Fundamental Symmetries and Neutrinos

Status of Targeted Initiatives

Krishna Kumar
Stony Brook University

NSAC Meeting, Rockville, MD, June 2, 2017

This talk would not have been possible without a great deal of input from many Fundamental Symmetries and Neutrinos colleagues

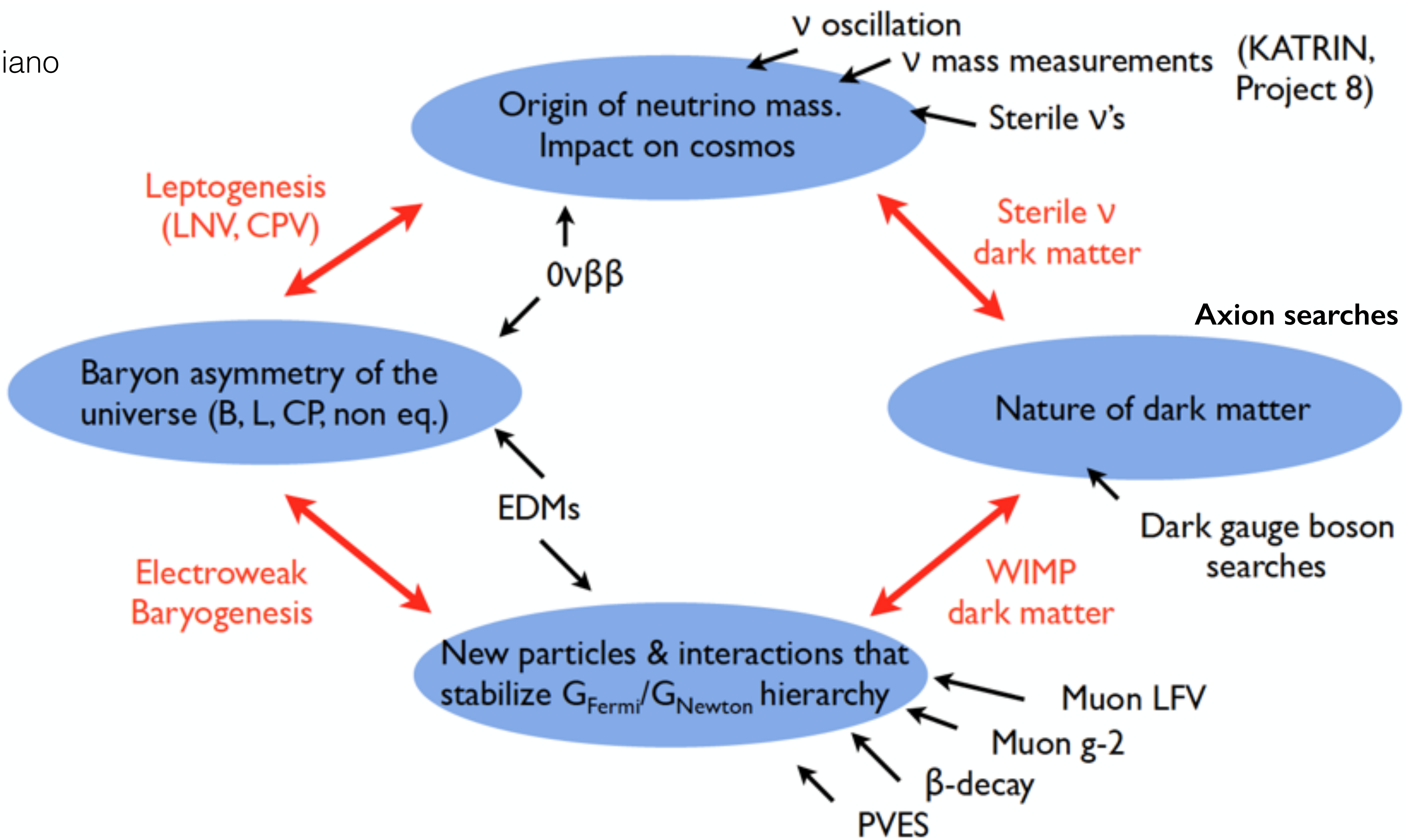
Tremendous activity level: will only hit high points on slides; strongly encourage looking them over later for full details!

Fundamental Symmetries in Nuclear Science

Connections to Big Questions

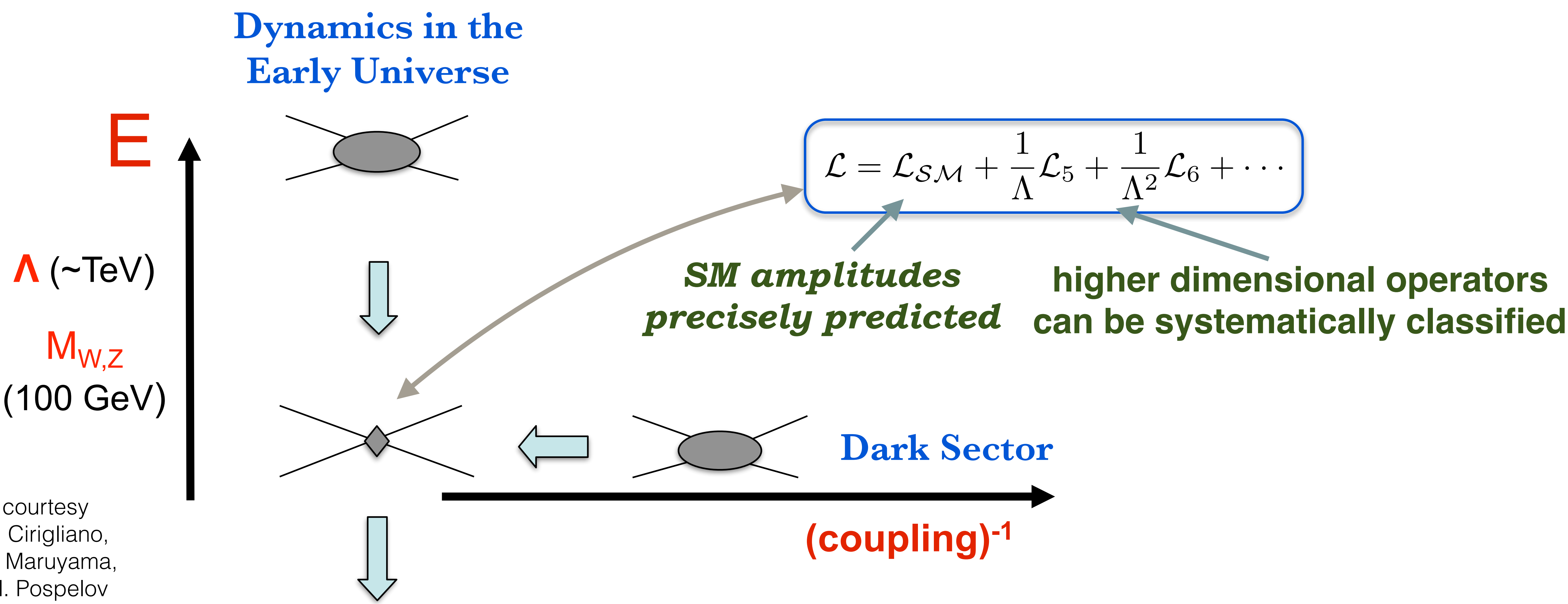
Nuclear Science Fundamental Symmetries experiments probe early universe dynamics often inaccessible in High Energy Physics and Astrophysics

V. Cirigliano



Fundamental Symmetries and Neutrinos

Observables at scales much lower than the scale of EW Symmetry Breaking



courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov
M. Ramsey-Musolf

Discoveries and Insights about Big Questions

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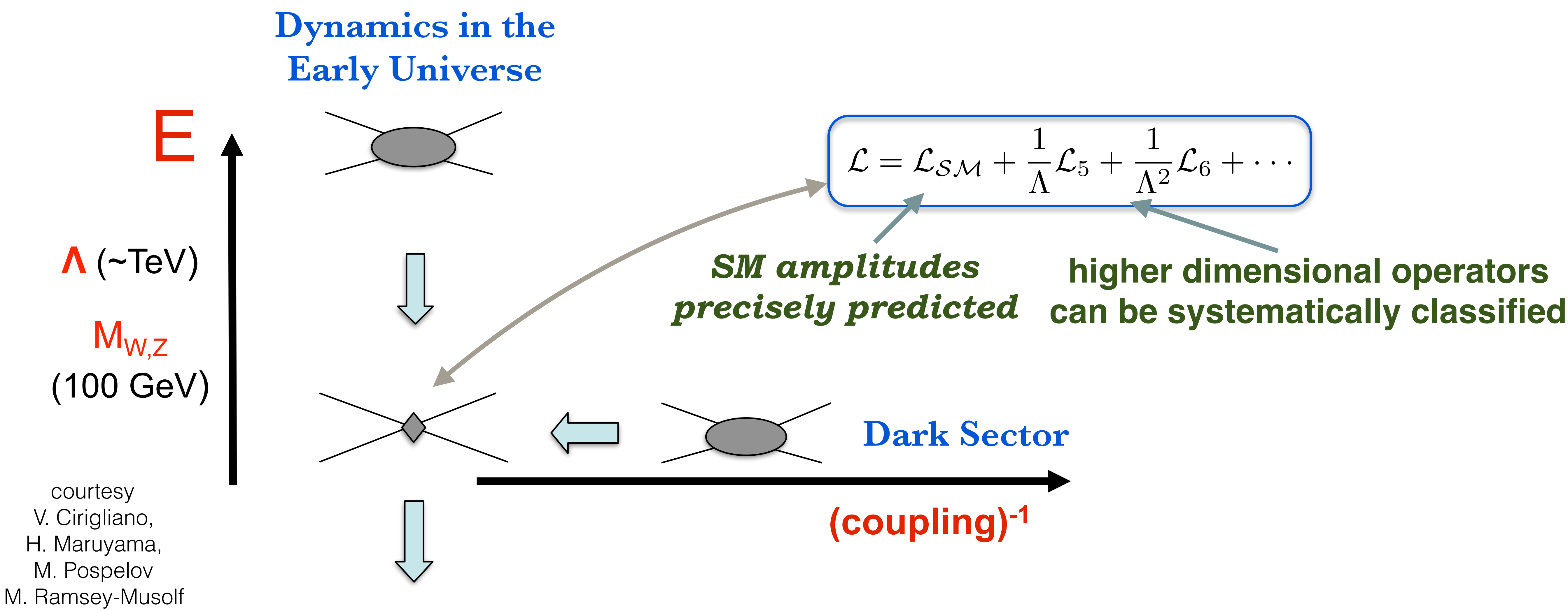

Discoveries and Insights about Big Questions

Measurements push several experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, resolution, precision, accuracy....

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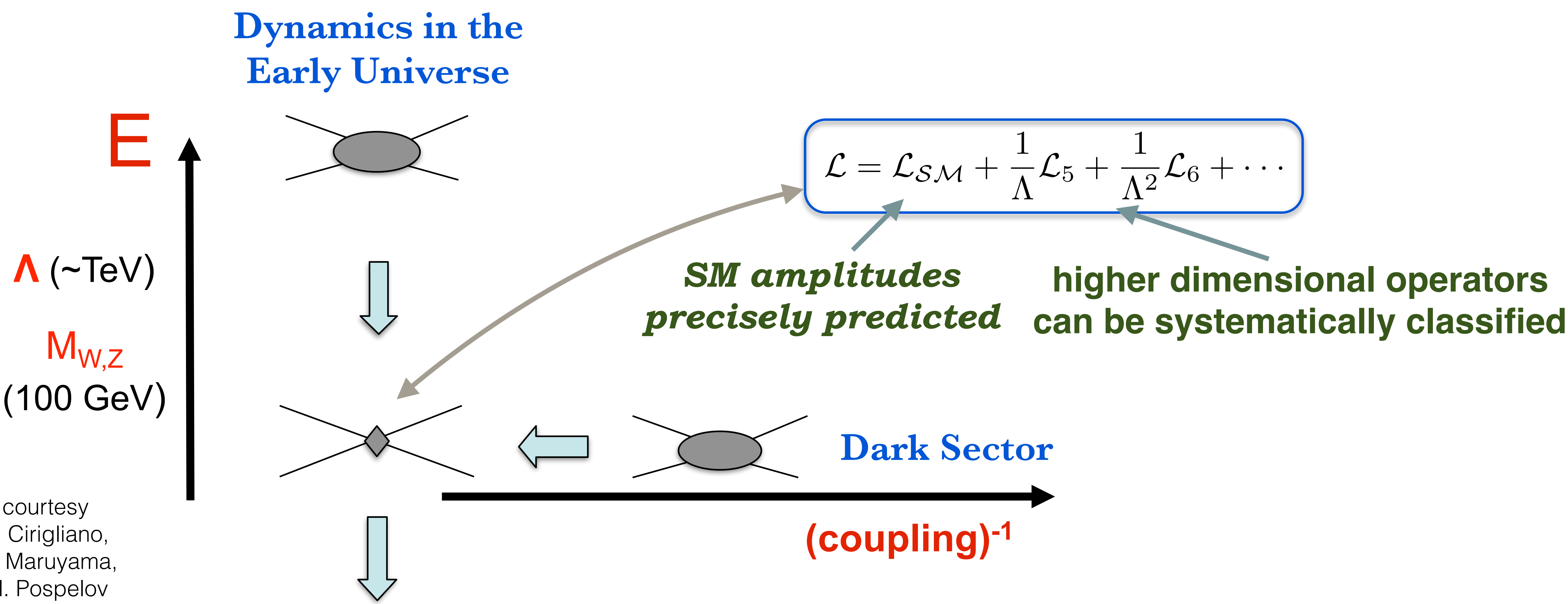

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Discoveries and Insights about Big Questions

Measurements push several experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, resolution, precision, accuracy....

In most cases, observables exploit a symmetry principle

Long Range Plan Context

RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

The targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model must be sustained.

Initiative for Detector Development

We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC.

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We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

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5. Fundamental Symmetries and Neutrinos

THE QUEST TO UNDERSTAND THE NATURE OF NEUTRINOS

- **Neutrinoless Double Beta Decay**
- **Neutrino Mass, Mixing, and Other Puzzles**

FURTHER PROBES OF THE NEW STANDARD MODEL

- **Precision Muon Physics**
- **Precision Neutron and Nuclear Decays**
- **Parity Violating Electron Scattering**
- **Hadronic Parity Violation**
- **Dark Photons and Hidden Sectors**

ELECTRIC DIPOLE MOMENTS

EXPERIMENTAL FACILITIES

THEORETICAL EFFORT

Neutrinoless Double Beta Decay ($0\nu\beta\beta$) and Lepton Number Violation (LNV)

Neutrinos have mass!

A conserved Lepton Number L defined by—

$L(\nu) = L(e^-) = -L(\bar{\nu}) = -L(e^+) = 1$ may not exist.

If it does not, then nothing distinguishes ν_i from $\bar{\nu}_i$

Are Neutrinos Their Own Anti-Particles?

(Dirac or Majorana?)

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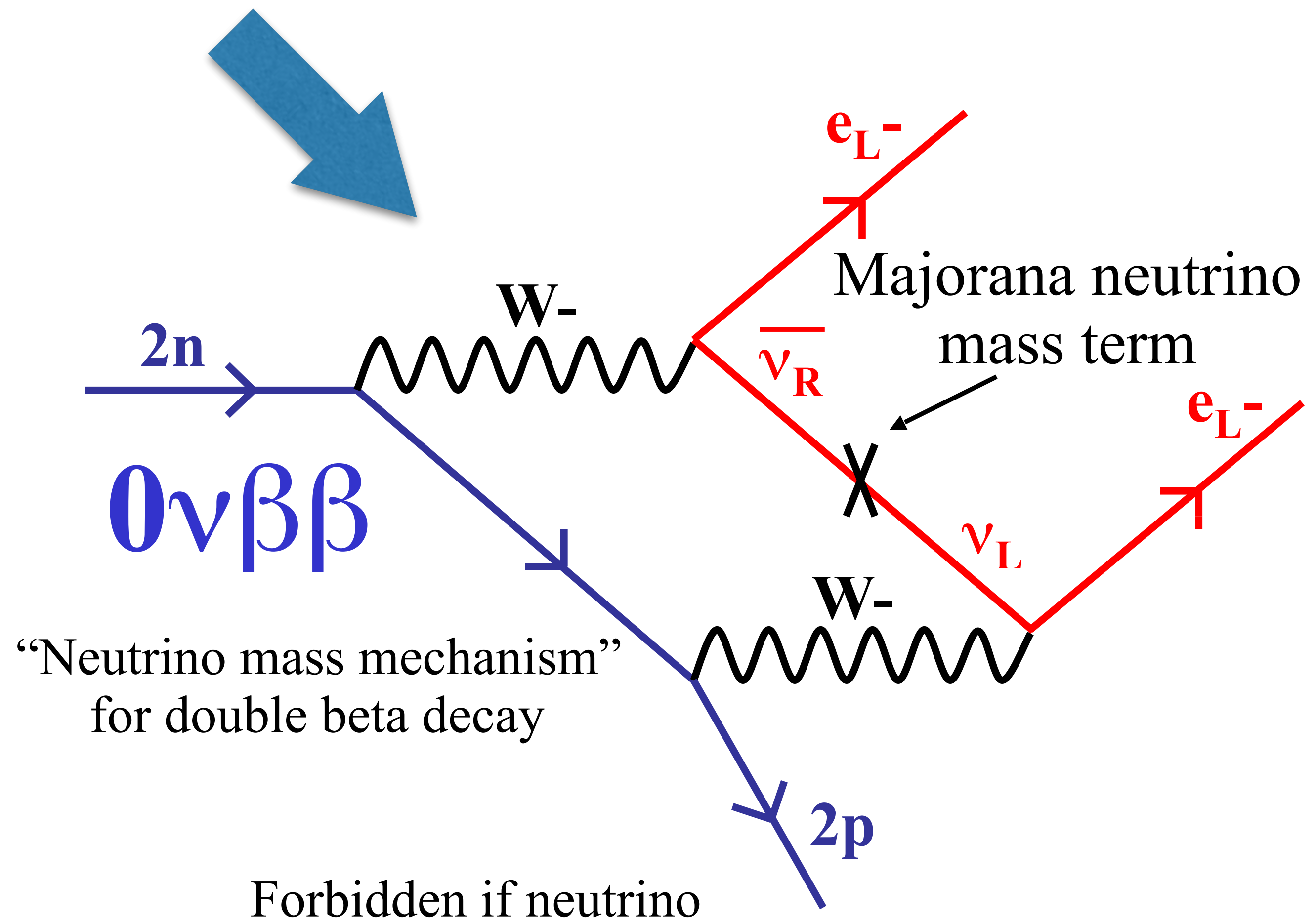

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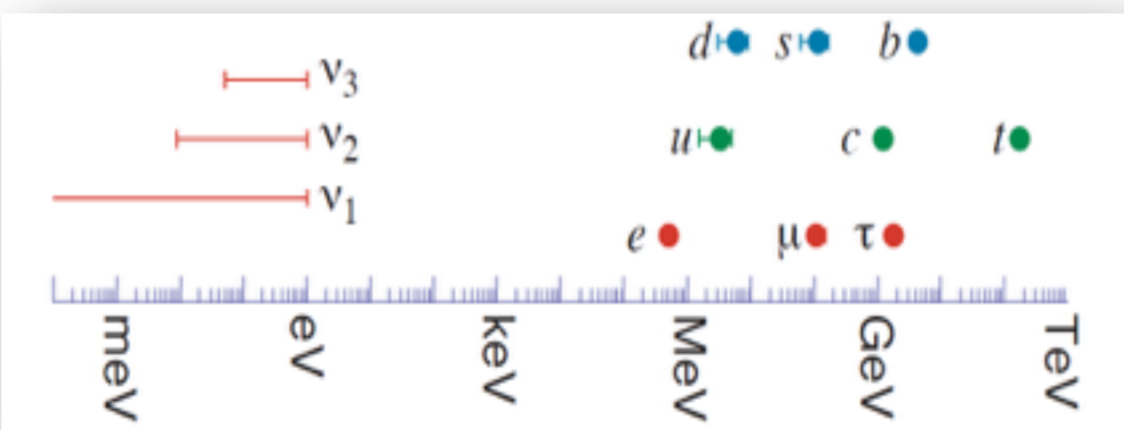
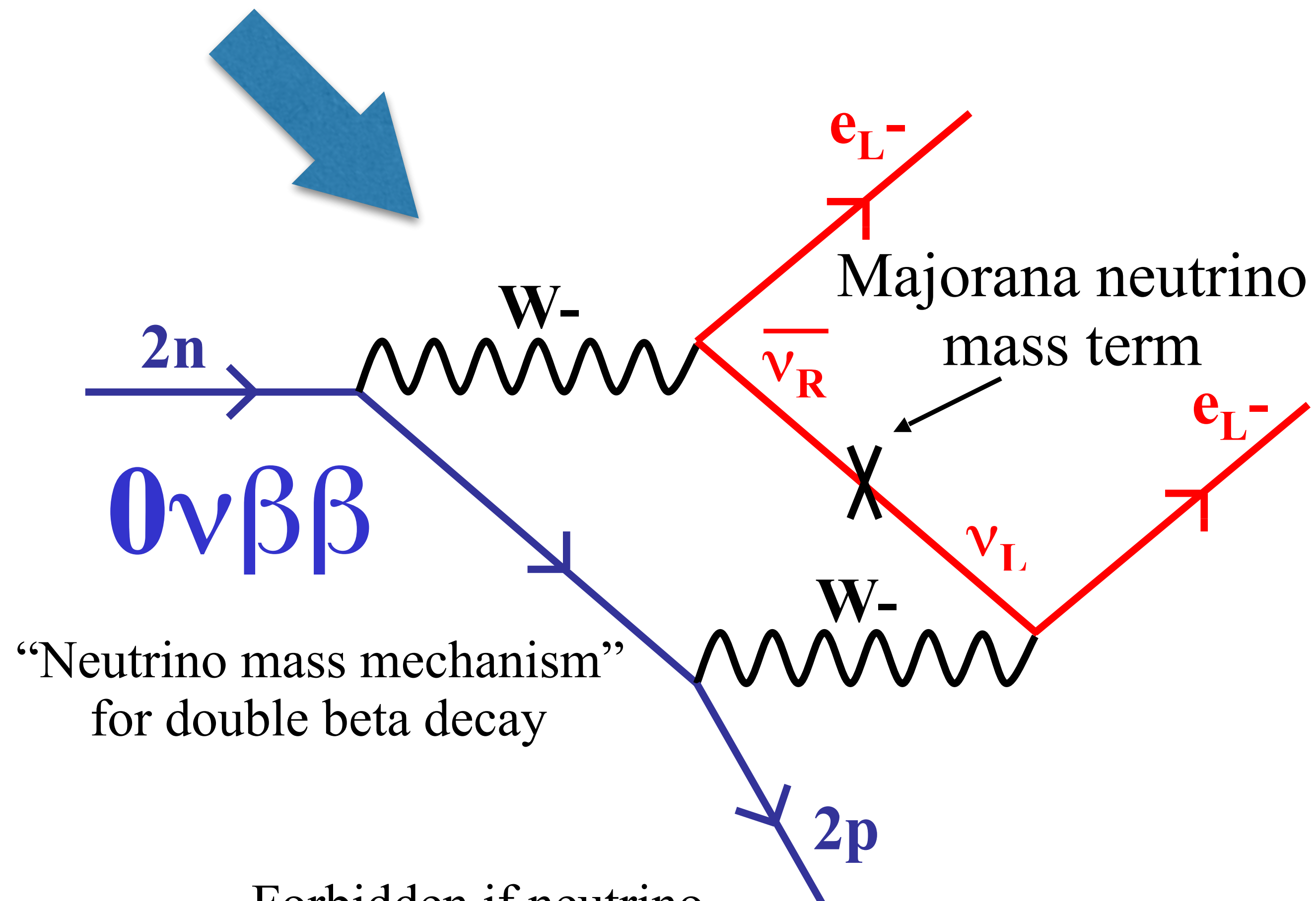


- **Higgs mechanism may not be the responsible for neutrino masses**
- **Leptogenesis might be responsible for the matter-antimatter asymmetry in the universe**



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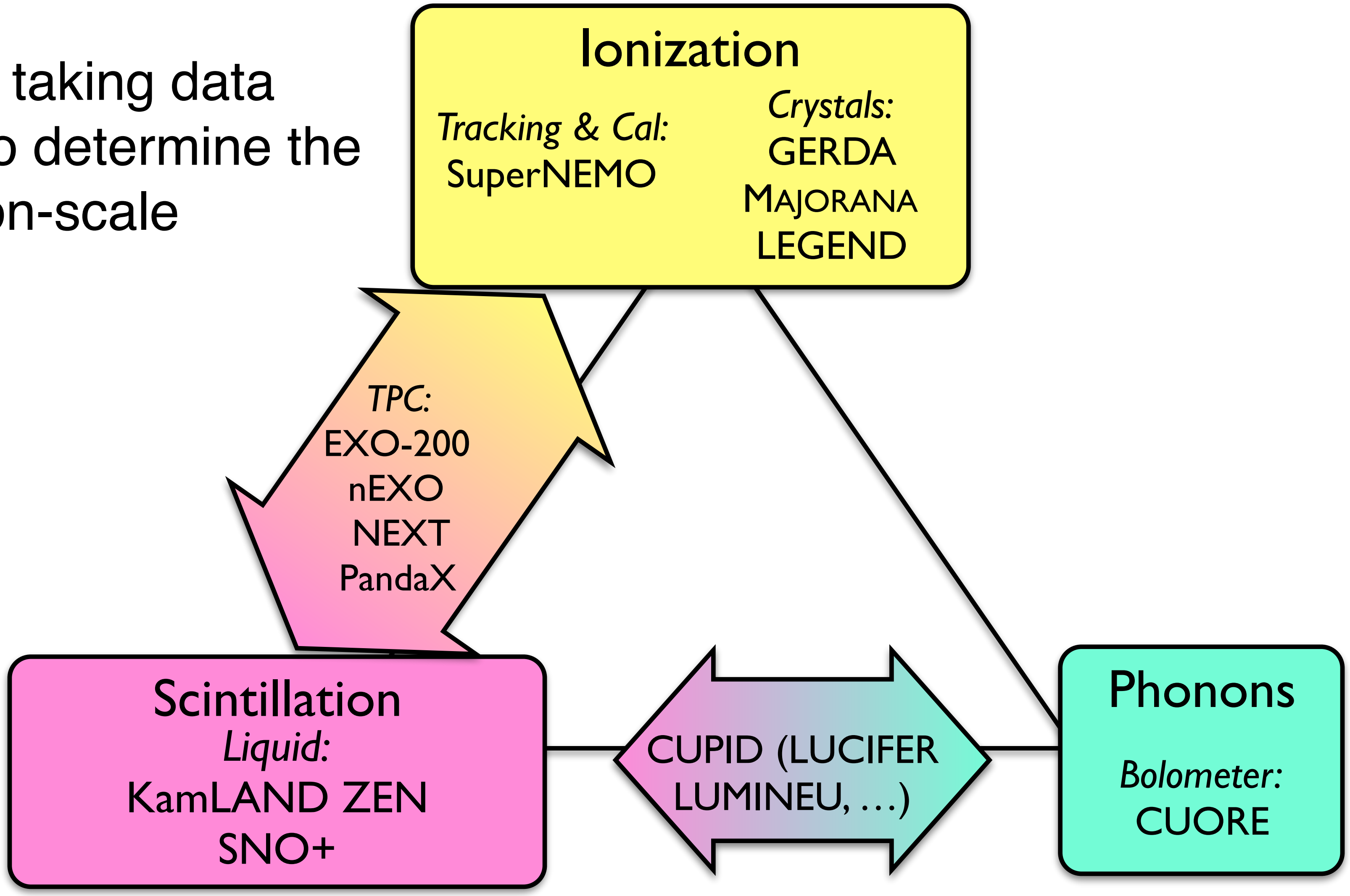
R&D Towards the Ton-Scale

US leadership sets up exploration of optimum paths to major discoveries

- 100 kg class experiments currently taking data
- In parallel, major R&D under way to determine the optimum path to discovery at the ton-scale



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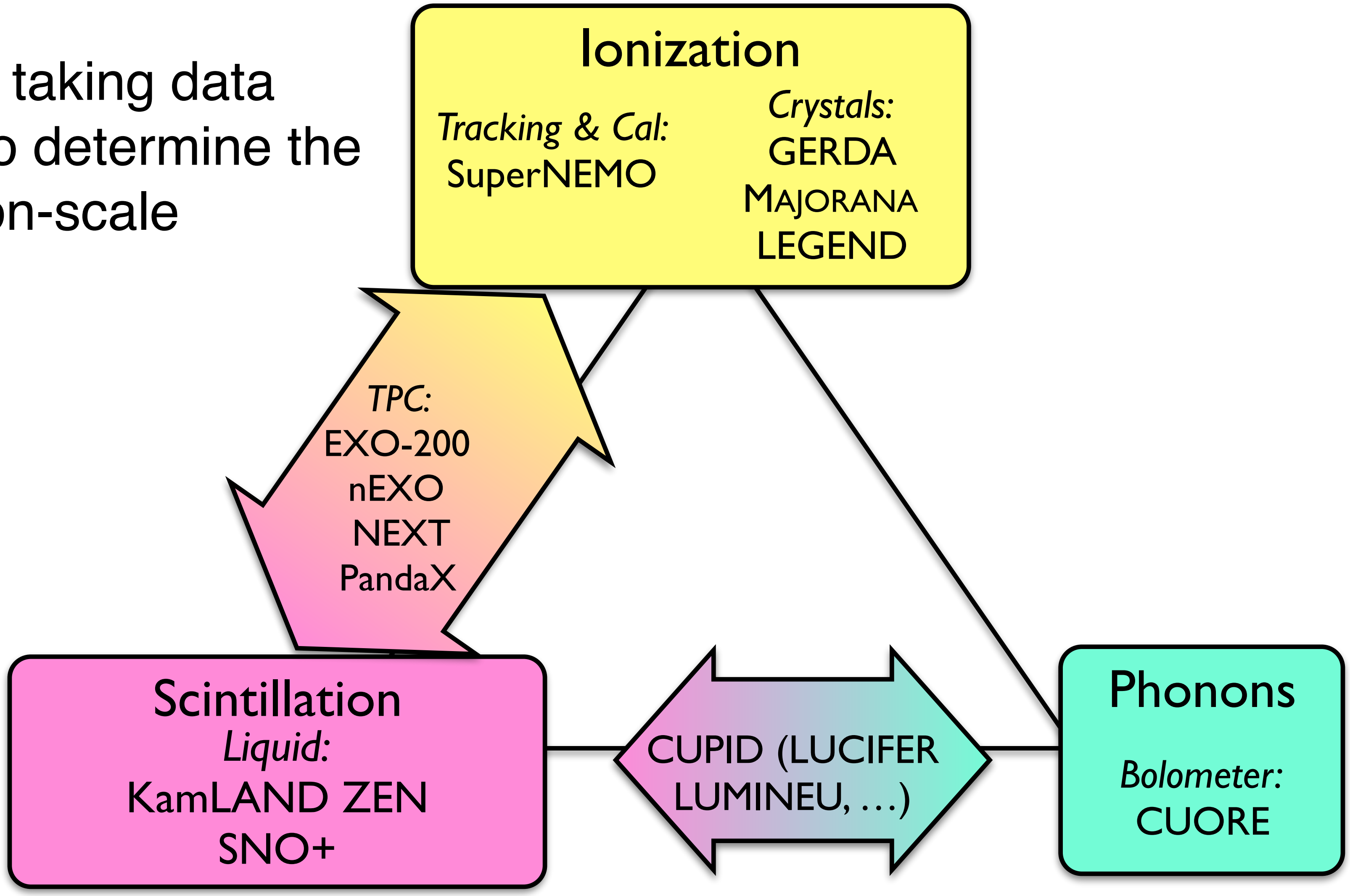

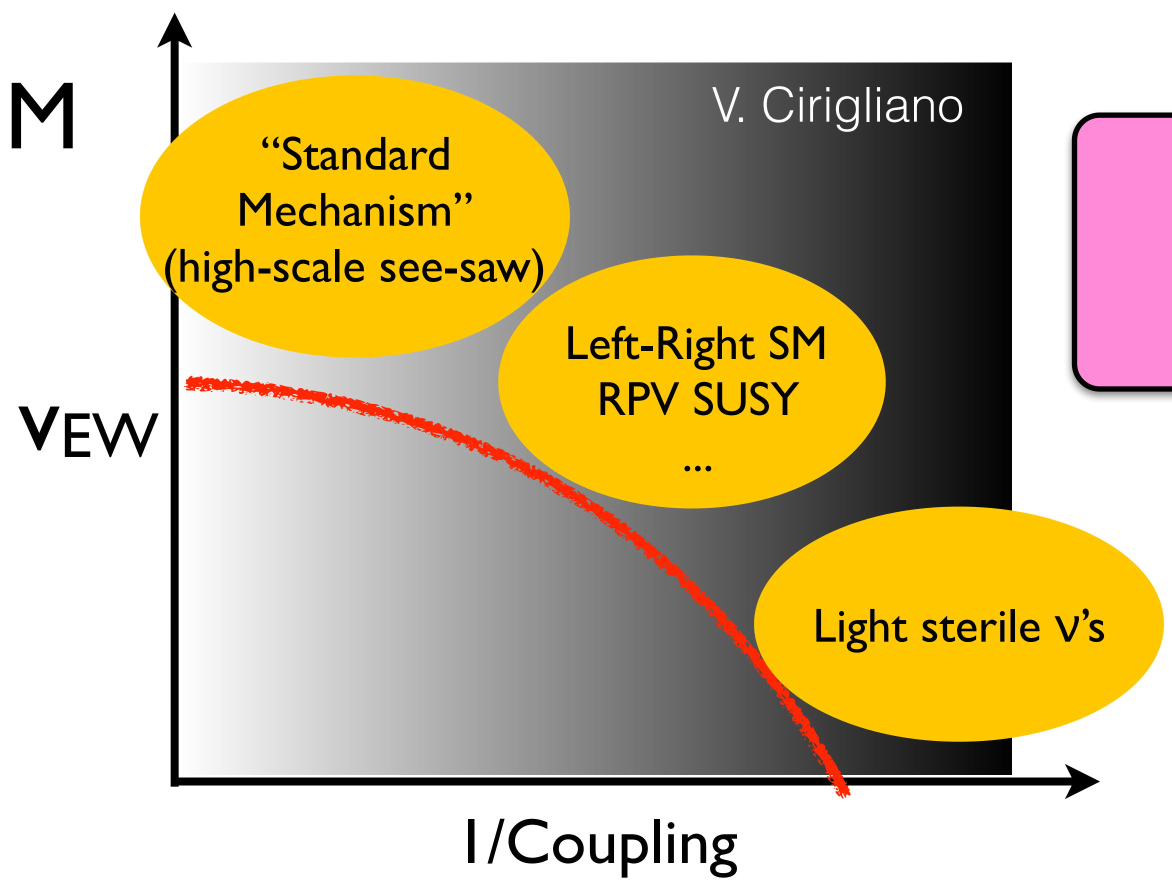

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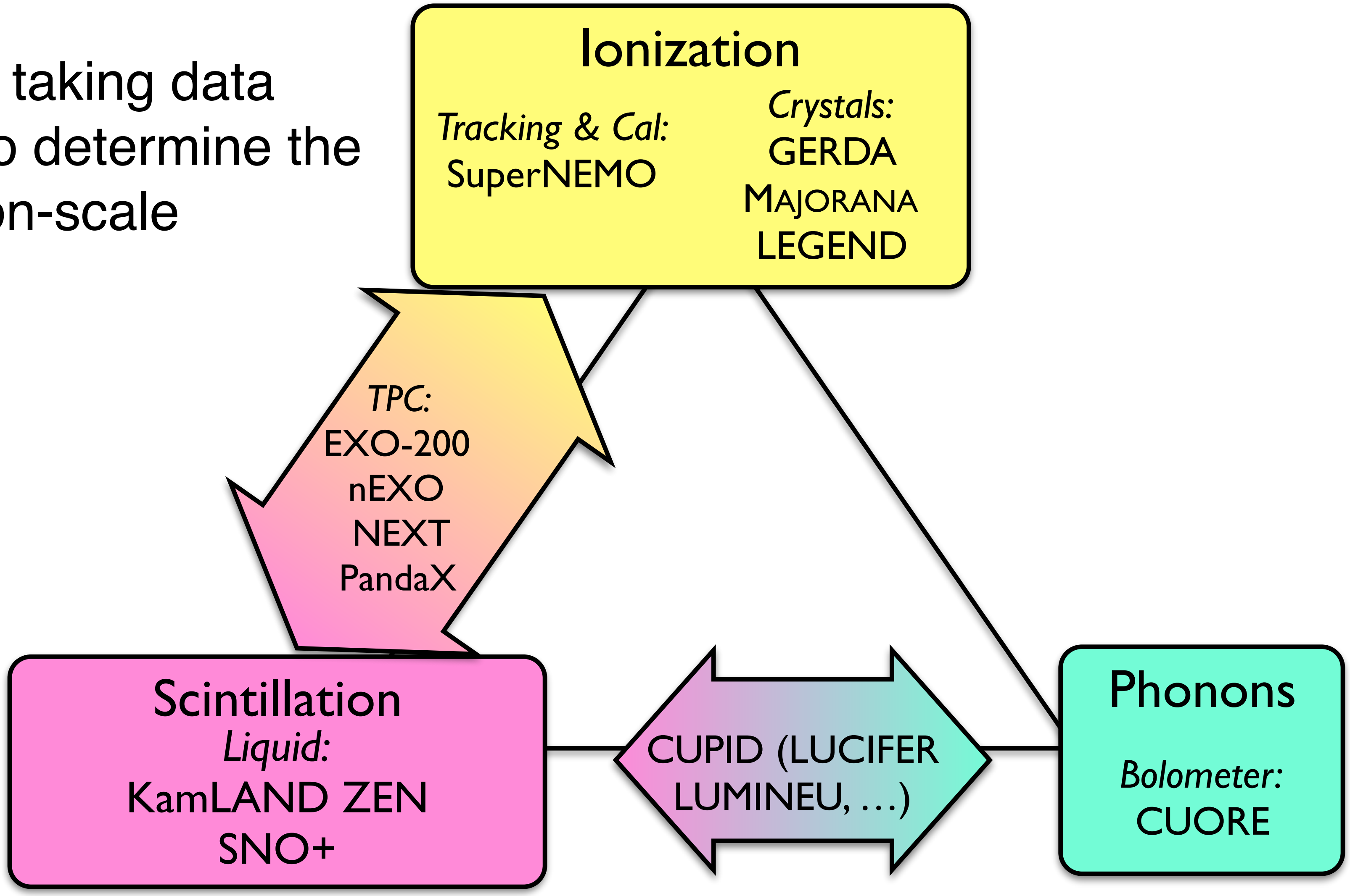

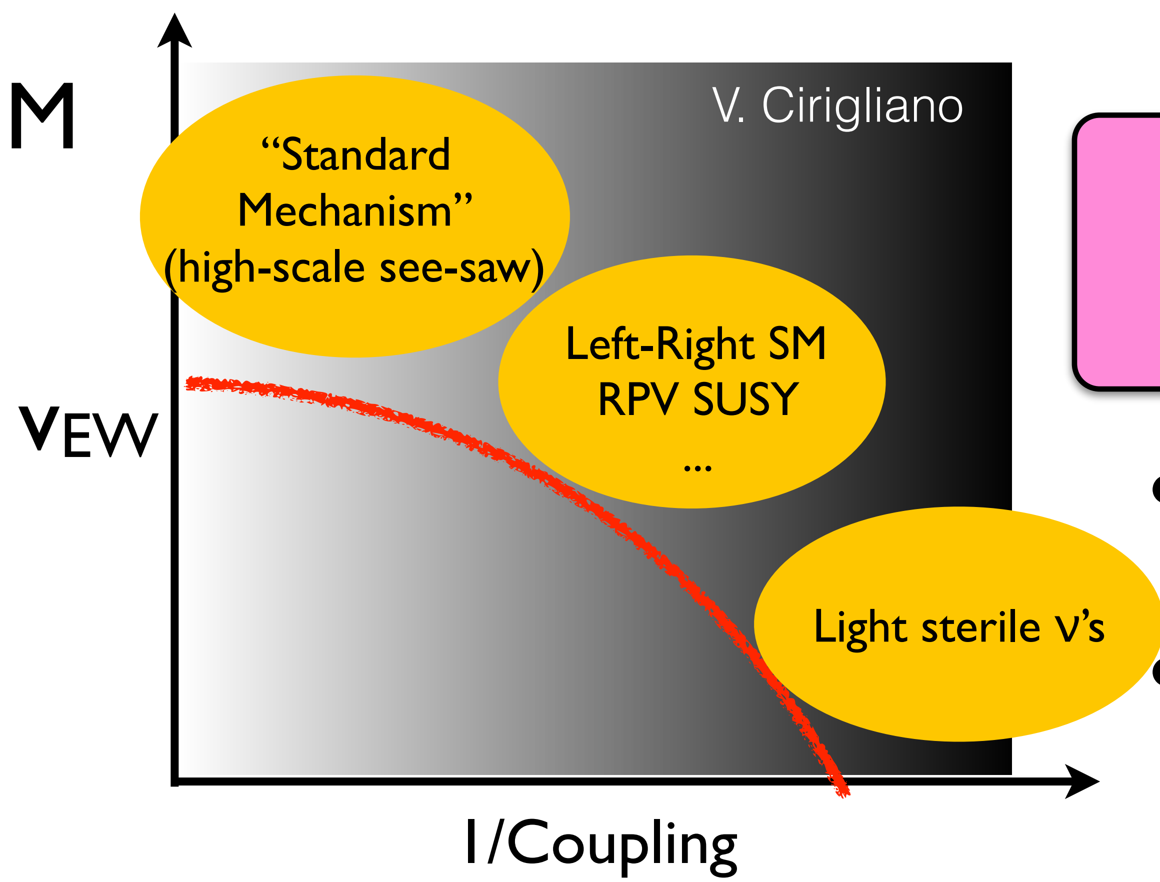

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms
- If light Majorana neutrinos are responsible for $0\nu\beta\beta$, then absolute neutrino mass scale determination within reach of ton-scale experiments

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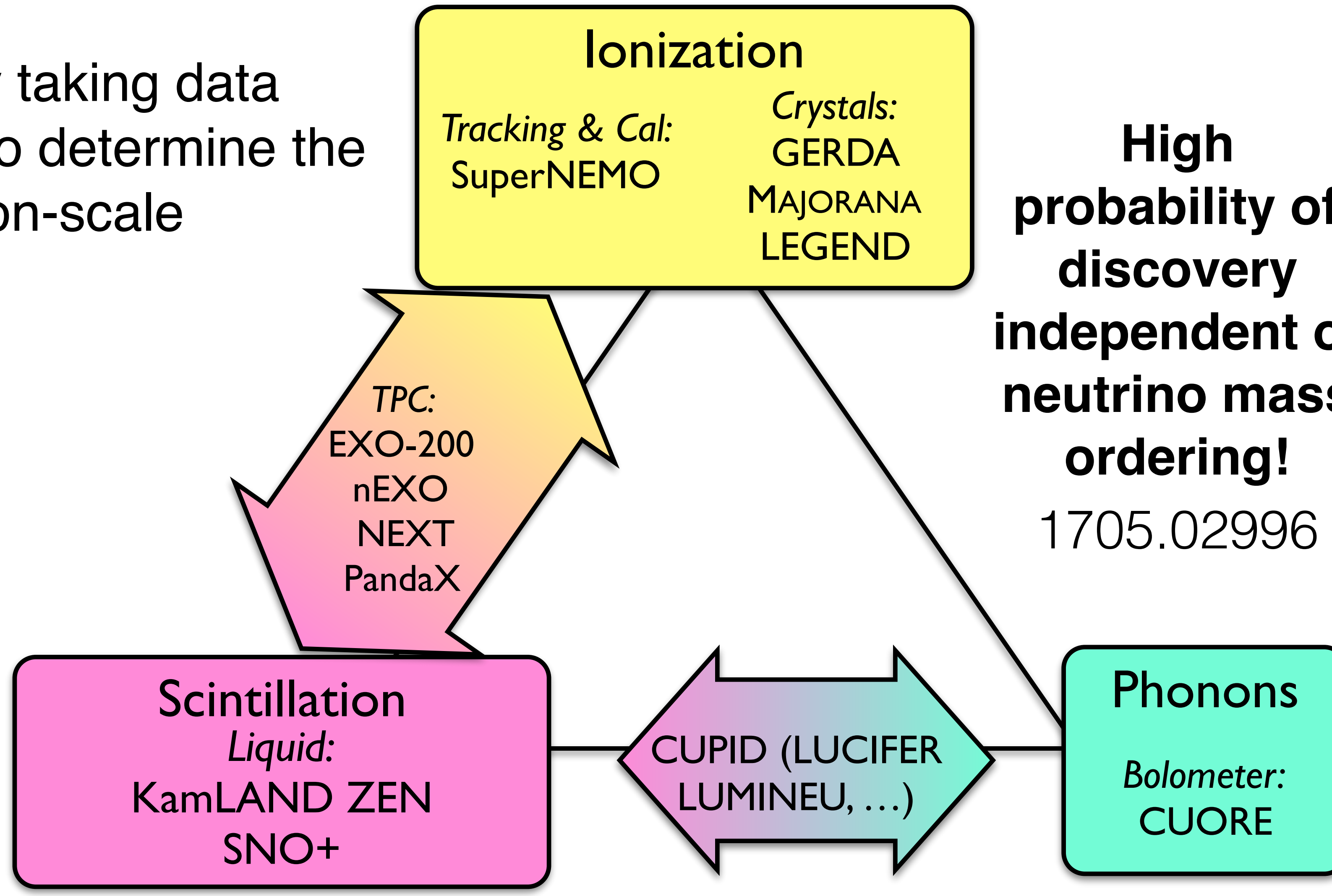
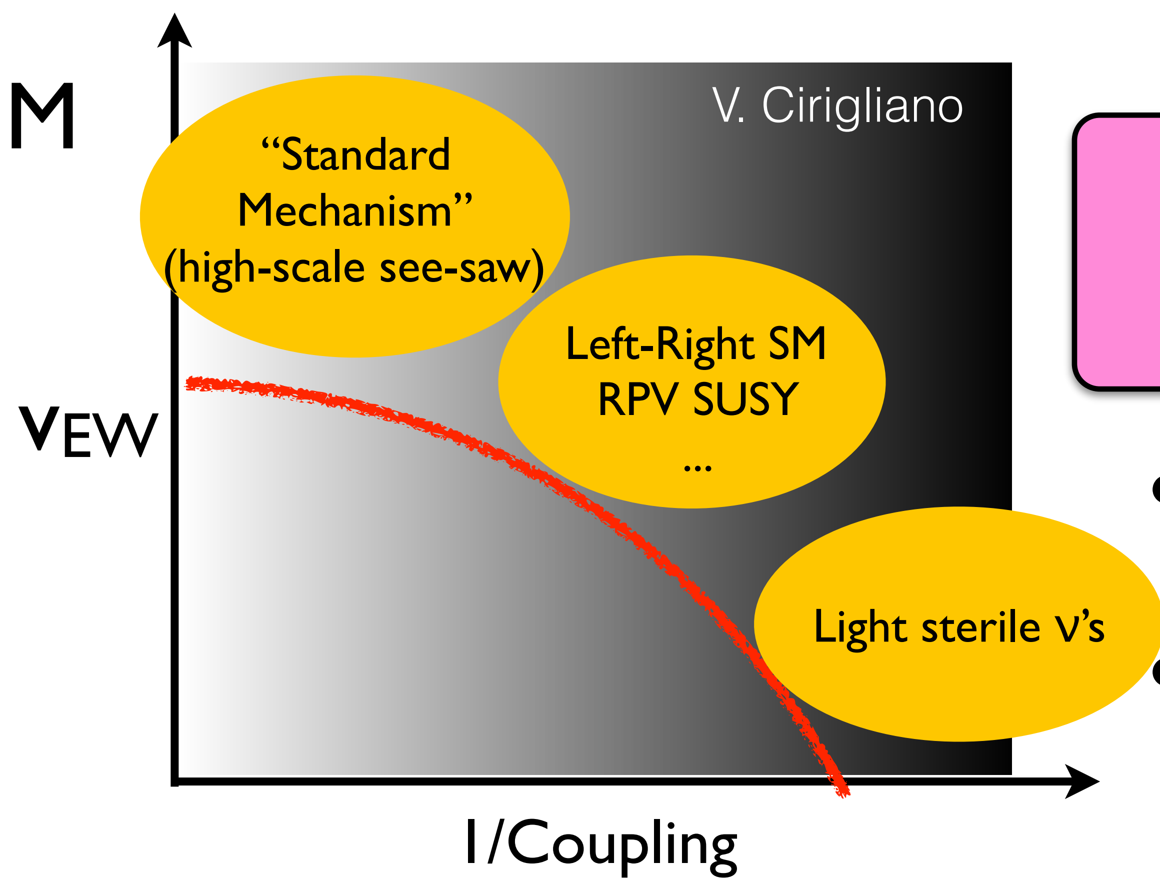


High probability of discovery independent of neutrino mass ordering!

1705.02996



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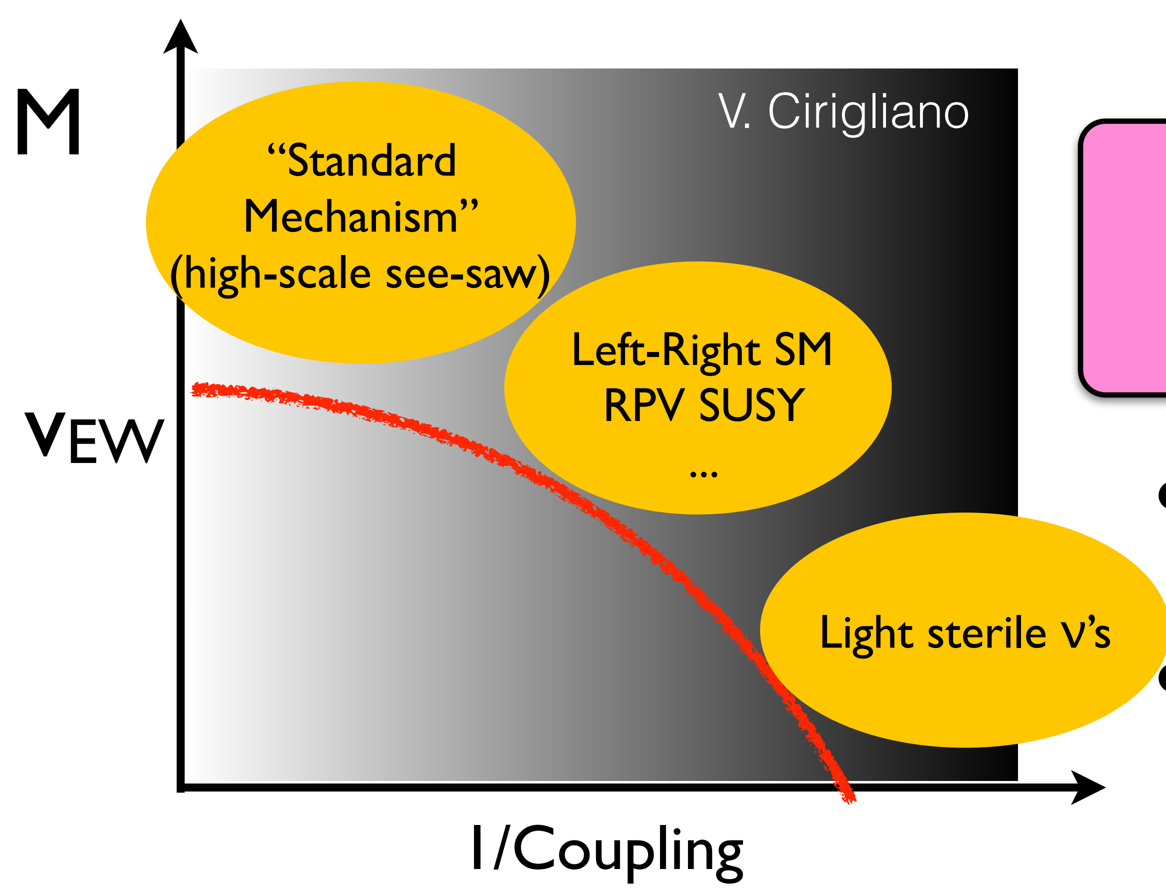
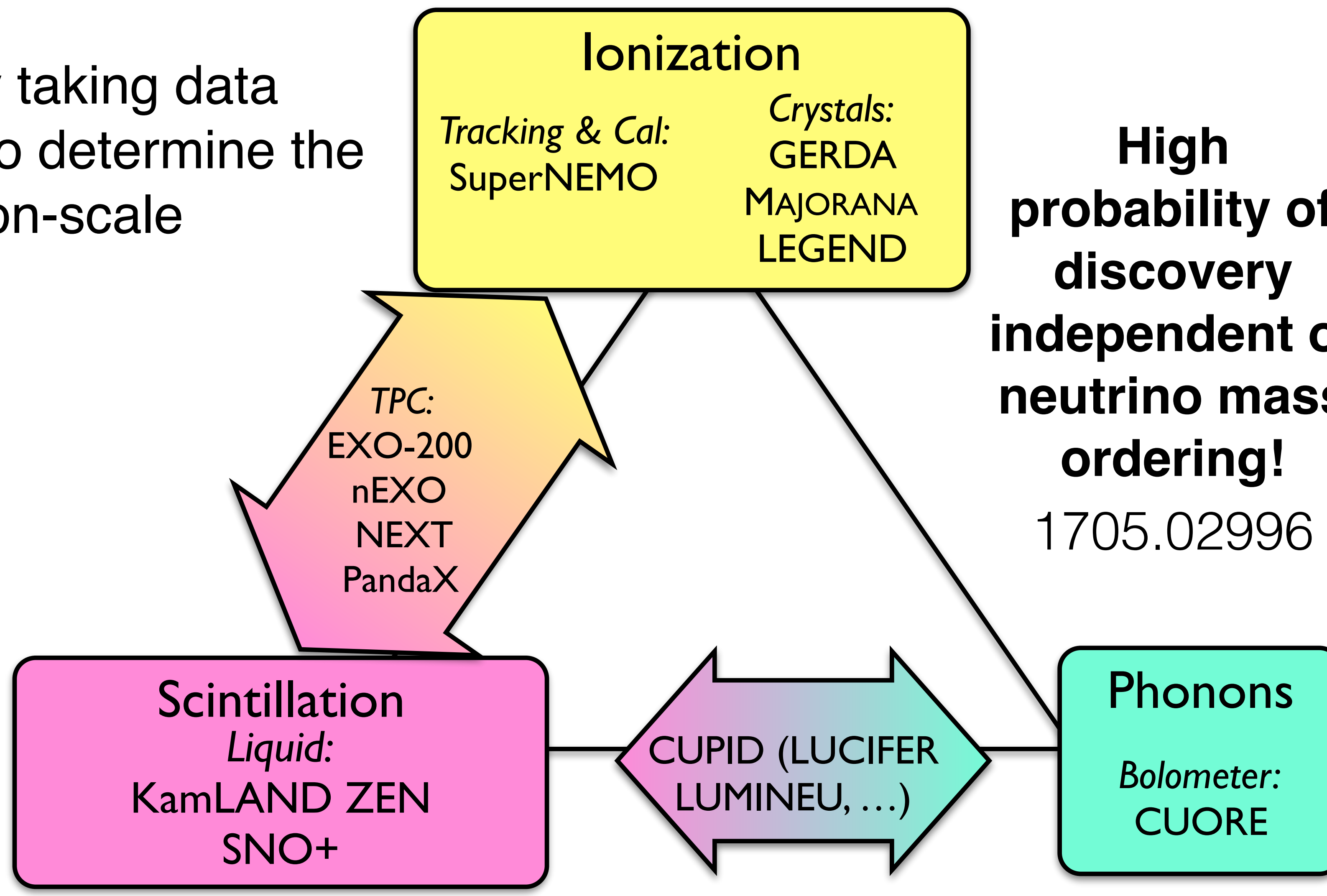
^{76}Ge, ^{130}Te, ^{136}Xe





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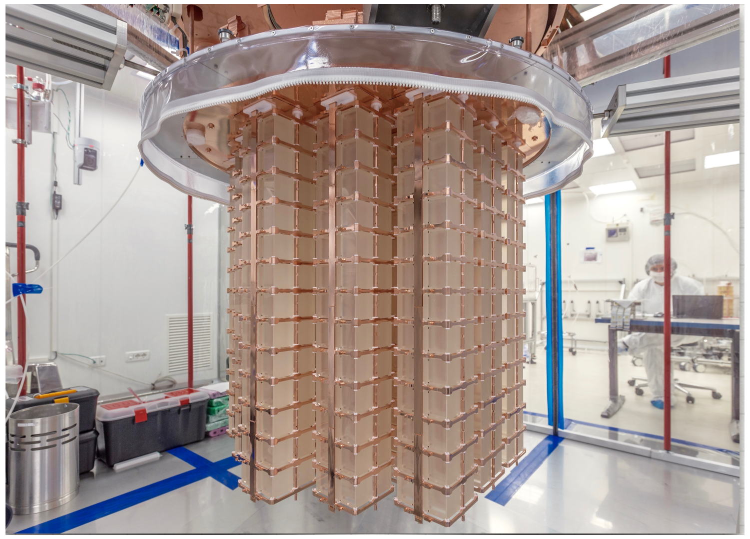
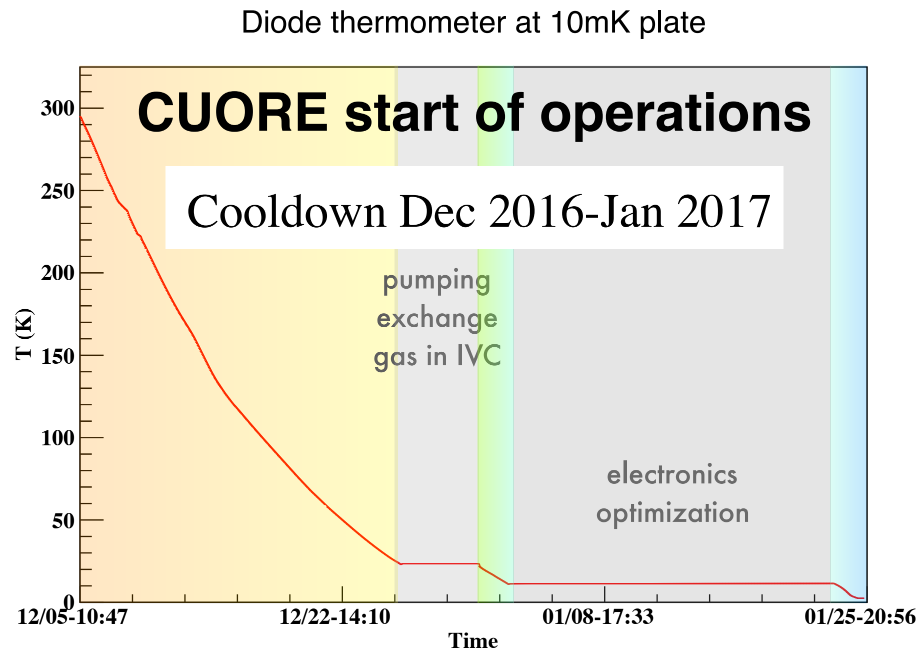
^{130}Te CUORE/CUPID

CUORE detectors installed





- CUORE Milestones:
  - Tower installation: Jul-Aug 2016
  - Cryostat closeout: Nov 2016
  - Cooldown: Dec-Jan 2016
  - Commissioning and initial performance optimization: Jan-May 2017
  - First science run: May 2017
- Cryostat performs very well: base T < 7 mK
- >95% of detectors operational
- First data to be reported in Summer 2017

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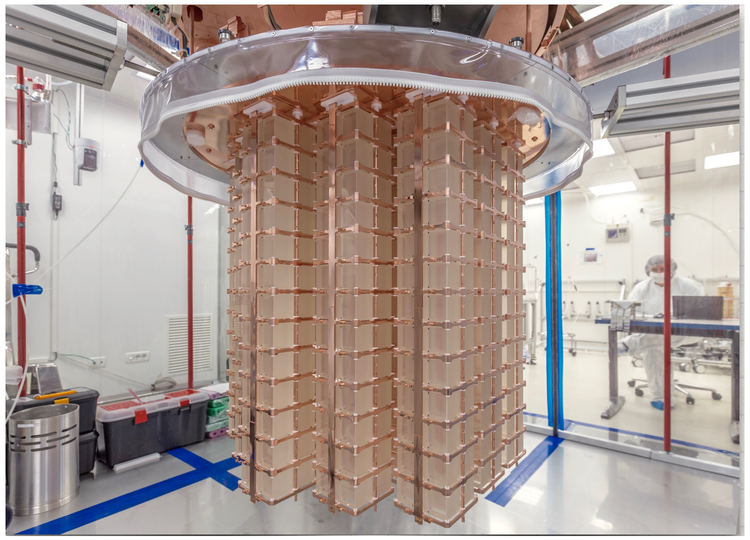

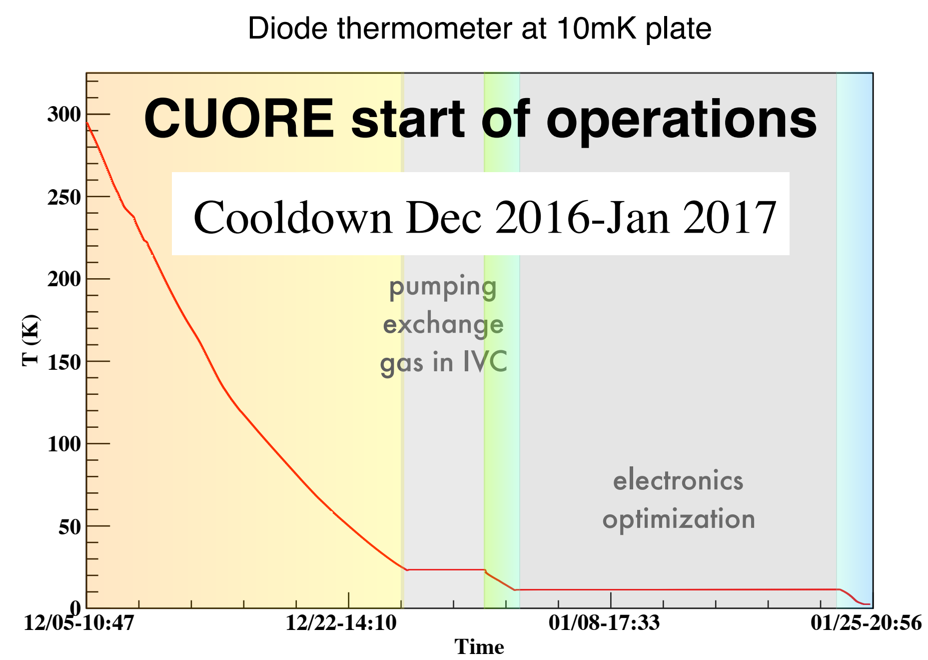

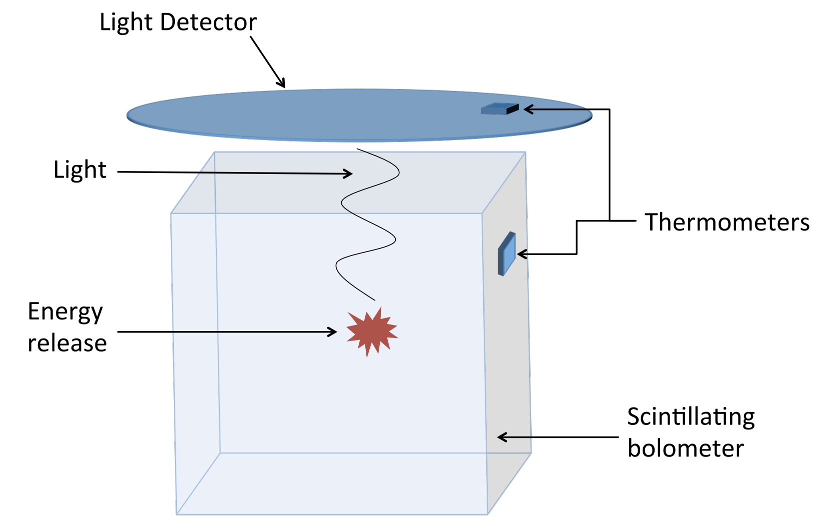

Next-generation bolometric tonne-scale experiment based on the CUORE design, proven CUORE cryogenics

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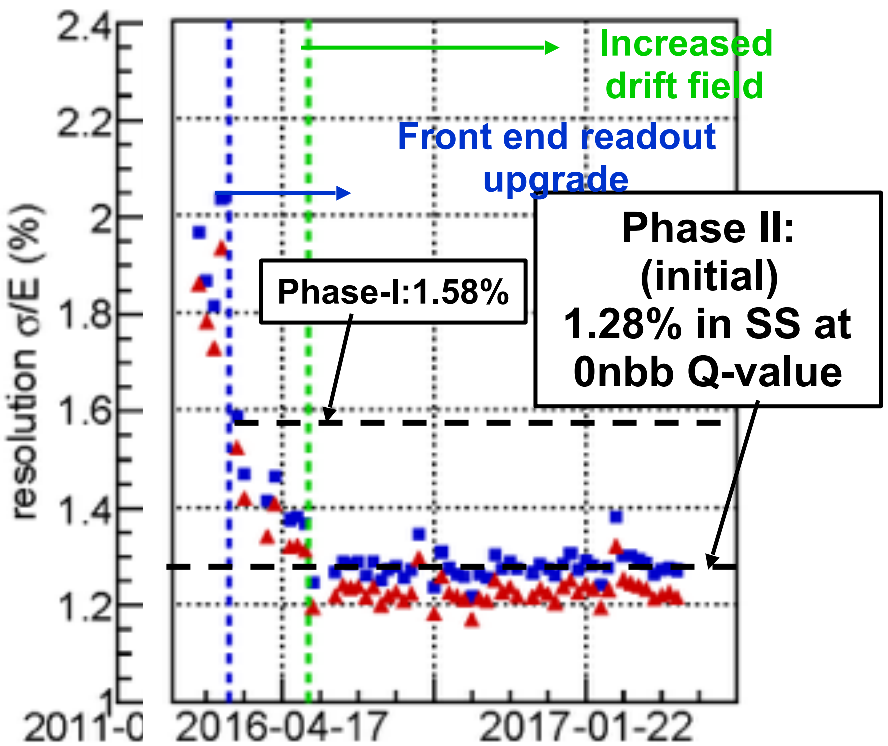
- Intense CUPID R&D effort in the next 2-3 years
  - ☞ US focus: $^{130}TeO_2$ enrichment and purification, high-resolution sensors for Cherenkov light
  - ☞ Complementary European efforts
  - ☞ Background goal is 0.1 cts/ROI-t-yr; achieve sensitivity to the full Inverted Hierarchy
  - ☞ Other important R&D: detailed background analysis, cosmogenic backgrounds @ LNGS — to be addressed before downselect
  - ☞ Worldwide efforts: 8 countries, 32 institutions
  - ☞ Data from CUORE and pilot detectors will drive technology and isotope choice

EXO-200/nEXO ^{136}Xe

EXO-200 Phase II Upgrade Performance
(Front End Readout Upgrade)



EXO-200/nEXO

^{136}Xe

nEXO: 31 institutions, 145 scientists

TPC/Cryostat Concept

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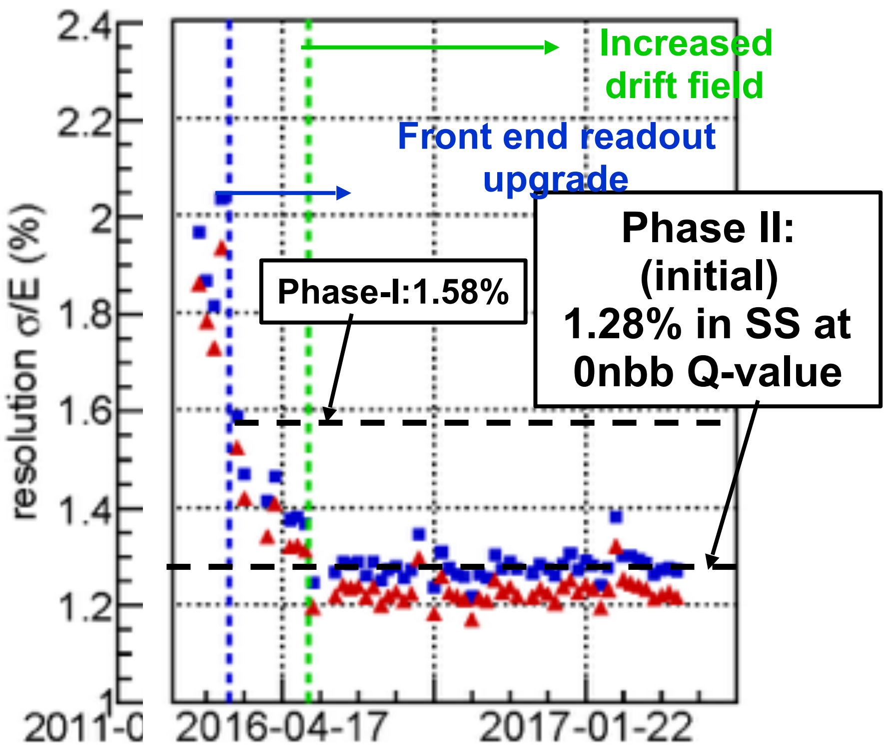

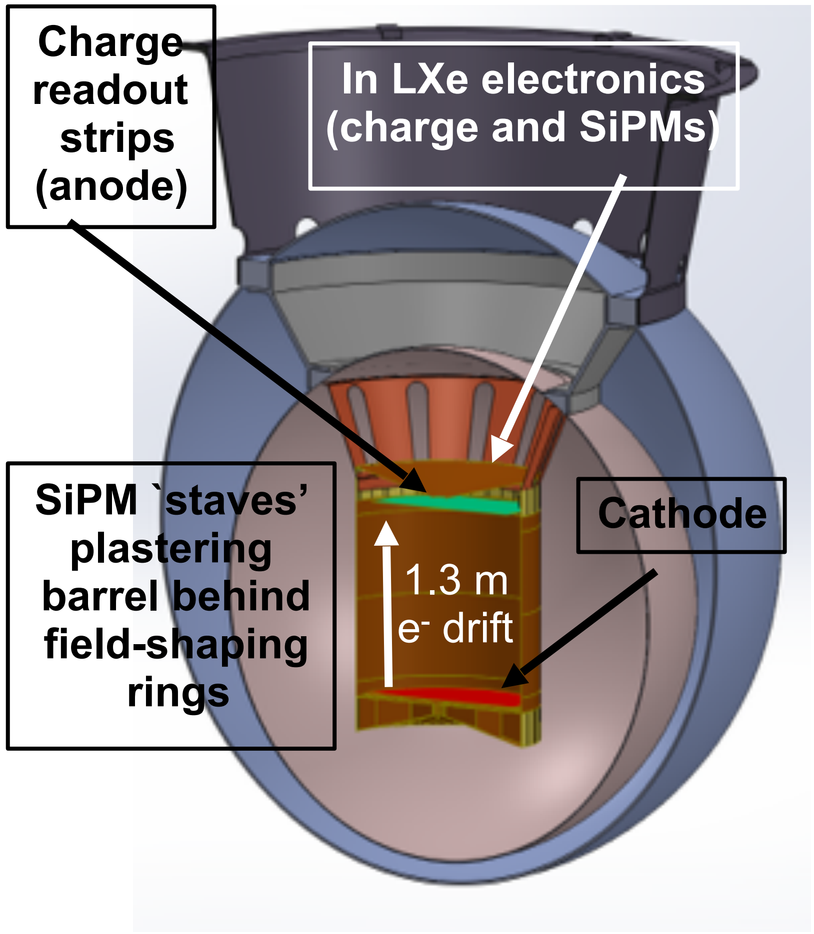

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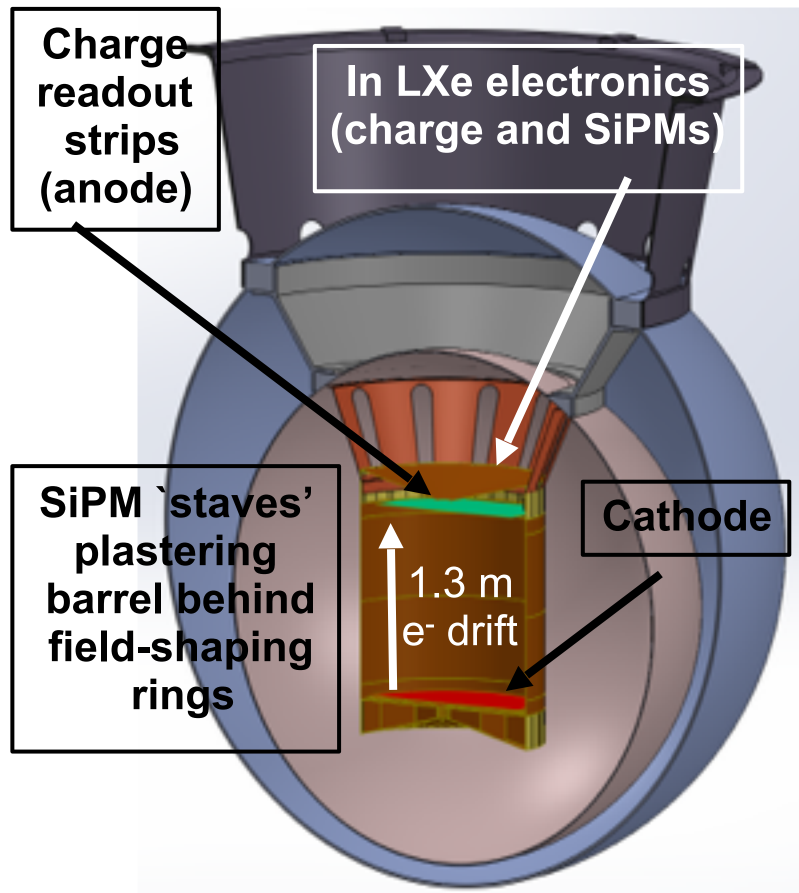

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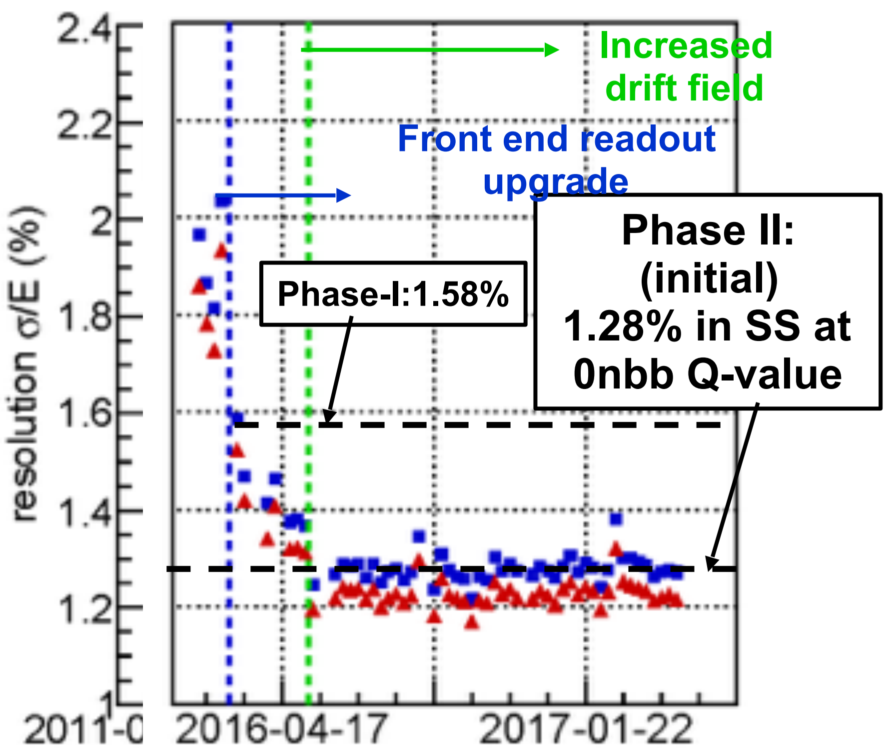

Background identification/rejection in larger nEXO fully utilizes energy, multiplicity and event position

➔ ***The power of the homogeneous detector; not just a calorimeter!***

Effectively reaches close to 0.1 cnt/ROI-t-yr over significant fraction of fiducial volume; entire volume used to precisely calibrate backgrounds

10 year 90% C.L. sensitivity reach: $T^{1/2}$ close to 10^{28} yr

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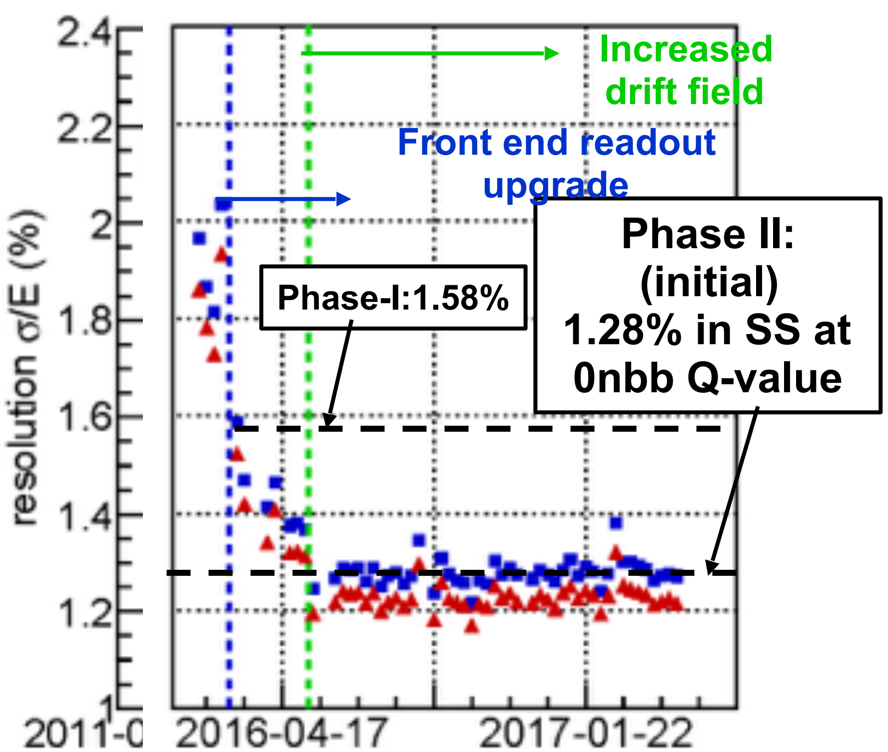

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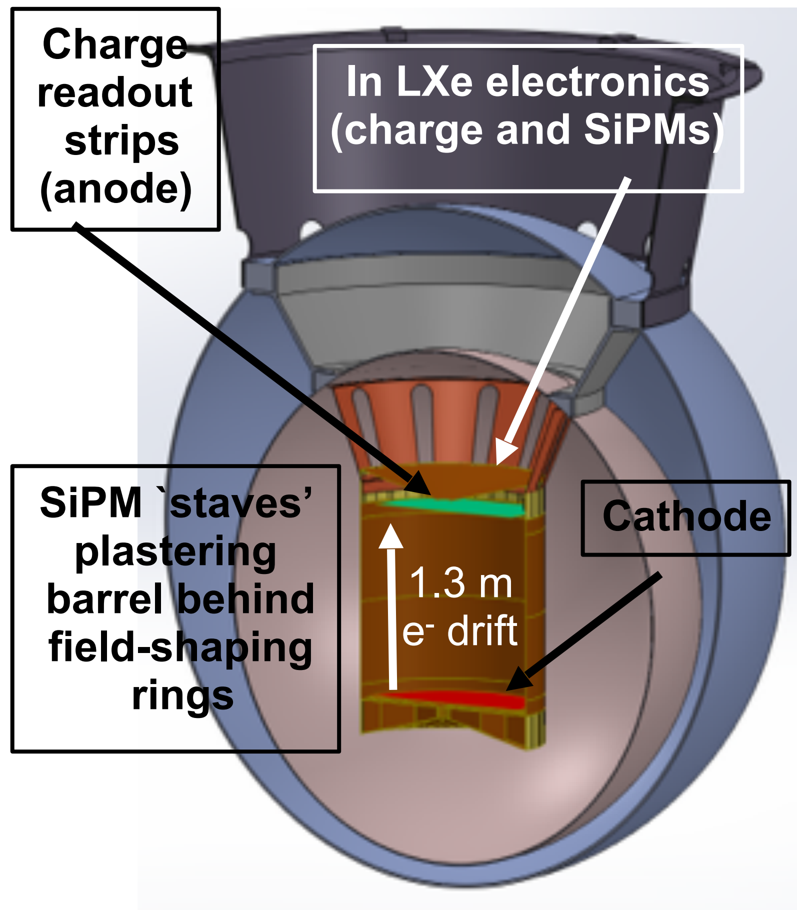
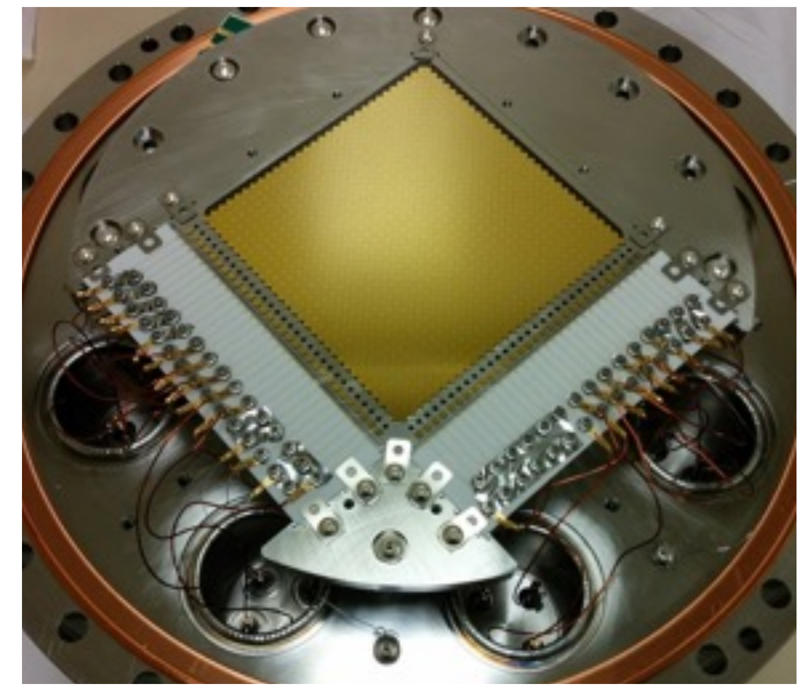


Prototype cathode strip readout in liquid xenon: self-supporting, silica base



Background identification/rejection in larger nEXO fully utilizes energy, multiplicity and event position

➔ ***The power of the homogeneous detector; not just a calorimeter!***

Significant R&D in progress:

- **High Voltage**
- **VUV SiPMs**
- **cold electronics**
- **TPC internals**
- **novel calibration techniques**
- **ultralow background materials**

Effectively reaches close to 0.1 cnt/ROI-t-yr over significant fraction of fiducial volume; entire volume used to precisely calibrate backgrounds

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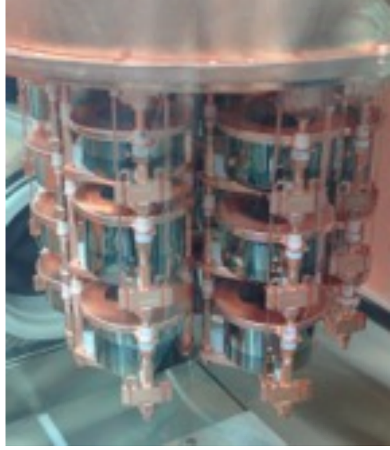
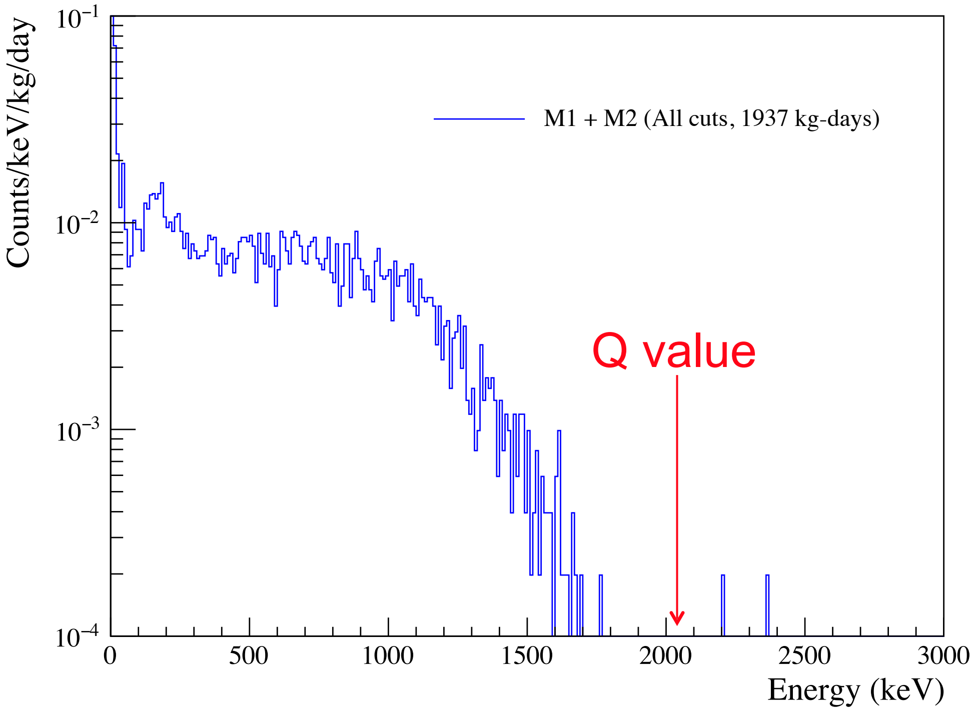
^{76}Ge MAJORANA Demonstrator & LEGEND



DEMONSTRATOR operating underground at 4850' Sanford Underground Research Facility



- **MAJORANA** ^{76}Ge enriched point contact detectors
  - have attained the best energy resolution (2.4 keV FWHM at 2039 keV) of any ββ-decay experiment.
  - excellent signal/background pulse shape discrimination
- The MAJORANA DEMONSTRATOR and GERDA are taking data in the "background free" regime having by an order of magnitude the lowest demonstrated backgrounds in the field.

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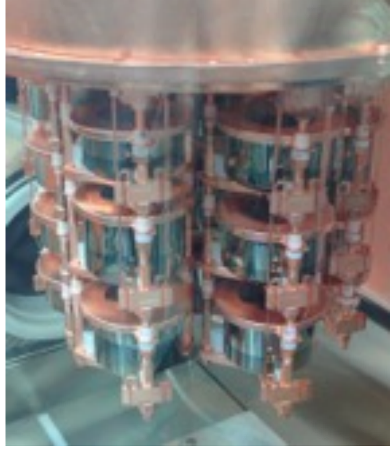

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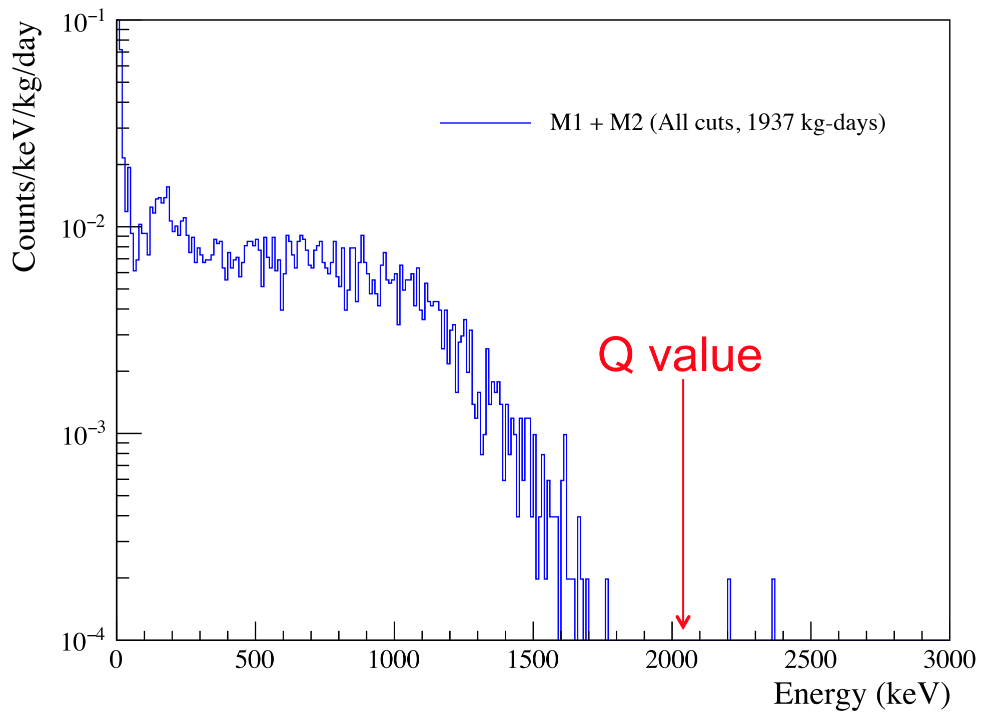

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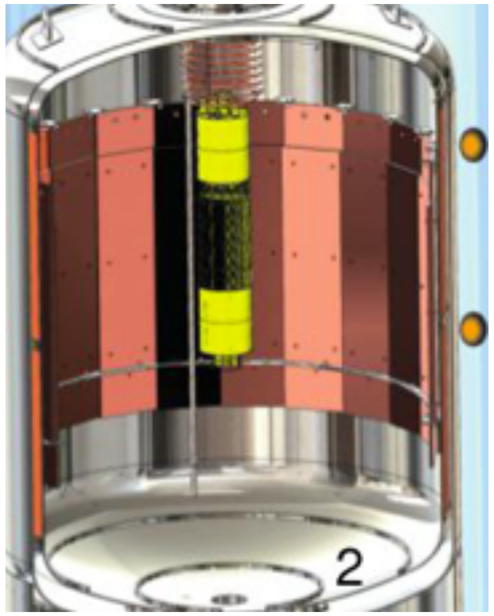
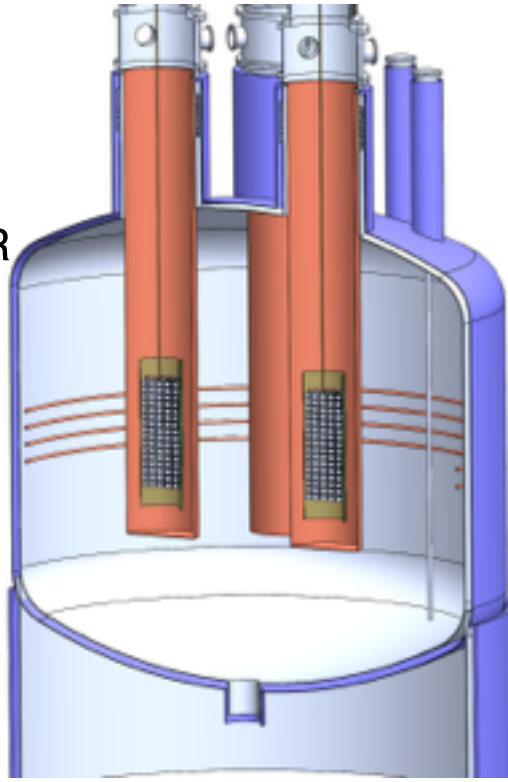


LEGEND 200 @Gran Sasso

LEGEND (47 institutions, 219 scientists)

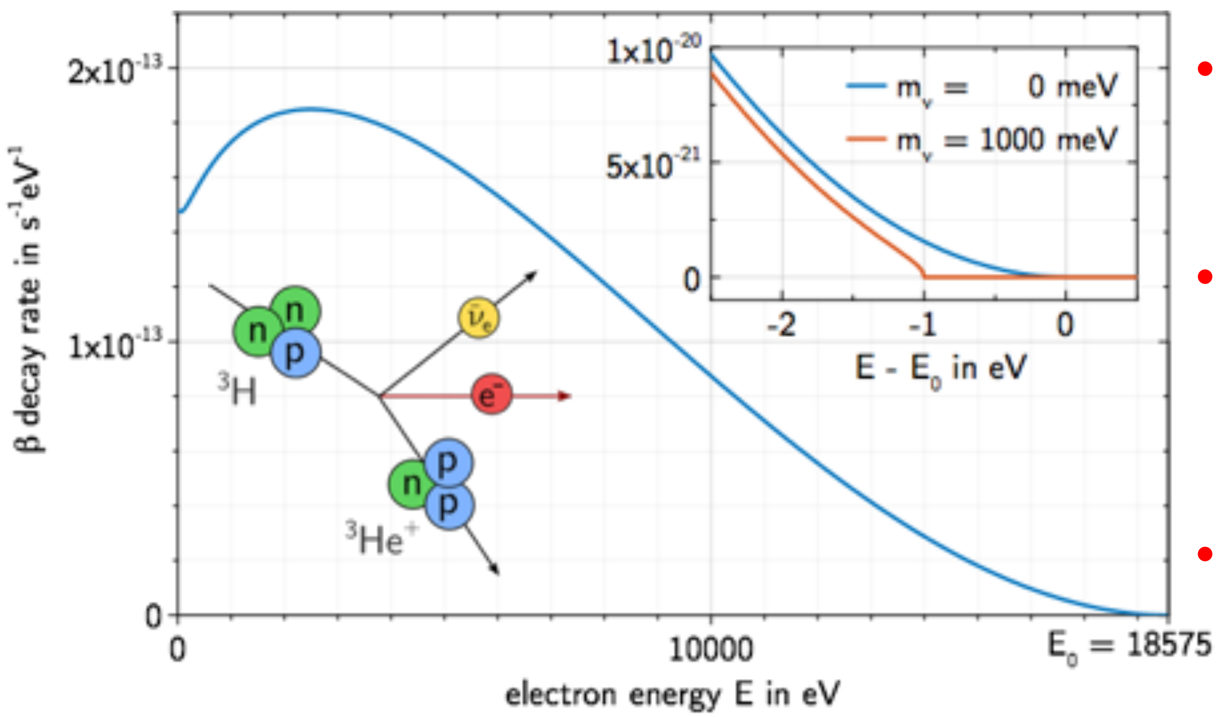
- Goal: exposure of 10 t y; background of 0.1 c / (FWHM t y);
- Best technologies from GERDA and the MAJORANA DEMONSTRATOR
- A **phased implementation**; *e.g.* 200 → 500 → 1000 kg
- LEGEND 200 uses existing resources to expedite physics.
- LEGEND 1000 baseline design established
- Only a factor ~x30 improvement needed from current backgrounds. Obtained by combining DEMONSTRATOR ultra-clean materials and GERDA active shield.
- Coupled with excellent energy resolution ^{76}Ge has a discovery potential at a half-life significantly longer than 10^{27} years.



LEGEND 1000

Towards Absolute Neutrino Mass Determination

KATRIN & Project 8

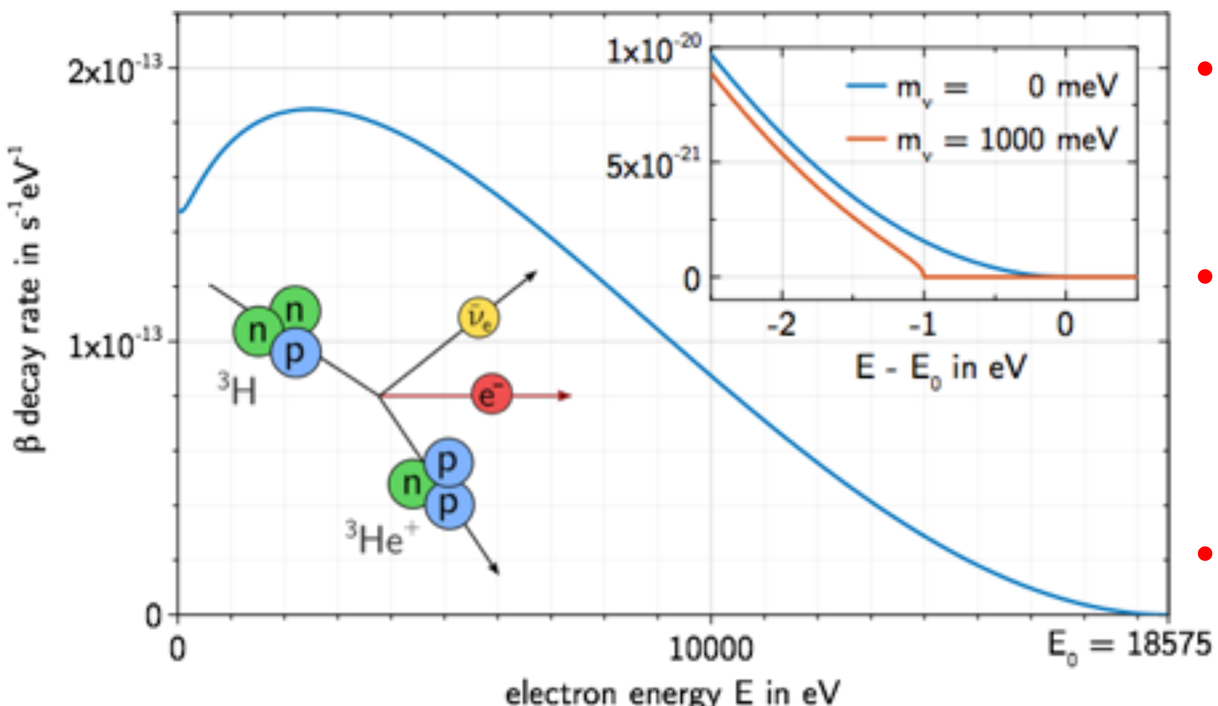


KATRIN timeline

- October 2016 - First light
  - Electrons traverse the 70 meter length of KATRIN
  - First operation of entire beam line
- July 2017 – ^{83m}Kr Spectrum
  - Precision measurement of a nuclear standard
  - Test scanning principles of tritium operation
  - Prototype of sterile neutrino search
- April 2018 – Beginning of tritium operation
  - Goal: 350 meV discovery potential
    200 meV sensitivity
    Probe quasi-degenerate region

Towards Absolute Neutrino Mass Determination

KATRIN & Project 8



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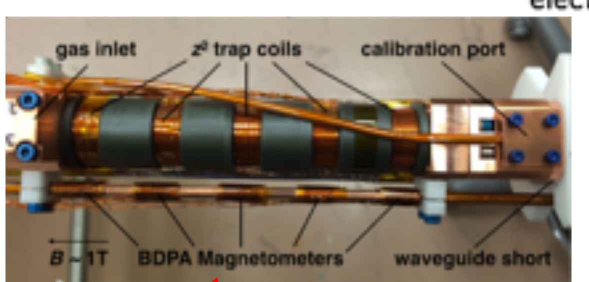
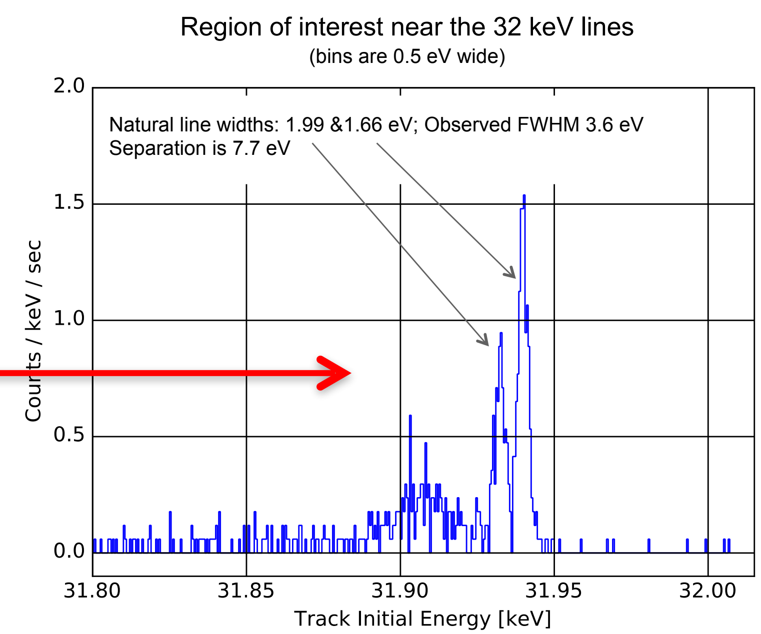


Project 8 Phase II
Waveguide Prototype

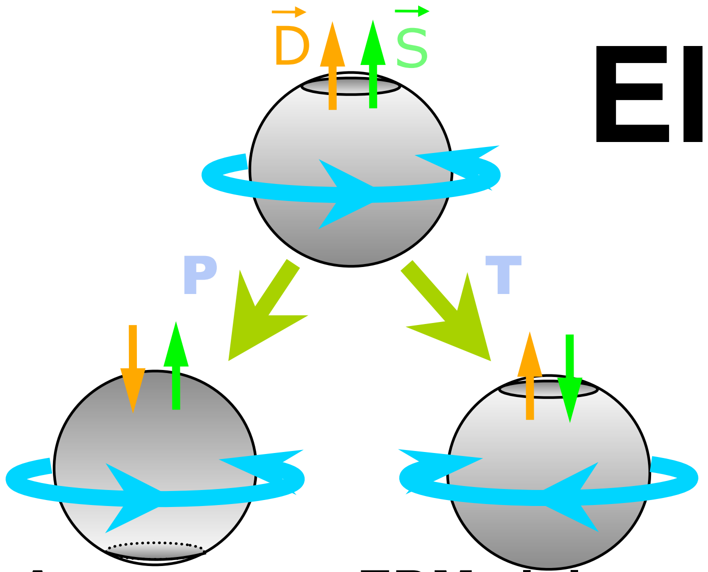
Phases and Goals of Project 8

Phase	Timeline	Source	R&D Milestones	Science Goals
I	2010–2017	^{83m}Kr	single electron detection proof of concept	conversion electron spectrum of ^{83m}Kr
II	2015–2018	T_2	Kurie plot systematic studies	Final-state spectrum test, ^{3}H–^{3}He mass difference, $m_\nu \lesssim 10–100\,eV/c^2$
III	2016–2021	T_2	high-rate sensitivity B field mapping	$m_\nu \lesssim 2\,eV/c^2$
IV	2017...	T	atomic tritium source	$m_\nu \lesssim 40\,meV/c^2$ measure m_ν or determine normal hierarchy



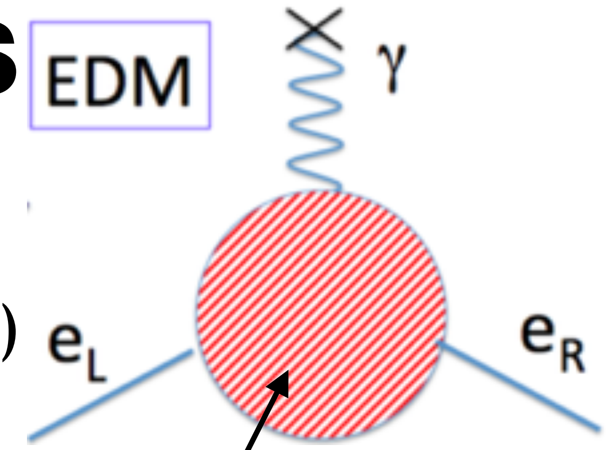
Project 8 timeline

- Currently commissioning Phase II waveguide prototype with ^{83m}Kr.
- First tritium operations in Summer 2017.
- Phase III design ongoing
- Early R&D for Phase IV with atomic tritium



A permanent EDM violates both parity (P) and time-reversal (T) Invariance

Electric Dipole Moments



High energy CP-violating dynamics

Current published limits

- Trapped Neutrons:
  - $d_n < 3 \times 10^{-26}$ e-cm (Institut Laue-Langevin)
- Diamagnetic Atom: ^{199}Hg
  - $d_{Hg} < 7 \times 10^{-30}$ e-cm (U. Washington)
- Paramagnetic Polar Molecule:ThO
  - $d_e < 1 \times 10^{-28}$ e-cm (ACME Collaboration)

- *A non-zero EDM of an elementary particle would constitute direct observation of non-conservation of Time Reversal Invariance*
- *Standard Model signal highly suppressed (< 10^{-34} e-cm)*
- *Next generation experiments probe scales of 100 to 1000 TeV for new physics*
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- *Important to search for EDMs for a variety of elementary particles*

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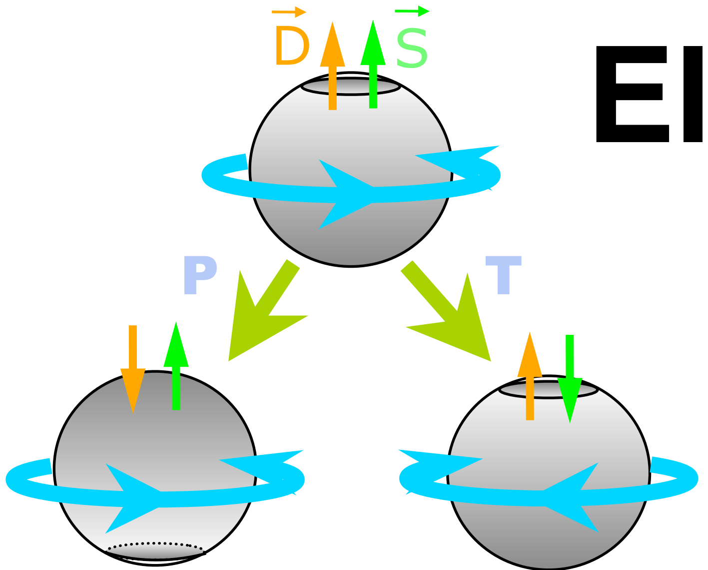

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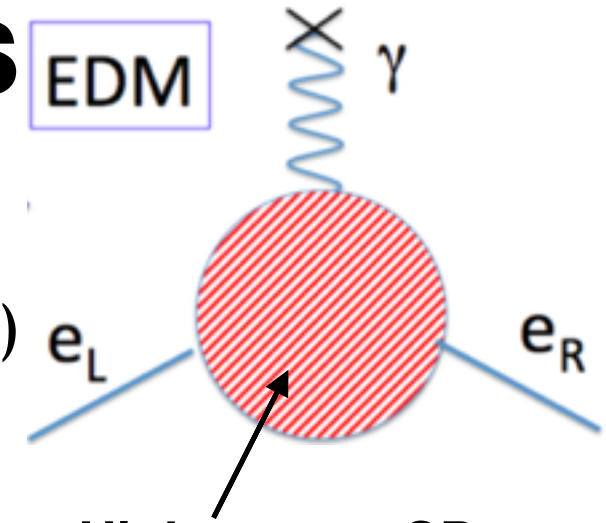

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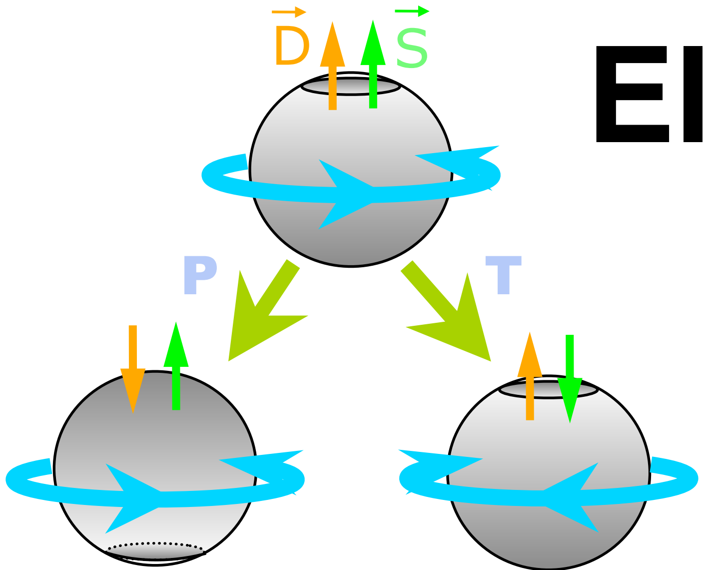

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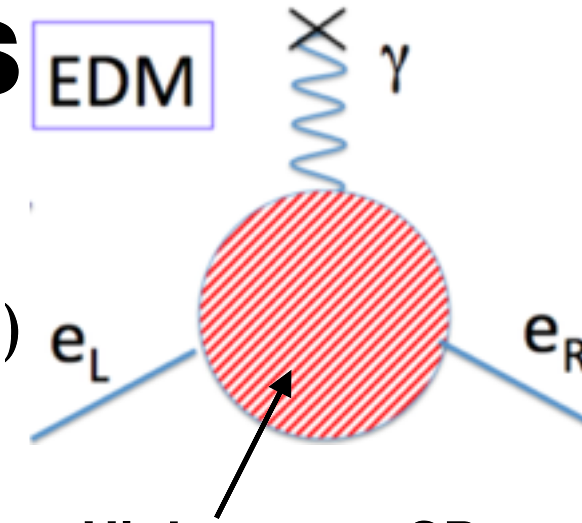

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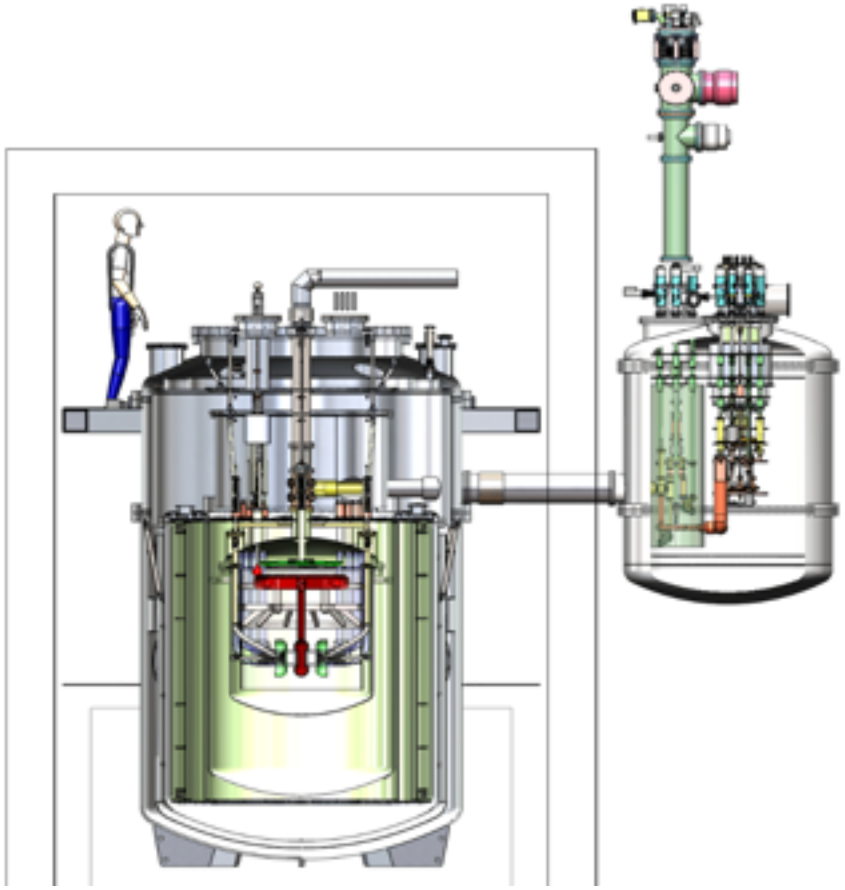
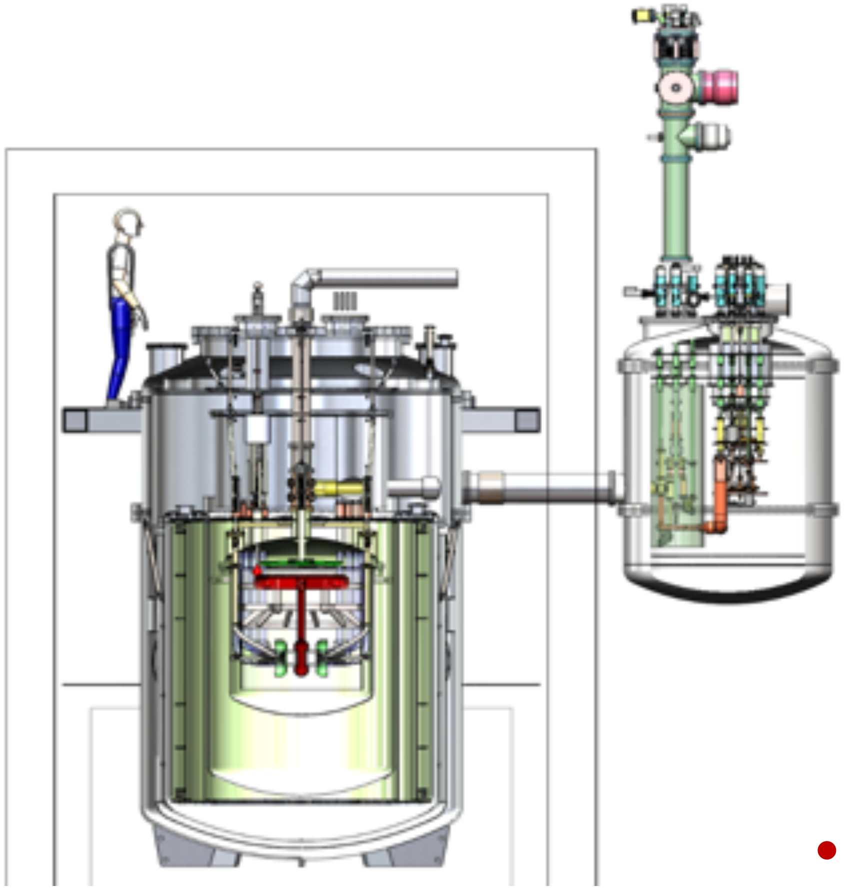
The race to a factor of 100 better sensitivity:
the nEDM experiment at the Fundamental Neutron Physics Beamline (FNPB)
at the Spallation Neutron Source (SNS)



nEDM at SNS

Sensitivity 2 x 10^{-28} e-cm

In-situ UCN production, polarized ^3He co-magnetometer, superconducting magnetic shield, simultaneous measurements in 2 cells with opposite E-fields, variation of central volume temperature…



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  - Build working, full-scale, prototypes of technically-challenging subsystems (can use some in full experiment)
  - 4yr National Science Foundation funds 4.5M$ for CCD
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  - LSI – Integrate Central Detector, Magnets and ^{3}He systems
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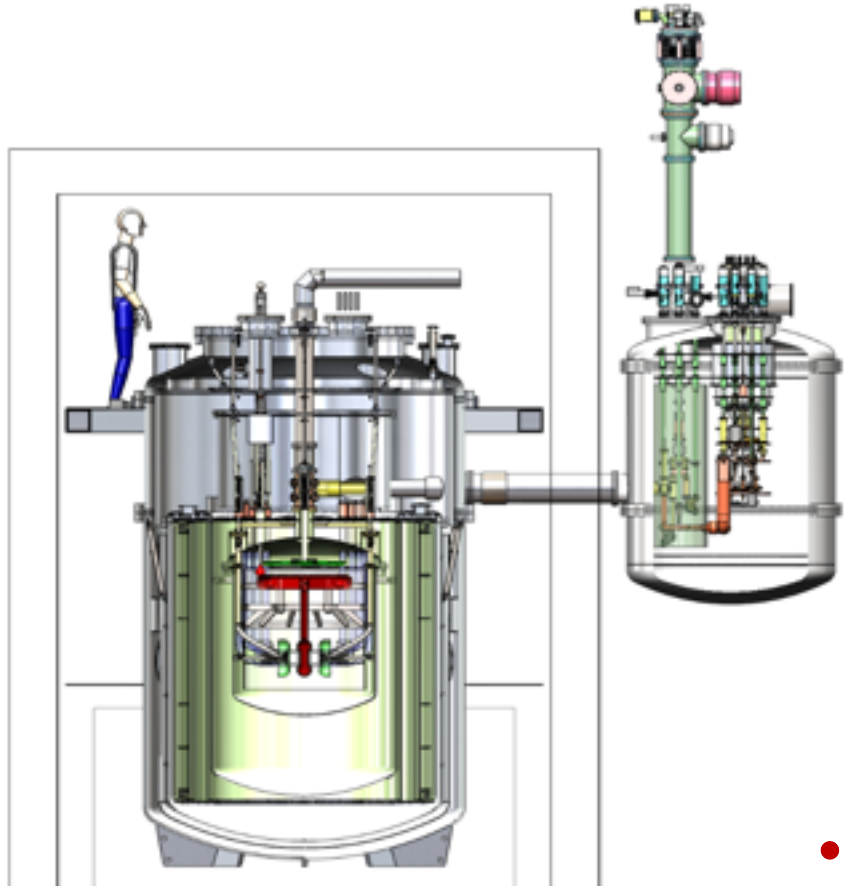

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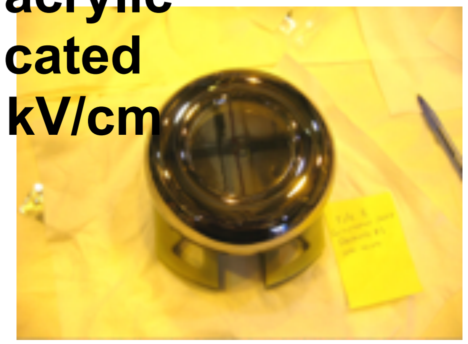
Thin-film-coated acrylic electrodes fabricated and tested to 80 kV/cm



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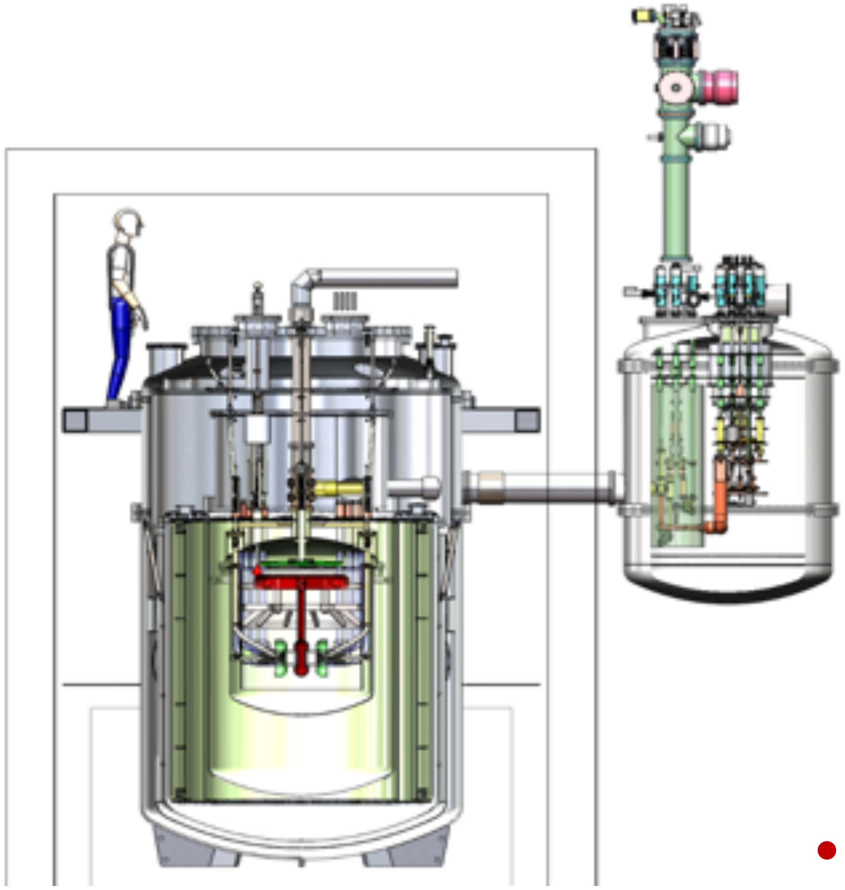

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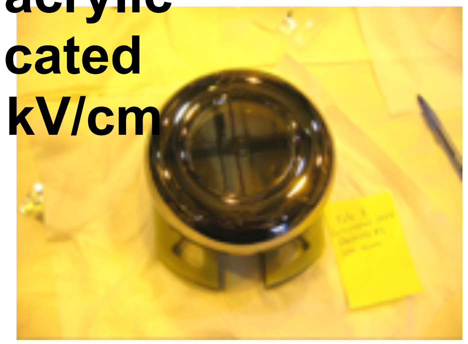
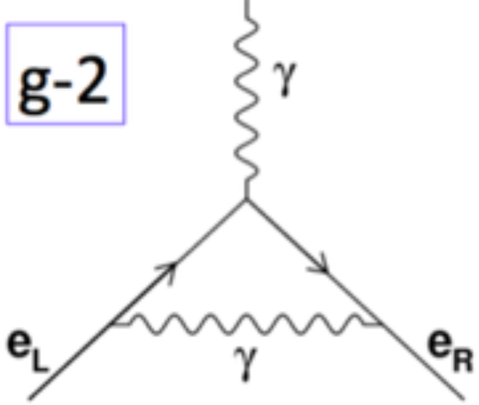


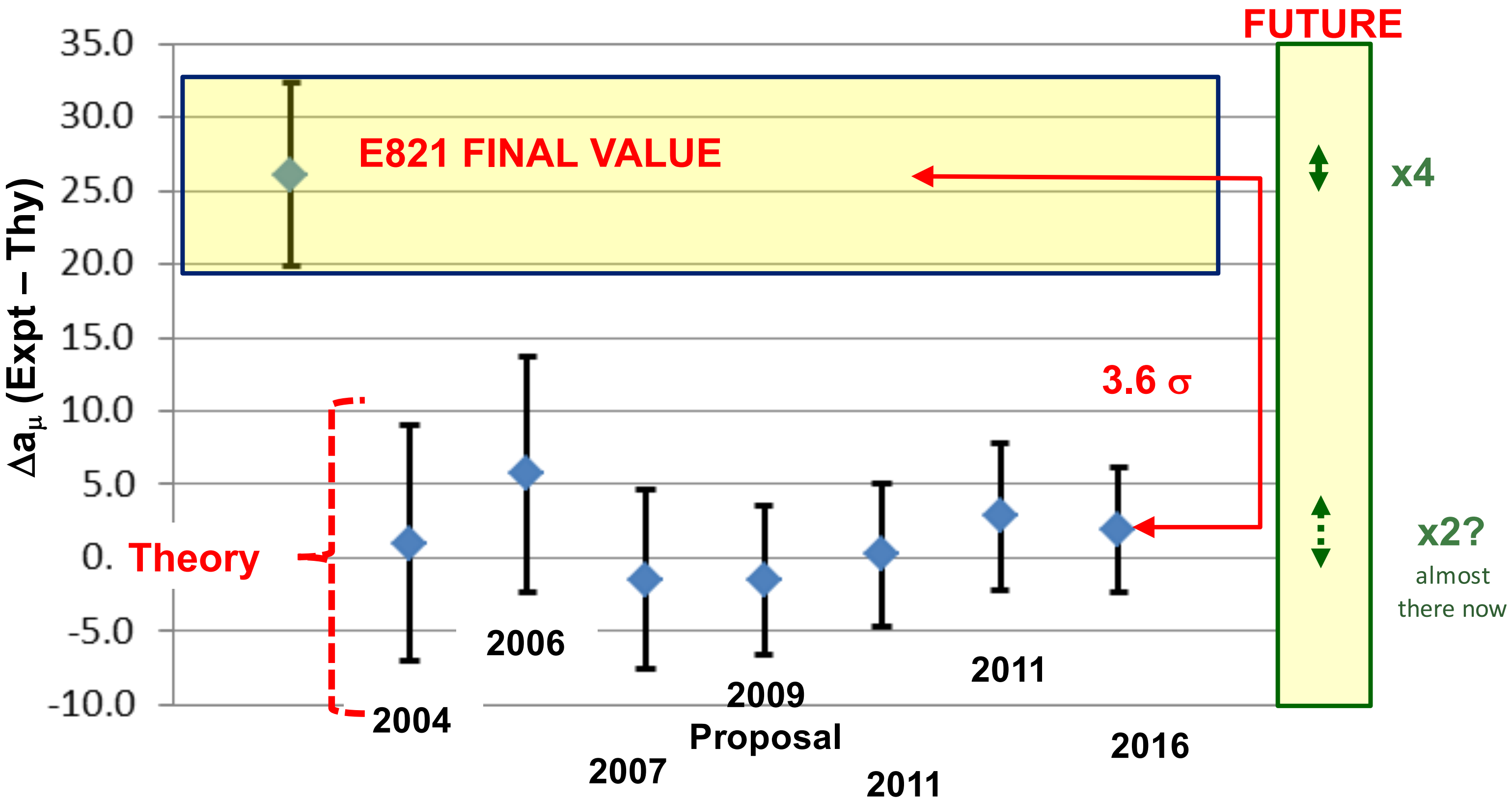
non-magnetic dilution refrigerator under construction

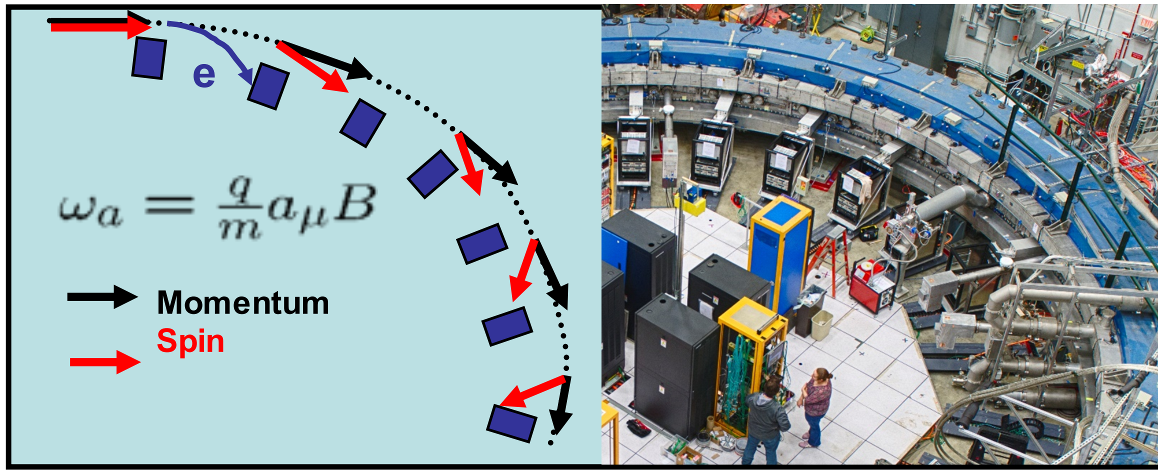


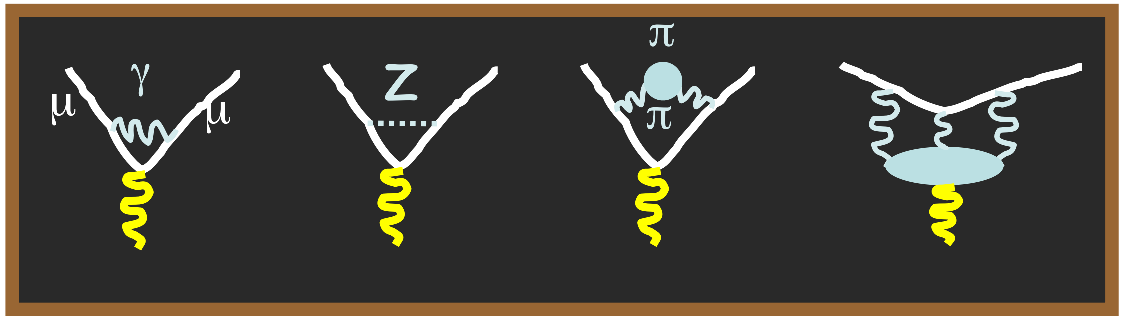
Highly sensitive probe of new physics at the TeV scale

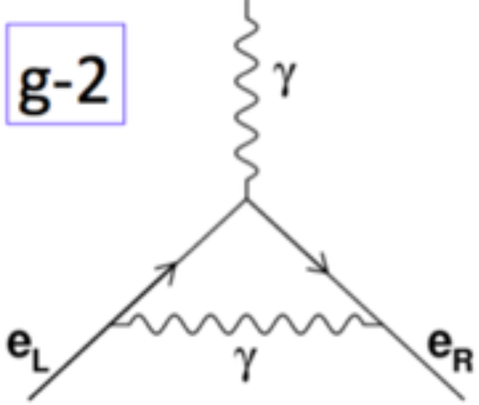
Muon g-2

In the 12 years since the BNL result, the "g-2 Test" continues to point to something interesting









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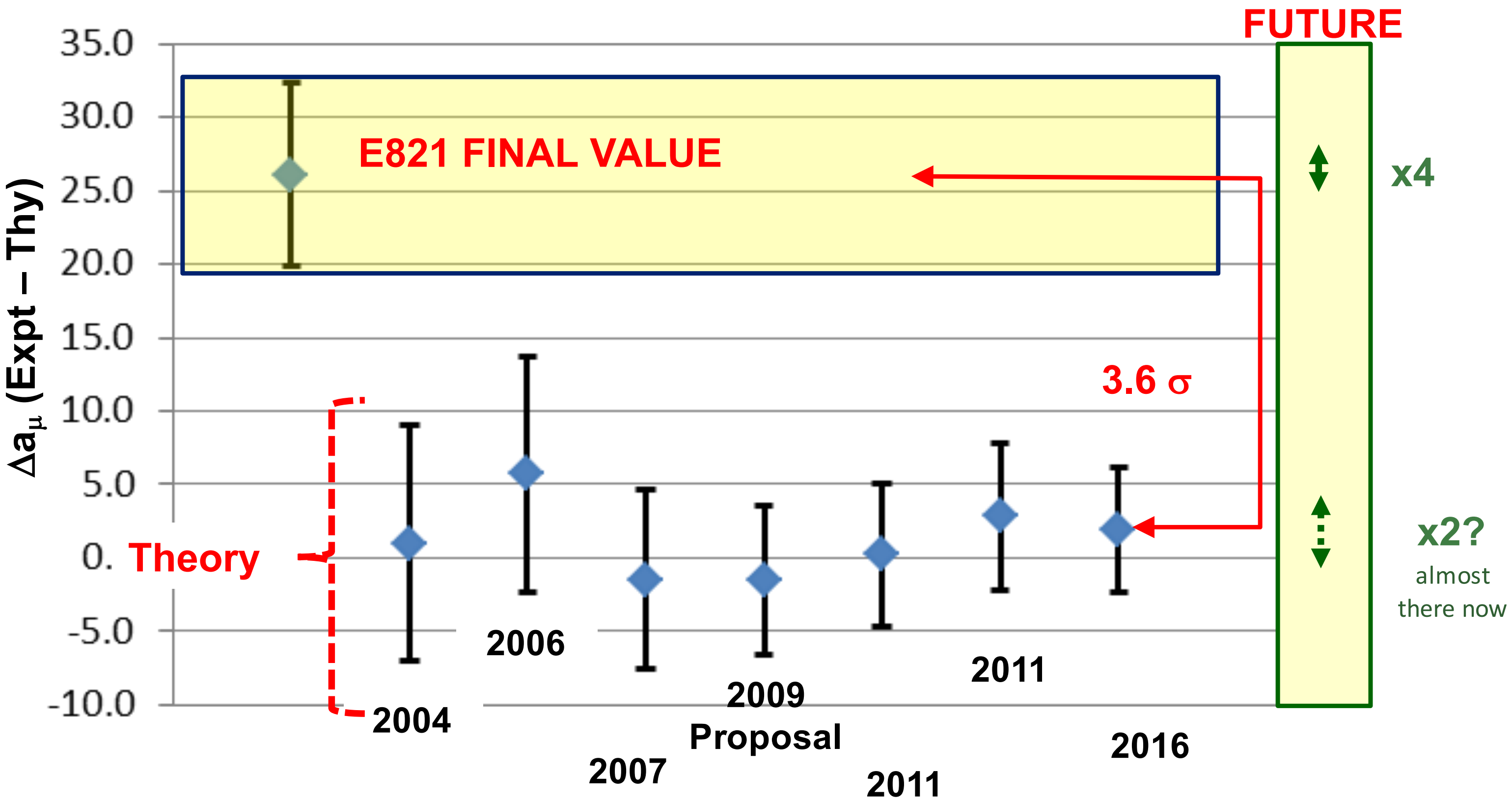
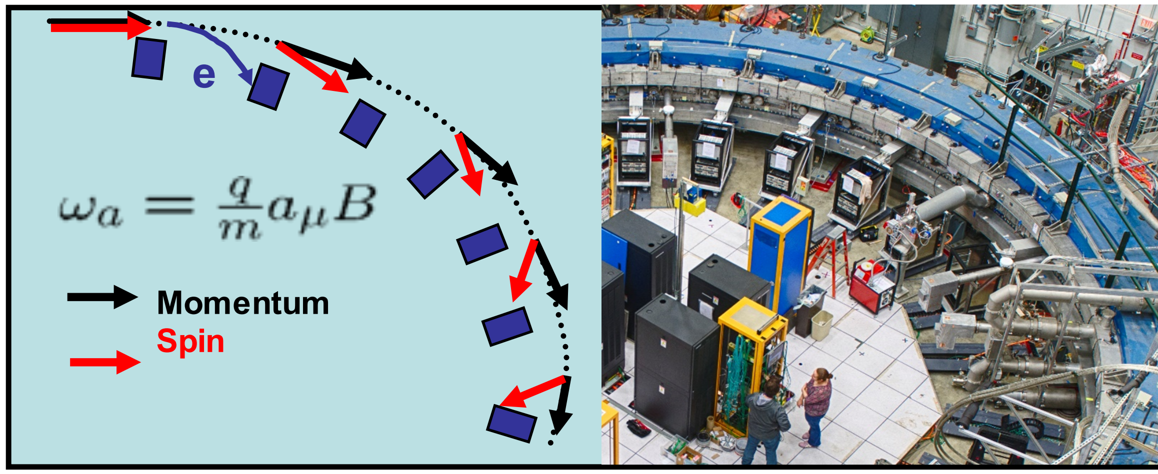
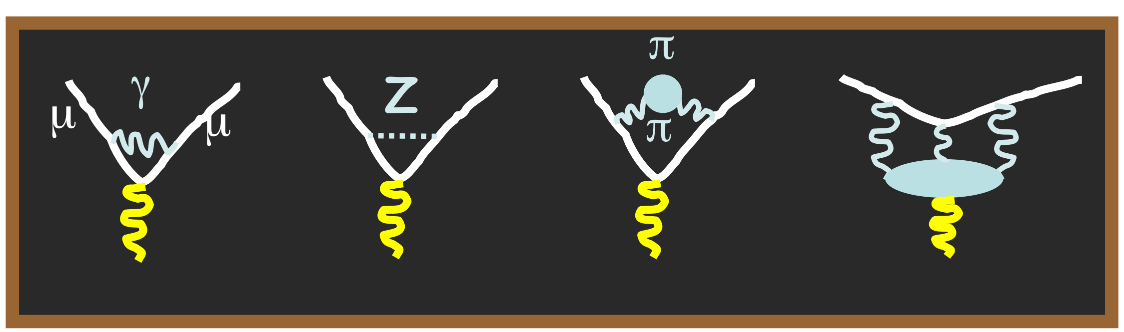
- James Madison

Additional Funding
- NSF MRI for wa instrumentation

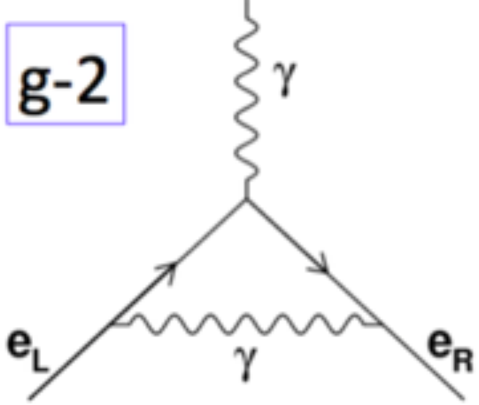






Commissioning NOW with beam to Storage Ring

Major Nuclear Physics group imprint on experiment, especially measuring instrumentation and analysis development



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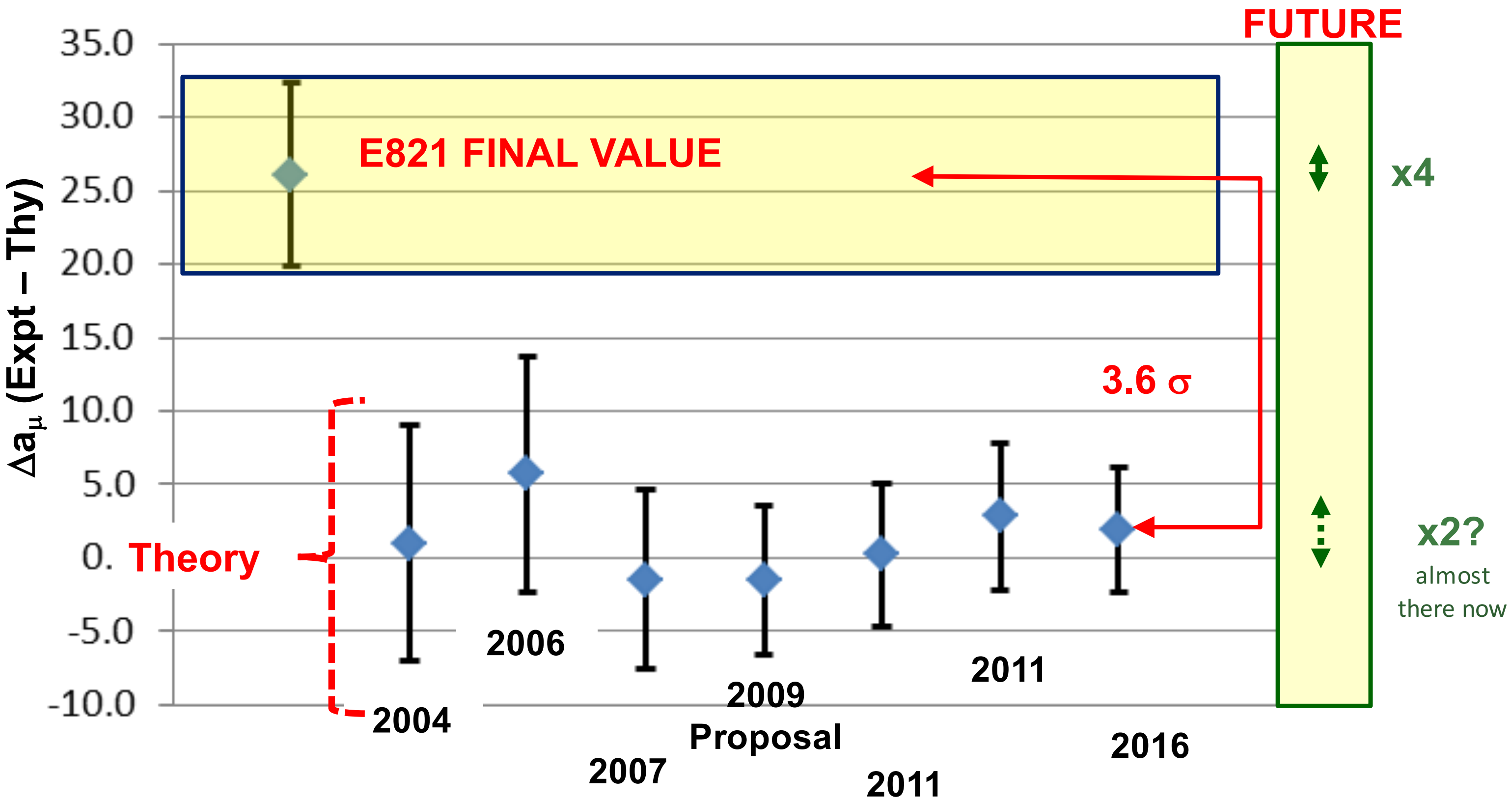
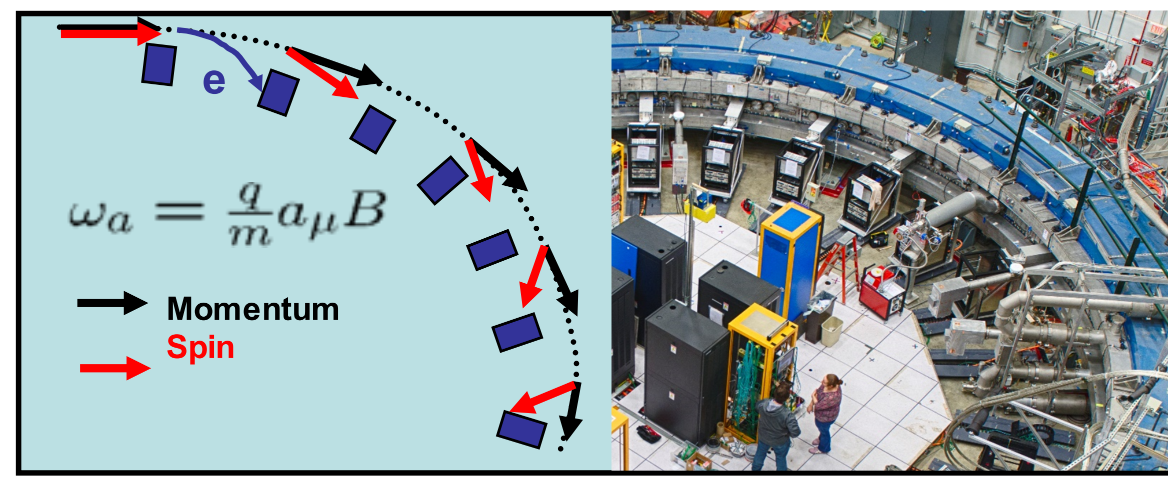
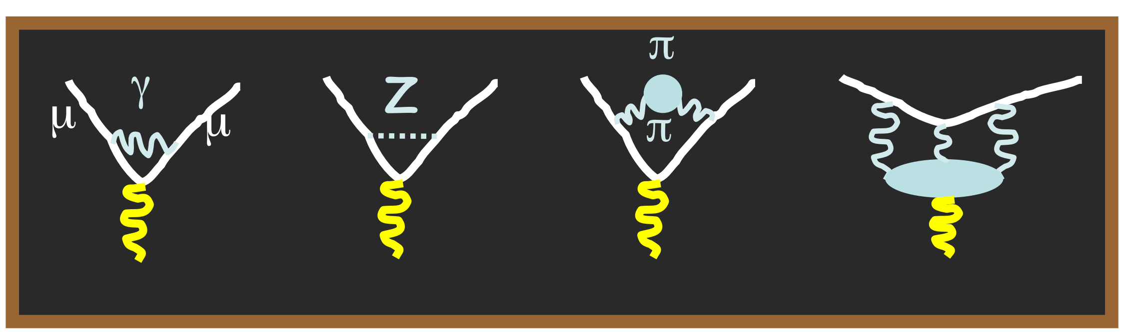




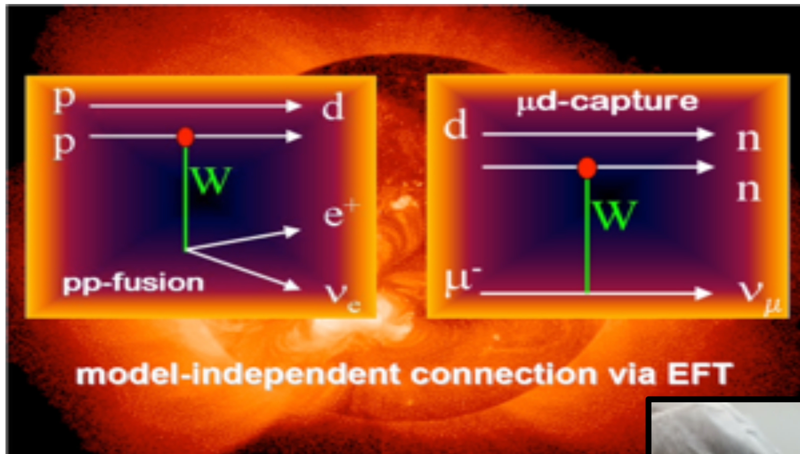


Commissioning NOW with beam to Storage Ring

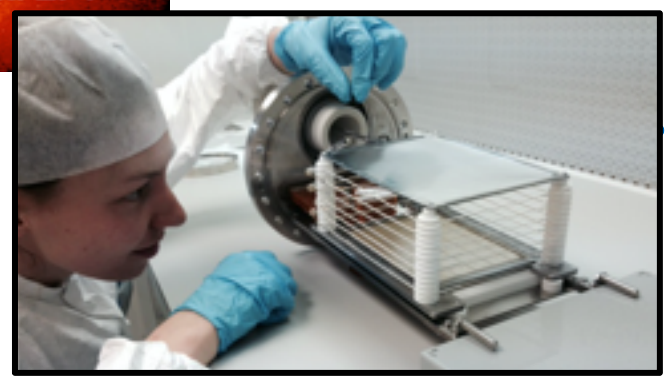
Major Nuclear Physics group imprint on experiment, especially measuring instrumentation and analysis development

- **Plan to obtain BNL-level statistics by early 2018 and have first physics result in summer 2018**
- **Then 5x BNL, then 25x BNL in coming year(s)**

MuSun and MUSE



MuSun @ PSI



Data taking completed Fall 2016

- Achieved full statistics and systematics tests as planned; analysis in progress
- Goal:
  - Determine axial current coupling to 2N system
- Method:
  - Measure μd capture rate to 1.5%
  - Extract Low Energy Constant in EFT, d^R
- Relevance
  - Calibrate fundamental astrophysics reactions
  - Important for EFT formulation of nuclear physics
  - Matrix elements for 0ν2β decay

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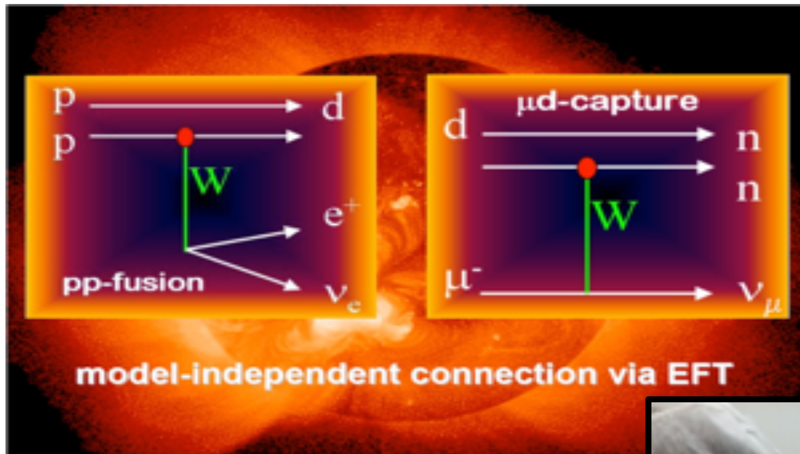

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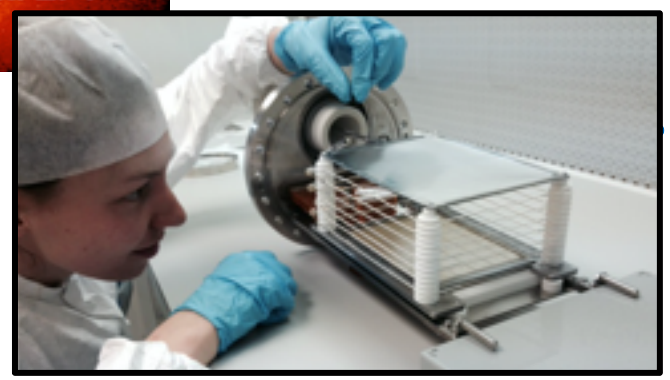

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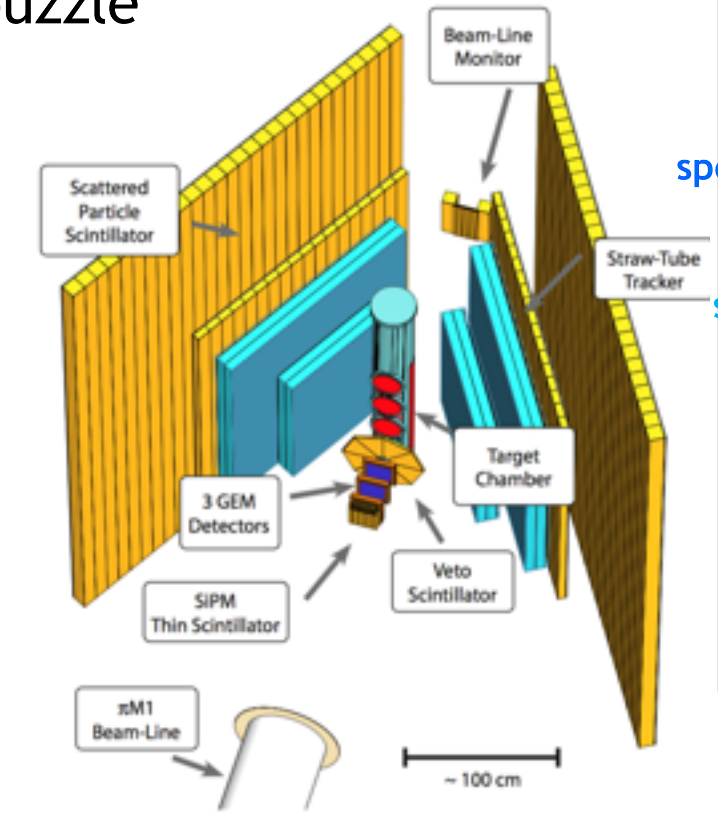
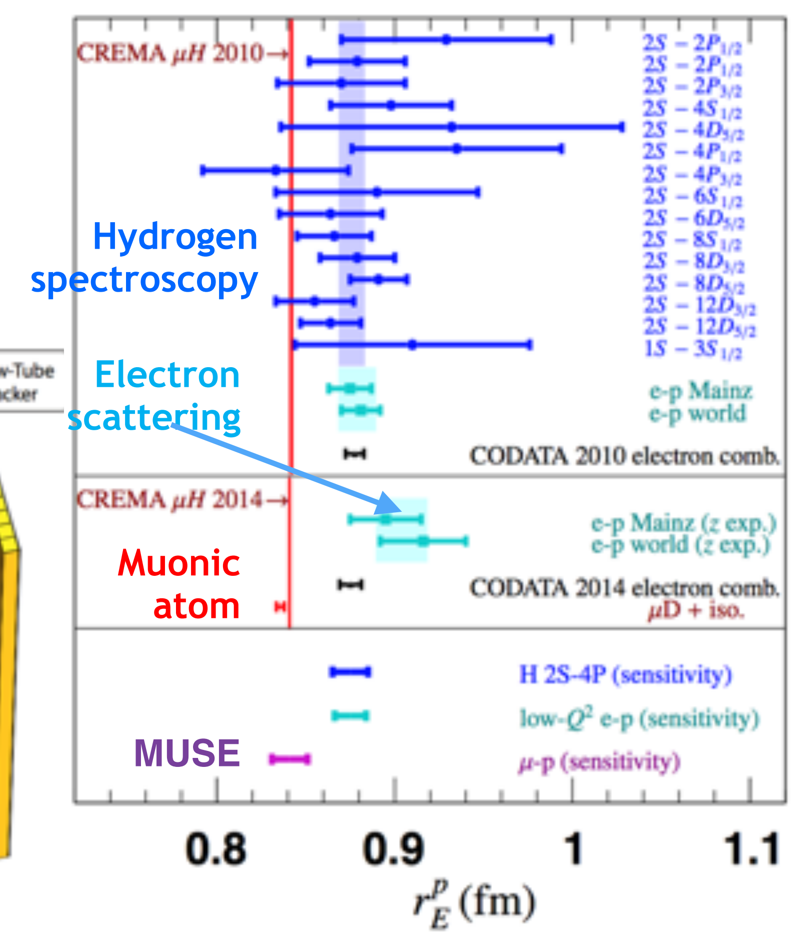
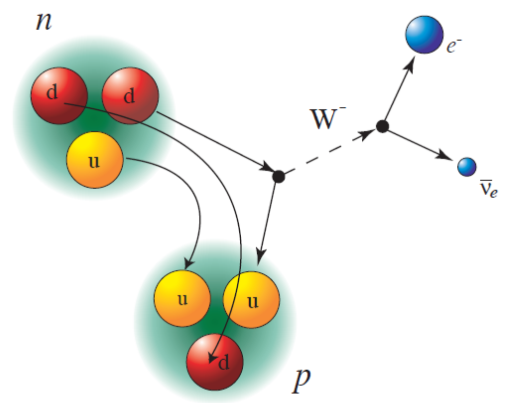
MUSE: Approved and under construction

- Impact on resolution of the "proton radius puzzle"
- NSF Midscale Award in September 2016
- Status:
  - Several beam tests
  - Tests of detectors and electronics
  - Target design in progress
  - Integration and alignment planning
  - Dress rehearsal late 2017
  - physics running in 2018/19



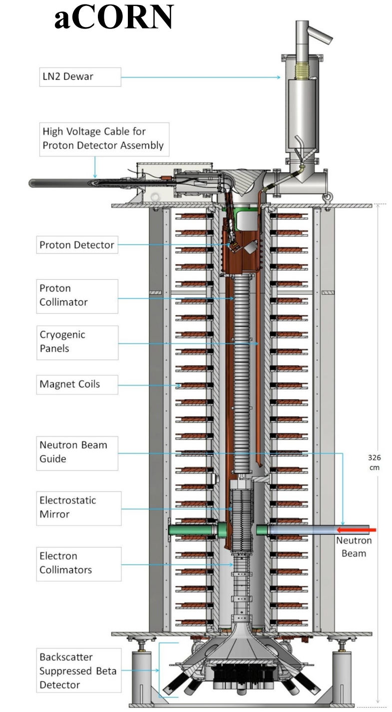




Precision Semi-leptonic Charged Current Interactions

Neutron Beta Decay

aCORN



Beta decay provides post-LHC-level constraints on BSM interactions and critical input for BBN and astrophysics

Experiments now operating or under construction approaching $0^+ \to 0^+$ level of precision

Lifetime

Angular Correlations, e.g.

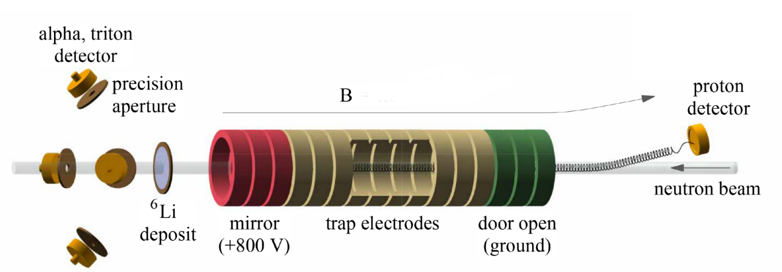
$$\frac{1}{\tau_n} \quad \& \quad \frac{dW}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \left\langle \frac{\vec{J}_n}{J_n} \right\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

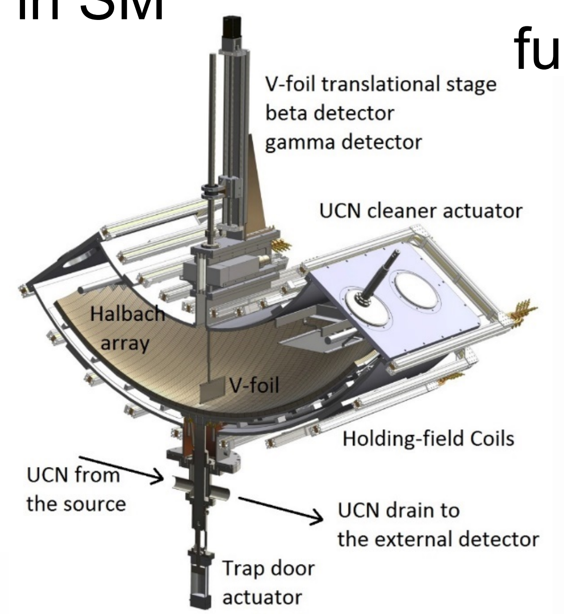
zero in SM

functions of g_A/g_V to leading order

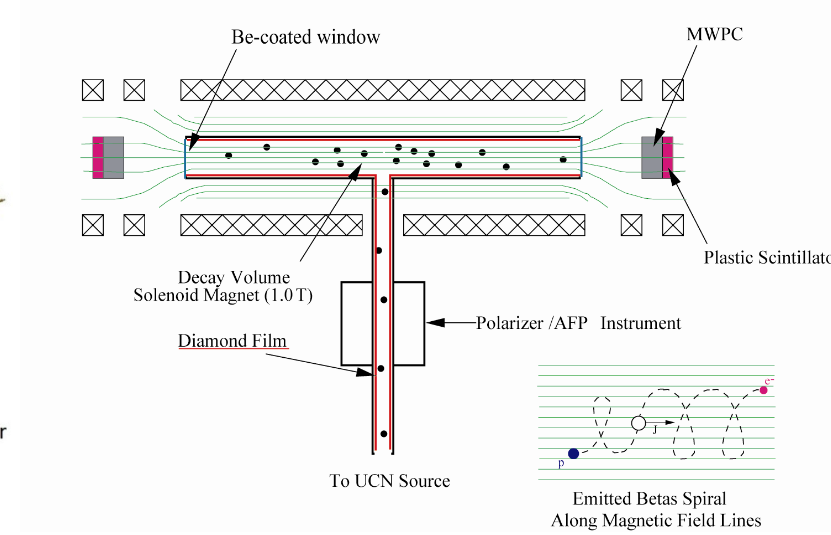
NIST BL2 and BL3

(absolute n flux measurement shown)

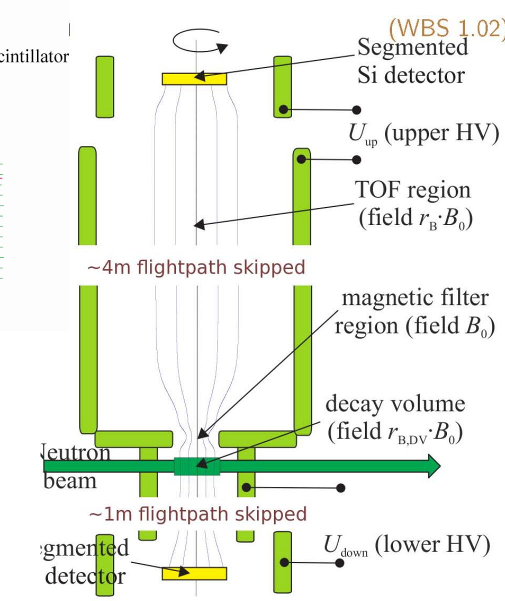




UCNτ



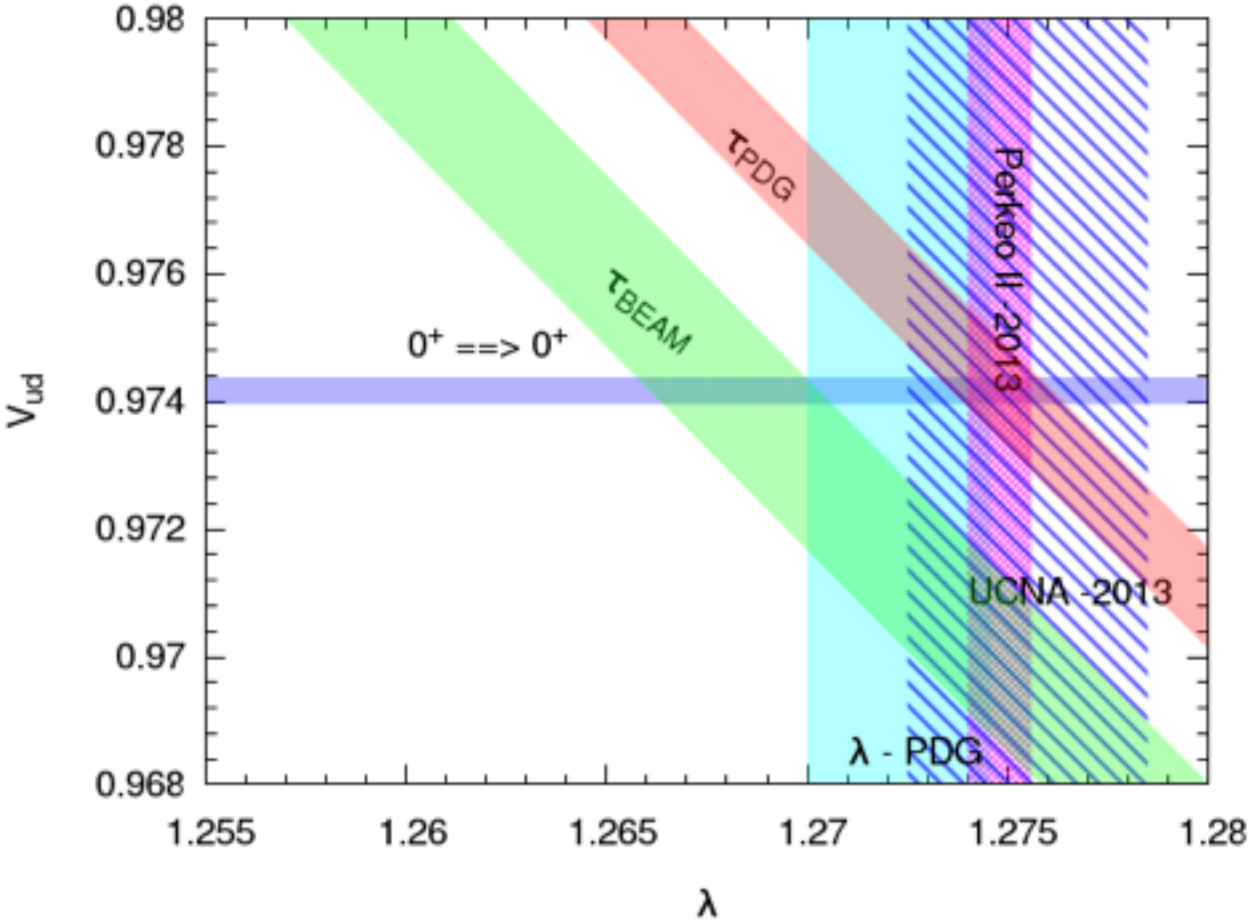
UCNA



Nab

Source upgrades successful at NIST (CN) and LANL (UCN)!

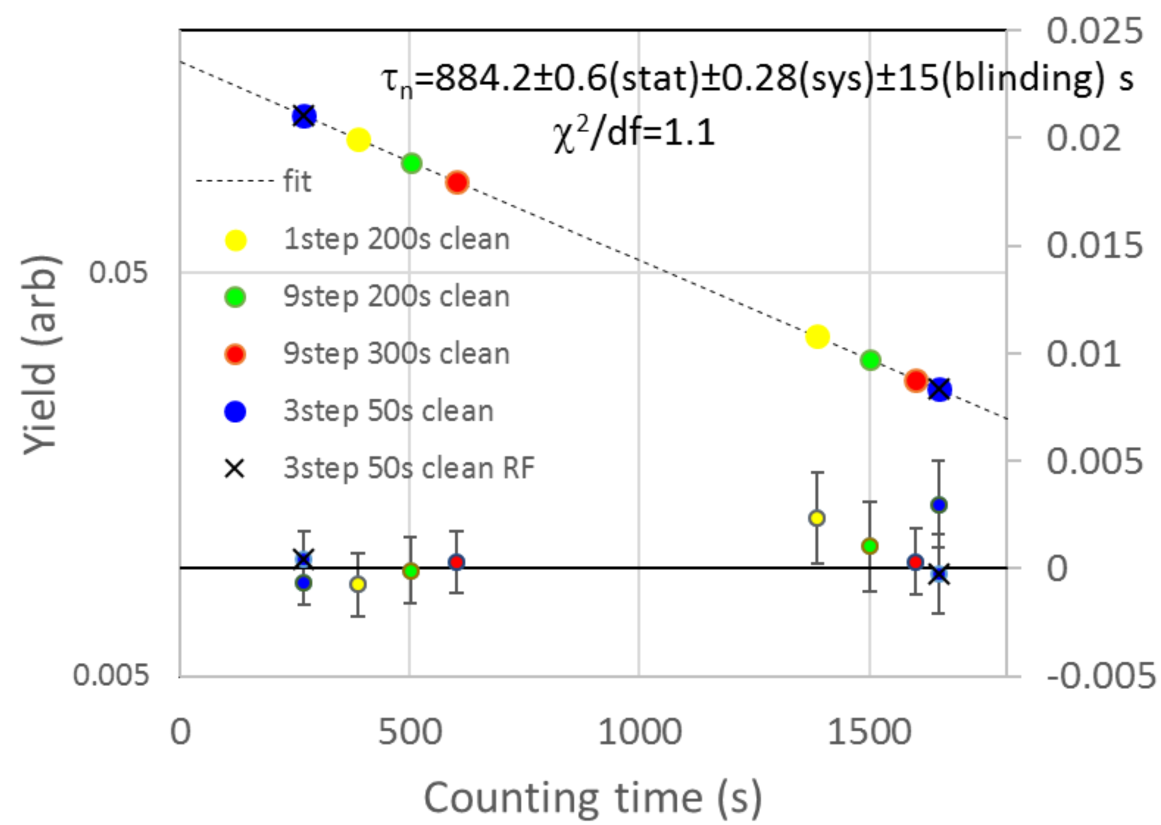
Neutron Decays: Recent Progress



Beam lifetime 2 at NIST

- Detector efficiency improvement: allows 1 second beam lifetime measurement; path to <0.3 s
- Currently on NGC beamline: commissioning Summer 17, then 2 year production run

UCNτ at LANL



2016-17 data unblinded!

statistical uncertainty at 0.6 s

publication imminent

systematic corrections small: anticipate further improvements

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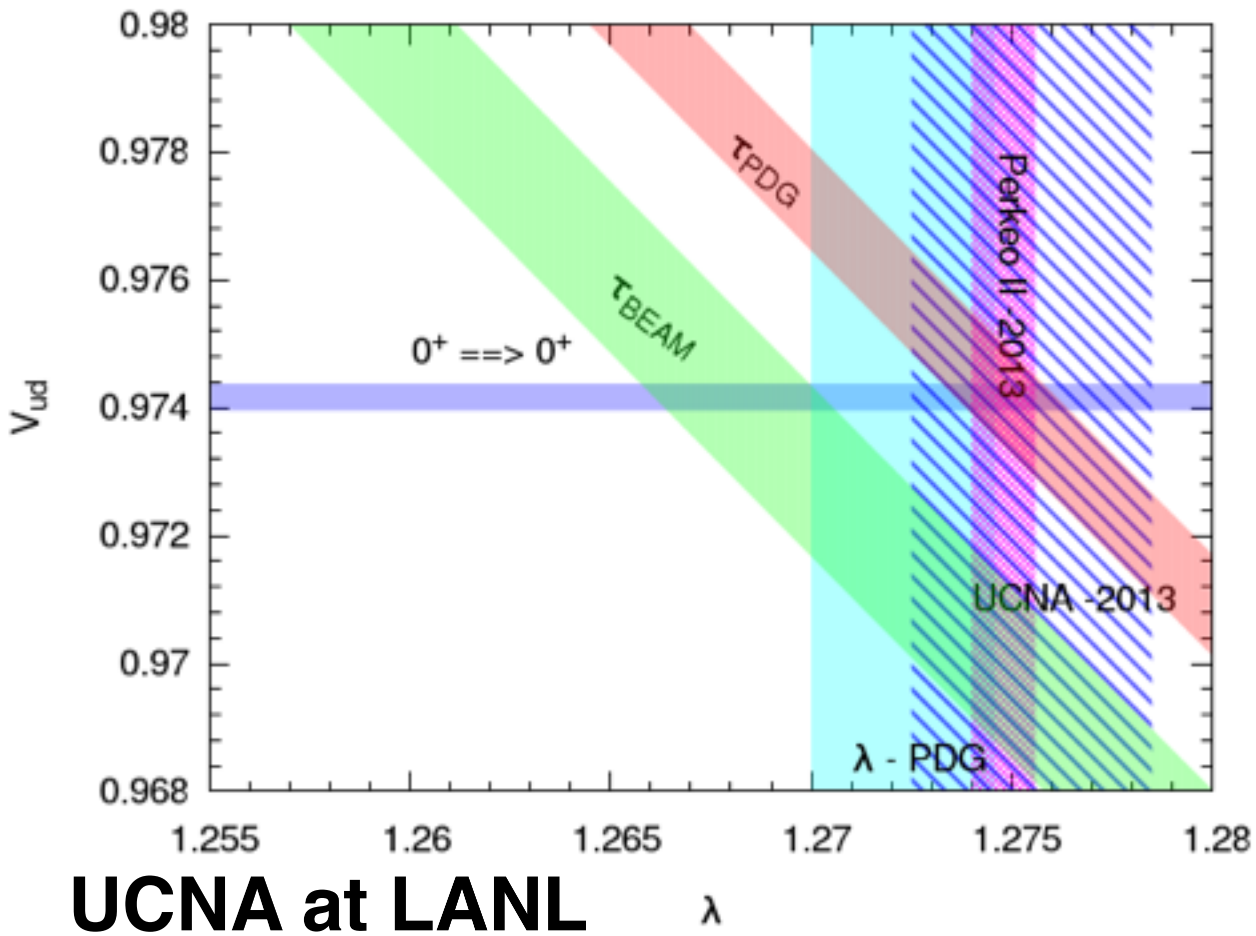

aCORN at NIST

- NG6 and NGC beam line data taking completed
- NG6 result submitted to PRL:
  - $a = -0.1090 \pm 0.0030(stat) \pm 0.0028(sys)$
- NGC data analysis: final uncertainty < 1.5%

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UCNA at LANL

2010 data: $A_0 = 0.11972(55)_{stat}(98)_{syst}$

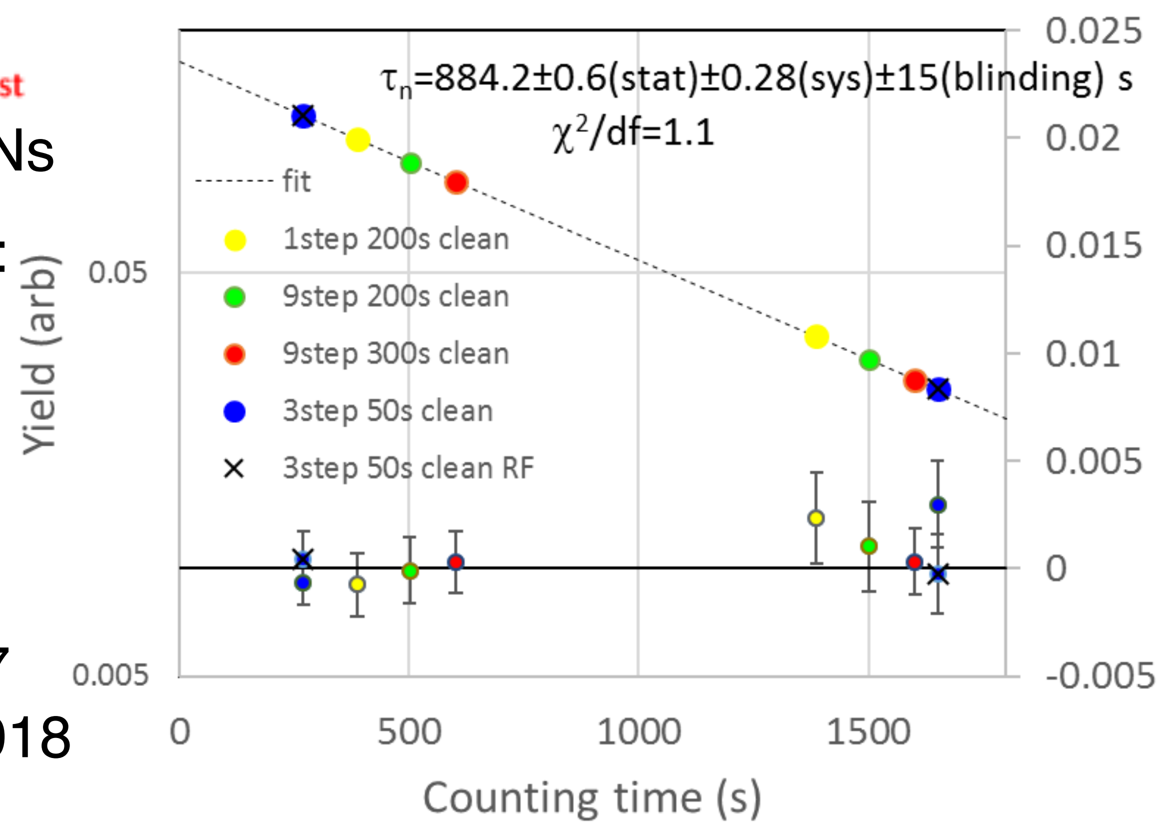
First angular correlation using UCNs

2011-13 data unblinding imminent: targeting precision below 0.7%

Preparations: Nab at SNS

- $\Delta a/a$=1e-3
- $\Delta b/b$=3e-3
- Magnet ships end of summer 2017
- Spectrometer commissioning in 2018
- 2 years of production data taking

UCNτ at LANL



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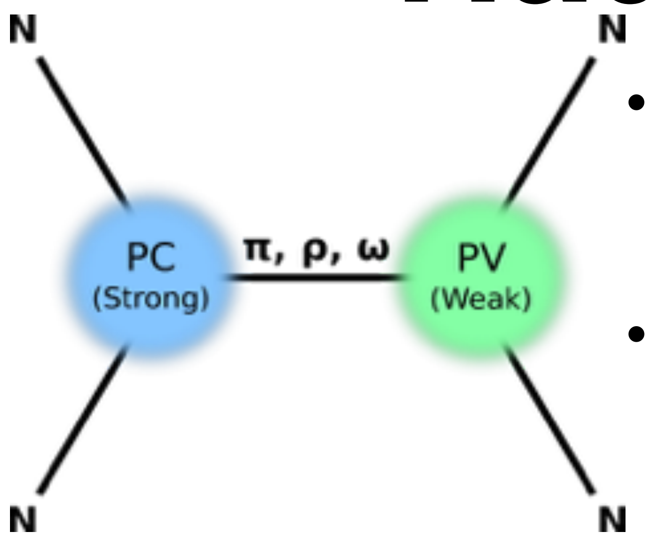
Hadronic Parity Violation



Parameters: $h_\pi^1, h_\rho^0, h_\rho^1, h_\rho^2, h_\omega^0, h_\omega^1$

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  - Not accessible directly due to presence of strong force
  - Accessible at low momentum transfers through PV measurements
- Multiple measurements isolate individual low energy weak couplings

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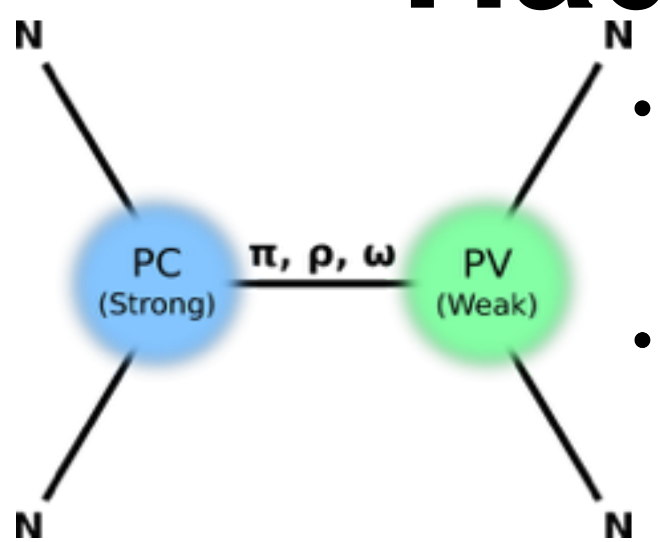

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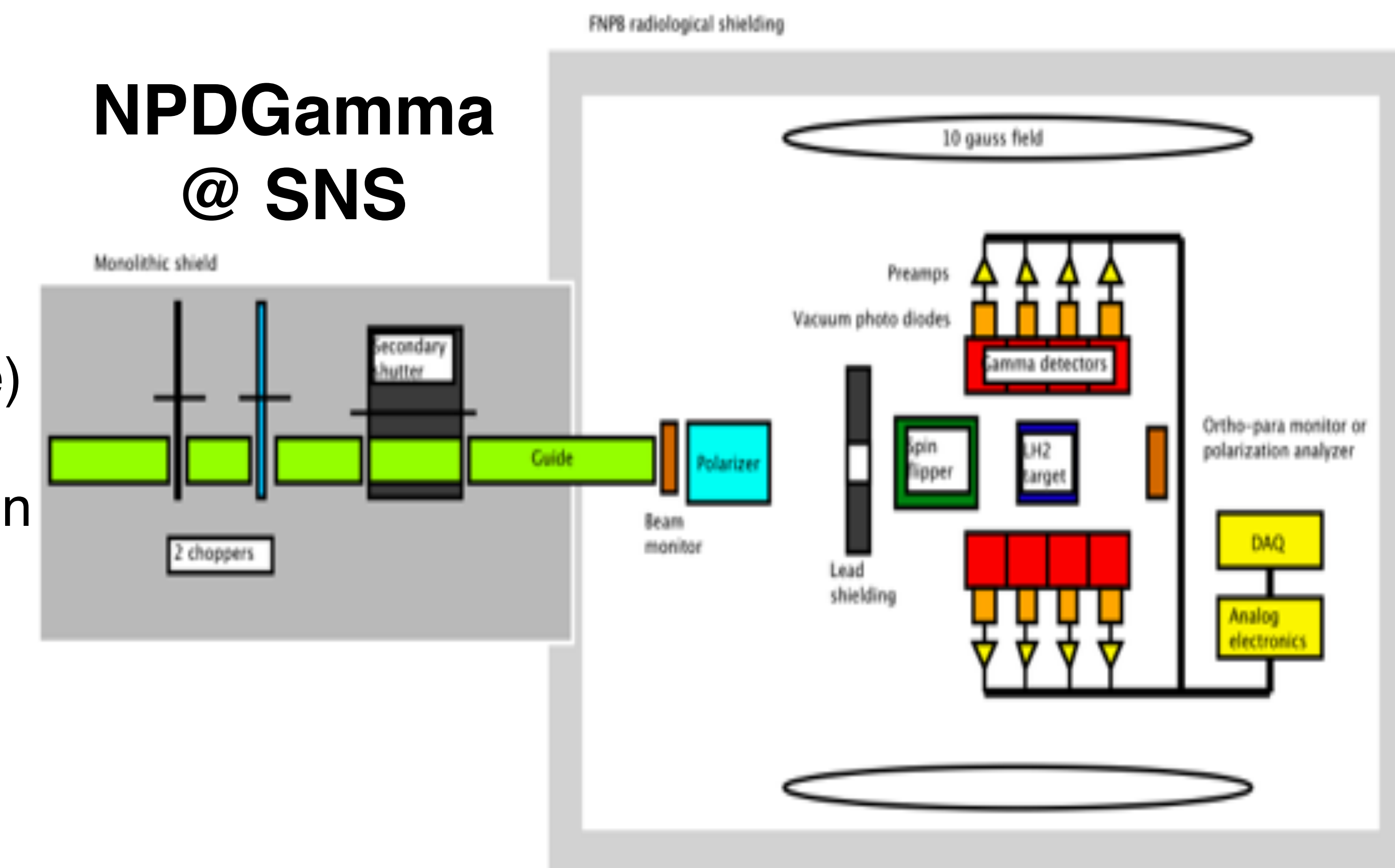
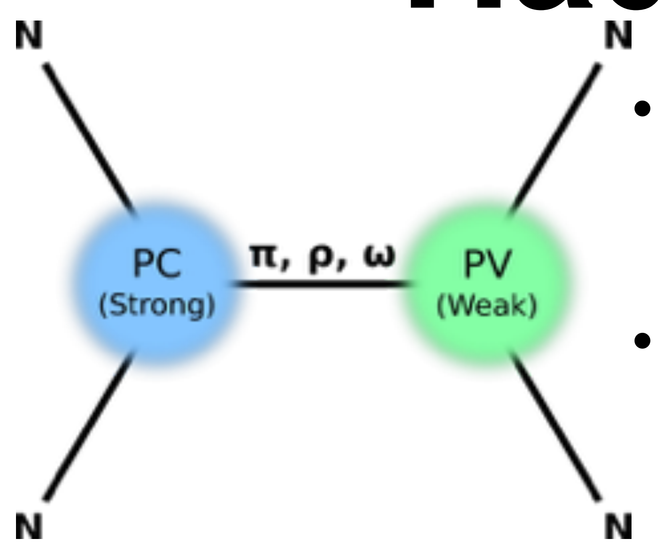
NPDGamma @ SNS



- n + p → d + γ (isolates ΔI=1, long-range)
- Data taking and analysis completed
- Manuscript with main result in preparation
- Uncertainty of <1.35e-8

Hadronic Parity Violation



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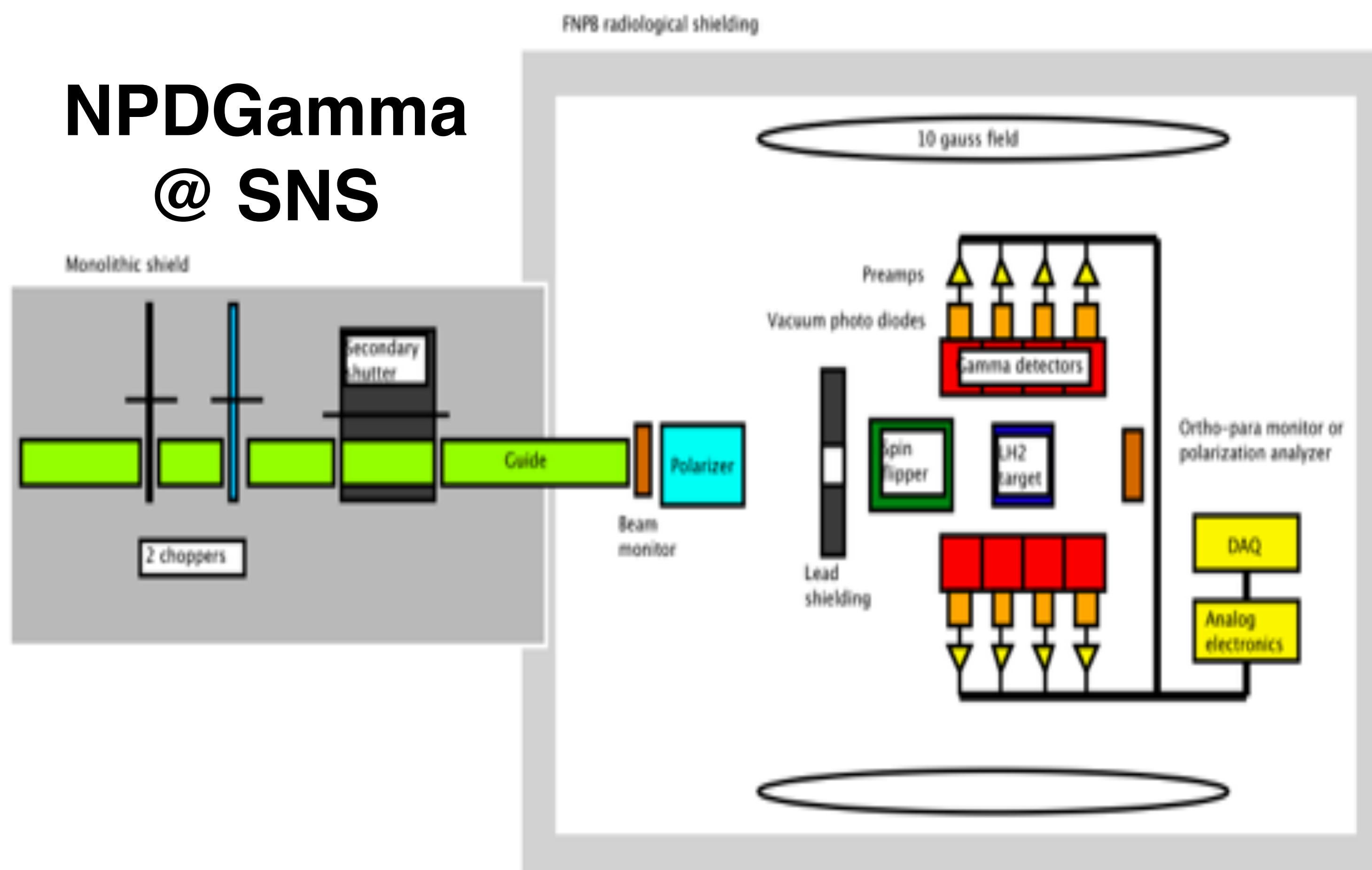
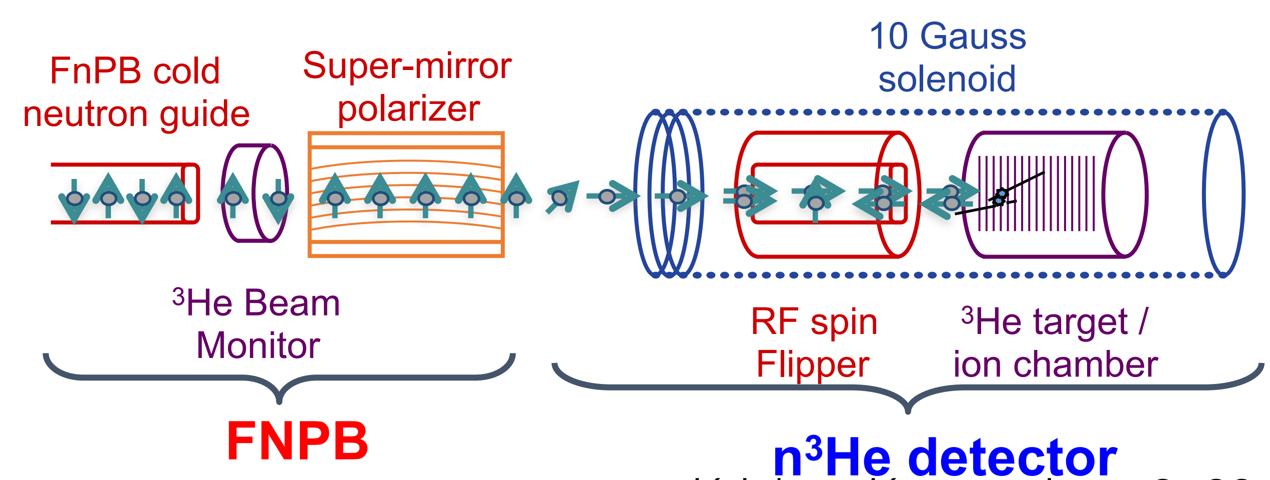
NPDGamma @ SNS



- n + p → d + γ (isolates ΔI=1, long-range)
- Data taking and analysis completed
- Manuscript with main result in preparation
- Uncertainty of <1.35e-8

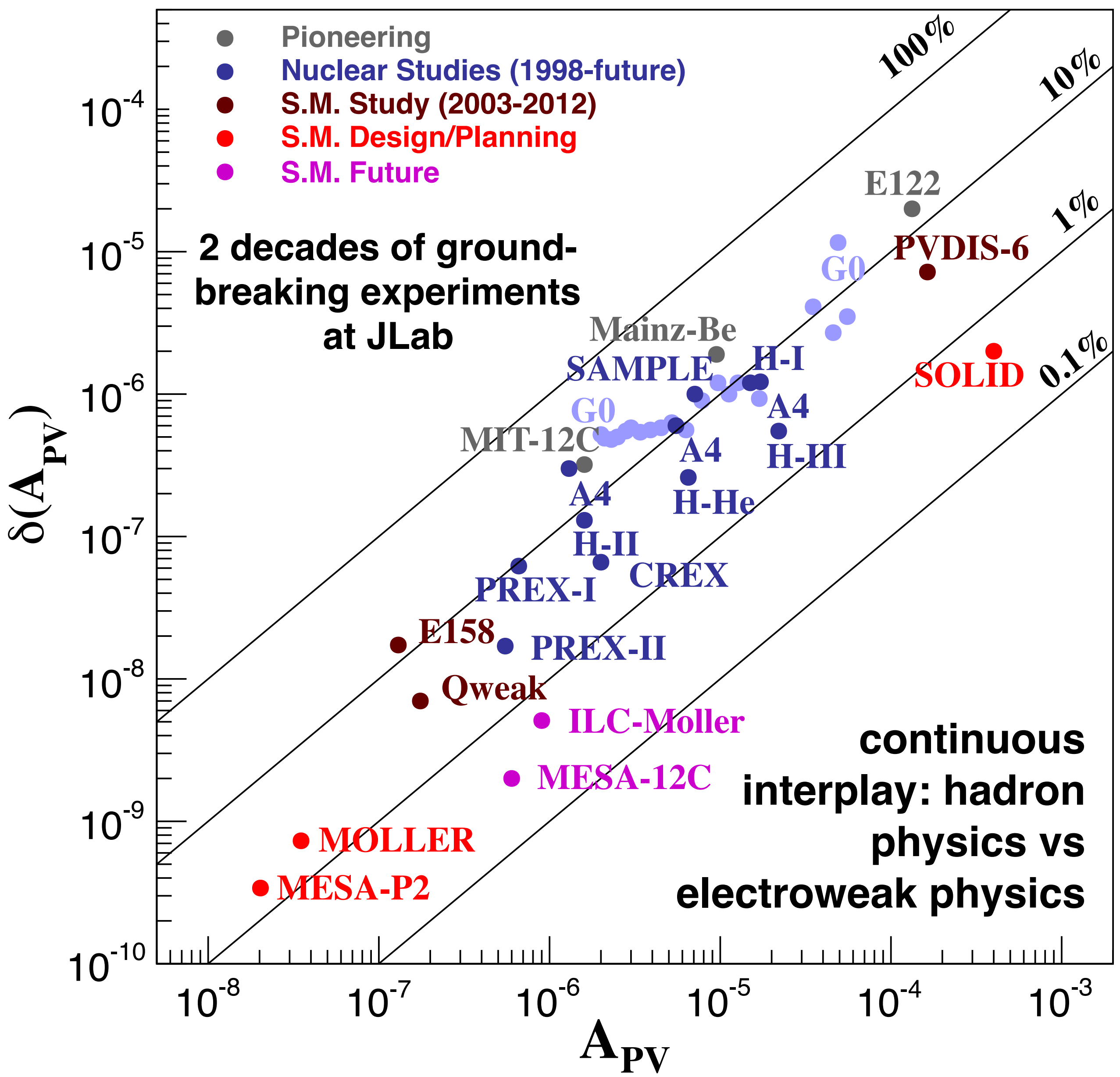
n-He-3 @ SNS

- n +^{3}He → ^{3}H + p
- Data taking completed, analysis in final stages, manuscript in preparation
- Uncertainty of ~1.0e-8

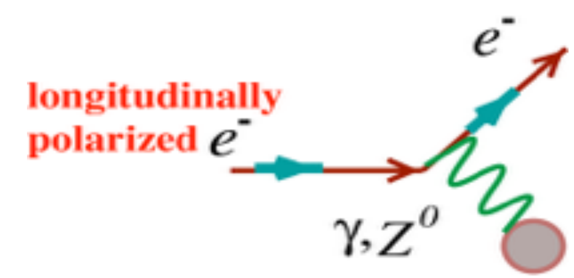


Semi-leptonic and purely leptonic neutral weak interactions at low energy

Parity-Violating Electron Scattering



Steady improvements in JLab accelerator and detector technology



Past Results

- Stringent limits on strange quark form factors
- Neutron skin result by PREX-I: 200+ citations
- PVDIS: first non-zero axial-vector e-q Z coupling

State of the Art

- sub-part per billion statistical reach and systematic control
- sub-1% normalization control

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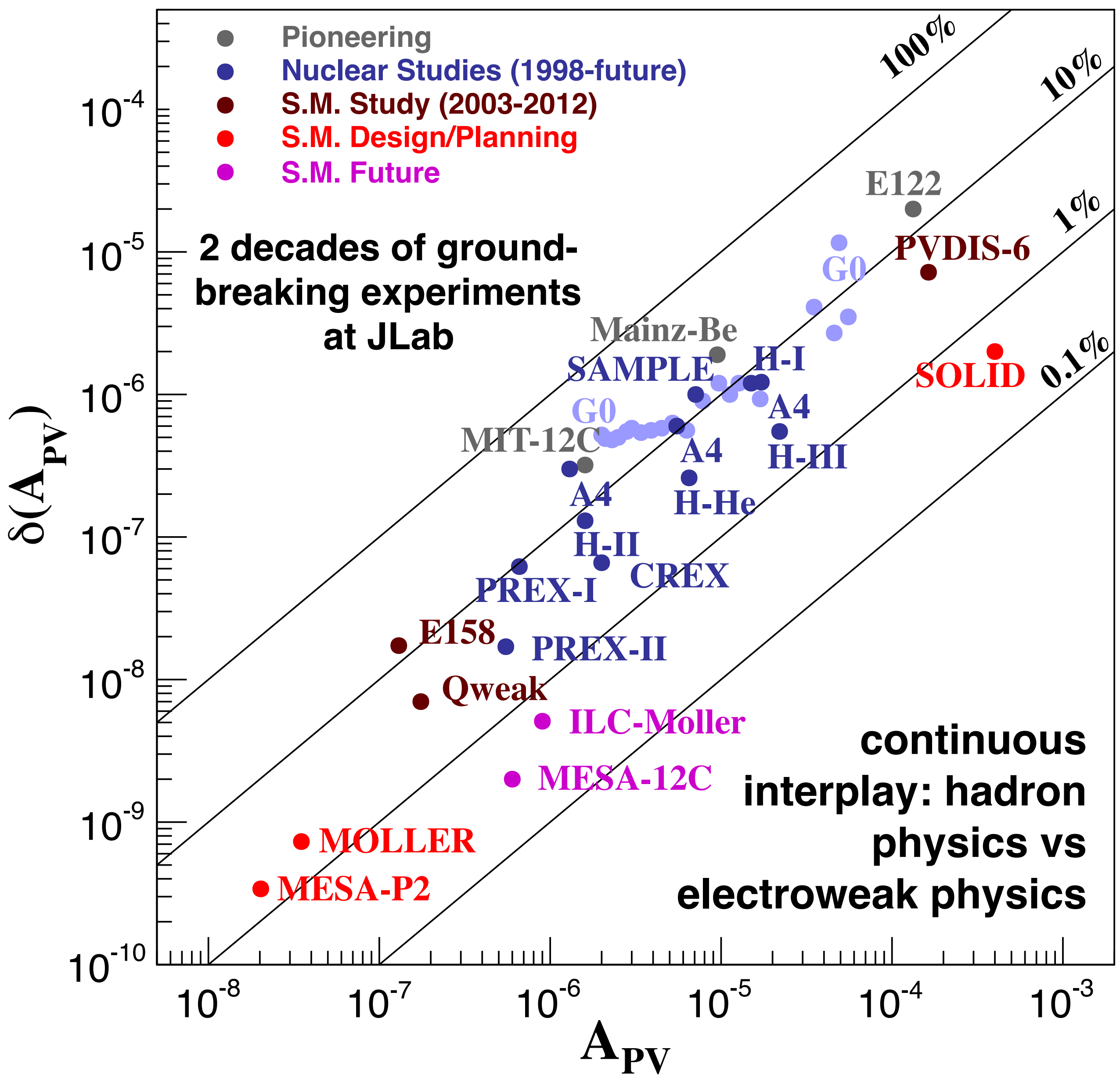

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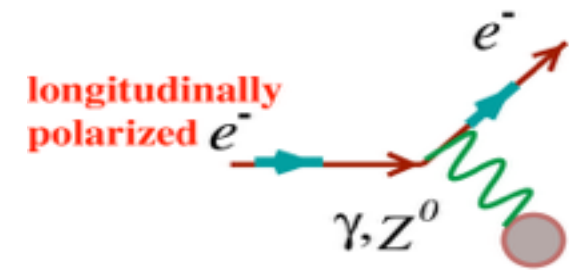

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  - **result unblinded**
  - **publication and high profile conference talks being prepared**

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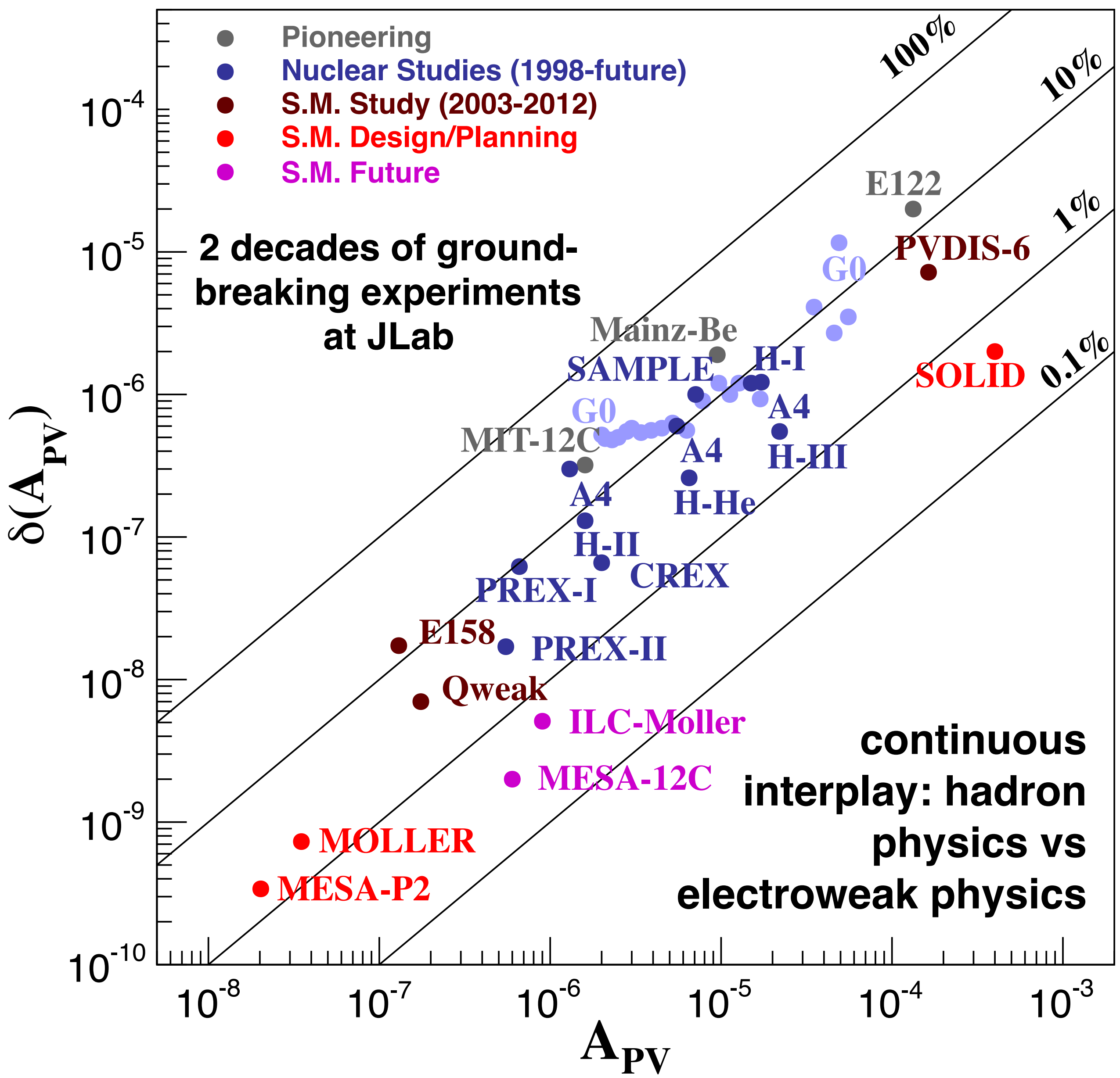

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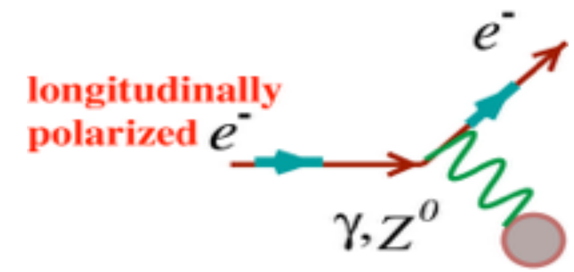

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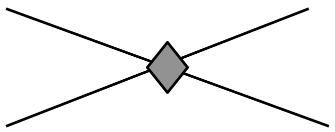
12 GeV Era (the future):

- PREX-II and CREX: anticipated results of broad interest
- MOLLER and SoLID: leverages upgraded beam to enable unprecedented sensitivity for physics beyond the Standard Model

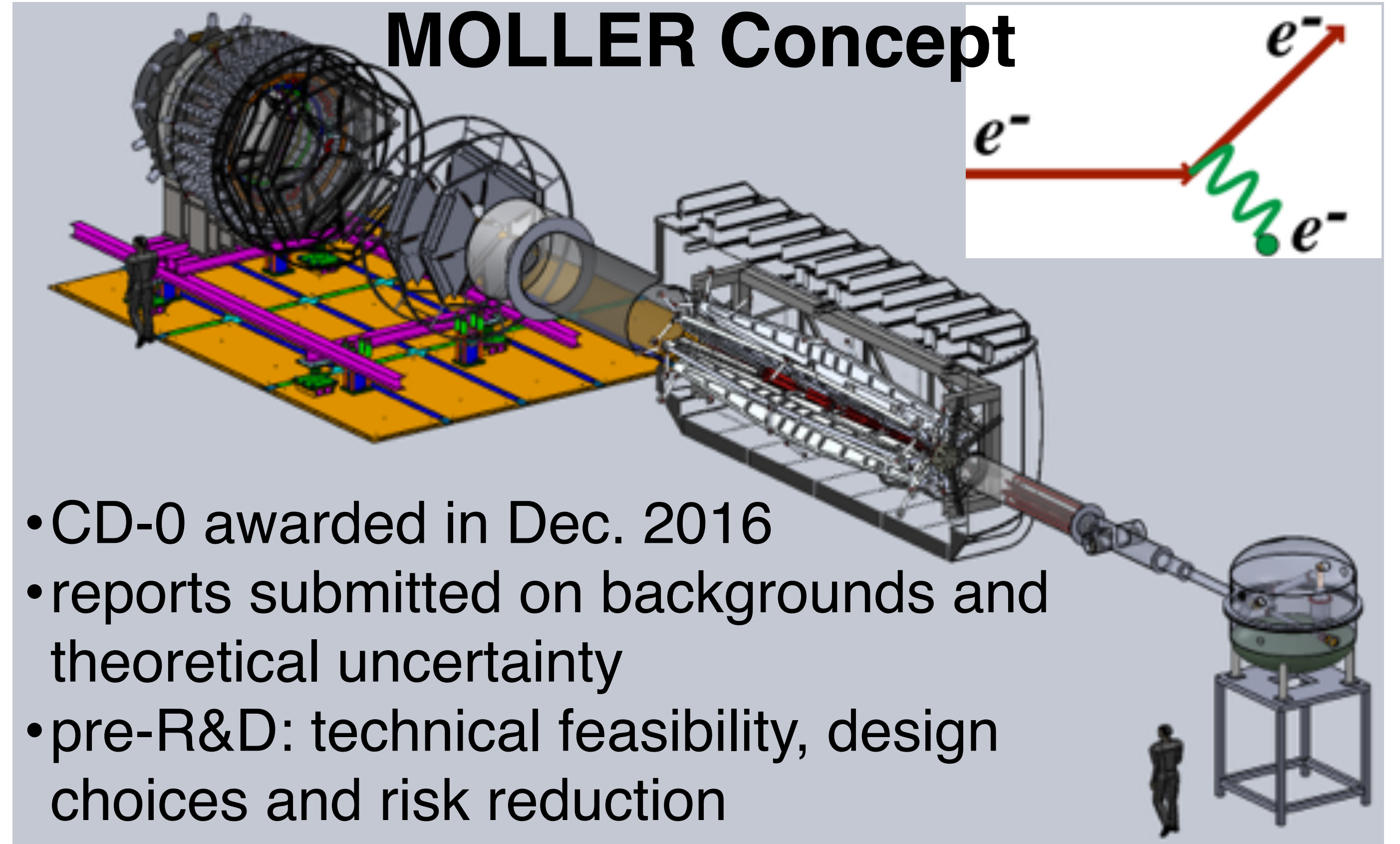
Pre-R&D in progress: tremendous enthusiasm and broad interest

MOLLER & SOLID at JLab



$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

MOLLER discovery reach at level of future linear colliders for four-lepton operators



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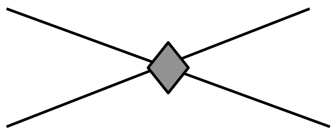

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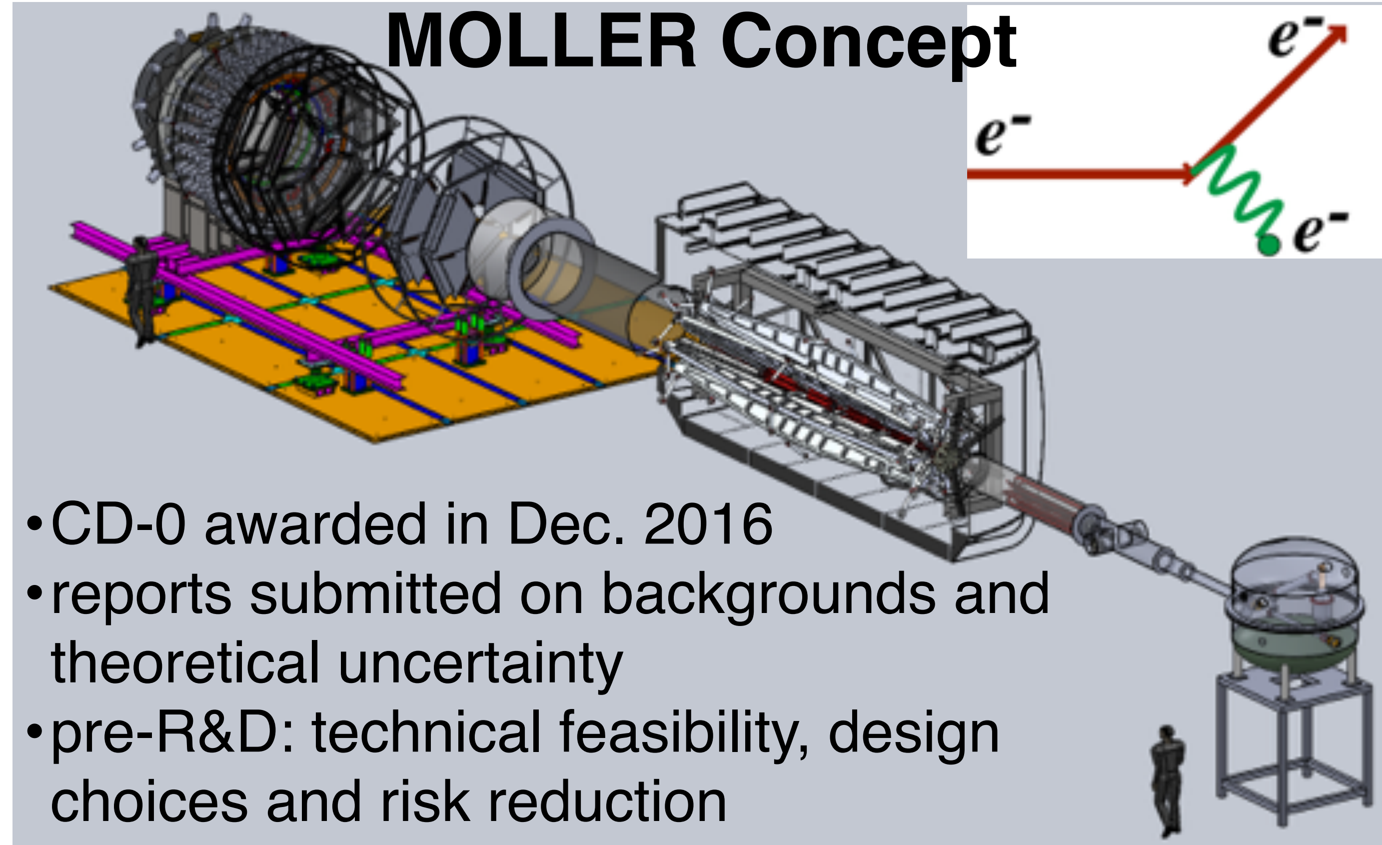

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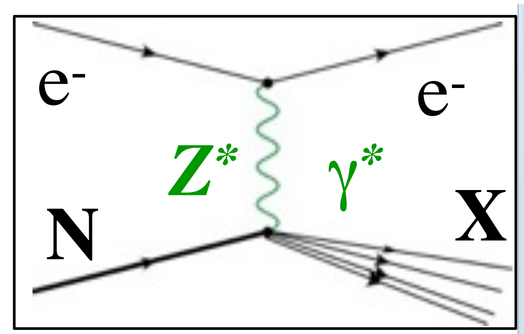
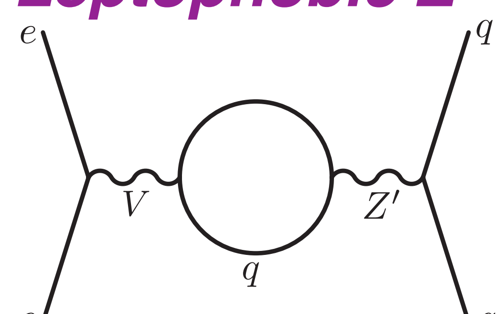
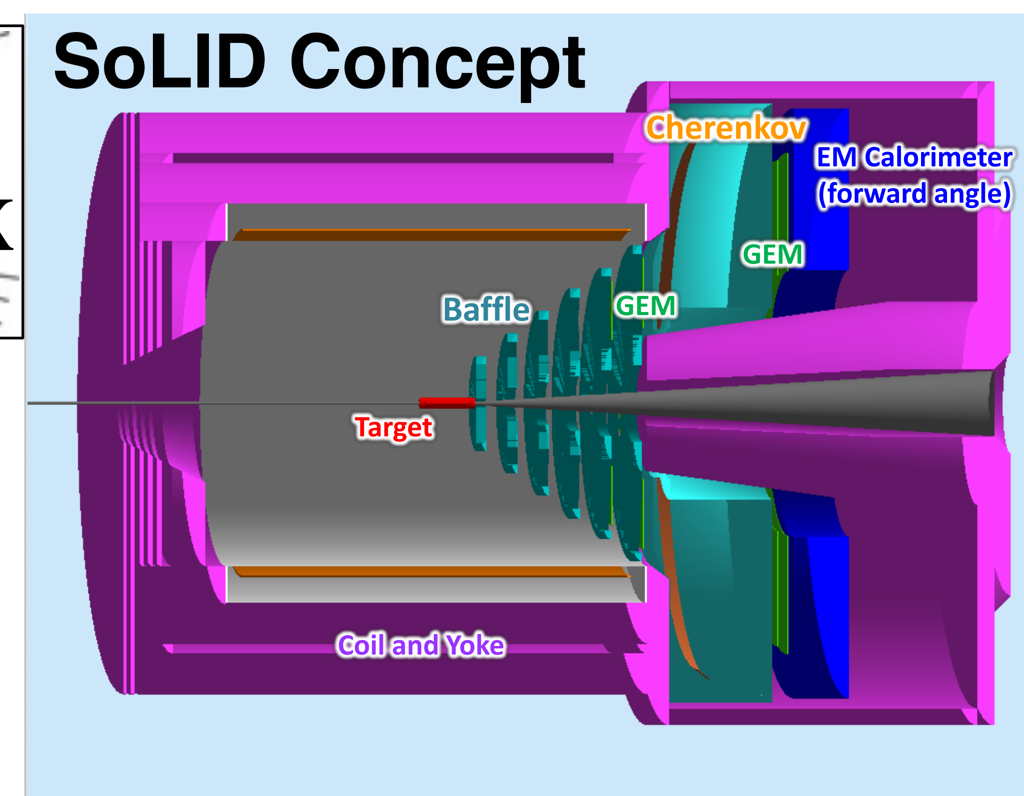
- reports submitted on backgrounds and theoretical uncertainty
- pre-R&D: technical feasibility, design choices and risk reduction



Leptophobic Z'





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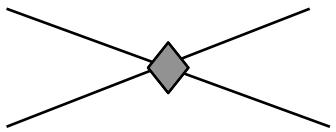

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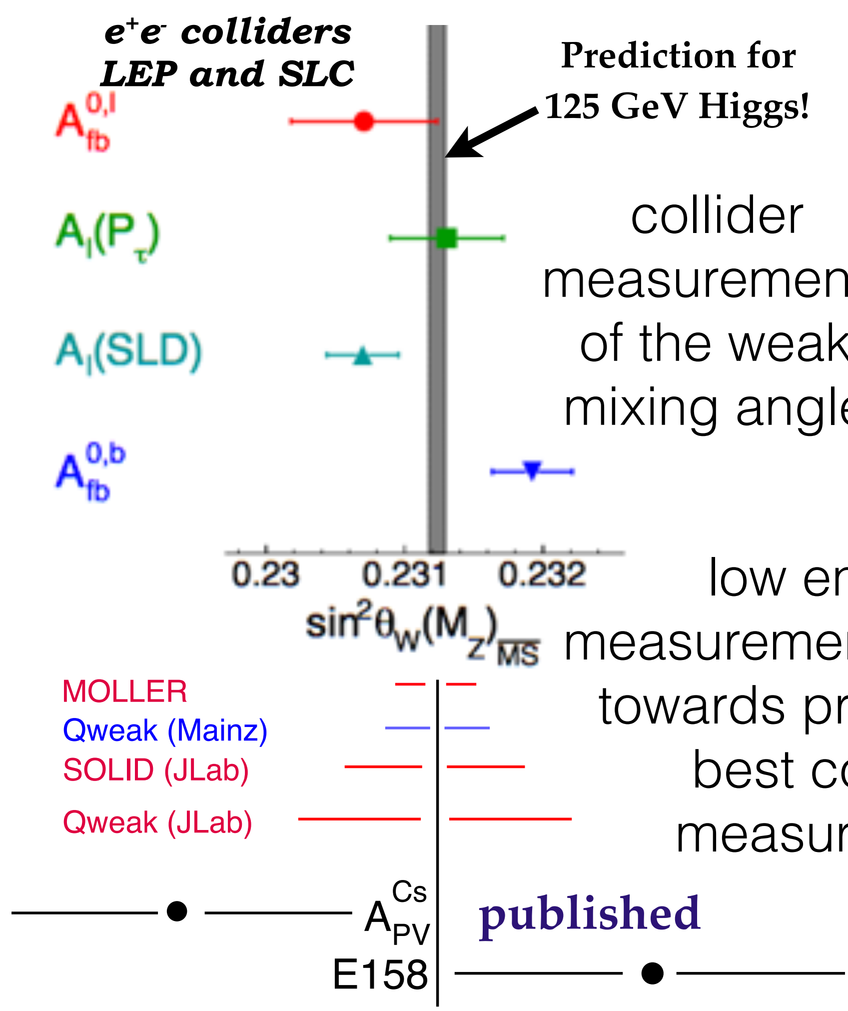
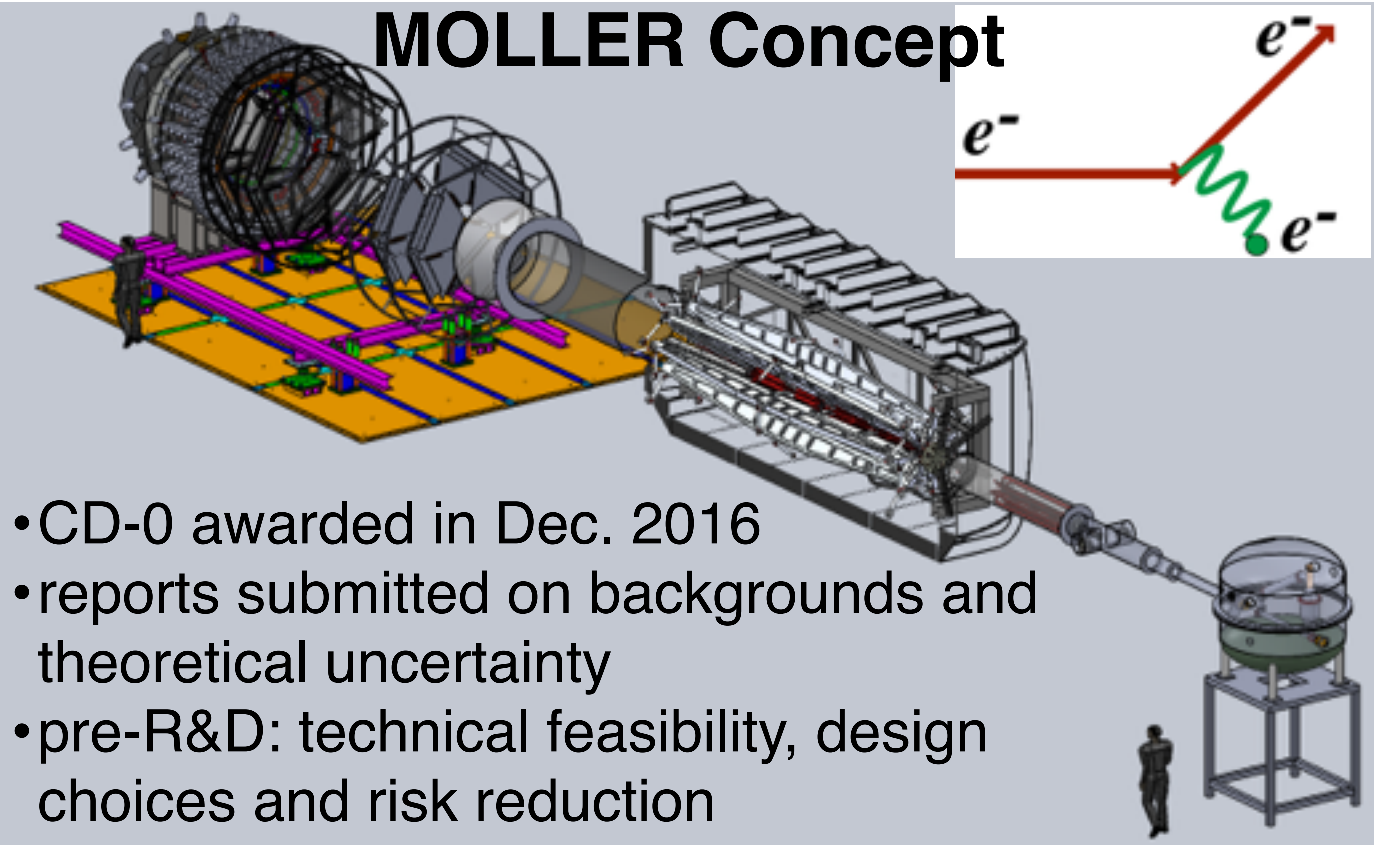
δ(sin²θ_W) = ± 0.00023 (stat.) ± 0.00012 (syst.)

→ ***~ 0.1%***



collider measurements of the weak mixing angle

low energy measurements headed towards precision of best collider measurement



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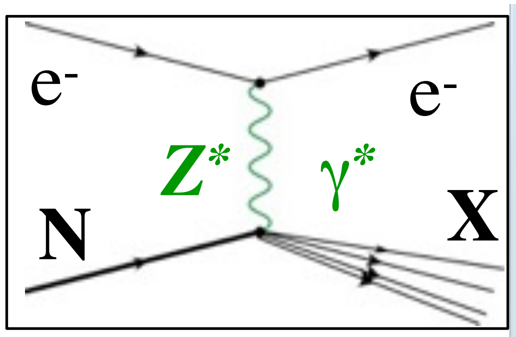

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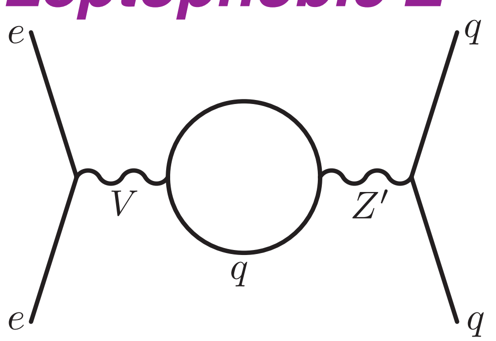

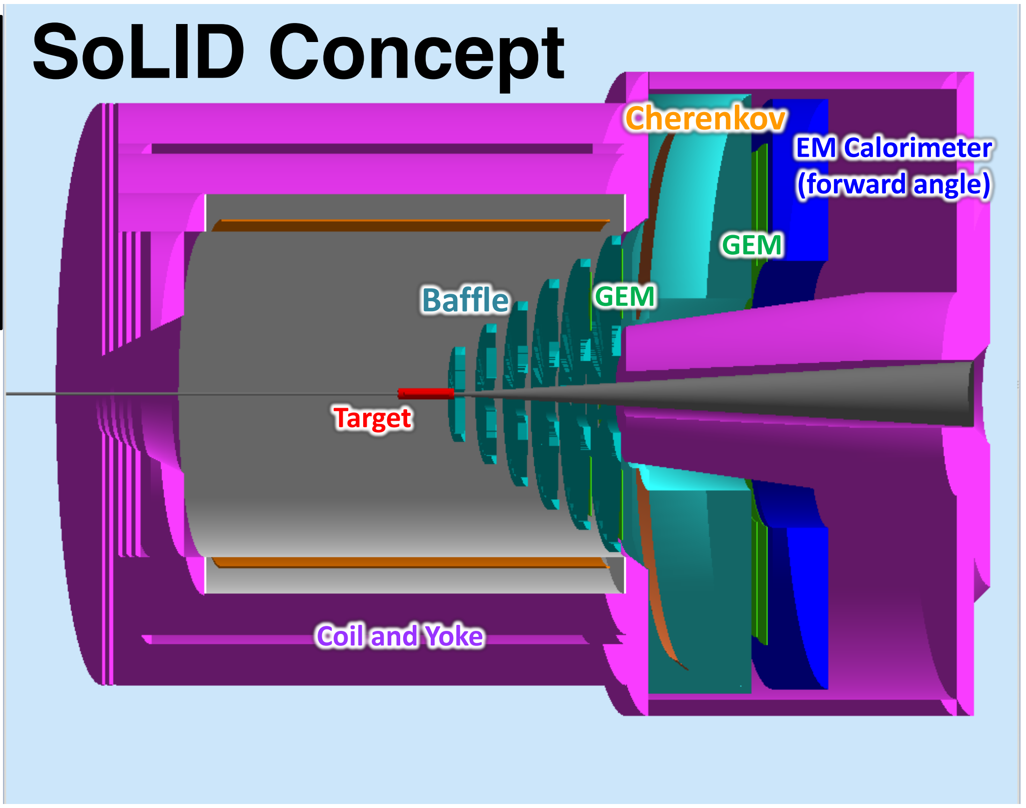

Other Recent Progress

Nuclear Weak Decays

- ^{37}K Beta Asymmetry: A_β measured to 0.3% (Texas A&M, TRIUMF): PRL submission soon
- Progress towards controlling isospin breaking in super-allowed beta decays (Texas A&M)
- Published: β-ν correlation in ^{8}Li to sub-1%: new limits on tensor currents (ANL)
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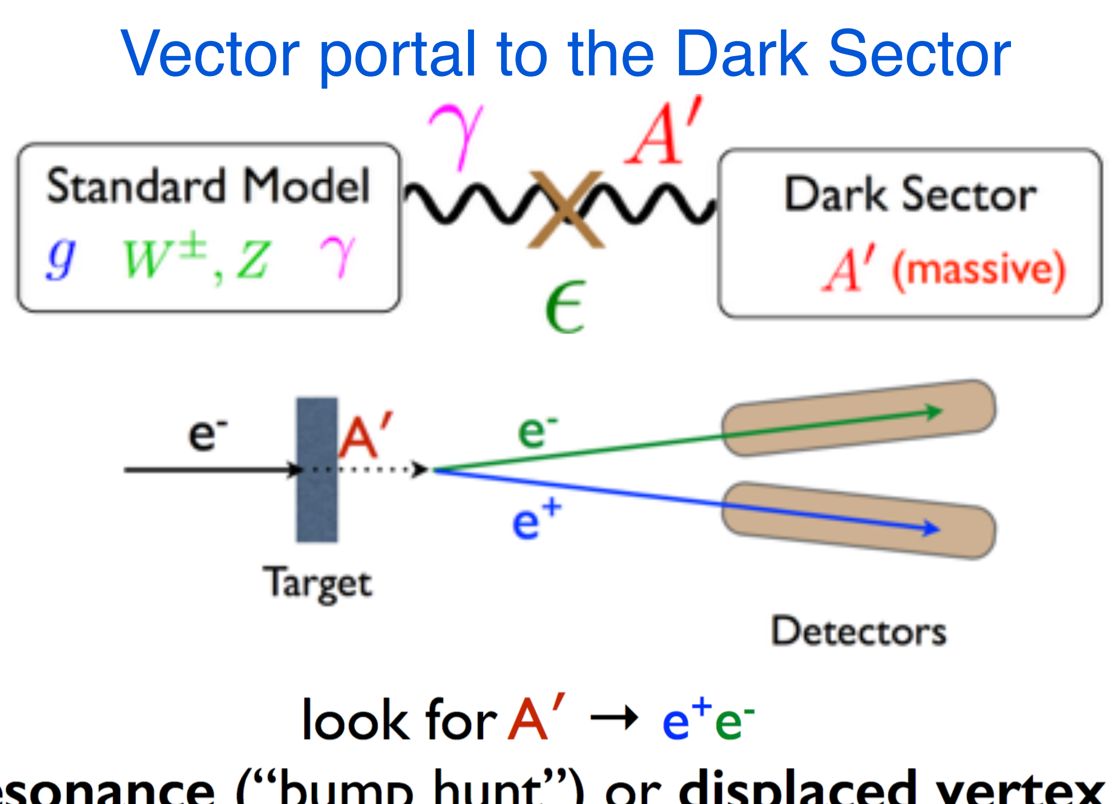
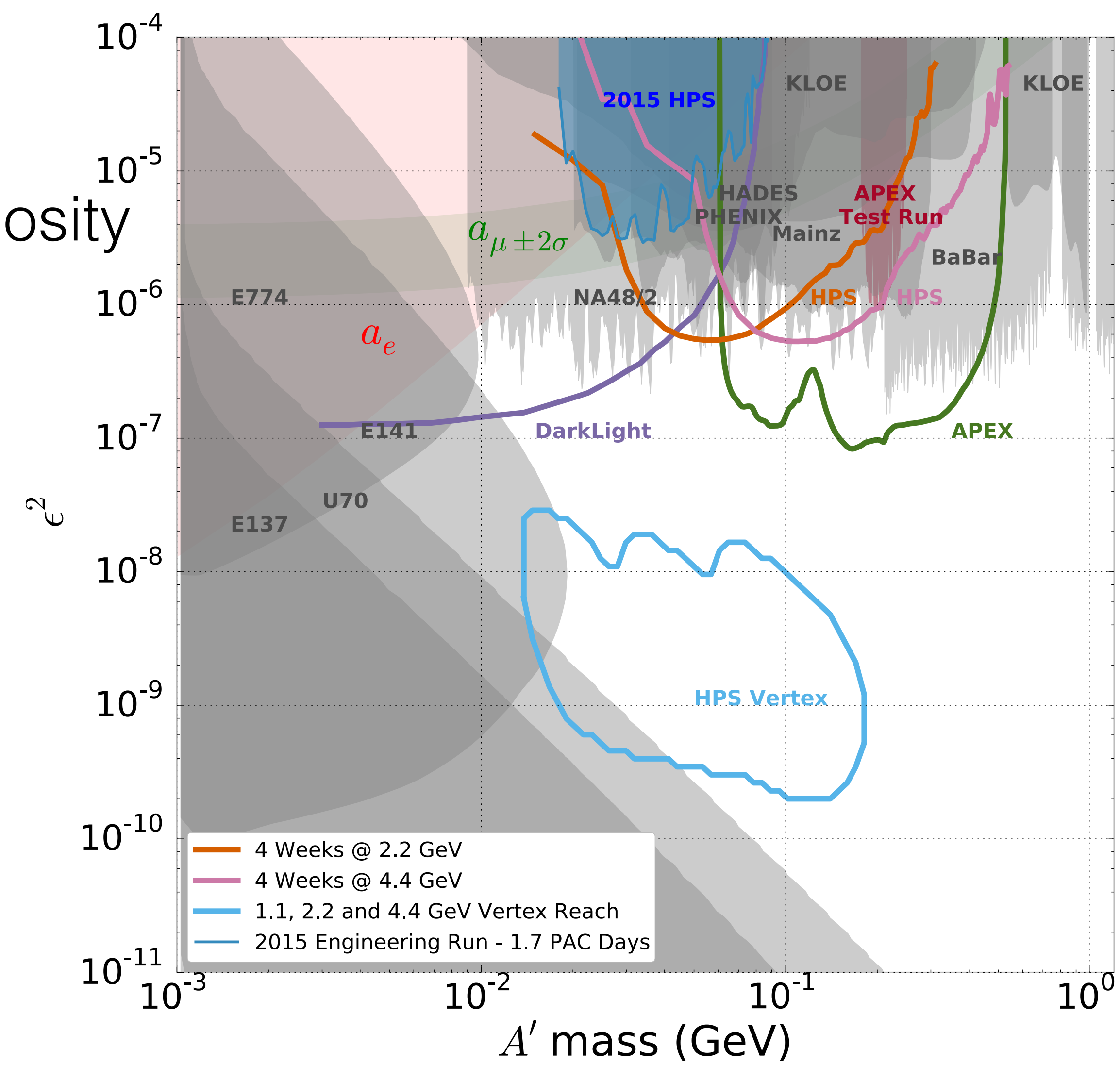
Dark Photon Searches: leveraging JLab luminosity





Conclusion and Outlook

- Fundamental Symmetries and Neutrinos in Nuclear Physics addresses big questions about the origin of all matter in the Universe and its implications for the characteristics of the basic forces of Nature

- A coherent strategy of targeted initiatives has evolved in three broad areas:
  - *The Quest to Understand the Nature of Neutrinos*
  - *The Search for Permanent Electric Dipole Moments*
  - *Further Probes of the New Standard Model*

- A variety of exciting initiatives have "taken off"; interesting results are emerging

- The subfield is enthusiastic about the projects on the "runway", with potential for profound new discoveries and insights into big questions

- In the process, we continue to attract and train talented and motivated students who are becoming leaders at universities, national labs and industry