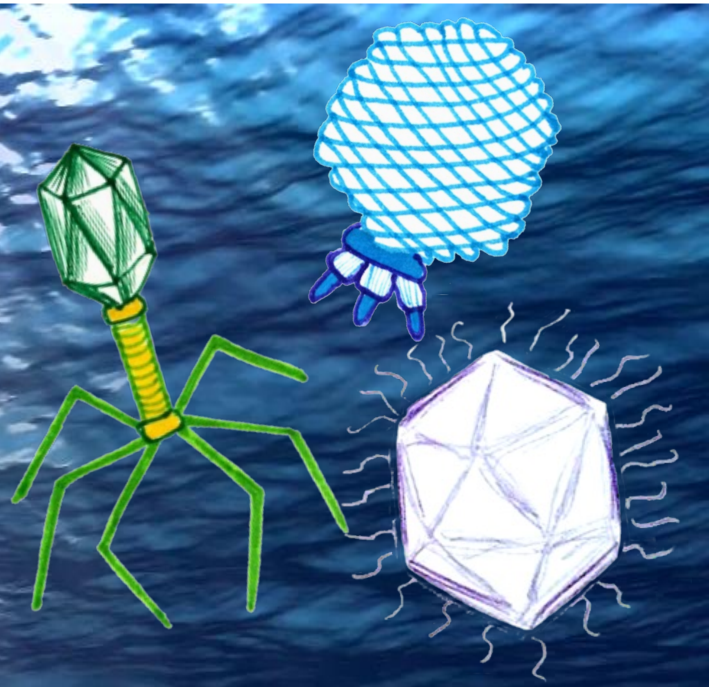
TARA
OCEANS



Tara Oceans and virus ecogenomics

Matthew B. Sullivan
Ohio State University
Professor of Microbiology and Civil, Environmental and Geodetic Engineering
Co-director OSU Infectious Disease Institute Microbial Communities Program
Founding Director OSU Center of Microbiome Science
NSF EMERGE Biology Integration Institute Executive Committee

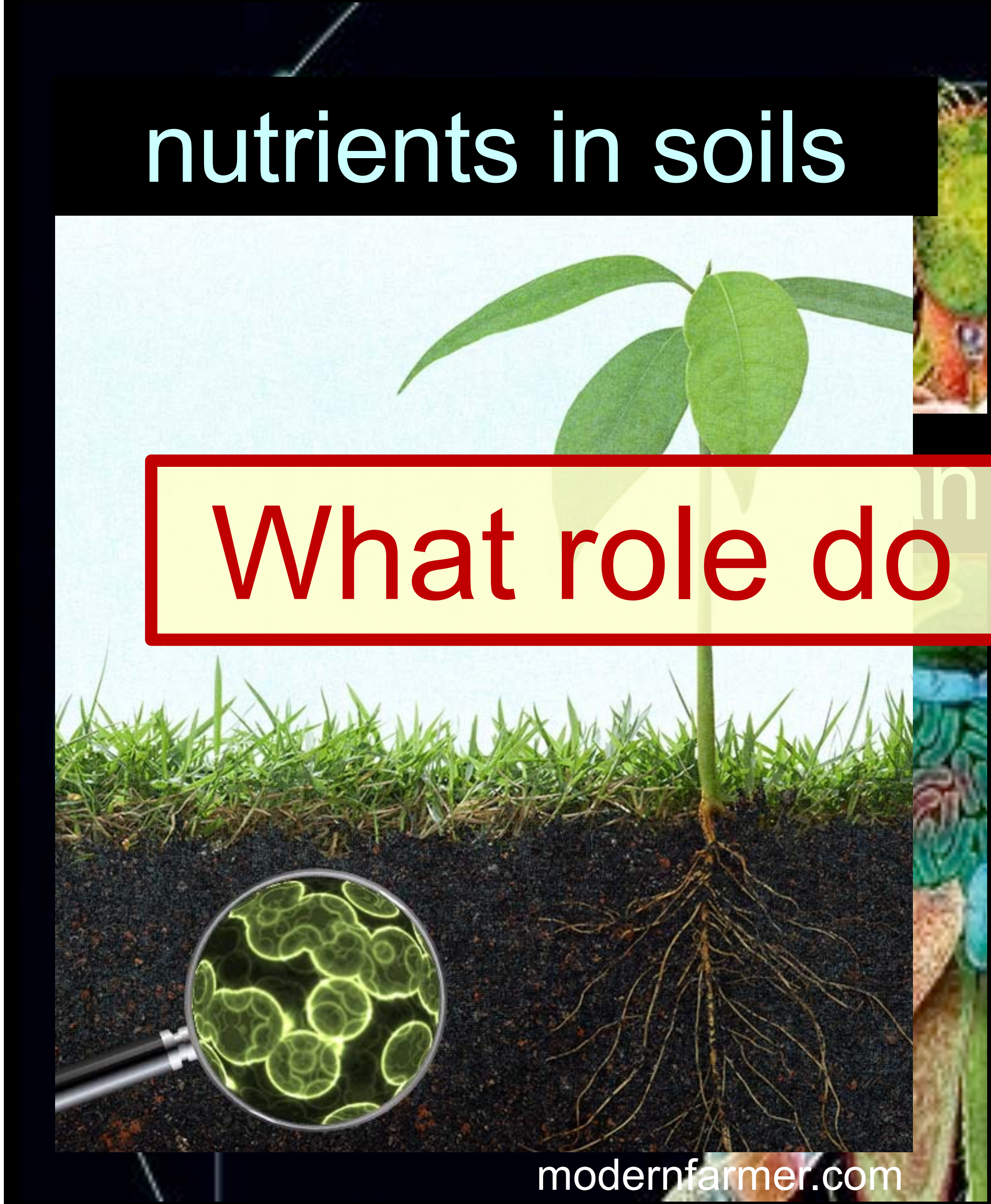
Where are we going?

Why and how do we study viruses of microbes?

Oceans – patterns, processes and paradigms

Microbes for …

nutrients in soils



modernfarmer.com

oxygen
(half of that in air is from *marine* microbes)

What role do viruses play?

Viruses impact microbes, in the oceans …

<1%

(can be cultured)

1/3

(cells killed per day)

50 *million* viruses in a mouthful of seawater

10^{29}

(genes moved per day)

Toxins

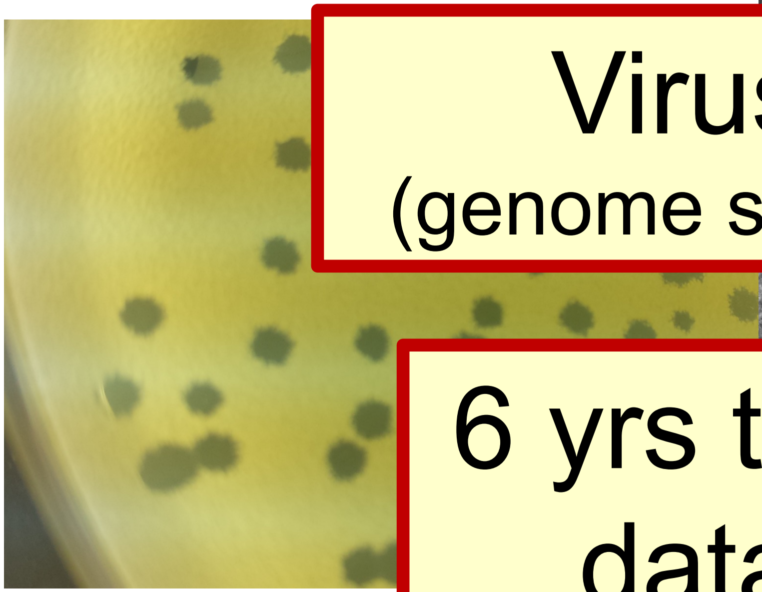
Ecosystem impacts ?

How can we study viruses?

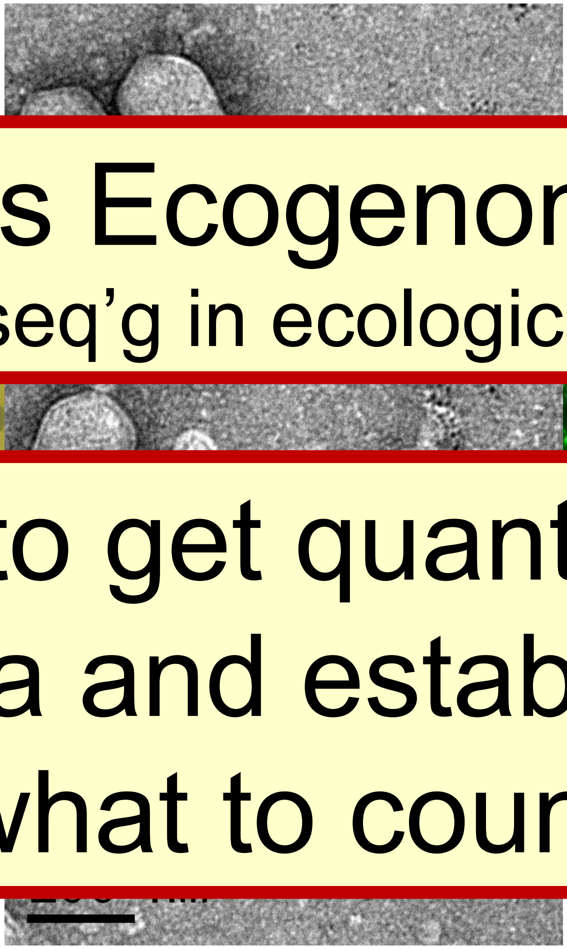
REQUIRES A CULTIVATED HOST

SHAPE, BUT NO HOST OR BIOLOGY

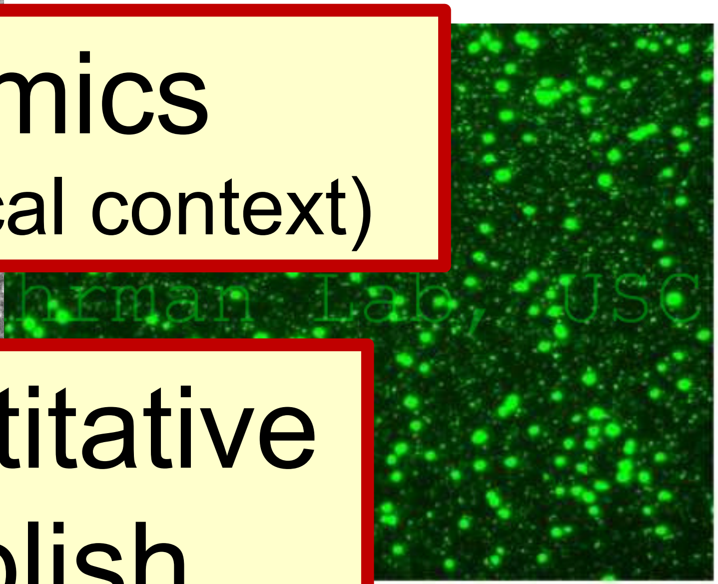
NUMBERS, BUT NO HOST OR BIOLOGY



Plaque



Electron microscopy



escence
scopy

Virus Ecogenomics
(genome seq’g in ecological context)

6 yrs to get quantitative data and establish what to count

Viruses in the global oceans

Patterns, Processes, Paradigms

Viruses in the global oceans

Patterns, Processes, Paradigms

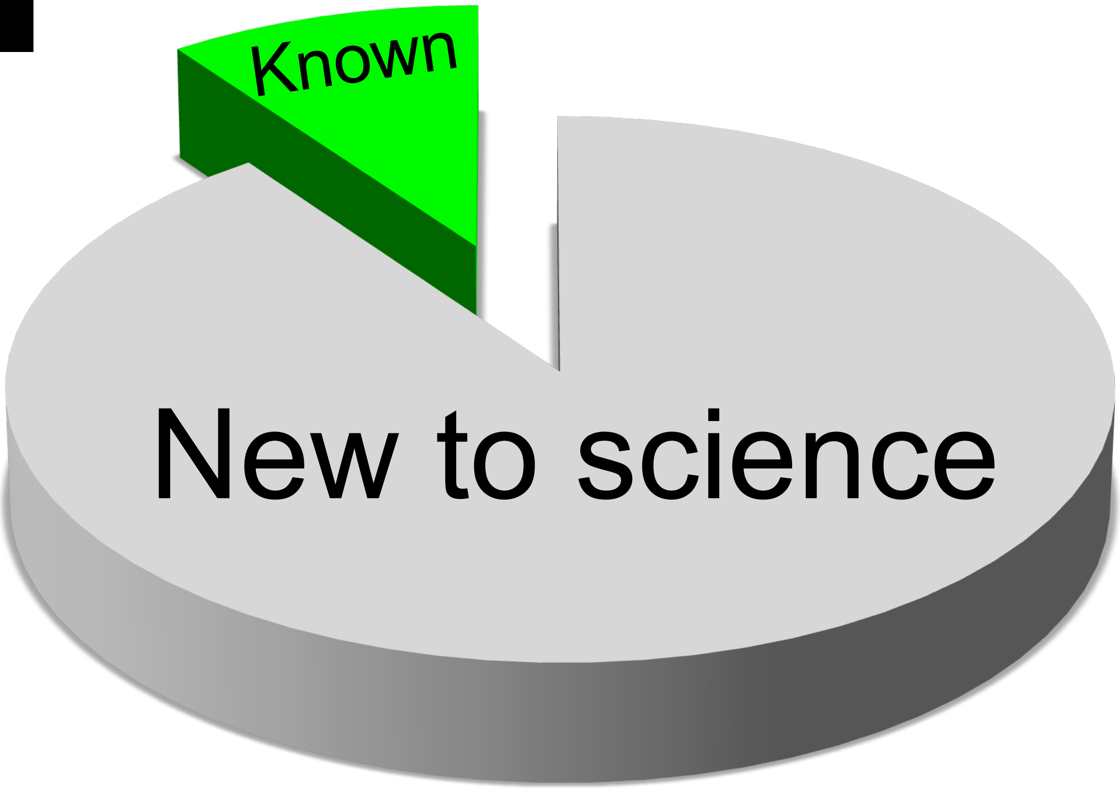
Tara Oceans:
A 30+ PI international consortium

The *Tara*:
Our research vessel

B

nic
ms

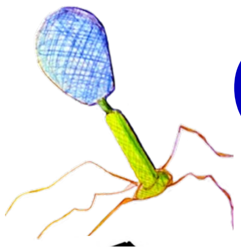
Most (90%) of what we observe is *unknown*

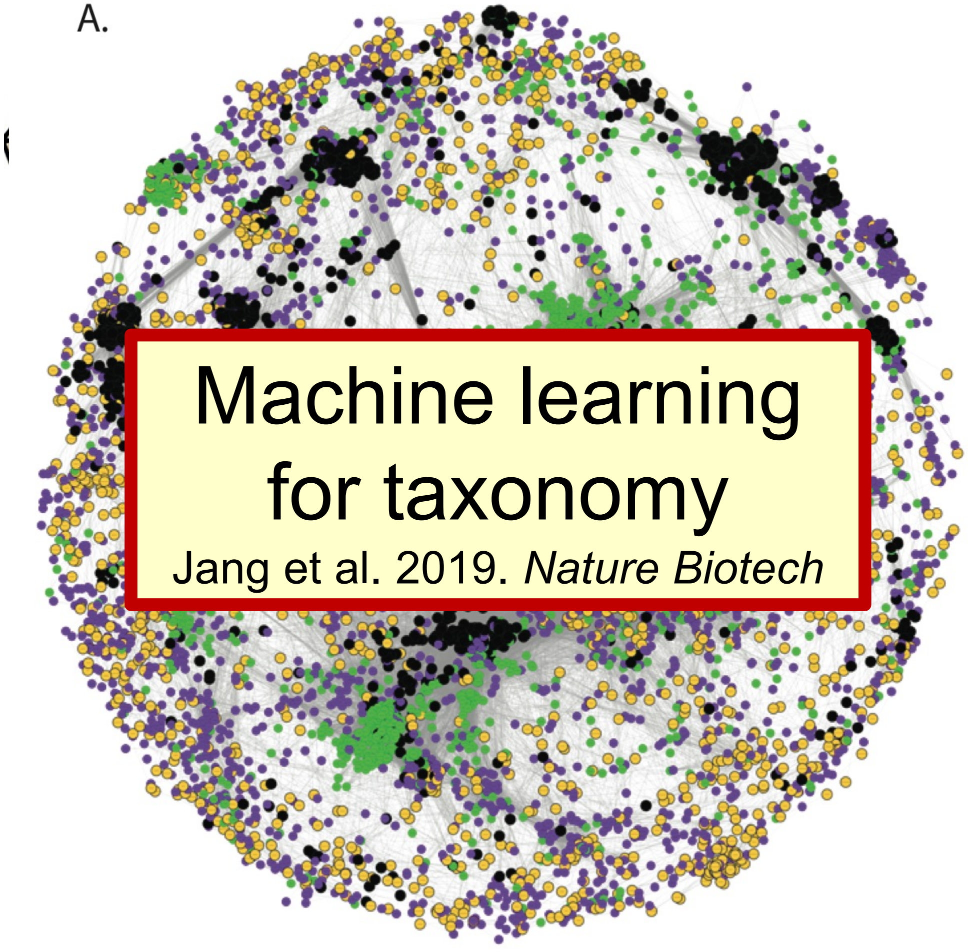


Brum, Ignacio-Espinoza, Roux et al. 2015*. Science.* 348: 1261498

Cataloging viruses – globally

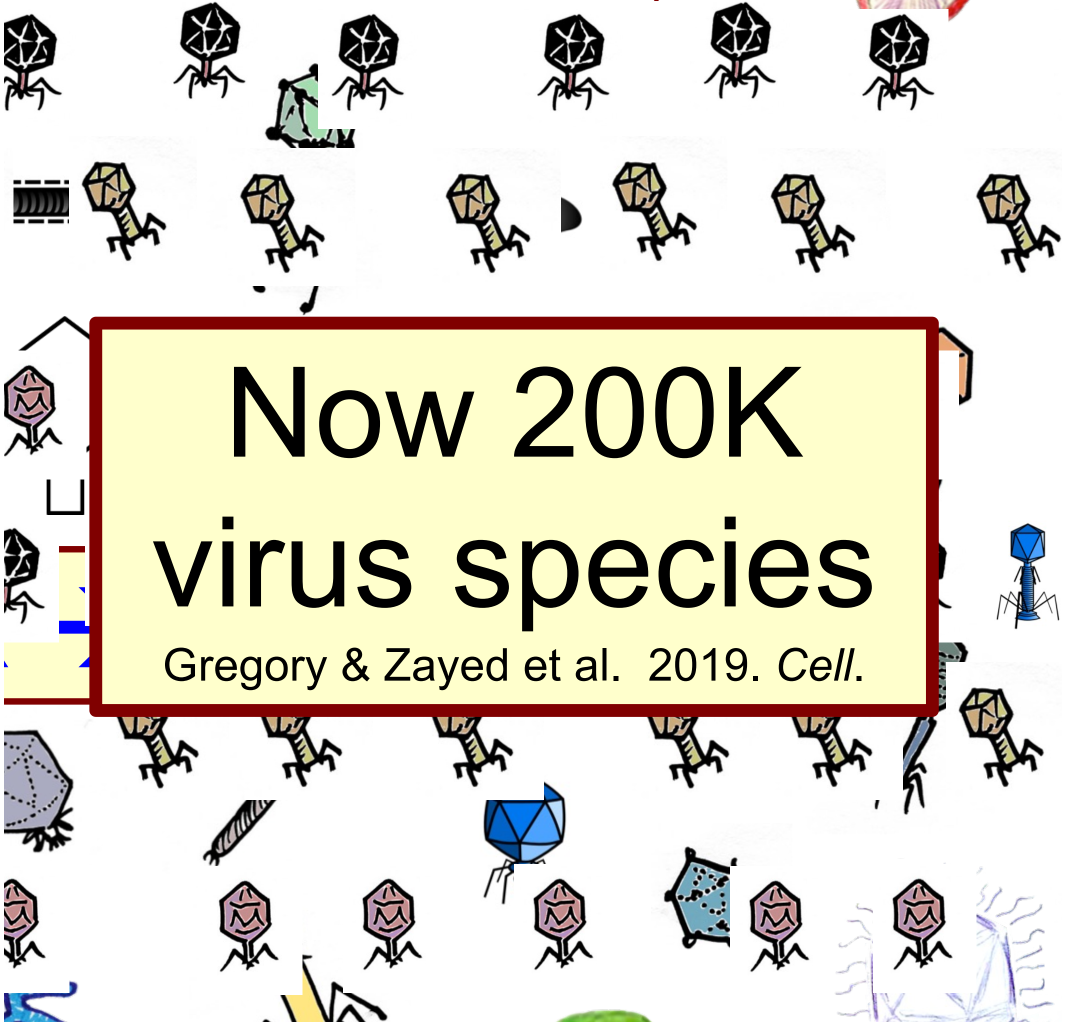
(1 picture ~ 1000 known viruses of microbes)





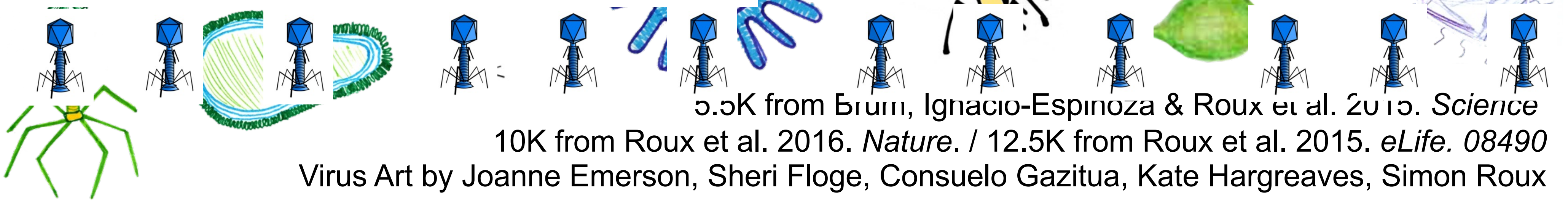
Machine learning for taxonomy

Jang et al. 2019. *Nature Biotech*



Now 200K virus species

Gregory & Zayed et al. 2019. *Cell*.

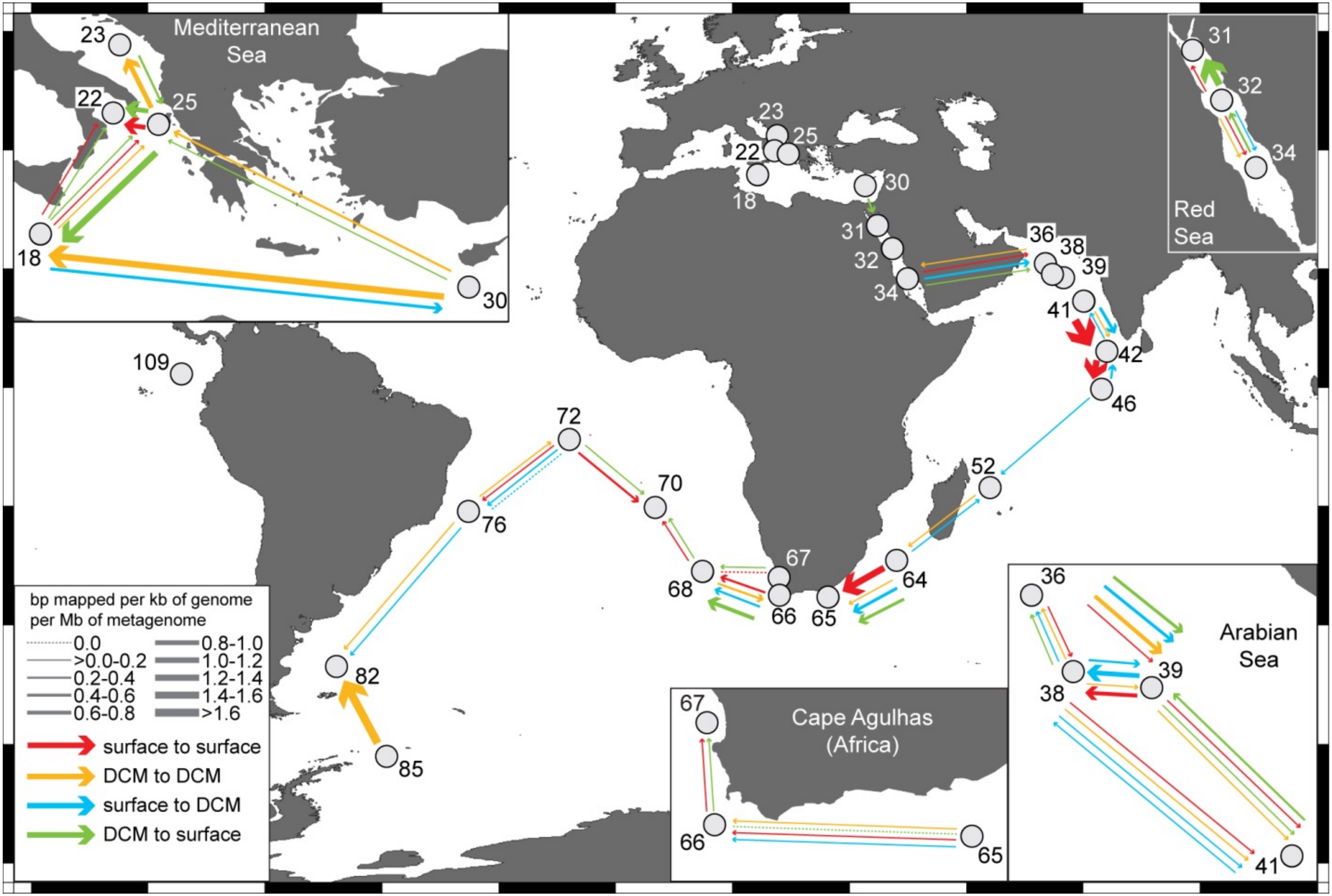


5.5K from Brum, Ignacio-Espinoza & Roux et al. 2015. *Science*

10K from Roux et al. 2016. *Nature*. / 12.5K from Roux et al. 2015. *eLife. 08490*

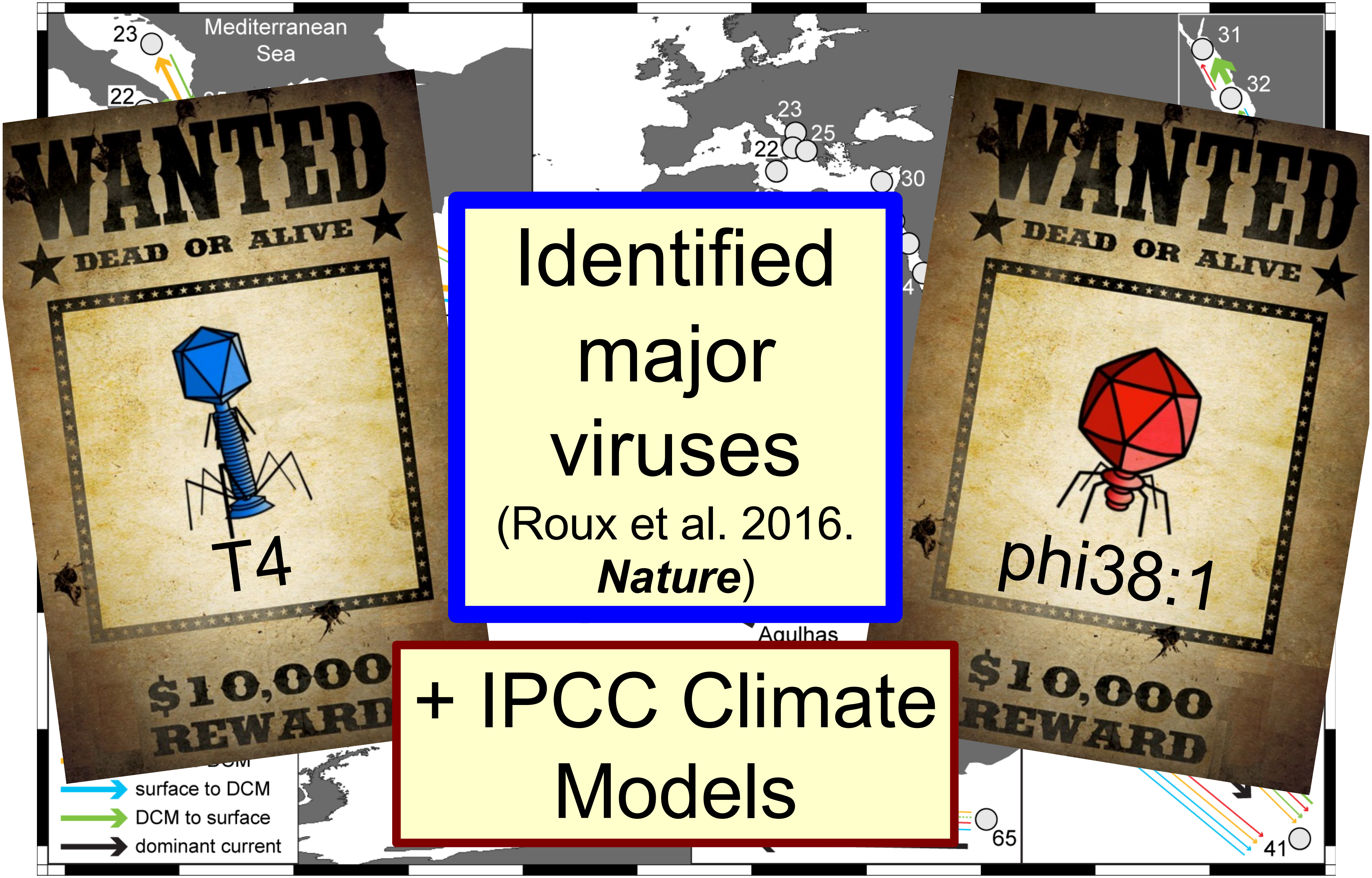
Virus Art by Joanne Emerson, Sheri Floge, Consuelo Gazitua, Kate Hargreaves, Simon Roux

Patterns: Genome-enabled virus tracking



Brum, Ignacio-Espinoza, Roux et al. 2015. *Science.* 348: no. 6237 1261498

Genomic tracking: Viruses ‘ride’ ocean currents



Identified major viruses

(Roux et al. 2016. ***Nature***)

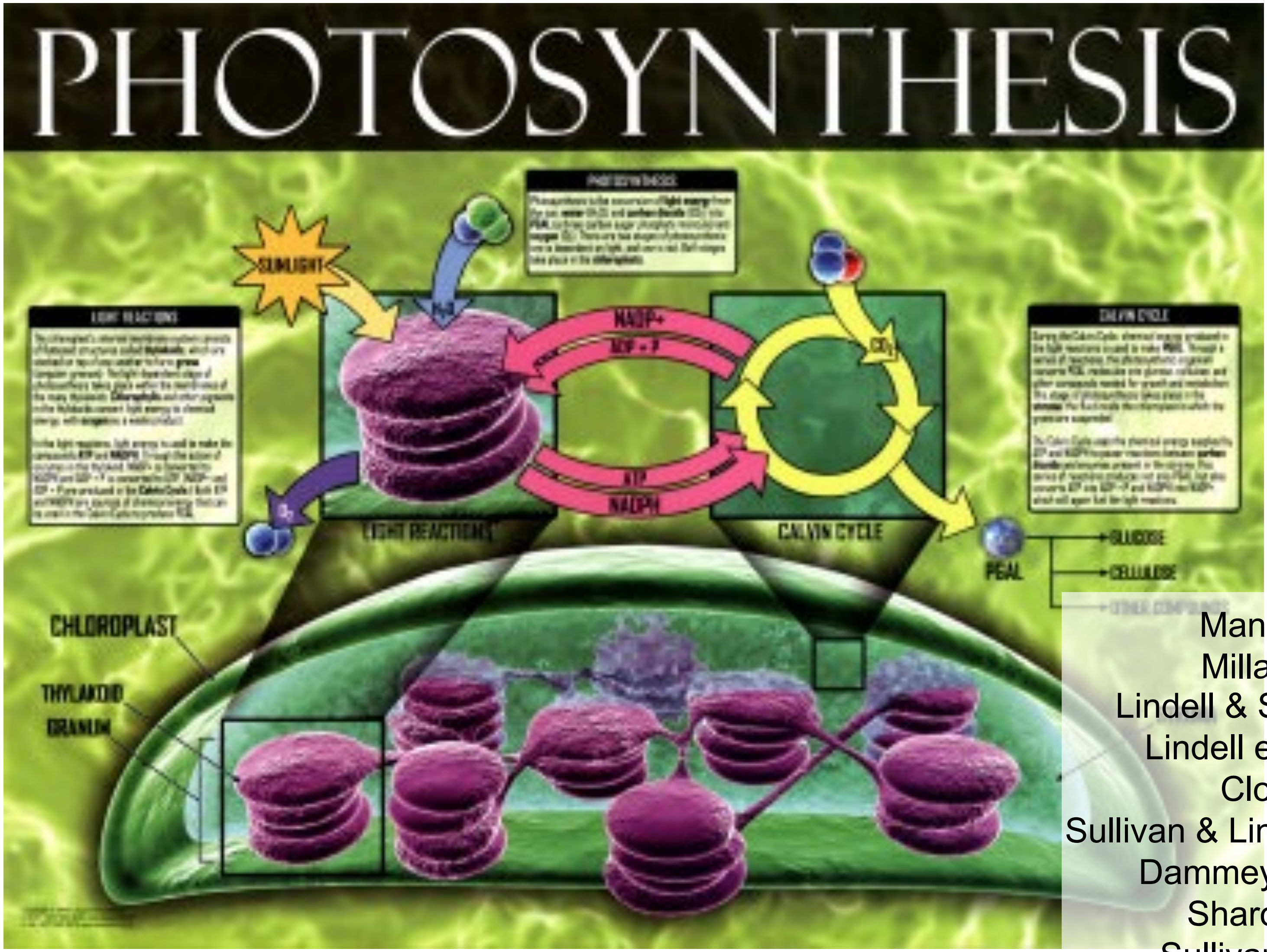
+ IPCC Climate Models

Brum, Ignacio-Espinoza, Roux et al. 2015. *Science.* 348: no. 6237 1261498

Viruses in the global oceans

Patterns, Processes, Paradigms

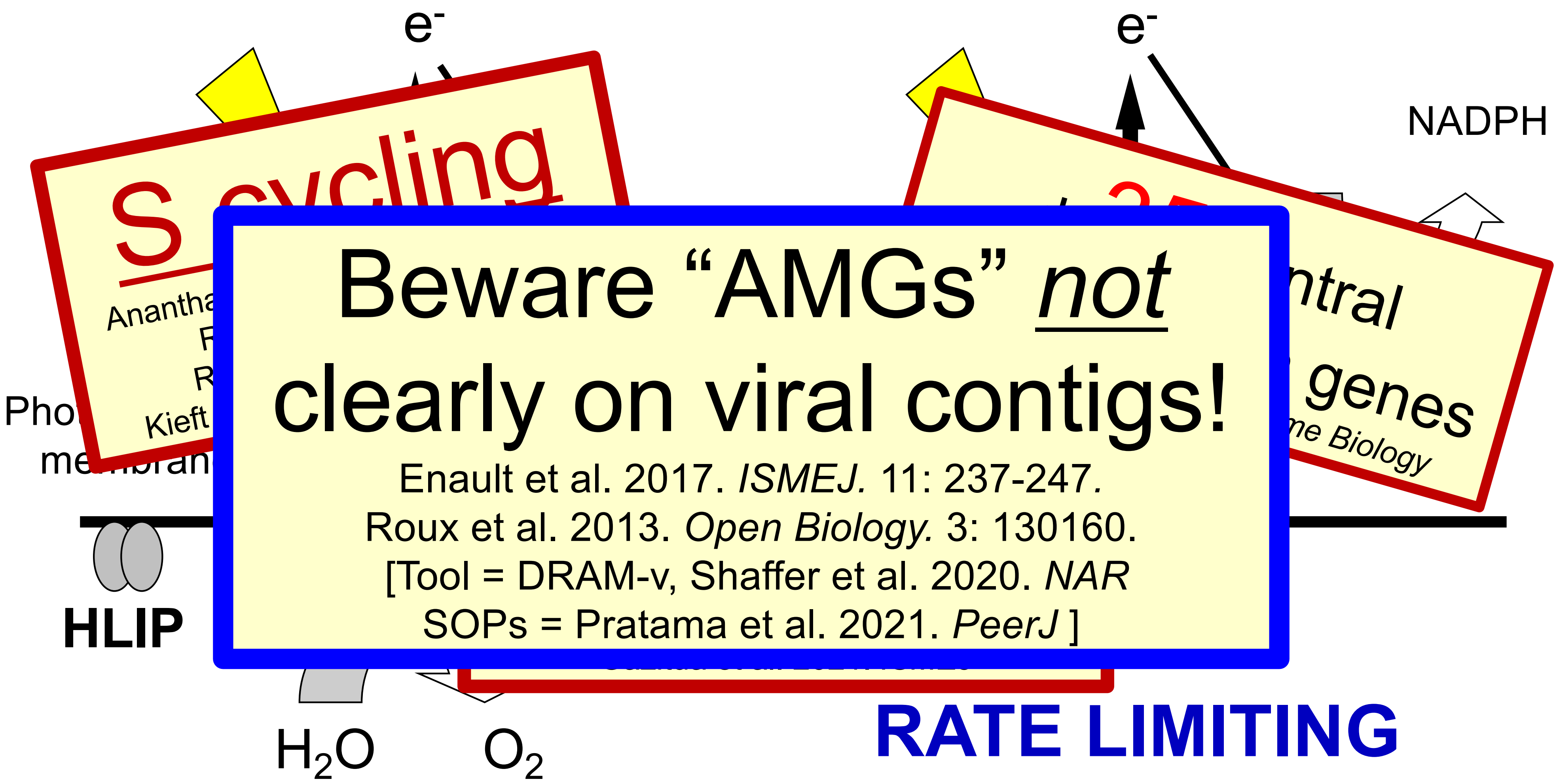
Viruses impact _processes_ through metabolic reprogramming by AMGs*



Mann et al. *Nature.* 2003.
Millard et al. *PNAS.* 2004
Lindell & Sullivan et al. *PNAS.* 2004.
Lindell et al. *Nature.* 2005, 2007.
Clokie et al. *EM*. 2006.
Sullivan & Lindell et al. *PLoS Biology.* 2006
Dammeyer et al. *Curr. Biol*. 2008.
Sharon et al. *Nature*. 2009.
Sullivan et al. *EM*. 2005, 2010.
Fridman et al. *Nature Microbiol*. 2017.

* AMGs = Auxiliary Metabolic Genes

“Virus” Photosynthesis



Beware “AMGs” _**not**_ clearly on viral contigs!

Enault et al. 2017. *ISMEJ.* 11: 237-247.
Roux et al. 2013. *Open Biology.* 3: 130160.
[Tool = DRAM-v, Shaffer et al. 2020. *NAR*
SOPs = Pratama et al. 2021. *PeerJ*]

RATE LIMITING STEPS

1. Photosynthesis is required
2. PsbA is replaced every ~30 mins.
3. Host transcription/translation shut-down

HYPOTHESIS: Phage (in)directly boost PSII activity

Mann et al. *Nature*. 2003
Millard et al. / Lindell & Sullivan et al. *PNAS*. 2004
Sullivan et al. *PLoS Biol.* 2005 / Mann et al. *J. Bact.* 2005

Viruses in the global oceans

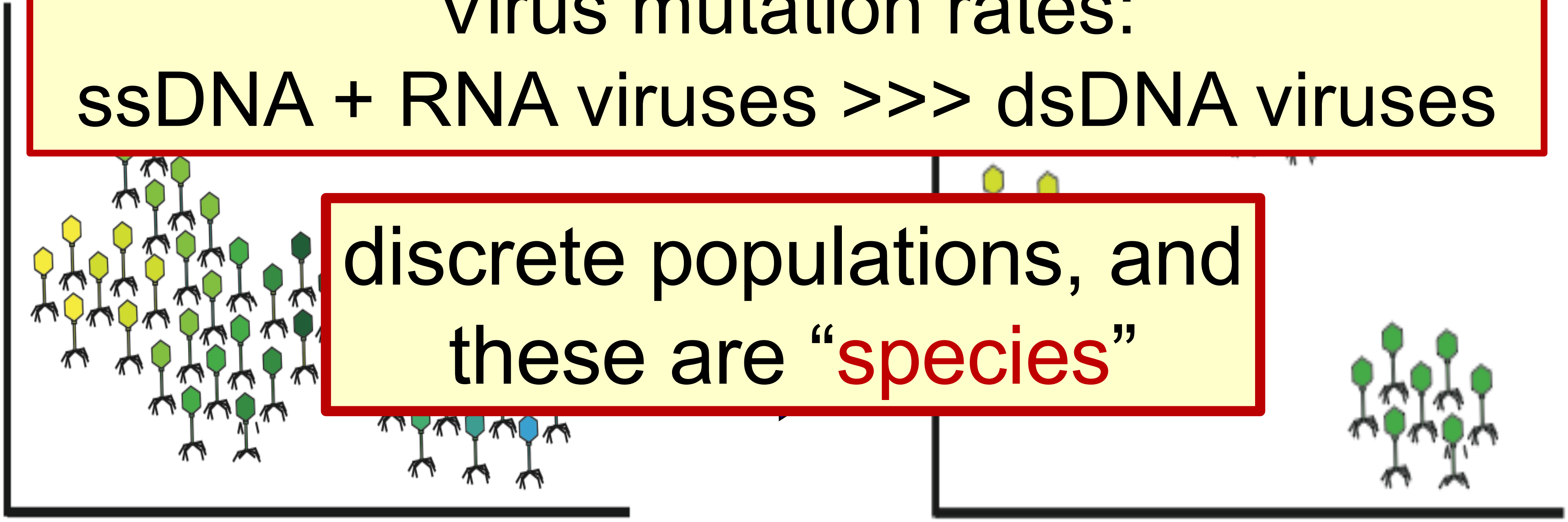
Patterns, Processes, Paradigms

Paradigms?

#1 – virus sequence space

Can we, and how do we identify viral ‘populations’ in environmental data?

The paradigm: viral genomes are subject to rampant mosaicism, so continuum expected



Virus mutation rates:
ssDNA + RNA viruses >>> dsDNA viruses

discrete populations, and
these are “species”

A continuum

Discrete populations

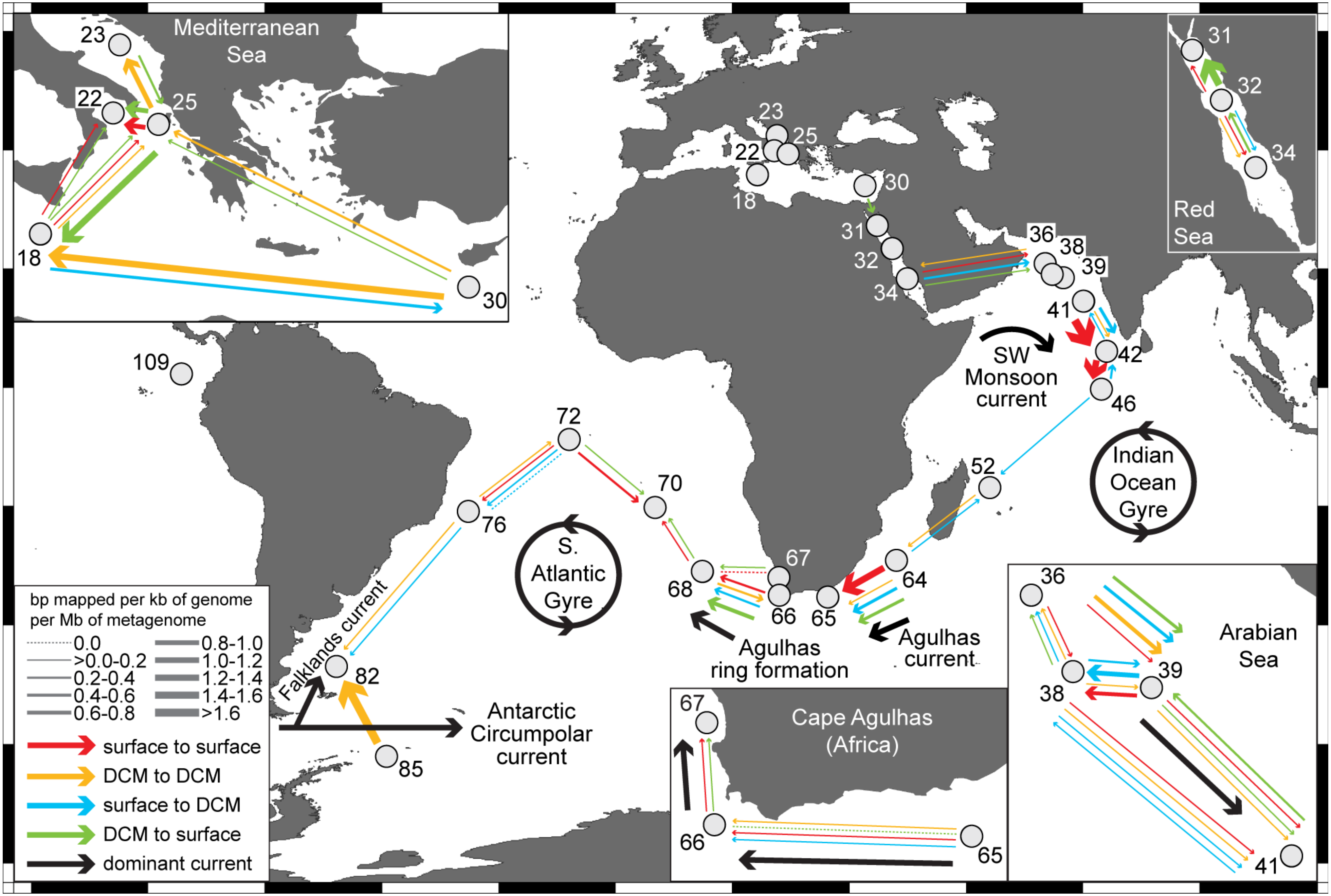
Deng & Ignacio-Espinoza et al. 2014. *Nature*; Brum et al. 2015. *Science*; Gregory et al. 2016. *BMC Genomics;* Duhaime et al. 2017. *Frontiers in Microbiology;* Gregory & Zayed et al. 2019. *Cell*.

Paradigms?

#1 – virus sequence space

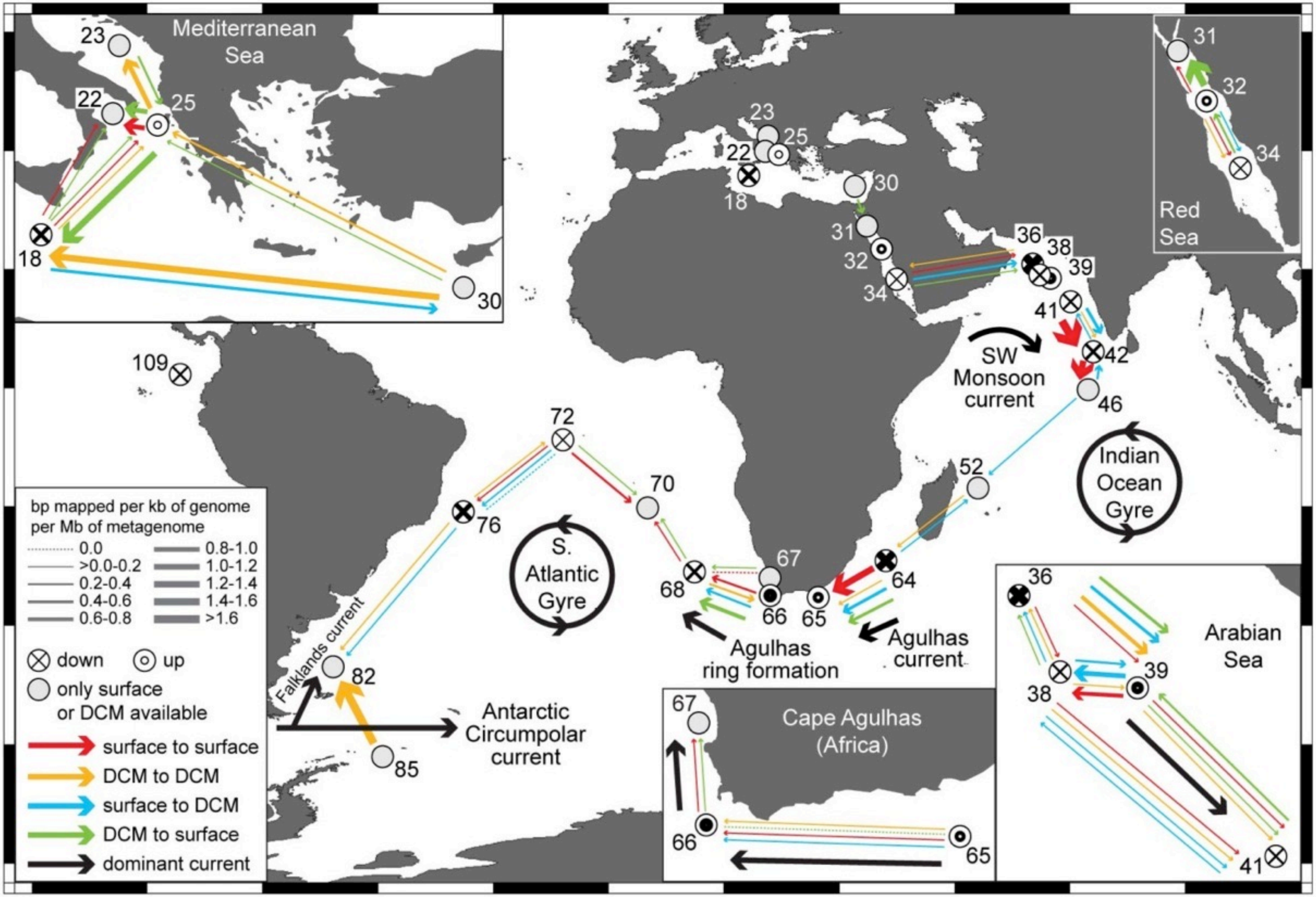
#2 – the ocean C pump

Genomic tracking: Viruses ‘ride’ ocean currents



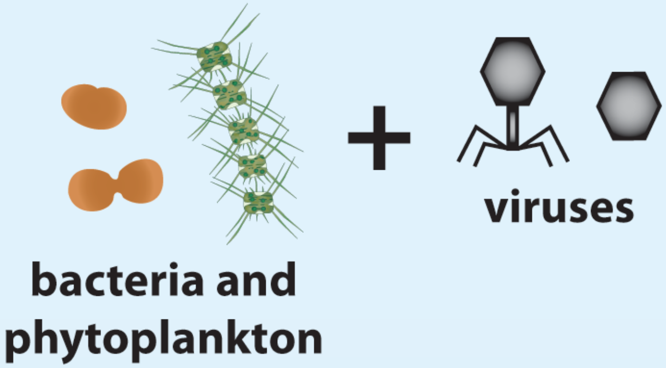
Brum, Ignacio-Espinoza, Roux et al. 2015. *Science.* 348: 1261498

Viruses ‘sink’ at many stations – why ?



Brum, Ignacio-Espinoza, Roux et al. 2015. *Science.* 348: 1261498

Paradigm:
Viral lysis increases recycling of organic matter



bacteria and
phytoplankton

+

viruses

slides from
Jenn Brum

Reviewed by Weinbauer. 2004.

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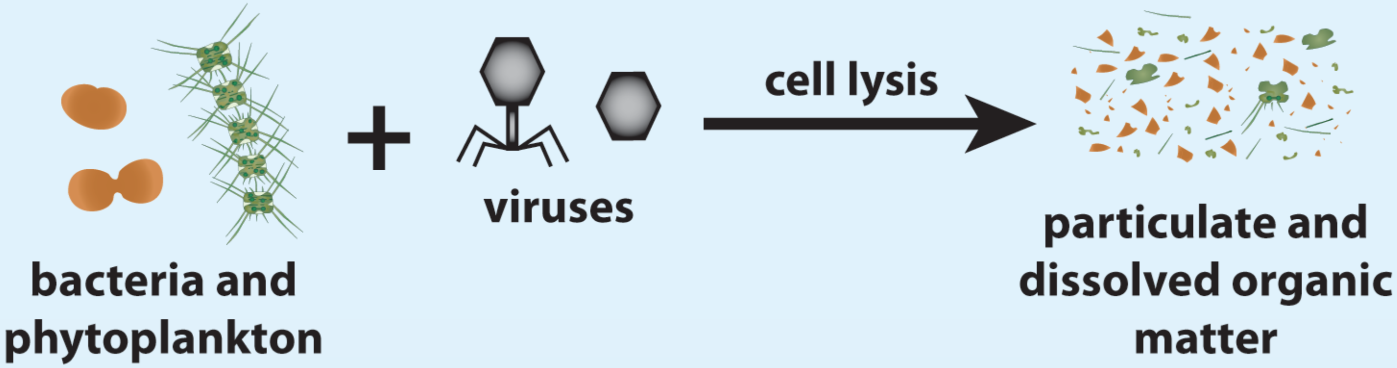

bacteria and phytoplankton

+

viruses

cell lysis

particulate and dissolved organic matter

slides from
Jenn Brum

Reviewed by Weinbauer. 2004.

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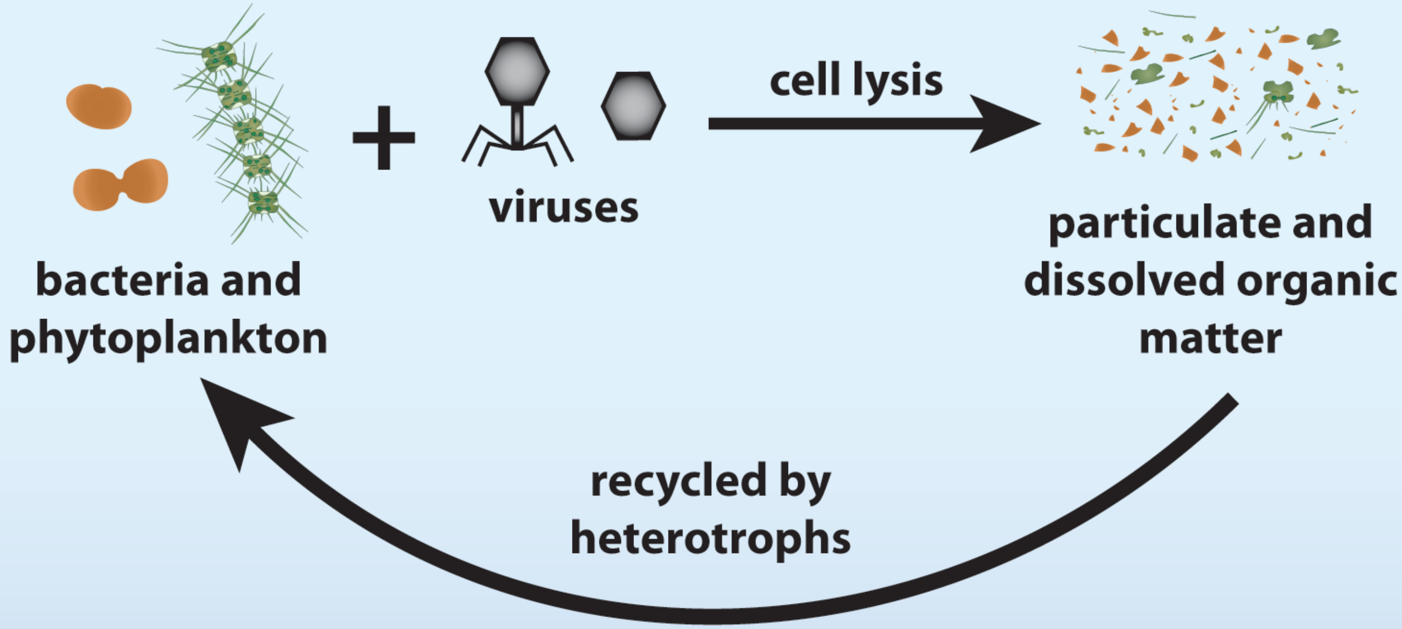


bacteria and phytoplankton

\+ viruses

cell lysis

particulate and dissolved organic matter

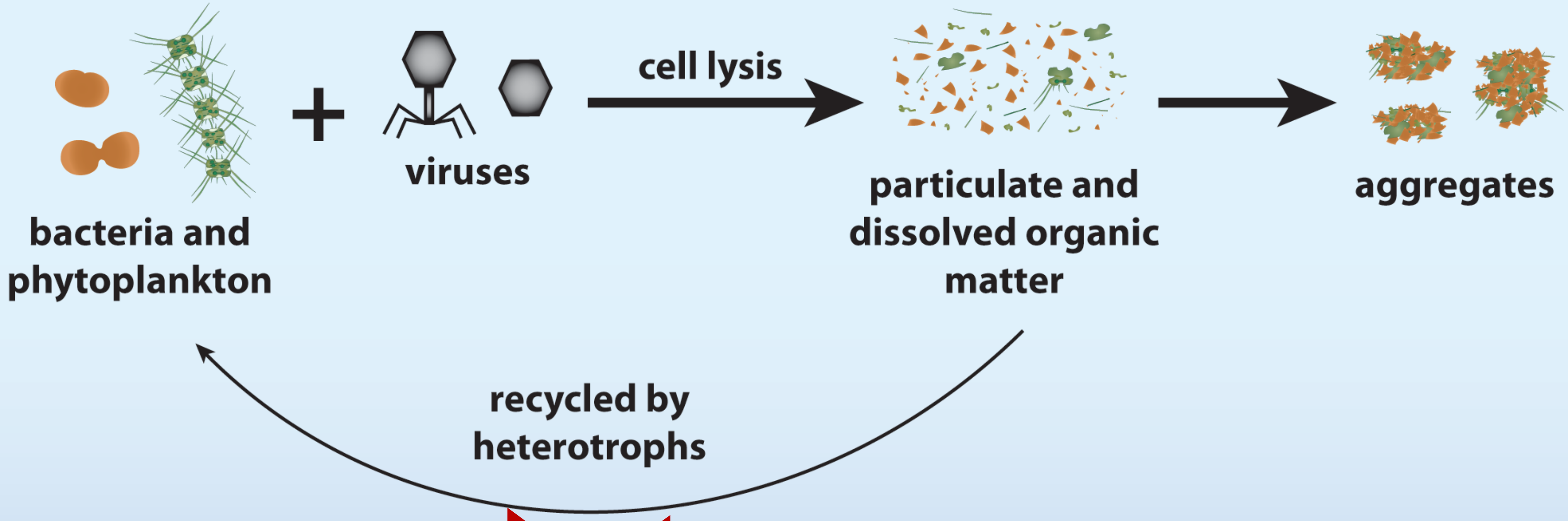
recycled by heterotrophs

The Viral Shunt

slides from
Jenn Brum

Reviewed by Weinbauer. 2004.

Alternative hypothesis: Viral lysis increases export via aggregate formation

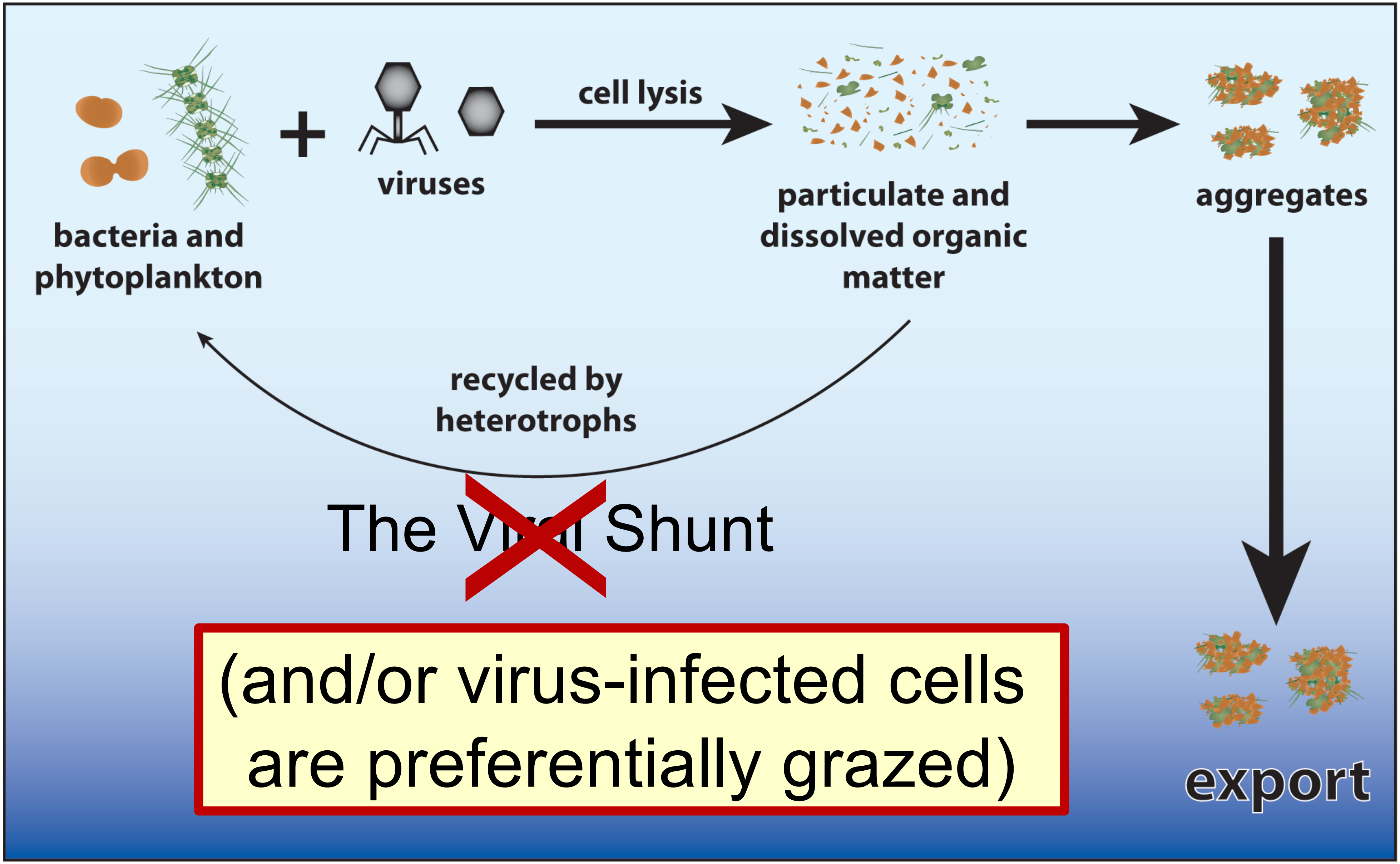


The ~~Viral~~ Shunt

slides from
Jenn Brum

Reviewed by Weinbauer. 2004.

Alternative hypothesis:
Viral lysis increases export via aggregate formation



bacteria and phytoplankton

+

viruses

cell lysis

particulate and dissolved organic matter

aggregates

recycled by heterotrophs

The ~~Viral~~ Shunt

export

(and/or virus-infected cells are preferentially grazed)

Reviewed by Weinbauer. 2004.

test by ‘genes-to-ecosystems’ modeling using *Tara* Oceans data

TARA OCEANS

Plankton networks driving carbon export in the oligotrophic ocean

Lionel Guidi[1,2]*, Samuel Chaffron[3,4,5]*, Lucie Bittner[6,7,8]*, Damien Eveillard[9]*, Abdelhalim Larhlimi[9], Simon Roux[10]†, Youssef Darzi[3,4], Stephane Audic[8], Léo Berline[1]†, Jennifer Brum[10]†, Luis Pedro Coelho[11], Julio Cesar Ignacio Espinoza[10], Shruti Malviya[7]†, Shinichi Sunagawa[11], Céline Dimier[8], Stefanie Kandels-Lewis[11,12], Marc Picheral[1], Julie Poulain[13], Sarah Searson[1,2], *Tara* Oceans Consortium Coordinators‡, Lars Stemmann[1], Fabrice Not[8], Pascal Hingamp[14], Sabrina Speich[15], Mick Follows[16], Lee Karp-Boss[17], Emmanuel Boss[18], Hiroyuki Ogata[19], Stephane Pesant[20,21], Jean Weissenbach[13,21,22], Patrick Wincker[13,21,22], Silvia G. Acinas[23], Peer Bork[13,24], Colomban de Vargas[8], Daniele Iudicone[25], Matthew B. Sullivan[10]†, Jeroen Raes[3,4,5], Eric Karsenti[7,14], Chris Bowler[7] & Gabriel Gorsky[1]

Guidi, Chaffron, Bittner & Eveillard et al. 2016. Nature. 532: 465-70.

Lucie Bittner

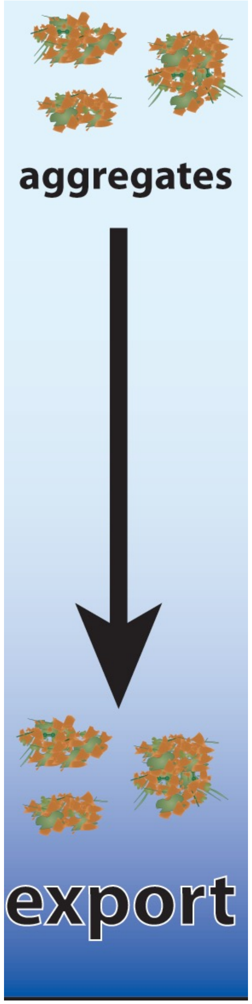
Samuel Chaffron

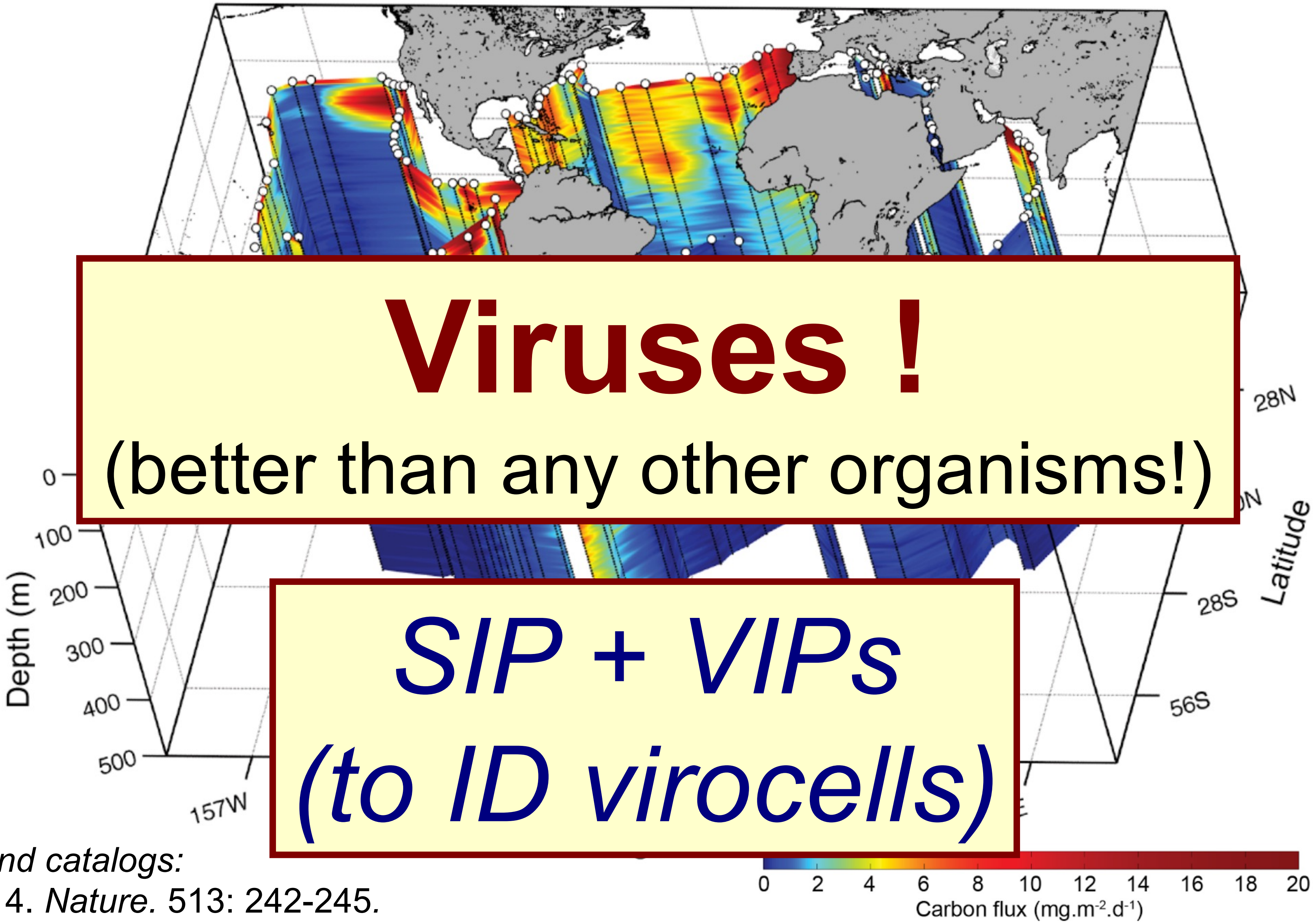
Lionel Guidi

Damien Eveillard

Which organisms drive carbon export in the oceans?

Viral lysis
forms …





Viruses !

(better than any other organisms!)

SIP + VIPs
(to ID virocells)

Viral ecology and catalogs:
Deng et al. 2014. *Nature.* 513: 242-245.
Brum et al. 2015. *Science.* 348: 1261498.
Roux et al. 2016. *Nature.* 537: 689-693.
Gregory et al. 2019. *Cell.* 177: 1109-23.

Genes-to-ecosystems modeling:
Guidi et al. 2016. *Nature.* 532: 465-70.

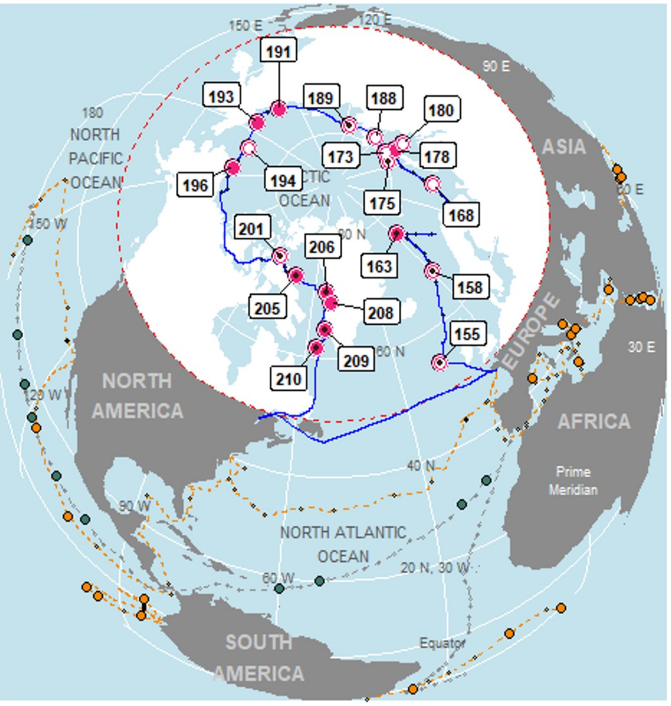
That was all DNA viruses …

what about RNA viruses?

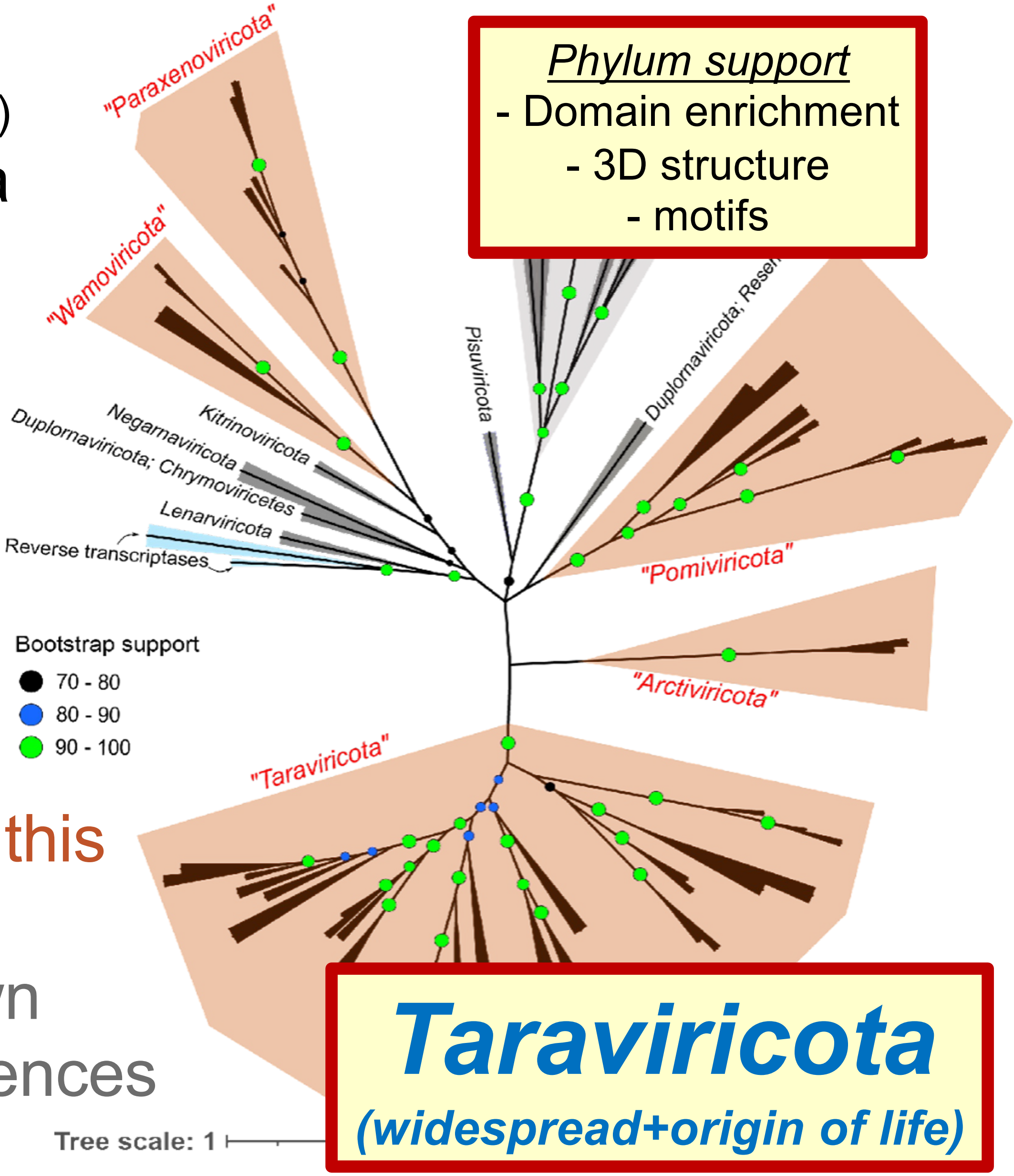
(likely more impt for eukaryotes)

RNA virus discovery, *doubles* known phyla

Oceans have ALL 20 classes,
49/103 families (**99.7% new spp**)
+ 5 new RNA virus phyla



28 Tb = 44K contigs =
6,686 "complete" RdRp



Phylum support
- Domain enrichment
- 3D structure
- motifs

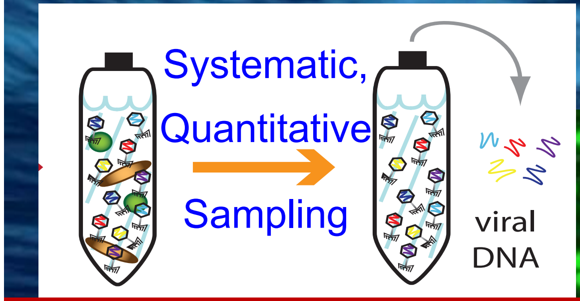
New, this study
Known sequences

Taraviricota
(widespread+origin of life)

Zayed, Wainaina & Dominguez-Huerta *et al.* 2022. *Science.* 376: 156-162.

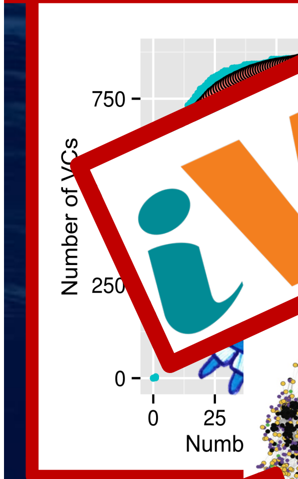
Also see "ecology" companion paper = Dominguez-Huerta & Zayed *et al.* 2022. *Science.* 376: 1202-8.

Oceans viruses

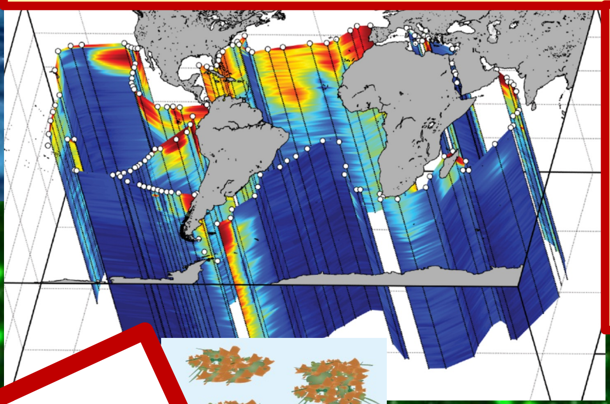

Systematic, Quantitative Sampling

viral DNA

A global catalog – 200K



Genes-to-ecosystems

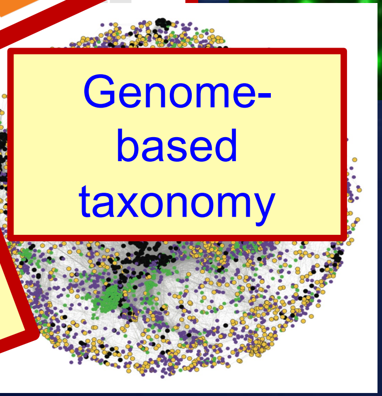


Population-based science (dsDNA)

TARA OCEANS

iVirus

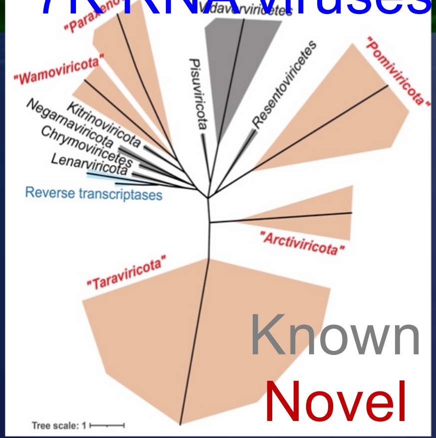
Viruses + C flux + VIPs



Genome-based taxonomy

AMGs

~7K RNA viruses



Known
Novel

Acknowledgements

Ben Bolduc, Jennifer Brum, Sheri Floge, Ann Gregory, Karin Holmfeldt, Cristina Howard-Varona, Bonnie Hurwitz, Ho Bin Jang, Simon Roux, Ahmed Zayed

GENOSCOPE Centre National de Séquençage

DOE Biological and Environmental Research Program

NSF

Gordon and Betty MOORE FOUNDATION

Brum & Sullivan. 2015. *Nat. Rev. Micro.* / Brum, Ignacio-Espinoza & Roux et al. 2015. *Science* / Roux et al. 2016. *Nature*. / Roux et al. 2015. *eLife. 08490* / Guidi, Bitner, Chaffron, Eveillard et al. 2016. *Nature* / Howard-Varona et al. 2018. *ISME J* / Gregory & Zayed et al. 2019. *Cell* / Jang & Bolduc et al. 2019. *Nature Biotechnology* / Howard-Varona et al. 2020. *ISME J* / Zayed, Wainaina & Dominguez-Huerta et al. 2022. *Science* / Dominguez-Huerta & Zayed et al. 2022. *Science*