Nucleon Decay Searches in Atmospheric Neutrino Detectors

Volodymyr Takhistov

(University of California, Los Angeles)

PANE-2018, ICTP-Trieste

(5.31.2018)

Baryon number violation

- Baryon number (B) is accidental global symmetry of Standard Model (SM)

  → lightest baryon (proton) stable

Baryon number violation

- Baryon number (B) is accidental global symmetry of Standard Model (SM)

  → lightest baryon (proton) stable

- Already within SM, B is violated by a tiny amount (t'Hooft instantons)

Baryon number violation

- Baryon number (B) is accidental global symmetry of Standard Model (SM)

  → lightest baryon (proton) stable

- Already within SM, B is violated by a tiny amount (t'Hooft instantons)

- SM incomplete, expect $\cancel{B}$ from BSM physics

  - requirement for baryogensis (Sakharov conditions)
  - occurs in well motivated theories (GUTs, SUSY, extra-dimensions)
  - global symmetries violated by quantum gravity

Baryon number violation

- Baryon number (B) is accidental global symmetry of Standard Model (SM)

  → lightest baryon (proton) stable

- Already within SM, B is violated by a tiny amount (t'Hooft instantons)

- SM incomplete, expect $\not{B}$ from BSM physics

  - requirement for baryogensis (Sakharov conditions)
  - occurs in well motivated theories (GUTs, SUSY, extra-dimensions)
  - global symmetries violated by quantum gravity

→ **proton decay**

Proton decay: GUTs

- Grand Unified Theories (GUTs) unify SM gauge groups

  -- explain charge quantization, unification of couplings, anomaly cancellation

  -- leptons <--> quarks interact via new gauge bosons --> mediate proton decay

Proton decay: GUTs

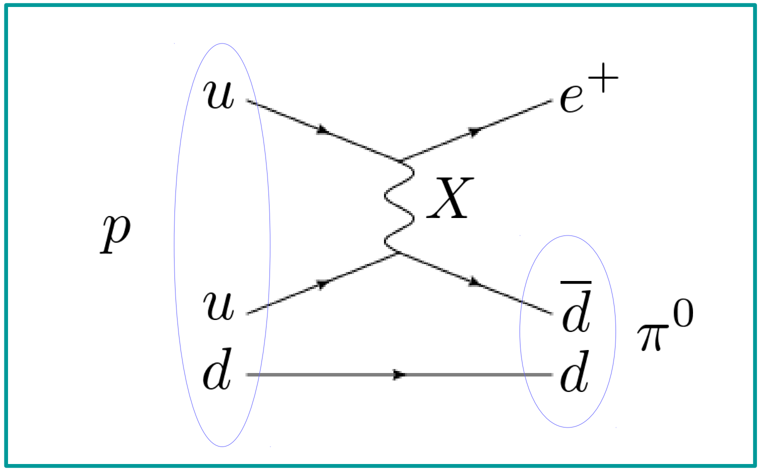
- Grand Unified Theories (GUTs) unify SM gauge groups

  -- explain charge quantization, unification of couplings, anomaly cancellation

  -- leptons <--> quarks interact via new gauge bosons --> mediate proton decay

- Dominant channel typically $\boxed{p \rightarrow e^+ \pi^0}$

$$SU(5)$$



lifetime

$$\tau = \frac{1}{\Gamma} \approx \left[\frac{M_X^2}{\alpha^2}\right]^2 m_p^5$$

Proton decay: GUTs

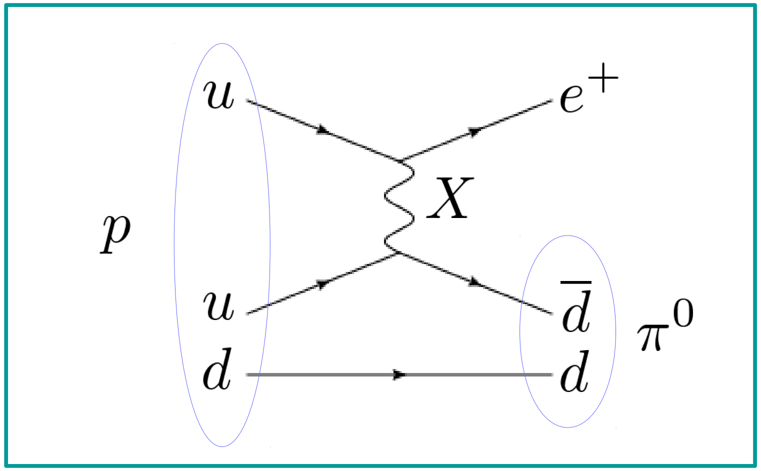
- Grand Unified Theories (GUTs) unify SM gauge groups

  -- explain charge quantization, unification of couplings, anomaly cancellation

  -- leptons <--> quarks interact via new gauge bosons --> mediate proton decay

- Dominant channel typically $\boxed{p \to e^+ \pi^0}$

$SU(5)$



lifetime

$$\tau = \frac{1}{\Gamma} \approx \left[\frac{M_X^2}{\alpha^2}\right]^2 m_p^5$$

- Predicted lifetime $\tau \sim 10^{29-36}$ yrs

- Minimal model ruled out (IMB-3, Kamiokande, Super-K)

Proton decay: SUSY GUTs

- Add supersymmetry (SUSY)

  -- gauge coupling unification becomes precise (at higher energies)

  -- super-partners can now also mediate proton decay

- Add supersymmetry (SUSY)

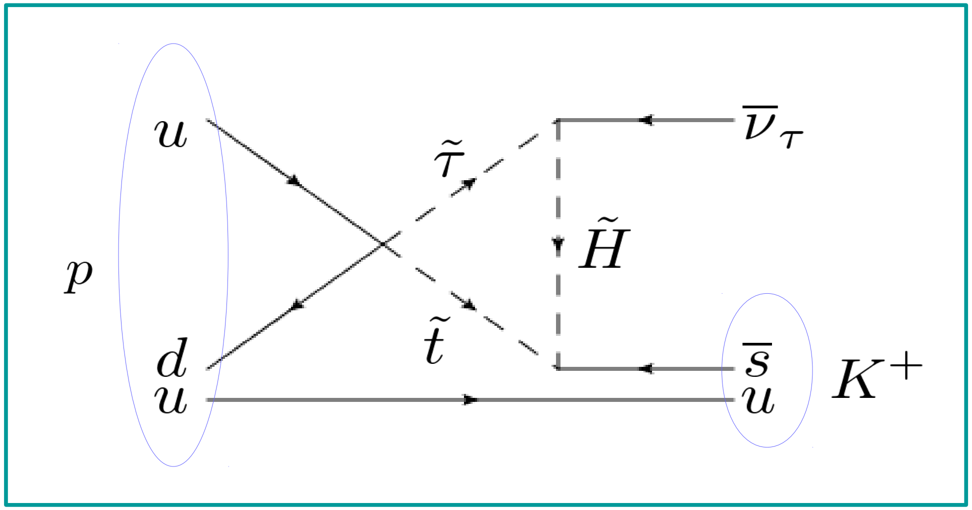
  -- gauge coupling unification becomes precise (at higher energies)

  -- super-partners can now also mediate proton decay

- Dominant channel typically $\boxed{p \to \overline{\nu} K^+}$

SUSY

$SU(5)$



lifetime

$$\tau = \frac{1}{\Gamma} \approx \left[\frac{M_{\tilde{s}} M_T}{\alpha^2}\right]^2 m_p^5$$

Proton decay: SUSY GUTs

- Add supersymmetry (SUSY)

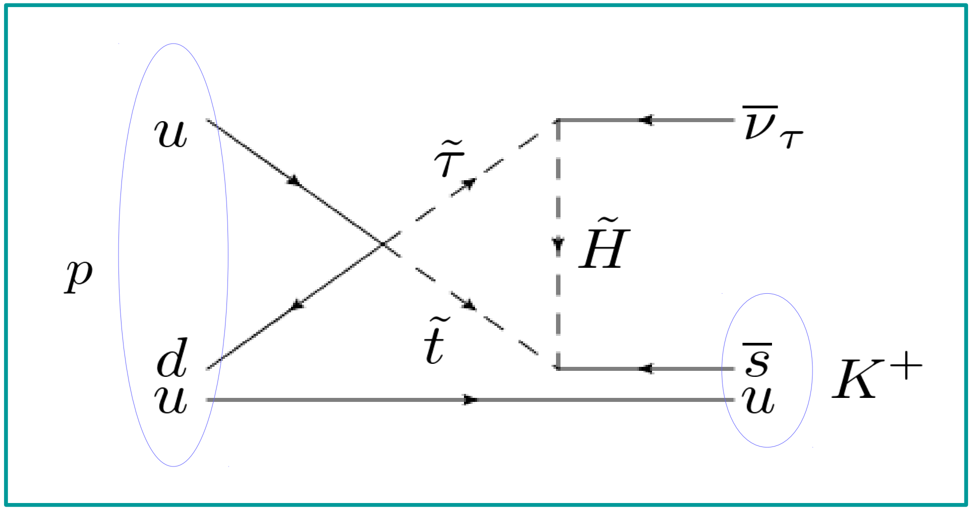
  -- gauge coupling unification becomes precise (at higher energies)

  -- super-partners can now also mediate proton decay

- Dominant channel typically $\boxed{p \to \overline{\nu} K^+}$

SUSY

$SU(5)$



lifetime

$$\tau = \frac{1}{\Gamma} \approx \left[\frac{M_{\tilde{s}} M_T}{\alpha^2}\right]^2 m_p^5$$

- Predicted lifetime $\tau \sim 10^{29-36}$ yrs

- Minimal (TeV-)SUSY model ruled out (Super-K) **[Kobayashi+ (SK), 2005]**

Proton decay: models

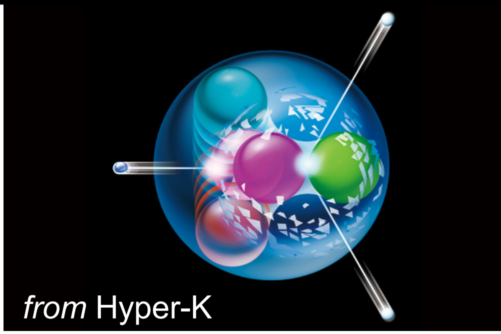
Model	Ref.	Modes	τ_N (years)
Minimal $SU(5)$	Georgi, Glashow [2]	$p \to e^+\pi^0$	$10^{30} - 10^{31}$
Minimal SUSY $SU(5)$	Dimopoulos, Georgi [11], Sakai [12] Lifetime Calculations: Hisano, Murayama, Yanagida [13]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{28} - 10^{32}$
SUGRA $SU(5)$	Nath, Arnowitt [14, 15]	$p \to \bar{\nu}K^+$	$10^{32} - 10^{34}$
SUSY $SO(10)$ with anomalous flavor $U(1)$	Shafi, Tavartkiladze [16]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$ $p \to \mu^+K^0$	$10^{32} - 10^{35}$
SUSY $SO(10)$ MSSM (std. $d=5$)	Lucas, Raby [17], Pati [18]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{33} - 10^{34}$ $10^{32} - 10^{33}$
SUSY $SO(10)$ ESSM (std. $d=5$)	Pati [18]	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d=5$)	Babu, Pati, Wilczek [19, 20, 21], Pati [18]	$p \to \bar{\nu}K^+$ $p \to \mu^+K^0$	$\lesssim 2 \cdot 10^{34}$ $B \sim (1-50)\%$
SUSY $SU(5)$ or $SO(10)$ MSSM ($d=6$)	Pati [18]	$p \to e^+\pi^0$	$\sim 10^{34.9\pm1}$
Flipped $SU(5)$ in CMSSM	Ellis, Nanopoulos and Wlaker[22]	$p \to e/\mu^+\pi^0$	$10^{35} - 10^{36}$
Split $SU(5)$ SUSY	Arkani-Hamed, *et. al.* [23]	$p \to e^+\pi^0$	$10^{35} - 10^{37}$
$SU(5)$ in 5 dimensions	Hebecker, March-Russell[24]	$p \to \mu^+K^0$ $p \to e^+\pi^0$	$10^{34} - 10^{35}$
$SU(5)$ in 5 dimensions option II	Alciati *et.al.*[25]	$p \to \bar{\nu}K^+$	$10^{36} - 10^{39}$
GUT-like models from Type IIA string with D6-branes	Klebanov, Witten[26]	$p \to e^+\pi^0$	$\sim 10^{36}$

TABLE I: Summary of the expected nucleon lifetime in different theoretical models.

A. Bueno et al. hep-ph/0701101

Plethora of Models

Proton decay: general


from Hyper-K

General consequence of $\cancel{B}$

proton decay

unique test of high energy scales, un-accessible to accelerators

determines ultimate fate of universe

constrain (rule out) theory models

often connected to other physics (neutrino masses, etc.)

Proton decay: general

General consequence of $\not{B}$

proton decay

unique test of high energy scales, un-accessible to accelerators

determines ultimate fate of universe

constrain (rule out) theory models

often connected to other physics (neutrino masses, etc.)

- Many related processes ($n-\overline{n}$, di-/tri-nucleon decays, exotic n-decays)
- Specific predictions for main channel and lifetimes strongly model-dependent

Proton decay: searches

- Proton lives $> 10^{30}$ years .... **how to test if decays?**

A) look at 1 proton for VERY long time

B) look at many protons simultaneously for few years

- Proton lives $> 10^{30}$ years .... **how to test if decays?**

~~A) look at 1 proton for VERY long time~~

B) look at many protons simultaneously for few years

Proton decay: searches

- Proton lives $> 10^{30}$ years .... **how to test if decays?**

~~A) look at 1 proton for VERY long time~~

B) look at many protons simultaneously for few years

large underground water Cherenkov experiments

many protons ✓

cheap, proven technology ✓

State of the Art

Super-Kamiokande

State of the Art

Super-Kamiokande

Kamioka Nucleon Decay Experiment

The Super-Kamiokande Experiment

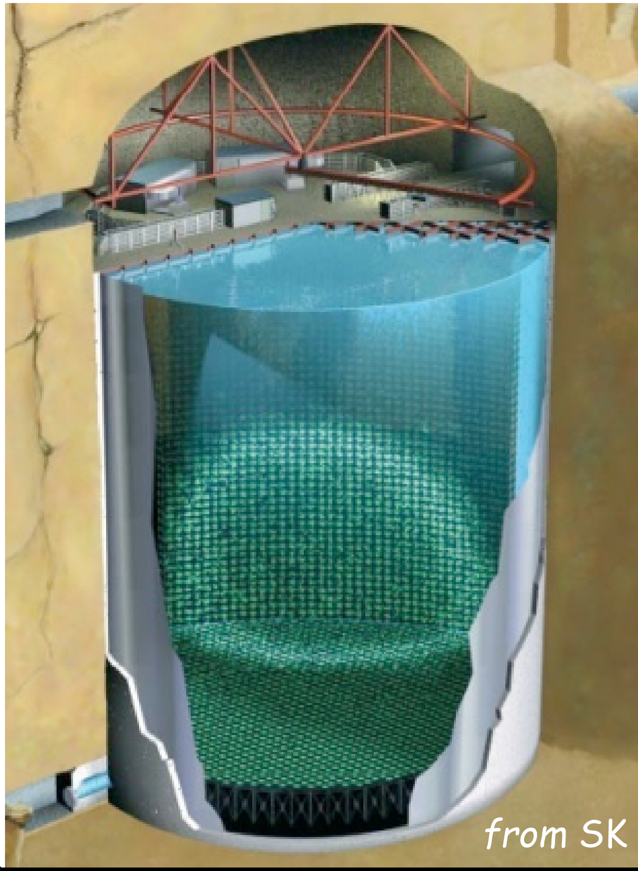
- Experimental setup (Kamioka, Japan)

  -- 22.5 kton fiducial volume

  -- inner (11k PMTs, 40% coverage) & outer (2k PMTs) detectors

  -- **4 run periods:**
  SK-I (1996 - 2001)
  SK-II (2003 - 2005): accident, $\frac{1}{2}$ PMT coverage
  SK-III (2006 - 2008): restore PMT coverage
  SK-IV (2008 - now): upgraded electronics

Super-Kamiokande (SK)



from SK

The Super-Kamiokande Experiment

- Experimental setup (Kamioka, Japan)

  -- 22.5 kton fiducial volume

  -- inner (11k PMTs, 40% coverage) & outer (2k PMTs) detectors

  -- **4 run periods:**
  SK-I (1996 - 2001)
  SK-II (2003 - 2005): accident, $\frac{1}{2}$ PMT coverage
  SK-III (2006 - 2008): restore PMT coverage
  SK-IV (2008 - now): upgraded electronics

- AMAZING multipurpose physics detector ($\sim 10 - 10^4$ MeV)

  -- ν-oscillations, Lorentz invariance, sterile-ν

  -- nucleon decay

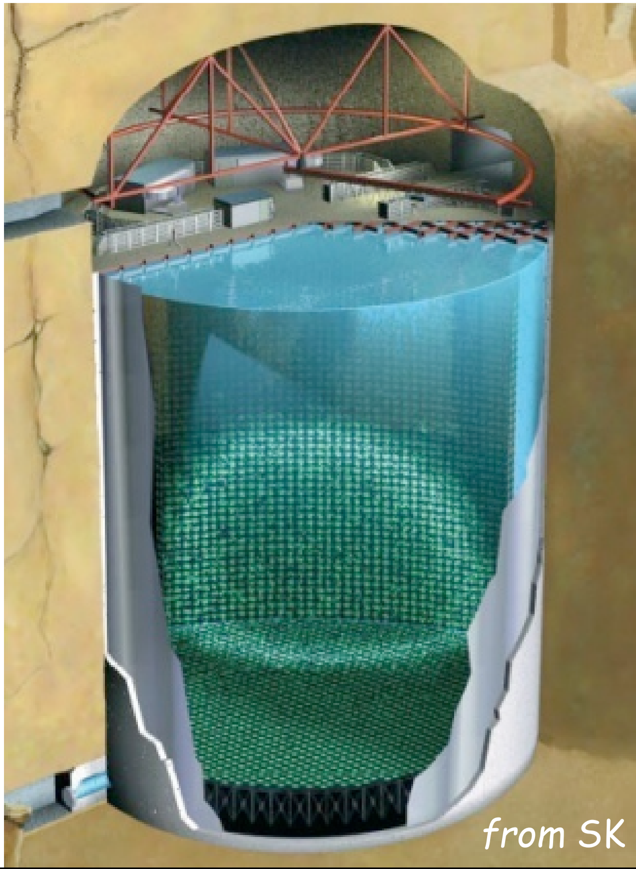
  -- solar-ν, day/night effect, supernovae relic ν's

  -- indirect dark matter detection

  -- exotics (monopoles, Q-balls, etc.)

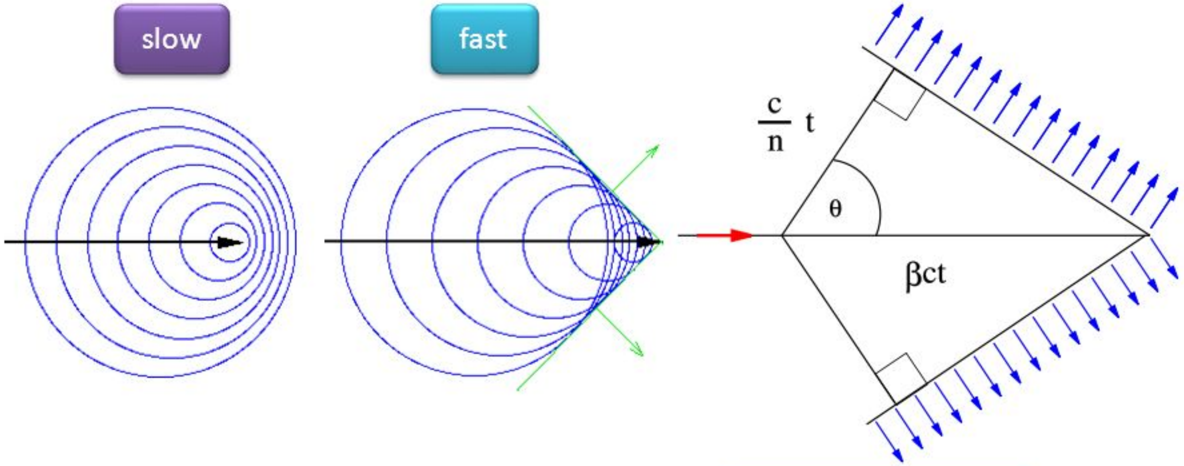
2015
Nobel Prize
(ν-oscillations)

Super-Kamiokande (SK)



from SK

Technique: Cherenkov ring imaging

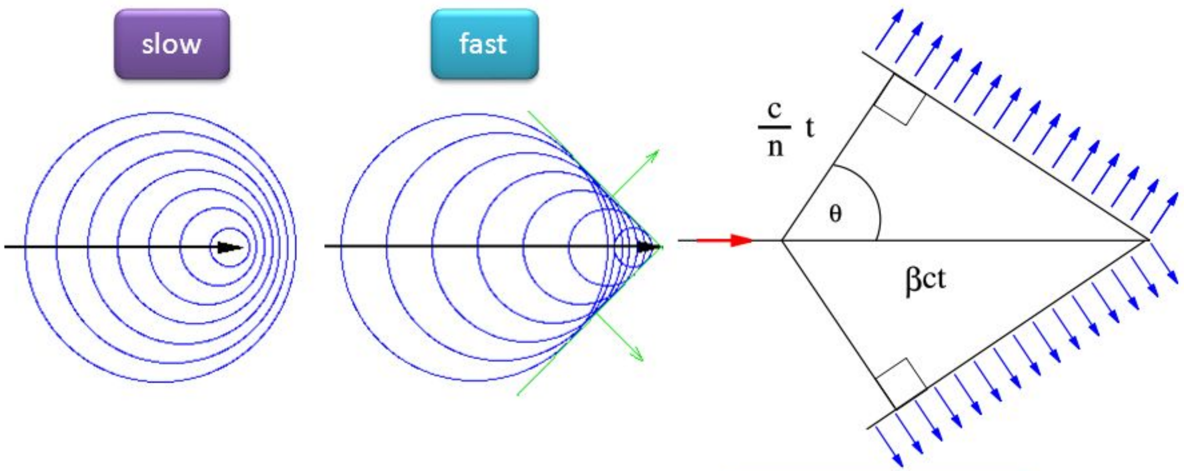


$$\cos\theta_c = 1/\beta n$$

Cherenkov radiation

charged particle travels
in medium (ref. index n)
faster than light,
builds up wave-front

Technique: Cherenkov ring imaging



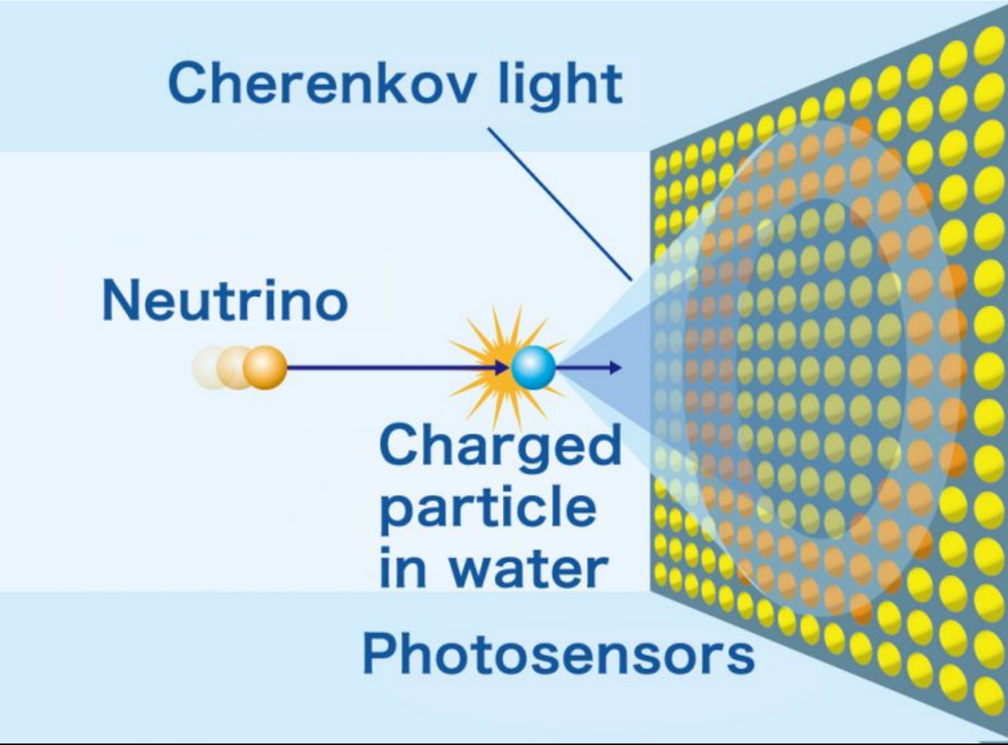
$$\cos\theta_c = 1/\beta n$$

Cherenkov radiation

charged particle travels
in medium (ref. index n)
faster than light,
builds up wave-front

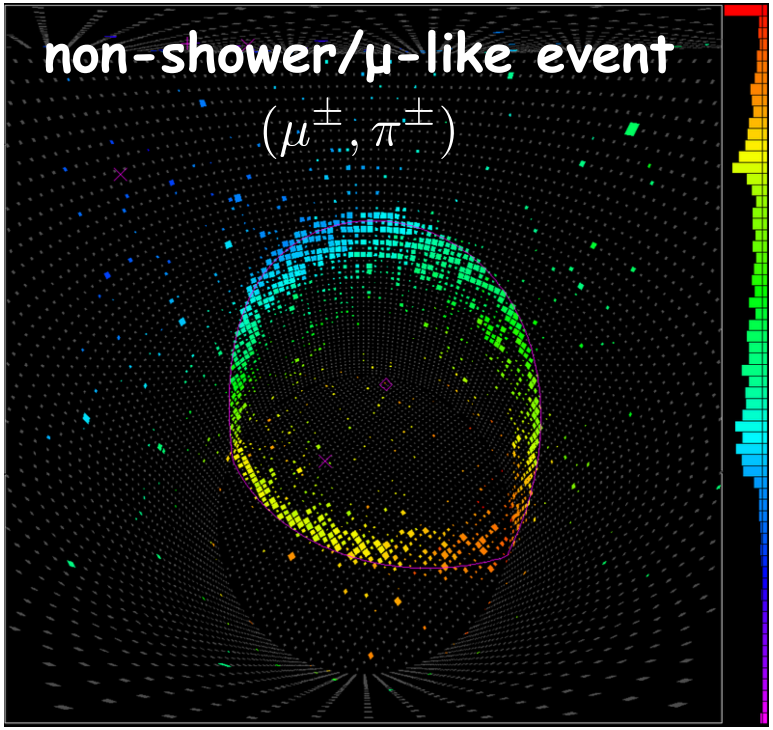
ring imaging

ring-shaped pattern
from Cherenkov radiation
detected by PMTs



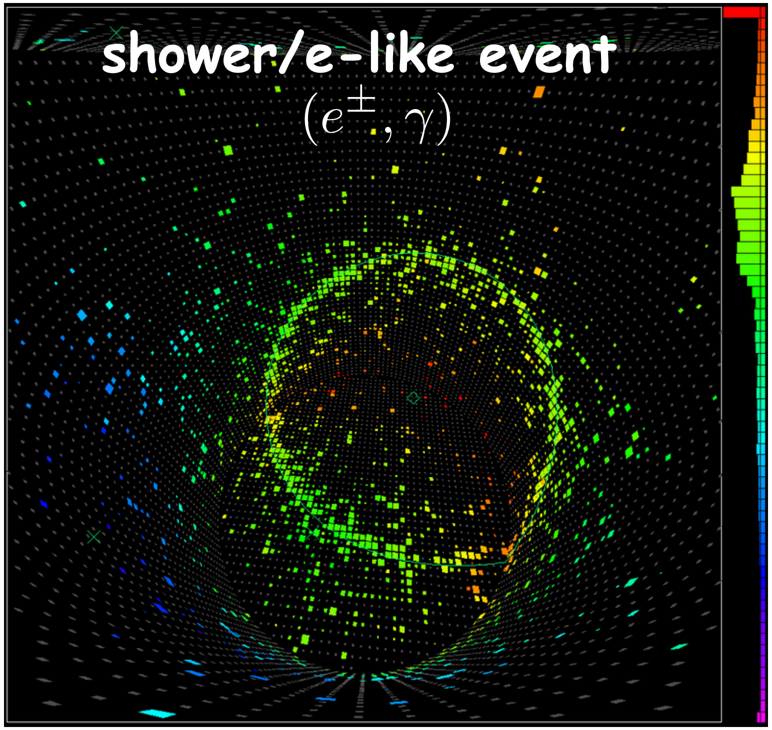
from physicsopenlab.org

SK event display



(recorded on 1998.04.04 08:35:22)

-- energy 603 MeV
-- time width 162 ns



(recorded on 1998.04.04 21:26:08)

-- energy 492 MeV
-- time width 130 ns

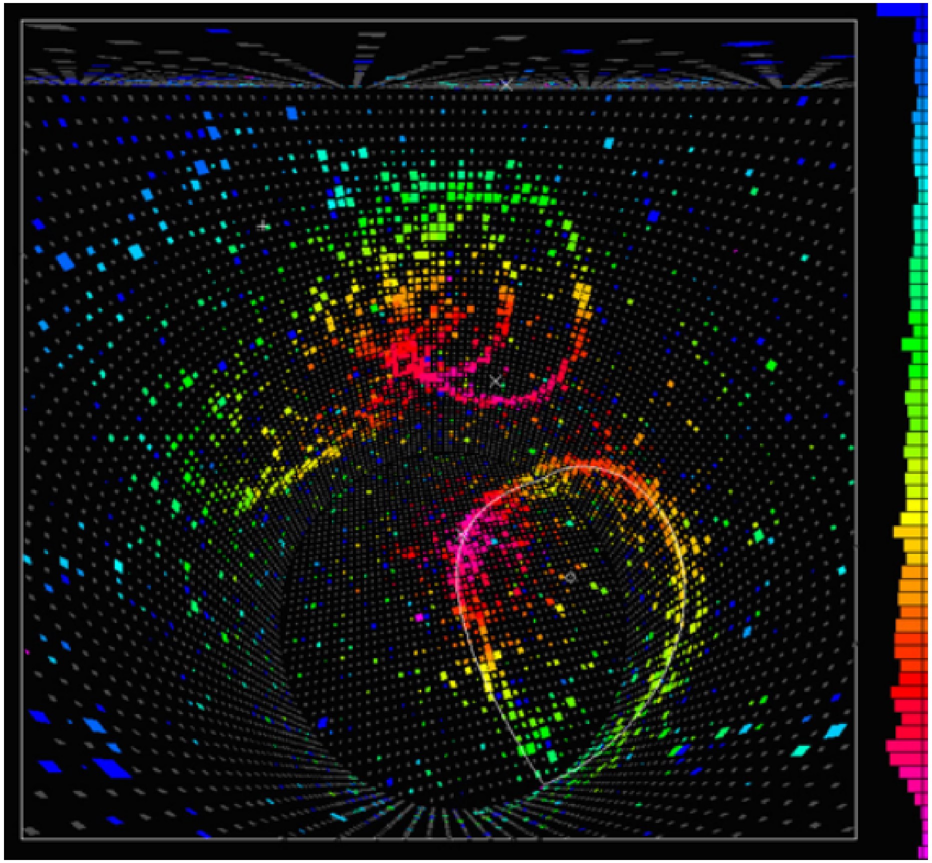
(1) Signal – proton decay

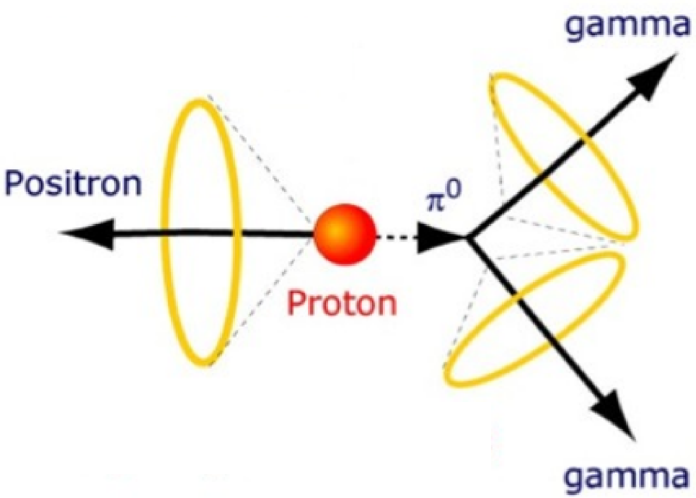
"Golden channel": $p \rightarrow \pi^0 e^+$

$\pi^0 \rightarrow 2\gamma$

$p_\pi = p_e = 459$ MeV

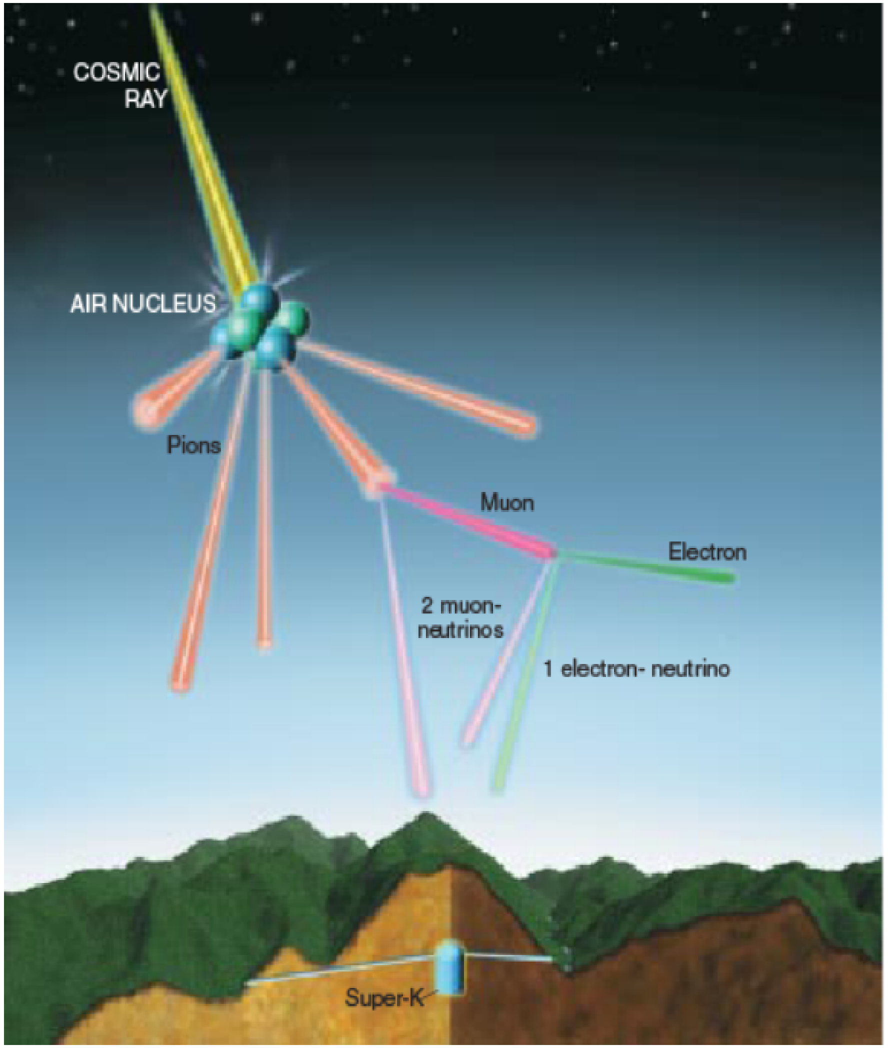
$p_{\gamma/\pi R} = 68$ MeV

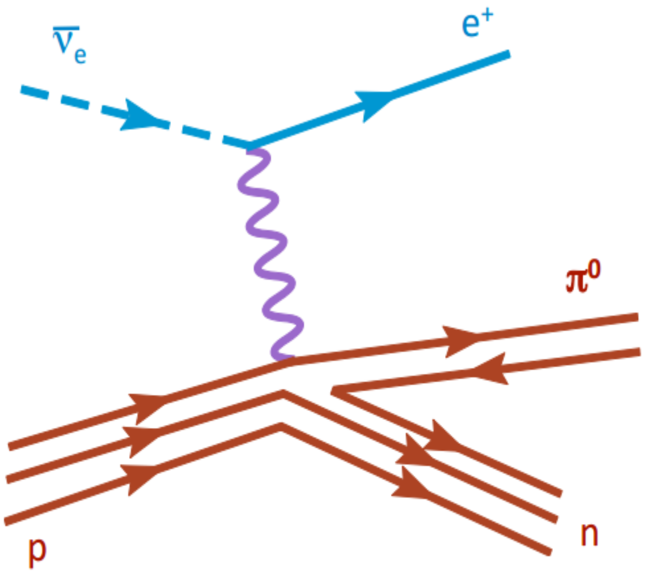




Detecting nucleon decay

(2) Background - atmospheric neutrinos





(3) Setting Limit

$$\frac{\tau}{B} = \frac{\lambda\varepsilon}{n-b}$$

n = number of observed events

b = expected number of background events

λ = exposure = $N_{proton} \cdot \Delta t$

ε = efficiency

$$\frac{\tau}{B} = \frac{\lambda\varepsilon}{S_{90}}$$

$$S_{90} = \frac{\int_0^{S_{90}} P_{poiss.}(n, x+b)dx}{\int_0^{\infty} P_{poiss.}(n, x+b)dx}$$

use Bayes' method to treat systematics

$$P(\Gamma \mid n) = \iiint \frac{e^{-\Gamma\lambda\varepsilon + b}(\Gamma\lambda\varepsilon + b)^n}{n!} P(\Gamma)\; P(\lambda)\; P(\varepsilon)\; P(b)\; d\Gamma\; d\lambda\; d\varepsilon\; db$$

Search: $\mathbf{p} \rightarrow \mathbf{e}^{+}\pi^{\mathbf{0}}$

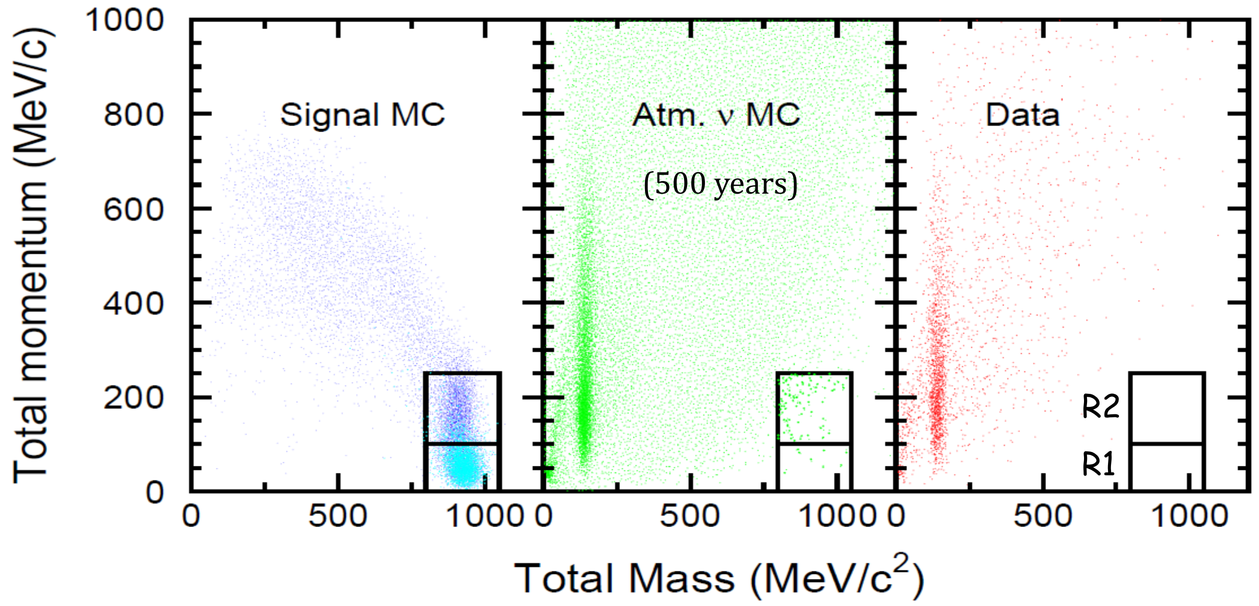
- **Motivation:** *"golden"* dominant GUT channel **[Abe+ (SK), 2016]**
- **Signature:** $e^{+}, \pi^{0}(\rightarrow 2\gamma)$ visible --> fully reconstruct parent proton
- **Analysis:**

- **Results:**

Search: $\mathbf{p \to e^+\pi^0}$

- **Motivation:** *"golden"* dominant GUT channel **[Abe+ (SK), 2016]**
- **Signature:** $e^+, \pi^0(\to 2\gamma)$ visible --> fully reconstruct parent proton
- **Analysis:**

SK I-IV



- **Results:**

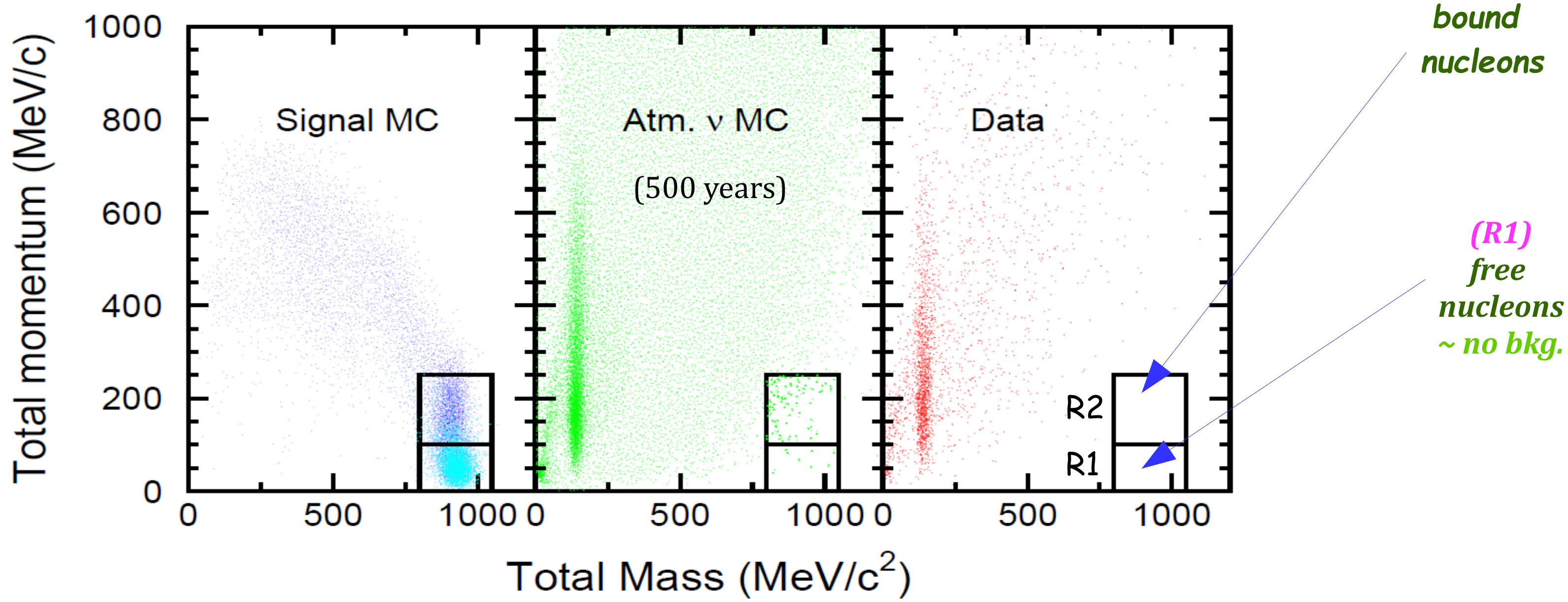
exposure: 306 kt-yrs

SK I-IV	R1+R2
Efficiency	~ 40 %
BKG	0.62
Data	0

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

- **Motivation:** *"golden"* dominant GUT channel [Abe+ (SK), 2016]
- **Signature:** $e^+, \pi^0(\to 2\gamma)$ visible --> fully reconstruct parent proton
- **Analysis:**

SK I-IV



- **Results:**

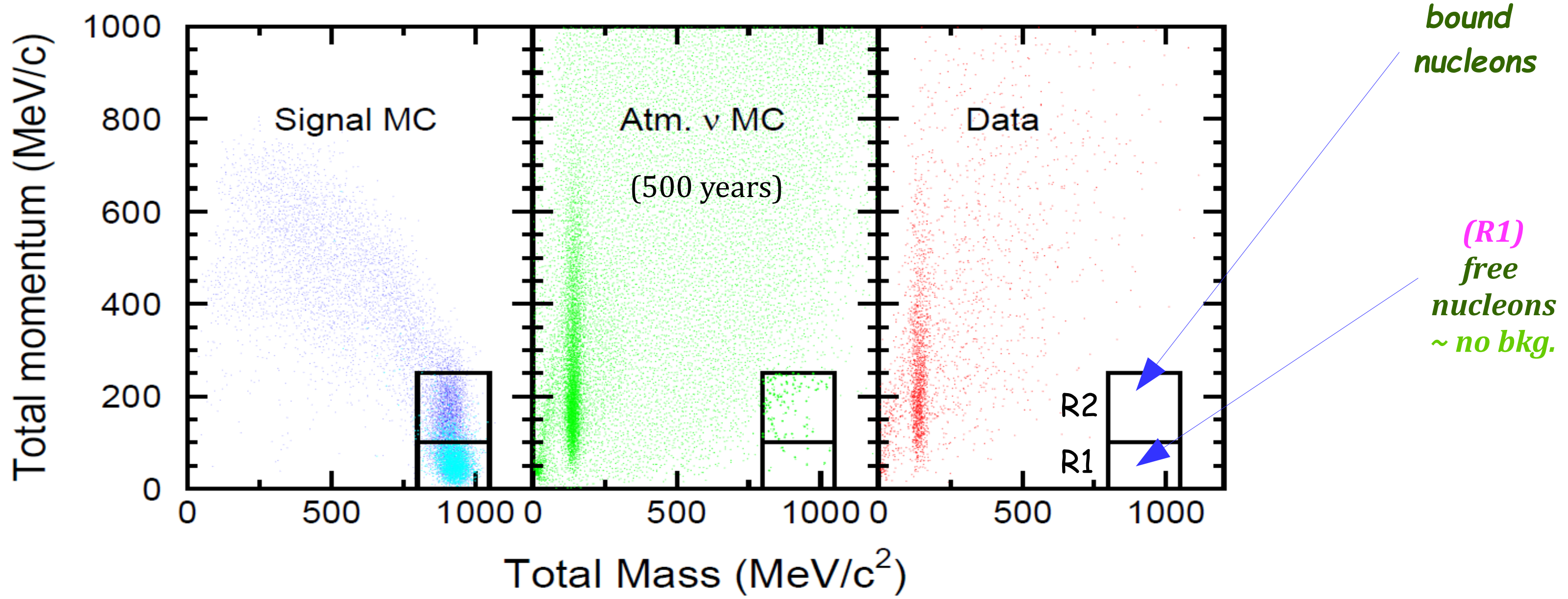
exposure: 306 kt-yrs

SK I-IV	R1+R2
Efficiency	~ 40 %
BKG	0.62
Data	0

Search: $\mathrm{p} \rightarrow \mathrm{e}^+\pi^0$

- **Motivation:** *"golden"* dominant GUT channel **[Abe+ (SK), 2016]**
- **Signature:** $e^+, \pi^0(\rightarrow 2\gamma)$ visible --> fully reconstruct parent proton
- **Analysis:**

SK I-IV



- **Results:** NO excess

limit → $\tau_p > 1.7 \times 10^{34}$ yrs.

exposure: 306 kt-yrs

SK I-IV	R1+R2
Efficiency	~ 40 %
BKG	0.62
Data	0

Search: $\mathbf{p} \rightarrow \mu^{+}\pi^{\mathbf{0}}$

[Abe+ (SK), 2016]

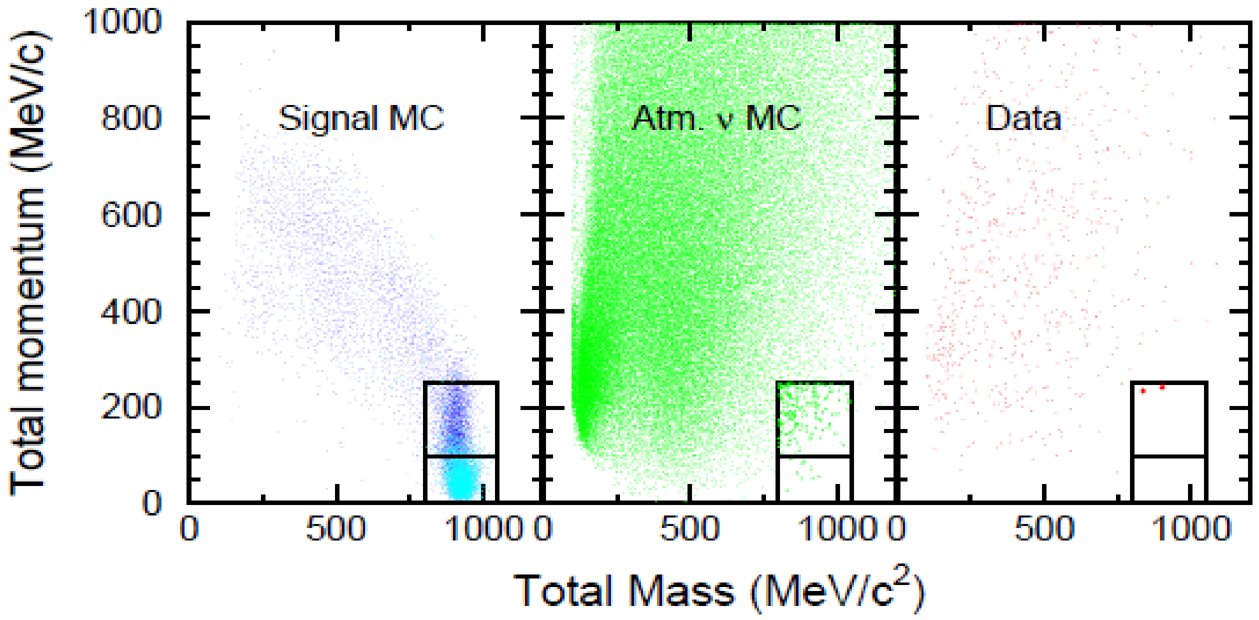
- **Motivation:** dominates in some models (flipped SU(5))
- **Signature:** $\mu^{+}(\rightarrow e^{+}\,2\nu), \pi^{0}(\rightarrow 2\gamma)$ visible --> fully reconstruct proton
- **Analysis**:
- **Results:**

Search: $p \rightarrow \mu^+\pi^0$

[Abe+ (SK), 2016]

- **Motivation:** dominates in some models (flipped SU(5))
- **Signature:** $\mu^+(\rightarrow e^+\,2\nu), \pi^0(\rightarrow 2\gamma)$ visible --> fully reconstruct proton
- **Analysis:**

SK I-IV



- **Results:**

exposure: 306 kt-yrs

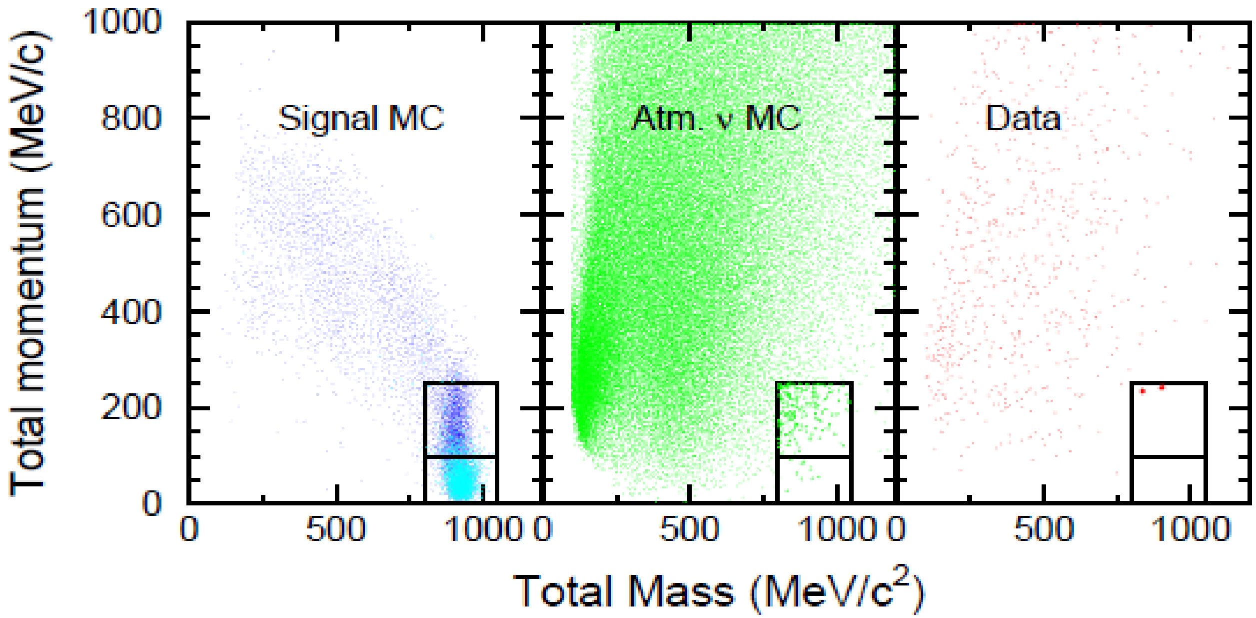
SK I-IV	R1+R2
Efficiency	~ 35 %
BKG	0.88
Data	2

Search: $\mathrm{p} \rightarrow \mu^+\pi^0$

[Abe+ (SK), 2016]

- **Motivation:** dominates in some models (flipped SU(5))
- **Signature:** $\mu^+(\rightarrow e^+ 2\nu), \pi^0(\rightarrow 2\gamma)$ visible --> fully reconstruct proton
- **Analysis:**

SK I-IV



- **Results:** 2 candidates, consistent with background

exposure: 306 kt-yrs

SK I-IV	R1+R2
Efficiency	~ 35 %
BKG	0.88
Data	2

NO excess $\xrightarrow{\text{limit}}$ $\boxed{\tau_p > 7.8 \times 10^{33} \text{ yrs.}}$

Search: $\mathbf{p \to \nu K^+}$

- **Motivation:** *"silver"* dominant SUSY-GUT channel **[Abe+ (SK), 2014]**
- **Signature:** $\nu, K^+(\to \mu^+\nu, \pi^0\pi^+)$ both invisible --> reconstruct Kaon decays
- **Analysis**:

Search: $\mathrm{p} \rightarrow \nu \mathrm{K}^+$

[Abe+ (SK), 2014]

- **Motivation:** *"silver"* dominant SUSY-GUT channel
- **Signature:** $\nu, K^+(\rightarrow \mu^+\nu, \pi^0\pi^+)$ both invisible --> reconstruct Kaon decays
- **Analysis:**

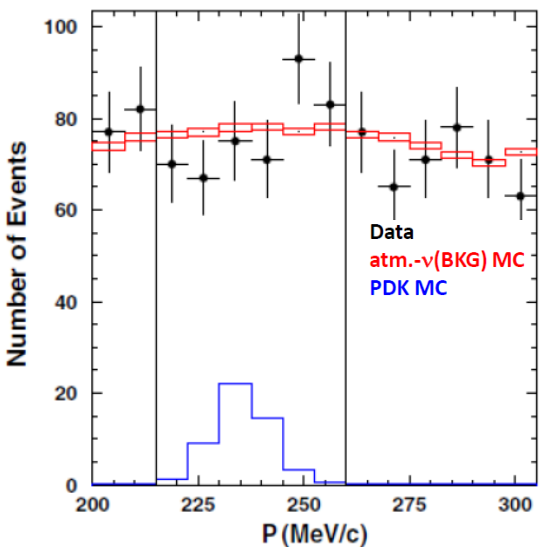
Search (A) $(K^+ \rightarrow \mu^+\nu)$ spectral fit to μ^+ momentum

Search (B) $(K^+ \rightarrow \mu^+\nu)$ tag γ from nuclear de-excitation

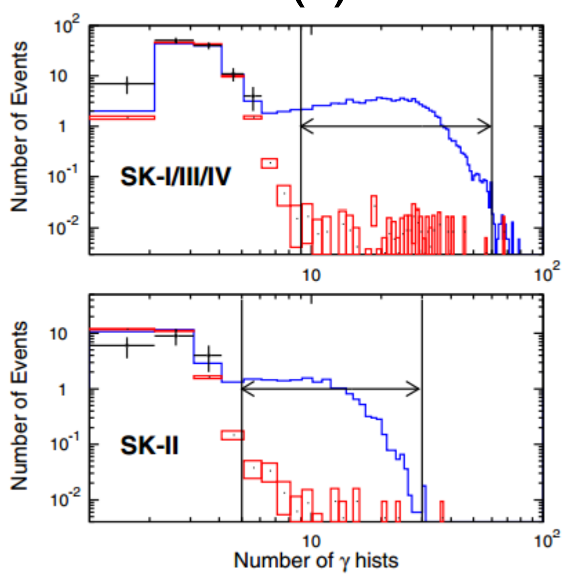
Search (C) $(K^+ \rightarrow \pi^0\pi^+)$ reconstruct pions

SK I-IV

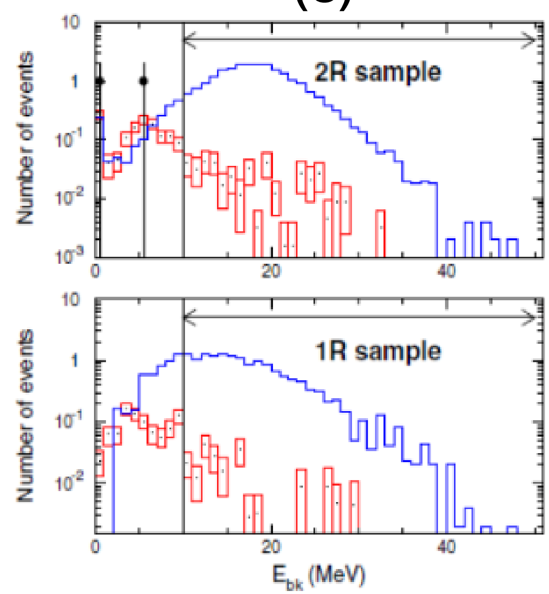
(A)



(B)



(C)



Search: $\mathrm{p} \rightarrow \nu \mathrm{K}^{+}$

- **Motivation:** *"silver"* dominant SUSY-GUT channel

[Abe+ (SK), 2014]

- **Signature:** $\nu, K^{+}(\rightarrow \mu^{+}\nu, \pi^{0}\pi^{+})$ both invisible --> reconstruct Kaon decays
- **Analysis:**

exposure: 260 kt-yrs

SK I-IV

SK I-IV	A	B	C
Efficiency	~ 34%	~ 8%	~ 8%
BKG	579.4	0.39	0.56
Data	566	0	0

- **Results:**

Search: $\mathrm{p} \rightarrow \nu \mathrm{K}^+$

- **Motivation:** *"silver"* dominant SUSY-GUT channel **[Abe+ (SK), 2014]**
- **Signature:** $\nu, K^+(\rightarrow \mu^+\nu, \pi^0\pi^+)$ both invisible --> reconstruct Kaon decays
- **Analysis:**

exposure: 260 kt-yrs

SK I-IV

SK I-IV	A	B	C
Efficiency	~ 34%	~ 8%	~ 8%
BKG	579.4	0.39	0.56
Data	566	0	0

- **Results:** NO excess $\xrightarrow{\text{limit}}$ $\boxed{\tau_p > 6.6 \times 10^{33} \text{ yrs.}}$

Search: $\mathrm{n} - \overline{\mathrm{n}}$ oscillation

- **Motivation:** $\Delta B = 2$, parametrizes $U(1)_{B-L}$ (as Majorana ν's), test intermediate scales
- **Signature:** $\overline{n}$ captured by nucleon (n or p) produces pions --> reconstruct initial state
- **Analysis**:

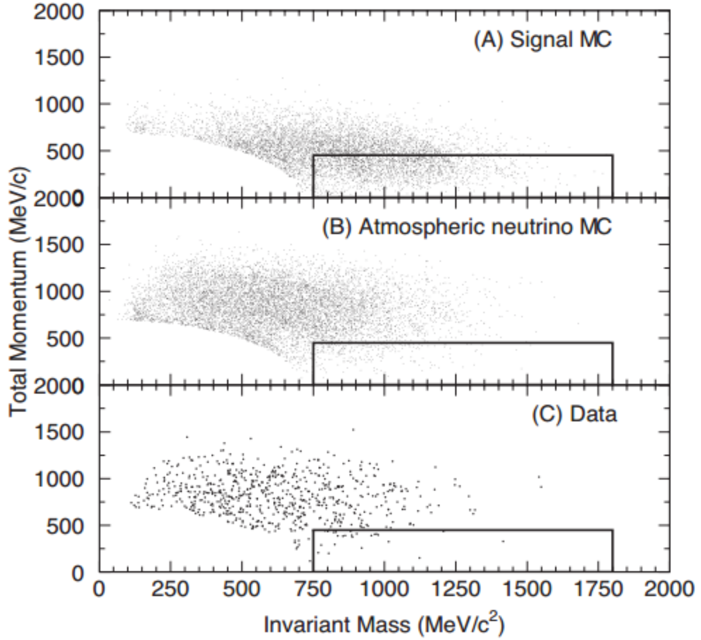
[Abe+ (SK), 2015]

- **Results:**

Search: $\mathrm{n} - \overline{\mathrm{n}}$ oscillation

- **Motivation:** $\Delta B = 2$, parametrizes $U(1)_{B-L}$ (as Majorana v's), test intermediate scales
- **Signature:** $\overline{n}$ captured by nucleon (n or p) produces pions --> reconstruct initial state
- **Analysis:**

SK I



[Abe+ (SK), 2015]

Exposure: 91.5 kt-yrs

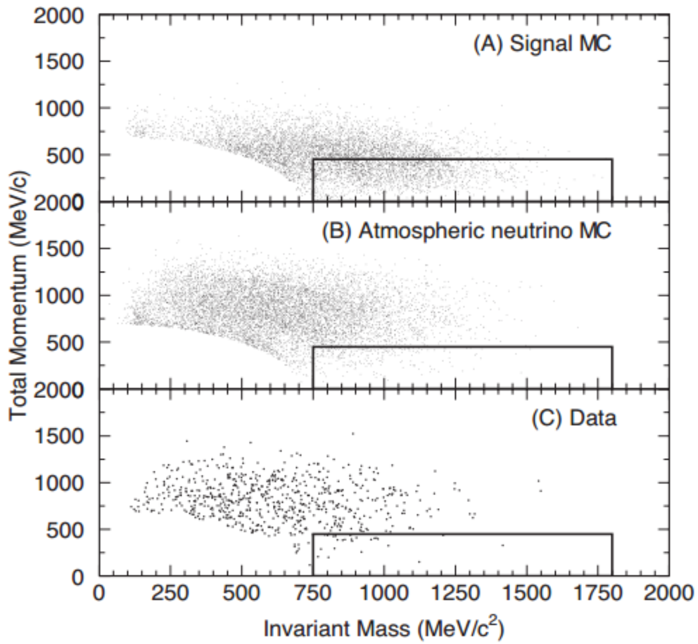
	SK I
Efficiency	~ 12%
BKG	24.1
Data	24

- **Results:**

Search: $n - \overline{n}$ oscillation

- **Motivation:** $\Delta B = 2$, parametrizes $U(1)_{B-L}$ (as Majorana ν's), test intermediate scales
- **Signature:** $\overline{n}$ captured by nucleon (n or p) produces pions --> reconstruct initial state
- **Analysis:**

SK I



[Abe+ (SK), 2015]

Exposure: 91.5 kt-yrs

	SK I
Efficiency	~ 12%
BKG	24.1
Data	24

- **Results:** NO excess $\xrightarrow{\text{limit}}$ $\boxed{\tau_{n-\overline{n}} > 1.9 \times 10^{32} \text{ yrs.}}$

(improved machine learning-based analysis on SK I-IV yields similar results)

Search: spectral 1-ring modes

- **Motivation:** broad search, Pati-Salam & extended Higgs models
- **Signature:** visible $e^+/\mu^+/\gamma$ --> spectral fit to ring momenta

[Takhistov+ (SK), *PRL* 2014]
[Takhistov+ (SK), *PRL* 2015]

- **Analysis**:
- **Results:**

Search: spectral 1-ring modes

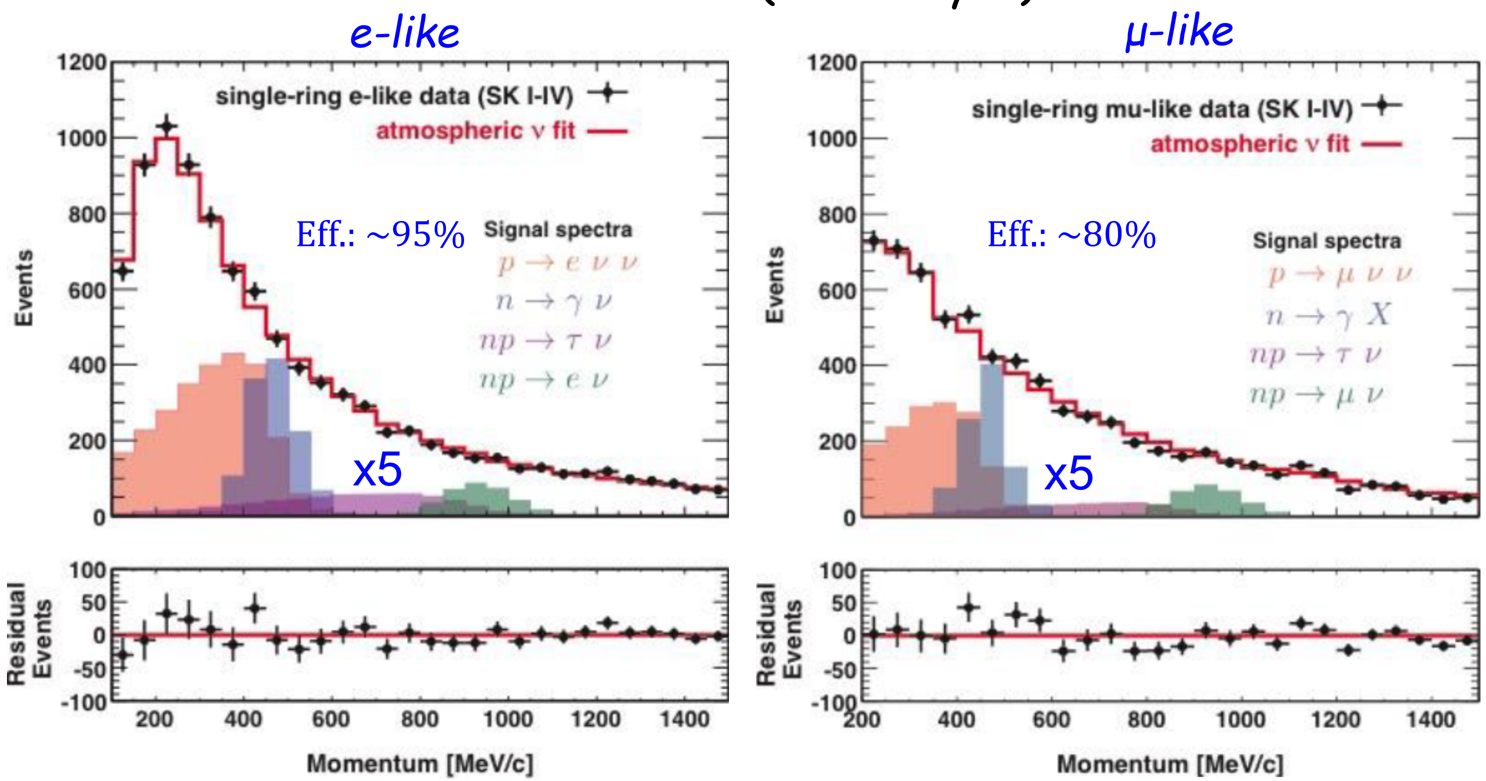
- **Motivation:** broad search, Pati-Salam & extended Higgs models
- **Signature:** visible $e^+/\mu^+/\gamma$ --> spectral fit to ring momenta

[Takhistov+ (SK), *PRL* 2014]
[Takhistov+ (SK), *PRL* 2015]

- **Analysis:**

$$p \to e^+\nu\nu$$
$$p \to \mu^+\nu\nu$$
$$p \to e^+X$$
$$p \to \mu^+X$$
$$np \to \mu^+\nu$$
$$np \to e^+\nu$$
$$np \to \tau^+\nu$$
$$n \to \gamma\nu$$

SK I-IV (263 kt-yrs)



- **Results:**

Search: spectral 1-ring modes

- **Motivation:** broad search, Pati-Salam & extended Higgs models
- **Signature:** visible $e^+/\mu^+/\gamma$ --> spectral fit to ring momenta

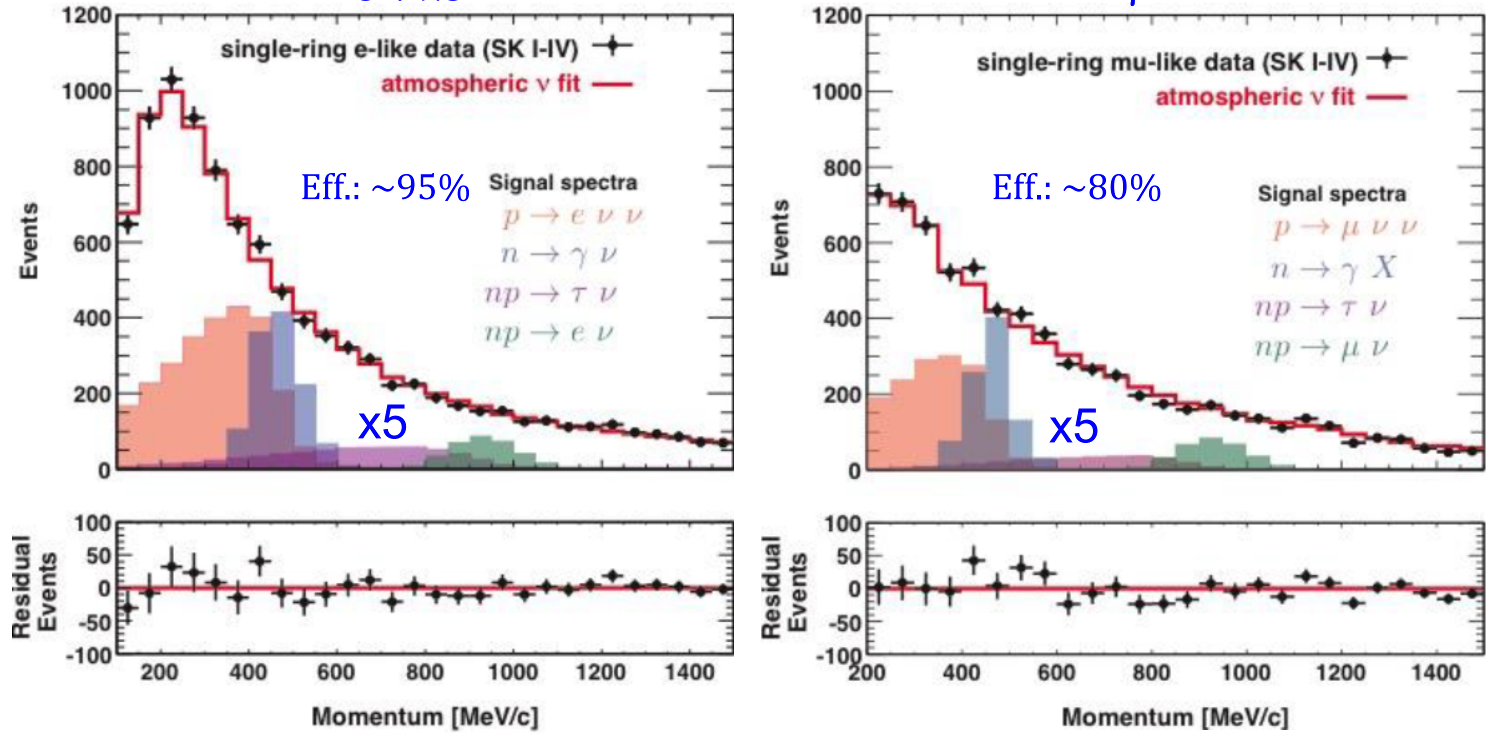
[Takhistov+ (SK), *PRL* 2014]
[Takhistov+ (SK), *PRL* 2015]

- **Analysis:**

$$\begin{array}{c} p \to e^+\nu\nu \\ p \to \mu^+\nu\nu \\ p \to e^+X \\ p \to \mu^+X \\ np \to \mu^+\nu \\ np \to e^+\nu \\ np \to \tau^+\nu \\ n \to \gamma\nu \end{array}$$

SK I-IV (263 kt-yrs)

e-like *μ-like*



- **Results:** NO excess $\xrightarrow{\text{limit}}$ $\boxed{\tau > \text{few} \times 10^{32}\ \text{yrs.}}$

Search: 2-body final states w/o hadrons

from **S. Sussman**
(PRELIMINARY)

- **Motivation:** broad search, extended Higgs, $H-\overline{H}$, probe low energy
- **Signature:** 2 visible leptons/gammas --> fully reconstruct initial state
- **Analysis:**
- **Results:**

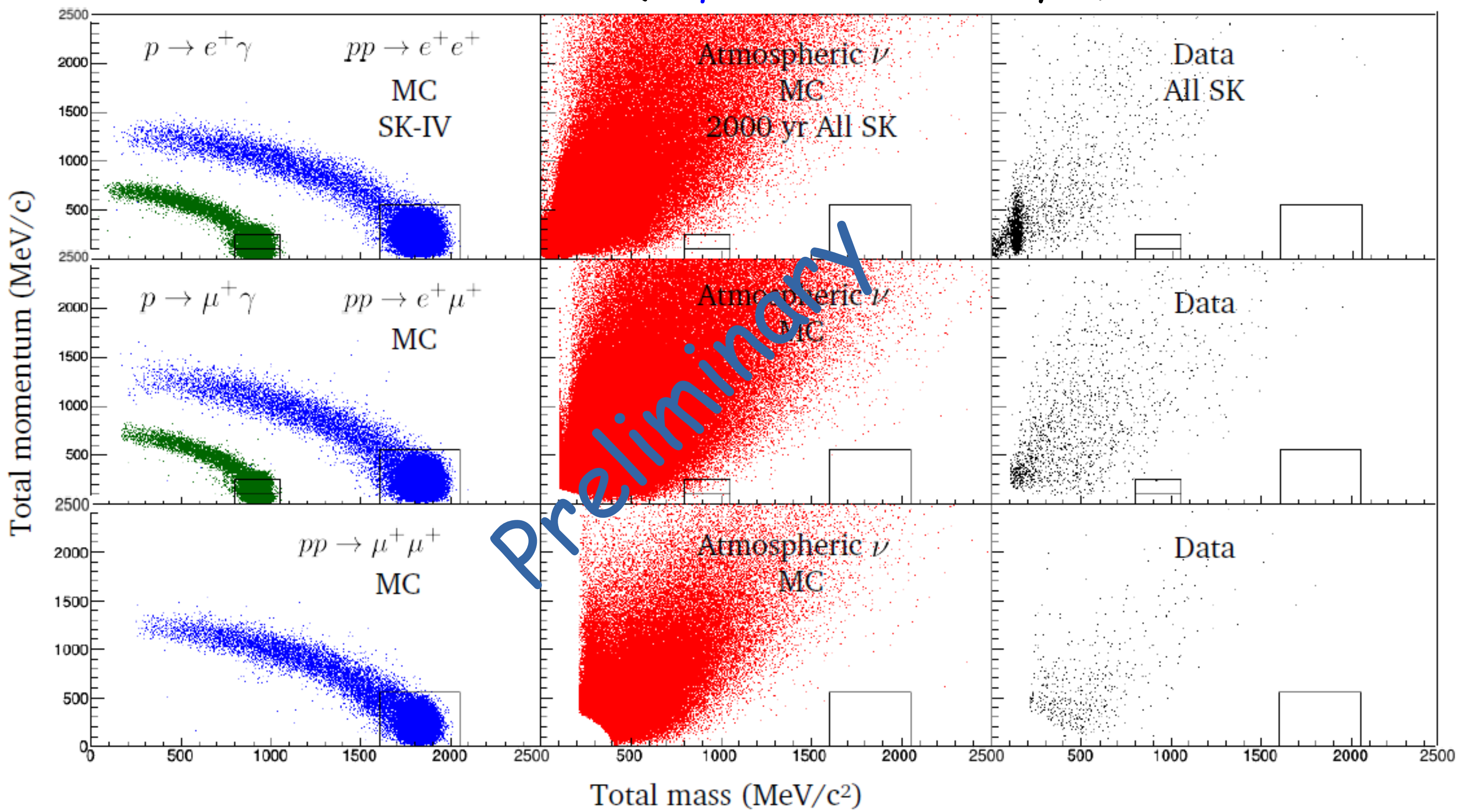
Search: 2-body final states w/o hadrons

- **Motivation:** broad search, extended Higgs, $H-\overline{H}$, probe low energy
- **Signature:** 2 visible leptons/gammas --> fully reconstruct initial state
- **Analysis:**

from **S. Sussman (PRELIMINARY)**

$p \to e^+\gamma$
$p \to \mu^+\gamma$
$pp \to e^+e^+$
$pp \to \mu^+e^+$
$pp \to \mu^+\mu^+$
$nn \to e^+e^-$
$nn \to \mu^+e^-$
$nn \to \mu^-e^+$
$nn \to \mu^+\mu^-$
$nn \to \gamma\gamma$

Eff.: ~80% SK I-IV (*Exposure:* 364.5 kt-yrs)



- **Results:**

Search: 2-body final states w/o hadrons

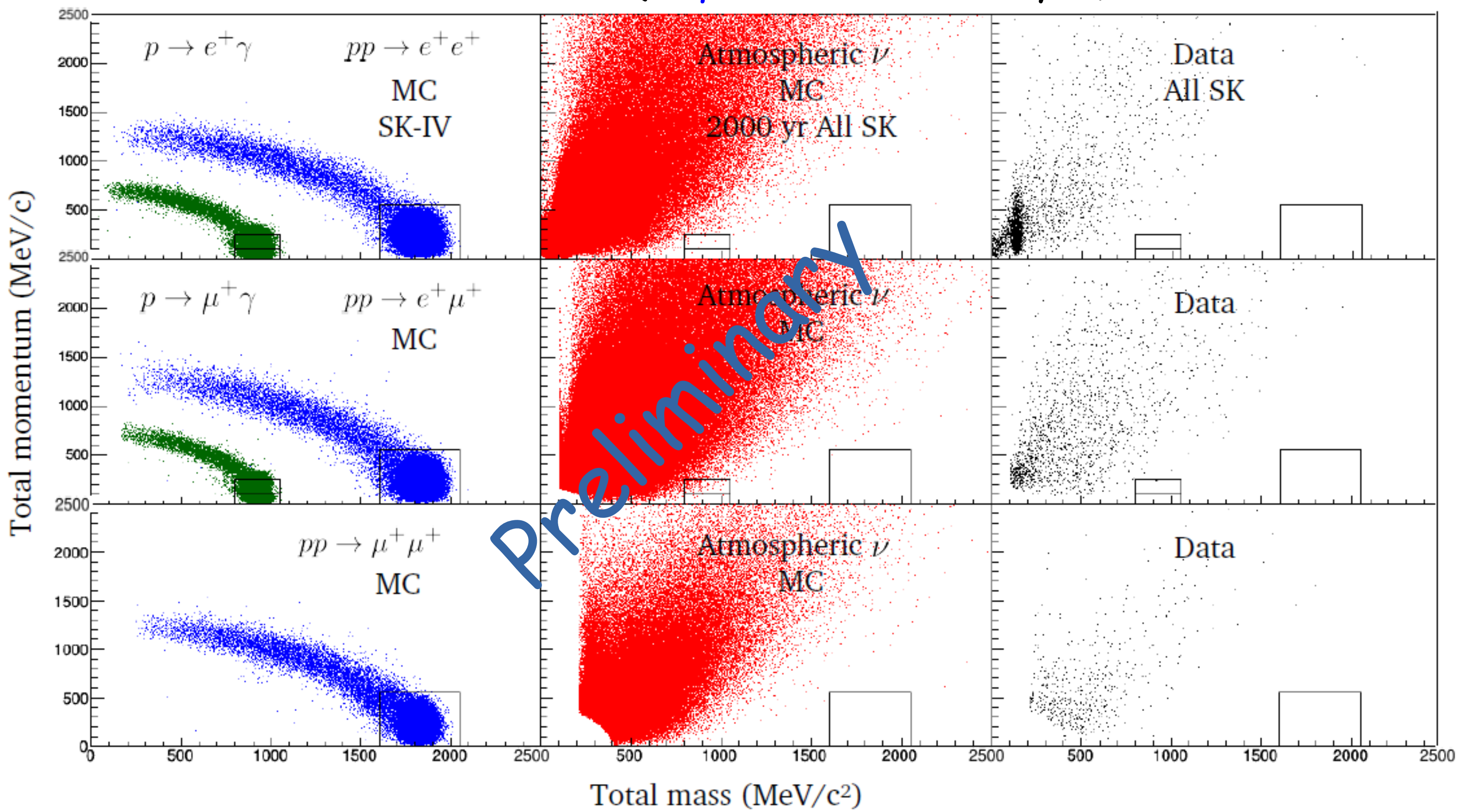
from **S. Sussman (PRELIMINARY)**

- **Motivation:** broad search, extended Higgs, $H-\overline{H}$, probe low energy
- **Signature:** 2 visible leptons/gammas --> fully reconstruct initial state
- **Analysis:**

$p \to e^+\gamma$
$p \to \mu^+\gamma$
$pp \to e^+e^+$
$pp \to \mu^+e^+$
$pp \to \mu^+\mu^+$
$nn \to e^+e^-$
$nn \to \mu^+e^-$
$nn \to \mu^-e^+$
$nn \to \mu^+\mu^-$
$nn \to \gamma\gamma$

Eff.: ~80%

SK I-IV (*Exposure:* 364.5 kt-yrs)

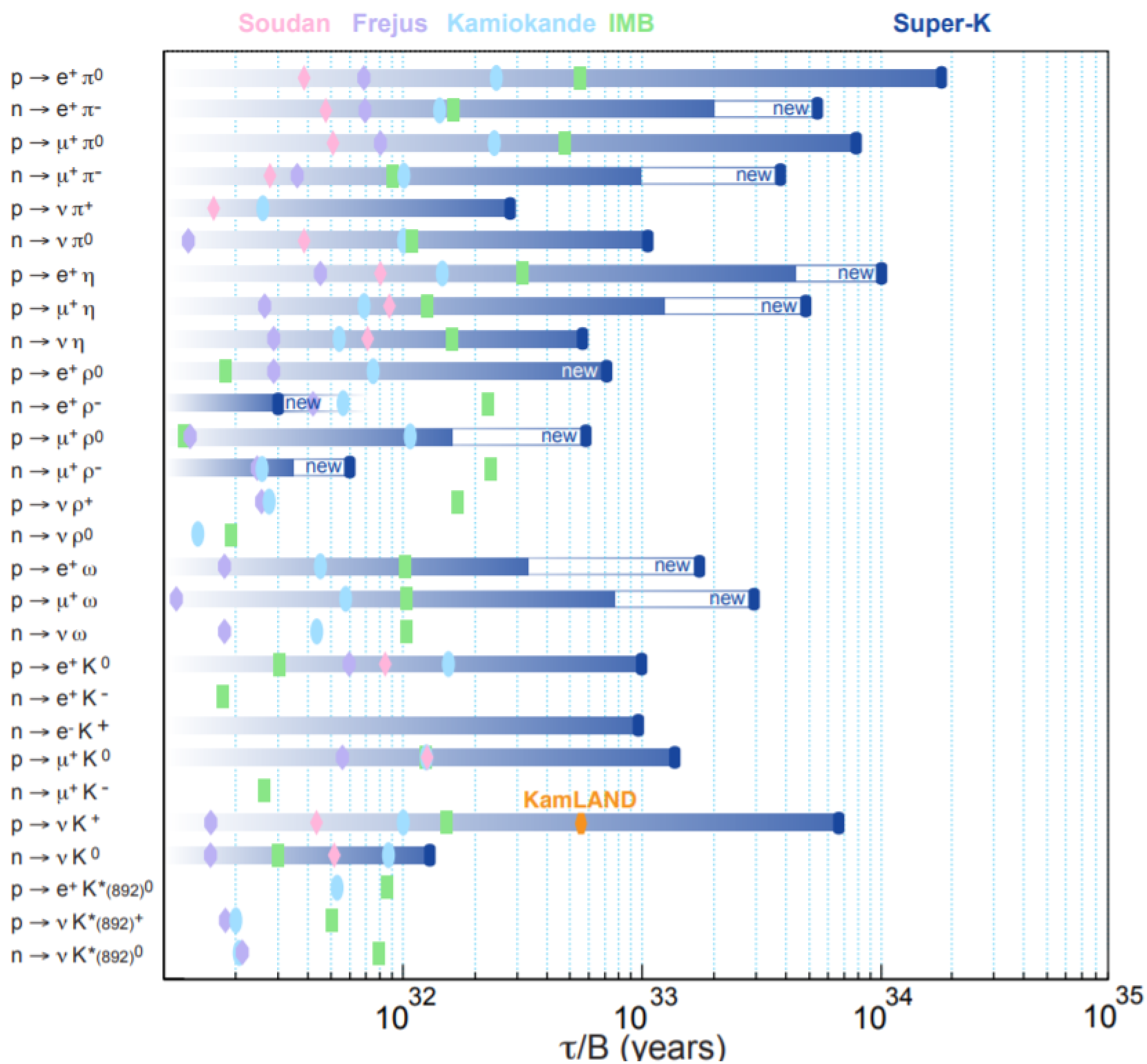


- **Results:** **NO excess** $\xrightarrow{\text{limit}}$ $\tau > \text{few} \times 10^{33}$ yrs.

Summary of Super-K Results

- SK searches improve >1 order over past results for most channels, some entirely novel

  --> constrain models

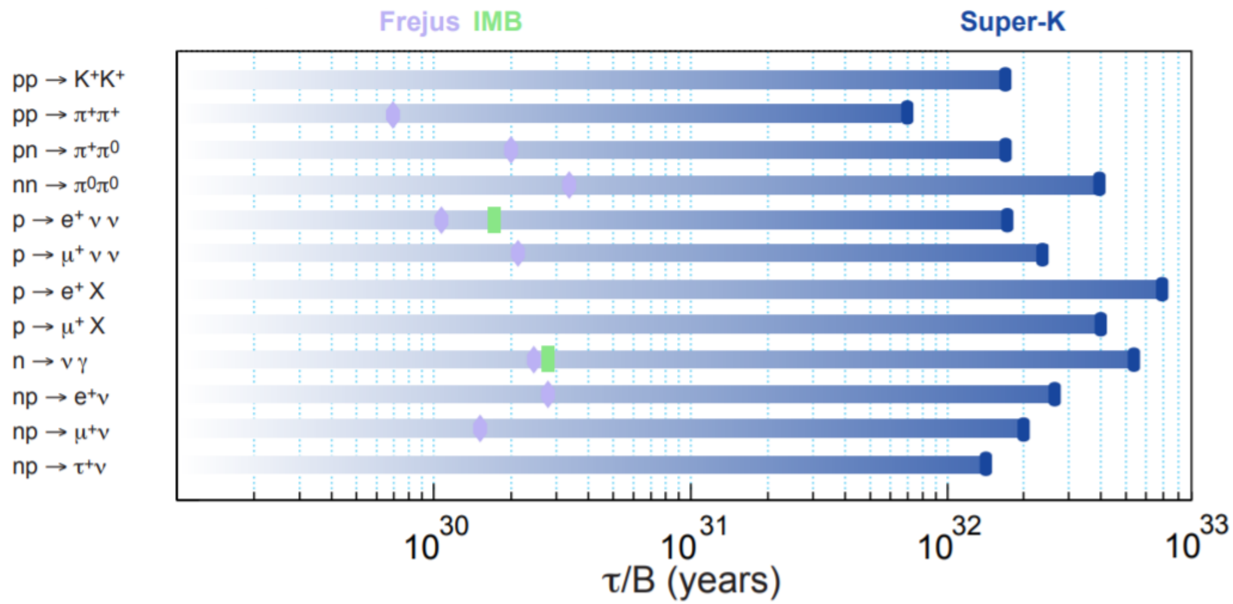


from E. Kearns

Summary of Super-K Results

- SK searches improve >1 order over past results for most channels, some entirely novel

  --> constrain models

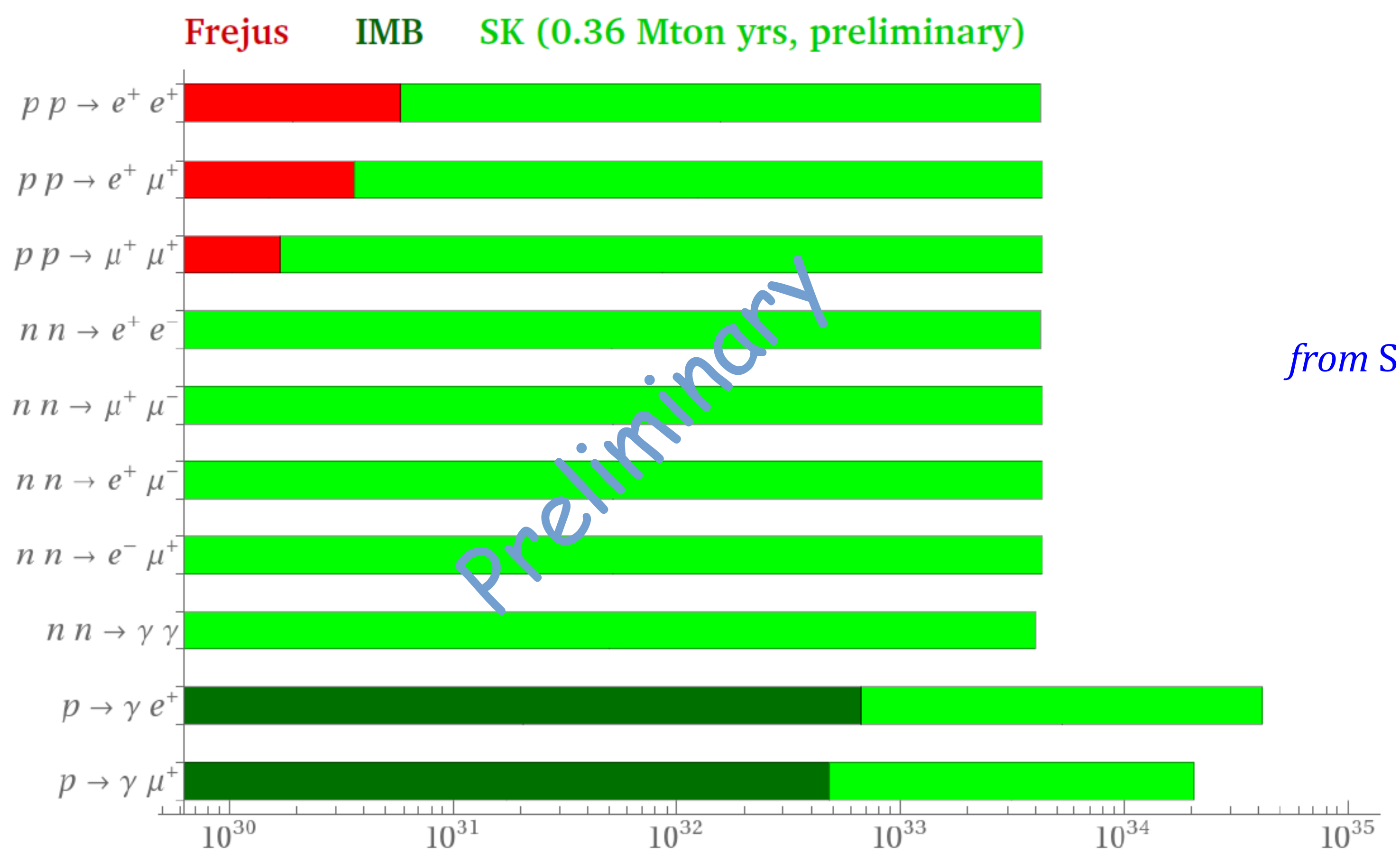


from E. Kearns

Summary of Super-K Results

- SK searches improve >1 order over past results for most channels, some entirely novel

  --> constrain models



from S. Sussman

Summary of Super-K Results

Probing lifetime $\tau \gtrsim 10^{32}\ \mathrm{yrs}$ across channels !

Future Prospects

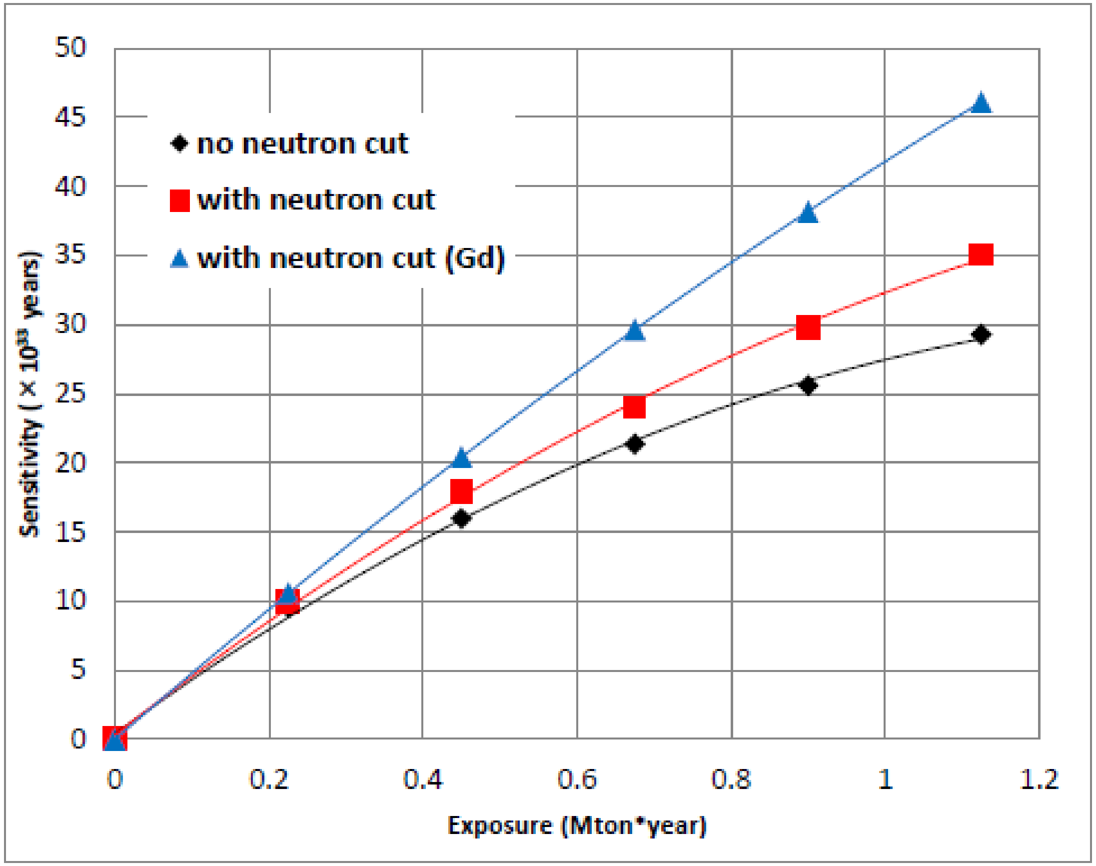
Near term (~2019): SK-Gd

- Super-K Gadolinium upgrade

--> efficient neutron tagging (~80%) will help reduce background

--> allows to claim discovery if candidates observed

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

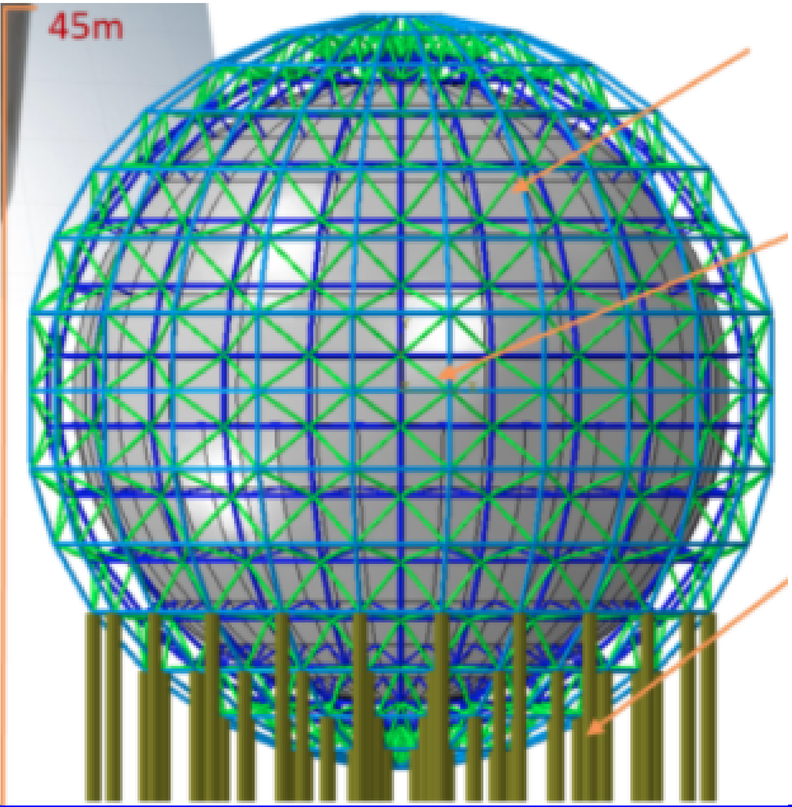


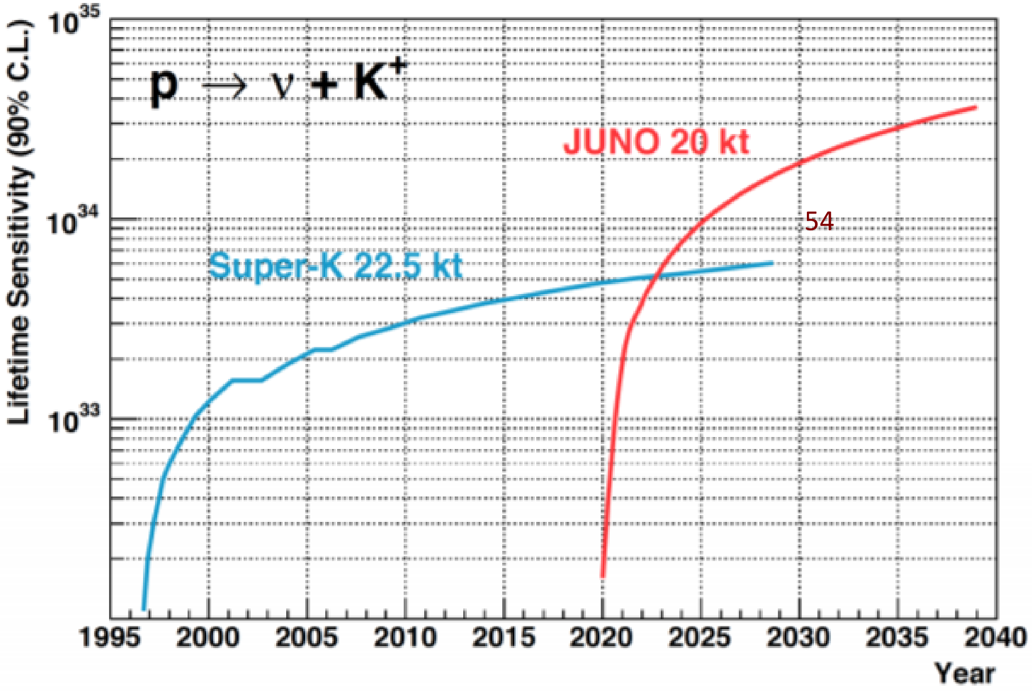
from M. Miura

Medium term (~2020+): JUNO

Large liquid scintillator detector

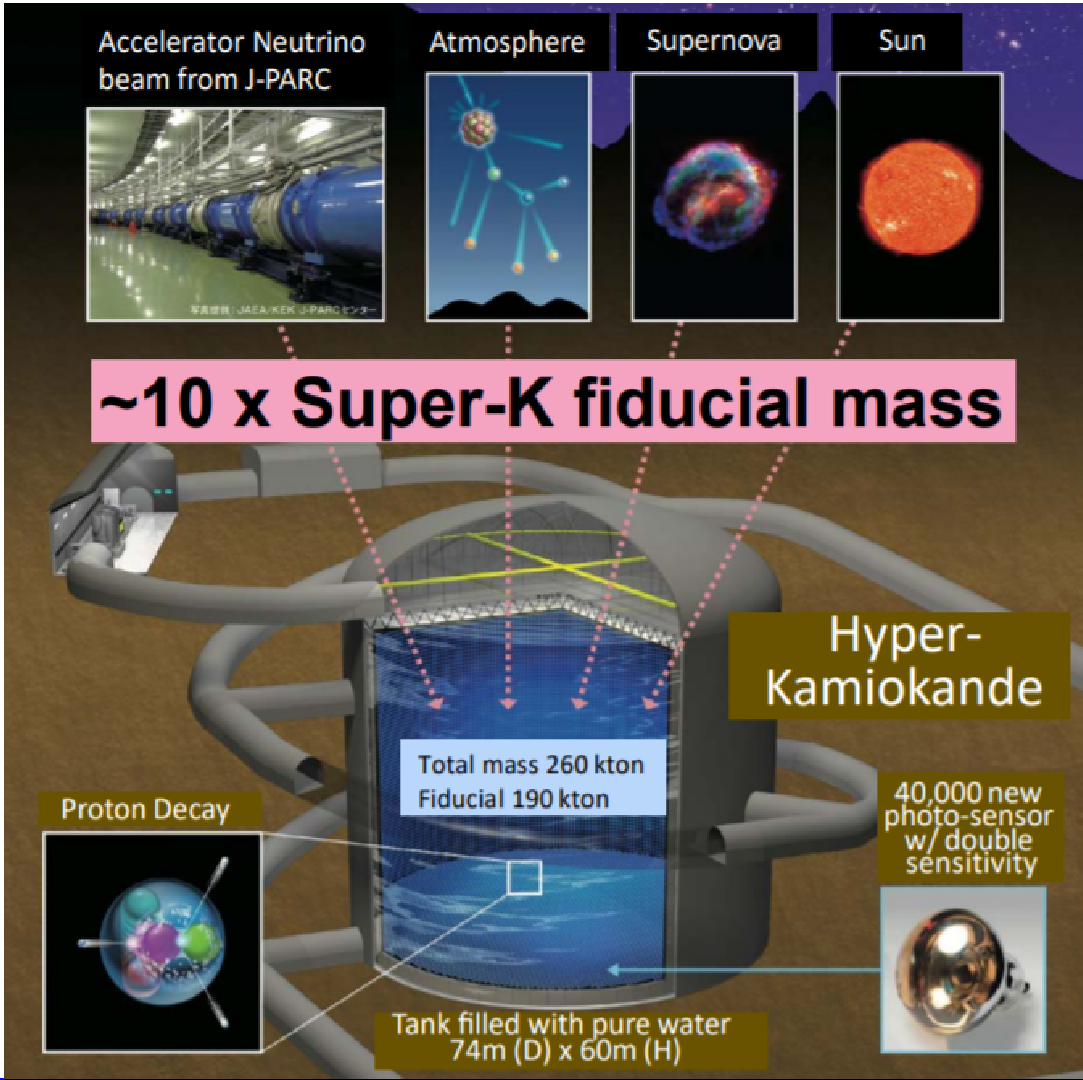
- 20 kt FV liquid scintillator (China)
- Clean timing signature --> specialize in charged Kaon (+ invisible mode)





Next generation water Cherenkov detector

- Well established technology, builds on success of Super-K
- 650m underground in Kamioka
- 10x Super-K FV
- Photo-sensors with 2x single-photon sensitivity



Long term (~2025): Hyper-Kamiokande

- Shear Hyper-K size allows up to an order gain in lifetime sensitivity across the board, can finally probe $\boxed{\tau \sim 10^{35}\ \text{yrs}}$

Mode	τ_{disc} 3σ [years]
$p \to e^+\pi^0$	$6.3\ (8.0)\times 10^{34}$
$p \to \overline{\nu}K^+$	$2.0\ (2.5)\times 10^{34}$
$p \to \mu^+\pi^0$	$6.9\ (8.7)\times 10^{34}$
$p \to e^+\eta^0$	$3.0\ (3.9)\times 10^{34}$
$p \to \mu^+\eta^0$	$3.4\ (4.7)\times 10^{34}$
$p \to e^+\rho^0$	$3.4\ (5.0)\times 10^{33}$
$p \to \mu^+\rho^0$	$1.3\ (1.6)\ \times 10^{33}$
$p \to e^+\omega$	$5.4\ (6.9)\times 10^{33}$
$p \to \mu^+\omega$	$0.78\ (1.0)\times 10^{34}$

Mode	τ_{disc} 3σ [years]
$n \to e^+\pi^-$	$1.3\ (1.6)\times 10^{34}$
$n \to \mu^+\pi^-$	$1.1\ (1.5)\times 10^{34}$
$n \to e^+\rho^-$	$1.1\ (1.5)\times 10^{33}$
$n \to \mu^+\rho^-$	$6.2\ (8.1)\times 10^{32}$

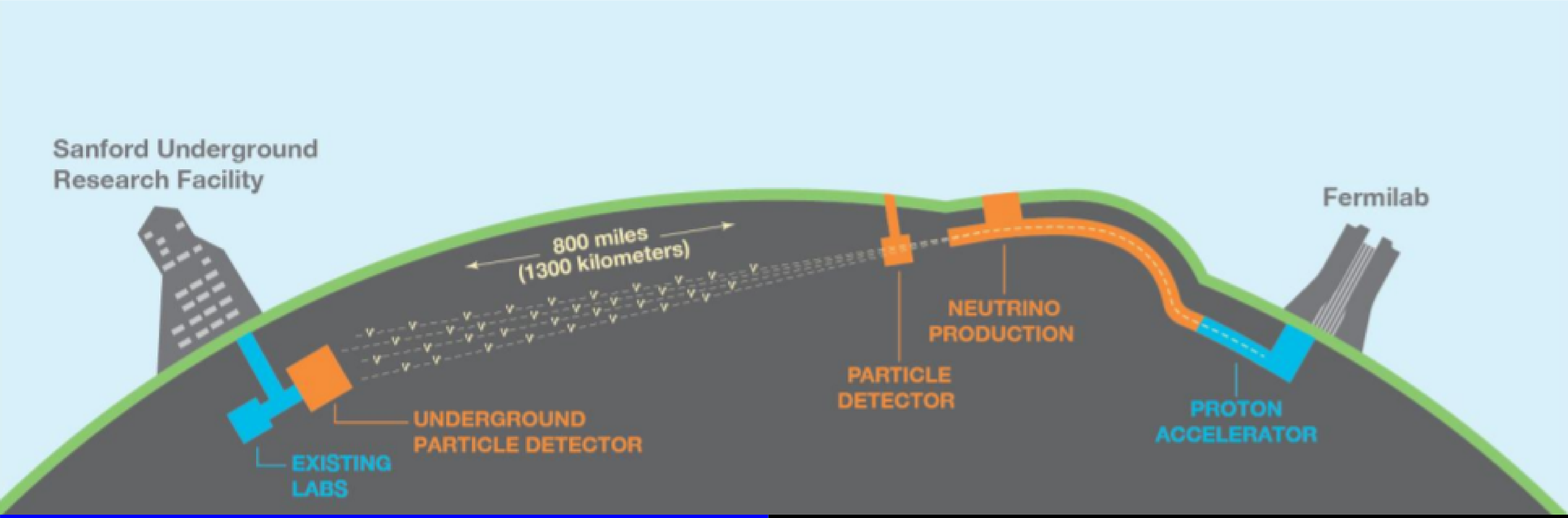
from HK design report

Long term (~2025): DUNE

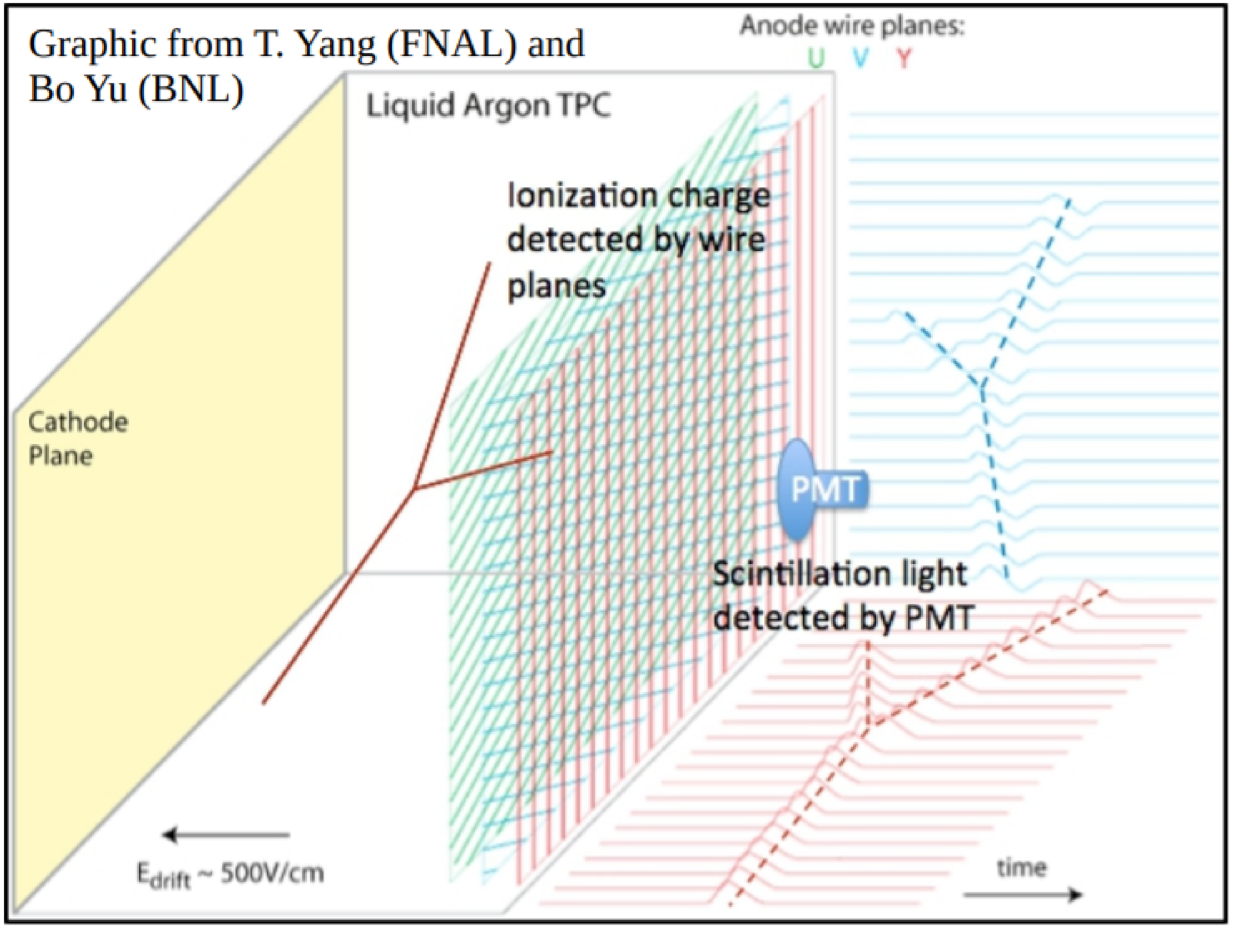
- **Deep Underground Neutrino Experiment (DUNE)**

  --> flagship experiment for US neutrino program

- 1 km underground in Sanford Lab (Homestake, South Dakota)
- 40 kton FV liquid Argon detector



LArTPC technique



Long term (~2025): DUNE

- Final state Kaon visible in LArTPC (below threshold in w. Cherenkov)

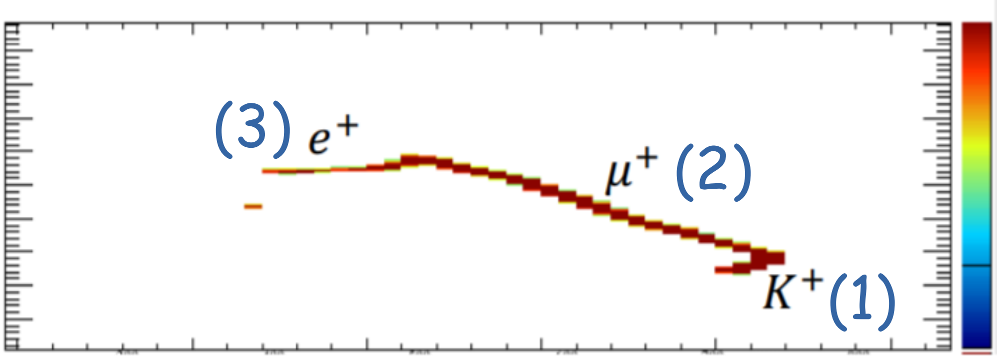
  --> well suited to probe SUSY modes

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

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

(2) $K^+ \to \mu^+ \nu_\mu$

(3) $\mu^+ \to e^+ \nu_e \overline{\nu_\mu}$

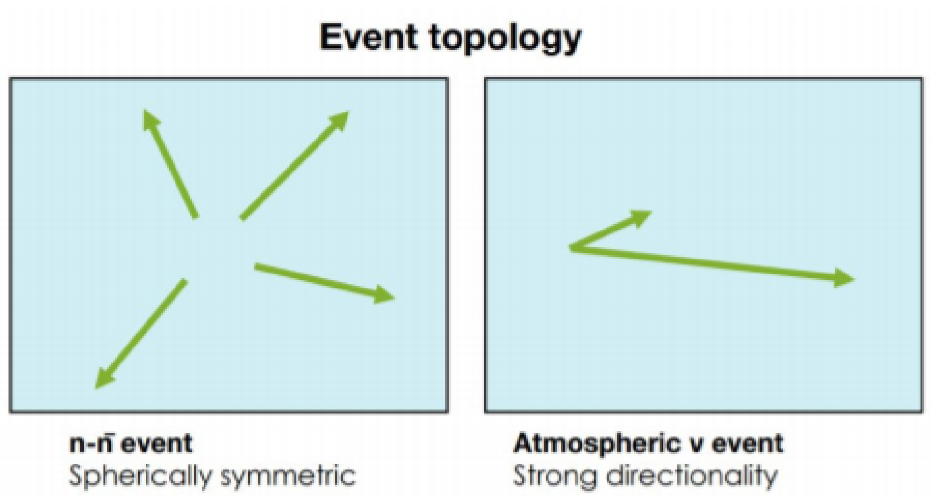


simulated event display (2D)

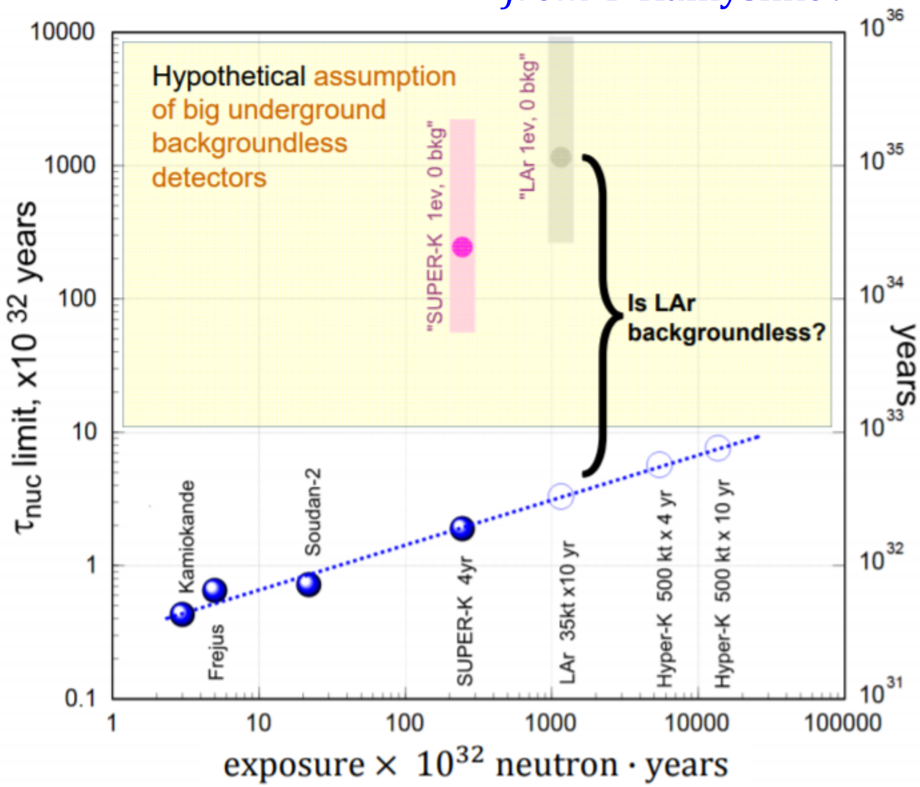
- Multi-prong events without neutrinos clearly visible

  --> potential for strong background descrimination

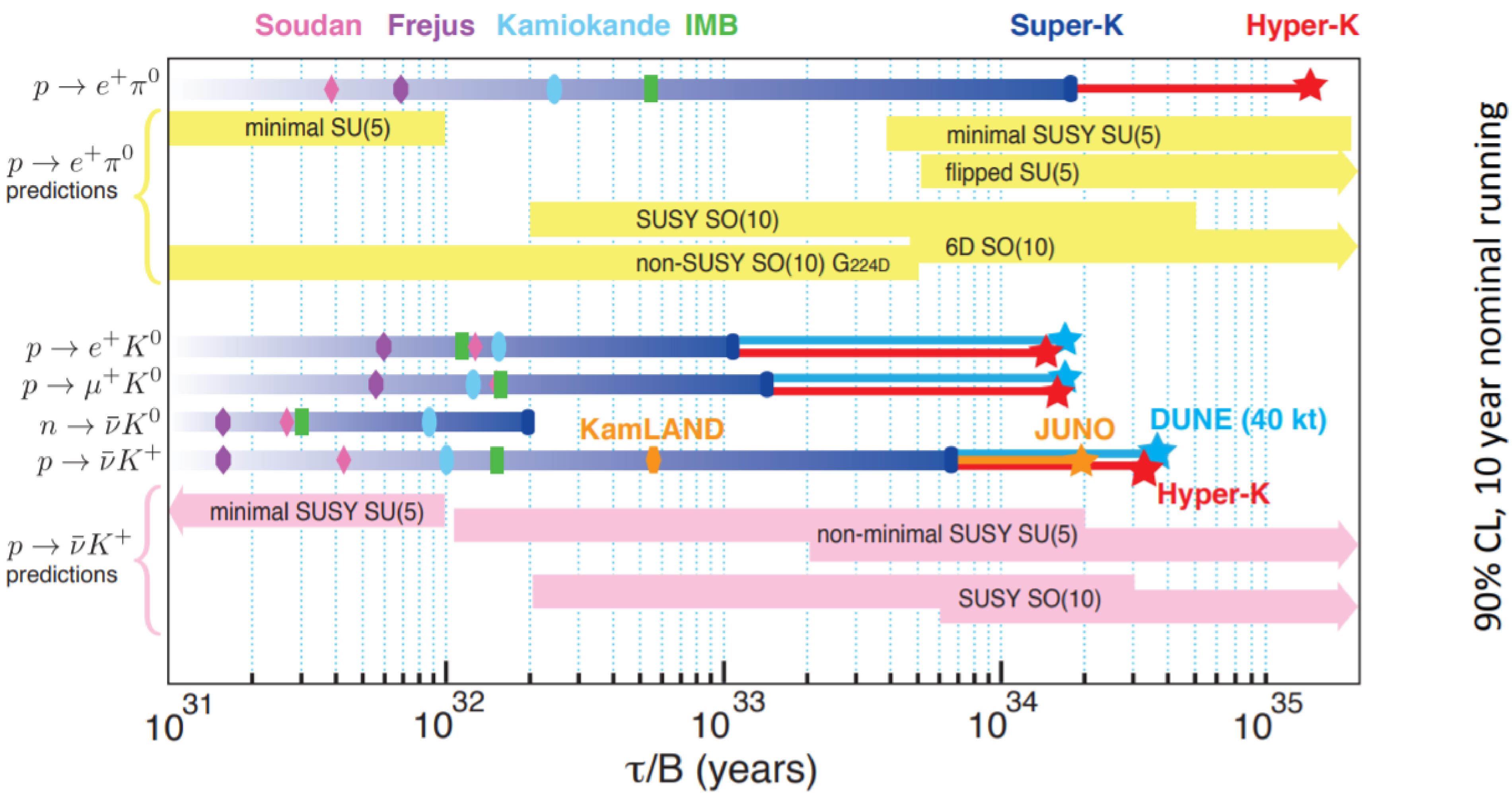
$$n - \overline{n}\ \text{oscillations}$$



from Y. Kamyshkov



Where do we stand?



from E. Kearns

Conclusions

- Probing baryon number violation remains a key experimental priority

Conclusions

- Probing baryon number violation remains a key experimental priority

- Nucleon decay and related processes offer unique window into energies not accessible to accelerators as well as plethora of BSM physics

Conclusions

- Probing baryon number violation remains a key experimental priority

- Nucleon decay and related processes offer unique window into energies not accessible to accelerators as well as plethora of BSM physics

- Uncertainty in theory predictions requires a broad search program, well suited for large underground experiments, with the field led by Super-K

  --> many modes left to search (e.g. $n \to \nu\nu\nu, p \to e^+e^-e^+$)

Conclusions

- Probing baryon number violation remains a key experimental priority

- Nucleon decay and related processes offer unique window into energies not accessible to accelerators as well as plethora of BSM physics

- Uncertainty in theory predictions requires a broad search program, well suited for large underground experiments, with the field led by Super-K

  --> many modes left to search (e.g. $n \to \nu\nu\nu, p \to e^+e^-e^+$)

- Approaching interesting limit range of $\tau \sim 10^{35}$ yrs.

  → great complimentary physics program to neutrinos (Hyper-K/DUNE)