EVOLUTIONARY CONTINUUM BETWEEN SMALL RNA AND DNA VIRUSES

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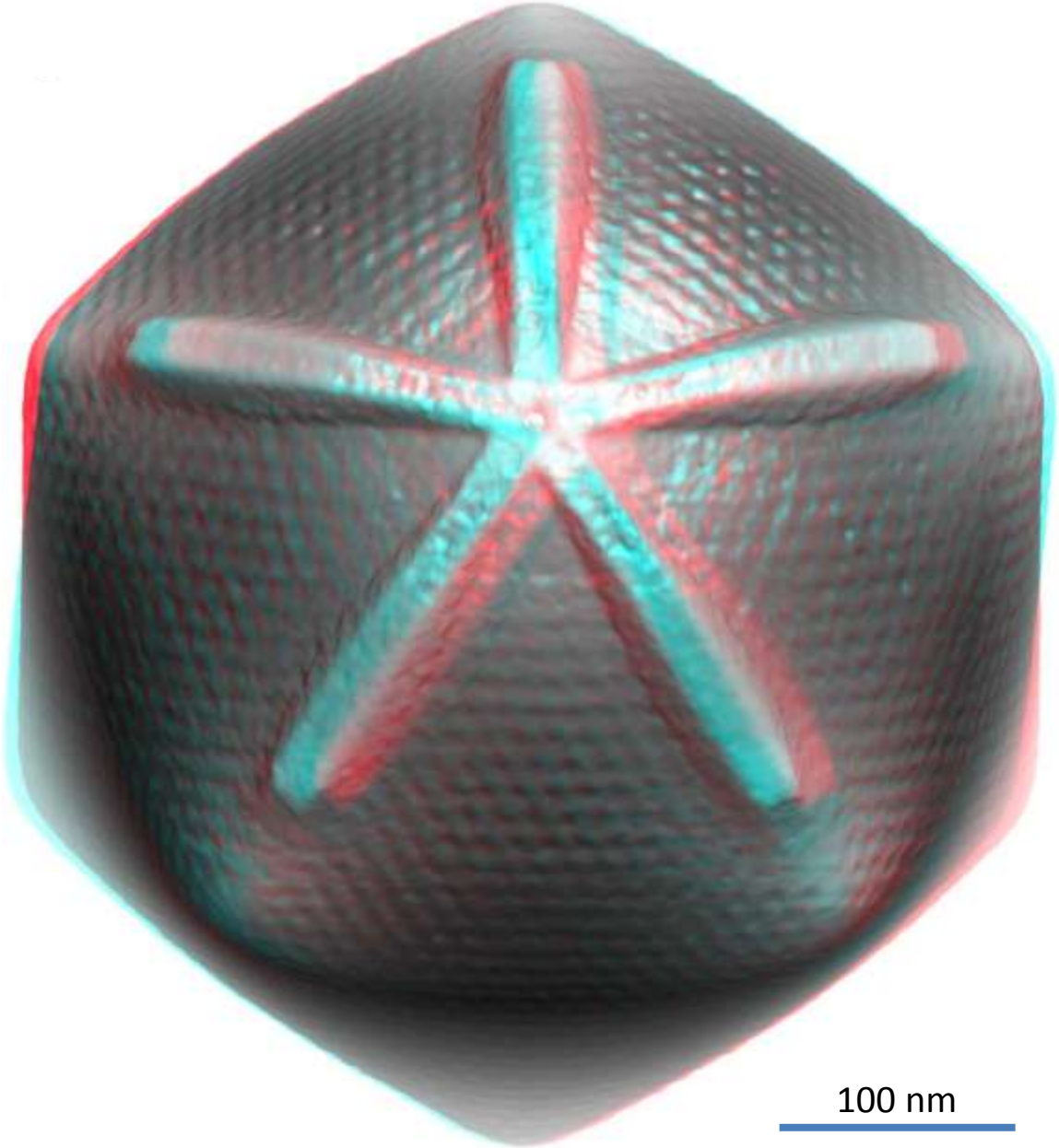
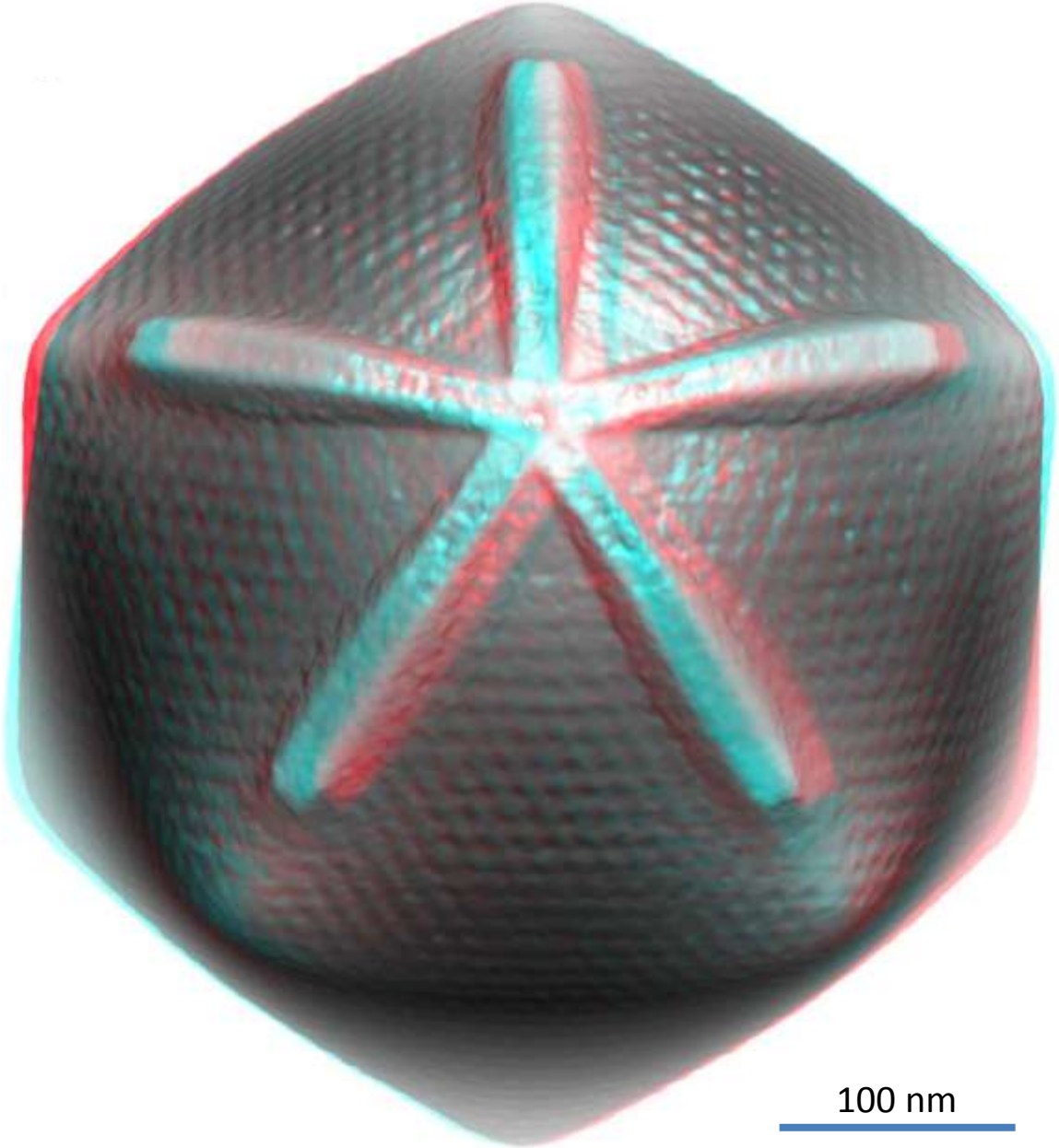

100 nm

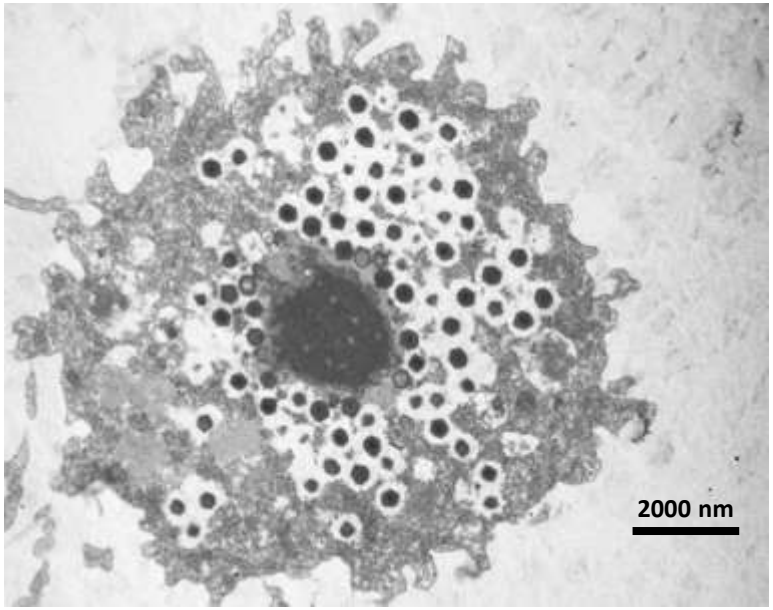


20 nm

Giant viruses versus tiny ones

Mimivirus

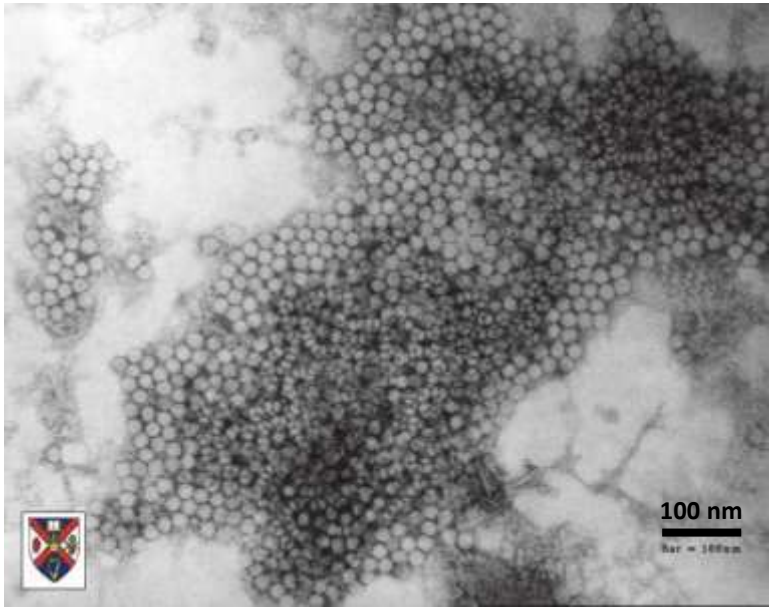
Capsid diameter: ~400 nm
Genome size: 1,181,404 bp
# of genes: 1,018



Courtesy Prof D. Raoult

Porcine circovirus 1

Capsid diameter: ~17 nm
Genome size: 1,758 nt
# of genes: 2



Courtesy Prof S. McNulty

The (described) virosphere: 120 distinct taxa

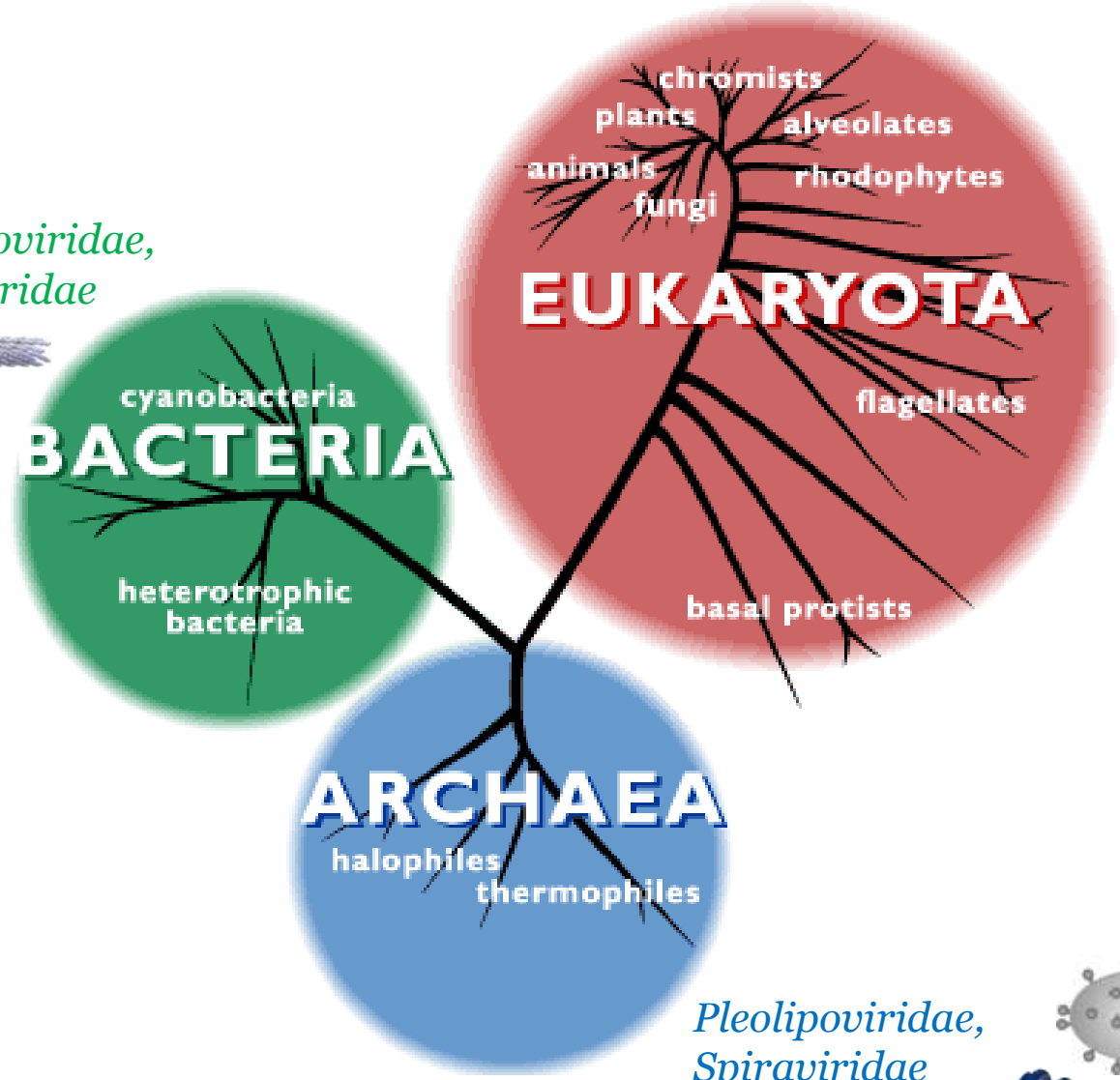
Adenoviridae, Alloherpesviridae, Alphaflexiviridae, Alphatetraviridae, Alvernaviridae, Amalgaviridae, Ampullaviridae, Anelloviridae, Arenaviridae, Arteriviridae, Ascoviridae, Asfarviridae, Astroviridae, Bacilladnavirus, Bacillarnavirus, Baculoviridae, Barnaviridae, Benyviridae, Betaflexiviridae, Bicaudaviridae, Bidnaviridae, Birnaviridae, Bornaviridae, Bromoviridae, Bunyaviridae, Caliciviridae, Carmotetraviridae, Caulimoviridae, Chrysoviridae, Cilevirus, Circoviridae, Clavaviridae, Closteroviridae, Coronaviridae, Corticoviridae, Cystoviridae, Deltavirus, Dicistroviridae, Dinodnavirus, Emaravirus, Endornaviridae, Filoviridae, Flaviviridae, Fuselloviridae, Gammaflexiviridae, Geminiviridae, 'Gemycircularvirus', Globuloviridae, Guttaviridae, Hepadnaviridae, Hepeviridae, Herpesviridae, Higrevirus, Hypoviridae, Hytrosaviridae, Idaeovirus, Iflaviridae, Inoviridae, Iridoviridae, Labyrnavirus, Leviviridae, Lipothrixviridae, Luteoviridae, Malacoherpesviridae, Marnaviridae, Marseilleviridae, Megabirnaviridae, Mesoniviridae, Metaviridae, Microviridae, Mimiviridae, Myoviridae, Nanoviridae, Narnaviridae, Nimaviridae, Nodaviridae, Nudiviridae, Ophioviridae, Orthomyxoviridae, Ourmiavirus, Papillomaviridae, Paramyxoviridae, Partitiviridae, Parvoviridae, Permutotetraviridae, Phycodnaviridae, Picobirnaviridae, Picornaviridae, 'Pleolipoviridae', Plasmaviridae, Podoviridae, Polemovirus, Polydnaviridae, Polyomaviridae, Potyviridae, Poxviridae, Pseudoviridae, Quadriviridae, Reoviridae, Retroviridae, Rhabdoviridae, Rhizidiovirus, Roniviridae, Rudiviridae, Salterprovirus, Secoviridae, Sobemovirus, Siphoviridae, Spiraviridae, 'Sphaerolipoviridae', Tectiviridae, Tenuivirus, Togaviridae, Tombusviridae, Totiviridae, Turriviridae, Tymoviridae, Umbravirus, Varicosavirus, Virgaviridae

The (described) virosphere: 120 distinct taxa

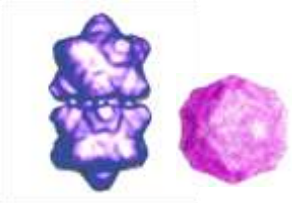
Adenoviridae, Alloherpesviridae, Alphaflexiviridae, Alphatetraviridae, Alvernaviridae, Amalgaviridae, Ampullaviridae, ***Anelloviridae,*** *Arenaviridae, Arteriviridae, Ascoviridae, Asfarviridae, Astroviridae,* ***Bacilladnavirus,*** *Bacillarnavirus, Baculoviridae, Barnaviridae, Benyviridae, Betaflexiviridae, Bicaudaviridae,* ***Bidnaviridae,*** *Birnaviridae, Bornaviridae, Bromoviridae, Bunyaviridae, Caliciviridae, Carmotetraviridae, Caulimoviridae, Chrysoviridae, Cilevirus,* ***Circoviridae,*** *Clavaviridae, Closteroviridae, Coronaviridae, Corticoviridae, Cystoviridae, Deltavirus, Dicistroviridae, Dinodnavirus, Emaravirus, Endornaviridae, Filoviridae, Flaviviridae, Fuselloviridae, Gammaflexiviridae,* ***Geminiviridae, 'Gemycircularvirus',*** *Globuloviridae, Guttaviridae, Hepadnaviridae, Hepeviridae, Herpesviridae, Higrevirus, Hypoviridae, Hytrosaviridae, Idaeovirus, Iflaviridae,* ***Inoviridae,*** *Iridoviridae, Labyrnavirus, Leviviridae, Lipothrixviridae, Luteoviridae, Malacoherpesviridae, Marnaviridae, Marseilleviridae, Megabirnaviridae, Mesoniviridae, Metaviridae,* ***Microviridae,*** *Mimiviridae, Myoviridae,* ***Nanoviridae,*** *Narnaviridae, Nimaviridae, Nodaviridae, Nudiviridae, Ophioviridae, Orthomyxoviridae, Ourmiavirus, Papillomaviridae, Paramyxoviridae, Partitiviridae,* ***Parvoviridae,*** *Permutotetraviridae, Phycodnaviridae, Picobirnaviridae, Picornaviridae,* ***'Pleolipoviridae',*** *Plasmaviridae, Podoviridae, Polemovirus, Polydnaviridae, Polyomaviridae, Potyviridae, Poxviridae, Pseudoviridae, Quadriviridae, Reoviridae, Retroviridae, Rhabdoviridae, Rhizidiovirus, Roniviridae, Rudiviridae, Salterprovirus, Secoviridae, Sobemovirus, Siphoviridae,* ***Spiraviridae,*** *'Sphaerolipoviridae', Tectiviridae, Tenuivirus, Togaviridae, Tombusviridae, Totiviridae, Turriviridae, Tymoviridae, Umbravirus, Varicosavirus, Virgaviridae*

ssDNA viruses belong to 12 out of 120 taxa

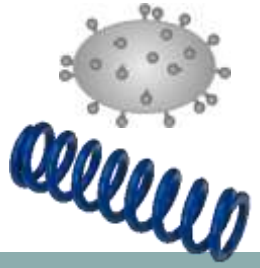
Microviridae,
Inoviridae



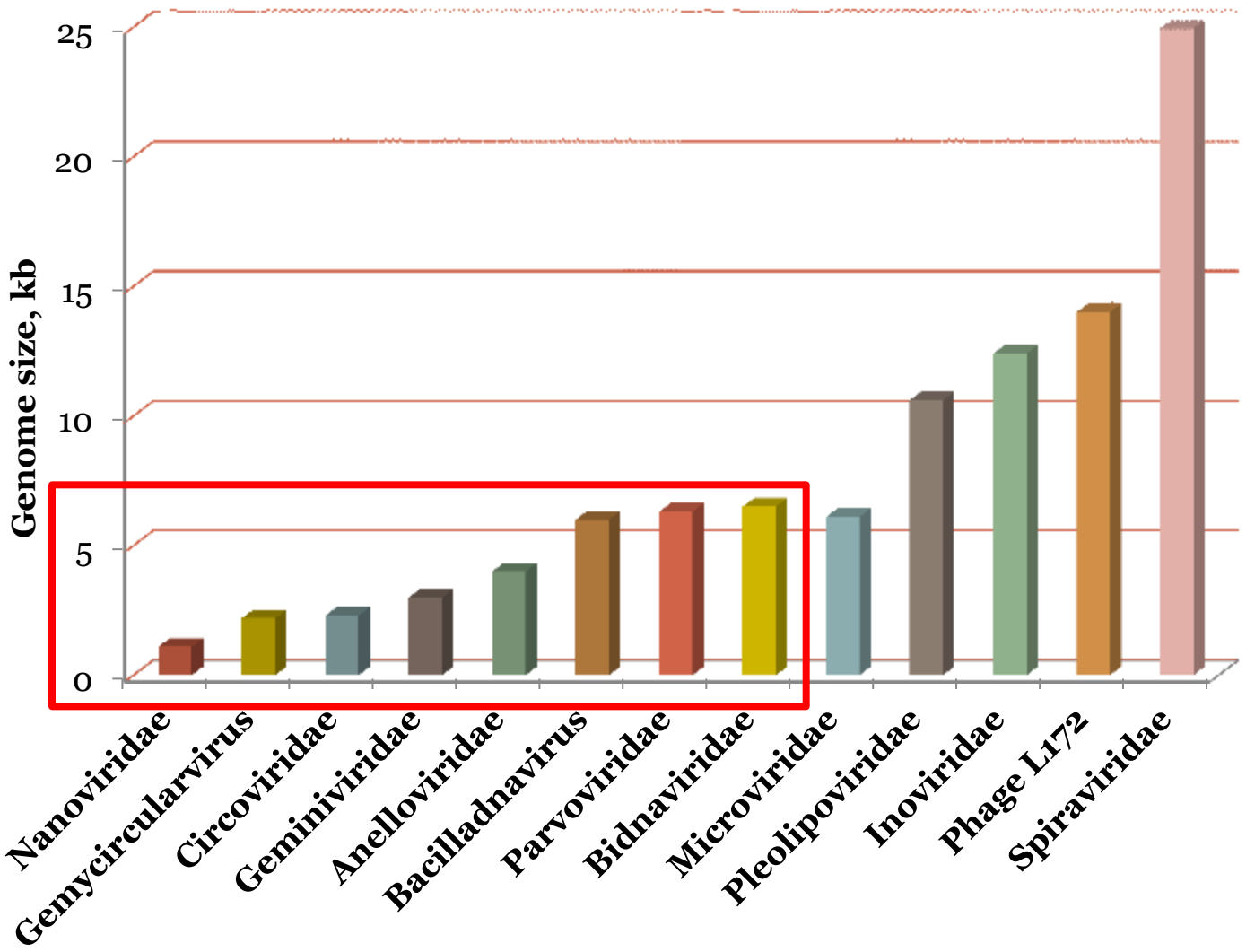
Anelloviridae,
Bidnaviridae,
Circoviridae,
Geminiviridae,
Nanoviridae,
Parvoviridae,
Bacilladnavirus,
Geminicyclovirus



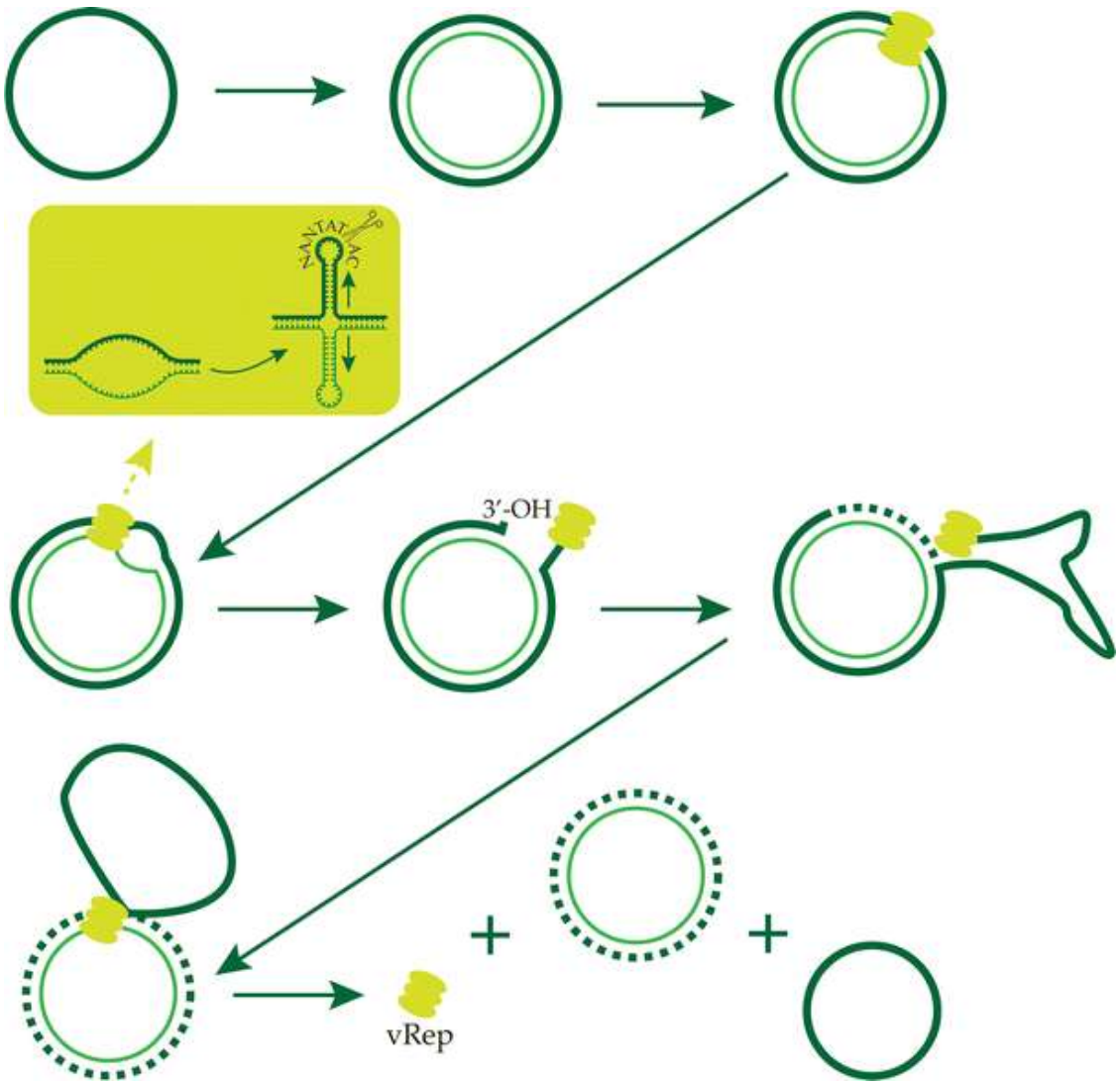
Pleolipoviridae,
Spiraviridae



Genomes of eukaryotic ssDNA viruses are <10 kb



Majority of ssDNA viruses replicate via RC mechanism



Rosario, Duffy, Breitbart, *Arch Virol* 2012

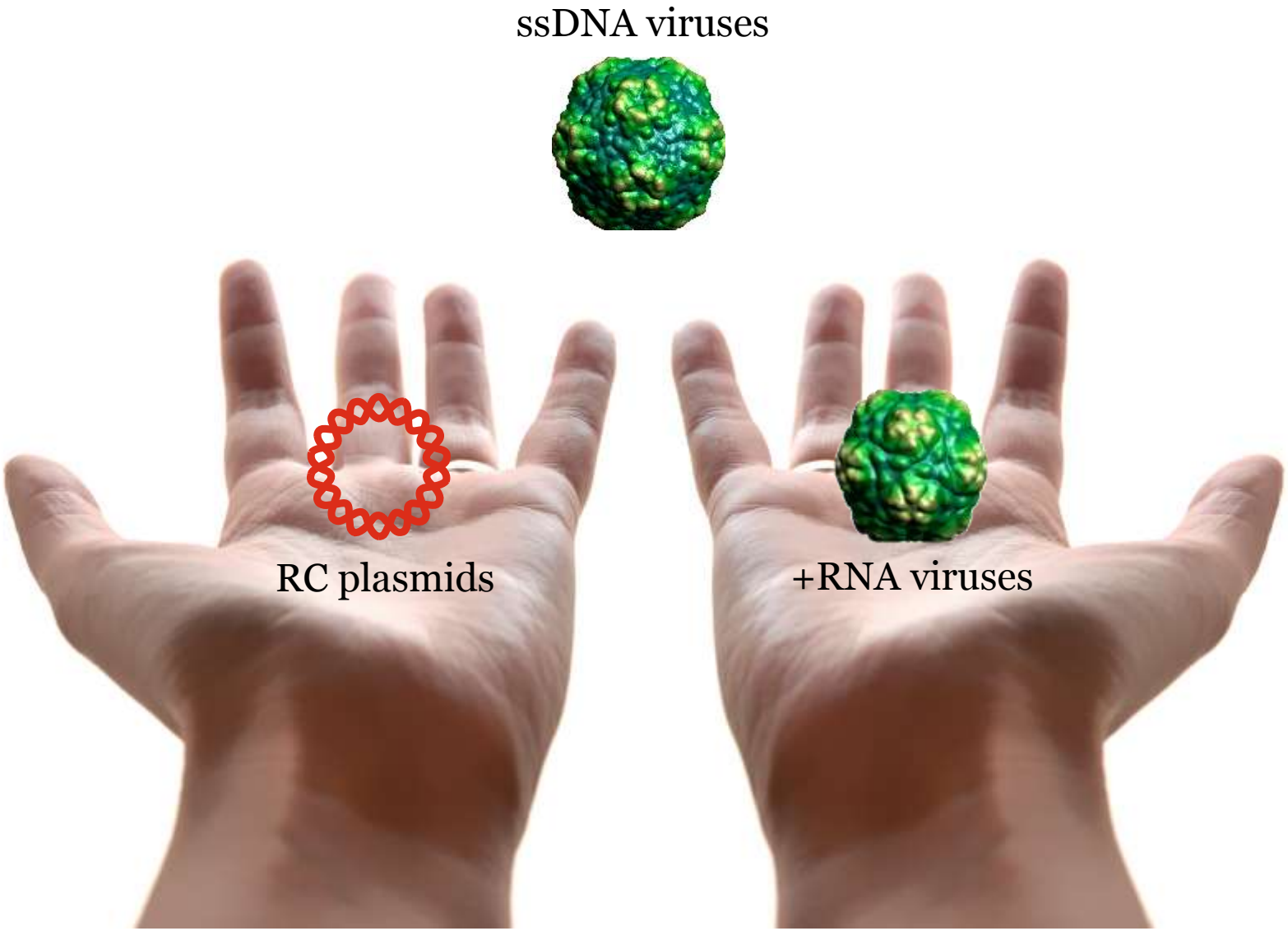
Overview of ssDNA viruses

Host/virus taxon	Virion morphology	CP fold	Genome topology	Genome size (kb)	Replication protein
Bacteria					
Microviridae	Icosahedral	Jelly-roll	Circular	4.4–6.1	RC-Rep
Inoviridae	Filamentous/ rod-shaped	α-Helix	Circular	4.5–12.4	RC-Rep
Mycoplasma virus L172 (unclassified)	Pleomorphic	NA	Circular	~14[b]	Unknown
Archaea					
Pleolipoviridae[a]	Pleomorphic	NA	Circular (ss or ds)	7–10.6	RC-Rep
Spiraviridae[a]	Coil-shaped	NA	Circular	24.9	Unknown
Eukarya					
Anelloviridae	Icosahedral	NA	Circular	2–4	RC-Rep (TBC)
Bidnaviridae	Icosahedral	NA	Linear, segmented, ITR	6–6.5 per segment	DNA Pol B
Circoviridae	Icosahedral	Jelly-roll	Circular	1.7-2.3	RC-Rep
Geminiviridae	Icosahedral (geminate)	Jelly-roll	Circular, segmented	2.5-3 per segment	RC-Rep
Nanoviridae	Icosahedral	NA	Circular, segmented	0.98–1.1 per segment	RC-Rep
Parvoviridae	Icosahedral	Jelly-roll	Linear, ITR	4–6.3	RC-Rep
Bacilladnavirus	Icosahedral	NA	Circular, partially ds	5.8–6	RC-Rep
Gemycircularvirus[a]	Icosahedral	NA	Circular	2.2	RC-Rep

TBC, to be confirmed; NA, not available; ITR, inverted terminal repeats.
[a] Taxa not (yet) approved by ICTV.
[b] Complete genome sequence is not available.

Krupovic, *Curr Opin Virol* 2013

Bilateral evolutionary relationship

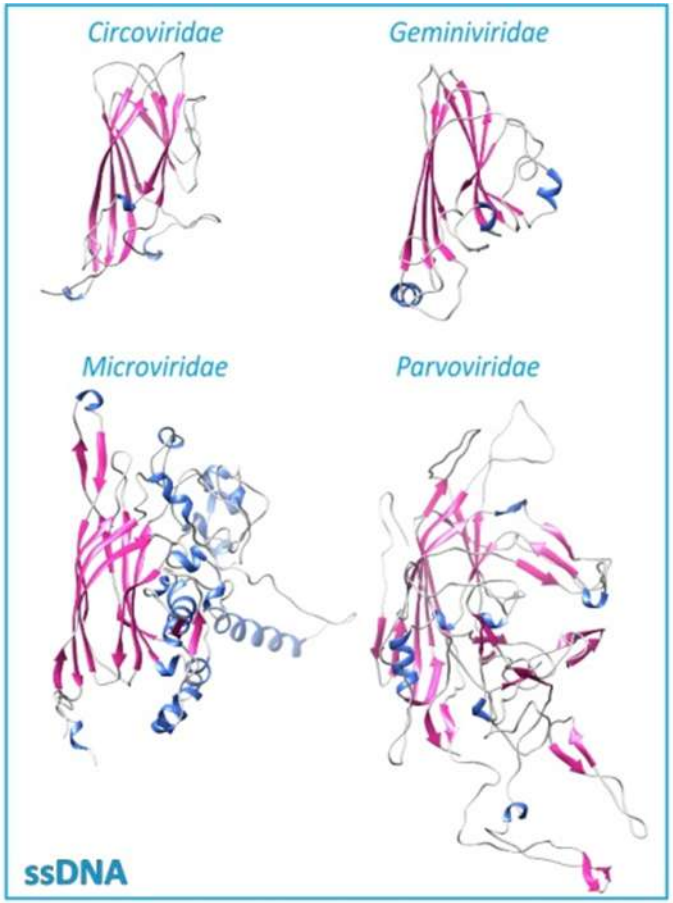


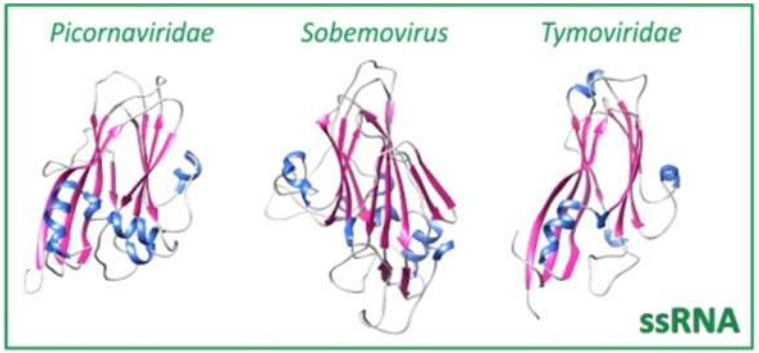
Relationship between ssDNA viruses and RC plasmids

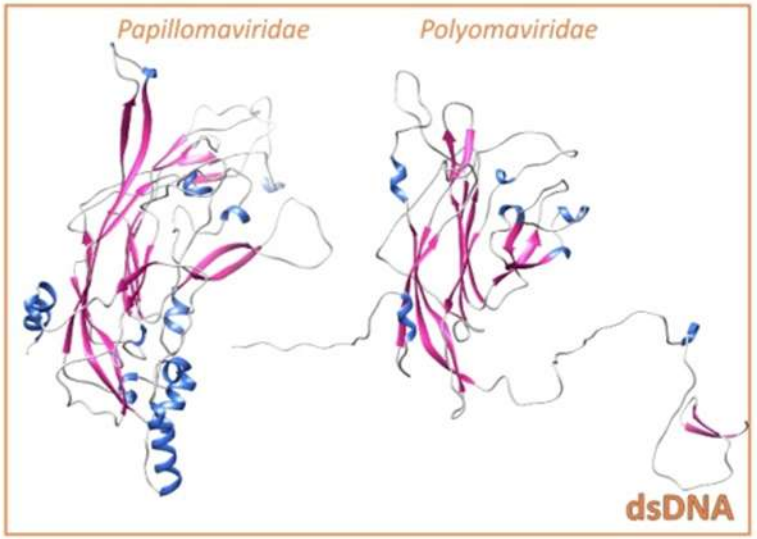
	RC endonuclease domain			SF3 helicase domain		
	Motif I	Motif II	Motif III	Walker A	Walker B	Walker C
Microviridae | ϕX174	IVFDTLTL	GRLHFHAVH	VGFYVAKYVN			
Inoviridae | ϕLf	WYFLTLTY	FRPHYHVML	CVGYLAKYAS			
Pleolipoviridae | HRPV-1	VMVTLTTD	GLPHLHVCV	VAGYLGKYLS			
Parvoviridae | AAV2	YEIVIKVP	SYFHMHVLV	IPNYLLPKTQ	WLFGPA-TTGKTNI	VIWWEEGK	PVIVTS
Circoviridae | PCV2	WVFTLNNP	RTPHLQGFA	NKEYCSKEGN	VIVGPP-GCGKSKW	VVVIDDFY	SILITS
Nanoviridae | BBTV	WMFTINNP	GTRHVQGYV	ARSYCMKEDT	WVYGPKGGEGKTTY	IVIFDIPR	EVIVMA
Geminiviridae | MSV	NTFLTYPH	GDMHLHALL	VRDYILKEPL	YIVGPT-RTGKSTW	YNIVDDIP	PTIILA
Gemycircularvirus | SsHADV-1	YVLLTYAQ	GGTHLHCFA	GYDYAIKDGD	VLYGPS-QTGKTSW	YAVFDDIR	PSIWCS
Bacilladnavirus | CsNIV	SQFTLNAQ	GALHAHIYF	AINYVLDDAK	ILYGAG-GTGKTTT	IVHFEEFT	TVIFTS
Porphyra | plasmid	LFFLTYPC	GYDHFHVLL	SLKYICKEGD	YIHGKP-GIGKTNM	AIGFDDVN	PKVFIS
Phytoplasma | pAYWB-II	CELVINAN	KSPHYHIYL	ALMYMTHANS	FITGQS-GSGKSTL	CIILDDLR	LIIITT
Lactococcus | pQA504	FGFTQQFK	KELHMHAVI	MLAYLVHAKD	YIQGAP-RMGKTFF	IVFMDDLR	VIVITS
Staphylococcus | SAP110B	TKFMYTQQ	VAEHLHVFI	GYLYLLHKTK	WIFGKS-STGKSMM	VLIIEEFR	LIIINT
Bifidobacterium | p4M	TDWLLTIR	GYRHYQIFA	AVGYCSKEKT	FLYGET-GVGKTSH	ILLLDEFT	RIWVVS
Polyomaviridae | SV40	ACFAIYTT	SYNHNILFF	YLMYSALTRD	LFKGPI-DSGKTTL	LVVFEDVK	PGIVTM
Papillomaviridae | HPV16	GWFYVEAV	WGMVVLLLV	AALYWYKTGI	LLYGAA-NTGKSLF	IGMLDDAT	PPLLIT

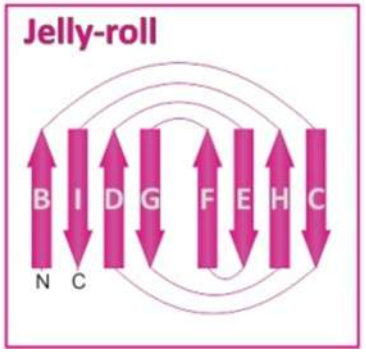
Prokaryotic ssDNA viruses *Eukaryotic ssDNA viruses* *Eukaryotic and bacterial plasmids* *dsDNA viruses with JR-CPs*

Krupovic, *Curr Opin Virol* 2013









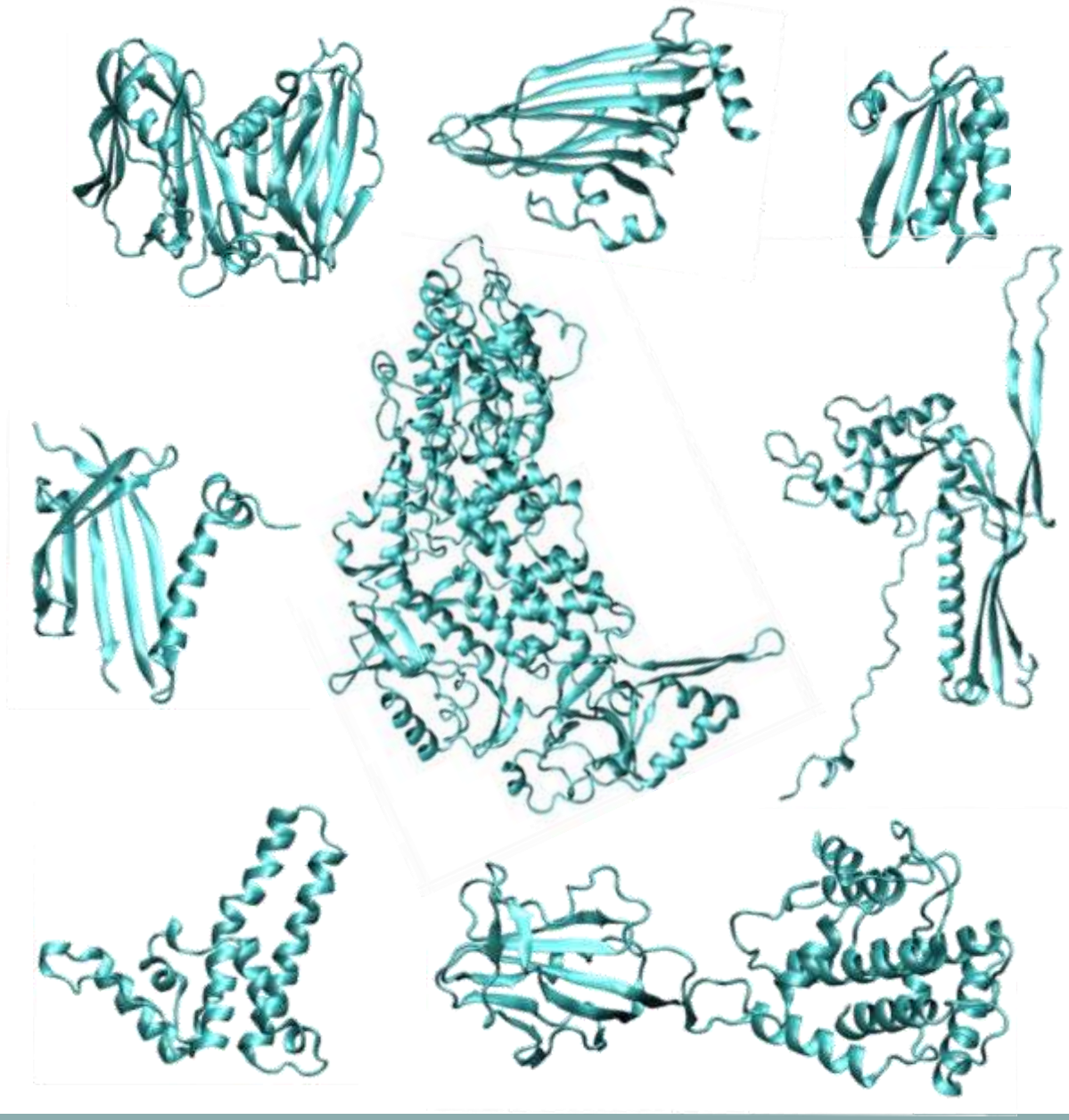
ssDNA viruses
Circoviridae
Geminiviridae
Microviridae
Parvoviridae

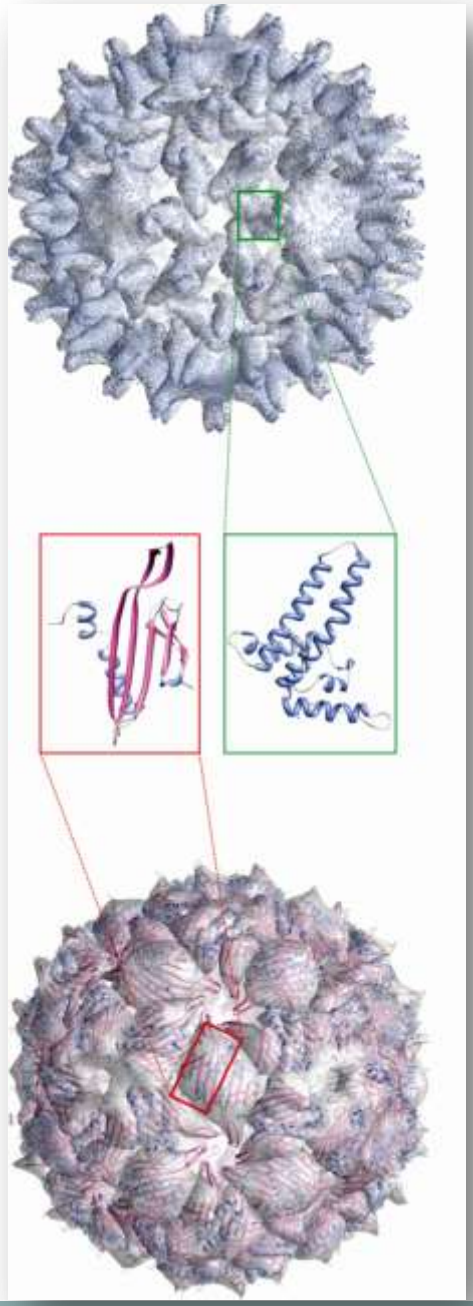
dsDNA viruses
Papillomaviridae
Polyomaviridae

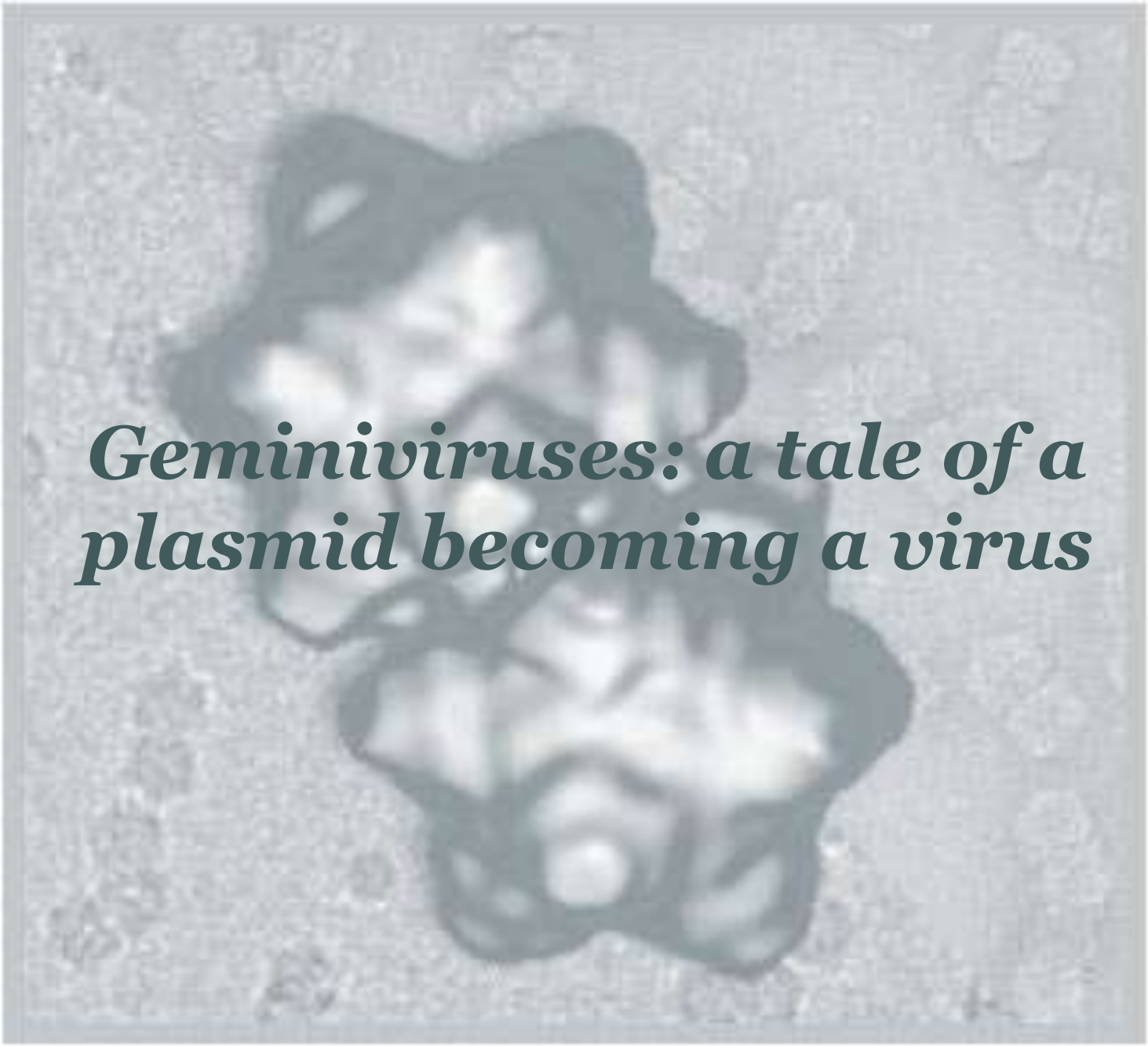
ssRNA viruses
Alphatetraviridae
Alvernaviridae
Astroviridae
Bromoviridae
Caliciviridae
Carmotetraviridae
Dicistroviridae
Hepeviridae
Iflaviridae
Luteoviridae
Marnaviridae
Nodaviridae
Picornaviridae
Secoviridae
Tombusviridae
Tymoviridae
Permutotetraviridae
Bacillarnavirus
Labyrnavirus
Sobemovirus
STNV-like satellites

dsRNA viruses
Birnaviridae

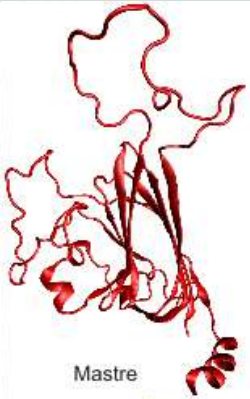
Krupovic, *Curr Opin Virol* 2013

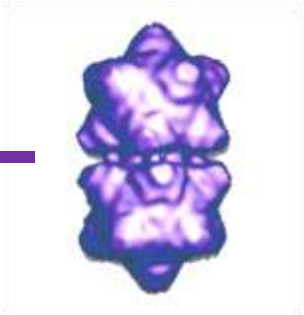




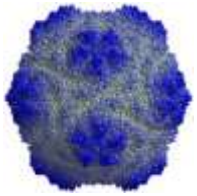


Geminiviruses: a tale of a plasmid becoming a virus

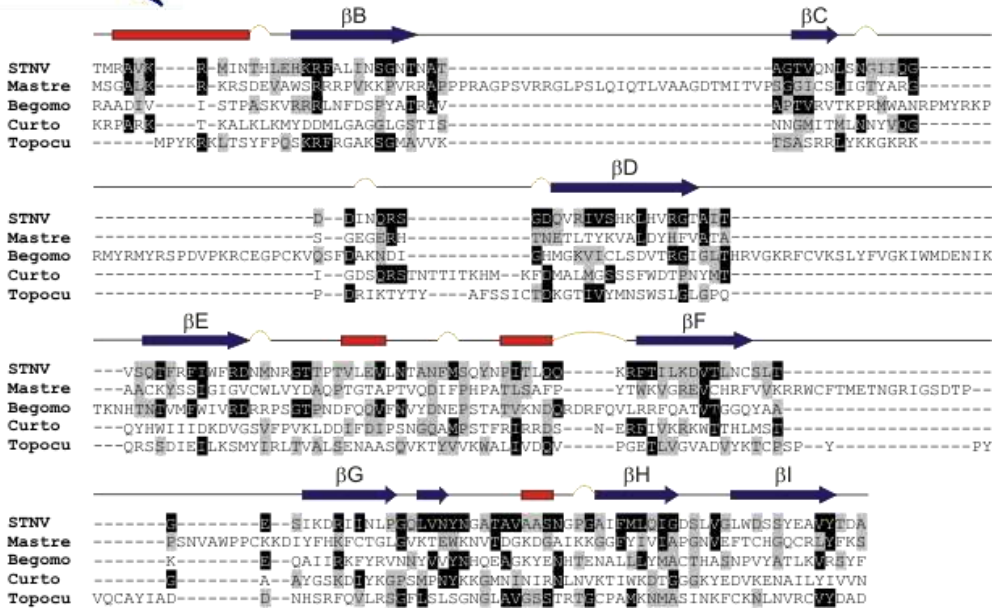




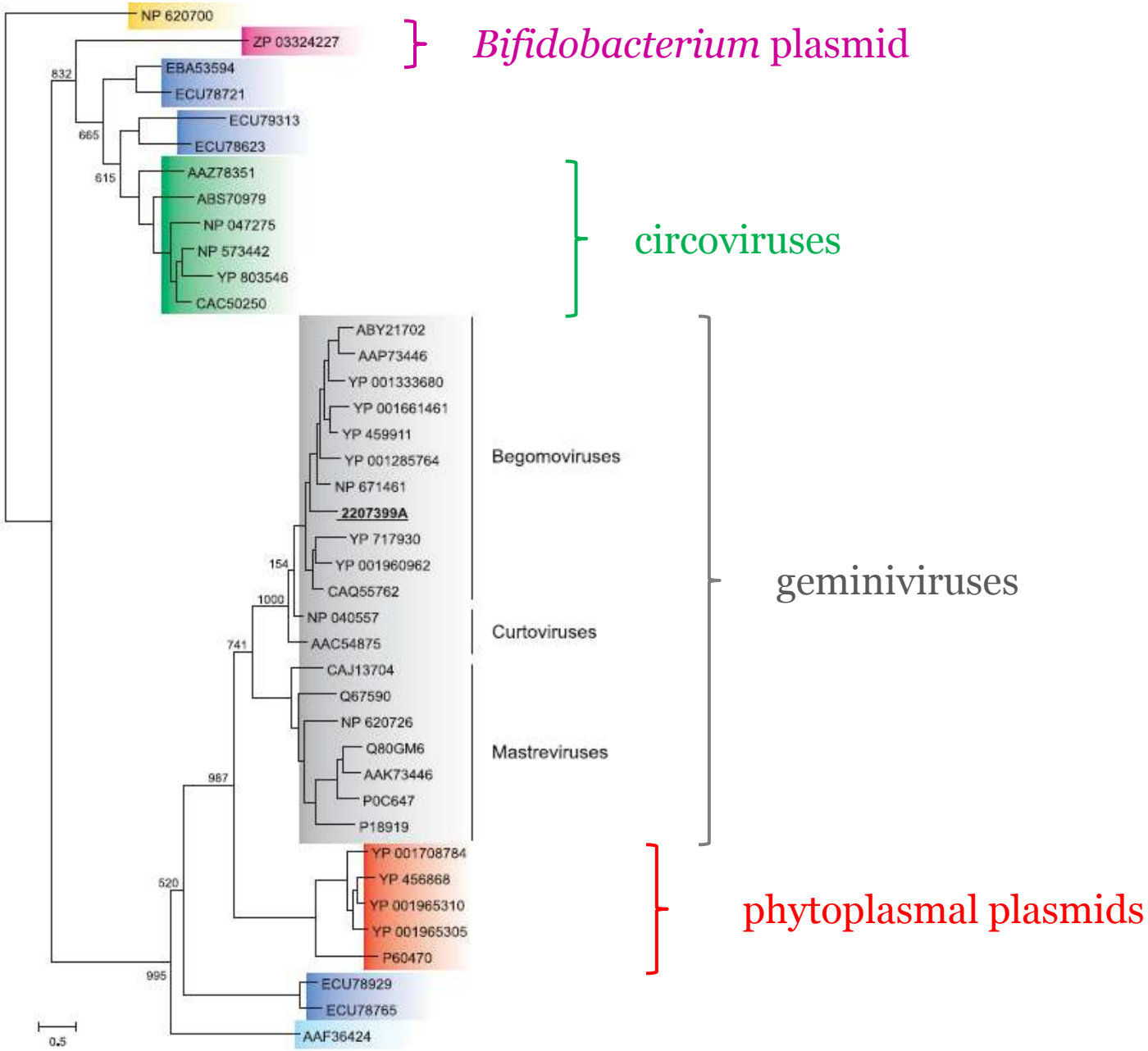
Geminiviridae
(ssDNA)



Satellite tobacco necrosis virus
(ssRNA)

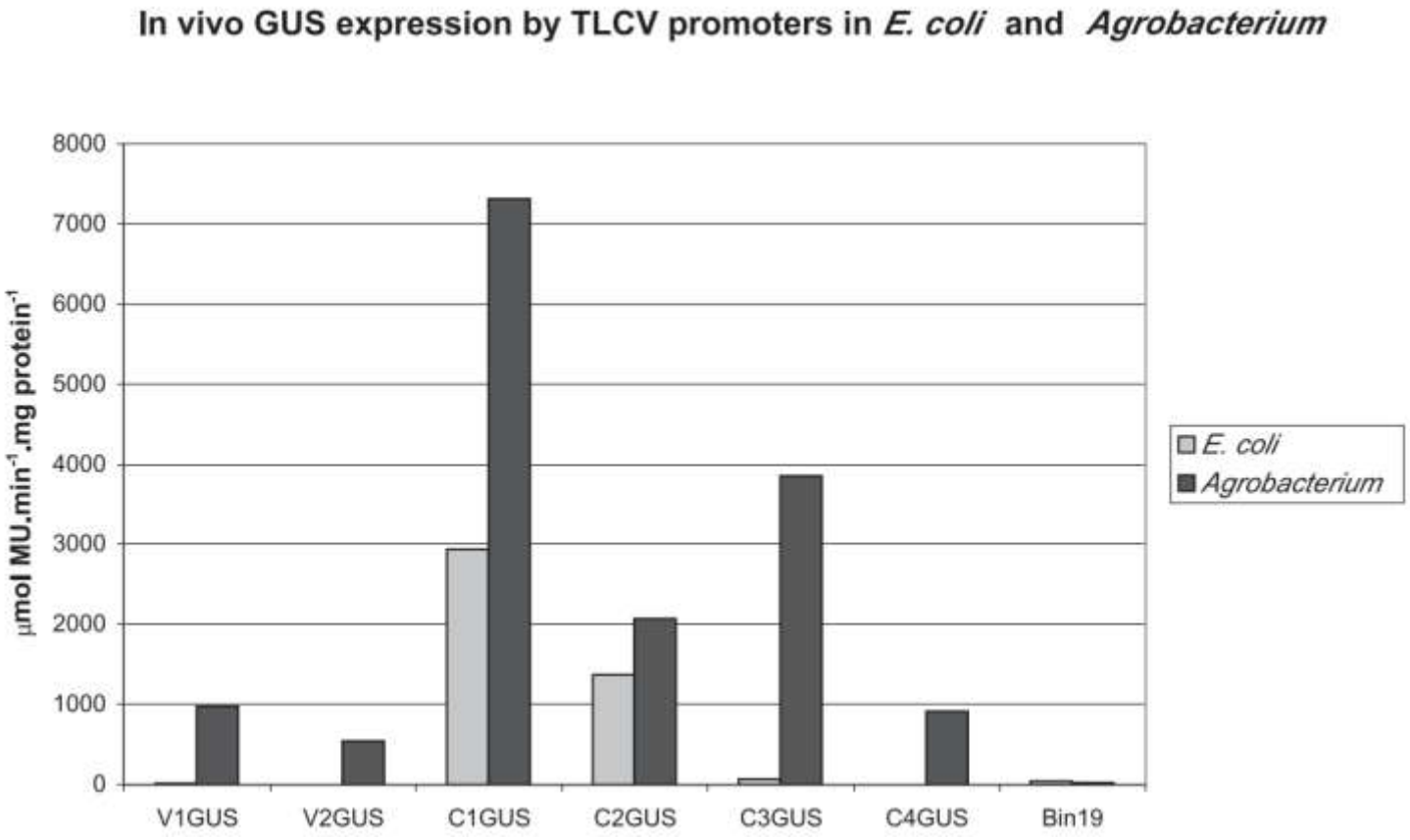


Krupovic, Ravantti, Bamford, *BMC Evol Biol* 2009



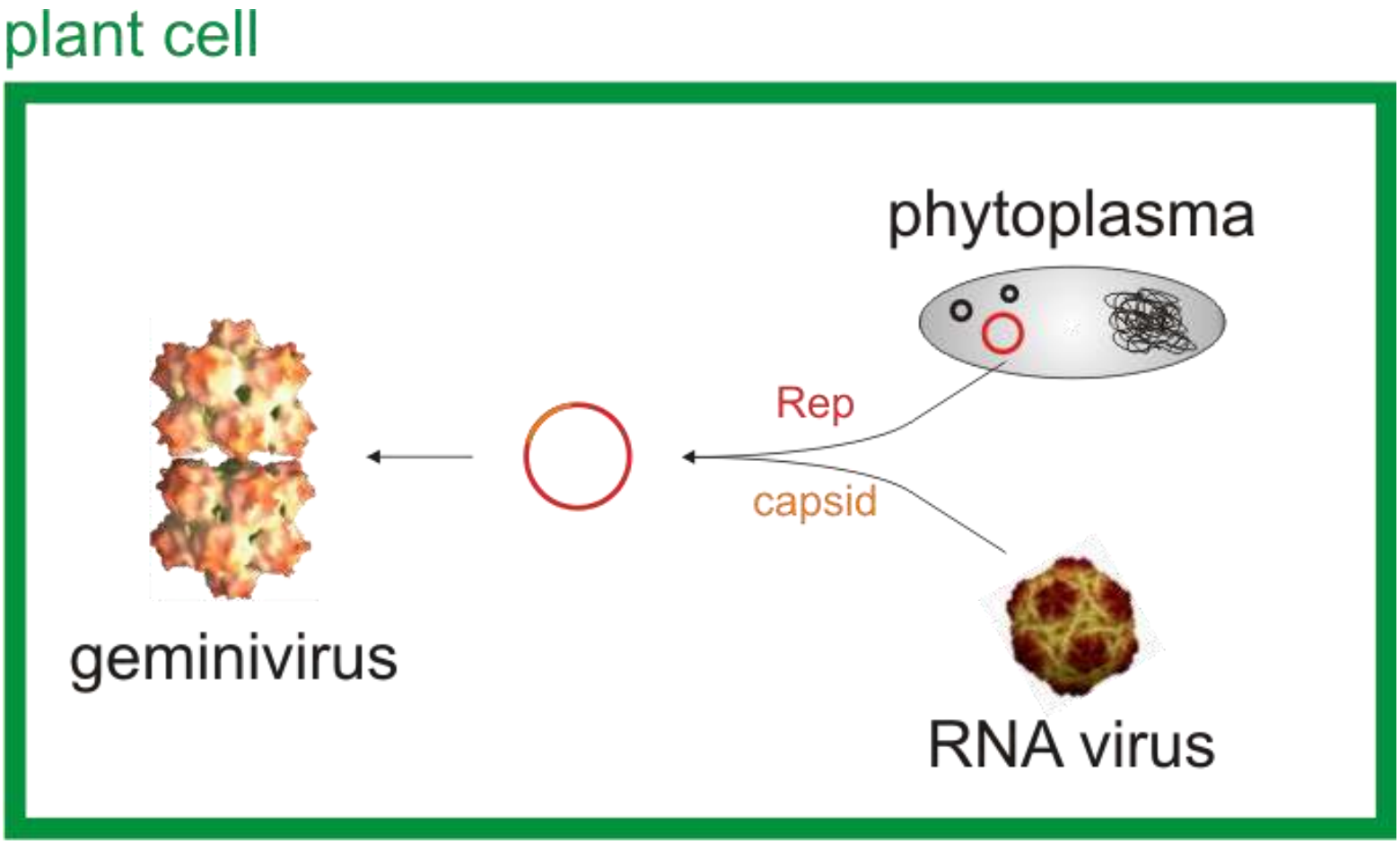
Krupovic, Ravantti, Bamford, *BMC Evol Biol* 2009

Geminiviruses contain prokaryotic promoters

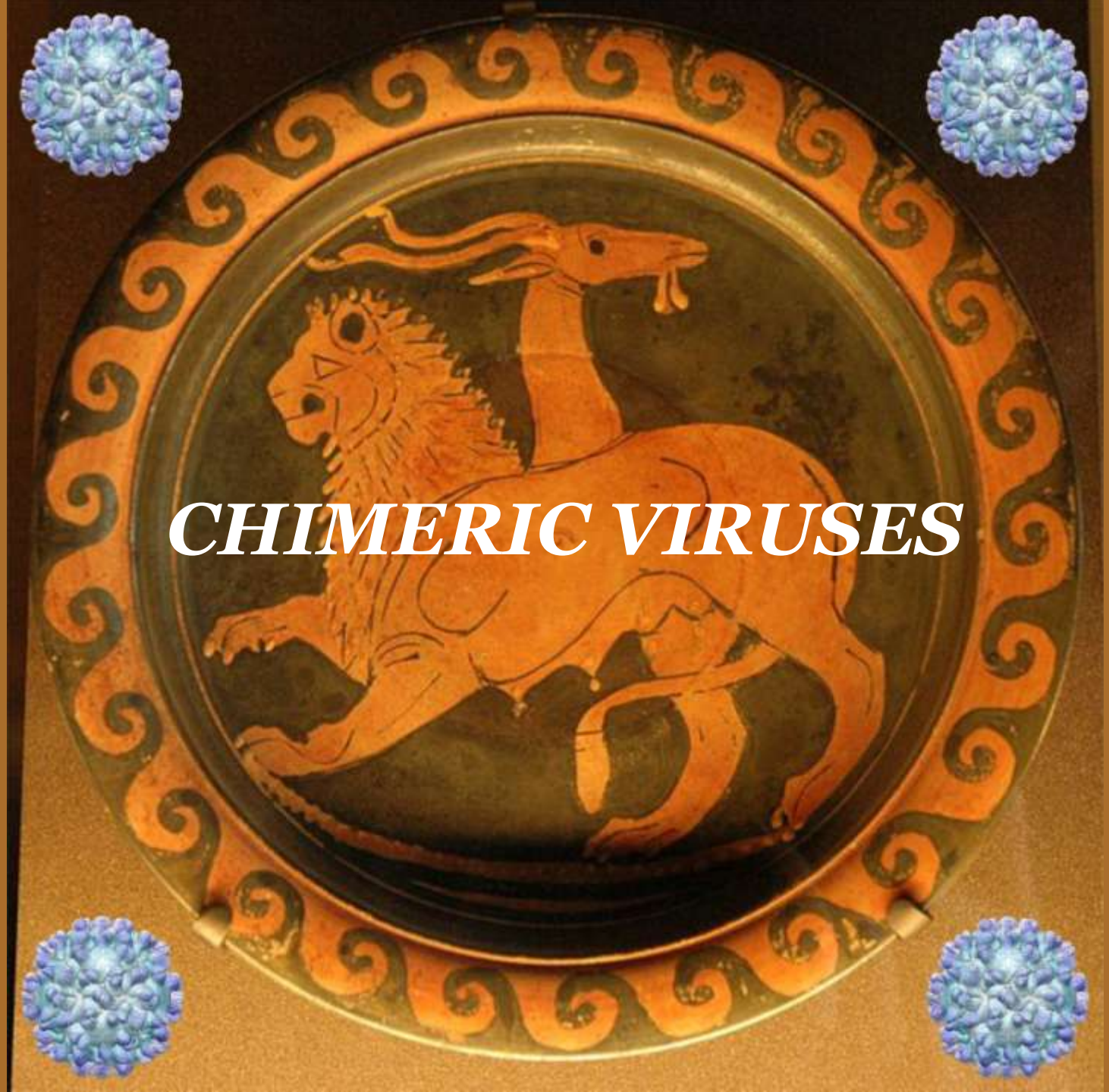


Selth, Randles, Rezaian, *FEBS Lett* 2002

Plasmid-to-virus transition



Krupovic, Ravantti, Bamford, *BMC Evol Biol* 2009



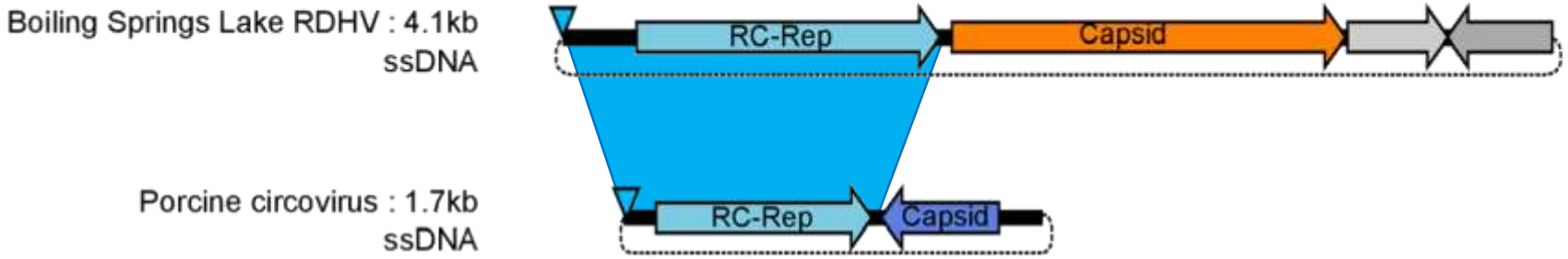
CHIMERIC VIRUSES

Chimeric viruses: RNA-DNA hybrid virus (RDHV)

Boiling Springs Lake RDHV : 4.1kb
ssDNA

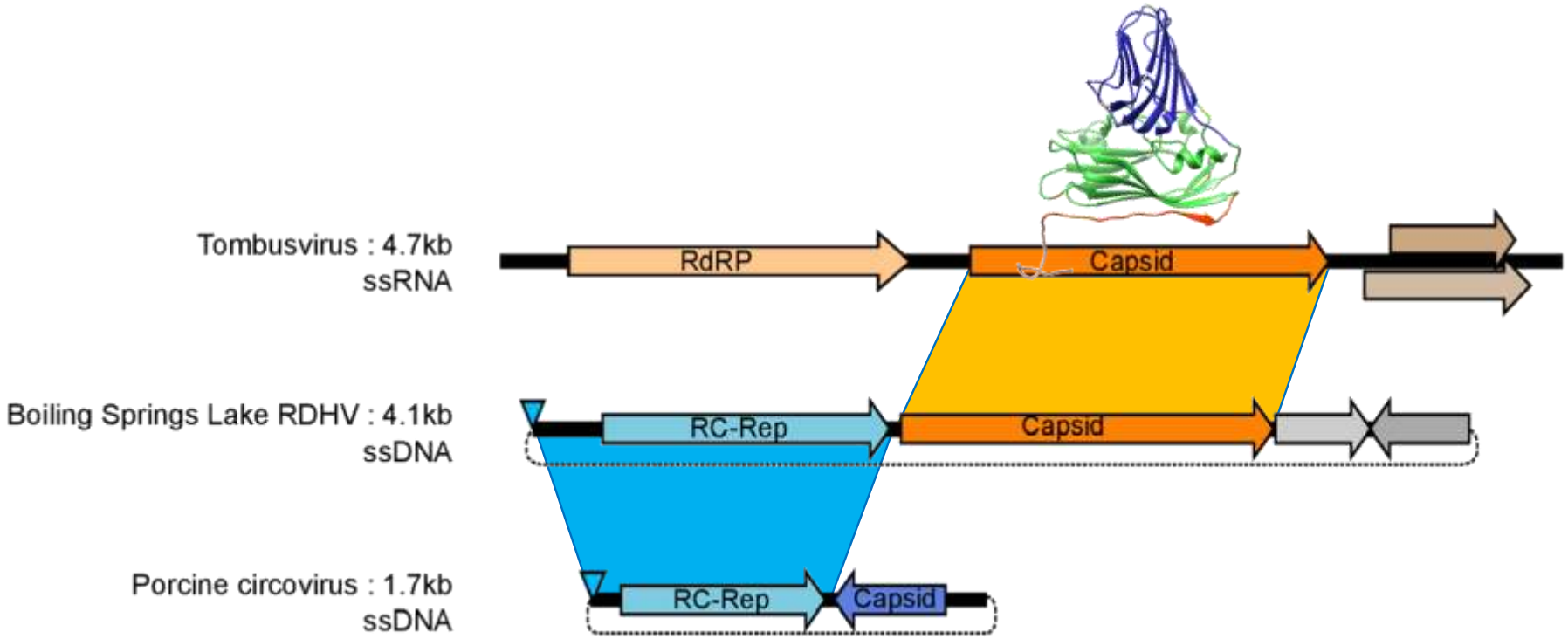
Diemer, Stedman, *Biol Direct* 2012

Chimeric viruses: RNA-DNA hybrid virus (RDHV)



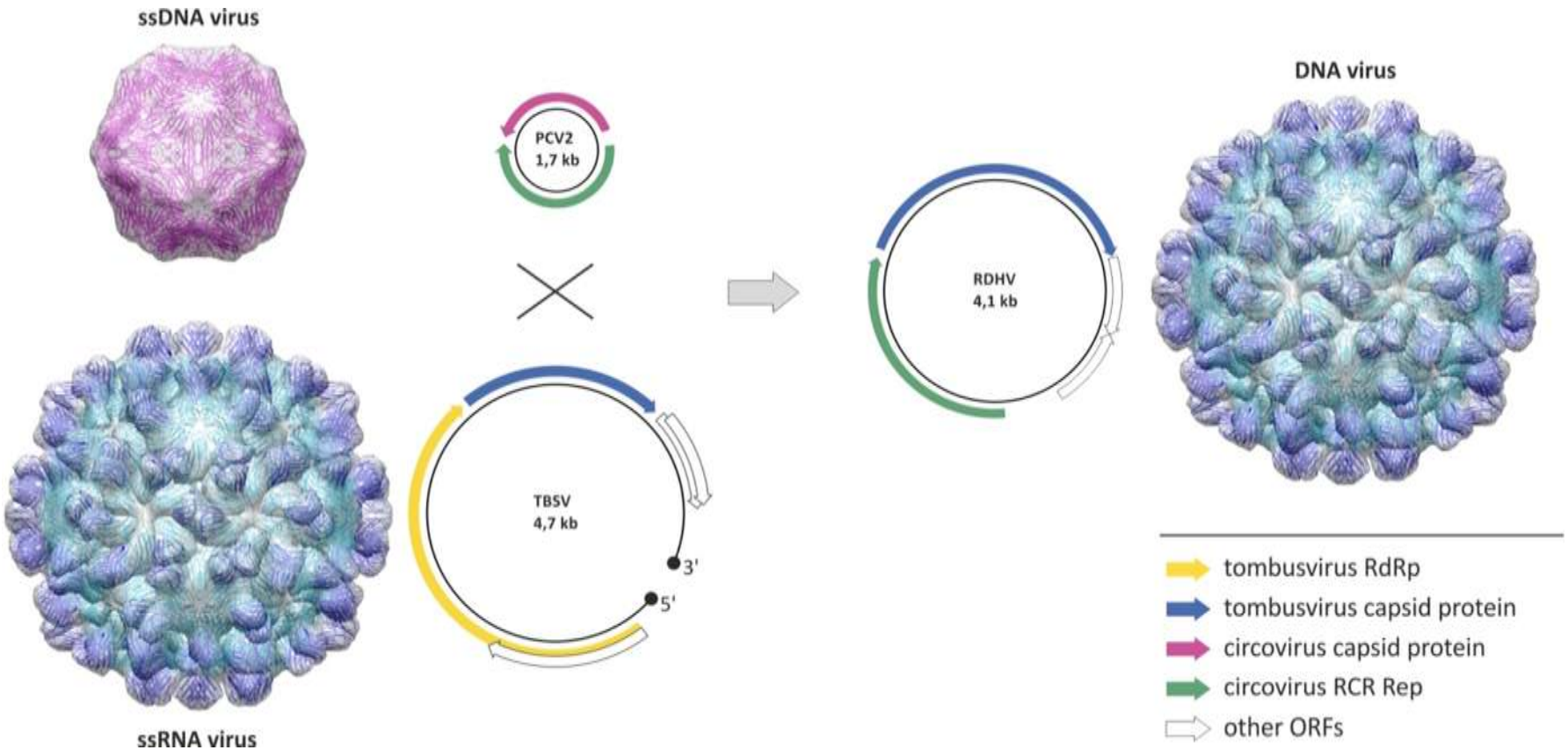
Diemer, Stedman, *Biol Direct* 2012

Chimeric viruses: RNA-DNA hybrid virus (RDHV)



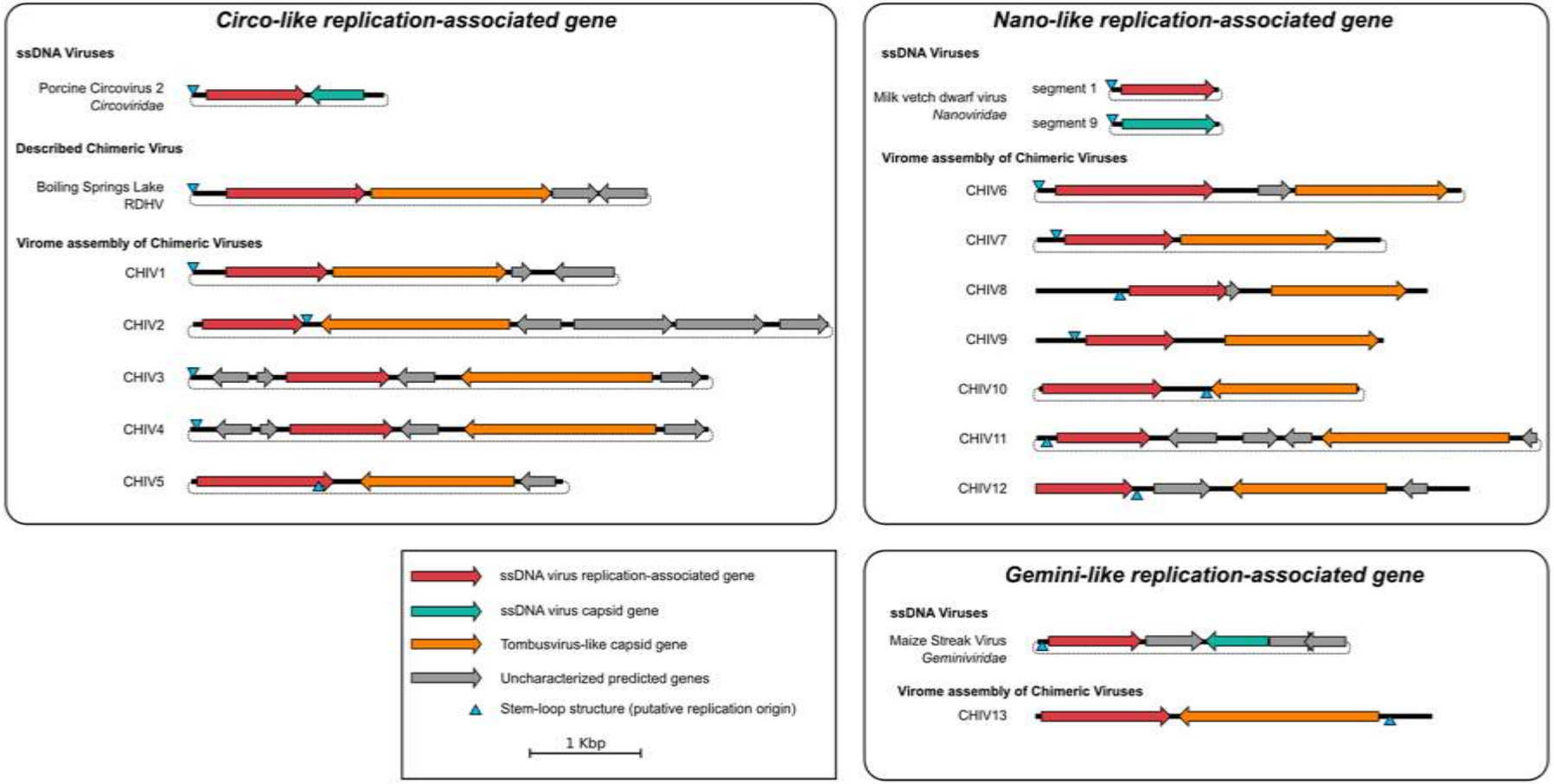
Diemer, Stedman, *Biol Direct* 2012

Recombination between RNA and DNA viruses



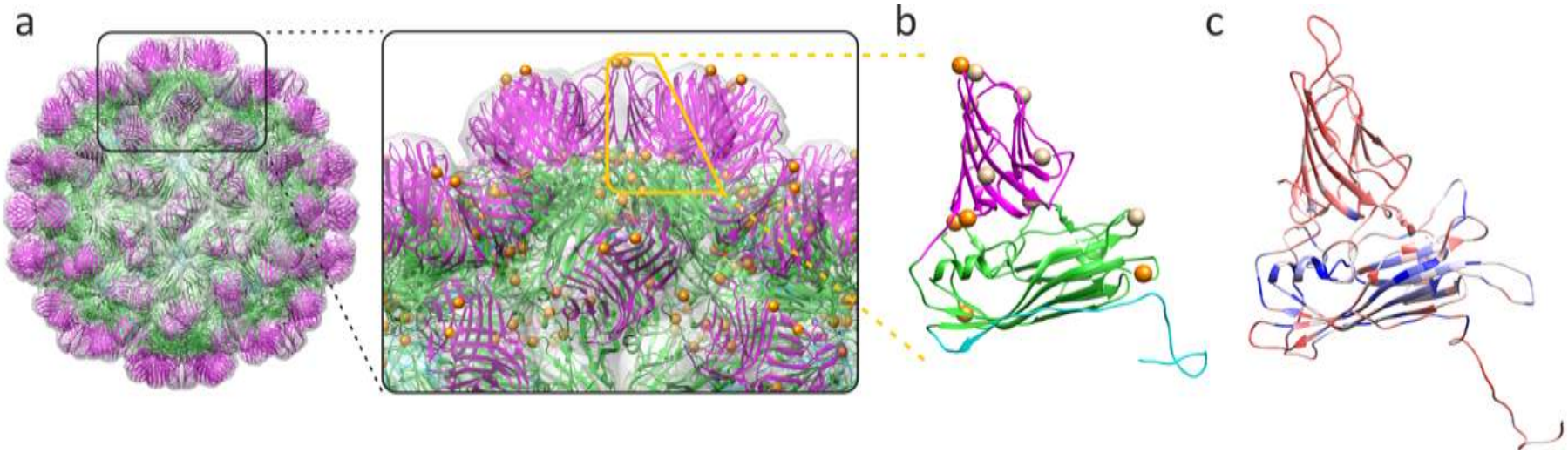
Krupovic, *BioEssays* 2012

Chimeric viruses display various genome organizations



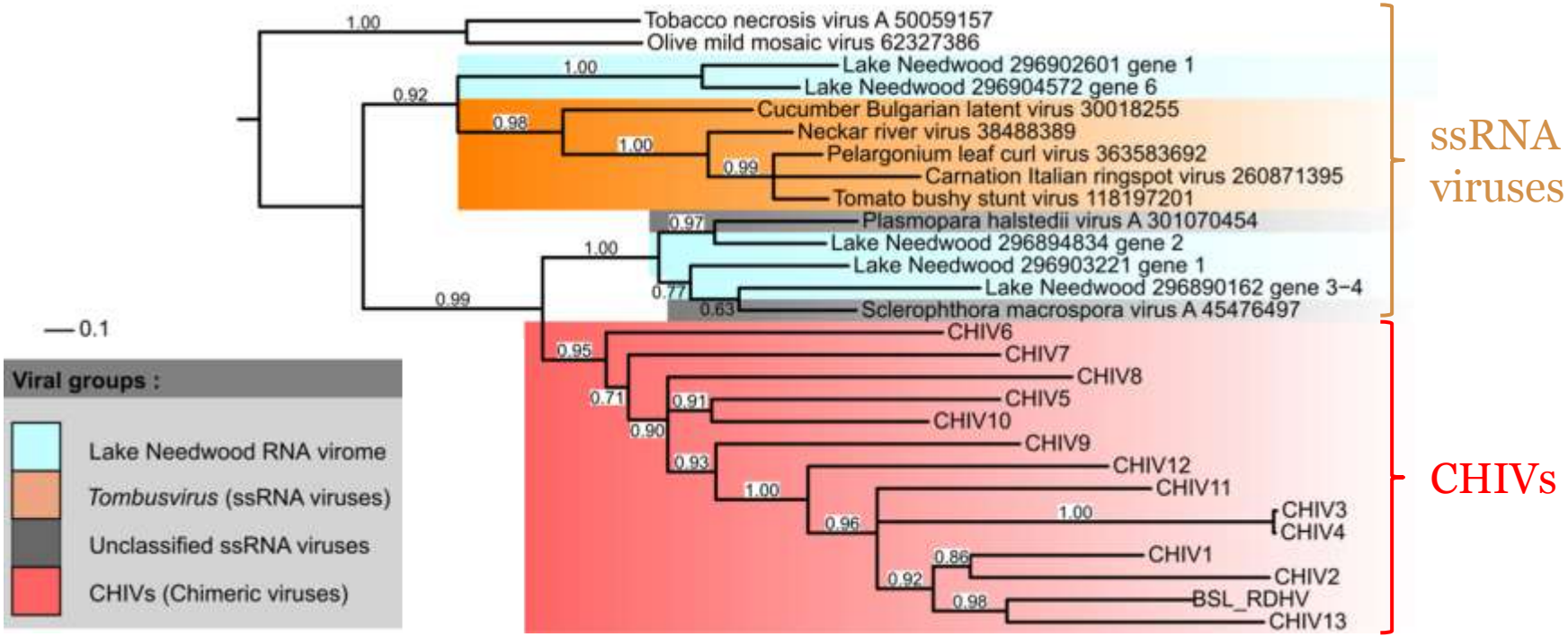
Roux, Enault, Bronner, Vaulot, Forterre, Krupovic, *Nature Commun* 2013

All chimeric viruses encode tombusvirus-like CPs



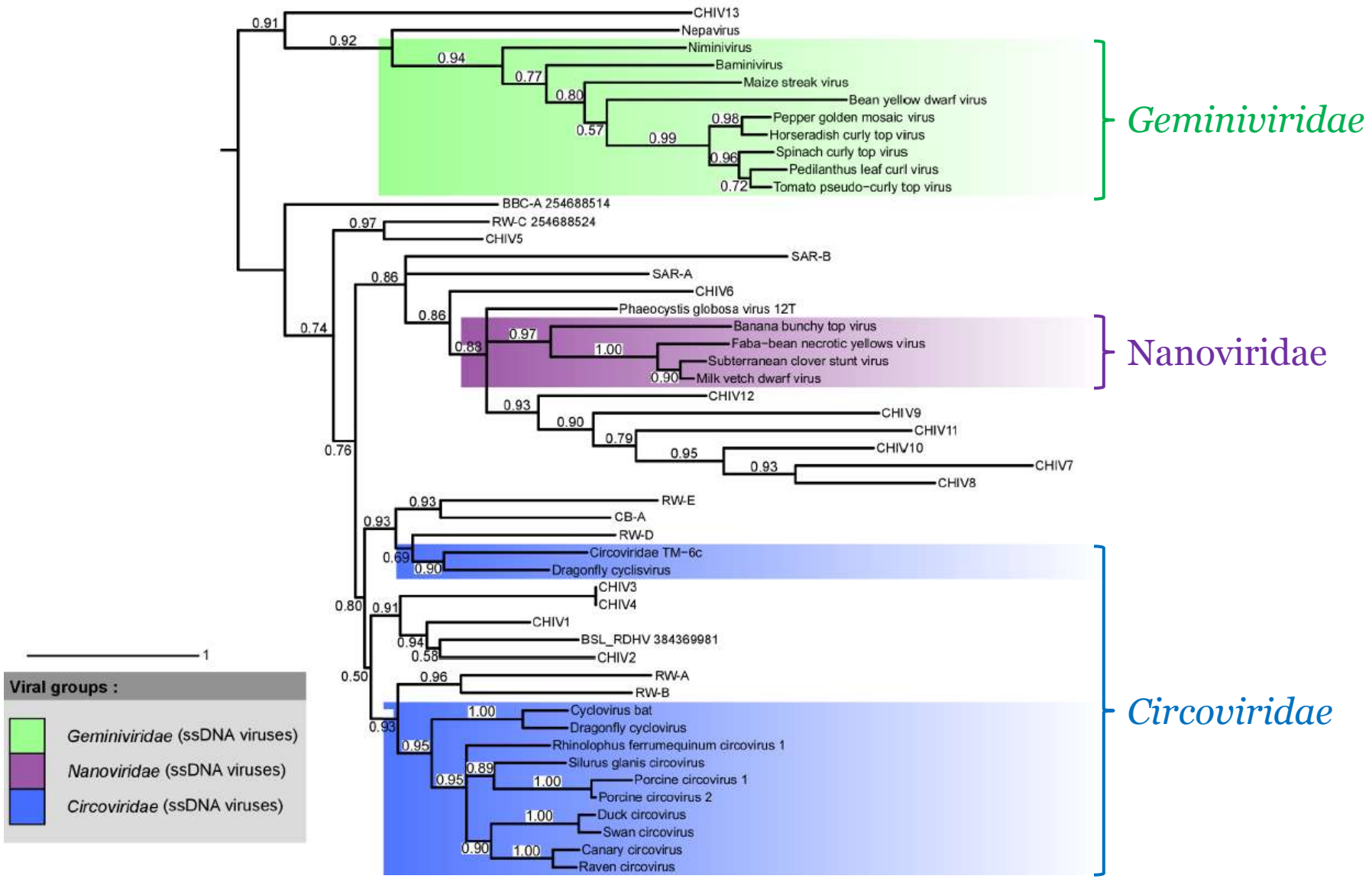
Roux, Enault, Bronner, Vaulot, Forterre, Krupovic, *Nature Commun* 2013

Unique CP gene transfer between RNA and DNA viruses



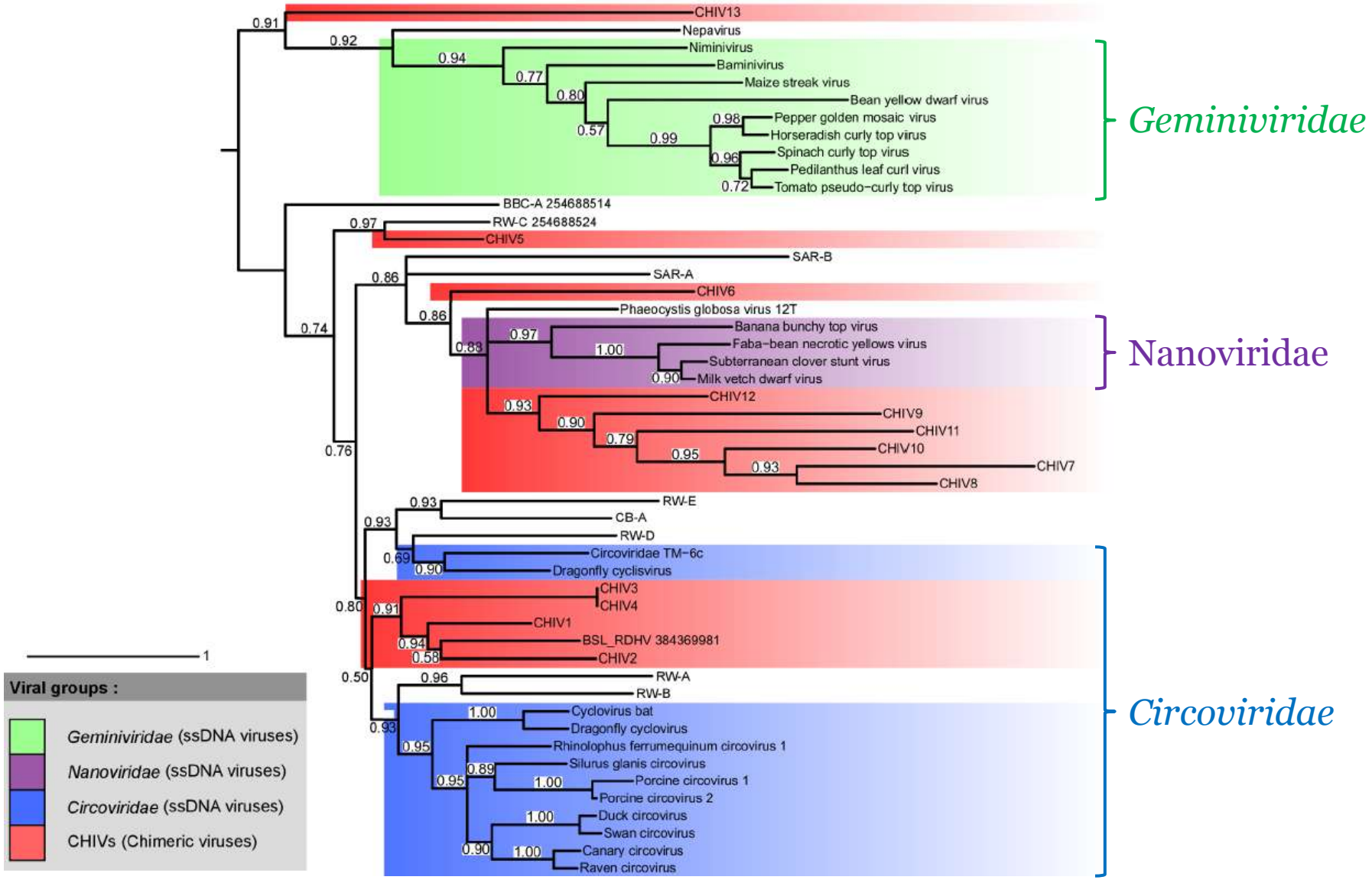
Roux, Enault, Bronner, Vaulot, Forterre, Krupovic, *Nature Commun* 2013

Multiple transfers of the RC Rep genes

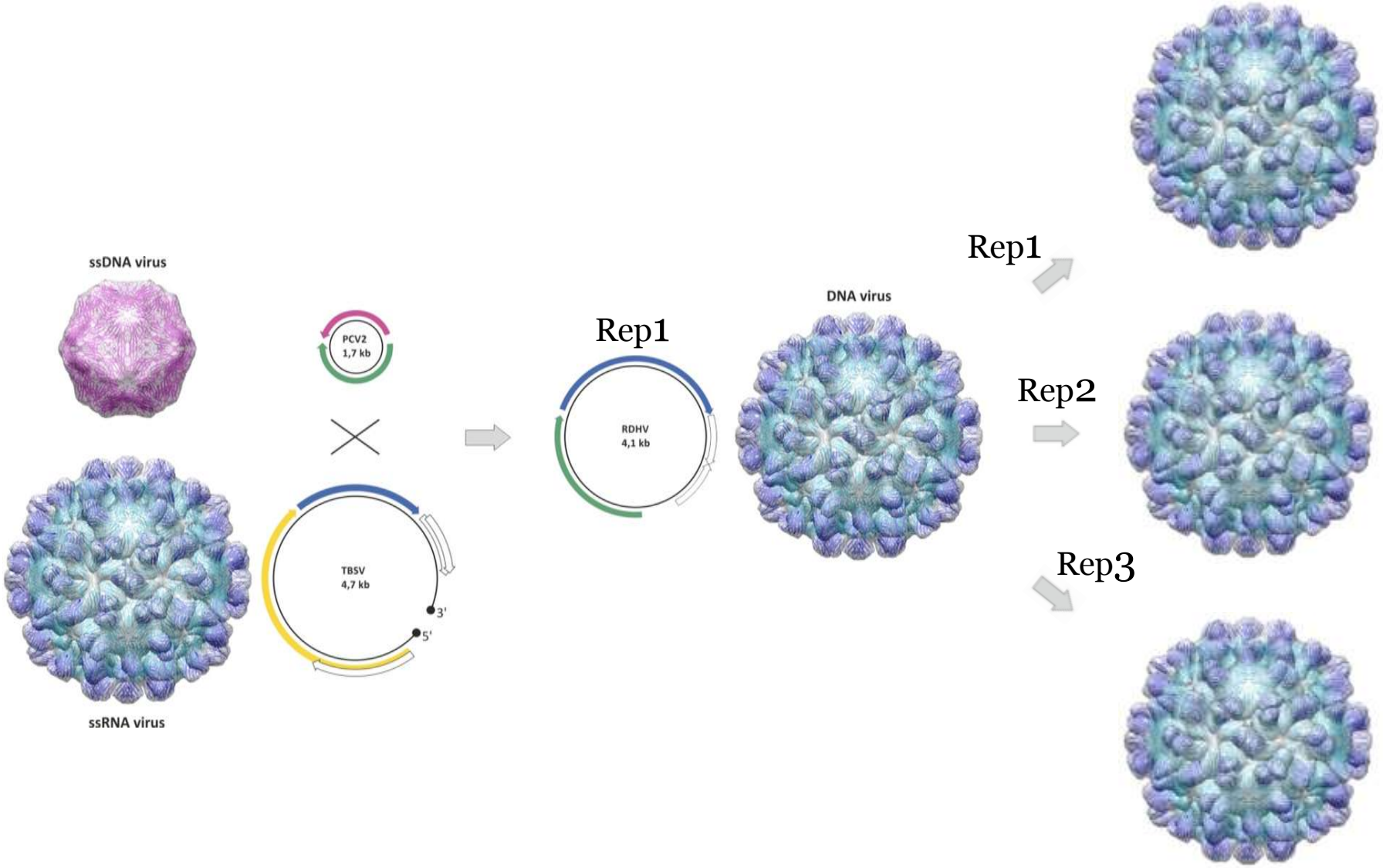


Roux, Enault, Bronner, Vaulot, Forterre, Krupovic, *Nature Commun* 2013

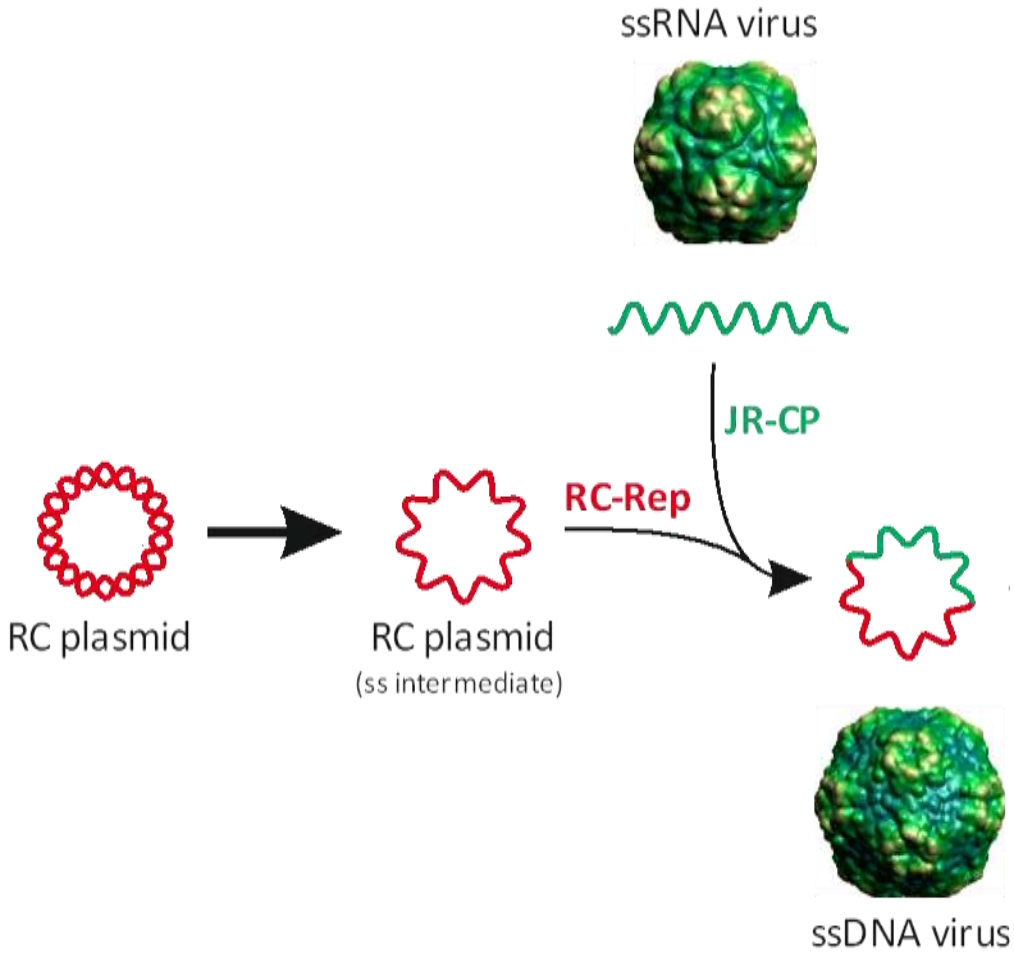
Multiple transfers of the RC Rep genes



Roux, Enault, Bronner, Vaulot, Forterre, Krupovic, *Nature Commun* 2013

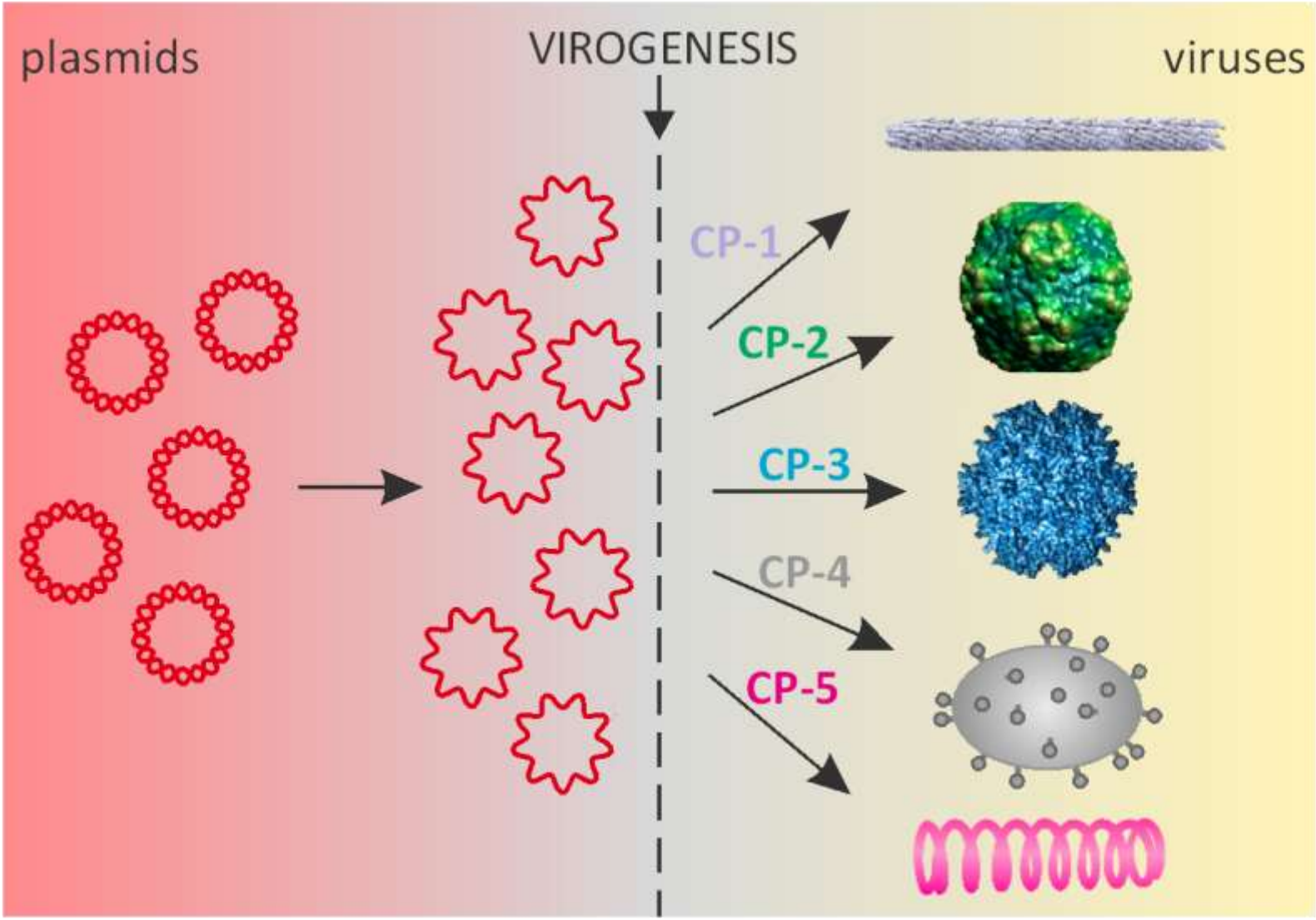

ssDNA virus
PCV2
1,7 kb
TBSV
4,7 kb
3'
5'
ssRNA virus
Rep1
RDHV
4,1 kb
DNA virus
Rep1
Rep2
Rep3

Evolutionary continuum between ssRNA and ssDNA viruses



Krupovic, *Curr Opin Virol* 2013

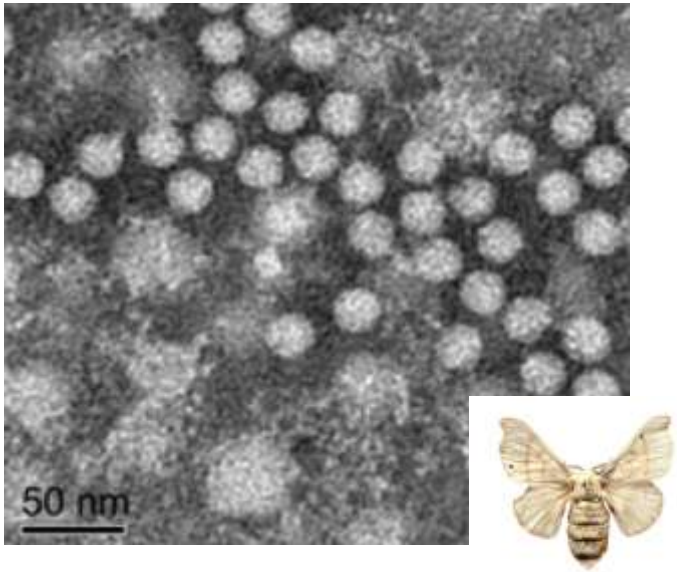
Polyphyletic origin of ssDNA viruses



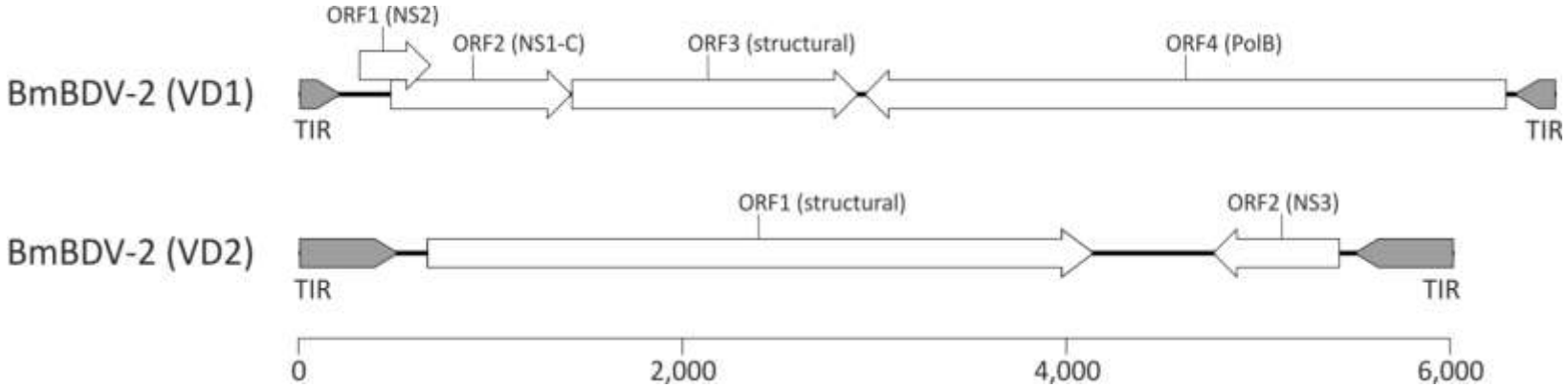
Krupovic, *Curr Opin Virol* 2013

Extreme genetic mosaicism in the Bidnaviridae

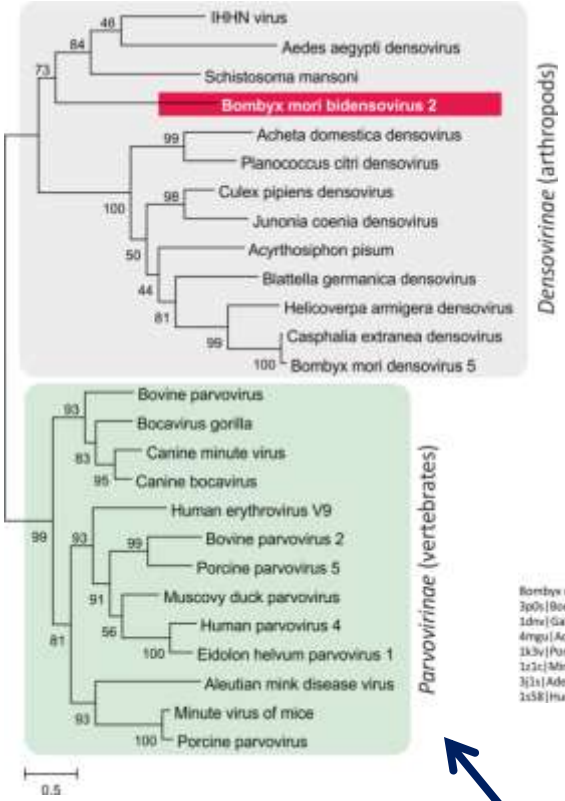
Bidnaviridae

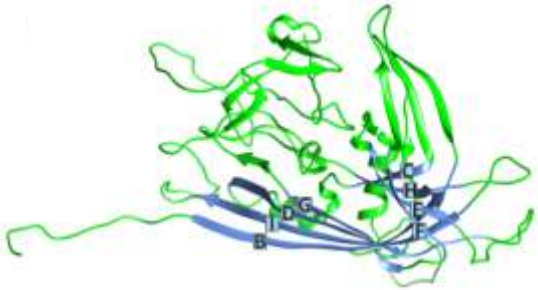


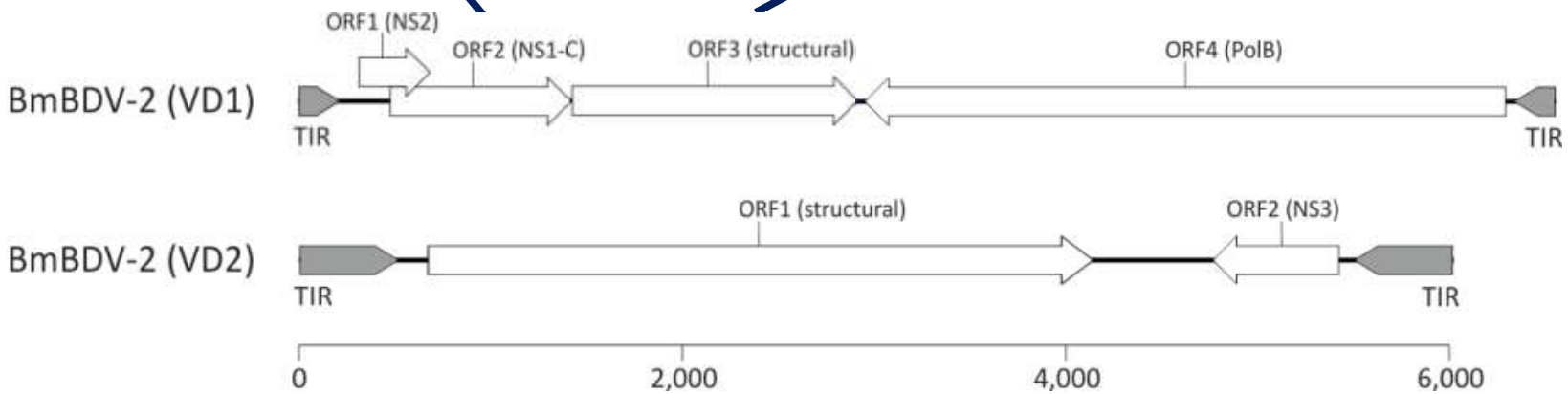
- Infect silkworm (*Bombyx mori*);
- Bipartite, linear ssDNA genome;
- Virions are spherical, non-enveloped;
- TIRs do not form typical T-shaped structures;
- Encode protein-primed PolB.



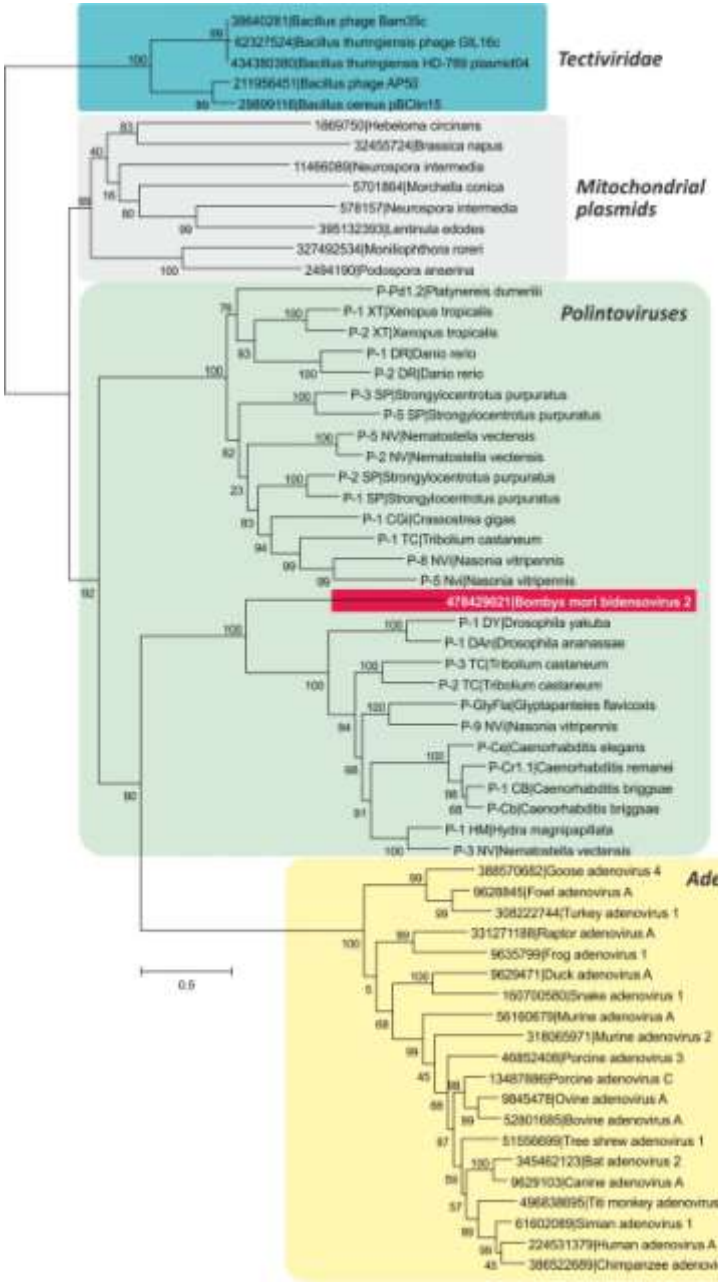
Hu, Li, Li, Yao, Chen, *Chin Sci Bull* 2013

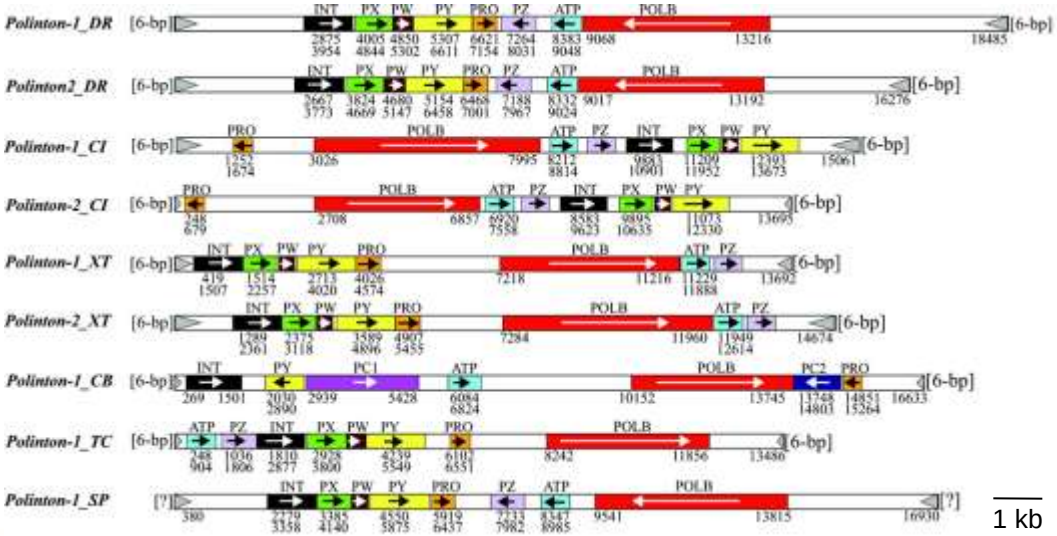






Krupovic and Koonin, *Sci Rep* 2014





Kapitonov and Jurka, *Proc Natl Acad Sci U S A* 2006

Krupovic and Koonin, *Sci Rep* 2014

Krupovic *et al. Biology Direct* 2014, **9**:6
http://www.biologydirect.com/content/9/1/6

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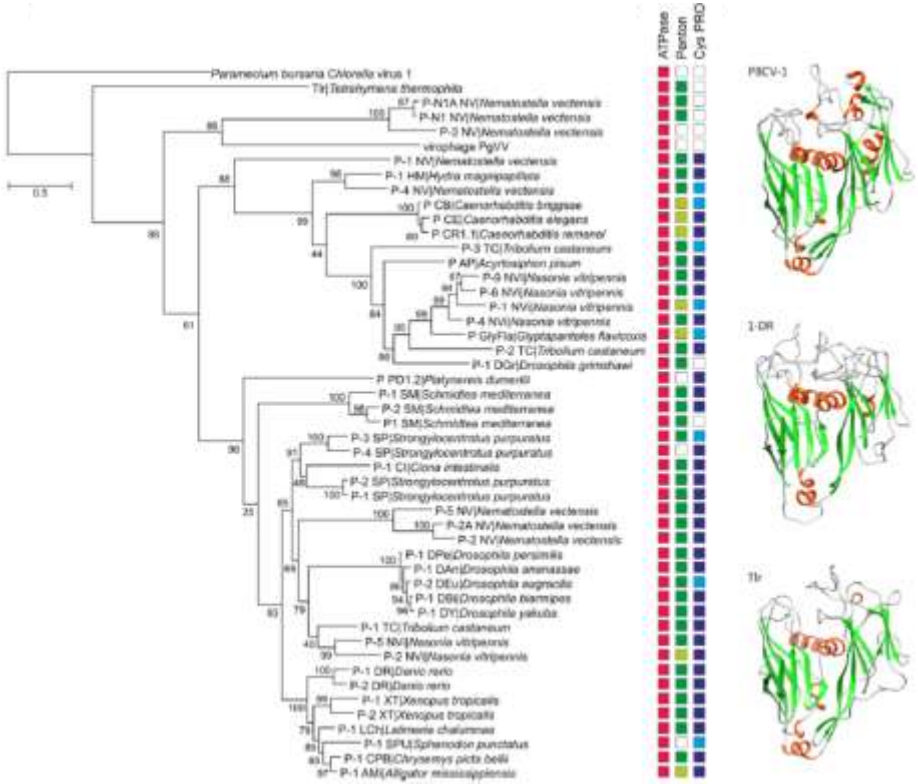
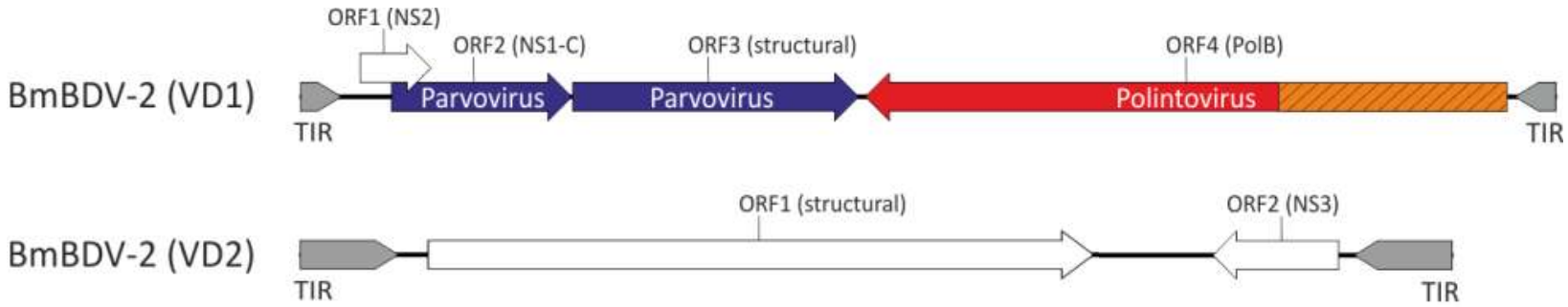
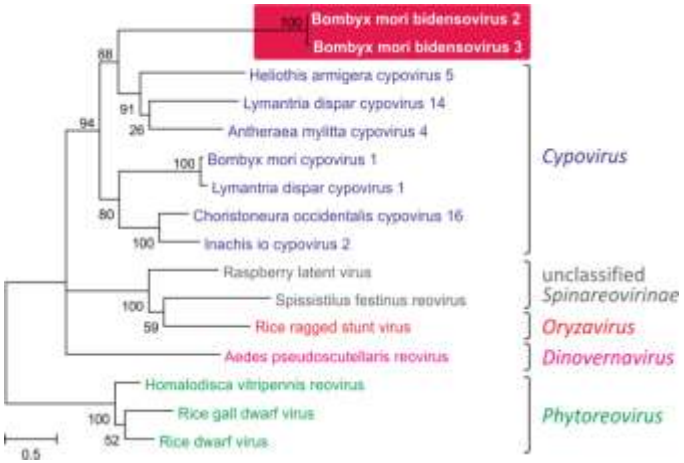
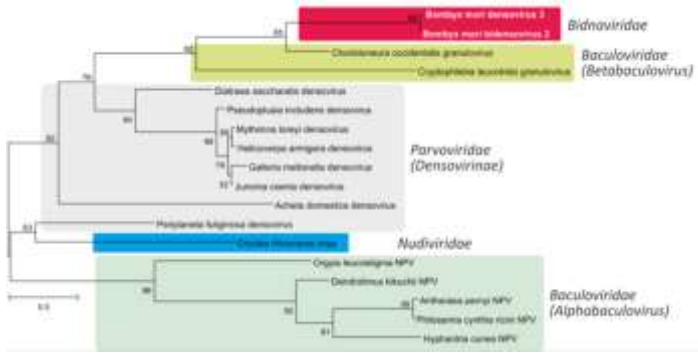
Conservation of major and minor jelly-roll capsid proteins in Polinton (Maverick) transposons suggests that they are bona fide viruses

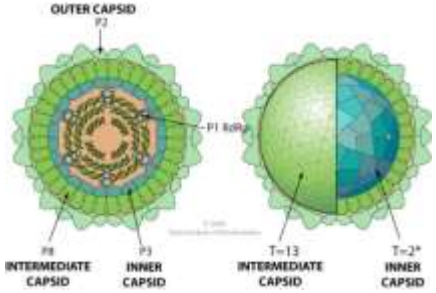
Mart Krupovic[1*], Dennis H Bamford[2] and Eugene V Koonin[3*]

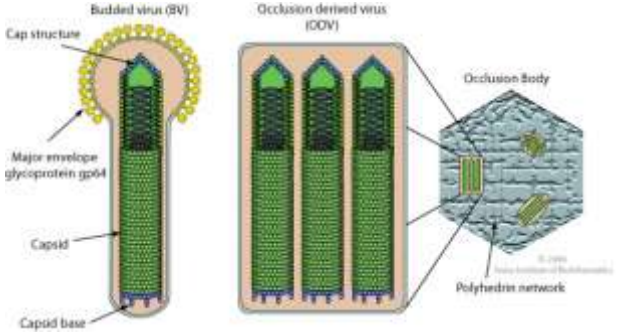




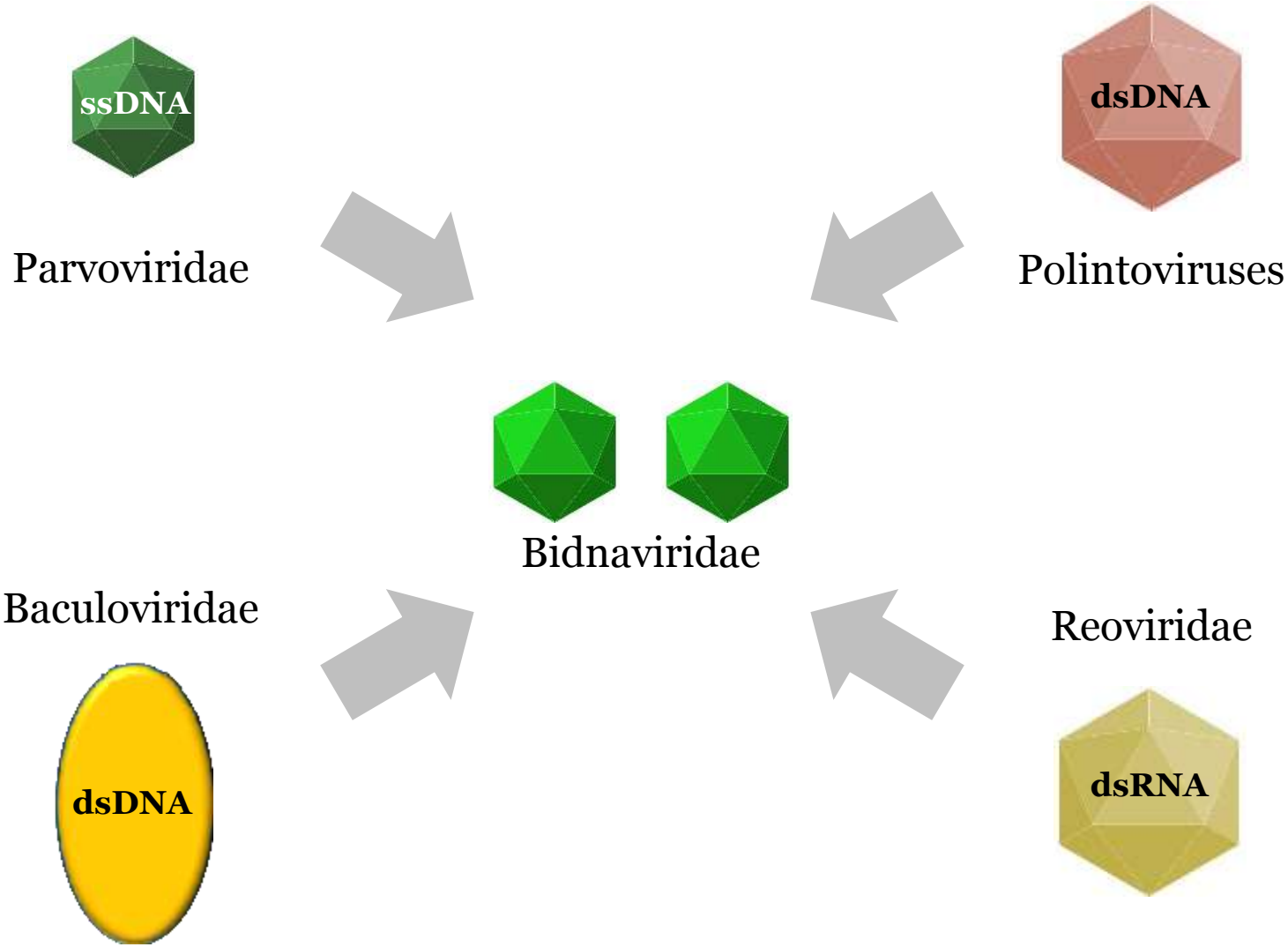


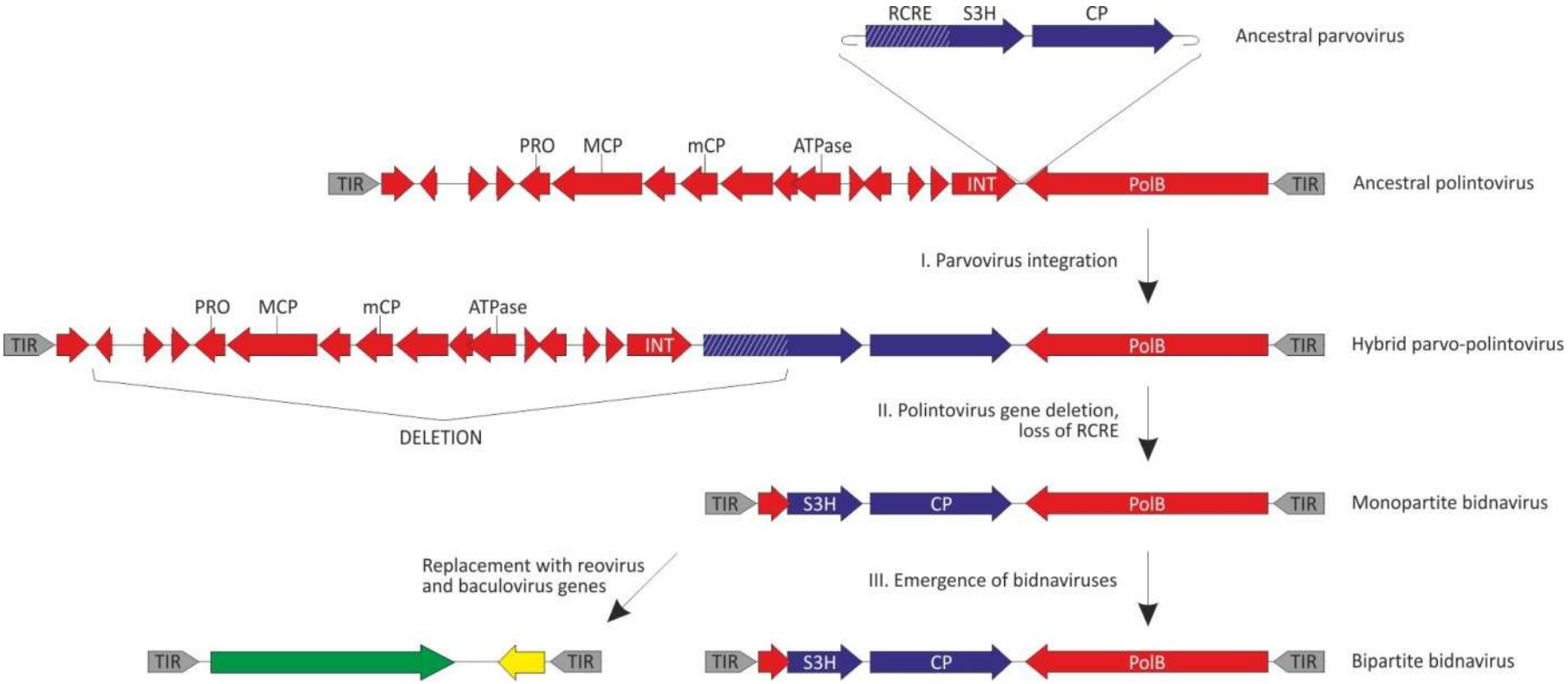






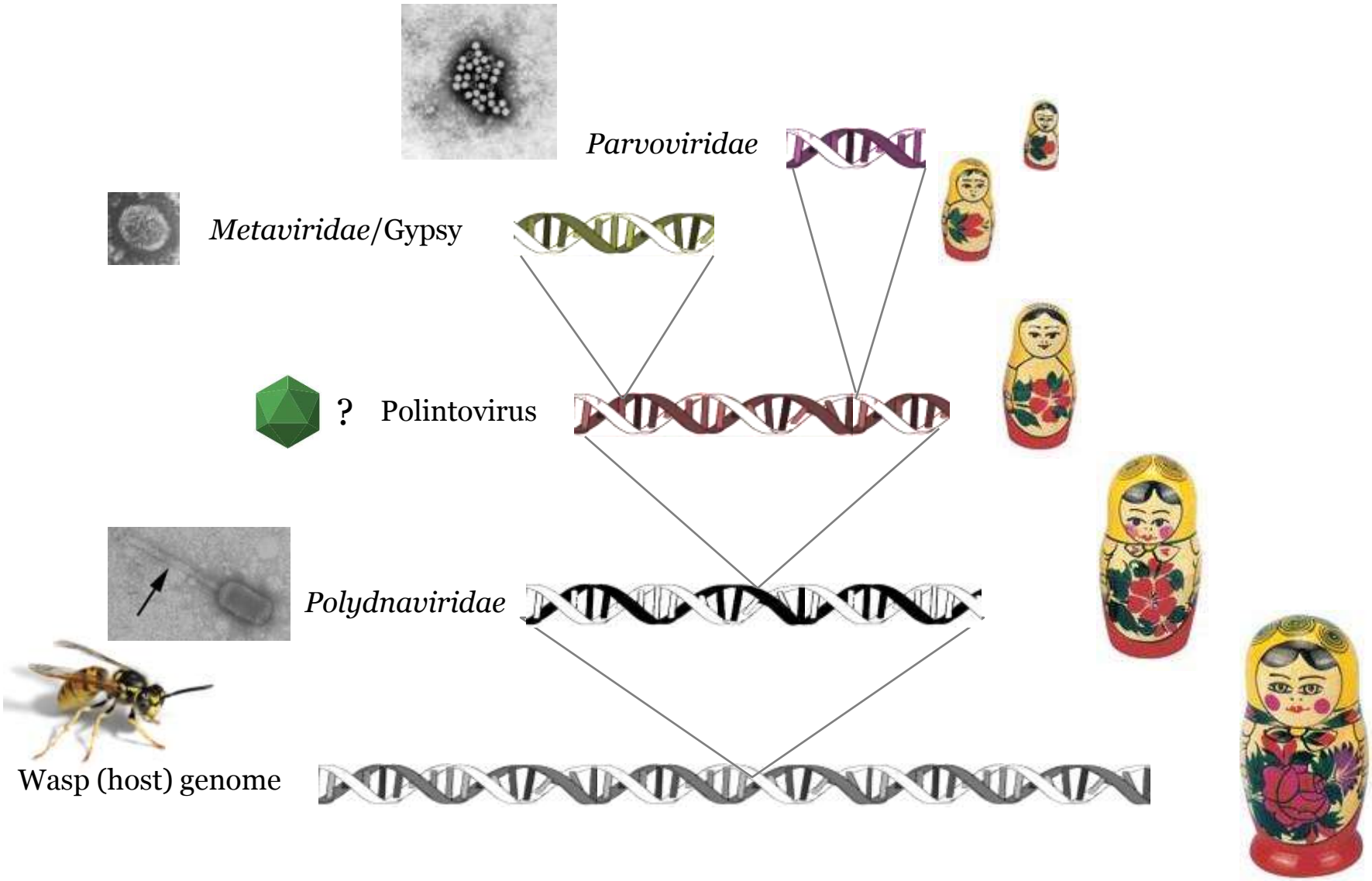
Krupovic and Koonin, *Sci Rep* 2014


ssDNA
Parvoviridae
dsDNA
Polintoviruses
Bidnaviridae
Baculoviridae
dsDNA
Reoviridae
dsRNA

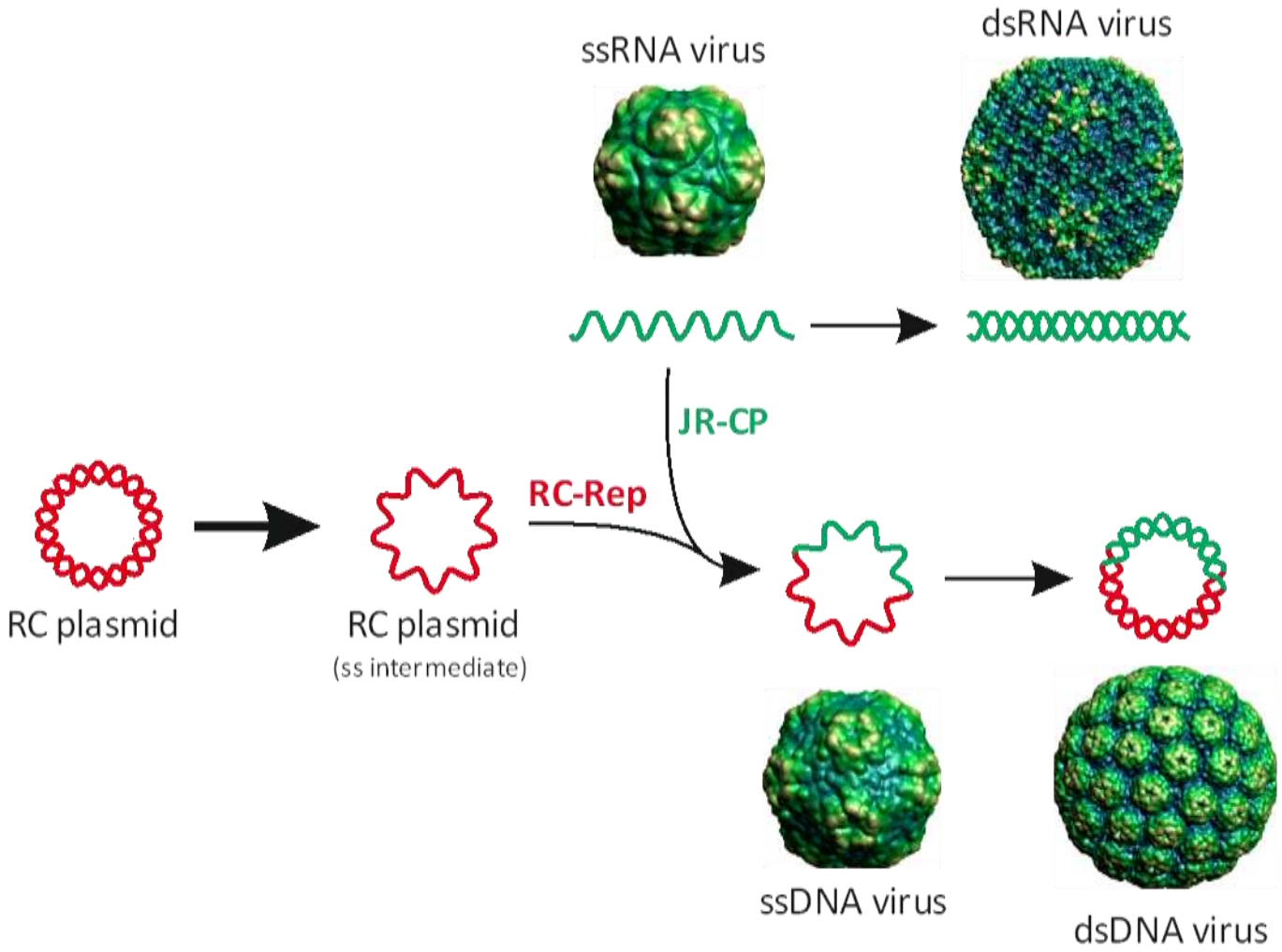


Krupovic and Koonin, *Sci Rep* 2014

Viral 'Russian doll'



Evolutionary continuum between small RNA and DNA viruses



Krupovic, *Curr Opin Virol* 2013

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