Connections between the Big and Small

Introduction to 31st SSI

John Ellis,
CERN

α

1 - Big-Bang Cosmology

2 - Particle Physics Beyond the Standard Model

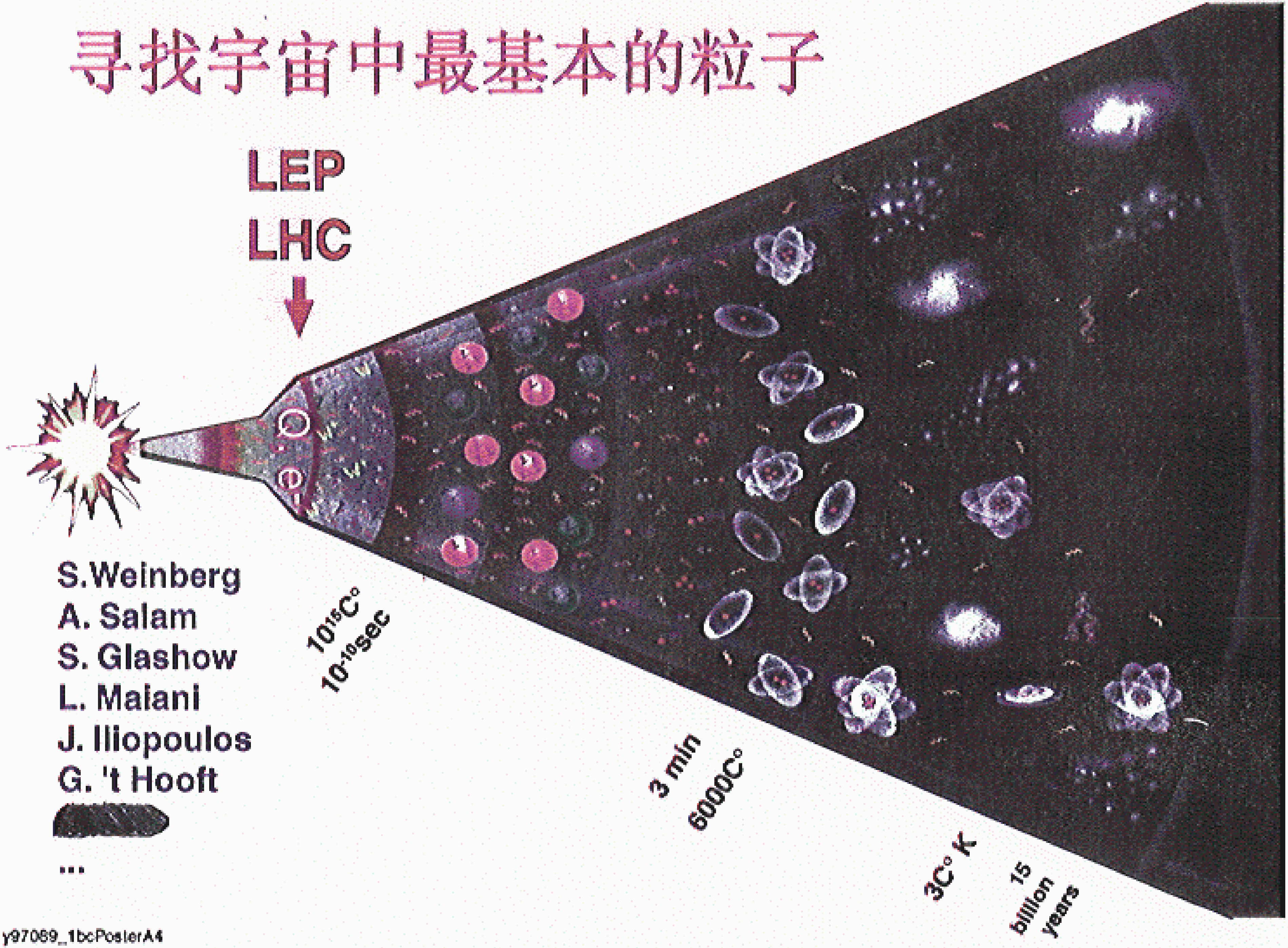
3 - Density Budget of Universe

4 - Formation of Structures

5 - Candidates for Dark Matter

6 - New Physics in Ultra-High-Energy Cosmic Rays

寻找宇宙中最基本的粒子



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1 - Big-Bang Cosmology

3 major pieces of evidence for Big Bang

1) Present-day Hubble expansion

all distant objects in Universe are receding from each other:

$$v = H \cdot d$$

velocity → v; d ← distance

Hubble constant: $H = h \cdot 100\,\mathrm{km/s/Mpc}$ (Mpc ← megaparsec)

$h \sim 0.7$

expansion ≈ homogeneous, isotropic

extrapolate backwards in time...

2) Microwave background radiation (~3°K)

relic of (re)combination of nuclei + electrons → atoms

$T \sim 1000 \times T_{\mu BR}$ $\qquad a \sim \frac{1}{1000} \times a_0$

(a ← scale size)

$t \sim 10^6\,y$ $\qquad$ best evidence for isotropy

extrapolate further back...

3) Light element abundances $D + {}^3He$, ${}^4He$, ${}^7Li$, ...

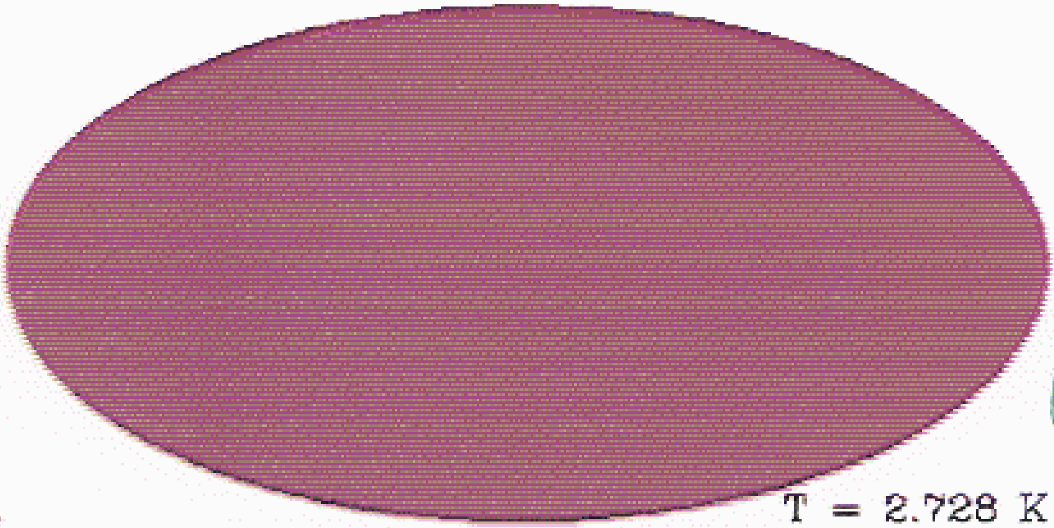
consistent with nuclear "cooking"

$T \sim 10^8$ to $10^9\,°K$ (0.1 to 1 MeV) $\qquad t \sim (1$ to $100)\,s$

and even earlier?

Cosmic Microwave Background

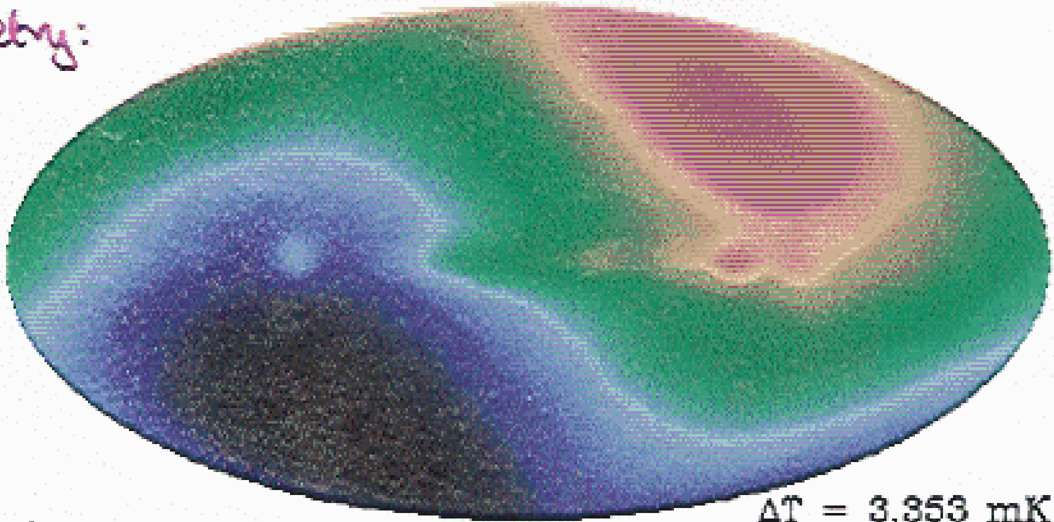
isotropic, thermal:



(Penzia
+Wilso

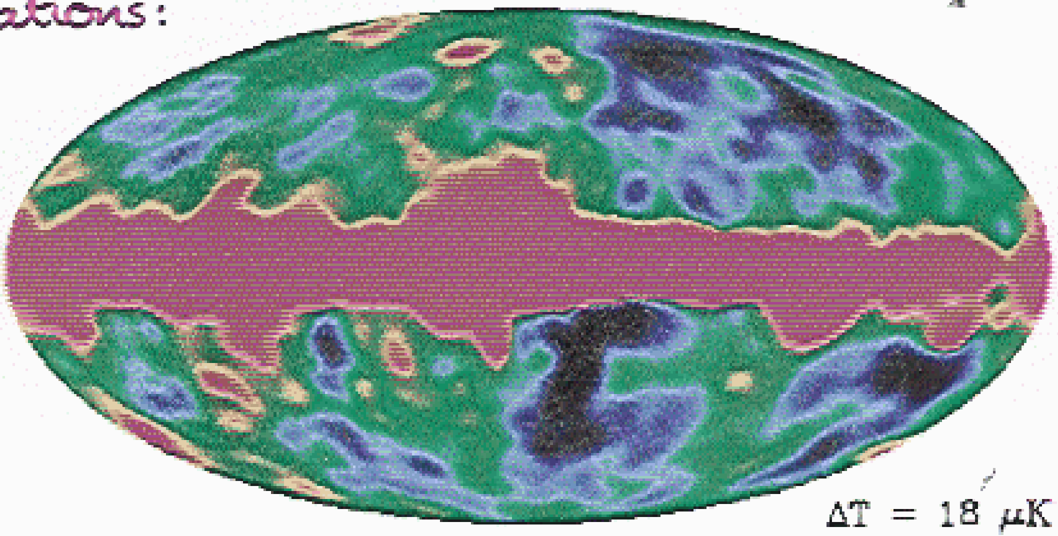
T = 2.728 K

dipole asymmetry:



ΔT = 3.353 mK

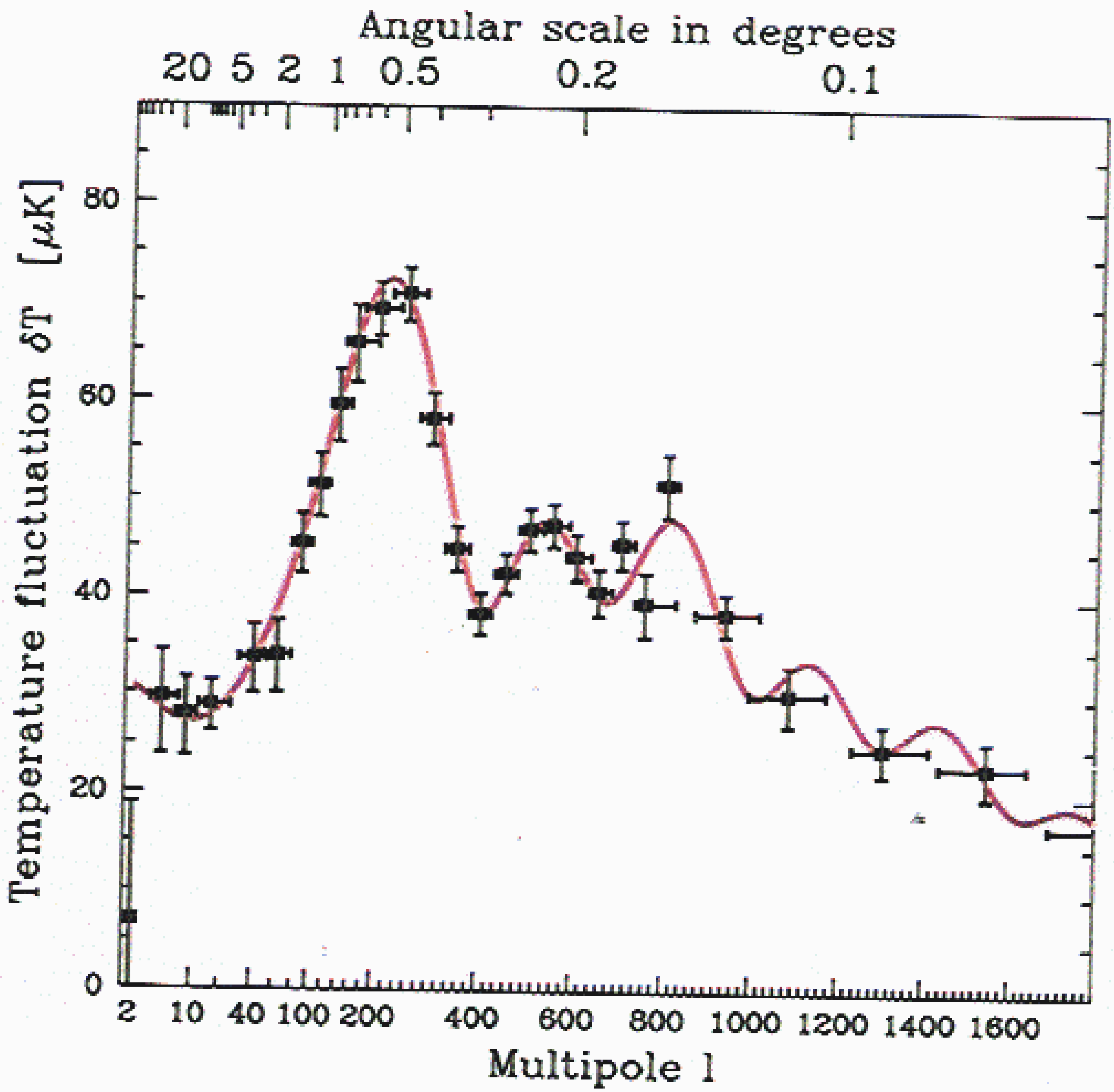
perturbations:



(COBE

ΔT = 18 μK

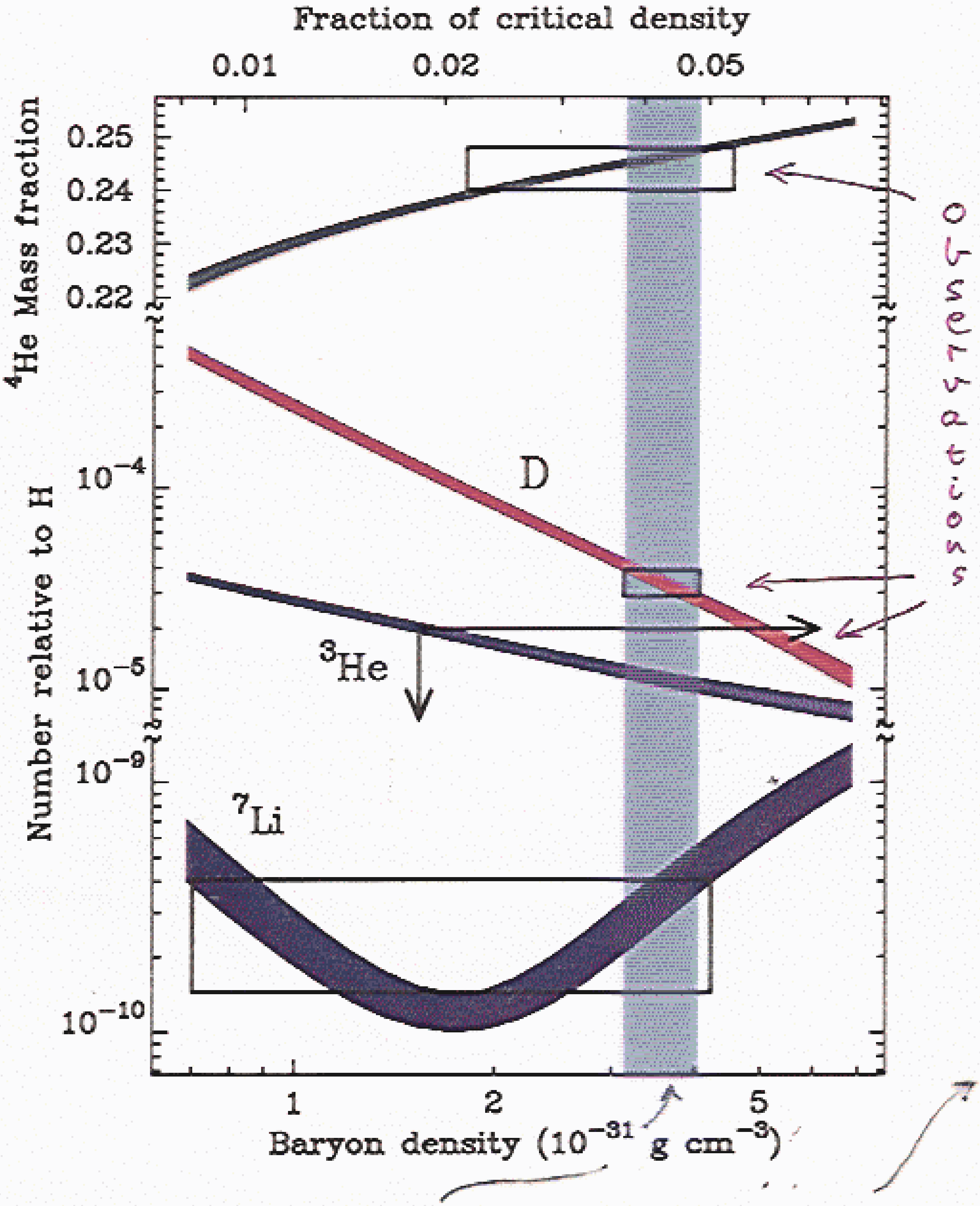
Cosmic Microwave Background before WMAP



(Tegmark)

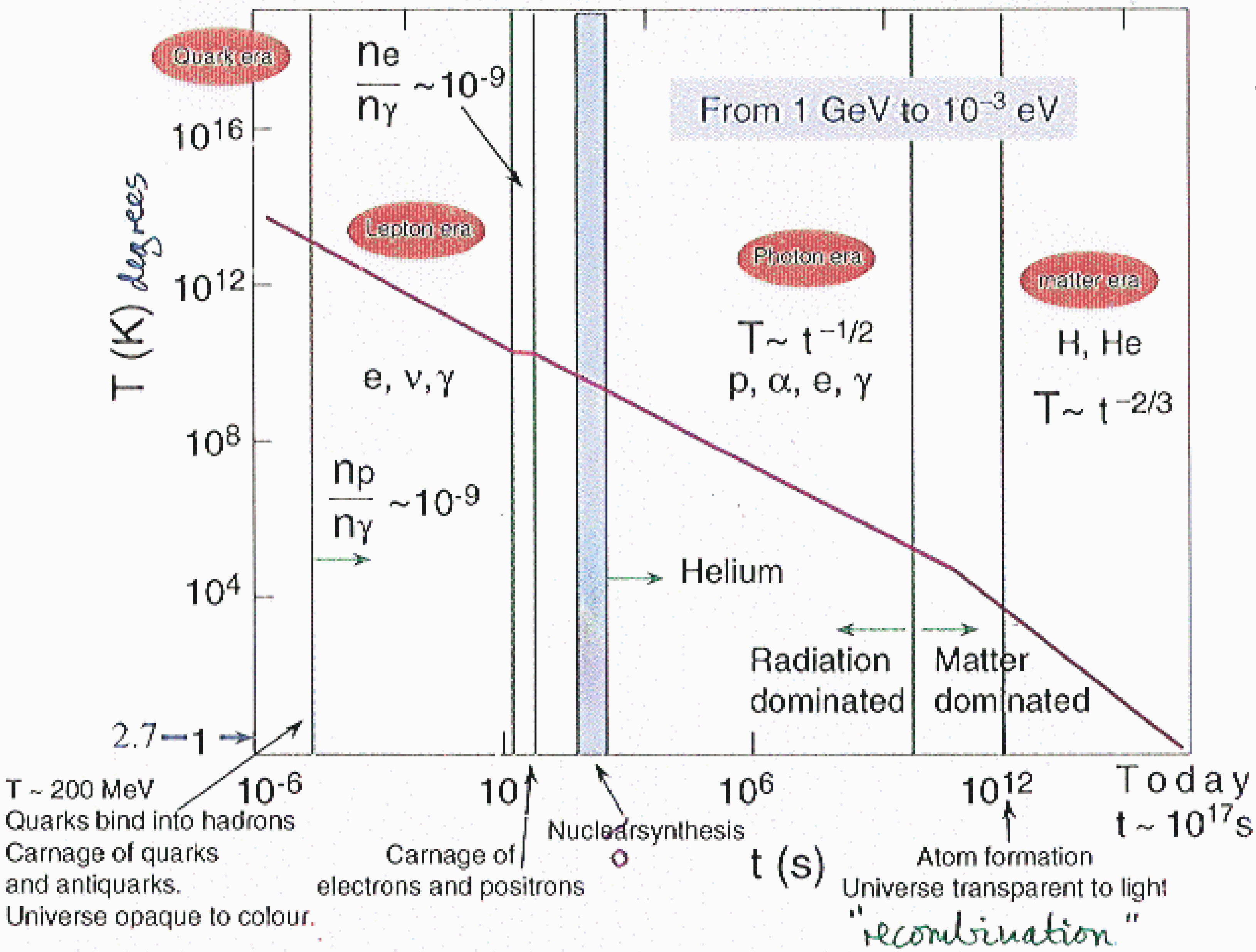
Light-Element Abundances

in Universe agree with calculations



conventional matter << critical density

TEMPERATURE OF THE UNIVERSE AS A FUNCTION OF TIME



Energy, Temperature, Time

during the expansion of the Universe
(↖ cosmic decelerator)

- expansion ⇒ cooling $T \sim 1/a$ ← size

- rate of expansion

$$t \sim a^2 \sim 1/T^2$$

(↗ age; ↖ when particle masses negligible)

- the first second ⇔ high temperatures

$$1 \text{ sec.} \sim 10^{10} \, {}^\circ K$$

and high particle energies

$$10^{10} \, {}^\circ K \sim 1 \text{ MeV}$$ cf electron mass ~ ½ MeV

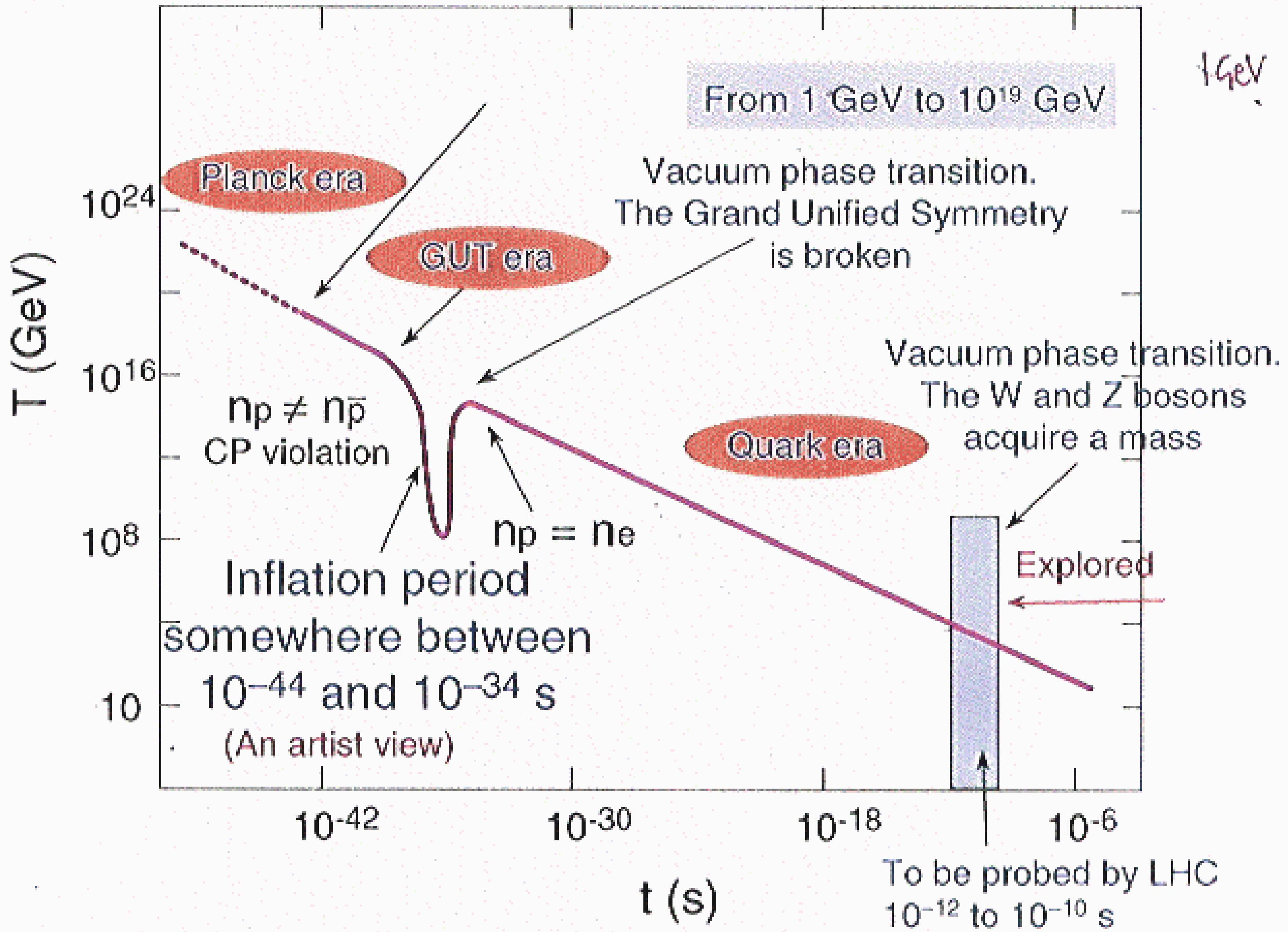
$$10^{13} \, {}^\circ K \sim 1 \text{ GeV}$$ cf proton mass ~ 1 GeV

- time - temperature relation:

$$t(\text{sec.}) \sim 1/T(\text{MeV})^2$$

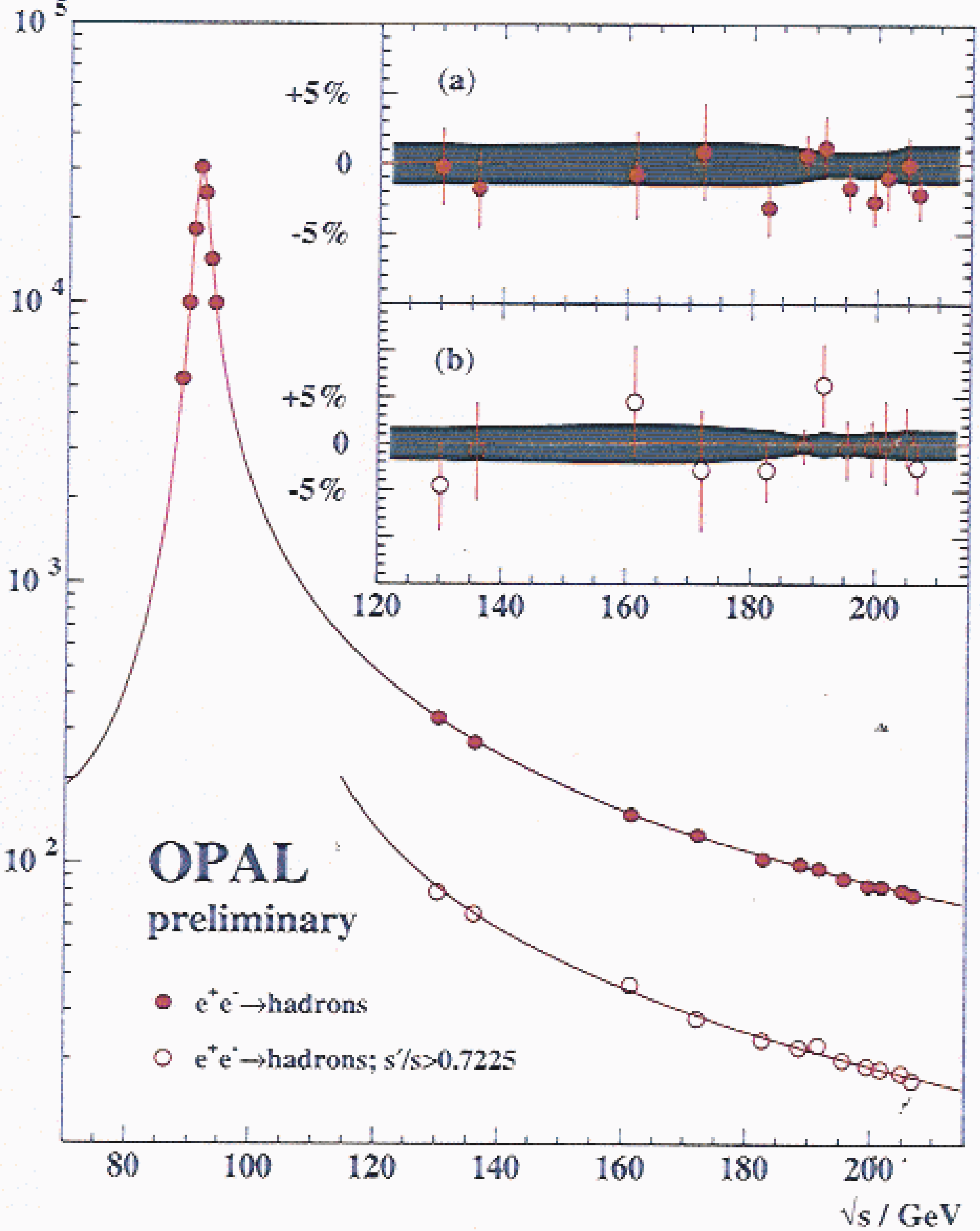
the history of the young Universe was dominated by elementary particles

TEMPERATURE OF THE UNIVERSE AS A FUNCTION OF TIME



1GeV ≈ 10

Tests of the Standard Model @ LEP



Roadmap to physics

2 - Beyond the Standard Model

open problems:

Standard Model

→ **Unification**

single framework for all gauge forces
Grand Unified Theory (GUT?)

→ **Flavour**

why so many types of q, l?
weak mixing? CP?
composite?
extra symmetries?

→ **Mass**

origin of particle masses
Higgs boson?
why are masse
so small?
supersymmetr

→ **Theory of Everything**

include gravity
reconcile it with quantum mechanics
origin of space-time
why 4 dimensions?
⋮
superstring?
M theory?

Defects of the Standard Model

it agrees with all confirmed accelerator data

But

is theoretically very unsatisfactory:

no explanations for particle quantum #'s Q, I, Y, C

contains ≥ 19 arbitrary parameters

- 3 gauge couplings g_3, g_2, g_1
- (1) CP-violating vacuum angle (θ_3)

untidy gauge structure: 3 independent groups

- 6 quark masses $m_{u,d,s,c,b,t}$
- 3 charged-lepton masses $m_{e,\mu,\tau}$
- 3 "Cabibbo" weak mixing angles α, β, γ
- (1) CP-violating Kobayashi-Maskawa phase (δ)

arbitrary Yukawa couplings

- 1 W mass m_W
- 1 Higgs mass m_H

as if that was not enough ...

3 neutrino masses $m_{1,2,3}$

3 neutrino mixing angles $\theta_{1,2,3}$

(3) CP-violating phases δ_ν

without even talking about mechanism for ν mass generation : more Higgs? heavy ν_R?...

and do not forget gravity:

1 Newton's constant $G_N = 1/m_P^2$

1 Cosmological "constant" Λ

↑ is it? or $\Lambda(t)$?

also keep in mind:

≥ 1 inflation parameter m_I

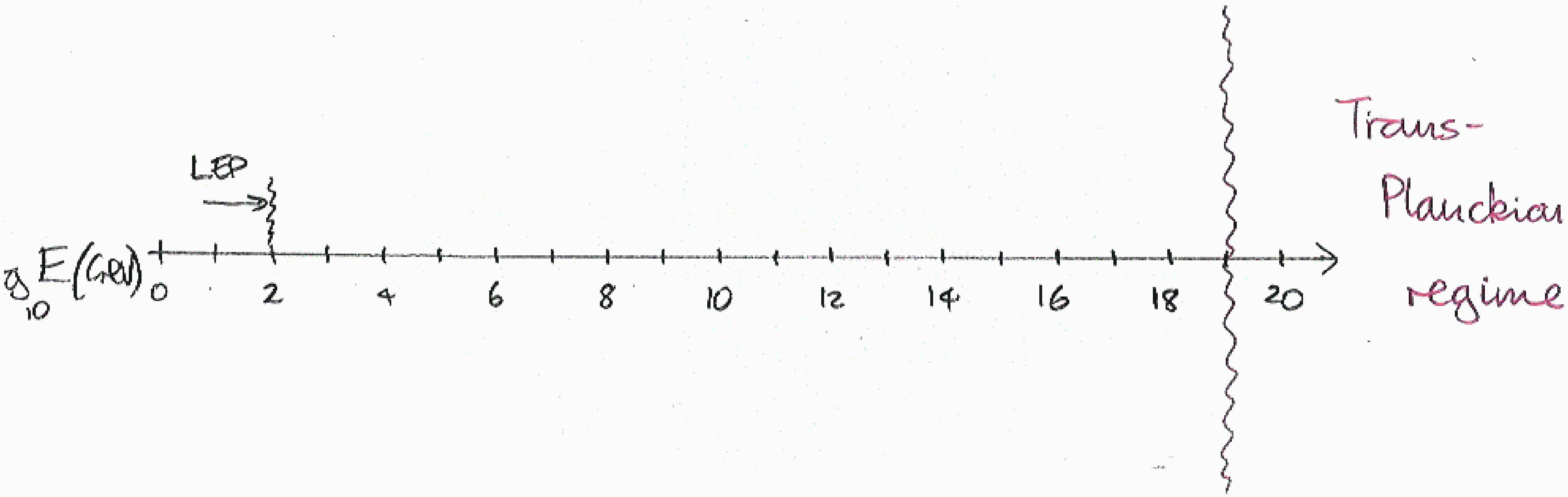
not Standard Model: $\frac{\delta T}{T} \propto \left(\frac{m_I}{m_P}\right)^2$

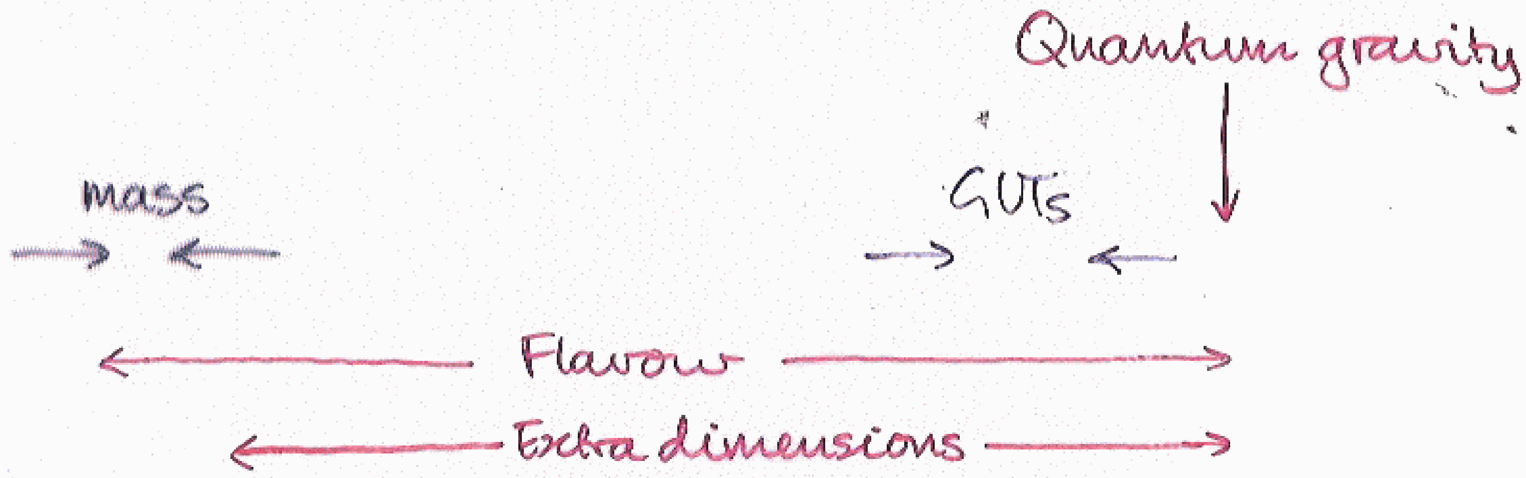
$10^{-5} \gg (m_W/m_P)^2$

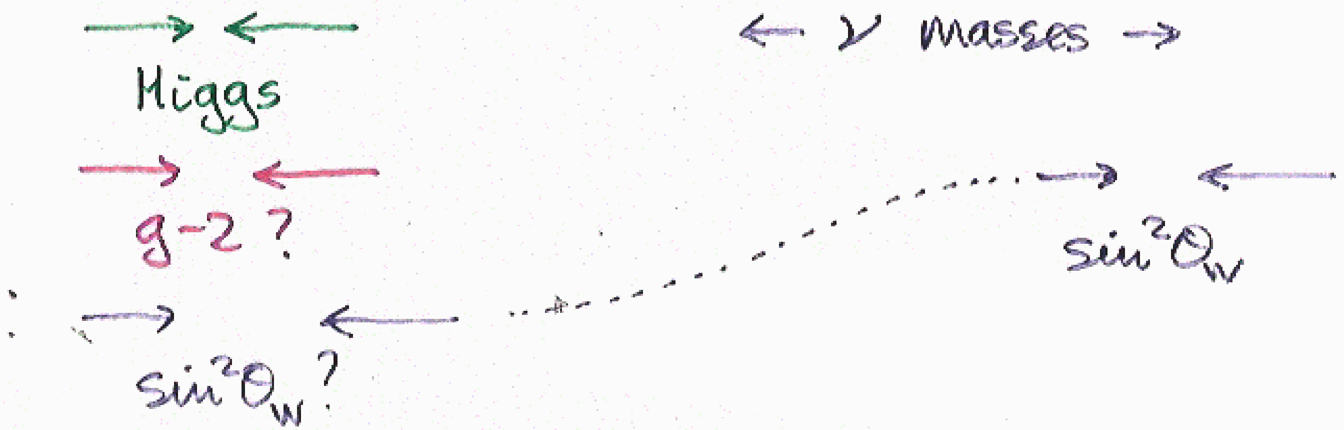
(≥ 1) parameter for baryon asymmetry n_B/n_γ

not Standard Model: $m_H > 90$ GeV

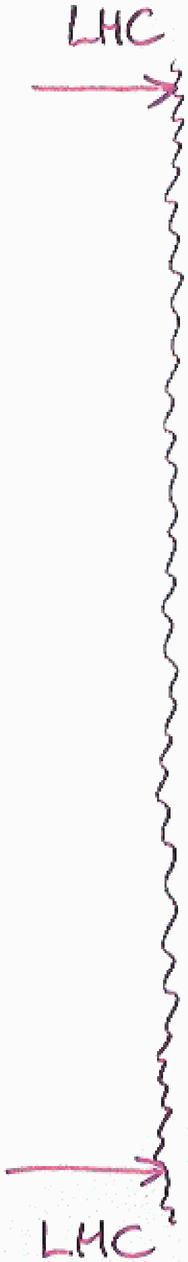
Where will New Physics Appear?




Quantum gravity
mass
GUTs
Flavour
Extra dimensions



Higgs
g-2 ?
sin²θ_W ?
ν masses
sin²θ_W


LHC
LHC


Dark Matter
Inflation
UHECR

3- Density Budget of the Universe

relative to critical density: $\Omega_i \equiv \rho_i / \rho_{crit}$

Ω_{tot} Inflation suggests $\Omega_{tot} = 1 \pm O(10^{-4})$

Supported by CMB data WMAP

Ω_b Nucleosynthesis suggests $\Omega_b = 0.04$

insufficient to explain all of ↓ WMAP

Ω_m Total matter density $\Omega_m \simeq 0.25$

clusters, CMB suggest < 1 WMAP

* Ω_{CDM} Cold Dark Matter $\Omega_{CDM} \sim \Omega_m$?

↑ structure formation theory suggests

* Ω_{HDM} Hot Dark Matter $\Omega_{HDM} h^2 \simeq \sum \left(\frac{m_\nu}{100 eV} \right)$

structure formation theory suggests $< \Omega_{CDM}$

atmospheric, solar $\nu \Rightarrow$ small masses?

WMAP

Ω_Λ Cosmological Constant $\Omega_\Lambda \sim 0.7$?

Great opportunity for quantum gravity.

The Size of the Universe

Why is the Universe so large?

$$a \gg l_{Pl} \sim 10^{-33}\,cm$$

Why is the Universe so old?

$$t \gg t_{Pl} \sim 10^{-43}\,sec$$

Why is its density so close to critical value

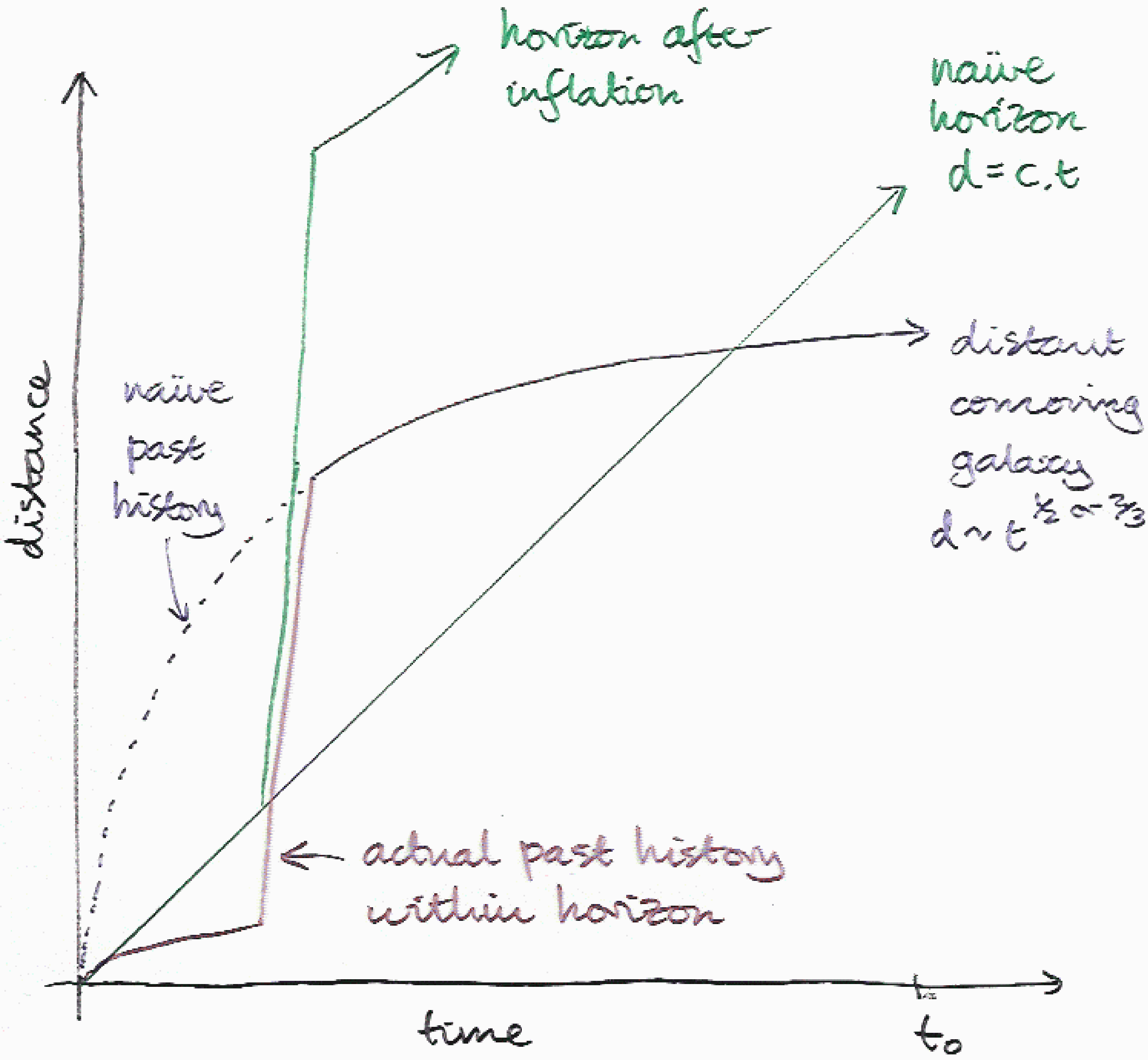
$$\rho > \frac{1}{10}\rho_{crit}$$

Why is geometry Euclidean?

Why is Universe so homogeneous?

on large scales

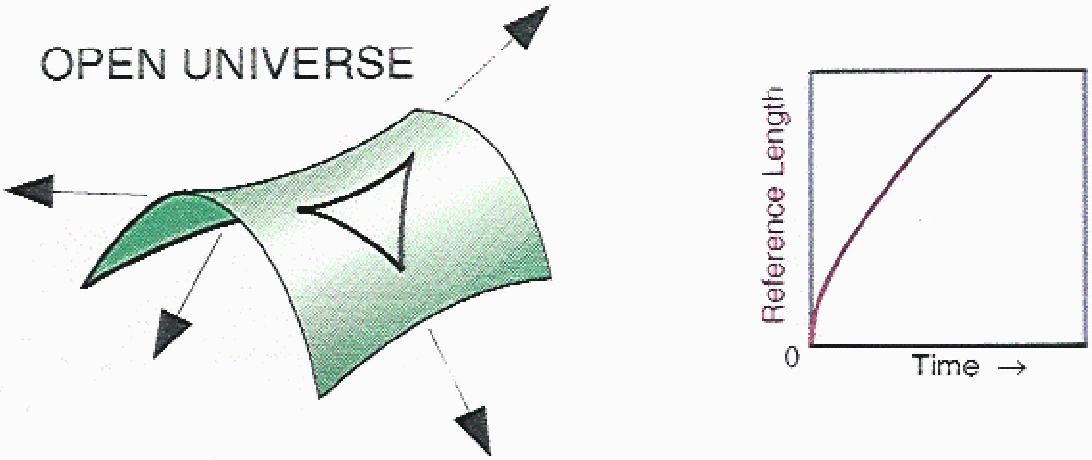
$$\delta T / T \lesssim 10^{-5}$$



Modus Operandi of Inflation

$\Omega \equiv \frac{\text{density}}{\text{critical}}$

OPEN UNIVERSE



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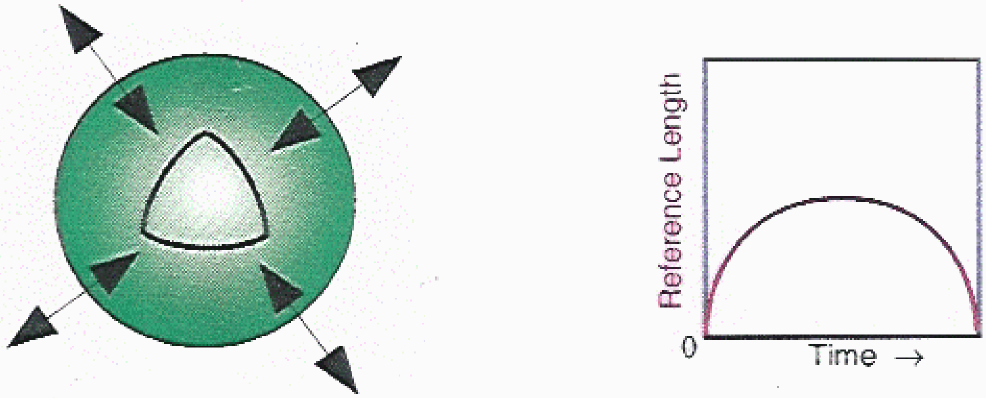
CLOSED UNIVERSE



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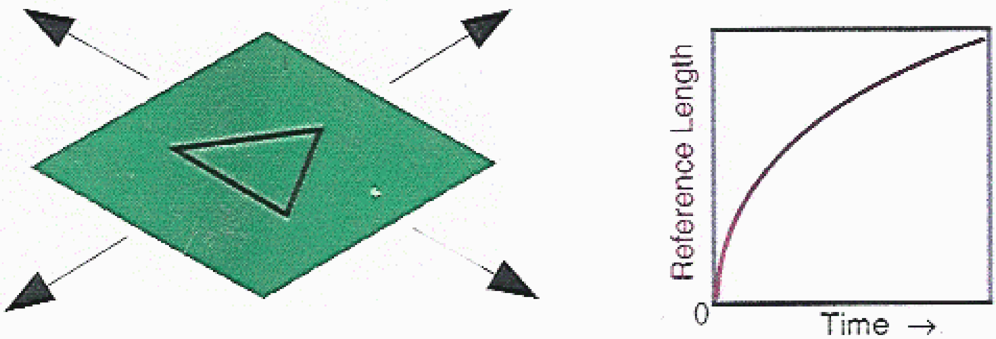
FLAT UNIVERSE

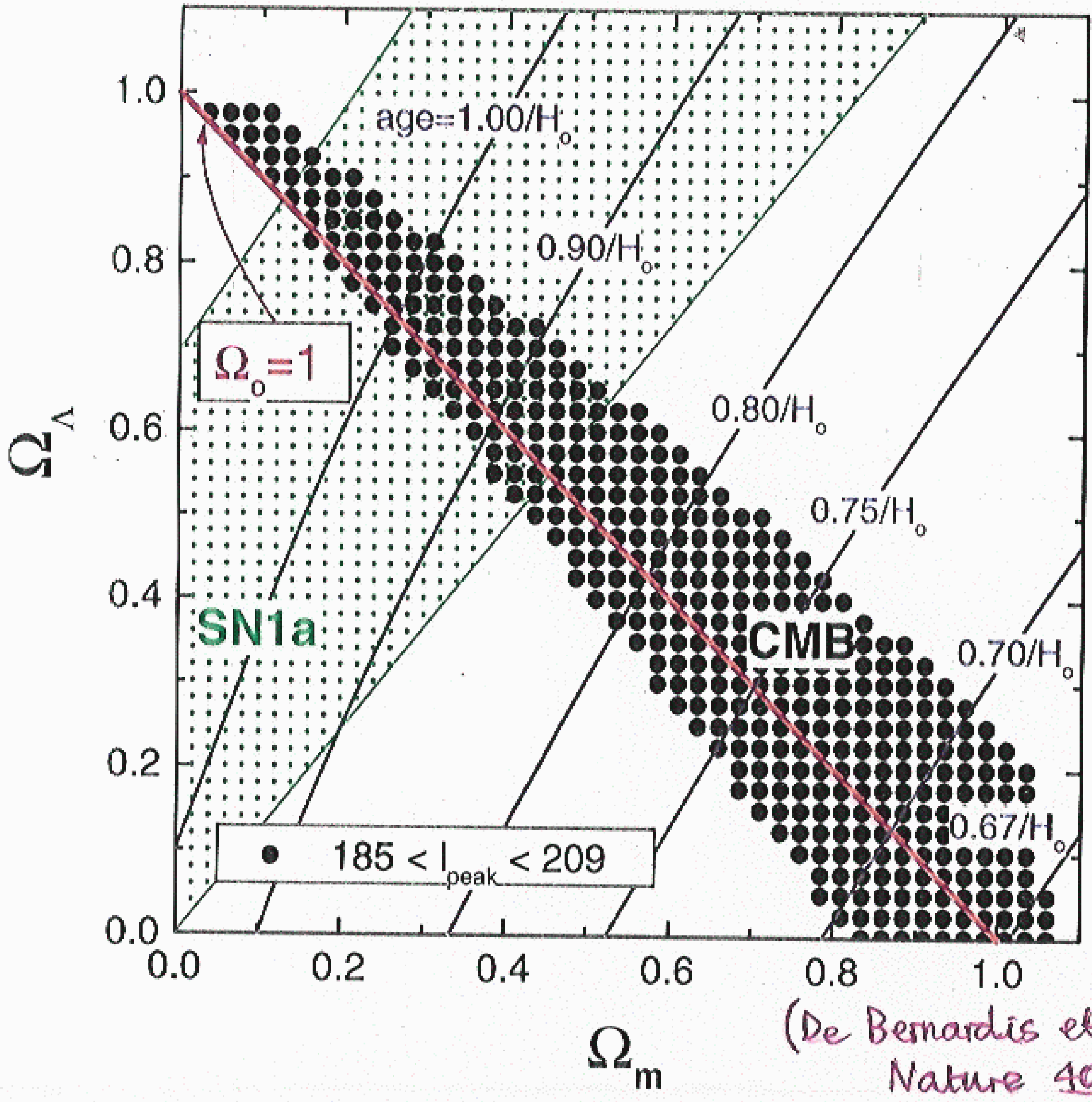


= 1

↳ inflation

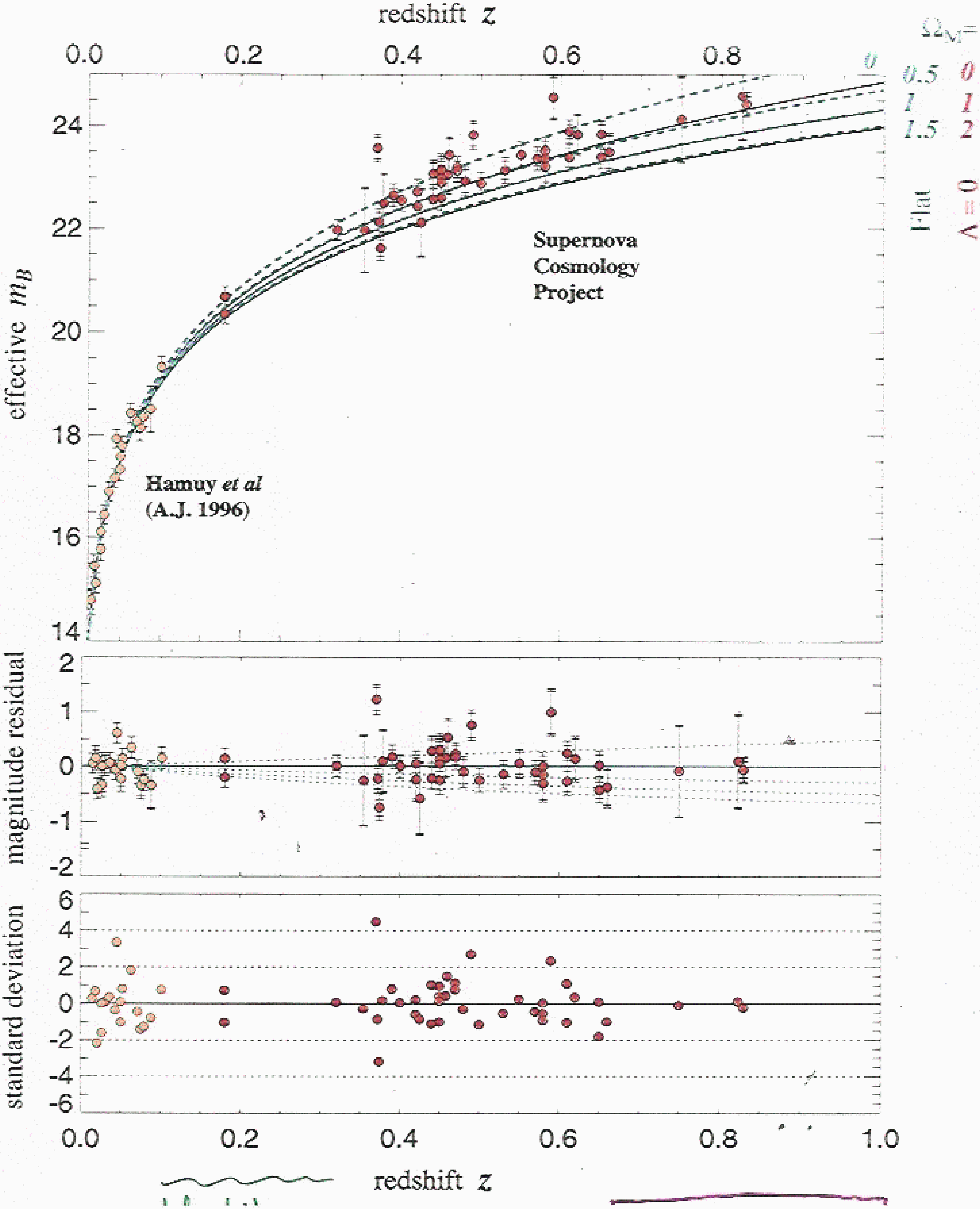
Constraints on Ω_m, Ω_Λ

pre-WMAP ...



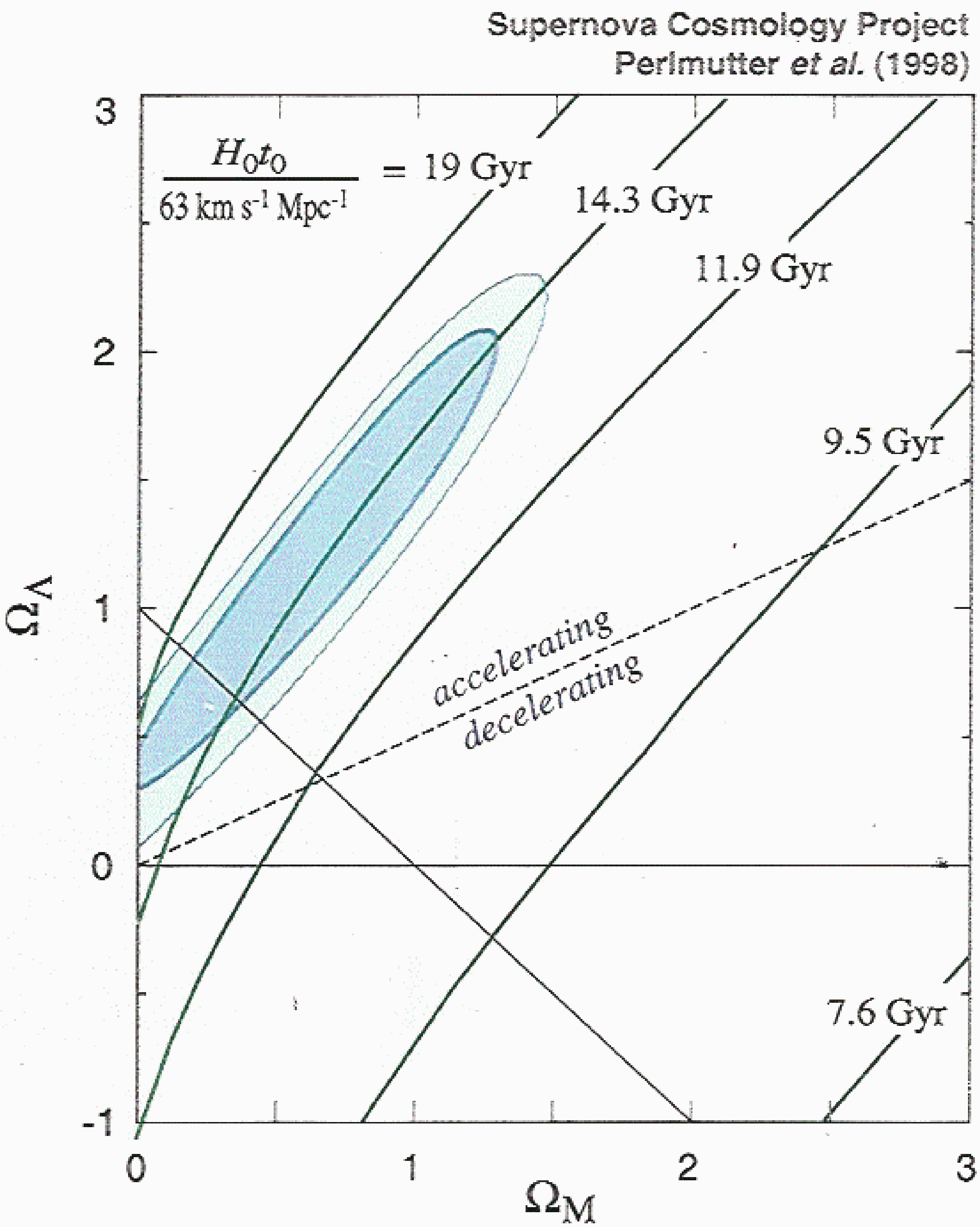
(De Bernardis et al.: Nature 404, 955 (2000))

High-Redshift Supernovae



Cosmological Vacuum Energy?

indicated by high-redshift supernovae



Best fit age of universe: $t_o = 14.5 \pm 1\ (0.63/h)$ Gyr

Best fit in flat universe: $t_o = 14.9 \pm 1\ (0.63/h)$ Gyr

Cosmological "Constant"

apparently non-zero (Perlmutter et al. / (Riess et al.

opportunity for theoretical physics

calculate it!

$$\Lambda = O\left(\frac{m_W}{m_P}\right)^8$$

is it a constant?

could vary with time:

$$w \equiv p/\rho$$

$$= -1 \text{ if constant}$$

observationally:

$$w \lesssim -\frac{1}{2}$$

dynamical relaxation of vacuum energy?

quintessence: scalar field (Steinhardt et al.

quantum gravity (J.E. + Mavromatos + Nanopoulos

Content of Universe

in units of amount required to stop Big Bang expansi[on]

ordinary matter ~ 2%

microwave background radiation, abundances of light elements

dark matter ~ 30% ?

vacuum energy ~ 70% ?

many more photons than protons, electrons

μwave background → photons

photons → also neutrinos

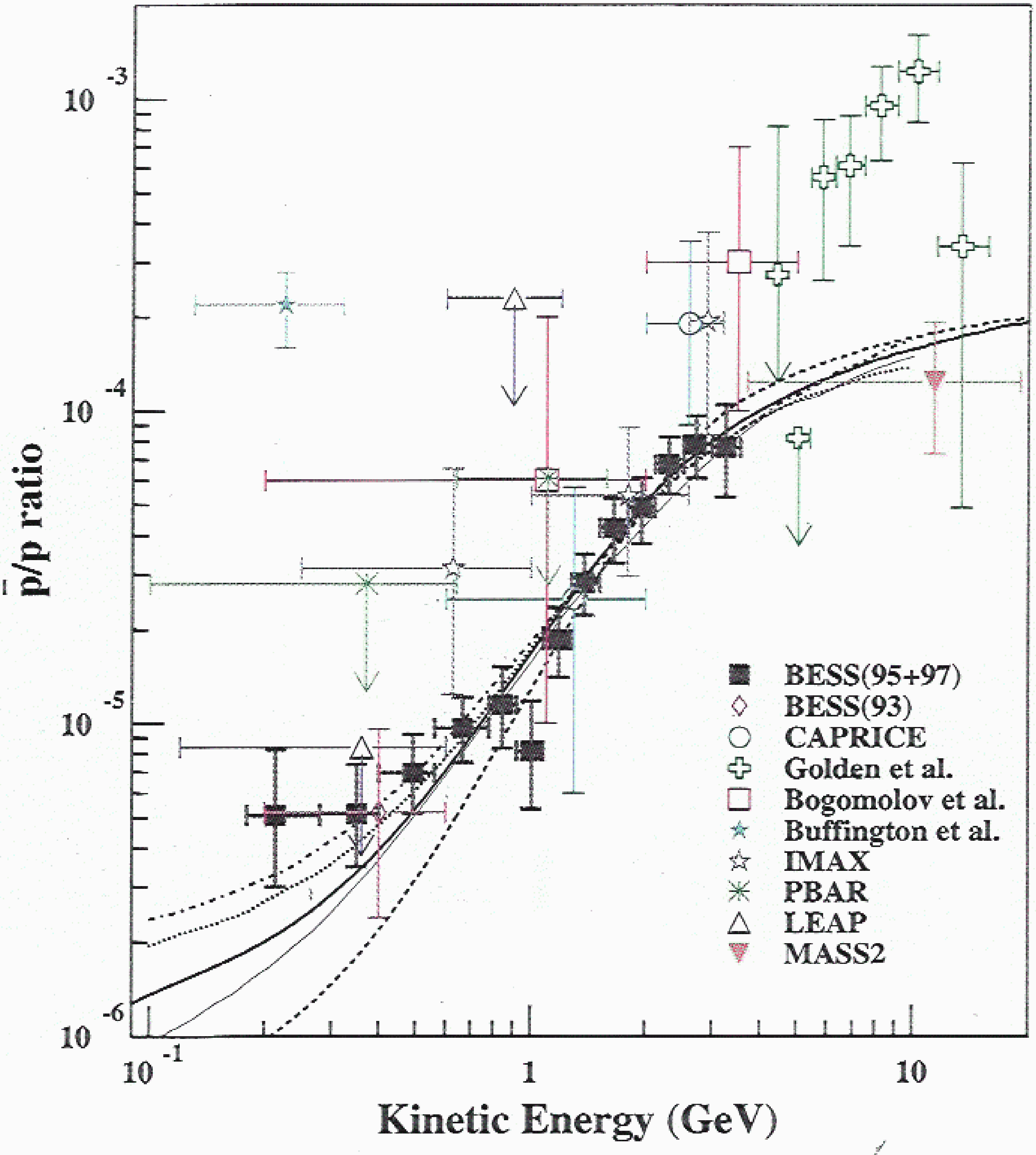
$$n_{p,e}/n_{\gamma} \sim 10^{-9} \text{ to } 10^{-10}$$

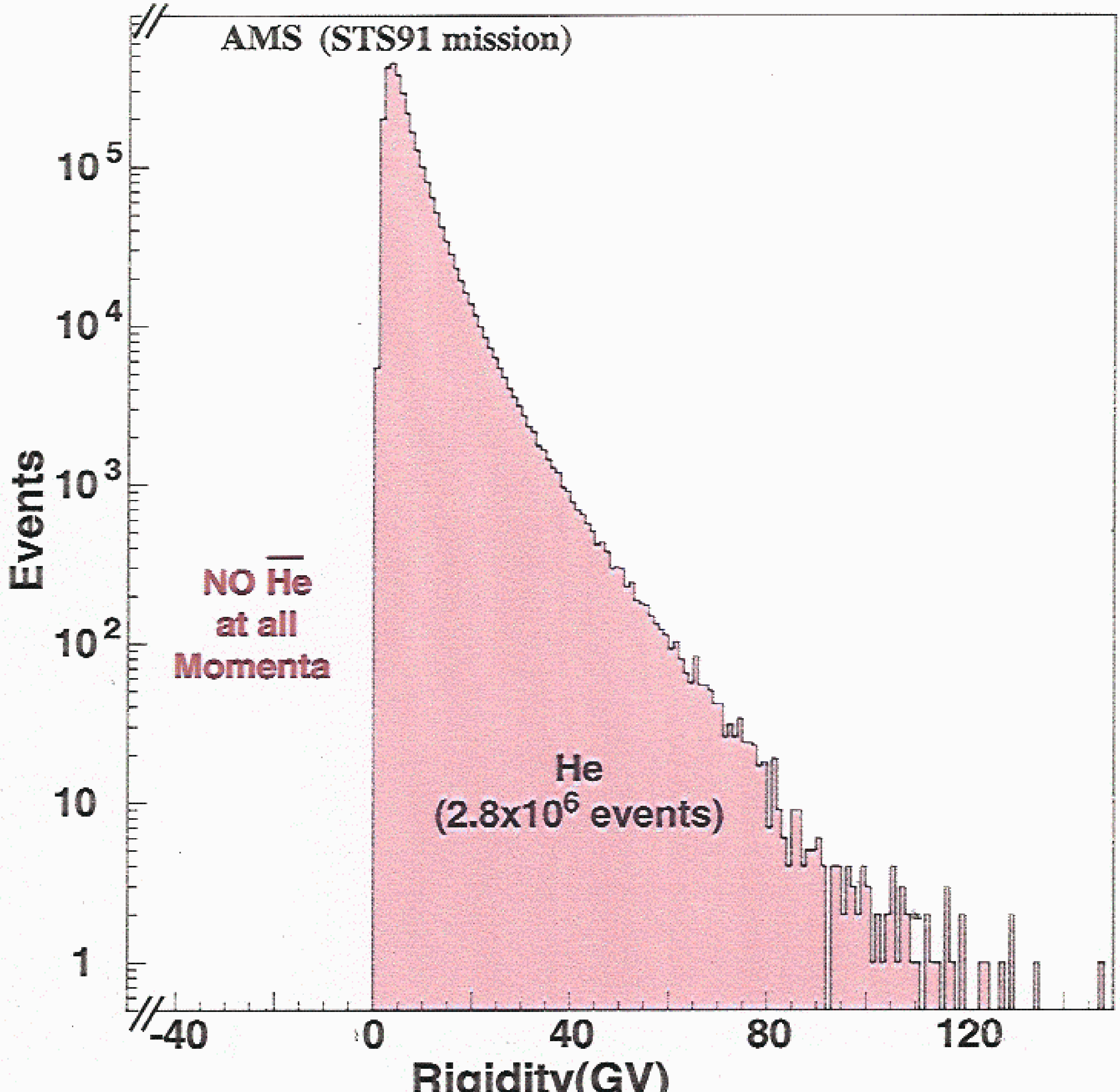
why so little matter?

why any at all?

why no antimatter?

Cosmic-Ray $\bar{p}$ Measurements





Assume $\overline{\text{He}}$ and He have the same spectrum up to 140 GV then $\overline{\text{He}}$ / He is $< \sim 1.1 \; 10^{-6}$

Back to the beginning of the Universe

early Universe very hot

$$\text{Temperature}\left(\begin{matrix}10^{10}\text{K}\\ \text{MeV}\end{matrix}\right) \sim 1/\sqrt{\text{age (seconds)}}$$

high temperatures ⇒ energetic particles

⇒ copious antimatter

SUPPOSE primordial soup had

$10^9 + 1$ quarks, 10^9 antiquarks

as Universe cools, annihilation:

(matter + antimatter) → radiation

odd quark left over   cf wallflower @ danc

1 matter particle 10^9 radiation

WHERE did matter-antimatter asymmetry come from?

was button pushed with this asymmetry?

anthropic principle?

or did laws of Nature generate asymmetry?

Conditions for generating matter asymmetry

(Sakharov 1'

need difference: matter ≠ antimatter

seen in laboratory

BREAK C symmetry

weak forces 1957

BREAK CP symmetry

kaons 1964

LOSE thermal equilibrium

otherwise effective T symmetry

of Boltzmann distributions: e^{-M}

POSSIBLE during phase transition:

Grand Unified Theory → strong, electrowe

probability ($X \to q$) ≠ probability ($\bar{X} \to \bar{q}$)

Electroweak Theory → electromagnetism

temperature ~ 10^{15} GeV ~ 10^{18} MeV ~ 10^{2} GeV ~ 10^{5} M

age ~ 10^{-36} s ← range → age ~ 10^{-10} s

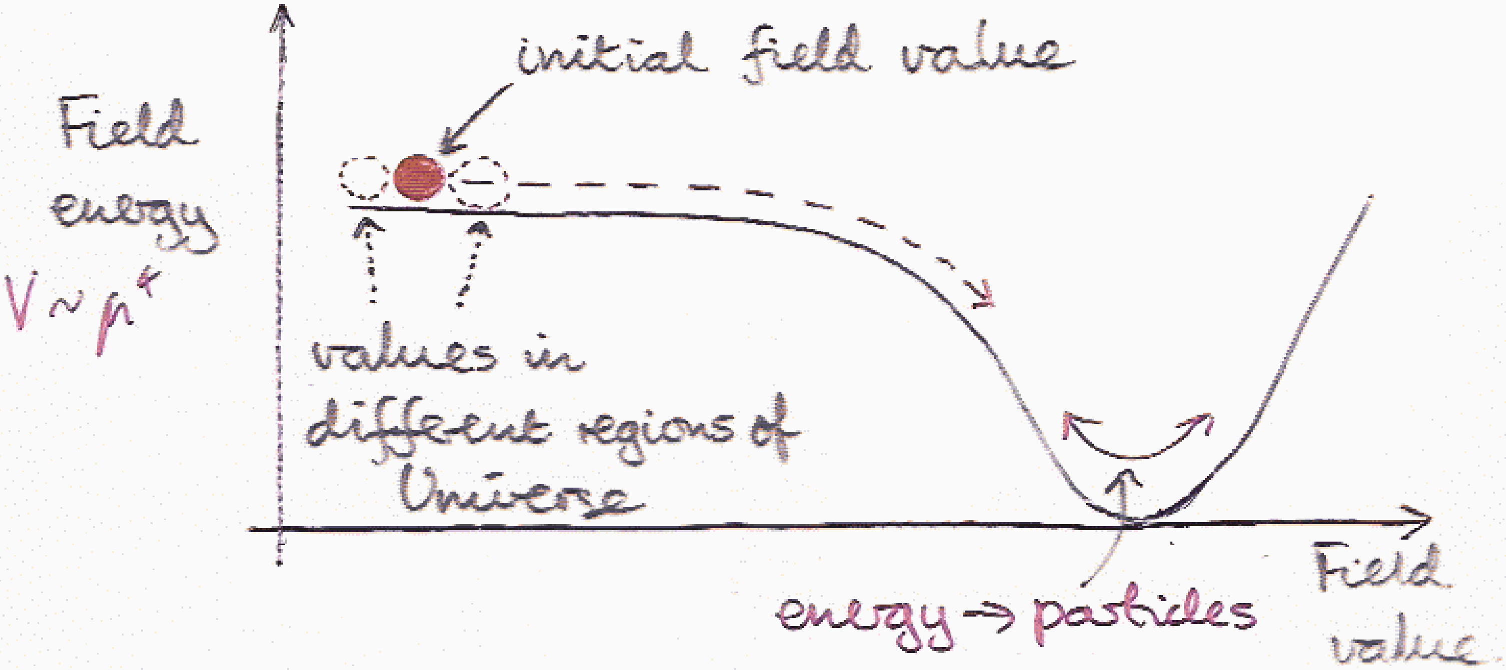
1985 in Gorki

4 - Density Perturbations

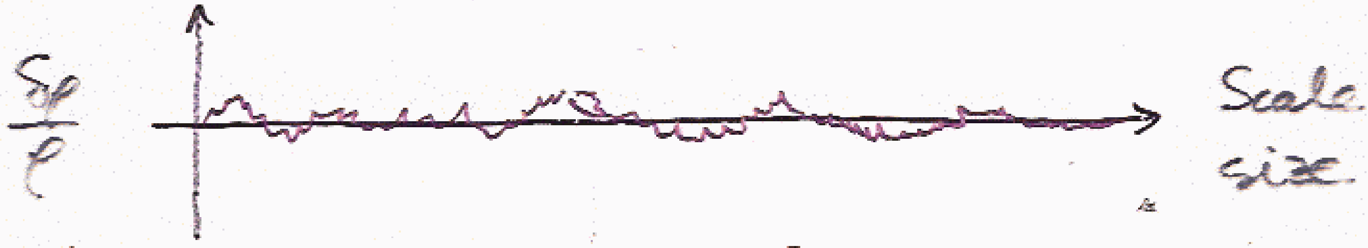
GUT Higgs
$\parallel$

quantum/thermal fluctuations in scalar field

$\Rightarrow$ different parts of Universe expand differently



$\Rightarrow$ Gaussian random field of perturbations



similar magnitudes at different scale sizes

wanted by astrophysicists (Harrison Zeldovich)

magnitude $\Leftrightarrow$ value of field energy

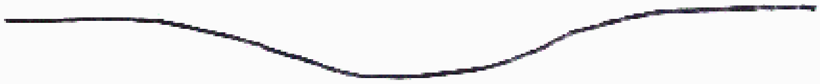
$$\left(\frac{\delta T}{T}\right) \sim \frac{\delta\rho}{\rho} \propto \mu^2 . G_N$$

consistent with COBE data $\quad \delta T/T \sim 10^{-5}$

$\boxed{\mu \sim 10^{16}\,\text{GeV} : \text{GUT energy?}}$

Structure Formation

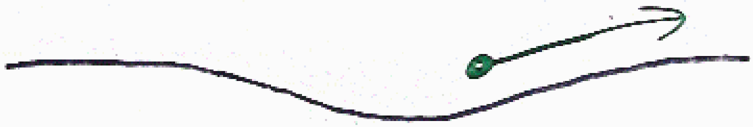
density perturbation ⇒ embryonic potential well



cold dark matter particles (non-relativistic)
fall in:

density contrast enhanced

hot dark matter particles (relativistic)
escape:



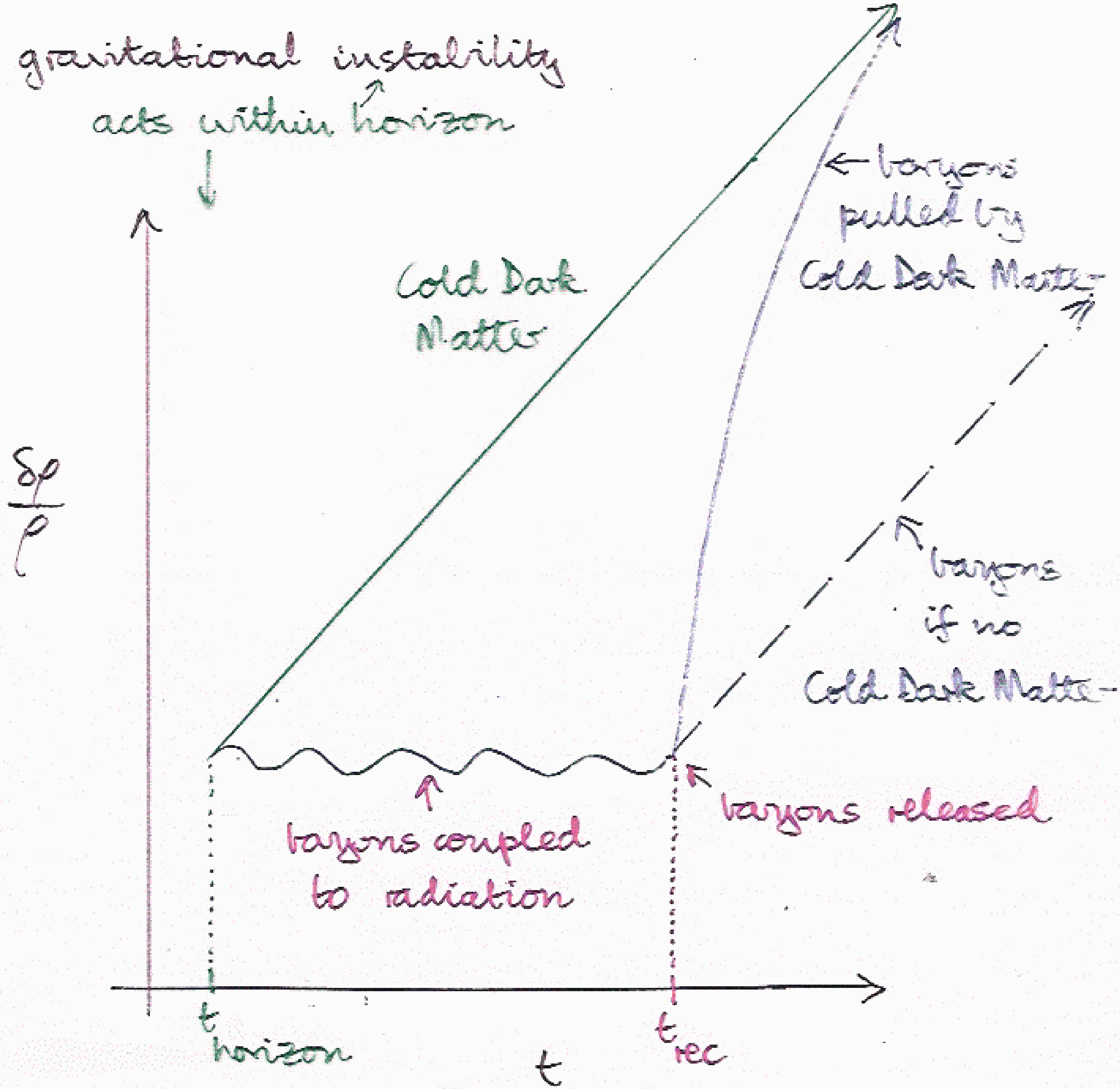
suppress growth of small-scale pert^{us}

amplification of perturbation depends on rate of expansion of universe

sensitive to cosmological constant

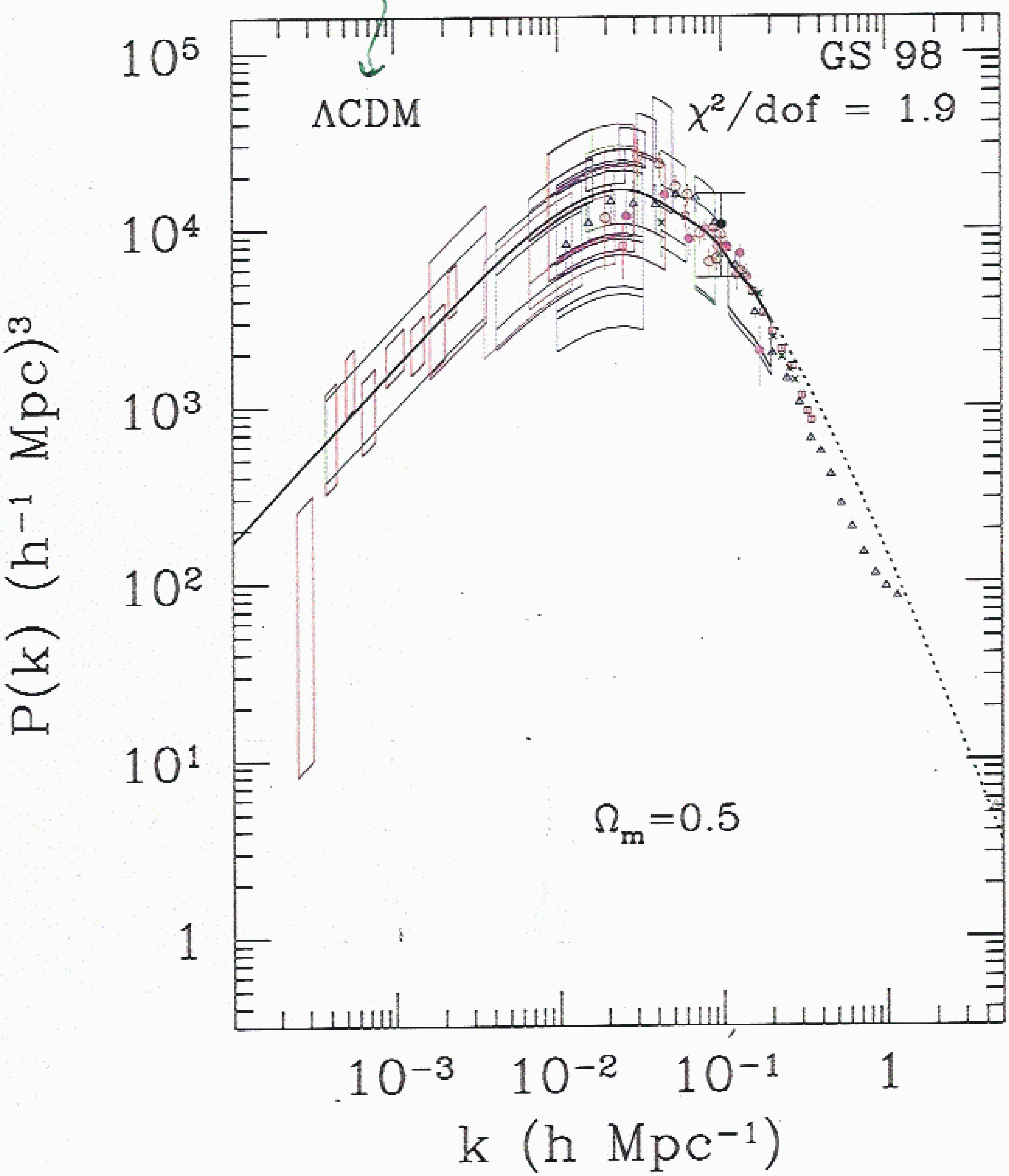
Amplification of Primordial Perturbations

by gravitational instability



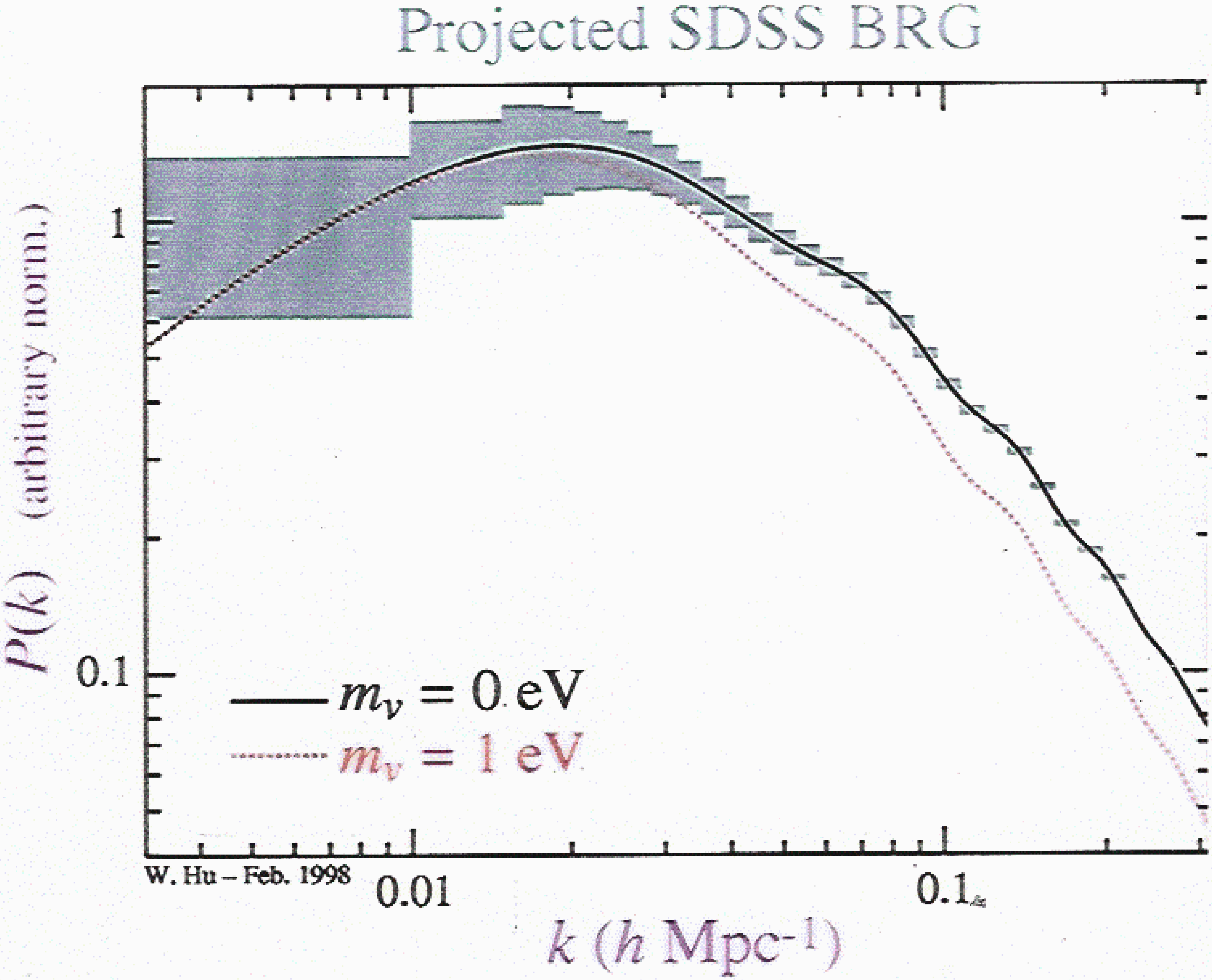
Microwave Background ⊕ Large-Scale Structure

cosmological constant ⊕ cold dark matter



(Gawiser + Silk)

Possible future data



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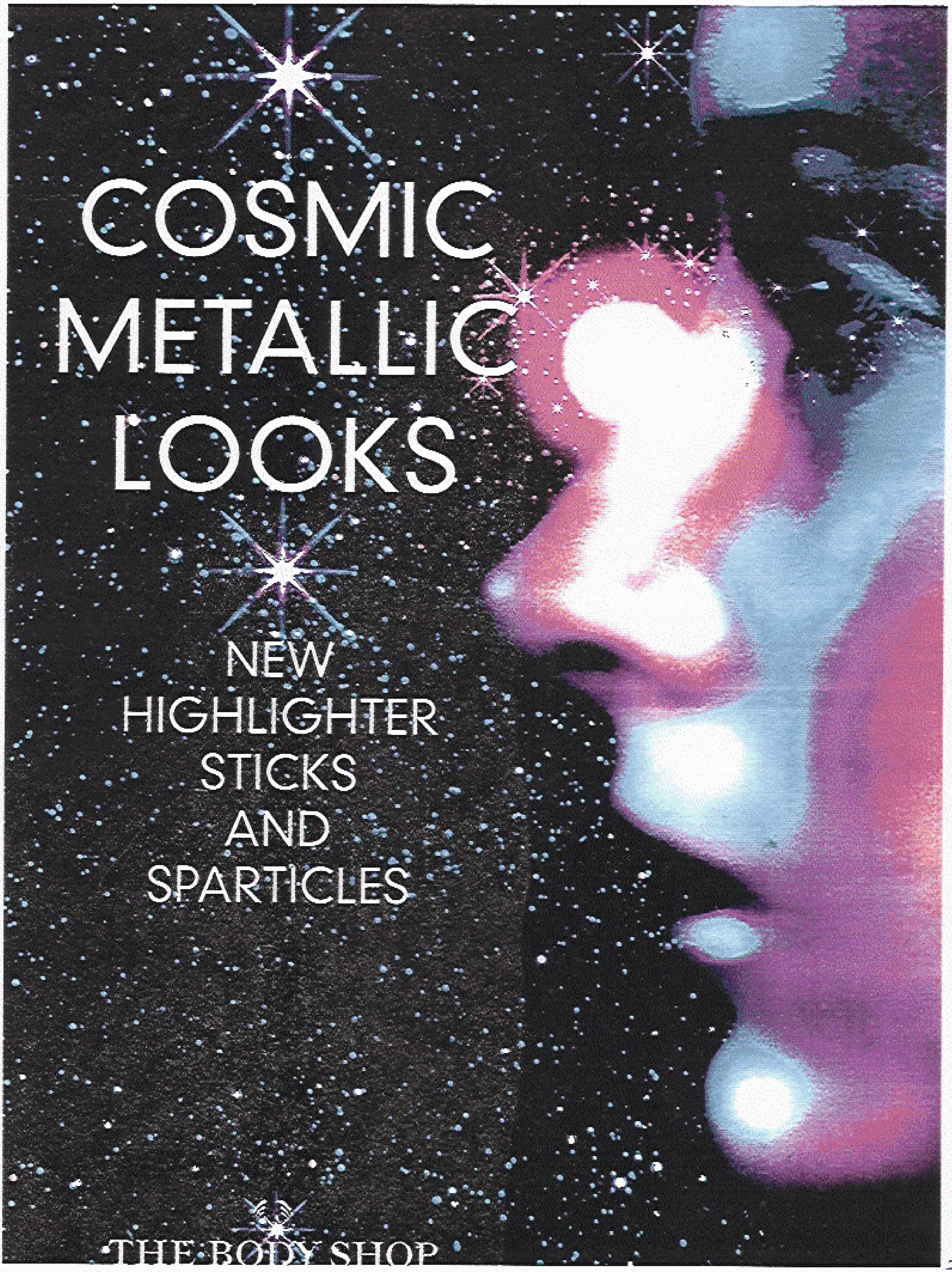

COSMIC
METALLIC
LOOKS
NEW
HIGHLIGHTER
STICKS
AND
SPARTICLES
THE BODY SHOP

Why Supersymmetry?

Hierarchy Problem:

why is $m_W \ll m_P$?

energy: gravity ~ other forces: $m_P \sim 10^{19}$ GeV

alternatively

why is $G_F \gg G_N$? $\quad \frac{1}{m_W^2} \sim 10^{34} \times \frac{1}{m_P^2}$

or

why is $V_{Coulomb} \gg V_{Newton}$? $\quad e^2 \gg G_N m^2 \sim m^2/m_P^2$

Set by hand?

what about quantum corrections?

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right) \Lambda^2 \gg m_W^2$$

↑ cut off $\Lambda \sim m_P$?

made **naturally** small by supersymmetry:

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right)\left(m_B^2 - m_F^2\right)$$

$$\lesssim m^2_{H,W} \quad \text{if} \quad |m_B^2 - m_F^2| \lesssim 1 \text{ TeV}^2$$

↑ Low-energy supersymmetry

5 - Searches for Dark Matter Particles

focus on neutralinos

- Annihilation in galactic halo (Silk + Srednicki

  $\tilde{\chi}\tilde{\chi} \to l^+l^-, \bar{q}q \to \bar{p}, e^+, \gamma, (\nu)$

  $\underbrace{\bar{p}, e^+, \gamma, (\nu)}$ cosmic rays?

  (Silk + Olive + Srednicki

  galactic centre

- Annihilation in Sun or Earth

  $\tilde{\chi}$ captured by elastic scattering, ΔE_{rec}

  $\tilde{\chi}\tilde{\chi} \to$ "high energy" ν ~ GeV

  underground detectors: ν or μ

- Elastic Scattering in Laboratory (Goodman + Witten

  $\tilde{\chi}N \to \tilde{\chi}N \Rightarrow$ detectable recoil energy

  $E \sim \text{keV} \times \left(\frac{m_{\tilde{\chi}}}{4\,\text{GeV}}\right)$

(- Inelastic Scattering

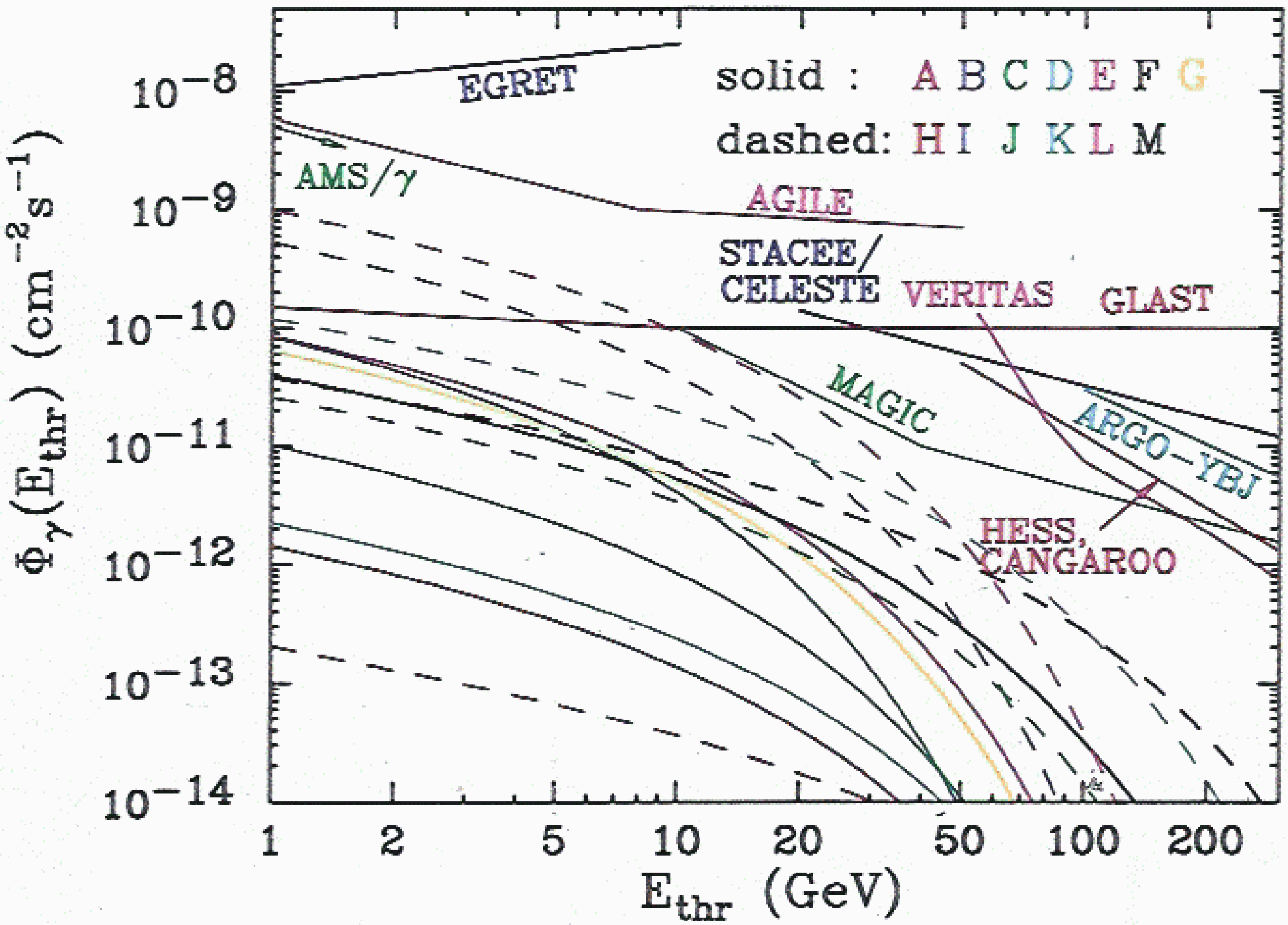
  $\tilde{\chi}N \to \tilde{\chi}(N^* \to N\gamma)$

  de-excitation ⊕ recoil energy: small rate)

Gamma-Ray Spectra

in supersymmetric benchmark scenarios

↕ uncertain concentration in galactic centre



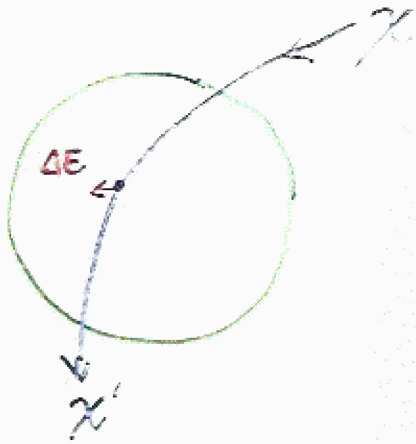
(J.E. + Feng + Ferstl + Matchev + Olive

Annihilation in Sun (Earth)

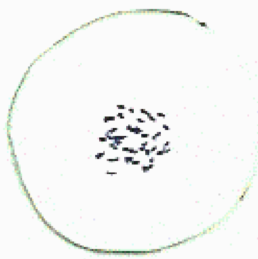
- Capture of relic particle due to recoil energy loss

  hyperbolic orbit ⇒ elliptic orbit

  perihelion (gee) < solar (earth) radius



- Repeated scattering, energy loss ⇒ quasi-isothermal distribution



- Population control by annihilation

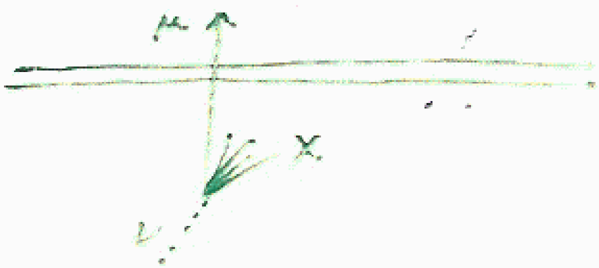
  $\chi\chi \to \nu + \ldots$

  evaporation negligible for $m_\chi >$ four GeV

- High-energy solar neutrinos (from core of Earth)

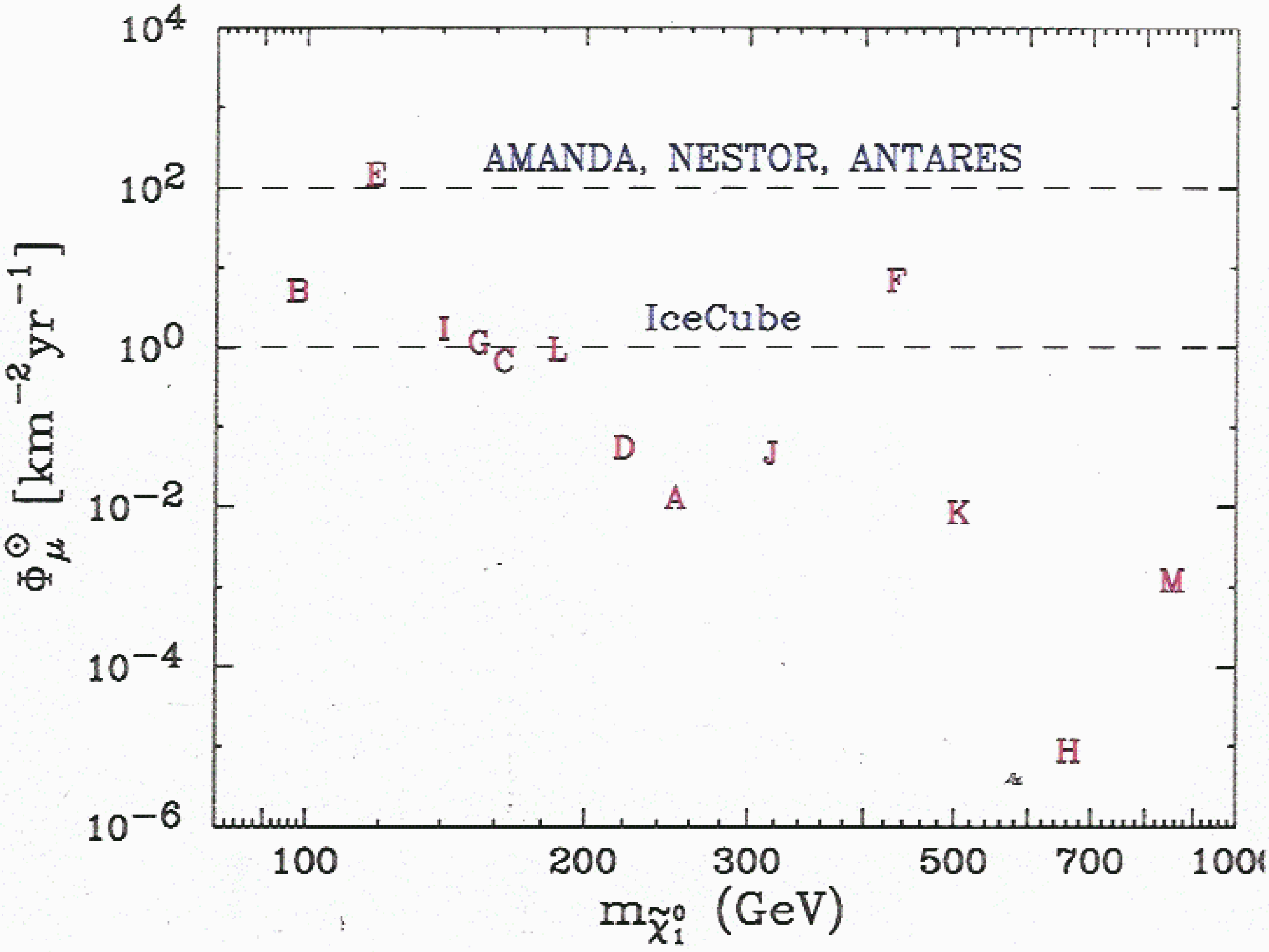
  $E_\nu \gtrsim$ GeV ← vulnerable to MSW ?!

- detect directly or via μ production



$\chi\chi \to \nu \to \mu$

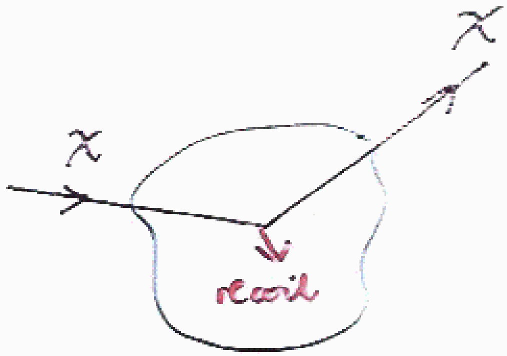
annihilation inside the Sun



(J.E. + Feng + Ferstl + Matchev + Olive

e.g. Direct Detection of Dark Matter

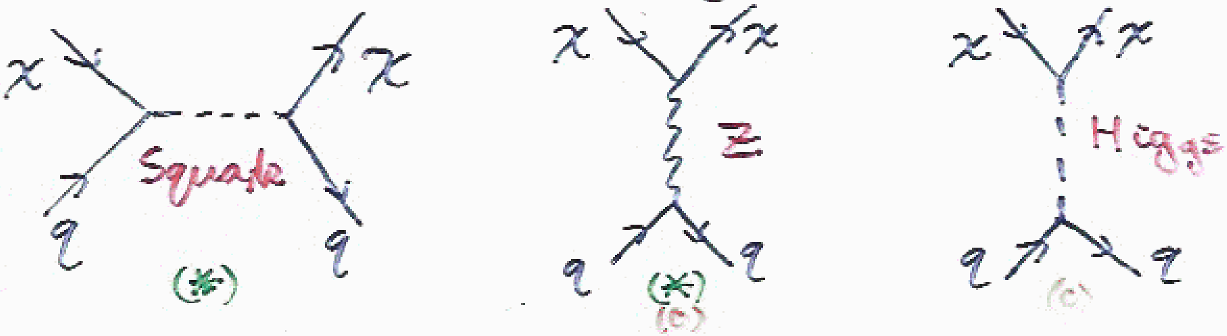
scattering of nucleus in laboratory:



recoil energy $E \sim m_\chi v^2/2$

$\sim$ keV

interaction mediated by exchanges of



two important types of interaction:

spin-dependent(*):

matrix element ∝ quark contributions to proton spin: $\mathcal{M} \sim \sum_i \Delta q_i\, c_i$

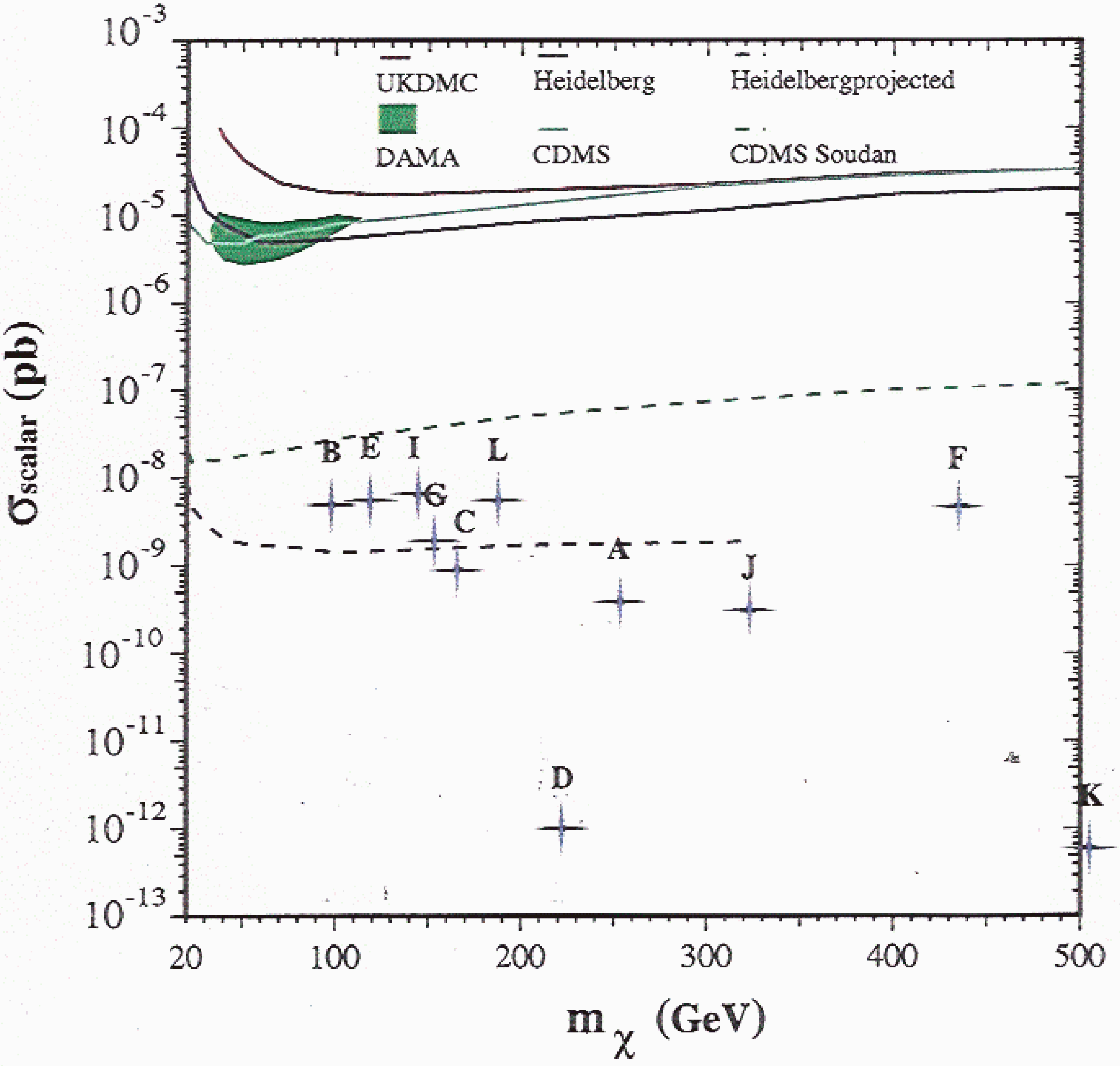
not coherent: important for small nuclei.

spin-independent(c):

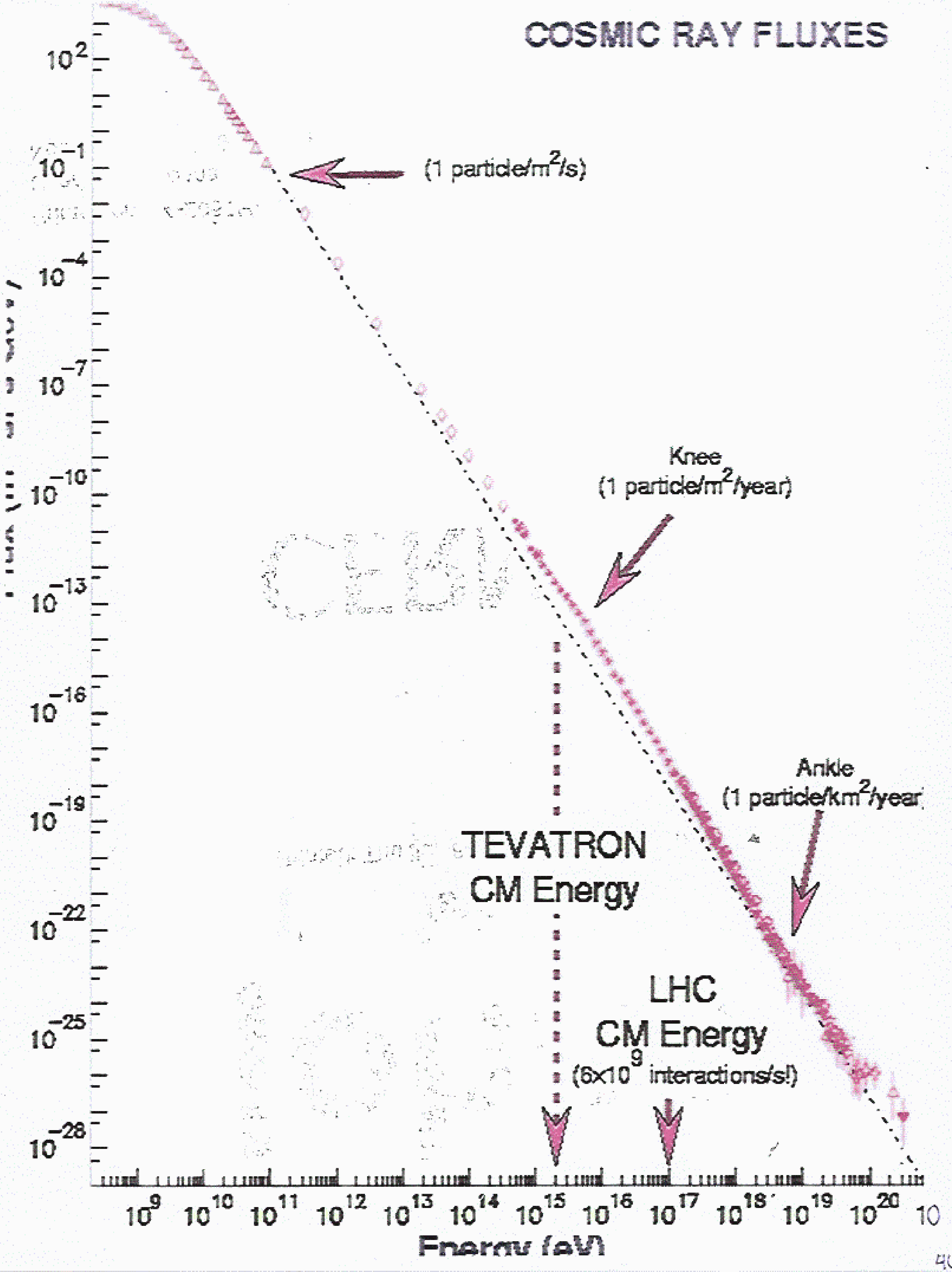
matrix element ∝ quark contributions to proton mass: coherent, important for heavy nuclei prospects for dark matter search

Spin-Independent Elastic Scattering

in supersymmetric benchmark scenarios



(J.E. + Feng + Ferstl + Matchev + Olive



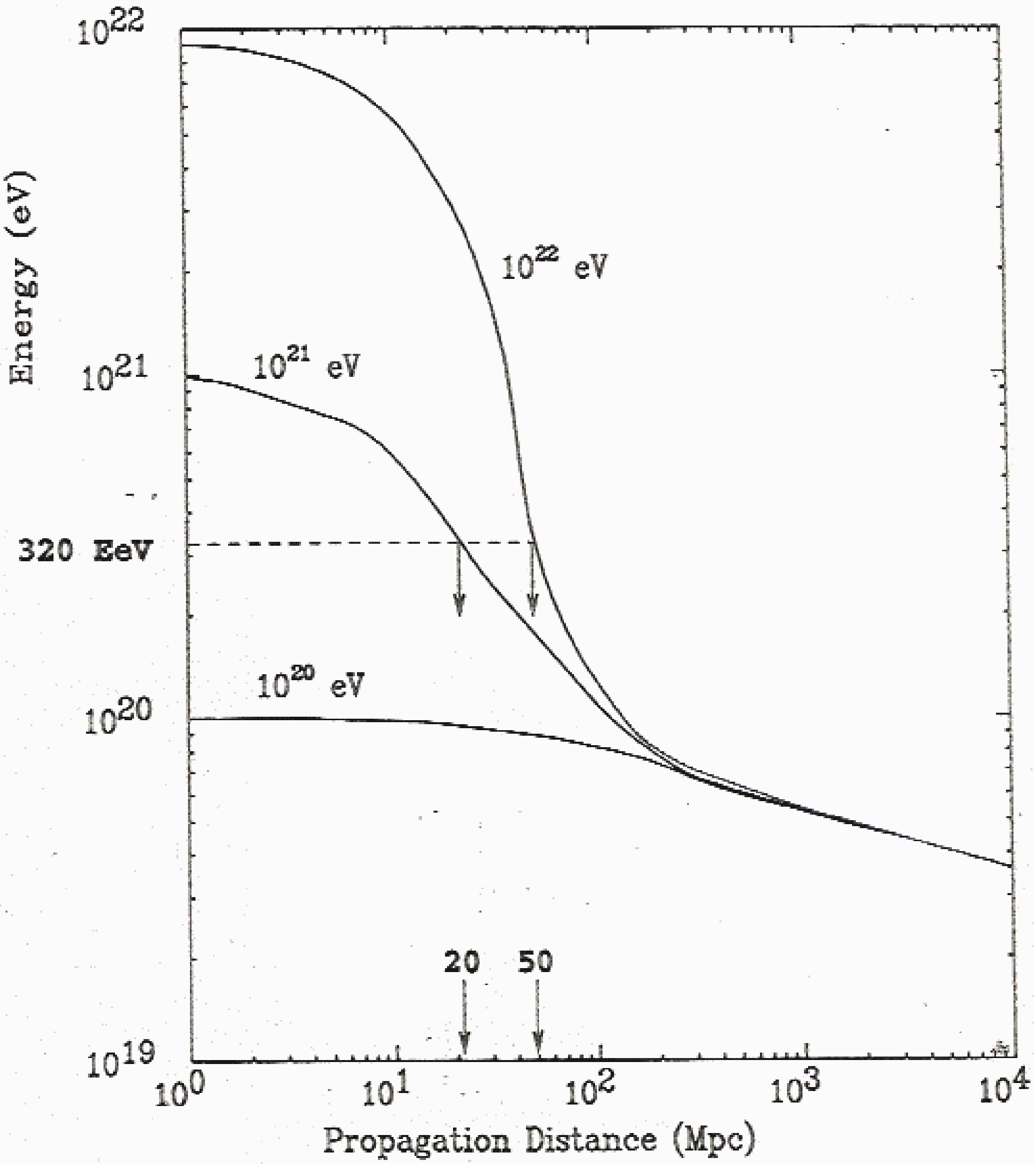
COSMIC RAY FLUXES
(1 particle/m^2/s)
Knee
(1 particle/m^2/year)
Ankle
(1 particle/km^2/year)
TEVATRON
CM Energy
LHC
CM Energy
(6×10^9 interactions/s!)
10^2
10^-1
10^-4
10^-7
10^-10
10^-13
10^-16
10^-19
10^-22
10^-25
10^-28
10^9
10^10
10^11
10^12
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20

absorption: $p + \gamma_{CMB} \to \pi + \ldots$

5

Energy at source

THE GZK CUTOFF



Energy attenuation of protons

Protons: photopion threshold @ ~50 EeV

Photons: pair production threshold @ ~200 TeV

Nuclei: photodisintegration above 50 EeV

Neutrinos: no problem!

For E>100 EeV, the source must be within ~50 Mpc

http://www-td-auger.fnal.gov:82/

AGASA goes beyond GZK

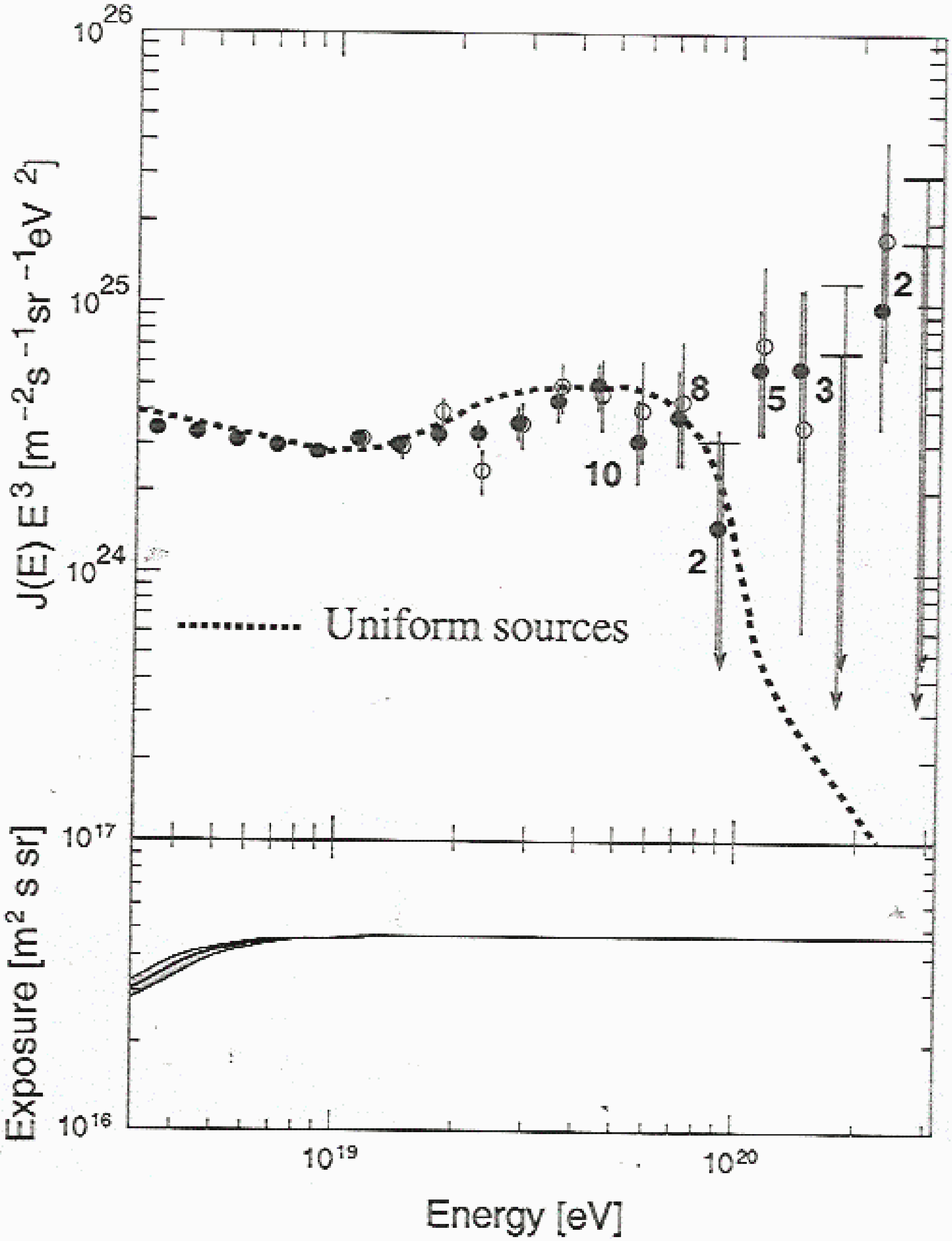


Fig. 14. Energy spectrum determined by AGASA and the exposure with zenith angles smaller than 45° up until July 2001. (Open circles: well contained events; Closed circles: all events) The vertical axis is multiplied by E^3. Error bars represent the Poisson upper and lower limits at 68% confidence limit and arrows are 90% C.L. upper limits. Numbers attached to the points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extra-galactic sources distributed uniformly in the Universe, taking account of the energy determination error. The uncertainty in the exposure is shown by the shaded region.

But HiRes does not

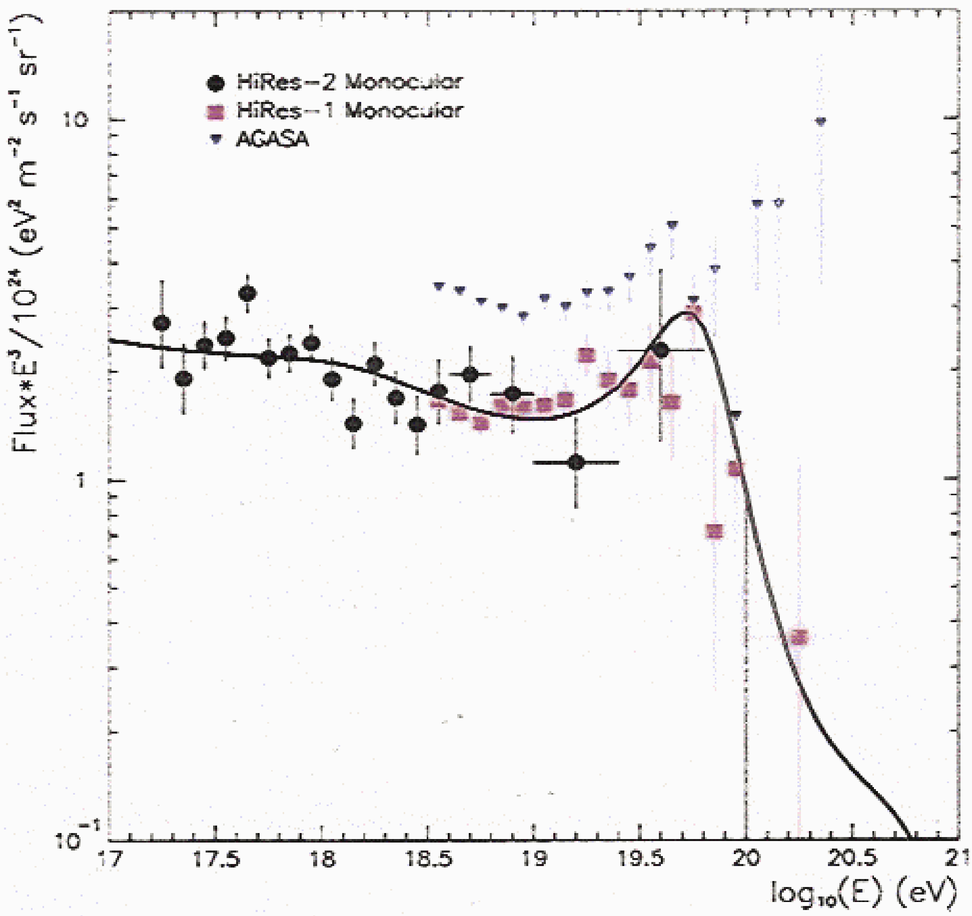


Fig. 14. E^3 times the UHE Cosmic Ray Flux. Results from the HiRes-I and HiRes-II detectors, and the AGASA experiment are shown. Also shown is a fit to the data assuming a model, described in the text, of galactic and extragalactic sources.

Possible Mechanisms

'Bottom-up'

acceleration by astrophysical sources:

gyromagnetic radius: size of cosmic 'accelerator'

$$R \sim 100/Z \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)\left(\frac{\mu G}{B}\right)$$

← magnetic field

upper limit on attainable energy

$$E \lesssim 10^{18}\, Z \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mu G}\right)\,\mathrm{eV}$$

finite time?
energy losses, ...

catalogue of possible sources ⇒ GRBs

expect clustering

'Top-down'

GUT-scale physics ⇒ energetic particles

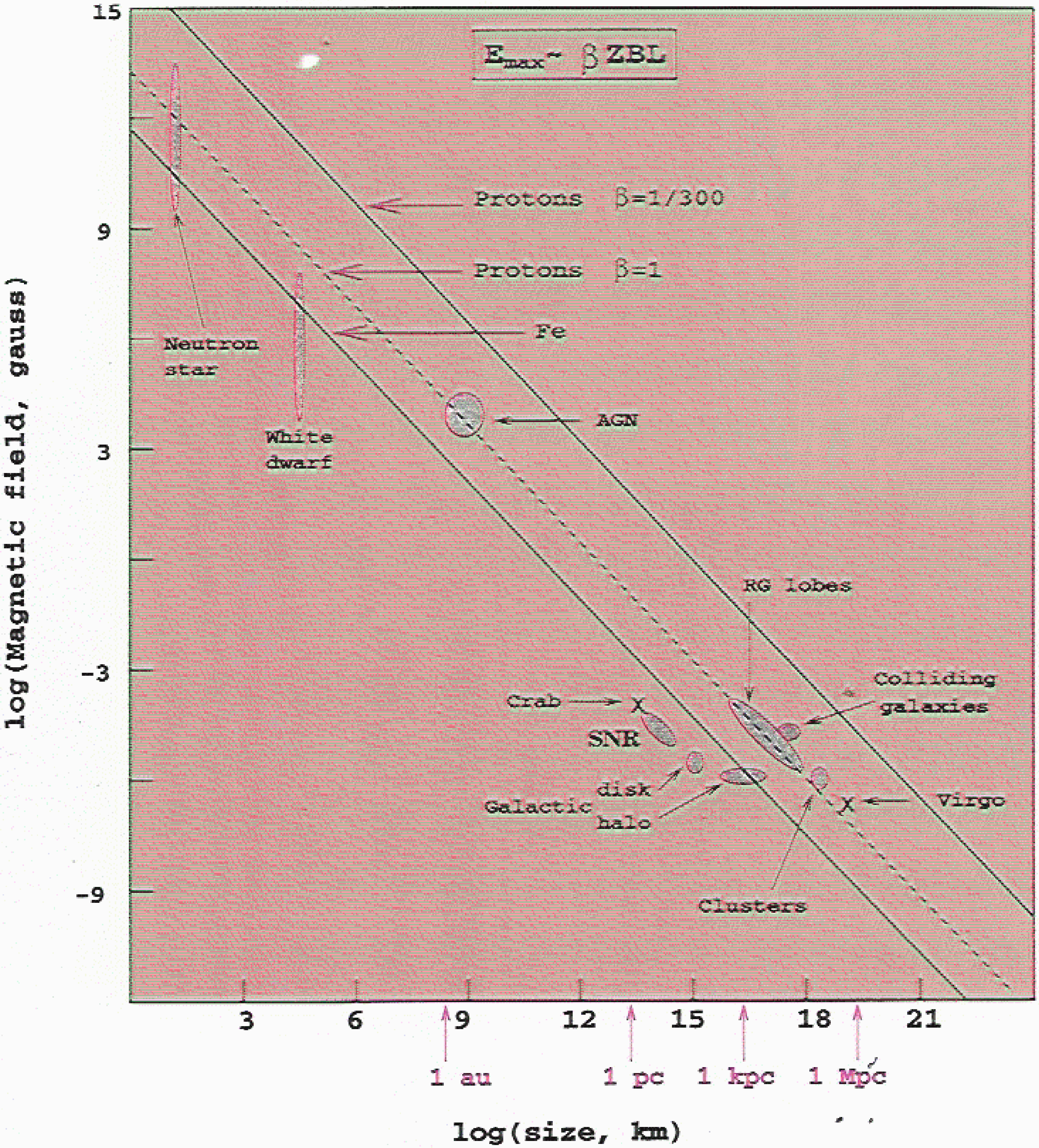
e.g. topological defects

metastable relic particles

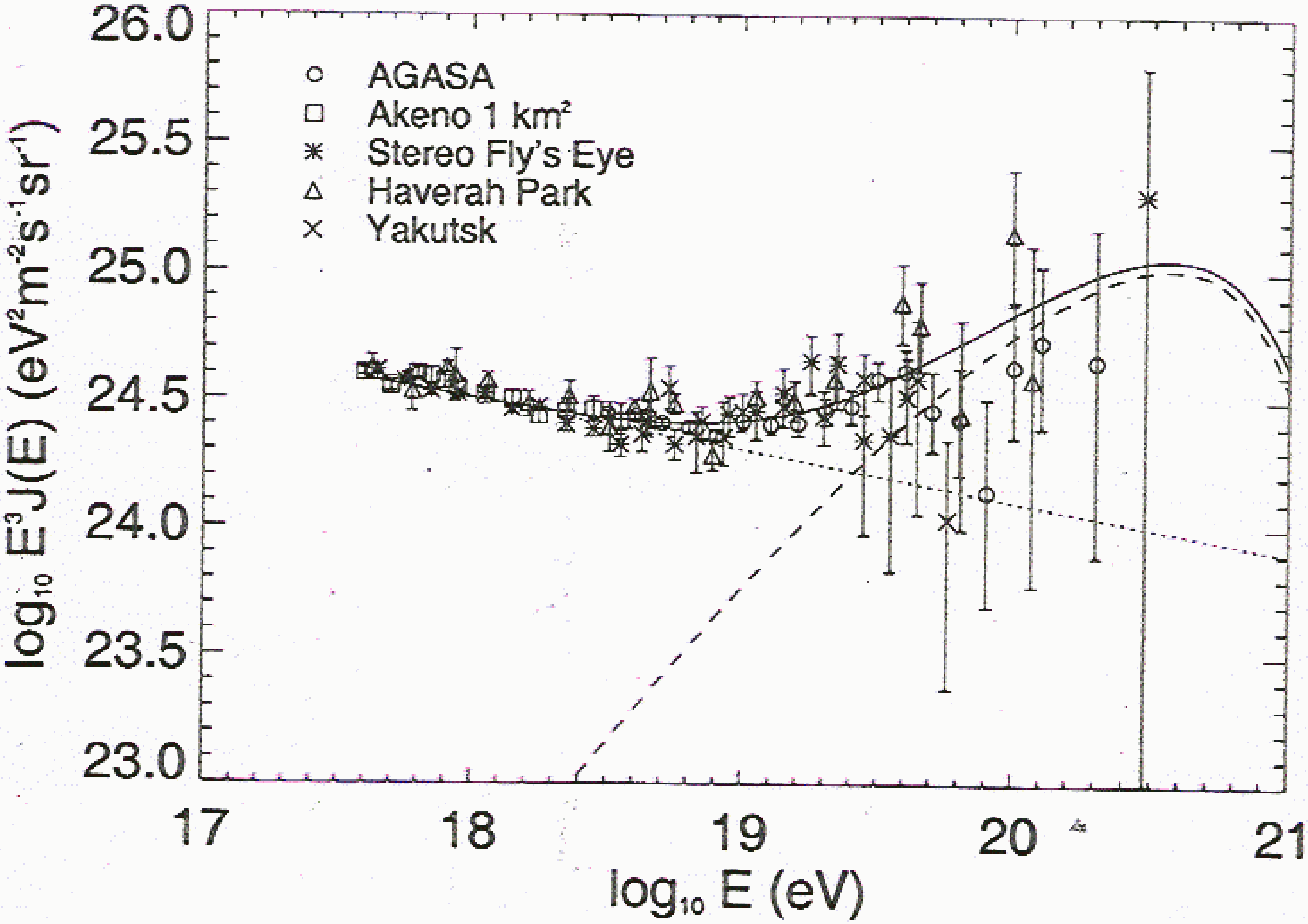
expect anisotropy

clustering?

Hillas-plot (candidate sites for E=100 EeV)



Top-Down Fit to UHECR Data



(Sarkar

Copernicus:

We do not live at the centre of the Universe

Modern astrophysicists:

We are not made of the same stuff as most matter in the Universe

The challenge: prove it!