Grand Unified Theories & Proton Decay

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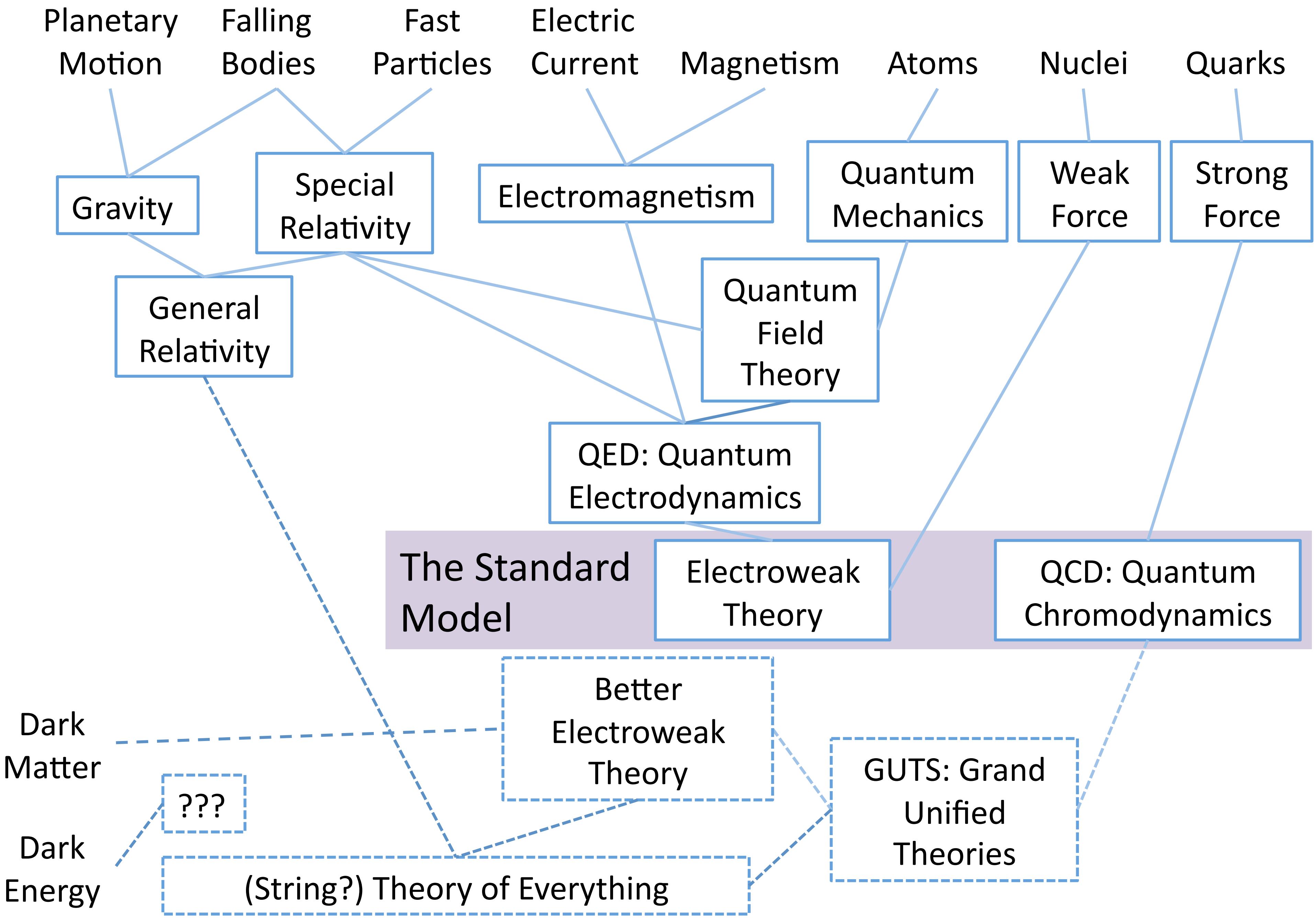
Boston University

NEPPSR 2009

What is unification?



Planetary Motion

Falling Bodies

Fast Particles

Electric Current

Magnetism

Atoms

Nuclei

Quarks

Gravity

Special Relativity

Electromagnetism

Quantum Mechanics

Weak Force

Strong Force

General Relativity

Quantum Field Theory

QED: Quantum Electrodynamics

The Standard Model

Electroweak Theory

QCD: Quantum Chromodynamics

Dark Matter

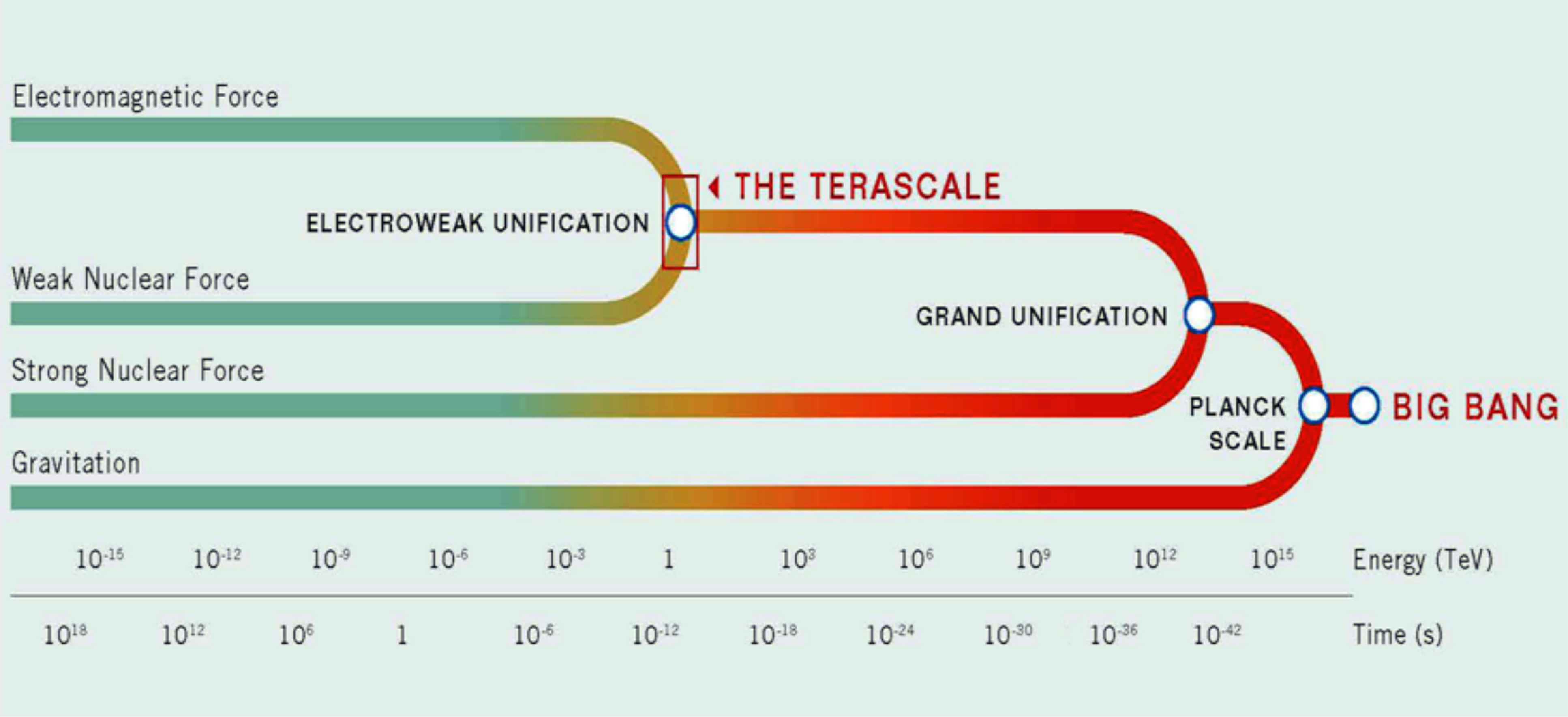
Better Electroweak Theory

GUTS: Grand Unified Theories

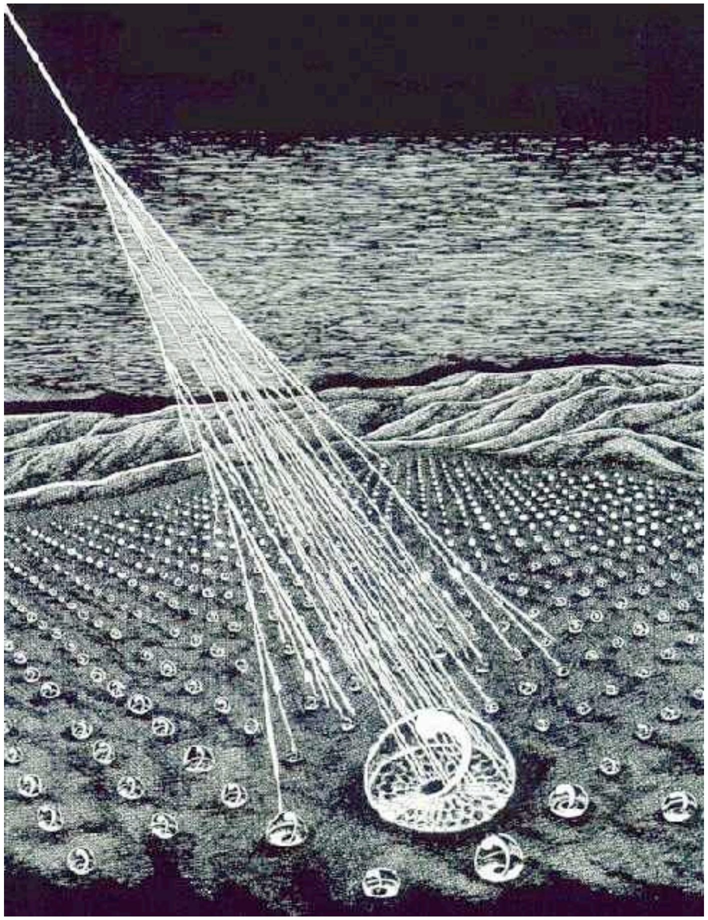
???

Dark Energy

(String?) Theory of Everything


Electromagnetic Force
THE TERASCALE
ELECTROWEAK UNIFICATION
Weak Nuclear Force
GRAND UNIFICATION
Strong Nuclear Force
PLANCK SCALE
BIG BANG
Gravitation
10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15}
Energy (TeV)
10^{18} 10^{12} 10^{6} 1 10^{-6} 10^{-12} 10^{-18} 10^{-24} 10^{-30} 10^{-36} 10^{-42}
Time (s)

100 EeV Cosmic Ray

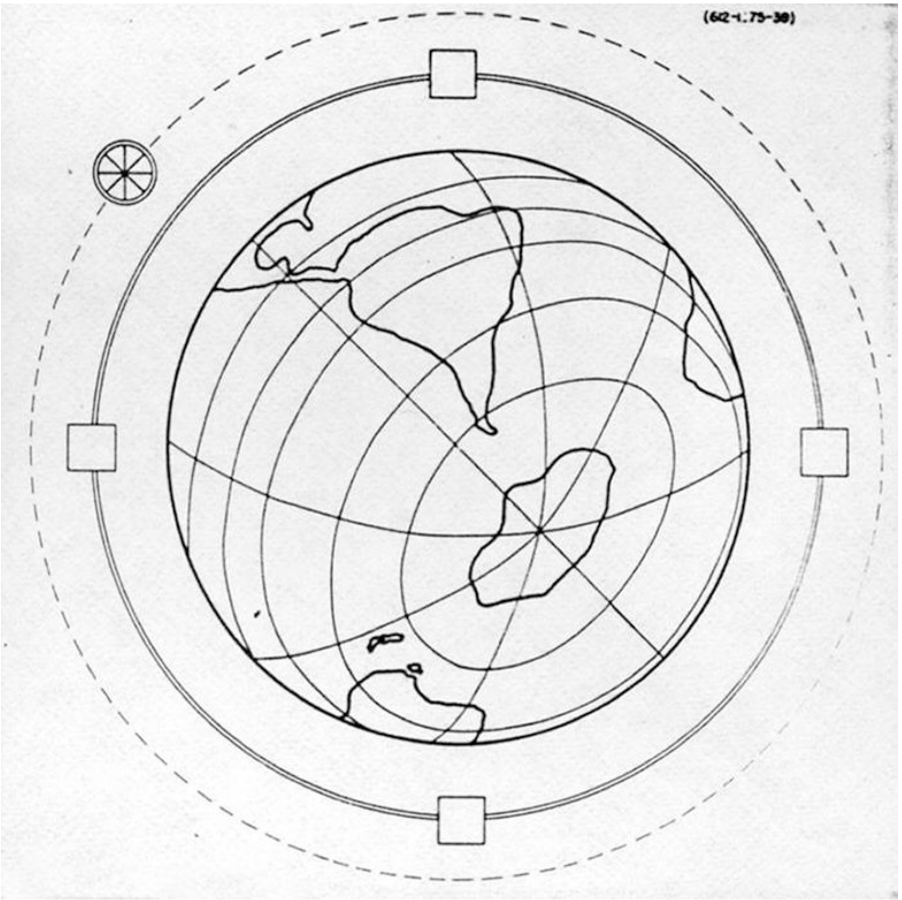


$$E_{cm} = \sqrt{2\,E\,m}$$

$$E \sim \sqrt{10^{20}\ \text{eV} \times 1\ \text{GeV}}$$

$$E \sim 10^{6}\ \text{GeV}$$

Enrico Fermi's Globatron

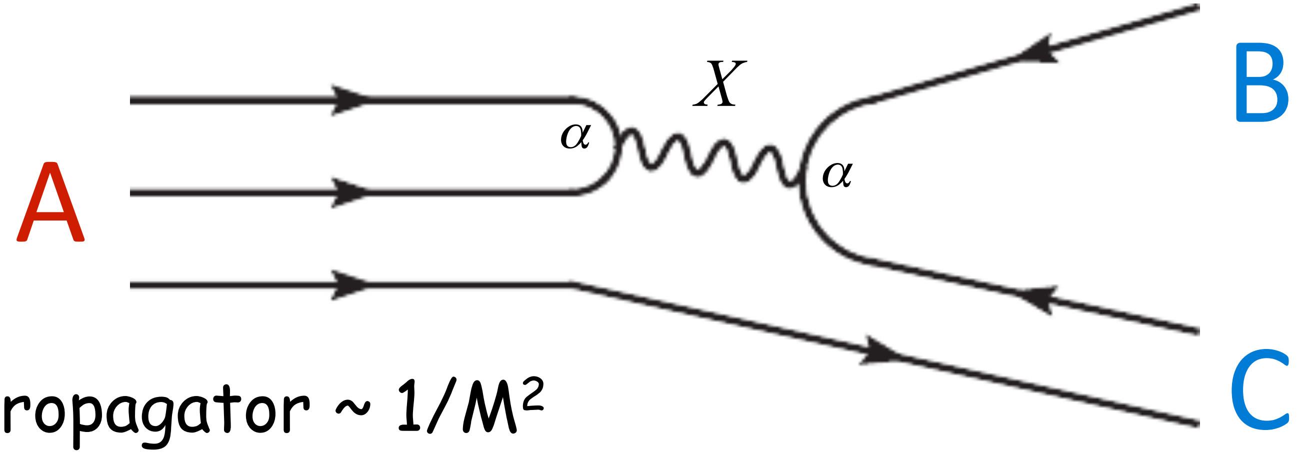


$$p = 0.3\ B[T]\ r[m]$$

$$p \sim 100\ T \times 10^{6}\ m$$

$$E \sim 10^{8}\ \text{GeV}$$

⇒ **only way to probe the grand unification scale is by virtual particle exchange**



propagator ~ $1/M^2$

$$\Gamma(A \rightarrow BC) = \frac{1}{\tau} \approx \frac{\left|\langle BC|A\rangle\right|^2 \left|\vec{p}_B\right|}{m_A^2} \approx \frac{\alpha^2 m_p^5}{M_X^4}$$

Proton (nucleon) decay turns out to be one of the most useful systems.

In the Standard Model, proton decay is forbidden by
Conservation of Baryon Number

Origins: baryon number conservation formulated by:

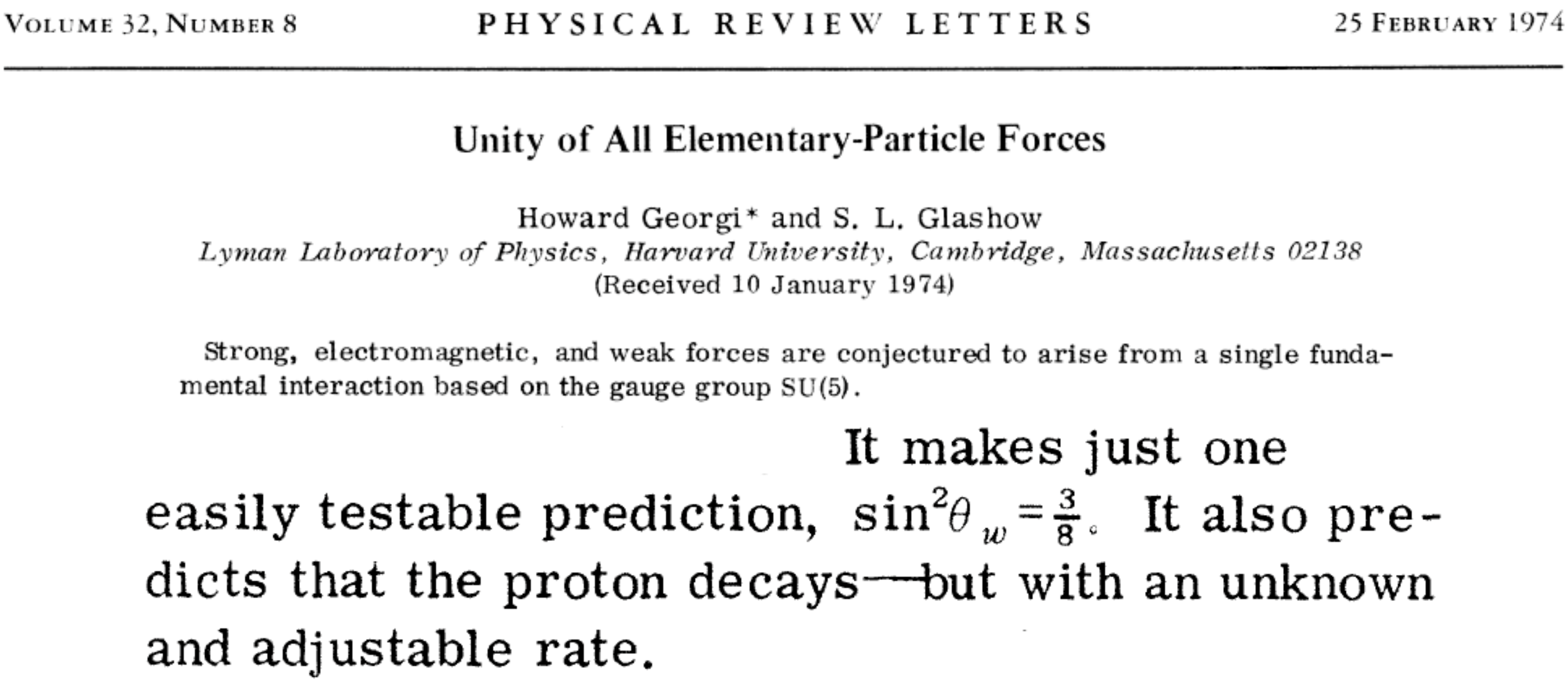
Weyl (1929), Stueckelberg (1938), Wigner (1949), Lee & Yang (1950) to explain stability of matter.

Phenomenological limits (1950's):

M. Goldhaber observes that life requires $\tau > 10^{16}$ years.
Isotope abundance requires $\tau > 10^{23}$ years.

Sakharov Conditions (1966):

Matter-Antimatter asymmetry requires baryon number non-conservation.



VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

It makes just one easily testable prediction, $\sin^2\theta_w = \frac{3}{8}$. It also predicts that the proton decays—but with an unknown and adjustable rate.

Other work of this era:

Pati and Salam: Is Baryon Number Conserved? PRL 31, 661 (1973)

Georgi, Quinn, and Weinberg: PRL 33, 451 (1974) proton lifetime ~ 6×10^{31} years.

Grand Unified Theories

Assume SU(3)⊗SU(2)⊗U(1) is part of a larger symmetry group

E.g. SU(5)

$$\bar{5} = \begin{pmatrix} \bar{d}_g \\ \bar{d}_r \\ \bar{d}_b \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad 10 = \begin{pmatrix} 0 & \bar{u}_b & -\bar{u}_r & -u_g & -d_g \\ & 0 & \bar{u}_g & -u_r & d_r \\ & & 0 & -u_b & -d_b \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}_L$$

$$24 = \left(\begin{array}{ccc|cc} G_{11} - \frac{2B}{\sqrt{30}} & G_{12} & G_{13} & \bar{X}_1 & \bar{Y}_1 \\ G_{21} & G_{22} - \frac{2B}{\sqrt{30}} & G_{23} & \bar{X}_2 & \bar{Y}_2 \\ G_{31} & G_{32} & G_{33} - \frac{2B}{\sqrt{30}} & \bar{X}_3 & \bar{Y}_3 \\ \hline X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{array}\right)$$

generators

Consequences:

- Single (unified) coupling
- Charge quantization: $Q_d=Q_e/3$, $Q_u=-2Q_d$ ⇒ $Q_p = -Q_e$
- New gauge interactions (X, Y bosons) ⇒ proton decay
- Other predictions of SU(5):
  magnetic monopoles, value of weak mixing angle (3/8 not so good), massless neutrinos (oops!)

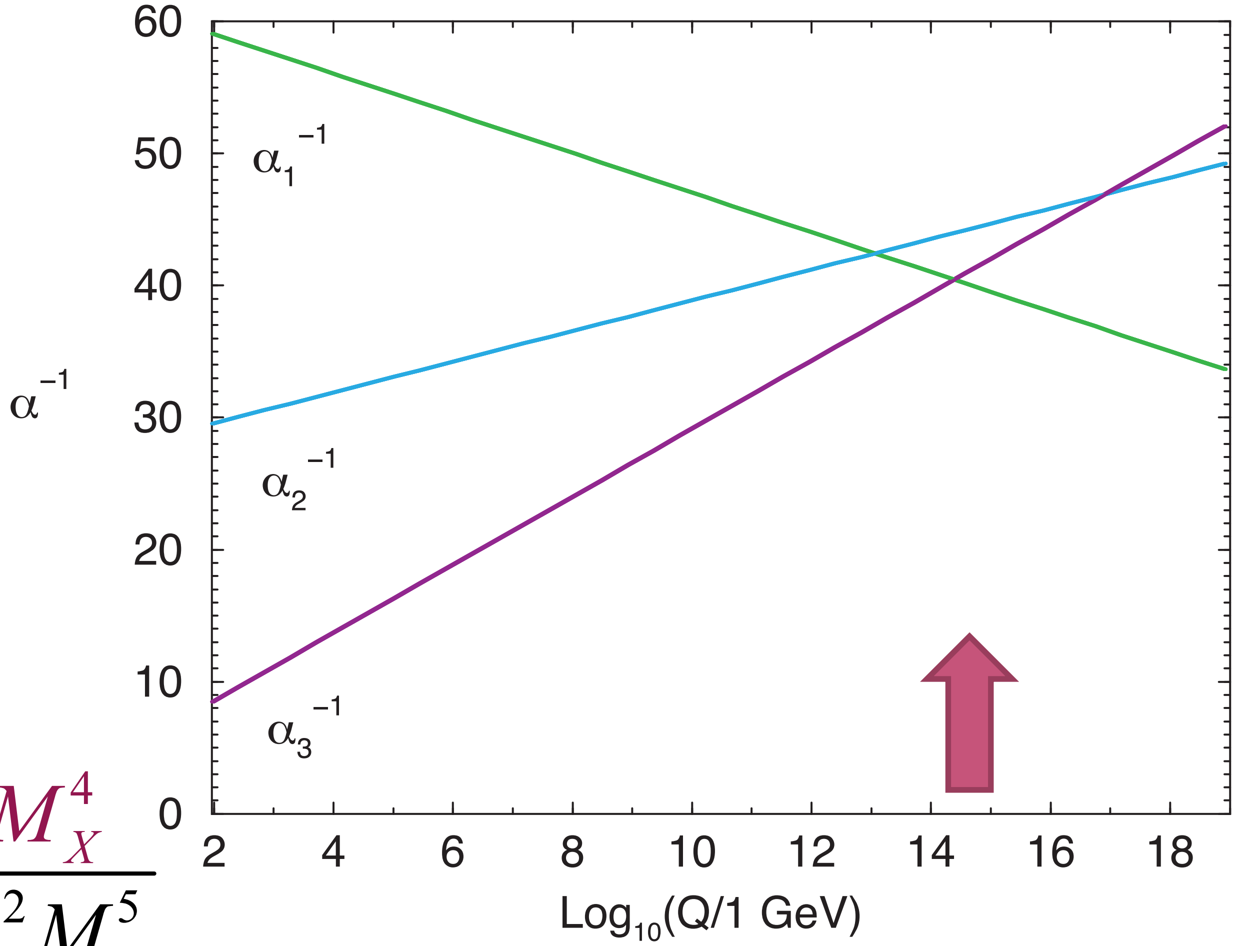
or SO(10)

$$16 = \begin{pmatrix} \nu_e \\ u_r \\ u_g \\ u_b \\ e^- \\ d_r \\ d_g \\ d_b \\ \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \\ e^+ \\ \bar{u}_r \\ \bar{u}_g \\ \bar{u}_b \\ \bar{\nu}_e \end{pmatrix}_L$$

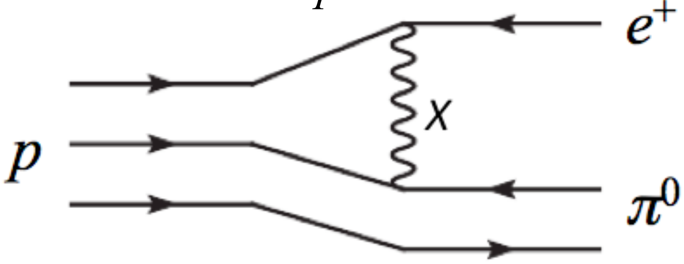
or E_6 or Flipped SU(5)
or G224 or ...

and would you like
SUSY with that?

Gauge Coupling Unification



$$\tau \approx \frac{M_X^4}{\alpha^2 M_p^5}$$



$$\tau(e^+\pi^0) = 4.5\times10^{29\pm1.7}\ years\ \text{(predicted)}$$

How can we find proton decay if protons live for 10^{30} years?

watch 1 proton for 10^{31} years

or

watch 10^{32} protons (~kton) for a month

or

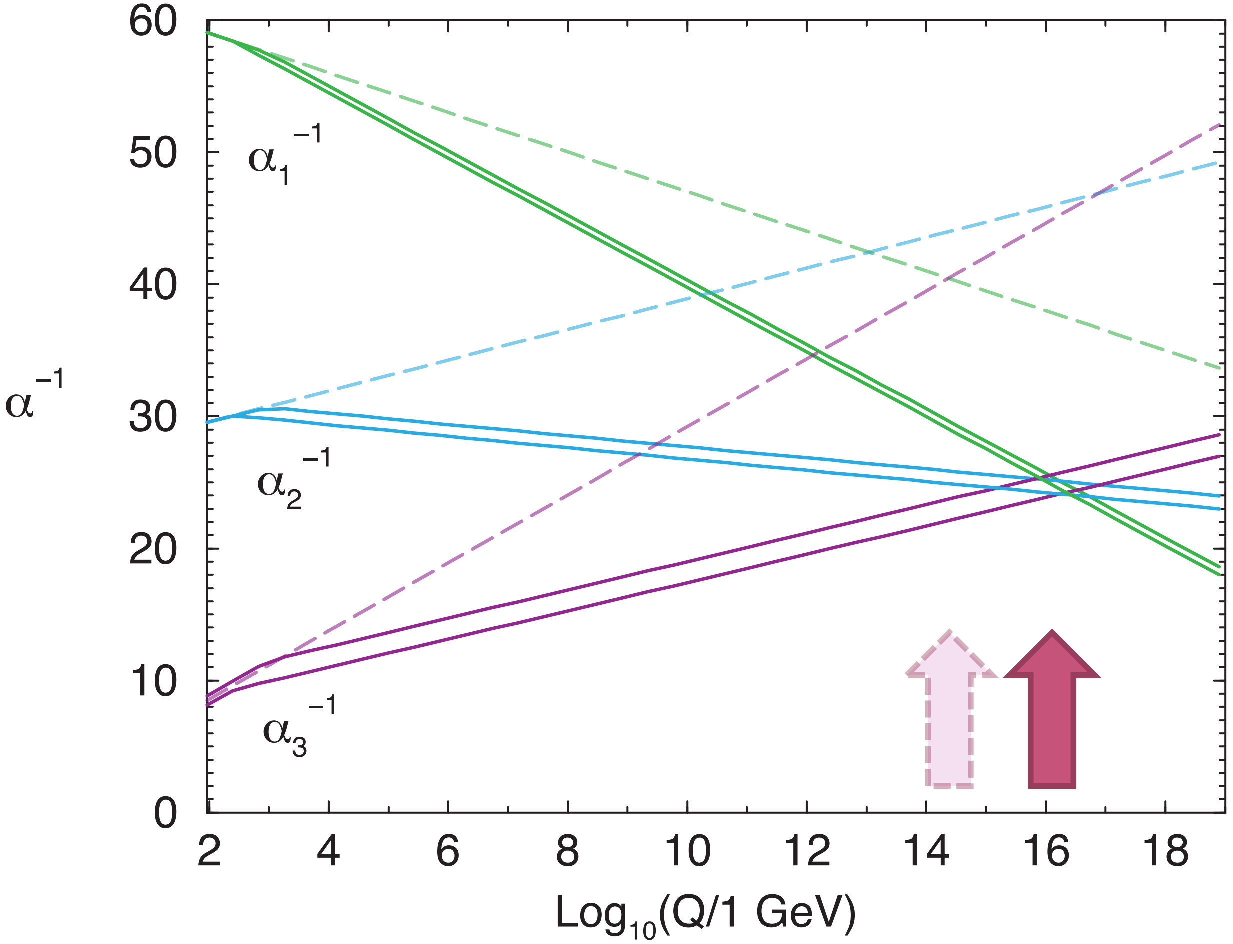
something in between

IMB Experiment

Morton Salt Mine, Ohio
610 meters deep – 1570 mwe
3.3 kton (fiducial volume)
2000 PMTs, 4% coverage
935 events in 851 live-days
no proton decay found
$\tau(e^+\pi^0) > 5.5 \times 10^{32}$ years (1990)

similar results from Kamiokande (1 kton)
both saw SN 1987a, both uncovered atmospheric neutrino anomaly
Kamiokande measured solar neutrinos

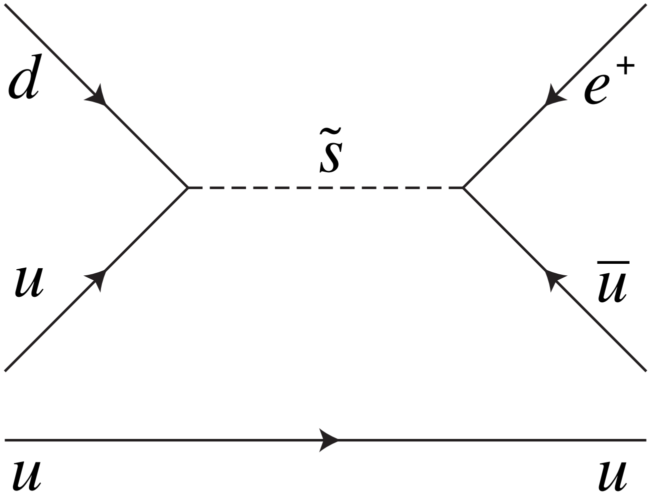
Problems solved by SUSY ...



Unification scale pushed up...

$$\tau(e^{+}\pi^{0}) \approx 10^{35-38}\ \text{years}$$

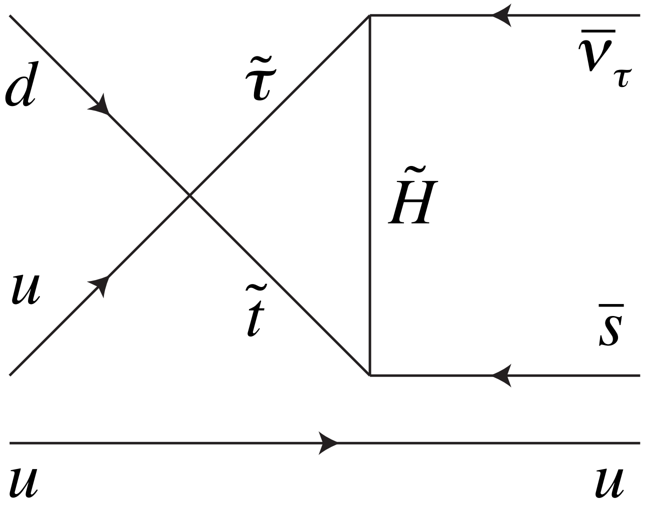
Problems introduced by SUSY …



Rapid proton decay:
Dimension = 4 operators
e.g. $U^cD^cD^c$ and QLD^c
M_{squark} ~ 1 TeV
proton lifetime ~ 1 second
that's OK – **saved by R-parity**

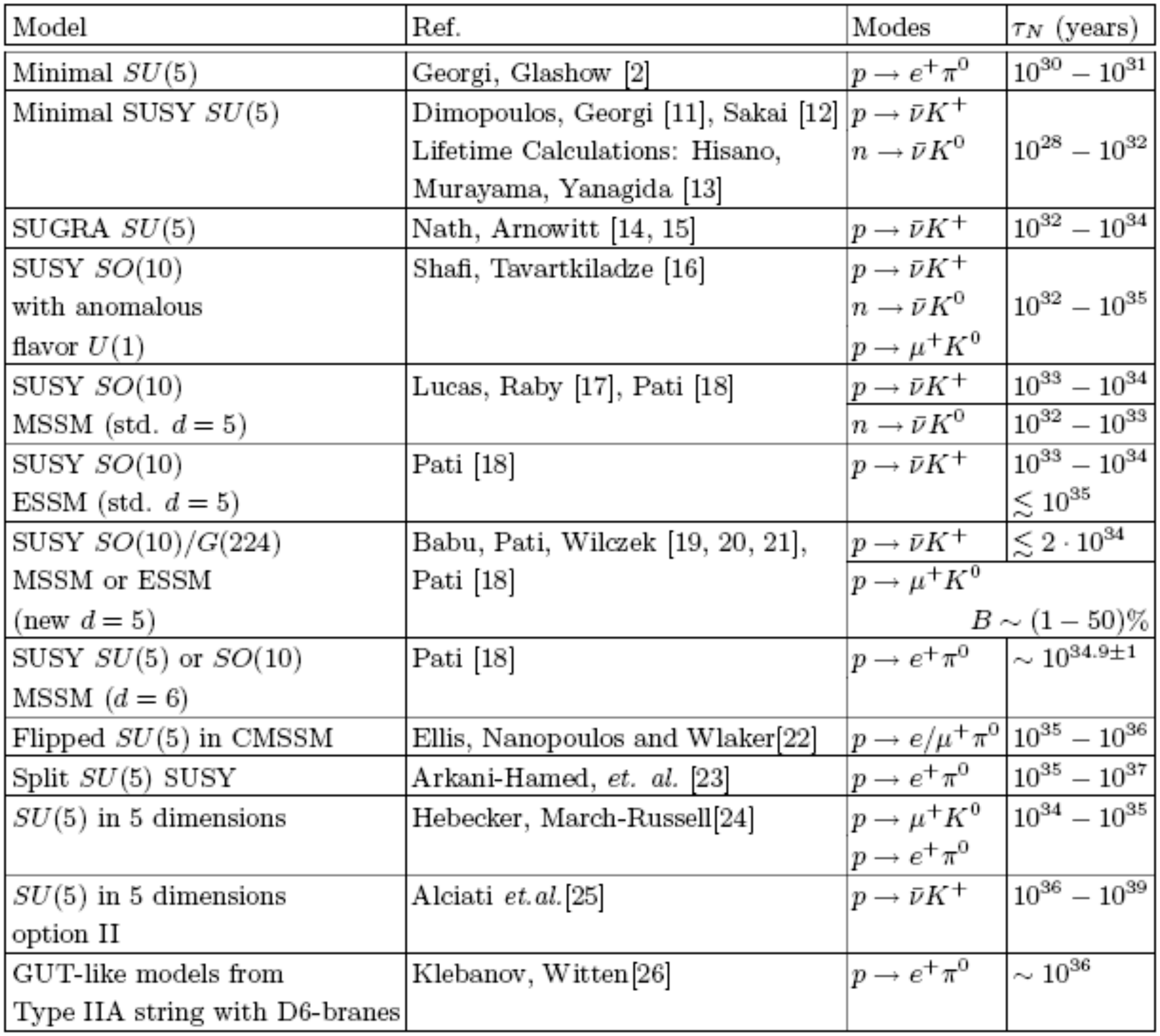
$$\tau \approx \frac{M_{\tilde{s}}^4}{m_p^5}$$

Dimension = 5 operators
e.g. $QQQL$
proton lifetime ~ $10^{29\text{-}35}$ years
something new to look for!



dimension counting: powers of (mass)^D for each field
fermion D = 3/2, boson D = 1, Lagrangian terms must be D=4

Many Other GUTs Beyond This Simple Story



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]	$p \to \bar{\nu}K^+$ $p \to \mu^+K^0$ $B \sim (1 - 50)\%$	$\lesssim 2 \cdot 10^{34}$
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

Uncertainties in the predictions:

Nuclear matrix elements updated w. lQCD, still:
x10 uncertainty in lifetime

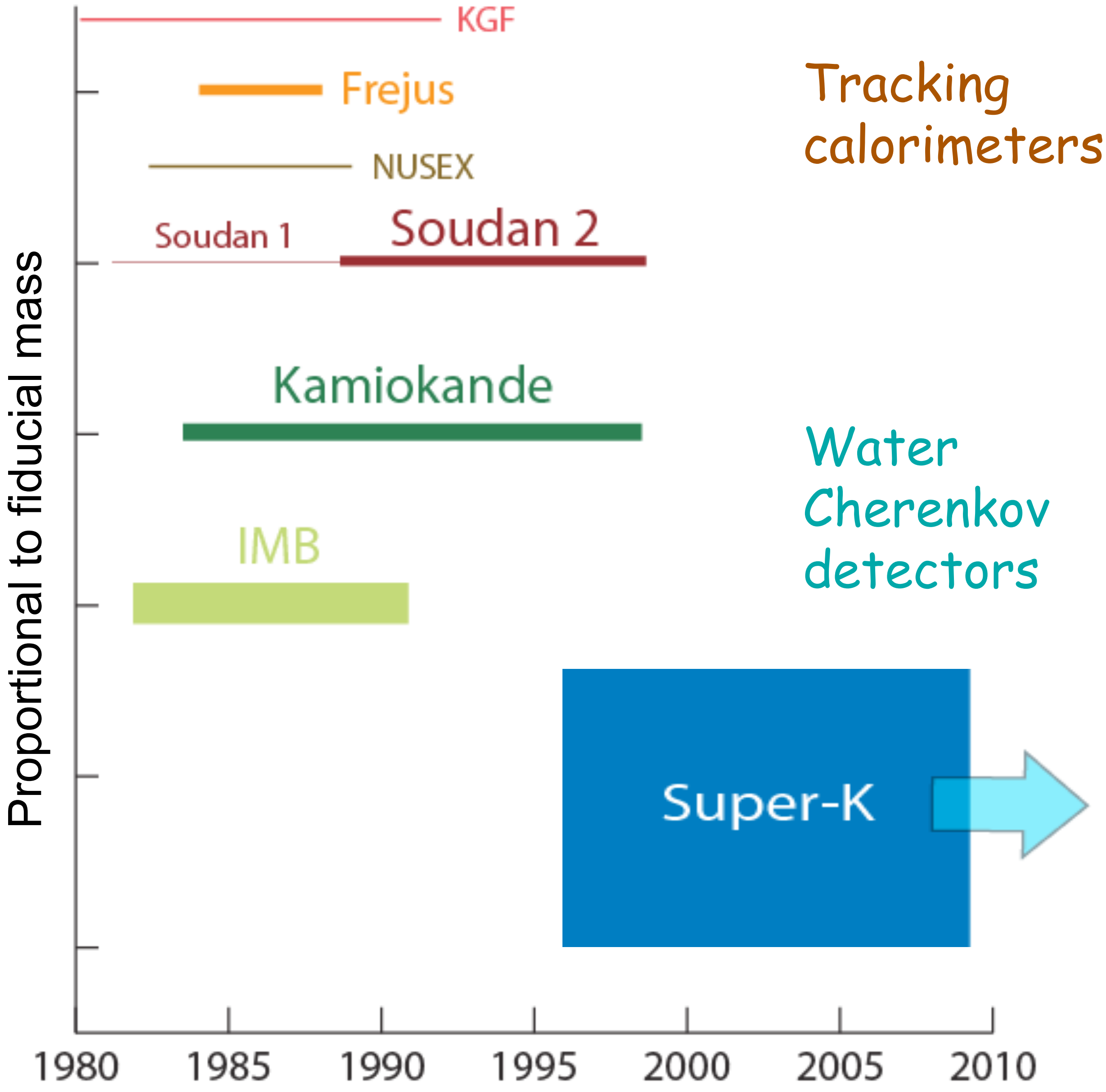
SUSY masses: ~ x100 uncertainty in lifetime

Modes beyond $e^+\pi^0$, $K^+\nu$

and other antilepton + meson decays

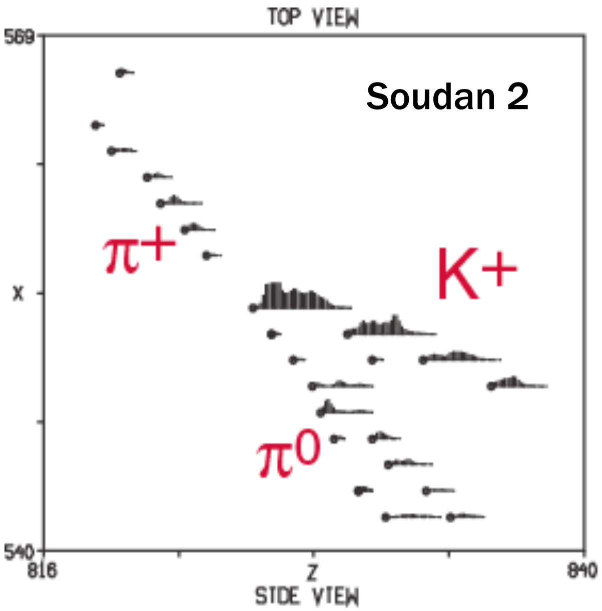
$p \rightarrow \mu^- \pi^+ K^+$	$B + L$
$n \rightarrow \bar{n}$	$\Delta \mathrm{B} = 2$, TeV < scale < GUT
$pp \rightarrow K^+ K^+$	$\lambda''_{\mathrm{uds}} < 10^{-8}$
$p \rightarrow e^- \pi^+ \pi^+ \nu\, \nu$	6 dimensions
$n \rightarrow \nu\, \nu\, \nu$	invisible
$p \rightarrow e^+\, \gamma$	radiative

there is plenty to keep us busy ...

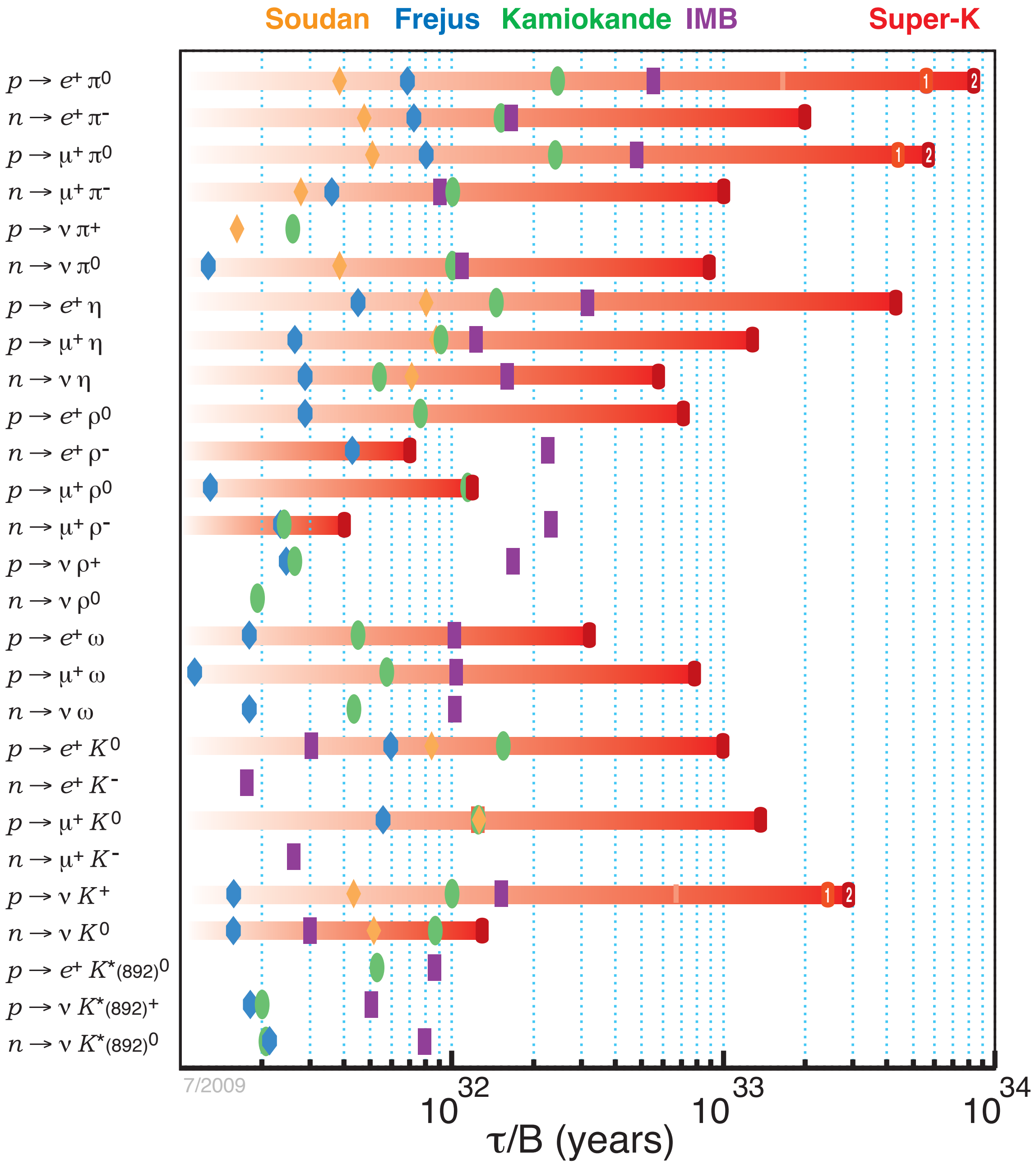


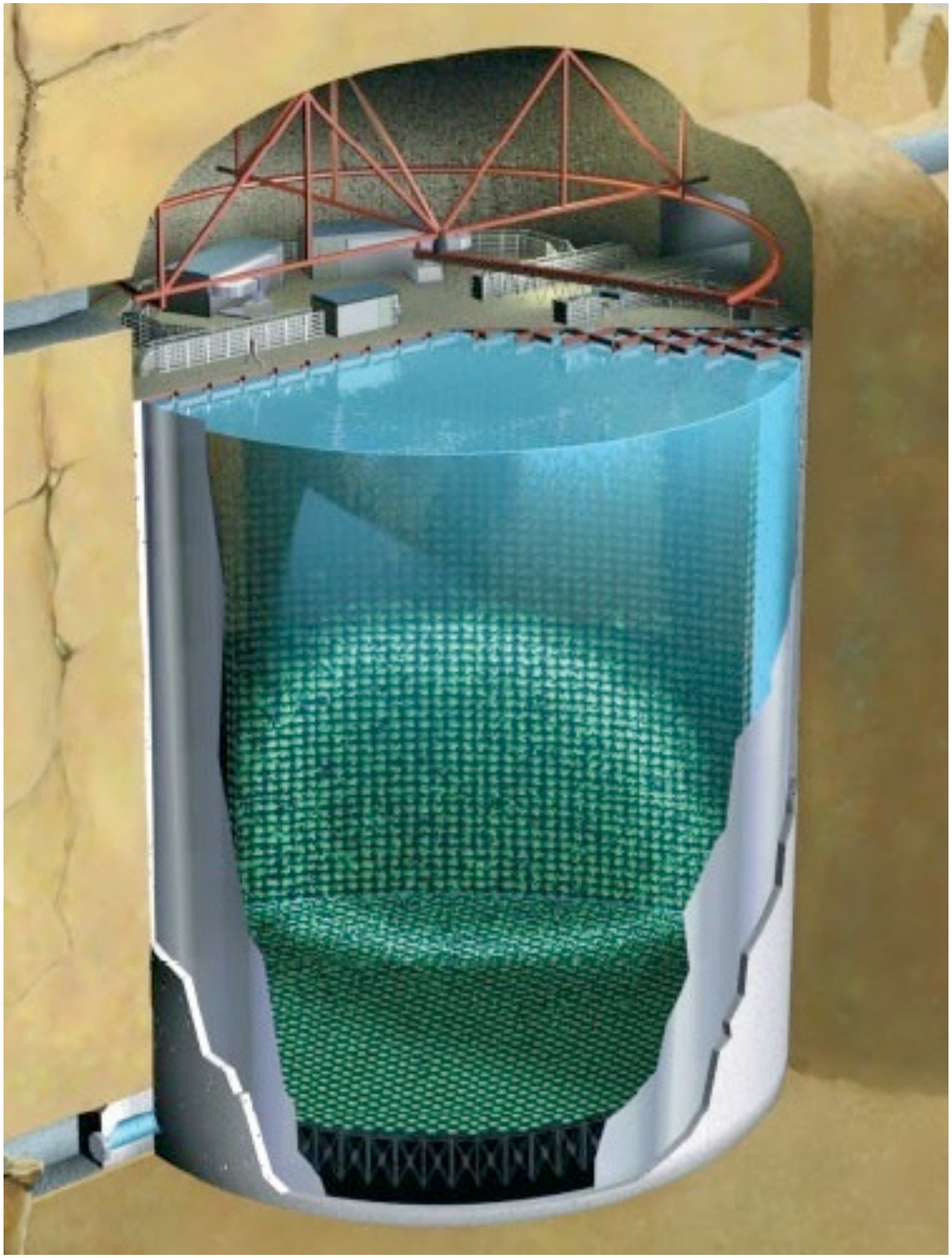
Tracking calorimeters

Water Cherenkov detectors



Antilepton + meson



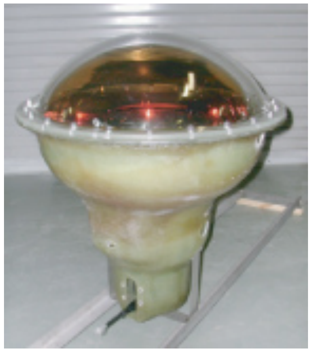


Super-Kamiokande

22.5 kton fiducial volume
$7.5\times10^{33}\,p + 6\times10^{33}\,n$

SK-I: 1996 - 2001

11146 50-cm inner PMTs , 40% coverage
1885 20-cm outer PMTs



SK-II: Jan 2003 - Oct 2005

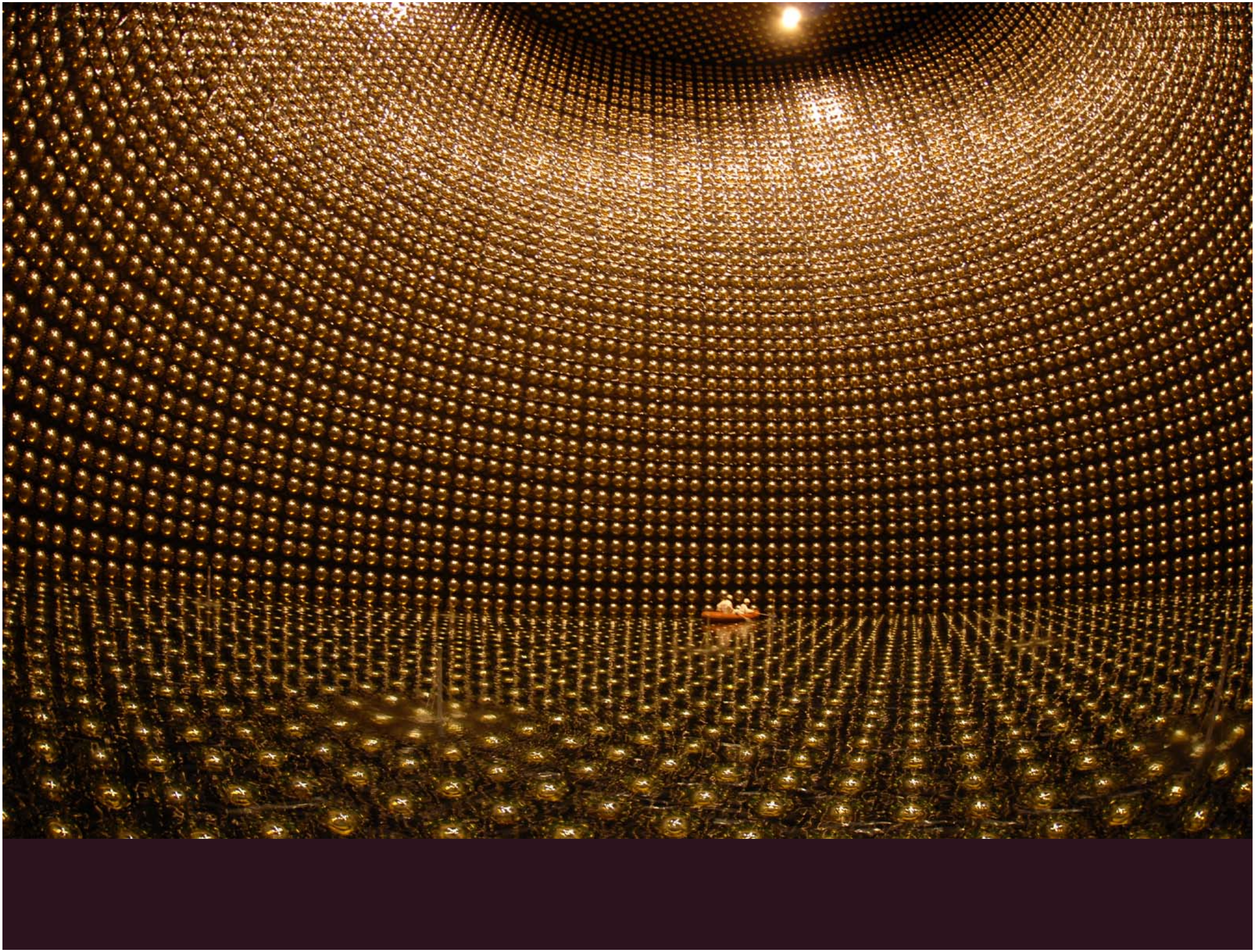
Recovery from accident
5182 50-cm inner PMTs
Acrylic + FRP protective
Outer detector fully restored

SK-III: May 2006 - August 2008

Restored 40% coverage
Outer detector segmented (top | barrel | bottom)

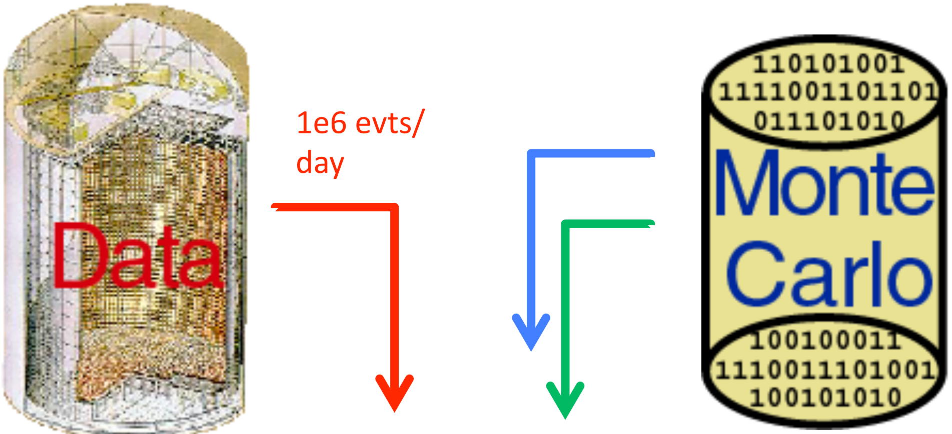
SK-IV: September 2008 -

SK-IV Replace all electronics – 2008
T2K beam – late 2009
Add gadolinium - 201?



(1) proton decay MC

(2) atmospheric neutrino MC



Reduction

no OD activity

remove flashing PMTs

etc.

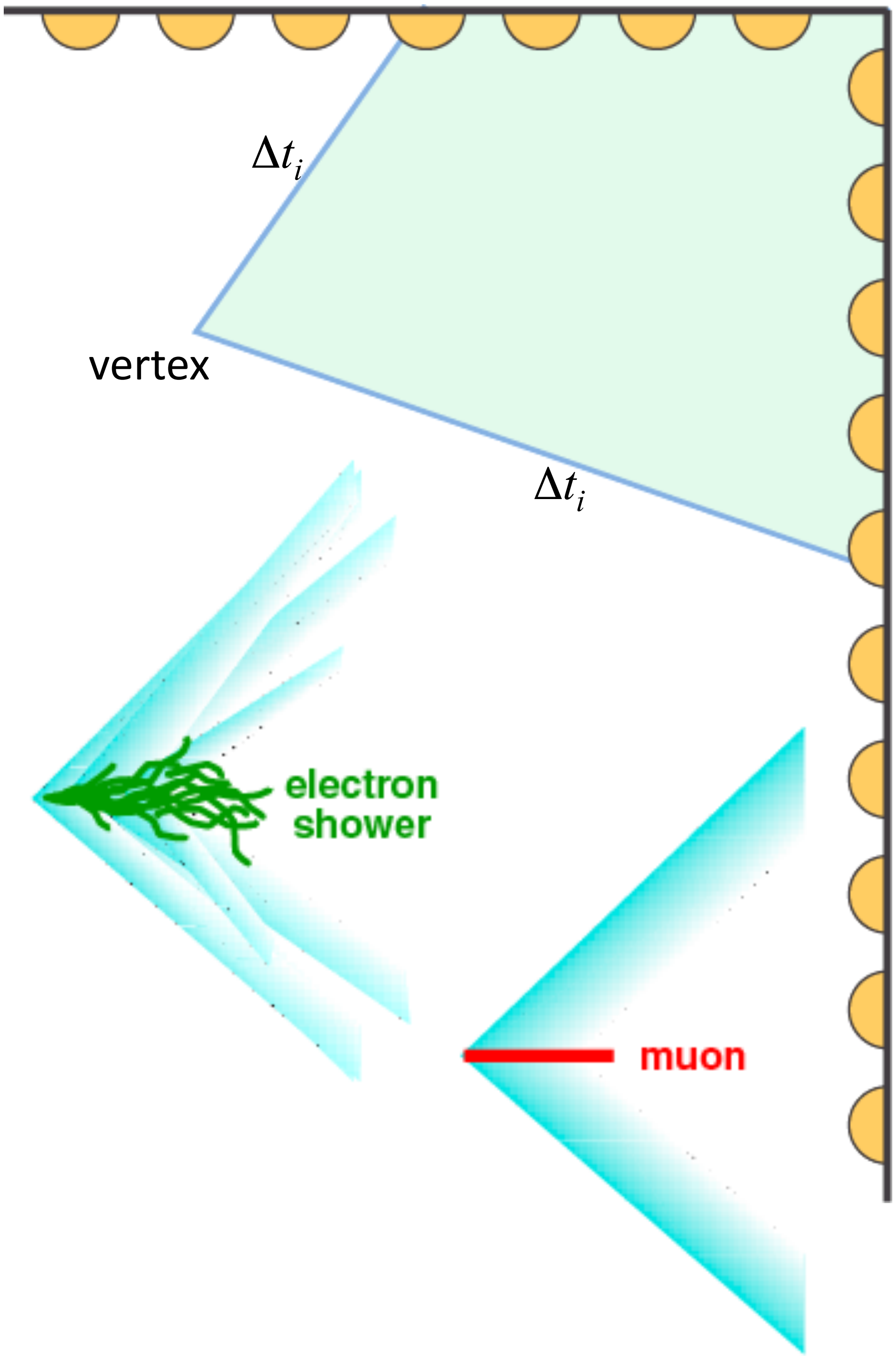
Reconstruction

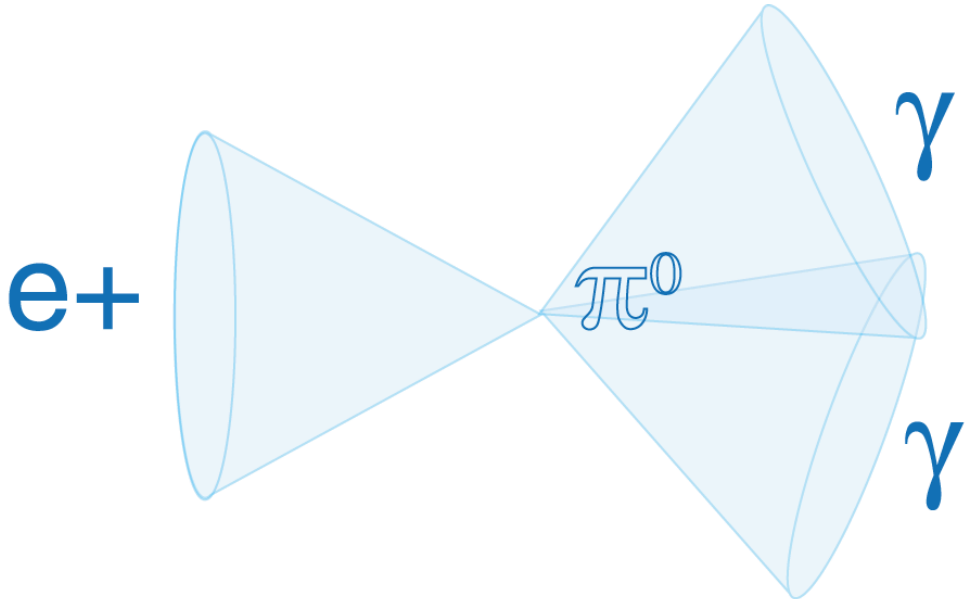
energy, vertex, ring counting,

particle identification, muon decay etc.

Final analysis

Good event criteria

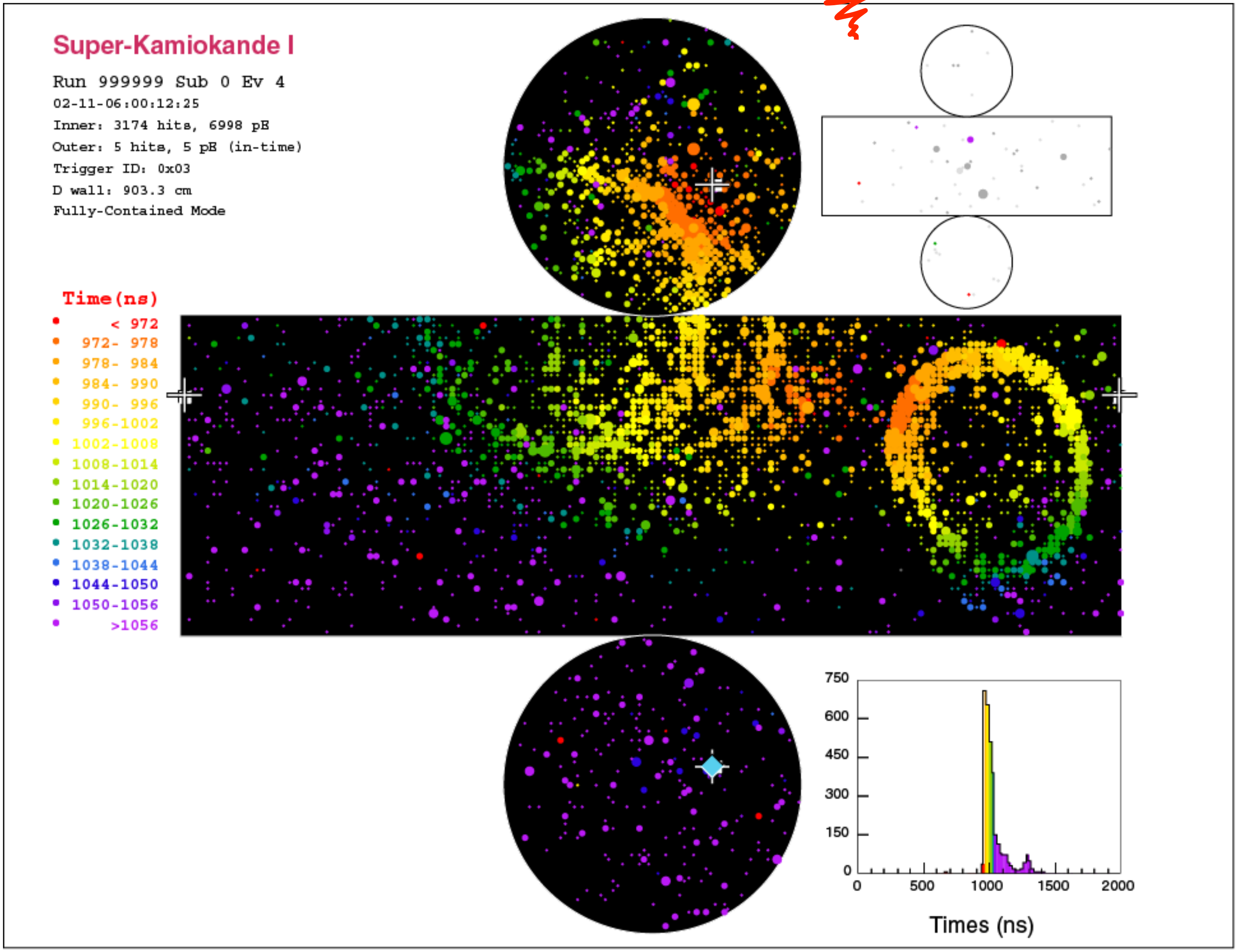




Good event criteria:

- Fully contained
- Fiducial volume
- 2 or 3 rings
- All rings are EM showers
- π^0 mass 85-185 MeV/c^2
- No μ-decay electrons
- Mass range 800-1050 MeV/c^2
- Net momentum < 250 MeV/c

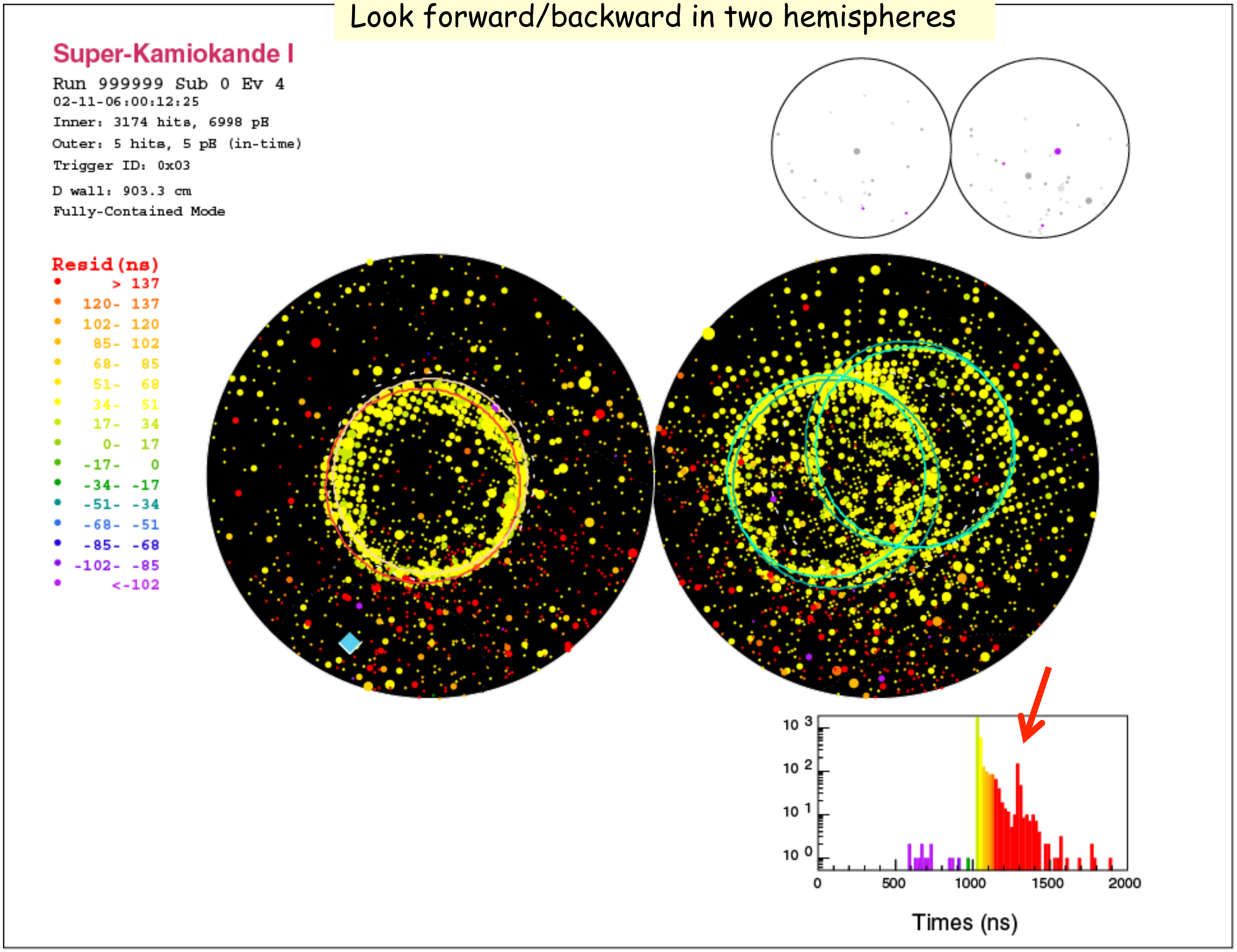
Example event: $(p\rightarrow\mu^+\pi^0)$



Super-Kamiokande I

Run 999999 Sub 0 Ev 4
02-11-06:00:12:25
Inner: 3174 hits, 6998 pE
Outer: 5 hits, 5 pE (in-time)
Trigger ID: 0x03
D wall: 903.3 cm
Fully-Contained Mode

Sit at reconstructed vertex and adjust Δt.
Look forward/backward in two hemispheres



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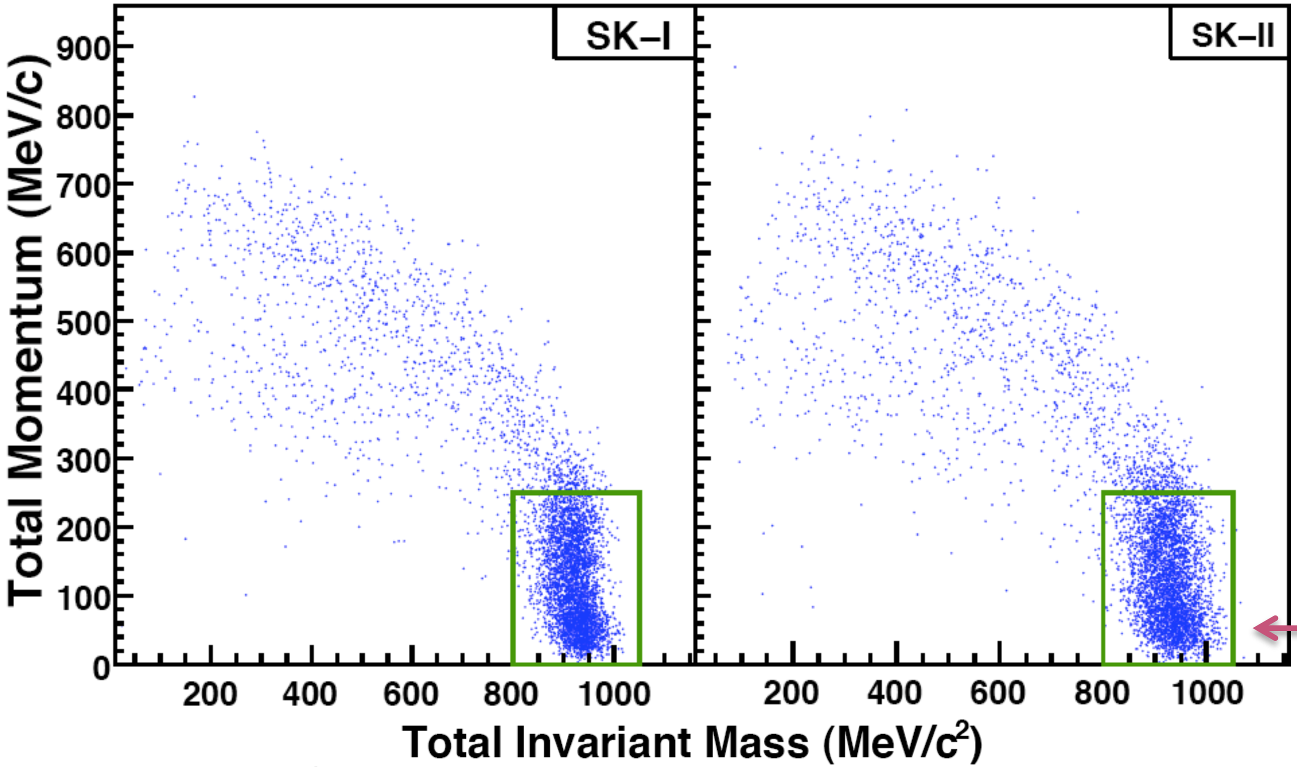
Inner: 3174 hits, 6998 pE
Outer: 5 hits, 5 pE (in-time)
Trigger ID: 0x03
D wall: 903.3 cm
Fully-Contained Mode

Proton Decay Signal Prediction (Monte Carlo)



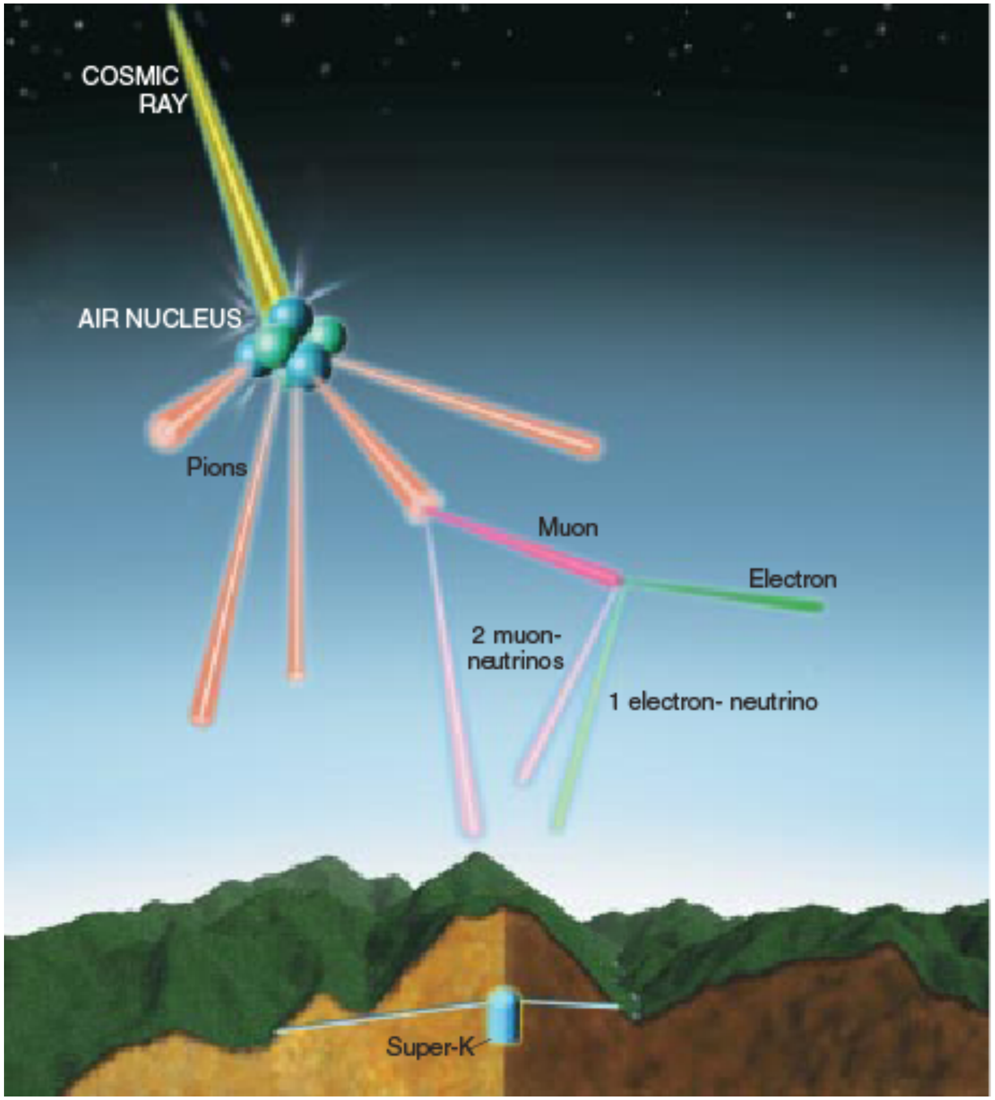
$p \to e^+ \pi^0$ MC

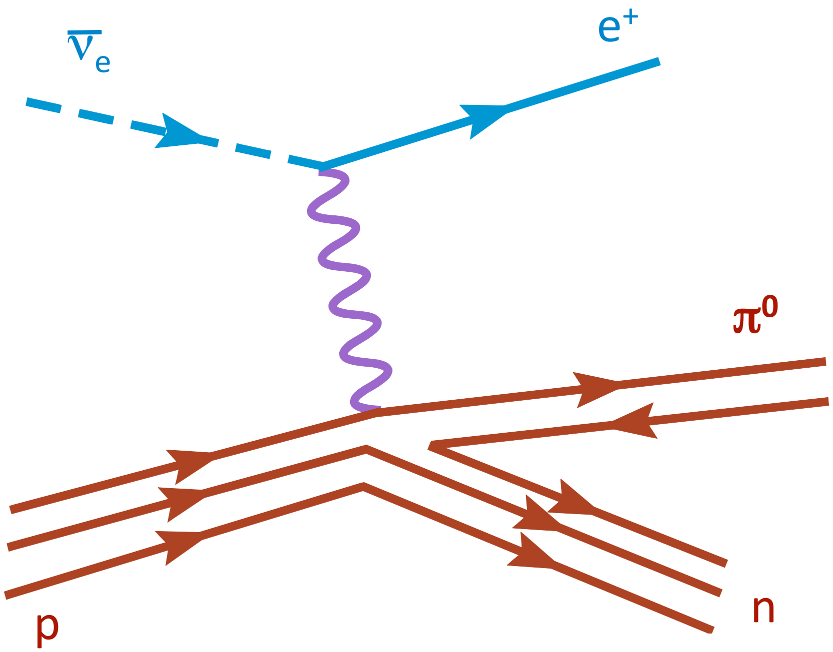
free protons (hydrogen)

- Effective mass in ^{16}O
- Correlation with other nucleons
- Fermi motion – by shell
- Initial position (Woods-Saxon)
- Nuclear de-excitation γ
- pion-nuclear interactions
  - Elastic Scattering
  - Charge Exchange
  - Absorption

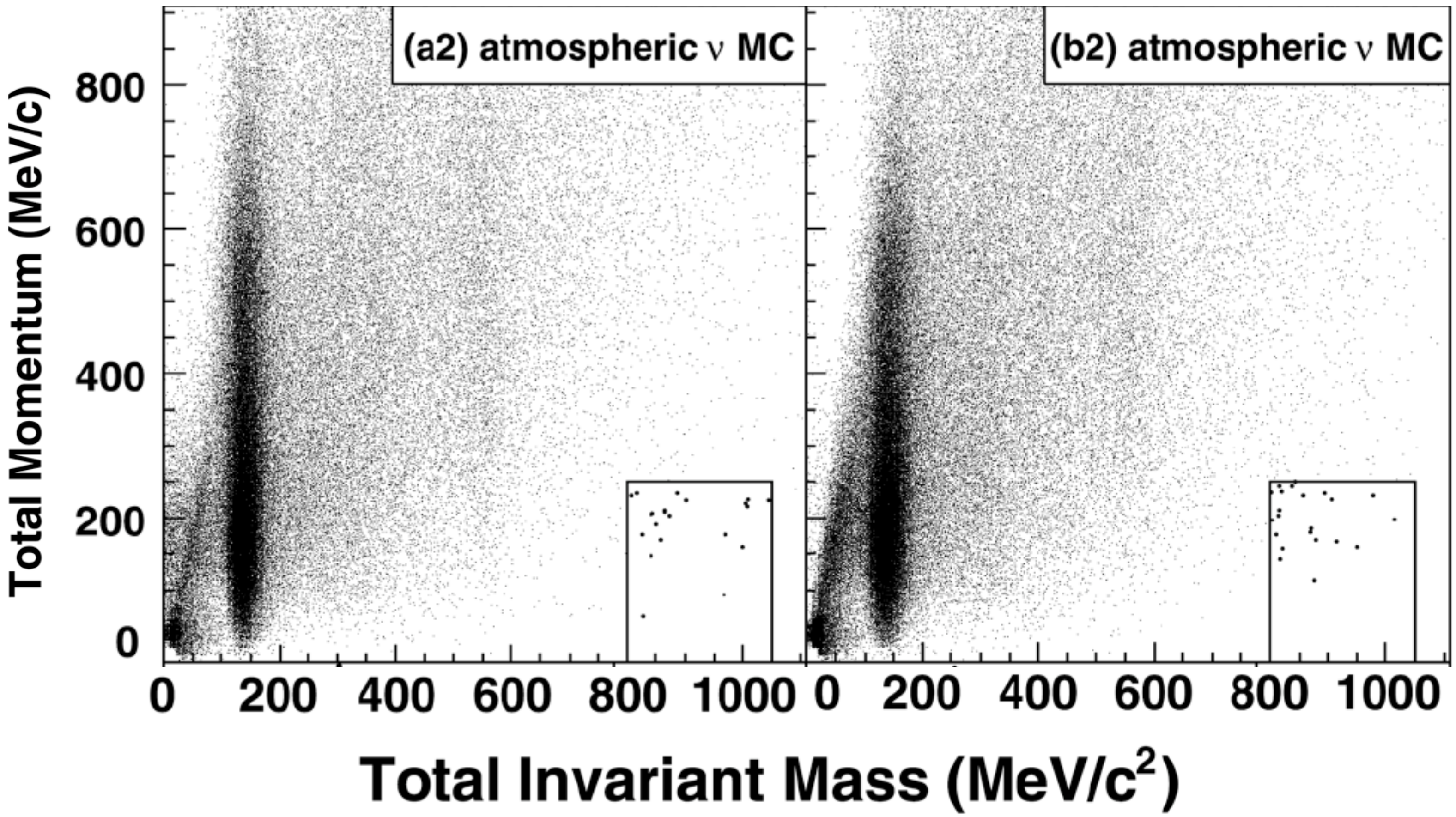
efficiency ~ 44%
main source of inefficiency:
π^0 absorption in ^{16}O nucleus

Background: Atmospheric Neutrinos





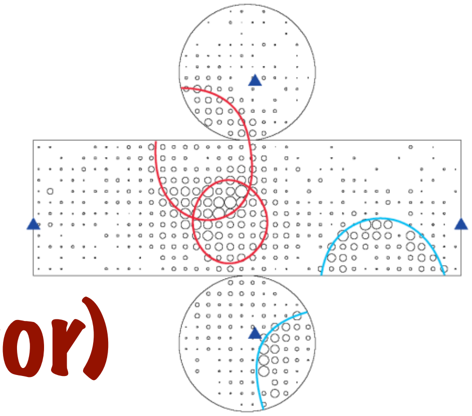
Atmospheric Neutrino Background (Monte Carlo)

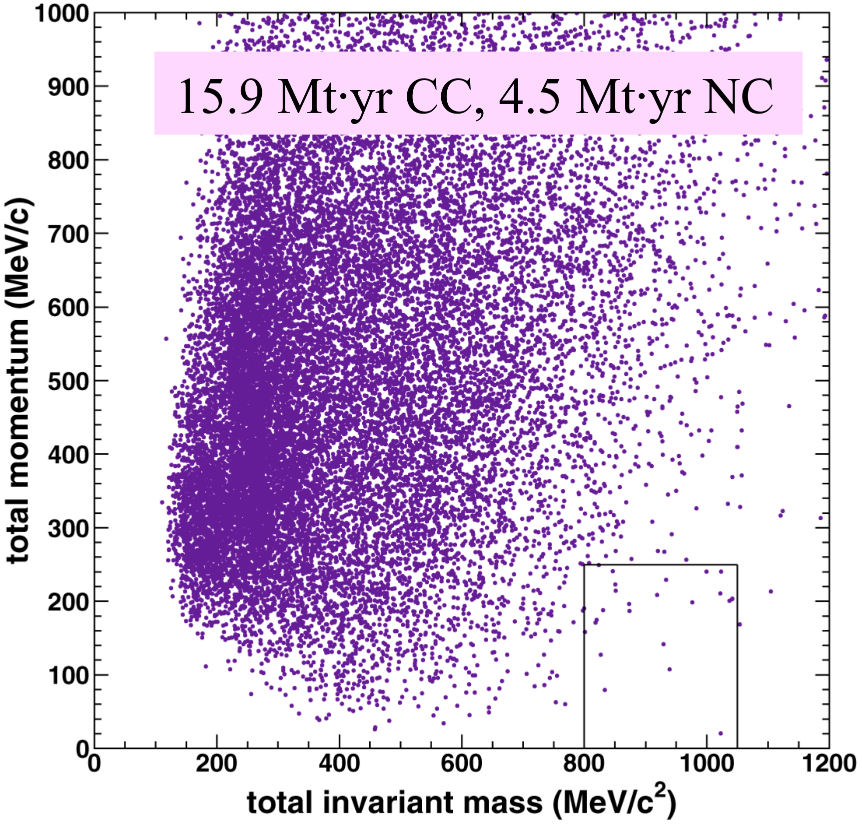


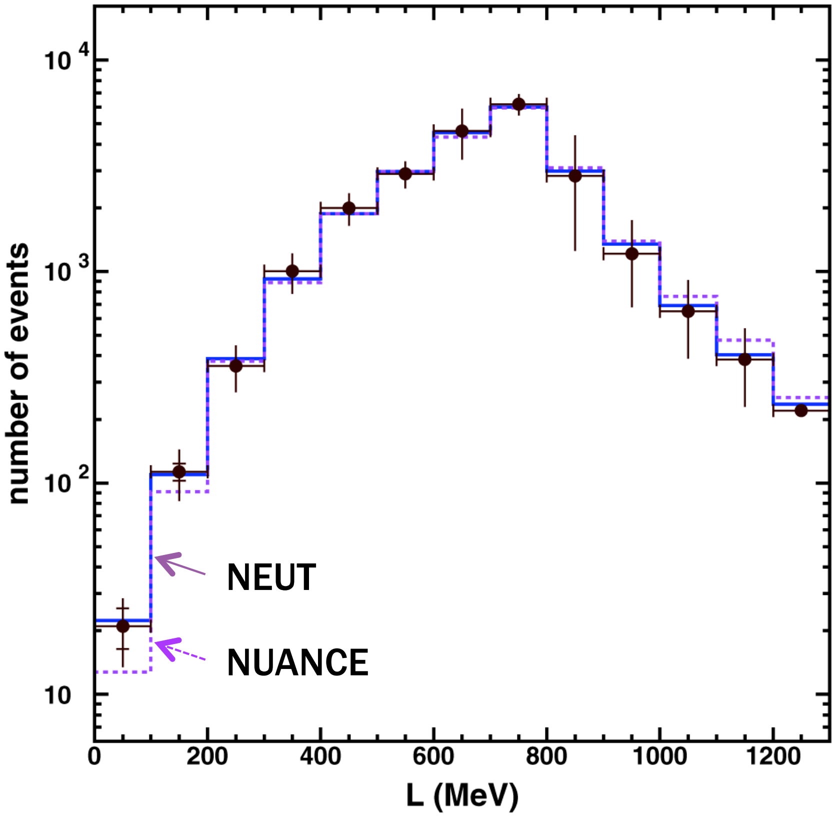
- Flux (E, flavor)
- Cross sections:
  - quasielastic
  - 1-π, multi-π
  - DIS

- Pauli blocking
- Intranuclear scattering
- ν oscillations

Direct measurement of proton decay background using K2K neutrino beam (1KT near detector)



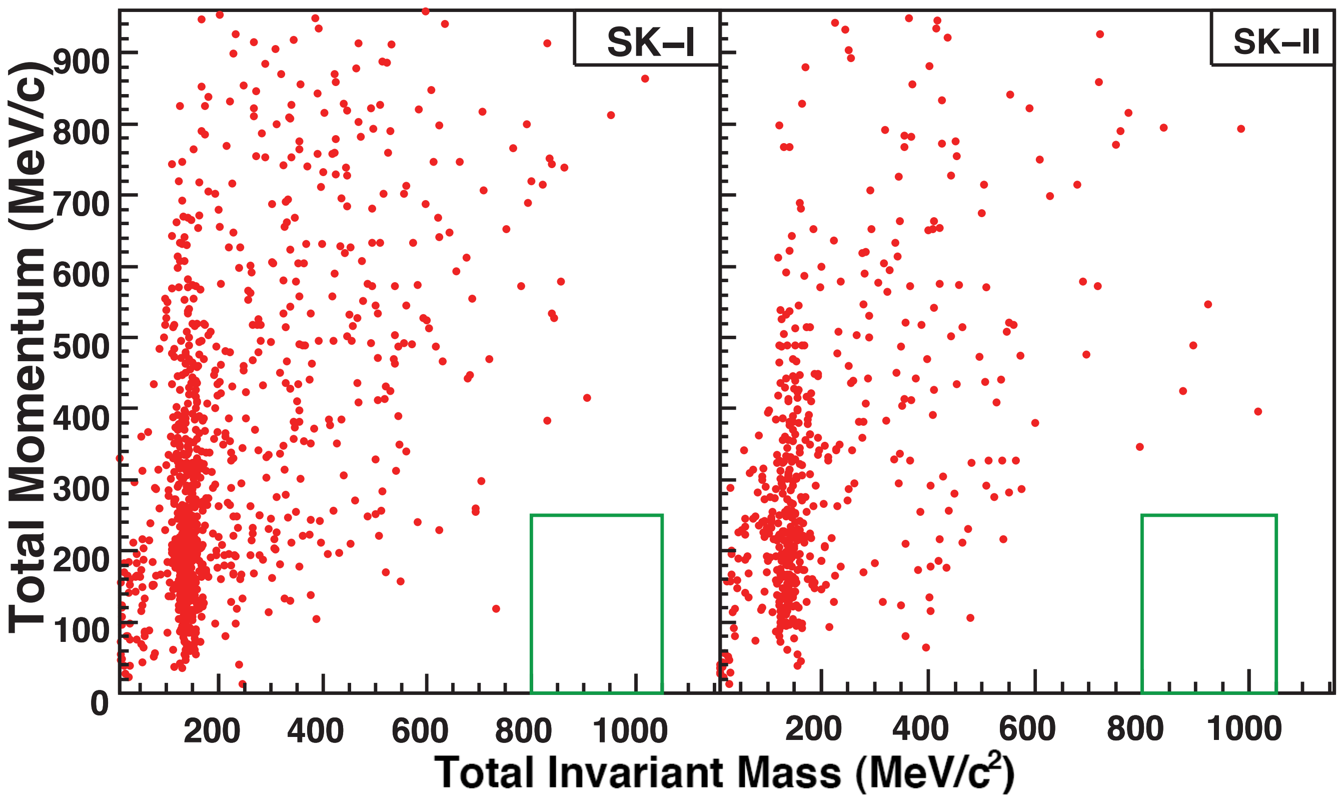




$$e^+\pi^0 \ \text{BG} = 1.63^{+0.42}_{-0.33}(\text{stat})^{+0.45}_{-0.51}(\text{sys.}) \ \text{evts/Mt} \cdot \text{yr}$$

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

Search Results: Super-K DATA



	SK-I	SK-II
Detection efficiency	44.6%±19%	43.6±19%
Background estimate	0.30±0.04±0.11	0.34±0.05±0.12
Exposure	1489.2 d (91.6 kt·yr)	798.6 d (49.1 kt·yr)
Data	0	0

Setting a limit

a simple calculation of the rate if we measured something:

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

n = number of observed events
b = expected number of background events
λ = exposure = $N_{proton} \cdot \Delta t$
ε = efficiency

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

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

$\Leftarrow$ a simple calculation of a 90% CL limit, but...
does not take into account n=0 properly (see F&C)
and does not take into account systematic uncertainty

$$\tau / B > 8.9 \times 10^{33} \text{ years}$$

treatment of limit using Bayes theorem to incorporate systematic uncertainty:

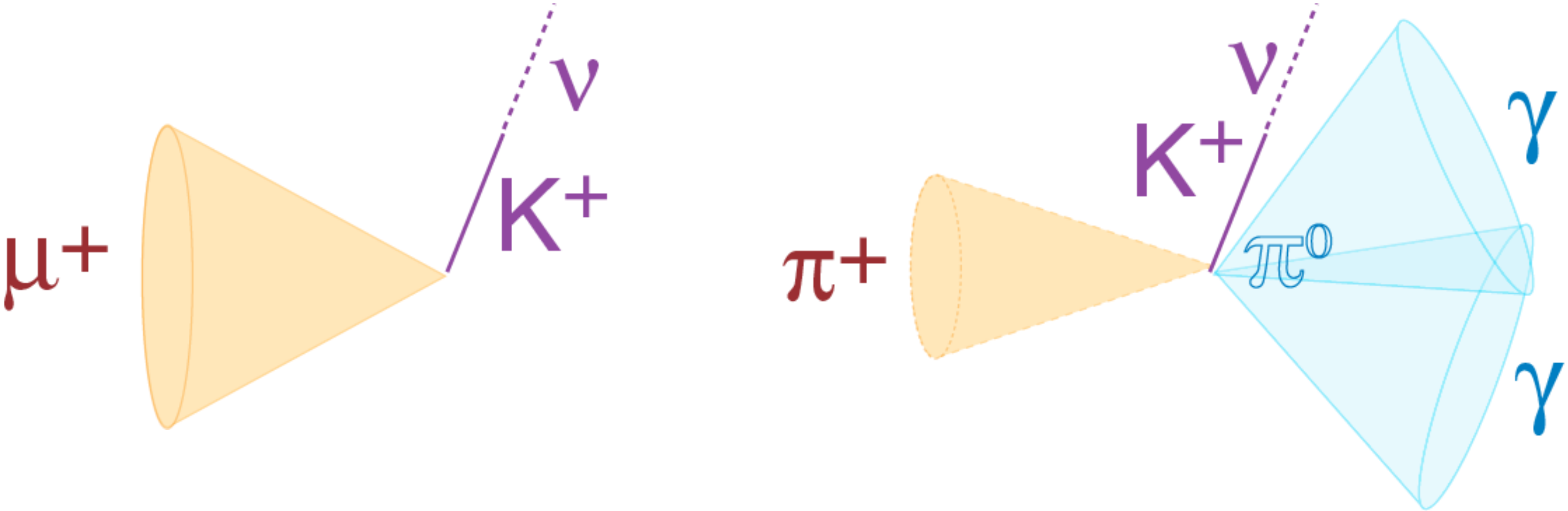
$$P(\Gamma \mid n) = \iiint \frac{e^{-\Gamma\lambda\varepsilon + b}(\Gamma\lambda\varepsilon + b)^n}{n!} P(\Gamma)\, P(\lambda)\, P(\varepsilon)\, P(b)\, d\Gamma\, d\lambda\, d\varepsilon\, db$$

$$\boxed{\tau / B(e^+\pi^0) > 8.2 \times 10^{33} \text{ years}}$$

$p \rightarrow K^+\nu$

Nuclear interaction is negligible
Kaon momentum s 340 MeV/c: is below Cherenkov threshold
essentially a search for kaon decay at rest

$K^+ \rightarrow \pi^+ \pi^0$	21%
$K^+ \rightarrow \mu^+ \nu_\mu$	65%



Some cleverness

Nuclear Shell Model:
$^{16}O\,(p_{3/2}) \rightarrow {}^{15}N^{*}$ + proton hole
de-excites by 6.3 MeV gamma

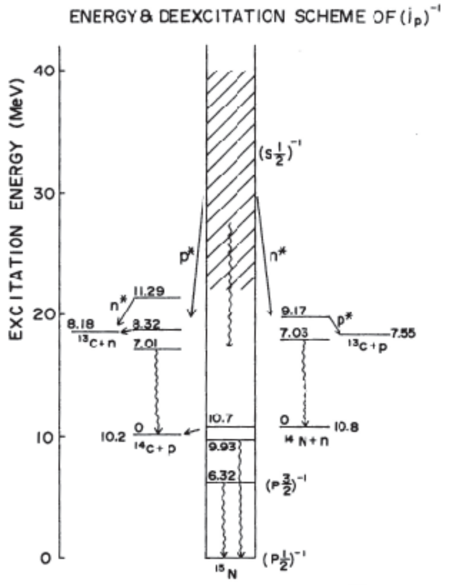
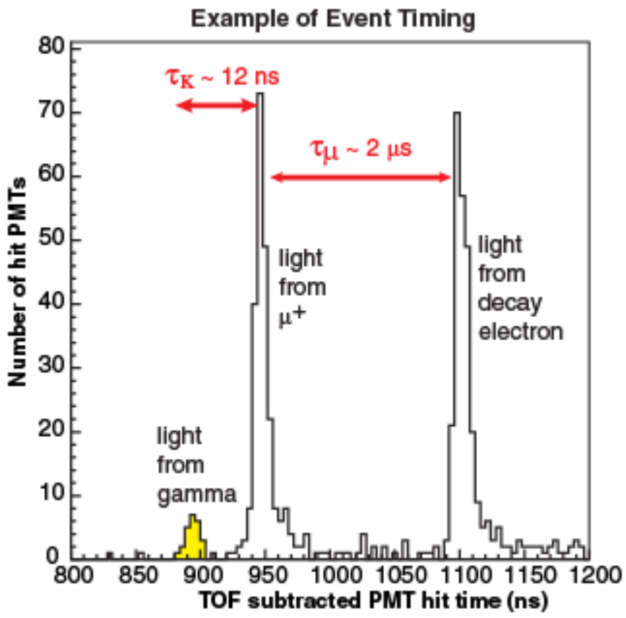
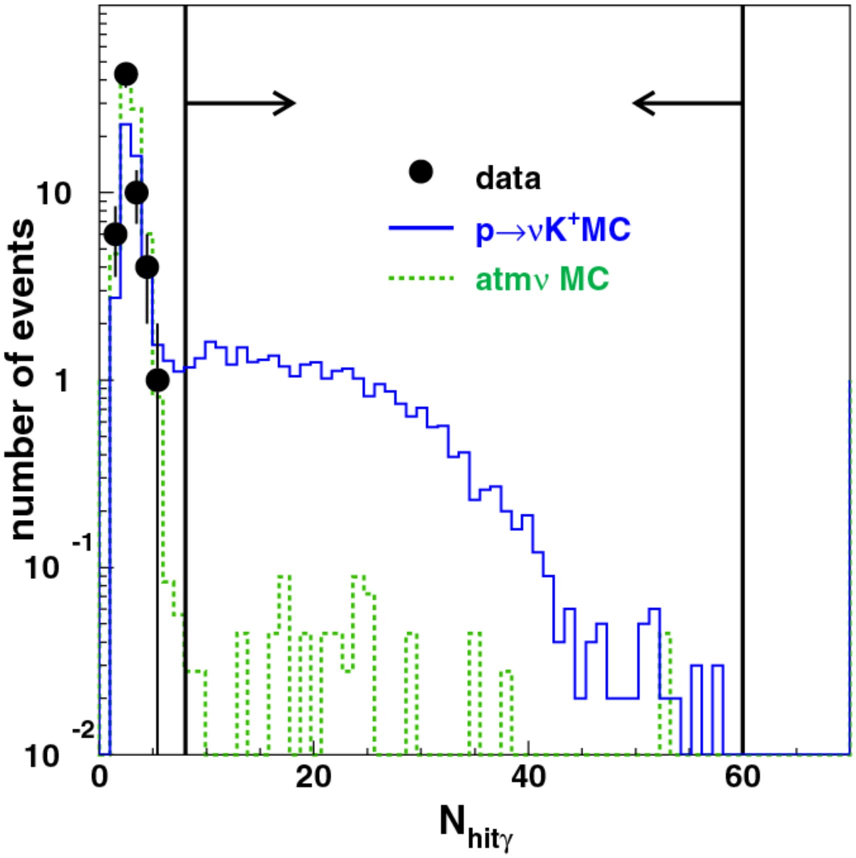


FIG. 2. Level scheme of proton-hole states in ^{151}N and their deexcitation modes. Energies are given in units of MeV. p^* and n^* are the protons and neutrons emitted from the continuum (unbound) region, respectively.

H.Ejiri Phys. Rev. C48 (1993) 1442

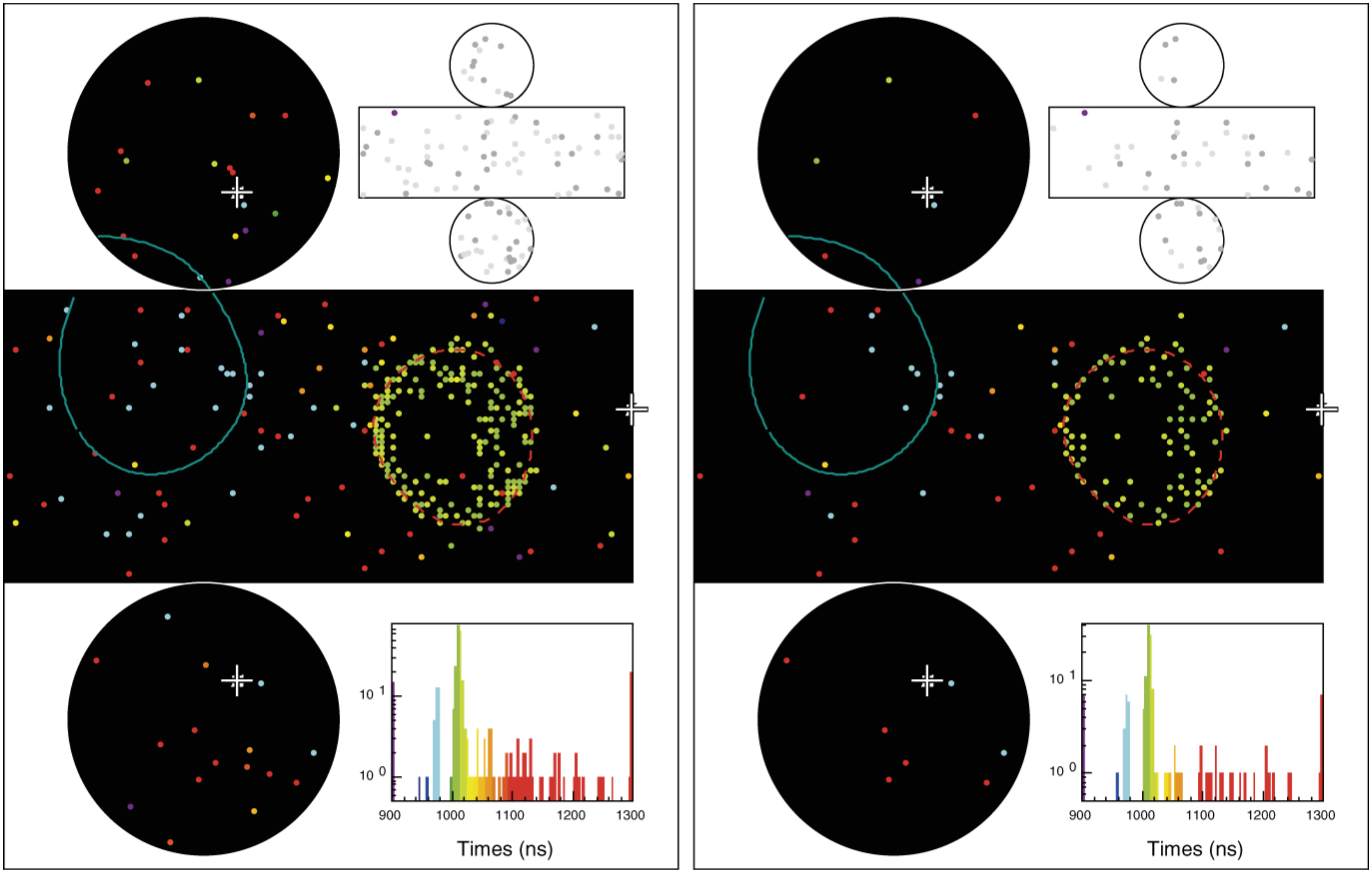




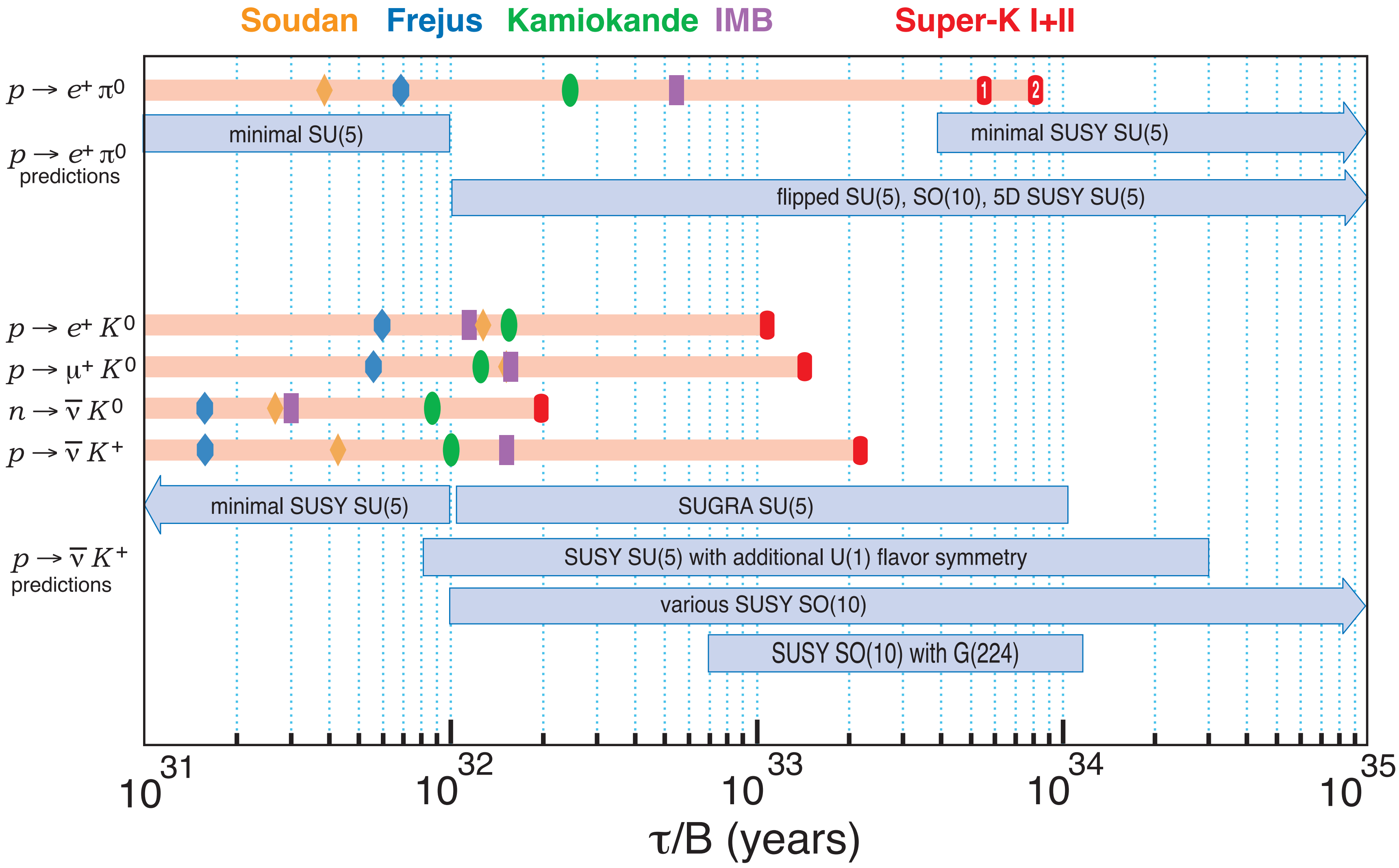
Gamma Tag Single Muon Search:

$BR\times\varepsilon = 8.6\pm20_{sys}\%$

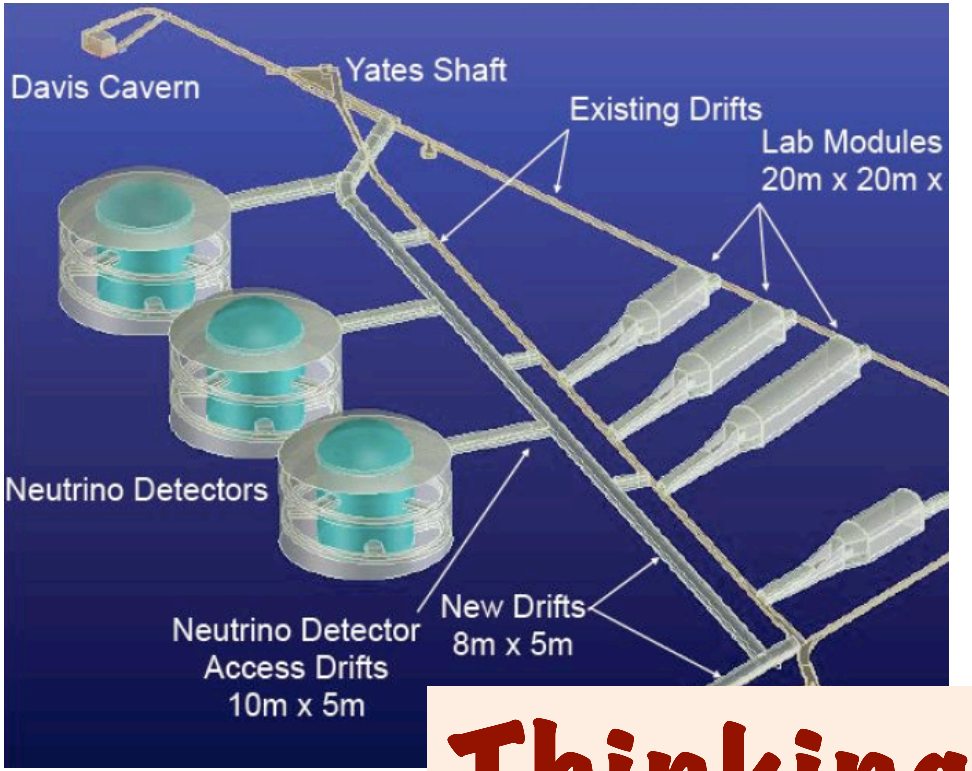
Background = 0.7 events (±59%)

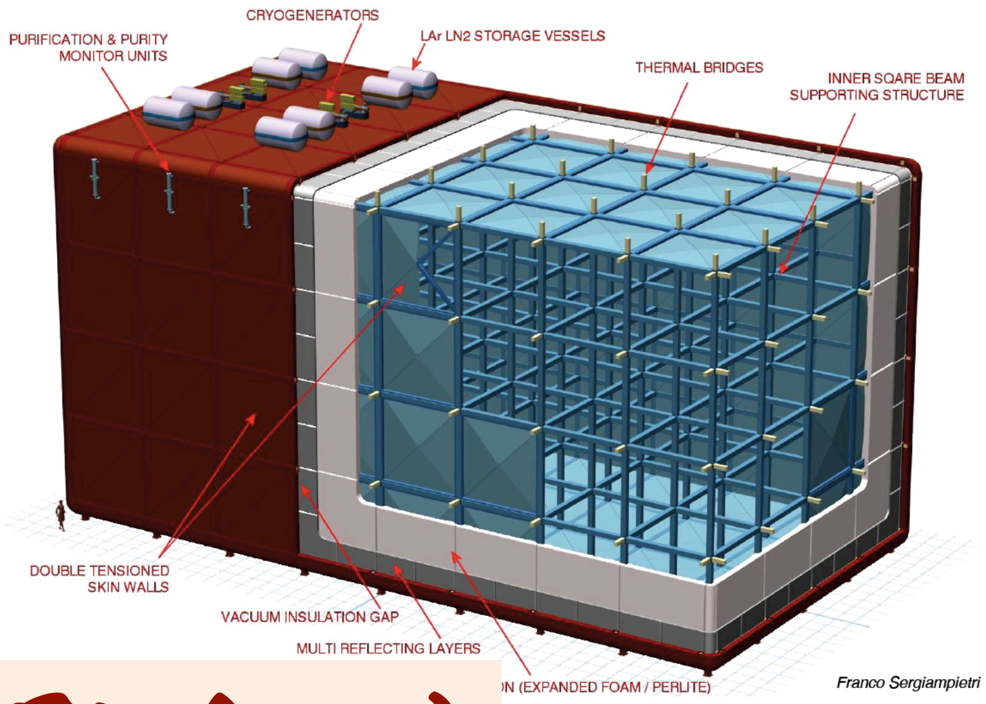

10 1
10 0
900
1000
1100
1200
1300
Times (ns)
10 1
10 0
900
1000
1100
1200
1300
Times (ns)

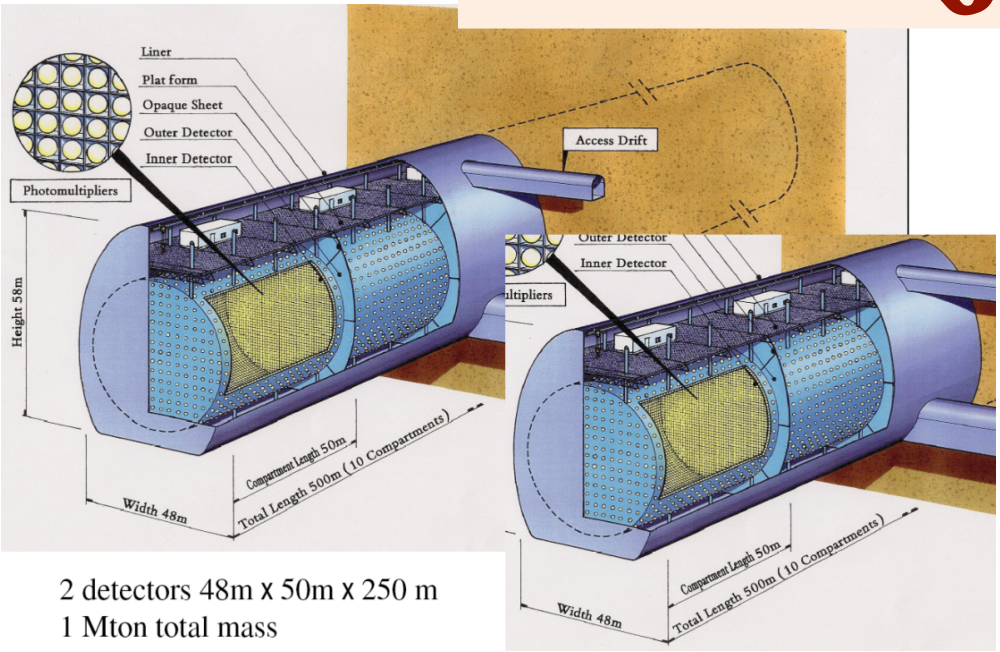
Limits in context with theory



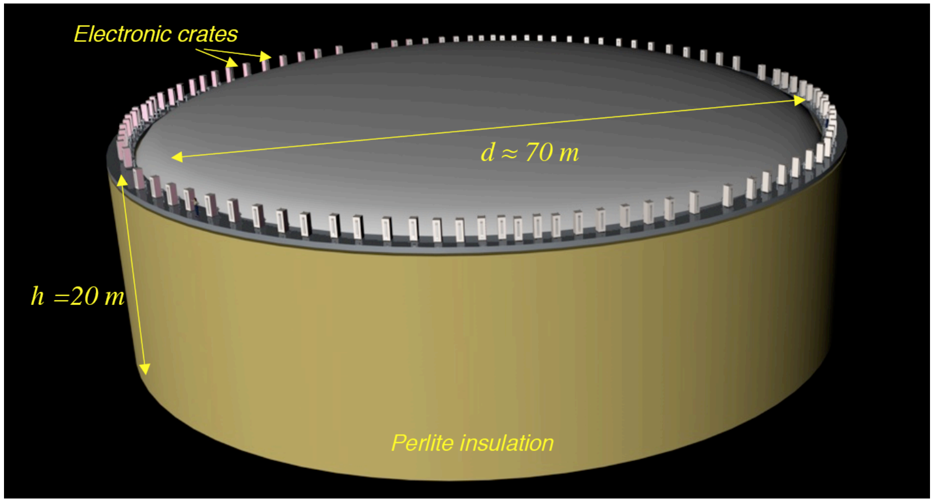
Thinking Big(ger)



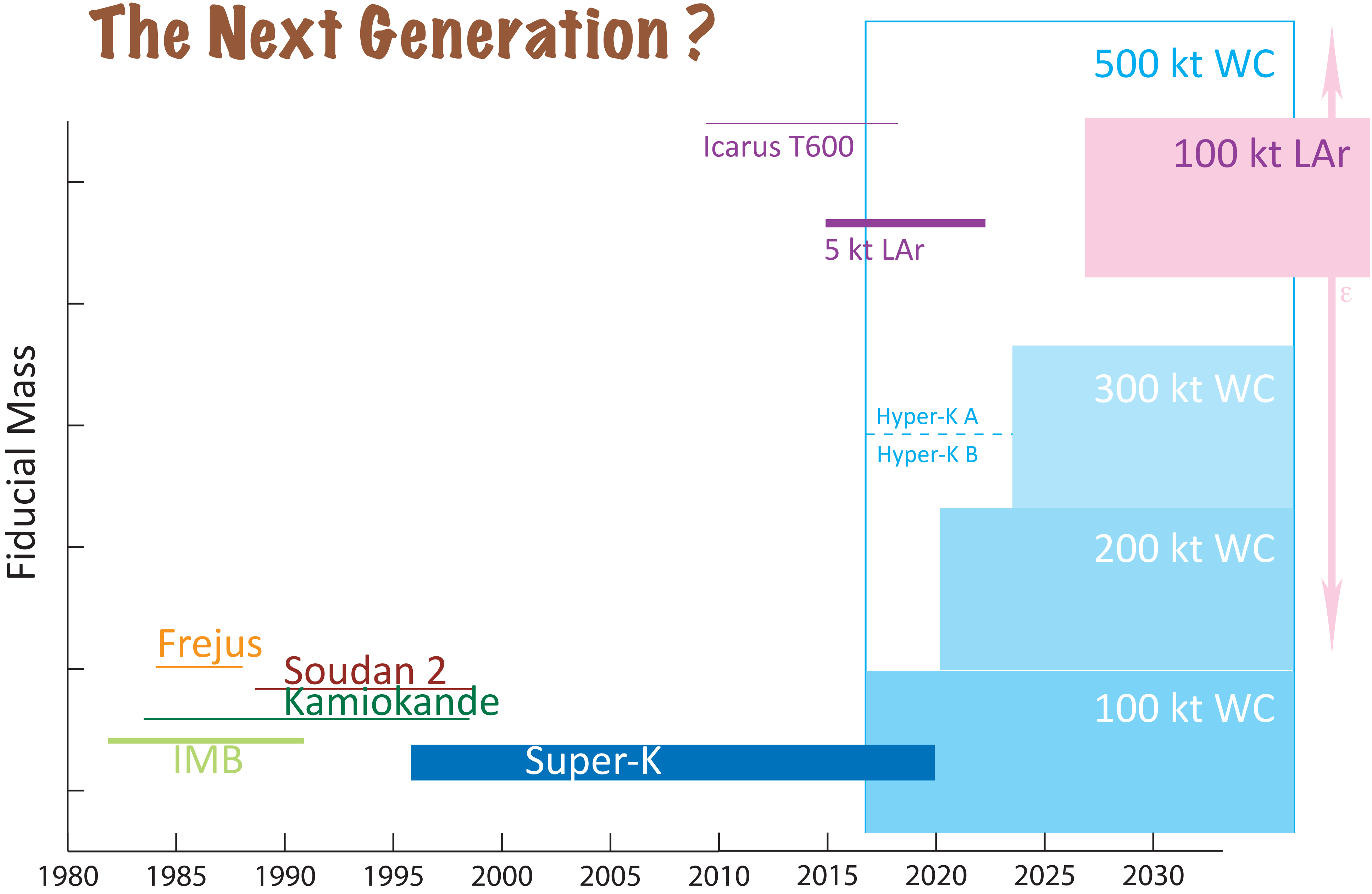




2 detectors 48m x 50m x 250 m
1 Mton total mass



The Next Generation ?

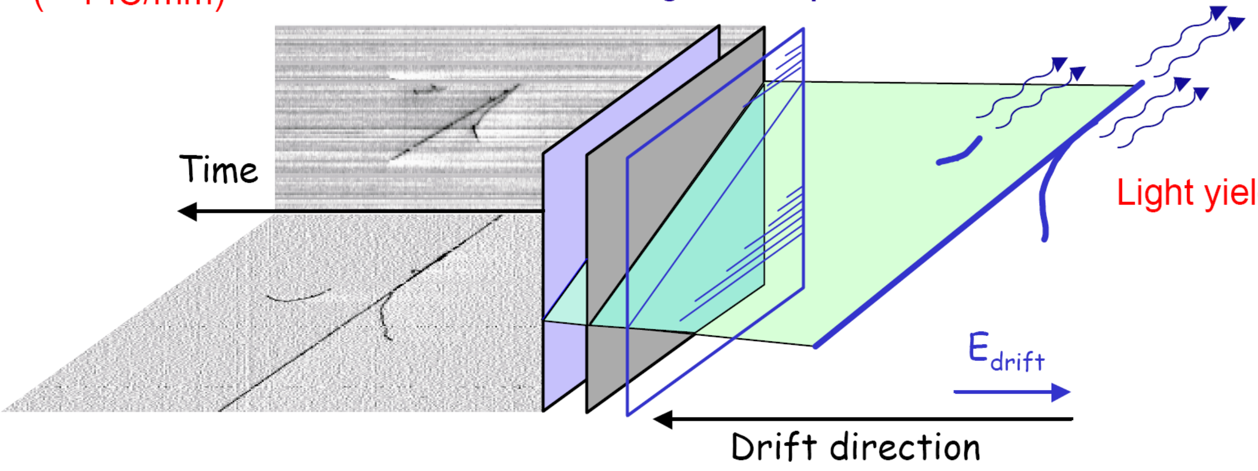


Liquid Argon Time Projection Chamber

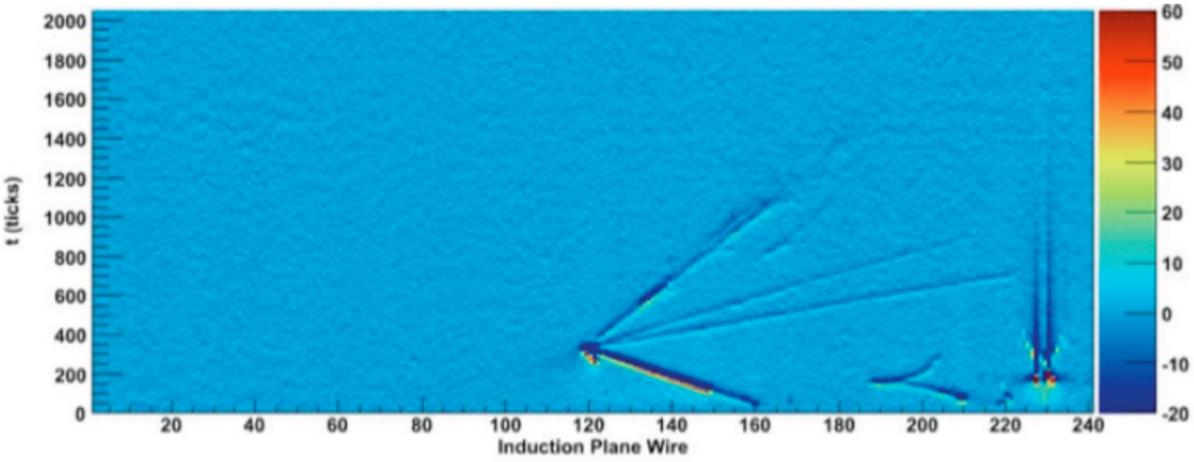
Charge yield ~ 6000 electrons/mm
(~ 1 fC/mm)

Charge readout planes: Q

UV Scintillation Light: L

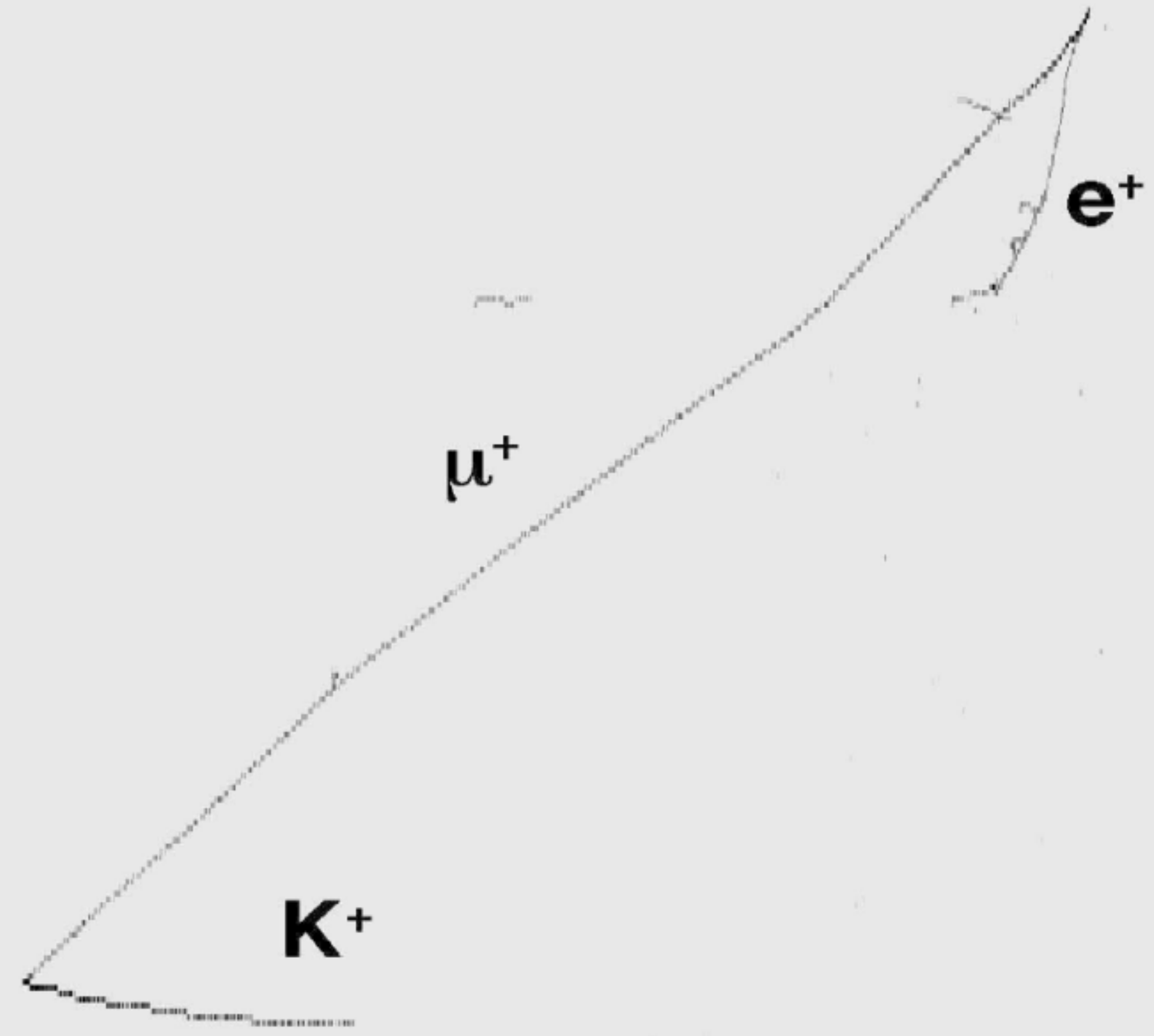


Light yield ~ 5000 γ/mm

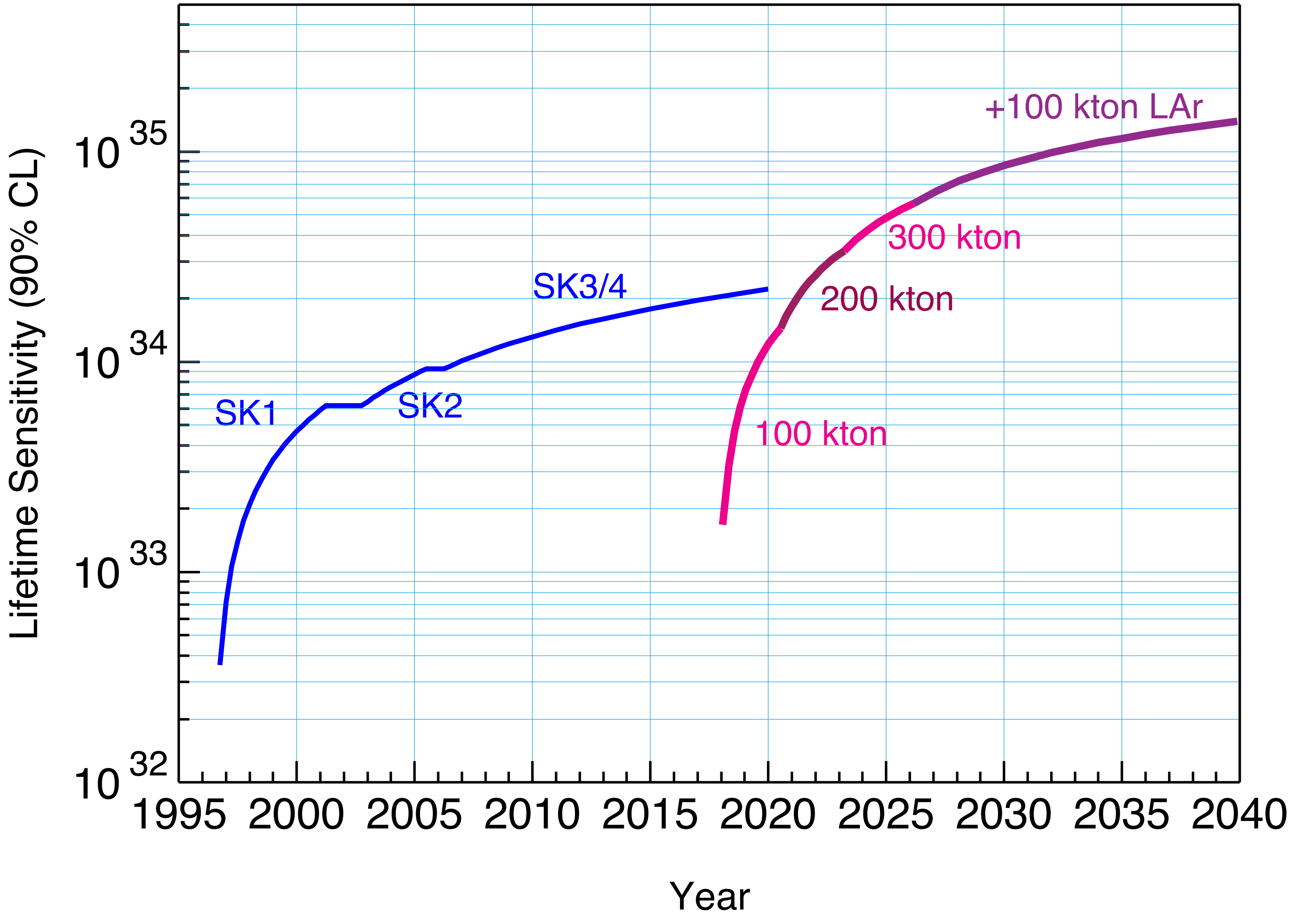


pixel size ~ mm
dE/dx
no Cherenkov threshold

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

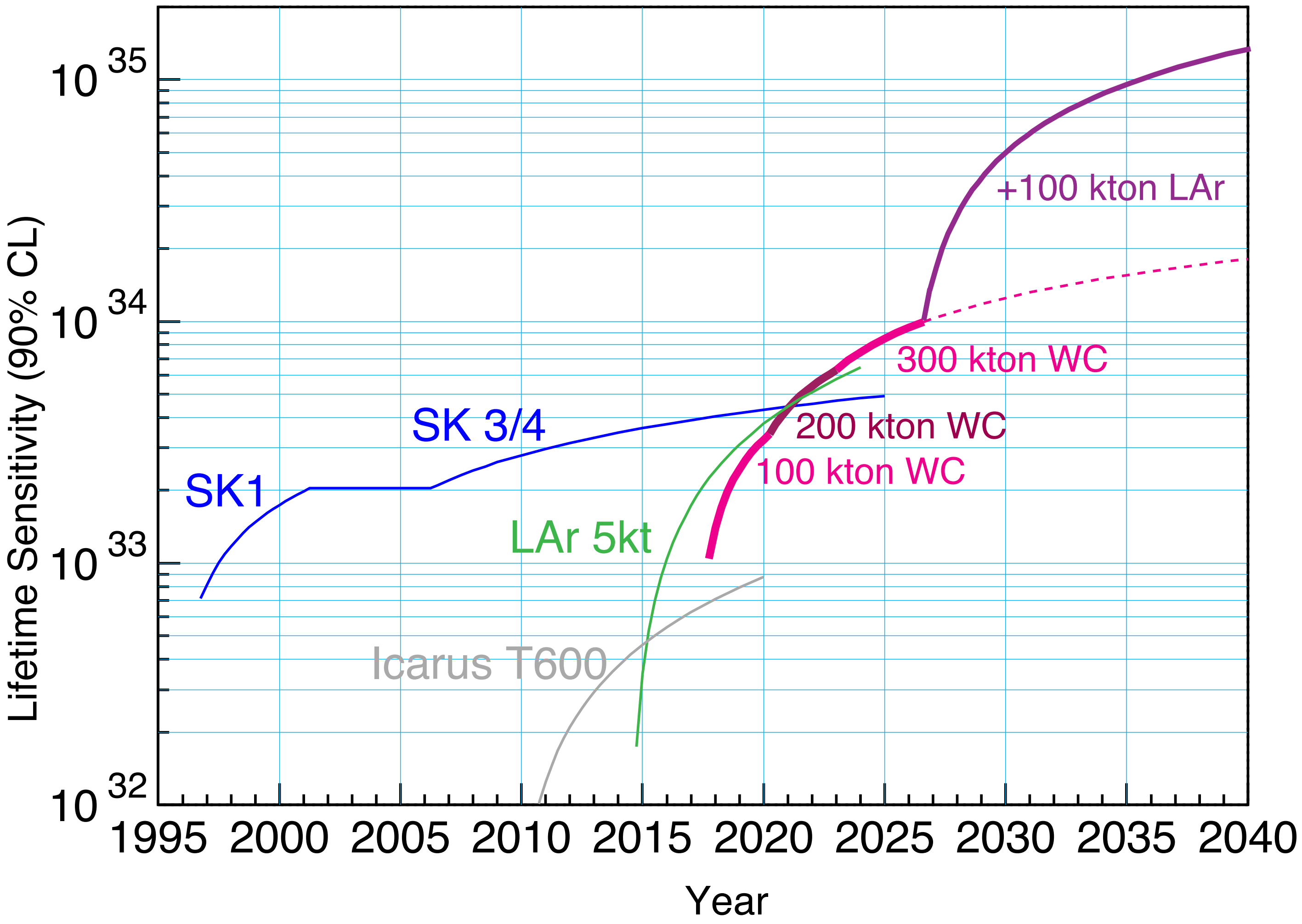


$p \rightarrow e^{+}\pi^{0}$



Efficiency = 0.45
BG = 0.2 evts/100 kty
Nobs = Nbg

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



WC efficiency = 0.14
BG = 1.2 evts/100 kty
Nobs = Nbg

LAr efficiency = 0.98
BG = 0.1 evts/100 kty
Nobs = Nbg

Many people think proton decay is important…

EPP2010 (2005)
Action Item 5: A Staged Neutrino and Proton Decay Research Program

HEP Future Facilities Roadmap (2003)
Scientific potential: “absolutely central”. Specific Facility: “Don’t know enough yet”.

NRC– Committee on the Physics of the Universe
Eleven Science Questions for the New Century (2003)
#8 Are protons unstable?

D. Gross *et al*. Ten Questions for the New Millenium (NYT August 15, 2000)
#3. What is the lifetime of the proton and how do we understand it?

D. Mermin rebuttal Ten Questions (Phys. Today, Feb. 2001)
#9. What indeed is the lifetime of the nucleus of the neutral hydrogen atom?

What does it take to get a new megaton-class detector started?

- firm theoretical predictions are unlikely
- discovery of SUSY at the LHC would help
- perhaps a candidate or two from Super-K?
- real progress in reducing costs (PMTs = $$$$)
- demonstrated feasibility of multi-kt LAr TPC
- a funded next generation neutrino beam