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# **Theoretical physics and theoretical astrophysics**

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2015 Institutional Review

10 February 2015

# Vision

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- Conduct world-leading theoretical particle physics and theoretical astrophysics research.
- Focus effort and core strength in key research areas directly related to the U.S. and worldwide experimental program.
- Influence and motivate the design of experiments, data analyses, and their interpretation.
- Train next generation of theorists in data-rich environment and educate young experimentalists.
- Provide a national resource for university physicists.
- Foster an intellectually vibrant atmosphere.

## Theoretical Physics

- Focus on aiding the experimental program in direct and indirect searches for New Physics.
- Primarily supports LHC, neutrino, muon programs.
- Key research areas: perturbative QCD, collider phenomenology, BSM model building, lattice QCD, neutrinos, applied formal physics.
- FY15: 13.5 scientists, 1 assoc. scientist, 8 RAs, 2 emeritus.

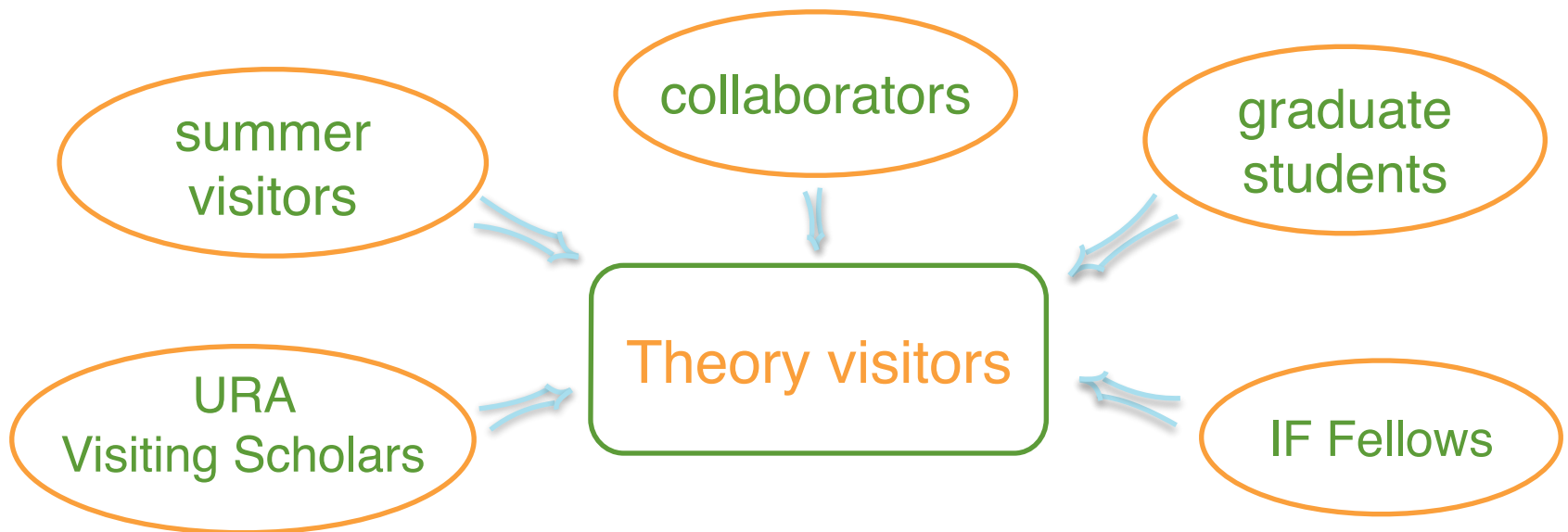
## Theoretical Astrophysics

- Focus on using astrophysical phenomena as a tool for understanding fundamental physics.
- Primarily supports cosmic frontier program.
- Key research areas: dark matter, dark energy, inflation, CMB, neutrinos, large scale structure.
- FY15: 5 scientists, 2 RAs.

Frequent interaction and collaboration between the two groups

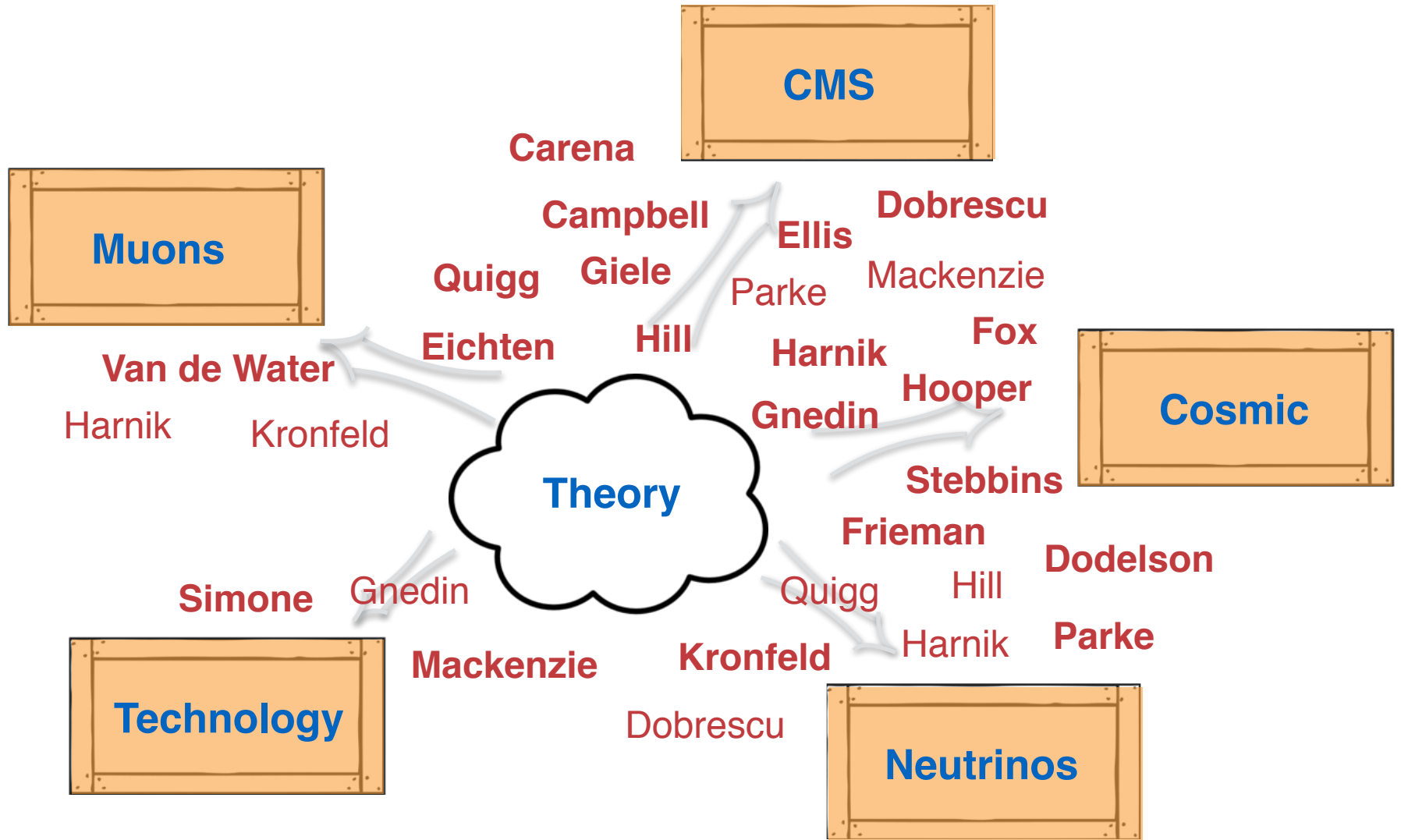
# Theory visitors

- Visitor programs and workshops create a bridge for increasing the frequency and value of interactions between university theorists and Fermilab scientists.
  - increase involvement between university theorists and Fermilab experimental programs.
  - visitors collaborate with and complement expertise of groups.





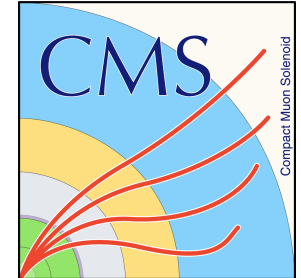
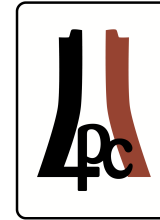
# Research overview



# Synergies with CMS program: overview

calculations in  
perturbative QCD

theoretical tools for  
phenomenology



strong dynamics of  
quarkonium, hadrons

confronting new  
models with data

measuring Higgs  
properties

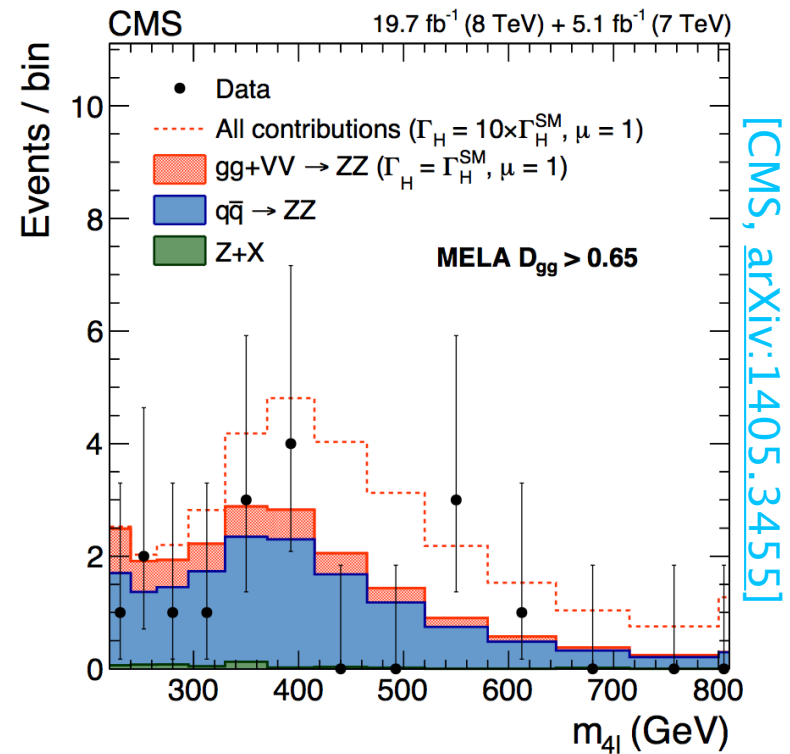
novel search  
strategies

precision determinations  
of quark masses,  $\alpha_s$

- Convenors of Snowmass QCD WG, quarkonium WG, authored LHC Higgs, Les Houches reports, PDG reviews.
- LPC ties: jointly-organized seminars, workshops.
- Organization of international conferences and schools, often explicit theory-experiment cross-talk (SUSY2011, HCPSS, TASI, ...).

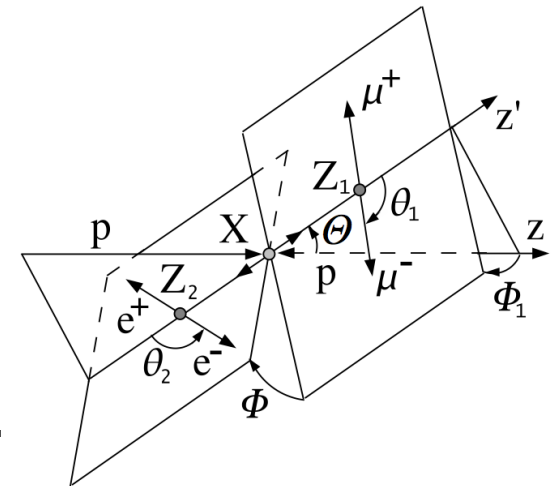
# Tools for the LHC

- **Development of NLO parton level code MCFM.**
  - SM background cross-sections.
  - **matrix elements used by CMS** to implement MELA algorithm for isolating Higgs boson events.
  - used by ATLAS and CMS to directly bound width of the Higgs boson, improving limits by two orders of magnitude.
- **Systematic improvement of parton showers, VINCIA and POWHEG-BOX.**
- Top quark phenomenology: measurement of couplings and spin correlations from LHC data.

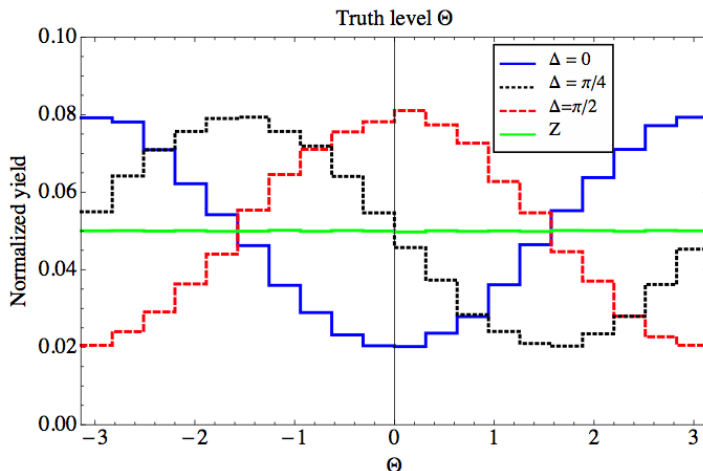


# Higgs discovery and properties

- Significant contributions to Higgs boson search, discovery and characterization.
  - ground-breaking work, with LPC colleagues, to extract Higgs coupling to gauge bosons  
→ CMS co-author, APS thesis award (2014).
  - global fit of coupling strengths, width.
  - demonstrated complementarity of LHC and EDM for Higgs CPV.



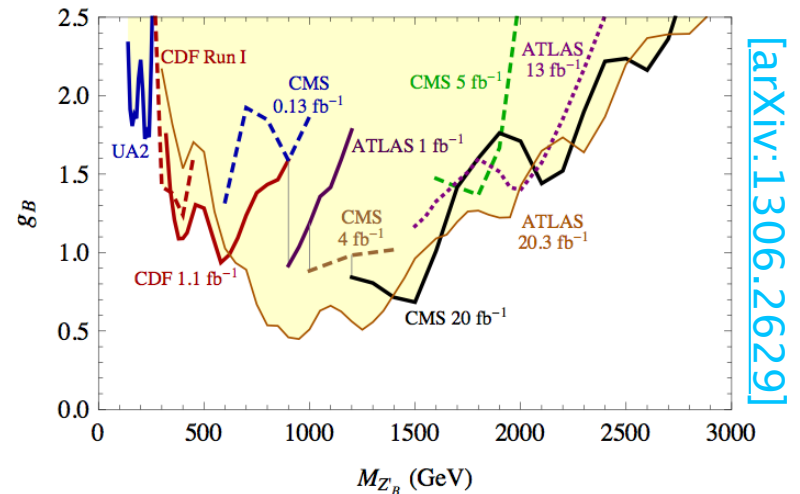
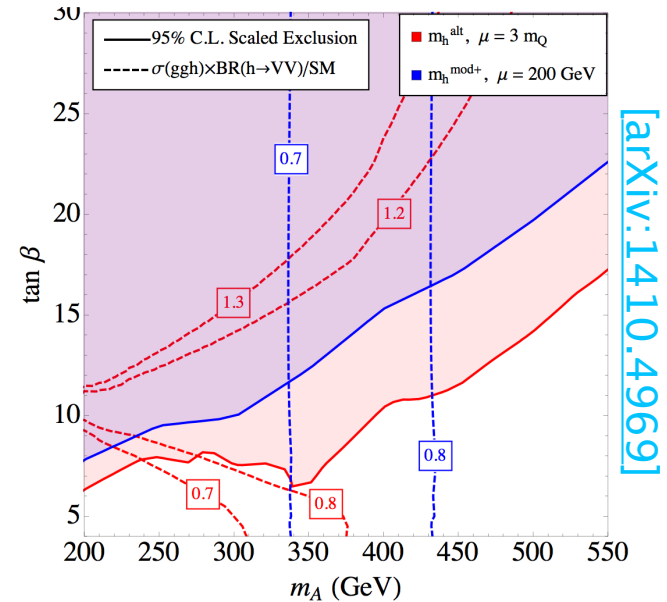
[arXiv:1308.1094]



- Exploration of signals in extended Higgs sectors.
  - proposed first LHC search for CPV in Higgs coupling to  $\tau$ 's.
  - CMS follow-up study.

# New physics searches at the LHC

- **Development of BSM benchmarks and analysis techniques.**
  - interpretations of searches for additional Higgs bosons now the **standard in CMS & ATLAS.**
  - showed complementarity of precision Higgs measurements, direct searches.
  - with CMS/LPC, developed LHC razor for SUSY multijet+MET, extended to sleptons, stops, DM.
  - Novel signatures for exotic particles: color-octet scalars, vector-like fermions, heavy gauge bosons, leptoquarks, ...



# Synergies with cosmic program: overview

dark matter

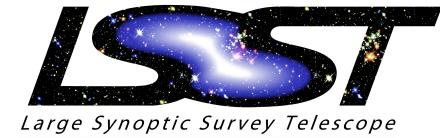
dark energy

inflation

galaxies and  
reionization



DARK ENERGY  
SURVEY

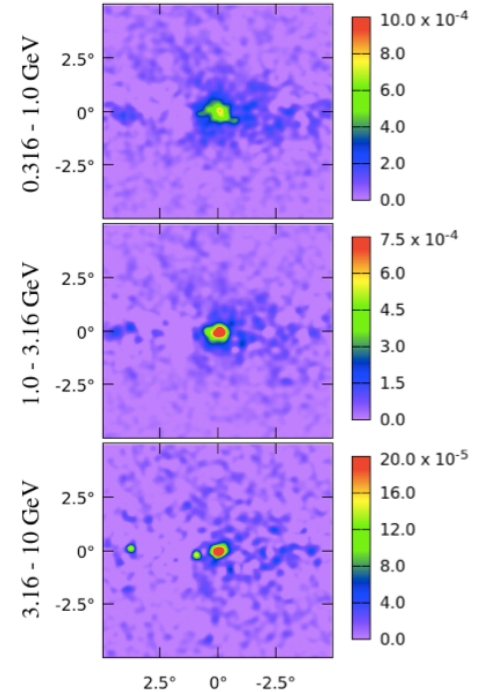


- Focus on astrophysical probes of New Physics.
- **Theorists initiated many experiments:** SDSS, Auger, DES, B-modes.
- Leadership roles in DES (director), LSST, South Pole Telescope, Tianlai 21cm redshift survey, Cosmological Computing Initiative.
- Close interaction with SuperCDMS, PICO, Holometer, DESI.
- Service on P5, astrophysics advisory committees, convenors of Snowmass dark matter, dark energy and CMB.

# Dark matter

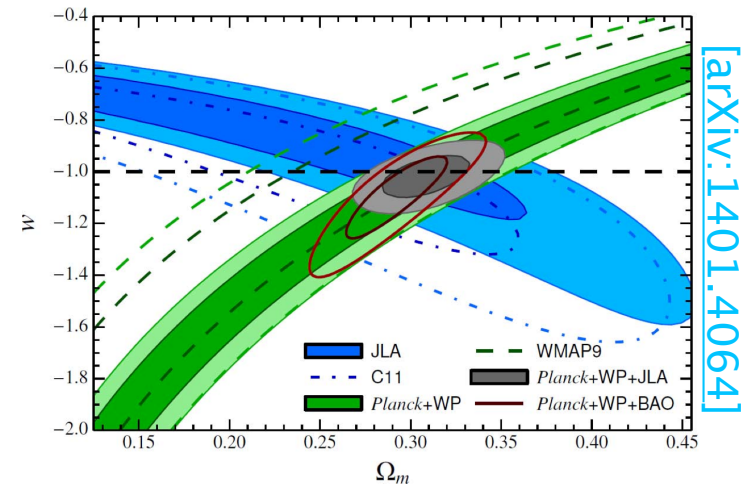
- Significant contributions to traditional direct and indirect searches for WIMP dark matter.
  - extraction of limits from AMS, COGENT, LUX, gamma-ray observation of galactic center, ...
  - improved analysis techniques being adopted by experiments.
- Identification of galactic center excess and subsequent DM model-building and pheno.
- Fermilab one of the pioneers of searches for DM at colliders through mono-jet and mono-photon signatures.
- Using Higgs-mediated DM interaction, interpreted invisible Higgs limits as direct detection limit → used by CMS & ATLAS.
- Frequent collaboration between theory groups.

[arXiv:1402.6703]



# Dark energy

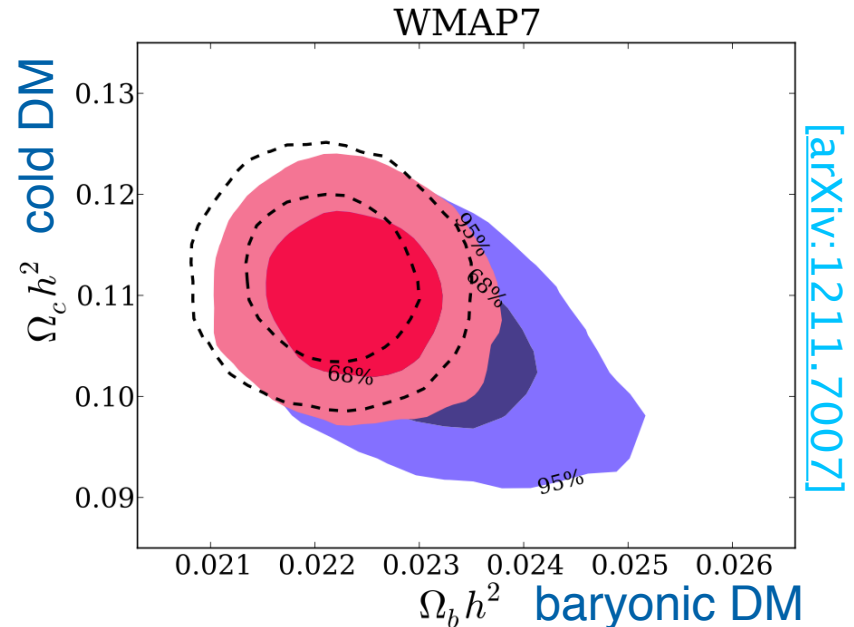
- Dark energy, beyond the cosmological constant, has its roots here, long before SNe-Ia bombshell.
  - including some of the first physics models of DE.
- Best constraints on DE/DM/modified gravity from combining complementary cosmic probes.
- e.g. growth of structure complements supernovae distances, the **main idea behind Dark Energy Survey**.
- Showed how combining data from DES, LSST, DESI, eBOSS improves cosmological constraints.
- **impacting design of cosmic surveys**  
→ will be extended to CMB program.
- **tightening constraints on dark energy models, improving control of systematic errors.**





# Cosmological simulations

- Detailed numerical simulation essential to interpreting cosmological data.
- Explored bias in extraction of cosmological constants from assumed cosmic reionization history.



- Produced simulation sets designed to explore baryonic effects on weak lensing and CMB modeling.
  - sets publicly available, maintained and will be extended.
- Cosmic Frontier Computational Collaboration is a **multi-lab national initiative**, partnering FNAL with ANL, SLAC, LBL, BNL.

# Synergies with neutrino program: overview

strategies for studying standard  $\nu$  paradigm

sensitivities of current, proposed experiments

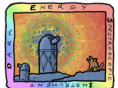


impact of light sterile  $\nu$ 's and non-SM interactions

proposals for future experiments



CMB-S4



improved determination of nuclear effects

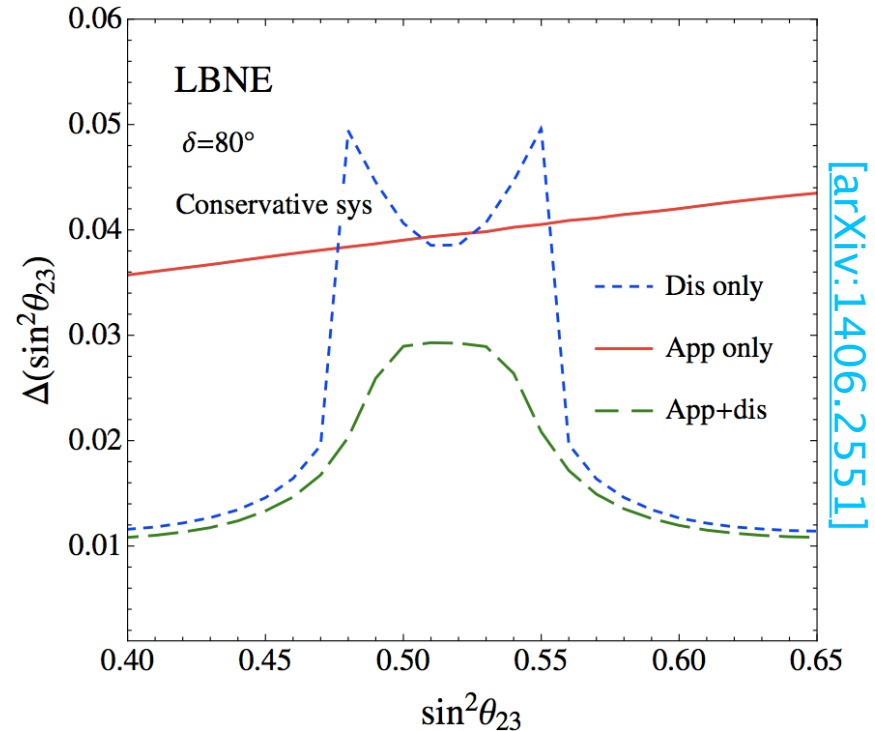
cosmic neutrinos



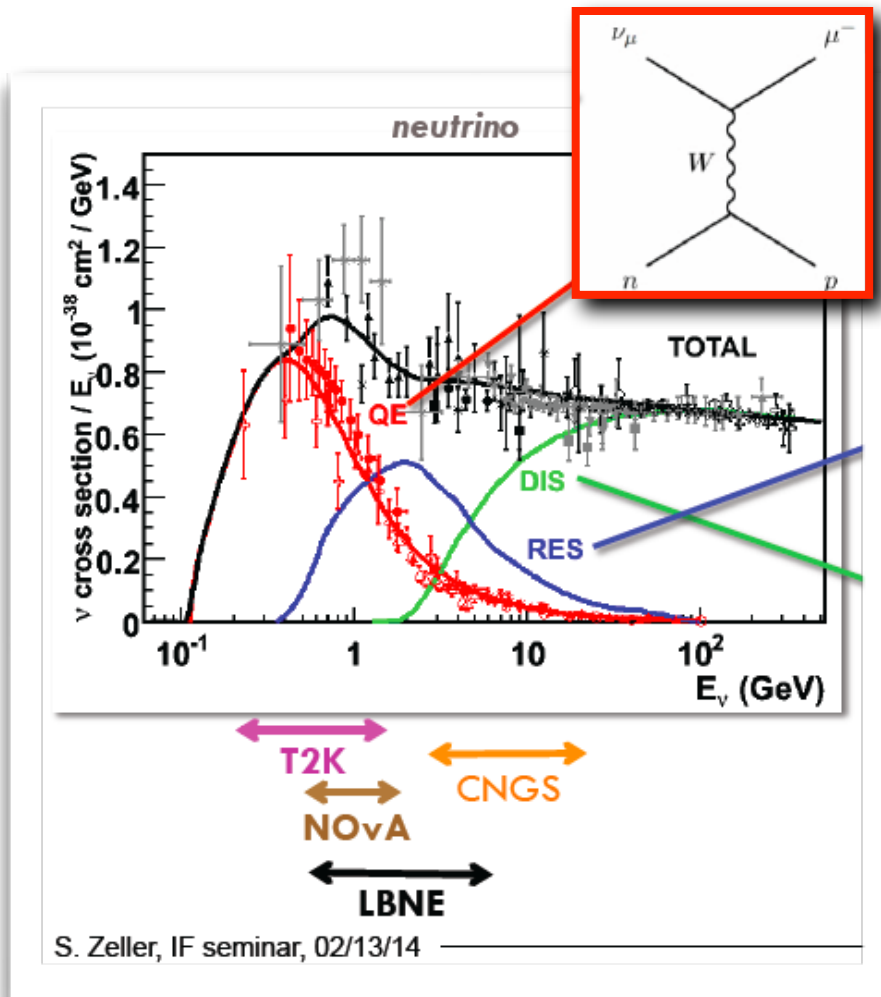
- Chair of International Neutrino Commission, members on FNAL Short-Baseline Neutrino Focus Group, member of SURF PAC, convenor of Snowmass  $\nu$  anomalies WG, Project X physics study.
- Organized academic lectures on neutrinos, “New Perspectives on dark matter” workshop on searches with  $\nu$  beams, “Lattice Meets Experiment” workshop highlighting lattice role in  $\nu$  experiments.

# Neutrino program planning

- History of support of the Long Baseline Neutrino program: MINOS, NOvA, LBNF.
- Co-authored report on LBNE configuration (pre-P5).
- Demonstrated improved sensitivity of LBNE when considering both appearance and disappearance channels.
  - better precision for  $\theta_{23}$  and  $\delta_{CP}$ .
- Multiple studies associated with short baseline neutrino program (MiniBooNE, MicroBooNE, LAr X).



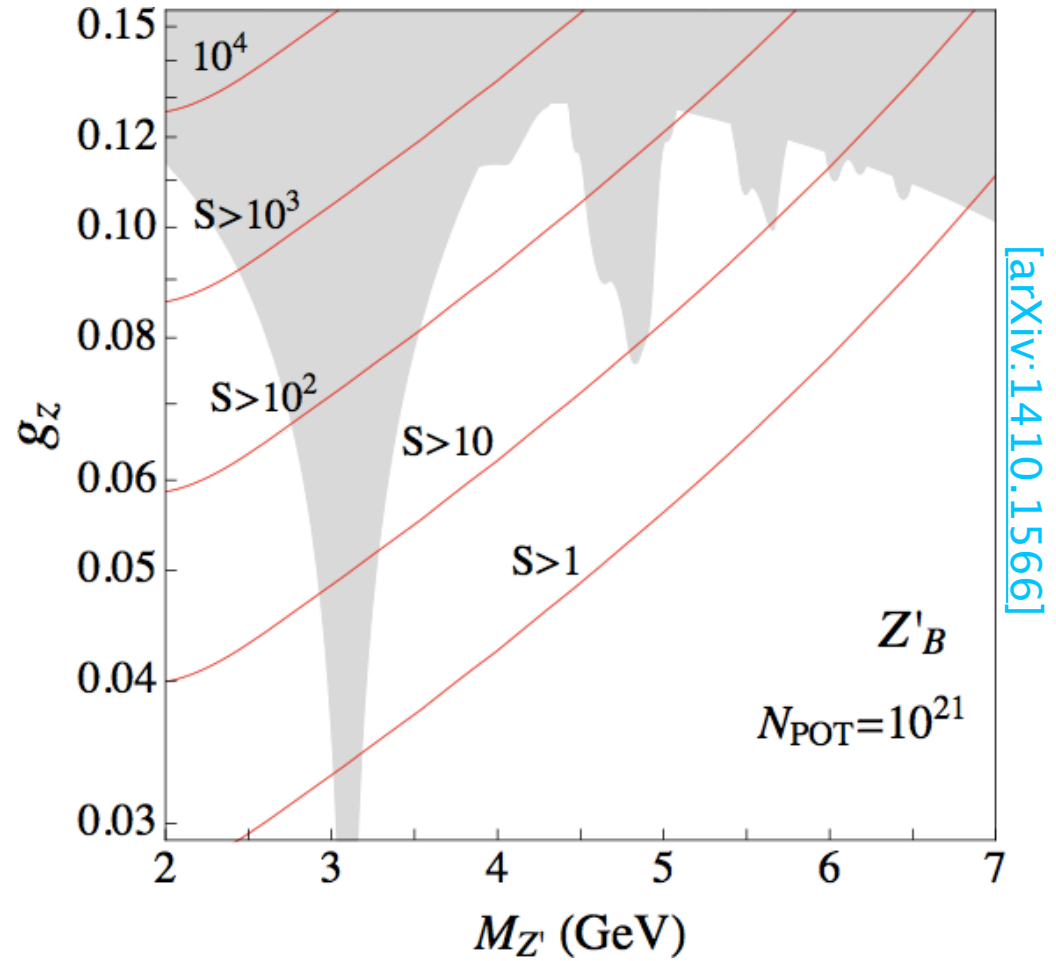
# Neutrino cross sections



- NOvA and ELBNF signal dominated by CCQE cross-section.
- Nucleon axial-vector form factor an important input in CCQE determination.
  - can be computed from first principles using analyticity and lattice QCD.
- Worked with UoC student, experimentalists to include QCD input in GENIE MC.
- Lattice calculation ongoing.

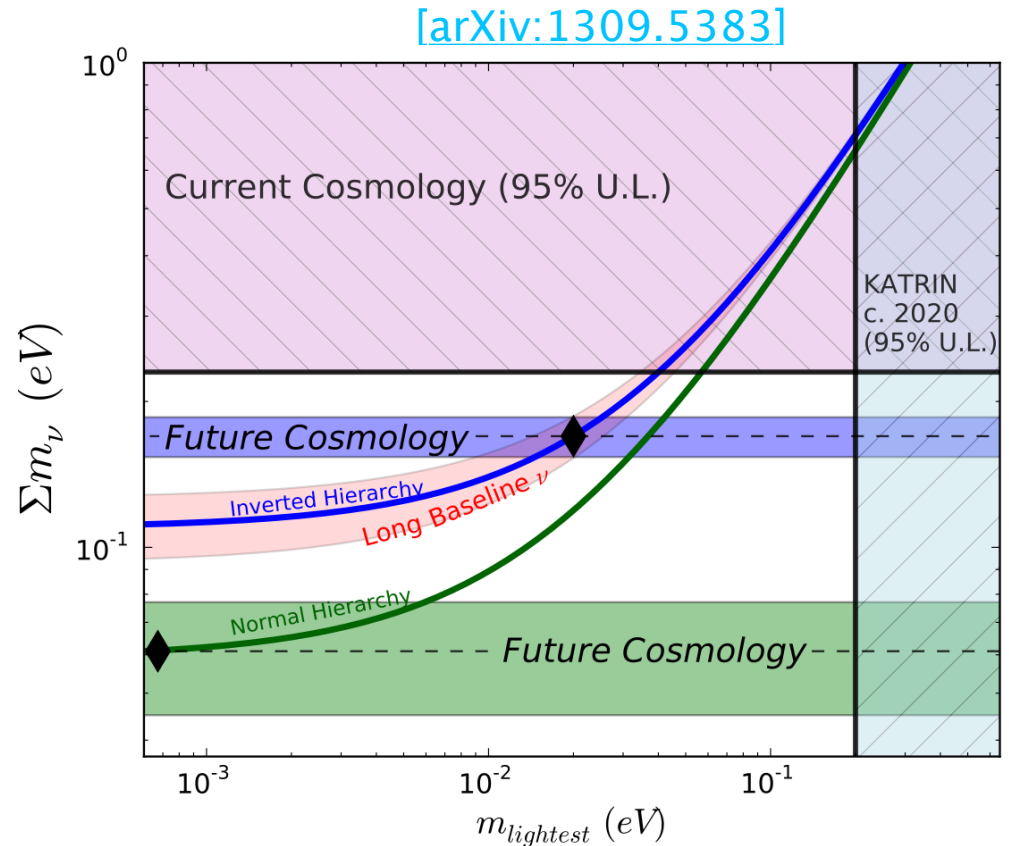
# Neutrinos and dark matter

- Leading efforts to use Fermilab neutrino expts. to search for DM.
  - NOvA near detector is sensitive to GeV DM.
- Also vice-versa: DM detectors as probes of neutrino properties.
  - showed that sterile neutrinos or  $\nu$  dipole moments could be discovered this way.



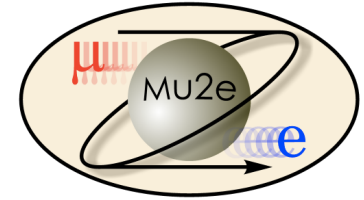
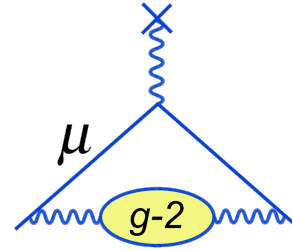
# Neutrino constraints from the cosmos

- Large-scale structure constrains sum of neutrino masses.
  - explored future constraints from DESI and CMB-S4.
- Explored synergy of cosmological constraints and neutrino-less  $\beta\beta$  decay experiments.



# Synergies with muon program: overview

hadronic vacuum polarization  
contributions to  $(g-2)_\mu$



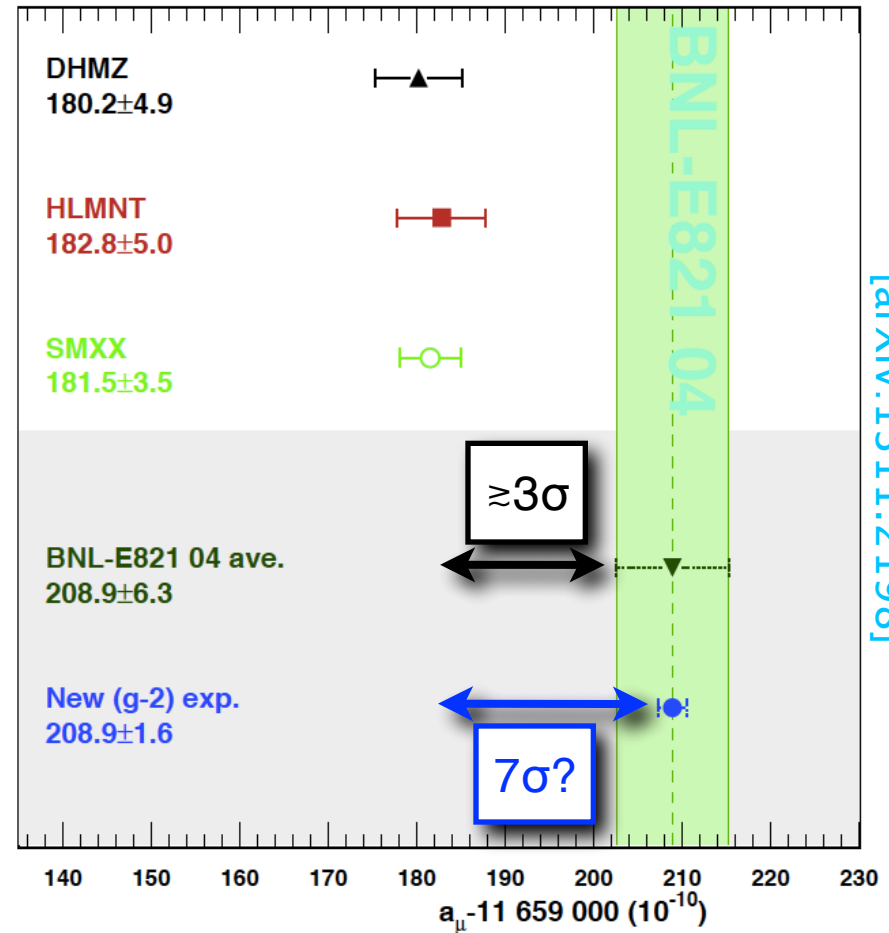
hadronic light-by-light  
contributions to  $(g-2)_\mu$

connections between Higgs  
boson and flavor violation

- Contributions to Snowmass Charged Lepton WG, talk at  $(g-2)_\mu$  collaboration meeting, extensive contributions to Project X physics study (editor, convenors, speaker).
- **Organized academic lectures on  $(g-2)_\mu$  and LFV**, “Lattice meets Experiment” workshop on roles in  $(g-2)_\mu$  and Mu2e experiments.

# Lattice-QCD calculations for $(g-2)_\mu$

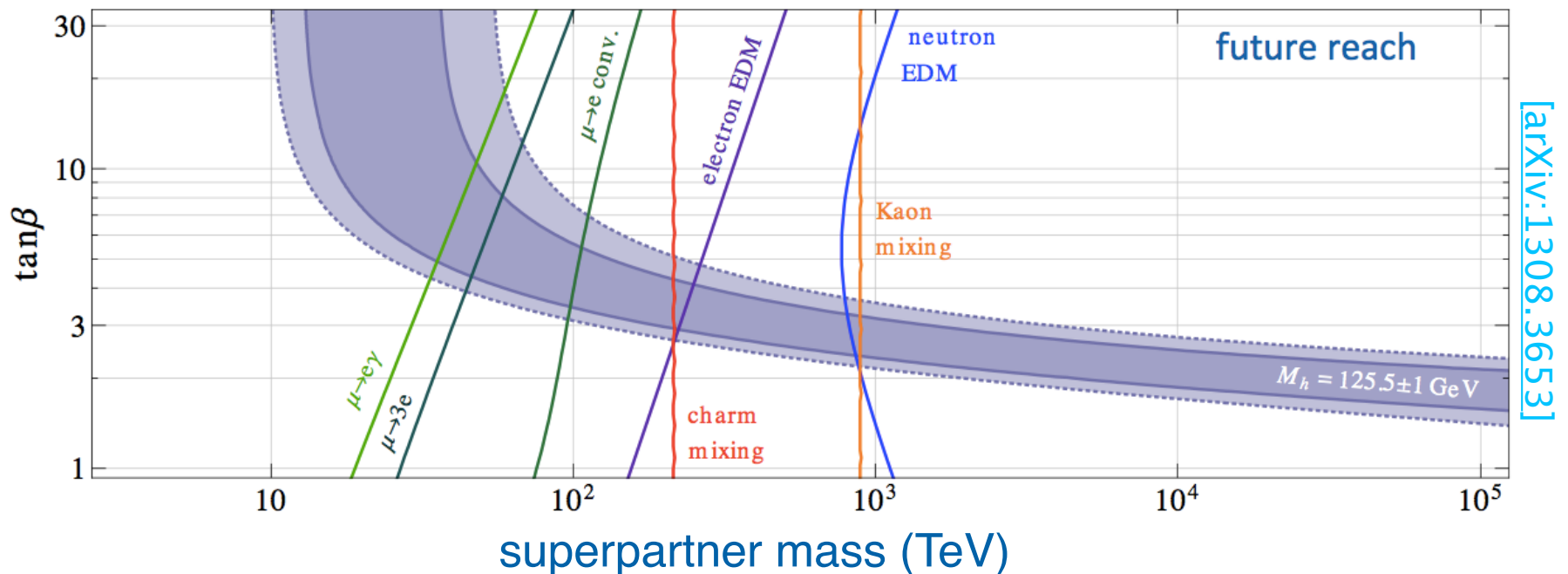
- Exploit reduced exp. error on  $(g-2)_\mu$  by reducing SM theory uncertainty on hadronic vacuum polarization (HVP), light-by-light (HLbL) contributions.
- **Fermilab lattice theorists undertaking first complete four-flavor calculations** of both.
  - New method for HVP will enable significant improvement in precision.
  - Devising and testing methods for HLbL.
  - Significant human effort and computing resources required.





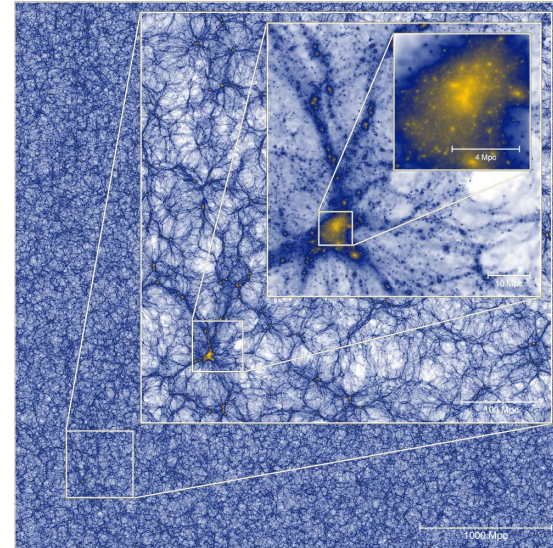
# Muons and Higgs flavor violation

- Fermilab Mu2e experiment will be strongest probe of Higgs flavor violating coupling to  $\mu$ -e, sensitive to  $BR(h \rightarrow \mu e) \sim 10^{-10}$ .
- Showed that simplest SUSY models that accommodate known Higgs mass predict 100 TeV-scale flavor violation that can be probed by Mu2e.

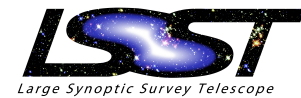


# Synergy with technology R&D: HPC for astrophysics

- Developing framework that runs on standard HPC clusters and will run on future exa-scale machines (e.g. ALCF at ANL)
  - to study the effect of baryons on matter clustering.
- Worked with Scientific Computing Division to design and develop **software frameworks to enable DES and LSST data analysis at HPC centers.**



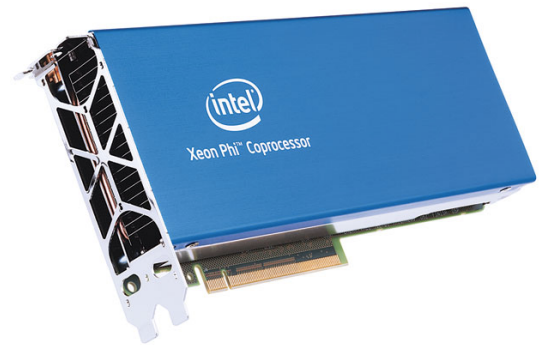
DARK ENERGY  
SURVEY



# Synergy with technology R&D: LQCD

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- **Develop and deploy large computing clusters and software frameworks for use by U.S. lattice-QCD community (USQCD).**
- Leading U.S. lattice effort: chair of USQCD exec. committee and PI of LQCD (hardware) and SciDAC (software) grants.
- **Hardware synergy with other projects.**
  - lab expertise in DAQ fed into LQCD.
  - early adoption of advanced networking by LQCD basis for subsequent DAQs for upcoming neutrino and muon expts.
  - first GPU cluster deployed at Fermilab for LQCD, similar cluster used for accelerator modeling and broad range of other projects.
- **Software collaboration** between LQCD and Accelerator Simulation, shared development and SciDAC plans.



# Summary

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- **Theoretical physics and astrophysics groups are essential for vibrant programs in all cross-cut areas.**
  - aligned with OHEP future plans according to P5 priorities.
  - significant past and current projects have grown out of, or been shaped by, the theory program.
- Proximity to experiment cross-fertilizes both theoretical and experimental research at Fermilab.
  - engaged with LPC and planned Neutrino Physics Center.
  - broader community benefits: visitors, seminars, conferences.
  - enlivens intellectual atmosphere.
- Strong service to lab, university, international communities.
- **High scientific productivity:** research output, program planning, postdoc and student training, future leaders of the field.