AST 1420

Galactic Structure and Dynamics

Q&A

Reminders

- Assignment 2 due next week!
  - Please use the slack for any questions!
- You should have received feedback on assignment 1

Evolution of small over densities

Proper and co-moving coordinates

$$\mathcal{L}(\mathbf{r}, \dot{\mathbf{r}}, t) = \frac{m|\dot{\mathbf{r}}^2|}{2} - m\Psi(\mathbf{r}, t)$$

- Why switch to co-moving coordinates?
  - The contribution to **r**(t) and the velocity from the expansion of the Universe is not interesting, so remove it by going to co-moving coordinates

$$H(\mathbf{x}, \mathbf{p}, t) = \frac{1}{2\,m\,a^2}\,\mathbf{p}^2 + m\Phi(\mathbf{x}, t)$$

$$\nabla^2\Phi(\mathbf{x}, t) = 4\pi\,G\overline{\rho}(t)\,a(t)^2\,\delta(\mathbf{x}, t)$$

  - Inside of a dark matter halo / galaxy, we don't use co-moving coordinates. Spherical collapse solution is in *proper coordinates* (initial expansion of all of the shells = expansion of the Universe)

Cold dark matter

- Before halo formation, dark matter is cold. What does that mean?
  - Qualitatively means that in the early Universe when structure formation starts, dark matter was moving a velocities << c and with a narrow velocity distribution (sigma << |v|)
  - For example, some dark matter particles' number density is set by *freeze out*:
    - After initially being in thermal equilibrium with photons, at a certain point the interaction rate falls below the expansion rate and DM <-> photon interactions cease
    - DM velocities are then set by $(v/c)^2 = kT/[mc^2]$ with m the DM mass and T the photon temperature at the time of freeze out:
      - Higher DM mass: slower velocities
      - Later freeze-out, T lower: slower velocities
  - Cold then means that the velocity distribution is very narrow: f(**r**,**v**) = dens(r) x delta(**v**-**v**')
    - Fine-grained distribution of cold dark matter should therefore be highly non-uniform, even after halo formation, but unobservable due to coarse graining

Growing and decaying mode

- Evolution of perturbations has a *growing* and a *decaying* mode
  - Decaying mode is typically H, which decreases in time, except in dark-energy only Universe
  - How long the decaying mode may be relevant depends on the exact cosmological model
  - E.g., EdS: $\text{delta}_{-} \sim a^{-3/2}$ while delta+ ~ a, so $\text{delta}_{+}/\text{delta}_{-} \sim a^{5/2}$

Growth of baryonic over densities

- Why ideal gas?
  - Ideal gas description works if mean free path << scale of interest
- Would structure form in a Universe without dark matter?
  - Depends on the cosmological parameters, but for example, a flat baryon-only Universe has fluctuations that grows as scale factor a like for dark matter on scales larger than the Jeans length (~ 10 comoving kpc)
  - However, from the CMB we know that delta_baryons ~ 1e-5 at a ~ 1/1000, so they could only grow to ~1e-2 today —> baryon-only Universe would not have structure today

Spherical collapse

Virial overdensity

- Why do people use an over density of 200 if the true value is 100 (or ~300 with respect to the mean matter density)?
  - If you are going to *not* use 200, value depends on cosmology, which changes every few years…
  - Often we don’t know when the halo forms, which sets the cosmological parameters that we should be using to compute the relevant over density
  - Because most galaxy-size halos form at z >~ 2, 200 is typically the relevant value

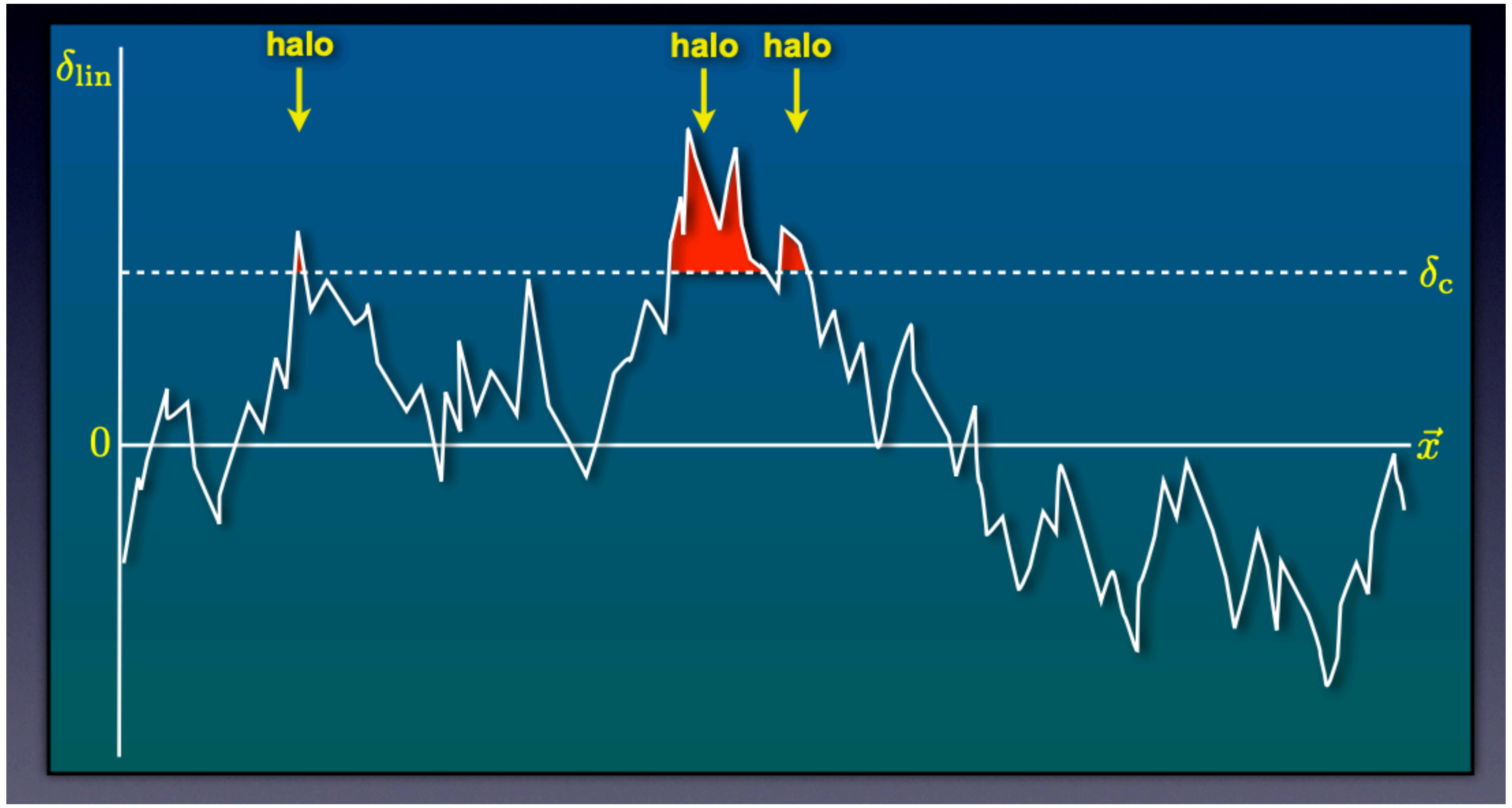
What happens to the baryons in halos?

- In CDM, dark matter overdensities start growing before the CMB forms (decoupling). Thus, they are larger than the overdensities in the baryons, which cannot grow before decoupling due to being coupled to the relativistic photons
- After decoupling, baryons become non-relativistic and fall into the potential wells that have been established by dark matter
- Dark matter halos form from the dark matter + baryons accumulated in overdensities
- At first, baryons and dark matter have ~ radial profile, but energy losses through processes like recombination radiation, collisional excitation and subsequent decay and Bremmsstahlung cause the baryons to cool into a disk
- In standard model, baryons and dark matter *only* interact gravitationally

Distribution of halo masses

Initial size of overdensities and their evolution

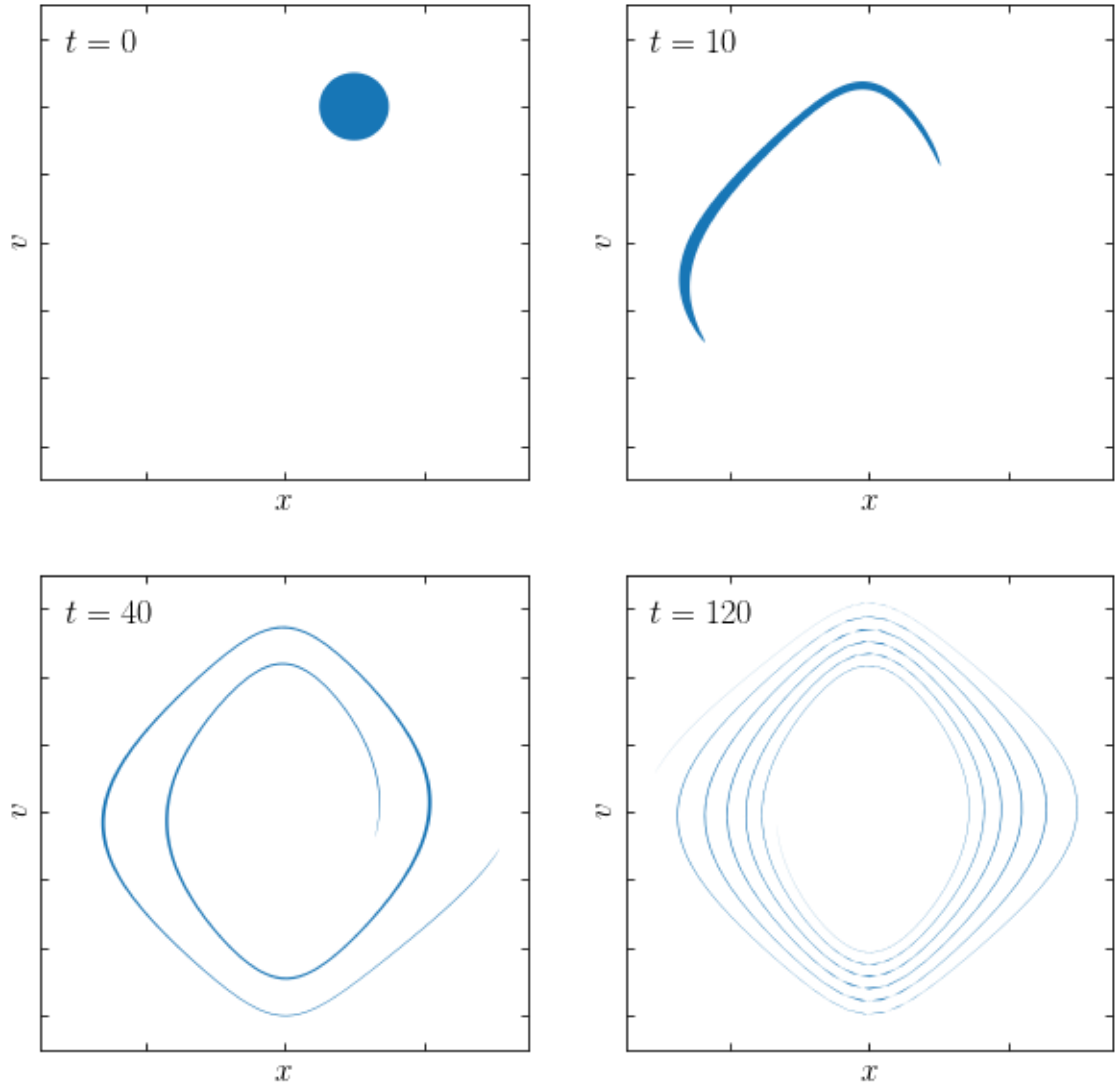
- In the Press-Schechter formalism, the initial density field delta grows in time and a halo forms when the overdensity smoothed over some scale is larger than the critical over density 1.686
- Initial spectrum of under- and over-densities is set by some process, perhaps inflation. In the standard model, the over densities are Gaussian and adiabatic and they have a power spectrum P(k) ~ 1/k
- P(k) ~ 1/k means that smaller scales (larger k) have larger variance. In CDM, variance on very small scales increases without bounds
- As long as over densities keep growing, eventually any initial over density > 1.686
    - But can take a long time (largest scales, e.g., clusters, super-clusters)
    - As Universe becomes dominated by dark energy, over densities stop growing



From van den Bosch

Phase mixing

Phase mixing



Phase mixing