Owen & Jackson (2012)

* hydrodynamic evaporation of close-in planets
* two regimes:
  + X-ray dominated, when the sonic point is closer to the planet than the ionization front
  + EUV-dominated, when the sonic point is past the ionization front
* Closer-in planets dominated by X-ray evaporation; further-out planet dominated by EUV-driven evaporation
* Ionization parameter scales with metallicity xi ~ Z^-0.77; how good is this scaling though?
* For EUV-dominated, isothermal EOS, P\_EUV = rho \* c\_EUV^2
* For X-ray-dominated: T = f(xi)
* Transition from EUV to X-ray occurs at the ionization front
* Metallicity simple scaling -> following Ercolano & Clarke 2010; not appropriate for very metal rich atmospheres
* They also assume radiative equilibrium (neglected PdV cooling) and radiative cooling; might also not be appropriate in some situations

Owen & Wu (2013)

* combine hydrodynamic evaporation with thermal evolution
* only low mass planets with hydrogen envelope are significantly affected by evaporation; evaporation able to remove hydrogen envelopes inward of ~0.1 AU for Neptune-mass objects; evaporation is negligible for Jupiter-mass planets
* evaporation is the driving force of evolution for close-in Kepler planets -> ~50% of Kepler planet candidates may have been significantly eroded
* bimodal distribution in planet radii because planets with 1% H-He envelope will lose it very quickly -> so envelope either larger than 1% H-He or no envelope
* Wu & Lithwick (2013) measured planet masses in a sample of TTV pairs and found that inner planets are denser, planet densities increase with decreasing orbital period => concluded that low-mass planets are composed of rocky cores + H/He envelopes that have been sculpted by evaporation
* EUV luminosity follows the same time evolution as X-ray luminosity -> how good is this assumption?
* Thermal structure of the envelope set to be initially adiabatic; planet radius = where tau = 2/3; this planet radius also the input radius in the evaporation model
* Planets composed on rocky core + H/He envelope with Solar metallicity
* They compare the initial cooling time with the protoplanetary disk lifetime 3Myrs (?)
* First applied model to hot Jupiters => find that evaporation does not affect the planet’s evolution, i.e. mass loss is <1%
* Calculations begin at 3Myr, AFTER disk dissipates and planet is fully formed
* Planets with shorter initial cooling times end up with smaller radii and larger densities than planets with longer initial cooling times
* From Mdot \* age plot (the maximum of which shows when mass loss is most significant), they find that most mass loss occurs when X-ray luminosity starts to decline
* From population study: at a given planet mass, a lower core mass results in initially larger planets => planets with smaller cores may lose their entire envelope at larger separations than planets with larger cores
* Convergent evolution: planets with initially the same core, but different envelope masses, may end up with somewhat identical structures => in some cases it may be difficult to retrieve a planet’s initial structure (but perhaps the degeneracy can be broken if initial thermal evolution is considered!)
* Dependence on stellar spectral types: X-ray flux can vary greatly, since late-type stars are significantly more luminous on Gyr timescales => they find that order-unity in planet final mass and radius when stellar type varies (e.g., a 0.5 Msun star loses its envelope completely, while a 1.5 Msun star still has ~3 Me envelope after 10Gyrs, for a 12.5 Me core; how is the X-ray flux factored in though?)
* Cooling associated with molecular species is neglected -> what if molecular species provide significant cooling?
* Radius gap because planets with 1% H-He envelope will lose it very quickly -> so envelope either larger than 1% H-He or no envelope
* Evaporation explains density-separation distribution for Kepler planets

Lopez et al. (2012)

* coupled thermal evolution with XUV-driven mass loss
* energy limited escape approximation for XUV escape
* “hot start ” for thermal evolution -> models start with initial large entropy; they don’t consider the actual atmosphere formation, they start the calculations once the planet is fully formed
* they find that the thermal evolution is generally insensitive to the initial entropy after ~100 Myrs -> how accurate is that?
* They find a mass loss threshold timescale => threshold can be used to provide limits on planet mass or radius for planets without measured density
* application to Kepler-11 b: Ikoma & Hori (2012) predict that if Kepler-11 b had formed in situ and was water-poor, then it’s enveloped was <1% H-He at formation; Lopez et al. model predicts Kepler-11 b was at least 82% H-He at 10 Myr => Kepler-11 b unlikely to have formed in situ. Same for Kepler-11 f => their results disfavor the in-situ formation of the system
* if Kepler-11 b had formed beyond the snow line => likely a system of water-rich sub-Neptunes; Kepler-11 b stable against mass loss if it’s a water world.
* the system could also be water-poor super-Earths that have undergone significant migration, but that’s less likely (this scenario still requires Kepler-11 b to have formed with ~90% H/He)
* future work: need more XUV observations of young (~10 Myr) stars; also more UV observations of transiting exospheres
* also more observations of XUV and flares from M dwarfs, which are highly active

Lopez & Fortney (2013)

* coupled thermal evolution and photoevaporation models applied to the Kepler-36 system
* they aim to explain the large density contrast between the two planets in the system, and find that this contrast is due to the difference in the masses of the planets’ cores, which impacts their mass-loss evolution
* present day composition: Kepler-36 b: consistent with rocky composition, and an Earth-like rock/iron ratio, with no H/He envelope; Kepler-36 c: much lower density => substantial H/He envelope (~10%)
* they determine each planet’s core mass: Kepler-36 b ~ 4.5 M\_E (just from TTVs since it’s assumed it has no H/He envelope), Kepler-36 c ~ 7.4 M\_E
* their current compositions can be explained by assuming that they formed with the same H/He composition (~20%), but that Kepler-36 b was much more vulnerable to mass loss -> why? the different in incident radiation is not enough to explain this; instead, it’s largely due to the difference in planetary masses
* the mass in heavy elements of the planet is a useful tool to estimate a planet’s mass-loss history
* gap in planetary radii that is also seen in observations; can be explained by mass-loss threshold -> planets with <~1% H/He cannot retain it=>either larger envelope or no envelope at all

Chiang & Laughlin (2013)

* premise: close-in super Earths (R ~ 2-5 Re and P < 100 days) are ubiquitous => more than 50% of Kepler stars should harbor one
* premise: close-in super Earths generally thought to have formed in the outer disk and migrated in; while orbital migration is well motivated, the underlying assumption in trying to understand their formation is that they formed in a way similar to that of the Solar system (i.e. similar disk profile etc.)
* disk-driven migration too poorly understood to connect meaningfully with observations => population synthesis studies fail to reproduce the observed population of S.E with P < 50 days through disk migration
* this paper therefore explores the possibility that these planets have formed in-situ => they build from scaratch a MMEN, starting from the observed Kepler population
* use 1925 planets with R < 5 Re and P < 100 d from Batahla+2013
* assume planets formed of rocky cores and with small gas envelopes (<~ 20% H-He); do not consider water worlds because water cannot condense in situ close-in
* assign each planet a surface density based on its mass and semi-major axis
* 2 resulting MMENs, the second one to account for the probability of transit
* assume an isothermal disk with T = 1000 K
* a simple estimate for the time for a core to double its mass (Mc/Mdotc) shows that the cores formed on typical scales of a few x 10^5 years, well before disk dissipation; their assumption is that SE form to completion while the full solar abundance component of the gas is present
* mass estimates (mass enclosed within Bondi or Hill) + the condition for gravitational stability (Q > 1) imply maximum envelope masses up to ~30%, thought typical is ~3%
* OOM calculation assuming energy limited escape shows that most (but not all) SE retain their envelopes
* SE stay in place after formation, on co-planar and nearly circular orbits
* They apply model to Kepler 11 system (works to OOM), Kepler-10 b (also consistent), GJ1214b (cannot readily applied model because host star is an M dwarf; also observations of its spectrum show it might have an atmosphere composed of heavy molecules, e.g. CO2 => seemingly incompatible with in-situ accretion scenario)
* M dwarfs and brown dwarfs should have close-in SE and Earths (since colder disk regions favor formation of rocky cores)

Ikoma & Hori (2012)

* study accretion of H-He envelopes on rocky bodies enveloped in warm disks (small separations), motivated by Kepler close-in low density SE
* found:
  + massive rocky bodies => atmospheres undergo runaway gas accretion
  + lighter bodies => atmospheres undergo significant erosion during disk dispersal
  + the heat content of the rocky core plays an important role in atmosphere erosion
  + atmosphere mass is sensitive to disk temperature
  + applied model to Kepler 11 system => in situ formation of thick atmospheres only possible under certain conditions, i.e. slow disk dissipation and/or cool environments
* explore the possibility of in-situ accretion of H-He atmospheres
* consider only grain-free atmospheres => atmospheric opacity includes only gas opacity
* new effects included: disk dissipation (rho\_disk decreases exponentially in time) and heating from the core
* contribution from the rocky core: L\_radio and C\_rock M\_rock dT\_c/dt
* for a core 4 Me and Td = 550 K: evolution with no disk dissipation leads to runaway accretion; when disk dissipation is included, atmosphere mass decreases, i.e. the atmosphere is eroded; this is due to atmospheric expansion: lower pressure gradient due to lower disk pressures pushes the atmosphere outer boundary outwards, to the point where gas seeps out of the planet’s gravitational sphere; this decrease in mass is significantly larger when the heating from the core is also included
* applied to Kepler-11 system: for standard case, Kepler-11 d, e, f, atmosphere masses inferred from modeling are much larger than the masses derived here => they are unlikely to have formed in-situ
* if disk dissipation is slower, however, inferred masses for Kepler-11 b and e are consistent with those derived here, though Kepler-11 f is still too massive
* they also consider mass loss: Kepler-11 is an old G dwarf (~8 Gyr) => low XUV irradiation level
* estimate mass loss via energy-limited escape => all Kepler-11 planets are likely to have lost similar amounts of gas ~0.1 Me
* they acknowledge other possibilities to explain their current H-He envelopes: degassing (seems insufficient), planets are water-dominated (possible)

Hansen & Murray (2012)

* show that in-situ assembly of close-in SE / mini-Neptunes is possible, with no migration post-assembly, if the mass of solid material inside 1 AU is ~50-100 Me
* cores of this size (i.e, sizes of observed populations) are large enough to capture gas from the nebula, but gas accretion is rapidly limited due to gap opening, i.e. tidal truncation(?)
* besides the ubiquity of SE inside 50-100 AU, there is also an upper edge in the mass vs. semi-major axis plot: max ~7 Me at 2 days and max ~20 Me at 50 days; in contradiction with populations synthesis models, which predict no M-a correlation for these types of planets
* although they study the formation of SE in situ, they consider the possibility of rocky material having migrated inwards from beyond the snow line
* use N-body code Mercury to simulate accumulation of planetary embryos around a 1 Msun star, from 0.05 to 1 AU, varying total mass and surface density profile
* surface density profile sigma ~ a^(-alpha), alpha = 0, 3/2, 5/2
* in-situ simulation results match the observed population of SE
* …

Naghighipour (2013, annual review)

* observations show that SE are more likely to form in short-period orbits and in multi-planet systems

Pascucci et al. (2011)

* disks around low-mass stars and brown dwarfs seem to have smaller scale heights than disks around Sun-like stars of similar age (Szucs+10)
* dust grains in disks around brown dwarfs seem to be more evolved than those in disks around Sun-like stars
* disk lifetimes show little variation for stars 0.3-3 Msun
* disk evolution and dispersal around isolated M-dwarfs is expected to proceed the same way as around Sun-like stars