

Title: Dark Sector Theory

Speakers:

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URL: <https://pirsa.org/23060067>

# Dark Matter

$$\frac{\Omega_{CDM}}{\Omega_m} = 0.84$$

→  
CDM + Baryons

## Outline

1. Evidence for DM
  2. Landscape for particle DM
  3. WIMPs
  4. Axions
- } know  
} here

# Evidence for DM

Today: DM's existence & properties

- ↳ 1. Rotation Curves
- 2. Bullet Cluster
- 3. CMB

# Prehistory

Zwicky (1930s): virial th<sup>m</sup> to Coma cluster

$$2\langle K \rangle + \langle U \rangle = 0 \Rightarrow \langle v^2 \rangle = \frac{GM}{R}$$
$$\left\langle \frac{1}{2} \sum_i m_i v_i^2 \right\rangle \quad \left\langle -GmMN \left\langle \frac{1}{r} \right\rangle \right\rangle \quad \Bigg| \quad \Rightarrow \quad M \gg M_*$$
$$= \frac{1}{2} Nm \langle v^2 \rangle \quad = -\frac{GmMN}{R}$$

# Rotation Curves (BFGH)

Warmup: planets



$$\frac{1AU v^2}{r} = \frac{GM_{\odot}}{r^2}$$

$$v = \sqrt{\frac{GM_{\odot}}{r}}$$

Determine with

$$G = 4.30091851 \times 10^{-6} (\text{km/s})^2 M_{\odot}^{-1} \text{ kpc}$$

$$\approx (30 \text{ km/s})^2 M_{\odot}^{-1} \text{ AU} \Rightarrow v_{\oplus} \approx 30 \text{ km/s}$$

CAUTION

BE CAREFUL NOT TO TOUCH THE HOT SURFACE OF THE BOARD

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## Units

$$\begin{aligned} 1 \text{ AU} &\approx 8 \text{ light minutes} \\ &= 8 \times 60 \text{ s} \times (3 \times 10^{10} \text{ cm/s}) \\ &\approx 1.5 \times 10^{13} \text{ cm} \end{aligned}$$

$$\begin{aligned} 1 \text{ pc} &= 3 \text{ light years} \\ &\approx 3 \times (\pi \times 10^7 \text{ s}) (3 \times 10^{10} \text{ cm/s}) \\ &\approx 3 \times 10^{18} \text{ cm} \end{aligned}$$

What about Pluto?

$$r = 40 \text{ AU}$$

$$v \approx \frac{v_{\oplus}}{\sqrt{40}} \approx \frac{v_{\oplus}}{2\sqrt{10}} \approx 5 \text{ km/s}$$

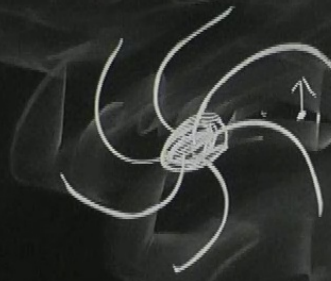
$\Rightarrow$  Keplerian orbit

$$v \propto \frac{1}{\sqrt{r}}$$

Ex: Show from Kepler 3.



# Andromeda

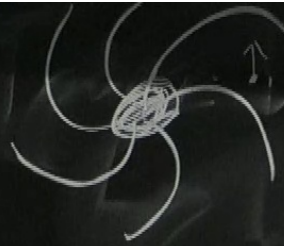


## Properties

- $d = 750 \text{ kpc}$
  - $R = 25 \text{ kpc}$
  - $N_* \approx 10^{11}$
  - Cylindrically sym.
- $\theta = 4^\circ$   
 $\theta_{\text{sun}} = 0.5^\circ$

CAUTION  
NO BARRIERS TO CROSS THE BARRIERS BEING  
MOVED AWAY IN THE DIRECTION OF THE BARRIERS  
IF YOU ENCOUNTER THE BARRIERS  
PLEASE CONTACT A STAFF MEMBER IMMEDIATELY





$$\begin{aligned} - d &= 750 \text{ kpc} \\ - R &= 25 \text{ kpc} \end{aligned} \left. \begin{array}{l} \theta = 4^\circ \\ \theta_{\text{sun}} = 0.5^\circ \end{array} \right\}$$

$$- N_* \approx 10^{11}$$

- Cylindrically sym.

Scale:  $r \approx 40 \text{ kpc}$

$$v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{4 \times 10^6 \times 10^{11}}{40}} \text{ km/s}$$

$$\approx 100 \text{ km/s}$$

OBS:

$$\Sigma_*(r) = \frac{M_* a^2}{2\pi} e^{-ar}$$

$$a^{-1} = 5.3 \text{ kpc}$$

Surface density of stars

$$[\text{Ms/kpc}^2]$$

From Poisson Eq<sup>n</sup> ( $\nabla^2 \Phi = 4\pi G \rho$ )

$$v^2(r) = \frac{1}{2} G M_* a^2 \left[ I_0(x) K_0(x) - I_1(x) K_1(x) \right]_{x=r/a}^{x=a}$$

CAUTION

$$\mu^*(r) = 2\pi a^{-1} \cdot 5 \text{ kpc}$$

Surface density of stars

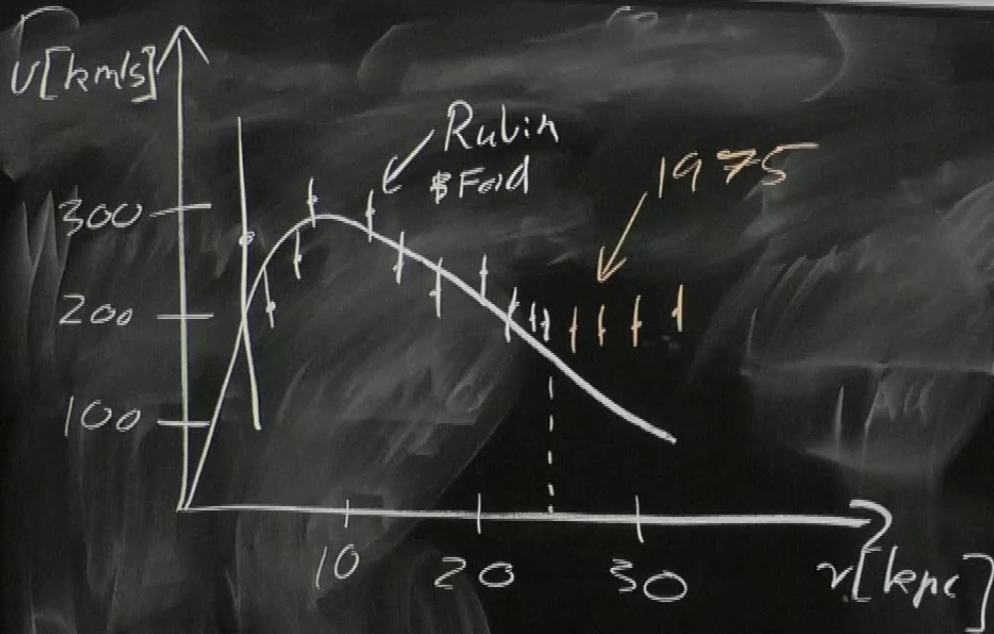
$$[\text{Ms/kpc}^2]$$

From Poisson Eq<sup>n</sup> ( $\nabla^2 \Phi = 4\pi G\rho$ )

$$v^2(r) = \frac{1}{2} G M_{\star} r^2 a^3 \left[ I_0(x) K_0(x) - I_1(x) K_1(x) \right] \quad x = ar/2$$

Ex: Show that  $\uparrow$  becomes

$$v^2 = \frac{GM}{r} \quad @ \quad r \gg a^{-1}, \quad \text{At what radius is that a good approx}$$



How to get  $v \propto \text{const.}$

$$\rho(r) \propto \frac{1}{r^2}$$

$$v^2 = \frac{GM_{\text{enc}}(r)}{r}$$

$$\propto \frac{1}{r} \int_0^r dv' \rho(r')$$

$$\propto \frac{1}{r} \int_0^r dr' r'^2 \frac{1}{r'^2}$$

$$\propto \text{const.}$$

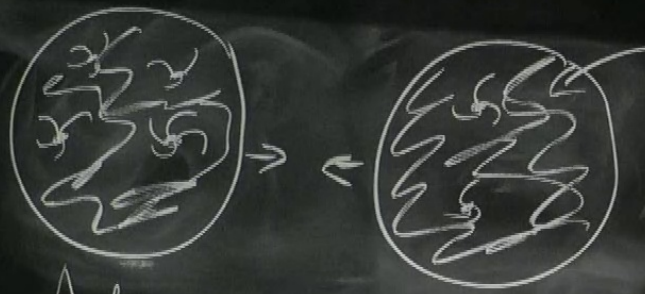
$$\rho(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}$$

Ex:  $M_{DM} = 10^{12} M_\odot$  &  $r_s = 35 \text{ kpc}$  what is  $v_{DM}^2(r)$  out to 200 kpc

If  $M_* = 10^{11} M_\odot$  &  $a = 5.3 \text{ kpc}$ , what is  $v^2$  from disk + DM?

Which dominates @ 8 kpc?

Dulles Cluster (200 Mpc)



gas

$$M \sim 10^{14} M_{\odot} \leftarrow \text{total}$$

$$r \sim \text{Mpc}$$

After



matter lensing

X-ray

$v$  [km/s]

300

200

100

CAUTION  
DO NOT TOUCH THE BOARD WHEN IT IS HOT  
OR IN IMMEDIATE PROXIMITY  
OF THE BOARD WHEN IT IS HOT

DM  $\approx$  collisionless

$$N_x G_{xx} < \pi r_{\text{halo}}^2$$

$\uparrow$

$$\frac{M_{\text{halo}}}{m_x} \Rightarrow \frac{G_{xx}}{m_x} < \frac{\pi r_{\text{halo}}^2}{M_{\text{halo}}}$$
$$= \frac{\pi (3 \times 10^{24} \text{ cm})^2}{2 \times 10^{48} \text{ g}}$$
$$\approx 15 \text{ cm}^2/\text{g}$$

Detailed analysis

$$\frac{G}{m} < 1 \text{ cm}^2/\text{g}$$

Ex: what is this bound  
if  $m_x = 1 \text{ GeV}$ ?

Is it a strong bound?