High speed intercommutation of type-II abelian-Higgs strings

Based on AA Verbiest, PRL 2010 1006.0979
Verbiest AA, 1106.4666

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PASCOS 2011

Intercommutation is an important process for the evolution and scaling behaviour of a cosmic string network, and for the detectability of strings

Fig: Polchinski 04

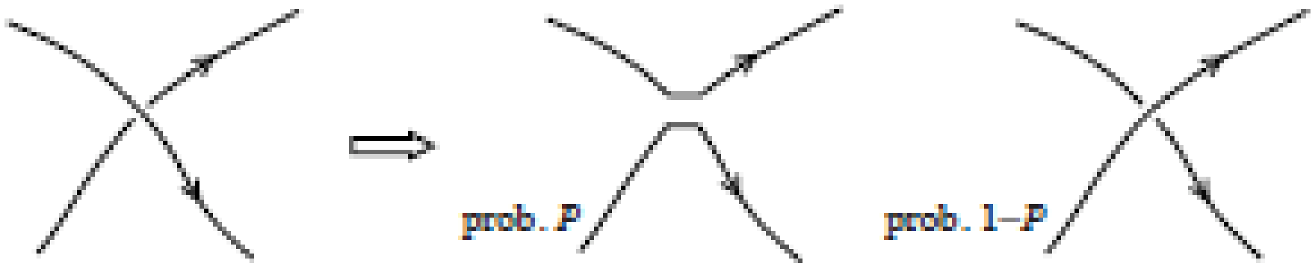


Figure 1: When two strings of the same type collide, they either reconnect, with probability P, or pass through each other, with probability $1-P$. For classical solitons the process is deterministic, and $P=1$ for the velocities relevant to the string network.

Every intercommutation produces small scale structure (**4 kinks**) and some produce **loops** as well

kinks and loops decay into **radiation**

If intercommutation happens with probability $P < 1$, expect the density of strings in the scaling solution to grow as $n \sim 1 / P$

($n \sim P^{-0,6}$ in expanding space **Avgoustidis Shellard 06**)

and the number of intercommutations to grow as $Pn^2 \sim 1 / P$, $\sim P^{-0,2}$

$P \sim 1$ for global and abelian Higgs strings

Shellard 87 **Matzner 88**

$P \sim 10^{-3} - 10^{-1}$ for F- and D- (super)strings

Jackson Jones Polchinski 04

Abelian Higgs strings,
type I vs type II

Nielsen Olesen 73

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

$$m_{scalar} = \sqrt{\lambda}\eta$$

$$m_{gauge} = \sqrt{2}e\eta$$

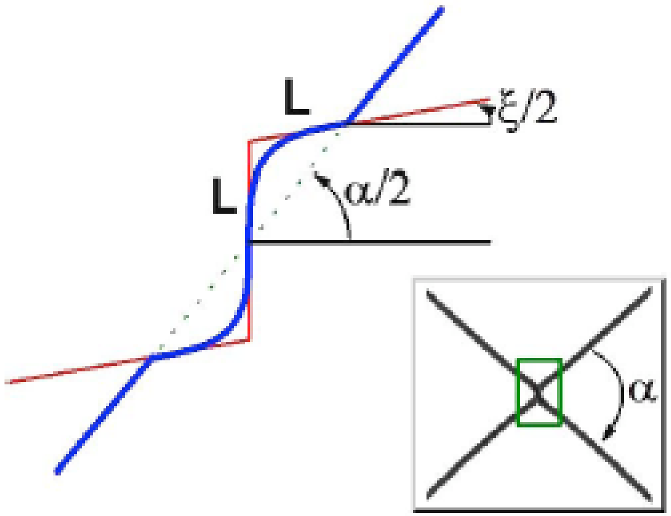
$\beta = m^2_{scalar} / m^2_{gauge} = \lambda / 2 e^2$

$\beta < 1$	**(type I)**	parallel vortices attract
$\beta = 1$	**(Bogomolnyi limit)**	no interaction
$\beta > 1$	**(type II)**	parallel vortices repel

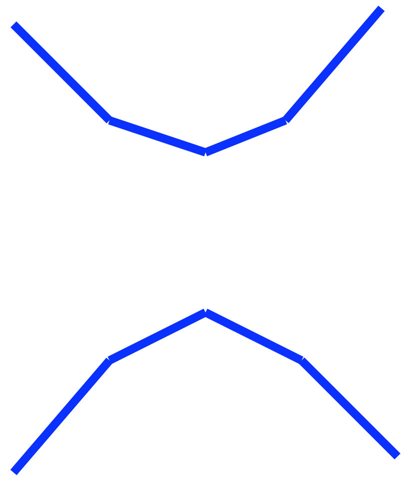
Jacobs Rebbi 79

Deep type II ($\beta >> 1$): colliding strings suffer torque

Torque distorsions



$$\xi = 2\alpha - \pi$$



actual collision angle larger than α, **effective** angle ξ smaller.
larger portion of string is annihilated

This talk:

Numerical simulation of collision at speeds up to 0.98 and β = 4, 8, 16, 32, 49, 64
(also β = 3.9 , 4.1 similar to β = 4 ; β = 31, 33 similar to β = 32)

Three **qualitative** differences between **deep type II** and **Nambu Goto** string intercommutation that could affect the small scale structure and radiation from strings

1) Multiple intercommutations
   - critical velocity for double intercommutation goes down
   - effective intercommutation probability less than one (*)
   - triple (even quadruple) intercommutations - rare!
   - more kinks, more clustered?

2) Nature of intermediate state after first intercommutation
   - loop forms in deep type II only (otherwise radiation)

3) Torque distorsions at high collision angles
   - actual collision angle larger, effective angle smaller
   - enhanced radiation from reconnections?

(*) *but Abelian Higgs strings never pass through, up to v ~ 0.98 !*

Previous simulations of cosmic string reconnection

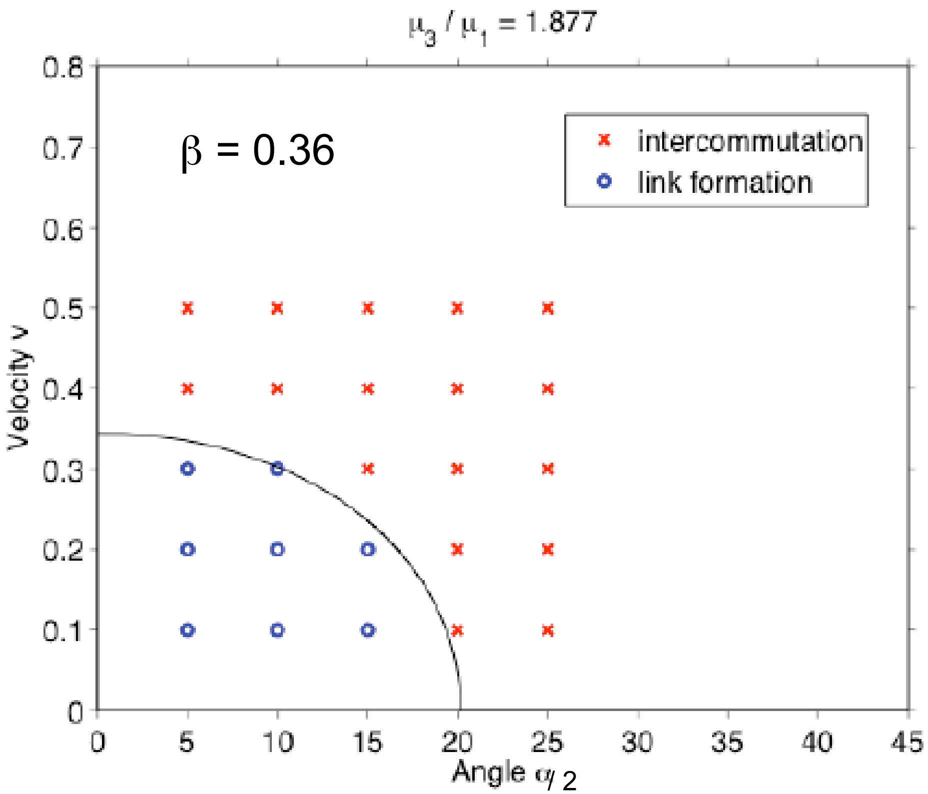
Shellard 87
Global strings intercommute for speeds $v < v_c \sim 0.9$ c
Loop formation

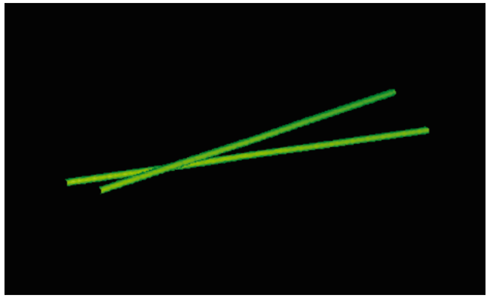
abelian Higgs strings
Matzner 88 (type II, β= 2)
Strings pass through each other for $v > v_c \sim 0.9$ c, loop
AA de Putter 06
double reconnection, v_c as a function of collision speed and angle

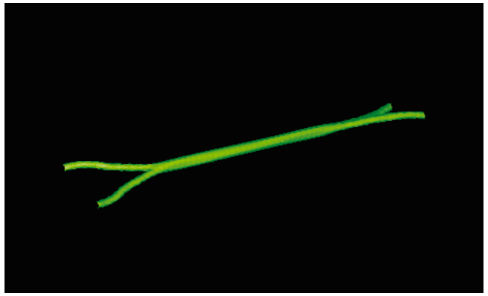
(type I) zippers, junctions (low v, small angle - strings stick together)
Laguna-Castillo Matzner 89
Bettencourt Laguna Matzner 97

(2D vortex scattering)
Moriarty Myers Rebbi 90 vortex-vortex scattering at 90^0
Myers Rebbi Strilka 92 vortex-vortex scattering
vortex-antivortex scattering: v~0.9c pair reforms
($\beta \leq 4$: in backward direction; $\beta \geq 8$ in forward direction)

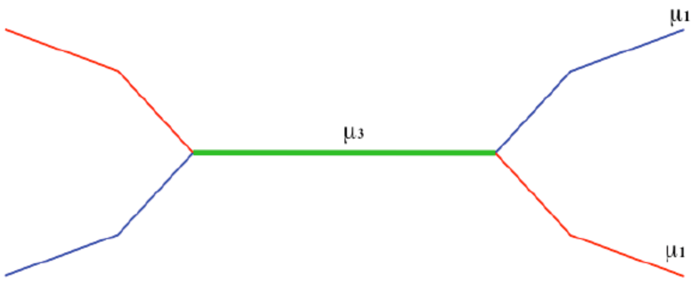
Nambu-Goto works very well for type I reconnections at small v, small angle







Bettencourt Kibble 94
Copeland Kibble Steer 06,07
Salmi AA Copeland Kibble Steer de Putter 08



High speed intercommutation

Strings always intercommute **once** -- even at $v = 0.98$

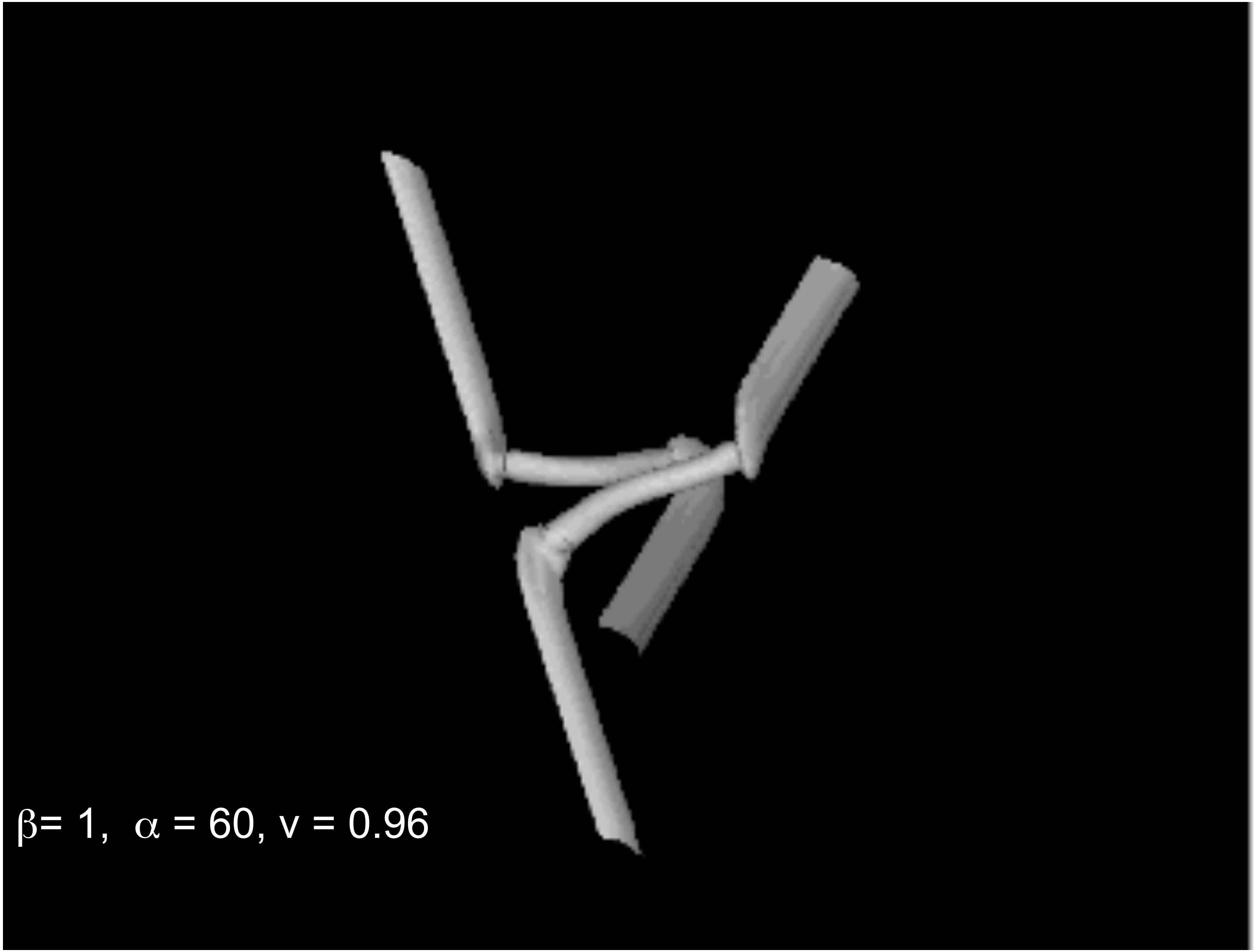
they never pass through

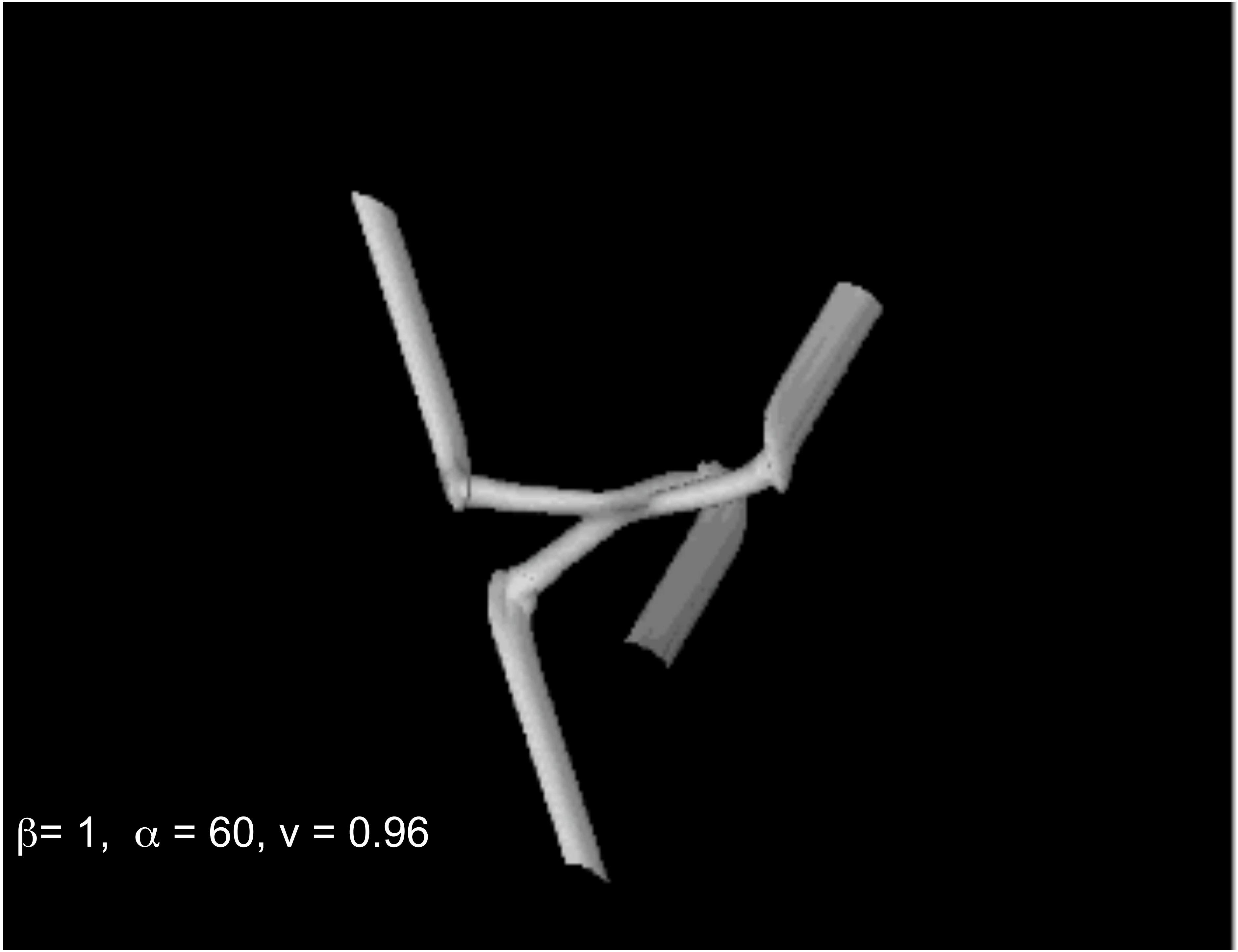
$P = 1$

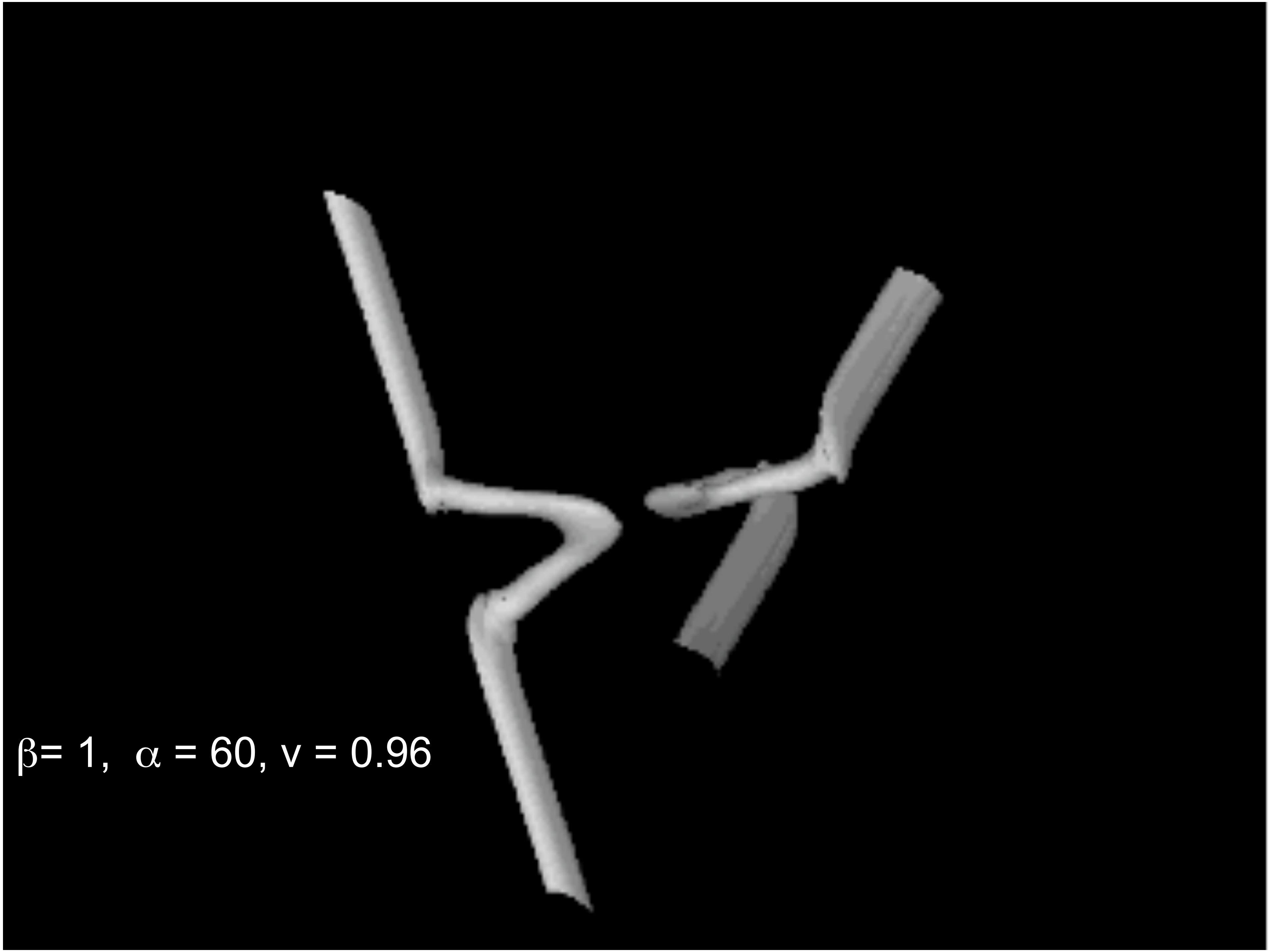
But sometimes there is a second intercommutation

$P_{effective} < 1$

Second intercommutation can happen directly (type I)
or via a loop (type II)

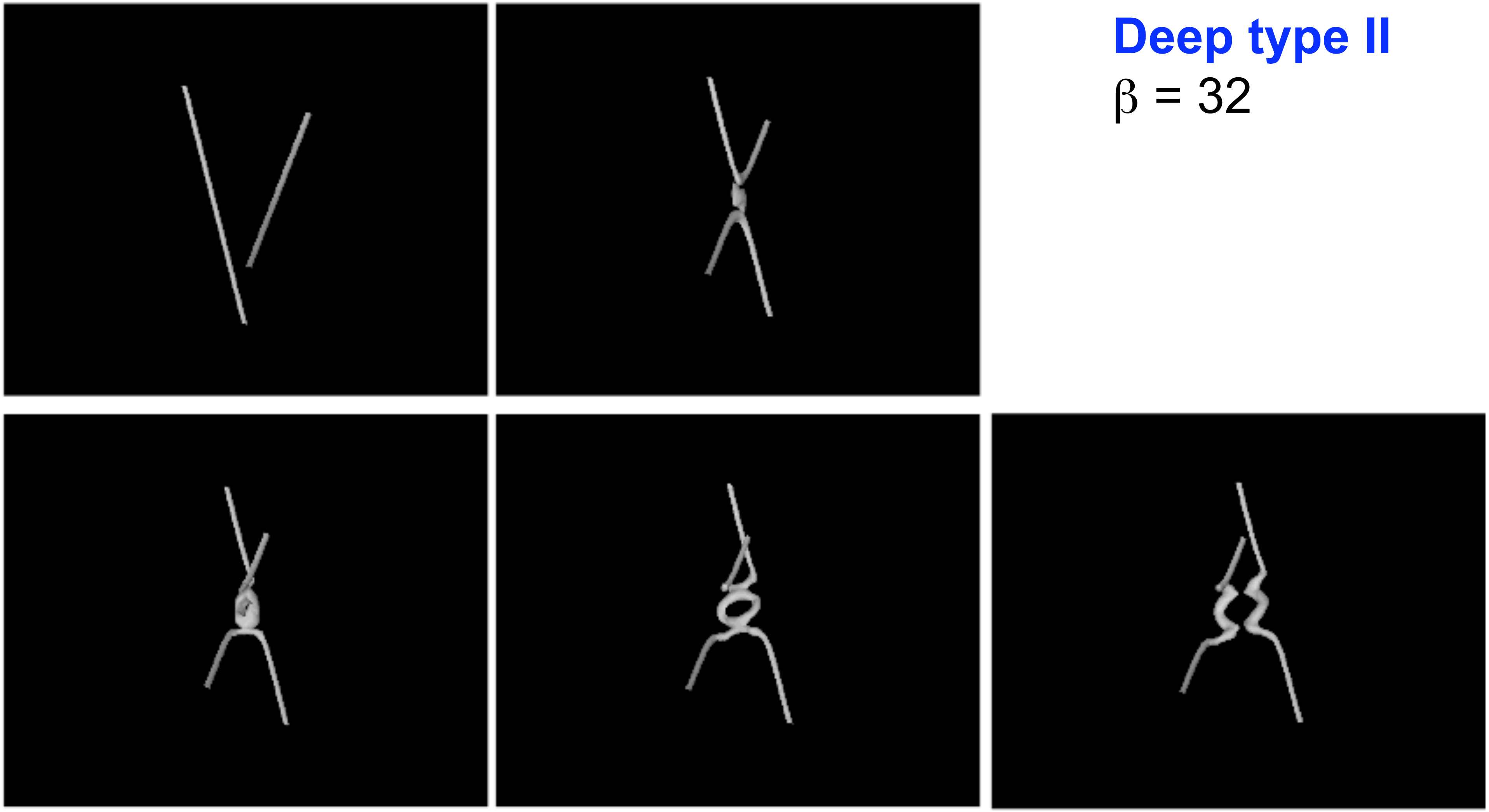

β= 1, α = 60, v = 0.96


β= 1, α = 60, v = 0.96


β= 1, α = 60, v = 0.96

Deep type II

$\beta = 32$

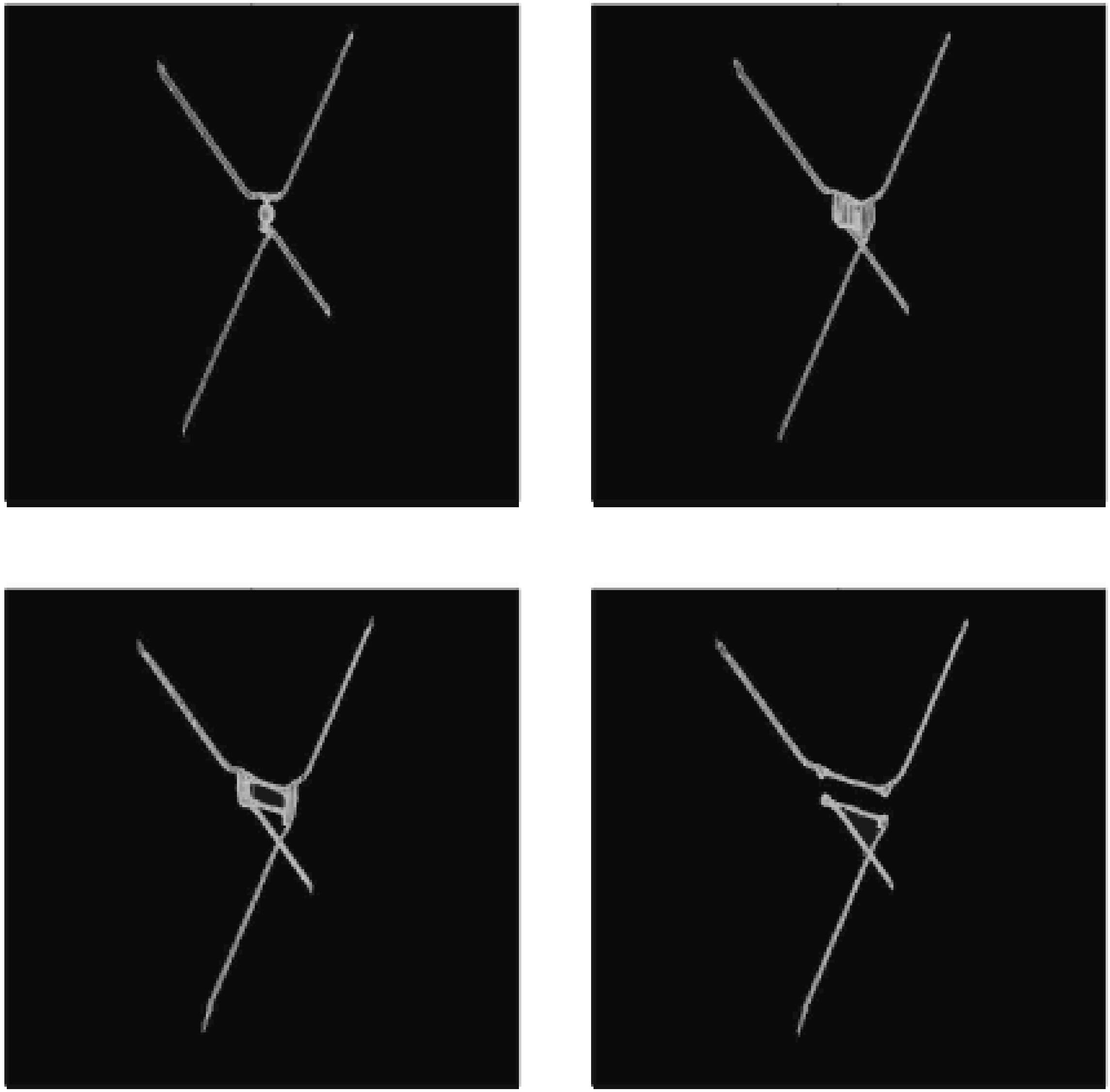


Double reconnection by loop formation

(8 kinks)

No loop for $4 \leq \beta \leq 8$, only radiation

$\beta=4$, $\alpha=122.7$, $v=0.98$



"loop" breaks and ls absorbed (not topological)

bridge forms

no extra kinks

High speed intercommutation: double reconnection

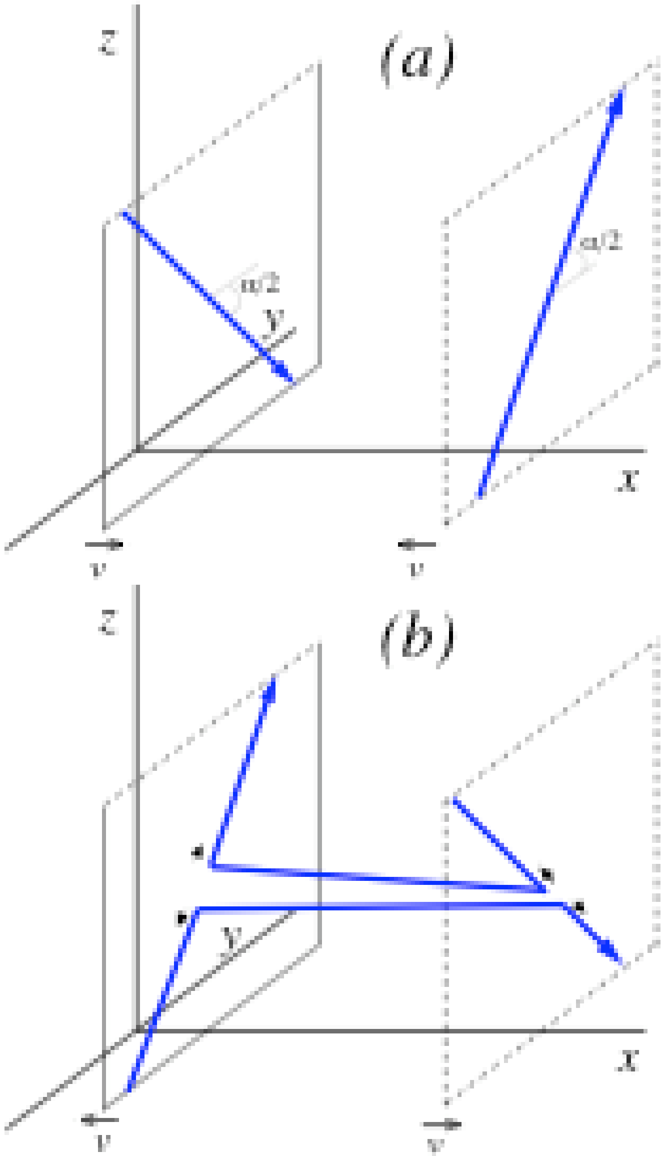
Nambu-Goto:

Vertical velocity of bridge segments

$$w = \frac{\sin(\alpha/2)}{\gamma(v)}$$

Angle between bridge segments

$$\cos(\delta/2) = \frac{\cos(\alpha/2)/(v\gamma(v))}{\sqrt{1+(\cos(\alpha/2)/(v\gamma(v)))^2}}$$

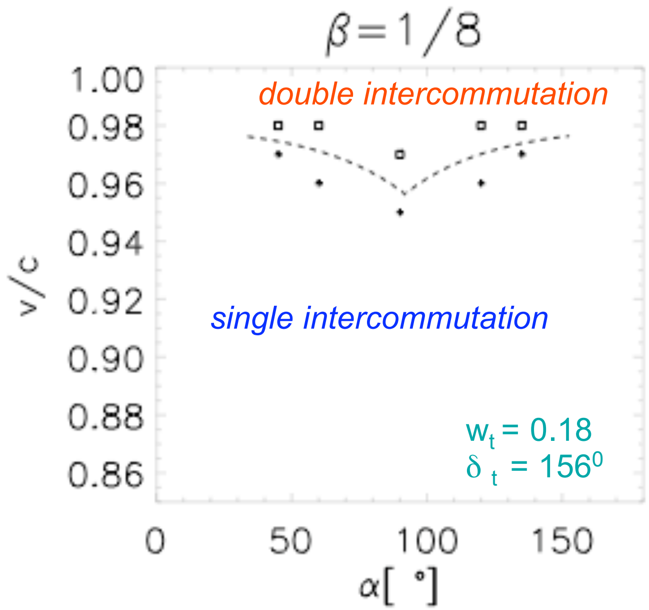


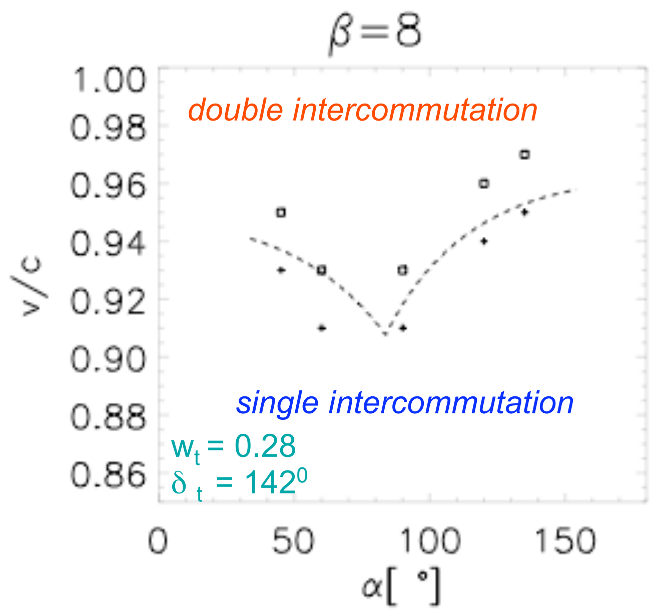
v ~ c bridge segments are static, antiparallel

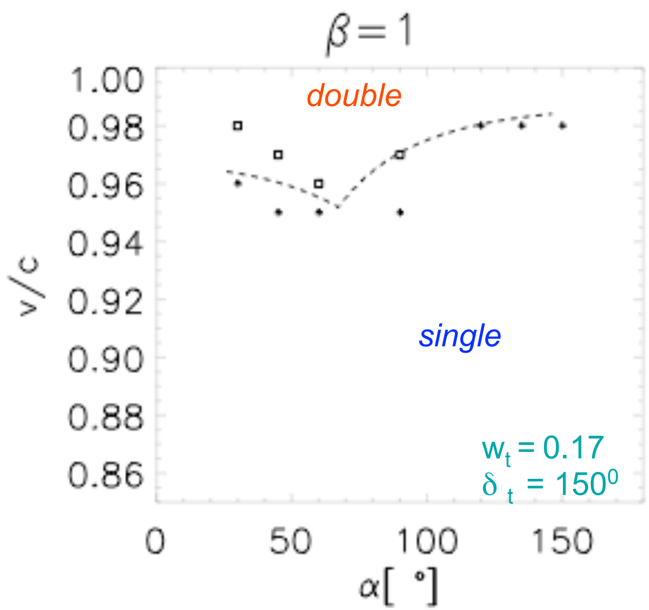
If **$w < w_t$** and **$\delta > \delta_t$**, expect they reconnect again:

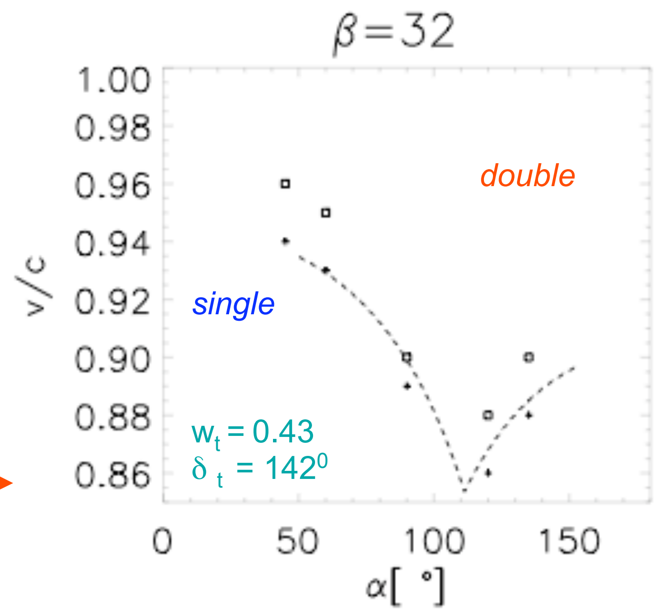
double intercommutation

Fit threshold values w_t and δ_t to data









critical v goes down with β →

AA de Putter 06

Nambu-Goto prediction in flat space is **$\langle v\rangle \sim 1/\sqrt{2} \sim 0.7$**

Numerical simulations of Abelian Higgs networks with $\beta = 1$ find, e.g.

from Moore, Shellard, Martins 01

$\langle v\rangle \sim 0.67\ (\pm\ 0.05)$ (Minkowski)
$\langle v\rangle \sim 0.63\ (\pm\ 0.05)$ (radiation era)
$\langle v\rangle \sim 0.57\ (\pm\ 0.05)$ (matter era)

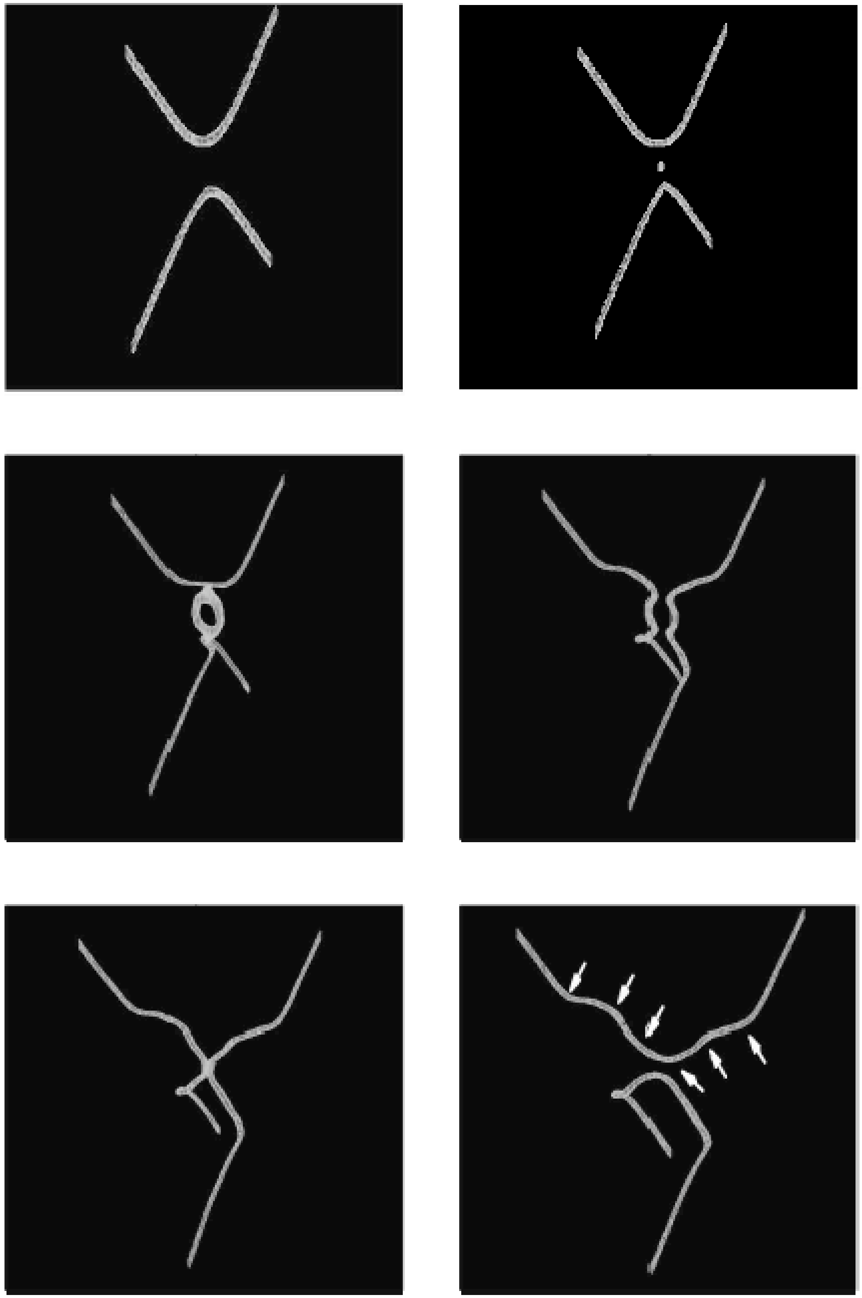
Field theory simulations of string collisions suggest a trend towards **lower critical velocities** for double intercommutation with increasing β

AA, de Putter 06

$\beta = 1$ $v_c \sim 0.96$
$\beta = 8$ $v_c \sim 0.92$
$\beta = 32$ **$v_c \sim 0.86$**

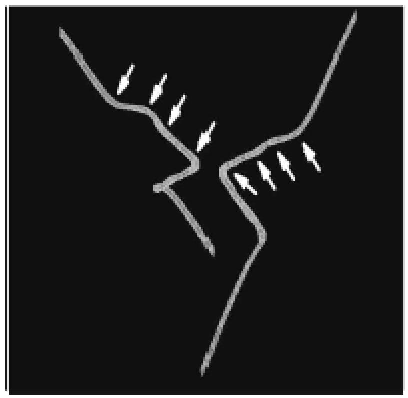
Is there a β for which $v_c \sim \langle v\rangle$?

(this was the motivation for this work, but then we found some surprises)

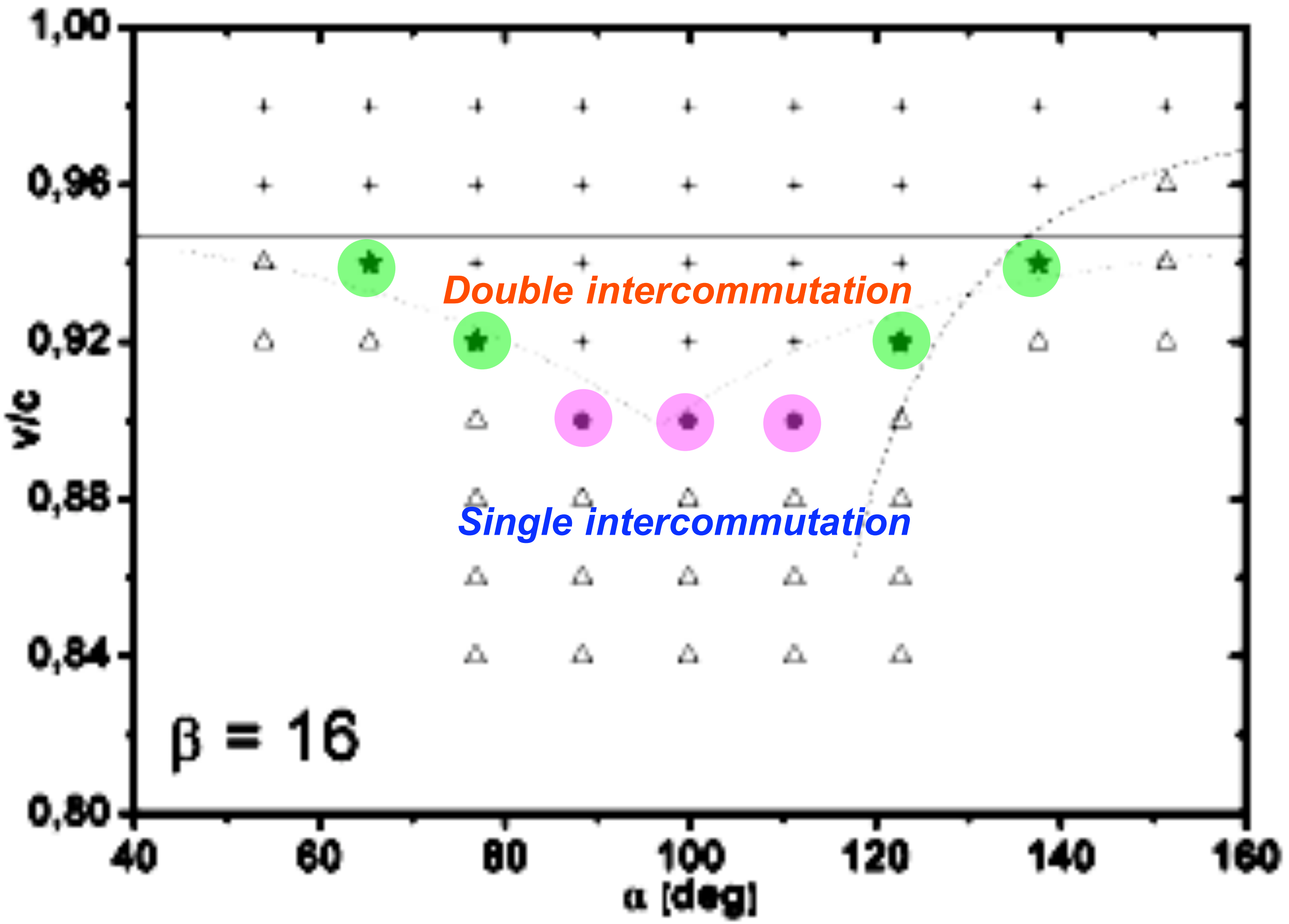


triple intercommutation
β=32,
α=122.7, v=0.88

quadruple intercommutation
β=16,
α=122.7, v=0.92



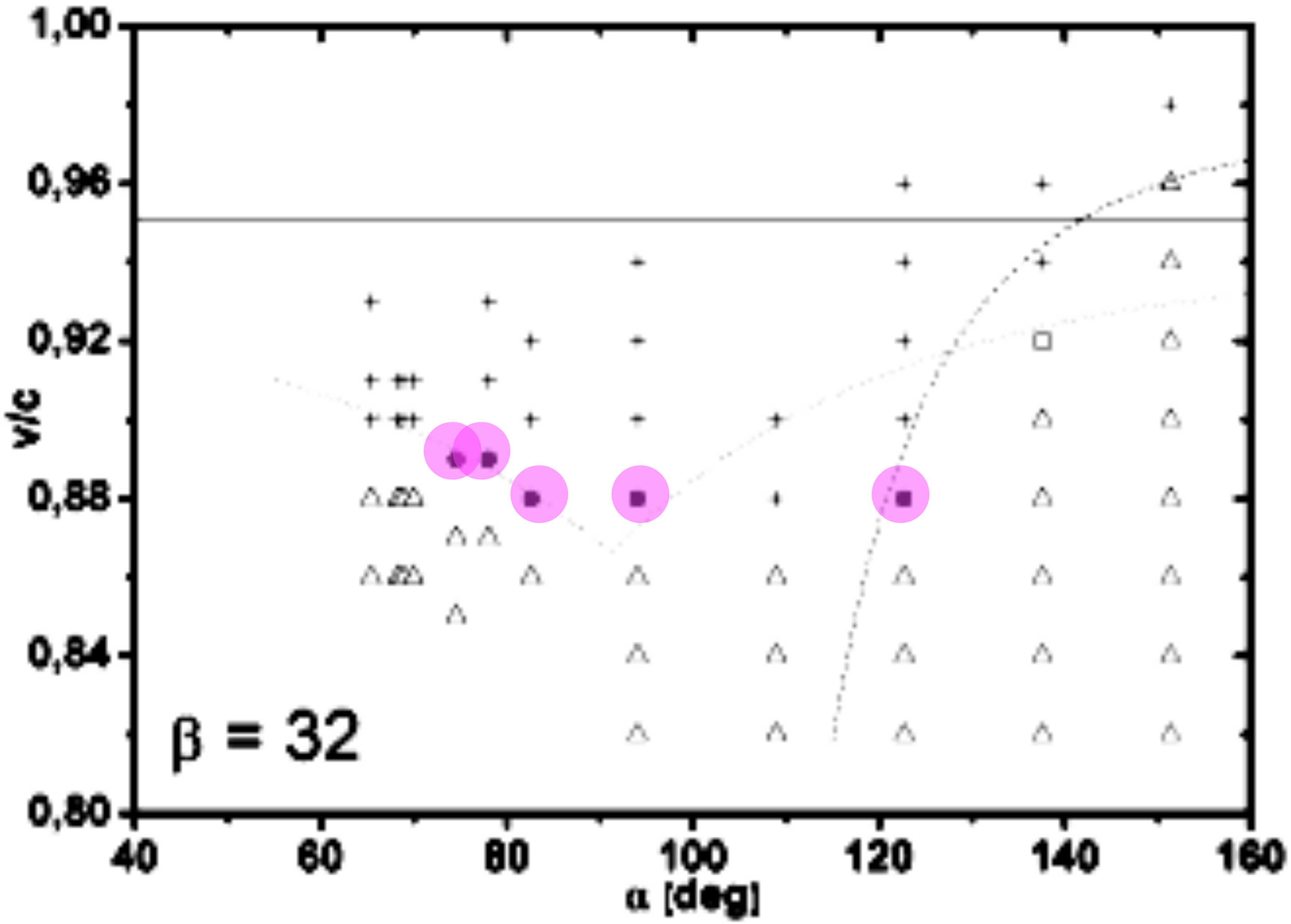
Multiple intercommutations, $\beta = 16$



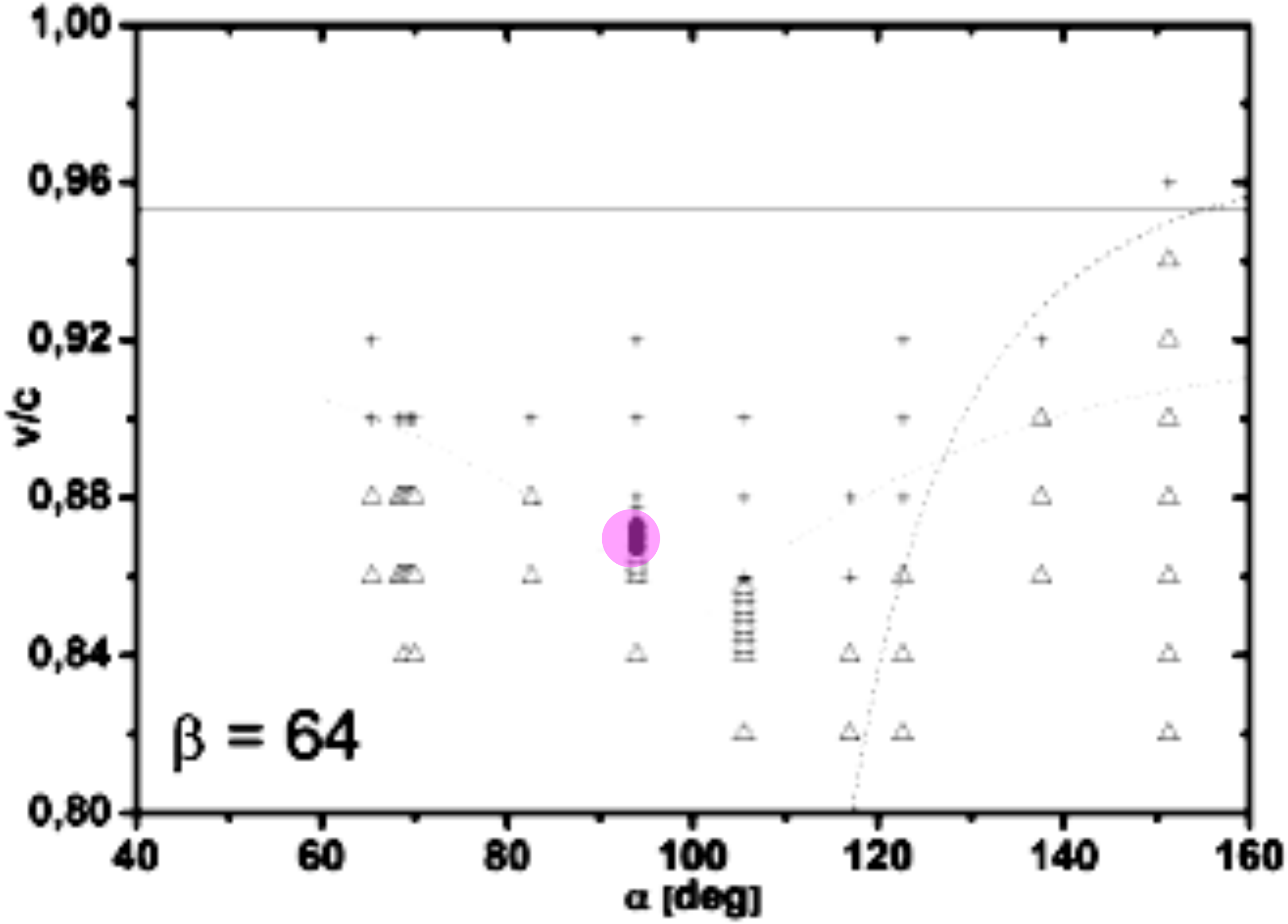
= 3

= 4

(in the boundary region between single and double)


1,00
0,96
0,92
0,88
0,84
0,80
v/c
40
60
80
100
120
140
160
α [deg]
β = 32

do they disappear at very large β or is it due to small box size ?



Intercommutation at high speed - type II - what's new

$\beta \leq 8$ modified Nambu-Goto analysis predicts v_c

bridge forms

previously reported "loop" is only radiation

$\beta \geq 16$ loop - mediated regime

predicted v_c fails at high collision angles

core interactions relevant at large collision angle: **torque**

multiple intercommutations (also triple, quadruple)

Qualitative differences with $\beta = 1$

Confirm lower v_c with increasing β ($v_c = 0.86$ for $\beta = 64$)

Consistent with (**our**) 2D v-av collisions

some **differences** with **Myers Rebbi Strilka 92**

Moduli space arguments give wrong result for v_c (as expected!)

(

2D vortex - antivortex head-on collision

Myers Rebbi Strilka 92 vortex-antivortex scattering

v~0.9c transition between

v-av pair pass through ($\beta \geq 8$)

bounce back ($\beta \leq 4$)

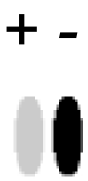
We find **no evidence of backscatter.** Instead:

$\beta > 6.4$: v-av pair pass through

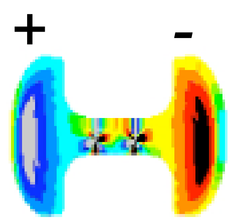
$\beta < 6.2$: radiation

β = 4 < 6.2 v = 0.95 v-av head-on collision

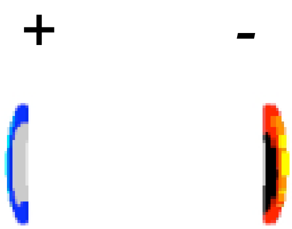
Magnetic field



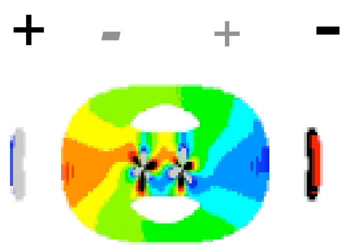
T=0



T=7



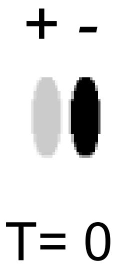
T=9

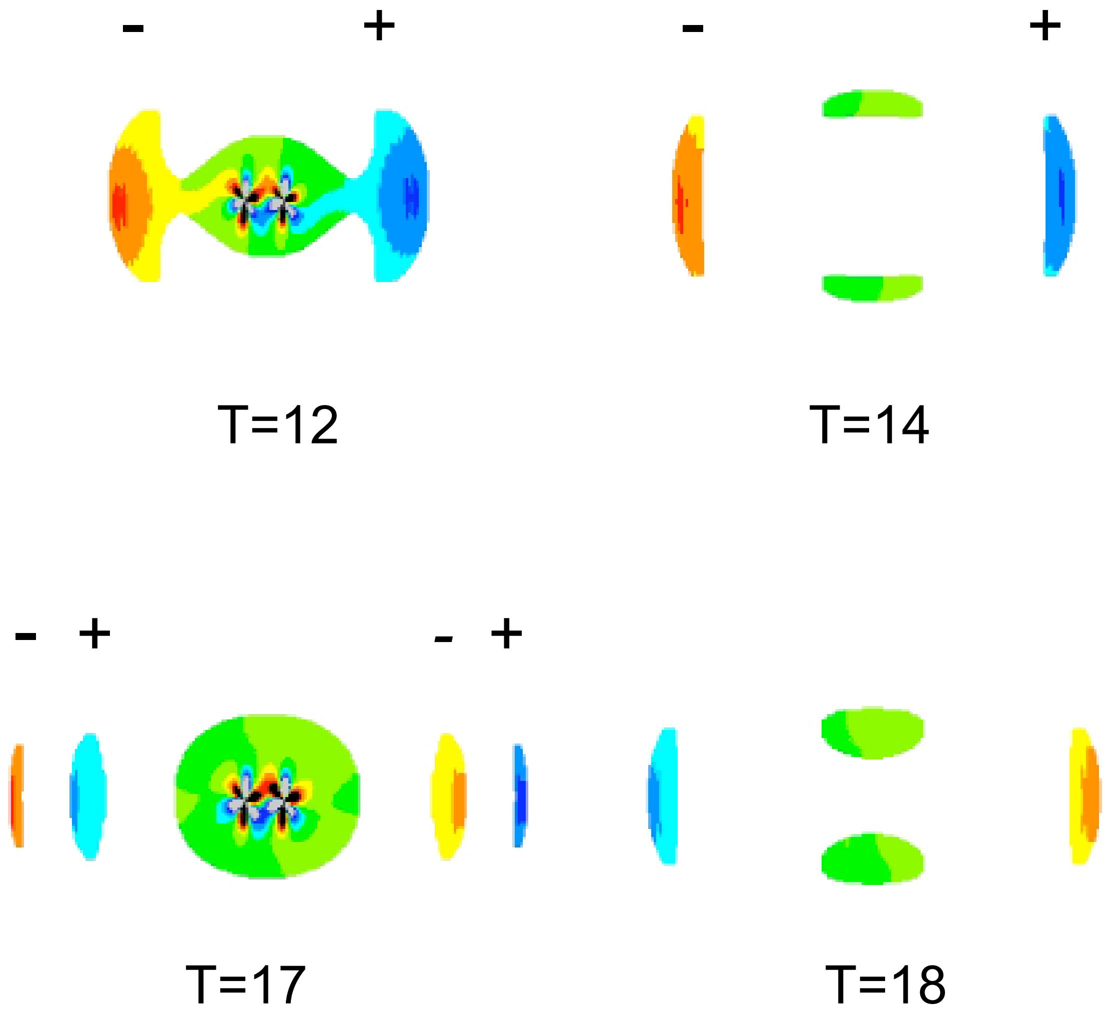


T=10

v-av pair bounce back? **no…**

… it is just radiation





2D vs 3D:

Moderate $\beta>1$: velocity for forward reemergence higher than we can probe in 2D, 3D simulations

2D, 3D always see radiation

$\beta >>1$ velocity for forward reemergence goes down below critical velocity for double intercommutation

2D see forward reemergence

3D we always see loop

(but don't expect exact matching)

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Summary: AA Verbiest, PRL 2010 1006.0979 Verbiest AA, 1106.4666

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actual collision angle larger, effective angle smaller
enhanced radiation from reconnections?

(*) *but Abelian Higgs strings never pass through, up to v ~ 0.98 !* **WHY??**