Baryon number violating processes

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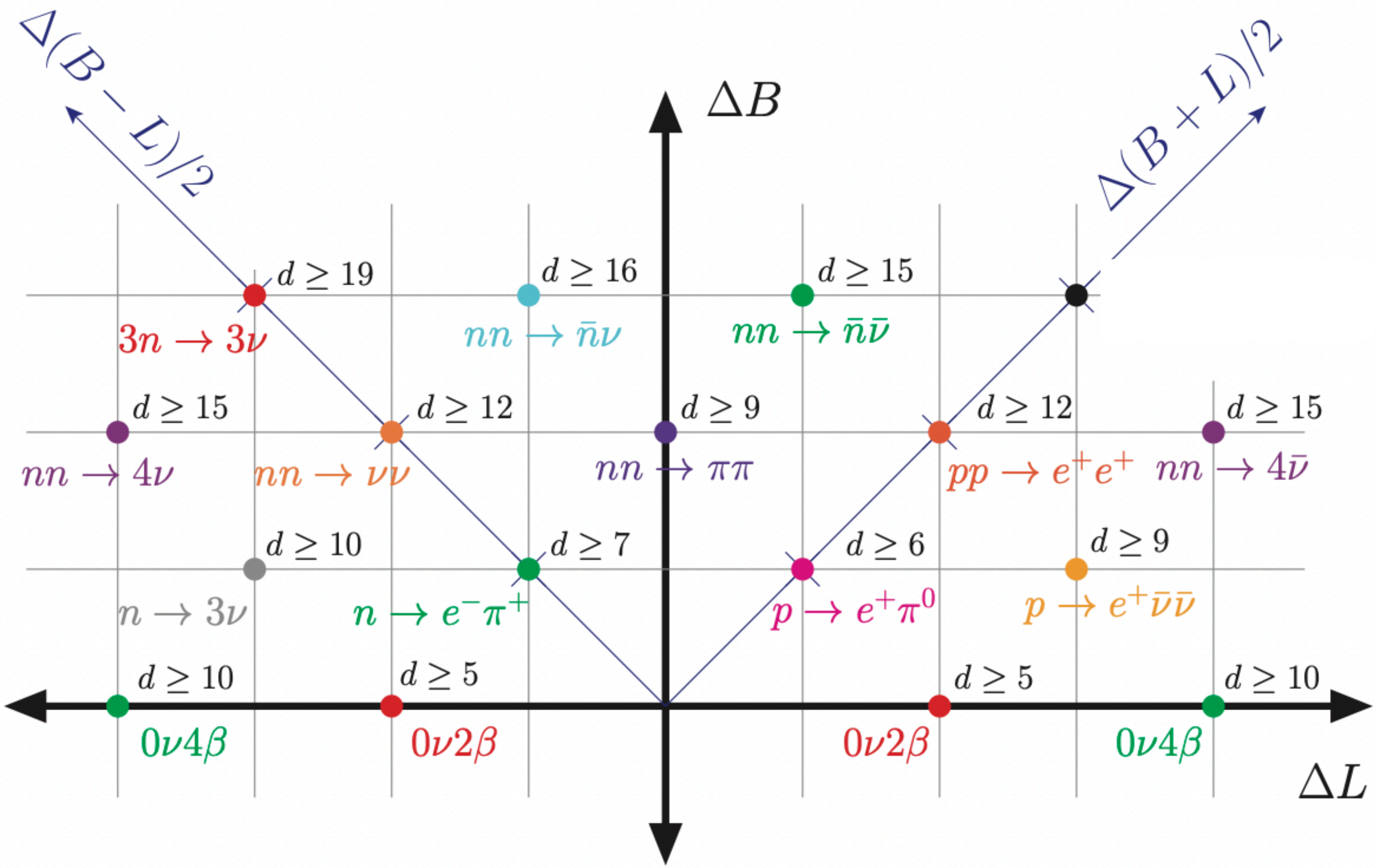
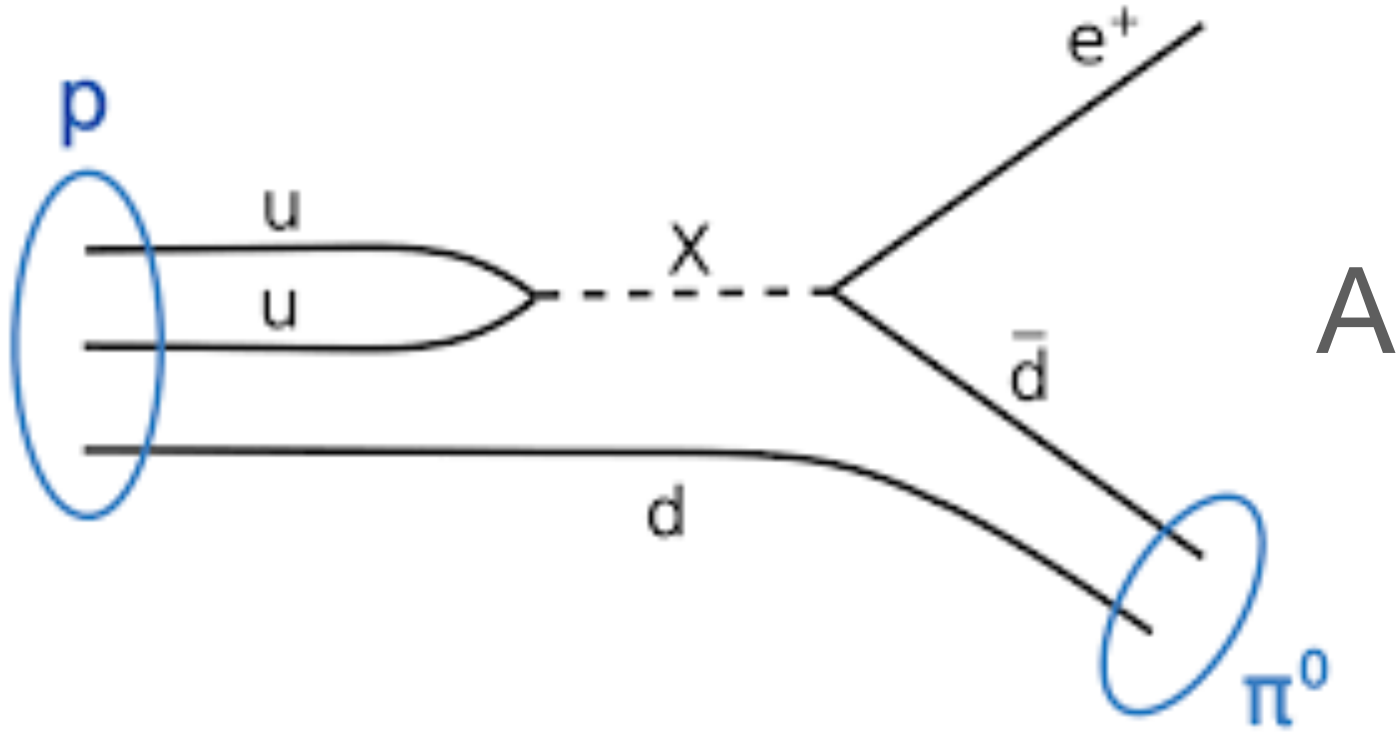
In collaboration with IISER-TVM, University of Delhi, Punjab University, BHU, IIT Roorkee ….

Effective operators: quark level….assuming perturbative new physics
But is it completely understood ? Will come back to it at the end



Julian Heeck and Volodymyr Takhistov
Phys. Rev. D 101, 015005

arXiv:1910.07647



Assuming perturbative couplings to ‘X’ particle

Quark level dim-6

$$\mathcal{O}_d^{(1)} = (\bar{d}^c_{iR} u_{jR})(\bar{u}^c_{kL} e_{dL} - \bar{d}^c_{kL} \nu_{dL})\epsilon_{ijk} \,,$$

$$\mathcal{O}_d^{(2)} = (\bar{d}^c_{iL} u_{jL})(\bar{u}^c_{kR} e_{dR})\epsilon_{ijk} \,,$$

$$\mathcal{O}_d^{(3)} = (\bar{d}^c_{iL} u_{jL})(\bar{u}^c_{kL} e_{dL} - \bar{d}^c_{kL} \nu_{dL})\epsilon_{ijk} \,,$$

$$\mathcal{O}_d^{(4)} = (\bar{d}^c_{iR} u_{jR})(\bar{u}^c_{kR} e_{dR})\epsilon_{ijk} \,.$$

Hadron level

$$\mathcal{O}_d^{(1)} = \alpha(\bar{e}^c_{dL} \mathrm{Tr}\, \mathcal{F}\xi B_L \xi - \bar{\nu}^c_{dL} \mathrm{Tr}\, \mathcal{F}' \xi B_L \xi),$$

$$\mathcal{O}_d^{(2)} = \alpha \bar{e}^c_{dR} \mathrm{Tr}\, \mathcal{F}\xi^\dagger B_R \xi^\dagger,$$

$$\mathcal{O}_d^{(3)} = \beta(\bar{e}^c_{dL} \mathrm{Tr}\, \mathcal{F}\xi B_L \xi^\dagger - \bar{\nu}^c_{dL} \mathrm{Tr}\, \mathcal{F}' \xi B_L \xi^\dagger),$$

$$\mathcal{O}_d^{(4)} = \beta \bar{e}^c_{dR} \mathrm{Tr}\, \mathcal{F}\xi^\dagger B_R \xi,$$

$$\begin{aligned}\mathcal{L}_{d=6} = {} & y^1_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha} u_{b,\beta})(\overline{Q}^C_{i,c,\gamma}\epsilon_{ij} L_{j,d}) \\ & + y^2_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{Q}^C_{i,a,\alpha}\epsilon_{ij} Q_{j,b,\beta})(\overline{u}^C_{c,\gamma}\ell_d) \\ & + y^3_{abcd}\epsilon^{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(\overline{Q}^C_{i,a,\alpha} Q_{j,b,\beta})(\overline{Q}^C_{k,c,\gamma} L_{l,d}) \\ & + y^4_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha} u_{b,\beta})(\overline{u}^C_{c,\gamma}\ell_d) + \text{h.c.}\,,\end{aligned}$$

$$\langle 0 | \epsilon_{ijk}(u^{iT} C P_R d^j) P_L u^k | p^{(s)} \rangle = \alpha P_L u^{(s)}$$

$$\langle 0 | \epsilon_{ijk}(u^{iT} C P_L d^j) P_L u^k | p^{(s)} \rangle = \beta P_L u^{(s)}$$

$$\Gamma(p \to e^+\pi^0) \simeq \frac{1}{2 \times 10^{34}\,\mathrm{yr}} \left| \frac{y^j_{1111}}{(3 \times 10^{15}\,\mathrm{GeV})^{-2}} \right|^2 .$$

Processes

- $p \to \mu^+/e^+\pi^0$, $p \to K^+\bar{\nu}$ Lepto-Quark and diquark (Benjamín Grinstein)
- $pp \to \mu^+\mu^+/\ e^+e^+$ Lepto-quark and diquarks (K. S. Babu, R. N. Mohapatra, et al), Weyl-Majorana(in preparation, **MTA**)

INO ?50 kiloton magnetized ICAL detector at the INO for 10 years

Ferjus Experiment with 900 ton iron tracking calorimeter?

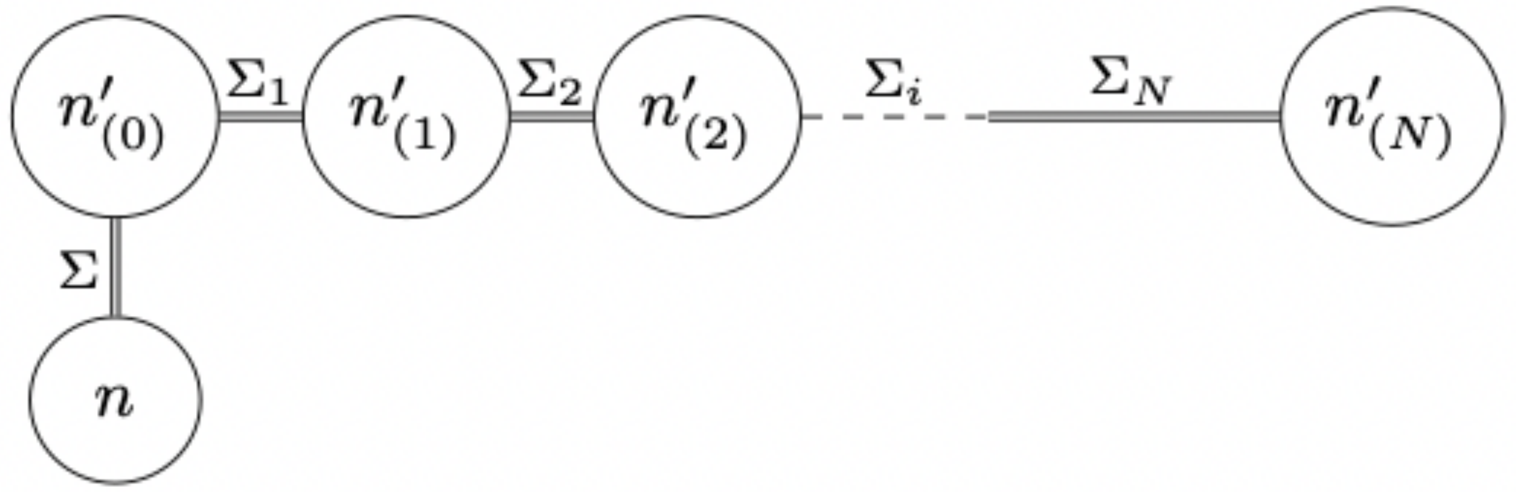
- $n - \bar{n}$ Six-dimensions (DC, **MTA)**, Linear-moose model (**MTA),** Lepto-quark and diquarks (K. S. Babu, R. N. Mohapatra, C. Grojean, J. D. Wells)

Proposed liquid scintillator ? Similar to SNO

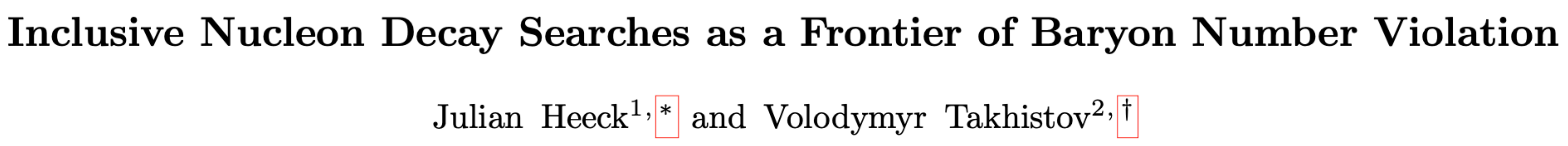
- $\nu n \to \bar{\nu}\bar{n}$

$$\Gamma(A \longrightarrow (A-2) + \text{mesons})$$

- $n \to n'$ mirror neutron models (Z. Berezhiani, D. McKeen, M. Pospelov), Linear-moose model (**MTA) (Purely non-perturbative confining)**

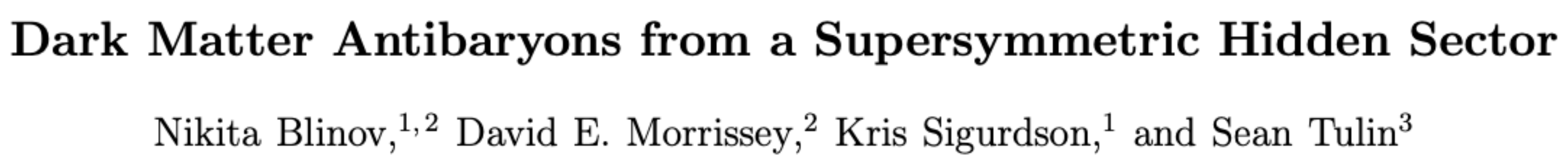


- Exotic Induced Nucleon Decays (IND)
- $DM + p \to n + e^+/\mu^+$ Dark Majorana fermion (Amarjit Soni)
- $DM + p \to DM + e^+/\mu^+$ Baryonic DM (Hooman Davoudiasl, Nikita Blinov) , Weyl-Majorana interaction manuscript (in preparation **MTA)**
- $DM + p \to DM + \bar{p} + \mu^+\mu^+/e^+e^+$ Weyl-Majorana interaction manuscript (in preparation **MTA)**
- $e^- + N(A,Z) \to e^+ + N'(A,Z-2)$
- $\mu^- + N(A,Z) \to e^+ + N'(A,Z-2)$ Weyl-Majorana(in preparation, **MTA**), Lepto-quark and diquarks (K. S. Babu, R. N. Mohapatra,)



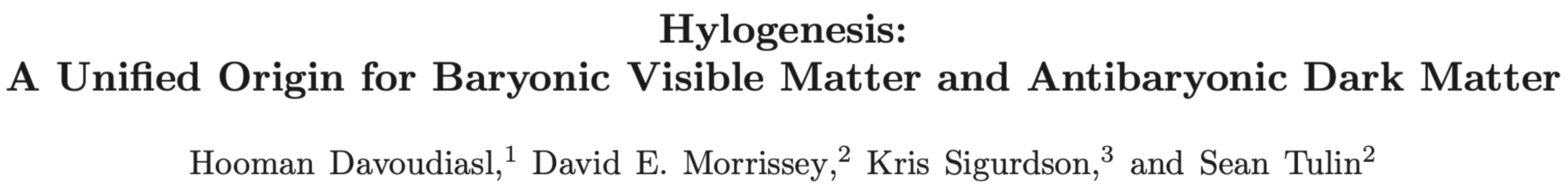
Inclusive Nucleon Decay Searches as a Frontier of Baryon Number Violation

Julian Heeck[1,*] and Volodymyr Takhistov[2,†]



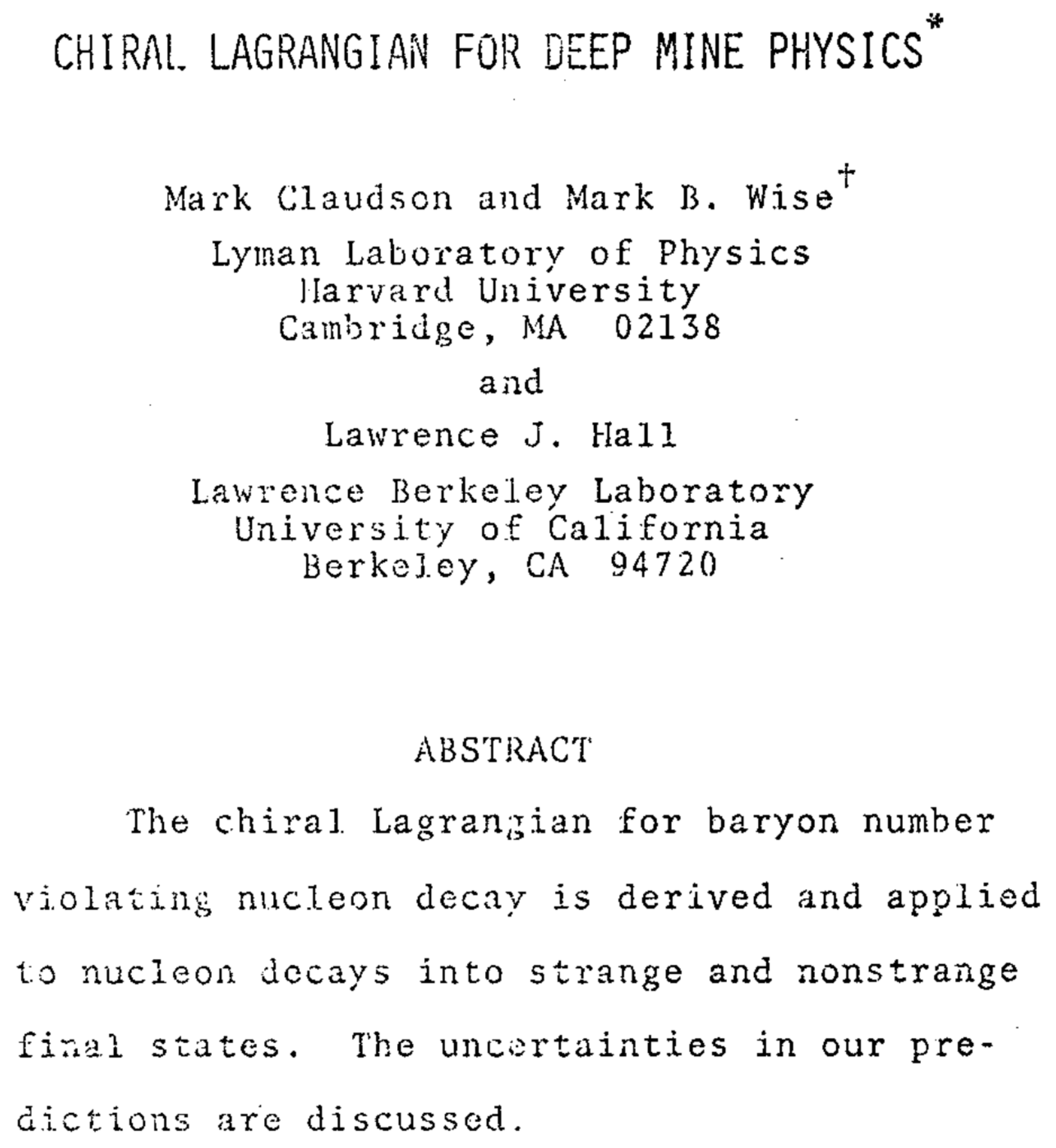
Dark Matter Antibaryons from a Supersymmetric Hidden Sector

Nikita Blinov,[1,2] David E. Morrissey,[2] Kris Sigurdson,[1] and Sean Tulin[3]



Hylogenesis:
A Unified Origin for Baryonic Visible Matter and Antibaryonic Dark Matter

Hooman Davoudiasl,[1] David E. Morrissey,[2] Kris Sigurdson,[3] and Sean Tulin[2]



CHIRAL LAGRANGIAN FOR DEEP MINE PHYSICS[*]

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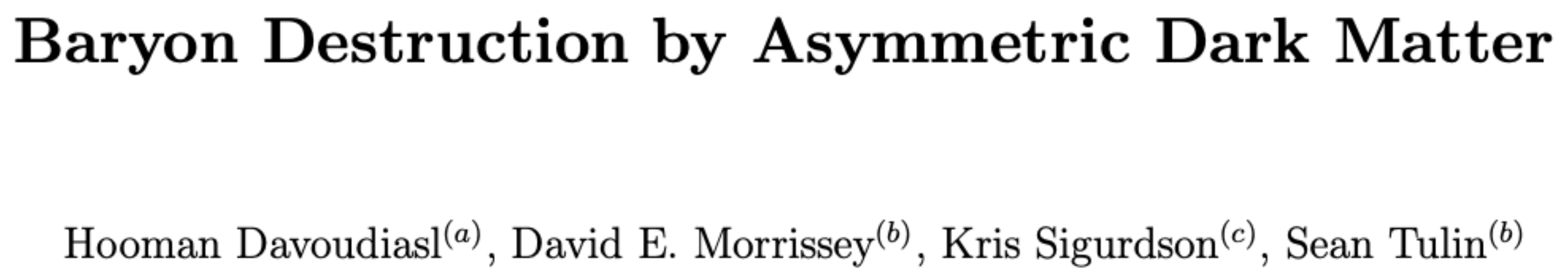
ABSTRACT

The chiral Lagrangian for baryon number violating nucleon decay is derived and applied to nucleon decays into strange and nonstrange final states. The uncertainties in our predictions are discussed.

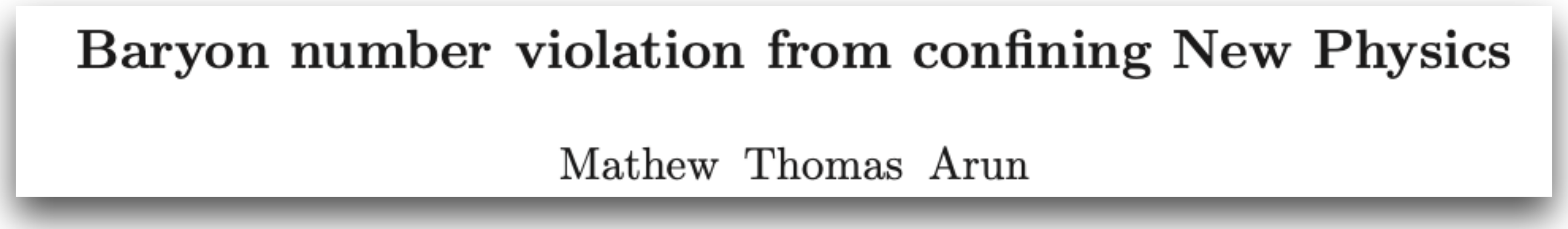


Baryon Destruction by Asymmetric Dark Matter

Hooman Davoudiasl[(a)], David E. Morrissey[(b)], Kris Sigurdson[(c)], Sean Tulin[(b)]

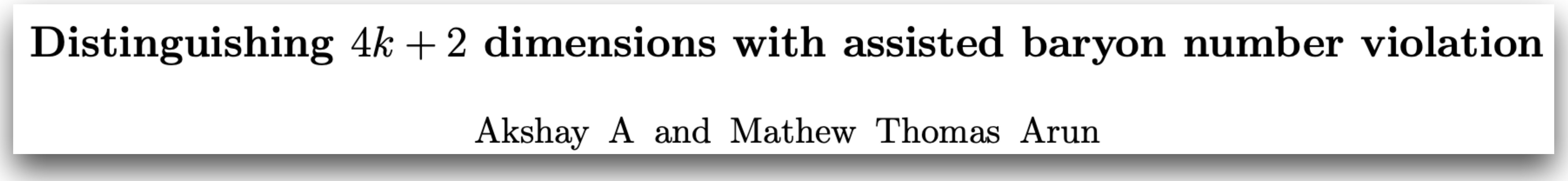
Neutron oscillation and Baryogenesis from six dimensions

Mathew Thomas Arun[1], Debajyoti Choudhury[2]



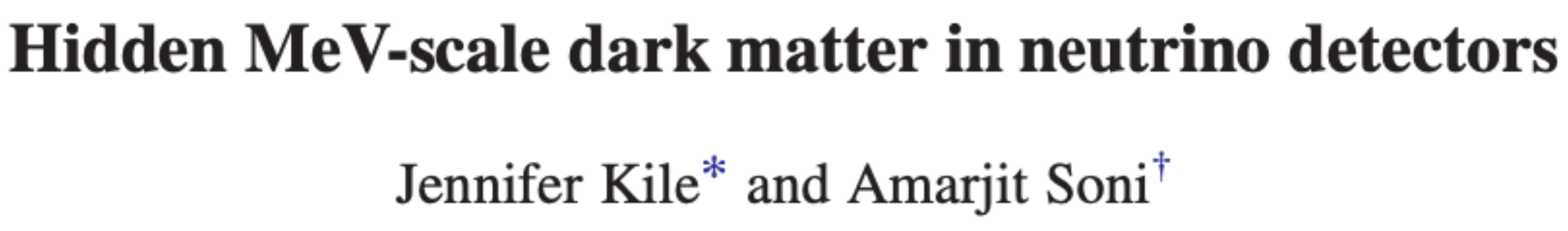
Baryon number violation from confining New Physics

Mathew Thomas Arun



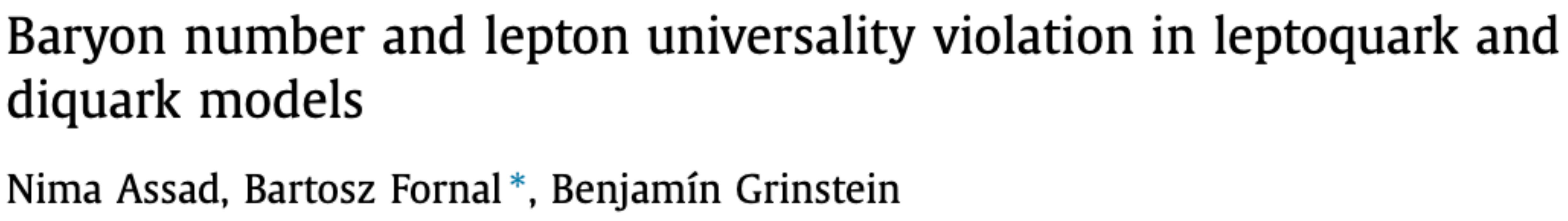
Distinguishing $4k + 2$ dimensions with assisted baryon number violation

Akshay A and Mathew Thomas Arun



Hidden MeV-scale dark matter in neutrino detectors

Jennifer Kile[*] and Amarjit Soni[†]

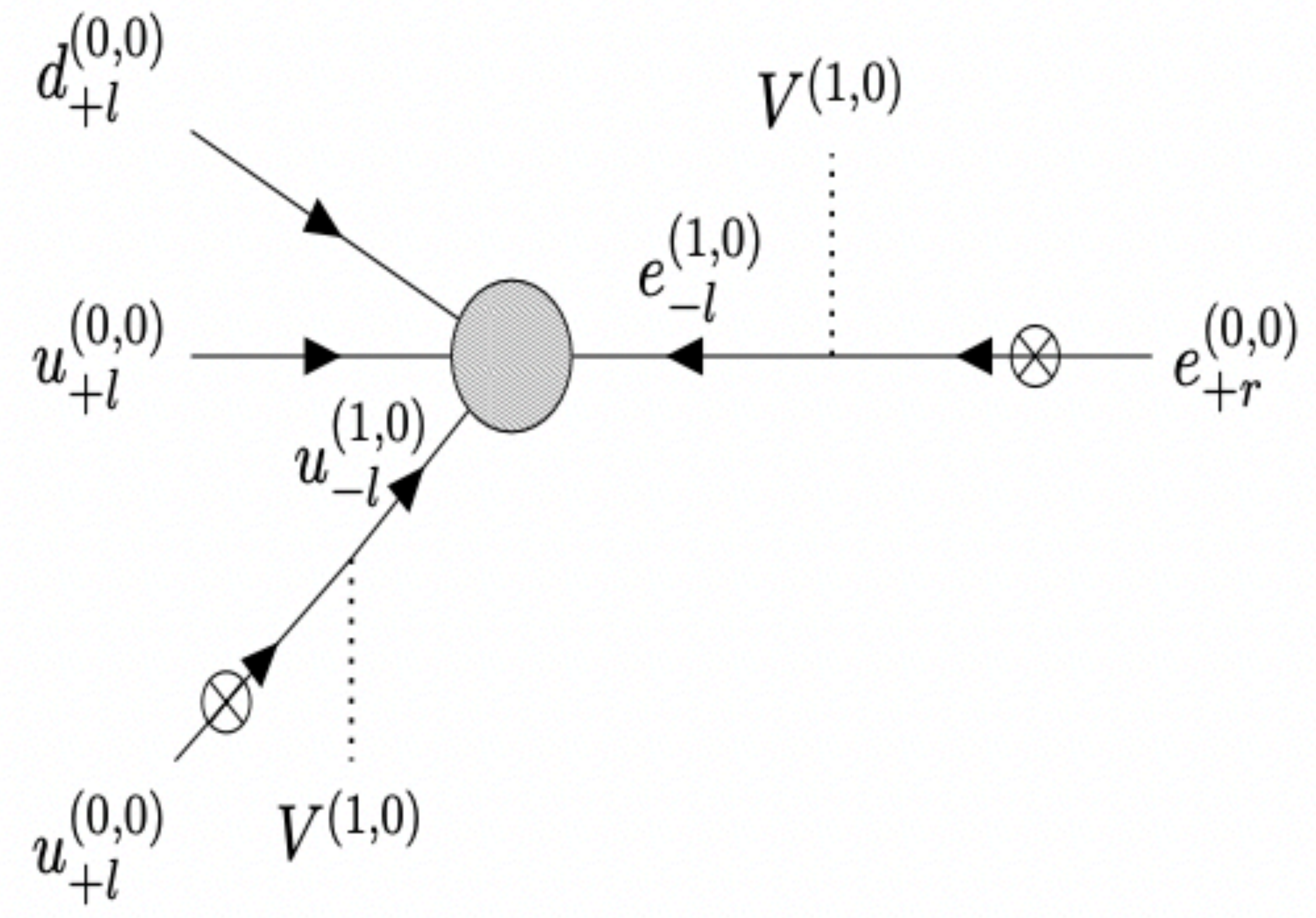


Baryon number and lepton universality violation in leptoquark and diquark models

Nima Assad, Bartosz Fornal[*], Benjamín Grinstein

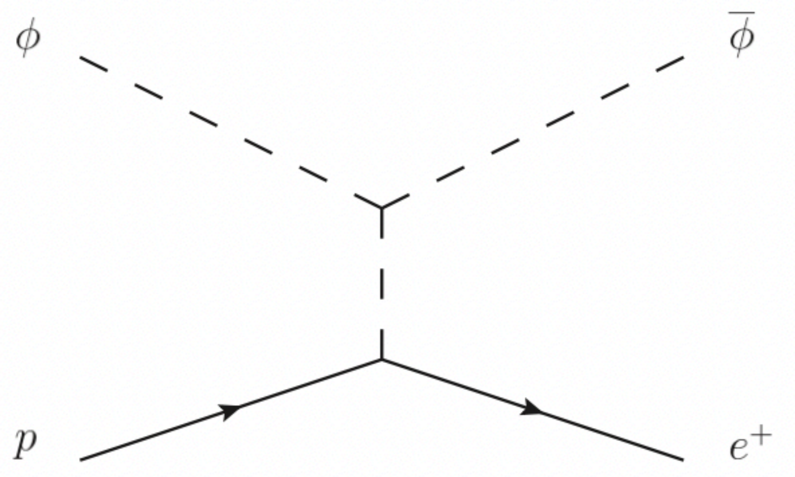
decays:
(Induced) Proton decay

- $p \to e^+ + \pi^0$
- $DM + p \to DM + e^+$
- $DM + p \to DM + e^+ + \pi^0$
- Baryonic Dark Matter

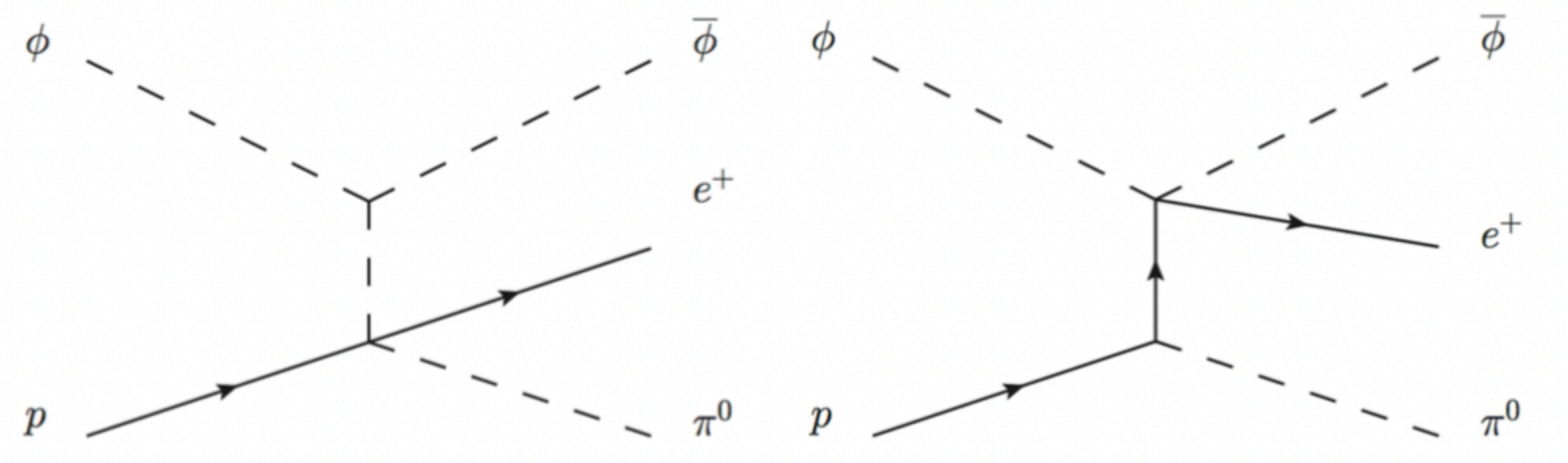


In preparation. Will help in distinguishing 4k+2 and 4k dimensions

Weyl-Majorana fermion and adjoint scalar DM



	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$	$U(1)_B$
X	$\mathbf{1}$	$\mathbf{1}(\mathbf{2})$	$1/2$	0	1
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	$1/2$	$1/2$
Φ_e	$\mathbf{1}$	$\mathbf{1}$	0	1	1



Huang, J., Zhao, Y.
J. High Energ. Phys. **2014,** 77 (2014)
arXiv:1312.0011

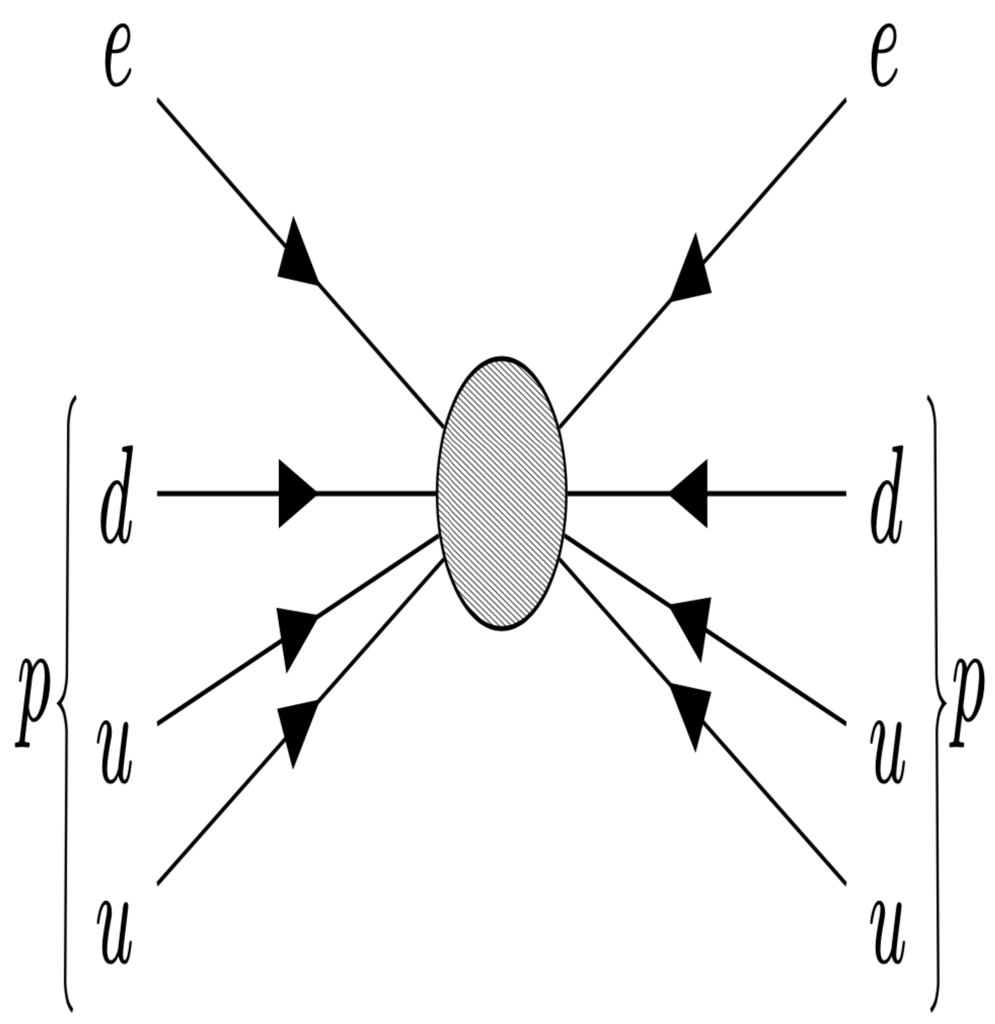
$$\Gamma(p \to e^+\pi^0) \simeq \frac{1}{2\times 10^{34}\,\mathrm{yr}}\left|\frac{y^j_{1111}}{(3\times 10^{15}\,\mathrm{GeV})^{-2}}\right|^2$$

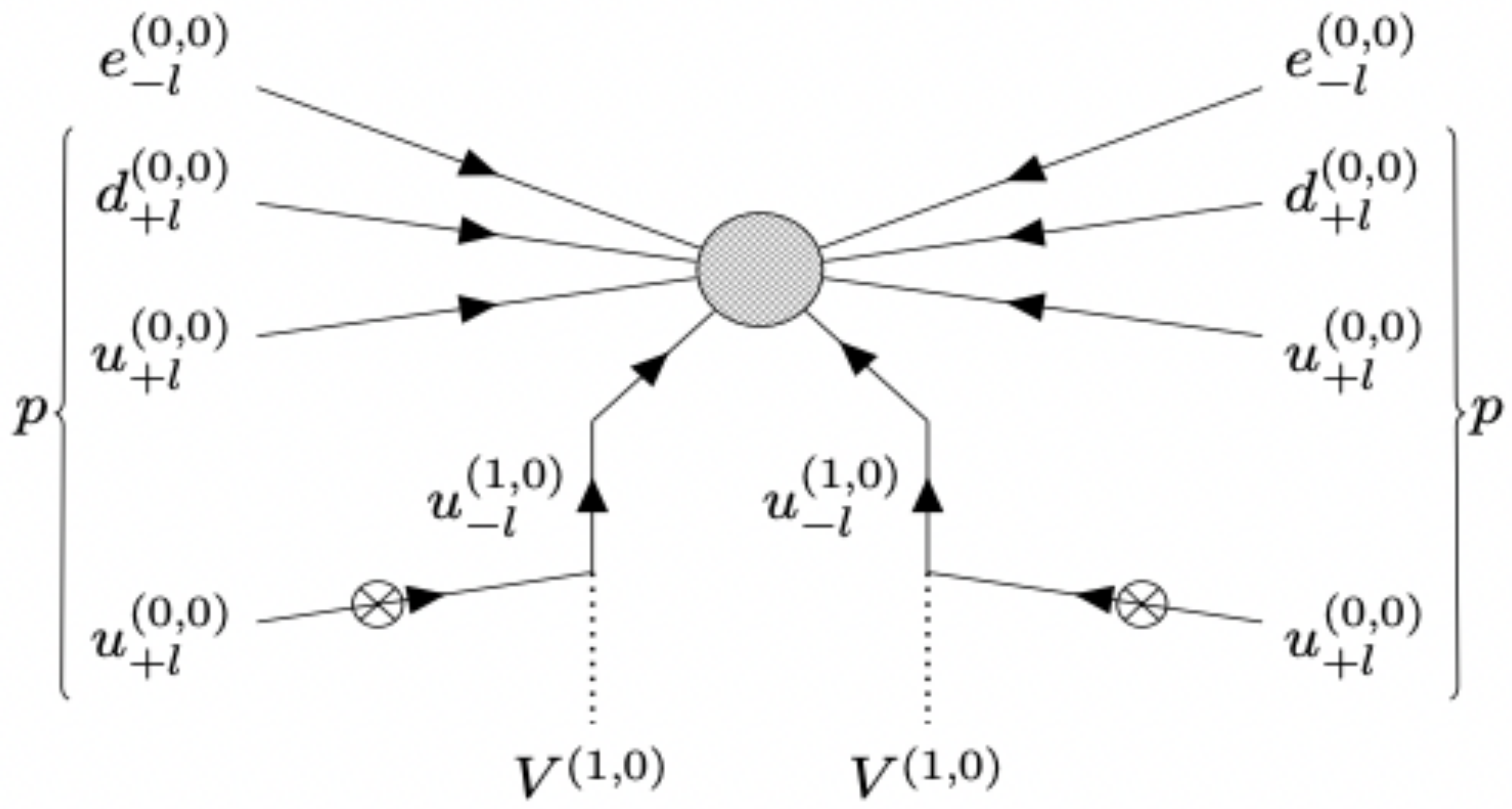
$$\tau_{\mathrm{eff}} = 1.5\times 10^{33}\mathrm{yr}\left(\frac{0.7\times 10^{-40}\mathrm{cm}^3/\mathrm{s}}{(\sigma v)_{\mathrm{IND}}}\right)$$

decays:
(Induced) Proton Proton annihilation / Hydrogen-antiHydrogen oscillation

- $p + p \to \mu^+ + \mu^+/e^+ + e^+$ (dim-12)
- $DM + p \to DM + \bar{p} + \mu^+\mu^+/e^+e^+$
- There could be striking signatures
- They arise from different operators

- How do you distinguish
- This is done by looking at the $\mu^+\mu^+/e^+e^+$ in the final state.
- $\Lambda \gtrsim 1.5TeV$ for perturbative new physics



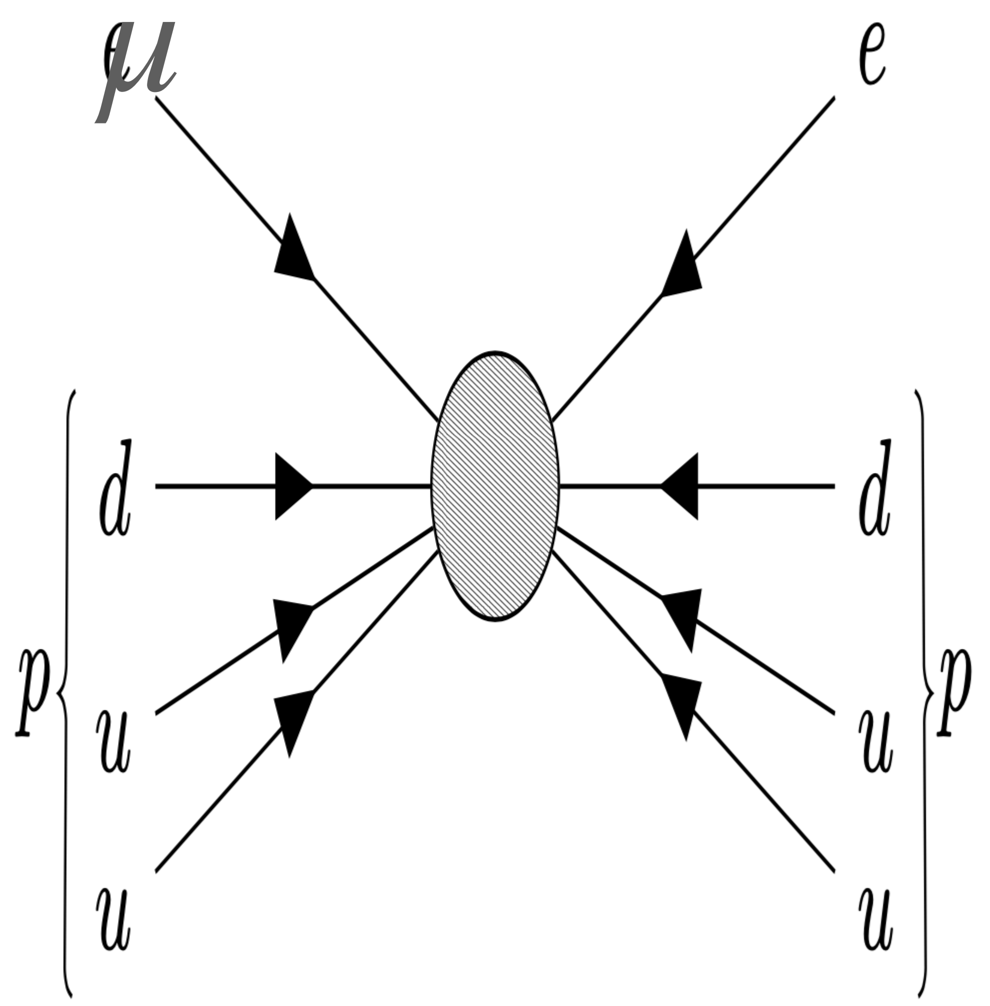


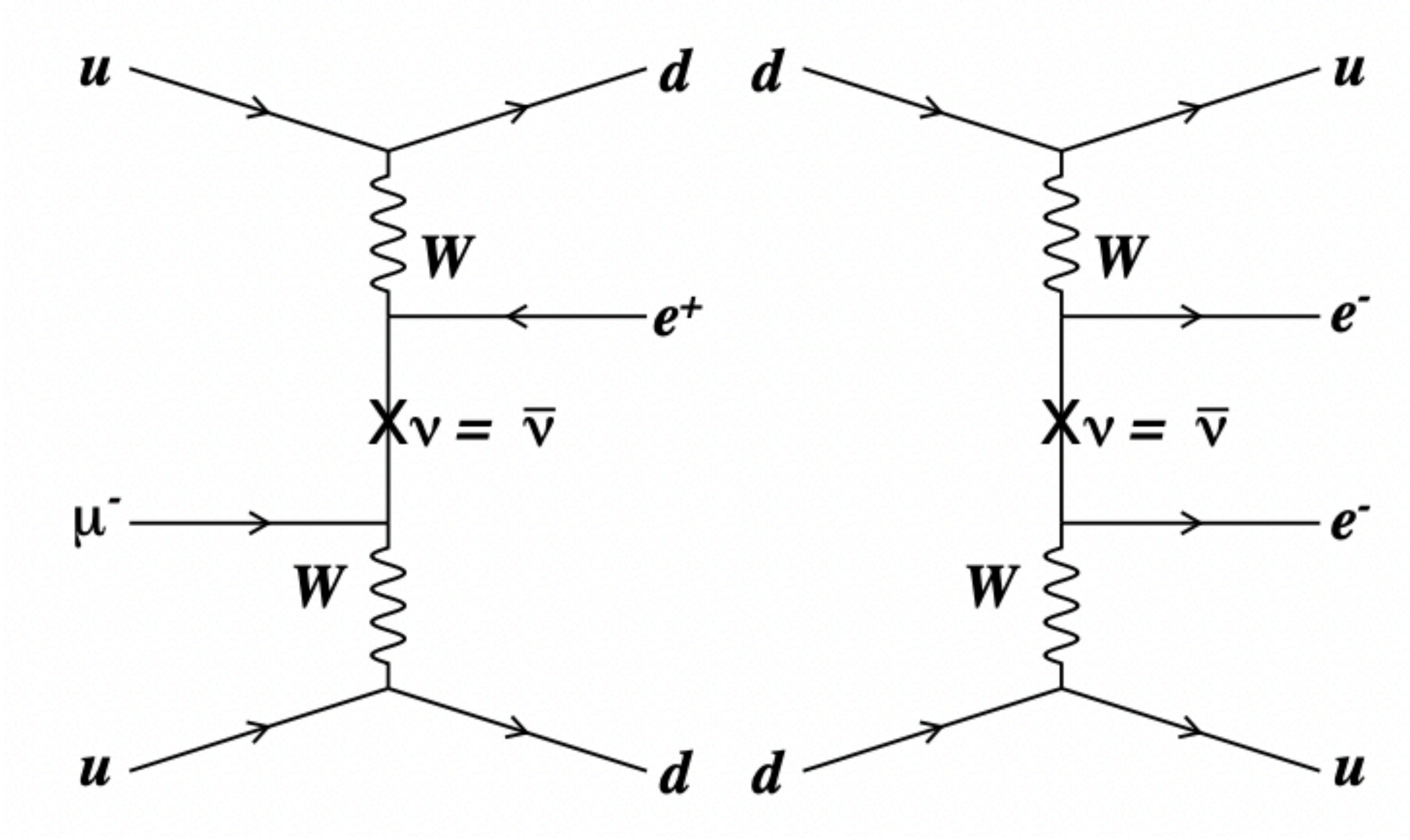
$$\Gamma^{\mathcal{O}_4}_{{}^{16}O \to {}^{14}C\ell^+\ell^+} = \frac{21}{4\pi^2}\left(\frac{m_p^2}{\Lambda_4^4}\right) r^{-3}$$

$$= (6.4 \times 10^{27}\ \text{yrs}^{-1}) \left(\frac{\text{GeV}}{\Lambda_4}\right)^4$$

Exotic decay:

$$\mu^- + N(A, Z) \rightarrow e^+ + N'(A, Z-2)$$





M.~Lee and M.~MacKenzie,

Universe 8, no.4, 227 (2022)
arXiv:2110.07093

$n - \bar{n}$ $\langle \bar{n} | \mathcal{H}_{\Delta B=2} | n \rangle = -\frac{1}{2} \epsilon \, \nu_{\bar{n}}^T C u_n$

Confining New Physics

Six-dimensions

$$ds_6^2 = b^2(x_5)[a^2(x_4)\eta_{\mu\nu}dx^\mu dx^\nu + dx_4^2] + dx_5^2$$

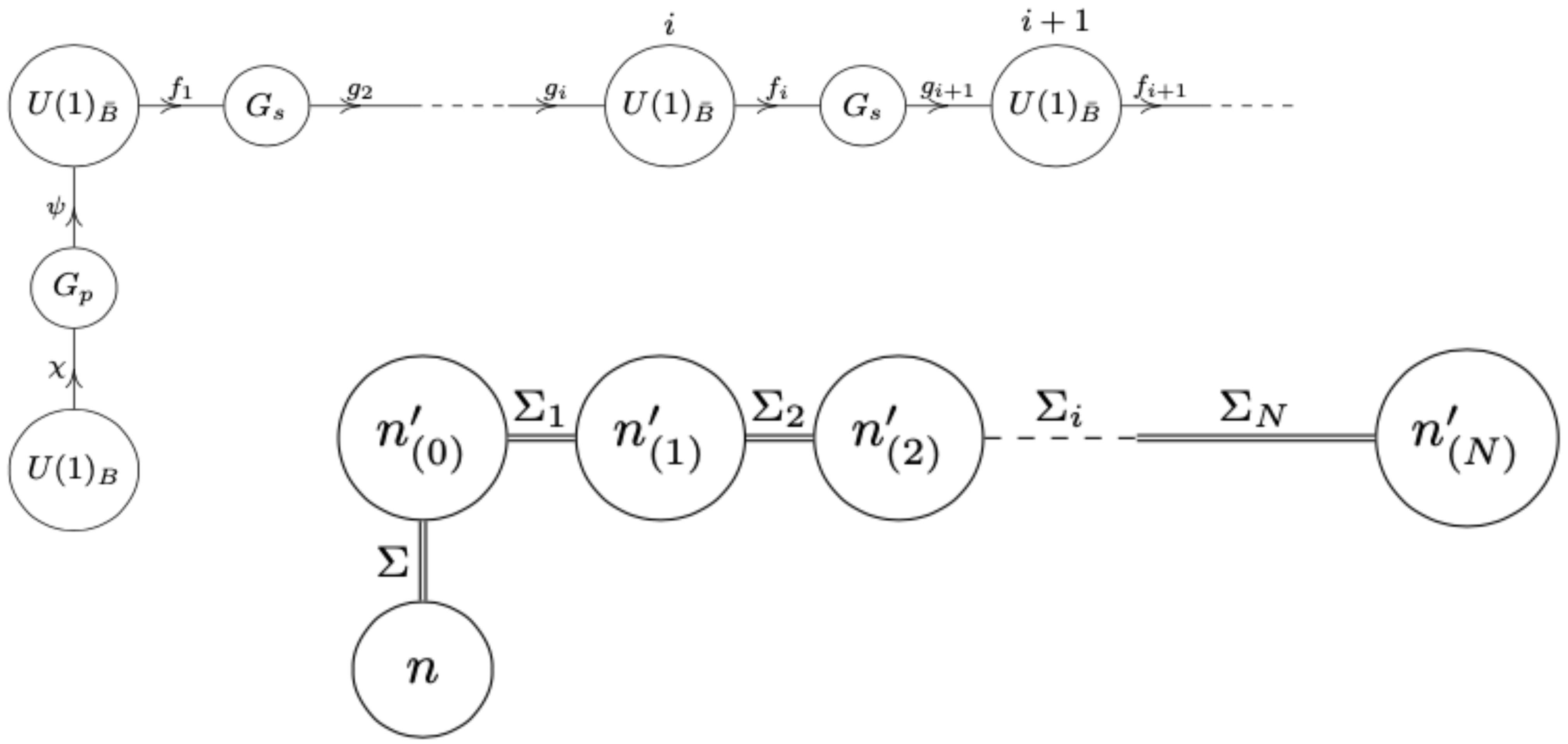
$$\begin{aligned}\mathcal{L} &= \sqrt{-g_6}\,(M_6^4 R_6 - \Lambda_6) \\ &+ \sqrt{-g_5}\,[V_1(x_5)\,\delta(x_4) + V_2(x_5)\,\delta(x_4 - \pi R_y)] \\ &+ \sqrt{-\tilde{g}_5}\,[V_3(x_4)\,\delta(x_5) + V_4(x_4)\,\delta(x_5 - \pi r_z)]\,.\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{int} &= \eta_{ud}\phi\overline{u^c}d + \eta_{ue}\phi^*\overline{u^c}e + \zeta_{dd}\omega^*\overline{d^c}d \\ &+ \rho M\phi^2\omega + h.c. \ ,\end{aligned}$$

where

$$\begin{aligned}\zeta_{dd} &= (2r_z)^{-1}z_{dd}\int dx_5 b^2\chi_\phi\chi_d^2 \\ \eta_{ud} &= (2r_z)^{-1}y_{ud}\int dx_5 b^2\chi_\phi\chi_u\chi_d \\ \rho &= (2r_z)^{-1}\lambda\int dx_5 b^2\chi_\phi^2\chi_\omega \\ \eta_{ue} &= y_{ue}b^2(0)\chi_\phi(0)\chi_u(0)\end{aligned}$$

κ	1	0.1	0.01	0.001
$m_\phi(\mathrm{TeV}) = m_\omega = M$	670	106	17	2.6
$m_\phi(\mathrm{TeV}) = m_\omega/3 = M/3$	345	55	9	1.4

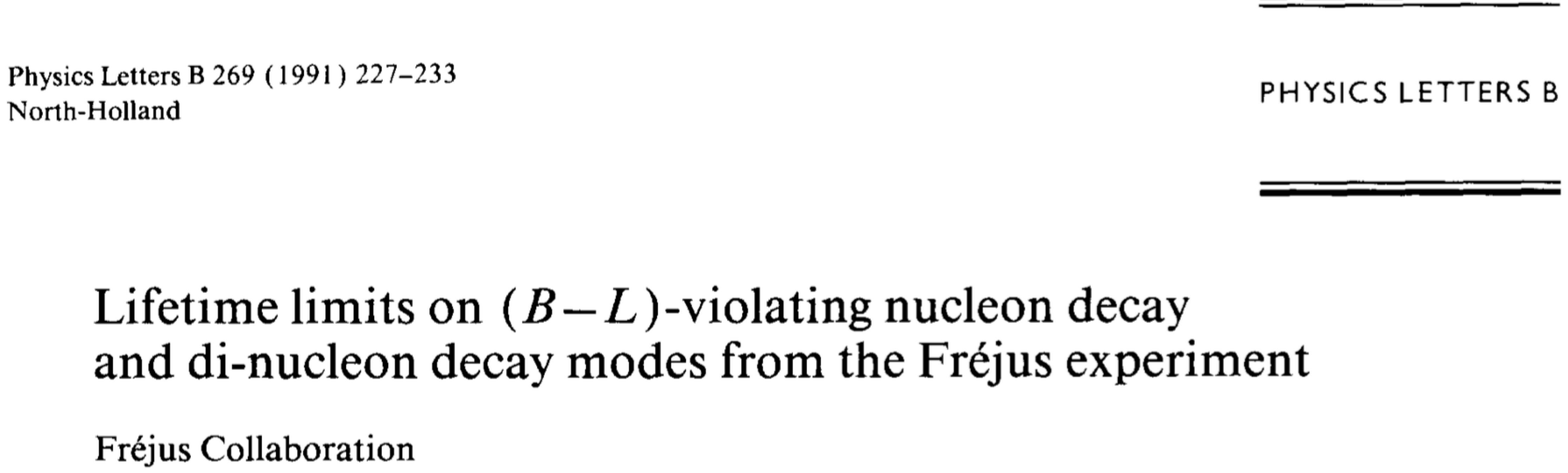


$$\mathcal{L} = i\bar{n}\gamma^\mu\partial_\mu n - \frac{m_n}{2}\left[\bar{n}n + \bar{n^c}n^c\right] - \frac{\epsilon}{2}\left[\bar{n^c}n + \bar{n}n^c\right]$$

$$\begin{aligned}\mathcal{V}_n &= \sum_{i=1}^{N}\Big(M\ n'^c_{(i)}n'_{(i-1)} - m\ n'^c_{(i)}n'_{(i)}\Big) - yv\ \bar{n}\ \ n'_{(0)} \\ &+ \mathcal{L}_{int}\ , \end{aligned} \qquad (6)$$

$$\begin{aligned}\mathcal{L} &= i\bar{n}\gamma^\mu\partial_\mu n - \frac{m_n}{2}\left[\bar{n}n + \bar{n^c}n^c\right] - \frac{(y_{eff}v)^2}{m_M}\bar{n^c}n \\ &+ \mathcal{L}_{int} + h.c.\ . \end{aligned} \qquad (10)$$

(induced) $pp \rightarrow \mu^+\mu^+$:
At INO 50 Kiloton (~10^9 Avogadro number)? e^+e^+ (with scintillators)
Frejus experiment ?

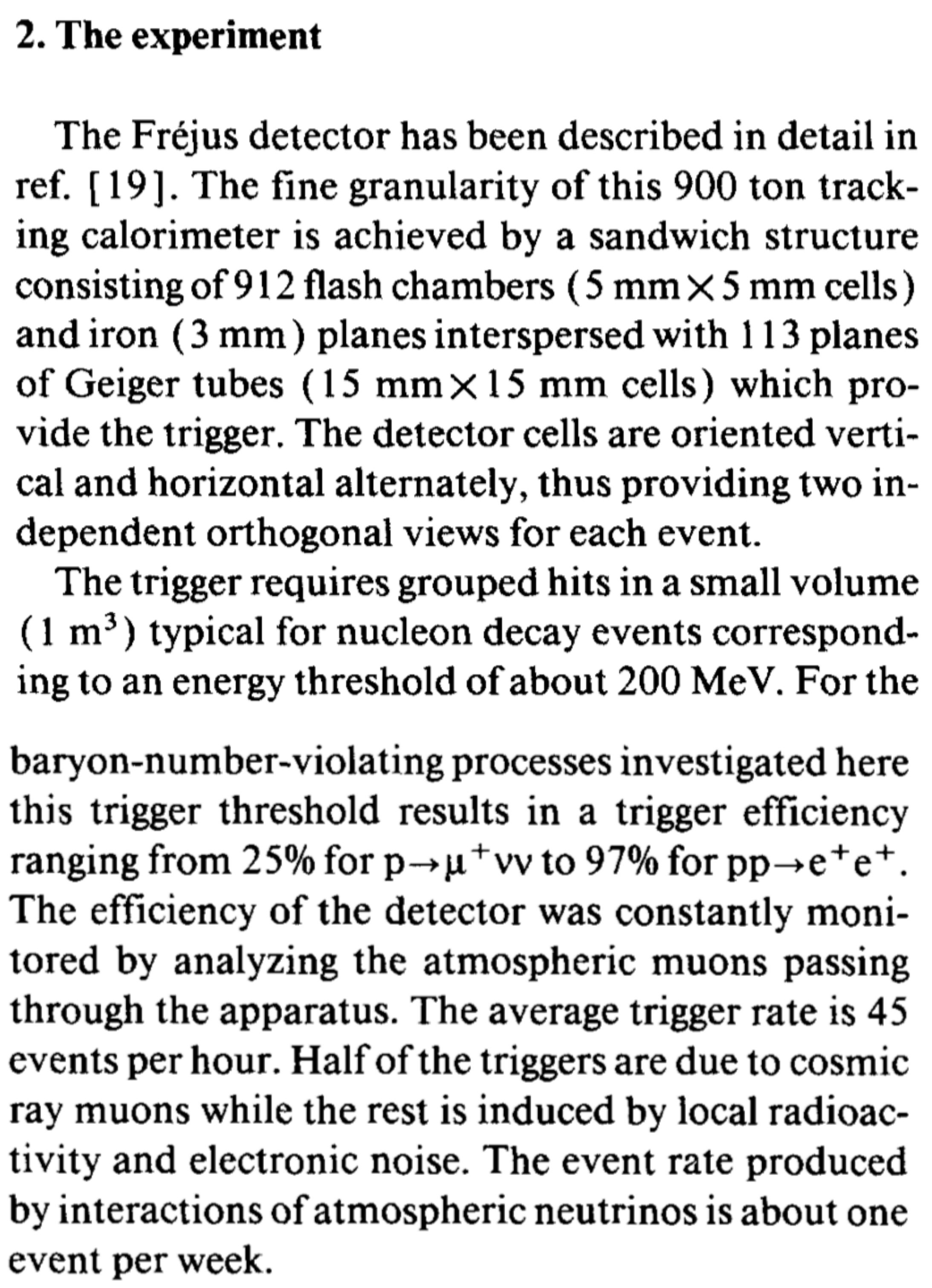


Physics Letters B 269 (1991) 227–233
North-Holland

PHYSICS LETTERS B

Lifetime limits on $(B-L)$-violating nucleon decay and di-nucleon decay modes from the Fréjus experiment

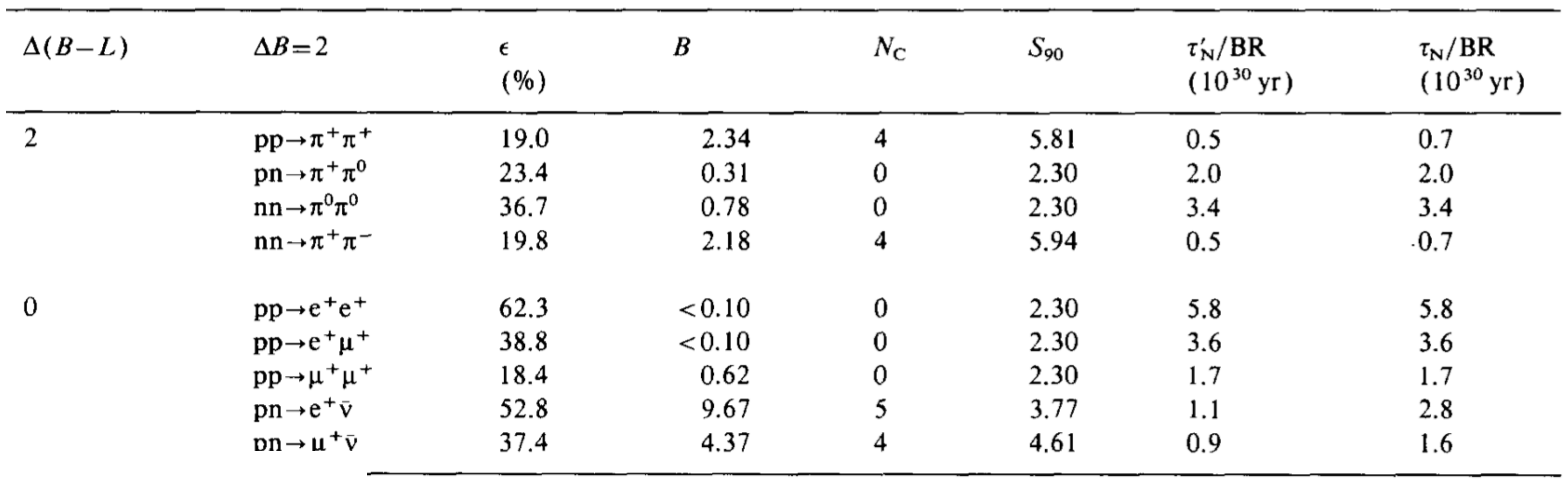
Fréjus Collaboration



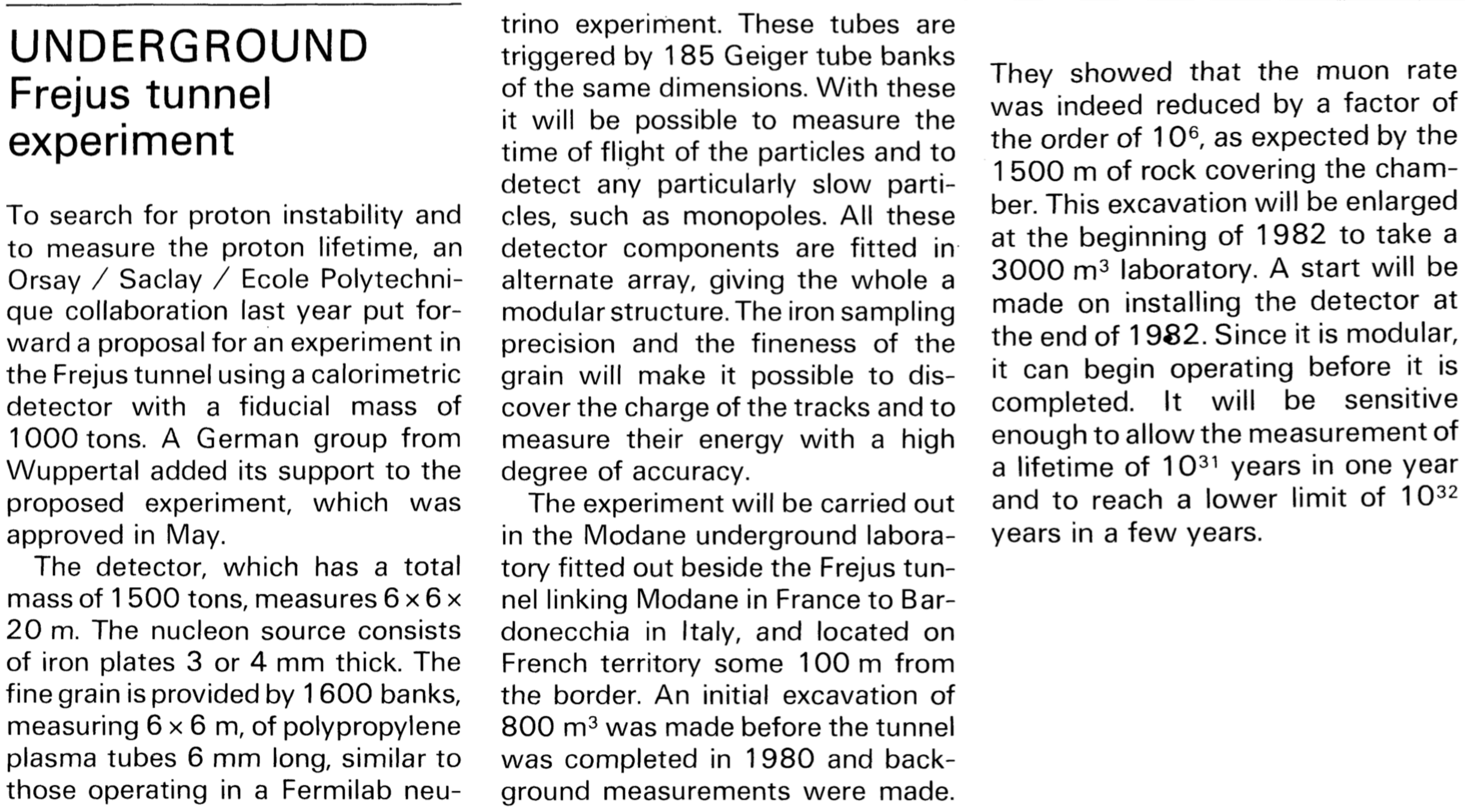
2. The experiment

The Fréjus detector has been described in detail in ref. [19]. The fine granularity of this 900 ton tracking calorimeter is achieved by a sandwich structure consisting of 912 flash chambers (5 mm × 5 mm cells) and iron (3 mm) planes interspersed with 113 planes of Geiger tubes (15 mm × 15 mm cells) which provide the trigger. The detector cells are oriented vertical and horizontal alternately, thus providing two independent orthogonal views for each event.

The trigger requires grouped hits in a small volume (1 m^3) typical for nucleon decay events corresponding to an energy threshold of about 200 MeV. For the baryon-number-violating processes investigated here this trigger threshold results in a trigger efficiency ranging from 25% for $p \rightarrow \mu^+\nu\nu$ to 97% for $pp \rightarrow e^+e^+$. The efficiency of the detector was constantly monitored by analyzing the atmospheric muons passing through the apparatus. The average trigger rate is 45 events per hour. Half of the triggers are due to cosmic ray muons while the rest is induced by local radioactivity and electronic noise. The event rate produced by interactions of atmospheric neutrinos is about one event per week.



$\Delta(B-L)$	$\Delta B=2$	ϵ (%)	B	N_C	S_{90}	τ'_N/BR (10^{30} yr)	τ_N/BR (10^{30} yr)
2	$pp \rightarrow \pi^+\pi^+$	19.0	2.34	4	5.81	0.5	0.7
	$pn \rightarrow \pi^+\pi^0$	23.4	0.31	0	2.30	2.0	2.0
	$nn \rightarrow \pi^0\pi^0$	36.7	0.78	0	2.30	3.4	3.4
	$nn \rightarrow \pi^+\pi^-$	19.8	2.18	4	5.94	0.5	0.7
0	$pp \rightarrow e^+e^+$	62.3	<0.10	0	2.30	5.8	5.8
	$pp \rightarrow e^+\mu^+$	38.8	<0.10	0	2.30	3.6	3.6
	$pp \rightarrow \mu^+\mu^+$	18.4	0.62	0	2.30	1.7	1.7
	$pn \rightarrow e^+\bar{\nu}$	52.8	9.67	5	3.77	1.1	2.8
	$pn \rightarrow \mu^+\bar{\nu}$	37.4	4.37	4	4.61	0.9	1.6



UNDERGROUND
Frejus tunnel experiment

To search for proton instability and to measure the proton lifetime, an Orsay / Saclay / Ecole Polytechnique collaboration last year put forward a proposal for an experiment in the Frejus tunnel using a calorimetric detector with a fiducial mass of 1000 tons. A German group from Wuppertal added its support to the proposed experiment, which was approved in May.

The detector, which has a total mass of 1500 tons, measures 6 × 6 × 20 m. The nucleon source consists of iron plates 3 or 4 mm thick. The fine grain is provided by 1600 banks, measuring 6 × 6 m, of polypropylene plasma tubes 6 mm long, similar to those operating in a Fermilab neutrino experiment. These tubes are triggered by 185 Geiger tube banks of the same dimensions. With these it will be possible to measure the time of flight of the particles and to detect any particularly slow particles, such as monopoles. All these detector components are fitted in alternate array, giving the whole a modular structure. The iron sampling precision and the fineness of the grain will make it possible to discover the charge of the tracks and to measure their energy with a high degree of accuracy.

The experiment will be carried out in the Modane underground laboratory fitted out beside the Frejus tunnel linking Modane in France to Bardonecchia in Italy, and located on French territory some 100 m from the border. An initial excavation of 800 m³ was made before the tunnel was completed in 1980 and background measurements were made. They showed that the muon rate was indeed reduced by a factor of the order of 10^6, as expected by the 1500 m of rock covering the chamber. This excavation will be enlarged at the beginning of 1982 to take a 3000 m³ laboratory. A start will be made on installing the detector at the end of 1982. Since it is modular, it can begin operating before it is completed. It will be sensitive enough to allow the measurement of a lifetime of 10^{31} years in one year and to reach a lower limit of 10^{32} years in a few years.

Dinucleon and Nucleon Decay to Two-Body Final States with no Hadrons in Super-Kamiokande

arXiv:1811.12430

The Super-Kamiokande (SK) water Cherenkov detector, with a fiducial volume of 22.5 kilotons, contains 1.2×10^{34} nucleons. SK lies one kilometer under Mt. Ikenoyama in Japan's Kamioka Observatory. The detector is cylindrical with a diameter of 39.3 meters and a height of 41.4 meters, optically separated into an inner and an outer region. Eight-inch photomultiplier tubes (PMTs) line the outer detector facing outwards and serve primarily as a veto for cosmic ray muons, and 20-inch PMTs face inwards to measure Cherenkov light in the inner detector [12].

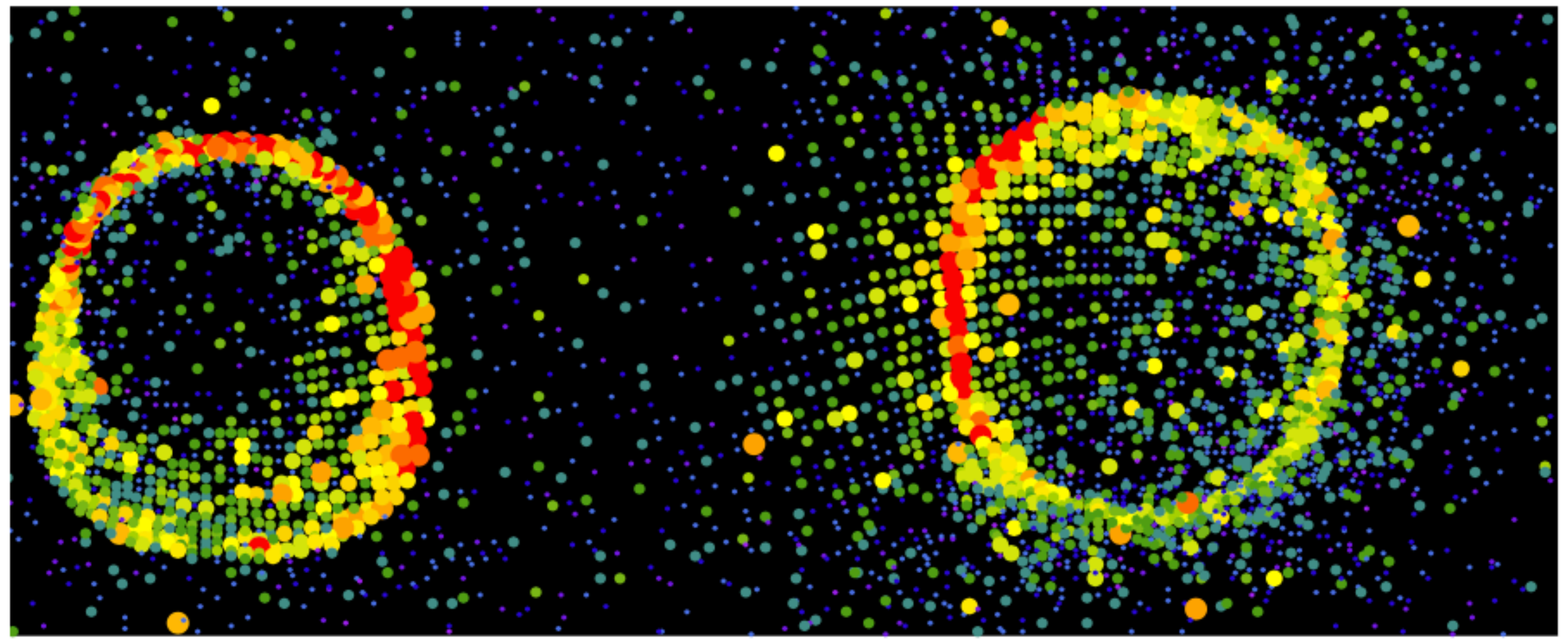
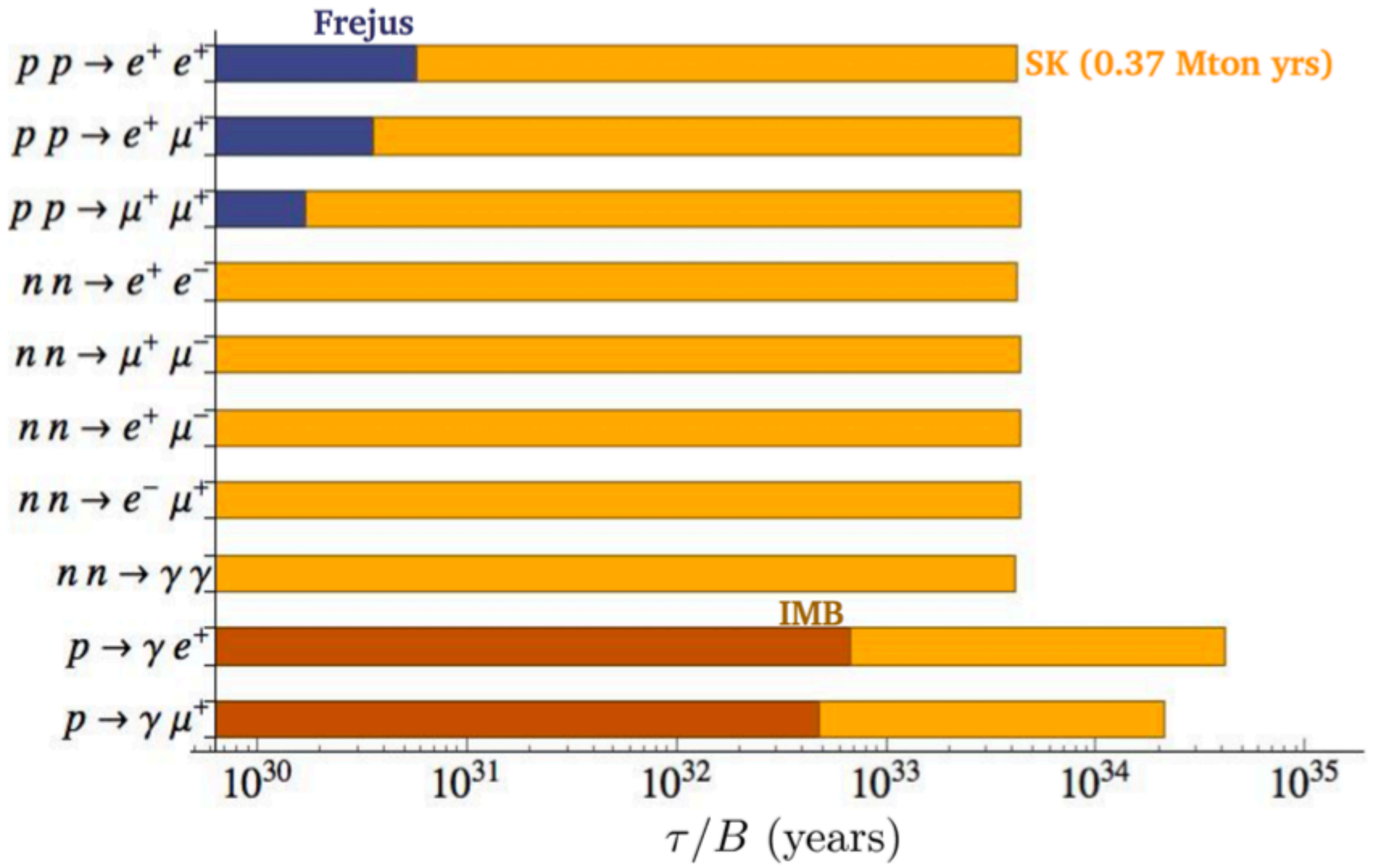


FIG. 1. (color online) An SK event display of a typical $pp \to e^+\mu^+$ event shown in θ-ϕ view. The non-showering ring (from the μ^+) is on the left and the showering ring (from the e^+) is on the right. The energy of each ring is approximately 900 MeV.



The following selection criteria are applied to signal MC, atmospheric ν MC, and data:

(A1) Events must be fully contained in the inner detector with the event vertex within the fiducial volume (two meters inward from the detector walls),

(A2) There must be two Cherenkov rings,

(A3) Both rings must be showering for the $pp \to e^+e^+$, $nn \to e^+e^-$, $nn \to \gamma\gamma$ and $p \to e^+\gamma$ modes; one ring must be showering and one ring must be non-showering for the $pp \to e^+\mu^+$, $nn \to e^+\mu^-$, $nn \to e^-\mu^+$ and $p \to \mu^+\gamma$ modes; both rings must be non-showering for the $pp \to \mu^+\mu^+$, $nn \to \mu^+\mu^-$ modes (see note in [19]),

(A4) There must be zero Michel electrons for the $pp \to e^+e^+$, $nn \to e^+e^-$, $nn \to \gamma\gamma$ and $p \to e^+\gamma$ modes; there must be less than or equal to one Michel electron for the $pp \to e^+\mu^+$, $nn \to e^+\mu^-$, $nn \to e^-\mu^+$ and $p \to \mu^+\gamma$ modes; there is no Michel electron cut for the $pp \to \mu^+\mu^+$, $nn \to \mu^+\mu^-$ modes (see note in [20]),

(A5) The reconstructed total mass, M_{tot}, should be $1600 \leq M_{tot} \leq 2050$ MeV/c^2 for the dinucleon decay modes; the reconstructed total mass should be $800 \leq M_{tot} \leq 1050$ MeV/c^2 for the nucleon decay modes,

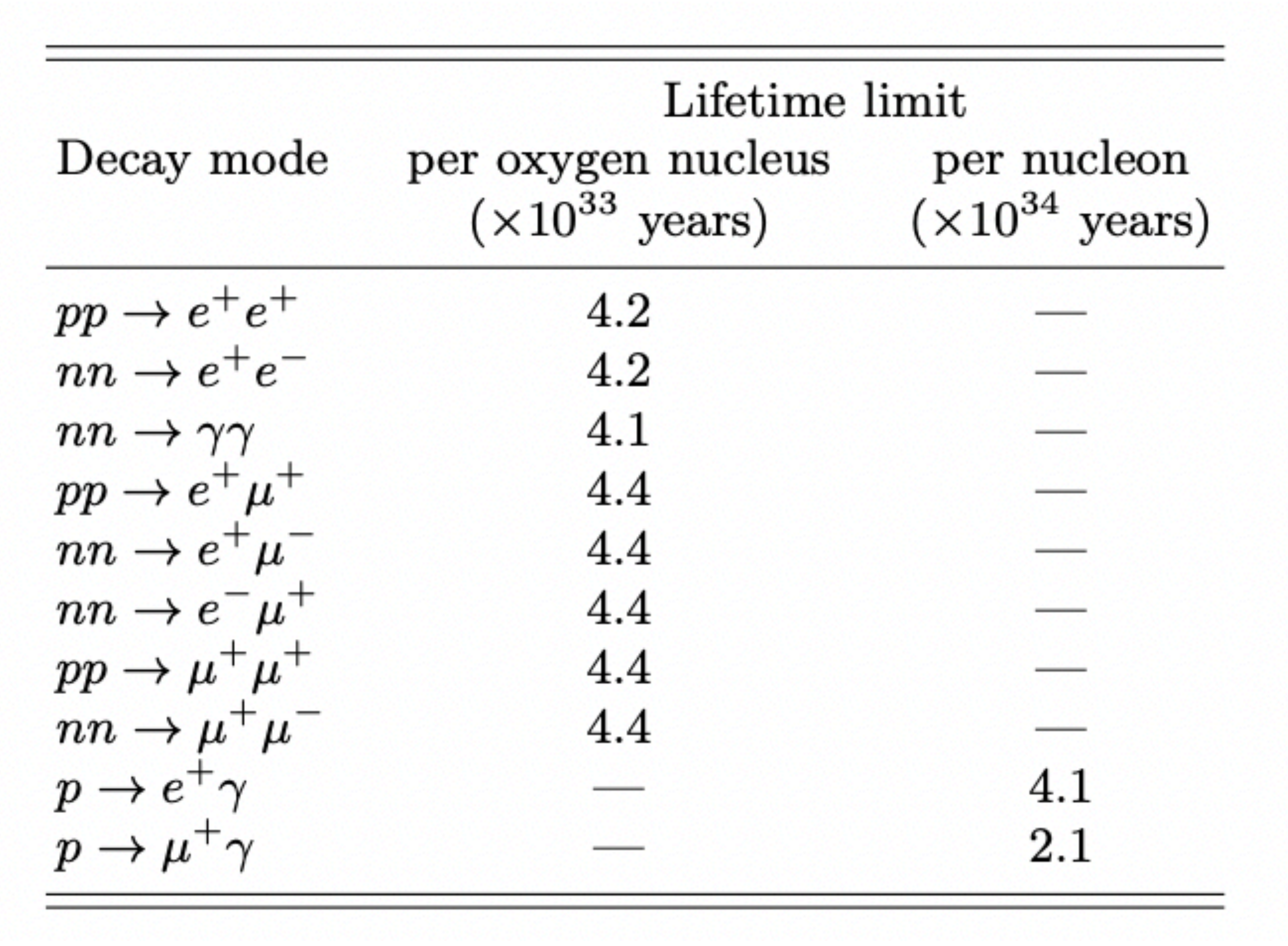
(A6) The reconstructed total momentum, P_{tot}, should be $0 \leq P_{tot} \leq 550$ MeV/c for the dinucleon decay modes; for the nucleon decay modes, it should be $100 \leq P_{tot} \leq 250$ MeV/c for the event to be in the "High $P_{\rm tot}$" signal box and $0 \leq P_{tot} \leq 100$ MeV/c for the event to be in the "Low $P_{\rm tot}$" signal box,

(A7) [SK-IV nucleon decay searches only] There must be zero tagged neutrons.

TABLE IV. Parameters of past (KAM [114, 115]), running (SK [116, 117]), and future (HK-3TankLD and HK-1TankHD) water Cherenkov detectors. The KAM and SK have undergone several configuration changes and parameters for KAM-II and SK-IV are referred in the table. The single-photon detection efficiencies are products of the quantum efficiency at peak ($\sim 400\,\mathrm{nm}$), photo-electron collection efficiency, and threshold efficiency. Most right column (HK-1TankHD) shows another design under study which consist of one tank instrumented with high density PMTs.

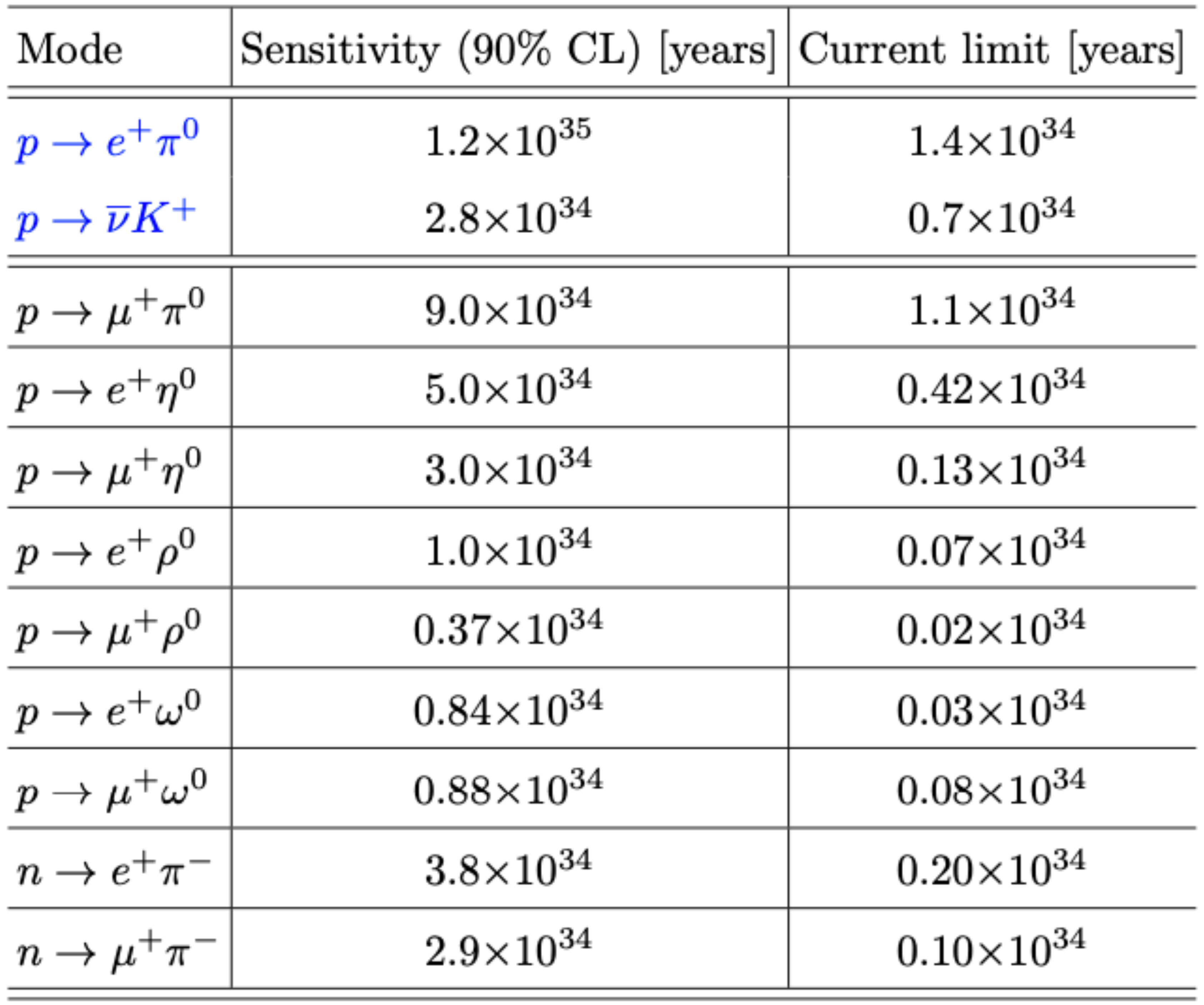
	KAM	SK	HK-3TankLD	HK-1TankHD
Depth	1,000 m	1,000 m	650 m	650 m
Dimensions of water tank				
diameter	15.6 m ϕ	39 m ϕ	74 m ϕ	74 m ϕ
height	16 m	42 m	60 m	60 m
Total volume	4.5 kton	50 kton	774 kton	258 kton
Fiducial volume	0.68 kton	22.5 kton	560 kton	187 kton
Outer detector thickness	~ 1.5 m	~ 2 m	$1 \sim 2$ m	$1 \sim 2$ m
Number of PMTs				
inner detector (ID)	948 (50 cm ϕ)	11,129 (50 cm ϕ)	40,000 (50 cm ϕ)	40,000 (50 cm ϕ)
outer detector (OD)	123 (50 cm ϕ)	1,885 (20 cm ϕ)	20,000 (20 cm ϕ)	6,700 (20 cm ϕ)
Photo-sensitive coverage	20%	40%	13%	40%
Single-photon detection efficiency of ID PMT	unknown	12%	24%	24%
Single-photon timing resolution of ID PMT	~ 4 nsec	2-3 nsec	1 nsec	1 nsec

Super-Kamiokande and Hyper-Kamiokande (~650 m)



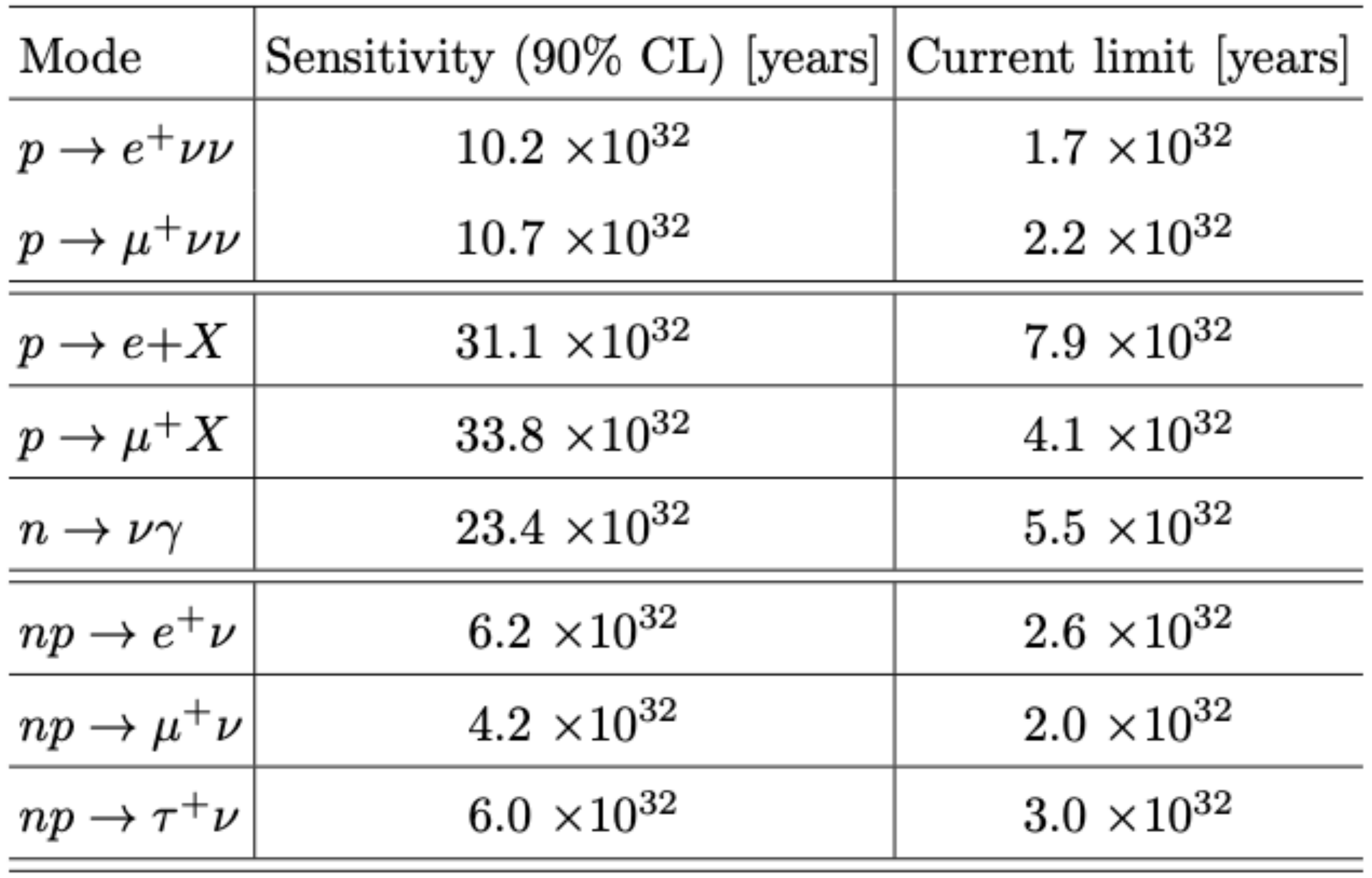
Decay mode	Lifetime limit per oxygen nucleus ($\times 10^{33}$ years)	per nucleon ($\times 10^{34}$ years)
$pp \to e^+e^+$	4.2	—
$nn \to e^+e^-$	4.2	—
$nn \to \gamma\gamma$	4.1	—
$pp \to e^+\mu^+$	4.4	—
$nn \to e^+\mu^-$	4.4	—
$nn \to e^-\mu^+$	4.4	—
$pp \to \mu^+\mu^+$	4.4	—
$nn \to \mu^+\mu^-$	4.4	—
$p \to e^+\gamma$	—	4.1
$p \to \mu^+\gamma$	—	2.1

arXiv:1811.12430 (Dinucleon and Nucleon Decay to Two-Body Final States with no Hadrons in Super-Kamiokande)



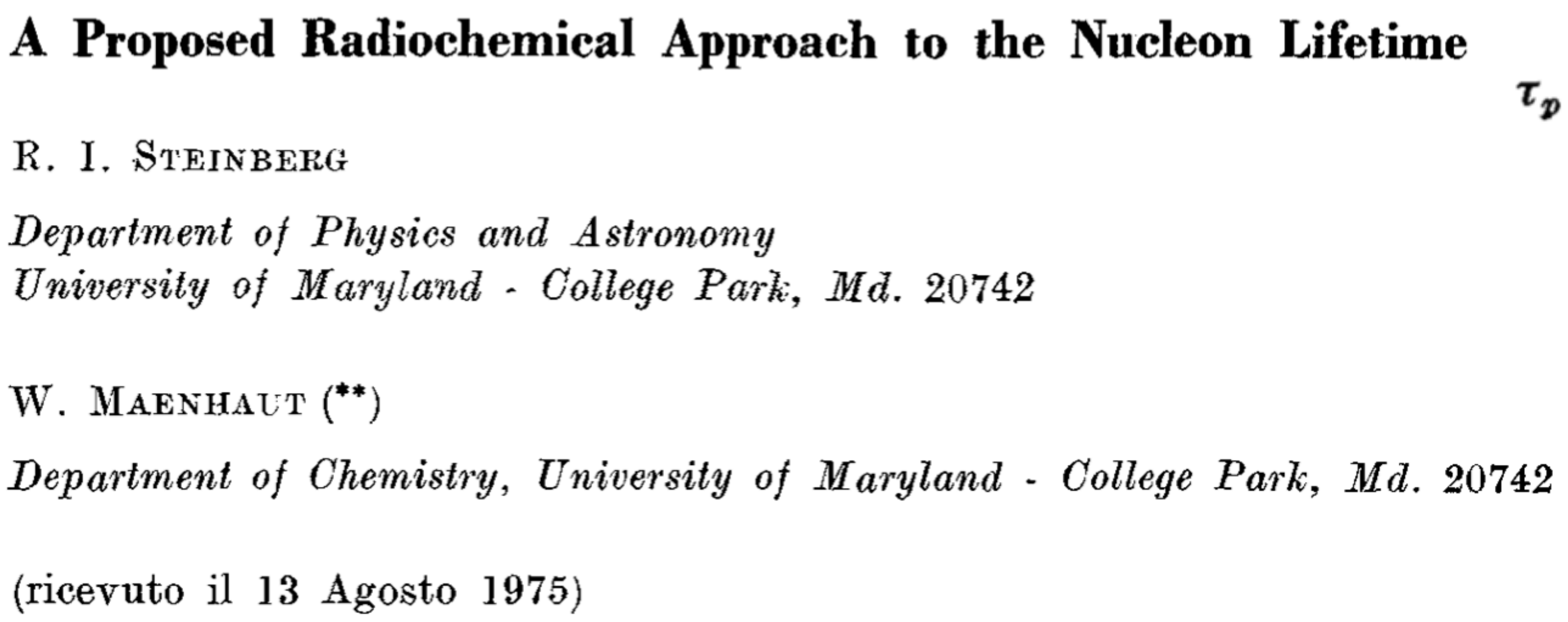
Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\pi^0$	1.2×10^{35}	1.4×10^{34}
$p \to \overline{\nu}K^+$	2.8×10^{34}	0.7×10^{34}
$p \to \mu^+\pi^0$	9.0×10^{34}	1.1×10^{34}
$p \to e^+\eta^0$	5.0×10^{34}	0.42×10^{34}
$p \to \mu^+\eta^0$	3.0×10^{34}	0.13×10^{34}
$p \to e^+\rho^0$	1.0×10^{34}	0.07×10^{34}
$p \to \mu^+\rho^0$	0.37×10^{34}	0.02×10^{34}
$p \to e^+\omega^0$	0.84×10^{34}	0.03×10^{34}
$p \to \mu^+\omega^0$	0.88×10^{34}	0.08×10^{34}
$n \to e^+\pi^-$	3.8×10^{34}	0.20×10^{34}
$n \to \mu^+\pi^-$	2.9×10^{34}	0.10×10^{34}

KEK Preprint 2016-21
(HYPER-KAMIOKANDE design report)



Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\nu\nu$	10.2×10^{32}	1.7×10^{32}
$p \to \mu^+\nu\nu$	10.7×10^{32}	2.2×10^{32}
$p \to e{+}X$	31.1×10^{32}	7.9×10^{32}
$p \to \mu^+X$	33.8×10^{32}	4.1×10^{32}
$n \to \nu\gamma$	23.4×10^{32}	5.5×10^{32}
$np \to e^+\nu$	6.2×10^{32}	2.6×10^{32}
$np \to \mu^+\nu$	4.2×10^{32}	2.0×10^{32}
$np \to \tau^+\nu$	6.0×10^{32}	3.0×10^{32}

Proposal:
Neutron lifetime/ Double proton decay



A Proposed Radiochemical Approach to the Nucleon Lifetime

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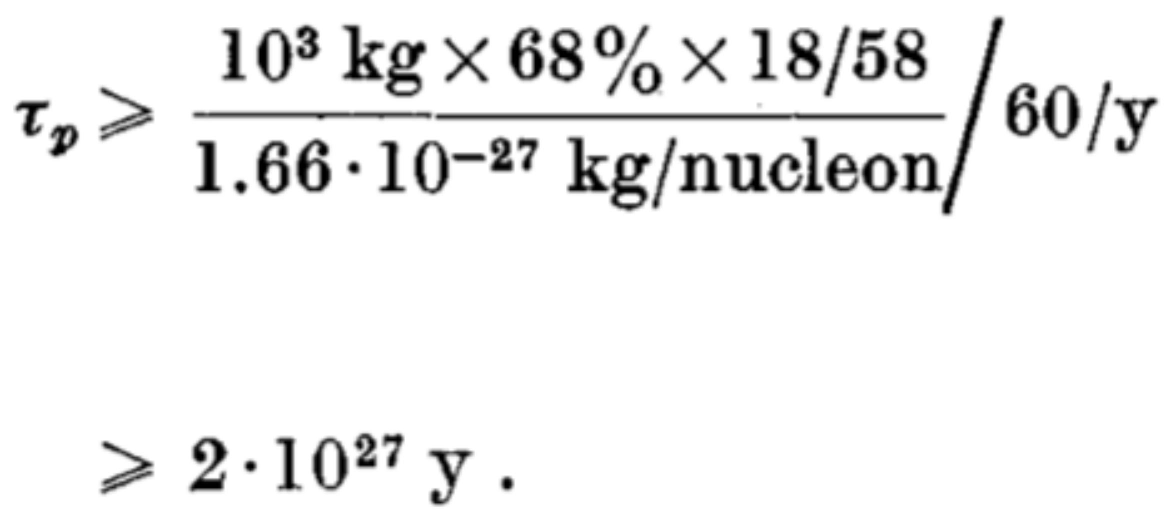
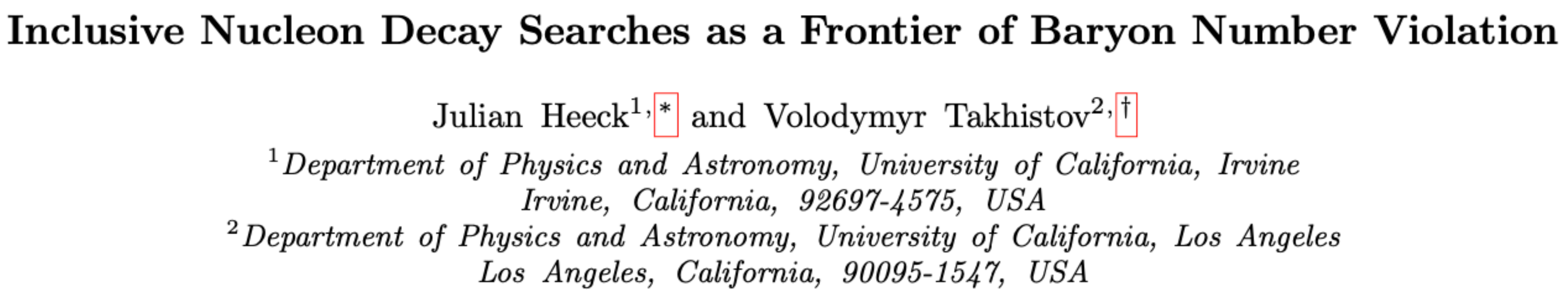
(ricevuto il 13 Agosto 1975)



$$\tau_p \geqslant \frac{10^3\ \text{kg}\times 68\%\times 18/58}{1.66\cdot 10^{-27}\ \text{kg/nucleon}}\Big/ 60/\text{y} \geqslant 2\cdot 10^{27}\ \text{y}\,.$$

- If one of the neutrons in ^{58}Ni should decay then ^{57}Ni would beta decay to ^{57}Co
- Look for the appearance of this activity in a large mass of well-shielded Ni.
- We can also look for the process $^{39}K \rightarrow {}^{37}Ar$ (Potassium acetate powder)
- Searching for dim-6,12



Inclusive Nucleon Decay Searches as a Frontier of Baryon Number Violation

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Proposal:

$3n \to 3\nu$ dim-18 at quark level/ dim-9 hadron level

$nn \to \bar{n}\bar{\nu}$ dim-15 at quark level/ dim-6 hadron level

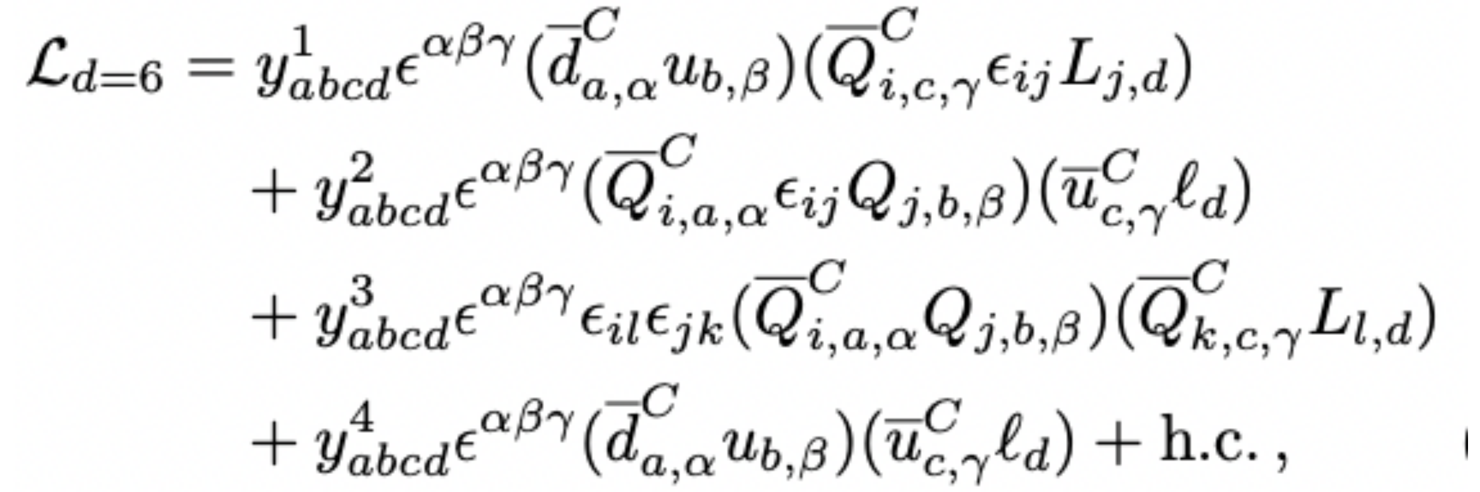
- High energy New Physics is out of question !!
- Could differentiate non-perturbative low-energy New Physics
- $^{59}Co \to {}^{56}Co \to {}^{56}Fe$
- Through 3n annihilation (probably no one has done this yet)
- 56Fe give out 846.8 KeV gamma rays. Need scintillators
- 6.4 KeV X ray of Fe would then allow the determination of the number of atoms of 59Co at source.

Summary:

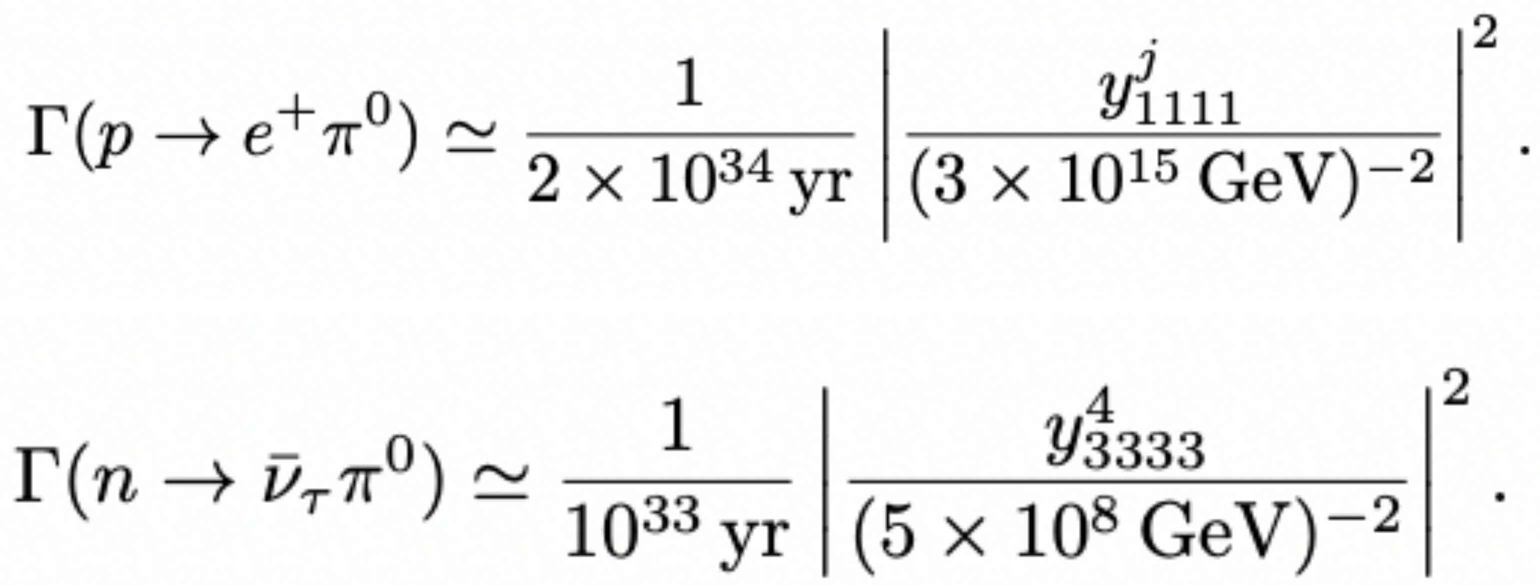
- $\Delta B = \Delta L = 2$ processes could indicate perturbative New Physics at 1.5 TeV
- Searches for DM induced nucleon decays
- Proposal: 50 Kton INO and liquid scintillators could already be in place to look for baryon number violating currents
- Flavour violating $\mu^- + N(A,Z) \to e^+ + N'(A,Z-2)$ could be interesting
- Proposal: ^{58}Ni should decay then ^{57}Ni would beta decay to ^{57}Co.
  $^{39}K \to {}^{37}Ar$ (Potassium acetate powder) to look for dim -6,12 processes
- Proposal: $^{59}Co \to {}^{56}Co \to {}^{56}Fe$ with 846.8 KeV gamma rays could differentiate non-perturbative low-energy New Physics

- Thank you for listening

Backup slides

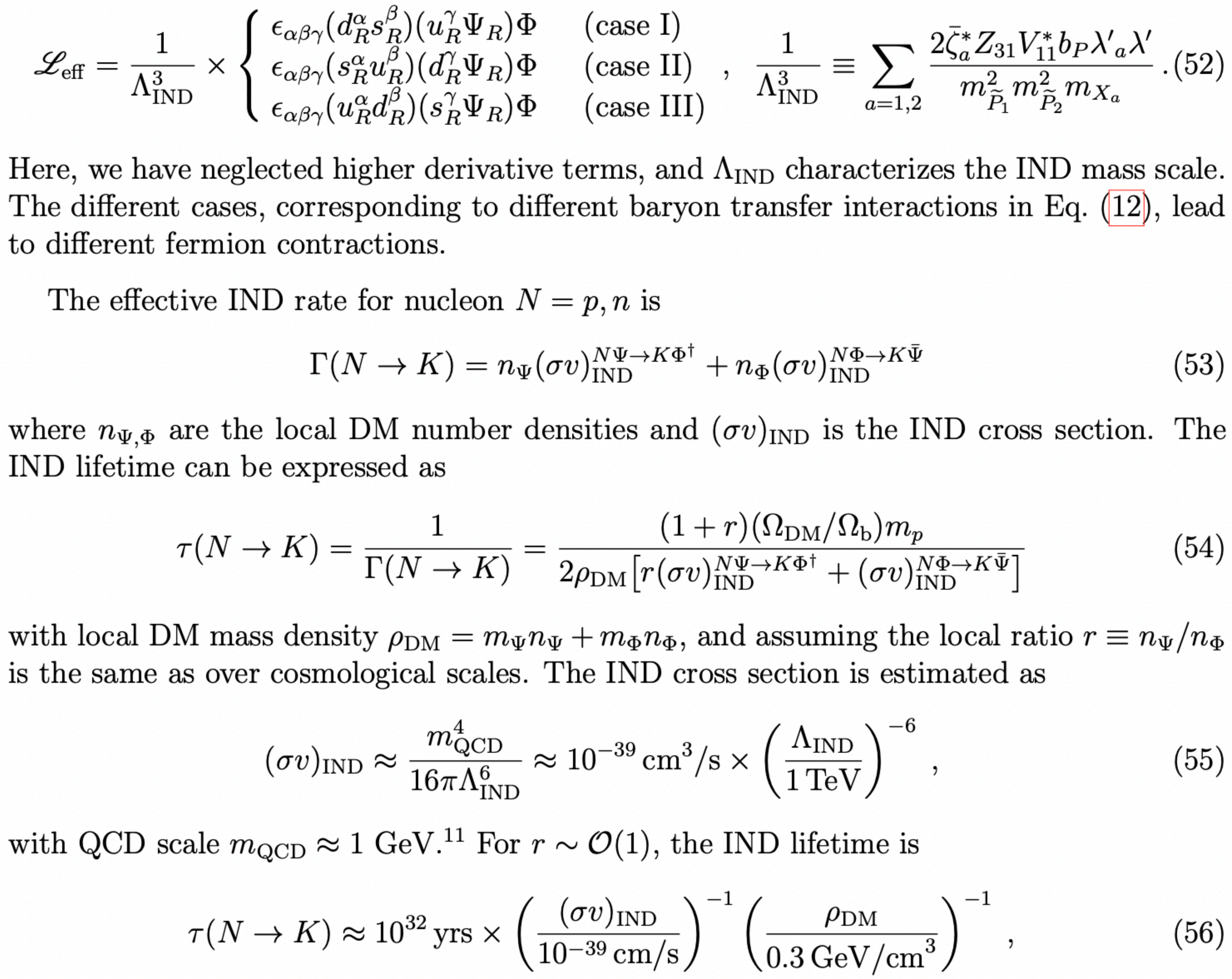


$$\begin{aligned}\mathcal{L}_{d=6} = {} & y^1_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{Q}^C_{i,c,\gamma}\epsilon_{ij}L_{j,d}) \\ & + y^2_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{Q}^C_{i,a,\alpha}\epsilon_{ij}Q_{j,b,\beta})(\overline{u}^C_{c,\gamma}\ell_d) \\ & + y^3_{abcd}\epsilon^{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(\overline{Q}^C_{i,a,\alpha}Q_{j,b,\beta})(\overline{Q}^C_{k,c,\gamma}L_{l,d}) \\ & + y^4_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{u}^C_{c,\gamma}\ell_d) + \text{h.c.}\,,\end{aligned}$$



$$\Gamma(p \to e^+\pi^0) \simeq \frac{1}{2\times 10^{34}\,\text{yr}}\left|\frac{y^j_{1111}}{(3\times 10^{15}\,\text{GeV})^{-2}}\right|^2 .$$

$$\Gamma(n \to \bar{\nu}_\tau\pi^0) \simeq \frac{1}{10^{33}\,\text{yr}}\left|\frac{y^4_{3333}}{(5\times 10^{8}\,\text{GeV})^{-2}}\right|^2 .$$



$$\mathscr{L}_{\text{eff}} = \frac{1}{\Lambda^3_{\text{IND}}} \times \begin{cases} \epsilon_{\alpha\beta\gamma}(d^\alpha_R s^\beta_R)(u^\gamma_R\Psi_R)\Phi & \text{(case I)} \\ \epsilon_{\alpha\beta\gamma}(s^\alpha_R u^\beta_R)(d^\gamma_R\Psi_R)\Phi & \text{(case II)} \\ \epsilon_{\alpha\beta\gamma}(u^\alpha_R d^\beta_R)(s^\gamma_R\Psi_R)\Phi & \text{(case III)} \end{cases} , \quad \frac{1}{\Lambda^3_{\text{IND}}} \equiv \sum_{a=1,2}\frac{2\bar{\zeta}^*_a Z_{31}V^*_{11}b_P\lambda'_a\lambda'}{m^2_{\widetilde{P}_1}m^2_{\widetilde{P}_2}m_{X_a}} . \quad (52)$$

Here, we have neglected higher derivative terms, and Λ_{IND} characterizes the IND mass scale. The different cases, corresponding to different baryon transfer interactions in Eq. (12), lead to different fermion contractions.

The effective IND rate for nucleon $N = p, n$ is

$$\Gamma(N \to K) = n_\Psi(\sigma v)^{N\Psi\to K\Phi^\dagger}_{\text{IND}} + n_\Phi(\sigma v)^{N\Phi\to K\bar{\Psi}}_{\text{IND}} \quad (53)$$

where $n_{\Psi,\Phi}$ are the local DM number densities and $(\sigma v)_{\text{IND}}$ is the IND cross section. The IND lifetime can be expressed as

$$\tau(N \to K) = \frac{1}{\Gamma(N\to K)} = \frac{(1+r)(\Omega_{\text{DM}}/\Omega_{\text{b}})m_p}{2\rho_{\text{DM}}\left[r(\sigma v)^{N\Psi\to K\Phi^\dagger}_{\text{IND}} + (\sigma v)^{N\Phi\to K\bar{\Psi}}_{\text{IND}}\right]} \quad (54)$$

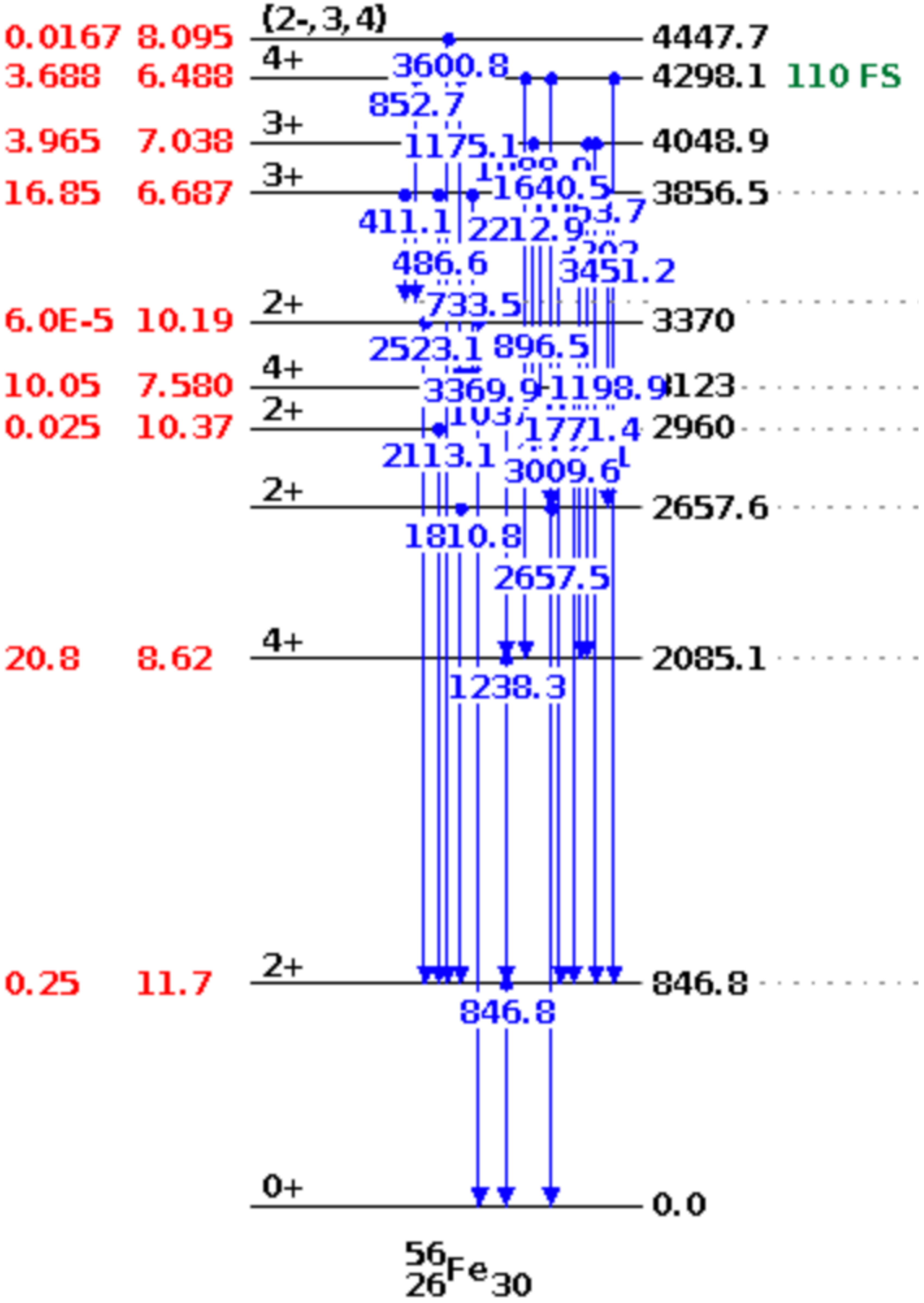
with local DM mass density $\rho_{\text{DM}} = m_\Psi n_\Psi + m_\Phi n_\Phi$, and assuming the local ratio $r \equiv n_\Psi/n_\Phi$ is the same as over cosmological scales. The IND cross section is estimated as

$$(\sigma v)_{\text{IND}} \approx \frac{m^4_{\text{QCD}}}{16\pi\Lambda^6_{\text{IND}}} \approx 10^{-39}\,\text{cm}^3/\text{s} \times \left(\frac{\Lambda_{\text{IND}}}{1\,\text{TeV}}\right)^{-6} , \quad (55)$$

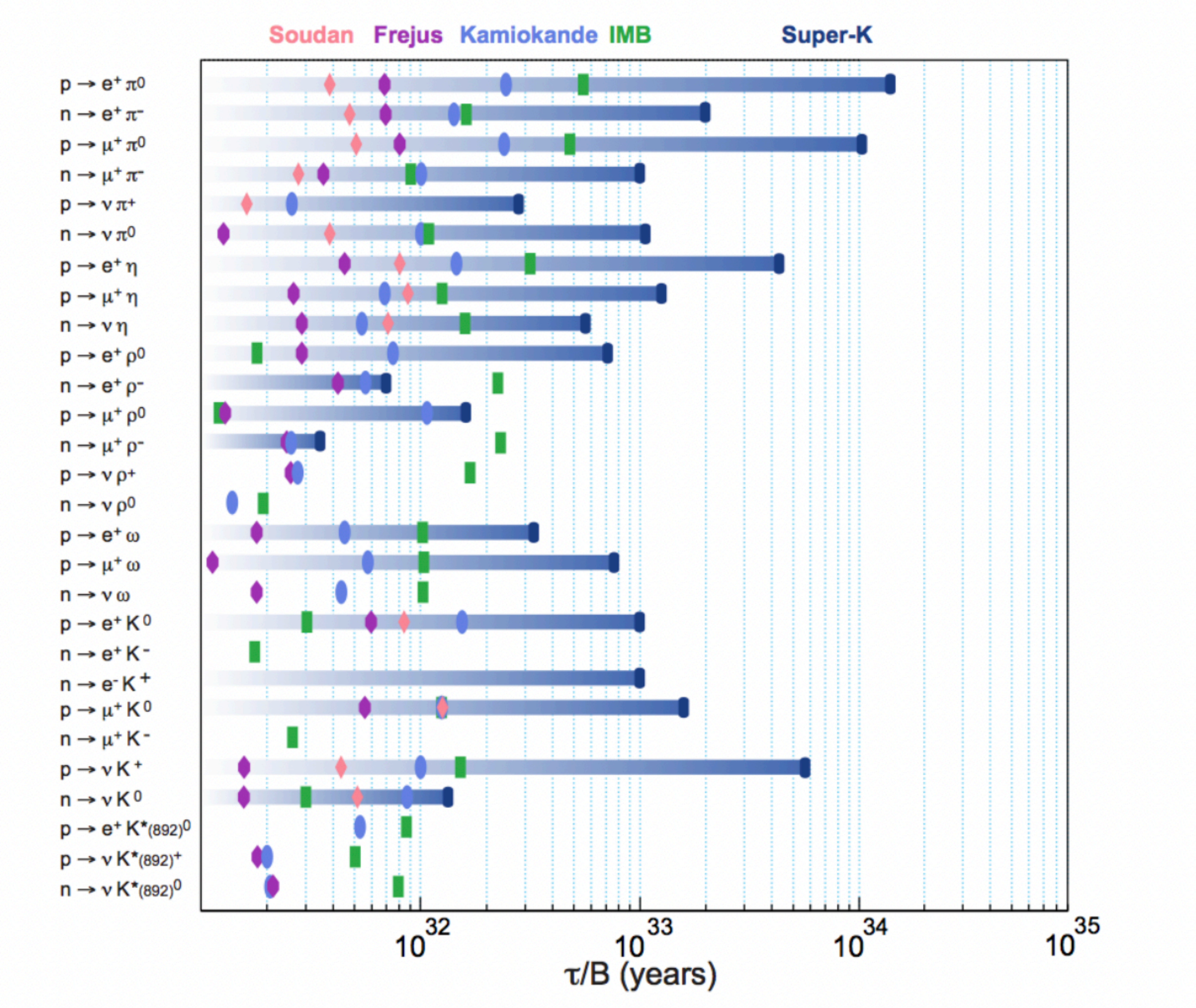
with QCD scale $m_{\text{QCD}} \approx 1$ GeV.[11] For $r \sim \mathcal{O}(1)$, the IND lifetime is

$$\tau(N \to K) \approx 10^{32}\,\text{yrs} \times \left(\frac{(\sigma v)_{\text{IND}}}{10^{-39}\,\text{cm/s}}\right)^{-1}\left(\frac{\rho_{\text{DM}}}{0.3\,\text{GeV/cm}^3}\right)^{-1} , \quad (56)$$

Backup slides



Backup slides



Backup slides

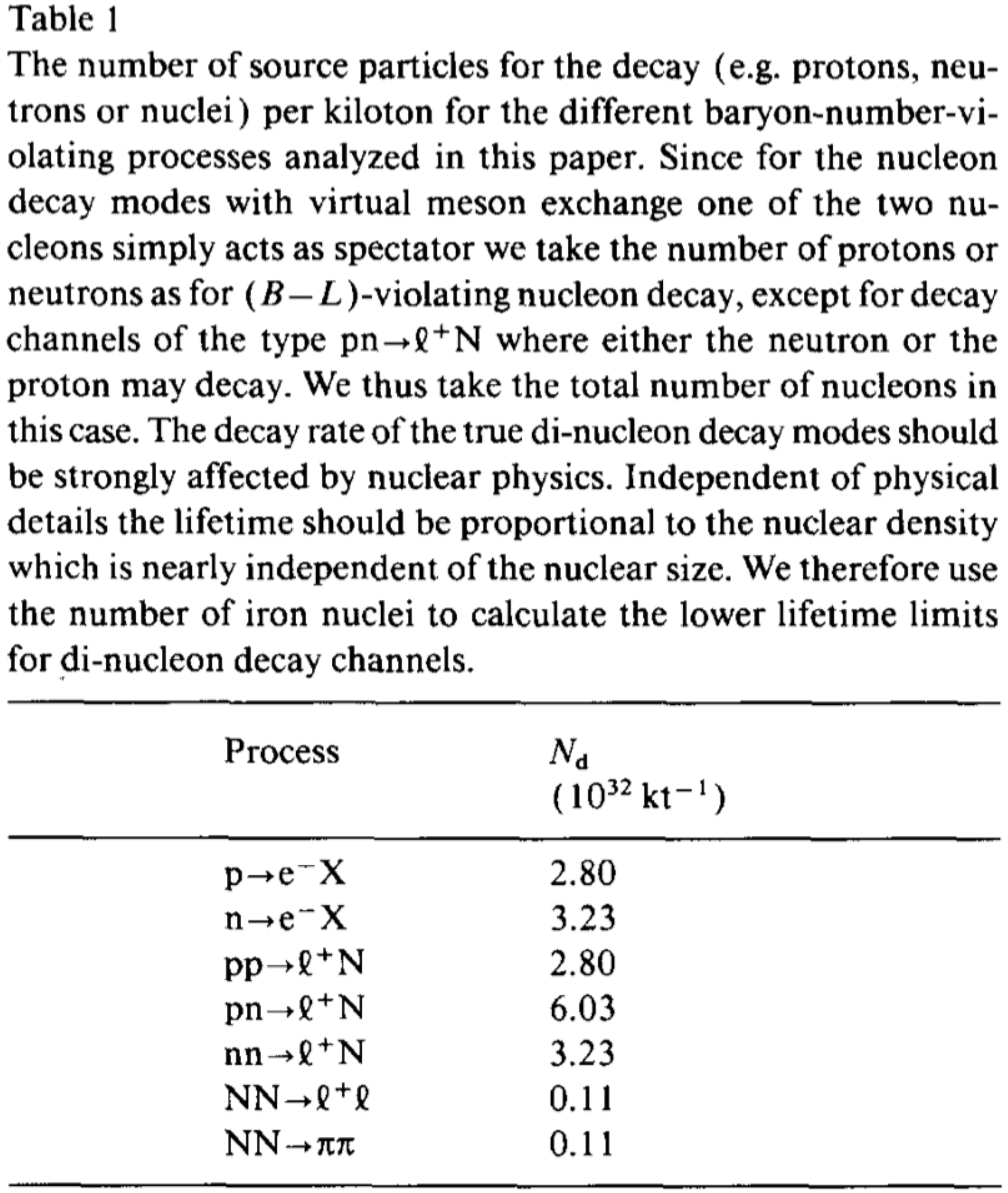
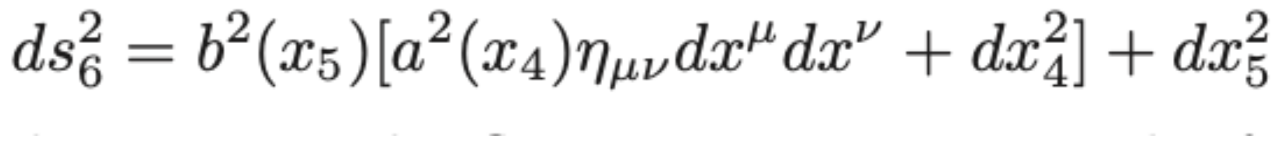


Table 1

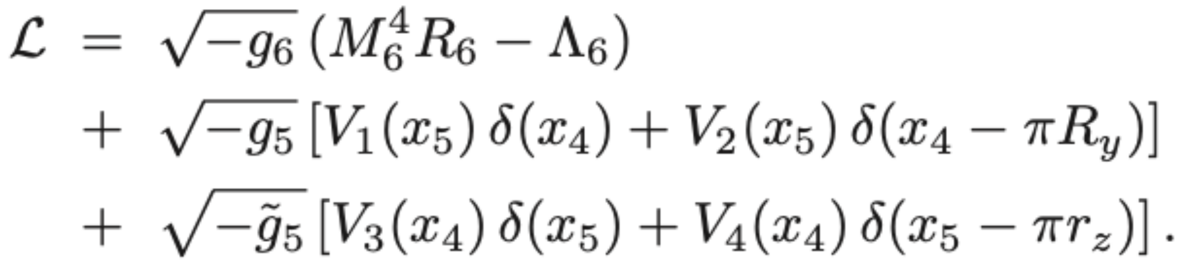
The number of source particles for the decay (e.g. protons, neutrons or nuclei) per kiloton for the different baryon-number-violating processes analyzed in this paper. Since for the nucleon decay modes with virtual meson exchange one of the two nucleons simply acts as spectator we take the number of protons or neutrons as for $(B-L)$-violating nucleon decay, except for decay channels of the type $pn \to \ell^+ N$ where either the neutron or the proton may decay. We thus take the total number of nucleons in this case. The decay rate of the true di-nucleon decay modes should be strongly affected by nuclear physics. Independent of physical details the lifetime should be proportional to the nuclear density which is nearly independent of the nuclear size. We therefore use the number of iron nuclei to calculate the lower lifetime limits for di-nucleon decay channels.

Process	N_d (10^{32} kt^{-1})
$p \to e^- X$	2.80
$n \to e^- X$	3.23
$pp \to \ell^+ N$	2.80
$pn \to \ell^+ N$	6.03
$nn \to \ell^+ N$	3.23
$NN \to \ell^+ \ell$	0.11
$NN \to \pi\pi$	0.11

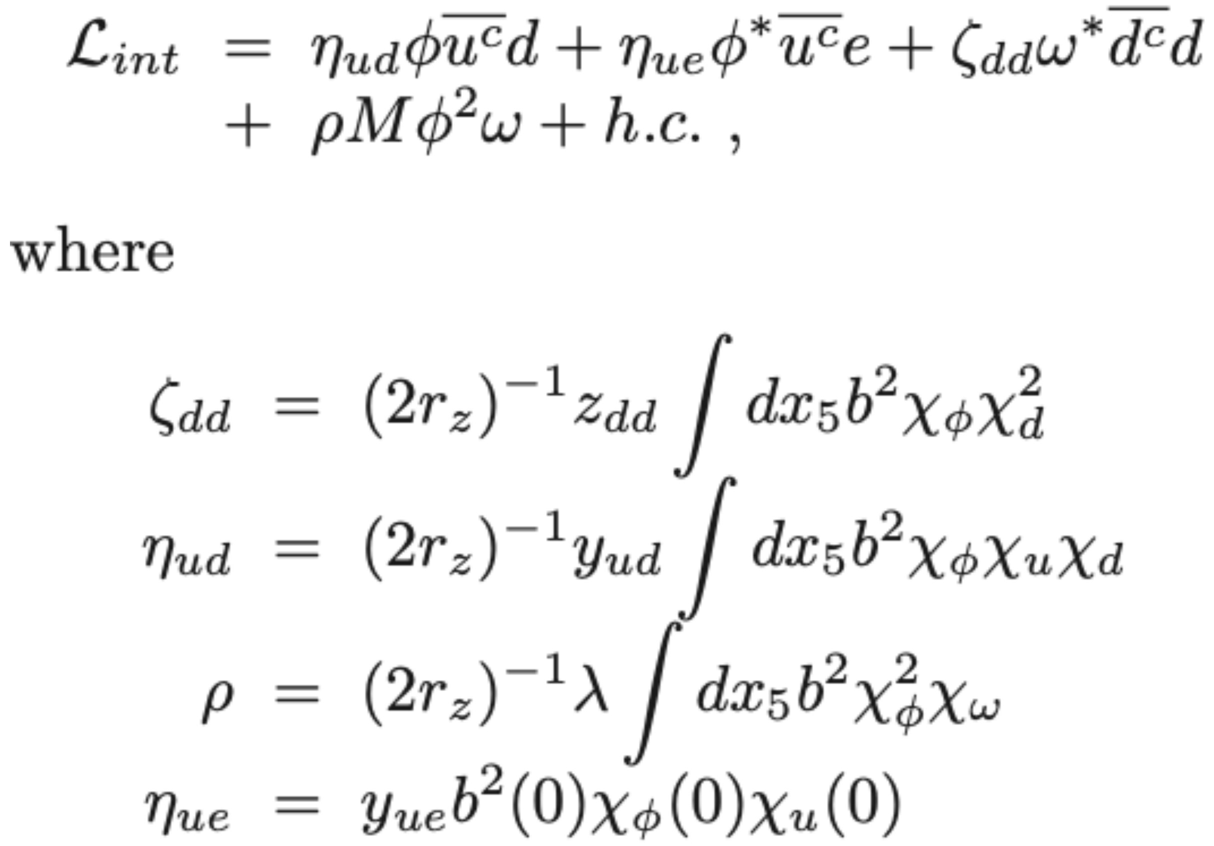
Backup slides (Neutron Oscillation and Baryogenesis from six dimensions)



$$ds_6^2 = b^2(x_5)[a^2(x_4)\eta_{\mu\nu}dx^\mu dx^\nu + dx_4^2] + dx_5^2$$



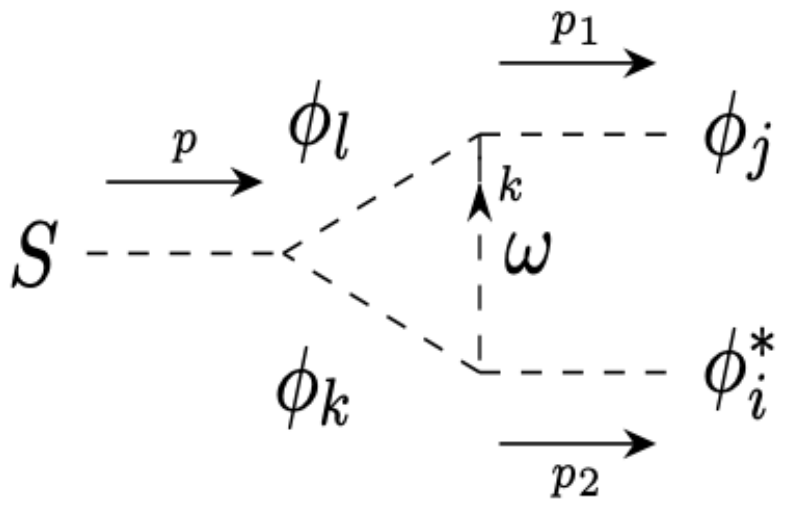
$$\begin{aligned}\mathcal{L} &= \sqrt{-g_6}\,(M_6^4 R_6 - \Lambda_6)\\ &+ \sqrt{-g_5}\,[V_1(x_5)\,\delta(x_4) + V_2(x_5)\,\delta(x_4 - \pi R_y)]\\ &+ \sqrt{-\tilde{g}_5}\,[V_3(x_4)\,\delta(x_5) + V_4(x_4)\,\delta(x_5 - \pi r_z)]\,.\end{aligned}$$

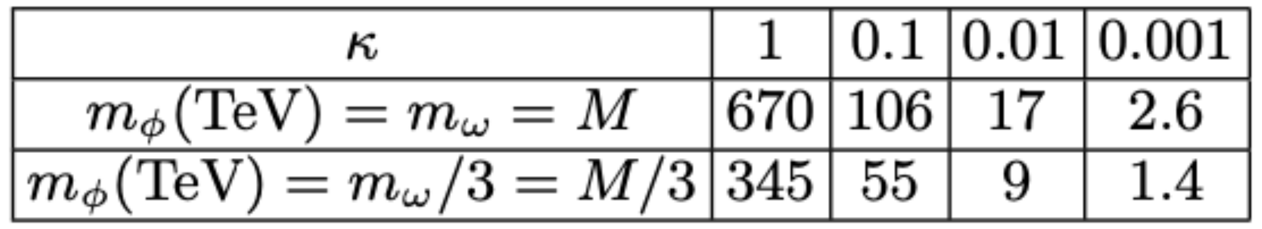


$$\begin{aligned}\mathcal{L}_{int} &= \eta_{ud}\phi\overline{u^c}d + \eta_{ue}\phi^*\overline{u^c}e + \zeta_{dd}\omega^*\overline{d^c}d\\ &+ \rho M\phi^2\omega + h.c.\ ,\end{aligned}$$

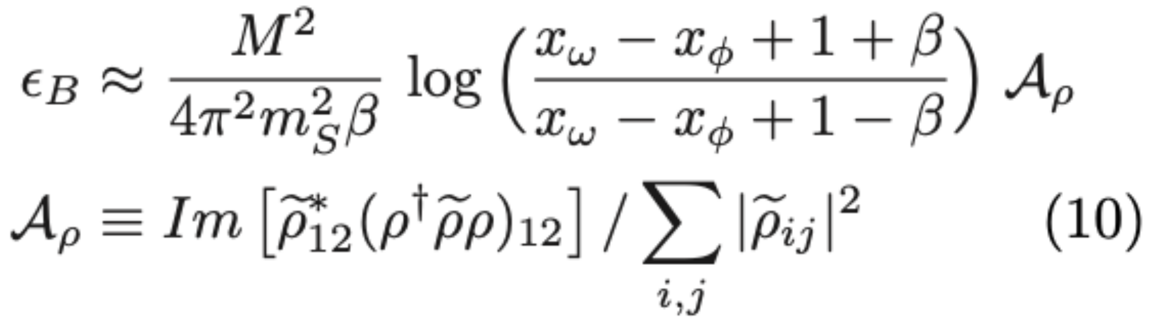
where

$$\begin{aligned}\zeta_{dd} &= (2r_z)^{-1}z_{dd}\int dx_5 b^2\chi_\phi\chi_d^2\\ \eta_{ud} &= (2r_z)^{-1}y_{ud}\int dx_5 b^2\chi_\phi\chi_u\chi_d\\ \rho &= (2r_z)^{-1}\lambda\int dx_5 b^2\chi_\phi^2\chi_\omega\\ \eta_{ue} &= y_{ue}b^2(0)\chi_\phi(0)\chi_u(0)\end{aligned}$$





κ	1	0.1	0.01	0.001
$m_\phi(\text{TeV}) = m_\omega = M$	670	106	17	2.6
$m_\phi(\text{TeV}) = m_\omega/3 = M/3$	345	55	9	1.4



$$\epsilon_B \approx \frac{M^2}{4\pi^2 m_S^2\beta}\log\left(\frac{x_\omega - x_\phi + 1 + \beta}{x_\omega - x_\phi + 1 - \beta}\right)\mathcal{A}_\rho$$

$$\mathcal{A}_\rho \equiv Im\left[\widetilde{\rho}_{12}^*(\rho^\dagger\widetilde{\rho}\rho)_{12}\right] / \sum_{i,j}|\widetilde{\rho}_{ij}|^2 \qquad (10)$$

Backup slides (Baryon number violation from confining New Physics)
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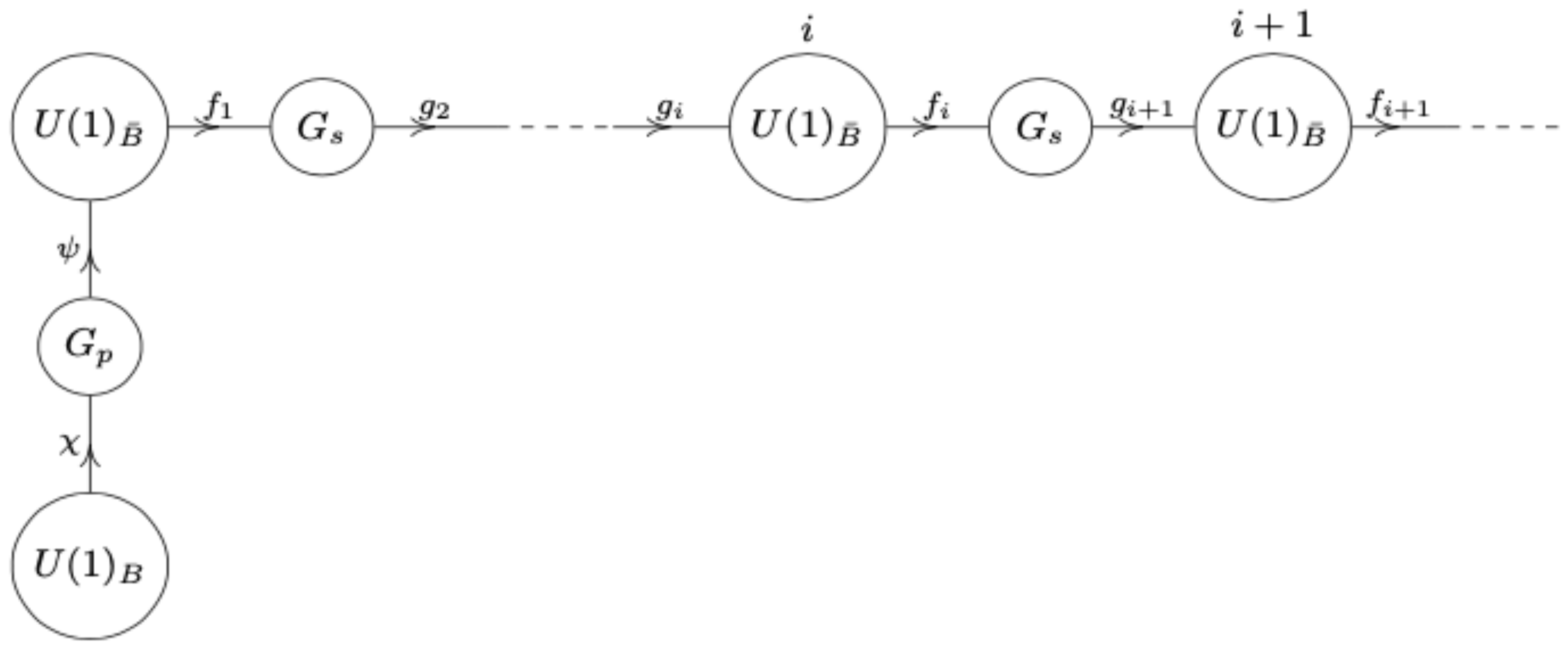

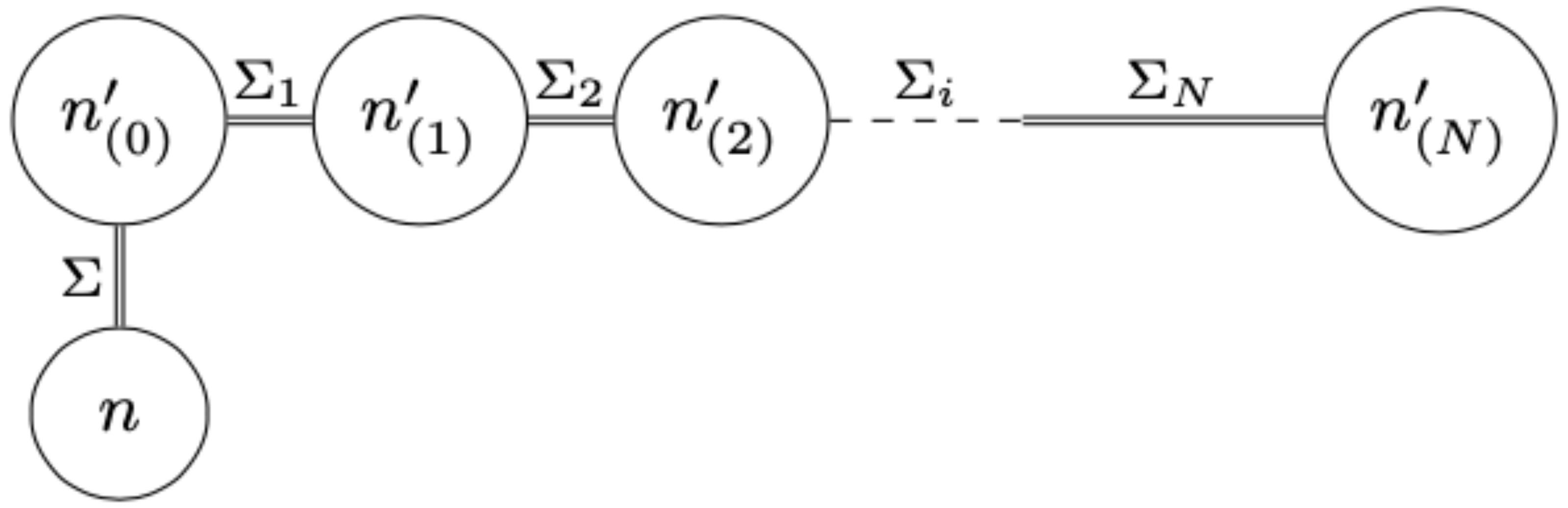

$$\mathcal{L} = i\bar{n}\gamma^{\mu}\partial_{\mu}n - \frac{m_n}{2}\left[\bar{n}n + \bar{n^c}n^c\right] - \frac{\epsilon}{2}\left[\bar{n^c}n + \bar{n}\bar{n^c}\right]$$

$$\begin{aligned}\mathcal{V}_n &= \sum_{i=1}^{N}\Big(M\ n'^{c}_{(i)}n'_{(i-1)} - m\ n'^{c}_{(i)}n'_{(i)}\Big) - yv\ \bar{n}\ \ n'_{(0)} \\ &+\ \mathcal{L}_{int}\ ,\end{aligned} \tag{6}$$

$$\langle\bar{n}|\mathcal{H}_{\Delta B=2}|n\rangle = -\frac{1}{2}\epsilon\ \nu^{T}_{\bar{n}}Cu_n$$

$$\begin{aligned}\mathcal{L} &= i\bar{n}\gamma^{\mu}\partial_{\mu}n - \frac{m_n}{2}\left[\bar{n}n + \bar{n^c}n^c\right] - \frac{(y_{eff}v)^2}{m_M}\bar{n^c}n \\ &+\ \mathcal{L}_{int} + h.c.\ .\end{aligned} \tag{10}$$

$$\begin{aligned}\sigma_{n^0\mathcal{N}} &= |C_{nn'}|^2|\langle n^0\mathcal{N}|(\bar{n^0}n)(\bar{q}q)|n\mathcal{N}\rangle|^2 \\ &\sim |C_{nn'}m_{\mathcal{N}}^2\sum_{q=u,d,s}f_q|^2\sigma_{n\mathcal{N}}\ ,\end{aligned}$$