$\Delta B = 2$:

A State of the Field, and Looking Forward

Michael Wagman

Rare Processes and Precision Frontier
Townhall Meeting

October 2, 2020

Fermilab

$\Delta\mathcal{B} = 2$: A State of the Field, and Looking Forward

A brief overview of theoretical and experimental physics opportunities from the participants of
The Amherst Center for Fundamental Interactions Workshop
Theoretical Innovations for Future Experiments Regarding Baryon Number Violation, Part 1
In Coordination with the Snowmass Rare Processes and Precision Frontier

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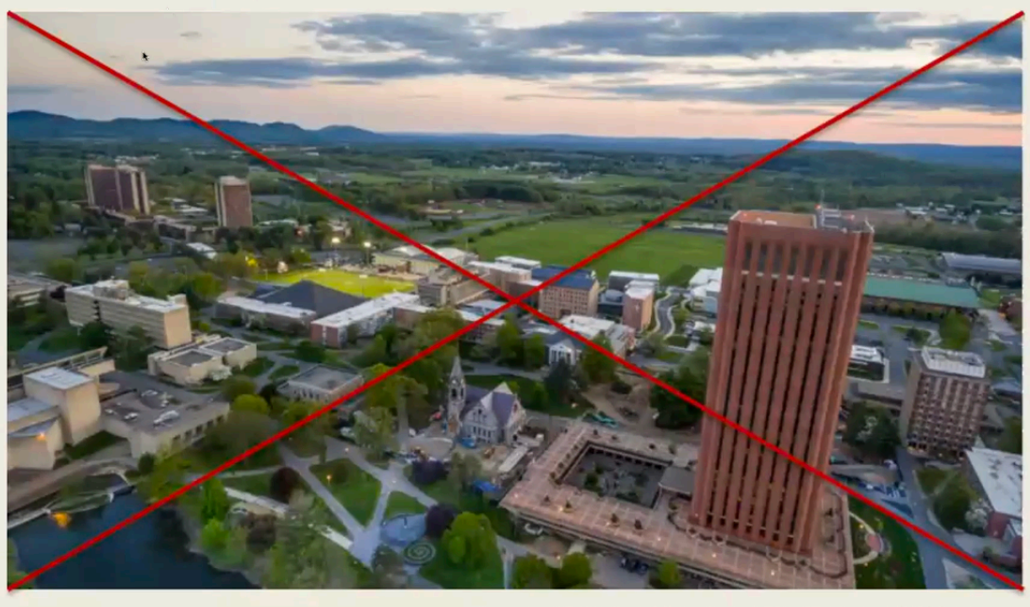
Theoretical Innovations for Future Experiments Regarding Baryon Number Violation by Two Units (part I)



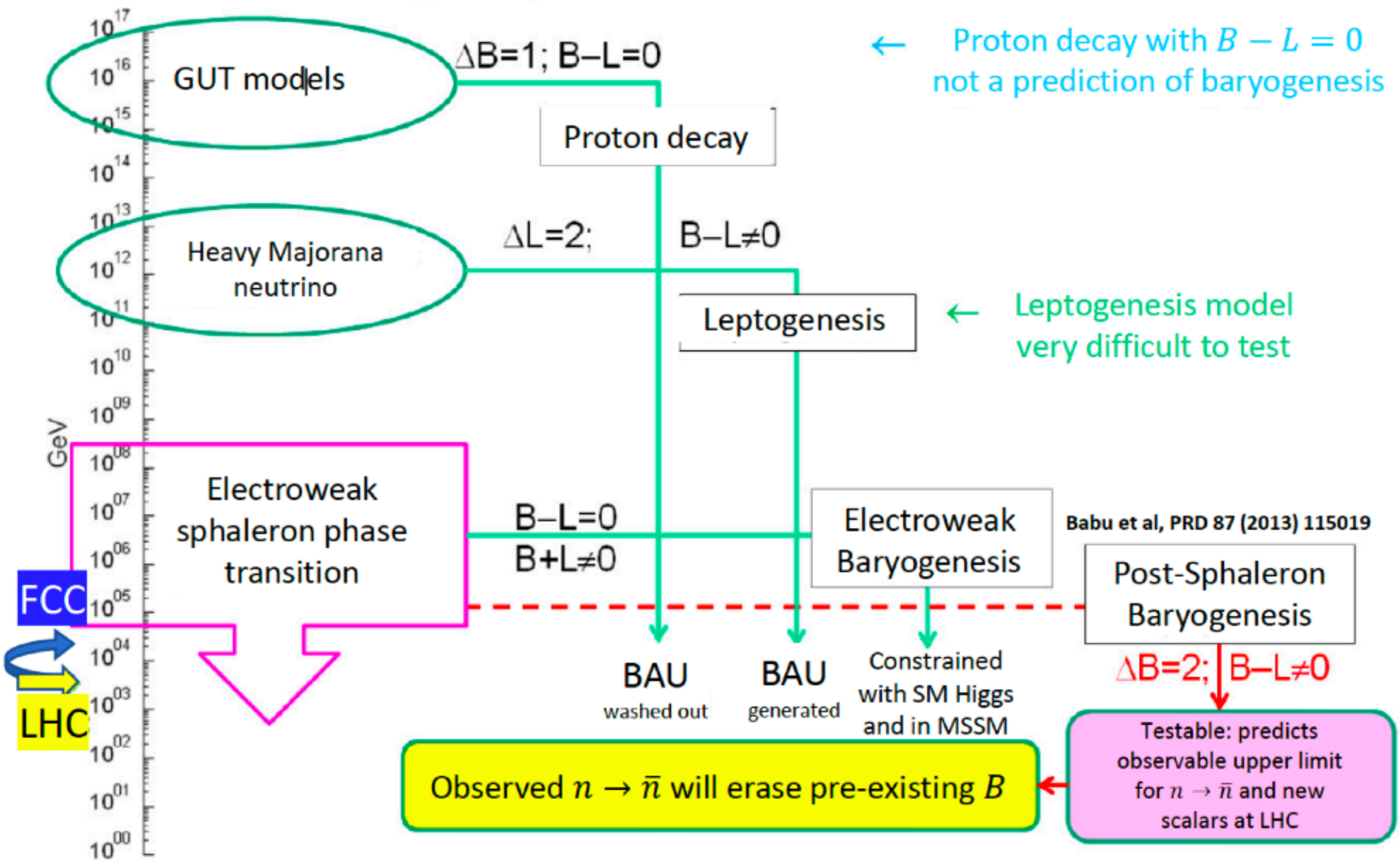
The first virtual ACFI workshop

J. de Vries

Also see recent review:

Addazi et al, arXiv:2006.04907

Motivations



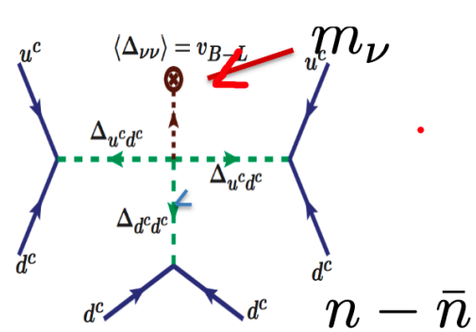
V. Sanatoro

New physics theory

Left-right symmetric gauge theories

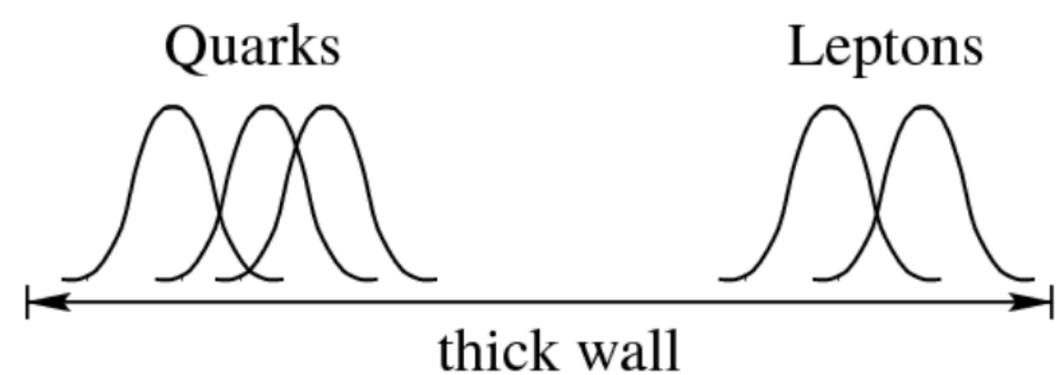
$$Q = I_{3L} + I_{3R} + \frac{B-L}{2}$$

Baryon and lepton numbers are connected: $\Delta L = 2$ nu mass connected to $\Delta B = 2$



R. N. Mohapatra

Large extra dimensional theories



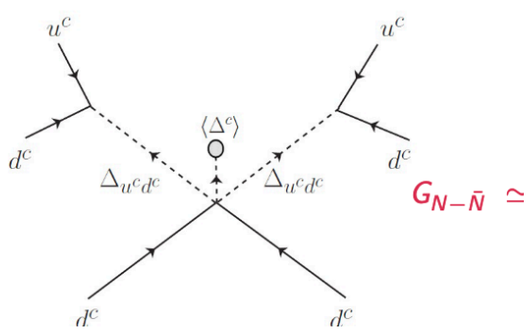
S. Girmohanta R. Shrock

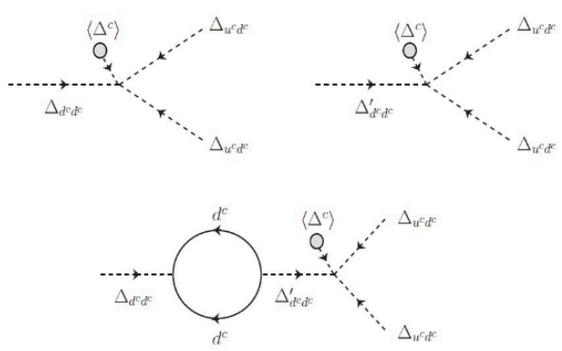
SO(10) Grand Unified Theories

$\tau_{n-\bar{n}}$ in $SO(10)$

GUT scale baryogenesis

transition is mediate by the diagram:



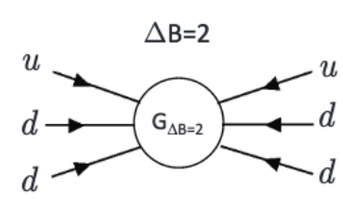


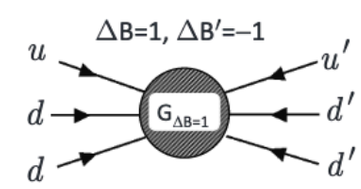
K. S. Babu

Dark / mirror sector oscillations

Neutron -mirror neutron mixing – (Active - sterile neutrons)

$$\frac{1}{M^5}(udd)(udd) \quad \& \quad \frac{1}{M^5}(udd)(u'd'd')$$





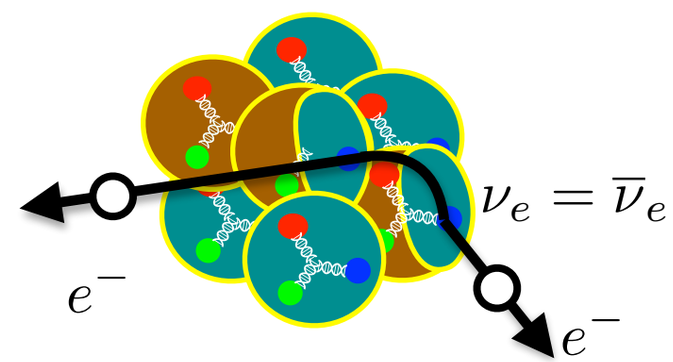
Z. Berezhiani

Standard Model EFT for *B-L* violation

B-L is an "accidental" symmetry of Standard Model operators with dim ≤ 4

Dim 5: ***B-L* violating**, *L* violating
Majorana neutrino mass

$$\mathcal{L}_5 \sim \left(\frac{1}{\Lambda_{BSM}}\right)(H^T\ell^*)(\bar{\ell}H)$$



Double-β decay

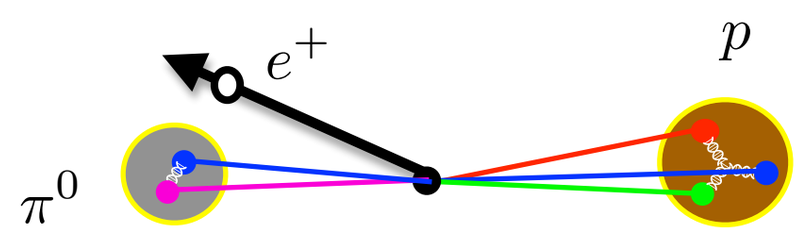
$\Lambda_{BSM} \gtrsim 10^{10}$ GeV

✓ Leptogenesis

Also dim 7, 9, … see e.g. Cirigliano et al JHEP 12 (2018)

Dim 6: ***B-L* conserving**, *B* violating
proton decay operators

$$\mathcal{L}_6 \sim \left(\frac{1}{\Lambda_{BSM}^2}\right) uude + \ldots$$



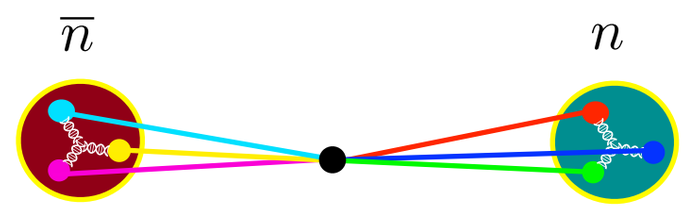
Proton decay

$\Lambda_{BSM} \gtrsim 10^{16}$ GeV

✗ Washed out by sphalerons

Dim 9: ***B-L* violating**, *B* violating
Majorana neutron mass

$$\mathcal{L}_9 \sim \left(\frac{1}{\Lambda_{BSM}^5}\right) uddudd + \ldots$$

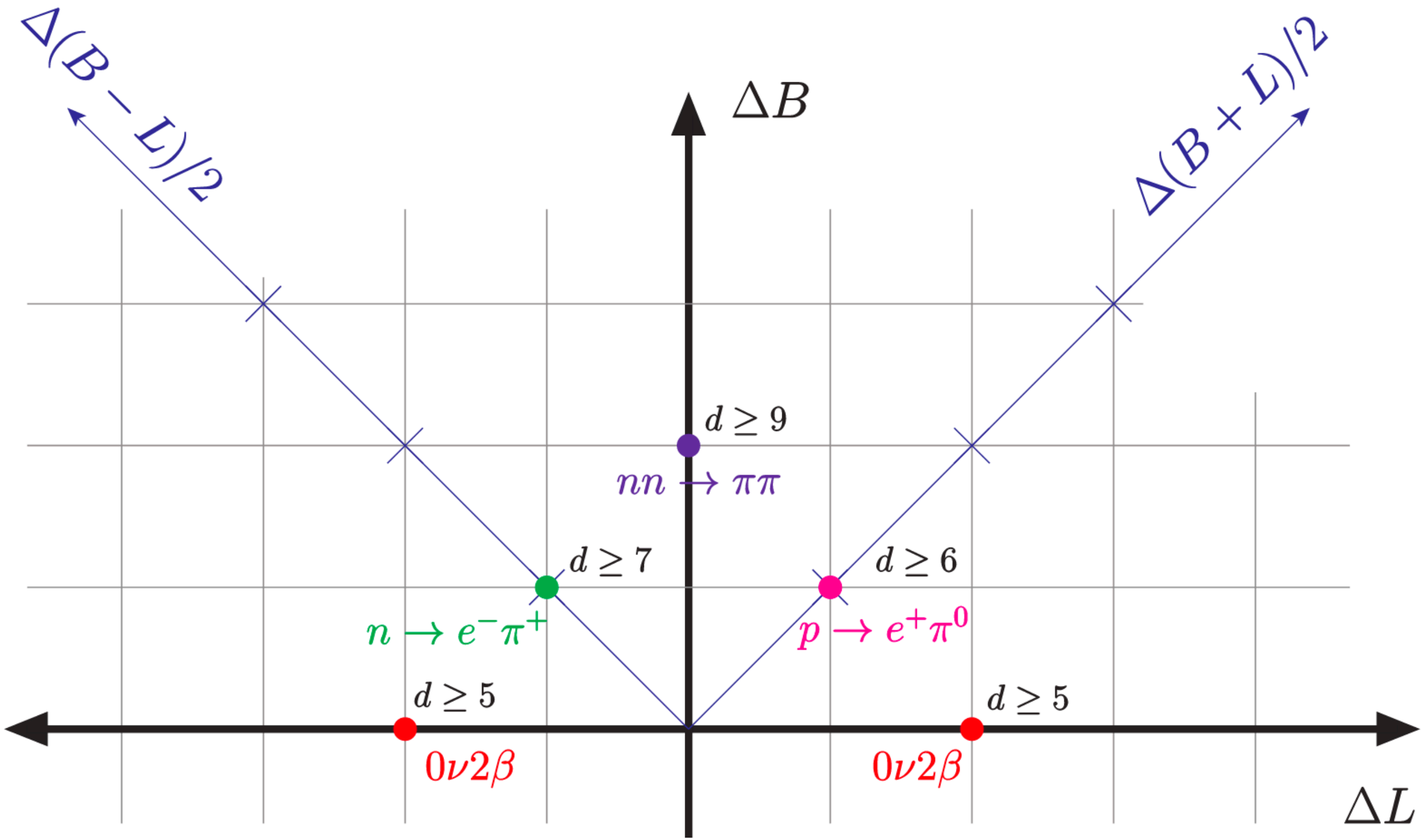


Neutron-antineutron oscillations

$\Lambda_{BSM} \gtrsim 10^{5}$ GeV

✓ Post-sphaleron baryogengesis

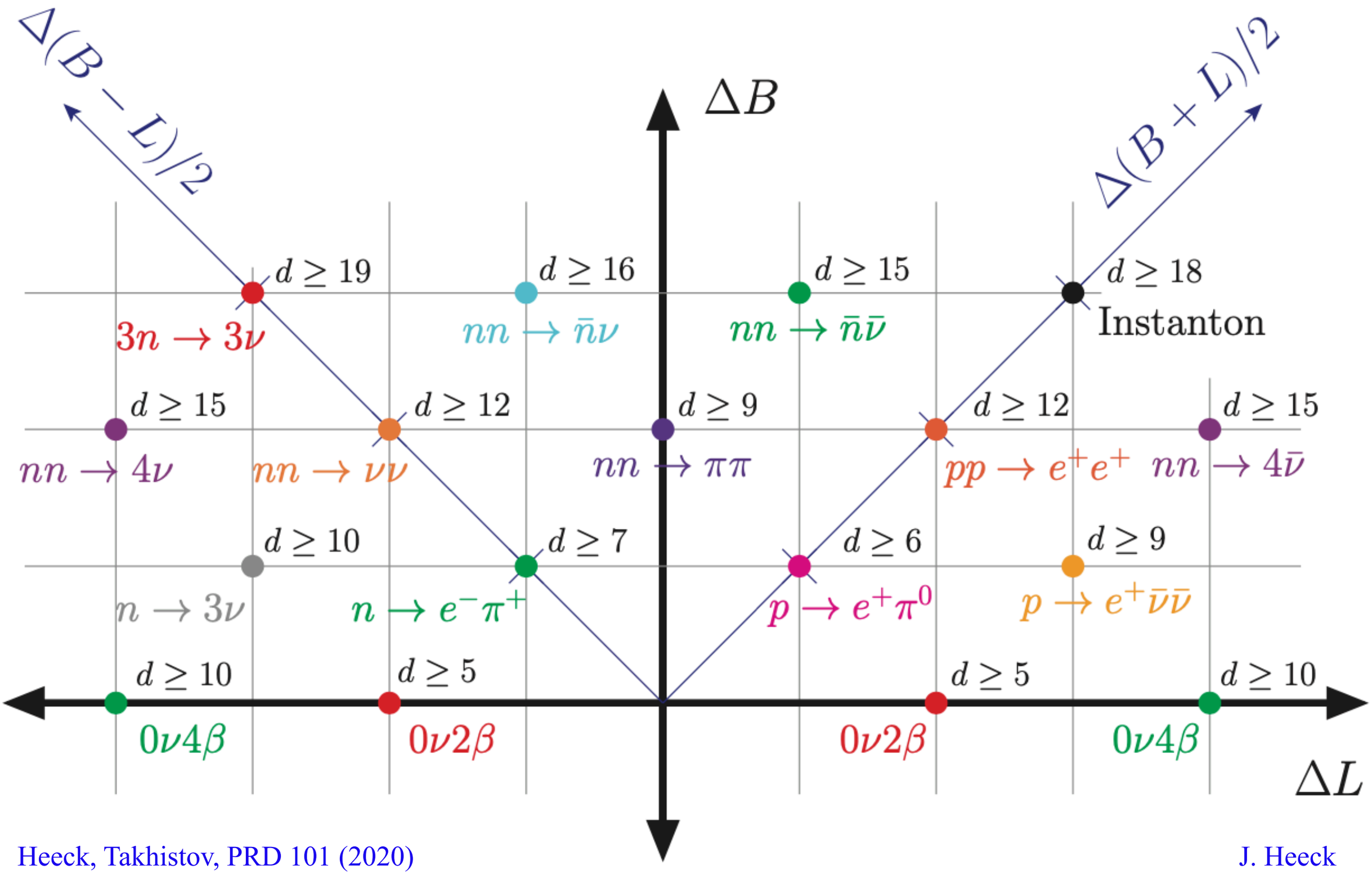
Charting *B* and *L* violation



Heeck, Takhistov, PRD 101 (2020)

J. Heeck

Charting *B* and *L* violation



Heeck, Takhistov, PRD 101 (2020)

J. Heeck

$n\bar{n}$ oscillations

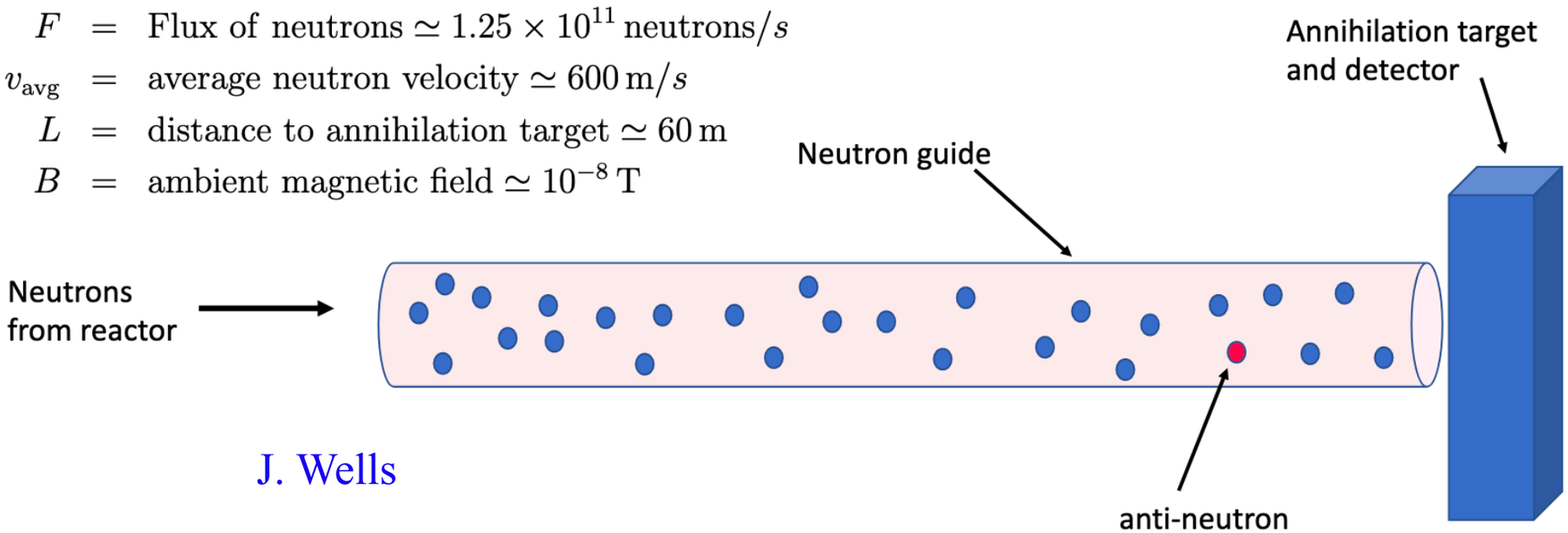
$n\bar{n}$ oscillation phenomenology similar to meson, neutrino oscillations

$$\mathcal{P}_{n\bar{n}} = \sin^2(t/\tau_{n\bar{n}})e^{-\Gamma_n t} \qquad \tau_{n\bar{n}}^{-1} = < \bar{n}|H_{n\bar{n}}|n >$$

Direct experimental constraints obtained from cold neutron beam experiments at the Institut Laue-Langevin (ILL) $\tau_{n\bar{n}} > 0.89 \times 10^8$ s

Baldo-Ceolin et al, Zeitschrift für Physik C Particles and Fields (1994)

$$\begin{aligned} F &= \text{Flux of neutrons} \simeq 1.25 \times 10^{11}\,\text{neutrons}/s \\ v_{\text{avg}} &= \text{average neutron velocity} \simeq 600\,\text{m}/s \\ L &= \text{distance to annihilation target} \simeq 60\,\text{m} \\ B &= \text{ambient magnetic field} \simeq 10^{-8}\,\text{T} \end{aligned}$$



J. Wells

From the average velocity data, the average time for the neutron to make it to the annihilation target is $t_{\text{avg}} = L/v_{\text{avg}} \simeq 0.1\,s$. This is where the state $|\psi\rangle(t)$ is measured and its wave function collapses to n or $\bar{n}$, at time $= t_{\text{avg}}$ when it interacts with the annihilation target.

$$P[\bar{n}(t_{\text{avg}})] \simeq \delta^2 t_{\text{avg}}^2 = 10^{-18}\left(\frac{10^8\,s}{\tau_{n\bar{n}}}\right)^2\left(\frac{t_{\text{avg}}}{0.1\,s}\right)^2, \Rightarrow \tau_{n\bar{n}} \simeq (2\times 10^8\,s)\left(\frac{F}{1.25\times 10^{11}\,\text{neutrons/s}}\right)^{1/2}\left(\frac{T_{\text{run}}}{1\,\text{yr}}\right)^{1/2}.$$

where $\tau_{n\bar{n}} \equiv 1/\delta$ (oscillation time)

~ Current limit!

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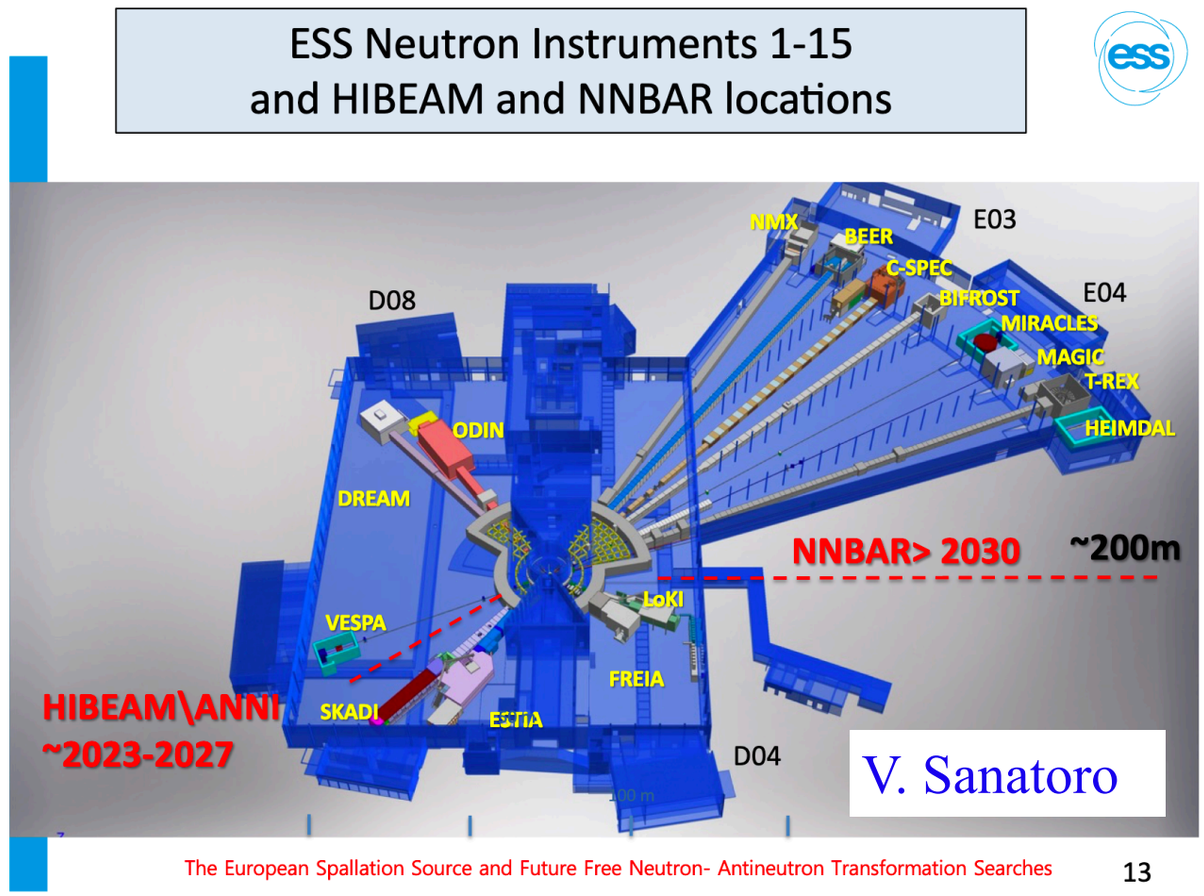
Future experiments

New experiments at the European Spallation Source (ESS) aim to increase sensitivity to $n\bar{n}$ oscillations by three orders of magnitude



HIBEAM (High Intensity Baryon Extraction and Measurement) at ESS will begin be constraining nn' oscillations

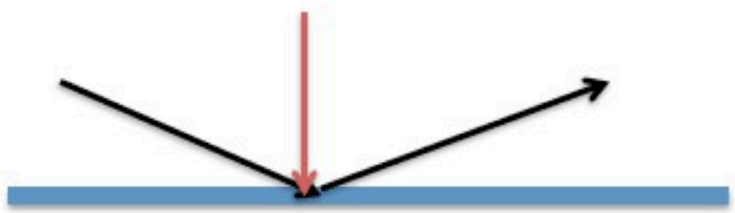
Future large underground volume detectors will search for dinucleon decay

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Hyper-Kamiokande

Experimental outlook

Advances in neutron optics could allow coherent oscillations in the presence of mirror reflections



Mirror reflection

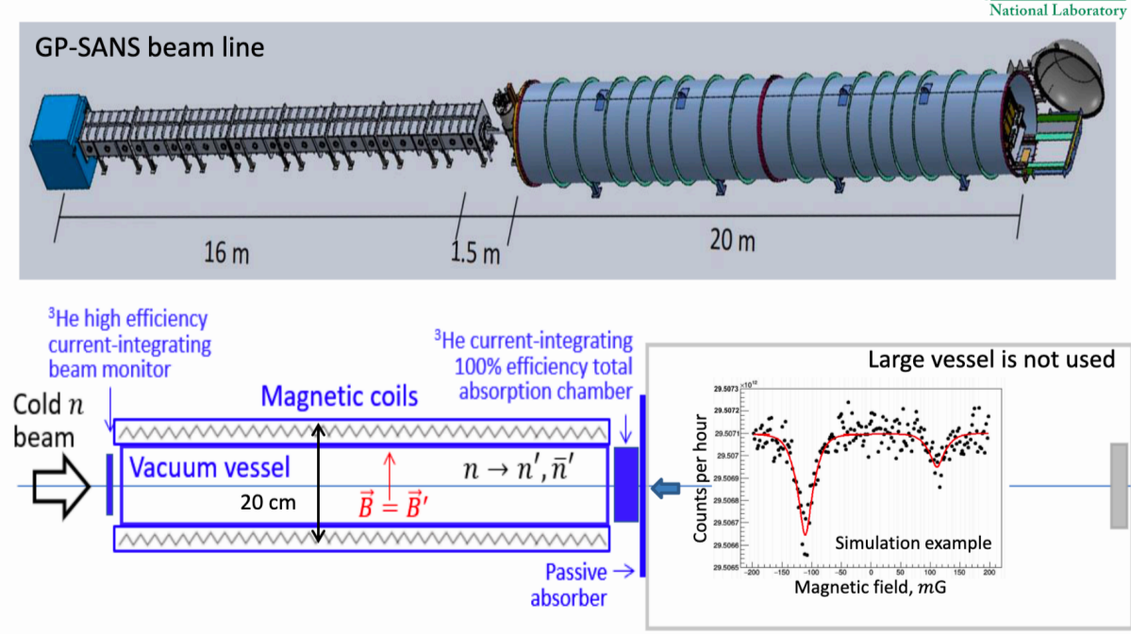
$$\begin{bmatrix} n \\ \bar{n} \end{bmatrix} \rightarrow \begin{bmatrix} n \\ \rho e^{i\varphi} \bar{n} \end{bmatrix}$$

W. M. Snow

High Flux Isotope Reactor (HFIR) can search for nn' oscillations

Y. Kamyshkov M. Demarteau

① HFIR disappearance experiment in 16-m guide vessel

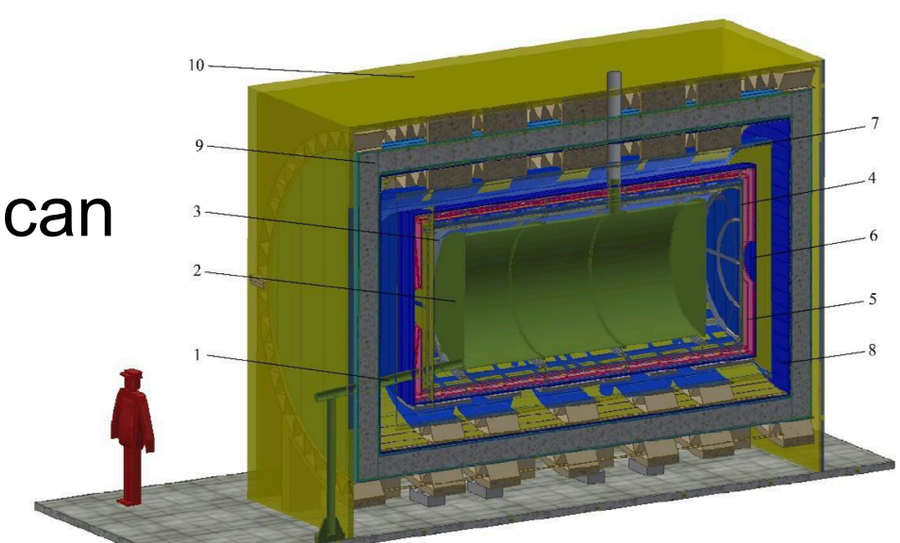


Detailed scan in the range of mag. field ± 1.0 Gauss with resolution few mG.
For 10 days beam time sensitivity reach $\tau_{nn'} > 24\ s$ @95% CL. (Detecting fraction~10^{-7})

L. Broussard et al, arXiv:1912.08264 [physics.ins-det] 11

Ultra-cold neutron storage experiments can provide independent $n\bar{n}$ searches

A. Fomin



QCD $n\bar{n}$ Results

Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)

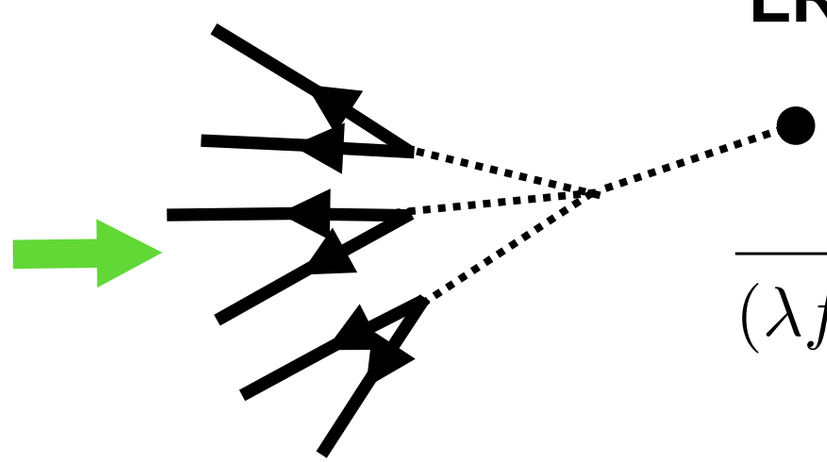
	$\mathcal{M}_I^{\overline{\rm MS}}(700\ {\rm TeV})\ [10^{-5}\ {\rm GeV}^6]$
Q_1	$-26(7)$
Q_2	$144(26)$
Q_3	$-47(11)$
Q_5	$-0.23(10)$

Standard Model EFT:

$$\tau_{n\text{-}\bar{n}}^{-1} = \frac{10^{-9}\ {\rm s}^{-1}}{(700\ {\rm TeV})^{-5}} \left| 4.2(1.1)\widehat{C}_1^{\overline{\rm MS}}(\mu) - 8.6(1.5)\widehat{C}_2^{\overline{\rm MS}}(\mu) + 4.5(1.1)\widehat{C}_3^{\overline{\rm MS}}(\mu) + 0.096(43)\widehat{C}_5^{\overline{\rm MS}}(\mu) \right|_{\mu=2\ {\rm GeV}}$$

ILL:

$$\tau_{n\bar{n}} > 0.89 \times 10^8\ {\rm s}$$

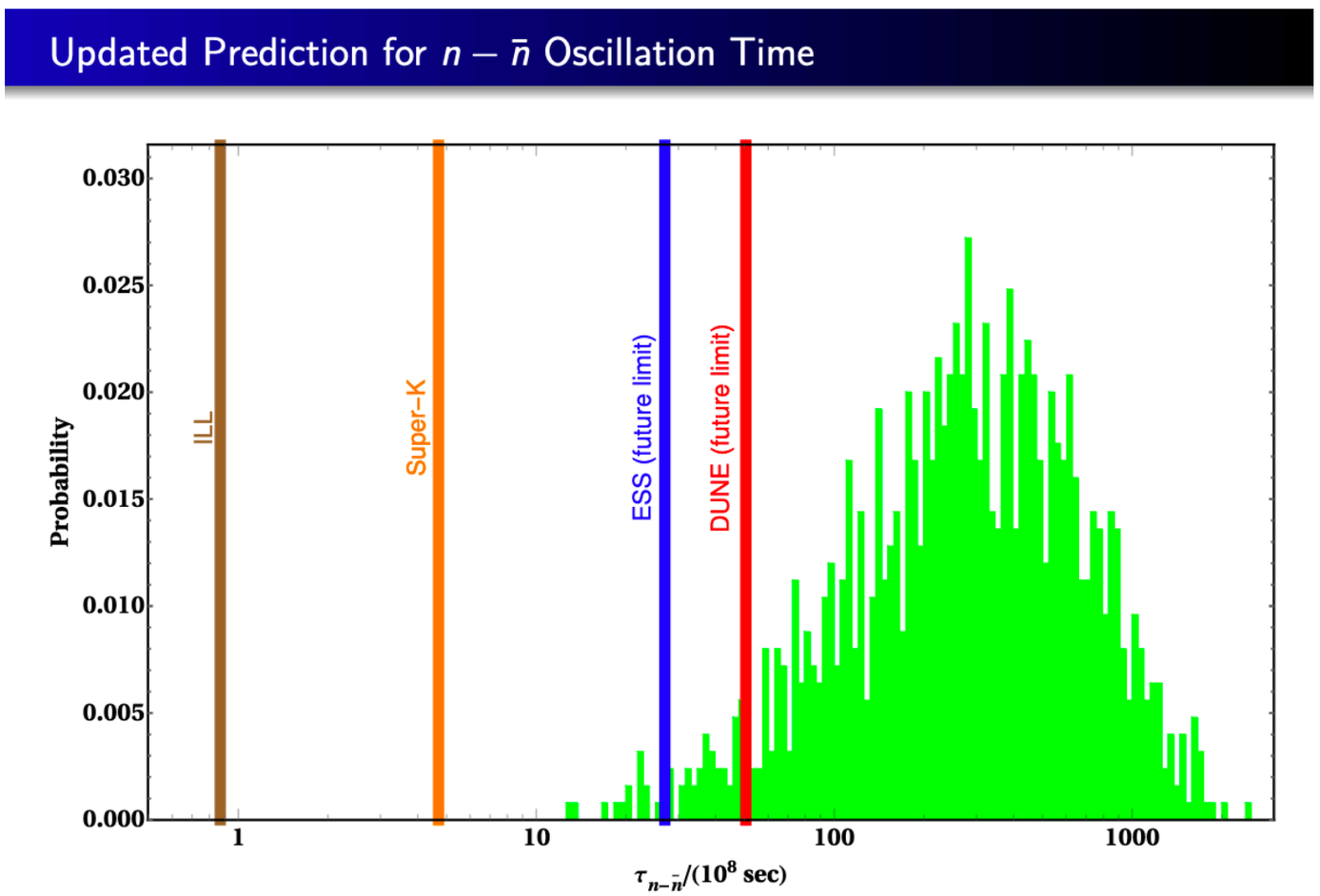


LR-symmetric example:

$$\frac{\Lambda_{BSM}}{(\lambda f^3 \widetilde{v}_{B-L})^{1/5}} > 390 \pm 22\ {\rm TeV}$$

Baryogengesis constraints

Post-sphaleron baryogengesis predictions updated to include lattice QCD matrix elements and current / projected limits

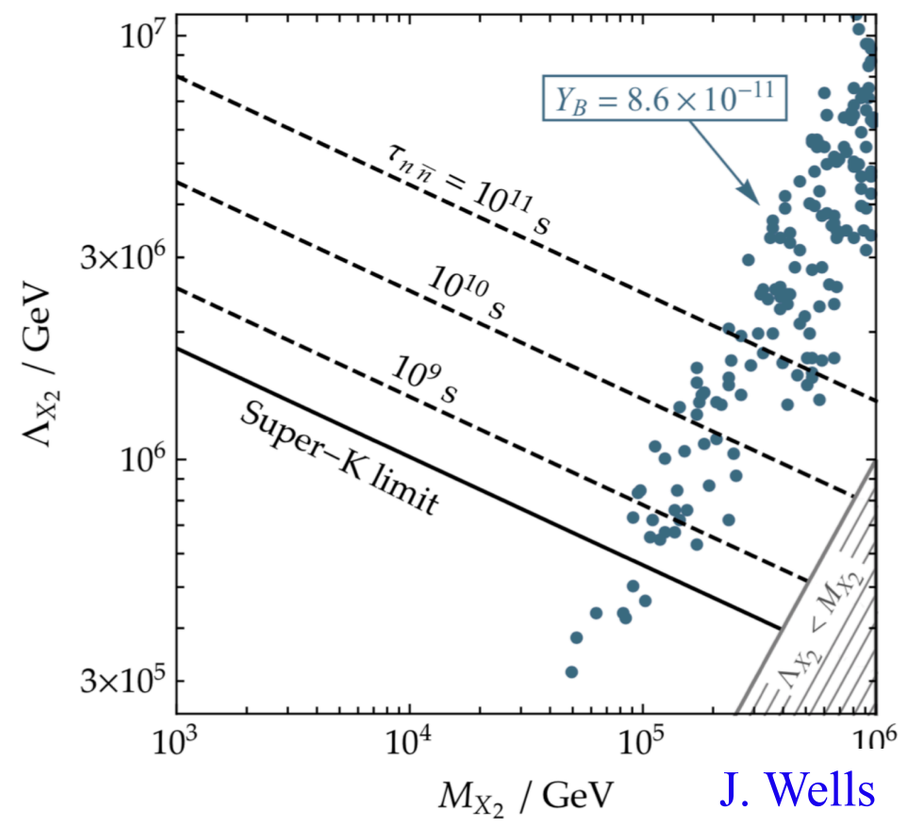


[Babu, Chauhan, BD, Mohapatra, Thapa (preliminary result)]

B. Dev

Constraints also studied for effective theories and simplified models of baryogengesis

J. Wells S. Gardner D. McKeen



J. Wells

Nuclear instability searches

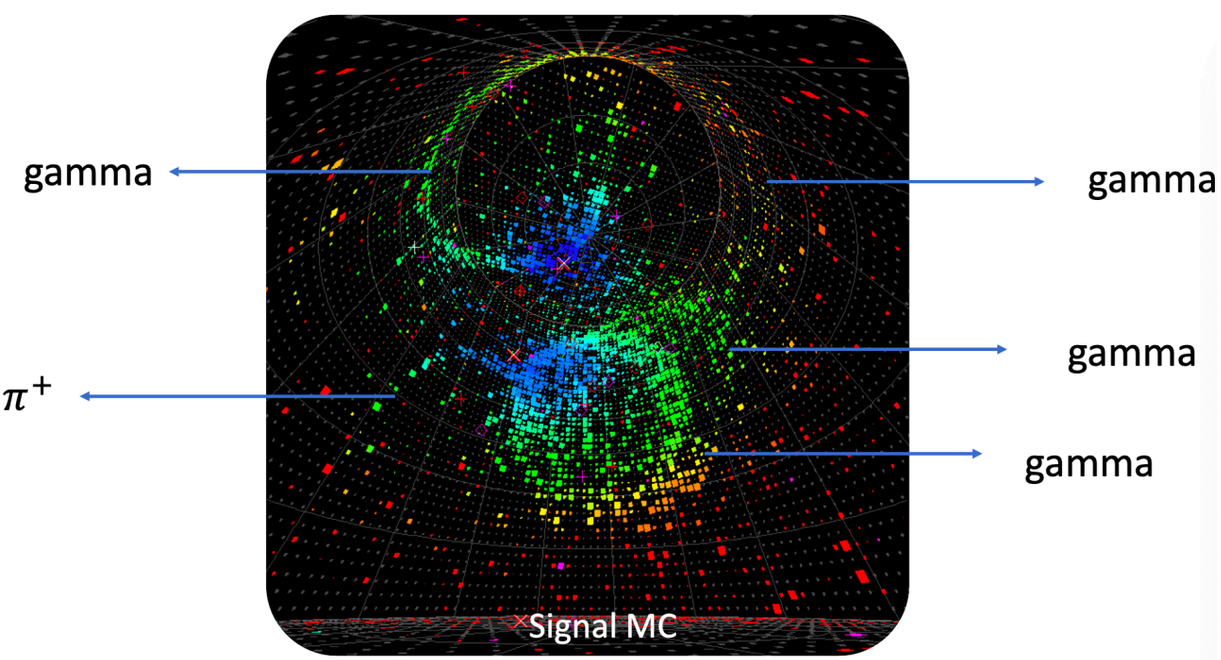
New constraints from Super K

$$\tau_{n\bar{n}} > 4.7 \times 10^8 \text{ s}$$

L. Wan

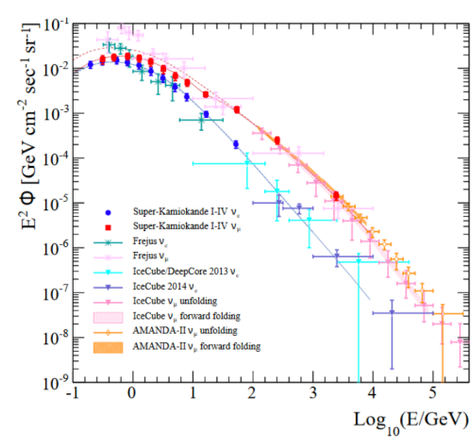
		$T_{n\bar{n}}(10^{32}$ years)	R $(10^{23}/\text{s})$	$\tau_{n\to\bar{n}}(10^8$ s)
^{16}O	SK-I-IV (this study)	3.6	0.517	4.7
^{16}O	SK-I [8] (2015)	1.9	0.517	3.4
^{16}O	Kamiokande [11] (1986)	0.4	0.517	1.6
^{2}H	SNO [9] (2017)	0.1	0.25	1.4
^{56}Fe	Soudan II [10] (2002)	0.7	1.4	1.3
^{56}Fe	Frejus [38] (1990)	0.7	1.4	1.2
^{16}O	IMB [12] (1984)	0.2	0.517	1.2
Free neutron	Grenoble [7] (1994)	-	-	0.9

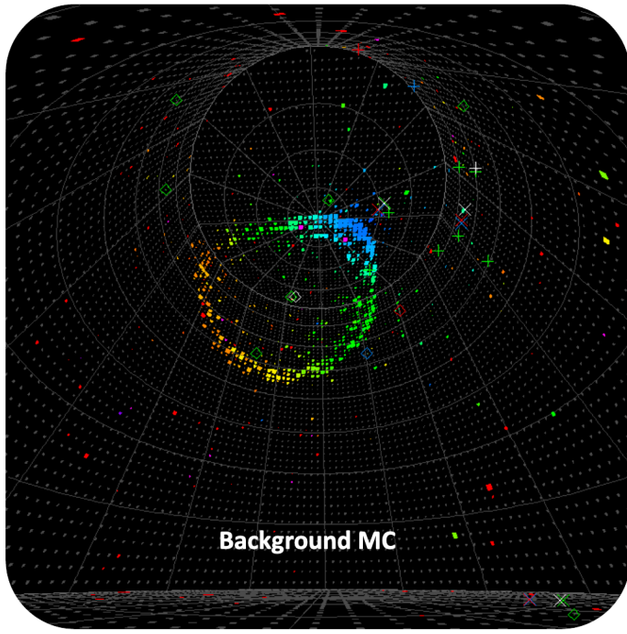
Simulated Signal Event



Background

The main background for this analysis at SK is **atmospheric neutrinos**.
Pion production processes and **deep inelastic scattering** produce a similar signature to signal.





Dinucleon decay in EFT

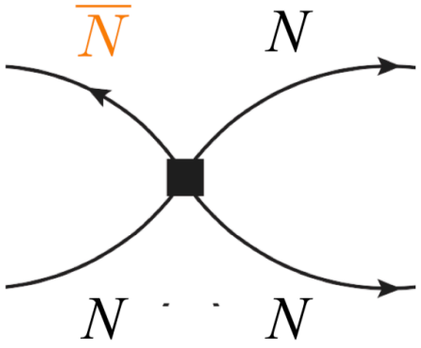
$\Delta B = 2$ deuteron decays arise from both long- and short-distance mechanisms in nuclear EFT, only short-distance constrained by LQCD

(For LQCD calculation on delta m, Rinaldi et al. '18 & '19)

nnbar oscillation

$$\mathcal{L}^{(2)}_{|\Delta B|=2} = -\delta m\, n^{c\dagger} n + \text{H.c.} + \ldots,$$

$$\tau_{n\bar{n}} = (\delta m)^{-1}[1 + \mathcal{O}(m_\pi^2/\Lambda_\chi^2)]$$



$$\mathcal{L}^{(4)}_{|\Delta B|=2} = i\tilde{B}_0[(N^T P_i N)^\dagger (N^{cT}\tau^2 Y_i^- N) - \text{H.c.}] + \ldots,$$

B. Long

$NN \leftrightarrow N\bar{N}$ interactions

$$R_d \equiv \Gamma_d^{-1}/\tau_{n\bar{n}}^2 = -\left[\frac{m_N}{\kappa}\text{Im}a_{\bar{n}p}(1 + \overset{NN\text{ range}}{0.40} + \overset{\text{Re}(a_{\text{nbar-p}})}{0.20} - \overset{\text{pion}}{0.13} \pm \overset{NN \leftrightarrow N\bar{N}\text{ w/ unknown } B_0}{0.4})\right]^{-1}$$
$$= (1.1 \pm 0.3) \times 10^{22}\ \text{s}^{-1}.$$

Further study needed to better constrain new short-distance coupling, test EFT power counting

Oosterhof, Long, de Vries, Timmermans, van Kolck, PRL 122 (2019)

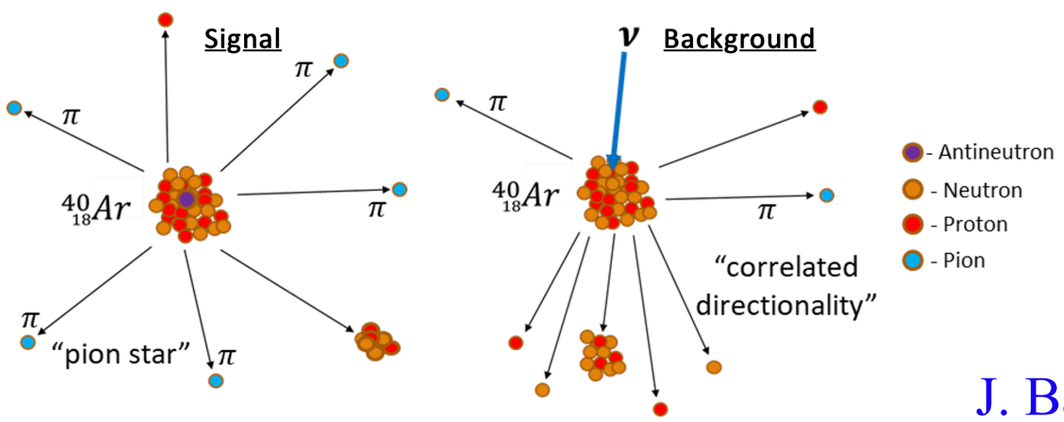
Haidenbauer, Meißner, Chin. Phys. C 44, no.3, 033101 (2020)

Dinucleon decay in larger nuclei

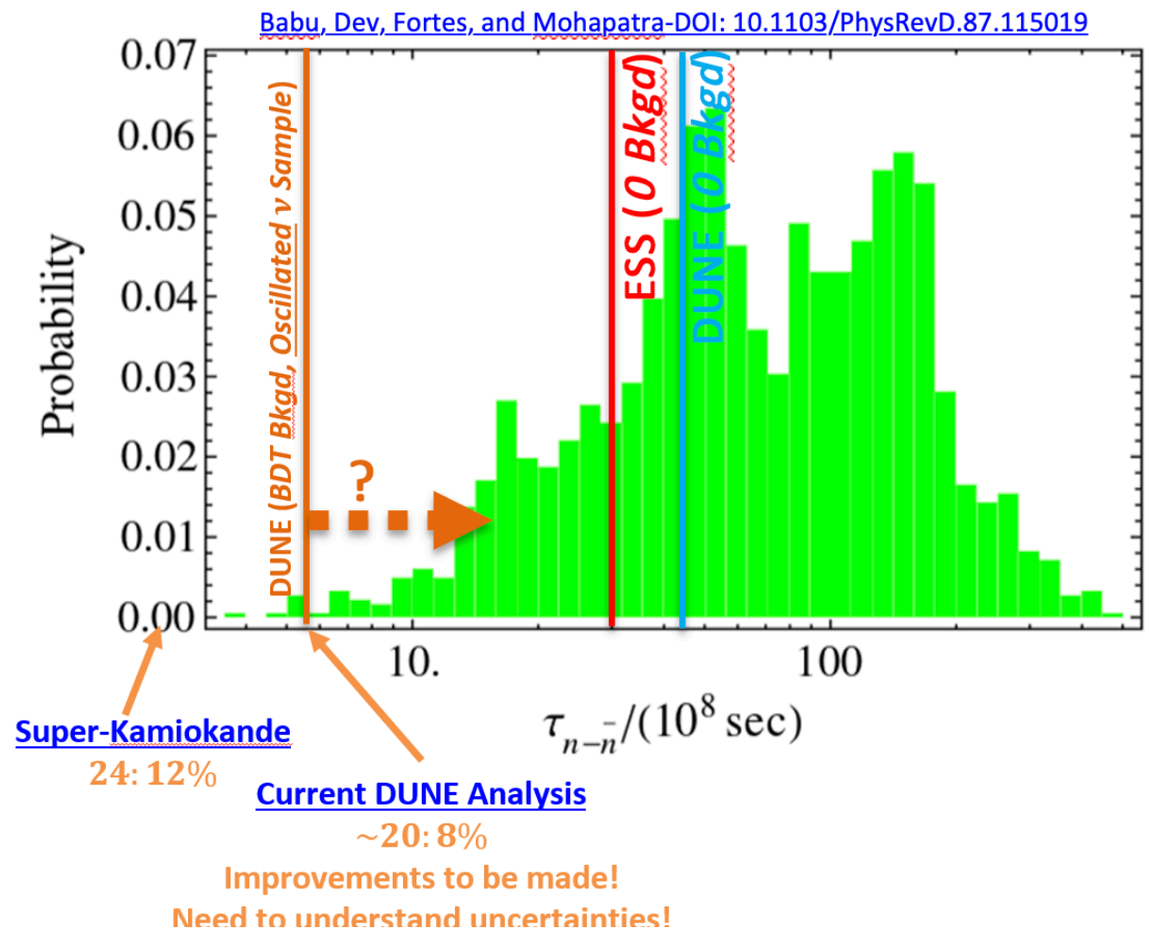
Phenomenological nuclear models used to determine nuclear suppression factor for deuteron, oxygen, iron, argon J. Richard J. Barrow

$$\tau_M = R \cdot \tau^2_{n\to\bar{n}}$$

Babu, Dev, Fortes, and Mohapatra-DOI: 10.1103/PhysRevD.87.115019



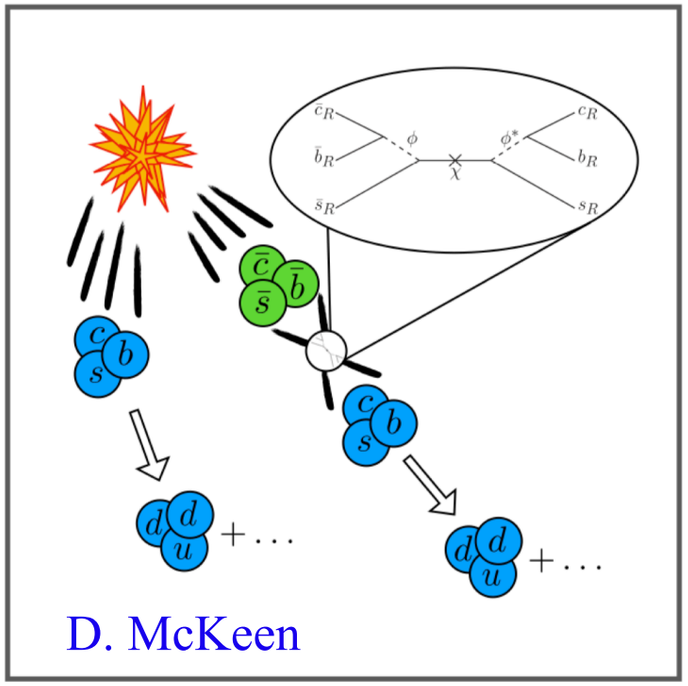
J. Barrow



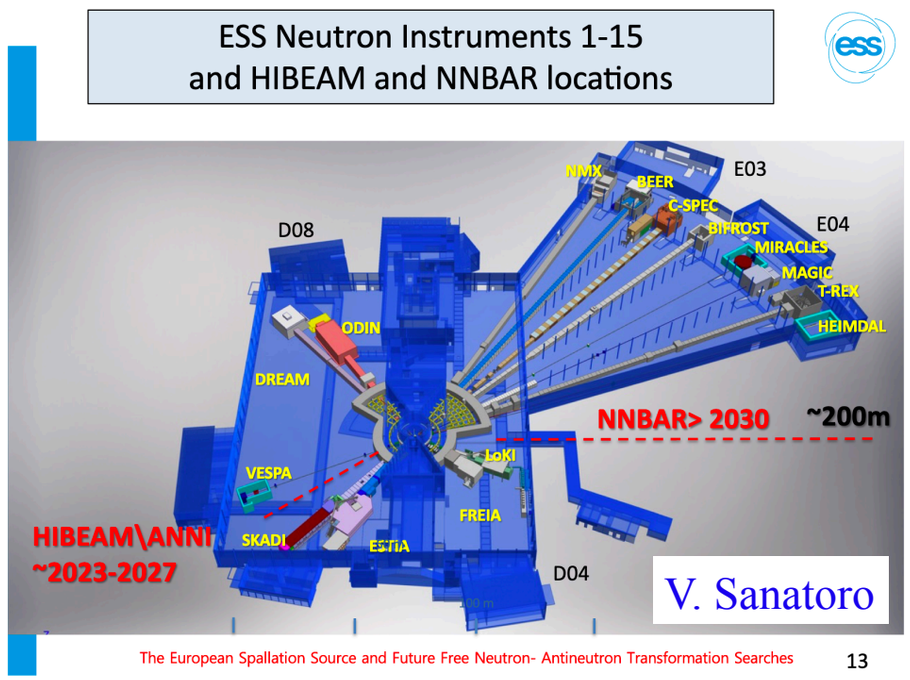
Providing controlled uncertainties on predictions of nuclear suppression factors as well as signal discrimination is crucial for understanding the reach of DUNE and Hyper-K into BSM parameter space

Outlook

$\Delta B = 2$ interactions provide a unique way to constrain theories of low-scale baryogengesis



Next-generation experiments at the ESS will search for $n\overline{n}$ oscillations at scales relevant for constraining post-sphaleron baryogengesis



Understanding theoretical uncertainties in $\Delta B = 2$ nuclear interactions is critical to understanding the new physics reach of current / future experiments. Fully controlled predictions will require coordinated effort from lattice QCD + nuclear EFT + event generators + …