
Features of an
Ancient
Liquid Crystal World

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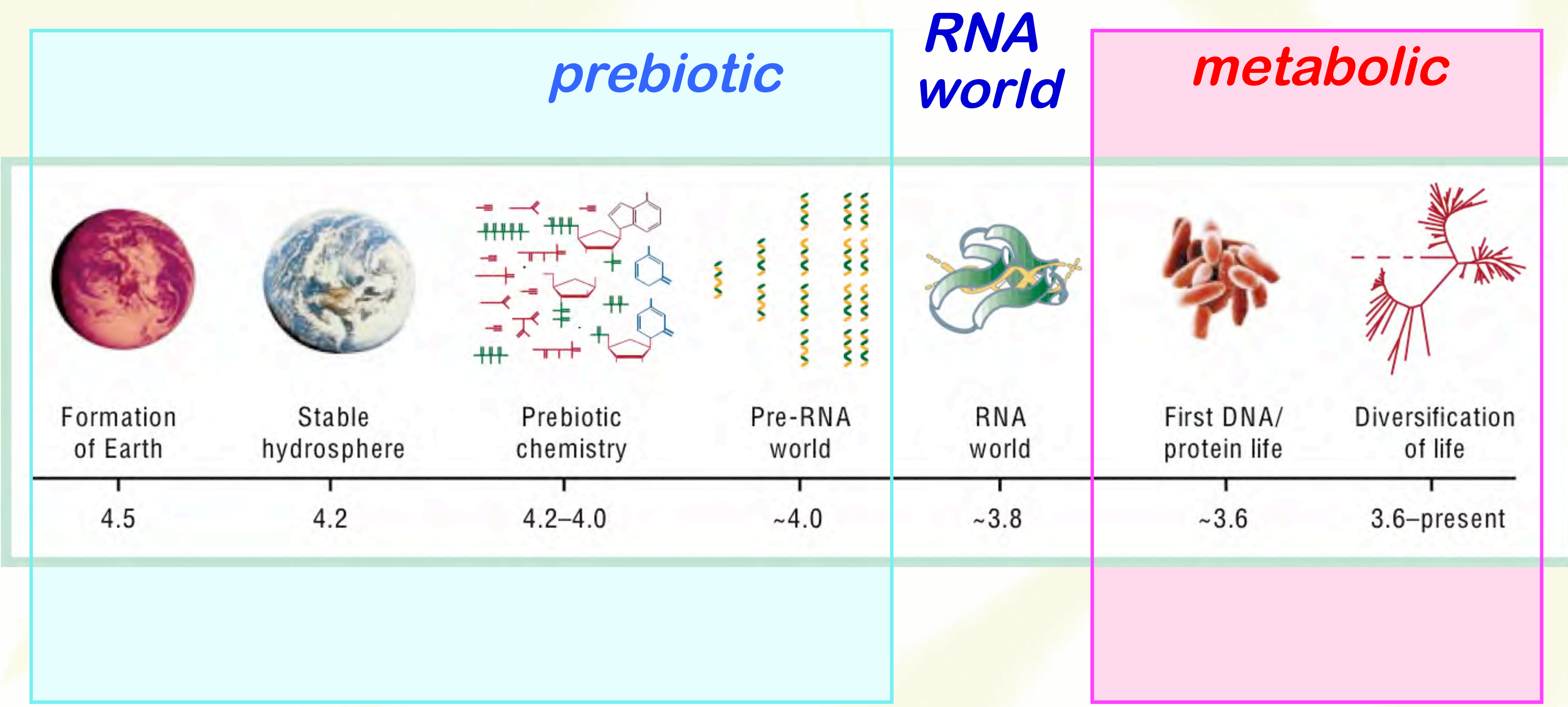
Science (2007) → Nat. Comm. (2015)

timeline of life on Earth

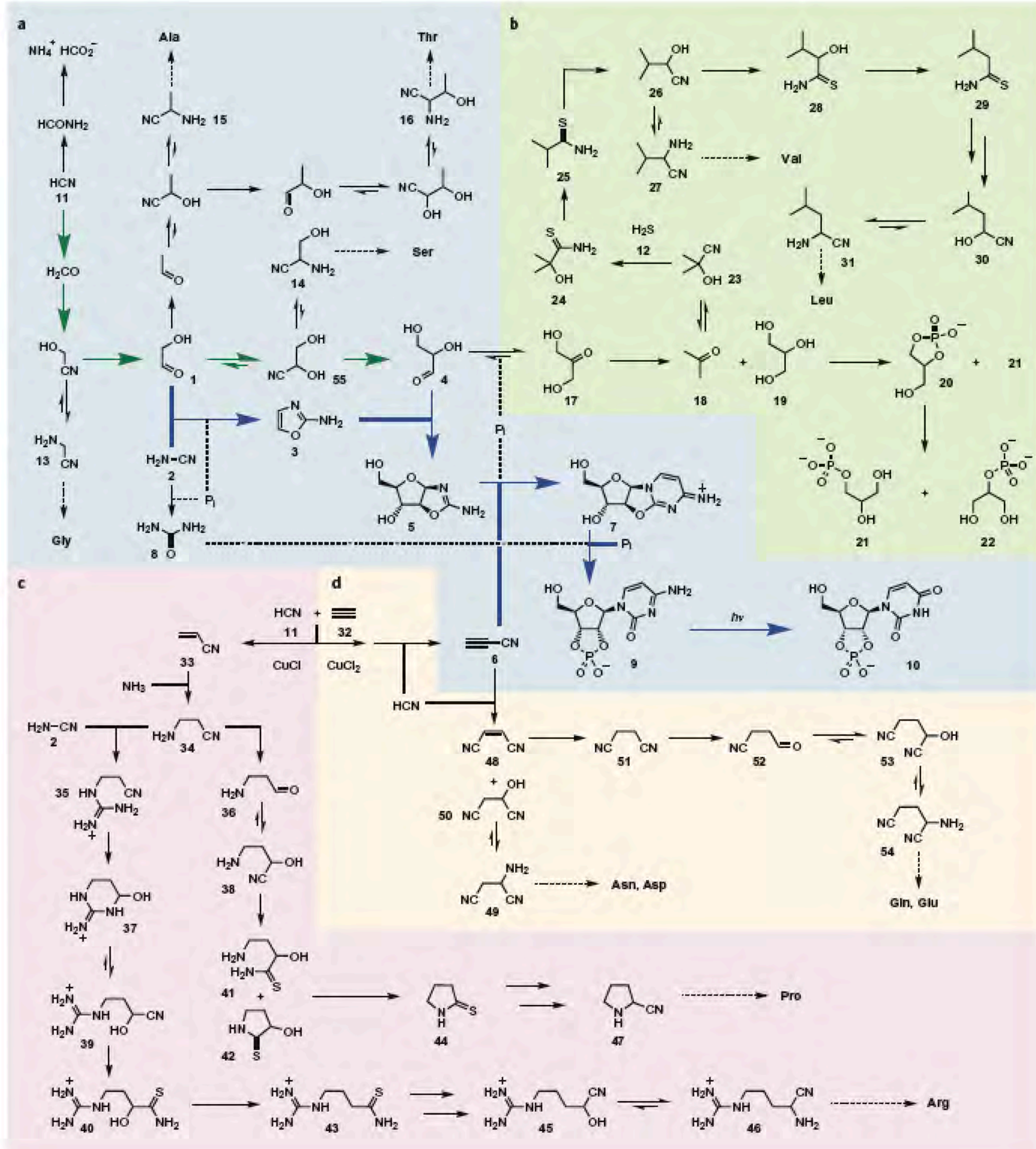


"The antiquity id RNA-based evolution", G. Joyce , Nature (2002)

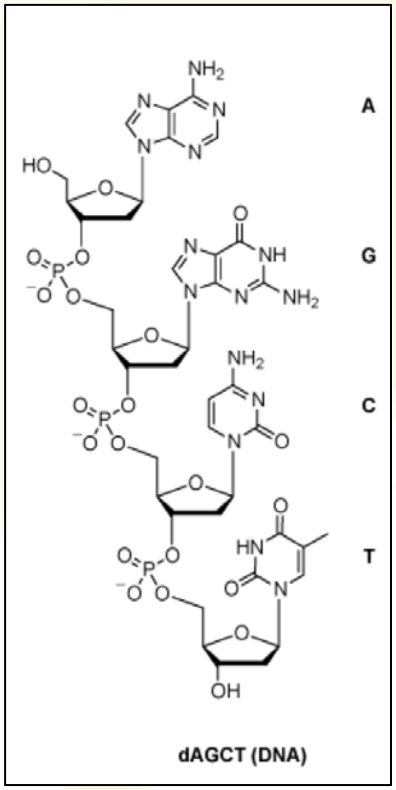
accidental prebiotic chemistry

"Common origins of RNA, protein, and lipid precursors in a cyanosulfidic protometabolism"

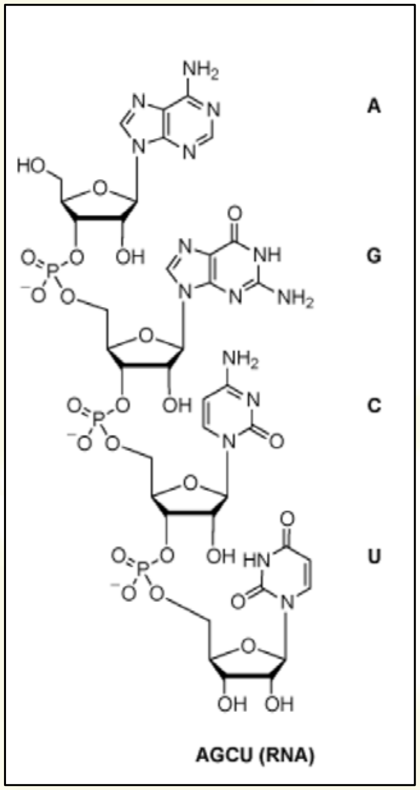
Patel, et al., Nat. Chem., (2015)



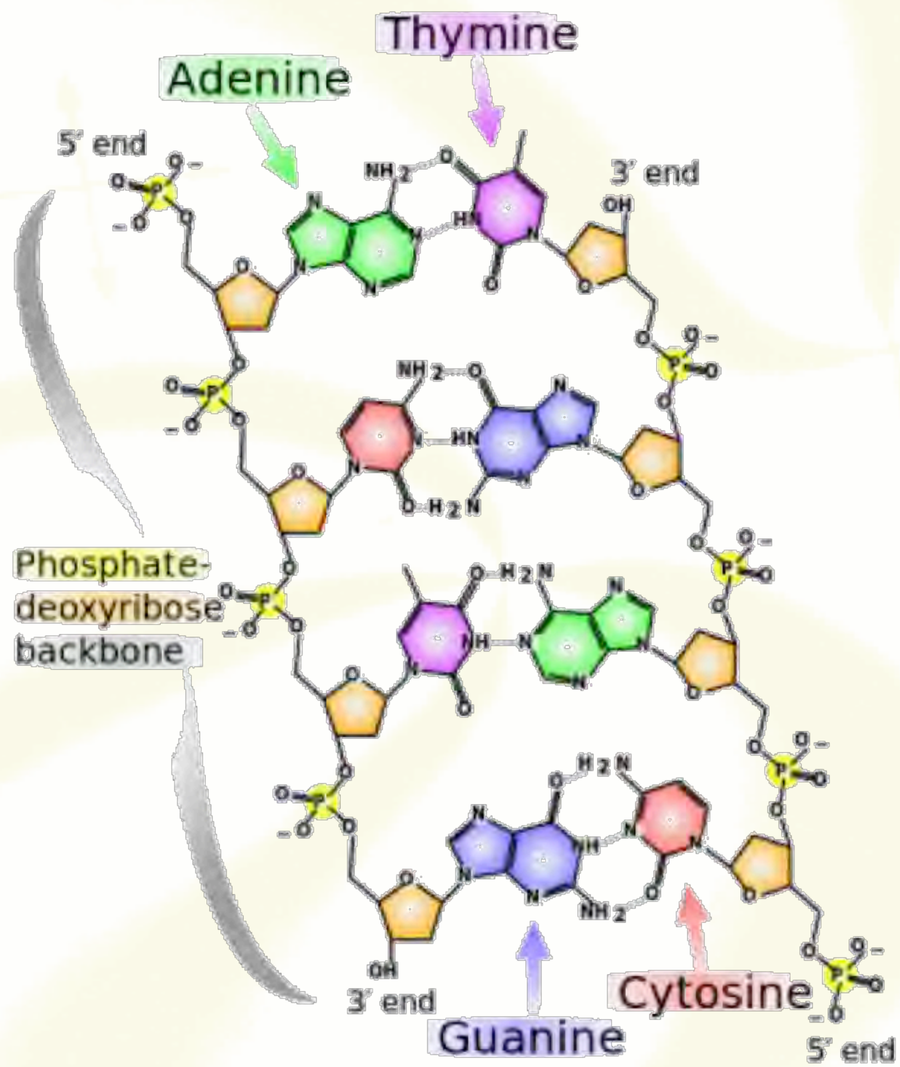
nucleic acids



DNA



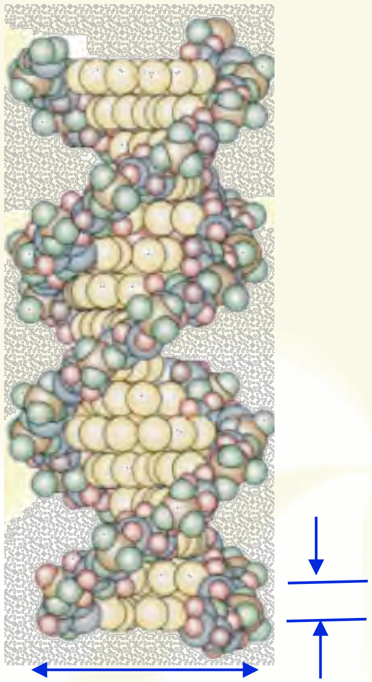
RNA



DNA Chemical Structure (CC0 by Madeleine Price Ball)

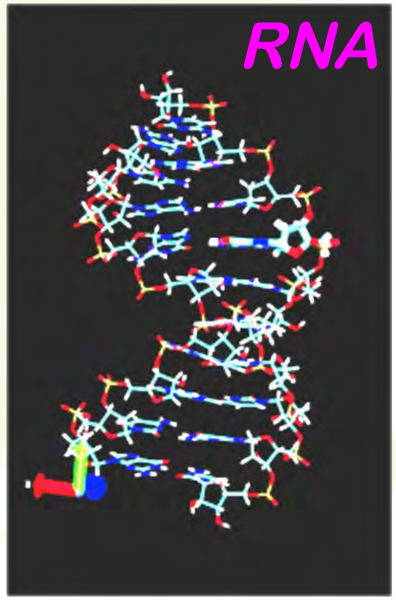
DNA & RNA

DNA



L_{bp} ~ 0.33 nm

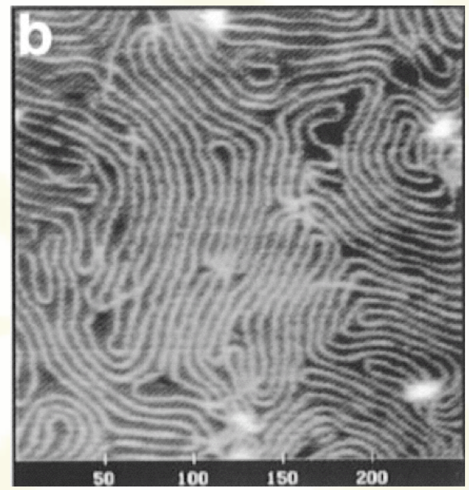
D ~ 2 nm



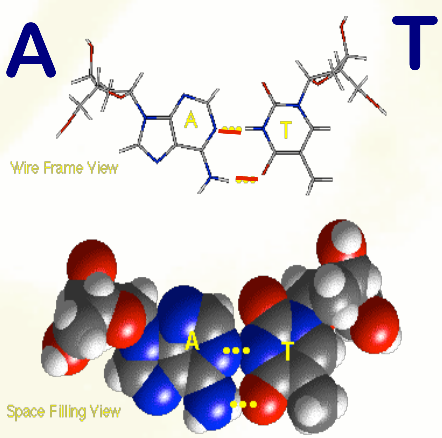
3'-CGCGAAAATTTTCGCG-5'

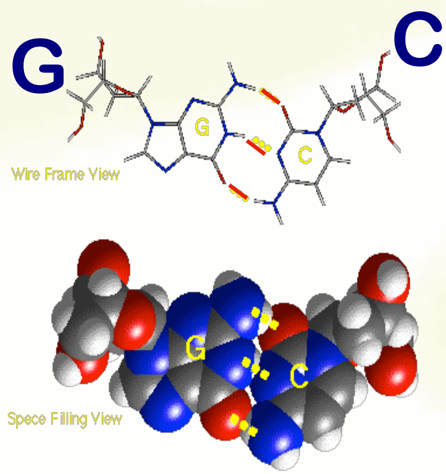
5'-GCGCTTTTAAAAGCGC-3'

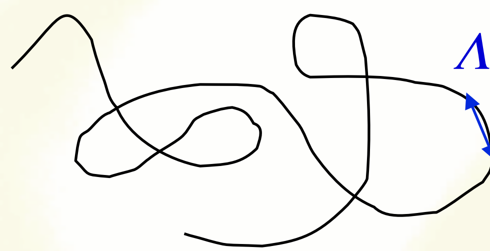
self-complementary 16-mer palindromes



Y. Fang, J. Phys. Chem B (1997)



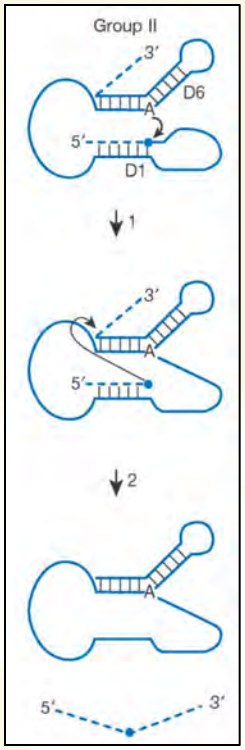




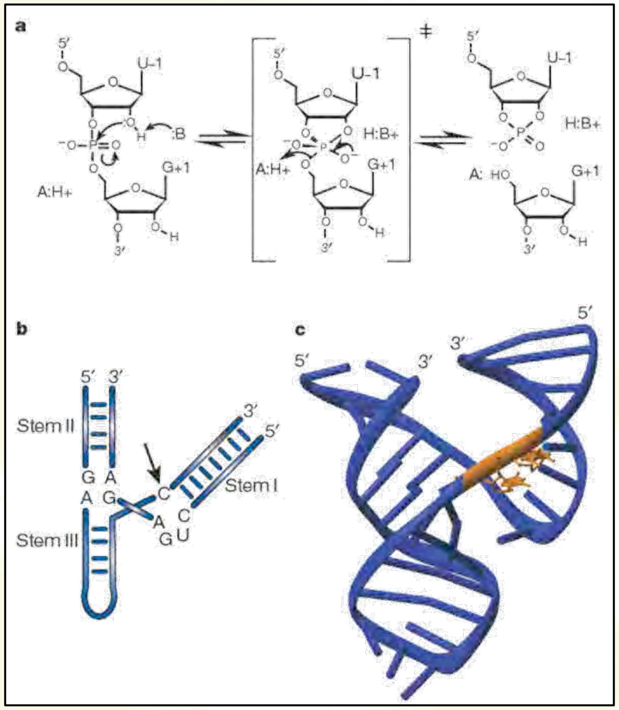
Λ_p ~ 50 nm

~ 150bp

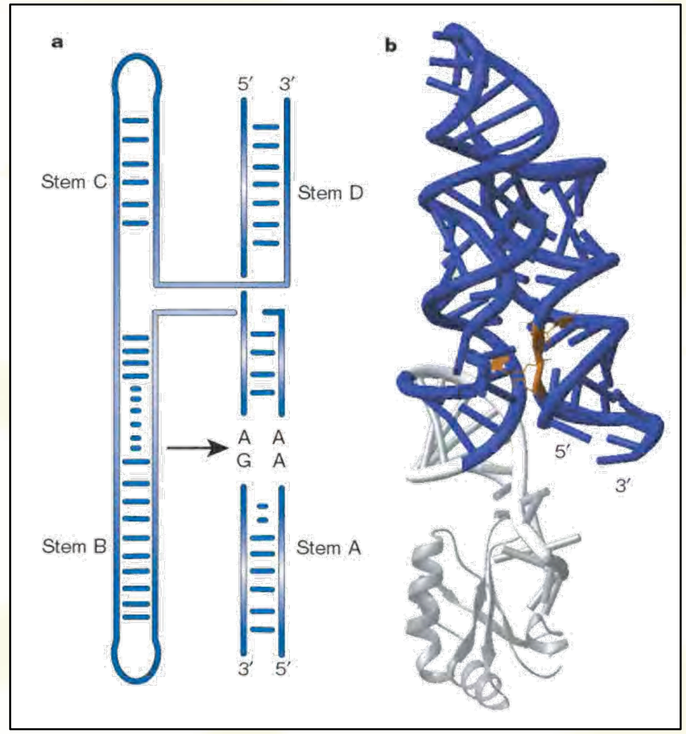
ribozymes



ligation



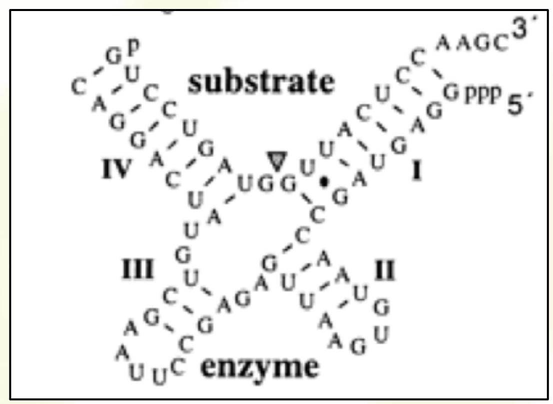
cleaving



J. Doudna, T. Cech , Nature (2004)

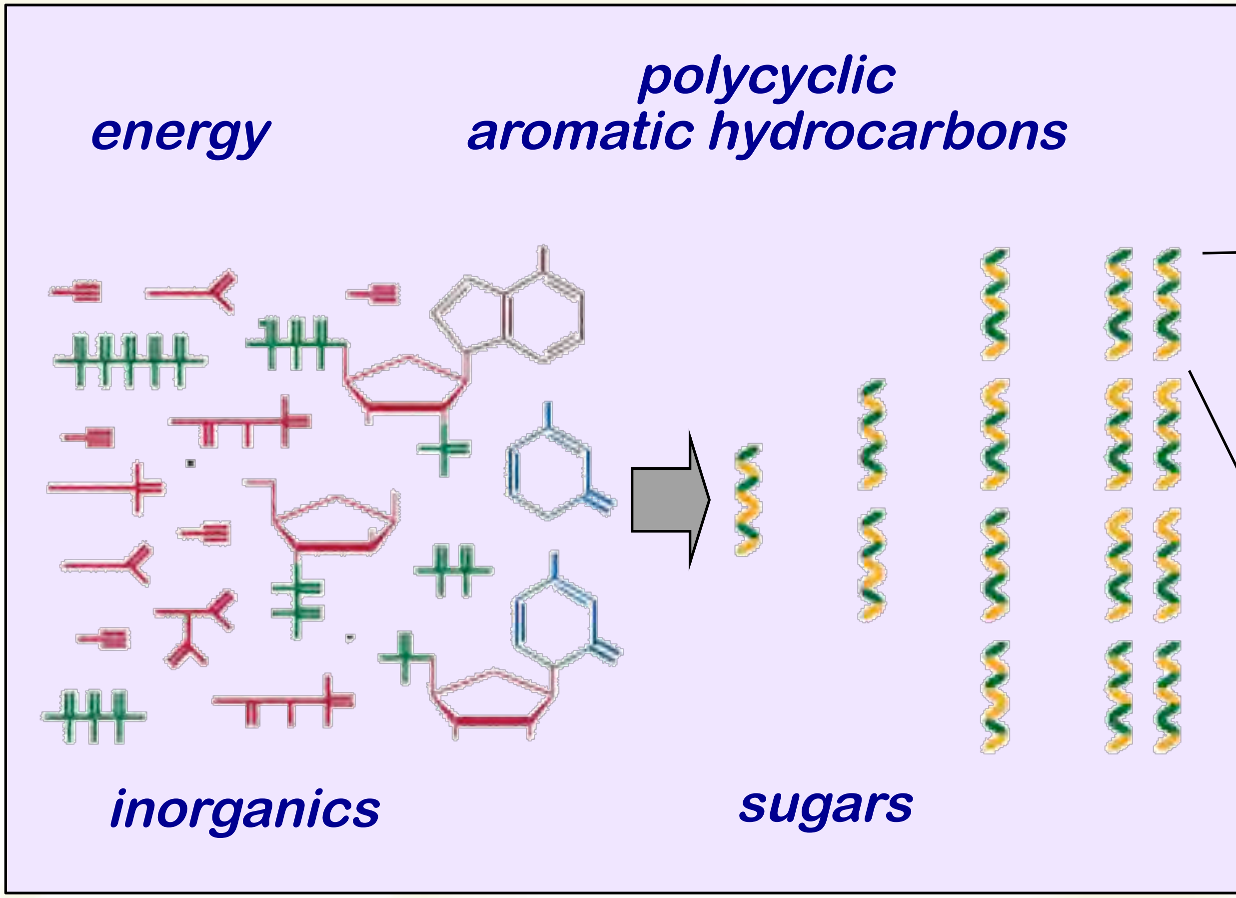
selection (replication)
catalysis
feedback

looks
like it has a
purpose
(life)

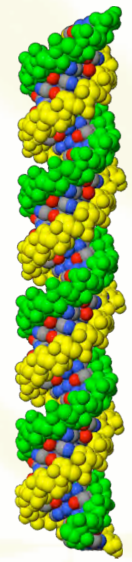


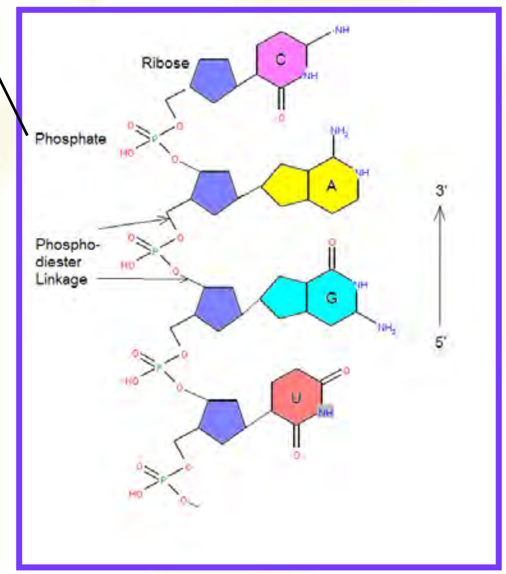
self-
splicing

"cluttered path to (nano) RNA"



G. Joyce , Nature (2002)

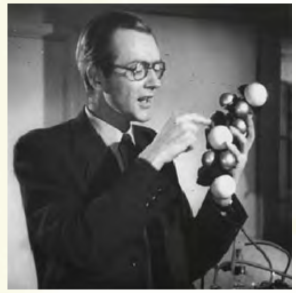




RNA

~35 bp
(or longer)

liquid crystals and DNA (Cambridge, 1953)

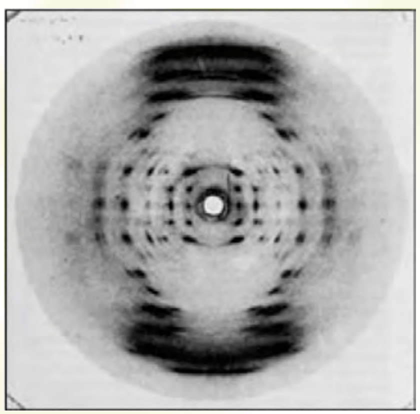


Wilkins

Franklin

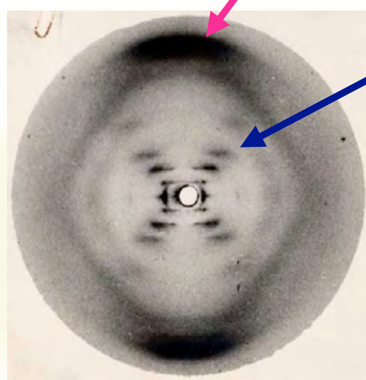
Crick, Watson

Crick-Watson model

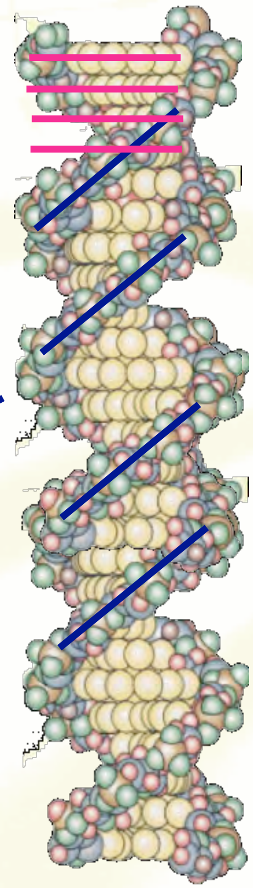


dehydrated

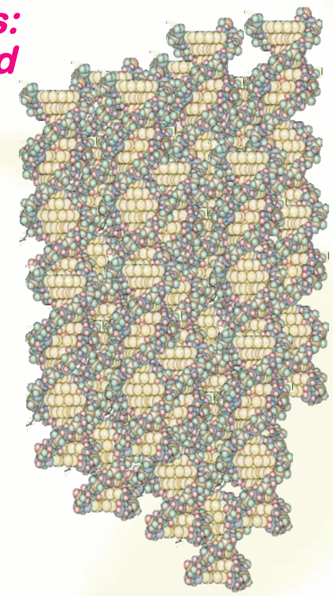
Franklin's "photo 51"



hydrated (LC phase)



no interchain correlations: a DNA liquid crystal!

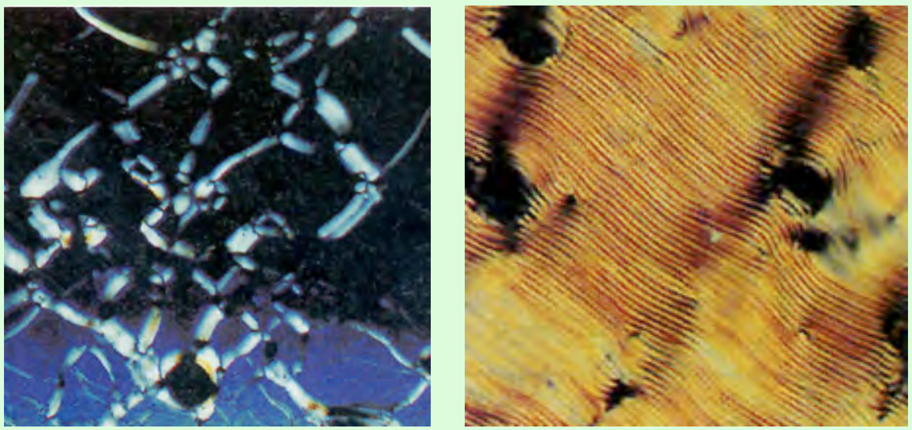


DNA LCs:

Luzzati, Nicolaieff, J. Mol. Bio. 1959
Robinson,Tetrahedron, 1961

duplex DNA chiral nematic phase

(N = 146 bp)

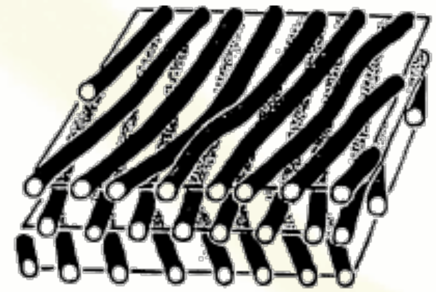


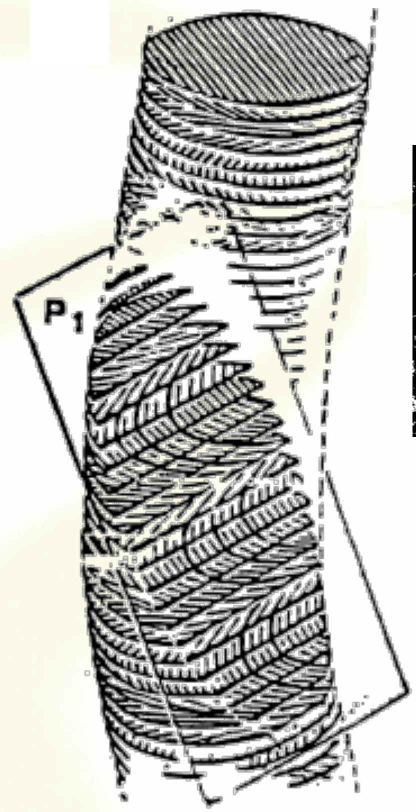
Strzelecka, Davidson, Rill, Nature (1988)

L = 50 nm ~ Λ_p

shape:

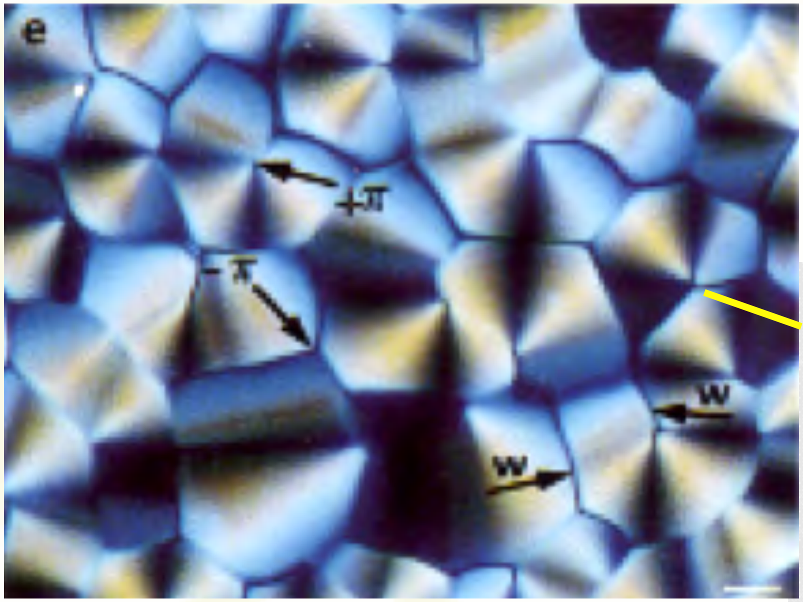
L/D ~ 25/1





dinoflagellate chromosome

duplex DNA columnar phase

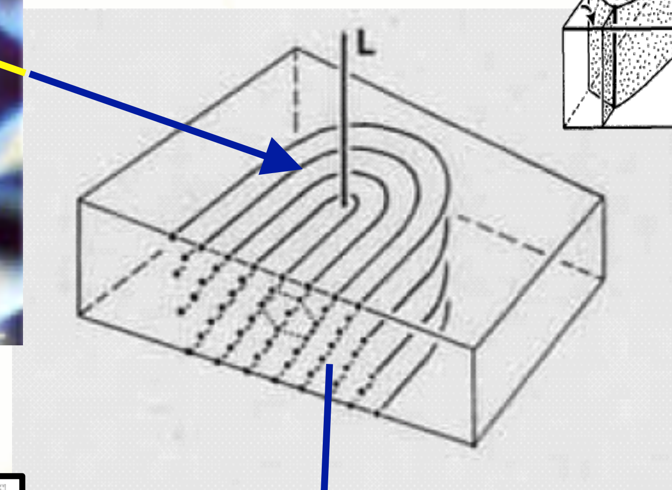


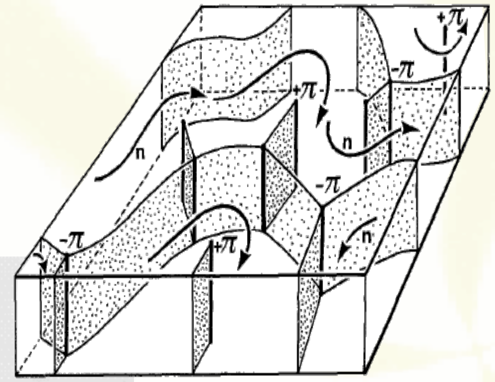
N = 146 bp, L = 50 nm, L/D = 25:1

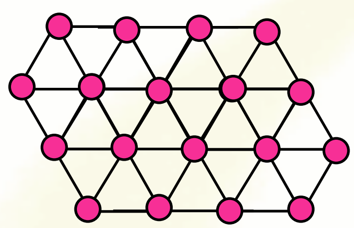
The highly concentrated liquid-crystalline phase of DNA is columnar hexagonal

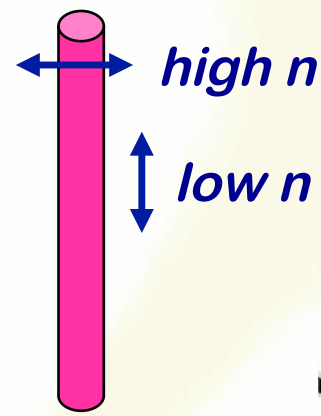
F. Livolant*, A. M. Levelut†, J. Doucet‡† & J. P. Benoit‡

Nature (1989)

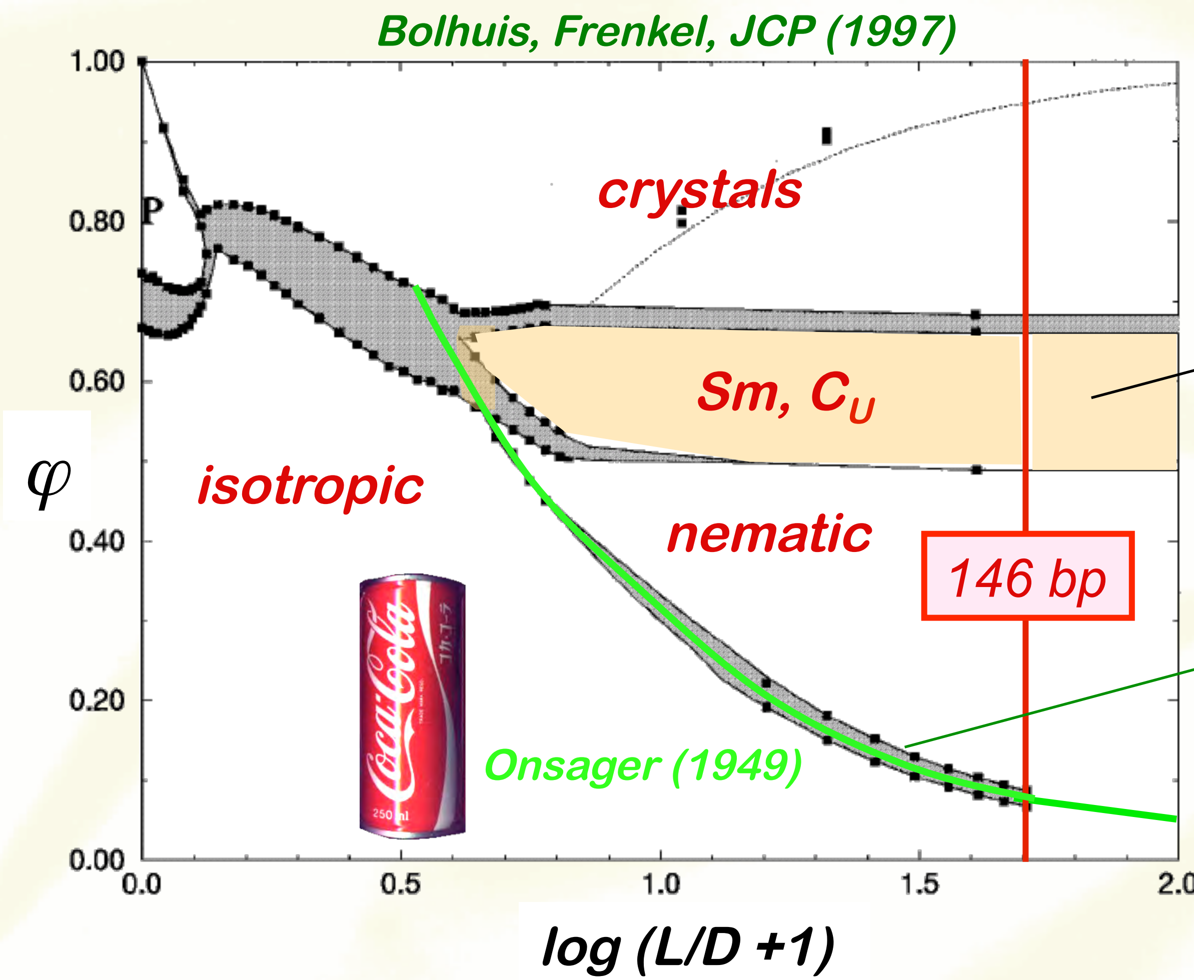


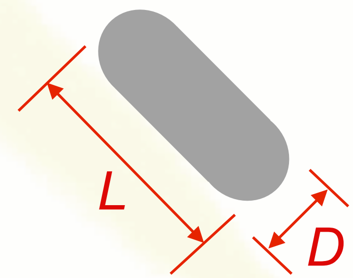




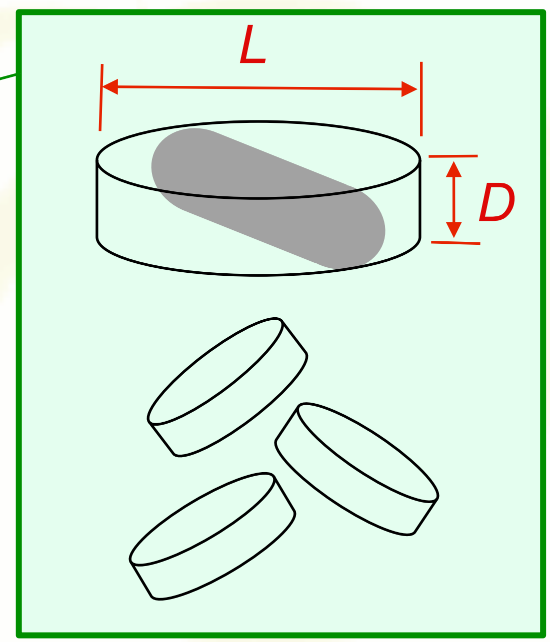


model: hard rods



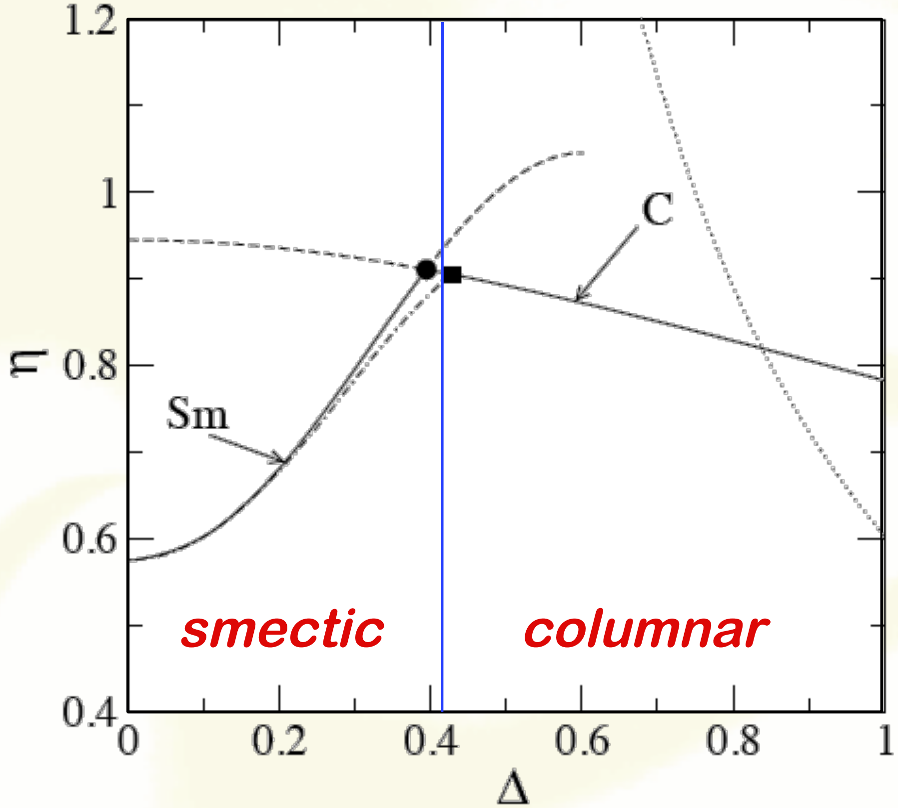


flexibility, polydispersity replaces smectic phase by columnar phase



nematic only for L > 5D

polydispersity in one dimension favors ordering in the other



density →

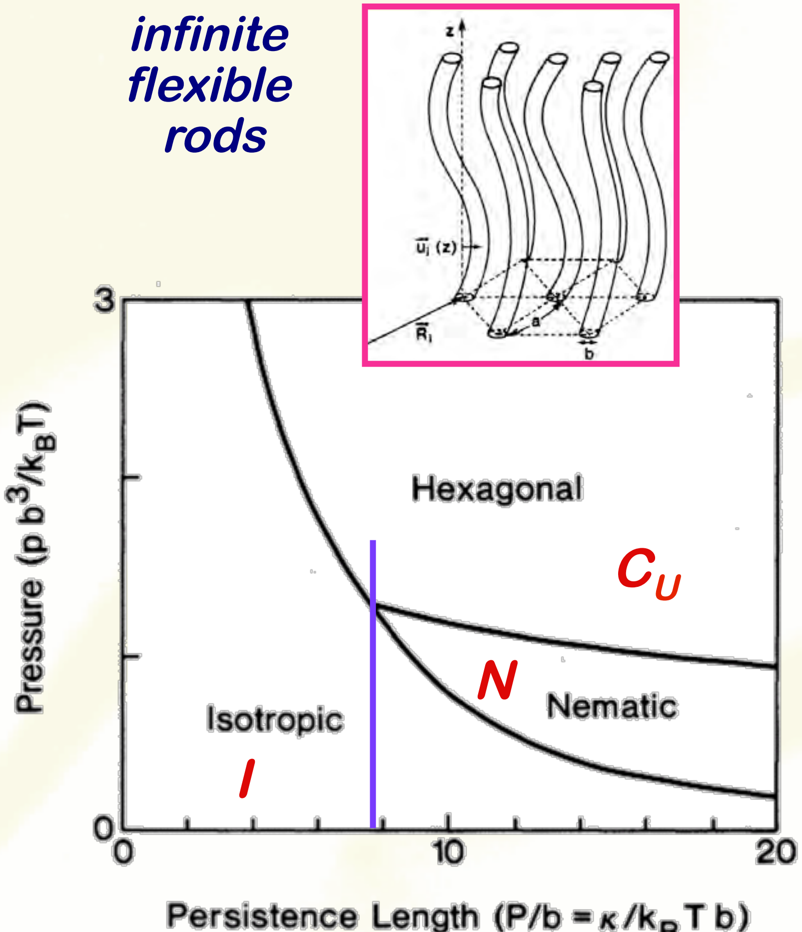
polydispersity in length →

parallel hard rods

Martınez-Raton & Cuesta (2009)

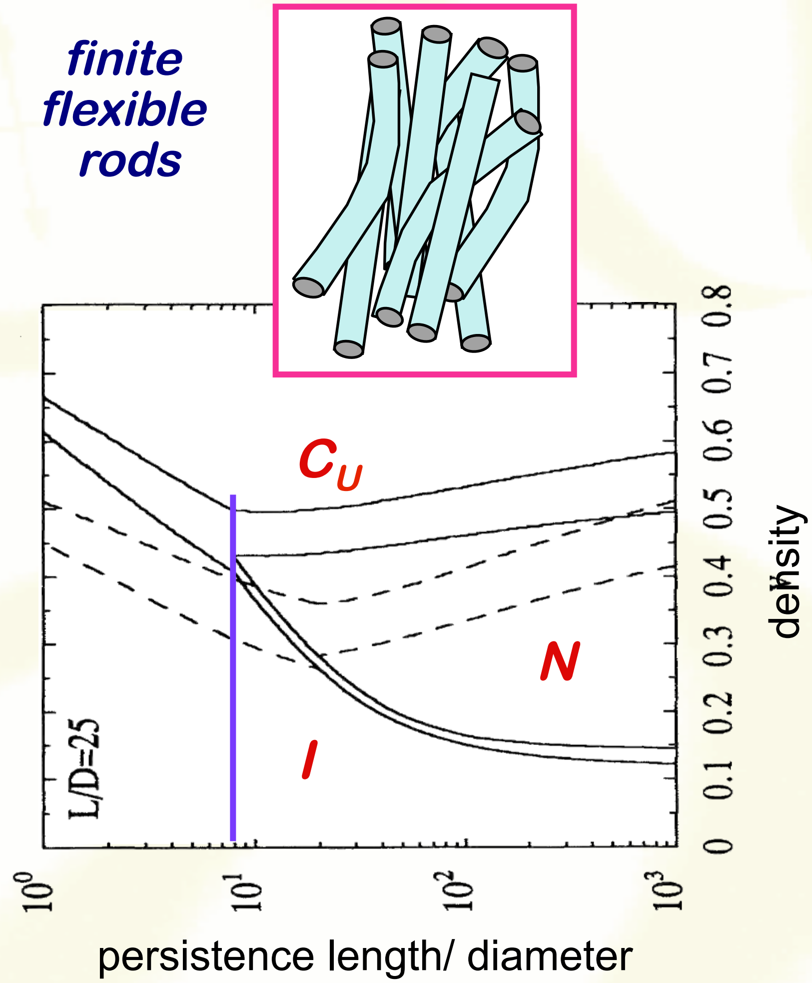
role of rigidity (rods too flexible give no nematic)

infinite flexible rods



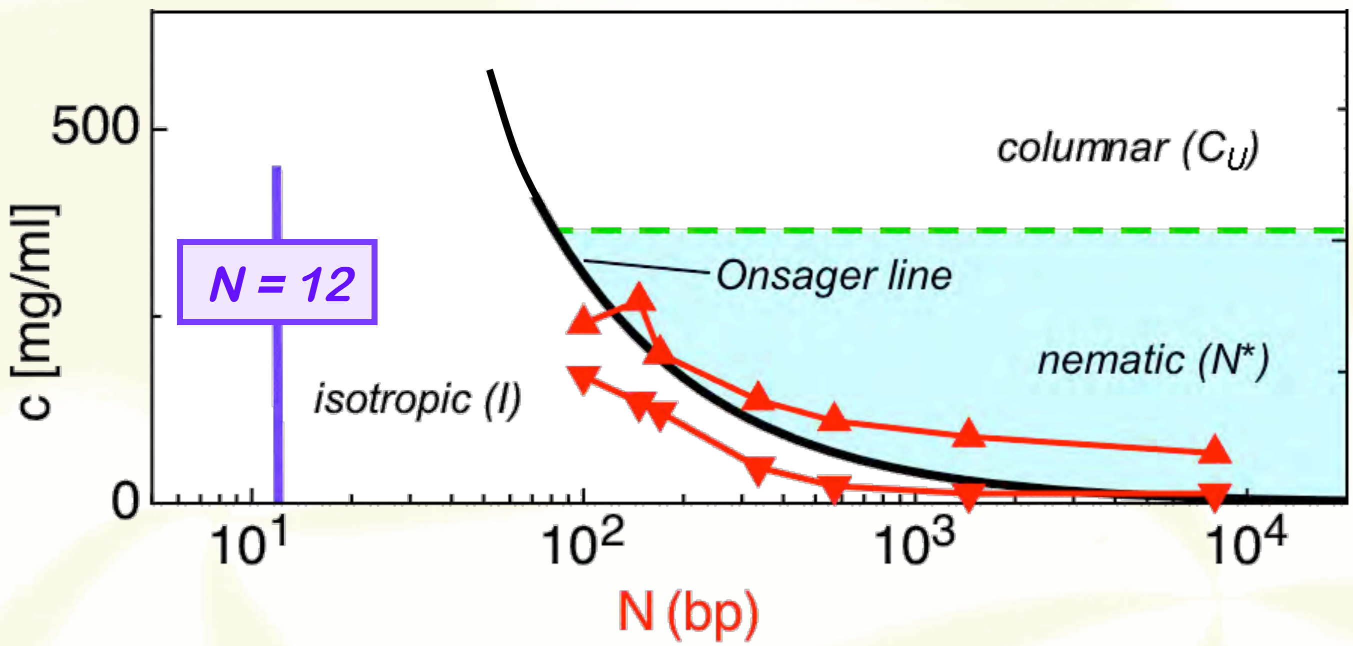
Selinger, Bruinsma, PRA (1991)

finite flexible rods

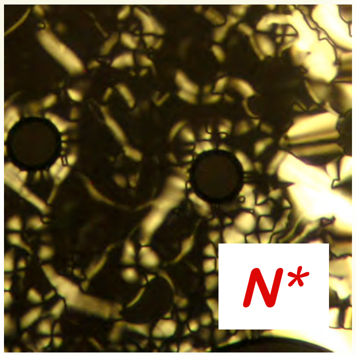


Hentschke, Herzfeld, PRA (1991)

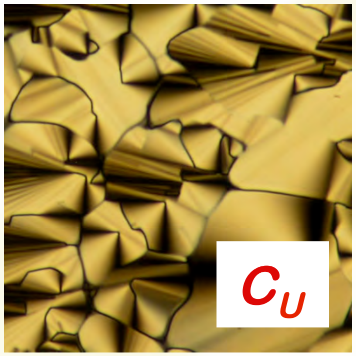
no LC phases expected for N = 12



N = 12 textures

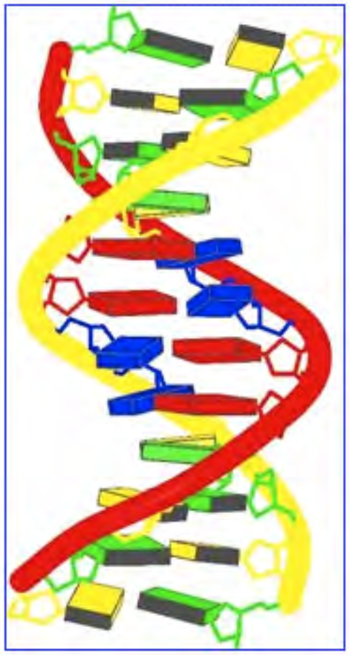


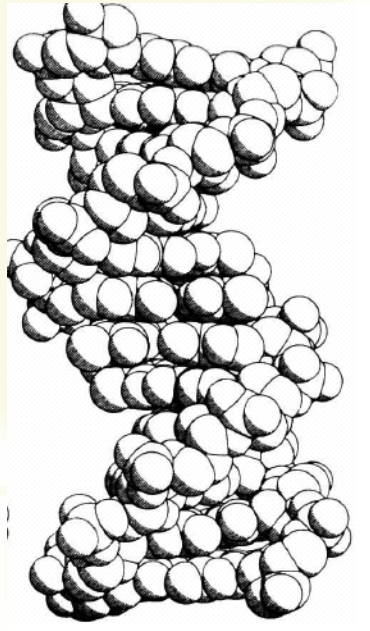
low c



high c

nanoDNA: Drew-Dickerson dodecamer (DD12)





12bp:

3’-GCGCTTAAGCGC-5’

self-complementary

$T_{melting}$ ~ 55ºC

(~750 papers on this molecule)

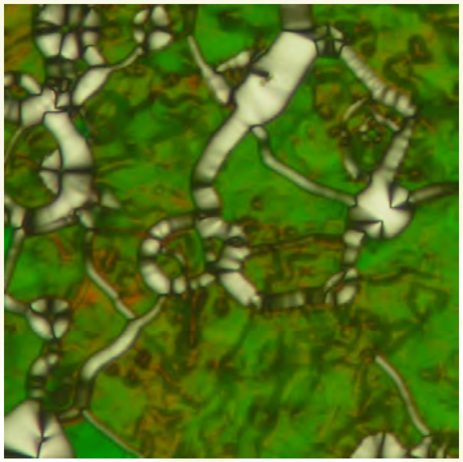
Crystal structure analysis of a complete turn of B-DNA

Richard Wing*, Horace Drew, Tsunehiro Takano, Chris Broka, Shoji Tanaka, Keiichi Itakura† & Richard E. Dickerson

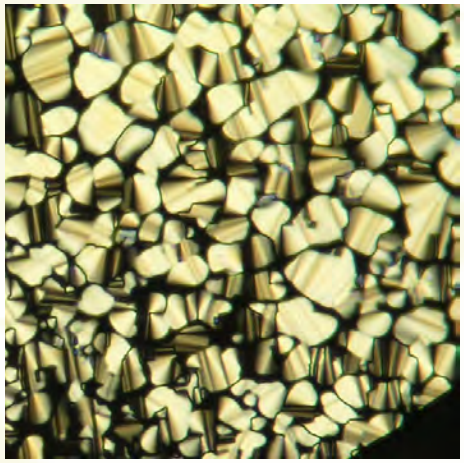
Nature 1980

nanoDNA liquid crystal textures (N=10)

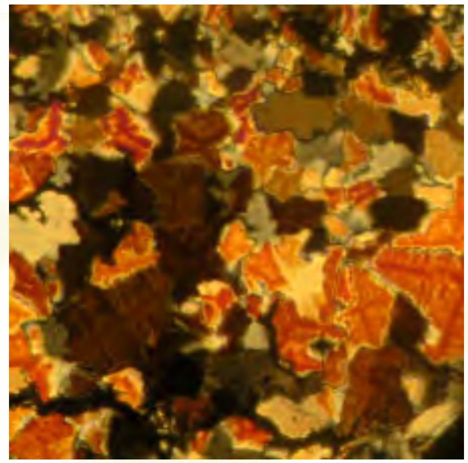
10bp: 5'-CGCAATTGCG-3' (~34.0A)



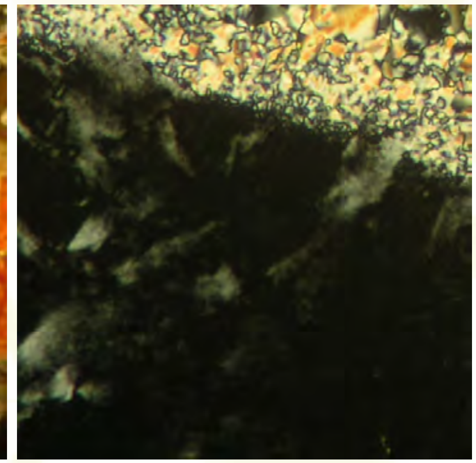
oily-streak texture (N*)



developable domain texture (C_U)



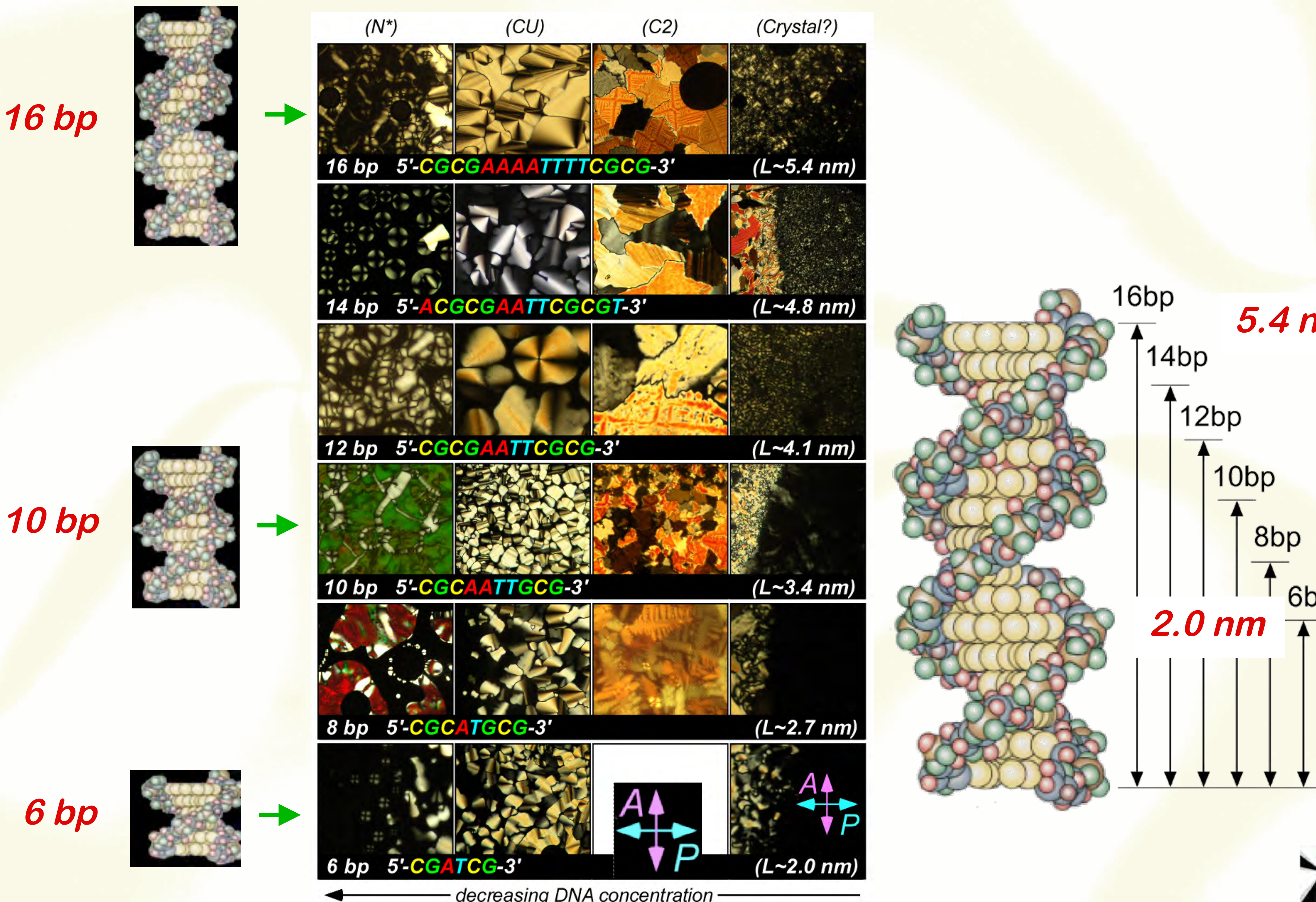
mosaic texture (C_2)



high density (crystal?, glass?)

increasing concentration →

liquid crystals of nanoDNA



"nanoDNA"

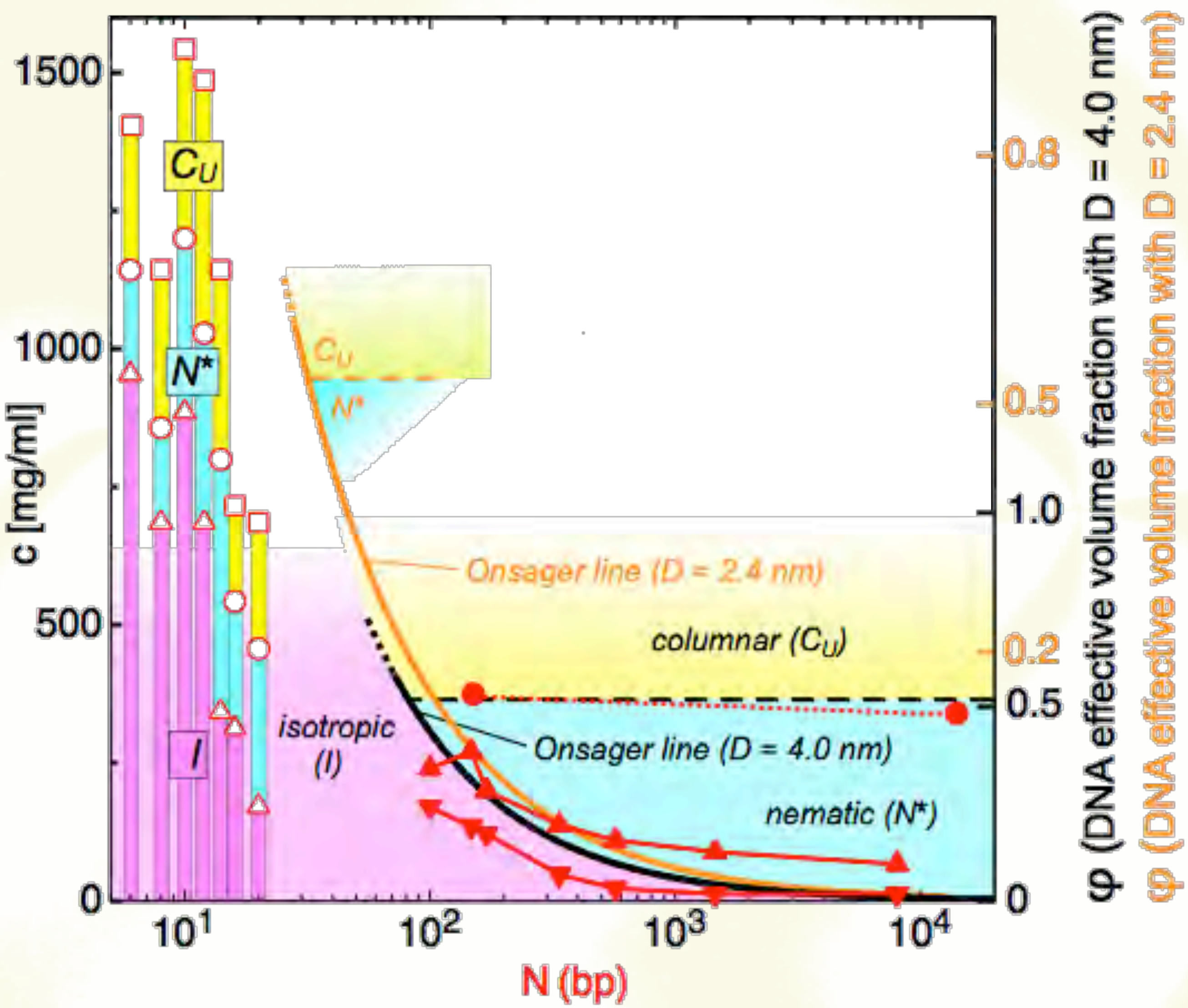
20bp	5'-AACGCAAAGATCTTTGCGTT-3'	(L ~ 6.1 nm)
16bp	5'-CGCGAAAATTTTCGCG-3'	(~ 5.4 nm)
14bp	5'-ACGCGAATTCGCGT-3'	(~ 4.8 nm)
12bp	5'-CGCGAATTCGCG-3'	(~ 4.1 nm)
12bp	5'-AACGCATGCGTT-3'	(~ 4.1 nm)
10bp	5'-CGCAATTGCG-3'	(~ 3.4 nm)
8bp	5'-CGCATGCG-3'	(~ 2.7 nm)
6bp	5'-CGATCG-3'	(~ 2.0 nm)

12bp 5'- CCTCAAAACTCC-3' +

5'- GGAGTTTTGAGG-3'

and many others!

nanoDNA phase diagram



Nakata et al. PNAS (2010)

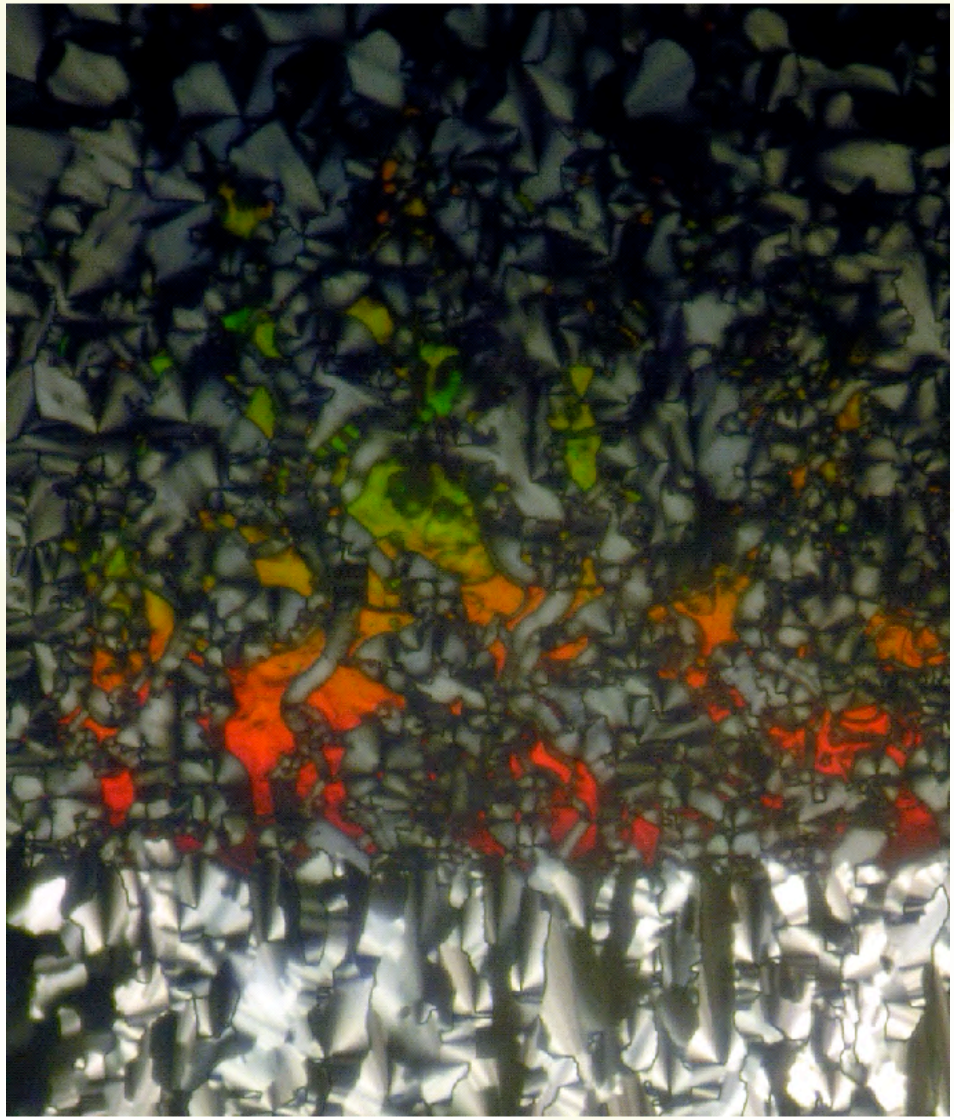
gradient cells

10bp: 5'-CGCAATTGCG-3' (~34.0A)

increasing concentration

N^*

C_U



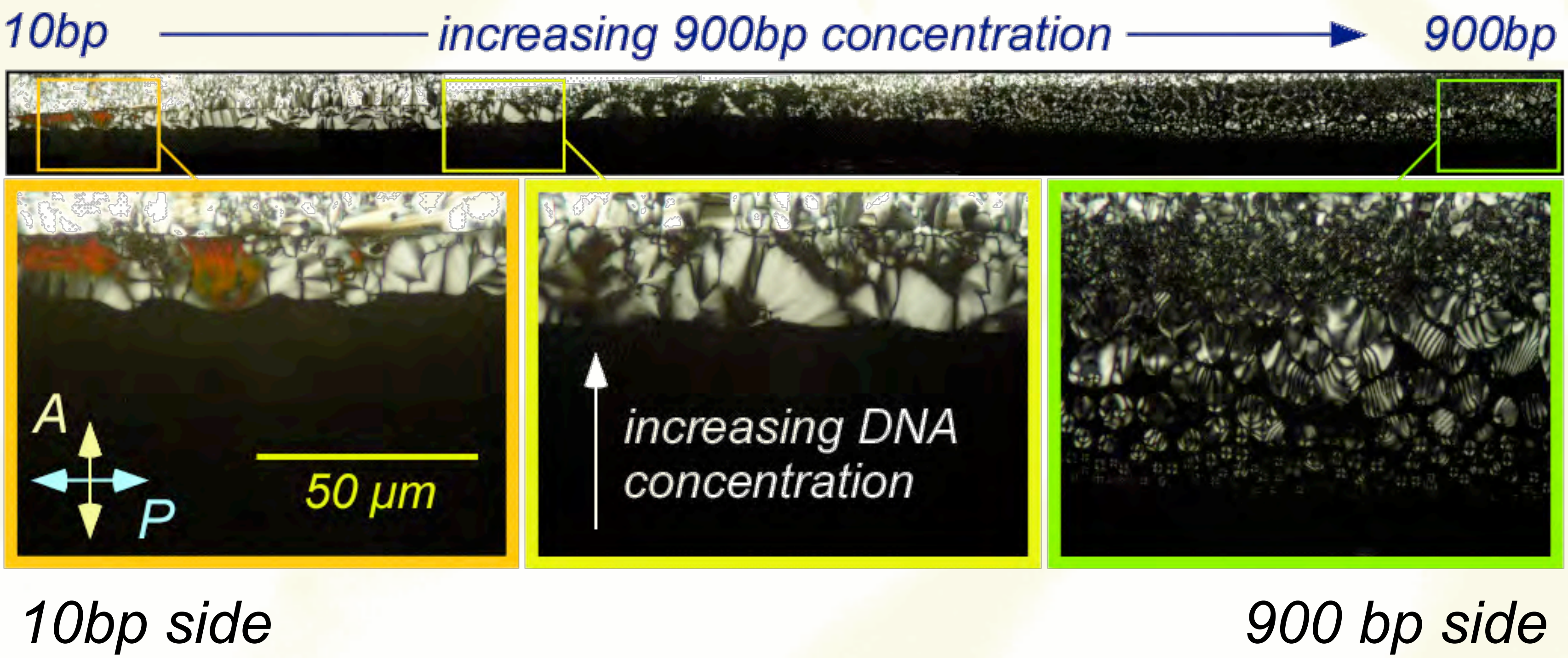
0.5 mg DNA /cell

7µm thick

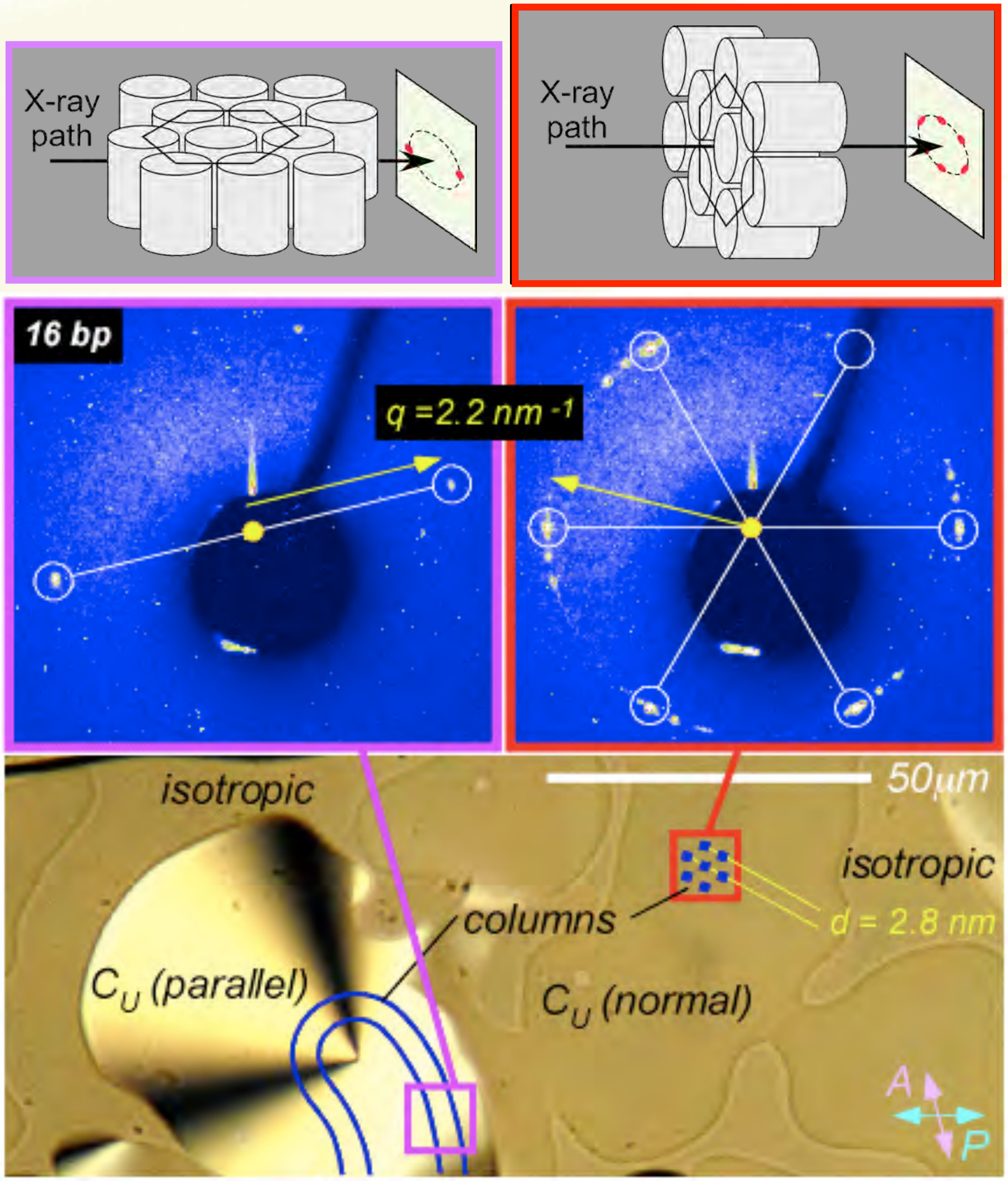
nanoDNA and longDNA: same liquid crystal phases

dual gradient contact cell

long DNA sample (salmon3 ~ 900bp)
nano DNA sample (10bp)



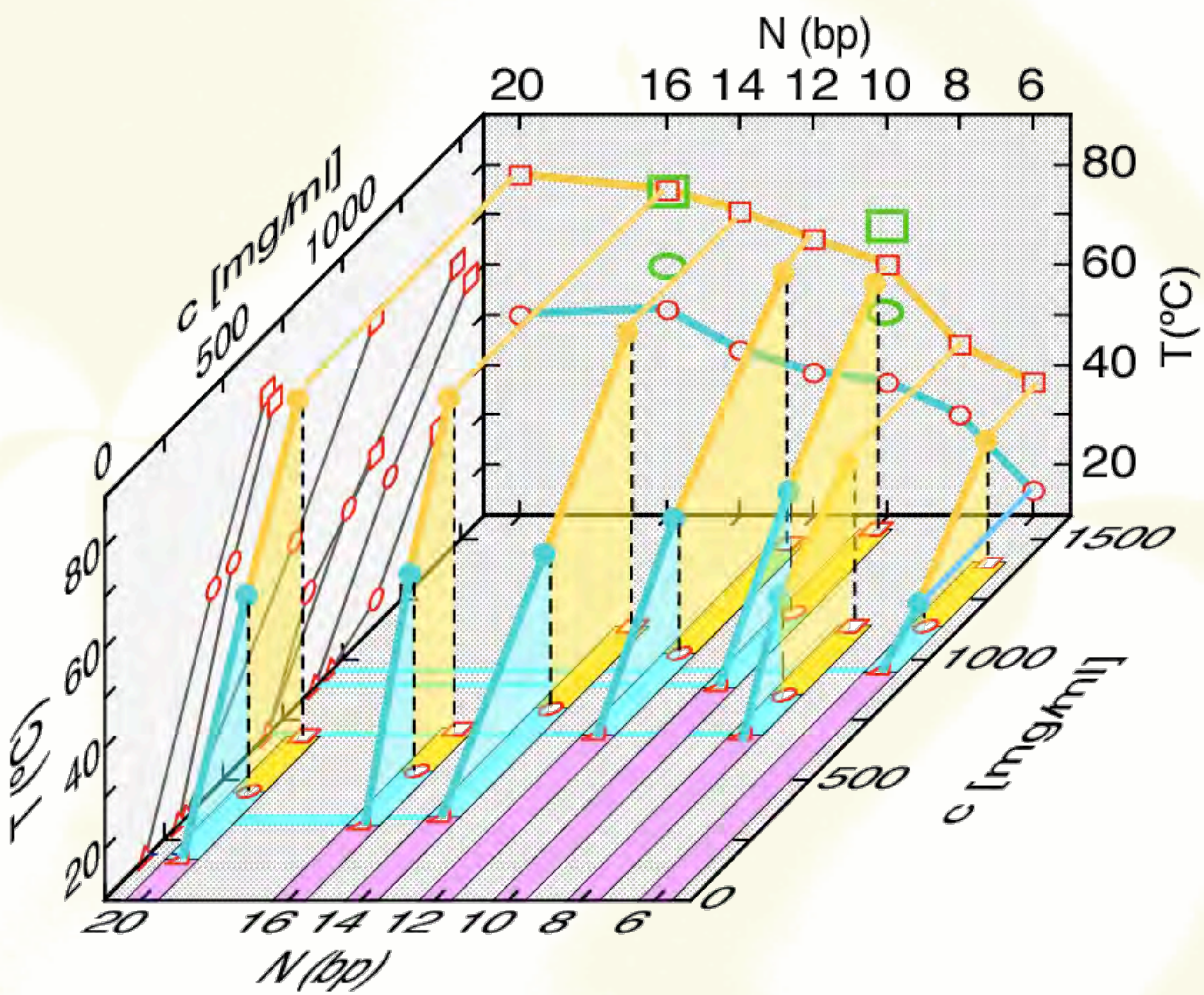
structure of the C_U phase



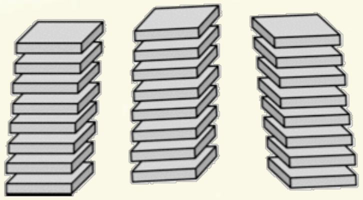
- ***x-ray microbeam diffraction***
- ***C_U phase***
- ***16bp***
- ***Advanced Photon Source***

Ron Pindak, NSLS
Brandon Chapman, NSLS
Julie Cross, APS
Chris Jones, CU

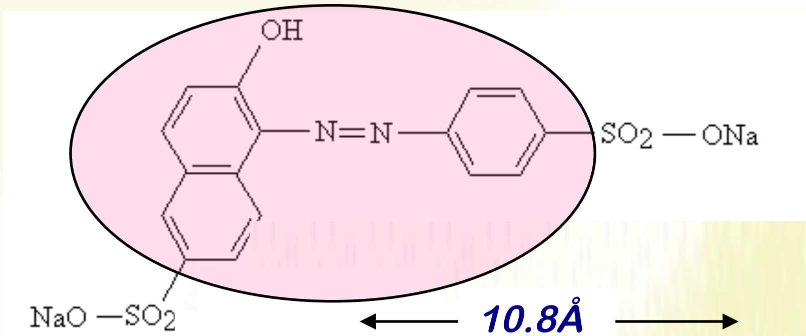
nanoDNA (c-N-T) phase diagram



the end of DNA

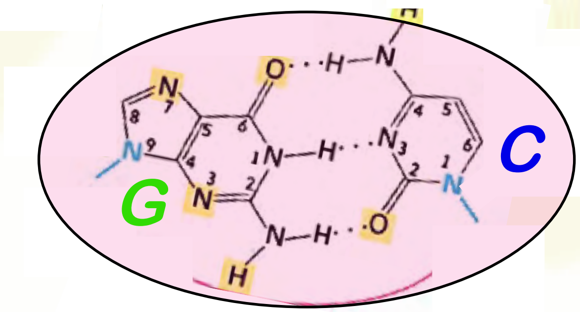


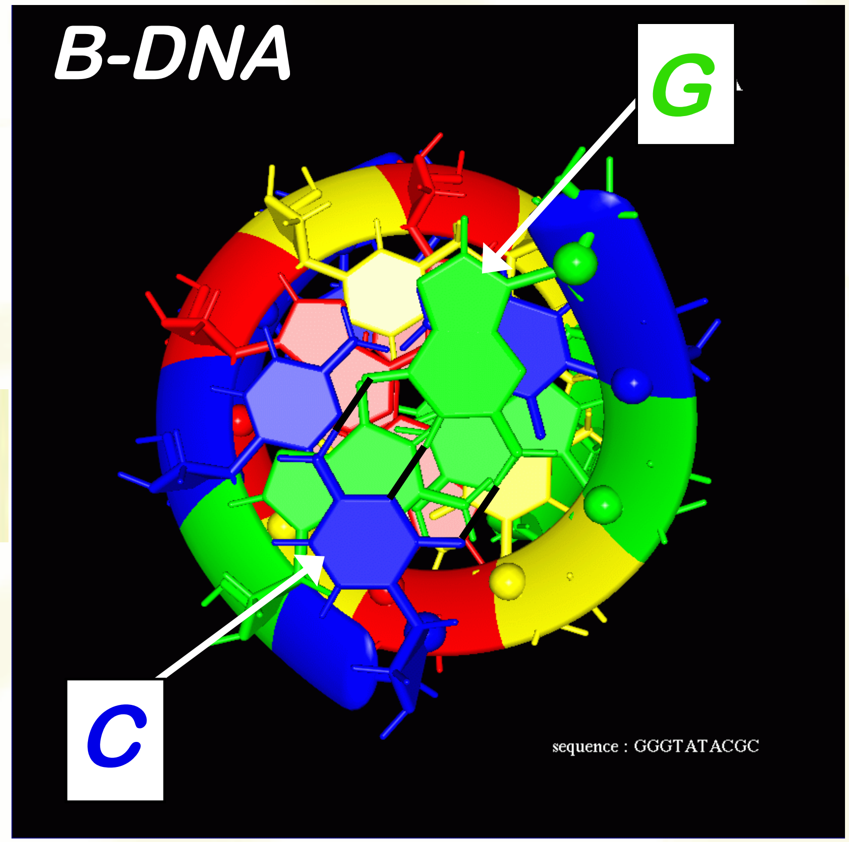
sunset yellow



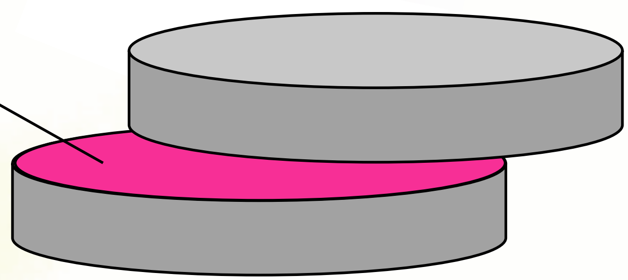
10.8Å

C - G



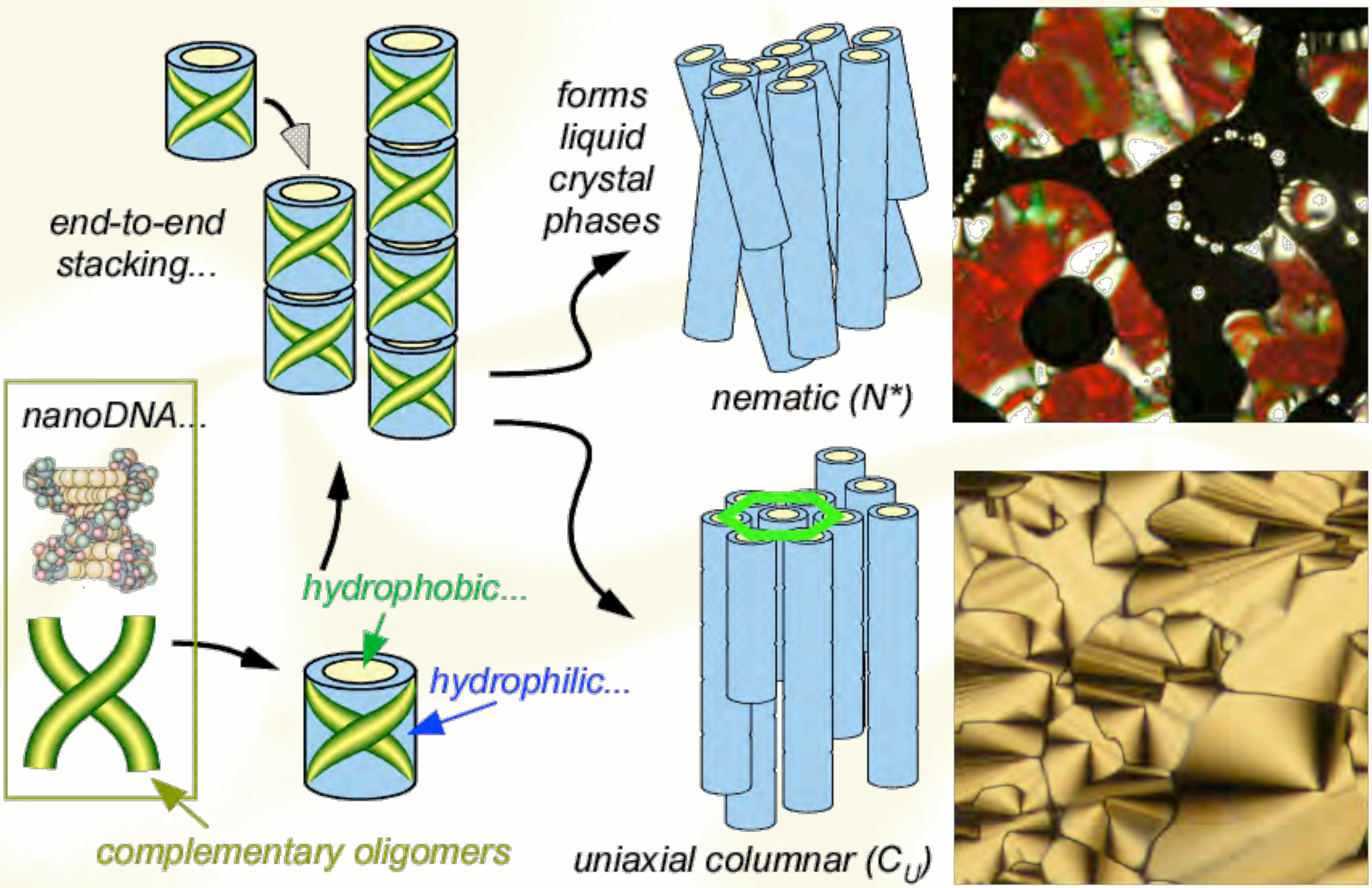


oil

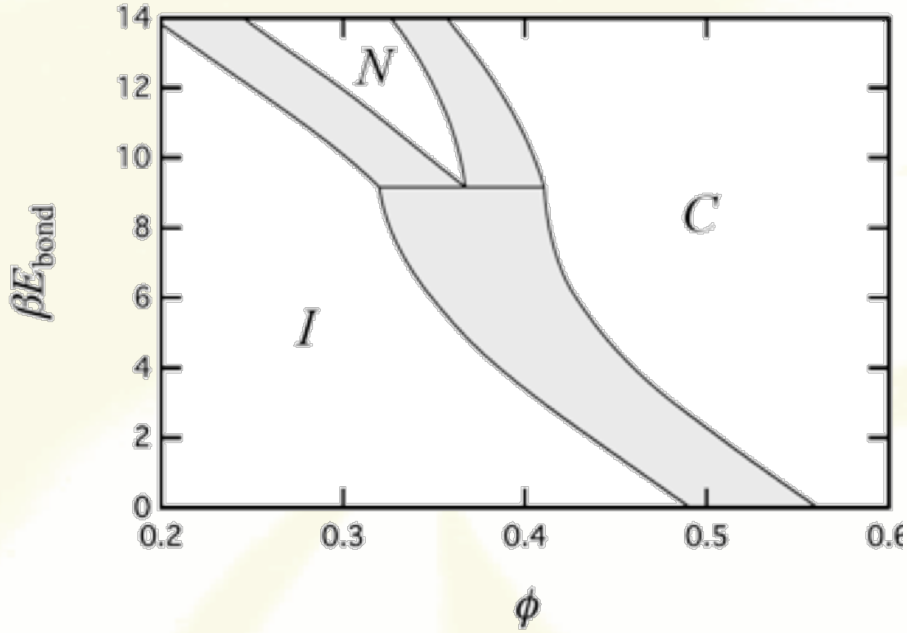


$\varepsilon \sim 2kT / 10Å^2$

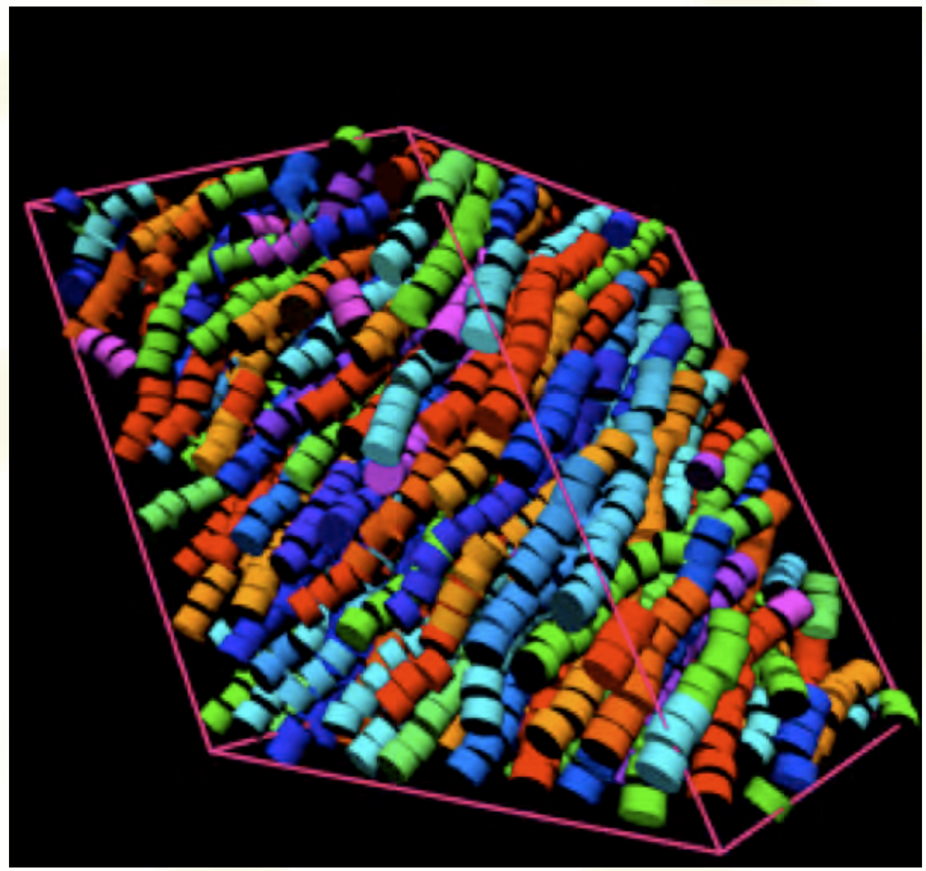
end-to-end adhesion



sticky ends → nemantic & columnar phases



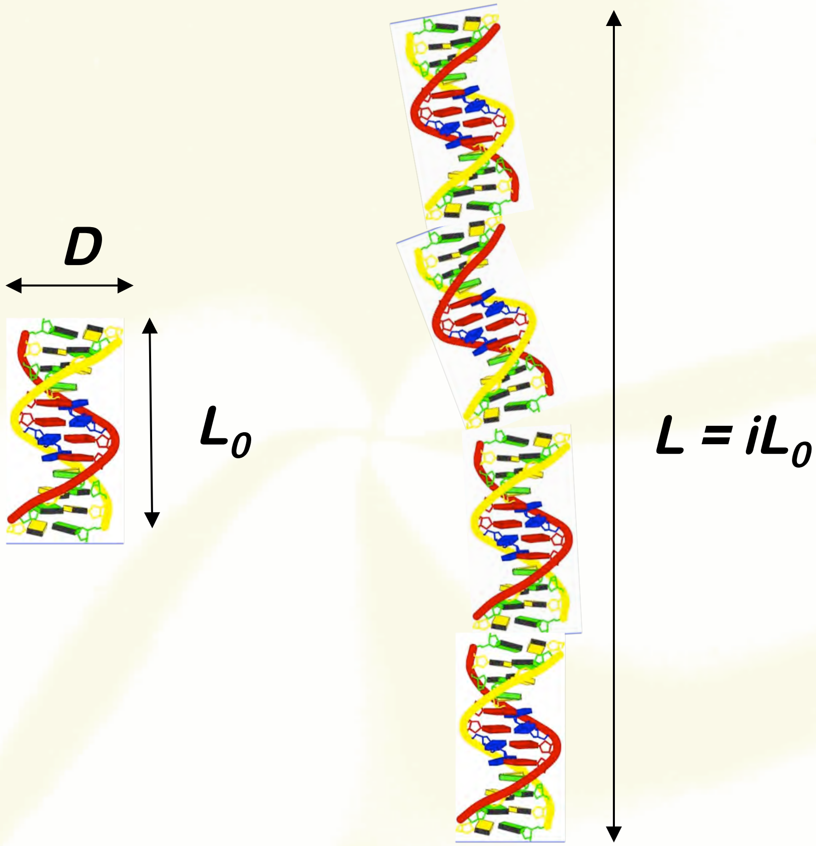
"living polymerization"



Kurablova, Betterton, Glaser, Advanced Materials (2010)

quantitative analysis

linear aggregate of i monomers



$$\langle i \rangle = \frac{1}{2}\left(1 + \sqrt{1 + 4\rho K}\right)$$

$$K = v_0 e^{\beta\varepsilon}$$

K: binding coefficient

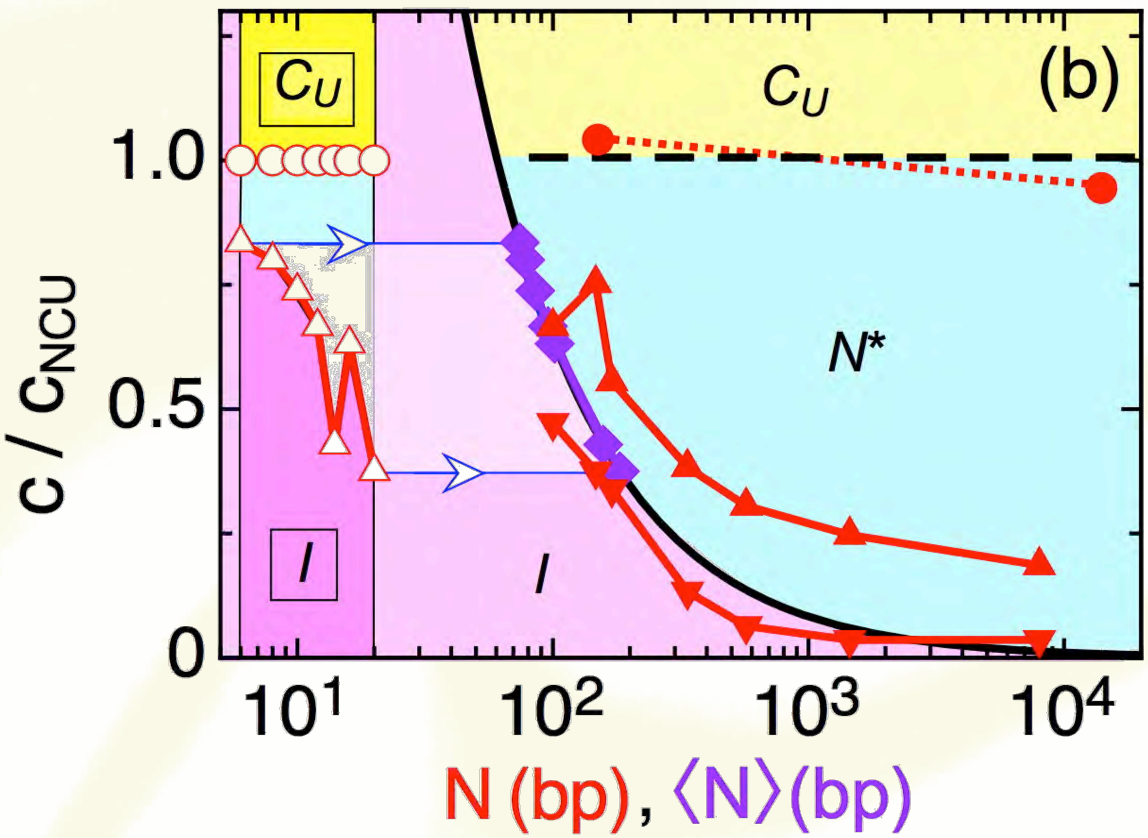
+

at the IN phase boundary

$$\langle i \rangle = \frac{4D}{\phi L_0}$$

Cates, Candau, JPCM, 1990
Lu, Kindt, J. Chem. Phys, 2004
Sciortino et al. J.Chem. Phys 2007

aggregation # <i> ~ 10



stacking energy
ε ~ 5 $K_B T$

isodesmic assembly

$$\langle i \rangle = \frac{1}{2}\left(1 + \sqrt{1 + 4\phi \frac{v_0}{v_p}\left(e^{\beta\varepsilon} - 1\right)}\right)$$

effect of DNA oligomer termination

12bp

OH-CGCGAAAATTTTCGCG-OH

OH-CGCGAAAATTTTCGCG-PO_4

} ***N*, CU, C2 LC phases***

PO_4-CGCGAAAATTTTCGCG-PO_4 — ***no LC phases***

12bp-T, 12bp-TT

C1 and C2 phase

no nematic phase

TTCGCGAAAATTTTCGCG

TTCGCGAAAATTTTCGCG

10bp-TTTTTTTTTT

No LC phases

TTTTTTTTTTCGCGAAAATTTTCGCG

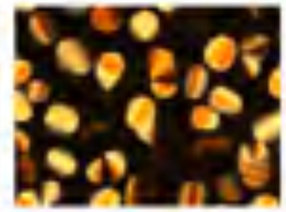
TTTTTTTTTTCGCGAAAATTTTCGCG

- ***termination matters***
- ***noncomplementary tails destabilize LC phases***

defected sequences

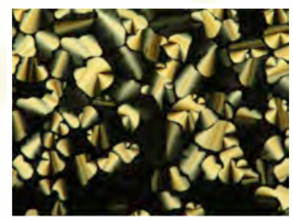
internal defects

both N and COL phases*



terminal defects

*COL phases, no N**

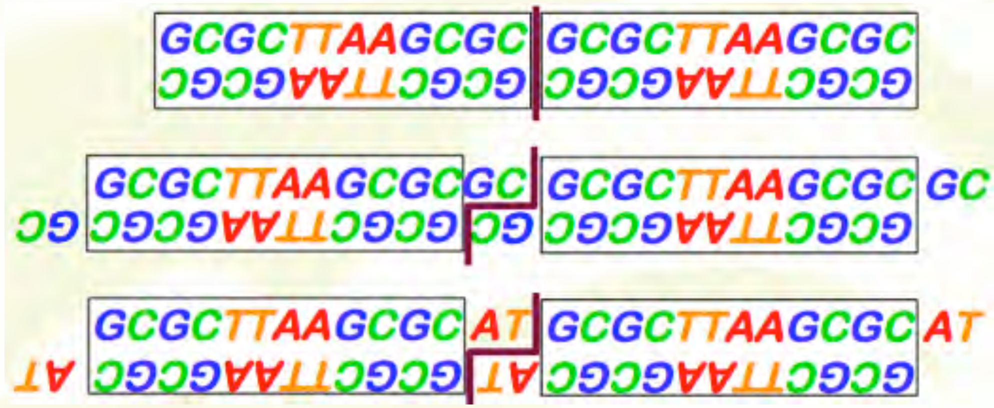


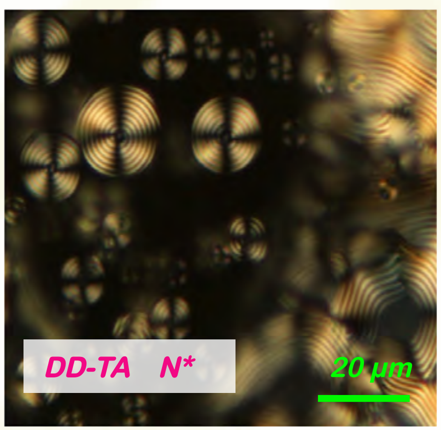
non-complementary shift

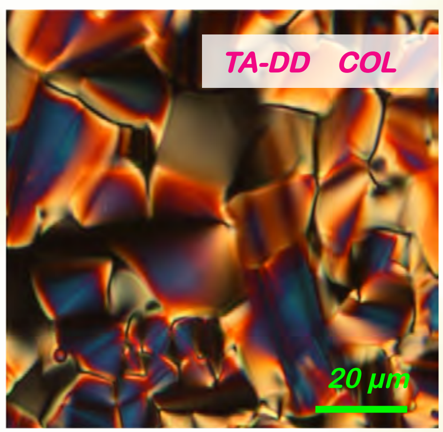
*no N*phases*

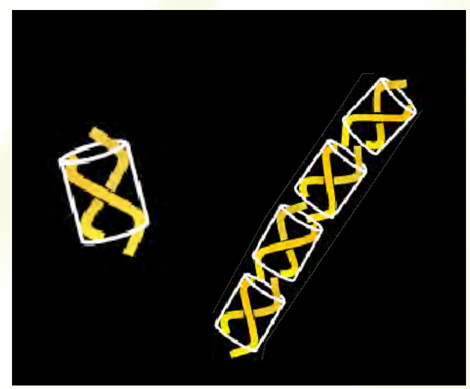
nanoDNA with sticky ends (12 (DD) +2 bp)

5'-AT CGCGAATTCGCG-3'
5'-TA CGCGAATTCGCG-3'
5'-CG CGCGAATTCGCG-3'
5'-GC CGCGAATTCGCG-3'
5'-CGCGAATTCGCG AT-3'
5'-CGCGAATTCGCG TA-3'
5'-CGCGAATTCGCG CG-3'
5'-CGCGAATTCGCG GC-3'

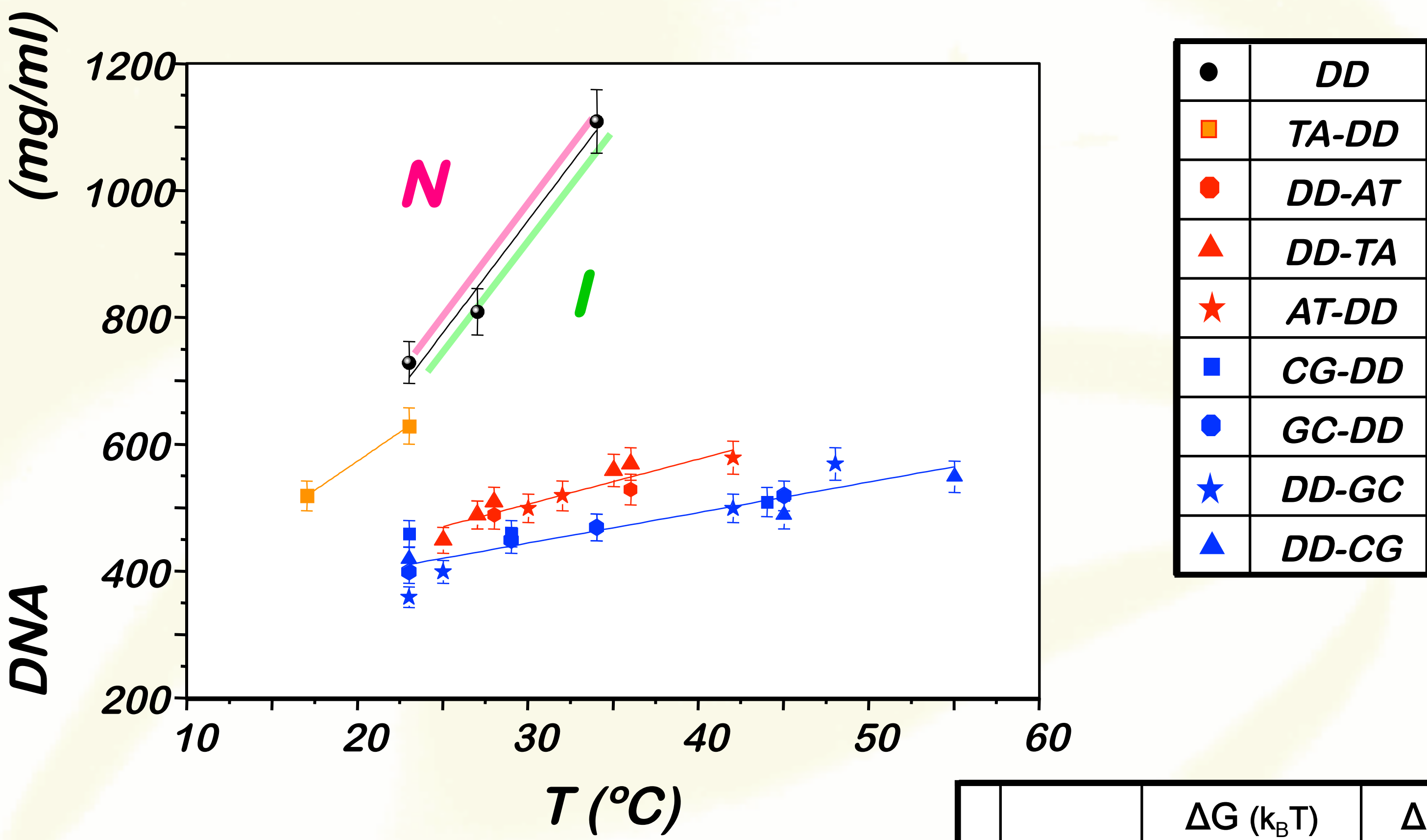






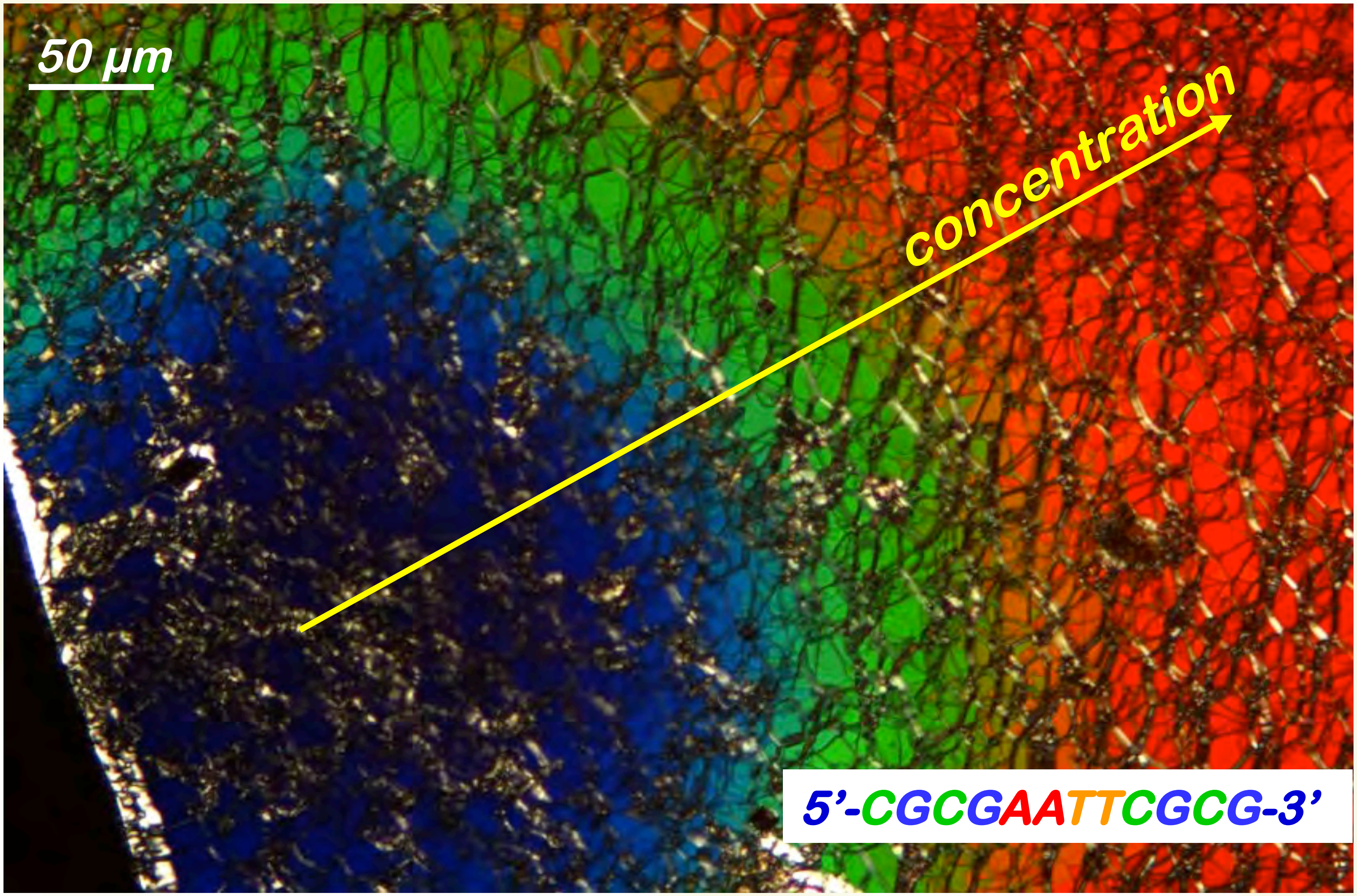


quantitative analysis



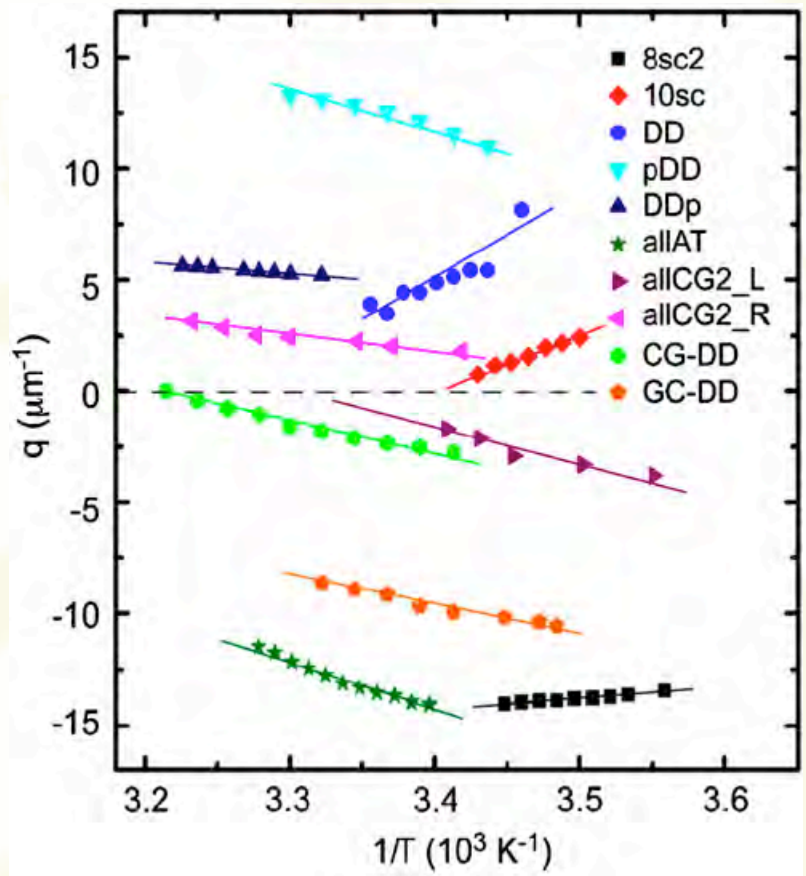
		ΔG (k_BT)	ΔH (k_BT)	ΔS (k_B)
	DD	-5.2 ±0.2	-28 ±6	-0.08 ±0.02
	TA-DD	-6.0 ±0.2	-20 ±10	-0.05 ±0.03
	"AT"	-7.0 ±0.2	-9 ±3	-0.01 ±0.01
	"CG"	-7.3 ±0.2	-7 ±4	0 ±0.008

propagation of chirality



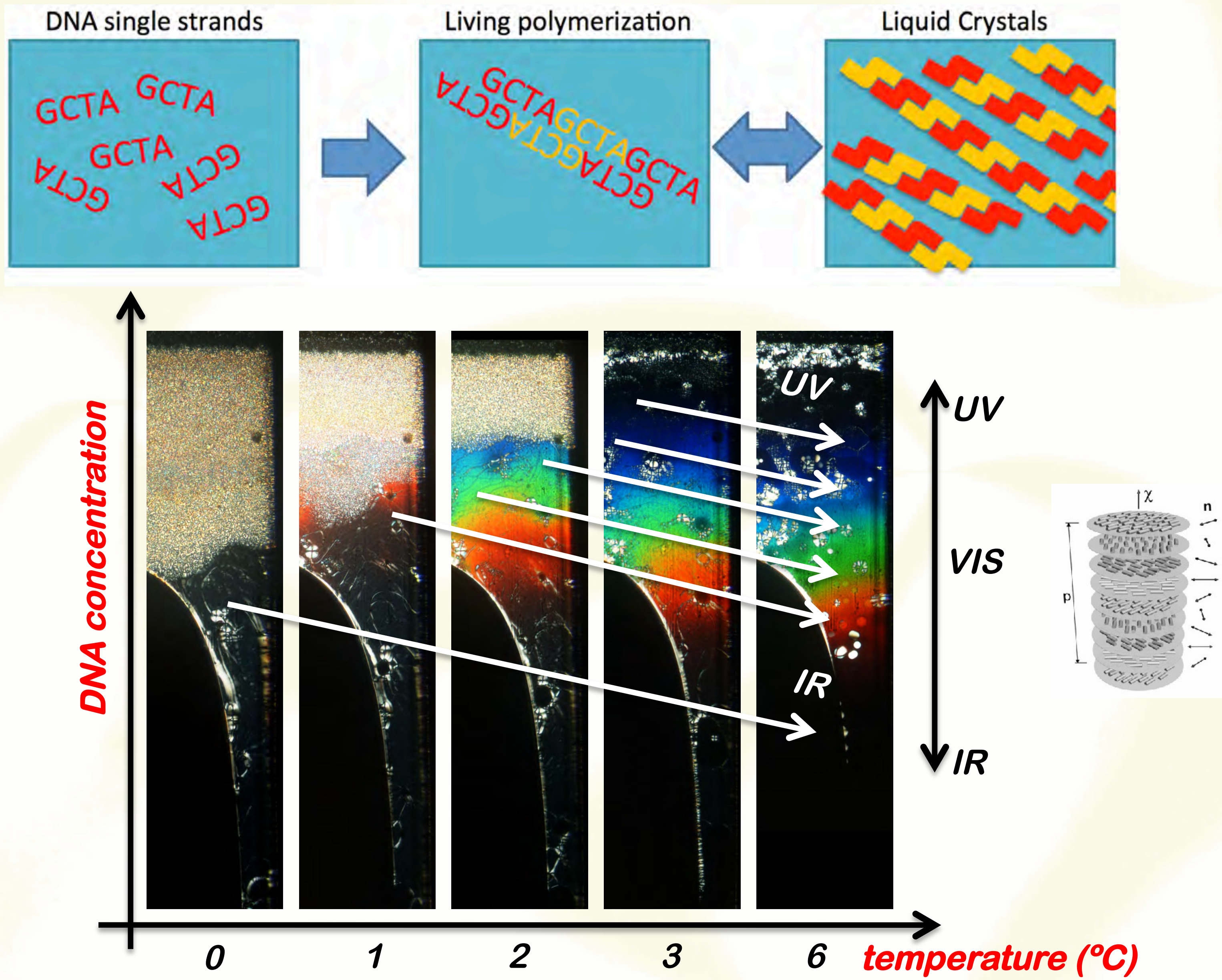
nanoDNA N* helix pitch and handedness

Sequence	Nickname	|p| range (μm)	H
CGAATTCG	8sc1	1–2	L
CGCATGCG	8sc2	0,45–0,8	L
CGCAATTGCG	10sc	0,4–∞	R
ATAAATTTAT	10allAT	1–3	R
CGCGAATTCGCG	DD	0,7–3	R
pCGCGAATTCGCG	pDD	0,35–1	R
CGCGAATTCGCGp	DDp	0,3–1	R
GCGCTTAAGCGC	antiDD	1–2	R
GGAGTTTTGAGG + CCTCAAAACTCC	12mc	0,7–2	R
ACCGAATTCGGT	ACC	1–3	R
AACGAATTCGTT	AAC	∞	A
AATGAATTCATT	AAT	1–2	L
AATAAATTTATT	allAT	0,5–1	L
CCGGCGCGCCGG	allCG1	1–3	L
CGCGCCGGCGCG	allCG2	0,3–∞	L,R
GCGCGAATTCGC	sDD	0,3–1	L
ACGCGAATTCGCGT	14Aterm	1–3	L
CGCGAAATTTCGCG	14sc	1–3	L
pCGCGAAATTTCGCG	p14sc	1–3	L
GCCGCGAATTCGCG	GC-DD	0.35–1	L
CGCGAATTCGCGGC	DD-GC	1–3	L
CGCGCGAATTCGCG	CG-DD	1–3	L
ATCGCGAATTCGCG	AT-DD	1–3	L
ACGCAGAATTCTGCGT	16Aterm	1–4	L
CGCGAAAATTTTCGCG	16sc	1–4	L
AACGCAAAGATCTTTGCGTT	20sc	1–4	L
CGCGAAUUCGCG	DD-RNA	0.3–1	R
—	long DNA	2–4	L

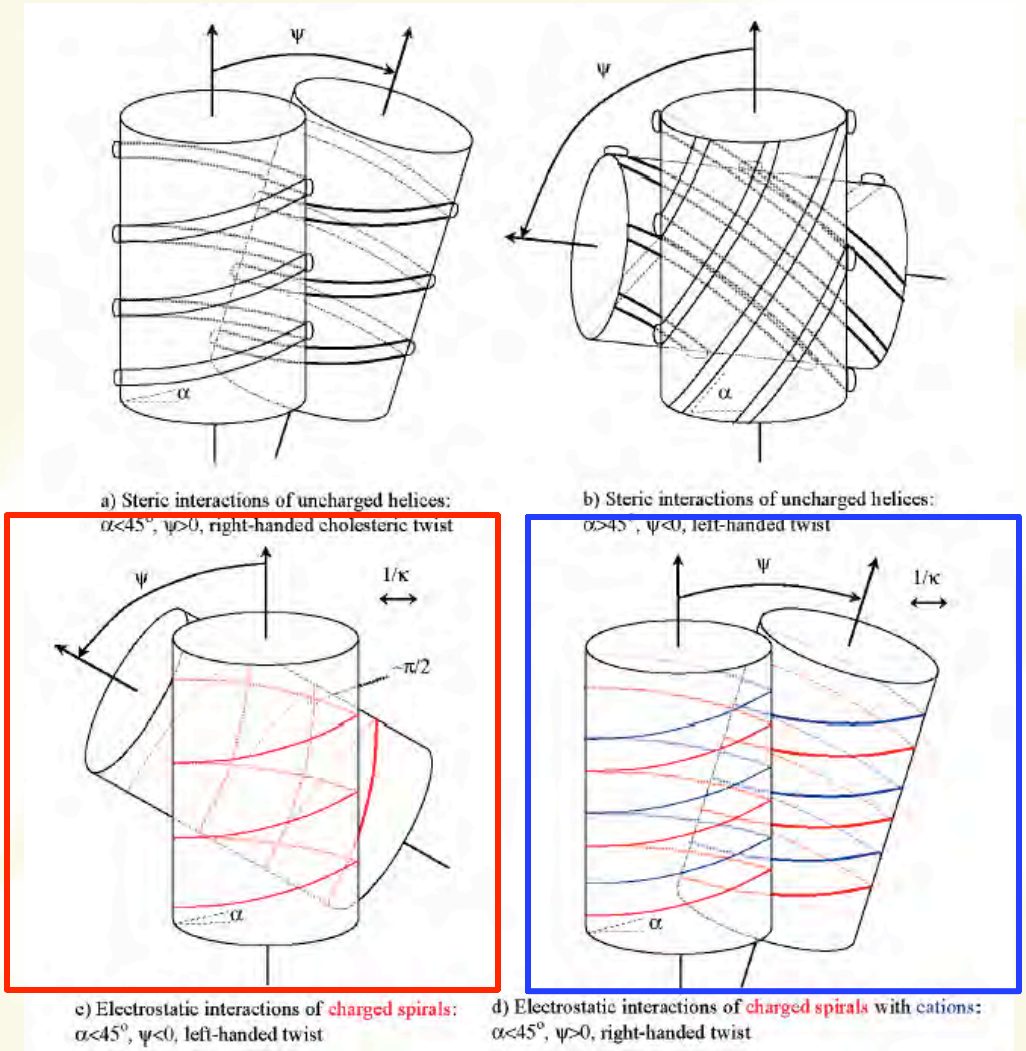


Zanchetta et al. PNAS (2010)

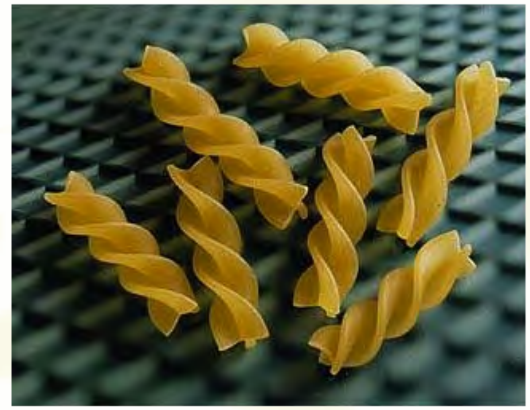
4 base pairs (GCTA)



chiral interactions



steric component: packing fusilli



Straley (1975)

DNA (B-DNA), RNA (A-RNA), G-quartets all have < 45° helices (A case)

electrostatic interactions:
phosphate charges only
with counterions adsorbed in the grooves too

Cherstvy (2008)

nanoDNA N phase

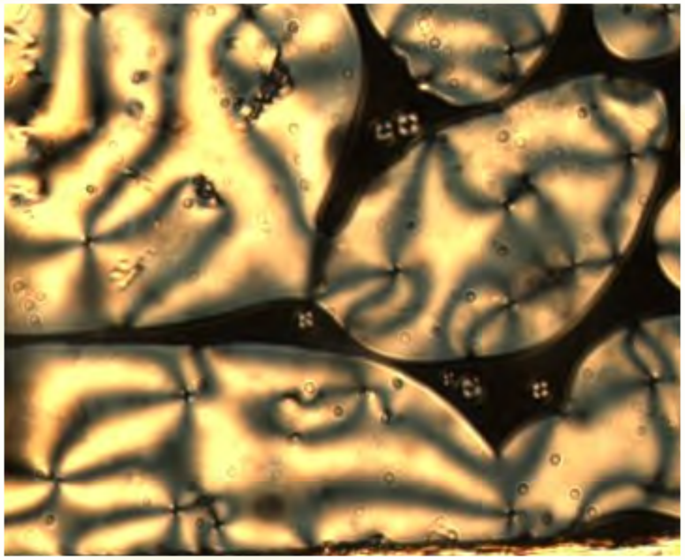
Blunt end < 14 bp = RIGHT handed N*

Blunt end > 14 bp = LEFT handed N*

Sticky end, any length = LEFT handed N*

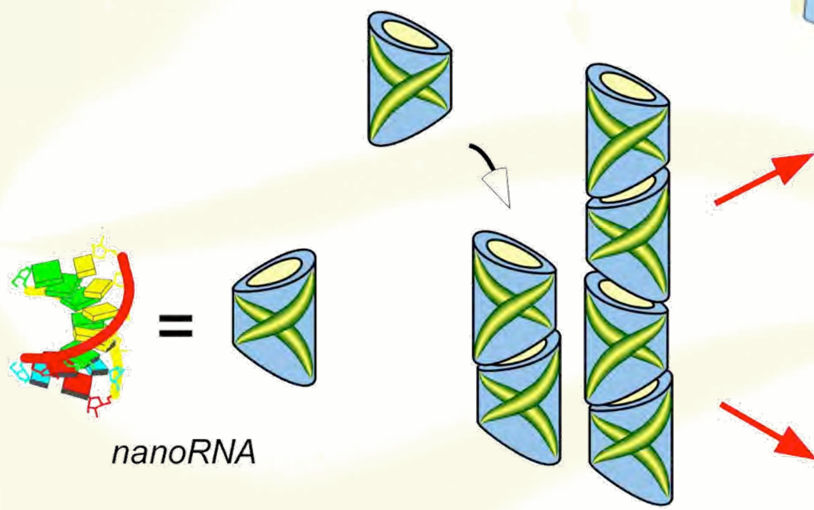
mixing right-handed 12mer with left-handed 20mer

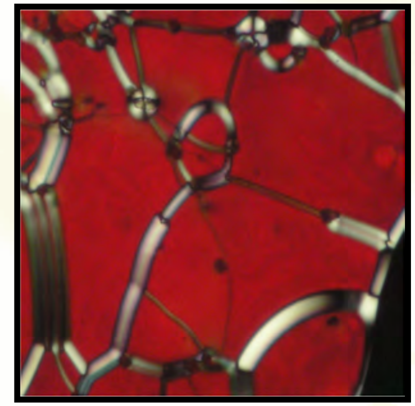
= achiral nematic

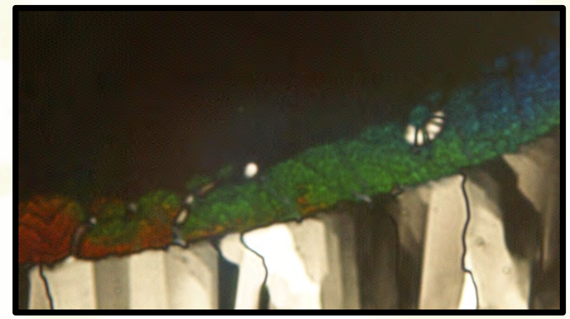


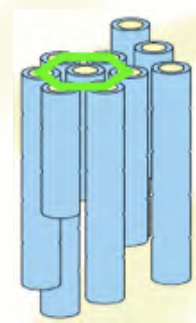
RNA: the same but with increased constraints

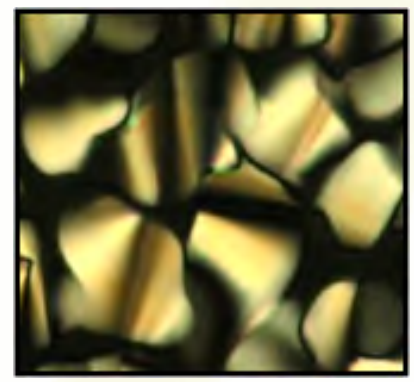
DNA – B form helix







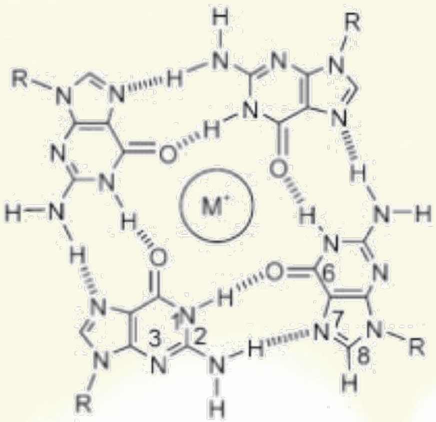


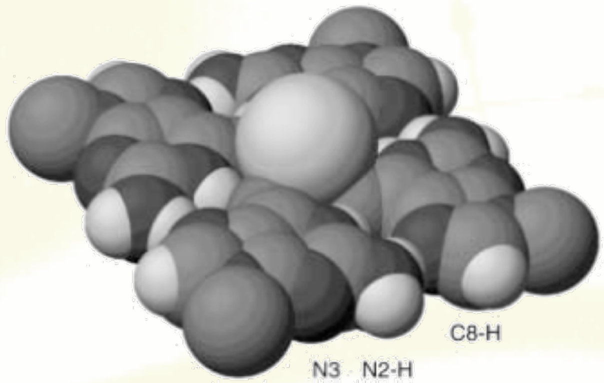


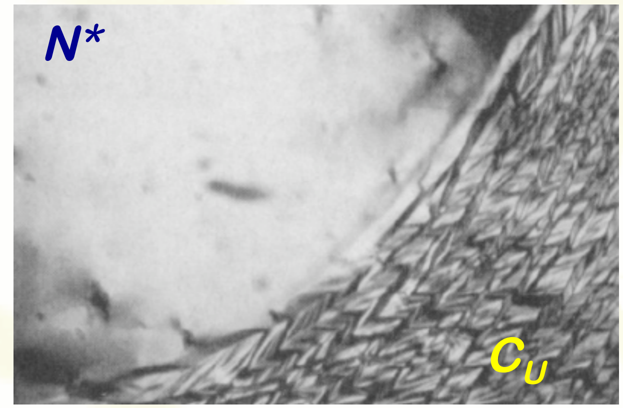
RNA – A form helix

Zanchetta et al. JACS (2008)

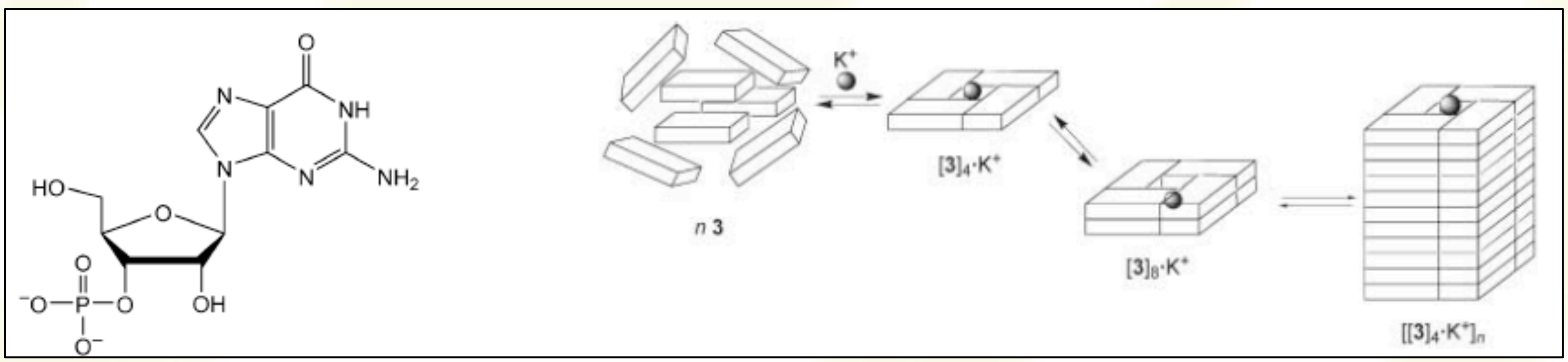
guanine quartets (G quartets)







Mariani, Mazabard, Garbesi, and Spada, JACS (1989)



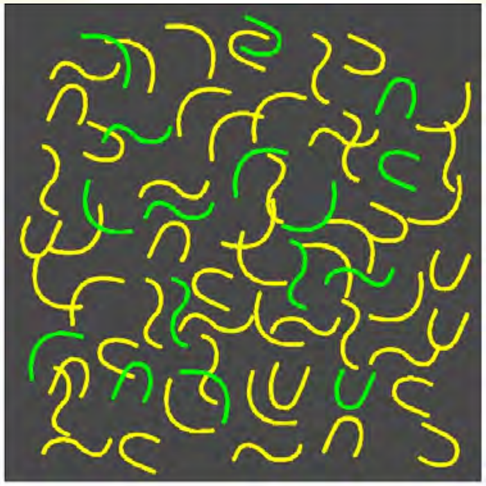
J.T. Davis, Ang. Chem. (2004)

liquid crystal condensation of nanoDNA and RNA

- ***mutually- but not self-complementary***

A: CCTCAAAACTCC

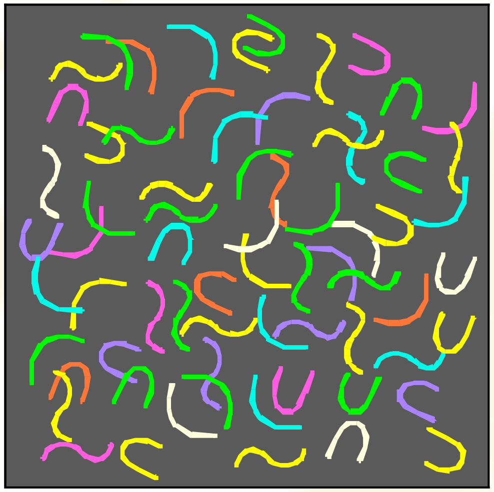
B: GGAGTTTTGAGG



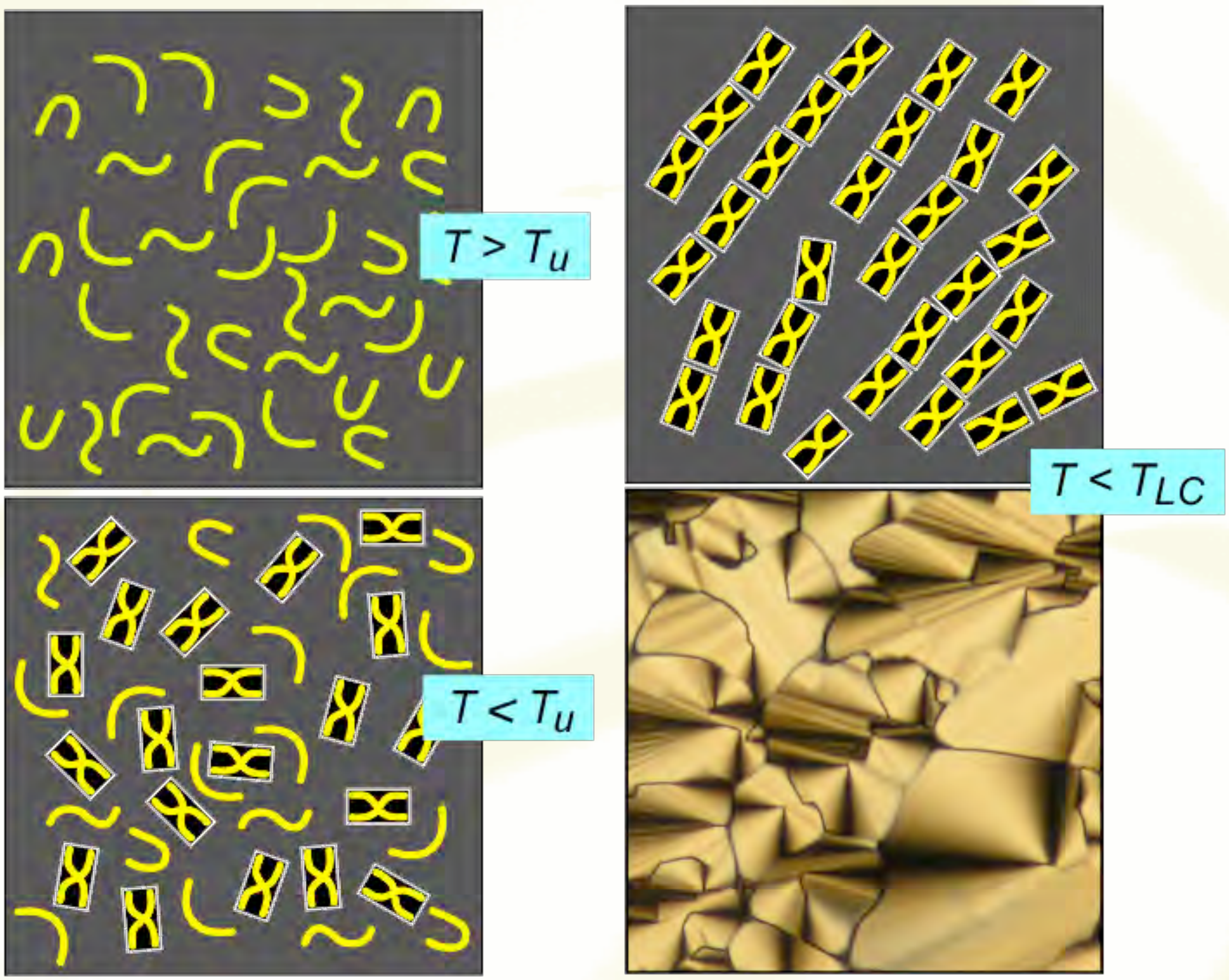
- ***self-complementary***

CGCGAAAATTTTCGCG

plus a mixture of non-complementary strands

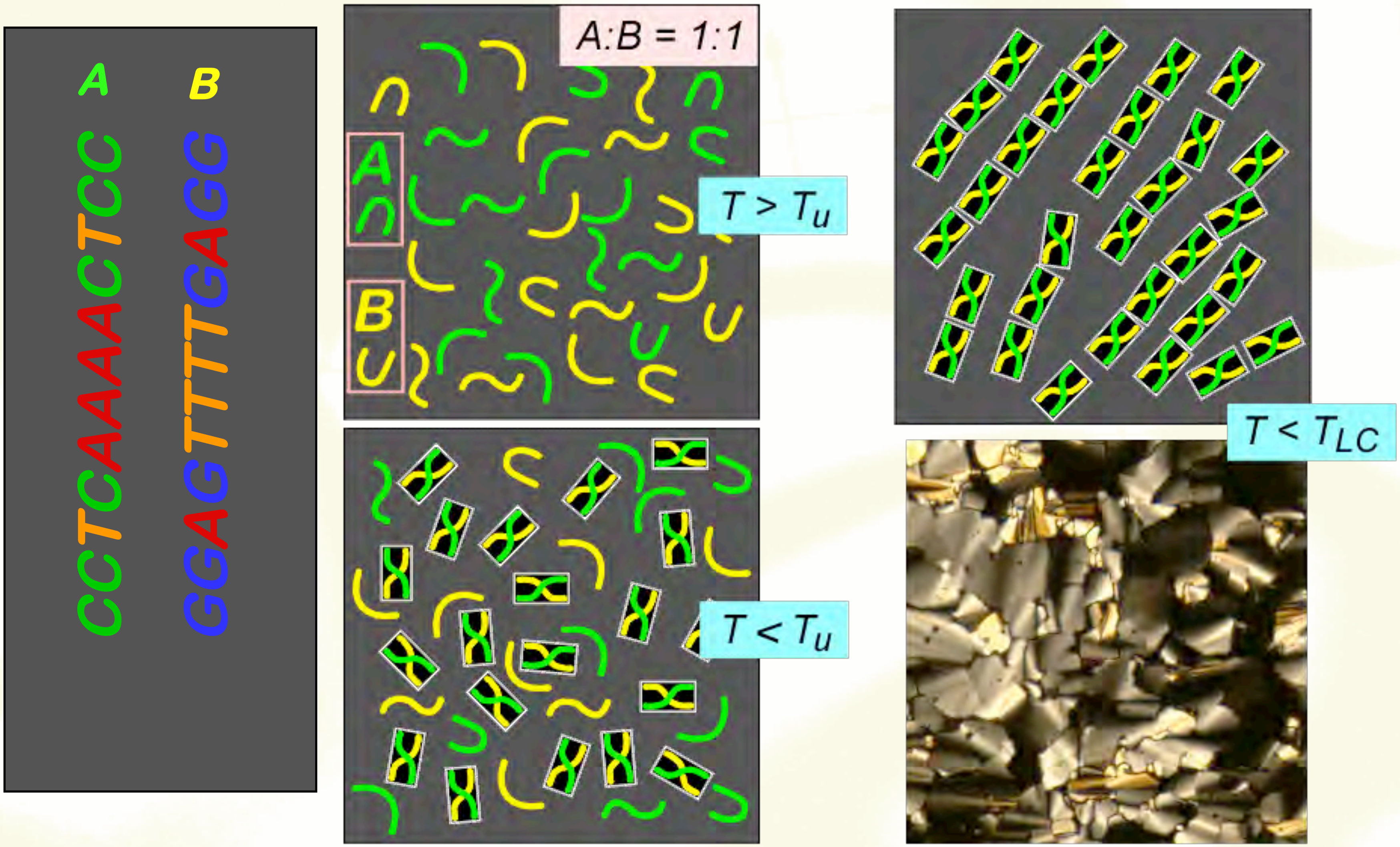


self-complementary pairs



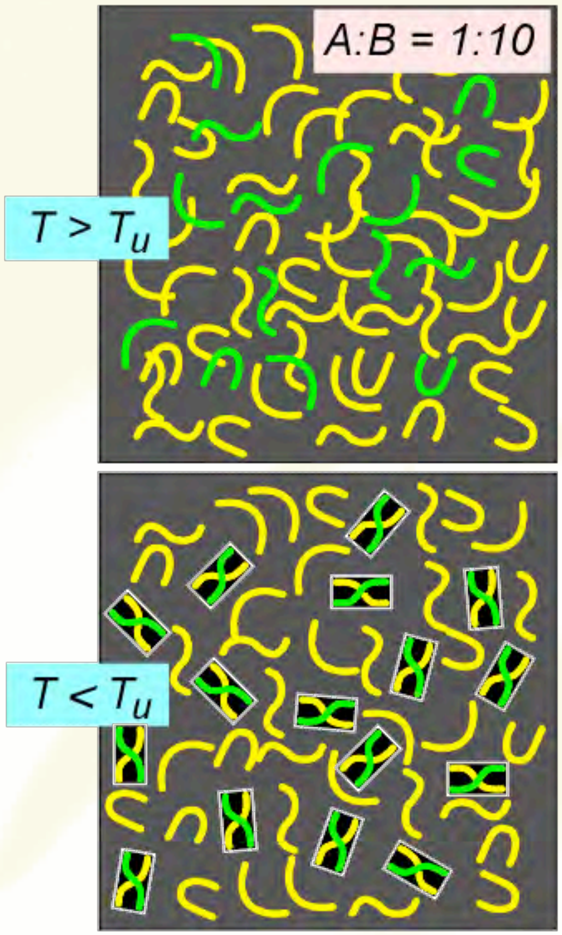
DNA

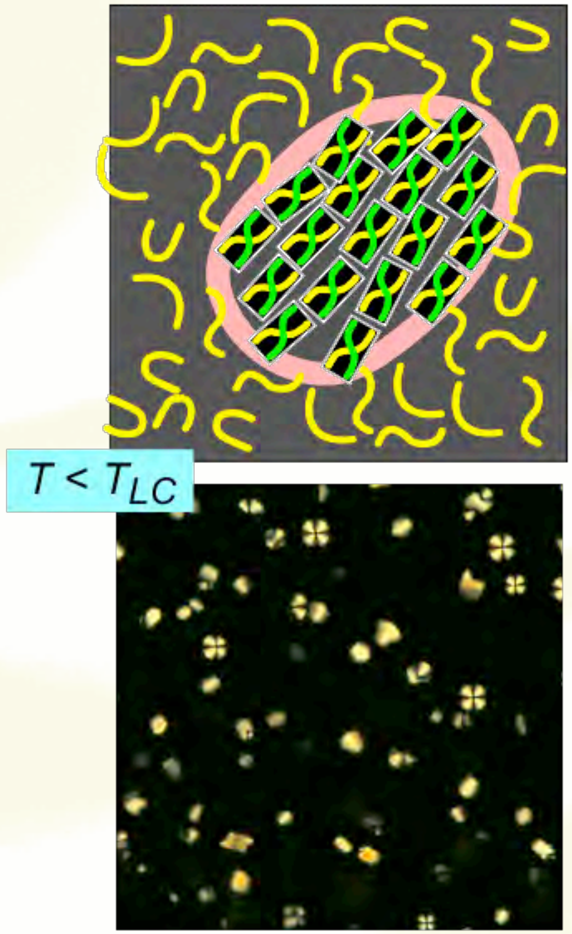
equimolar complementary pairs



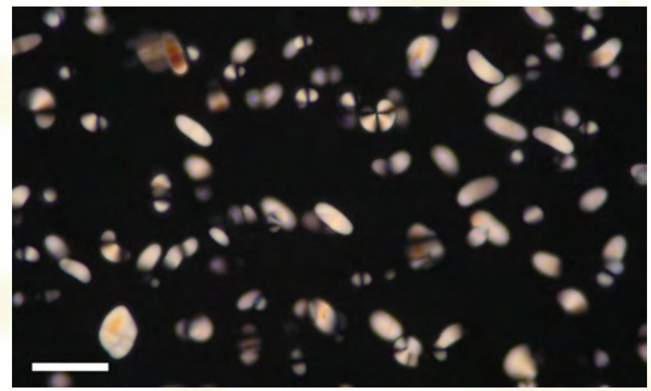
DNA

LC condensation of complementary strands from A:B mixtures





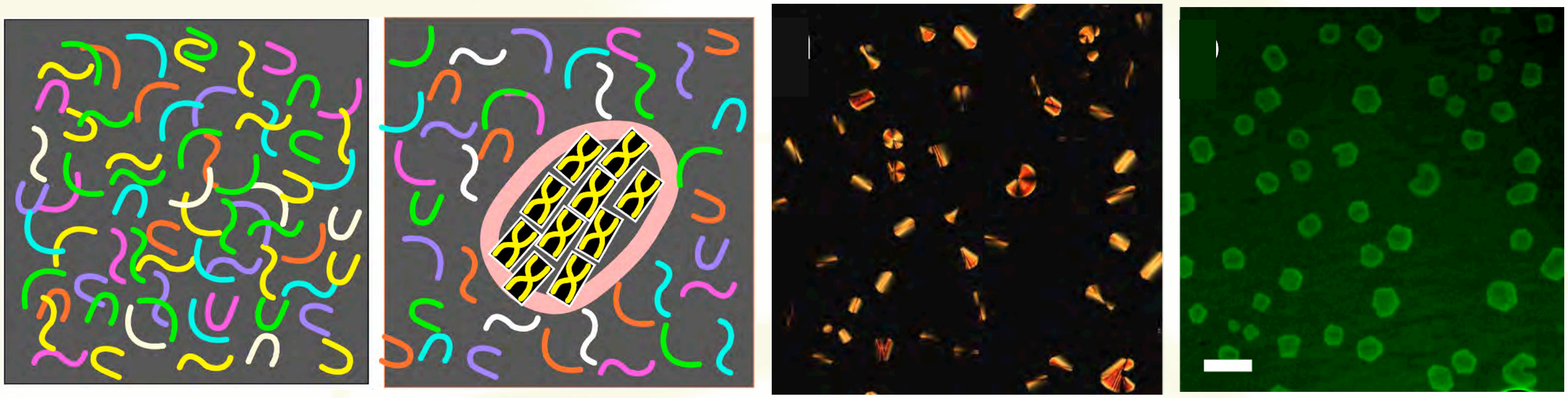
DNA



RNA (A:B = 1:5)

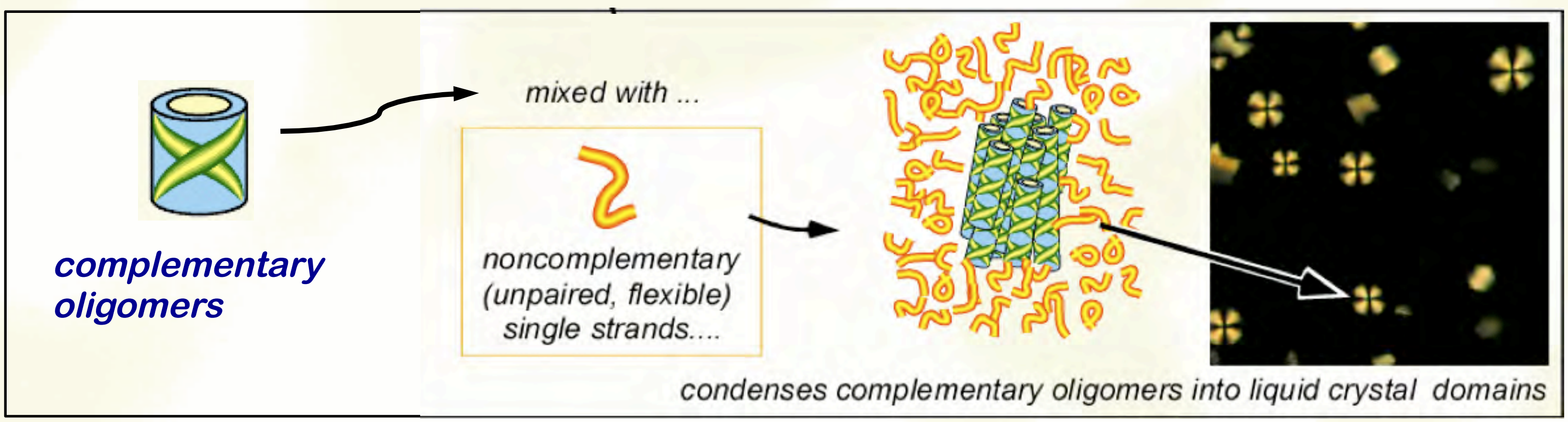
LC condensation from complementary / random mixtures

down to 10:1 molar ratio

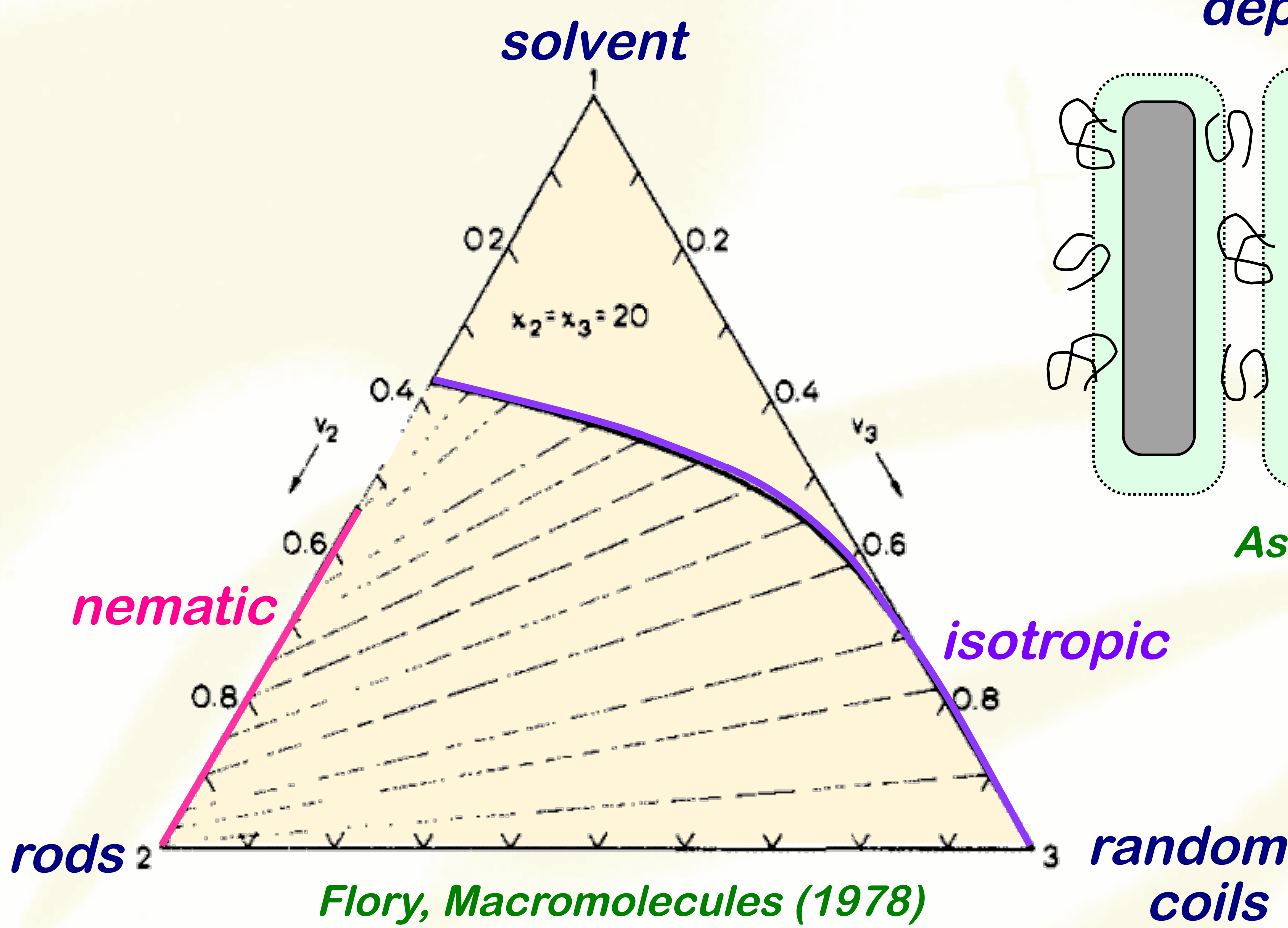


Zanchetta, Nakata, Buscaglia, Bellini, Clark, PNAS (2008)

In either case the demixing is between rigid and flexible solutes, driven by entropic / depletion-type forces

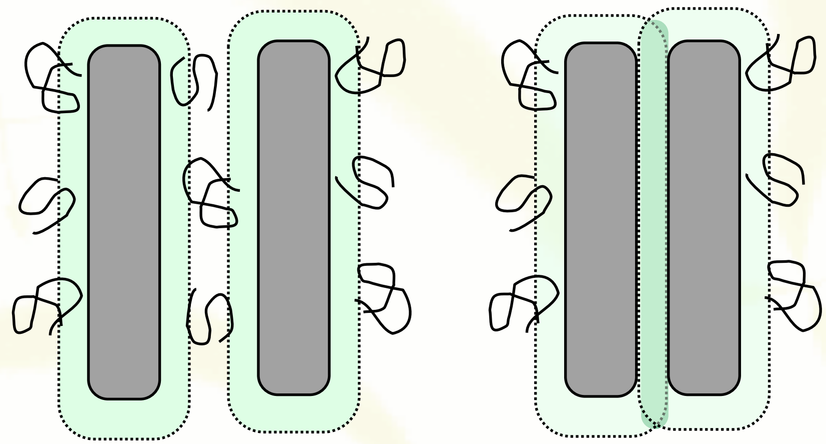


condensation mechanisms



Flory, Macromolecules (1978)

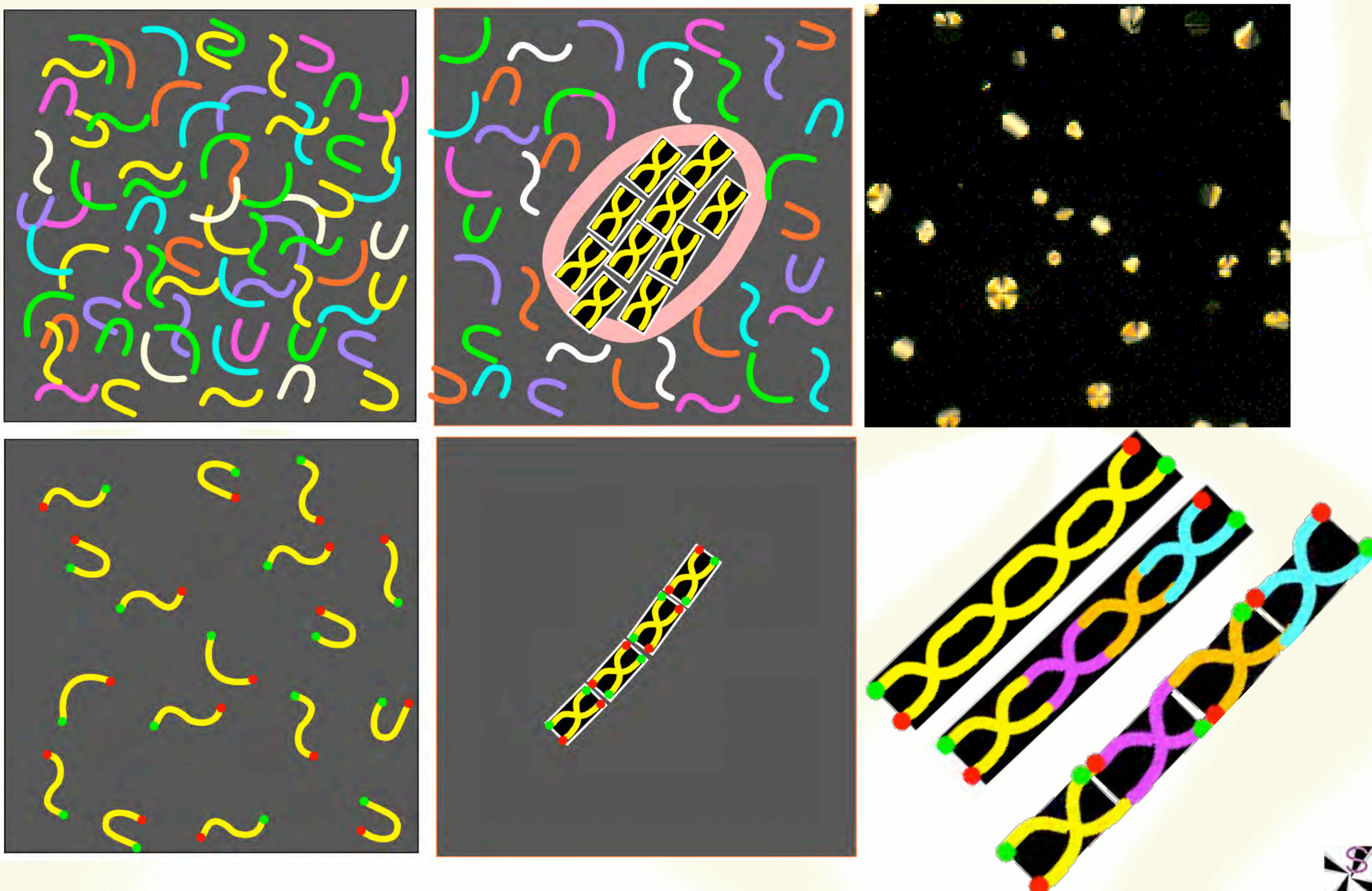
depletion attraction



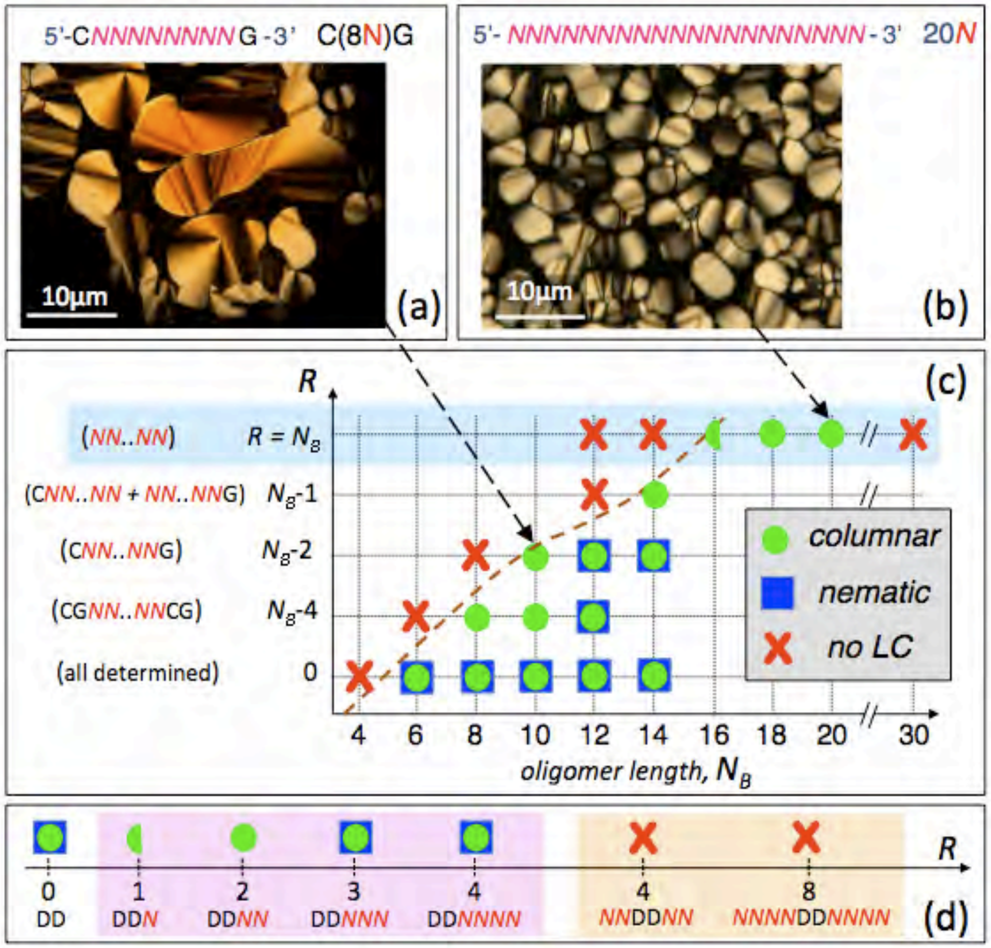
Asakura, Oosawa, JCP (1954)

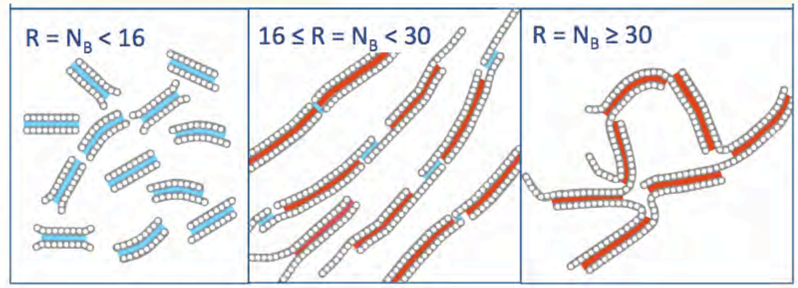
Kulp, Herzfeld (1995, 2004): self-assembled filaments with different flexibilities
Dogic et al., PRE (2004) I-N transition in suspensions of filamentous virus + Dextran

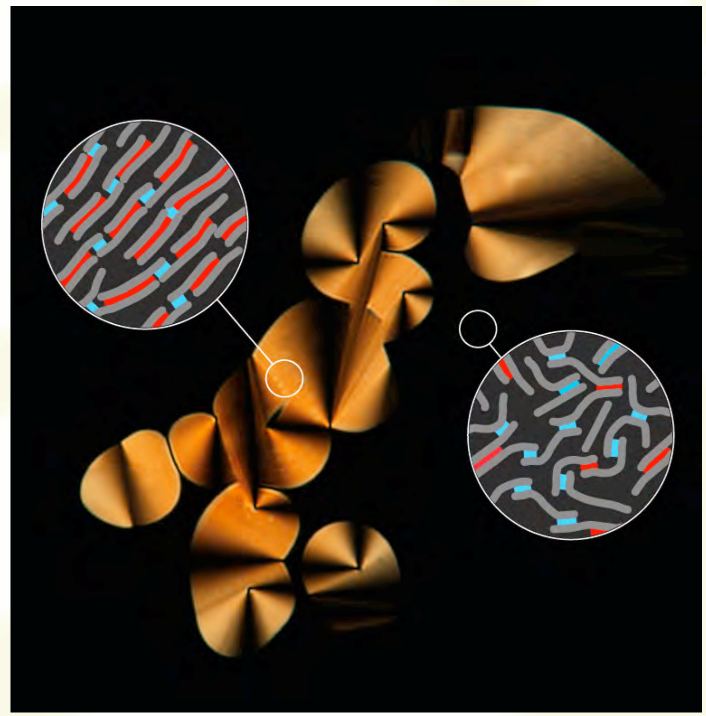
liquid crystal condensation of complementary strands



random sequence DNA





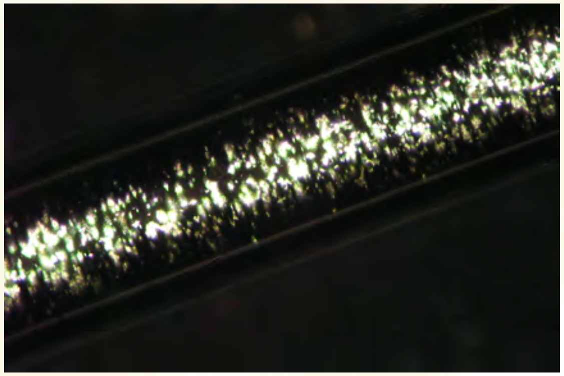


<14 mers – association too weak: no LCs

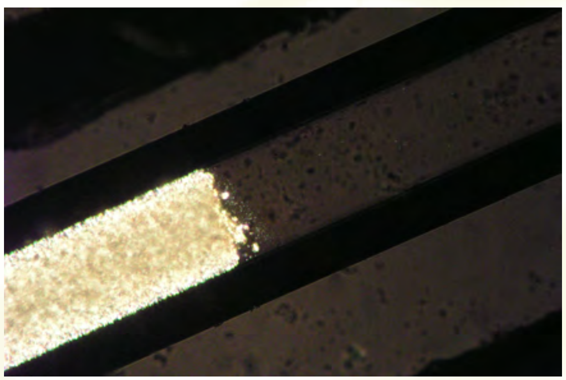
14-20 mers – kinetic arrest into duplexes with random tails: gives LCs

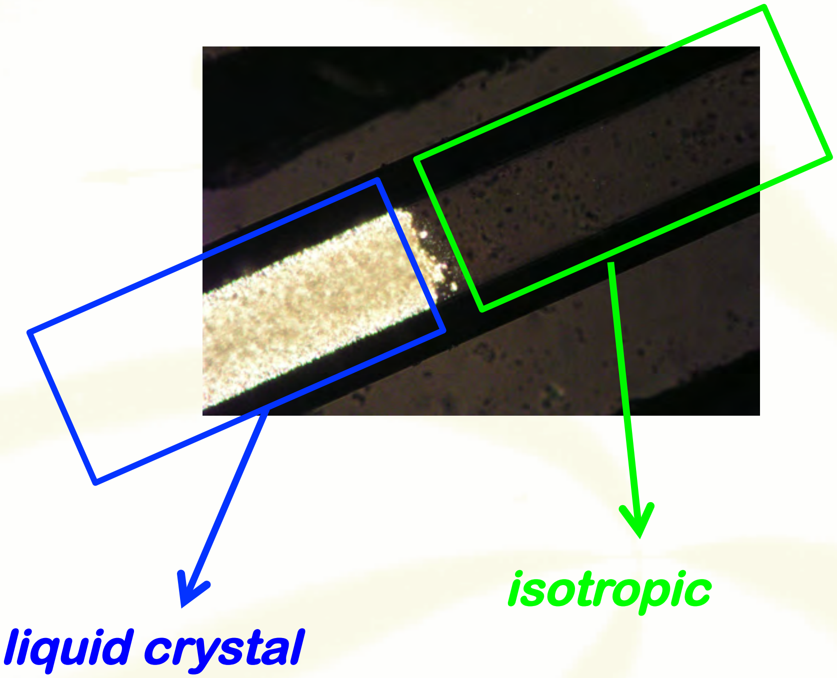
>30 mers – kinetic arrest into a gel: no LCs

centrifugation



30 min @ 14,000g



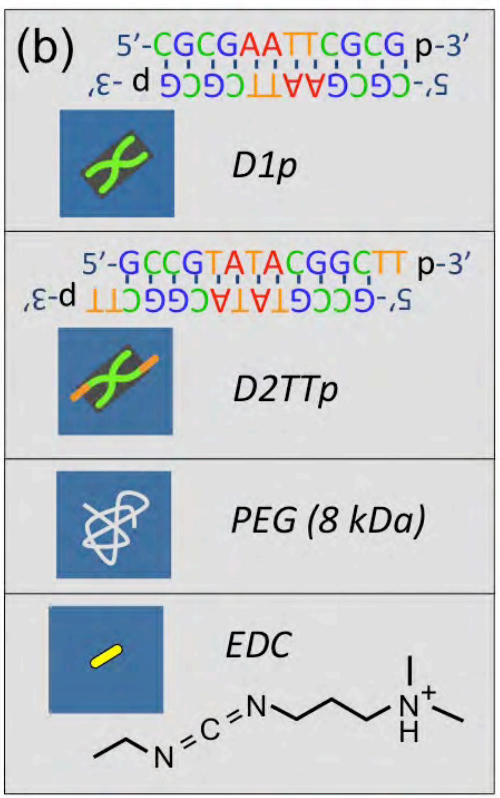


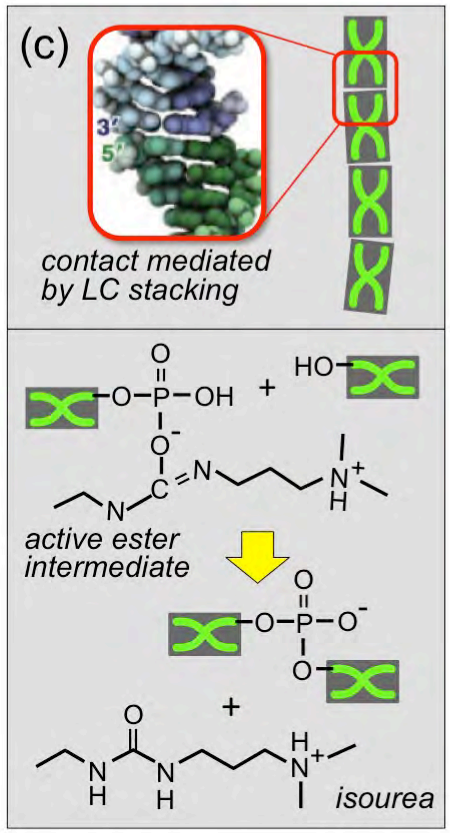
...physical separation of complementary and noncompementary oligomers

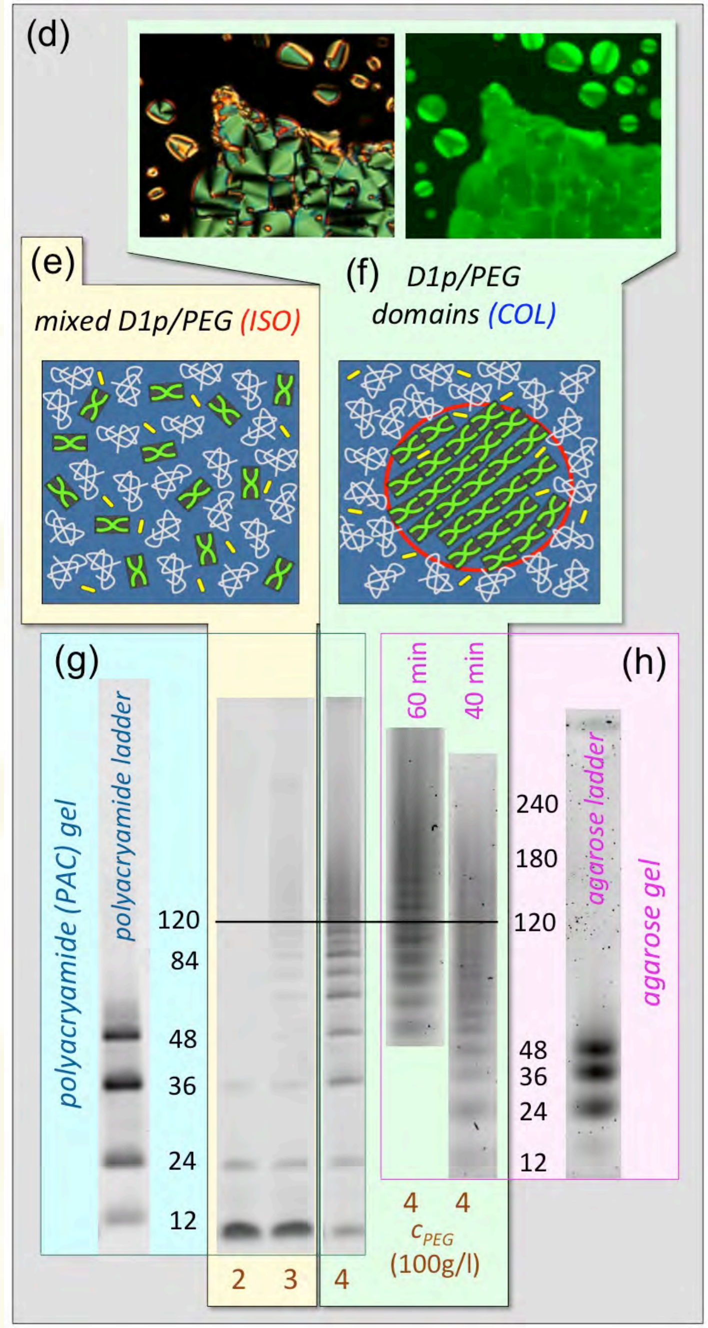
add ligation ...

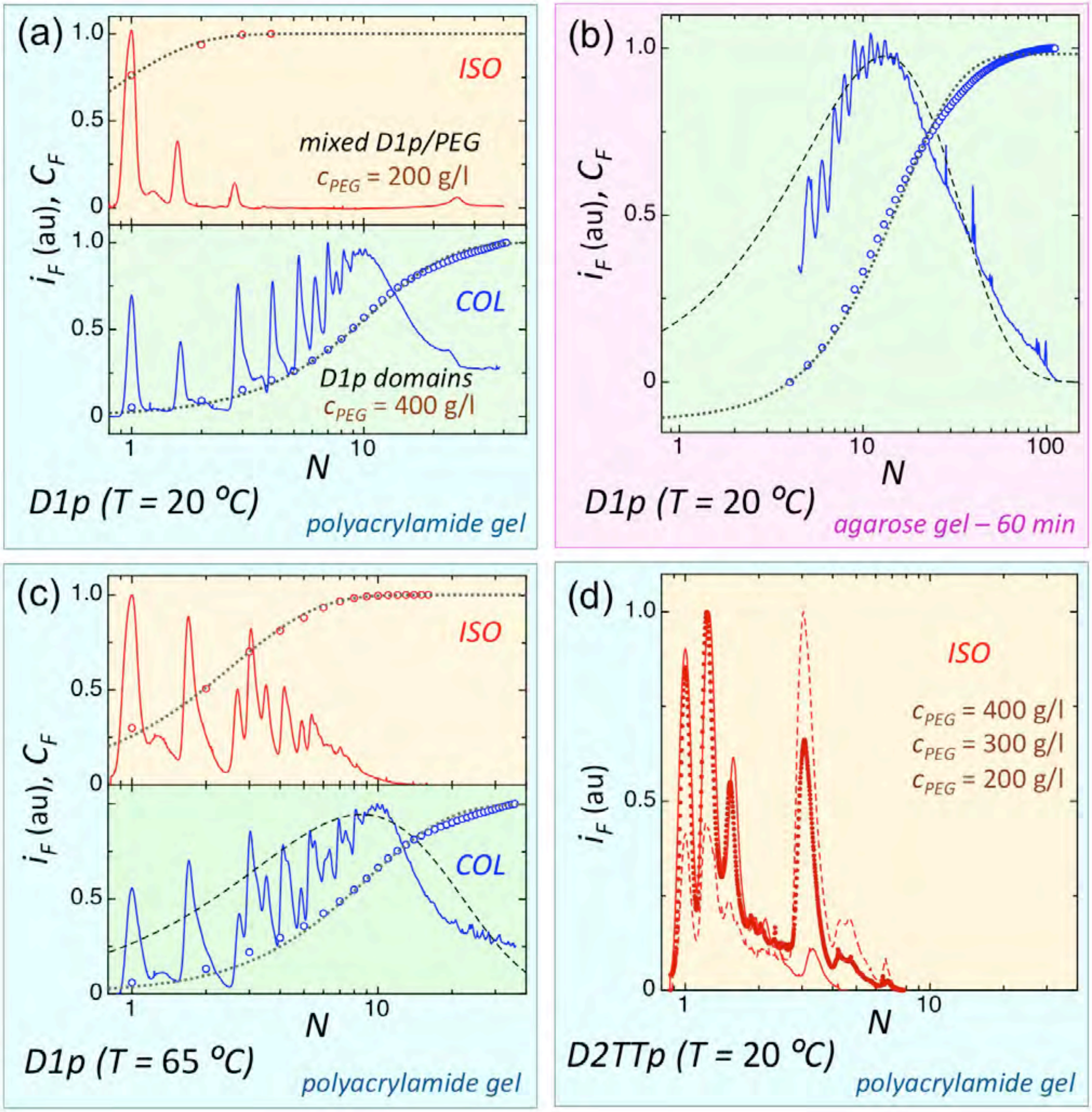
in a race to make longer complimentary oligomers, which will win?

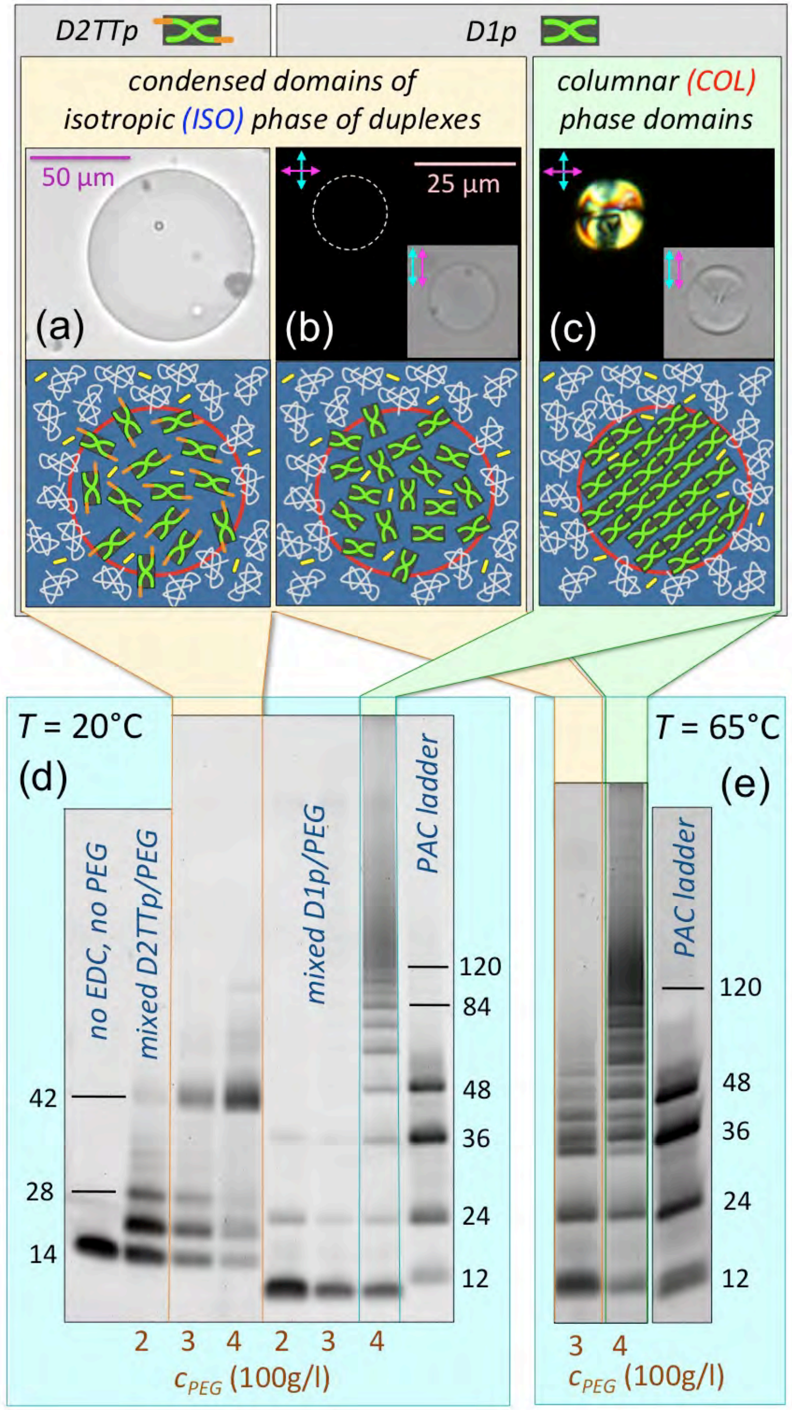
liquid crystal autocatalysis





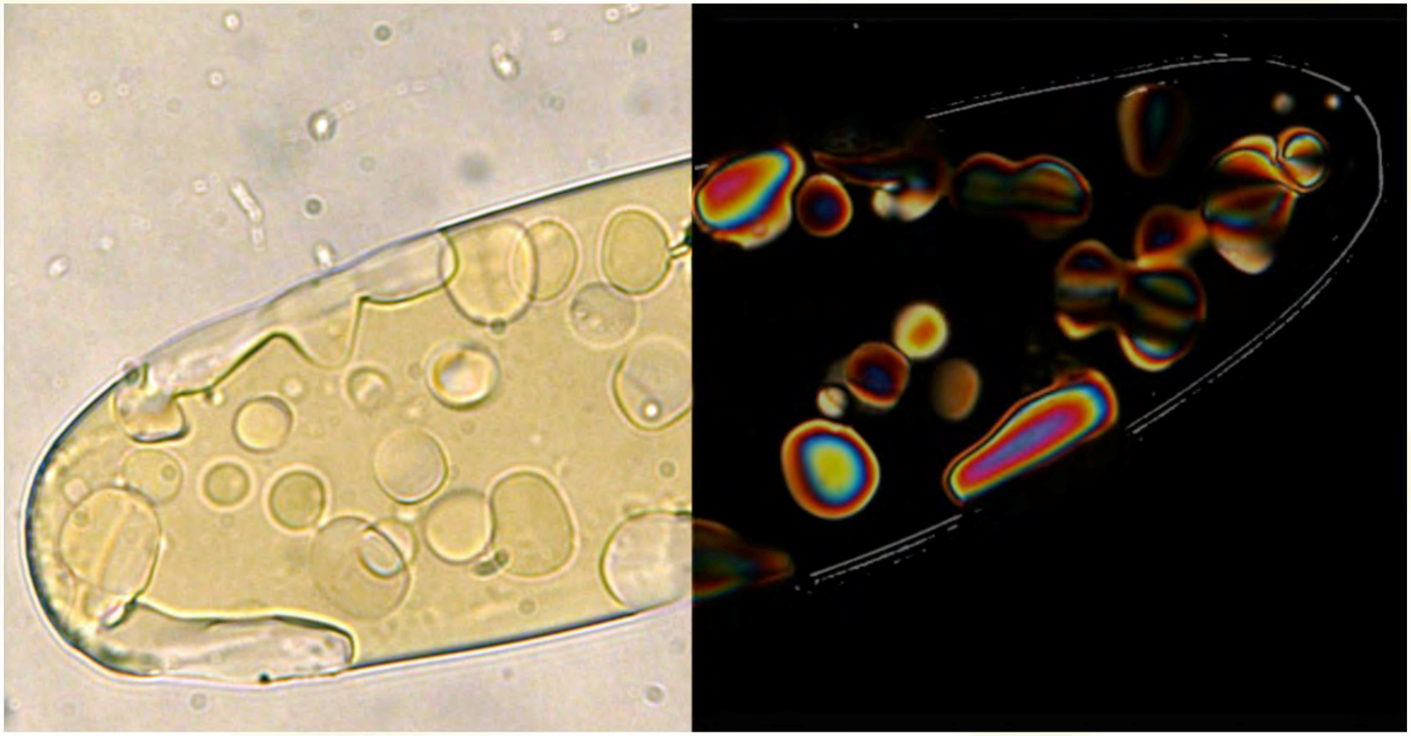



(a)
ISO
mixed D1p/PEG
c_{PEG} = 200 g/l
COL
D1p domains
c_{PEG} = 400 g/l
i_F (au), C_F
N
D1p (T = 20 °C)
polyacrylamide gel
(b)
i_F (au), C_F
N
D1p (T = 20 °C)
agarose gel – 60 min
(c)
ISO
COL
i_F (au), C_F
N
D1p (T = 65 °C)
polyacrylamide gel
(d)
ISO
c_{PEG} = 400 g/l
c_{PEG} = 300 g/l
c_{PEG} = 200 g/l
i_F (au)
N
D2TTp (T = 20 °C)
polyacrylamide gel

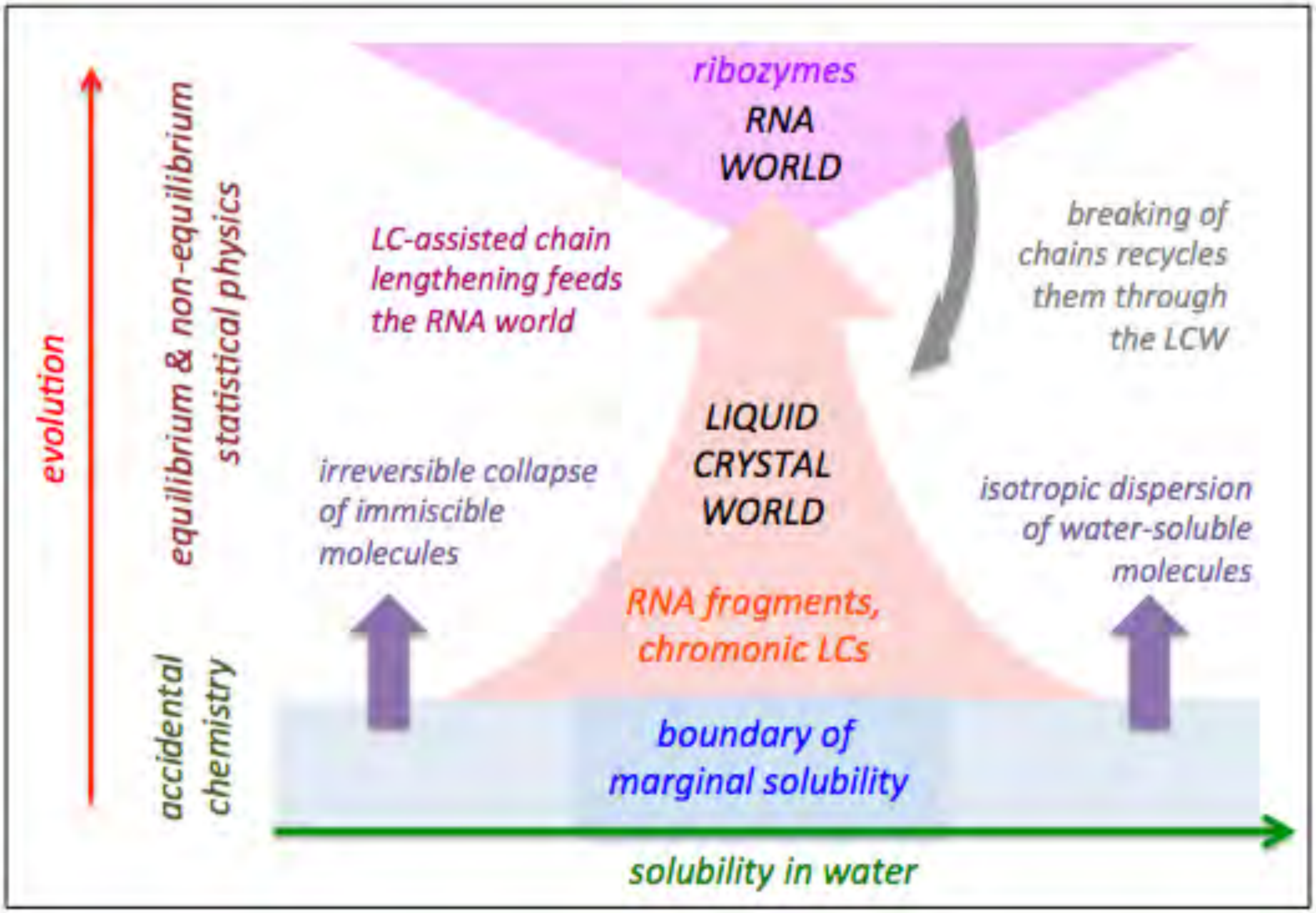


D2TTp
D1p
condensed domains of isotropic (ISO) phase of duplexes
columnar (COL) phase domains
50 µm
25 µm
(a)
(b)
(c)
T = 20°C
(d)
no EDC, no PEG
mixed D2TTp/PEG
mixed D1p/PEG
PAC ladder
42
28
14
120
84
48
36
24
12
2 3 4 2 3 4
c_{PEG} (100g/l)
T = 65°C
(e)
PAC ladder
120
48
36
24
12
3 4
c_{PEG} (100g/l)

condensed nanoDNA droplet reactor



features of an ancient liquid crystal world

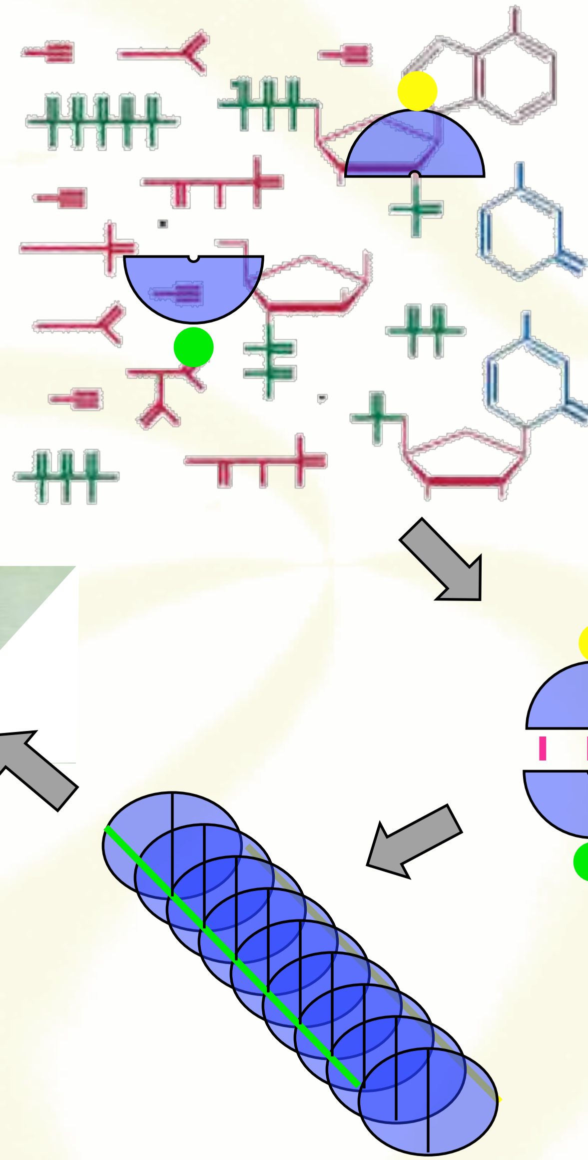


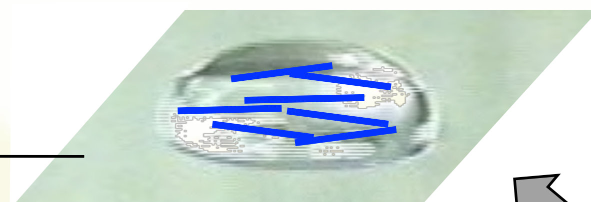
a liquid crystal droplet can provide…

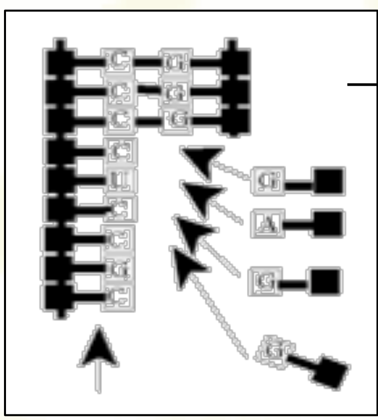
- *a structural paradigm*

  (broken symmetry)
- *spatial segregation*
- *supermolecular self assembly*
- *selection*

  (four cascaded stages)
- *fluidity*
- *templating*







Orgel

the bottom line

There was an era in the appearance and evolution of life during which…

the bottom line

There was an era in the appearance

and evolution of life during which…

…the sole purpose of life

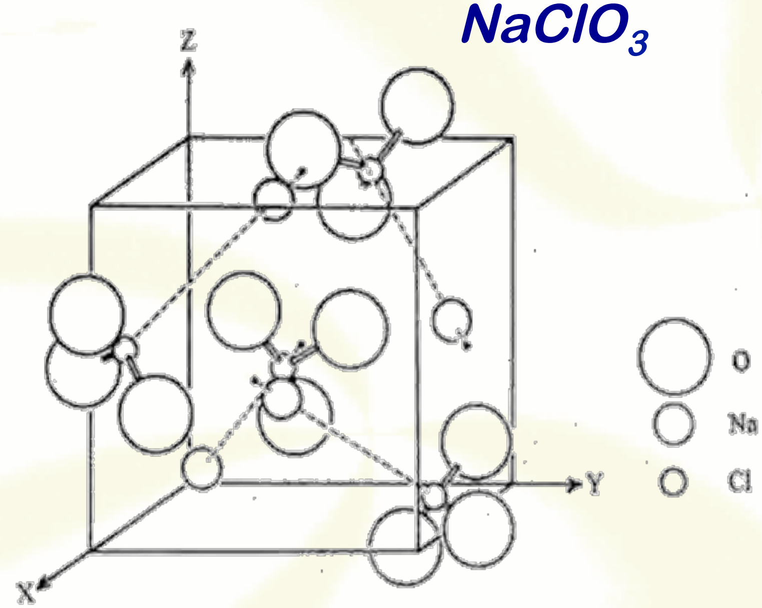
was to make liquid crystals…

deracemization by stirring and grinding

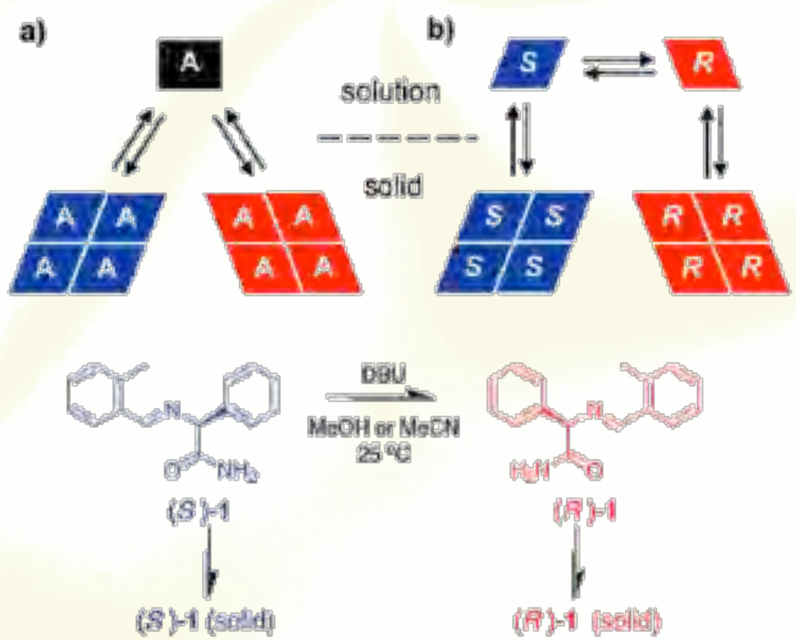
C. Viedma, PRL (2005)

crystal conglomerates

$NaClO_3$



amino acid derivative



W. Noorduin et al., JACS (2008)

emergence of chirality

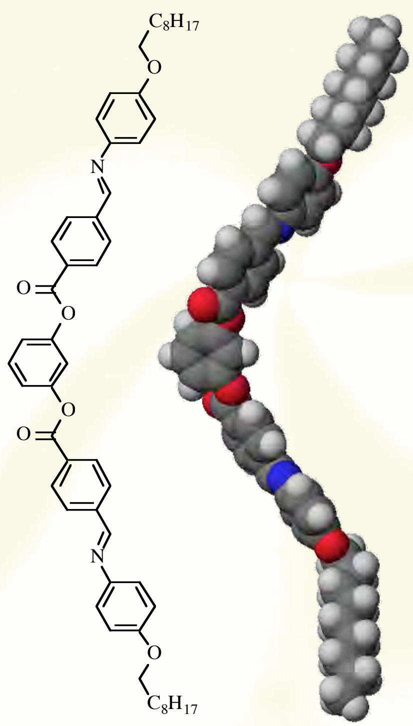
Frank, F. C. Biochim. Biophys. Acta 11, 459–463 (1953)

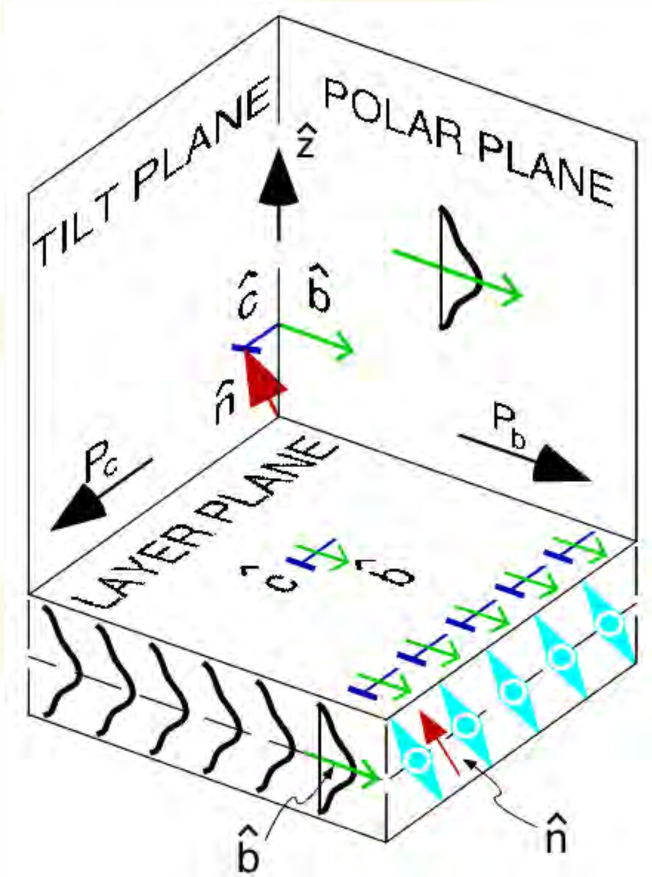
"I have long supposed that this was no problem on the basis of a supposition that the initial production of life is a rare event."

He went on to prove mathematically that, in a system containing entities that both copy themselves and destroy their mirror images, an initial random event that provides a tiny excess of one hand would necessarily lead to the exclusive occurrence of that form, even if mirror-image versions could also form randomly. He concluded: "A laboratory demonstration may not be impossible." This seminal paper was Frank's sole contribution to biology — he is better known for his insights concerning the mechanisms of crystal growth. He might have been gratified to learn that his own field is supplying increasingly convincing laboratory demonstrations to support his biological model.

B2 banana phases

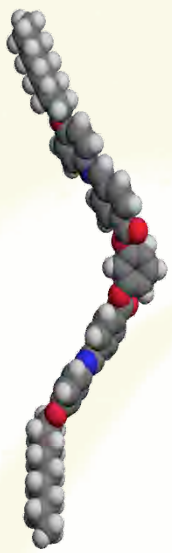
tilt & polarity ⇨ *chirality*

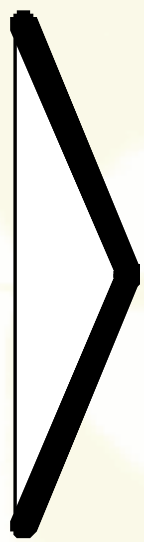


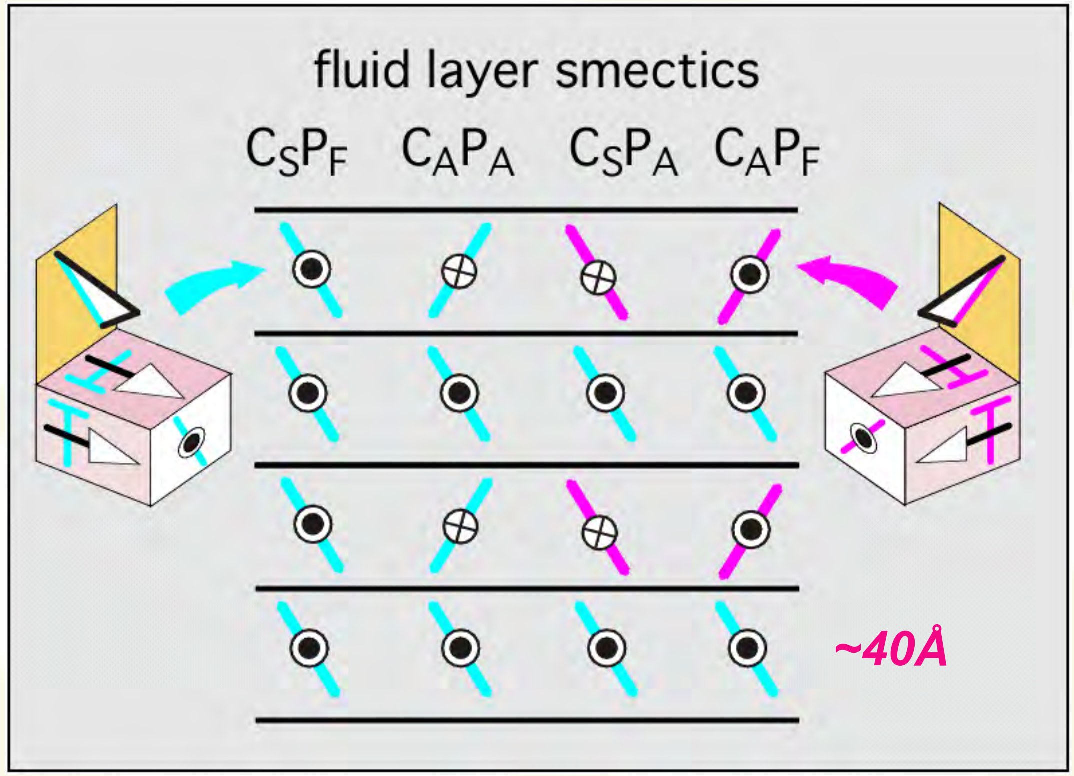


Walba, Clark, Science (1997) ➔

the "B2" banana phases: fluid layer smectics

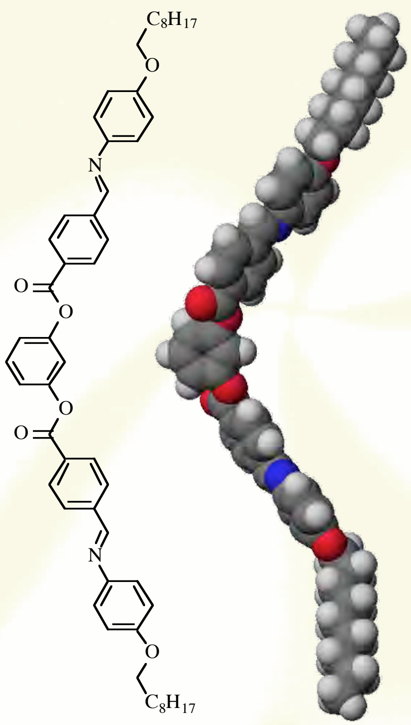


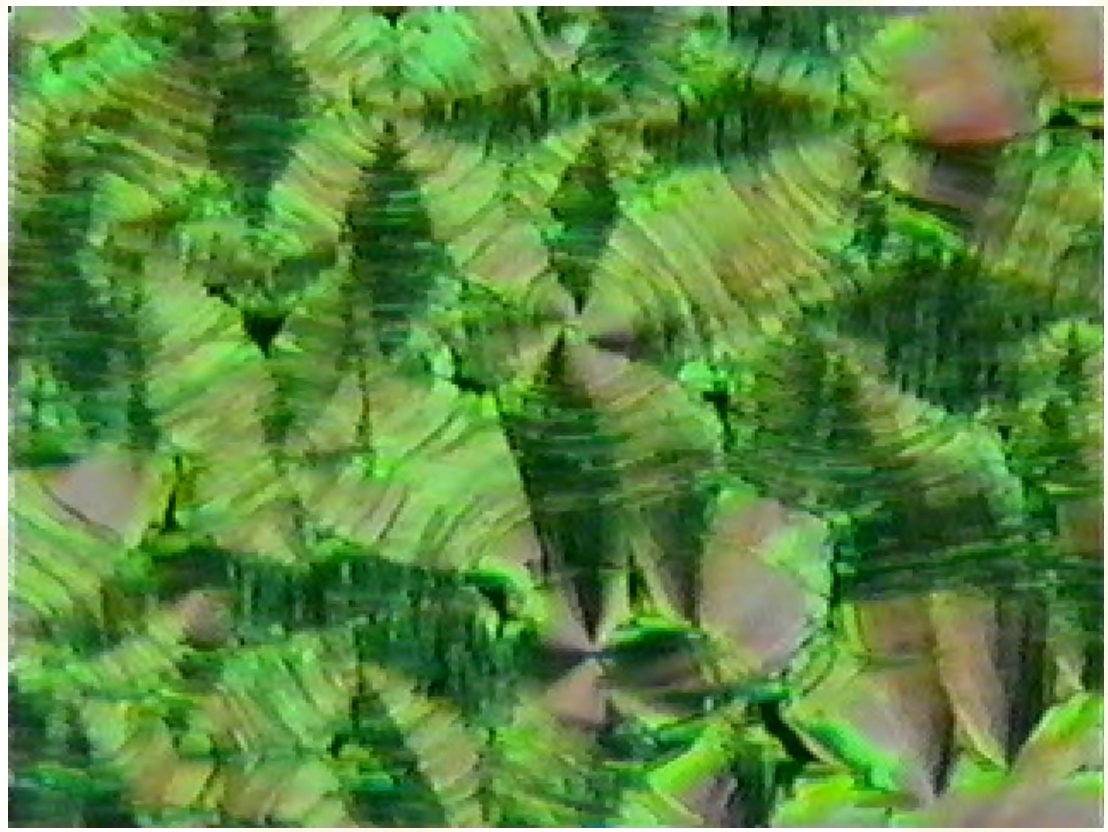




conglomerate EO in NOBOW

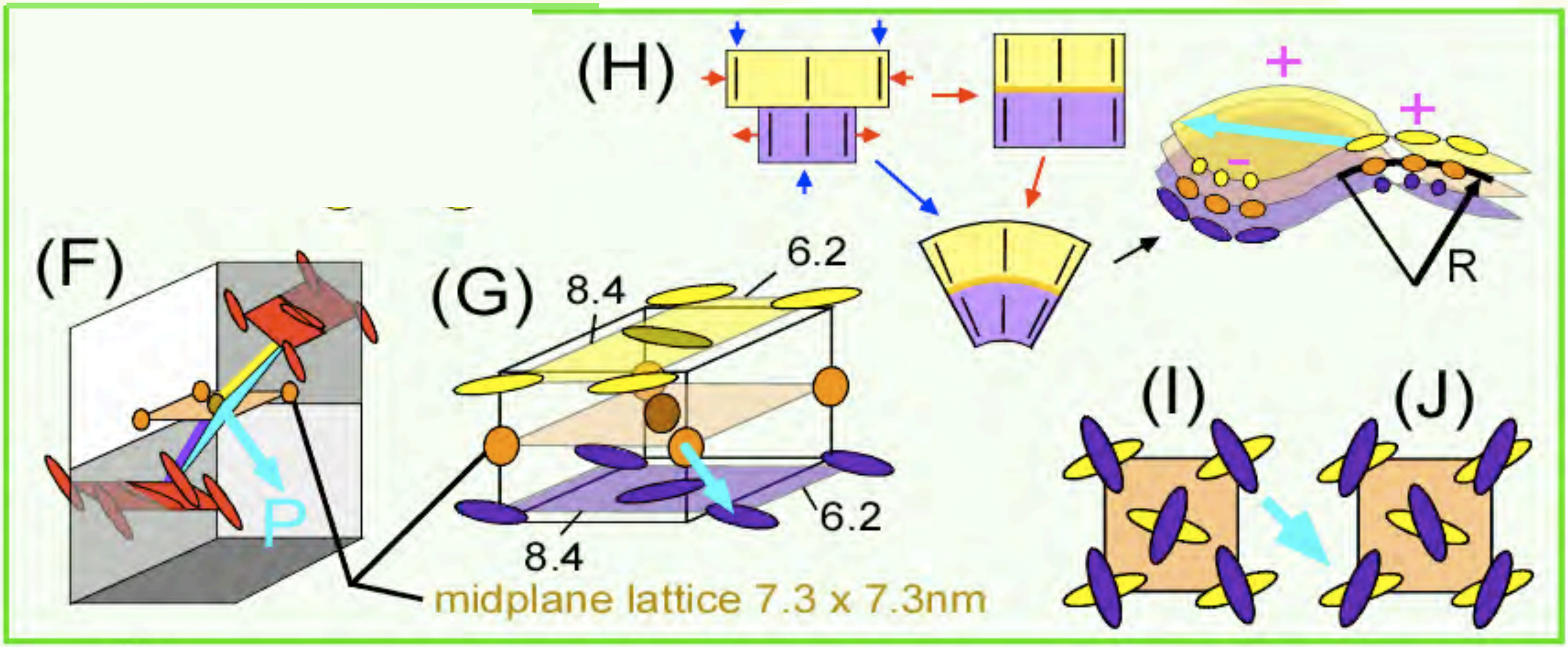
spontaneous reflection symmetry breaking



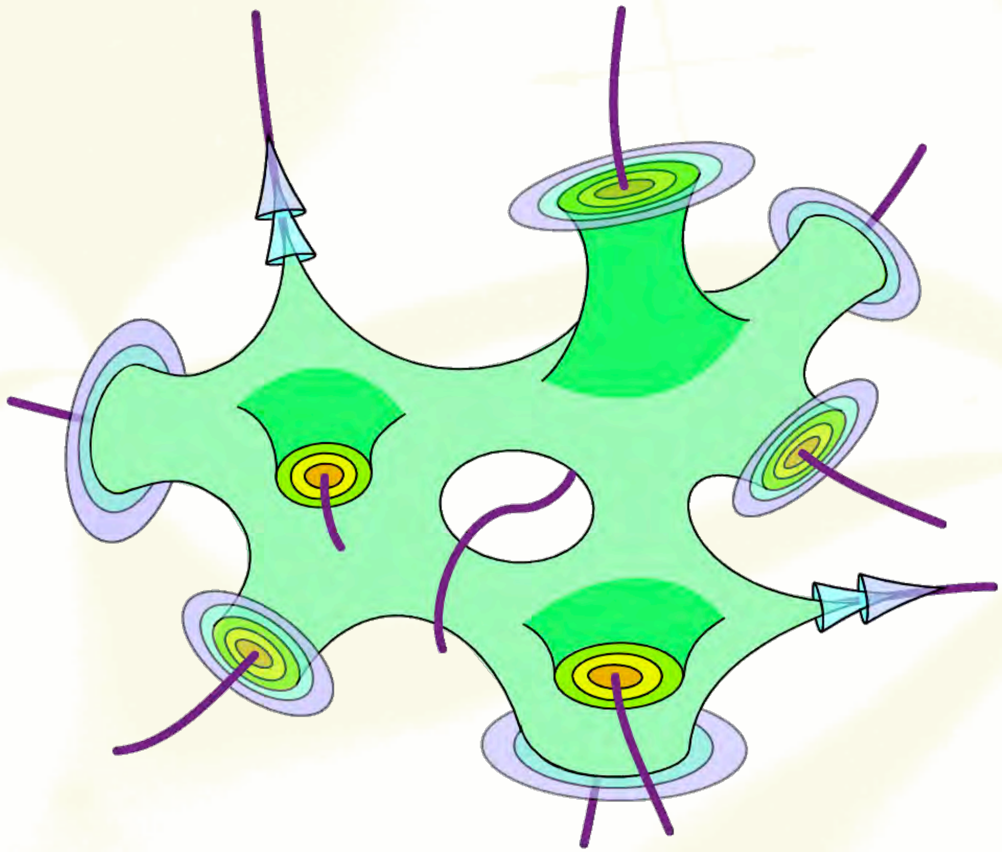


NonylOxyBOW (NOBOW): B4 — 155“ B2 — 173“ I

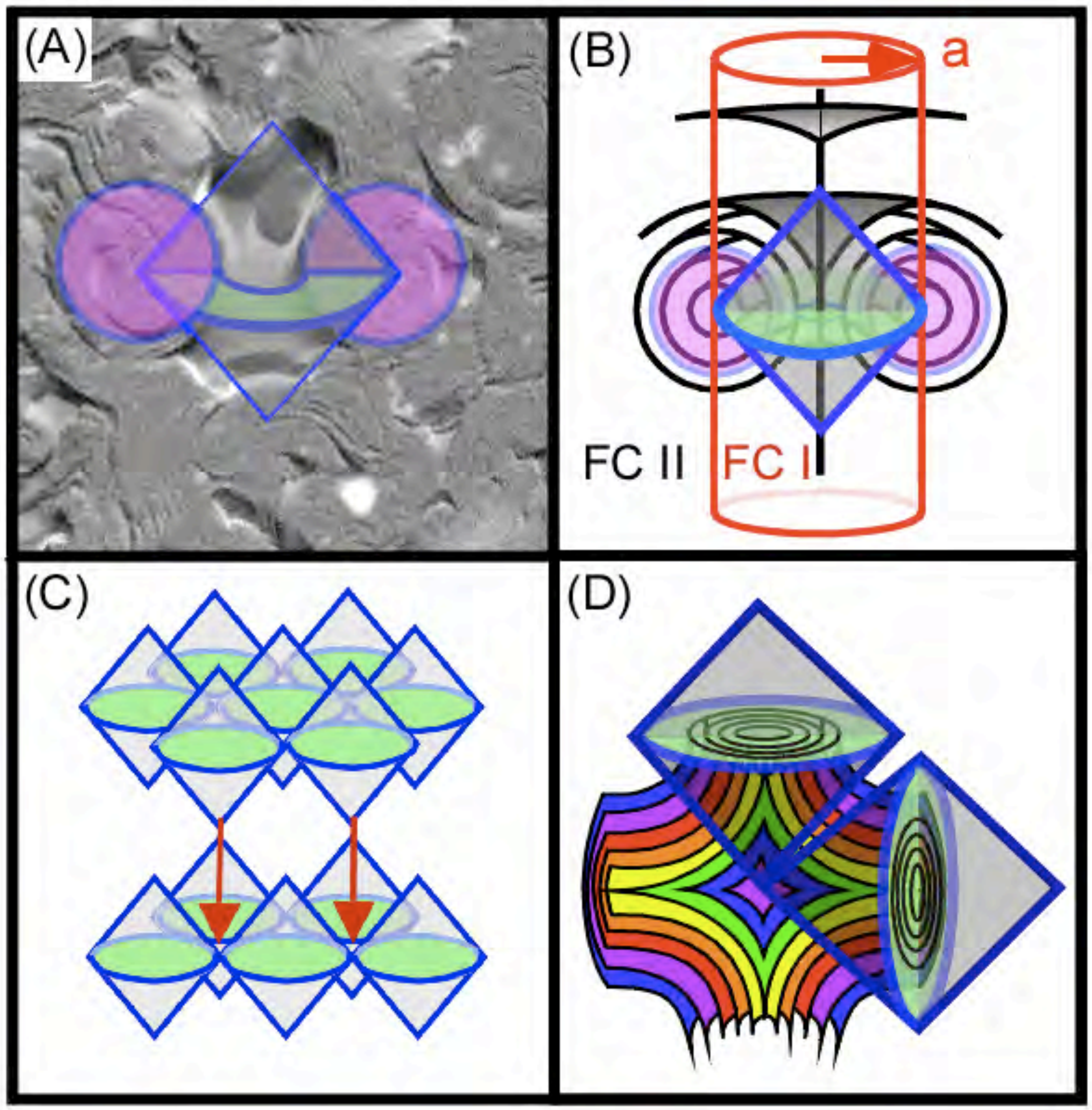
in-layer structure



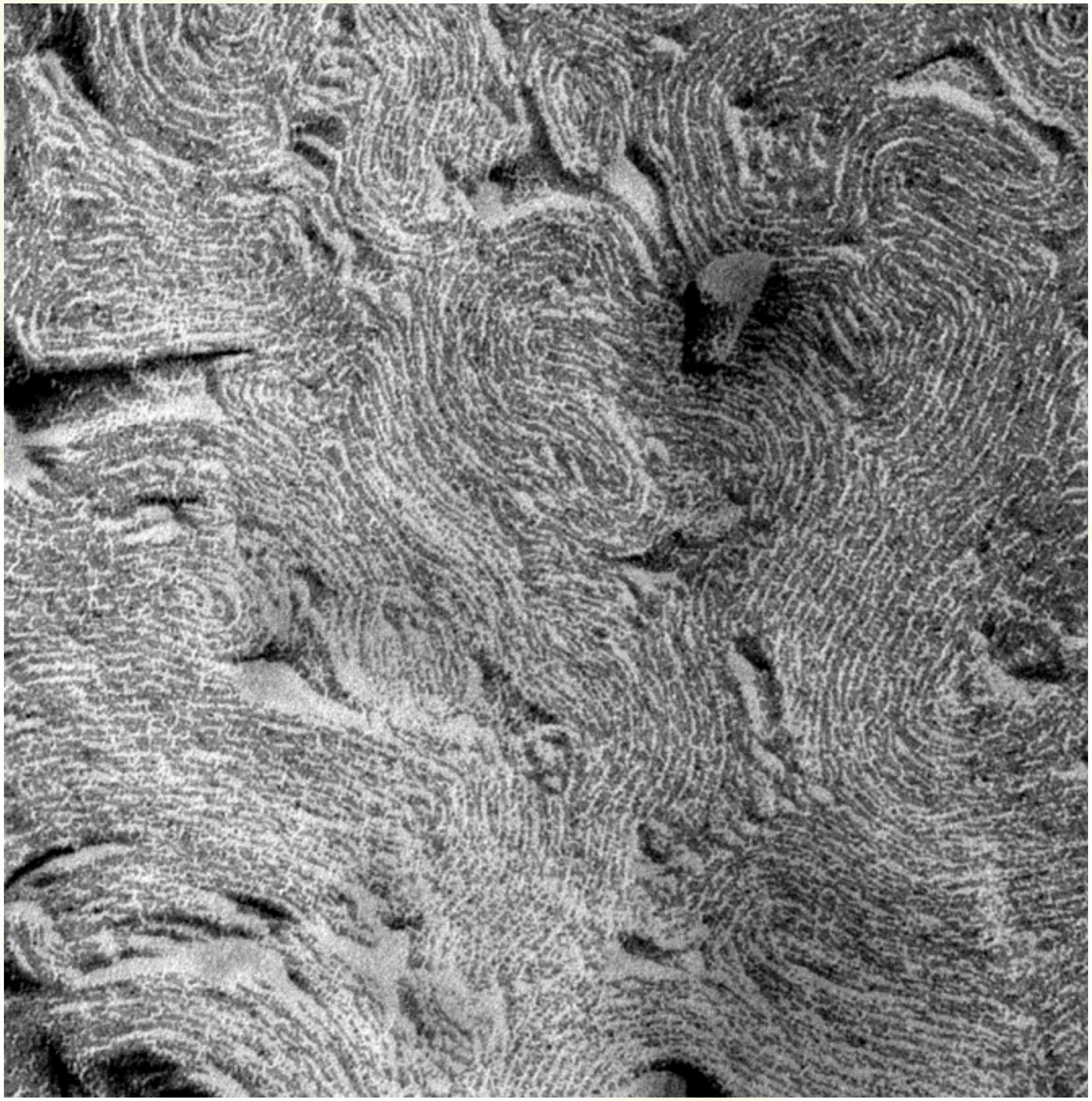
thermotropic sponge phase



apply to focal conic arrays



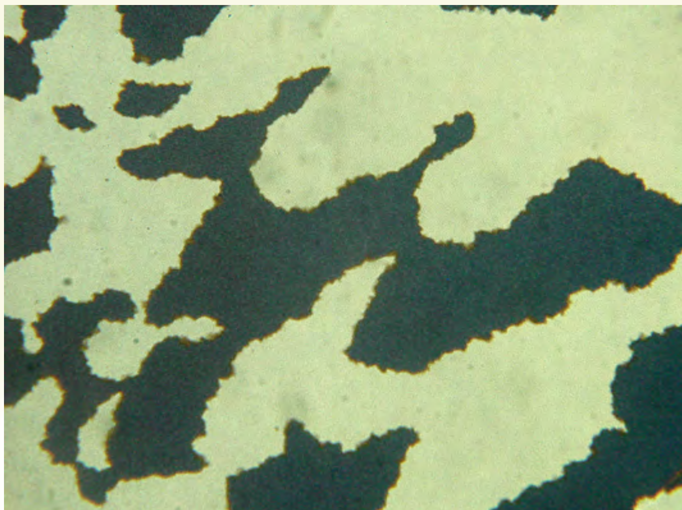
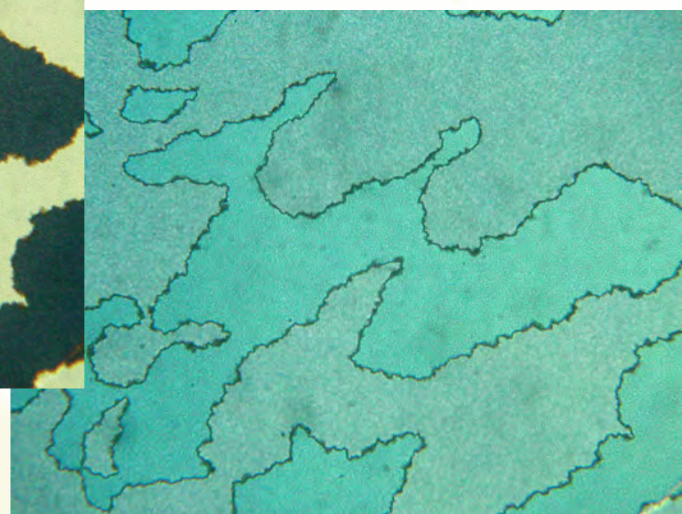
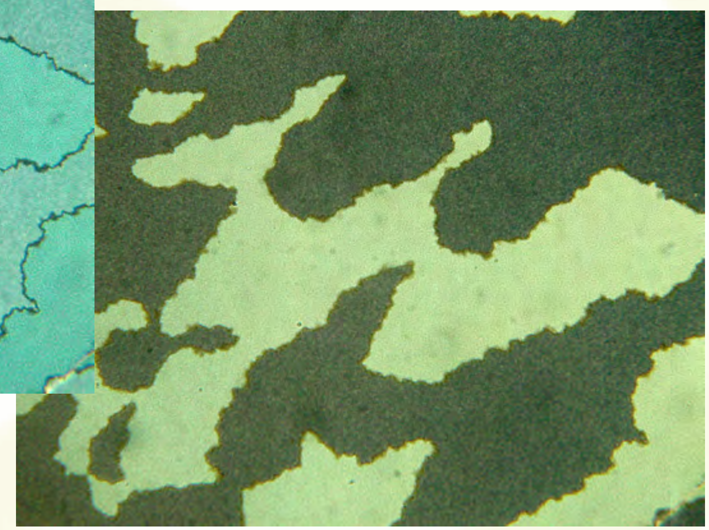
W508 “fingerprints”



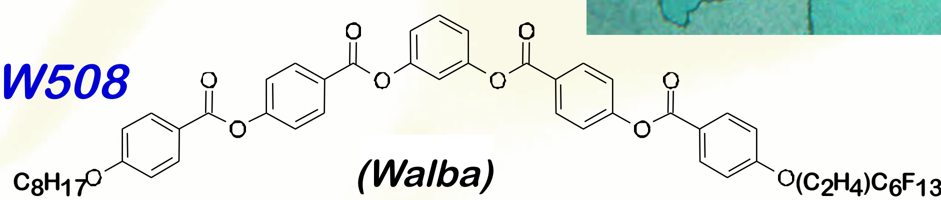
conglomerate domains in an isotropic fluid of achiral molecules

upon cooling from the isotropic a second isotropic phase appears in many materials

- optically isotropic fluid phase
- spontaneously & homogeneously chiral

W508

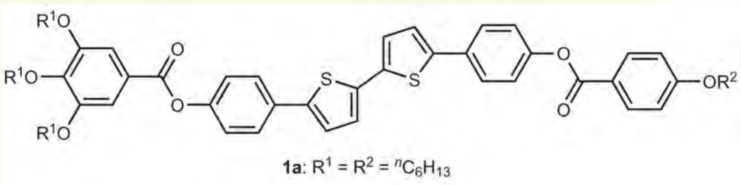


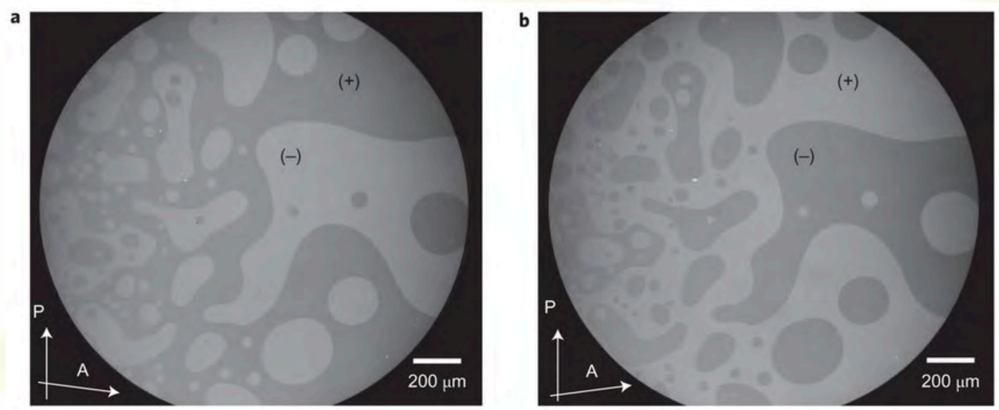
Cooling: I – 172 – Dark cg – 133 – X
Heating: X – 145 – SmCP – 175 – I

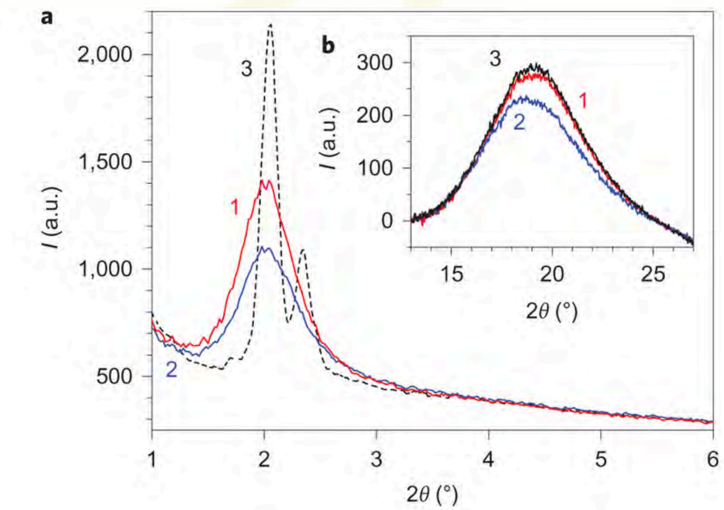
“dark conglomerates”

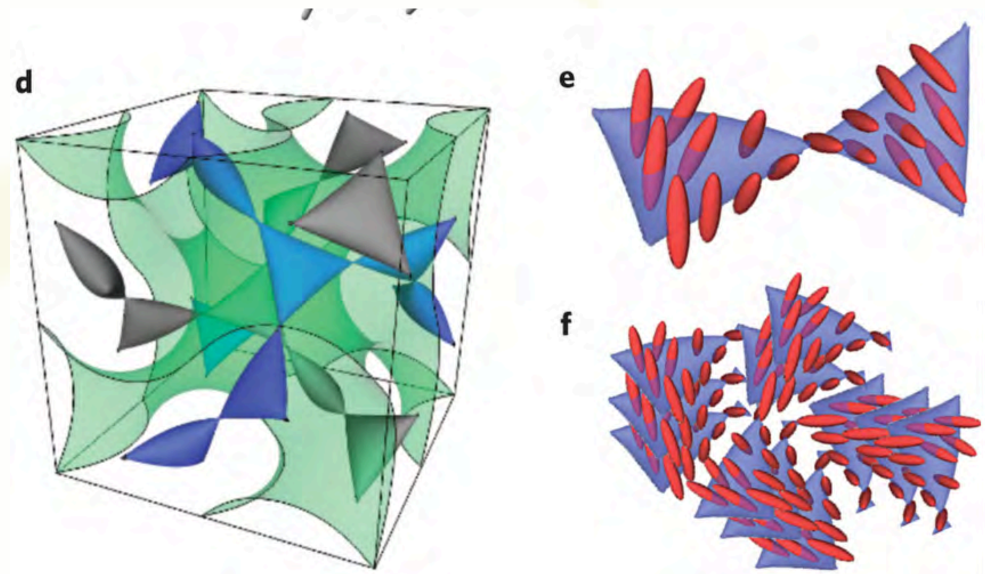
conglomerate domains in an isotropic fluid crystal of achiral molecules

C. Tschierske, Nat. Chem. (2014)

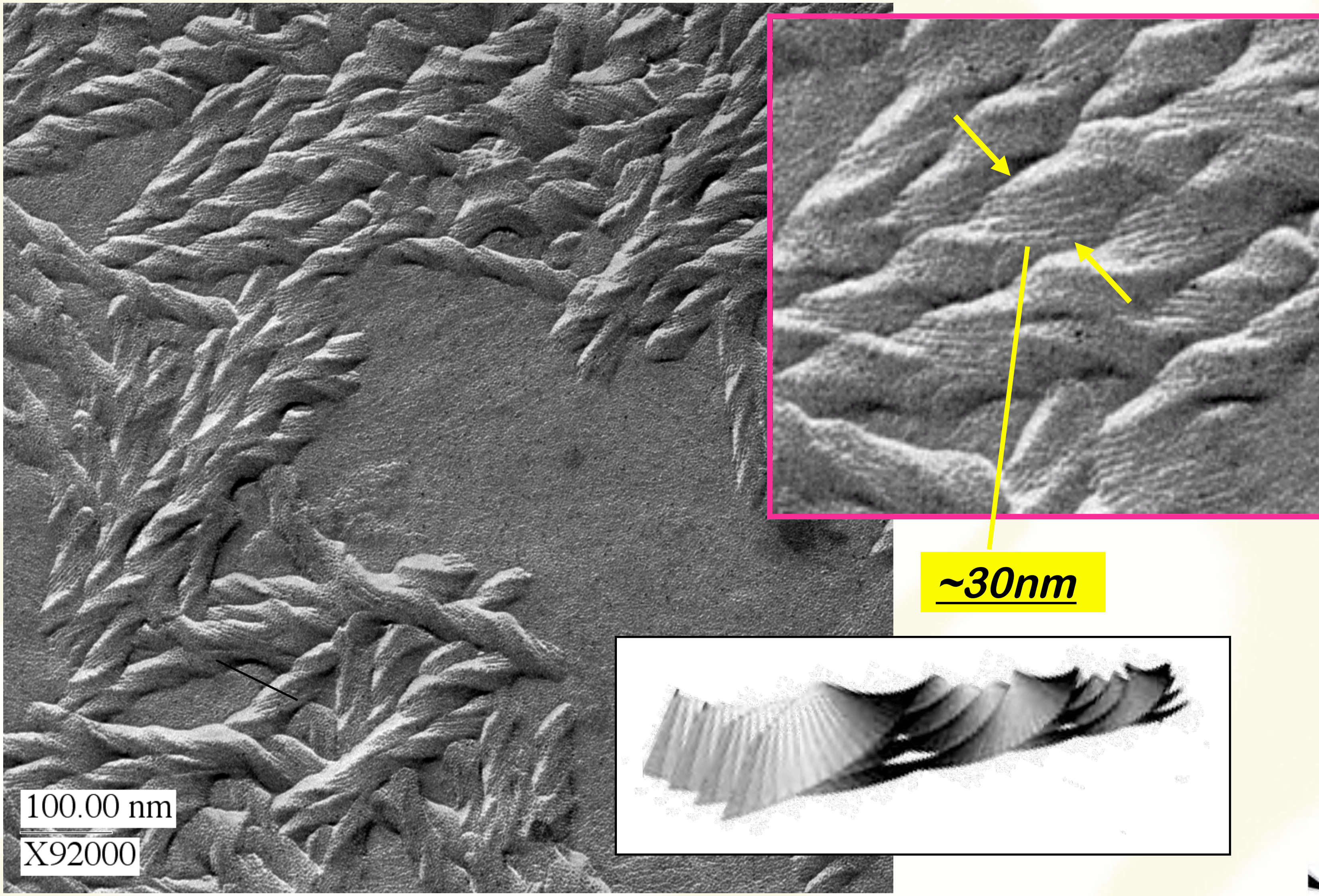




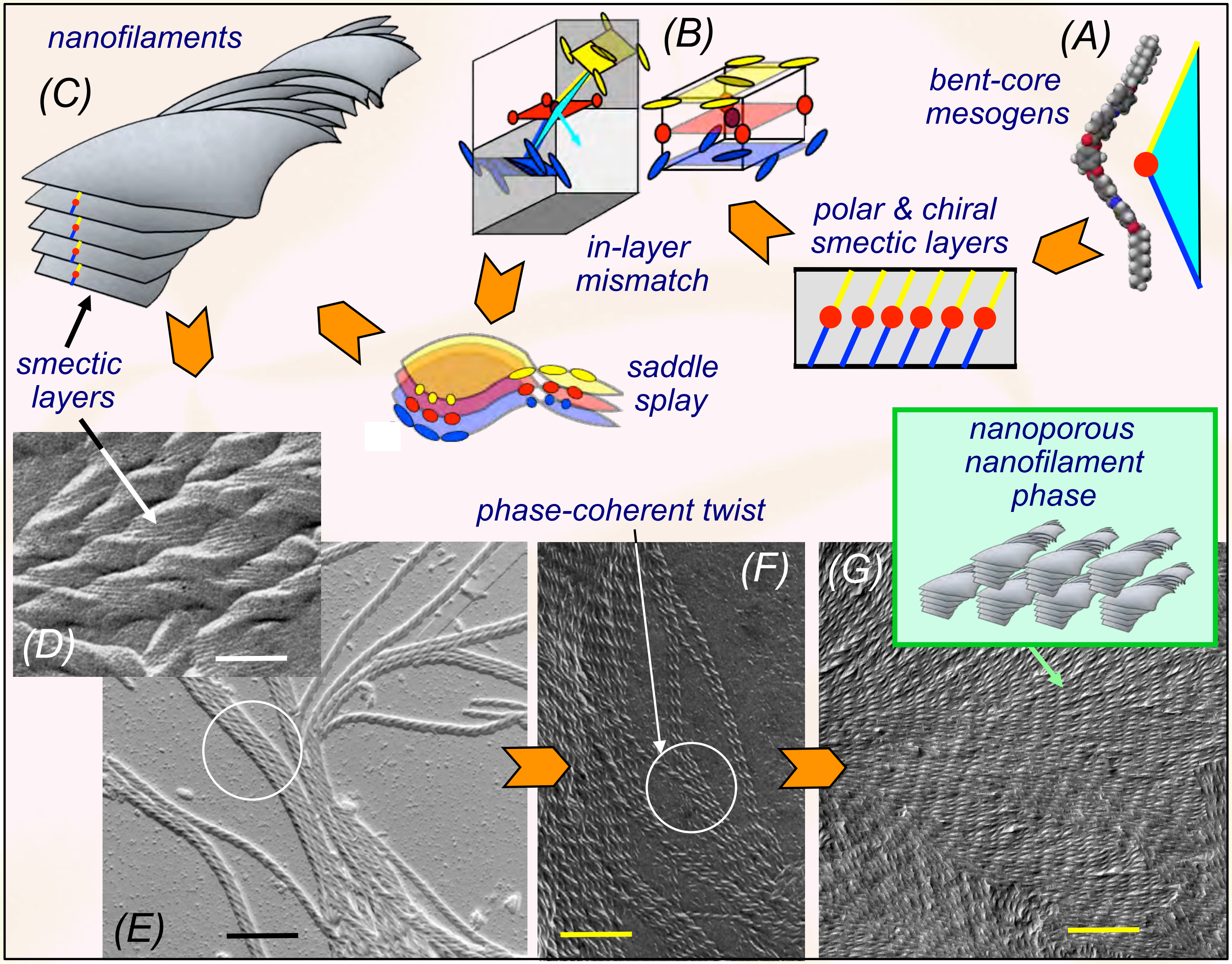




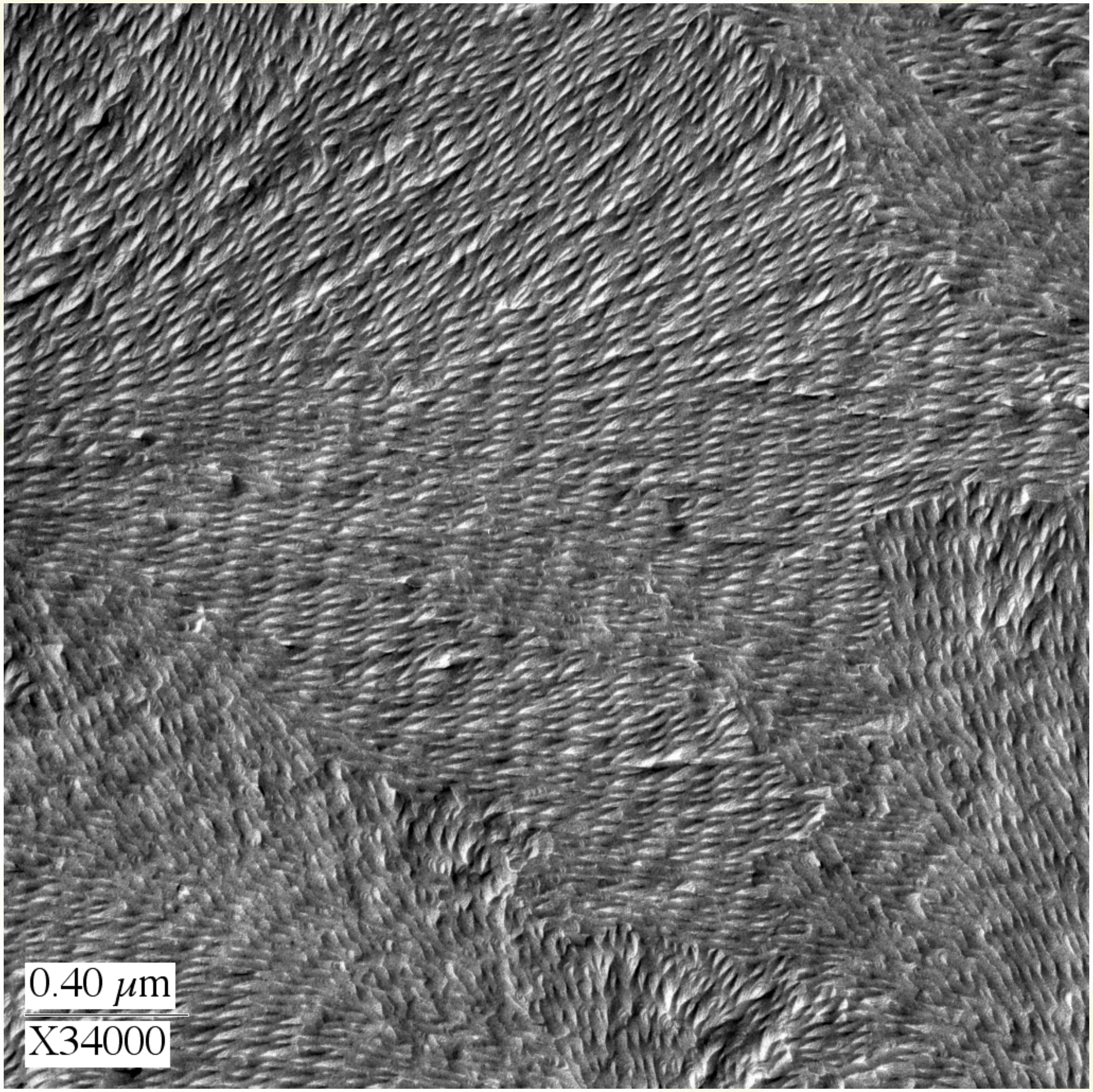
filaments are helical



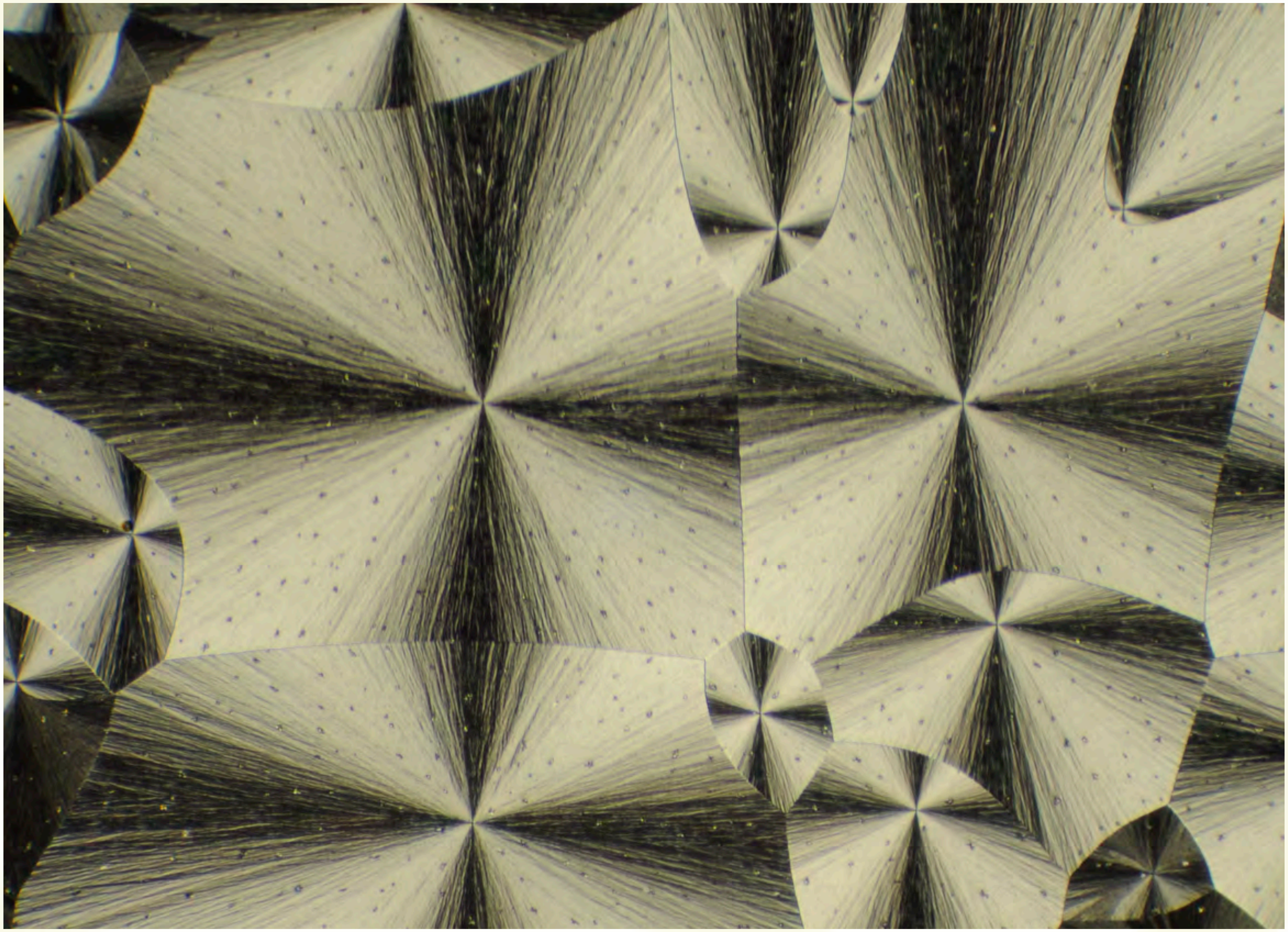
twisted nanofilaments



B4 freeze fracture



spherulitic domains in 60% NOBOW – 40% CE8



50% 7O.5* in NOBOW