Talk given by

Professor Alexander Vilenkin

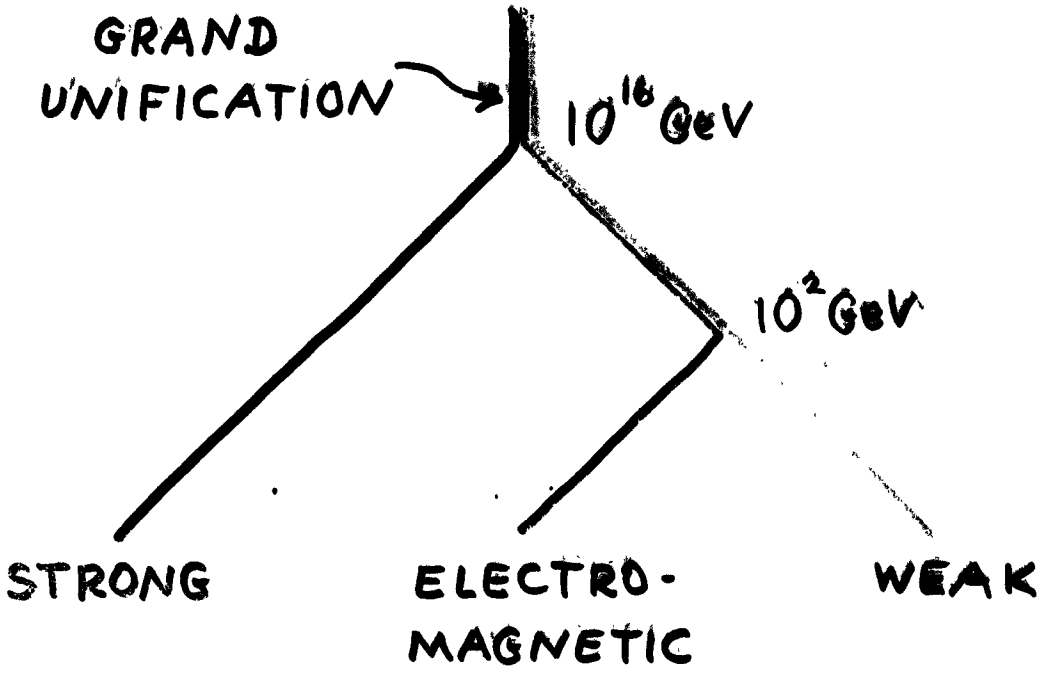
of Tufts University

LIGO Science Meeting

Tuesday November 26, 1996

COSMOLOGICAL PHASE TRANSITIONS

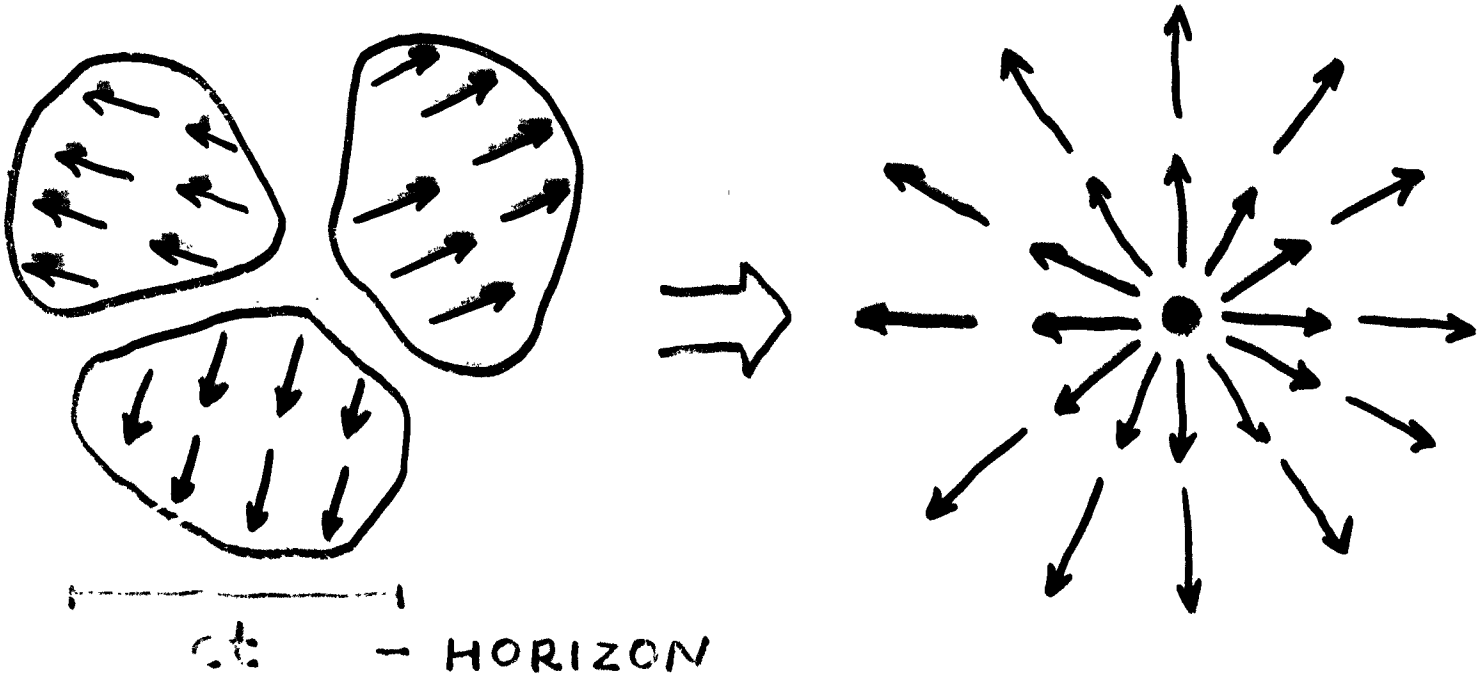
Kirzhnitz



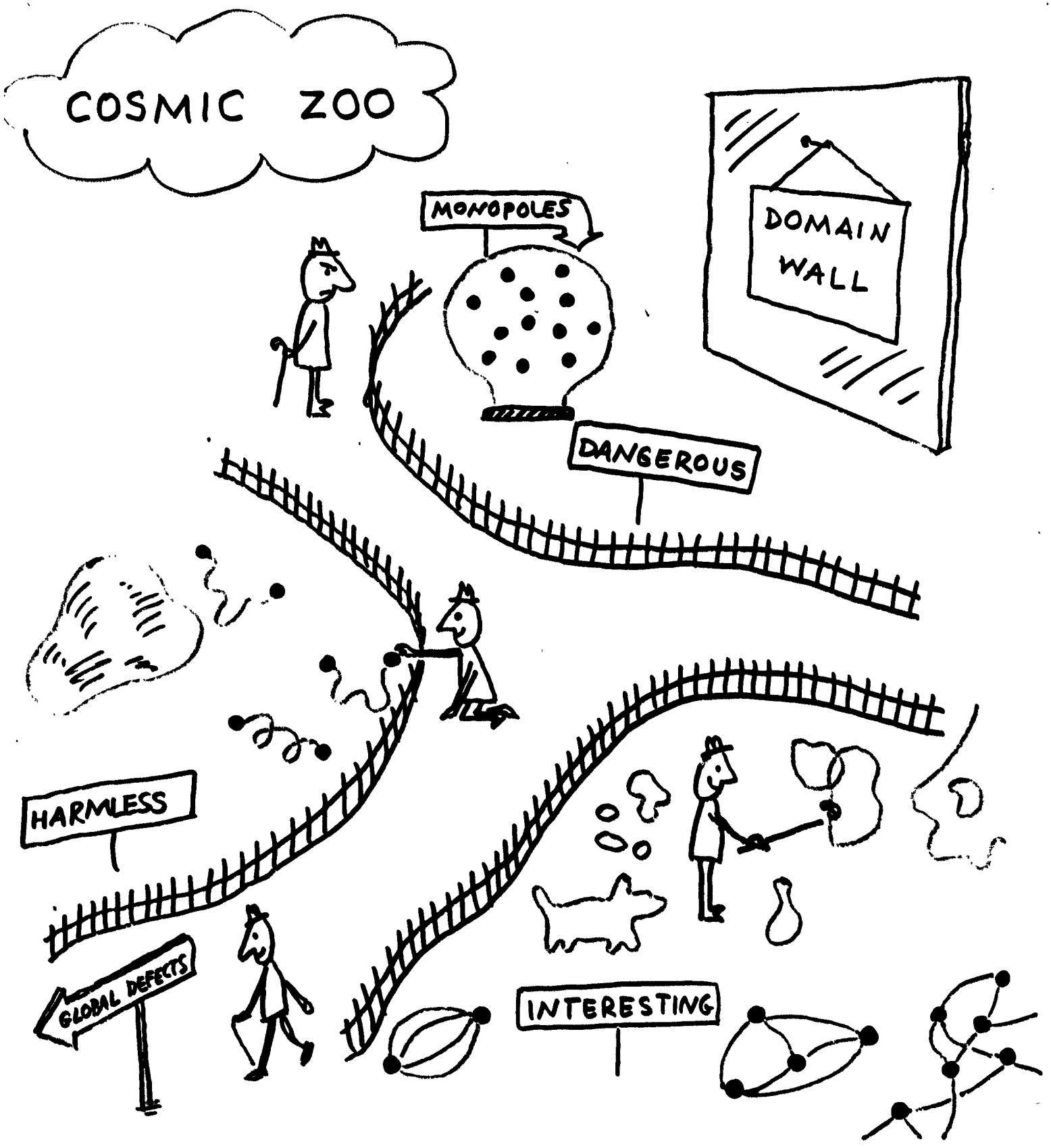
SYMMETRY BREAKING

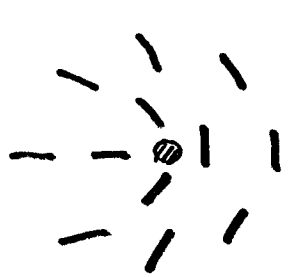
DEFECTS

KIBBLE



DOMAIN WALLS, STRINGS, MONOPOLES


COSMIC ZOO
MONOPOLES
DOMAIN WALL
DANGEROUS
HARMLESS
GLOBAL DEFECTS
INTERESTING



DEFECT FORMATION IN LIQUID CRYSTALS

Bowick et. al.

LIQUID HELIUM EXPERIMENTS

Hendry et. al.

GRAVITATIONAL RADIATION FROM TOPOLOGICAL DEFECTS

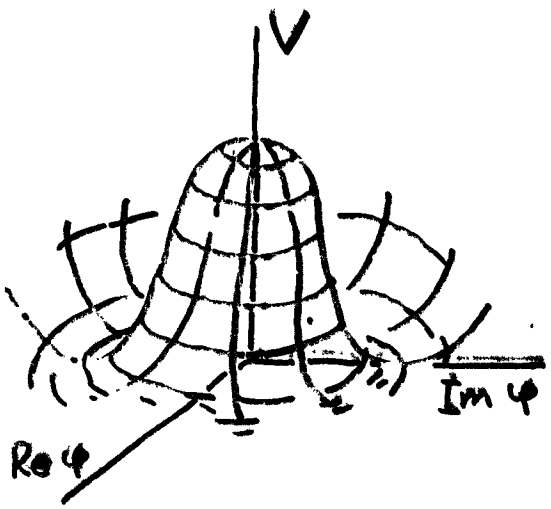
1. STRINGS
   - PROPERTIES AND EVOLUTION
   - GRAVITATIONAL WAVE BACKGROUND
2. HYBRID DEFECTS
   (with X. Martin)

STRINGS

$\hbar = c = 1$

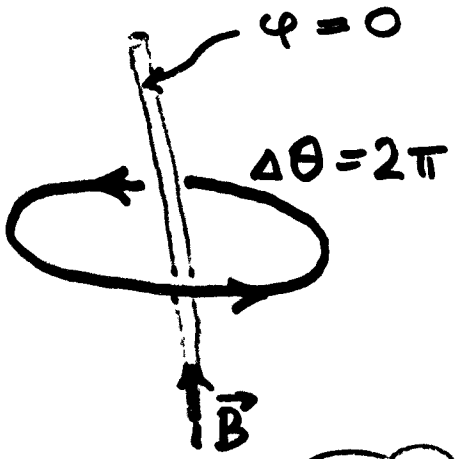
A SIMPLE MODEL: Nielsen + Olesen

$$\mathcal{L} = D_\mu \varphi^+ D^\mu \varphi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} \lambda (\varphi^+ \varphi - \eta^2)^2$$



$$\langle \varphi \rangle = \eta e^{i\theta}$$

$$U(1) \to \emptyset$$



SIMILAR TO ABRIKOSOV VORTICES

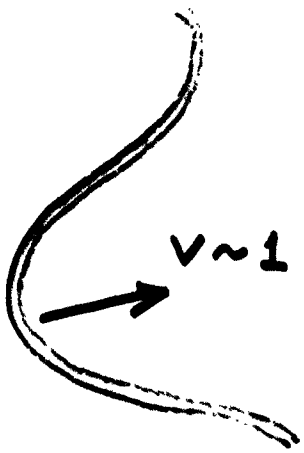
STRING THICKNESS: $\delta \sim \eta^{-1}$

MASS PER UNIT LENGTH: $\mu \sim \eta^2$

$\eta \sim 10^{16}$ GeV: $\mu \sim 10^{22}$ g/cm

$\eta \sim 10^{2}$ GeV: $\mu \sim 10^{-6}$ g/cm

STRING TENSION $= \mu$

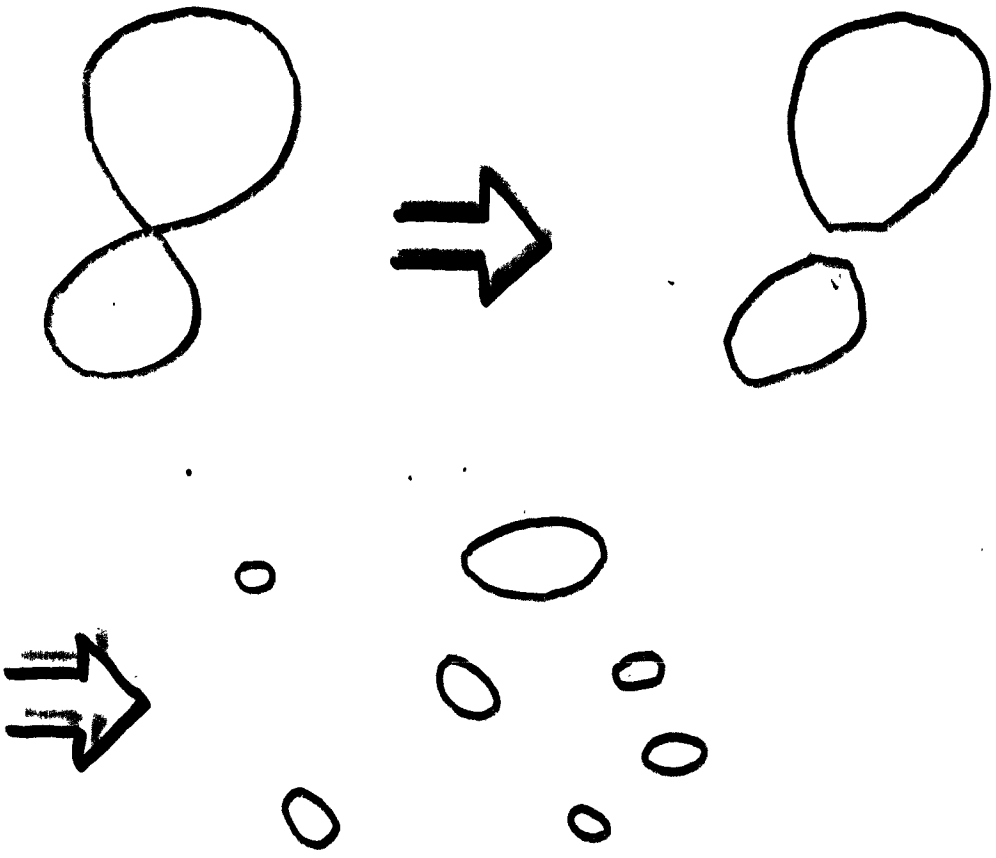


CRITICAL TEMPERATURE:

$T_c \sim \eta$

RECONNECTION

Shellard



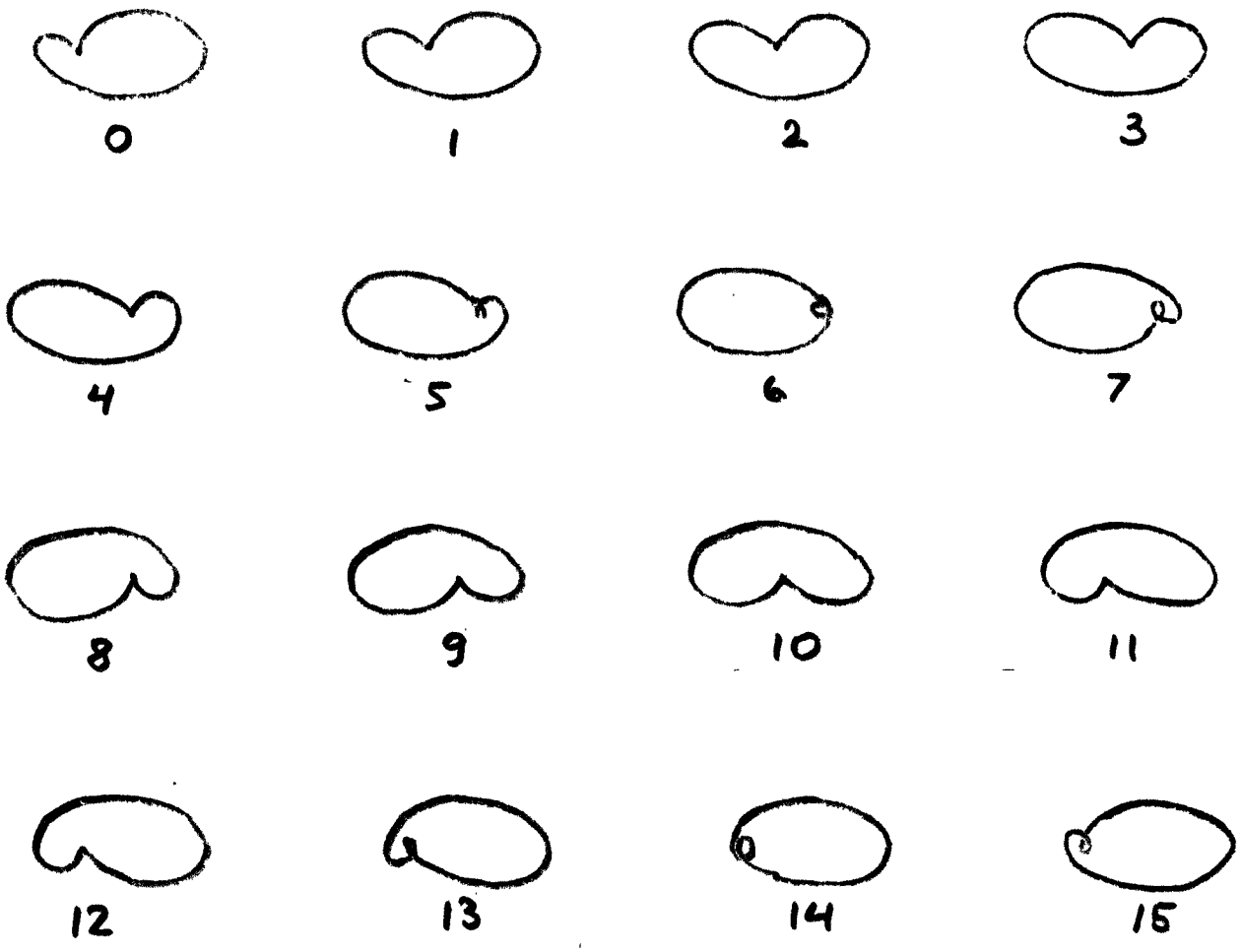
NON-INTERSECTING LOOPS
LOSE THEIR ENERGY
BY GRAVITATIONAL RADIATION

OSCILLATING LOOPS

NAMBU ACTION:

$$S = -\mu \int d\sigma$$

MOTION OF LOOPS IS PERIODIC : $T = L/2$.



GRAVITATIONAL RADIATION FROM LOOPS

$\nu \sim L^{-1}$

$$\dot{E} \sim G\dddot{Q}^2, \qquad Q \sim ML^2$$

$$\dddot{Q} \sim \nu^3 ML^2 \sim \mu$$

$M = \mu L$

$$\dot{E} \sim G\mu^2$$

NUMERICAL RESULTS: Vachaspati + A.V. Burden, Allen + Casper

$$\dot{E} = \Gamma G \mu^2, \qquad \Gamma \sim 100$$

SPECTRUM:

$dE/d\nu \propto \nu^{-4/3}$ (LOOPS WITH CUSPS)

$\propto \nu^{-2}$ (LOOPS WITH KINKS)

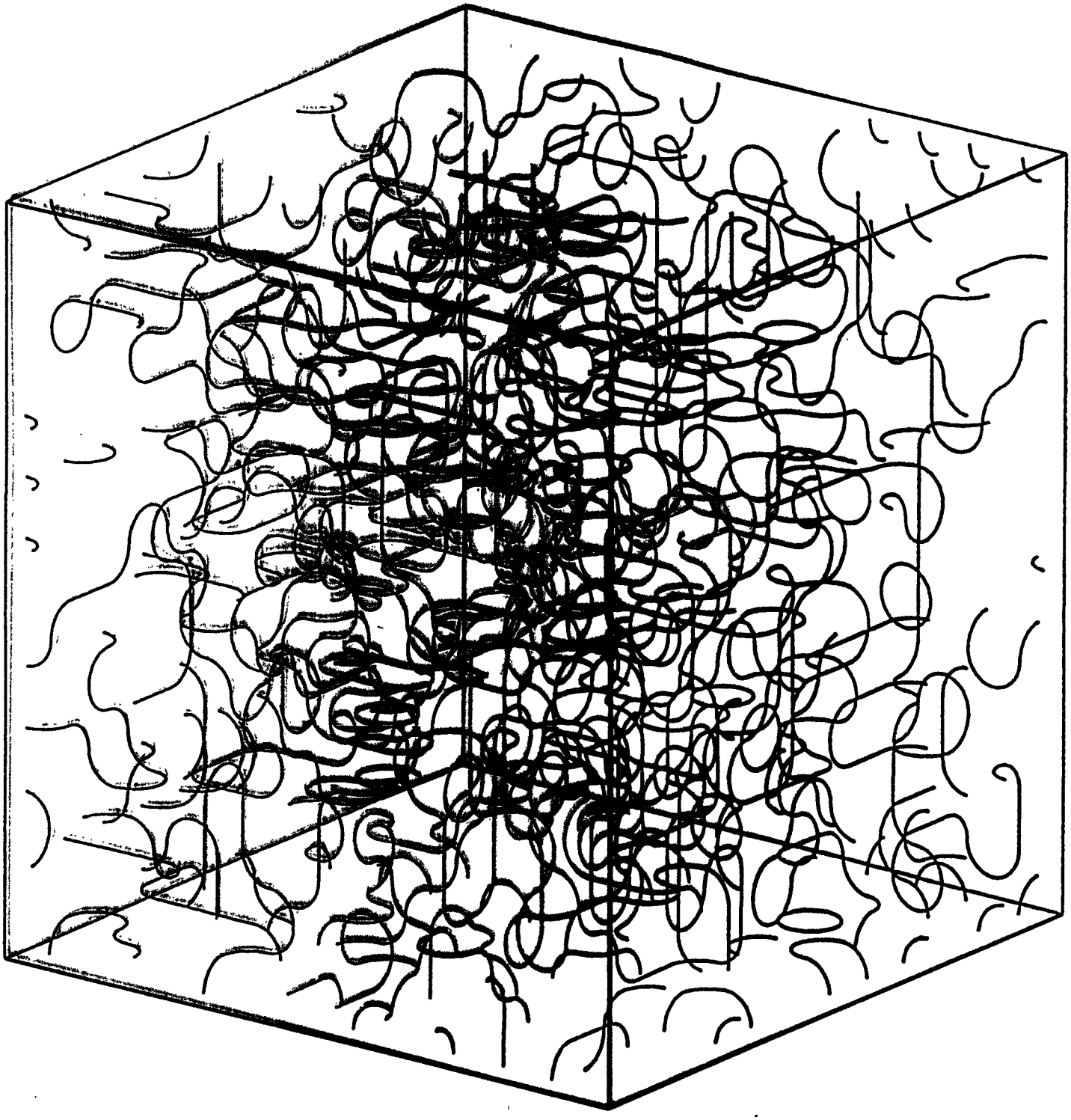
LIFETIME: $$\tau \sim \frac{M}{\dot{E}} \sim \frac{L}{\Gamma G \mu}$$

$$G\mu \sim \frac{\eta^2}{m_P^2}$$

FOR GUT STRINGS:

$\eta \sim 10^{16}$ GeV $\Rightarrow$ $G\mu \sim 10^{-6}$

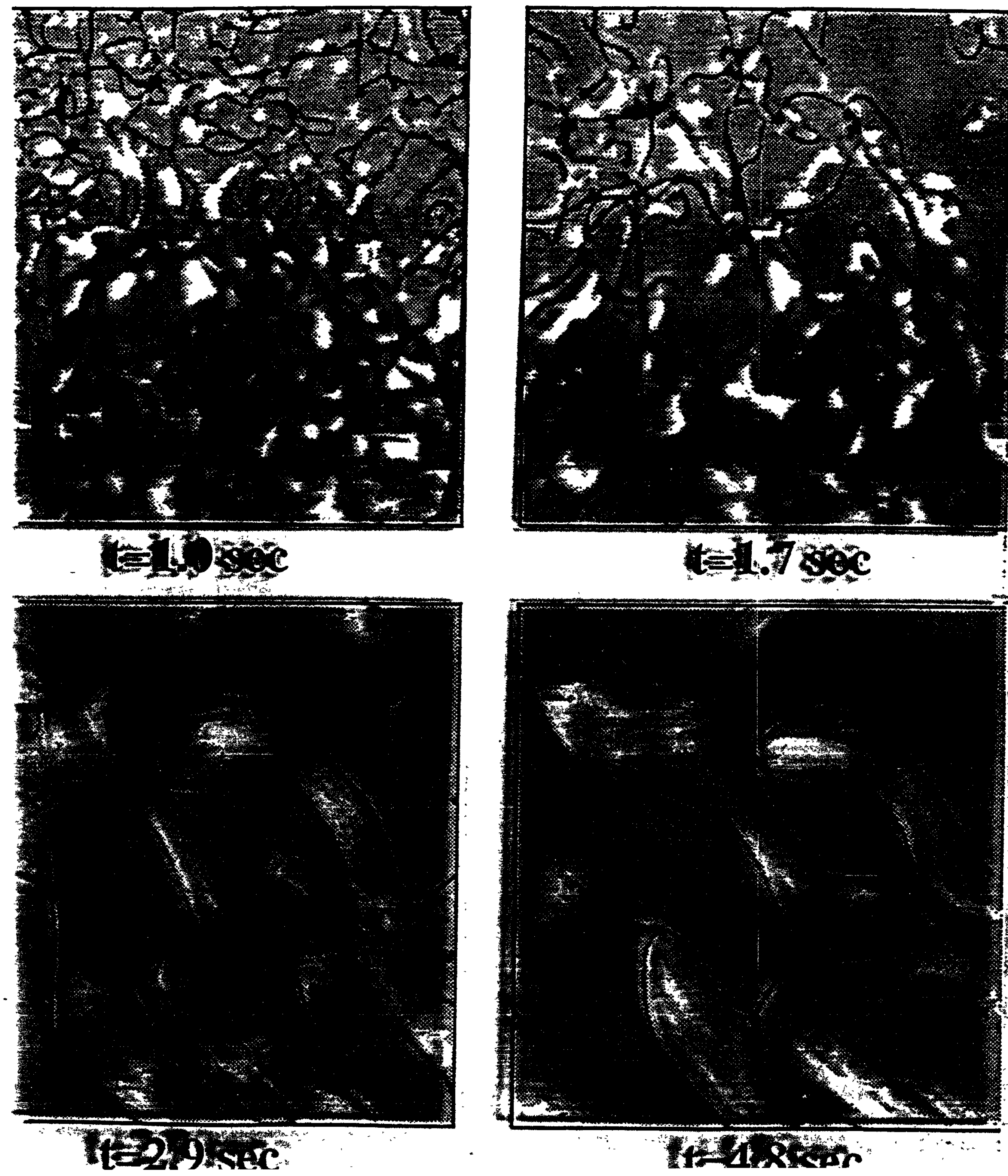
$\tau \sim 10^4 L$



INFINITE STRINGS ~ 80%

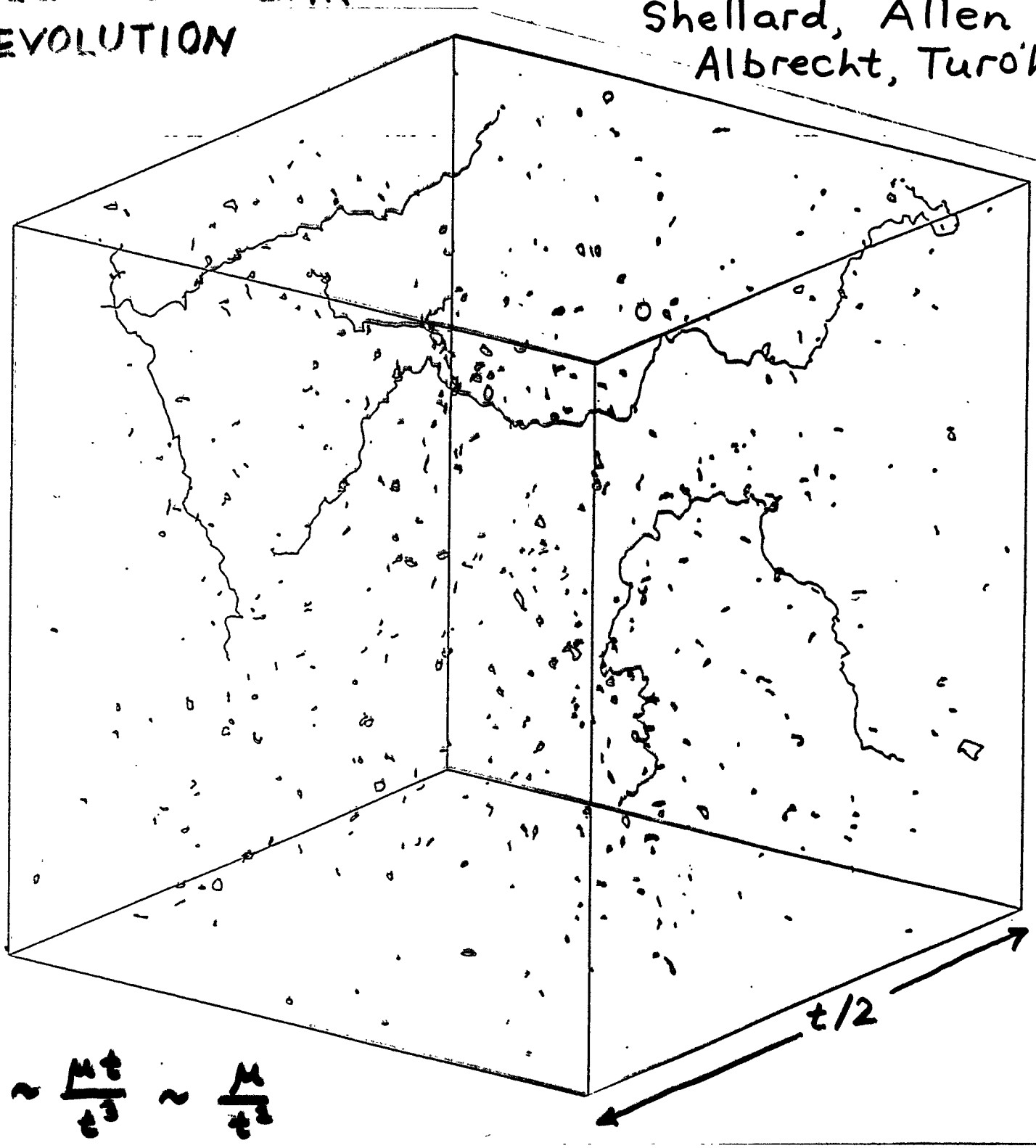
LOOPS ~ 20%

Vachaspati + A.V.


t=1.0 sec
t=1.7 sec
t=2.9 sec
t=4.8 sec

SELF-SIMILAR EVOLUTION

Bennett, Bouchet
Shellard, Allen
Albrecht, Turok



$$\rho_s \sim \frac{\mu t}{t^3} \sim \frac{\mu}{t^2}$$

NUMERICAL: $\rho_s \approx 16\mu/t^2$

$\rho_r = 3/32\pi G t^2 \Rightarrow \rho_s/\rho_r \approx 500 G\mu$

LOOP SIZES: $\ell \sim \Gamma G\mu t \Rightarrow \tau \sim t$

$\nu \sim 1/2$

STOCHASTIC BACKGROUND OF GRAVITATIONAL WAVES

$$\Omega_g(\nu) = \frac{\nu}{\rho_c}\frac{d\rho_g}{d\nu}$$

FOR WAVES EMITTED DURING RADIATION ERA:

A.V. Vachaspati
Bennett + Bouchet

$$\Omega_g(\nu) \sim 300\, G\mu\, (N/N_\nu)^{1/3}\, \Omega_r$$

$$\nu(t) \propto a^{-1}(t)$$

AT PRESENT:

$$\Omega_g(\nu)h^2 \sim 6\times 10^{-3}\, G\mu\, (N/N_\nu)^{1/3}$$

$(N/N_\nu)^{1/3} \sim 0.2 - 1$

WAVES OF PRESENT FREQ. ν WERE EMITTED AT

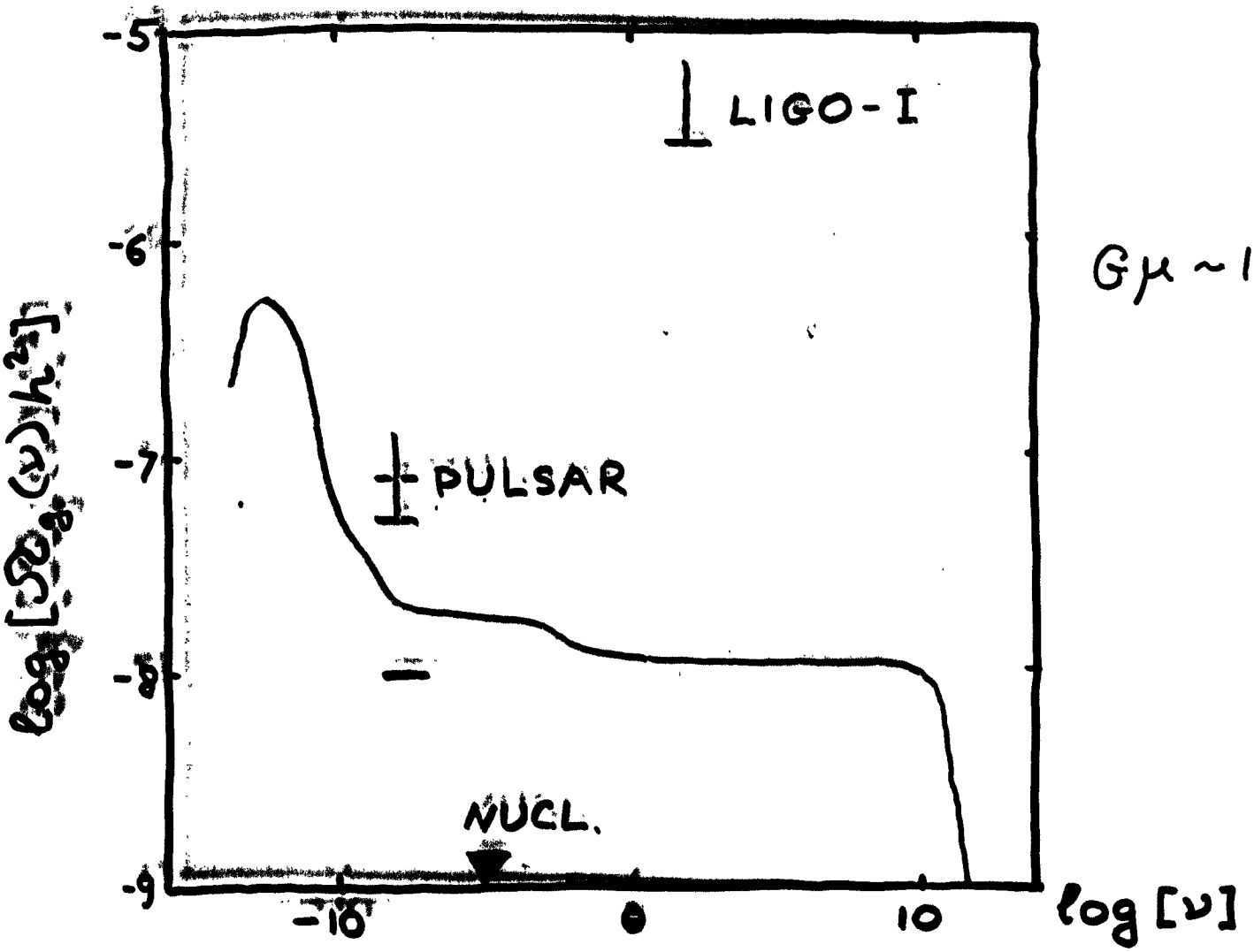
$$t_\nu \sim 10^{-10}\left(\frac{G\mu}{10^{-6}}\right)^{-2}\left(\frac{\nu}{1H_3}\right)^{-2} s.$$

FOR $G\mu \sim 10^{-6}$: $\quad 10^{-8}H_3 < \nu < 10^{10}H_3$

LIGO: $\quad \nu \sim 10^2 H_3 \Rightarrow t_\nu \sim 10^{-14}s$

PULSAR: $\quad \nu \sim 10^{-8} H_3 \Rightarrow t_\nu \sim 10^6 s$

CALDWELL + ALLEN:



$G\mu \sim 10^{-6}$

OBSERVATIONAL BOUNDS ON $G\mu$:

· PULSAR:

Kaspi, Taylor + Ryba: $G\mu < 3 \times 10^{-6}$

Mc Hugh et. al.: $G\mu < 5 \times 10^{-6}$

[Thorsett + Dewey: $G\mu < 6 \times 10^{-7}$]

NUCLEOSYNTHESIS: $\Omega_g(\text{nucl}) \lesssim 0.05$

$\Rightarrow G\mu \lesssim 10^{-5}$

COBE: $G\mu \approx 1.1 \times 10^{-6}$ ← Allen et. al.

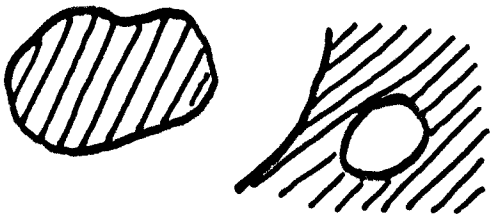
WALLS BOUNDED BY STRINGS

EXAMPLE:

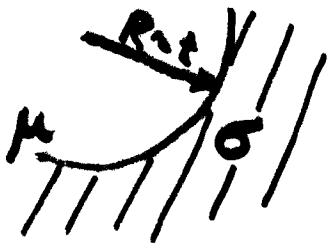
$$G \to K \times Z_2 \to K$$

STRINGS WALLS

Kibble
Lazarides
Shafi



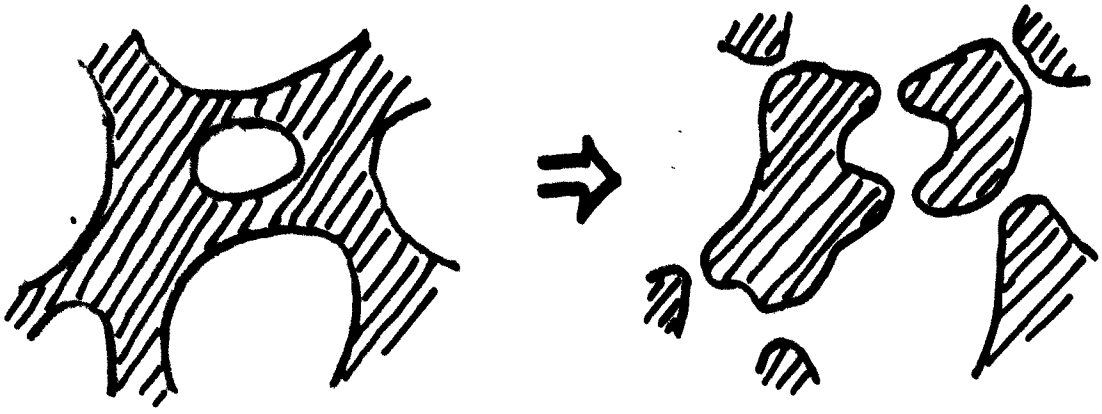
NUMERICAL SIMULATION OF FORMATION: THE SYSTEM IS DOMINATED BY ONE INFINITE CLUSTER



FORCE PER UNIT LENGTH:

$$f_s \sim \mu/t, \qquad f_w \sim \sigma \sim \eta_w^3$$

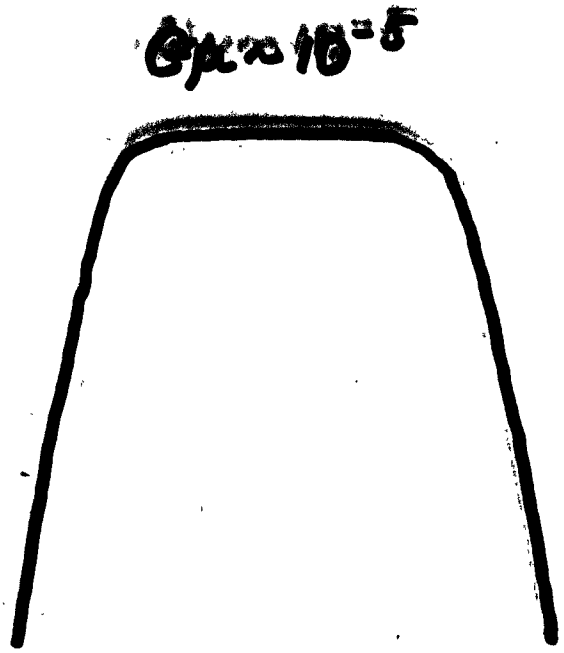
WALL TENSION BECOMES IMPORTANT AT $t_* \sim \mu/\sigma$



Everett + AV

EXAMPLE: $G\mu \sim 10^{-5}$, $\eta_w \sim 10^3$ GeV $\Rightarrow$ $t_* \sim 1$s.

$\Rightarrow \nu \gtrsim 10^{-6} H_3$


$\Phi_{pc} \approx 10^{-5}$

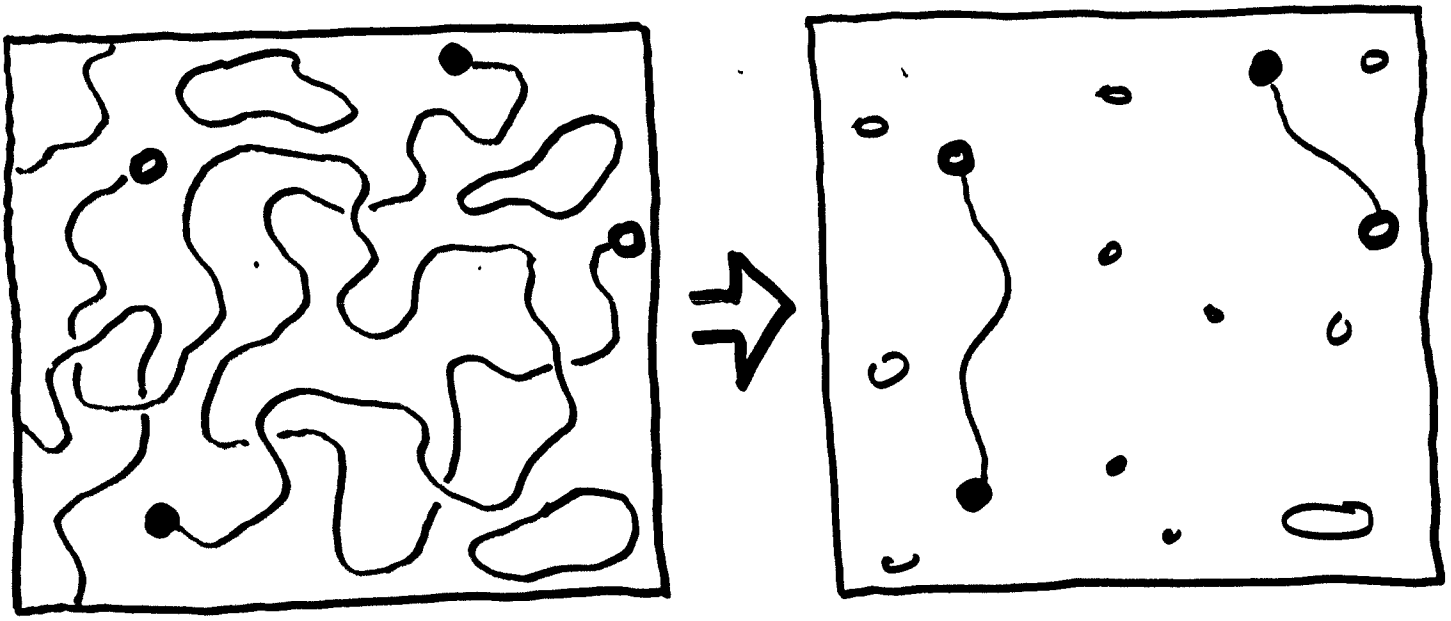
MONOPOLES CONNECTED BY STRINGS

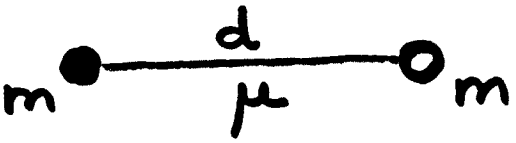
DURING INFLATION

$$G \to U(1) \times H \to H$$

MONOPOLES

STRINGS





$$\gamma \sim \mu d/m \gg 1$$

$$\dot{\mathcal{E}} \approx -8 G \mu^2 \cdot \ln \gamma$$

FLAT SPECTRUM

$$d^{-1} \lesssim \nu \lesssim \gamma^2 d^{-1}$$

X. Martin + A.V.