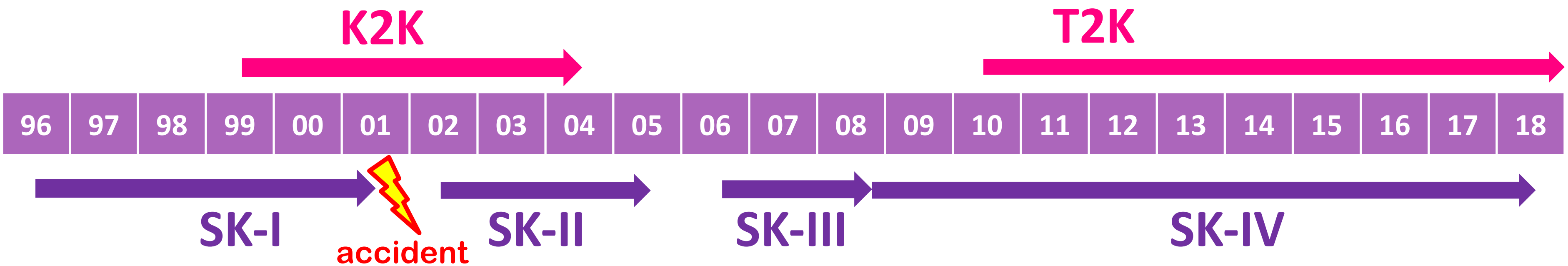
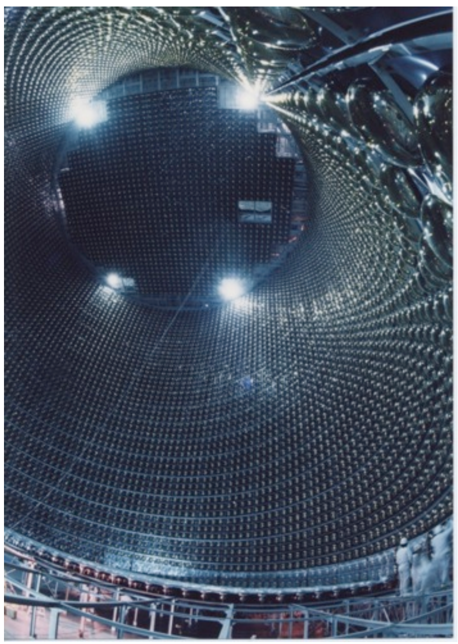
2019 DPF Northeastern

Physics with the Upgraded Super-K Detector

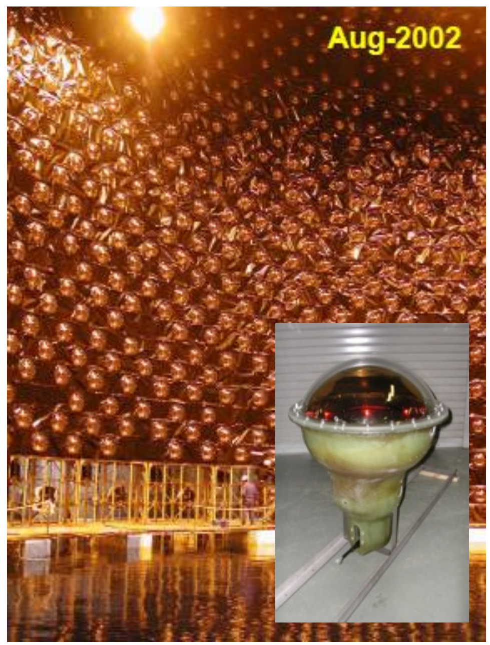
Ed Kearns – Boston University

Super-Kamiokande Experimental Phases

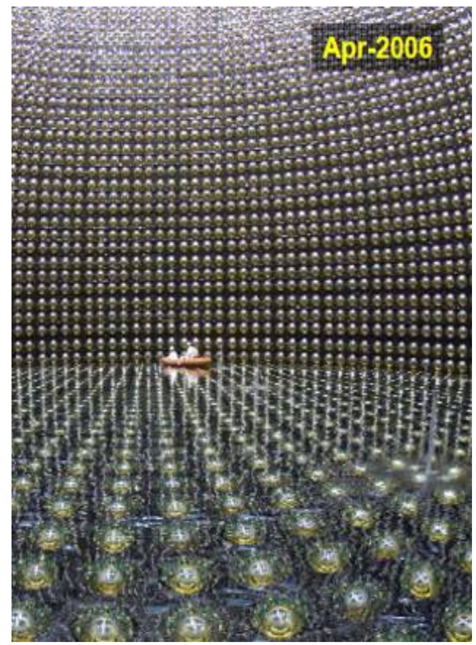




11146 ID PMTs
(40% coverage)



5182 ID PMTs
(19% coverage)



11129 ID PMTs
(40% coverage)

Electronics
Upgrade

Super-Kamiokande Experimental Phases

T2K including T2K-II

18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40

SK-Gd

Hyper-K including T2HK

Big job for Super-K collaboration in 2018:

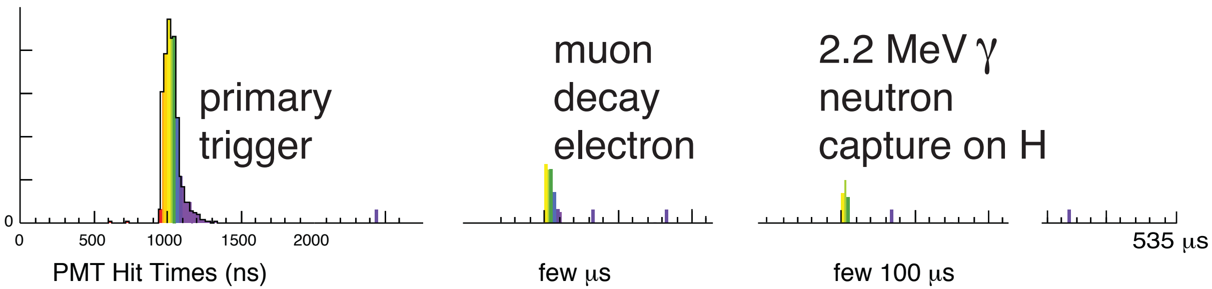
Fix leak
Clean structure
Replace PMTs
Upgrade water system
Work fast: no T2K beam

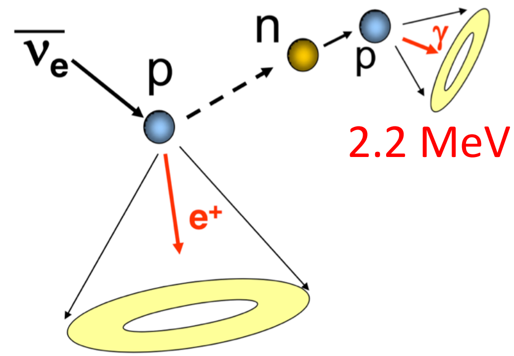
250 persons
11 countries
2751 person-shifts

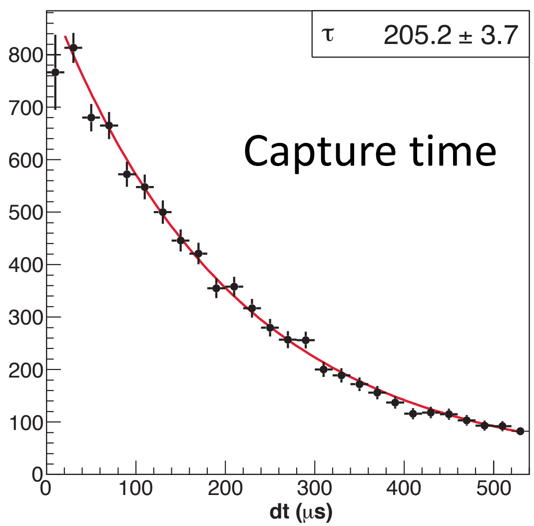
Neutron Capture in SK-IV

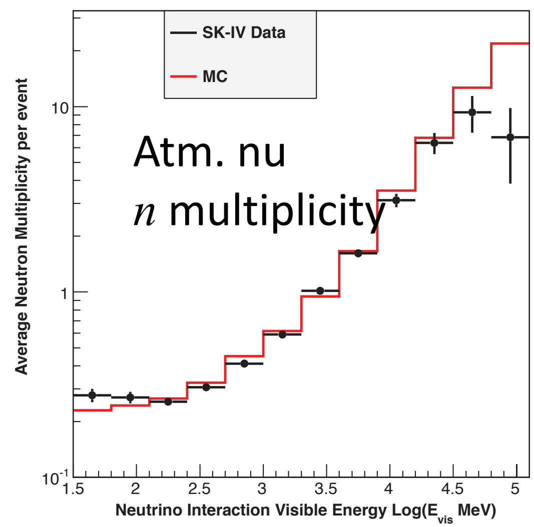
SK-IV Electronics and DAQ upgrade has allowed us to use neutron capture on hydrogen

- $n + p \rightarrow {}^{2}_{1}H + \gamma$ (2.2 MeV)
- 25% efficiency
- 200 μs capture time





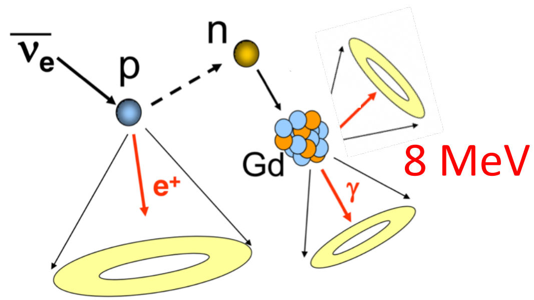


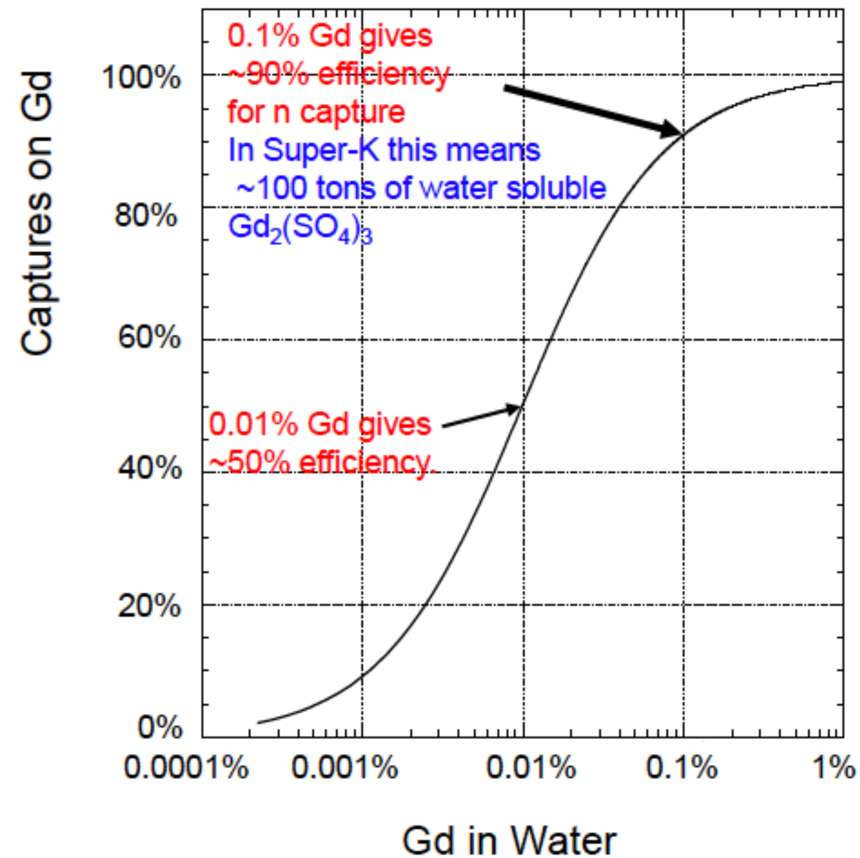


Neutron Capture with SK-Gd

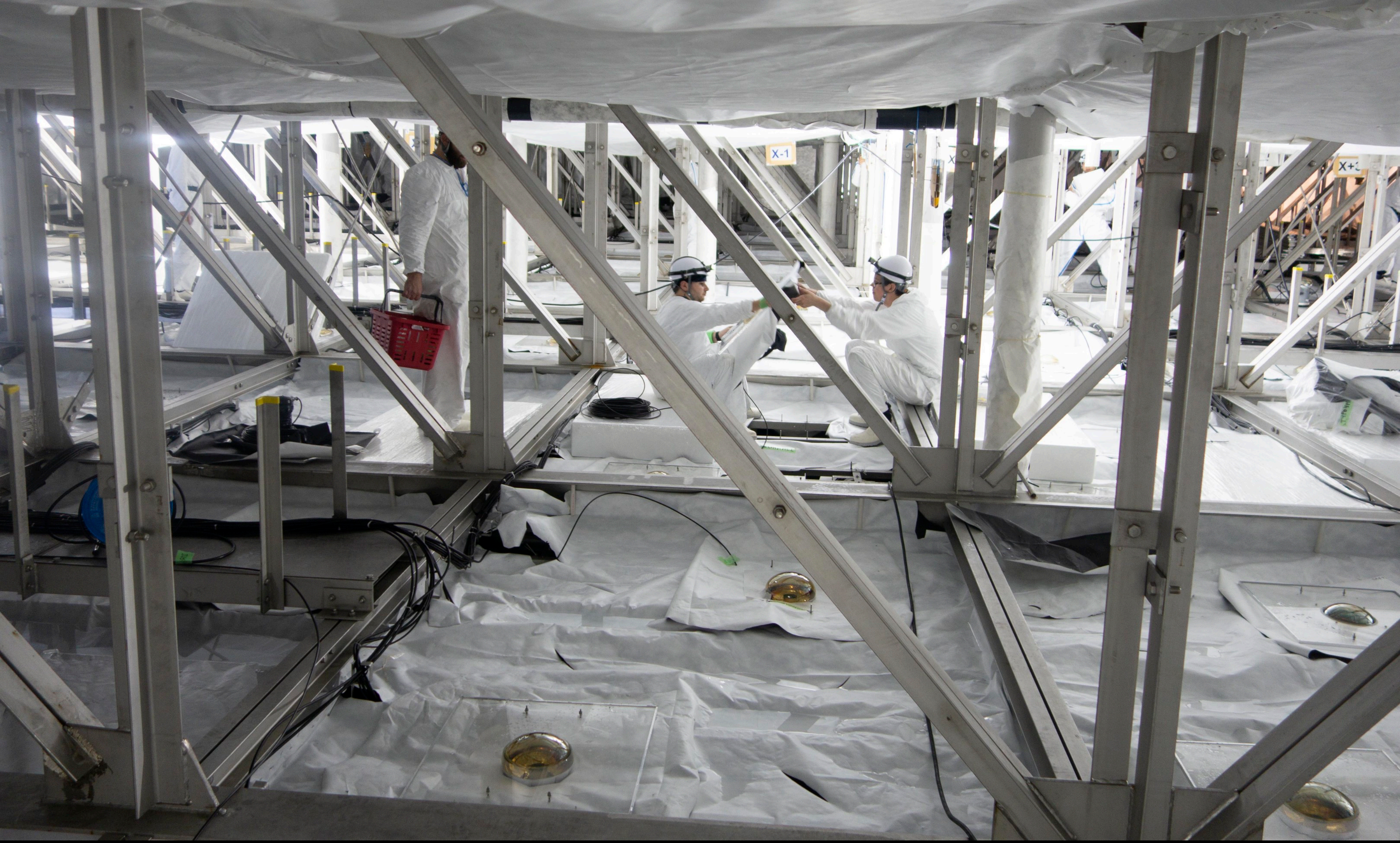
We have developed techniques to add Gd ions to SK water

- Gd has an enormous neutron capture cross section
- Produces 8 MeV gamma cascade
- Shorter capture time (~ 30 μs)
- Capture vertex resolution 40 cm (2x better)

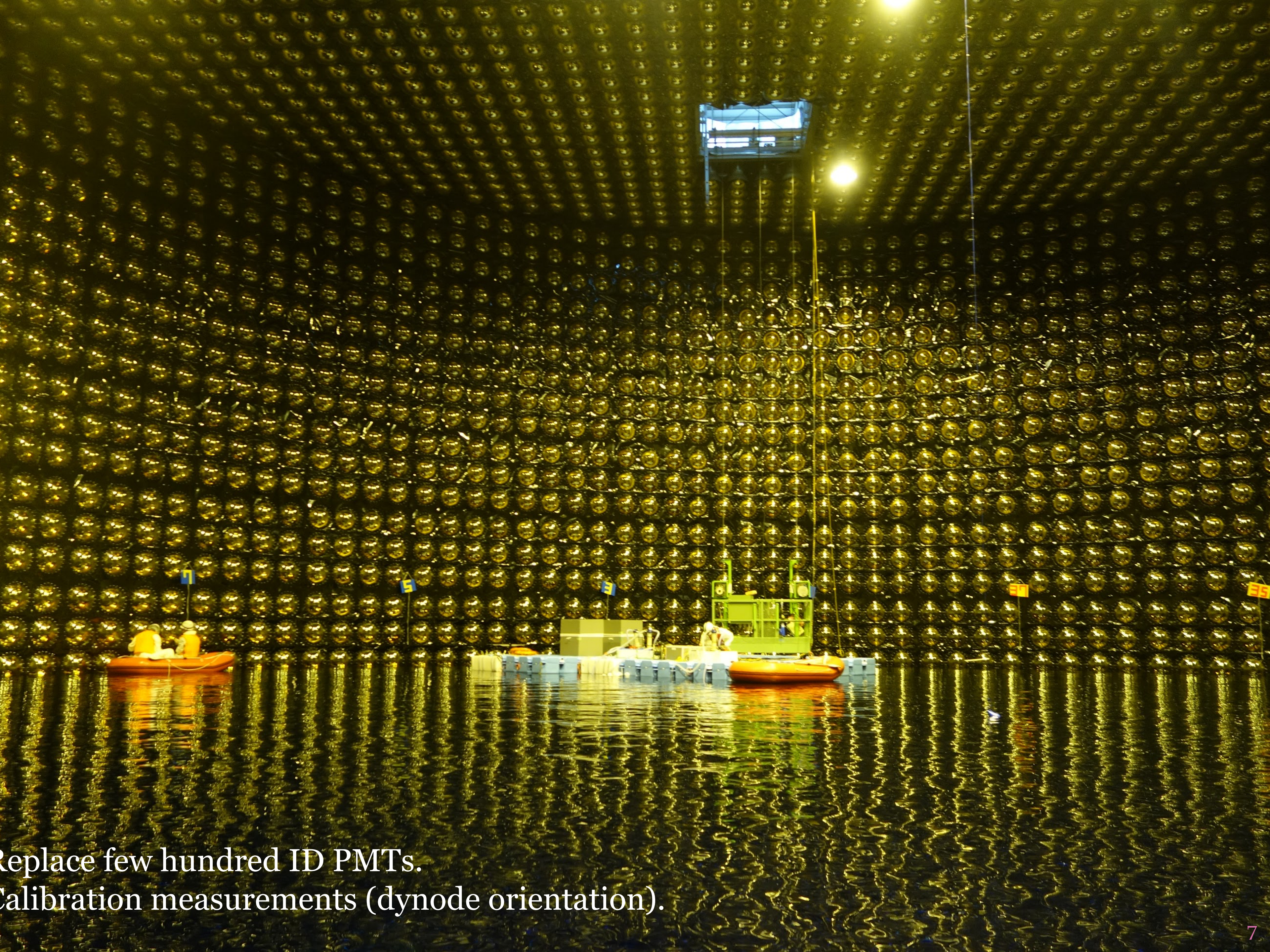




- Challenges:
  - Purify water without removing Gd
  - Maintain high light transparency
  - Maintain low radioactivity
  - No degradation or corrosion of materials
  - Prevent any Gd-water from leaking into the environment



Work starts on the “top”, water level is just below.
Many outer detector PMTs to replace (more than 30 years old from IMB)



Replace few hundred ID PMTs.

Calibration measurements (dynode orientation).

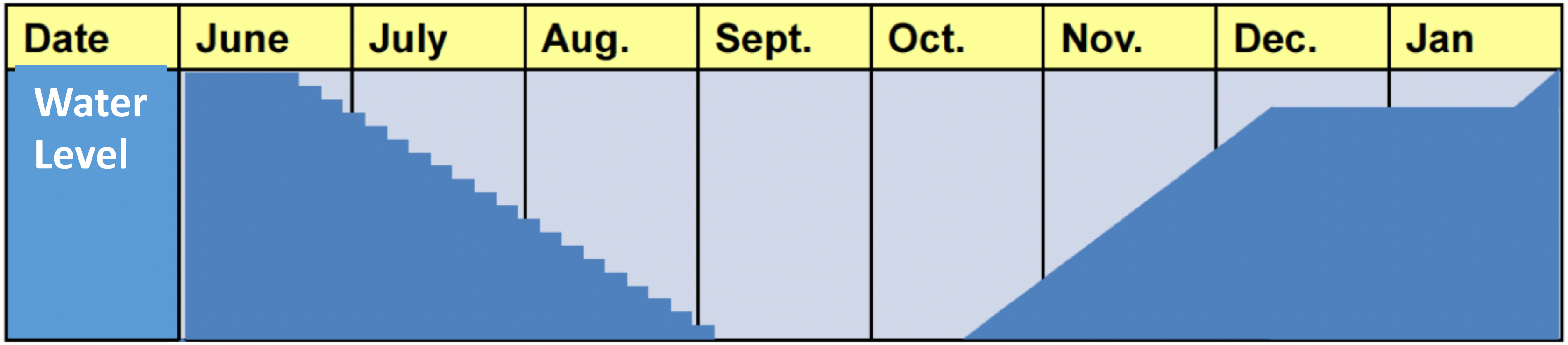
Fix leak: sealant applied at all seams.
Cleaning: remove oxidation and dust.

Replace all outer detector Tyvek reflector

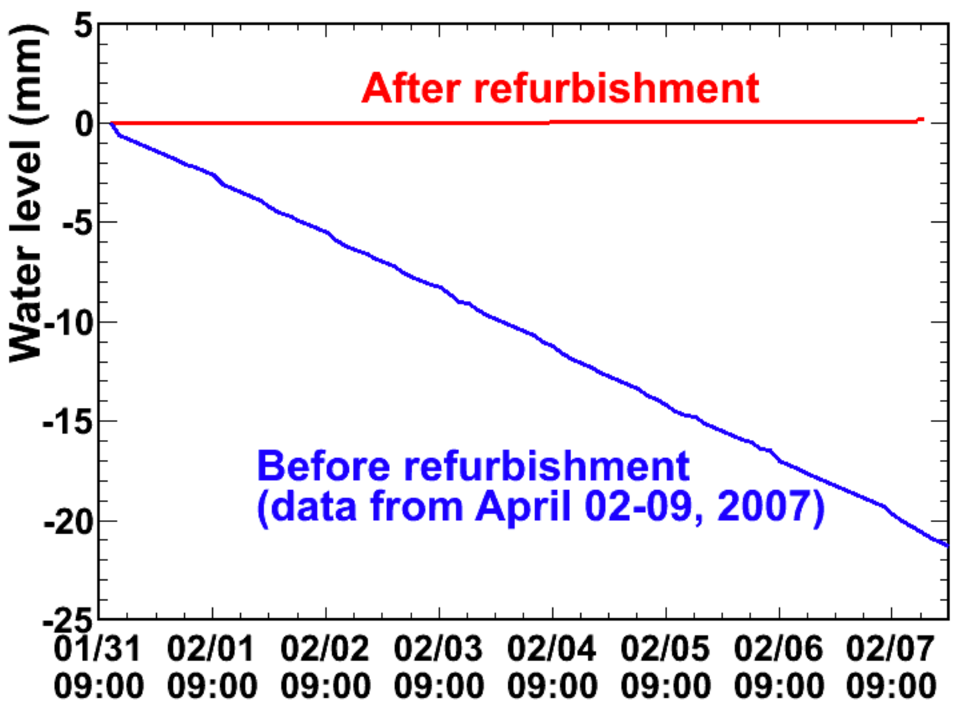
Work goes quickly on the bottom

Refilling started in October 2018

Refilling finished in January 2019



Result of leak repairs ...

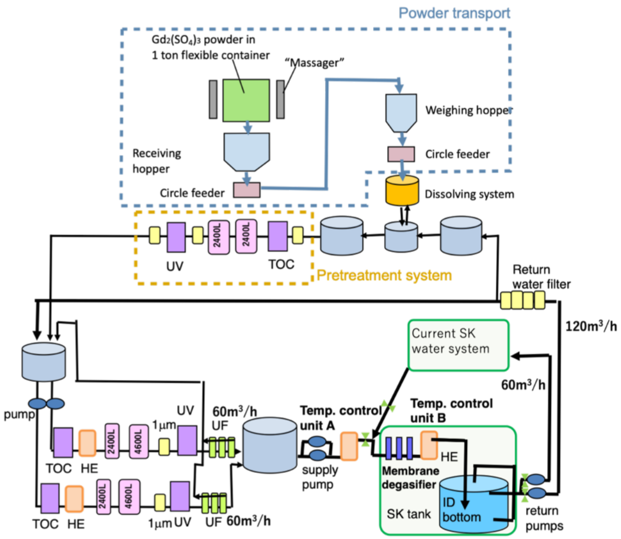


No leakage*
(< 15 L/day)

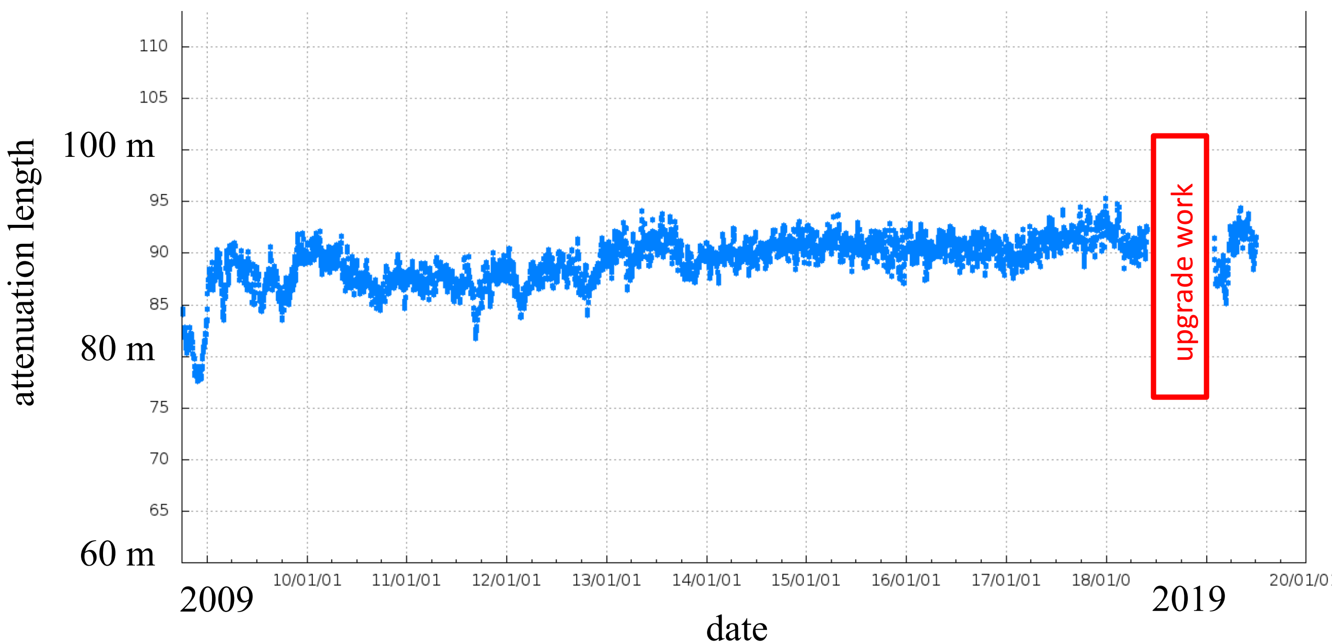
*actually 0.2 mm increase in water level, consistent with thermal expansion

3600 L/day

Upgraded water system for SK-Gd



Water transparency measured with cosmic ray muons



Fill-while-recirculate:
SK detector
resumed data
taking with
good water
transparency

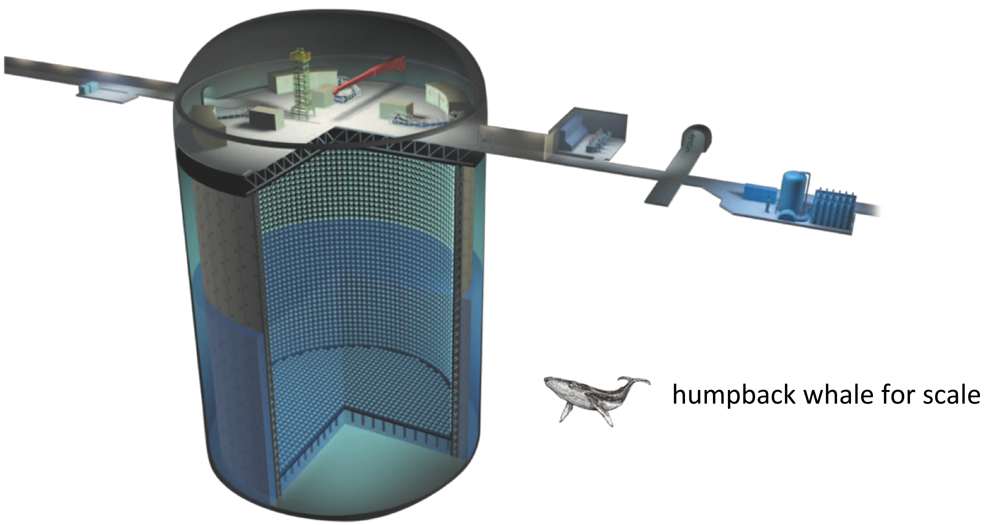
Science Goals for Upgraded Super-K

this talk **1** Study the science of **supernova neutrinos**

this talk **2** Continue to extract information from **atmospheric neutrinos**

this talk **3** Continue the search for **nucleon decay**

4 Continue to extract information from **solar neutrinos**



+ Be the far detector for **T2K**

Supernova

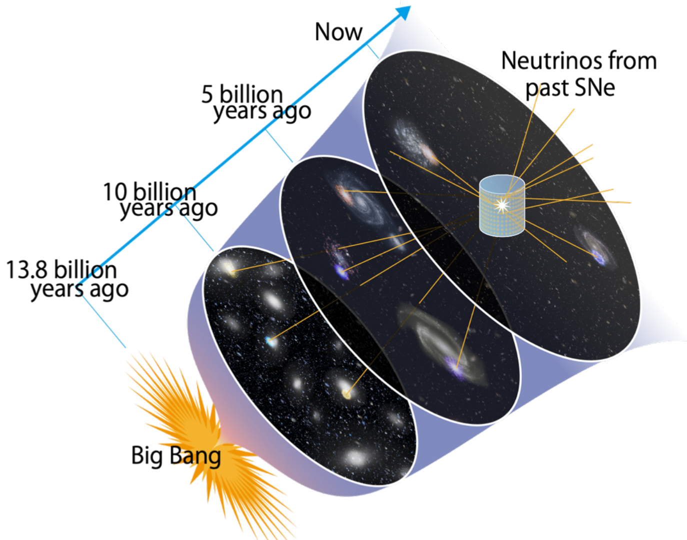
Science Goals for Supernova ν

Gravitational Collapse Supernova Neutrinos:

- guaranteed signal … eventually
  few % chance per year in Milky Way
- 3000 to 7000 events **in a few seconds** (at 10 kpc)
- real time monitor for prompt alert to community including participation in SNEWS
  neutrinos arrive few hours before optical brightening
- can provide pointing (few degrees)
- astrophysical model predictions are quite variable
- exciting possible signatures:
  Si-burning, black hole formation, gravitational wave coincidence, …
- fundamental neutrino physics may be revealed, including the neutrino mass hierarchy

Diffuse Supernova Neutrinos:

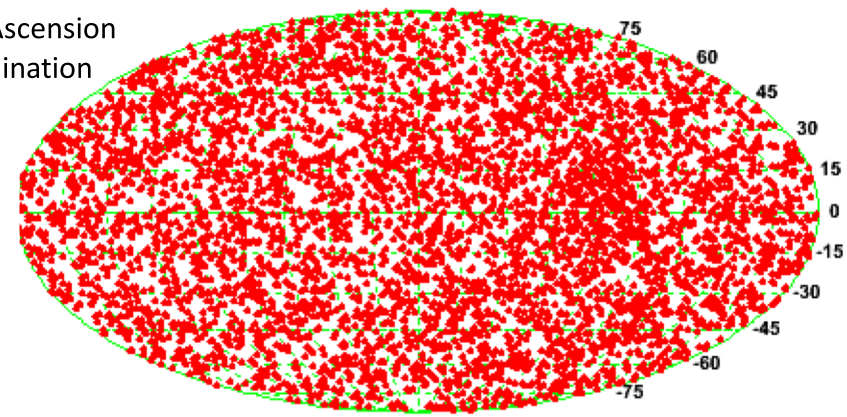
- as yet undetected source of ν
- sensitive to stellar formation rate
- major motivation for SK-Gd
- 5 to 30 signal events over
  10 to 30 background events (10 years)



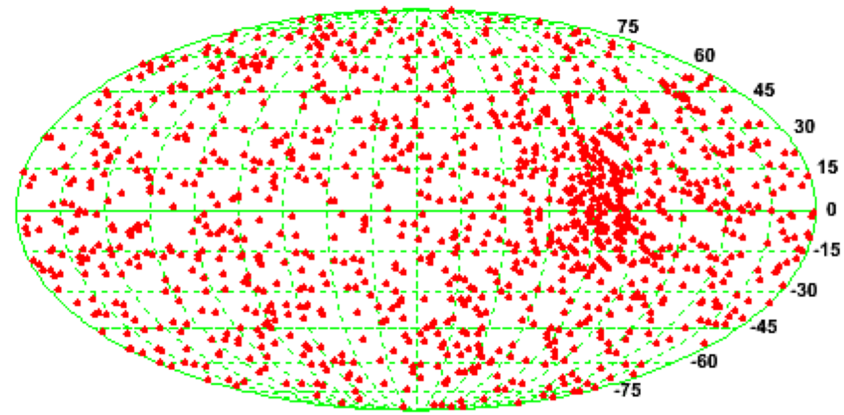
Galactic Supernova at 10 kpc

all events

Right Ascension
vs Declination



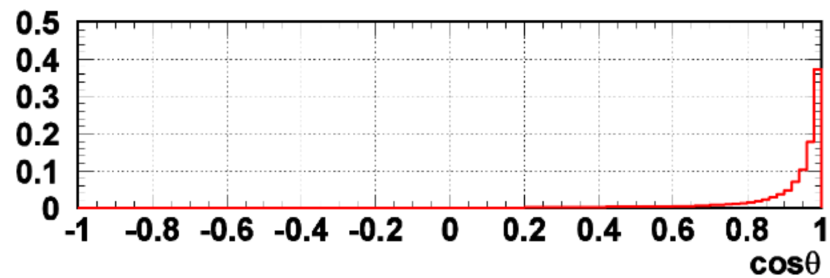
n-tag removed with 80% efficiency



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

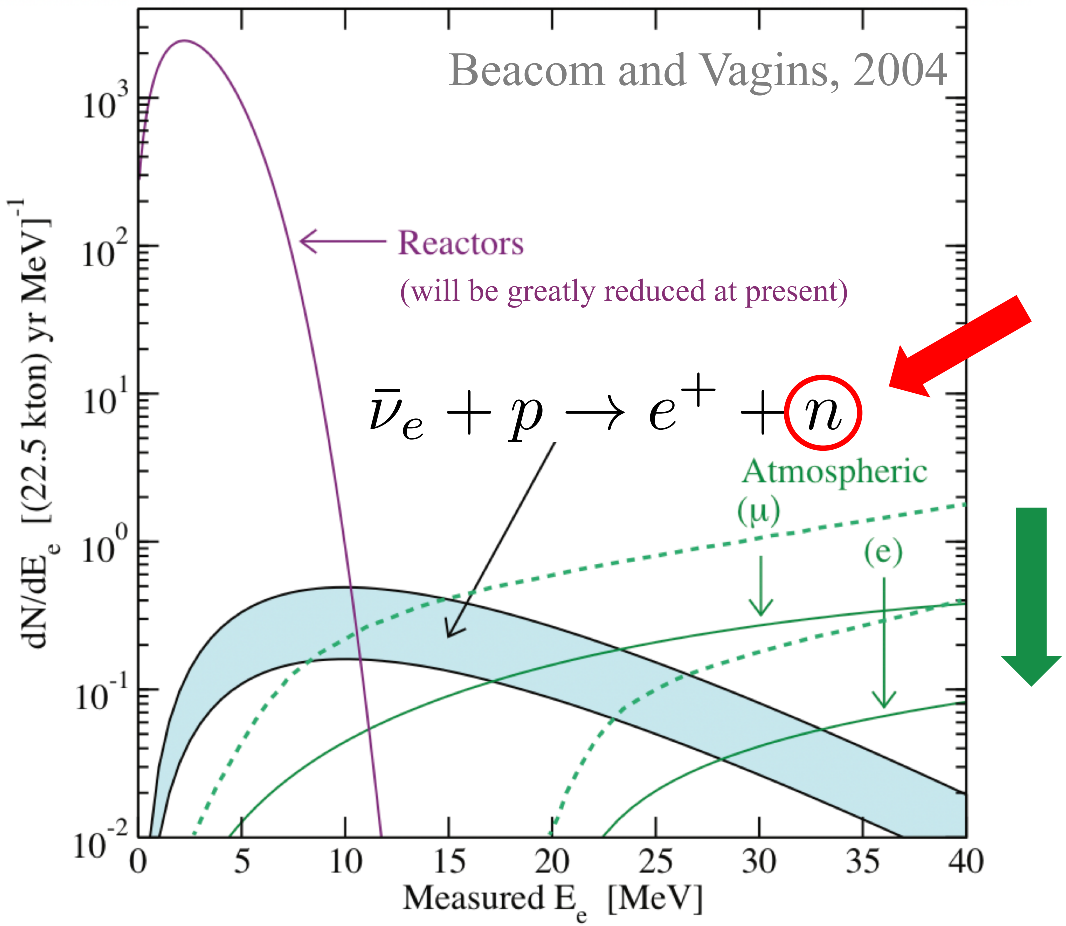
	Livermore	Nakazato
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

$$\nu + e^- \rightarrow \nu + e^-$$



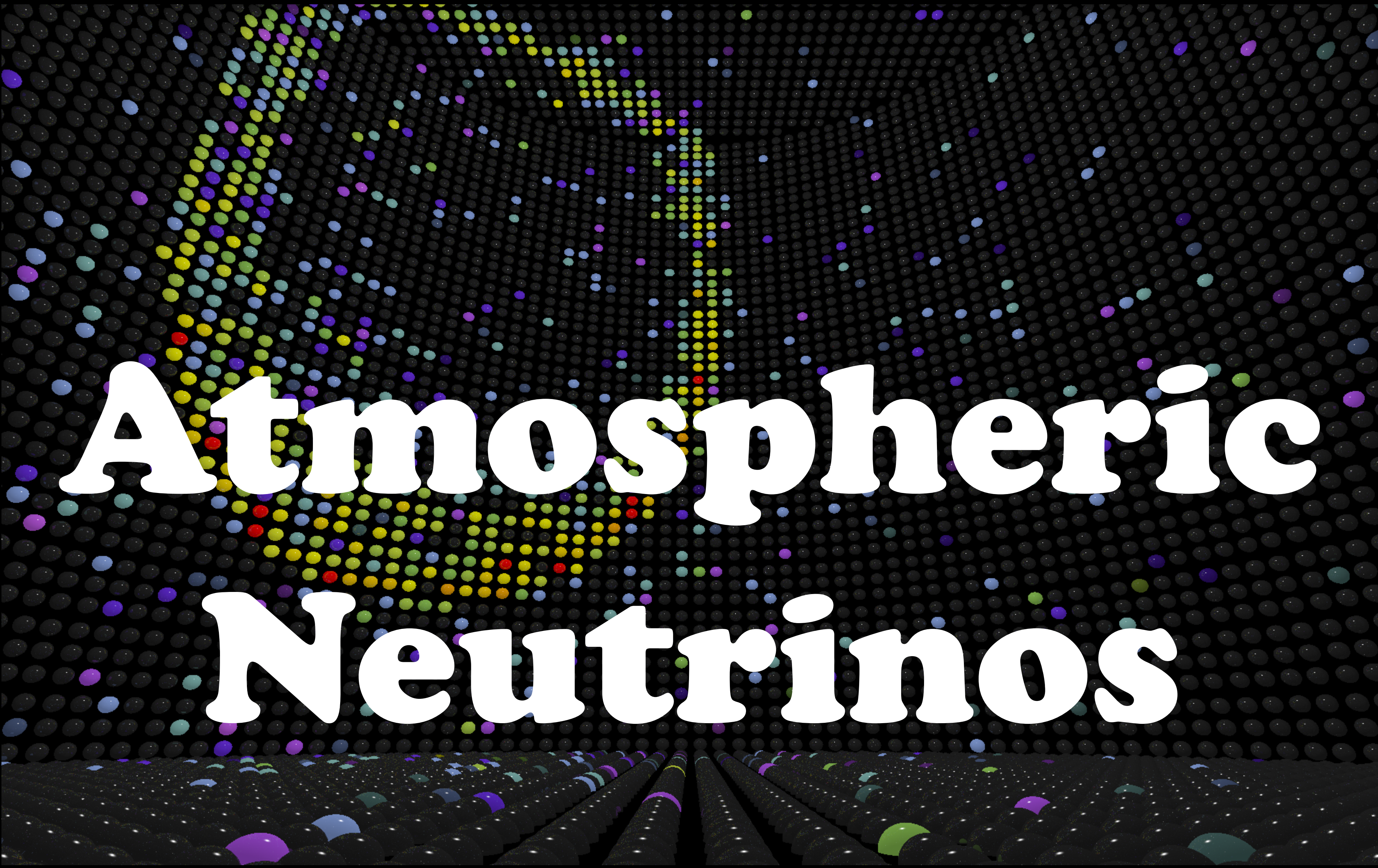
Angular resolution ~ 2x improved

Diffuse Relic Supernova Neutrinos



Efficiency increase allows other cuts to loosen

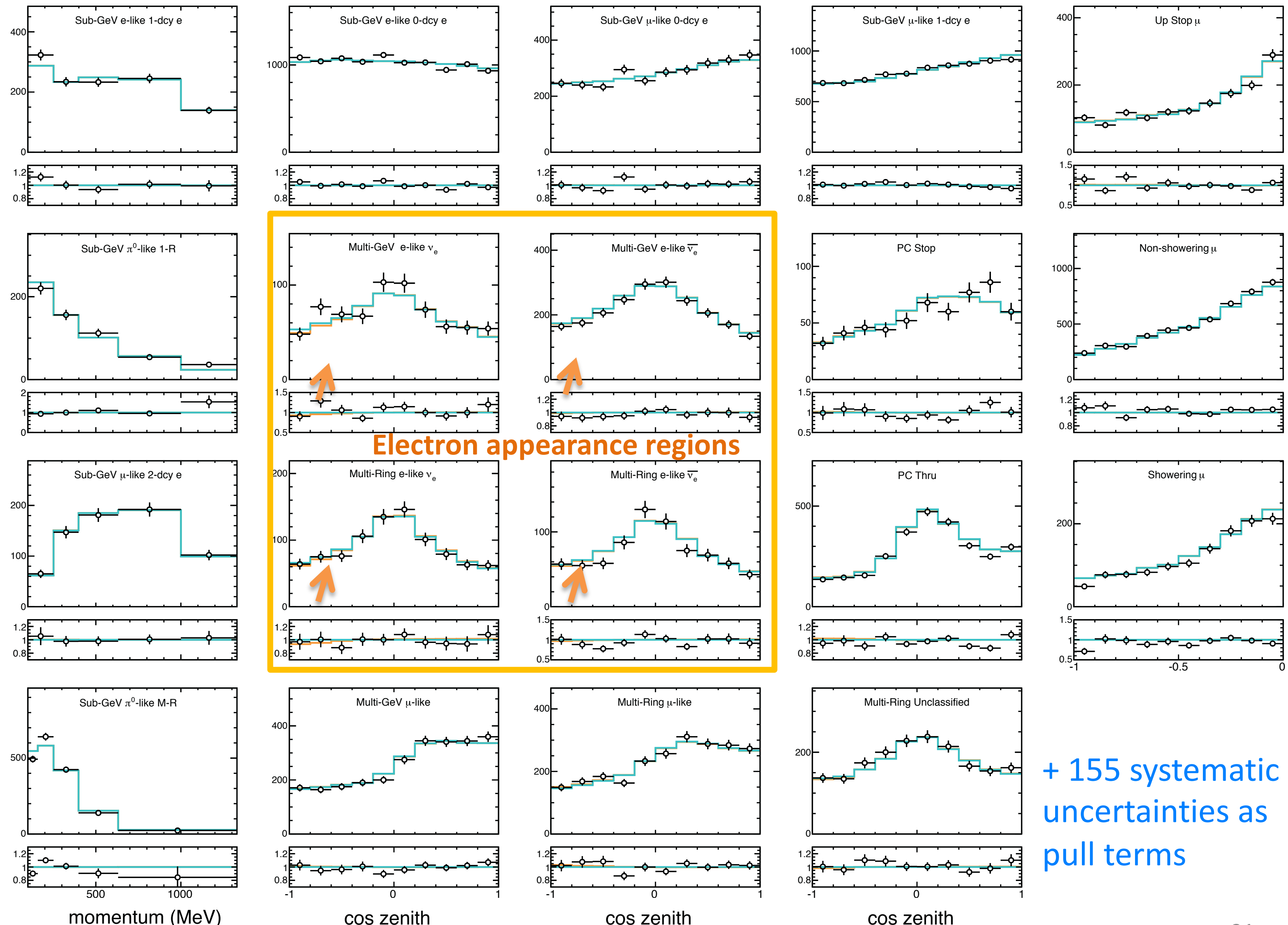
background reduction



Atmospheric Neutrinos

520 Bin Analysis

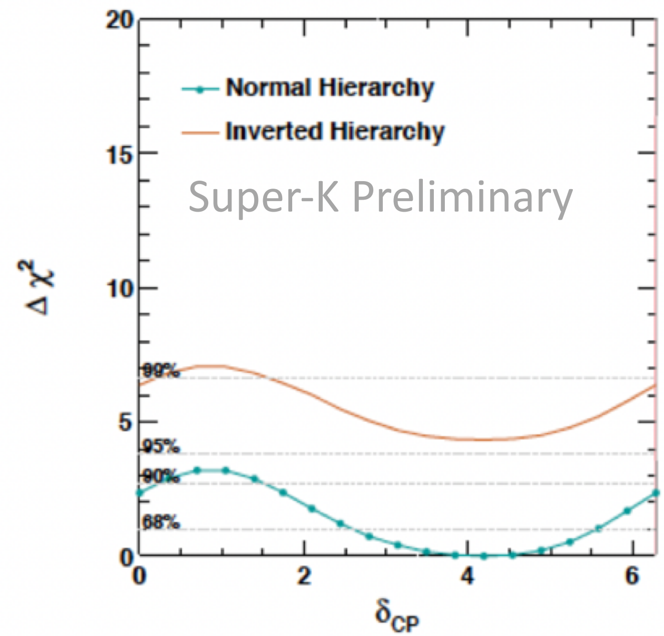
Super-K Preliminary



+ 155 systematic uncertainties as pull terms

Science Goals with Atmospheric ν

- Continue to extract information on:
  - Neutrino mass hierarchy
  - θ_{23} Octant
  - CPV δ
- … alone and in combination
  - with T2K – cancel systematics
  - global fit
- Determine energy scale for T2K
- Provide control samples for T2K studies



Improvements in progress:

- Include τ-like sample in fit
- Increase fiducial volume 22.5 kton → 27 kton
- Improved reconstruction
- New event classification multi-variables
- Neutron tag for event classification
- Neutron tag as proxy for hadronic energy

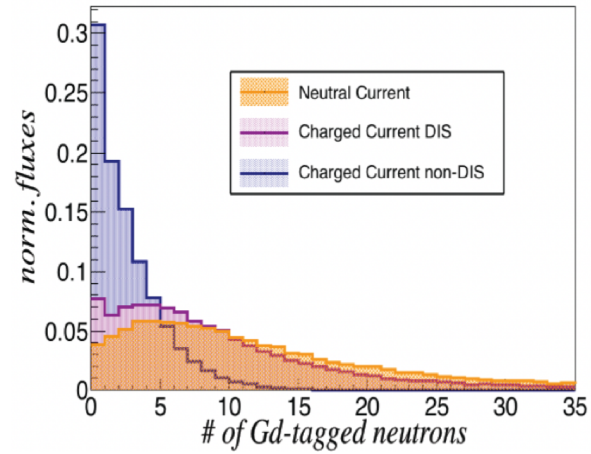
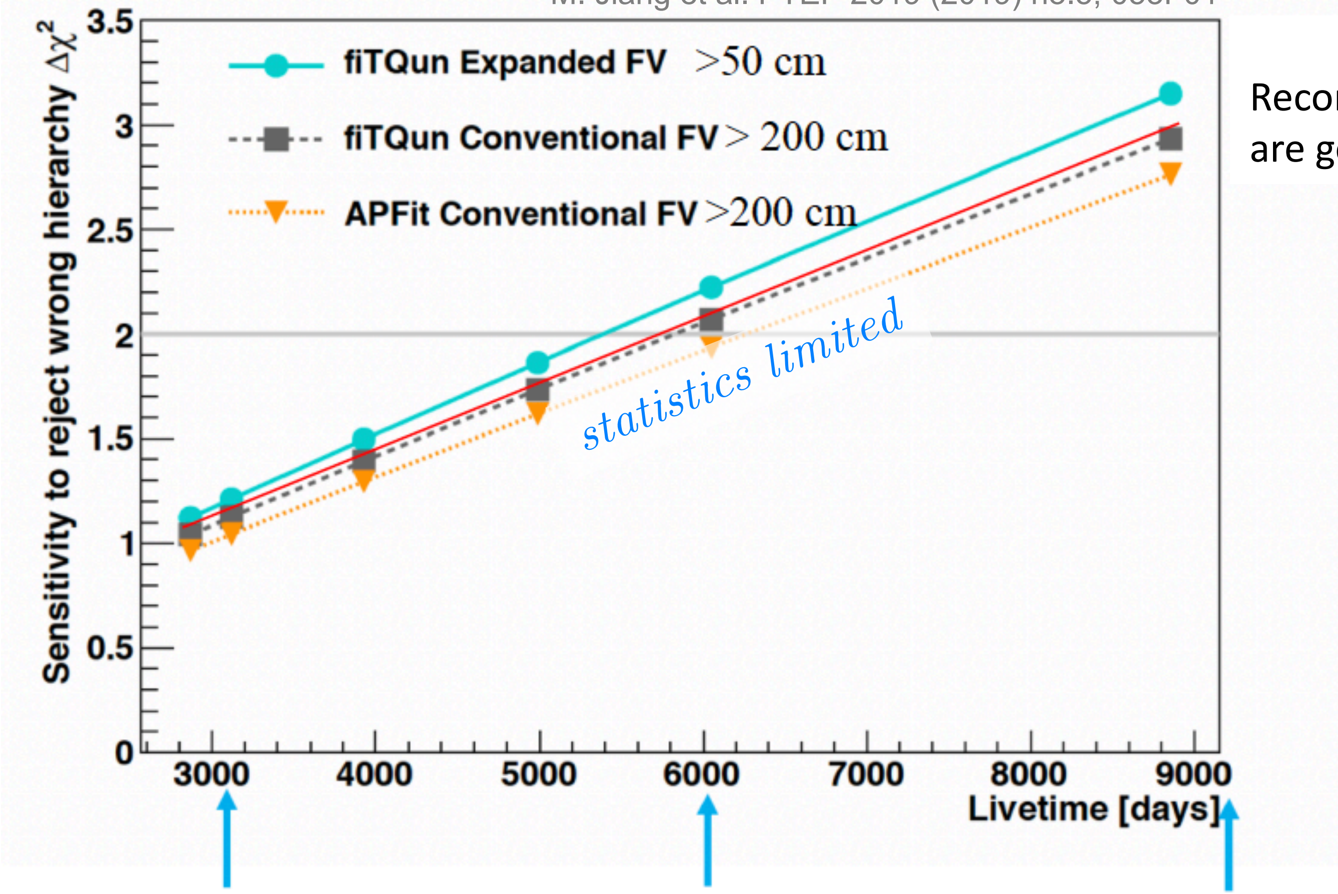


Figure 13 Tagged neutron multiplicity of multi-ring e-like atmospheric neutrino events.

Neutrino Mass Hierarchy

M. Jiang et al. PTEP 2019 (2019) no.5, 053F01



Reconstruction improvements are generally in this range

SK-IV Data

SK-I~IV Data

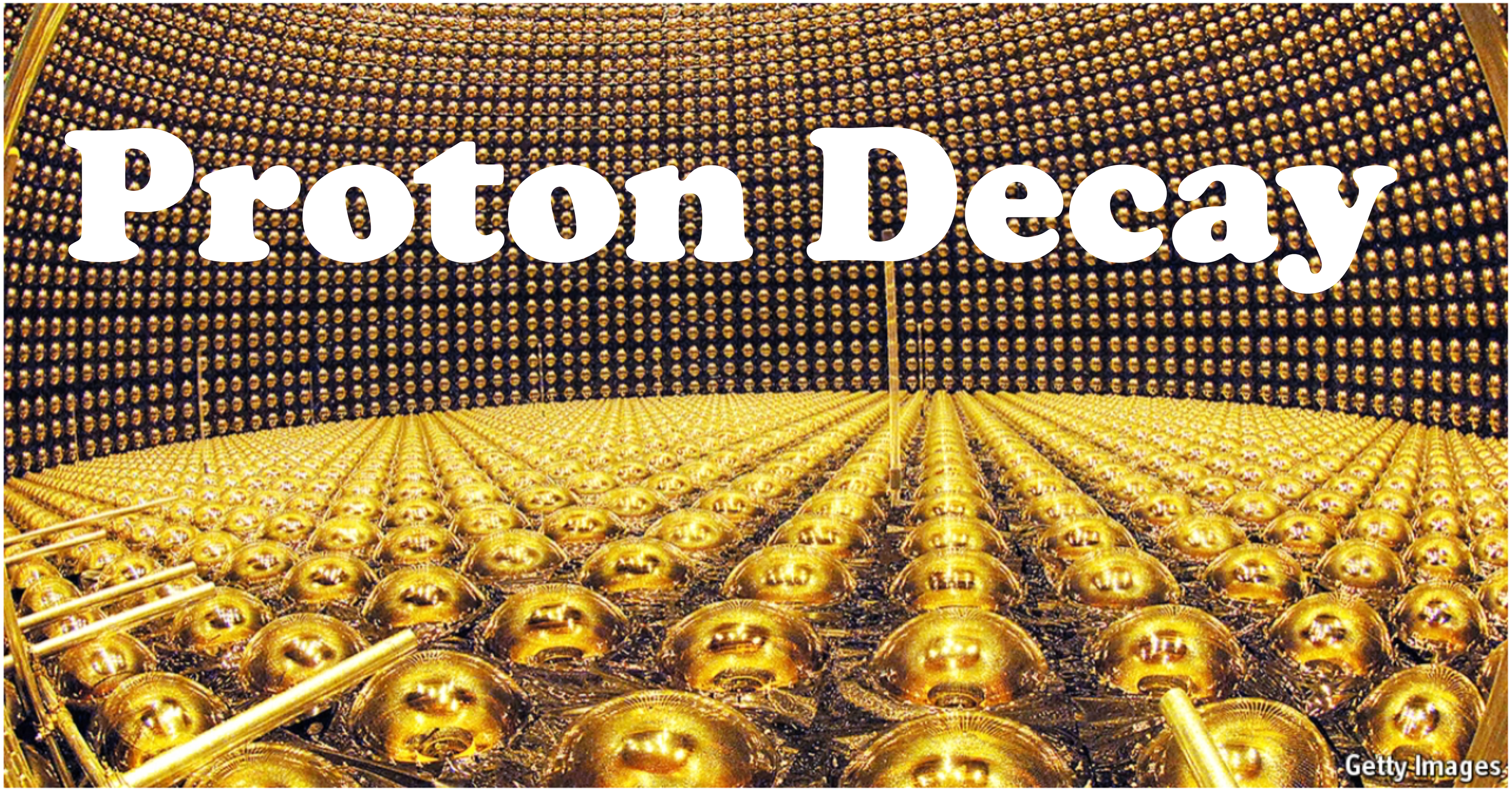
Projected Data Set by 2026

Particle physics

Fundamental physics is frustrating physicists

No GUTs, no glory

Jan 13th 2018

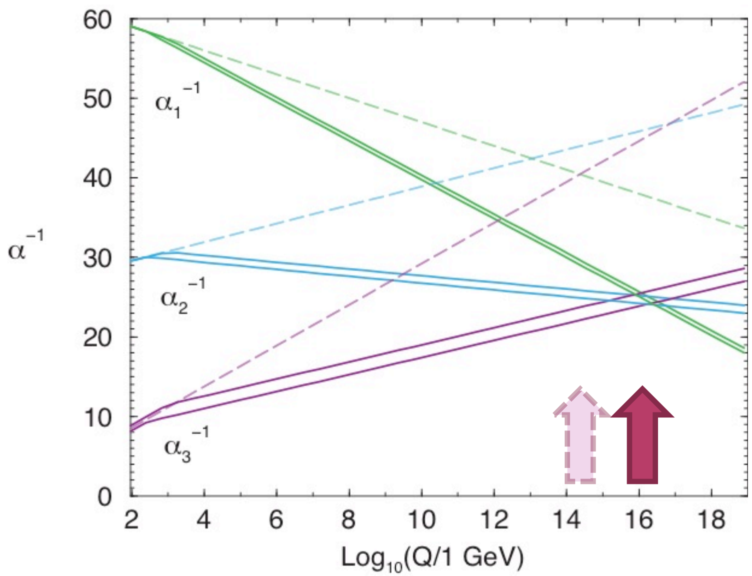


https://www.economist.com/news/science-and-technology/21734379-no-guts-no-glory-fundamental-physics-frustrating-physicists

Science Goals for Proton Decay

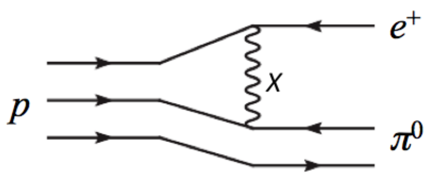
Baryon number violation:
Very well motivated BSM physics

- Sakharov condition
- Grand Unified Theories
  – circumstantial evidence
- Many SUSY motivated models
- Violation of B and L, or just B, or …
- Exotic ideas
  – dark matter induced, extra dimensions, …

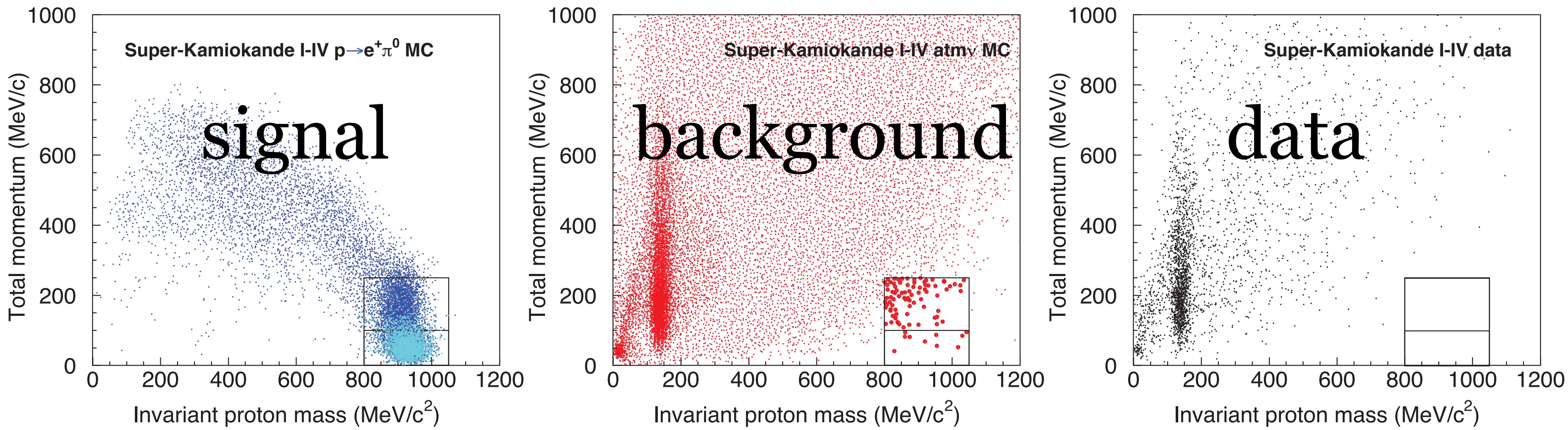


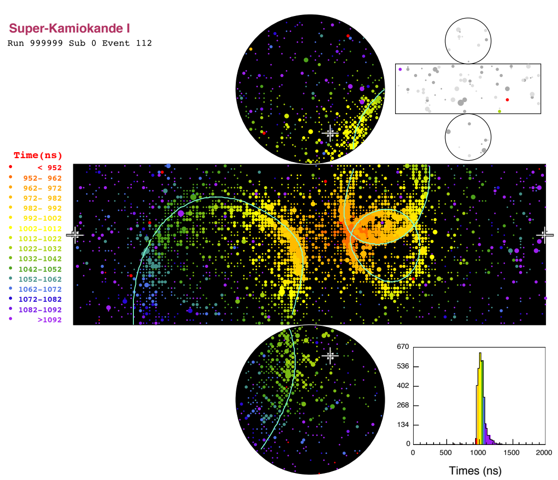
- ❖ Current limits penetrate interesting regions
- ❖ and are quite restrictive
- ❖ hard to make progress thanks to long exposure of existing Super-K results
- ❖ new analysis handle: neutron capture for background reduction

(1) push onward for favored modes
(2) cover many channels (unknown branching ratios, look for new ideas)

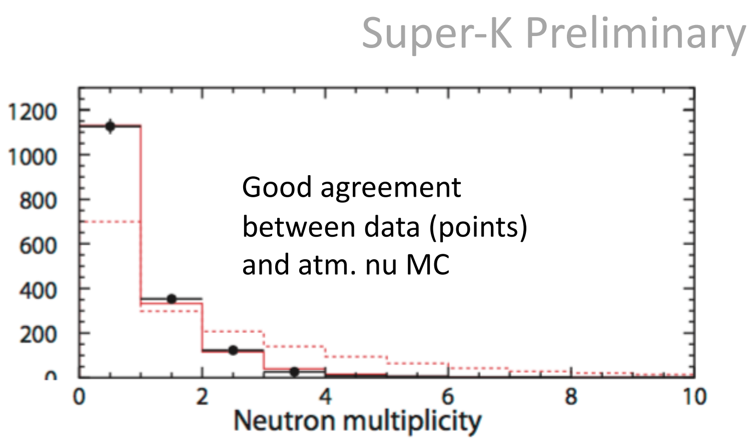

p
X
e^+
π^0

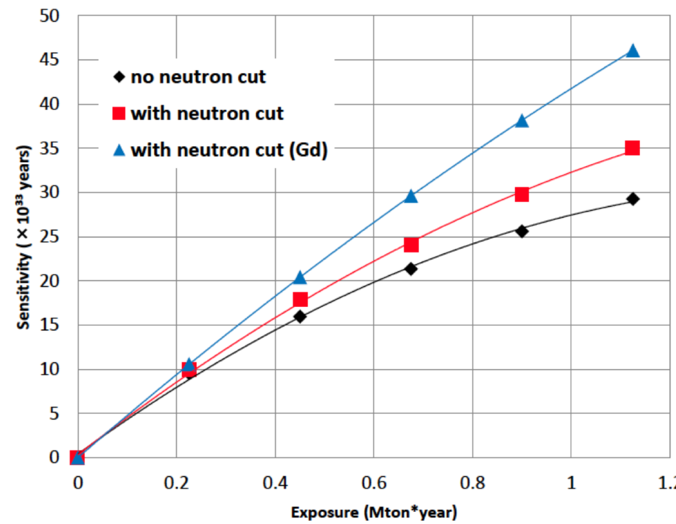
$$p \to e^+\pi^0$$


Super-Kamiokande I-IV p→e+π0 MC
signal
Super-Kamiokande I-IV atmν MC
background
Super-Kamiokande I-IV data
data
Total momentum (MeV/c)
Invariant proton mass (MeV/c2)
0
200
400
600
800
1000
1200


Super-Kamiokande I
Run 999999 Sub 0 Event 112
Time(ns)
< 952
952- 962
962- 972
972- 982
982- 992
992-1002
1002-1012
1012-1022
1022-1032
1032-1042
1042-1052
1052-1062
1062-1072
1072-1082
1082-1092
>1092
Times (ns)

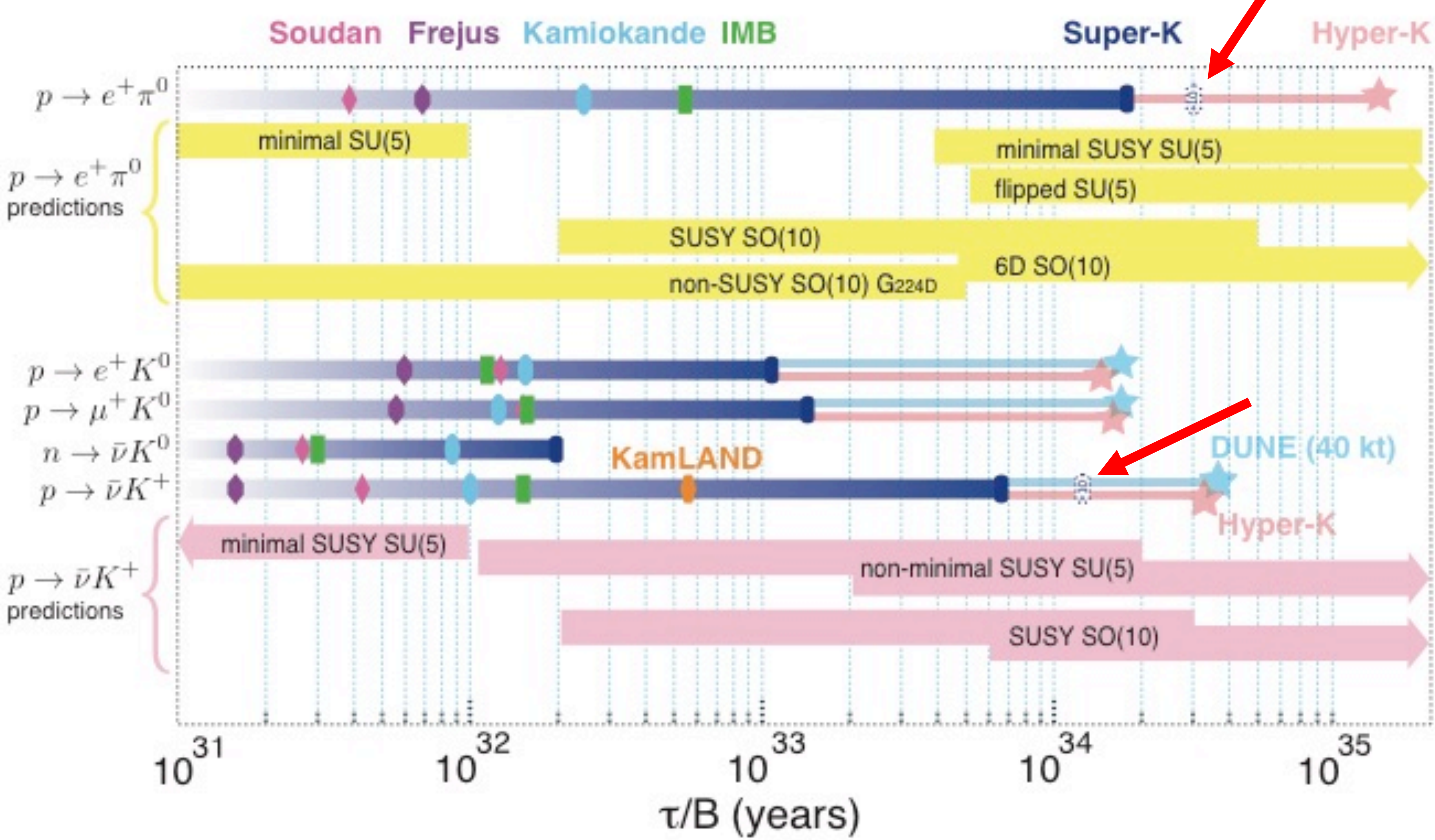
e+ pi0 search in Super-K





Signal Efficiency (%)	SK-I	SK-II	SK-III	SK-IV w. n cap.
$100 < p_{net} < 200$ MeV/c	20.4 ± 3.1	20.2 ± 3.1	20.5 ± 3.2	19.4 ± 1.2
$p_{net} < 100$ MeV/c	18.8 ± 0.9	18.3 ± 1.0	19.6 ± 1.3	18.7 ± 1.2
Background (evts/Mt y)	**SK-I**	**SK-II**	**SK-III**	**SK-IV w. n cap.**
$100 < p_{net} < 200$ MeV/c	2.4 ± 0.7	2.4 ± 0.8	1.9 ± 0.6	1.1 ± 0.4
$p_{net} < 100$ MeV/c	0.33 ± 0.11	0.20 ± 0.07	0.09 ± 0.03	0.15 ± 0.05

background reduction
with neutron capture
on hydrogen



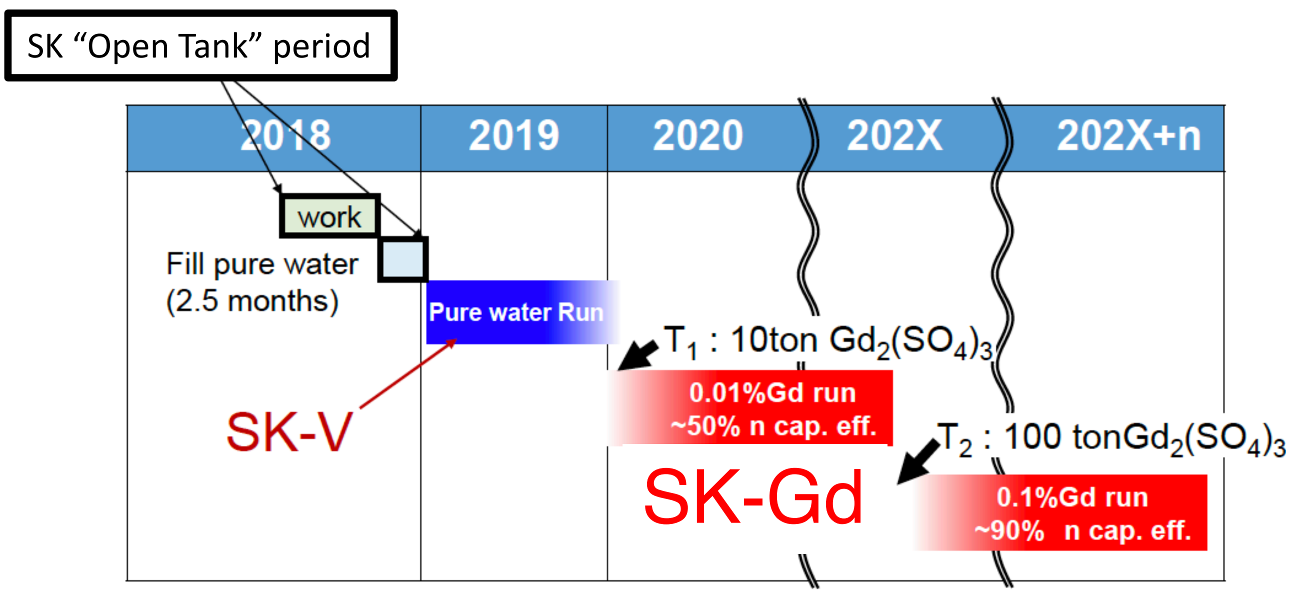
10 years SK-Gd

80% tagging efficiency

Conclusion

SK-V is underway: everyone currently working on Understanding the new detector, getting ready for T2K etc.

here's the schedule for SK-GD: first addition in early 2020

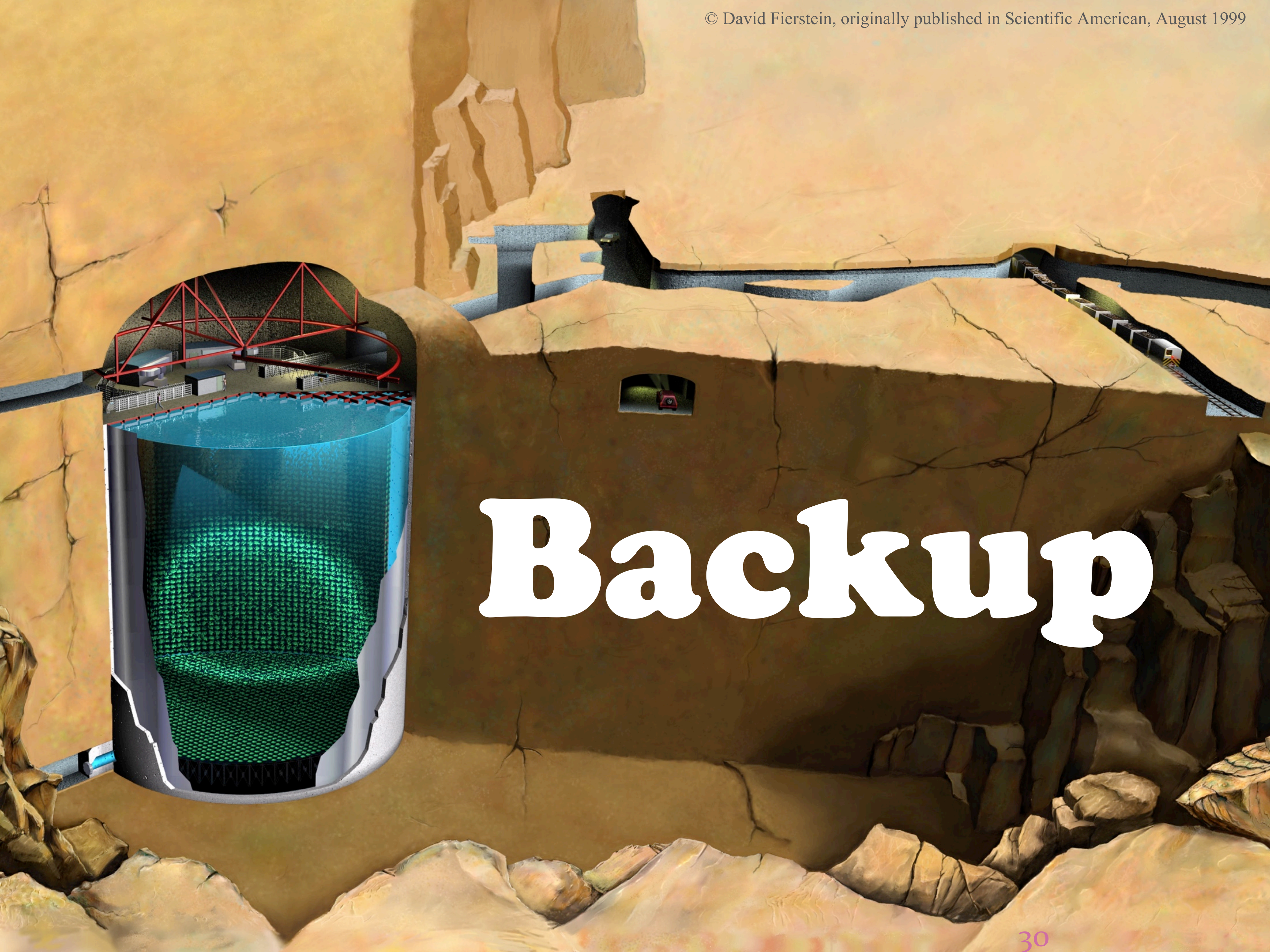


(adjusting schedule with T2K)

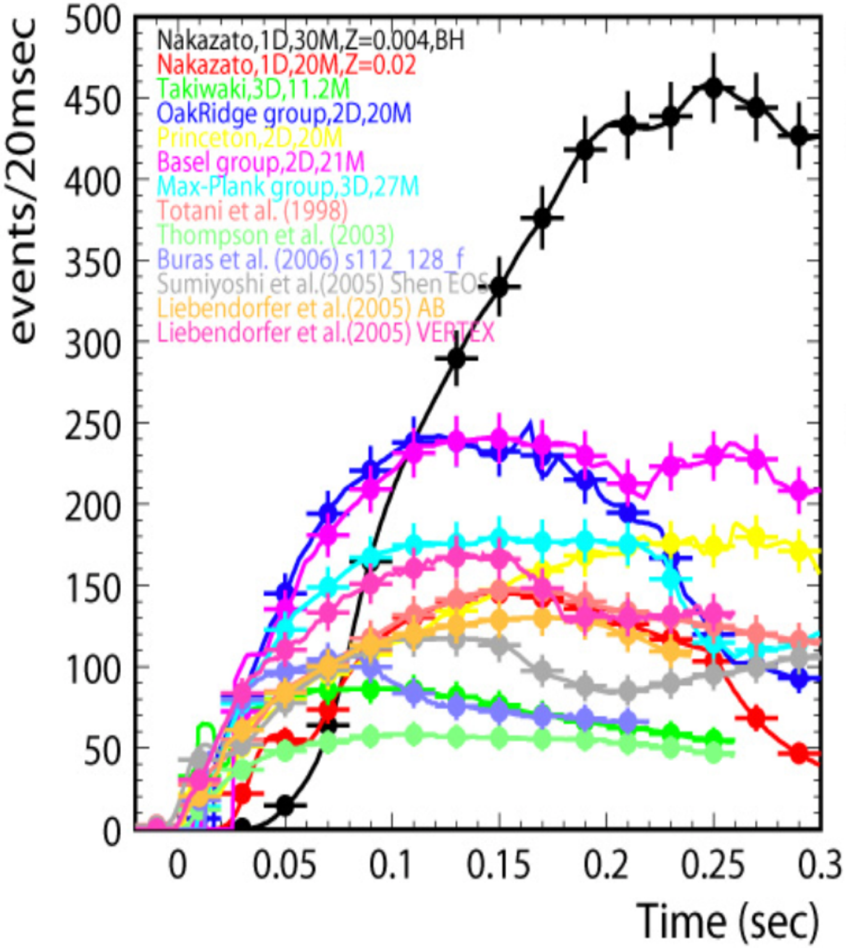
Supported by

Office of Science
U.S. DEPARTMENT OF ENERGY

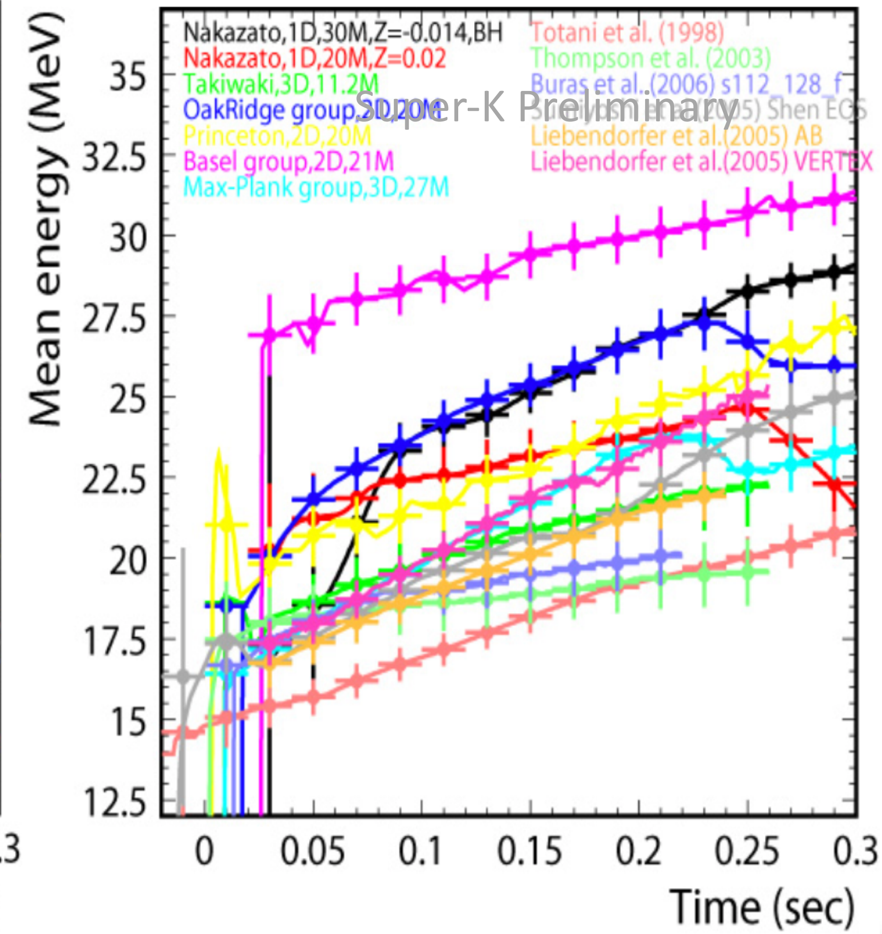
Backup



Time variation of event rate



Time variation of mean energy



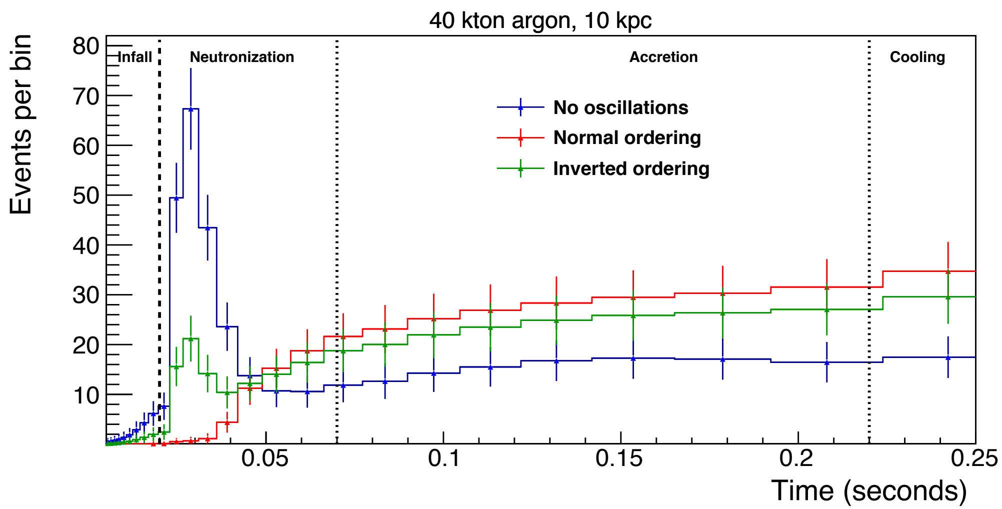
Neutrino Mass Hierarchy Signatures with SN

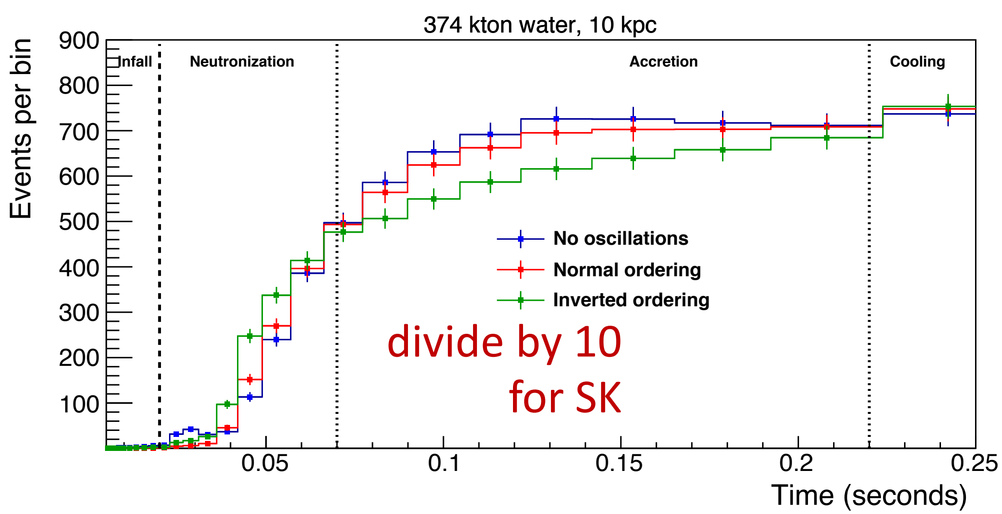
- Neutronization burst
- Early time profile
- Shock wave effects
- Spectral swaps and splits
- Earth matter effect

flavor dependent

ν_e most sensitive

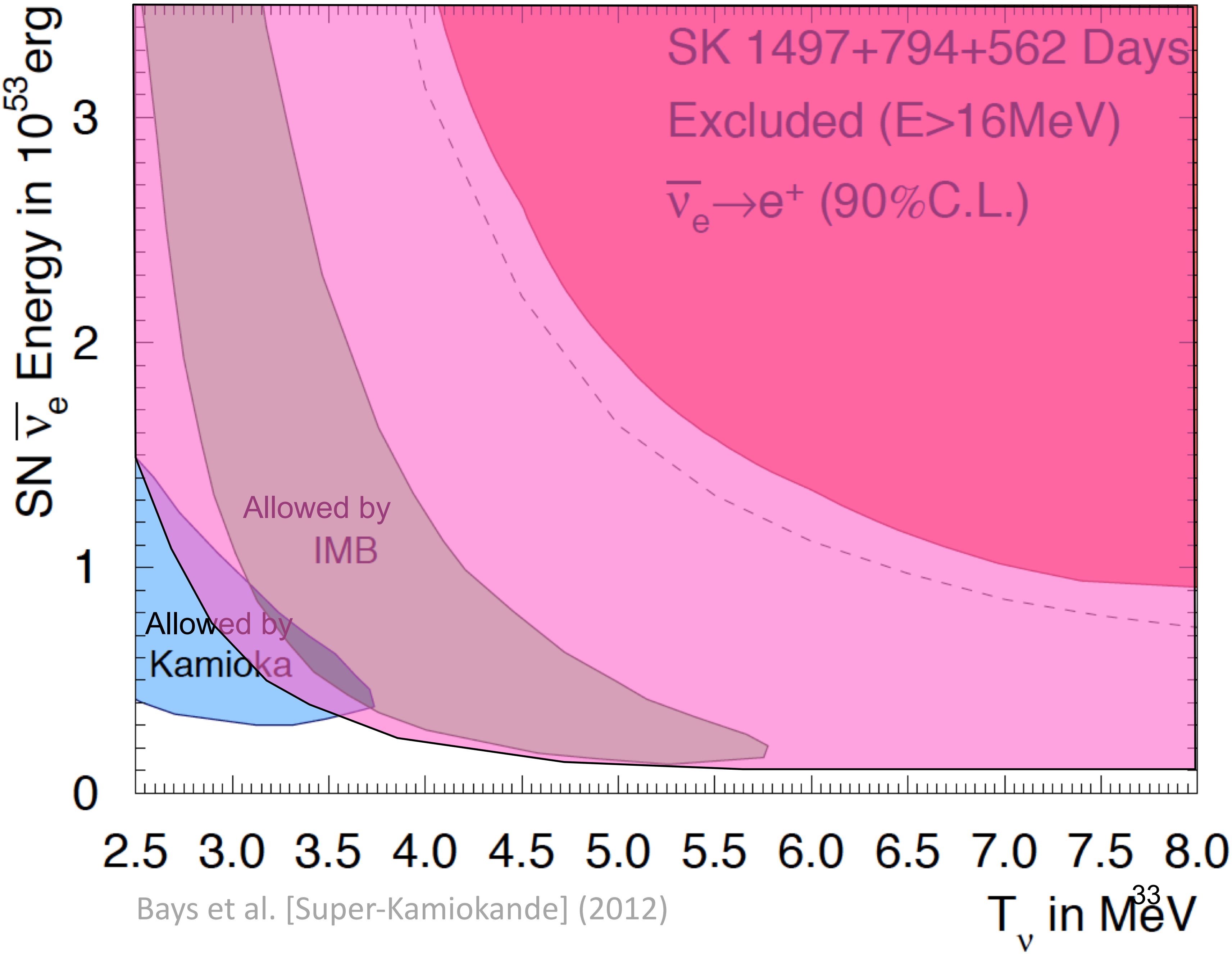
experiments can be complementary





Scholberg arXiv:1707.06384

DSNB Sensitivity Region After Six Years With Gd In SK



Bays et al. [Super-Kamiokande] (2012)

Science Goals for Solar Neutrinos

Solar neutrinos (SK with others)

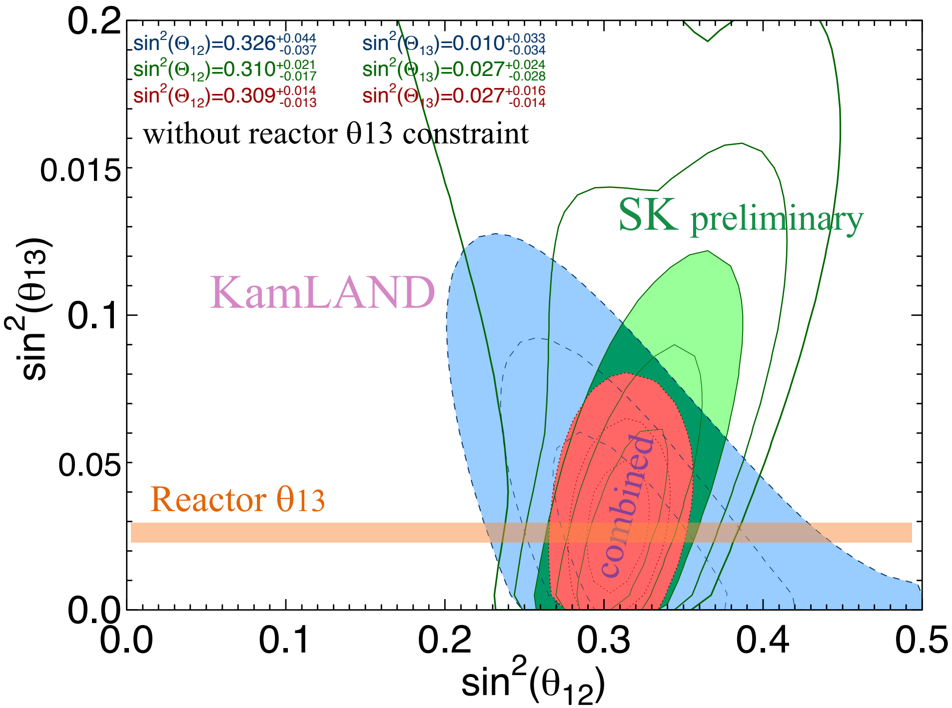
Have delivered:

- θ_{12}, Δm_{12} values in rough agreement with KamLAND
- ν_1 ν_2 ordering (mass hierarchy)
- General picture of solar cycle (*pp*, *pep*, ^{7}Be, ^{8}B)
- day/night asymmetry from matter effect in the earth (SK)

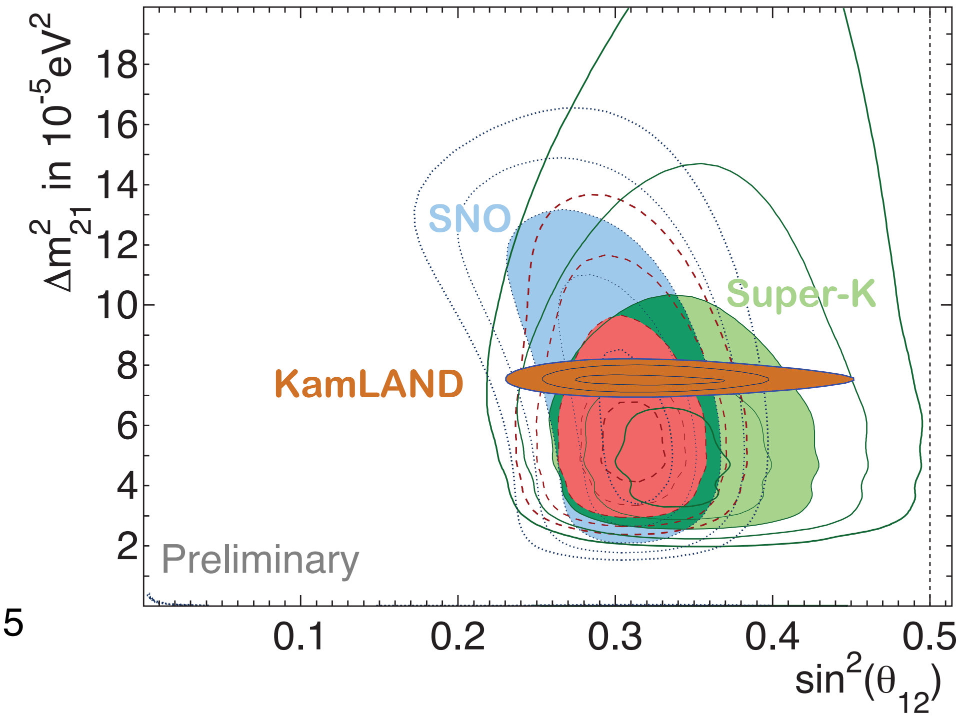
Not yet:

- Spectral distortion of ^{8}B
- *hep* neutrinos
- CNO neutrinos
- Precise agreement with KamLAND

Current State of Affairs



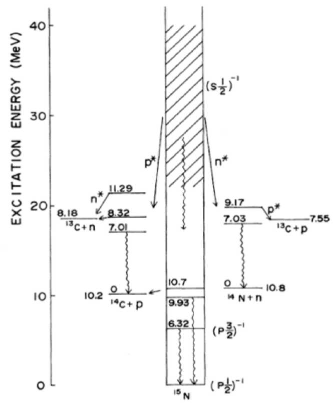
Mixing angles in good agreement
with reactor (Daya Bay, RENO, Double Chooz)

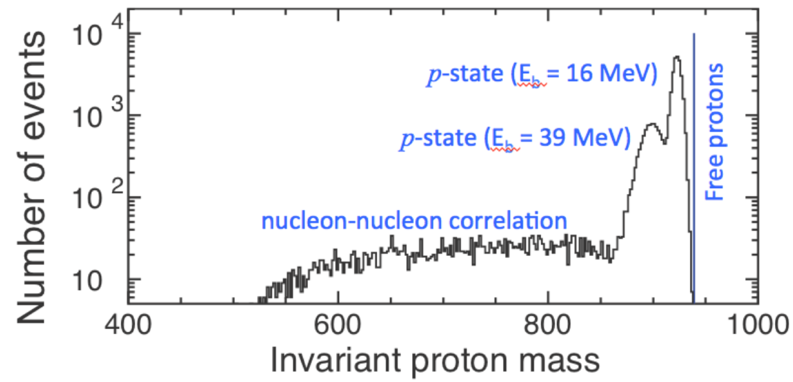


2σ tension in Δm^2_{12}
between solar and KamLAND

Nuclear Physics of Proton Decay

- 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





H. Ejiri Phys. Rev. C48 (1993)

Hole	Residual	States	(k)	E_γ	E_p	E_n	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}N	0	0	0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	^{15}N	6.32	0	0	0.41
	9.93	$\frac{3}{2}^-$	^{15}N	9.93	0	0	0.03
	10.70	$\frac{3}{2}^-$	^{15}N	0	0.5	0	0.03
$(s_{1/2})_p^{-1}$	g.s.	1^+	^{14}N	0	0	~ 20	0.02
	7.03	2^+	^{14}N	7.03	0	~ 13	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	1.6	~ 11	0.01
	g.s.	0^+	^{14}C	0	~ 21	0	0.02
	7.01	2^+	^{14}C	7.01	~ 14	0	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	~ 11	~ 2	0.03
$(j)_p^{-1}$	others		many states	≤ 3–4			0.16