Particle Physics and Particle Astrophysics Experiment

2025 Graduate Student Orientation

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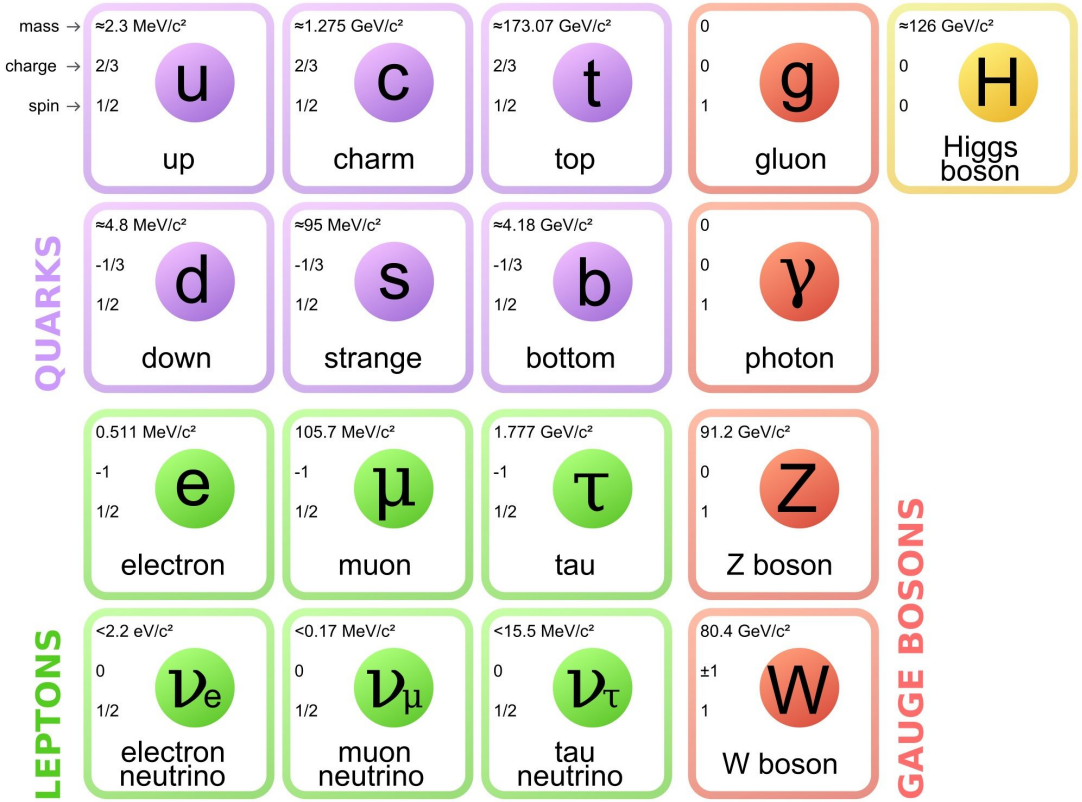
MARGUERITE STOP

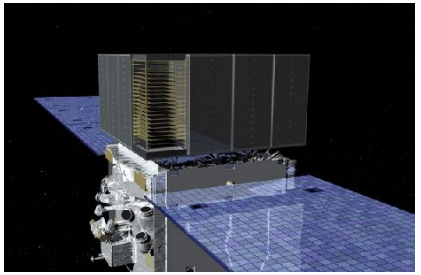
PARTICLE PHYSICS

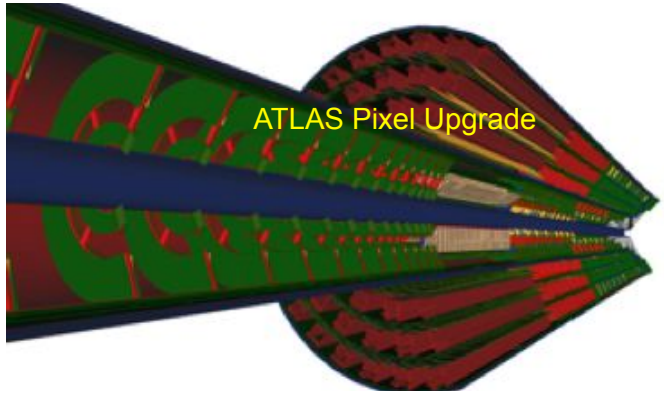


Whatever else it takes for us to understand the interactions and how they result in the universe as we “see” it.

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

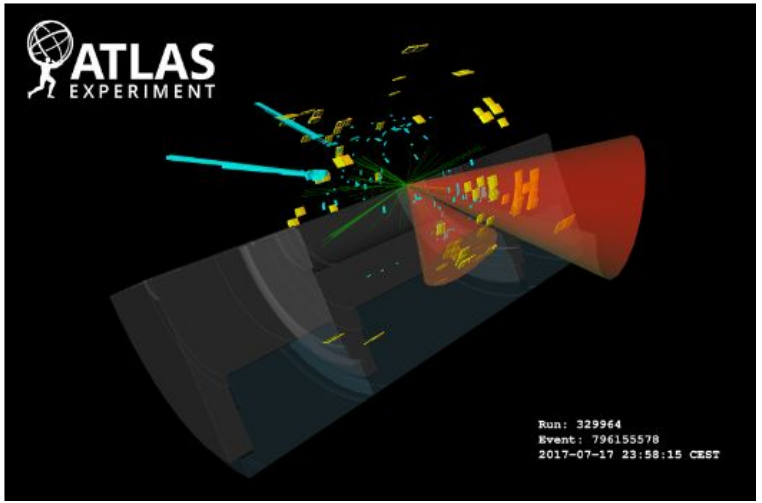


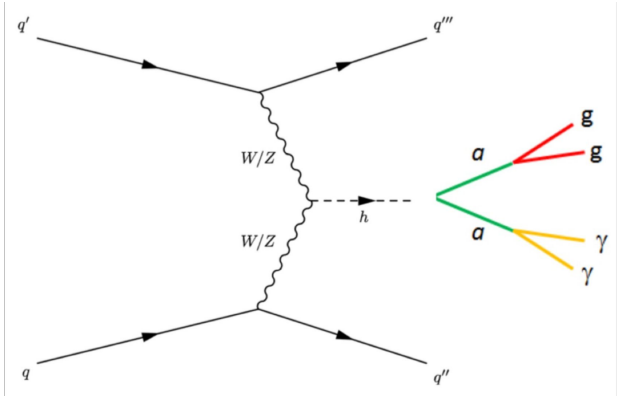


APOLOGIES

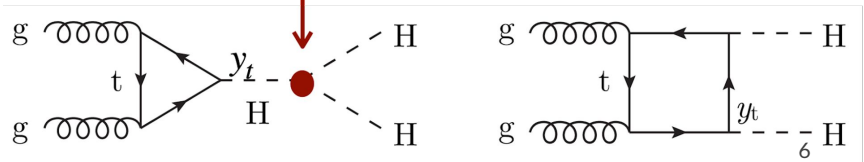
New physics at the Large Hadron Collider (LHC)

- Use the Higgs boson as a new tool for discovery:
  - Higgs self coupling
  - SM, exotic Higgs decays such as a light scalar *a* (h→*aa*)
  - Extended Higgs sector
- Explore exotic and/or challenging detector signatures
  - long-lived particles, dark sectors
  - via machine learning and anomaly detection



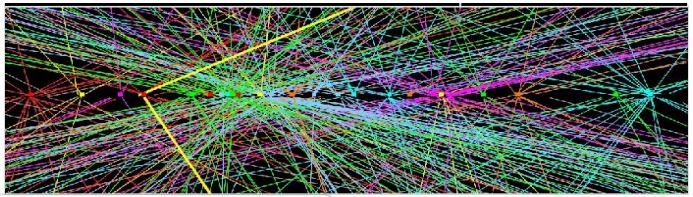


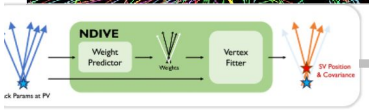
$$\lambda = \frac{m_H^2}{2v^2} = 0.13$$



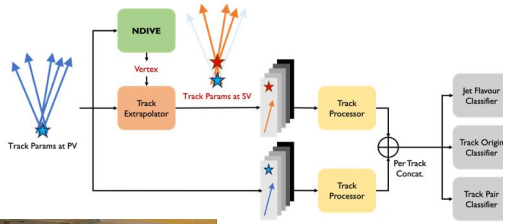
Challenges and Opportunities with ATLAS

- Detector/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
  - Real-time ML for anomaly detection trigger for 2025 data-taking
- 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
    - Towards future colliders

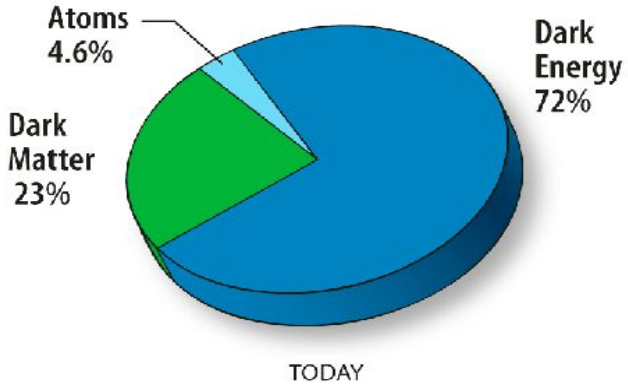


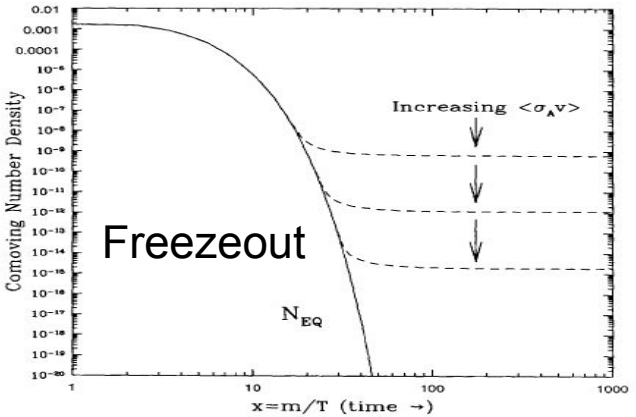


Differentiable Vertex Reconstruction For jet flavor tagging

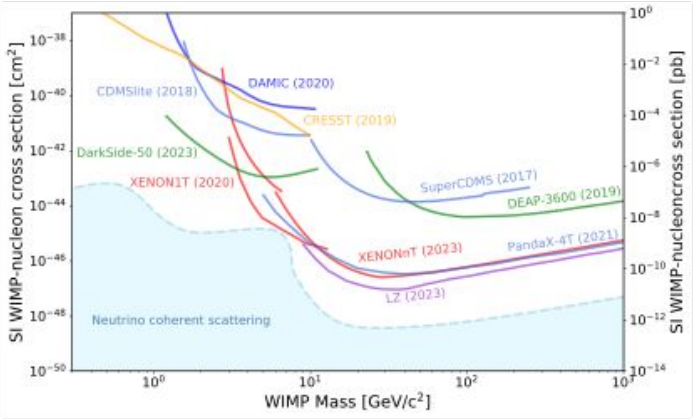


DARK MATTER





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

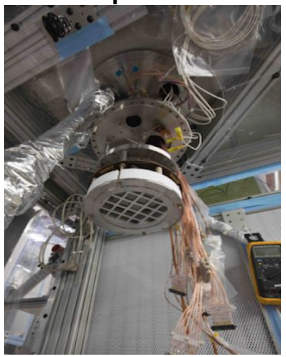


Contacts: Dan Akerib akerib@slac, Tom Shutt tshutt@slac, Ann Wang (awang5@slac)

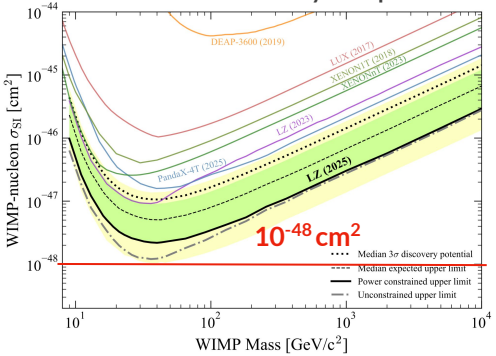
DARK MATTER SEARCH WITH LUX-ZEPLIN + XLZD

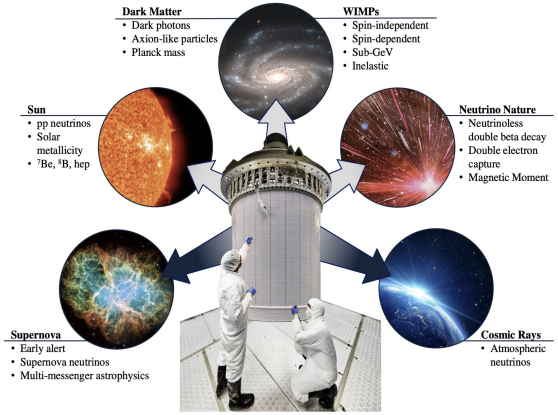
- World leading results with 10-ton LXe TPC detector
- Multiple years of data taking to come: science analysis, ML
- R&D towards next generation XLZD
  - HydroX → low mass WIMPs
  - Xenon purification / radon reduction
  - Cold readout development / SiPMs
  - Synergy with new LAr γ ray detector development
  - Large HV electrodes & electron emission phenomena

R&D platforms



Latest: 4.2 tonne-yr exposure





XLZD: 100-ton next generation rare event observatory

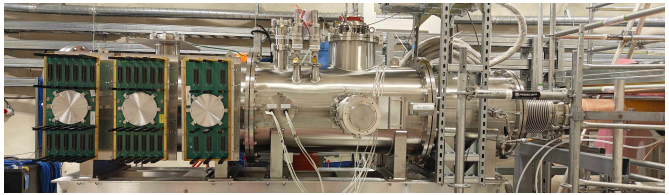
SLAC

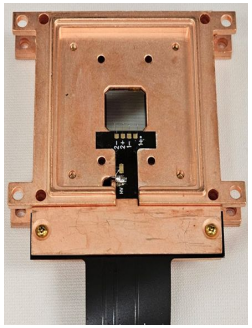
Contact: kstifter@slac.stanford.edu
kurinsky@slac.stanford.edu

Dark Matter Search with SuperCDMS SNOLAB

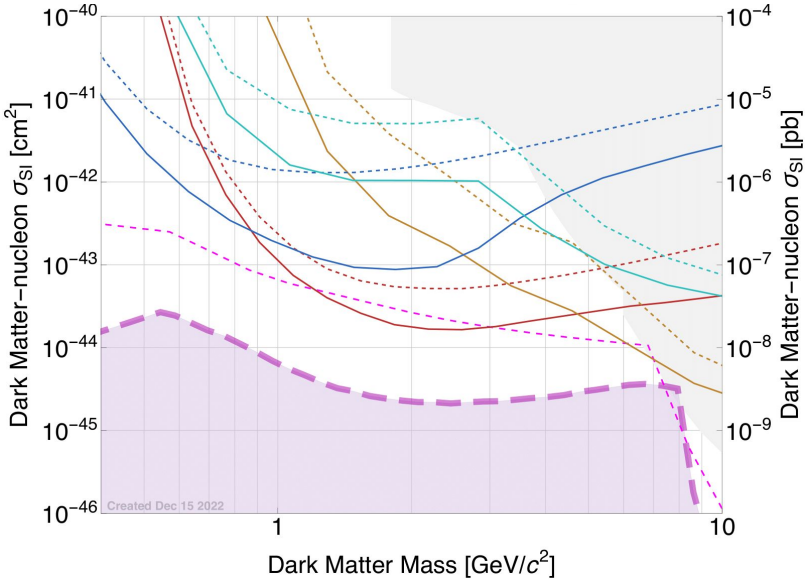
SLAC is the lead lab for the SuperCDMS SNOLAB experiment, which will operate a cryogenic payload underground at SNOLAB.

- Cooldown & commissioning in 2025
- First science data in 2026, followed by 3 years of data-taking & science analysis
- Exciting results from active instrumentation R&D program





Projected world-leading limits in low-mass regime:



Cyan: Si iZIP
Mustard: He iZIP
Blue: Si HV
Red: Ge HV

Dashed: Optimum Interval
Solid: PLR
Shaded: Limits as of 2022

Magenta: Neutrino “fog”, 1 neutrino detection limit

DMQIS group:
Quantum Sensors for Rare Event Searches

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kstifter@slac.stanford.edu

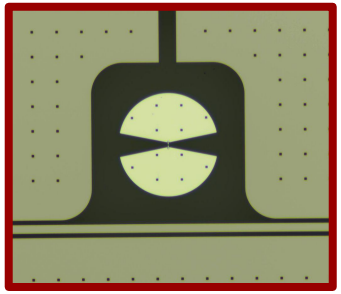
Pairing qubit-derived sensors…

With novel substrates…

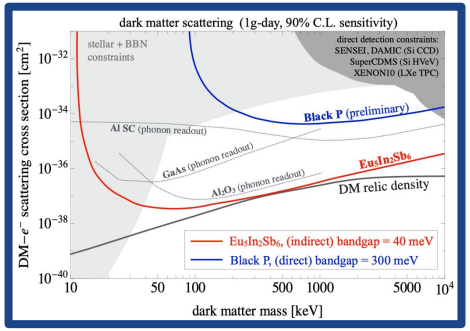
Enabled by cross-cutting technologies…

For many applications!

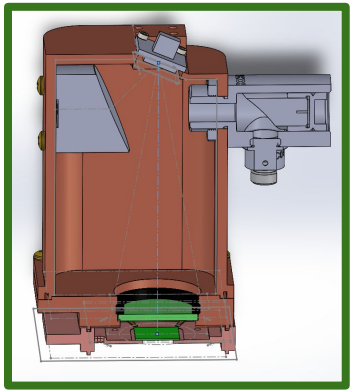
Dark matter, axions, sterile neutrinos, nuclear non-proliferation, radiation-protected qubits, and more



SQUATs: phonon and/or photon detection, meV-scale sensing



Low-band-gap designer materials for DM + direct charge sensing



Focal plane scanning calibration with free-space tunable photons down to THz

HUSEV
Splendor
THE BeEST
BREAD COLLABORATION

Student leadership in all parts of experiment lifecycle:

- Sensor design and fabrication
- Detector response modeling and simulation
- Device readout and operation
- Detector characterization and calibration
- Data analysis and physics results!

SLAC

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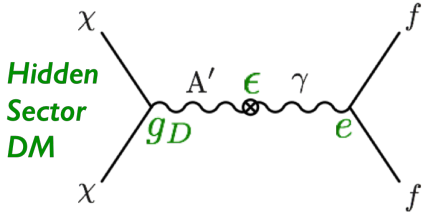
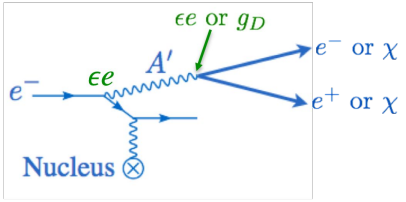
HIDDEN SECTORS AND SUB-GeV DARK MATTER

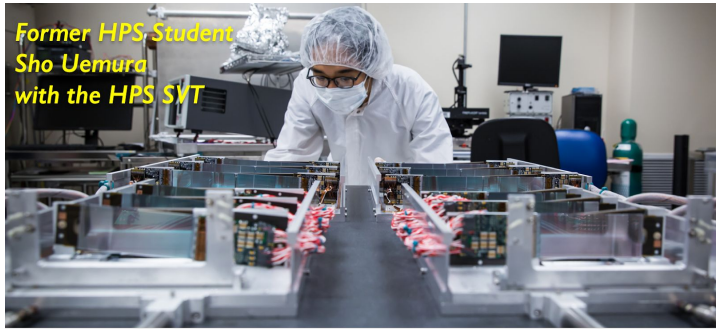
*Sub-GeV thermal relic DM (similar to WIMPs) **must** couple through new forces to standard model particles.*

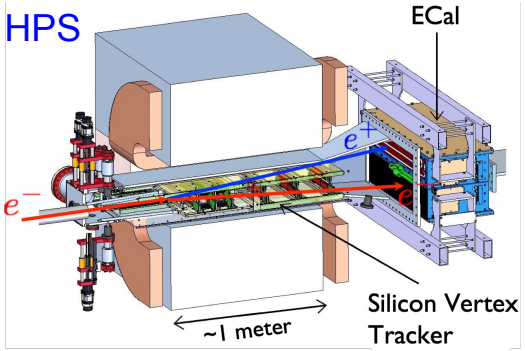


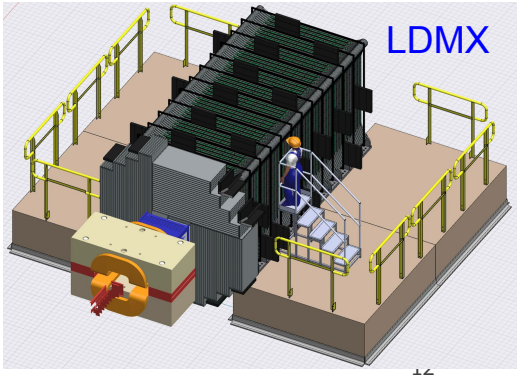
- New particles *and* forces = "hidden sector"
  - Benchmark example: dark photon, A′
- Searches for hidden sectors and sub-GeV DM at accelerators
  - A′ decaying to SM particles: HPS @ JLab
  - Production of sub-GeV Dark Matter: LDMX @ SLAC
- Unique theory/experiment collaboration at SLAC



dark bremsstrahlung

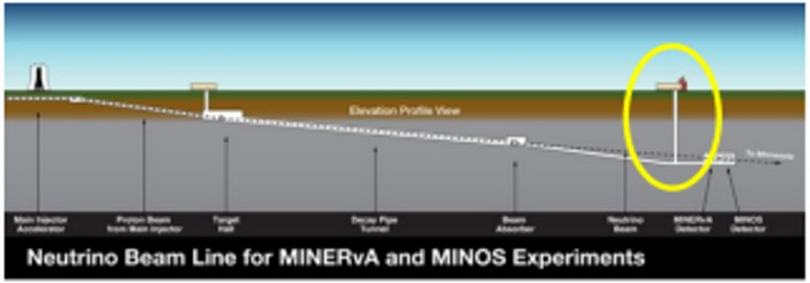






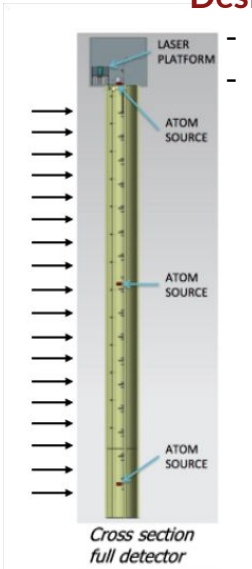
MAGIS-100: Ultralight Dark Matter and Gravity Waves

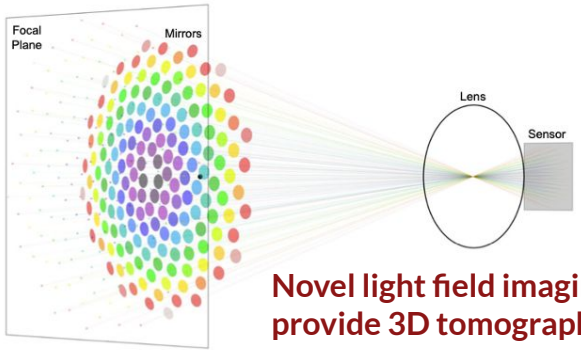
Matter Wave Atomic Gradiometer Interferometric Sensor:
Largest atom interferometer in the world
Under construction at Fermilab

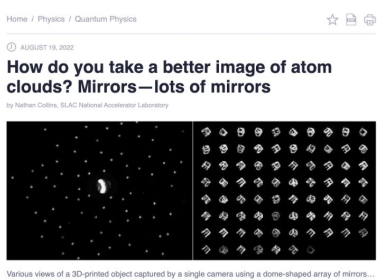


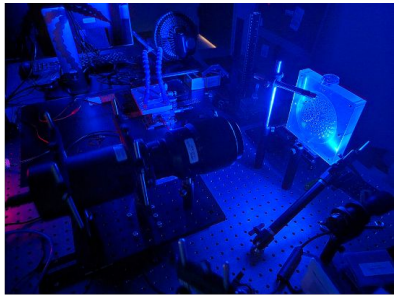
Design of imaging systems:

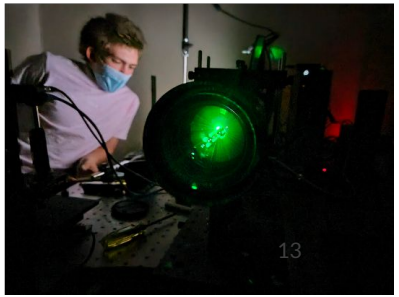
- Diagnostics imaging system
- Super-Aperture light-field imager









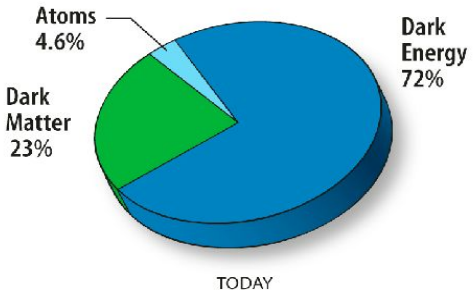


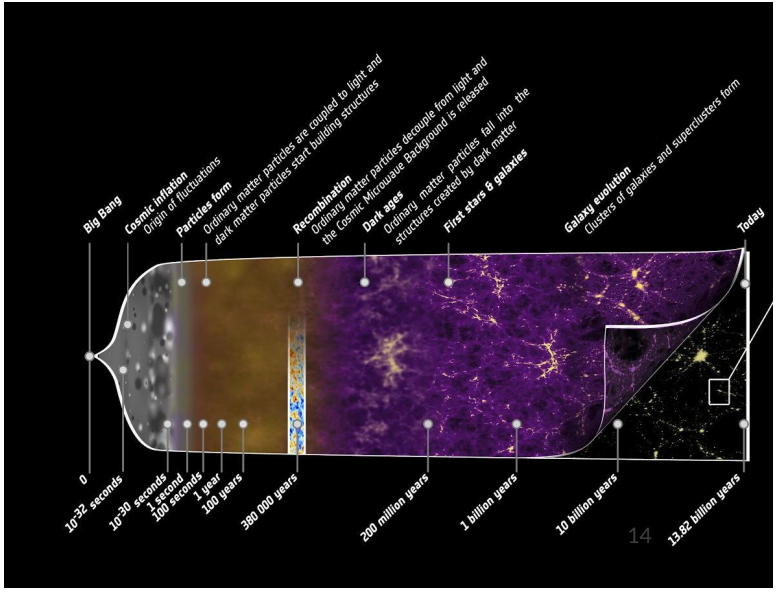
Novel light field imaging device provide 3D tomographic reconstruction of atom clouds
Machine learning differentiable simulators and reconstruction

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

COSMIC ACCELERATION: DARK ENERGY AND INFLATION

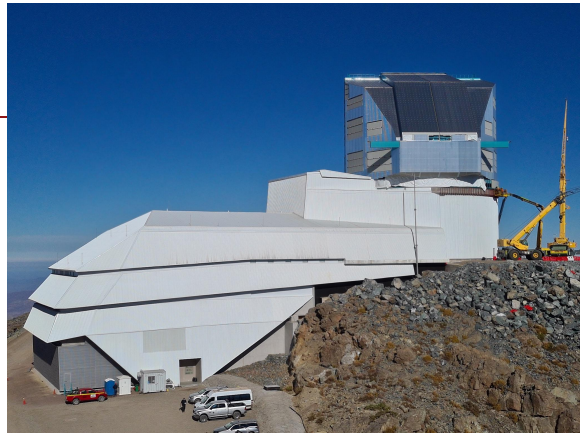
- Dark Energy:
  - Late-time expansion of the universe
    - Cosmological Constant? Quantum Field? General Relativity wrong?
  - Observables:
    - Expansion (scale vs. redshift) or growth (matter clumping vs. redshift) history by mapping galaxies, supernovae, quasars
    - CMB Weak lensing
  - Surveys/Experiments:
    - Imaging (Dark Energy Survey, Rubin Observatory)
    - Spectroscopy (DESI)
    - CMB (SPT, Simons Observatory)
- 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

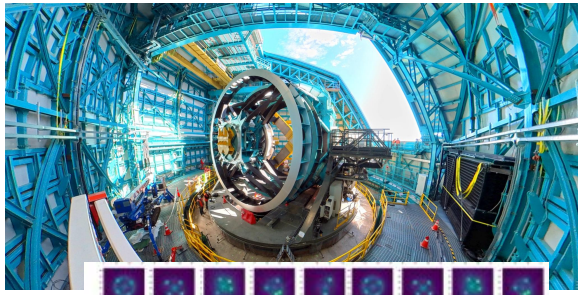


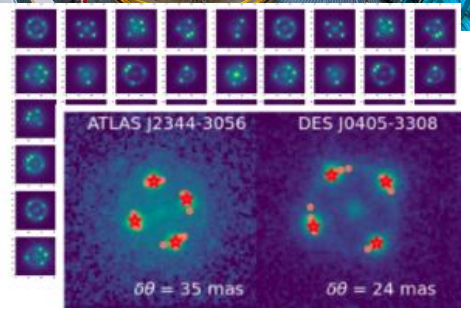


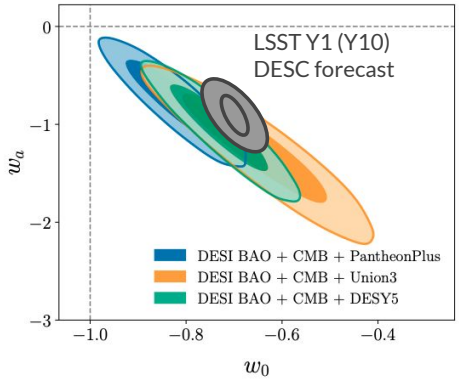
Rubin Observatory / LSST

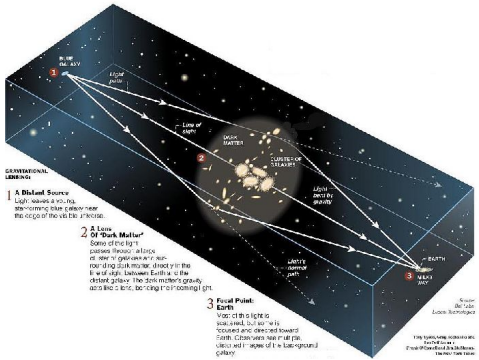
- Wide field survey with world's biggest camera
- Dark Energy
  - Structure evolution with weak lensing and galaxy clustering, clusters of galaxies
  - 1 million supernovae and thousands of strong gravitational lenses
- First Look June 2025, LSST starts late 2025
- Contact Aaron Roodman (roodman@slac.stanford.edu) or Phil Marshall (pjm@slac.stanford.edu)





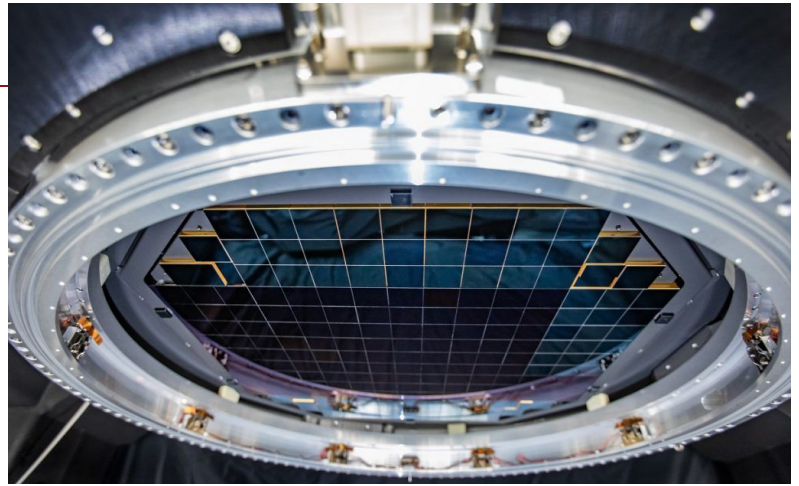


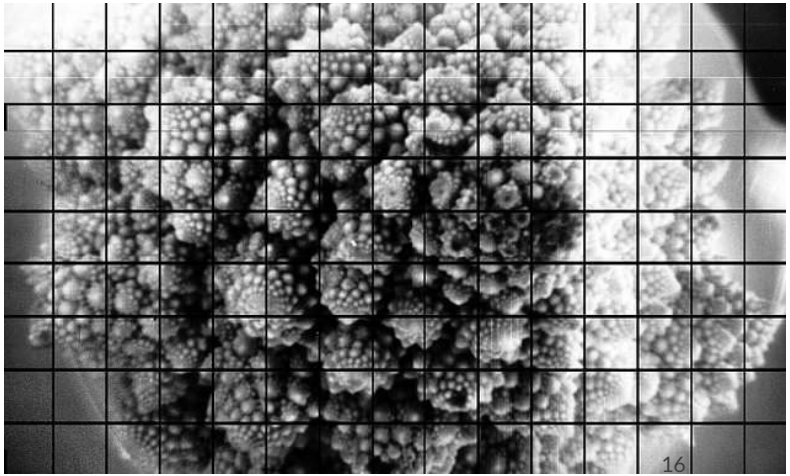




LSST CAMERA

- Camera assembled and tested at SLAC
  - Characterize and minimize systematics
- Shipped to Rubin Observatory in Chile (1st light in April)
  - Commissioning under way
- 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

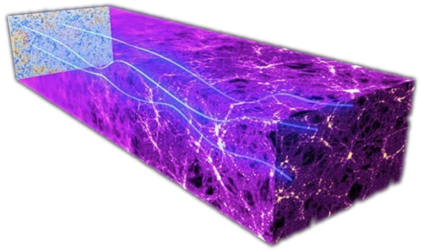




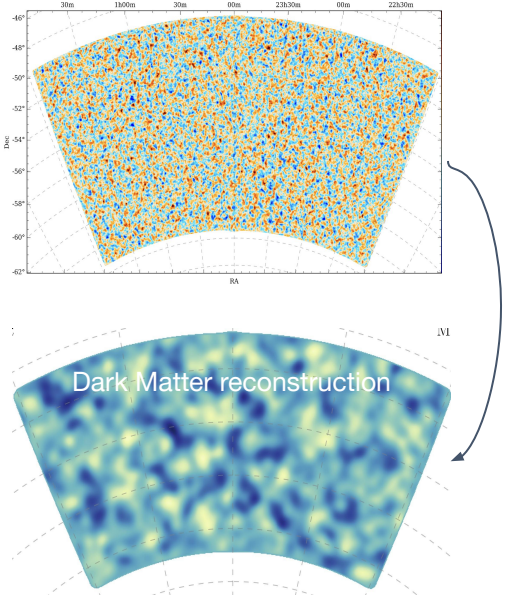
CMB Experiments: BICEP, SPT, Simons Observatory

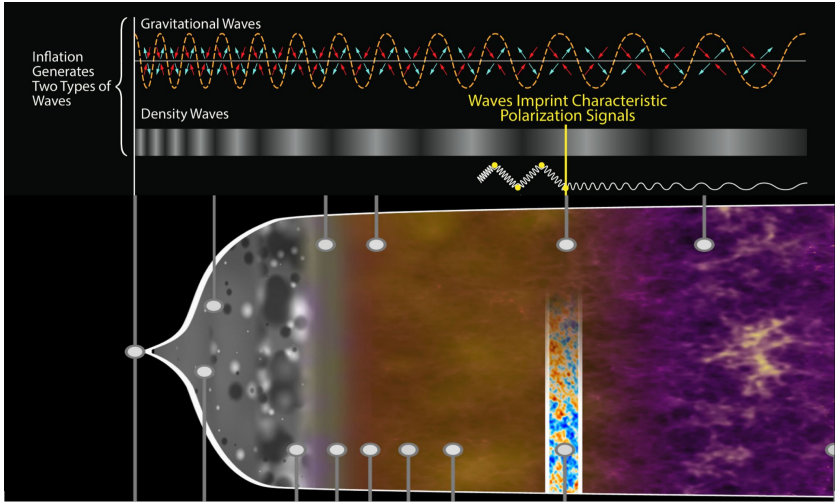
Key science themes:

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



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





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.

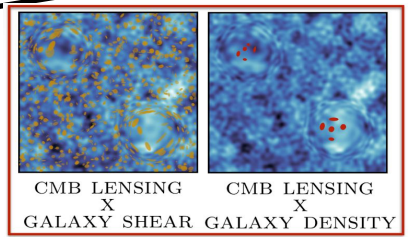
Contact: zeesh@slac.stanford.edu

CMB Experiments: BICEP, SPT, Simons Observatory

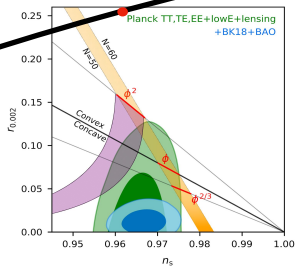
Broad program spanning superconducting sensor development, camera and instrumentation design through simulations, observations and scientific results from CMB experiments

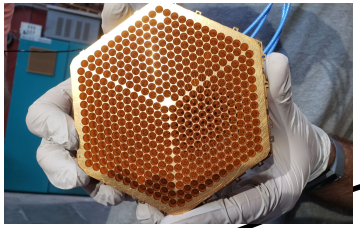
Opportunities for substantial impact by graduate students in any of these areas!

Multi-dataset cross-correlation and cosmology

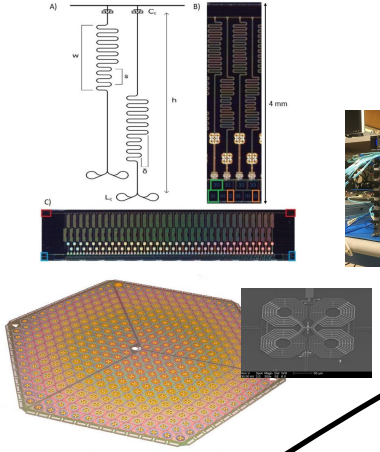


CMB pipeline, data analysis, science



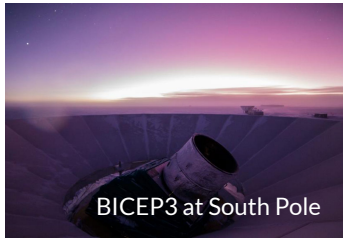


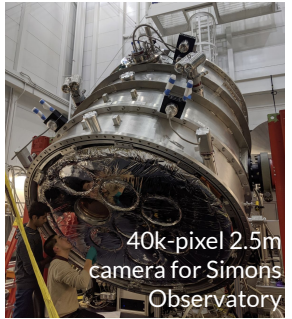
Integrated detector and CMB camera systems



Readout Electronics, data acquisition for CMB cameras

Cryogenic, Superconducting Detectors, Resonators and Amplifiers of CMB Cameras

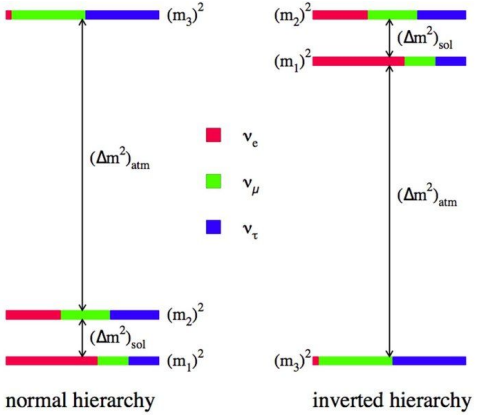




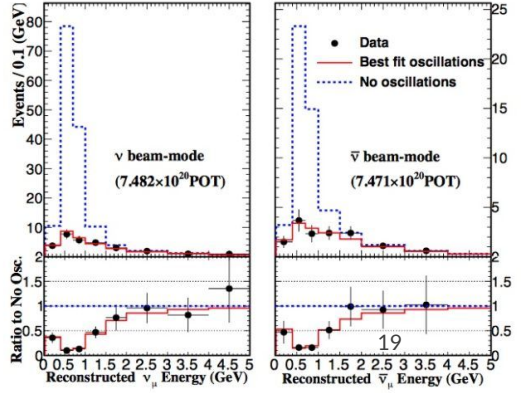
SLAC

NEUTRINOS

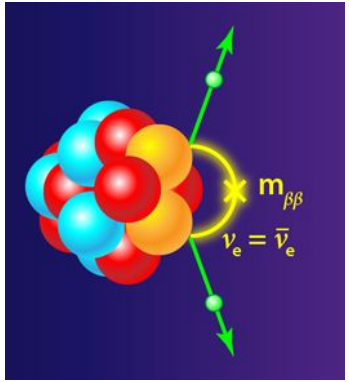
- The most abundant particle in the universe after photons
  - Neutrino properties have enormous implications for cosmology and particle physics
- Neutrino oscillations:
  - Probe neutrino mass/flavor mixing by precession of neutrino flavor
  - Direct evidence of neutrino mass (physics beyond standard model)
- What are the nature and origin of neutrino masses?
  - Are they “Majorana” or “Dirac”? Is lepton number violated?
    - Neutrinoless double beta decay (“0v2β”) only possible for Majorana particles
- Fundamental questions remain:
  - What are the neutrino masses? Why do neutrino have mass?
  - Do neutrinos, antineutrinos oscillate differently?
  - Is there more to this picture?

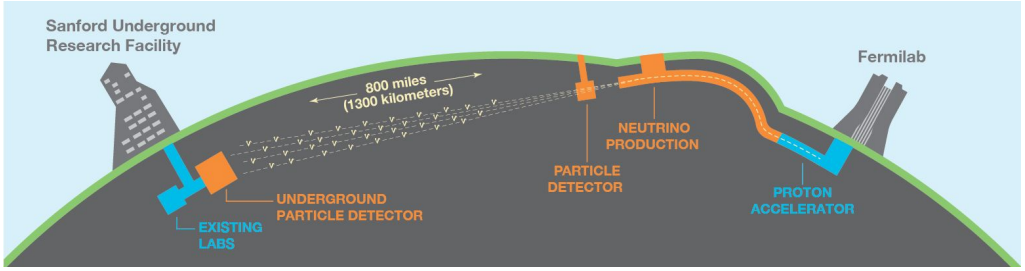


Muon neutrinos oscillating other neutrino flavors over 295 km at T2K



0v2β decay





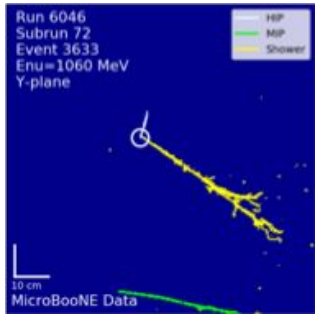
SLAC

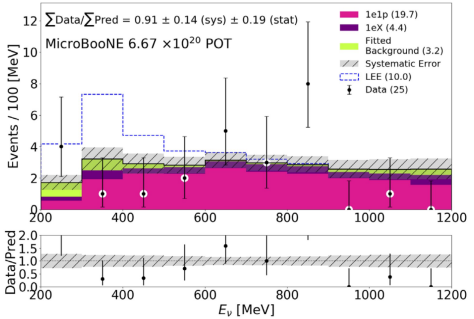
Neutrino oscillation experiments

ACCELERATOR NEUTRINO PROGRAM

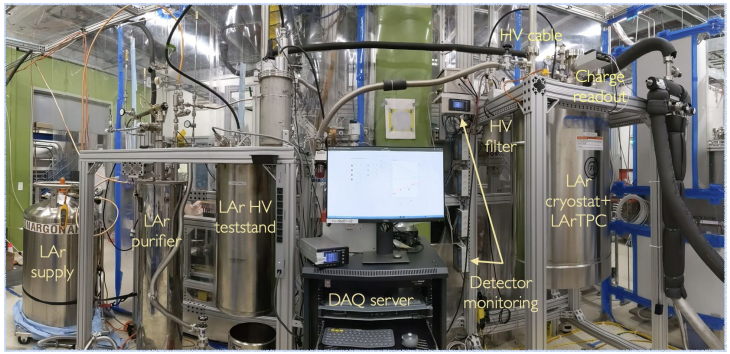
- Short Baseline Neutrinos (μBooNE, ICARUS)
  - Search for exotic neutrinos properties e.g. excess of ν_e interactions
  - Study of neutrino-argon interactions
- Neutrino Detector R&D and construction
  - Near detector for DUNE:
    - 7x5 array of 1x1x3m^3 LArTPCs + 1kt muon spectrometer
  - Future DUNE far detector modules:
    - New readout schemes for enormous ~17 kton LArTPCs

μBooNE search for excess ν_e-like interactions

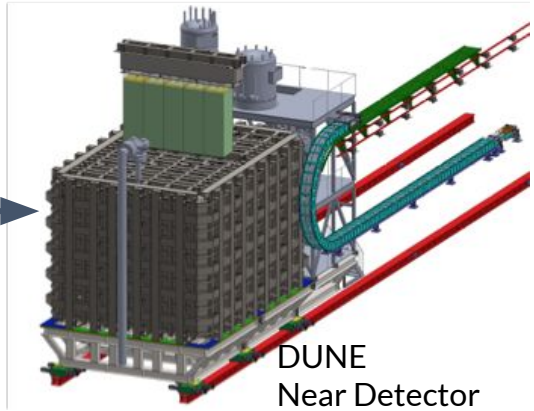




LAr platform at SLAC



First full-scale prototype



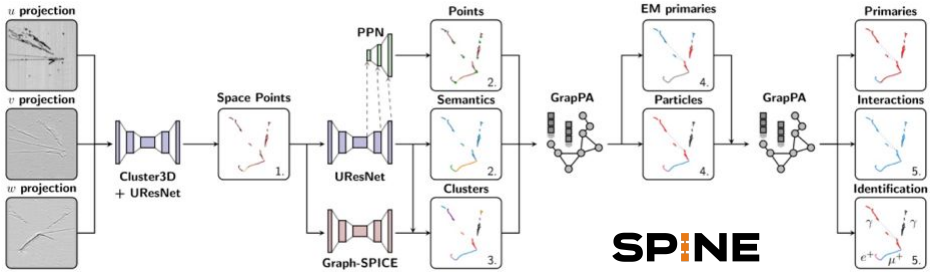
DUNE
Near Detector

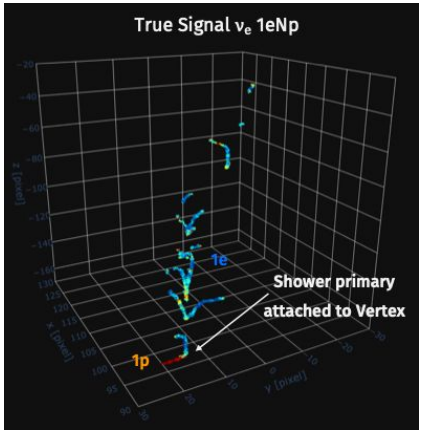
Contact: Mark Convery (convery@slac.stanford.edu)
Hirohisa Tanaka (tanaka@slac.stanford.edu)
Kazuhiro Terao (kterao@slac.stanford.edu)

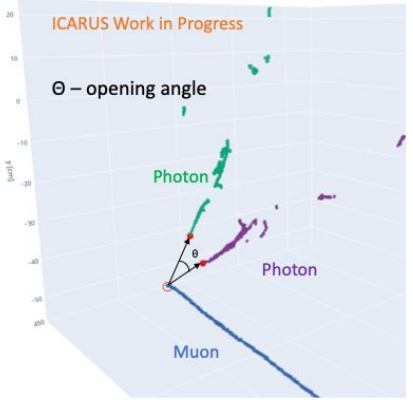
Accelerator neutrino programs

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.

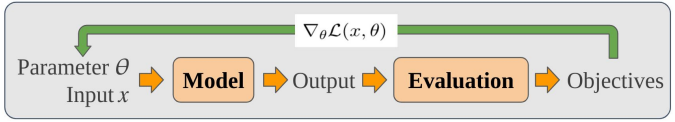




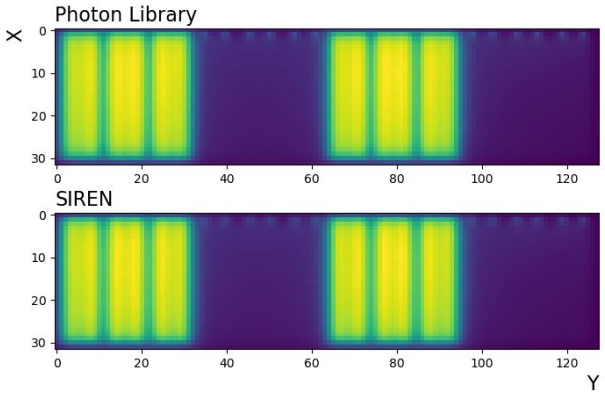


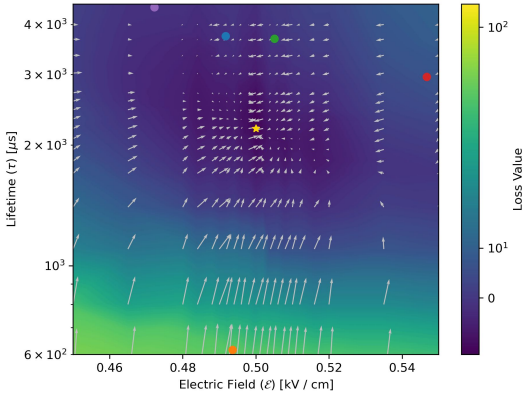
Differentiable physics simulator for inference & design optimization

Expand breakthroughs in computing to unlock new analysis paradigms (e.g. automated, data-driven detector physics calibration)



SLAC PyTorch





Low-energy neutrino physics

Contacts:
Brian Lenardo (blenardo@slac.stanford.edu),
Brian Mong (bung@slac.stanford.edu)

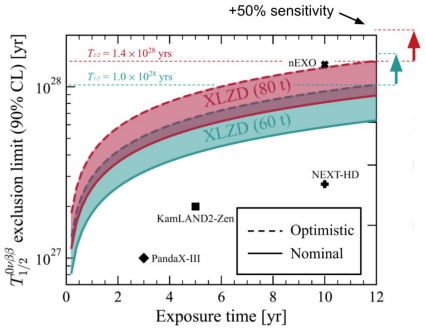
What is the nature and origin of neutrino masses?

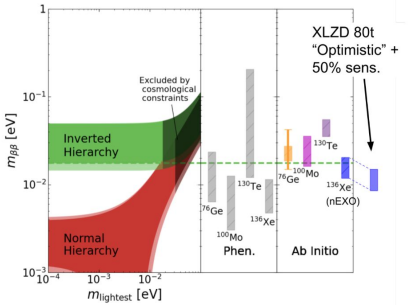
- Are neutrinos Majorana or Dirac fermions?
- Is lepton number conserved?
- What is the absolute neutrino mass scale?
- Do right-handed "sterile" neutrinos exist?

0νββ in XLZD: Enhancing the search for lepton-number-violating nuclear decays in liquid xenon TPCs

→ Test of Majorana neutrino hypothesis

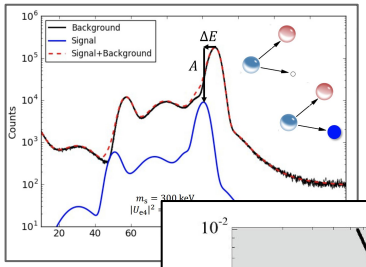
Collaboration with XLZD group

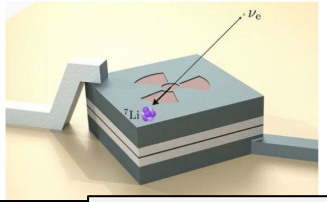


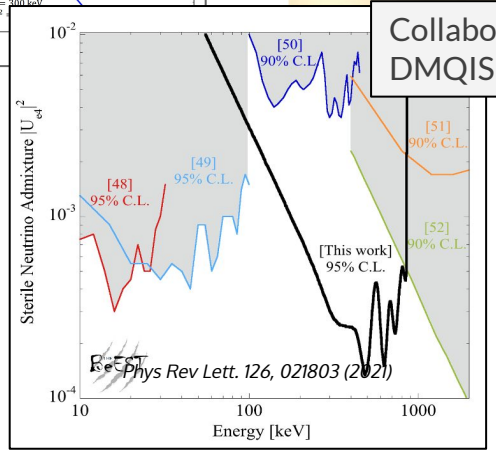


BeEST: precision measurements of radioactive decays with superconducting detectors

→ Search for sterile neutrinos and other invisible particles coupling to weak interaction

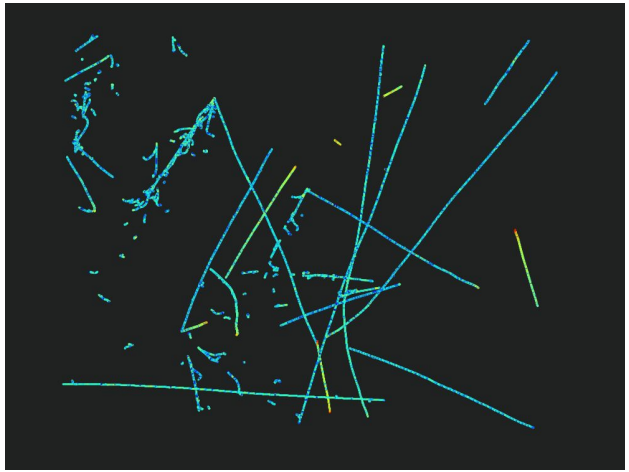
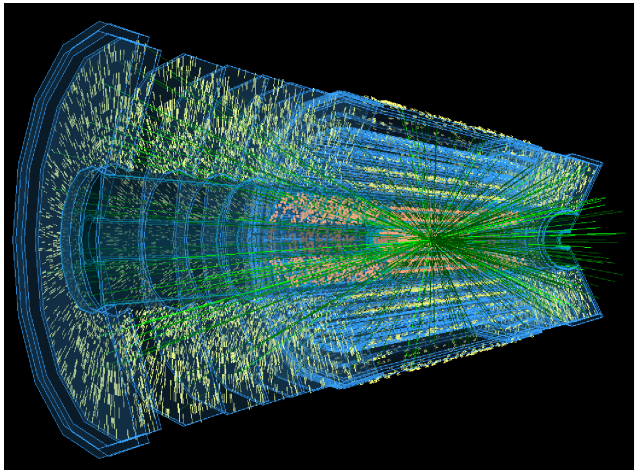
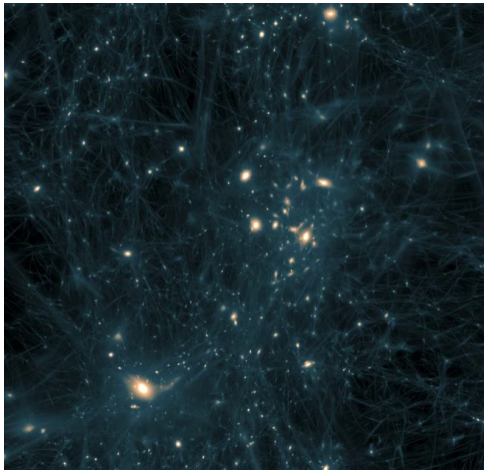






Collaboration with DMQIS group

HEP Research “with” / “for” Machine Learning & AI

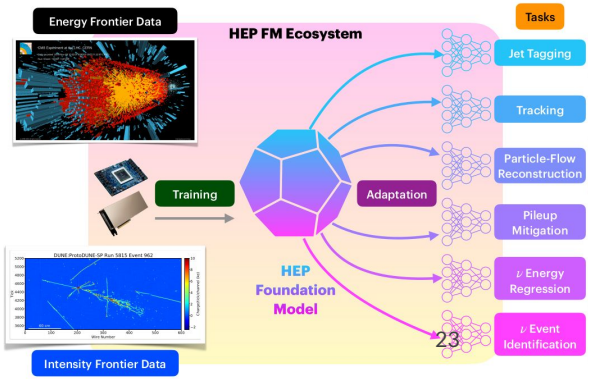




AI/ML revolutionizing physics workflow

- Advanced pattern recognition capabilities in structured (i.e. images) and unstructured (i.e. graphs) datasets
- Automated optimization without human interventions (months down to days) for algorithms and designs
- A large (i.e. industry+academia) software and hardware ecosystem R&D

HEP: unique the AI/ML R&D opportunities

- Multi-modal, high dimension physics data with extreme precision
  - Foundation Model or “Physical AI” = self-learning machine
- High fidelity physics simulator with extremely detailed physics information
- An extreme data rate push new AI/ML algorithms and hardware @ the edge

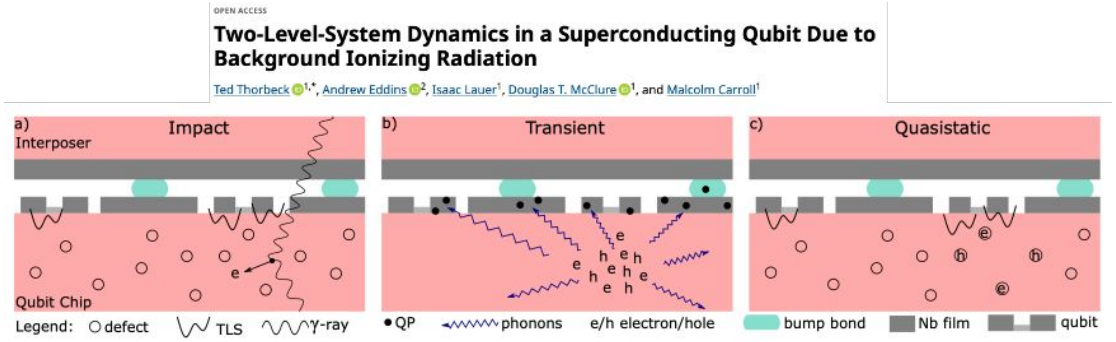


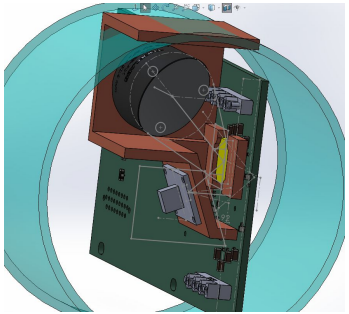
Contact: kurinsky@slac.stanford.edu
kstifter@slac.stanford.edu

HEP Research “with” / “for” Quantum Information

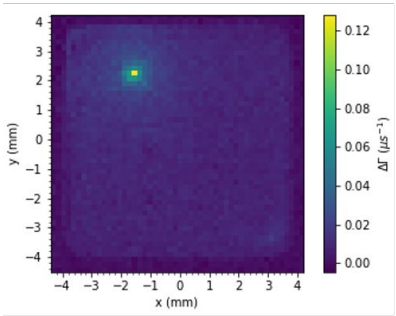
Using HEP Tools to Understand Radiation Effects on Spin and Superconducting Qubits

- G4CMP simulation used to model decoherence and TLS detuning
- Controlled experiments to improve background environment for standard devices

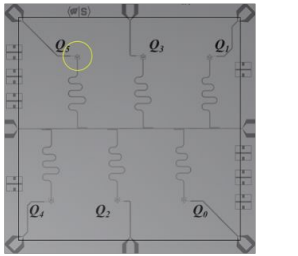


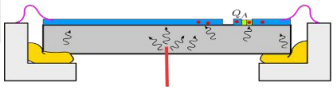


Degradation of T_1 with local optical pulses using MEMS scanner



$$\Delta\Gamma_1 = \frac{1}{T_1} - \frac{1}{T_1^b}$$

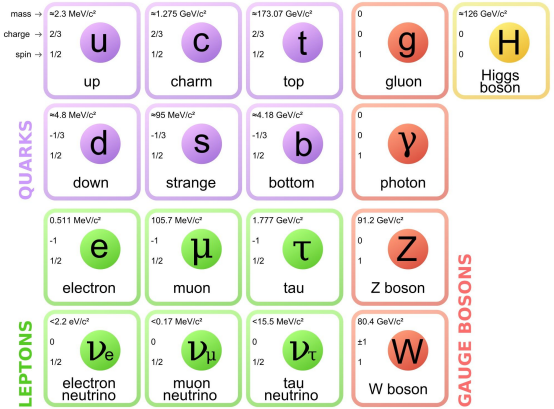


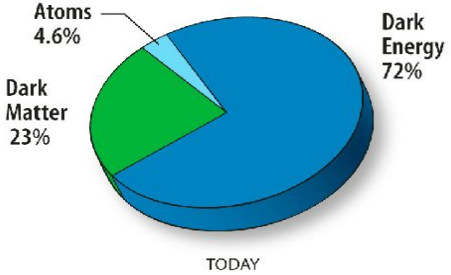


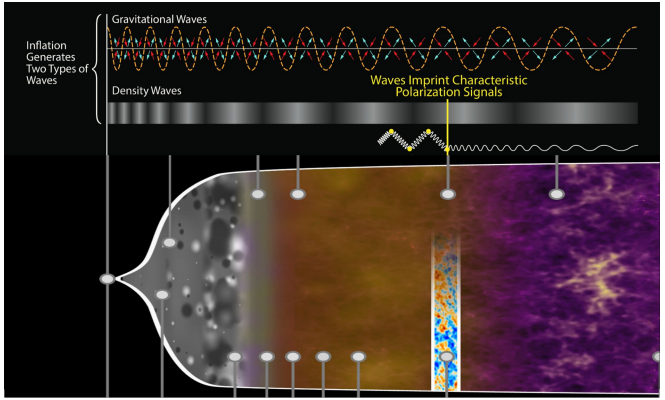
Designing Novel Experiments to Better Study Radiation Response

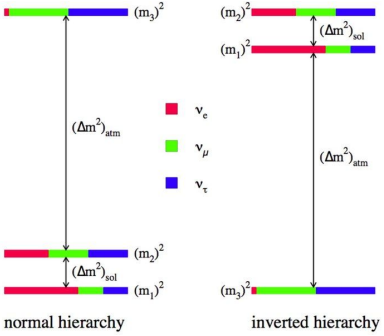
- Using steerable optical illumination to dose superconducting qubit arrays to study phonon/charge position and time dependence
- Developing similar techniques for HRL-fabricated spin qubit test structures

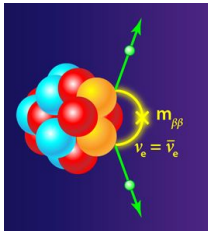
OPPORTUNITIES



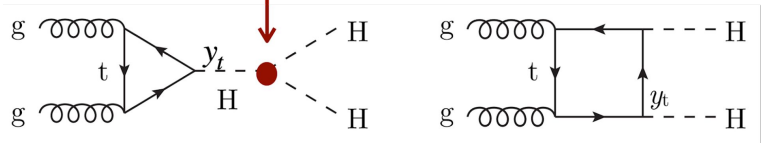


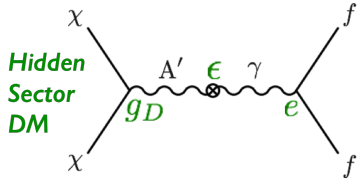


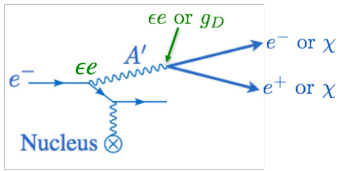




$$\lambda = \frac{m_H^2}{2v^2} = 0.13$$







dark bremsstrahlung

At SLAC

- ATLAS, Future Colliders (e^+e^-)
- LZ, HydroX
- SuperCDMS, DMQIS
- Fermi-LAT
- HPS + LDMX
- DES
- LSST
- SBN: (MicroBooNE, ICARUS)
- DUNE
- nEXO
- BICEP, SPT, Simons Observatory
- DM Radio

"F" for Facilities: LNTF, DMF, B33, S3DF

Talk to poster presenters about office/lab visits this afternoon