# Particle Physics and Particle Astrophysics Experiment

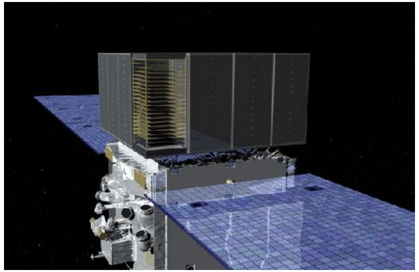
*2023 Graduate Student Orientation*

*H. A. Tanaka*

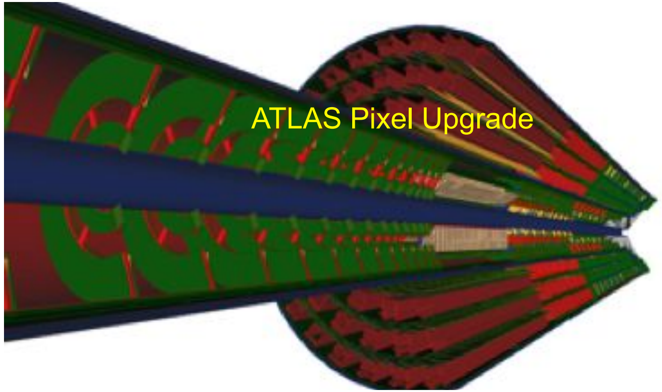
SLAC

# Experimental program at SLAC

- Rich history of discovery at SLAC
- Particle physicists: detector development, data analysis have had big impact on cosmology and astrophysics
- SLAC + Stanford: unique partnership

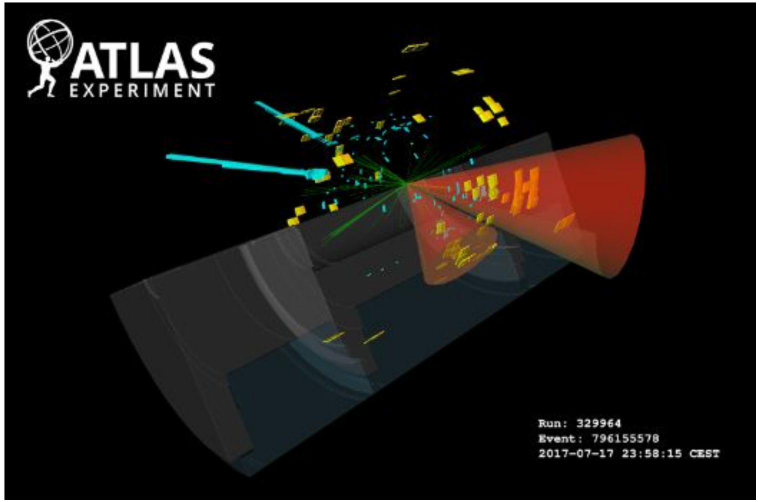



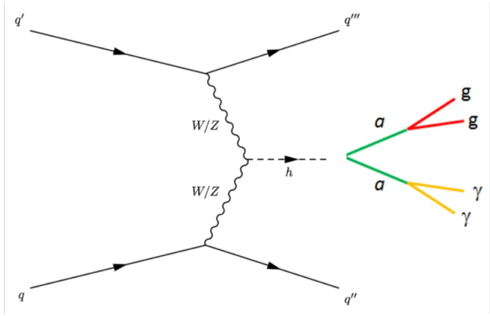




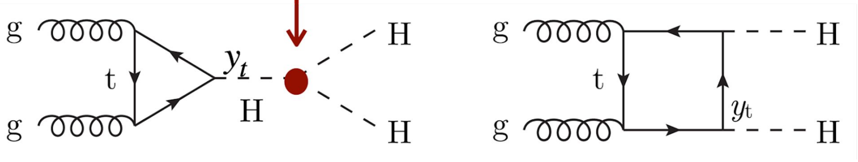
# Higgs portal for new physics at the Large Hadron Collider

- Use the Higgs boson as a new tool for discovery and Explore the unknown:
  - Higgs self coupling
  - SM and exotic Higgs decays such as light scalar *a* in h→*aa* decays
  - Extended Higgs sector
  - Search for long-lived particles



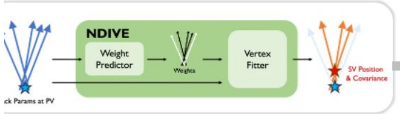




$$\lambda = \frac{m_{\mathrm{H}}^2}{2v^2} = 0.13$$

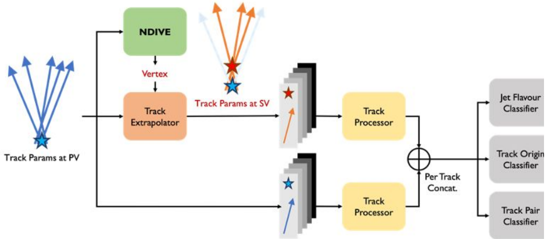


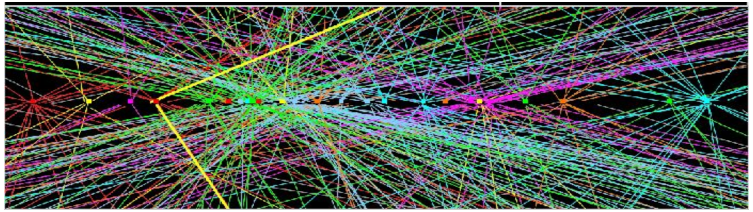
# Challenges and Opportunities with ATLAS

- Detector and physics performance in challenging LHC environment:
  - Advanced b, c quark jet tagging
  - Jet substructure reconstruction and pile-up mitigation
  - Tracking and vertexing in dense environment
- Advanced ML tools/applications such as deep learning, simulation, ML-based triggers, differential programming
- Detector operations and upgrades
  - HL-LHC Inner pixel assembly at SLAC
  - Trigger & DAQ with modern real time platforms
  - Future detector R&D

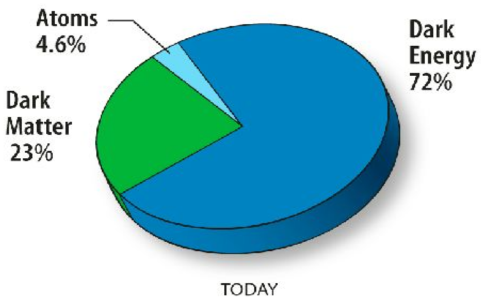


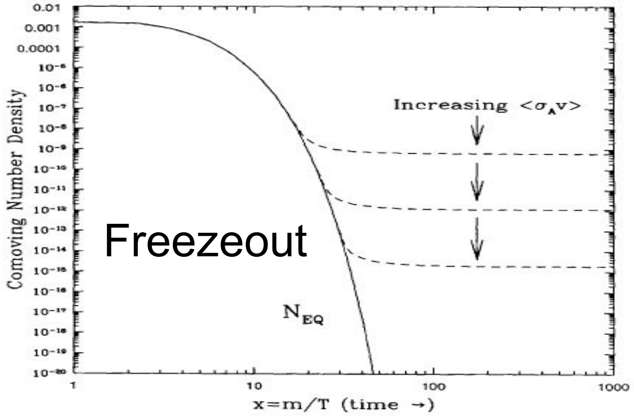

*Differentiable Vertex Reconstruction*
*For jet flavor tagging*

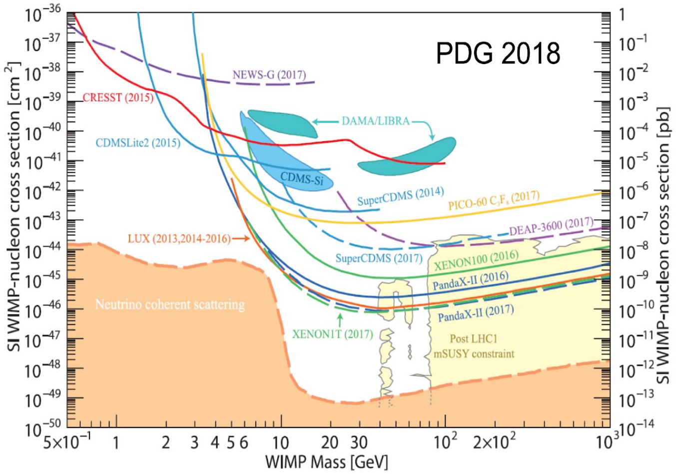


# DARK MATTER

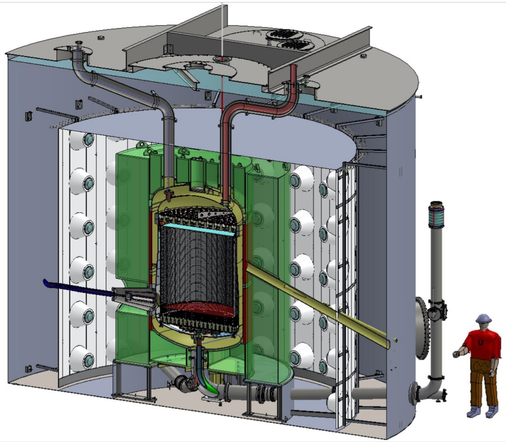


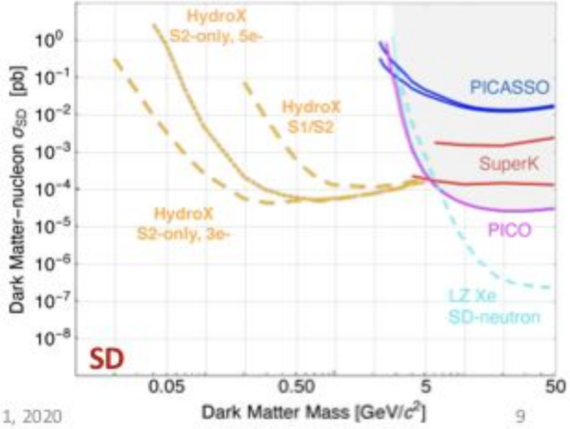




- WIMPs (Weakly Interacting Massive Particles)
- Beyond WIMPs
  - Sub GeV DM: Asymmetric, other light
  - Dark Photon, dark sector
  - Axions + strong CP problem
  - A new sociology

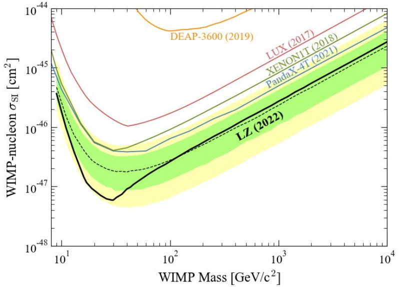
# DARK MATTER SEARCH WITH LUX-ZEPLIN

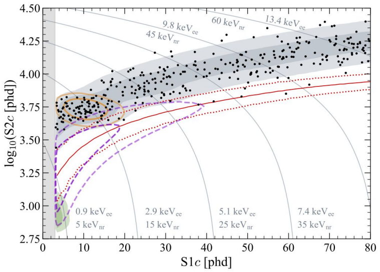


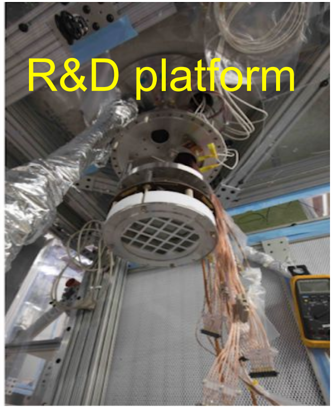
- Science Run 1: world leading
- Multiple years of data taking, science analysis, M/L
- R&D
  - HydroX low mass search
  - Xenon purification
  - New LAr γ ray detector development

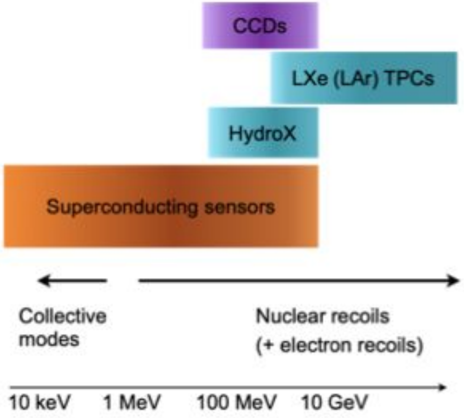



## LZ science underway



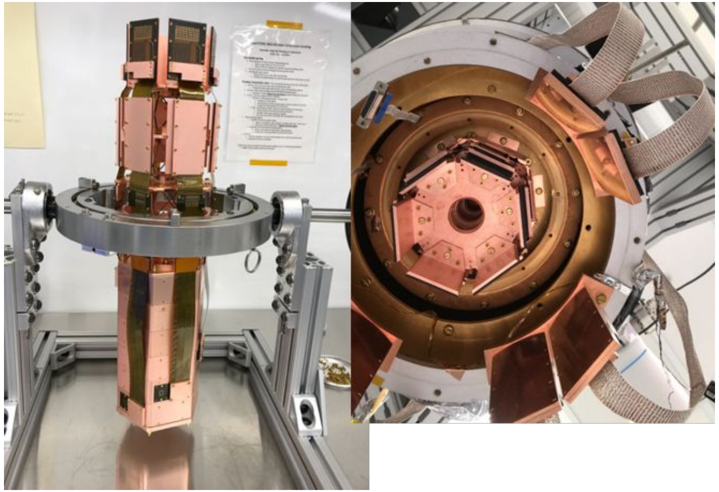



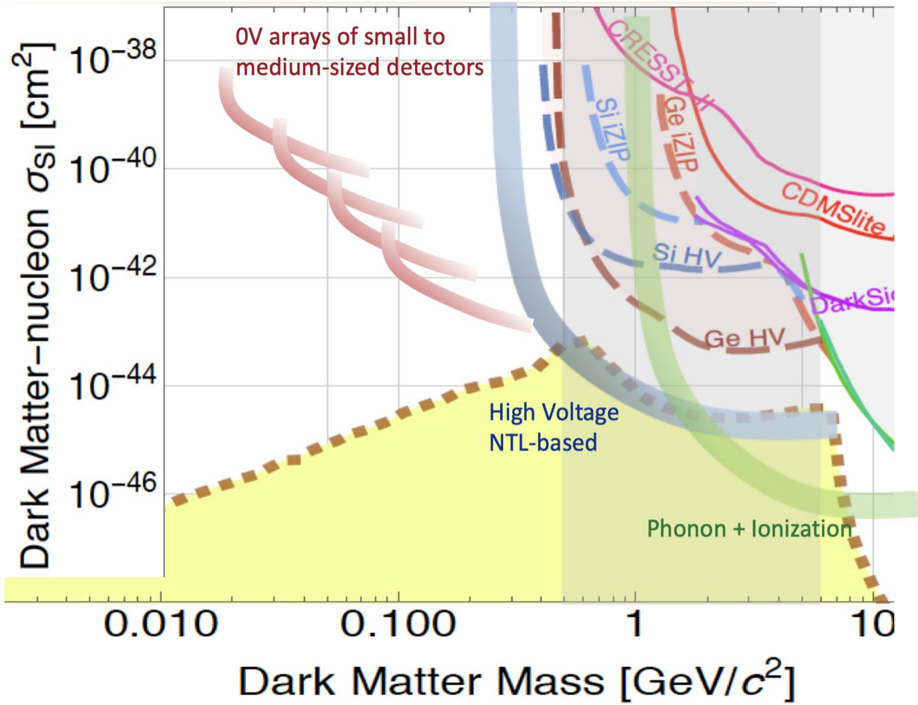



# Dark Matter Search with SuperCDMS SNOLAB

SLAC is the lead lab for the SuperCDMS SNOLAB experiment, which will operate a cryogenic payload underground at SNOLAB.

- Construction is complete
- First science results expected in 2024
- Many results from the R&D program in the interim!



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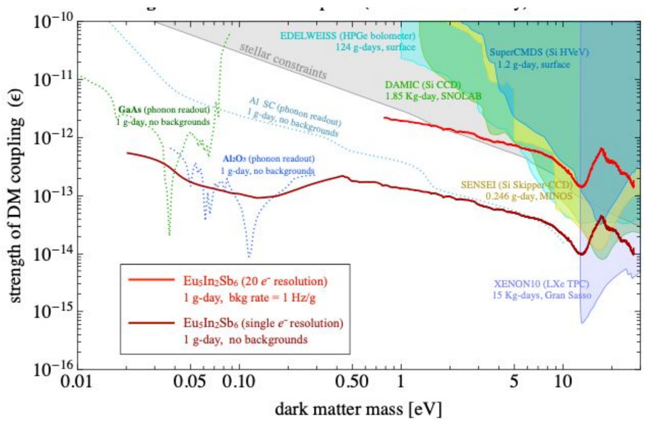
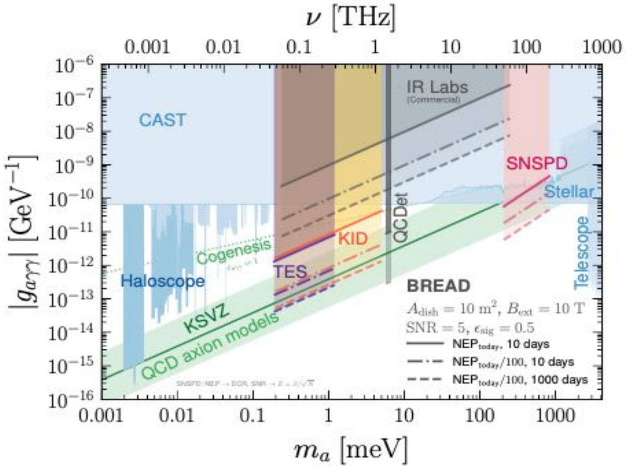
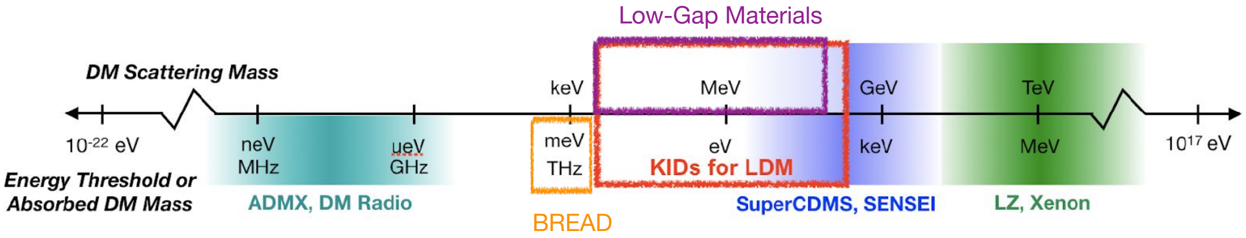
# QUANTUM SENSING FOR DARK MATTER SEARCHES

- Utilize superconducting sensors to search for dark matter in the meV-MeV regime, currently not probed by existing experiments
  - KIDs for phonon sensing
  - meV-gap materials with single charge readout (SPLENDOR)
  - Single THz, IR photon sensors for wide-band axion searches (BREAD)
  - Sensors derived from qubit co-design work; heavy overlap with QIS
  - Heavy on device R&D and quick science results
    - demonstrations for larger follow-on experiments
- Smaller scale projects suitable for one student and postdoc, dark matter searches done on site at SLAC!

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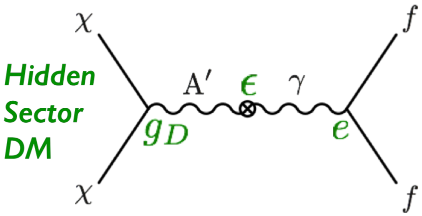
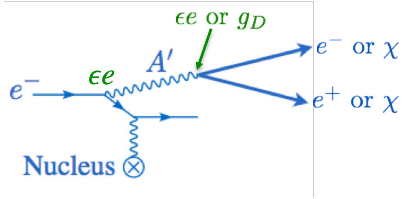
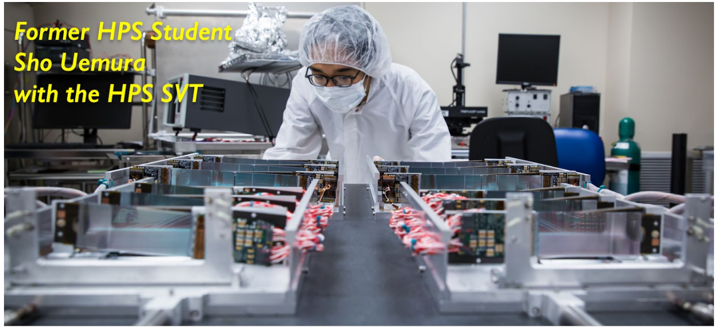
# "HIDDEN SECTOR" DARK MATTER

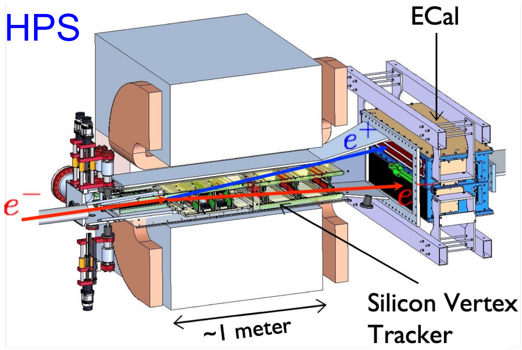
- Dark matter couples through hidden sector to standard model particles.
- Benchmark case: dark photon, A′
- Search for hidden sectors at accelerators
    - A′ decaying to SM particles: HPS @ JLab
    - Production of hidden sector Dark Matter: LDMX @ SLAC
- Unique theory/experiment collaboration at SLAC

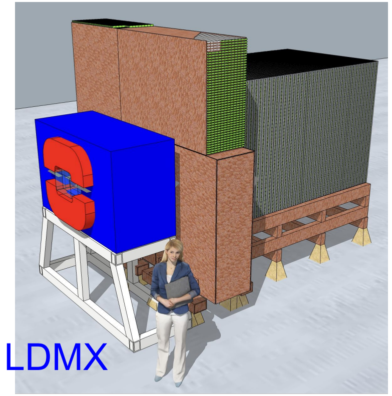



*dark bremsstrahlung*

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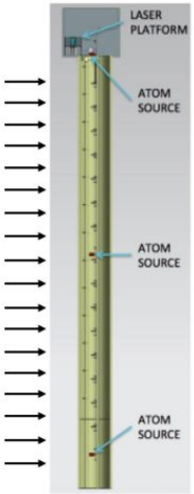
# MAGIS-100: Ultralight Dark Matter and Gravity Waves

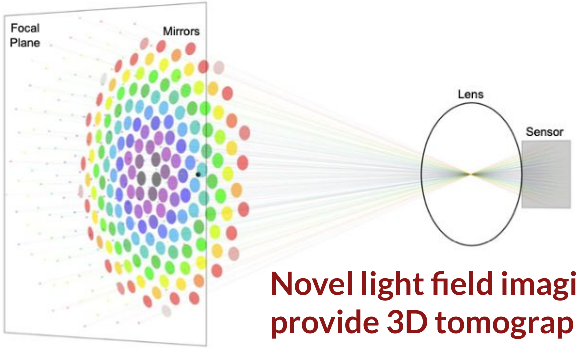
**Matter Wave Atomic Gradiometer Interferometric Sensor**:
Largest atom interferometer in the world
Under construction at Fermilab



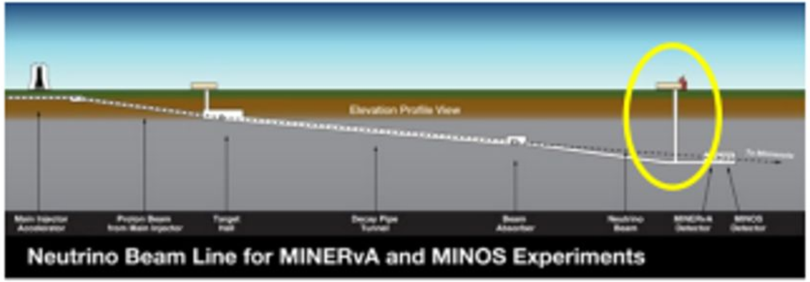

*Cross section full detector*

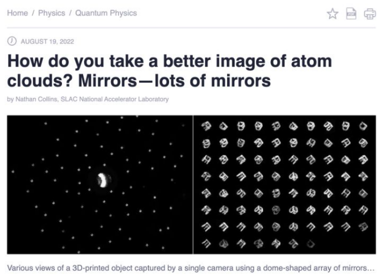
**Design of imaging systems:**

- Diagnostics imaging system
- Super-Aperture light-field imager




**Novel light field imaging device provide 3D tomographic reconstruction of atom clouds**
Machine learning differentiable simulators and reconstruction



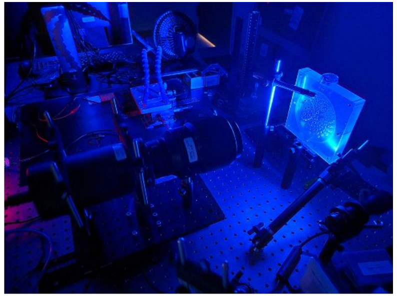


Home / Physics / Quantum Physics

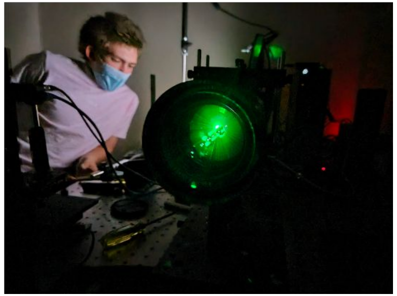
AUGUST 19, 2022

**How do you take a better image of atom clouds? Mirrors—lots of mirrors**

by Nathan Collins, SLAC National Accelerator Laboratory

Various views of a 3D-printed object captured by a single camera using a dome-shaped array of mirrors...

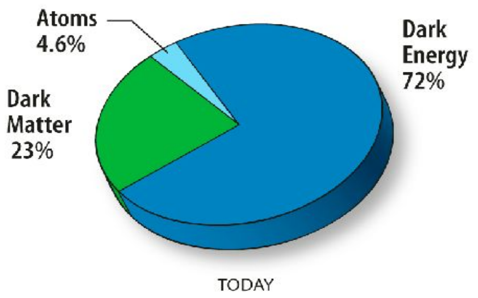


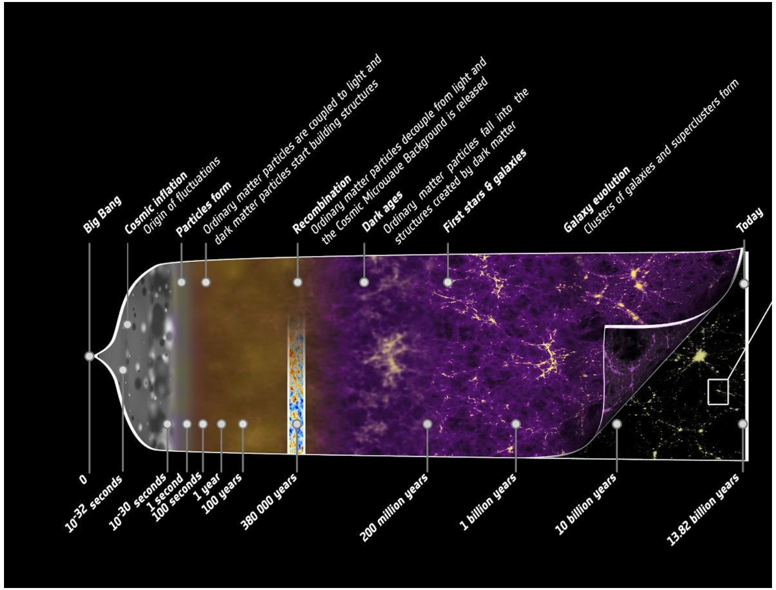


Exciting opportunities to design/build/test novel imaging hardware and machine learning 3D tomographic reconstruction software

# COSMIC ACCELERATION: DARK ENERGY AND INFLATION

- Dark Energy:
  - Late-time expansion of the universe
    - Cosmological Constant? Quantum Field?  General Relativity wrong?
  - Observables:
    - Expansion (scale vs. redshift) or growth (matter clumping vs. redshift) history by mapping galaxies, supernovae, quasars
    - CMB Weak lensing
  - Surveys/Experiments:
    - Imaging (Dark Energy Survey, Rubin Observatory)
    - Spectroscopy (DESI)
    - CMB (SPT, Simons Observatory, CMB-S4)
- Inflation:
  - Accelerated expansion of the early universe
    - Scalar field with shallow potential drives expansion
    - Converts quantum fluctuations to classical scales
    - Plants seeds for large-scale structure seen today
  - Observables:
    - Imprint of gravitational  waves in CMB polarization
  - Surveys/Experiments:
    - BICEP, CMB-S4

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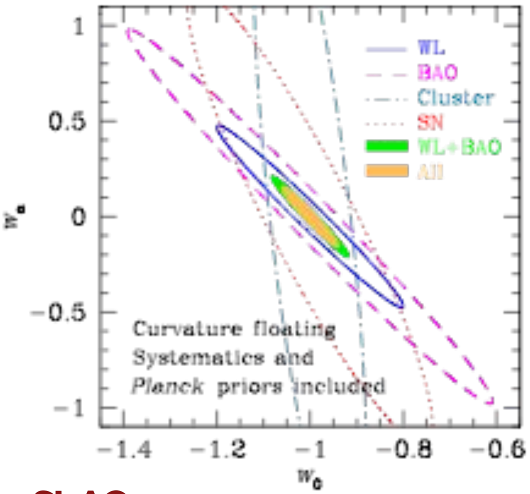
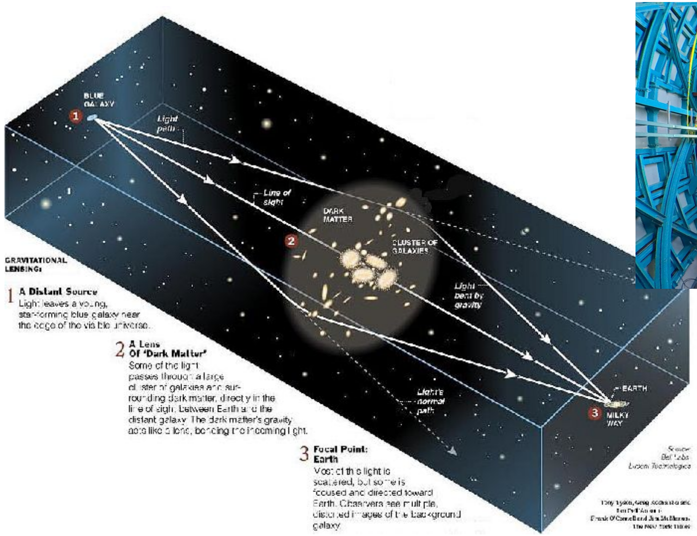
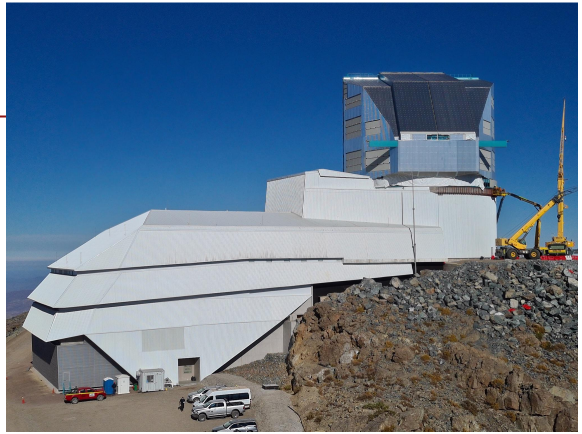
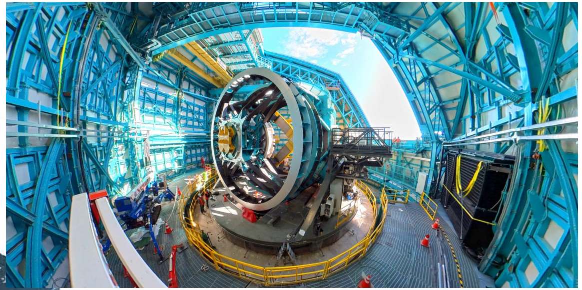
# Rubin Observatory / LSST

- Wide field survey with massive camera
- Dark energy
  - Independent measures of structure evolution
  - 1 million supernovae
- First light in 2024



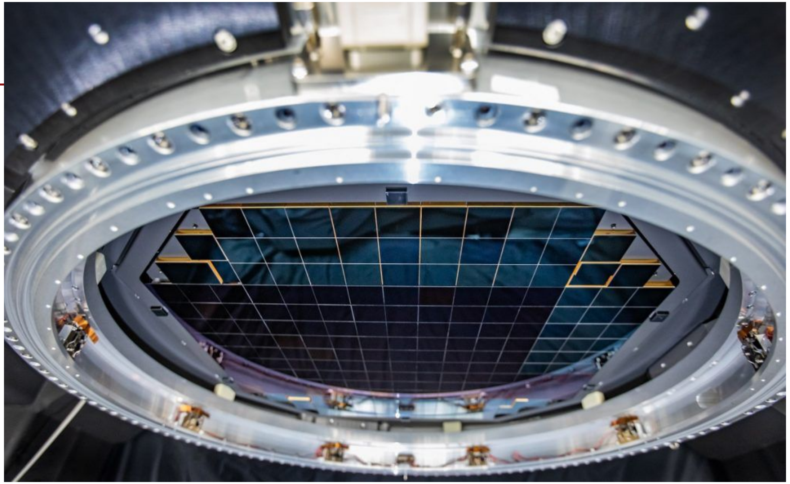



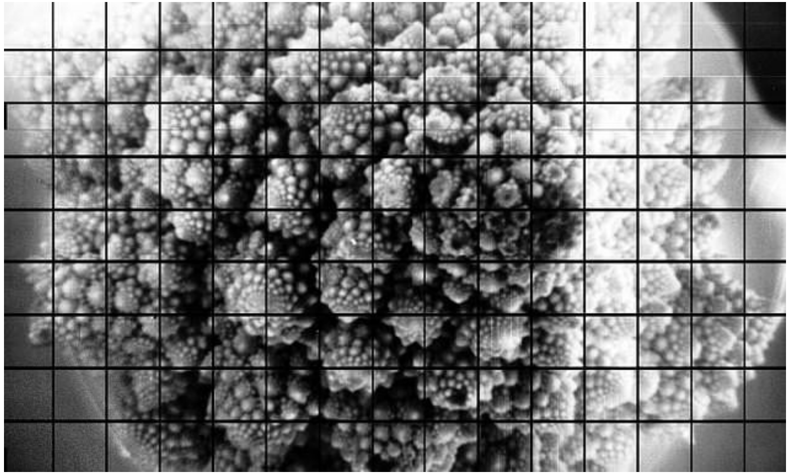





# LSST CAMERA

- Camera assembled and tested at SLAC
  - Large effort to characterize and minimize systematics
- Wealth of other astrophysics topics
  - Dark matter from weak lensing
  - Extensive map of Milky Way
  - Strong Gravitational Lensing
  - Cross-correlation with CMB, etc...
  - Time domain: transients and variable objects
  - etc...





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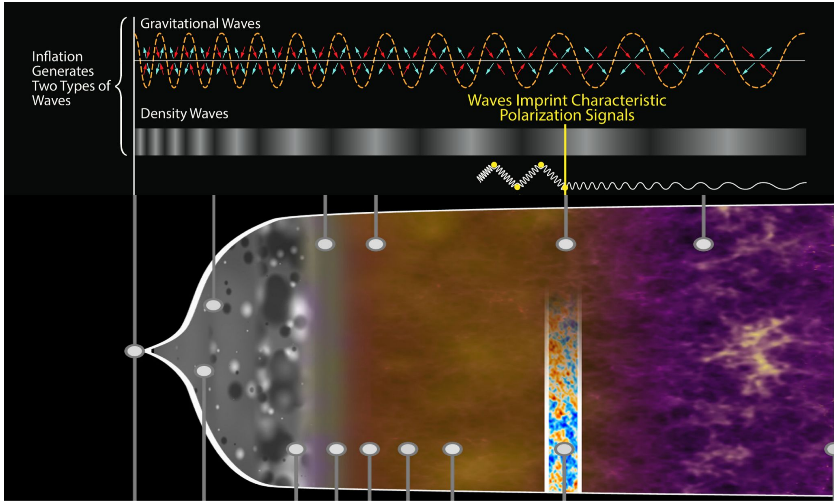
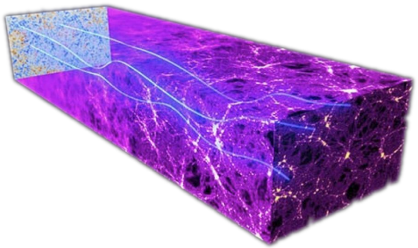
# CMB Experiments: BICEP, SPT, Simons Observatory, CMB-S4

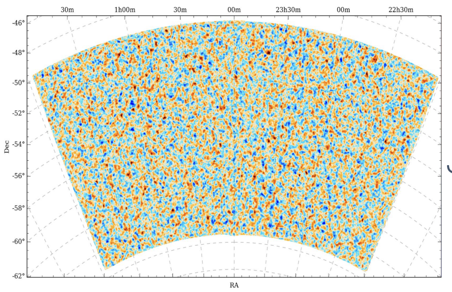
Key science themes:

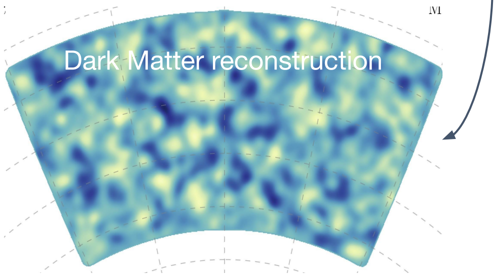
- Search for evidence of cosmic inflation
- Understand dark energy, dark matter and large-scale structure by using CMB as a backlight




Primordial gravitational waves are generated by inflation just like scalar density waves (seeds of all structure we see today). Those GWs imprint into the polarization of CMB photons when they were released and might be detectable today.






CMB backlight: Photons are deflected by cosmic structure as they travel, but can help reconstruct dark matter distribution along the way!

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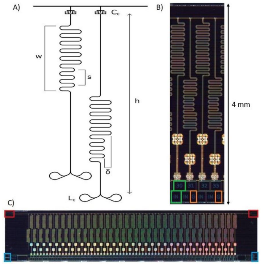
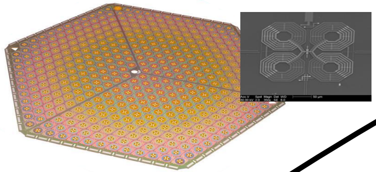
# CMB Experiments: BICEP, SPT, Simons Observatory, CMB-S4

Broad program spanning superconducting sensor development, camera and instrumentation design through simulations, observations and scientific results from CMB experiments

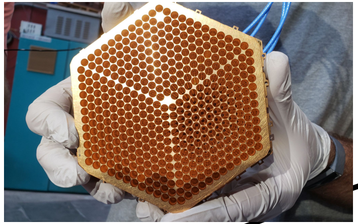
Opportunities for substantial impact by graduate students in any of these areas!



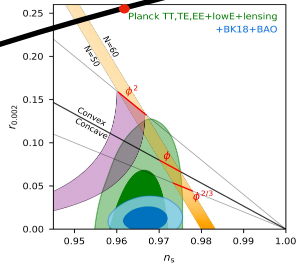
Cryogenic, Superconducting Detectors, Resonators and Amplifiers of CMB Cameras

Readout Electronics, data acquisition for CMB cameras

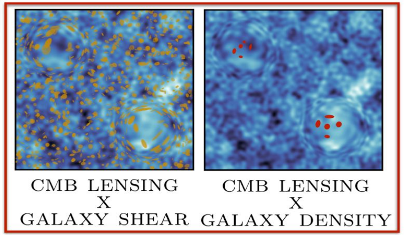


Integrated detector and CMB camera systems

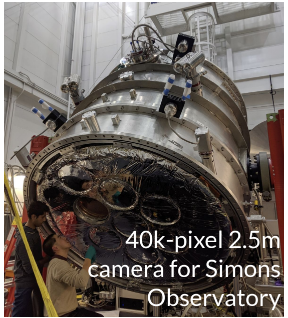
CMB pipeline, data analysis, science

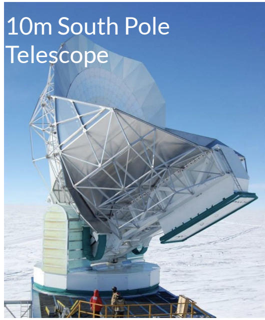



Multi-dataset cross-correlation and cosmology





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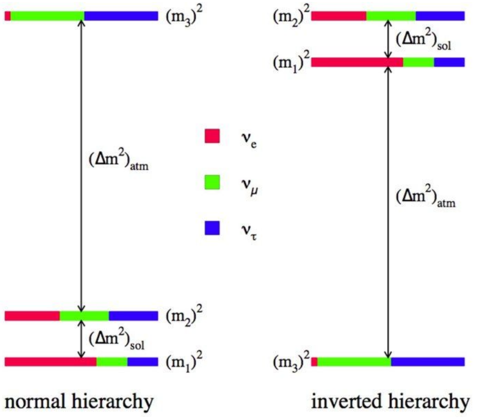
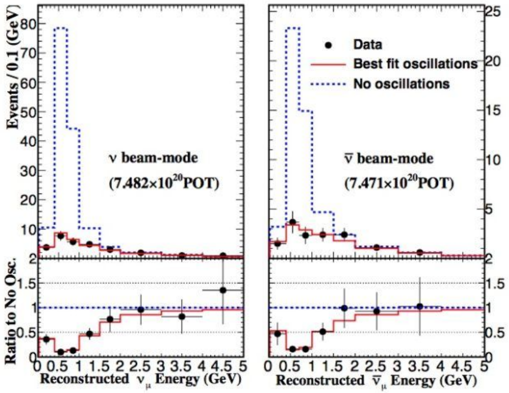
# NEUTRINOS

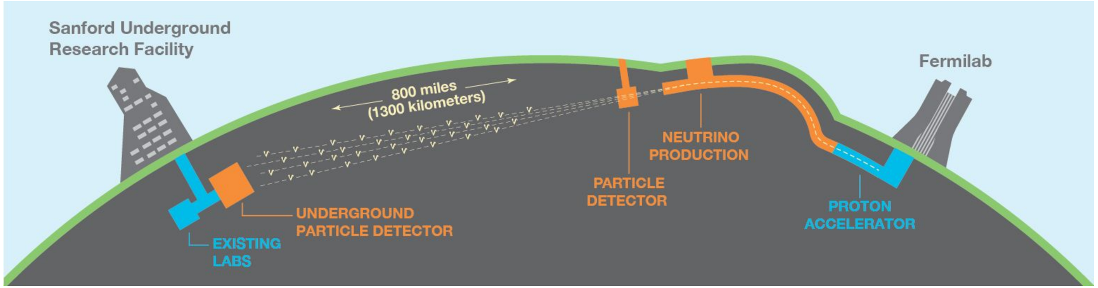
- The most abundant particle in the universe after photons
  - Neutrino properties have enormous implications for cosmology
- Neutrino oscillations:
  - Probe neutrino mass/flavor mixing by precession of neutrino flavor
  - Direct evidence of neutrino mass (physics beyond standard model)
- Fundamental questions remain:
  - What are the nature and origin of neutrino masses?
  - What are the neutrino masses?  Do neutrinos, antineutrinos oscillate differently?
  - Is there more to this picture?
    - Additional neutrino states? “Non-standard” interactions?




Muon neutrinos oscillating other neutrino flavors over 295 km at T2K




**DUNE:**
Future experiment to study neutrino oscillations over 1285 km

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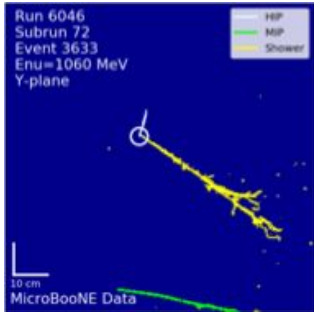
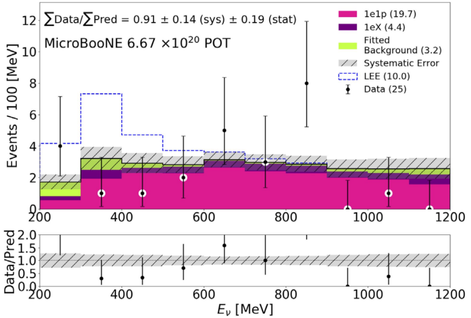
# ACCELERATOR NEUTRINO PROGRAM

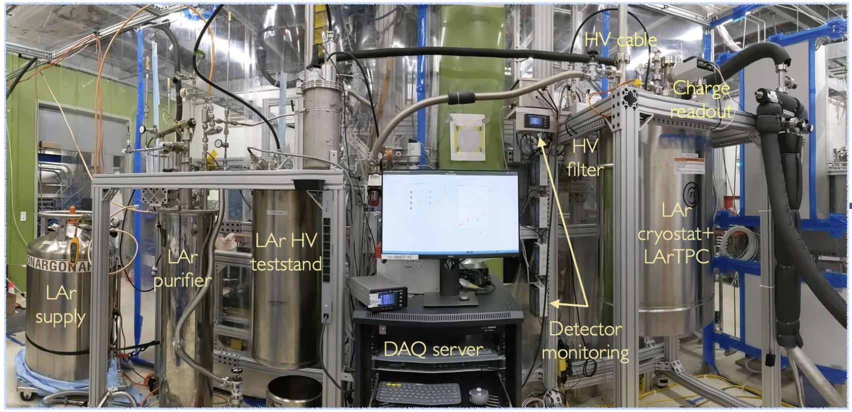
μBooNE search for excess $\nu_e$-like interactions

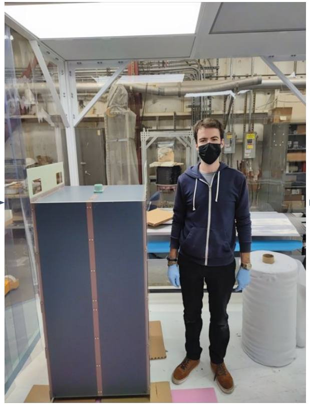
- Short Baseline Neutrinos (μBooNE, ICARUS)
  - Search for exotic neutrinos properties e.g. excess of $\nu_e$ interactions
  - Study of neutrino-argon interactions
- R&D/Prototyping of LAr Time Projection Chambers
  - Near detector for DUNE
    - 7x5 array of 1x1x3m$^3$ LArTPCs + 1kt muon spectrometer
  - Future DUNE far detector modules:
    - New readout schemes for enormous ~17 kton LArTPCs



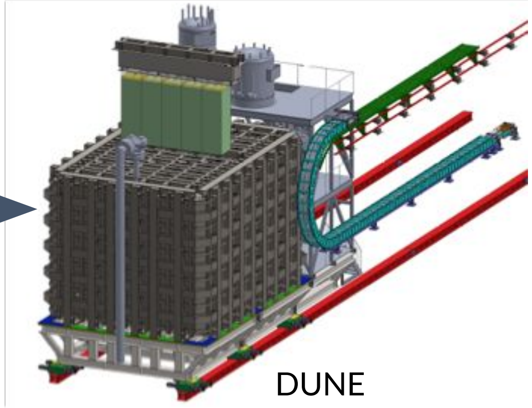




LAr platform at SLAC



Mid-scale prototype

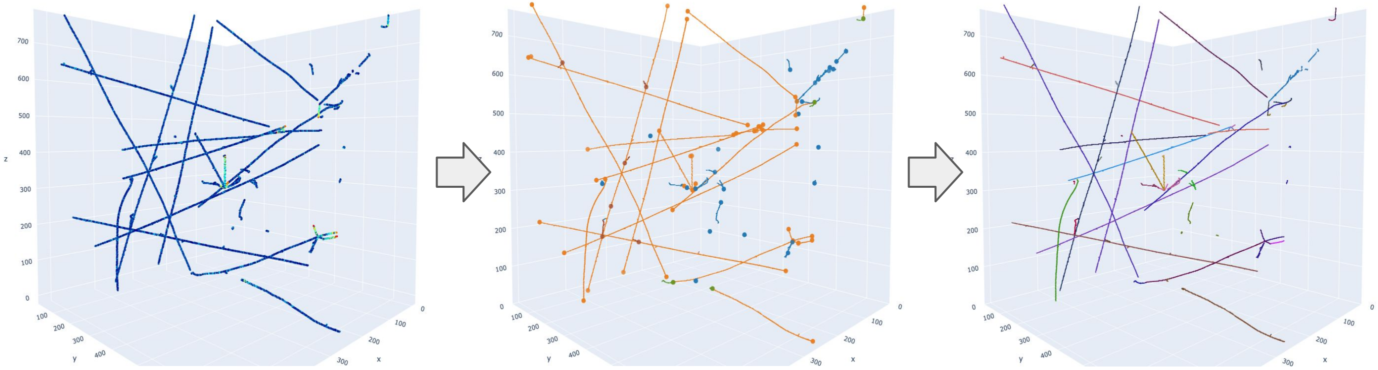


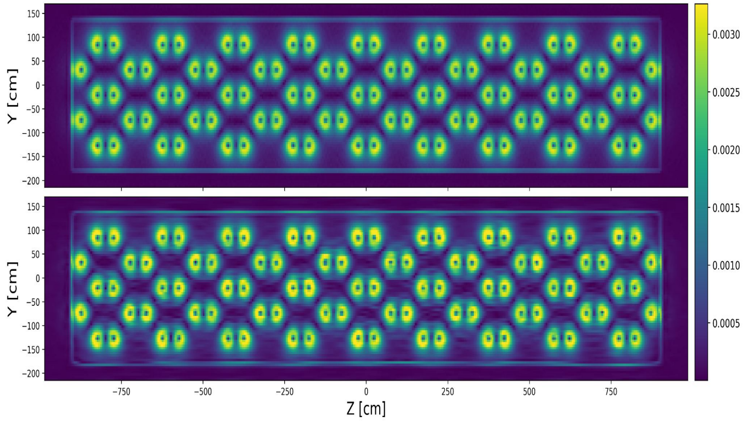
DUNE Near Detector

SLAC

# Accelerator neutrino programs

**First ML-based full reconstruction chain for neutrino experiments**
Automated full chain optimization, orders of magnitude acceleration using HPC, enable physics goals for DUNE/SBN.






**Novel physics simulator: differentiable physics models for inference & design optimization**
Expand breakthroughs in computing to unlock new physics analysis paradigms
(e.g. automated, data-driven detector physics calibration)

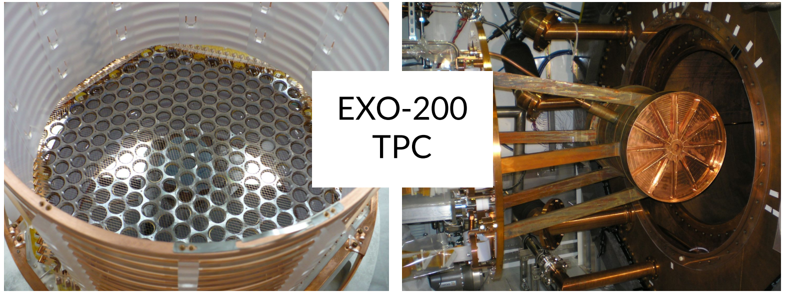
# nEXO: NEUTRINOLESS DOUBLE BETA DECAY SEARCH

## Are neutrinos Majorana or Dirac ?

## Is Lepton Number Violated ?

Program follows successful EXO-200 experiment with 100 kg liquid xenon (enriched in $^{136}$Xe) TPC - search for neutrinoless double beta decay - *only possible for Majorana neutrinos.*

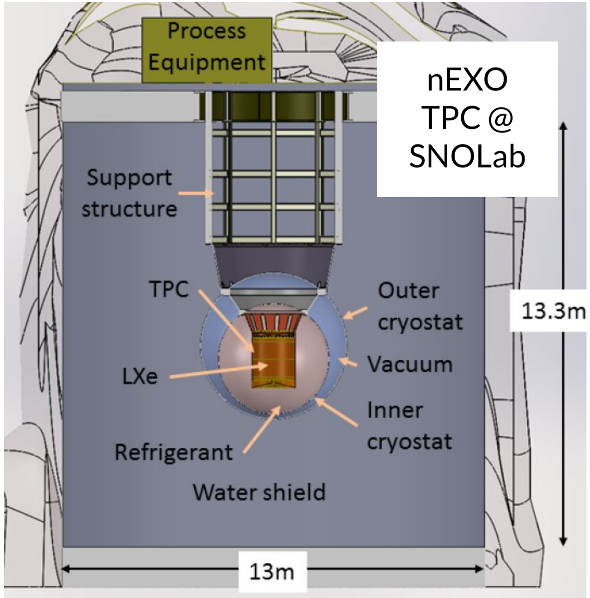
- First observation of SM ($2\nu\beta\beta$) in $^{136}$Xe : $2.17 \pm 0.06 \times 10^{21}$ yr HL
- Set $>10^{25}$ yr HL limit on neutrinoless ($0\nu\beta\beta$) decay



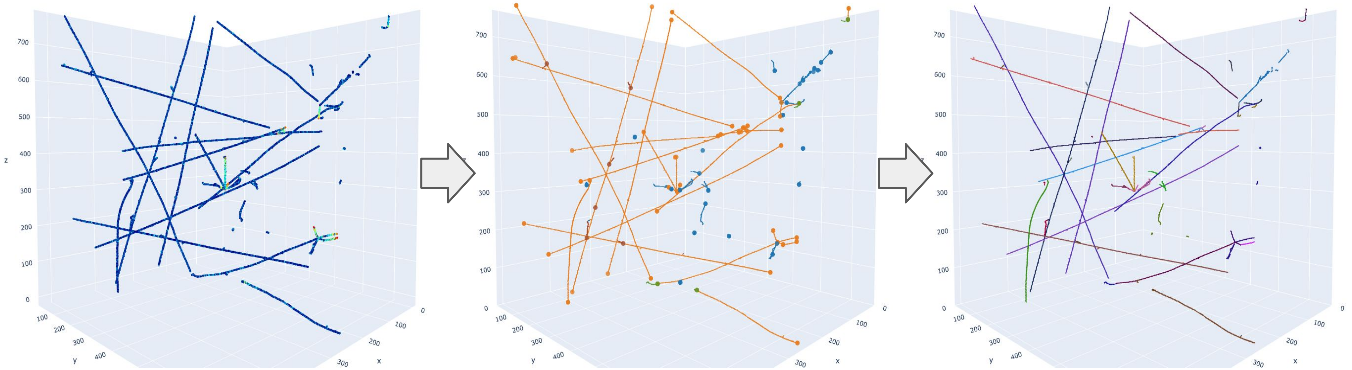


**nEXO is the planned 5 ton enriched Xe TPC with 100 times more sensitivity**

**Opportunities for students**

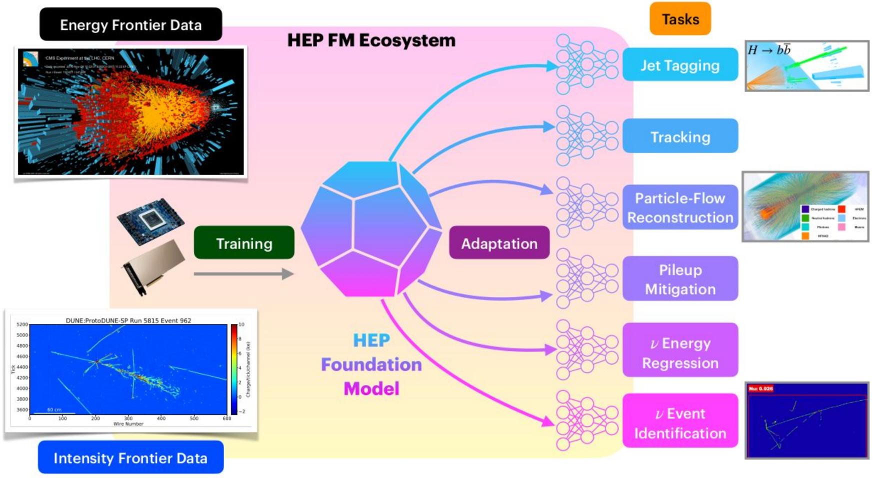


# HEP Research "with" / "for" Machine Learning & AI



**Machine Learning for data reconstruction & analysis of HEP experiments**
Automated full reco chain optimization, orders of magnitude acceleration using HPC, enable/expand physics reach.

**Novel physics simulator: differentiable physics models for inference & design optimization**
Expand breakthroughs in computing to unlock the new analysis paradigms (e.g. automated detector design optimization & calibration)




**Generic, multi-tasking AI models for particle physics**
Big, general purpose AI models directly trained on real data (e.g. GPT-3) can be shared across multiple tasks and experiments. HEP research challenges offer a unique R&D environment for this area of AI research

# AT SLAC

- ATLAS
- LZ, HydroX
- SuperCDMS, DMQIS
- Fermi-LAT
- HPS + LDMX
- DES
- LSST
- MicroBooNE, ICARUS
- DUNE, T2K
- nEXO
- BICEP, SPT, Simons, CMB-S4
- DM Radio

Talk to poster presenters about office/lab visits this afternoon

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