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# Formation of Exoplanetary Atmospheres

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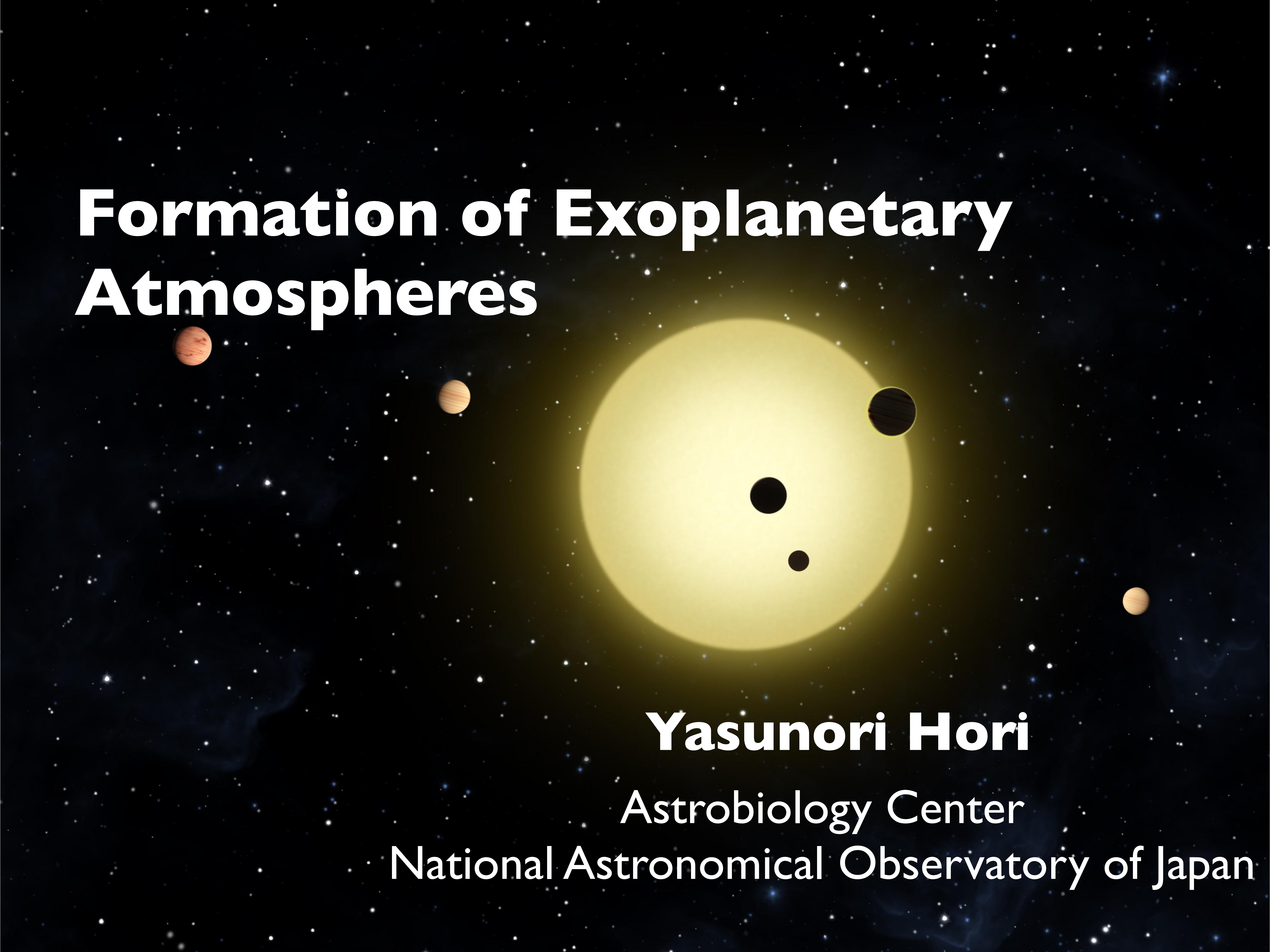
Close-in super-Earths are common among over 4,000 exoplanets. Most of them have low mean-densities, which mean the existence of an atmosphere. In fact, transmission spectra in the atmosphere of low-density super-Earths suggest they have either hydrogen-dominated atmospheres (with clouds/haze) or hydrogen-poor atmospheres such water vapor and carbon dioxide. Hydrogen-rich atmospheres, the so-called primordial atmospheres, are likely to originate from an accreting disk gas during planet formation phase, whereas hydrogen-poor ones are produced by impact-driven degassing from accreted material and outgassing related to geological activities such as volcanoes. In this talk, we focus on accumulation of the primordial atmospheres onto super-Earths in the course of planet formation. First, we review atmospheric compositions of planets in the Solar System. Second, we summarize our current understanding of exoplanetary atmospheres based on transmission spectroscopy. Finally, we present several proposed ideas on formation of hydrogen-rich atmospheres onto super-Earths through accretion of a disk gas: i) disk-regulated processes such as disk dissipation and disk wind, ii) the delay of atmospheric cooling due to enhanced opacities and tidal heating, iii) recycling of gas flow around a planet, and iv) rapid formation of super-Earths via pebble accretion.



# Formation of Exoplanetary Atmospheres

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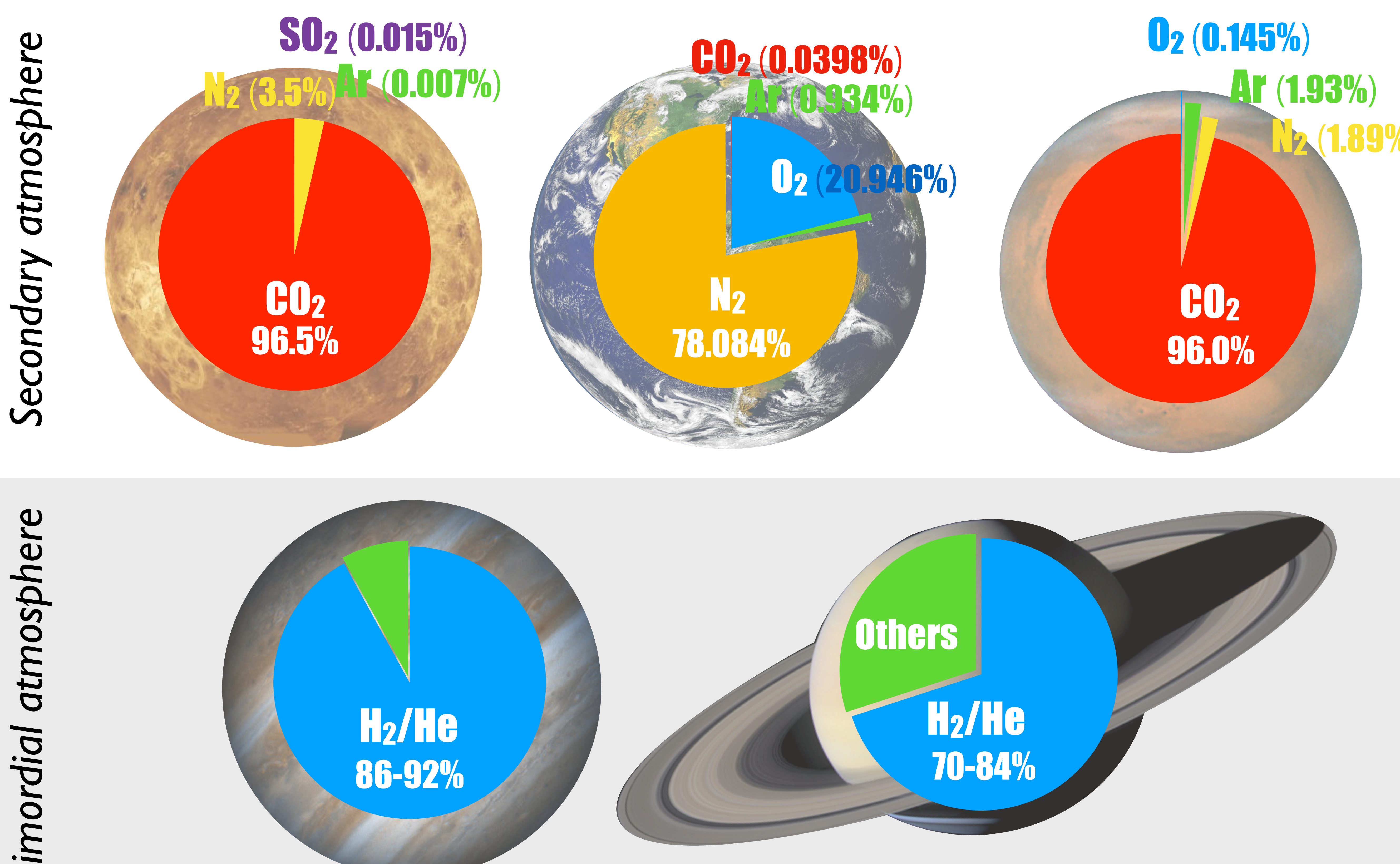
# Atmospheres of the Solar System Objects

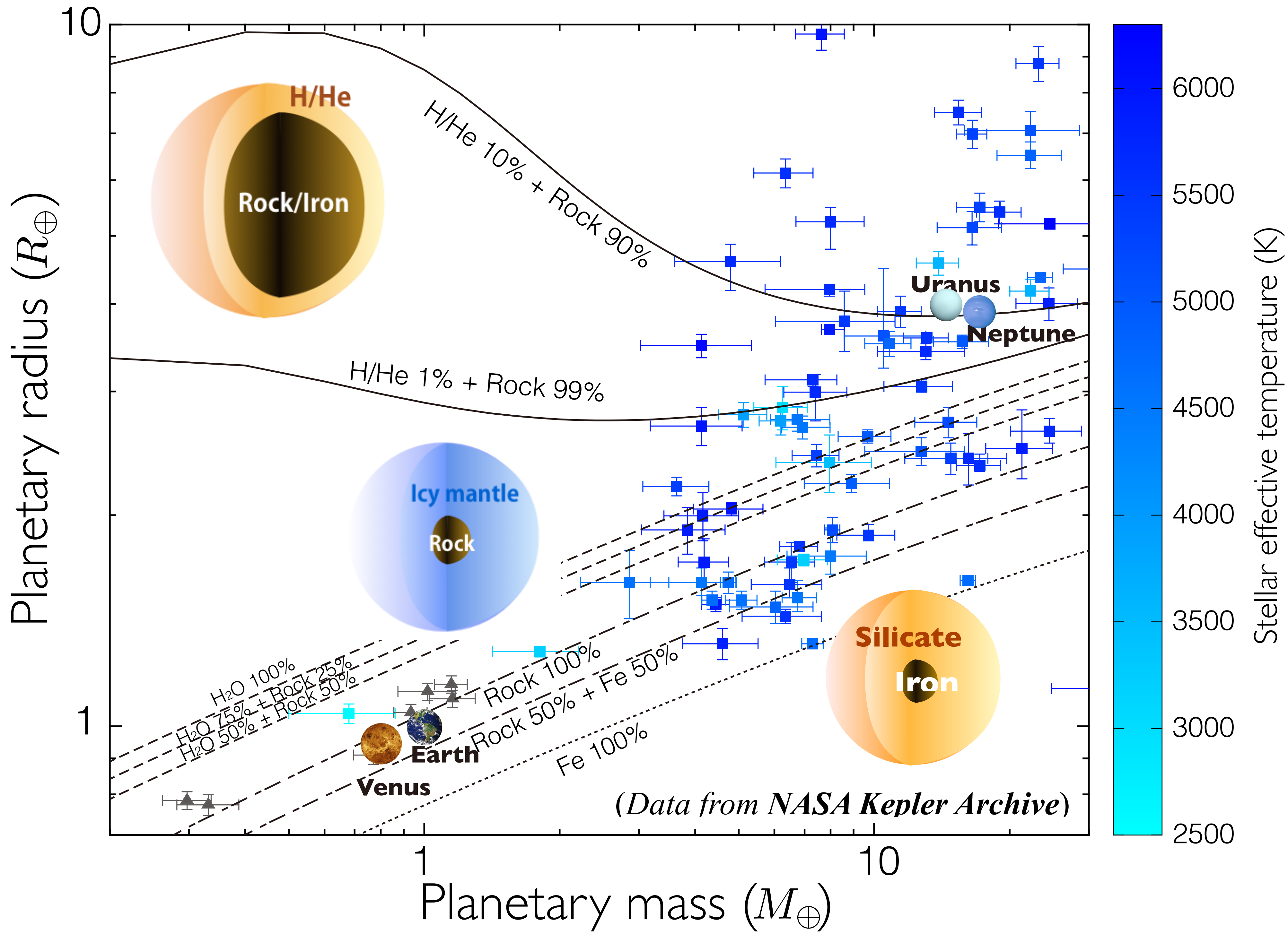



(Wahl *et al.*, 2017)

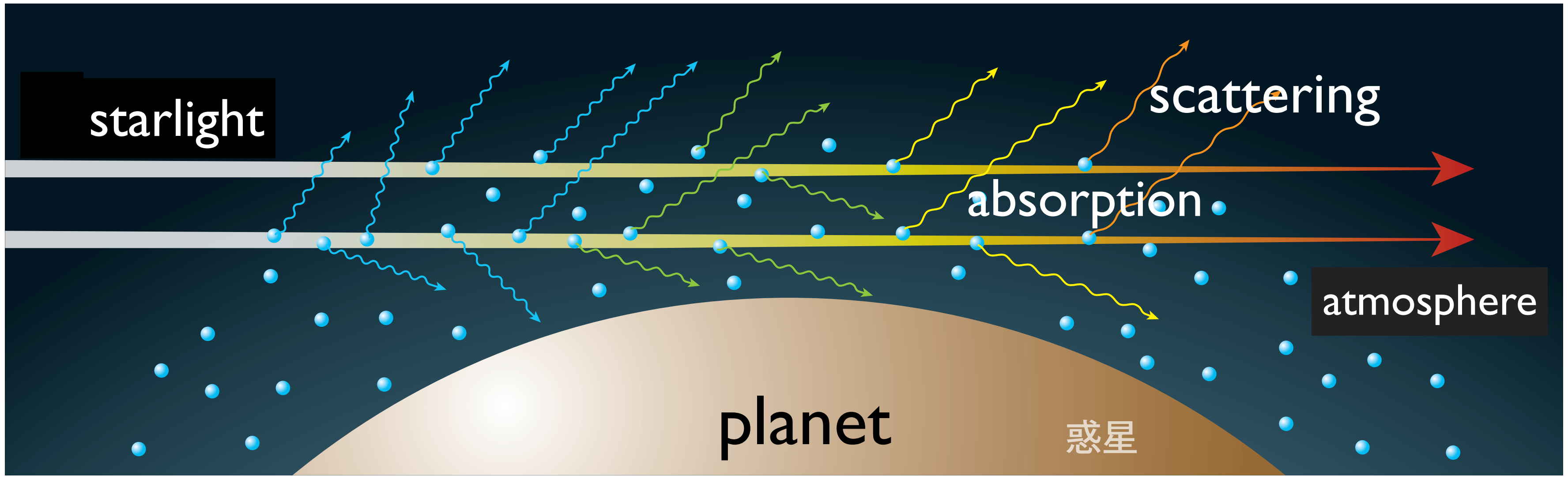
(Helled & Guillot, 2013)

# Mass-Radius Relation of Observed Exoplanets

Exoplanet census suggests that small planets are common around various stars, i.e., FGKM-type stars (e.g. Howard+10;11;Mayor+11;Petigura+13; Mulders+15; Dressing & Charbonneau,2015)

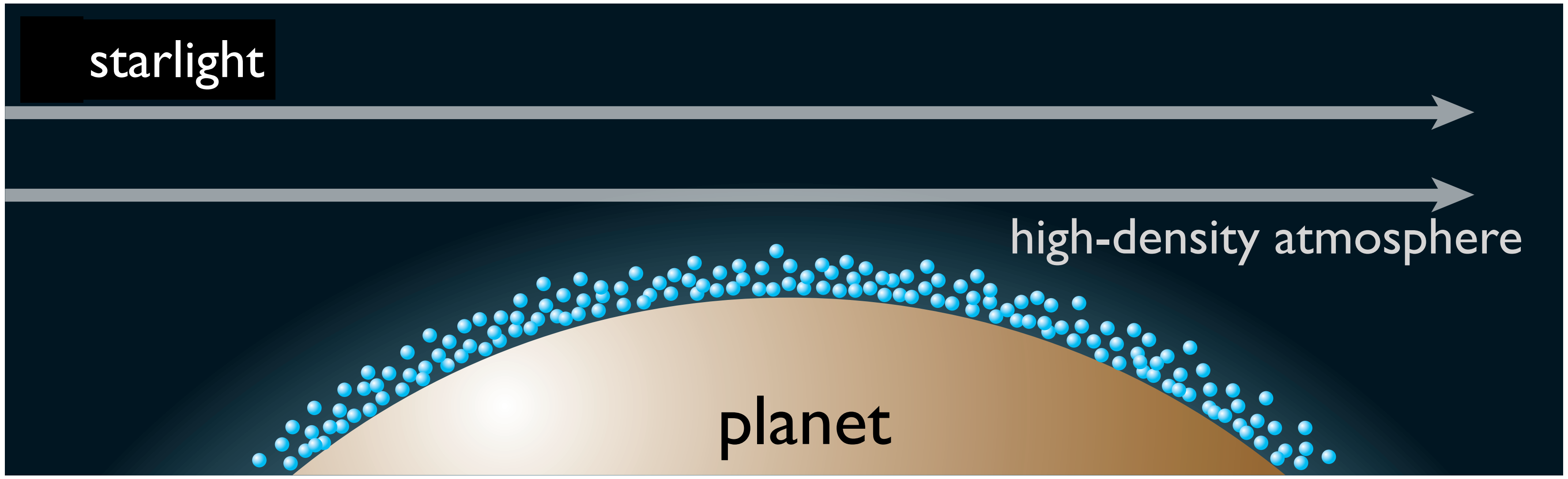


# Peer deep into Exoplanetary Atmospheres



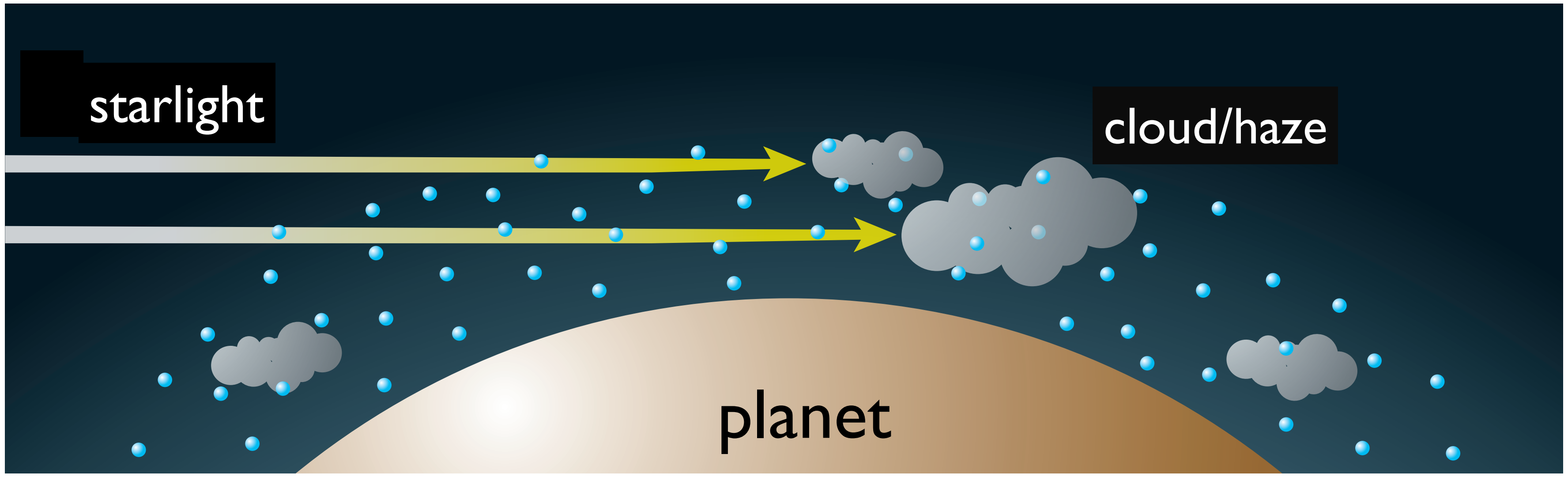


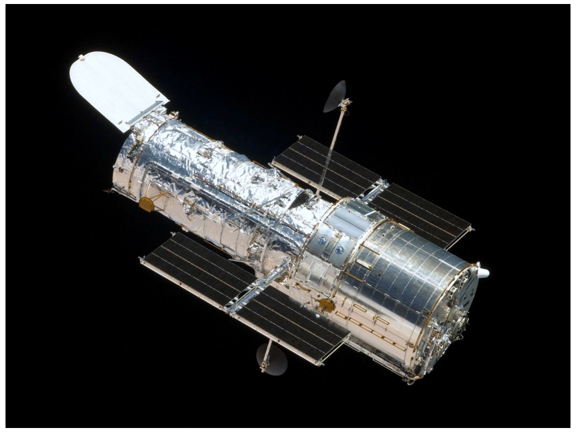
Hawaii 8.2m Subaru telescope





Okayama 188cm telescope





Hubble Space telescope

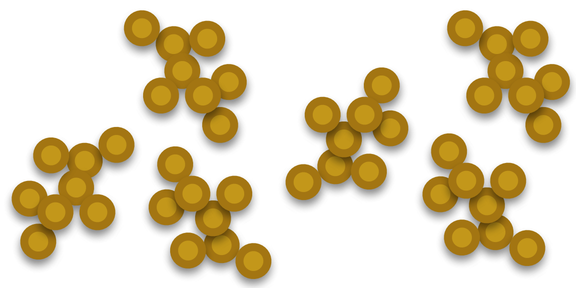
# Atmospheric Compositions of Low-mass Planets

Transmission spectroscopy revealed atmospheric properties of 16 low-mass planets, six of which orbit around TRAPPIST-1:

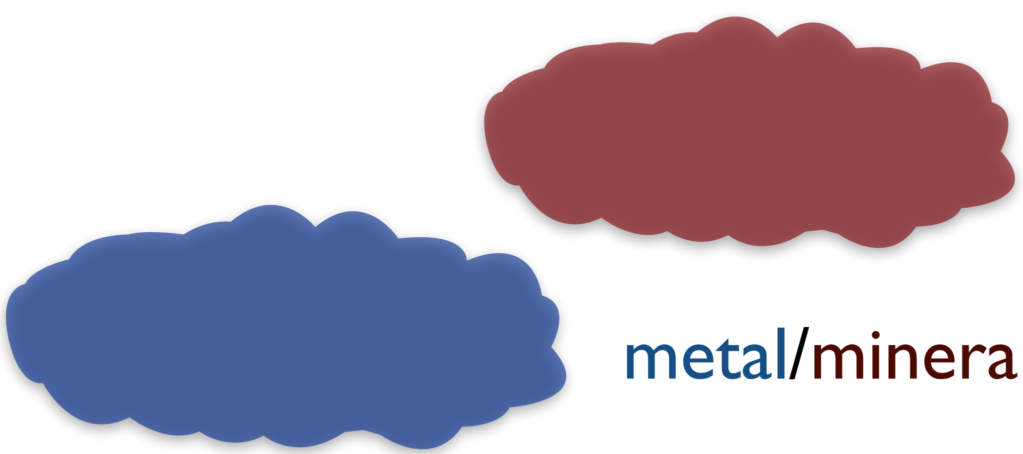
| | Mass (Me) | Radius (Re) | Teq | Rayleigh slope | Composition |
|---|---|---|---|---|---|
| GJ 1132b | 1.58-1.66 | 1.16-1.43 | 300-644 K | No? | **high-μ** or no atmosphere |
| Kepler-51b | 2.1 | 7.1 | 543 K | ? | **high-μ** or **$H_2$-rich** (w/cloud, haze) |
| Kepler-51d | 7.6 | 9.7 | 381 K | ? | **high-μ** or **$H_2$-rich** (w/cloud, haze) |
| GJ 1214b | 6.26-6.55 | 2.27-2.85 | 547-604 K | No? | **high-μ** or **$H_2$-rich** (w/cloud, haze) |
| HD 97658b | 7.55-9.5 | 2.25-2.4 | 757 K | ? | **high-μ** or **$H_2$-rich** (w/cloud, haze) |
| 55 Cancri e | 7.81-8.63 | 1.91-2.17 | 1,958 K | ? | **high-μ** or **$H_2$-rich** |
| GJ 3470b | 13.9-14.1 | 3.88-4.83 | 593-615 K | Yes | **$H_2$-rich** |
| HAT-P-26b | 18.75-22 | 6.33-7.1 | 1,000 K | No? | **high-μ** |
| GJ 436b | 21.7-25.4 | 3.96-4.22 | 649-686 K | ? | **high-μ** or **$H_2$-rich** (w/cloud, haze) |
| HAT-P-11b | 24-29 | 4.36-4.73 | 838-878 K | ? | **$H_2$-rich** |
| TRAPPIST-1b | 1.017 | 1.121 | 400 K | ? | **high-μ** or no atmosphere |
| TRAPPIST-1c | 1.156 | 1.095 | 342 K | ? | **high-μ** or no atmosphere |
| TRAPPIST-1d | 0.297 | 0.784 | 288 K | ? | **high-μ** or no atmosphere |
| TRAPPIST-1e | 0.772 | 0.910 | 251 K | ? | **high-μ** or no atmosphere |
| TRAPPIST-1f | 0.934 | 1.046 | 219 K | ? | **high-μ** or no atmosphere |
| TRAPPIST-1g | 1.148 | 1.148 | 199 K | ? | **high-μ** or **$H_2$-rich** or no atmosphere |

# Atmospheric Compositions of Low-mass Planets

organic haze



photochemically produced by stellar UV irradiation

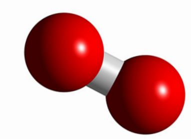


metal/mineral cloud

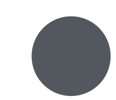
high-temperature condensates such as KCl & $Na_2S$ etc

**hydrogen-rich atmosphere**

(low mean-molecular weight)



hydrogen

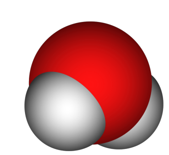


helium

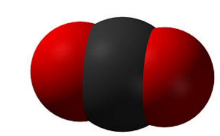
(e.g.) Jupiter & Saturn

**hydrogen-poor atmosphere**

(high mean-molecular weight)



water vapor



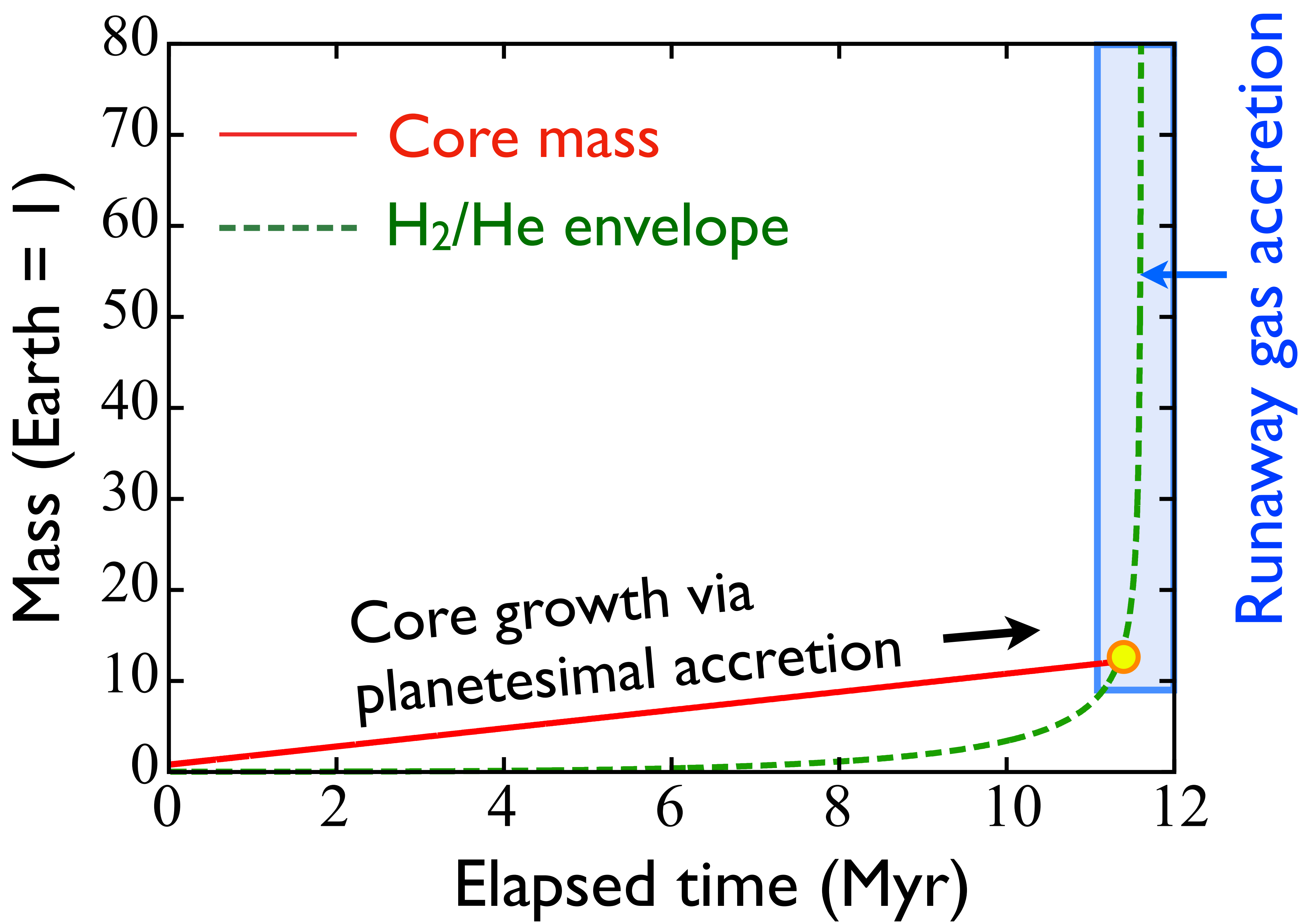
carbon dioxide

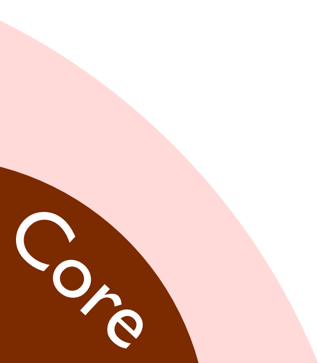
(e.g.) Venus & Mars

Planetary surface

# Can Disk Accretion Make Super-Earths Having Less Massive Atmospheres?

Super-Earth cores, which are more massive than a critical core mass, capture a disk gas in a runaway fashion



# Possible Formation Pathways of Super-puffs

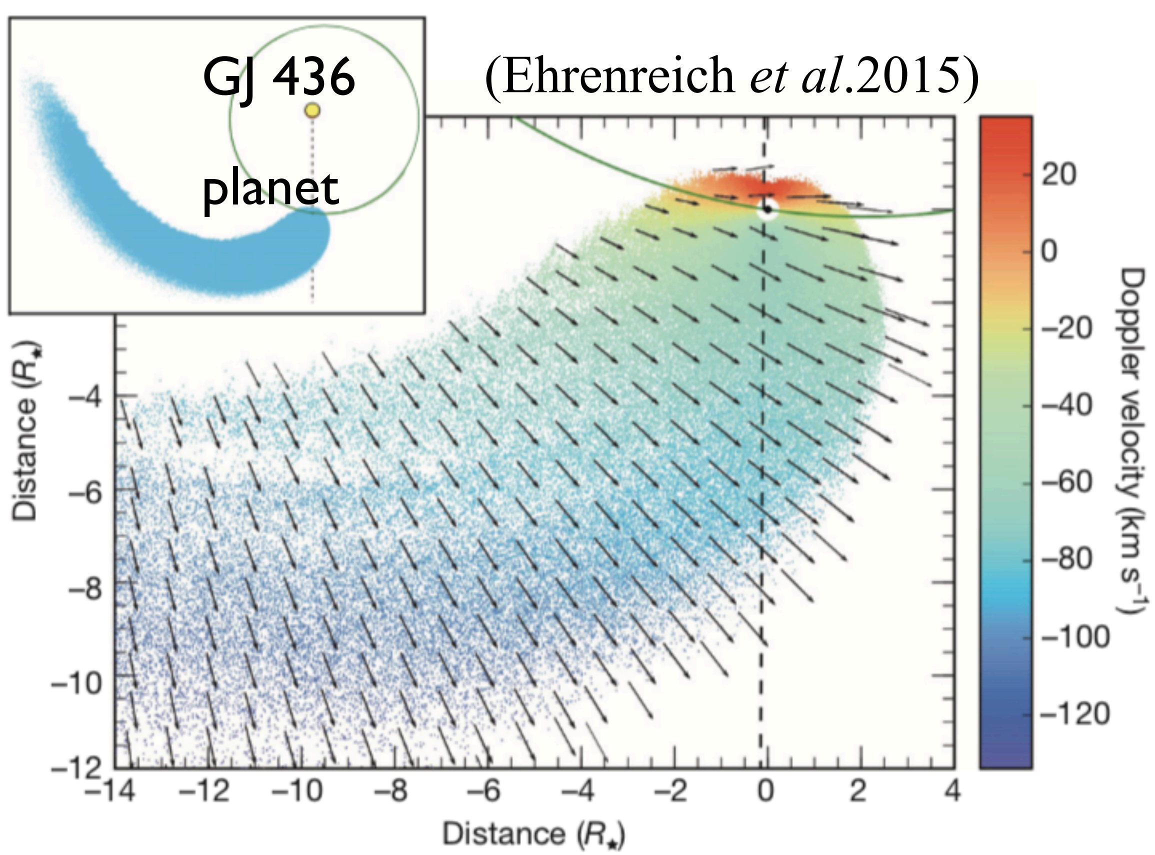
***Atmospheric loss*** *of* ***super-Earths*** *driven by* ***post-formation processes:***

(a) **Hydrodynamic escape** driven by strong stellar X-ray/EUV irradiation

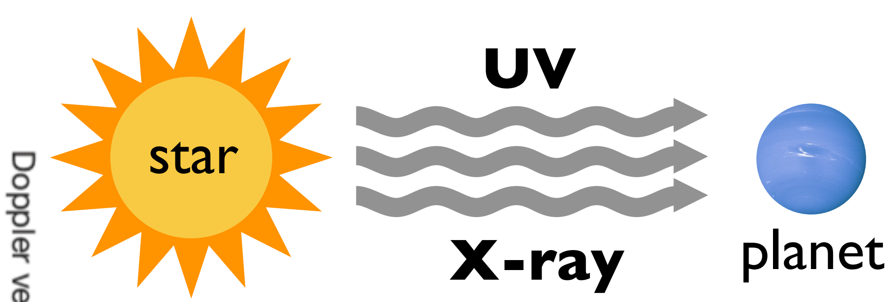
(*cf*) mass loss enhanced by core cooling? (Ginzburg+17)

(e.g. Lammer+12;Owen & Wu,2013;Lopez & Fortney,2013;Kurosaki,Ikoma,**YH**,2014; **see Itoh/Cubillos talk**)

(b) **Non-thermal processes** via ion-pick up caused by a stellar wind and a coronal mass ejection (e.g. Khodachenko+07; **see Cubillos/Brain/Terada-san talk**)




(Ehrenreich *et al.*2015)



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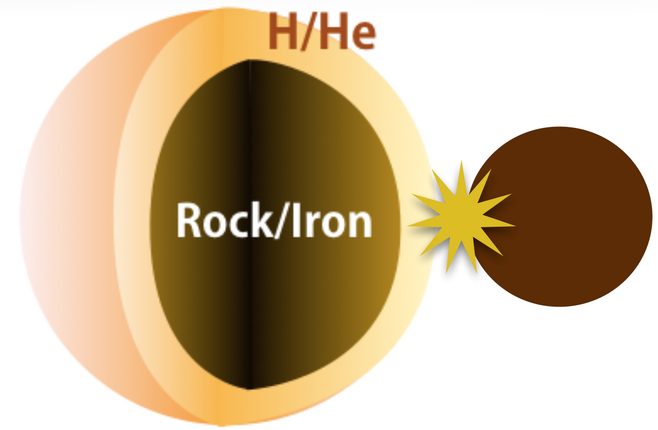
(b) **Non-thermal processes** via ion-pick up caused by a stellar wind and a coronal mass ejection (e.g. Khodachenko+07; **see Cubillos/Brain/Terada-san talk**)

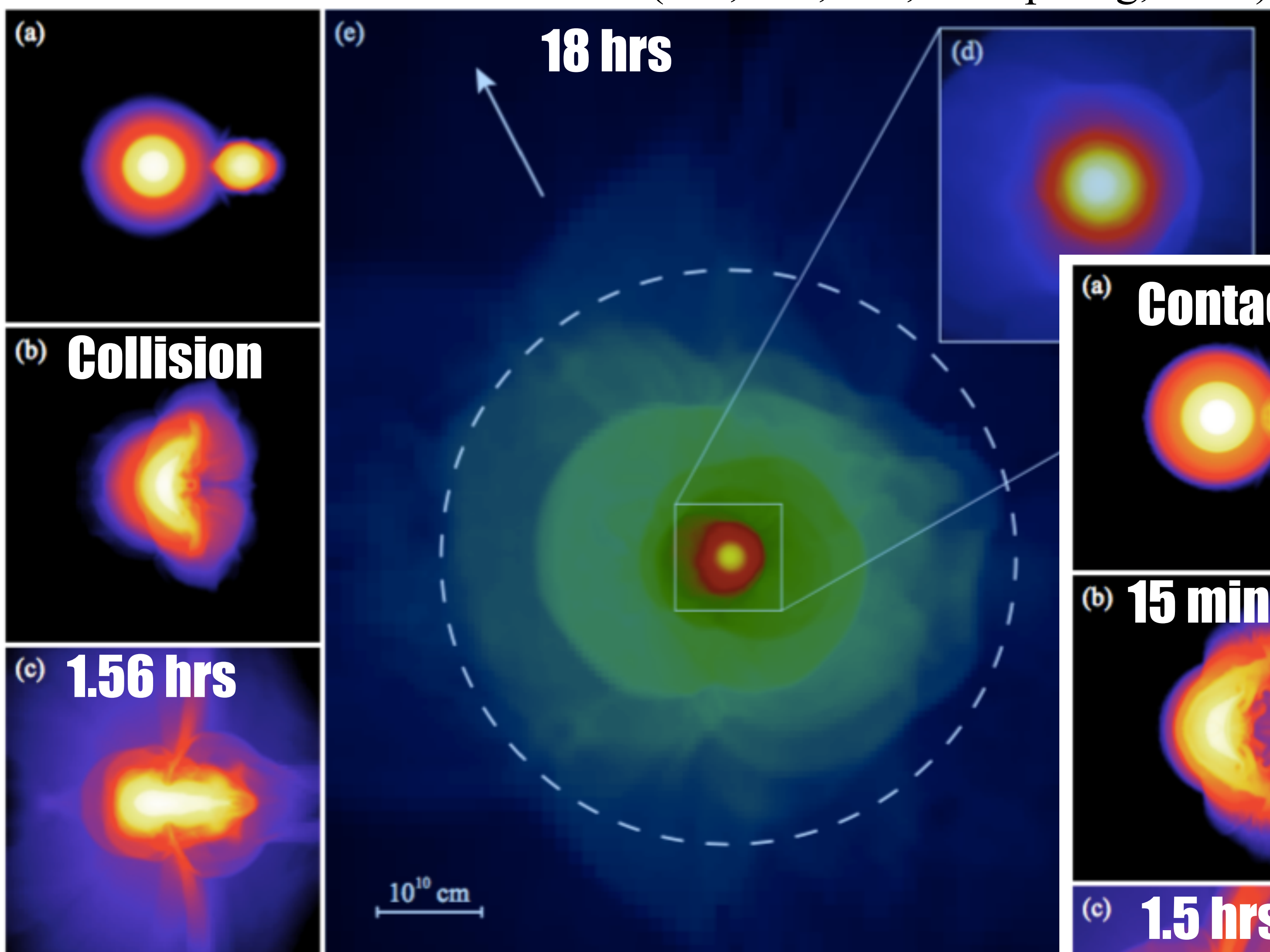
(c) Atmospheric escape by **magnetically driven wind**
(Tanaka+13,15; **see Suzuki-san talk**)

(d) **Giant impacts** between a super-Earth and planetary embryo
(Liu,**YH**, Lin, & Asphaug,2015; Schlichting+15;Inamdar+16;Yalinewich & Schlichting,2018)

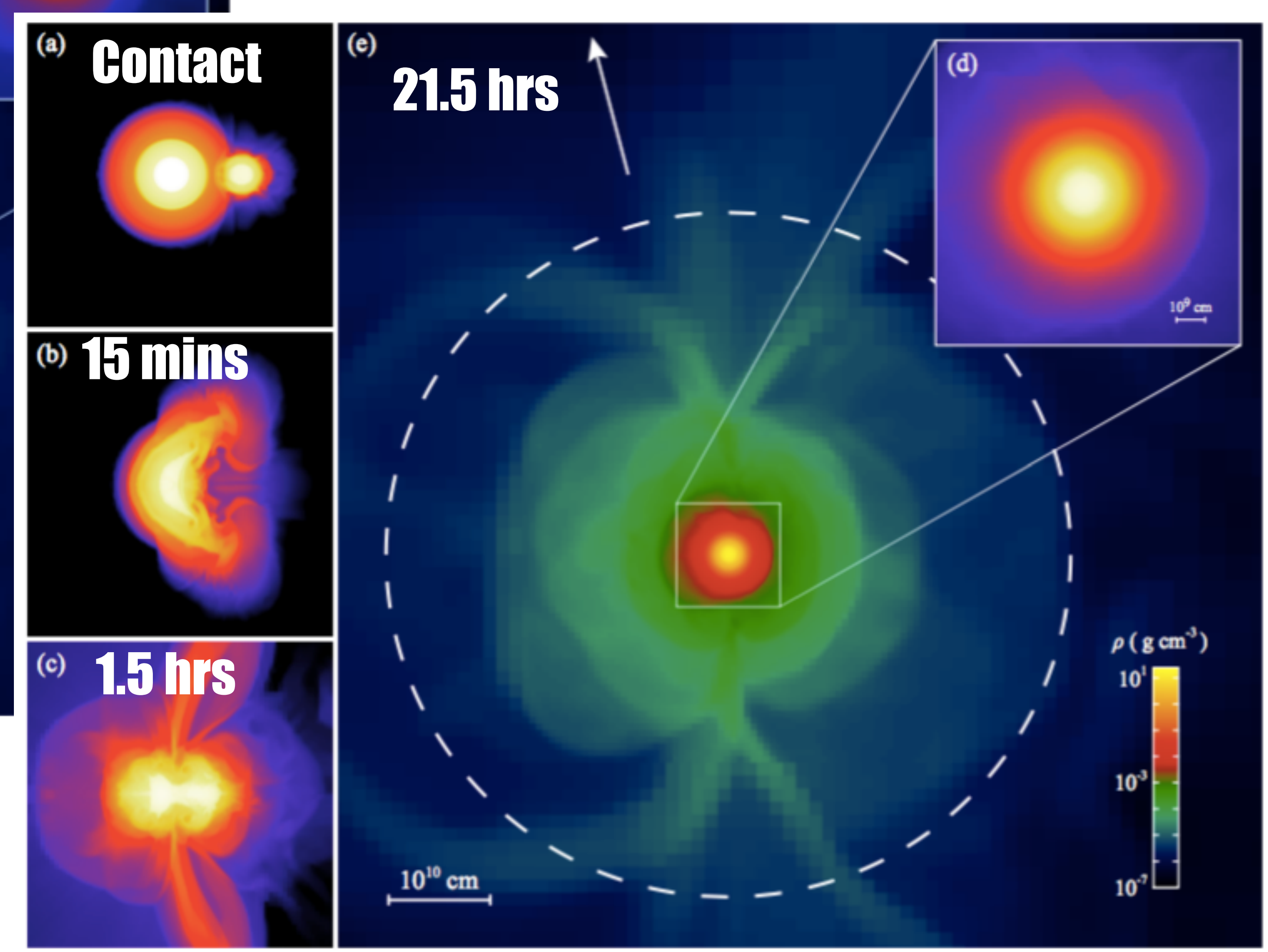
# What if a Head-on Collision of a planetary embryo on a Super-Earth Occurs?




(Liu, YH, Lin, & Asphaug, 2015)




**Low-speed impact**




**High-speed impact**

# Possible Formation Pathways of Super-puffs

## Gas accretion onto a Super-Earth during planet formation

(a) ***Disk-regulated processes:***

*In-situ* accumulation of the disk gas in a dissipating disk (Ikoma & **YH,** 2012)

Disk accretion related to a disk wind (Ogihara & **YH**, 2018)

(b) ***Delay of atmospheric cooling:***

Dust opacity & metallicity of the disk gas (Ikoma & **YH,** 2012;Lee *et al*., 2014)

Tidal heating (for eccentric super-Earths with e > 0.2 & P< 10days)

(Ginzburg & Sari,2016)

(c) ***Gas flow*** *around a super-Earth*

(Ormel+15a,b; Cimerman+17;Lambrecht & Legg,2017;Kurokawa+18;Kuwahara+19)

(d) *Formation of Super-Earths via* ***Pebble accretion*** (Ogihara & **YH**, *in prep*.)

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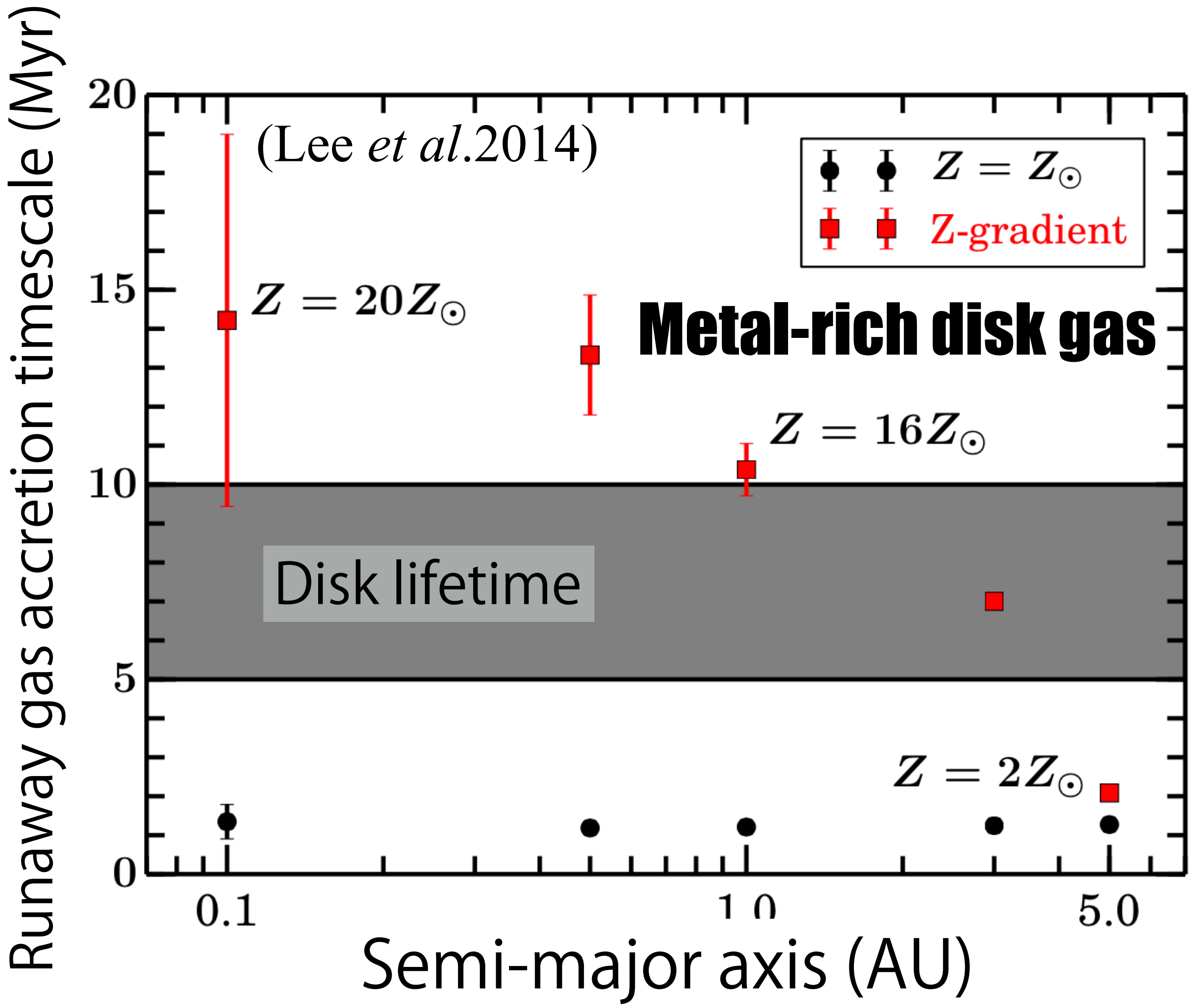


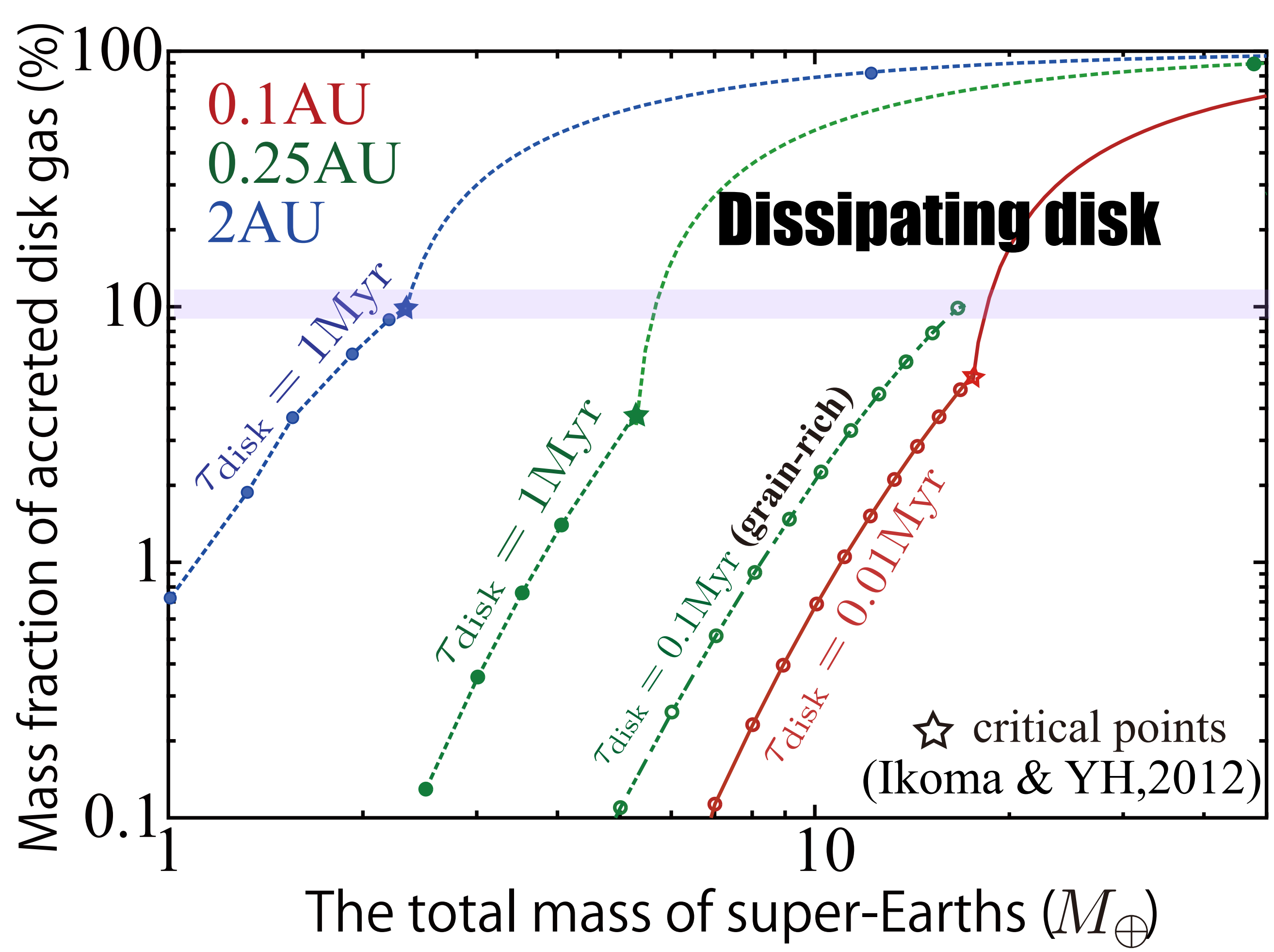

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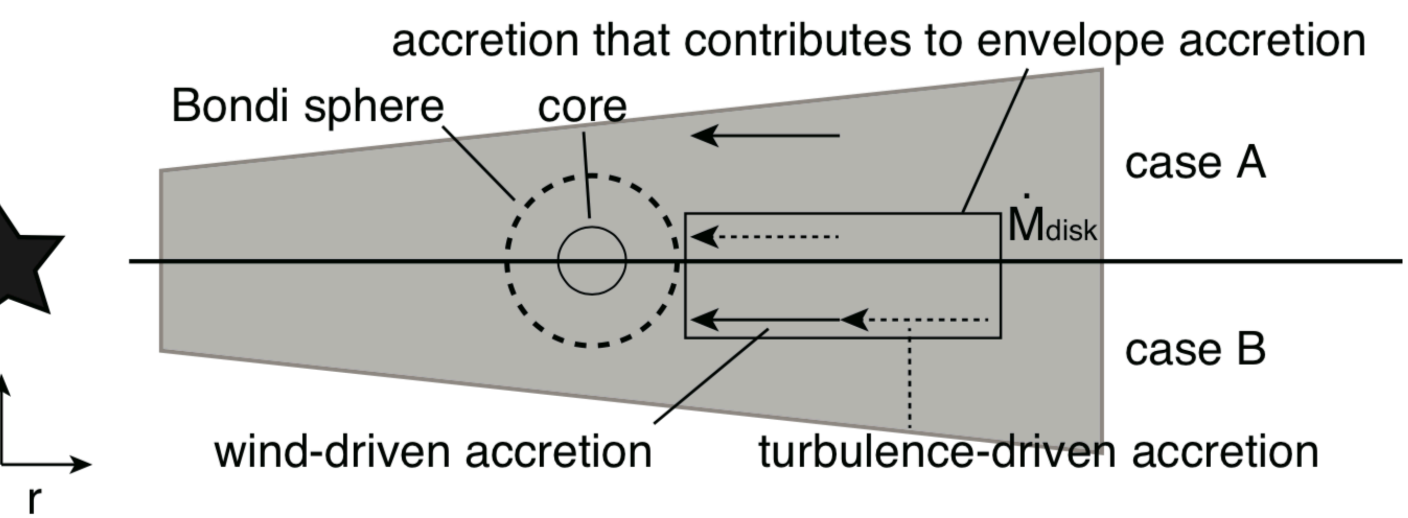
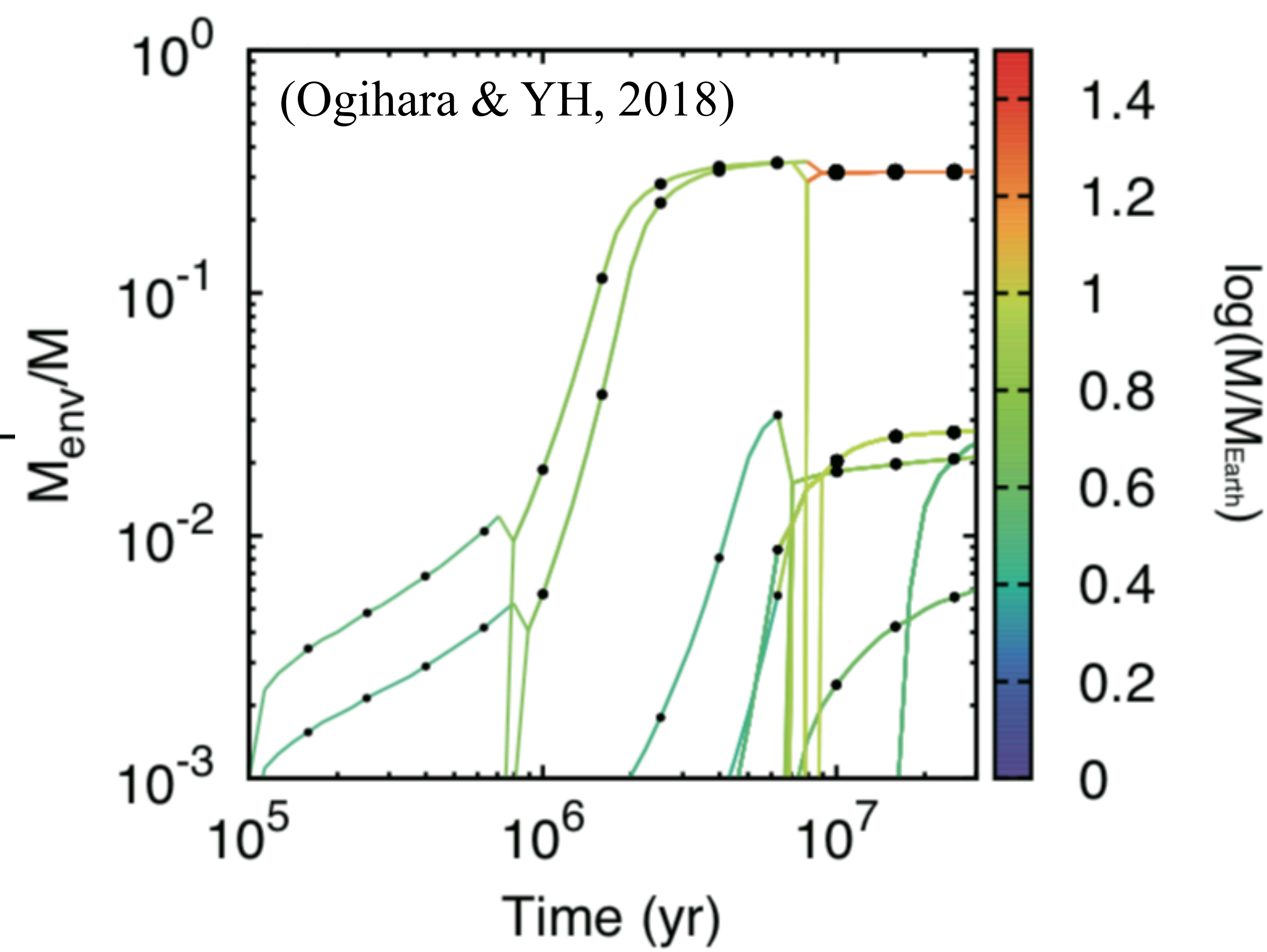
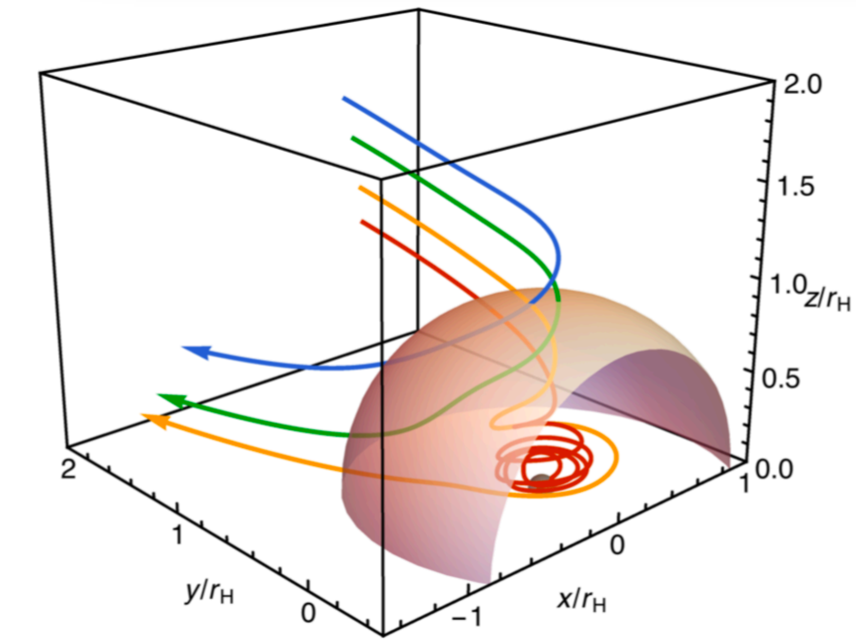
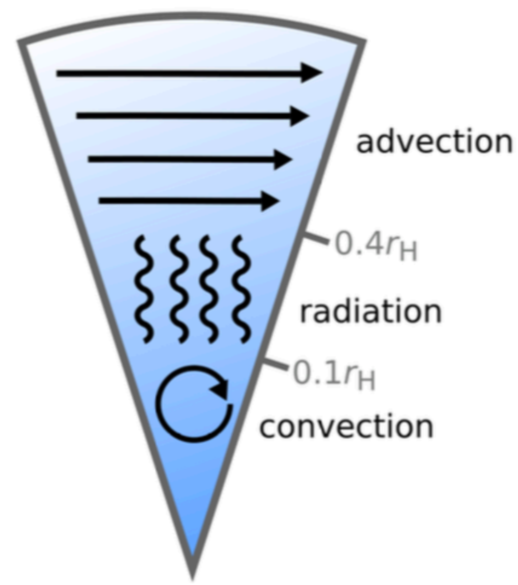


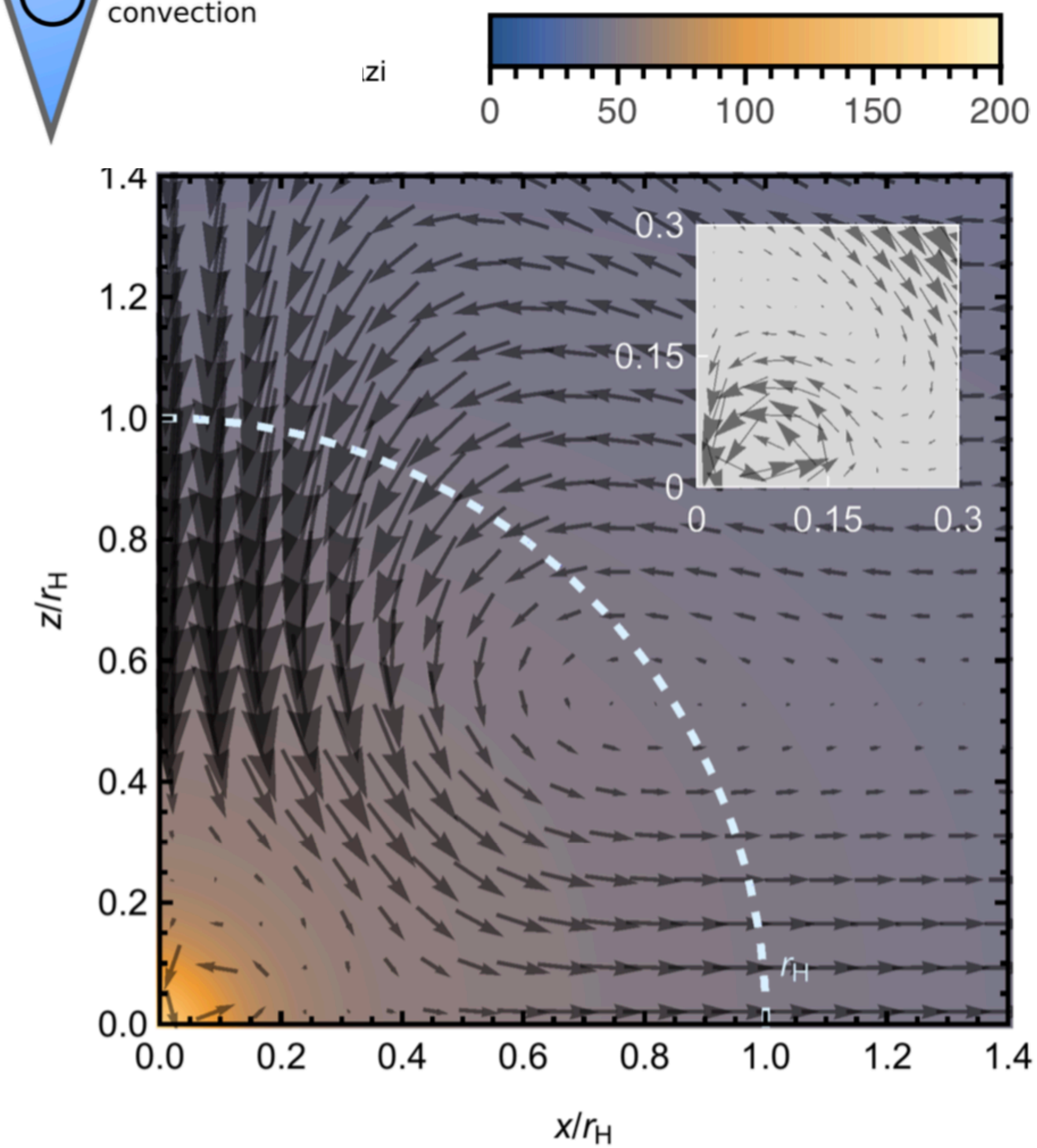
# Gas Flow around a Super-Earth

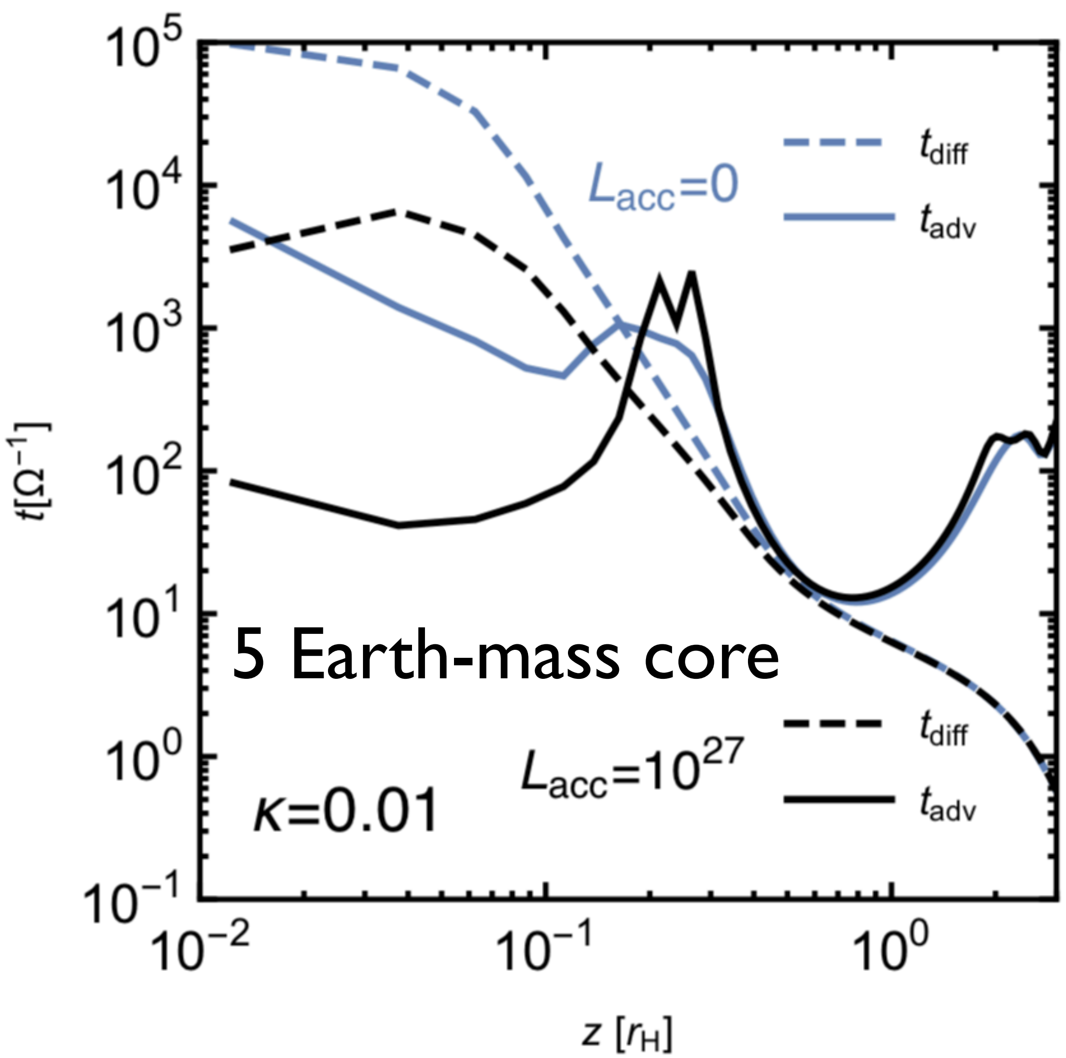
(Lambrecht & Legg,2017)




Azimuthally-averaged velocity field and temperature (K)



# Summary

Super-Earths, some of which are likely to possess (less massive) atmospheres, are common around various stars.

There are two possible atmospheric compositions of 16 super-Earths: (i) a primordial ($H_2$/He) atmosphere and (ii) a high-$\mu$ atmosphere

The expected amount of a $H_2$/He atmosphere onto a super-Earth can be controlled by

(a) inefficient accretion of the disk gas (such as the delay of atmospheric cooling and rapid recycling of an atmospheric gas)

(b) atmospheric loss driven by stellar activity (such as XUV and CME) and giant impact events