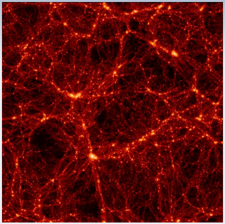

Determination of the local Dark Matter density in our Galaxy

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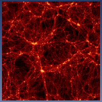
8th June 2010

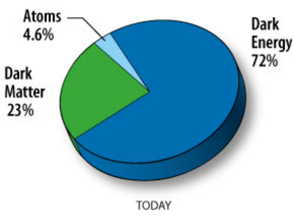
Karlsruhe Institute of Technology



Outline

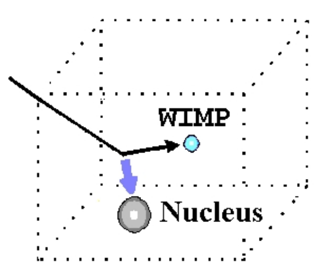
Why is the local DM density important?

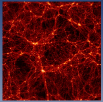
- DM content of the Universe $\approx$ 23 %
- Nature of DM unknown
- weakly interacting, massive particle (WIMP) well-motivated DM candidate



Why is the local DM density important?

- important for direct search for DM
  → counting rate depends on local DM density

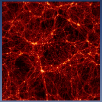




How can the local DM density be estimated?

- velocities of stars and gas $\propto$ gravitational potential $\propto$ total matter density
- measurement of velocities strongly depends on the standard frame of rest
- rotation velocity defines the mass inside the orbit (if halo spherical)
- assume circular rotation:

$$\frac{v^2}{r} = G \cdot \frac{M}{r^2} = \frac{G}{r^2} \cdot \int_0^r \rho(r) dr'$$



Visible matter density

Galactic bulge

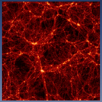
$$\rho_b(r,z) = \rho_{b,0} \cdot \left(\frac{\tilde{r}}{r_{0,b}}\right)^{-\gamma_b} \cdot \left(1 + \frac{\tilde{r}}{r_{0,b}}\right)^{\gamma_b - \beta_b} \exp\left(-\frac{\tilde{r}^2}{r_t^2}\right)$$

$$\tilde{r}^2 = \sqrt{x^2 + y^2 + (z/q_b)^2}$$

Visible matter density

Galactic disc (exponential decrease)

$$\rho_d(r, z) = \rho_{d,0} \cdot exp(-r/r_d) \cdot exp(-z/z_d)$$



Dark Matter Density

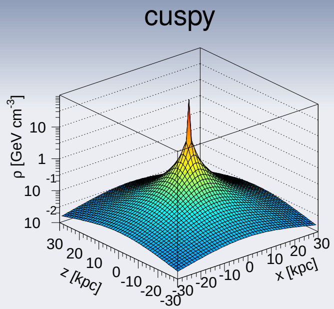
DM halo profile

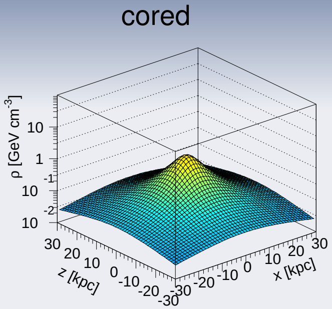
$$\rho_\chi(r) = \rho_{\odot,\mathrm{DM}} \cdot \left(\frac{\tilde{r}}{r_\odot}\right)^{-\gamma} \cdot \left[\frac{1 + \left(\frac{\tilde{r}}{a}\right)^{\alpha}}{1 + \left(\frac{r_\odot}{a}\right)^{\alpha}}\right]^{\frac{\gamma-\beta}{\alpha}}$$

$$\tilde{r} = \sqrt{x^2 + \frac{y^2}{\epsilon_{xy}^2} + \frac{z^2}{\epsilon_z^2}}$$

- $\rho_\chi(r) \propto r^{-\gamma}$ $(r \ll a) \rightarrow$ galactic centre
- $\rho_\chi(r) \propto r^{-\alpha}$ $(r \approx a)$
- $\rho_\chi(r) \propto r^{-\beta}$ $(r \gg a) \rightarrow$ outer galaxy

Dark Matter Density





Profile	α	β	γ	a [kpc]
NFW	1.0	3.0	1.0	20.0
PISO	2.0	2.0	0.0	5.0

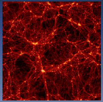
Astronomical constraints

- Total matter density at the Sun
- Local rotation velocity
- Velocity distribution in the Galactic disc
- Surface density at the Sun
- Mass within 60 kpc
- Height of the interstellar gas

Total matter density at the Sun

$$\begin{aligned} \rho_{\odot,\mathrm{tot}} &= \rho_{\odot,\mathrm{vis}} + \rho_{\odot,\mathrm{DM}} \\ &\approx 0.09 + 0.01\ \mathrm{M_\odot\ pc^{-3}} \\ &= 0.102 \pm 0.01\ \mathrm{M_\odot\ pc^{-3}} \end{aligned}$$

- so-called “Oort limit”
- from vertical motion of stars (*Holmberg & Flynn (2004)* [0405155])



Rotation velocity at the Sun

$$\frac{v_\odot}{r_\odot} = 29.45 \pm 0.15 \text{ km s}^{-1} \text{ kpc}^{-1}$$

- obtained from the observation of Sgr* A
  $\longrightarrow$ probably the centre of the MW (*Reid & Brunthaler (2004)* [0808.2870])

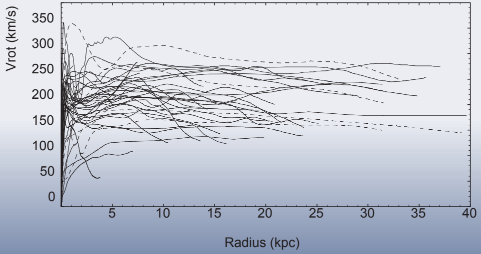
$$r_\odot = 8.33 \pm 0.35 \text{ kpc}$$

- obtained from the motion of stars around Sgr* A $\longrightarrow$ *Reid & Brunthaler (2004)* [0808.2870]

$$v_\odot = 244 \pm 10.2 \text{ km s}^{-1}$$

Rotation curves

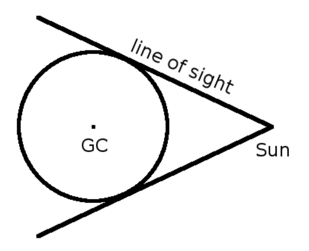
- velocities of interstellar gas and stars are important tracers for the gravitational potential of the galaxy
- measurement of the redshift of stars, atomic hydrogen and carbon monxide in the galactic disc

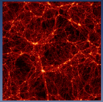


Inner rotation curve of the Milky Way

Tangent point method

- assuming that gas rotates on circular orbit
- line-of-sight tangential to gas orbit
- measurement of the redshift $\rightarrow v_{rot}$





Outer rotation curve of the Milky Way

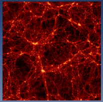
Merrifield method

- no tangent point to rotation orbit
- assuming that gas rotates on circular orbit

$$\frac{v_{los}}{\sin(l)\cos(b)} = \frac{r}{r_\odot} v(r) - v_\odot = constant$$

- how to find galactocentric distance
- height of interstellar gas $\propto$ galactocentric distance

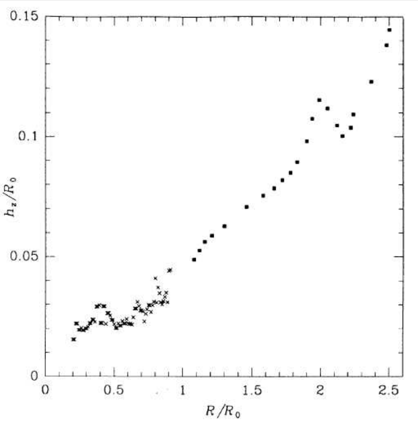
$$h_b = 2\arctan\left(\frac{h_z/2r_\odot}{\cos(l) + \sqrt{(r/r_\odot)^2 - \sin^2(l)}}\right)$$



Outer rotation curve of the Milky Way

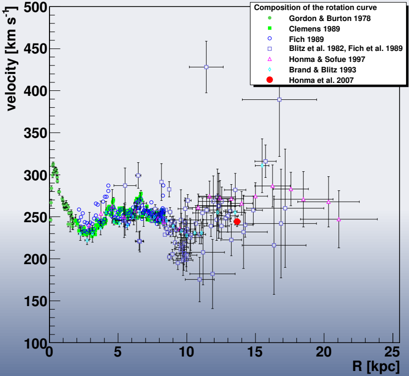
Merrifield method

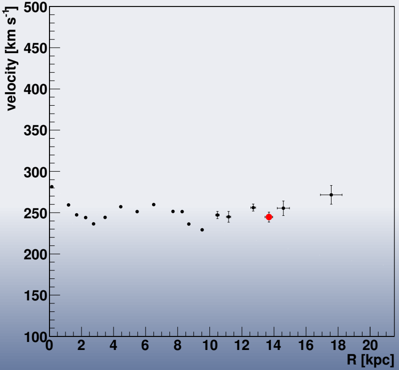
- need results from gas survey
- fit $h_z/r_\odot(r/r_\odot)$
- measuring the height h_z instead of the distance r



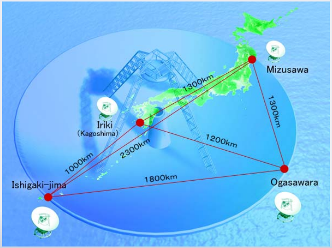
Rotation curve of the Milky Way

- 8 independent data sets
- measurements averaged in 18 radial bins



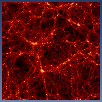


Rotation curve of the Milky Way



Maser interferometry

- VLBI = Very Long Baseline Interferometry
- Measurement of the distance to an H_2O maser sources for a long time $\longrightarrow$ accurate distance and velocity
- strong constraint for outer rotation curve



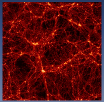
Surface density at the Sun

$$
\begin{aligned}
\Sigma\left(|z| < 1.1\ \mathrm{kpc}\right) &= \int\limits_{-1.1\mathrm{kpc}}^{1.1\mathrm{kpc}} \rho(z')\, dz' \\
&= \frac{1}{2\pi G} \cdot \int\limits_{0}^{1.1\mathrm{kpc}} \Delta\Phi(r,\varphi,z')\, dz' \qquad (\Delta\Phi = 4\pi G\rho(r)) \\
&= \frac{1}{2\pi G} \cdot \int\limits_{0}^{1.1\mathrm{kpc}} \left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Phi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2\Phi}{\partial\varphi^2} + \frac{\partial^2\Phi}{\partial z'^2}\right) dz' \\
&= \frac{1}{2\pi G} \cdot \left[\frac{\partial\Phi}{\partial z} + \int\limits_{0}^{1.1\mathrm{kpc}} \left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Phi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2\Phi}{\partial\varphi^2}\right) dz'\right] \\
&\approx \frac{1}{2\pi G} \cdot \left(\frac{\partial\Phi}{\partial z}\right) \quad \text{(if RC is flat)}
\end{aligned}
$$

Surface density: Visible matter

- counting experiments of visible objects in the vicinity of the Sun ($\approx$ 200 pc)
- used to constrain the contribution of luminous matter at the Sun

Contribution	Surface density [$M_\odot$ pc^{-2}]	Reference
Visible stars	35 ± 5	*Gilmore et al. (1989)*
	27	*Gould (1995)*
	30	*Zheng et al. (2001)*
Stellar remnants	3 ± 1	*Mera (1998)*
Interstellar gas	8 ± 5	*Dame (1993)*
	13 - 14	*Olling et al. (2001)*
Σ_{vis}	35-58	

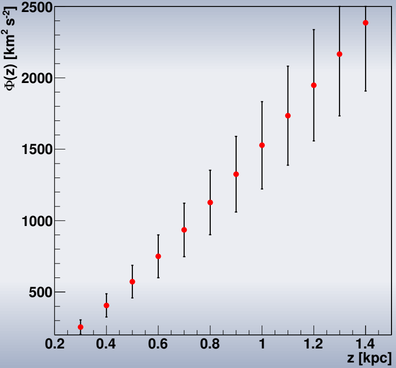


Total surface density

- determined from the vertical motion of gas and stars

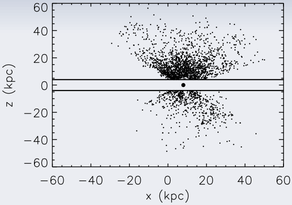
$$\Sigma(z < 1.1\text{kpc}) = 74 \pm 6\ M_{\odot}\text{pc}^{-2}$$

(Holmberg & Flynn (2004) [0405155])



Mass within 60 kpc

- Sloan Digital Sky Survey (SDSS)
- observation of about 2400 halo stars
- $|z| > 4$ kpc
- circular rotation curve
- $M(60\text{ kpc}) = 4.0 \pm 0.7 \cdot 10^{11}\ \mathrm{M}_\odot$

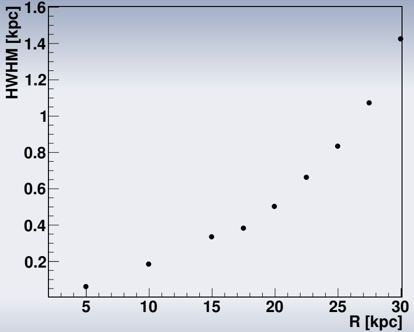


(Xue et al. () [0801.1232])

Gas flaring

$$f(z) = \rho_0 \cdot \exp\left(-\frac{\Phi(z)}{\sigma^2}\right)$$

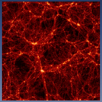
- ρ_0 = density at the Galactic disc
- σ = velocity dispersion of the gas
- gas flaring needs DM component in the Galactic disc



(Kalberla et al. (2007) [0704.3925])

Parameters:

Free Parameters				
	Parameter	Symbol	Value	Unit
Halo	Local DM density	$\rho_{\odot,\mathrm{DM}}$	-	GeV/cm^{-3}
Halo	Scale Parameter	a	-	kpc
Disc	Density at GC	$\rho_{\mathrm{d},0}$	-	GeV cm^{-3}
Disc	scale length	r_{d}	-	kpc
Constraints				
All	Mass inside 60 kpc	$M_{\mathrm{R<60kpc}}$	4.0 ± 0.7	10^{11} $M_\odot$
Local	Rotation speed Sun	$v_\odot$	244± 10	km s^{-1}
Local	Total Surface Density	$\Sigma_{\lvert z\rvert<1.1}$	71 ± 6	$M_\odot$ pc^{-2}
Local	Visible Surface Density	Σ_{vis}	48 ± 9	$M_\odot$ pc^{-2}
Local	Mass Density	ρ_{tot}	0.102 ± 0.01	$M_\odot$ pc^{-3}



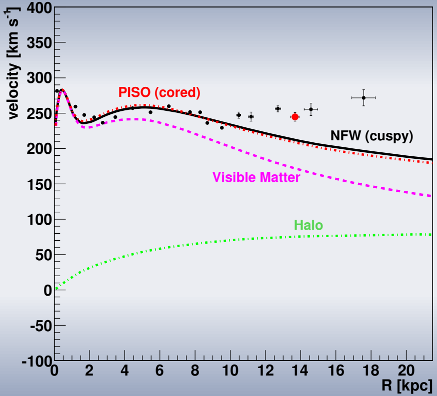
χ^2 function

$$\chi^2 = \sum \frac{(x - \bar{x})^2}{\sigma^2}$$

- minimization using MINUIT
- large correlation between visible and dark matter density

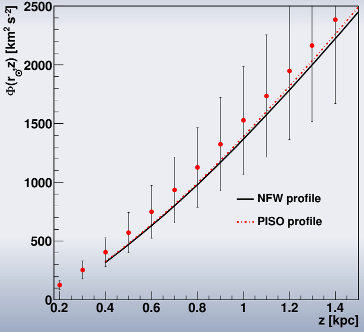
Rotation curve of the Milky Way

- density distribution at the Galactic centre dominated by the visible matter
- good description at the inner galaxy
- poor description at the outer galaxy

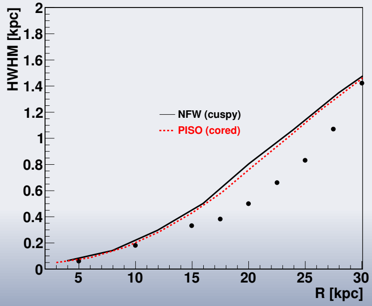


Potential & gas flaring

vertical potential

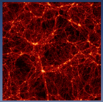


gas flaring

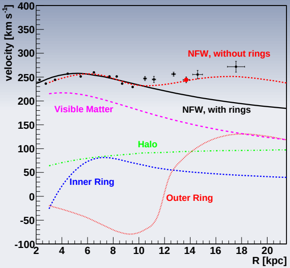


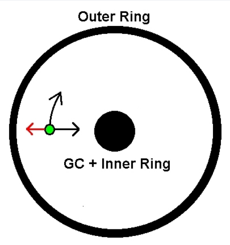
Result

- $\rho_{\odot,\mathrm{DM}} = 0.3 \pm 0.1$ GeV cm^{-3}
  $\rightarrow$ in agreement with Salucci et al. (2010) ([1003.3101])
- flattened halo ($\epsilon_z = 0.7$) $\rightarrow \rho_{\odot,\mathrm{DM}} \approx 0.7$ GeV cm^{-3}
- large uncertainty because of uncertain determination of local visible matter
- vertical gravitational potential well described
- outer rotation curve ↯
- height of the interstellar gas distribution ↯
- minimization with Markov Chain algorithms yield more accurate local density ([arXiv:0907.0018])
  $\rightarrow \rho_{\odot,\mathrm{DM}} = 0.389 \pm 0.025$ GeV cm^{-3}
  $\rightarrow$ unknown reason for discrepancy so far



Rotation curve of the Milky Way



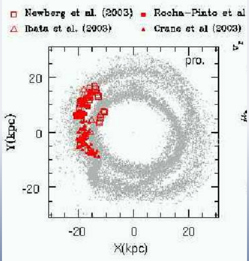


- introduction of 2 DM rings describes change of slope at $r \approx 10$ kpc
- inner ring at r ≈ 4 kpc
  $\longrightarrow$ ring of gas and dust
- outer ring at r ≈ 13 kpc
  $\longrightarrow$ ghostly ring of stars (Monoceros ring)

$\Rightarrow \rho_{\odot,\mathrm{DM}} \lesssim 1.0\ \mathrm{GeV\ cm}^{-3}$

Rotation curve of the Milky Way

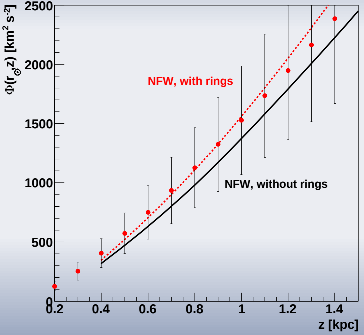
- DM rings expected from infall of dwarf galaxies
  → dwarf galaxies are disrupted by tidal forces
  → circular tidal streams are formed
- rings could be part of a dark disc of the MW



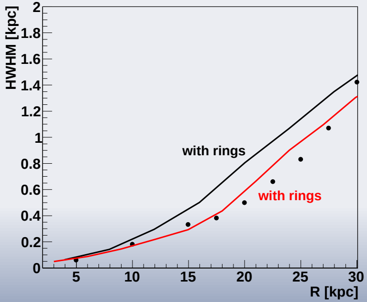
(Penarrubia et al. (2004) [0410448]

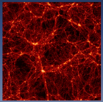
Potential & gas flaring

vertical potential

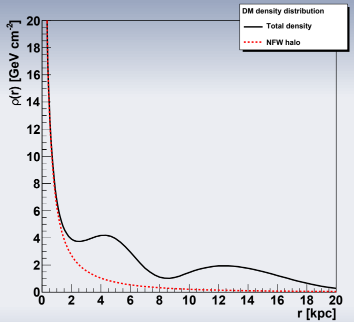


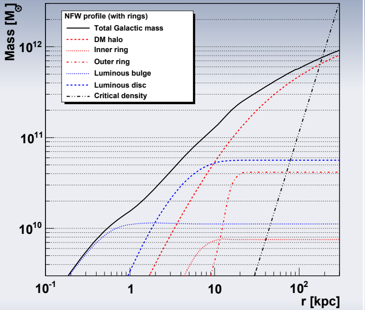
gas flaring



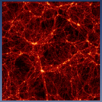


Density and Mass profile





- Total mass of the Galaxy $M_{tot} \approx 8 \cdot 10^{11}\ M_\odot$
- Ring masses: $M_{IR} = 7.5 \cdot 10^9\ M_\odot$, $M_{OR} = 4 \cdot 10^{10}\ M_\odot$
- Ring masses about 5% of total mass

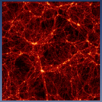


Summary

1. Rotation curve, surface density and height of the interstellar gas determine gravitational potential
2. Rotation curve shows change of slope at about 10 kpc
3. $\rho_{\odot,\mathrm{DM}}$ = 0.3 ± 0.1 GeV cm^{-3}
   (oblate halo → 0.7 GeV cm^{-3})
   (*Weber & de Boer (2009)* [0910.4272])
4. Ringlike DM substructure in the disc explains rotation curve & height of the Galactic gas distribution
5. DM rings consistent with surface density at the Sun
6. $\rho_{\odot,\mathrm{DM}}$ up to 1.0 GeV cm^{-3}

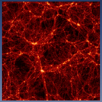
Thank you!

BACKUP



Direct search

- cross section $\propto A^2$
  $\rightarrow$ heavy nuclei
- recoil energy $\approx$ keV
- annual modulation of the signal
- counting rate: 1-10 events / kg / year



Oort constants (A and B)

- most precise determination

$$A \equiv -\frac{1}{2}\left[\frac{\partial v_\varphi}{\partial r} - \frac{v_\varphi}{r} + \frac{1}{r}\frac{\partial v_r}{\partial \varphi}\right]_{r=r_\odot}$$

$$B \equiv -\frac{1}{2}\left[\frac{\partial v_\varphi}{\partial r} + \frac{v_\odot}{r_\odot} - \frac{1}{r}\frac{\partial v_r}{\partial \varphi}\right]_{r=r_\odot}$$

- A describes azimuthal shear
- B describes local vorticity

Oort constants (C and K)

- most precise determination

$$
\begin{aligned}
C &\equiv -\frac{1}{2}\left[\frac{v_r}{r} - \frac{\partial v_r}{\partial r} + \frac{1}{r}\frac{\partial v_\varphi}{\partial \varphi}\right]_{r=r_\odot} \\
K &\equiv -\frac{1}{2}\left[-\frac{v_r}{r} - \frac{\partial v_r}{\partial r} - \frac{1}{r}\frac{\partial v_\varphi}{\partial \varphi}\right]_{r=r_\odot}
\end{aligned}
$$

- C describes radial shear
- K describes local divergence