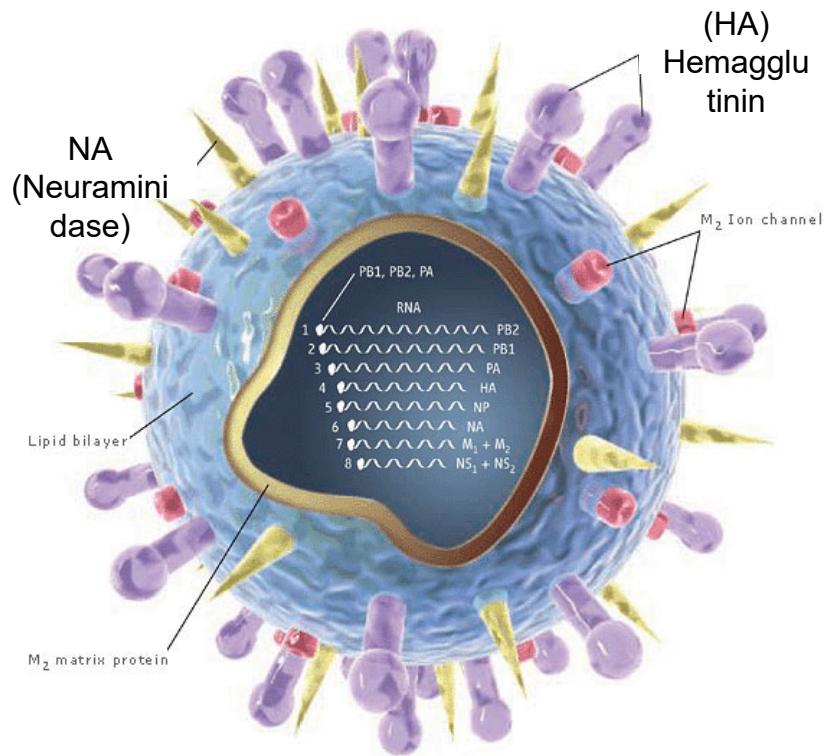


## ACUTE VIRAL INFECTIONS

Unit 3  
Paul Thomas  
[Paul.Thomas@stjude.org](mailto:Paul.Thomas@stjude.org)  
Department of Immunology  
St. Jude Children's Research Hospital

# INFLUENZA A VIRUS

- Negative sense, segmented RNA virus
- *Orthomyxoviridae*
- Eight genes, 11 proteins (three alternate reading frames)
- Two non-structural proteins (NS<sub>1</sub> and PB<sub>1</sub>-F<sub>2</sub>)
- Surface proteins HA and NA determine serotype



Modified from: Kaiser. *Science* 2006, 312:380-382.

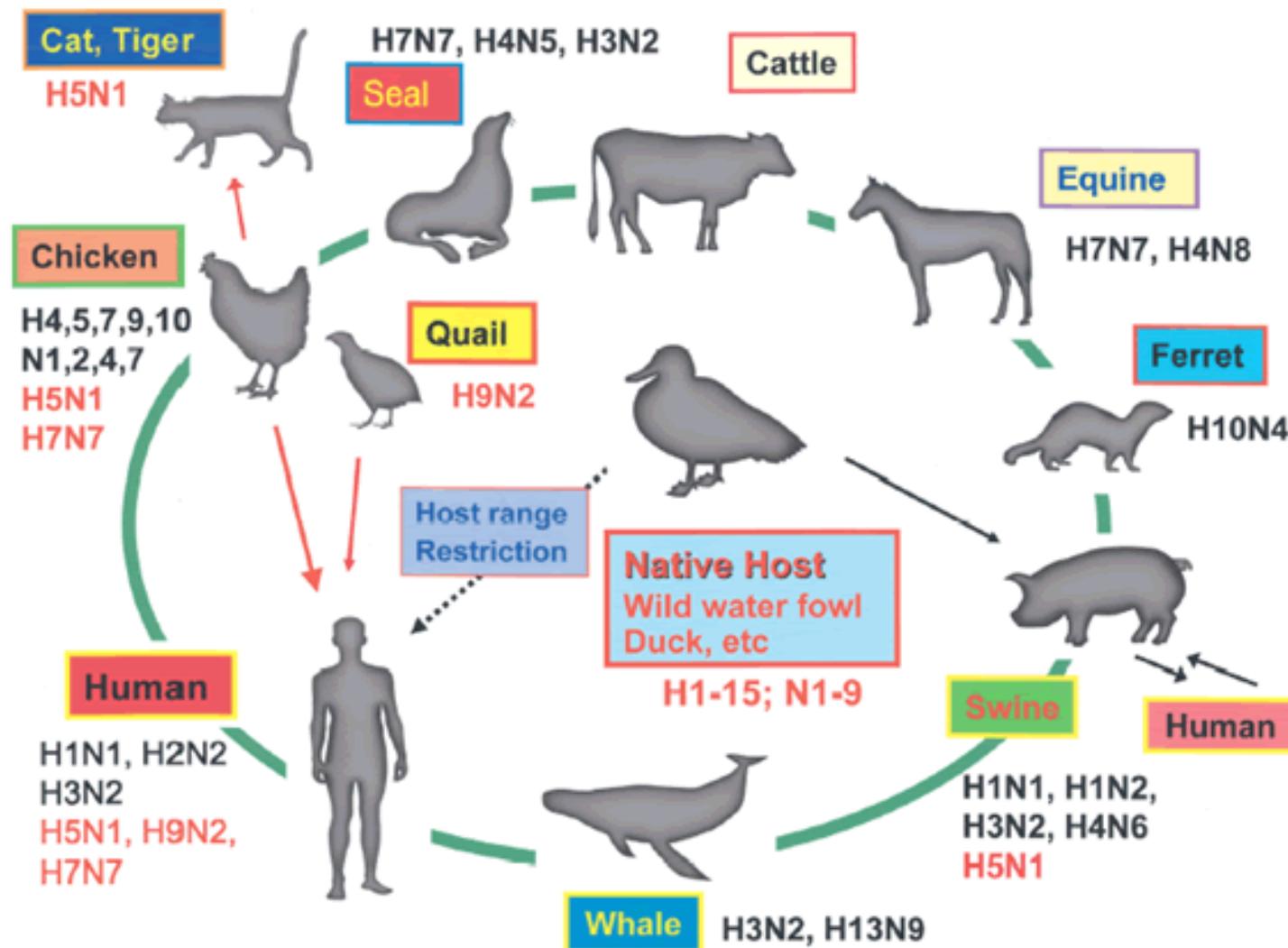
# Influenza A HA and NA Subtypes

H1			
H2			
H3			 Other Animals
H4			 Other Animals
H5			 Other Animals
H6			
H7			 Other Animals
H8			
H9			
H10			
H11			
H12			
H13			
H14			
H15			
H16			

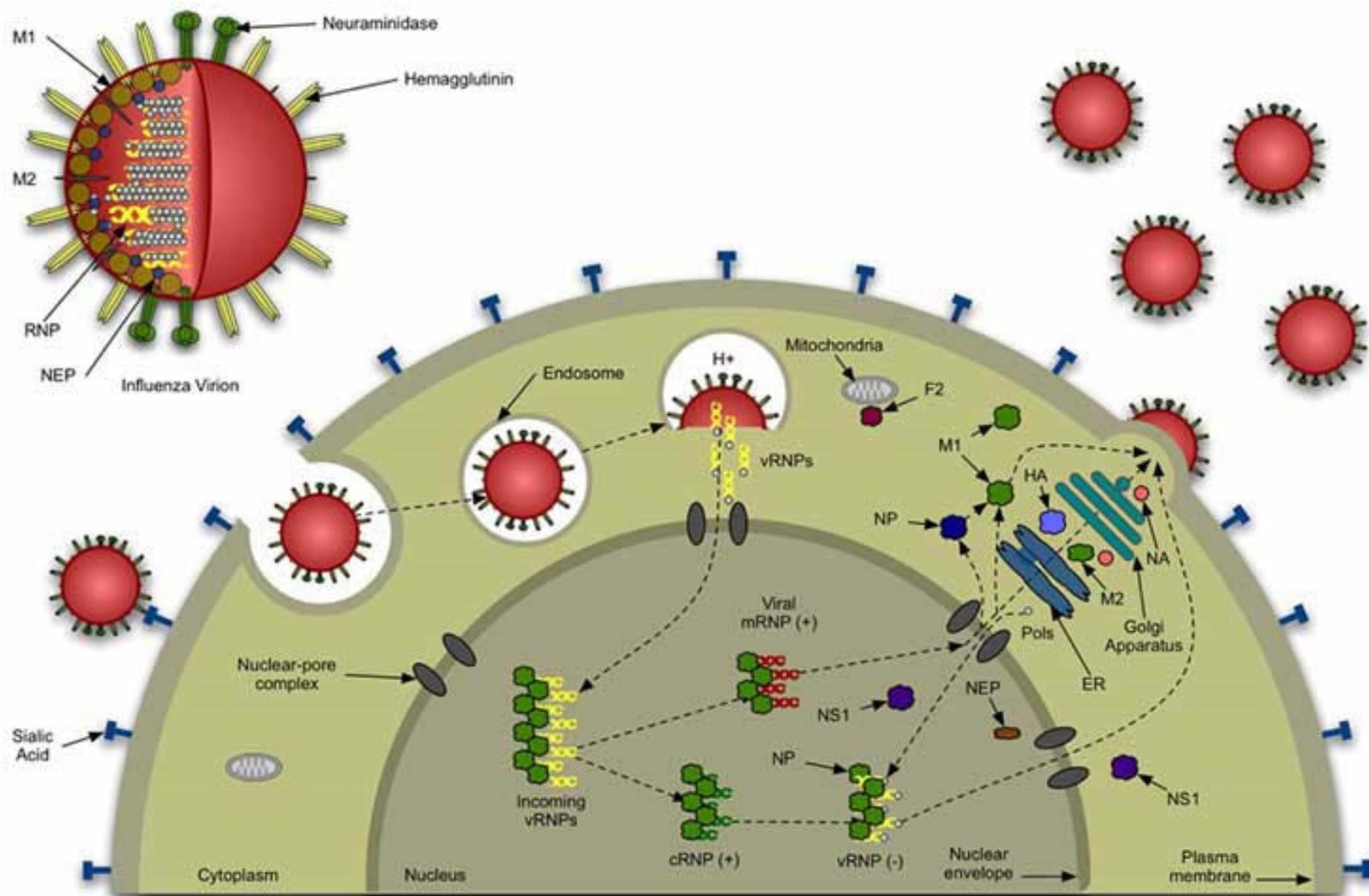
N1			
N2			
N3			
N4			
N5			
N6			
N7			 Other Animals
N8			 Other Animals
N9			



# DIVERSE HOST TROPISM ALLOWS RESTRICTION AND RECOMBINATION

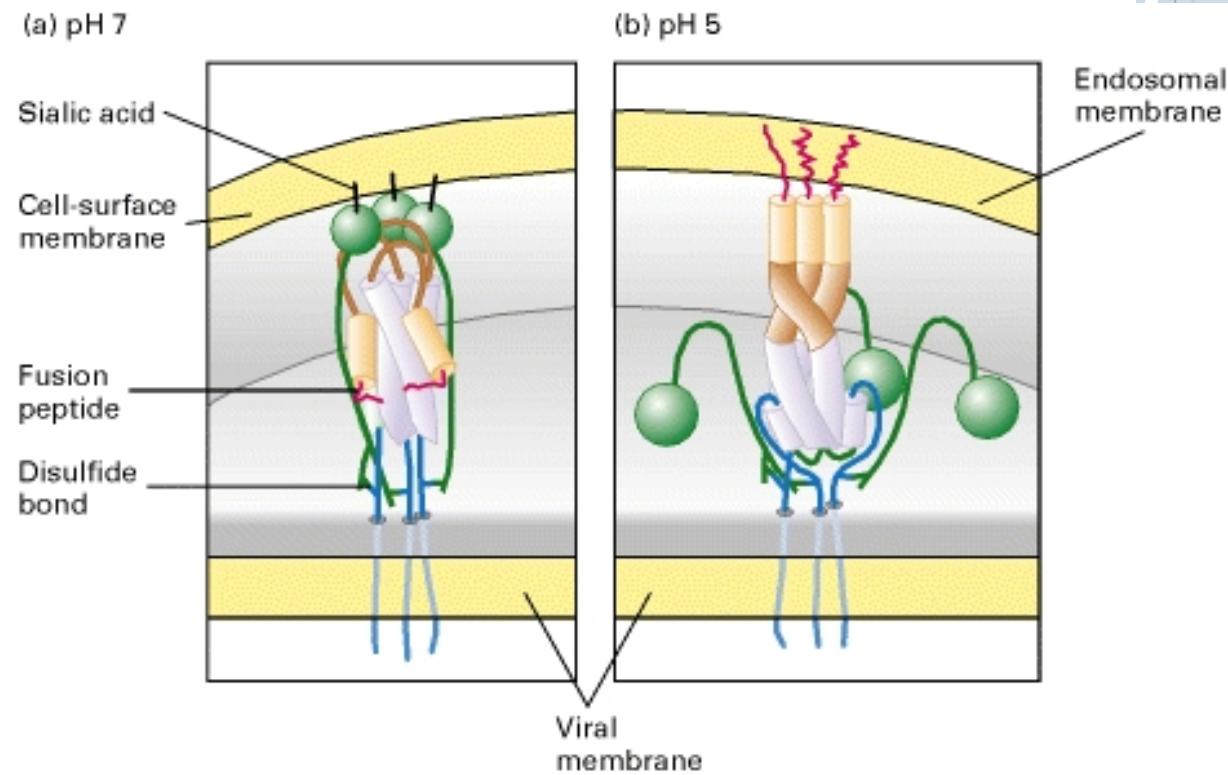


# INFLUENZA LIFE CYCLE



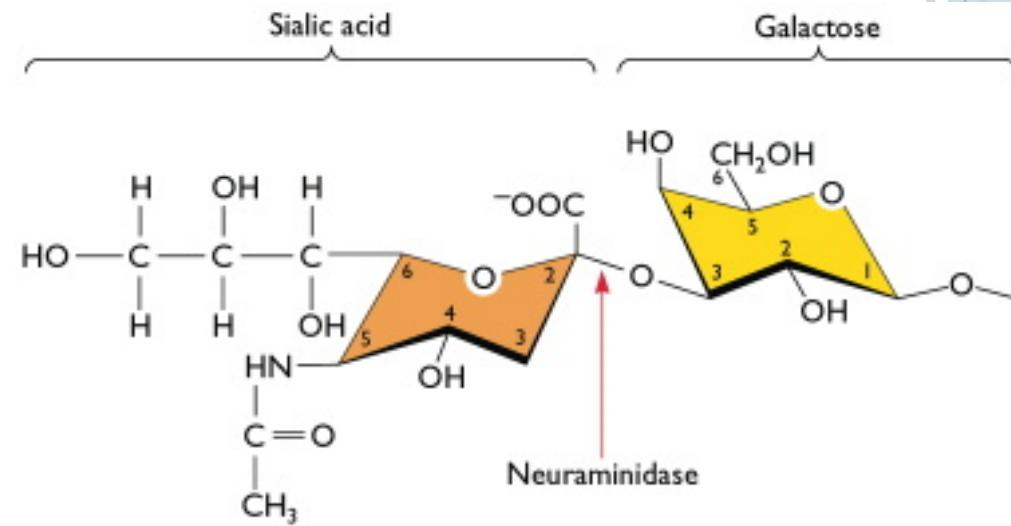
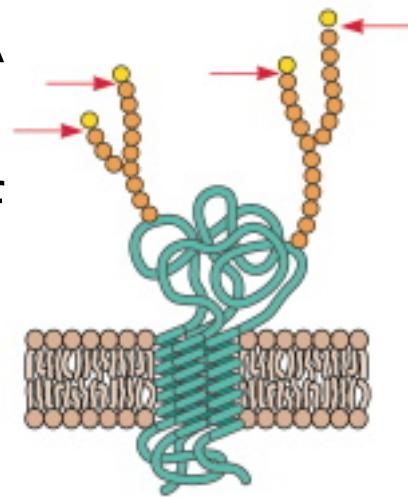
# HA IS REQUIRED FOR CELL ENTRY

- HA binding to sialic acid on the surface of cells mediates initial attachment
- Virus is endocytosed, where the endosome is acidified
- This triggers a conformational change in the virus, resulting in membrane fusion
- For HA to be active, it needs to be cleaved by a protease into two pieces—this protease is generally restricted to the respiratory epithelium



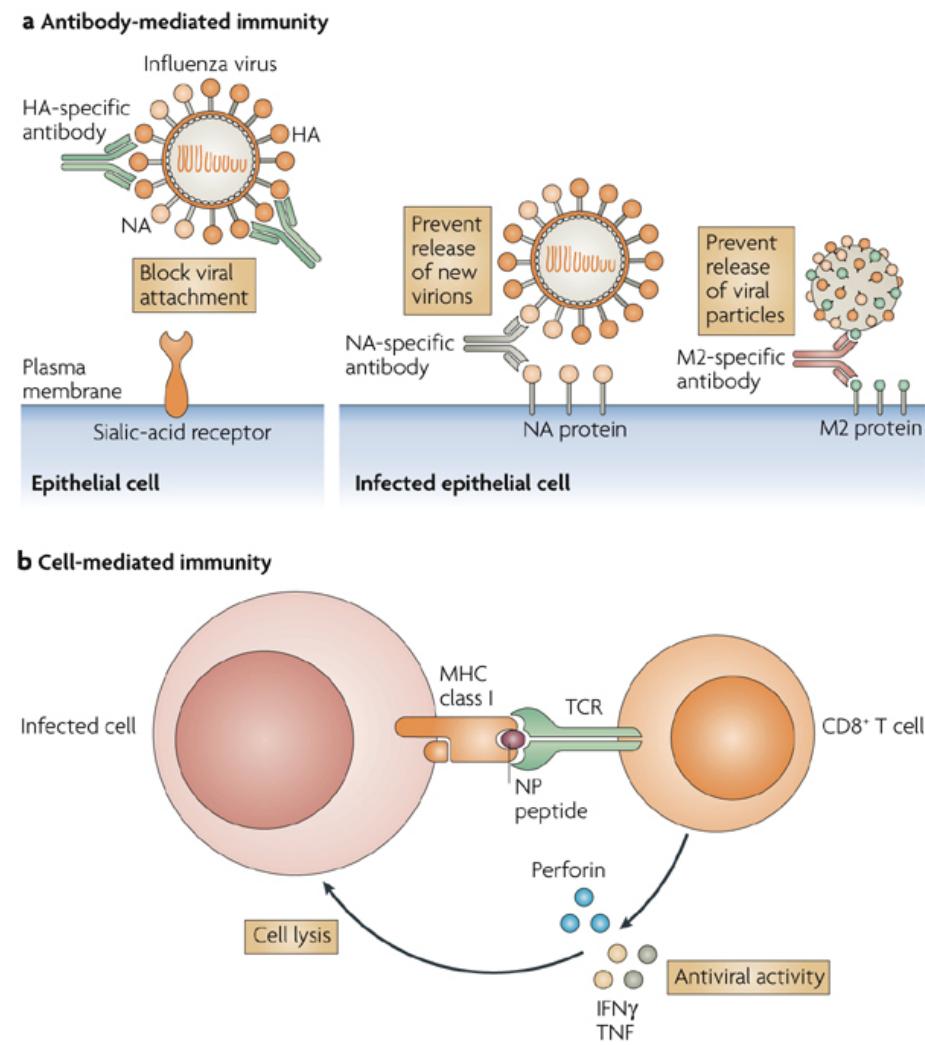
# NEURAMINIDASE ACTS TO CLEAVE THE SIALIC ACID RECEPTORS FROM THE CELL SURFACE

- IAV must balance the binding and entry activity of HA with the sialic acid cleavage activity of NA so that virus efficiently enters and buds from the cell surface—thus HA and NA are often “matched” for activity



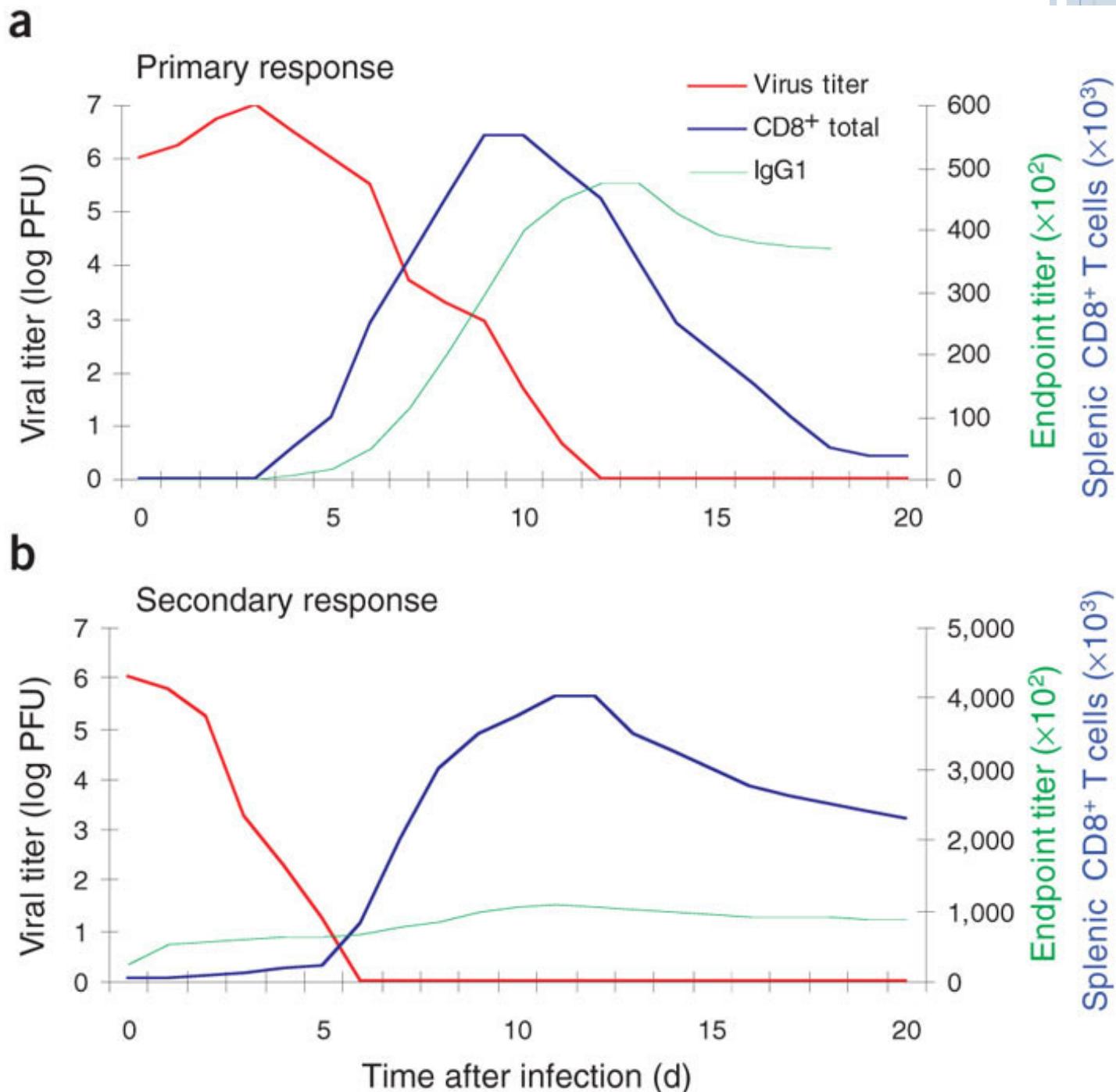
# IMMUNE MECHANISMS OF PROTECTION

- Antibody mediated immunity exerts the most pressure on the virus, leading to seasonal antigenic drift and pandemic strains of antigenic shift
- Internal proteins are relatively conserved allowing heterologous cellular protection
- Mutation of dominant CD8 epitopes over time suggests that CTLs provide immunological pressure

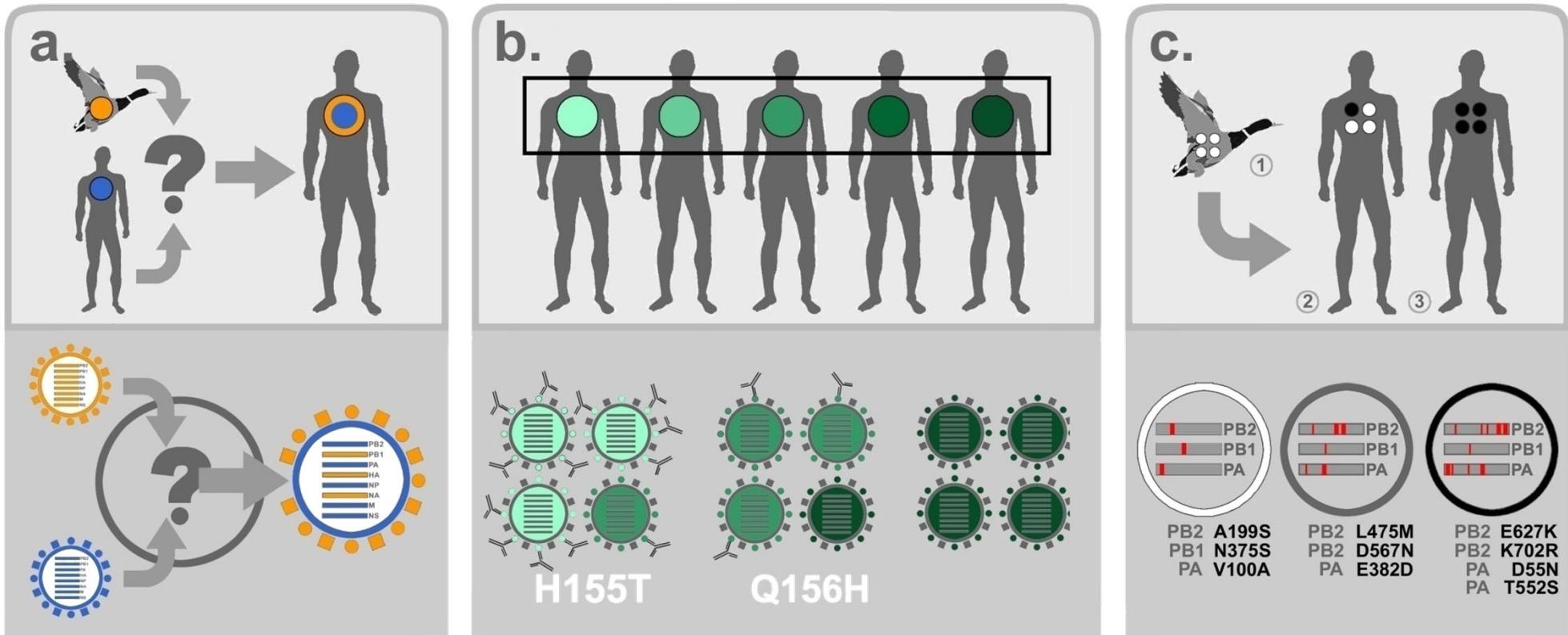


# IMMUNE COURSE OF INFLUENZA INFECTION

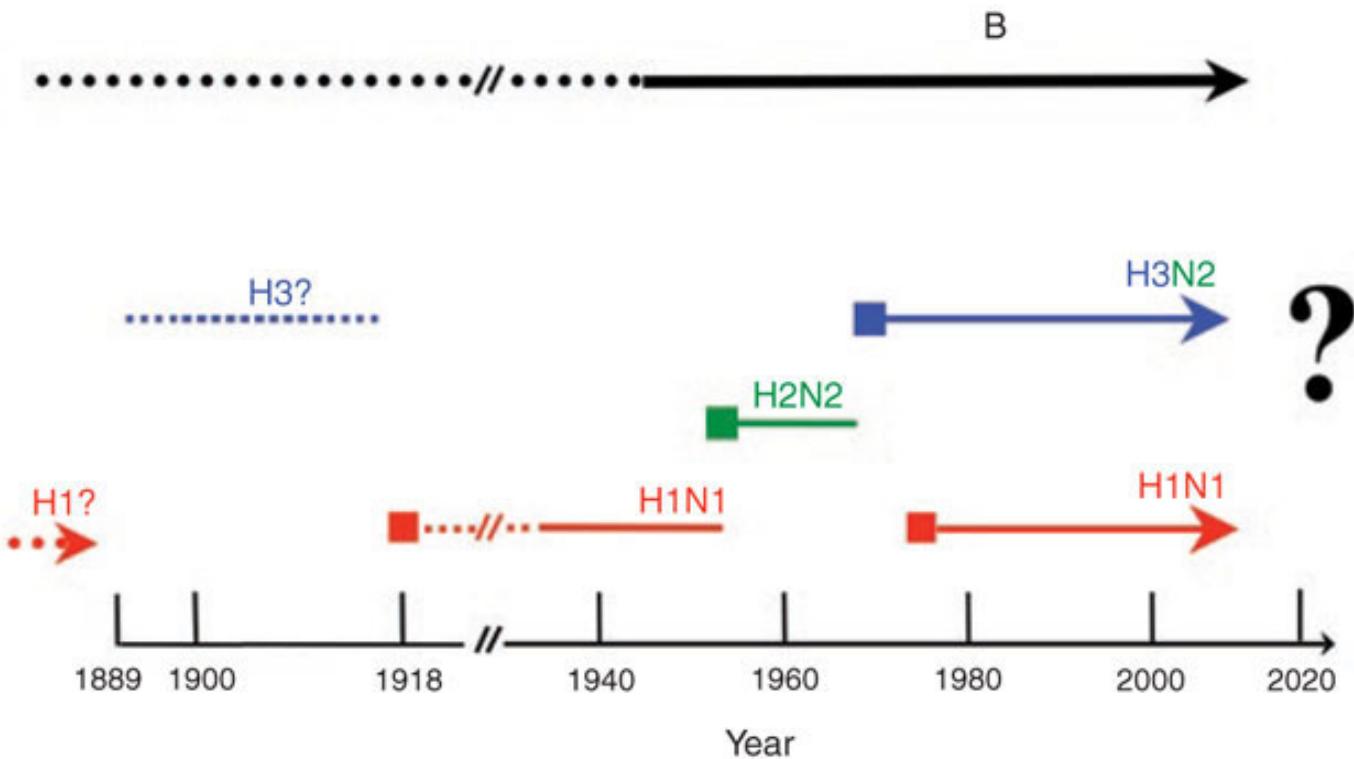
- Influenza is initially controlled by antibody and CD8+ T cells
- Secondary infection with heterologous virus is cleared with CD8+ T cell activity much more rapidly
- Homologous infection can be prevented by antibody (sterilizing immunity)



# INFLUENZA EVOLUTION

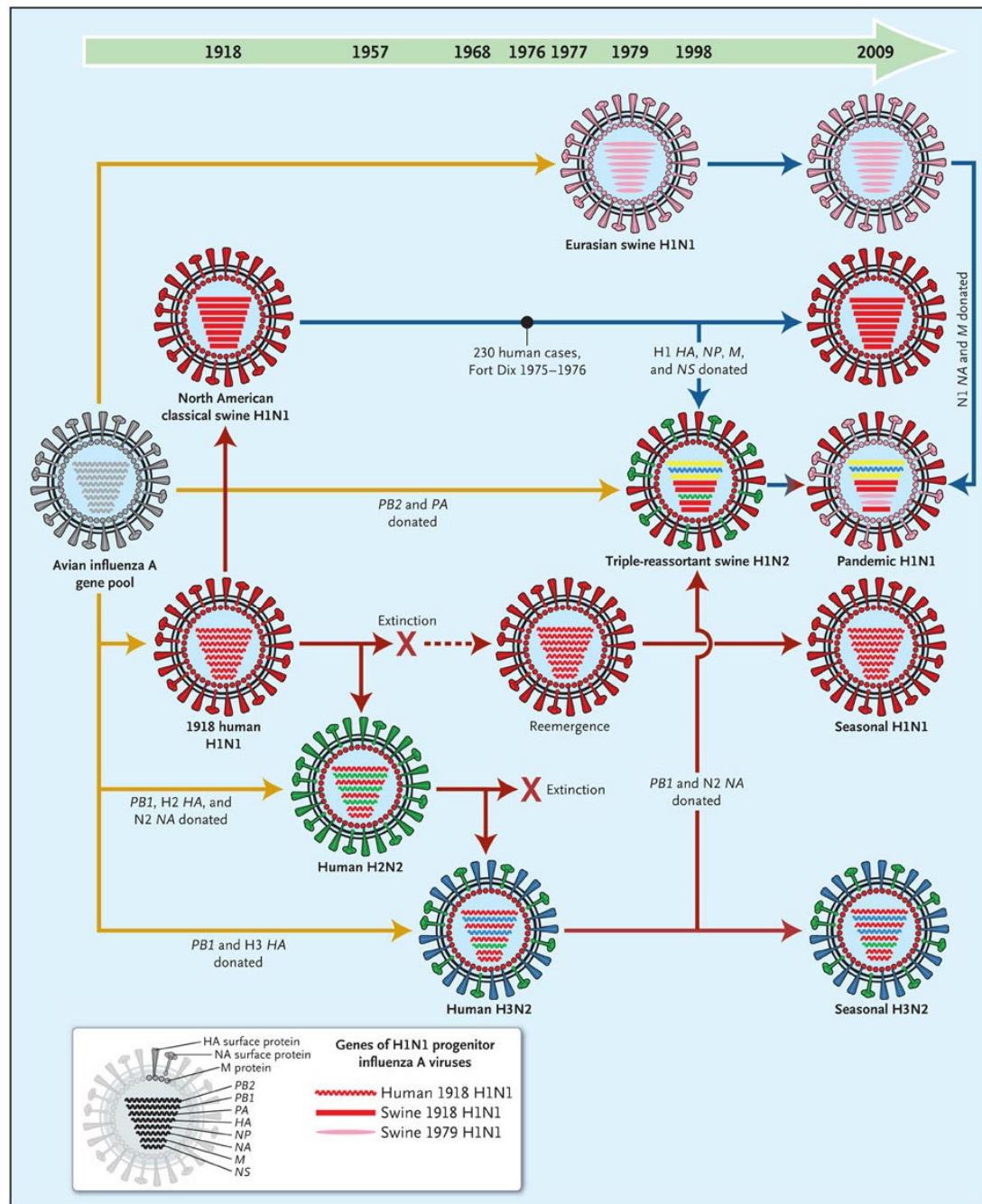


# HUMAN INFLUENZA PANDEMICS



# EVOLUTION OF HUMAN INFLUENZA FROM 1918

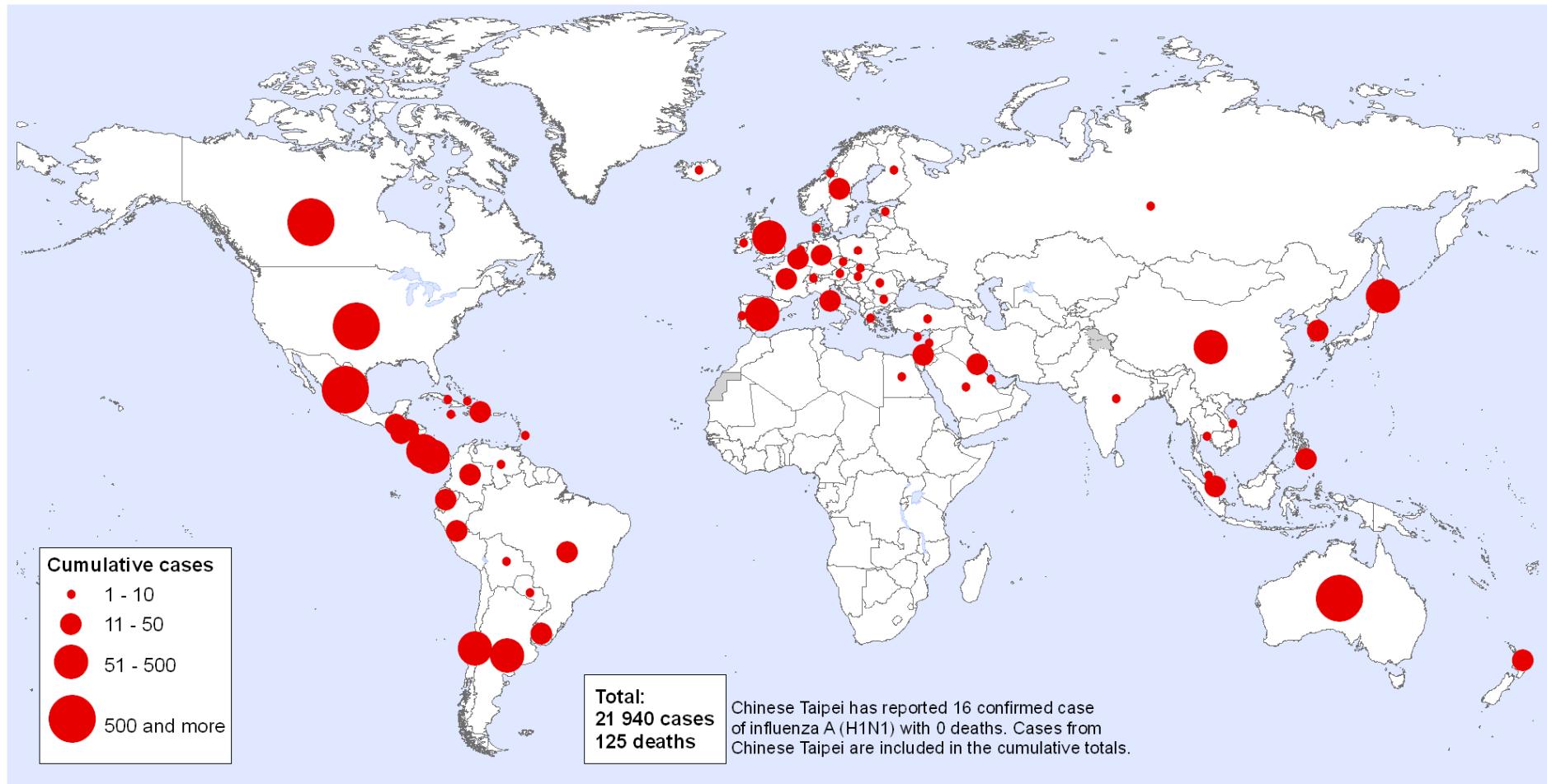
- All current human influenza is majority-derived from the 1918 pandemic
- Distinct reservoirs have allowed evolution to occur with varying pressures, providing diverse sources for new gene introductions into the human pool



# SWINE-ORIGIN H1N1 INCIDENCE

New Influenza A (H1N1),  
Number of laboratory confirmed cases as reported to WHO

Status as of 05 June 2009  
06:00 GMT



The boundaries and names shown and the designations used on this map do not imply the expression of any opinion whatsoever on the part of the World Health Organization concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Dotted lines on maps represent approximate border lines for which there may not yet be full agreement.

Data Source: World Health Organization  
Map Production: Public Health Information and Geographic Information Systems (GIS)  
World Health Organization

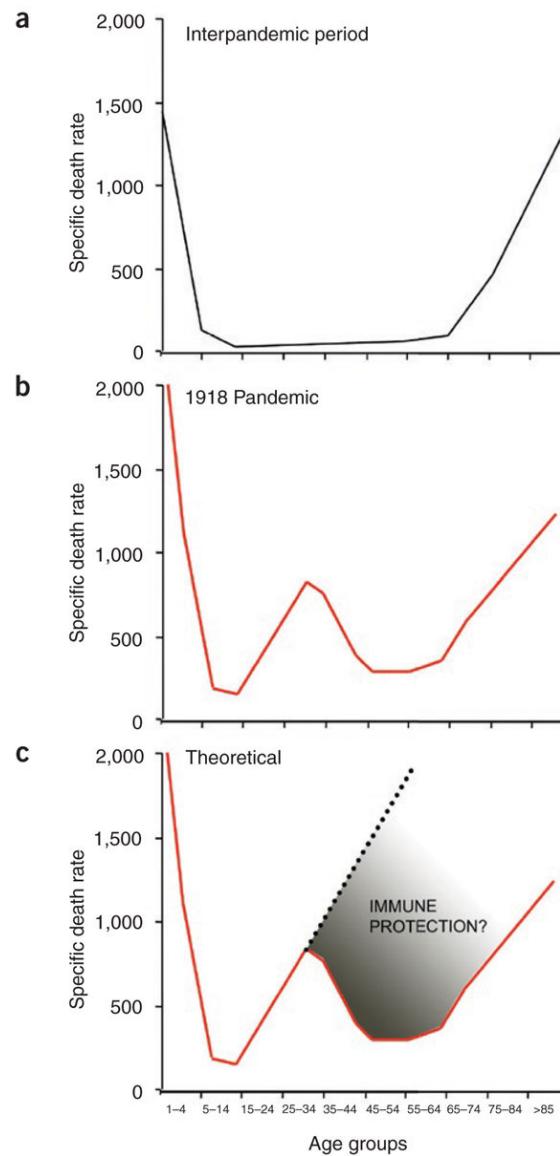


© WHO 2009. All rights reserved

Map produced: 05 June 2009 08:10 GMT

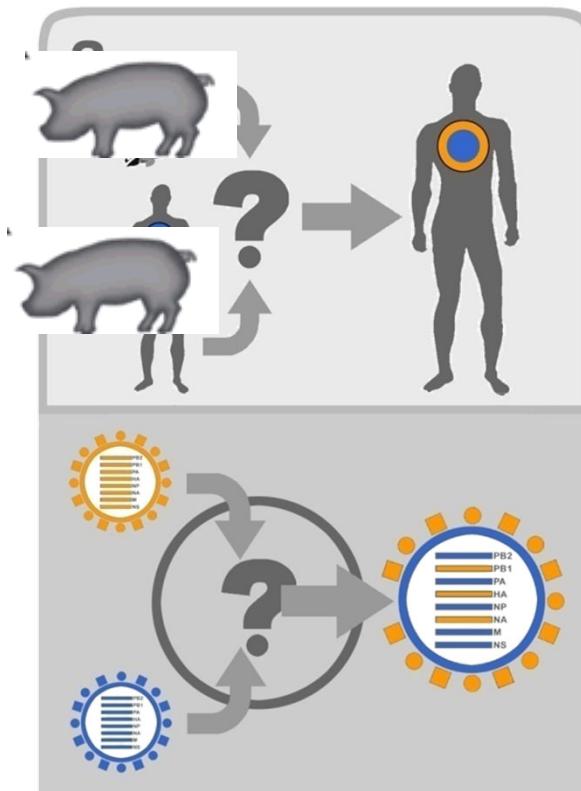
# 1918 (AND POSSIBLY SwORH1N1) MORTALITY CURVES SUGGEST PREVIOUS EXPOSURE

- The “U” shaped curve of regular influenza infection demonstrates the highest mortality among children (naïve) and the elderly (immunocompromised)
- The 1918 pandemic had a “W” shaped curve, with a spike in deaths among young adults—immunopathology or prior protection for ~40 year olds?



# PREDICTIONS OF THE 2009/H1N1 PANDEMIC

- The 2009 H1N1 pandemic emerged as a particularly novel threat: an antigenic shift event between two swine viruses, without the “human” virus component expected to be required
- The initial rapid spread bred fears of an equally high incidence of severe morbidity and mortality (~90,000 deaths in the US, ~1.8 million hospitalizations)



# PRE-EXISTING CROSS-REACTIVE IMMUNITY TO 2009/H1N1

ORIGINAL ARTICLE

## Cross-Reactive Antibody Responses to the 2009 Pandemic H1N1 Influenza Virus

Kathy Hancock, Ph.D., Vic Veguilla, M.P.H., Xiuhua Lu, M.D., Weimin Zhong, Ph.D., Ebeneé N. Butler, M.P.H., Hong Sun, M.D., Feng Liu, M.D., Ph.D., Libo Dong, M.D., Ph.D., Joshua R. DeVos, M.P.H., Paul M. Gargiullo, Ph.D., T. Lynnette Brammer, M.P.H., Nancy J. Cox, Ph.D., Terrence M. Tumpey, Ph.D., and Jacqueline M. Katz, Ph.D.

**Table 1.** Cross-Reactive Microneutralization Antibody Response against Pandemic Influenza A (H1N1) Virus in Pediatric and Adult Recipients of Seasonal Trivalent Inactivated Influenza Vaccines.\*

Type of Vaccine, Influenza Season, and Influenza Virus Used in Assay	Age Group	No. of Subjects	Increase in Antibody Titer by a Factor of $\geq 4$	Geometric Mean Titer†		Microneutralization Titer of $\geq 40$ for Children or $\geq 160$ for Adults‡				
				%	Before Vaccination (95% CI)	After Vaccination (95% CI)	Before Vaccination	After Vaccination		
<b>Children</b>										
Trivalent inactivated influenza vaccine										
2005–2007	6 mo to 9 yr	33								
Seasonal H1N1			67	26 (16–40)	267 (171–418)	45	94			
Pandemic H1N1			0	5 (5–6)	6 (5–6)	0	0			
2007–2008	5 yr to 9 yr	13								
Seasonal H1N1			85	42 (22–80)	575 (303–1093)	54	100			
Pandemic H1N1			0	10 (7–15)	12 (8–17)	8	15			
2008–2009	6 mo to 23 mo	9								
Seasonal H1N1			100	5 (4–7)	285 (202–402)	0	100			
Pandemic H1N1§			0	5	5	0	0			
Trivalent inactivated influenza vaccine with adjuvant										
2008–2009	6 mo to 59 mo	45¶								
Seasonal H1N1			96	12 (8–18)	193 (134–280)	24	100			
Pandemic H1N1			2	6 (5–7)	8 (7–9)	0	4			

# TABLE CONTINUED

			Vaccine	Vaccine	Vaccine	Vaccine	Vaccine
<b>Adults</b>							
Trivalent inactivated influenza vaccine							
2007–2008	18 yr to 64 yr	148					
	Seasonal H1N1		75	48 (40–58)	598 (497–720)	29	93
	Pandemic H1N1		22	25 (21–31)	54 (44–65)	7	25
2008–2009	18 yr to 40 yr	83					
	Seasonal H1N1		78	29 (22–38)	546 (418–713)	20	88
	Pandemic H1N1		12	11 (9–14)	21 (16–26)	6	7
<b>Older adults</b>							
Trivalent inactivated influenza vaccine							
2007–2008	≥60 yr	63					
	Seasonal H1N1		54	31 (22–42)	143 (105–194)	14	54
	Pandemic H1N1		5	92 (71–121)	97 (74–127)	33	43
2008–2009	≥60 yr						
	Seasonal H1N1	49**	18	22 (17–28)	51 (39–66)	6	14
	Pandemic H1N1	50**	0	47 (36–61)	51 (39–65)	8	8

# EARLY PANDEMIC H1N1: APRIL – JULY 2009

Table 2. Estimates of pandemic (H1N1) 2009-related cases and rates of illness and hospitalization by age distribution of confirmed case-patients, United States, April–July 2009

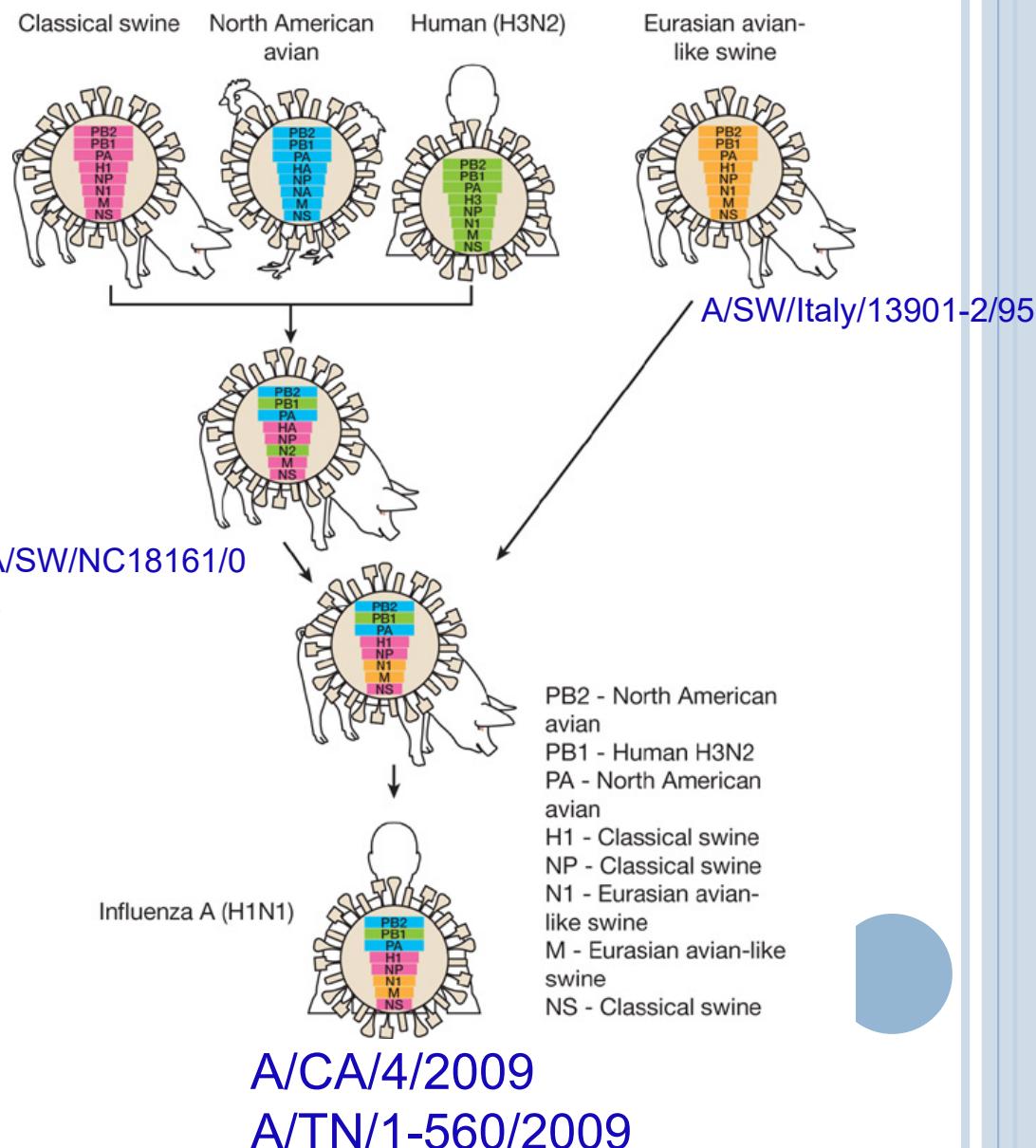
Parameter	Estimated no. case-patients		Estimated rate/100,000*	
	Median	90% range	Median	90% range
Total no. case-patients by age group, y†	3,052,768	1,831,115–5,720,928	997	598–1,868
0–4	397,033	238,149–744,045	1,870	1,122–3,505
5–24	1,820,284	1,091,845–3,411,237	2,196	1,317–4,115
25–49	612,862	367,608–1,148,511	577	346–1,081
50–64	180,297	108,146–337,879	319	192–599
≥65	42,292	25,368–79,256	107	64–201
No. hospitalized case-patients by age group, y	13,764	9,278–21,305	4.5	3.0–7.0
0–4	2,768	1,866–4,285	13.0	8.8–20.2
5–24	4,991	3,364–7,725	6.0	4.1–9.3
25–49	3,440	2,319–5,324	3.2	2.2–5.0
50–64	1,912	1,289–2,959	3.4	2.3–5.2
≥65	654	441–1,012	1.7	1.1–2.6
Multiplier				
Hospitalized	2.7	1.7–4.5	–	–
Nonhospitalized	79	47–148	–	–
Through May 12	33	23–49	–	–
After May 12	84	50–163	–	–

\*United States Population Estimates, 2009.

†Age distributions from line list and aggregate reports of laboratory-confirmed cases and hospitalizations to the Centers for Disease Control and Prevention through July 23, 2009.

# 2009 PANDEMIC H1N1

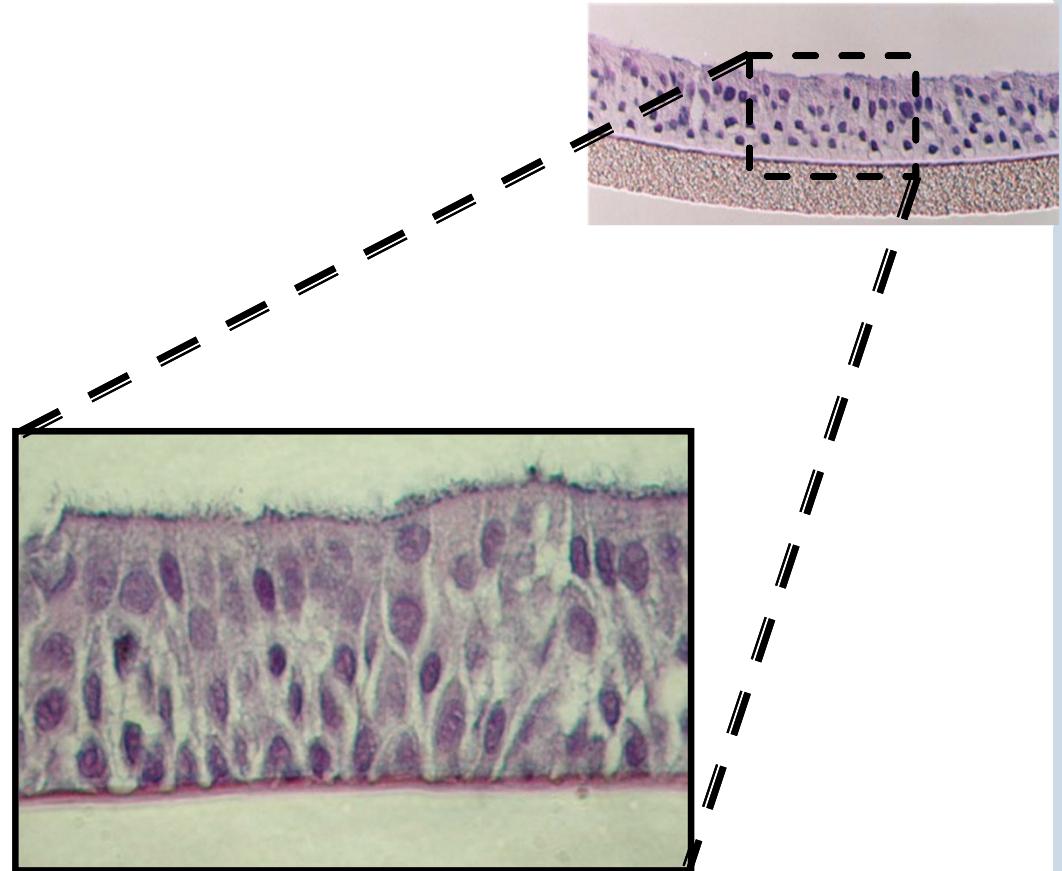
- 2009/H1N1 resulted from the recombination of two viruses (American and Eurasian Swine)
- The American Swine virus was itself a recombinant of three viruses that established itself in 1998
- These viruses are genetically distant from the human seasonal H1N1 (reference strain A/Brisbane/59/07)



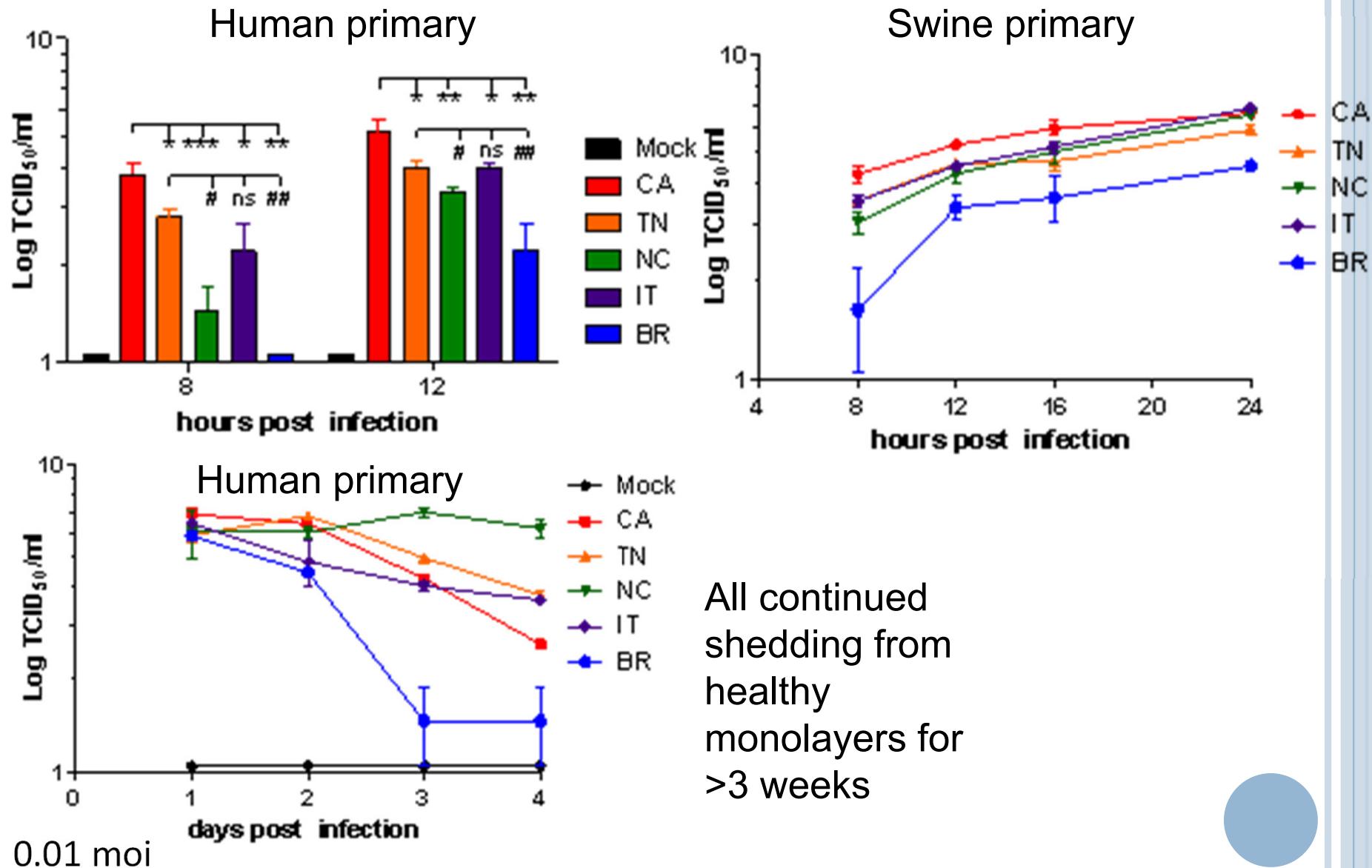
# H1N1 SWINE FLU STUDIES: RESPONSE IN HUMAN CELLS

## Measures:

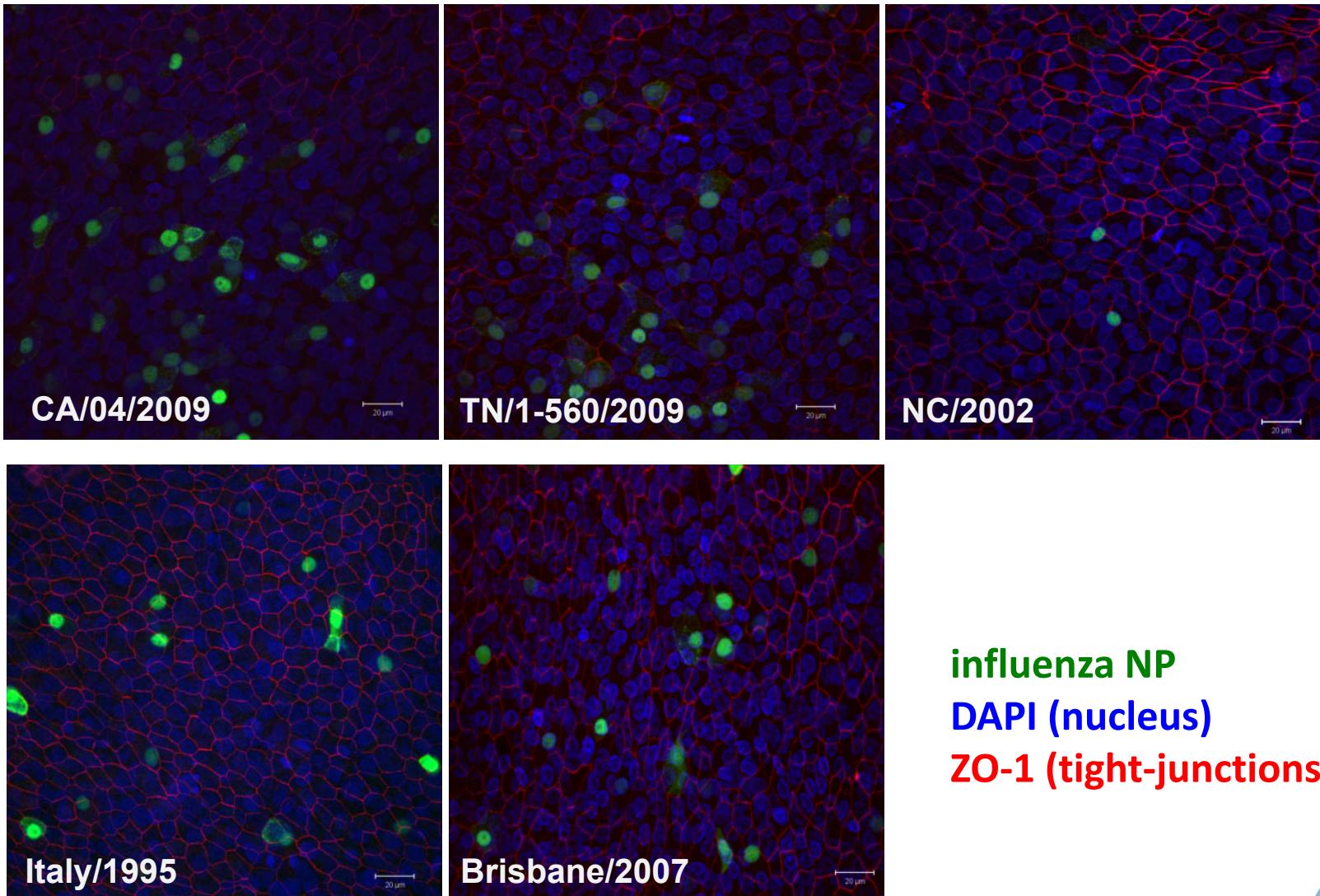
- Infectivity and growth of virus (TCID<sub>50</sub>, immunofluorescence)
- Secretion of inflammatory mediators from apical and basolateral surfaces (multiplexed immunoassay)
- Transcriptional response over the first 24 hours (Exon arrays, fluidigm analysis)
- Confirm results by “swapped viruses” made by reverse genetics



# VIRAL GROWTH KINETICS IN HAE CELLS

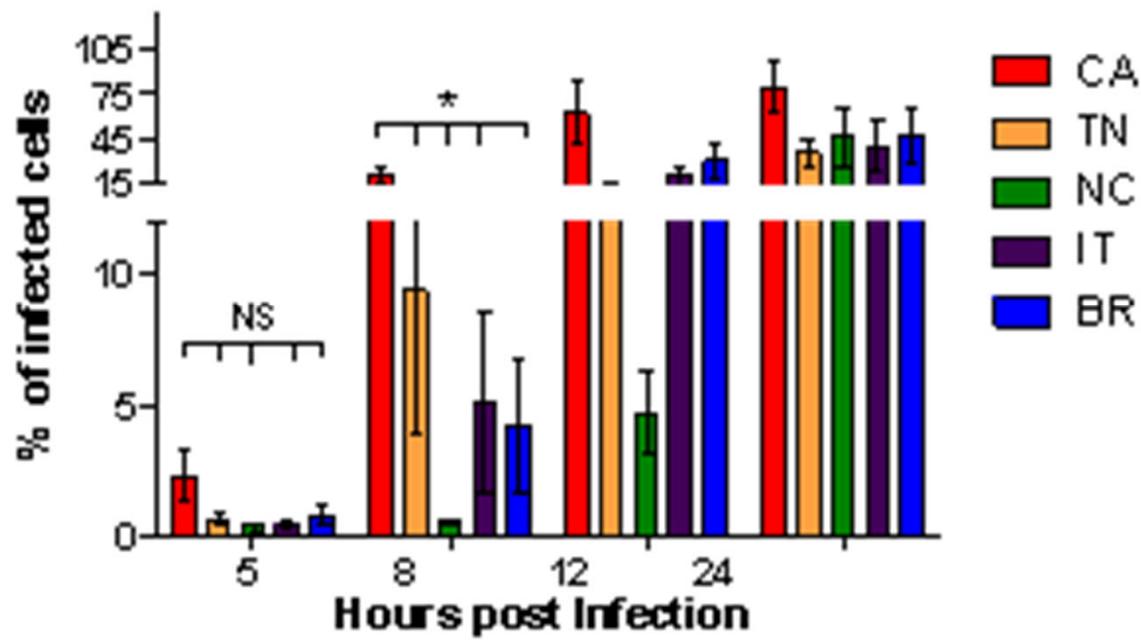


# Influenza NP detection in 3D HAE cultures viral growth kinetics in HAE cells



8 hr post infection- 0.01 moi

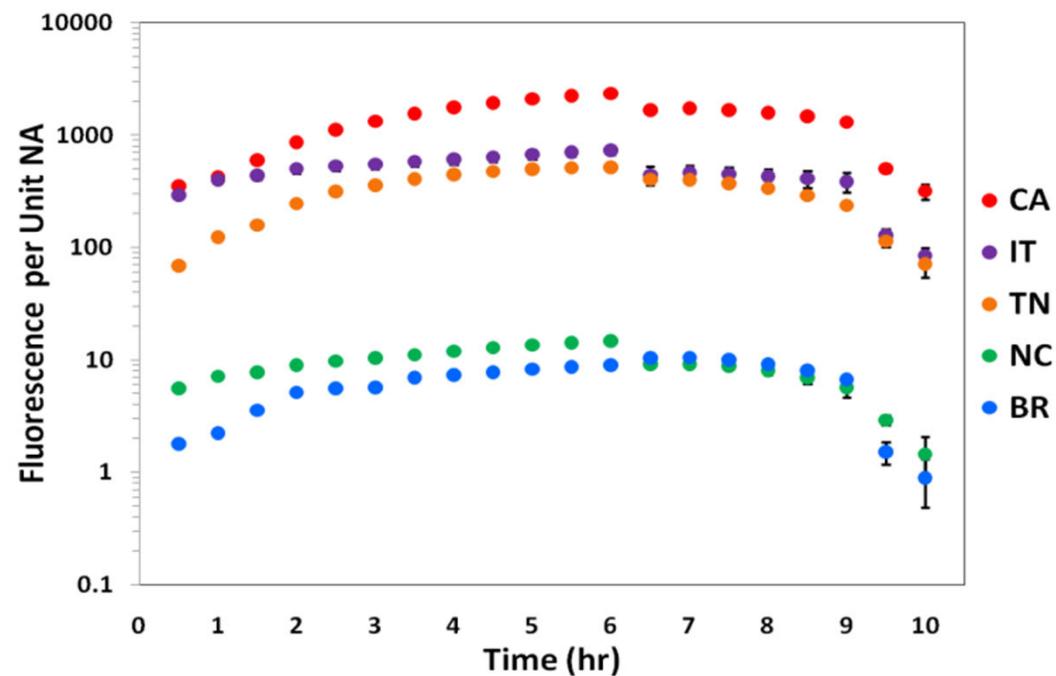
# MORE RAPID COLONIZATION OF CULTURE BY PANDEMIC AND ESW VIRUS



By 12 hours, pandemic strains and Italy have infected ~50%-75% of the culture

# HIGHER NA ACTIVITY IN PANDEMIC AND ESw

- NA activity measured as ability to convert sialic acid containing substrate
- Results normalized to functional viral titer, so NA activity/infectious virion
- Higher NA activity may relate to ability of virus to spread efficiently



## GROWTH SUMMARY

- The pandemic virus acquired a rapid growth phenotype in human cells similar to the Esw virus
- This phenotype associates with both the NA and M of Esw virus
- The Esw virus transmits more efficiently in ferrets
- Titer and infected cell number can be de-coupled across infections/individuals



# ODE MODEL OF INFLUENZA INFECTION—ANDREAS HANDEL, UGA

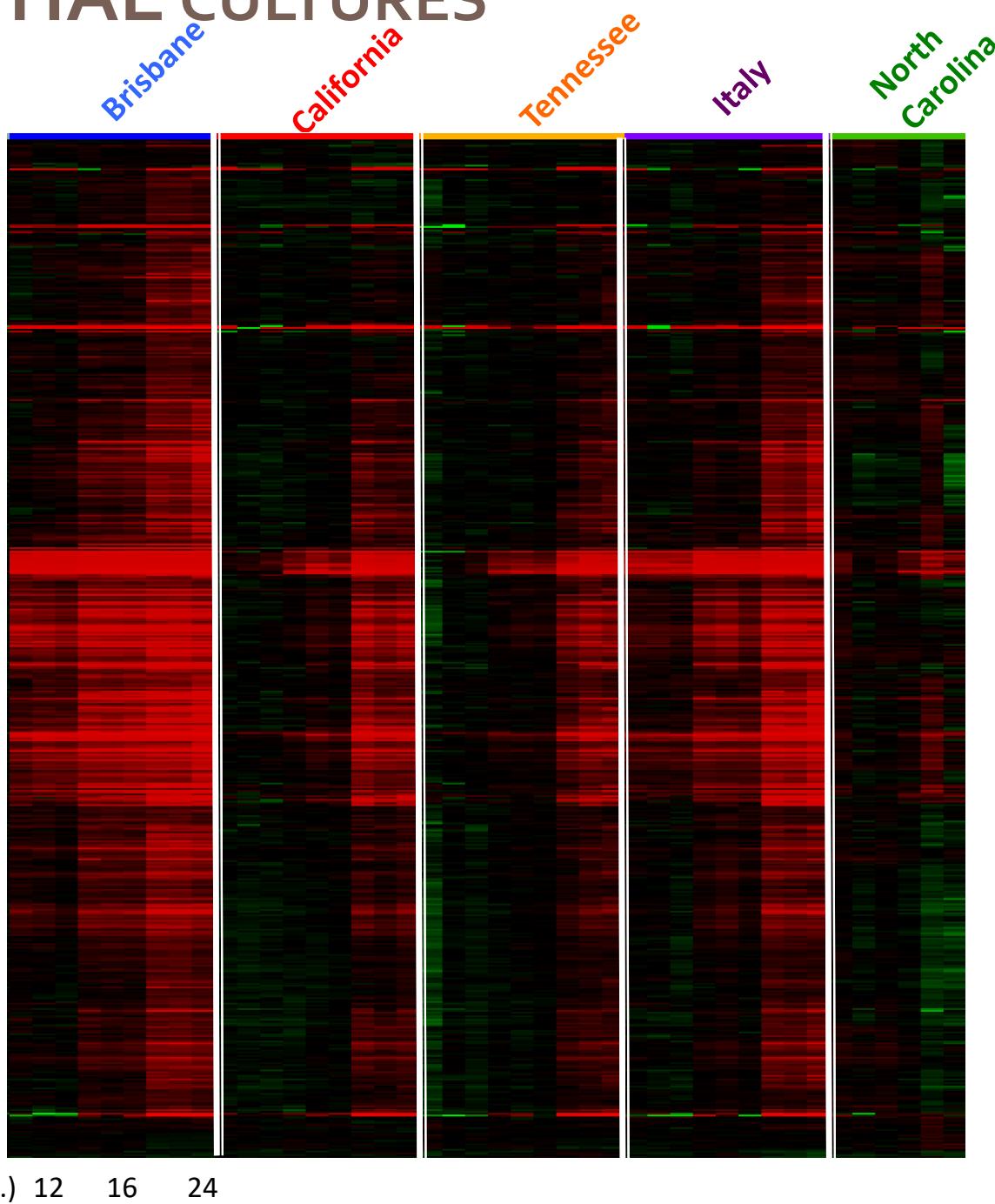
$$\begin{aligned}\frac{dU}{dt} &= \lambda D - \frac{b}{1 + s_1 X} UV && \text{uninfected cells} \\ \frac{dE}{dt} &= \frac{b}{1 + s_1 X} UV - \frac{g}{1 + s_3 X} E && \text{latent infected cells} \\ \frac{dI}{dt} &= \frac{g}{1 + s_3 X} E - dI && \text{productively infected cells} \\ \frac{dD}{dt} &= dI - \lambda D && \text{dead cells} \\ \frac{dV}{dt} &= \frac{p}{1 + s_2 X} I - cV - \gamma \frac{b}{1 + s_1 X} VU && \text{free virus}\end{aligned}$$

Why wasn't the Esw virus a pandemic?



# TRANSCRIPTOME ANALYSIS OF PANDEMIC VIRUS INFECTED HAE CULTURES

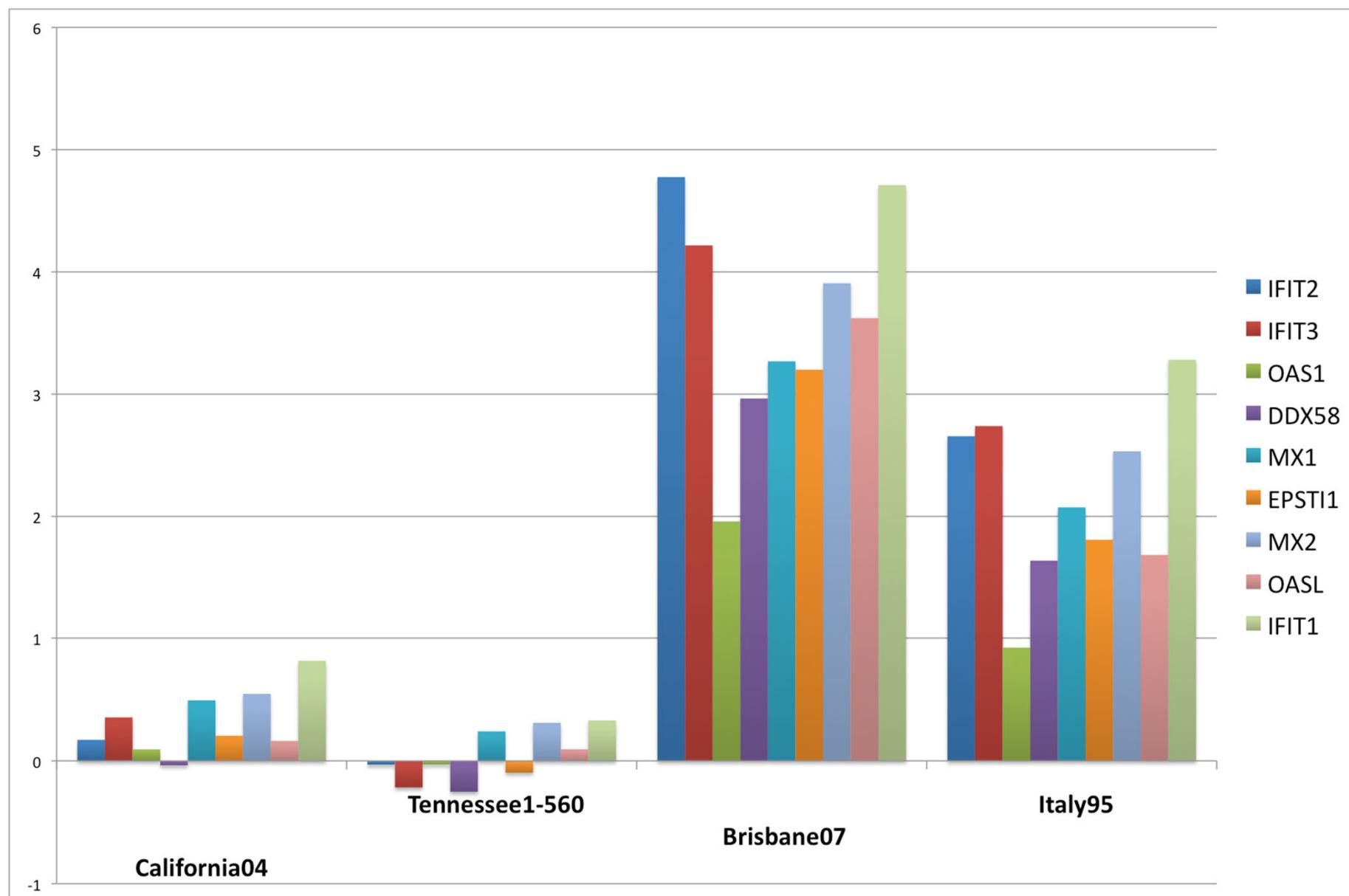
mRNA expression in  
hAE cultures  
infected at  
MOI=0.01



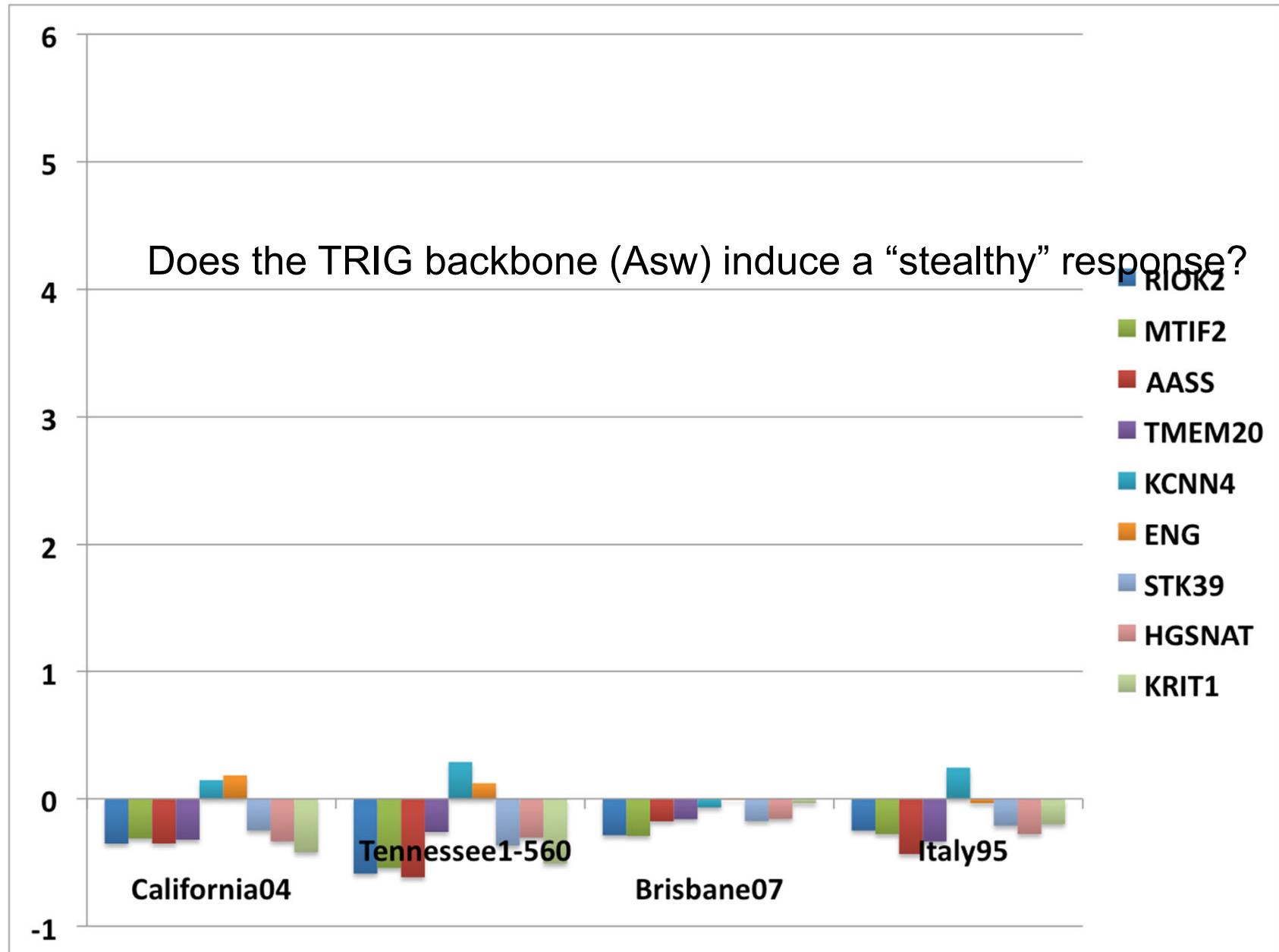
BIC applied to k-means clustering:  
2 clusters  
271 upregulated in all  
24 downregulated or differential



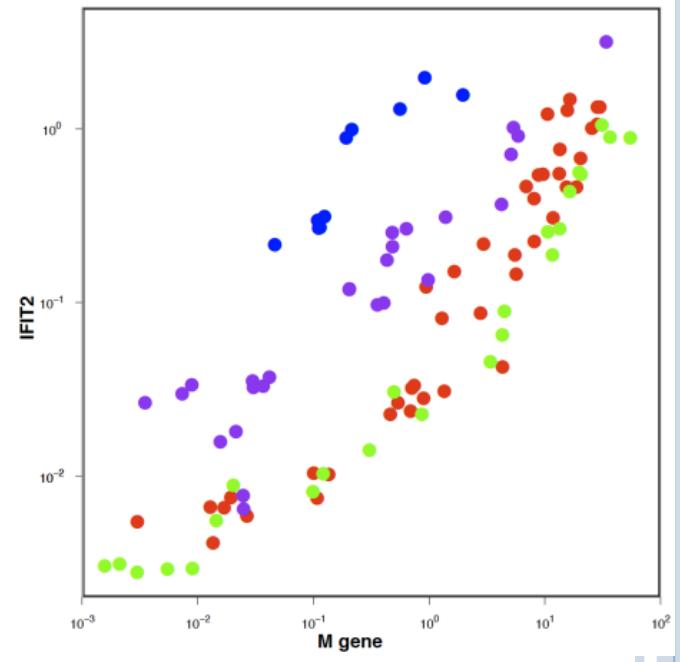
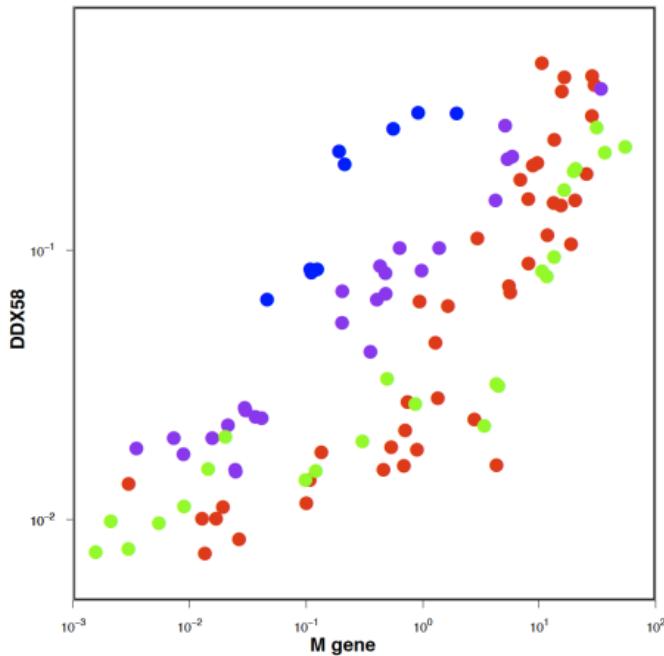
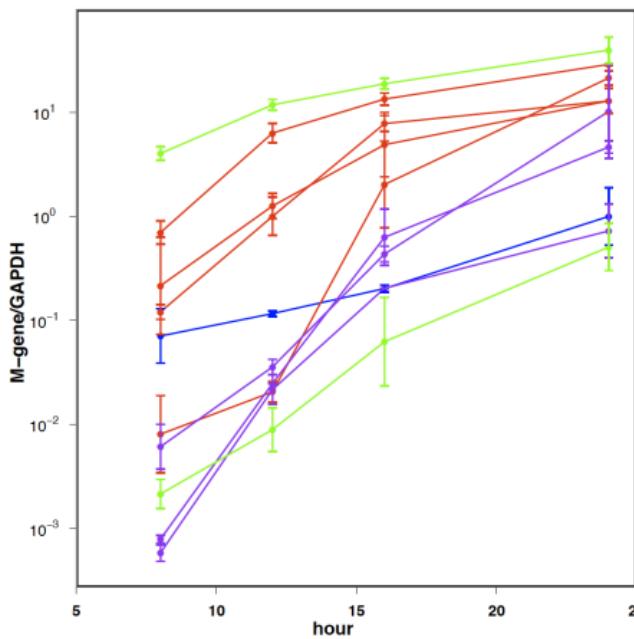
# TOP 9 MOST SIGNIFICANT DIFFERENTIALLY EXPRESSED GENES 12 HOURS POST-INFECTION WITH A/BRISBANE/59/2007(H1N1)



# TOP 9 MOST SIGNIFICANT DIFFERENTIALLY EXPRESSED GENES AT 12 HOURS POST-INFECTION WITH A/CALIFORNIA/04/2009(H1N1)



# HOST RESPONSE AS A FUNCTION OF VIRUS



Brisbane      California      Italy

North  
Carolina

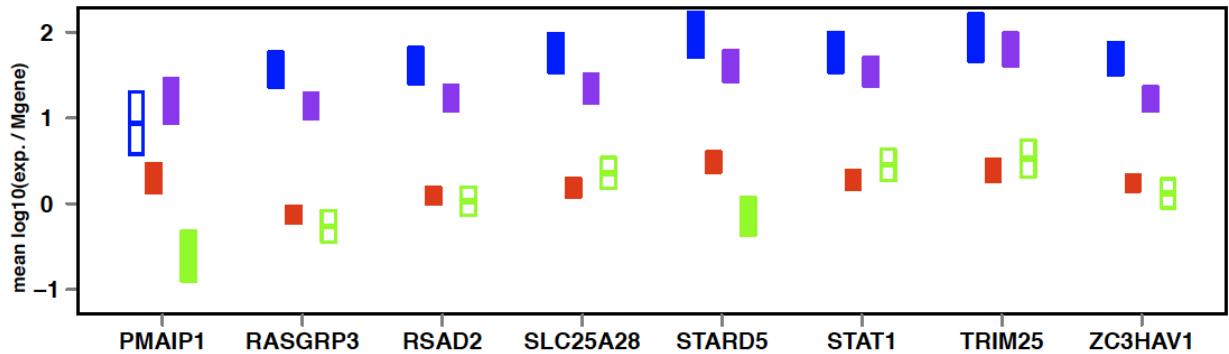
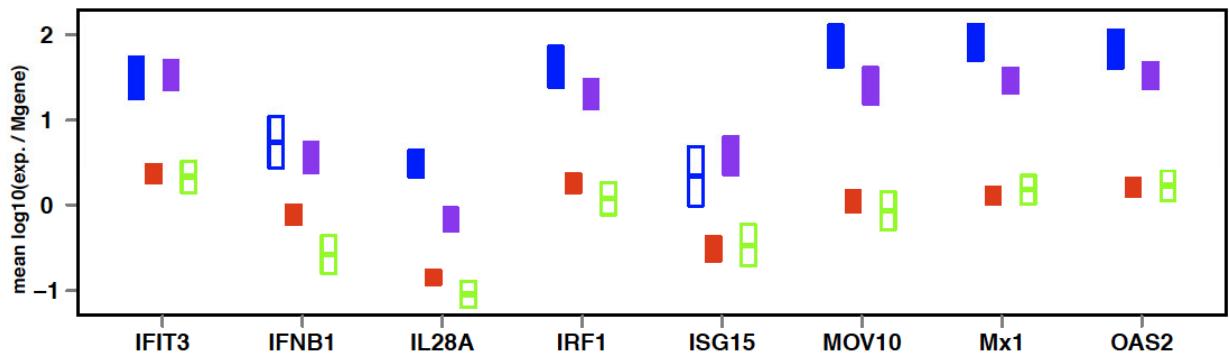
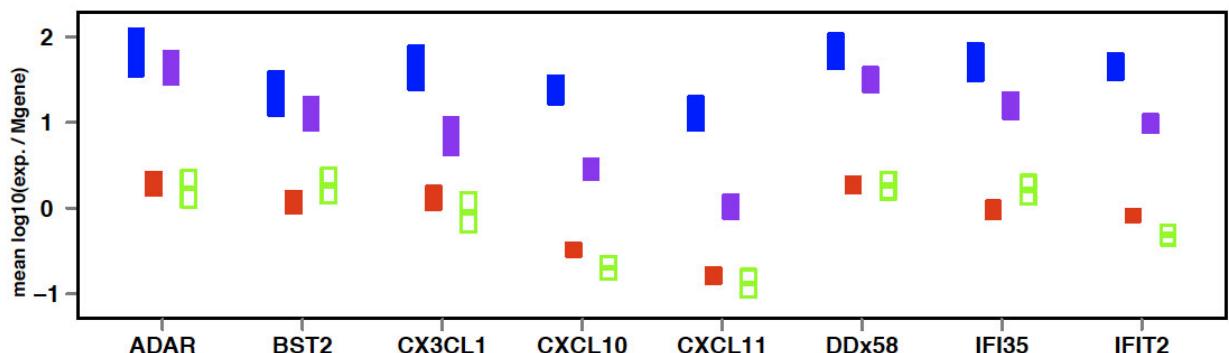
Fluidigm Real Time PCR from  
primary human cell infections  
(2 donors)



# HOST RESPONSE AS A FUNCTION OF VIRUS II

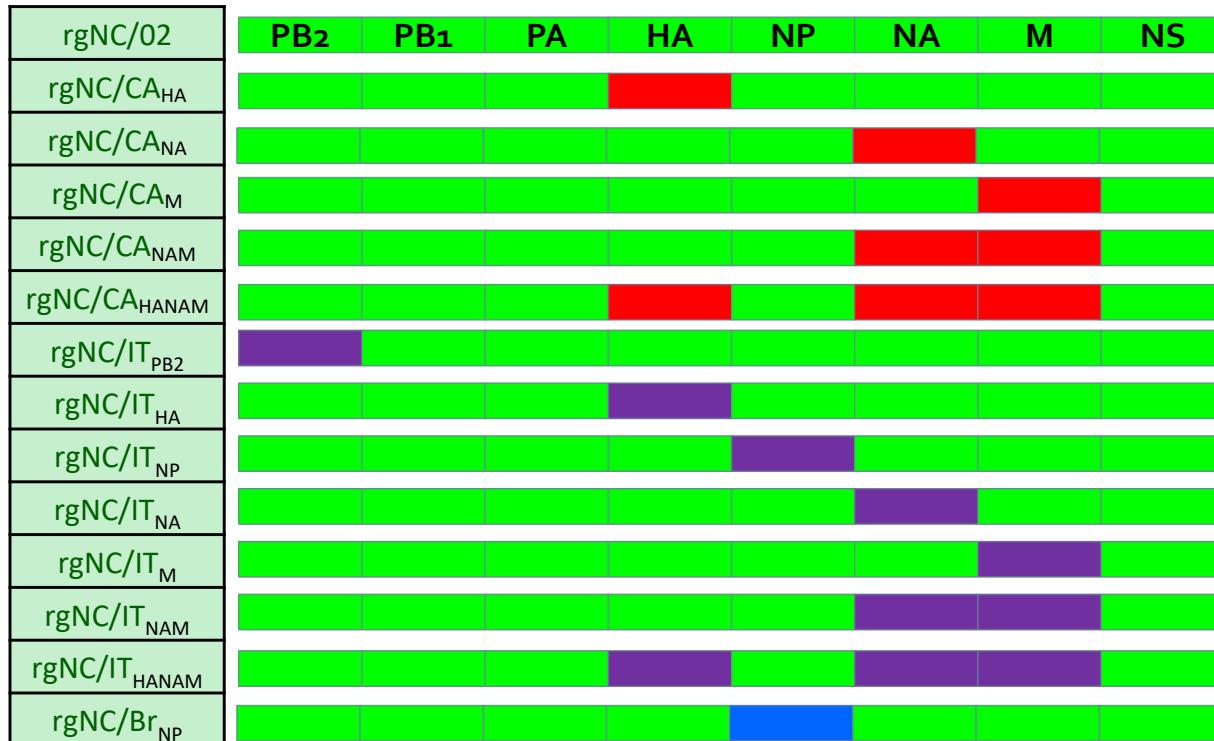
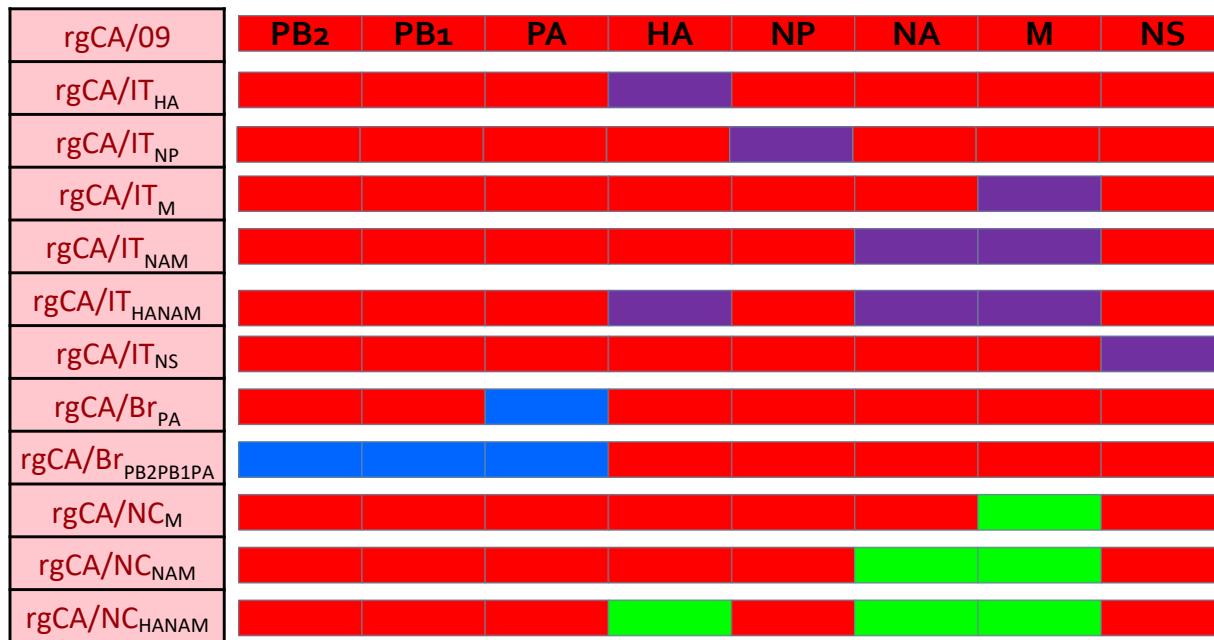
Brisbane      California  
 Italy            North Carolina

$$\frac{\text{expression} - \text{expression}_{\text{mock}}}{\max(\text{expression})} \quad M_{\text{gene}}$$



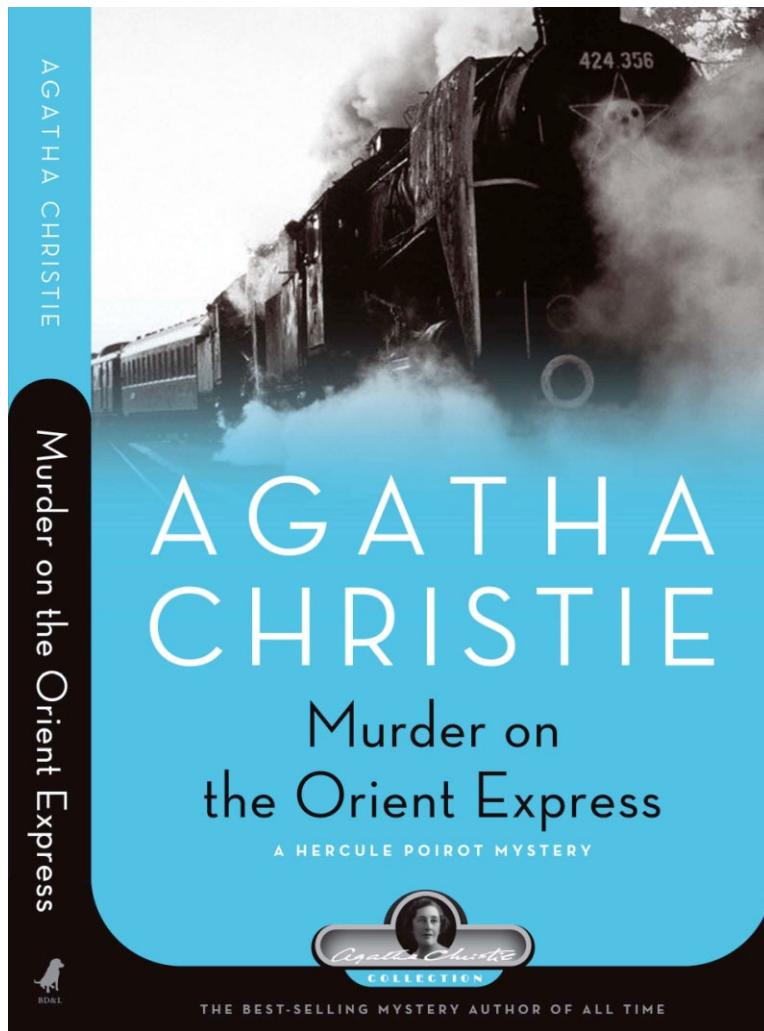
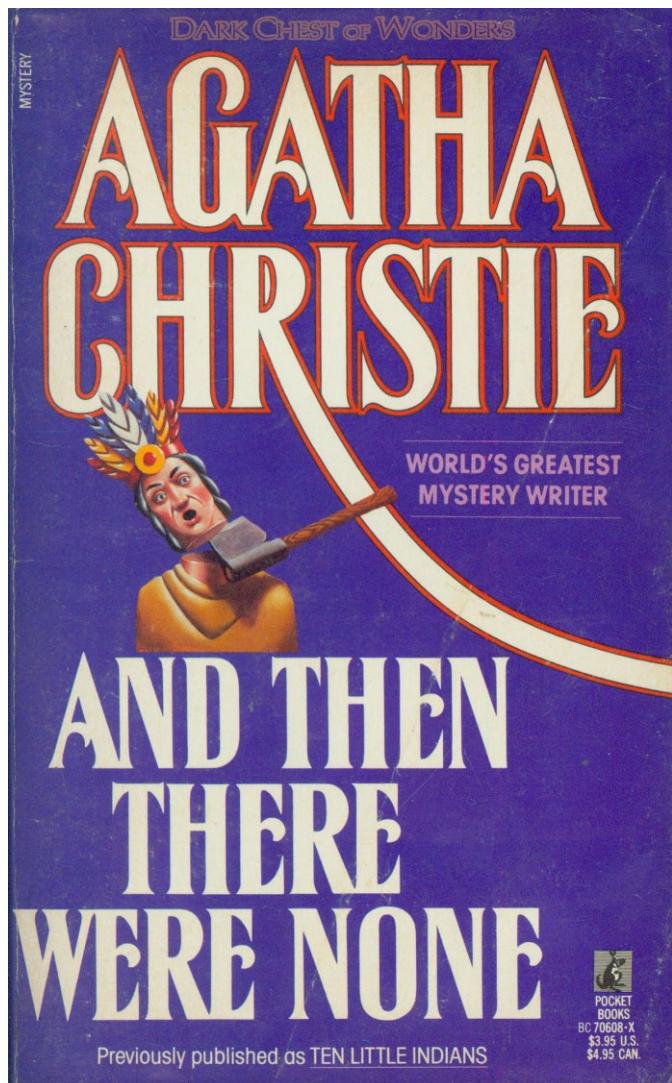
# SWAPS

What's the mechanistic basis of the stealthy (or noisy) phenotype?

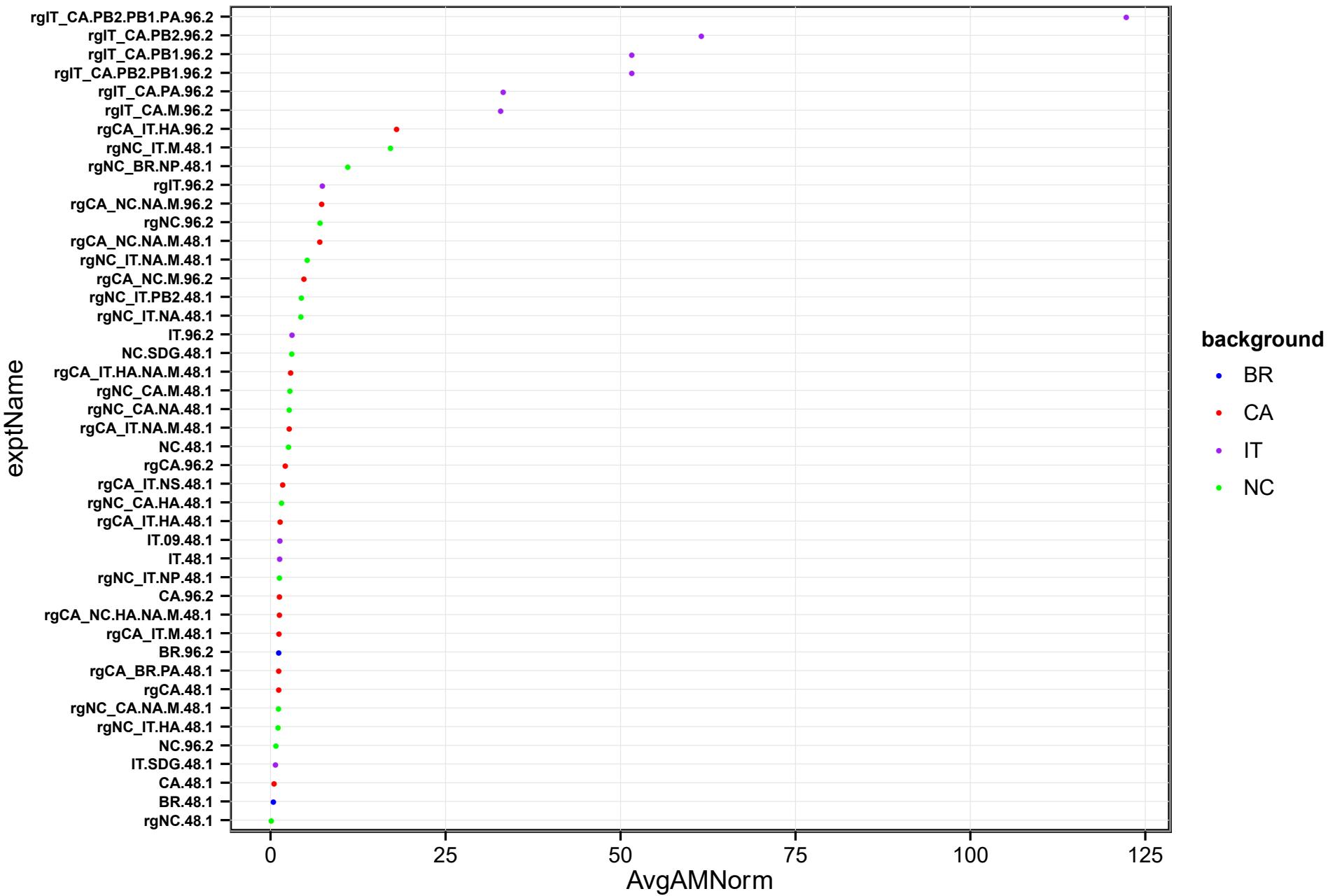


CA  
IT  
BR  
N  
C

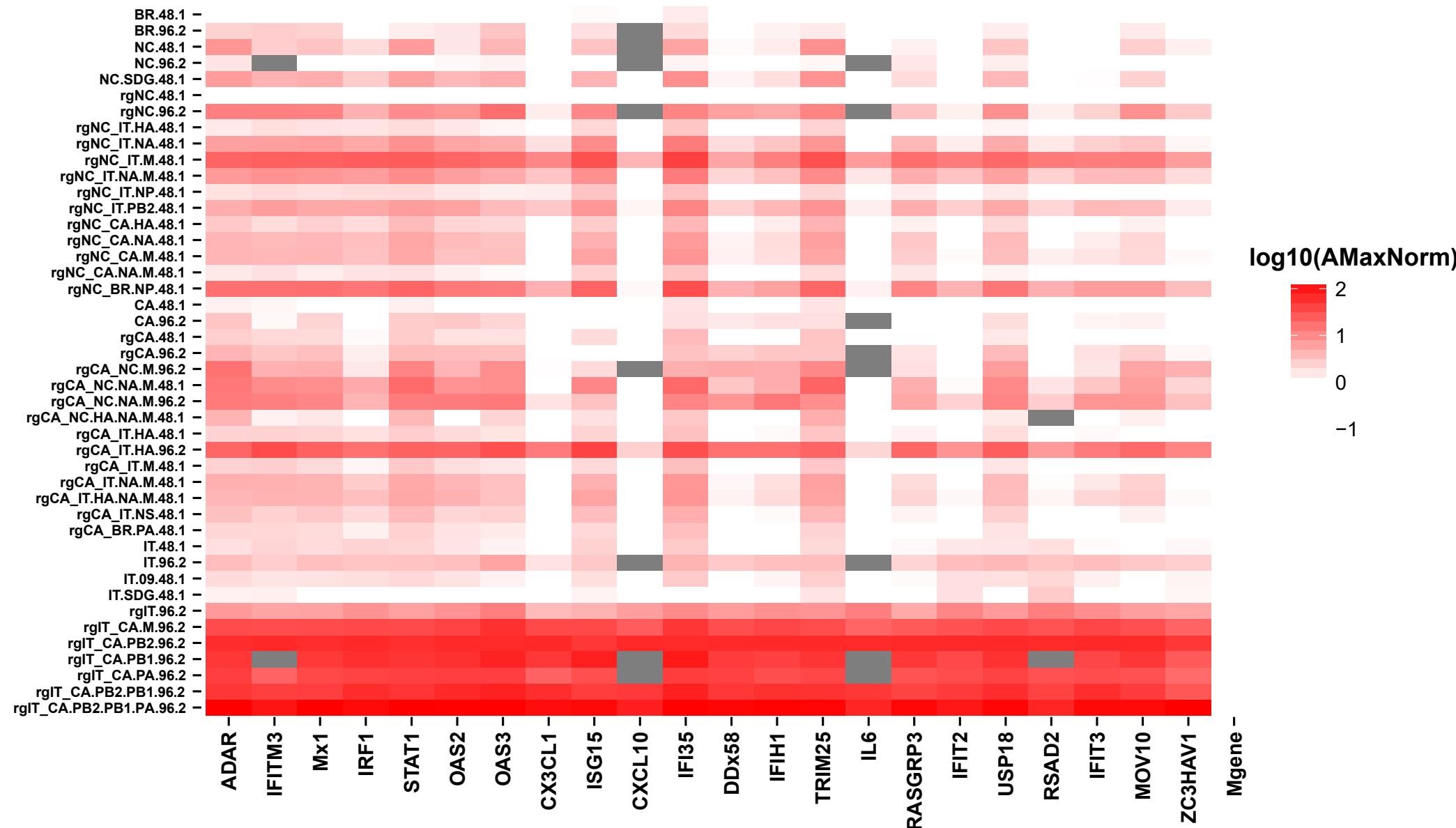
CA  
IT  
BR  
N  
C



# Average amplitude across all genes normalized to M-gene



# Amplitude (“A”) normalized to M-gene



# THE PANDEMIC STRAIN IS EFFICIENT AND STEALTHY

- Rapid + stealthy growth = Pandemic

[Morbidity and Mortality Weekly Report](#)

## Limited Human-to-Human Transmission of Novel Influenza A (H3N2) Virus — Iowa, November 2011

- The set of genes induced by diverse viruses is largely equivalent in the first 24 hours— “the flu program”
- The pandemic strategy is distinct from the well-adapted human seasonal virus
- Kinetic differences in the first ~18 hours of infection are critical to the quality and quantity of the later response
- The stealthy phenotype is mediated by contributions of the P-gene complex, with potential roles for NP and NS

## ODE MODEL OF INFLUENZA INFECTION

$$\frac{dU}{dt} = \lambda D - \frac{b}{1 + s_1 X} UV \quad \text{uninfected cells}$$

$$\frac{dE}{dt} = \frac{b}{1 + s_1 X} UV - \frac{g}{1 + s_3 X} E \quad \text{latent infected cells}$$

$$\frac{dI}{dt} = \frac{g}{1 + s_3 X} E - dI \quad \text{productively infected cells}$$

$$\frac{dD}{dt} = dI - \lambda D \quad \text{dead cells}$$

$$\frac{dV}{dt} = \frac{p}{1 + s_2 X} I - cV - \gamma \frac{b}{1 + s_1 X} VU \quad \text{free virus}$$

$$\frac{dX}{dt} = wI - \delta X \quad \text{innate immune response (IFN)}$$

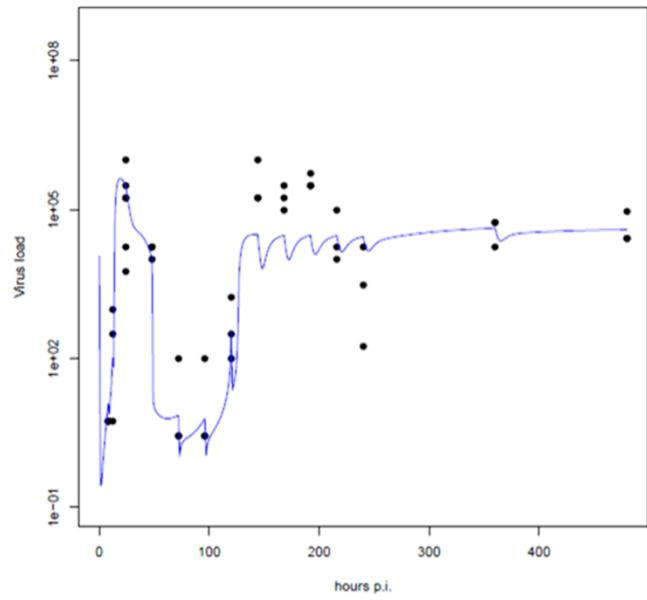
# AICc VALUES OF 8 DIFFERENT MODELS

- 1. No IR and no cell-regrowth
- 2. No IR, with cell-regrowth
- 3. With IR reducing virus production, no cell-regrowth
- 4. With IR reducing infection rate, no cell-regrowth
- 5. With IR prolonging latency, no cell-regrowth
- 6. With IR reducing virus production, with cell-regrowth
- 7. With IR reducing infection rate, with cell-regrowth
- 8. With IR prolonging latency, with cell-regrowth

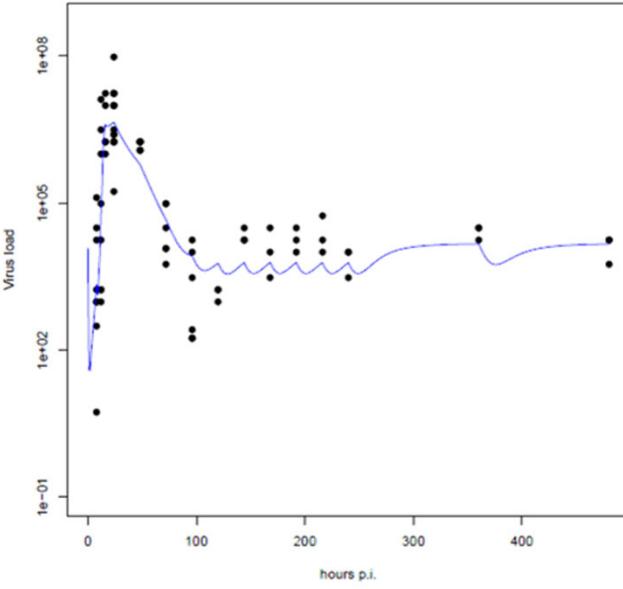
Model	BB	CA	IT	NC
1	54.5	54.7	33.1	28.2
2	48.8	-22.6	0.8	28.5
3	52.8	24.8	17.0	30.3
4	59.9	33.2	38.3	33.6
5	53.2	32.1	24.6	31.7
6	-11.6	-17.6	-11.1	33.2
7	54.5	-17.7	6.1	29.3
8	56.1	-17.3	6.2	34.3

# FITS FOR MODEL 6—IR REDUCES VIRUS PRODUCTION AND CELLS REGROW

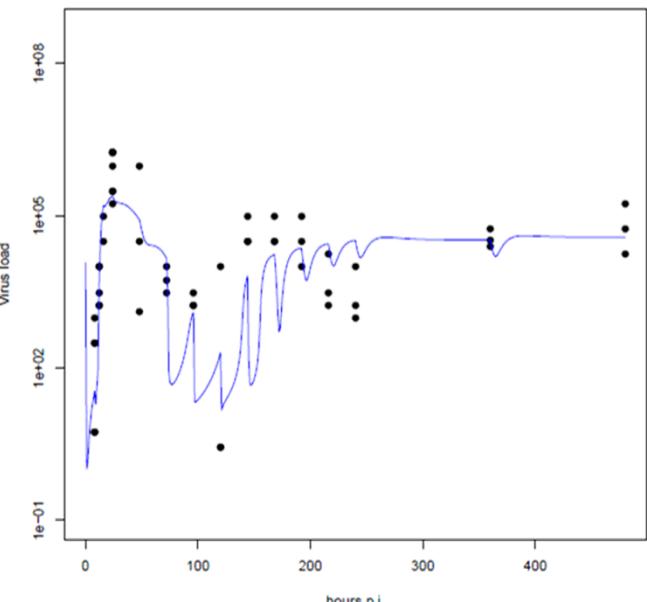
BR



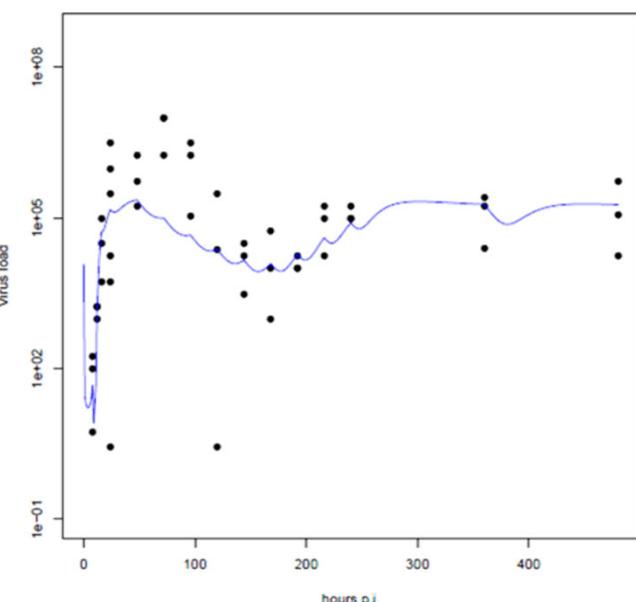
CA



IT



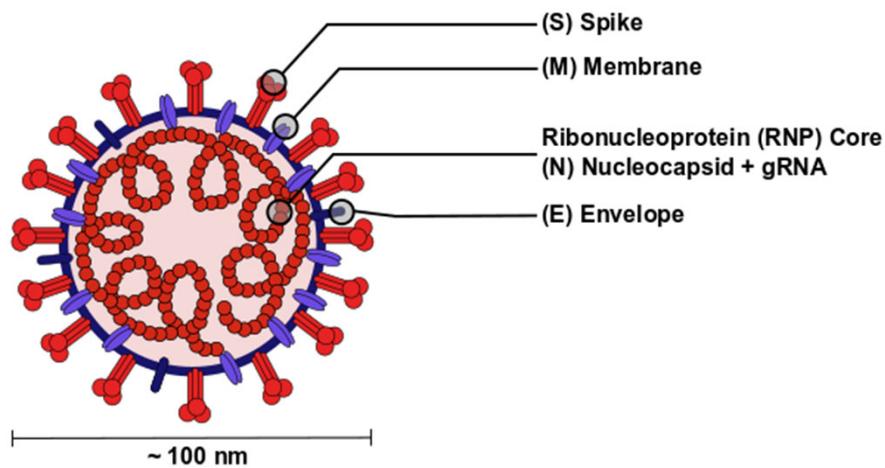
NC





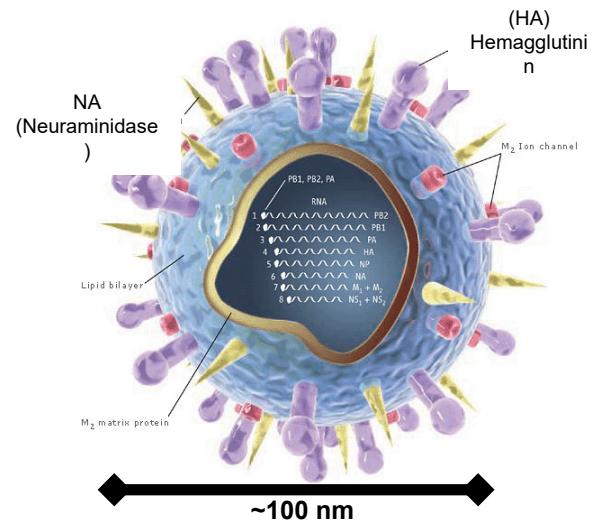
# SARS-CoV-2 VS. INFLUENZA VIRUS

The Coronavirus Virion



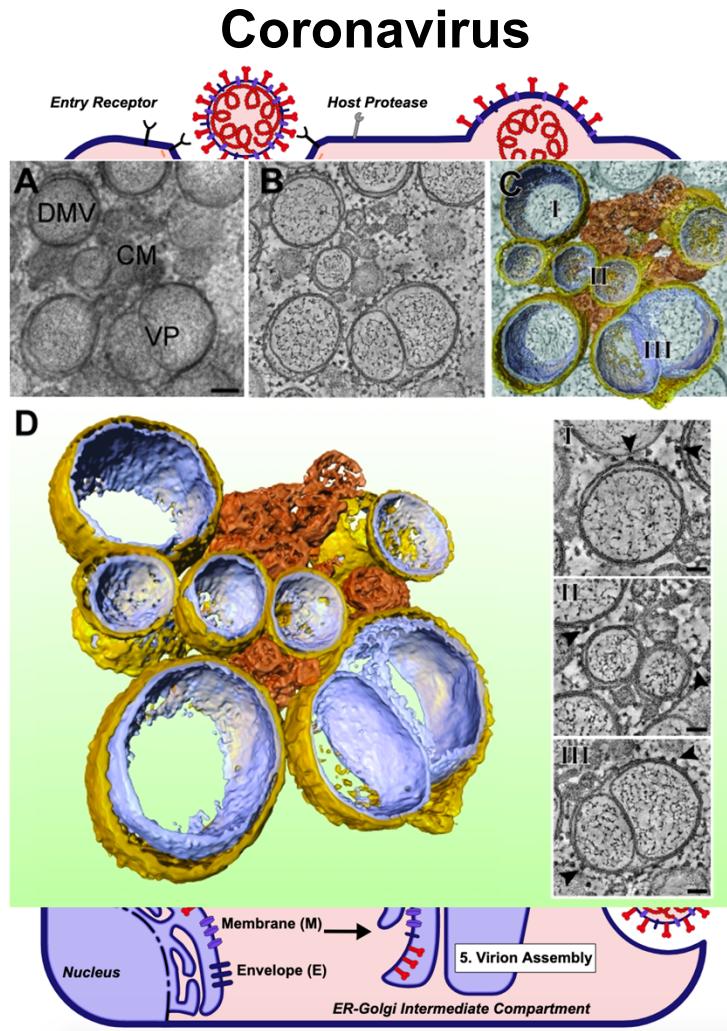
(+) ssRNA genome ~28-32 Kb  
29 proteins

The Influenza Virus Virion

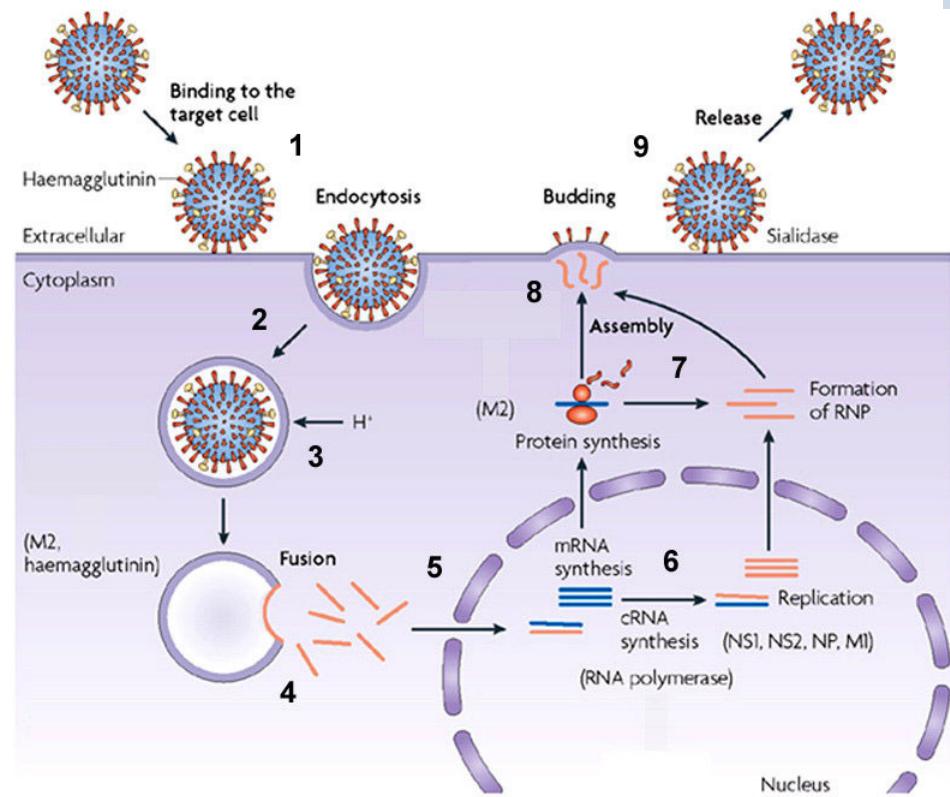


(-) segmented ssRNA genome ~28-32 Kb  
~14 Kb, 10-14 proteins

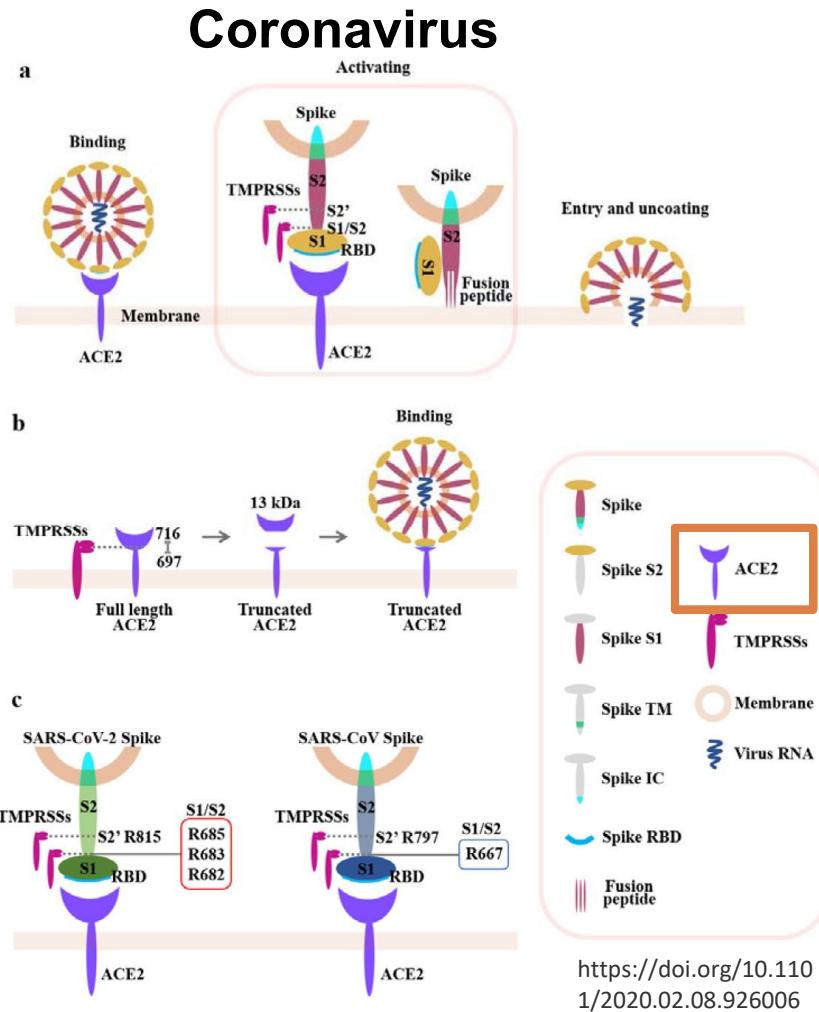
# Coronavirus and influenza virus replication cycles



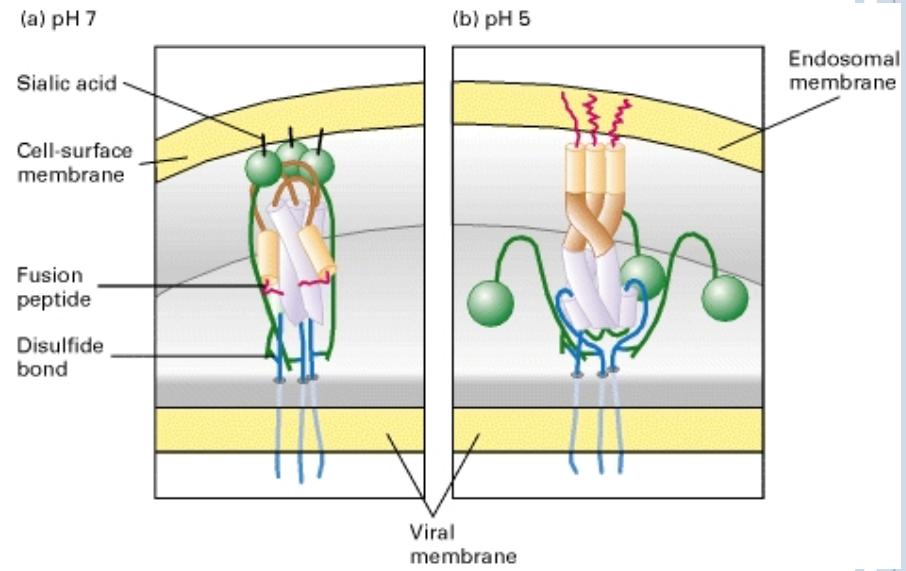
## Influenza virus



# DISTINCT RECEPTOR BINDING FEATURES OF SARS VS. INFLUENZA VIRUSES

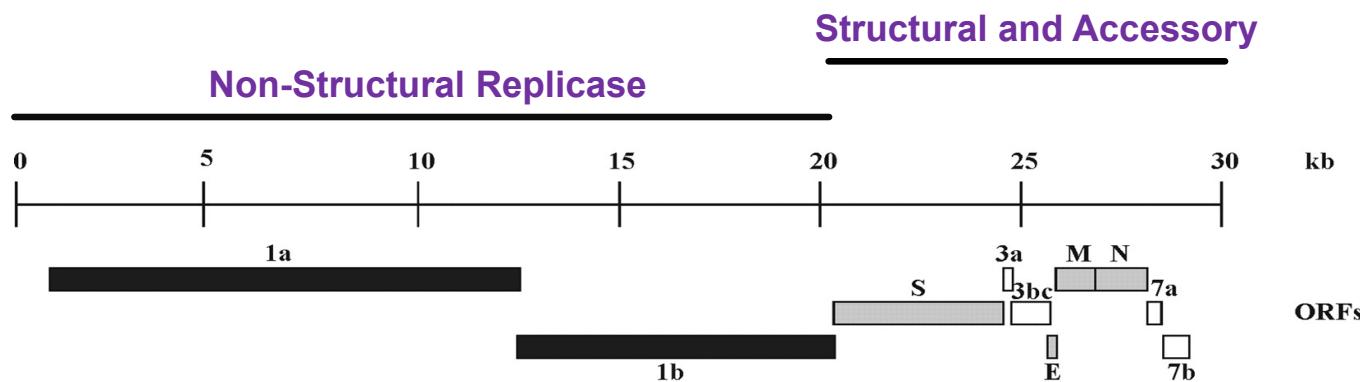


## Influenza virus



Influenza HA binds to sialic acid residues on diverse surface proteins

# Coronavirus Genome Encodes Several IFN Antagonists



## 1. Non-Structural Proteins (nsp1-16)

Conserved across CoVs

Various, required functions

IFN antagonists: nsp1, PLP2

(nsp3)

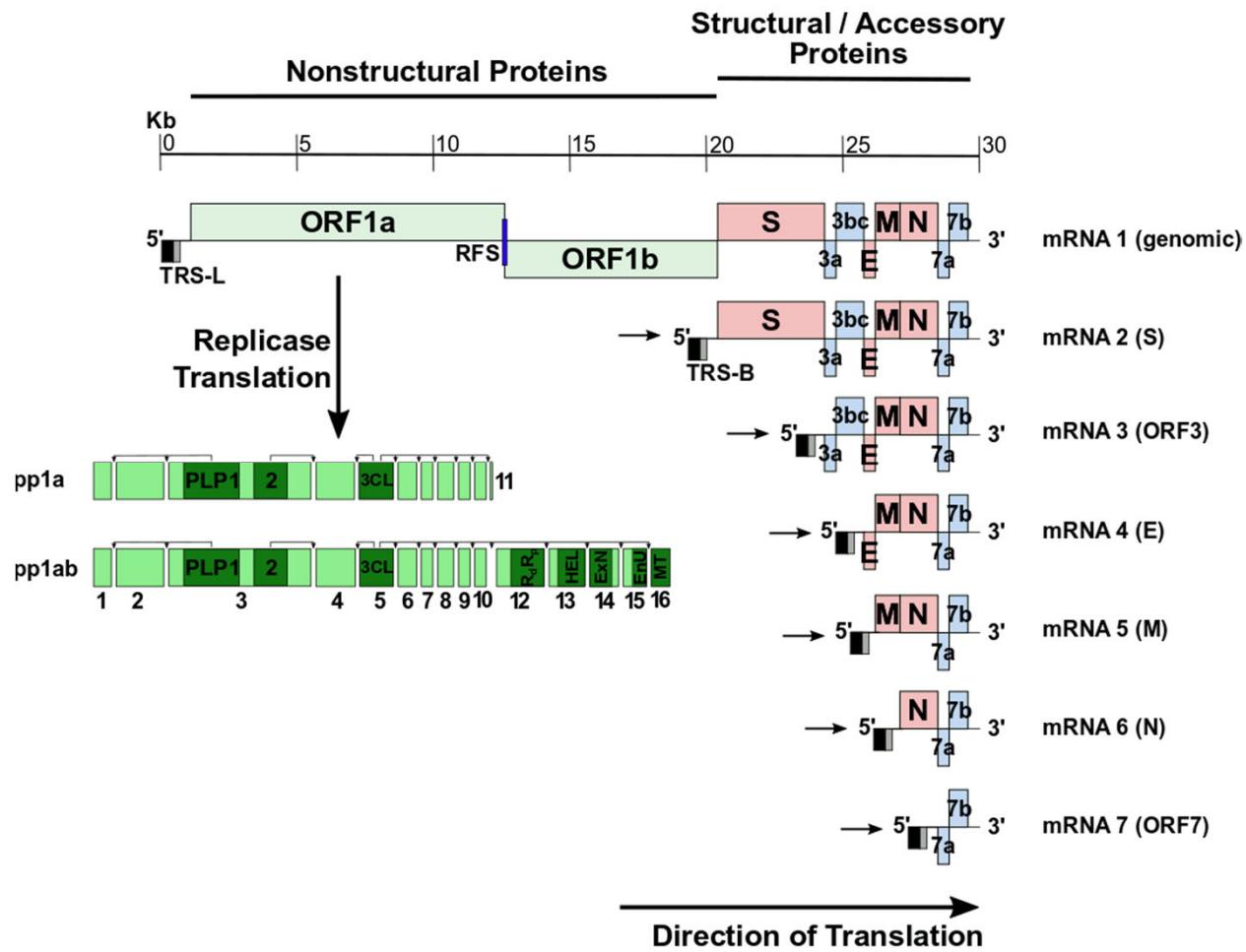
## 2. Accessory Proteins

Unique to subfamilies and species

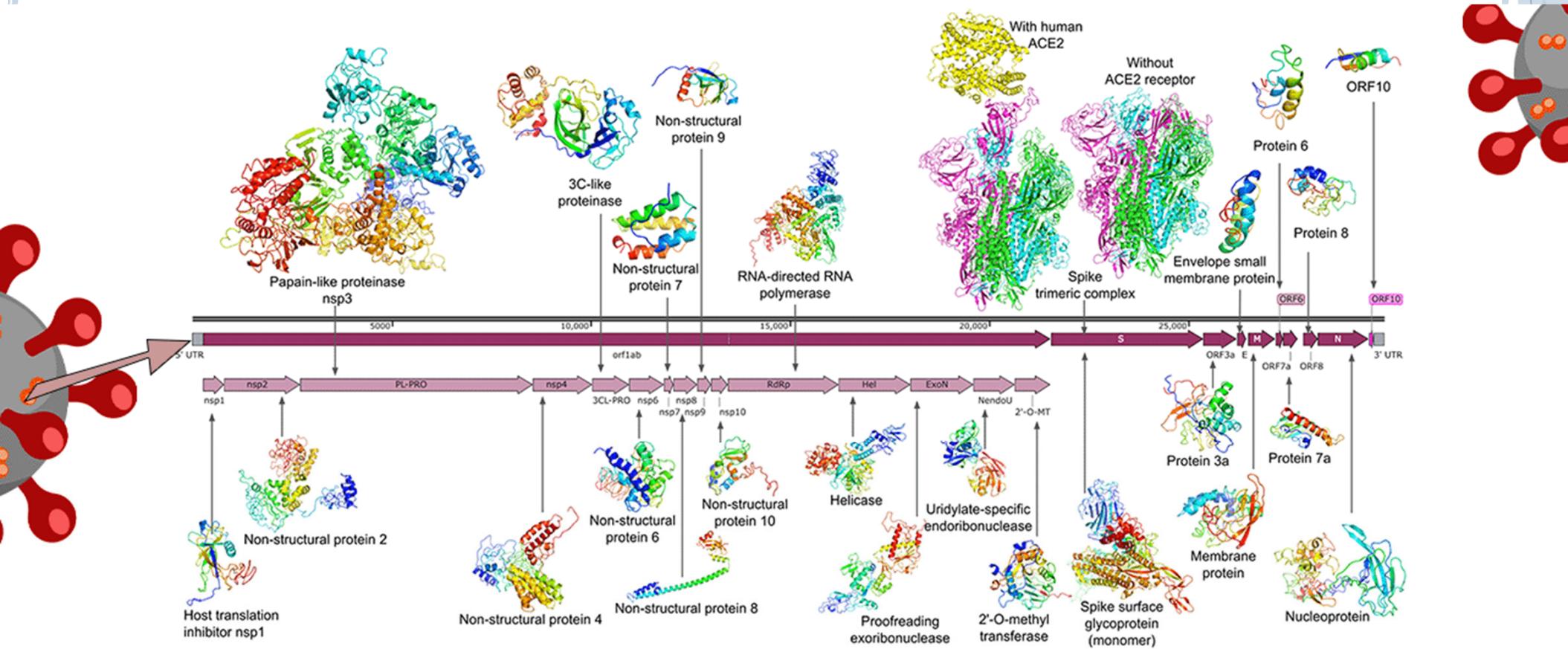
Function dispensable for replication

Encode virulence factors

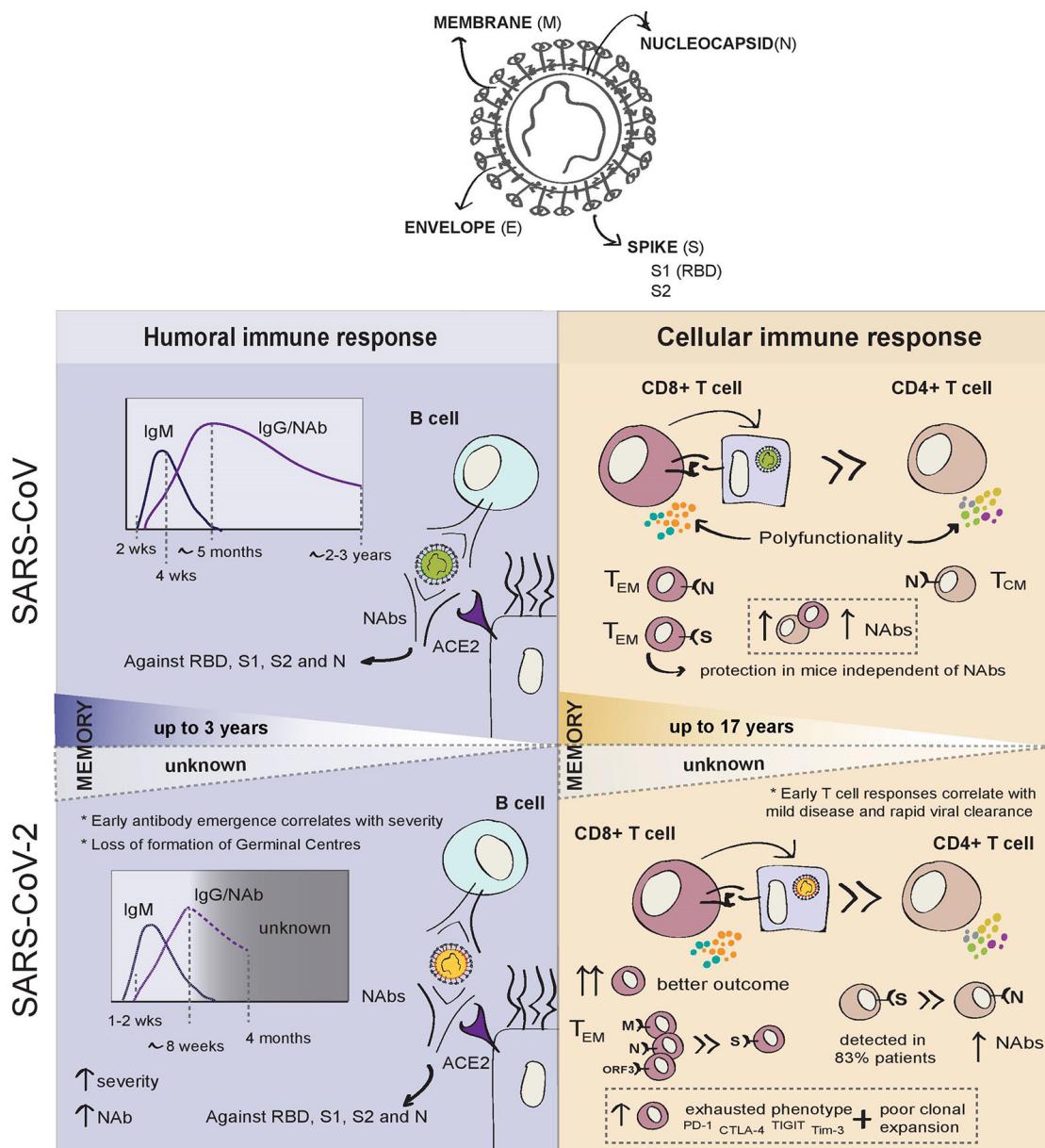
# Coronavirus Genome Structure and Duplication



# LARGE SARS-COV-2 PROTEOME CONTAINS MANY IMMUNOMODULATORY NON-STRUCTURAL PROTEINS



# PROTECTIVE IMMUNITY AGAINST SARS-CoV-2



## SARS-CoV-2 VS. INFLUENZA VIRUS SUMMARY

### SARS-CoV-2

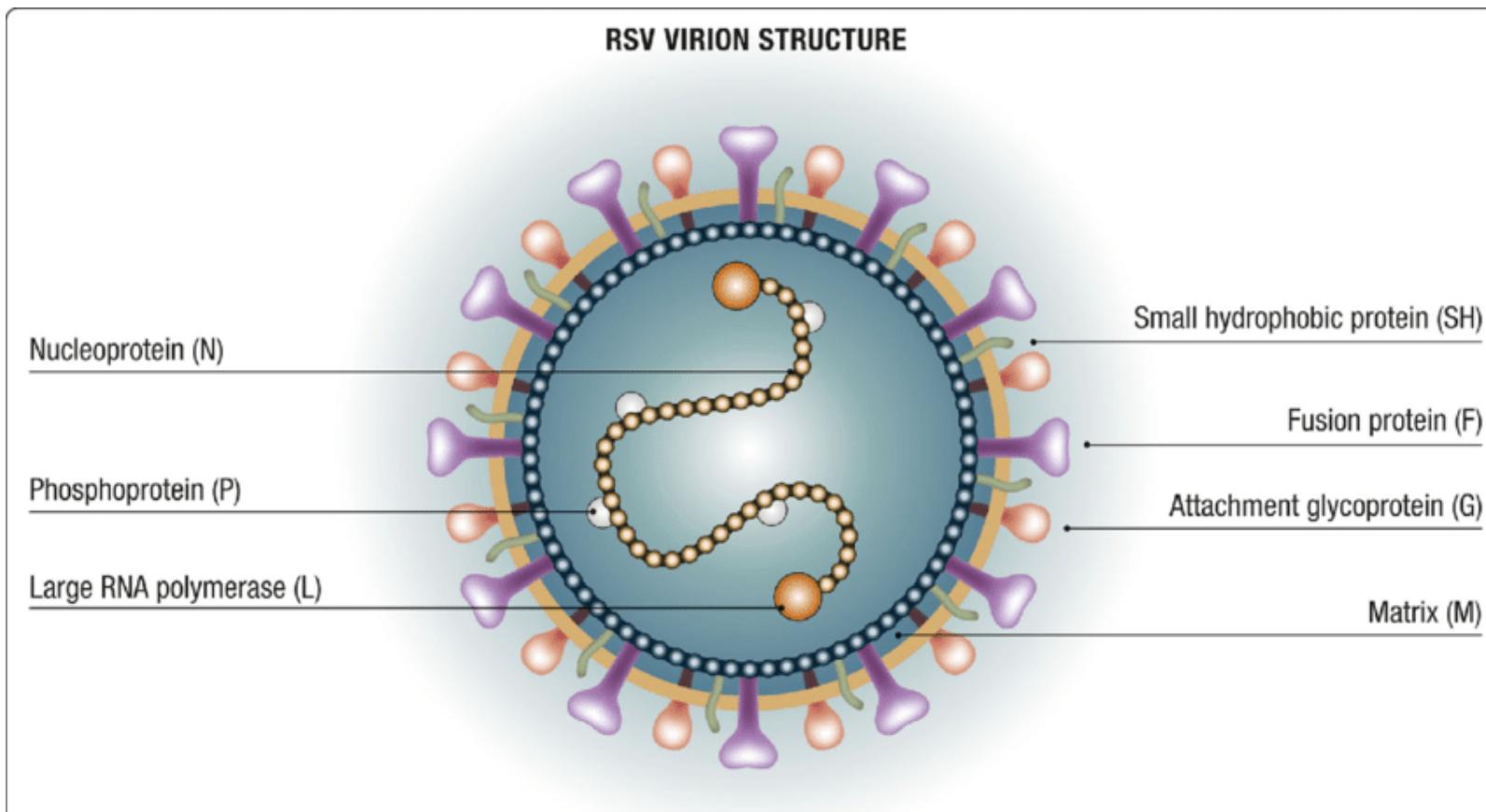
- RNA virus (+ sense)
- Single segment
- Large genome
- Multiple immune antagonists
- Specific receptor (ACE2)

### Influenza virus

- RNA virus (- sense)
- 8 segments
- Much smaller genome (than CoV)
- Single immune antagonist (ds RNA sequestration)
- Non-specific receptor



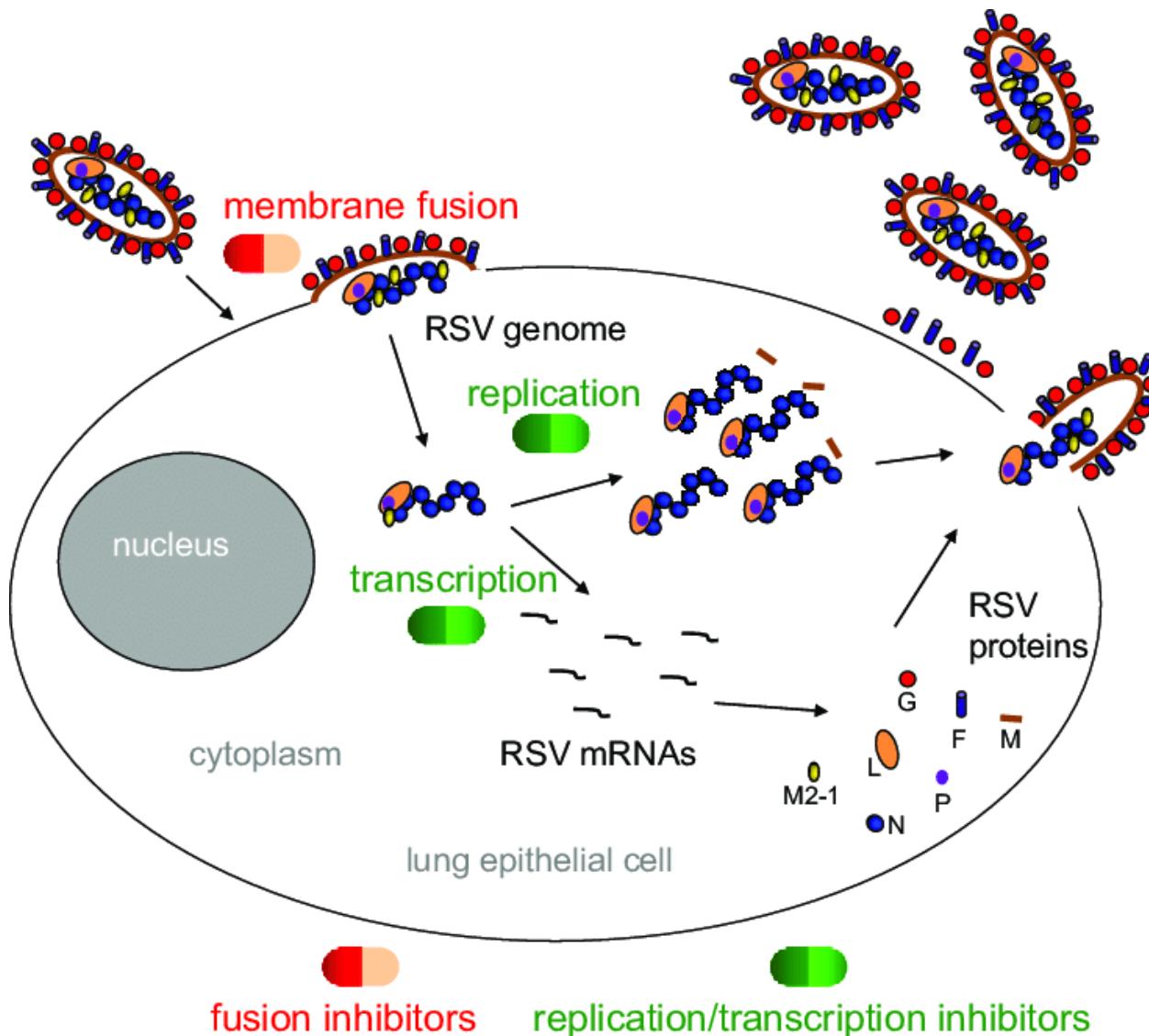
# RSV VIRION STRUCTURE



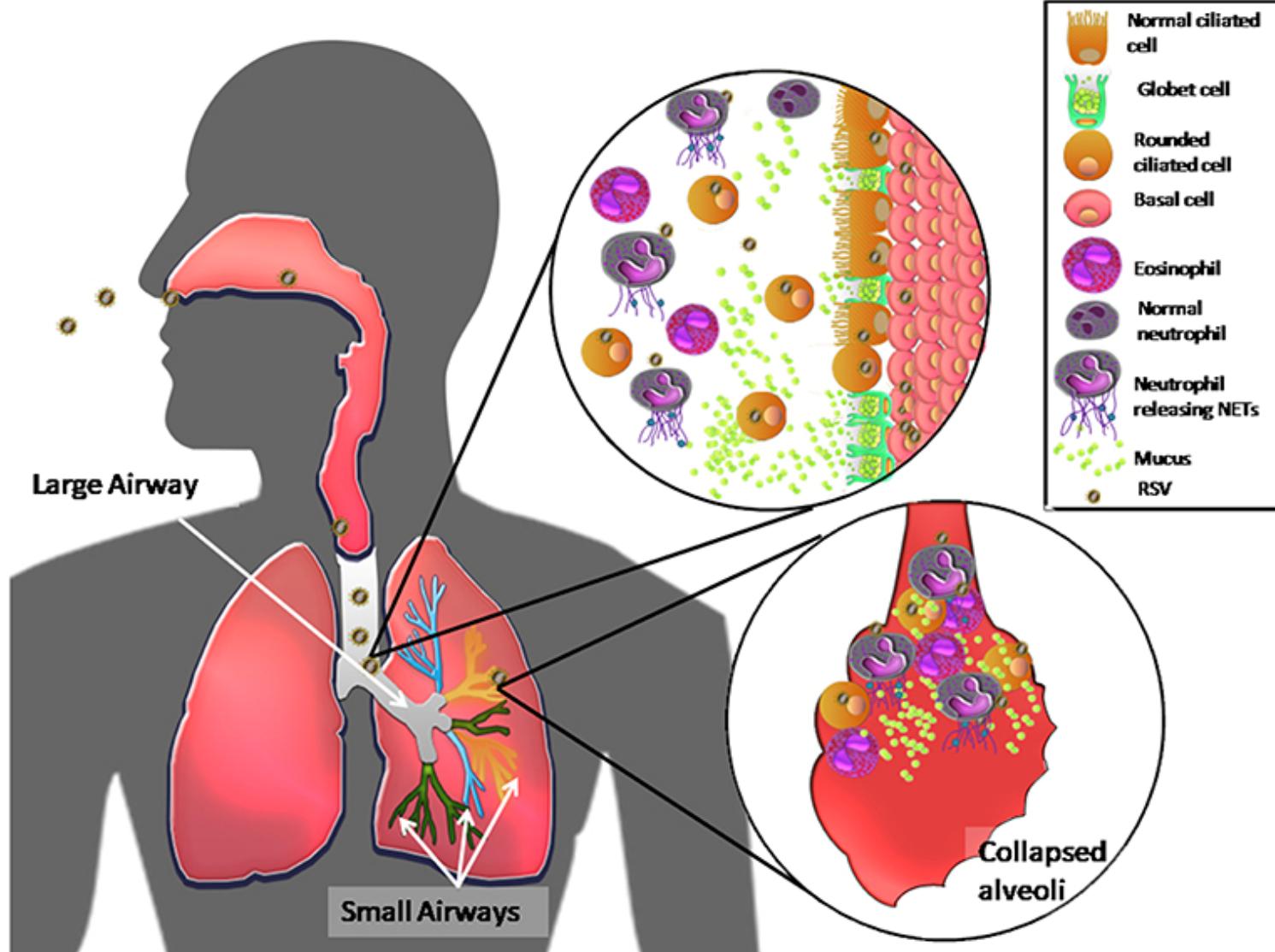
Epidemiology and prevention of respiratory syncytial virus infections in children in Italy.  
Italian Journal of Pediatrics. 47. 198.  
10.1186/s13052-021-01148-8

New antiviral approaches for respiratory syncytial virus  
and other mononegaviruses: Inhibiting the RNA  
polymerase

# RSV REPLICATION

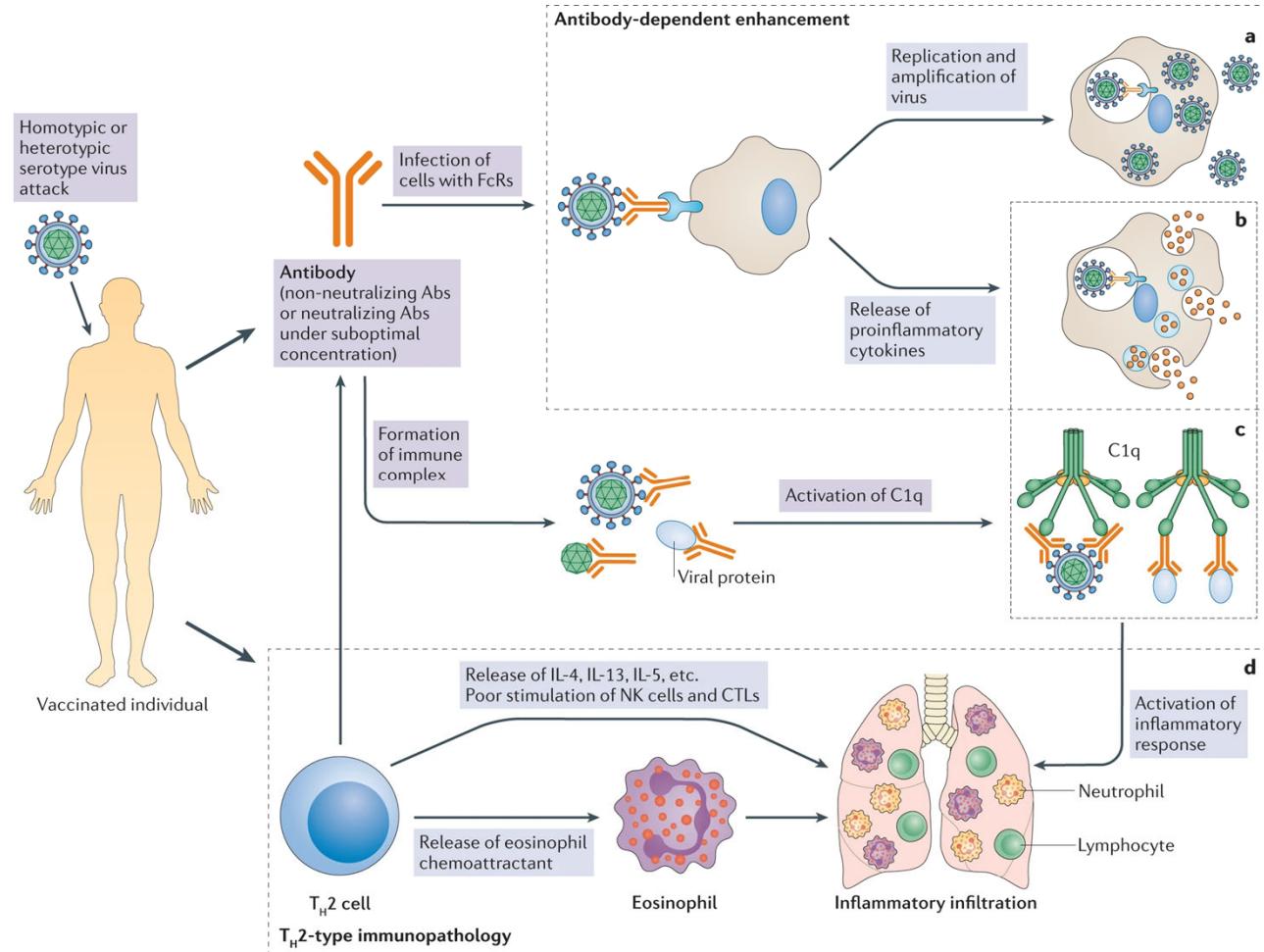


# UNIQUE FEATURES OF RSV PATHOGENESIS



# RSV VACCINATION FAILURE

1960 era  
vaccine  
80% of children  
suffered severe  
disease after  
infection  
Two deaths



Published: 14 December 2008

**Lack of antibody affinity maturation due to poor Toll-like receptor stimulation leads to enhanced respiratory syncytial virus disease**

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