

Field Theoretical Approach to the Formation of Junctions of Cosmic Strings



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COSMO-07, University of Sussex

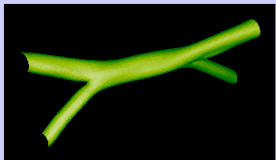
Tom Kibble

Ed Copeland

Danielle Steer

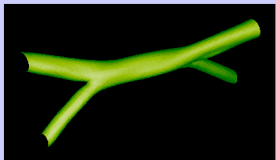
Ana Achúcarro

Roland de Putter



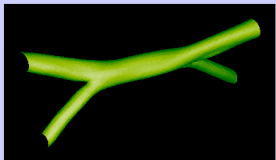
Outline

1. Cosmic Strings
2. Cosmic Superstrings
3. When Do the Junctions Form?
4. Field Theory Set-Up: Abelian-Higgs Model
5. Simulations
6. Results
7. Discussion



Cosmic Strings

- **Vortex solutions** in the Abelian-Higgs model (Nielsen and Olesen, Nucl. Phys. B 61, 1973).
- Formation of defects in the early Universe (Kibble, J. Phys. A9, 1976).
- String **networks scale**: strings could contribute a fixed fraction of the total energy density of the Universe, $\Omega_{\text{strings}} \ll \Omega_{\text{total}} \approx 1$.



Cosmic Strings II

Strings at cosmic scales have **observable signatures**:

1. CMB power spectrum

Durrer *et al.*, 2002

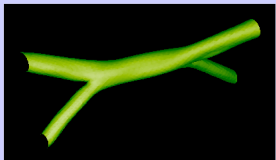
Pogosian *et al.*, 2004 -

Bevis *et al.*, 2004 -

2. Gravitational waves

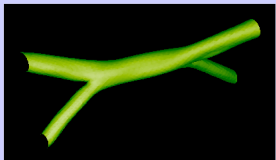
3. Gravitational lensing

(for observing loops at radio frequencies see
Mack, Wesley and King, astro-ph/0702648)



Cosmic Superstrings

- “No-Go”: too high tension, break-up instability
(Witten, Phys. Lett. B153, 1985).
- These problems can be circumvented: e.g. strings can have **lower tensions** due to warping, they can be **produced in brane inflation**, etc.
(see e.g. Sarangi and Tye, Phys. Lett. B536, 2002).



Cosmic Superstrings II

- Possibility of networks of fundamental **F-strings** and Dirichlet **D-strings** and their bound states, **(p,q) -strings**.

(Copeland, Myers and Polchinski, JHEP 0406, 2004;
Firouzjahi, Leblond and Tye, JHEP 0605, 2006)

- The evolution of the string network with junctions is of interest: **scaling** or a **frozen** network?

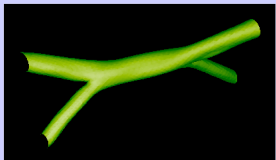
(see e.g. Saffin, JHEP 0509, 2005;

Hindmarsh and Saffin, JHEP 0608, 2006;

Leblond and Wyman, Phys. Rev. D 75, 2007;

Avgoustidis and Shellard, 0705.3395 [astro-ph];

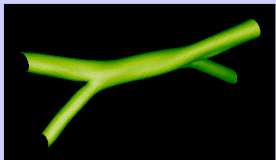
Rajantie, Sakellariadou and Stoica, 0706.3662 [hep-th])

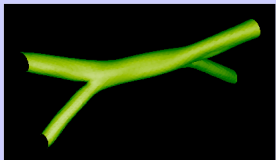
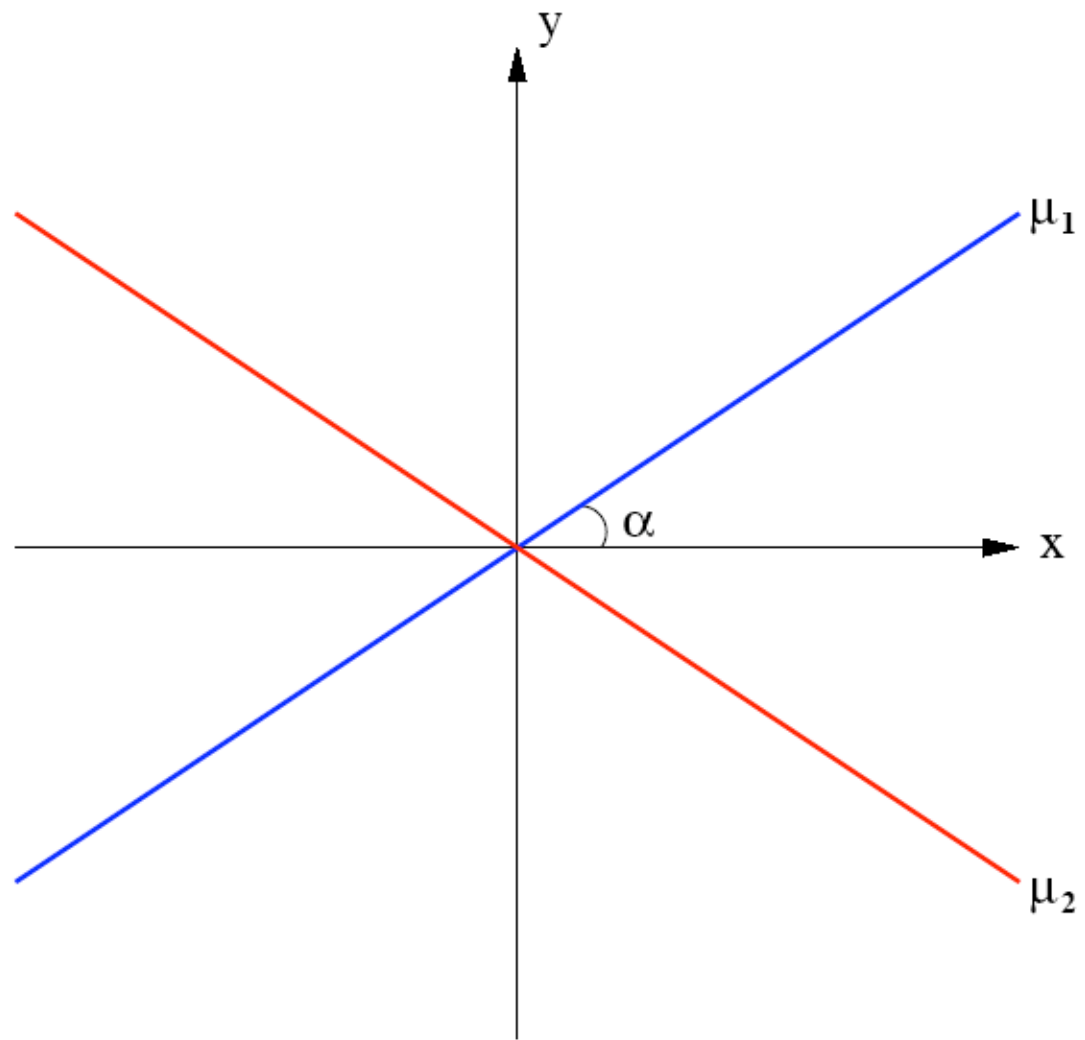


When Do the Junctions Form?

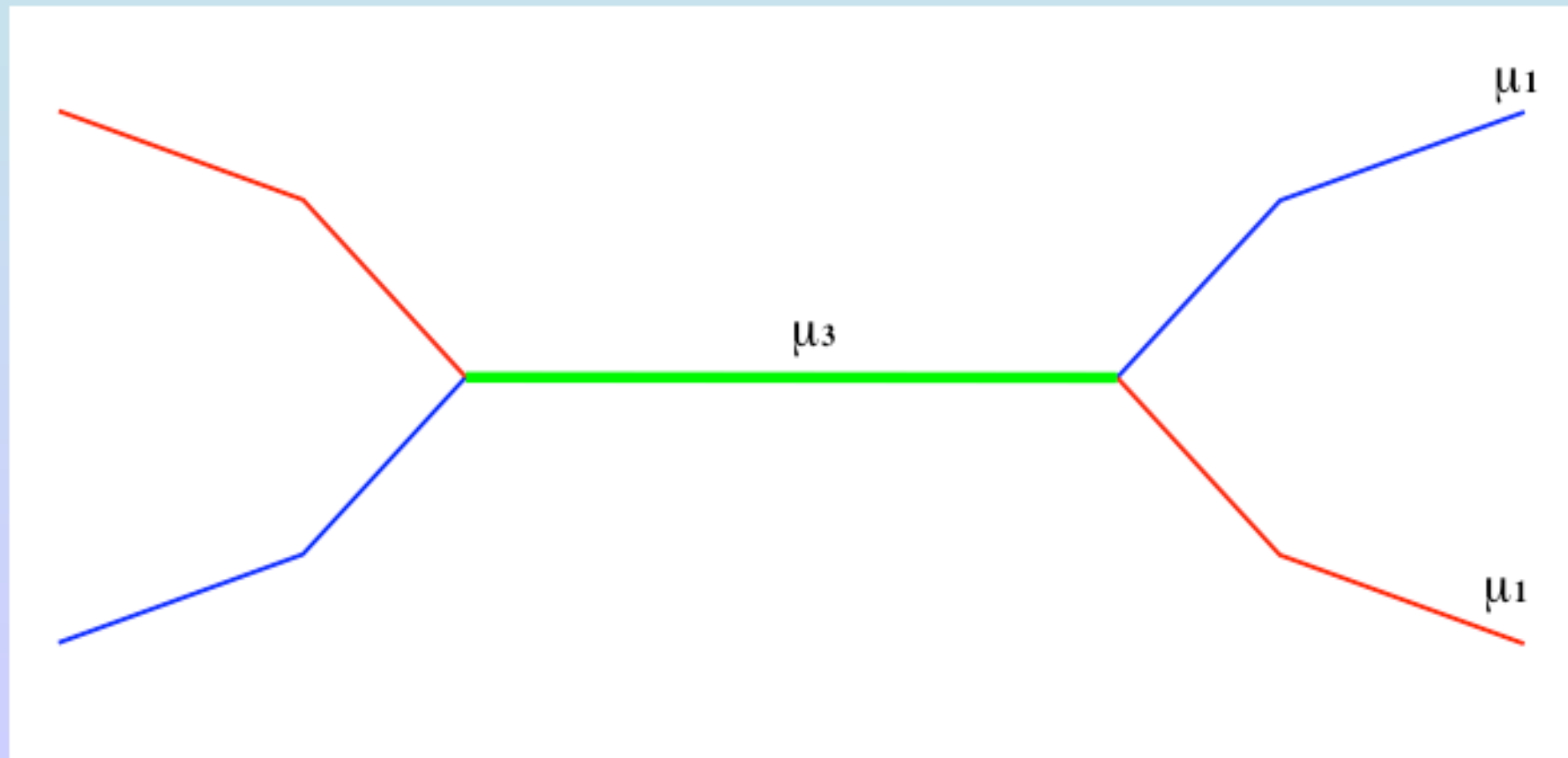
Starting from the string action (Nambu-Goto),
kinematic constraints have been derived for
the formation of the bound state when two
strings collide

(Copeland, Kibble and Steer,
Phys. Rev. Lett. 97, 2006; Phys. Rev. D 75, 2007).





$$\alpha < \arccos\left(\frac{\gamma\mu_3}{2\mu_1}\right)$$



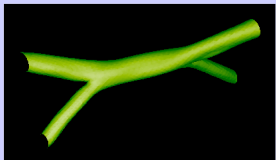
Field Theory Set-Up

Abelian-Higgs model

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

has only one parameter

$$\beta = m_{\text{scalar}}^2 / m_{\text{vector}}^2 = \lambda / 2q^2$$



Field Theory Set-Up II

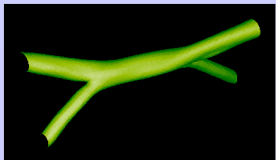
Vortex solutions

$$\phi = e^{in\theta} f(r) \quad A_\theta = -\frac{na(r)}{qr}$$

where

$$f'' + \frac{1}{r} f' - \frac{n^2 f}{r^2} (a-1)^2 - \frac{\lambda}{2} f (f^2 - 1) = 0$$

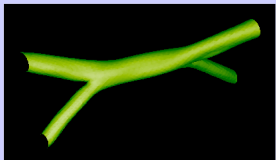
$$a'' - \frac{1}{r} a' - 2q^2 f^2 (a-1) = 0$$



Field Theory Set-Up III

Key Property - Type I regime: $\beta < 1$

$$\mu(n = 2, \beta) < 2\mu(n = 1, \beta)$$

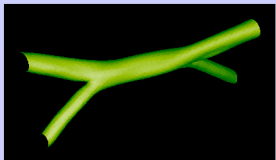


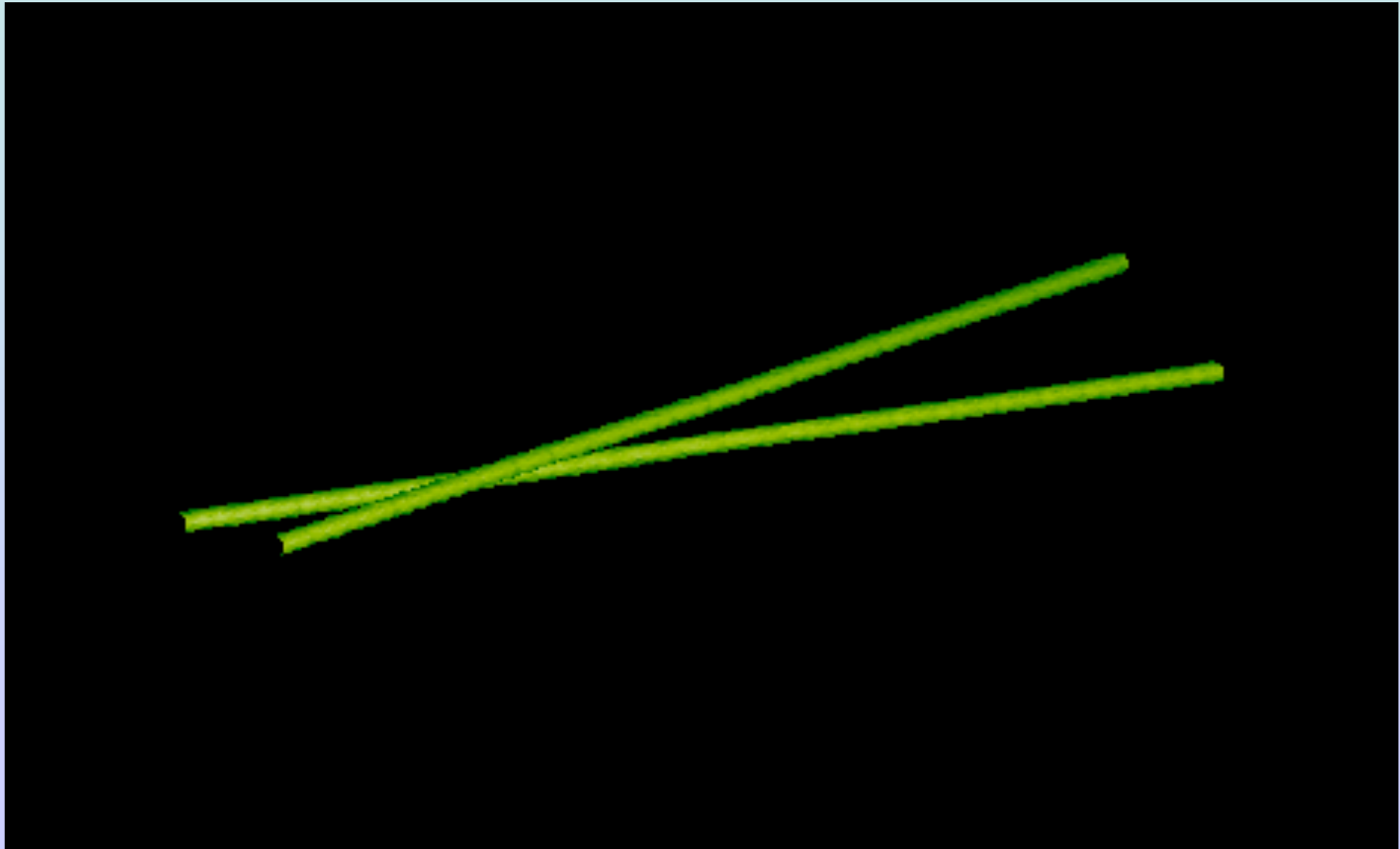
Simulations

Dutch National Computer Cluster **Lisa** in Almere

- 1360 Intel Xeon processors
 - ★ 3.4 GHz
 - ★ 2 GB
- bandwidth: 800MB/sec

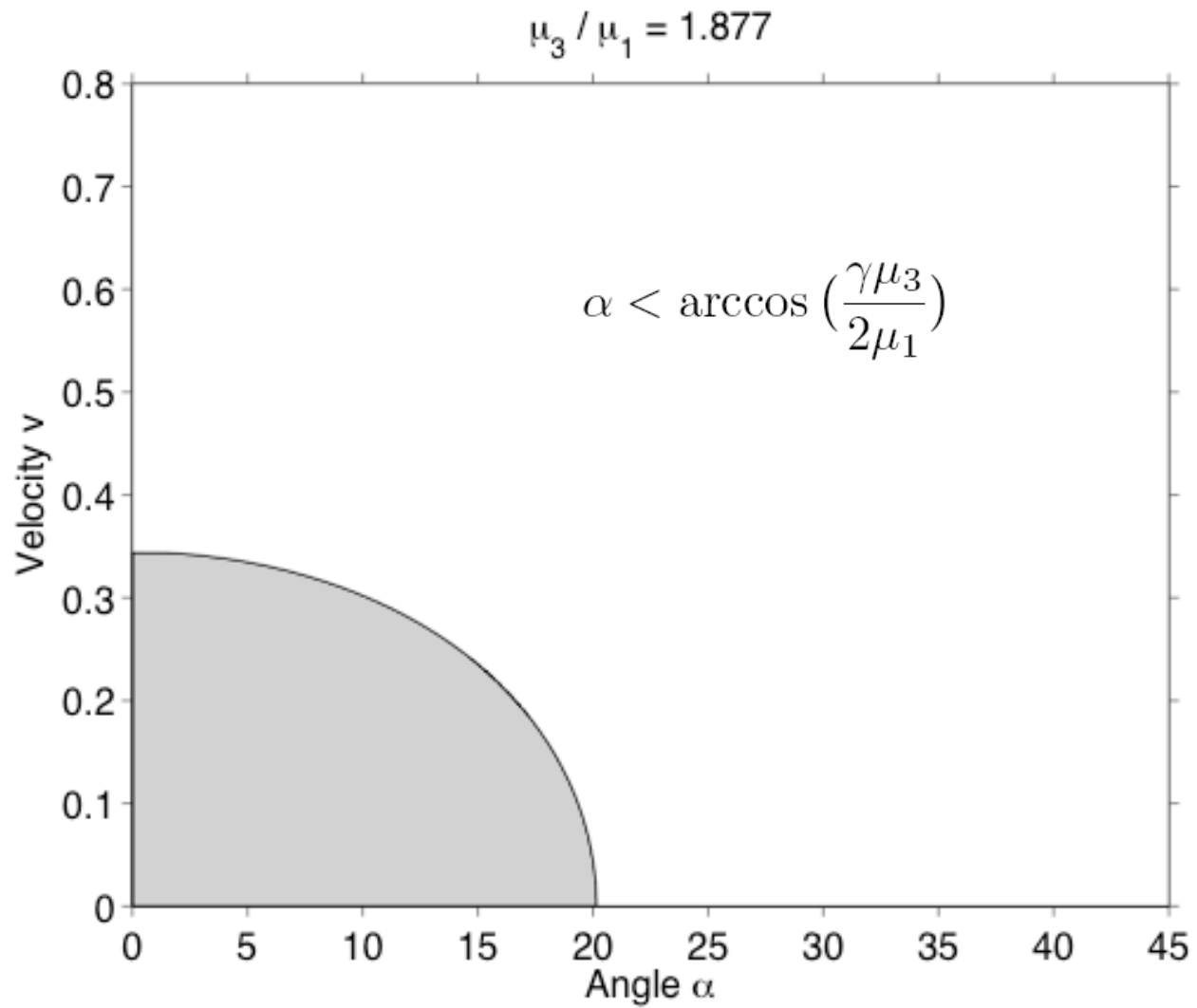
Parallel code and use of 20 to 60 processors simultaneously allows grids of size 400^3 to 600^3 .



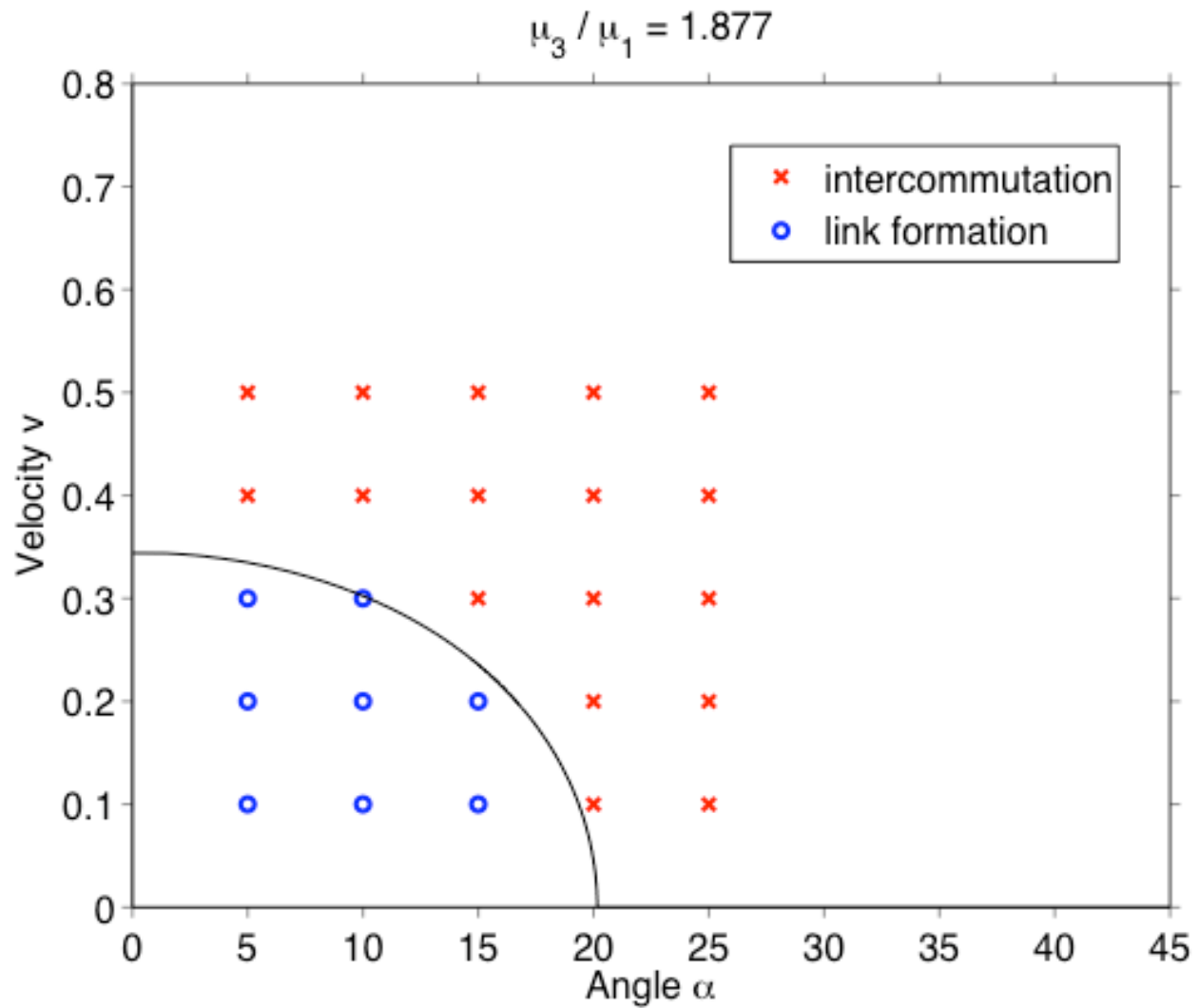




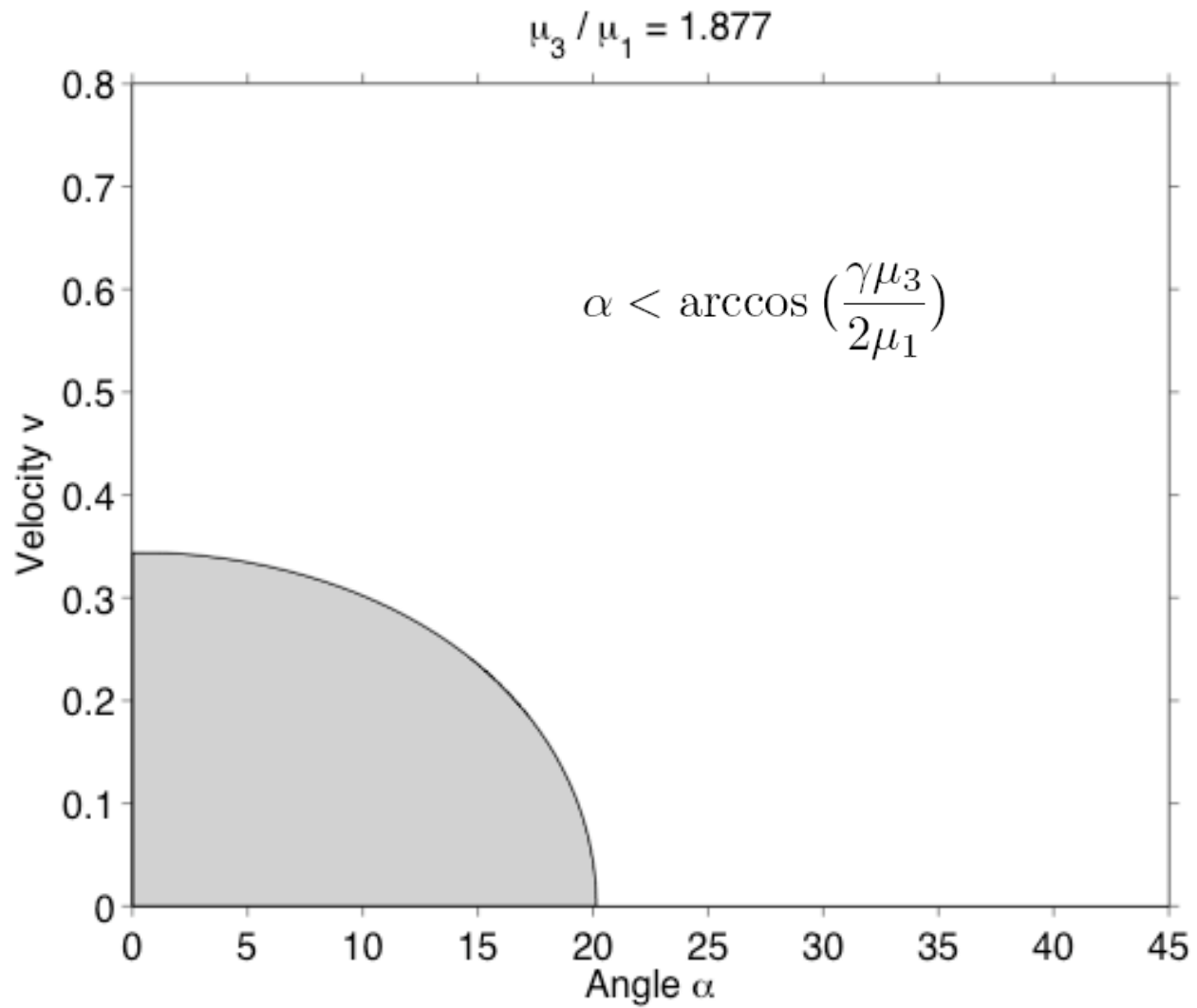
$$\beta = 0.36$$



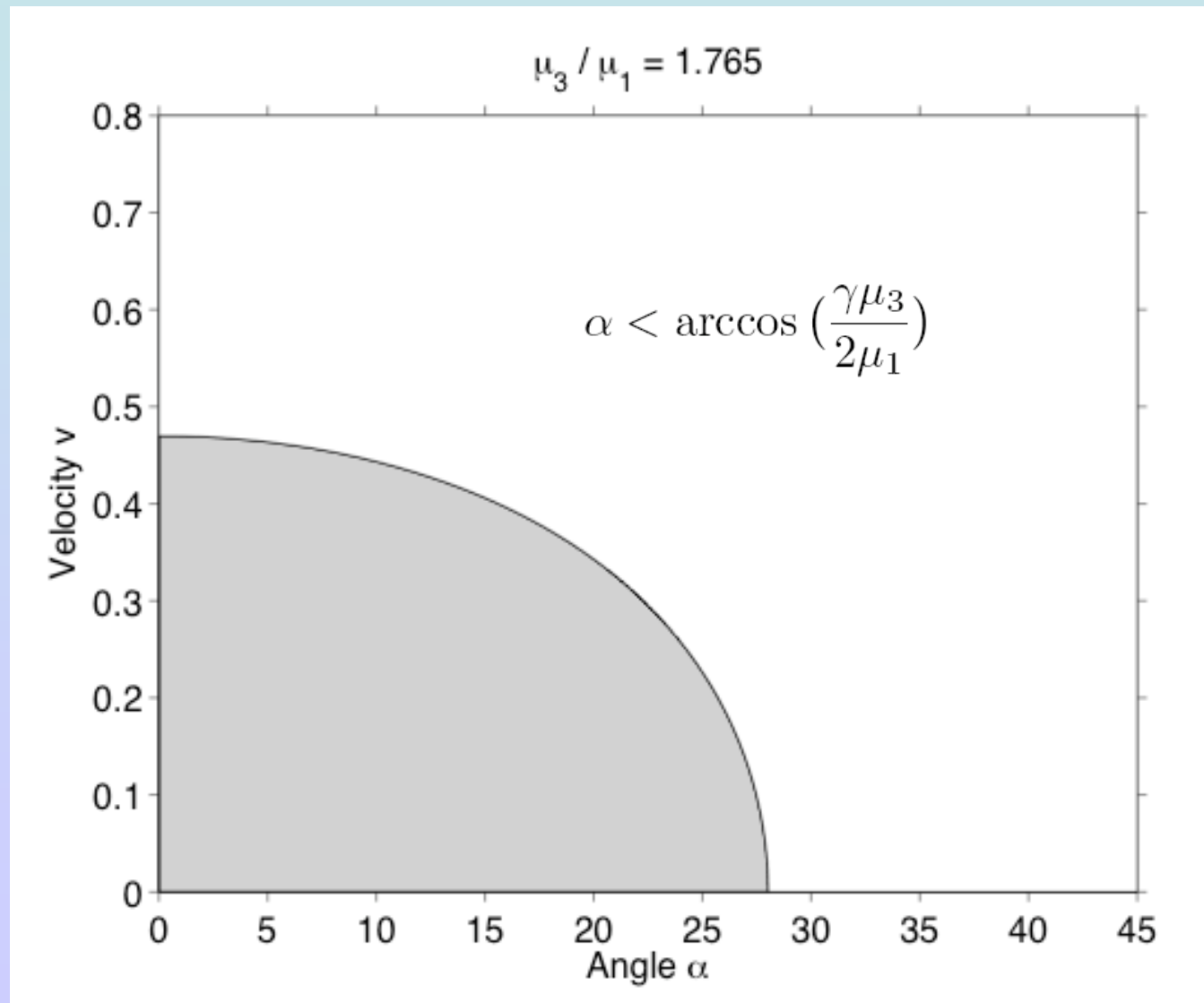
$$\beta = 0.36$$



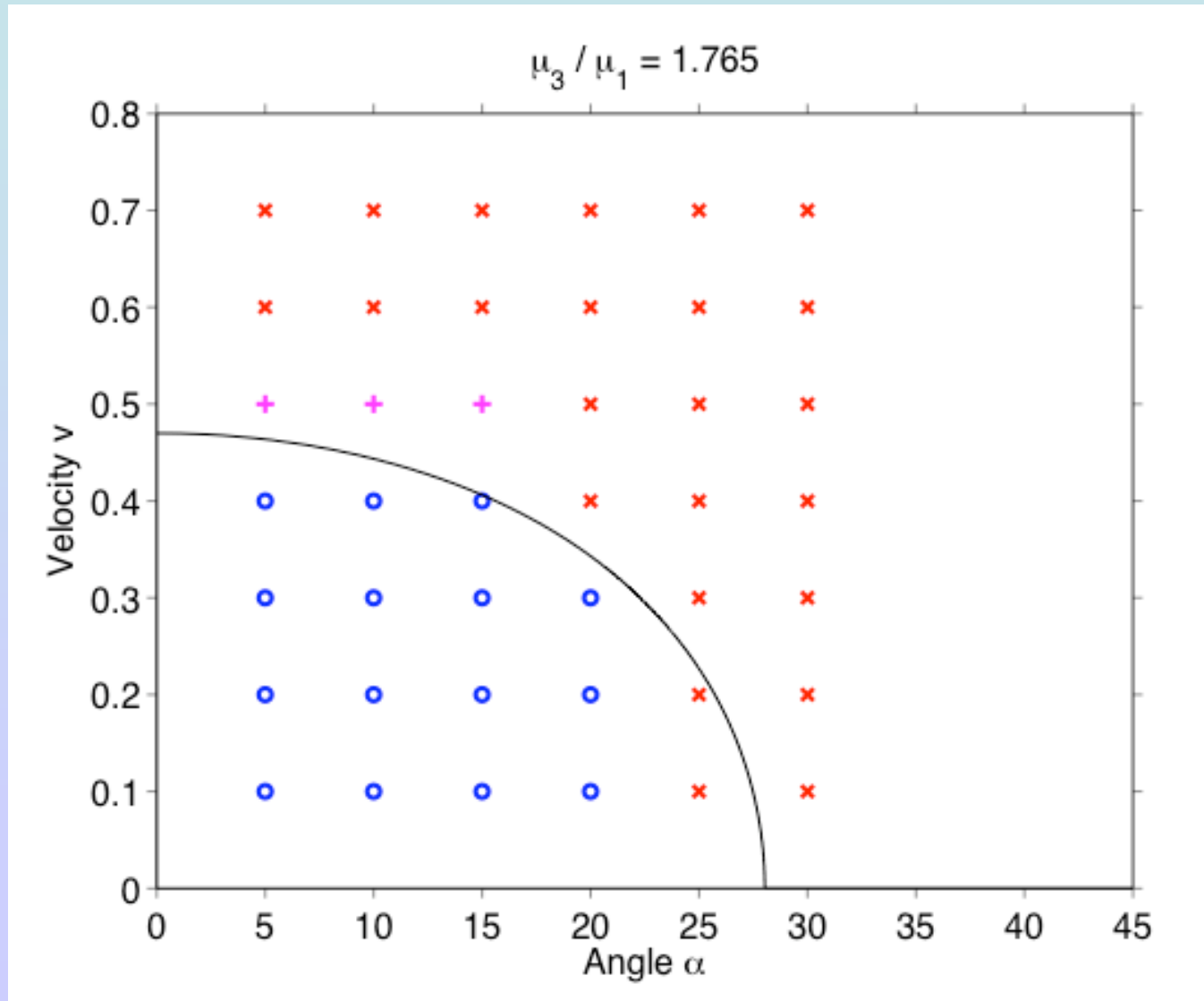
$$\beta = 0.36$$



$$\beta = 0.125$$

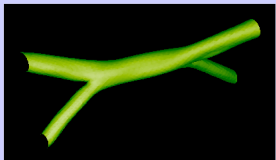


$$\beta = 0.125$$



Discussion

- Simulations of Abelian-Higgs model are in **good agreement with predictions** based on string action:
 1. no links with larger velocities or angles
 2. links do generally form when allowed to do so
- Potential input for analytic modelling of networks - turning the results into **realistic probabilities** in the network evolution.



Discussion II

Abelian strings:

- maybe strings with higher winding n can appear in the networks too.
- Abelian strings always intercommute - sometimes even twice.
(at ultra-relativistic velocities see:
Achúcarro and de Putter, Phys. Rev. D 74, 2006)

