



---

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

---

# Fermilab Neutrino Theory

Stephen Parke

Fermilab Institutional Review

12 February 2015

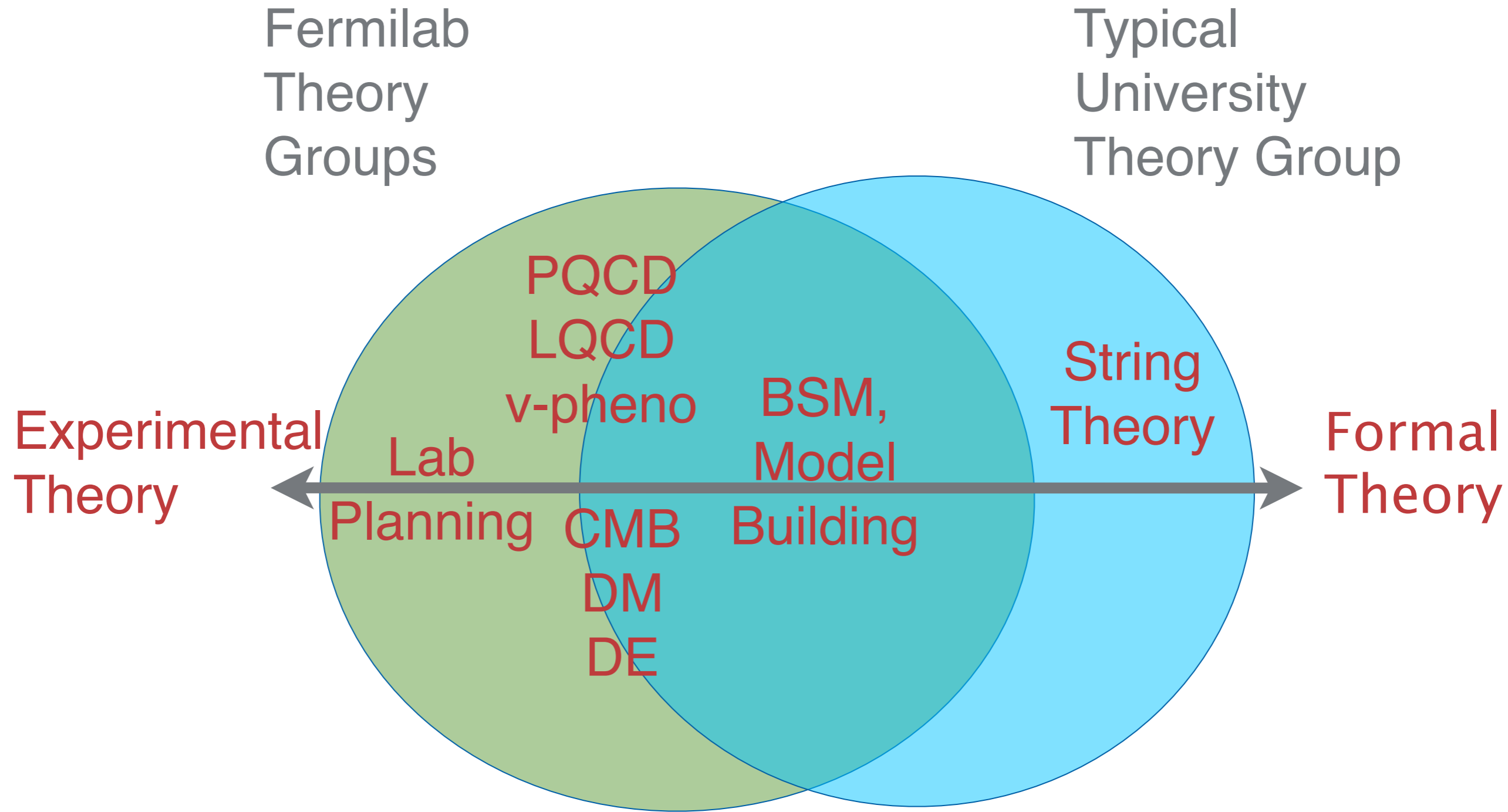
# Theoretical Physics Department Vision

---

- Conduct world-class theoretical particle-physics and astrophysics research.
- Focus effort and core strength in key research areas directly related to U.S. and worldwide experimental programs.
- 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.

Overlapping, complementary and synergistic with  
Laboratory experimental program &  
University theory research program

# Where are we?



# Scientists

---

## Associate Scientist:

Ruth Van de Water (9/12) (LQCD)

## Scientists I–III:

John Campbell (pQCD/Collider Physics)

Marcela Carena (BSM)

Estia Eichten (muon collider)

Keith Ellis (pQCD/Collider Physics)

Paddy Fox (BSM)

Walter Giele (pQCD/Collider)

Roni Harnik (BSM)

Christopher Hill (scale symmetry; axions)

Andreas Kronfeld (LQCD)

Joe Lykken (7/2014 became Deputy Director)

Paul Mackenzie (LQCD)

Bogdan Dobrescu (BSM)

Stephen Parke (Neutrinos, Top Quark)

Chris Quigg (SM, Quarkonium)

Jim Simone (1/2 FTE – LQCD)

## Retired Scientists:

Bill Bardeen (2010) — Emeritus

Boris Kayser (2013) — Emeritus guest

<http://theory.fnal.gov>

# Research Associates

---

FY15 (8+1):

Prateek Agrawal (→Harvard) (BSM)

Pilar Coloma (Neutrinos)

Claudia Frugiuele (→Weizmann) (BSM)

Elisabetta Furlan (pQCD)

Jack Kearny (BSM)

Daniel Mohler (→Mainz) (LQCD/pheno)

Raoul Rontsch (→Karlsruhe) (pQCD)

Ran Zhou (LQCD)

Katrin Gemmler\* (pheno)

New FY16 (→9)

Kiel Howe (BSM)

Seyda Ipek (BSM)

Ye Li (pQCD)

Zhen Liu (BSM)

Aarti Veenala (LQCD)

Our Post Docs work closely with faculty members as well as frequently write papers without senior collaborators → path to independent researchers!

\* funded by  
German Fellowship

<http://theory.fnal.gov/people/ellis/alumni.html>

# Neutrino theory research program

- Fermilab neutrino theory research efforts in Theoretical Physics & Astrophysics Departments cover wide range of topics
  - Two full-time neutrino phenomenologists (Parke + RA Coloma), one active emeritus scientist (Kayser) + several others involved part-time in study of connections between neutrinos and dark matter, cosmology, etc...baseline oscillation experiments

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

BooNE  
BOOSTER NEUTRINO EXPERIMENT

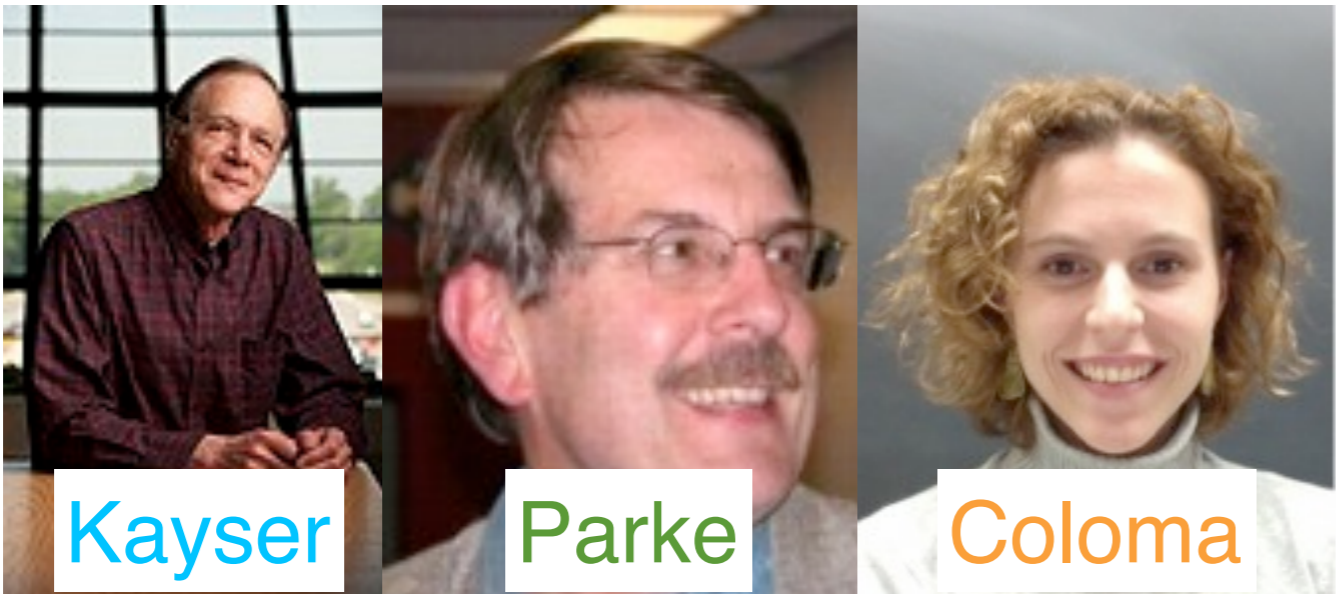


improved determination of nuclear effects

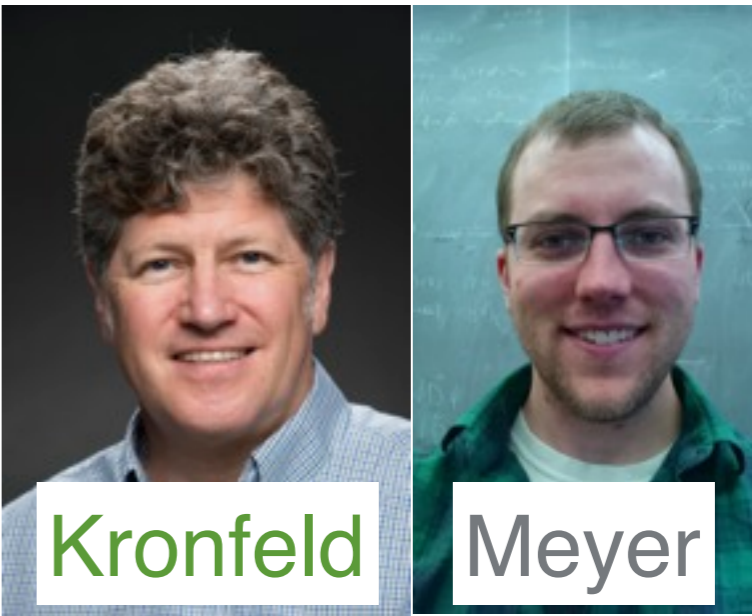
cosmic neutrinos

# Neutrino theory researchers (Emeritus, Scientists, RAs, Student)

## Phenomenology



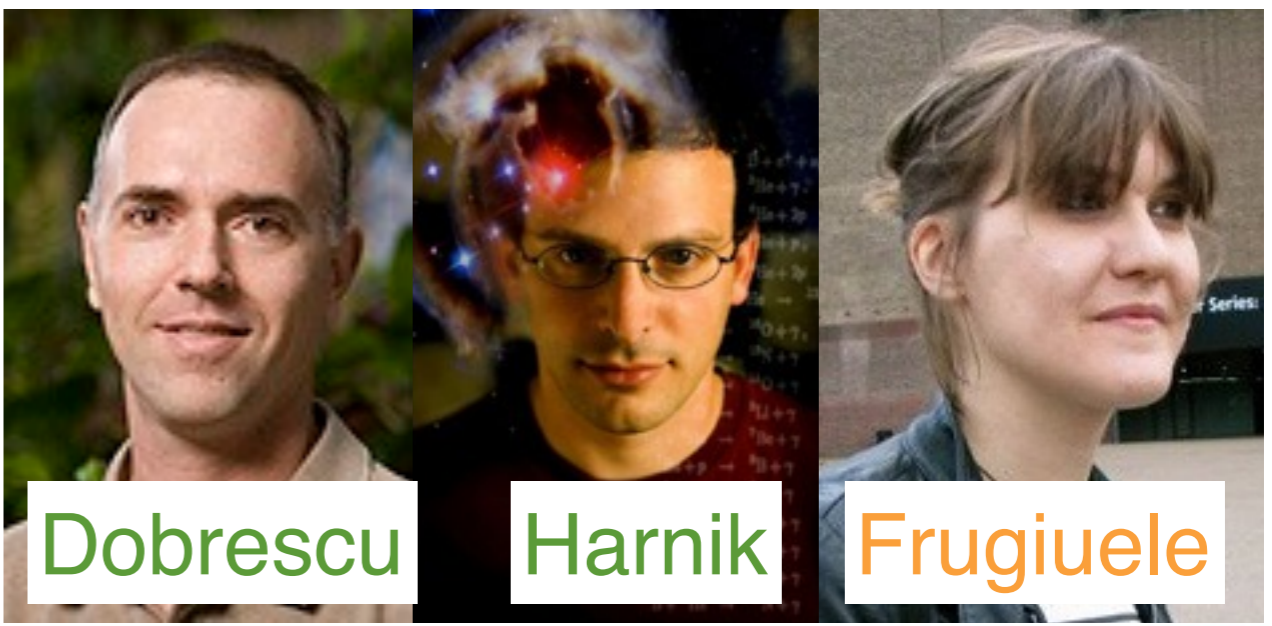
## Lattice QCD



## Cosmic constraints



## DM searches



# Neutrino theory visitors

---

- **Andre de Gouvea (Northwestern)** spends about one day a week at Fermilab
- Collaborators spend many person-weeks a year here, in particular:
  - **Hisakazu Minakata (Sao Paulo)**
  - Others include **Hiroshi Nunokawa, Renata Zukanovich Funchal, ...**
- Invisibles Network (Europe): **Silvia Pascoli (Durham)** spends between one and two months at the Lab and frequently brings students and RAs. Also member of Fermilab PAC.
- **Providing partial support to nuclear theorists**
  - **Luis Alvarez-Ruso (Valencia)** to interface between nuclear theory and Monte Carlo used in neutrino experiments
  - **Joe Carlson (LANL)** in Fall (will bring two RAs)
- **Neutrino visitors complement expertise of group members.**



---

# Synergistic activities

# Laboratory activities

---

- Fermilab theorists devote significant energy to help formulate and evaluate possible future programs for Fermilab
  - Rotating permanent slot on Fermilab PAC **Eichten (current), Parke, Kayser, ...**
  - **Parke & Kayser** contributed to numerous studies for both Short- and Long-Baseline Neutrino programs
- **Theoretical Physics Department** hosts weekly Joint Experimental–Theoretical Physics (“Wine & Cheese”) Seminar
- **Harnik & Quigg** organized academic lecture series “The Allure of UltraSensitive Experiments.”
  - Pedagogical lectures included 4 talks on  $g-2$ , 4 on LFV, 13 on neutrinos, ...
  - Fermilab theorists **Agrawal (RA), Altsmanshoffer (former RA), Dodelson, Fox, Harnik, Kayser, Kronfeld, Parke, Stebbins**, gave talks.
- **Kronfeld & Quigg** proposed Project X Physics Study which culminated in the physics part of the Project X Physics Book (**Kronfeld co-editor**).
  - Lays broad experimental program that could be mounted with a new intense proton source at Fermilab, including  $\text{Mu}2e$ ,  $g-2$ , EDMs, ELBNF, ...
  - **Quigg** WG convener for neutron–antineutron WG/chapter; **Van de Water** convener for lattice–QCD WG/chapter

# Community leadership

---

- Fermilab theorists authors on 18 Snowmass reports. In particular:
  - **Kayser** co-convener Neutrino WG on Anomalies and New Physics
  - **Van de Water** co-convener of Lattice Field Theory/Computing Frontier WG, and co-convener of Lattice QCD task force of the Quark Flavor/Intensity Frontier WG
- Fermilab theorists serve on numerous domestic and international scientific councils and advisory boards. In particular:
  - **Parke** chair of the International Neutrino Commission and custodian of the International Conference on Neutrino Physics and Astrophysics
  - **Kayser** on Program Advisory Committee of Sanford Underground Research Facility
- Fermilab theorists organized numerous conferences and workshops related to neutrino physics including:
  - **Kronfeld, Mackenzie (chair), & Van de Water** co-organized the 2014 “Lattice Meets Experiment” workshop. Topics included  $g-2$ , Mu2E, and neutrinos.
  - **Fox & Harnik** (with Batell) organized “New approaches in the Search for Dark Matter.” Topics included searches for light DM and light mediators with neutrino beams.
- Fermilab theorists organized & lectured at numerous schools including:
  - **Kayser** co-founded 1<sup>st</sup> Fermilab/KEK Neutrino Physics Summer School, lectures annually
  - **Parke** lectures regularly at invisibles Network School

---

# Scientific research

# Neutrino Phenomenology: Research summary

---

- Develop strategies for **precision studies of the Standard 3-neutrino paradigm**
- Assess the stated sensitivities of present and proposed experiments
- Study the **impact of light sterile neutrinos**, should they exist, on long-baseline oscillation experiments
- Suggest new kinds of experiments to probe the existence and explore the physics of light sterile neutrinos
- Explore the possible existence and impact of **non-Standard-Model neutrino interactions** of a kind not considered before
- **Help develop proposals for future experiments**
- **Participate in experimental collaborations**
- Consider the possible connection of CP violation in neutrino oscillation to the matter-antimatter asymmetry of the universe
- Confront the subtle quantum mechanics underlying neutrino oscillation
- **Determine nuclear effects** on the measurement of neutrino oscillation parameters

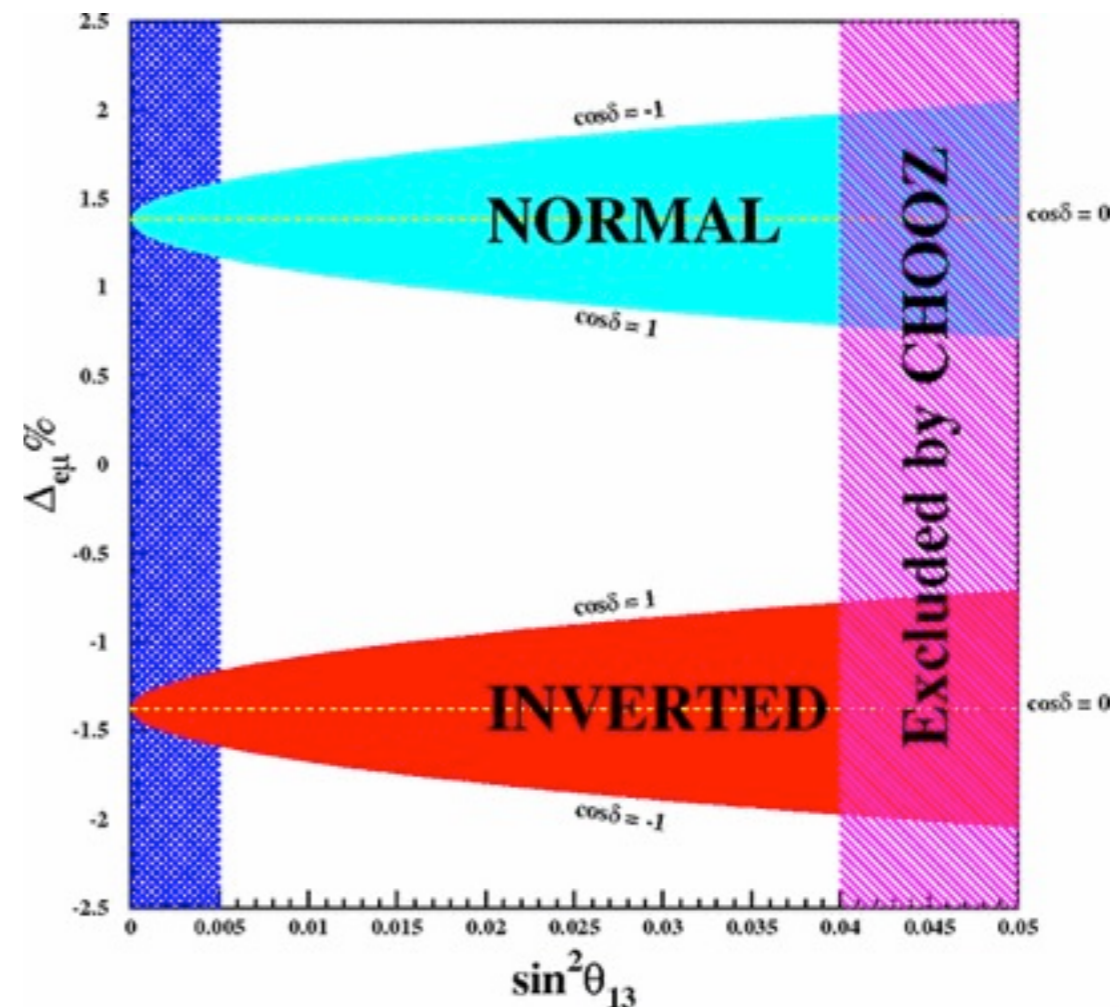
# Phenomenology example: determining the mass hierarchy

- In neutrino disappearance experiments, the effective  $\delta m^2$  measured at the first oscillation minimum is the flavor average of  $\delta m^2_{32}$  and  $\delta m^2_{31}$  :

$$\text{MINOS } (\nu_\mu): \quad \delta m^2_{\mu\mu} = \cos^2 \theta_{12} \delta m^2_{32} + \sin^2 \theta_{12} \delta m^2_{31}$$

$$\text{Daya Bay } (\nu_e): \quad \delta m^2_{ee} = \sin^2 \theta_{12} \delta m^2_{32} + \cos^2 \theta_{12} \delta m^2_{31}$$

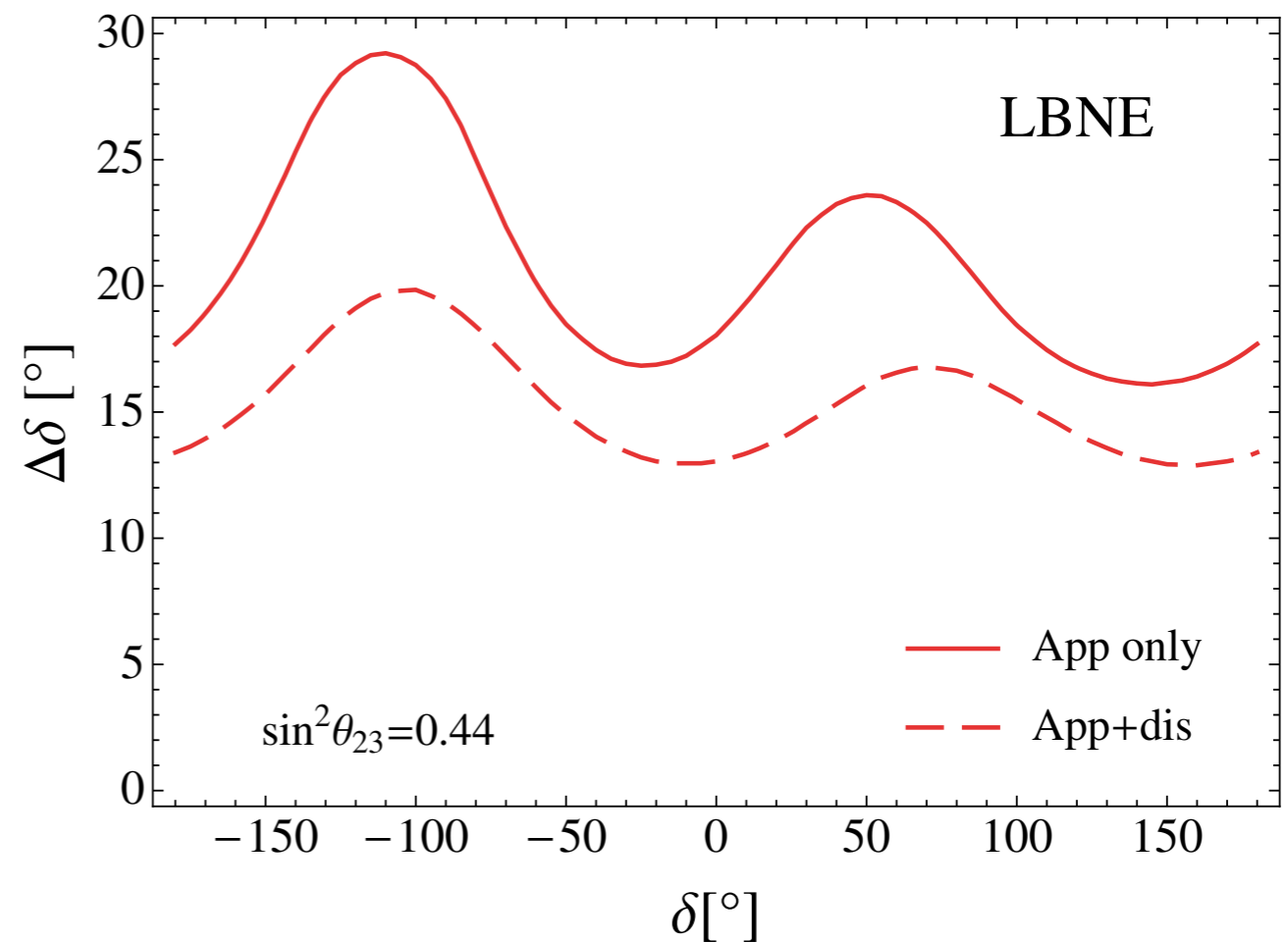
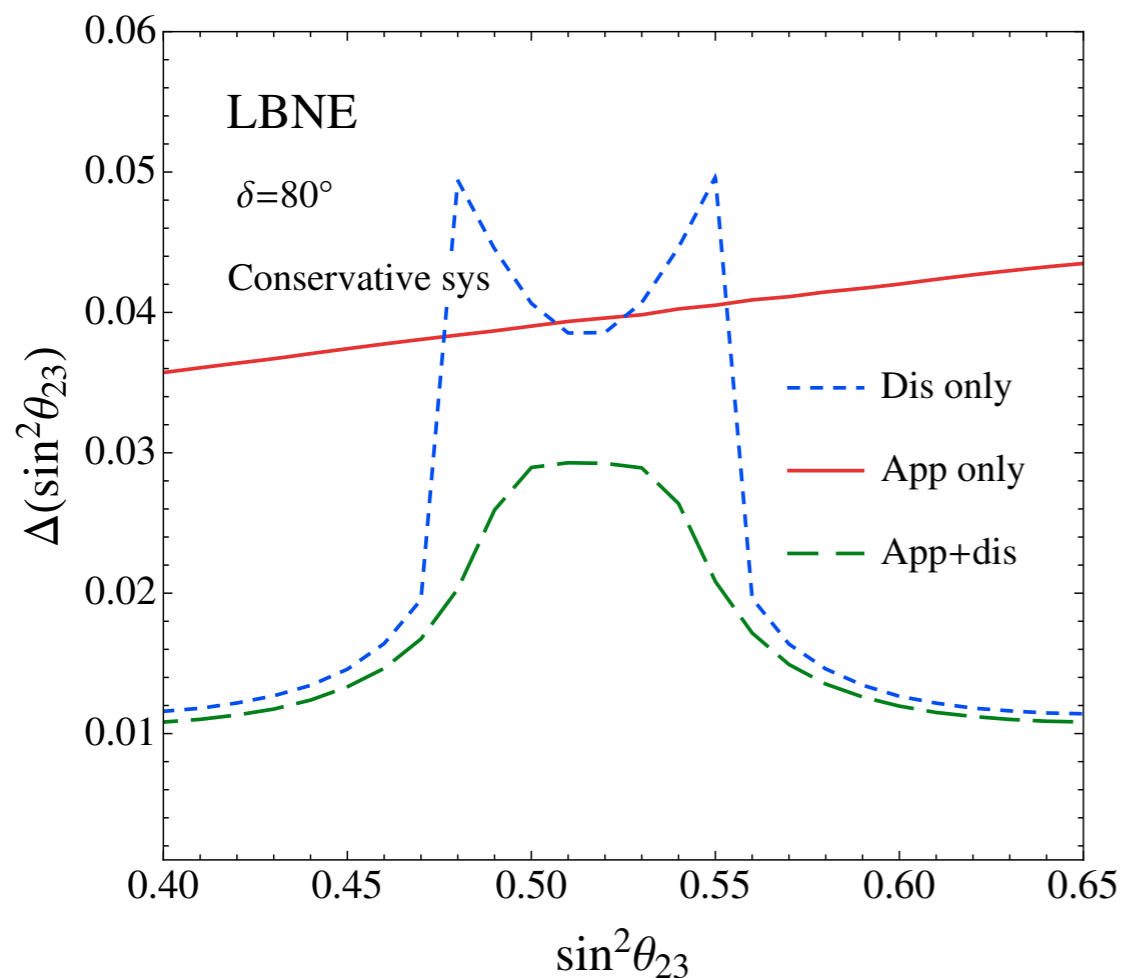
- In principle could be used to determine mass hierarchy with precision measurements of both [Nunokawa, Parke, Zukanovich Funchal, PRD72 (2005) 013009].



# Phenomenology example: determining the mixing angle $\theta_{23}$

- Long Baseline Neutrino Program: **MINOS, MINOS+, NOvA & ELBNF**
  - Many papers over last 15 years
- Determination of  $\theta_{23}$  using appearance and disappearance channels and the impact of  $\theta_{23}$  on determination of CP-violating parameter  $\delta$  [Coloma, Minakata, Parke]

[1406.2551]



# Long-baseline neutrino studies

- Many long-baseline studies over the years
  - E.g. LBNE reconfiguration circa 2012 (pre-P5)

## Physics Working Group Report to the LBNE Reconfiguration Steering Committee

J. Appel<sup>1</sup>, M. Bass<sup>2</sup>, M. Bishai<sup>3</sup>, S. Brice<sup>1</sup>, E. Blucher<sup>4</sup>, D. Cherdack<sup>2</sup>, M. Diwan<sup>3</sup>, B. Fleming<sup>5</sup>,  
G. Gilchriese<sup>6</sup>, Z. Isvan<sup>3</sup>, B. Lundberg<sup>1</sup>, W. Marciano<sup>3</sup>, M. Messier<sup>7</sup>, S. Parke<sup>1</sup>, J. Reichanadter<sup>8</sup>,  
G. Rameika<sup>1</sup>, K. Scholberg<sup>9</sup>, M. Shochet<sup>4</sup>, J. Thomas<sup>10</sup>, R. Wilson<sup>2</sup>, E. Worcester<sup>3</sup>, C. Young<sup>8</sup>, G. Zeller<sup>1</sup>,

(Dated: August 6, 2012)

This document summarizes the physics capabilities of a long-baseline neutrino experiment employing a liquid argon detector and fed by an intense neutrino beam from Fermilab. The locations considered for the detector are at the Homestake mine in South Dakota, the Soudan mine in Minnesota, and the Ash River, Minnesota site of the NOvA detector. The experimental reach as a function of detector mass is given for the neutrino mass hierarchy and CP violation phase as well as for proton decay, atmospheric neutrino studies, and neutrinos from supernova explosions.

This is the “10 ktons on surface at Homestake” study!



# Short-baseline neutrino studies

- Short Baseline Neutrino Program: **MiniBooNE, MicroBooNE, LAr X, (NuSTORM)**
  - **Parke and Kayser** involved in many studies over the years

FERMILAB-FN-0947  
June 7, 2012

## SHORT-BASELINE NEUTRINO FOCUS GROUP

### REPORT

S. J. Brice (FNAL), B. Fleming (Yale), S. Geer (FNAL), A. de Gouvea (NW), D. Harris (FNAL), P. Huber (Virginia Tech), B. Kayser (FNAL), G. Mills (LANL), K. Nishikawa (KEK), S. Parke (FNAL), C. Polly (FNAL), A. Rubbia (Zurich), R. Tschirhart (FNAL), R. Van de Water (LANL), G. Zeller (FNAL), R. Zwaska (FNAL)

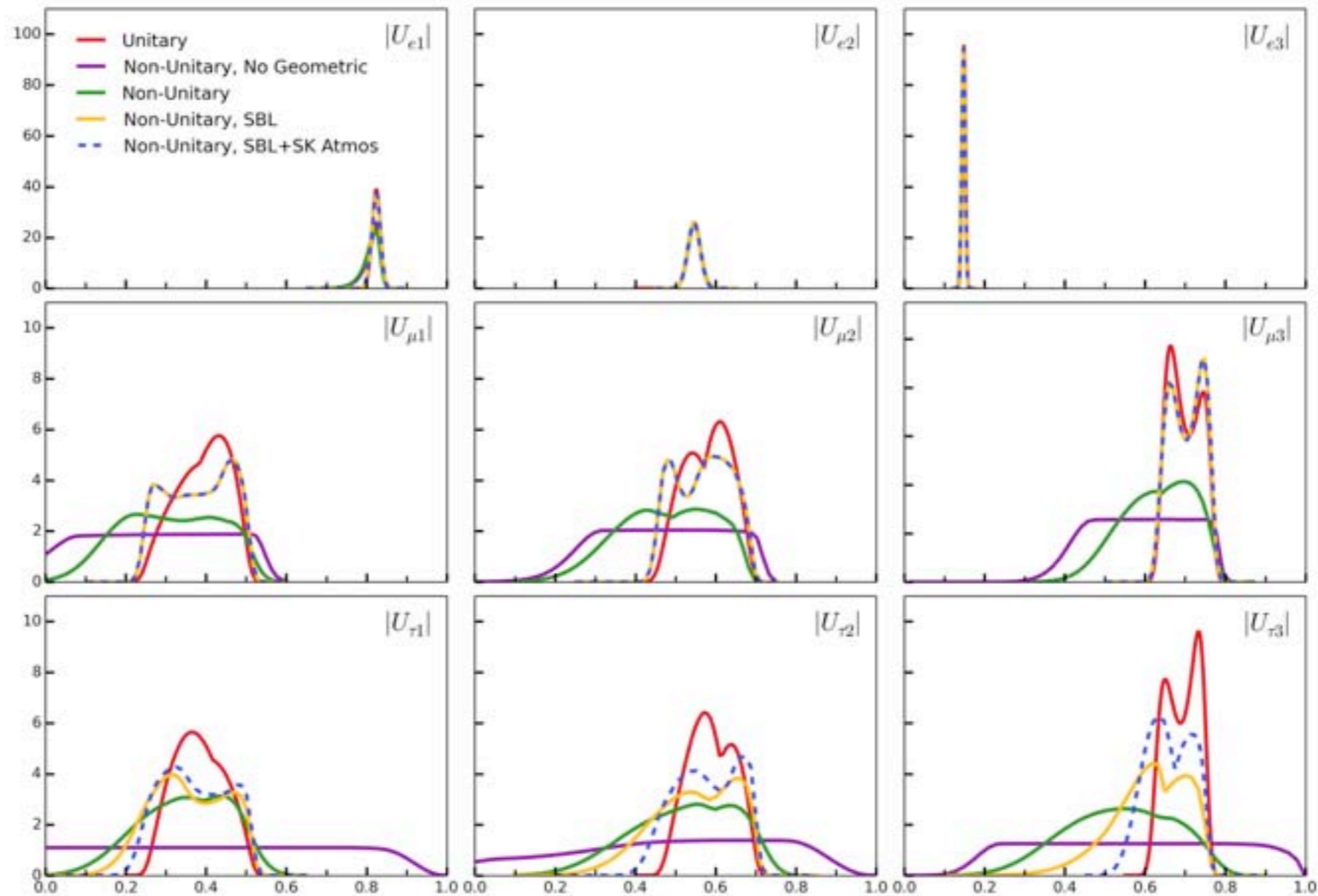
### Light sterile neutrino sensitivity at the nuSTORM facility

D. Adey,<sup>1</sup> S.K. Agarwalla,<sup>2</sup> C.M. Ankenbrandt,<sup>3,\*</sup> R. Asfandiyarov,<sup>4</sup> J.J. Back,<sup>5</sup> G. Barker,<sup>5</sup> E. Baussan,<sup>6</sup> R. Bayes,<sup>7,†</sup> S. Bhadra,<sup>8</sup> V. Blackmore,<sup>9</sup> A. Blondel,<sup>4</sup> S.A. Bogacz,<sup>10</sup> C. Booth,<sup>11</sup> S.B. Boyd,<sup>5</sup> S.G. Bramsiepe,<sup>7</sup> A. Bravar,<sup>4</sup> S.J. Brice,<sup>1</sup> A.D. Bross,<sup>1</sup> F. Cadoux,<sup>4</sup> H. Cease,<sup>1</sup> A. Cervera,<sup>12</sup> J. Cobb,<sup>9</sup> D. Colling,<sup>13</sup> P. Coloma,<sup>14</sup> L. Coney,<sup>15</sup> A. Dobbs,<sup>13</sup> J. Dobson,<sup>13</sup> A. Donini,<sup>12</sup> P. Dornan,<sup>13</sup> M. Dracos,<sup>6</sup> F. Dufour,<sup>4</sup> R. Edgecock,<sup>16</sup> M. Geelhoed,<sup>1</sup> M.A. Uchida,<sup>13</sup> T. Ghosh,<sup>12</sup> J.J. Gómez-Cadenas,<sup>12</sup> A. de Gouvêa,<sup>17</sup> A. Haesler,<sup>4</sup> G. Hanson,<sup>15</sup> P.F. Harrison,<sup>5</sup> M. Hartz,<sup>8,‡</sup> P. Hernández,<sup>12</sup> J.A. Hernando Morata,<sup>18</sup> P. Hodgson,<sup>11</sup> P. Huber,<sup>14</sup> A. Izmaylov,<sup>12</sup> Y. Karadzhov,<sup>4</sup> T. Kobilarcik,<sup>1</sup> J. Kopp,<sup>19</sup> L. Kormos,<sup>20</sup> A. Korzenev,<sup>4</sup> Y. Kuno,<sup>21</sup> A. Kurup,<sup>13</sup> P. Kyberd,<sup>22</sup> J.B. Lagrange,<sup>23</sup> A. Laing,<sup>12</sup> A. Liu,<sup>1</sup> J.M. Link,<sup>14</sup> K. Long,<sup>13</sup> K. Mahn,<sup>24</sup> C. Mariani,<sup>14</sup> C. Martin,<sup>4</sup> J. Martin,<sup>25</sup> N. McCauley,<sup>26</sup> K.T. McDonald,<sup>27</sup> O. Mena,<sup>12</sup> S.R. Mishra,<sup>28</sup> N. Mokhov,<sup>1</sup> J. Morfín,<sup>1</sup> Y. Mori,<sup>23</sup> W. Murray,<sup>16</sup> D. Neuffer,<sup>1</sup> R. Nichol,<sup>29</sup> E. Noah,<sup>4</sup> M.A. Palmer,<sup>1</sup> S. Parke,<sup>1</sup> S. Pascoli,<sup>30</sup> J. Pasternak,<sup>13</sup> R. Plunkett,<sup>1</sup> M. Popovic,<sup>1</sup> P. Ratoff,<sup>20</sup> M. Ravonel,<sup>4</sup> M. Rayner,<sup>4</sup> S. Ricciardi,<sup>16</sup> C. Rogers,<sup>16</sup> P. Rubinov,<sup>1</sup> E. Santos,<sup>13</sup> A. Sato,<sup>21</sup> T. Sen,<sup>1</sup> E. Scantamburlo,<sup>4</sup> J.K. Sedgbeer,<sup>13</sup> D.R. Smith,<sup>22</sup> P.J. Smith,<sup>11</sup> J.T. Sobczyk,<sup>31</sup> L. Soby,<sup>32</sup> F.J.P. Soler,<sup>7</sup> M. Sorel,<sup>12</sup> P. Snopok,<sup>33,§</sup> P. Stamoulis,<sup>12</sup> L. Stanco,<sup>34</sup> S. Striganov,<sup>1</sup> H.A. Tanaka,<sup>35</sup> I.J. Taylor,<sup>5</sup> C. Touramanis,<sup>26</sup> C. D. Tunnell,<sup>9,¶</sup> Y. Uchida,<sup>13</sup> N. Vassilopoulos,<sup>6</sup> M.O. Wascko,<sup>13</sup> A. Weber,<sup>9</sup> M.J. Wilking,<sup>24</sup> E. Wildner,<sup>32</sup> and W. Winter<sup>36</sup>  
(The nuSTORM Collaboration)

arXiv:1402.5250v1

# Global PMNS Fits without Unitarity [Parke, Ross-Lonergan]

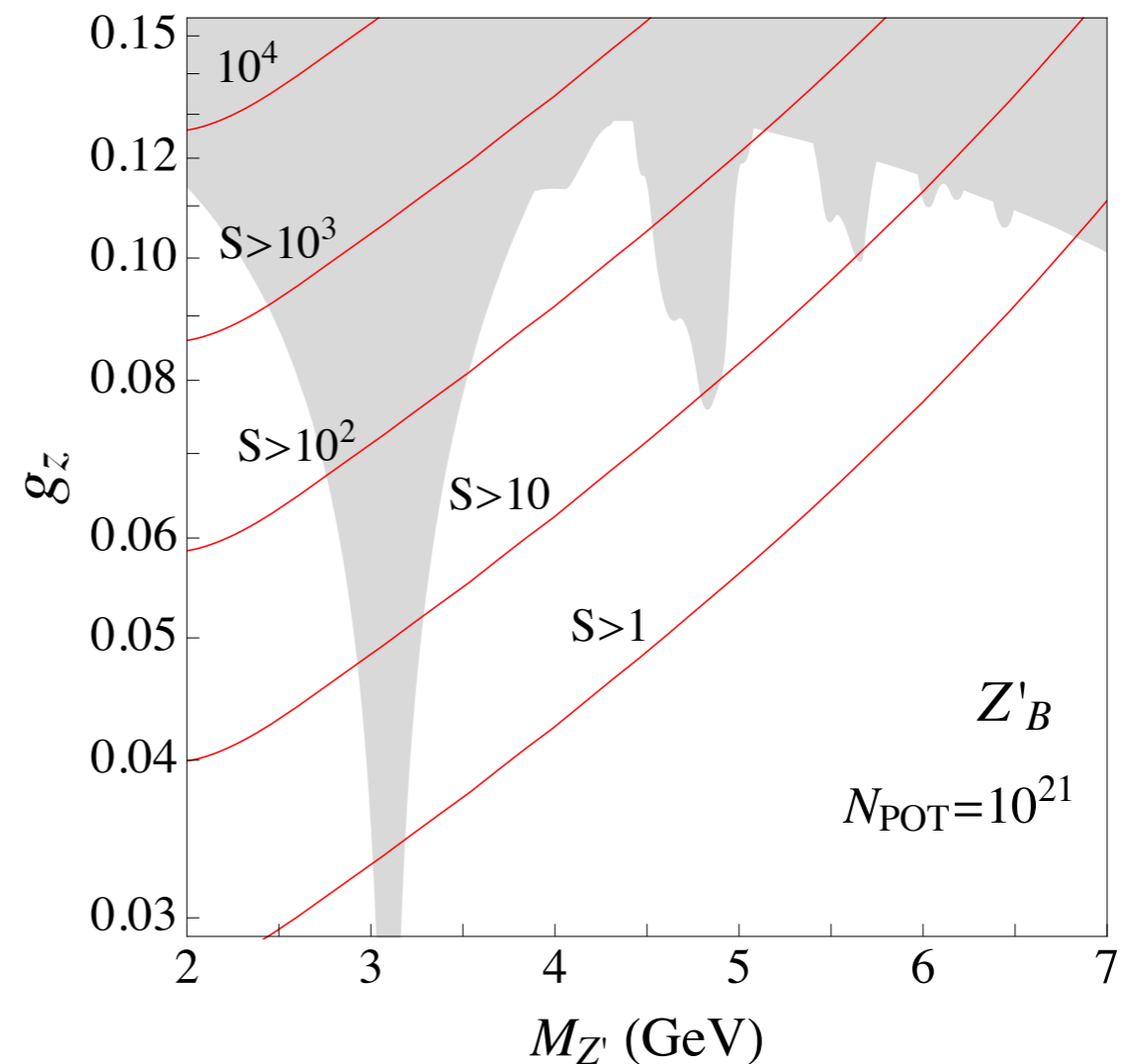
- What do we really know about the PMNS matrix? (in preparation)
  - with Mark Ross-Lonergan (graduate student, Durham U. via Invisibles Network)



# Dark matter in neutrino experiments

- Fermilab  $\nu$ -beams are also intense fixed target facilities.
  - Can take part in the search for dark sectors.
- April 2014: Fermilab Theory hosted a workshop on search for DM at low energy beams and other novel DM searches.

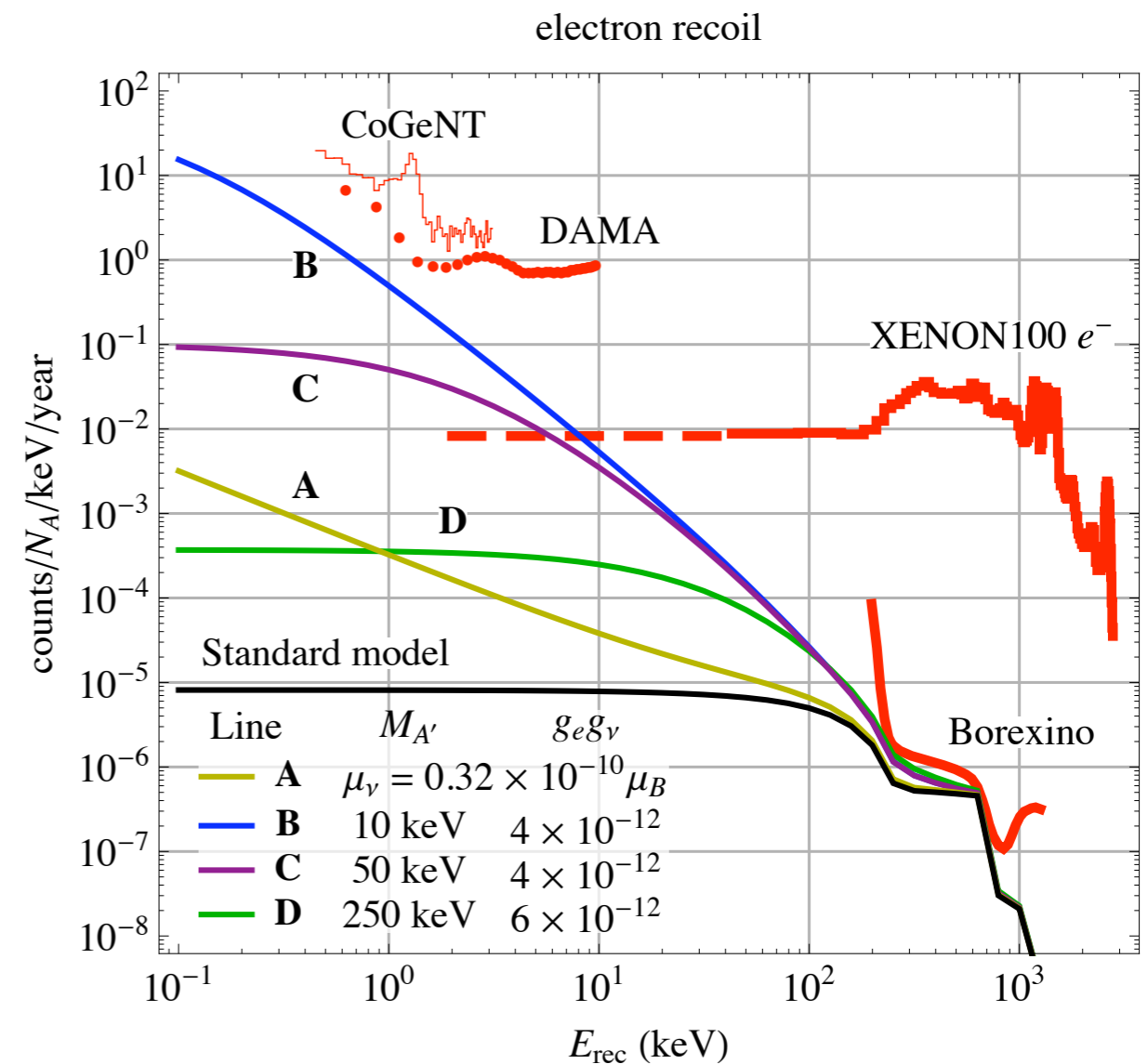
Dobrescu & Frugiuele (2014):  
NOvA can search for GeV DM.



# Neutrinos on dark-matter experiments

- DM Experiments are within striking distance of “Solar Neutrino floor”.
- New Physics in the neutrino sector can raise this floor.  $\nu$ 's can fake DM.
- Can discover light gauge bosons, sterile  $\nu$ 's, or  $\nu$  dipole moments.
- **CONNIE** (Coherent Neutrino-Nucleus Interaction) reactor experiment (J. Estrada, Fermilab LDRD) will probe this model space

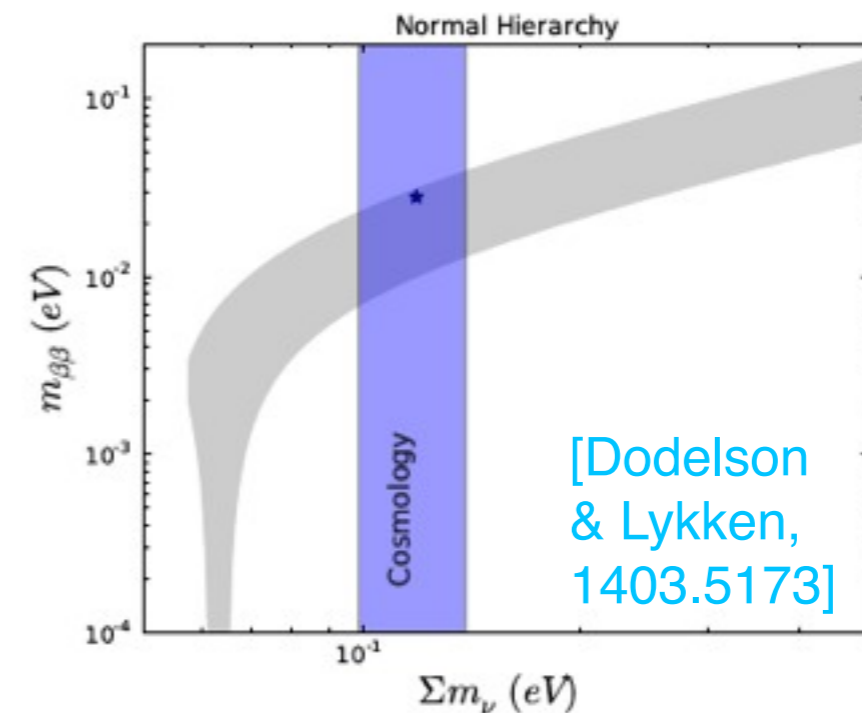
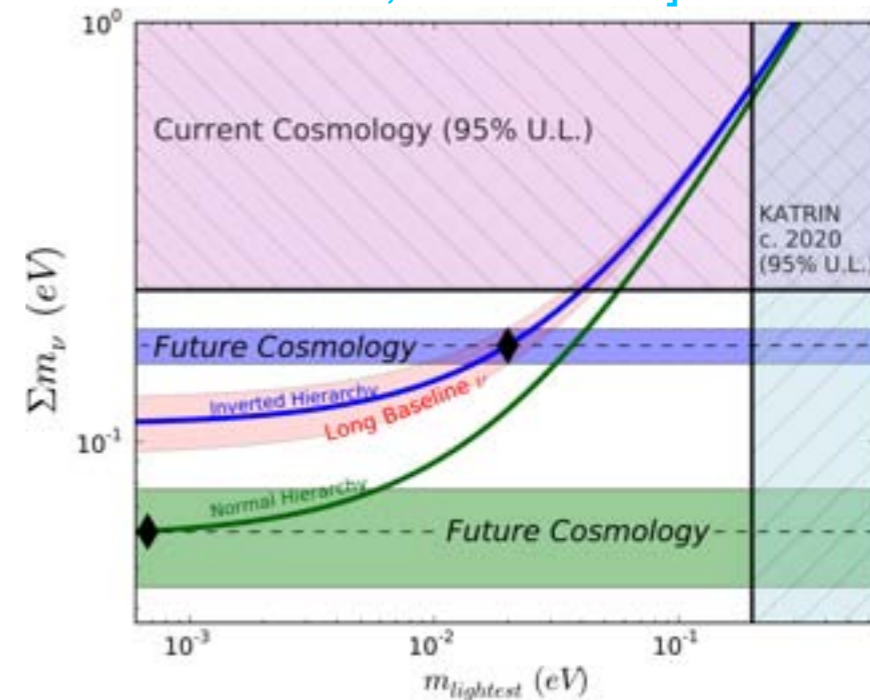
Harnik, Kopp (RA),  
Machado (Latin American student – 2011)



# Neutrinos constraints from the cosmos [Stebbins; Dodelson, Lykken]

- Large-scale structure simultaneously constrains sum of neutrino masses.
- Neutron star coalescence may explain fast radio bursts, associated 10–50 MeV  $\nu$ 's could constrain neutrino masses.
- Cosmological constraints inform  $\nu$ -less  $\beta\beta$  decay:
  - Could provide lower limit on rate
  - Could jointly constrain Majorana phase.

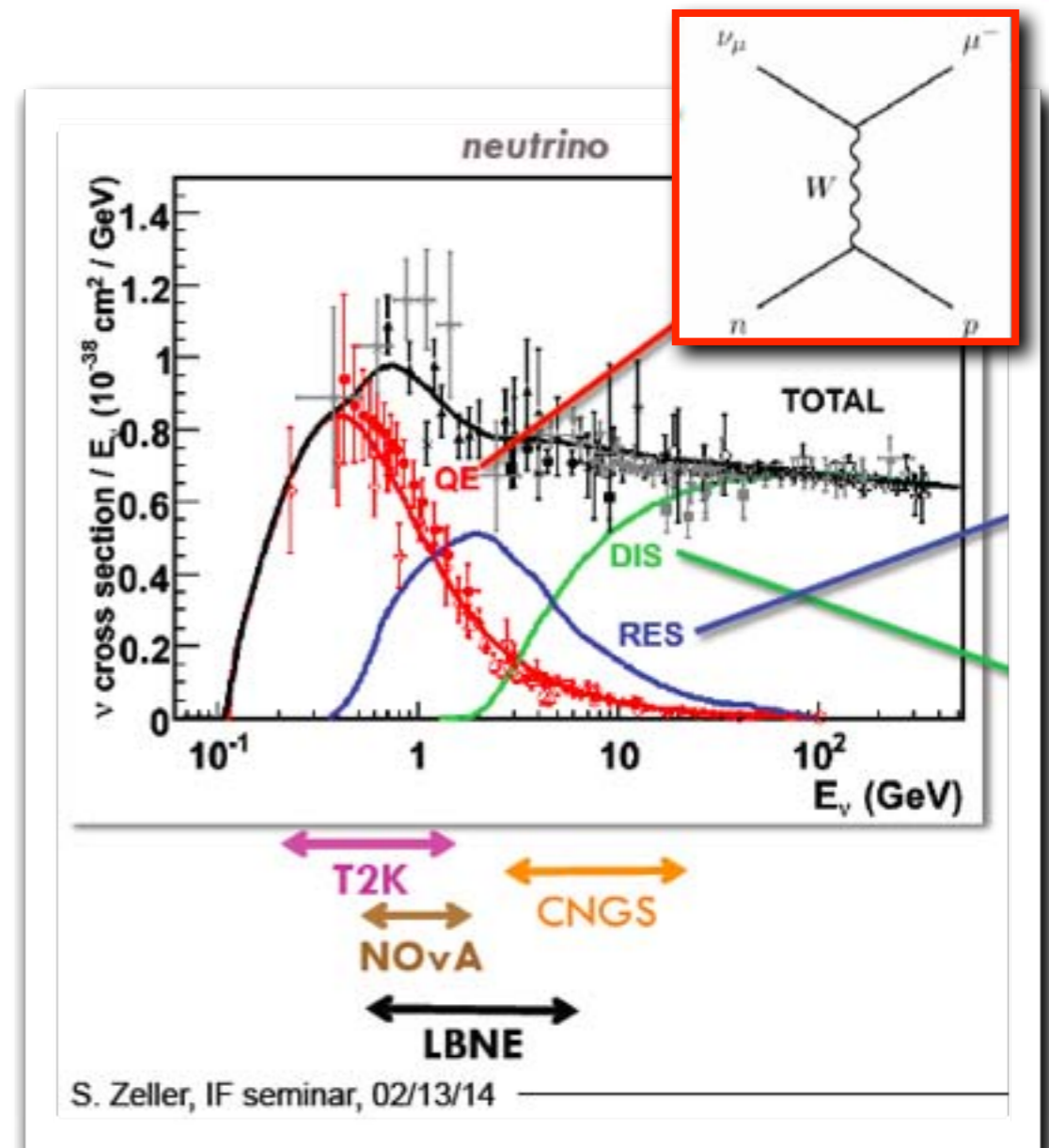
[Snowmass Dark Energy and CMB WG, 1309.5383]



[Dodelson & Lykken, 1403.5173]

# Nucleon axial-vector form factor from lattice QCD

- Nucleon axial-vector form factor important input into determination of CCQE X-section, which gives largest contribution to signal sample in many accelerator-based neutrino experiments (T2K, NOvA, ELBNF)
- **Kronfeld** co-supervising U. Chicago student Aaron Meyer★ on first-principles calculation of  $F_A(q^2)$  merging analyticity constraints with lattice QCD
  - **Completed work** implementing z-parameterization & external QCD input into standard GENIE Monte Carlo
  - **Beginning lattice calculation** with physical-mass pions to avoid large chiral-extrapolation errors of other works
  - Engagement and interest from **MINERvA**, **MicroBooNE**, and other experiments



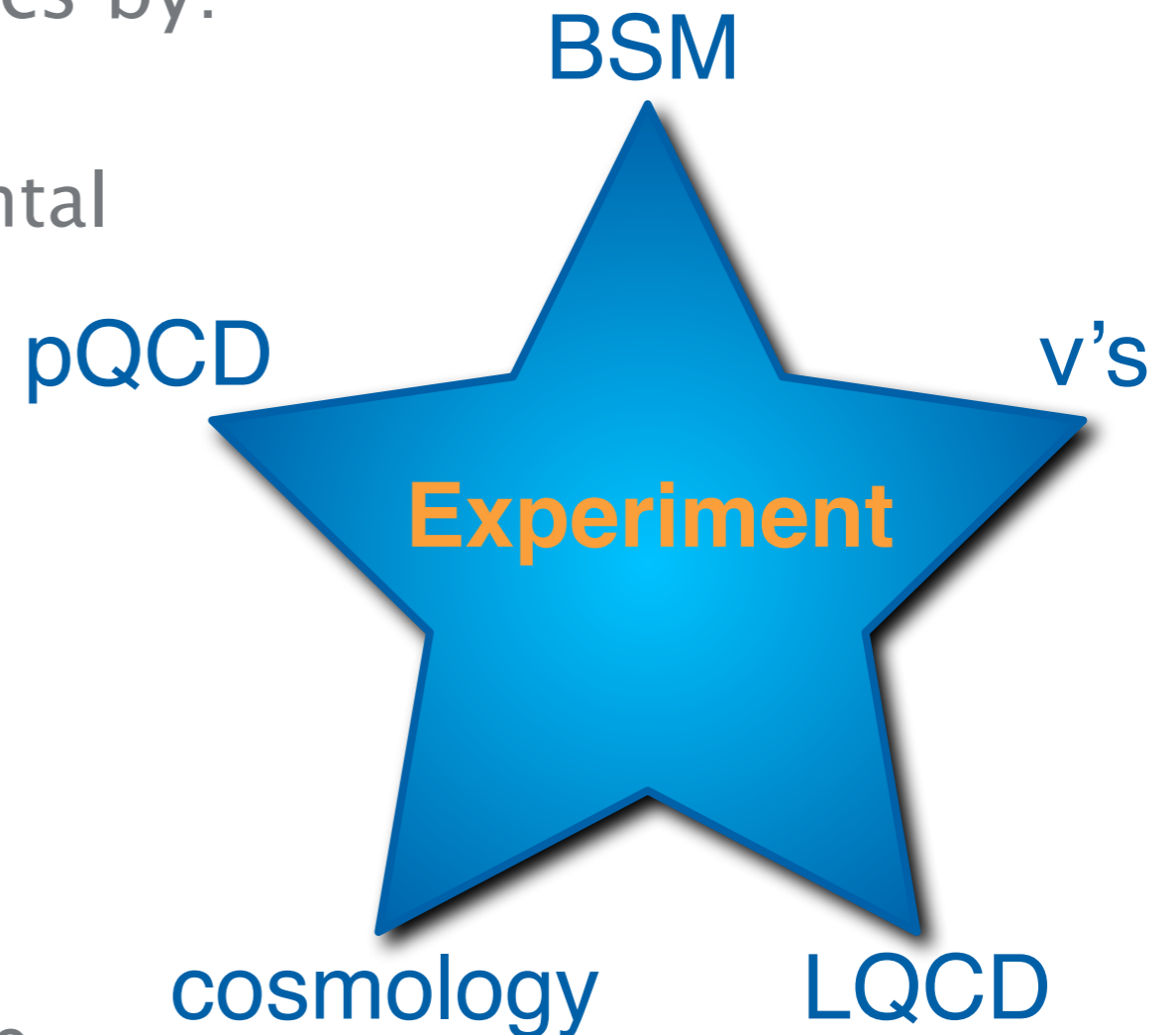
★ Received URA Visiting Scholars' Award for this research in 2015, and DOE Office of Science Graduate Student Research Award to complete it in 2015–2016.

---

# Strategic vision

# Research vision

- Continue to support and guide Fermilab and worldwide experimental programs to search for new physics by:
  - Providing analytic formulae and numerical tools used in experimental analyses
  - Providing Standard-Model and new-physics predictions
  - Devising new models and search strategies
  - Interpreting experimental data
- Diverse theory expertise enables important connections to be made between subfields
- Close proximity to experiments vital!





# Theoretical Physics Staffing

## Current:

14.5 staff, 8→9 RAs,  
0.5 FTE guests/visitors

Expect ~3 retirements every 5 years  
for next 10 years

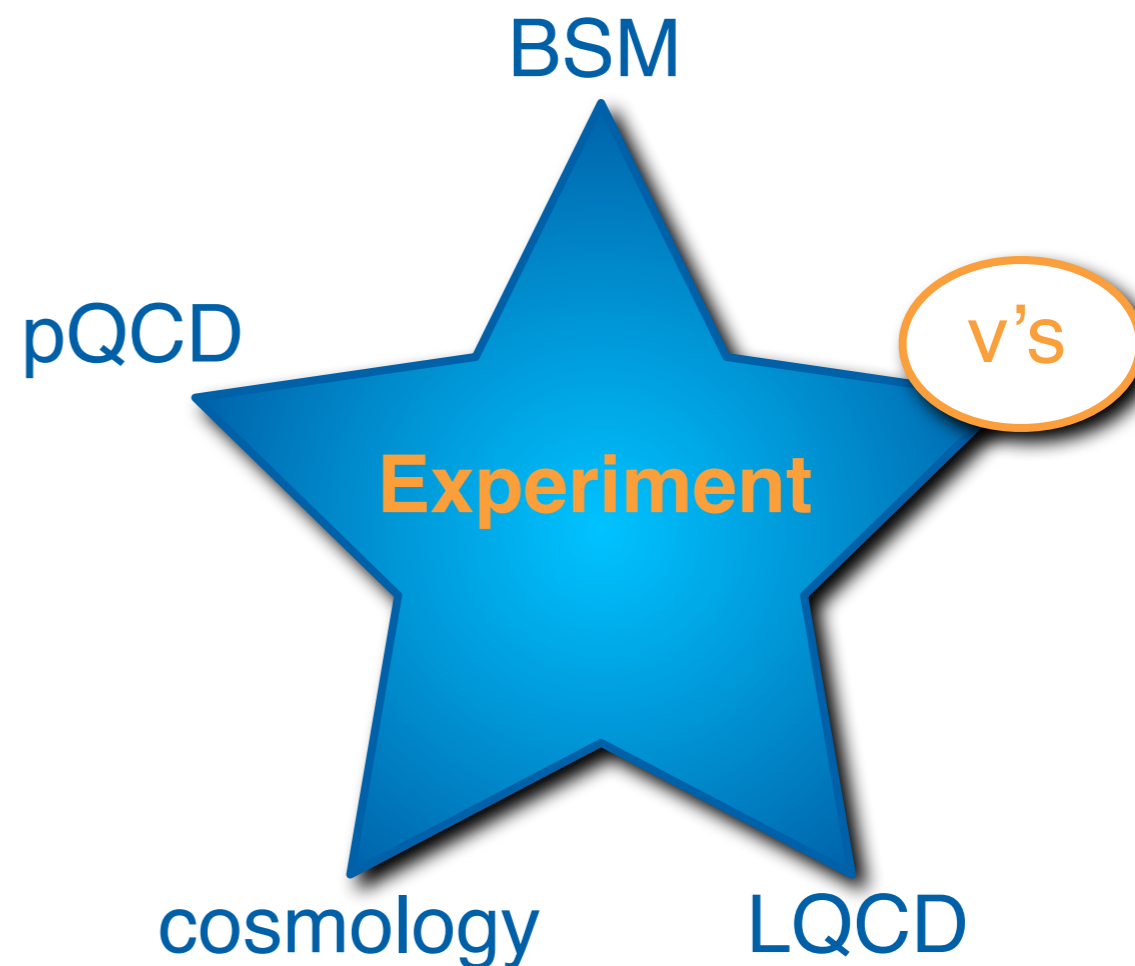
## Within 10 years:

~12 staff, ~12 RAs,  
~2 FTE guests/visitors

## Last Hires:

John Campbell (pQCD, 12/09), Paddy Fox (BSM, 3/07),  
Roni Harnik (BSM, 3/10), Ruth Van de Water (LQCD, 9/12)

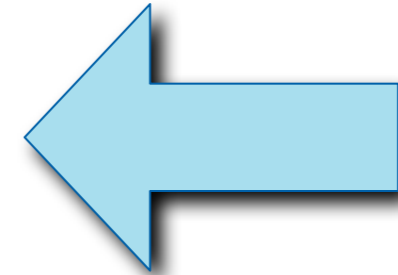
**Last Retirement:** Boris Kayser (neutrinos, 12/12)



# Neutrino Staff Hire(s)

---

- Would like to hire at least one additional junior Staff Scientist whose primary interest is neutrino physics
- What kind of neutrino theorist(s)?
  - Neutrino model building
  - Broad phenomenologist (vSM & beyond vSM)
  - Supernova phenomenologist
  - Nuclear theorist for  $\nu$ -nucleus cross sections



Must be an exceptional physicist  
and be able to talk to and interact with  
members of the Theoretical Physics Department  
AND  
the neutrino experimentalists!

# Neutrino Physics Center

---

- Fermilab theorists engaged with the LHC Physics Center in numerous ways including:
  - Co-organize of LPC's Topic of the Week seminar.
  - Partial support for "Theorist of the Week"
  - Participate in LPC Physics Forum
  - Discussions and collaborations with LPC members & visitors

➡ Led to substantial contributions to wide range of CMS papers
- Look forward to similar relationship with Neutrino Physics Center
  - Joint seminars & visitors
  - Fruitful discussions & scientific collaborations
- Cross-fertilization of neutrino phenomenologists, nuclear theorists, lattice-QCD theorists, etc., will be essential for progress on understanding neutrino scattering cross sections

# Neutrino Physics Summer School

---

- Fermilab theorists & experimentalists co-founded 1<sup>st</sup> Fermilab/KEK Neutrino Physics Summer School
  - Now combined with annual NuFACT workshop
- Fermilab theorists chair/organize joint CERN/Fermilab Hadron Collider Physics Summer School:
  - Provides training in theoretical and experimental aspects and draws students from both areas
  - Alternates location between CERN & Fermilab
- **Want to bring and/or establish a regular Summer school on neutrino physics at Fermilab like the HPCSS**
  - Joint experiment–theory effort
  - Broad program covering all types of neutrino experiments (oscillation,  $0\nu\beta\beta$ , ...) and phenomenology ( $\nu$ SM, sterile  $\nu$ 's, cosmic constraints, ...)

# Summary

---

- **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, 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.

---

# Extra material

# Current Theoretical Physics Department G&V Program

---

- For **FY2014**, spent
  - ~\$50K on 39 visitors (9 Summer visitors)
  - ~\$23K on theory seminar speakers
  - ~\$12K on JETP seminar speakers
- Typical visitor costs are \$6K–\$7K per person–month

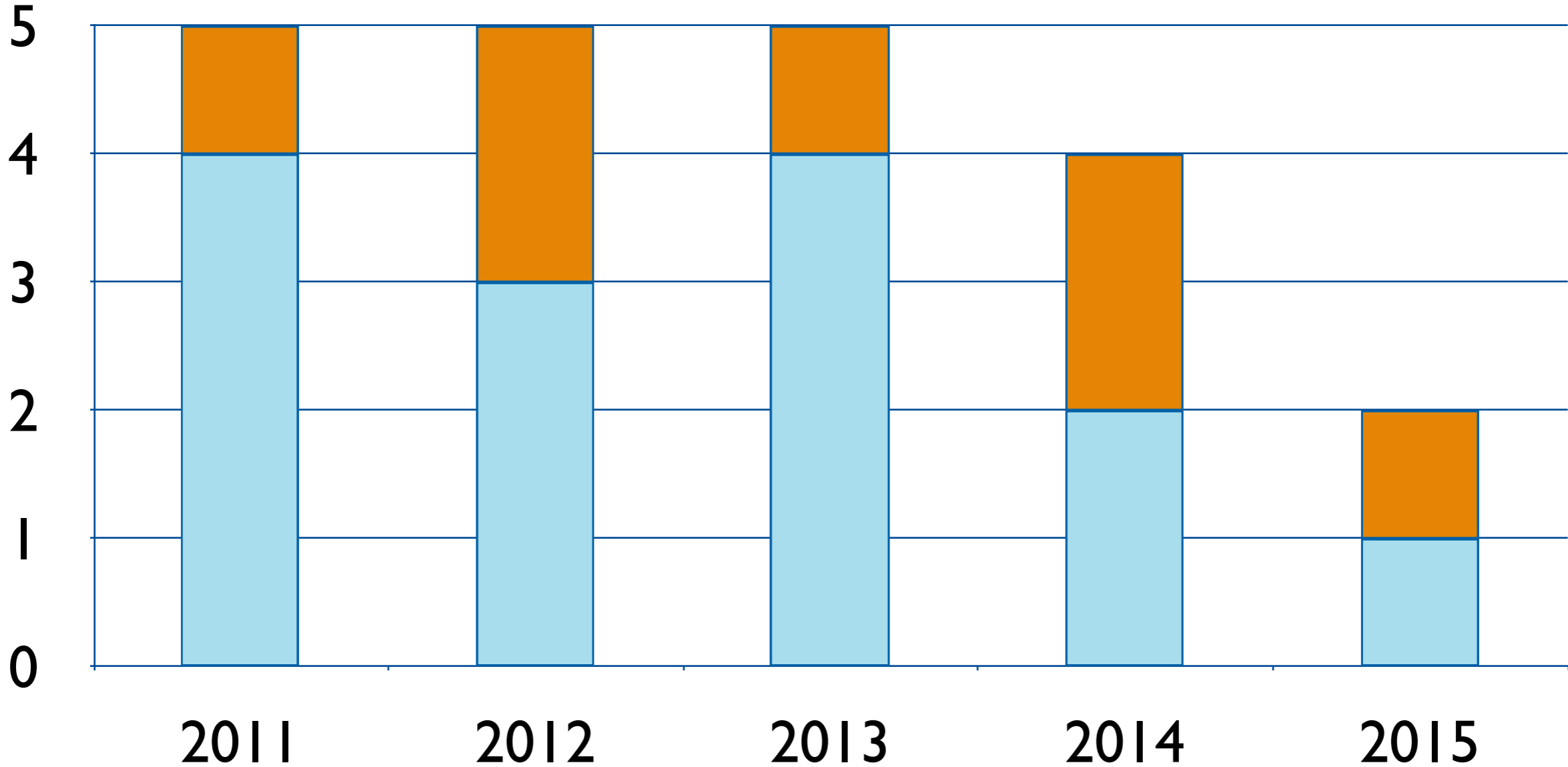
# New visitor program

---

- In addition to usual guest and visitor program, providing partial support to:
  - Nuclear theorists Luis Alvarez–Ruso & Joe Carlson
  - LPC “Theorist of the week”
- Planning significant addition to the current Theory Visitors’ programs involving multi–year commitment to come about one month per year
- Key goals of new program include:
  - Strengthening ties to university community
  - More transparency and inclusiveness
  - Details will be announced soon...



# Graduate Student Fellows



# Honors and awards

---

APS Fellows: 12 Particle / 4 Astro      AAAS Fellows: 6 / 1

American Academy of Arts and Sciences: Bardeen

Honorary Fellow Royal Astronomical Society: Frieman

Institute of Astrophysics of Paris Medal: 2014 Stebbins

J.J. Sakurai Prize:      2011 Eichten & Quigg

2009 Ellis

1996 Bardeen

National Academy of Science: Bardeen

Royal Society of London: Ellis

Alexander Von Humboldt Foundation Senior Scientist: 2011–2015 Carena

2007–2011 Quigg

Hans Fischer Senior Fellowship at TUM–IAS: 2014–2017 Kronfeld

Simons Distinguished Scholar (KITP, UCSB): 2013 Carena