Searching for nucleon decays with JUNO
JUNO实验寻找核子衰变的潜力

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第三届“江门中微子实验相关的理论与唯象学”研讨会——大统一专题

Outline

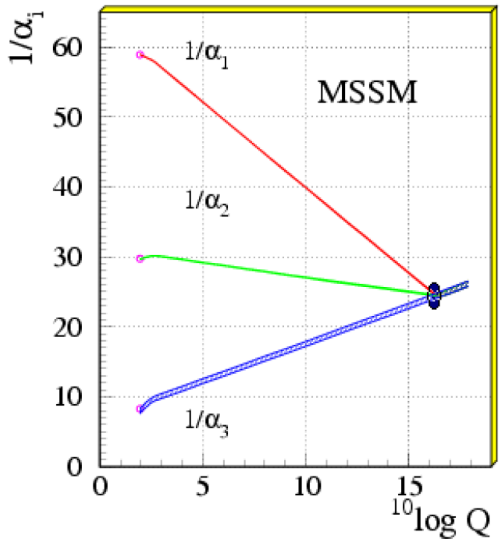
1. GUTs and Nucleon Decays
2. Nucleon decay experiments
3. JUNO potential to Nucleon decays
4. Search for other new physics

(1) Grand United Theories (GUT) and Nucleon Decays

(1) GUTs and Nucleon Decays

Grand United Theories (GUTs):

1. A larger symmetry group, e.g. SU(5) ,SO(10), SUSY SU(5)…
2. Spontaneously breaks into the SM group: SU(3)⊗SU(2)⊗U(1).
3. Unify the strong, weak and electromagnetic interactions.



Consequences:

- Single (unified) coupling
- Charge quantization
- New gauge bosons → Baryon number violation
- → **Proton decay, B-violation neutron decay**
- B-violation is one of three Sakharov basic ingredients
- Massive neutrinos from SO(10)…
- Other predictions: **Magnetic Monopoles** …

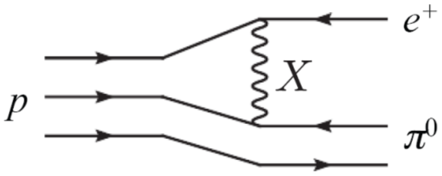
How to test GUTs?

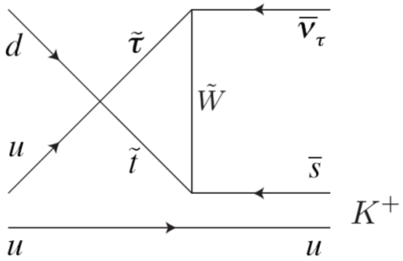
Theoretic predictions and current limits

Two favorite decay channels:

$p \rightarrow e^{+}\pi^{0}$

Non-SUSY GUTs

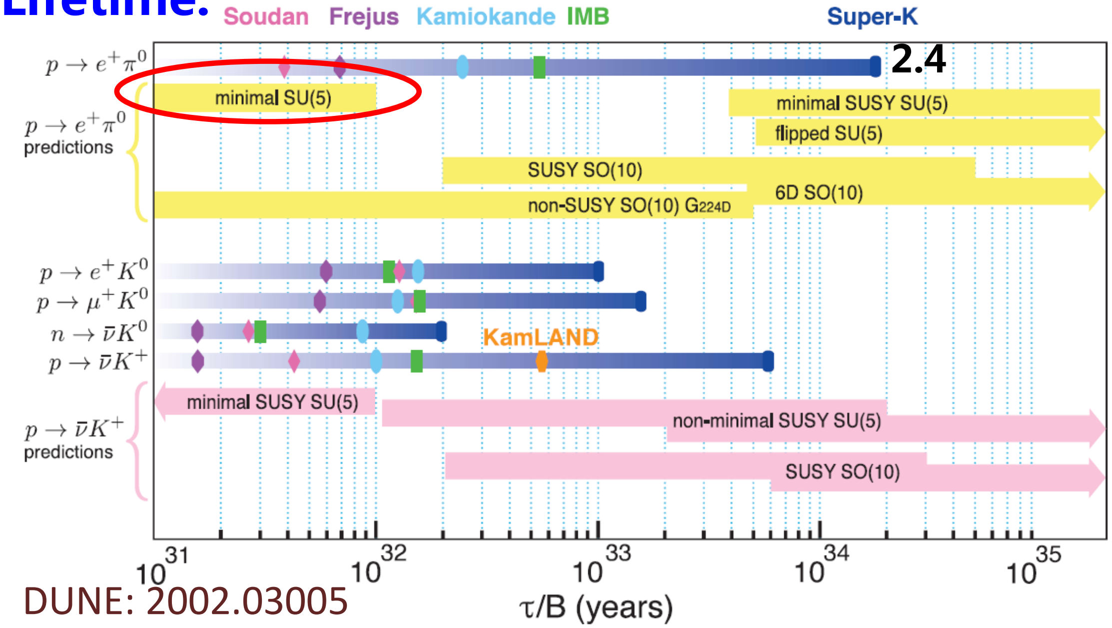




$p \rightarrow \overline{\nu}\, K^{+}$

SUSY GUTs

Lifetime:



DUNE: 2002.03005

Branching Ratios:

	Br.(%)				
	SU(5)				SO(10)
References	[72]	[73]	[74]	[75]	[75]
$p \to e^+\pi^0$	33	37	9	35	30
$p \to e^+\eta^0$	12	7	3	15	13
$p \to e^+\rho^0$	17	2	21	2	2
$p \to e^+\omega^0$	22	18	56	17	14
Others	17	35	11	31	31
τ_p/τ_n	0.8	1.0	1.3		

Hyper-K:1109.3262

How many Nucleon decay channels have been measured?

Mode		Partial mean life (10^{30} years)	Scale Factor/ Conf. Level	P(MeV/c)
Antilepton + meson				
τ_1 $N \to e^+\pi$	B	> 5300 (n), > 16000 (p)	CL=90%	459
τ_2 $N \to \mu^+\pi$	B	> 3500 (n), > 7700 (p)	CL=90%	453
τ_3 $N \to \nu\pi$		> 1100 (n), > 390 (p)	CL=90%	459
τ_4 $p \to e^+\eta$		> 10000	CL=90%	309
τ_5 $p \to \mu^+\eta$		> 4700	CL=90%	297
τ_6 $n \to \nu\eta$		> 158	CL=90%	310
τ_7 $N \to e^+\rho$		> 217 (n), > 720 (p)	CL=90%	149
τ_8 $N \to \mu^+\rho$		> 228 (n), > 570 (p)	CL=90%	113
τ_9 $N \to \nu\rho$		> 19 (n), > 162 (p)	CL=90%	149
τ_{10} $p \to e^+\omega$		> 1600	CL=90%	143
τ_{11} $p \to \mu^+\omega$		> 2800	CL=90%	105
τ_{12} $n \to \nu\omega$		> 108	CL=90%	144
τ_{13} $N \to e^+K$	B	> 17 (n), > 1000 (p)	CL=90%	339
τ_{14} $p \to e^+K^0_S$				337
τ_{15} $p \to e^+K^0_L$				337
τ_{16} $N \to \mu^+K$	B	> 26 (n), > 1600 (p)	CL=90%	329
τ_{17} $p \to \mu^+K^0_S$				326
τ_{18} $p \to \mu^+K^0_L$				326
τ_{19} $N \to \nu K$		> 86 (n), > 5900 (p)	CL=90%	339
τ_{20} $n \to \nu K^0_S$		> 260	CL=90%	338
τ_{21} $p \to e^+K^*(892)^0$		> 84	CL=90%	45
τ_{22} $N \to \nu K^*(892)$		> 78 (n), > 51 (p)	CL=90%	45
Antilepton + mesons				
τ_{23} $p \to e^+\pi^+\pi^-$		> 82	CL=90%	448
τ_{24} $p \to e^+\pi^0\pi^0$		> 147	CL=90%	449
τ_{25} $n \to e^+\pi^-\pi^0$		> 52	CL=90%	449
τ_{26} $p \to \mu^+\pi^+\pi^-$		> 133	CL=90%	425
τ_{27} $p \to \mu^+\pi^0\pi^0$		> 101	CL=90%	427
τ_{28} $n \to \mu^+\pi^-\pi^0$		> 74	CL=90%	427
τ_{29} $n \to e^+K^0\pi^-$		> 18	CL=90%	319
Lepton + meson				
τ_{30} $n \to e^-\pi^+$		> 65	CL=90%	459
τ_{31} $n \to \mu^-\pi^+$		> 49	CL=90%	453
τ_{32} $n \to e^-\rho^+$		> 62	CL=90%	150
τ_{33} $n \to \mu^-\rho^+$		> 7	CL=90%	115
τ_{34} $n \to e^-K^+$		> 32	CL=90%	340
τ_{35} $n \to \mu^-K^+$		> 57	CL=90%	330
Lepton + mesons				
τ_{36} $p \to e^-\pi^+\pi^+$		> 30	CL=90%	448
τ_{37} $n \to e^-\pi^+\pi^0$		> 29	CL=90%	449
τ_{38} $p \to \mu^-\pi^+\pi^+$		> 17	CL=90%	425
τ_{39} $n \to \mu^-\pi^+\pi^0$		> 34	CL=90%	427
τ_{40} $p \to e^-\pi^+K^+$		> 75	CL=90%	320
τ_{41} $p \to \mu^-\pi^+K^+$		> 245	CL=90%	279
Antilepton + photon(s)				
τ_{42} $p \to e^+\gamma$		> 670	CL=90%	469
τ_{43} $p \to \mu^+\gamma$		> 478	CL=90%	463
τ_{44} $n \to \nu\gamma$		> 550	CL=90%	470
τ_{45} $p \to e^+\gamma\gamma$		> 100	CL=90%	469
τ_{46} $n \to \nu\gamma\gamma$		> 219	CL=90%	470
Antilepton + single massless				
τ_{47} $p \to e^+X$		> 790	CL=90%	
τ_{48} $p \to \mu^+X$		> 410	CL=90%	
Three (or more) leptons				
τ_{49} $p \to e^+e^+e^-$		> 793	CL=90%	469
τ_{50} $p \to e^+\mu^+\mu^-$		> 359	CL=90%	457
τ_{51} $p \to e^+\nu\nu$		> 170	CL=90%	469
τ_{52} $n \to e^+e^-\nu$		> 257	CL=90%	470
τ_{53} $n \to \mu^+e^-\nu$		> 83	CL=90%	464
τ_{54} $n \to \mu^+\mu^-\nu$		> 79	CL=90%	458
τ_{55} $p \to \mu^+e^+e^-$		> 529	CL=90%	463
τ_{56} $p \to \mu^-e^+e^+$		$> 1.90 \times 10^{+4}$	CL=90%	463
τ_{57} $p \to \mu^+\mu^+\mu^-$		> 675	CL=90%	439
τ_{58} $p \to \mu^+\nu\nu$		> 220	CL=90%	463
τ_{59} $p \to e^-\mu^+\mu^+$		> 6	CL=90%	457
τ_{60} $n \to 3\,\nu$		$> 5 \times 10^{-4}$	CL=90%	470
τ_{61} $n \to 5\,\nu$				470
Inclusive modes				
τ_{62} $N \to e^+$ anything		> 0.6 (n, p)	CL=90%	
τ_{63} $N \to \mu^+$ anything		> 12 (n, p)	CL=90%	
τ_{64} $N \to \nu$ anything				
τ_{65} $N \to e^+\pi^0$ anything		> 0.6 (n, p)	CL=90%	
τ_{66} $N \to$ 2 bodies, ν-free				
$\Delta B = 2$ dinucleon modes				
τ_{67} $p\,p \to \pi^+\pi^+$		> 72.2	CL=90%	
τ_{68} $p\,n \to \pi^+\pi^0$		> 170	CL=90%	
τ_{69} $n\,n \to \pi^+\pi^-$		> 0.7	CL=90%	
τ_{70} $n\,n \to \pi^0\pi^0$		> 404	CL=90%	
τ_{71} $p\,p \to K^+K^+$		> 170	CL=90%	
τ_{72} $p\,p \to e^+e^+$		> 5.8	CL=90%	
τ_{73} $p\,p \to e^+\mu^+$		> 3.6	CL=90%	
τ_{74} $p\,p \to \mu^+\mu^+$		> 1.7	CL=90%	
τ_{75} $p\,n \to e^+\bar{\nu}$		> 260	CL=90%	
τ_{76} $p\,n \to \mu^+\bar{\nu}$		> 200	CL=90%	
τ_{77} $p\,n \to \tau^+\bar{\nu}_\tau$		> 29	CL=90%	
τ_{78} $n\,n \to$ invisible		> 1.4	CL=90%	
τ_{79} $n\,n \to \nu_e\bar{\nu}_e$		> 1.4	CL=90%	
τ_{80} $n\,n \to \nu_\mu\bar{\nu}_\mu$		> 1.4	CL=90%	
τ_{81} $p\,n \to$ invisible		> 0.06	CL=90%	
τ_{82} $p\,p \to$ invisible		> 0.11	CL=90%	

From PDG 2023

Total Channels: 82

Mesons: $\pi^\pm, \pi^0, K^\pm, K^0,\ \eta,\ \rho,\ \omega,\ K^*(892)$;

Leptons: $e^\pm, \mu^\pm, \nu$; **Photon:** γ

Are there other interesting channels?

Are there other nucleon decay channels ?

Proton 3-body:

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$p \to e^- + e^+ + e^+$	0	793 [46]
$p \to e^- + e^+ + \mu^+$	0	529 [46]
$p \to e^+ + e^+ + \mu^-$	0	529* [46]
$p \to e^- + \mu^+ + \mu^+$	0	6 [73] (359* [46])
$p \to e^+ + \mu^- + \mu^+$	0	359 [46]
$p \to \mu^- + \mu^+ + \mu^+$	0	675 [46]
$p \to e^+ + 2\nu$	0,2	170 [81]
$p \to \mu^+ + 2\nu$	0,2	220 [81]
$p \to e^- + 2\pi^+$	2	30 [52] (82* [46])
$p \to e^- + \pi^+ + \rho^+$	2	
$p \to e^- + K^+ + \pi^+$	2	75 [46]
$p \to e^+ + 2\gamma$	0	100 [82] (793* [46])
$p \to e^+ + \pi^- + \pi^+$	0	82 [46]
$p \to e^+ + \rho^- + \pi^+$	0	
$p \to e^+ + K^- + \pi^+$	0	75* [46]
$p \to e^+ + \pi^- + \rho^+$	0	
$p \to e^+ + \pi^- + K^+$	0	75* [46]
$p \to e^+ + 2\pi^0$	0	147 [46]
$p \to e^+ + \pi^0 + \eta$	0	
$p \to e^+ + \pi^0 + \rho^0$	0	
$p \to e^+ + \pi^0 + \omega$	0	
$p \to e^+ + \pi^0 + K^0$	0	
$p \to \mu^- + 2\pi^+$	2	17 [52] (133* [46])
$p \to \mu^- + K^+ + \pi^+$	2	245 [46]
$p \to \mu^+ + 2\gamma$	0	529* [46]
$p \to \mu^+ + \pi^- + \pi^+$	0	133 [46]
$p \to \mu^+ + K^- + \pi^+$	0	245* [46]
$p \to \mu^+ + \pi^- + K^+$	0	245* [46]
$p \to \mu^+ + 2\pi^0$	0	101 [46]
$p \to \mu^+ + \pi^0 + \eta$	0	
$p \to \mu^+ + \pi^0 + K^0$	0	
$p \to \nu + \pi^+ + \pi^0$	0,2	
$p \to \nu + \pi^+ + \eta$	0,2	
$p \to \nu + \pi^+ + \rho^0$	0,2	
$p \to \nu + \pi^+ + \omega$	0,2	
$p \to \nu + \pi^+ + K^0$	0,2	
$p \to \nu + \rho^+ + \pi^0$	0,2	
$p \to \nu + K^+ + \pi^0$	0,2	

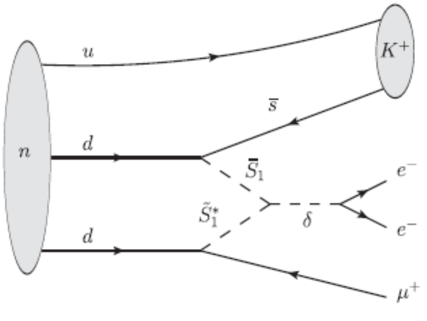
Neutron 3-body:

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$n \to \nu + e^- + e^+$	0,2	257 [46]
$n \to \nu + e^- + \mu^+$	0,2	83 [46]
$n \to \nu + e^+ + \mu^-$	0,2	83* [46]
$n \to \nu + \mu^- + \mu^+$	0,2	79 [46]
$n \to 3\nu$	0,2,4	0.58 [83]
$n \to e^- + \pi^+ + \pi^0$	2	29 [52] (52* [46])
$n \to e^- + \pi^+ + \eta$	2	
$n \to e^- + \pi^+ + \rho^0$	2	
$n \to e^- + \pi^+ + \omega$	2	
$n \to e^- + \pi^+ + K^0$	2	
$n \to e^- + \rho^+ + \pi^0$	2	
$n \to e^- + K^+ + \pi^0$	2	
$n \to e^+ + \pi^- + \pi^0$	0	52 [46]
$n \to e^+ + \pi^- + \eta$	0	
$n \to e^+ + \pi^- + \rho^0$	0	
$n \to e^+ + \pi^- + \omega$	0	
$n \to e^+ + \pi^- + K^0$	0	18 [82]
$n \to e^+ + \rho^- + \pi^0$	0	
$n \to e^+ + K^- + \pi^0$	0	
$n \to \mu^- + \pi^+ + \pi^0$	2	34 [52] (74* [46])
$n \to \mu^- + \pi^+ + \eta$	2	
$n \to \mu^- + \pi^+ + K^0$	2	
$n \to \mu^- + K^+ + \pi^0$	2	
$n \to \mu^+ + \pi^- + \pi^0$	0	74 [46]
$n \to \mu^+ + \pi^- + \eta$	0	
$n \to \mu^+ + \pi^- + K^0$	0	
$n \to \mu^+ + K^- + \pi^0$	0	
$n \to \nu + 2\gamma$	0,2	219 [46]
$n \to \nu + \pi^- + \pi^+$	0,2	
$n \to \nu + \rho^- + \pi^+$	0,2	
$n \to \nu + K^- + \pi^+$	0,2	
$n \to \nu + \pi^- + \rho^+$	0,2	
$n \to \nu + \pi^- + K^+$	0,2	
$n \to \nu + 2\pi^0$	0,2	
$n \to \nu + \pi^0 + \eta$	0,2	
$n \to \nu + \pi^0 + \rho^0$	0,2	
$n \to \nu + \pi^0 + \omega$	0,2	
$n \to \nu + \pi^0 + K^0$	0,2	

Dinucleon decay:

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$nn \to \pi^0 + \phi$	2	
$nn \to 2\eta$	2	
$nn \to \eta + \rho^0$	2	
$nn \to \eta + \omega$	2	
$nn \to \eta + \eta'$	2	
$nn \to \eta + K^0$	2	
$nn \to \eta + K^{*,0}$	2	
$nn \to \eta + \phi$	2	
$nn \to 2\rho^0$	2	
$nn \to \rho^0 + \omega$	2	
$nn \to \eta' + \rho^0$	2	
$nn \to K^0 + \rho^0$	2	
$nn \to K^{*,0} + \rho^0$	2	
$nn \to \rho^0 + \phi$	2	
$nn \to \rho^- + \rho^+$	2	
$nn \to K^+ + \rho^-$	2	
$nn \to K^{*,+} + \rho^-$	2	
$nn \to K^- + \rho^+$	2	
$nn \to K^{*,-} + \rho^+$	2	
$nn \to 2\omega$	2	
$nn \to \eta' + \omega$	2	
$nn \to K^0 + \omega$	2	
$nn \to K^{*,0} + \omega$	2	
$nn \to \omega + \phi$	2	
$nn \to \eta' + K^0$	2	
$nn \to \eta' + K^{*,0}$	2	
$nn \to K^- + K^+$	2	170* [116]
$nn \to K^+ + K^{*,-}$	2	
$nn \to K^- + K^{*,+}$	2	
$nn \to 2K^0$	2	
$nn \to K^{*,0} + K^0$	2	
$nn \to K^0 + \phi$	2	
$nn \to 2K^{*,0}$	2	
$nn \to K^{*,-} + K^{*,+}$	2	

4-body decay:



From PRD 101, 015005 (2020)

Others?

(2) Nucleon decay experiments

Experimental tests of nucleon decays before GUTs

- In 1954, Reines, Cowan and Goldhaber give the first limit: $\tau(p) > 10^{22}$ yrs
- Before the discovery of $\bar{\nu}_e$ in 1956.

Phys. Rev.96, 1157 (1954)

Authors	Experiment	Decay mode	Depth (mwe)	τ_{min} (yrs)
Reines, Cowan, and Goldhaber 1954 [4]	300 ℓ liquid scint.	All (E_{ch} > 100 MeV)	200	10^{22}
Reines, Cowan and Kruse 1958 [49]	As above, with delayed neutron pulse	All	200	$4 \cdot 10^{23}$
Backenstoss et al. 1960 [8]	50 ℓ liquid Cerenkov, upward rel. sec.	At least one secondary of > 250 MeV	2400	$3 \cdot 10^{26}$
Giamati and Reines 1962 [50] Kropp and Reines 1965 [51]	200 ℓ liquid scint.	All	1760	$6 \cdot 10^{27}$ $\sim 10^{28}$
Gurr et al. 1967 [52]	Scint. hodoscope	All	8000	$2 \cdot 10^{28}$

D.H Perkins, 1984

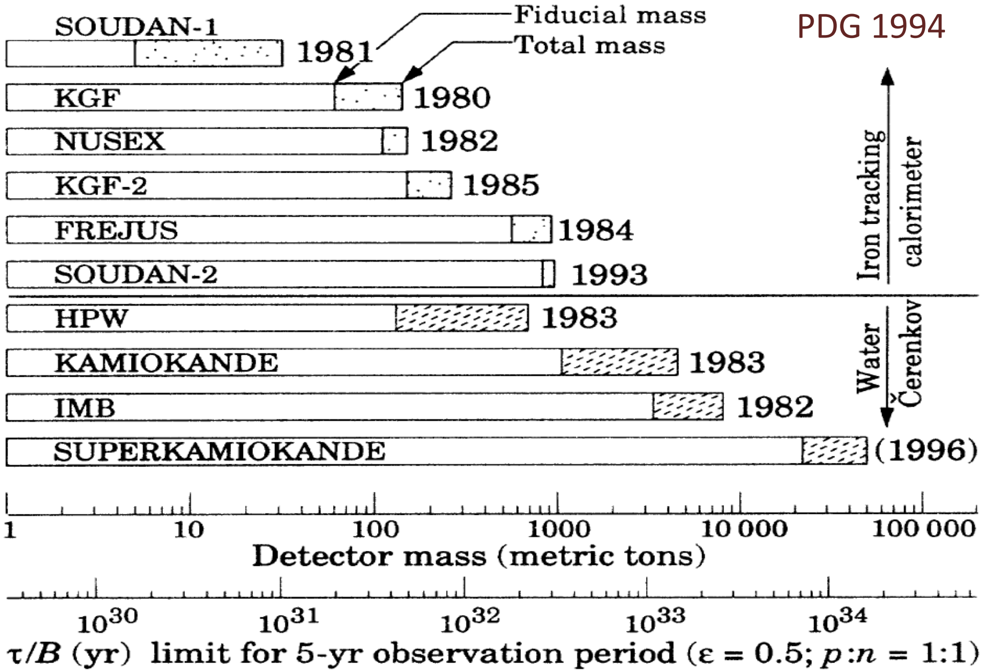
First generation of proton decay experiments

In 1974, Georgi and Glashow give SU(5) GUT, ➔ proton lifetime $\sim 10^{29}$ yrs

➔ Detector with about 1000 ton mass can test the SU(5) GUT

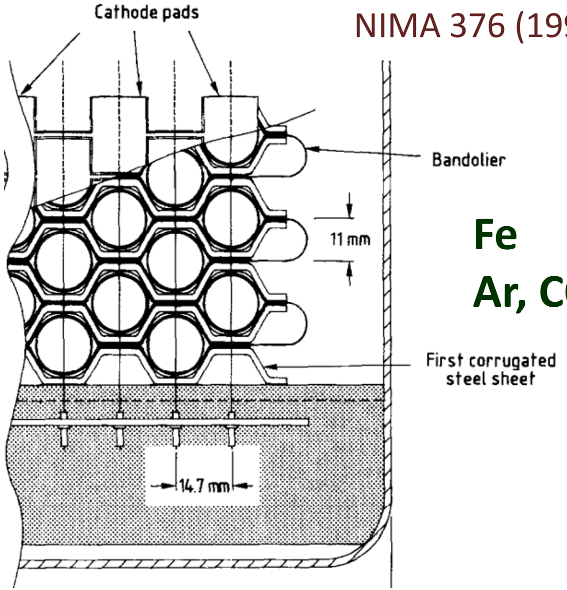
➔ The first generation of experiments are proposed and constructed

PDG 1994



SOUDAN-2 Iron tracking claorimeter

NIMA 376 (1996) 36

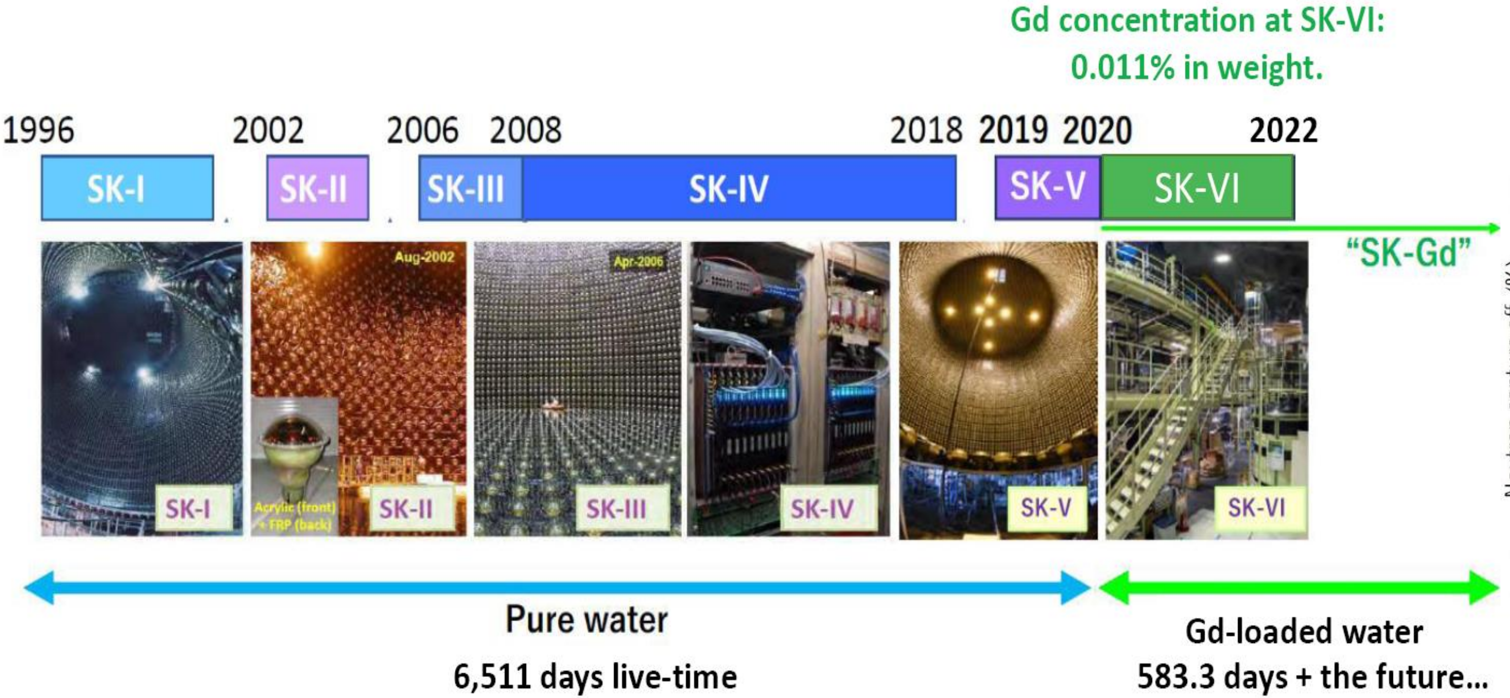


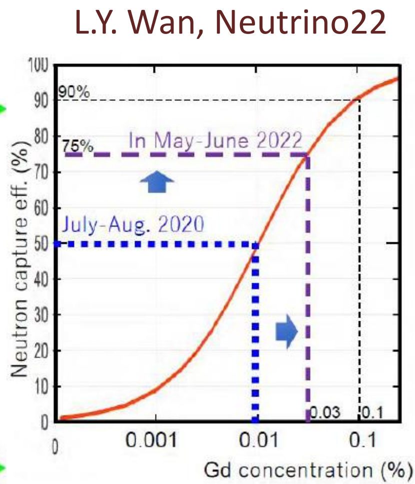
Fe

Ar, CO_2

They do not find the evidence for proton decay, excluding minimal SU(5)!

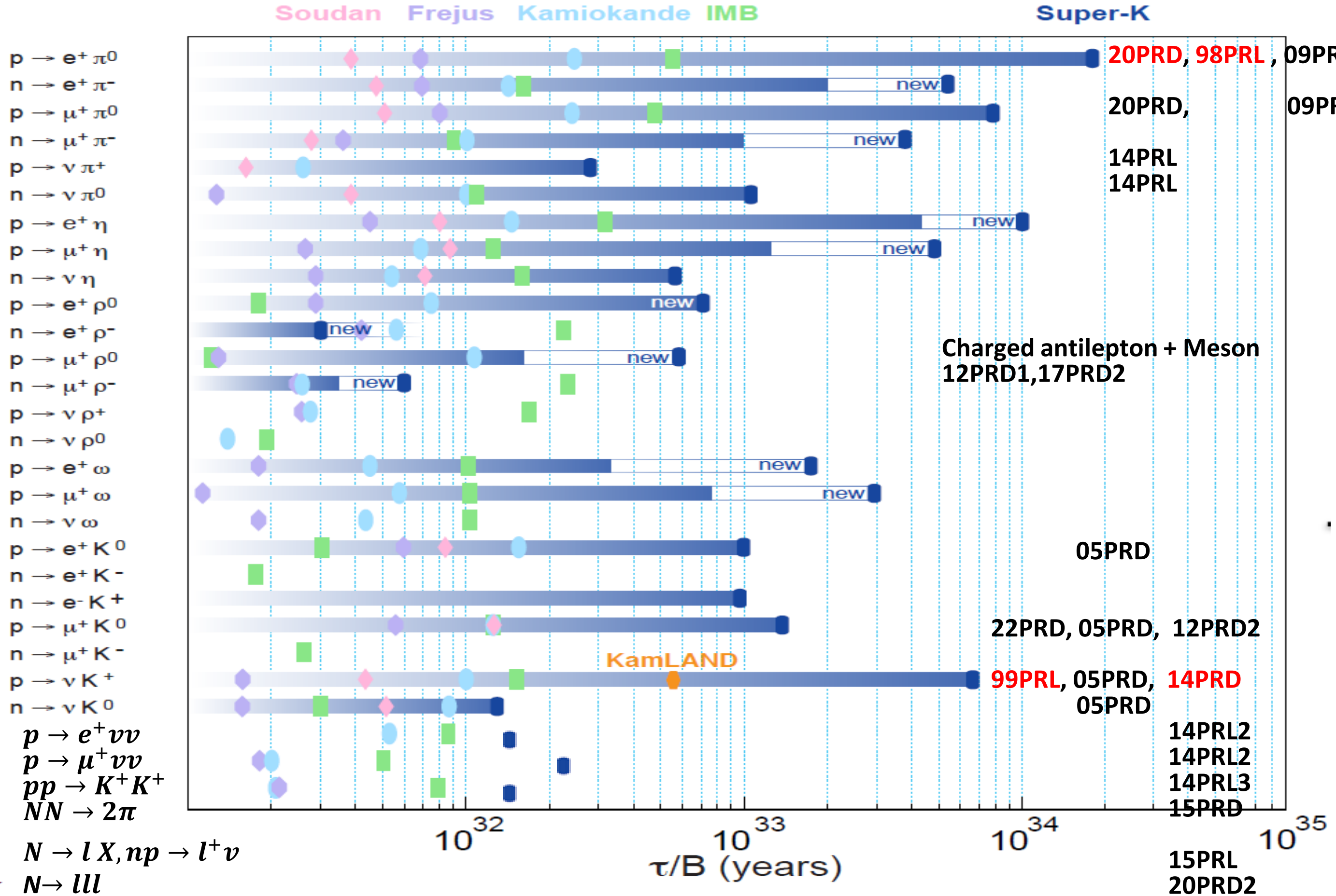
Super-Kamiokande: Water Cerenkov, 50 kton → 22.5 kton





After 2000, some neutrino experiments, such as KamLAND, SNO and Borexino, have also give several limits on nucleon decays.

Super-K results on nucleon decays



$p \to e^+ \nu\nu$

$p \to \mu^+ \nu\nu$

$pp \to K^+ K^+$

$NN \to 2\pi$

$N \to l\,X, np \to l^+\nu$

$N \to lll$

20PRD, 98PRL , 09PRL,17PRD

20PRD, 09PRL,17PRD

14PRL

14PRL

Charged antilepton + Meson
12PRD1,17PRD2

05PRD

22PRD, 05PRD, 12PRD2

99PRL, 05PRD, 14PRD

05PRD

14PRL2

14PRL2

14PRL3

15PRD

15PRL

20PRD2

38 decay modes:

N: 31; NN: 7

17 paper:

7 PRL, 10 PRD

Most after 2012

Cites:

98PRL：208

17PRD: 304

20PRD: 80

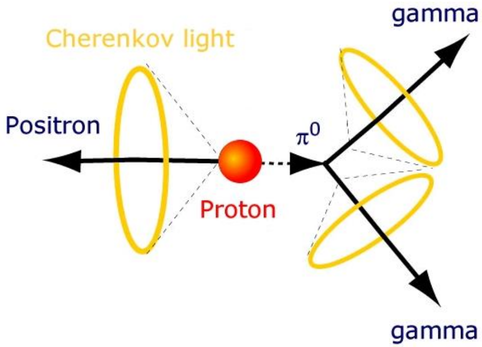
99PRL：201

14PRD: 212

Super-K searching for $p \to e^+\pi^0$

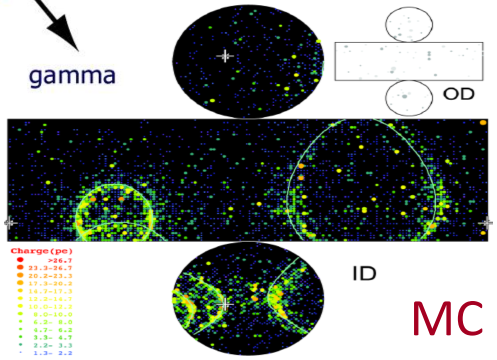
Signal features:

- Momentum of e^+ and π^0 is 460 MeV
- Kinetic energy :459 MeV and 344 MeV



Event selection:

A. Two or three rings
B. e-like rings
C. Invariant mass of π^0 (135MeV) : 85-185MeV
D. No Michel electron
E. $\vec{P}_{tot}$ (<250MeV) and M_{invar}(800-1050 MeV)



MC

Results:

450 kton years
Efficiency: ~20%
Background: ~0.6

$$\tau/B(p \to e^+\pi^0) > 2.4 \times 10^{34}\ \mathrm{yrs}$$

$\nu N \longrightarrow \ell N' \pi^0$
$\nu N \longrightarrow \nu N' \pi($

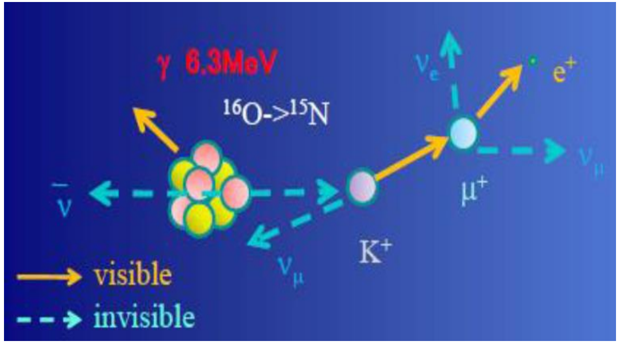
PRD 102, 112011 (2020)

Super-K searching for $p \to \overline{\nu} K^+$

Signal features:

- Momentum of $\overline{\nu}$ and K^+ is 339 MeV (105 MeV)
- 89% K^+ decay at rest (12.38ns):

  $K^+ \to \mu^+ \nu_\mu (63.43\%)$, $K^+ \to \pi^+ \pi^0 (21.13\%)$,



Event selection:

1: $K^+ \to \mu^+ \nu_\mu$ $\to$ $\gamma(6.3\text{MeV}, 41\%)$ from $^{16}\text{O} + \mu^+ +$ Michel e^+

2: $K^+ \to \mu^+ \nu_\mu$ $\to$ Monoenergetic μ^+ (p = 236MeV)

3: $K^+ \to \pi^+ \pi^0$ $\to$ two rings from π^0 (M_{inv}, p)+ π^+(direction , e^+)

$\nu\, p \to \nu\, K^+ \Lambda$ (48%),
ν_μ CCQE (25%),

CC 1π^0 with μ (38%),
kaon production (37%),
NC multi-π(11%)

Results:

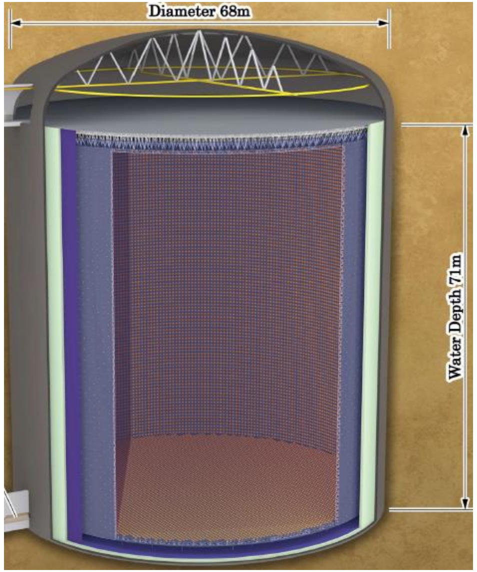
260 kton years
Efficiency: ~8.4%, 9%
Background:~ 0.24, 0.45

$\tau / B(p \to \overline{\nu}\, K^+) > 5.9 \times 10^{33}$ yrs

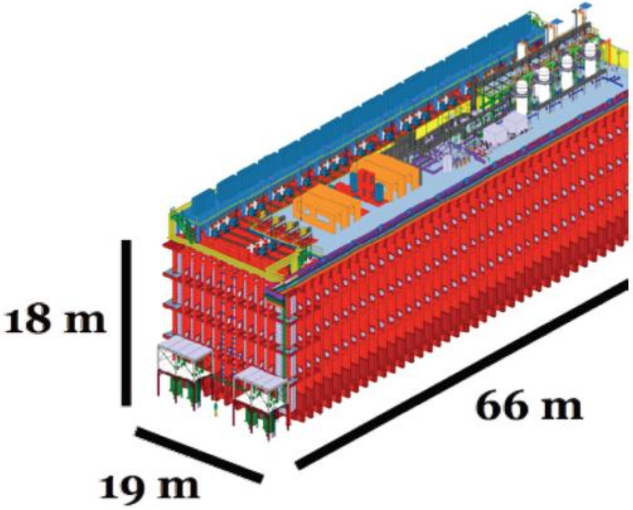
PRD 90, 072005 (2014)

Future Nucleon Decay Experiments

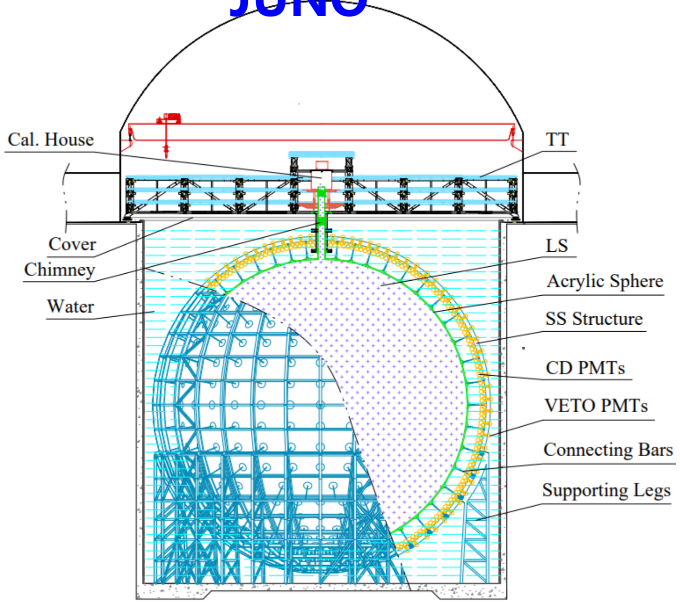
Hyper-K



DUNE



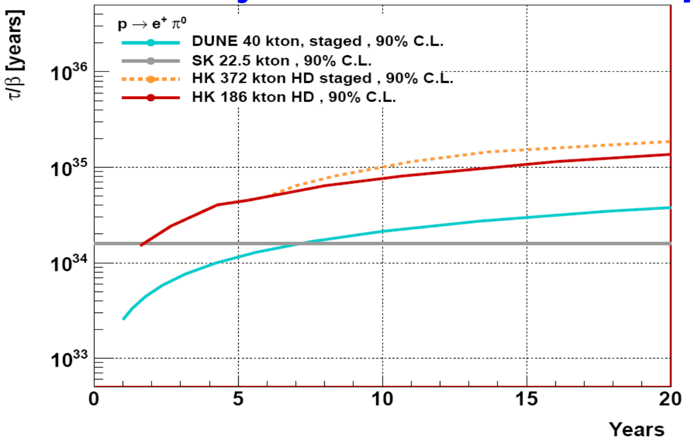
JUNO

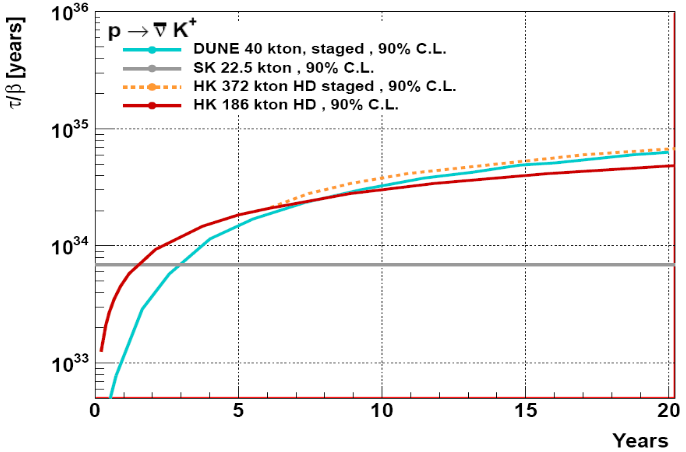


	Hyper-K	DUNE	JUNO
Mass (kton)	258 (186)	4*17 (4*10)	20
Target Nucleus	H_2O	Ar40	12% H， 88% C12
Technology	Water Cerenkov	LAr TPC	Liquid Scintillator
Start Time	2027	2030	2024

Nucleon decay searches in Hyper-K

Similar analysis methods with Super-K:





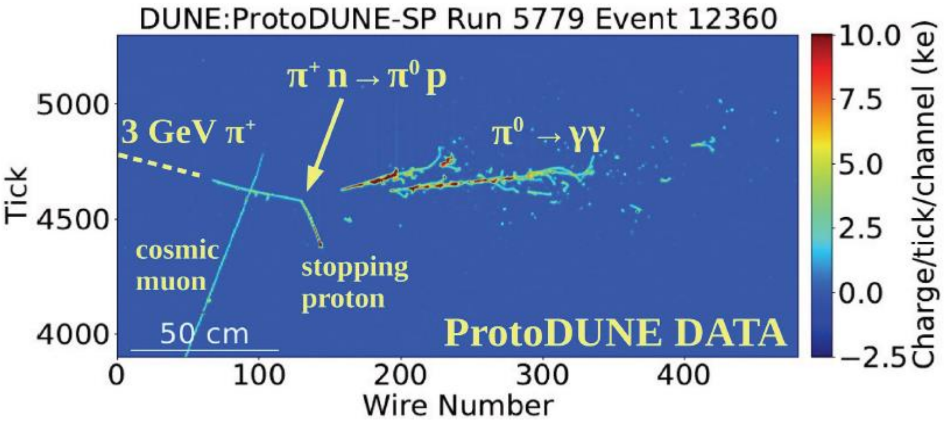
10 years sensitivity with 1 TANK:

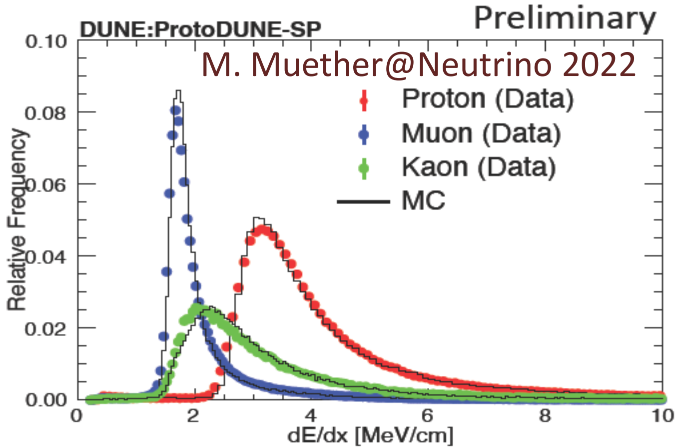
Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \rightarrow e^+\pi^0$	7.8×10^{34}	1.6×10^{34}
$p \rightarrow \overline{\nu}K^+$	3.2×10^{34}	0.7×10^{34}
$p \rightarrow \mu^+\pi^0$	7.7×10^{34}	0.77×10^{34}
$p \rightarrow e^+\eta^0$	4.3×10^{34}	1.0×10^{34}
$p \rightarrow \mu^+\eta^0$	4.9×10^{34}	0.47×10^{34}
$p \rightarrow e^+\rho^0$	0.63×10^{34}	0.07×10^{34}
$p \rightarrow \mu^+\rho^0$	0.22×10^{34}	0.06×10^{34}
$p \rightarrow e^+\omega^0$	0.86×10^{34}	0.16×10^{34}
$p \rightarrow \mu^+\omega^0$	1.3×10^{34}	0.28×10^{34}
$n \rightarrow e^+\pi^-$	2.0×10^{34}	0.53×10^{34}
$n \rightarrow \mu^+\pi^-$	1.8×10^{34}	0.35×10^{34}

Hyper-Kamiokande Design Report: 1805.04163

Liquid Argon TPC: DUNE

4x10 kton, LArTPC, 87 K, 1475m, 1300 km → δ_{CP}, MH, B-violation

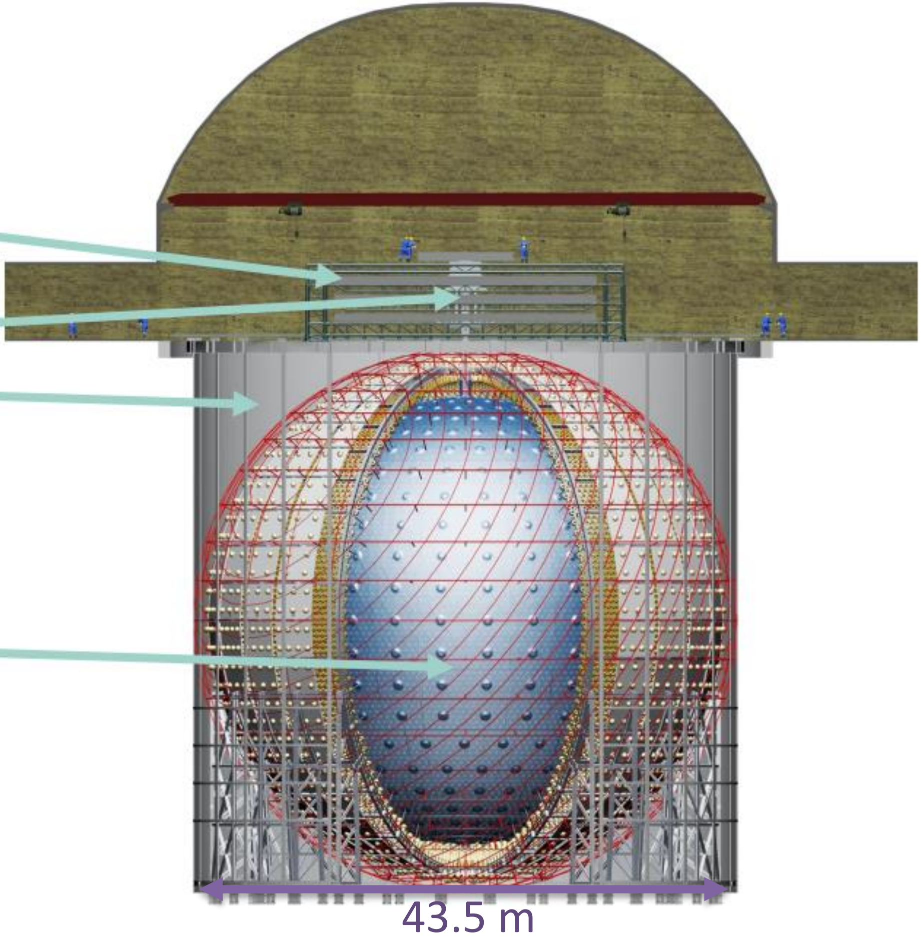




400 kton yrs ➡ $\tau/B(p \to e^+\pi^0) > 0.87 - 1.1 \times 10^{34}$ yrs (*E* smearing)

$\tau/B(p \to \bar{\nu}\, K^+) > 1.3 \times 10^{34}$ yrs, (30%, 0.4 bkg) DUNE Physics 2002.03005

JUNO: Detector



Top Tracker (TT)
- Precise μ tracker
- 3 layers of plastic scintillator
- ~ 60% of area above WCD

Calibration House

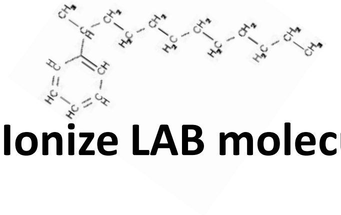
Water Cherenkov Detector
- 35 kton ultra-pure water
- 2.4k 20" PMTs
- High μ detection efficiency
- Protects CD from external radioactivity & neutrons from cosmic-rays

Central Detector
- Acrylic sphere with 20 kton liquid scint
- 17.6k 20" PMTs + 25.6k 3" PMTs
- 3% energy resolution @ 1 MeV

arXiv:2104.02565
JUNO physics and detector, Progress in Particle and Nuclear Physics 123, 103927 (2022)

Features of JUNO LS detector

How to measure a physical signal:



Charged particles propagate in LS → Ionize LAB molecule → fluor from de-excitation → Propagate in LS

~ 10000 photons/MeV

↓

PPO shift wavelength → Photon electron via photoelectric effect on PMT photocathode → PMT collects PE and amplification → Waveform Reconstruct PEs

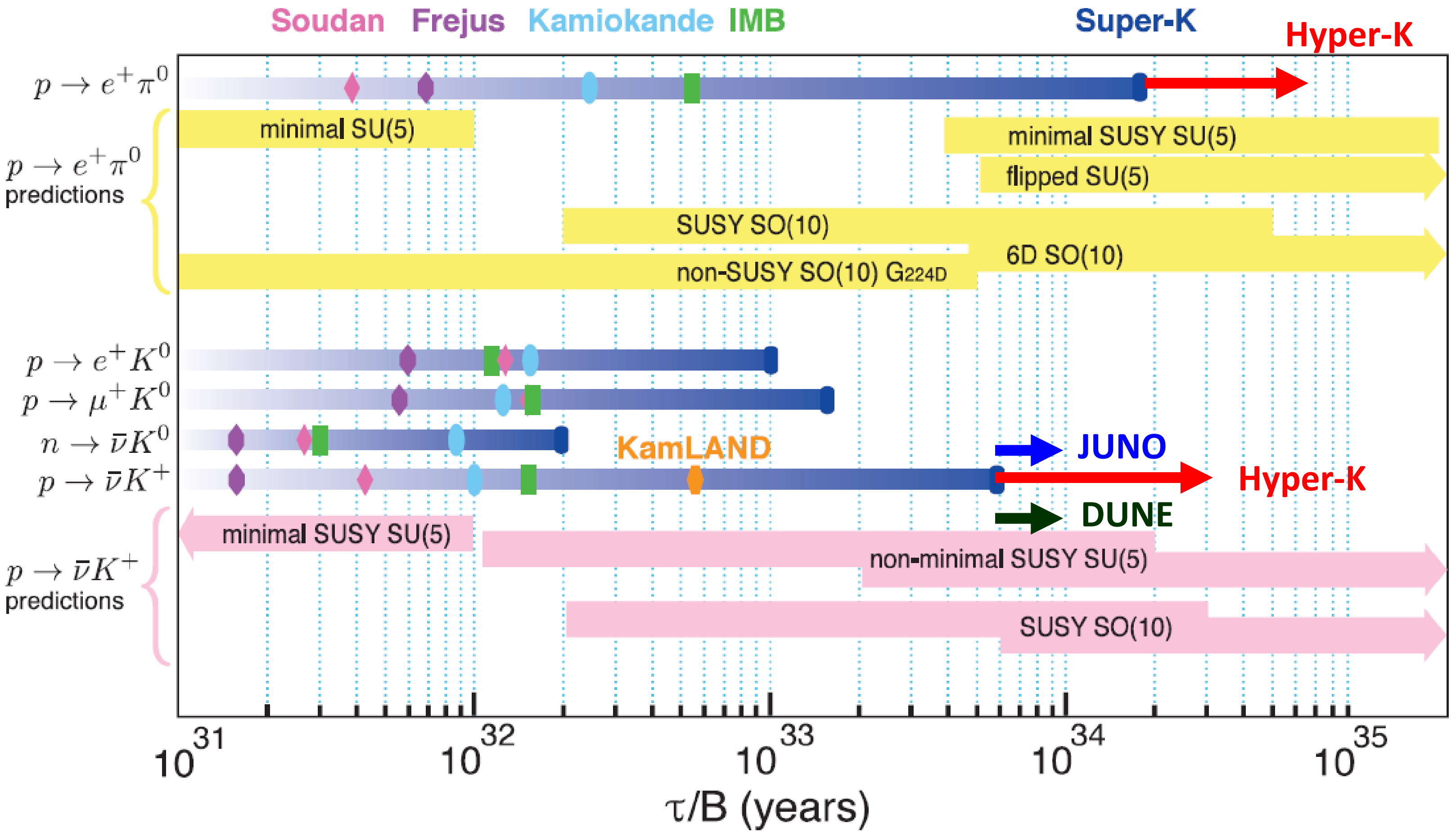
~1345/MeV

➡ **Excellent energy resolution: $\sigma_E \approx \sqrt{1345}/1345 \approx 3.0\%$@1MeV**
Excellent energy threshold: 0.7 MeV

If a new physics process can produce the ionization signal in LS, JUNO has the potential to test this new physics!!!

Nucleon decay, Dark Matter, Monopole, neutron-antineutron oscillation…

Future sensitives of 10yrs on two favor channels



Comparison of Hyper-K, DUNE and JUNO

	Hyper-K	DUNE	JUNO
Mass (kton)	258 (186)	4*17 (4*10)	20
Target Nucleus	H_2O	Ar40	12% H， 88% C12
Technology	Water Cerenkov	LAr TPC	Liquid Scintillator
Start Time	2027	2030	2024
Advantages	Large mass and cheap Good particle Identification Good direction resolution	Excellent track reconstruction Excellent particle Identification Good energy resolution	Excellent energy resolution 3% Excellent *E* threshold 0.7MeV
Shortcomings	Cerenkov threshold	Complex FSI for Ar40	Direction information lost

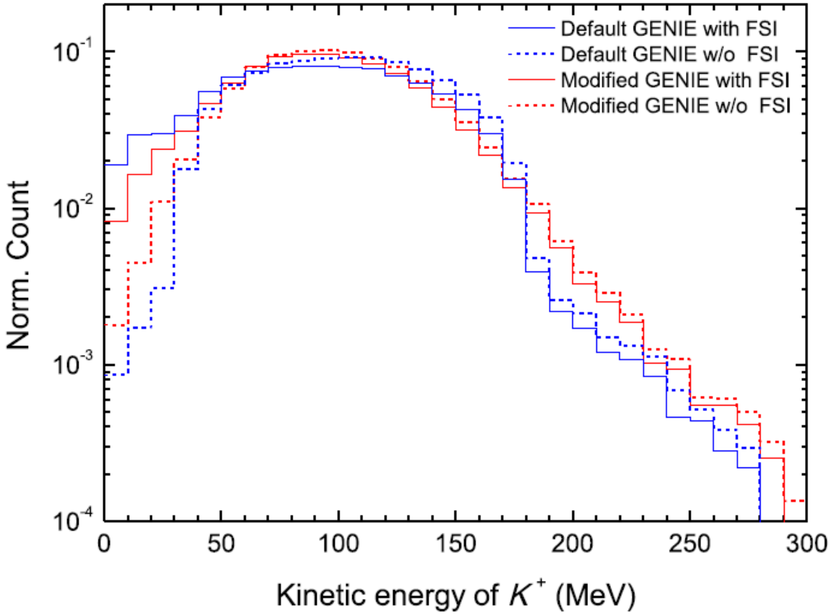
(3) JUNO potential to Nucleon decays

Search for $p \to \overline{\nu} K^+$ in JUNO

20 kton LS: Free proton: 1.45×10^{33}
Bound proton: 5.30×10^{33}

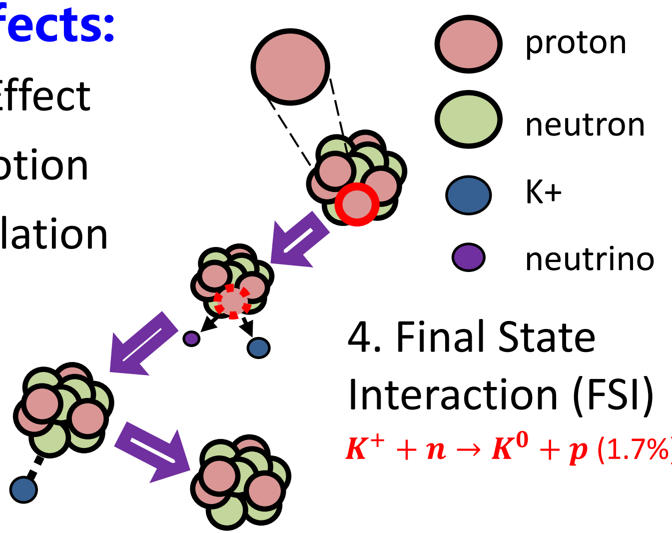
Kinetic energy of K^+

Free proton → 105 MeV
Bound proton: ↓



Nuclear Effects:

1. Binding Effect
2. Fermi Motion
3. *NN* correlation



4. Final State Interaction (FSI)
$K^+ + n \to K^0 + p$ (1.7%)

5. De-excitation of remaining nuclear: could emit **γ/p/n.**

- **Modify GENIE generator**
- **Implement de-excitation with TALYS**

H. Hu, W.L. Guo et al, PLB 831, 137183(2022)

Signal characters of $p \to \bar{\nu} K^+$ in JUNO

Triple coincident signals :

Decay mode	Branching ratio (%)	Kinetic energy sum (MeV)
$K^+ \to \mu^+\nu_\mu$	63.55 ± 0.11	152
$K^+ \to \pi^+\pi^0$	20.66 ± 0.08	354
$K^+ \to \pi^+\pi^+\pi^-$	5.59 ± 0.04	75
$K^+ \to \pi^0 e^+\nu_e$	5.07 ± 0.04	265–493
$K^+ \to \pi^0\mu^+\nu_\mu$	3.353 ± 0.034	200–388
$K^+ \to \pi^+\pi^0\pi^0$	1.761 ± 0.022	354

First pulse: K^+ kinetic energy of ~105 MeV, decay at rest 15 cm, 1.2ns

$K^+ \to \upsilon_\mu + \mu^+$

Second pulse $\to \mu^+ \to e^+ + \upsilon_e + \bar{\upsilon}_\mu$

152 MeV (μ^+) or 354 MeV(π^+, π^0)

$K^+ \to \pi^+ + \pi^0$

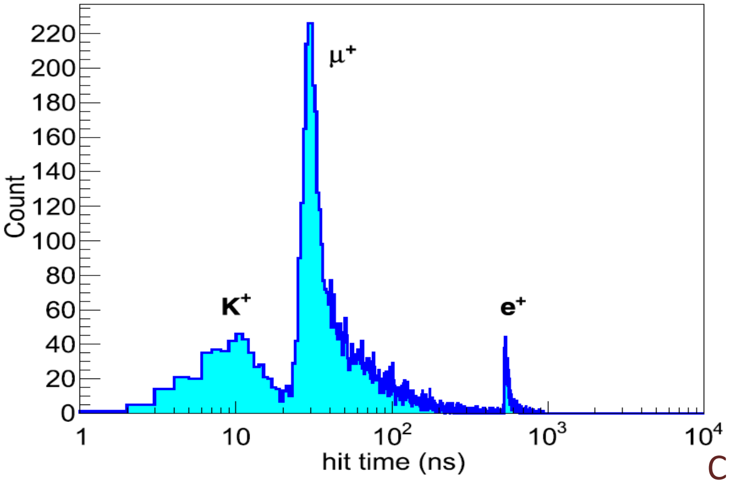
Second pulse

$\pi^0 \xrightarrow{8.4\times10^{-8}\text{ ns}} 2\gamma$

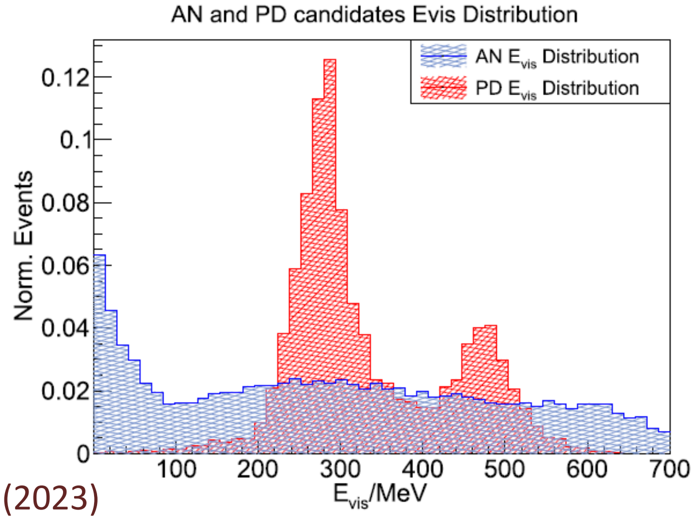
$\pi^+ \to \upsilon_\mu + \mu^+$

Third pulse: Michel e^+

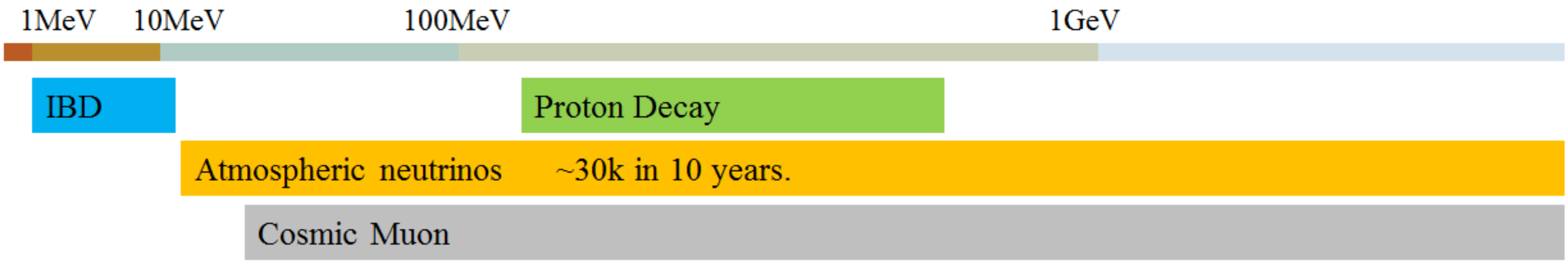
$\mu^+ \to e^+ + \upsilon_e + \bar{\upsilon}_\mu$



CPC 47, 113002 (2023)



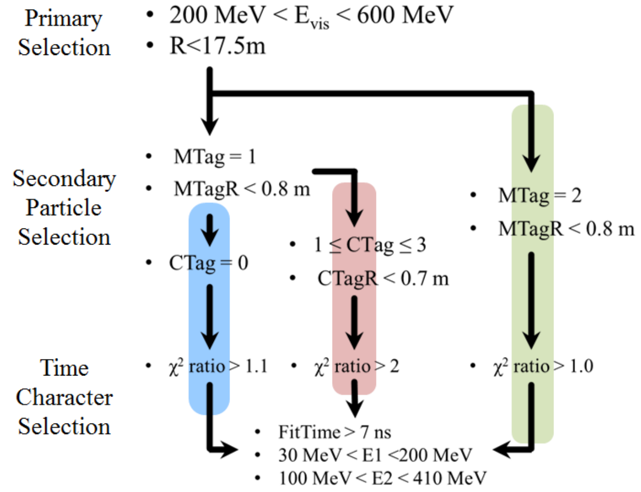
Backgrounds

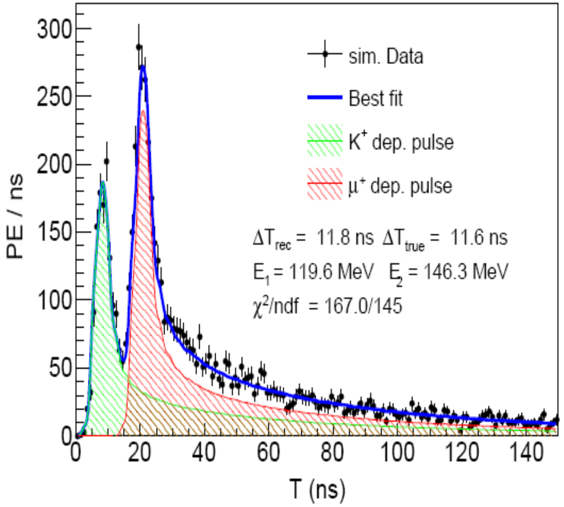


Type	Ratio (%)	Ratio with E_{vis} in [100 MeV, 600 MeV](%)	Interaction	Signal characteristics
NCES	20.2	15.8	$\nu + n \rightarrow \nu + n$ $\nu + p \rightarrow \nu + p$	Single Pulse
CCQE	45.2	64.2	$\bar{\nu}_l + p \rightarrow n + l^+$ $\nu_l + n \rightarrow p + l^-$	Single Pulse
Pion Production	33.5	19.8	$\nu_l + p \rightarrow l^- + p + \pi^+$ $\nu + p \rightarrow \nu + n + \pi^+$	Approximate Single Pulse (Second pulse too low)
Kaon Production	1.1	0.2	$\nu_l + n \rightarrow l^- + \Lambda + K^+$ $\nu_l + p \rightarrow l^- + p + K^+$	Double Pulse

- **If energetic neutrons do not lost most of the energy within ~10ns**
- **Kaon Production has a negligible contribution!**

Event Selection





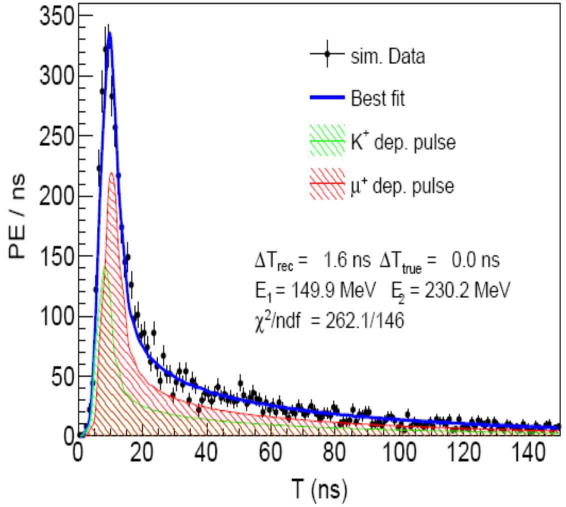


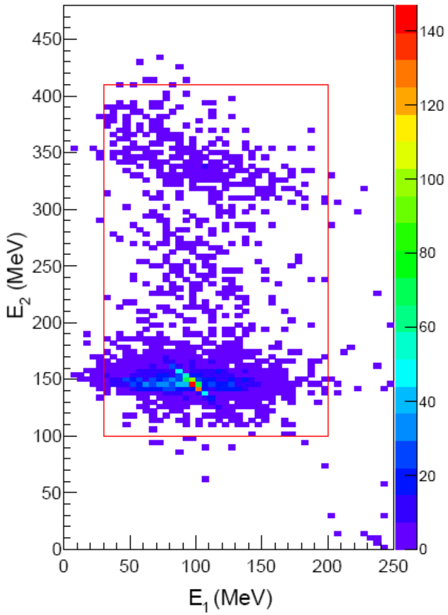
TABLE II. Detection efficiencies of $p \to \bar{\nu}K^+$ and the number of atmospheric ν background after each selection criterion. The total amount of atmospheric ν background simulated is 160 k, which corresponds to an exposure of 890 kton-years.

Criteria		Survival rate of $p \to \bar{\nu}K^+$ (%)			Survival count (fraction) of atmospheric ν		
		Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
basic selection	E_{vis}	94.6			51299 (32.1%)		
	R_V	93.7			47849 (29.9%)		
Delayed signal selection	N_M	74.4		4.4	20739 (13.0%)		1143 (0.7%)
	ΔL_M	67.0		4.4	13796 (8.6%)		994 (0.6%)
	N_n	48.4	17.9	–	5403 (3.4%)	6857 (4.3%)	–
	ΔL_n	–	16.6	–	–	4472 (2.8%)	–
Time character selection	R_χ	45.9	9.0	3.8	4326 (2.7%)	581 (0.4%)	716 (0.4%)
	ΔT	28.3	7.7	2.4	121 (0.07%)	18 (0.01%)	30 (0.02%)
	E_1, E_2	27.4	7.3	2.2	1 (0.0006%)	0	0
Total		36.9			1		

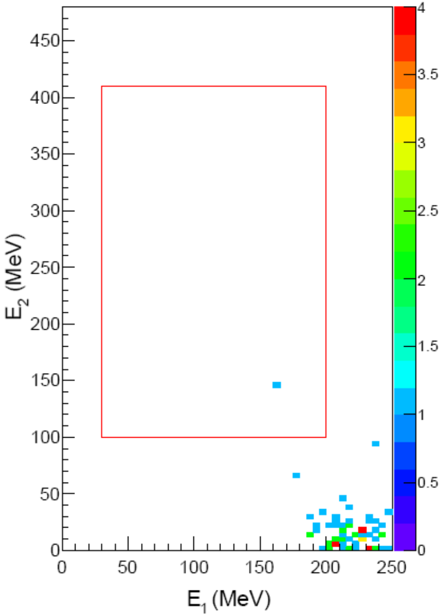
Efficiency uncertainties:

Source	Uncertainty
Statistic	1.6%
Position reconstruction	1.7%
Nuclear model	6.8%
Energy deposition model	11.1%
Total	13.2%

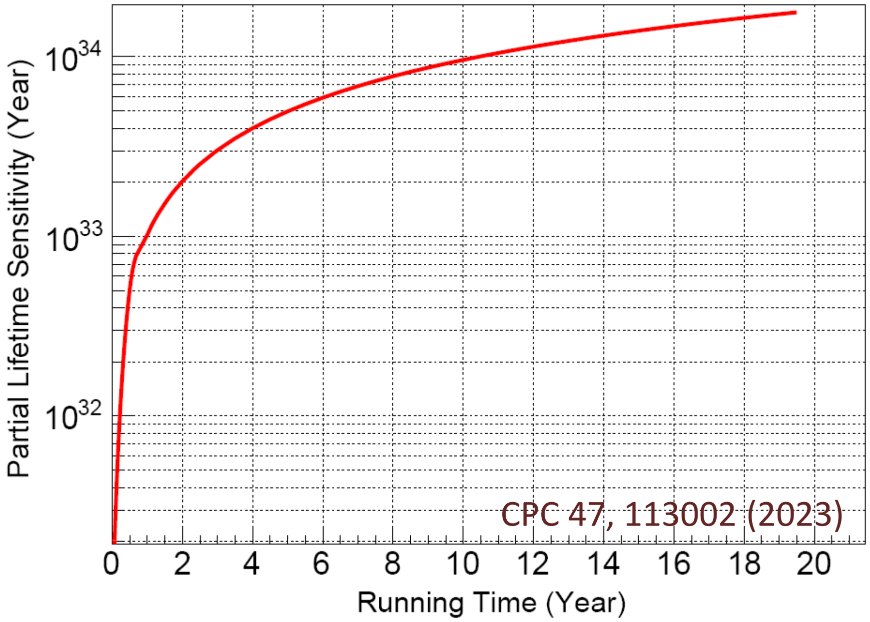
Sensitivity to $p \to \overline{\nu}\, K^+$



(a) $p \to \bar{\nu} K^+$



(b) atmospheric ν



Background： 0.2/10years
Efficiency： 36.9%

$\tau / B(p \to \overline{\nu}\, K^+) > 0.96 \times 10^{34}$ yrs

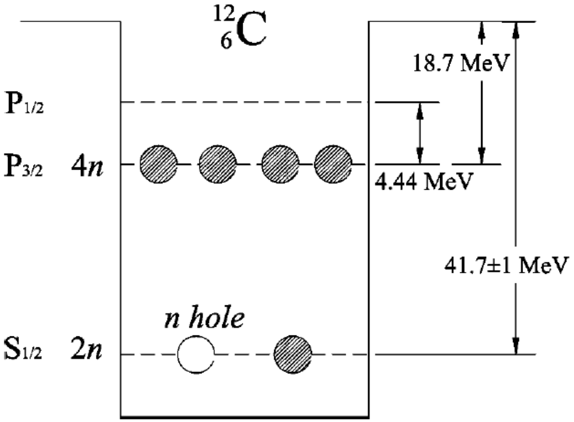
$$n \to \mu^- K^+, \quad p \to e^+ K^*(892)^0, \quad n \to \nu K^*(892)^0, \quad \text{and} \quad p \to \nu K^*(892)^+$$

Neutron invisible decays in JUNO

Bounded neutrons in ^{12}C :

- $n \to inv$ $(^{12}C \to {}^{11}C^*)$
- $nn \to inv$ $(^{12}C \to {}^{10}C^*)$

Invisible particle:
neutrinos, NP particles



s-shell neutron decays:

Detect de-excitation products of $^{11}C^*$ and $^{10}C^*$ in LS to search the invisible decay

Triple coincident signals :

Prompt(1st)
- Proton recoil by neutron
- Neutron inelastic with ^{12}C
- γ (3.35 MeV) and proton (0.922 MeV)

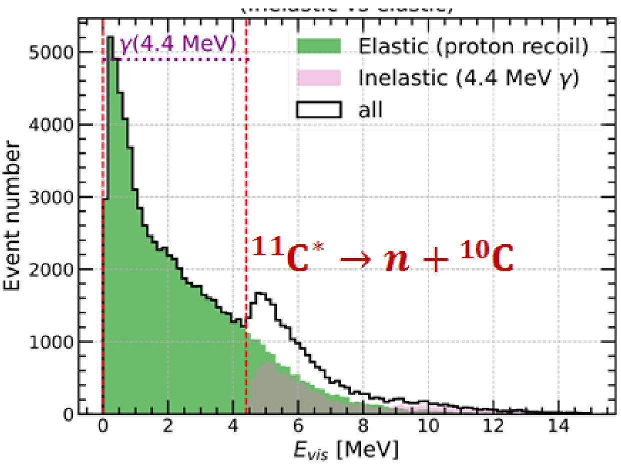
Delayed(2nd)
- Neutron capture (220 μs, 2.2 MeV)

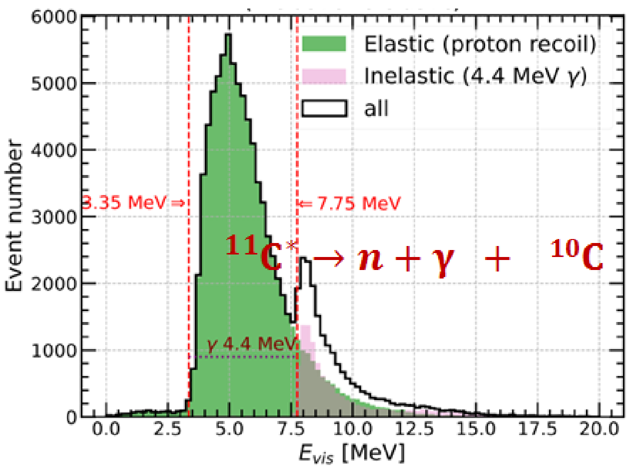
		Half-life Q value
$^{11}C^* \to n + {}^{10}C$	$(B_{n1} = 3.0\%)$	[19.3 s, 3.65 MeV]
$^{11}C^* \to n + \gamma + {}^{10}C$	$(B_{n1} = 2.8\%)$	[19.3 s, 3.65 MeV]
$^{10}C^* \to n + {}^{9}C$	$(B_{nn1} = 6.2\%)$	[0.13 s, 16.5 MeV]
$^{10}C^* \to n + p + {}^{8}B$	$(B_{nn1} = 6.0\%)$	[0.77 s, 18.0 MeV]

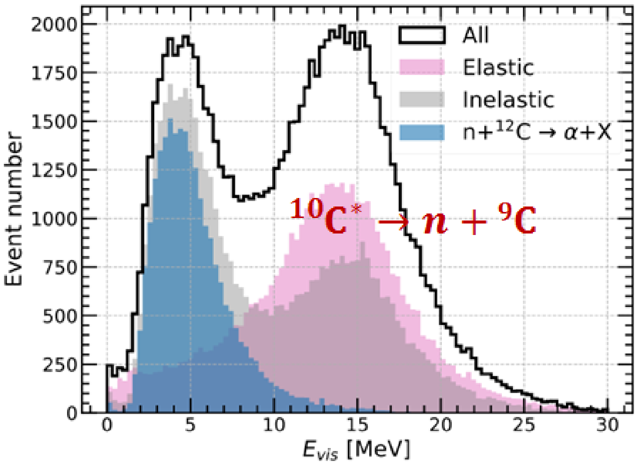
Decay (3rd)
- β^+ decay of ^{10}C, ^{9}C, ^{8}B

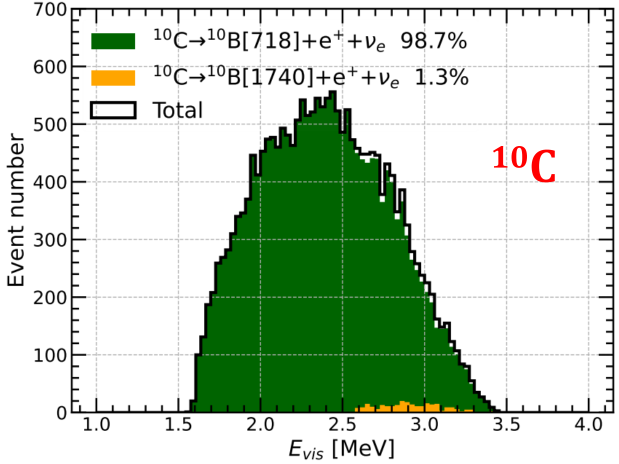
Y. Kamyshkov and E. Kolbe, PRD 67, 076007 (2003)

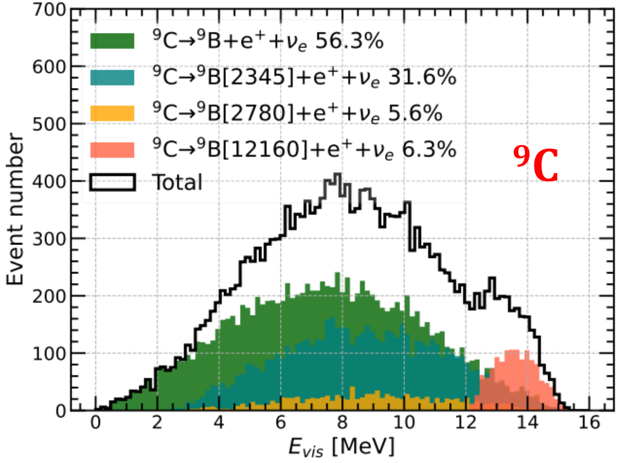
Signal Characteristics in LS

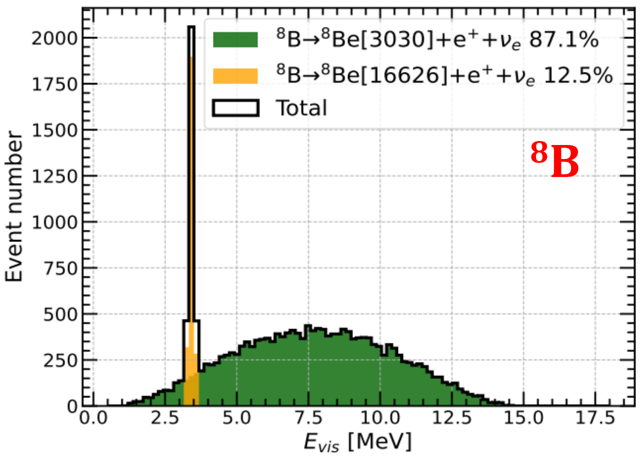










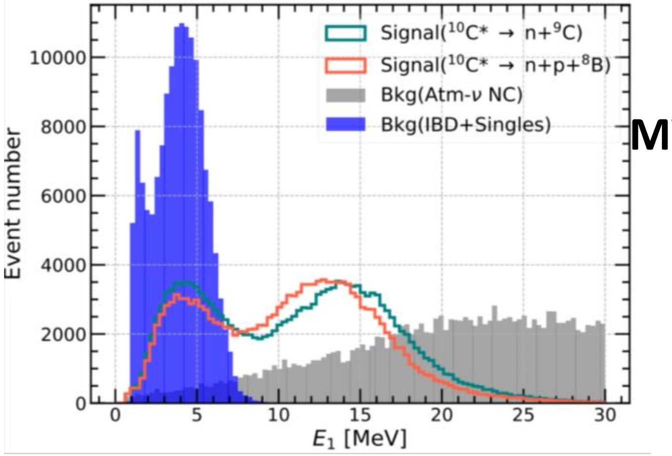


Distributions of signal and background after event selection

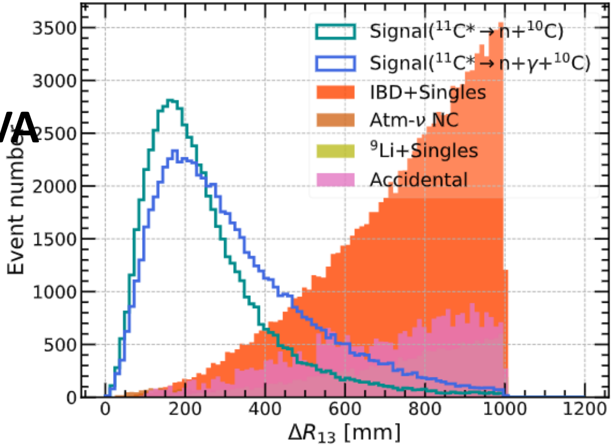
Summary of event selection				
	$n \to inv$		$nn \to inv$	
Muon veto				
Fiducial volume	$r < 16.7$ m		$r < 16.7$ m	
Selection criteria	$\Delta T_{12} < 1$ ms $\Delta T_{23} \in [0.002, 100]$ s $\Delta R_{12} < 1.5$ m $\Delta R_{23} < 1.5$ m $\Delta R_{13} < 1.0$ m $E_1 \in [0.7, 12]$ MeV $E_2 \in [1.9, 2.5]$ MeV $E_3 \in [1.5, 3.5]$ MeV		$\Delta T_{12} < 1$ ms $\Delta T_{23} \in [0.002, 3.0]$ s $\Delta R_{12} < 1.5$ m $\Delta R_{23} < 1.5$ m $\Delta R_{13} < 1.0$ m $E_1 \in [0.7, 30]$ MeV $E_2 \in [1.9, 2.5]$ MeV $E_3 \in [3.0, 16]$ MeV	
Multiplicity cut				
Total efficiency (%)	$^{11}C^* \to n + {}^{10}C$	$^{11}C^* \to n + \gamma + {}^{10}C$	$^{10}C^* \to n + {}^{9}C$	$^{10}C^* \to n + p + {}^{8}B$
	35.6 ± 0.2	43.6 ± 0.2	53.9 ± 0.3	49.1 ± 0.3

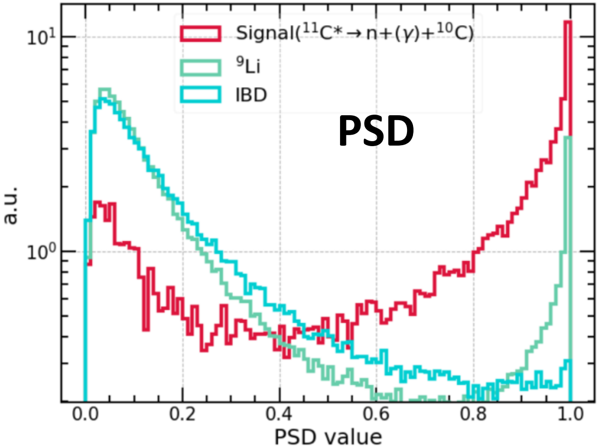
Background Source:

1. IBD (Inverse Beta decay),
2. Isotope from cosmic muons,
3. Radioactivity,
4. Fast neutrons,
5. Atm-ν NC



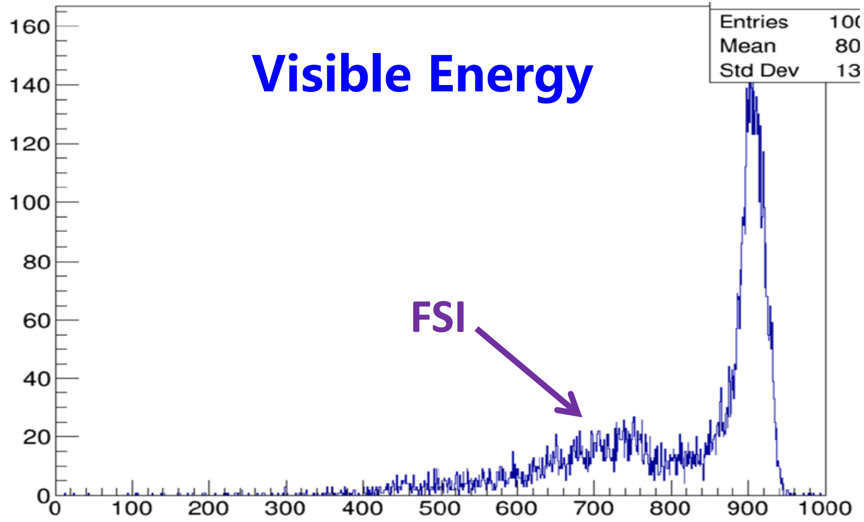
MVA

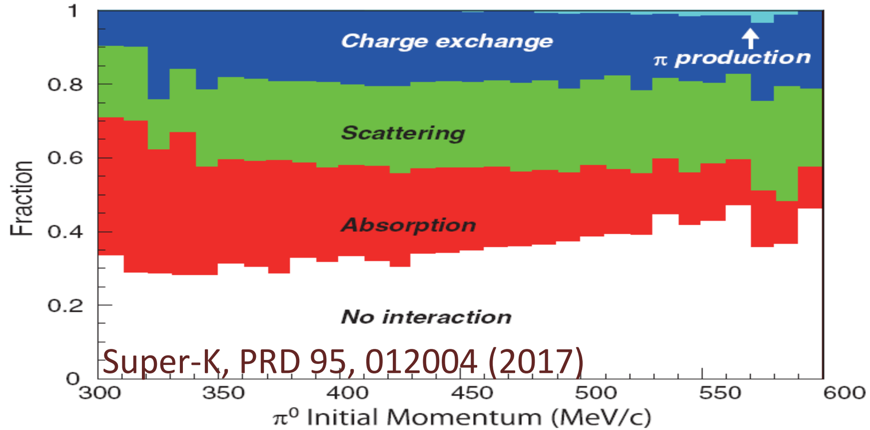




Preliminary Sensitivity: up to 10^{31} yr for $n \to inv$, improve results in 10^{32} yr range for $nn \to inv$

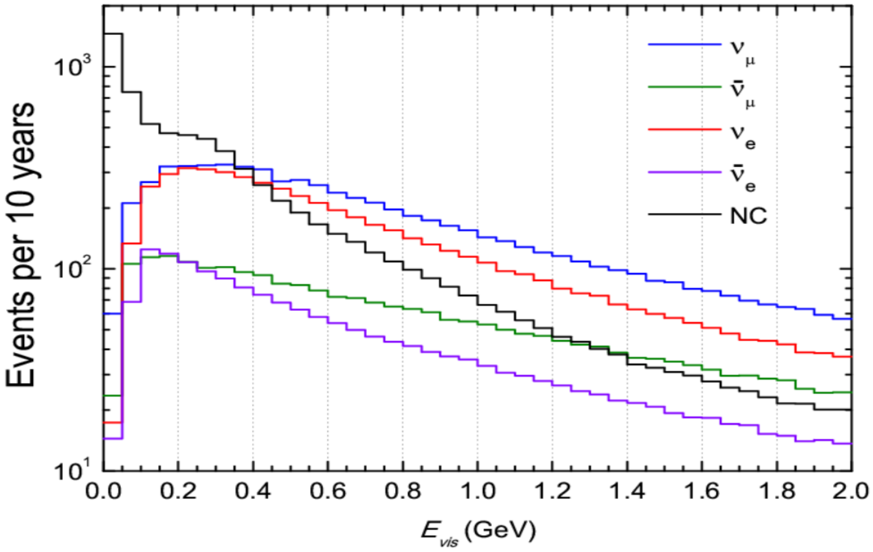
Search for $p \to e^{+} + \pi^{0}$ in JUNO





Super-K, PRD 95, 012004 (2017)

Atmospheric ν backgrounds:



10 years:

0.05-1GeV→ **18114**

(CC:11714; NC:6400)

Sensitivity estimation for $p \rightarrow e^{+} + \pi^{0}$

Event Selection: 860 MeV < Evis < 940 MeV; no Michel; no neutron capture

➡ **Signal Efficiency :** 50.9%; **Background:** 97.8/10years

$\tau/B(p \rightarrow e^{+}\pi^{0}) > 0.19 \times 10^{34}$ yrs ($\ll 2.4 \times 10^{34}$ yrs from Super-K)

How to estimate sensitivity?

$$N_{S_i} = N_{decay} \cdot B_i \cdot \epsilon_i = B_i \cdot \epsilon_i \cdot N_0 \frac{t}{\tau} \rightarrow \frac{\tau}{B_i} = \frac{N_0 \cdot \epsilon_i}{N_{90}} t$$

N_{S_i}: Signal number
N_0: Nucleon umber $= 6.75 \times 10^{33}$
ϵ_i : Signal Efficiency $= 50.9\%$
t : Running Time $= 10$ years
N_{90}: 90% CL upper limit $= 17.7$
N_B: Expected BG number $= 97.8$

90% CL upper limit N_{90}:

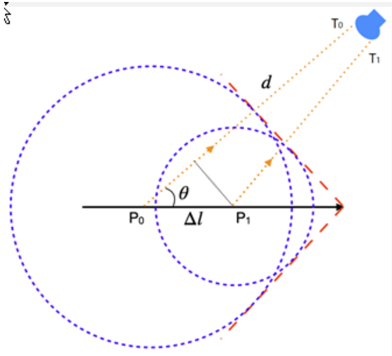
$$L(N_{obs}, N_S) = \frac{(N_S + N_B)^{N_{obs}}}{N_{obs}\,!} e^{-(N_S+N_B)} \rightarrow 90\% = \frac{\int_0^{N_{90}} L(N_{obs}, N_S) dN_S}{\int_0^{\infty} L(N_{obs}, N_S) dN_S}$$

$N_{obs} = N_B$	0.0	1.0	2.0	5.0	10	20	50	100	200	1000
N_{90}	2.3	3.3	3.9	5.2	6.6	8.8	13.0	17.8	24.6	53.3

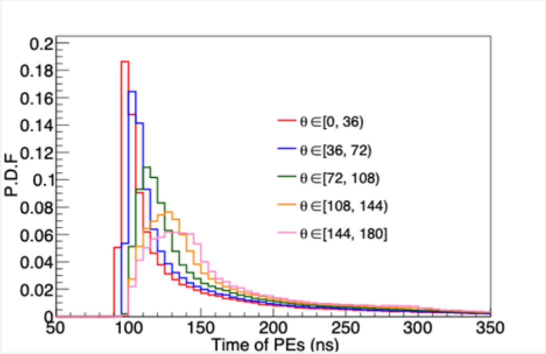
BKG number is the key quantity!!! → How to suppress BKG?

How to suppress BKG ? → Momentum information

ν directional information reflects in each PMT waveform



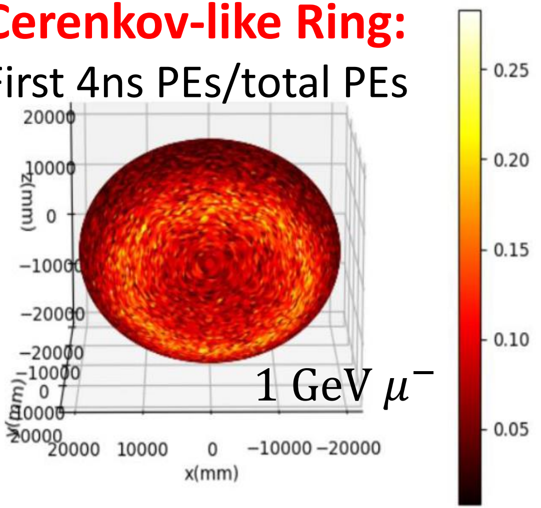
$$\frac{\Delta l}{\Delta t} \propto \frac{1}{|1 - n\beta\cos\theta|}$$

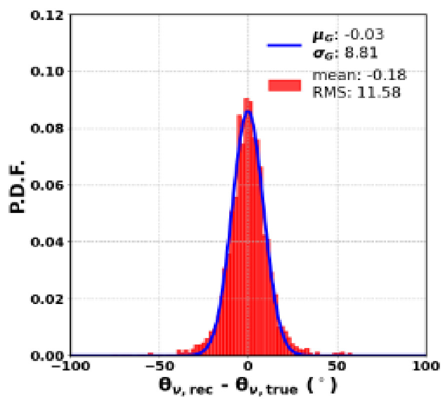


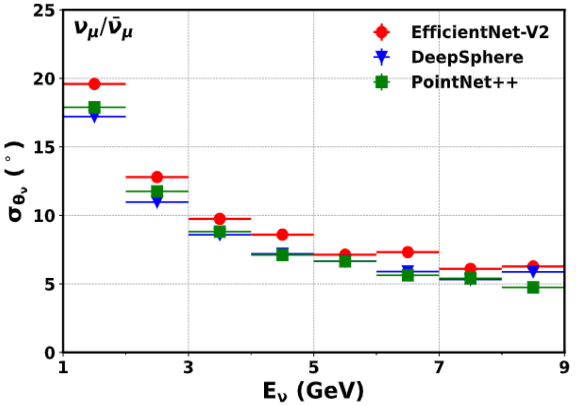
Distribution of the number of photoelectrons (PEs) over time for PMTs with different angles θ to the particle track

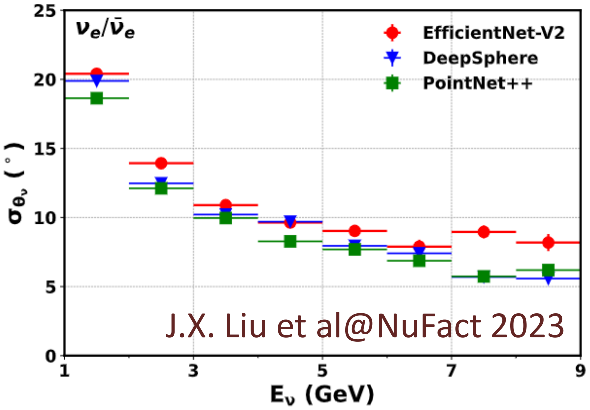
Cerenkov-like Ring:

First 4ns PEs/total PEs









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Simply estimate JUNO sensitivities to other channels (1)

Antilepton+ Meson									
ID	Channels	n_b	n_{90}	$\epsilon(\%)$	$\tau_{10}(10^{33}yrs)$	$\tau_3(10^{33}yrs)$	$\tau_{exp}(10^{33}yrs)$	TECN	Rank
1	$p \to e^+\pi^0$	97.8	17.7	50.9	1.9	1	24	SKAM(20)	E
*1	$n \to e^+\pi^-$	1943.0	73.9	83.44	0.578	0.312	5.3	SKAM(17D)	E
2	$p \to \mu^+\pi^0$	152.6	21.7	54.68	1.6	0.9	16	SKAM(20)	E
*2	$n \to \mu^+\pi^-$	2101.3	76.8	85.14	0.568	0.306	3.5	SKAM(17D)	E
3	$p \to \overline{\nu}\pi^+$	7172.09,3405.55	162.8	91.24	0.366	0.199	0.39	SKAM(14E)	D
*3	$n \to \overline{\nu}\pi^0$	2668.9	86.3	59.06	0.351	0.189	1.1	SKAM(14E)	E
4	$p \to e^+\eta$	97.8	17.7	30.62	1.1	0.56	10	SKAM(17D)	E
5	$p \to \mu^+\eta$	134.1	20.4	30.62	1	0.5	4.7	SKAM(17D)	E
6	$n \to \overline{\nu}\eta$	336.1	37.8	31.42	0.528	0.2657	0.158	IMB3(99)	B
7	$p \to e^+\rho^0$	4398.9	110.4	91.11	0.5384	0.2918	0.72	SKAM(17D)	D
*7	$n \to e^+\rho^-$	2067.5	76.1	83.75	0.564	0.304	0.217	IMB3(99)	B
8	$p \to \mu^+\rho^0$	3067.4	92.4	93.48	0.6600	0.3566	0.57	SKAM(17D)	C
*8	$n \to \mu^+\rho^-$	2323.6	80.6	87.71	0.557	0.301	0.228	IMB3(99)	B
9	$p \to \overline{\nu}\rho^+$	1657.6,1394.7,102.8	81.8	70.17	0.559	0.300	0.162	IMB3(99)	B
*9	$n \to \overline{\nu}\rho^0$	214.1	25.5	41	0.8237	0.432	0.019	IMB(88)	A
10	$p \to e^+\omega$	1:1024.2,97.8 2:4398.9	106.1	30.61	0.1947	0.1052	1.6	SKAM(17D)	E
11	$p \to \mu^+\omega$	1:116.2, 118.7 2:3067.4	45.5	30.44	0.4425	0.2303	2.8	SKAM(17D)	E
12	$n \to \overline{\nu}\omega$	1: 640 2:4398.9	92.2	28.23	0.1623	0.087	0.108	IMB3(99)	C

Three and more leptons									
ID	Channels	n_{bkg}	n_{90}	$\epsilon(\%)$	$\tau_{10}(10^{33}yrs)$	$\tau_3(10^{33}yrs)$	$\tau_{exp}(10^{33}yrs)$	TECN	Rank
49	$p \to e^+e^+e^-$	97.8	17.7	77.78	2.9	1.5	34	SKAM(20)	E
50	$p \to e^+\mu^+\mu^-$	24.5	9.6	79.24	5.38	2.58	9.2	SKAM(20)	D
51	$p \to e^+\overline{\nu}\nu$	2460.1	83	90.83	0.714	0.386	0.17	SKAM(14)	B
52	$n \to e^+e^-\overline{\nu}$	1255.7	59.7	88.39	0.758	0.408	0.257	IMB3(99)	B
53	$n \to \mu^+e^-\overline{\nu}$	1256.7	59.7	90.75	0.779	0.419	0.083	IMB3(99)	A
54	$n \to \mu^+\mu^-\overline{\nu}$	115.4	19.1	89.37	2.397	1.237	0.079	IMB3(99)	A
55	$n \to \mu^+e^+e^-$	133.9	20.4	83.3	2.1	1.1	23	SKAM(20)	E
56	$n \to \mu^+\mu^+\mu^-$	0.0	2.4	83.15	17.7	5.3	10	SKAM(20)	A
57	$p \to \mu^+\overline{\nu}\nu$	983.1	52.9	82.33	1.015	0.544	0.22	SKAM(20)	B
58	$p \to e^-\mu^+\mu^+$	23.1	9.29	68.43	4.8	2.3	11	SKAM(20)	D

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Only use:

1. Energy
2. Michel $e^{\pm}$
3. n capture
4. Some assumptions about FSI

VS Super-K?

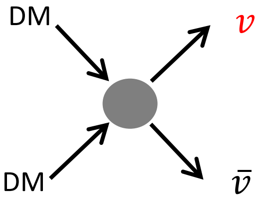
Simply estimate JUNO sensitivities to other channels (2)

ID	Channels	n_{bkg}	n_{90}	$\epsilon(\%)$	$\tau_{10}(10^{33}yrs)$	$\tau_3(10^{33}yrs)$	$\tau_{exp}(10^{33}yrs)$	TECN	Rank
Antilepton+Mesons									
23	$p \to e^+\pi^+\pi^-$	4398.9	110.4	91.11	0.5384	0.2918	0.082	IMB3(99)	A
24	$p \to e^+\pi^0\pi^0$	214.1	25.5	41	1.049	0.550	0.147	IMB3(99)	A
25	$n \to e^+\pi^-\pi^0$	2067.5	76.1	83.75	0.564	0.304	0.052	IMB3(99)	A
26	$p \to \mu^+\pi^+\pi^-$	3067.4	92.4	93.48	0.6600	0.3566	0.133	IMB3(99)	B
27	$p \to \mu^+\pi^0\pi^0$	3591.5	99.9	93.84	0.613	0.332	0.101	IMB3(99)	A
28	$n \to \mu^+\pi^-\pi^0$	2323.6	80.6	87.71	0.557	0.301	0.074	IMB3(99)	A
29	$n \to e^+\pi^-K^0$	2932.3,460.2	96	96.71	0.516	0.279	0.018	IMB3(91)	A
Lepton+Meson									
30	$n \to e^-\pi^+$	1070.4,818.8,163.2	66	80.13	0.622	0.333	0.065	FREJ(88)	A
31	$n \to \mu^-\pi^+$	1308.9,118,219	40	79.98	1.024	0.534	0.049	IMB(88)	A
32	$n \to e^-\rho^+$	1657.6,1394.7,102.8	81.8	70.17	0.439	0.236	0.062	IMB(88)	A
33	$n \to \mu^-\rho^+$	1899.5,192.398,197.6	42.6	74.56	0.897	0.472	0.007	IMB(88)	A
34	$n \to \mu^-K^+$	257.7,132.0	33	59.54	0.924	0.583	0.032	FREJ(91B)	A
35	$n \to \mu^-K^+$	42.6,27.7	14.5	58.95	2.083	1.053	0.057	FREJ(91B)	A
Lepton+Mesons									
36	$p \to e^-\pi^+\pi^+$	534.7,46.6,76.6	27.2	41.06	0.985	0.502	0.03	FREJ(91B)	A
37	$n \to e^-\pi^+\pi^0$	1657.6,1394.7,102.8	81.8	70.17	0.439	0.236	0.029	FREJ(91B)	A
38	$p \to \mu^-\pi^+\pi^+$	79.4,0.6,53.6	7.5	54.06	4.702	1.763	0.017	FREJ(91B)	A
39	$n \to \mu^-\pi^+\pi^0$	1899.5,192.398,197.6	42.6	74.56	0.897	0.472	0.034	FREJ(91B)	A
40	$p \to e^-\pi^+K^+$	32.9,314.8,581.3	19.2	57.54	1.955	0.963	0.075	IMB3(99)	A
41	$p \to \mu^-\pi^+K^+$	0.1,89.3,0.5	3.2	63.48	12.942	4.284	0.245	IMB3(99)	A
Antilepton+Photon(s)									
42	$p \to e^+\gamma$	97.8	17.7	75.88	2.8	1.442	0.67	IMB3(99)	A
43	$p \to \mu^+\gamma$	100.1	17.9	77.83	2.8366	1.4647	0.478	IMB3(99)	A
44	$n \to \overline{\nu}\gamma$	1011.0	53.7	86.69	0.827	0.444	0.55	SKAM(15)	C
45	$p \to e^+\gamma\gamma$	97.8	17.7	76.04	2.8	1.44	0.1	FREJ(91)	A
46	$n \to \overline{\nu}\gamma\gamma$	1552.3	66.2	88.83	0.987	0.370	0.219	IMB3(99)	B

A: Its result is much better than the best limit so far, if we get 3 years' events, we can come out on top.In this rank, τ_3 is at least 3 times bigger than τ_{exp}.
B: In this rank, τ_3 is bigger than τ_{exp}.And this channel is worthwhile studying more.
C: We have a better result than before for 10 years' data, but $\tau_3 < \tau_{exp}$.
D: $\tau_{10} < \tau_{exp}$, The disparity between our outcome and theirs is a litte big. We can do more but may do in vain.
E:There is a big tap comparing to current limit τ_{exp}, we would better give up it.
OPEN:There is a better method to take event selection or the result is not very reliable.

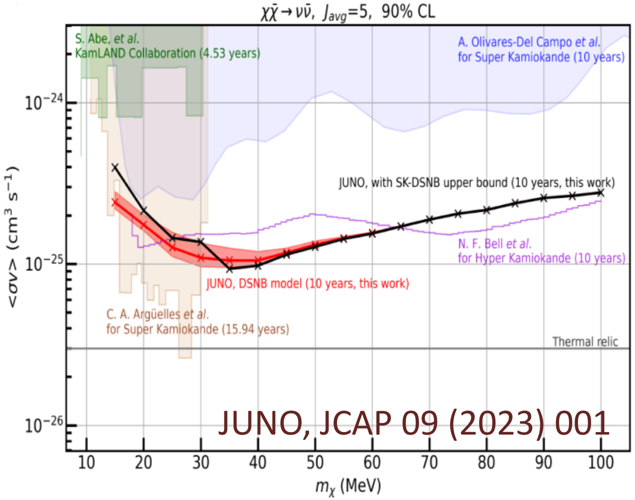
(4) Search for other new physics

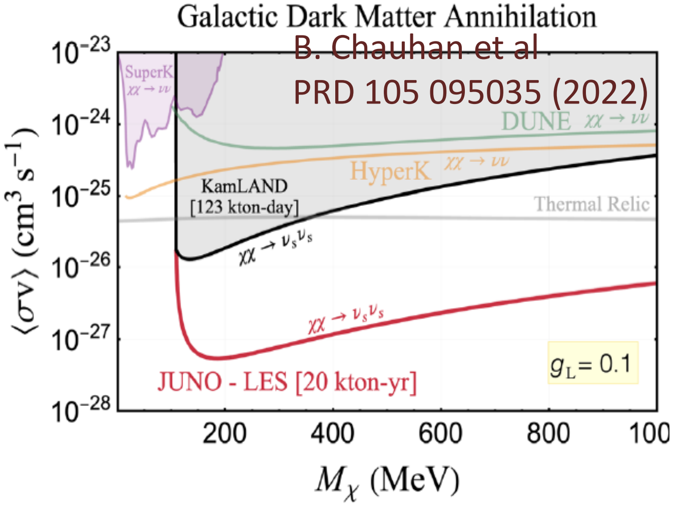
DM annihilation in the Milk Way and Sun…:



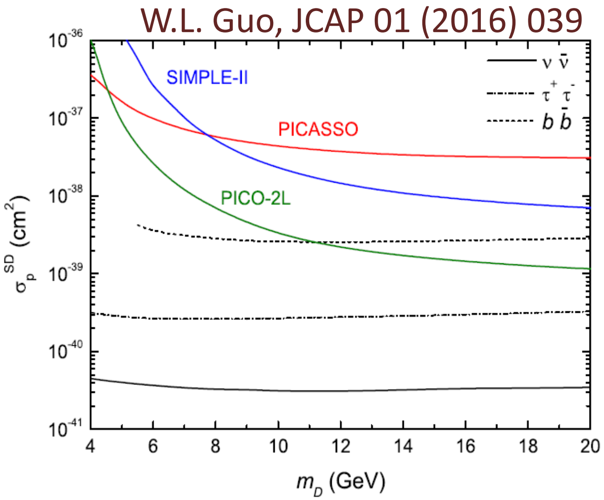
- ✓ Monoenergetic neutrinos: $E_v = m_{DM}$;
- ✓ Produce both **coincident** and **single signals**;
- ✓ Singles is complementary to $\bar{v}_e$ analysis

DM annihilation in the Milky Way:





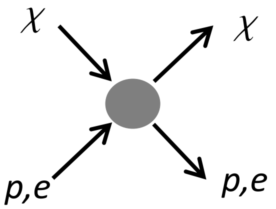
in Sun:



Detect: $\bar{v}_e + p \to e^+ + n$ **(IBD)** $\quad v_s + p \to v_s + p \quad$ $v_e/\bar{v}_e$ **CC**

Dark matter direct searches

Usual Dark Matter (WIMP) scatters in JUNO:



DM Velocity: $v_\chi \approx 10^{-3} c = 300\ km/s$

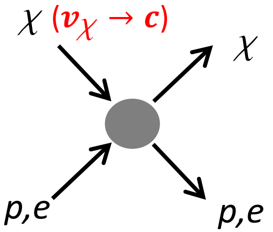
Recoil energy: $T_N = m_N v^2 * 2\cos^2\theta * \frac{m_D{}^2}{(m_D+m_N)^2} \approx m_N v^2 = \begin{cases} 12\text{keV} & (^{12}C) \\ 1\ \text{keV} & (p) \\ 1\ \text{eV} & (e^-) \end{cases}$ $\ll$ **0.7 MeV**

Two possible mechanisms → $E_{vis} > 1$ MeV :

Change initial state:

$v_\chi \to c$

Kinetic energy → E_{vis}

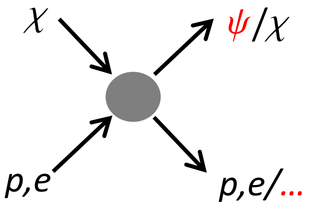


Boosted Dark Matter (BDM)

Change final state:

$\sum m_{\text{final}} < m_\chi + m_{p,e}$

Mass energy → E_{vis}



Explosive Dark Matter

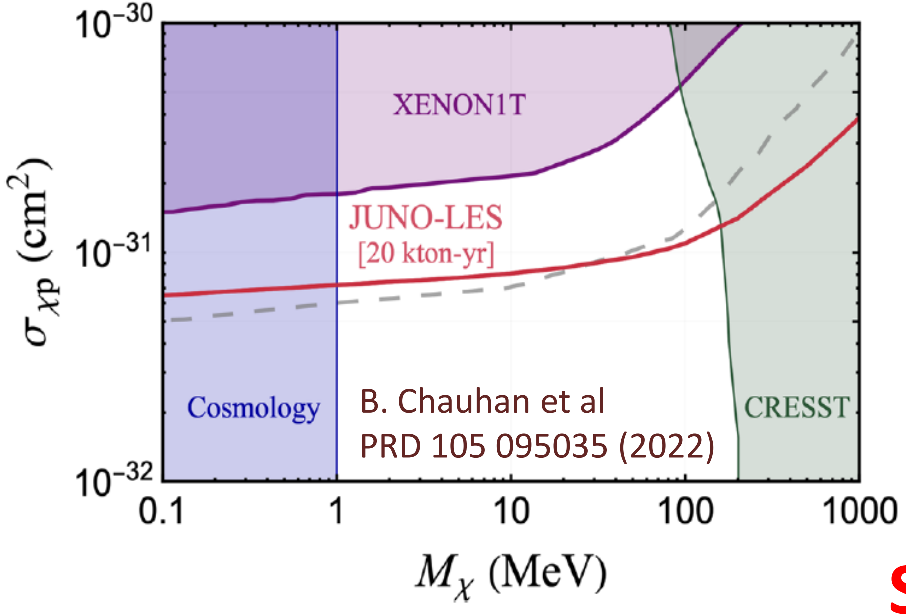
Multiply Interacting Massive Particles

MIMP

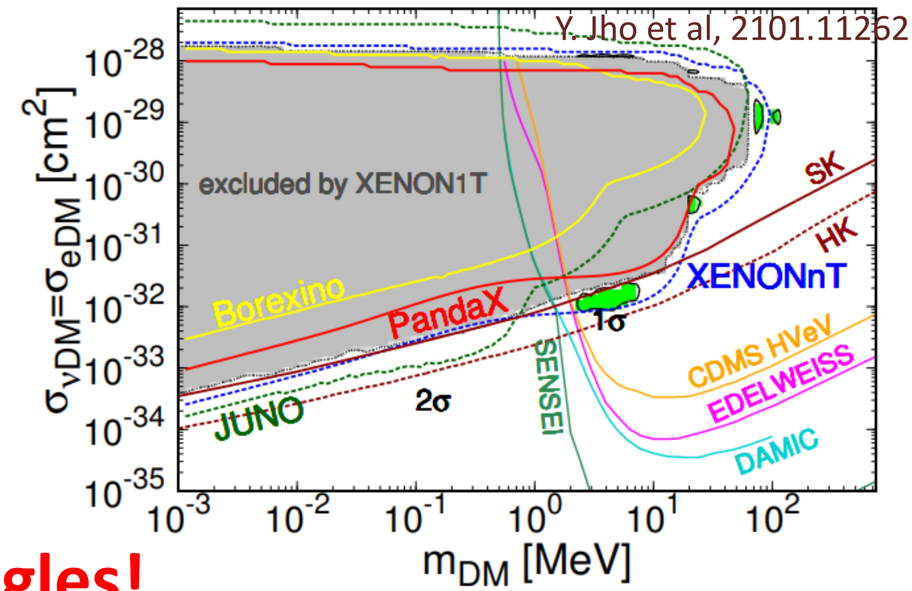
There are many new physics models, can produce the relativistic DM. Please refer to 2207.02882 (Snowmass 2021) for more references.

Predicted JUNO sensitivities from theoretical papers

CR Boosted Dark Matter



Sun-like Star ν BDM:



Singles!

Detect: $\mathbf{DM} + p \rightarrow \mathbf{DM} + p$ $\qquad$ $\mathbf{DM} + e^- \rightarrow \mathbf{DM} + e^-$

Comparison between Super-K, DUNE, JUNO for proton recoil:

Super-K(Hyper-K): Kinetic energy >585 MeV can produce a ring used to reconstruction

DUNE: has not the free proton

JUNO: Kinetic energy > 25 MeV → Evis>15 MeV **Monoenergetic BDM!**

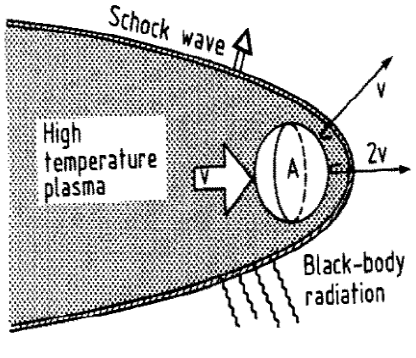
Low velocity massive particles (Nuclearizes,Monopole,MIMP)

Strange Quark Matter (SQM):

- SQM is a hypothetical strongly interacting matter composed of roughly equal numbers of u, d, s quarks and a small amount of electrons; **Absolutely stable;** $\rho_N = 3.6 \times 10^{14}\mathrm{g/cm^3}$
- A > 10^7 **Nuclearites (奇异核素),** typical $\beta \sim 10^{-3}$ (galaxy velocity)

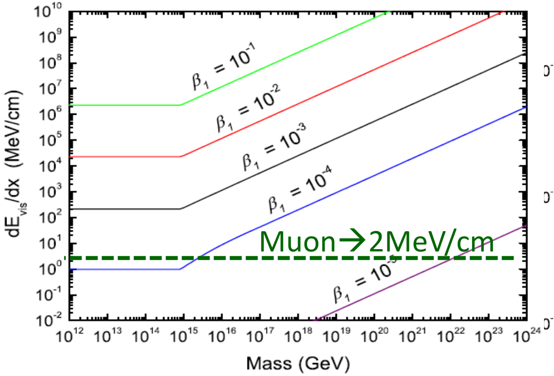
GUT magnetic monopoles:

- GUTs predict existence of monopoles, which can be produced in the very early Universe
- Mass: $M_M \sim 10^{16} - 10^{18}$ GeV; Velocity: $\beta \sim 10^{-3}$; Charge : $g = n\, g_D$

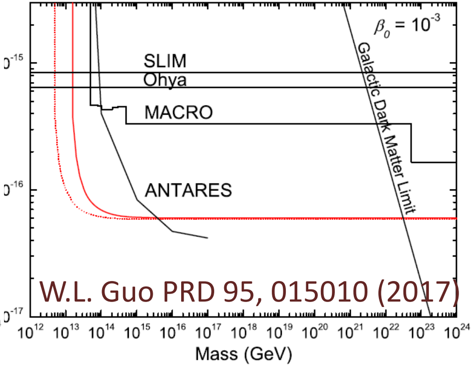


(a)

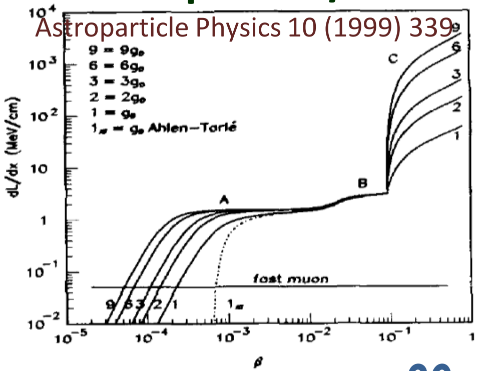
Nuclearites dE/dx



Nuclearites sensitivity



Monopole dL/dx

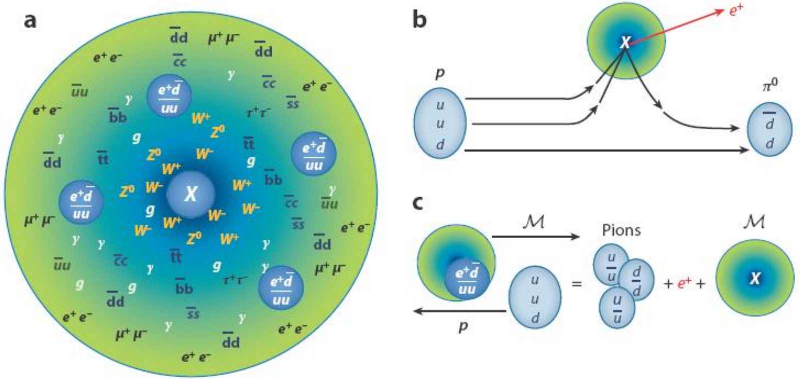


Continuous trigger events in a line with the same energy for long time in JUNO LS!!!

Proton decays catalyzed by GUT monopoles

Monopole catalyze proton decays:

- **Rubakov-Callen effect,** GUT model dependent
- Catalysis cross section σ_R is the order of **strong interaction**



Monopole propagate in LS:

Discrete trigger events in a line with the same energy for long time in JUNO LS!!!

Detect neutrinos from Monopole-catalyzed proton decay in Sun:

$M + p \to M + \mu^+ + K^0,\ K^0 + p \to K^+ + n, K^+ \to \mu^+ + \nu_\mu (236\ \mathrm{MeV})$ H.Hu, W.L. Guo et al, JCAP 06 (2022) 003

$n-\bar{n}$ oscillation:

$\bar{n}$ + nucleon annihilation in nucleus:

ID	Channel	ID	Channel
1	$p+\bar{n}\rightarrow\pi^{+}+\pi^{0}$	9	$n+\bar{n}\rightarrow 2\pi^{0}$
2	$p+\bar{n}\rightarrow\pi^{+}+2\pi^{0}$	10	$n+\bar{n}\rightarrow\pi^{+}+\pi^{-}+\pi^{0}$
3	$p+\bar{n}\rightarrow\pi^{+}+3\pi^{0}$	11	$n+\bar{n}\rightarrow\pi^{+}+\pi^{-}+2\pi^{0}$
4	$p+\bar{n}\rightarrow 2\pi^{+}+\pi^{-}+\pi^{0}$	12	$n+\bar{n}\rightarrow\pi^{+}+\pi^{-}+3\pi^{0}$
5	$p+\bar{n}\rightarrow 2\pi^{+}+\pi^{-}+2\pi^{0}$	13	$n+\bar{n}\rightarrow 2\pi^{+}+2\pi^{-}$
6	$p+\bar{n}\rightarrow 2\pi^{+}+\pi^{-}+2\omega$	14	$n+\bar{n}\rightarrow 2\pi^{+}+2\pi^{-}+\pi^{0}$
7	$p+\bar{n}\rightarrow 3\pi^{+}+2\pi^{-}+\pi^{0}$	15	$n+\bar{n}\rightarrow\pi^{+}+\pi^{-}+\omega$
8	$n+\bar{n}\rightarrow\pi^{+}+\pi^{-}$	16	$n+\bar{n}\rightarrow 2\pi^{+}+2\pi^{-}+2\pi^{0}$

Similar with Nucleon decays, ~ 2 GeV, more FSI

Will be analyzed in future

Summary

- JUNO is one of future three influential nucleon decay experiments.
- JUNO has competitive sensitivities for some nucleon decay channels!
- JUNO can search some other new physical processes.

Thanks for your attention!