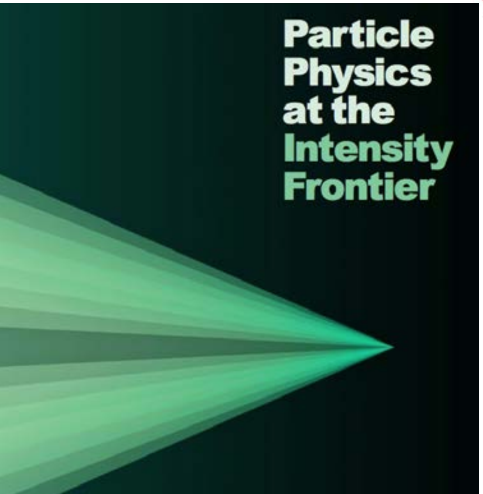
Intensity Frontier Overview

Summary of “CSS2013 Summary” at HEPAP

September 5, 2013; NSF



Particle
Physics
at the
Intensity
Frontier

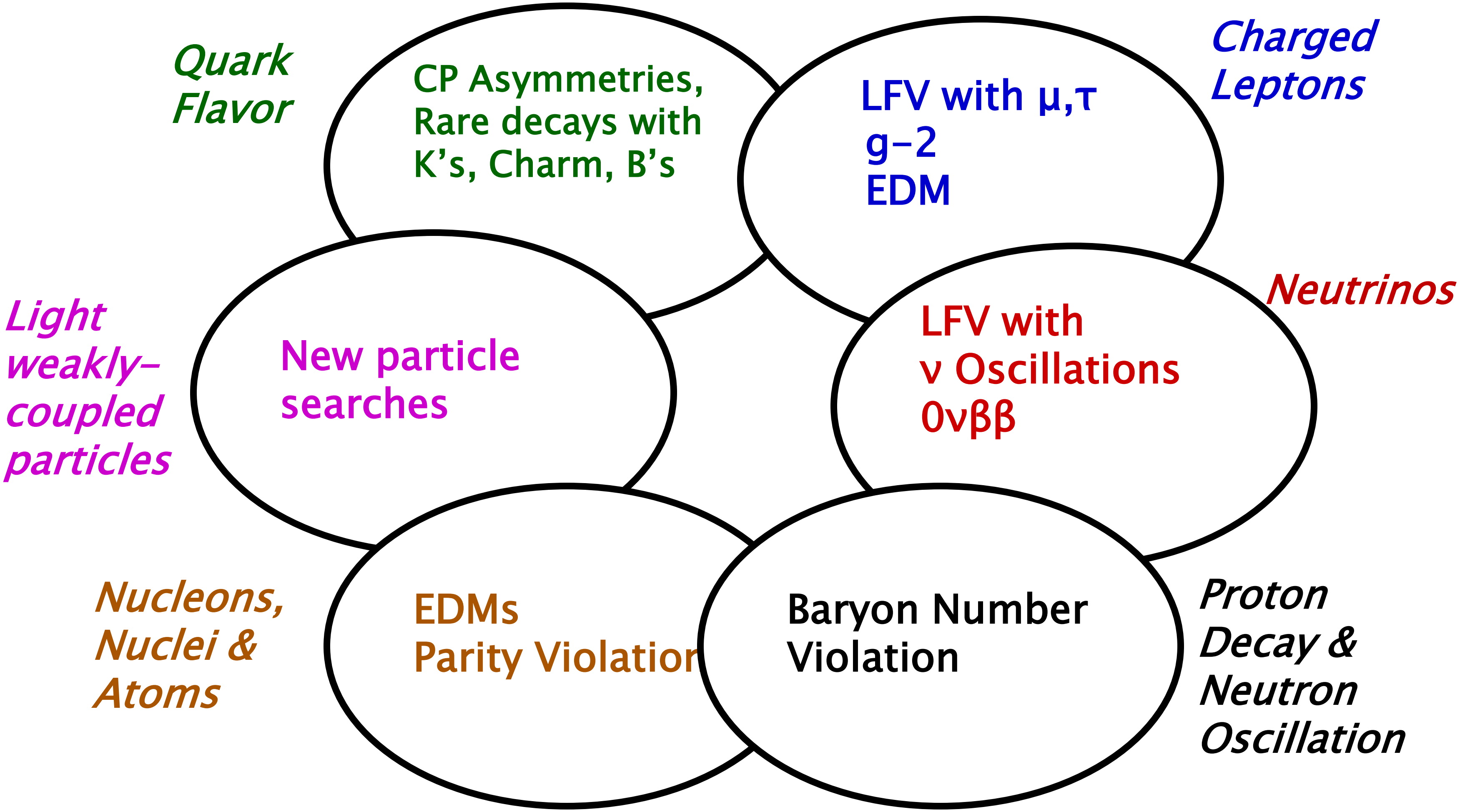
J. Hewett, H. Weerts

BIG thanks to JoAnne who can not be here today

Well deserved vacation on Hawaii

The Intensity Frontier Program

The Intensity Frontier is a broad and diverse, yet connected, set of science opportunities



Quark Flavor

CP Asymmetries,
Rare decays with
K's, Charm, B's

Charged Leptons

LFV with μ,τ
g−2
EDM

Light weakly-coupled particles

New particle
searches

Neutrinos

LFV with
ν Oscillations
0νββ

Nucleons, Nuclei & Atoms

EDMs
Parity Violation

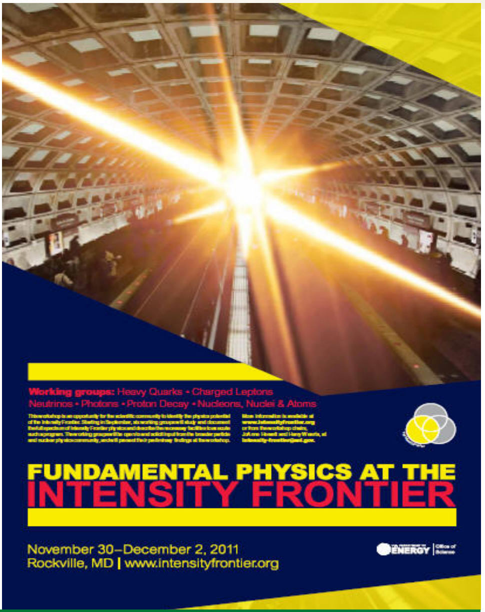
Proton Decay & Neutron Oscillation

Baryon Number
Violation

CSS13 Intensity Frontier Working Groups

Quark Flavor Physics Joel Butler, Zoltan Ligeti, Jack Ritchie	K, D & B Meson decays/properties
Charged Lepton Processes Brendan Casey, Yuval Grossman, David Hitlin	Precision measurements with muons, taus
Neutrinos Andre deGouvea, Kevin Pitts, Kate Scholberg, Sam Zeller	All experiments for properties of neutrinos. Accelerator & non-accel.
Baryon Number Violation Kaladi Babu, Ed Kearns	Proton decay, Neutron Oscillation
New Light, Weakly Coupled Particles Rouven Essig, John Jaros, William Wester	“Dark” photons, paraphotons, axions, WISPs
Nucleons, Nuclei & Atoms Krishna Kumar, Z.-T. Lu, Michael Ramsey-Musolf	Properties of nucleons, nuclei or atoms (EDM), as related to HEP

Intensity Frontier Workshop



Working groups: Heavy Quarks • Charged Leptons
Neutrinos • Photons • Proton Decay • Nucleons, Nuclei & Atoms

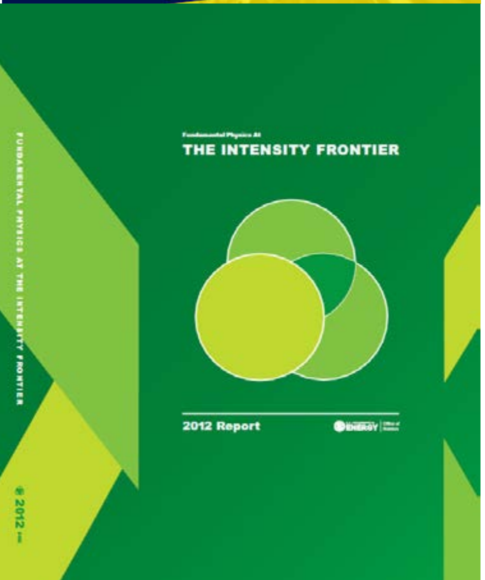
FUNDAMENTAL PHYSICS AT THE
INTENSITY FRONTIER

November 30–December 2, 2011
Rockville, MD | www.intensityfrontier.org

Fundamental Physics at the Intensity Frontier: Rockville, MD Nov 30-Dec 2, 2011

Charge:

Document the science opportunities at the Intensity Frontier, Identify experiments and facilities needed for components of program



Fundamental Physics At
THE INTENSITY FRONTIER

2012 Report

arXiv:1205.2671

Defines Intensity Frontier

Focus mainly on opportunities for this decade

All-hands Intensity Frontier meeting, Argonne National Lab, April 2013

Numerous subgroup meetings during the last year

Intensity Frontier Science

Addresses many of the **Unifying Questions** that came out of Snowmass

(Hadley's HEPAP talk)

Examples of questions addressed by Intensity Frontier:

- Are there sources of CP Violation beyond θ_{CKM}?
- Is there CP Violation in the leptonic sector?
- What are the properties of the neutrino?
- Do the forces unify?
- Is there a weakly coupled Hidden Sector and is it linked to the Dark Side?
- Are apparent symmetries (B,L) violated at high scales?
- What can we learn about the flavor sector of new physics?
- What is the new physics mass scale?

Exploring High Energy Scales

- **Precision measurements @ Intensity Frontier explore high mass scales via indirect effects**

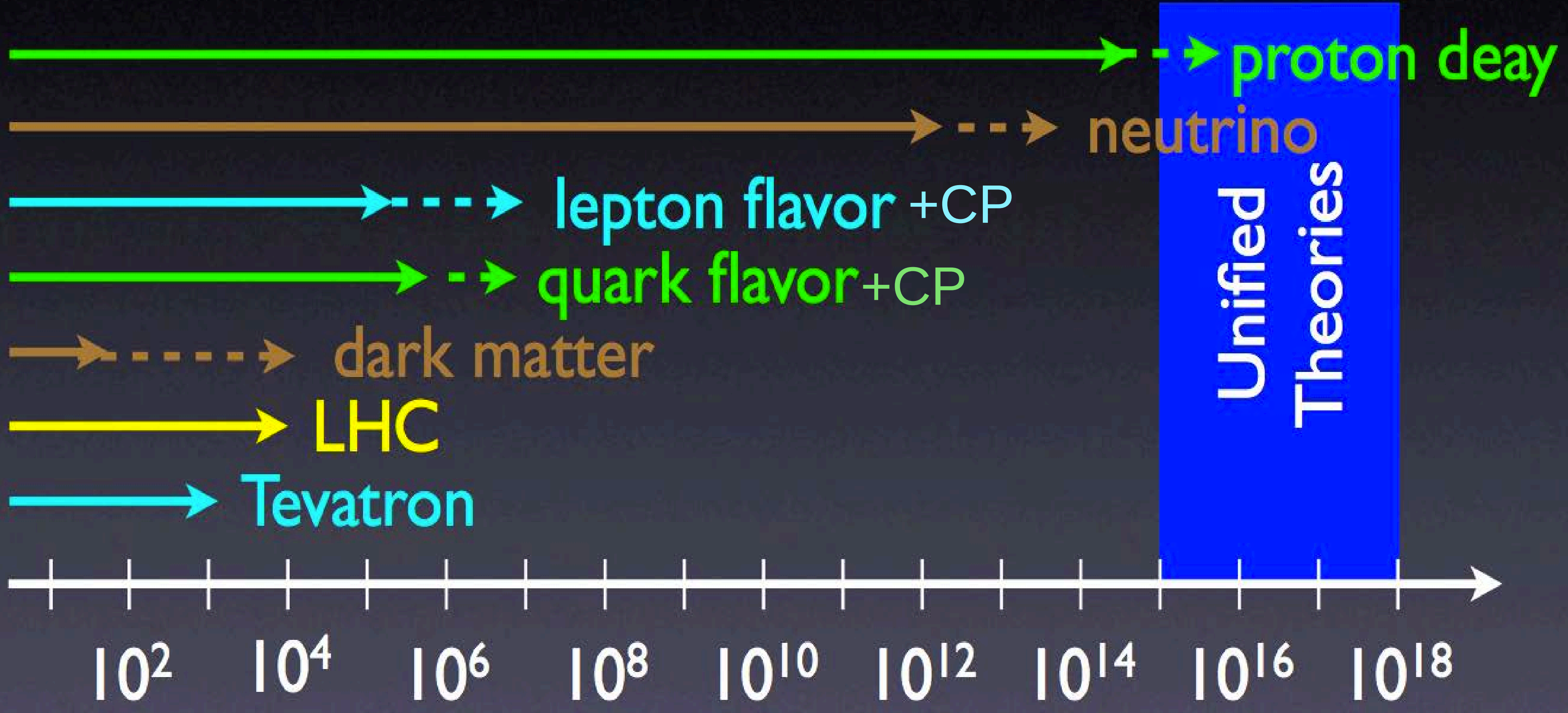
Flavor Physics: New physics & SM both appear @ loop-level

$$\mathcal{A} = \mathcal{A}_0 \left[\frac{c_{SM}}{M_W^2} + \frac{c_{NP}}{\Lambda^2} \right]$$

Neutrinos: Only Dim-5 operator allowed by SM symmetries

$$\frac{1}{\Lambda}(y_\nu LH)(y_\nu LH) + h.c. \quad \rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda^2} \overline{\nu_L} \nu_R^c$$

Power of Expedition

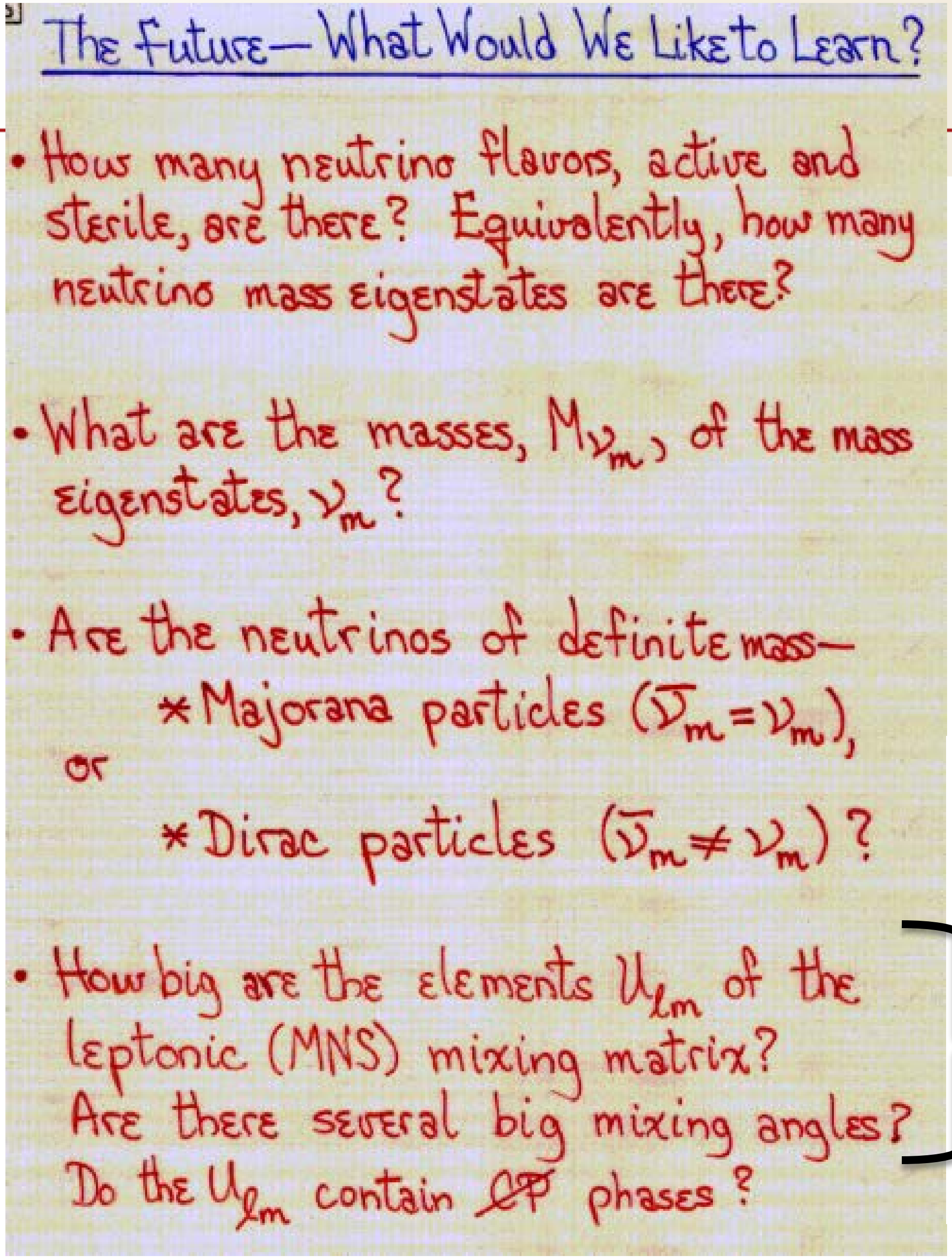


Λ experimental reach [GeV]

(with significant simplifying assumptions)

courtesy Ligeti/Murayama

Snowmass 2001

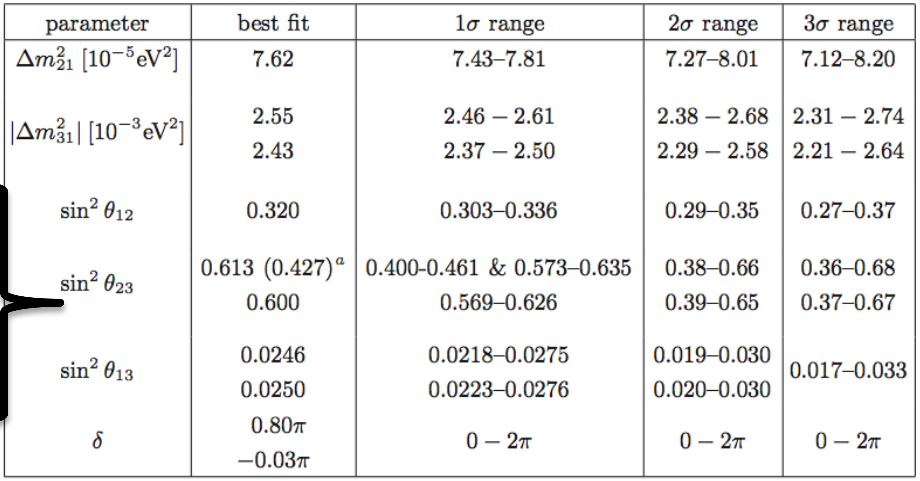


The Future — What Would We Like to Learn?

- How many neutrino flavors, active and sterile, are there? Equivalently, how many neutrino mass eigenstates are there?
- What are the masses, M_{ν_m}, of the mass eigenstates, ν_m?
- Are the neutrinos of definite mass —
  - * Majorana particles ($\bar{\nu}_m = \nu_m$),

  or
  - * Dirac particles ($\bar{\nu}_m \neq \nu_m$)?
- How big are the elements $U_{\ell m}$ of the leptonic (MNS) mixing matrix? Are there several big mixing angles? Do the $U_{\ell m}$ contain $\not{C}\not{P}$ phases?

- neutrino summary from Snowmass 2001 (Boris Kayser)



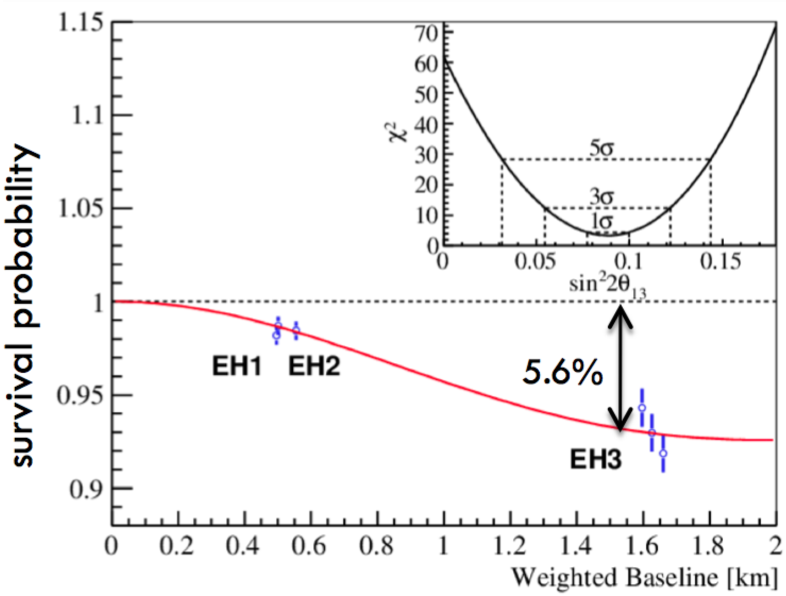
parameter	best fit	1σ range	2σ range	3σ range
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.62	7.43–7.81	7.27–8.01	7.12–8.20
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	2.55 2.43	2.46 – 2.61 2.37 – 2.50	2.38 – 2.68 2.29 – 2.58	2.31 – 2.74 2.21 – 2.64
$\sin^2\theta_{12}$	0.320	0.303–0.336	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	0.613 (0.427)[a] 0.600	0.400-0.461 & 0.573–0.635 0.569–0.626	0.38–0.66 0.39–0.65	0.36–0.68 0.37–0.67
$\sin^2\theta_{13}$	0.0246 0.0250	0.0218–0.0275 0.0223–0.0276	0.019–0.030 0.020–0.030	0.017–0.033
δ	0.80π -0.03π	$0 - 2\pi$	$0 - 2\pi$	$0 - 2\pi$

(arXiv:1205.4018)

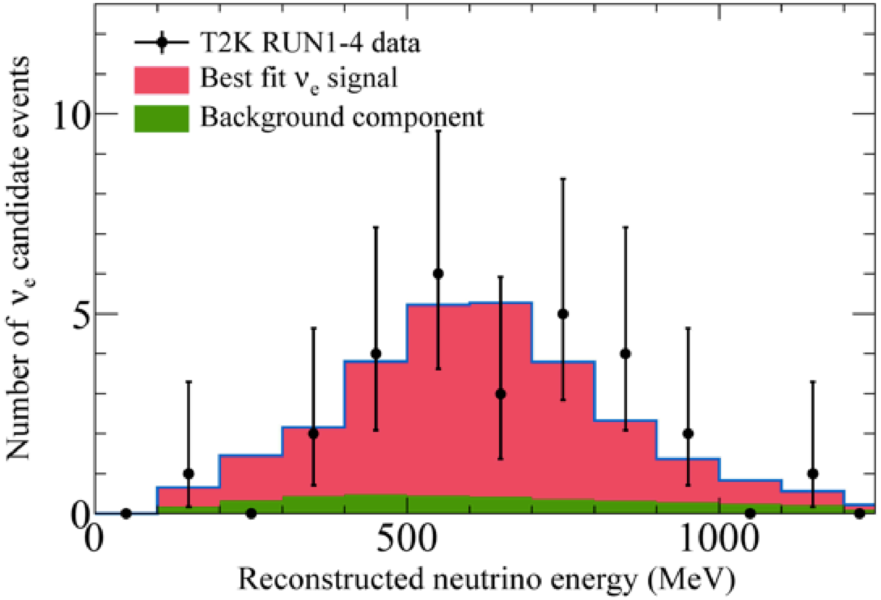
The new era of precision neutrino physics

- We are entering the era of precision neutrino physics

Daya Bay: anti-ν_e disappearance



T2K: nue appearance



Neutrino Oscillations

- Successful measurement of the last mixing angle (θ_{13}) has recently provided some important clarity
- ➔ we now know where we want to go
- We have a clear path forward both for precision tests of the 3-flavor paradigm and exploration of anomalies building off of these successes
  - There is an established program to measure the CP violating phase, mass hierarchy and 0vββ
- Given the challenges associated with precision measurements in the neutrino sector, complementary baselines, sources, and detection techniques will be required to piece together a sharp picture, as well as probe new phenomena

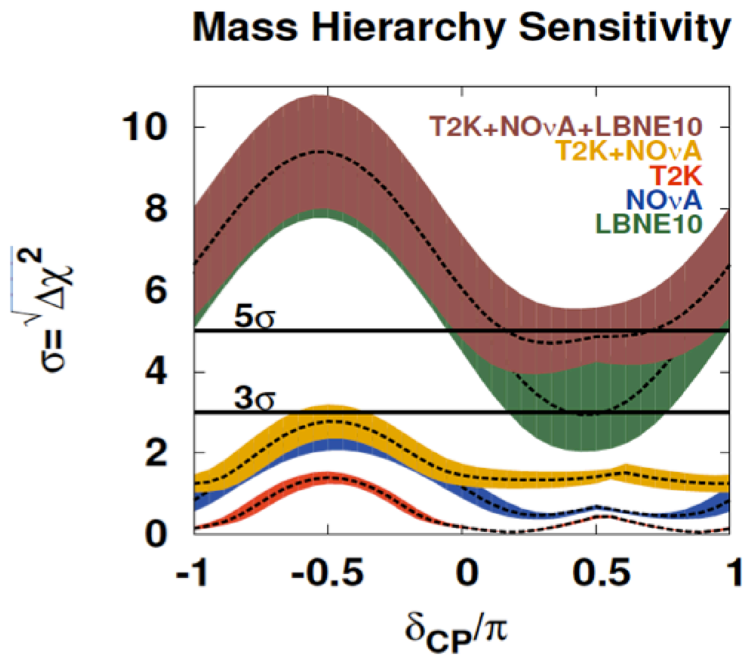
Neutrino Oscillations

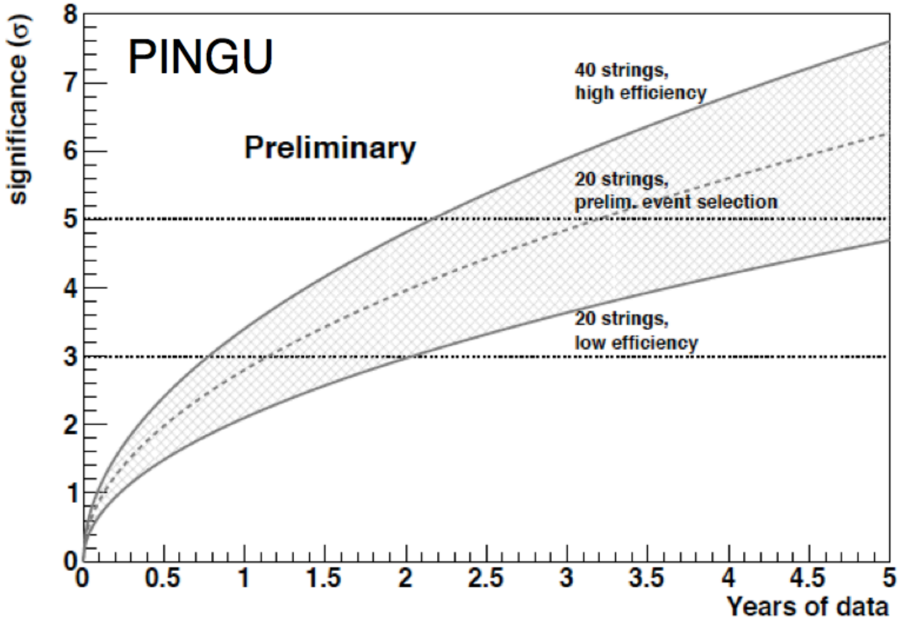
- The U.S. with the Long-Baseline Neutrino Experiment (LBNE) and a future multi-megawatt beam from Project-X is uniquely positioned to lead an international campaign to test the 3-flavor paradigm, measure CP violation and go beyond.
- An underground location for a far detector significantly enhances the physics breadth & allows for the study of atmospheric ν's, nucleon decay, & precision measurement of ν's from a galactic supernova explosion

This is now considered phase I

- Next-next generation experiments will require a qualitatively better neutrino beam. Options include neutrinos from muon storage rings (NuMAX) and very intense sources of pion decay at rest (DAEδALUS)

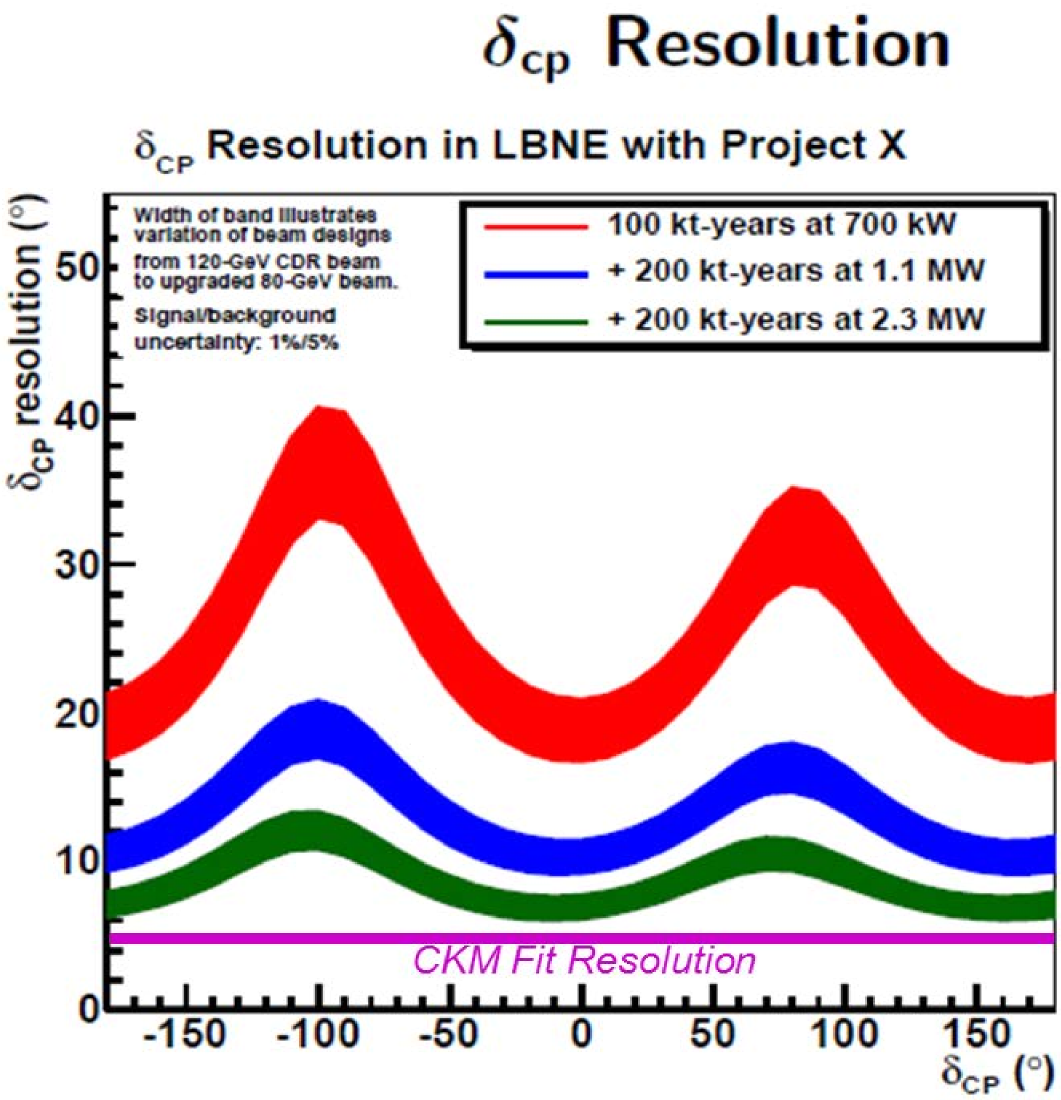
Mass hierarchy





- MH determination by long-baseline experiments “guaranteed” with sufficient exposure
- Other possibilities are promising; systematics challenging
  - PINGU IceCube infill: atmospheric neutrinos
  - JUNO/RENO-50 reactor experiments
- There could also be information from cosmology

CP Violation @ LBNE



LBNE + Project X enable an era of high-precision neutrino oscillation measurements.

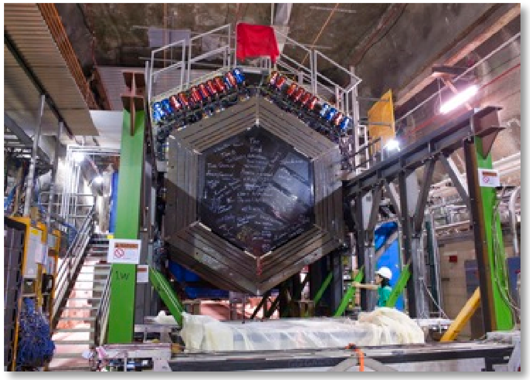
Neutrino Anomalies

- The confirmation of any of the existing anomalies would change the course of neutrino research, for example by discovering new neutrino states.
- Anomalies can be addressed by variety of experimental approaches, and sources including reactors, accelerators and radioactive isotopes.
- Clarifying the nature of the existing short-baseline neutrino anomalies is important → we need definitive reactor, source, and accelerator-based experiments
- Given the experiments that are already being prepared, we can anticipate significant progress before the next "Snowmass"

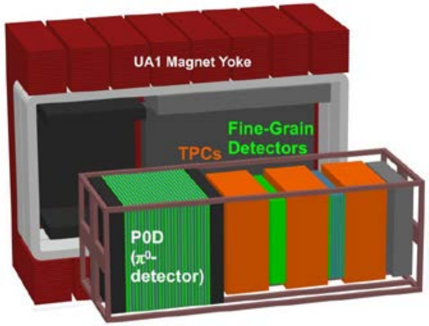
  - next 3-5 years: MicroBooNE, MINOS+, radioactive source experiments, new reactor measurements

Study of Neutrino Interactions

- We need to fully characterize neutrino-matter interactions to enable deeper understanding of ν oscillations, supernova dynamics, and dark matter searches. Studies of ν interactions in themselves also serve as standard model tests and as important probes of nuclear structure.
- These activities can be pursued in “near detectors” associated with large long-baseline projects or alongside R&D projects related to next-next generation neutrino beams.

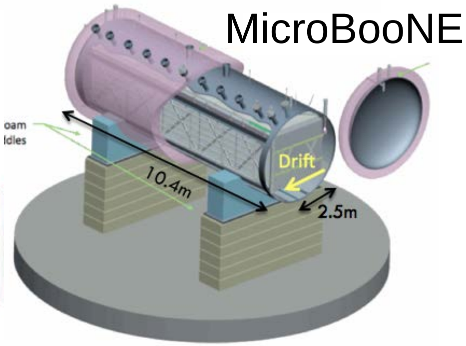


MINERvA

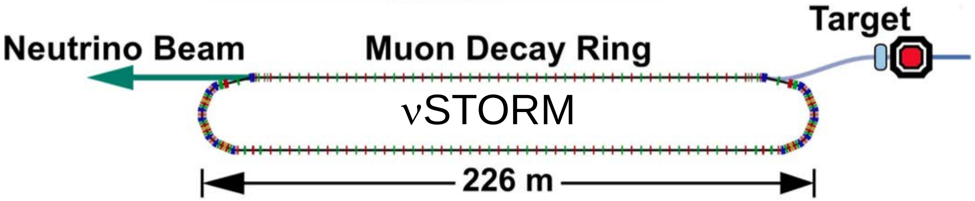


T2K
ND280

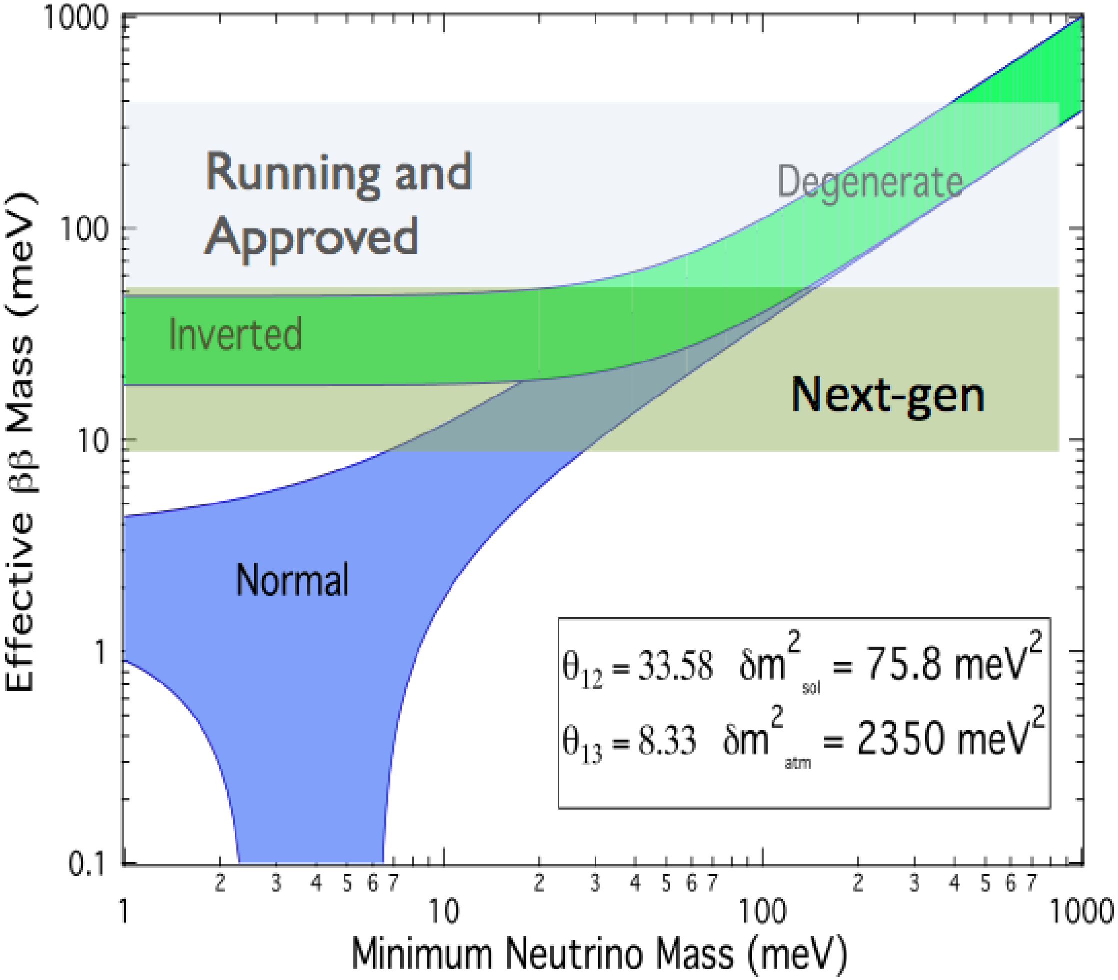
MicroBooNE



NOvA ND



Goals for Next Generation 0νββ



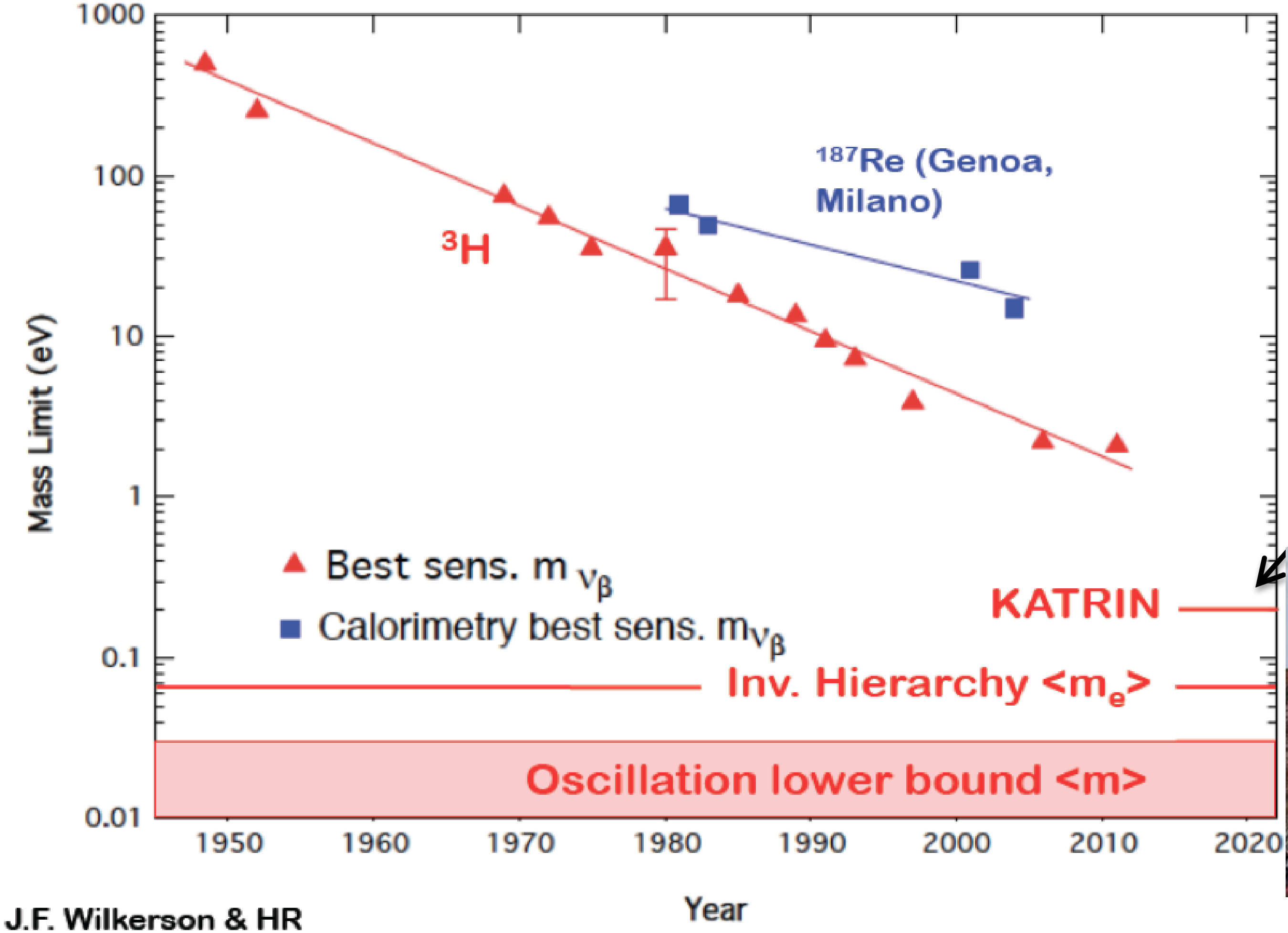
- current technology demos ~100kg scale running

- next generation 0νββ experiments (ton scale) must cover the entire allowed region of the inverted hierarchy

- also allows us to pick a technology for the future

(L. Kaufman, CSS2013)

Direct Neutrino Mass Measurements



J.F. Wilkerson & HR

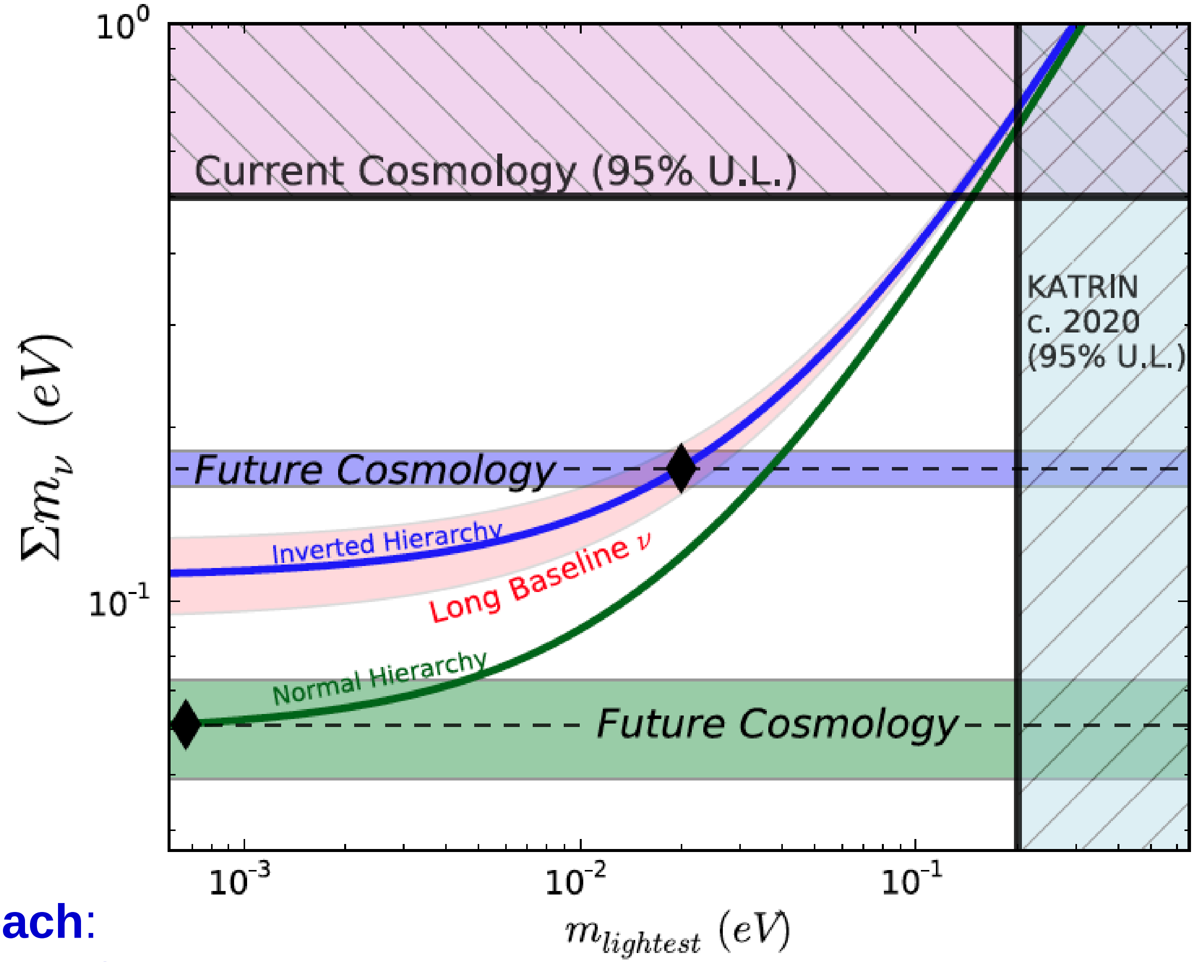
have been doing this since the 1950’s

where we are headed

(Hamish Robertson, Friday session)

experiments in R&D to push beyond this
Project 8, ECHo, PTOLEMY

Neutrinos and Cosmology



Already shown in CF summary

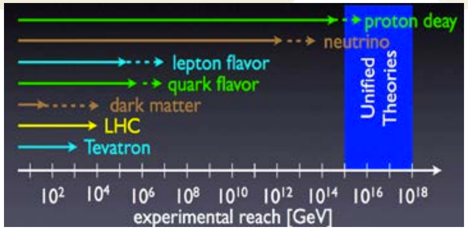
Projected Reach:
2013-2016: Σm_ν ~0.1 eV
2016-2020: Σm_ν ~ 0.06 eV
2020-2025: Σm_ν ~ 16 meV

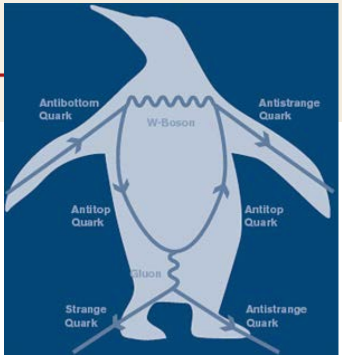
Complementarity !

New Physics Flavor Problem

New physics is constrained by flavor physics observables

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C_{\text{NP}}}{\Lambda^2} O_{ij}$$



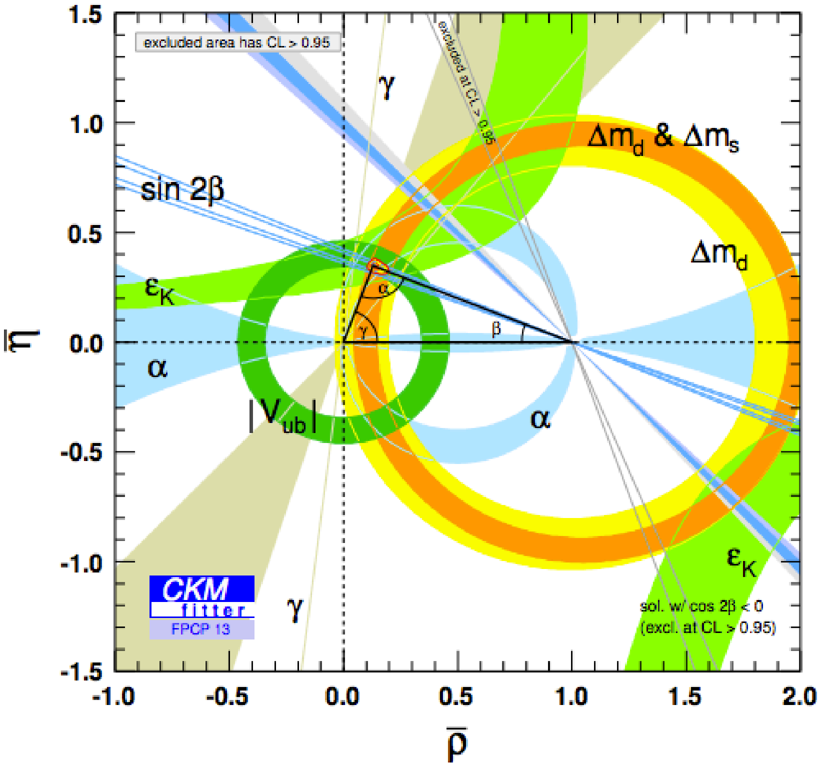


ΔF=2 Operator	Bounds on Λ [TeV] $(C=1)$		Bounds on C $(\Lambda = 1\,\text{TeV})$		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

If there is new physics at the TeV scale, its flavor sector is unnatural

Status of the CKM Fit

- The level of agreement between the measurements is often misinterpreted
- Allowed region is much larger if NP is included in the fit, more parameters, which changes the fit completely
- $\mathcal{O}(20\%)$ NP contributions to most loop processes (FCNS) are still allowed



- Need experimental precision and theoretical cleanliness to increase NP sensitivity

Talk by Z. Ligeti

New Physics in $B_{d,s}$ Mixing

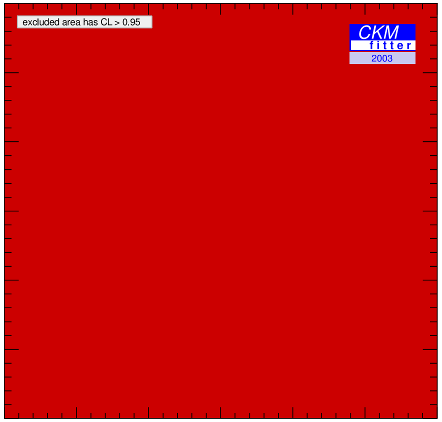
Let $M_{12} = M_{12}^{SM}$ x $(1+he^{2i\sigma})$

New physics
in amplitude

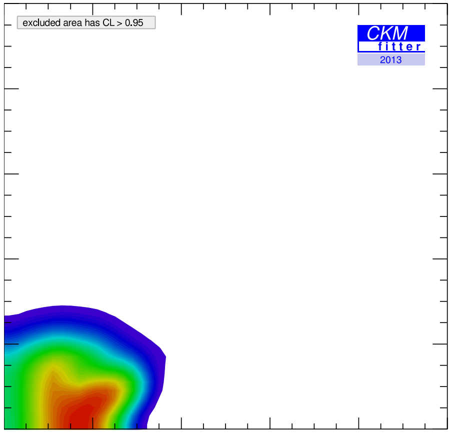
New physics
in phase

(Assumes CKM unitarity and SM-dominated tree-level decays)

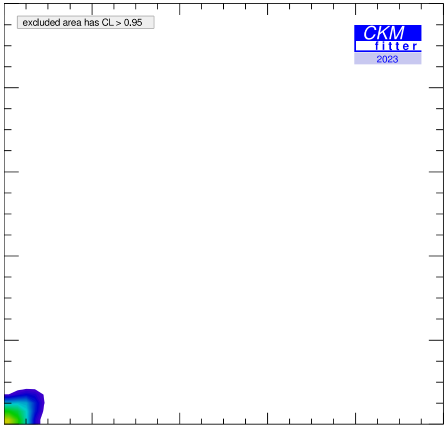
2003



2013



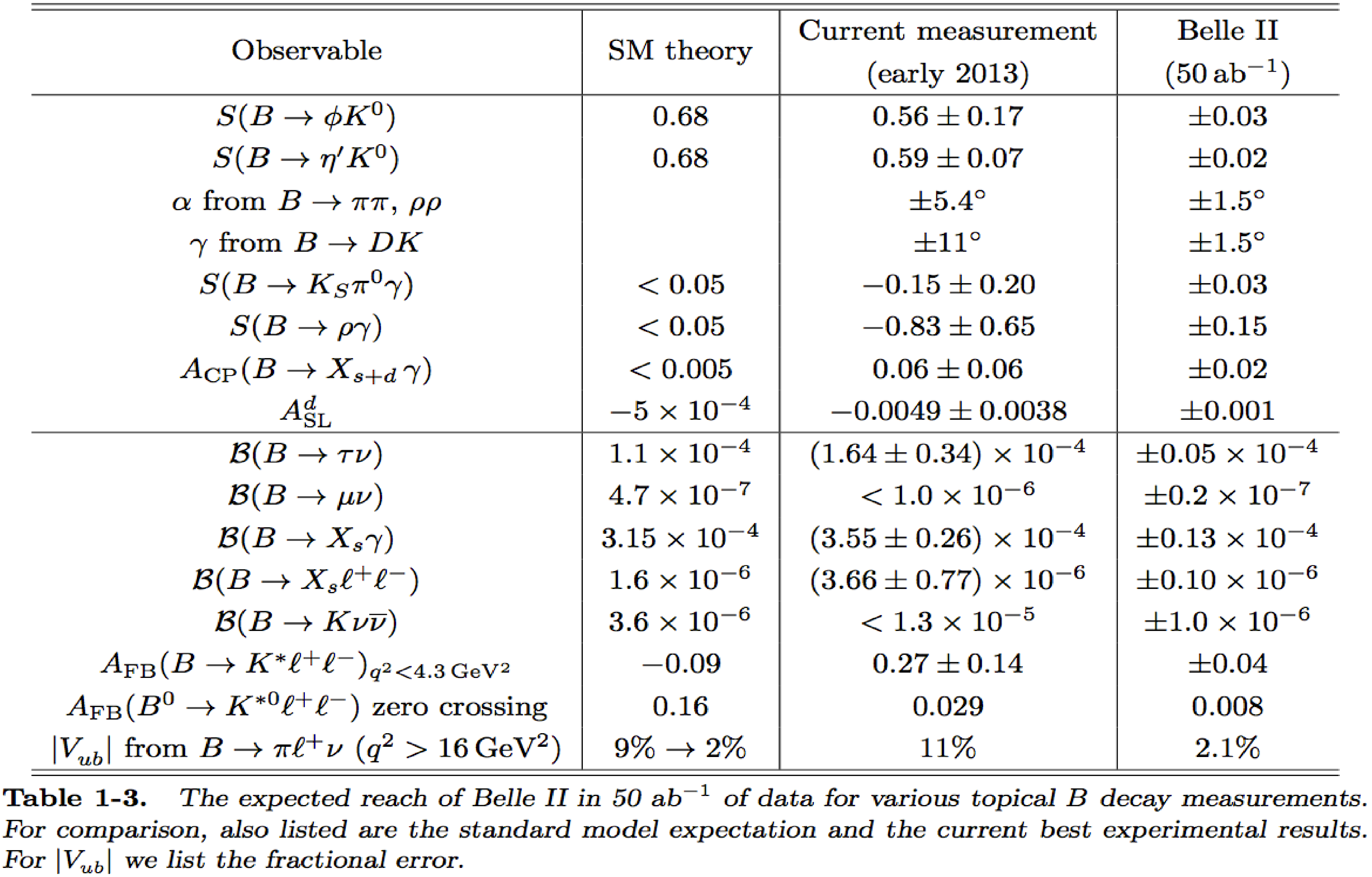
50 ab^{-1} B_d + 50 fb^{-1} B_s
Belle-II + LHCb



Charles etal
Preliminary

Future Sensitivity: Belle II

Errors shrink by ~8

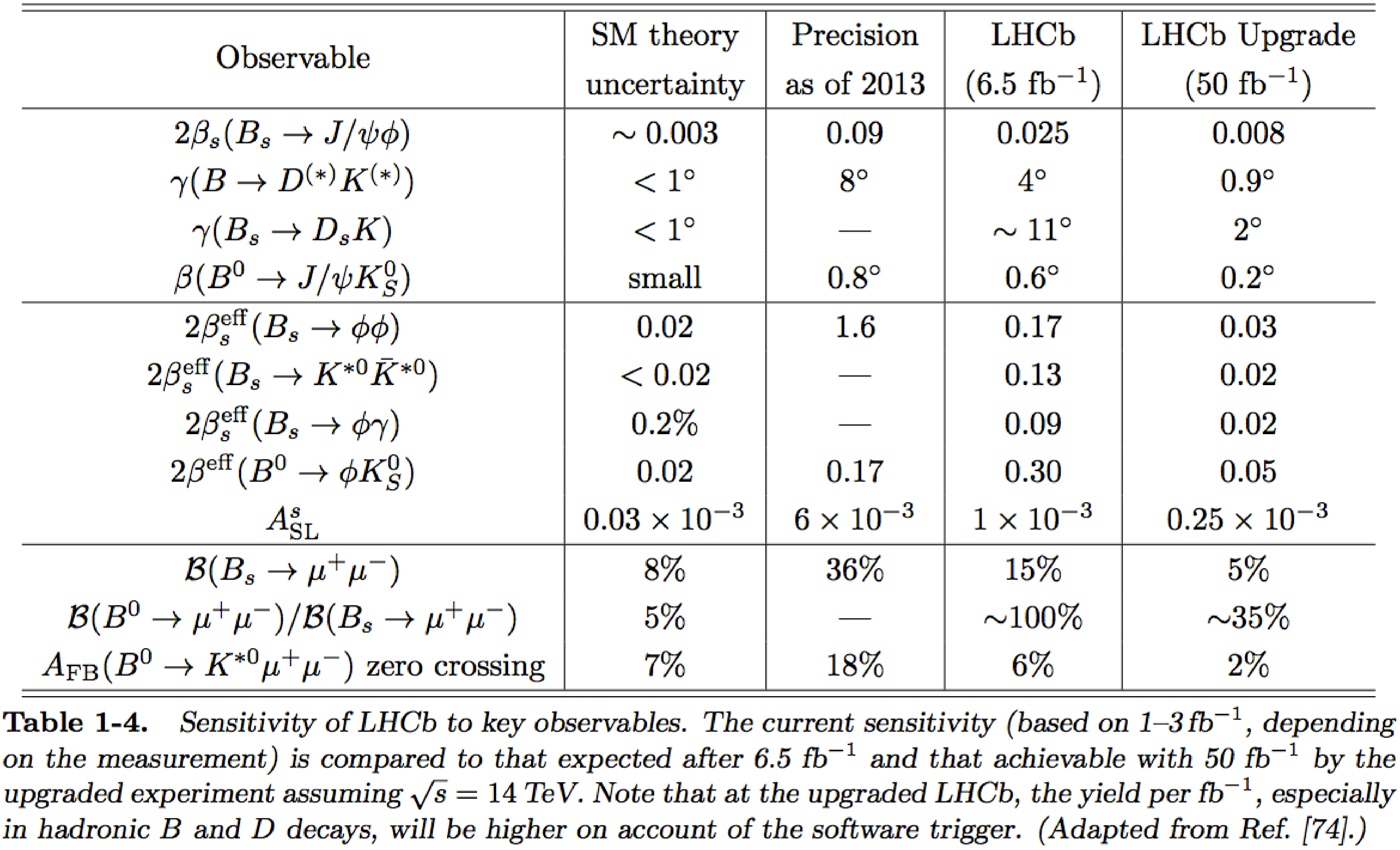


Observable	SM theory	Current measurement (early 2013)	Belle II ($50\,\mathrm{ab}^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.03
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.02
α from $B \to \pi\pi, \rho\rho$		$\pm 5.4^\circ$	$\pm 1.5^\circ$
γ from $B \to DK$		$\pm 11^\circ$	$\pm 1.5^\circ$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.03
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.15
$A_{\mathrm{CP}}(B \to X_{s+d}\,\gamma)$	< 0.005	0.06 ± 0.06	± 0.02
A_{SL}^d	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 0.05 \times 10^{-4}$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\pm 0.2 \times 10^{-7}$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 0.13 \times 10^{-4}$
$\mathcal{B}(B \to X_s \ell^+\ell^-)$	1.6×10^{-6}	$(3.66 \pm 0.77) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$\mathcal{B}(B \to K\nu\bar{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 1.0 \times 10^{-6}$
$A_{\mathrm{FB}}(B \to K^*\ell^+\ell^-)_{q^2<4.3\,\mathrm{GeV}^2}$	-0.09	0.27 ± 0.14	± 0.04
$A_{\mathrm{FB}}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing	0.16	0.029	0.008
$\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ ($q^2 > 16\,\mathrm{GeV}^2$)	$9\% \to 2\%$	11%	2.1%

Table 1-3. *The expected reach of Belle II in 50 ab^{-1} of data for various topical B decay measurements. For comparison, also listed are the standard model expectation and the current best experimental results. For $\lvert V_{ub}\rvert$ we list the fractional error.*

Future Sensitivity: LHCb Upgrade

Errors shrink by ~5



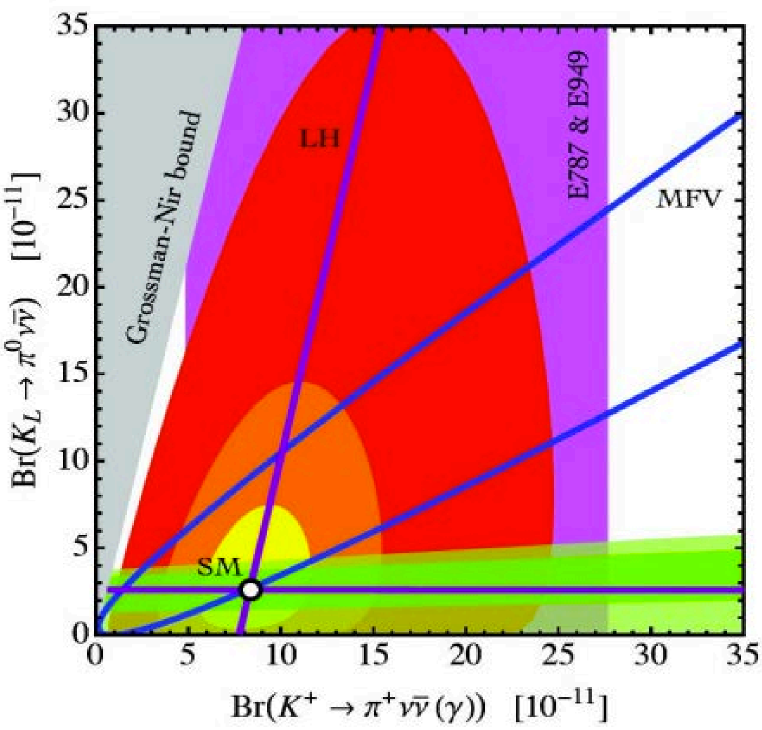
Observable	SM theory uncertainty	Precision as of 2013	LHCb (6.5 fb^{-1})	LHCb Upgrade (50 fb^{-1})
$2\beta_s(B_s \to J/\psi\phi)$	~ 0.003	0.09	0.025	0.008
$\gamma(B \to D^{(*)}K^{(*)})$	$< 1^\circ$	8°	4°	0.9°
$\gamma(B_s \to D_s K)$	$< 1^\circ$	—	$\sim 11^\circ$	2°
$\beta(B^0 \to J/\psi K^0_S)$	small	0.8°	0.6°	0.2°
$2\beta_s^{\text{eff}}(B_s \to \phi\phi)$	0.02	1.6	0.17	0.03
$2\beta_s^{\text{eff}}(B_s \to K^{*0}\bar{K}^{*0})$	< 0.02	—	0.13	0.02
$2\beta_s^{\text{eff}}(B_s \to \phi\gamma)$	0.2%	—	0.09	0.02
$2\beta^{\text{eff}}(B^0 \to \phi K^0_S)$	0.02	0.17	0.30	0.05
A^s_{SL}	0.03×10^{-3}	6×10^{-3}	1×10^{-3}	0.25×10^{-3}
$\mathcal{B}(B_s \to \mu^+\mu^-)$	8%	36%	15%	5%
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-)$	5%	—	~100%	~35%
$A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$ zero crossing	7%	18%	6%	2%

Table 1-4. *Sensitivity of LHCb to key observables. The current sensitivity (based on 1–3 fb^{-1}, depending on the measurement) is compared to that expected after 6.5 fb^{-1} and that achievable with 50 fb^{-1} by the upgraded experiment assuming $\sqrt{s} = 14$ TeV. Note that at the upgraded LHCb, the yield per fb^{-1}, especially in hadronic B and D decays, will be higher on account of the software trigger. (Adapted from Ref. [74].)*

Kaon Program

- Worldwide goal to achieve precision measurements

Sensitivity to new physics



Haisch

SM Prediction:

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$$

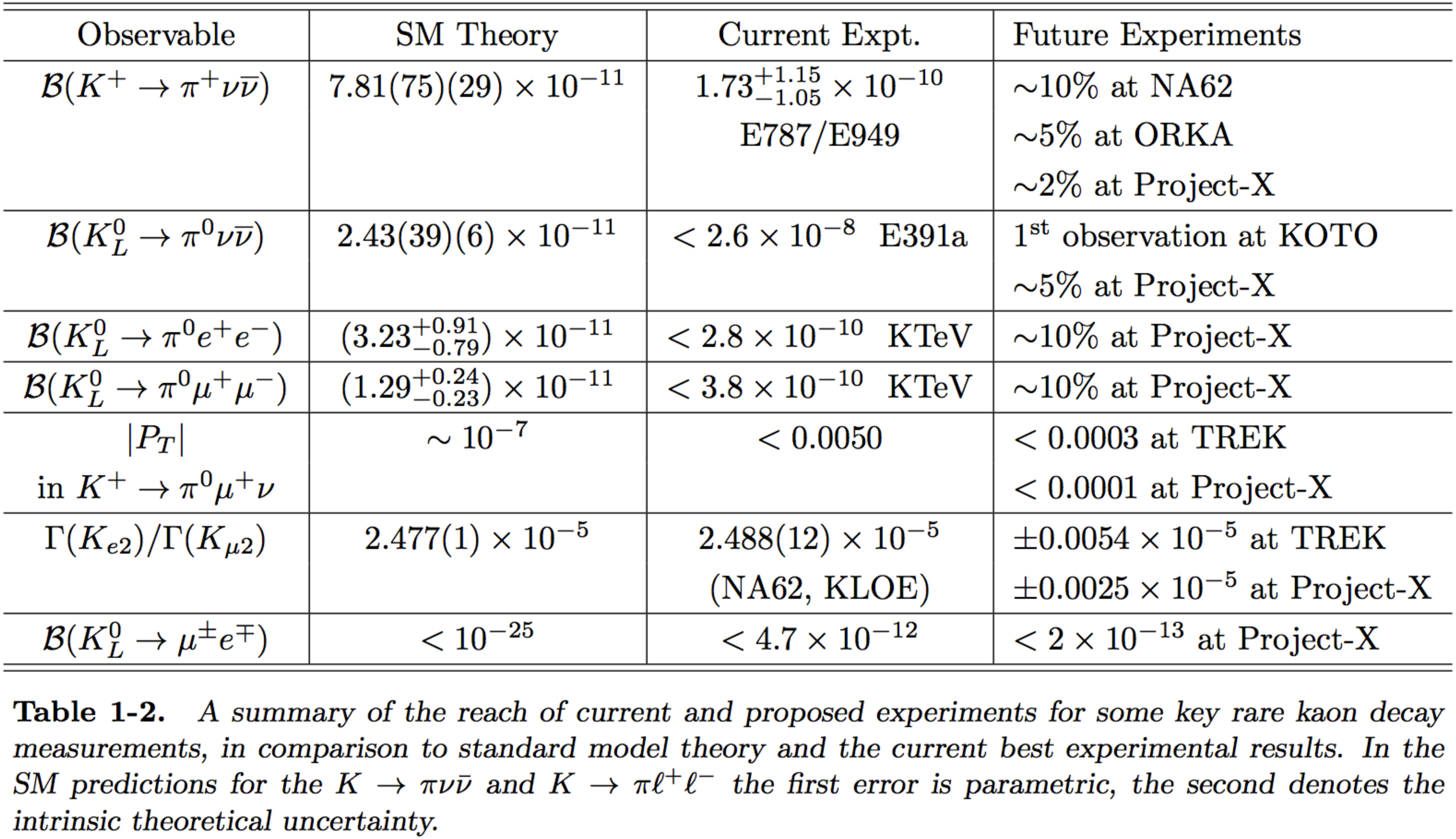
$$B(K^0 \to \pi^0 \nu\bar{\nu}) = (2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$$

Theoretically clean decays

Charged mode:
NA62: near-term (10% precision)
ORKA: Proposed,
1000 events w/ Main Injector

Neutral mode:
KOTO: near term (few events)
Projected: 5% precision @ Project X

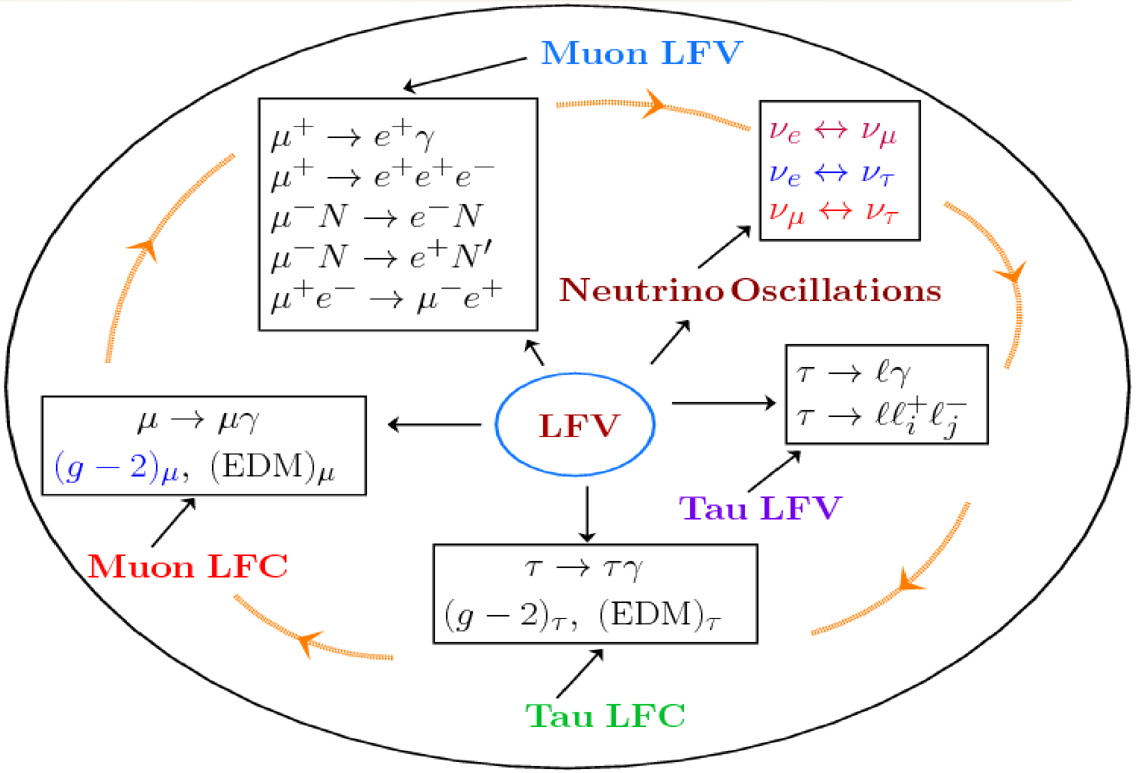
Future Sensitivity: Rare Kaon Decays



Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	$\sim$10% at NA62 $\sim$5% at ORKA $\sim$2% at Project-X
$\mathcal{B}(K^0_L \to \pi^0 \nu \bar{\nu})$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1st observation at KOTO $\sim$5% at Project-X
$\mathcal{B}(K^0_L \to \pi^0 e^+ e^-)$	$(3.23^{+0.91}_{-0.79}) \times 10^{-11}$	$< 2.8 \times 10^{-10}$ KTeV	$\sim$10% at Project-X
$\mathcal{B}(K^0_L \to \pi^0 \mu^+ \mu^-)$	$(1.29^{+0.24}_{-0.23}) \times 10^{-11}$	$< 3.8 \times 10^{-10}$ KTeV	$\sim$10% at Project-X
$\lvert P_T \rvert$ in $K^+ \to \pi^0 \mu^+ \nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 at TREK < 0.0001 at Project-X
$\Gamma(K_{e2})/\Gamma(K_{\mu 2})$	$2.477(1) \times 10^{-5}$	$2.488(12) \times 10^{-5}$ (NA62, KLOE)	$\pm 0.0054 \times 10^{-5}$ at TREK $\pm 0.0025 \times 10^{-5}$ at Project-X
$\mathcal{B}(K^0_L \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ at Project-X

Table 1-2. *A summary of the reach of current and proposed experiments for some key rare kaon decay measurements, in comparison to standard model theory and the current best experimental results. In the SM predictions for the $K \to \pi \nu \bar{\nu}$ and $K \to \pi \ell^+ \ell^-$ the first error is parametric, the second denotes the intrinsic theoretical uncertainty.*

Charged Lepton Physics



Muon LFV

$\mu^+ \to e^+\gamma$
$\mu^+ \to e^+e^+e^-$
$\mu^-N \to e^-N$
$\mu^-N \to e^+N'$
$\mu^+e^- \to \mu^-e^+$

$\nu_e \leftrightarrow \nu_\mu$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_\mu \leftrightarrow \nu_\tau$

Neutrino Oscillations

$\mu \to \mu\gamma$
$(g-2)_\mu, \ (\text{EDM})_\mu$

LFV

$\tau \to \ell\gamma$
$\tau \to \ell\ell_i^+\ell_j^-$

Tau LFV

Muon LFC

$\tau \to \tau\gamma$
$(g-2)_\tau, \ (\text{EDM})_\tau$

Tau LFC

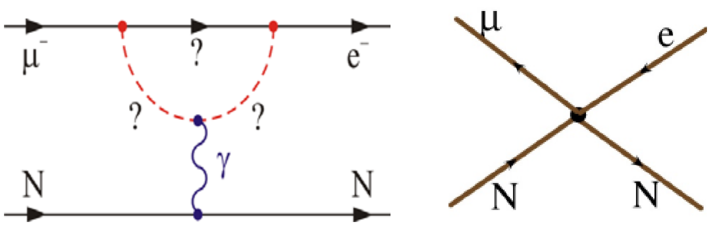
- Charged Leptons easy to produce & detect
  ⇒ precise measurements are possible
- SM rates negligible in some cases so new physics stands out
- Directly probe couplings of new particles to leptons
- Diverse set of independent measurements

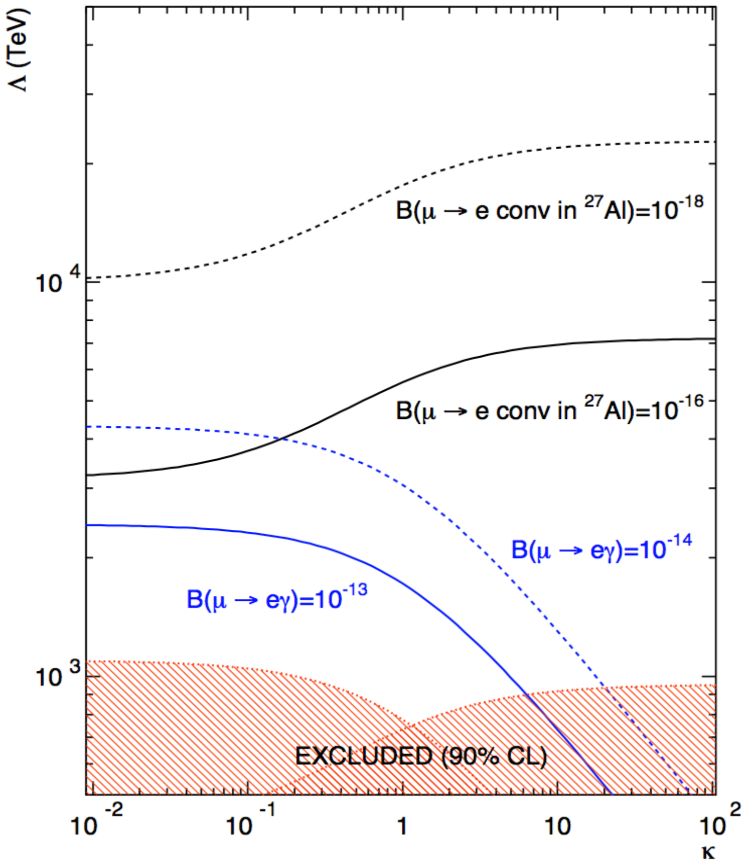
Charged Lepton Flavor Violation

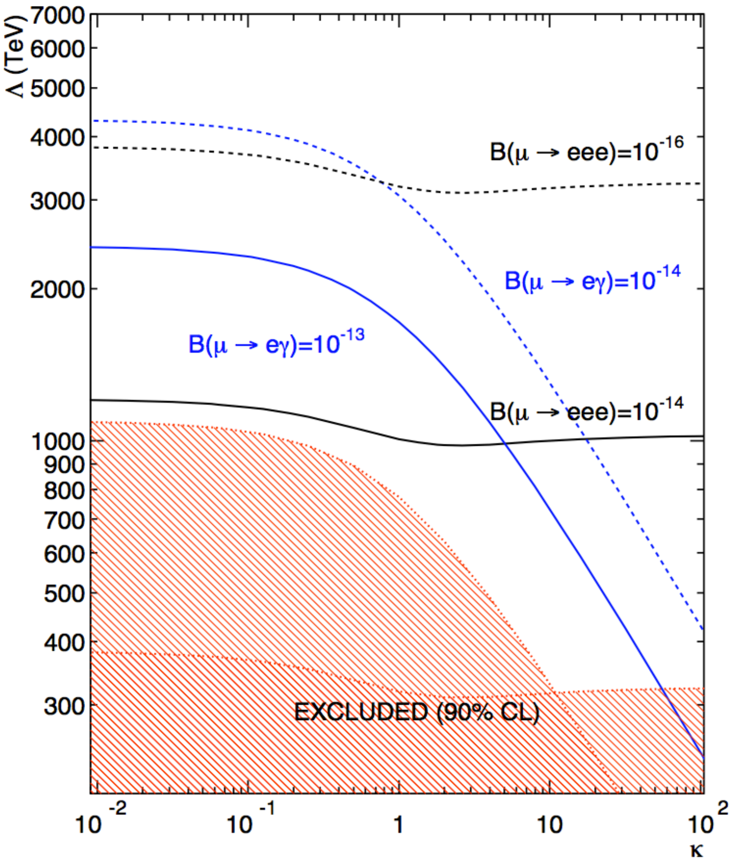
Model independent reach

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$

$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c..$$

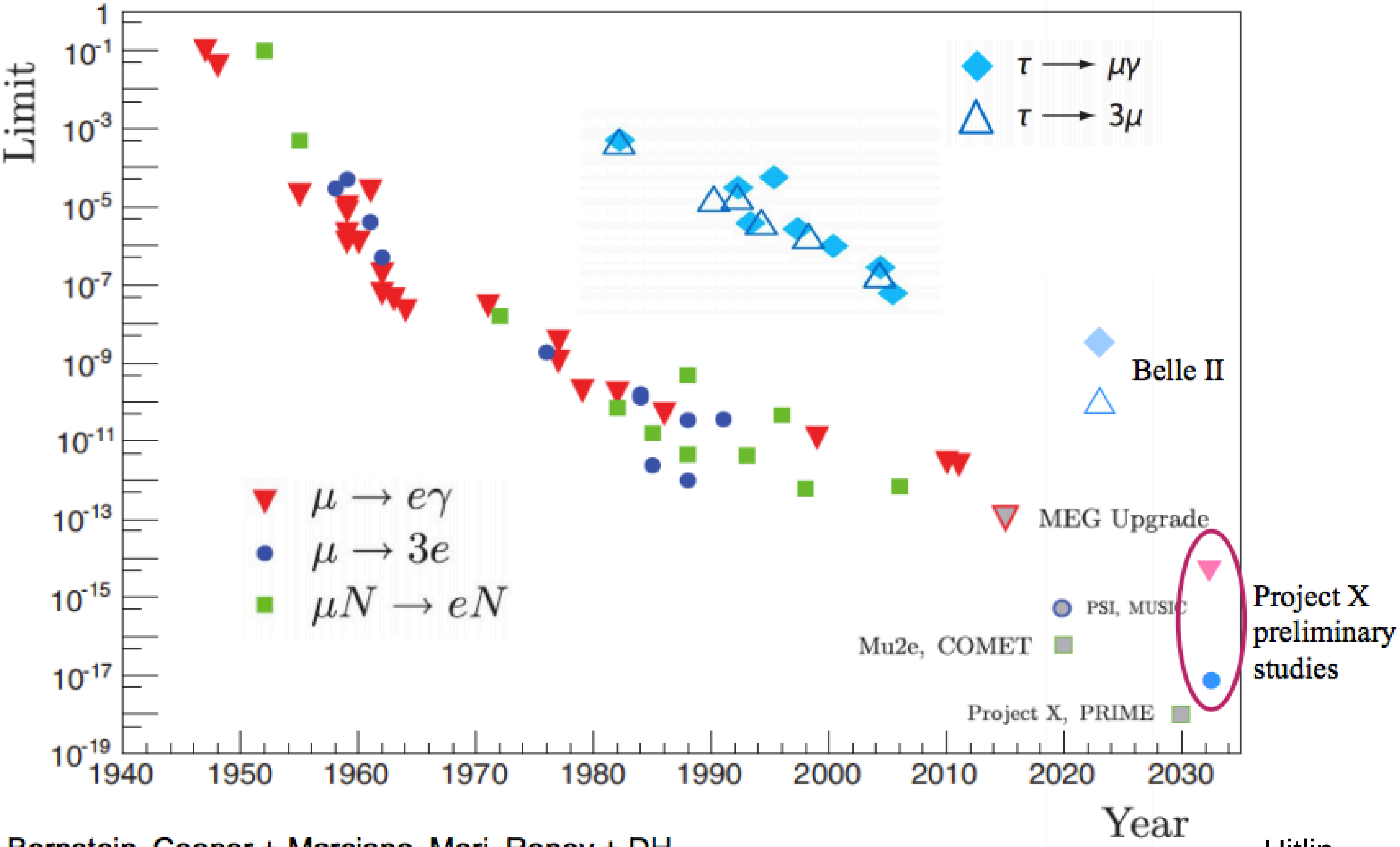






deGouvea,
Vogel
1303.4097

CLFV Timeline



Bernstein, Cooper + Marciano, Mori, Roney + DH

Hitlin

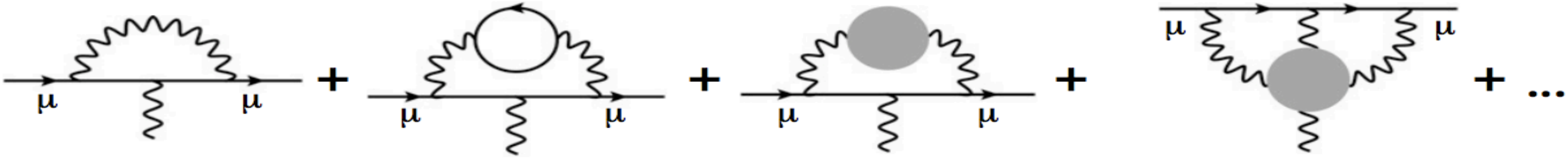
Anomalous Magnetic Moment of the Muon

- Discrepancy between exp’t and SM at 3.6σ : $\Delta a_\mu = 287(80) \times 10^{-11}$
- Ring has arrived at Fermilab
  - Run begins 2016/17
- Lattice/analytic results can reduce theory uncertainty
  - How well can this be calculated?

Van de Water

Hadronic vacuum polarization (HVP):

Hadronic light-by-light (HLbL):



QED (4 loops) & EW (2 loops)

from experimental result for $e^+e^- \to$ hadrons plus dispersion relation

estimated from models such as large N_c, vector meson

HVP: Theory error reduced to 2% due to theoretical improvements and more CPU on timescale of exp’t

HLBL: 15% precision possible, but not guaranteed. Lattice community working hard!

Electric Dipole Moments

Electric dipole moments:

Program in place to measure all

Neutrons

CKM-theory: 10^{-31} *e* cm Exp: <2.9×10^{-26} *e* cm → 5×10^{-28} *e* cm

2018 → 10^{-28} *e* cm

Nucleus (Hg)

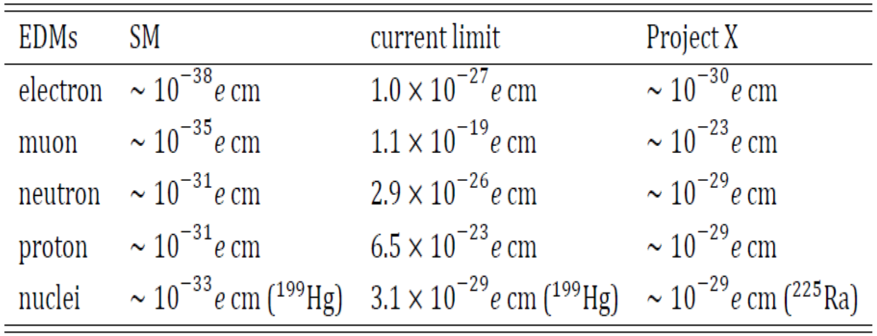
CKM-theory: 10^{-33} *e* cm Exp: <10^{-27} *e* cm → 10^{-32} *e* cm

Electrons (cold molecules of YbF, ThO possible Fr)

CKM-theory: 10^{-38} *e* cm Exp: <1.05×10^{-27} *e* cm → 3×10^{-31} *e* cm

Excellent probes of new physics!

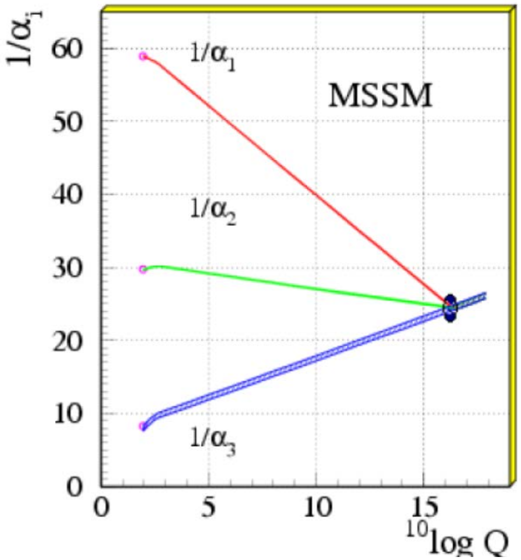
Table 2: SM predictions and current and expected limits on selected examples of EDMs.

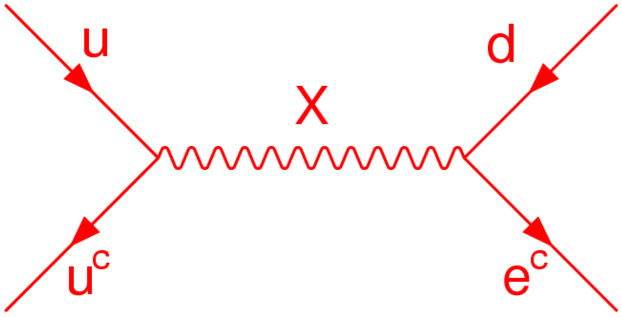


EDMs	SM	current limit	Project X
electron	$\sim 10^{-38}$ *e* cm	1.0×10^{-27} *e* cm	$\sim 10^{-30}$ *e* cm
muon	$\sim 10^{-35}$ *e* cm	1.1×10^{-19} *e* cm	$\sim 10^{-23}$ *e* cm
neutron	$\sim 10^{-31}$ *e* cm	2.9×10^{-26} *e* cm	$\sim 10^{-29}$ *e* cm
proton	$\sim 10^{-31}$ *e* cm	6.5×10^{-23} *e* cm	$\sim 10^{-29}$ *e* cm
nuclei	$\sim 10^{-33}$ *e* cm (^{199}Hg)	3.1×10^{-29} *e* cm (^{199}Hg)	$\sim 10^{-29}$ *e* cm (^{225}Ra)

Grand Unified Models

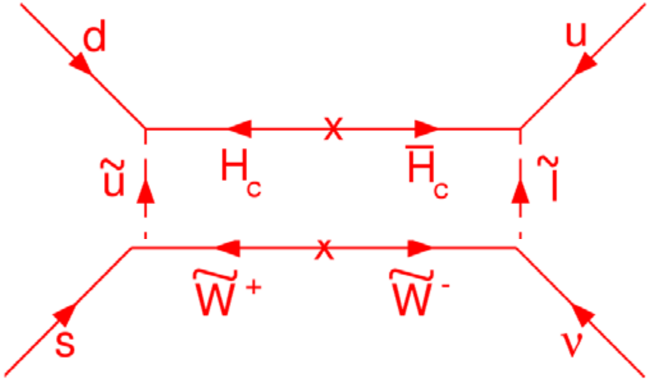
- Three gauge couplings unify nicely with low-energy SUSY
- SO(10) GUTs predict neutrino masses via seesaw mechanism naturally
- Baryon number violation predicted – – leads to proton decay





$p \to e^+\pi^0$

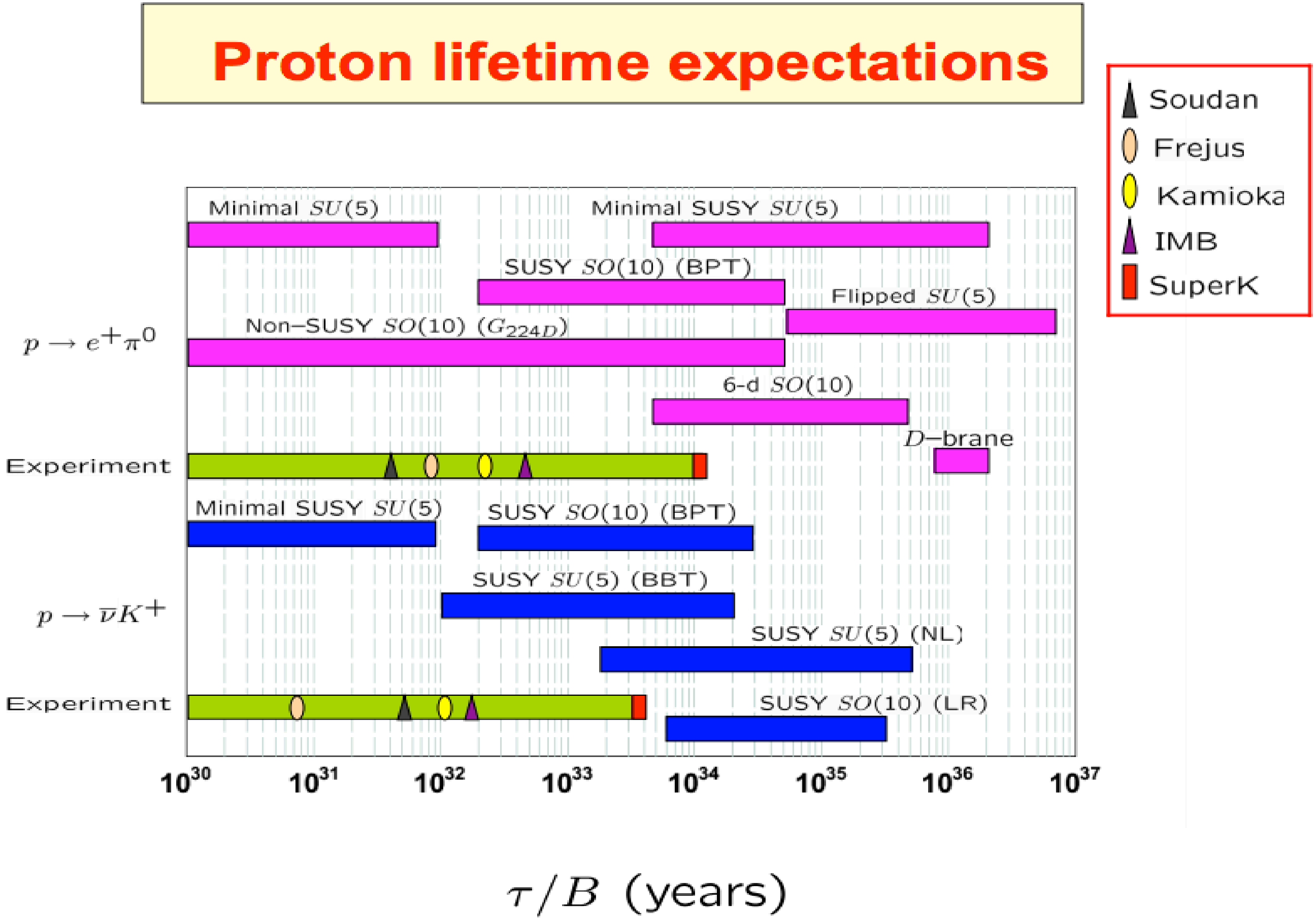
Hyper-K



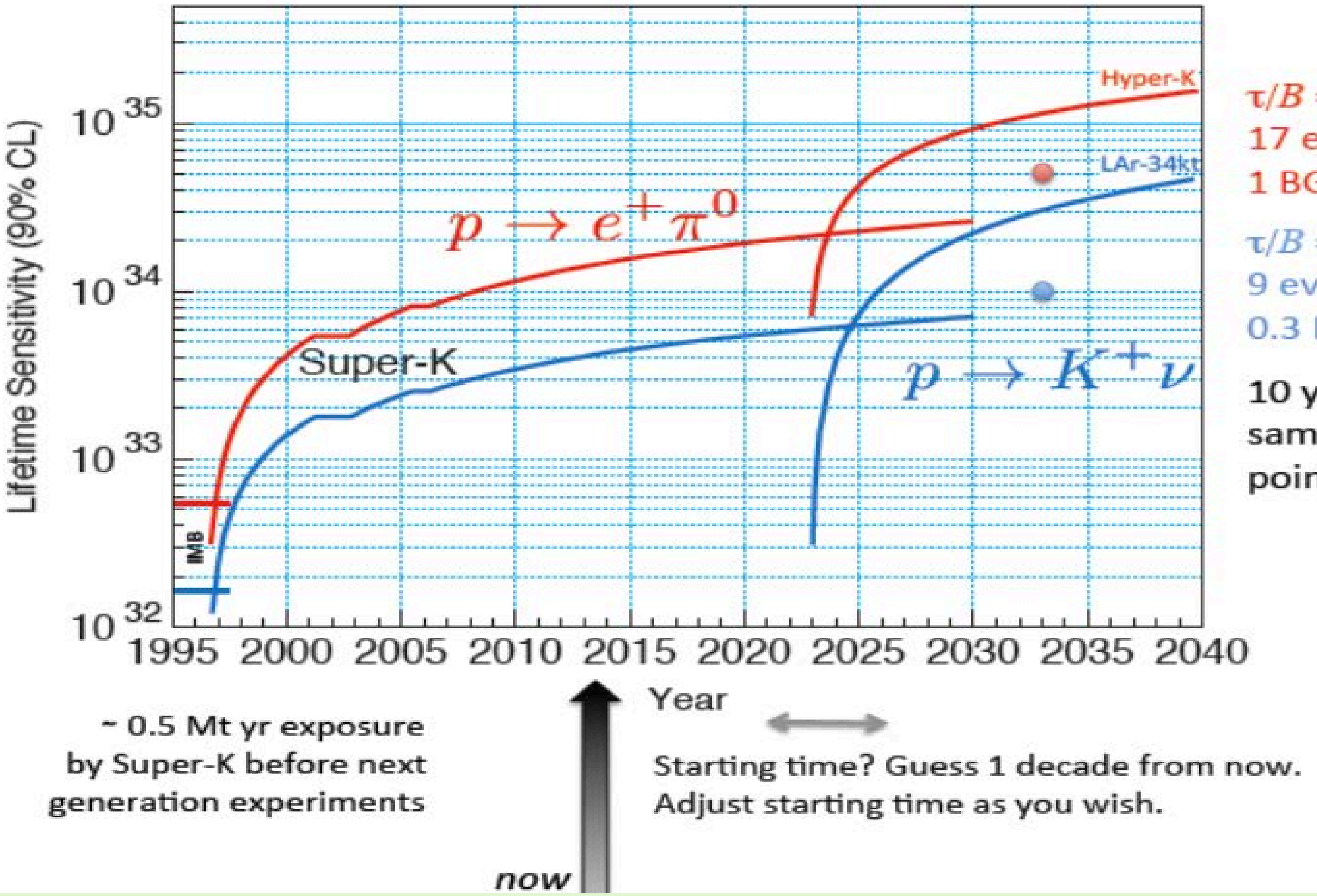
SUSY mode: $p \to \overline{\nu} K^+$

LBNE LAr

Proton Decay



Proton Decay Search Territory



~ 0.5 Mt yr exposure by Super-K before next generation experiments

Starting time? Guess 1 decade from now.
Adjust starting time as you wish.

The observation of proton decay would change the way everyone thinks about the world

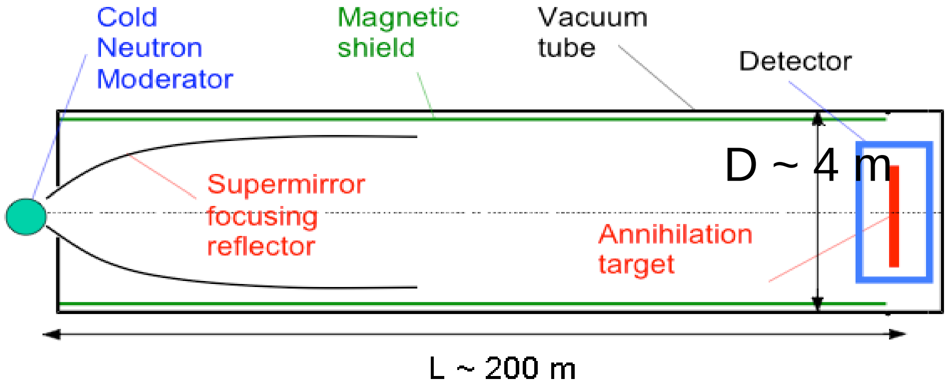
Neutron-Antineutron Oscillations

If baryon number is violated by 2 units, Neutron-antineutron oscillations can occur, in analogy to $K^0 \to \bar{K}^0$ mixing:

$$\mathcal{M}_{\mathcal{B}} = \begin{pmatrix} m_n - \vec{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix}$$

$$P(n \to \bar{n}, t) \simeq \left[\delta m \cdot t\right]^2 \qquad \delta m : B - \text{violating mixing}$$

Oscillation probability can be probed with new expt. at Project X with improved sensitivity of up to 1000 compared to ILL (1994)



NNbarX Collaboration

See Project X white paper

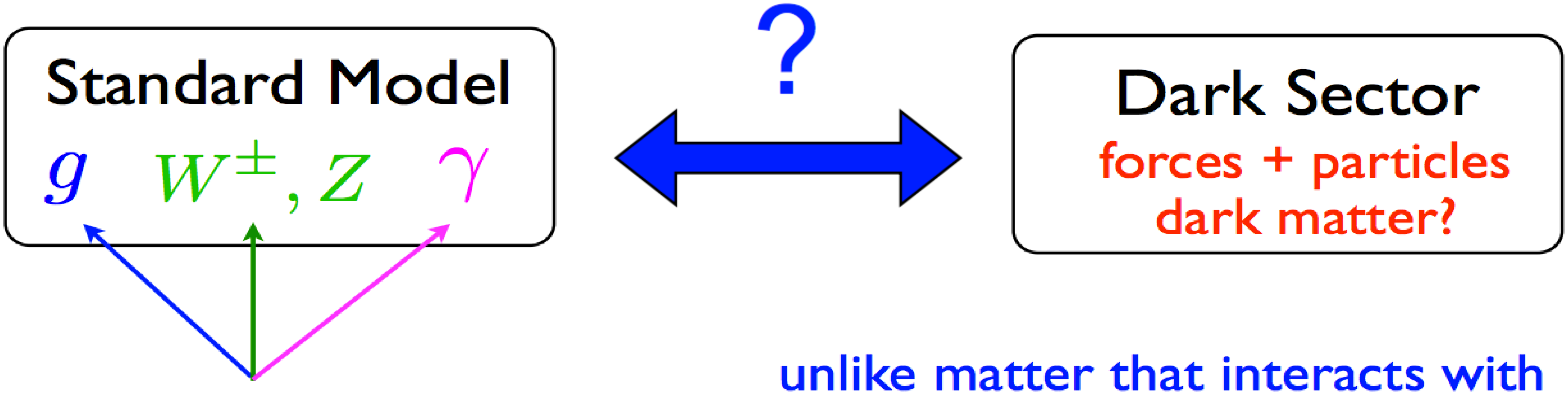
Probes Baryon violation scale of $10^5 - 10^6$ GeV.

Can test low-scale Baryogenesis schemes

New Light Weakly Coupled Particles

Dark Sectors

A dark sector consists of particles that do not interact with known forces



Standard Model

$g \quad W^{\pm}, Z \quad \gamma$

?

Dark Sector

forces + particles
dark matter?

Known Forces

strong, weak, EM

unlike matter that interacts with known forces, dark sector particles can be *well below* *Weak-scale*

Essig

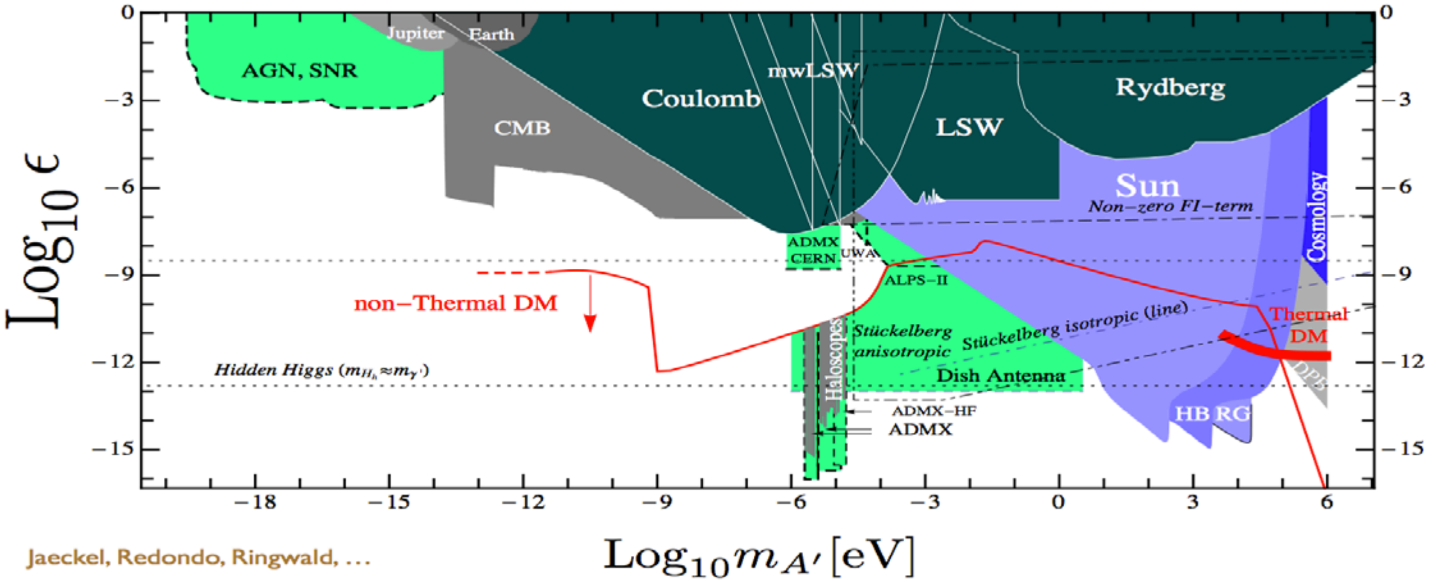
New Light Weakly Coupled Particles

Portals

• “Axion”	$\frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a$	axions & axion-like particles (ALPs)
• “Vector”	$\epsilon\, F^{Y,\mu\nu} F'_{\mu\nu}$	dark photon A′
• “Higgs”	$\lambda\, H^2 S^2 + \mu\, H^2 S$	exotic Higgs decays?
• “Neutrino”	$\kappa\, (HL) N$	sterile neutrinos?

Essig

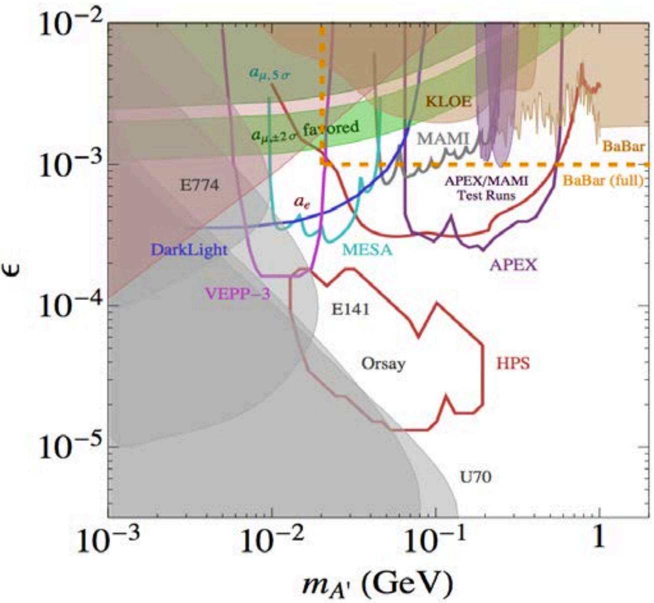
Ultra–weak Hidden Sectors



Jaeckel, Redondo, Ringwald, …

Effective coupling to SM vs Mass plane

$m_{A'} < 1\mathrm{ev}$



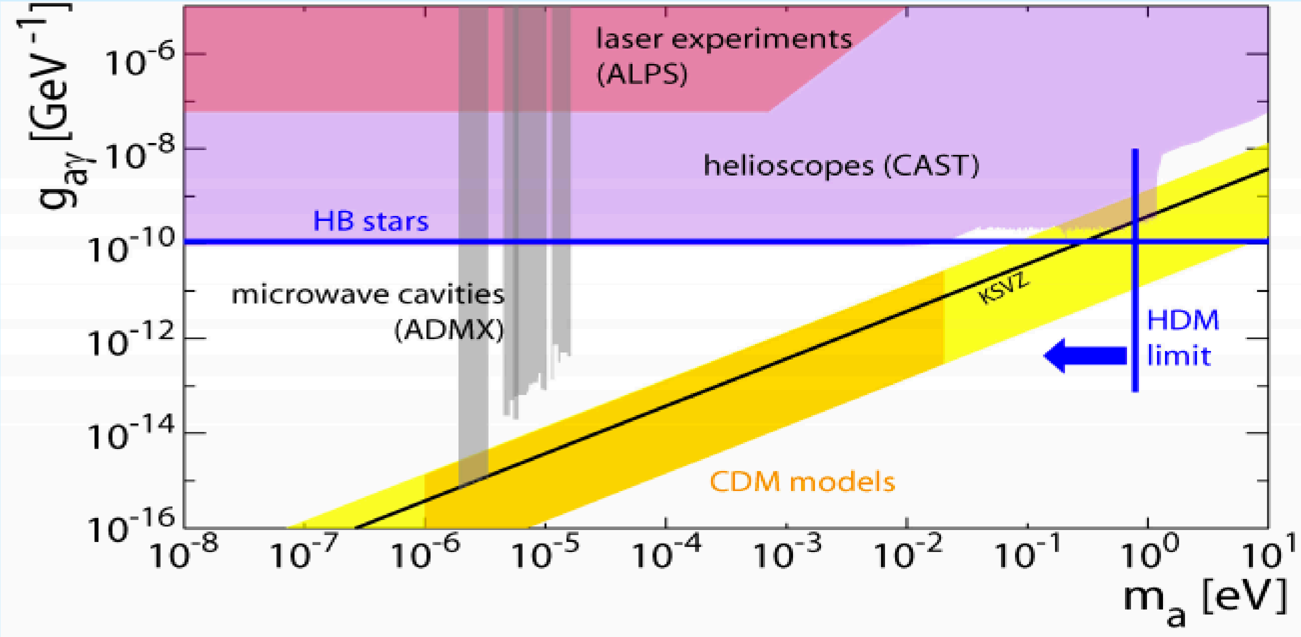
Hidden Sector Vector Portal:
Couplings to SM small enough to have missed so far, but big enough to find

Several planned experiments; reach indicated by non colored regions

$m_{A'} > 1\mathrm{ev}$

Current constraints

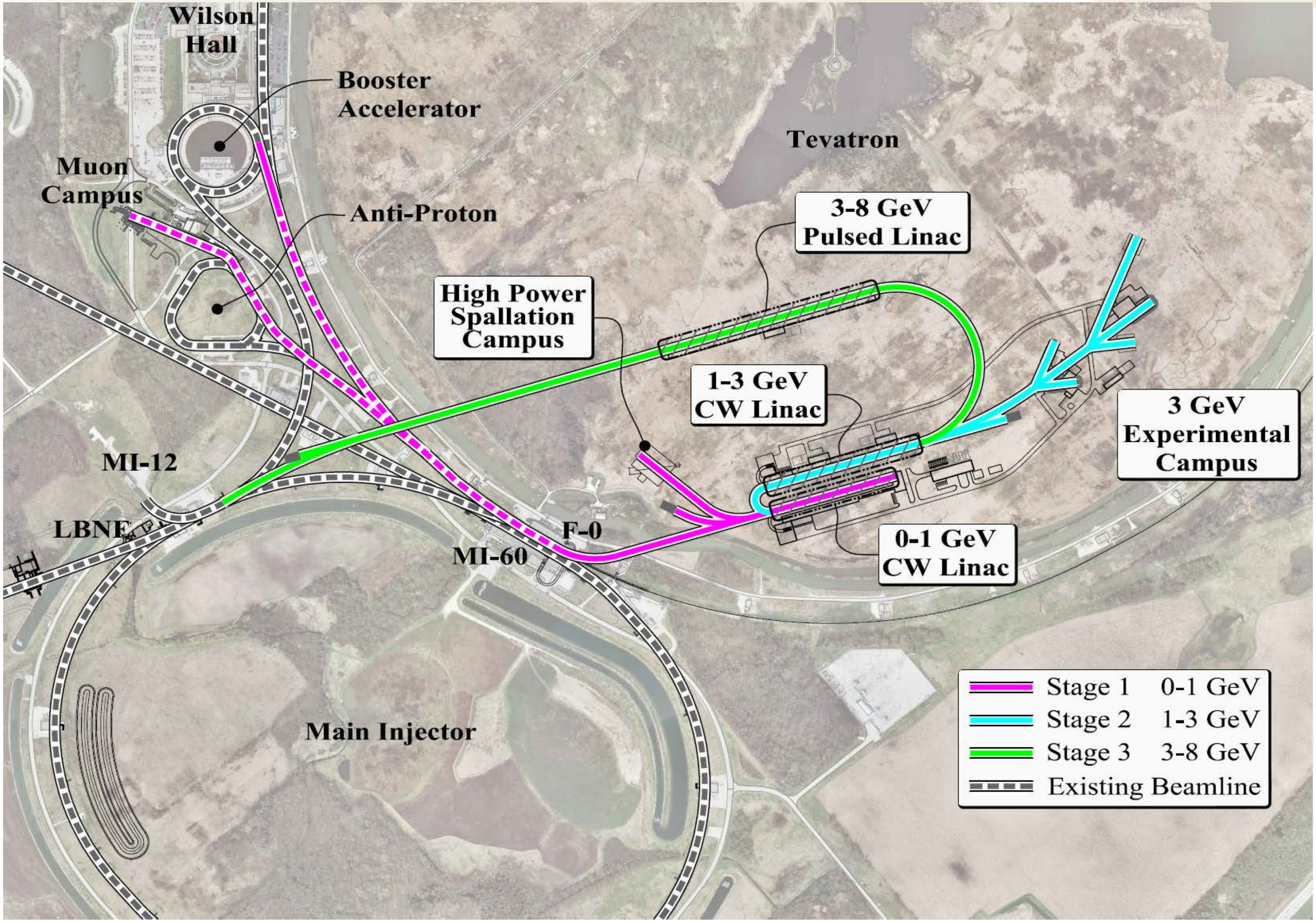
- Axion and ALP parameters are constrained by astrophysical and experimental measurements
  - Stars don’t burn out and hot dark mater not likely.
  - Laser, microwave cavity, solar telescopes (helioscopes) are a partial list of techniques that provide experimental bounds.



M Pivovaroff

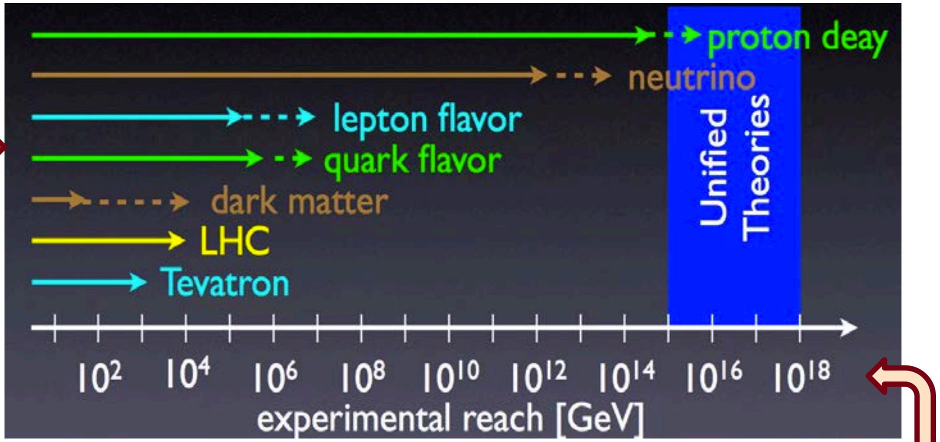
Staging of Project X

Project-X enables reach in Intensity Frontier



Intensity Frontier Science Summary

Precision neutrino physics in next two decades



Quark & Charged Lepton Flavor experiments

Proton Decay & NNbar oscillations

Electric Dipole Moments (EDMs)

New light, weakly coupled particles

Rapid progress from last 2 years will continue

Intensity & Cosmic Frontiers

Probe mass scales of possible New Physics with multiple approaches

Particle explanation of Dark Sector

Intensity Frontier Science summary II

Earlier questions

- Are there sources of CP Violation beyond θ_{CKM}?
- Is there CP Violation in the leptonic sector?
- What are the properties of the neutrino?
- Do the forces unify?
- Is there a weakly coupled Hidden Sector linked to the Dark Side?
- Are apparent symmetries (B,L) violated at high scales?
- What can we learn about the flavor sector of new physics?
- What is the new physics mass scale?

- *Intensity Frontier addresses these questions with a diverse and focused program*
- *Potential of paradigm-changing discoveries*
- *Synergy with other frontiers ➔ stronger HEP program*

END

The Intensity Frontier

Exploration of Fundamental Physics with

- **intense sources**
- **ultra-sensitive, sometimes very massive, detectors**

Intensity frontier science searches for

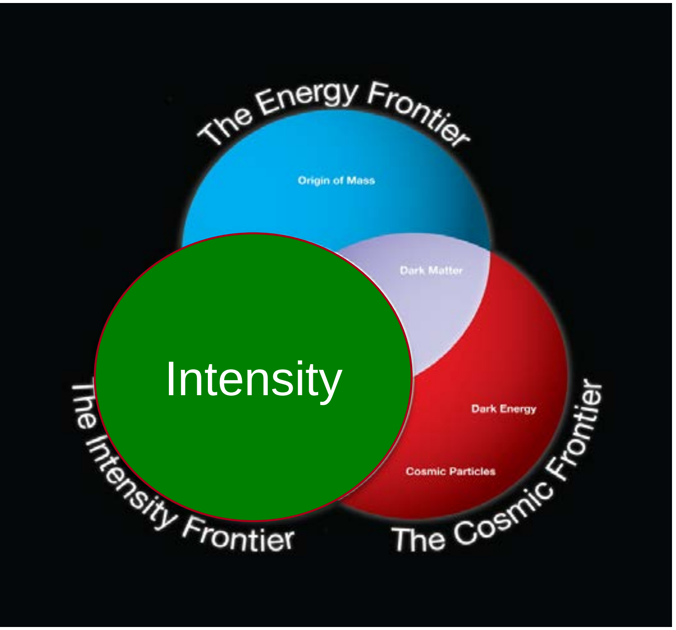
- **Extremely rare processes**
- **Tiny deviations from Standard Model predictions**

Precision measurements that indirectly probe quantum effects

Extends outside of HEP – Nuclear Physics sponsors some programs

HEP and the Frontiers

The Frontiers represent experimental approaches

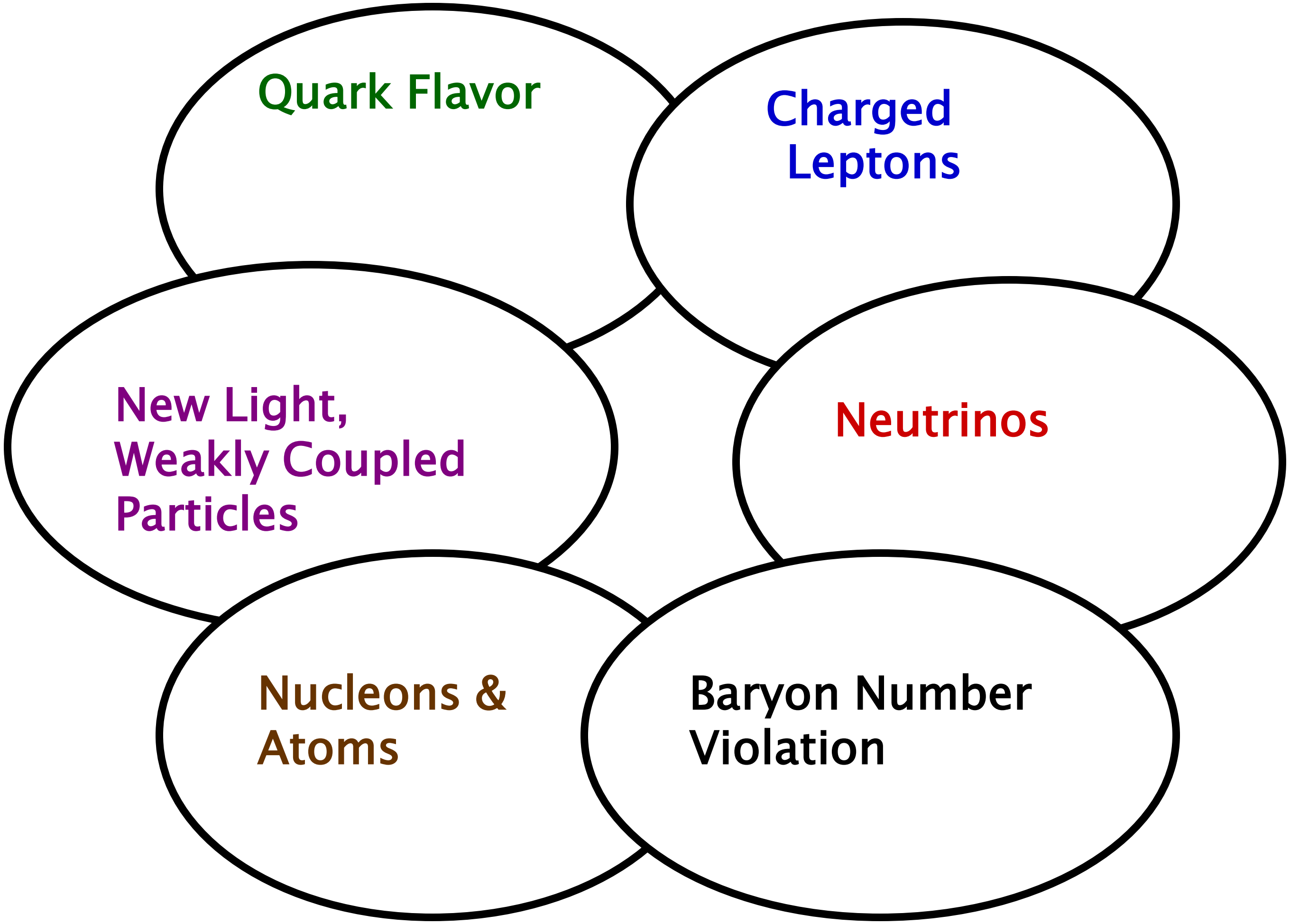


Shows multi-pronged approach to search for new physics

- **Direct Searches**
- **Precision Measurements**
- **Rare and Forbidden Processes**
- **Fundamental Properties of Particles and Interactions**
- **Cosmological observations**

The Intensity Frontier Program

The Intensity Frontier is a broad and diverse, yet connected, set of science opportunities



Quark Flavor

Charged Leptons

New Light, Weakly Coupled Particles

Neutrinos

Nucleons & Atoms

Baryon Number Violation

CSS13 Working Groups

Quark Flavor Physics: Joel Butler, Zoltan Ligeti, Jack Ritchie	K, D & B Meso decays/pr es
Charged Lepton Processes Brendan Casey, Yuval Grossman, David Hitlin	Preci easurements wi ons, taus
Neutrinos Andre deGouvea, Kevin Pitts, Kate Scholberg, Sam Zeller	All experiments for properties of neutrinos. Accelerator & non-accel.
Baryon Number Violatio Kaladi Babu, Ed Kearn	Proton decay, Neutron Oscillation
New Light, Weakl Coupled Partic Rouven Ess n Jaros, William V	“Dark” photons, paraphotons, axions, WISPs
Nuc Nuclei & Atoms K a Kumar, Z.-T. Lu, Mic ael Ramsey-Musolf	Properties of nucleons, nuclei or atoms (EDM), as related to HEP

Thanks to our conveners for doing a heroic job the last 2 years!

The Nature of Neutrinos

On Electroweak Symmetry Breaking

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC and charged-lepton flavor violation may provide more information.

Searches for nucleon decay provide the only handle on a new energy scale (3) if that new scale happens to be very small. Unique capability!

The Nature of Neutrinos

- Our questions are very fundamental

  - what is the absolute neutrino mass scale

  - are neutrinos Majorana or Dirac?

  - what is the neutrino mass ordering?

  - is CP violated in the neutrino sector?

  - to what extent does the 3ν paradigm describe nature?

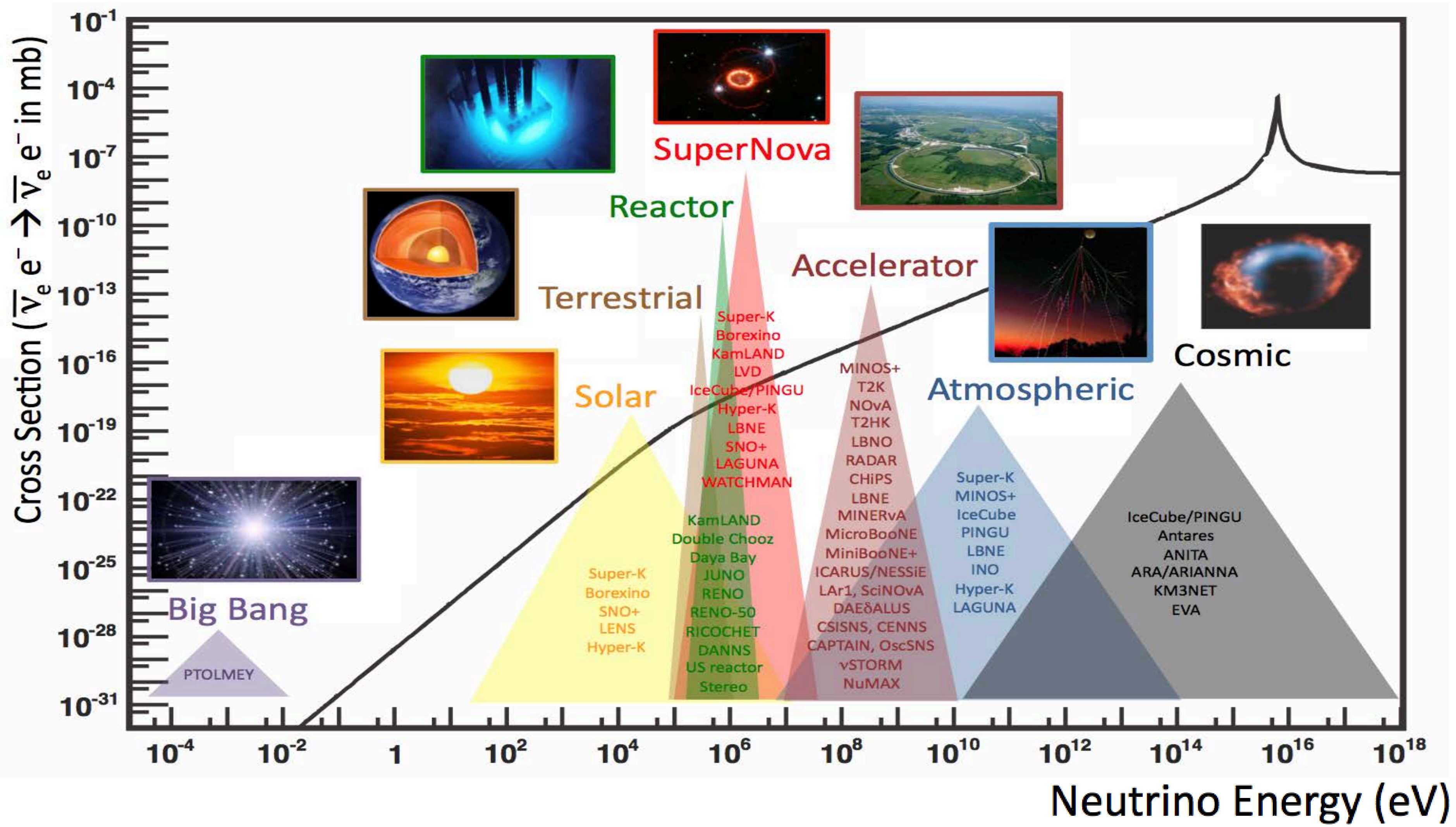
  - are there hints of new physics in existing data?

  - what new knowledge will neutrinos from astrophysical sources bring?

- We know this information for every other particle!
- We know more about the Higgs than we do about neutrinos

Neutrino Sources

many sources ➔ many experimental opportunities



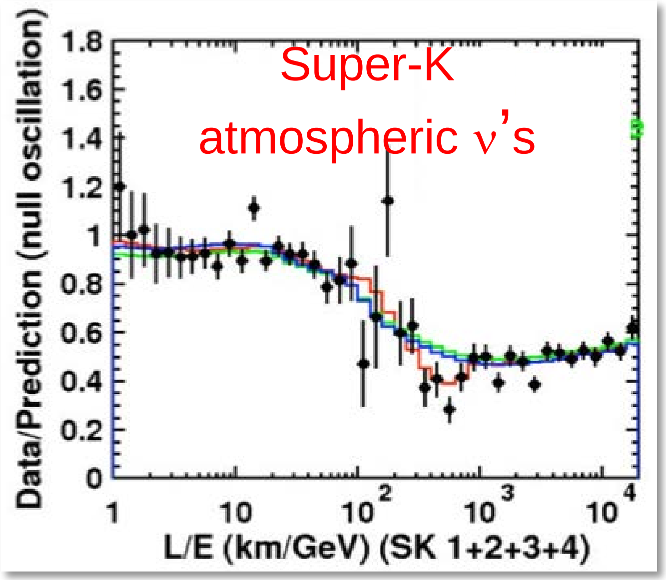
Nature of the Neutrino

- Neutrinoless double beta decay (0νββ) search experiments are critical as the only realistic way to elucidate a key part of the picture: the question of whether neutrinos are Majorana or Dirac fermions.

- The class of 100-kg-class neutrinoless double beta decay search experiments should reach effective masses in the 100 meV range; beyond that, there are opportunities for multi-ton-class experiments that will reach sub 10 meV effective mass sensitivity, pushing below the inverted hierarchy region.

Neutrino Oscillations

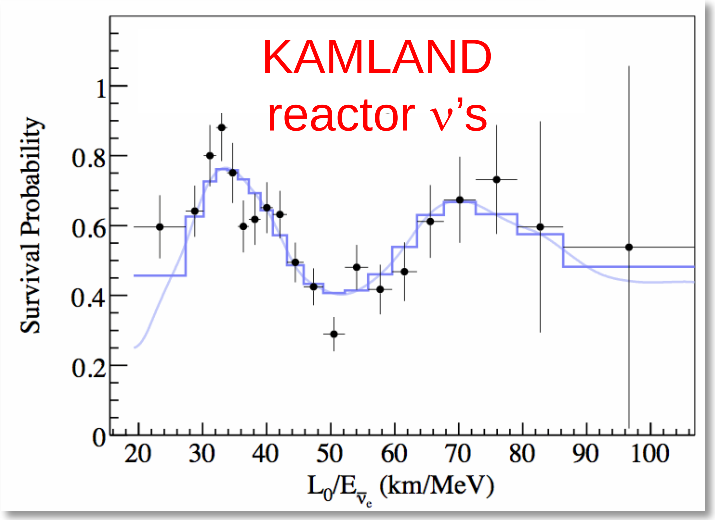
we have made much of progress …


Super-K

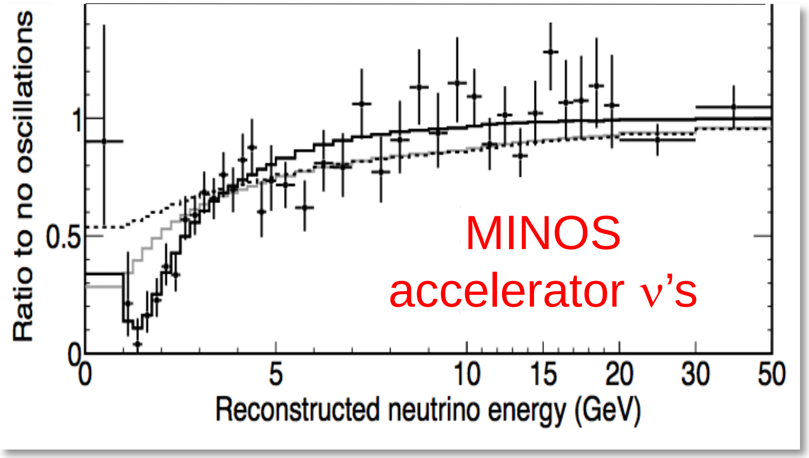
atmospheric ν's

- experiments with solar, atmospheric, accelerator, and reactor ν's have clearly demonstrated that ν's oscillate

- we see the characteristic L/E pattern in multiple sources & experiments

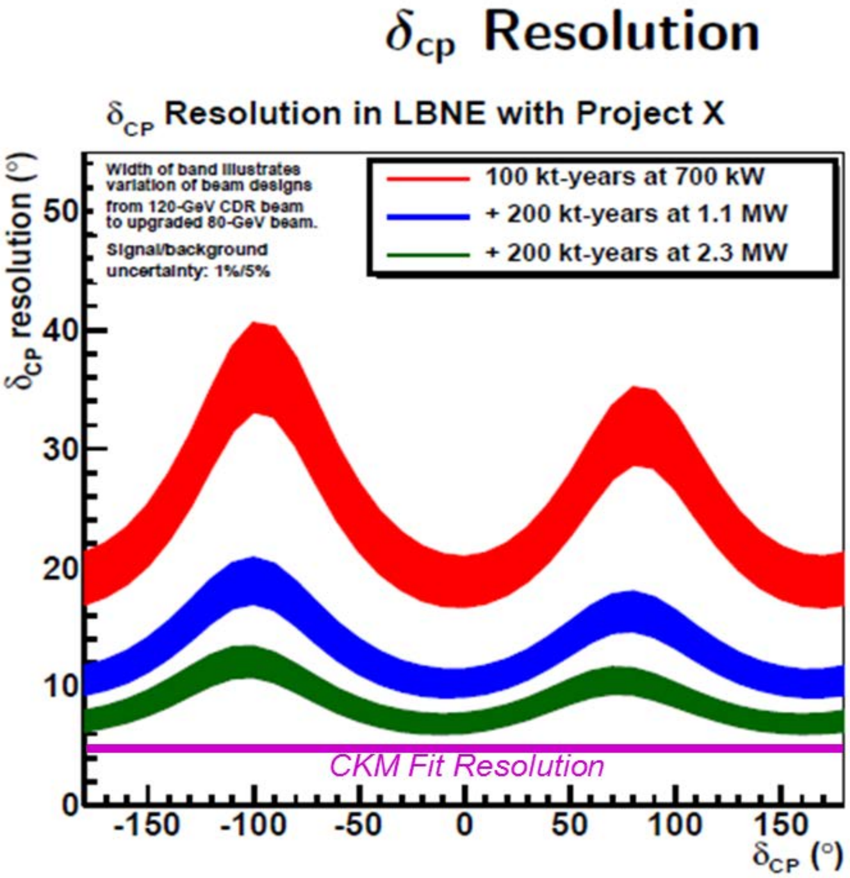

KAMLAND

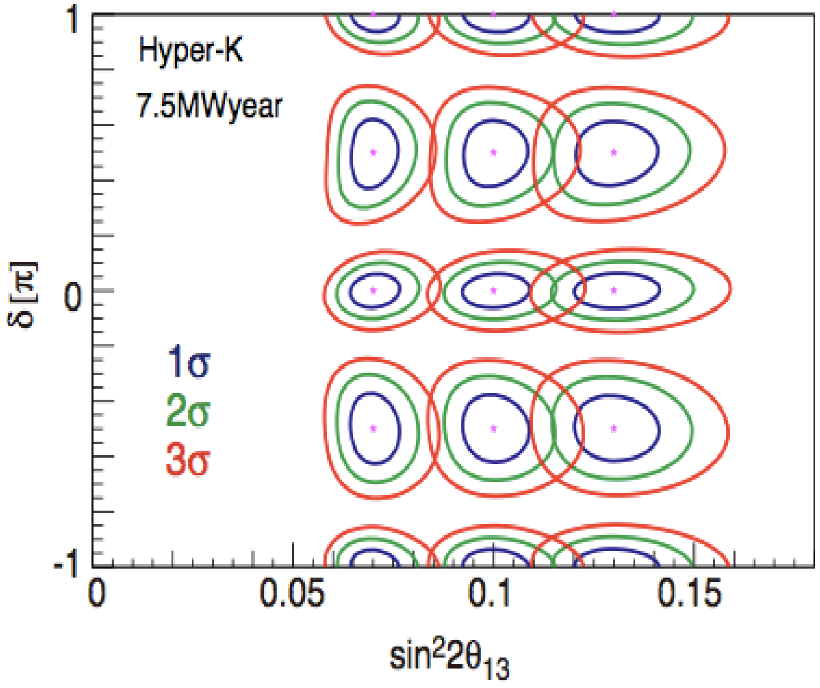
reactor ν's


MINOS

accelerator ν's

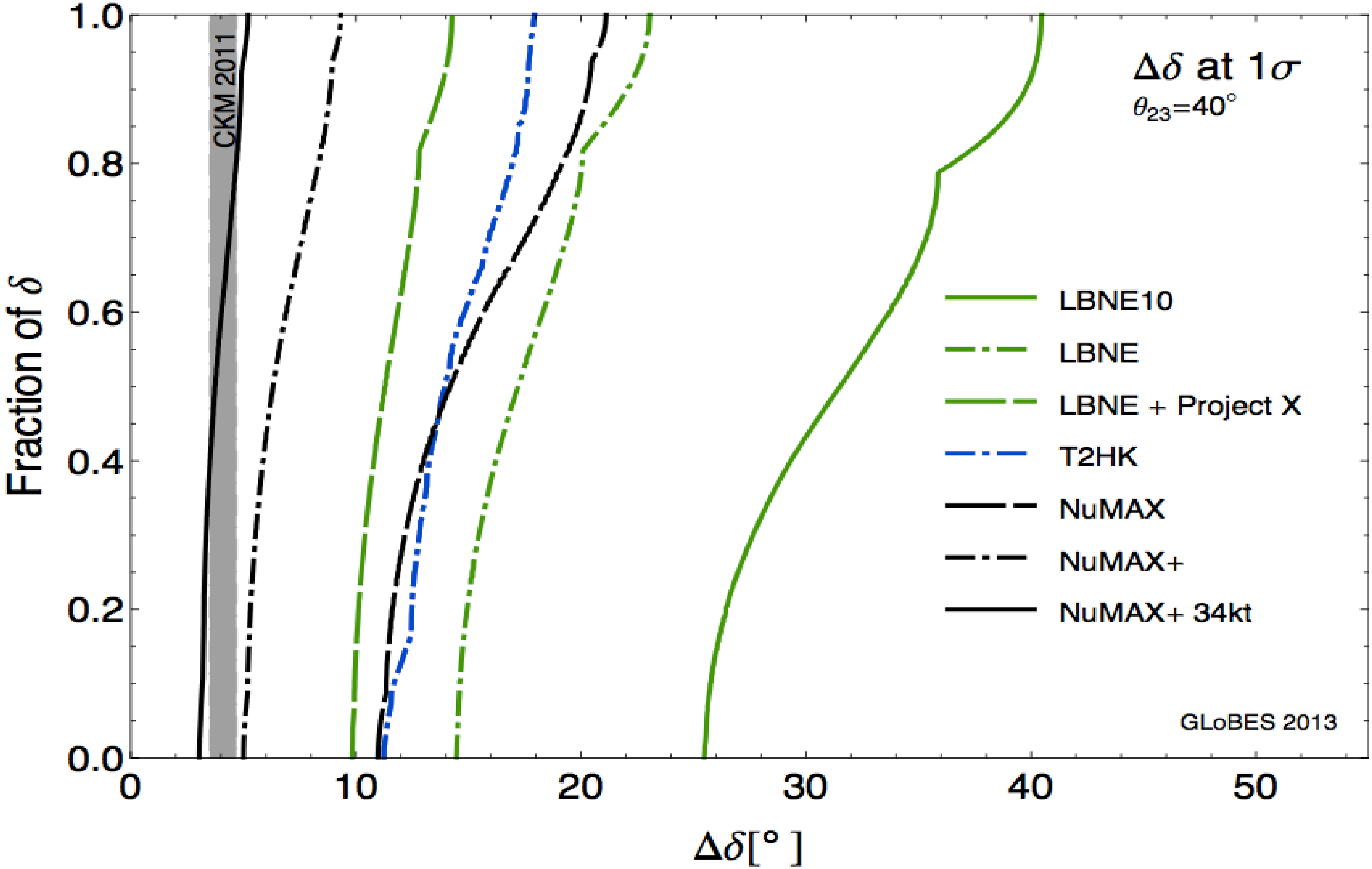
CP Violation @ LBNE and Hyper-K





LBNE + Project X enable an era of high-precision neutrino oscillation measurements.

Far Future Precision



Neutrino Mass

- Understanding of absolute neutrino mass is vital for a complete picture of fundamental particle masses, and is crucial information for cosmology and theories of flavor.

- The next generation of tritium-beta-decay experiments will directly probe neutrino masses a factor of 10 smaller the best current bounds; innovative new ideas may help to go beyond this level of sensitivity.

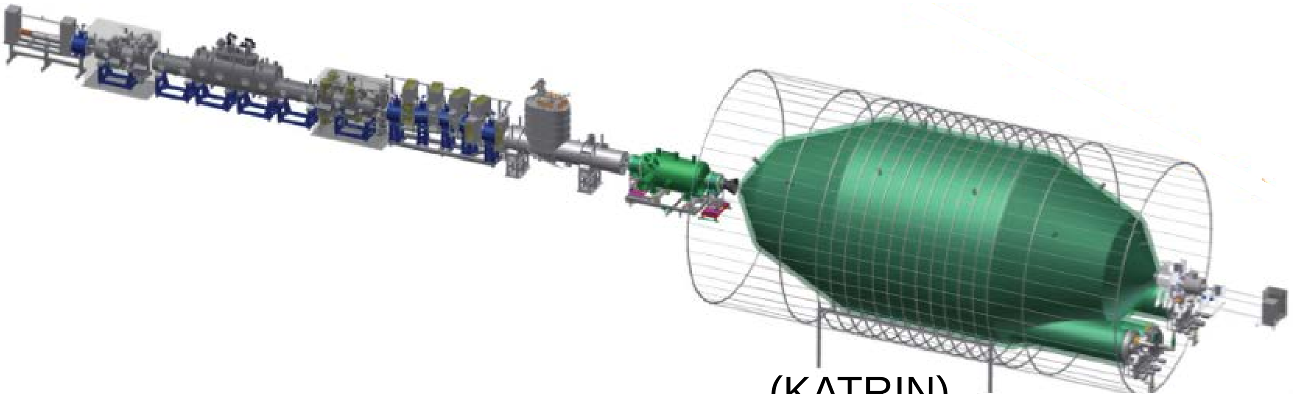
Neutrino Mass

- direct neutrino mass measurements are a clean approach to a fundamental physics question
  - Majorana or Dirac
  - no nuclear matrix elements or complex phases
  - no cosmological degrees of freedom

- present laboratory limit $m_\nu<1.8$ eV from Mainz/Troitsk

- one experiment under construction now in Karlsruhe, Germany
  - KATRIN (2015 start, $m_\nu<0.2$ eV)

- three experiments in R&D to push beyond this
  - Project 8
  - ECHo
  - PTOLEMY



(KATRIN)

Astrophysical Neutrinos

Neutrinos come from natural sources as close as the Earth and Sun, to as far away as distant galaxies, and even as remnants from the Big Bang. They range in kinetic energy from less than one meV to greater than one PeV, and can be used to study properties of the astrophysical sources they come from, the nature of neutrinos themselves, and cosmology.

supernova neutrinos

solar neutrinos

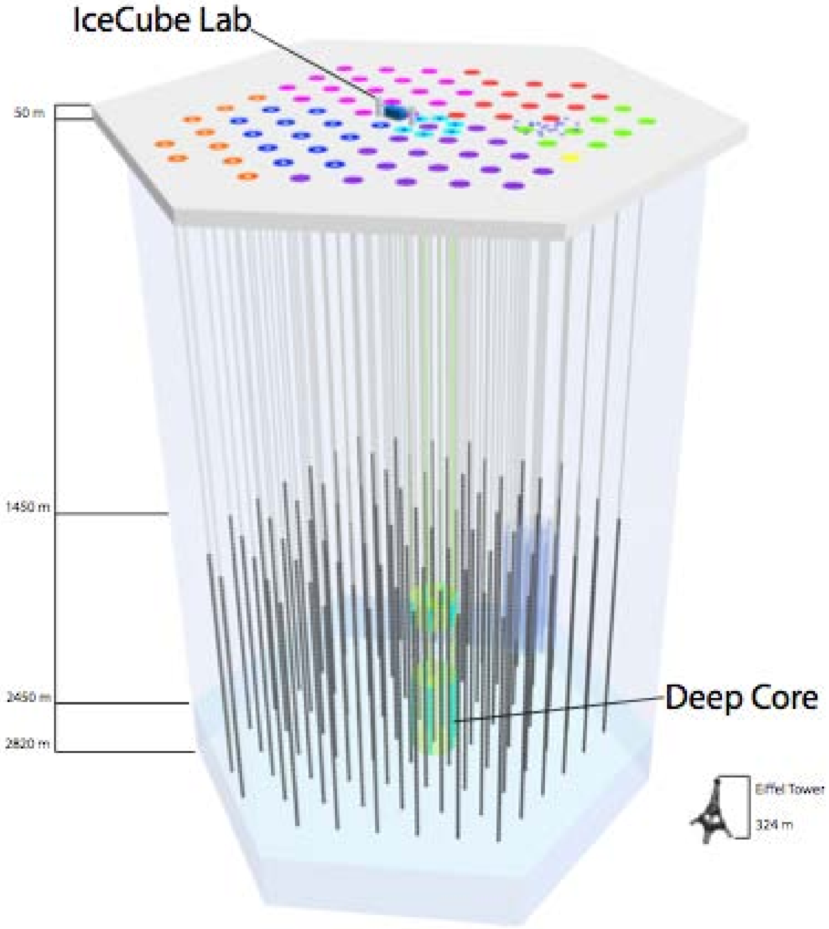
atmospheric neutrinos

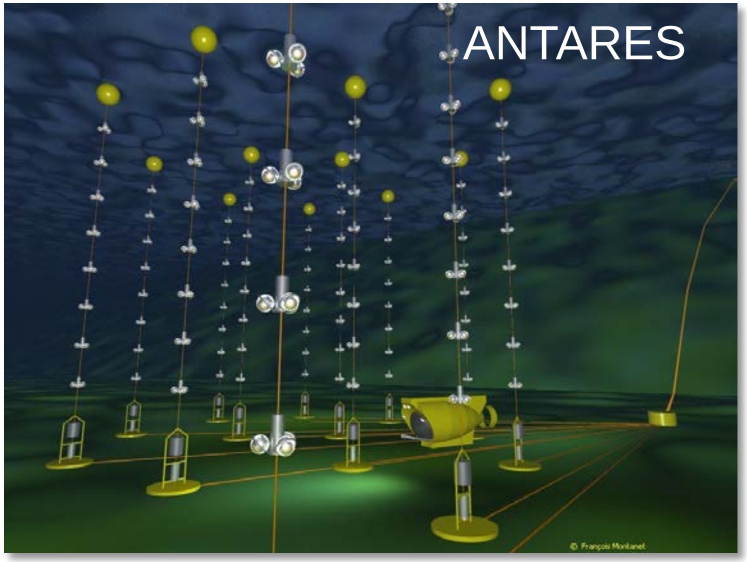
cosmic neutrinos

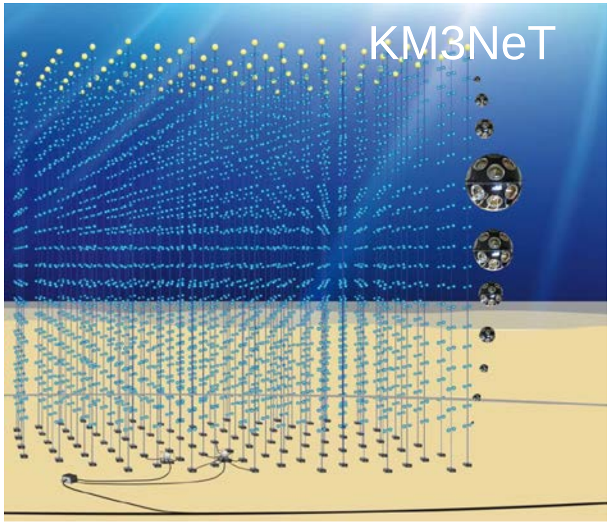
low energy ⟷ high energy

High Energy Astrophysical ν Detectors

IceCube/PINGU




ANTARES


KM3NeT

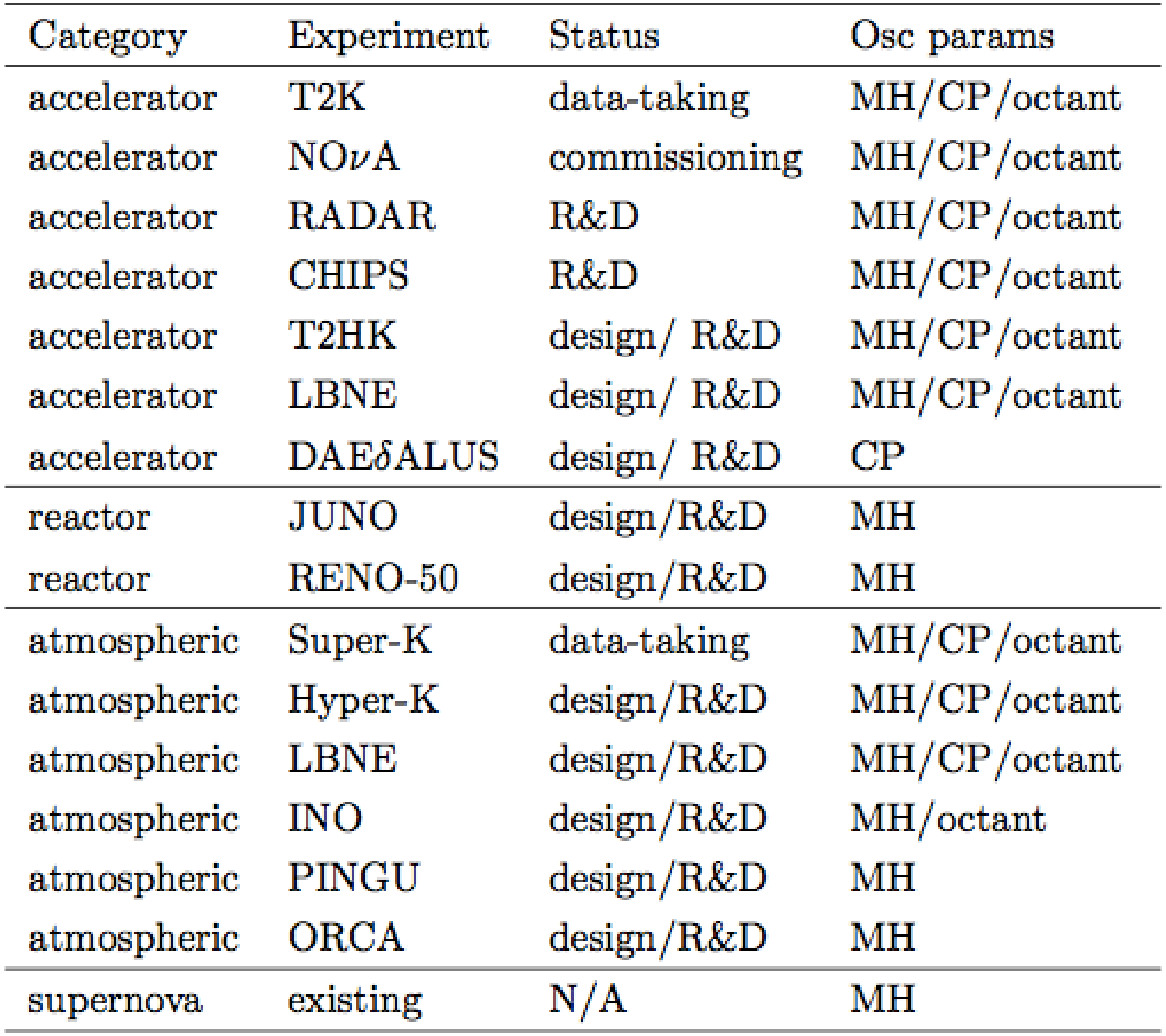
Rough scales for future experiments…

Small	Medium	Large
OscSNS, CSISNS, CENNS, RICOCHET, US reactor, WATCHMAN, CAPTAIN, MiniBooNE+/II, SciNOνA, PTOLEMY, SOX, CeLAND, DANSS, Stereo	**LENS, PINGU, RADAR, CHIPS, LAr1, NuStorm, Project 8, IsoDAR, ARA, ARIANNA, EVA,** JUNO, RENO-50, INO, Daya Bay Source, ORCA	**LBNE, DAEδALUS, NUMAX,** Hyper-K, LAGUNA

Bold means “US-based”

Important to have experiments at a variety of scales for a robust program

Opportunities in ν Oscillations



Category	Experiment	Status	Osc params
accelerator	T2K	data-taking	MH/CP/octant
accelerator	NOνA	commissioning	MH/CP/octant
accelerator	RADAR	R&D	MH/CP/octant
accelerator	CHIPS	R&D	MH/CP/octant
accelerator	T2HK	design/ R&D	MH/CP/octant
accelerator	LBNE	design/ R&D	MH/CP/octant
accelerator	DAEδALUS	design/ R&D	CP
reactor	JUNO	design/R&D	MH
reactor	RENO-50	design/R&D	MH
atmospheric	Super-K	data-taking	MH/CP/octant
atmospheric	Hyper-K	design/R&D	MH/CP/octant
atmospheric	LBNE	design/R&D	MH/CP/octant
atmospheric	INO	design/R&D	MH/octant
atmospheric	PINGU	design/R&D	MH
atmospheric	ORCA	design/R&D	MH
supernova	existing	N/A	MH

T2HK plays an important role

Next Generation Searches for Sterile ν' s

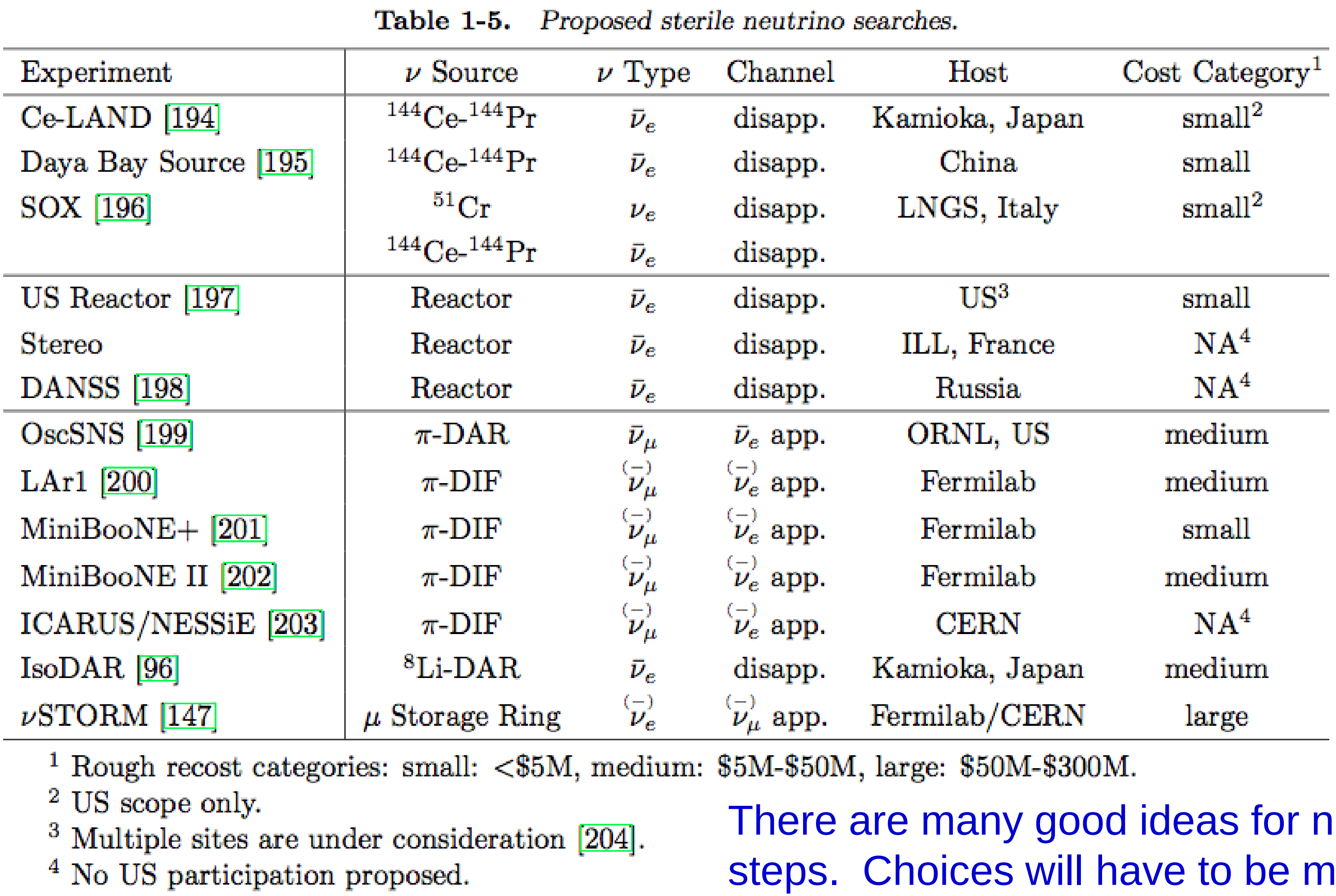


Table 1-5. *Proposed sterile neutrino searches.*

Experiment	ν Source	ν Type	Channel	Host	Cost Category[1]
Ce-LAND [194]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	Kamioka, Japan	small[2]
Daya Bay Source [195]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	China	small
SOX [196]	^{51}Cr	ν_e	disapp.	LNGS, Italy	small[2]
	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.		
US Reactor [197]	Reactor	$\bar{\nu}_e$	disapp.	US[3]	small
Stereo	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	NA[4]
DANSS [198]	Reactor	$\bar{\nu}_e$	disapp.	Russia	NA[4]
OscSNS [199]	π-DAR	$\bar{\nu}_\mu$	$\bar{\nu}_e$ app.	ORNL, US	medium
LAr1 [200]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
MiniBooNE+ [201]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	small
MiniBooNE II [202]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
ICARUS/NESSiE [203]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	CERN	NA[4]
IsoDAR [96]	^{8}Li-DAR	$\bar{\nu}_e$	disapp.	Kamioka, Japan	medium
νSTORM [147]	μ Storage Ring	$\overset{(-)}{\nu}_e$	$\overset{(-)}{\nu}_\mu$ app.	Fermilab/CERN	large

[1] Rough recost categories: small: <\$5M, medium: \$5M-\$50M, large: \$50M-\$300M.

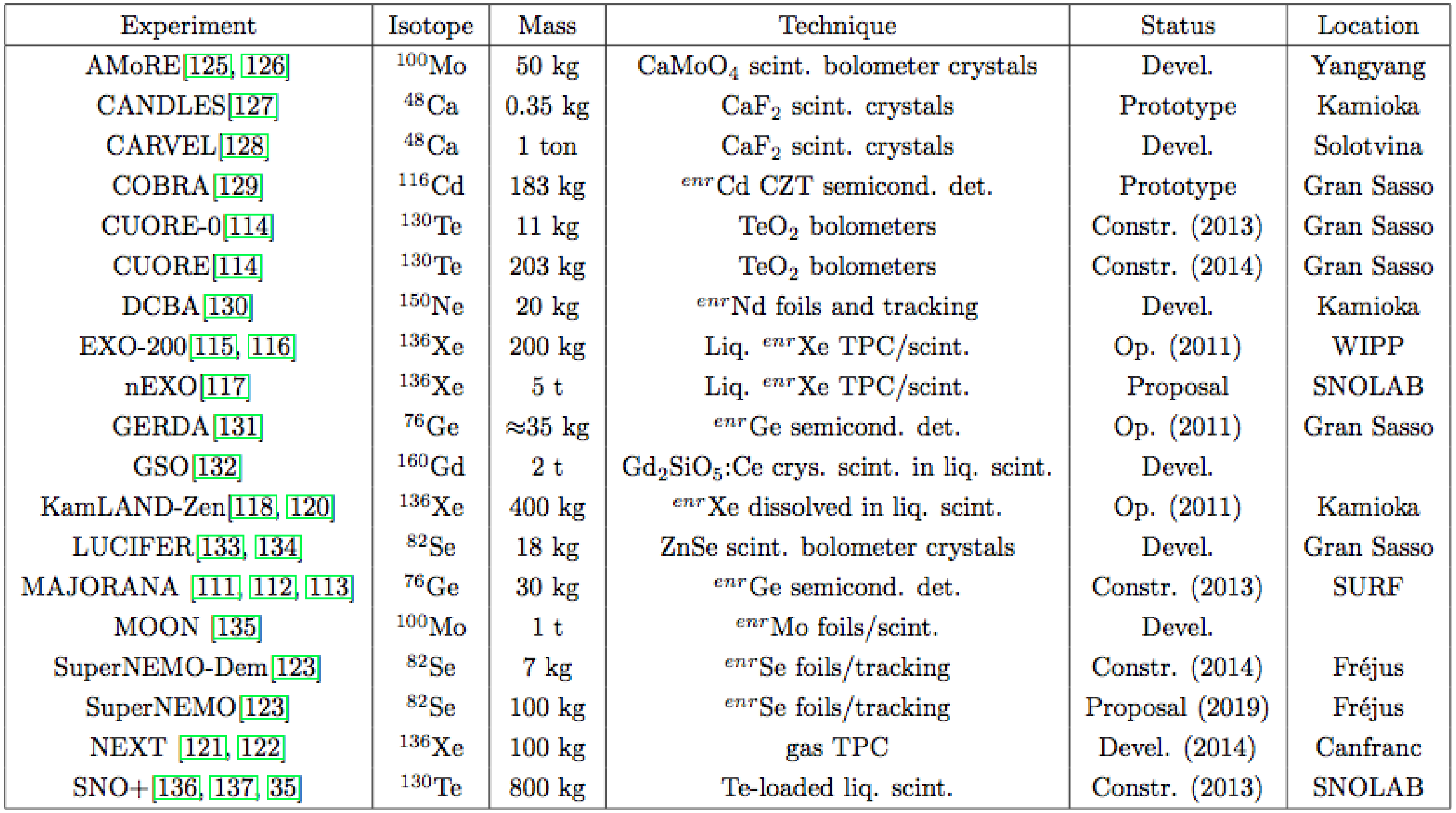
[2] US scope only.

[3] Multiple sites are under consideration [204].

[4] No US participation proposed.

There are many good ideas for next steps. Choices will have to be made

0νββ Experiments and Proposals



Experiment	Isotope	Mass	Technique	Status	Location
AMoRE[125, 126]	^{100}Mo	50 kg	CaMoO$_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES[127]	^{48}Ca	0.35 kg	CaF$_2$ scint. crystals	Prototype	Kamioka
CARVEL[128]	^{48}Ca	1 ton	CaF$_2$ scint. crystals	Devel.	Solotvina
COBRA[129]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[114]	^{130}Te	11 kg	TeO$_2$ bolometers	Constr. (2013)	Gran Sasso
CUORE[114]	^{130}Te	203 kg	TeO$_2$ bolometers	Constr. (2014)	Gran Sasso
DCBA[130]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200[115, 116]	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
nEXO[117]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLAB
GERDA[131]	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO[132]	^{160}Gd	2 t	Gd$_2$SiO$_5$:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen[118, 120]	^{136}Xe	400 kg	^{enr}Xe dissolved in liq. scint.	Op. (2011)	Kamioka
LUCIFER[133, 134]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [111, 112, 113]	^{76}Ge	30 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [135]	^{100}Mo	1 t	^{enr}Mo foils/scint.	Devel.	
SuperNEMO-Dem[123]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO[123]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [121, 122]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
SNO+[136, 137, 35]	^{130}Te	800 kg	Te-loaded liq. scint.	Constr. (2013)	SNOLAB

Table 1-4. *A summary list of neutrinoless double-beta decay proposals and experiments.*

(see Michael Ramsey-Musolf's talk after the break)

- multiple isotopes and several complementary experiments are needed for confirmation of a signal
- significant overlap in technologies/facilities with DM community

Low Energy Astrophysical ν Detectors

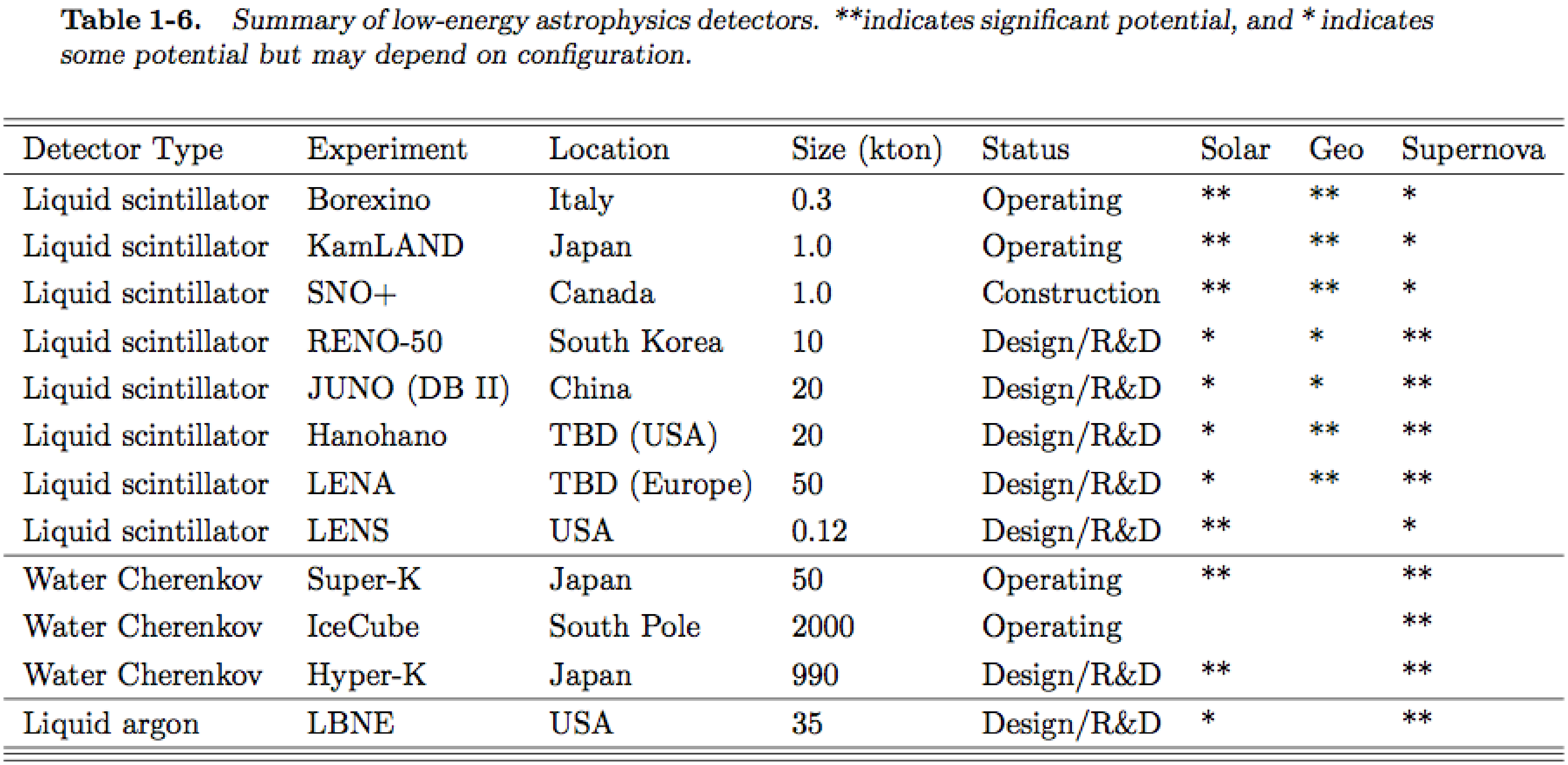
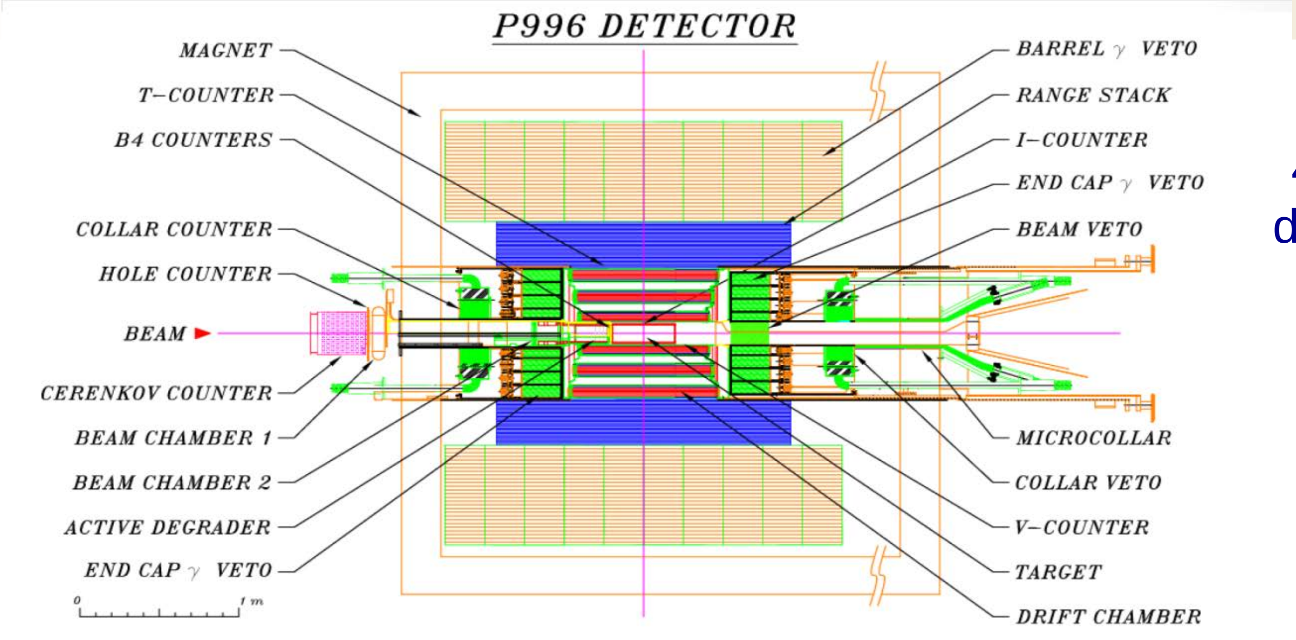


Table 1-6. *Summary of low-energy astrophysics detectors. **indicates significant potential, and * indicates some potential but may depend on configuration.*

Detector Type	Experiment	Location	Size (kton)	Status	Solar	Geo	Supernova
Liquid scintillator	Borexino	Italy	0.3	Operating	**	**	*
Liquid scintillator	KamLAND	Japan	1.0	Operating	**	**	*
Liquid scintillator	SNO+	Canada	1.0	Construction	**	**	*
Liquid scintillator	RENO-50	South Korea	10	Design/R&D	*	*	**
Liquid scintillator	JUNO (DB II)	China	20	Design/R&D	*	*	**
Liquid scintillator	Hanohano	TBD (USA)	20	Design/R&D	*	**	**
Liquid scintillator	LENA	TBD (Europe)	50	Design/R&D	*	**	**
Liquid scintillator	LENS	USA	0.12	Design/R&D	**		*
Water Cherenkov	Super-K	Japan	50	Operating	**		**
Water Cherenkov	IceCube	South Pole	2000	Operating			**
Water Cherenkov	Hyper-K	Japan	990	Design/R&D	**		**
Liquid argon	LBNE	USA	35	Design/R&D	*		**

ORKA



4th generation detector designed around proven techniques

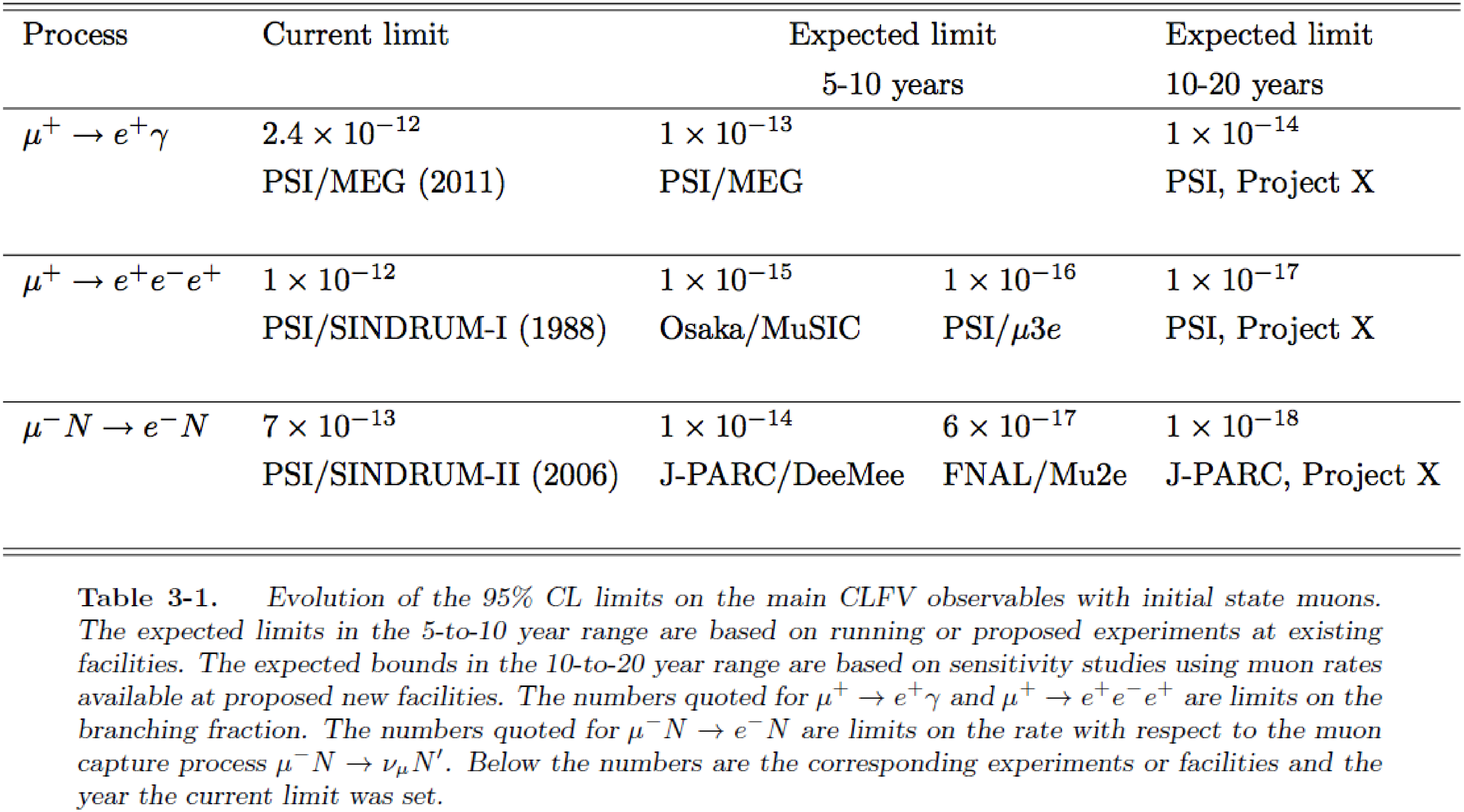
Expect ×100 sensitivity relative to BNL experiment:
×10 from beam and ×10 from detector

ASU
UNBC
INFN
INFN
Ole Miss
UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ
ILLINOIS
UBC
THE UNIVERSITY OF TEXAS AT AUSTIN
TSING HUA UNIVERSITY
UNIVERSITY OF TEXAS ARLINGTON
BROOKHAVEN NATIONAL LABORATORY
JOINT INSTITUTE FOR NUCLEAR RESEARCH
TRIUMF

Already a very strong collaboration

Charged Lepton Flavor Violation

95% CL limits in CLFV with muons

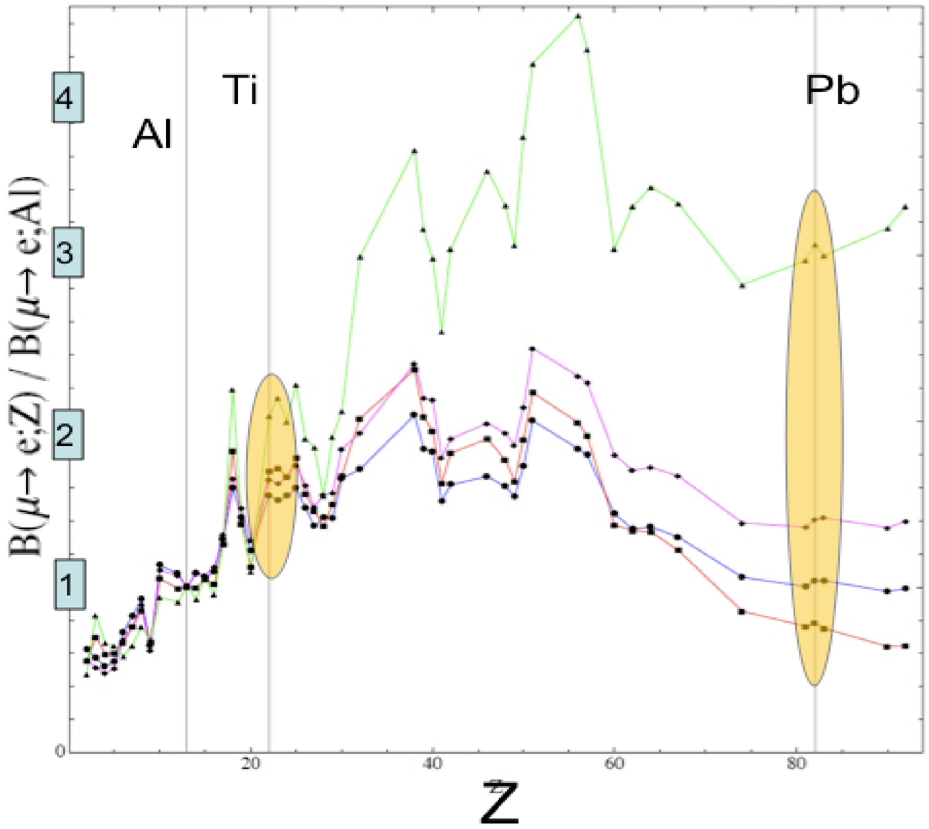


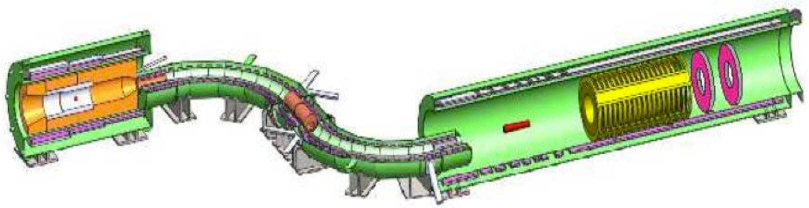
Process	Current limit	Expected limit 5-10 years		Expected limit 10-20 years
$\mu^+ \to e^+\gamma$	2.4×10^{-12} PSI/MEG (2011)	1×10^{-13} PSI/MEG		1×10^{-14} PSI, Project X
$\mu^+ \to e^+e^-e^+$	1×10^{-12} PSI/SINDRUM-I (1988)	1×10^{-15} Osaka/MuSIC	1×10^{-16} PSI/$\mu 3e$	1×10^{-17} PSI, Project X
$\mu^- N \to e^- N$	7×10^{-13} PSI/SINDRUM-II (2006)	1×10^{-14} J-PARC/DeeMee	6×10^{-17} FNAL/Mu2e	1×10^{-18} J-PARC, Project X

Table 3-1. *Evolution of the 95% CL limits on the main CLFV observables with initial state muons. The expected limits in the 5-to-10 year range are based on running or proposed experiments at existing facilities. The expected bounds in the 10-to-20 year range are based on sensitivity studies using muon rates available at proposed new facilities. The numbers quoted for $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$ are limits on the branching fraction. The numbers quoted for $\mu^- N \to e^- N$ are limits on the rate with respect to the muon capture process $\mu^- N \to \nu_\mu N'$. Below the numbers are the corresponding experiments or facilities and the year the current limit was set.*

Model Determination with Mu2e

If charged lepton flavor violation is discovered, Mu2e can determine the origin!





Vector (Z_μ)

- Z couples predominantly to neutrons
- γ couples to protons

Vector (γ_μ)

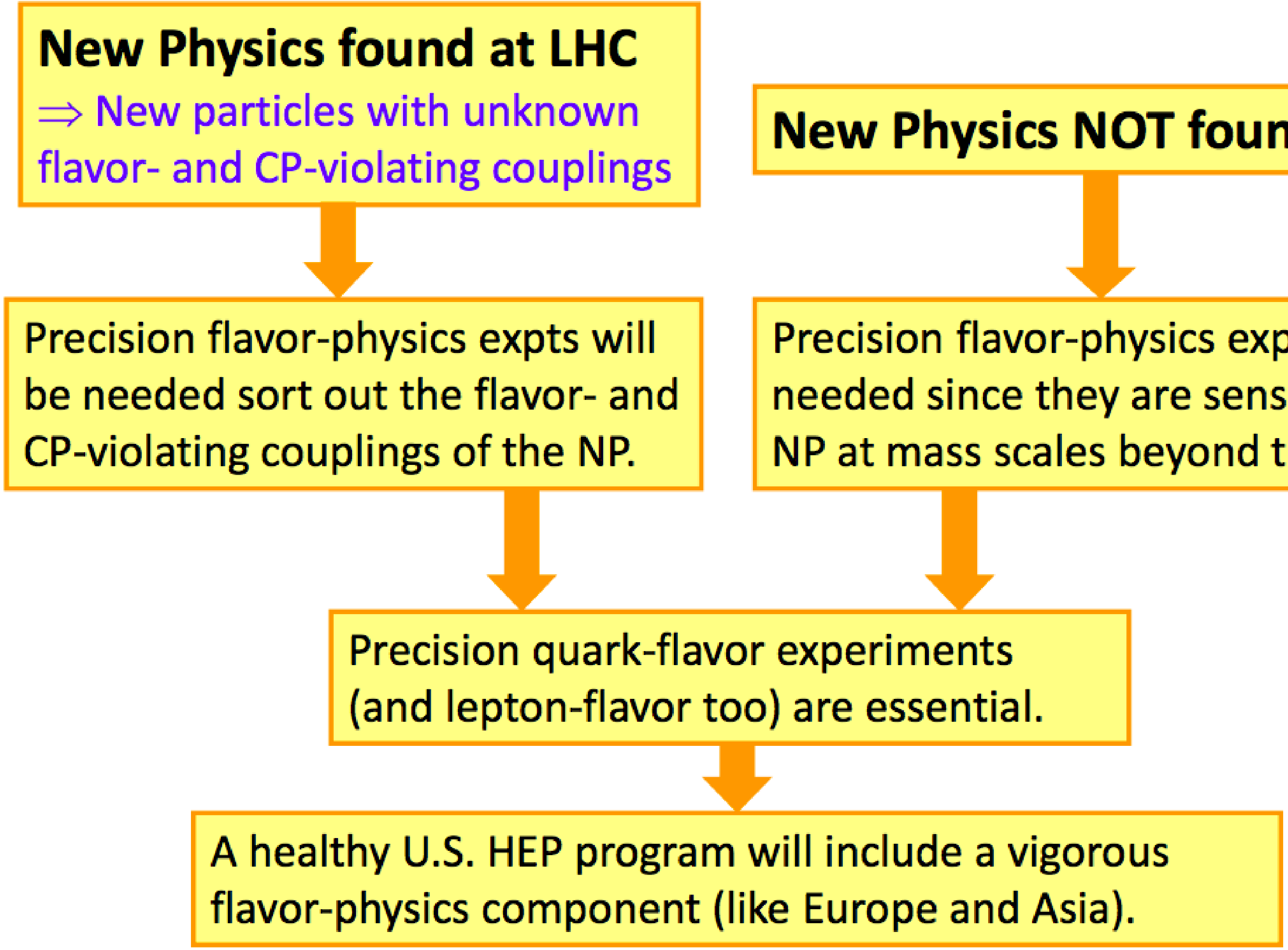
Dipole

Scalar

Cirigliano, Kitano, Okada, Tuzon
0904.0957

5% measurement of the ratio Ti/Al needed to discriminate between models
Theory uncertainty mainly cancels in ratio

Flavor in the LHC Era



New Physics found at LHC
⇒ New particles with unknown flavor- and CP-violating couplings

New Physics NOT found at LHC

Precision flavor-physics expts will be needed sort out the flavor- and CP-violating couplings of the NP.

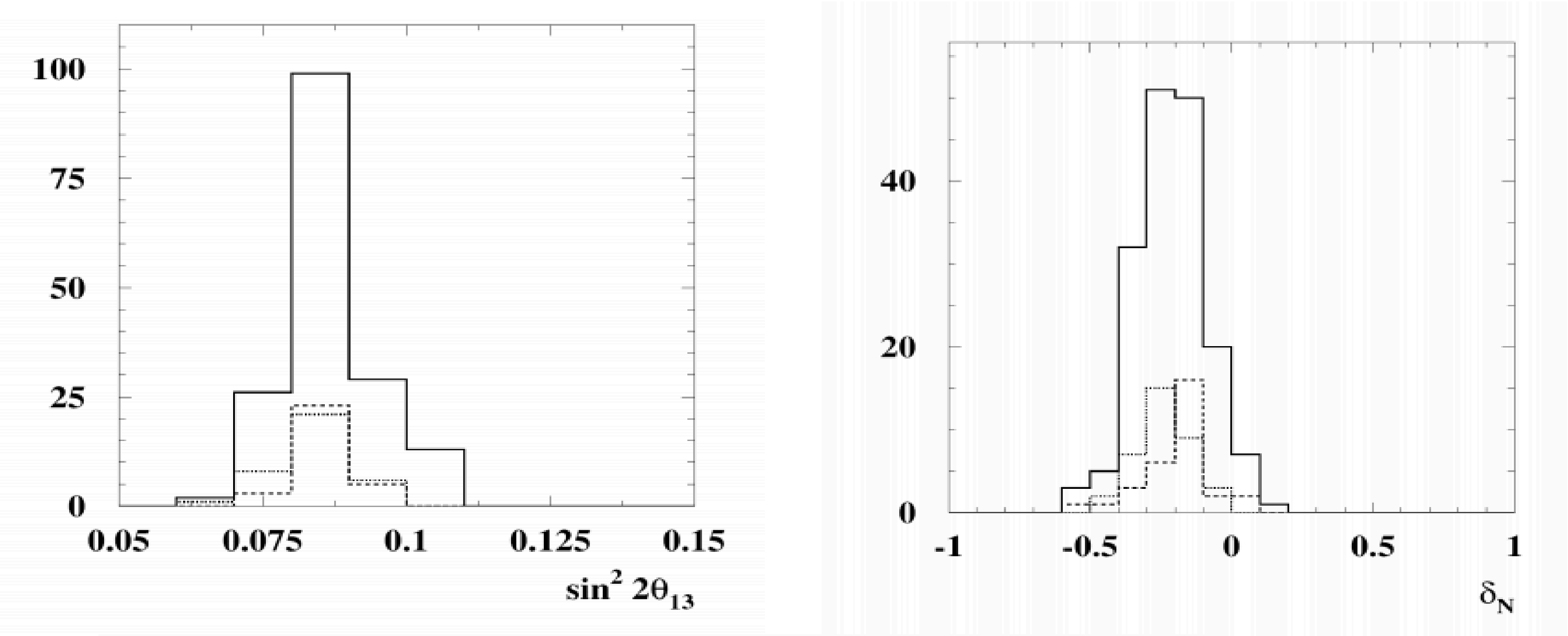
Precision flavor-physics expts will be needed since they are sensitive to NP at mass scales beyond the LHC.

Precision quark-flavor experiments (and lepton-flavor too) are essential.

A healthy U.S. HEP program will include a vigorous flavor-physics component (like Europe and Asia).

Grand Unified Models

Theta(13) in Minimal SO(10)



$\sin^2 2\theta_{13}$ and CP violating phase δ_N

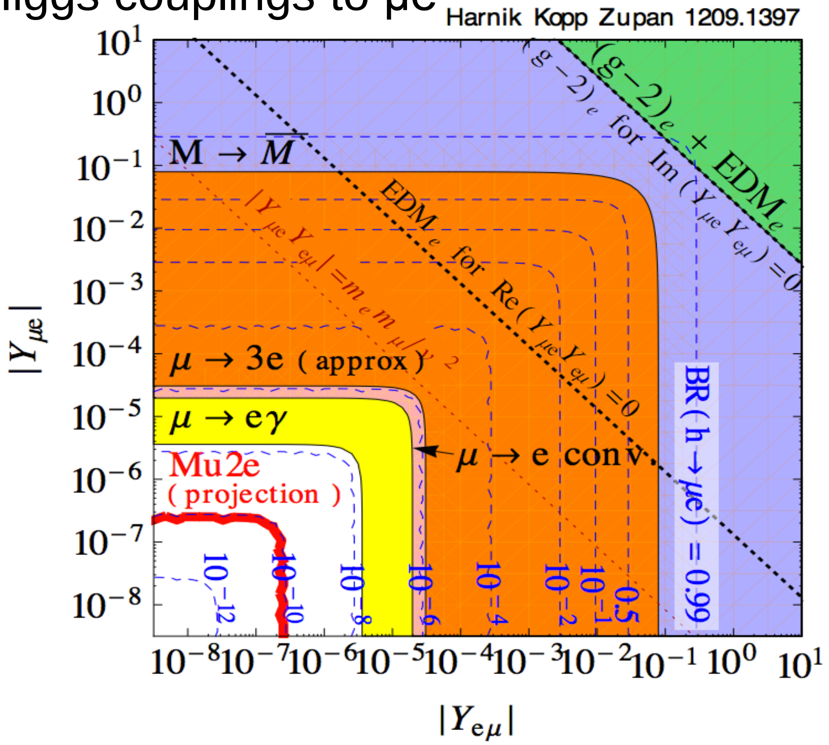
K.S. Babu and C. Macesanu (2005)

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$ Daya Bay (2012)

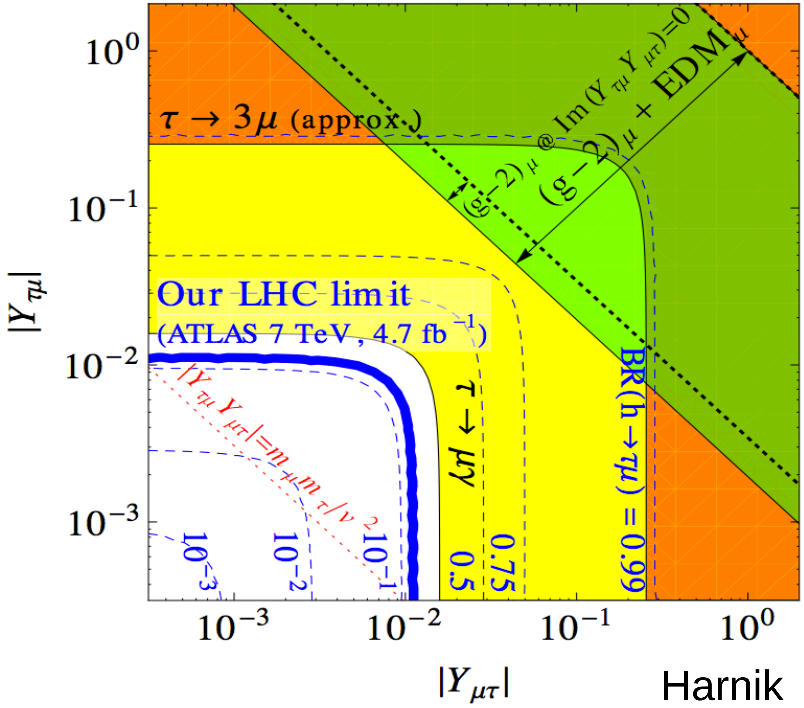
Lepton Flavor Violating Higgs Decays

- Connection between Intensity and Energy Frontiers!
  - Demonstration of complementarity
- Operator expansion w/ 2-Higgs doublets to generate off-diagonal couplings

Higgs couplings to μe



Higgs couplings to τμ



Harnik

Example Project X Research Program

Tschirhart, SLAC Summer Institute

Program:	Onset of NOvA operations in 2013	**Stage-1:** 1 GeV CW Linac driving Booster & Muon, n/edm programs	**Stage-2:** Upgrade to 3 GeV CW Linac	**Stage-3:** Project X RDR	**Stage-4:** Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW +0-50kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

Staging of Project X

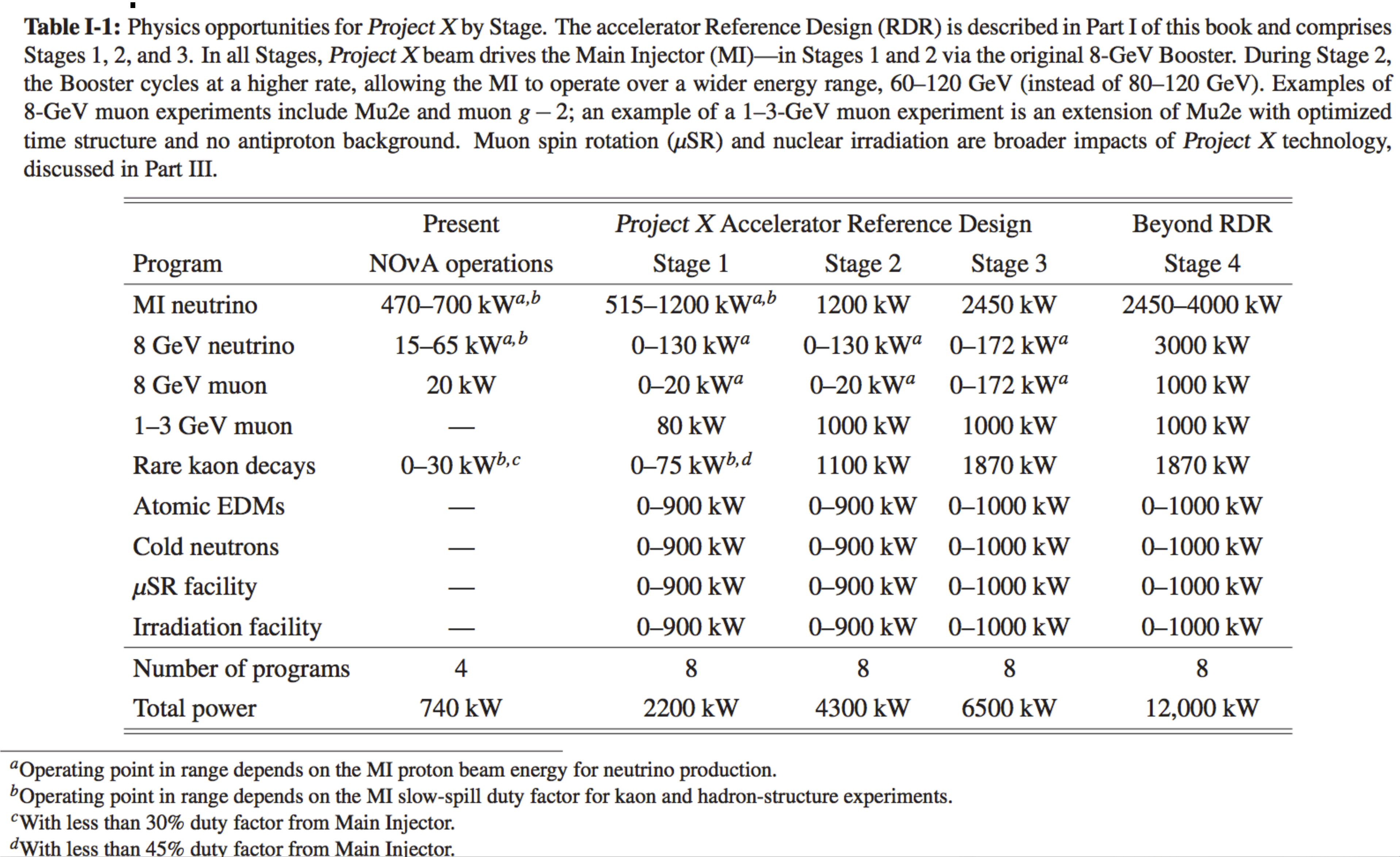


Table I-1: Physics opportunities for *Project X* by Stage. The accelerator Reference Design (RDR) is described in Part I of this book and comprises Stages 1, 2, and 3. In all Stages, *Project X* beam drives the Main Injector (MI)—in Stages 1 and 2 via the original 8-GeV Booster. During Stage 2, the Booster cycles at a higher rate, allowing the MI to operate over a wider energy range, 60–120 GeV (instead of 80–120 GeV). Examples of 8-GeV muon experiments include Mu2e and muon $g-2$; an example of a 1–3-GeV muon experiment is an extension of Mu2e with optimized time structure and no antiproton background. Muon spin rotation (μSR) and nuclear irradiation are broader impacts of *Project X* technology, discussed in Part III.

	Present	*Project X* Accelerator Reference Design			Beyond RDR
Program	NOνA operations	Stage 1	Stage 2	Stage 3	Stage 4
MI neutrino	470–700 kW[a,b]	515–1200 kW[a,b]	1200 kW	2450 kW	2450–4000 kW
8 GeV neutrino	15–65 kW[a,b]	0–130 kW[a]	0–130 kW[a]	0–172 kW[a]	3000 kW
8 GeV muon	20 kW	0–20 kW[a]	0–20 kW[a]	0–172 kW[a]	1000 kW
1–3 GeV muon	—	80 kW	1000 kW	1000 kW	1000 kW
Rare kaon decays	0–30 kW[b,c]	0–75 kW[b,d]	1100 kW	1870 kW	1870 kW
Atomic EDMs	—	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Cold neutrons	—	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
μSR facility	—	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Irradiation facility	—	0–900 kW	0–900 kW	0–1000 kW	0–1000 kW
Number of programs	4	8	8	8	8
Total power	740 kW	2200 kW	4300 kW	6500 kW	12,000 kW

---

[a] Operating point in range depends on the MI proton beam energy for neutrino production.

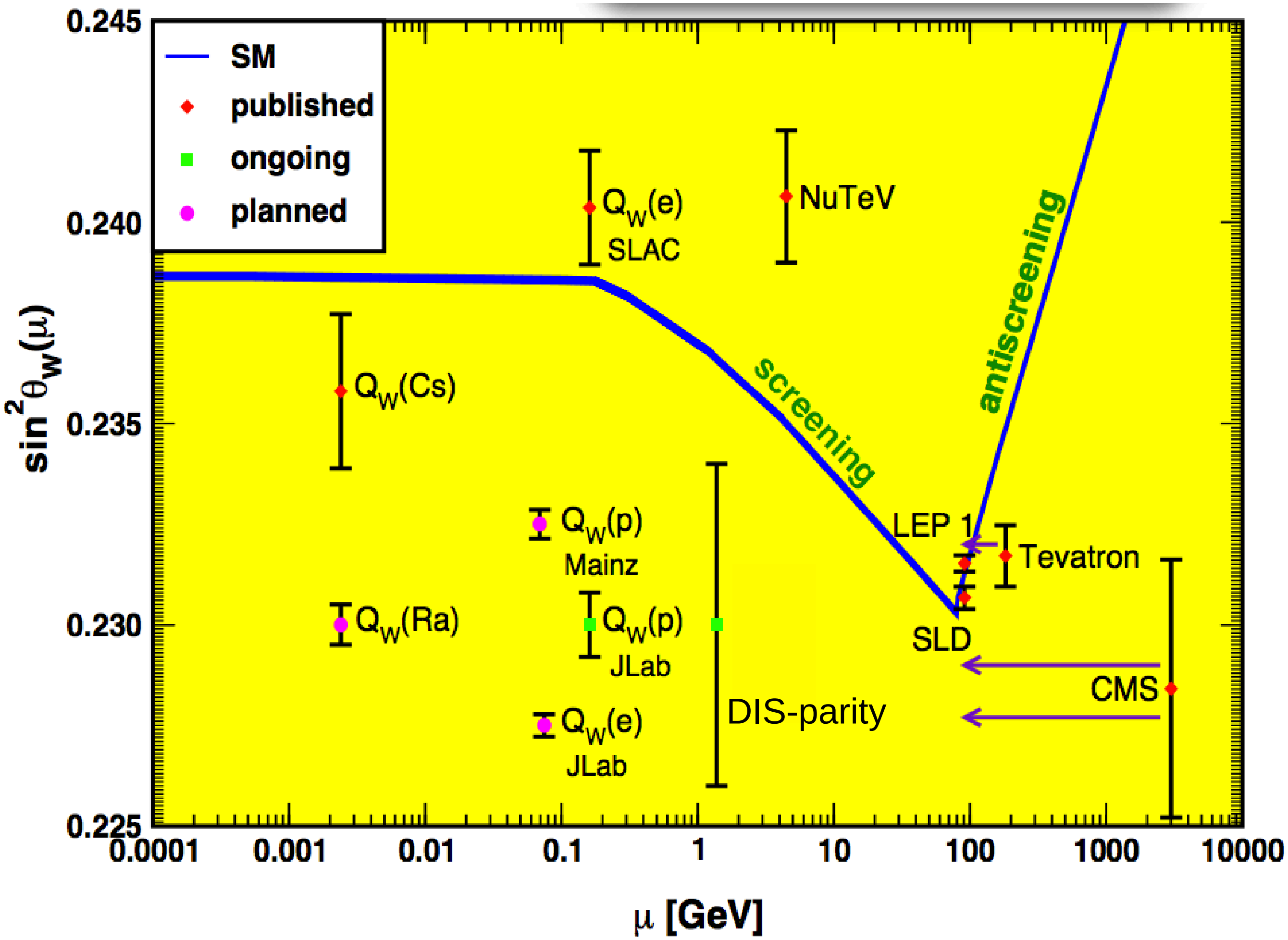
[b] Operating point in range depends on the MI slow-spill duty factor for kaon and hadron-structure experiments.

[c] With less than 30% duty factor from Main Injector.

[d] With less than 45% duty factor from Main Injector.

Low-Energy EW Precision Tests

Test running of weak mixing angle in new generation of low-energy parity violation exp’ts



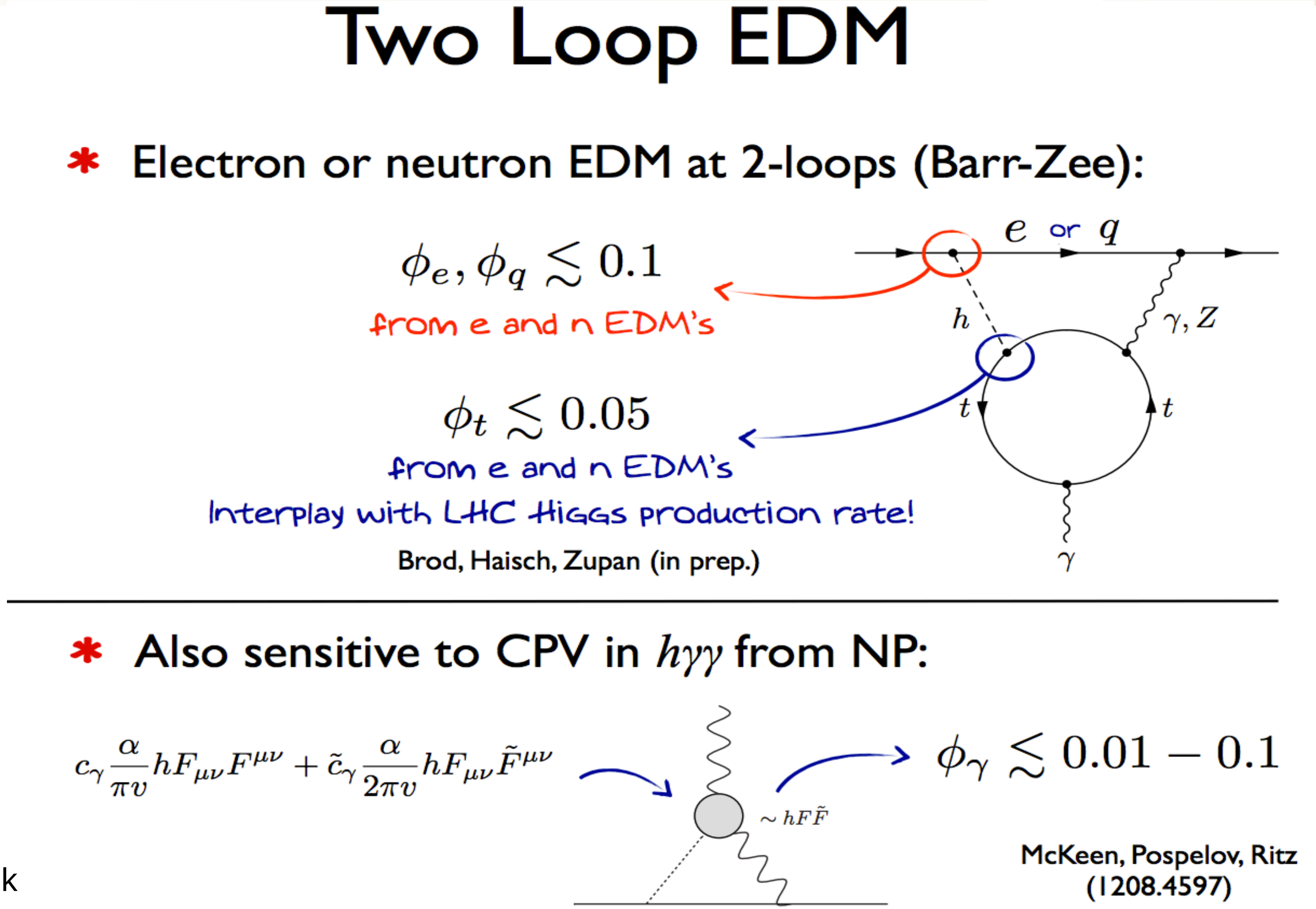
Current and future measurements

Future: indicate expected errors and value of μ

Details in talk by Ramsey-Musolf

S. Su

edm's and the Higgs



Two Loop EDM

- Electron or neutron EDM at 2-loops (Barr-Zee):

$\phi_e, \phi_q \lesssim 0.1$

from e and n EDM's

$\phi_t \lesssim 0.05$

from e and n EDM's

Interplay with LHC Higgs production rate!

Brod, Haisch, Zupan (in prep.)

- Also sensitive to CPV in $h\gamma\gamma$ from NP:

$$c_\gamma \frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu} + \tilde{c}_\gamma \frac{\alpha}{2\pi v} h F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$\phi_\gamma \lesssim 0.01 - 0.1$

McKeen, Pospelov, Ritz
(1208.4597)

edm's and SUSY

pMSSM benchmark points

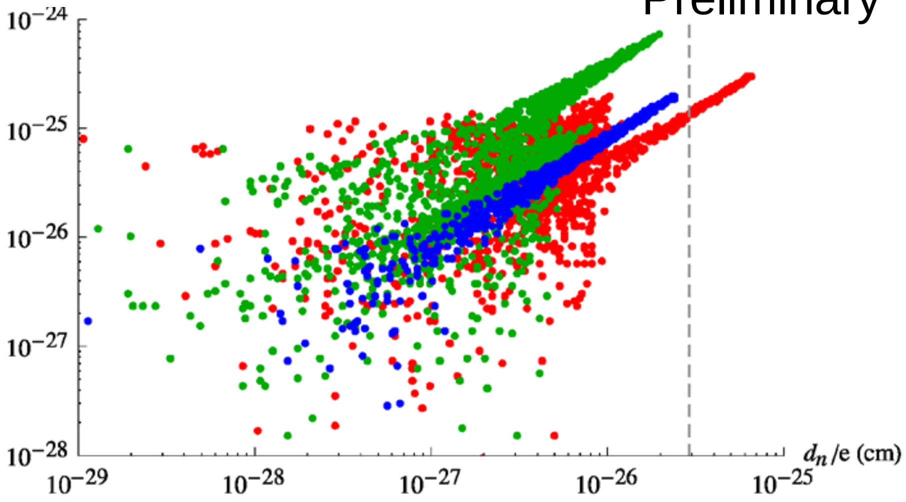
- 19 weak-scale parameters
- No high-scale assumptions
- All sparticle masses < 4 TeV
- All points consistent with global data set
- Assume MFV ➔ perform expansion in MFV
- Scan over phases

Same points studied across all 3 frontiers!!

Low fine-tuning models
Survive 300 fb^{-1} @ 14 TeV LHC
Survive 3 ab^{-1} @ 14 TeV LHC

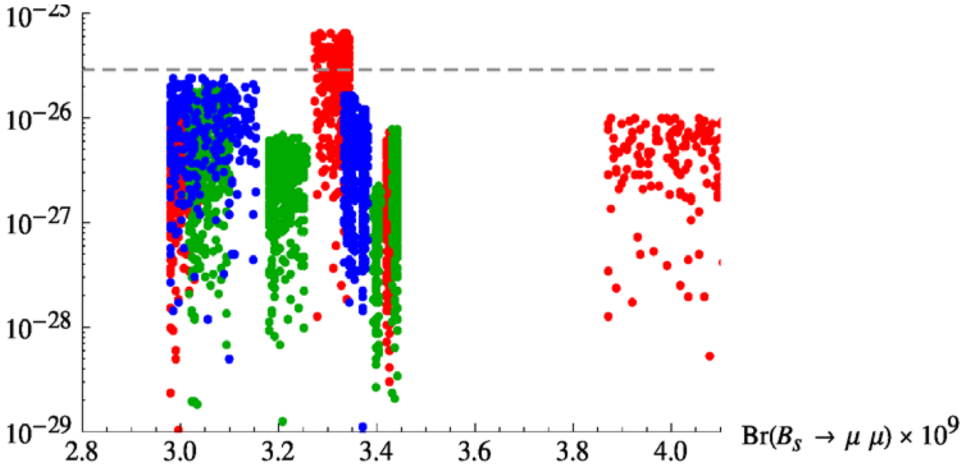
J. Berger etal
Preliminary

μ edm



Neutron edm

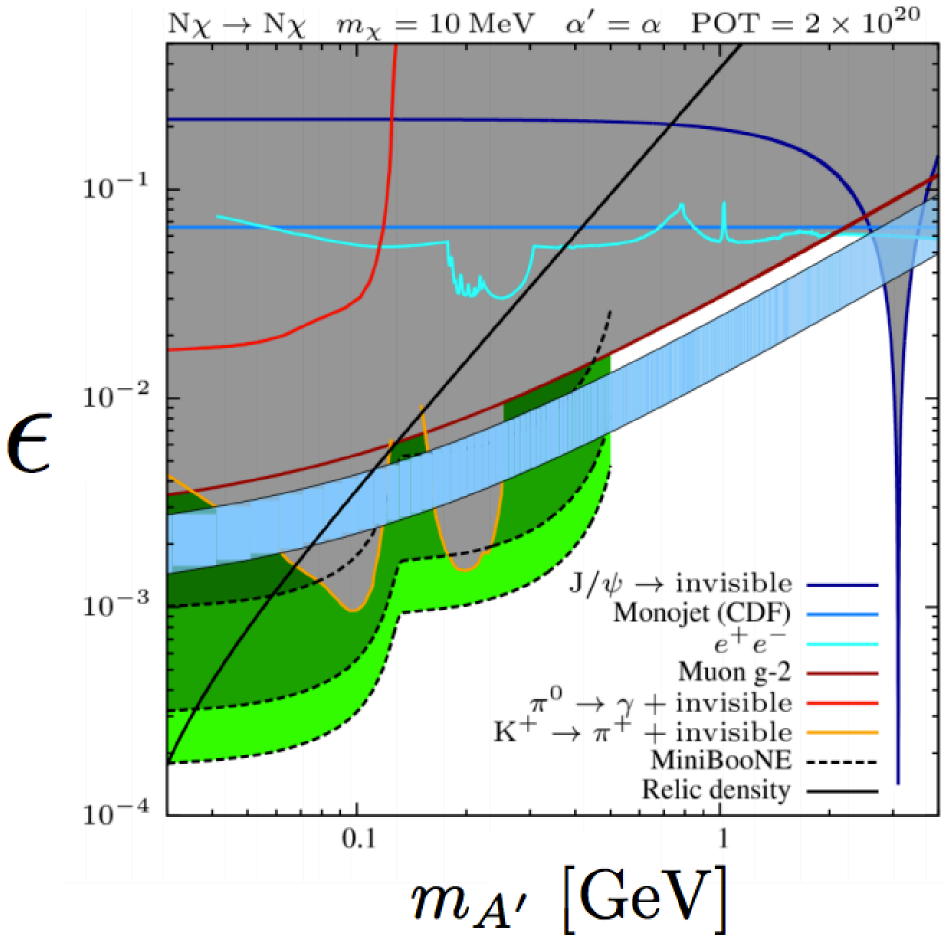
Neutron edm



Proton–beam based searches

MiniBooNE proposal for sub-GeV DM search

Aguilar-Arevalo et.al. (MiniBooNE proposal)



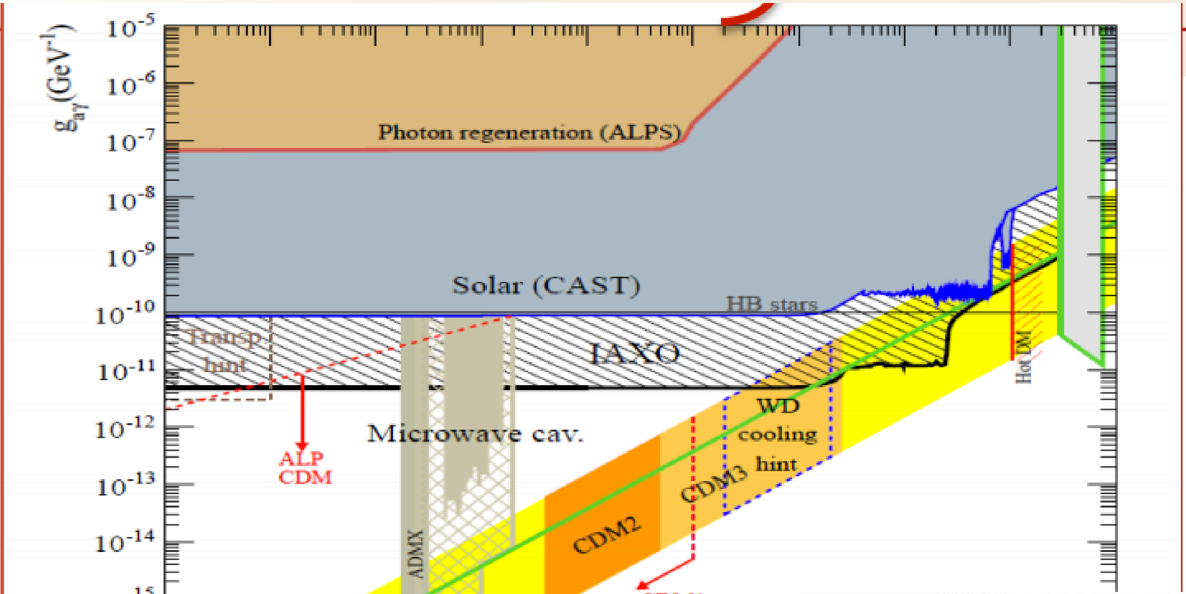
e.g. $m_{\mathrm{DM}} = 10$ MeV

pioneering search for sub-GeV dark matter using a neutrino factory

relatively inexpensive, no new facility

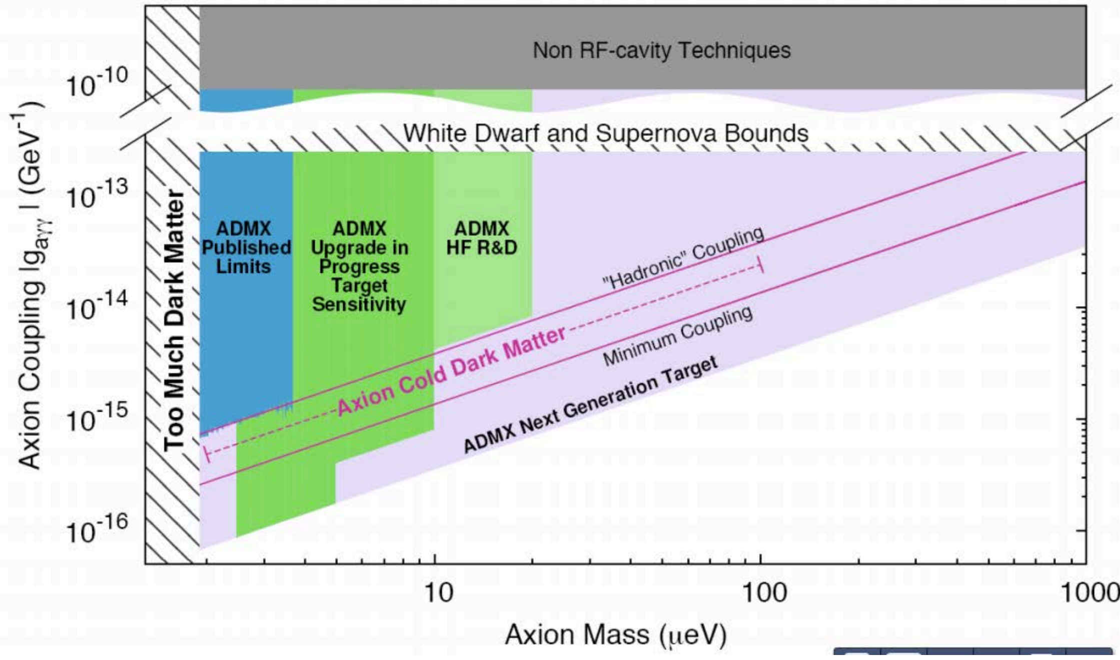
Essig

Future Sensitivity



Helioscopes

ADMX



Future sensitivity reaches the level of the CDM prediction