# The Formation of Super-Earths and Mini-Neptunes with Giant Impacts

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## Abstract

The majority of discovered exoplanetary systems harbour a new class of planets, bodies that are typically several times more massive than the Earth but that orbit their host stars well inside the orbit of Mercury. The origin of these close-in super-Earths and mini-Neptunes is one of the major unanswered questions in planet formation. Unlike the Earth, whose atmosphere contains less than $10^{-6}$ of its total mass, a large fraction of close-in planets have significant gaseous envelopes, containing 1-10 per cent or more of their total mass. It has been proposed that close-in super-Earths and mini-Neptunes formed in situ either by delivery of 50-100$M_{\oplus}$ of rocky material to the inner regions of the protoplanetary disc, or in a disc enhanced relative to the minimum mass solar nebula. In both cases, the final assembly of the planets occurs via giant impacts. Here we test the viability of these scenarios. We show that atmospheres that can be accreted by isolation masses are small (typically $10^{-3}$-$10^{-2}$ of the core mass) and that the atmospheric mass-loss during giant impacts is significant, resulting in typical post-giant impact atmospheres that are $8\times10^{-4}$ of the core mass. Such values are consistent with terrestrial planet atmospheres but more than an order of magnitude below atmospheric masses of 1-10 per cent inferred for many close-in exoplanets. In the most optimistic scenario in which there is no core luminosity from giant impacts and/or planetesimal accretion, we find that post-giant impact envelope accretion from a depleted gas disc can yield atmospheric masses that are several per cent the core mass. If the gravitational potential energy resulting from the last mass doubling of the planet by giant impacts is released over the disc dissipation time-scale as core luminosity, then the accreted envelope masses are reduced by about an order of magnitude. Finally we show that, even in the absence of type I migration, radial drift time-scales due to gas drag for many isolation masses are shorter than typical disc lifetimes for standard gas-to-dust ratios. Given these challenges, we conclude that most of the observed close-in planets with envelopes larger than several per cent of their total mass likely formed at larger separations from their host stars.

## Isolation Masses

- Close-in super-Earths and mini-Neptunes are amongst the most common planets in our galaxy
- Many observed close-in planets have massive atmospheres ≳1-10% the total mass[1]
  - ⇒ **How and where these planets formed remains an outstanding question in planet formation**
- It has been suggested[2,3] that close-in planets formed *in situ*, via enhancement of the stellar nebula or preferential delivery of rocky material to the inner disc
- By examining the effect of core accretion on atmospheric masses, others[4] have concluded that it is likely they formed further out at several AU
- During latter stages of planet formation, oligarchic growth leads to Moon-sized masses clearing their neighborhoods of remaining planetesimals[5]
  - ⇒ **Isolation masses ($M_{\rm iso}$)**
- In the outer disc, $M_{\rm iso}$~$M_{\rm Nep}$, but in the inner disc, $M_{\rm iso} \lesssim M_{\oplus}$
  - ⇒ **Formation in the inner disc requires a phase of giant impacts (GIs) to assemble ~ terrestrial planet masses**
  - ⇒ **If close-in planets formed *in situ*, they likely underwent GIs**
- We calculated atmospheric masses accreted by isolation masses before GIs, examined how much mass they lose during GIs, and accreted masses after GIs[6]

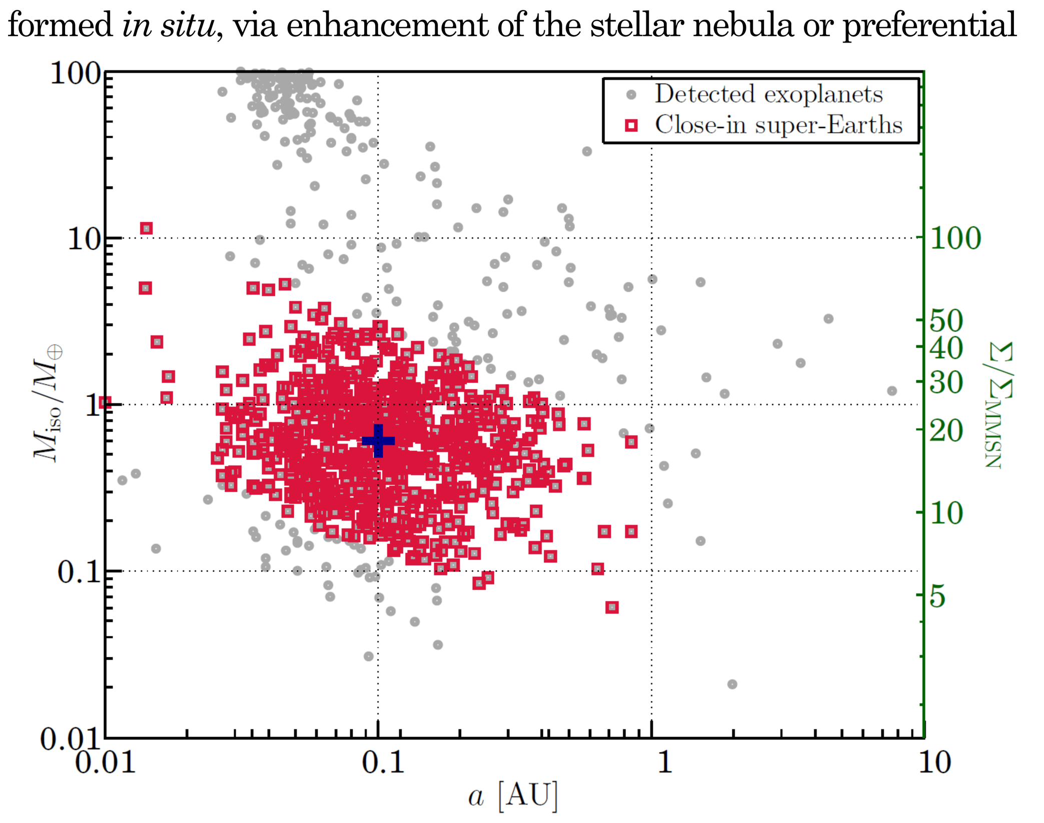



**Figure:** Isolation masses $M_{\rm iso}$ for observed close-in planets (red). $\Sigma_s = M_p/(2\pi a\Delta a)$, with corresponding enhancement in Σ relative to MMSN calculated. A typical close-in planet at ~0.1 AU has $M_{\rm iso}$~$0.6M_{\oplus}$, corresponding to an enhancement relative to the MMSN of ~**20** (**+**). Exoplanet data: `http://exoplanet.eu/`

## Pre-Giant Impact Gas Accretion

- Accreted atmospheric masses were calculated for a range of $M_{\rm iso}$ cores
  - ⇒ **Two limiting cases considered: $L = L_{\rm acc}$, and $L_{\rm acc} = 0$ but $L = \int T(dS/dt)dm$**
- Equations of hydrostatic equilibrium integrated from $r_{\rm min}$, smaller of the Hill or Bondi radius, to $R_{\rm core}$
- Opacity is dominated by dust at cooler temperatures ($T \lesssim$ 1800 K), includes contributions from molecular scattering at higher temperatures
- Disc assumed to have MMSN-like density profile where gas to dust ratio ~200[7]
  - ⇒ **Enhancement in disc relative to MMSN determined by $M_{\rm iso}$ calculation**
- Disc temperature[8] is 1500 K for $a \leq 0.1$ AU and scales as $a^{-2/3}$ for $a > 0.1$ AU
- Volumetric density $\rho_g$ found using gas scale height $H = c_s/\Omega_K$: $\rho_g \approx \Sigma_g/(2H)$
- Typical atmospheres posses a thin outer region in radiative equilibrium with disc, and an inner convective region
- Typical atmospheric mass accreted by an isolation mass core at 0.1 AU is ~$10^{-3}M_{\rm atm}/M_{\rm core}$

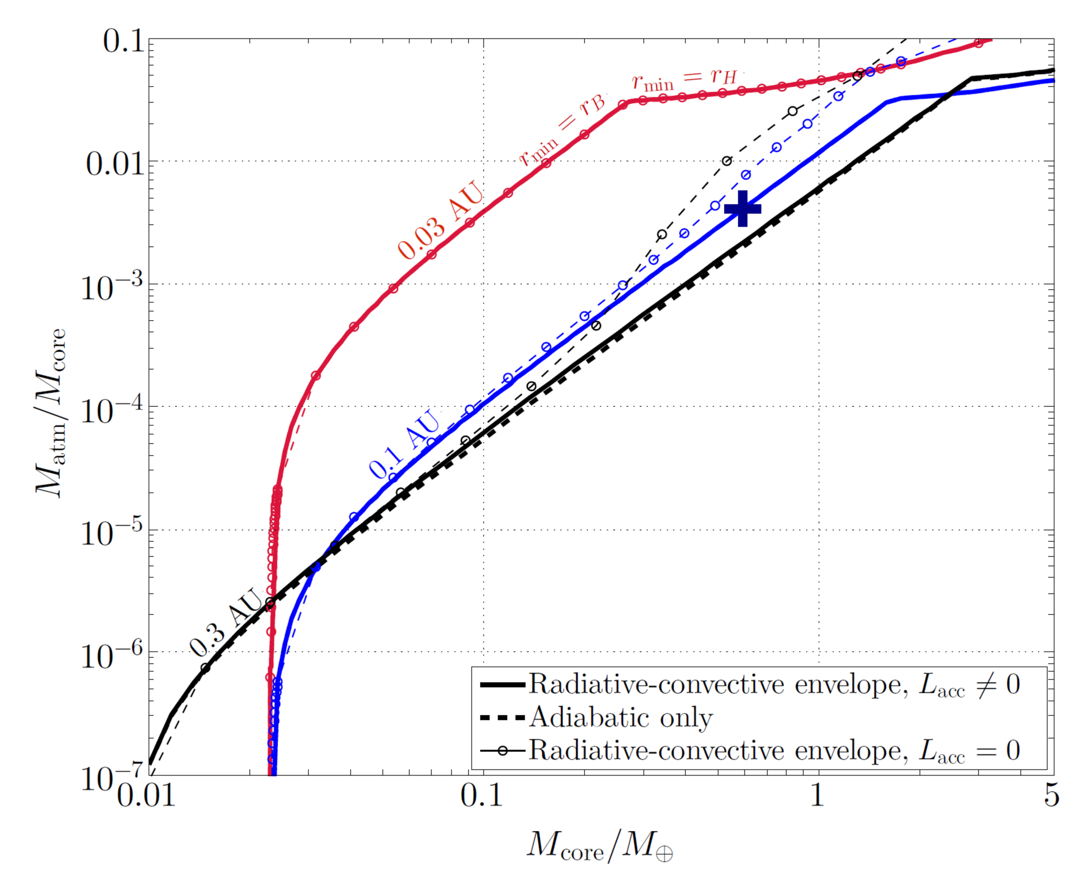
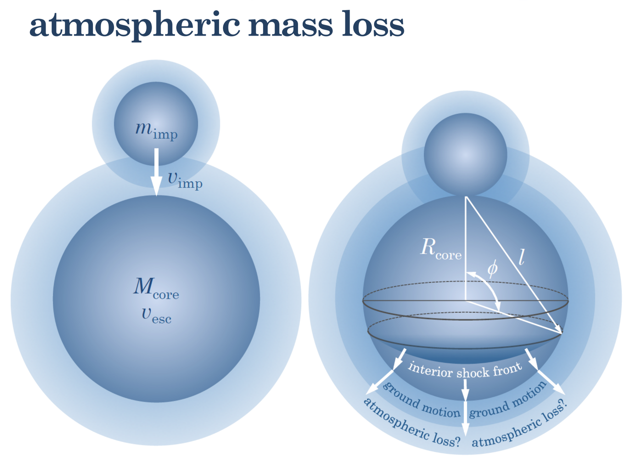



**Figure:** Accreted atmospheric masses before GI. A typical isolation mass at ~0.1 AU has $M_{\rm atm}/M_{\rm core}$~$4\times10^{-3}$ (**+**).

## Impact-Induced Atmospheric Mass Loss

- An impact between two planetesimals leads to shock throughout the interior of the bodies
  - ⇒ **Interior shock induces ground motion over the surface of the core**
  - ⇒ **Ground motion launches a shock into the atmosphere, potentially leading to hydrodynamic escape and atmospheric mass loss**




- We performed hydrodynamic shock simulations to characterize atmospheric mass loss as a function of impactor mass and velocity
  - ⇒ **Based on isolation masses, we performed Monte Carlo simulations to determine atmospheric mass loss during assembly due to giant impacts**

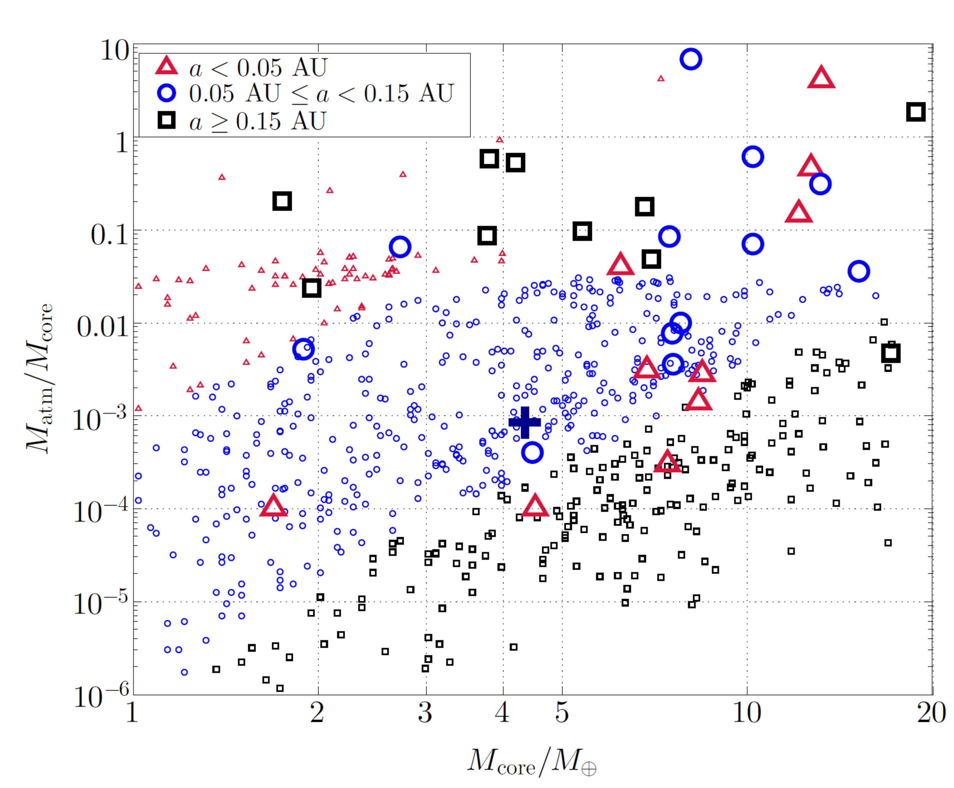



**Figure:** Results of Monte Carlo simulations of GIs for observed close-in planets. Median $M_{\rm atm}/M_{\rm core}$ after GIs is $8\times10^{-4}$ (**+**). Data points: Lopez & Fortney (2014).

## Post-Giant Impact Gas Accretion

- Typical $M_{\rm atm}/M_{\rm core}$~ $10^{-3}$ is reduced to by factors of $10^{-3}$ to $10^{-1}$ after GIs
  - ⇒ ***In situ* formation pre-GI yields atmospheric masses that are ~$10^{-6}$ – $10^{-4}M_{\rm atm}/M_{\rm core}$, much smaller than observed**
- We also considered post-GI gas accretion by fully assembled core masses
  - ⇒ **We calculated atmospheric masses by fully assembled cores in a post-GI disc in which gas surface density $\Sigma_g$ has been depleted to roughly the level of solids: $\Sigma_g$~$\Sigma_s$**
  - ⇒ **Depletion in gas density allows GIs to proceed by damping out high *e* motion required for orbit crossings[9]**
  - ⇒ **Considered two cases: $L_{\rm acc}$ = 0 and $L_{\rm acc}$ due to the release of gravitational potential from last mass doubling over the disc dissipation timescale**

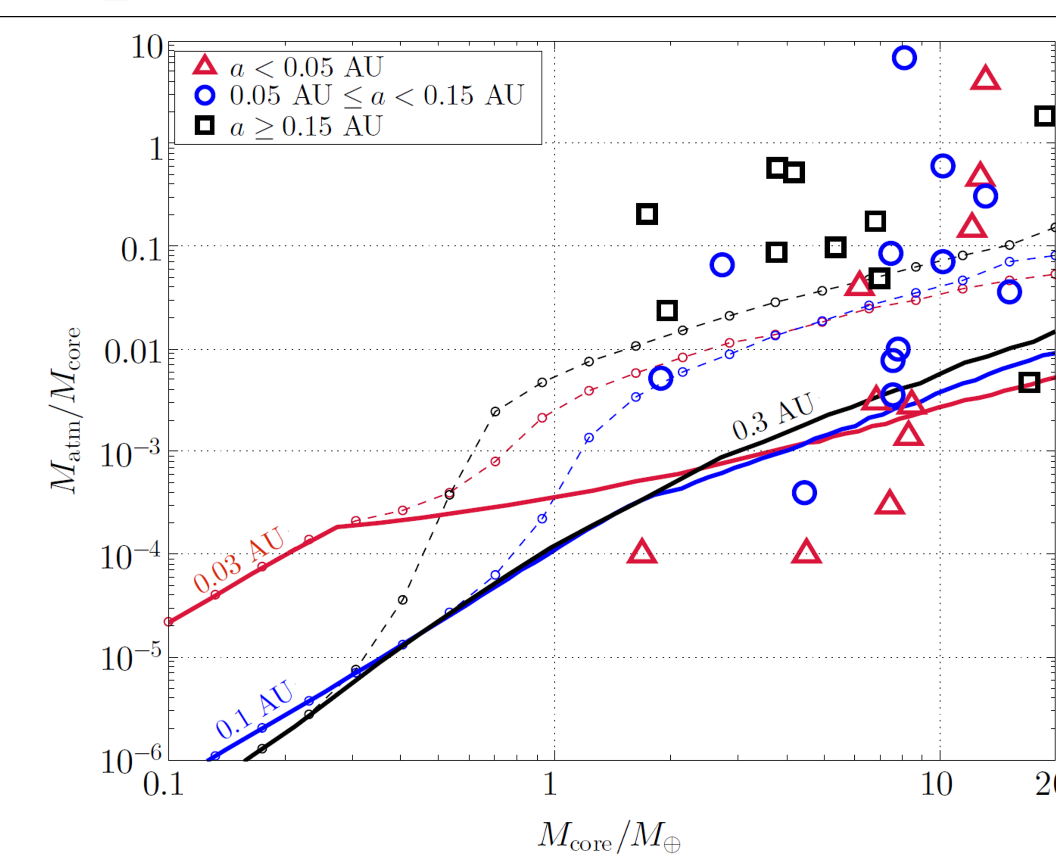



**Figure:** Accreted atmospheric masses after GI, with $\Sigma_g$ 200× smaller than pre-GI. **Cores are now fully assembled**. Solid lines assume $L_{\rm acc}$ is gravitational potential from last mass doubling released over disc dissipation timescale. Dotted lines are atmospheric masses after ~800 kyr of cooling $L_{\rm acc}$ = 0. Data points: Lopez & Fortney (2014).

## Summary and Conclusions

- Pre-GI atmospheric accretion and atmospheric mass loss due to GI lead to atmospheric masses ~$10^{-4}$-$10^{-2}M_{\rm atm}/M_{\rm core}$
- Results are consistent with terrestrial-type planets with small atmospheres, but unable to account for planets with envelopes that are 1-10% of their total mass
- We also considered post-GI atmospheric accretion
  - ⇒ **Assuming the gravitational potential energy from last mass doubling due to giant impacts is released over disc dissipation timescale, atmospheric masses are still smaller than observed for many close-in planets**
  - ⇒ **In the limiting case that $L_{\rm acc}$ = 0, atmospheric masses increase by an order of magnitude**

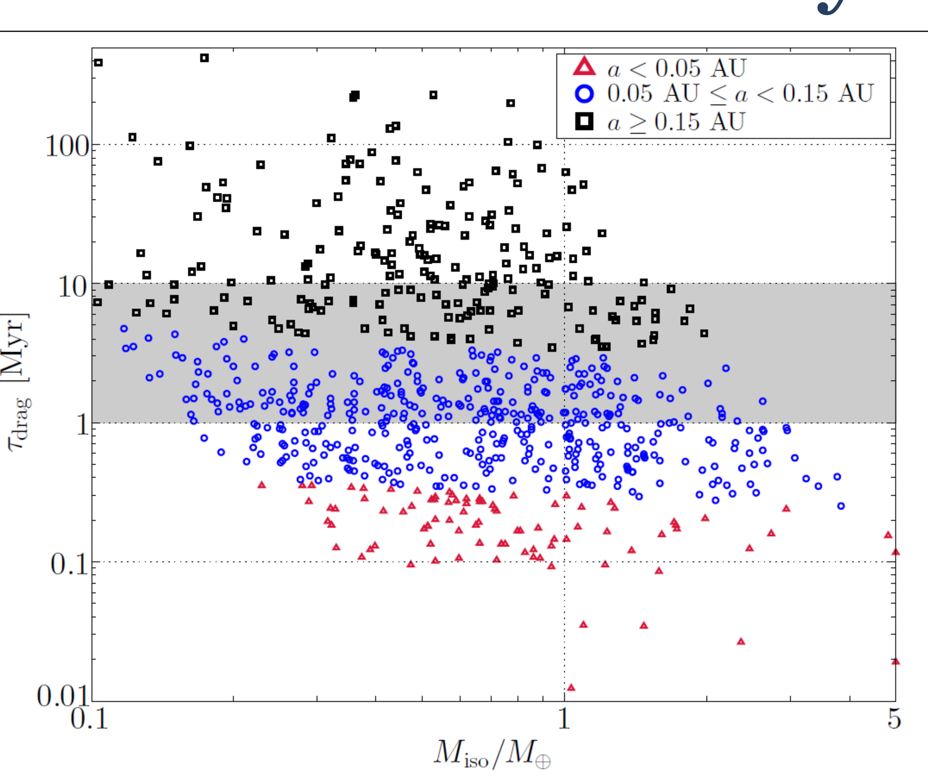



**Figure:** Timescale $\tau_{\rm drag}$ associated with radial drift for isolation masses before the phase of giant impacts. Most close-in planet isolation masses would have migrated deep into the inner disc or fallen into their host star over typical disc timescales (1-10 Myr; shaded region).

- Another impediment to *in situ* formation is the short inward drift timescale due to gas drag for isolation masses
  - ⇒ **For many close-in Kepler planet isolation masses, the inward radial drift timescale is shorter than the typical disc lifetime**
- Atmospheric masses dependent on a number of factors
  - ⇒ **Uncertainty in opacity, cooling time, luminosity model/accretion history drive variability in post-GI masses**
- Formation at larger semimajor axes circumvents many of the problems faced for the *in situ* formation of close-in planets with atmospheres that are several percent of the total mass

## References

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