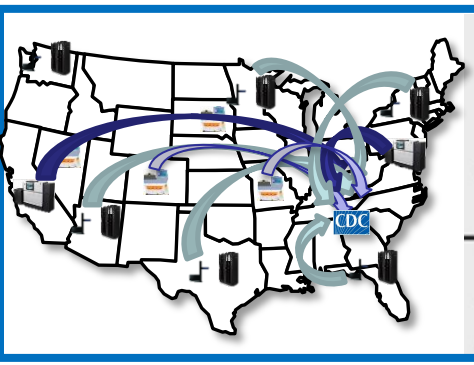
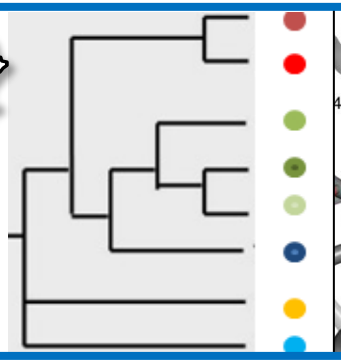
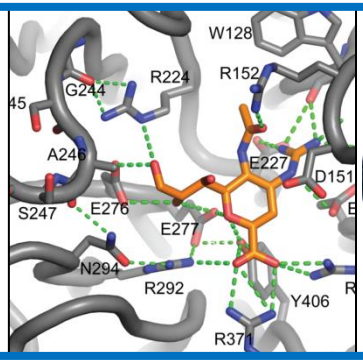
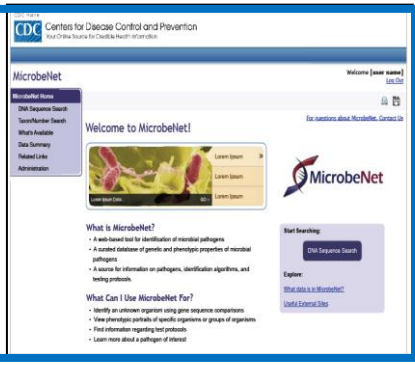
CDC PUBLIC HEALTH GRAND ROUNDS

# Advanced Molecular Detection for Improving Public's Health



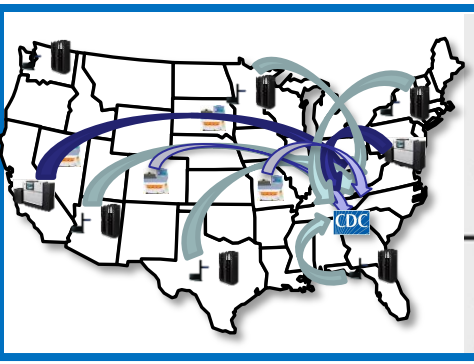


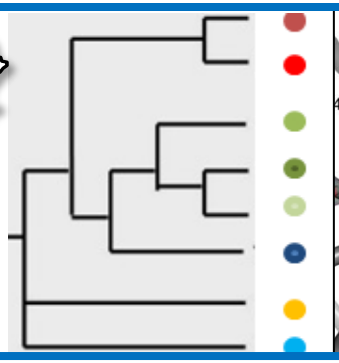


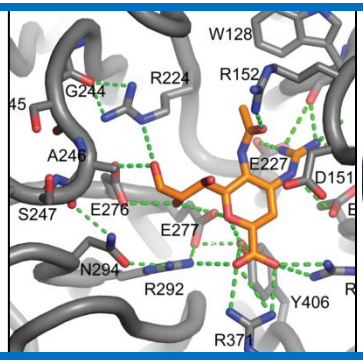

December 3, 2013

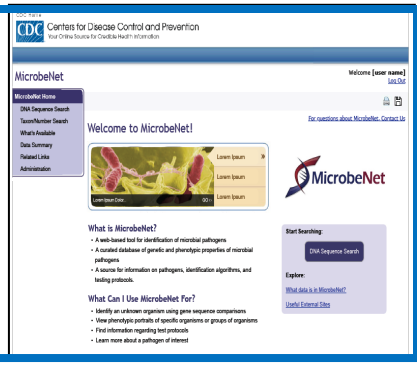
U.S. Department of Health and Human Services
Centers for Disease Control and Prevention

# What is Advanced Molecular Detection?








**Duncan MacCannell, PhD**

*Senior Advisor for Bioinformatics*

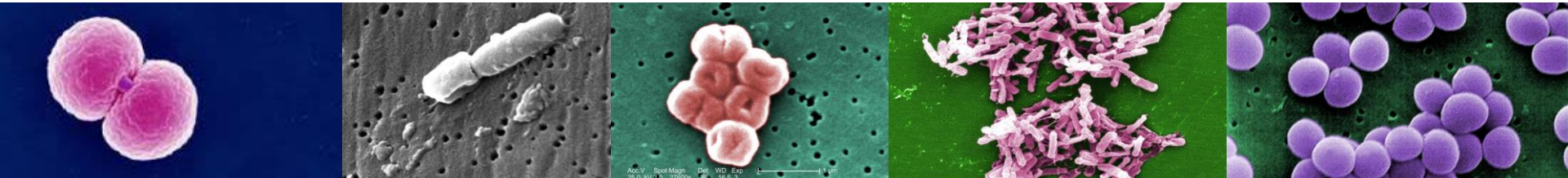
National Center for Emerging and Zoonotic Infectious Diseases, CDC



U.S. Department of Health and Human Services
Centers for Disease Control and Prevention

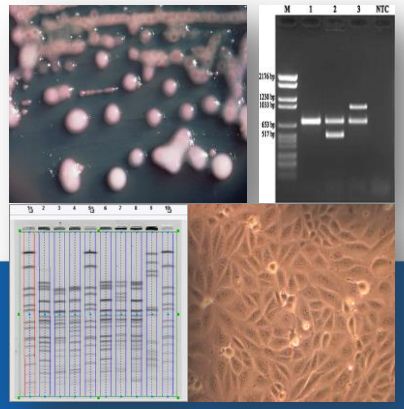
# Emerging Threats

- **Pathogens**
  - Highly resistant pathogens in health care settings
  - Pathogens that jump from animals to humans
  - Globalization and the emergence of new and virulent pathogens
  - 5 pathogens are resistant to nearly all available drug treatments
- **Economic cost**
  - 1 in 6 Americans (48 million people) get sick from contaminated food products each year
    - Cost: $77B/year in healthcare treatment, workplace, and other economic losses
  - Each year, flu alone costs businesses ~$10.4B in direct costs for adult hospitalizations and outpatient visits

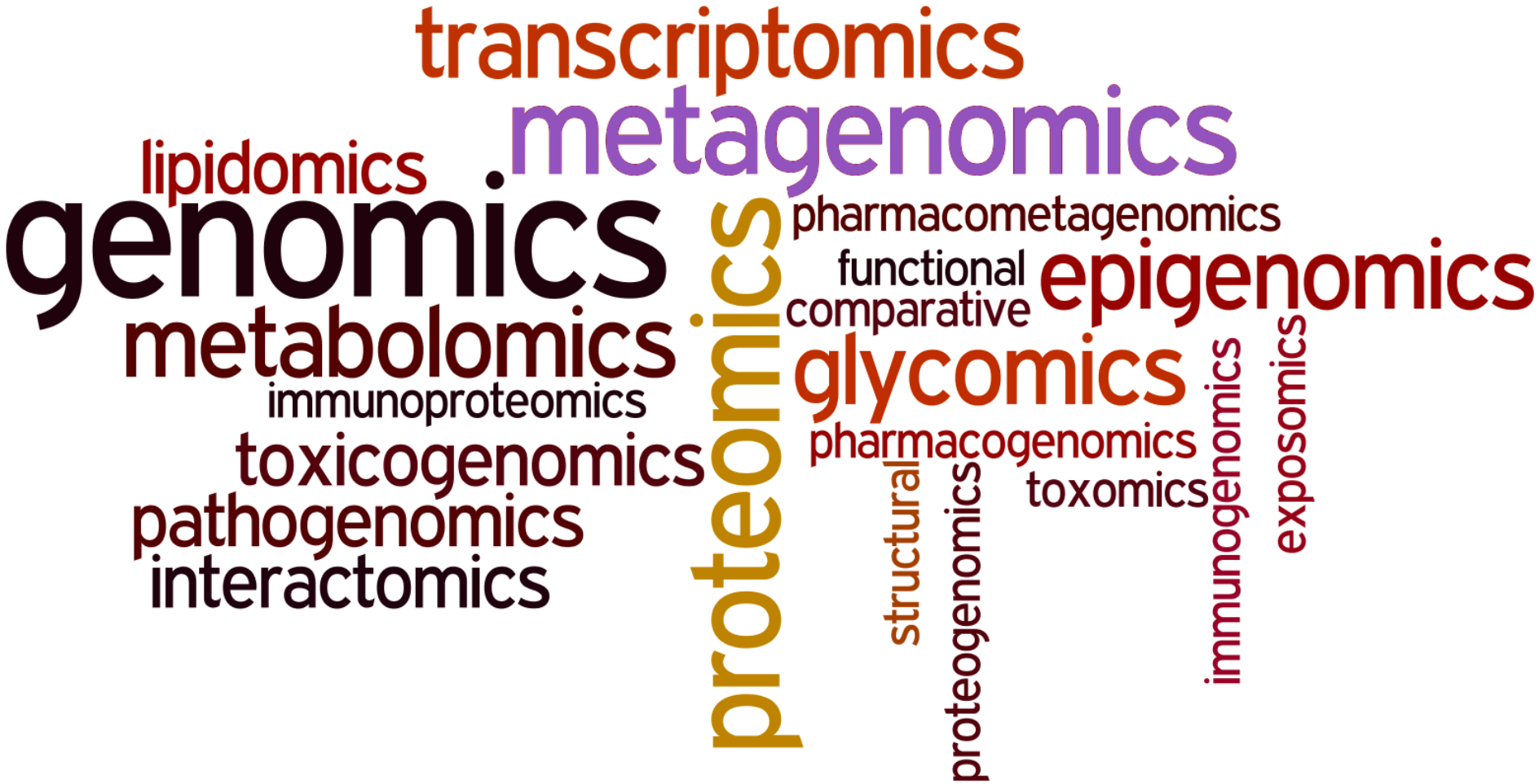


# Challenges and Opportunities

- **Decades-old methods of detecting microbes and understanding their effect on human health are limiting our ability to respond to infectious disease threats**
- **The era of "-omics" and bioinformatics**
  - Allows improvements in cost, throughput, and accuracy
  - Represents a new paradigm for public health laboratories



# The "-omics" at CDC




Metagenomics: Study of the genetic material of all the microbes in a specimen

Genomics: Study of the genetic material of an organism

Transcriptomics: Study of the transcriptome, the set of all RNA molecules in one cell or a population of cells

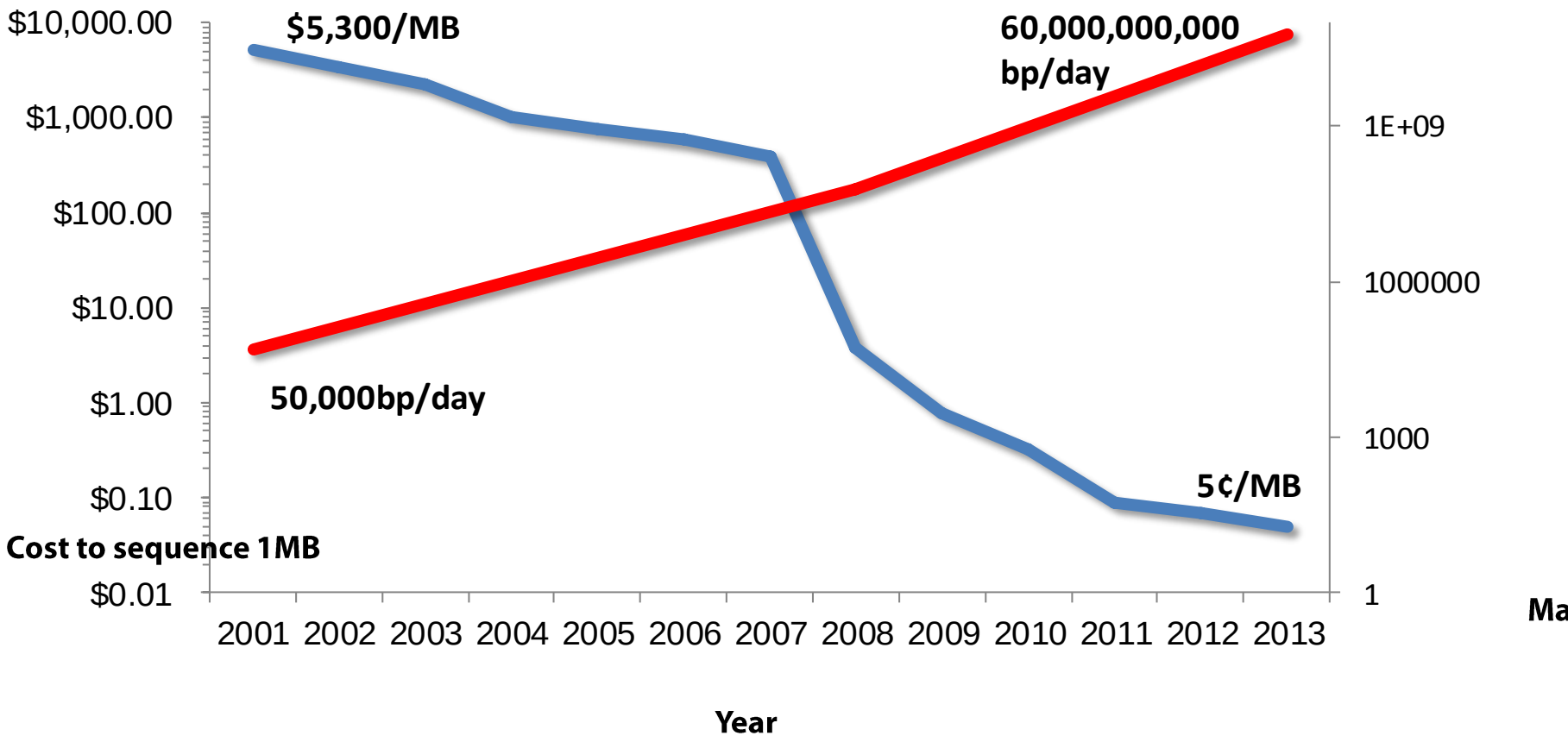
# Examples of Advanced Molecular Detection Technologies at CDC

- **Genomics, metagenomics, and transcriptomics**
  - Next generation sequencing: high-throughput deep sequencing
  - RNA sequencing
  - Functional/comparative genomics, metagenomics
  - New, massively-parallel PCR- and array-based methods
- **Proteomics**
  - MALDI-TOF (matrix-assisted laser desorption/ionization–time of flight)

**Bioinformatics and advanced data analytics**

The challenge is no longer doing the testing but having the computational infrastructure needed to **manage, analyze, and interpret the data**

# Next Generation Sequencing
# A Fundamental Change in Molecular Microbiology




Source: NHGRI, http://www.genome.gov/sequencingcosts
Bp, Base pairs
MB, Million bases

# Next Generation Sequencing Advantages

- **Advantages**
  - To learn about the microbe's phylogenetic history
    - "Where has it been—where it came from"
  - Try to predict "where it is going"
    - Is it on its way to become resistant to antimicrobial drugs?
    - Will its potential for human-to-human transmission change?
- **Examples of practical applications: Identification of**
  - Microbial clusters
  - Genetic markers for virulence and antimicrobial resistance
  - Evidence of bioengineering
  - New pathogens

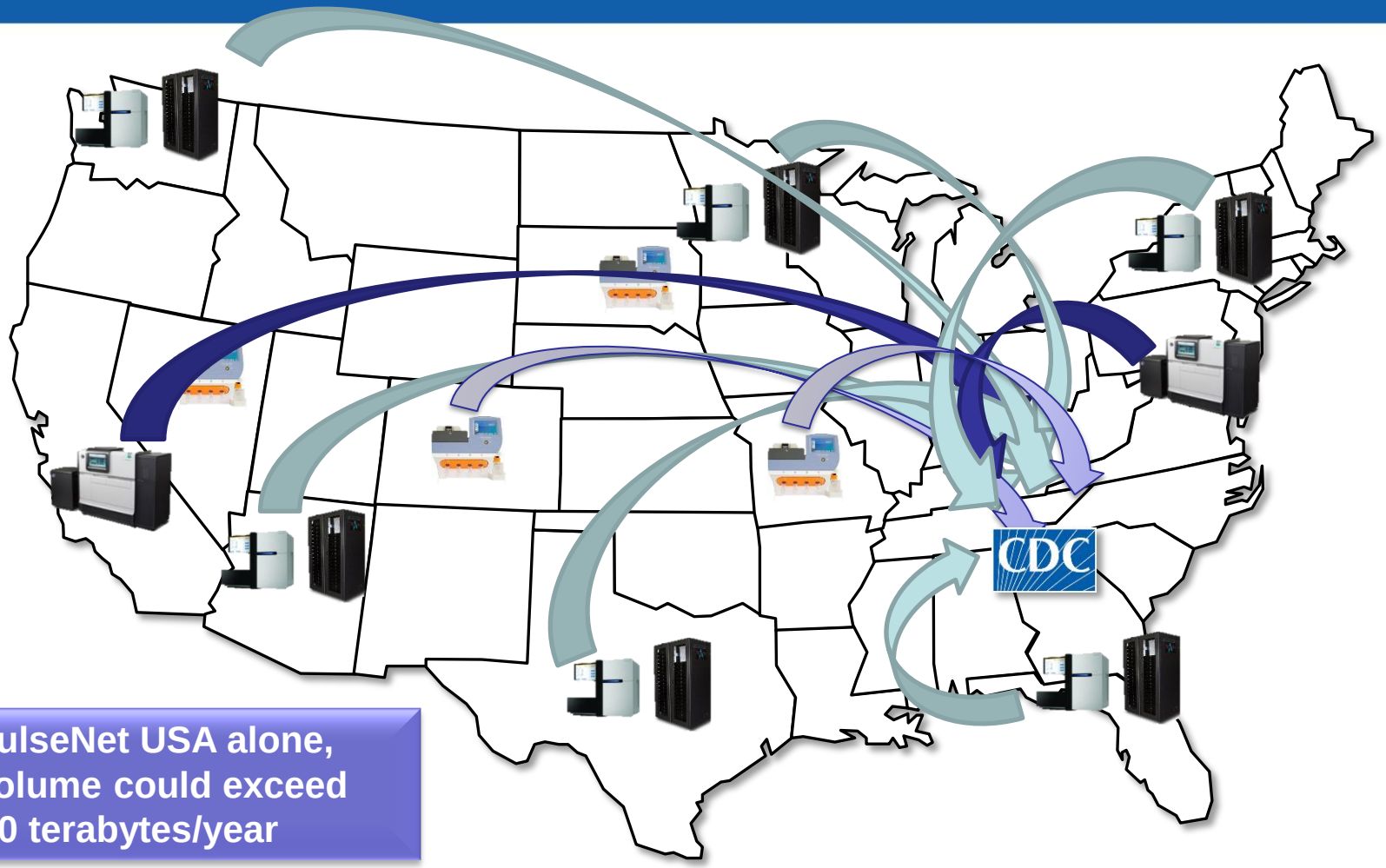
National Human Genome Research Institute, http://www.genome.gov/sequencingcosts

# Next Generation Sequencing Challenges

- **Sheer volume of generated sequence data**
  - Management and storage
  - Analysis and statistical interpretation
    - Technical reproducibility
  - Public health application of laboratory information
- **Constant evolving of new technologies and protocols**
- **New skills and capabilities in the public health workforce**
  - Bioinformatics
  - Laboratory technology
  - Data science

http://www.genome.gov/sequencingcosts

# A Larger Challenge
# Integrating AMD into Public Health Surveillance




**For PulseNet USA alone, data volume could exceed 250 terabytes/year**

www.cdc.gov/pulsenet

# AMD Initiative: A New Landscape for Combating Infectious Diseases

- **Proposed in the President's 2014 budget**
- **A major enhancement of CDC's current microbiology and bioinformatics capabilities to more accurately and rapidly (and with decreased cost)**
  - Diagnose infectious diseases
  - Investigate and control outbreaks
  - Understand transmission patterns
  - Determine antimicrobial resistance
  - Develop and target prevention measures, including vaccines

http://www.cdc.gov/AMD

# AMD Initiative: Critical Components

Leverage emerging **molecular sequencing** technologies and **bioinformatics** to enable CDC to build and integrate critical capacities at the **national and state** levels to enhance infectious disease prevention and control

# AMD In Action: Outbreak Investigation

**Human**
**Animal**
**Environmental**
**Samples**

## IDENTIFY

Same pathogen?
Does it fit the clinical syndrome?
Is it present in all your cases?
Is it absent in your controls?

## SUBTYPE

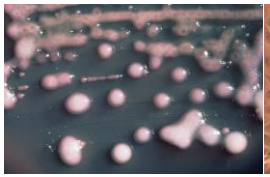
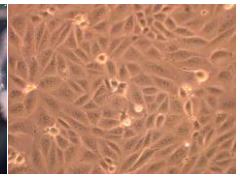
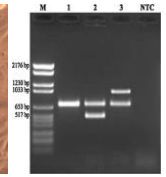
Same strain?
If different, how different?
Chain of transmission?

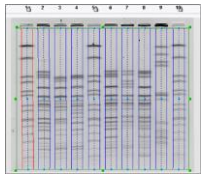
## CHARACTERIZE

Important features?
Are there characteristics affecting its pathogenicity, transmissibility, and resistance to drugs that could explain its emergence or affect public health response?

**CULTURE, PHENOTYPIC and MOLECULAR**

Timeframe: DAYS/WEEKS



**AMD**

Timeframe: HOURS

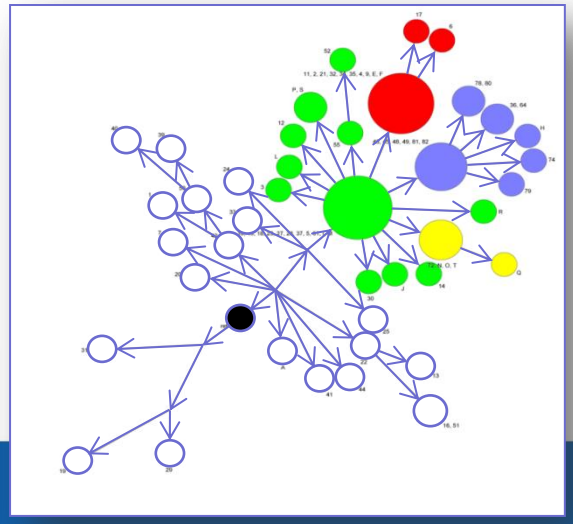
# AMD Initiatives

1. Improve identification and detection of pathogens
2. Adapt new diagnostics to meet evolving public health needs
3. Help states meet future reference testing needs in a coordinated manner
4. Implement enhanced, sustainable, and integrated laboratory information systems
5. Develop prediction, modeling, and early recognition tools

# 1. Improve Identification and Detection of Pathogens

- **Expand capacity for rapid DNA sequencing and molecular characterization of pathogens**
  - Improve capabilities for data analysis and interpretation
- **Develop tools for genome-scale molecular epidemiology, and help CDC apply them to its laboratory and surveillance activities**

- **Outcome**
  - Rapid progress toward modernizing PulseNet and other critical laboratory-based surveillance systems

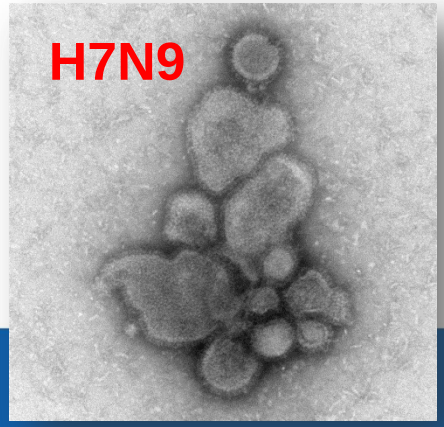


**Today's example:**
**Detection of TB outbreaks**
**J Posey**

# 2. Adapt New Diagnostics to Meet Evolving Public Health Needs

- **Establish leading capability to adapt the next generation of rapid, semi-automated, point-of-need molecular tests to meet evolving public health requirements**

- **Outcome**
  - Enhance CDC's ability to detect outbreaks early
  - Develop new test during outbreaks
  - Better characterize infectious disease threats




**Today's example:**
**Detection of resistance in flu viruses**
**M Shaw**

# 3. Help States Meet Future Reference Testing Needs in a Coordinated Manner

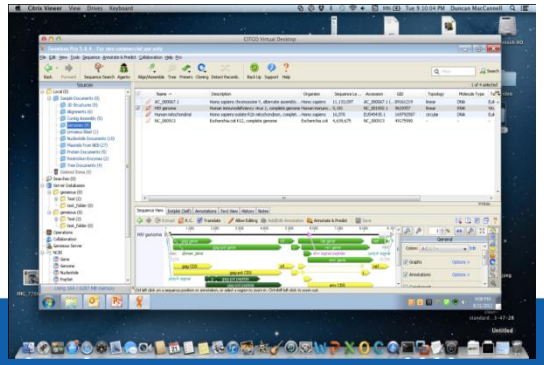
- **Help state and local public health laboratories to transition from culture-based methods to new molecular technologies**
- **Expand capacity for rapid DNA sequencing and molecular characterization to state/local level and improve capabilities for data analysis and interpretation**

- **Outcome**
  - More effective and better integrated outbreak response activities

**Today's example:**
**Reference Databases and MicrobeNet™**
**J McQuiston**

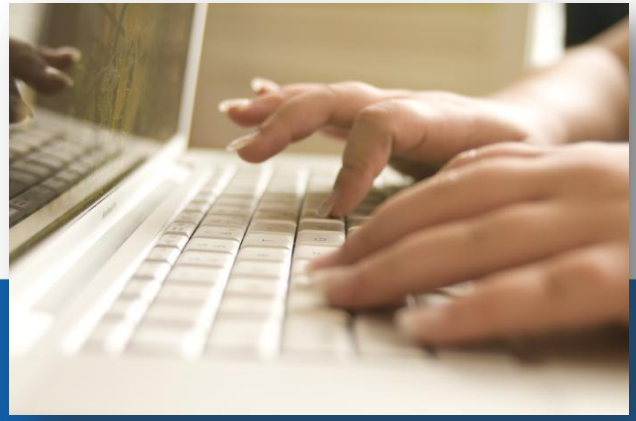
# AMD Initiative: Strategic Investments (1)

- **Core scientific infrastructure**
  - Critical laboratory and bioinformatics infrastructure at CDC, state/local public health laboratories, and key overseas laboratories
    - Sequencers, mass-spectrometer, other instrumentation, reagents
    - High-performance computing, scientific workstations
    - Data storage, networking; data integration, knowledge management
    - Service contracts, software licensing, etc.



# AMD Initiative: Strategic Investments (2)

- **Workforce development**
  - Training for CDC and public health laboratories workforce
    - Bioinformatics, genomics, -omics
  - New or retooled fellowship programs
    - Genomics
    - Bioinformatics: Partnership with Association of Public Health Laboratories
  - Recruitment of new staff and skill sets
    - Bioinformaticians, data scientists, laboratory specialists



# AMD Initiative: Strategic Investments (3)

- **Consortia, partnerships, and alignment of efforts**
  - Academic institutions
  - State and Federal: NIH, FDA, DHS, DoD, DoE/National Laboratories
  - Nonprofit/Nongovernmental organizations
  - International community
  - Commercial/for-profit
- **Pilot projects with state, local, and other partners**
  - Outbreak detection, investigation and response
  - Leverage existing laboratory-based surveillance systems

NIH, National Institutes of Health; FDA, Food and Drug Administration
DHS, Department of Homeland Security
DoD, Department of Defense, DoE, Department of Energy

# Advanced Molecular Detection Initiative

## IMPROVED DETECTION

Enhanced recognition of emerging microbial threats and antimicrobial resistance

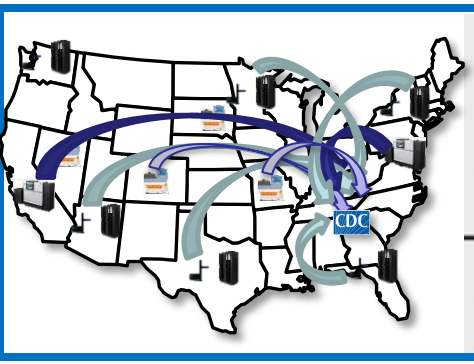
Better targeting of proven prevention strategies and development of new ones

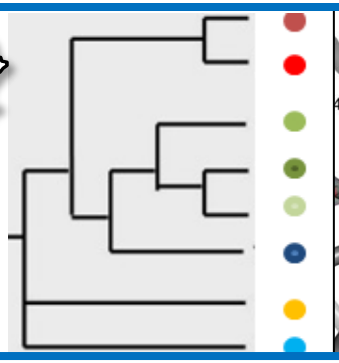
## IMPROVED SURVEILLANCE

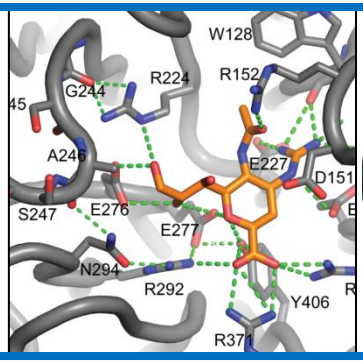
Improved surveillance information on the transmission of infections and the extent and spread of outbreaks

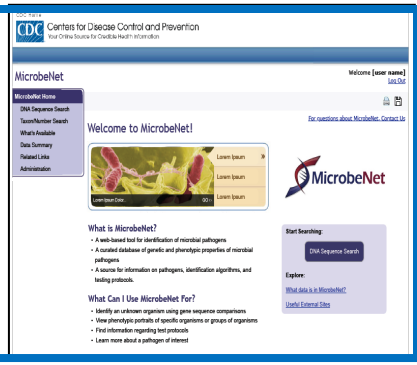
Faster, more effective control efforts

# Investigation of Tuberculosis Outbreaks Using Whole Genome Sequencing








**James Posey, PhD**

*Lead, Applied Research Team*

*Division of Tuberculosis Elimination*

National Center for HIV/AIDS, Viral Hepatitis, STD, and TB Prevention, CDC

U.S. Department of Health and Human Services
Centers for Disease Control and Prevention

# National TB Genotyping Service 2004–present

- **Goal**
  - Genotype one *Mycobacterium tuberculosis* isolate from each culture-positive TB case
  - PCR-based methods used
    - Spoligotyping: Variation in direct repeat locus
    - MIRU-VNTR: Variation at 24 distinct loci
- **Results**
  - >80,000 isolates genotyped
  - ~95% coverage in recent years
  - 2010–2012
    - 14,429 genotypes
    - 50% of isolates are in one of 2,520 clusters

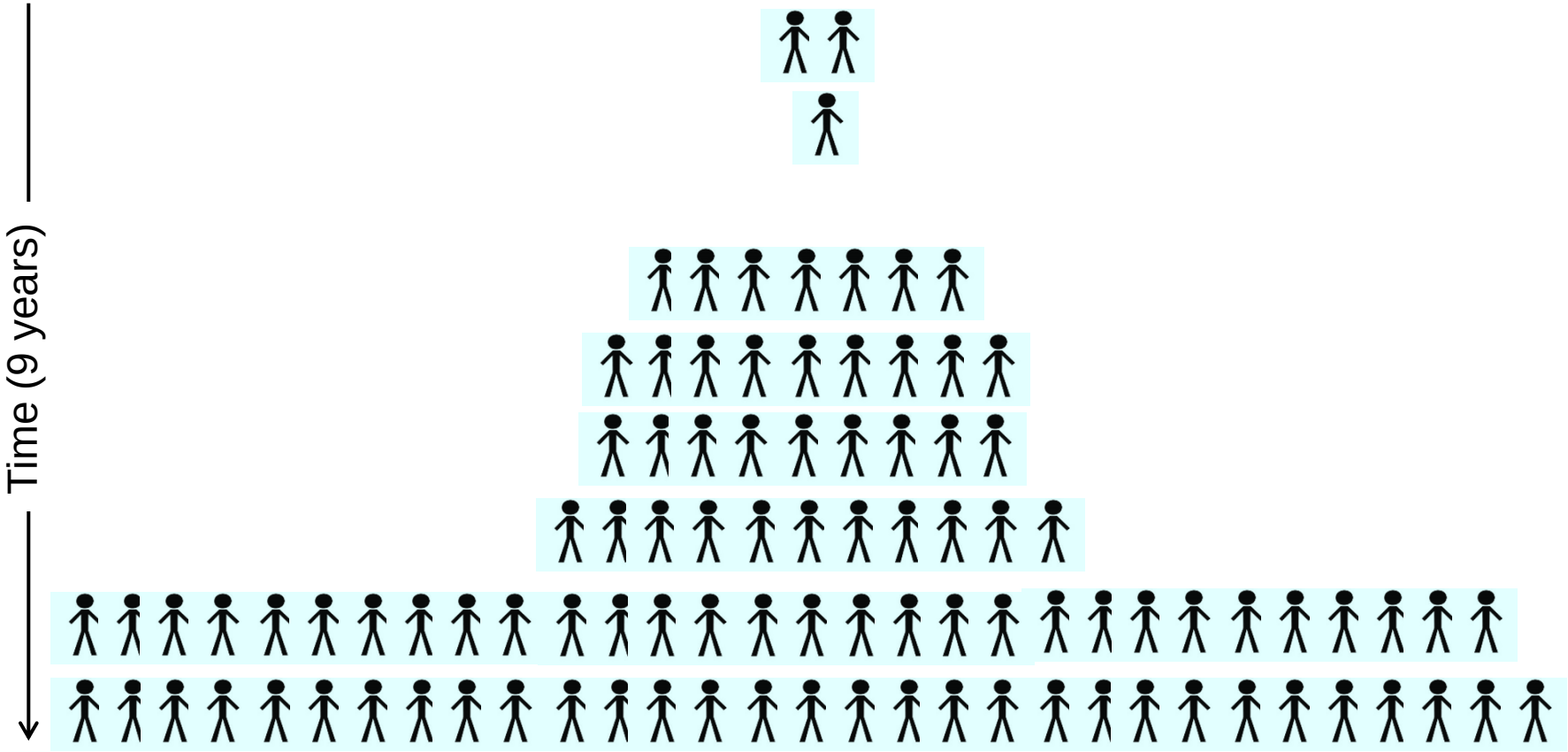
PCR, Polymerase chain reaction
MIRU-VNTR, Mycobacterial interspersed repetitive unit-variable number of tandem repeats

# Conventional Genotyping Complemented with Whole Genome Sequencing

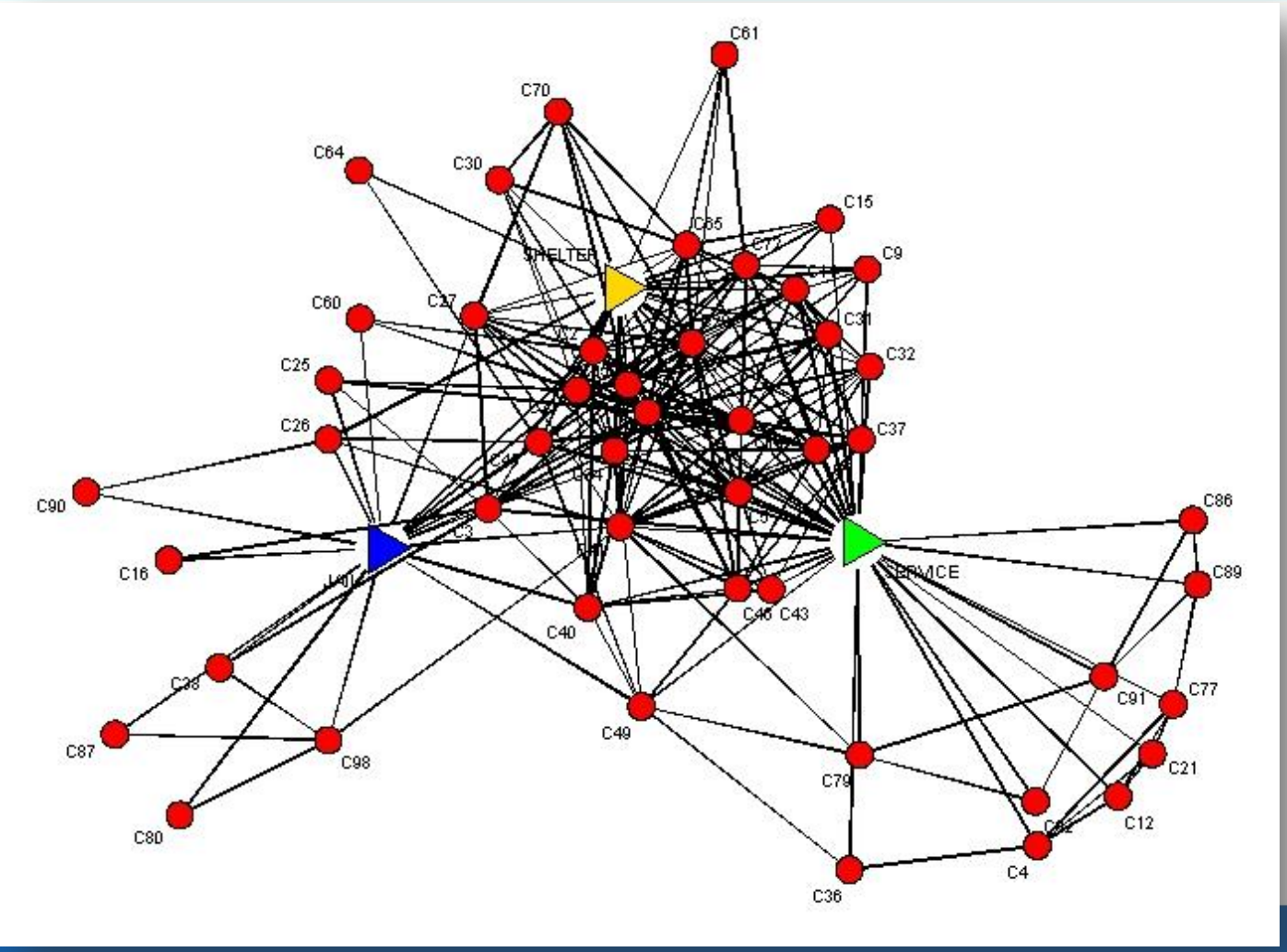
- **Conventional genotyping**
  - Represents <1% of the pathogen's genome
  - Targets are stable over long periods of time
  - Data is difficult to interpret when highly related strains remain circulating in community for long periods of time
- **Whole genome sequencing**
  - Represents ~90% of the pathogen's genome
  - Mutations accumulate at the rate of 0.5 SNP/year

SNP, Single nucleotide polymorphism

# Large TB Cluster



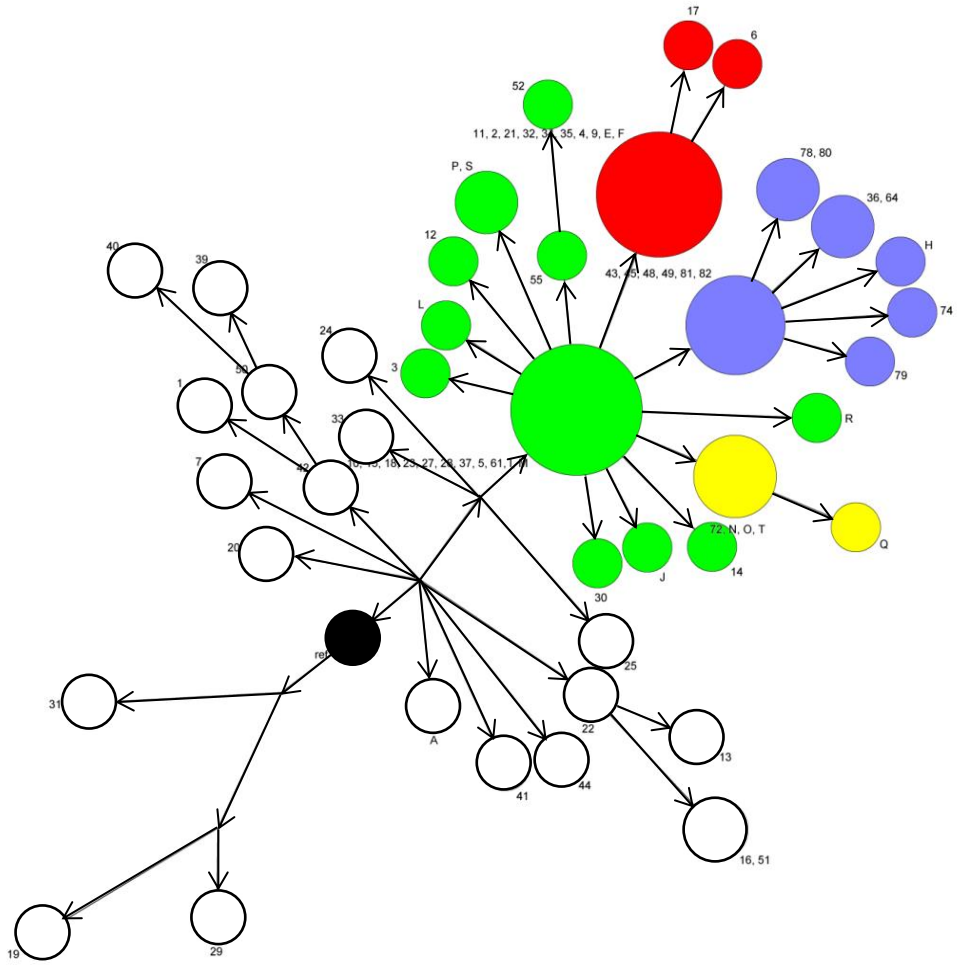
# "Social Network" of the Patients




Patients

Transmission sites

# Whole Genome Sequencing Results
## Answers About Exposure and Transmission

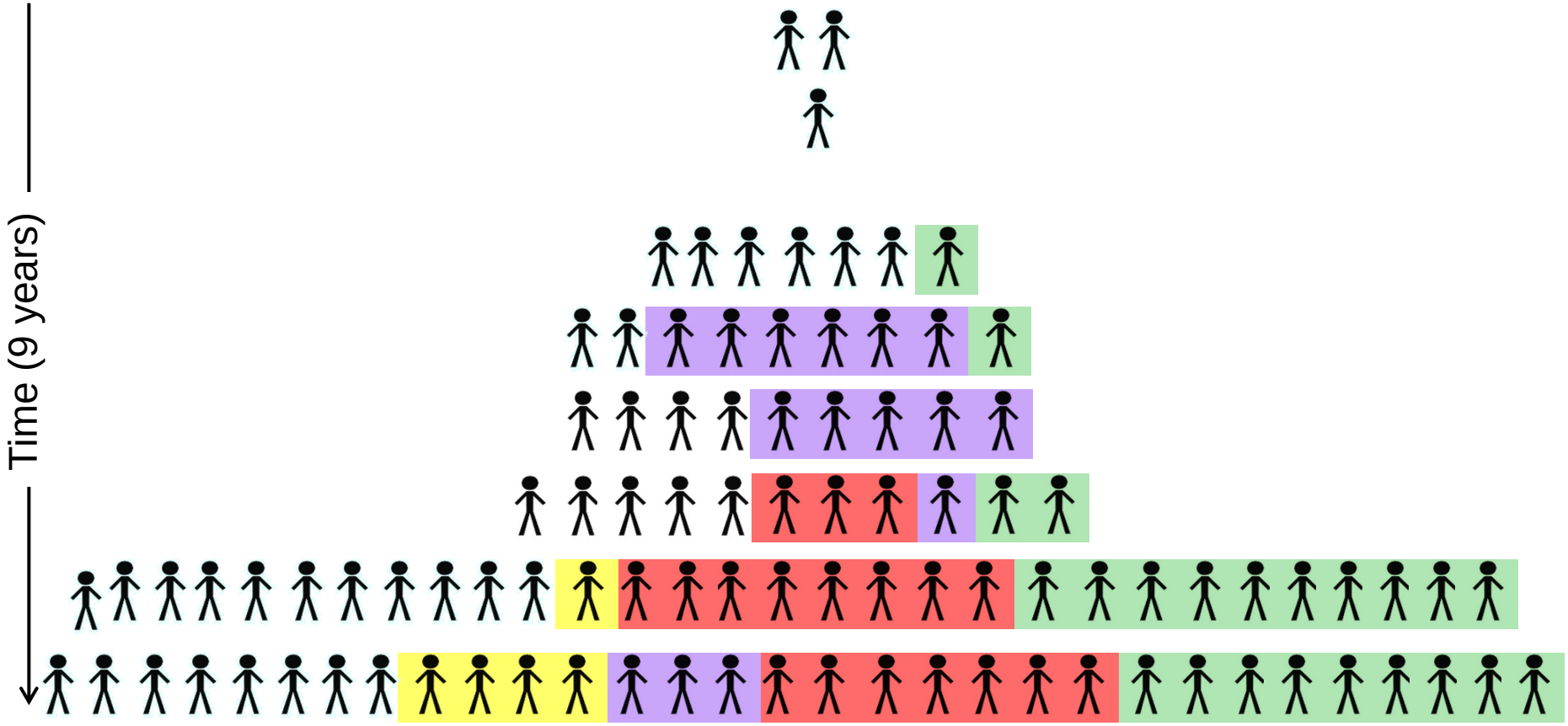



72 Isolates
102 SNPs
41 Genomic types
4 Clusters

Branch length = Number of differences between 2 genomic types

Circle size = Number of isolates within a genomic type

# Large TB Cluster



# Pairing Whole Genome Sequencing and Epidemiological Data

- Identified cases that were part of transmission chains
- Identified cases that were remotely exposed
- Confirmed sites where transmission likely occurred
- Identified sites where transmission was not likely to have occurred

**Now: Retrospective analysis**
**In the future: Real-time analysis**

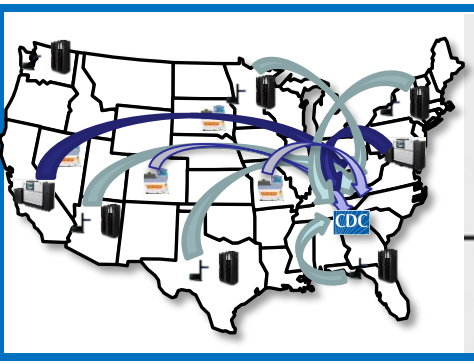
# From Knowledge to Action

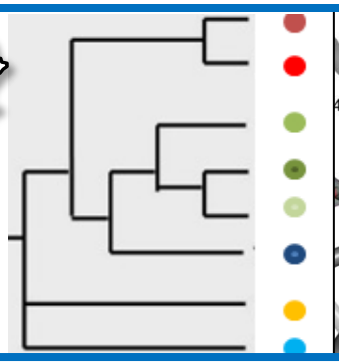
**Focus and prioritize efforts during outbreak investigations**

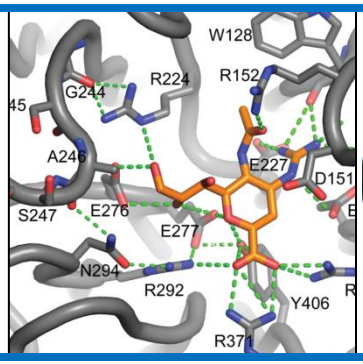
**Expand contact investigations around identified source cases**

**Prioritize TB screening at those sites where transmission was confirmed**

# Detecting Drug Resistance in Novel Influenza Viruses





**Michael Shaw, PhD**

*Associate Director for Laboratory Science*

Influenza Division

National Center for Immunization and Respiratory Diseases, CDC

U.S. Department of Health and Human Services
Centers for Disease Control and Prevention

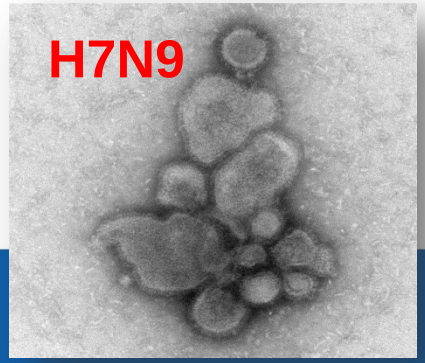
# Influenza Antiviral Drugs

- **2 classes of drugs are FDA-approved for treatment of influenza infections in the United States**
  - M2 inhibitors: Amantadine and Rimantadine
  - NA inhibitors (NAIs): Oseltamivir and Zanamivir
    - Peramivir is approved in Japan, South Korea, and China
    - Laninamivir is approved in Japan
- **Drug susceptibility monitoring and assessment**
  - Monitoring: An integral part of virological surveillance
  - Assessment: Based on sequence analysis and/or phenotypic testing
- **Laboratory correlates for clinically relevant resistance to NAIs have not yet been established**

NA, Neuraminidase

# Recognition of Novel Influenza A H7N9

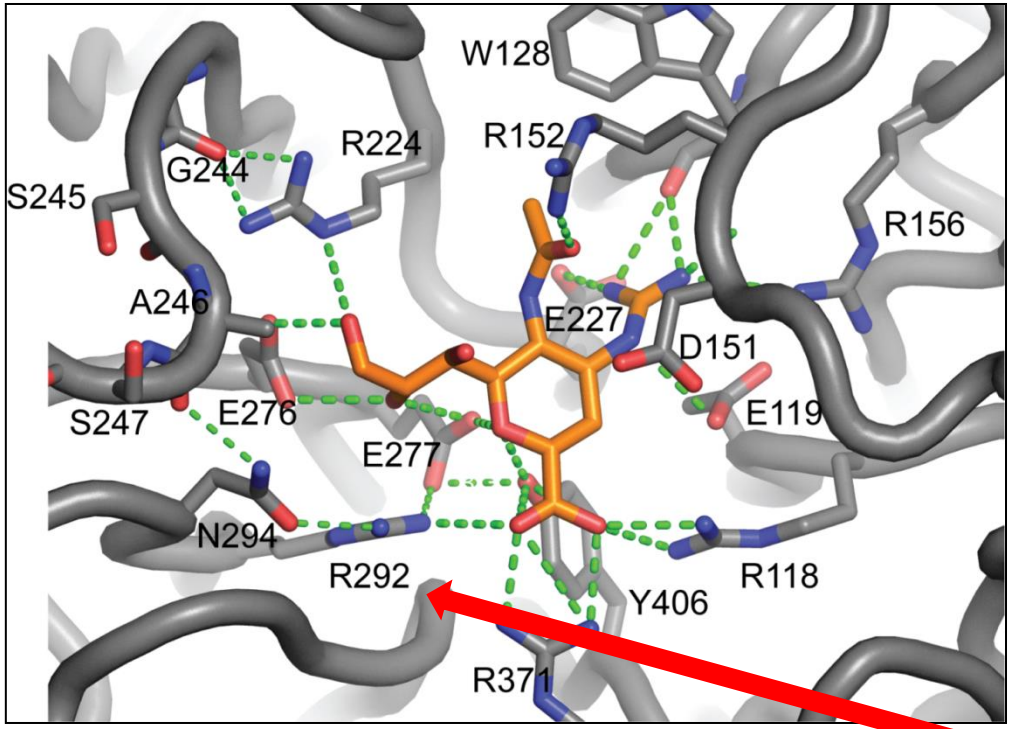
- **On March 31, 2013, the China Health and Family Planning Commission notified WHO of 3 cases of human infection with influenza A (H7N9)**
  - All 3 cases presented with respiratory tract infection with progression to severe pneumonia and breathing difficulties
  - 2 deaths, 1 patient in critical condition
  - China CDC (Beijing) immediately released full genome sequence information fo



# Laboratory Investigation During Response

- **Partial or complete genetic sequences from 54 cases have been posted**
  - All 8 genes are from avian origin
- **Genetic changes in the sequences have been associated with adaptations leading to**
  - Enhanced virus binding to mammalian respiratory cells
  - Enhanced replication in mammalian respiratory cells
  - Increased severity of infection
- **Antiviral susceptibility**
  - Overall, susceptible to oseltamivir and zanamivir
  - Viruses from 6 cases have genetic markers for resistance to oseltamivir and zanamivir; clinical relevance is unknown
  - Resistant to amantadine and rimantadine

# Key Neuraminidase Molecular Markers




| NA | 119 | 136 | 151 | 222 | 224 | 247 | 274 | 276 | 292 | 294 | 371 |
|---|---|---|---|---|---|---|---|---|---|---|---|

# Recombinant NAs Used for Antiviral Susceptibility Assessment

## Application of Genetic Sequence Information

- **Proteomics: Transient expression system for the neuraminidase (NA) enzyme using H7N9 framework**
  - Allows mutations to be introduced into the NA
  - Mutations R292K, E119V, I222R, I222K, and other mutations were detected in H7N9 viruses recovered from drug-treated patients in China
- **Expressed NA can be evaluated for susceptibility to licensed antiviral drugs**
  - R292K conferred significant resistance

NA, Neuraminidase

# Susceptibility of A/Taiwan/1 (H7N9) to NA Inhibitors

- Recovered from a patient after oseltamivir treatment with standard dose (5 days) + double dose (5 days)
- R292K was detected and reported
- Viruses passed in eggs, were tested in pyrosequencing assays

| A/Taiwan/1 | R292K (%) | I222R (%) | I222K (%) | E119V (%) |
|---|---|---|---|---|
| Passage 1 | 30 | 53 | 6 | 6 |
| Passage 2 | 9 | 45 | 4 | 33 |

Chang SY, et al. Lancet 2013;381:1621
Nguyen HT, et al. Antiviral Therapy 2012;17:159-73
Egg isolate (E1), kindly provided by Taiwan CDC, was propagated US CDC

# Antiviral Susceptibility Assay A/Taiwan/1/2013 with 4 Mutations

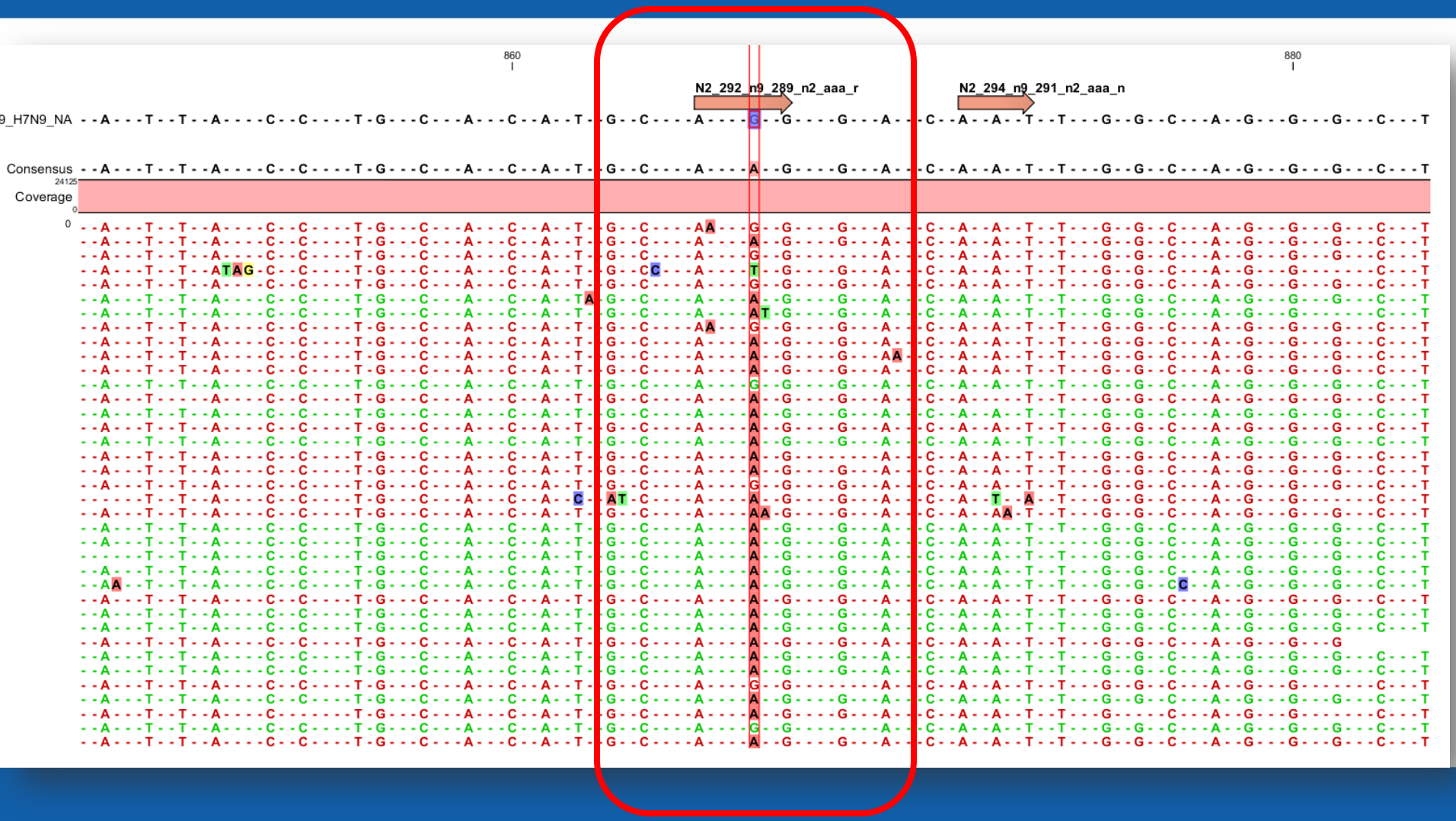
| Mutation | Oseltamivir* | Zanamivir* | Peramivir | Laninamivir |
|---|---|---|---|---|
| **R292K** | >1000 | 55 | >1000 | 22 |
| I222K | 32 | 8 | 6 | 13 |
| I222R | 3 | 12 | 2 | 14 |
| E119V | 84 | 9 | 1 | 2 |

*** Licensed for use in the United States**

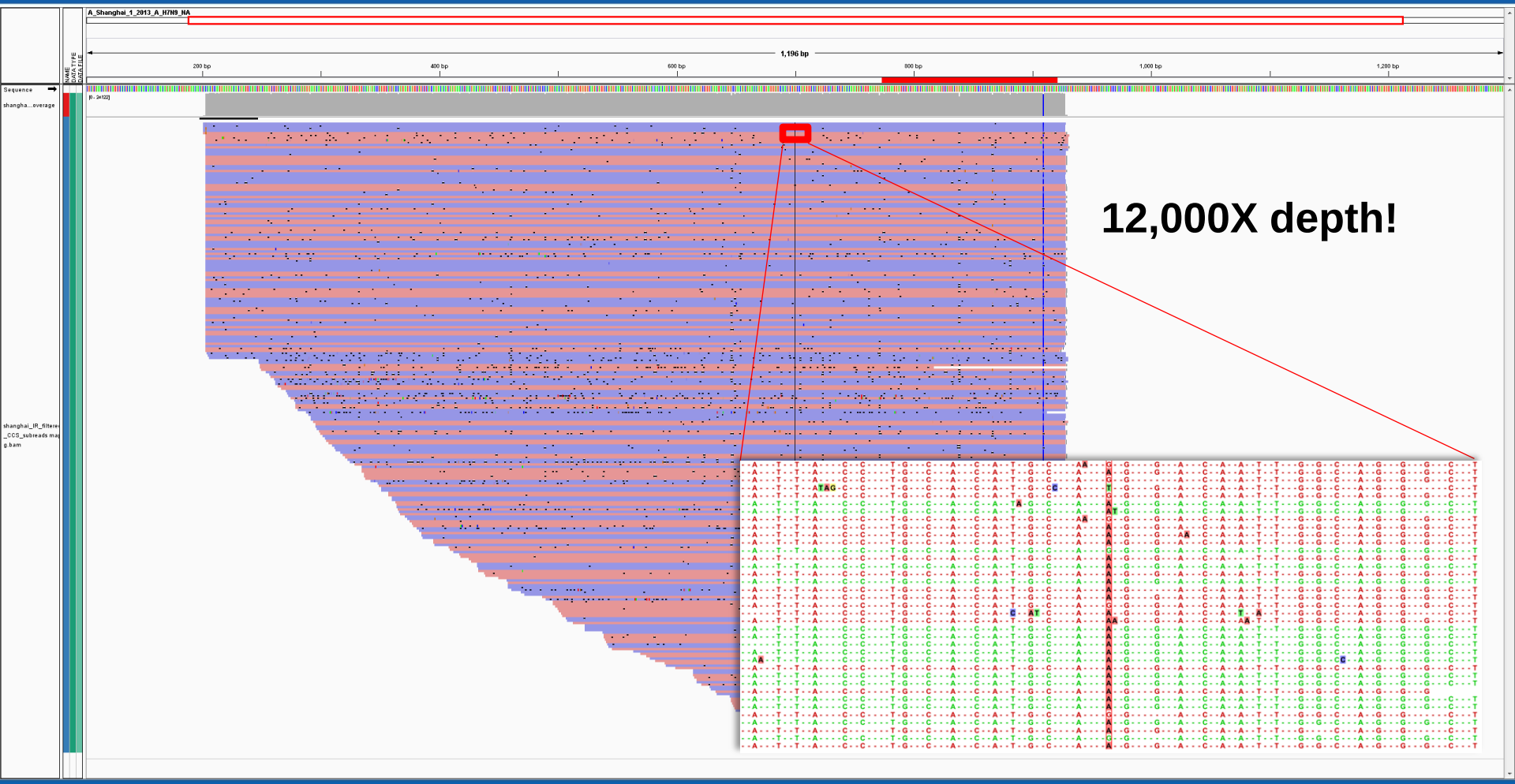
| | |
|---|---|
| Normal: | <10 fold |
| Reduced: | 10–100 fold |
| Highly reduced: | >100 fold |

Sleeman K, et al. (submitted for publication)

# Detect Nucleotide Changes Resulting from Laboratory Passage



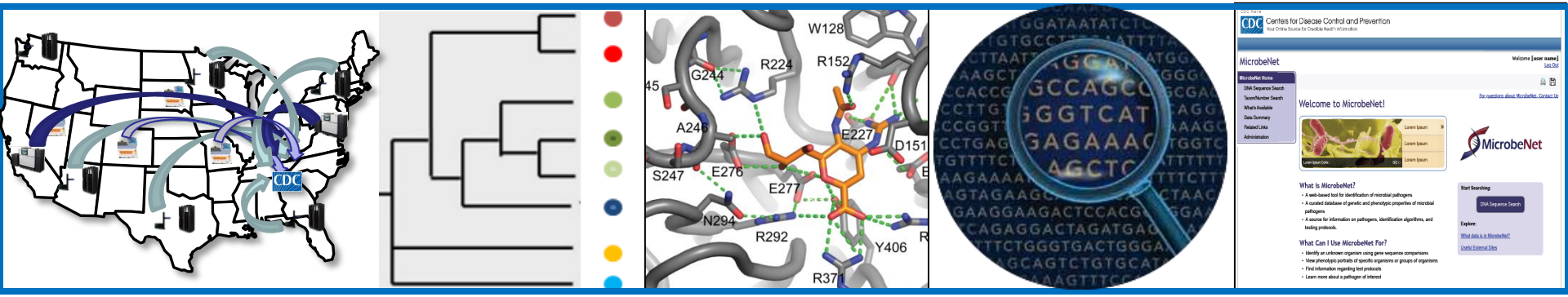
# Deep Sequencing is Really Deep for Influenza



# Public Health Implications

- **Genetic sequence data**
  - Can rapidly identify genetic changes that may impact the effectiveness of antiviral agents
- **Proteomics and analysis of the variant population**
  - Allows monitoring for mutations that might herald the emergence of new phenotypes affecting transmissibility, viral fitness, and vaccine design
- **Deep sequence analysis of variant populations within a single clinical specimen**
  - Allows detection of linked mutations that might affect the progression and severity of disease within an individual patient

# MicrobeNet™: Connecting Public Health Laboratories





**John R. McQuiston, PhD**

*Team Lead, Special Bacteriology Reference Laboratory*

*Division of High Consequence Pathogens and Pathology*

National Center for Emerging and Infectious Diseases, CDC


U.S. Department of Health and Human Services
Centers for Disease Control and Prevention

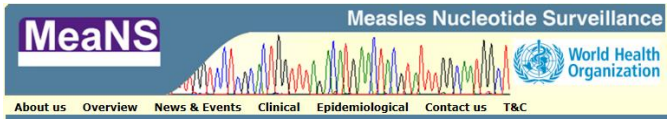
# Examples of Existing Databases

- **GenBank**
  - At the National Center for Bioinformatics Information/NIH
  - An annotated collection of all publicly available DNA sequences http://www.ncbi.nlm.nih.gov/genbank

- **Global Initiative on Sharing All Influenza Data**
  - http://platform.gisaid.org/epi3/frontend#4f52ba

- **Measles Nucleotide Surveillance (MeaNS)**
  - http://www.hpa-bioinformatics.org.uk/Measles/Public/Web_Front/main.php

- **Polio Nucleotide Surveillance**
  - Similar to MeaNS (under construction)



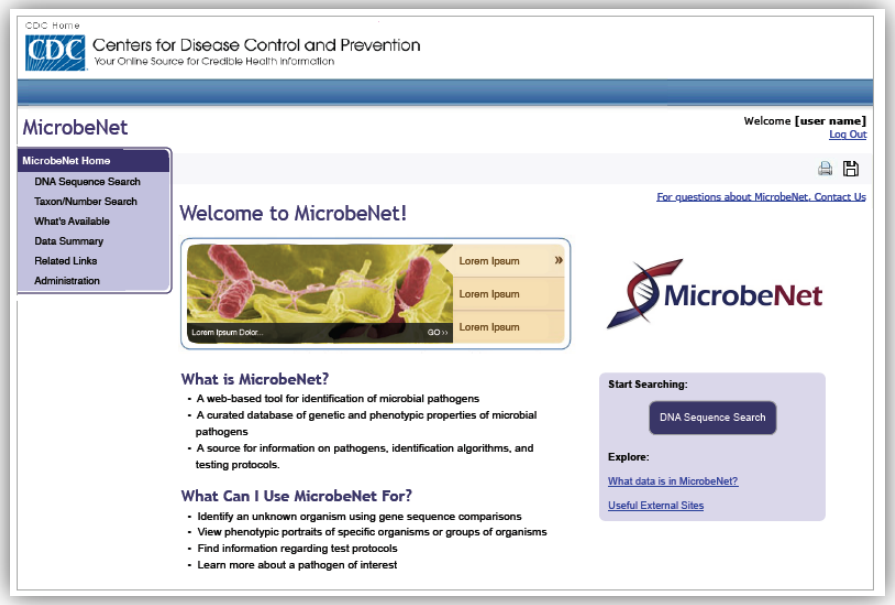
- **An online tool developed at CDC for the public health and clinical laboratories to access CDC-based technology and databases**
- **MicrobeNet™ will connect public health laboratories with CDC subject matter experts for help with identifying pathogens**
  - Each tool or module helps identify the genus or species level and also connects the user back to the supporting data on the diverse pathogens

| **Genus** | **species** |
|---|---|
| ***Mycobacterium*** | ***tuberculosis*** |

**https://microbenet.cdc.gov**

# MicrobeNet™ Capabilities

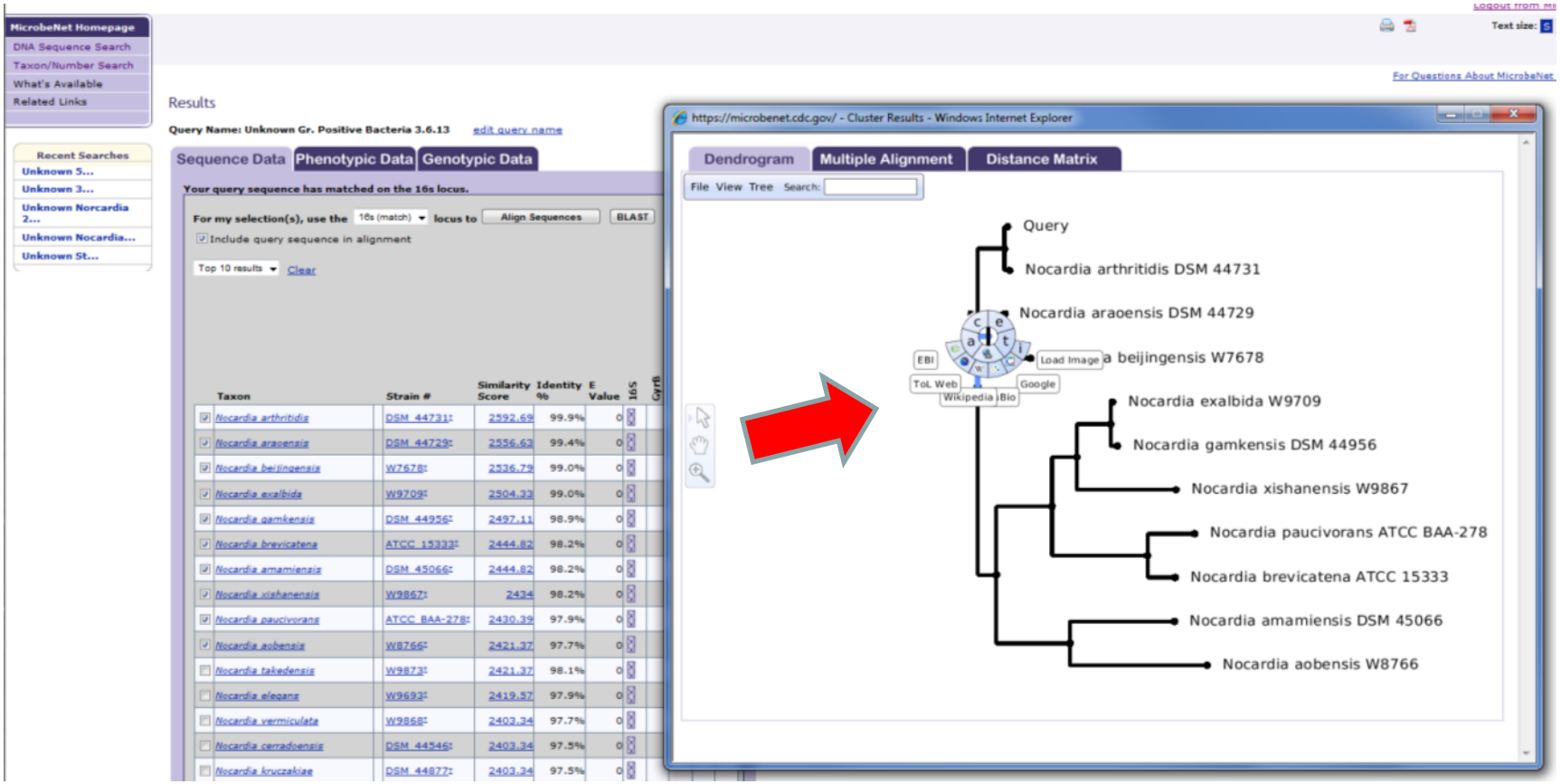
- **Current**
  - DNA sequence
- **Future**
  - Phenotypic data
  - Biochemical tests
    - Fermentation of sugar
    - Production of catalase
  - Proteomics
    - MALDI-TOF mass spectrometry
  - Genomics



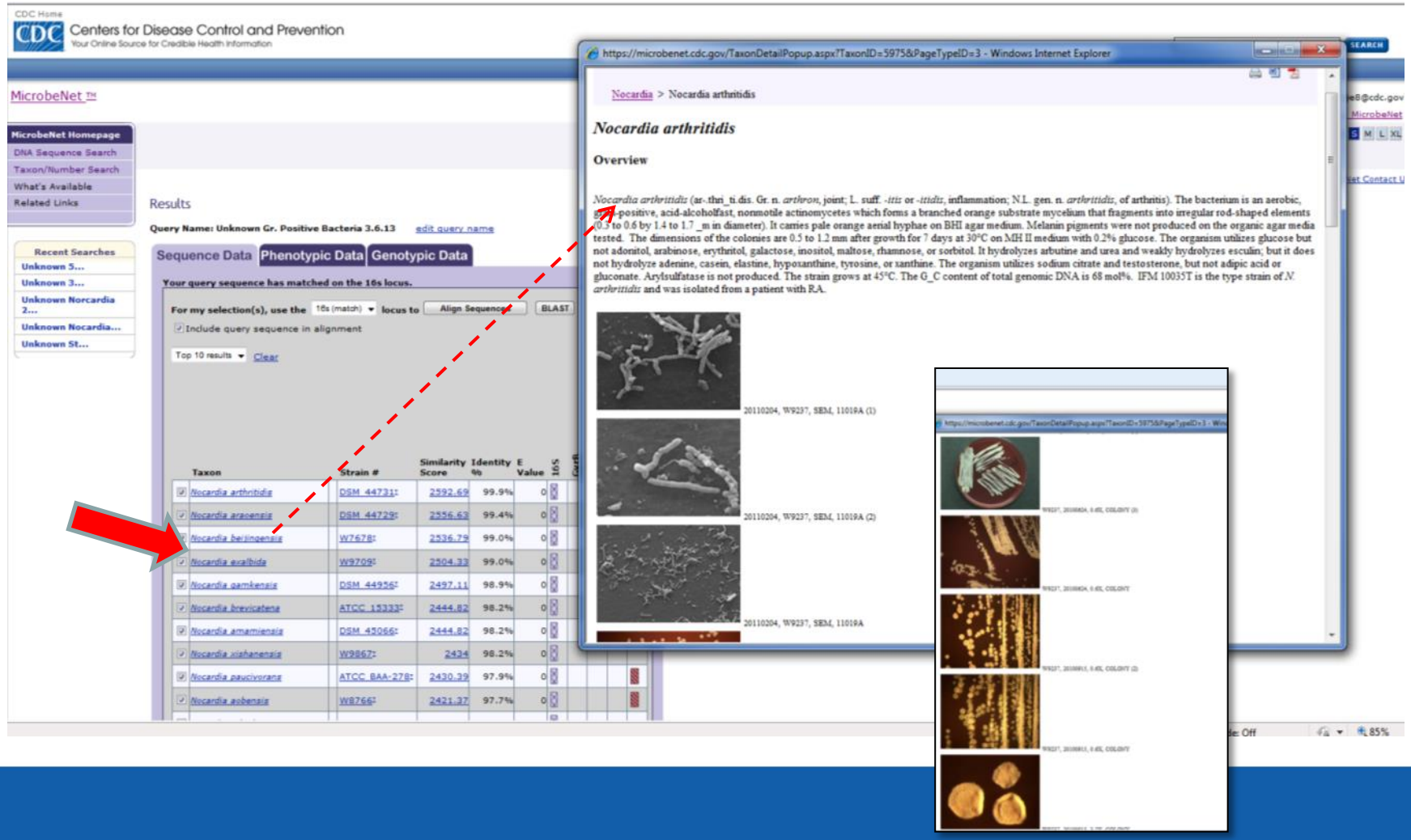

**https://microbenet.cdc.gov**

MALDI-TOF, matrix-assisted laser desorption/ionization–time of flight

# Searching MicrobeNet™ to Identify an Unknown Sequence



# Information in MicrobeNet™



# Information in MicrobeNet™

Centers for Disease Control and Prevention
Your Online Source for Credible Health Information

MicrobeNet ™

MicrobeNet Homepage
DNA Sequence Search
Taxon/Number Search
What's Available
Related Links

Recent Searches
Unknown 5...
Unknown 3...
Unknown Norcardia 2...
Unknown Nocardia...
Unknown St...

Results

Query Name: Unknown Gr. Positive Bacteria 3.6.13 edit query name

Sequence Data | Phenotypic Data | Genotypic Data

Your query sequence has matched on the 16s locus.

For my selection(s), use the 16s (match) locus to Align Sequences BLAST

Include query sequence in alignment

Top 10 results Clear

| Taxon | Strain # | Similarity Score | Identity % | E Value | 16S | GyrB |
|---|---|---|---|---|---|---|
| Nocardia arthritidis | DSM 44731T | 2592.69 | 99.9% | 0 | | |
| Nocardia araoensis | DSM 44729T | 2556.63 | 99.4% | 0 | | |
| Nocardia beijingensis | W7678T | 2536.79 | 99.0% | 0 | | |
| Nocardia exalbida | W9709T | 2504.33 | 99.0% | 0 | | |
| Nocardia gamkensis | DSM 44956T | 2497.11 | 98.9% | 0 | | |
| Nocardia brevicatena | ATCC 15333T | 2444.82 | 98.2% | 0 | | |
| Nocardia ansamiensis | DSM 45066T | 2444.82 | 98.2% | 0 | | |
| Nocardia xishanensis | W9867T | 2434 | 98.2% | 0 | | |
| Nocardia paucivorans | ATCC BAA-278T | 2430.39 | 97.9% | 0 | | |
| Nocardia aobensis | W8766T | 2421.37 | 97.7% | 0 | | |

Done

https://microbenet.cdc.gov/ - Strain Detail - Windows Internet Explorer

## Nocardia arthritidis

**Strain Number: DSM_44731T**

Synonymous Strain Number(s): IFM_10035T, W9237T

Type Strain: Yes

Sequence | Phenotype | Data Sources | References

Panel: **Actinomycetes Panel**

MicrobeNet #:

Actinomycetes Panel

**Antimicrobial Susceptibilities**

| | |
|---|---|
| Amikacin: | <0.25 (S) |
| Amoxicillin/Clavulanate: | 1/0.5 (S) |
| Ampicillin: | 2 (S) |
| Ceftriaxone: | 2 (S) |
| Ciprofloxacin: | >8 (R) |
| Clarithromycin: | 4 (I) |
| Imipenem: | >32 (R) |
| Linezolid: | 2 (S) |
| Minocycline: | 2 (I) |
| Trimetho/Sulfa: | 0.25/4.8 (S) |
| Vancomycin: | >32 (R) |

**Acid production from Gordon Sugars**

| | |
|---|---|
| Adonitol: | - |
| Cellobiose: | - |
| D-Fructose: | + |
| D-Galactose: | - |

https://microbenet.cdc.gov/ - Strain Detail - Windows Internet Explorer

| | |
|---|---|
| Glycerol: | + |
| i-Erythritol: | - |
| i-myo-Inositol: | - |
| Lactose: | - |
| L-Arabinose: | - |
| L-Rhamnose: | - |
| Maltose: | - |
| Mannose: | - |
| Melibiose: | - |
| Raffinose: | - |
| Salicin: | +w |
| Sucrose: | - |
| Trehalose: | - |

**Growth Characteristics**

| | |
|---|---|
| Growth in Lysozyme: | + |
| Growth at 25°C: | + |
| Growth at 35°C: | + |
| Growth at 45°C: | + |

**Other Characteristics**

| | |
|---|---|
| Arylsulfatase production: | - |
| Utilization of citrate: | - |
| Nitrate reduction (Routine): | - |
| Utilization of acetamide: | - |

**Hydrolysis of**

| | |
|---|---|
| Adenine: | - |
| Casein: | - |
| Hypoxanthine: | - |
| Tyrosine: | - |
| Xanthine: | - |
| Esculin: | dark |
| Urea: | + |

# MicrobeNet™ and Genomics Reference Laboratory of the Future

## Public Health Laboratory A

- Performs whole genome sequencing
- Selects tests they want to perform through MicrobeNet™

| Tests Requested | Results of Tests |
|---|---|
| ☑ Genus | *Mycobacterium* |
| ☑ Species | *tuberculosis* |
| ☐ Biochemical profile | |
| ☑ AST profile | Rifampin (R) Isoniazid (R)<br>Ethambutol (S) Pyrazinamide (S) |
| ☐ SNP profile | |
| ☑ Spoligotype | Spoligotype: 000000000030771 |
| ☐ MLST | |

AST, Antimicrobial susceptibility testing
SNP, Single nucleotide polymorphism (mutation)
MLST, Multi-locus sequence typing

# Current Searches for Unusual Pathogens
# Jan–Sep 2013, 747 Searches

***Nocardia***
***Neisseira***
***Brevibacterium***
***Corynebacterium***
***Gordonia***
***Klebsiella***
***Haemophilus***

# Current Searches for Unusual Pathogens Jan–Sep 2013

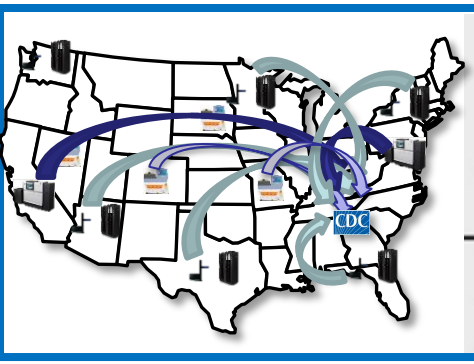
- **Who is using MicrobeNet™ now?**
  - 64 users from 28 state health departments
  - 3 international users from Brazil and Republic of Georgia
- **Training**
  - 2 workshops completed in February and April 2013
  - 1 workshop planned for December 2013
  - Collaborative effort with Association of Public Health Laboratories and National Laboratory Training Network

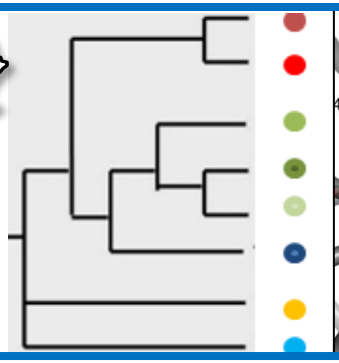
# MicrobeNet™ Future Applications

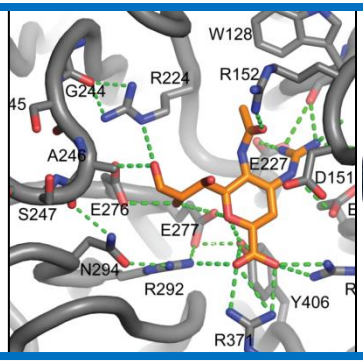
- **New tools (modules) for enhanced search capability**
  - Phenotypic: Fermentation of sugars, other biochemical tests
  - Gene sequence typing: E.g., MLST
  - Protein mass spectrometry: E.g., MALDI-TOF
- **Expanded databases for**
  - Fungal and viral pathogens
  - Additional bacterial pathogens (from current 200 to 3,000 species)
- **Whole genome search capability**
- **Geographic location capacity**
- **Enhanced communication with public health partners**
  - Contact information (CDC Branch) available for each species

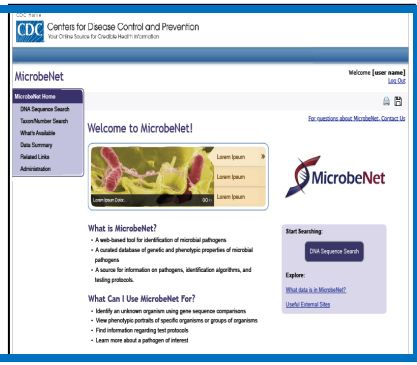
MLST, Multi-locus sequence typing
MALDI-TOF, Matrix-assisted laser desorption/ionization–time of flight

# Advancing AMD








**David M Engelthaler**

*Director, TGen North*

Translational Genomics Research Institute, Flagstaff, Arizona

tgen CDC
CENTERS FOR DISEASE CONTROL AND PREVENTION

U.S. Department of Health and Human Services
Centers for Disease Control and Prevention

# The Public Health Need for AMD and CDC

- **CDC is well placed to seize the momentum**
  - Advances in both genomic science and technology
- **Not if, but when … Nice To Have to Need To Have**
  - Public Health Needs: Genomics, proteomics, bioinformatics, and big data science and technology
- **AMD**
  - **Science evolution to public health revolution**

# What Will It Take

- **Key pieces**
  - Genomics and proteomics cores
    - With development and improvement strategies
  - Advanced and accessible bioinformatics
    - Big data needs big investment
  - Willingness to adopt and adapt the state of the science
    - Example: Human microbiome to population microbiome
    - Next: Incorporation of the community microbiome into population health surveillance and response strategies

# Leadership

- **AMD needs 21st century leadership**
  - A grave and growing public health need
    - CDC has always led the world in public health response
  - A culture of advanced science at CDC
    - Adapt and adopt the state of the science to once again create state-of-the-art public health
  - Commitment in the face of challenges
    - Leadership will drive this change, not funding

# Good News!

- **CDC has the leadership to make this happen at all levels**
  - From program to director
- **The science and technology exists**
  - Rapid adoption, adaptation, and advancement is already occurring
- **AMD will be a reality**
  - Federal, state, and local public health

# AMD Is Changing the Landscape for Combatting Infectious Diseases

"We are on the verge of revolutionizing our ability to diagnose infectious diseases, investigate and control outbreaks, understand transmission patterns, develop and target vaccines, and determine antimicrobial resistance—all with increased timeliness and accuracy and decreased costs"

=

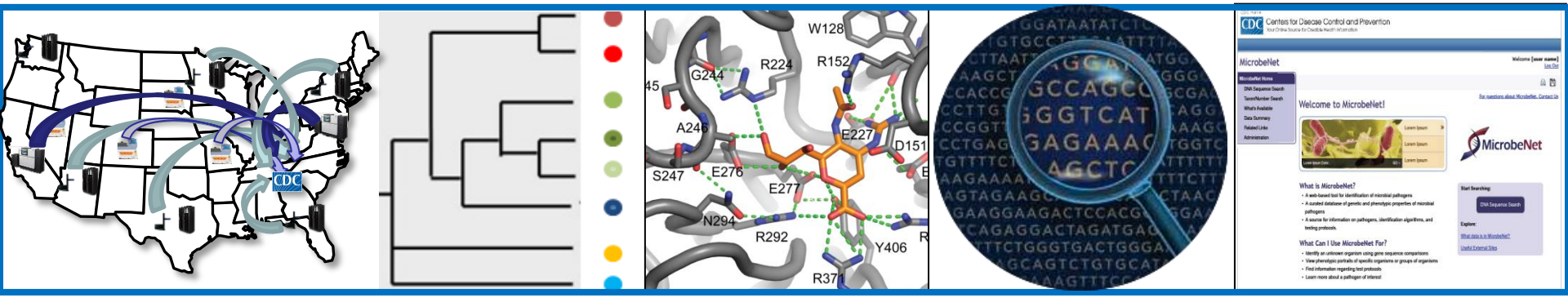
=

http://www.cdc.gov/AMD

# The Way Forward

- **CDC AMD cores**
  - Proteomics
  - Genomics: Deep sequencing
  - Bioinformatics
- **A connected public health system**
  - Program expertise
  - Local support
  - Global vision and partnerships

# The Future

- A global genomics perspective will allow us to better understand health, disease, and the human condition
- Through the AMD Initiative, CDC is poised to lead public health into the 21st century

# Advanced Molecular Detection for Improving Public's Health