Language: 英語/English

KEK 物理セミナー Physics Seminar

10月28日 (火) October 28 (Tue)
16:00 ~ 17:00

4号館 345号室 Room 345 in the 4th Building

Dark Matter: the evidence from astrophysics and cosmology, and observational limits for candidate particles

Matts Roos
(Univ. of Helsinki)

- Abstract:
Dark matter has been introduced to explain many independent gravitational effects at different astrophysical scales, even at cosmological scale. However, what constitutes dark matter is not known, in fact the list of ruled out candidates is much longer than the list of possible candidates. This review talk is intended for particle physicists with little or no knowledge of astrophysics and cosmology.

Past presentations are archived at our home page, http://seminar.kek.jp/physics/ .

Organizers: T. Komatsubara and I. Adachi

2003.9.16

DARK MATTER

Matts Roos
University of Helsinki

- PRIMORDIAL CONDITIONS
- THE EVIDENCE FOR DM
- CANDIDATES FOR DM
- CONCLUSIONS

DM-1

PRIMORDIAL CONDITIONS

IMAGINE A PLASMA COMPOSED OF EQUAL DENSITIES OF MATTER ρ_m AND RADIATION ρ_r

$$\rho_m = \rho_r$$

AT TEMPERATURE $1\,eV \simeq 10000\,^{\circ}K$.

MATTER (IONIZED)

BARYONIC H^+, $^4He^{++}$, $^2D^+$, $^3He^{++}$

LEPTONIC $e^{\pm}$, neutrinos

OTHER KINDS OF MATTER ?

THE DENSITIES ρ_m, ρ_r FLUCTUATE ADIABATICALLY

$$\frac{\delta\rho_m}{\rho_m} \propto \frac{\delta\rho_r}{\rho_r}$$

THIS WAS THE STATE OF OUR UNIVERSE WHEN 60.000 YRS OLD

SOME DEFINITIONS:

THE CRITICAL DENSITY $\rho_c = \frac{3H_0^2}{8\pi G}$

THE HUBBLE CONSTANT $H_0 = h \cdot 100 \frac{km}{s \cdot Mpc}$

THE DENSITY PARAMETERS

$$\Omega_m \equiv \frac{\rho_m}{\rho_c} \qquad \Omega_r \equiv \frac{\rho_r}{\rho_c} \qquad \Omega_V = \frac{\rho_V}{\rho_c}$$

DM-3

AT TEMPERATURE 3000 °K

IONS AND ELECTRONS COMBINE

INTO ATOMS ,

RADIATION DECOUPLES*) FROM MATTER,

THE RADIATION FLUCTUATIONS FREEZE.

THE INFORMATION WE HAVE FROM PRIMORDIAL TIMES IS

- THE BARYONIC DENSITY ρ_B IS SMALL

$$\Omega_B \equiv \frac{\rho_B}{\rho_c} = 4.4 \pm 0.4\ \%$$

(CMB)

- THE COSMIC MICROWAVE BACKGROUND RADIATION $\Omega_r = 4.90 \cdot 10^{-5}$

AND ITS

FLUCTUATION SPECTRUM $\Delta T/T = 10^{-5}$

POLARIZATION —"— $\lesssim 10^{-7}$

---

*) PARTICLES COLLIDE AT A RATE

$$\Gamma = \langle N v \sigma(E) \rangle$$

NUMBER DENSITY ↑ ↑ COLLISION CROSS SECTION

PARTICLES REMAIN IN THERMAL EQUILIBRIUM WHEN $\Gamma \gtrsim H$.

IF $\Gamma < H$, THEY DECOUPLE.

THE EVIDENCE FOR DARK MATTER

I. GLOBAL PARAMETER FITS.

1) CMB TEMPERATURE ANISOTROPIES ARE ANALYZED BY EXPANSION IN SPHERICAL HARMONICS

⇒ POWER SPECTRUM IN MULTIPOLES ℓ

CMB POLARISATION ANISOTROPIES, TOO.

⇒ POWER SPECTRA DEPEND ON

$\Omega_m h^2$, $\Omega_b h^2$ AND 8 OTHER PARAMETERS.

2) THE DISTRIBUTION OF GALAXIES SHOWS FLUCTUATIONS ON LARGE SCALE; EXPAND IN SPHERICAL HARMONICS.

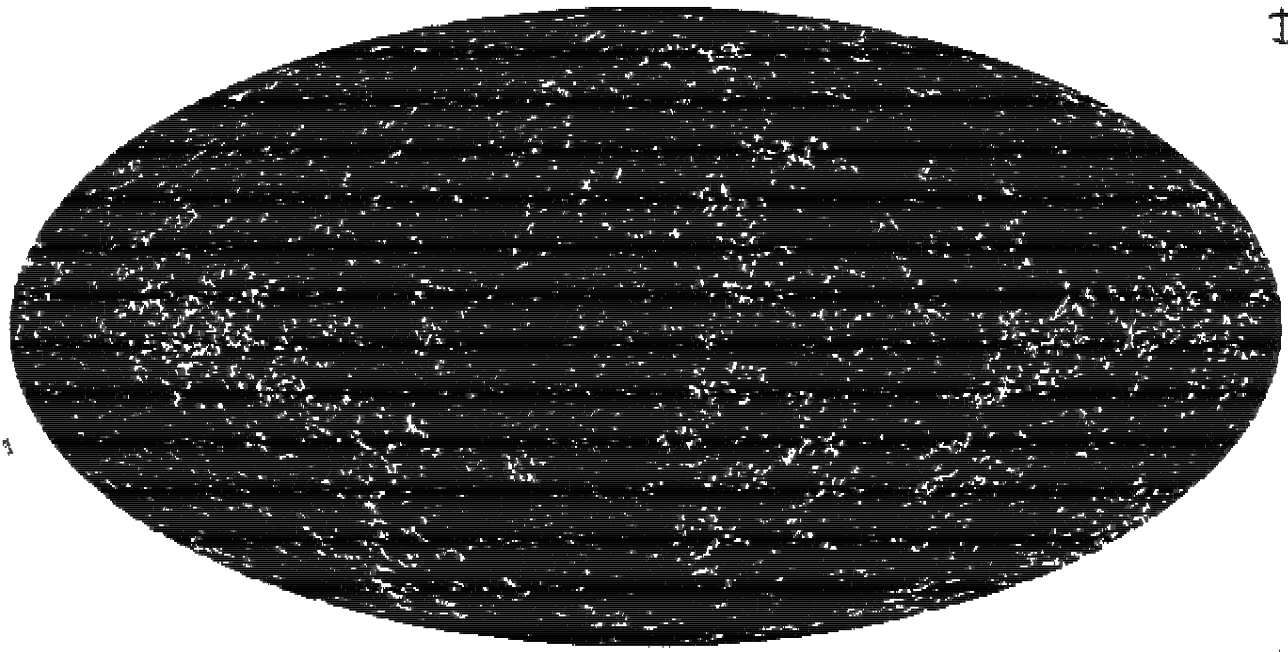
⇒ POWER SPECTRUM DEPENDS ON

$\Omega_m h$, $\Omega_b h$, $\Omega_\nu h$ AND 30 OTHER PARAMETERS

3) SEVERAL METHODS TO DETERMINE DISTANCE AND REDSHIFT (= VELOCITY) TO LUMINOUS OBJECTS

⇒ h

DM-7



COSMOLOGY AFTER WMAP'S FIRST YEAR'S RESULTS

COSMIC MICROWAVE BACKGROUND POWER SPECTRUM

TT = TEMPERATURE

TE = TEMPERATURE - POLARIZATION CORRELATION

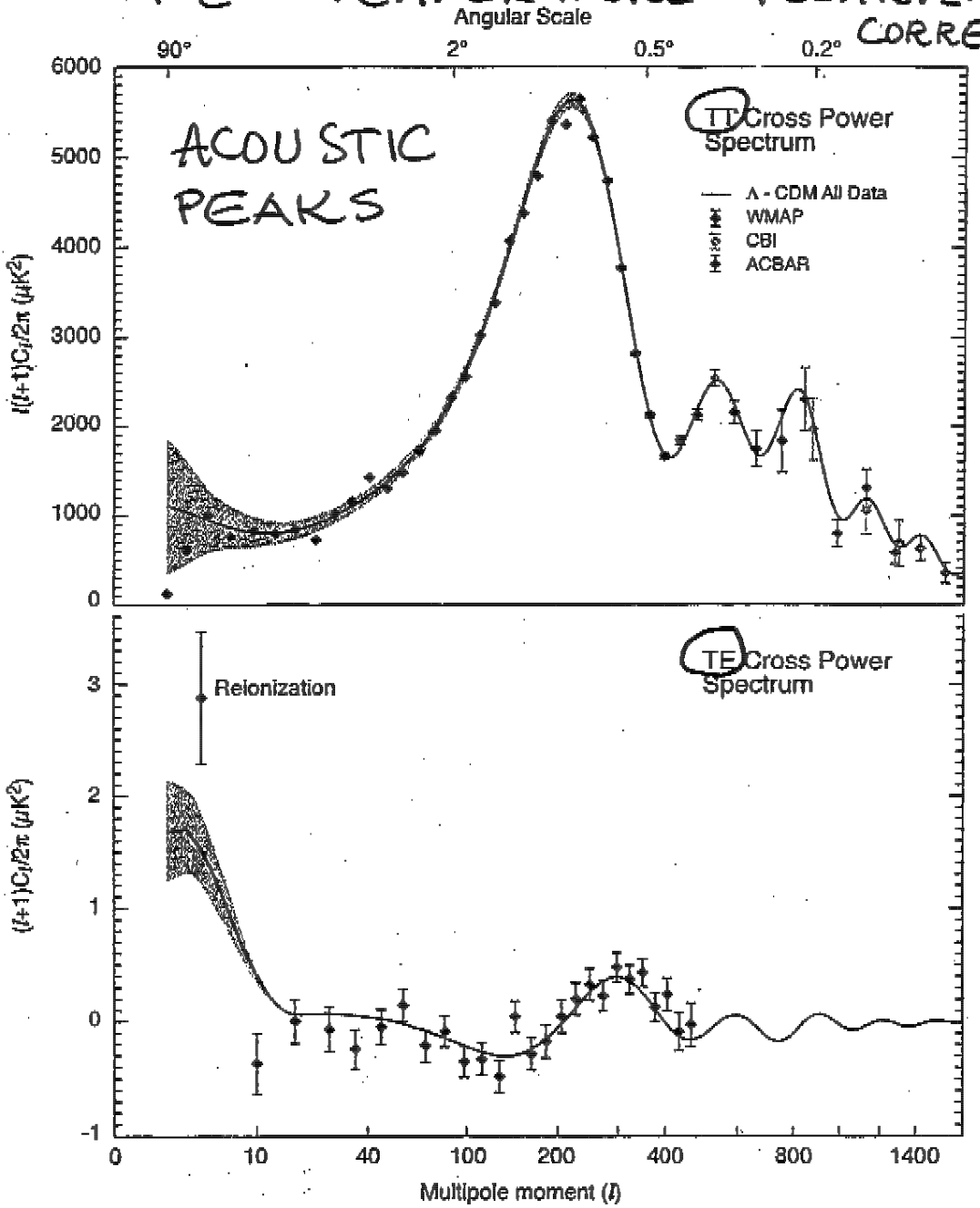


Fig. 54

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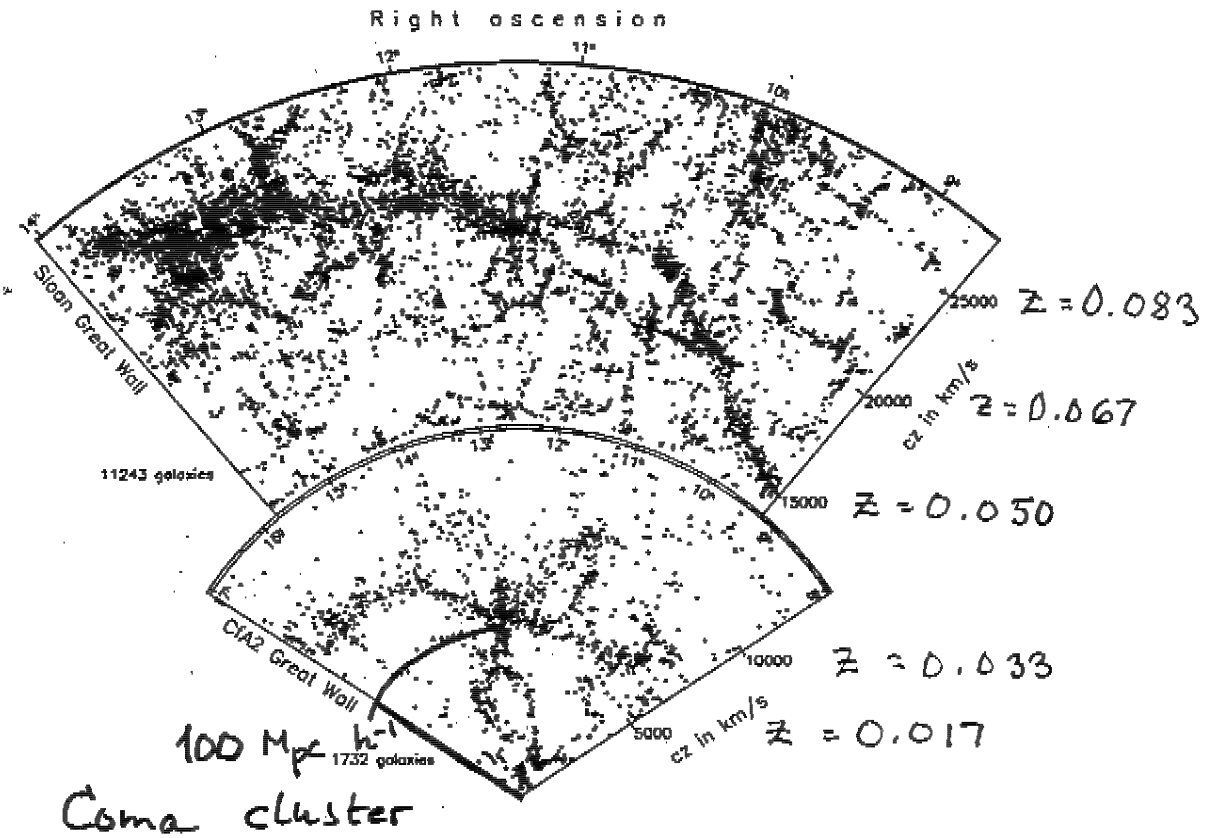

Fig. 9.— Sloan Great Wall compared to CfA2 Great Wall at the same scale in co-moving coordinates. Equivalent redshift distances cz are indicated. The Sloan slice is 4° wide, the CfA2 slice is 12° wide to make both slices approximately the same physical width at the two walls. The Sloan Great Wall extends from 14h to 9h. It consists of one strand at the left, which divides to form two strands between 11.3h and 9.8h, which come back together to fom one strand again (like a road that becomes a divided highway for a while). The CfA2 Great Wall (which includes the Coma cluster in the center), has been plotted on a cone and then flattened onto a plane. Total numbers of galaxies shown in each slice are also indicated.

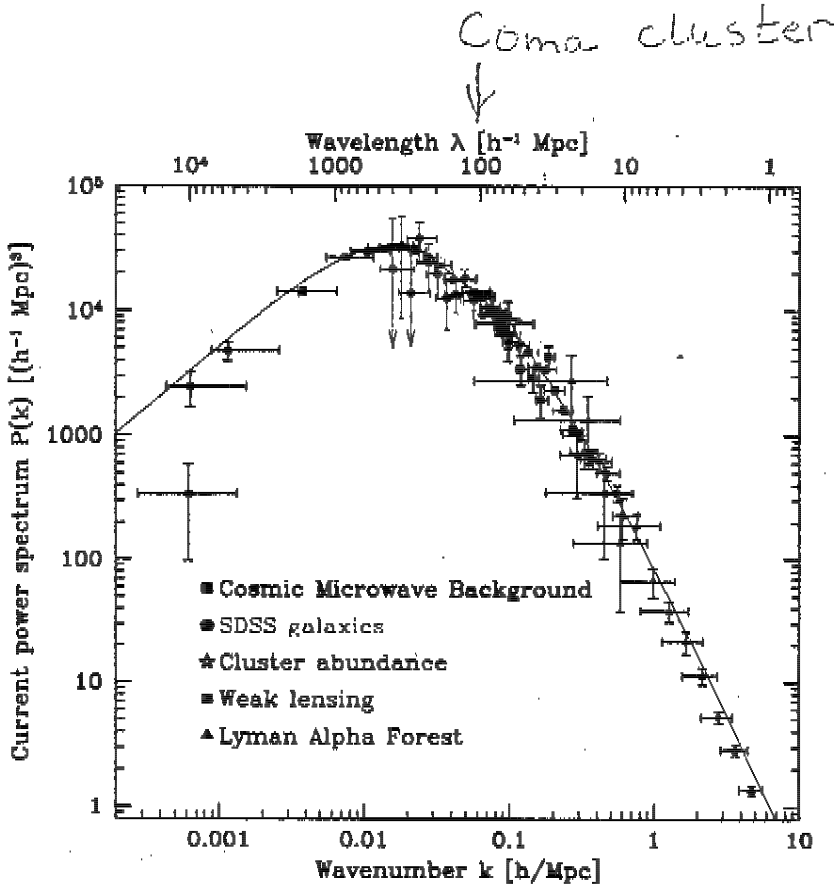

FIG. 11 Power spectrum of density inhomogeneity today obtained from a variety of measurements including large-scale structure, CMB, weak lensing, rich clusters and the Lyman-alpha forest. The curve is the theoretical prediction for the consensus cosmology model (from Tegmark *et al.*, 2002).

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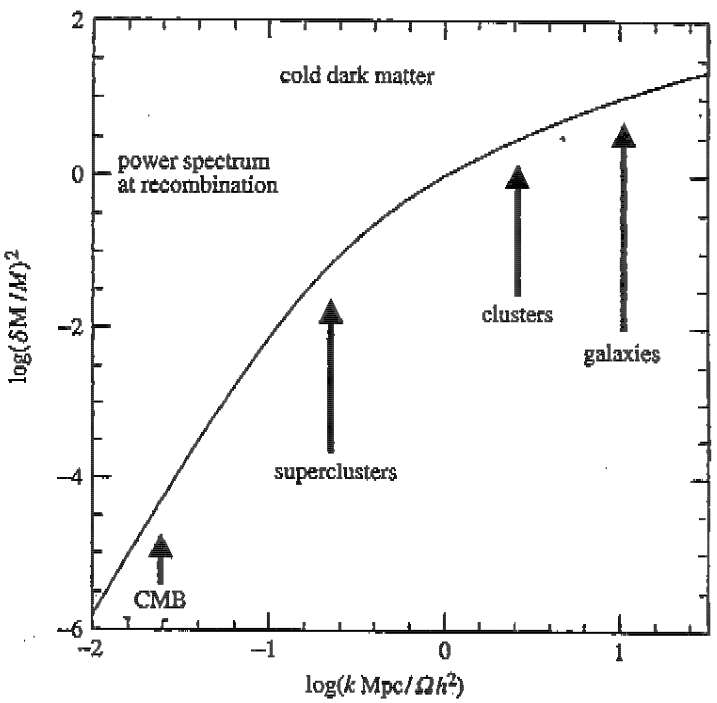

Figure 9.7 The power function $P(k)$ as a function of the density fluctuation wavenumber k in units of h^2 Mpc^{-1}. This can also be expressed by the angular scale in degrees or by the linear size L of present cosmic structures in units of Mpc $\Omega_m^{-1}h^{-1}$. Courtesy of C. Frenk and J. Peacock

to redshift-space distortions of the correlation as shown in Figure 9.3. We have previously referred to large-scale bulk flows of matter observed within the LSC attributed to the 'Great Attractor', an overdensity of mass about $5.4 \times 10^{16} M_\odot$ in the direction of the *Hydra-Centaurus* cluster, but far behind it, at a distance of some $44h^{-1}$ Mpc. The 2dFGRS has verified that both types of redshift-space distortions occur, the 'Fingers of God' due to nearby peculiar velocities and the flattening due to infall at larger distances. These results are quantified by the parameter value

$$\beta = \Omega_m^{0.6}/b = 0.43 \pm 0.07. \tag{9.42}$$

With a large-scale bias of $b = 1$ to a precision of about 10%, the β error dominates, so that one obtains

$$\Omega_m = 0.25 \pm 0.07, \tag{9.43}$$

in good agreement with other determinations.

The WMAP collaboration [1] obtained a value for the characteristic amplitude of velocity fluctuations within 8 Mpc h^{-1} spheres at $z = 0$,

$$\sigma_8 = 0.9 \pm 0.1,$$

by setting $\beta = \sigma_8 \Omega_m^{0.6}$.

COMBINING 1), 2), 3) WE FIND

$\Omega_m = \Omega_b + \Omega_\nu$

$\Omega_\nu \rightarrow < 1.5\ \%$

$\Omega_b \rightarrow 4.4 \pm 0.4\ \%$

$\Omega_m \rightarrow 27 \pm 4\ \%$

MISSING MATTER 23% !

II. GALAXY FORMATION

THE DENSITY OF MATTER $\Rightarrow$ DM-10 DM-11
IS FLUCTUATING.
AS IT COOLS AND CONDENSES
$\Rightarrow$ **GALAXIES FORM.**

IF ALL MATTER IS ~~BARYONIC~~

$\Rightarrow$ AMPLITUDE OF FLUCTUATIONS
MUST BE VERY LARGE
BECAUSE ρ_b, Ω_b IS VERY SMALL.

THE CMB FLUCTUATIONS HAVE
VERY SMALL AMPLITUDE, AND,
REMEMBER THE ADIABATICITY CONDITION

GALAXY FORMATION IN PURELY BARYONIC MATTER IS RULED OUT.

III. SPIRAL GALAXIES

ARE BOUND SYSTEMS IN WHICH MATTER = STARS & INTERSTELLAR GAS + ?

THE OBSERVABLE MATTER FORMS A THIN DISK IN WHICH STARS AND GAS TRAVEL AROUND THE GALACTIC CENTER ON ≈ CIRCULAR ORBITS.

M = GALAXY MASS

v = CIRCULAR VELOCITY AT RADIUS r

STABILITY CONDITION : CENTRIFUGAL ACCELERATION = GRAVITATIONAL PULL

$$\frac{v^2}{r} = \frac{GM}{r^2}$$

$$\therefore \quad v(r) = \sqrt{\frac{GM}{r}}$$

VISIBLE STARLIGHT TRACES VELOCITY OUT TO ≈ 10 kpc (MILKY WAY RADIUS)

INTERSTELLAR GAS SEEN IN X-RAYS OUT TO 20-50 kpc.

ROTATION CURVES STAY CONSTANT AFTER ≈ 5 kpc, $v(r) = \text{const.}$

⇒ **INVISIBLE HALO:** $\Omega_{halo} = (3-10)\Omega_{luminous}$

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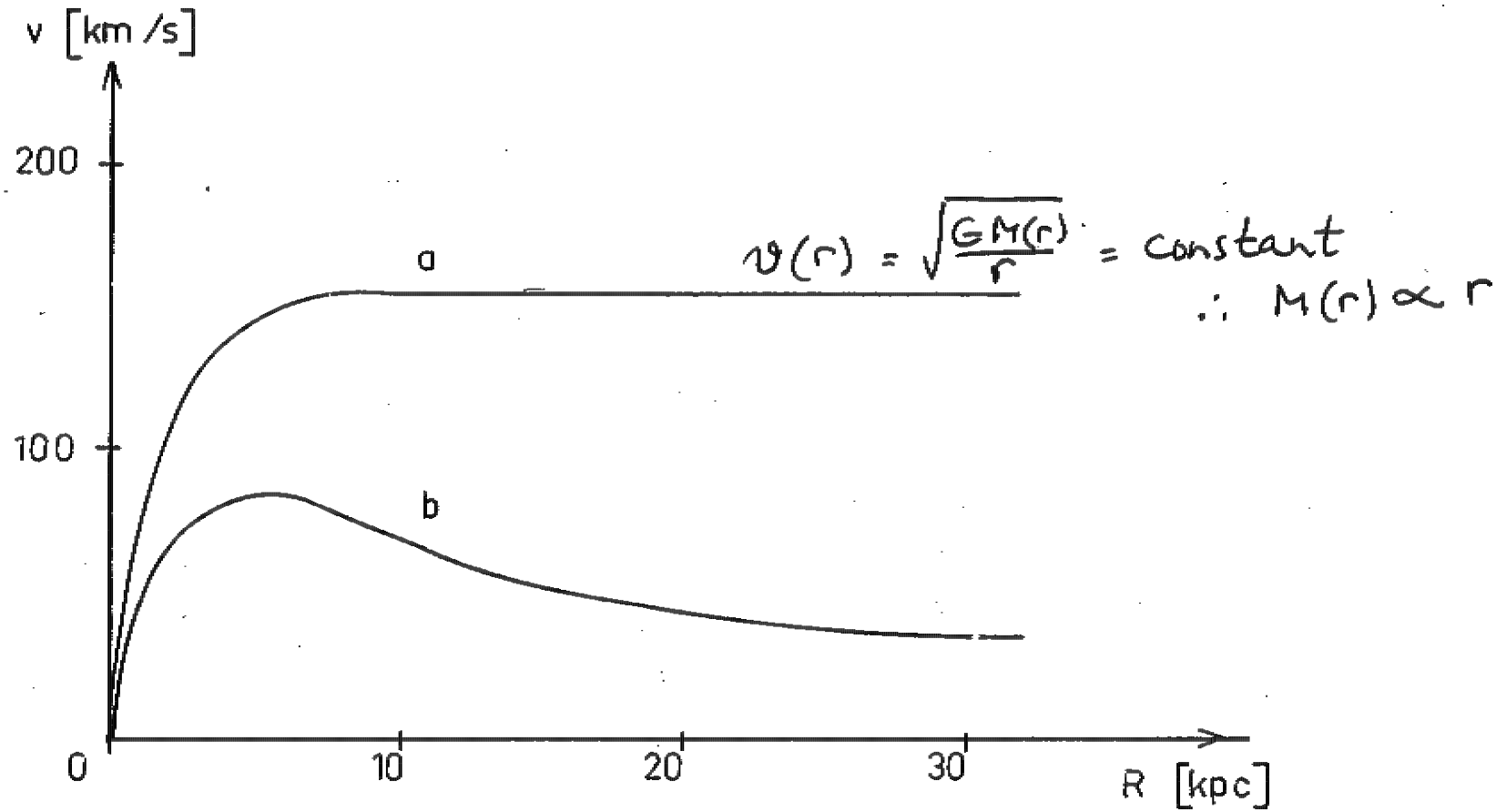


Fig.42

DM-14

THE HALO OF OUR GALAXY

CONTAINS MATTER, EQUIVALENT TO

$0.3\ \text{GeV}/\text{cm}^3 \approx 0.3\ \text{protons}/\text{cm}^3$

BARYONIC MATTER IN THE HALO
= MASSIVE AND COMPACT OBJECTS,
CONTRIBUTE NEGLIGIBLY.

THE SOLAR SYSTEM TRAVELS
THROUGH THIS HALO AT VELOCITY

$v = 220\ \text{km/s}$

$\therefore$ A FLUX OF SEVERAL $* 10^6/\text{m}^2\text{s}$
OF DARK MATTER PARTICLES
IS CROSSING THE EARTH.

FIND THEM!

IV. SMALL GALAXY GROUPS

EMBEDDED IN HOT GAS,
SEEN BY ITS X-RAY RADIATION.

RADIATION INTENSITY
$\Rightarrow$ TOTAL AMOUNT OF GAS

BARYONIC MASS = GAS + LUMINOUS MATTER

RADIATION TEMPERATURE
$\Rightarrow$ STRENGTH OF GRAVITATIONAL FIELD
$\Rightarrow$ TOTAL GRAVITATING MATTER.

BUT $\dfrac{\text{GRAVITATING MASS}}{\text{BARYONIC MASS}} \gtrsim 3$

A DARK HALO MAY BE NEEDED

V. THE LOCAL SUPERCLUSTER LSC

THE GALAXIES FOLLOW 3 MOVEMENTS

1) HUBBLE FLOW = RADIAL EXPANSION

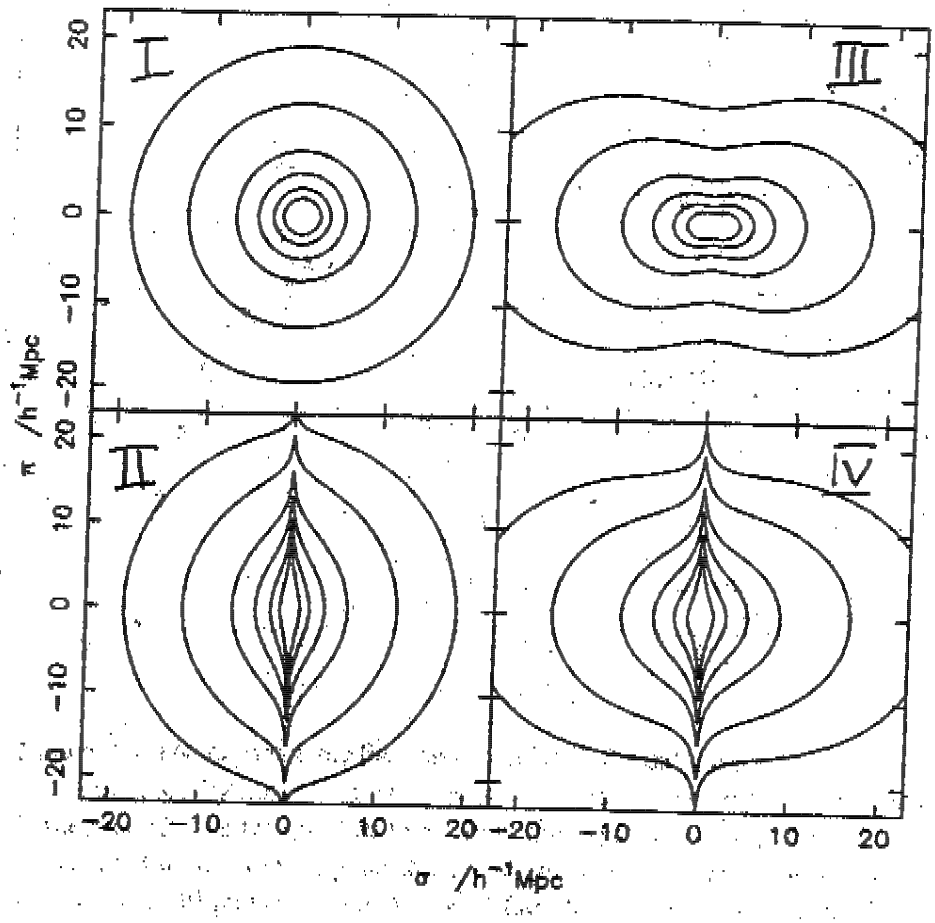
2) RANDOM "PECULIAR VELOCITIES"
$\Rightarrow$ AFFECTS RADIAL DISTANCE MEASUREMENTS

3) INFALL TO LSC (AT DISTANCES WHERE PECULIAR VELOCITIES CAN BE NEGLECTED)

"FINGERS OF GOD", FUNCTION OF Ω_m.

RADIAL
COORDINATE π

TRANSVERSAL COORDINATE σ



σ IS ALWAYS EXACT

FIG. I IS UNDISTORTED

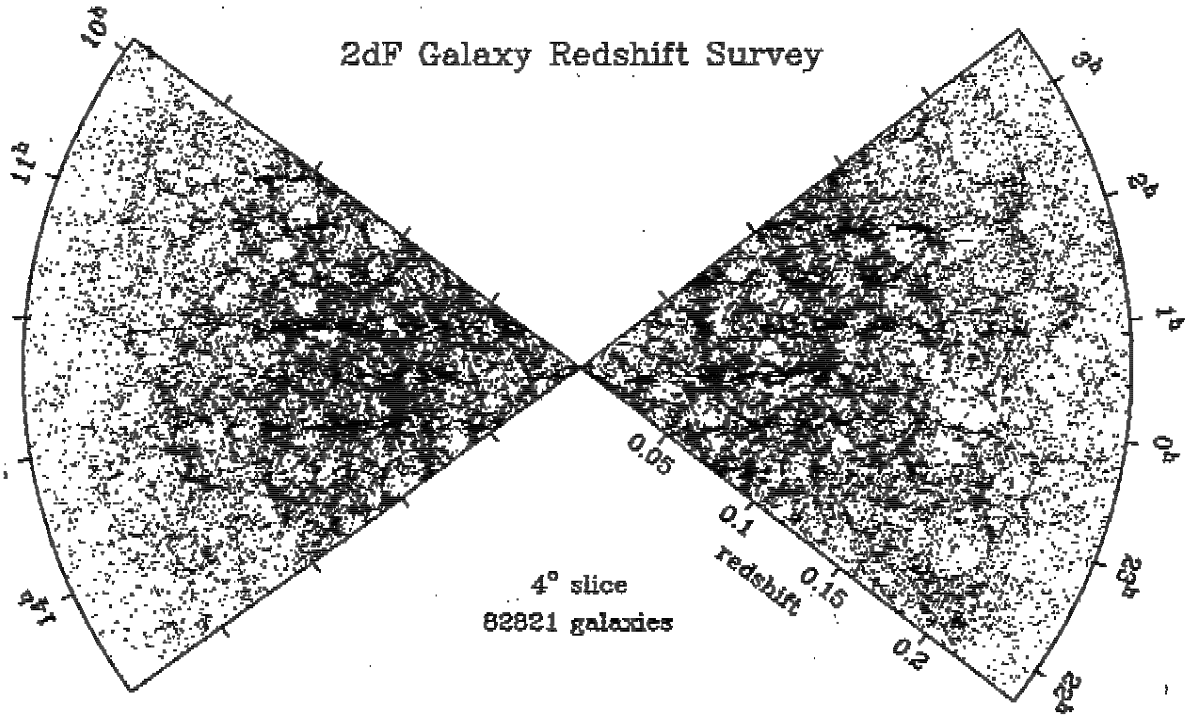
π IS AFFECTED BY RANDOM INDIVIDUAL VELOCITIES FOR NEARBY GALAXIES $\longrightarrow$ Fig. II

π IS AFFECTED BY INFALL FOR DISTANT GALAXIES $\longrightarrow$ Fig. III

FIG. IV : COMBINED EFFECT

Fig. 9.3

DM-17


2dF Galaxy Redshift Survey
10h
11h
12h
9h
8h
1h
0h
23h
22h
0.05
0.1
0.15
0.2
redshift
4° slice
82821 galaxies

VI. RICH GALAXY CLUSTERS

GALAXIES WHICH ARE GRAVITATIONALLY BOUND IN CLUSTERS CANNOT MOVE TOO FAST.

THE VIRIAL THEOREM

(FOR A STATISTICALLY STEADY, SPHERICAL, SELF-GRAVITATING CLUSTER OR OTHER OBJECTS):

THE TOTAL KINETIC ENERGY OF N OBJECTS WITH AVERAGE RANDOM PECULIAR VELOCITIES v

$= -\frac{1}{2} \times$ TOTAL GRAVITATIONAL POTENTIAL.

m = AVERAGE MASS

r = AVERAGE SEPARATION

$$N \frac{mv^2}{2} = \frac{1}{2} \frac{N(N-1)}{2} \frac{Gm^2}{r}$$

FOR A LARGE CLUSTER OF MASS

$$M = Nm$$

$$\Rightarrow \quad M = \frac{2rv^2}{G}$$

MEASUREMENTS SHOW THAT

$$\Omega_{grav} = \Omega_m = 0.2 - 0.3 \gg \Omega_b$$

THE CLUSTERS HAVE A DARK HALO

VII. LARGE-SCALE DISTRIBUTION OF MATTER IN THE UNIVERSE.

GRAVITATIONAL LENSING TRANSFORMS A CIRCULAR BACKGROUND GALAXY INTO AN ELLIPSE.

STATISTICAL ANALYSIS OF ELLIPTICITIES AND CORRELATIONS GIVES INFORMATION ON THE MATTER FIELD.

THE SKY IS COVERED BY A "WALL PAPER" OF FAINT AND DISTANT BLUE GALAXIES
$\approx$ 20000 - 40000 ON AN AREA OF THE SIZE OF THE MOON.

PRELIMINARY RESULTS:

$$\Omega_m \approx 0.3 \pm 0.1$$

MUCH WORK IS STILL NEEDED.

DM-21

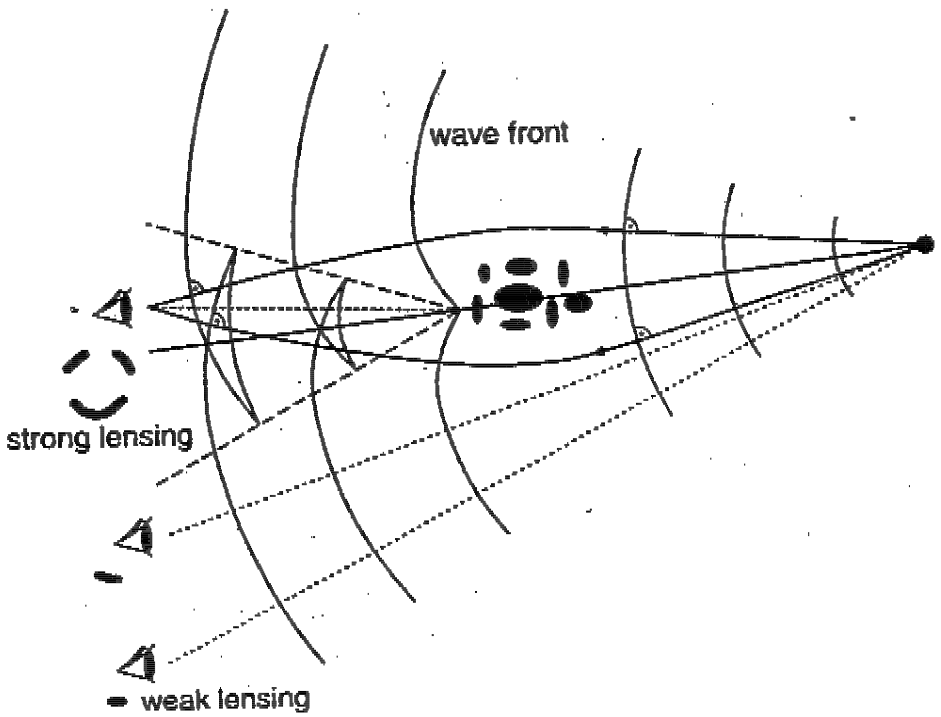
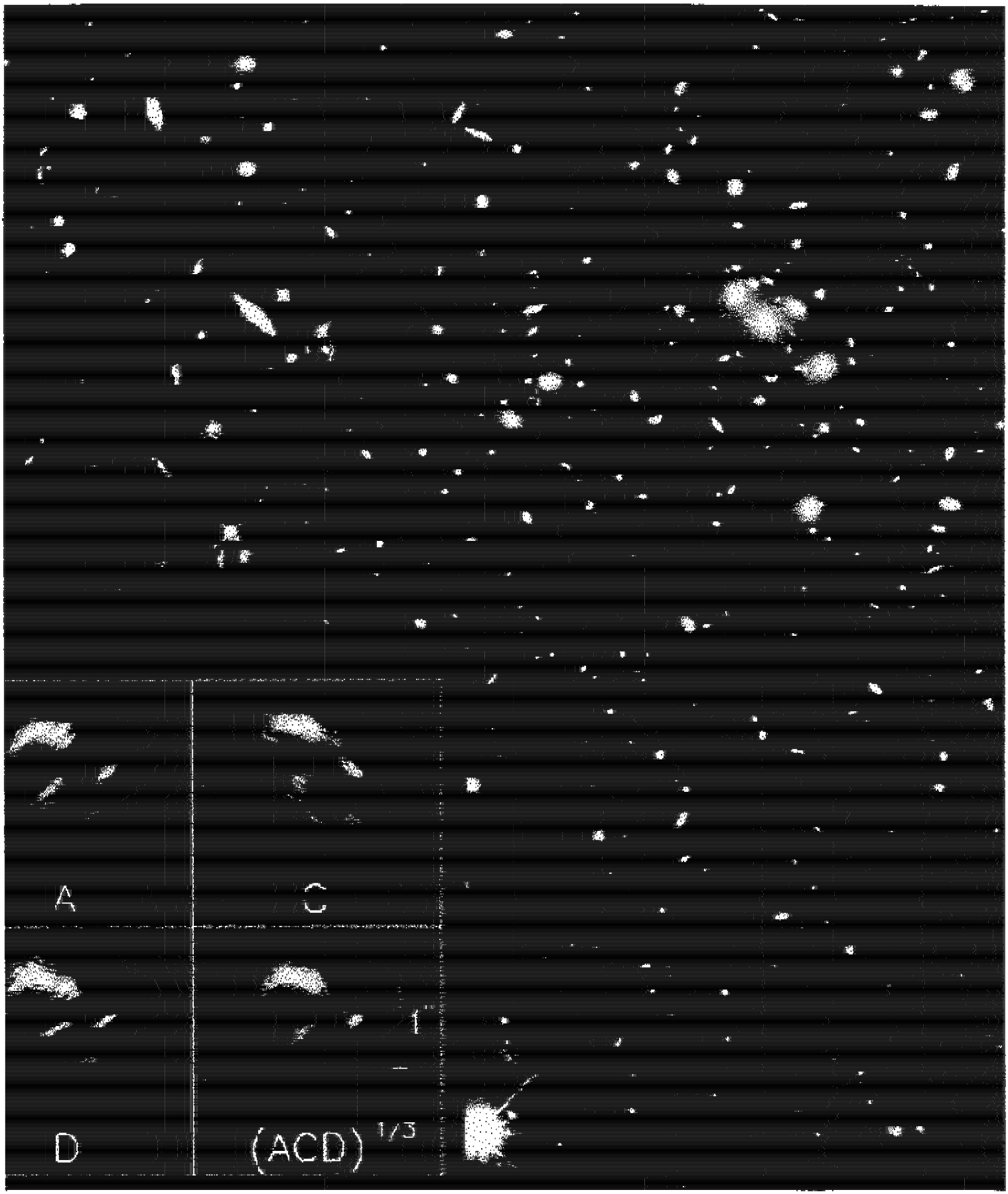


Fig. 3.3

LINS : GALAXGRUPP LENS = GROUP

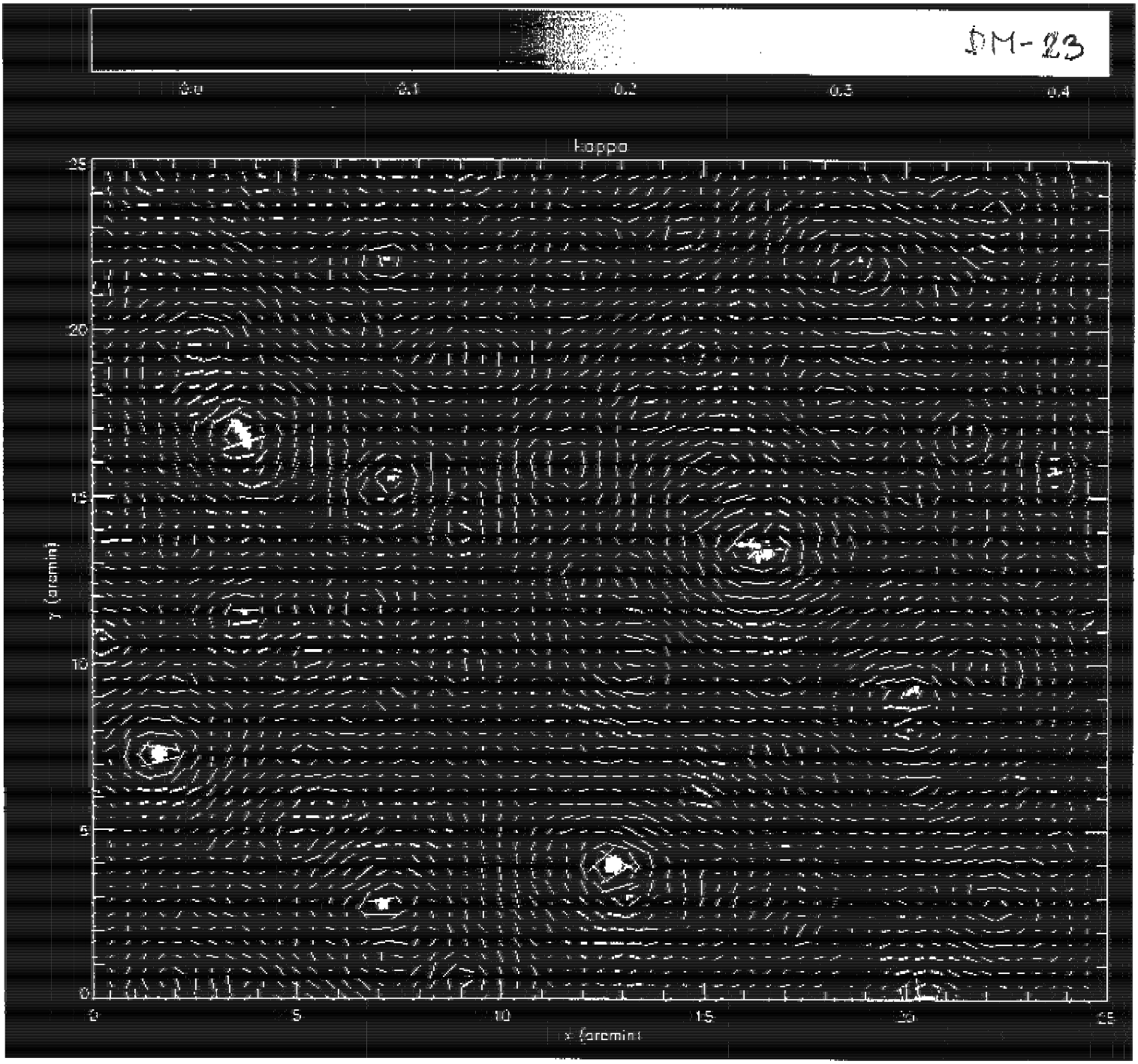
KÄLLA : GALAX SOURCE = GALAXY

-22



← REKONSTRUERAD KÄLLA

← RECONSTRUCTED SOURCE


DM-23
0.0
0.1
0.2
0.3
0.4
kappa
25
20
15
10
5
0
y (arcmin)
0
5
10
15
20
25
x (arcmin)

SHEAR MAP

CANDIDATES FOR DM

I. DARK BARYONIC MATTER IS NOW RULED OUT (WMAP!)

COLD GAS	WILL START TO RADIATE
COLD DUST	RE-RADIATES STAR LIGHT IN THE INFRARED. SO MUCH IS NEEDED THAT IT WOULD AFFECT STAR COMPOSITION.
SNOWBALLS	WILL SUBLIMATE AND BECOME GAS CLOUDS
JUPITERS AND BROWN DWARFS (MACHOS)	TOO FEW HAVE BEEN FOUND BY MICROLENSING.
BLACK HOLES	DO NOT SOLVE THE SPIRAL GALAXY PROBLEM. DM MUST BE RADIALLY SMOOTHLY DISTRIBUTED.

II. LEPTONIC HOT DM ALSO.

VERY HEAVY NEUTRINOS = HOT DM, DOES NOT CLUSTER ON GALACTIC SCALES OR CLUSTER SCALES

RULED OUT BY 2dFGRS AND WMAP

III. WARM DM ALSO.

STERILE NEUTRINOS

GRAVITINOS

FREE-STREAM TOO FAR, DO NOT CLUSTER RIGHT (2dFGRS SIMULATIONS)

IV. COLD DM IN THE FORM OF WIMPs (WEAKLY INTERACTING MASSIVE PARTICLES)

LIGHTEST SUSY PARTICLE (LSP)

NEUTRALINO $\tilde{Z}_1$. **REACTIONS:**

$\tilde{Z}_1 N$ SCATTERING, NUCLEAR RECOIL

$\tilde{Z}_1$ ANNIHILATION

FURTHER CONSTRAINTS

$\tilde{Z}_1$ CONCENTRATION = RELIC DM DENSITY

MORE CONCENTRATED IN THE INTERIOR OF THE EARTH, THE SUN ?

RARE DECAYS $b \to s\gamma$, $B_s \to \mu^+\mu^-$.

ANOMALOUS μ MOMENT $a_\mu = (g-2)_\mu$

FOR DETAILS, SEE hep-ph/0305191

WIMP MODELS

m SUGRA

HAS 4 FREE PARAMETERS AND SIGN(μ)

SO(10) SUSY GUT

HAS 6 FREE PARAMETES

GAUGINO MEDIATED SUSY BREAKING IN 5-DIMENSIONS OR MORE

EVENT RATE IN DETECTORS

$$\propto \sigma_{WIMP} A^2$$

A^2 ← DETECTOR MATERIAL NUCLEAR MASS NUMBER

σ_{WIMP} ← SPIN-INDEPENDENT ELASTIC SCATTERING, FROM THEORY

$10^{-48}\ cm^2 - 10^{-41}\ cm^2$

EXAMPLE: $m_{WIMP} = 50$ GeV

EVENT RATE = $5 \cdot 10^{-7} - 5$ $\frac{events}{kg\ Ge}$

THE DETECTOR MUST BE ABLE TO DISTINGUISH NUCLEAR RECOILS FROM X, γ, e^-, n RECOILS.

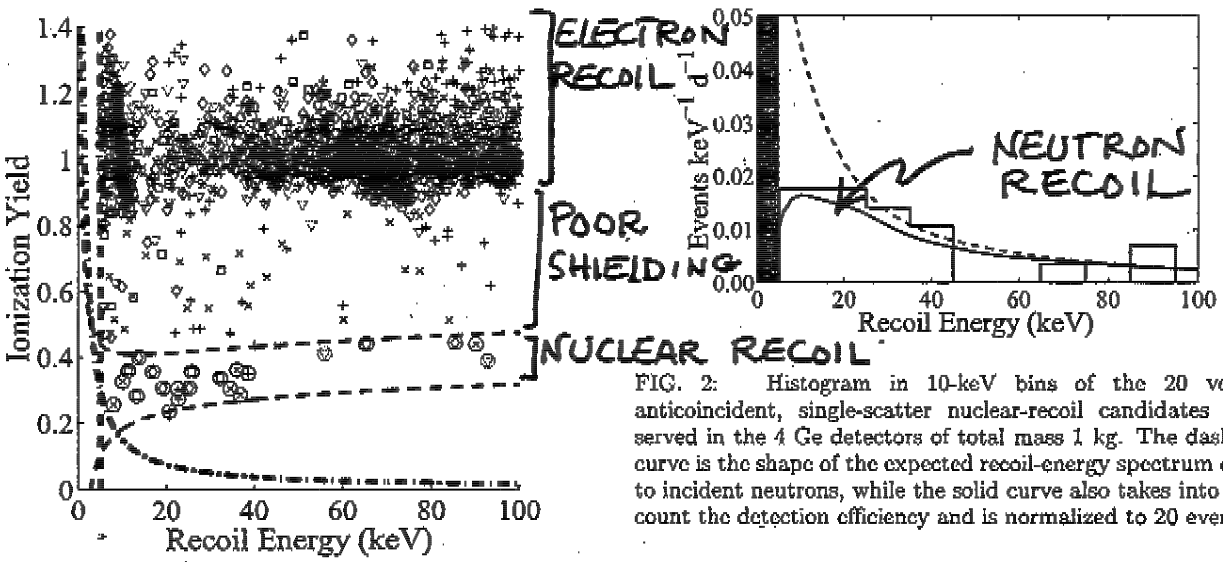


FIG. 1: Ionization yield (Y) vs. recoil energy for veto-anticoincident single scatters in the 4 Ge (black ×, diamond, square, and +) and 1 inner Si (grey triangle) detectors above the 5 keV analysis threshold (dashed vertical line). Twenty events (circled) lie within the mean nominal 95% nuclear-recoil acceptance region (dashed curves), above the ionization threshold (dot-dashed curve). Most of the events with $0.5 < Y < 0.8$ are in the top Ge detector (×), whose top face is unshielded, or in the bottom Ge detector (+), whose bottom disk region faces the contaminated Si detector.

FIG. 2: Histogram in 10-keV bins of the 20 veto-anticoincident, single-scatter nuclear-recoil candidates observed in the 4 Ge detectors of total mass 1 kg. The dashed curve is the shape of the expected recoil-energy spectrum due to incident neutrons, while the solid curve also takes into account the detection efficiency and is normalized to 20 events.

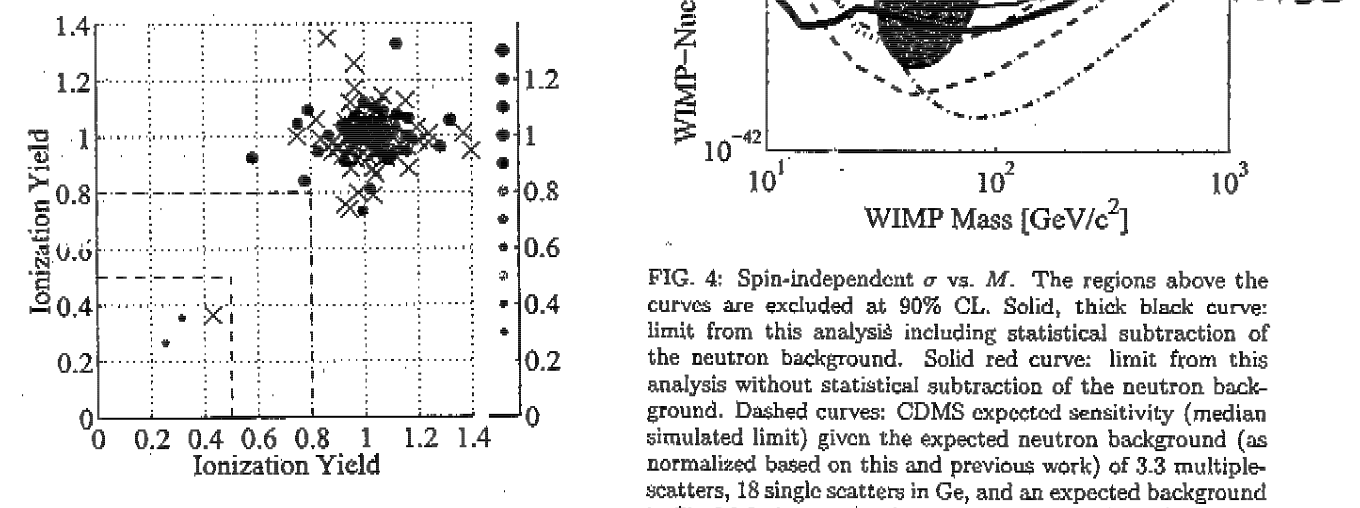


FIG. 3: Scatter plot of ionization yields for veto-anticoincident triple scatters (filled circles) and non-nearest-neighbor double scatters (×'s) with all scatters between 5 and 100 keV and within the fiducial volume. For triple scatters, the size and color of the circle indicates the ionization yield in the third detector. Note both neutron triple-scatter candidates show low yield in all three detectors, while no other triple scatters have low yield in any detector. As expected for such events, there is clearly negligible contamination from surface events.

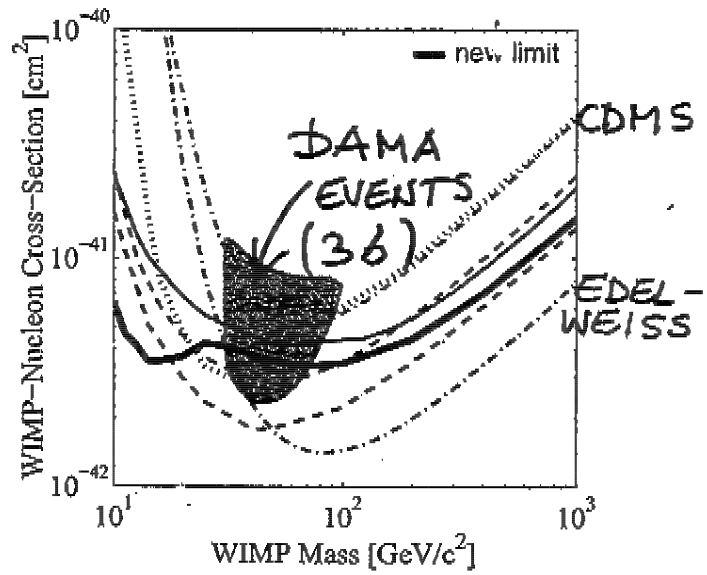


FIG. 4: Spin-independent σ vs. M. The regions above the curves are excluded at 90% CL. Solid, thick black curve: limit from this analysis including statistical subtraction of the neutron background. Solid red curve: limit from this analysis without statistical subtraction of the neutron background. Dashed curves: CDMS expected sensitivity (median simulated limit) given the expected neutron background (as normalized based on this and previous work) of 3.3 multiple-scatters, 18 single scatters in Ge, and an expected background in Si of 0.8 electrons and 3.6 neutrons, with (black) or without (red) neutron subtraction. Blue dotted curve: previous CDMS upper limit [6]. Green dot-dashed curve: DAMA limit using pulse-shape analysis [10]. The DAMA 3σ allowed region not including the DAMA limit [11] is shown as a shaded region. Above 30 GeV c^{-2}, the EDELWEISS [12] (purple dot-dashed curve) experiment provides more sensitive limits. All curves are normalized following [5], using the Helm spin-independent form-factor, A^2 scaling, WIMP characteristic velocity $v_0 = 220$ km s^{-1}, mean Earth velocity $v_E = 232$ km s^{-1}, and $\rho = 0.3$ GeV c^{-2} cm^{-3}.

DIRECT SIGNAL OF ASTROPHYSICAL ORIGIN : ANNUAL MODULATION.

THE SUN MOVES WITH $v_\odot = 220 \frac{km}{s}$.

THE EARTH MOVES AROUND THE SUN WITH $v = 15 \frac{km}{s}$.

∴ THE SUMMER/WINTER MODULATION

$$v = 220 \pm 15 \frac{km}{s}$$

THE WIMP FLUX IS EXPECTED TO VARY SINUSOIDALLY WITH AMPLITUDE

$$\lesssim 5\%$$

THIS VARIATION HAS BEEN

- CLAIMED
- REFUTED (ALSO BY KAMIOKA NaF SPIN-DEPENDENT DETECTOR)

∴ WAIT AND SEE

NEUTRALINO - PROTON CROSS-SECTION FOR VARIOUS CHOICES OF mSUGRA PARAMETERS.

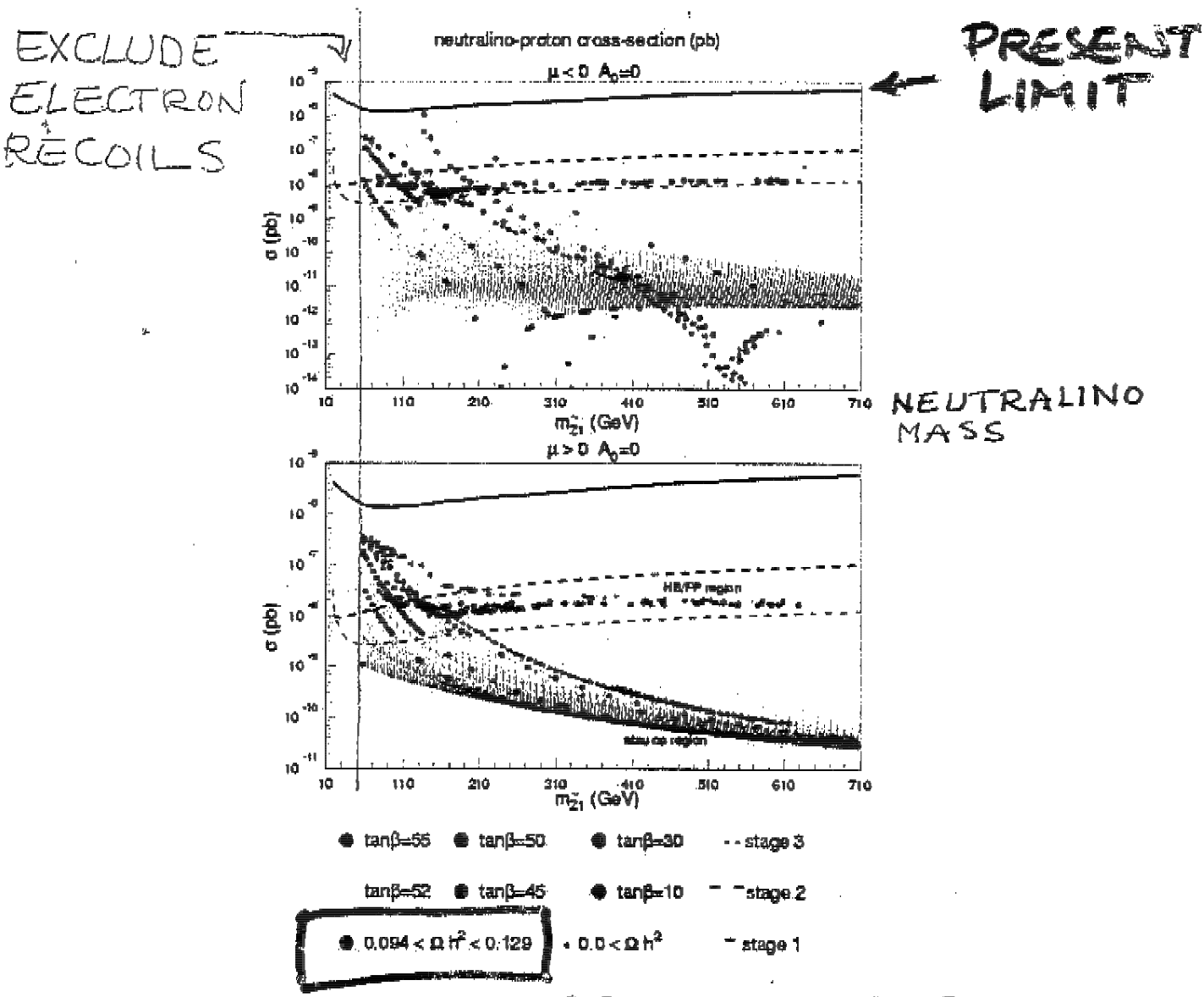
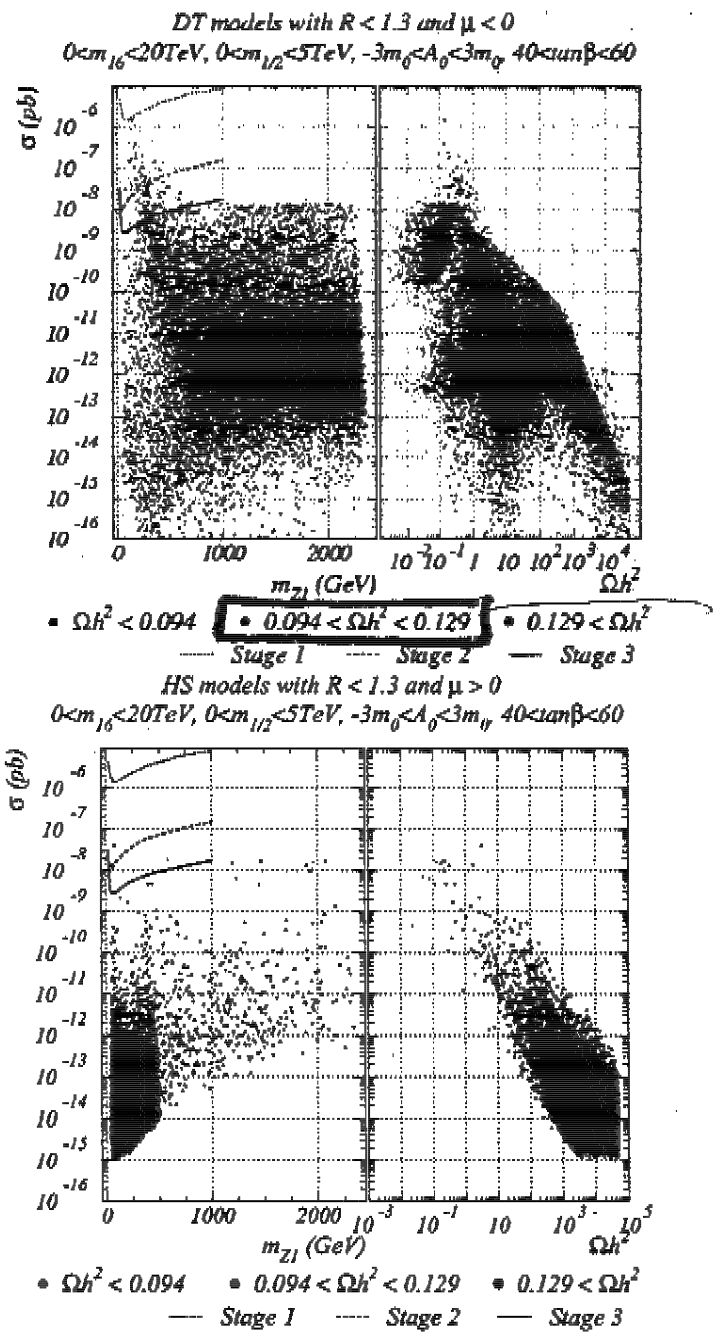


Figure 2: σ_{SI} versus neutralino mass

$\mu > 0$ is shown in frames *c.*) and *d.*). In the case of $\mu < 0$, much lower cross-sections are allowed, due to the above mentioned cancellations in quark-neutralino effective couplings. However, it is the $\mu < 0$ sign which is more restricted by a_μ and $BF(b \to s\gamma)$ constraints.

SO(10) SUSY GUT MODELS



RELIC DENSITY GREEN DOTS

Figure 5: Scattering spin-independent neutralino-proton rates versus neutralino mass(left) and Ωh^2(right) for DT(top) and HS(bottom) models

model) *i.e.*

$$m_Q^2 = m_E^2 = m_U^2 = m_{16}^2,$$

INDEPENDENT GAUGINO MASS SCENARIO

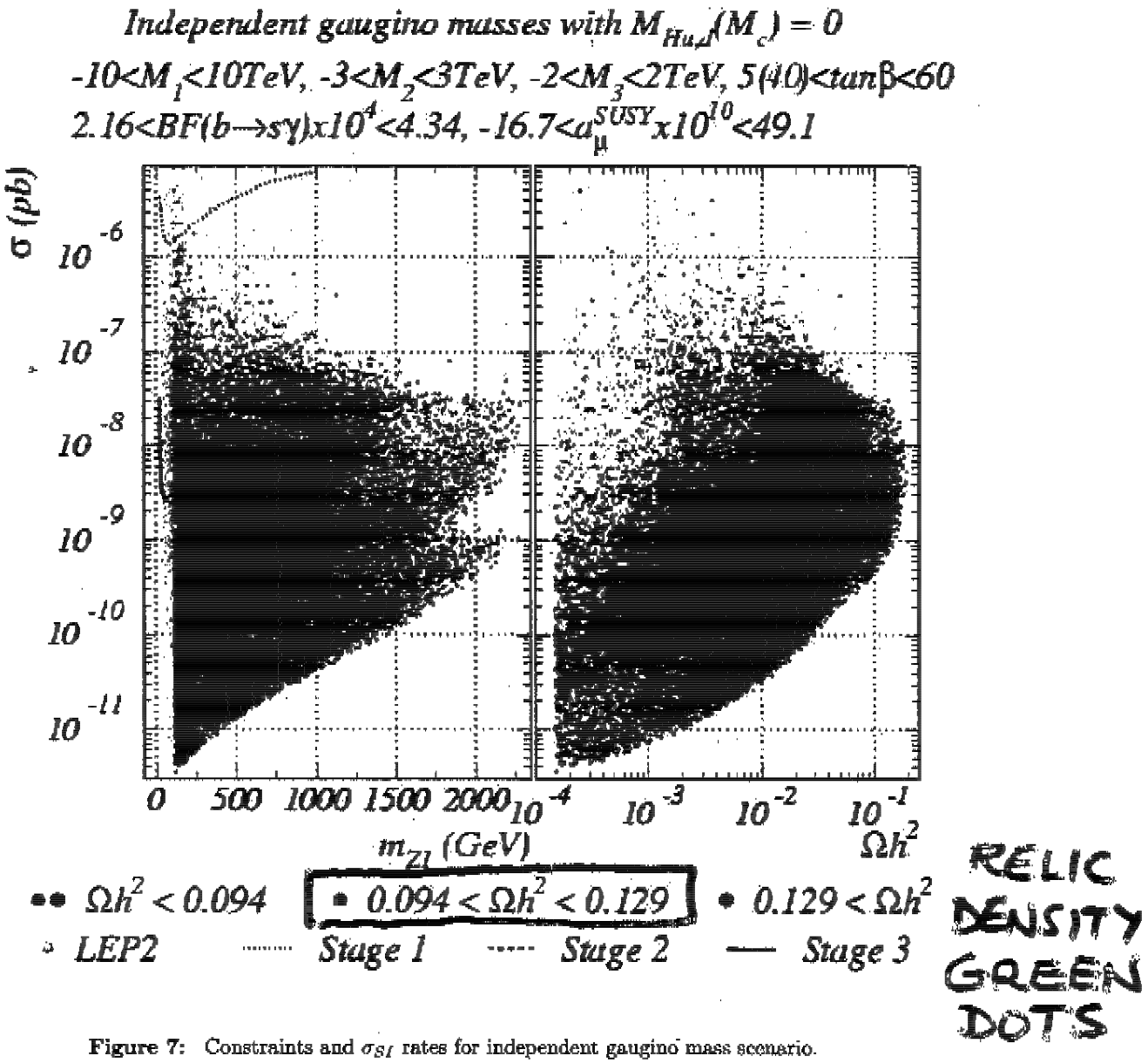


Figure 7: Constraints and σ_{SI} rates for independent gaugino mass scenario.

assuming that neutralino dark matter makes up the bulk of the local relic density.

If case 3 with $SO(10)$ breaking to the Pati-Salam group is invoked, then the parameter space becomes more restrictive, since now M_1 is determined by the choice of M_2 and M_3. In this case, we again plot parameter space in Fig. 9 in the M_2 *vs.* M_3 plane for $\tan\beta = 5$ (left) and 10 (right), with $\mu > 0$. The viable parameter space is again denoted by the green color, with experimental constraints indicated by various contours. Much higher values of $\tan\beta$ result in almost no viable parameter space[63]. The yellow-green regions again denote parameter space accessible to Stage 3 experiments.

DM-32

CONCLUSIONS

- DARK MATTER DOMINATES OVER BARYONIC MATTER ON EVERY SCALE.
- THE ONLY CANDIDATE IS SOME KIND OF COLD DM, NOT YET IDENTIFIED.

CAVEAT

ALSO CDM IS A BAD CANDIDATE. SIMULATIONS FAIL TO REPRODUCE THE LARGE-SCALE STRUCTURES OF MATTER.

WHAT IS NEEDED IS SOME **DARK ENERGY** REPRESENTING **A REPULSIVE FORCE.**

"COSMOLOGICAL CONSTANT" OR "QUINTESSENCE" OR NEW GRAVITY.

BUT THIS IS ANOTHER STORY ....