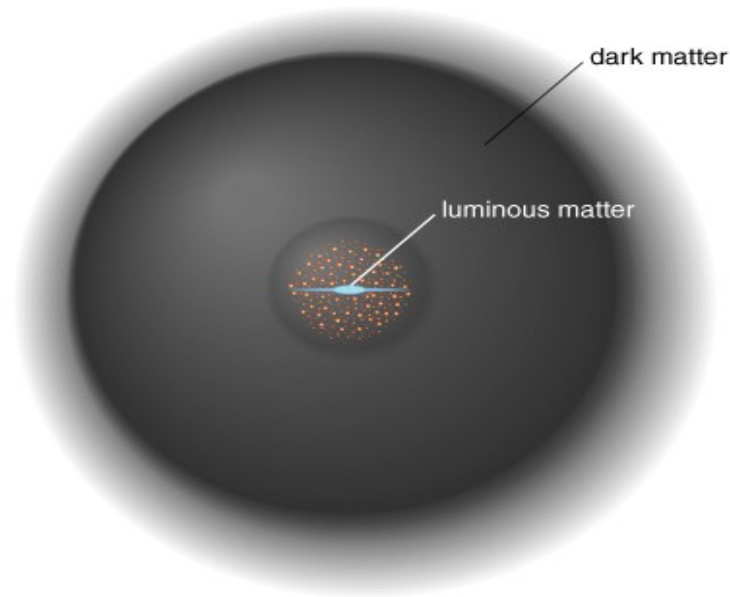


DIRECT DETECTION OF DARK MATTER



© Addison-Wesley Longman

Soumini Chaudhury
SINP, Kolkata

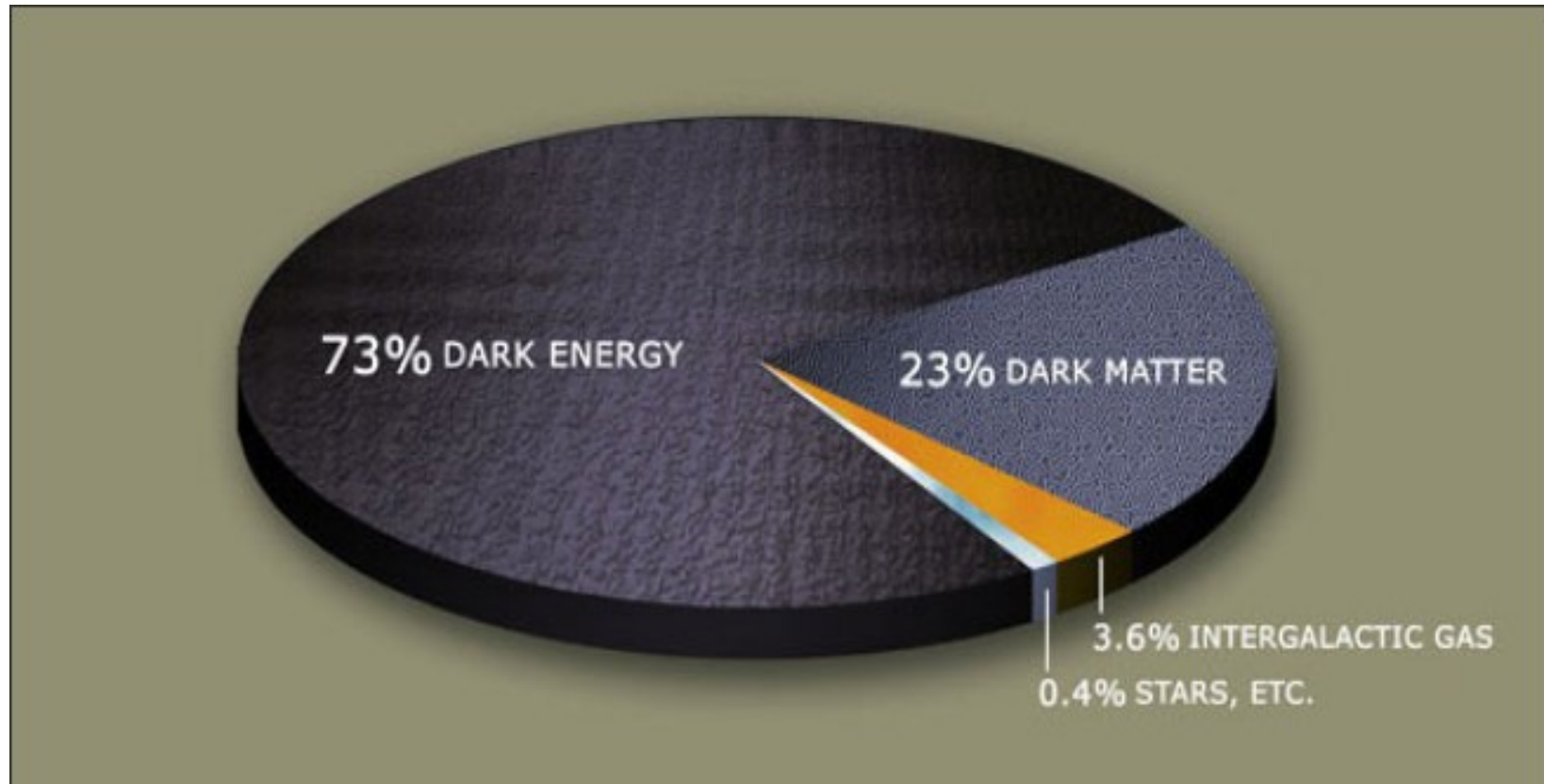
PLAN OF THE TALK

- INTRODUCTION TO DARK MATTER (DM)..
- A PROBABLE MODEL FOR DISTRIBUTION FUNCTION (DF) OF DM
- IMPLICATION FOR DETECTION EXPERIMENTS

introduction

DARK MATTER; DIRECT DETECTION

COMPOSITION OF THE UNIVERSE



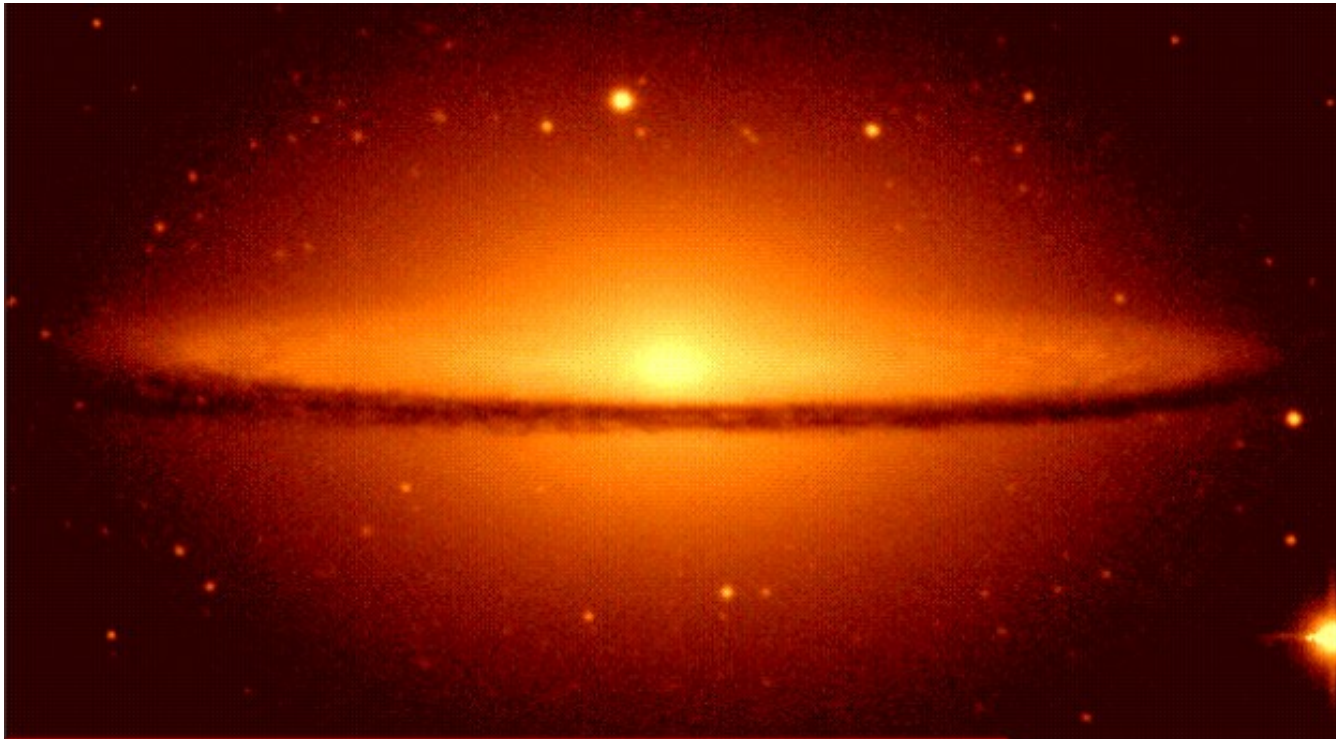
DARK MATTER; DIRECT DETECTION

COSMOLOGICAL SCALE TO GALACTIC SCALE

DARK MATTER; DIRECT DETECTION

TYPICAL MILKY WAY TYPE GALAXY

- Houses about 10^{11} stars.
- We are located at approx 8-8.5 kpc from the centre.

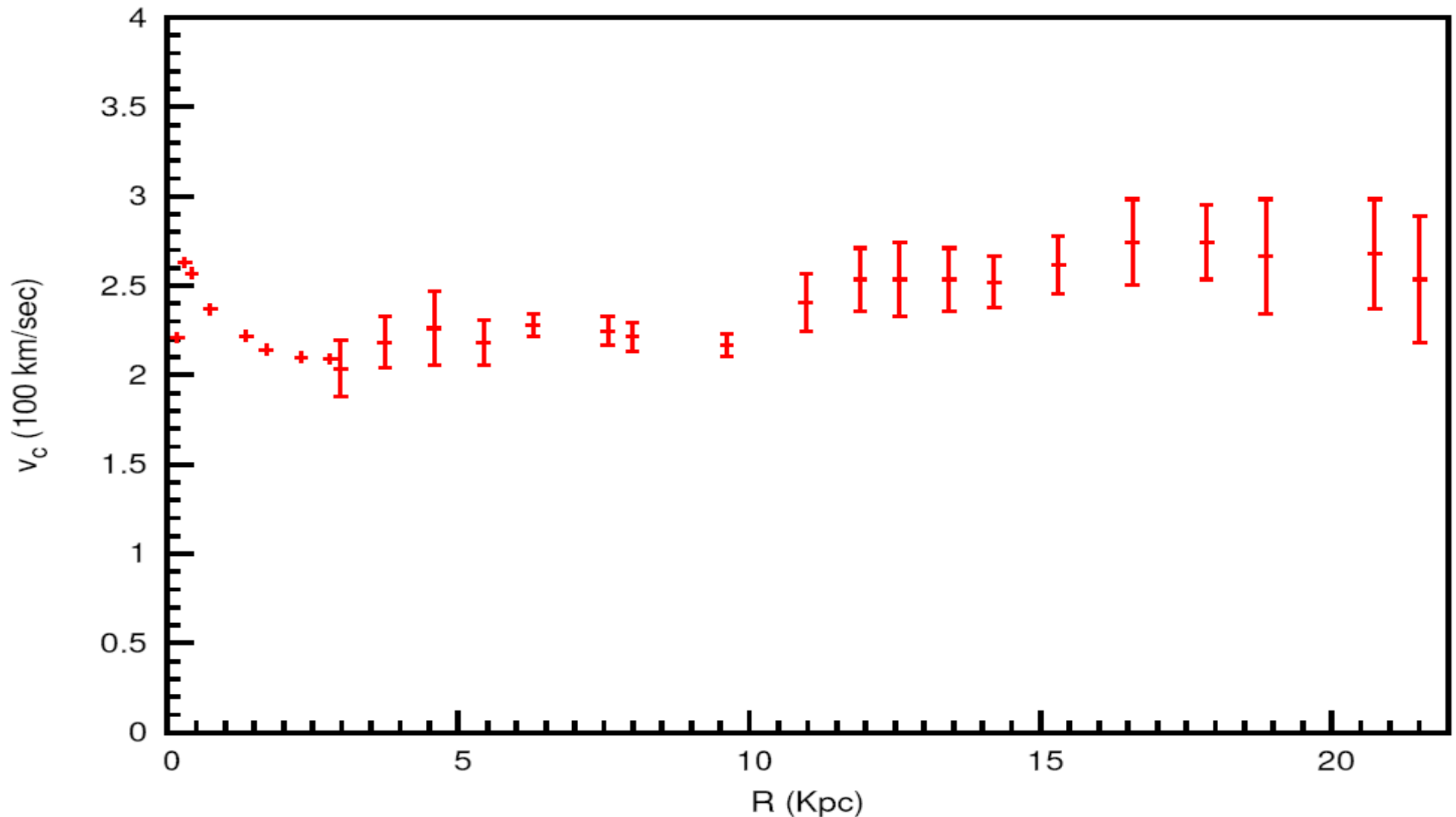


DARK MATTER; DIRECT DETECTION

ROTATION VELOCITY DATA

M. Honma and Y. Sofue, PASJ 49 (1997) 453.

standard: ($r_{\text{sn}} = 8.5$ kpc, $v_{\text{sn}} = 220$ km/sec)



VM COMPONENTS

- Central bulge:

$$\rho_b(r) = \rho_0 \left(1 + \frac{r^2}{a^2} \right)^{-3/2}$$

- Exponential disk:

$$\rho_d(R, z) = \frac{\Sigma}{2h} e^{-\frac{R-R_0}{R_d}} e^{-\frac{|z|}{h}}$$

Contribution From Visible Matter- (Bulge+Disk)

- Density profiles known from constant mass-luminosity ratio.

$$\rho_{VM} = \rho_{Bulge} + \rho_{Disk}$$

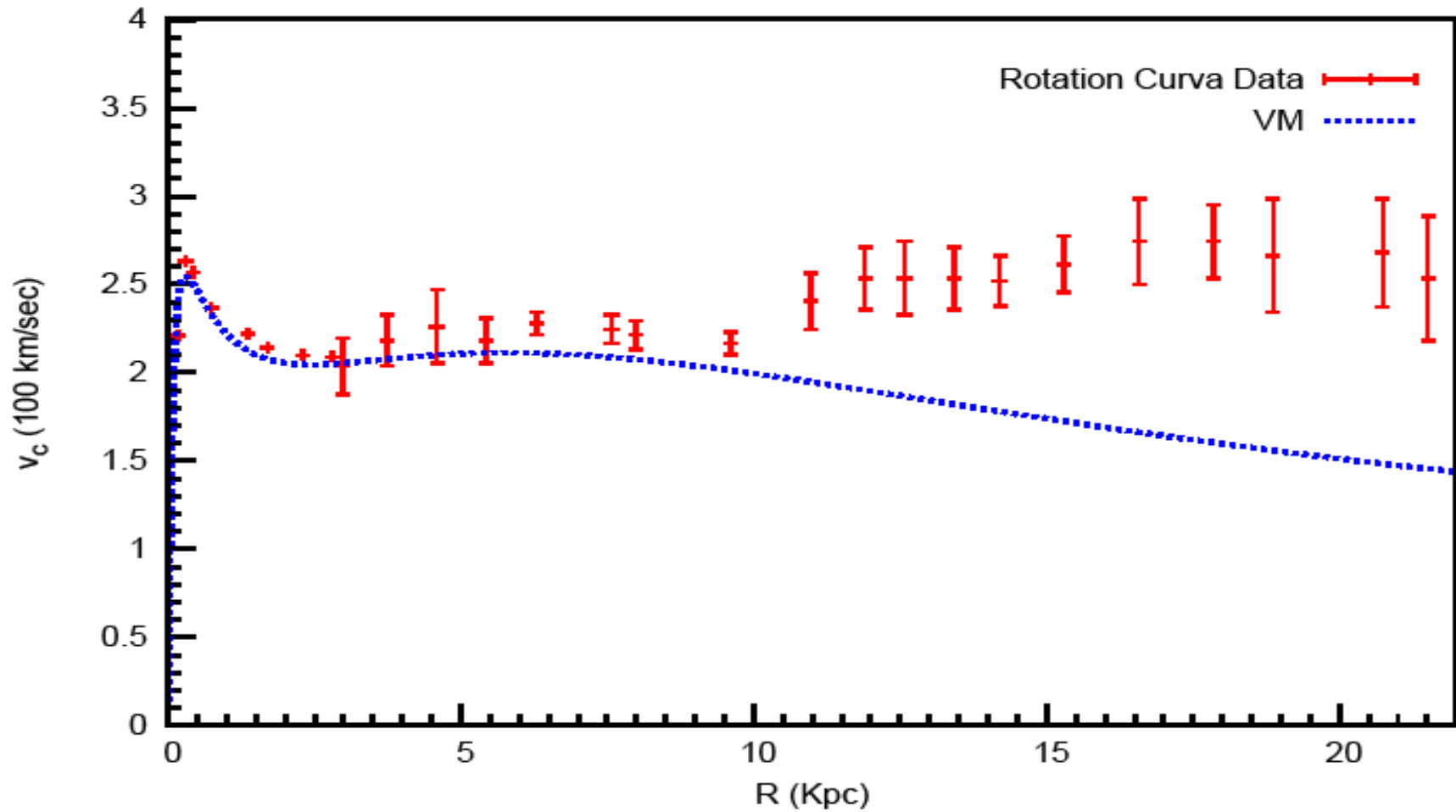
- Solving Poisson's equation.

$$\nabla^2 \Phi_{VM} = 4\pi G \rho_{VM}$$

- Rotation velocity(r) follows from

$$v_c(R) = \sqrt{-R \nabla \Phi(R, z)_{(z=0)}}$$

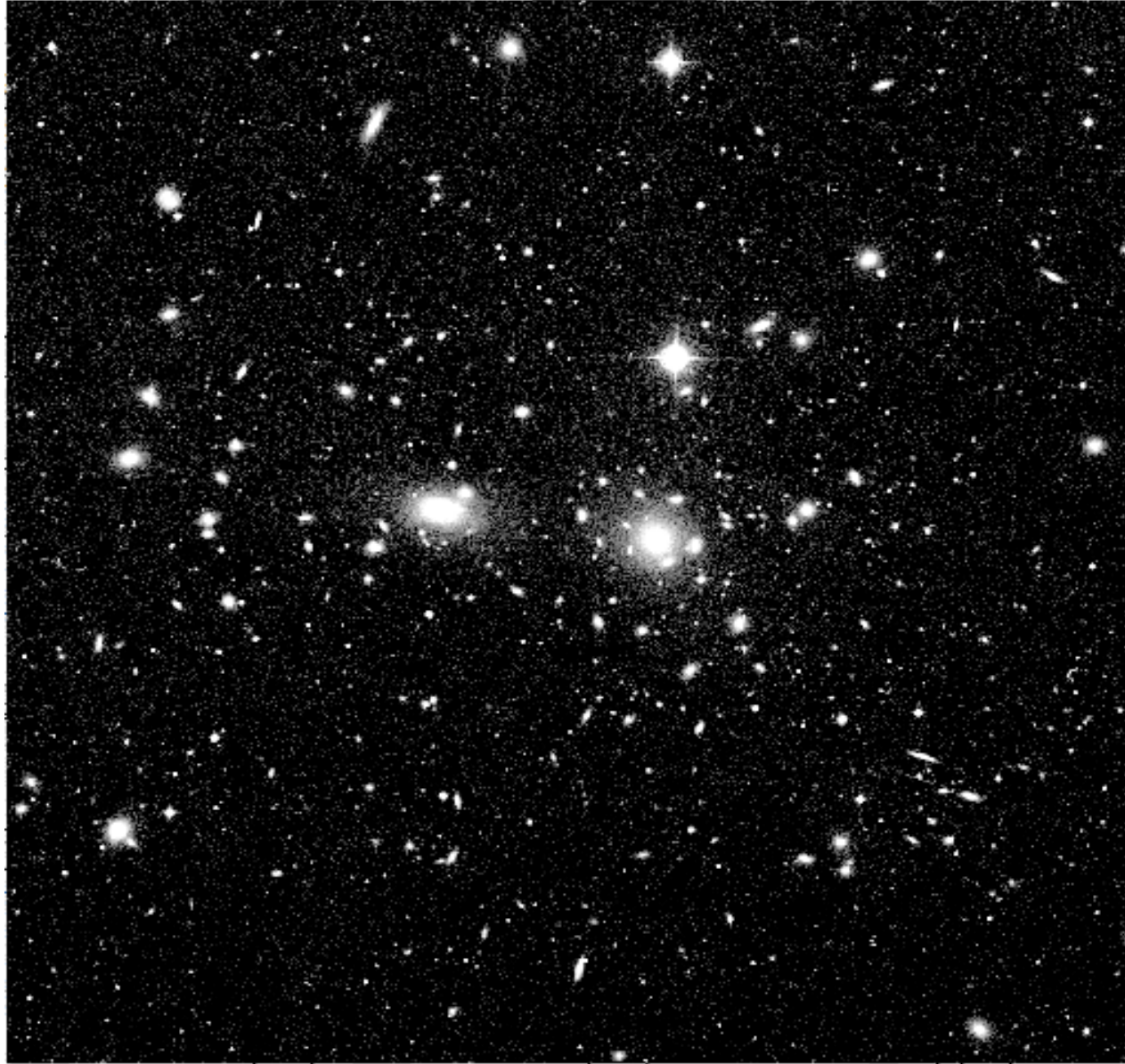
WITH VM ONLY



NEED SOME DARK MATTER!

FIRST EVIDENCE

C
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ZWICKY'S WORK

- F.Zwicky in 1933 measured the dispersions (1019 \pm 360 km/sec) of 7 galaxies of coma cluster and estimated total dynamic mass of the cluster by virial theorem.

$$2 \langle T \rangle = - \langle V \rangle \qquad \langle v^2 \rangle = \frac{GM_{tot}}{r_g}$$

- Estimated the Mass with the mass to Light ratio of nearby spirals with luminosity concluded :

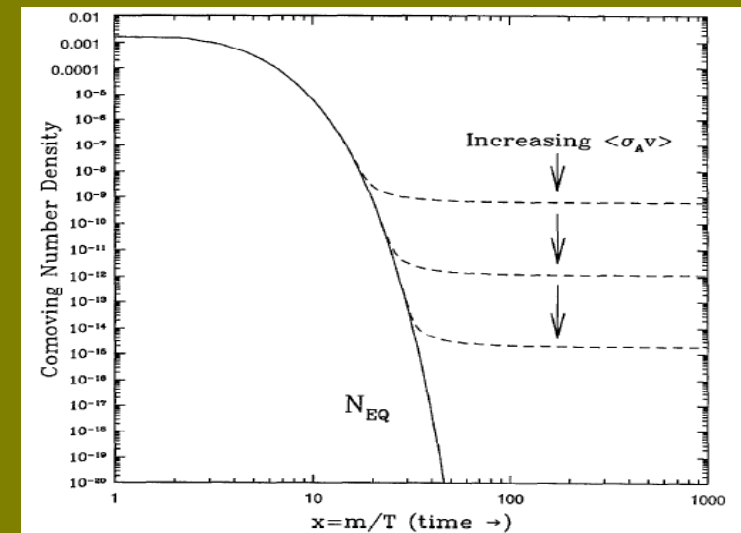
$$M_{tot} \approx 400 \times M_{VisibleMass}$$

- Same conclusion for unaccounted mass was drawn by Smith in 1936 for virgo cluster

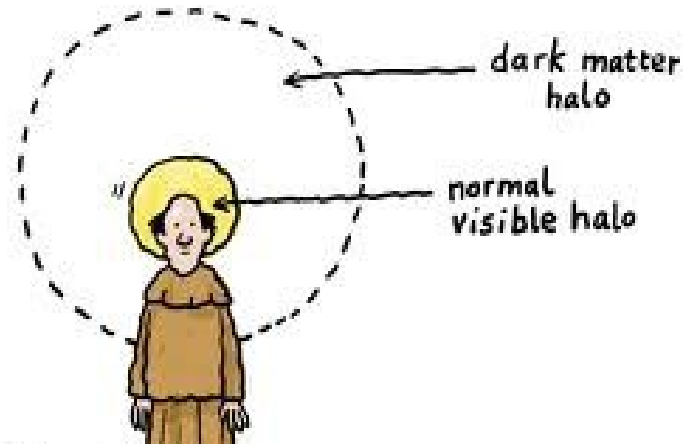
- WIMP (Weakly Interacting Massive Particles)-s are currently the most favoured candidate for DM.
- WIMP-s are candidates at GeV-TeV scale that produce the DM thermal relic density at EW scale.

- Boltzman Equation

$$d n_{\chi} / d t + H n_{\chi} = - \langle \sigma v \rangle [n_{\chi}^2 - n_{eq}^2]$$



- They belong to CDM class. CDM simulations support LSS formation by hierarchical clustering as confined by observations.



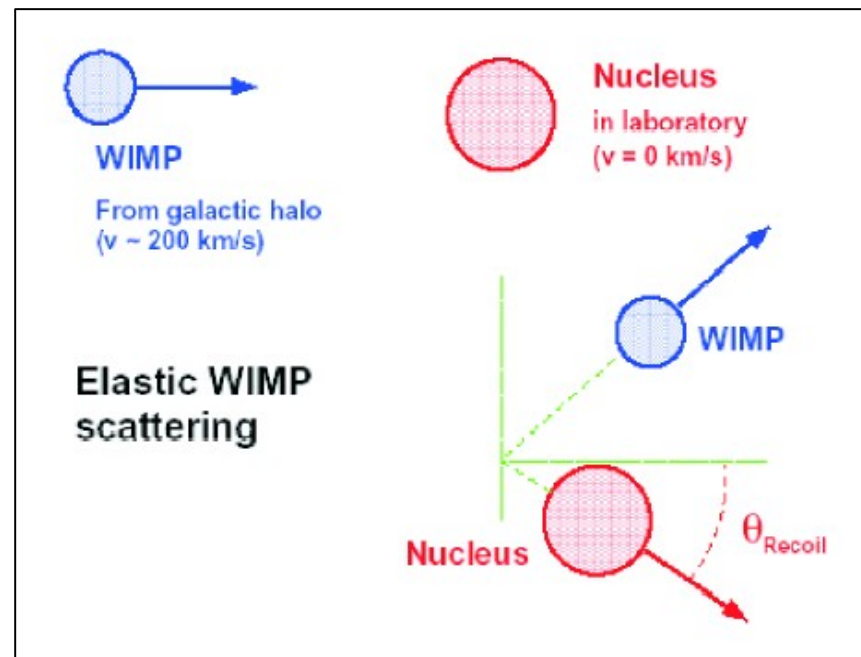
How to detect them on earth?

DARK MATTER; DIRECT DETECTION

DETECTION METHODS

- DIRECT DETECTION**

studying DM-nucleus recoil spectra in deep underground mines to minimise the background radioactivity, cosmic rays etc.



DIFFERENTIAL SPECTRUM

$$\frac{dR(E_R)}{dE_R} = \frac{\sigma_{n\chi}^0 \rho_\chi}{2\mu_{n\chi}^2 m_\chi} [CF^2(E_R)]_{SD/SI} \int_{v_m}^{v_{max}^{earth}} \frac{f_{earth}(\vec{v}, t)}{v} d\vec{v}$$

$$\mu_{n\chi} = \frac{m_\chi m_n}{m_\chi + m_n}$$

$$v_m = \sqrt{\frac{1}{2E_R m_N} \left[\frac{E_R m_N}{\mu_{N\chi}^2} + \delta \right]}$$

m_χ = mass of WIMP

ρ_χ = local density of WIMP

$\delta = m_2 - m_1$: mass splitting

$\sigma_{n\chi}$ = WIMP-nucleon cross section

model dependent inputs : ρ_χ , $f_{earth}(\vec{v}, t)$

The conventional process has been..

- $f(v)$ taken to be Maxwellian
- $\rho_\chi = 0.3 \text{ GeV/cc}$ as proposed by Oort (1937) by observing the local velocity and distribution of stars
- If we want to include the gravitational effect of VM on DM we need to start from the **Distribution Function (DF)** level

.

Distribution Function

$$f(\vec{x}, \vec{v}, t)$$

STANDARD HALO MODEL

- DF with $f(v)$: Maxwellian is the Isothermal DF: $f(E)$
- DF for an isolated self gravitating system
- Few drawbacks-

- Infinite system and $M(r) \sim r$
- $f(v)$ abruptly truncated at a chosen value of v_{esc}
- Recent simulation indicate departure from Maxwellian profile

we proceed as..

- Since DM is very WI so study solutions of Collisionless Boltzmann Equation (CBE) for $f(x,v,t)$.
- It guides the behavior of DF for a conservative system of interacting particles.
- **Jean's Theorem:**
equilibrium solution \longrightarrow $f(\text{integrals of motion ie. } E, L \text{ etc.. of the system})$

A More Realistic Model:

LOWERED ISOTHERMAL OR KING MODEL

LOWERED ISOTHERMAL OR KING MODEL

- DF:

$$f(\vec{x}, \vec{v}) = f(E) = \frac{\rho_1}{(2\pi\sigma^2)^{3/2}} \left[e^{\frac{\psi - \frac{v^2}{2}}{\sigma^2}} - 1 \right]$$

SHM

- Where,

$$\psi = \Phi_0 - \Phi(\vec{r})$$

- Since , $f(E) = 0$ if $E \leq 0$ therefore $v_{max}(\vec{r}) = \sqrt{2\psi(\vec{r})}$

- Parameters: (ρ_1, Φ_0, σ)

DENSITY PROFILE

- Density:

$$\rho(\vec{r}) = \int_0^{v_{max}} f(E) d^3 v$$

$$\rho(\vec{r}) = \rho_1 \left[e^{\frac{\psi}{\sigma^2}} \operatorname{erf} \frac{\sqrt{\psi}}{\sigma} - \sqrt{\frac{4\psi}{\pi\sigma^2}} \left(1 + \frac{2\psi}{3\sigma^2} \right) \right]$$

- $\rho(r) = 0$ at truncation radius (r_t) $\rightarrow \Phi_0 = \Phi(r_t)$
- Changing parameters: $(\rho_1, \Phi_0, \sigma) \rightarrow (\rho_{sun}, r_t, \sigma)$

SOLVING EQUATIONS

$$\nabla^2 \Phi_{VM} = 4\pi G \rho_{VM}$$

$$\nabla^2 \Phi_{DM} = 4\pi G \rho_{DM}$$

$$\Phi_{total} = \Phi_{VM} + \Phi_{DM}$$

COUPLING TO VM

$$v_c(R) = \sqrt{-R \nabla \Phi_{total}(R, z)_{(z=0)}}$$

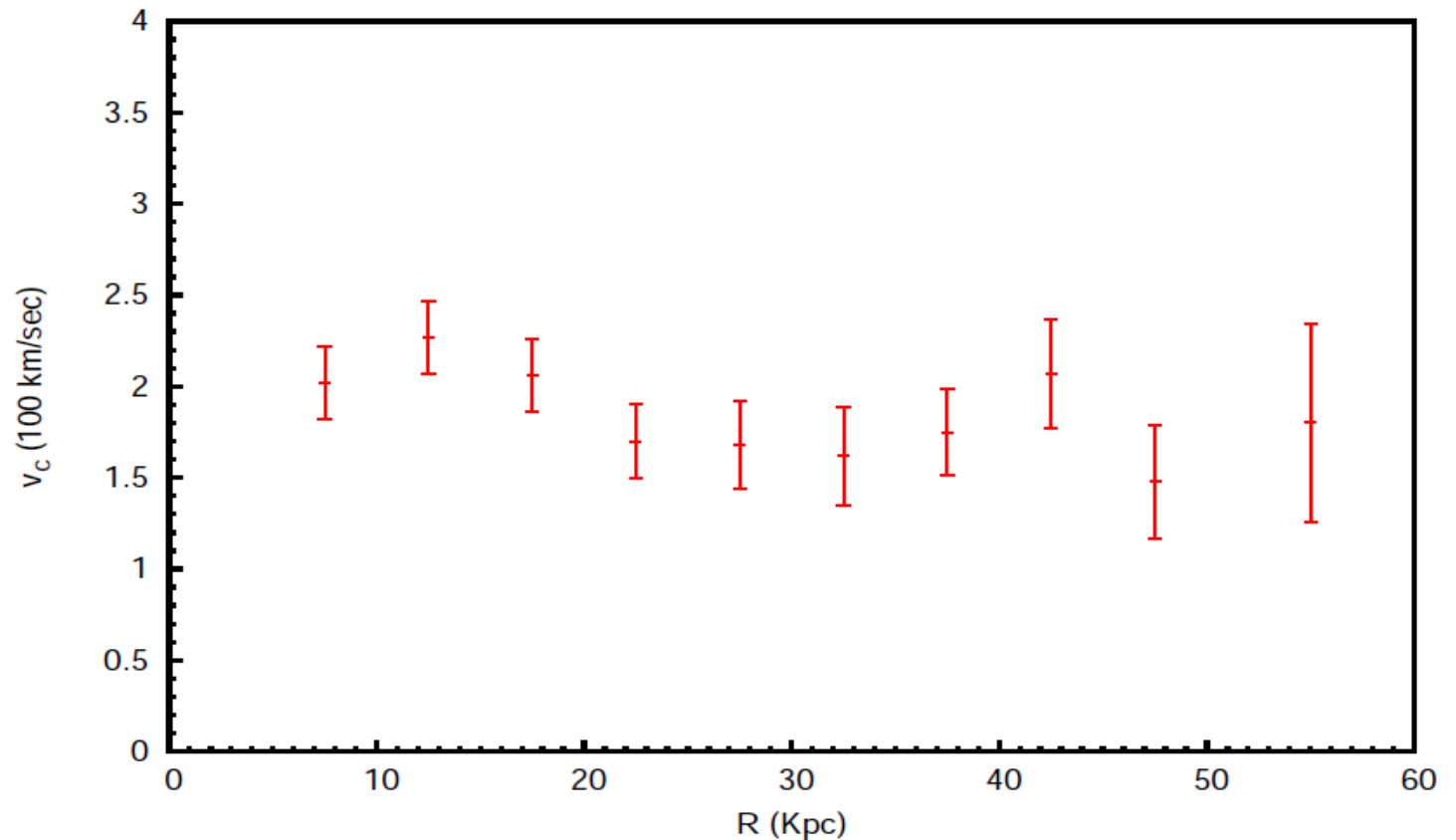
NEW ROTATION CURVE DATA

upto 60 kpc

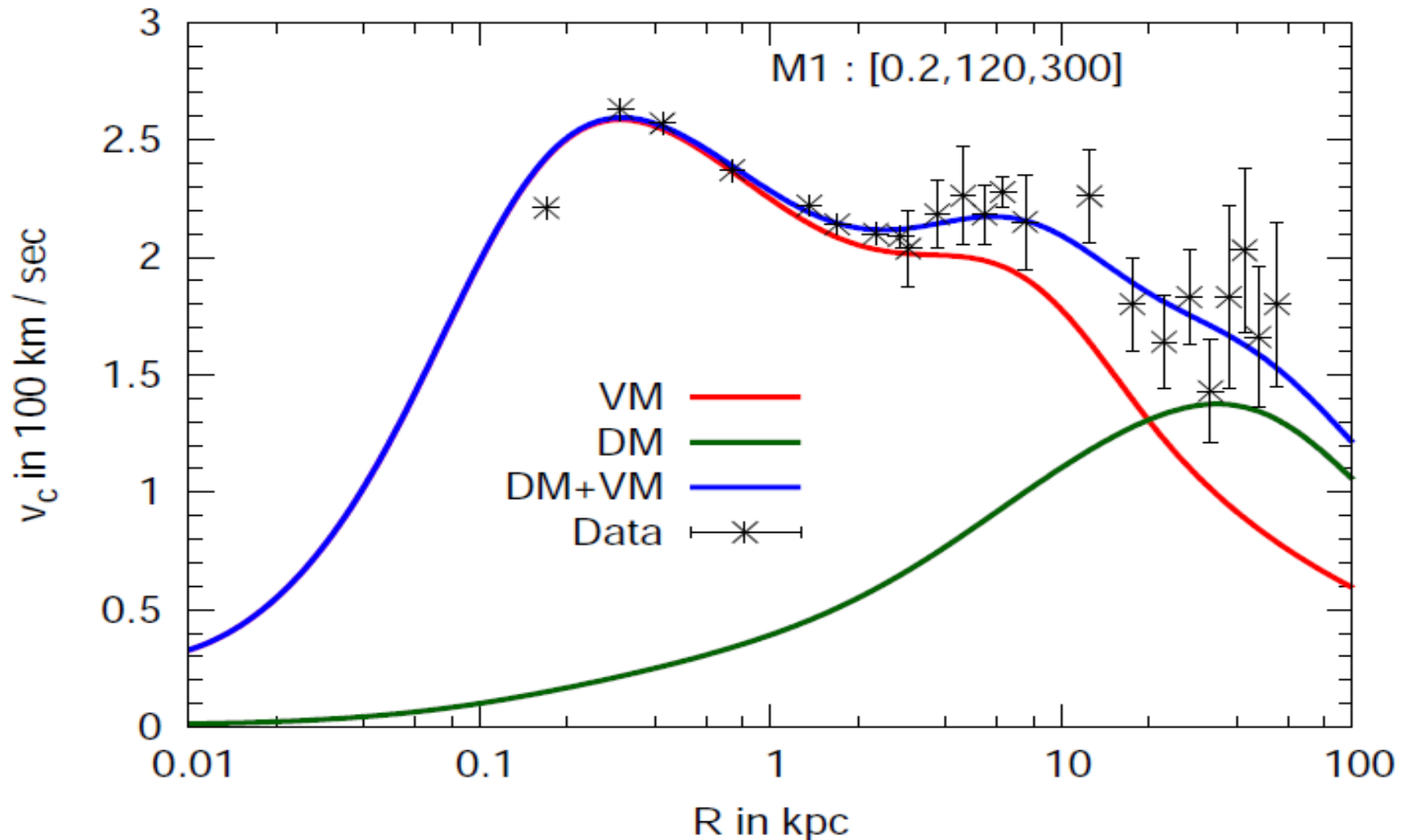
Xue et.al., Astrophys.J.684:1143-1158,2008

standard: ($r_{sn} = 8.0$ kpc, $v_{sn} = 220$ km/sec)

-
- The trend of the data is governed by the standards significantly.



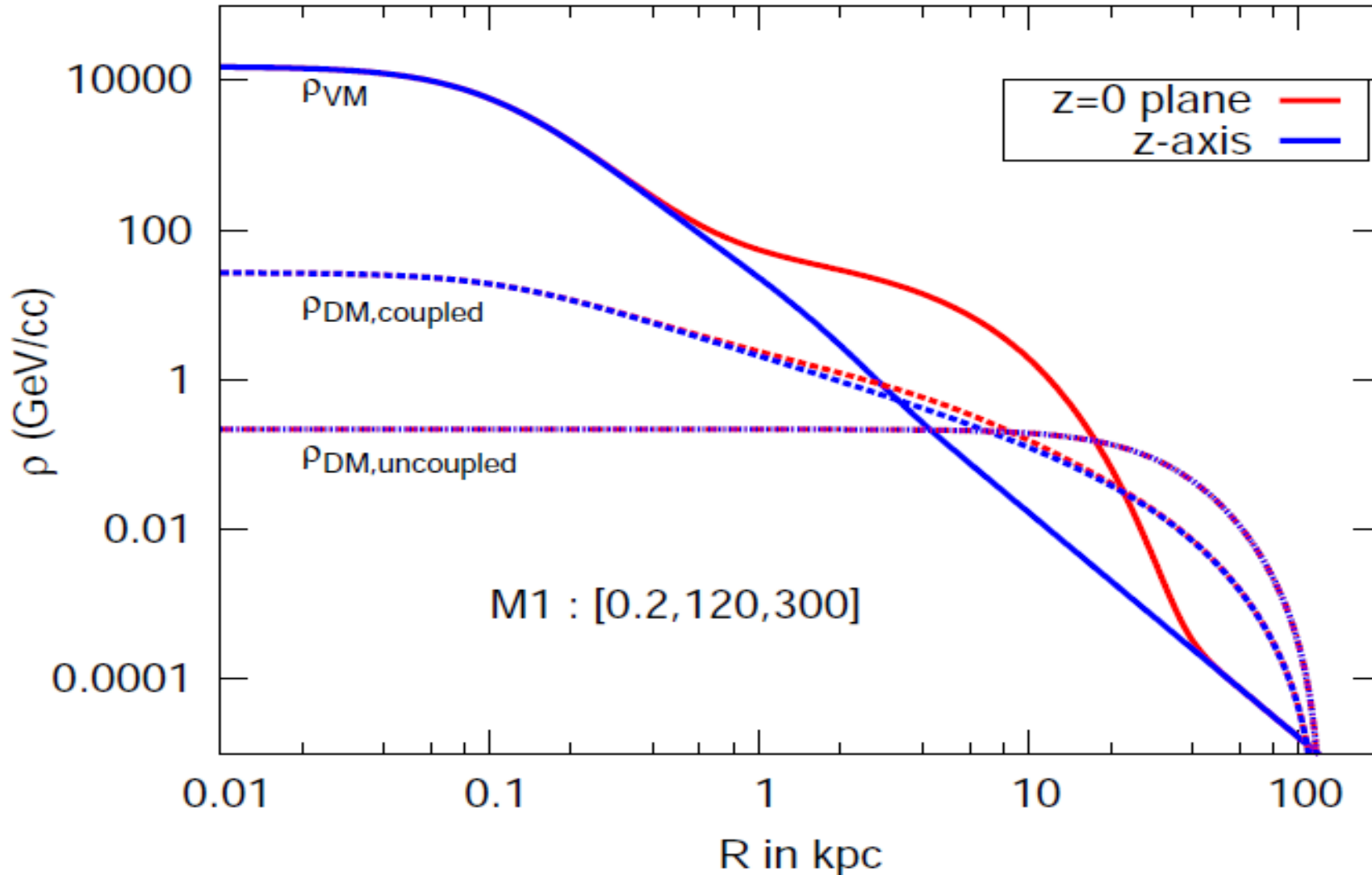
SELF CONSISTENT SOLUTION: BEST FIT ROTATION CURVE



DARK MATTER; DIRECT DETECTION

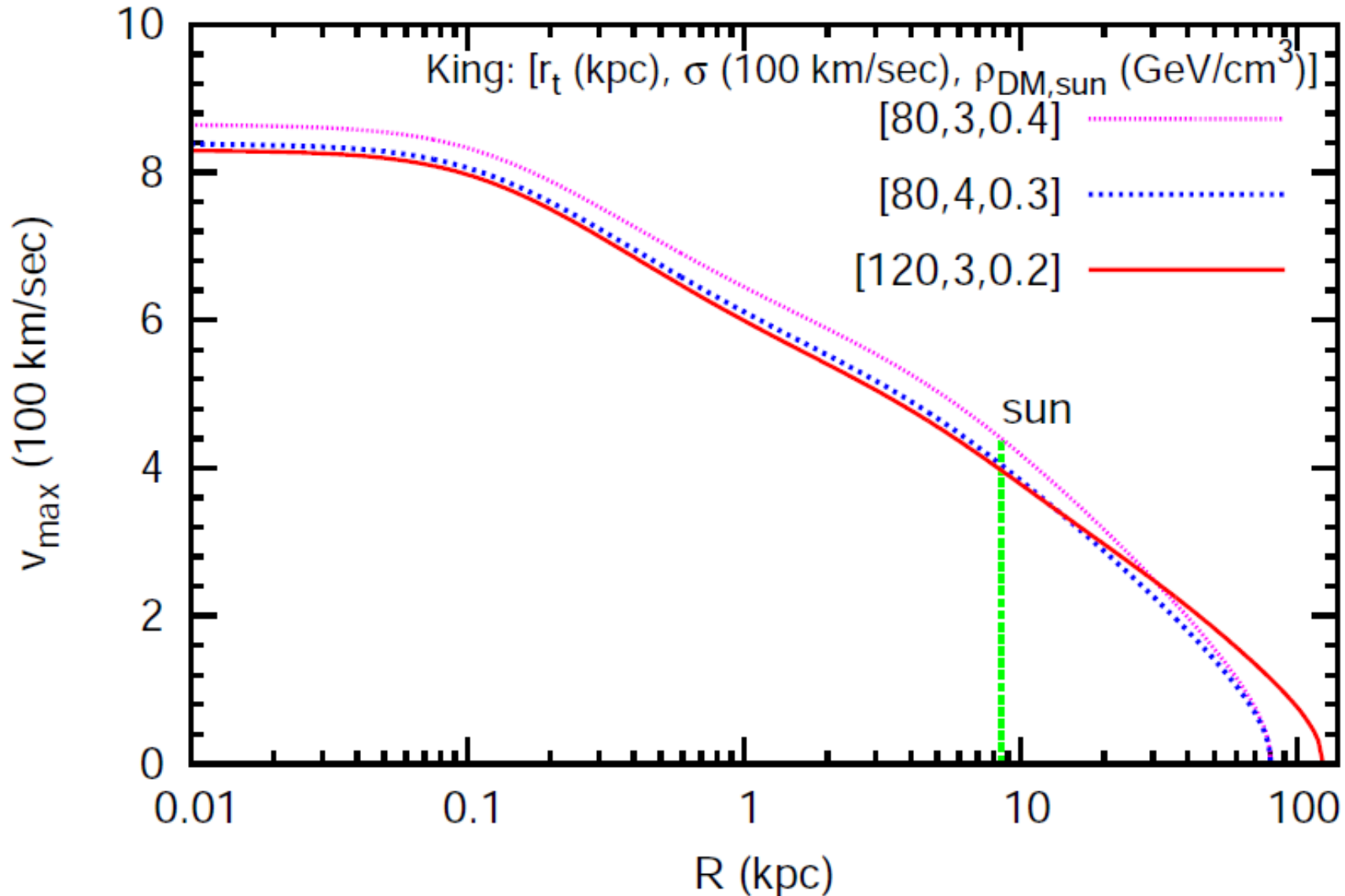
DENSITY PROFILE;

30-40% FLATTENING DUE TO GRAVITATIONAL EFFECT OF VM



DARK MATTER; DIRECT DETECTION

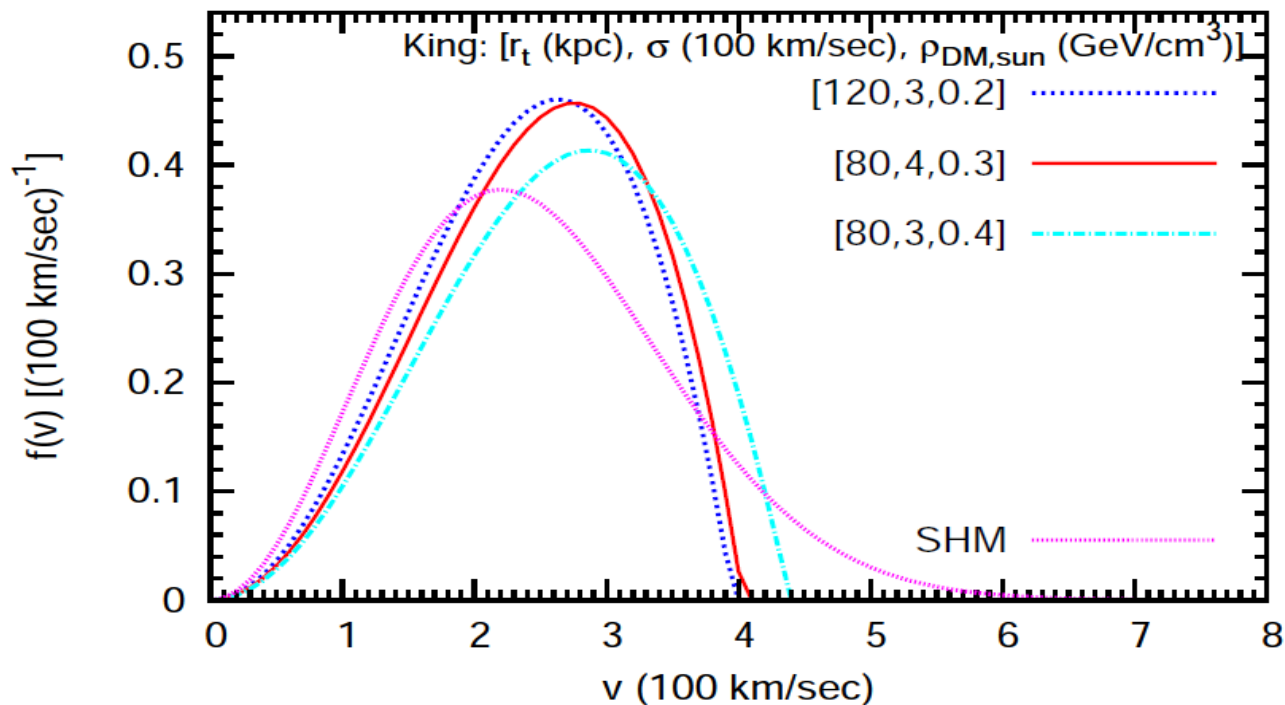
MAXIMUM VELOCITY PROFILES



DARK MATTER; DIRECT DETECTION

VELOCITY DISTRIBUTION FUNCTION IN GALACTIC REST FRAME

$$f_{sun}(\vec{v}) = \frac{f(R=8.5 \text{ kpc}, z=0, \vec{v})}{\rho_{sun}}$$

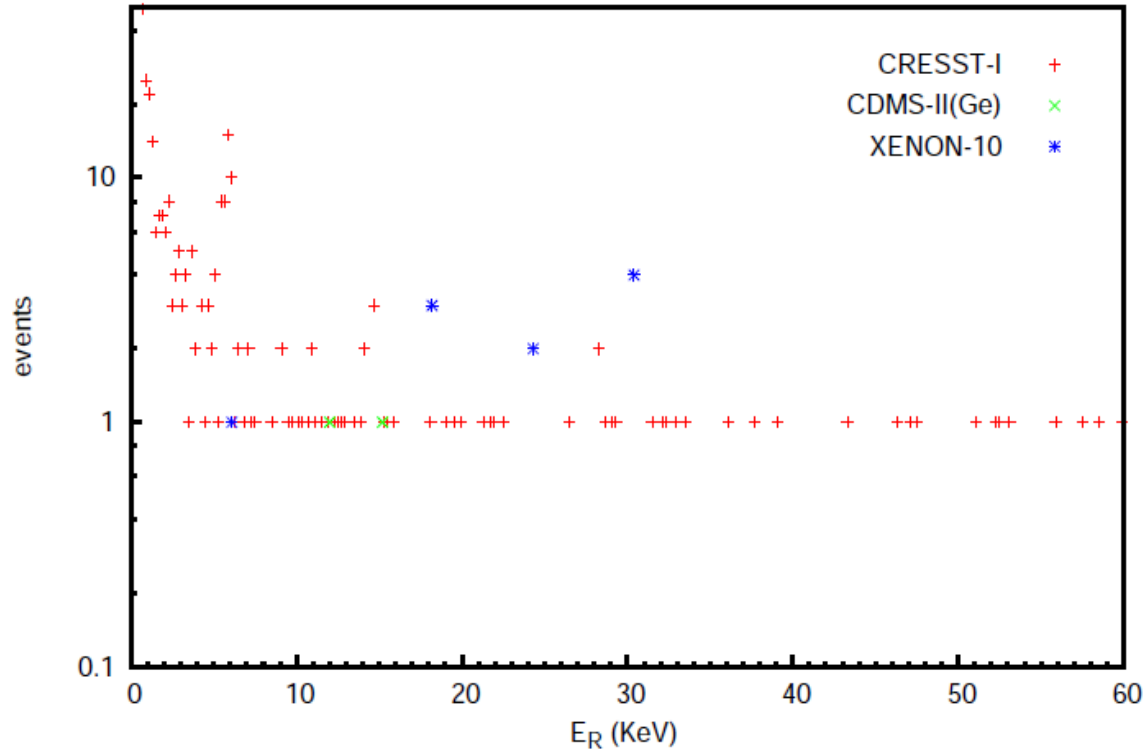


Such deviation from SHM is also indicated by simulations.

DIRECT DETECTION EXPERIMENTS

DARK MATTER; DIRECT DETECTION

EXPERIMENTS WITHOUT SIGNAL

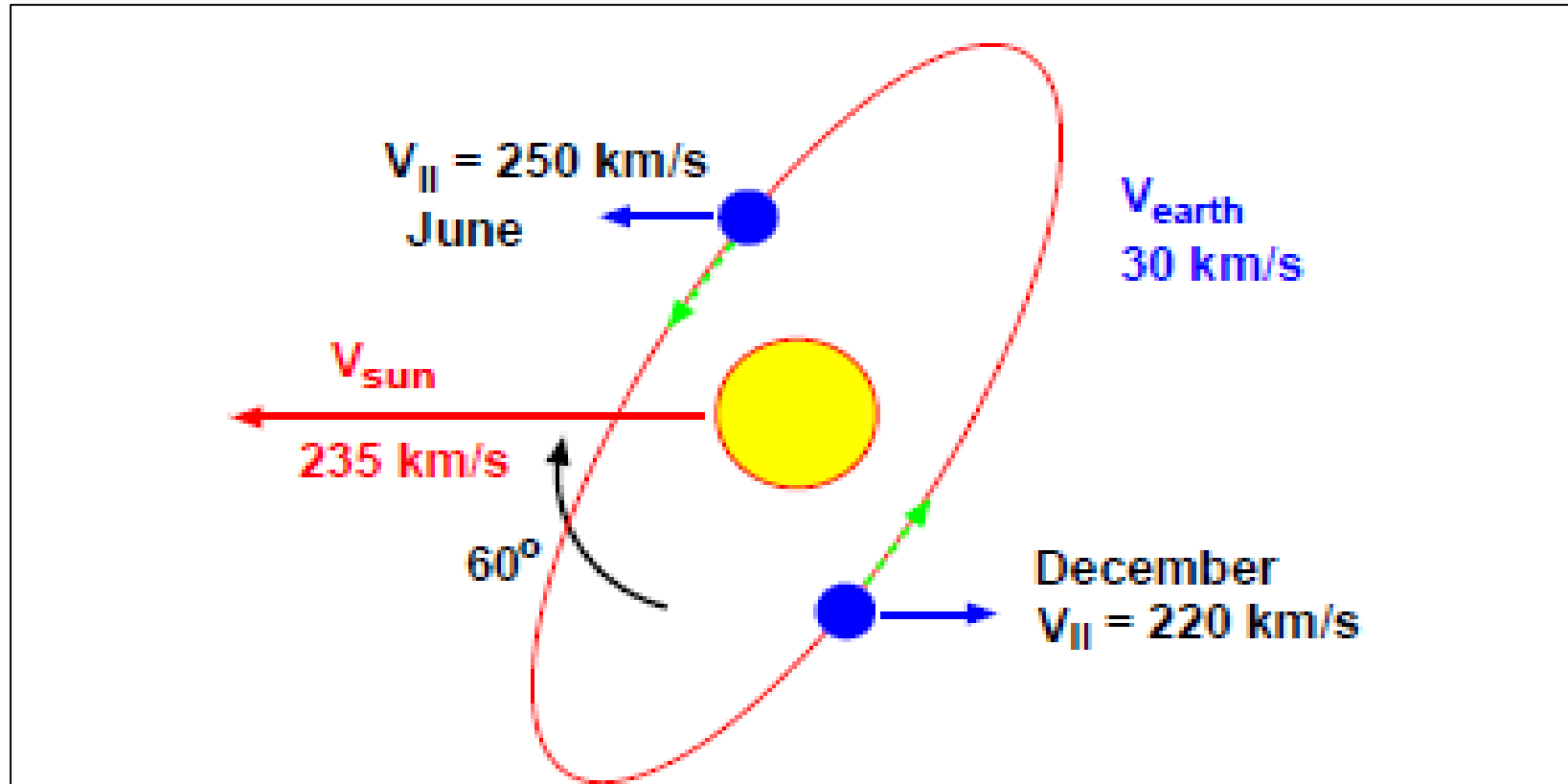


Experiment	Target	Effective exposure (kg-days)	Threshold (keV)
CDMS-II [11]	Ge	304.5 (SI), 23.5 (SD)	10
CDMS-II [43]	Si	12.1 (SI), 0.57 (SD)	7
CRESST-I [12]	Al ₂ O ₃	1.51 (SI), 0.53 (SD)	0.6
XENON10 [13, 14]	Xe	136 (SI), 64.7 (SD)	6.1

DARK MATTER; DIRECT DETECTION

Some experiments claim to have
detected signal..
DAMA, CoGeNT

ANNUAL MODULATION

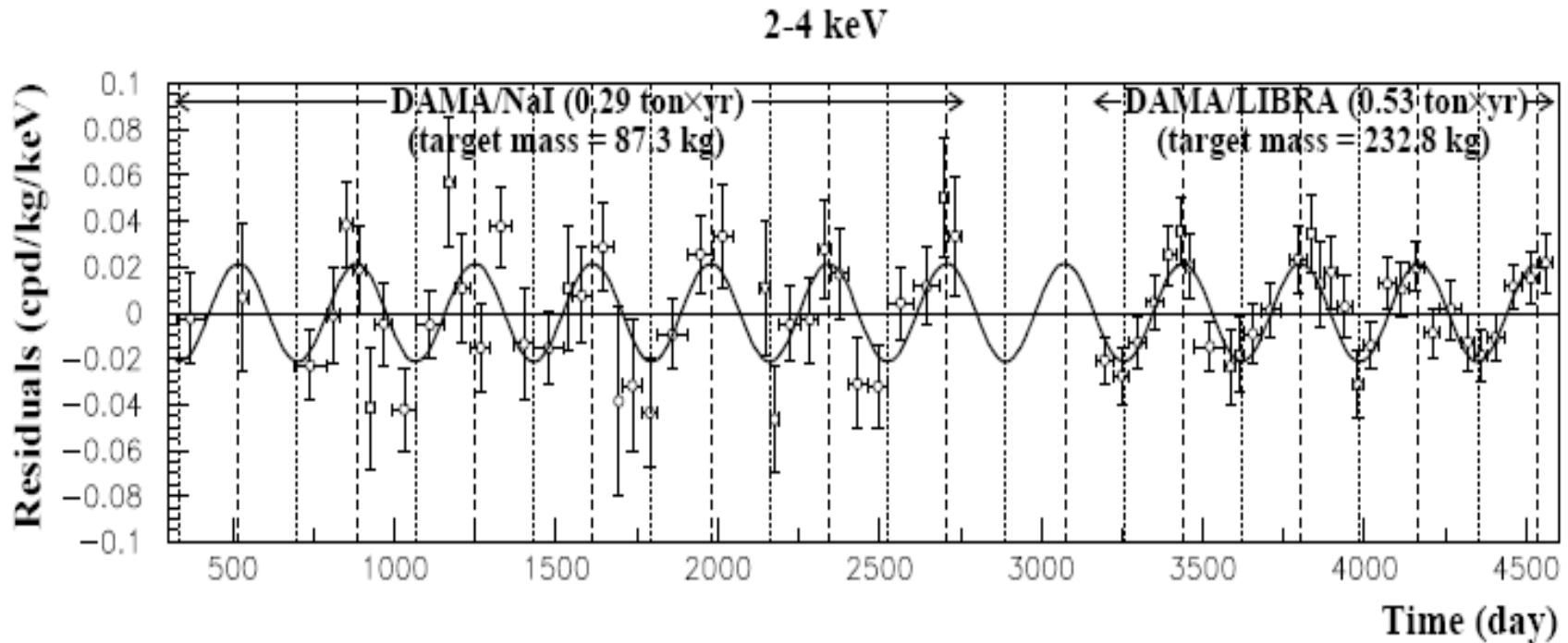


$$v_e = v_{\text{sun}} (= 220 + 12) + v_{\text{orb}} \cos \gamma (= 60) \cos[\omega(t - t_0 (\text{june}2^{\text{nd}}))]]$$

DAMA SIGNAL (2-BIN)

R. BERNABEI ET AL, ARXIV:0804.2741

DAMA NaI+LIBRA



Energy (keVee)	Modulation Amplitude (S_m) (counts/day/kg/keVee)
2 - 6	0.0131 ± 0.0016
6 - 14	0.0009 ± 0.0011

DARK MATTER; DIRECT DETECTION

TRANSFORMATION

$$f_{sun}(\vec{v}) = \frac{f(R=8.5kpc, z=0, \vec{v})}{\rho_{sun}}$$

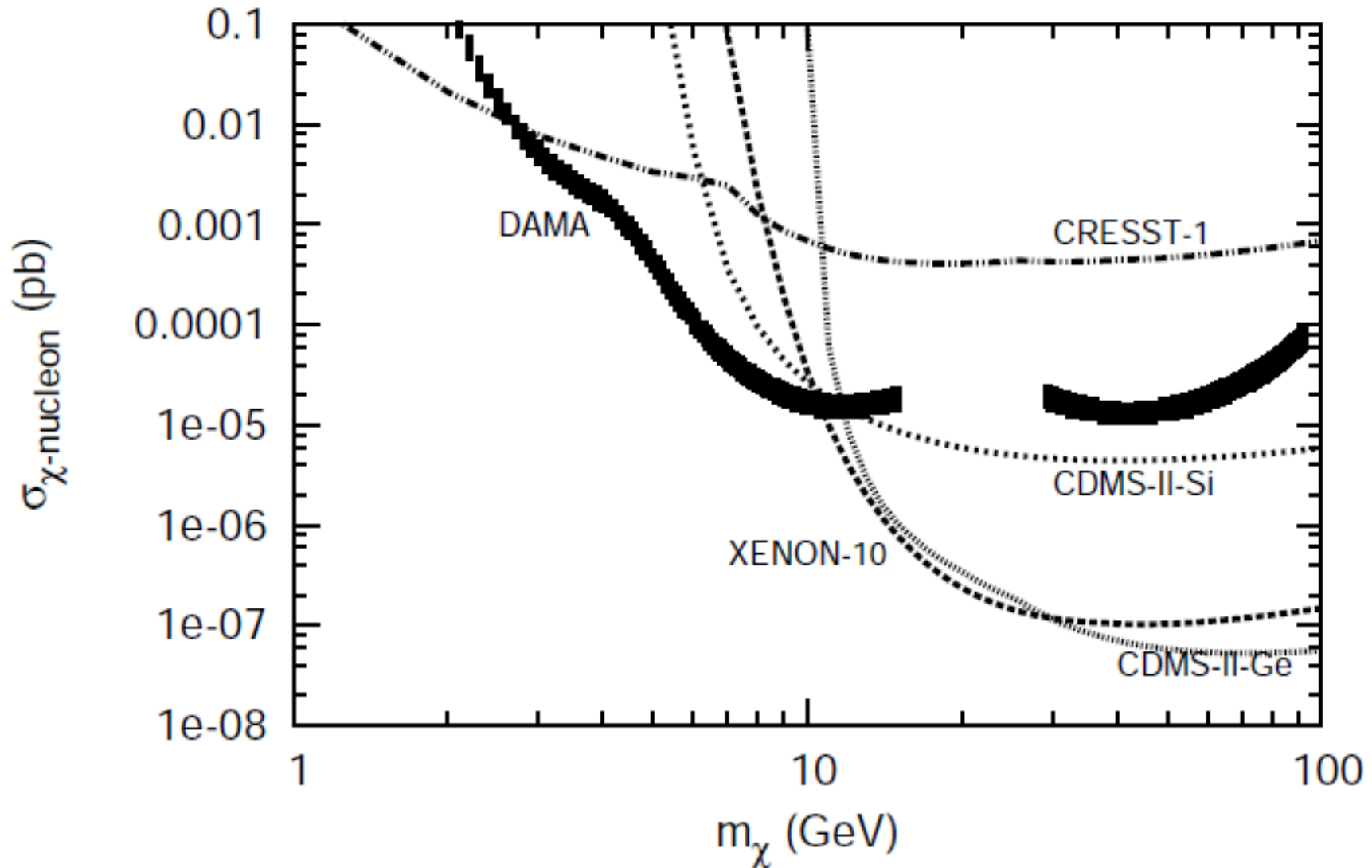
$$f_{earth}(\vec{v}, t) = f_{sun}(\vec{v}_e(t) + \vec{v})$$

- $\mathbf{v}_e(\mathbf{t})$ accounts for the boost to earth's frame
- Therefore the \mathbf{v}_{max} should also be transformed to earth's frame to get the upper limit on $\mathbf{f}_{earth}(\mathbf{v}, \mathbf{t})$

RESULTS

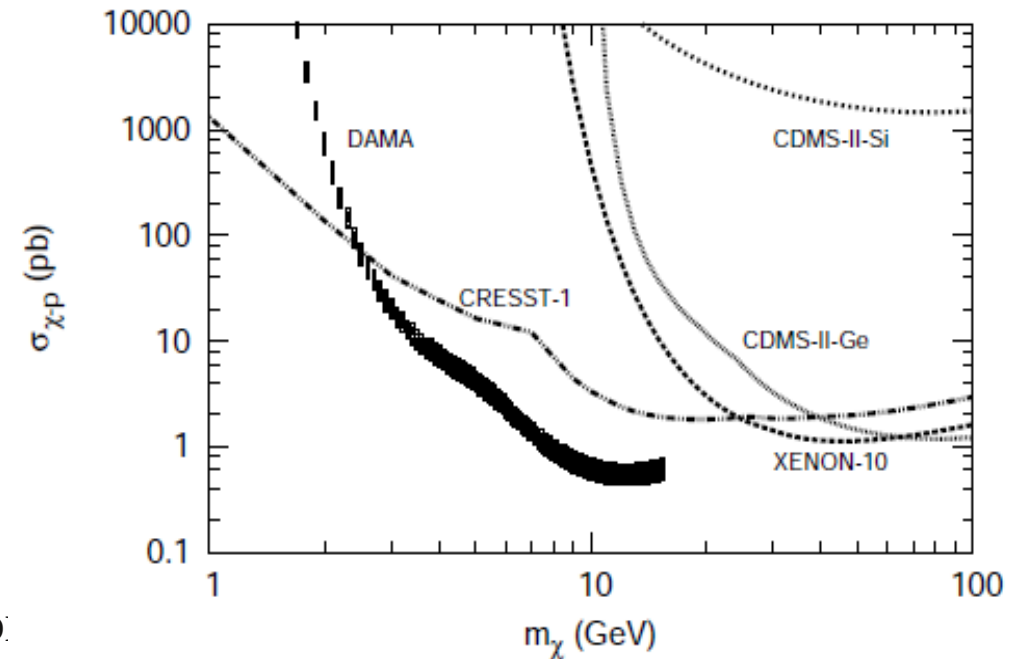
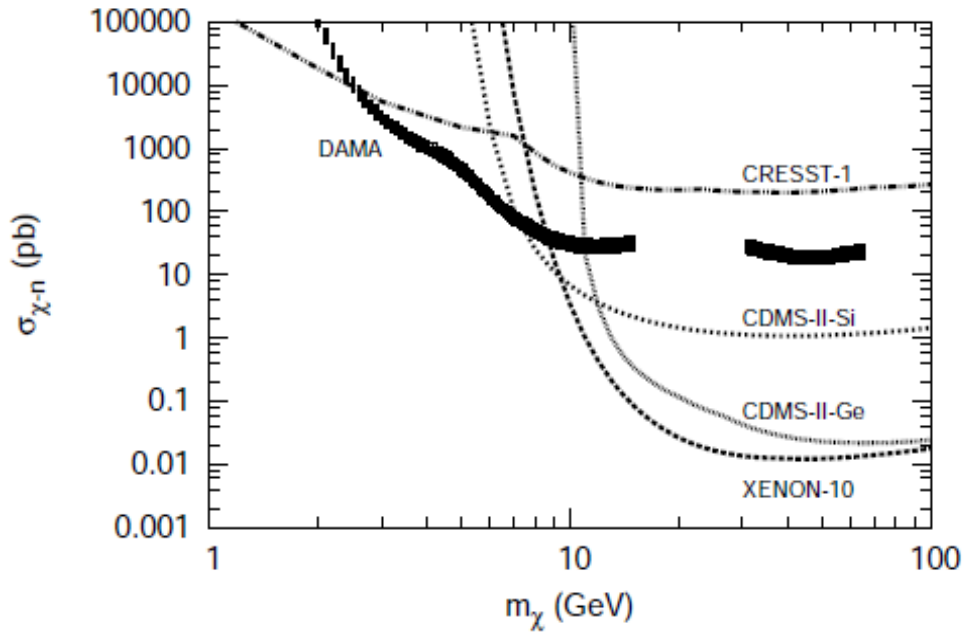
DARK MATTER; DIRECT DETECTION

ELASTIC SCATTERING



DARK MATTER; DIRECT DETECTION

SPIN DEPENDENT SCATTERING



DARK MATTER; D

SUMMARY

- DM expected to be a WI non-baryonic matter: WIMP-s being a favourable class
- Obtained best fit profile with extended rotation data upto 60 kpc
- Coupling with VM leads to flattening of the halo, pulls in DM towards the centre.

- **Best fit model:**

$$R_t = 120 \text{ kpc}, V_{\text{max}} = 396 \text{ km/sec} \quad M_{\text{total}} = 2.1 \times 10^{11} M_{\text{sun}}$$

- The DAMA compatible region strengthen possibility of low mass WIMPS as DM candidate.

– **Journal Ref. : JCAP09(2010)020**



Work done in collaboration with:

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McDonnell Center for the Space Sciences and Department of Physics,
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DARK MATTER; DIRECT DETECTION

DARK MATTER; DIRECT DETECTION

UPSCALING

- The doppler shifts and hence the radial velocities of the CO and H1 lines of ISG is measured:

$$v_R = W^i(R) \sin(l)$$

$$W^i(R) = \left[\Theta(R) \frac{R^i}{R} - \Theta^i \right]$$

CANDIDATE DETAILS

- **AXION**: axions are used to explain CP violation in GUT scale, depending on SUSY breaking model axion can be the LSP..so can be a DM candidate..1.can form by decay of next higher LSP,2.why had i the idea that axion are athermally produced?may be not..!may form by reaheating,
- WIMP-s (GeV-TeV) are the favourable ones.
- WIMP as Cold Dark Matter candidates like Neutralino(χ): LSP in SUSY are the most favourable ones.
- χ produce the proper DM relic density as observed today at WI scale and CDM simulations support LSS formation hierarchical clustering.
- Other candidates are sterile neutrino,gravitino (WDM), neutrino (HDM), Axions etc.

- **COMPONENTS OF UNIVERSE:**
-
- **Visible Matter:** *It's all that we can see..stars,galaxies, gases,dust etc.*
- **Dark Matter:***Mostly new form of non-baryonic matter..outside SM*
- **Dark Energy:***Exerts negative pressure..leads to accelerated expansion of universe in present epoch..type-1a supernovae with known intrinsic brightness can be taken as standard candles to estimate the expansion rate of universe..*
showed nonlinear Hubble relationship due to acceleration..how?

MODULATION

$$\frac{dR(E_r, t)}{dE_r} \approx S_0(E_r) + S_i(E_r) \cos[\omega(t - t_0)]$$

$$S_m(E_r) = \frac{1}{2} \left[\frac{dR(E_r, \text{June } 2^{\text{nd}})}{dE_r} - \frac{dR(E_r, \text{Dec } 2^{\text{nd}})}{dE_r} \right]$$

Scintillation : Recoil energy of nucleus taken up by electrons which radiate through scintillation detected by photomultiplier tubes. **[DAMA, XENON]**

Ionization : As the nucleus moves through the target mass it ionizes other target atoms and Electrostatic field detected. **[CDMS, CoGeNT, XENON]**

Phonons : Detected by semiconductor and superconductor-junction sensors.

Heat : Recoil energy is detected by change of semiconductor (doped Ge) resistance in a bolometer under cryogenic condition (<50 mK). **[CDMS, CRESST?]**