Theory at Fermilab

Marcela Carena

PAC, November 17, 2021

Overview of the theoretical physics program at the laboratory

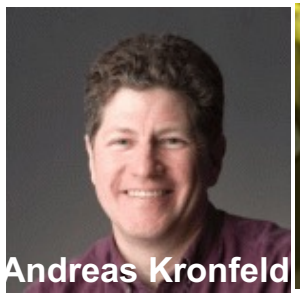
Charge to the PAC:

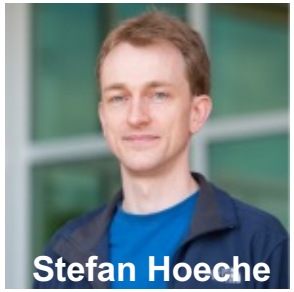
- review the theoretical physics program at the laboratory,
- comment on the role of the new division,
- assess whether the laboratory integrates in and contributes effectively to community efforts including (but not limited to) the Neutrino Network, Lattice, g-2 Theory Initiative.

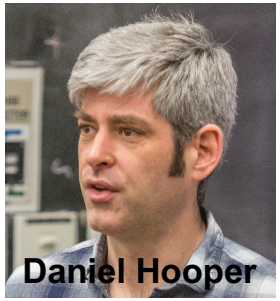
Mission of Fermilab Theory Program

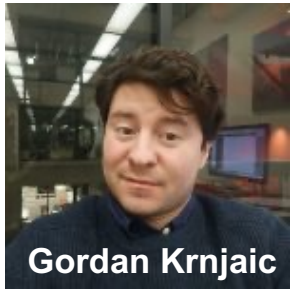
- Conducts world-leading theoretical particle physics, astrophysics, and quantum science research.
- Focus effort and core strength in key research areas directly related to the U.S. and worldwide experimental programs.
- Leads and supports national and international theory consortia and networks focused on areas of special importance to the DOE HEP program.
- Influences and motivates the design of experiments, data analyses, and their interpretation.
- Trains next generation of theorists in data-rich environment
- Provides a national resource for university physicists.
- Fosters an intellectually vibrant atmosphere at the lab.

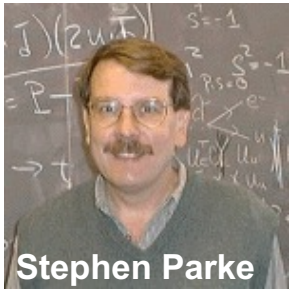
Scientists

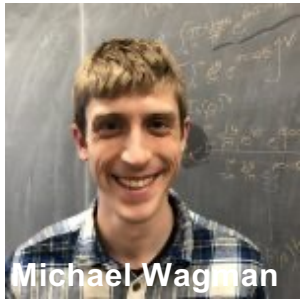












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Scientists main areas of research include:

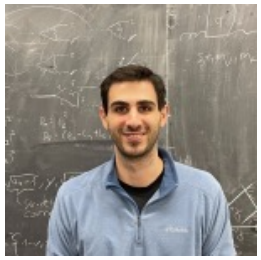
- **Astrophysics and Cosmology**: Gnedin (computational cosmology), Stebbins (probes of large scale structure and interferometric surveys), with strong involvement from Krnjaic, Hooper (DM and neutrino cosmology), Carena (baryogenesis, phase transitions, GW)
- **Dark Matter/Dark Sectors**: Hooper, Krnjaic, Fox, Berlin, Carena, Hill, Harnik.
- **Higgs Physics**: (collider, Model building, phase transitions) Campbell, Carena, Hoeche
- **Lattice QCD**: (first principles calc. of nucleon properties & nuclear effects, muon g-2 HVP, quark-flavor physics) Kronfeld, Van de Water, Wagman; Simone (SCD)
- **Perturbative QCD**: **(**for LHC and future colliders) Campbell, Hoeche, Giele
- **Neutrino Physics**: (model building, pheno high energy and nuclear, generators, AI techniques) Parke, Machado, Wagman, Rocco, Giele, Hoeche
- **New Physics**: (model building, collider pheno) Berlin, Carena, Fox, Dobrescu, Harnik, Hill
- **QIS and QFT Simulation**: (quantum simulation of HEP-QFT) Lamm, Carena, Wagman
- **QIS/Quantum Sensing**: (new experimental ideas for dark sectors, gravitational waves, axions) Berlin, Harnik

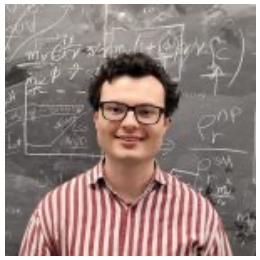
Postdocs: the lifeblood of the Division

Postdocs work broadly across all Departments and topics

Large International component due to our standing in field

Supported by DOE Theory direct funding


Benoit Assi


Elias Bernreuther


Abhish Dev


Sam McDermott

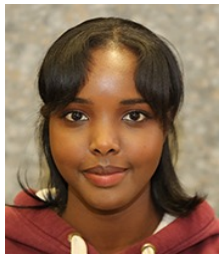

Alexis Nikolakopoulos


Elena Pinetti

Postdocs: the lifeblood of the Division

Leveraging limited resources through JA/other funding

University Funding, Early Career Award, Humboldt Foundation, Office of Science Distinguished Fellowship program, QuantISED grant, SQMS Center


Asli Abdullahi


Arka Banerjee


Vedran Brdar (JA)


Christina Gao (JA)

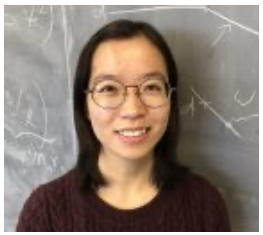

Erik Gustafson


Florian Herren (HF)


Josh Isaacson


Ryan Janish


Shirley Li


Ying Ying Li

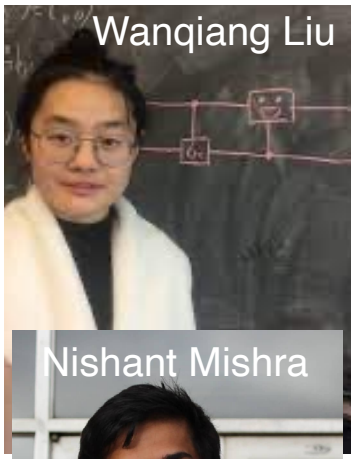

Anastasia Sokolenko (JA)

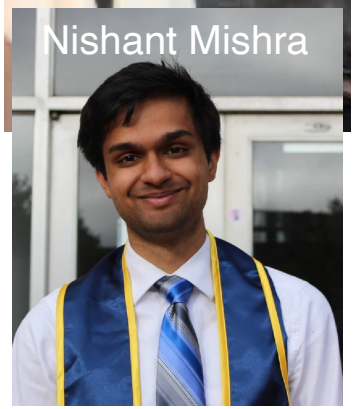

Judah Unmuth-Yockey

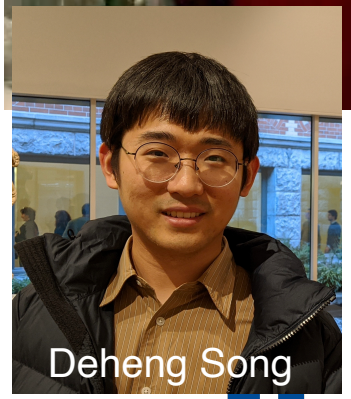
Students

Supported by URA, SCGSR program, QuantISED grant, SULI program

- No Theory DOE direct funding for students -







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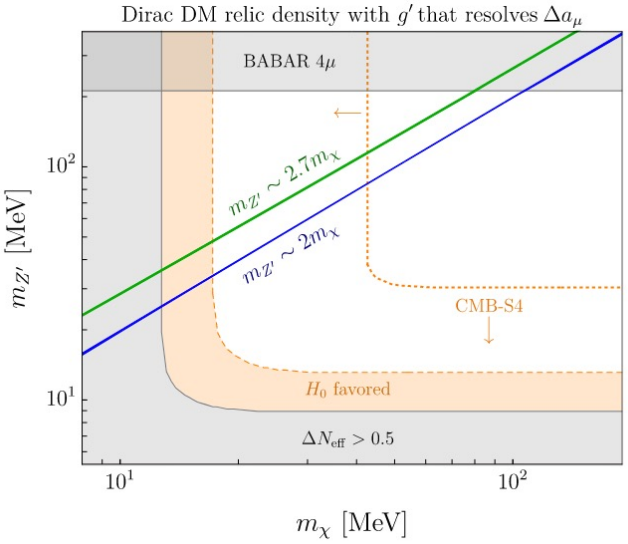
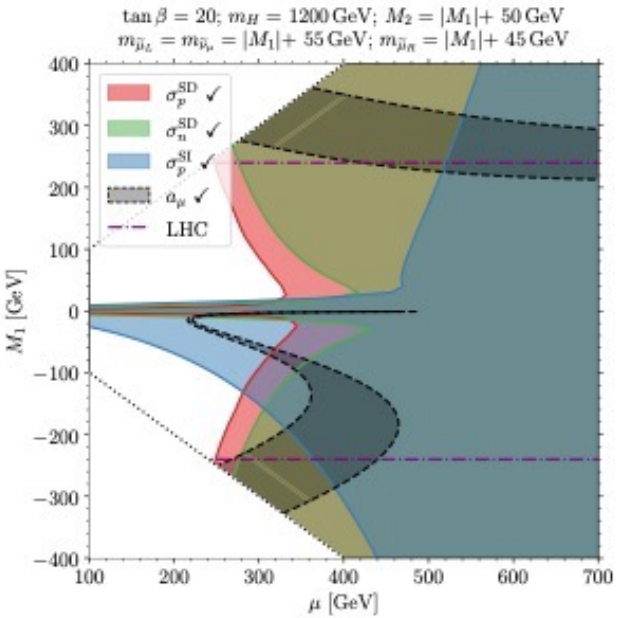
Astroparticle/Particle Highlights

- **Muon g-2 Connections to Cosmic Puzzles, Dark Matter Detection, LHC and future colliders**
  - ➢ Leptophilic gauge boson at accelerator-based exp. (NA62, NA64μ, M^3, DUNE) and CMB-S4



Hooper, Krnjaic et al. arXiv:2107.09067

  - ➢ Supersymmetric solution with light dark matter, new scalars and fermions@ the LHC and DM Direct Detection experiments



(see Wagner's talk)

Carena et al: arXiv: 2104.03302

Particle Highlights

- **Developing the Physics of Neutrino Simulations for the DUNE Era**

➢ **Neutrino-Nucleon Cross-Section Model Tuning in GENIE v3**

Giele et al. arXiv: 2104.09179

➢ **Machine-learning-based architecture for atomic nuclear interaction description with external electroweak probes for neutrino oscillation exp.**

. Rocco: et al. arXiv: 2010.12703 (Phys Rev C)

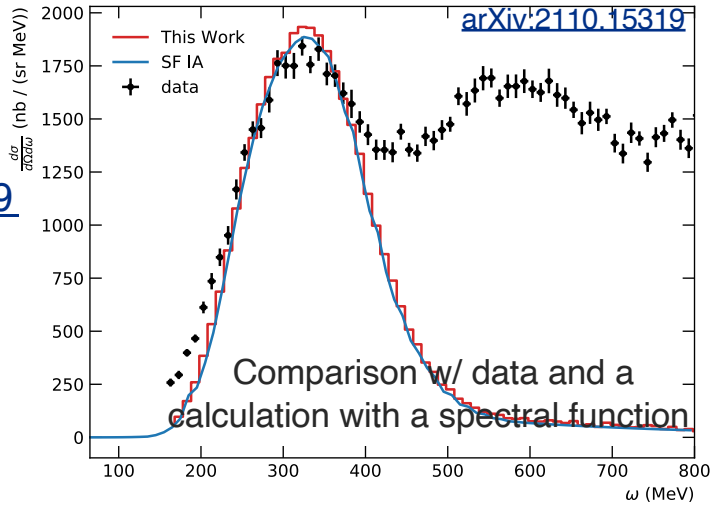
➢ **Novel event generator for the automated simulation of neutrino scattering**

RA Isaacson, Höche, UGS Lopez-Gutierrez, Rocco arXiv:2110.15319

➢ **New approach to intranuclear cascades with quantum Monte Carlo configurations**

RA Isaacson, RA Jay, Lovato, Machado, Rocco arXiv:2007.15570

Electron-Carbon scattering (1300 MeV, 37°)



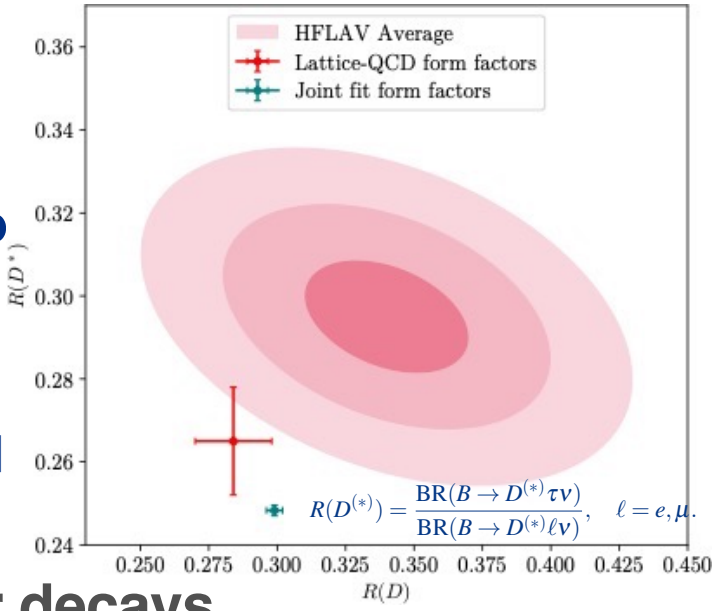
Particle Highlights:

- **Quark Flavor Physics**

  - **Semileptonic form factors for B → D*lν at nonzero recoil from 2+1-flavor lattice QCD**

    tension remains for CKM element $|V_{cb}|$ from inclusive and exclusive decays as well as in the SM calculation of $R(D^*)$

    Kronfeld, Mackenzie, Simone, Van de Water [+Fermilab Lattice + MILC] arXiv:2105.14019



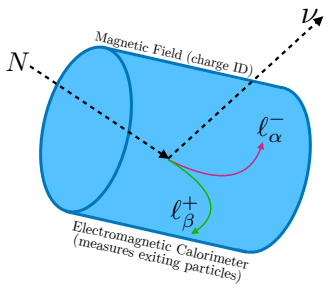
- **Heavy Neutral Leptons characterized via their decays**

  - Exploring HNL Majorana or Dirac nature at gaseous Argon TPC via its 3-body decay

    Fox, Kayser, RA Kelly, de Gouvêa arXiv:2109.10358

    RA Kelly (now CERN) joined ArgoNeut to carry out the search —Wine & Cheese seminar Oct. 8, 2021.

  - Many other NHL searches (Machado's talk)



Schematic representation of the decay $N \to \nu\ell_\alpha^-\ell_\beta^+$ occurring within the proposed gaseous argon time projection chamber.

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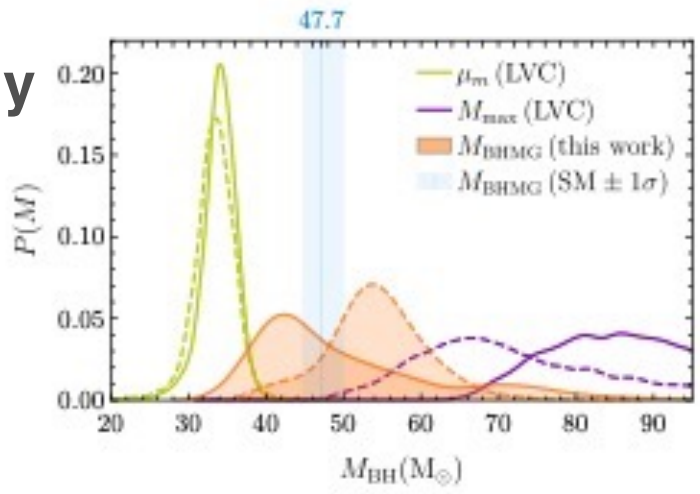
Astrophysics Highlights

- **Pushing the Frontiers of Particle Cosmology**



➢ **Black Hole population analysis with an astrophysically motivated Mass Function**

results establish the edge of the anticipated black hole mass gap at a value compatible with the expectation from standard stellar structure theory. Black hole mass function fits well LIGO data, contrary to claims from other groups

McDermott et al arXiv:2104.02685

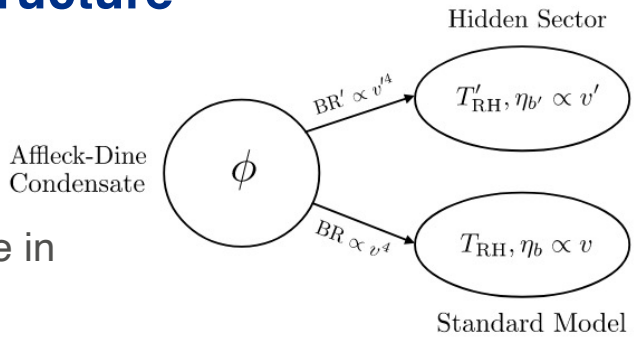
➢ **Progress in the Hydrodynamics of Large-Scale Structure**

Gnedin et al. arXiv:2101.11627,2011.07099,arXiv:2109.06194

➢ **Twin-Higgs like model of Dark atoms to solve Hubble tension**

the required "coincidence" that recombination occurs at the same time in the visible and hidden sectors is dynamically enforced

RA Blinov, Krnjaic, RA Li, arXiv:2108.11386



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Quantum Theory Department (New and growing!)

Quantum Simulation of Quantum Field Theory

New field at the QIS HEP interface, leveraging the strong experience in lattice QFT:

- Identifying (toy) HEP problems ripe for quantum advantage.
- Mapping of gauge theories and general QFT's to devices (qubits or analog).
- Improved lattice Hamiltonians
- Running simulations on NISQ devices
- Noise estimates with classical simulation
- Initial state preparation for QFT simulation
- Defining motivated observables (PDFs, plasma viscosity)
- Tensor networks for lattice simulations
- Lattice quantum gravity

Quantum Sensing to Probe Fundamental Physics

New ideas for testing elusive new physics (SRF-Dark, MAGIS100, Skipper-CCD for quantum imaging)

- Searches for axion and dark photon DM with SRF cavities.
- Light shining through wall searches.
- DM searches and GW studies @MAGIS100
- DM searches with optomechanical systems near quantum limit
- Gravitational wave detection with EM cavities.
- Searches for new particles with quantum optics.

Particle/Quantum Highlights

- **Real-time Lattice Gauge Theory Actions**

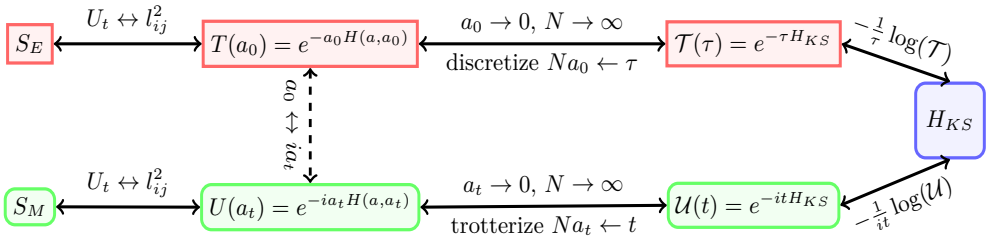
➢ **Unitarity, convergence, and path integral contour deformations**

- real-time lattice QCD of interest e.g. fragmentation functions.
- derive a class of real-time lattice gauge theory actions based on Wick rotation of the Euclidean heat-kernel action that allows for path integral contour deformation to obtain a convergent representation for U(1) and SU(3)

Wagman et al. arXiv:2103.02602

- **Quantum Computations for QFT**

➢ **Lattice Renormalization for Quantum Simulation**



- show that trotterized time-evolution operators can be related by analytic continuation to the Euclidean transfer matrix on an anisotropic lattice ←→ renormalization of lattice spacings
- use tools of Euclidean lattice field theory to determine Minkowski lattice spacings
- fixed anisotropy approach to the continuum to reduce circuit depth and # of indep. simulations

Carena, Lamm, RA Y.-Y. Li and GS W. Liu arXiv:2107.01166 (PRD)

Quantum Simulation of Quantum Field Theory

Off to a productive start!

Large scale multi-node simulations of $\mathbb{Z}_2$ gauge theory quantum circuits using Google Cloud Platform #2

Erik Gustafson (Fermilab), Burt Holzman (Fermilab), James Kowalkowski (Fermilab), Henry Lamm (Fermilab), Andy C.Y. Li (Fermilab) et al. (Oct 14, 2021)

e-Print: 2110.07482 [quant-ph]

Tensor field theory with applications to quantum computing #7

Yannick Meurice (Iowa U.), Ryo Sakai (Iowa U.), Judah Unmuth-Yockey (Syracuse U. and Fermilab) (Oct 13, 2020)

e-Print: 2010.06539 [hep-lat]

Quantum Simulation of Dihedral Gauge Theories

M. Sohaib Alam (LBL, Berkeley), Stuart Hadfield (NASA, Ames and RIACS, Mtn. View), Henry Lamm (Fermilab), Andy C.Y. Li (Fermilab) (Aug 30, 2021)

e-Print: 2108.13305 [quant-ph]

Parton physics on a quantum computer #13

NuQS Collaboration • Henry Lamm (Maryland U.) et al. (Aug 27, 2019)

Published in: *Phys.Rev.Res.* 2 (2020) 1, 013272 • e-Print: 1908.10439 [hep-lat]

Simulations of Quantum Circuits with Approximate

Sergei V. Isakov (Fermilab), Dvir Kafri (Fermilab), Orion Martin (Fermilab), Catherine Vollgraff Heidweiller (Fermilab)

Wojciech Mru

e-Print: 211

Quantum Algorithms for Open Lattice Field Theory #6

Jay Hubisz (Syracuse U.), Bharath Sambasivam (Syracuse U.), Judah Unmuth-Yockey (Syracuse U. and Fermilab) (Dec 9, 2020)

e-Print: 2012.05257 [hep-lat]

Lattice Renormalization of Quantum Simulations

Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Henry Lamm (Fermilab), Ying-Ying Li (Fermilab), Wanqiang Liu (Chicago U.) (Jul 2, 2021)

e-Print: 2107.01166 [hep-lat]

Quantum Simulation of Quantum Field Theory

Prospects for Simulating a Qudit Based Model of (1+1)d Scalar QED

Erik Gustafson (Iowa U.) (Apr 20, 2021)

Published in: *Phys.Rev.D* 103 (2021) 11, 114505 • e-Print: 2104.10136 [quant-ph]

Off to a productive start!

Toward quantum simulations of $\mathbb{Z}_2$ gauge theory without state preparation

Erik J. Gustafson (Iowa U.), Henry Lamm (Fermilab) (Nov 23, 2020)

Published in: *Phys.Rev.D* 103 (2021) 5, 054507 • e-Print: 2011.11677 [hep-lat]

Effective $\mathbb{Z}_3$ model for finite-density QCD with tensor networks #1

Jacques Bloch (U. Regensburg (main)), Robert Lohmayer (U. Regensburg (main)), Sophia Schweiss (U. Regensburg (main)), Judah Unmuth-Yockey (Fermilab) (Oct 18, 2021)

Contribution to: Lattice 2021 • e-Print: 2110.09499 [hep-lat]

Newtonian binding from lattice quantum gravity

Mingwei Dai (Syracuse U.), Jack Laiho (Syracuse U.), Marc Schiffer (U. Heidelberg, ITP), Judah Unmuth-Yockey (Syracuse U. and Fermilab) (Feb 8, 2021)

Published in: *Phys.Rev.D* 103 (2021) 11, 114511 • e-Print: 2102.04492 [hep-lat]

Quantum algorithms for transport coefficients in gauge theories

Thomas D. Cohen (Maryland U.), Henry Lamm (Fermilab), Scott Lawrence (Colorado U.), Yukari Yamauchi (Maryland U.) (Apr 5, 2021)

e-Print: 2104.02024 [hep-lat]

Tensor lattice field theory with applications to the renormalization group and quantum computing

Yannick Meurice (Iowa U.), Ryo Sakai (Iowa U.), Judah Unmuth-Yockey (Syracuse U. and Fermilab) (Oct 13, 2020)

e-Print: 2010.06539 [hep-lat]

Quantum Highlights

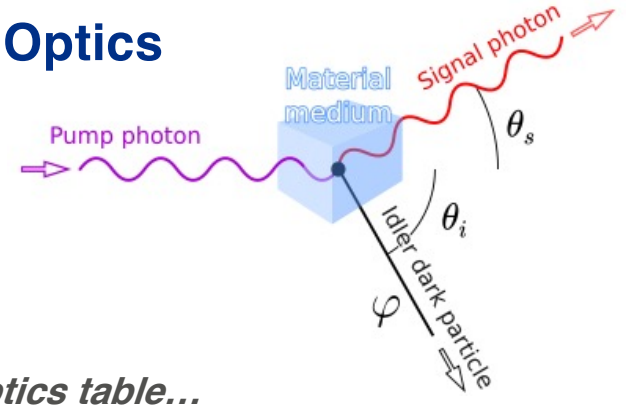
- **Quantum Sensing Efforts**

➢ Searching for Dark Particles with Quantum Optics

First proposal to use tools of Quantum optics in lab searches for axions and dark photons

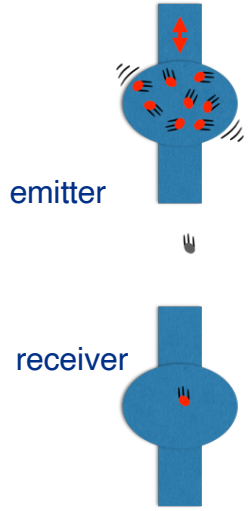
Estrada, Harnik et al. arXiv:2012.04707
(to appear in **PRX Quantum**)

"Dark Spontaneous Parametric Down conversion" (dSPDC)



Missing energy at the optics table…

➢ Dark- SRF: Light-shining-through-the-wall experiment



- currently running at SQMS with theory involvement from its inception.
- expected to improve limits on dark Photon by orders of magnitude
- Fermilab theorists involved on future improvements and extending the search to axions (Harnik, RA Gao)

Fermilab

Fermilab Theory and National/International Initiatives

- **Neutrino Theory Network**: 14 universities and 6 labs participating. Managed by Fermilab Theory but almost all funds go out the door. New, highly competitive NTN postdoctoral fellow program aim at strengthening the theoretical neutrino physics research effort in the US and its impact on the experimental programs.

  Two fellows started in Fall 2021

  and two new fellows expected in FY22

  Info @https://ntn.fnal.gov

Zahra Tabrizi
(Northwestern U.)

Bijaya Acharya
(ORNL)

- **QuantISED Theory Consortium**:
  National Consortium launched 2018 , Carena PI, with Caltech and U. Wash, renewed 2020 adding QuantISED pilot PIs from UIUC, MIT, and Purdue.
  Other Universities expressed interest in joining

Fermilab Theory and National/International Initiatives

- **Muon g-2 Theory Initiative**

  Outgrowth of the Distinguished Scholar Program, supporting the Muon *g*–2 Experiment. The Initiative highlights Fermilab role as a hub. (El Khadra's talk)

- **Lattice QCD**:

  Active leadership of the USQCD Collaboration, which is the national framework of lattice infrastructure, including Kronfeld as member of the USQCD Executive Committee (Chair until 9/20/2021)
  Kronfeld PI of the Exascale Computing Project for lattice QCD
  Close collaboration with the LQCD extension III computing program (managed in Fermilab SCD).

Other Fermilab Theory Initiatives

- **Distinguished Fermilab Scholars**
  Rotating multi-year appointments for U.S. theorists at Fermilab, with at least one-month residence per year (bring postdocs/students). This program strengthens the connections between lab & university theory and increases the local expertise supporting Fermilab exp.

- **Postdoc Joint Appointments:**
  In past 4 years Northwestern(4), U. Chicago(2), U. Maryland, U. Kentucky, IIT, UIUC, ANL.
  Have been contacted by at least other 4 Univ. to do JAs.
  Pursuing structured initiatives: Kadanoff Institute at UChicago (quantum).

- **Cross-division cross-fertilization for experiments:**

  BSM searches with ArgoNeuT: milicharges, PRL 124 (2020); HNLs , PRL 127 (2021)

  BSM programs for DUNE and SBN

  Two quantum experiments underway (MAGIS100 and Dark SRF)

  SQMS Physics and Sensing Focus area

  Directional nuclear recoils in gas Ar; Muon Missing Momentum (M^3)
  Skipper CCD for quantum imaging; Strong connections with LPC, CPC, NPC

Theory Division (ThD)

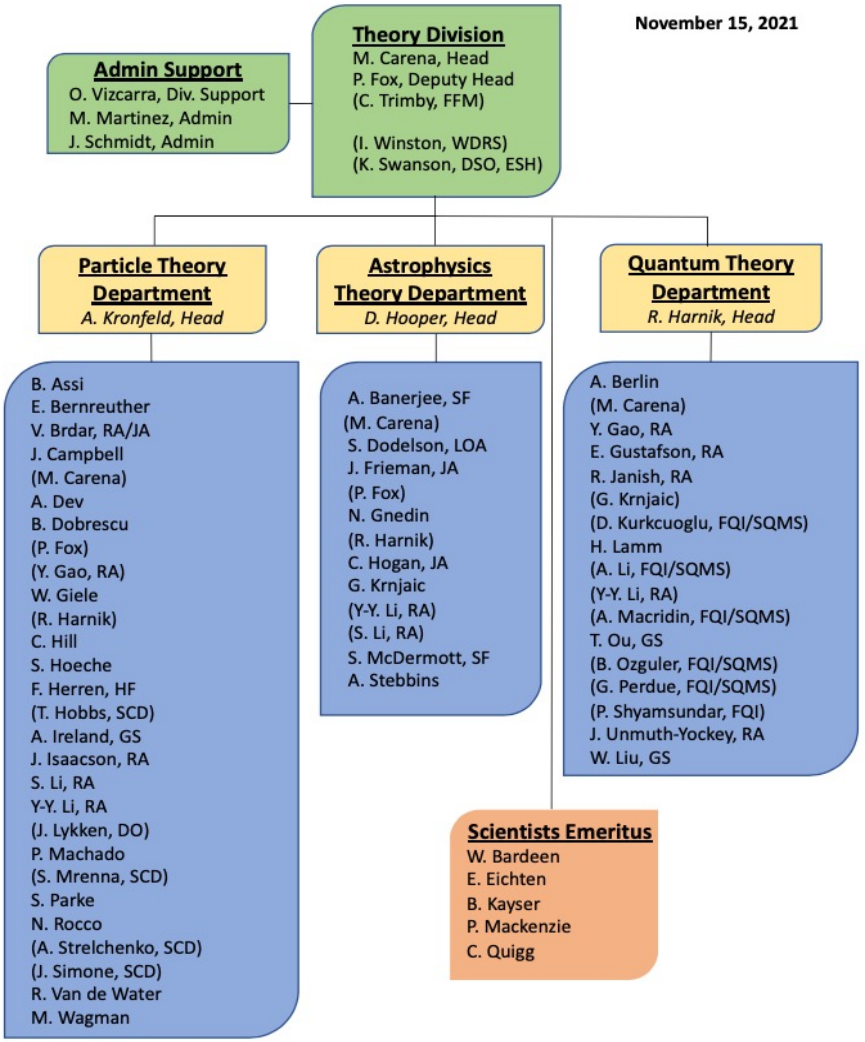
- Fully running as a division since October 1st, 2021

Rationale to create a Division:

Theory department was functioning more like a division inside PPD

- Highly Active and lab-wide Program with comparable number of scientists as the smaller divisions at the Lab (e.g., ND)
- Leading National Programs
- Leading cross-division activities to broadening existing and developing new experiments
- Seeding joint postdoctoral/faculty positions at local Universities and Argonne Lab
- Hosting over 125 visitors/year pre-Covid time
- Hosting several international workshops

Org Chart



DO – Director's Office
DSO – Division Safety Officer
ESH – Environmental, Safety & Health
FFM – Field Financial Manager
FQI – Fermilab Quantum Institute
GS – Graduate Student
HF – Humboldt Fellow
JA – Joint Appointment
LOA – Leave of Absence
RA – Research Associate
SCD – Scientific Computing Division
SF – Schramm Fellow
SQMS – Superconducting Quantum Materials and Systems
WDRS – Workforce Development & Resources Section

Fermilab

Theory output in numbers:

143 papers with 576 citations in the past year in key research areas directly related to the U.S. and worldwide experimental programs

Special emphasis during Covid maximal teleworking policy period to mentor postdocs and keep connected

Quantum Theory Department

- Provides a single home for lab theorists working in Quantum
- Involvement from other division scientists and postdocs.
- Pursuing an expanding area at the interface of HEP and quantum science.
- Strong efforts in quantum simulation and in quantum sensing.
- Latest hires: Hank Lamm (quantum simulation of HEP-QFT - March 2021)and Asher Berlin (Quantum Sensing – November 2021) strong additions to the program
- Synergy with SQMS (via SQMS science thrust lead Harnik) and FQI
- Supported fully by **non-base** funding:

  QuantISED DOE grant (PI Carena) and SQMS Center

Astrophysics Theory Department

- Well integrated with the Fermilab Cosmic Program
- Absence of Scott Dodelson (LOA) and Josh Frieman (now only 2 months/yr Fermilab) leaves major gaps in scientific expertise and leadership that we need to fill
- Lates Hire: Gordan Krnjaic (Dark Matter and Neutrino Cosmology, December 2018) strong addition to the program
- Want to build/leverage on our strong connections to the Kavli Institute and Astronomy Dept. at U. Chicago
- Similarly for our connections to the CIERA astrophysics center at Northwestern

Particle Theory Department

- Well integrated with the Fermilab LPC, Muon and Neutrino Programs
- Latest hires: Noemi Rocco (neutrino nuclear – October 2020) and Mike Wagman (lattice neutrinos and QFT – December 2019) strong additions to the program
- Successful efforts of leveraging through SciDAC, ECA, Exascale and International connections such as European Networks and Humboldt Foundation
- Strong connections with colleagues at US Universities and abroad that attract students and postdocs to come to Fermilab

Snowmass Contributions

- Snowmass Conveners:

Fox: Theory – Model building (TF08)

Harnik: Theory – Quantum Information Science (TF10)

Hoeche: Precision QCD (EF05)

Machado: Understanding Neutrino Anomalies (NF02)

- Many LOI's.
- Examples of notable white papers –

Neutrinos and lattice QCD (Wagman)
Quantum simulation of QFT's (Lamm, Carena)
Computational needs for lattice field theory (Kronfeld)

Summary

Theory Division will help to

- enable a more strategic outward-looking theory leadership,
- promote more new initiatives, strengthen existing ones
- increase leveraging of DOE funds
- succession plan for future leadership

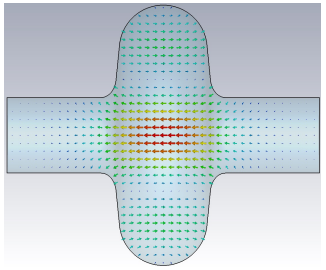
It has strong support from DOE and the Lab, although some details still under development

EXTRAS

Highly Leveraged Program

- Postdoc leveraging: non-DOE/DOE = **25%** (in average)
- Postdocs leveraging: non-DOE-Theory/DOE Theory = **230%**
- Scientists leveraging: non-DOE-Theory/DOE Theory = **30%**
- Visitor leveraging: non-DOE/DOE = **65%**
- This leveraging is time-consuming and the new organization makes more time for the Head of Theory to focus on these growth opportunities while building the experience needed for the next level down to assume leadership in years to come

Quantum Highlights



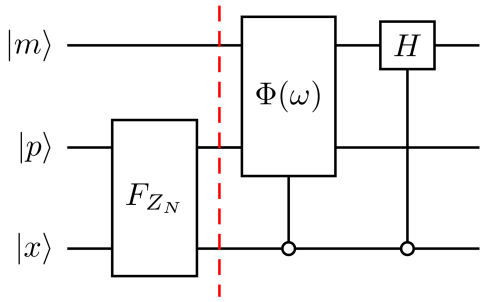
- **Efforts within SQMS (Harnik, SQMS Science Thrust Lead)**

➢ SQMS Physics and Sensing Focus Area

- Dedicated systems based on SRF Cavities can be used to search for new physics (DM, axions, gravity waves, etc)
- An R&D effort is underway to test existing hardware and optimize cavity designs, with strong participation of Berlin and Harnik. (cavity design for an axion DM search shown above).

➢ SQMS Algorithms Thrust

- Lamm is leading an effort for simulation of gauge theories on SQMS hardware.
- First paper on D4 gauge theories on Rigetti 2D devices (Lamm et al. 2108.13305 [quant-ph]).
- A key part of benchmarking plan for SQMS 3D devices.



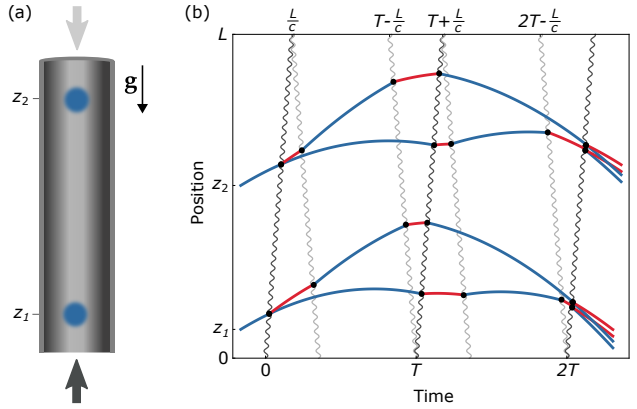
Circuit computing the Fourier transform of the D_N ($N = 2^n$ for some n) group.

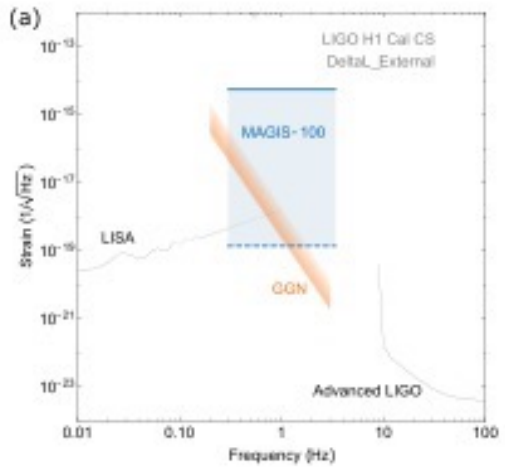
Quantum Highlights

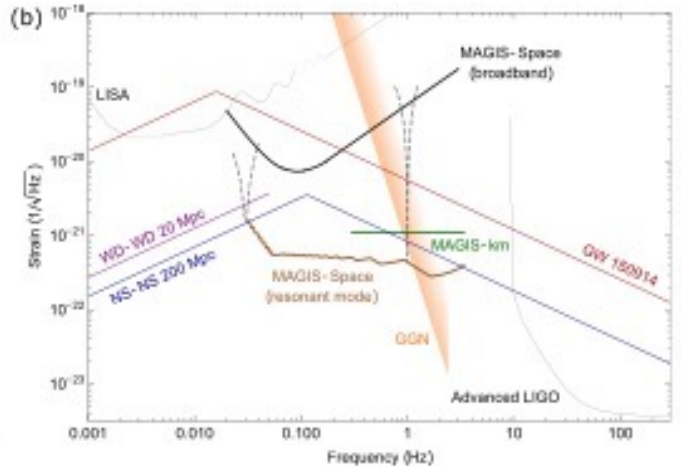
- **MAGIS-100**

➢ Gravitational Waves and DM with Atom Interferometry:

- MAGIS is a 100 meter atomic gradiometer, a prototype gravitational wave detector with sensitivity to dark matter.
- Harnik initiated the contact between the Stanford AMO group and Fermilab, enabling the project. Involved in formulating the science case and gravity gradient background estimates.







- See: *Quantum Sci.Technol.* 6 (2021) 4, 044003 e-Print: 2104.02835