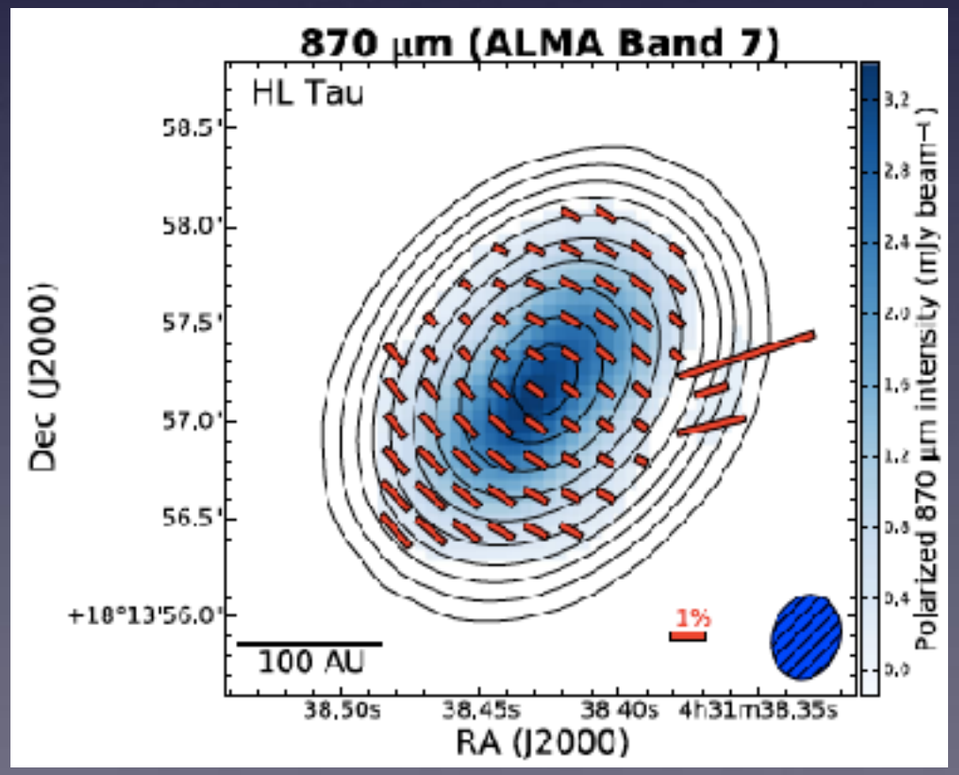




Origin of dust gaps

also see Akiyama et al 2016

Polarization



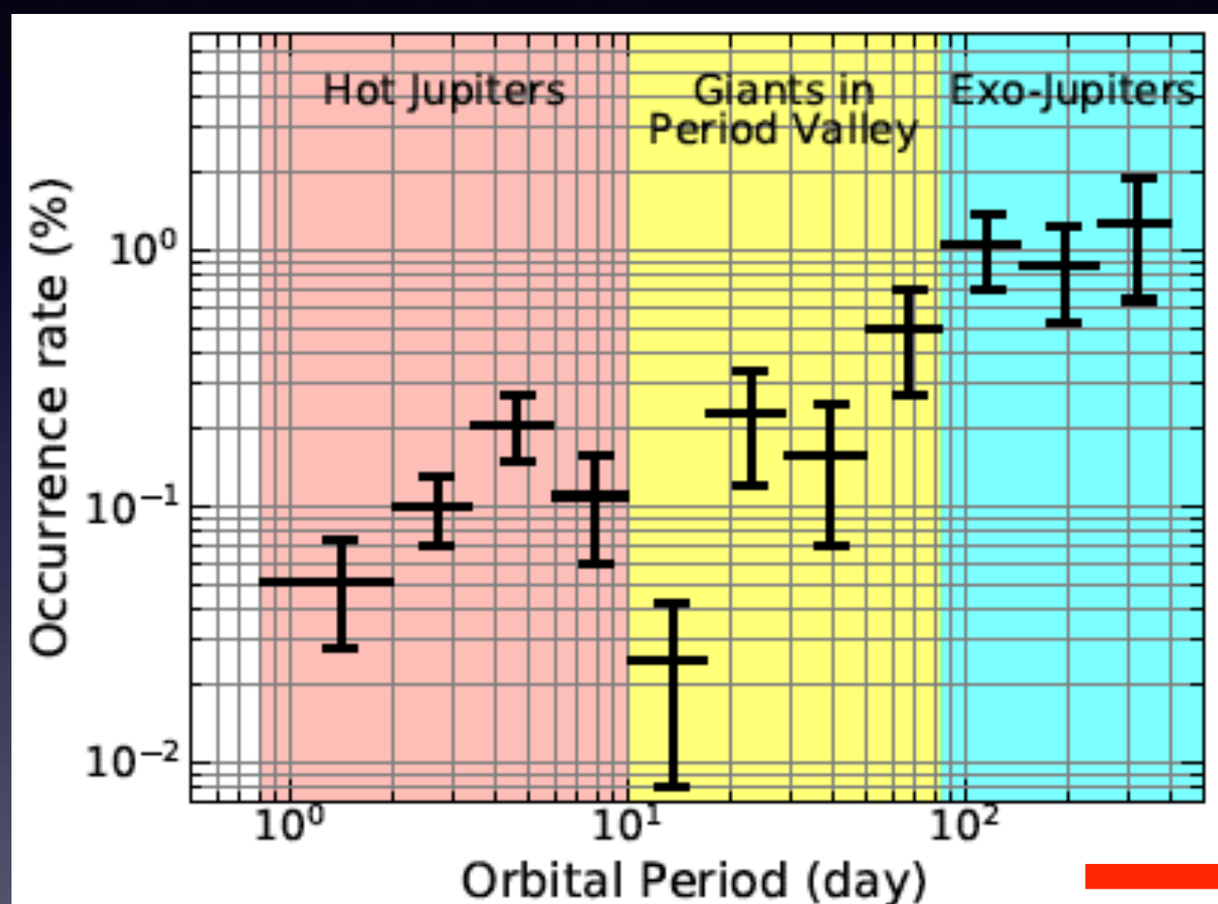
Kataoka et al 2017, Stephens et al 2017

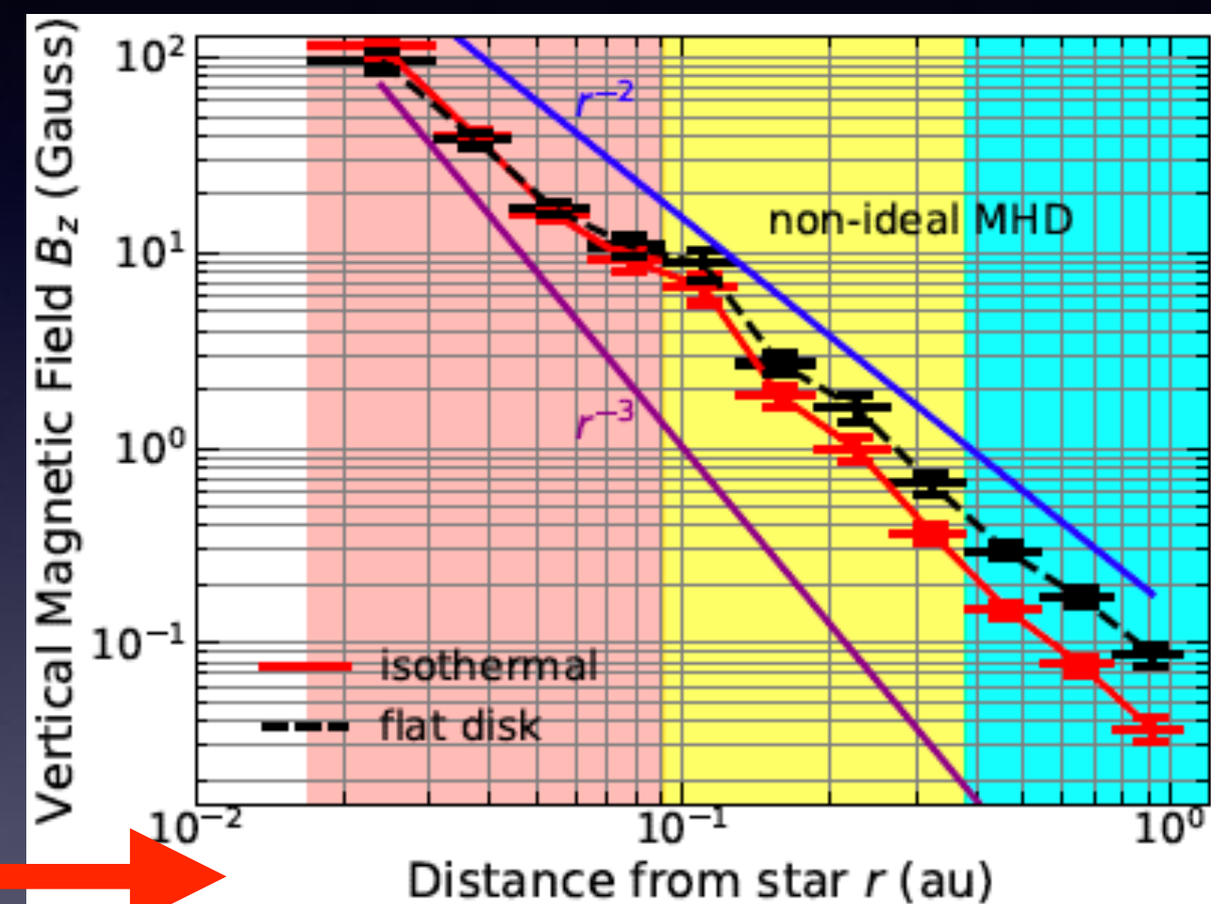
Summary

Hasegawa et al 2017, ApJ, 845, 31

- ALMA observations of the HL Tau disk can advance our understanding of **disk evolution**
- Subsequent radiative transfer modeling suggests a higher degree of dust settling for the actively accreting disk
- Developed the simple, semi-analytical model, taking into account magnetically induced disk winds
- Our results indicate the importance of **magnetically induced disk winds** to fully reproduce the global configuration
- Followup work will be performed to obtain a better understanding of **polarization** observations and to identify the origins of observed **multiple gaps** in the HL Tau disk

Close-in Giant Planets via In-situ Gas Accretion & Their Natal Disk Properties



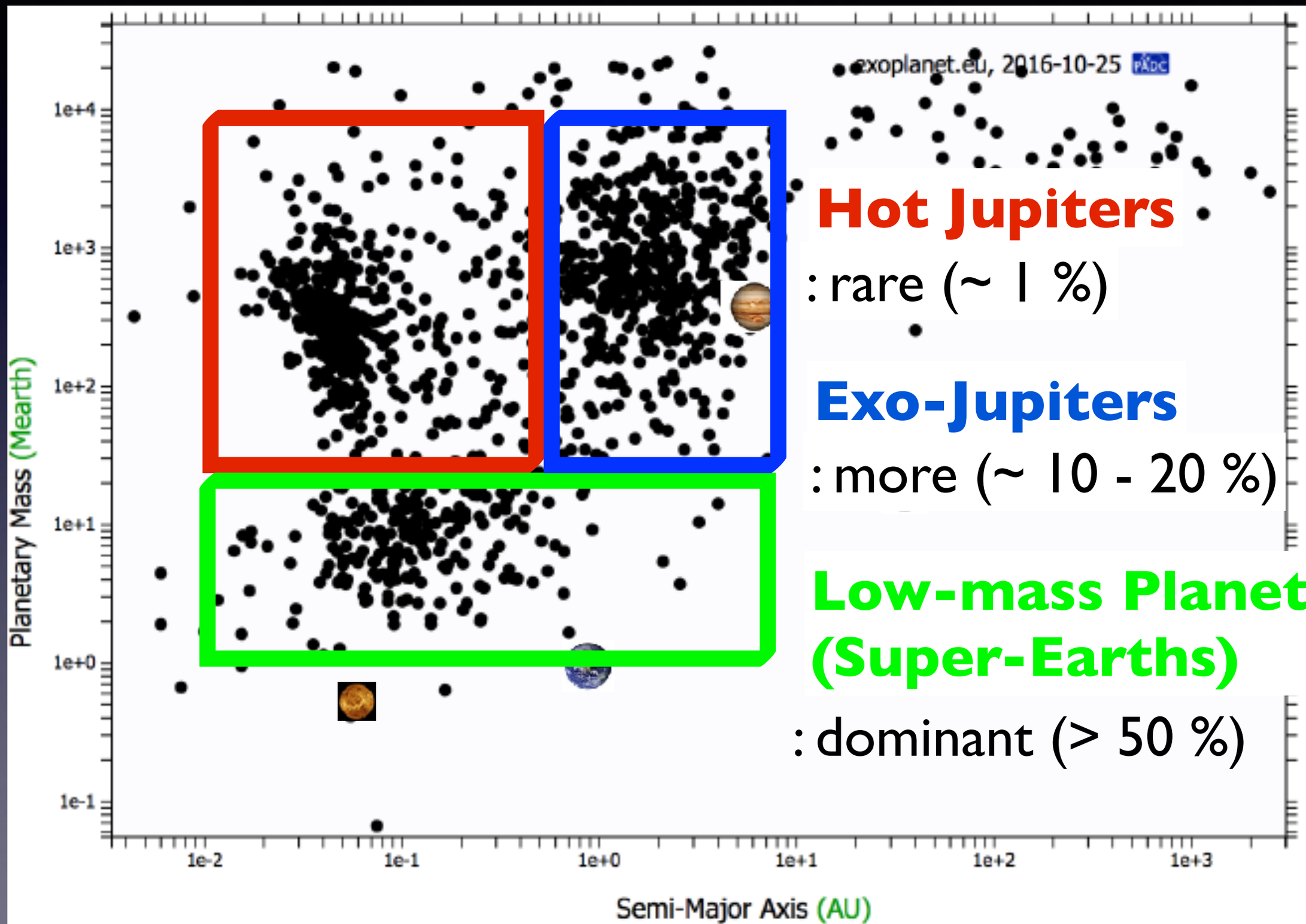


Santerne et al 2016

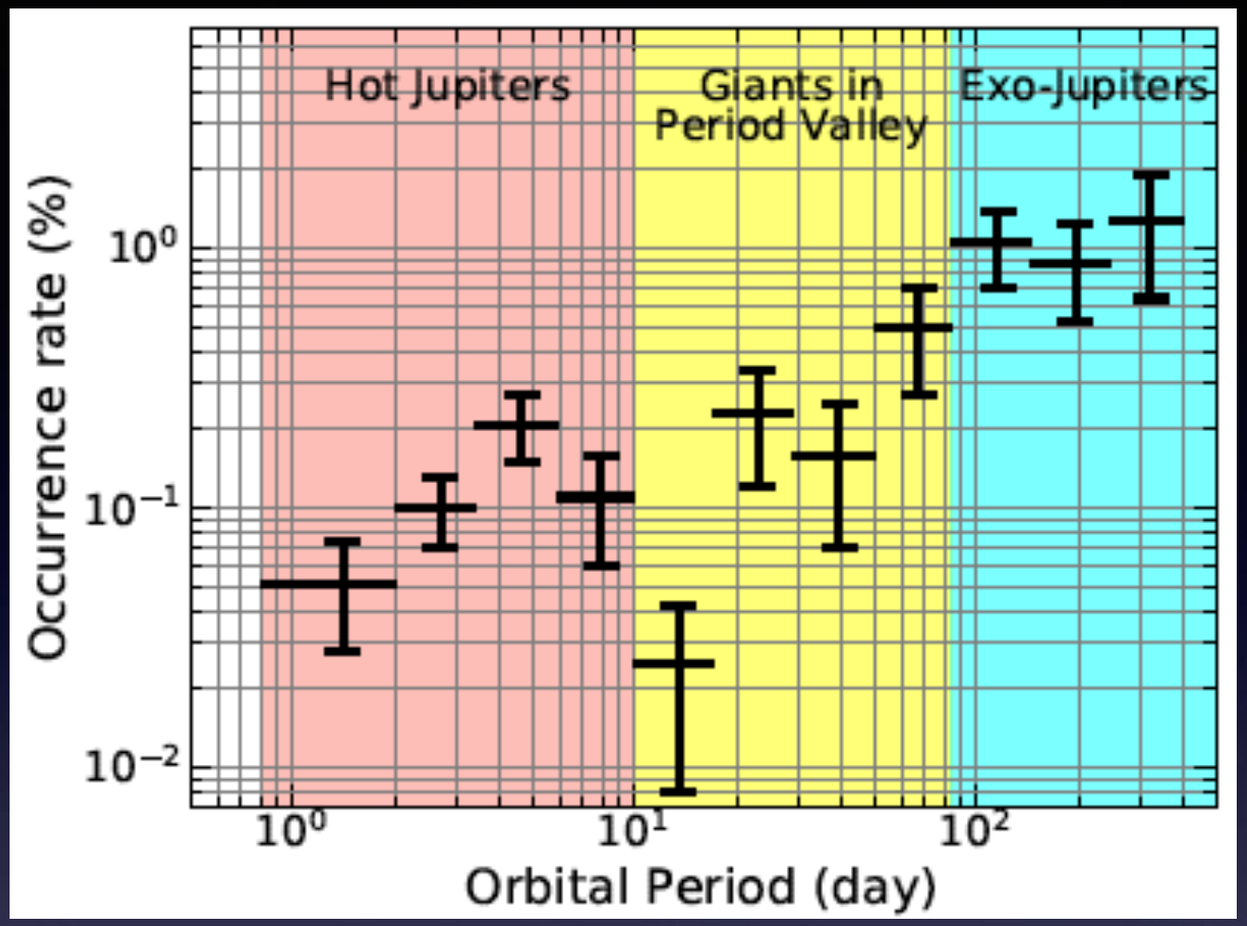
in collaboration with
Mathew Yu (UCLA) and Brad Hansen (UCLA)

Exoplanetary Populations

e.g., Winn & Fabrycky 2015 for a review

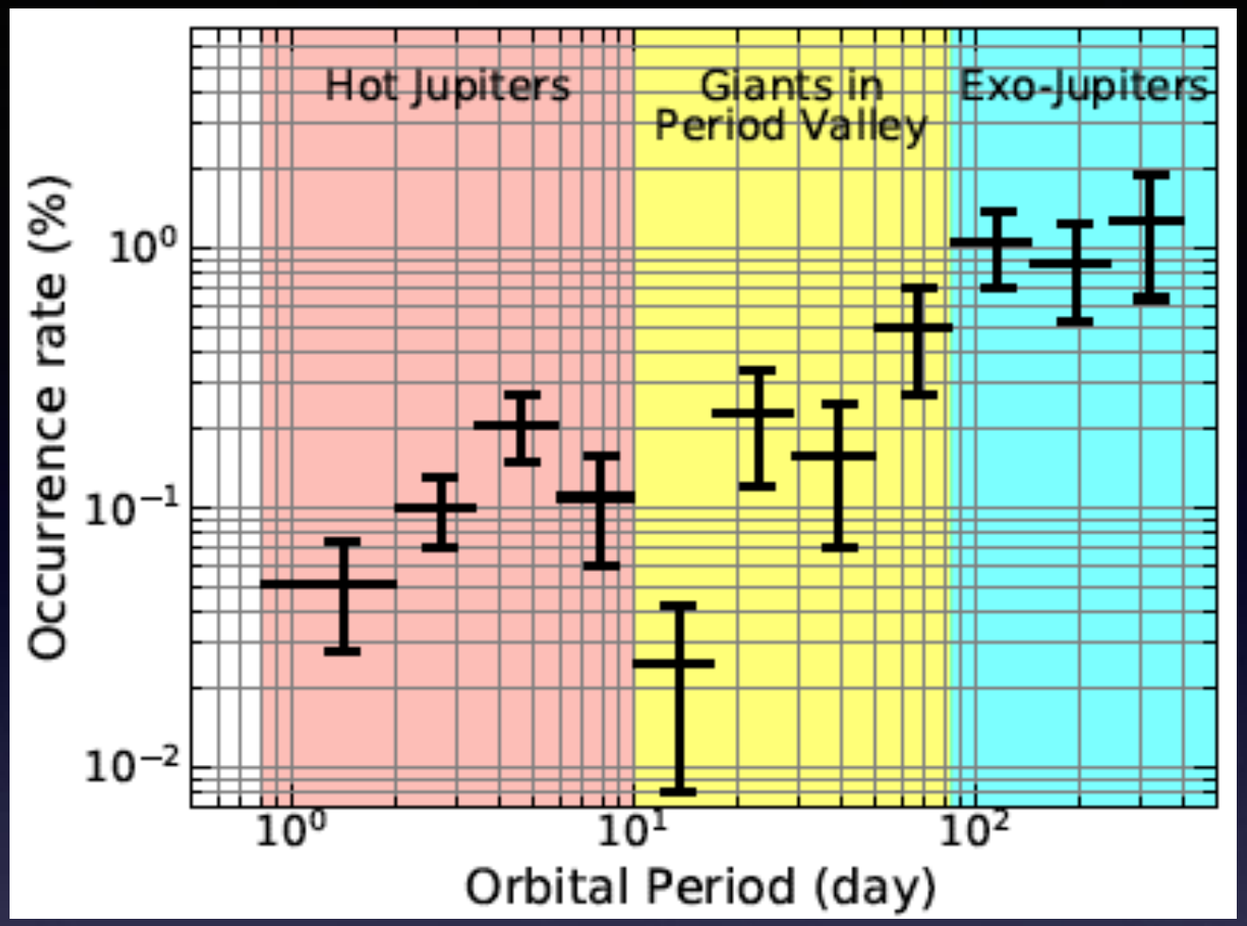


Santerne et al 2016



How to form close-in gas giants?

Santerne et al 2016



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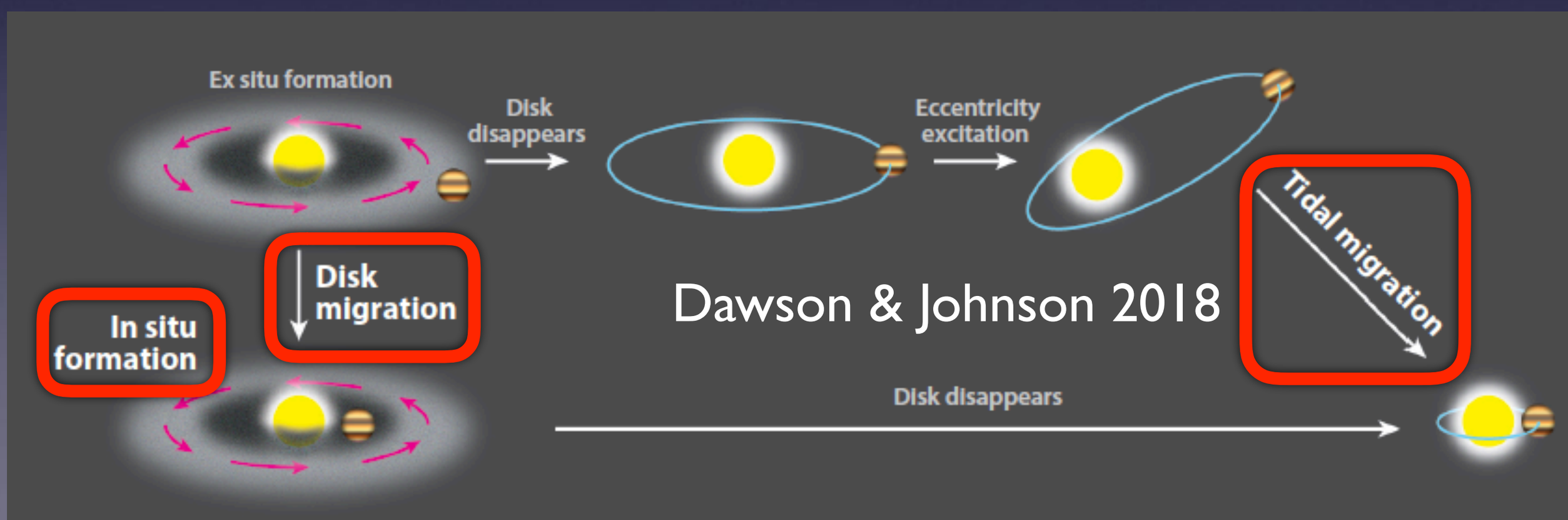
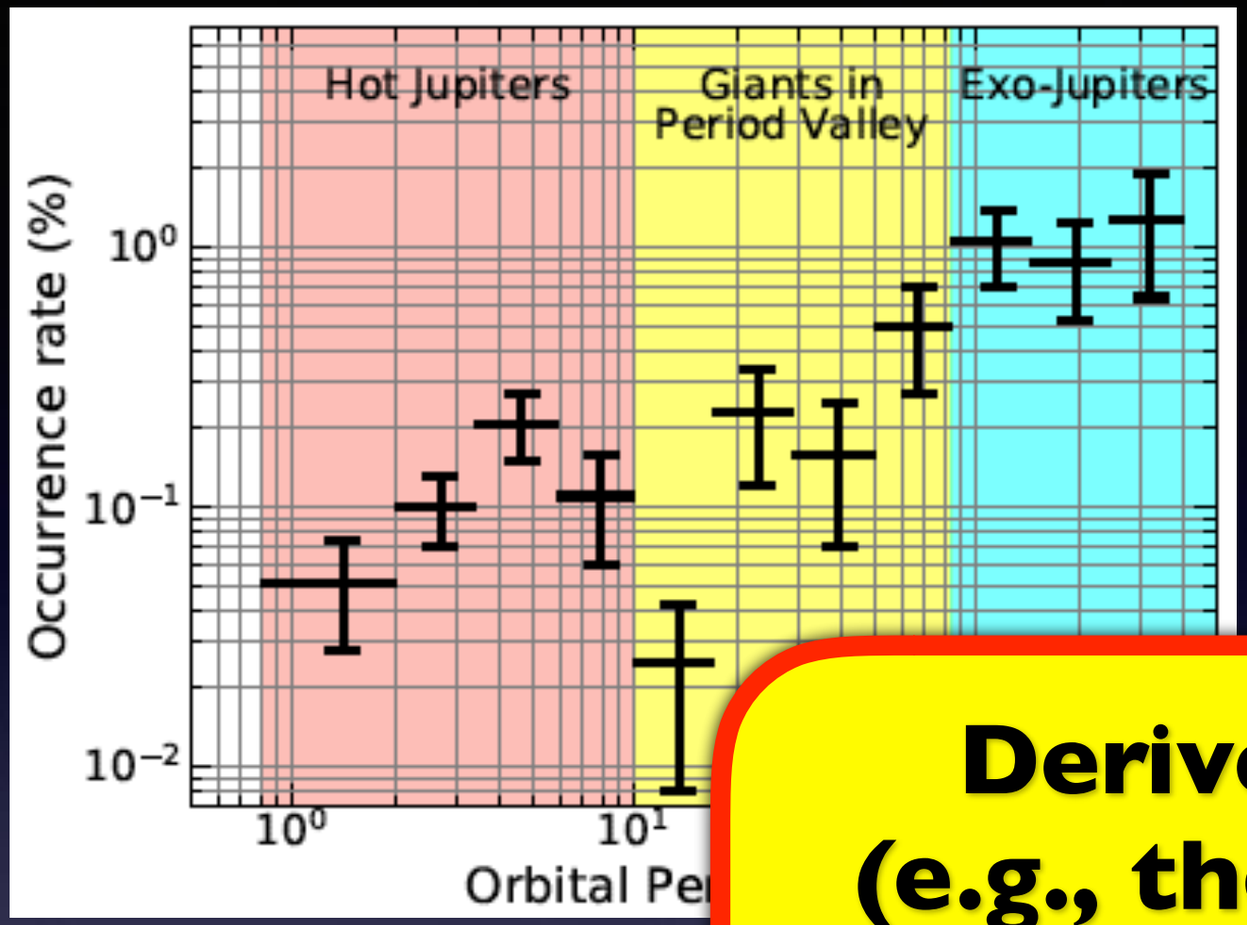


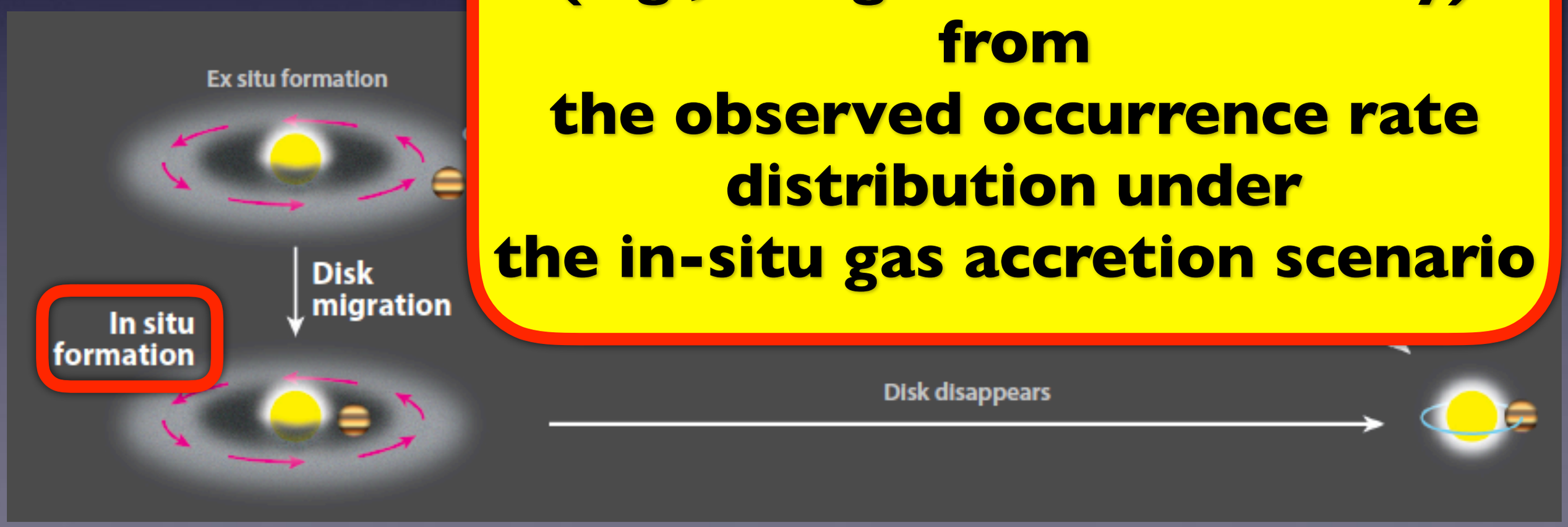
Dawson & Johnson 2018

Santerne et al 2016



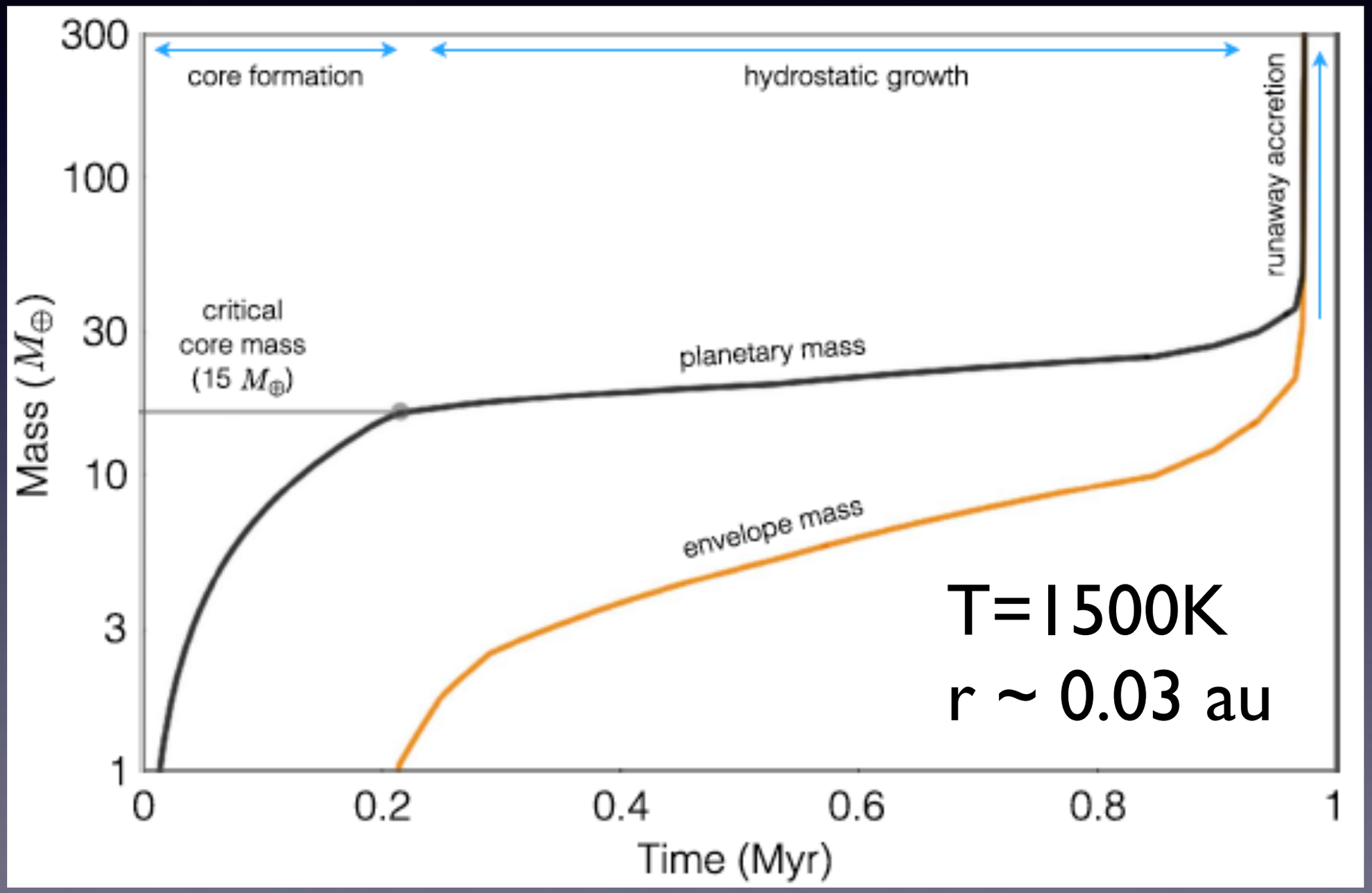
How to form close-in gas giants?

Derive some observables (e.g., the gas surface density) from the observed occurrence rate distribution under the in-situ gas accretion scenario



In-situ gas accretion IS possible in the vicinity of the central star

e.g., Bodenheimer et al 2000, Batygin et al 2016



Basic Hypothesis:

the occurrence rate ~ gas accretion onto planets

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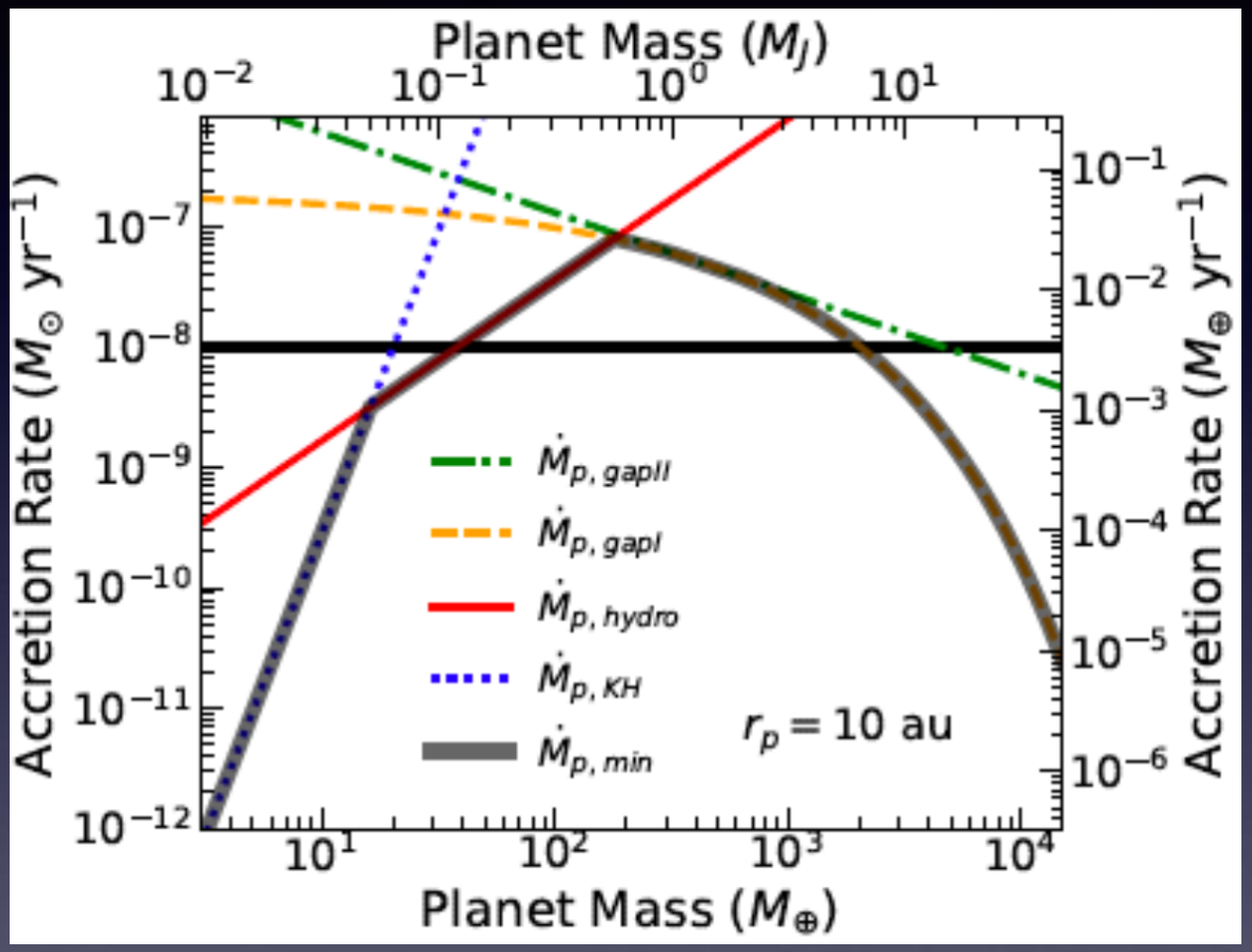
the occurrence rate ~ gas accretion onto planets



Hasegawa et al 2019a

Gas accretion

Kelvin-Helmholtz contraction

↓

Disk-limited accretion

↓

Accretion through gas gaps

Basic Hypothesis:

the occurrence rate ~ gas accretion onto planets

$$\dot{M}_p \simeq 0.29 \left(\frac{H_{\rm g}}{r_p}\right)^{-2} \left(\frac{M_p}{M_*}\right)^{4/3} \Sigma_{\rm g} r_p^2 \Omega$$

Tanigawa & Ikoma 2007

Gas accretion

Kelvin-Helmholtz contraction

Disk-limited accretion

Accretion through gas gaps

the occurrence rate $\propto \dot{M}_p \equiv f(T_{\rm d}, \Sigma_{\rm g})$

Steady State Disk Accretion Model

Disk accretion rate: $\dot{M}_{\rm d} = 3\pi\nu\Sigma_{\rm g}$

Turbulent viscosity: $\nu = \alpha H_{\rm g}^2 \Omega$ Shakura & Sunyaev 1973

Disk temperature: $T_{\rm d}^4 = \frac{27\tau}{128\sigma_{\rm SB}}\Sigma_{\rm g}\nu\Omega^2$ Ruden & Lin 1986

Opacity:

The metal grain case

The case of evaporation of metal grains

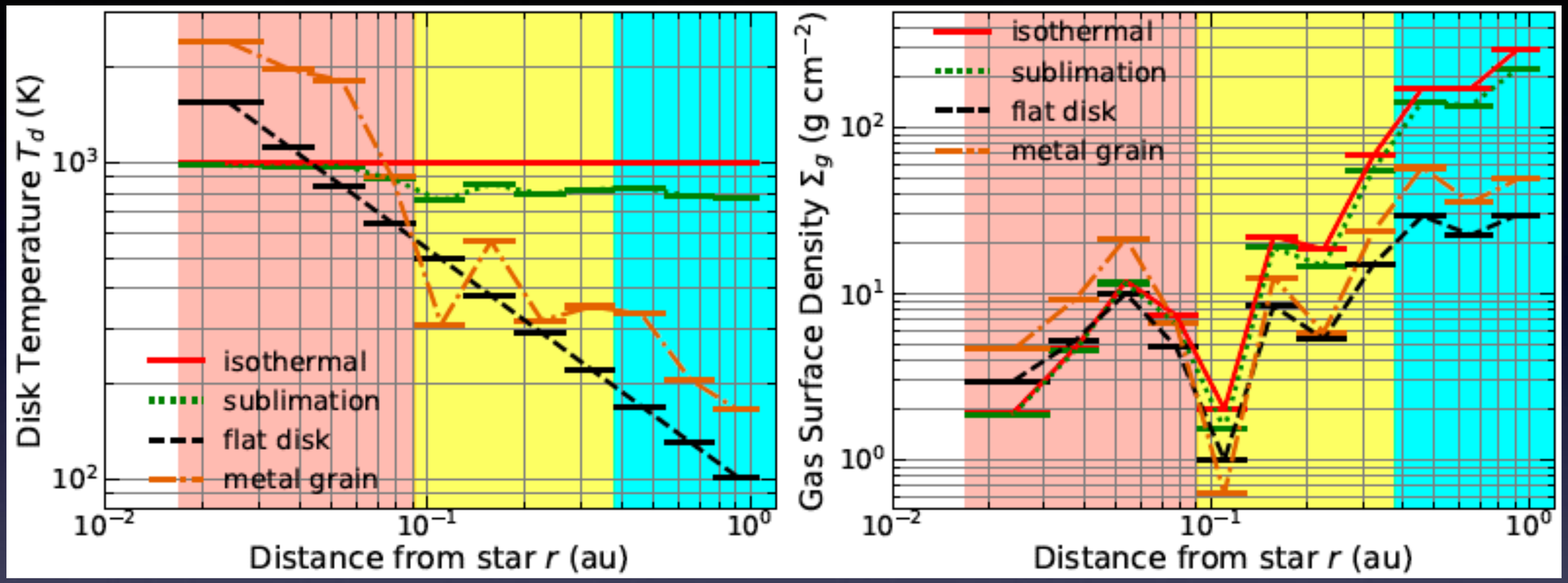
Bell et al 1997

Analytic Rosseland Mean Opacity in (cm^2 g^{-1}): $\kappa = \kappa_n \rho^{\alpha_n} T^{\beta_n}$.

n	κ_n	α_n	β_n	Max. Temp. (K)	Reference
1.....	1×10^{-4}	0	2.1	132	HS
2.....	3×10^{0}	0	−0.01	170	HS
3.....	1×10^{-2}	0	1.1	375	HS
4.....	5×10^{4}	0	−1.5	390	HS
5.....	1×10^{-1}	0	0.7	580	HS
7.....	2×10^{-2}	0	0.8	960[a]	HS
8.....	2×10^{81}	1	−24	1570[a]	BL

$$\Sigma_{\rm g} \propto f(\text{Occurrence rate})$$

Results: Disk Properties

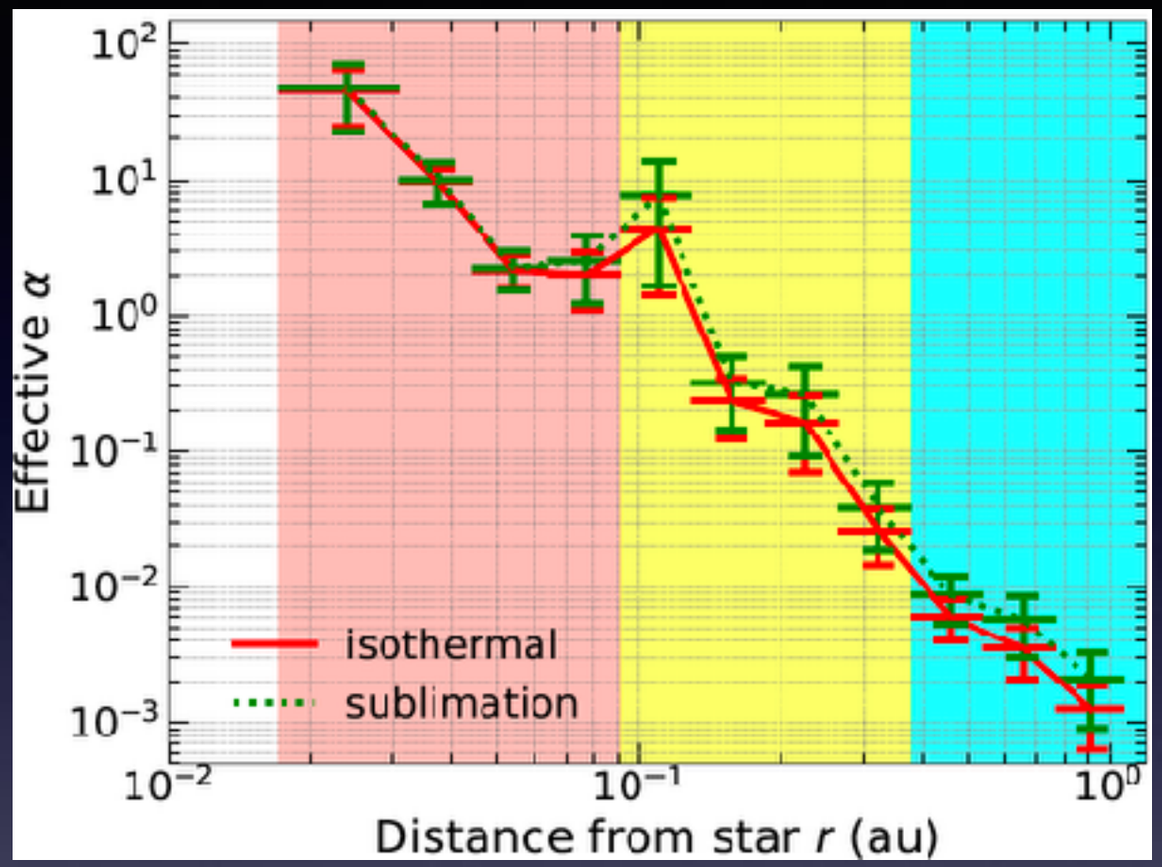


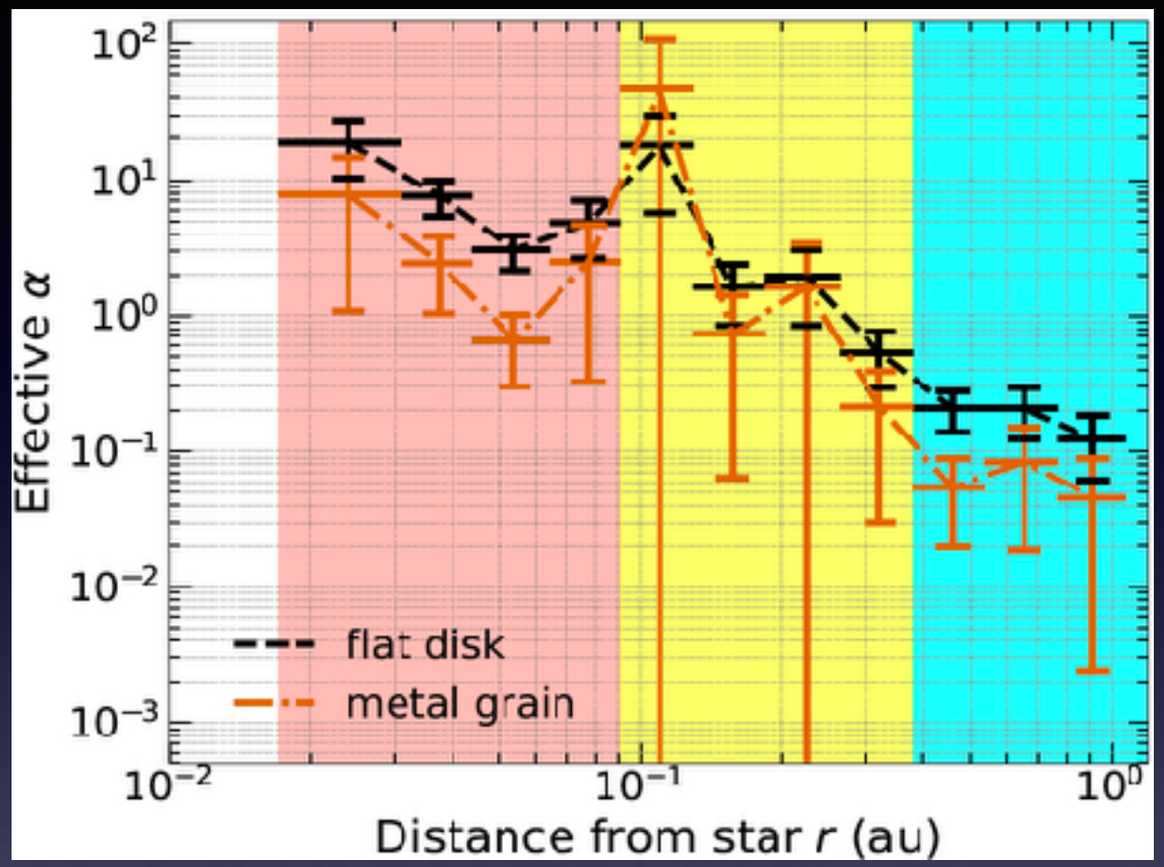
The sublimation case is well represented by the isothermal case

The metal grain case is well represented by the flat disk case

Gas surface density increases with increasing the distance from the central star (cf. Minimum-mass solar nebula $\propto r^{-3/2}$)

Results: Disk Properties





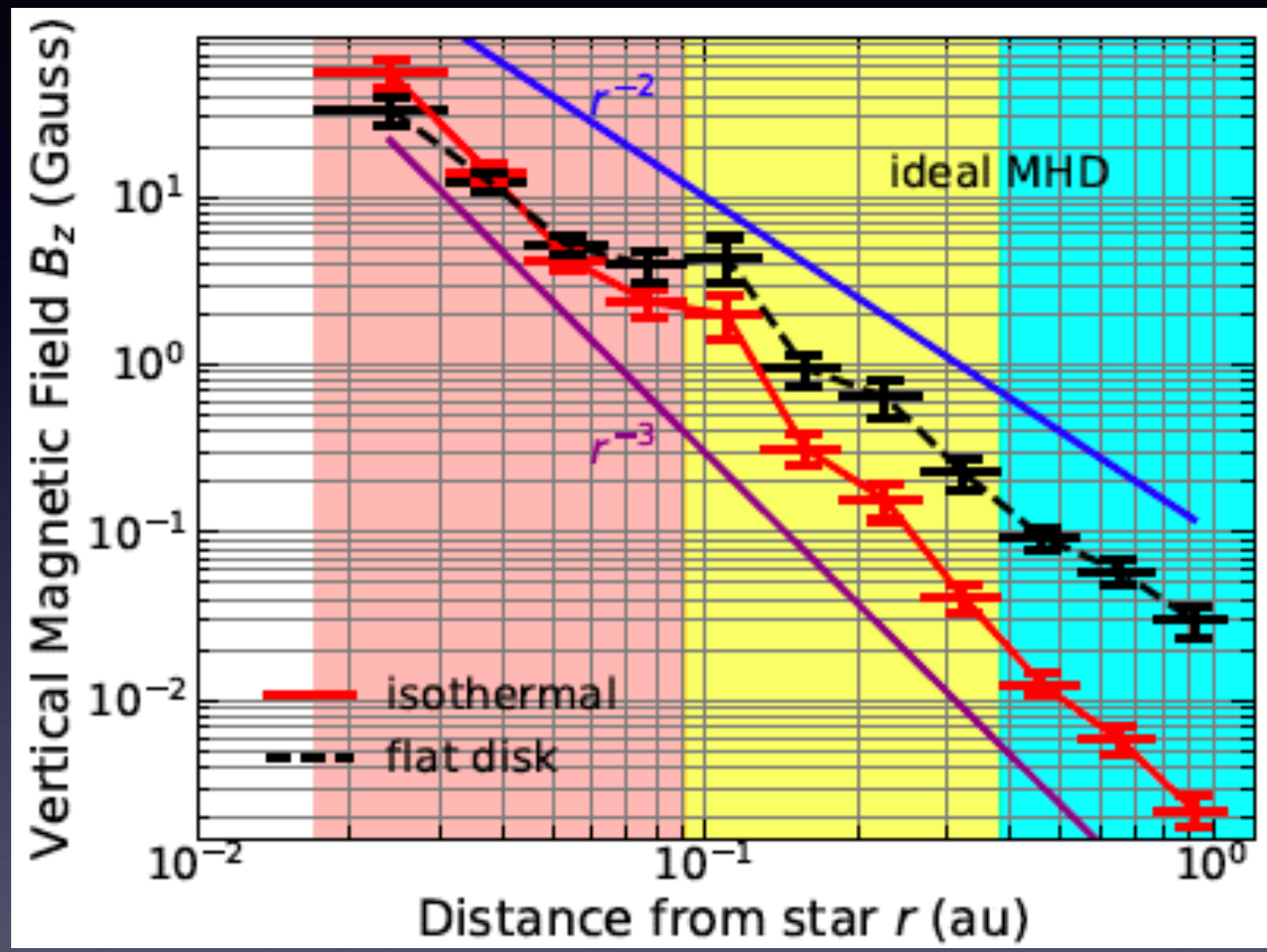
The sublimation case is well represented by the isothermal case

The metal grain case is well represented by the flat disk case

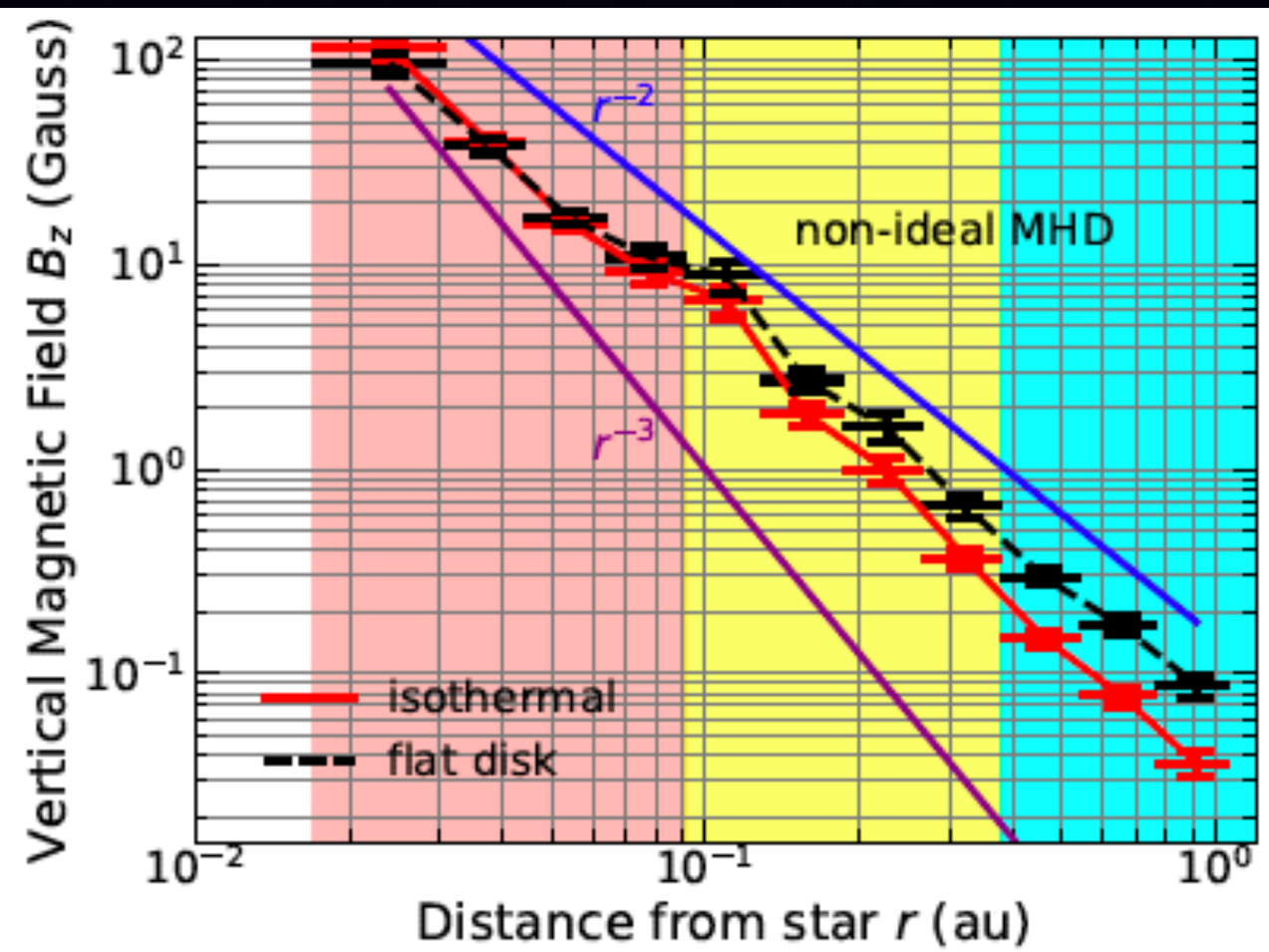
The effective alpha is inversely proportional to the gas surface density, as expected

Results: Magnetic Field Profiles from $\beta_z = \frac{\rho_g c_s^2}{B_z^2/8\pi}$

ideal MHD case



non-ideal MHD case



$$\alpha_{\rm ideal} = 11\beta_z^{-0.53}$$

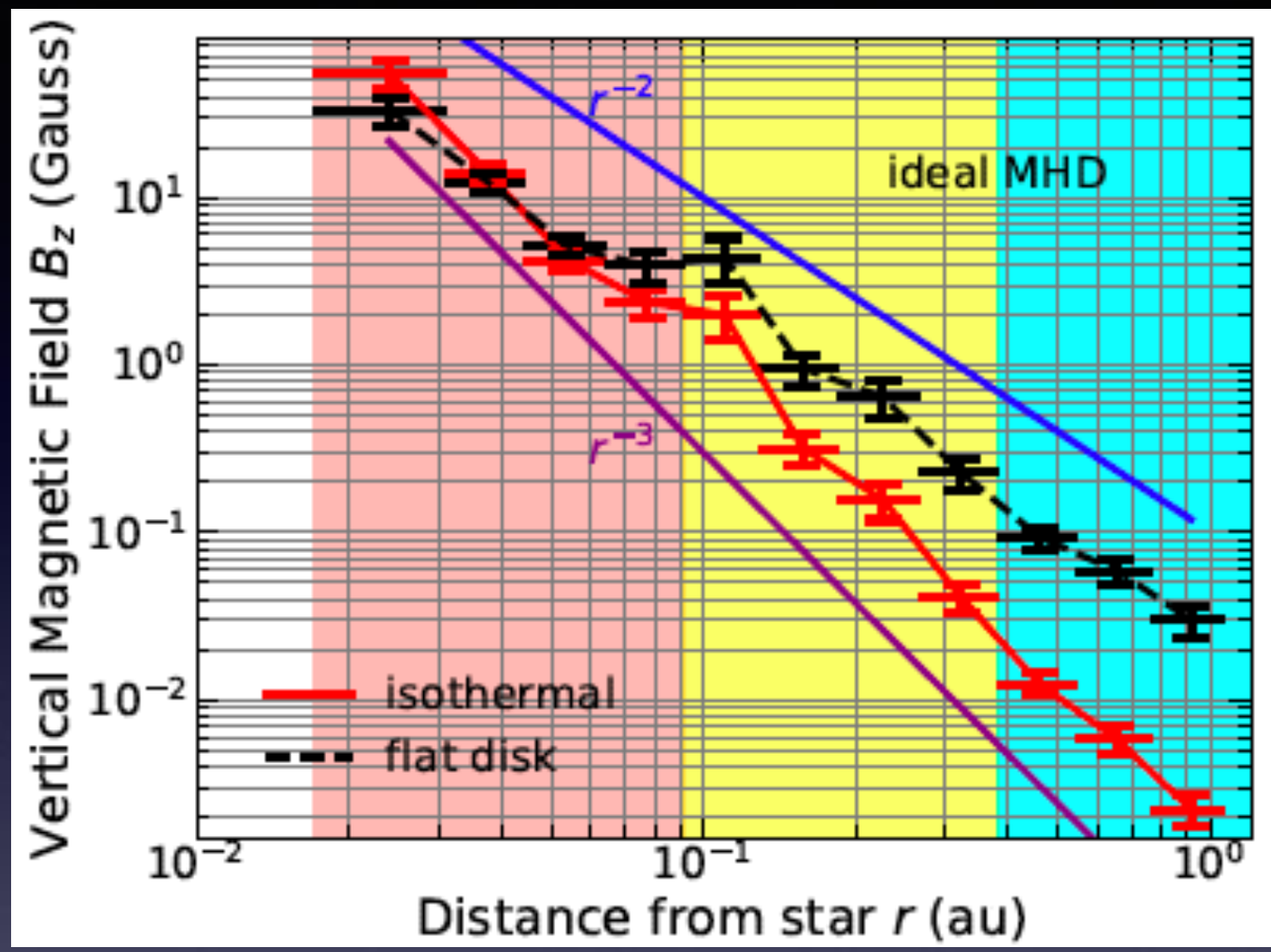
Salvesen et al 2016

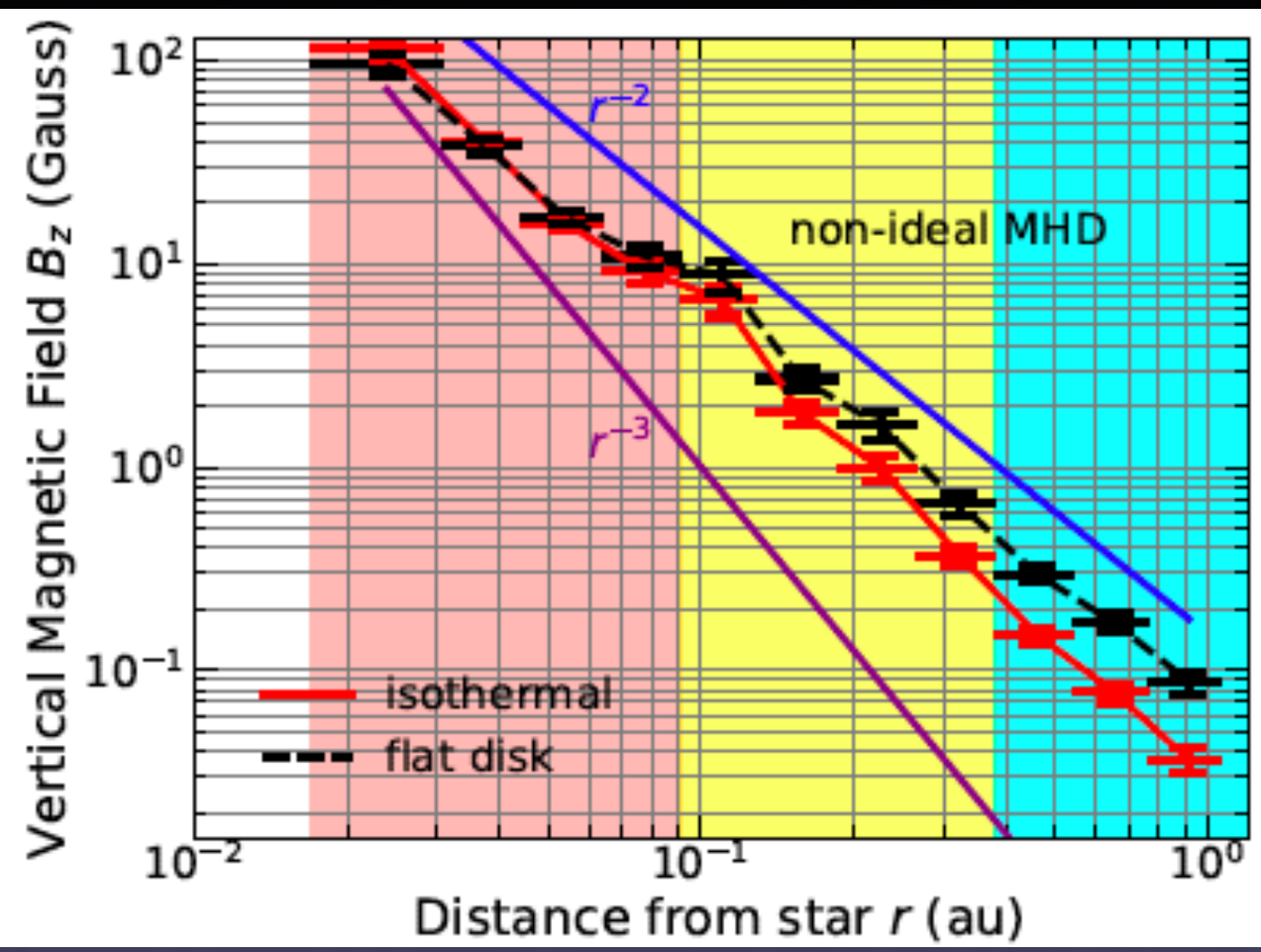
$$\alpha_{\rm non-ideal} = \frac{4r}{3\sqrt{\pi}H_{\rm g}} W_{z\phi}$$

$$W_{z\phi} = 0.23\left(\frac{r}{1{\rm au}}\right)^{0.46} \beta_z^{-0.66}$$

Bai 2013

Implications





Stellar dipole fields

$$B_s \simeq 10^3 \left(\frac{r}{1.5 R_\odot}\right)^{-3} \text{ G}$$

$$\simeq 41 \left(\frac{r}{2 \times 10^{-2} \text{ au}}\right)^{-3} \text{ G}$$

Large-scale disk fields

$$B_\mathrm{d} \simeq 0.1 \left(\frac{r}{1 \text{ au}}\right)^{-2} \text{ G}$$

Okuzumi et al 2014

Summary

Hasegawa et al, 2019b, submitted

- The origin of close-in giant planets is still unclear
- The occurrence rate distribution has some intriguing structure
- Developed the simple, semi-analytical model under the hypothesis that the occurrence rate distribution may reflect gas accretion rates onto protoplanets
- The gas surface density increases with increasing the distance from the central star (cf. MMSN model)
- The occurrence rate distribution may trace the magnetic field profile - stellar dipole fields dominate at $r < 0.1$ au and the large scale field may be important at $r > 0.1$ au

Summary

- Planet formation is the long journey from small dust grains to large planets
- A number of important advances in planet formation thanks to astonishing observations
- As examples, theoretical modeling of the HL Tau disk, the origin of heavy elements in observed exoplanets, and the origin of close-in planets via in-situ gas accretion are discussed
- further synergies between planetary and exoplanetary sciences will be undertaken to draw a better picture of planet formation and examine the origin of the solar and extrasolar planetary systems