Window to High Energy Physics
with Superconducting Cosmic Strings

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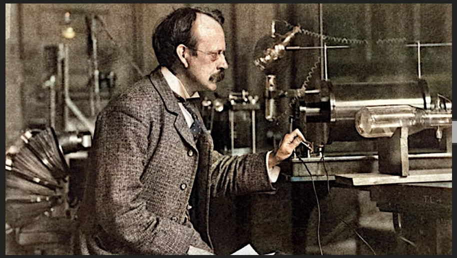
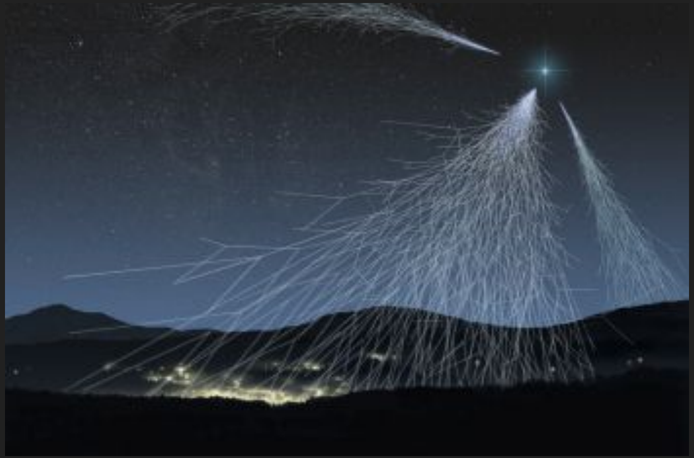
Física de Altas Energías*
Universidad Zaragoza

18/12/2023

Discovery of elementary particles

Birthday of Sir Thomson

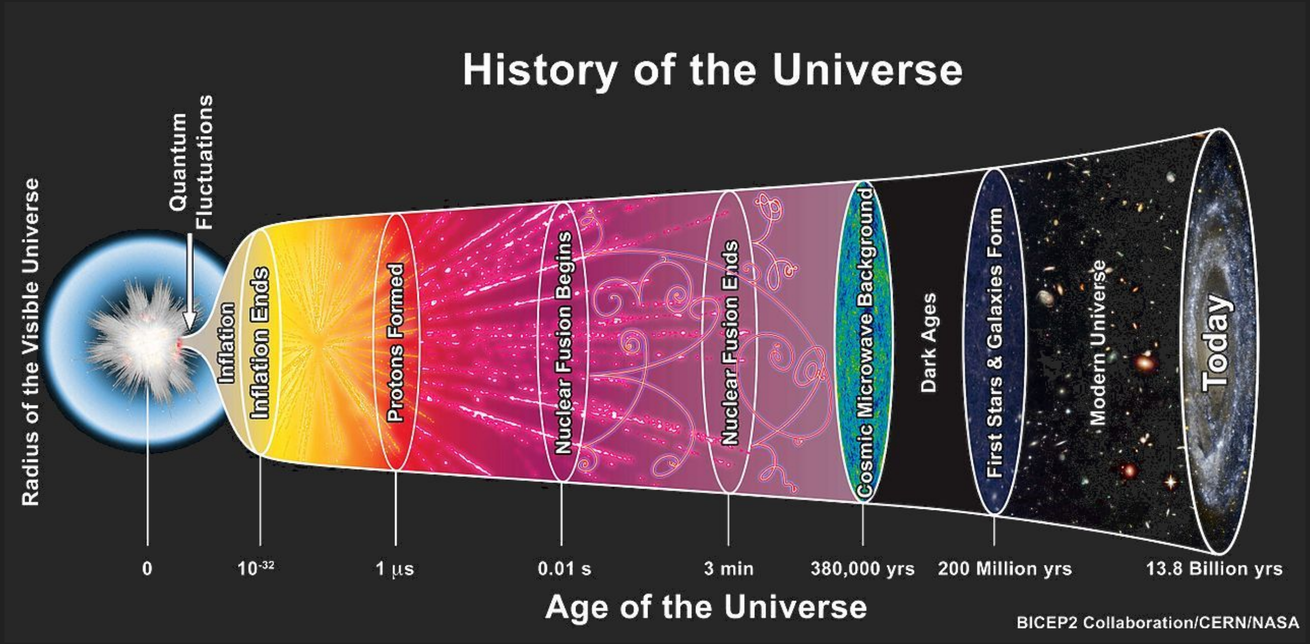




1897	electron
1919	proton
1932	neutron, positron
1937	muon
1955	antiproton
1956	electron neutrino
1962	muon neutrino
1969	quarks
1979	gluon
1983	W,Z bosons
2000	tau neutrino
2012	Higgs boson

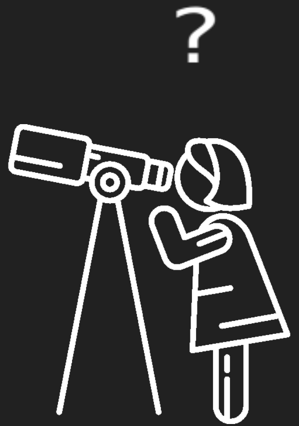
...

How cosmology can help to probe high energy physics?



time

temperature ~ energy



- ★ *Cosmological consequences of spontaneous violation of discrete symmetry*

[YB Zel'dovich, IY Kobzarev, LB Okun Zh. Eksp. Teor. Fiz., 1974]

- ★ *Topology of cosmic domains and strings*

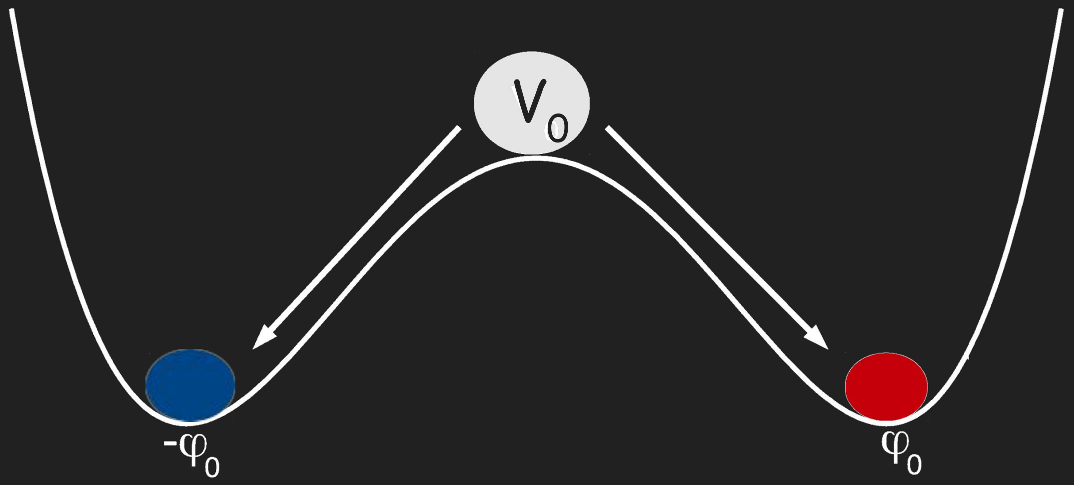
[TWB Kibble, J. Phys. A, 1976.]

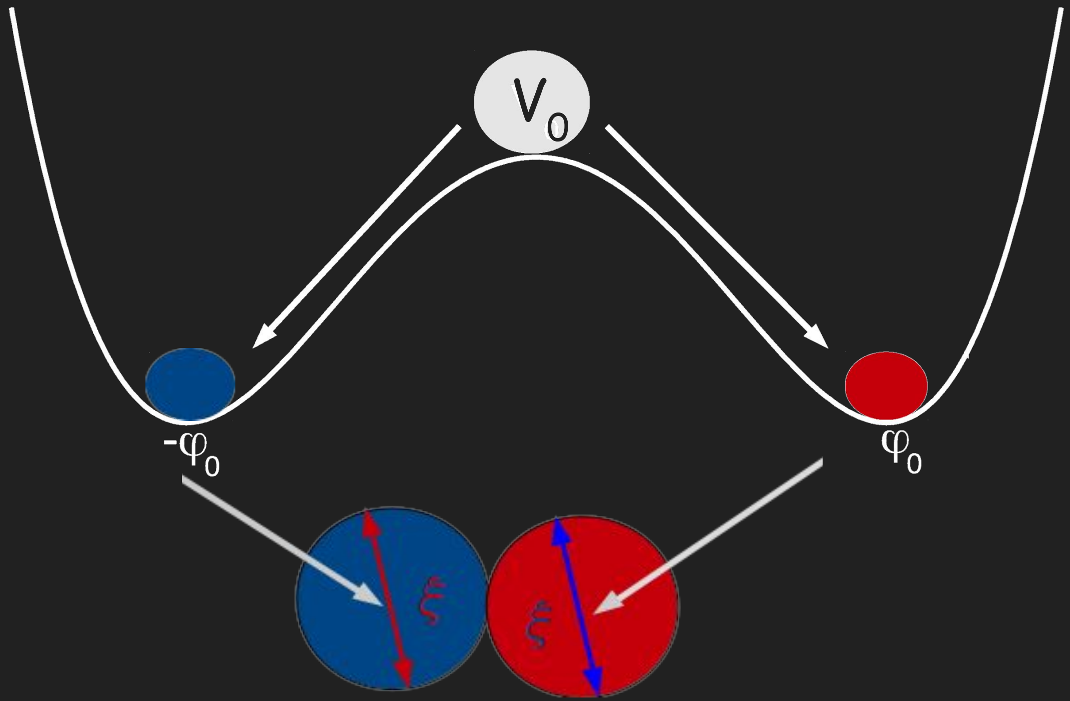
Domain walls and discrete symmetry

$$\mathcal{L} = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V_0\left(1 - \frac{\varphi^2}{\varphi_0^2}\right)^2$$

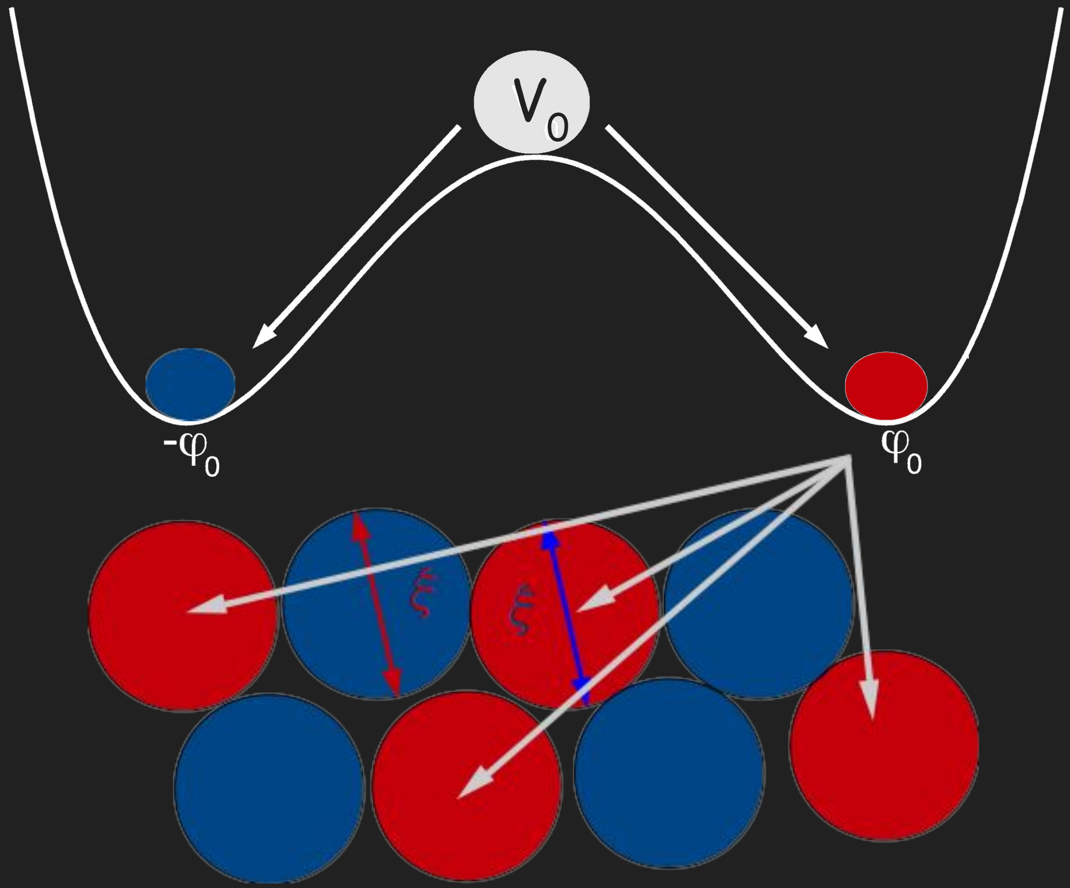
Symmetry (Z_2)

$$\varphi \longrightarrow -\varphi$$

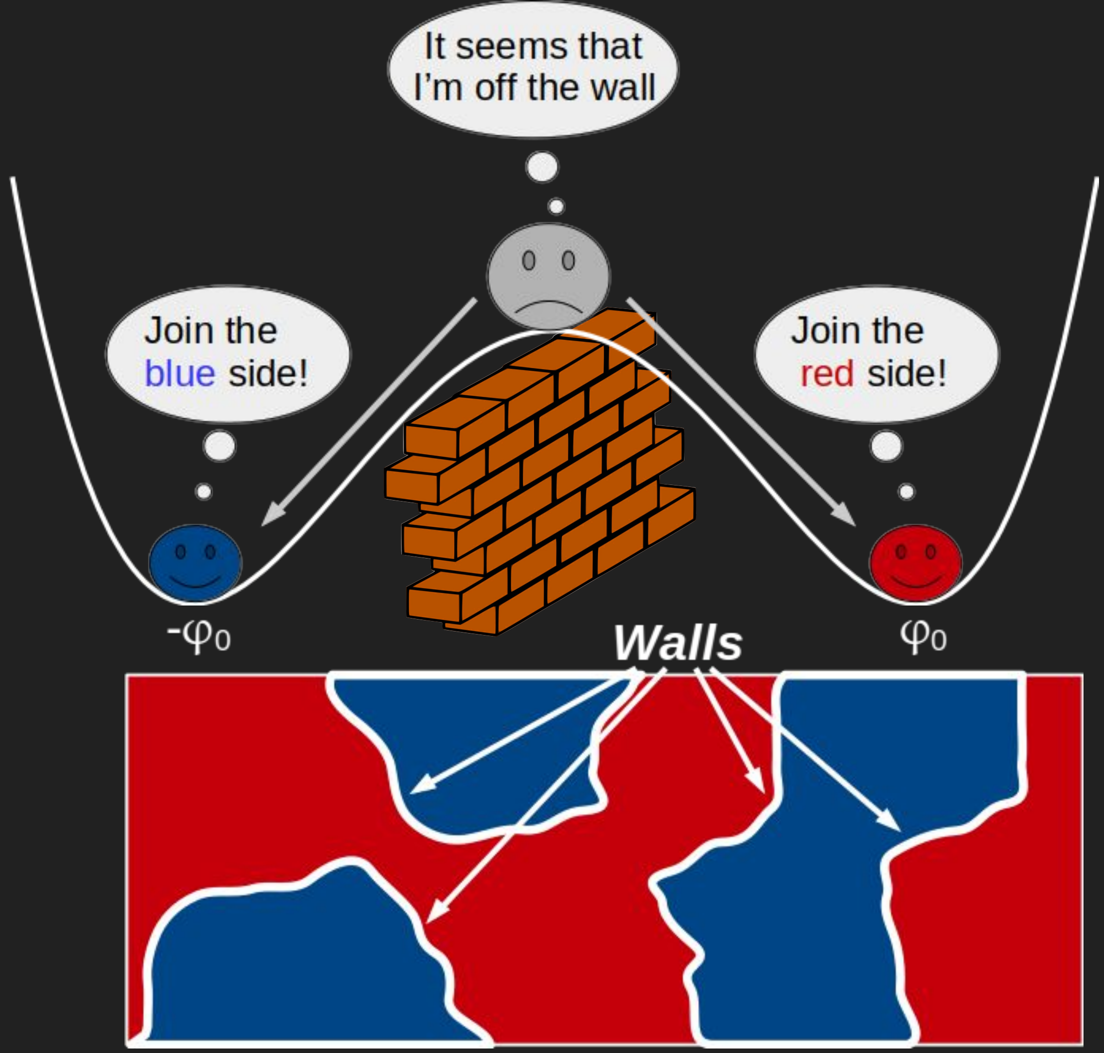




V_0
$-\varphi_0$
φ_0
ξ
ξ



V_0
$-\varphi_0$
φ_0
ξ
ξ


It seems that I'm off the wall
Join the blue side!
Join the red side!
$-\varphi_0$
φ_0
Walls

How do domain walls look like?

Energy density:

$$\rho = \frac{\mu_0}{L}$$

μ_0 - mass per unit area

Characteristic length:

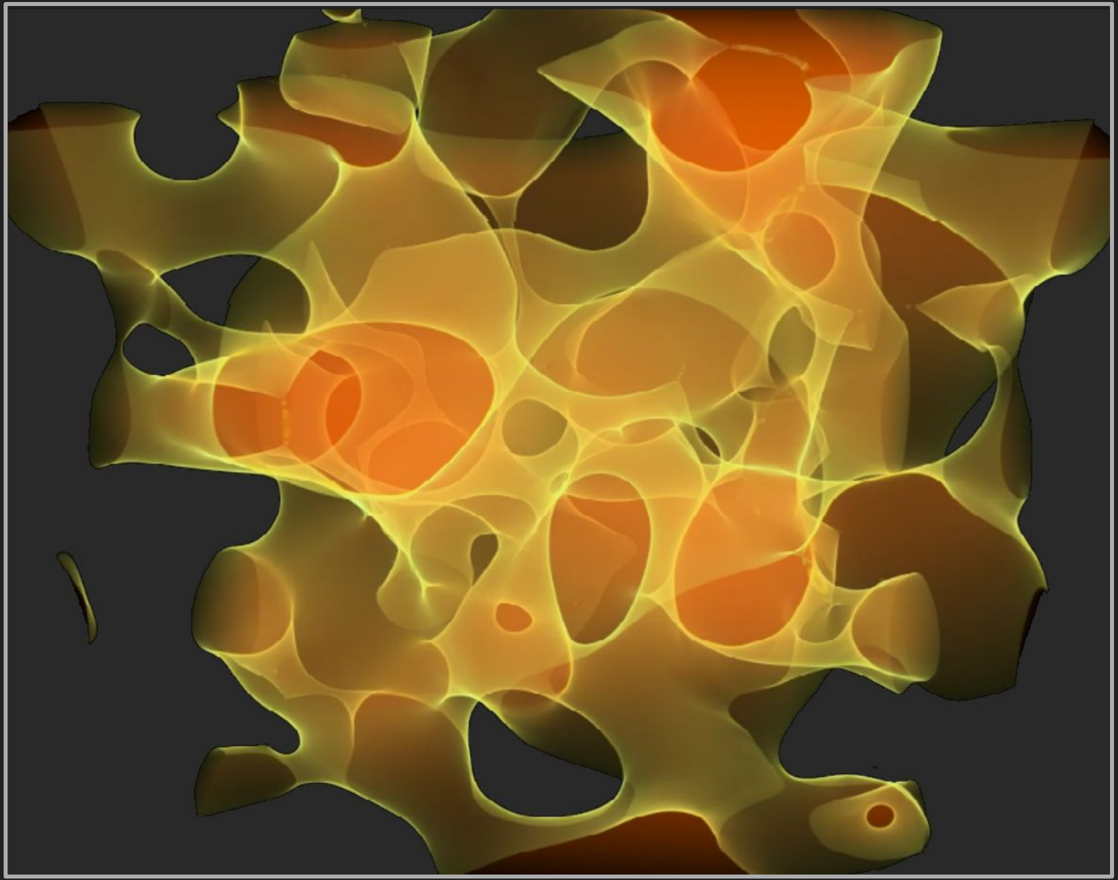
$$L \sim t$$

RMS velocity:

$$v$$

$V_0 < 1\text{Mev}$

[A Lazanu, C.J.A.P. Martins, E.P.S. Shellard, Phys.Lett.B 747 (2015) 426-432]



[C.J.A.P. Martins, I.R., A. Avgoustidis, E.P.S. Shellard, Phys.Rev.D 93 (2016) 4, 043534; Phys.Rev.D 94 (2016) 11, 116017]

Formation of cosmic strings

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F_{\mu\nu} + (D_\mu\varphi)^* D_\mu\varphi - [-\mu^2\varphi^*\varphi + \lambda(\varphi^*\varphi)^2]$$

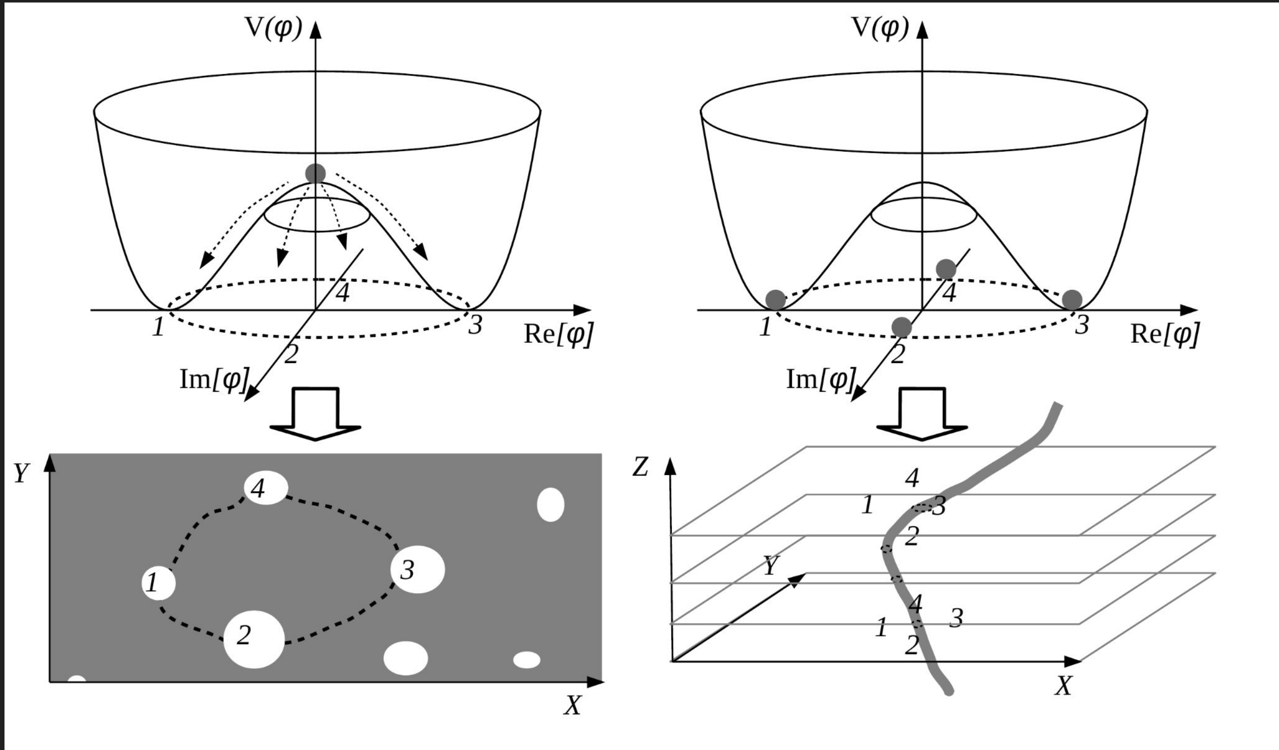
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad D_\mu\varphi = (\partial_\mu - ieA_\mu)\varphi$$

U(1) symmetry of Lagrangian:

$$\varphi(x) \quad \rightarrow \quad \varphi'(x) = \mathrm{e}^{i\alpha(x)}\varphi(x)$$

$$A_\mu(x) \quad \rightarrow$$

$$A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x)$$



How do cosmic strings look like?

Energy density:

$$\rho = \frac{\mu_0}{L^2}$$

μ_0 - tension

Characteristic length:

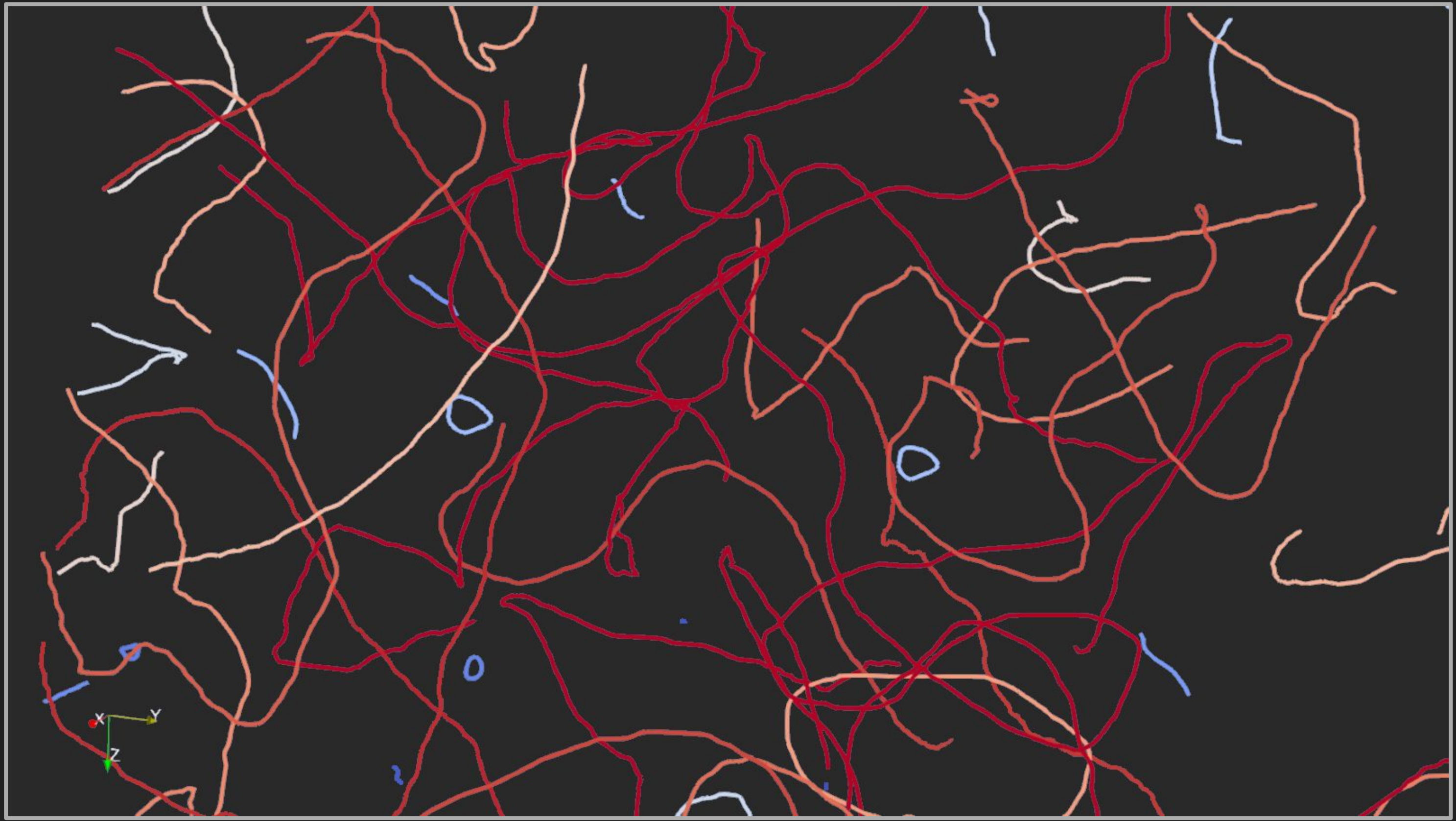
$$L \sim t$$

RMS velocity:

$$v$$

$$G\mu_0 < 10^{-7}$$

[J Lizarraga, et al *JCAP 10 (2016) 042*]



[J.R.C.C.C. Correia, C.J.A.P. Martins, *Astron.Comput.* 32 (2020) 100388; *Astron.Comput.* 34 (2021) 100438]

How to understand a string network evolution?

- Field theory simulations $\beta = m_\varphi^2/m_A^2$
  - ➢ local U(1) with critical coupling (Higgs and vector masses are identical): $\beta = 1$

$$\left.\begin{array}{l} v \sim \text{const.} \\ L \sim \xi t \end{array}\right\} \boxed{\text{scaling}}$$

[M. Hindmarsh, S. Stuckey,N. Bevis, Phys. Rev. D 79,(2009);
M. Hindmarsh, J. Lizarraga, J. Urrestilla, D. Daverio, M. Kunz, Phys.Rev.D 96 (2017);
J.R.C.C.C. Correia, C.J.A.P. Martins,Phys.Rev.D 104 (2021) 6, 063511, ….]

  - ➢ local U(1), Type I: $\beta < 1$

scaling

[M. Hindmarsh, J. Lizarraga, J. Urrestilla, D. Daverio, M. Kunz, Phys.Rev.D 99 (2019),
T. Hiramatsu, Y. Sendouda, K. Takahashi, D. Yamauchi, C.-M. Yoo, Phys.Rev.D 88 (2013)]

  - ➢ global U(1) (or local Type II $\beta \to \infty$)

scaling?

[M. Yamaguchi, J. Yokoyama Phys.Rev.D 67 (2003),
M. Hindmarsh, J. Lizarraga, A. Lopez-Eiguren, J. Urrestilla, Phys.Rev.D 103 (2021), ...
M. Gorghetto, E. Hardy, G. Villadoro, JHEP 07 (2018) 151,
A. Vaquero, J. Redondo, J. Stadler, JCAP 04 (2019),
M. Buschmann et al, Nature Commun. 13 (2022) 1, …]

- Nambu-Goto simulations

scaling

[C.J.A.P. Martins, E.P.S. Shellard, Phys.Rev.D 73 (2006) 043515,
C. Ringeval, M. Sakellariadou, F. Bouchet, JCAP 02 (2007) 023,
J. J. Blanco-Pillado, K. D. Olum, B. Shlaer, Phys.Rev.D 83 (2011) 083514]

[Topology of cosmic domains and strings TWB Kibble, J. Phys. A, 1976.]

Are cosmic strings common?

Classification:

$\pi_0\,(G/K) \neq I$ - walls;

$\pi_1\,(G/K) \neq I$ - strings;

$\pi_2\,(G/K) \neq I$ - monopoles;

$\pi_3\,(G/K) \neq I$ - textures.

- ❖ The dynamical generation of right-handed-neutrino masses in the early Universe naturally entails the formation of cosmic strings.

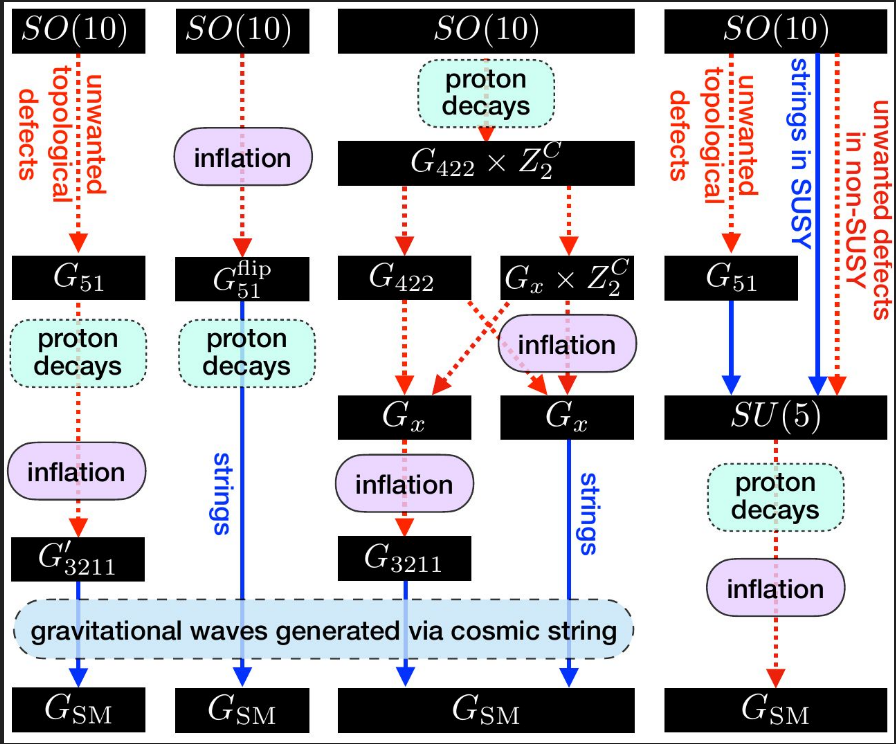
  [S. Blasi, V. Brdar, K. Schmitz, Phys. Rev. Research 2, 043321 (2020)]

- ❖ QCD color fluxes (deconfinement to confinement)

  [Yamada, Yonekura, Phys.Rev.D 106 (2022) 12]

- ❖ Complementarity to proton decay to probe viability of GUT SO(10)

  [S. F. King, S. Pascoli, J. Turner, Y.-L. Zhou, JHEP 10 (2021) 225]

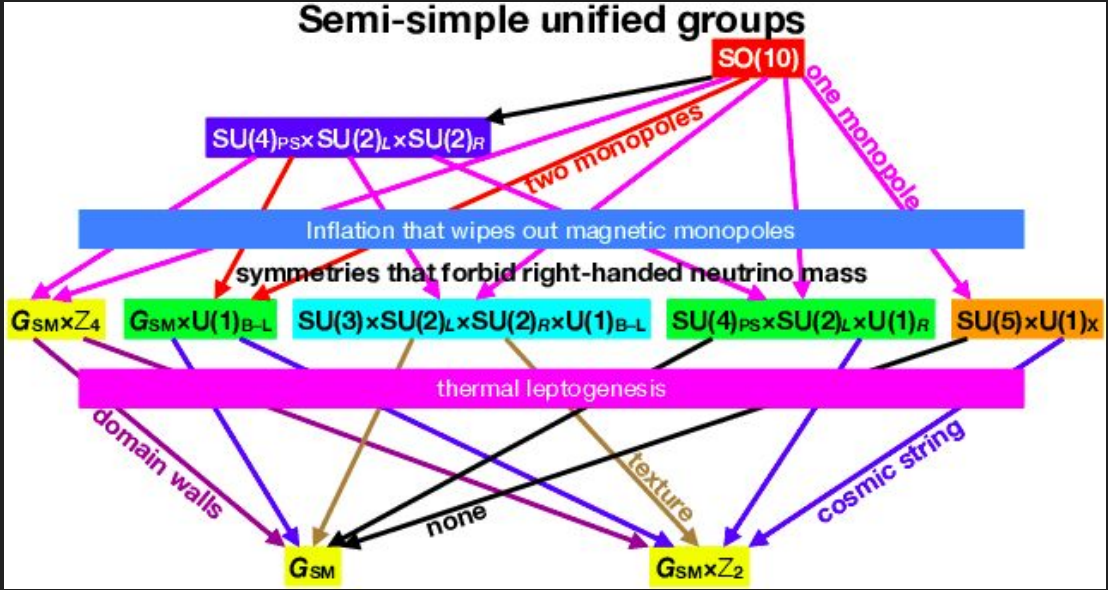


[S. F. King, S. Pascoli, J. Turner, Y.-L. Zhou, Phys. Rev. Lett. 126, 021802 (2021)]

… and many others

Do we simulate/model **realistic** cosmic strings?

Fields that produce cosmic string core can be coupled with other fields in a different way. We have to go beyond "vanilla" cosmic string to make accurate predictions.



[J. A. Dror, T. Hiramatsu, K. Kohri, H. Murayama, G. White, Phys. Rev. Lett. 124, 041804, 2020]

Are U(1) models accurate enough?

"Everything should be made as simple as possible, but not simpler"

How common superconducting strings?

List of mechanisms:

- Another field coupled with cosmic string; [B. Hartmann, F. Michel, P. Peter, Phys. Rev. D 96, 123531, (2017)]
- Fermions trapped along the string; [C.Ringeval, Phys.Rev.D64,123505,2001]
- Cosmic strings from SUSY models; [S.C.Davis et.al, Phys.Lett.B405,257-264,1997]; [E. Allys, JCAP 04 (2016) 009]
- Trapped vector flux; [A.E.Everett, Phys.Rev.Lett.61,1807-1810,1988]
- Non-abelian strings; [Lilley, Di Marco, Martin, P. Peter, Phys. Rev.D82, 023510 (2010]
- Spontaneous current generation; [P. Peter, Phys.Rev.D 49 (1994) 5052-5062]
- Yang-Mills-Higgs theory; [T. Vachaspati, Phys.Rev.D 107 (2023) 3]
- others... [M.Hindmarsh,et.al. Phys.Rev.Lett.117,25,251601,2016]

Axion strings are superconducting;

[G. Lazarides, Q. Shafi, Phys. Lett. B. 151 (2): 123–126]
[H. Fukuda, A. V. Manohar, H. Murayama, O. Telem, 10.1007/JHEP06(2021)052];
[Y. Abe, Y. Hamada, K. Yoshioka, 10.1007/JHEP06(2021)172];

Example of superconducting cosmic strings

[Witten, Nucl.Phys. B249 (1985) 557-592, D. Haws, M. Hindmarsh, N. Turok, Phys.Lett.B 209 (1988) 255-261]

Symmetry of Lagrangian: $U(1) \times \tilde{U}(1)$

$$\mathcal{L} = \frac{1}{2}\left(\mathcal{D}_\mu \varphi\right)^* \mathcal{D}^\mu \varphi + \frac{1}{2}\left(\tilde{\mathcal{D}}_\mu \sigma\right)^* \tilde{\mathcal{D}}^\mu \sigma - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} \tilde{F}_{\mu\nu} \tilde{F}^{\mu\nu} - V(\sigma, \varphi)$$

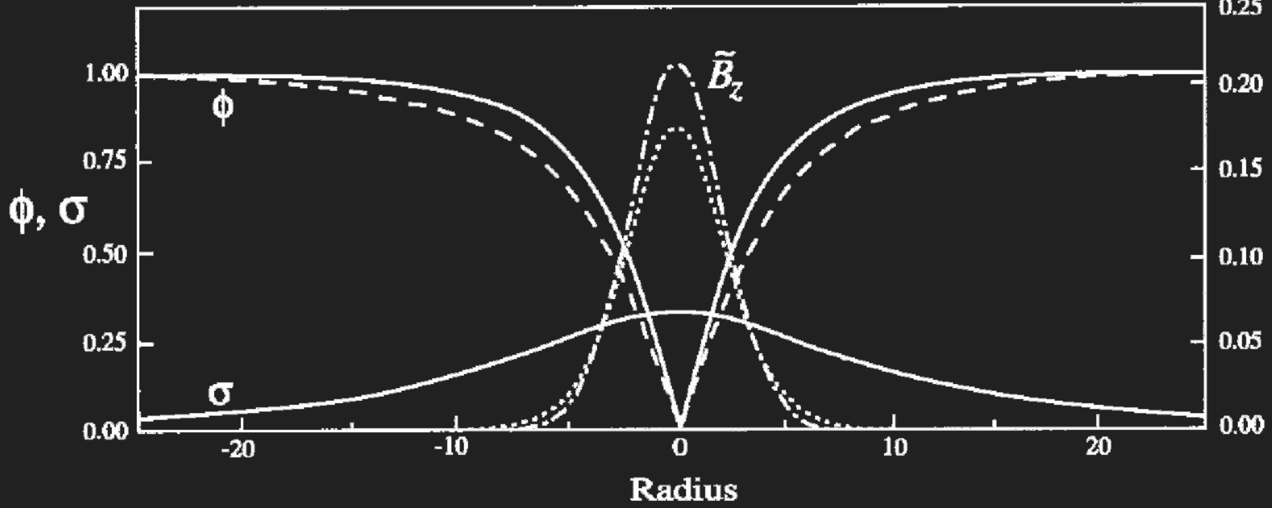
where $V(\sigma,\varphi)=\frac{1}{8}\lambda\left(|\varphi|^2-\mu^2\right)^2+\frac{1}{4}\tilde{\lambda}|\sigma|^4+f|\sigma|^2|\varphi|^2-m^2|\sigma|^2$

vacuum: $\varphi=\mu \quad \sigma=0$

string core: $\varphi=0 \quad \sigma\neq 0$

$\mu^2, m^2, f|\varphi|^2-m^2>0$

simulation?



Effective description

We can integrate out heavy transverse modes and obtain effective action:

(on a 2-d worldsheet conserved current can be represented by a derivative of a scalar field)

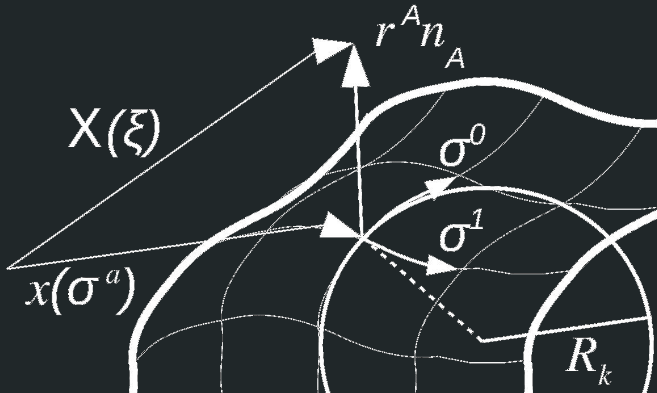
$$S = -\mu_0 \int \underline{f(\kappa)} \sqrt{-\gamma}\, \mathrm{d}\sigma^0 \mathrm{d}\sigma^1$$

master function

defines properties of the string that mimic original field-theory model.

where 4-current: $\kappa = \kappa_0 \gamma^{ab} \phi_{;a} \phi_{;b}$

and induced metric: $\gamma_{ab} = g_{\mu\nu} X^{\mu}_{,a} X^{\nu}_{,b}$

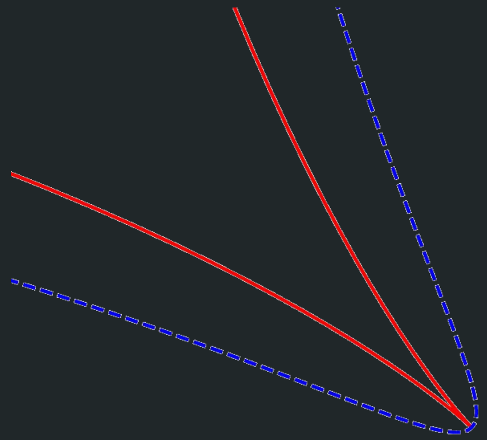


Dynamics of the current is absorbed in the variable κ .

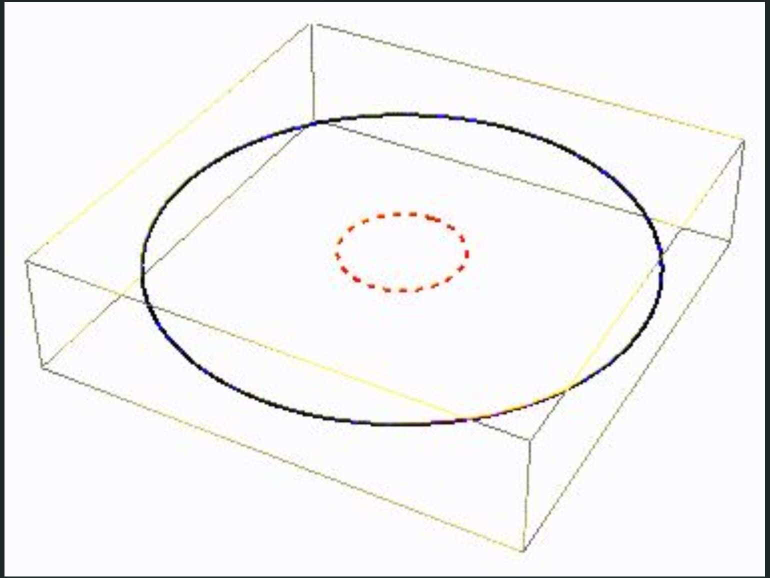
Absence of cusps, possibility of vortons

[B. Carter, Phys.Rev.D41, 3869 (1990),
hep-th/9705172, (1997),
IR, Phys.Rev.D 102 (2020) 8, 083516]

Possible shapes of the cusp:



Oscillation of the loop:



When $X(\sigma,\tau)$ describes the string worldsheet, $\varphi(\sigma,\tau)$ is a propagating current on this worldsheet. Then we cannot find such (σ_0,τ_0): $\gamma_{00} \to 0$, $\gamma_{11} \to 0$ whenever $\varphi(\sigma_0, \tau_0) \neq 0$ and $f'_\kappa \neq 0$. (no cusps)

Gravitational wave emission from current-carrying loops

Power of gravitational radiation: $P = G\mu_0^2\Gamma$

Efficiency of radiation: $\Gamma \equiv \sum_{j=0}^{\infty}\Gamma_j = \sum_{j=0}^{\infty}\int \omega_j^2 \frac{\left|I_j^{22} - I_j^{33}\right|^2 + \left|I_j^{23} + I_j^{32}\right|^2}{2^3\pi T_\ell^2} d\Omega$

where $I_j^{23} = I_+^i I_-^k n_{(2)i} n_{(3)k}$ and $I_\pm^\mu = \frac{T_\ell}{\pi}\int_0^{2\pi} \underline{X_\pm'^\mu} \mathrm{e}^{-\frac{iT_\ell}{2\pi} k_\nu X_\pm^\nu} d\sigma_\pm$

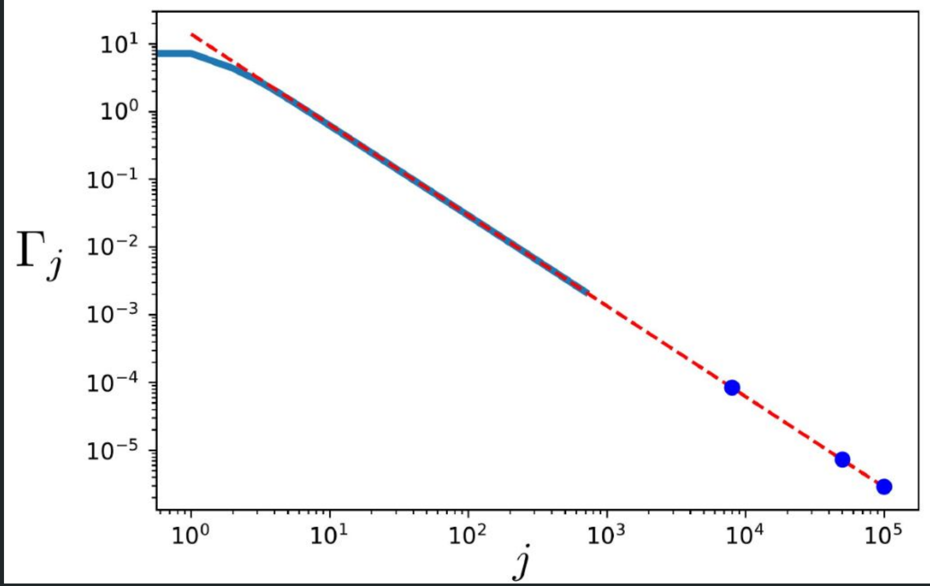
We apply these expressions to study gravitational radiation efficiency for cusp-like points and Burden types of loops, also for kinks and cuspless loops.

[I.R., L. Sousa, JCAP 11 (2022) 024]

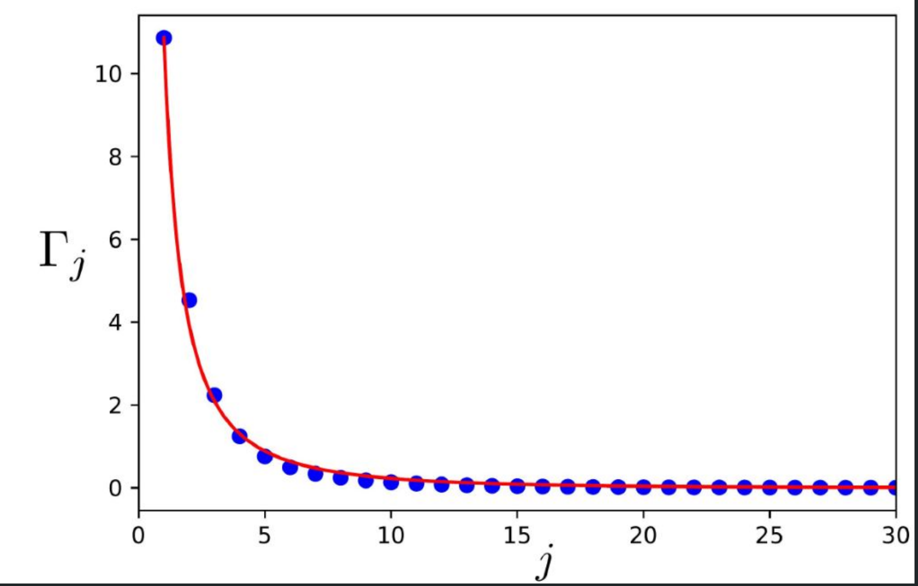
Burden type of loops.

Radiation efficiency depending on harmonic modes.

For loops without current



For "symmetric" $G`_{\pm}$=0.9 current

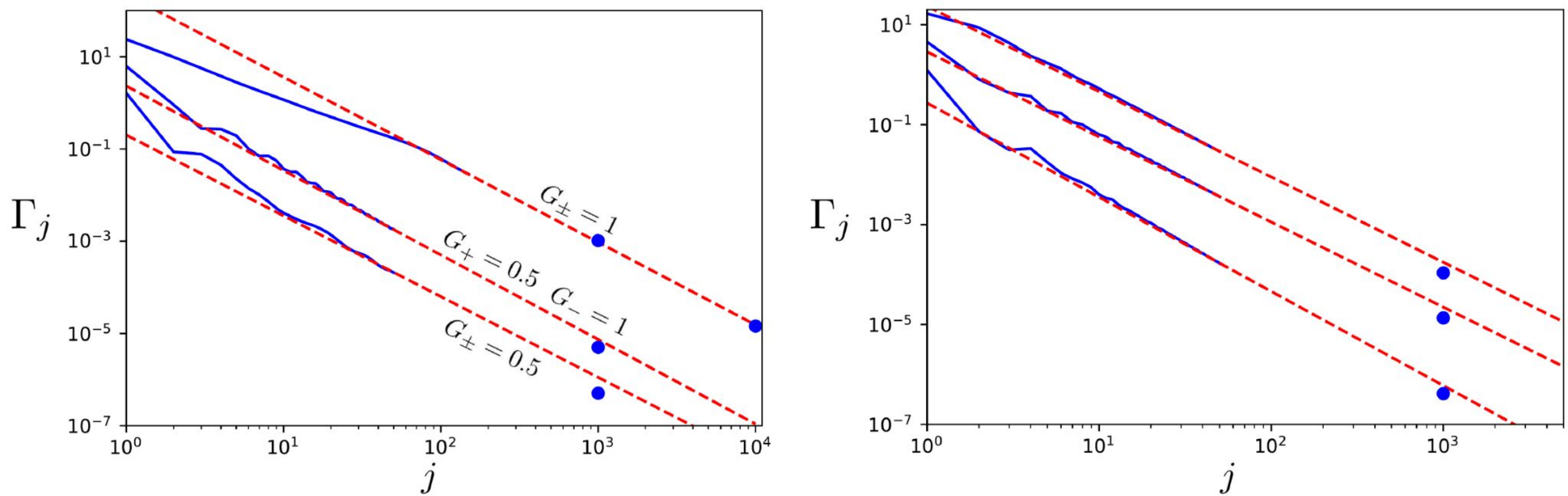


we established the following relations

$$\Gamma_j \sim j^{-q} \mathrm{e}^{-j f_m(G_\pm)} \qquad f_m(G_\pm) = a_m(1 - \sqrt{G_\pm})^{b_m} \qquad G_\pm = \sqrt{1 - F'^2_\pm(\sigma_\pm)}$$

Kinks and Cuspless type of loops.

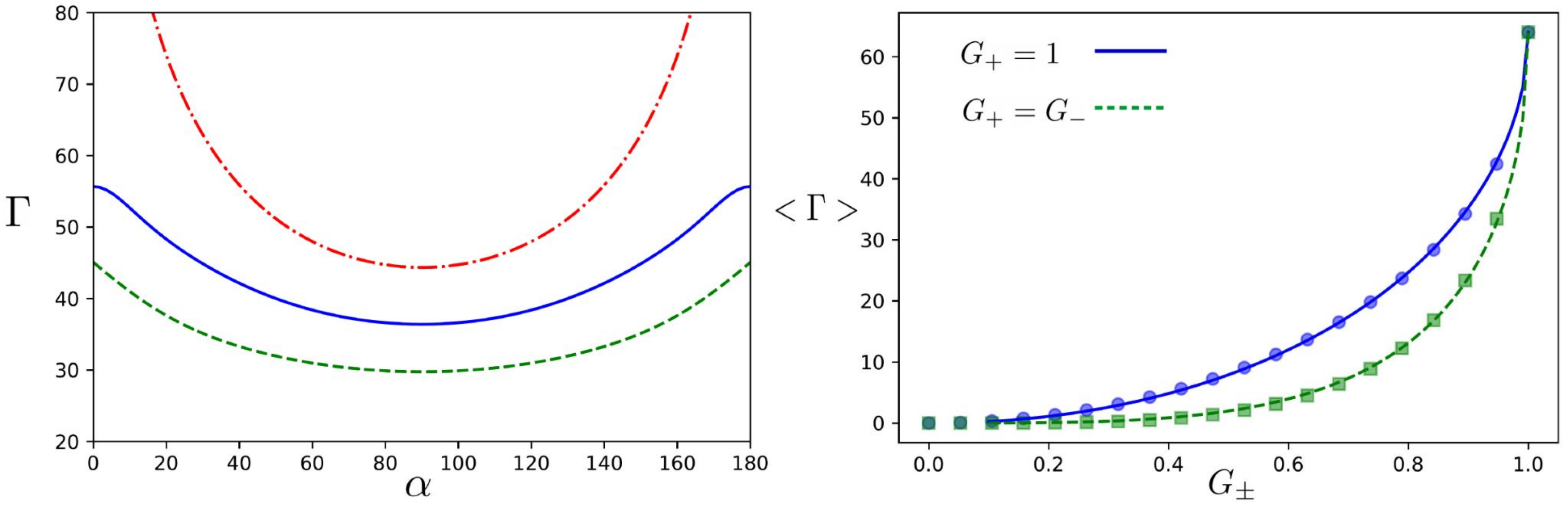
Radiation efficiency decays as a power law for kinks.



[I.R., L. Sousa, JCAP 11 (2022) 024]

Cusspless type of loops.

The same phenomenological relation for gravitational radiation efficiency: $\Gamma_G^m = \Gamma_0(1-|F'_\pm|)^{B_\Gamma^m}$

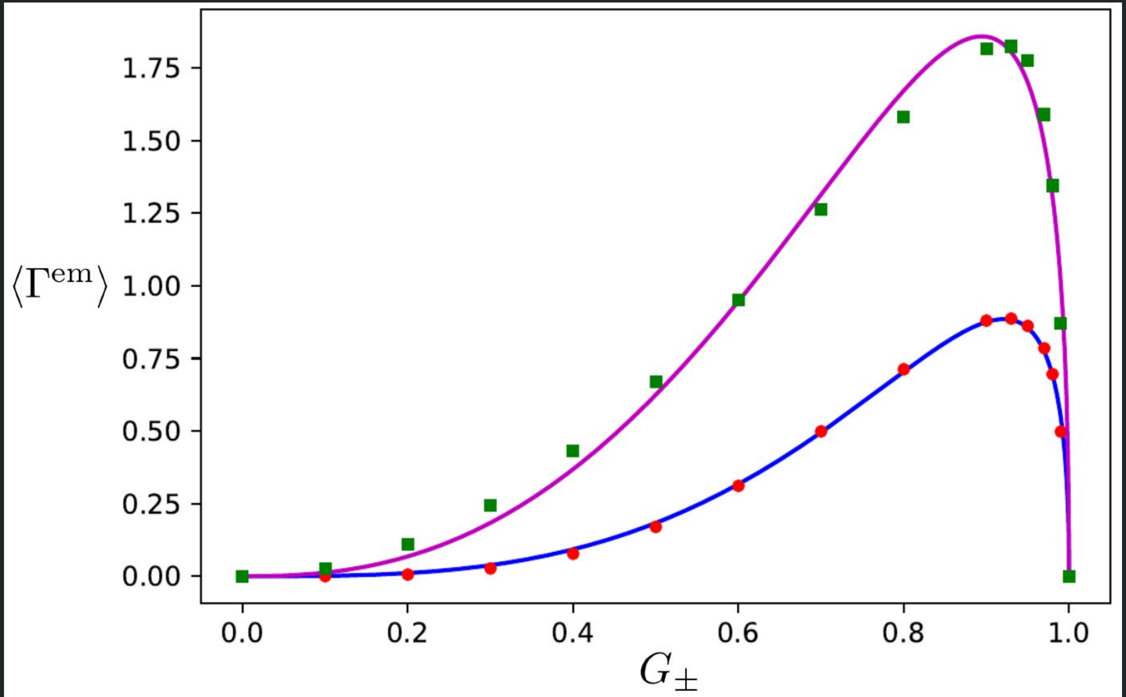


B_Γ^s	1.89	1.56	1.46	1.56	1.89
$\sqrt{2}B_\Gamma^c$	1.68	1.27	1.14	1.27	1.68

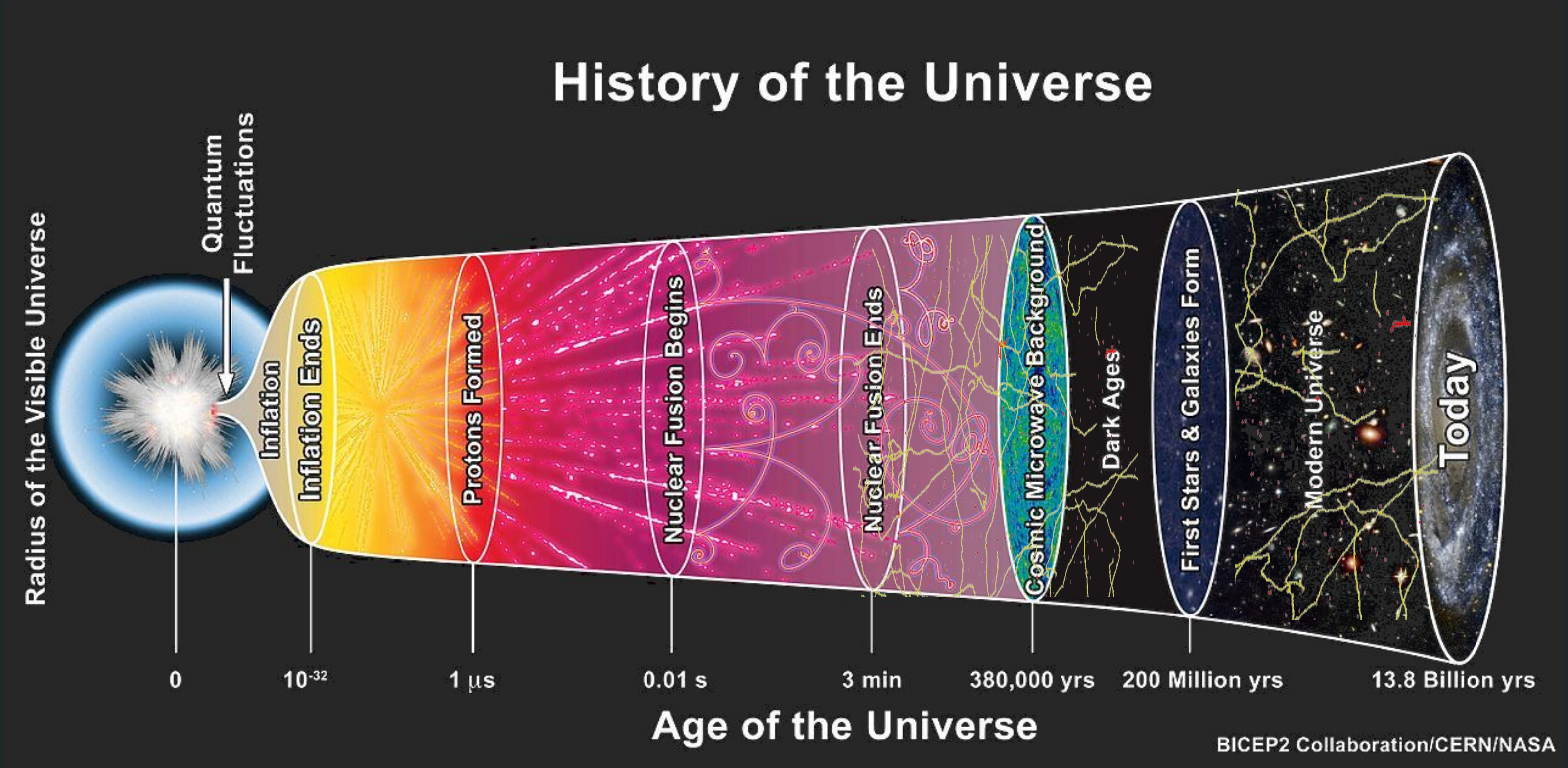
Burden type of loops.

Preliminary

Radiation from cusps exponentially suppressed for high harmonic modes, the radiation efficiency can be described by $\langle \Gamma^{\rm em} \rangle = A_\Gamma |F_\pm| \left(1 - |F_\pm|\right)^{D_\Gamma}$



To predict possible signals, we need
to understand the macroscopic description of
a string network evolution in the expanding universe.



[C.J.A.P. Martins, P. Peter, I. R., E.P.S. Shellard, Phys.Rev.D 103 (2021)]

Macroscopic evolution.

Charge-velocity-dependent one-scale (CVOS) model, provides qualitative extension of the standard cosmic string network to a superconducting one.

$$S = \mu_0 \int f(\kappa)\sqrt{-\gamma}\, \mathrm{d}\sigma^0 \mathrm{d}\sigma^1$$

Averaging: $\langle \mathcal{O} \rangle \equiv \dfrac{\int \mathcal{O}\epsilon\, \mathrm{d}\sigma}{\int \epsilon\, \mathrm{d}\sigma}$

$$\epsilon^2 = \frac{\mathbf{x}'^2}{1-\dot{\mathbf{x}}^2}$$

String core energy:

$$E_0 = a\mu_0 \int \epsilon\, \mathrm{d}\sigma = \frac{\mu_0 V}{\xi_c^2 a^2}$$

Full energy:

$$E = a\mu_0 \int \bar{U}\epsilon\, \mathrm{d}\sigma = \frac{\mu_0 V}{L_c^2 a^2}$$

Thermodynamical variables:

RMS velocity:	v
Characteristic length:	L_c
Charge:	Y
Chirality:	K

Energy loss terms

Loops production mechanism:

[C.J.A.P. Martins, E.P.S. Shellard, Phys.Rev.D 54 (1996)]

$$\frac{\dot{\xi}_c}{\xi_c} = \cdots + \frac{\tilde{c}}{2}\frac{v}{\xi_c}$$

Loss of charge due to loops:

[M.F. Oliveira, A. Avgoustidis, C.J.A.P. Martins, Phys.Rev.D 85 (2012) 083515]

$$\frac{\dot{L}_c}{L_c} = \cdots + g(J,Q)\frac{\tilde{c}}{2}\frac{v}{\xi_c}$$

Charge/current leakage mechanism(?):

[Y. Abe, Y. Hamada, K. Saji, JHEP 02 (2023) 004]

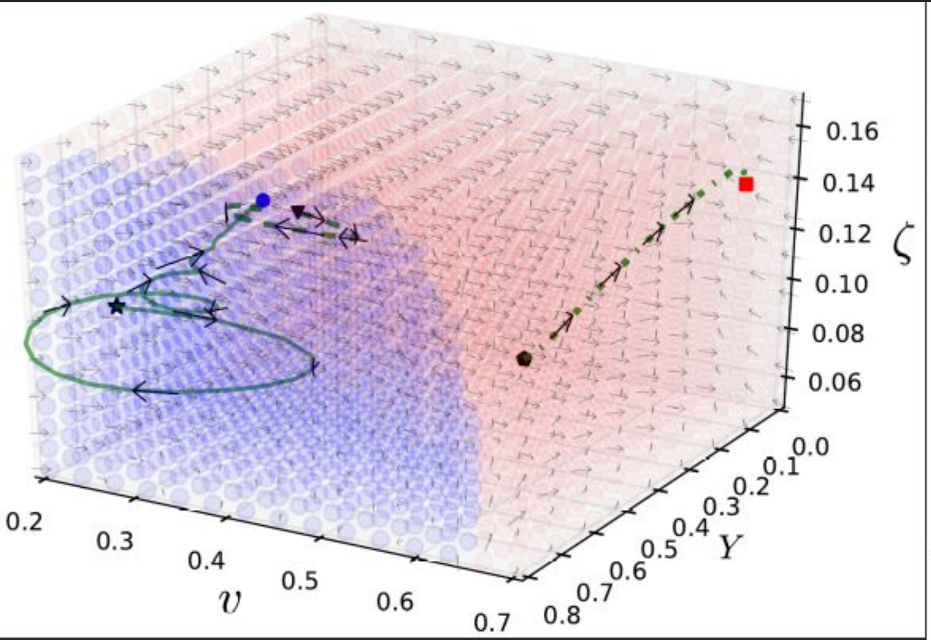
$$\left.\frac{\mathrm{d}Y}{\mathrm{d}\tau}\right|_{\mathrm{leakage}} = -A\frac{Y}{\xi_c}$$

Evolution

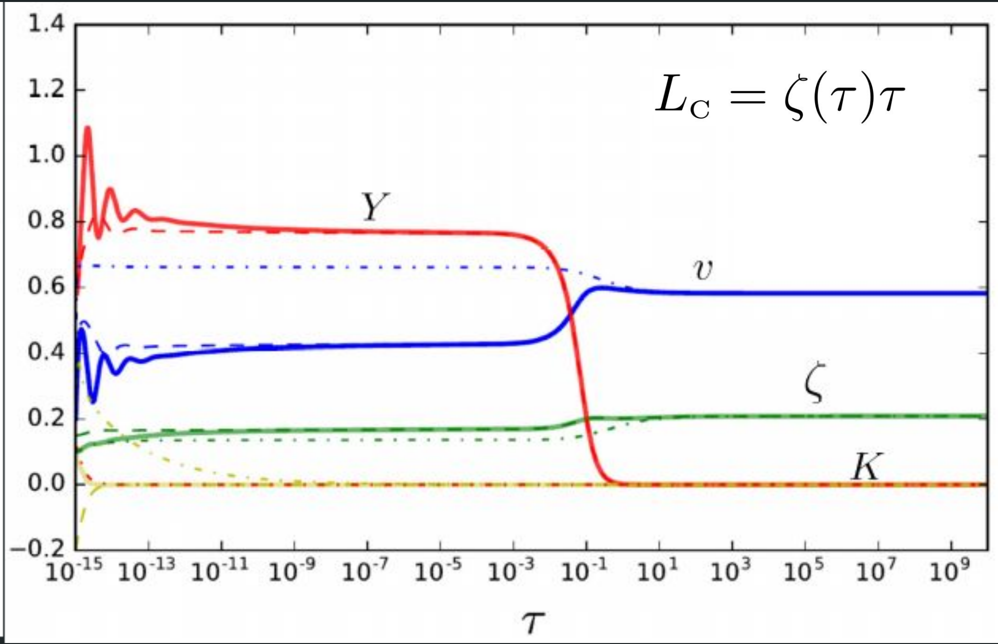
[I.R., C.J.A.P. Martins, P. Peter, E.P.S. Shellard, Phys.Rev.D 107 (2023) 12]

Dynamics of the CVOS model for linear equation of state. Depending on initial conditions, the network can be charged or standard. Approaches linear scaling

[C.J.A.P. Martins, P. Peter, I. R., E.P.S. Shellard, Phys.Rev.D 104 (2021)]



Phase portrait for CVOS. Colors define regions of initial conditions.



Evolution during radiation-matter dominated periods.

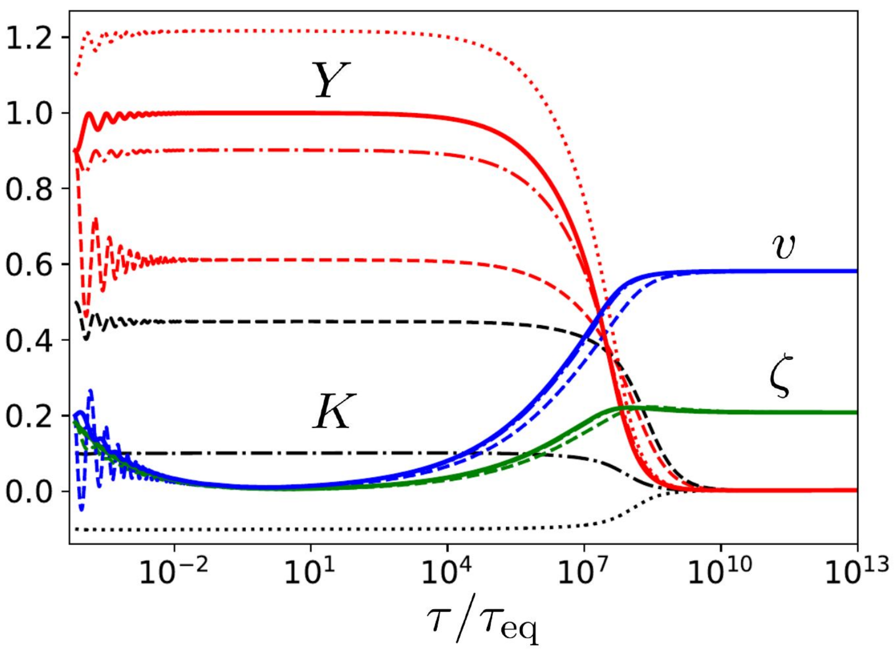
Critical current

[I.R., C.J.A.P. Martins, P. Peter, E.P.S. Shellard, Phys.Rev.D 107 (2023) 12]

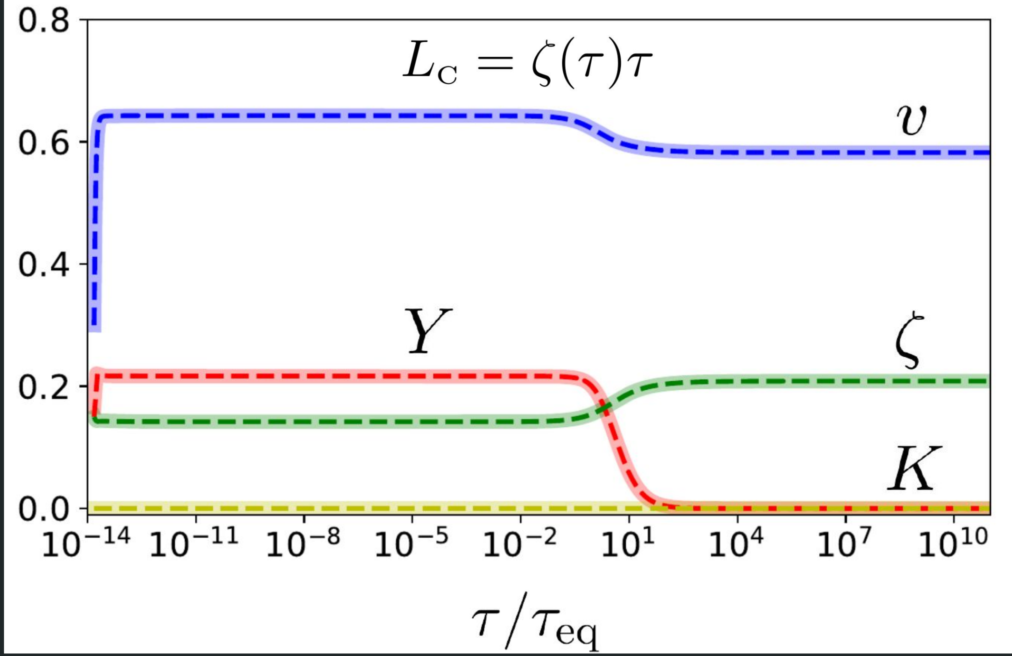
Frozen network is possible only when the charge cannot escape the string: *A=0*

Charge leakage function:

$$A \to A_\alpha(Y) = \frac{B}{1 - \mathrm{e}^{-(Y-Y_{\mathrm{cr}})^2}}$$



Evolution of the frozen network during radiation-matter dominated epochs.

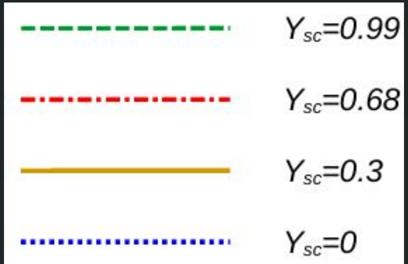


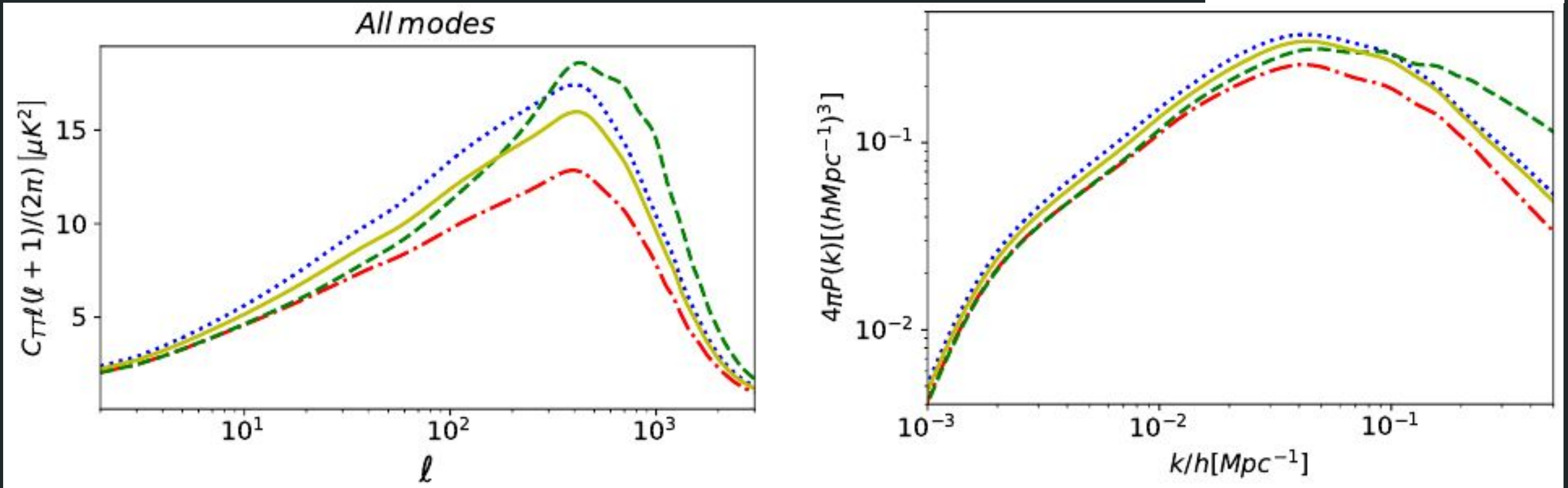
Evolution with critical current during radiation-matter dominated periods.

CMB generated by a current-carrying cosmic string network.

We extended CMBACT code [L. Pogosian, T. Vachaspati, Phys.Rev.D 60 (1999)]

Linear scaling regime, Y_{SC} is a scaling value for radiation dominated period.





CMB generated by a current-carrying cosmic string network.

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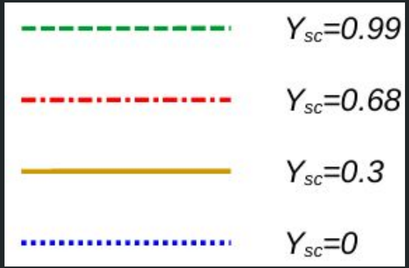
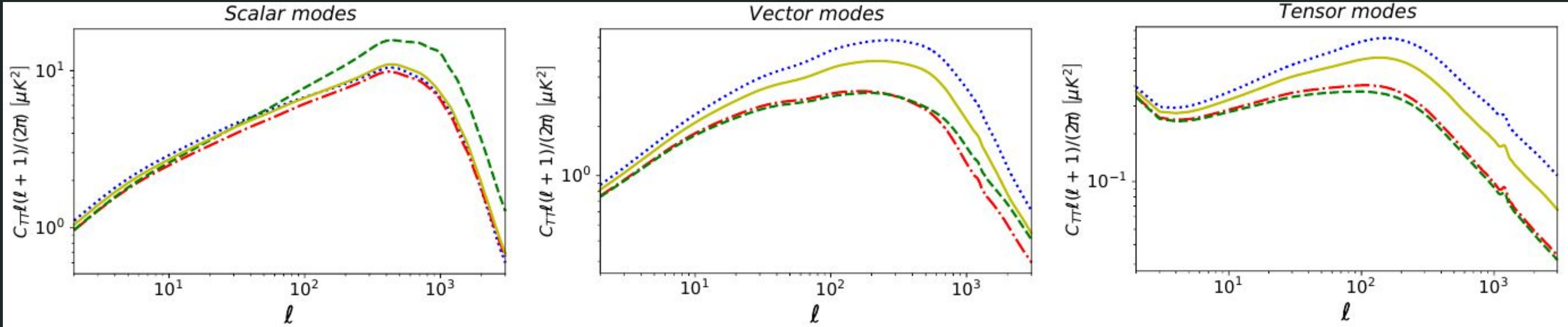
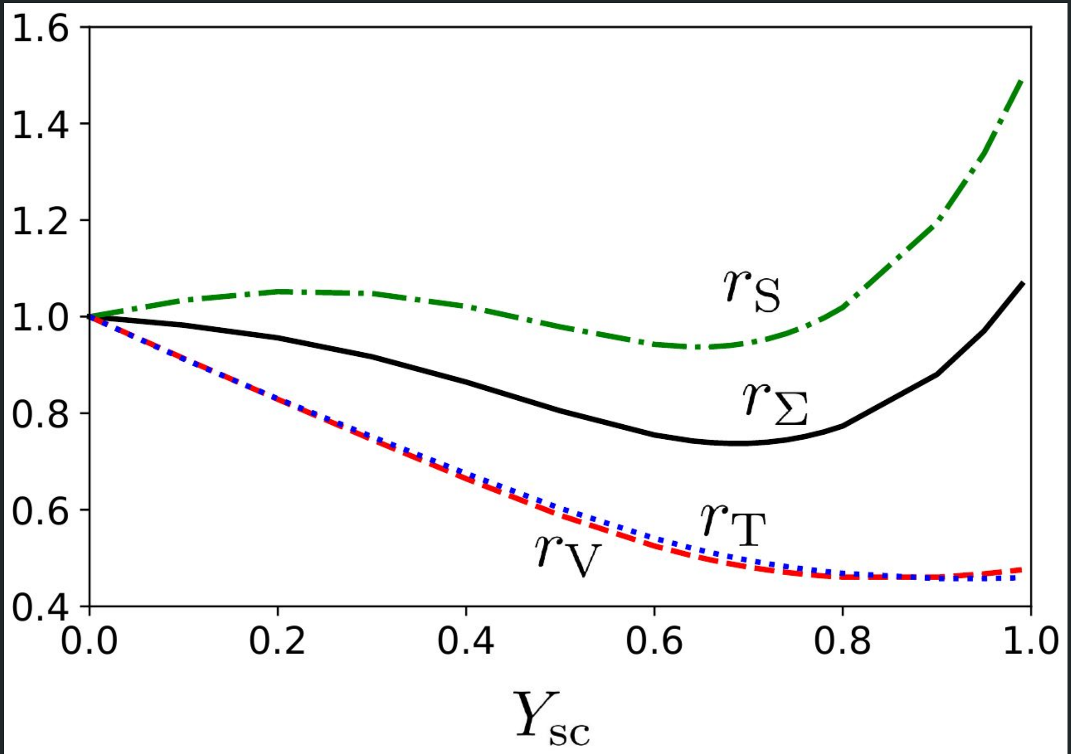




CMB signature of current-carrying cosmic strings

[I.R., C.J.A.P. Martins, P. Peter, E.P.S. Shellard, upcoming]

Peak of anisotropies for scalar, vector and tensor modes depending on charge



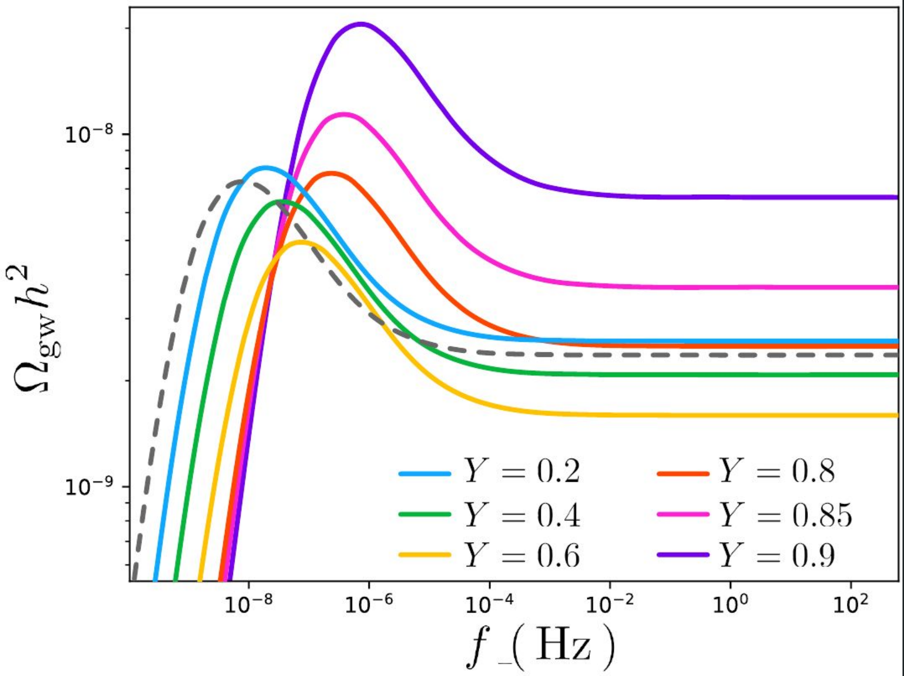
SGWB generated by loops with kinks

[I.R., L. Sousa, JCAP 11 (2022) 024]

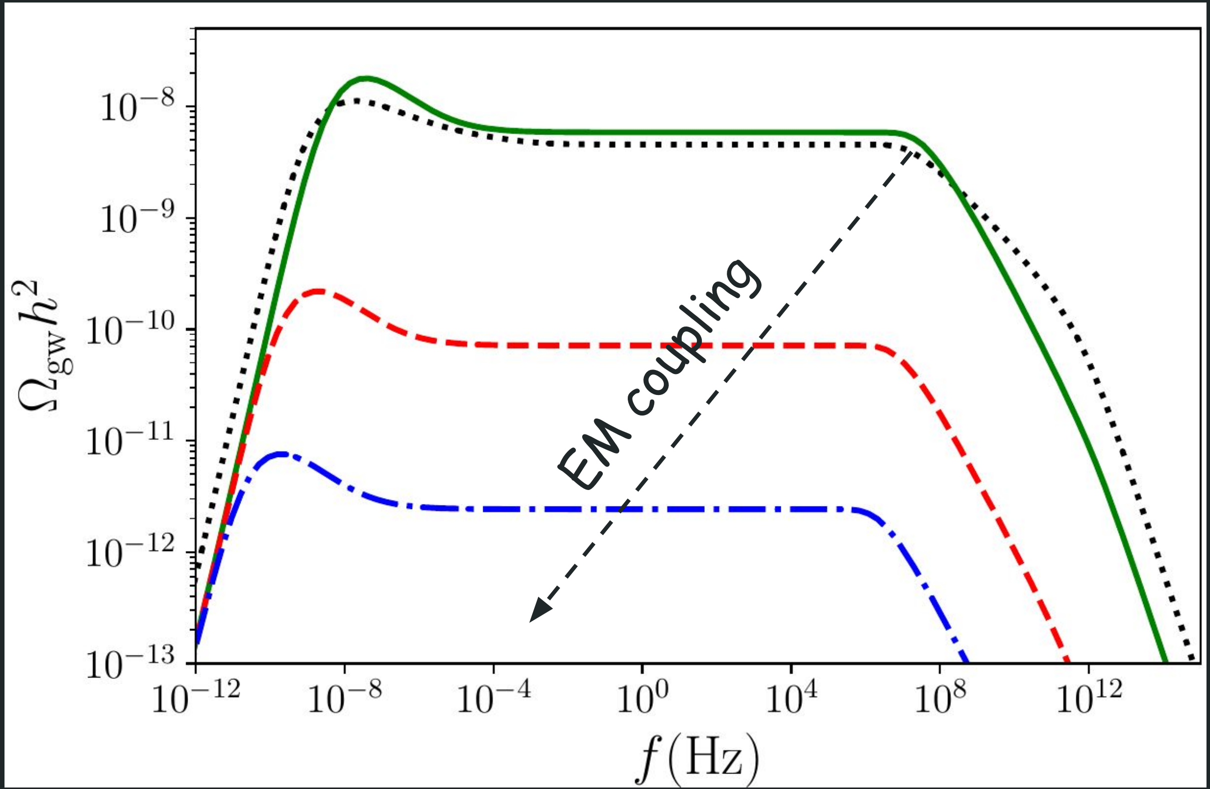
$$\Omega_{\rm gw}(f) = \frac{16\pi}{3}\left(\frac{G\mu_0}{H_0}\right)^2 \frac{1}{f}\int_{t_i}^{t_0} dt' \left(\frac{a(t')}{a(t_0)}\right)^5 \sum_{j=1}^{+\infty} j\Gamma_j n(\ell_j(t'), t')$$

Kinks are main sources of radiation, since they are not exponentially suppressed by current.

Complete spectrum and a template for future constraints will come soon . . .



With vector emission



SGWB for the string network with tension $G\mu_0 = 10^{-10}$ and with different values of the coupling with vector field.

take-home message:

1. Current-carrying strings might be essential for accurate constraints and to probe couplings of the high-energy models.

2. Compared to the Nambu-Goto case, the current propagation on the string suggests suppression of radiation.

3. SGWB is affected by properties of radiation and by evolution of the current-carrying string network.

4. CMB anisotropies generated by current-carrying cosmic strings predict increase of scalar modes and decrease of vector/tensor modes.

Thank you for your attention!