Cosmic Strings: an update

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P. Avelino, P. Wu etc.

- Cosmic string evolution in 3D.
- Brane inflation & cosmic strings
- String evolution with $D \geq 3$
- Gravitational effects / lensing
- CMB anisotropies
- Gravitational waves etc
- Why defects

"[___ ____] are the best possible signature of superstring theory"

Henry Tye (7/04)

Ans: Cosmic strings

Famous string theorist (attrib): (3/04)

"You need two books to understand string theory these days ....[ ] [ ]"

Ans 1: Superstring theory (Polchinsk

Ans 2: . . .

The Scaling Solution

- **Background matter density**

  Radiation $\rho = \frac{3}{32\pi G t^2}$ Matter $\rho = \frac{1}{6\pi G t^2}$

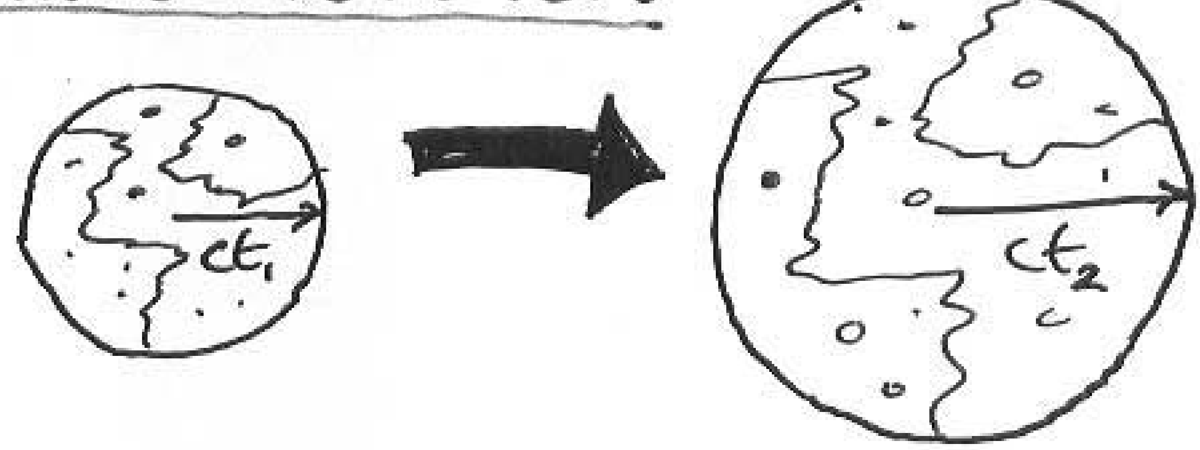
- **Brownian string network**

  $$\rho = \frac{\mu}{L^2} \propto \frac{1}{t^2}$$

  Inter-string distance L

- **Scale-invariant evolution**

  $$\underline{\underline{L = \xi t}}$$



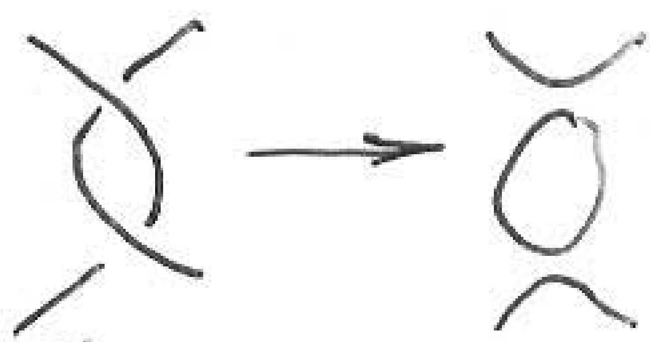
- **Dynamical processes**
  - Stretching

    $L = \frac{a}{a_0} L_0$

+ redshifting of velocities

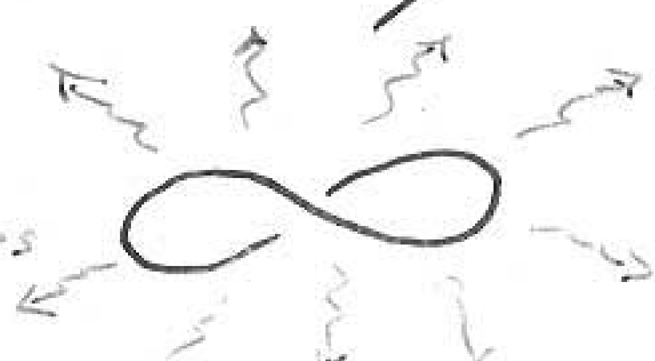
  - Reconnection

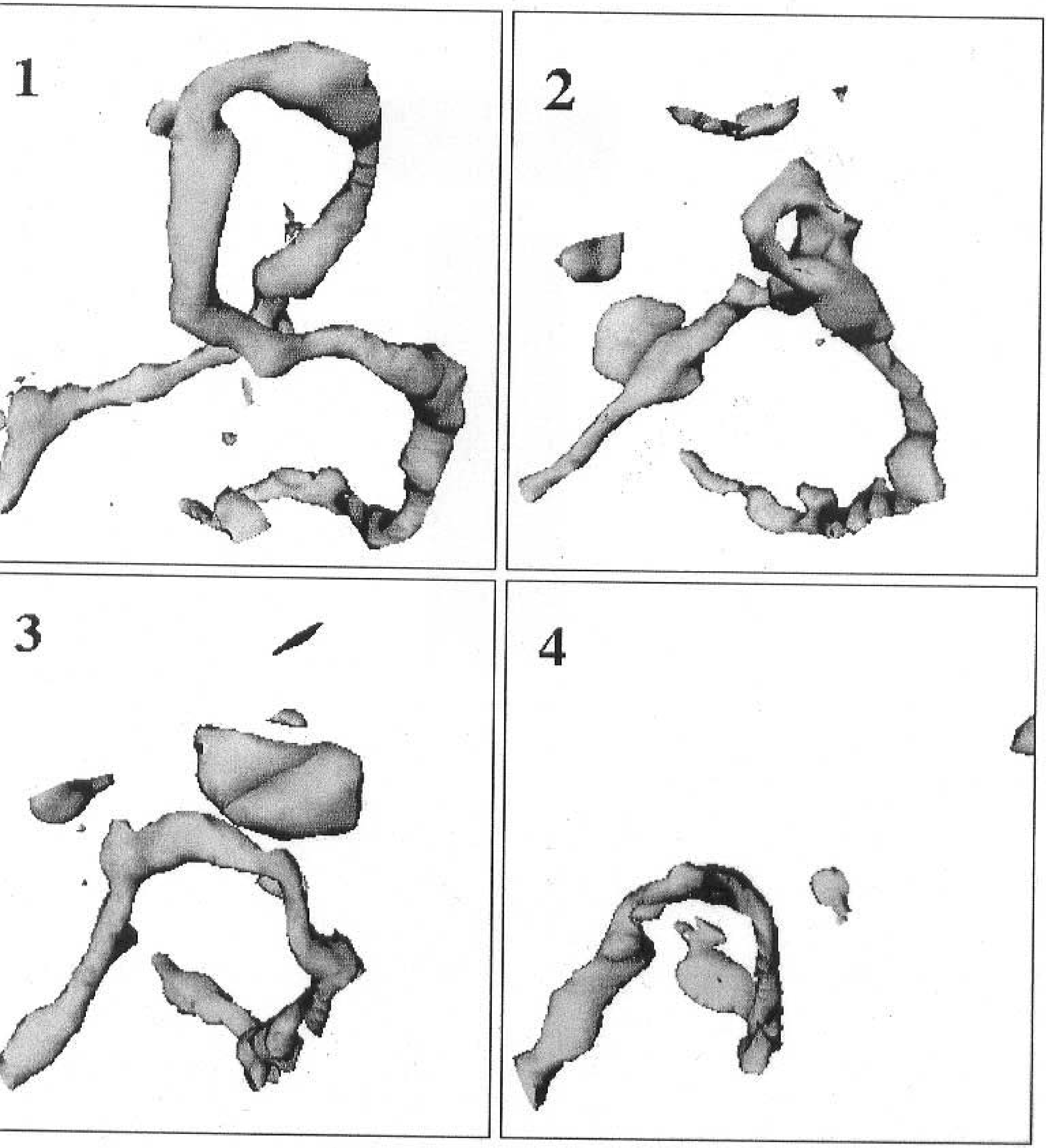
  - Loop formation



  - Radiation

Oscillating loops

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Defect cosmology

- ## Domain walls

Wall tension $\sigma \sim \eta^3$

Scaling density $\boxed{\rho \sim \sigma/t}$

Cosmological bound $\eta \lesssim 1\ \text{MeV}$

- ## Local monopoles

Monopole mass $m \sim \frac{4\pi}{e}\eta$

Dominate energy density $\boxed{\rho_m \propto t^{-3/2}}$

Observational bounds $\eta \lesssim 1\ \text{TeV}$

- ## Global monopoles

Monopole mass $m \sim 4\pi\eta^2 R$

Evolution through effective annihilatio

Scaling density / horizon volume

$\boxed{4 \pm 1.5 \text{ monopoles}}$

- ## Global textures

Evolve through collapse & topological unwindin

Event no. / horizon volume / Hubble time

$\boxed{0.04 \text{ texture unwindings}}$

VOS MODEL

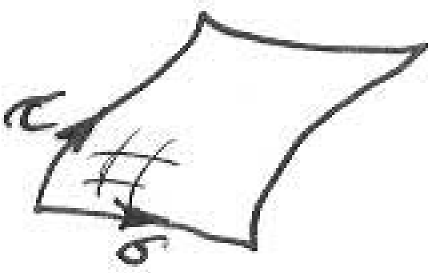
Velocity-dependent One-Scale Model

Martins & EPS, 2004 (PRL) — see web 7/04

$D = 3$ FRW backgrnd $\quad ds^2 = a^2(t)\left[d\tau^2 - d\mathbf{x}^2\right]$

★ Microphysical string equations

- Position $\mathbf{x}(\sigma,\tau)$ — Gauge choice $\xi^0 = \tau, \quad \dot{\mathbf{x}}\cdot\mathbf{x}' = 0$



$$\underbrace{\ddot{\mathbf{x}}}_{\text{Accel.}} + \underbrace{2\frac{\dot a}{a}(1-\dot{\mathbf{x}}^2)\dot{\mathbf{x}}}_{\text{Hubble damping}} = \underbrace{\frac{1}{\epsilon}\left(\frac{\mathbf{x}'}{\epsilon}\right)'}_{\text{Curvature.}}$$

- Energy density $\quad \epsilon(\sigma,\tau) = \dfrac{\mathbf{x}'^2}{1-\dot{\mathbf{x}}^2}$

$$\dot\epsilon = -2\frac{\dot a}{a}\epsilon\,\dot{\mathbf{x}}^2$$

★ Averaged quantities

- **Energy:**

$$E = \mu\, a(\tau)\int \epsilon\, d\sigma$$

- **Velocity:**

$$v^2 = \langle \dot{\mathbf{x}}^2\rangle = \frac{\int \dot{\mathbf{x}}^2 \epsilon\, d\sigma}{\int \epsilon\, d\sigma}$$

- **Correlation length:** (Brownian network $E = \frac{\mu V}{L^2}$

$$\rho = \mu/L^2$$

- **Reconnection rate:** $\quad \propto L/(L^3) \to \tilde{c}/L^2$

★ Averaged VOS equations

Correlation length:

$$\frac{dL}{dt} = \frac{\dot a}{a}L(1+v^2) + \underbrace{\tilde{c}v}_{\text{Loop prod}^{n}}$$

Velocity:

$$\frac{dv}{dt} = (1-v^2)\left[\underbrace{\frac{k(v)}{L}}_{\text{curvature}} - \underbrace{2\frac{\dot a}{a}v}_{\text{Hubble damping}}\right]$$

Scaling solutions

VOS model equations

$$\frac{dL}{dt} = \frac{\dot a}{a} L (1+v^2) + \tilde c v$$

$$\frac{dv}{dt} = (1-v^2)\left[\frac{k(v)}{L} - 2\frac{\dot a}{a} v\right]$$

- Momentum parameter k

$$\frac{k}{L} \equiv \langle \dot{\underset{\sim}{x}} \cdot \underset{\sim}{u} \, (1-\dot{\underset{\sim}{x}}^2)\rangle / v(1-v^2)$$

i.e. correlation between curvature & velocity

with curvature vector $\underset{\sim}{u} = \frac{d^2 x}{a\, ds^2}$

- Non-rel. limit: $\dot{\underset{\sim}{x}} \parallel \underset{\sim}{u} \Rightarrow k = \frac{2\sqrt2}{\pi}$
- Rel. limit (flat space): $\langle \dot{\underset{\sim}{x}}^2\rangle = \frac12 \Rightarrow k=0$

Tested ansatz: $k(v) = \frac{2\sqrt2}{\pi}\frac{(1-8v^6)}{(1+8v^6)}$

Linear scaling

$a(t) \propto t^\beta$, β const.

$\Rightarrow L \propto t \propto H^{-1}$, $v = \text{const.}$

$$\rho = \frac{4\beta(1-\beta)}{k(k+\tilde c)}\left(\frac{\mu}{t^2}\right) \qquad v^2 = \frac{k(1-\beta)}{\beta(k+\tilde c)}$$

- Numerical simulations fix one free parameter

$$\tilde c = 0.23 \pm 0.04.$$

Radiation $\rho = 13\, \mu/t^2$, Matter $\rho = 4\, \mu/t^2$

Transition era well-matched.

Friction-dominated evolution (formation)

Stretching regime $L \propto t^{1/2}$, $v \propto t$

Kibble regime $L \propto t^{5/4}$, $v \propto t^{1/4}$

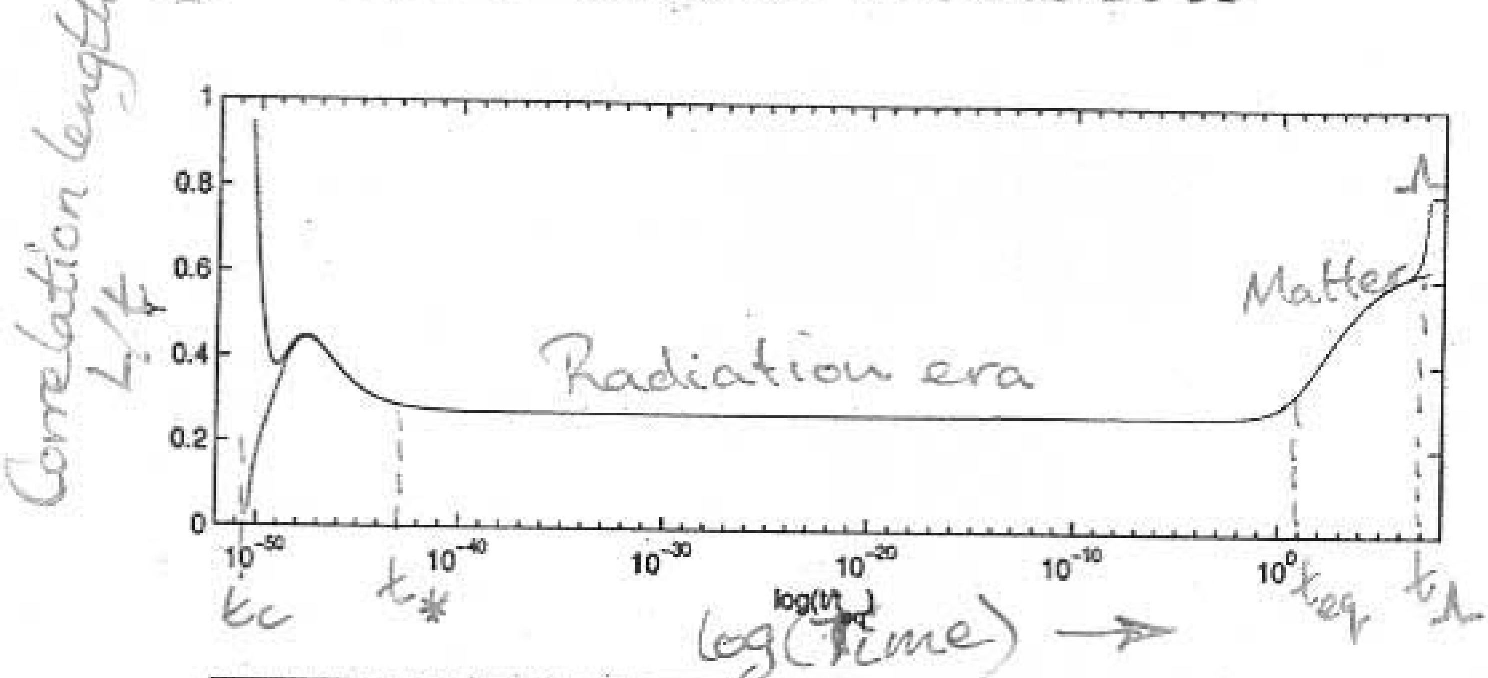
Accelerating universe (Λ-domination)

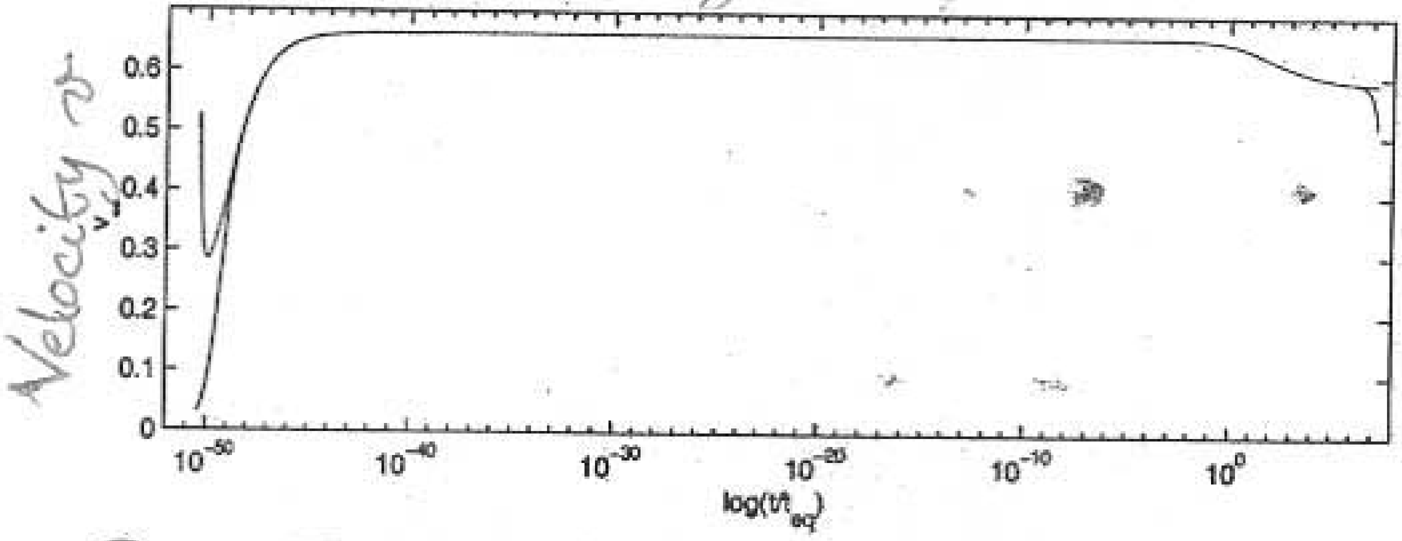
$L \propto a$, $v \propto a^{-1}$ with $Lv = \frac{2\sqrt2}{\pi} H$

COSMOLOGICAL HISTORIES

Martins & Shellard '96, Martins '97, Martins & Shellard '00

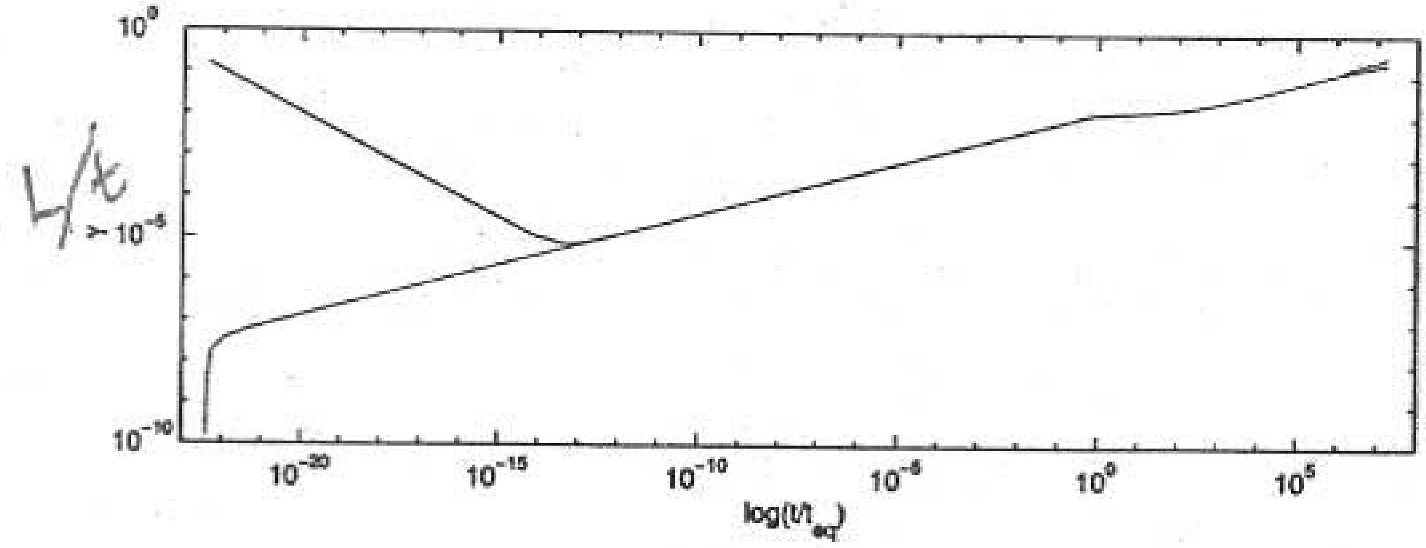
GUT–scale network

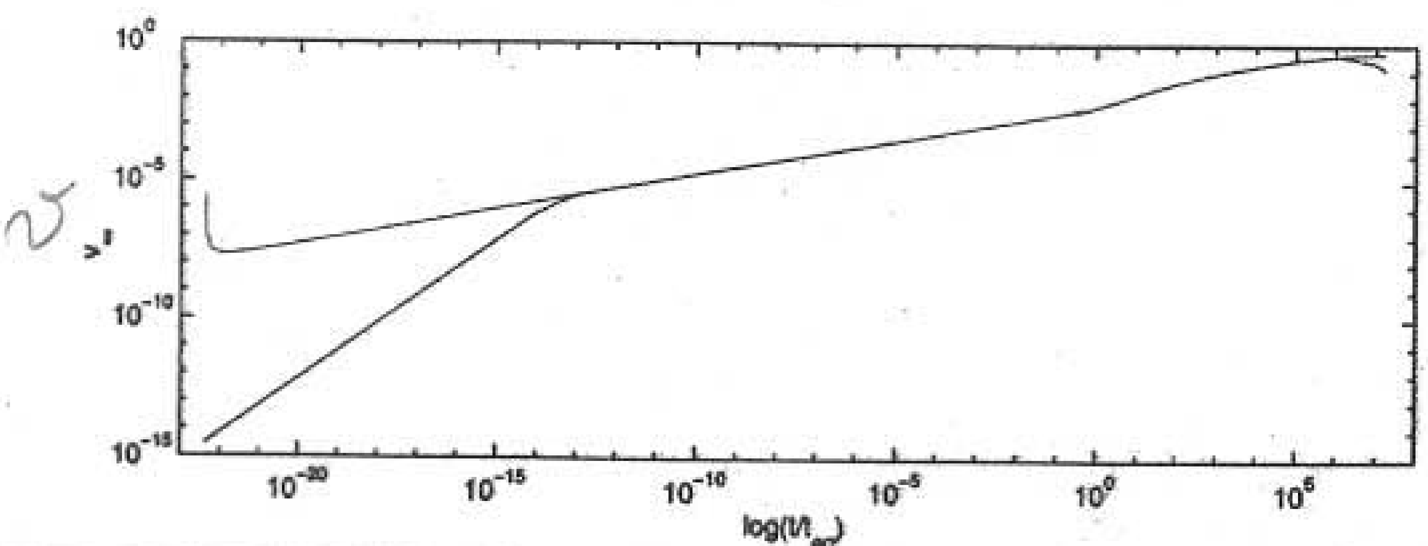




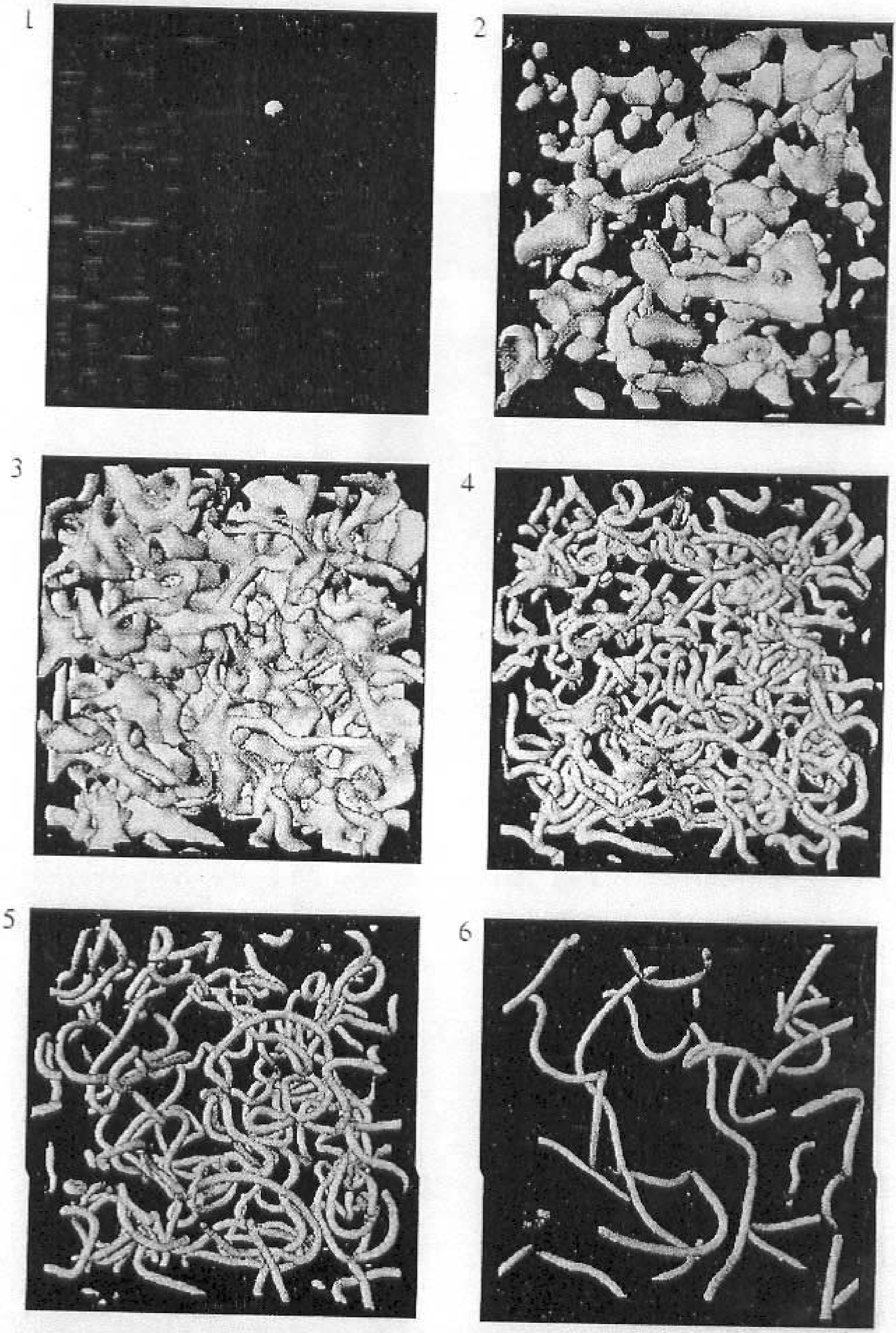
- During the entire period relevant for structure formation, the network is not in scaling regime!
- Initial conditions are erased quickly.
- Quick departure from matter evolution once Λ dominates.

EW–scale network





- During damped evolution epoch, the network retains a 'memory' of its initial conditions, and of properties of the background cosmology!
- For Ω_m=1, the network is relativistic today; for the best–fit model, it is always non–relativistic.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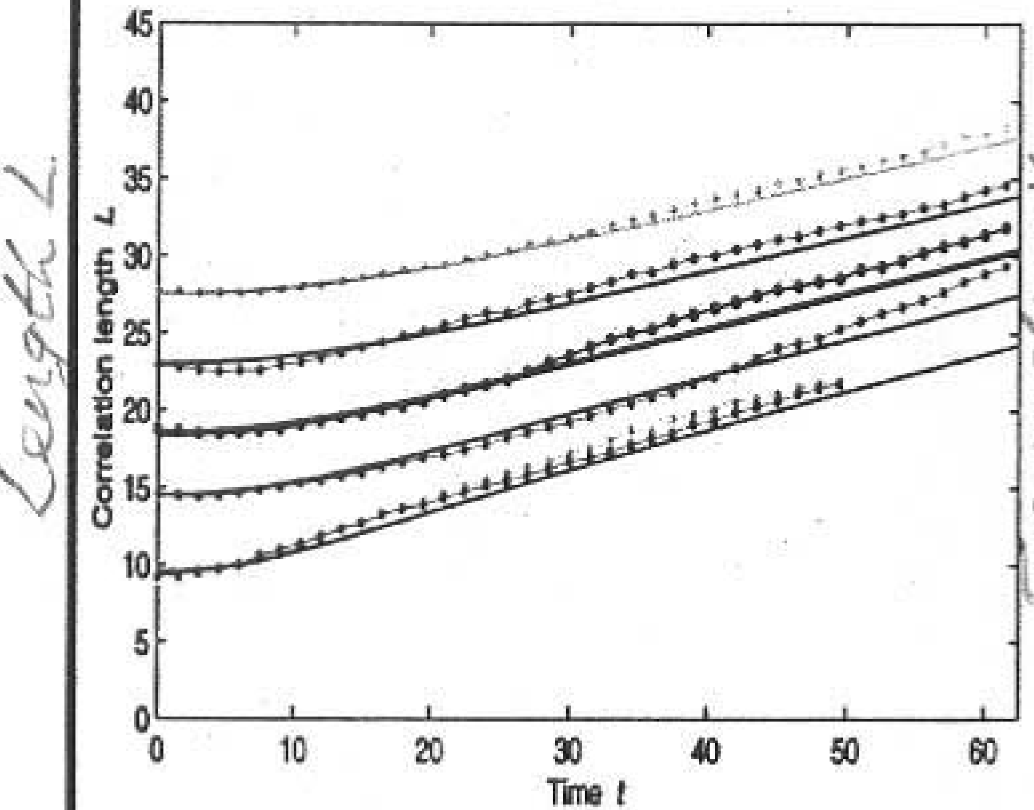
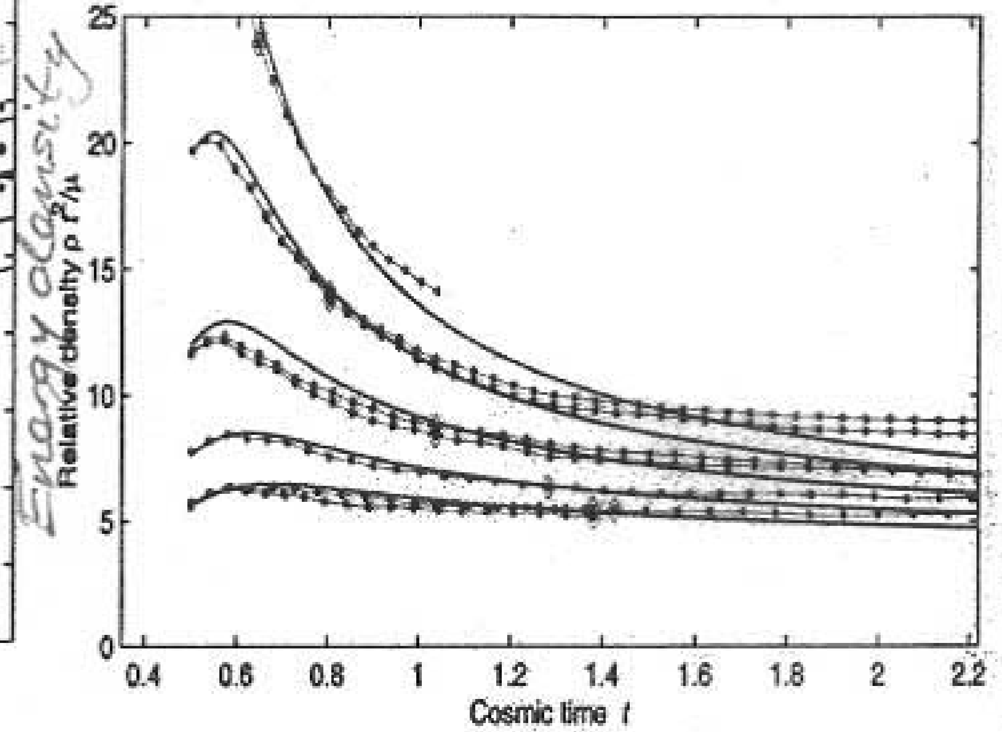
ANALYTIC MODEL FITS FOR ABELIAN–HIGGS

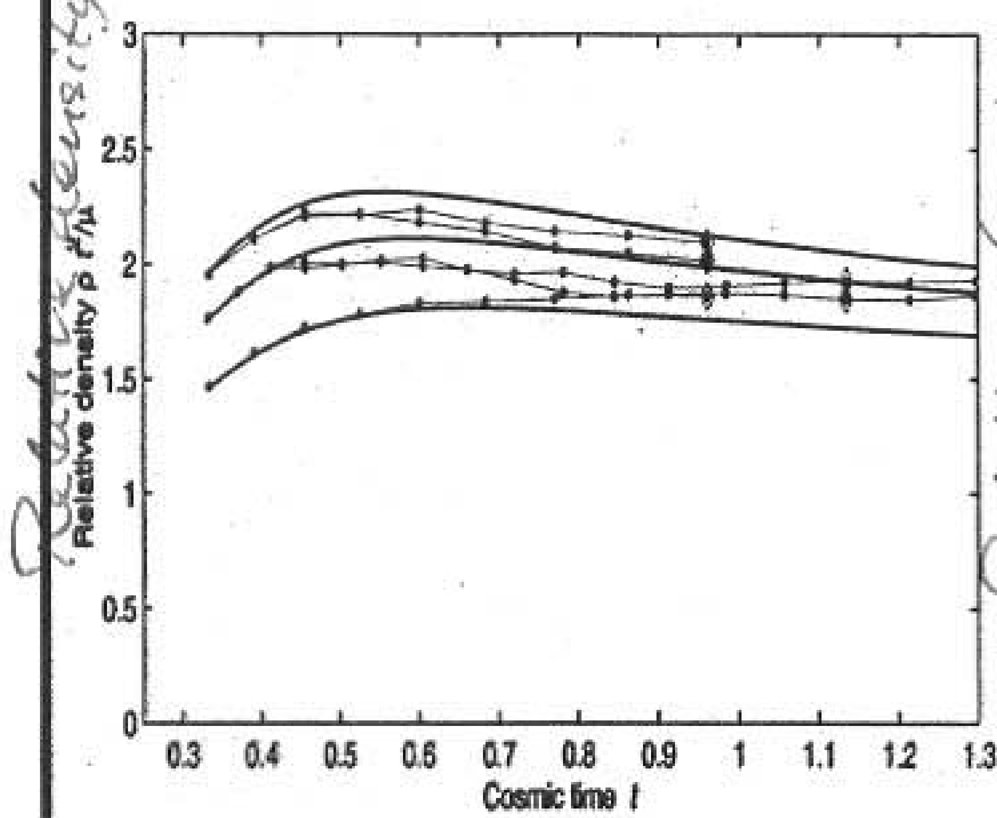
Flat
$c = 0.57, \ \Sigma = 0.5$



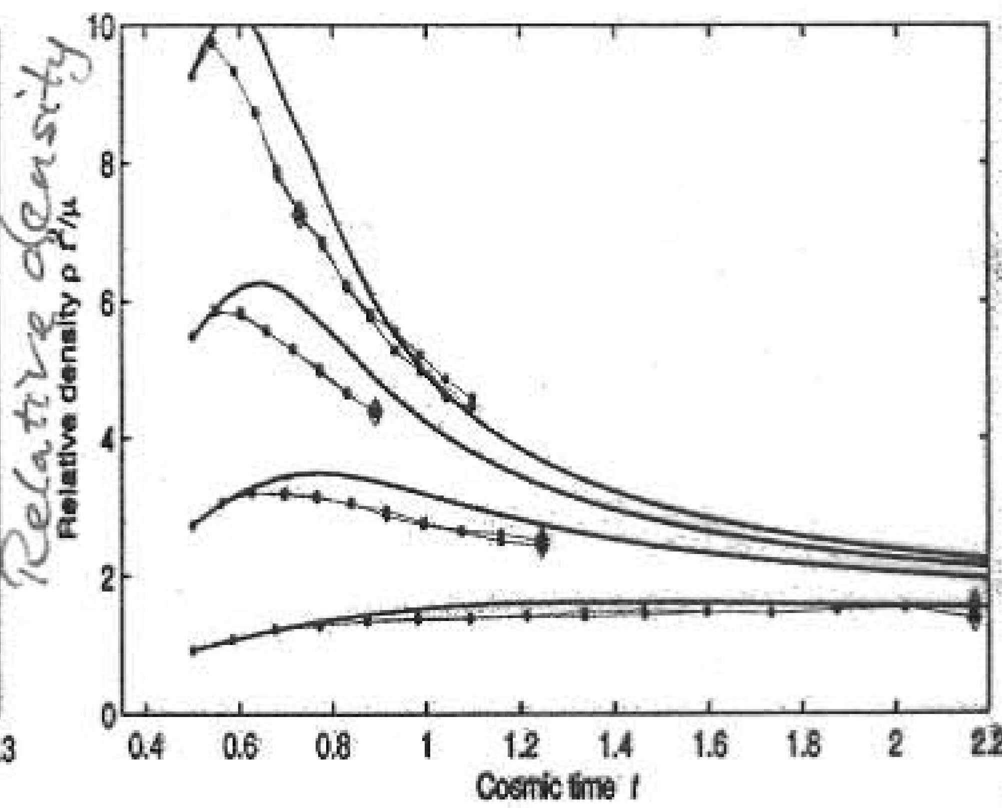
Radiation
$c = 0.57, \ \Sigma = 0.5$



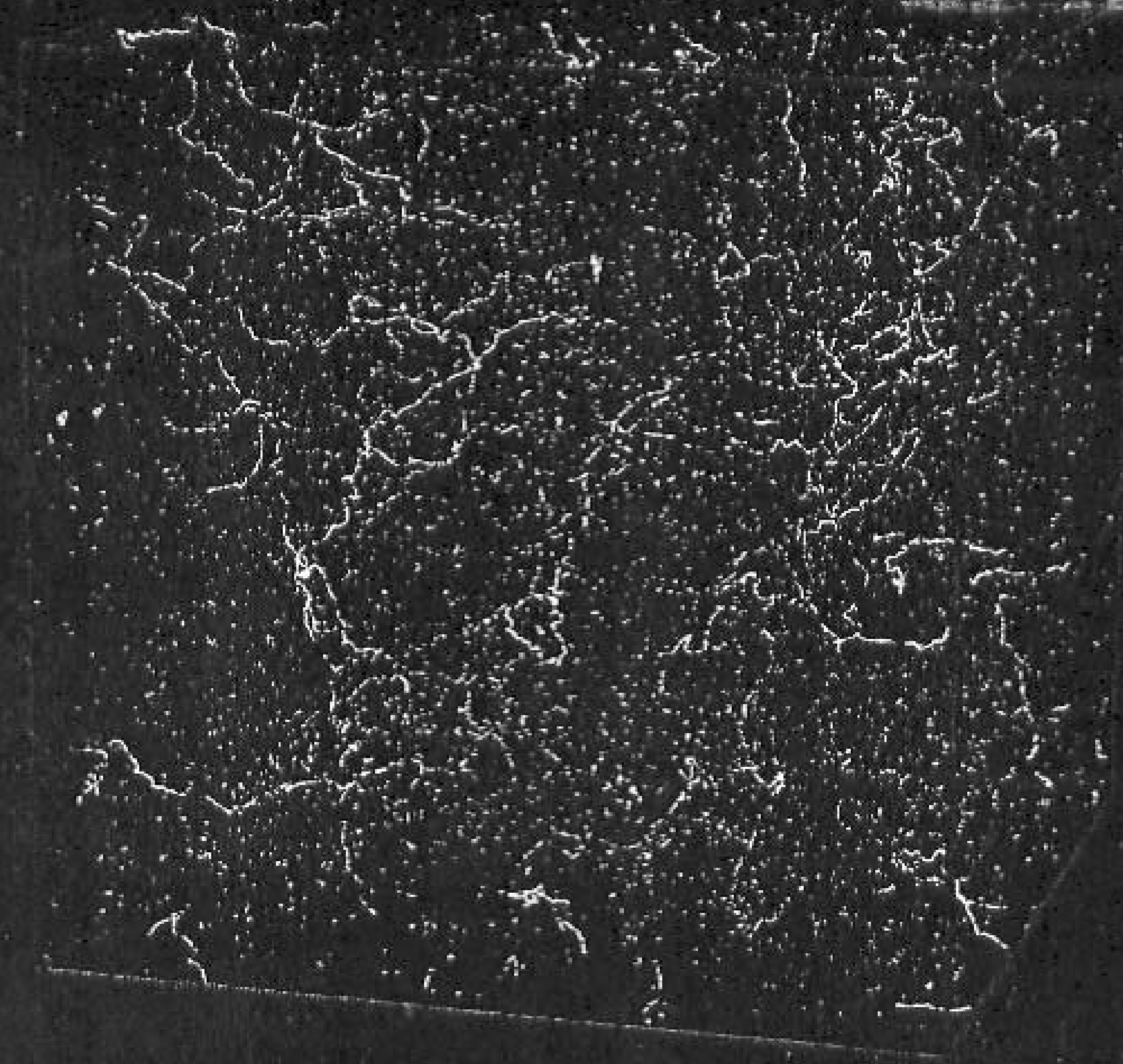
Matter
$c = 0.57. \ \Sigma = 0.5$



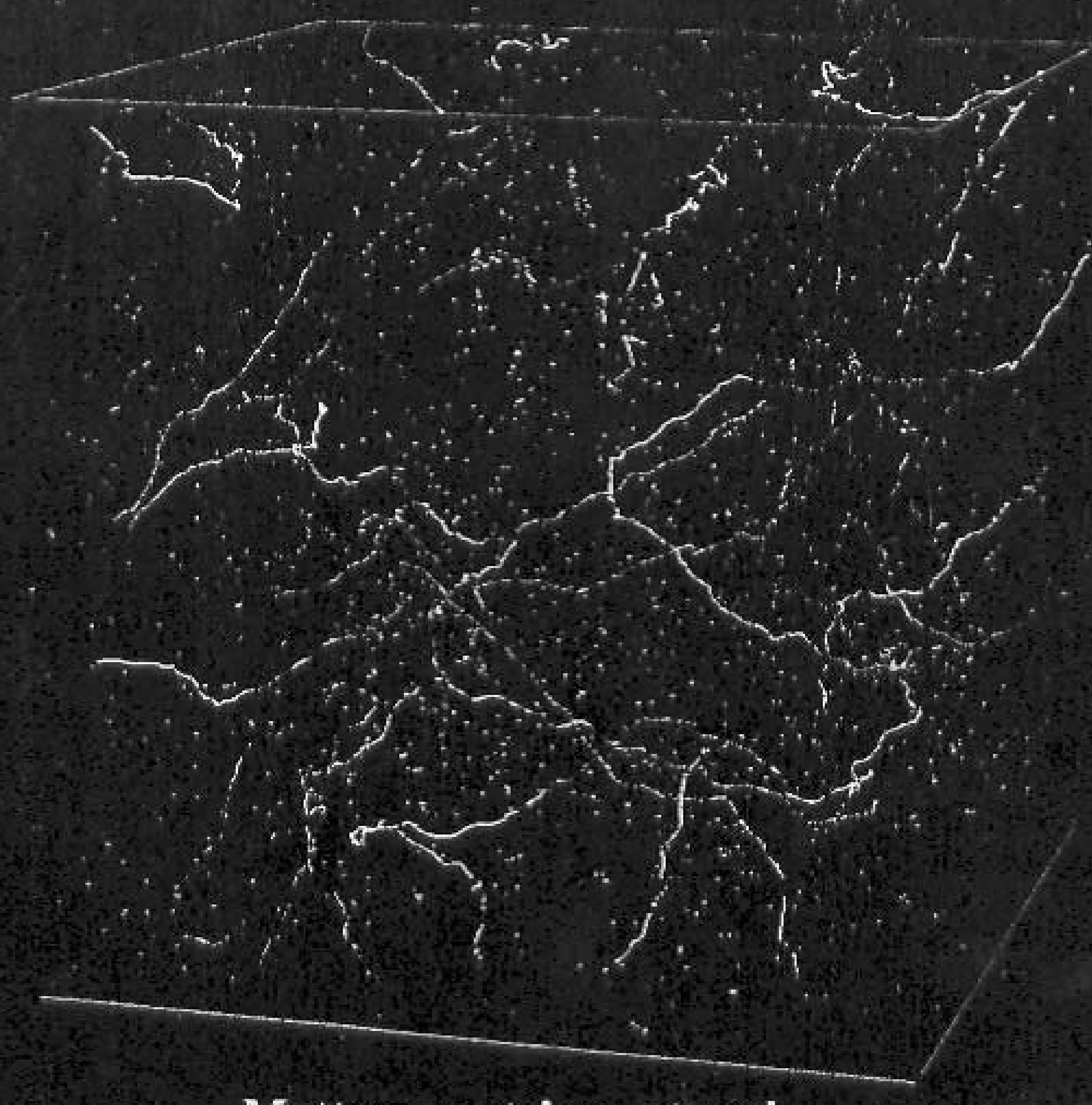
Global
$c = 0.57. \ \Sigma = 1.1$



☞ All field theory simulations are 'flat space' simulations from the point of view of small-scale structures!



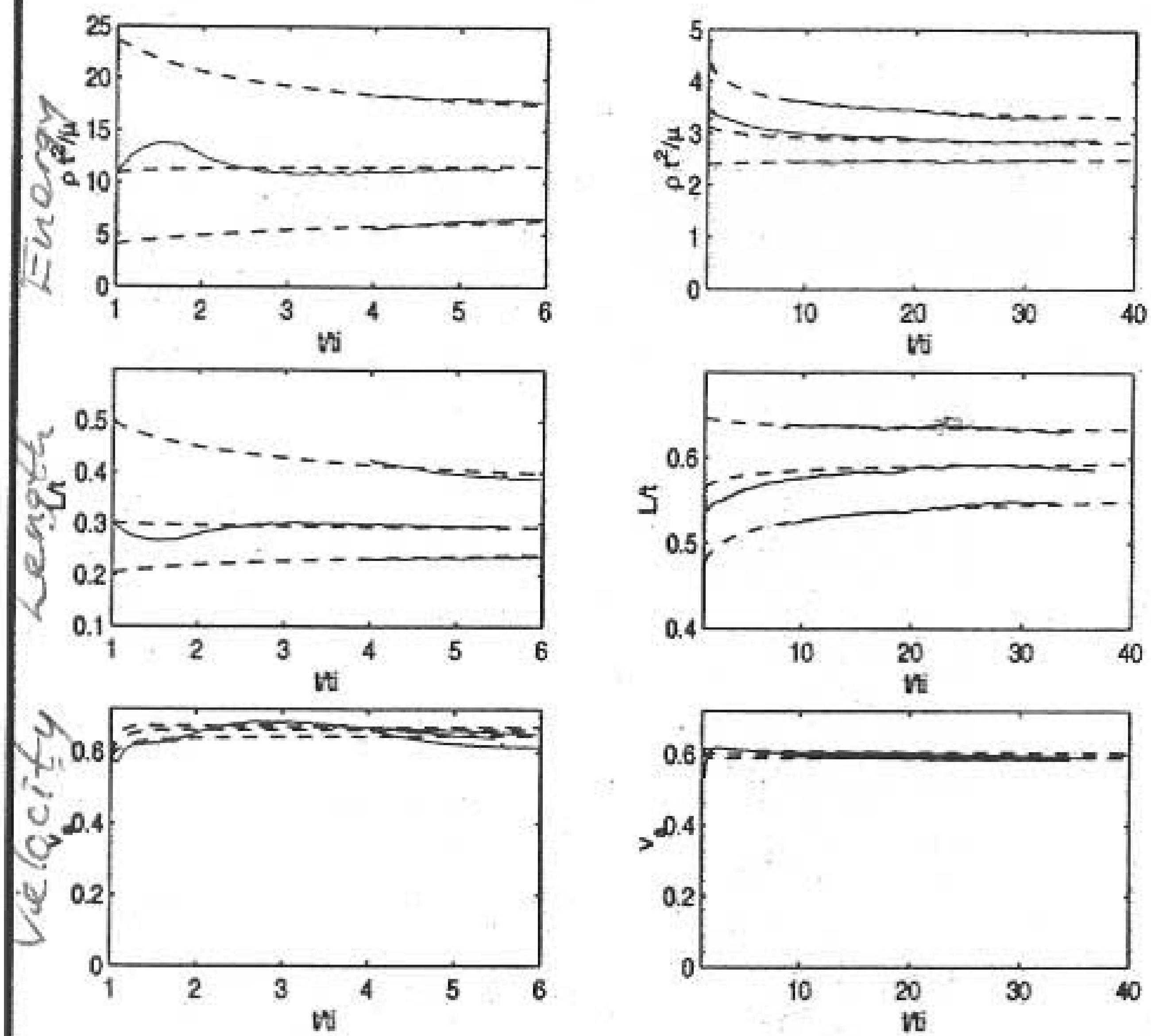
Radiation era string network



Matter era string network

SCALING PROPERTIES

☆ Testing the velocity-dependent one-scale model...

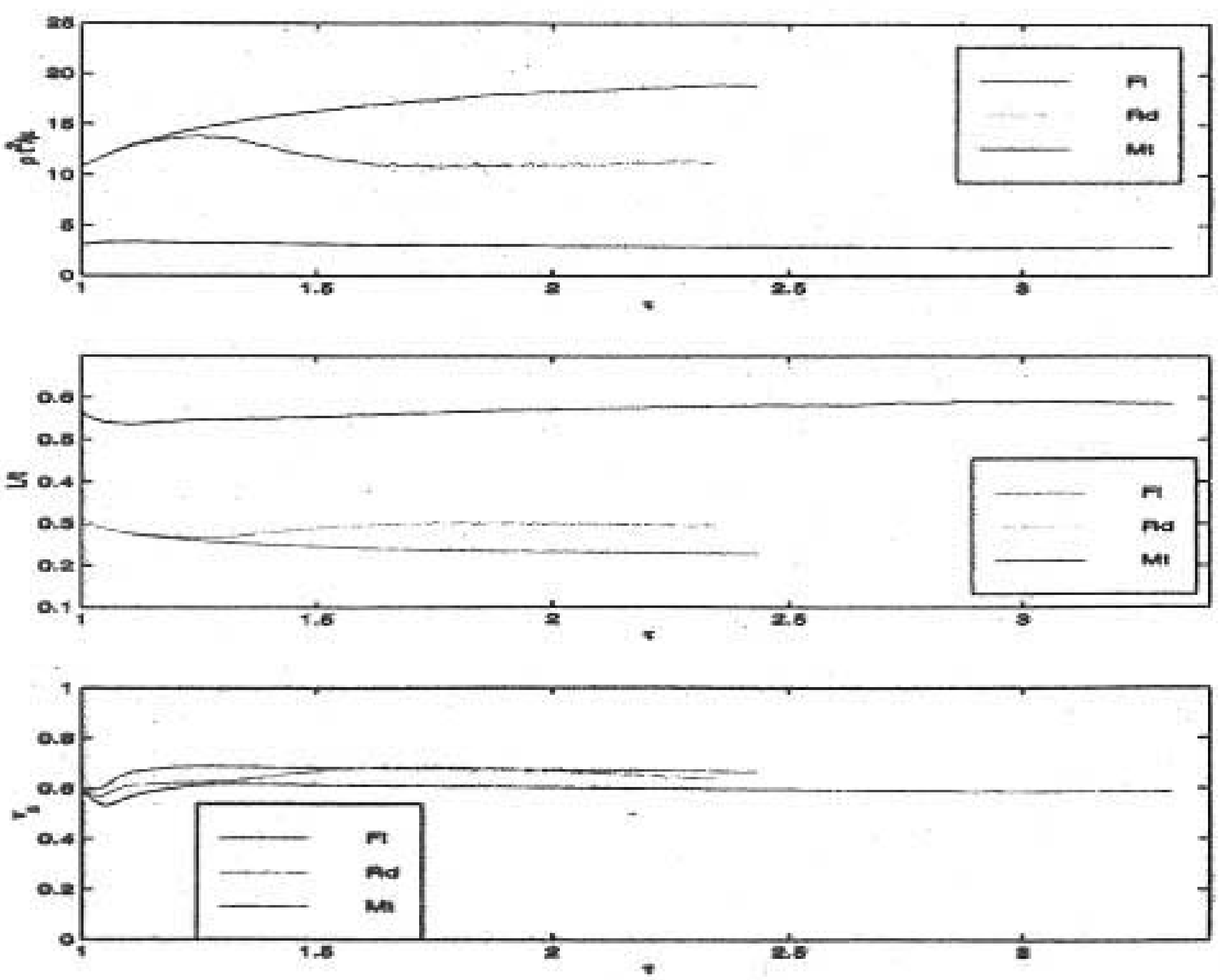


☞ Excellent fit to the results, with fixed $\tilde{c}$:

$\tilde{c} = 0.23 \pm 0.04$

☞ Changes to scaling values (effect of the much better resolution).

☆ What about Minkowski space?



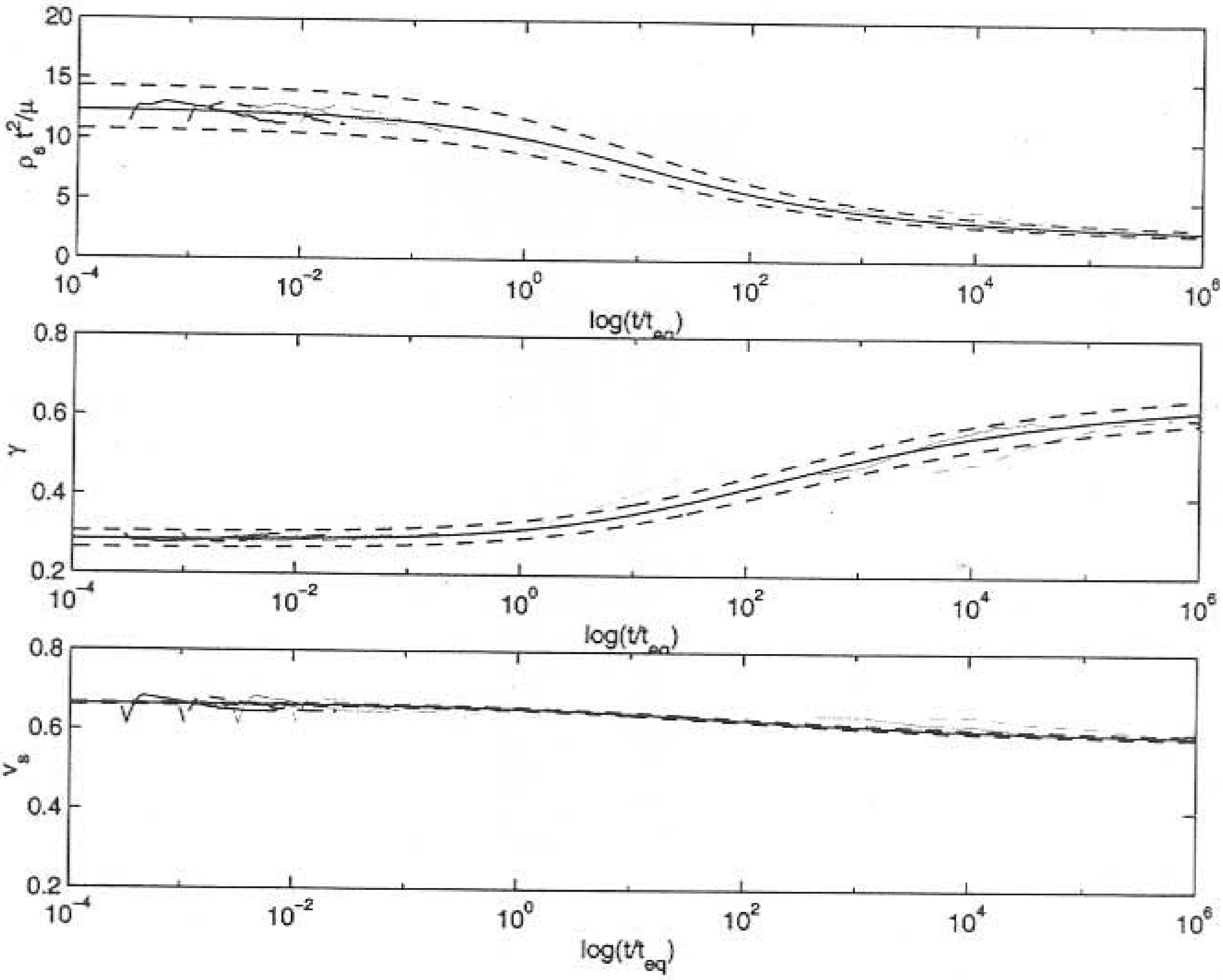
☞ The scaling behaviour is qualitatively different:

$\tilde{c}_{flat} = 0.57 \pm 0.04$

$\tilde{c}_{exp} = 0.23 \pm 0.04$

☞ Why is this? Why should we care?

THE TRANSITION EPOCH



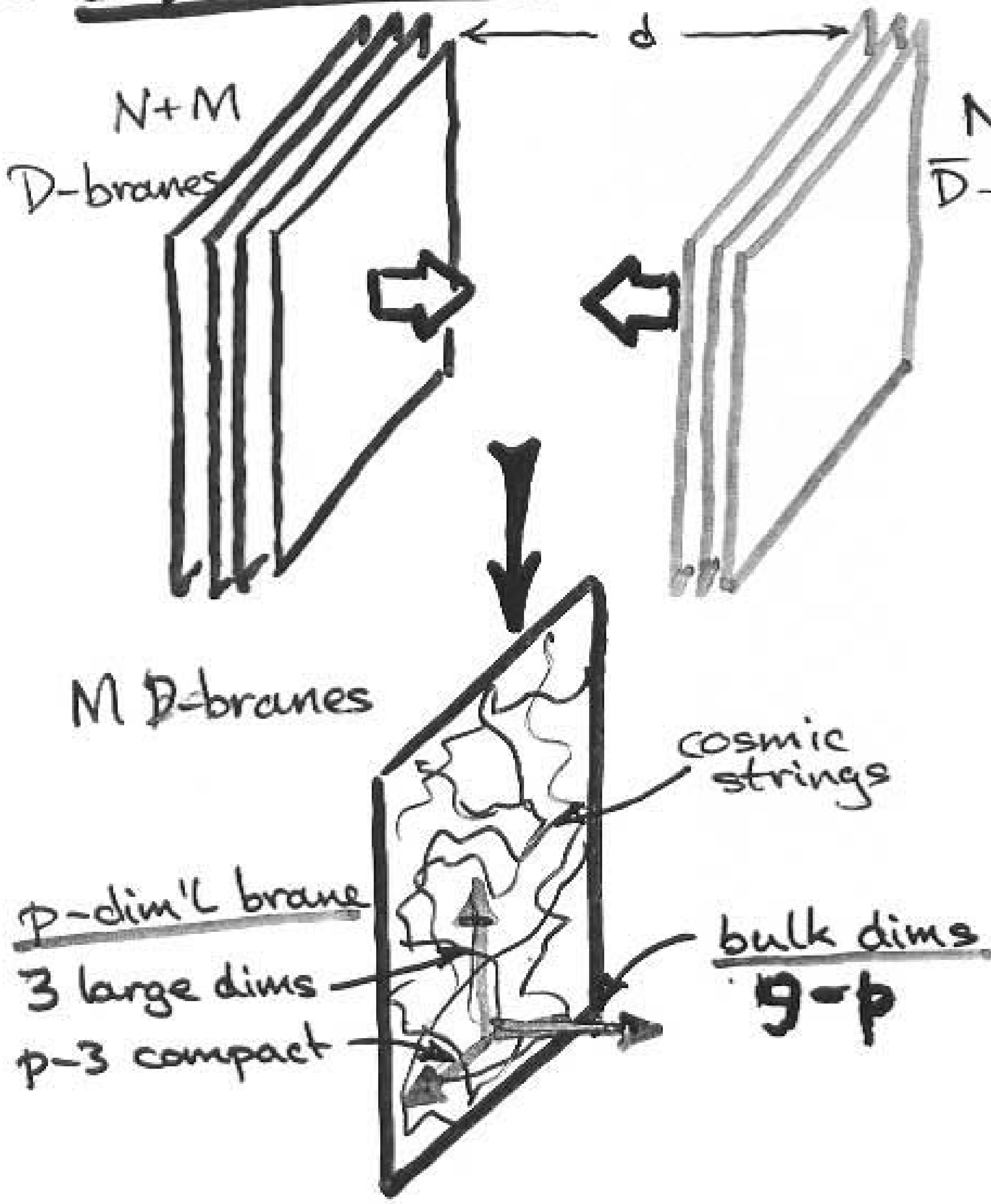
- The transition is very slow, as predicted
  (eg, Martins & Shellard '96)
- The velocity-dependent one-scale model provides an excellent fit (without any free parameters) to the large-scale results.
- Three different timescales in the problem:
  - change of expansion rate
  - relaxation of large-scale properties
  - relaxation of small-scale structures

Brane inflation & cosmic strings

★ $D\bar{D}$ model

Cf. Fernando Quevedo lecture

Refs: Jones, Stoica, Tye 2002 hep-th/0303269
Copeland, Myers & Polchinski, 2003 hep-th/0312067



- Branes move slowly together
- Inflation occurs (distance apart ⇔ inflaton)
- Tachyonic reheating as branes collide & annihilate.
- Cosmic strings inevitably form

★ Alternative models

$D\bar{D}$ collision
D3 – D7 collision
D4 – D6 intersecting branes

KLMT

eg. hep-th/0308055

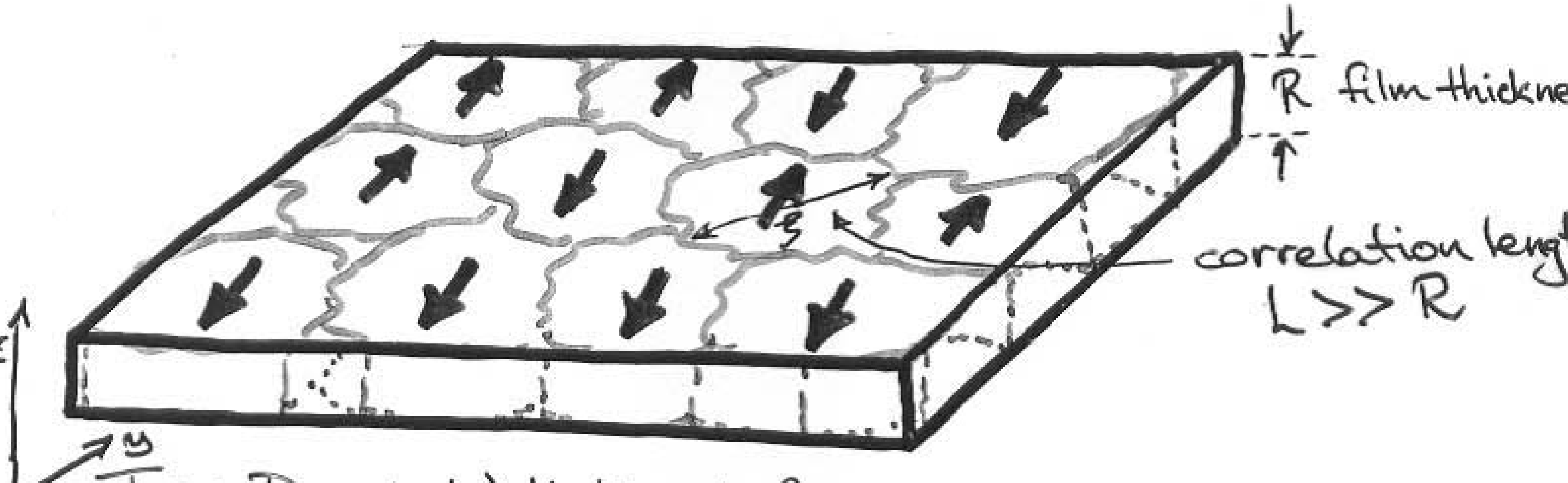
★ Why strings?

- Only co-dimension 2 branes can form ie D(p-2)
- { Kibble mechanism ensures they must form
- { Compactification of all but 3 large dims.

implies D(p-2) branes are effectively cosmic strings

Strings in Branes

★ D=3 analogue: DW formation in a thin film



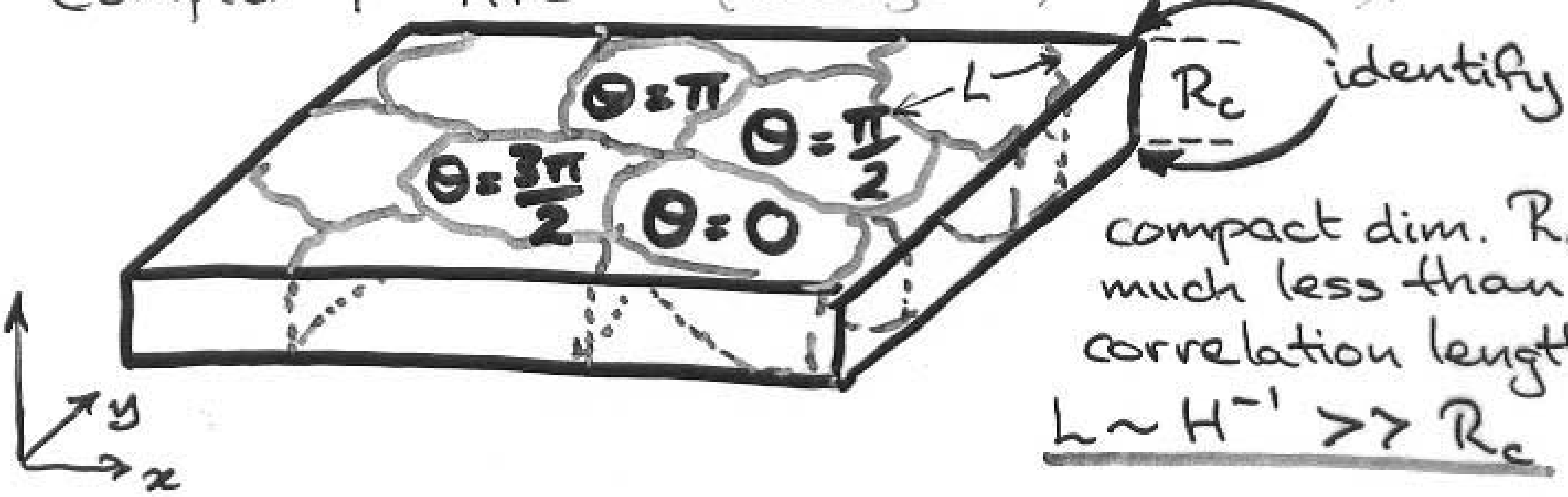
True Domain Wall dim $\doteq 2$

Effective DW dim. $= 2-1 = 1$ in two large dims.

In periodic case, DW tubes equiv. 1D strings

★ D=4 example: $U(1) \to I$ (defect co-dim. 2)

Complex $\phi = |\phi| e^{i\Theta}$ (tachyon potential).

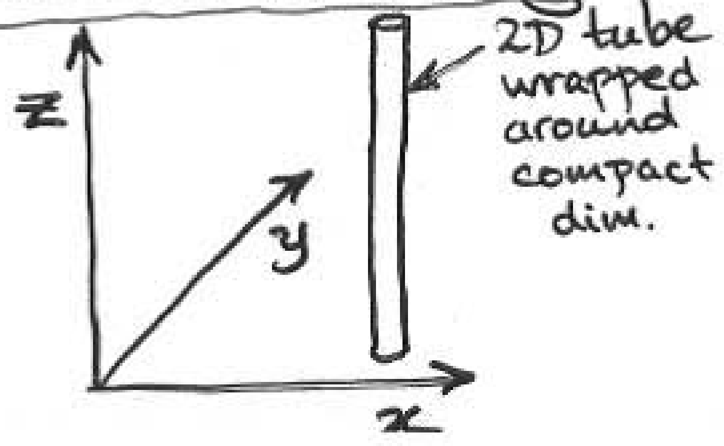


compact dim. R_c much less than correlation length L

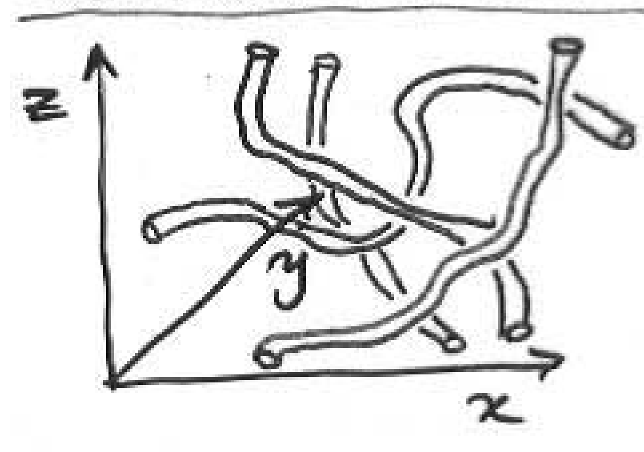
$L \sim H^{-1} >> R_c$

3D ordinary space

z-directed string



General network



Strings in Branes

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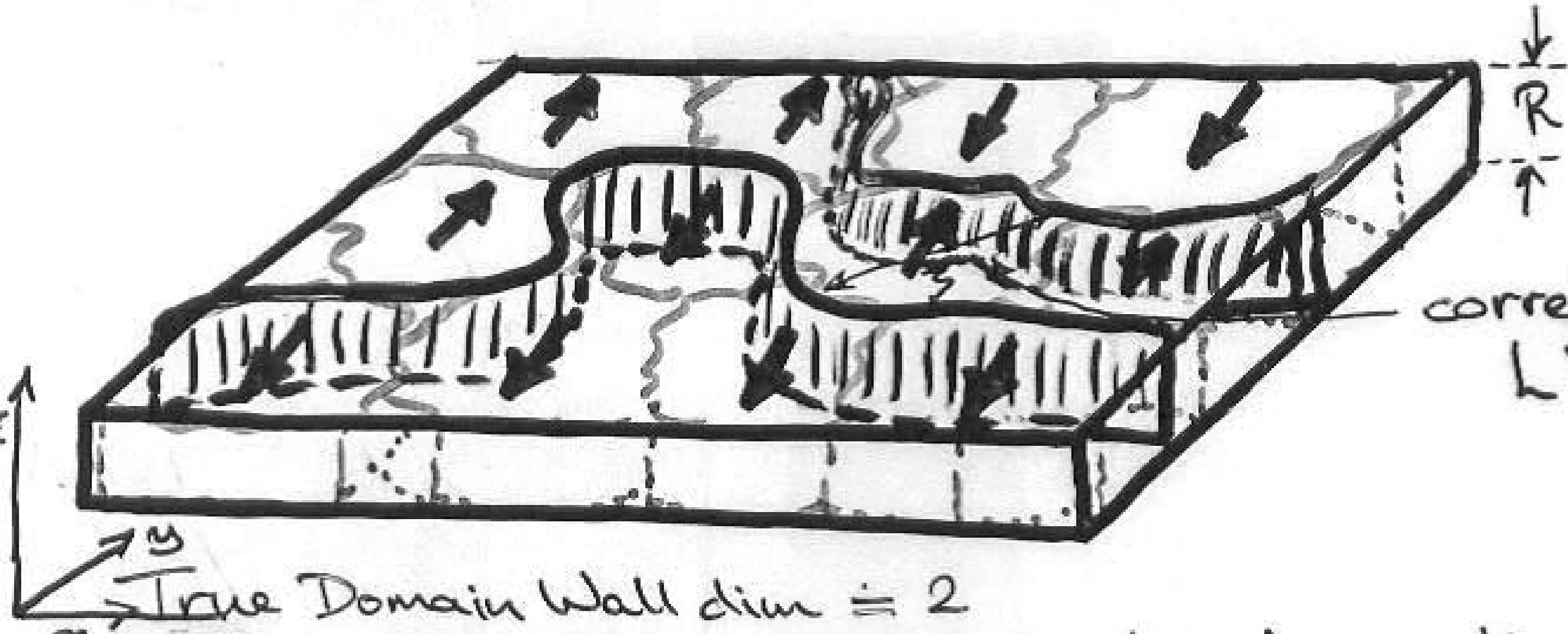

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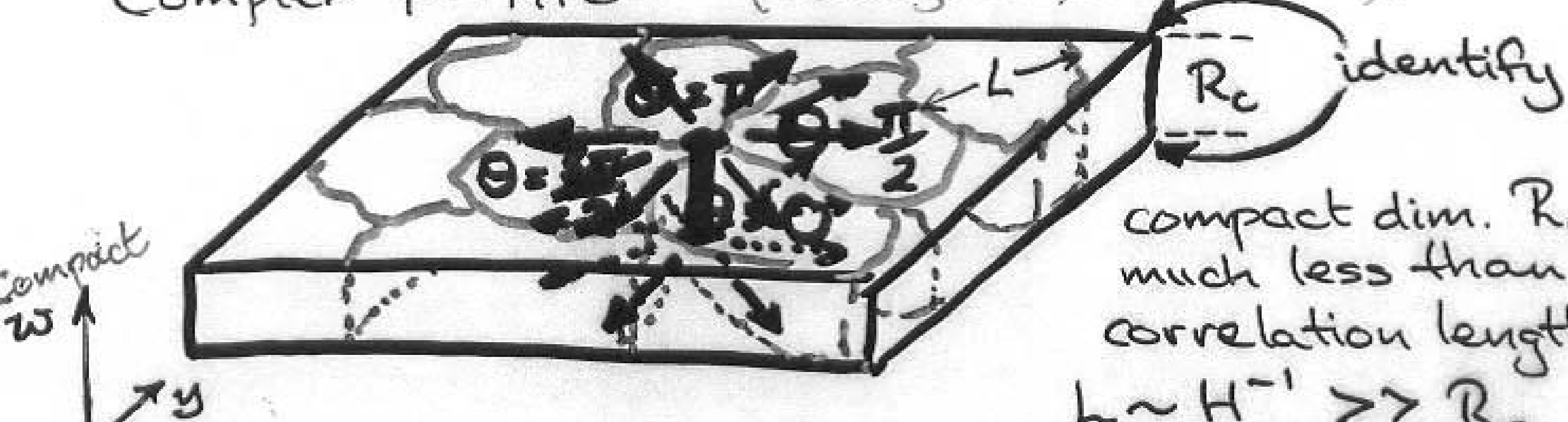

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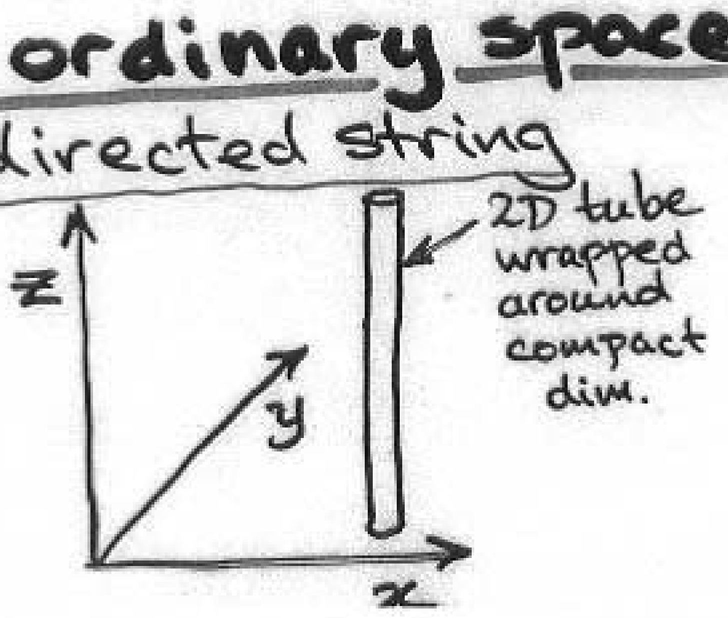

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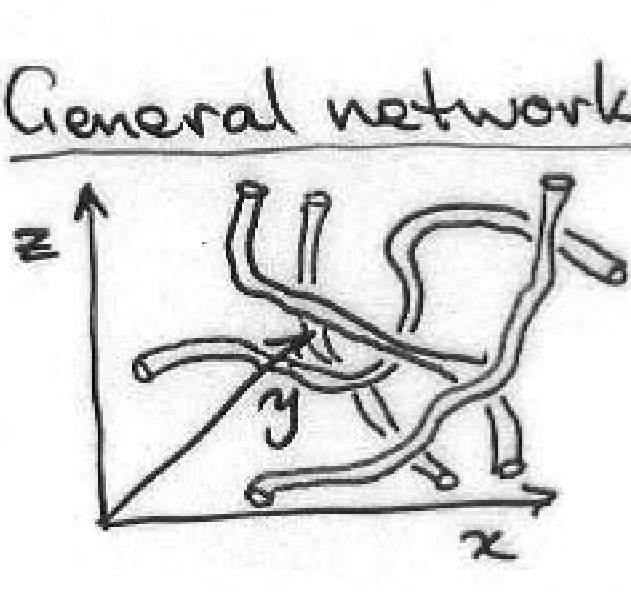
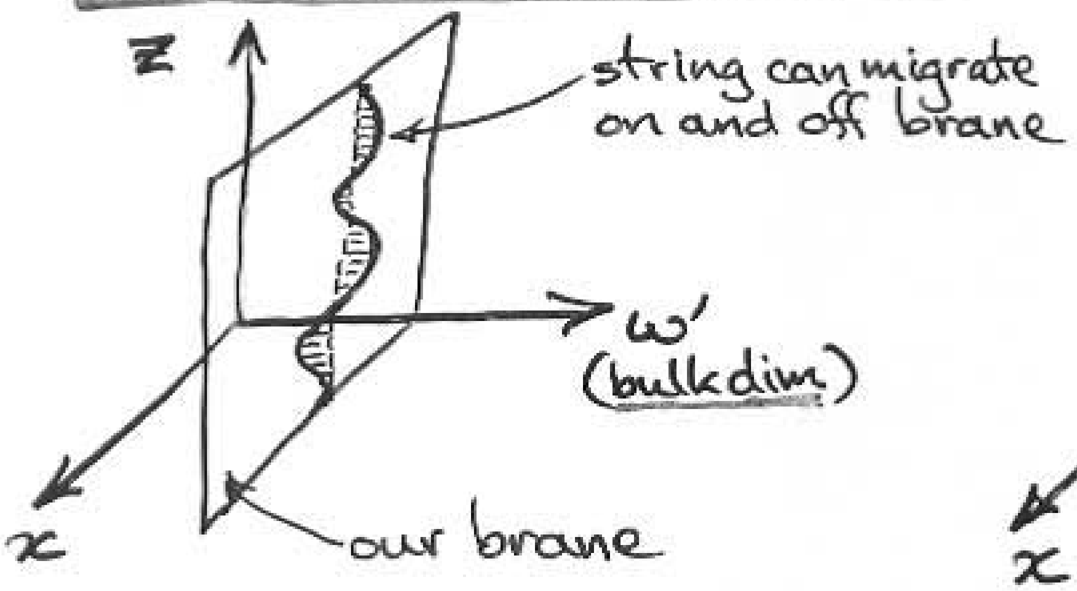


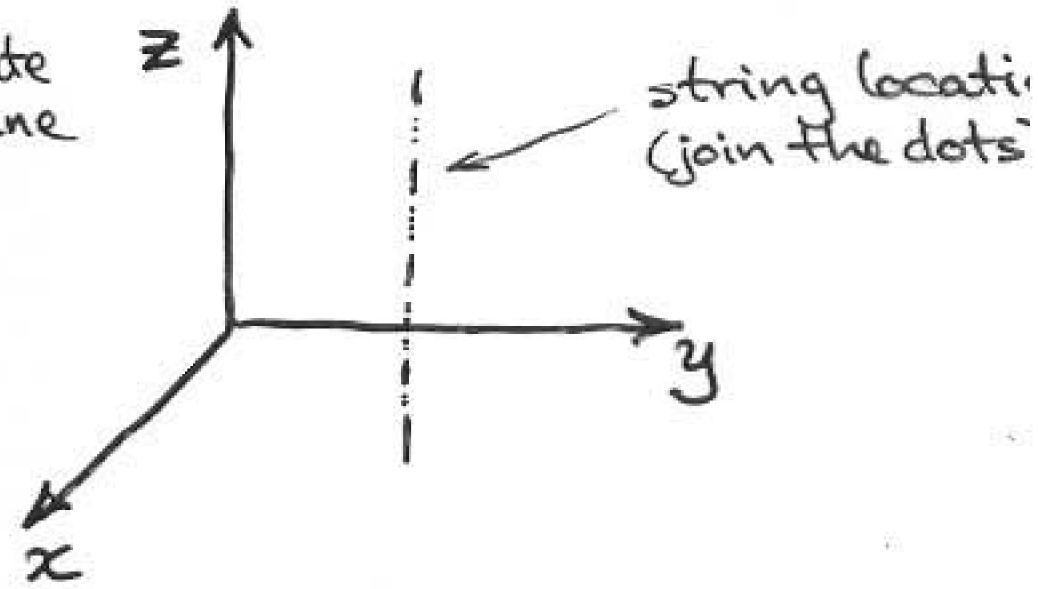
Strings & the Bulk

Strings live in a $D = 19 - p + 3$ dim'l space
(i.e. $D - 3 = 19 - p$ compact bulk dims + large 3D)

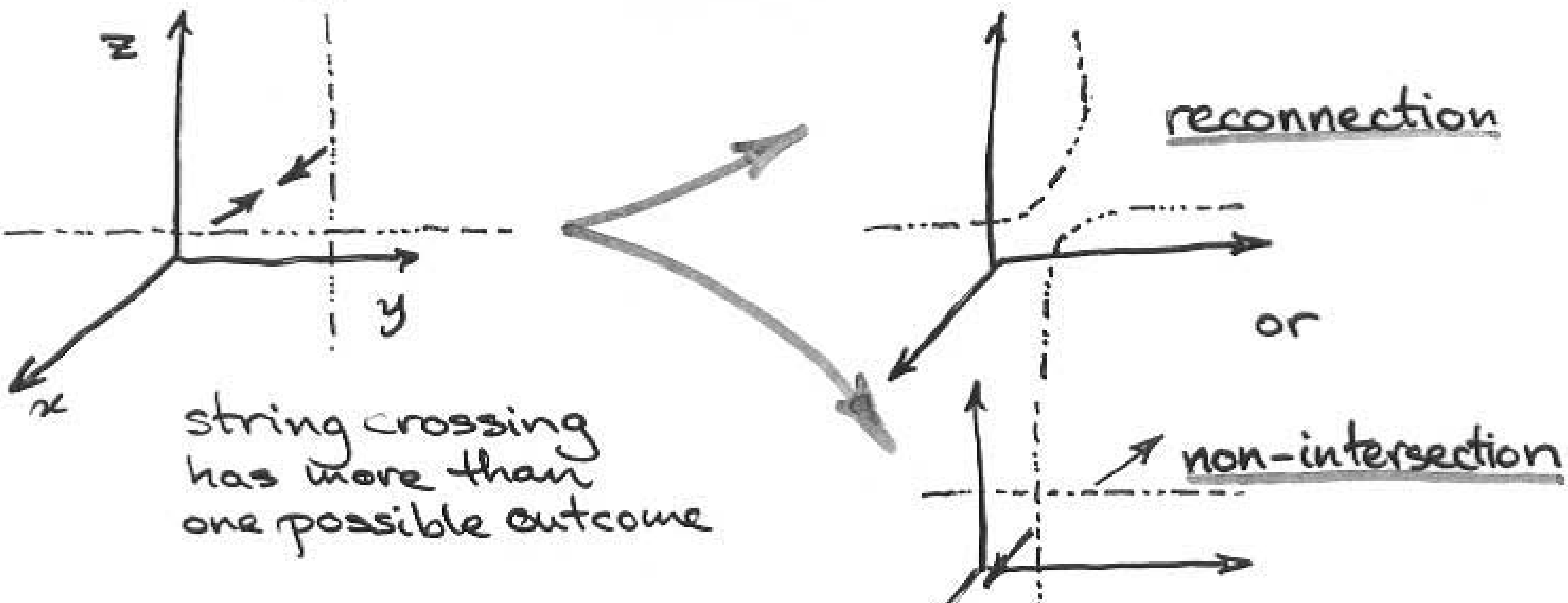
★ z-directed string

Include bulk dimension | Ordinary 3D space





★ String crossing in 3D



★ Reconnection probability

Proportional to string collision x-sect σ over compact bulk volume

$$P \approx \left(\frac{\delta}{R_c}\right)^{D-3} \sim (M_s R_c)^{3-D}$$

where $\delta \sim M_s^{-1}$ (superstring scale) – "string capture width"

Caveat: Effective reconnection prob. $P_{eff} \neq P$

due to small scale structure eg. $P_{eff} \sim \sqrt{P}$ (as $P < 0.3$)

$D \geqslant 3$ Cosmic Strings

Avgoustidis & EPS, 2004

D+1 spacetime background

$$ds^2 = a^2(\tau)\left[d\tau^2 + d\mathbf{x}^2\right] + b^2(\tau)\, d\boldsymbol{\ell}^2$$

with spatial splitting $\mathbf{y} = (\mathbf{x}, \boldsymbol{\ell})$

3dim'l FRW   D−3 bulk.

★ Microphysical equations

$$\ddot{\mathbf{x}} + \left[\frac{\dot a}{a}\left(1-\dot{\mathbf{x}}^2-\left(\frac{\mathbf{x}'}{\epsilon}\right)^2\right) + \frac{b\dot b}{a^2}\left(\dot{\boldsymbol{\ell}}^2-\left(\frac{\boldsymbol{\ell}'}{\epsilon}\right)^2\right)\right]\dot{\mathbf{x}} = \frac{1}{\epsilon}\left(\frac{\mathbf{x}'}{\epsilon}\right)'$$

$$\ddot{\boldsymbol{\ell}} + \left[2\frac{\dot b}{b} - \frac{\dot a}{a}\left(1-\dot{\mathbf{x}}^2-\left(\frac{\mathbf{x}'}{\epsilon}\right)^2\right) + \frac{b\dot b}{a^2}\left(\dot{\boldsymbol{\ell}}^2-\left(\frac{\boldsymbol{\ell}'}{\epsilon}\right)^2\right)\right]\dot{\boldsymbol{\ell}} = \frac{1}{\epsilon}\left(\frac{\boldsymbol{\ell}'}{\epsilon}\right)'$$

$$\dot\epsilon = -\epsilon\left[\frac{\dot a}{a}\left(1+\dot{\mathbf{x}}^2-\left(\frac{\mathbf{x}'}{\epsilon}\right)^2\right) + \frac{b\dot b}{a^2}\left(\dot{\boldsymbol{\ell}}^2-\left(\frac{\boldsymbol{\ell}'}{\epsilon}\right)^2\right)\right]$$

★ Averaged quantities (b=1)

- Energy/correlation length

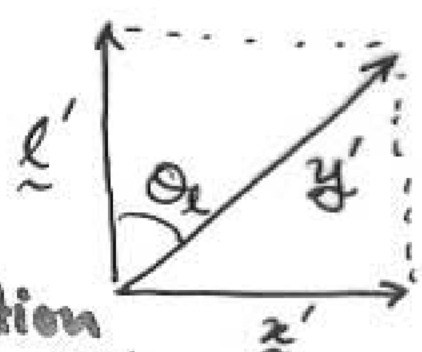
$$E = \mu a \int \epsilon\, d\sigma \qquad \rho = \frac{\mu}{L^{D-1}}$$

- Velocities $v^2 = v_x^2 + v_\ell^2$

$$v_x^2 = \langle \dot{\mathbf{x}}^2 \rangle \qquad v_\ell^2 = \langle \dot{\boldsymbol{\ell}}^2 \rangle$$

- Orientation angle

$$\cos^2\theta_\ell \equiv \left\langle \frac{\boldsymbol{\ell}'^2}{\boldsymbol{\ell}'^2 + \mathbf{x}'^2} \right\rangle \approx \bar\mu_\ell$$



extra dim. renormalisation

Equipartition approx. suggests $(\overset{\mathbf{x}'}{\boldsymbol{\ell}'} \leftrightarrow \overset{\dot{\mathbf{x}}}{\dot{\boldsymbol{\ell}}})$

$$\left\langle \frac{\ell'^2}{\ell'^2 + x'^2} \right\rangle \approx \left\langle \frac{\dot\ell^2}{\dot\ell^2 + \dot x^2} \right\rangle \approx \frac{v_\ell^2}{v^2}$$

$D \geqslant 3$ VOS MODEL

Correlation length

$$\frac{dL}{dt} = \frac{\dot{a}}{a}\frac{2L}{(D-1)}\left[(1-v^2) + \frac{1}{2}\frac{v_\ell^2}{v^2}(1-2v^2)\right] + \frac{2\tilde{c}}{(D-1)} P_{\text{eff}}\, v$$

3D velocity

$$\frac{dv_x}{dt} = (1-v^2)\left[\frac{k_x}{L} - 2\frac{\dot{a}}{a}v_x\left(1-\frac{v_\ell^2}{v^2}\right)\right]$$

Bulk velocity

$$\frac{dv_\ell}{dt} = (1-v^2)\frac{k_\ell}{L} - 2\frac{\dot{a}}{a}v_\ell(1-2v^2)\left(1-\frac{v_\ell^2}{v^2}\right)$$

Additional constraint $kv = k_x v_x + k_\ell v_\ell$

e.g. $k_x = \frac{v_{xc}}{v_c}k(v)$.

$k_\ell = \frac{v_{\ell c}}{v_c}k(v)$.

★ Velocity behaviour

- Damping terms

With $P_{\text{eff}} \to 0$ flat space limit: $v^2 \to \frac{1}{2}$

Hence

$$\left.\frac{dv_\ell}{dt}\right|_{\text{damp}} \propto \frac{\dot{a}}{a}(1-2v^2)v_\ell << \left.\frac{dv_x}{dt}\right|_{\text{damp}} \propto \frac{\dot{a}}{a}(1-v^2)v_x$$

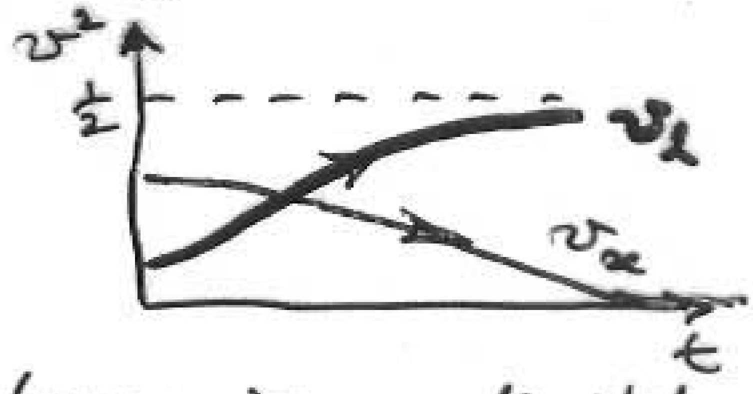
- 1. Generic solution appears to have:

$$v_\ell^2 \to \frac{1}{2} \quad \text{and} \quad v_x^2 \to 0$$

I.e. strings stop moving in 3D

Interpret as renorm. $\bar{\mu}_\ell$?

— pathological!

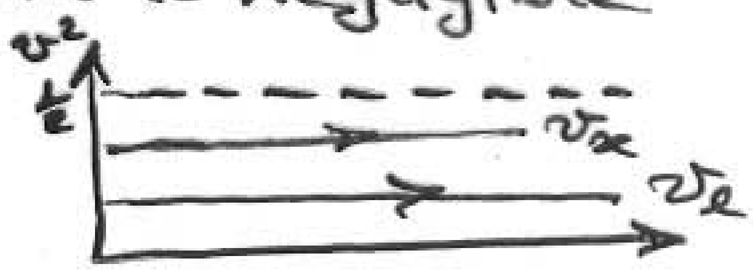


- 2. Unless $\frac{k_\ell}{L}$ source term is negligible

Then

$$v_\ell^2 \to \text{const.}$$

$$v_x^2 \to \frac{1}{2} - v_\ell^2$$



Brane inflation strings

★ Example ingredients (D5-D5, Jones et al 2003)

- Compactification radius $R_c \gtrsim \frac{1}{M_s}$ $(R_c M_s \simeq 30)$
  $M_s \approx 10^{14}\,\mathrm{GeV} \Rightarrow G\mu \equiv \left(\frac{M_s}{M_p}\right)^2 \simeq 10^{-8}$.
- Effective string "width": $\delta \sim \frac{1}{M_s}$ (capture radius)
- Hubble radius during inflation $H \approx M_s^2/M_p$
- Initial correlation length $L \sim H^{-1} >> R_c$

★ String formation

- Kibble mechanism produces strings (wrapped branes) in 3 large dimensions

$$\rho \simeq \frac{\mu}{L^2} \quad \text{(as before)}$$

- Small curvature projection in bulk dimensions

$$\frac{k_\ell}{L} = \left\langle \frac{\underset{\sim}{\ell}\cdot\underset{\sim}{u}\,(1-\underset{\sim}{y}^2)}{v_\ell(1-v^2)} \right\rangle \ll \frac{k_x}{L}$$

Initial upper limit $\frac{k_\ell}{k_x} \approx \mathcal{O}\left(\frac{R_c}{L}\right) < 0.15$
i.e. below critical value for $v_\ell = \text{const}$, $v_x \neq 0$ so

★ String evolution

- Initial velocity preserved $v_\ell = \text{const.}$ (bulk
  - Negligible damping (friction or radiation backreaction?)
  - Brane collision or thermal effects induce significant v_ℓ?
- 3D velocity $v_x^2 \approx \frac{1}{2} - v_\ell^2$ (move more slowly)
- String density significantly enhanced.

$$\rho \approx (P_{eff})^{-2}\rho_0$$

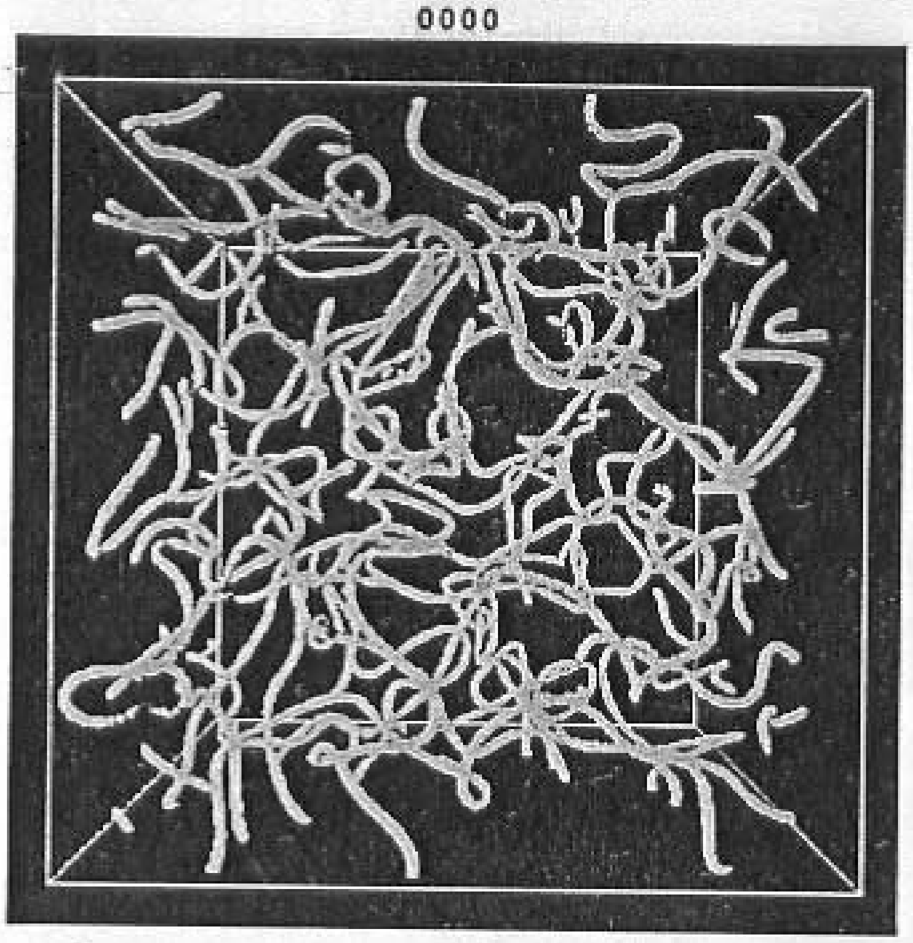
intercommuting prob. effect under investigation

- similar scaling solns to 3D

★ Many open questions

complex string models

0000



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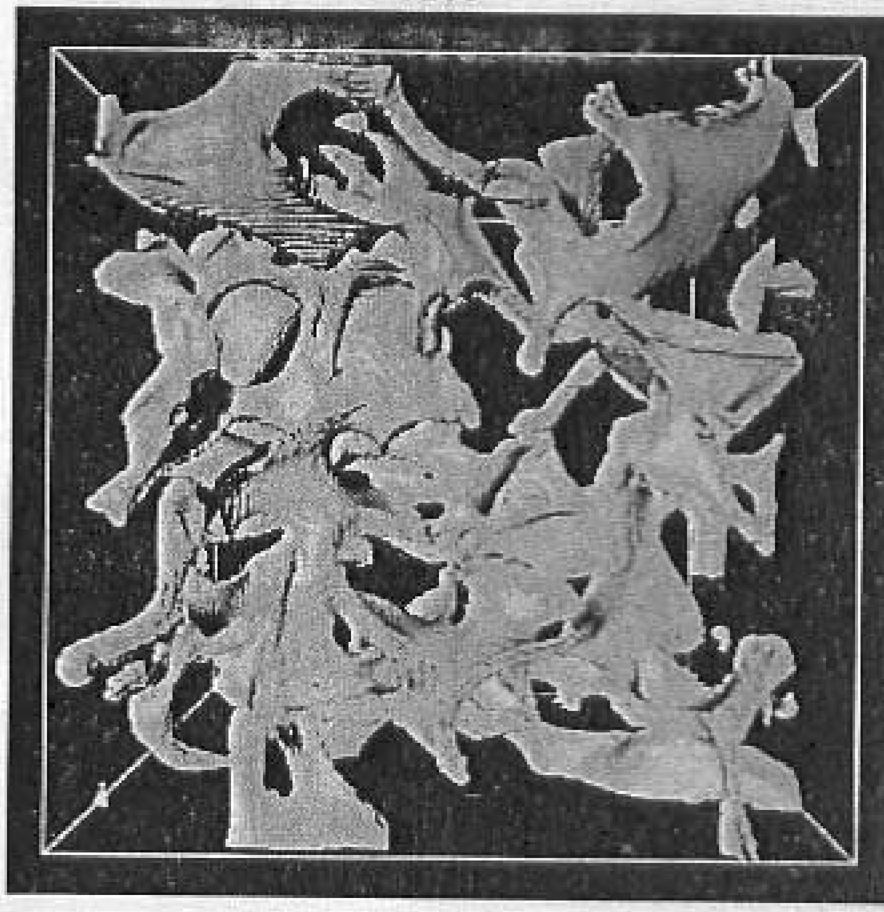

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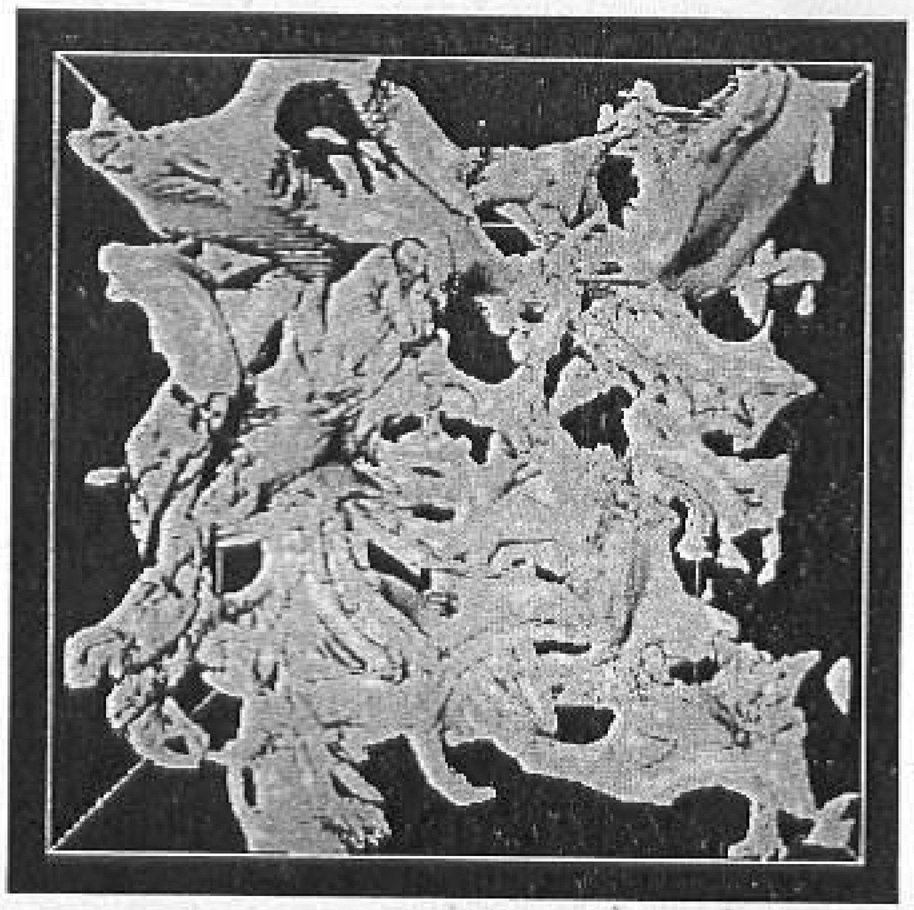

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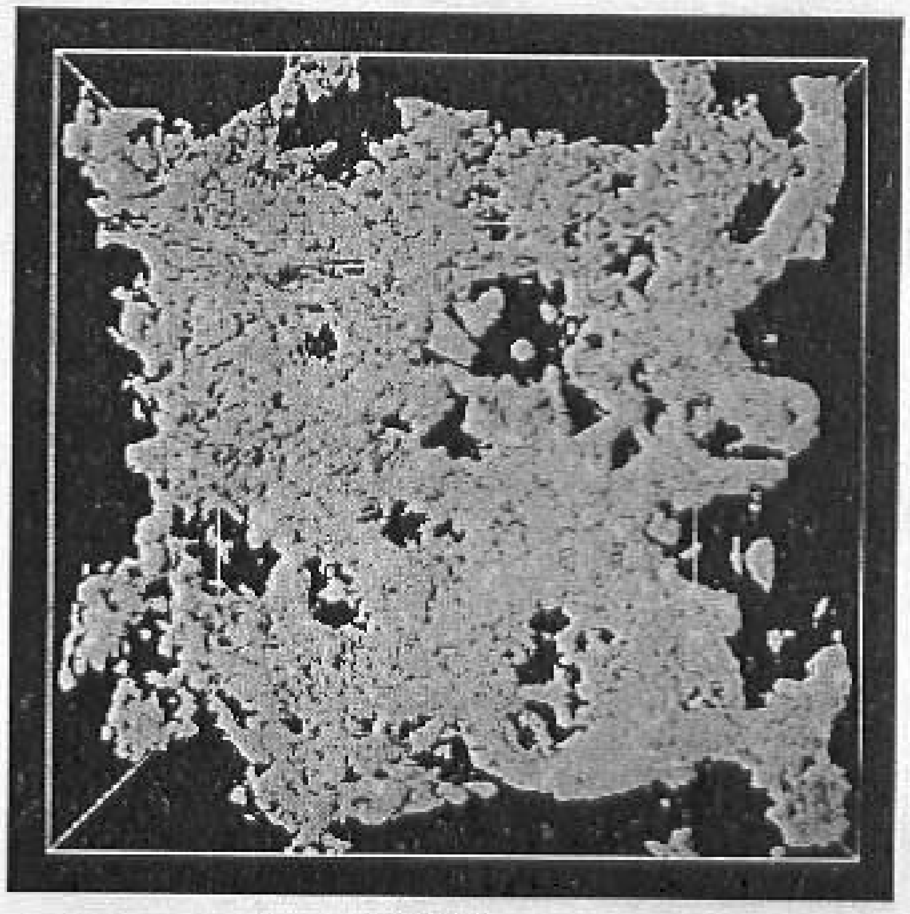

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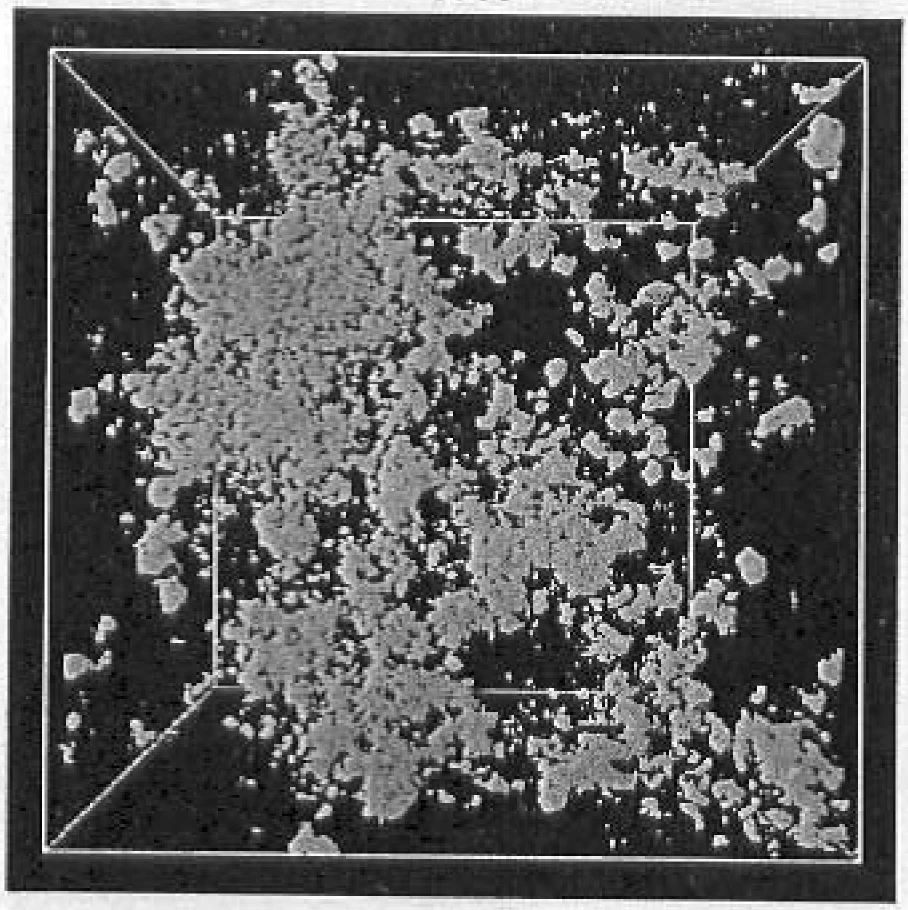

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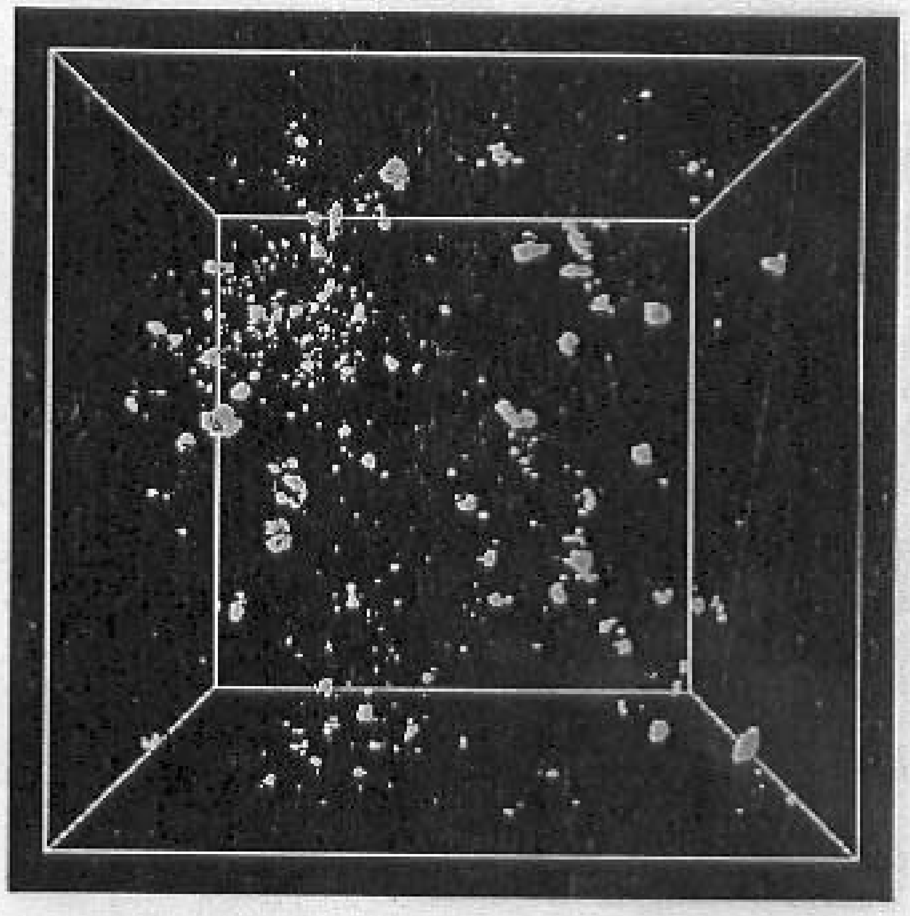


The Conical Geometry

Straight string solution

$$ds^2 = dt^2 - dz^2 - dr'^2 - r'^2 d\theta'^2$$

$$0 \le \theta' < 2\pi(1 - 4G\mu)$$

Deficit angle

$$\underline{\underline{\Delta = 8\pi G\mu}}$$

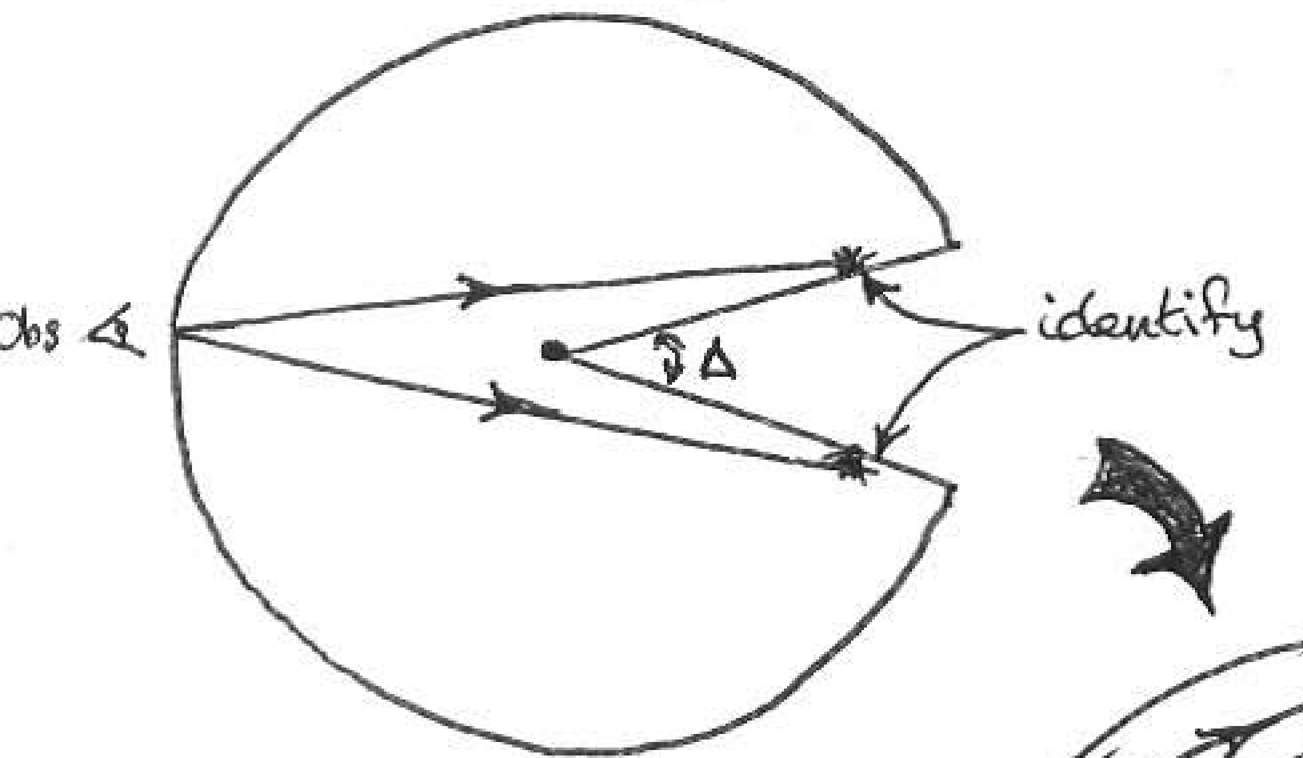
Double images

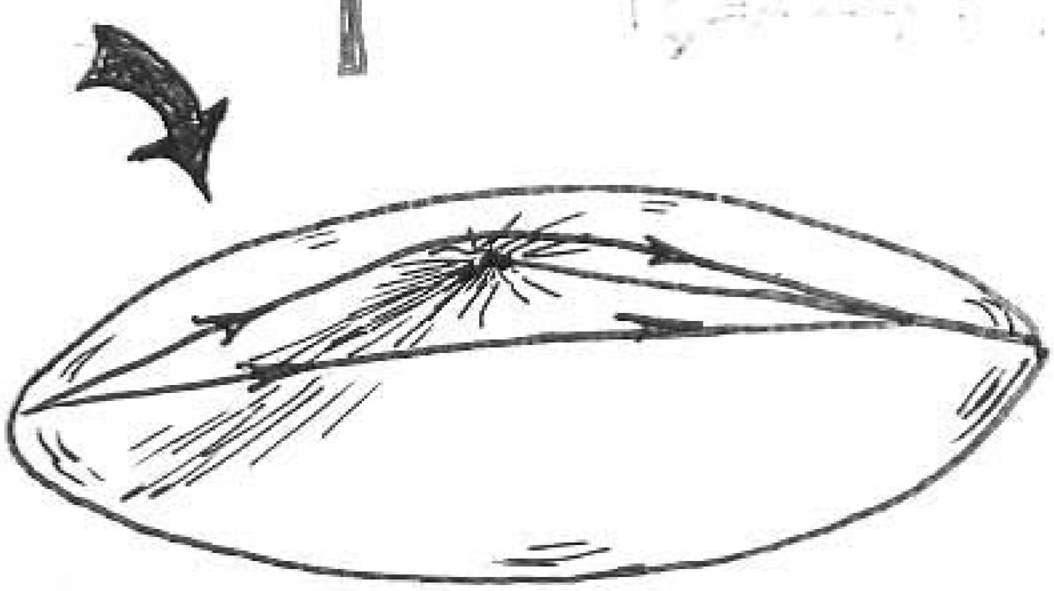
$$G\mu \sim \left(\frac{\eta}{m_{pl}}\right)^2$$

$p_z = -\rho \ , \ p_x = p_y = 0$

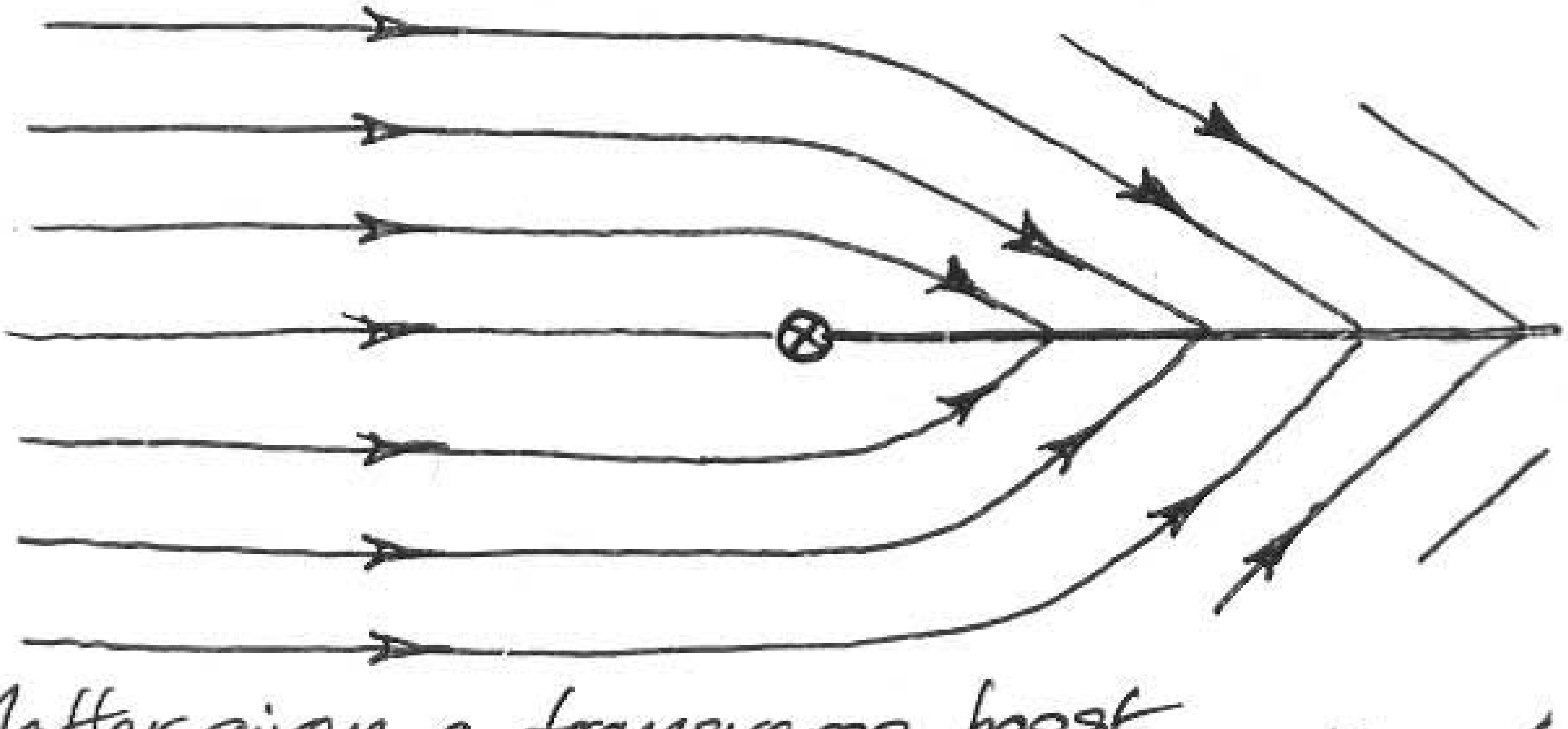
Newtonian potential.

$$\nabla^2 \Phi = 4\pi G(\rho + p_1 + p_2 + p_3) = 0$$





Wake formation

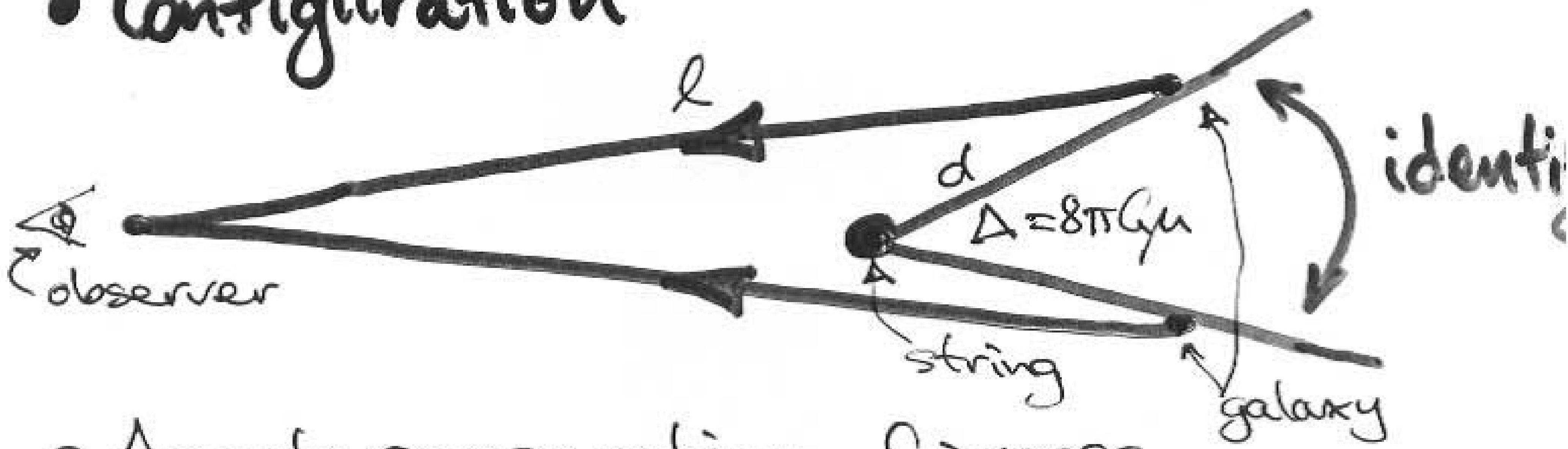


Matter given a transverse boost

$$u_i = 4\pi G\mu v_s \gamma_s$$

Gravitational Lensing

- Configuration



- Angular separation of images

$$\delta\varphi \approx 8\pi G\mu \frac{\ell}{\ell + d}$$

GUTs
$G\mu \approx 10^{-6}$
$\delta\varphi \approx 5''$

- Both images are <u>identical</u>
  - ★ only means w/o distortions
  - ★ v. small freq. shift due to string vel.

- Lensing probability for sources at $z \sim 1$

$$P(z \sim 1) \sim 100\, G\mu$$

- <u>Cosmic string discovery?</u>
  - Naples group (Sazhin 2003) report candidate CSL-1 a possible string lensin

$$\delta\varphi \approx 2'' \rightarrow G\mu \approx 4 \times 10^{-7} \quad (z = 0..$$

  - Follow-up observations at higher res. planne
    - should see other lensed galaxies within 1'
      (Huterer & Vach. 200

  - Prelim. Japanese search for $\delta\varphi = 5''$ string lenses yielded no sig. evidence
    (Shirasaki et al 2003)

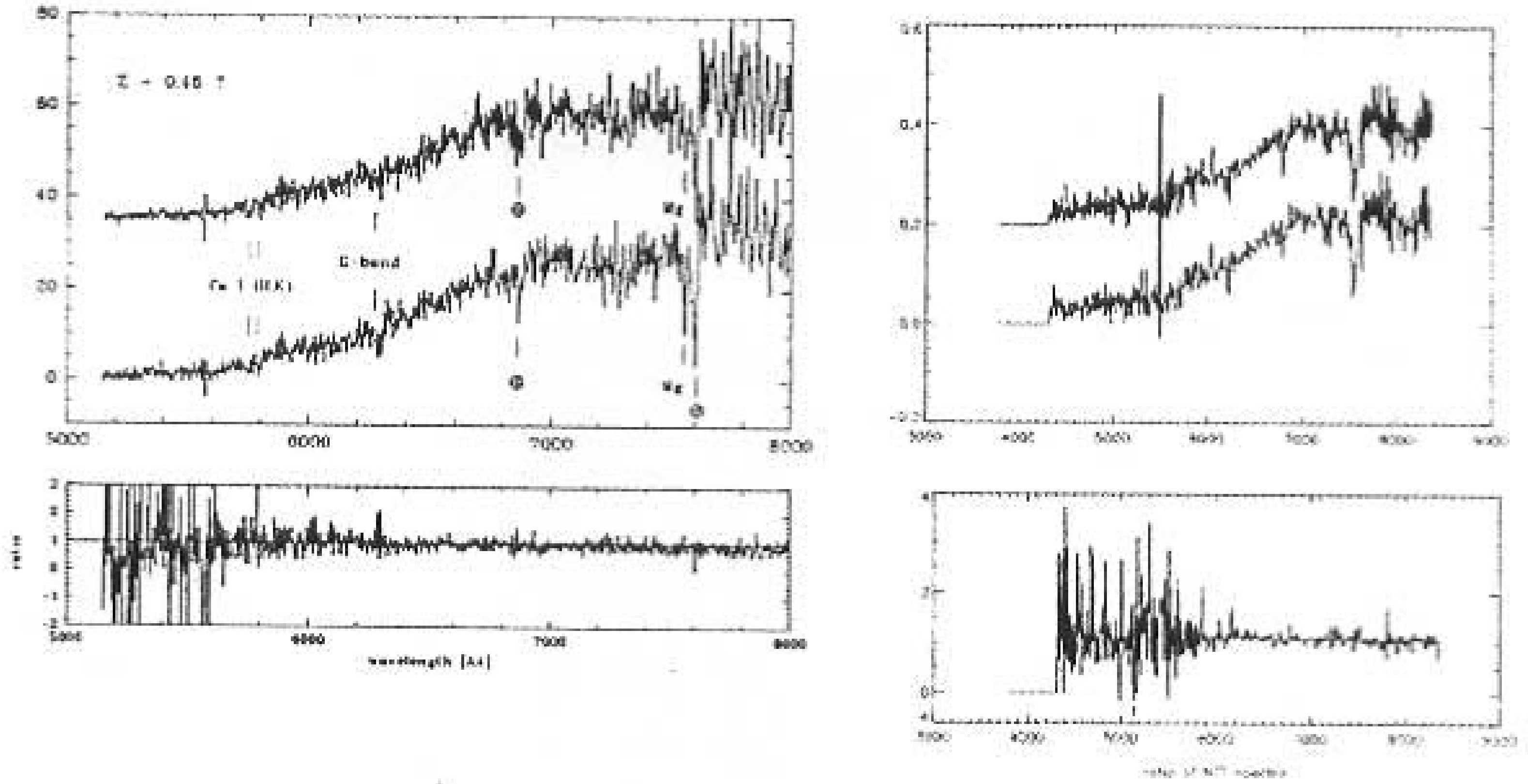


Figure 3. Left panel: TNG spectra of the components of CSL-1 . Right panel: NTT spectra. A vertical shift was introduced for visualization purposes only. Lower panels: corresponding ratios obtained by dividing the spectra of the two components.

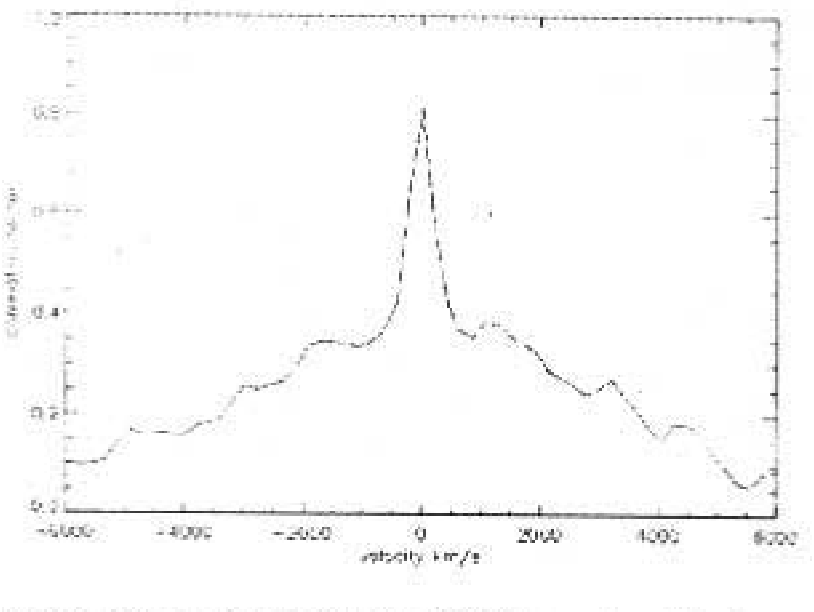


Figure 4. Correlation coefficient of NTT spectra of the two components of CSL-1 with background profile removed.

Figure 5. Solid line: observed H band profile for CSL-1 ; dashed line: profile expected in the H band following the procedure described in the text (dust index n=1).

Kpc, it would be by far the largest such structure ever observed; second, in order to produce identical and symmetric sources it should have a perfectly tailored shape. Furthermore, even in such unlikely case, such an obscuring layer would fail to reproduce the light profiles observed at the various wavelengths.

To prove it quantitatively we performed a simple simulation. The underlying hypothetical galaxy was modeled assuming, as previously done, a de Vaucouleurs profile and for the dust lane a standard absorbing law given by $exp(-\tau(x))$, where x is the coordinate along the profile and τ is the geometry factor describing the distribution of dust at a given x: $\tau(x) = \frac{f(x)}{\lambda^n}$. In this formula, n is the so called dust index (cf. Hildebrand (1983); Ferrari (2002); Chini (1984)) which, from optical to radio, assumes values inside the range $1 \div 2$. The above formulae allow us to derive the light profile to be expected in any given band relative to the R frame assumed as template. In Figure 5 we show the expected and the observed H profiles for a dust lane capable to reproduce the dip observed in the R profile.

As an additional test, in order to investigate whether the combined effects of dust extinction and very strong colour gradients could reproduce the observed morphology, we measured colour in the wings and between peaks of the B, V, and R profiles. The results show that colour gradients, if present, are smaller than 0.1 mag and therefore are of no help in explaining the observed morphology by means of a dust lane.

Therefore we are left with only two possible explanations for CSL-1 . Either we are dealing with i) the projection of two giant elliptical galaxies which are identical (at a 99% level of confidence) in terms of magnitudes, colours, morphology and, what is more relevant, also in terms of spectral properties, or ii) we are seeing the effects of an

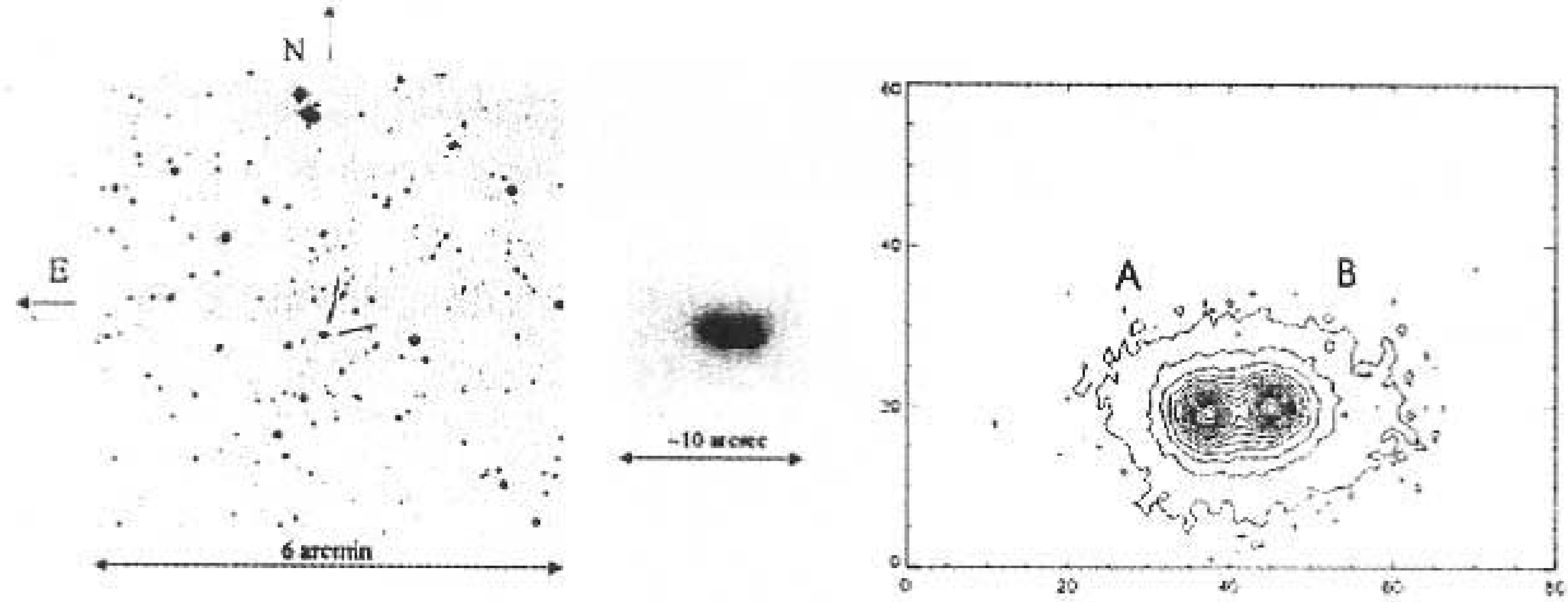


Figure 1. Left panel and central inset: appearance of CSL-1 in the R band. Right panel: 2D contours of CSL-1 from the near IR (λ914) image. Coordinates are in pixels (1 px = $0''.238$) and the two components are labeled A and B as in the text.

Band	FWHM A [arcsec]	FWHM B [arcsec]	FWHM PSF [arcsec]	mag A	mag B	r_e^A [arcsec]	$\frac{r_e^A}{r_e^B}$
B	1.59	1.67	1.14	22.73±.15	22.57±.15		
V	1.59	1.67	1.01	20.95±.13	21.05±.13	6.3	1.4
R	1.98	1.98	0.98	19.67±.20	19.66±.20	3.0	2.5
H	1.19	1.11	0.85				
A753	1.11	1.19	0.87				
A770	1.27	1.27	0.86			7.4	0.6
A791	1.67	1.59	0.97				
A914	1.27	1.27	0.79			8.8	1.4

Table 2. FHWM, magnitudes and effective radii for the two components of CSL-1 . Column 1: photometric band; column 2 and 3: FWHM size of component A and B, respectively; column 4: FWHM of the PSF measured in a region close to CSL-1 ; column 5 and 6: integrated magnitudes of components A and B respectively. These values are provided only for the bands where accurate absolute photometry could be performed. Column 7 and 8: effective radius for the A component and ratio of the effective radii for the two components, respectively. These values are provided only for those bands where the profile was extended enough to allow a reliable fit to a de Vaucouleurs law.

could be performed only for the first candidate (CSL-1), which turned out to be a rather interesting case.

This paper is structured as follows: in Section 2 we summarize the measured photometric and spectroscopic properties of CSL-1 and in Section 3 we discuss the possible explanations of the observables. In Section 4, after introducing some aspects of the string phenomenology, we present our model for the lensing by a cosmic string and the simulation performed in order to assess whether it may explain the strange properties of CSL-1. Finally, in Section 5 we sumarise our results and discuss possible future observations.

2 THE OBSERVED PROPERTIES OF CSL-1

2.1 Morphological and photometric properties

CSL-1 consists of two sources (A and B, as marked in Fig. 1) separated by 1.9 arcsec. Visual inspection shows that in morphology: a bright nucleus surrounded by a faint halo with undistorted and almost circular isophotes.

In Table 2 we list, in each of the OACDF broad bands, the measured FHWM of the two components together with the FWHM of the PSF measured on non-saturated stars near the position of CSL-1 . Also in Table 2 we give the integrated magnitudes of the two components in the various bands. It is apparent that, within the errors, the colors of the two components are identical.

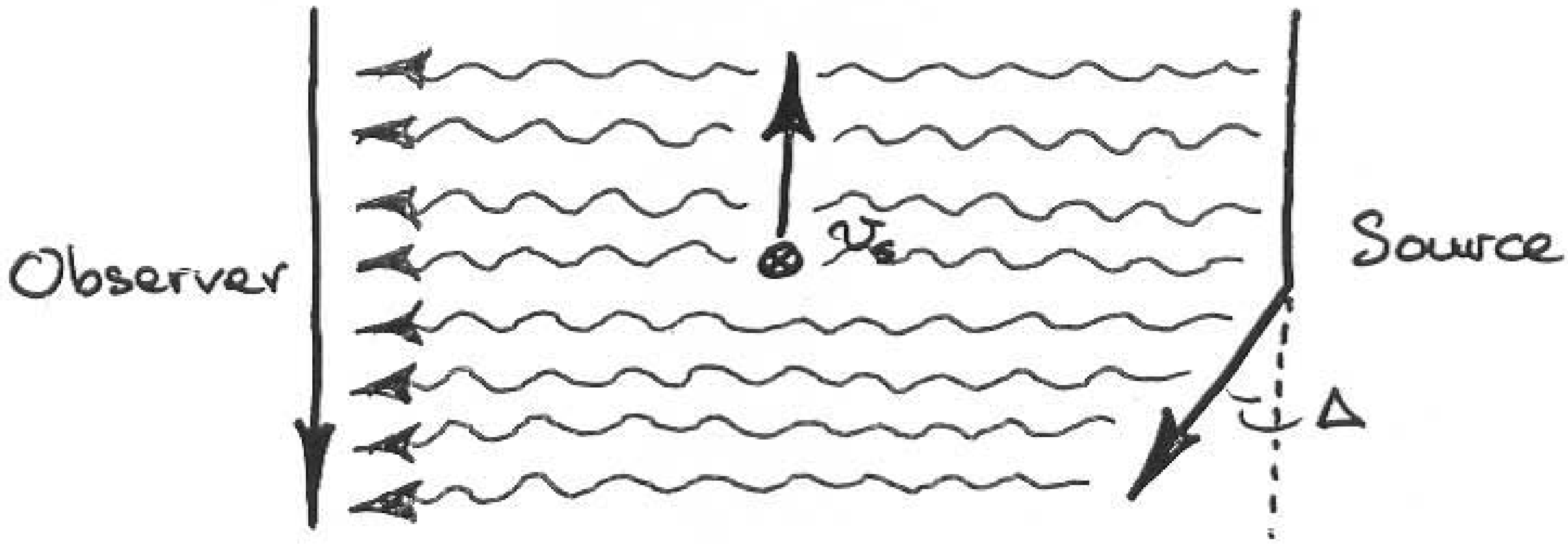
In order to investigate the light profile, we performed a two dimensional fit of the observed light distribution with a 2-D Sersic profile $I_S(r) = I_0 exp(-b(\frac{r}{r_e})^{1/n})$ convolved with the measured PSF, where:

$$r^2 = \frac{1+e}{2}(x^2+y^2) + \frac{1-e}{2}(x^2+y^2)\cos 2\psi + \frac{1-e}{2} xy \sin 2\psi$$

x and y being the Cartesian coordinates measured from the central peak, e the ellipticity of the corresponding isophote, and ψ the position angle of the isophote. The best fit was

Microwave Anisotropies

- Doppler shifts



- Temperature discontinuity

$$\frac{\Delta T}{T} = \delta u = 8\pi G\mu v_s \gamma_s$$

Misalignment affects

$\hat{n}$ — line of sight unit vector
$\hat{s}$ — string direction

$$\frac{\Delta T}{T} = \delta \underset{\sim}{u} \cdot \underset{\sim}{n} = 8\pi G\mu \gamma_s \hat{\underset{\sim}{n}} \cdot (\underset{\sim}{v_s} \times \underset{\sim}{s})$$

Average over directions with $v_{rms} \approx 0.6$

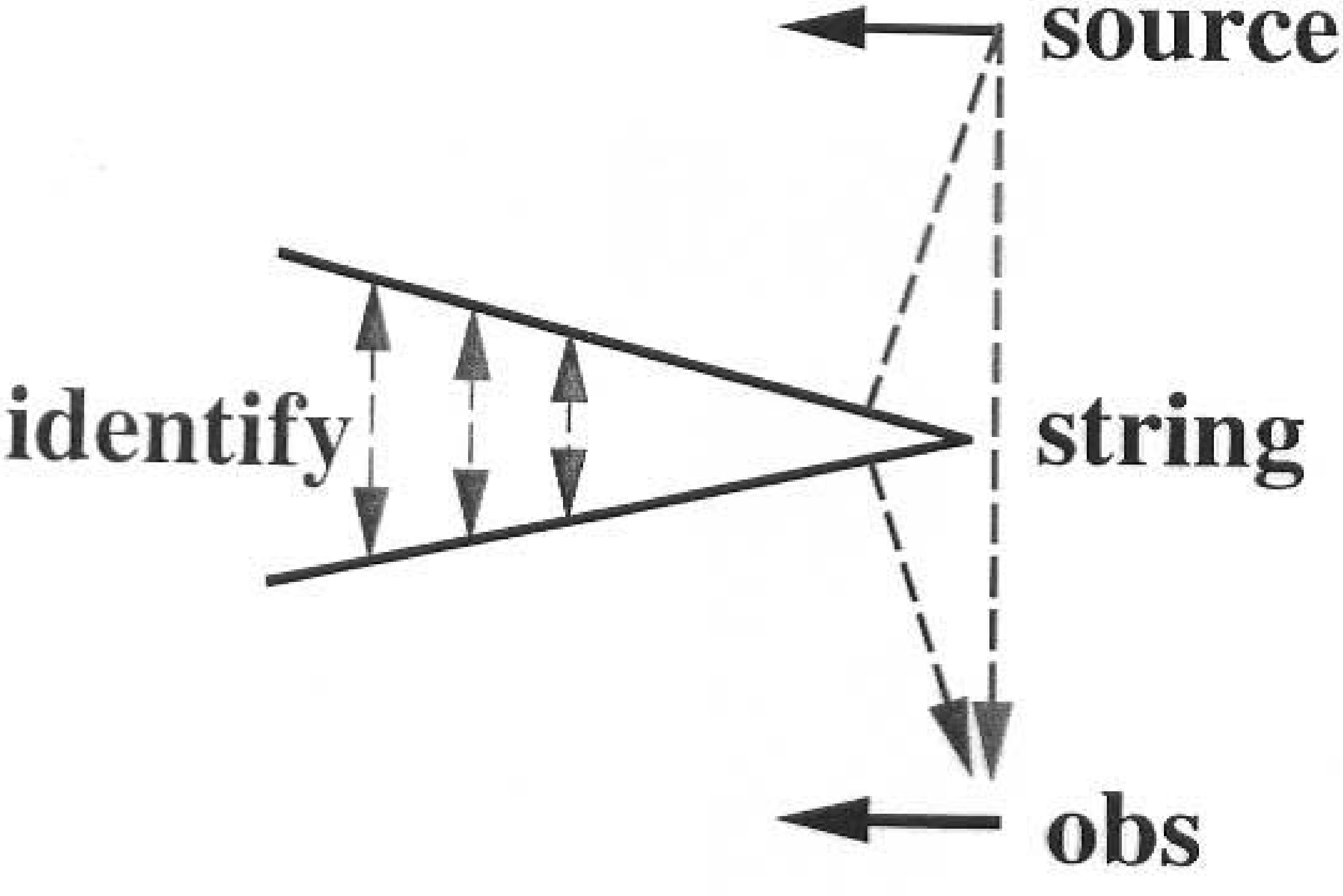
$$\frac{\Delta T}{T} \sim 13 G\mu$$

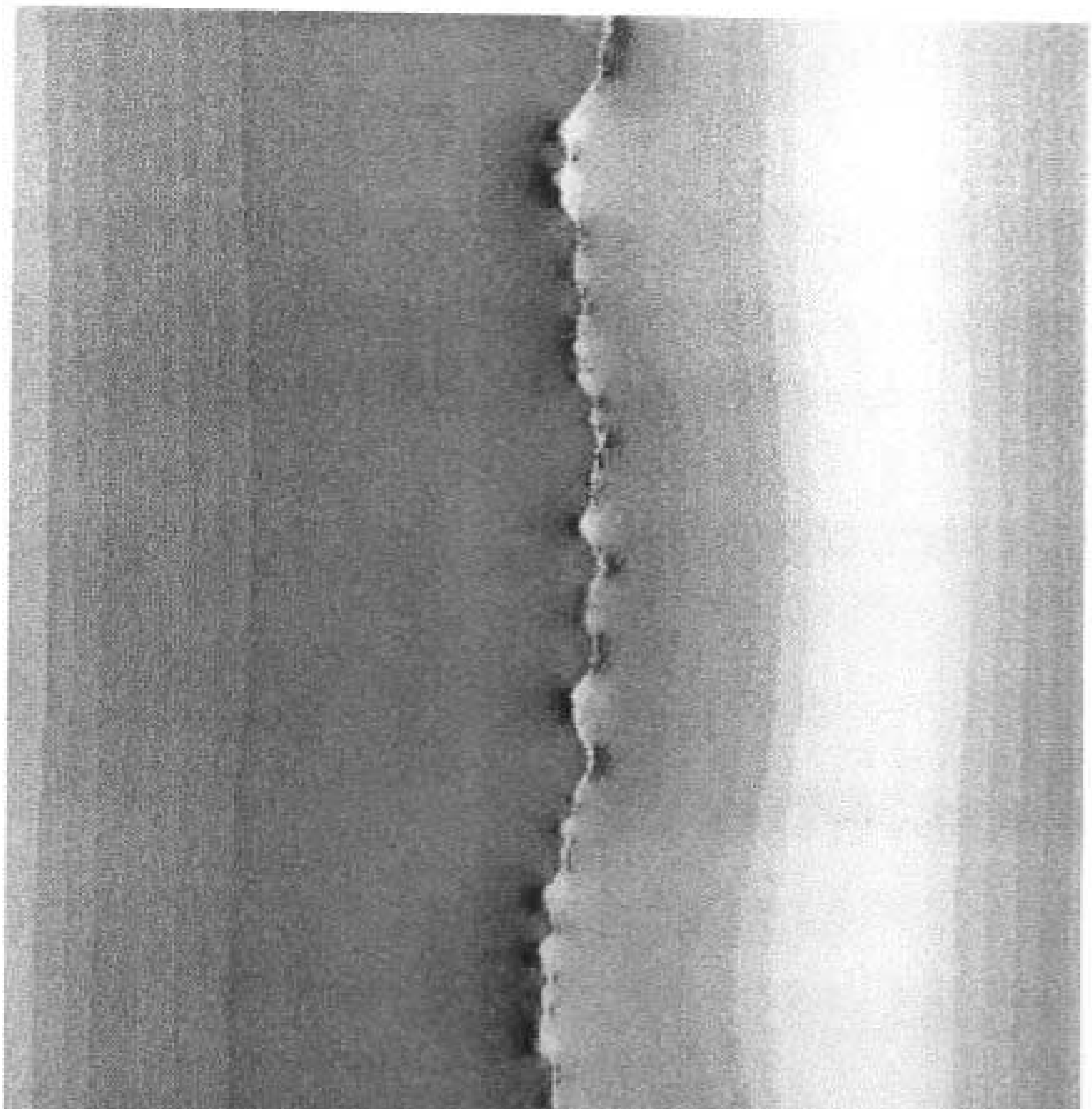
- Last scattering surface

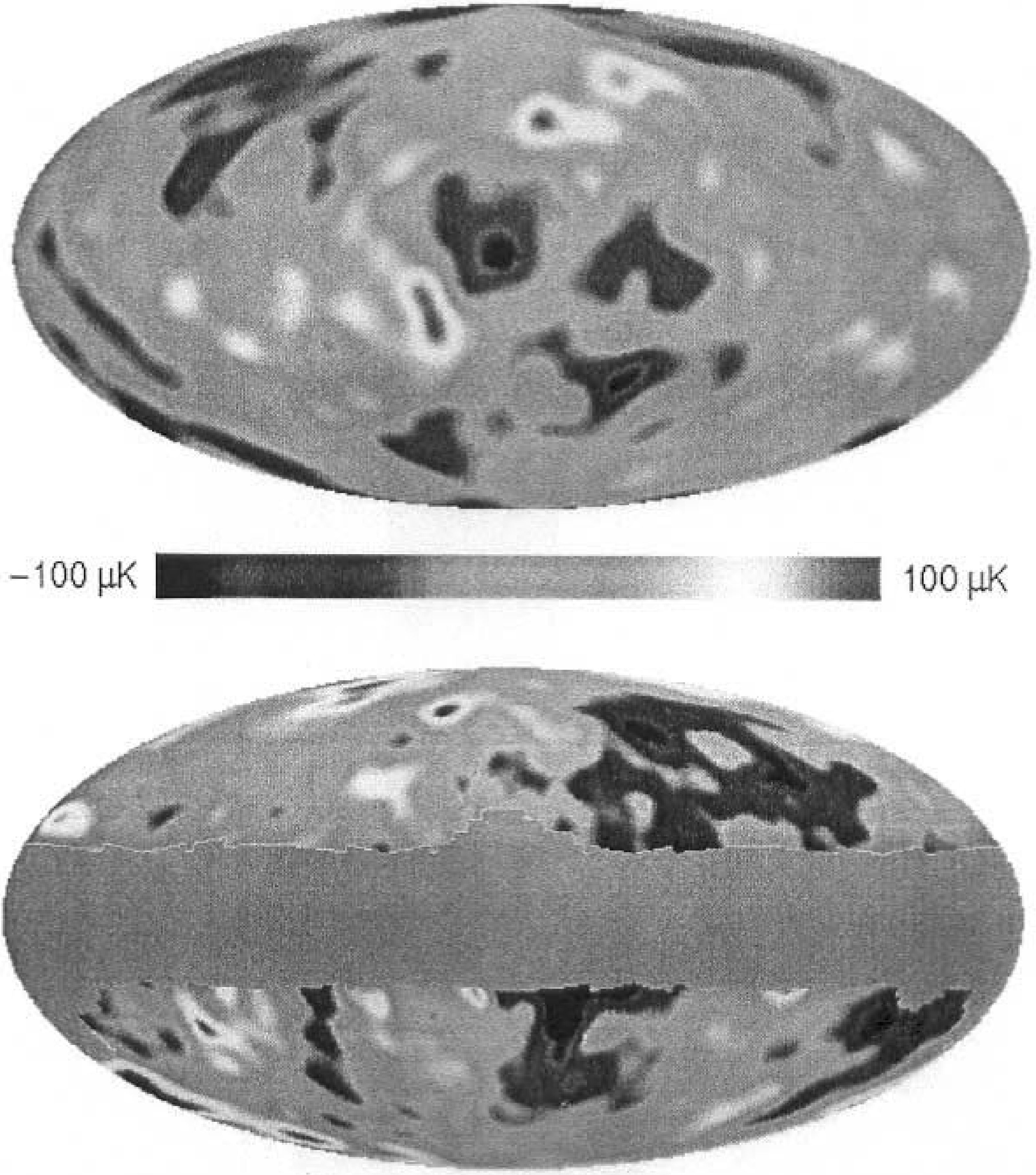
Horizon size $\theta_H \approx z_{ls}^{-\frac{1}{2}}$ rad $\approx 1.8^\circ \left(\frac{z_{ls}}{10^3}\right)^{-\frac{1}{2}}$

For a scaling string network, projected angular string length scales as $\sqrt{z}$.

Kaiser–Stebbins effect






−100 μK
100 μK

CMB & Strings

- Large-angle CMB normalization

$$G\mu \lesssim 7 \times 10^{-7}$$

Landriau & EPS, 2003

Incorporates string small-scale structure
Weak dependence on cosmological consta

- Small-angle search for nongaussianit

Strings & inflation   Pogosian et al 2003

Battye et al '99, Magueijo et al '98, Martins et al '98

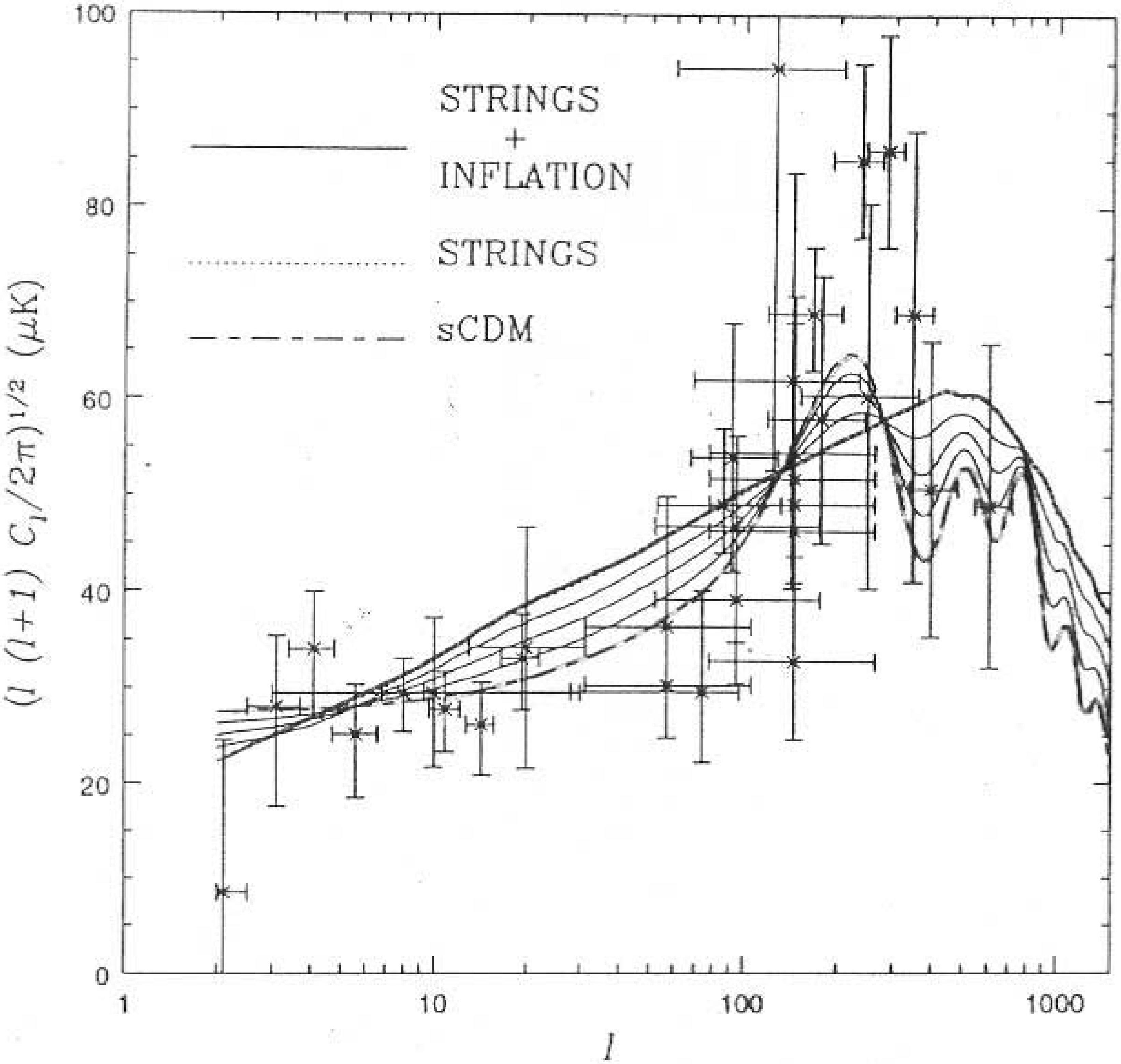


FIG. 1. The CMB power spectra predicted by cosmic strings, sCDM, and by inflation and strings with $R_{\rm SI} = 0.25, 0.5, 0.75$. The large angle spectrum is always slightly tilted. The Doppler peak becomes a thick Doppler bump at $\ell = 200 - 600$, modulated by mild undulations.

$\Omega_m = 0.5,\ \Omega_\Lambda = 0.5$

G. W. Constraints

STOCHASTIC BACKGROUNDS

- Nucleosynthesis (massless deg. of freedom $N_\nu \lesssim 3.8$)

$$G\mu \lesssim 6\times10^{-6}$$

Bennett & Bouchet 1990

- Pulsar timing residuals

$$G\mu \lesssim 5.4\,(\pm1.1)\times10^{-6}$$

McHugh, 199

- Forthcoming observations

LIGO II & LISA expect sensitivities with $\Omega_{gw} \sim 1\times10^{-8}$

$$\Rightarrow \quad G\mu \sim 1\times10^{-7}$$

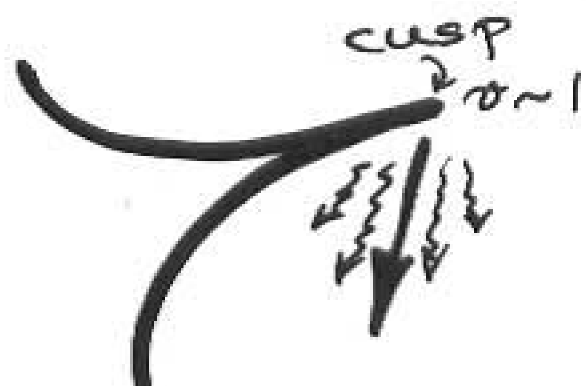
$10^{-6}\,\mathrm{Hz} \lesssim f \lesssim 10^{4}$

G.W. BURSTS FROM CUSPS & KINKS

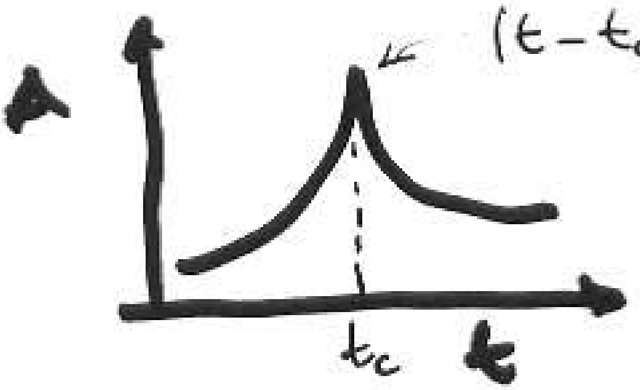
- Strong beaming at cusps implies bursts can be detected by LIGO & LISA for

$$G\mu \gtrsim 10^{-13}$$

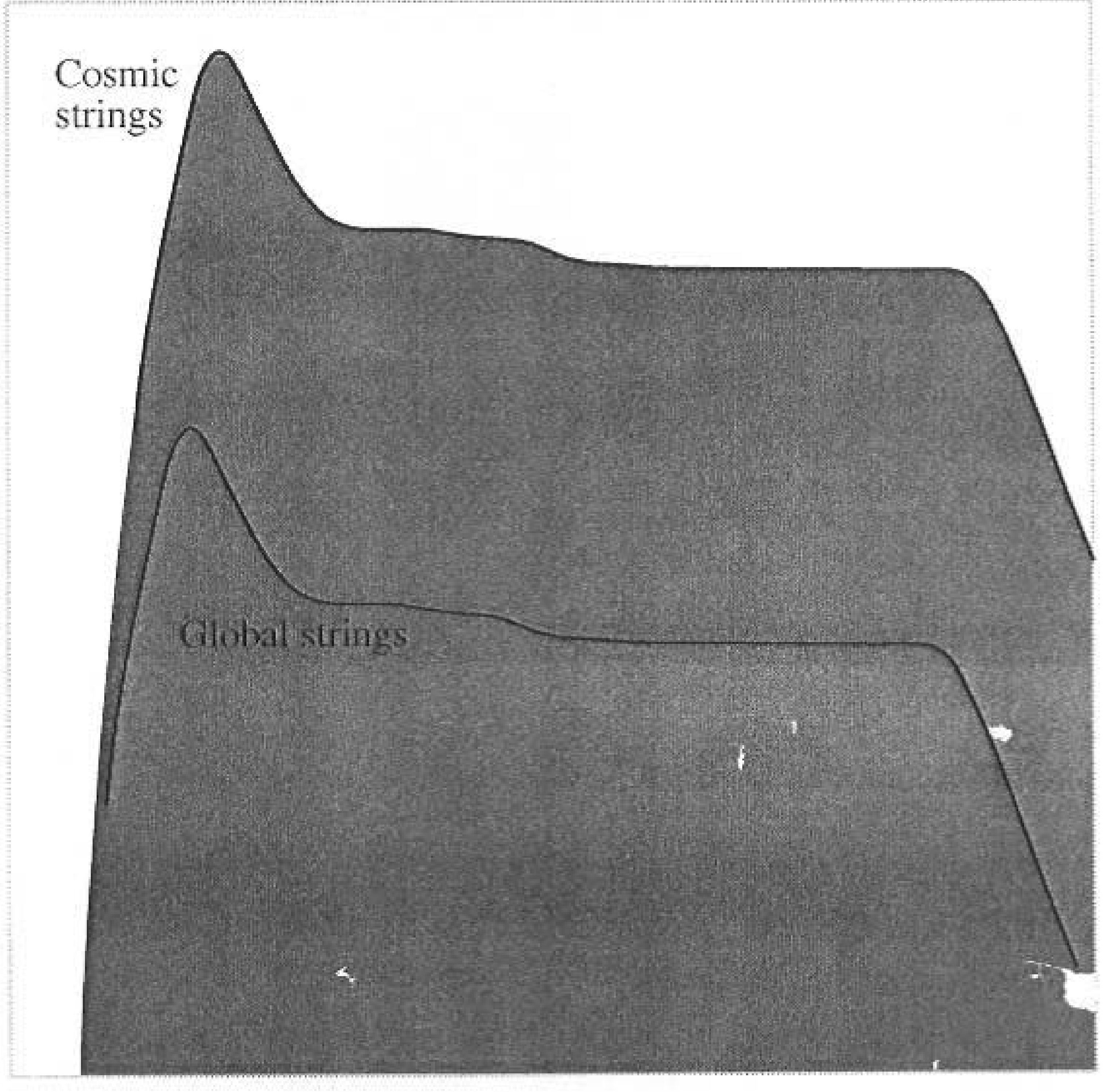
(Damour & Vilenkin, 2001)

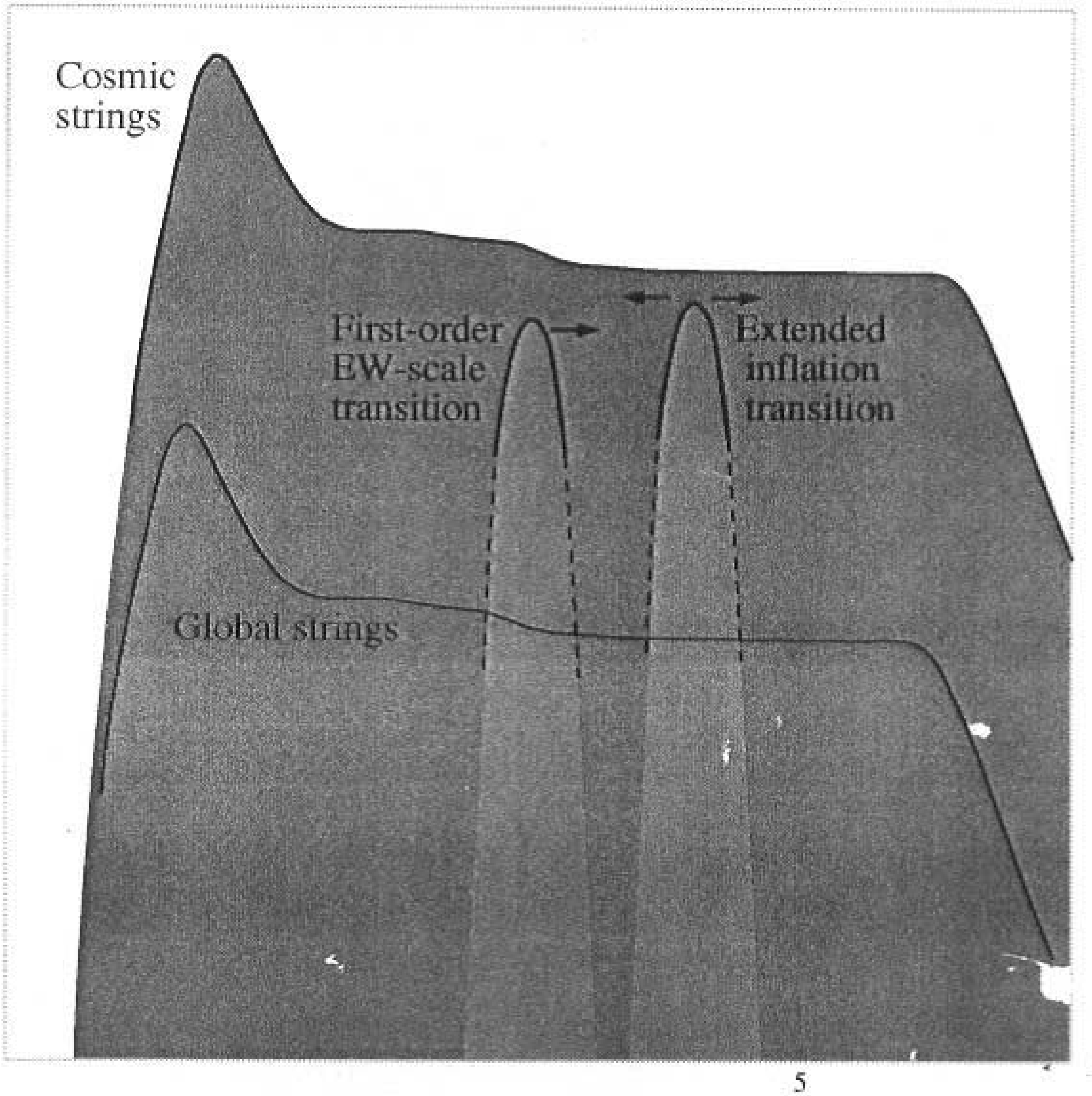


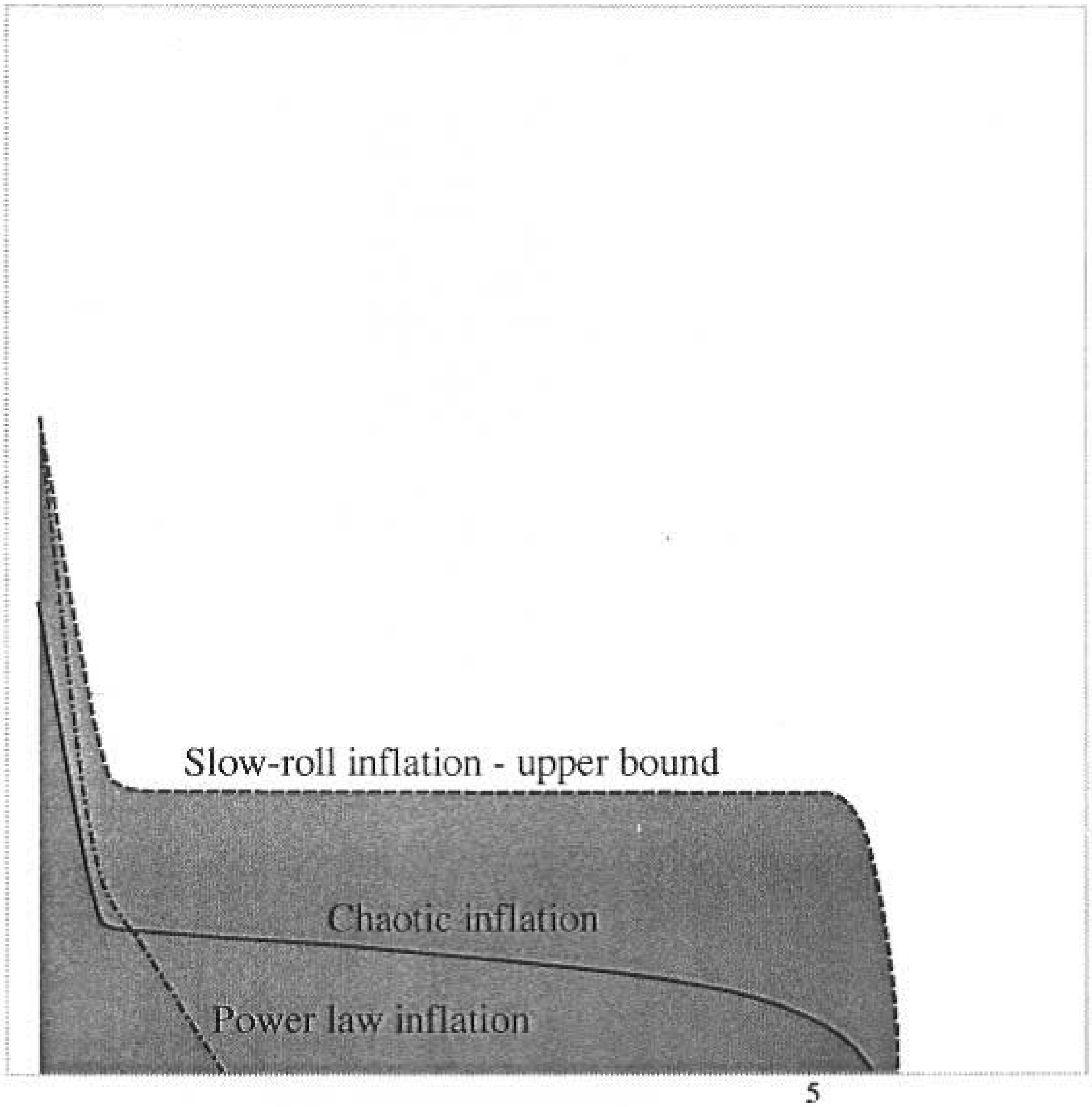
- Sharp 'spike' in waveforms



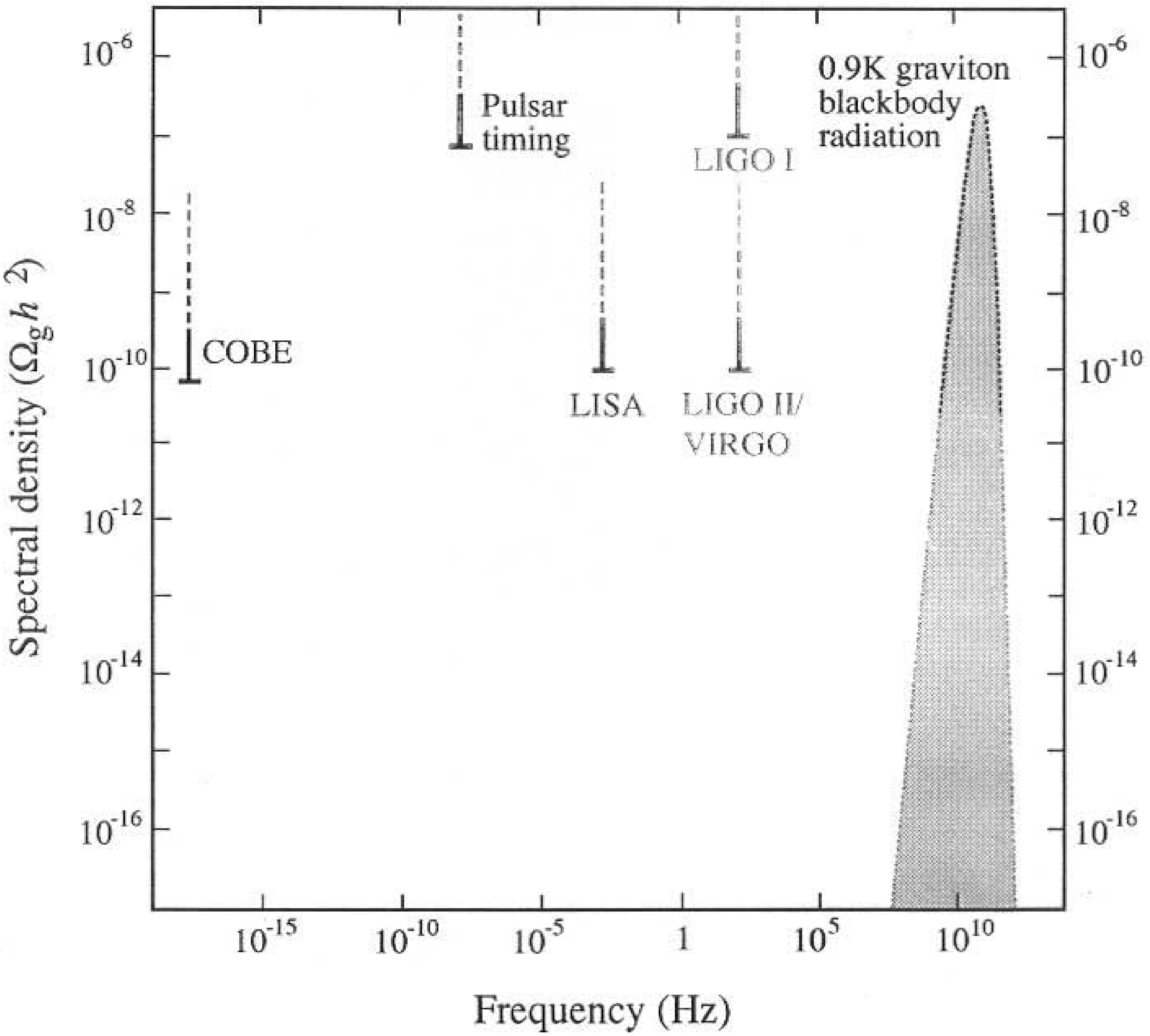
Search above noise with 'designer template'


Cosmic
strings
Global strings

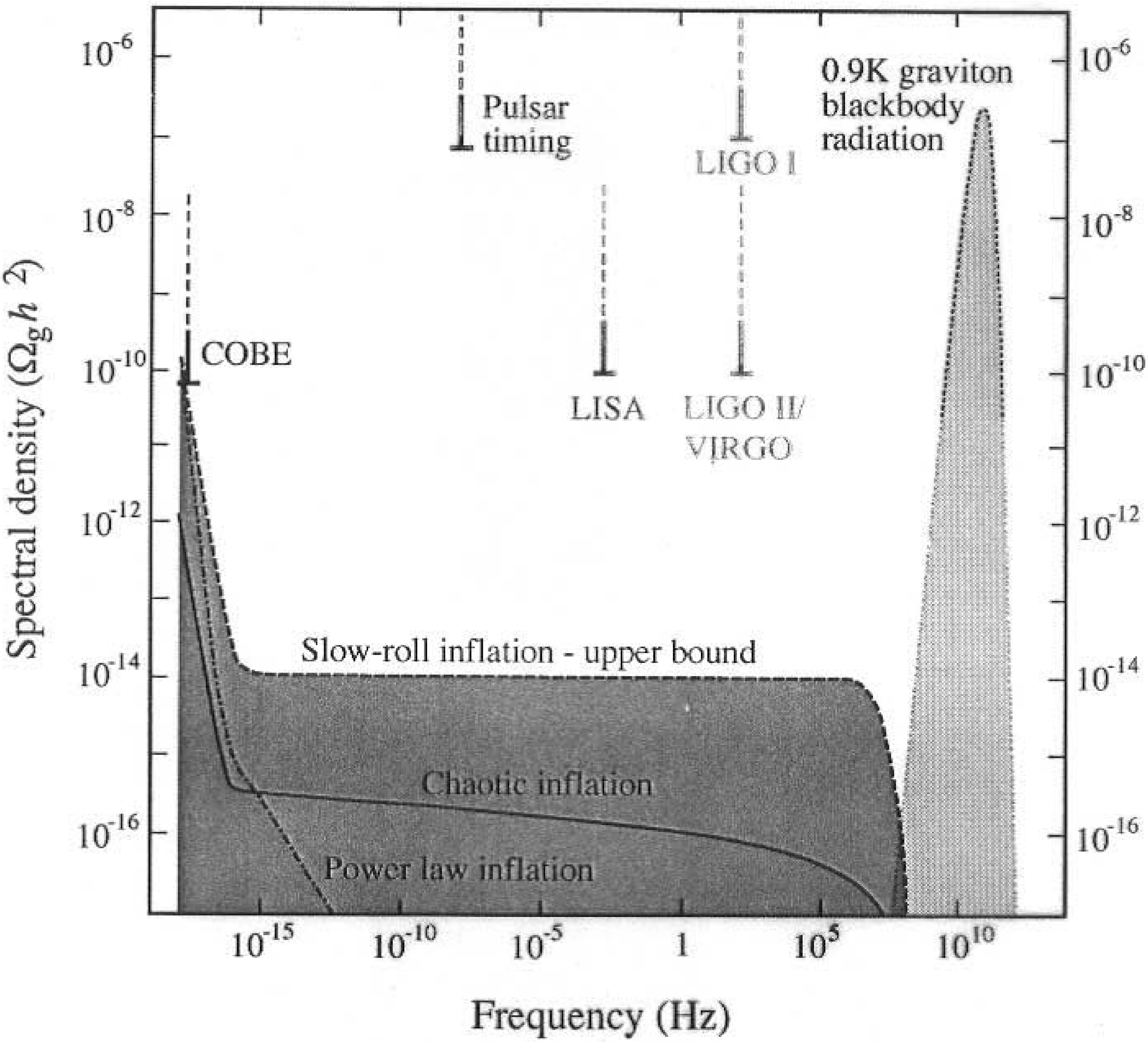

Cosmic strings
First-order EW-scale transition
Extended inflation transition
Global strings


Slow-roll inflation - upper bound
Chaotic inflation
Power law inflation
5

Detector sensitivities and cosmological sources



Detector sensitivities and cosmological sources



Dark Matter & Energy

AXIONS

- Standard thermal scenario $U_{PQ}(1) \to 1$ at $10^{10}\,\mathrm{GeV} \lesssim f_{PQ} \lesssim 10^{12}\,\mathrm{GeV}$
- Axion strings created $\longrightarrow$ radiate axions (pseudoGoldstone boson
- Integrating over all contributions

$$\Omega_{CDM} \approx \left(\frac{f_{PQ}}{10^{11}\,\mathrm{GeV}}\right) \Rightarrow \quad m_a \approx 10^{-5}\,\mathrm{eV}$$

(Battye & EPS, '96

- Current searches near $m_a \lesssim 10^{-6}\,\mathrm{eV}$.

VORTONS

★ Creation density is model-dependent
- phase transition details $(t = t_c)$
- min. winding N_{min} of stable vortons
- adiabaticity of approach to vorton state

★ Approx. density

$$\rho_v \sim \frac{\mu^2}{N_{min}^2}\left(\frac{t_c}{t}\right)^{3/2}$$

← matte... (cf. mon... proble...

★ Electroweak-scale vortons possible DM (m_v ~ 10^7 GeV

CHUMPS

FRUSTRATED DEFECT NETWORKS

★ Non-intercommuting strings or domain walls form a tangled network with $\xi \ll d_H$.

★ Eqn of state: strings $\omega \approx -\frac{1}{3}$
domain walls $\omega \approx -\frac{2}{3}$

★ Accel. (dws) difficult to distinguish from some quintessence models

Violent Phenomena

UHE COSMIC RAYS

Enigmatic events with $E \gtrsim 10^{11}$ GeV
(NB GZK cutoff → nearby source or non-int. partic

- annihilation of monopole/antimonopole pairs
  (violates n_M constraints for nec. fl
- cosmic string cusps (flux too low, Blanco-Pillado & Olum, 1999)
- $M\bar{M}$ pairs connected by strings
  - eg. $m_M \sim 10^{14}$ GeV, $\mu \sim (100\,\text{GeV})^2$
  - decay lifetime $\tau \sim t_0$ (age of universe)
  - local decays in galaxy halo (track CP
- Metastable vorton decays (as above)
  (Masperi & Silva 19
- Cosmic defects themselves (eg accel. monopol

GAMMA RAY BURSTS

Superconducting string loops ($\eta \sim 10^{14}$ GeV)
can emit intense EM bursts
- create ultrarel. jets & shocks → γ-rays
  (Berezinsky et al, 2001)
- related/correlated to UHE cosmic rays
  & GW bursts ...

Baryon asymmetry

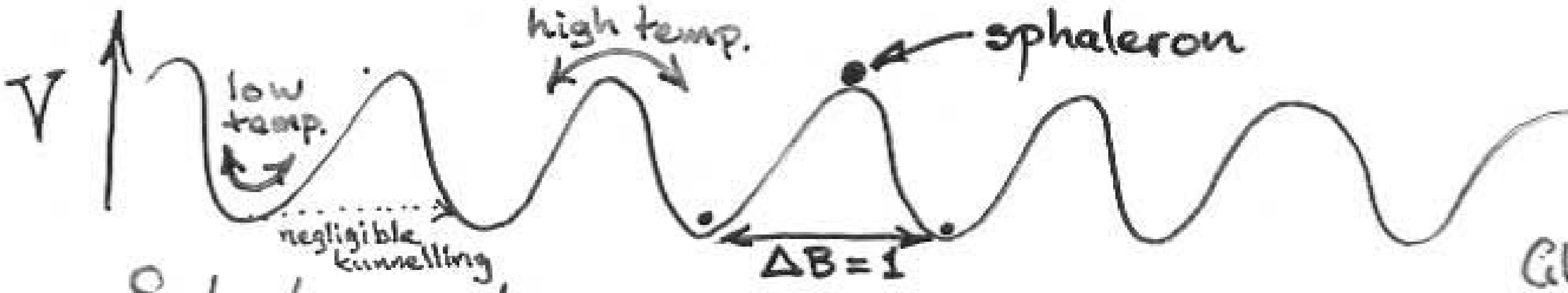
- **Observed baryon number of the universe**

$$\frac{n_B}{s} \sim (2-4)\times 10^{-11} \gg n_{\bar{B}}$$

Naive estimates: $T_D \simeq 22\,\mathrm{MeV}$, $n_B \sim 10^{-18}$, $l \sim 100\,\mathrm{pc} \ll H_0^{-1}$

- **Baryogenesis** (Sakharov's criteria)
  1) Baryon-number-violating processes: $n_B \neq 0$
  2) C & CP violation: so that $n_B \neq n_{\bar{B}}$
  3) Out-of-equilibrium processes:
     since $m_B = m_{\bar{B}}$, $\mu_B = 0 \Rightarrow n_B = n_{\bar{B}}$.

- **Electroweak sphalerons** [Klinkhammer & Manton, 1984]
  - Standard model Θ-vacua (local textures)



  - Sphaleron transitions change baryon no.
  - At low temp. sphaleron rate: $\Gamma \propto \exp(-E_{sp}/T)$
    but for $T \gtrsim 100\,\mathrm{GeV}$, E_{sp} small, Γ large.

Global chan anomaly for fermic coupled t gauge fiel

- **GUT-scale baryogenesis**
  - Sphalerons may remove B-asymmetry (not B−L)
  - Inflation removes monopoles & baryons
    — high enough reheat temp. $T_R \gtrsim 10^{12}\,\mathrm{GeV}$ difficul

Why defects?

- **Because they are there**

  Symmetry breaking plus causality ⟹ inevitability

- **Cosmological enigmas**

  Density fluctuations / CMB anisotropies
  Origin of matter/antimatter asymmetry
  Origin of dark matter
  Monopole problem
  Primordial magnetic fields

- **Improving observational data**

  Large-scale structure surveys
  CMB experiments
  Cosmic rays, gravitational waves etc

- **Insight into fundamental theory**

  Grand unification & beyond.
  Terrestrial particle accelerators vs HBB

- **Nonlinear dynamics**

COSLAB