



# VISIONS OF THE FUTURE

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MAJOR PARADIGM CHANGE  
IN PARTICLE PHYSICS AND COSMOLOGY

COSMIC SUPERSTRINGS

# CONSTANTS OF NATURE:

PARTICLE MASSES

COUPLING CONSTANTS

$G_N$ ,  $P_V$ .

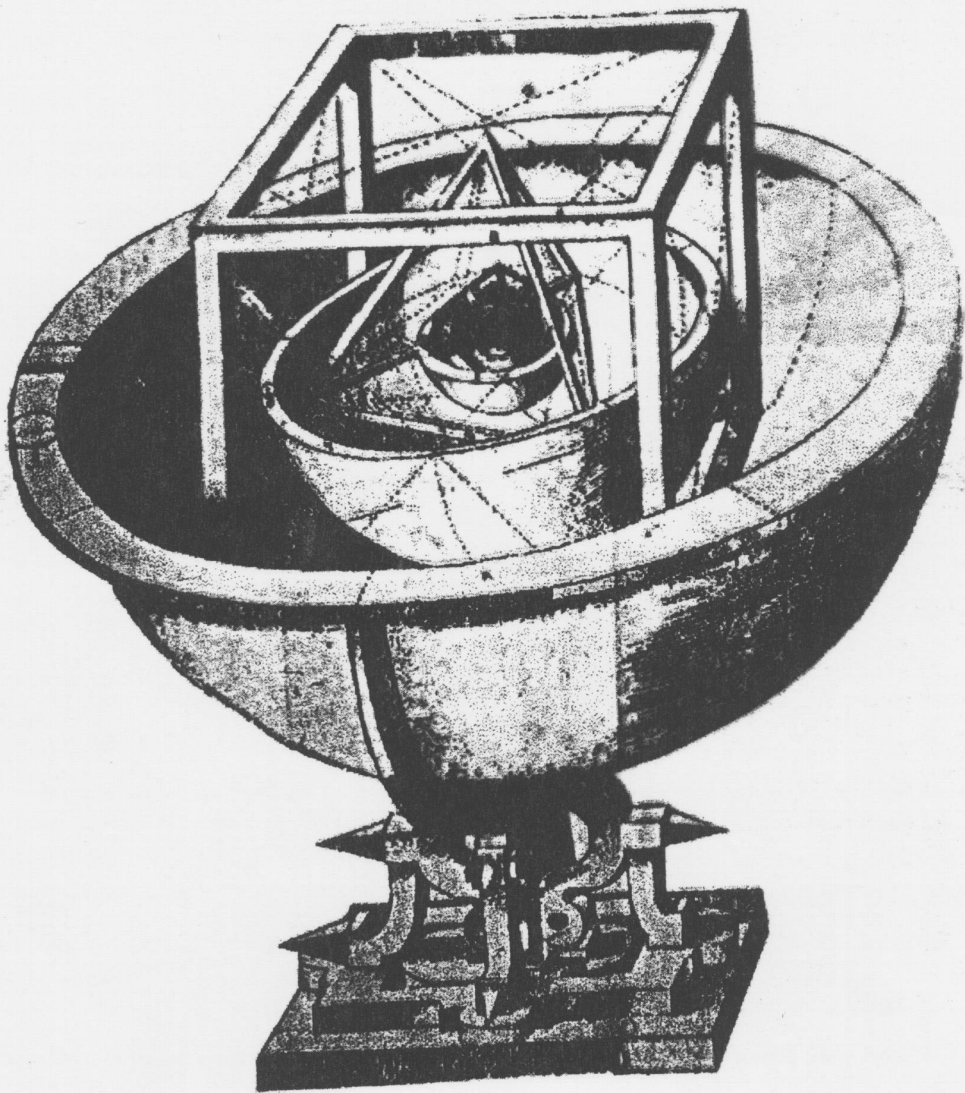
WHAT DETERMINES THEIR VALUES?

— . —

## FUNDAMENTALIST" APPROACH:

ALL CONSTANTS OF NATURE  
ARE TO BE DETERMINED FROM  
THE FUNDAMENTAL THEORY.

⇒ VERY LIMITED SUCCESS.



CAN EVERYTHING BE CALCULATED  
FROM FIRST PRINCIPLES?





"INNUMERABLE SUNS EXIST.  
INNUMERABLE EARTHS REVOLVE  
AROUND THESE SUNS ...  
LIVING BEINGS INHABIT THESE WORLDS."

GIORDANO BRUNO, 1584.

## ANTHROPIC WORLDVIEW

CONSTANTS OF NATURE ARE STOCHASTIC VARIABLES AND TAKE DIFFERENT VALUES IN DIFFERENT PARTS OF THE UNIVERSE.

⇒ THE VALUES WE OBSERVE ARE DETERMINED BY CHANCE AND ANTHROPIC SELECTION.

ALLOWS QUANTITATIVE PREDICTIONS AT SPECIFIED CONFIDENCE LEVEL.



# THE COSMOLOGICAL CONSTANT

$\rho_v$  - VACUUM ENERGY DENSITY

## THEORY:

NATURAL" VALUE:  $\rho_v \sim M^4$ .

$l \sim M_p \Rightarrow \rho_v \sim 10^{120} \rho_m$ .

SUPERSYMMETRIC THEORIES:

$M \sim M_{\text{susy}} \gtrsim 10^3 \text{ GeV}$

$\Rightarrow \rho_v \gtrsim 10^{60} \rho_m$ .

## OBSERVATIONS:

$$\rho_v \sim 2 \rho_m$$

## COSMOLOGICAL CONSTANT PROBLEMS:

1) WHY IS  $\rho_v$  SO SMALL?

OLD CCP

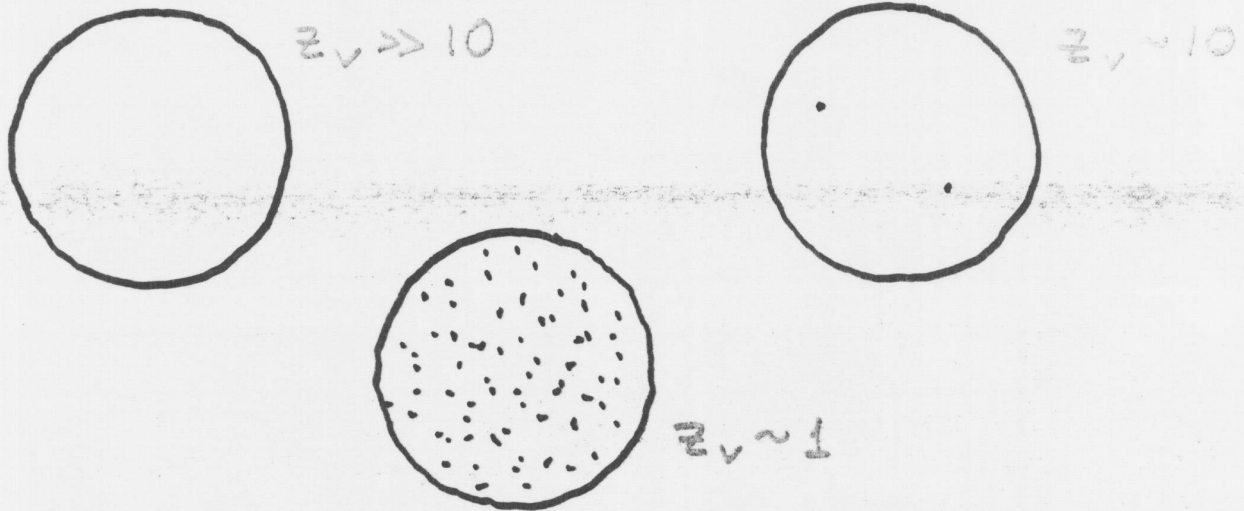
WHY DO WE LIVE AT THE EPOCH WHEN  $\rho_v \sim \rho_m$ ?

COINCIDENCE PROBLEM



OTHER PARAMETERS FIXED  
SUPPOSE  $\rho_v$  TAKES DIFFERENT VALUES  
IN DIFFERENT PARTS OF THE UNIVERSE.

STRUCTURE FORMATION STOPS AT  $z \sim z_v$



MOST GALAXIES ARE IN REGIONS  
WHERE  $z_v \lesssim 1$ .

$$\rho_v = (1+z_v)^3 \rho_m \lesssim 8 \rho_m$$

$\rho_v \ll \rho_m$  IS UNLIKELY DUE TO SMALL RANGE.

EXPLAINS COINCIDENCE!

[SIMILAR ANALYSIS FOR  $\rho_v < 0$ .]

# PROBABILITY DISTRIBUTION FOR $P_V$

$$P(P_V) dP_V = n_G(P_V) P_{\text{prior}}(P_V) dP_V$$

# OF GALAXIES  
PER UNIT VOLUME

FRACTION  
OF VOLUME

$P_{\text{prior}}(P_V)$  - FROM FUNDAMENTAL THEORY  
+ INFLATION

CONST IN THE  
NATURAL RANGE

$n_G(P_V)$  - STANDARD ASTROPHYSICAL PROBLEM.

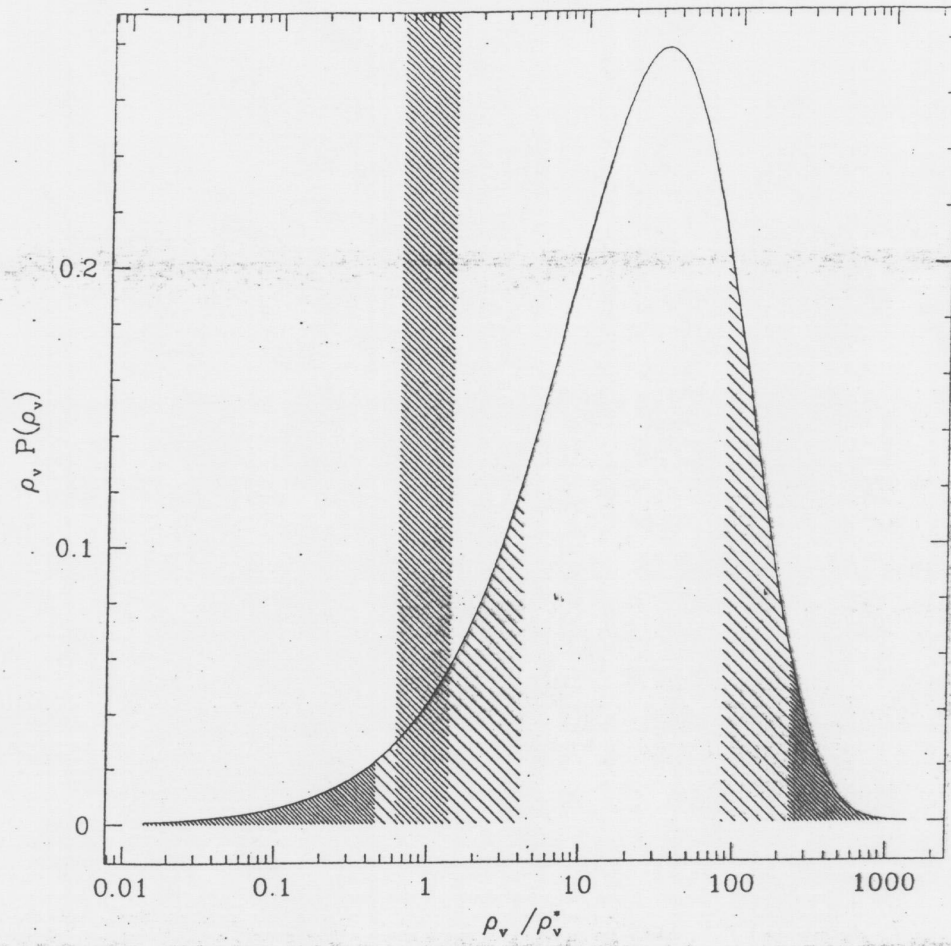
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$$n_{\text{obs}} \propto n_G.$$

PRINCIPLE OF "MEDIOCRITY":

WE EXPECT TO BE WITHIN 95%  
OF THE DISTRIBUTION.

PREDICTION AT 95%  
CONFIDENCE LEVEL



## INTHROPIC SOLUTION TO CCP's

Weinberg 87

Linde 86

Barrow + Tipler 86

A.V. 95

Efstathiou 95

Martel, Shapiro + Weinberg 98

Garriga, Livio + A.V. 00

Bludman 00

OBSERVATIONAL EVIDENCE FOR CC: 1998.



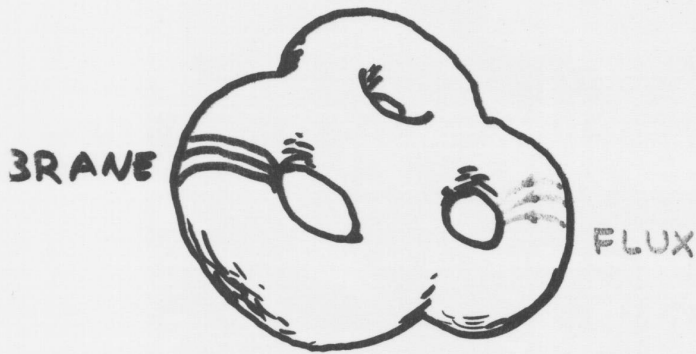
## ANTHROPIC APPROACH REQUIRES:

A PARTICLE PHYSICS MODEL WITH  
A VARIABLE  $p_v$ .

A COSMOLOGICAL "MULTIVERSE" MODEL.

# STRING THEORY "LANDSCAPE"

MULTITUDE OF DIFFERENT VACUA.



Bousso + Polchinski 01

Susskind 02

Douglas 03

$$P_V = P_\Lambda + \sum_{a=1}^N F_a^2$$

$N \sim 100$

FLUXES

DIFFERENT COMPACTIFICATIONS, BRANES, ETC.

$\Rightarrow \sim 10^{500}$  VACUA

WITH DIFFERENT VALUES OF  $P_V$ .

OTHER LOW-ENERGY CONSTANTS  
ARE ALSO DIFFERENT!

## SOME INTRIGUING POSSIBILITIES

$\Lambda_{EW} \sim 10^2 \text{ GeV}$  MAY BE ANTHROPOLOGICALLY SELECTED

IF  $M_{EW}$  WERE DIFFERENT BY 1 ORDER OF MAGNITUDE, THERE WOULD BE NO SUPERNOVA EXPLOSIONS.

⇒ NO HEAVY ELEMENTS LIKE C, O, ETC.

THEN THERE IS NO MOTIVATION FOR LOW-ENERGY SUSY.

⇒  $M_{SUSY} \gg M_{EW}$  (?)

FERMIONS OF SSM MAY STILL BE LIGHT (PROTECTED BY CHIRAL SYMMETRY).

NO LIGHT SCALARS (EXCEPT FOR THE HIGGS)

UNIFICATION OF GAUGE COUPLINGS IS UNAFFECTED.

Arcani-Hamed + Dimopoulos 04.

$P_{\text{prior}}(M_{SUSY})$  MAY OR MAY NOT FAVOR LOW-ENERGY SUSY.

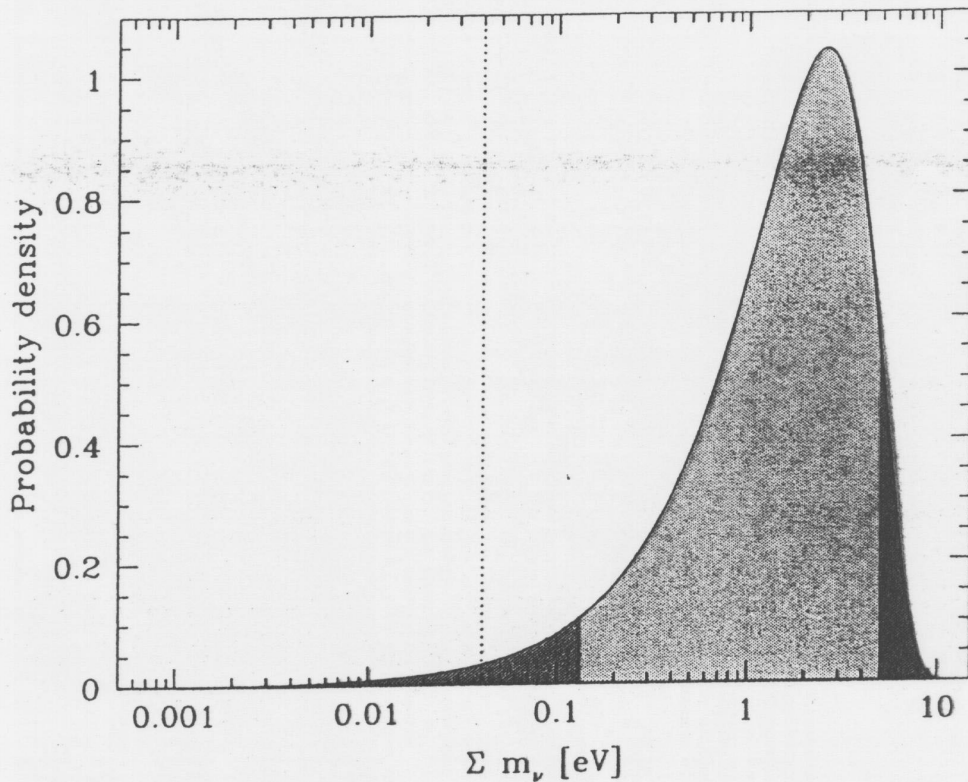
Banks, Dine + Gorbatorov 03

Douglas et al. 03, 04; Susskind 04.

IMPLICATIONS FOR CDM + ACCELERATOR EXPERIMENTS.

# NEUTRINO MASSES MAY BE ANTHROPOLOGICALLY SELECTED.

Tegmark, A.V. + Pogosian 94



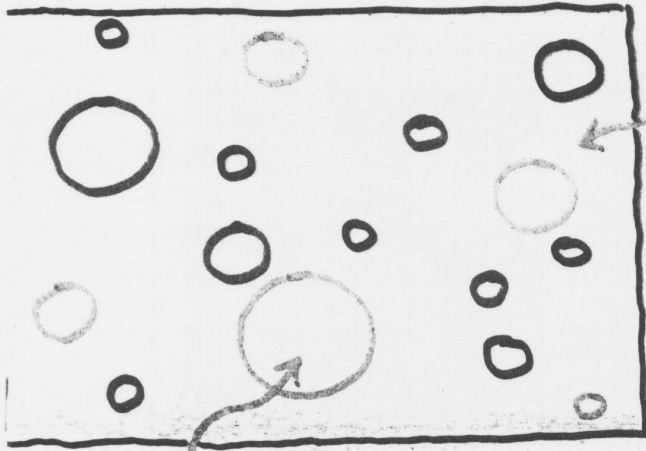
PREDICTION:  $\Sigma m_\nu > 0.1 \text{ eV}$  (90% c.l.)

(WITH CERTAIN ASSUMPTIONS ABOUT PRIOR).

$$\Rightarrow \Delta m_\nu \ll m_\nu$$



COMBINE THIS WITH INFLATION:



EXPONENTIALLY EXPANDING  
FALSE VACUUM

BUBBLES OF DIFFERENT  
VACUA NUCLEATE + EXPAND



LARGE REGIONS WITH  
ALL POSSIBLE VALUES  
OF THE CONSTANTS.

WE ARE HERE

# MAIN CHALLENGES:

ALCULATION OF  $P_{\text{prior}}(\alpha_j)$

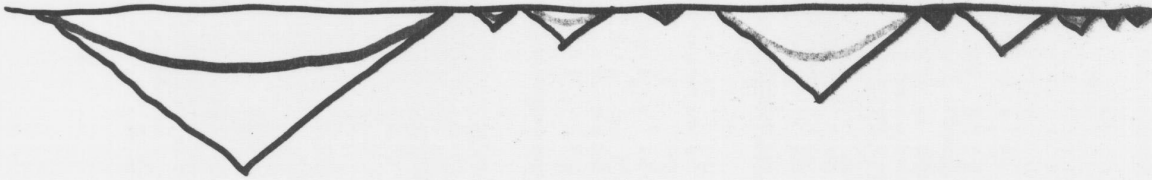
VARIABLE  
PARAMETERS

STATISTICS OF  
STRING THEORY VACUA

Douglas et. al

ENHANCEMENT FACTORS DUE TO INFLATION.

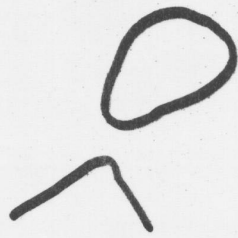
Garriga + A.V.



PHYSICS OF "ALTERNATE UNIVERSES"

WITH DIFFERENT VALUES OF  $\rho_v$ ,  $\delta\rho/\rho$ ,  $n_B$ , ...

# IMPORTANT DIFFERENCE



WITH SOME  
PROBABILITY  $P$ .

$P = 1$  FOR ORDINARY STRINGS

$P < 1$  FOR COSMIC SUPERSTRINGS

(CAN BE  $\ll 1$ ).

# OF LONG STRINGS PER HORIZON:

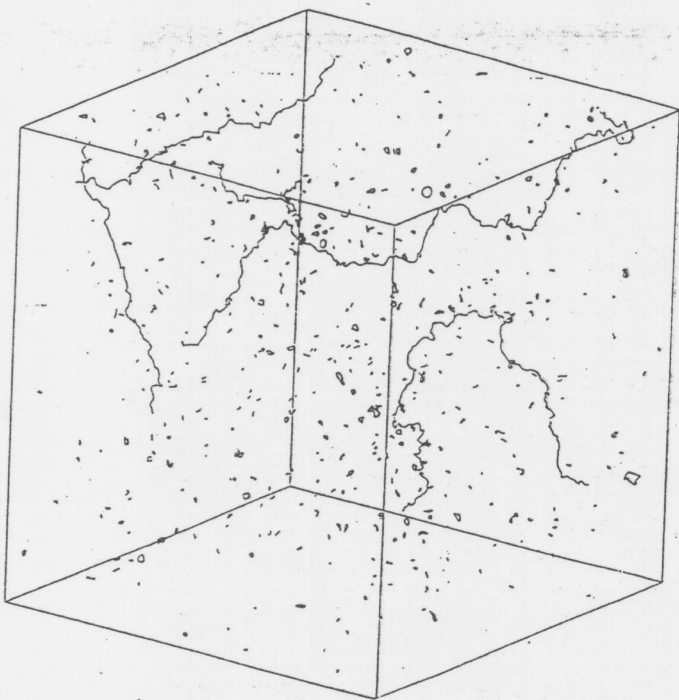
$$N \sim \frac{1}{P}.$$

# COSMIC SUPERSTRINGS

- AND D-STRINGS COULD BE FORMED IN THE EARLY UNIVERSE.

Tye et. al. 03, 04 ; Dvali + A.V. 04  
Copeland, Myers + Polchinski 04

MILAR TO "ORDINARY" STRINGS.

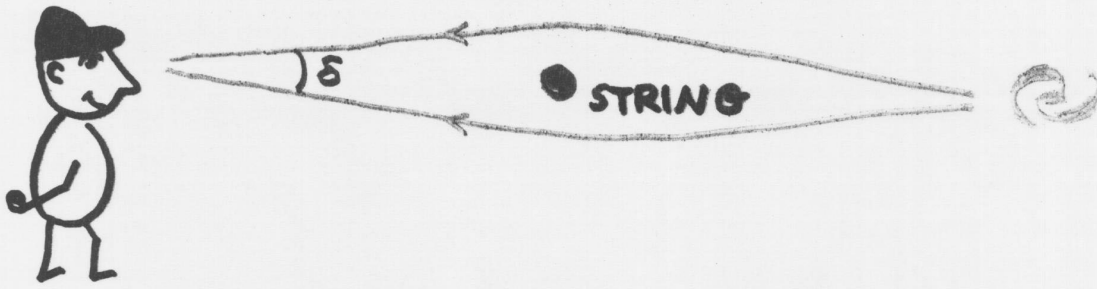


HORIZON  
VOLUME

OBSERVATIONAL EFFECTS :

- GRAVIT. WAVES
- CMB
- GRAVIT. LENSING
- GRB's
- COSMIC RAYS

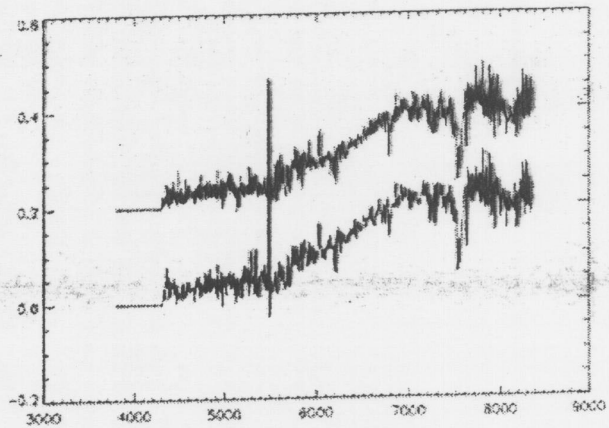
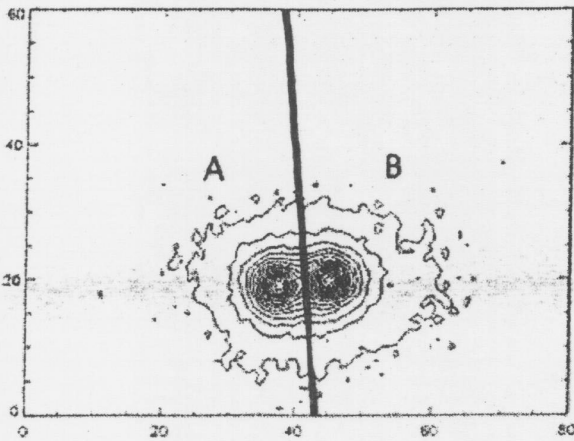




$$\delta \sim 8\pi G\mu$$

MASS PER UNIT  
LENGTH OF STRING

iazhin et.al. 03



$$G\mu \sim (\text{few}) \times 10^{-7}$$

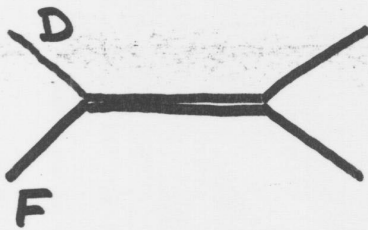
NEED ADDITIONAL TESTS.

# CHALLENGES

FORMATION MECHANISMS

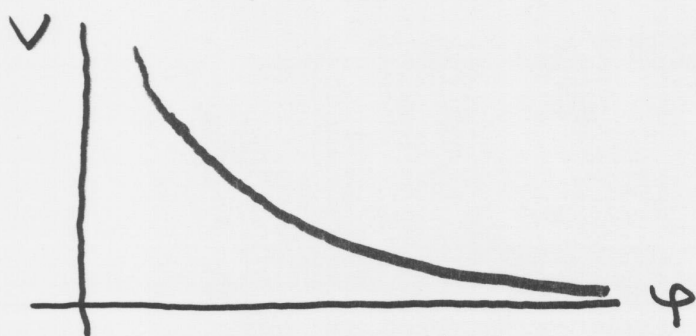
EVOLUTION — BIG GAPS IN UNDERSTANDING

FD-NETWORKS — POORLY UNDERSTOOD



OBSERVATIONAL PREDICTIONS

# QUINTESSENCE ?



Peebles + Ratra 88

Wetterich 88

Zlatev, Wang  
+ Steinhardt 99

$$V(\varphi) = M^{4+\alpha} \varphi^{-\alpha}$$

T EARLY TIMES

$$\rho_{\varphi} / \rho_m \sim \varphi^2 / M_p^2.$$

$\varphi$  DOMINATES AT  $\varphi \sim M_p$

⇒ ACCELERATED EXPANSION.

AN ADJUST  $M$  SO THAT  $\varphi \sim M_p$  AT PRESENT

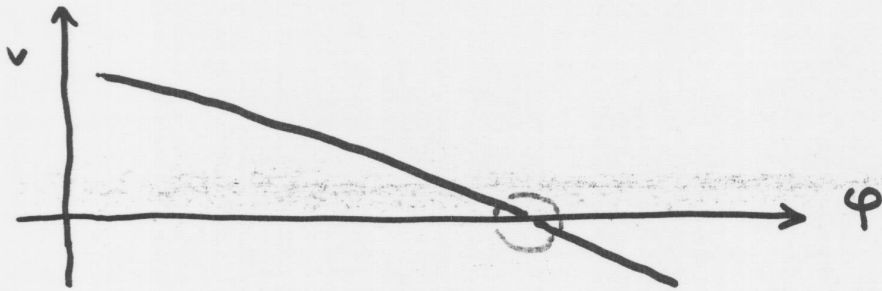
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# SCALAR FIELD MODELS

$$p_v = p_\Lambda + V(\varphi)$$

$\sim M_{\text{SUSY}}^4$

VERY FLAT



$p$  IS RANDOMIZED BY QUANTUM FLUCTUATIONS DURING INFLATION.

NEED A SCALAR FIELD WITH A VERY FLAT POTENTIAL.

Weinberg 01

Dvali + AV 01

Dimopoulos + Thomas 03