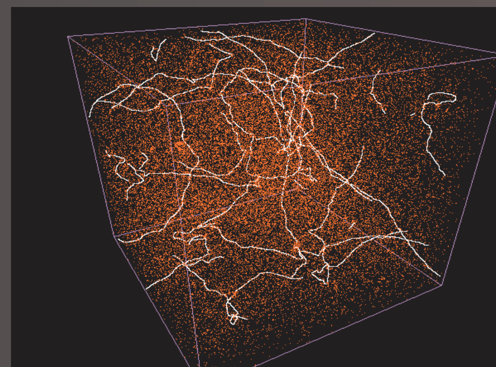
recent developments on cosmic string dynamics



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outline

- cosmic string evolution in a FLRW background
  - numerical results

    ringeval, **m.s.**, bouchet JCAP 0702 (2007) 023

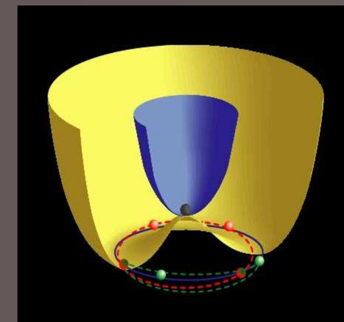
  - analytical model

    lorenz, ringeval, **m.s.** JCAP 1010 (2010) 003

- cosmic string evolution in an anisotropic background

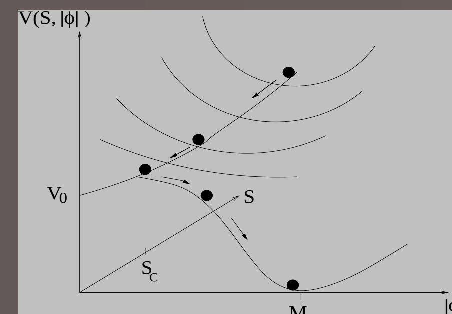
  kunze, **m.s.** arXiv:1106.4434

formation



kibble-zurek mechanism

generically formed at the end of F- or D-term inflation within SUSY GUTs



$$G_{\rm GUT} \xrightarrow{M_{\rm GUT}} H_1 \xrightarrow[\Phi_+\Phi_-]{M_{\rm infl}} H_2 \longrightarrow G_{\rm GM}$$

$$G_{\rm GUT} \times U(1) \xrightarrow{M_{\rm GUT}} H \times U(1) \xrightarrow[\Phi_+\Phi_-]{M_{\rm infl}} H \longrightarrow G_{\rm GM}$$

jeannerot, m.s., rocher PRD 68 (2003) 103514

evolution (NG cosmic string code)

- FLRW
- fixed unity comoving volume with periodic b.c.
- initial scale factor is normalised to unity
- initial horizon size is a free parameter
- comoving horizon size grows and evolution is stopped before it fills the whole unit volume
- VV initial conditions

ringeval , m.s. , bouchet JCAP 0702 (2007) 023

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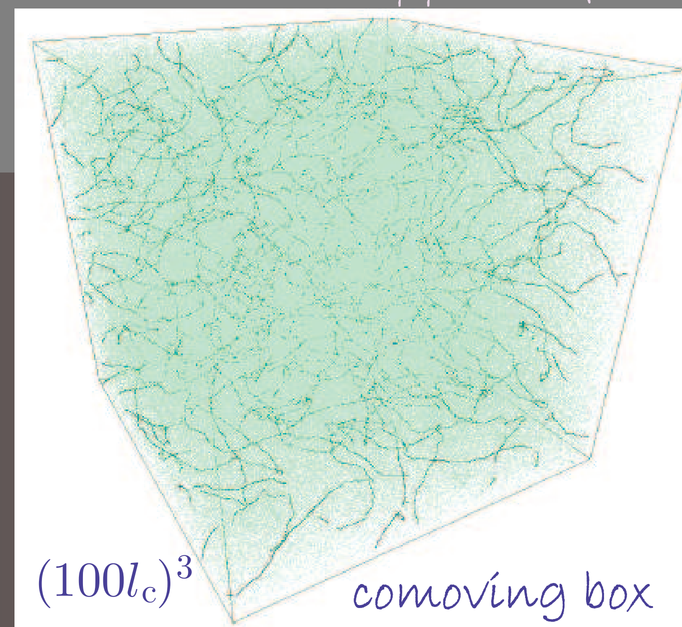

initial string sampling of 20 ppcl

$d_{h_0} = 0.063$ MDE

$d_{h_0} = 0.057$ RDE

dynamic range:
520 (MDE) and 308 (RDE) in physical time

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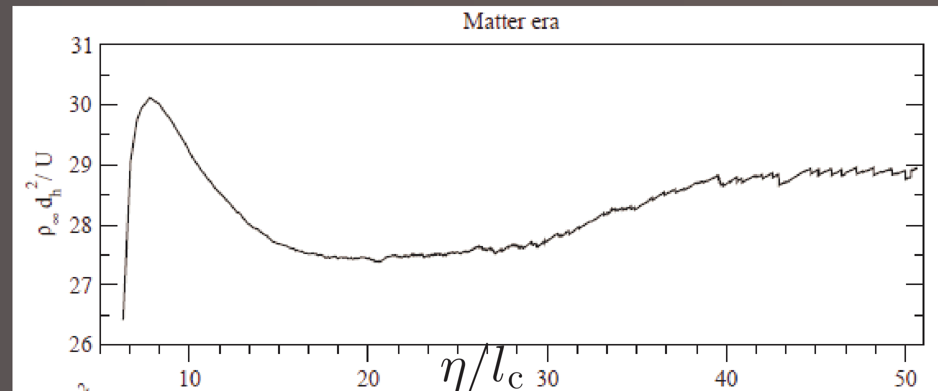
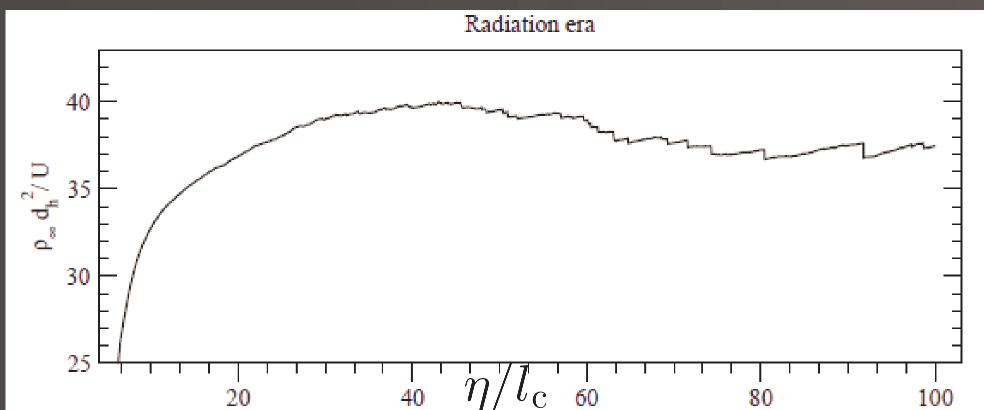
scaling regime of long (super-horizon) strings





$$\rho_\infty \propto 1/d_{\rm h}^2$$

$$\rho_\infty \frac{d_{\rm h}^2}{U} =_{\rm mat} 28.4 \pm 0.9, \qquad \rho_\infty \frac{d_{\rm h}^2}{U} =_{\rm rad} 37.8 \pm 1.7$$

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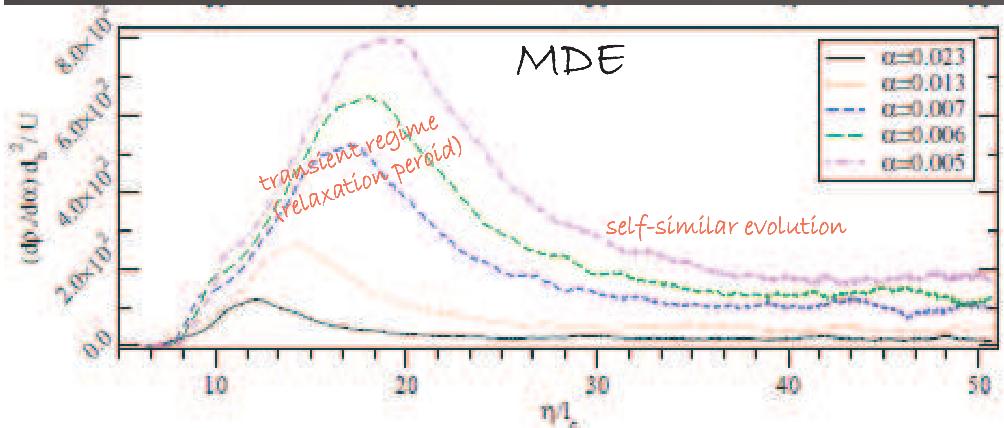
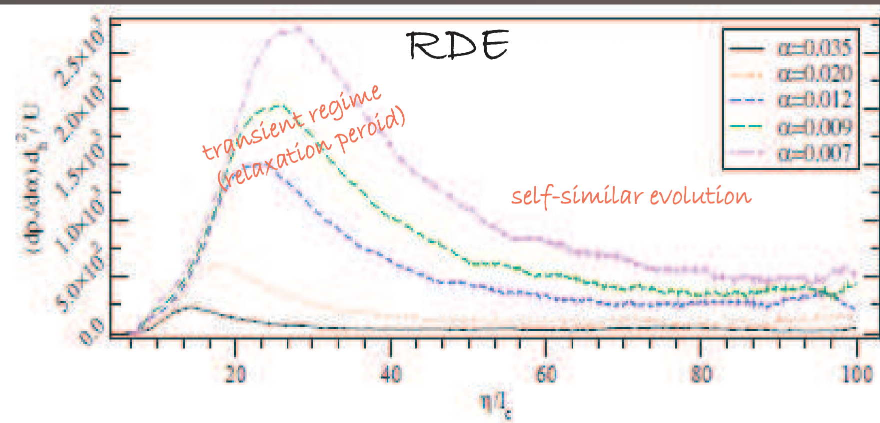
scaling evolution for loops as small as a few thousandths the horizon size





$$d\rho_\circ \propto 1/d_{\rm h}^2$$

$$l_{\rm phys} = \alpha d_{\rm h}$$

$d\rho_0(\alpha)$: energy density carried by loops whose length, in units of $d_{\rm h}$, is in the range α to $\alpha + d\alpha$

ringeval , m.s. , bouchet JCAP 0702 (2007) 023

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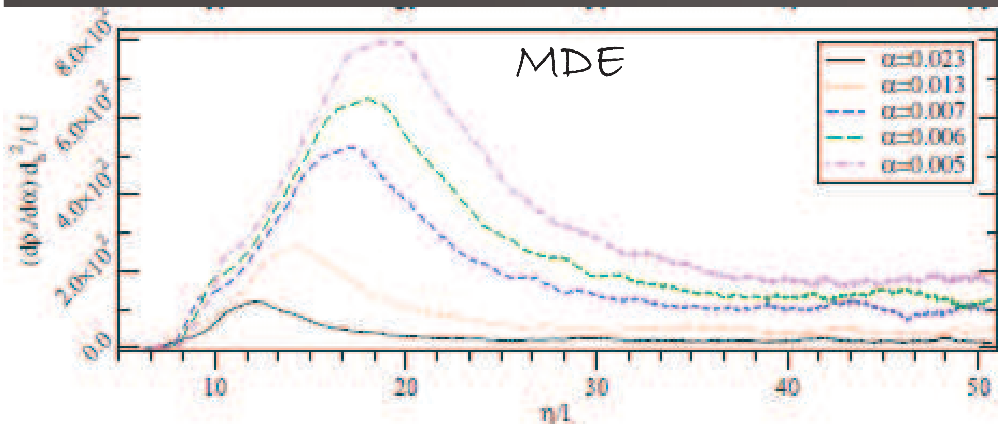

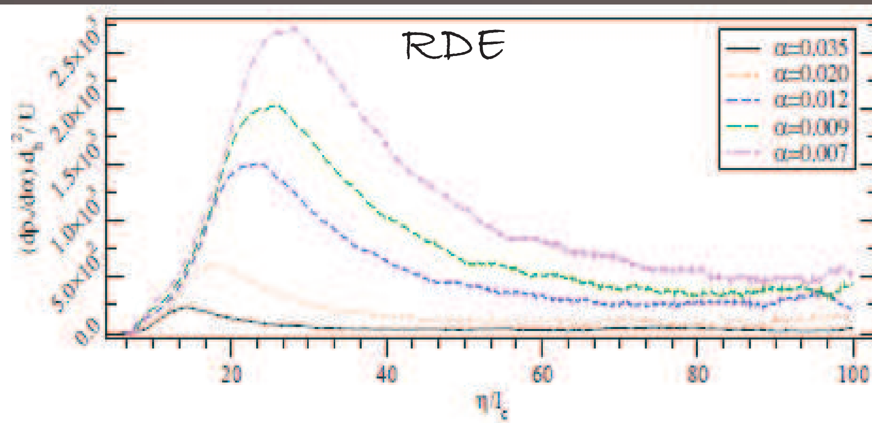

$$\mathrm{d}\rho_\circ \propto 1/d_\mathrm{h}^2$$

$$l_\mathrm{phys} = \alpha d_\mathrm{h}$$

$d\rho_\mathrm{o}(\alpha)d_\mathrm{h}^2$ remains stationary, for all values of α down to approximately 5×10^{-3}

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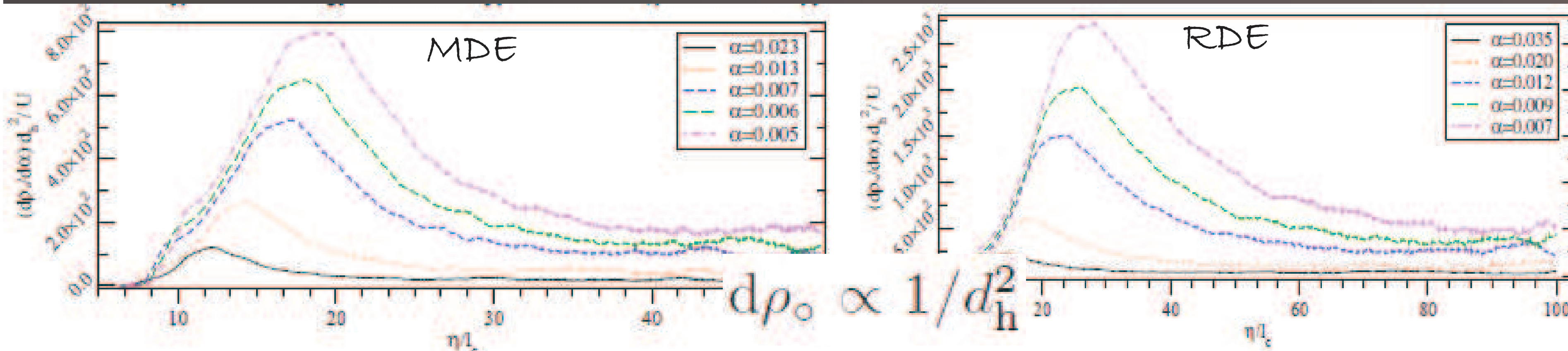
scaling evolution for loops as small as a few thousandths the horizon size



$$d\rho_\circ \propto 1/d_{\mathrm{h}}^2$$

intersection processes which create loops from long strings is similar to that for loops themselves

loop self-interactions give rise to more numerous smaller loops

→ a constant energy flow cascades from long strings to smallest loops

reconnection process of small loops to long strings/larger loops is negligible

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string dynamics and intercommutation lead to a scaling regime:

$$\frac{\mathrm{d}\rho_\circ}{\mathrm{d}\alpha} = \mathcal{S}(\alpha)\frac{U}{d_{\mathrm{h}}^2}, \qquad \frac{\mathrm{d}n}{\mathrm{d}\alpha} = \frac{\mathcal{S}(\alpha)}{\alpha\, d_{\mathrm{h}}^3}$$

$$\mathcal{S}(\alpha) = C_\circ\, \alpha^{-p}$$

$$\left\{ \begin{array}{ccc} p & \underset{\mathrm{mat}}{=} & 1.41\,^{+0.08}_{-0.07} \\ C_\circ & \underset{\mathrm{mat}}{=} & 0.09\,^{-0.03}_{+0.03} \end{array} \right. , \quad \text{and} \quad \left\{ \begin{array}{ccc} p & \underset{\mathrm{rad}}{=} & 1.60\,^{+0.21}_{-0.15} \\ C_\circ & \underset{\mathrm{rad}}{=} & 0.21\,^{-0.12}_{+0.13} \end{array} \right.$$

loop formation is the dominant energy carrying mechanism

(scaling regime does not rely on gravitational back reaction effects)

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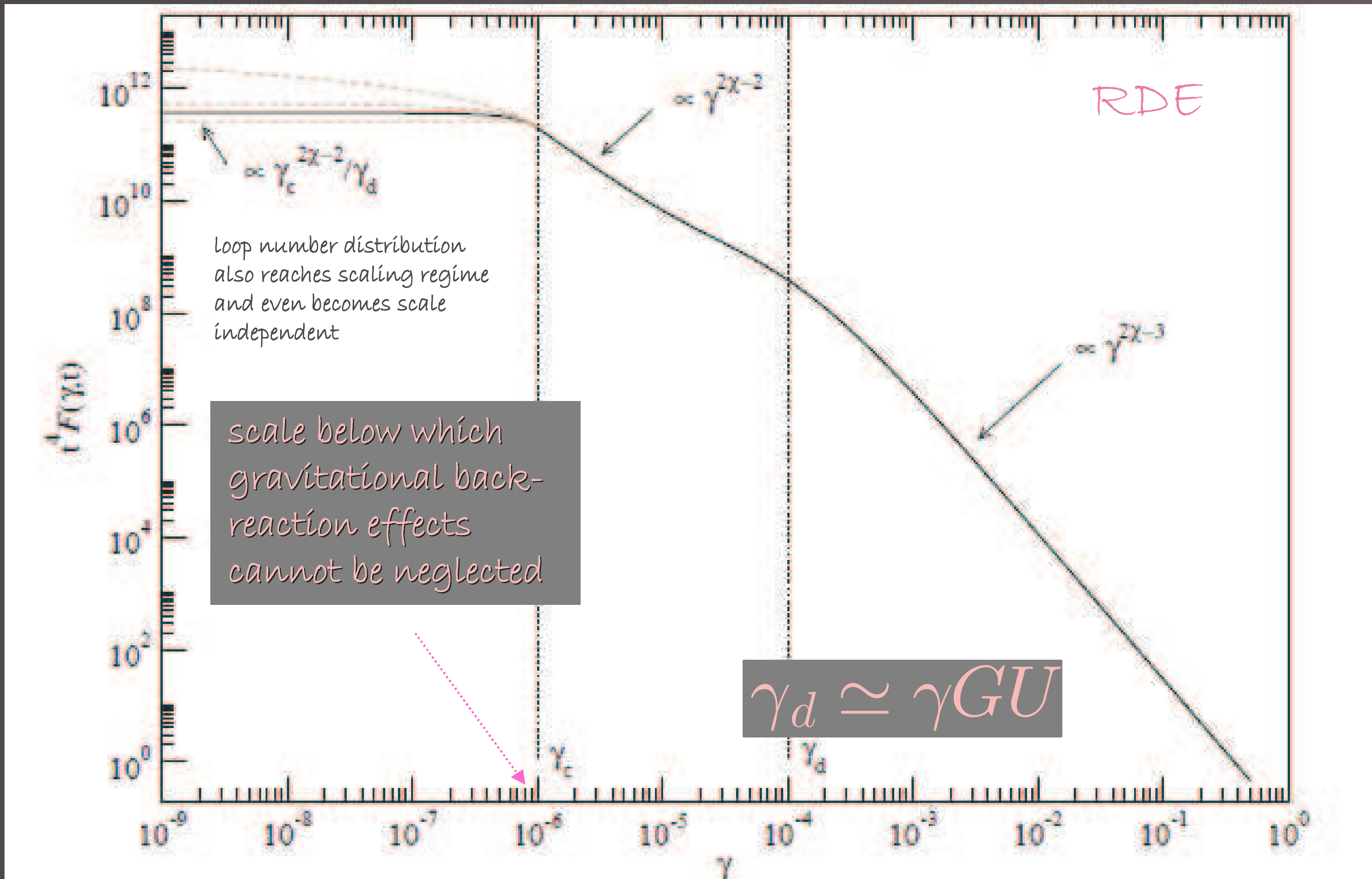
model based on polchinski-rocha loop production function,

$$\frac{\partial}{\partial t}\left(a^3\frac{\mathrm{d}n}{\mathrm{d}\ell}\right) - \gamma_\mathrm{d}\frac{\partial}{\partial \ell}\left(a^3\frac{\mathrm{d}n}{\mathrm{d}\ell}\right) = a^3\mathcal{P}(\ell, t)$$

$$\frac{\mathrm{d}\ell}{\mathrm{d}t} = -\gamma_\mathrm{d}$$

adjusted to fit simulations and considering loop decay by GW and string smoothing due to gravitational back-reaction

lorenz, ringeval , m.s. JCAP 1010 (2010) 003

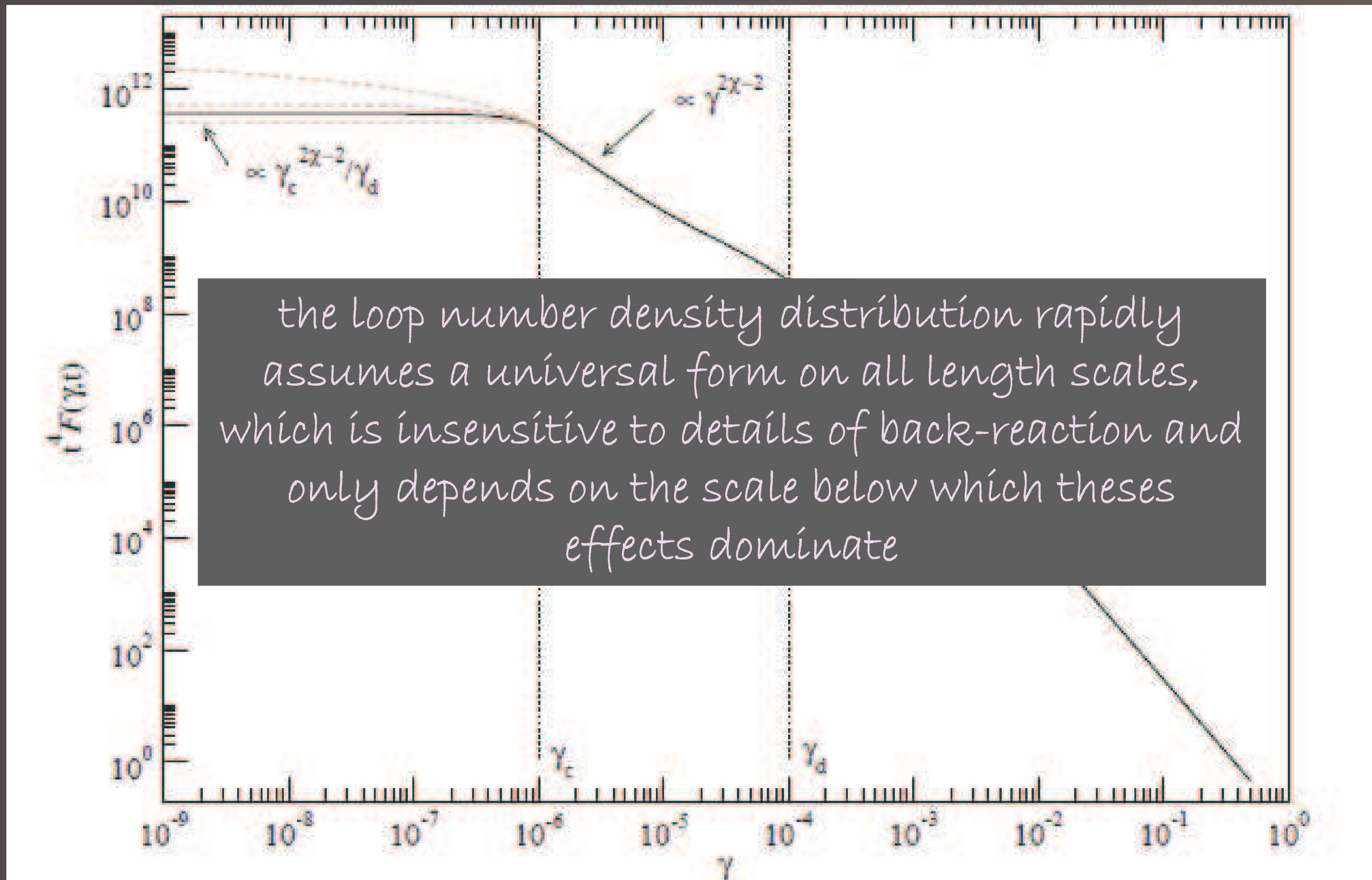


$$\chi = 1 - \frac{p}{2}$$

$$\gamma(\ell, t) \equiv \frac{\ell}{t}$$

$$\mathcal{F}(\gamma, t) \equiv \frac{dn}{d\ell}$$

lorenz, ringeval, m.s. JCAP 1010 (2010) 003



the loop number density distribution rapidly assumes a universal form on all length scales, which is insensitive to details of back-reaction and only depends on the scale below which theses effects dominate

$$\gamma(\ell,t) \equiv \frac{\ell}{t}$$

$$\mathcal{F}(\gamma,t) \equiv \frac{\mathrm{d}n}{\mathrm{d}\ell}$$

lorenz, ringeval , m.s. JCAP 1010 (2010) 003

- *how long does it take to relax towards this universal form ?*

for any reasonable initial distribution and string formation temperature, the loop distribution reaches full scaling well before BBN

$$\forall \ GU > 10^{-28} \quad (\sqrt{U} > 100 \ \text{TeV})$$

any initial loop remnants have been radiated away at $z_{\text{eq}} \approx 10^4$

lorenz, ringeval , m.s. JCAP 1010 (2010) 003

- *can we still observe traces of loops formed in the RDE in the matter loop distribution ?*

loop number density distribution is today in full scaling on all length scales provided $\gamma_\mathrm{d} > 10^{-14}$

if $\gamma_\mathrm{d} < 10^{-14}$ then some loops having a size $\gamma_\mathrm{c} < \gamma \leq \gamma_\mathrm{d}$ have been formed in RDE; on the other length scales the distribution matches with the MDE attractor

in the MDE, the loop distribution reaches full scaling, up to some residual loops from the RDE which may be present for extremely low string tension

lorenz, ringeval , m.s. JCAP 1010 (2010) 003

energy density parameter of loops: $\Omega_\circ \simeq 0.10 \times (GU)^{0.59}$

→ for $GU \simeq 7 \times 10^{-7}$

the energy density cannot exceed 10^{-5}

→ NG strings cannot provide DM candidate

lorenz, ringeval, m.s. JCAP 1010 (2010) 003

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lower limit of loop number density $n_L \simeq 5.5 \times 10^{-6}\,\mathrm{Mpc}^{-3}$ small number

$n_\mathrm{L} \propto (GU)^{-1.65}$ loops from very light CS are more numerous

lensing from loops are more frequent for low values of GU

lorenz, ringeval, m.s. JCAP 1010 (2010) 003

effects of anisotropic dynamics on cosmic strings

motivation

- anomalies in the WMAP data
  (alignment of the moments in the lowest multipoles
  suppression of the qudrupole)
- overshoot problem in inflation

avelino, martins (2000, 2003)

avgoustidis, shellard (2005)

kunze, m.s. arXiv:1106.4434

moving straight string $x^i(\zeta, \tau) = b^i(\tau) + c^i\zeta$

moving straight string $x^i(\zeta,\tau) = b^i(\tau) + c^i\zeta$

- isotropic case

$$v(1-v^2)^{-\frac{1}{2}} \propto a^{-2}$$

$$v^i = \dot{b}^i$$

moving straight string $x^i(\zeta,\tau) = b^i(\tau) + c^i\zeta$

- isotropic case

$$v(1-v^2)^{-\frac{1}{2}} \propto a^{-2}$$

- anisotropic case

$$\dot{v}^i + \left[2\frac{\dot{a}_i}{a_i} - \frac{\dot{a}_1}{a_1} - \sum_j \frac{a_j\dot{a}_j}{a_1^2}\left(v^{j\ 2} - \left(\frac{c^i}{\epsilon}\right)^2\right)\right] v^i = 0$$

physical velocity of the string $V^i = a_i\frac{dx^i}{dt} = \frac{a_i}{a_1}v^i$

$$\epsilon = \left(\frac{\sum_i a_i^2(c^i)^2}{a_1^2 - \sum_i a_i^2(v^i)^2}\right)^{\frac{1}{2}}$$

moving straight string $x^i(\zeta,\tau) = b^i(\tau) + c^i\zeta$

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physical velocity of the string $V^i = a_i\frac{dx^i}{dt} = \frac{a_i}{a_1}v^i$

numerical solutions indicate that the behaviour of a velocity component is inversely proportional to the scale factor in that direction

kunze, m.s. arXiv:1106.4434

small perturbations on a static straight string $x^i = c^i \zeta + \delta x^i$

kunze, m.s. arXiv:1106.4434

small perturbations on a static straight string $x^i = c^i\zeta + \delta x^i$

$$\delta\ddot{x}^i + \left[2\frac{\dot{a}_i}{a_i} - \frac{\dot{a}_1}{a_1} + M\right]\delta\dot{x}^i - N(\delta x^i)'' = 0$$

$$M \equiv \frac{\sum_j a_j \dot{a}_j c^j\ {}^2}{\sum_m a_m^2 (c^m)^2}$$

$$N = \frac{a_1^2}{\sum_m a_m^2 (c^m)^2}$$

kunze, m.s. arXiv:1106.4434

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one component $c^j \neq 0$ and the 2 perturbation components $\delta x^i \neq 0$ $(i \neq j)$

one perturbation amplitude $\delta x^j \neq 0$ and the 2 components $c^i \neq 0$ $(i \neq j)$

kunze, m.s. arXiv:1106.4434

small perturbations on a static straight string $x^i = c^i\zeta + \delta x^i$

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$$\delta x^i = A^i(\tau) e^{ik\zeta}$$

kunze, m.s. arXiv:1106.4434

- irregularities on super-horizon scales are <u>not</u> frozen-in

(string becomes wigglier or straightens out, depending on the ratio of scale factors)

↓

re-entering the horizon wiggliness may augment

↓

generation of more GW

limits on global anisotropy of early universe

constraints on minimum number of e-folds

kunze, m.s. arXiv:1106.4434

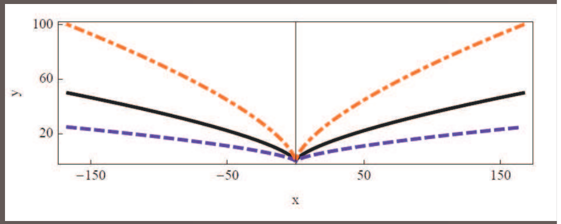
effects of anisotropic dynamics on strings loops:

- if the size of a loop is smaller than the horizon (expansion neglected) periodic solutions exist
- derivatives of right- & left-movers describe closed curves on an ellipsoid
- well inside the horizon the condition for cusps formation is the same as for an isotropic and flat geometry

⇒ the number of cusps is the same

but

- the shape or opening of the cusp changes
- the string velocity at the cusp may not be the luminal one



kunze, m.s. arXiv:1106.4434