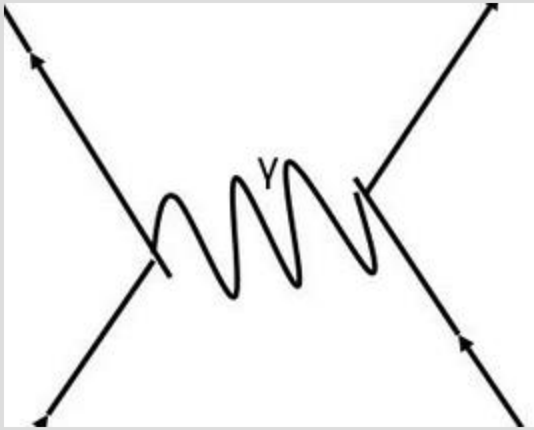
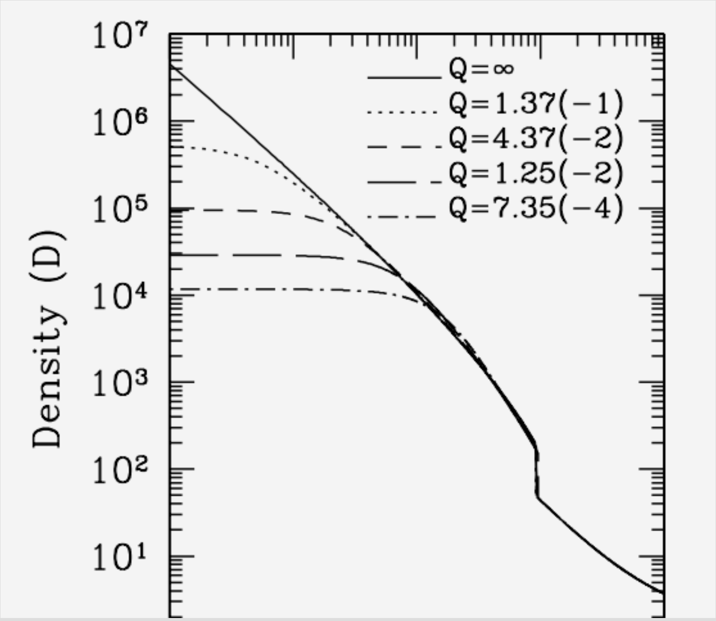
Self-Interacting Dark Matter: cuspy or flat?





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Crossroad of Astrophysics and Particle Physics

홍천 소노벨

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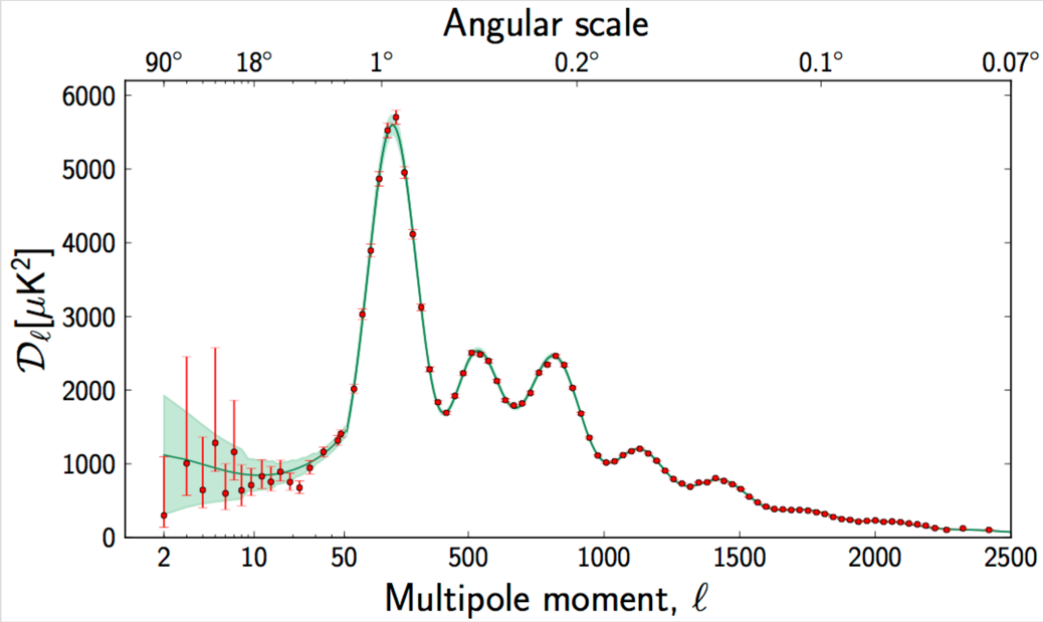
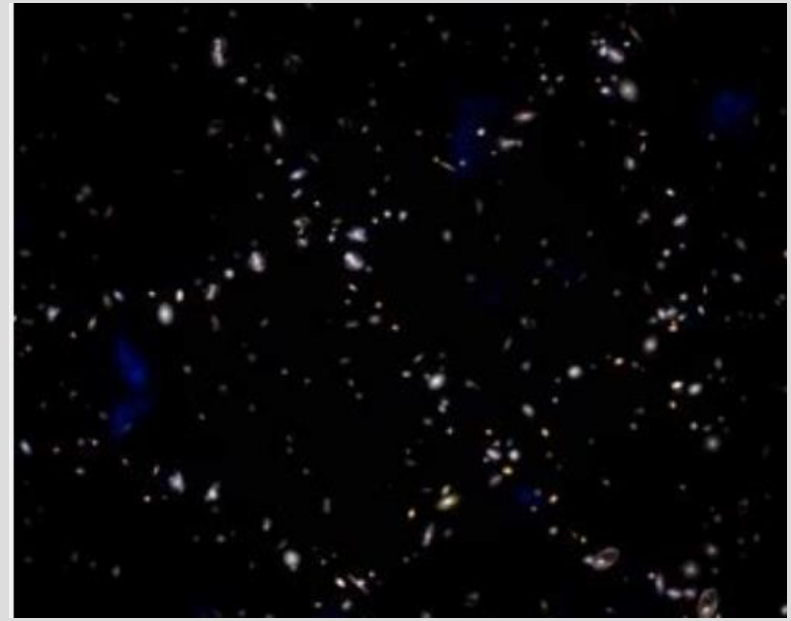
ΛCDM (standard) cosmology still OK

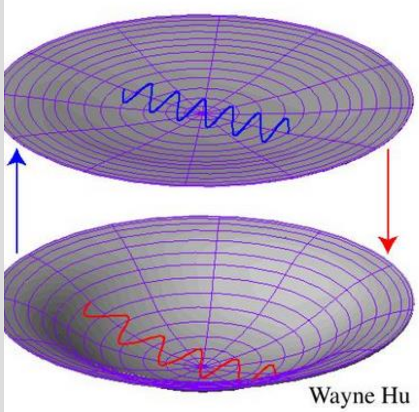


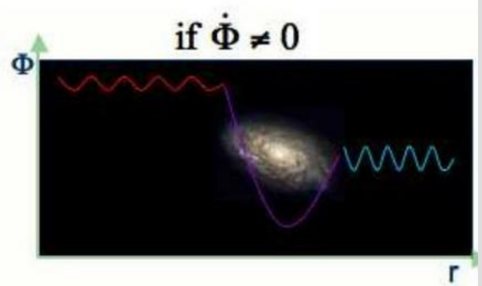


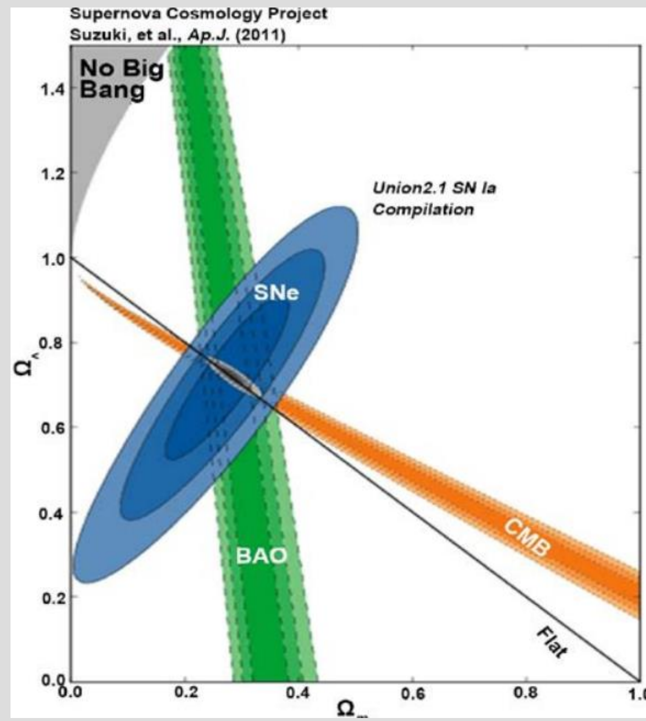
Integrated Sachs-Wolfe

- Time varying gravitational potentials
- Early and late ISW

$$\frac{\delta T}{T} = -2\int \dot{\Phi}(\tau)d\tau$$







good and cozy

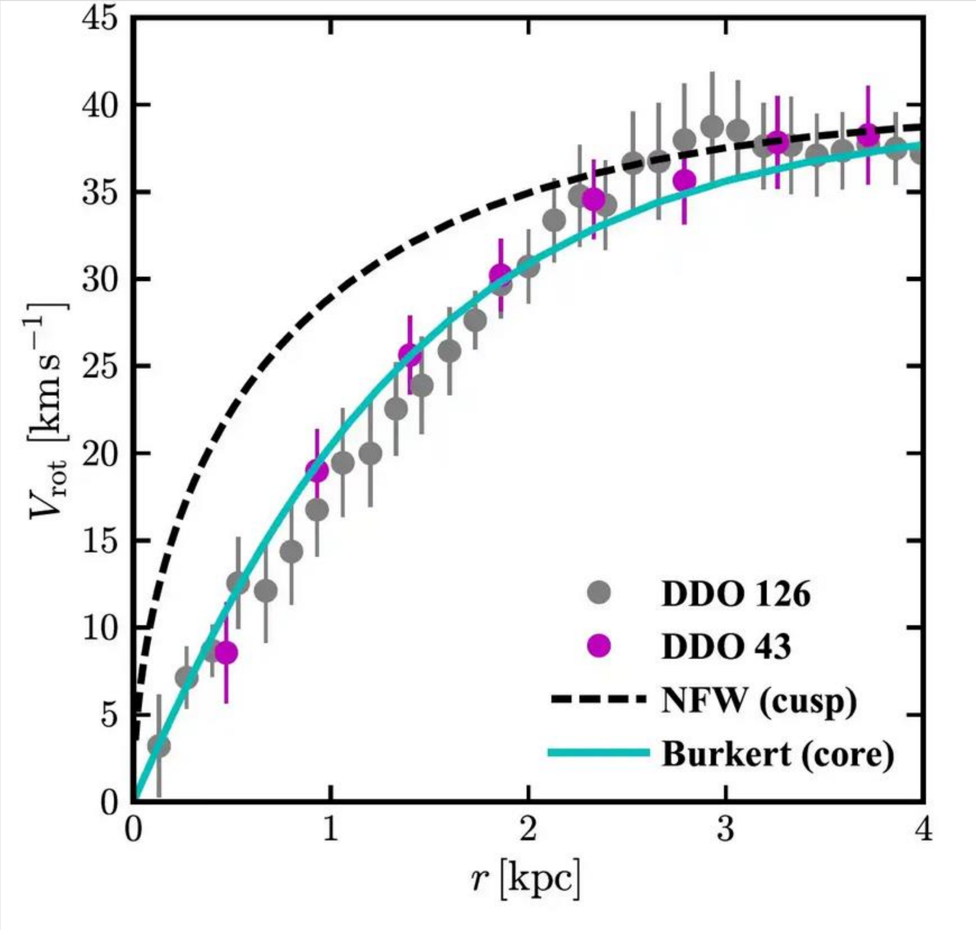
- dark matter: WIMP
  - "practically" collisionless
- dark energy: Λ
- flat geometry

Challenges in structure formation

Not too cozy

- Halo core–cusp problem
  (see Seheon's talk)

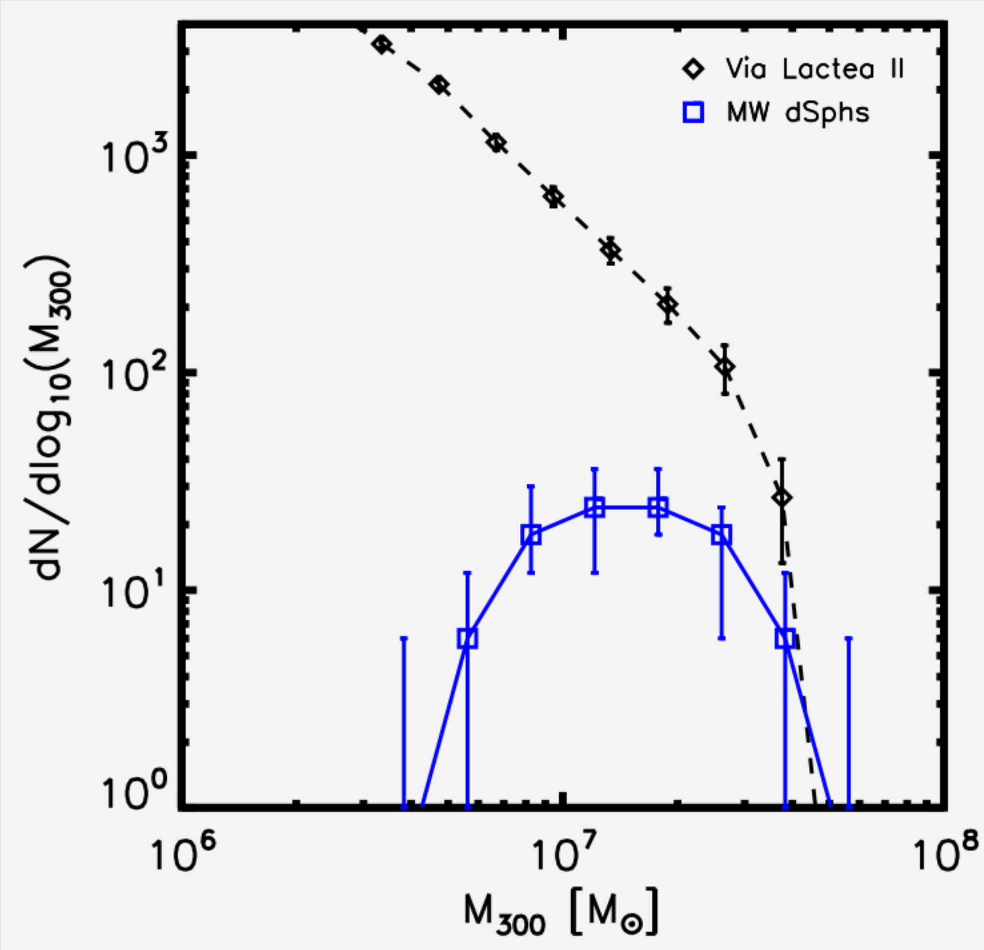
- Missing satellite problem



Not too cozy

- Halo core–cusp problem

- Missing satellite problem
(see Jihoon, Hoseong,
Chagnbom's talk)



Not too cozy

- Halo core–cusp problem

- Missing satellite problem

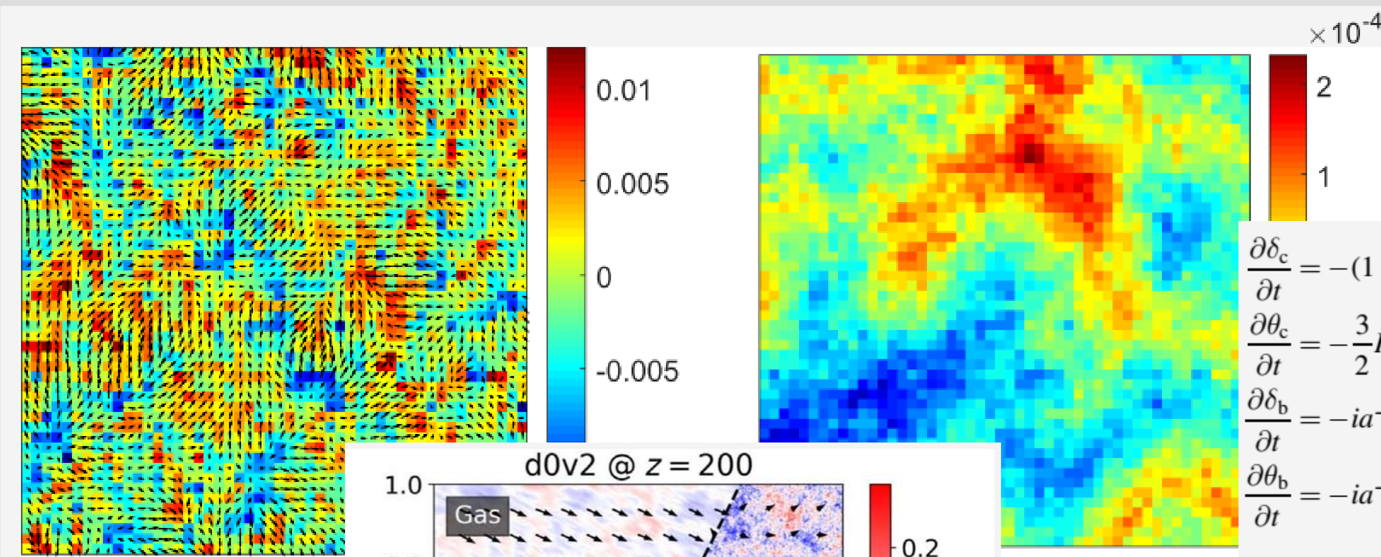
- small–scale (large k) regime
  - overlap with baryon physics (talk by Jihoon)
  - (roughly) Jeans instability boundary: pressure force ~ gravity

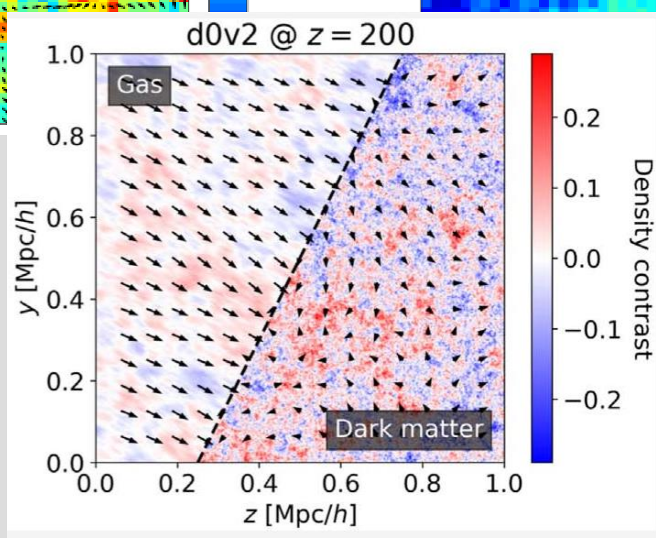
$$a^{-2}c_s^2k^2 \sim H^2\delta$$

  - baryonic “confusion” unavoidable

DM & baryon has different footings → suppression of galaxies

- KA (2015); KA & Smith (2018); Park, KA, Yoshida, Hirano (2020)
- BCCOMICS (github.com/KJ-Ahn/BCCOMICS)





$$\frac{\partial \delta_c}{\partial t} = -(1 + \Delta_c)\theta_c - \Theta_c \delta_c,$$

$$\frac{\partial \theta_c}{\partial t} = -\frac{3}{2}H^2\Omega_m(f_c\delta_c + f_b\delta_b) - 2H\theta_c,$$

$$\frac{\partial \delta_b}{\partial t} = -ia^{-1}\mathbf{V}_{bc}\cdot\boldsymbol{k}\delta_b - (1 + \Delta_b)\theta_b - \Theta_b\delta_b,$$

$$\frac{\partial \theta_b}{\partial t} = -ia^{-1}\mathbf{V}_{bc}\cdot\boldsymbol{k}\theta_b - \frac{3}{2}H^2\Omega_m(f_c\delta_c + f_b\delta_b) - 2H\theta_b + a^{-2}\frac{k_B\bar{T}}{\mu m_H}k^2\{(1 + \Delta_b)\delta_T + (1 + \Delta_T)\delta_b\},$$

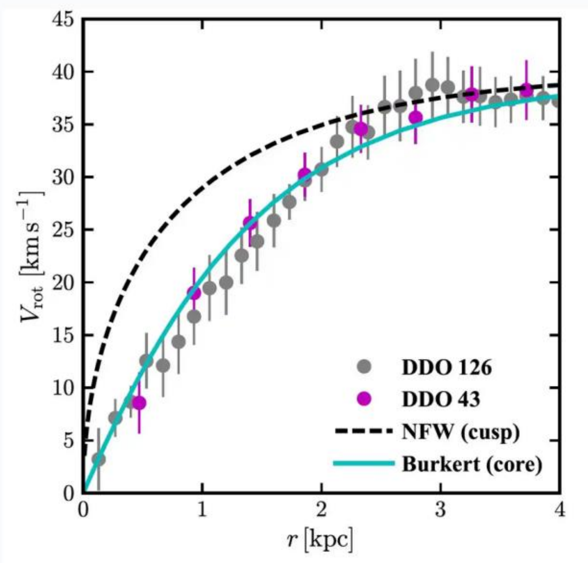
$$\frac{\partial \delta_T}{\partial t} = \frac{2}{3}\left\{\frac{\partial \delta_b}{\partial t} + \frac{\partial \Delta_b}{\partial t}(\delta_T - \delta_b) + \frac{\partial \delta_b}{\partial t}(\Delta_T - \Delta_b)\right\} - \frac{x_e(t)}{t_\gamma}a^{-4}\frac{\bar{T}_\gamma}{\bar{T}}\delta_T.$$

halo structure with SIDM

(KA & Shapiro 2005)

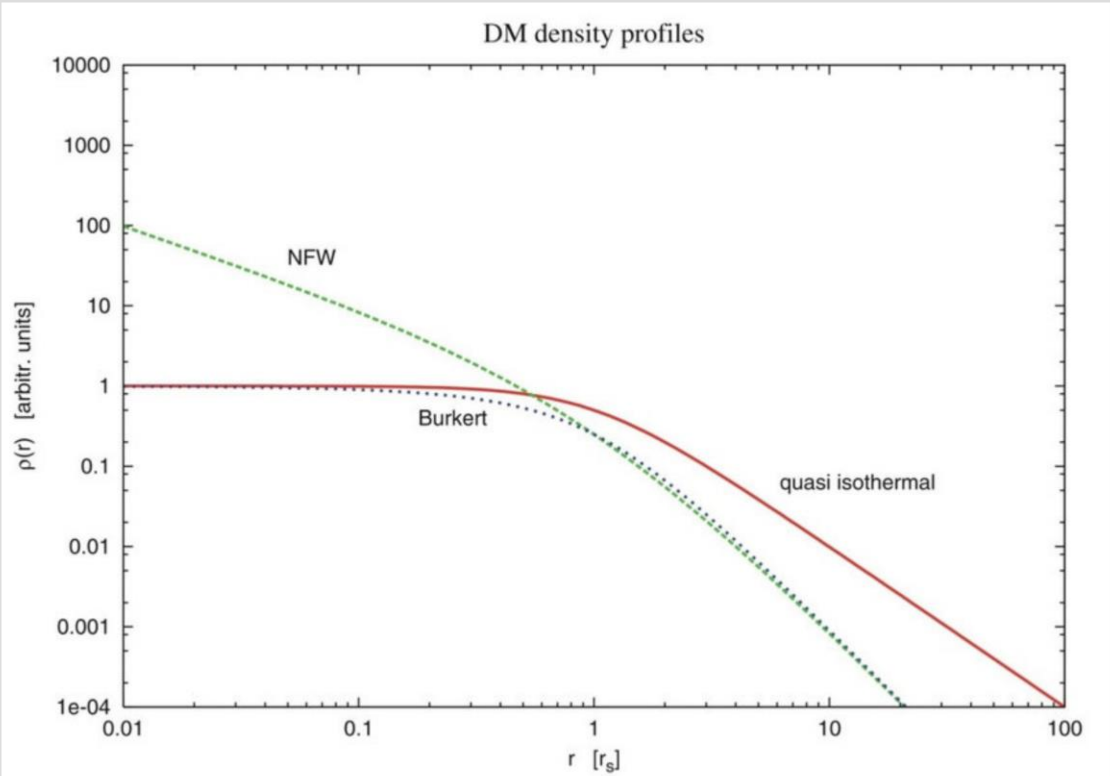
Motivation

- Halo core-cusp problem
- SIDM (Spergel & Steinhardt 2000)



The cusp core problem. Here the orbital speeds of the stars for the inner area of typical galaxies are shown over the distance from the center in kiloparsecs (kpc; 1 kpc = 3260 light years). It is the inner part of the rotation curve. The black dashed line shows the rotation curve to be expected according to the simulations based on the model of Navarro, Frenk and White (NFW), as it results in simulations of dark matter. Since the mass is strongly concentrated in the center, the speed increases rapidly with the distance, because there is a lot of mass in the vicinity of the center. The gray and purple symbols show measurement points of actual galaxies, as well as an approximation according to Burkert with constant density in the interior of the galaxy. Here the rotation curve rises flatter, because with the radius the proportion of the circled mass grows more slowly than with NFW. Astronomers speak of a core distribution of matter over the entire core area of the galaxy.

(Image: James S. Bullock & Michael Boylan-Kolchin, 2017)



Methodology

- moments of collisionless Boltzmann equation in spherical symmetry

$$\frac{\mathrm{d}f}{\mathrm{d}t} = 0.$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{r^2 \partial r}[r^2(\rho u)] = 0,$$

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial r}\left(p_r + \rho u^2\right) + \frac{2}{r}\left(p_r - p_\theta + \rho u^2\right) = -\rho \frac{Gm}{r^2}$$

$$\rho \frac{D}{Dt}\left(\frac{p_r}{2\rho}\right) + p_r \frac{\partial u}{\partial r} = \Gamma_1,$$

$$\rho \frac{D}{Dt}\left(\frac{p_\theta}{2\rho}\right) + \frac{p_\theta u}{r} = \Gamma_2,$$

$$\vdots$$

Methodology

- moments of collisionless Boltzmann equation

$$\frac{\mathrm{d}f}{\mathrm{d}t} = 0.$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{r^2 \partial r}[r^2(\rho u)] = 0,$$

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$$\rho \frac{D}{Dt}\left(\frac{p_\theta}{2\rho}\right) + \frac{p_\theta u}{r} = \Gamma_2,$$

$$\vdots$$

$$p_r \equiv \rho \left\langle (v_r - \langle v_r \rangle)^2 \right\rangle,$$

$$p_\theta \equiv \rho \left\langle (v_\theta - \langle v_\theta \rangle)^2 \right\rangle = \rho \left\langle v_\theta^2 \right\rangle,$$

$$p_\phi \equiv \rho \left\langle (v_\phi - \langle v_\phi \rangle)^2 \right\rangle = \rho \left\langle v_\phi^2 \right\rangle,$$

$$\Gamma_1 = \frac{\rho}{r}\left\langle 2\left(v_r - \langle v_r \rangle\right) v_\theta^2 \right\rangle - \frac{1}{2r^2}\frac{\partial}{\partial r}\left[r^2 \rho \left\langle (v_r - \langle v_r \rangle)^3 \right\rangle\right],$$

$$\Gamma_2 = -\frac{1}{4r^4}\frac{\partial}{\partial r}\left[r^4 \rho \left\langle (v_r - \langle v_r \rangle) v_\theta^2 \right\rangle\right]$$

Methodology

- velocity dispersion: symmetric + skewless

$$\frac{\mathrm{d}f}{\mathrm{d}t} = 0$$

$$p_r \equiv \rho \left\langle (v_r - \langle v_r \rangle)^2 \right\rangle ,$$

$$p_\theta \equiv \rho \left\langle (v_\theta - \langle v_\theta \rangle)^2 \right\rangle = \rho \left\langle v_\theta^2 \right\rangle ,$$

$$p_\phi \equiv \rho \left\langle (v_\phi - \langle v_\phi \rangle)^2 \right\rangle = \rho \left\langle v_\phi^2 \right\rangle ,$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{r^2 \partial r}[r^2(\rho u)] = 0,$$

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial r}\left(p_r + \rho u^2\right) + \frac{2}{r}\left(p_r - p_\theta + \rho u^2\right) = -\rho \frac{Gm}{r^2}$$

$$\rho \frac{D}{Dt}\left(\frac{p_r}{2\rho}\right) + p_r \frac{\partial u}{\partial r} = \Gamma_1,$$

$$\rho \frac{D}{Dt}\left(\frac{p_\theta}{2\rho}\right) + \frac{p_\theta u}{r} = \Gamma_2,$$

$$\Gamma_1 = \frac{\rho}{r}\left\langle 2(v_r - \langle v_r \rangle) v_\theta^2 \right\rangle - \frac{1}{2r^2}\frac{\partial}{\partial r}\left[r^2 \rho \left\langle (v_r - \langle v_r \rangle)^3 \right\rangle\right],$$

$$\Gamma_2 = -\frac{1}{4r^4}\frac{\partial}{\partial r}\left[r^4 \rho \left\langle (v_r - \langle v_r \rangle) v_\theta^2 \right\rangle\right]$$

$$\frac{D}{Dt}\left(\frac{3p}{2\rho}\right) = -\frac{p}{\rho}\frac{\partial}{r^2 \partial r}(r^2 u)$$

Methodology

- equivalent to hydrodynamics in spherical symmetry (of polytropic gas with $\gamma = 5/3$)

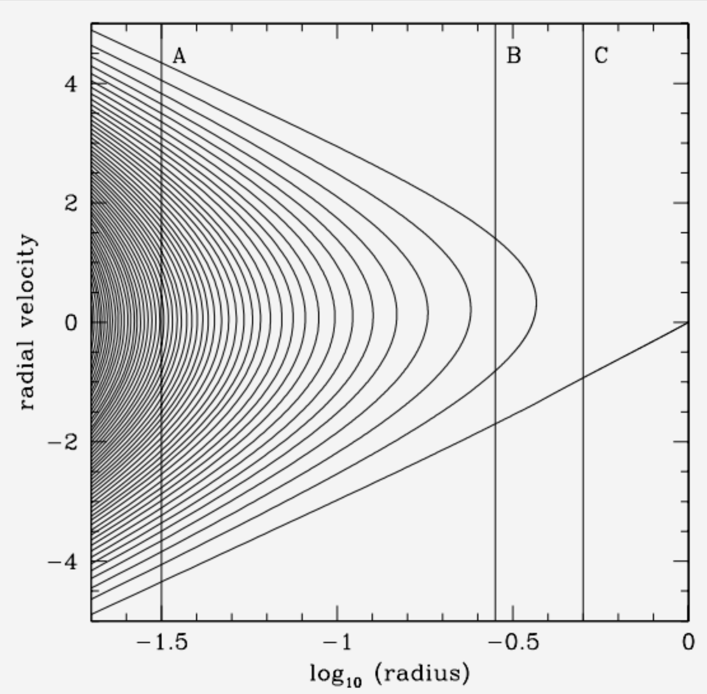
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{r^2 \partial r}[r^2(\rho u)] = 0,$$

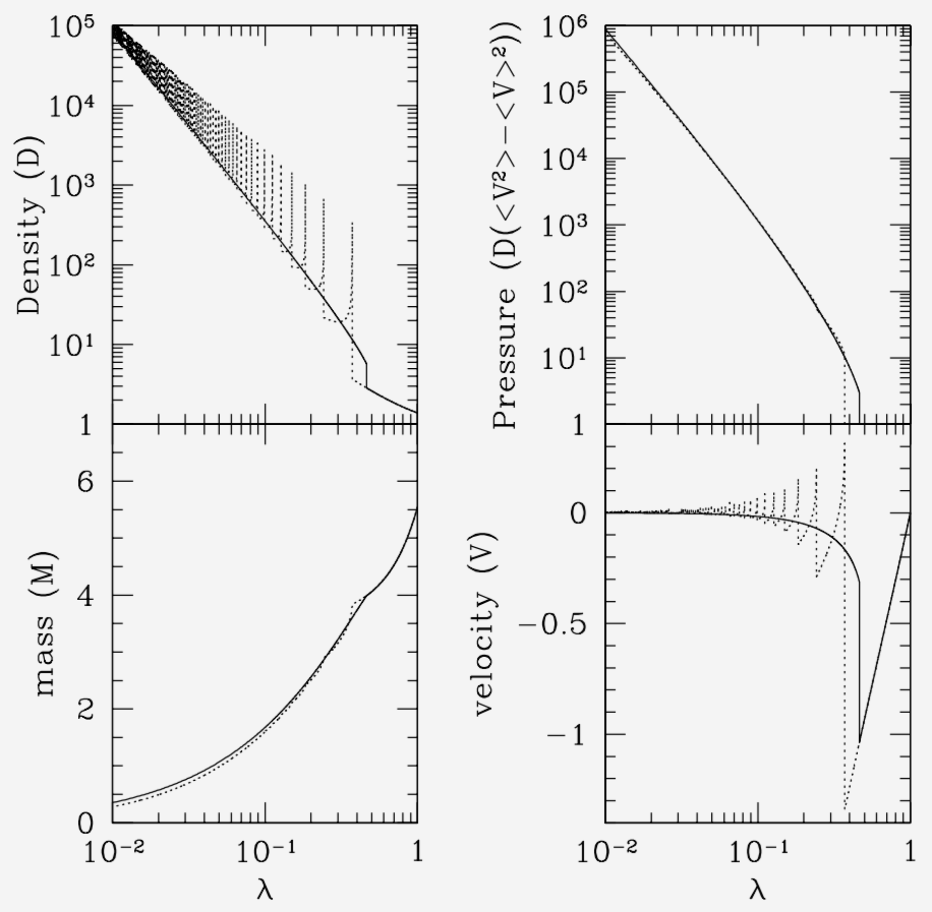
$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial r}\left(p + \rho u^2\right) + \frac{2}{r}\rho u^2 = -\rho \frac{Gm}{r^2}$$

$$\frac{D}{Dt}\left(\frac{3p}{2\rho}\right) = -\frac{p}{\rho}\frac{\partial}{r^2 \partial r}(r^2 u).$$

Methodology

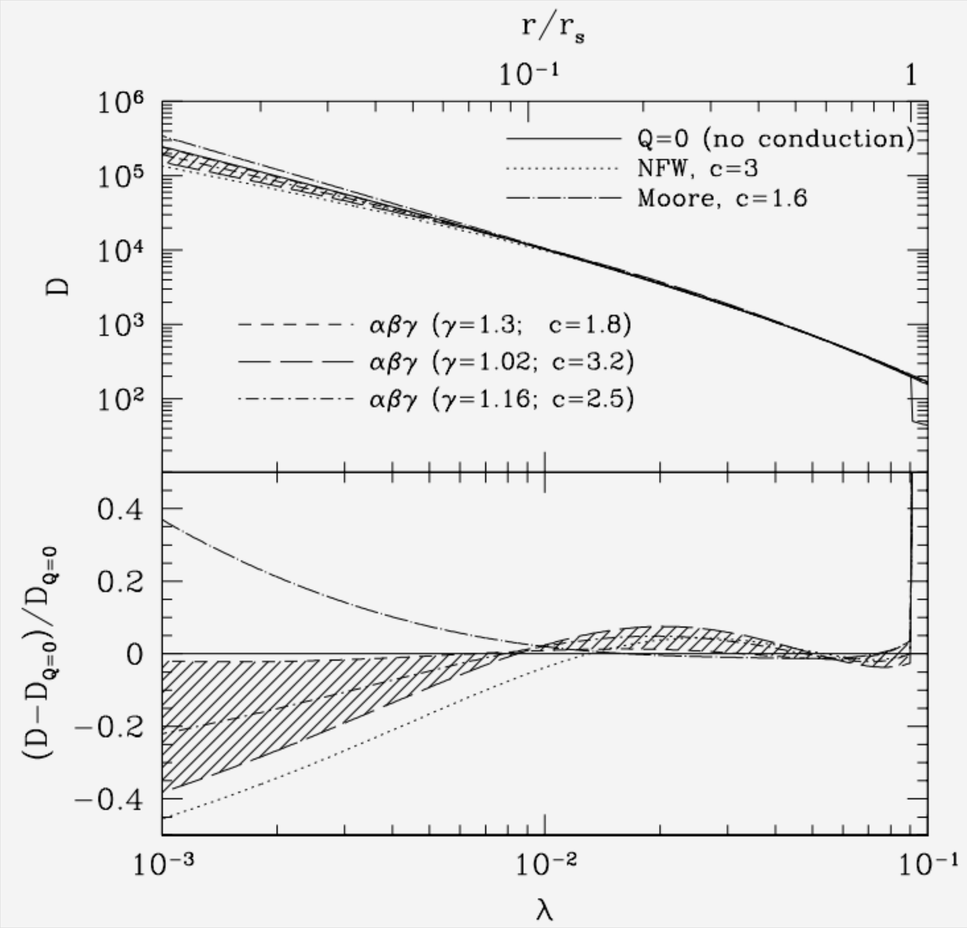
- Is this OK? Test against Bertschinger (1985) solution
  - spherical symmetry
  - radial only dispersion
  - collisionless
  - 되네? 가즈아~





Methodology

- Is this OK? Test against N-body halo structure
  - spherical symmetry
  - isotropic velocity dispersion
  - collisionless
  - 되네? 가즈아~



Summary & Prospect

- SIDM halo
  - impact on small-galactic scale structure (~200 cm^2/g)
  - constraints coming from merging cluster systems (talk by Myungkook)

- 21cm dipole (& quadrupole) spectrum → global 21cm background → WIMP or millicharged?

- Integrated Sachs-Wolfe effect for 21cm → global 21cm background → WIMP or millicharged?