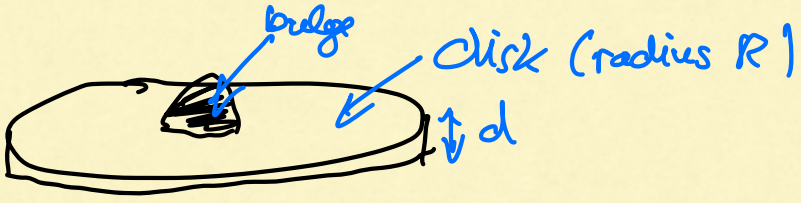
3. Dark Matter

3.1 Evidence for DM

- Galaxy Rotation Curves
  (Jan Oort 1932, Vera Rubin 1970)



1) Bulge (approx. spherical)

$$F = \frac{G\,m\,M(r)}{r^2} \overset{!}{=} m\,\frac{v^2(r)}{r}$$

($M(r)$: mass enclosed within r)

$$v(r) = \sqrt{\frac{G \cdot M(r)}{r}} = \sqrt{\frac{4}{3}\pi G r^2 \rho_{bulge}}$$

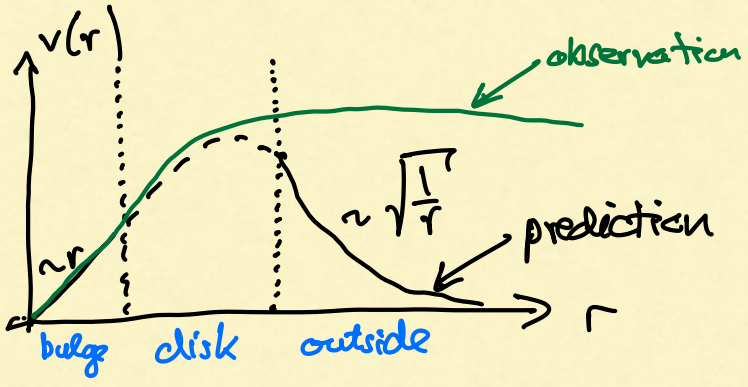
2) Disk: a little more complicated

3) Outside the disk

↳ galaxy can be treated as ~ pointlike

$$F = \frac{G\,m\,M(R)}{r^2} \overset{!}{=} m\,\frac{v^2(r)}{r}$$

$$\hookrightarrow v(r) = \sqrt{\frac{G \cdot M(R)}{r}}$$



↳ Conclusion: to explain the large orbital velocities far away from the Galactic center, postulate existence of extra matter

- **Dynamics of galaxy clusters**

  Fritz Zwicky 1933

  Virial theorem: $\sum E_{kin} = -\frac{1}{2} \sum E_{pot}$

  - $\sum$: sum over galaxies
  - E_{kin}: kinetic energy (from Doppler shifts)
  - E_{pot}: grav. potential energy (from brightness)

  Observation: $\sum E_{kin} \simeq -\frac{1}{2} \cdot 170 \sum E_{pot}$

- **The Cosmic Microwave Background (CMB)**

  At $t \simeq 300{,}000$ yrs, e^- and p^+ combine to form H

  ↳ Universe becomes transparent

  ↳ Thermal radiation present at this epoch can still be observed today.

  T at recombination was $\mathcal{O}(0.1\,eV)$ ($< 13.6\,eV$ because the high-E tail of the photon distribution, combined with $n_\gamma / n_{p,e} \sim 10^{10}$ kept e^- and p^+ apart for longer)

  Today: photons have been redshifted to

  $$T_0 = 2.73\ K$$

Tiny fluctuations in T across the sky from primordial quantum fluctuations can be observed on the CMB.

The primordial plasma oscillates as matter is drawn towards overdense regions, falls in, gets pushed back by radiation pressure, etc.

↳ CMB power spectrum

$$T(\theta,\phi) = \sum_{l,m} a_{lm}\, Y_{lm}(\theta,\phi)$$

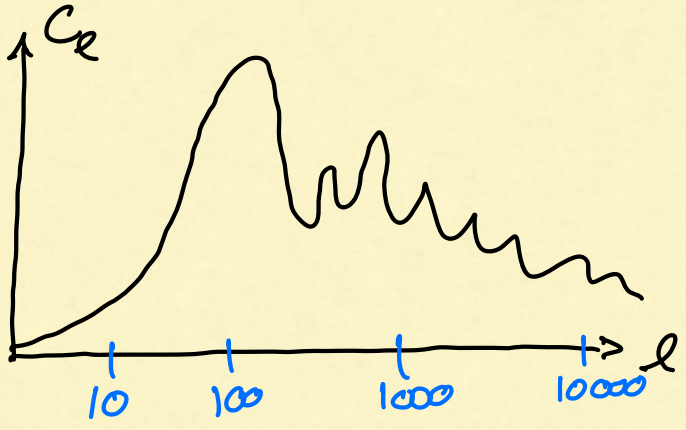
$T(\theta,\phi)$: temperature map in galactic coordinates

$Y_{lm}(\theta,\phi)$: spherical harmonics

$$a_{lm} = \int d\cos\theta\, d\phi\, Y^*_{lm}(\theta,\phi) \cdot T(\theta,\phi)$$

define $$\boxed{C_l \equiv \frac{1}{2l+1} \sum_m |a_{lm}|^2}$$

CMB Power Spectrum



Peaks correspond to maxima / minima of the oscillations of the primordial plasma

For instance: First peak around $\ell \sim 100$ corresponds to an oscillation mode whose oscillations were interrupted by recombination when it had reached its first maximum

More DM tends to suppress the peaks because photons have to travel out of deeper potential wells
↳ more gravitational redshift.

- **Structure Formation**

  ↳ see Scugan Lecture

  Primordial density fluctuation from the CMB

  ↓

  calculate subsequent evolution of fluctuations until today, where they have evolved into galaxies

  ↓

  compare predicted distribution of galaxies to observations to constrain properties of DM

  Conclusion: DM should be non-relativistic early on.

3.2 DM candidates — Overview

- Weakly Interacting Massive Particles (WIMPs)
- Axions
- Sterile Neutrinos
- Primordial black holes