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SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

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DARK MATTER IN THE UNIVERSE

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Please note: These are preliminary notes intended for internal distribution only.

[redacted]

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I. Cosmology
- A. Evidence for Dark Matter
- B. Evidence for Nonbaryonic Dark Matter
- C. Local Halo Density

II. Dark-Matter Candidates
- A. MACHOS B. Light ν's
- C. Axions: Properties + Detection
- D. Weakly-Interacting Massive Particles (WIMPs)
  - 1. Properties 2. SUSY candidates
  - 3. Detection

III. Cosmic Microwave Background
- A. Determination of Ω_0, Ω_b, ...
- B. Tests of Inflation
  - 1. Anisotropies 2. Polarization

For More Information:

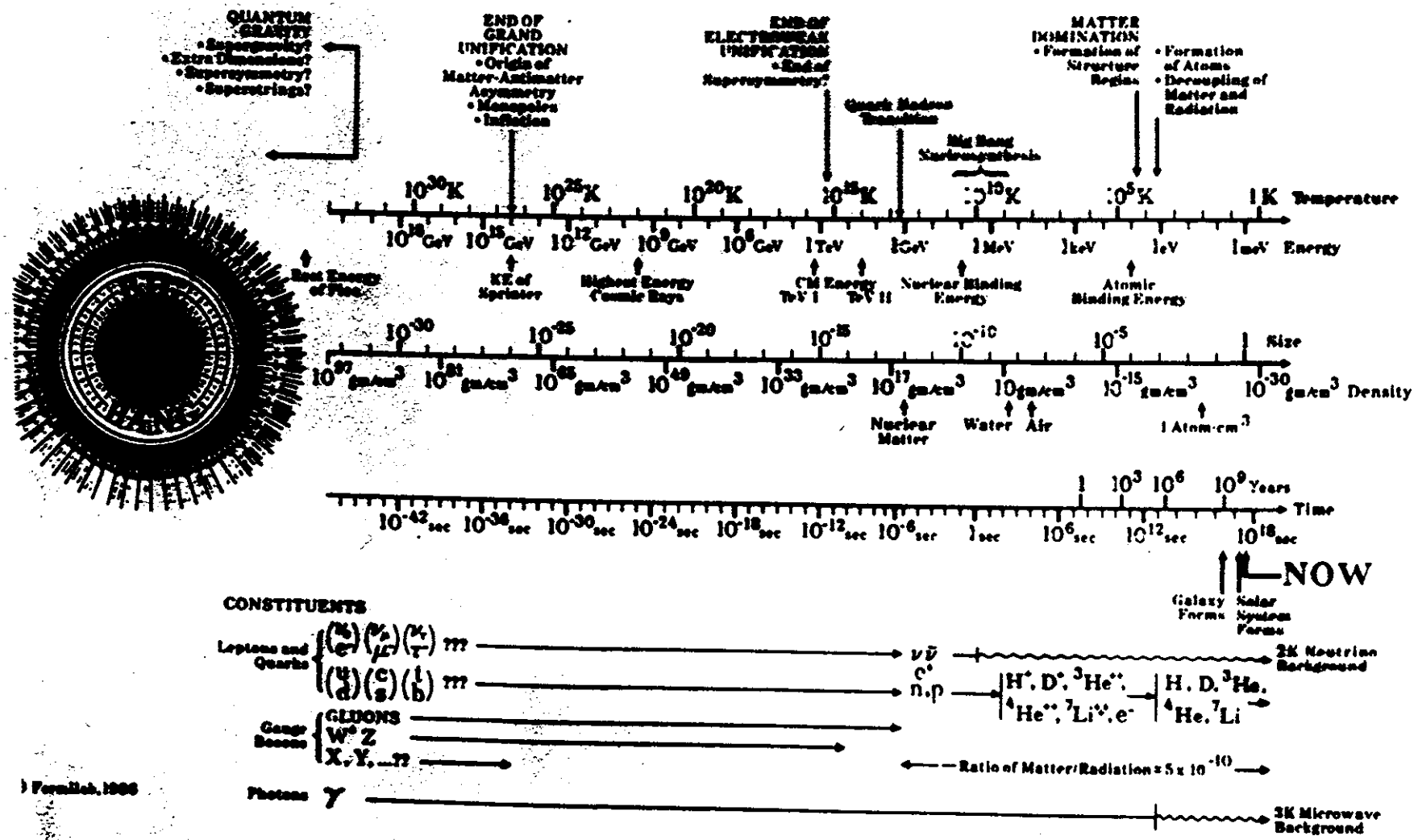
(1) Evidence for Dark Matter, WIMPs, 545 DM:
G. Jungman, M. Kamionkowski, + K. Griest,
Phys. Repts. 267, 195 (1996).

(2) Axions:
M. S. Turner, Phys. Rpts. 197, 67 (1990).
G. Raffelt, Phys. Rpts. 198, 1 (1990).
G. Raffelt's Book (U. Chicago Press).

(3) MACHOs
B. Paczyński,

(4) Thermodynamics Early-Universe, Light v's:
Kolb + Turner, Early Universe

(5) Cosmic Microwave Background:
Jungman, MK, Kosowsky, + Spergel,
Phys. Rev. D 54, 1332 (1996)
MK, Kosowsky, + Stebbins, astro-ph/9611125
Phys Rev. D (in press)



) Fermilab, 1986

PHYSICS REPORTS

Physics Reports 267 (1996) 195–373

Supersymmetric dark matter

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Abstract

There is almost universal agreement among astronomers that most of the mass in the Universe and most of the mass in the Galactic halo is dark. Many lines of reasoning suggest that the dark matter consists of some new, as yet undiscovered, weakly interacting massive particle (WIMP). There is now a vast experimental effort being surmounted to detect WIMPs in the halo. The most promising techniques involve direct detection in low-background laboratory detectors and indirect detection through observation of energetic neutrinos from annihilation of WIMPs that have accumulated in the Sun and/or the Earth. Of the many WIMP candidates, perhaps the best motivated and certainly the most theoretically developed is the neutralino, the lightest superpartner in many supersymmetric theories. We review the minimal supersymmetric extension of the standard model and discuss prospects for detection of neutralino dark matter. We review in detail how to calculate the cosmological abundance of the neutralino and the event rates for both direct- and indirect-detection schemes, and we discuss astrophysical and laboratory constraints on supersymmetric models. We isolate and clarify the uncertainties from particle physics, nuclear physics, and astrophysics that enter at each step in the calculations. We briefly review other related dark-matter candidates and detection techniques.

What IS the Dark Matter??

BBN: $\Omega_b < 0.1$

Nonrelativistic matter density: $\Omega_0 > 0.1$

- **Dynamics/LSS** ($\Omega_0 > 0.3$)
- **Quasar-Lensing Statistics**
- **Dicke Coincidence:** $\Omega_0 = 1$
- **Horizon Problem** $\Rightarrow$ **Inflation** (more than meets the eye)

$\Longrightarrow$ **Nonbaryonic Dark Matter**

also, Clusters: $\Omega_0 \gg \Omega_b$

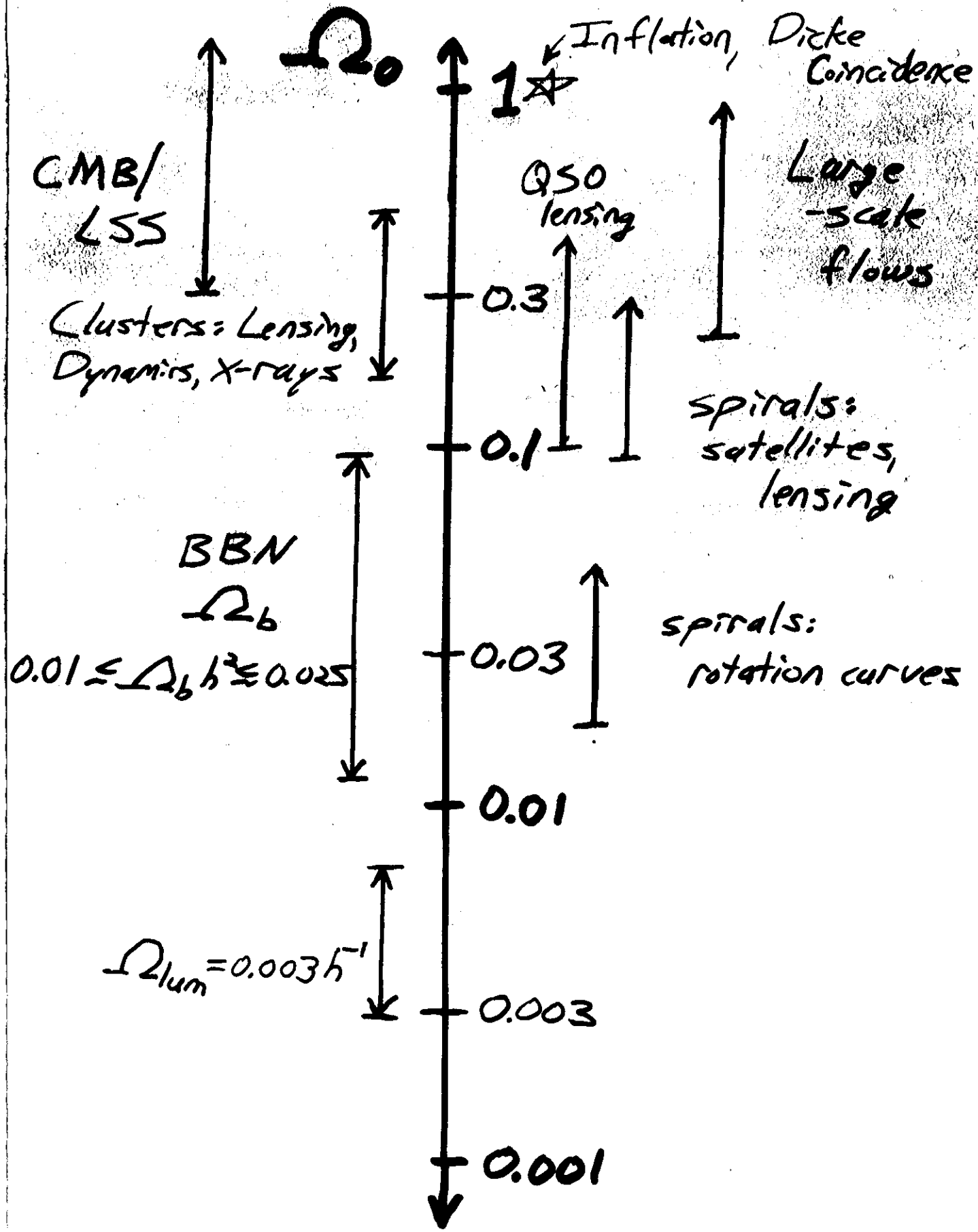
Massive Neutrinos??

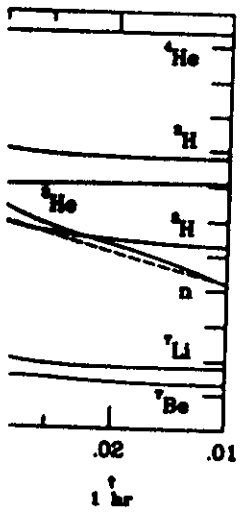
- Structure formation difficult
- Tremaine-Gunn (or Pauli principle): Can't pack so many light neutrinos into halo.

MACHOS??

- Why would halo baryons be dark??
- What if $\Omega_{halo} > \Omega_b$??
- μL in LMC: verdict not in

$\Longrightarrow$ DM = Something Else


Ω_0
1
Inflation, Dicke Coincidence
CMB/ LSS
Clusters: Lensing, Dynamics, X-rays
QSO lensing
Large-scale flows
0.3
0.1
spirals: satellites, lensing
BBN
Ω_b
$0.01 \leq \Omega_b h^2 \leq 0.025$
spirals: rotation curves
0.03
0.01
$\Omega_{lum} = 0.003 h^{-1}$
0.003
0.001



nthesis. The dashed line is the
n of ^{4}He, and the number aban-

io: $T_F \propto g_*^{1/6}$, at a higher
he dependence of T_F upon
of additional light particle

), $X_A \propto \eta^{A-1}$. For a larger
l build up slightly earlier,
rlier, when the neutron-to-
und the time ^{4}He synthesis
-proton ratio is only slowly
nsitivity of ^{4}He production
mount of D and ^{3}He left
asing η). This sensitivity
D and ^{3}He decreasing as
of $\eta \simeq 3 \times 10^{-10}$ results
, one which dominates at

ss fraction of ^{4}He is $Y_P =$
$0.014[\tau_{1/2}(n) - 10.6\ \text{min}]$.

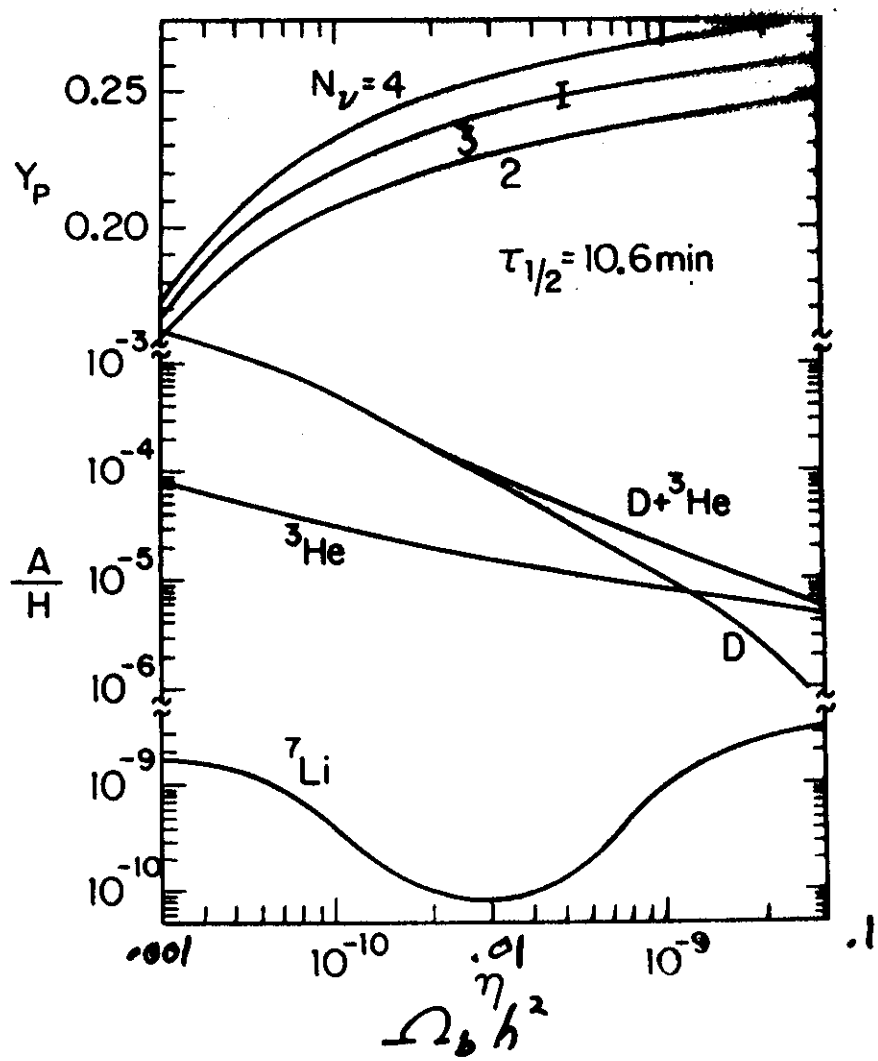


Fig. 4.4: The predicted primordial abundances of the light elements as a function of η. The error bar indicates the change in Y_P for $\Delta\tau_{1/2} = \pm 0.2$ min.

(1) Dark Matter is Abundant:

$$\Omega_0 >> \Omega_{lum}$$

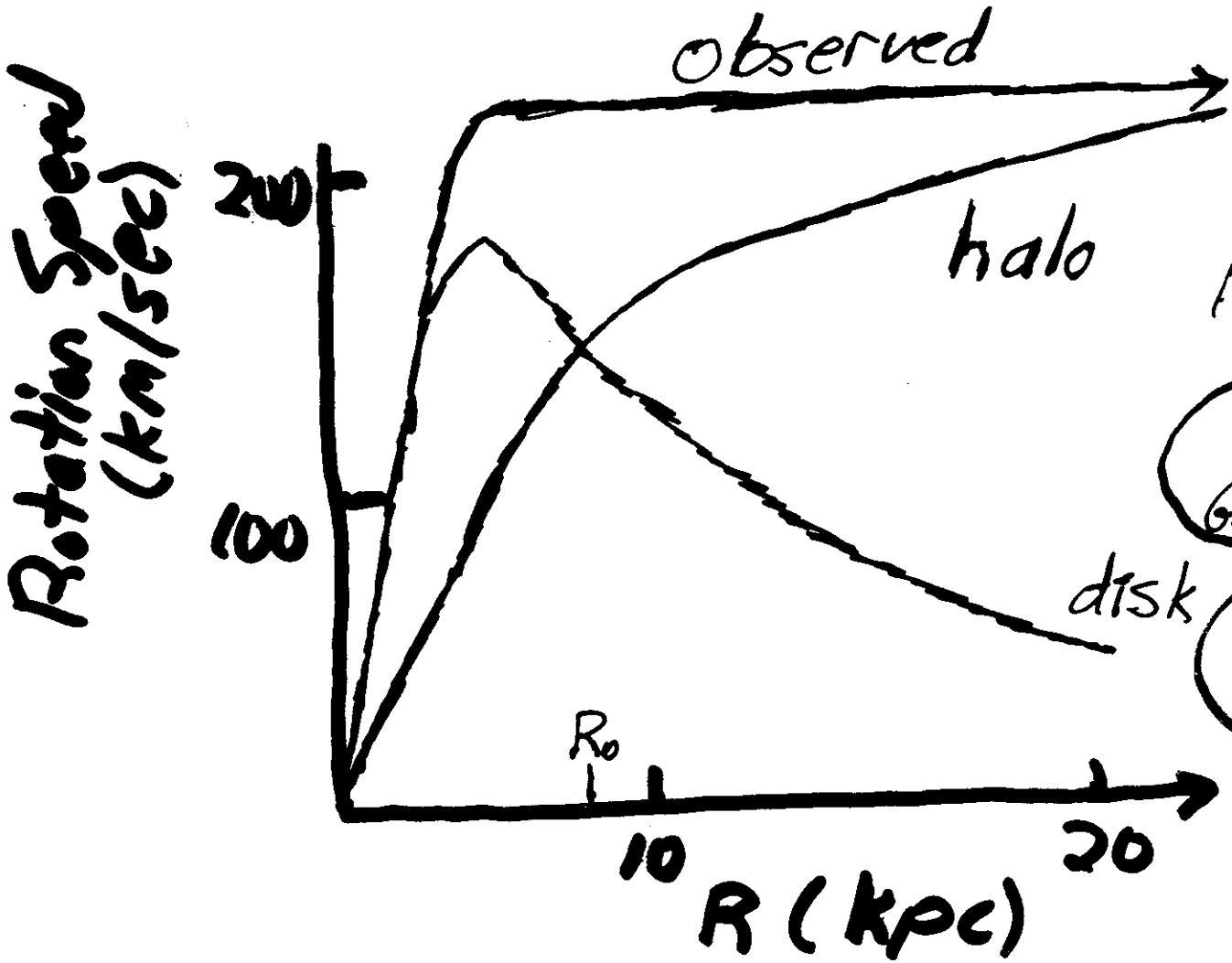
(2) There is Nonbaryonic Dark Matter:

$$\Omega_0 > \Omega_b$$

(Clusters: $\Omega_0 \gtrsim 3\Omega_b$

(3) Not Enough Baryonic Matter to Make Up All of Halo (probably).

$\Rightarrow \exists$ nonbaryonic matter in Galactic halo



Simple Halo Model:

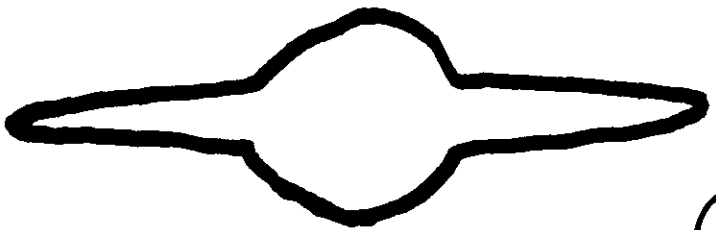
$$\rho(R) = \rho_0 \frac{R_0^2 + a^2}{R^2 + a^2}$$

~~0.005 – 0.013 $M_\odot / pc^3$~~

$0.2 \lesssim \rho_0 \lesssim 0.5$ GeV/cm^3

$\langle V^2 \rangle^{1/2} \simeq 270 \pm 70$ km/sec

(If halo flattened, $\rho_0 \uparrow$, $\langle V^2 \rangle^{1/2}$ unchanged)



$\Omega_{halo} \gtrsim 0.1$

Local Halo Dark-Matter Density:

Halo: $\rho_h(r) = \dfrac{\rho_0 (a^2 + r_0^2)}{a^2 + r^2}$

(ρ_0: local halo density; $r_0 \sim 8.5$ kpc (Galactocentric radius); a: scale factor)

DM velocity distribution:

(cored) isothermal sphere

$$f(\vec{v}) = \frac{e^{-\vec{v}^2/v_0^2}}{\pi^{3/2} v_0^3}$$

Circular speed: (from halo)

$$v_h^2(r) = 4\pi G \rho_0 (r_0^2 + a^2)\left[1 - \frac{a}{r}\arctan\frac{r}{a}\right]$$

$$\frac{a}{r_0}\arctan\frac{r_0}{a} = 1 - \frac{v_h^2(r_0)}{v_0^2} \leftarrow \text{fixes } a/r_0 \text{ given } v_h(r_0)/v_0$$

$v_0 = 220 \pm 30$ km/sec $= v_h(\infty)$ (since disk is finite)

$$\Rightarrow \rho_0 = \frac{v_0^2}{4\pi G r_0^2 [1 + (a/r_0)^2]}$$

$$= 0.47 \frac{\text{GeV}}{\text{cm}^3}\left(\frac{v_0}{220 \text{ km/s}}\right)^2 \left(\frac{r_0}{8.5 \text{ kpc}}\right)^{-2} \left[1 + \left(\frac{a}{r_0}\right)^2\right]^{-1}$$

Also, $v_0 = v_\infty$ $\quad \bar{v} = \langle v^2 \rangle^{1/2} = \sqrt{\frac{3}{2}} v_0 \simeq 270 \frac{\text{km}}{\text{s}}$

What is $V_d(r_0)$?

V_d ← disk contribution

$$V_{tot}^2(r) = V_h^2(r) + V_d^2(r)$$

↑ total rot speed

Disk contribution: $V_d^2(r_0) \simeq \left(37 \frac{km}{s}\right)^2 \left(\frac{\Sigma_0}{50 M_\odot pc^{-2}}\right)$

$$\Sigma_0 = 37\text{–}65 \; M_\odot / pc^2$$

$$\Rightarrow \quad 118 \; km/s < V_d(r_0) < 155 \; km/s.$$

$$150 \; km/s < V_h(r_0) < 185 \; km/s \quad (\text{for } V_0 = 220)$$

$$\Rightarrow \quad 0.06 \leq \frac{q}{r_0} \leq 0.9$$

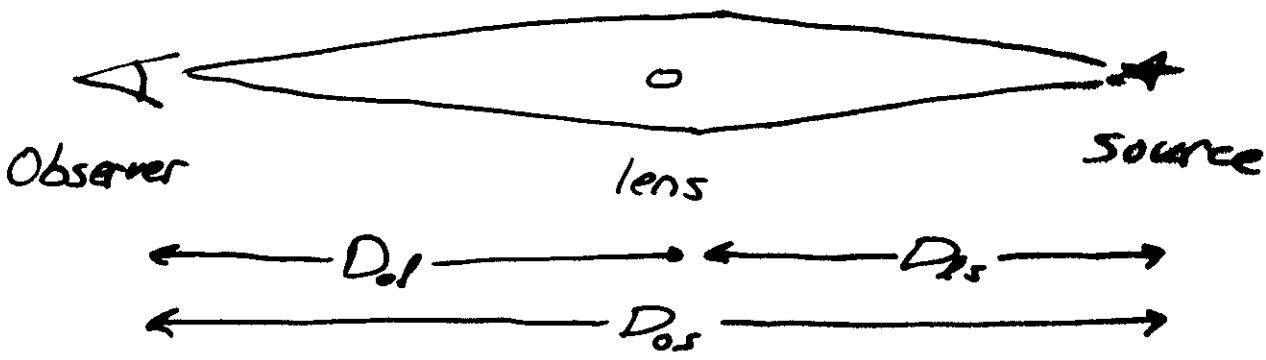
$$\Rightarrow \quad \rho_0 = 0.26 - 0.47 \; GeV/cm^3$$

(for $\Sigma_0 = 50$, $\frac{q}{r_0} = 0.6$ $\rho_0 = 0.35 \; GeV/cm^3$

If halo flattened $\rho_0 \nearrow$

$$\Rightarrow 0.1 \frac{GeV}{cm^3} \lesssim \rho_0 \lesssim 0.7 \frac{GeV}{cm^3}$$

Gravitational Microlensing and MACHOs in the Halo?

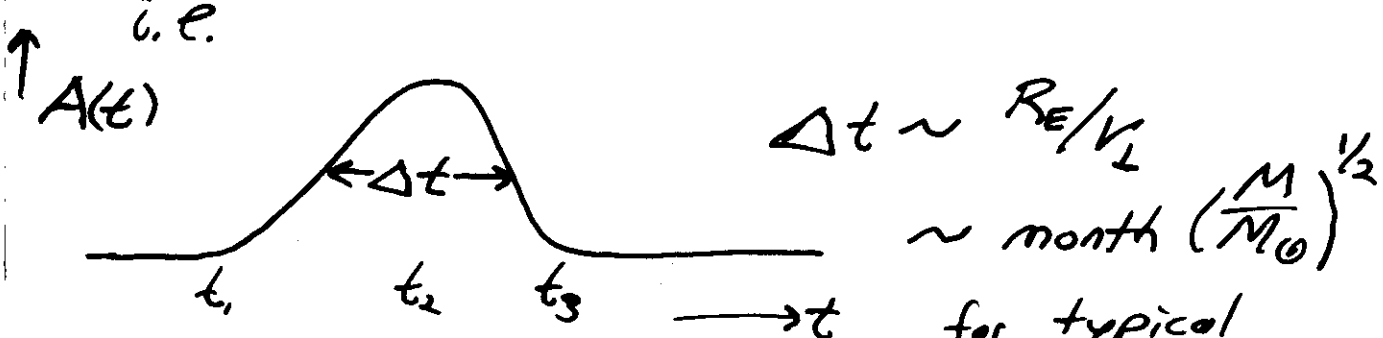


If lens lies within

$$R_E = \left[\frac{4GM_l}{c^2}\,\frac{D_{ol}D_{ls}}{D_{os}}\right]^{1/2}$$

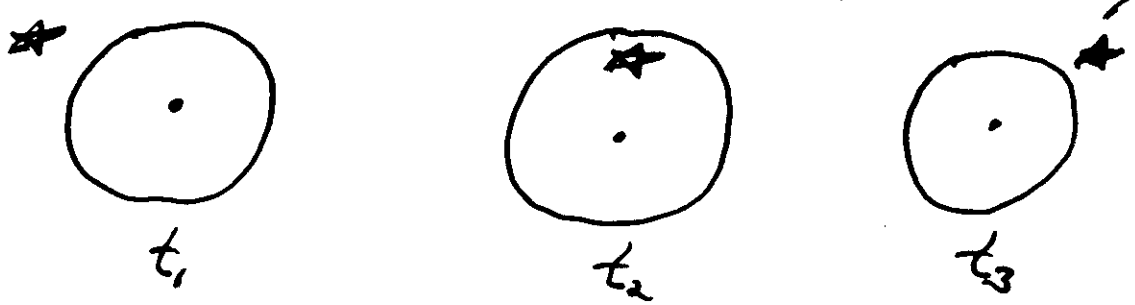
of observer-source line of sight, then the source is amplified by $A > 1.2$

i.e.



$$\Delta t \sim R_E/V_L \sim \text{month}\left(\frac{M}{M_\odot}\right)^{1/2}$$

for typical halo velocity



If n = number density of lenses,

"optical depth" $\tau \sim \pi R_E^2 D_{os} n$

is probability any given source is being lensed at any given time.

Expect $\tau \sim 10^{-6}$ for all-MACHO halo

50 kpc

LMC

Observed: 6–8 events toward LMC in 2 yrs data

$\Rightarrow$ 30–50% (± a lot) of halo in MACHOs

$\langle M_\ell \rangle \sim 0.4\, M_\odot$

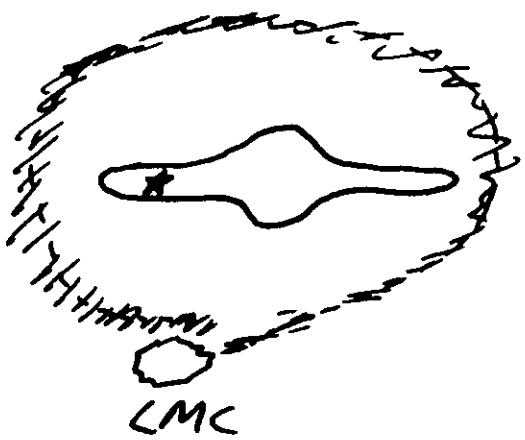
$\Rightarrow$ White Dwarfs?

However: $\tau^{obs}_{Bulge} \sim 2\text{–}3\ \tau^{pred}_{Bulge}$

— Why WD's in halo but absolutely no low-mass stars or stellar remnants?

— new variable stars? LMC lensing LMC? warp in our disk?

Another possible explanation:



Could be that faint LMC tail provides small stellar population just in front of LMC (Zhao 1998)

Recent: Zaritsky et al. find anomalous stellar population toward LMC which can be accounted for by an LMC tail at 40 kpc.

Are there MACHOs in the halo?

Verdict is still out.

Observations might be explained by conventional astrophysics; no halo.

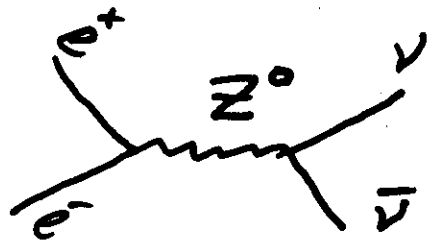
New observations will clarify.

Cosmological Abundance of Light ν

($m_\nu \lesssim$ [redacted] MeV)

Early Universe:

$\nu\bar{\nu} \longleftrightarrow e^+e^-$



$n_\nu \sim T^3$ $\quad \sigma(\nu\bar{\nu} \to e^+e^-) \simeq G_F^2 T^2$

(for $T \gg m_\nu$) $\quad \Gamma(\nu\bar{\nu} \longleftrightarrow e^+e^-) \simeq n\sigma v$

$\cong G_F^2 T^5$ ($\nu\bar{\nu}$ annihilation rate)

Expansion Rate: $H^2 \sim T^2/m_{pl}$

$\Gamma > H$ for $T \gtrsim$ MeV $\quad \nu\bar{\nu} \longleftrightarrow e^+e^-$

$\Gamma \lesssim H$ for $T \lesssim$ MeV $\quad \nu\bar{\nu} \not\longleftrightarrow e^+e^-$

$\therefore$ After $T \simeq$ MeV, $\nu\bar{\nu}$ annihilation "freezes out", and number of neutrinos per comoving volume remains constant:

$n_\nu a^3 = \text{const} \Rightarrow (n_\nu a^3)_{\text{today}} = (n_\nu a^3)_{T \simeq \text{MeV}}$

$(\text{Entropy}/\text{Comoving Volume}) = \text{const}$

Entropy density: $s \propto g_* T^3$

$$g_* = \sum_{\text{bosons}} g_i + \frac{7}{8}\sum_{\text{fermions}} g_i$$

(Effective # of relativistics degrees of freedom)

$T \simeq 1\,\text{MeV}$, $g_* = \frac{11}{2}$ $(g_\gamma = 2,\ g_{e^\pm} = 4)$

$T \simeq 2.7\,\text{K}$ (today) $g_* = 2$ $(g_\gamma = 2)$

Since $g_* T^3 a^3 = \text{const}$, $\left(\frac{T_\nu}{T_\gamma}\right)_{\text{today}} = \left(\frac{4}{11}\right)^{1/3}$

i.e., $n_\nu = \frac{3}{4}\left(\frac{4}{11}\right) n_\gamma$ today

(Fermi vs. Bose) ↑

So, $\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{m_\nu n_\nu}{\rho_c}$ $\quad n_\gamma = 411\ \text{cm}^{-3}$ $\quad \rho_c = 10^4 h^2\ \text{eV/cm}^3$

$$\Rightarrow \Omega_\nu h^2 = \frac{m_\nu}{90\,\text{eV}}$$ for two-component neutrino

e.g., if $h = 0.5$, $m_\nu = 5\,\text{eV} \Rightarrow \Omega_\nu = 0.2$

$m_\nu \simeq 25\,\text{eV} \Rightarrow \Omega_\nu \simeq 1$

Gunn-Tremaine Bound:

(Can't pack too many light fermions into galactic halo)

Heisenberg: $\Delta x \Delta p \gtrsim 1$

ν number density: $n_\nu = \frac{\rho_{halo}}{m_\nu}$

typical ν momentum: $\Delta p \simeq m_\nu \bar{v}$

for $\rho_{halo} = 0.3\ GeV/cm^3$

$\bar{v} \simeq 300\ km/sec$

$$m_\nu \gtrsim 10\ eV \left(\frac{\rho}{0.3\ GeV/cm^3}\right)^{1/4} \left(\frac{\bar{v}}{300\ km/s}\right)^{-3/4}$$

Dwarf galaxies: $\bar{v} \downarrow \Rightarrow m_\nu \uparrow$

QM: Light ν unlikely halo DM

Axions: Particle DM Candidate

Electromagnetism: $H_{em} \sim \vec{E}^2 + \vec{B}^2$

Strong Interactions (Quantum Chromodynamics):

$$H_{QCD} \sim \vec{E}_s^2 + \vec{B}_s^2 + a\,\vec{E}_s \cdot \vec{B}_s$$

Neutron Electric Dipole Moment:

$d_n \lesssim 10^{-25}$ e-cm $\Rightarrow$ coupling $a \lesssim 10^{-10}$!

Strong-CP Problem: Why a so small?

Peccei-Quinn Solution:

Make a dynamical variable,

Potential $V(a) \propto a^2$

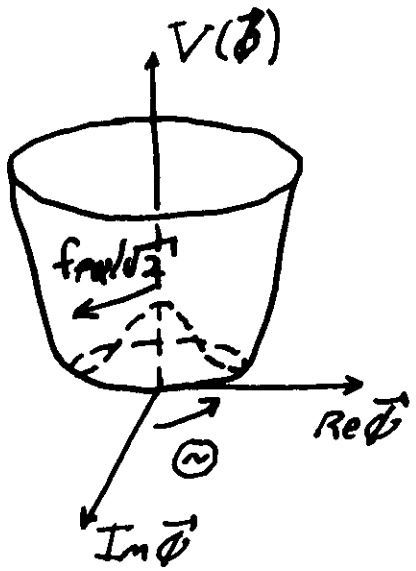
$\Rightarrow$ V minimized at $a=0$.

i.e., a is a scalar field;

its quanta are axions

(Wilczek, Weinberg)

A priori, $10^{-??} \lesssim m_a \lesssim 10^{19}$ GeV



Cosmological Production of Axions

$$V(\vec{\phi}) = \lambda\left(|\vec{\phi}|^2 - f_{PQ}^2/2\right)^2$$

$$\langle|\vec{\phi}|\rangle = f_{PQ}/\sqrt{2}$$

NG field: $a = f_{PQ}\,\theta$

$T \gg \Lambda_{QCD} \Rightarrow m_a = 0$

$T \ll \Lambda_{QCD}$, $V(a) = m_a^2 f_{PQ}^2\left(1 - \cos\left[\frac{a}{f_{PQ}}\right]\right)$

$$\simeq \frac{1}{2} m_a^2 a^2 + \cdots$$

$$m_a \simeq \frac{1}{2}\frac{f_\pi m_\pi}{f_{PQ}} \simeq 0.62\,eV\,\frac{10^7\,GeV}{f_{PQ}}$$

i.e. at $T \sim \Lambda_{QCD}$, instanton effects tip the Mexican hat.

then, θ oscillates: $\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$

soln: $\rho_a = \frac{1}{2} f_{PQ}^2\left[\langle\dot{\theta}^2\rangle + m_a\langle\theta^2\rangle\right]$

$\propto a^{-3}$

$\therefore$ axions form cold nonrelativistic condensate

Estimate of cosmological axion mass density:

$$\frac{\rho_a}{s} \simeq \frac{m_a^2 f_{PQ}^2 \theta^2/2}{2\pi^2 g_* T_{QCD}^3/45} = \text{const}$$

$T_{QCD} \simeq$ GeV $\quad g_* \simeq 60 \quad m_a f_{PQ} \simeq m_\pi f_\pi$

$$\Rightarrow \frac{\rho_a}{s} \simeq 500\,\text{eV}$$

$$\Omega_a = \frac{\rho_a}{\rho_c} = \frac{(\rho_a/s)\, s_{\text{today}}}{\rho_c}$$

$s_{\text{today}} \leftarrow 2970\ \text{cm}^{-3}$

$\rho_c \leftarrow 10^4 h^2\ \text{eV/cm}^3$

$$\Rightarrow \Omega_a h^2 \simeq 100$$

More precisely:

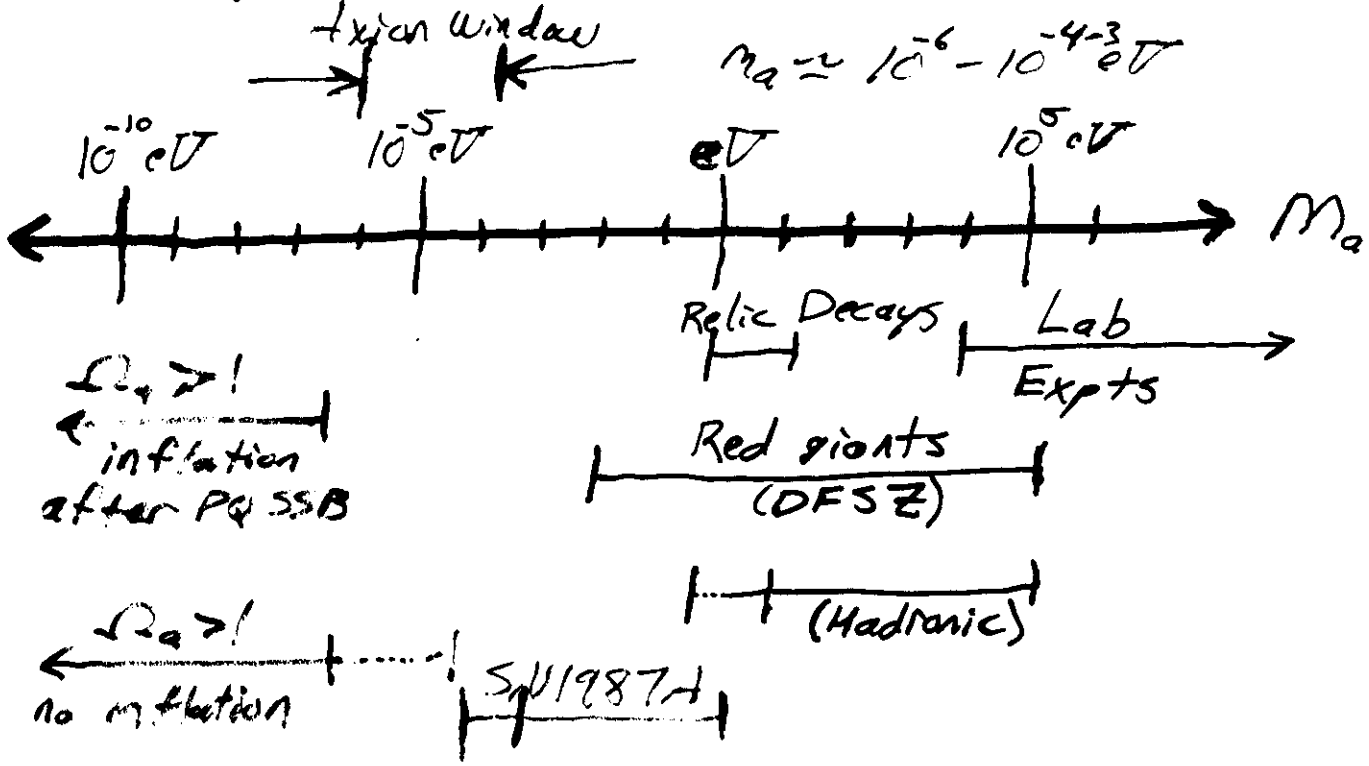
$$\Omega_a h^2 = 0.1 \times 10^{\pm 0.4}\, \theta_i^2 \left(m_a/10^{-5}\text{eV}\right)^{-1}$$

or

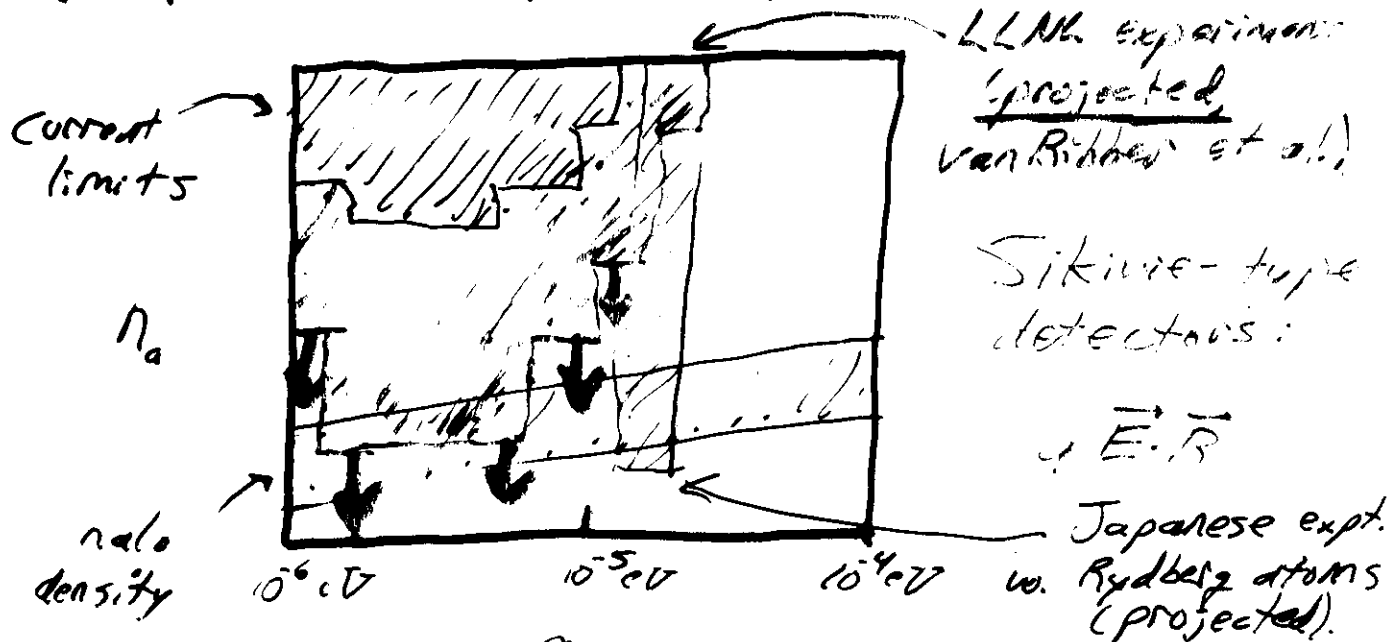
$$= 0.85 \times 10^{\pm 0.4} \left(m_a/10^{-5}\text{eV}\right)^{-1}$$

if $\langle \theta^2 \rangle = \pi^2/3$

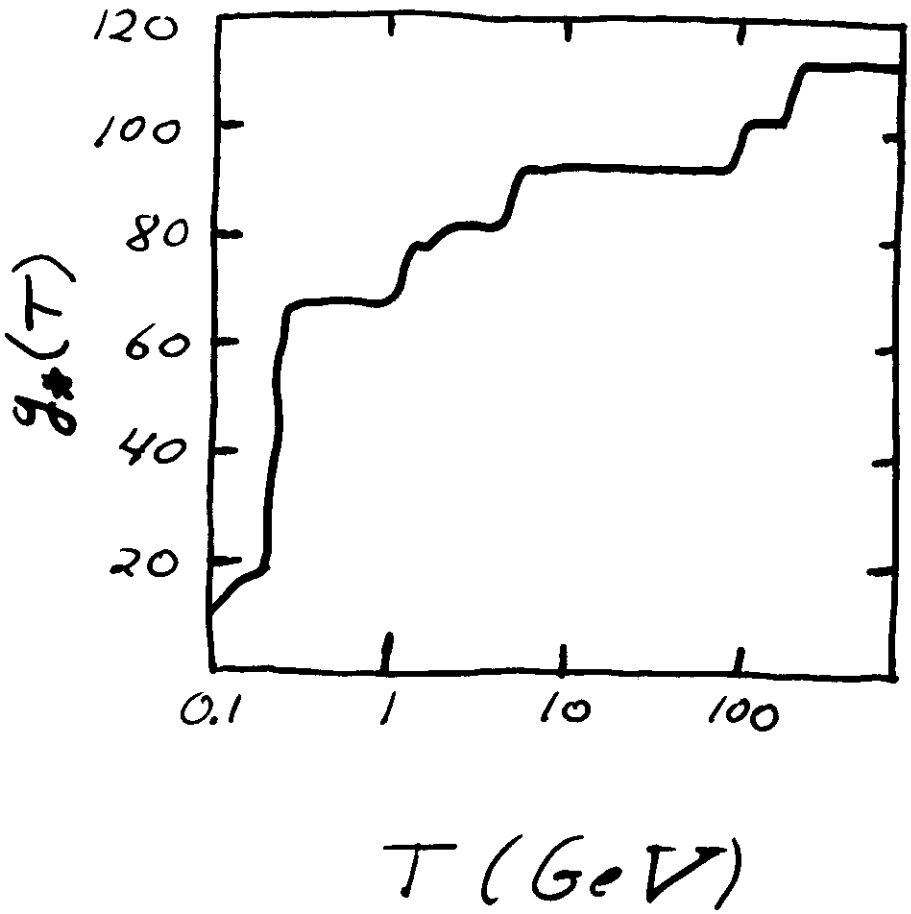
Axion Mass Constraints

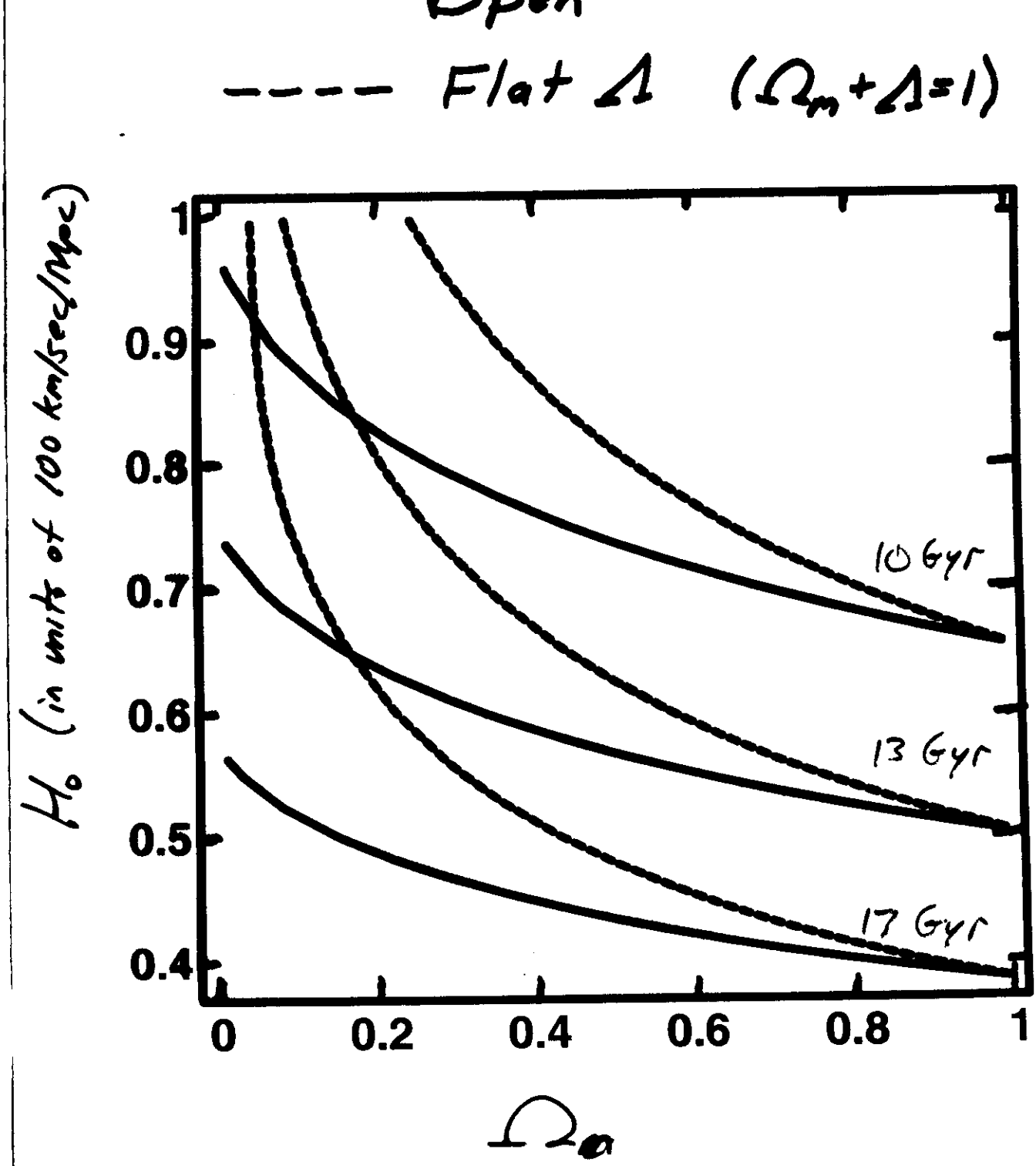


PROBING THE AXION WINDOW:

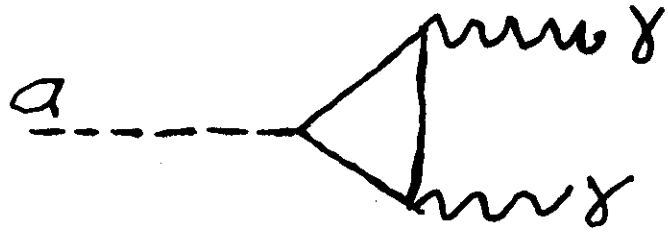


See van Bibber et al. Particle Astrophysics, 1990 ed. Cline + Perkins


120
100
80
60
40
20
$g_*(T)$
0.1
1
10
100
T (GeV)


Open
Flat Λ (Ω_m + Λ = 1)
H_0 (in units of 100 km/sec/Mpc)
1
0.9
0.8
0.7
0.6
0.5
0.4
0
0.2
0.4
0.6
0.8
1
Ω_0
10 Gyr
13 Gyr
17 Gyr

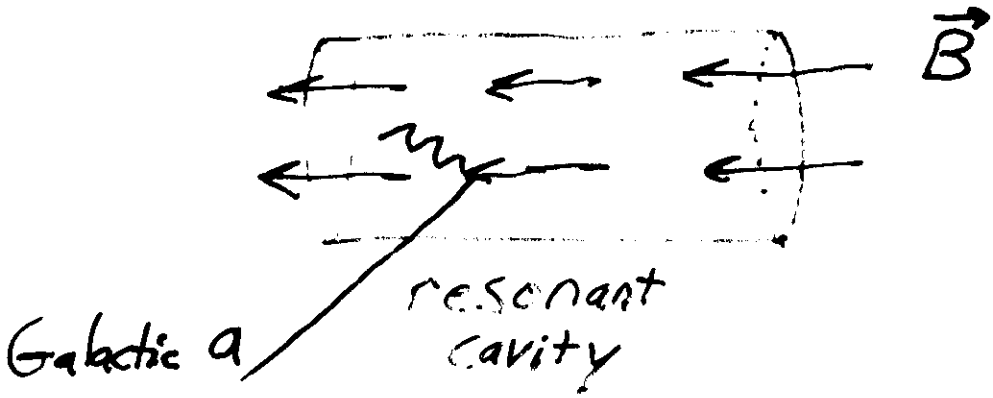
Axion Detection:



$$\tau_{a\to\gamma\gamma} \sim 10^{50}\,\text{sec}\left(\frac{m_a}{10^{-5}\,\text{eV}}\right)^{-5} >> t_u$$

!

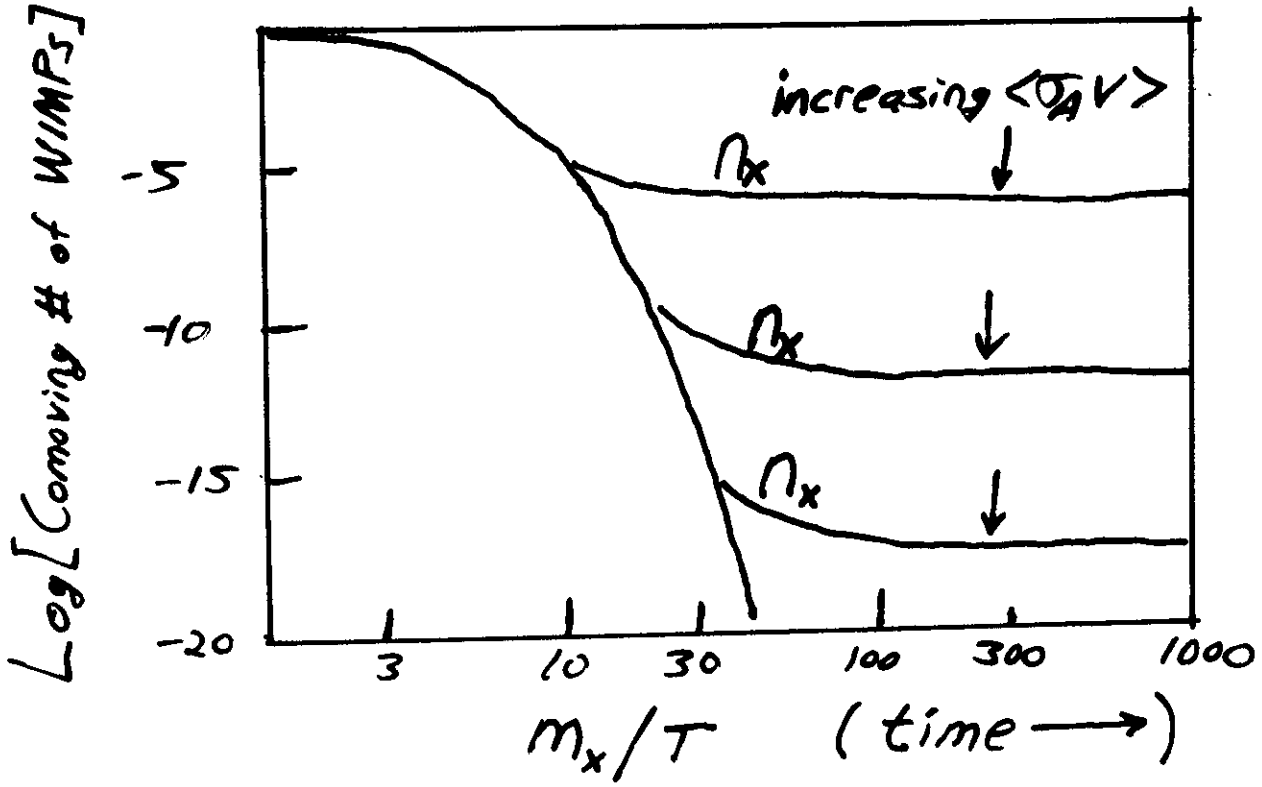
$$\mathcal{L}_{int} \propto a\vec{E}\cdot\vec{B}$$



Convert Galactic axions to fundamental-mode excitations of resonant cavity in strong $\vec{B}$ field.

(Sikivie)

Cosmological Abundance of WIMPs:



Thermal Equil. from $(X\bar{X} \leftrightarrow q\bar{q}, \ell\bar{\ell}, W^+W^-, \ldots\ldots)$

Rate $\Gamma(X\bar{X} \to \text{stuff}) = n_x \langle\sigma_A v\rangle$

Expansion Rate: $H \sim \sqrt{G\rho} \sim T^2/m_{Pl}$

Early: $T \gg m_x$ $\quad n_x \sim T^3 \sim n_\gamma$ $\quad \Gamma^{-1} \gg H$

Late: $T \ll m_x$ $\quad n_x^{eq} \sim e^{-m_x/T}$ $\quad \Gamma^{-1} \ll H$

$\Rightarrow$ Freezeout at $\Gamma \simeq H$

Also $\Omega_x \propto \langle\sigma_A v\rangle^{-1}$

Relic Abundance of WIMP:

Equilibrium # density: $n_\chi^{eq} = \frac{g}{(2\pi)^3}\int f(\vec{p})\, d^3\vec{p}$

$$f(\vec{p}) = \frac{1}{e^{-E/kT} \pm 1}$$

$T >> m_\chi$: $n_\chi^{eq} \propto T^3 \sim n_\gamma$

$T << m_\chi$: $n_\chi^{eq} \simeq g\left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$

$T >> m_\chi$: $\chi\bar{\chi} \leftrightarrow l\bar{l}$ ← maintains equil. # density

$l = \{\nu, e, \mu, \tau, u, s, d, c, b, t, W^\pm, Z^0, H^0, \ldots\}$

Interconversion rate: $\Gamma = \langle \sigma_A v \rangle n_\chi$

More generally, n_χ satisfies Boltzmann eq:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

$H(T) = 1.66 g_*^{1/2} T^2/m_{pl}$

$T \gtrsim m_\chi$, $H \propto T^2$, $n_\chi \propto T^3$, $H << \langle \sigma_A v \rangle n_\chi$

$T \lesssim m_\chi$, $n_\chi^{eq} \sim e^{-m_\chi/T}$, $n_\chi \langle \sigma_A v \rangle << H$

$\Rightarrow$ n_χ "freezes out" at temperature T_f

when $\Gamma(T_f) \simeq H(T_f)$ $\quad T_f \sim m_\chi/20$

After freezeout, $\frac{n_\chi}{s} \simeq \text{const}$, $s \simeq 0.4 g_{*s} T^3$

Using $\Gamma = \langle \sigma_A v \rangle n_\chi = H$ at freezeout,

$$\left(\frac{n_\chi}{s}\right)_0 = \left(\frac{n_\chi}{s}\right)_f \simeq \frac{100}{m_\chi m_{pl} g_*^{1/2} \langle \sigma_A v \rangle}$$

$$= \frac{10^{-8}}{\left[\left(m_\chi/\text{GeV}\right)\left(\langle \sigma_A v \rangle / 10^{-27}\,\text{cm}^3/\text{sec}\right)\right]}$$

$s_0 \simeq 4000\ \text{cm}^{-3}$ $\quad \rho_c \simeq 10^{-5} h^2\ \text{GeV/cm}^3$

$$\Rightarrow \Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq \frac{3 \times 10^{-27}\,\text{cm}^3/\text{sec}}{\langle \sigma_A v \rangle}$$

More accurately:

$$\sigma_A v = a + b v^2 + \cdots$$

$$\Omega_\chi h^2 = 2.82 \times 10^8 \gamma_\infty \left(m_\chi/\text{GeV}\right)$$

$$\gamma_\infty^{-1} = 0.264\, g_*^{1/2} m_{pl} m_\chi \left\{ \frac{a}{x_f} + 3\frac{(b - \frac{1}{4}a)}{x_f^2} \right\}$$

$$x_f = \ln\left[0.0764\, m_{pl} \left(a + \frac{6b}{x_f}\right) c(2+c) m_\chi / \left(g_*^{1/2} x_f^{1/2}\right) \right]$$

$g_* = g_*(T_f)$ $\quad c \simeq 1/2$

Boltzmann Eqn:

$$\Rightarrow \Omega_x h^2 \simeq \left(\frac{\langle \sigma_A v \rangle}{3 \times 10^{-27}\ \mathrm{cm^2\ sec^{-1}}} \right)^{-1}$$

Suppose $X \equiv$ new particle with electroweak interactions

$$\Rightarrow \sigma \sim \frac{\alpha^2}{(100\ \mathrm{GeV})^2}$$

(α^2 ← fine-structure constant; $100\ \mathrm{GeV}$ ← typical EW mass)

$\therefore$ If $\sigma_A v \sim$ electroweak scale

$$\Rightarrow \Omega_x \sim 1 \quad !!$$

(i.e. If $\exists$ another stable EW particle, it should be the dark matter.)

E.g. X = Heavy ν ($m_\nu \lesssim$ TeV; $m_\nu \gtrsim$ GeV)

More plausible: Lightest Supersymmetric Particle.

(Relevant) Aside:

Model-Independent Bound to WIMP Mass:

(Kamionkowski + Griest, PRL 64 1991)

$$\Omega_x h^2 \simeq \frac{3\times10^{-27}\ \mathrm{cm^3/sec}}{\langle \sigma_A v\rangle}$$

$t_u \gtrsim 10\ \mathrm{Gyr} \Rightarrow \Omega_x h^2 \lesssim 1$

Unitarity (i.e., probability ≤ 1):

$$\langle \sigma_A v\rangle \lesssim \frac{3\times10^{-22}\ \mathrm{cm^3/sec}}{(m_x/\mathrm{TeV})^2}$$

$$\Rightarrow \langle \sigma_A v\rangle \gtrsim 3\times10^{-27}\ \mathrm{cm^3/sec}$$

$$\Rightarrow \boxed{m_x \lesssim 300\ \mathrm{TeV}}$$

= for strong interaction

for weak interaction σ reduced by α^2;

so expect $m_x \lesssim 3\ \mathrm{TeV}$ for WIMP

Supersymmetry:

New symmetry between fermions/bosons
(like isospin for proton/neutron).

For every fermion, ∃ bosonic partner + vice versa.
(e.g. electron ↔ selectron, quark ↔ squark)

Why?

(1) Explains Mass Hierarchy (EW: 10^{15-19} GUT/Planck)

(2) Gravity (3) Strings (4) Aesthetics

(5) Coupling-Constant Unification (6), (7), ...

Cosmology:

New symmetry (R parity) ⇒ Lightest SUSY particle is stable

and weakly interacting ⇒ $\Omega_{LSP} \sim 1$

Undetermined SUSY Parameters:

M (gaugino mass)

μ (higgsino mass)

$\tan\beta$ ($\langle \phi_2 \rangle / \langle \phi_1 \rangle$)
$= m_t/m_b$

Determine Mass and Composition of $\tilde{\chi}$

$M_{\tilde{q}}$ (squark masses)
$> m_\pi$

M_{H^0} (mass of lightest Higgs)
$< m_Z$

Qualitative Results Relatively Insensitive to Most Parameters

~~m_t (top quark mass)~~

~~20 – 200 GeV~~

$6^2 3$ parameters in minimal SUSY SM

predicted by, e.g., GUTs, SUGRA, strings

Most models: LSP is neutralino: (Ellis et al 1984)

$$\tilde{\chi} = \alpha_\gamma \tilde{\gamma} + \alpha_z \tilde{Z} + \alpha_1 \tilde{H}_1 + \alpha_2 \tilde{H}_2$$

(e.g. photino, higgsino, Z-ino, gaugino, B-ino, W_3-ino)

Spin $\frac{1}{2}$ Majorana (its own antiparticle)

$$10\ \text{GeV} \lesssim m_\chi \lesssim \text{few TeV}$$

To get relic abundance, need annihilation cross section for:

$$\tilde{\chi}\tilde{\chi} \rightarrow \{ q\bar{q},\ l\bar{l},\ W^+W^-,\ Z^0Z^0,$$
$$\text{Higgs bosons, etc.} \}$$

Griest, MK, Turner (1990): Monte Carlo survey of SUSY parameter space $\Rightarrow \Omega_\chi \sim 1$ in most models! (also in Jungman, MK, + Griest 1996)

χ
χ
Z°
W-
W+
H1°
H2°
χ1+
χ1+
χ2+
χ1+

V. CONCLUSIONS

In this paper, we have studied in some detail the possibility of a "heavy" neutralino ($m_{\tilde\chi} > m_W$), mapping out completely the cosmologically allowed regions of parameter space. The main difference between a heavy and a light ($m_{\tilde\chi} < m_W$) neutralino is that additional annihilation channels open up (various pairs of Higgs and gauge bosons). We have calculated the annihilation cross sections into these new channels for a general neutralino state. In large regions of the parameter space for the minimal supersymmetric extension of the standard model (μ, M, $\tan\beta$, $m_{H_1^0}$, m_f, and m_t) the new channels make a substantial contribution to the annihilation cross section, and for a neutralino that is Higgsino-like, the gauge-boson final states (W^+W^-, ZZ) often dominate all the other channels by a factor of 10. On the other hand, for a heavy neutralino that is gauginolike, the new final states are typically subdominant. The new channels contribute and cannot be ignored for neutralinos that are mixed states.

Using our results for the new annihilation channels along with previous results for the fermion final states, we have calculated the total annihilation cross section for heavy neutralinos and, from this, the relic cosmological abundance of heavy neutralinos. We find that for a large portion of the parameter space, a heavy neutralino of mass between m_W and 3200 GeV can have a cosmologically interesting relic abundance, i.e., $0.025 \lesssim \Omega_{\tilde\chi} h^2 \lesssim 1$. Thus, we conclude that a heavy neutralino is a well motivated and viable dark-matter candidate. Based upon the cosmological constraint $\Omega_{\tilde\chi} h^2 \lesssim 1$, we have mapped out the regions of parameter space that are cosmologically forbidden. In particular, for $m_t < 180$ GeV, one can completely rule out a neutralino that is heavier than about 3200 GeV. For a neutralino that is Higgsino-like, the bound is about 3000 GeV, while if the neutralino is gauginolike, the bound is about 550 GeV. (If a top quark of mass less than 120 GeV is discovered, the general bound drops to 2000 GeV.) As noted in the Introduction, Olive and Srednicki[6] have recently considered the case of a heavy neutralino that is either pure gaugino or pure Higgsino. In these limiting cases and for the values of m_t and $\tan\beta$ they have considered, our results agree with theirs. Finally, it is interesting to note that the cosmological upper bound to the neutralino mass is comparable to that which follows by insisting that low-energy supersymmetry "solve" the hierarchy problem.

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APPENDIX A: CROSS SECTION FOR $\tilde\chi\tilde\chi \to W^+W^-$

First let us review the masses and mixing parameters of the minimal supersymmetric standard model. The quantities M, M', and μ are the masses that appear in the neutralino mass matrix Y, Eq. (C38) of Ref. 1, and Z_{ij} are the elements of the *real* orthogonal matrix that diagonalizes Y. The masses of the four neutralinos are the absolute values of the eigenvalues of Y, $m_{\tilde\chi_i}$; one should keep in mind the fact that the $m_{\tilde\chi_i}$ *may* be negative. The mass of the lightest neutralino is the nth eigenvalue of Y which we shall denote by $m_{\tilde\chi}$. The chargino masses $m_{\tilde\chi_i^+}$, given by Eq. (C18) in Ref. 1, are *always positive*. The quantities ϕ_- and ϕ_+, determined from formulas given in Ref. 22, describe the mixing of the charginos. The squares of the Higgs-boson masses ($m^2_{H_1^0}$ and $m^2_{H_2^0}$), α, and β are given in Appendix A of Ref. 11. Finally, the quantities g and g' are, respectively, the U(1) and SU(2) gauge couplings. In this appendix only, some quantities are scaled by m_W in order to simplify some of the equations. Specifically,

$$\omega = \left[\frac{m_{\tilde\chi}}{m_W}\right]^2, \quad \kappa_i = \left[\frac{m_{\tilde\chi_i^+}}{m_W}\right]^2,$$
$$\zeta = \left[\frac{m_Z}{m_W}\right]^2, \quad s = \frac{(p_1+p_2)^2}{m_W^2}, \tag{A1}$$

where sm_W^2 is the square of the center-of-mass energy, and p_1 and p_2 are the four-momenta of the incoming neutralinos. (In Appendix B, these same quantities will be rescaled by m_Z.)

Next we define the quantities

$$\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = 2\left[\frac{Z_{n3}}{\sqrt{2}}\begin{bmatrix}\sin\phi_- \\ \cos\phi_-\end{bmatrix} + Z_{n2}\begin{bmatrix}\cos\phi_- \\ -\sin\phi_-\end{bmatrix}\right],$$
$$\begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = 2\left[\frac{-Z_{n4}}{\sqrt{2}}\begin{bmatrix}\sin\phi_+ \\ \epsilon\cos\phi_+\end{bmatrix} + Z_{n2}\begin{bmatrix}\cos\phi_+ \\ -\epsilon\sin\phi_+\end{bmatrix}\right], \tag{A2}$$

where $\epsilon = \det X/|\det X|$ and X is the matrix defined in Eq. (C9) of Ref. 1. From these we define

$$C_i^{(1)} = e_i^2 f_i^2, \quad C_i^{(2)} = e_i^3 f_i + e_i f_i^3,$$
$$C_i^{(3)} = e_i^4 + f_i^4, \quad C_i^{(5)} = e_i^2 - f_i^2, \quad C_i^{(6)} = e_i^2 + f_i^2,$$
$$D^{(1)} = e_1^2 e_2^2 + f_1^2 f_2^2, \quad D^{(2)} = e_2^2 e_1 f_1 + f_2^2 e_1 f_1, \tag{A3}$$
$$D^{(3)} = e_1^2 f_2^2 + e_2^2 f_1^2, \quad D^{(4)} = e_1^2 e_2 f_2 + f_1^2 e_2 f_2,$$
$$D^{(5)} = 2 e_1 e_2 f_1 f_2,$$

where $i = 1,2$.

The following dimensionless quantities are also useful:

$$\gamma=\left[\left(1-\frac{4\omega}{s}\right)\left(1-\frac{4}{s}\right)\right]^{1/2},$$

$$L_i=\frac{1}{\gamma s}\ln\left|\frac{(1+\gamma)s-2-2\omega+2\kappa_i}{(1-\gamma)s-2-2\omega+2\kappa_i}\right|,$$

$$K_i=\frac{1}{\gamma s}\left[\frac{1}{(1+\gamma)s-2-2\omega+2\kappa_i}-\frac{1}{(1-\gamma)s-2-2\omega+2\kappa_i}\right], \tag{A4}$$

$$A=\frac{m_{\tilde\chi}}{m_W}\sin\alpha+2[Q\sin(\beta-\alpha)-R\sin\alpha],$$

$$C=\frac{m_{\tilde\chi}}{m_W}\cos\alpha-2[Q\cos(\beta-\alpha)+R\cos\alpha],$$

where

$$Q=\frac{Z_{n3}}{g}(gZ_{n2}-g'Z_{n1}),$$

$$R=\frac{1}{2m_W}(MZ_{n2}^2+M'Z_{n1}^2-2\mu Z_{n3}Z_{n4}), \tag{A5}$$

$$F=Z_{n3}^2-Z_n^2.$$

The total cross section, averaged over neutralino spin for the process $\tilde\chi\tilde\chi\to W^+W^-$ is given by

$$\sigma_{WW}=\frac{1}{32\pi s m_W^2}\left[\frac{s-4}{s-4\omega}\right]^{1/2}\times(X_{ZZ}+X_{HH}+X_{\tilde\chi^+\tilde\chi^+}+X_{\tilde\chi^+\tilde\chi^+}+X_{Z\tilde\chi^+}+X_{H\tilde\chi^+}). \tag{A6}$$

The quantities X_{ii} arise from squaring the matrix element given by the Feynman diagrams in Fig. 2, summing over final state polarizations and averaging over initial neutralino spins. Specifically, X_{ZZ} comes from the square of the Z-exchange diagram, X_{HH} comes from the square of the Higgs-boson-exchange diagrams, $X_{\tilde\chi^+\tilde\chi^+}$ comes from the sum of the squares of the t- and u-channel exchange of the charginos, $X_{\tilde\chi^+\tilde\chi^+}$ comes from the interference between the t- and u-channel exchange of the charginos, and $X_{Z\tilde\chi^+}$ and $X_{H\tilde\chi^+}$ come from the interference of the chargino-exchange diagrams with the Z- and Higgs-boson-exchange diagrams. The interference between the Z- and Higgs-boson-exchange diagrams vanishes. The quantities X_{ii} are given by

$$X_{ZZ}=\frac{g^4F^2}{24}\frac{(s-4)(s-4\omega)(s^2+20s+12)}{(s-\zeta)^2+(\Gamma_Z/m_Z)^2},$$

$$X_{HH}=\frac{g^4}{8\sin^2\beta}\left[2+\left|\frac{s}{2}-1\right|^2\right](s-4\omega)A'^2,$$

$$X_{\tilde\chi^+\tilde\chi^+}=\frac{g^4}{16}\sum_i\left[C_i^{(1)}G_i^{(1)}+\frac{m_{\tilde\chi_i^+}}{m_W}\frac{m_{\tilde\chi}}{m_W}C_i^{(2)}G_i^{(2)}+C_i^{(3)}G_i^{(3)}\right],$$

$$X_{\tilde\chi^+\tilde\chi^+}=\frac{g^4}{8}\left[D^{(1)}G^{(4)}+\frac{m_{\tilde\chi}}{m_W}\left[\frac{m_{\tilde\chi_1^+}}{m_W}D^{(2)}+\frac{m_{\tilde\chi_2^+}}{m_W}D^{(4)}\right]G^{(5)}-D^{(3)}G^{(6)}+\frac{m_{\tilde\chi_1^+}}{m_W}\frac{m_{\tilde\chi_2^+}}{m_W}D^{(5)}G^{(7)}\right], \tag{A7}$$

$$X_{Z\tilde\chi^+}=\frac{g^4F}{8[(s-\zeta)^2+(\Gamma_Z/m_Z)^2]^{1/2}}\sum_i C_i^{(5)}G_i^{(8)},$$

$$X_{H\tilde\chi^+}=\frac{-g^4A'}{8\sin\beta}\sum_i\left[\frac{m_{\tilde\chi}}{m_W}C_i^{(6)}G_i^{(9)}+2\frac{m_{\tilde\chi_i^+}}{m_W}e_if_iG_i^{(10)}\right],$$

where Γ_Z is the Z width. Here

$$A'=\frac{A\cos(\beta-\alpha)}{[(s-m_{H_1^0}^2/m_W^2)^2+(\Gamma_{H_1^0}/m_W)^2]^{1/2}}+\frac{C\sin(\beta-\alpha)}{[(s-m_{H_2^0}^2/m_W^2)^2+(\Gamma_{H_2^0}/m_W)^2]^{1/2}}, \tag{A8}$$

where $\Gamma_{H_i^0}$ is the width of the H_i^0, and the G are given by

$$G_i^{(1)} = 4\kappa_i K_i[-(\kappa_i-\omega-2)^2 s + 4(\kappa_i-\omega-1)^2+2\omega+36] - \tfrac{1}{6}[2s^2+s(40-8\omega-36\kappa_i)+24\omega-12(\kappa_i-\omega)^2+120\kappa_i]$$
$$+4L_i\{s^2(4\kappa_i-2\kappa_i^2-\kappa_i\omega)+s[8-9\kappa_i-12\omega+14\kappa_i^2-6\omega\kappa_i+4\omega^2-3\kappa_i(\kappa_i-\omega)^2]$$
$$+6\kappa_i-8\omega+9\omega^2-13\kappa_i^2+6\omega\kappa_i+8\kappa_i(\kappa_i-\omega)^2-(\kappa_i-\omega)^4\},$$

$$G_i^{(2)} = 24K_i[2-(\kappa_i+\omega)^2-(\kappa_i-\omega)^2]+16-4s$$
$$+\frac{8L_i}{s-2-2\omega+2\kappa_i}\{s^2(\kappa_i-1)+s[(\kappa_i-\omega)^2-6\kappa_i+2\omega+4]-7(\kappa_i-\omega)^2+5\kappa_i-7\omega+2\},$$

$$G_i^{(3)} = 2K_i(\kappa_i[(\kappa_i-\omega-2)^2 s+\kappa_i[\kappa_i(\kappa_i-4\omega-2)+6\omega^2+6\omega+5]-2(\omega+2)(2\omega^2-\omega+2)]+(\omega-1)^2(\omega+2)^2)$$
$$+\frac{L_i}{s-2-2\omega+2\kappa_i}\{s^2(3\kappa_i^2+\omega^2-8\kappa_i+4)+2s[5\kappa_i^3-(11\omega+14)\kappa_i^2+(7\omega^2+16\omega+17)\kappa_i-\omega^3-10\omega^2+3\omega-8]$$
$$+4[2(\kappa_i-\omega)^4-4(\kappa_i-\omega)^3-\kappa_i(\kappa_i-\omega)^2+8\kappa_i^2+9\omega\kappa_i+9\kappa_i-(\omega-4)(\omega+1)]\}$$
$$-\tfrac{1}{12}[-2s^2+(12\kappa_i-16\omega-40)s+36(\kappa_i-\omega)^2-24\kappa_i+88\omega+48],$$

$$G^{(4)} = -\frac{L_2}{\kappa_1-\kappa_2}[s(\kappa_2-\omega-2)^2\kappa_2+(\kappa_2-\omega)^4+2(\omega-\kappa_2)^3+5\kappa_2^2-8\kappa_2-(\omega+2)(3\omega-2)]+(1\leftrightarrow 2)$$
$$+\frac{\omega L_2}{2+2\omega-\kappa_1-\kappa_2-s}[\kappa_2 s^2+s[(\kappa_2-\omega)^2-6\kappa_2+2\omega-3]-4(\kappa_2-\omega)^2+8\kappa_2+2\omega+2]+(1\leftrightarrow 2)$$
$$-\tfrac{1}{12}[-2s^2+(6\kappa_1+6\kappa_2-16\omega-40)s+9(\kappa_1+\kappa_2)^2-(36\omega+12)(\kappa_1+\kappa_2)+3(\kappa_1-\kappa_2)^2+4(9\omega^2+22\omega+12)],$$

$$G^{(5)} = 8-2s-\frac{6L_2}{\kappa_1-\kappa_2}[-(\kappa_2-\omega)^2+2-\kappa_2-\omega]+(1\leftrightarrow 2)$$
$$+\frac{L_2}{s-2-2\omega+\kappa_1+\kappa_2}[s^2(2\kappa_2-2)+s[2(\kappa_2-\omega)^2-6\kappa_2-2\omega+11]-2(\kappa_2-\omega)^2+4\kappa_2-8\omega-2]+(1\leftrightarrow 2),$$

$$G^{(6)} = \frac{18\omega}{\kappa_1-\kappa_2}(\kappa_2 L_2-\kappa_1 L_1)+\frac{s^2}{6}-\frac{s}{12}[6(\kappa_1+\kappa_2)+8\omega-40]-[\tfrac{1}{2}(\kappa_1+\kappa_2)-\omega]^2+\kappa_1+\kappa_2-\tfrac{1}{4}(\kappa_1-\kappa_2)^2+\tfrac{3}{2}\omega$$
$$+\frac{L_2}{2+2\omega-\kappa_1-\kappa_2-s}\{s^2(4\kappa_2-\kappa_2^2)+s[-2\kappa_2(\kappa_2-\omega)^2+8\kappa_2^2-8\omega\kappa_2-9\kappa_2+4(\omega-2)(\omega-1)]$$
$$-(\kappa_2-\omega)^4+4\kappa_2(\kappa_2-\omega)^2-5\kappa_2^2+(2\omega+2)\kappa_2+9\omega^2-8\omega\}+(1\leftrightarrow 2),$$

$$G^{(7)} = \frac{L_2}{\kappa_1-\kappa_2}[s(\kappa_2-\omega-2)^2-4(\kappa_2-\omega)^2+8\kappa_2-28\omega-4]+(1\leftrightarrow 2)$$
$$+\frac{L_2}{s-2-2\omega+\kappa_1+\kappa_2}[s^2(\omega-\kappa_2)+s[-(\kappa_2-\omega)^2+6(\kappa_2-\omega)]+4(\kappa_2-\omega)^2-8(\kappa_2+\omega)+4]+(1\leftrightarrow 2)+2s-8,$$

$$G_i^{(8)} = L_i\{\kappa_i s^2(4+\omega-\kappa_i)+s[4\kappa_i^2-5(\kappa_i+3\omega)-(\kappa_i-\omega)^3-10\omega\kappa_i+6\omega^2+8]+2(\kappa_i-\omega)^3-8\omega(\kappa_i-\omega)-6\kappa_i-10\omega+4\}$$
$$+\tfrac{1}{6}\{-s^3+s^2(3\kappa_i+\omega-18)+s[6(\kappa_i-\omega)^2-12\kappa_i+36\omega+28]-12(\kappa_i-\omega)^2-12\kappa_i+44\omega+24\},$$

$$G_i^{(9)} = L_i\{-\kappa_i s^2+s[\kappa_i-2+3\omega-(\kappa_i-\omega)^2]+4-2(\kappa_i+\omega)-2(\kappa_i-\omega)^2\}+\tfrac{1}{4}[2s^2+4(\kappa_i-\omega-1)s+8(\kappa_i-\omega+2)],$$

$$G_i^{(10)} = s(1-s/2)+L_i[\tfrac{1}{2}(\kappa_i+\omega)s^2-s(2+\kappa_i+3\omega)+12\omega].$$

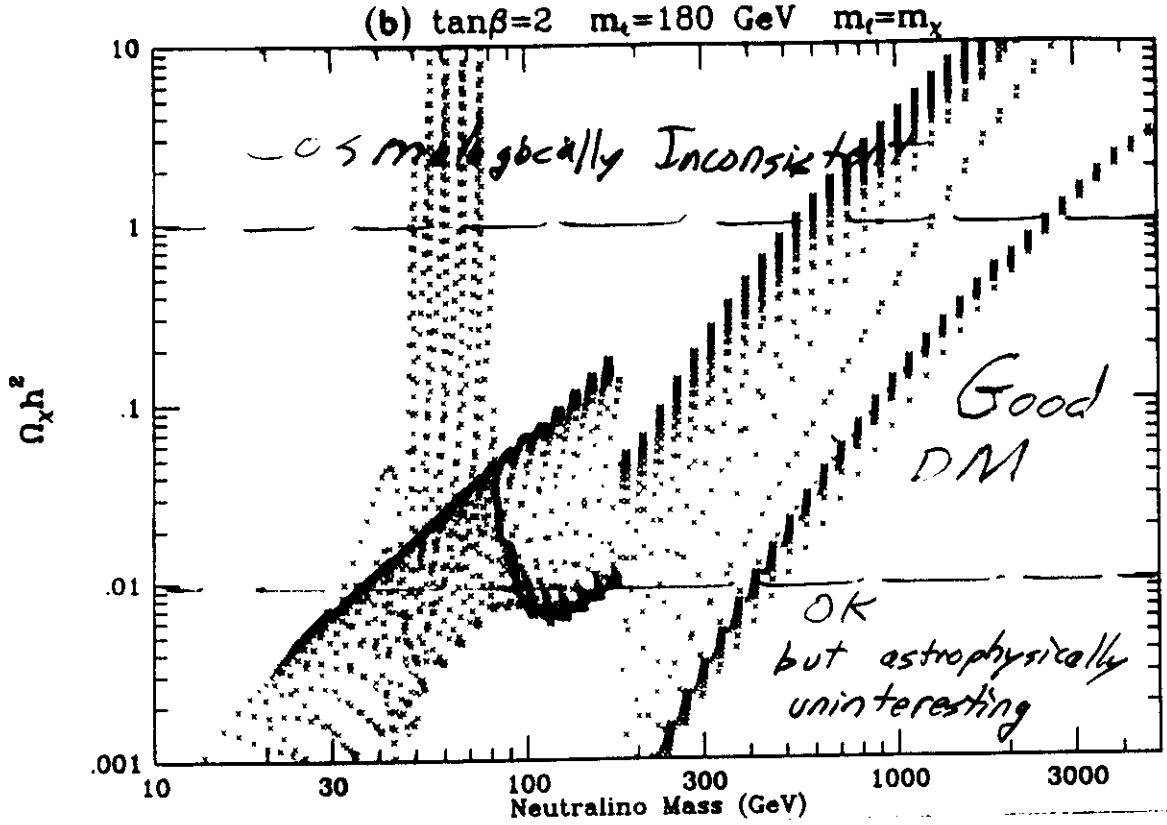
At zero velocity, the Higgs-boson- and Z-exchange diagrams vanish, and only the chargino-exchange diagrams remain. The rather lengthy expression for σ_{WW} times the relative velocity reduces to

$$(\sigma_{WW}v)(v\to 0) = \frac{g^4(\omega-\cdot)^{3/2}}{128\pi|m_{\tilde\chi}|m_W}\left|\frac{e_1^2+f_1^2}{1-\omega-\kappa_1}+\frac{e_2^2+f_2^2}{1-\omega-\kappa_2}\right| \quad (A10)$$

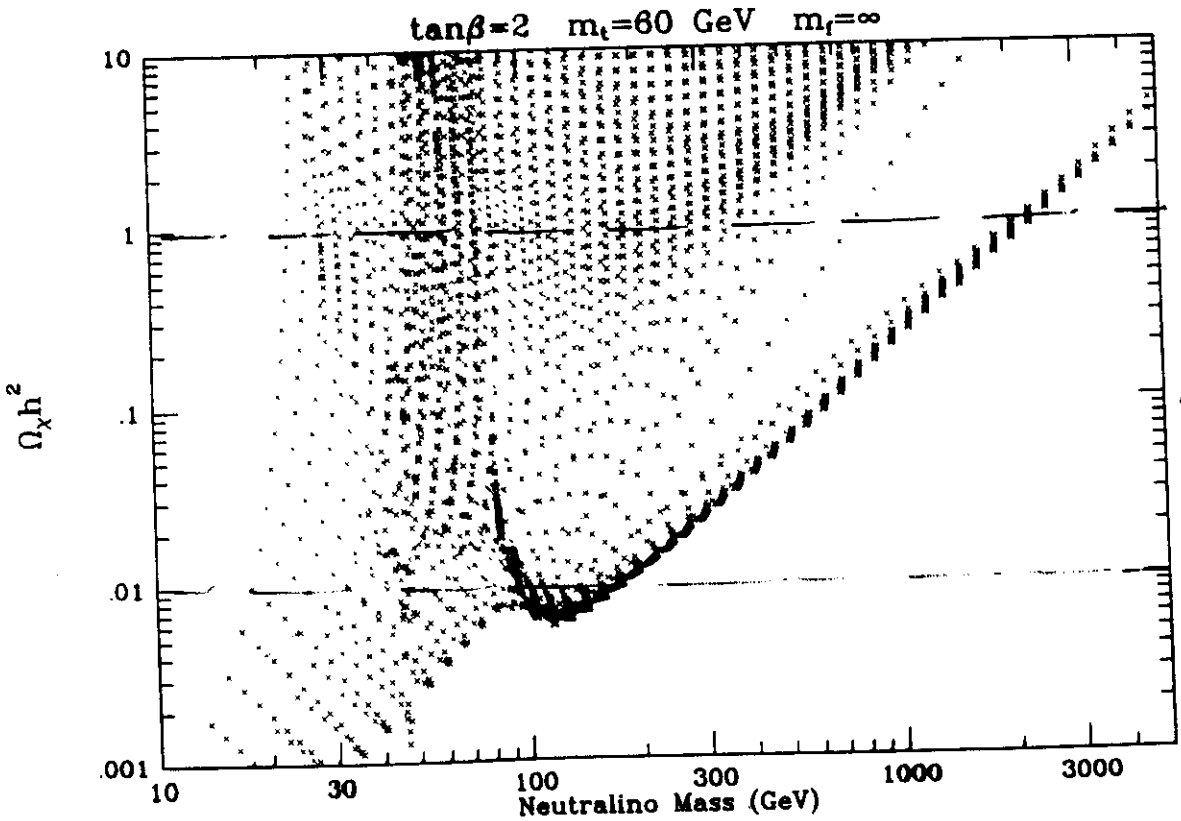
In the early Universe, $\omega=\frac{1}{4}$ at freeze-out and the v^2 terms are most certainly of importance. However, in the galactic halo, neutralino-neutralino relative velocities are of order $v^2=v_{\rm halo}^2\approx 0$, and to a good approximation, the annihilation cross section times relative velocity should be given by $\sigma_{WW}v(v\to 0)$ (unless it vanishes).

APPENDIX B: CROSS SECTION FOR $\tilde\chi\tilde\chi\to Z^0Z^0$

The matrix element for the process $\tilde\chi\tilde\chi\to Z^0Z^0$ is given by the Feynman diagrams shown in Fig. 3, and the total

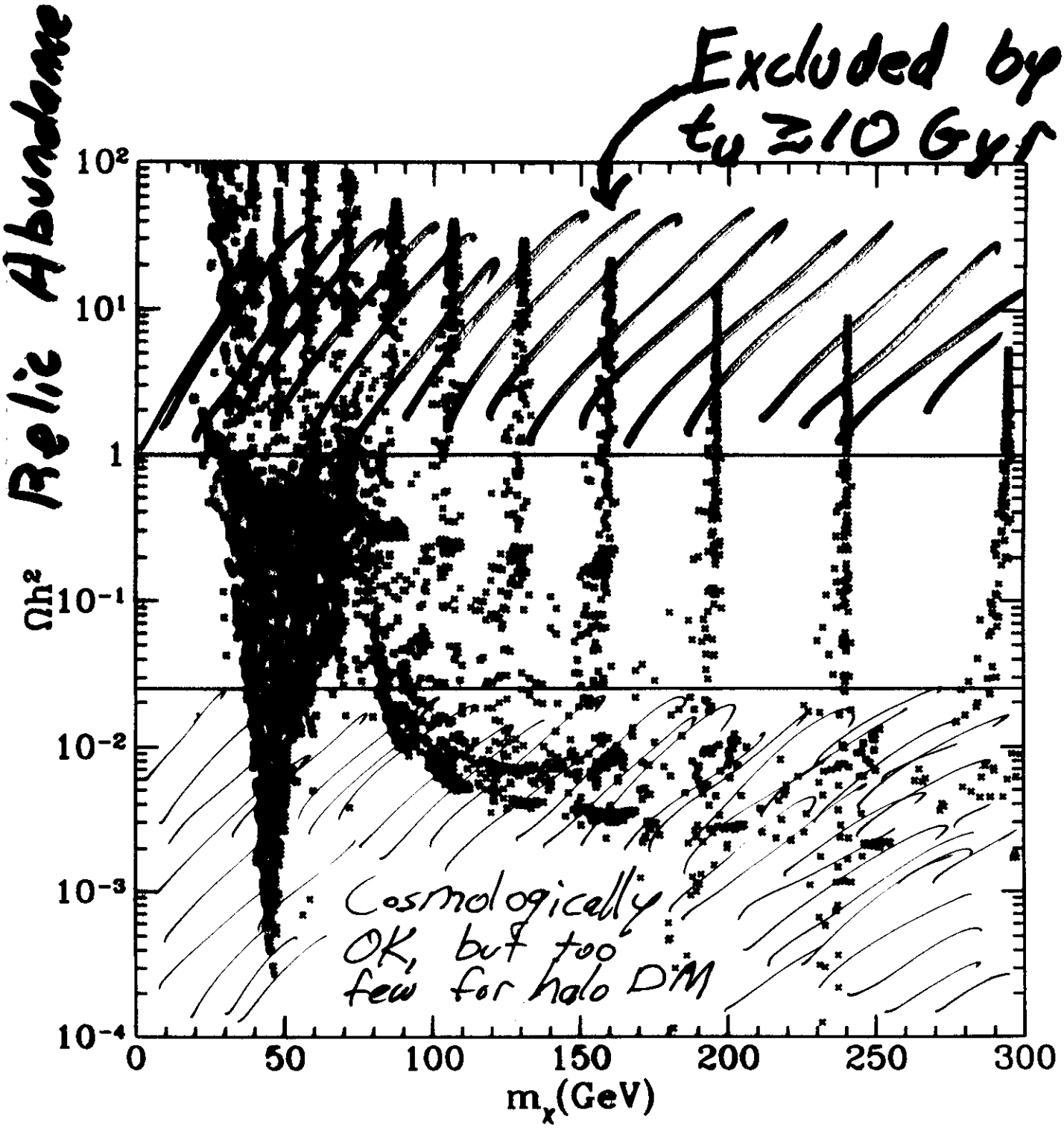


$t\bar{t}$ final states dominate for $m_\chi > 120$



$f\bar{f}$ final states negligible

Griest, Kamionkowski, + Turner 1990



WIMP mass (i.e., neutralino) mass

Jungman, MK, + Griest 1996

"The Junk-Bond days of early-Universe cosmology are over"

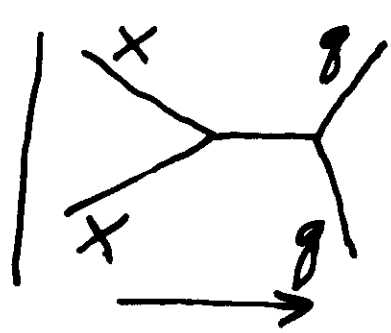
J. Harvey

We've talked the talk.

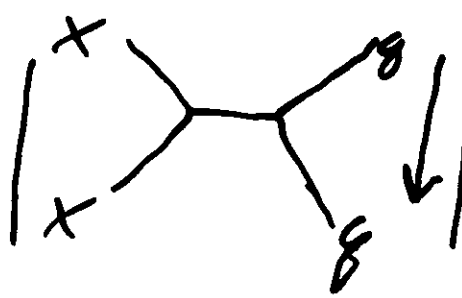
Now it's time to walk the walk.

WIMP Detection:

$\Omega_\chi \sim 1 \Longrightarrow$

$\sigma_A \sim$ 

$\sim \frac{\alpha^2}{m^2_{weak}} \sim 10^{-38}\ cm^2$

$\sigma_{detect} \sim$ 

$\sim \sigma_{ann}$

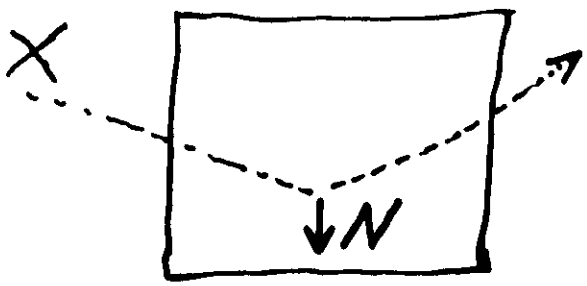
More Carefully:

$$\chi q \xrightarrow{QCD} \chi n \xrightarrow[physics]{nuclear} \chi N$$

quark — nucleon — nucleus

WIMP DETECTION

DIRECT

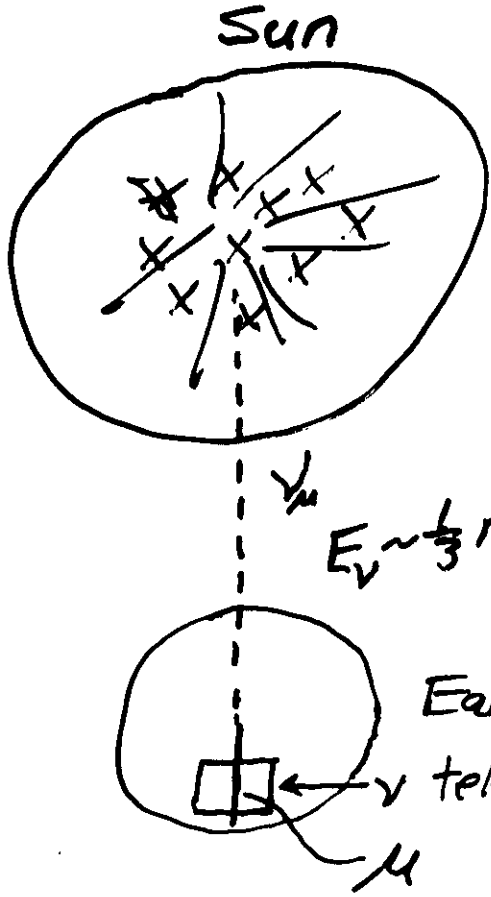


Low-Background Detector

(e.g., N = Ge)

E_R(10 keV)

INDIRECT



Direct WIMP Detection Experiments

Cryogenic Detectors:

CDMS	Stanford	Ge, Si
CRESST	Gran Sasso	Al_2O_3
EDELWEISS	Frejus	Al_2O_3, Ge
Tokyo	Tokyo	
Milano/Gran Sasso	Gran Sasso	TeO_2

Semiconductors - Ionization @ 77 K:

Ahlen/Avignone/Drukier	Homestake	Ge
UCSB/UCB/LBL	Oroville Dam	Ge
Caltech/PSI/Neuchatel	St. Gotthard	Ge
Zaragoza/PNL/USC	Canfranc Tunnel	Ge
Heidelberg/Moscow	Gran Sasso	Ge
UCSB/UCB/LBL/Saclay	Oroville	Ge

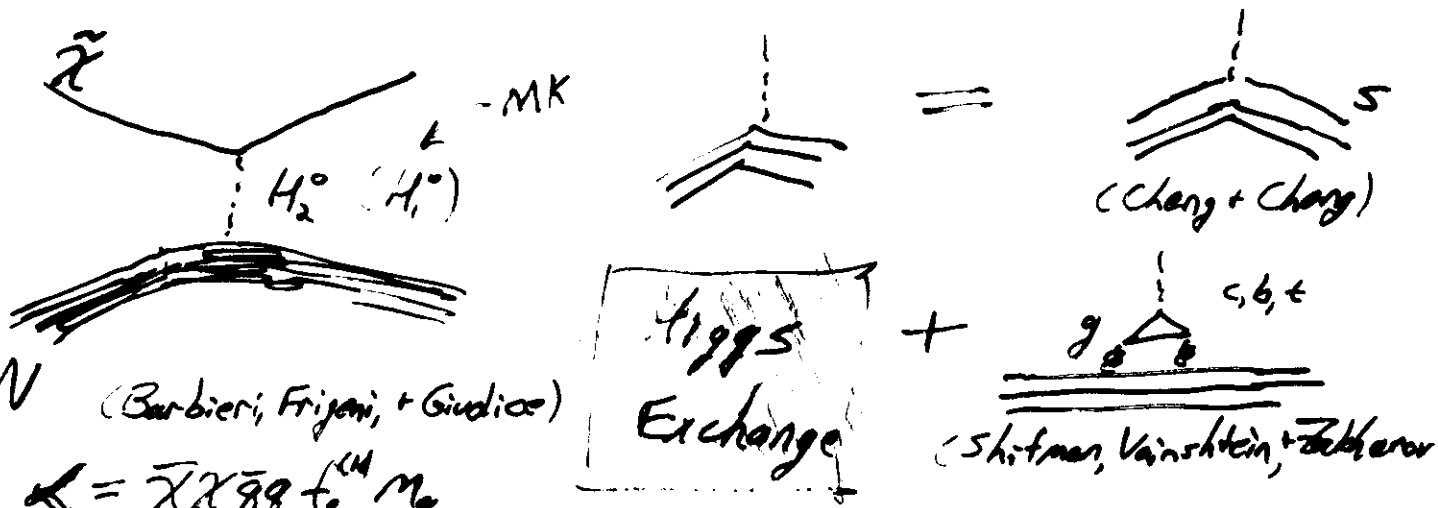
Scintillators:

Beijing/Paris/Rome/Saclay	Gran Sasso	NaI
Zaragoza/PNL/USC	Canfranc	NaI
Osaka	Kamioka	NaI, CaF_2
UKDM	Boulby	NaI
DAMA (Rome)	Gran Sasso	Liq. Xe
ICARUS WIMPs	Mont Blanc	Liq. Xe

Energetic-ν Experiments

Frejus	Past	Frejus
IMB	Past	Cleveland
Baksan	Current	Baikal, Siberia
Kamiokande-II	Past	Japan
MACRO	Current	Gran Sasso
Super-Kamiokande	Current	Japan
AMANDA	Current/Future	South Pole
NESTOR	Future	Greece
HANUL	Future (proposed)	Korea

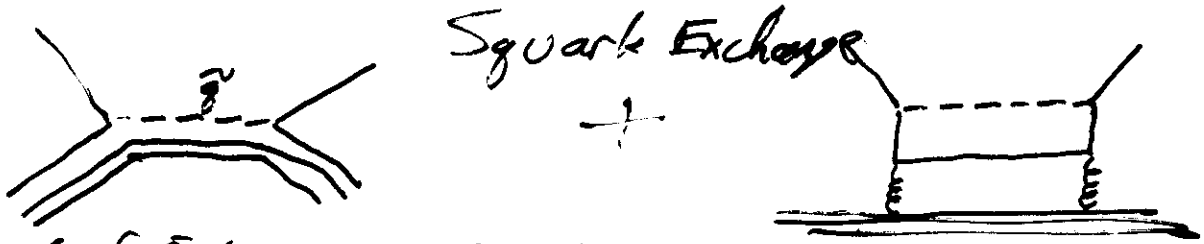
Elastic Scattering of χ off of N:



$\mathcal{L} = \bar{\chi}\chi\bar{q}q f_q^{(N)} m_q$

Important for mixed-state neutralinos. (+ models w. squark mixing)
H_2^0 is always light so this matrix element is ~~small~~ large even for heavy neutralinos.
χ interacts coherently with entire N, so $\sigma_{N^0} \sim m_N^4 e^{-m_i}$

Squark Exchange

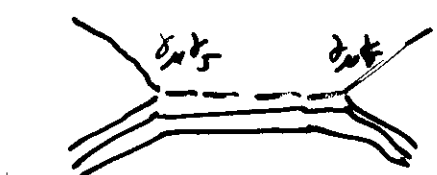


$\mathcal{L} = f_q \bar{\chi}\chi\bar{q}q$ (Scalar Interaction)

also important for mixed-states, coherent, and $\sigma_q \sim m_N^4$
but generally, $\sigma_q < \sigma_{N^0}$

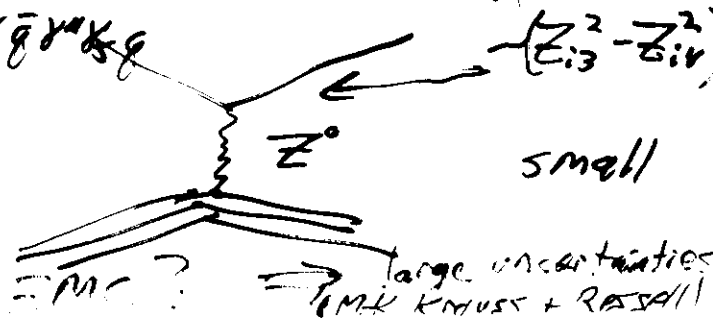
Spin-dependent Interaction (Axial) $\sigma \sim$ ~~large~~ $\vec{S}^2$ Nuclear Physics

$\mathcal{L} = d_q \bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q$



Important B-ino scattering off H in Sun

+



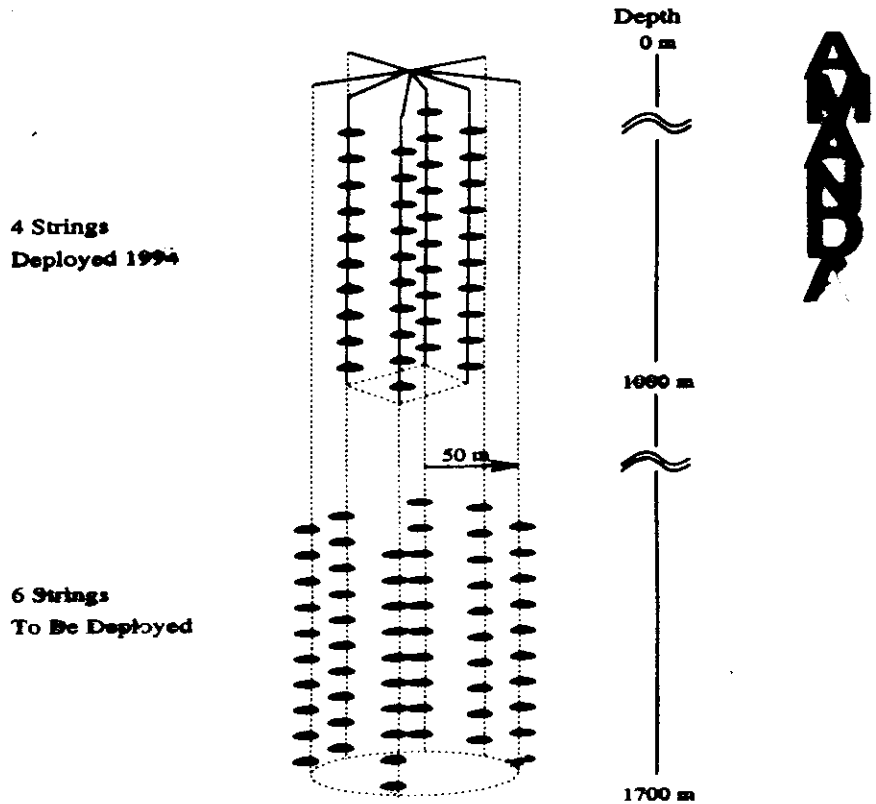


Figure 28. Diagram of the AMANDA neutrino detector [319]. The final configuration may differ slightly from that shown here.

the Sun. WIMPs accumulate in the Sun or Earth by capture from the galactic halo and are depleted by annihilation. If N is the number of WIMPs in the Sun (or Earth), then the differential equation governing the time evolution of N is

$$\dot{N} = C - C_A N^2, \tag{9.4}$$

where the dot denotes differentiation with respect to time. Here, C is the rate of accretion of WIMPs onto the Sun (or Earth). The determination of C is straightforward and will be discussed in detail below, and if the halo density of WIMPs remains constant in time, C is of course time-independent.

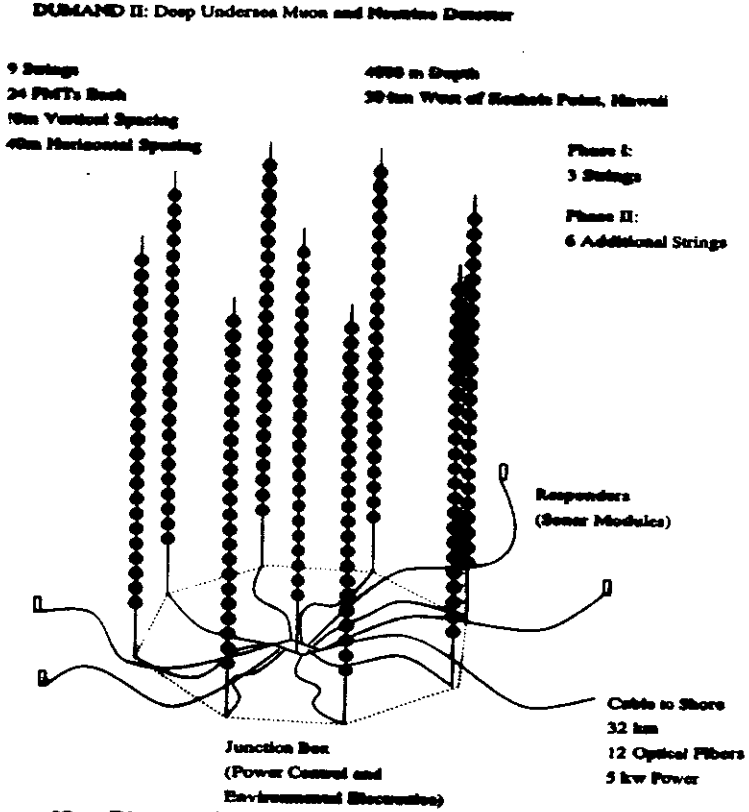
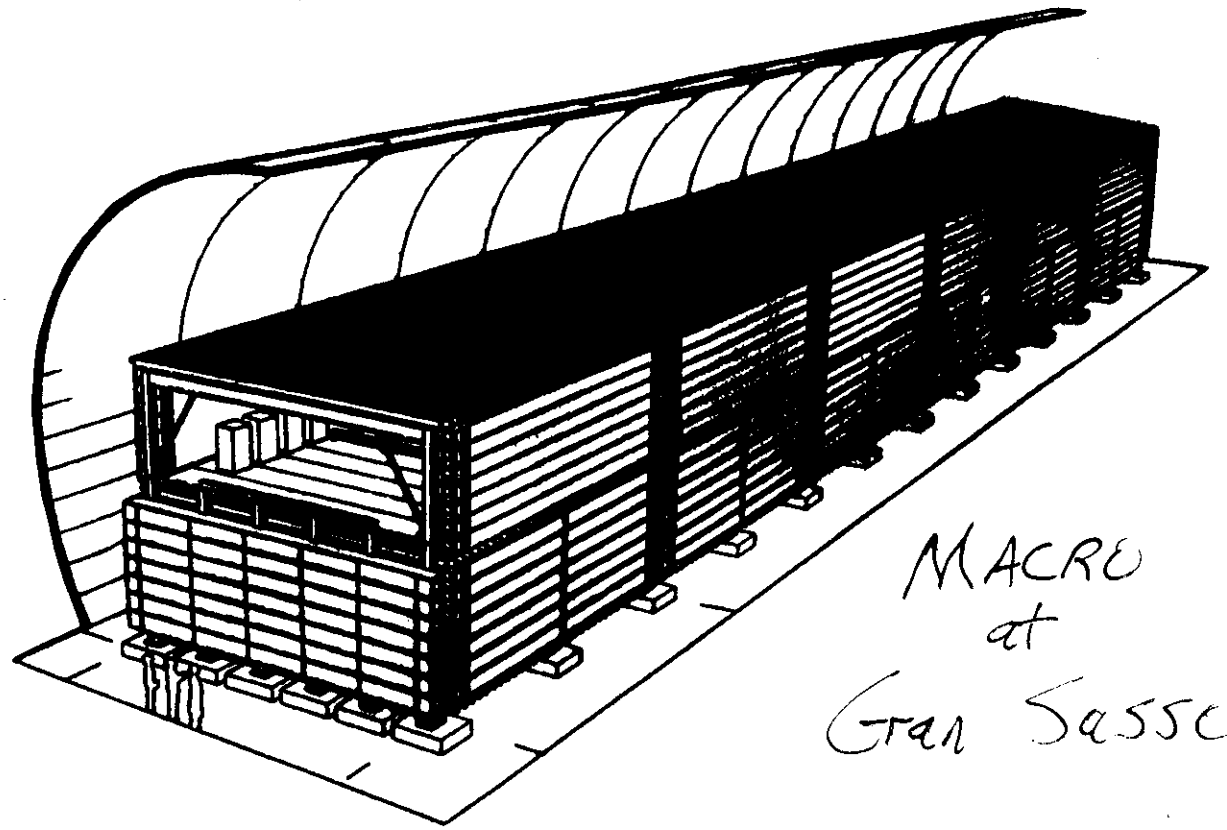


Figure 27. Diagram of the DUMAND neutrino detector [318].

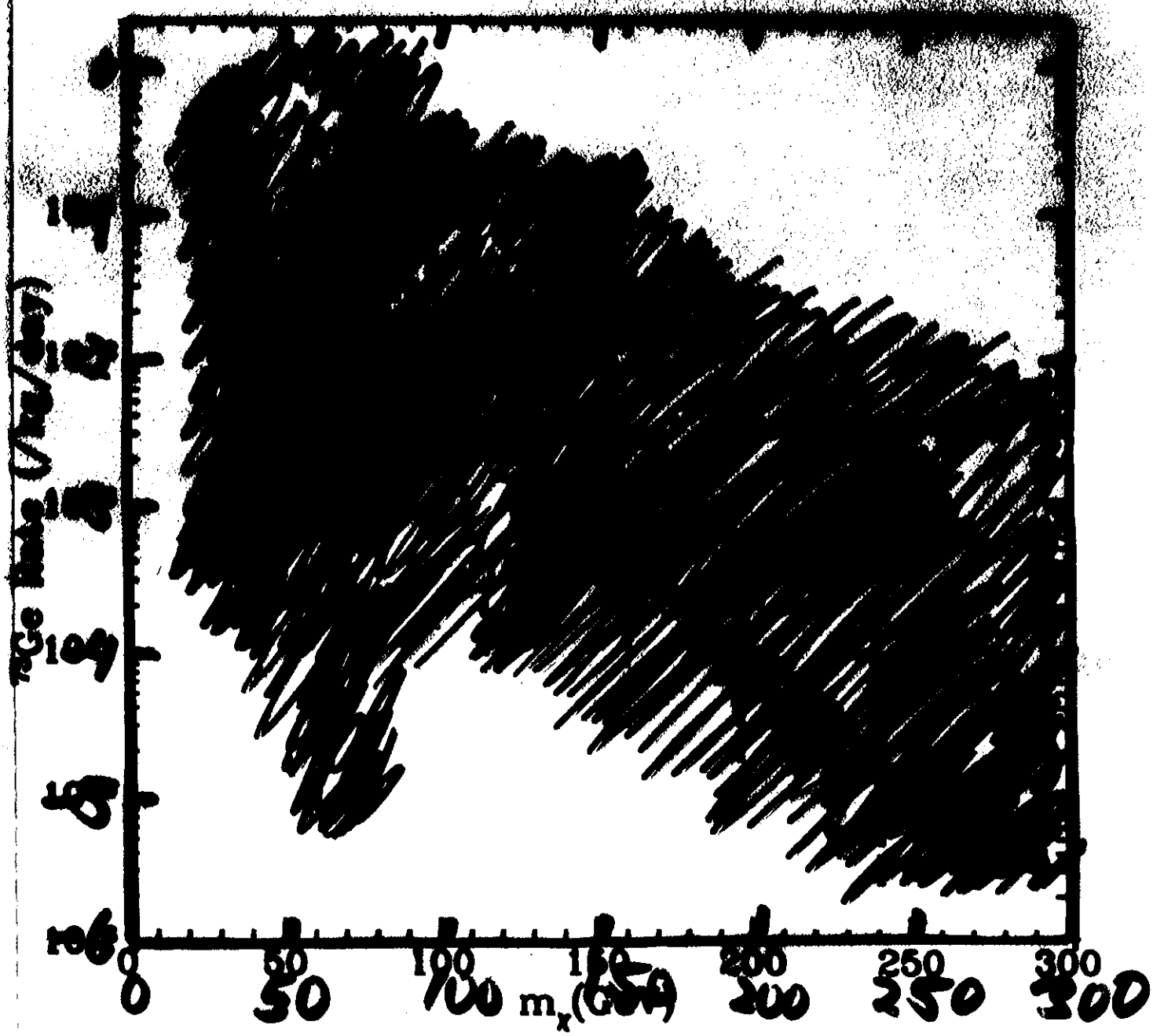
be expanded to 3000 m^2. The NESTOR (Neutrinos from Supernovae and TeV Sources Ocean Range) experiment is a similar effort located off the coast of Greece. An exposure area of 3×10^4 m^2 is forecast [320]. The Antarctic Muon and Neutrino Detector Array (AMANDA) is situated at the South Pole [319]. Although ice near the surface is opaque, the ice a km below the surface is relatively clear and has an attenuation length comparable to water. AMANDA is expected to have an exposure of 1000 m^2.

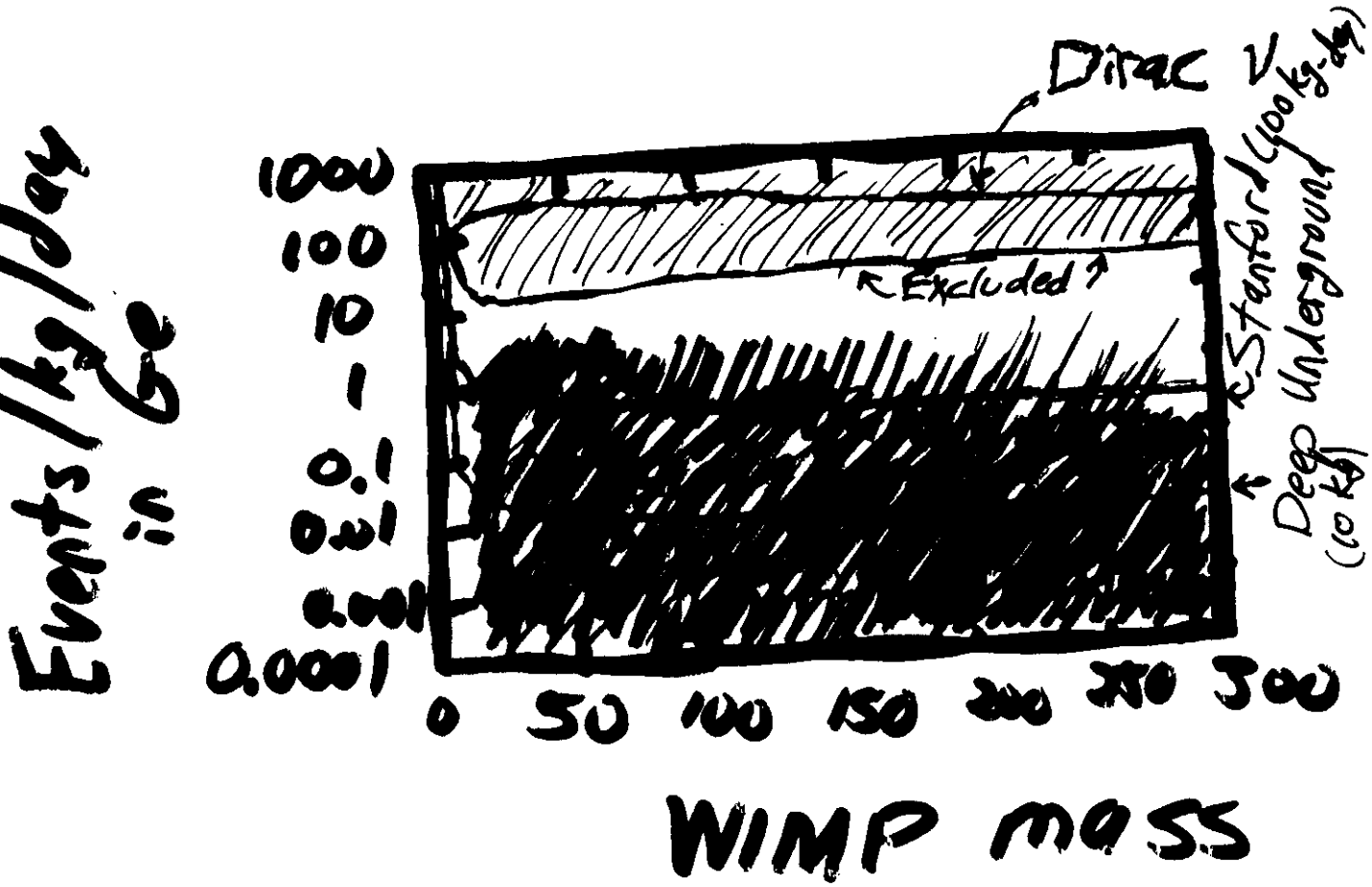
9.3. Annihilation Rate in the Sun and Earth

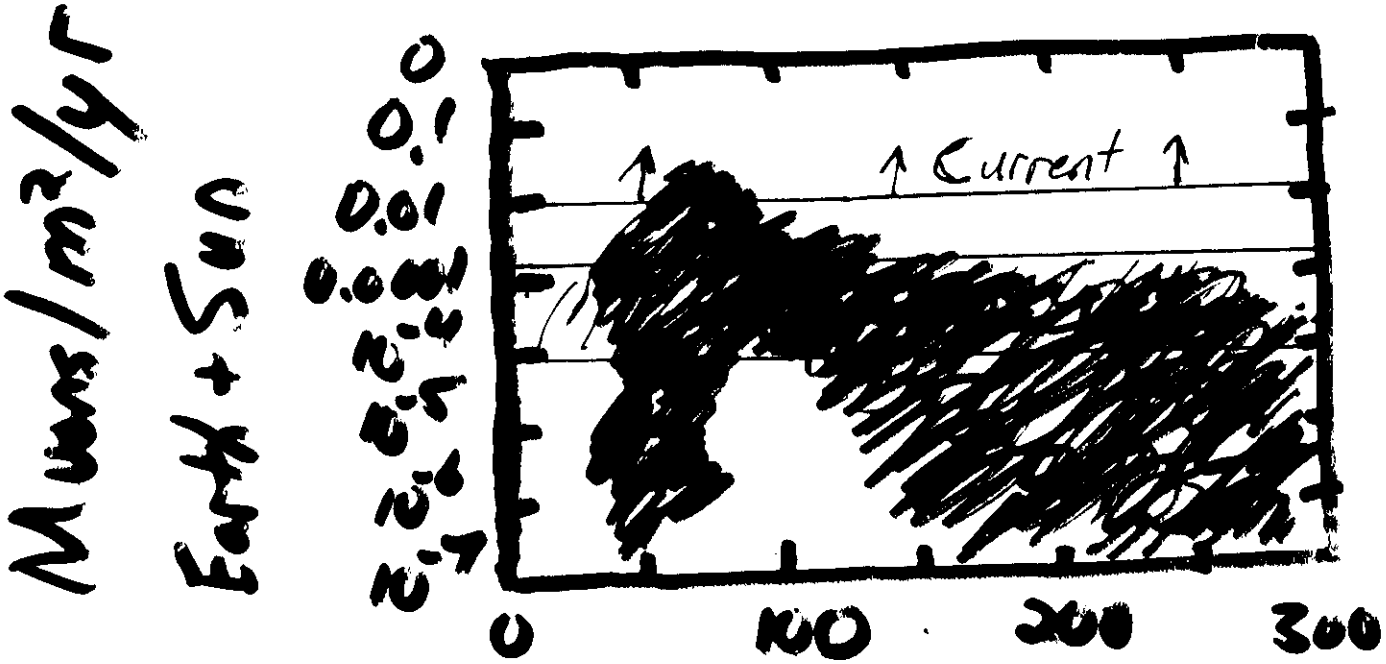
The first step in calculating the rate for WIMP-induced neutrino events from the Sun is the determination of the rate at which WIMPs annihilate in



MACRO
at
Gran Sasso


m_χ(GeV)


Dirac V
Excluded
Standard (100 kg-day)
Deep Underground (10 kg)
Events/kg/day in Ge
1000
100
10
1
0.1
0.01
0.001
0.0001
0
50
100
150
200
250
300
WIMP mass


Muons/m²/yr
Earth + Sun
Current
0
100
200
300

Direct vs Indirect Detection: Which is Better?

MK, Griest, Jungman, Sadoulet 1995
Jungman, MK + Griest 1996 Fraser + MK 1987
Richt Tao 1994

Two Types WIMP-nucleon interactions:

(i) Scalar	(ii) Axial-Vector
X couples to mass of nucleus	X couples to spin of nucleus
Direct More Sensitive	Indirect More Sensitive

Backgrounds:

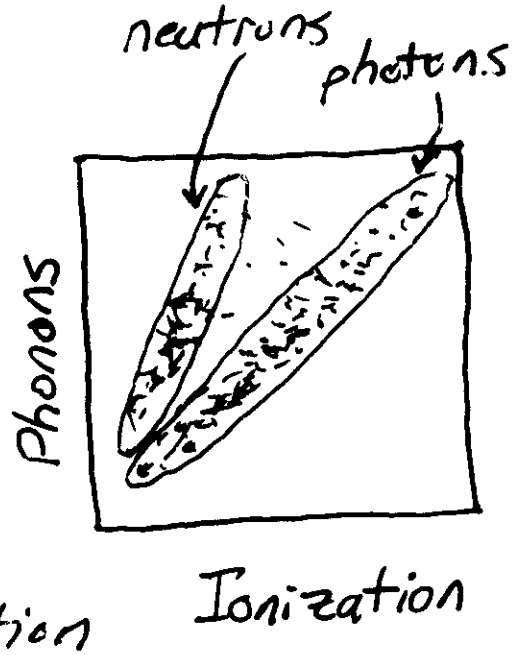
Sensitivity $\propto \sqrt{\frac{\text{Background flux}}{\text{Exposure}}}$

e.g., Direct Detection

γ-ray background

Discriminate with Ionization + Phonons

>99% Background Rejection



Energetic ν's:

Atmospheric-ν Background

Reducible with higher threshold (but bigger at South Pole)

With predicted μ angular and energy distribution, can improve S/N.

(Bergstrom, Edsjö + Kamionkowski '96)

Cosmic Rays from WIMP Annihilation in Halo?

$\chi\chi \longrightarrow *!\#@\# \longrightarrow e^+, \bar{p}, \gamma, \ldots\ldots$

Signatures:

excess e^+ at high energies

excess: $\bar{p}$ at low energies

monochromatic γ ($E_\gamma = m_\chi$)

However:

fluxes appreciable in only very small fraction of models.

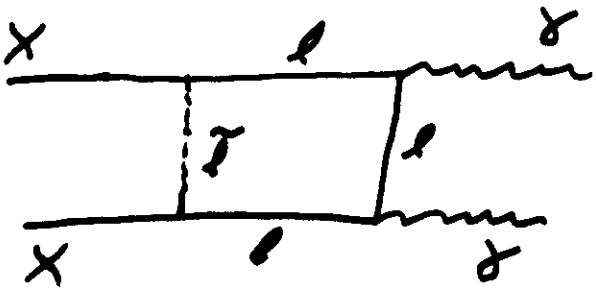
Very difficult to distinguish from uncertain backgrounds

Will need to be very lucky to detect WIMPs with CRs.

Null results can <u>not</u> be used to constrain WIMP models.

Gamma Rays from WIMP Annihilation in the Galactic Halo:

Signature #1: Monoenergetic γ Rays



$$E_\gamma = m_\chi \left(1 \pm 10^{-6}\right)$$

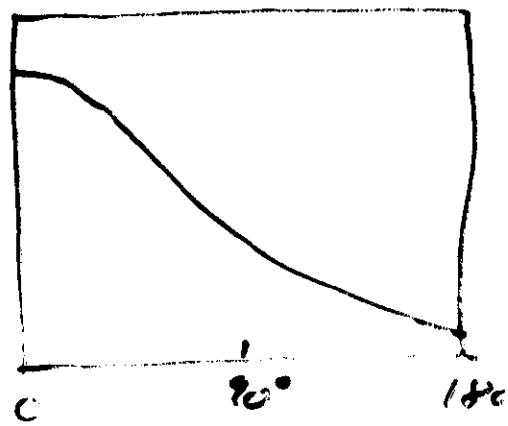
$\left(v_{halo}^2/c\right)$

(e.g. Jungman + Kamionkowski 1994)

Signature #2: Directional Dependence

ψ = angle between line of sight and Galactic Center

$\mathcal{F}(\psi)$ = flux of γ-rays

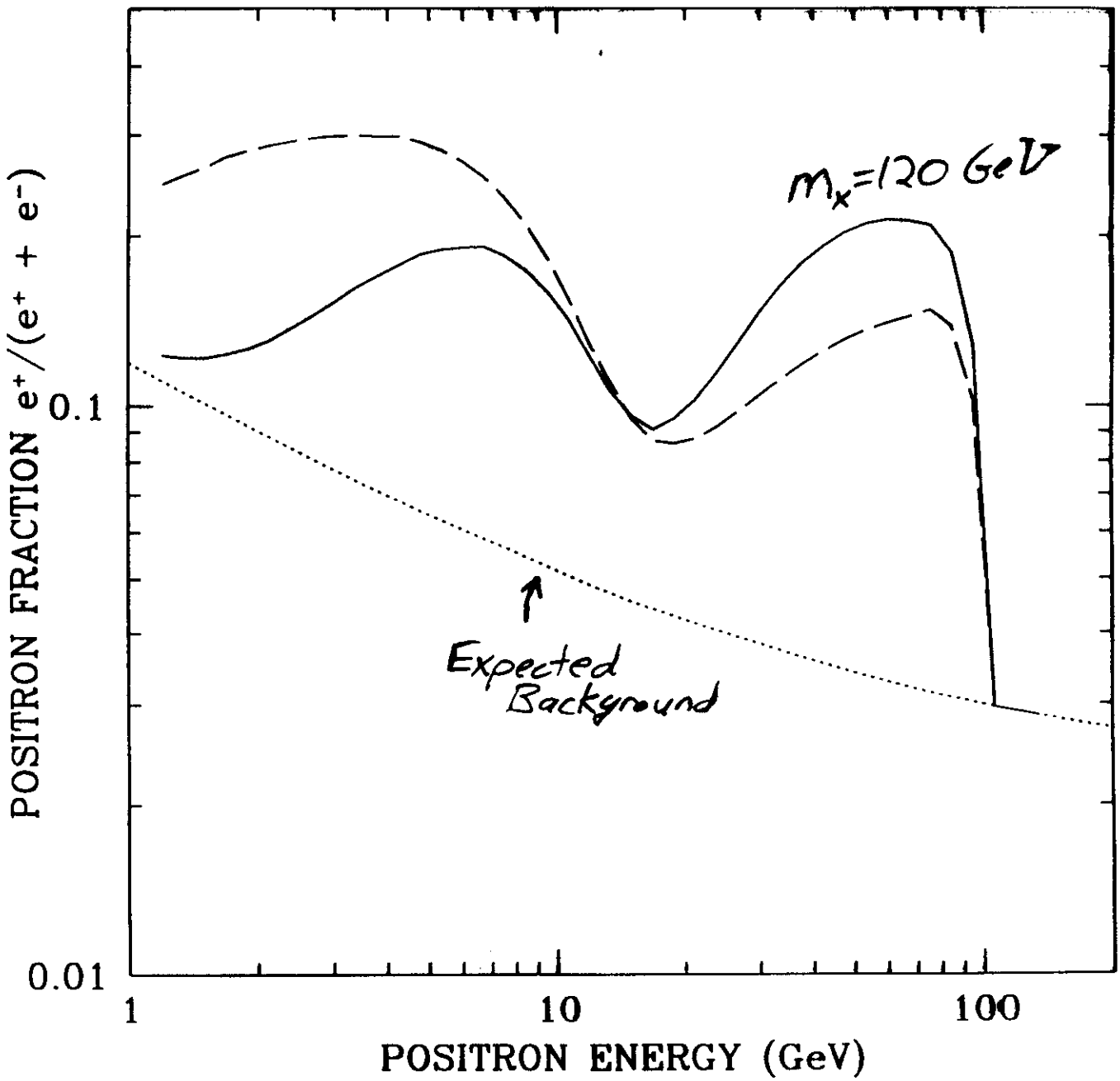


$\tilde{\mathcal{F}}(\psi)$

Gunn et al. 1978
Turner 1986

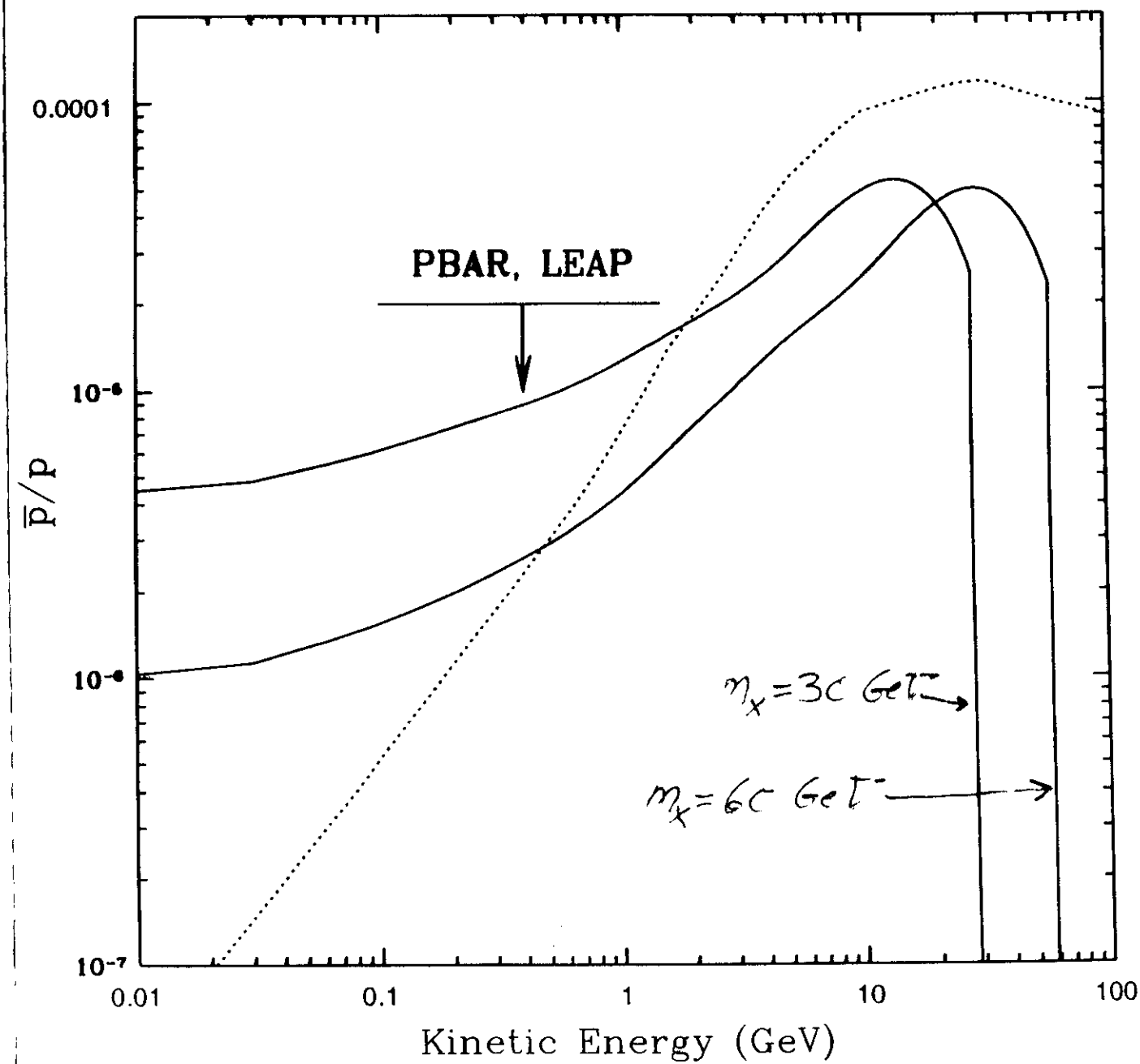
(e.g. Whipple Observatory, GLAST)

Cosmic-Ray Positrons from $\chi\chi \to W^+W^- \to e^+ e^- \nu_e \bar{\nu}_e$



Kamionkowski + Turner 1991

Cosmic-Ray Antiprotons from WIMP Annihilation in the Halo



Jungman + Kamionkowski 1994

Can a Stable Massive ($\gtrsim$ GeV) ν be Halo DM?

Dirac: (Coherent Vector Interaction) m_ν

Heidelberg-Moscow: ~~$26\,\text{GeV} - 4.7\,\text{TeV}$~~

LEP: ~~$\lesssim 45\,\text{GeV}$~~

Unitarity: ~~$\lesssim \mathcal{O}(\text{TeV})$~~

(MK, Griest, PRL 64, 615 (1990))

NO!

Majorana: (Axial-Vector)

No constraints from direct detection

Kamiokande: ~~$\mathcal{O}(10\,\text{GeV}) - \mathcal{O}(500\,\text{GeV})$~~

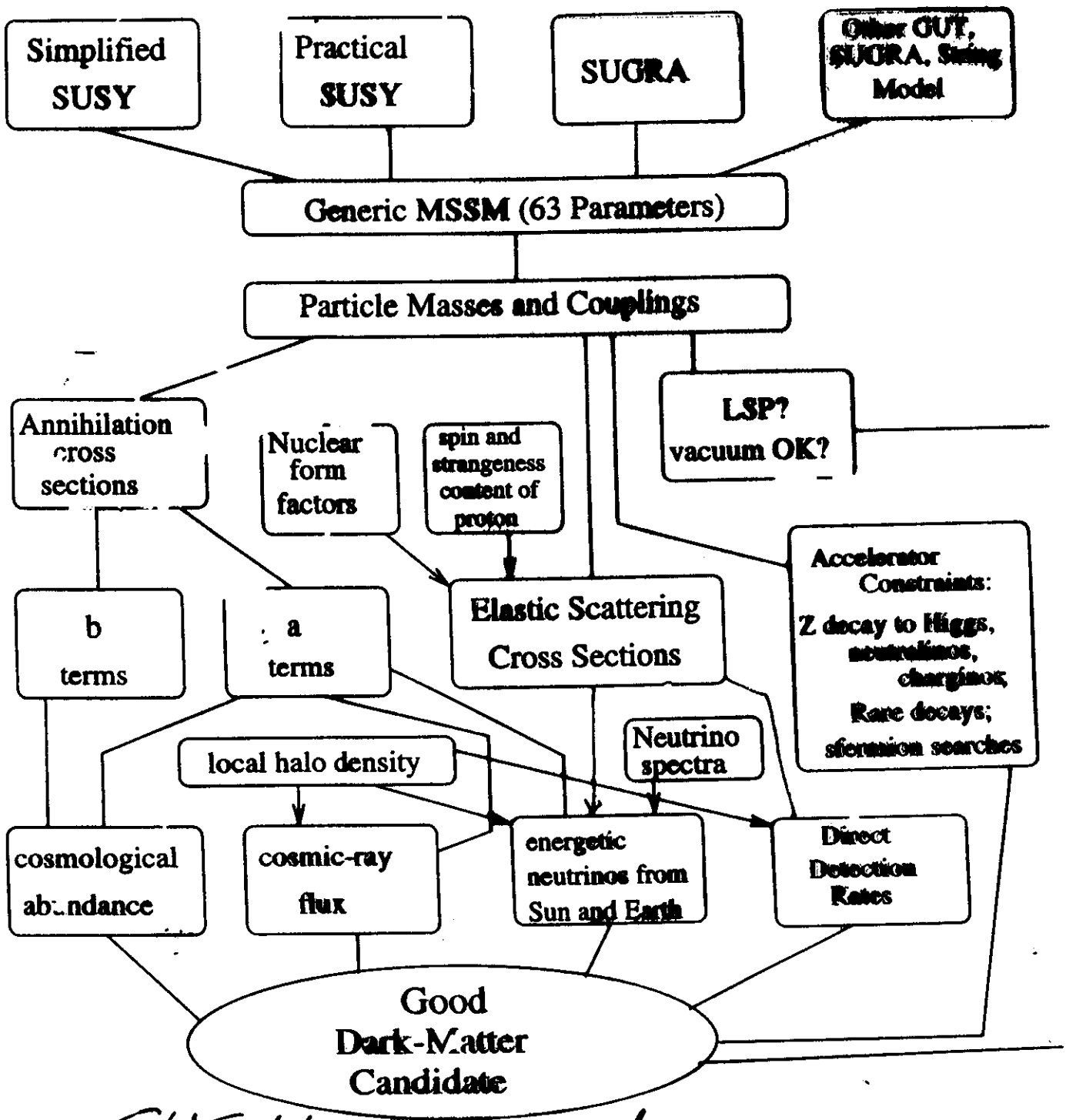
LEP: ~~$\lesssim 45\,\text{GeV}$~~

Unitarity: ~~$\lesssim \mathcal{O}(\text{TeV})$~~

OK for $\frac{1}{2}\,\text{TeV} \lesssim m_\nu \lesssim \text{TeV}$

Sneutrinos? ~ Dirac ν

No.



SUSY DM code

contact kamion@phys.columbia.edu
jungman@[illegible]ias.edu
kgriest@ucsd.edu

Summary:

WIMPs, axions arise in leading solutions to fundamental problems in particle physics.

If $\exists$, have $\Omega_x \sim 1$

$\Rightarrow$ cosmologically relevant

$\Rightarrow$ likely the nonbaryonic DM

Good fraction of viable models will be probed experimentally

If Detected:

Would revolutionize cosmology + physics

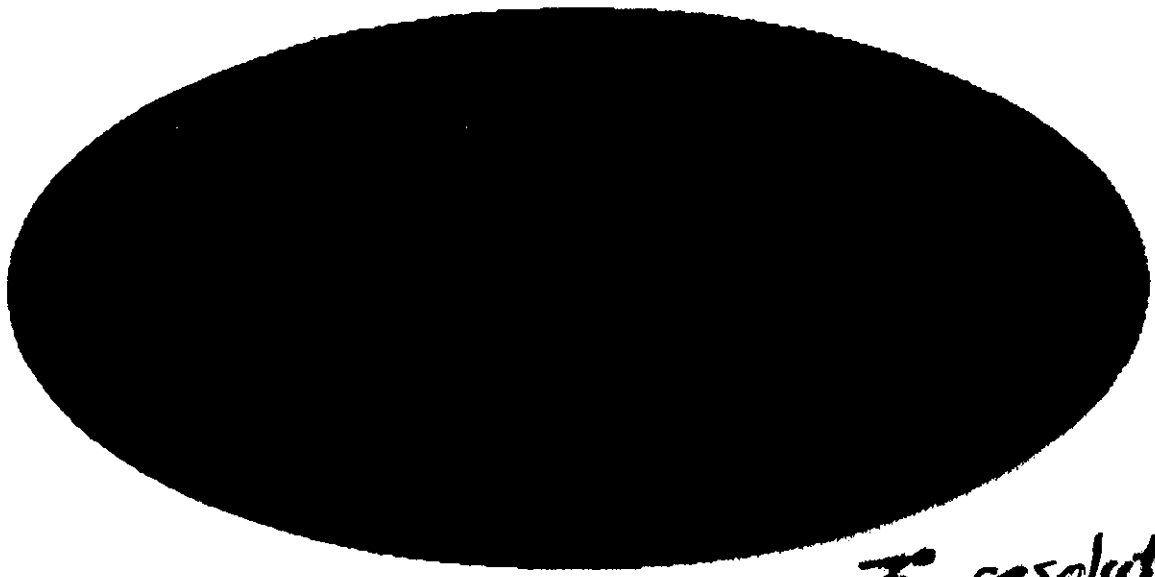
Important for LSS, galaxy formation, galaxy structure.

Could determine phase-space distribution of MW halo

.....

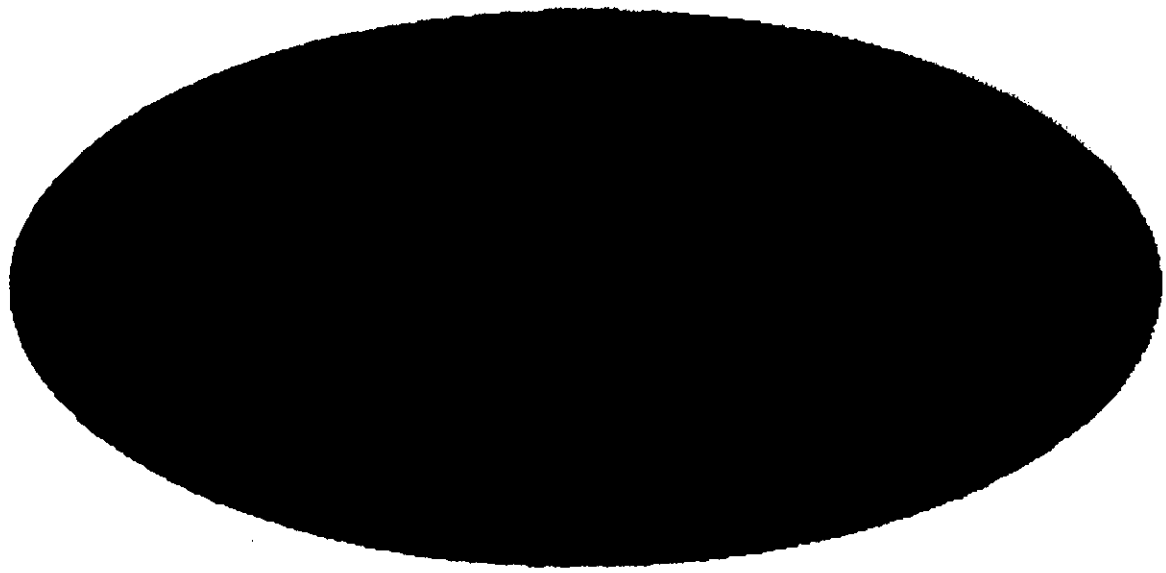
Cosmology $\Longleftrightarrow$ Particle Physics

COBE DMR 4-Year Sky Map

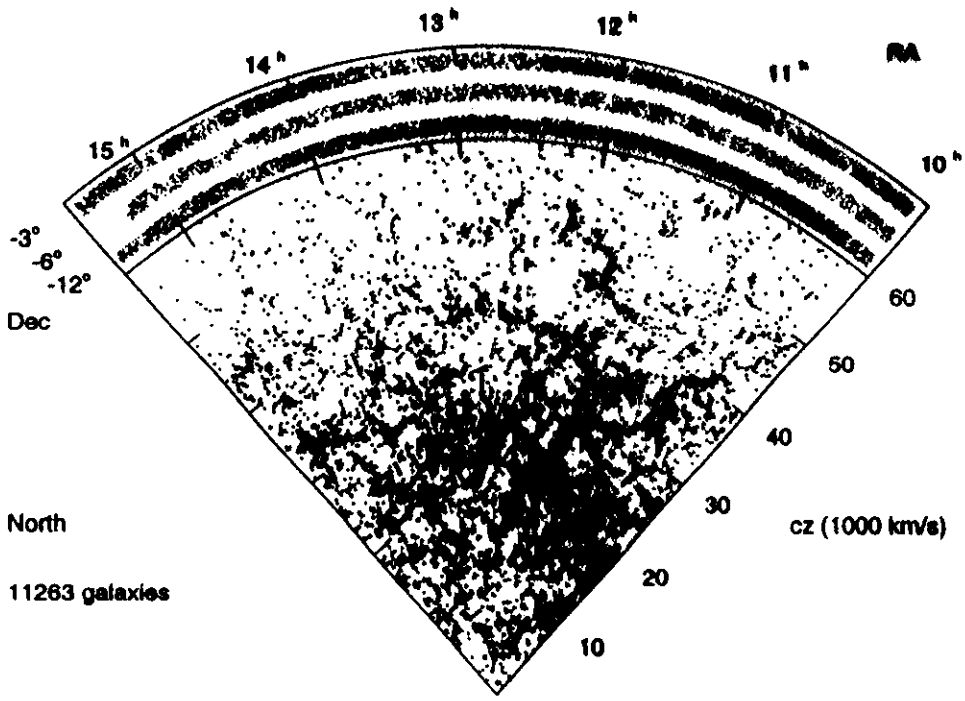


7° resolution

MAP Simulated Sky Map



0.3° resolution


13 h
12 h
14 h
11 h
RA
15 h
10 h
-3°
-6°
-12°
Dec
60
50
40
30
20
10
North
11263 galaxies
cz (1000 km/s)

Large-Scale Structure:

$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

$$\delta_{\vec{k}} = \int d^3\vec{x}\, e^{i\vec{k}\cdot\vec{x}}\, \delta(\vec{x})$$

Power Spectrum: $P(k) \propto \langle |\delta_k|^2 \rangle$

Leading Paradigm:* (Peebles-Harrison-Zeldovich ~1970)
(Inflation ~1980)

$P(k)$ from gravitational infall of $P_{prim}(k) \propto k^n$ with $n \simeq 1$. (Adiabatic)

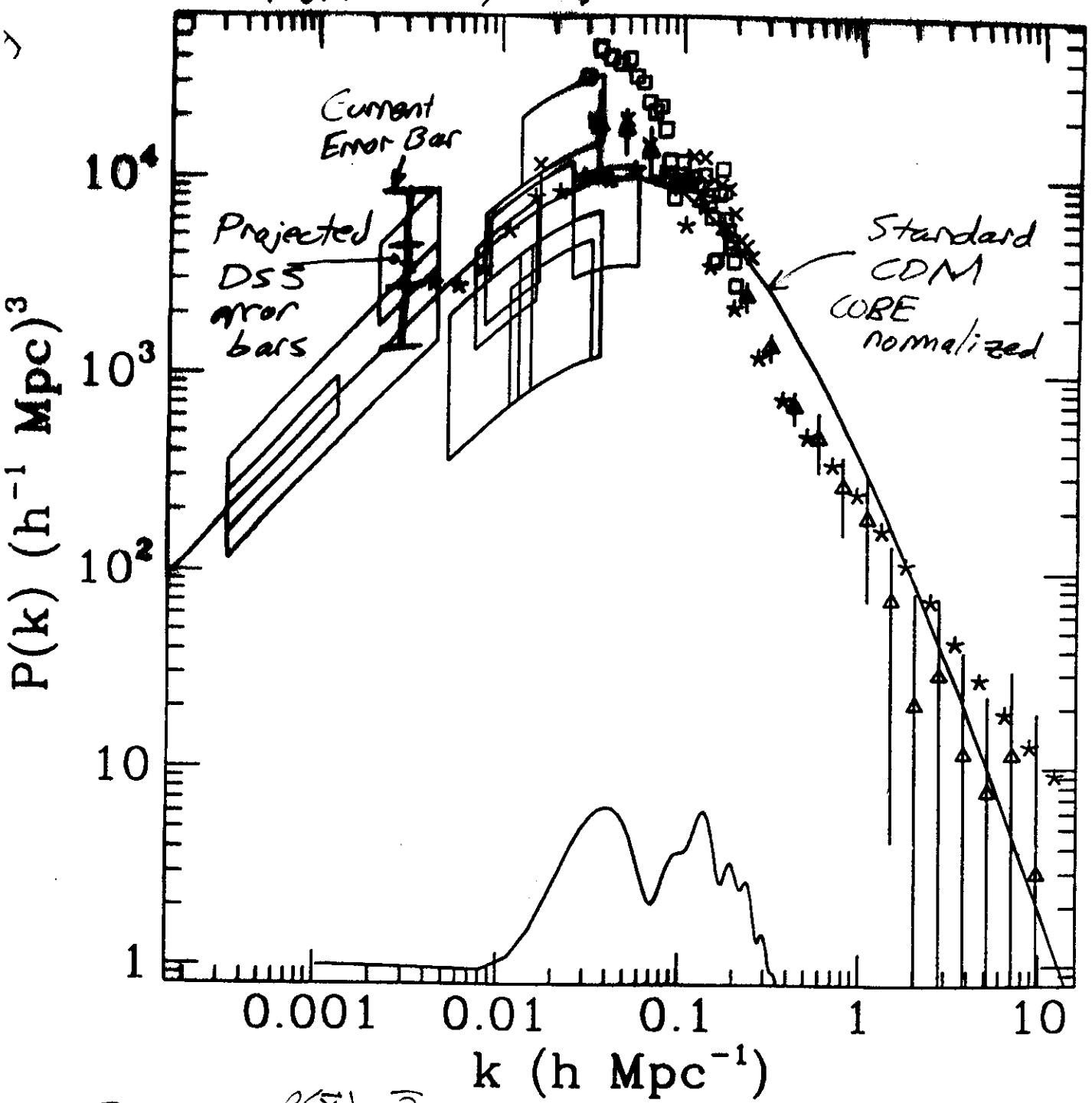
Then, $P(k) \propto \begin{cases} k^n & \frac{k}{h\,\mathrm{Mpc}^{-1}} \lesssim 0.1\,\Omega_0 h \\ k^{n-4} & \frac{k}{h\,\mathrm{Mpc}^{-1}} \gtrsim 0.1\,\Omega h \end{cases}$

For given $\Omega_0, h, \Lambda, \Omega_\nu, \Omega_b, \ldots$.

get Standard CDM, ΛCDM, open CDM, tilted CDM, MDM, ...

* Runner Up: Topological defects (cosmic strings, textures, global monopoles....)

from White, Scott & Silk 1994

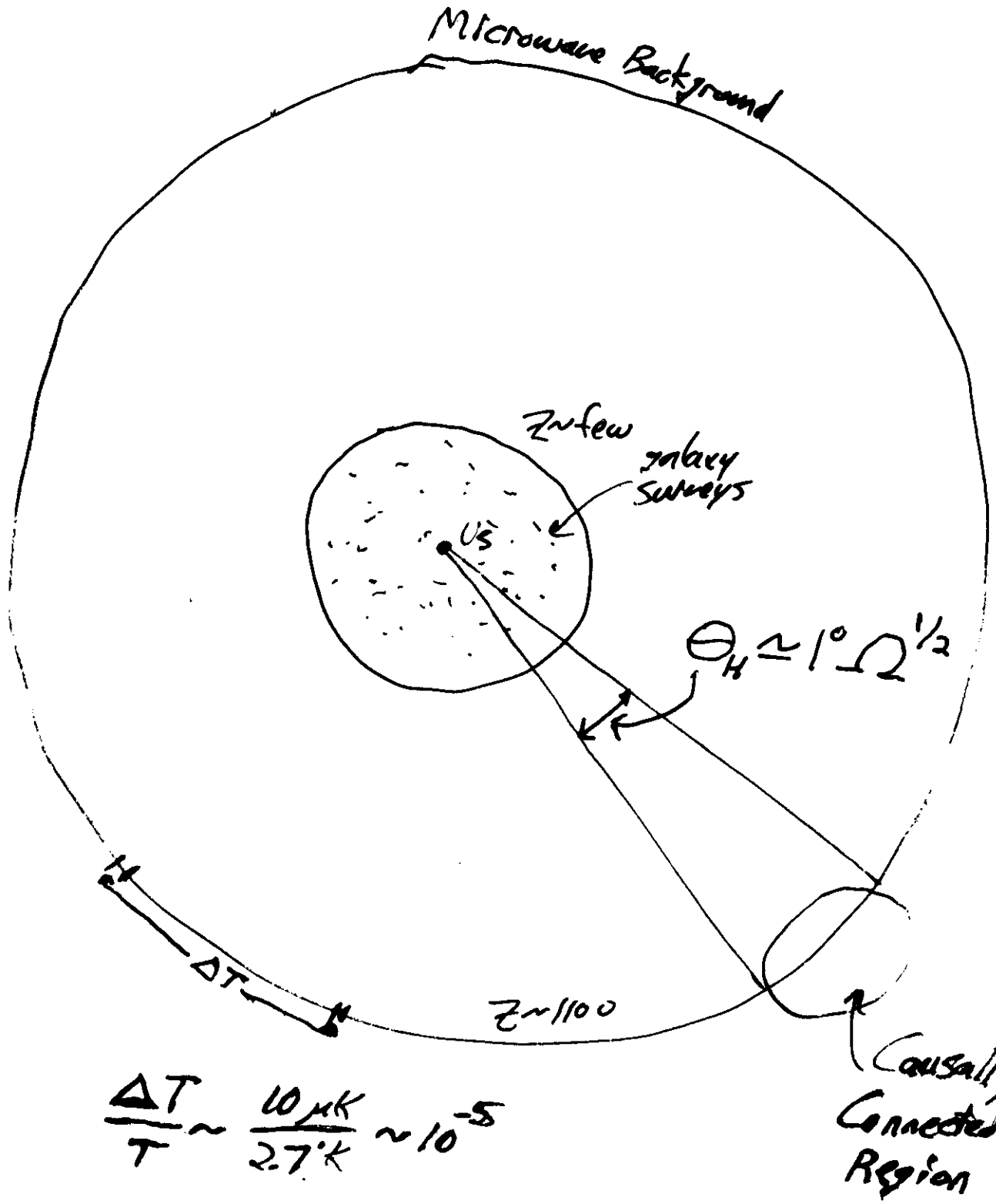


$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

$$\delta_{\vec{k}} = \int d^3x\, e^{i\vec{k}\cdot\vec{x}}\, \delta(\vec{x})$$

$$P(k) \propto |\delta_k|^2$$

$$\frac{\Delta T}{T} \sim \frac{\Delta \phi}{\phi} \qquad \nabla^2 \phi = 4\pi G \delta \rho$$



$$\frac{\Delta T}{T} \sim \frac{10\,\mu K}{2.7\,K} \sim 10^{-5}$$

Cosmic Microwave Background Anisotropies:

Measure $a_{lm} = \int d\Omega \, Y_{lm}(\Omega) \frac{\Delta T}{T}(\Omega)$

and $C_l = \sum_m \frac{|a_{lm}|^2}{2l+1}$

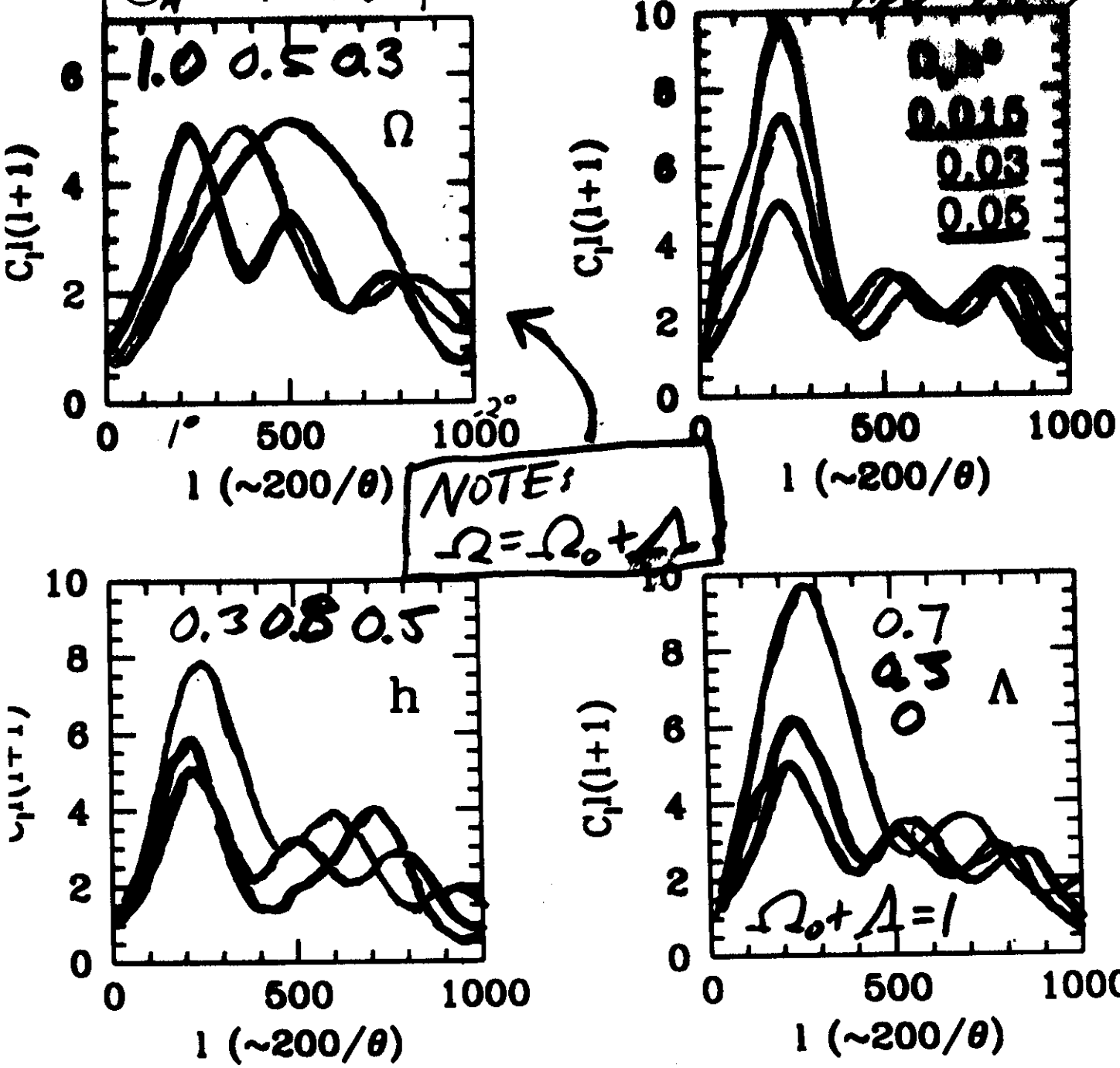
Theory predicts each a_{lm} has to be picked from Gaussian distribution with variance $\langle C_l \rangle$.

Given set of parameters $\{\Omega_0, h, \Lambda, \Omega_b, n, \ldots\}$, can calculate the $\langle C_l \rangle$.

Note: $C_l \sim \left(\frac{\Delta T}{T}\right)^2 \left(\frac{\theta}{\text{deg}} \sim \frac{200}{l}\right)$

Heavy Curves: $\Omega=1$, $\Lambda=0$, $\Omega_b h^2=0.015$, $h=0.5$

$\theta_H \simeq 1^\circ \Omega^{1/2}$ (Kamionkowski, Spergel, + Sugiyama)



NOTE: $\Omega=\Omega_0+\Lambda$

Similarly, for n, Q, Q_T, n_T, τ

(Note: $\Omega_b h^2 \simeq 3\times10^{-7}\eta$)

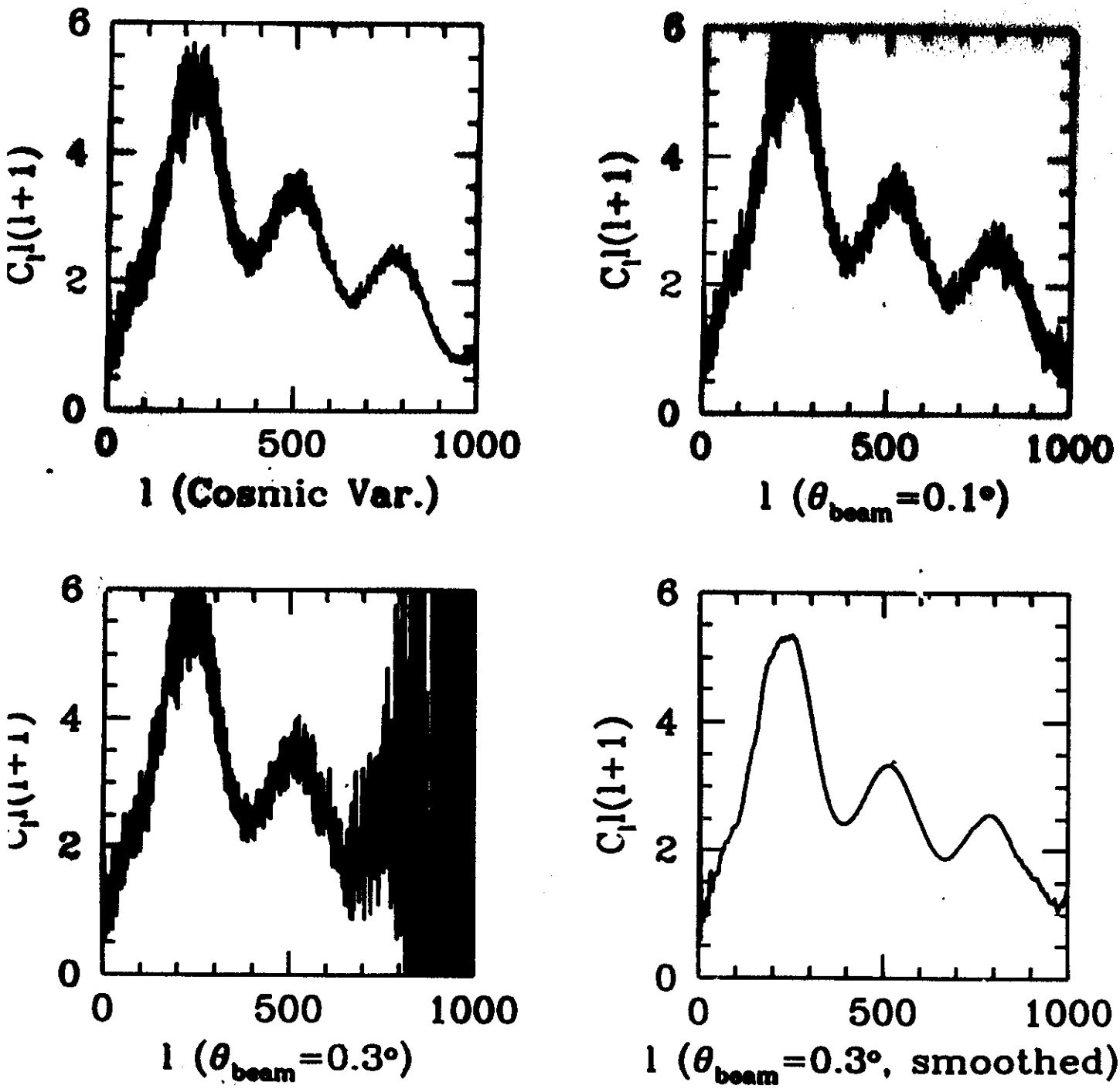
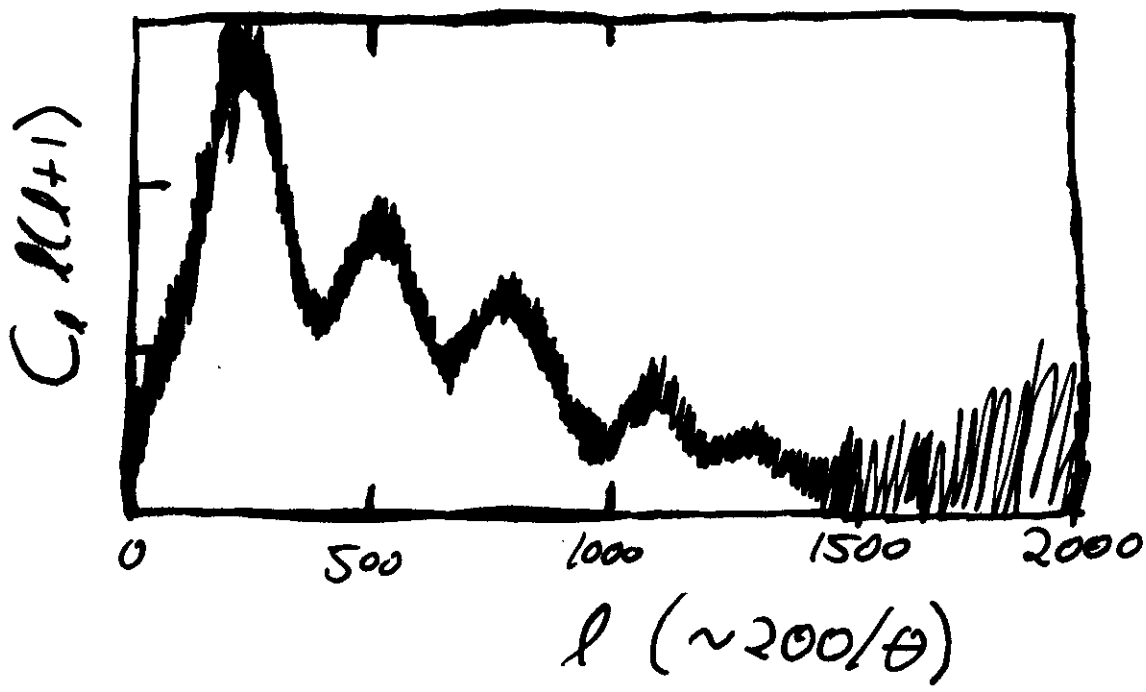


FIG. 2. Simulated data that might be obtained with a CMB mapping experiment, for beam sizes of 0.3° and 0.1°.



"Simulated" COBRAS/SAMBA

(probably conservative)

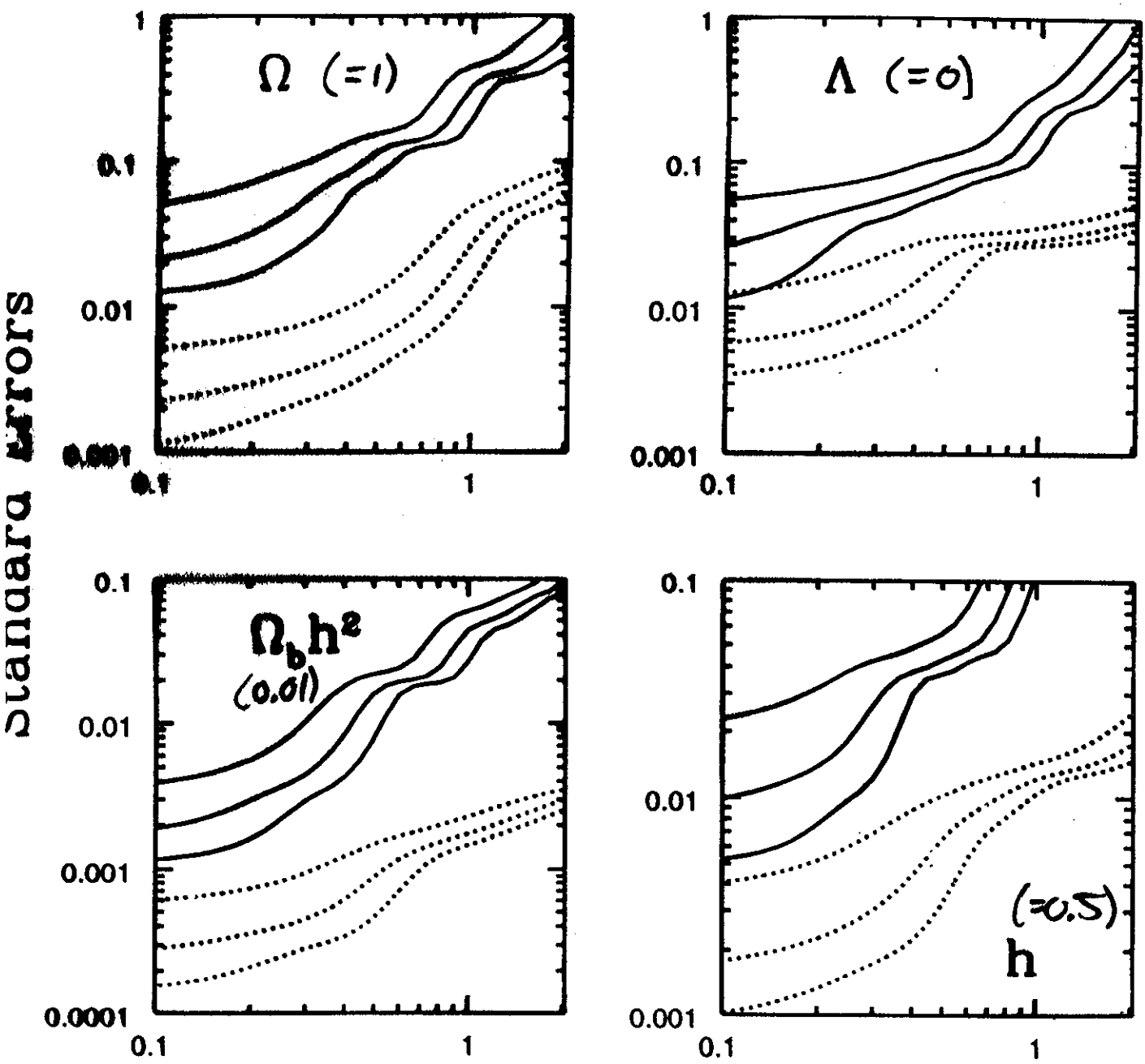


FIG. 3. The standard errors for Ω, Λ, $\Omega_b h^2$, and h that can be obtained with a full-sky mapping experiment as a function of the beam width $\theta_{\rm fwhm}$ for noise levels $w^{-1} = 2 \times 10^{-15}$, 9×10^{-15}, and 4×10^{-14} (from lower to upper curves). The underlying model is "standard CDM." The solid curves are the sensitivities attainable with no prior assumptions about the values of any of the other cosmological parameters. The dotted curves are the sensitivities that would be attainable assuming that all other cosmological parameters, except the normalization (Q), were fixed. The results for a mapping experiment which covers only a fraction $f_{\rm sky}$ of the sky can be obtained by [redacted] scaling by $f_{\rm sky}^{-1/2}$ [c.f., Eq. (20)].

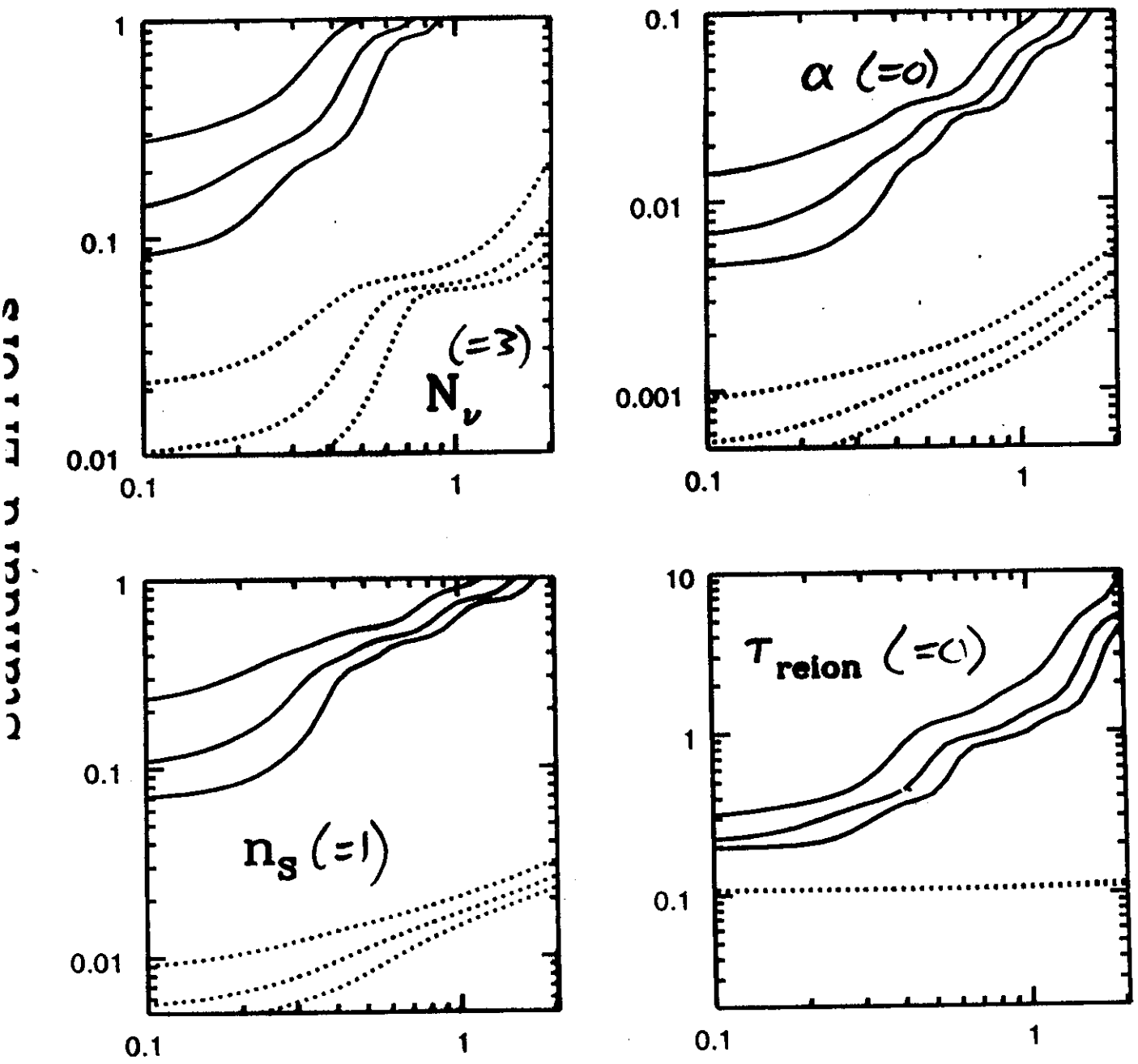


FIG. 4. Like Fig. 4, but for α, N_ν, τ_{reion}, and n_S.

Jungman, MK, Kosowsky, + Spergel (1996)

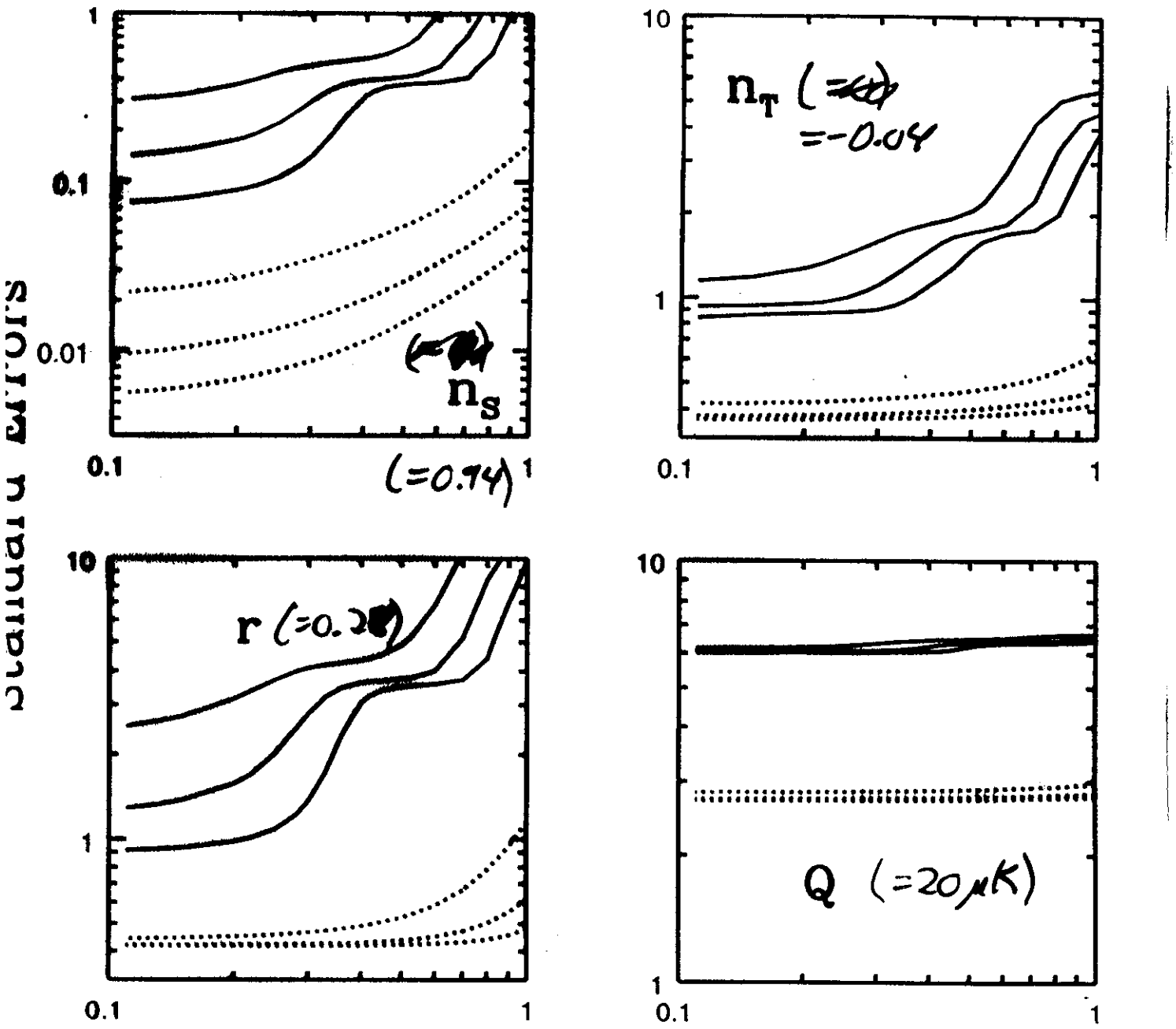


FIG. 5. The standard errors on the inflationary observables, n_S, n_T, $r \equiv Q_T^2/Q_S^2$, and Q, that can be obtained with a full-sky mapping experiment as a function of the beam width $\theta_{\rm fwhm}$ for noise levels $w^{-1} = 2 \times 10^{-15}$, 9×10^{-15}, and 4×10^{-14} (from lower to upper curves). The parameters of the underlying model are the "standard=CDM" values, except we have set $r = 0.28$, $n_S = 0.94$, and $n_T = -0.04$. The solid curves are the sensitivities attainable with no prior assumptions about the values of any of the other cosmological parameters. The dotted curves are the standard errors that would be attainable by fitting to only these four inflationary observables and assuming all other cosmological parameters are known. (Note that this differs from the dotted curves in Fig. 4.) The results for a mapping experiment which covers only a fraction $f_{\rm sky}$ of the sky can be obtained by [redacted] scaling by $f_{\rm sky}^{-1/2}$ [c.f., Eq. (20)].

Polarization and Gravitational Radiation

MK, Kosowsky, and Stebbins, astro-ph/9609132; Seljak and Zaldarriaga, astro-ph/9609169, astro-ph/9609170 9611125

Anisotropic Compton scattering ⇒ linear polarization

Temperature: $T(\hat{n})$

Polarization: "$\vec{P}$" $(\hat{n})$

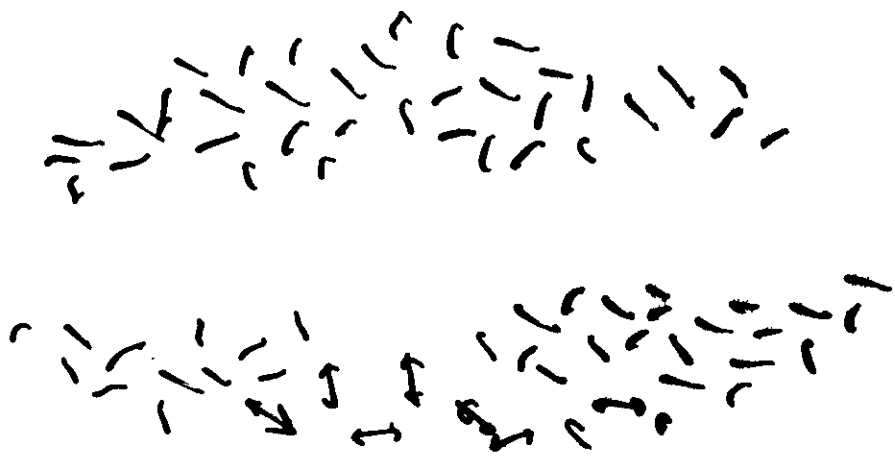
Vector field has curl and curl-free part:

$$\vec{P}(\hat{n}) = \vec{\nabla} A + \vec{\nabla} \times \vec{B}$$

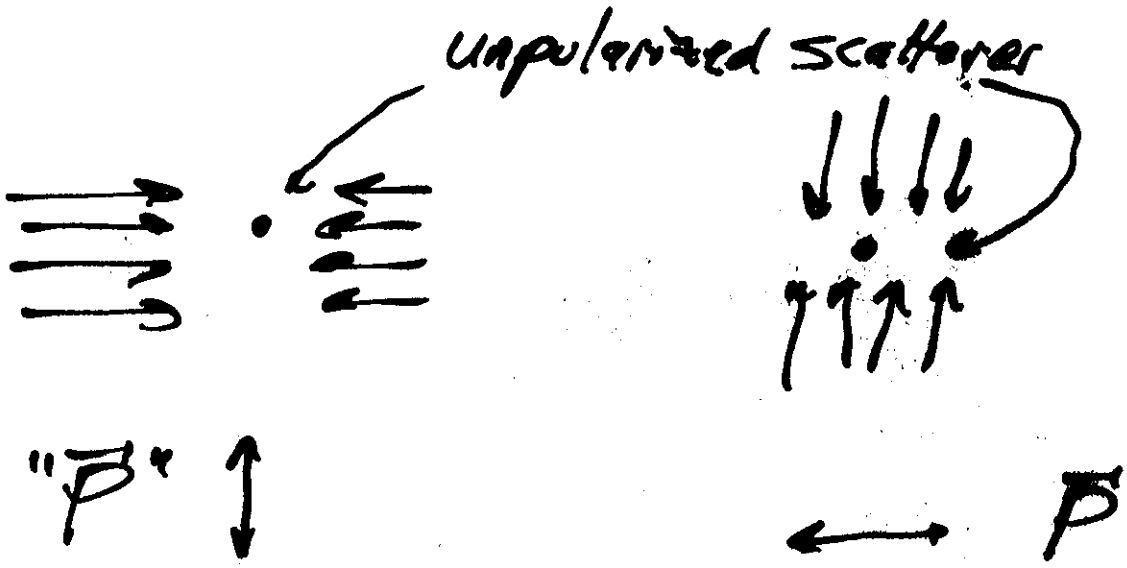
Density perturbations ⇒ $\vec{\nabla} \times \vec{P} = 0$ (i.e., scalar perturbations have no "handedness")

Gravitational waves ⇒ $\vec{\nabla} \times \vec{P} \neq 0$ (i.e., gravitational waves have "handedness")

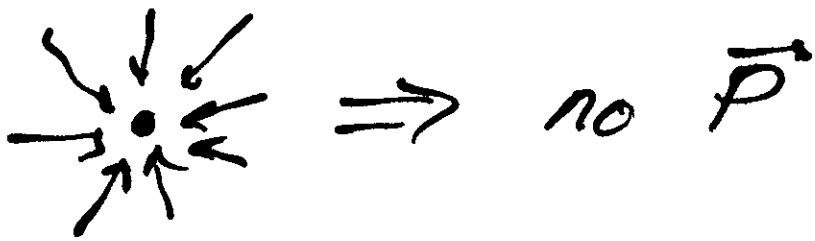
Polarization map ⇒ model-independent probe of long-wavelength gravitational waves



Polarization:



isotropic:



Tensor Harmonics:

Polarization Tensor: P_{ab}

symmetric: $P_{ab} = P_{ba}$ trace-free $P_{ab} g^{ab} = 0$

e.g., $(\theta, \phi) \Rightarrow g_{ab} = \begin{pmatrix} 1 & 0 \\ 0 & \sin^2\theta \end{pmatrix}$

$$\boxed{P_{ab}(\hat{n}) = \frac{1}{2}\begin{pmatrix} Q(\hat{n}) & -U(\hat{n})\sin\theta \\ -U(\hat{n})\sin\theta & -Q(\hat{n})\sin^2\theta \end{pmatrix}}$$

Temperature Map $T(\hat{n})$:

$$\frac{T(\hat{n})}{T_0} = 1 + \sum_{l=1}^{\infty} \sum_{m=-l}^{l} a^T_{(lm)} Y_{(lm)}(\hat{n})$$

$$a^T_{(lm)} = \frac{1}{T_0}\int d\hat{n}\, T(\hat{n}) Y^*_{(lm)}(\hat{n}) \qquad \int Y^*_{(lm)} Y_{(l'm')} d\hat{n} = \delta_{ll'} \cdot \delta_{mm'}$$

Polarization Map:

$$\frac{P_{ab}(\hat{n})}{T_0} = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} \left[a^G_{(lm)} Y^G_{(lm)ab}(\hat{n}) + a^C_{(lm)} Y^C_{(lm)ab}(\hat{n}) \right]$$

$$a^G_{(lm)} = \frac{1}{T_0}\int d\hat{n}\, P_{ab}(\hat{n}) Y^{G\,ab*}_{(lm)}(\hat{n}) \qquad a^C_{(lm)} = \frac{1}{T_0}\int d\hat{n}\, P_{ab}(\hat{n}) Y^{C\,ab*}_{(lm)}(\hat{n})$$

$$\int d\hat{n}\, Y^{X*}_{(lm)ab} Y^{X'\,ab}_{(l'm')} = \delta_{ll'} \cdot \delta_{mm'} \cdot \delta_{XX'} \leftarrow \text{orthonormality}$$

$$\{X, X'\} = \{G, C\}$$

Statistics:

$$\langle a^{X}_{(lm)} a^{X'}_{(l'm')} \rangle = C_l^{XX'} \delta_{ll'} \delta_{mm'}$$

for $X = \{T, G, C\}$

$Y_{(lm)}$, $Y^{G}_{(lm)ab}$ parity $(-)^l$

$Y^{G}_{(lm)ab}$ parity $(-)^{l+1}$ $\Rightarrow C_l^{TC} = C_l^{GC} = 0$

∴ Statistics of Temp/Pol. map specified (completely for Gaussian theories) by $\boxed{C_l^{TT},\ C_l^{GG},\ C_l^{TG},\ C_l^{CC}}$

Scalar modes $\Rightarrow C_l^{CC} = 0$

$$\overline{(\Delta T)^2} = T_0^2 \sum_{l=2}^{\infty} \frac{2l+1}{4\pi} C_l^{TT}$$

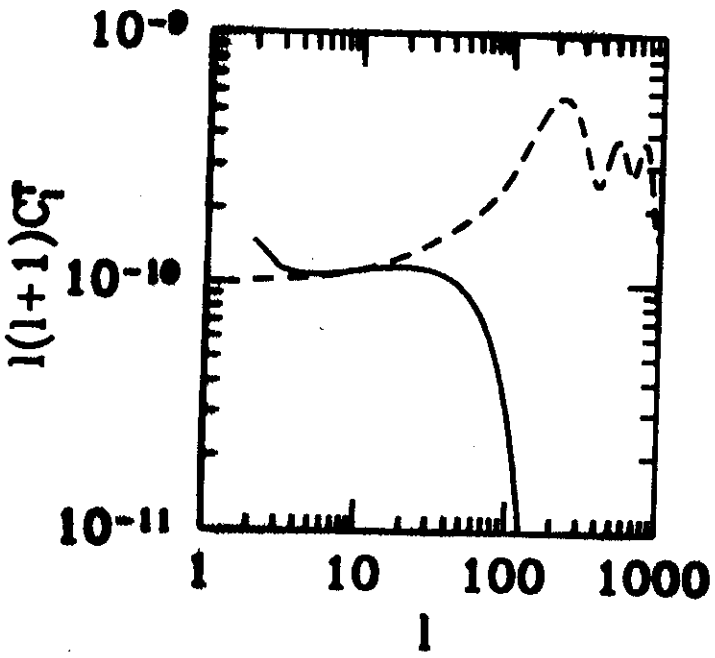
mean square ΔT

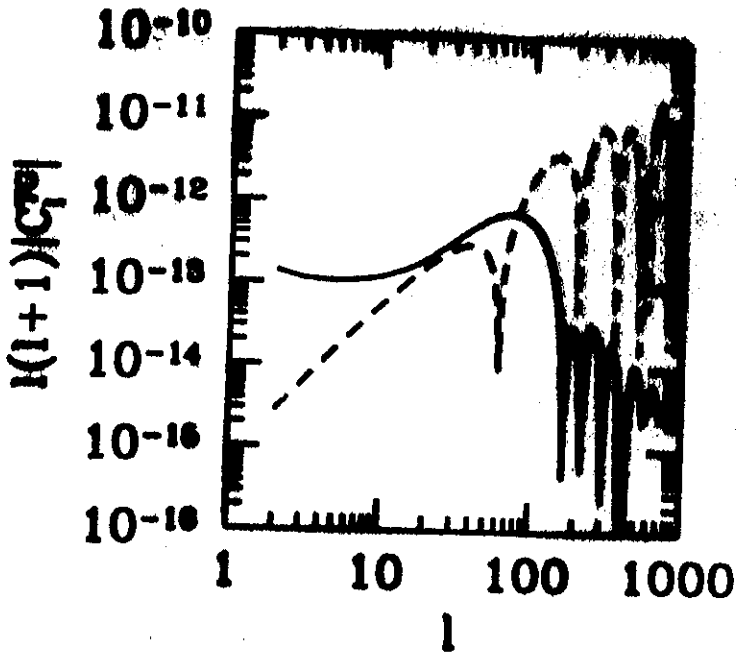
$$\overline{P^2} \equiv \overline{Q^2 + U^2} = \overline{P_G^2} + \overline{P_C^2}$$

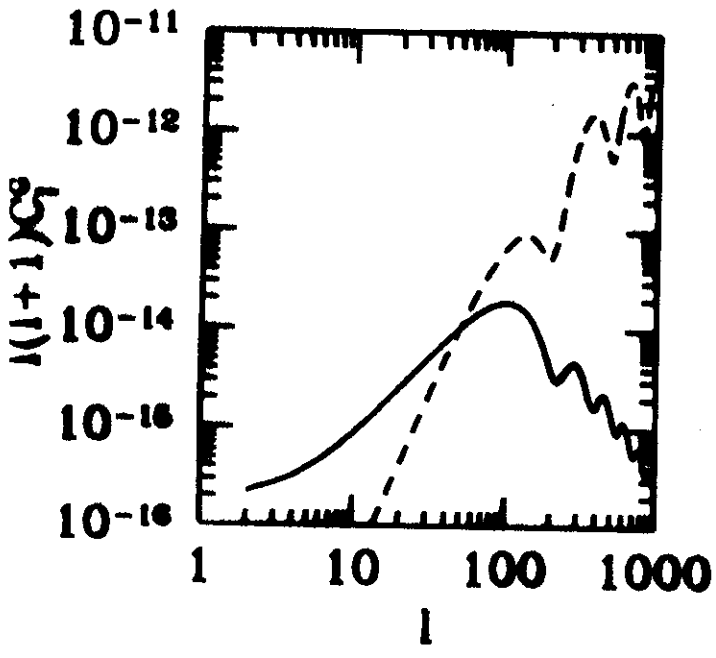
mean square polarization

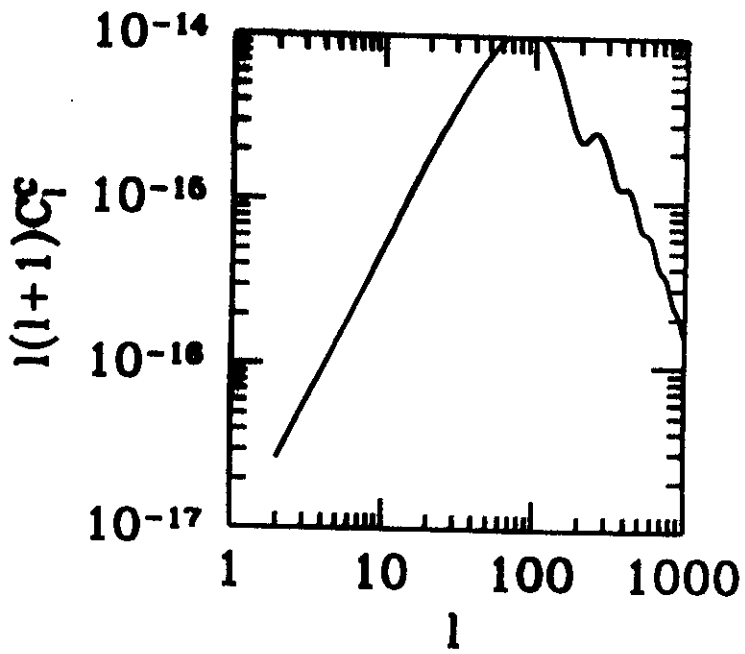
$$\overline{P_G^2} = T_0^2 \sum_{l=2}^{\infty} \frac{2l+1}{8\pi} C_l^{G}$$

$$\overline{P_C^2} = T_0^2 \sum_{l=2}^{\infty} \frac{2l+1}{8\pi} C_l^{C}$$

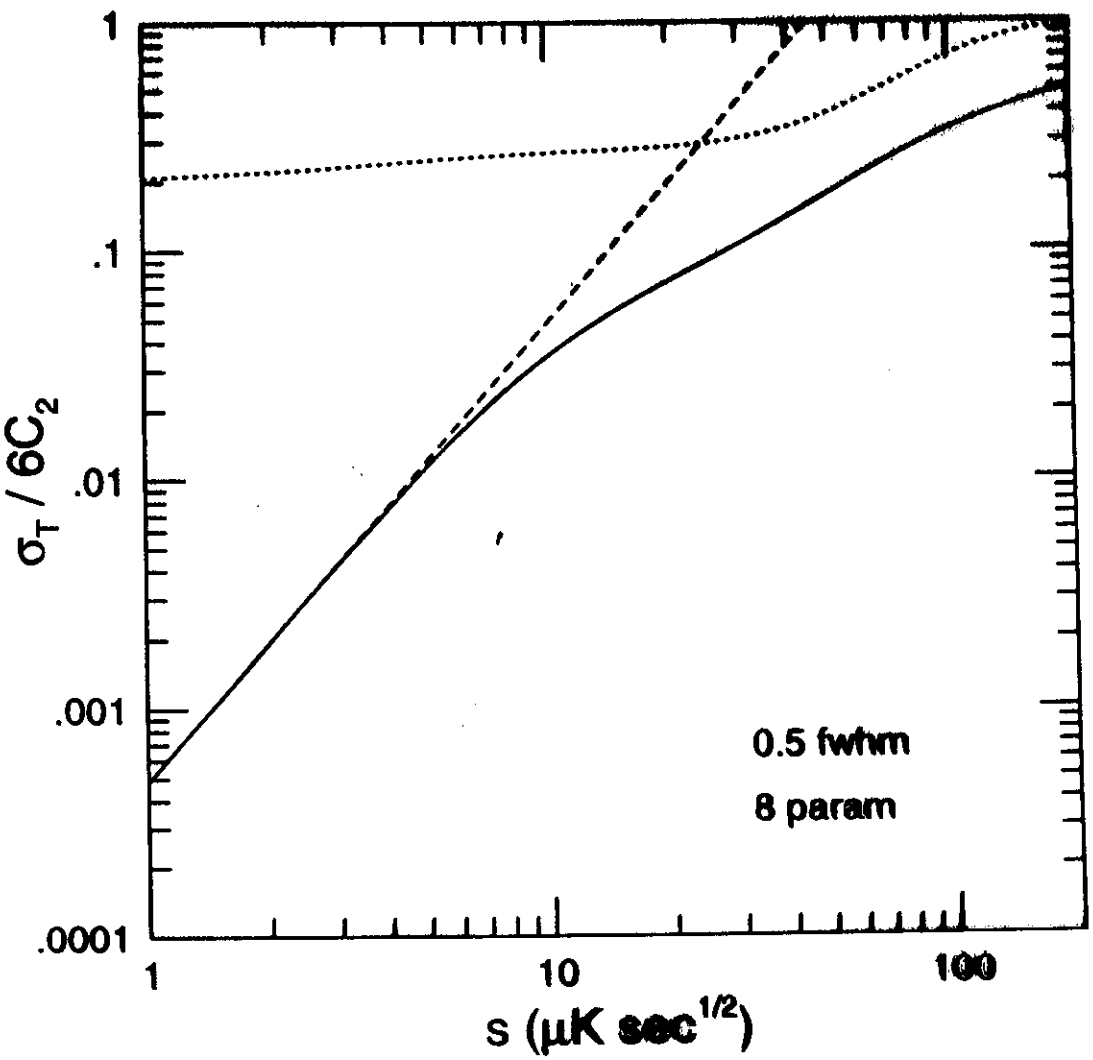

10⁻⁹
10⁻¹⁰
10⁻¹¹
l(l+1)C_l
1
10
100
1000
l

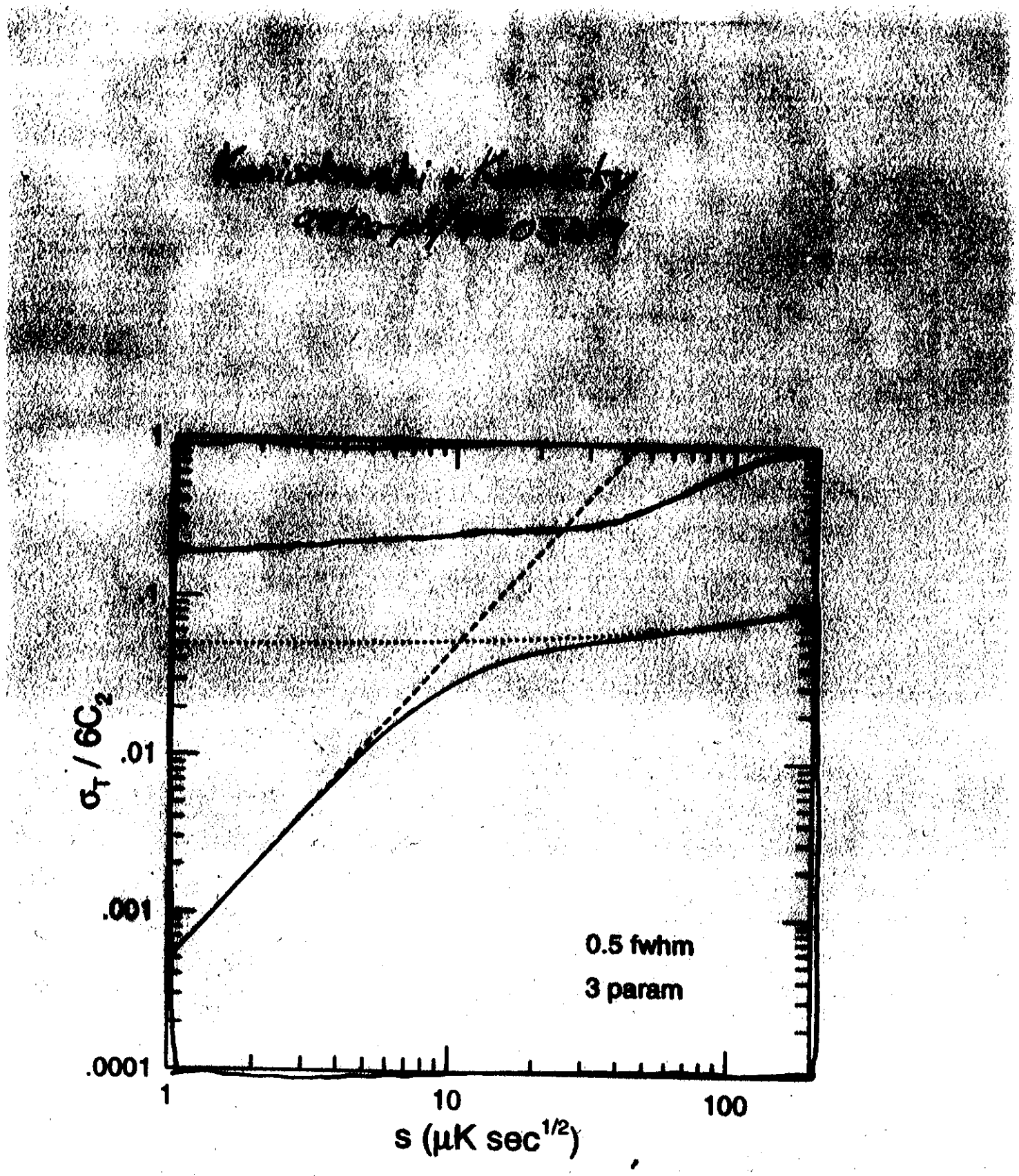

10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
l(l+1)C_l
1
10
100
1000
l


10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
l(l+1)C_l
1
10
100
1000
l

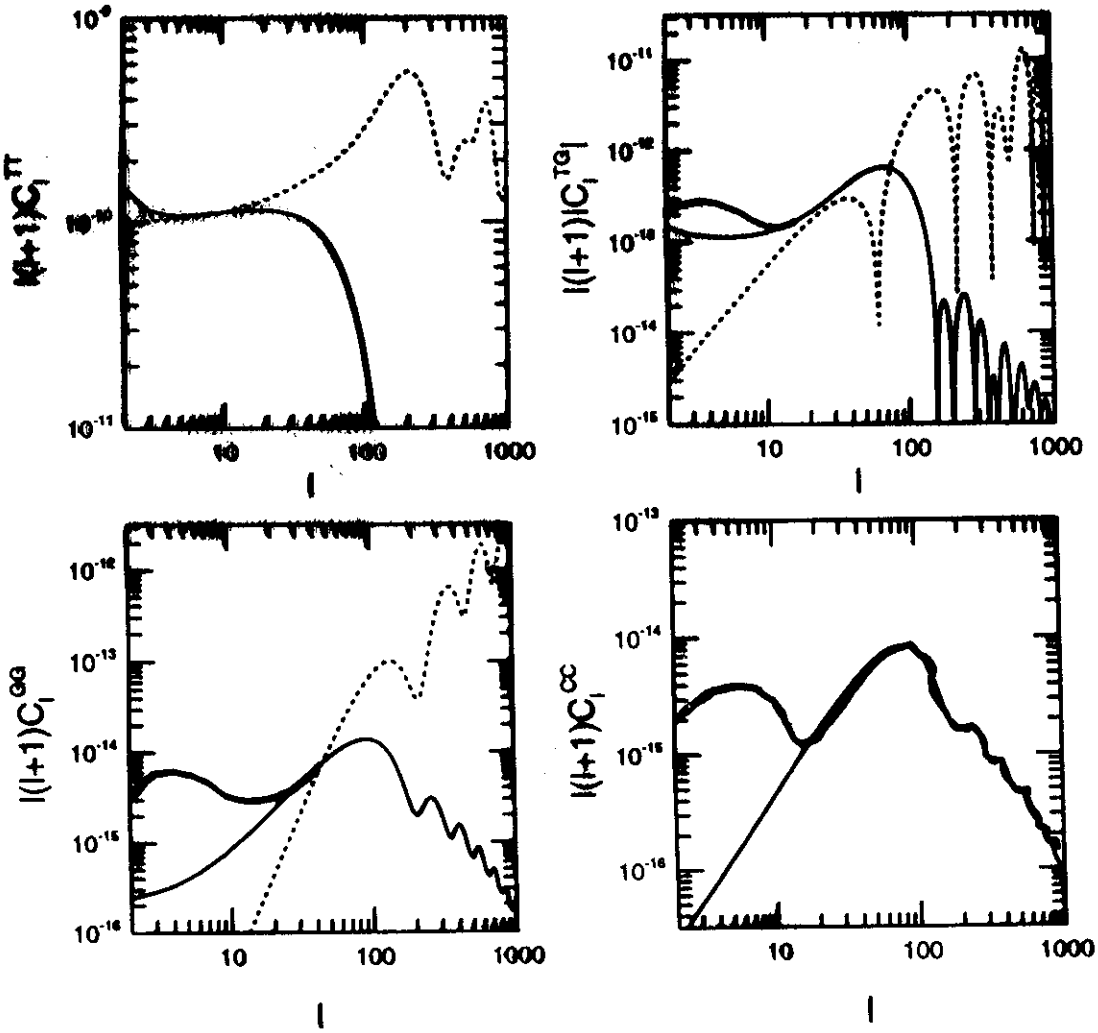

10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
l(l+1)C_l
1
10
100
1000
l

Kamionkowski + Kosowsky
astro-ph/9705219




1
.01
.001
.0001
$\sigma_T / 6C_2$
0.5 fwhm
3 param
1
10
100
s (μK sec$^{1/2}$)

Reionization:



Conclusions

CMB maps will likely provide information about:

- geometry and cosmological parameters
- structure formation
- ionization history
- long-wavelength gravitational waves
- new tests of inflation

Other uses:

- Matter/CMB correlations $\Longrightarrow \Omega_0$
- tests for non-Gaussian statistics $\Longrightarrow$ structure-formation theories
- Sunyaev-Zeldovich effect:
  - H_0
  - learn about clusters
- Blackbody spectrum
  - constrains ionization history
  - constrains exotic phenomena in early Universe