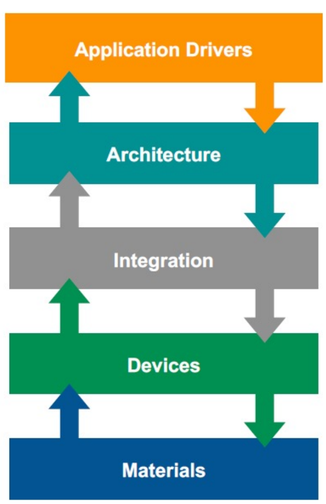
Threadwork: A Transformative Co-Design Approach to Materials and Computer Architecture Research

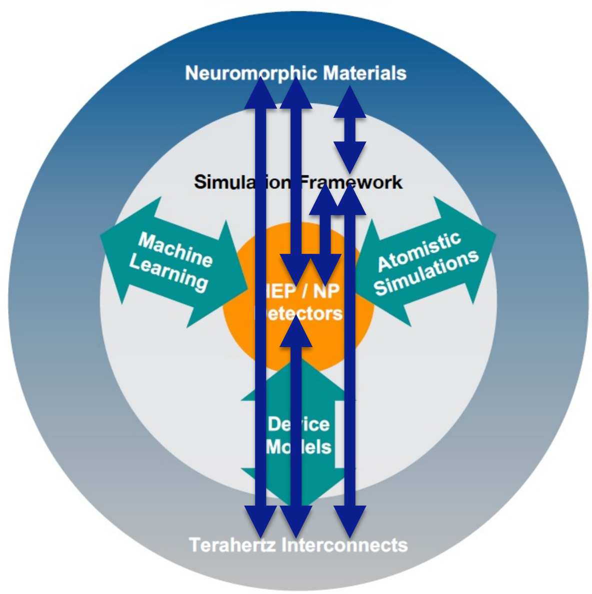
Andrew A Chien
Argonne National Laboratory and
University of Chicago

1

Status Quo:



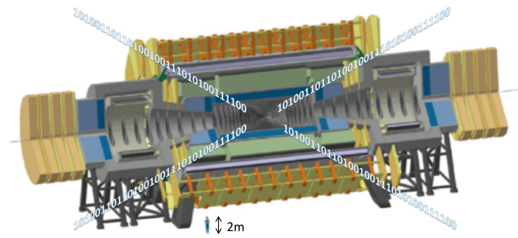
Threadwork



2

Applications: Future HEP/NP Detectors

- Very complex, large-scaled engineered devices
- Major challenge for data collection & analysis
- Future Circular Collider FCC-hh detector
  - 100s TB/s at 40 MHz bunch crossing
- Complex events, fast classification
- Requires real-time analysis at the sensors



➢ *Investigate and develop a technical path for using neuromorphic computing algorithm/devices in future detectors*

➢ *Investigate interconnect possibilities and develop design point requirements for future detectors*

3

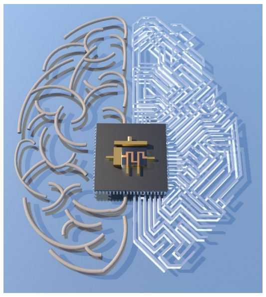
Detectors at Colliders: LHC Example

- Today:
  - Colliders – L1 trigger latency (ASIC/FPGA) of 10 microsec, selecting 100K events/sec to the high-level trigger (CPU/GPU/FPGA), which selects about 1000 events
- Future:
  - Higher luminosity, bunching (temporal), more intelligent selection
  - With higher luminosity, pile-up challenges (multiple collisions per bunch crossing), both in-time and out-of-time
  - Power/speed requirements difficult with current technology extrapolations
  - Opportunities in more intelligent selection: pattern recognition, particle classification, more

4

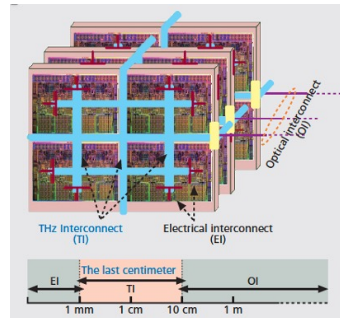
Materials Research

Neuromorphic Materials



- *Focus on scaling down device parameters, critical to achieving low power operation*
- *Explore relationship between materials parameters and gate tunability of memtransistor synaptic response for learning*

THz Interconnects



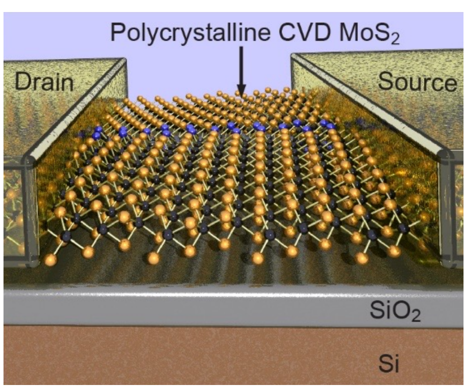
- *Create frequency-agile wireless antennas to transmit and receive THz signals on a small footprint*
- *Focus on THz plasmonics*

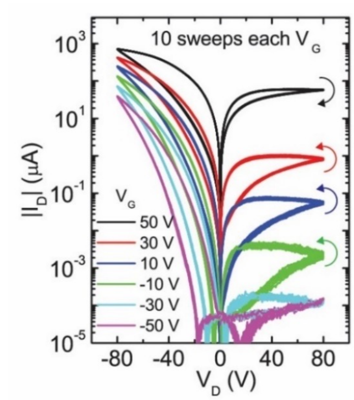
U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

5

Memtransistors Based on 2D Polycrystalline MoS_2





- Field-driven defect motion in 2D polycrystalline MoS_2 shows a 2-terminal memristive response
- Weak screening in atomically thin materials enables gate tunability like a transistor

Proposed Research:

- Reduce device dimensions and operating voltage/power by controlling grain size and defect structure in 2D polycrystalline MoS_2 in addition to novel dielectrics (e.g., ferroelectrics) and contacts (e.g., THz plasmonics, topological semimetals)

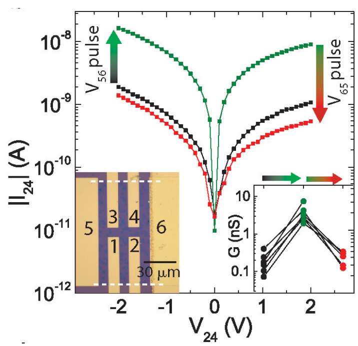
U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

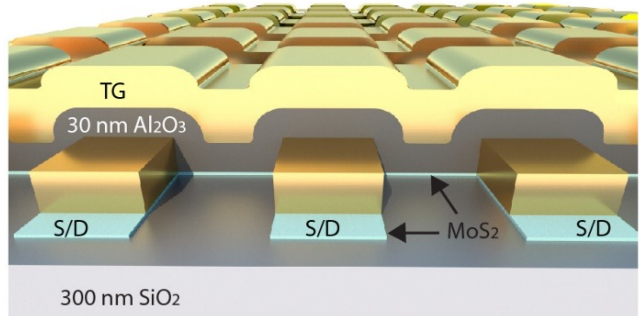
6

Multi-Terminal Memtransistors for Co-Design

Heterosynaptic Responses



Dual-Gated Memtransistor Crossbar Arrays

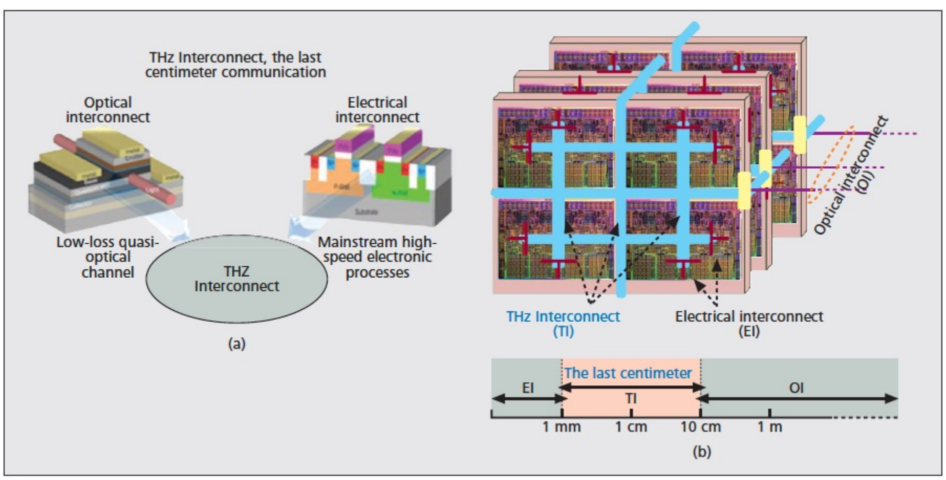


Proposed Research:

- Utilize the diverse synaptic responses enabled by multi-terminal memtransistors for advanced learning paradigms informed by Threadwork co-design

7

THz interconnects: Bridging the Optical and Electrical



Dissipation becomes prohibitive using conventional interconnects for > 1mm in the THz regime.

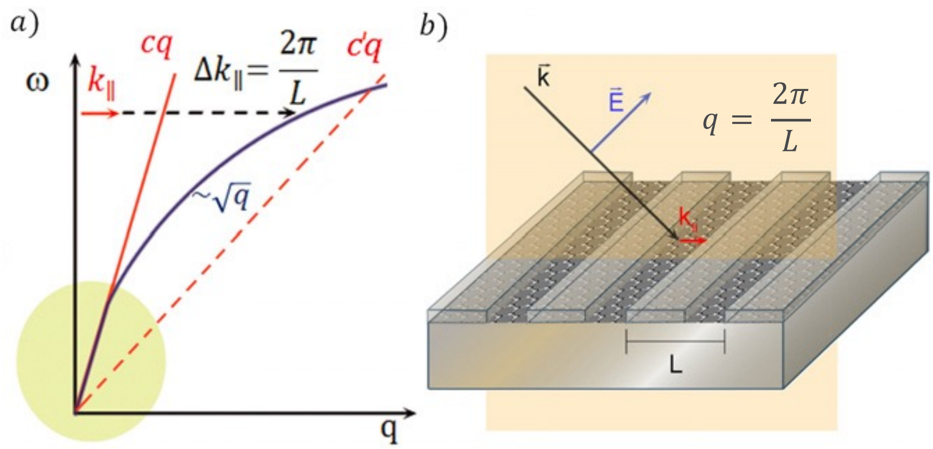
THz Plasmonic waveguides can bridge this gap

Q.J. Gu, *IEEE Communications Magazine* p.206 April 2015.

8

Plasmonics with Dirac Materials (including topological semimetals)

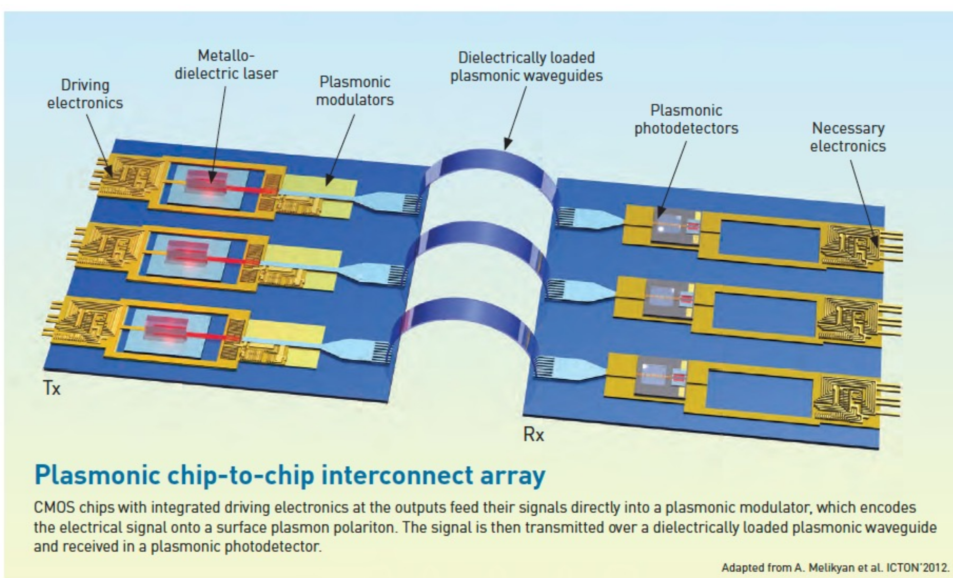
$\omega_p \sim n^{1/4}\sqrt{q}$



Advantage of Dirac materials : very strong confinement of plasmons, lower dissipation

9

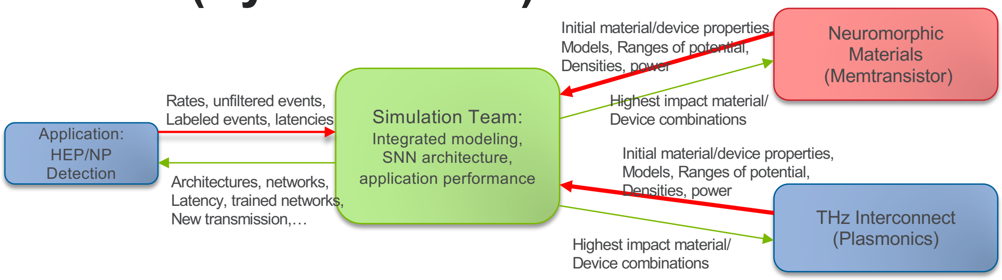
Example of a Plasmonic Interconnect



J. Leuthold et al., Optics and Photonic News, May 2013.

10

Simulations (System View)



- Represent pairwise relationships
- Includes traditional simulation models and surrogate models for:
  - materials, devices, circuits and systems, applications
- Include atomistic and device models
- *Facilitate co-design for the following:*
  - *application of novel memories for SNNs for triggering in HEP/NP detectors*
  - *application of novel materials for plasmonic interconnects*

11

Co-design Activities (Opportunities)

Optimized Spiking Neural Network Architectures for novel devices
- density, power
- continuous learning
- rich multi-terminal interconnections

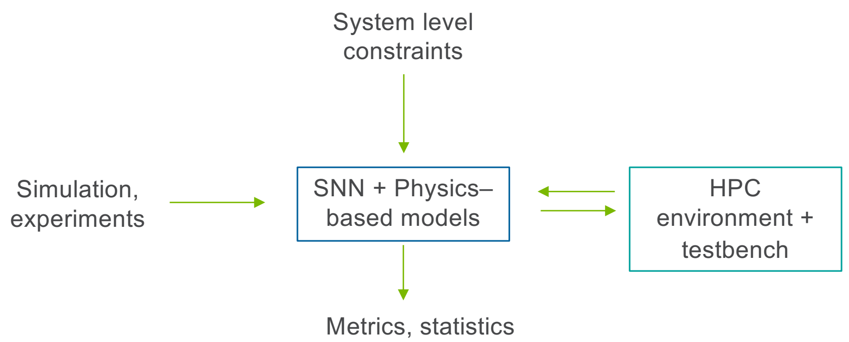
Optimized Devices for Spiking Neural Network Architectures
- native spike processing in "Dual-gated Gaussian Hetero-junction Ts"
- dense layouts and crossbars
- large dynamic range
- synaptic responses
- plasticity

Multi-level optimization for Plasmonics
- materials systems combinations
- angles for design (performance, system implications)
- system capability optimization

12

Demonstrating and Benchmarking Non-trivial Computing

Extend SNNs to implement gating mechanisms that will allow context-dependent processing and learning as well as explore non-local / volume modulation leveraging the different length scales of plasmonic and memtransistor devices



(stretch goal: SPICE / HDL connection)

Key ideas:

Current design tools cannot incorporate emergent technologies

Custom models can be run on leadership computing facilities in a massively parallel fashion

Models will be integrated to optimization engines to optimize over the design space (materials, devices, limited network architecture)

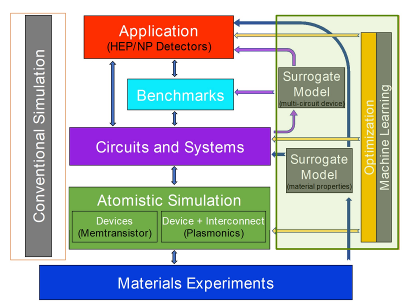
U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

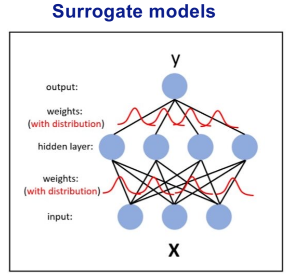
13

Accelerating Exploration with Surrogate Models

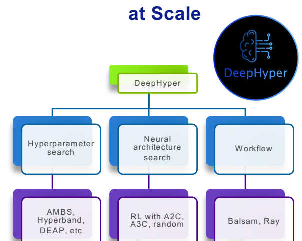
- Probabilistic machine learning-based surrogates that capture the heterogeneity and complexity of the data while accounting for the noise and uncertainty.
- Information-theoretic and Sparse Bayesian neural network with physics-informed constraints (wherever possible) will the leveraged for surrogate modeling.
- Active learning approaches (traditional Bayesian optimization, Monte Carlo tree-search) that can be used for mixed-integer optimization in the simulation campaign.
- Implemented and scaled on HPC through the Auto-ML framework DeepHyper.
- Interfaced at various stages (atomistic simulations, circuits, benchmarks and application).



Probabilistic and Physics-Informed Surrogate models



Multi-objective Optimization at Scale

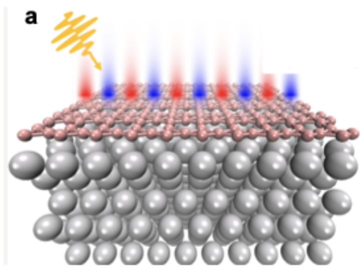


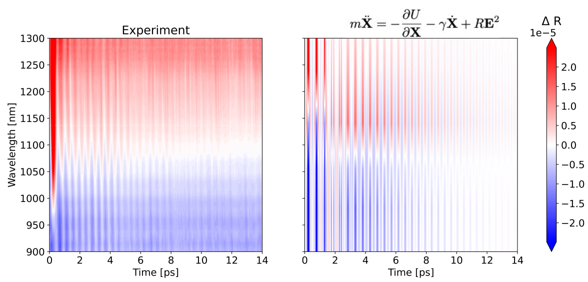
U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

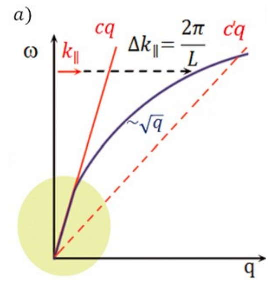
Argonne NATIONAL LABORATORY

14

Material-Informed Models of THz Emission







Key ideas:

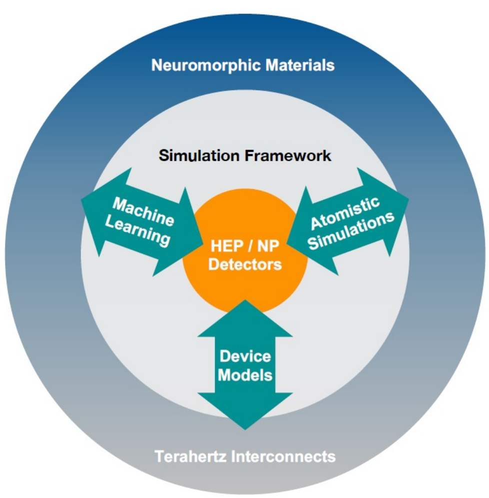
- Optimize dielectric environment to increase plasmonic density of states through substrate engineering
- Reduce THz response to Physics-informed ODE/PDE for (i) response function and (ii) internal state

U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

15

Threadwork Deliverables



energy efficient neuromorphic devices

simulations for the pairwise relationships

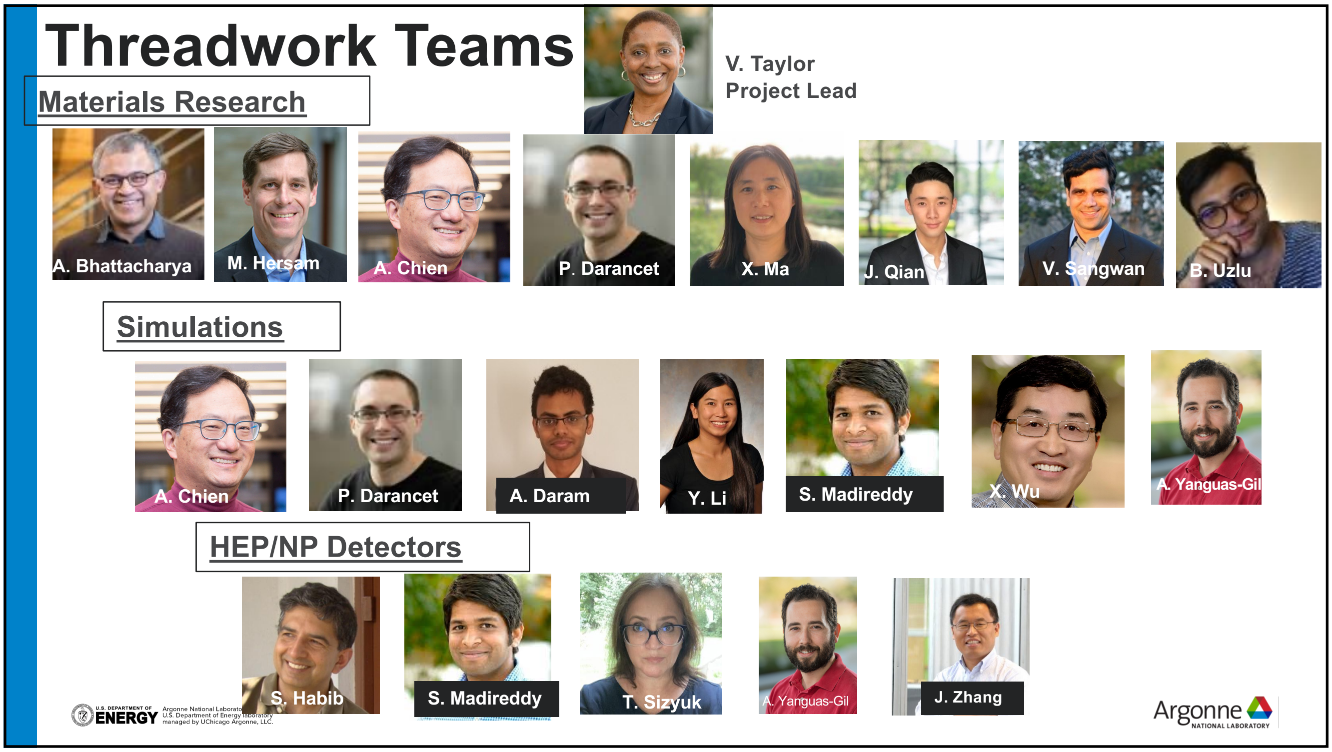
intelligent HEP/NP detector applications

novel plasmonic-optical interconnects

U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

16


Threadwork Teams
V. Taylor
Project Lead
Materials Research
A. Bhattacharya
M. Hersam
A. Chien
P. Darancet
X. Ma
J. Qian
V. Sangwan
B. Uzlu
Simulations
A. Chien
P. Darancet
A. Daram
Y. Li
S. Madireddy
X. Wu
A. Yanguas-Gil
HEP/NP Detectors
S. Habib
S. Madireddy
T. Sizyuk
A. Yanguas-Gil
J. Zhang
ENERGY
Argonne
NATIONAL LABORATORY

17


Questions?
This work is supported by the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research and Office of Basic Energy Sciences, Microelectronics Co-design Research Program.
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.
Argonne
NATIONAL LABORATORY

18

Questions?

19