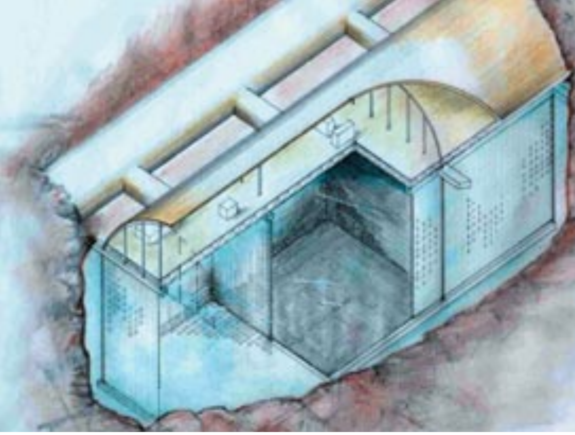
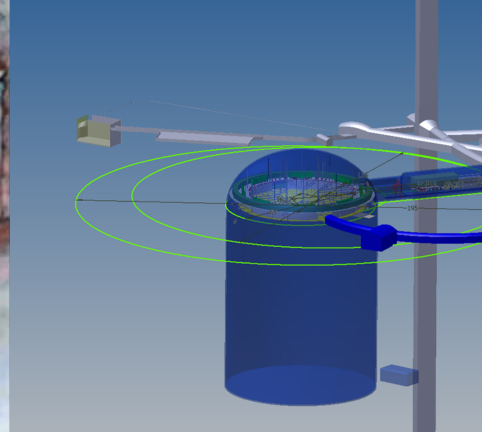
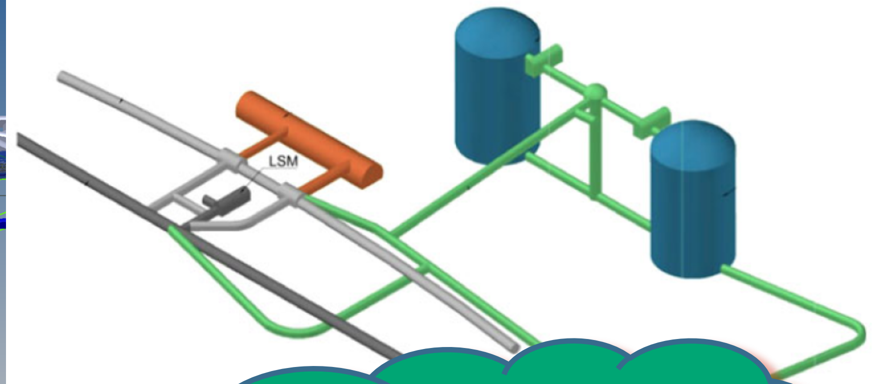
Physics with Massive Water Cherenkov Detectors

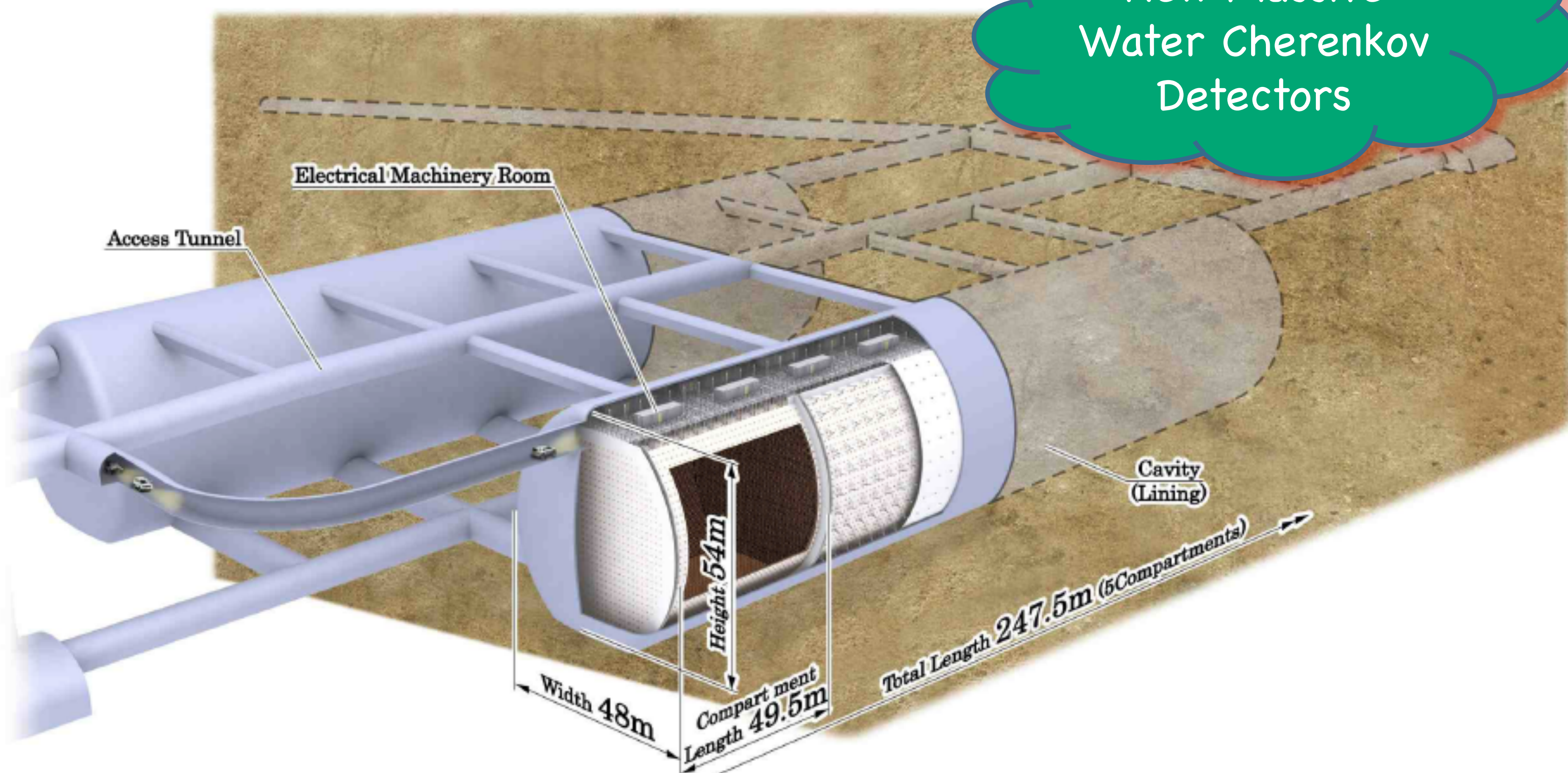
Ed Kearns
Boston University
NNN 2013
Kavli IPMU, Kashiwa Japan







New Massive
Water Cherenkov
Detectors

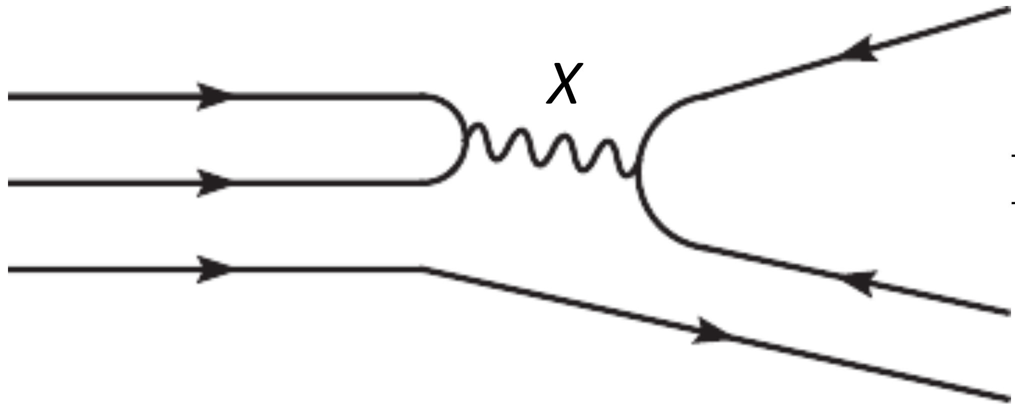


Physics Areas – Prioritized for WC!

1 Nucleon Decay
2 Long-Baseline Neutrino Oscillation
3 Supernova Neutrino Burst
4 Diffuse Relic Supernova Neutrinos
5 Atmospheric Neutrinos
6 Indirect Dark Matter Neutrinos
7 Solar Neutrinos

1 Best detector technology overall for proton decay, mass needed for next generation.
2 Other detectors such as LArTPC can do at least equally well.
3 Best detector for anti-nu-e. Next generation desirable to go beyond the Milky Way.
4 No sign so far. Next generation probably needed. Unique to WC.
5 Simply an SK scale up. LArTPC, magnetized detectors or huge ice detector are novel.
6 No hints so far. Competitive at low WIMP mass.
7 Physics of ^{8}B neutrinos is largely explored already. (Skip)

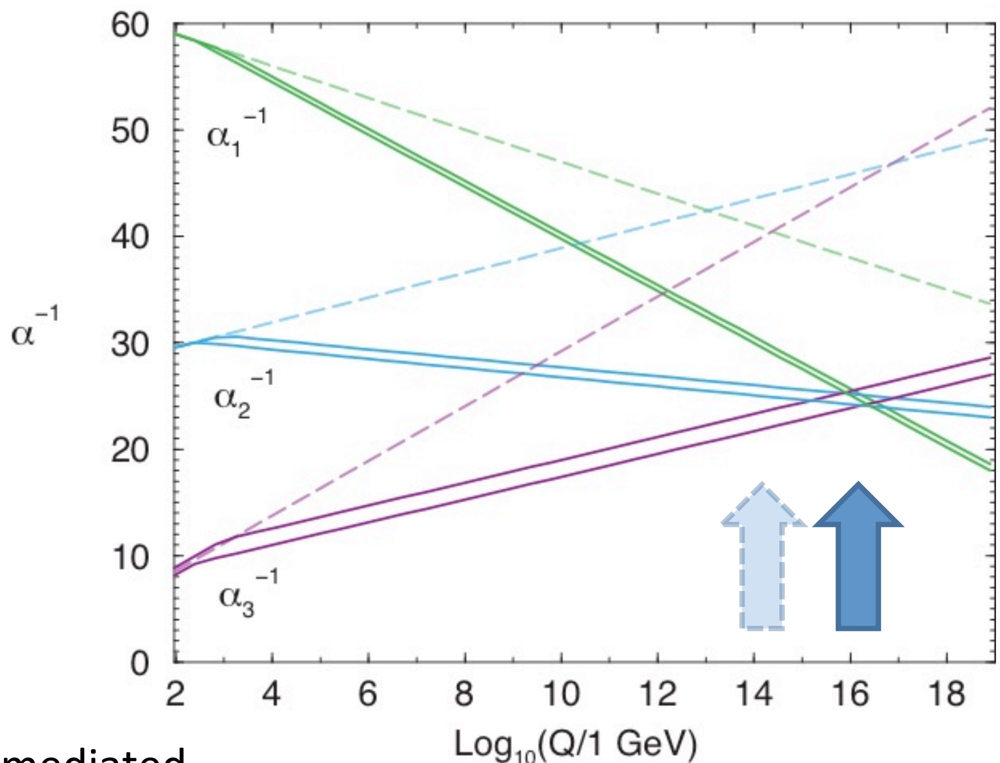
(1) Nucleon Decay



$$\Gamma \sim \frac{\alpha M_X^4}{m_p^5}$$

- ★ Highly prized physics motivation:
  Grand Unification of quarks and leptons, and strong, weak, and electromagnetic forces!
- ★ Test of unexplained symmetry: baryon number.
- ★ Connections to neutrino mass, cosmology, baryon asymmetry of universe ...
- ★ Supersymmetric versions of GUTs are of great theoretical interest.
- ★ ~10^{15} GeV energy scale – inaccessible to accelerators.
- ★ (If no discovery) limits are valuable: new models must work hard to accommodate.

Theoretical Context

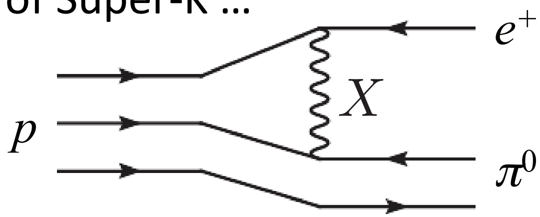


In the MSSM case, the sparticle mass thresholds are varied between 250 GeV and 1 TeV, and $\alpha_3(m_Z)$ between 0.113 and 0.123. Two-loop effects are included.

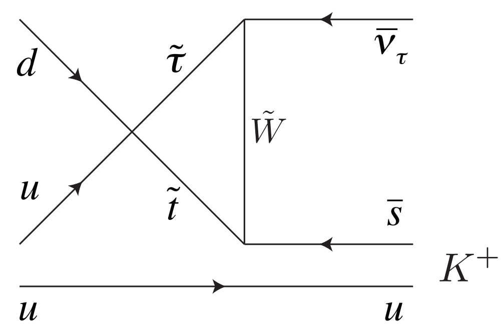
[Martin, Supersymmetry Primer]

SUSY raises the GUT scale …

… rescuing gauge mediated proton decay from the strict limits of Super-K …

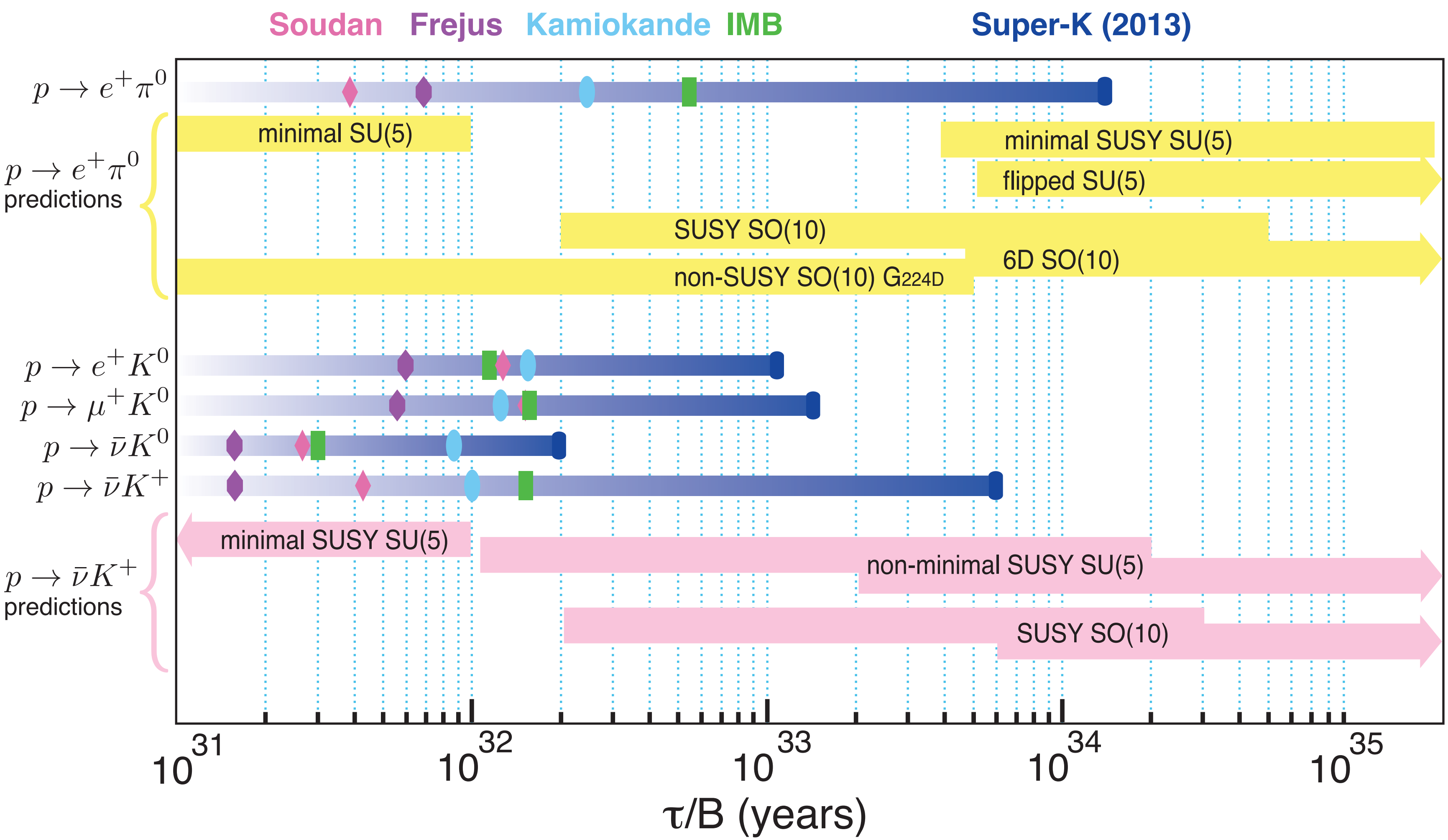


… but which may still be within reach …

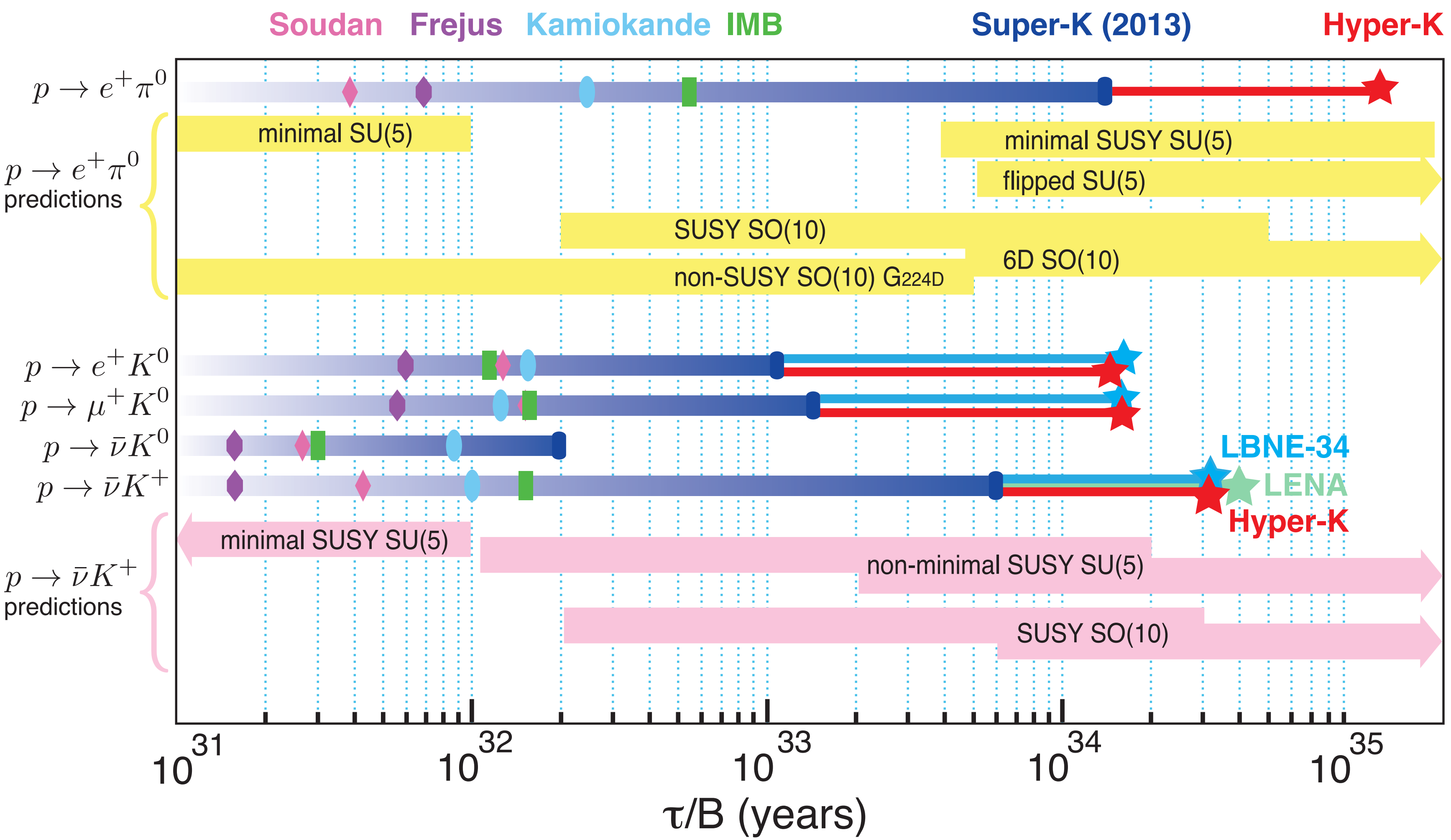


… and allows d=5 modes that may also be within reach.

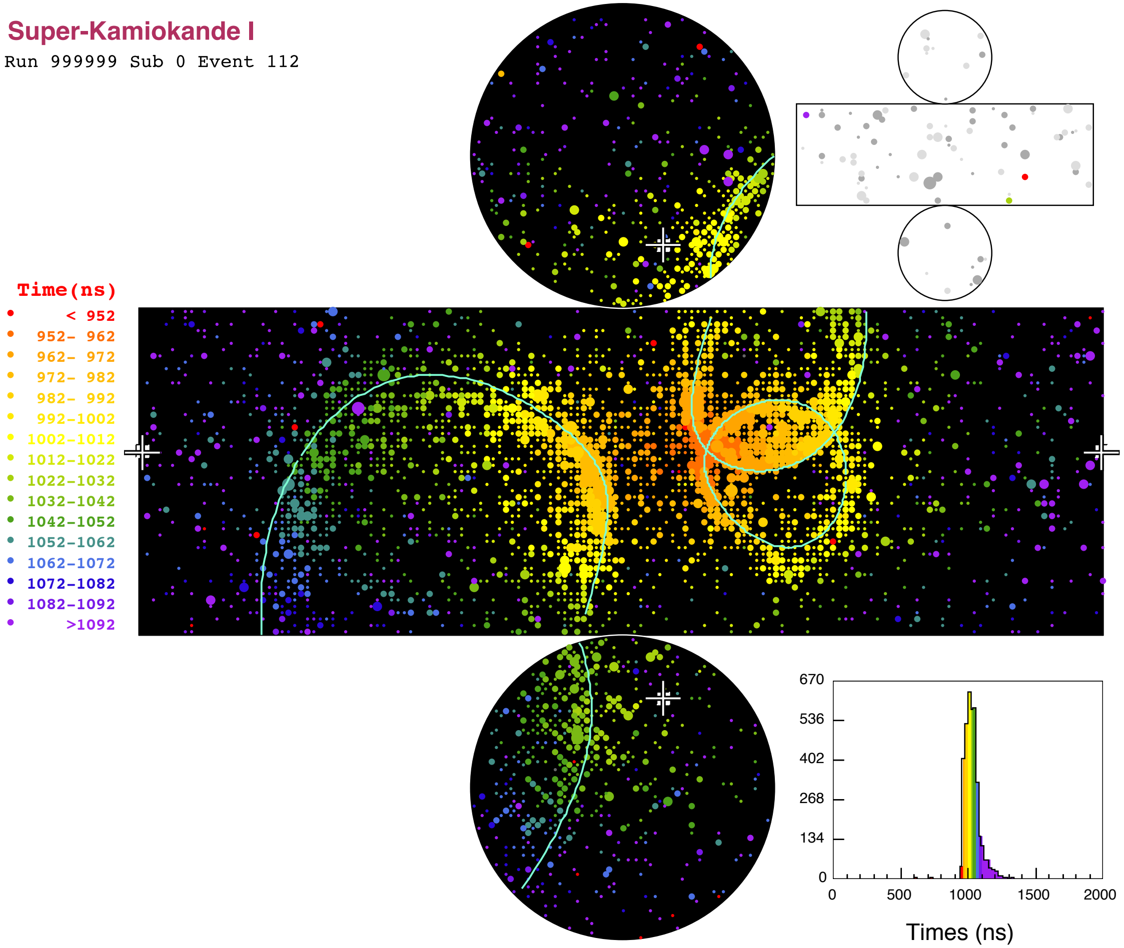
Theoretical Context



Theoretical Context

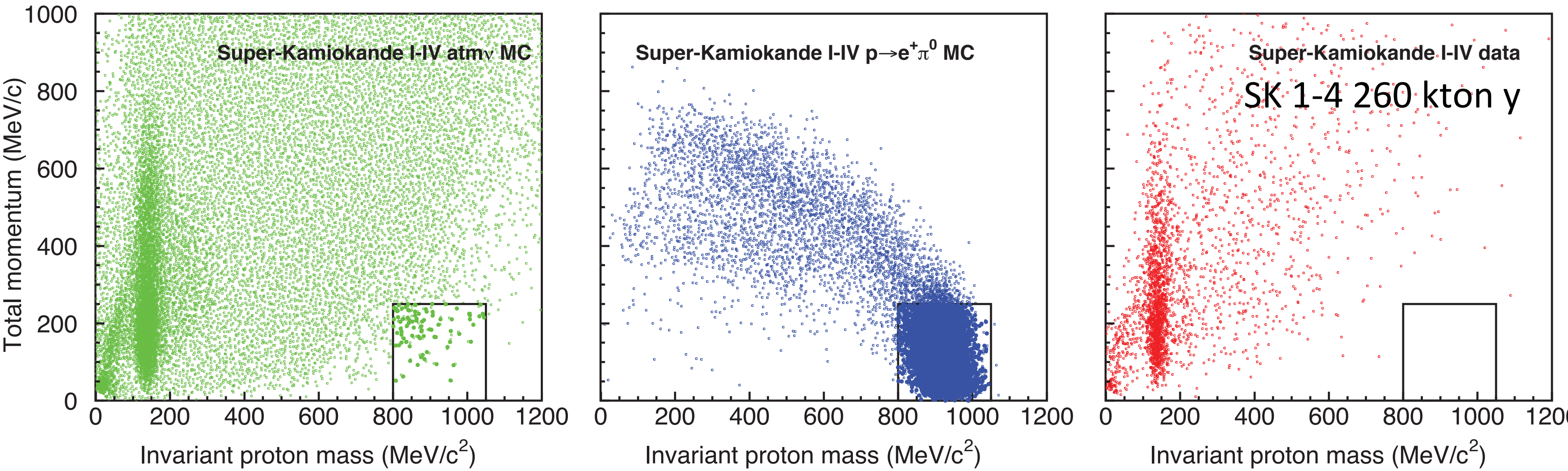


Single Event Discovery is Possible



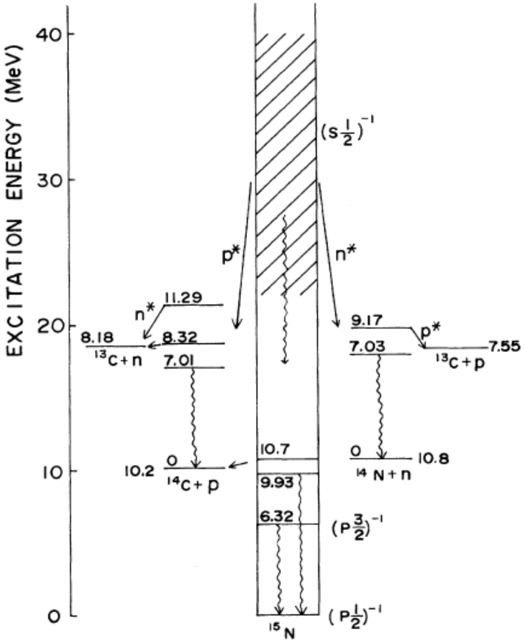
$$p \to e^+ \pi^0$$

Sensitivity from SK Studies



$p \rightarrow e^+\pi^0$	SK1	(20% coverage) SK2	SK3	(new electronics) SK4
Efficiency	39.2±0.7 %	38.5±0.7 %	40.1±0.7 %	39.5±0.7 %
Background rate (/Mt y)	2.1±0.5	2.2±0.5	1.9±0.5	1.6±0.4
Background rate (/Mt y)	K2K 1kton check $1.63^{+0.42}_{-0.33}(\text{stat})^{+0.45}_{-0.51}(\text{sys.})$			

Photocoverage is not an issue for such an energetic mode.
Sensitivity is easy to calculate: efficiency and backgrounds are reliably predicted)



Nuclear Physics of Proton Decay in ^{16}O

Spectroscopic factors measured in $^{16}O(e,ep)^{15}N$ experiment

Gamma-ray emission measured in $^{16}O(p,2p)^{15}N$ experiment

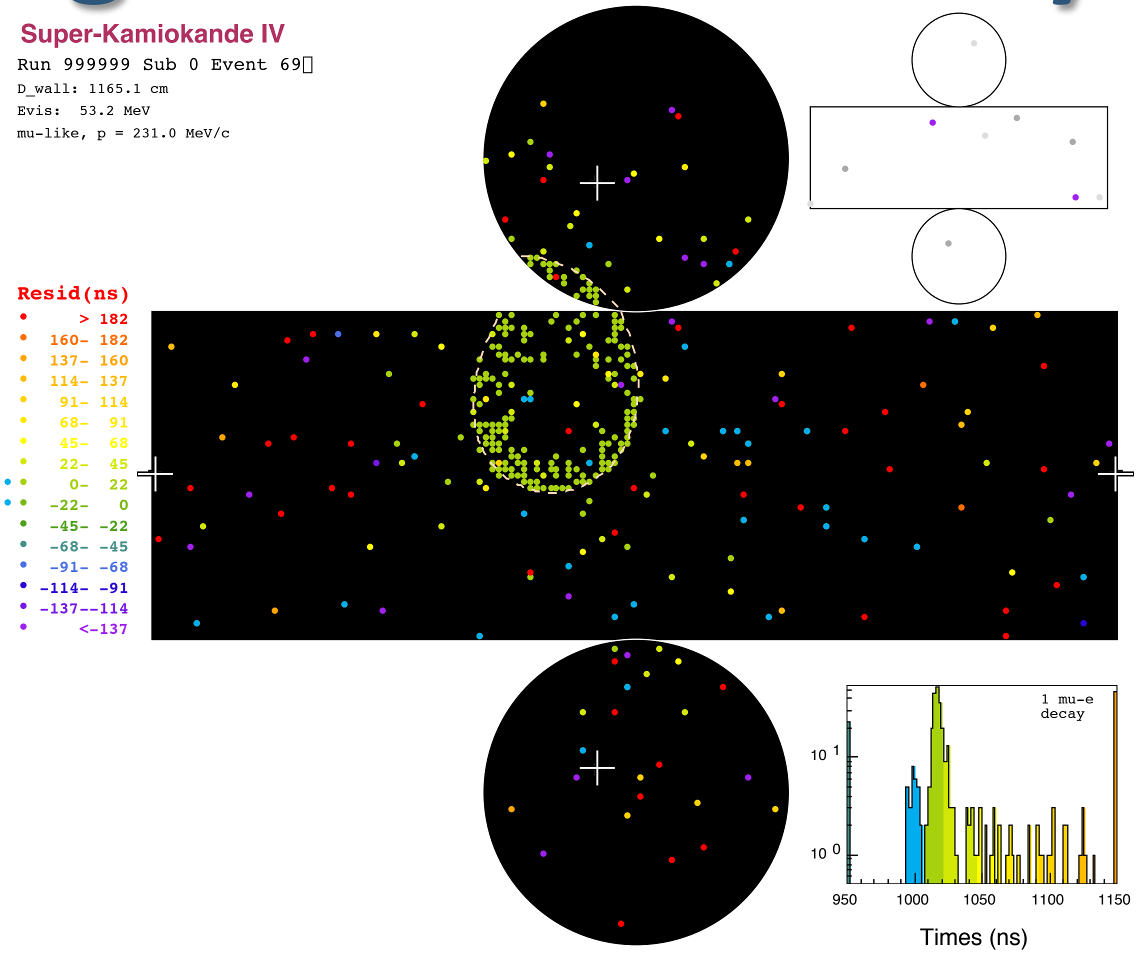
Hole	Residual	States	(k)	E_γ	E_p	E_n	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}N	0	0	0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	^{15}N	6.32	0	0	0.41
	9.93	$\frac{3}{2}^-$	^{15}N	9.93	0	0	0.03
	10.70	$\frac{3}{2}^-$	^{15}N	0	0.5	0	0.03
$(s_{1/2})_p^{-1}$	g.s.	1^+	^{14}N	0	0	~ 20	0.02
	7.03	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

some gammas

few neutrons

H. Ejiri Phys. Rev. C48 (1993)

Single Event Discovery is Possible



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

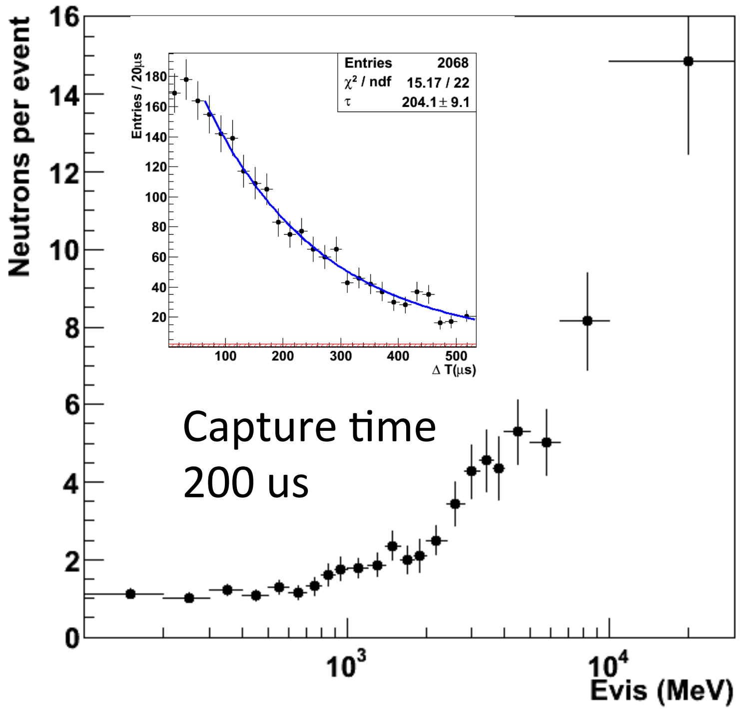
kaon decay
to single muon
with gamma tag

Photocoverage
is an issue for
this mode.

γ-tag plus $\pi^+\pi^0$	SK1	(20% coverage) SK2	SK3	(new electronics) SK4
Efficiency	15.7 %	13.0 %	15.6 %	19.1 %
Background rate (/Mt y)	2.8±0.5	6.2±0.8	2.3±0.5	2.0±0.3

Improvements for Proton Decay

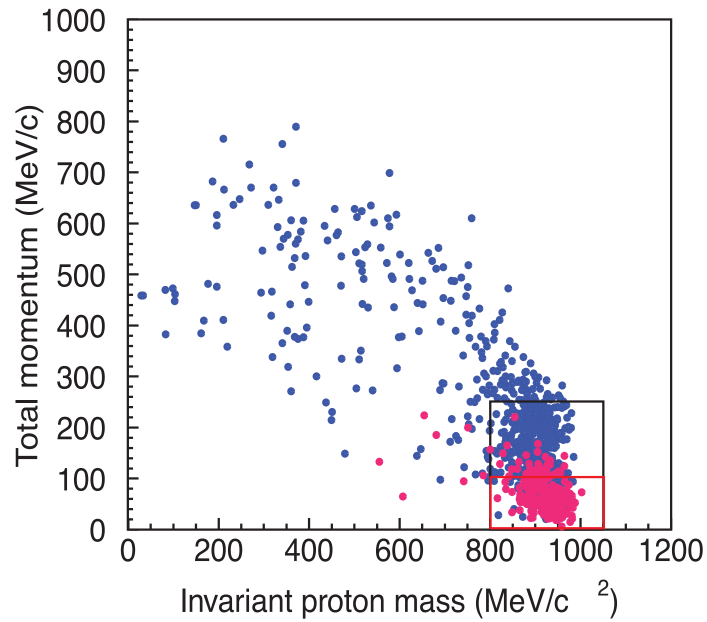
★Background reduction by neutron tag:
- add 0.2% $GdNO_3$
- n + Gd → 8 MeV γ, Δt = 20 μs
- many atmospheric ν events accompanied by n
- see posters this NNN



★Free protons:
- Free protons are an advantage for WC no nuclear abs., no Fermi motion
- E.g. Tighten cuts for free proton (at expense of efficiency)
- Cross-over in sensitivity: $\mathcal{O}$(10+ Mton·yr)

$\varepsilon \approx$ 40% → roughly 17%

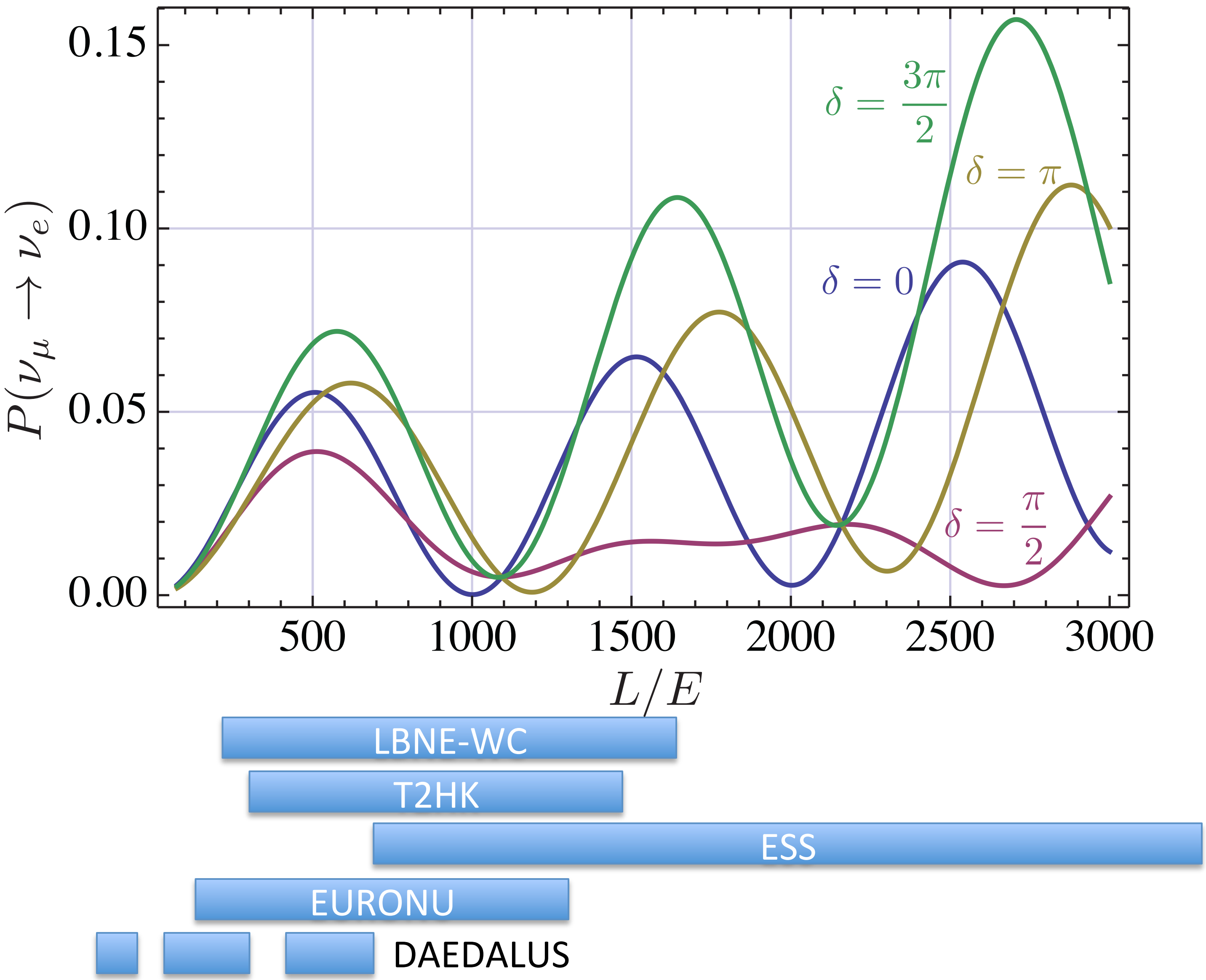
BG ≈ 0.2 → 0.015 evts/100 kty



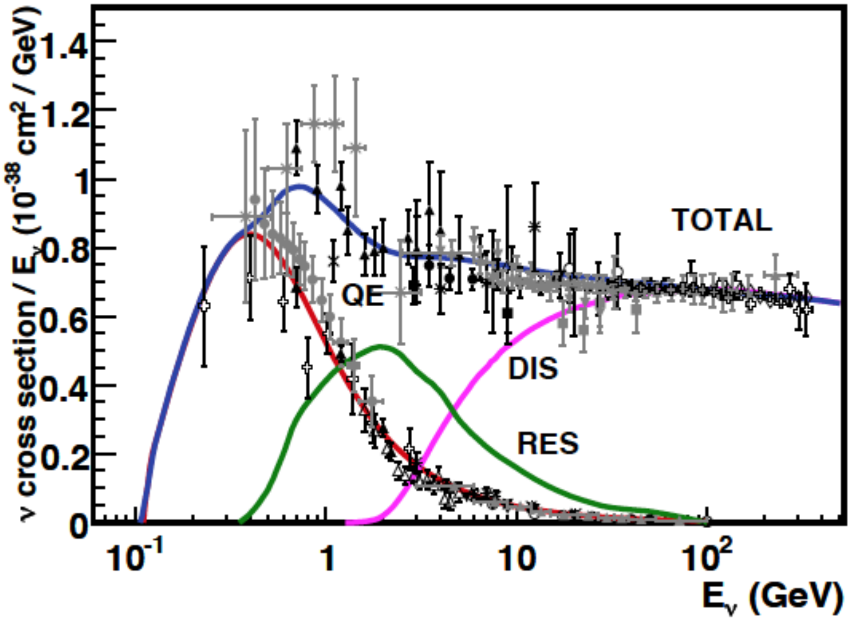
(2) Long-Baseline Neutrino Oscillation

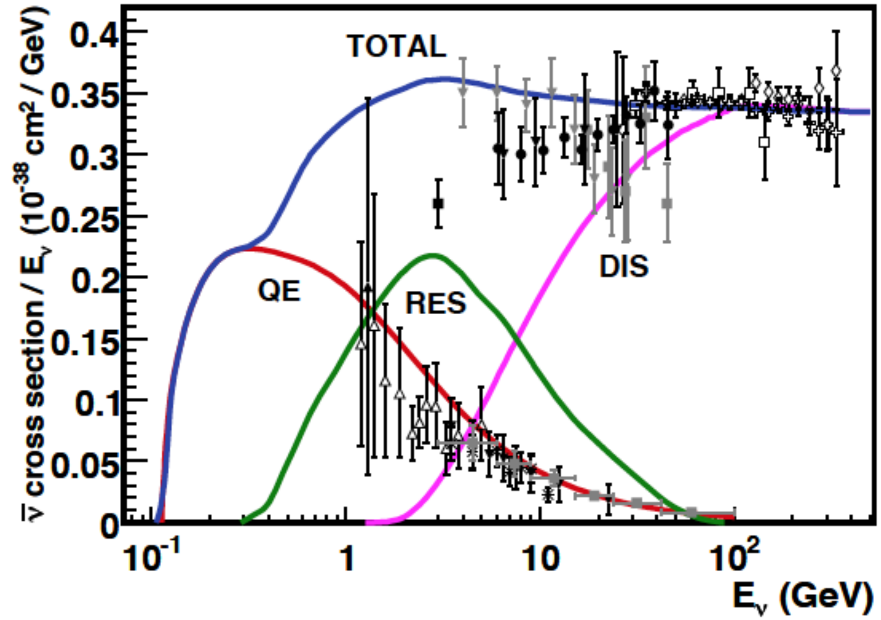
- ★ Massive water Cherenkov detectors have been and are considered for a wide range of accelerated-made neutrino beams.
- ★ Since θ13 is large, the gateway is open for Mass Hierarchy and CP-violation.
- ★ Numerous experiments consider using Water Cherenkov.

Three Flavor Oscillation (L/E)



Neutrino Cross Sections





LBNE-WC

T2HK

ESS and EURONU

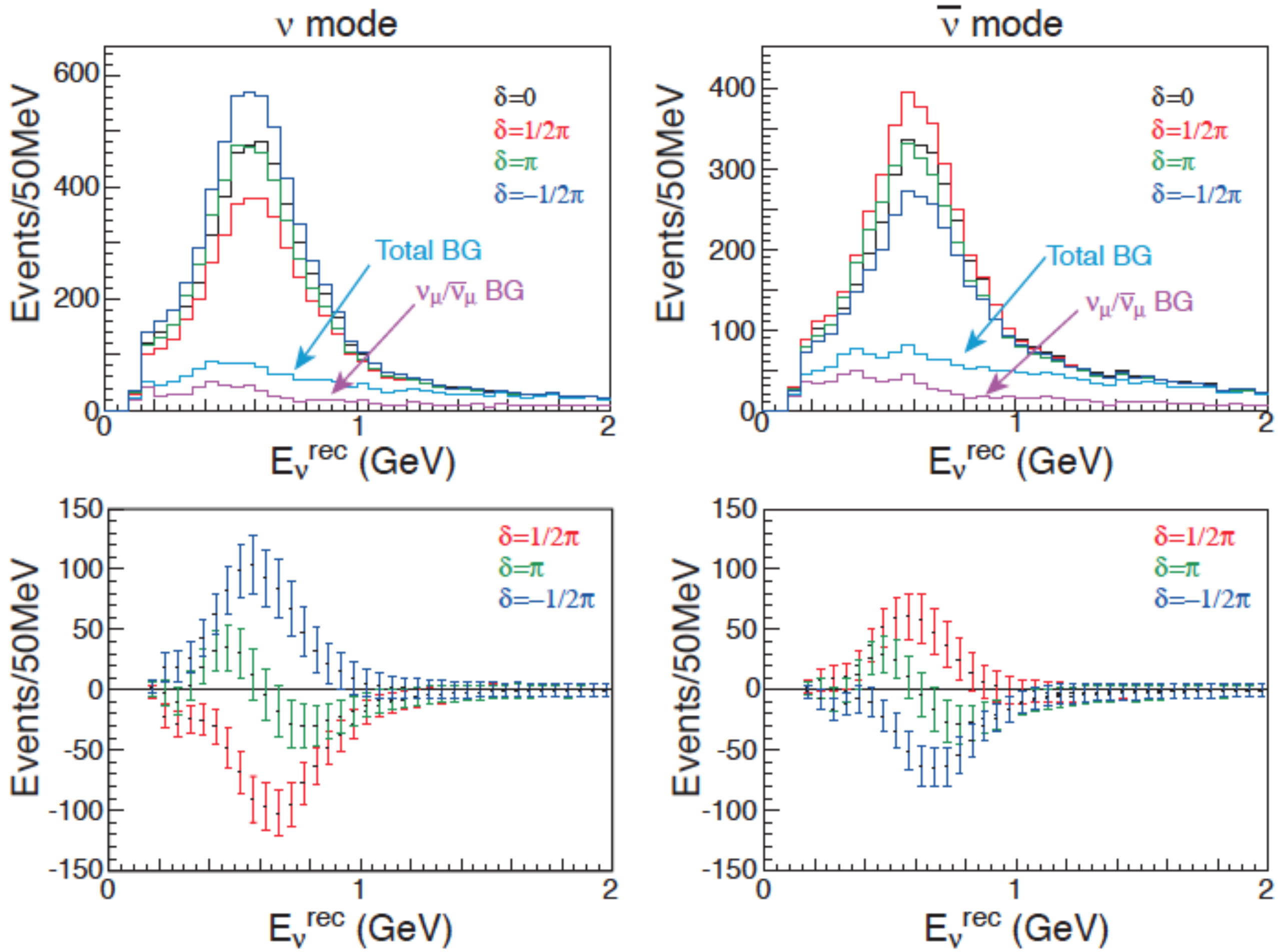
DAEDALUS

Ideal range for beam neutrino studies is below 1 GeV:

$$E_\nu = \frac{ME_l - m^2/2}{M - E_l + p_l cos\theta}$$

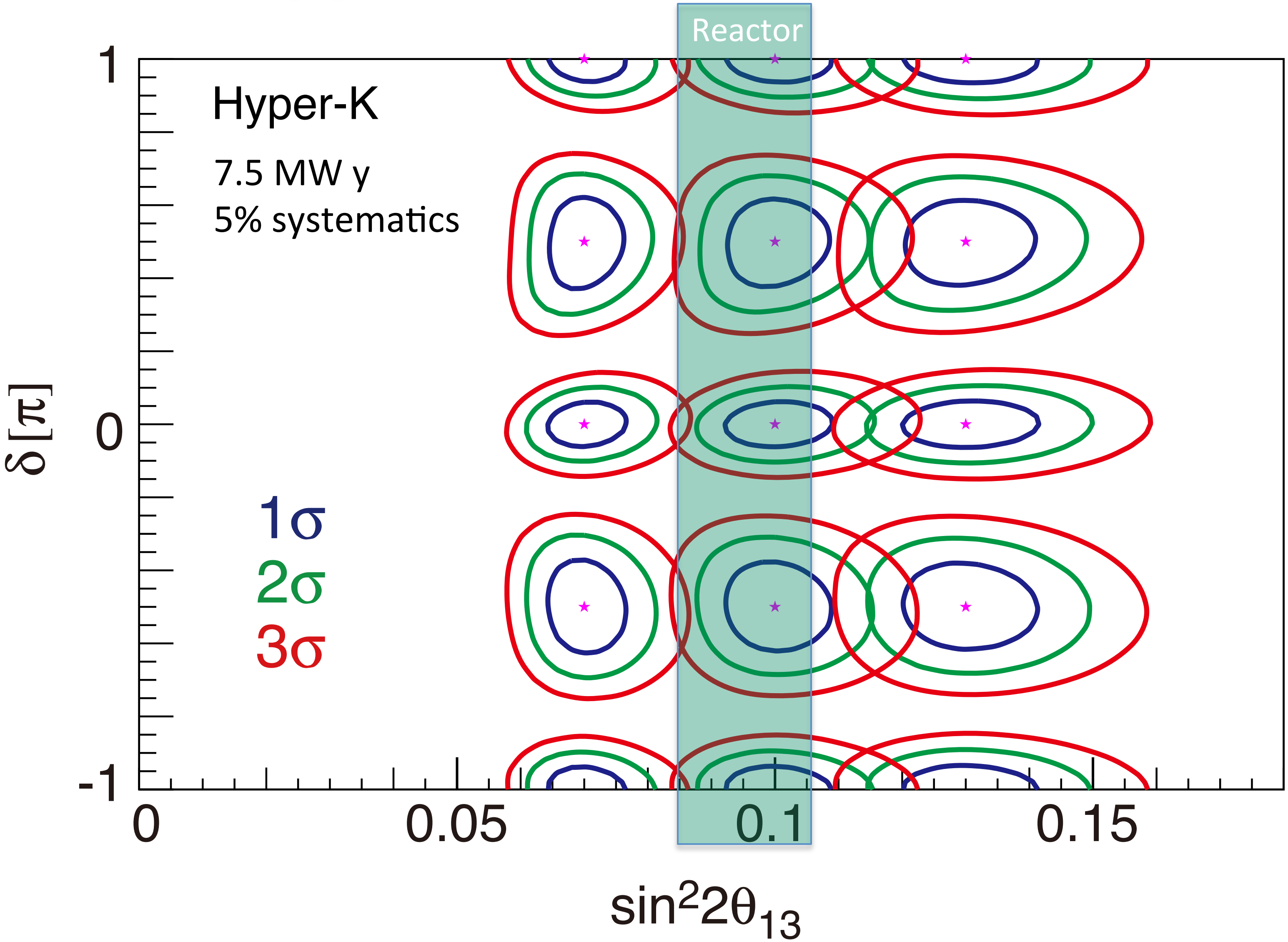
for QE scattering

Hyper-K Spectral Analysis



7.5 MW y

Hyper-K CP Precision

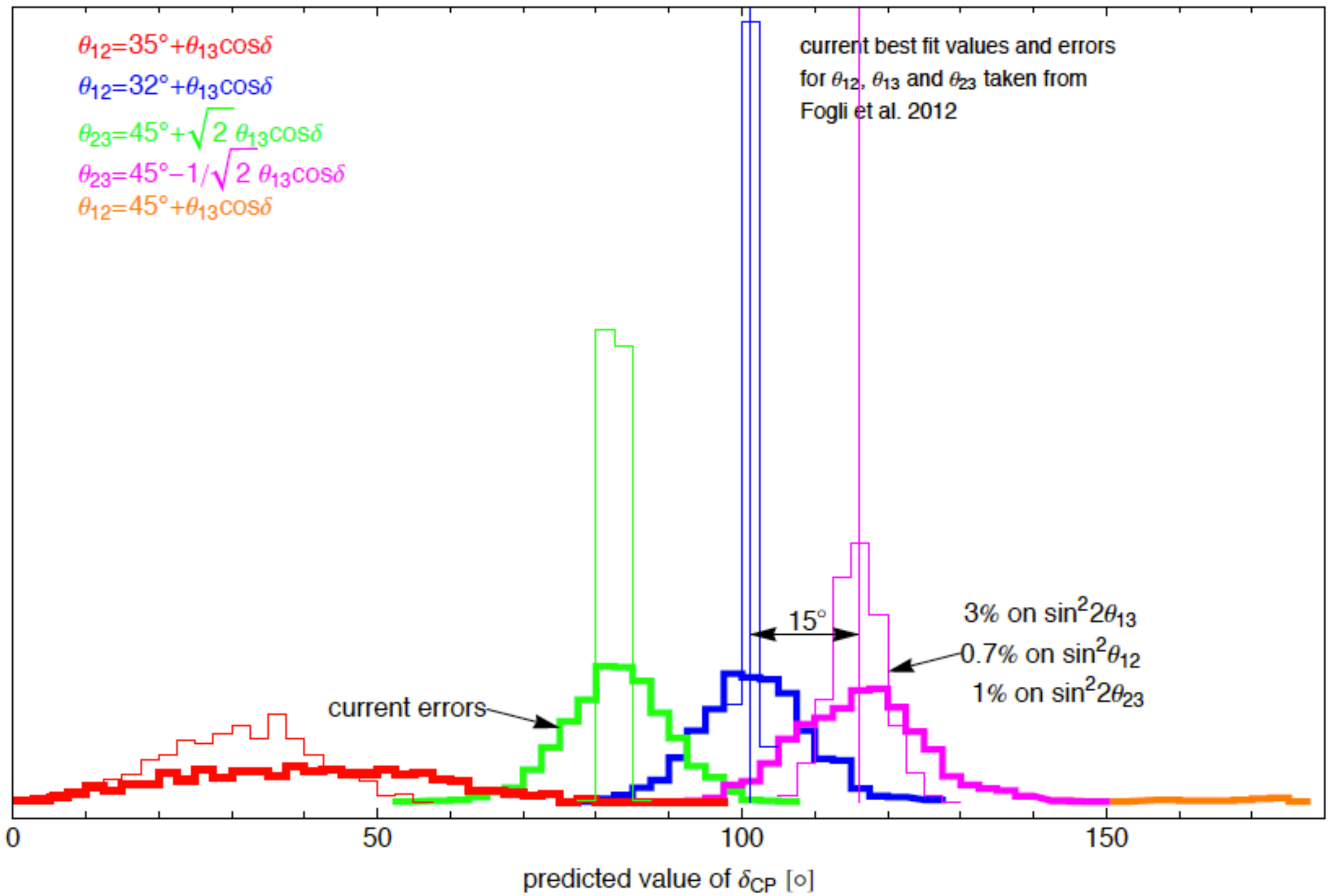


15 degrees

Assumes mass hierarchy is determined! – by other experiments, combinations, atm. neutrinos

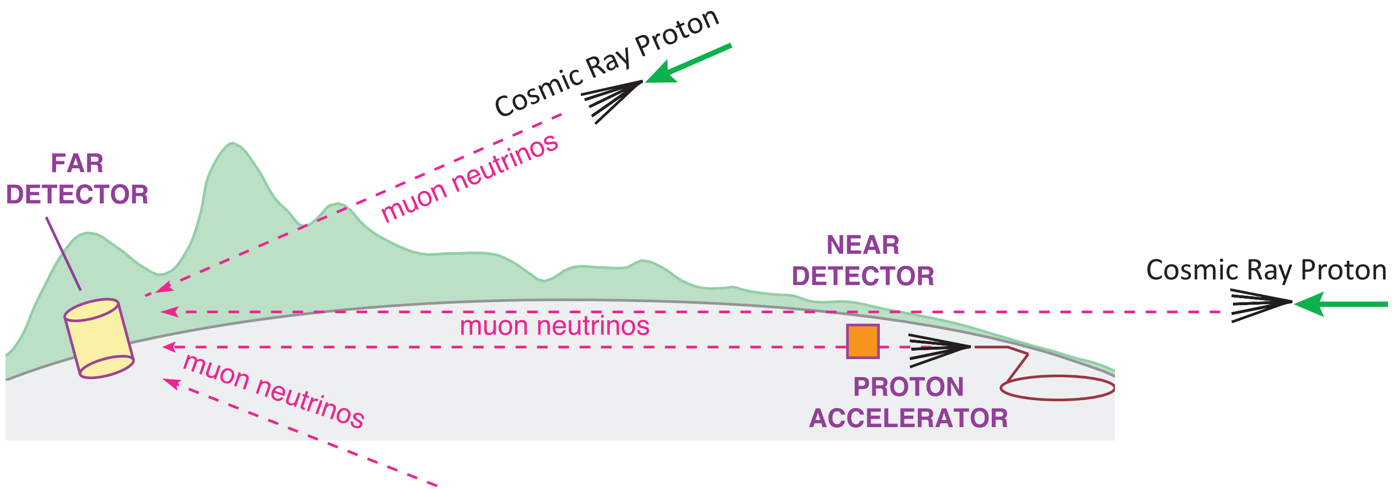
Precision Benchmark

15 degree precision allows for discrimination of some selected sum rules

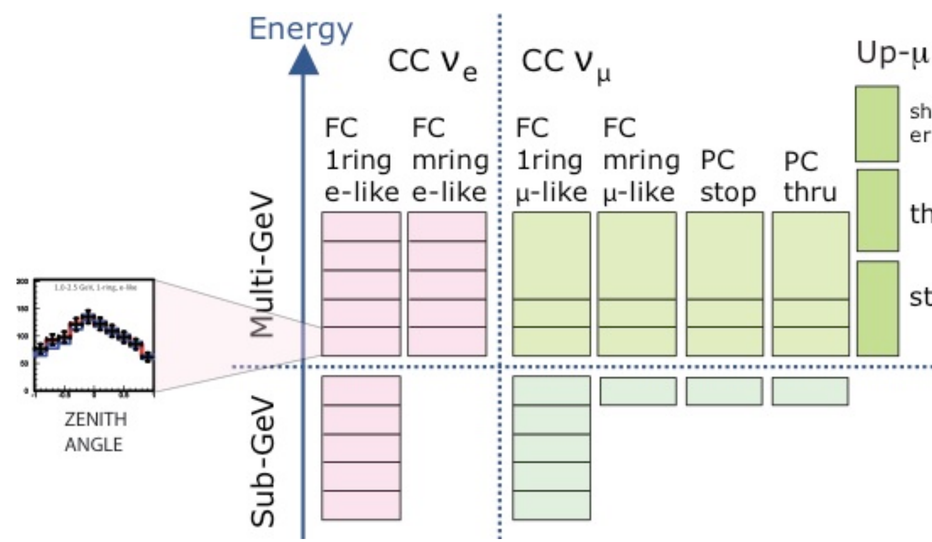


http://arxiv.org/abs/arXiv:1310.4340

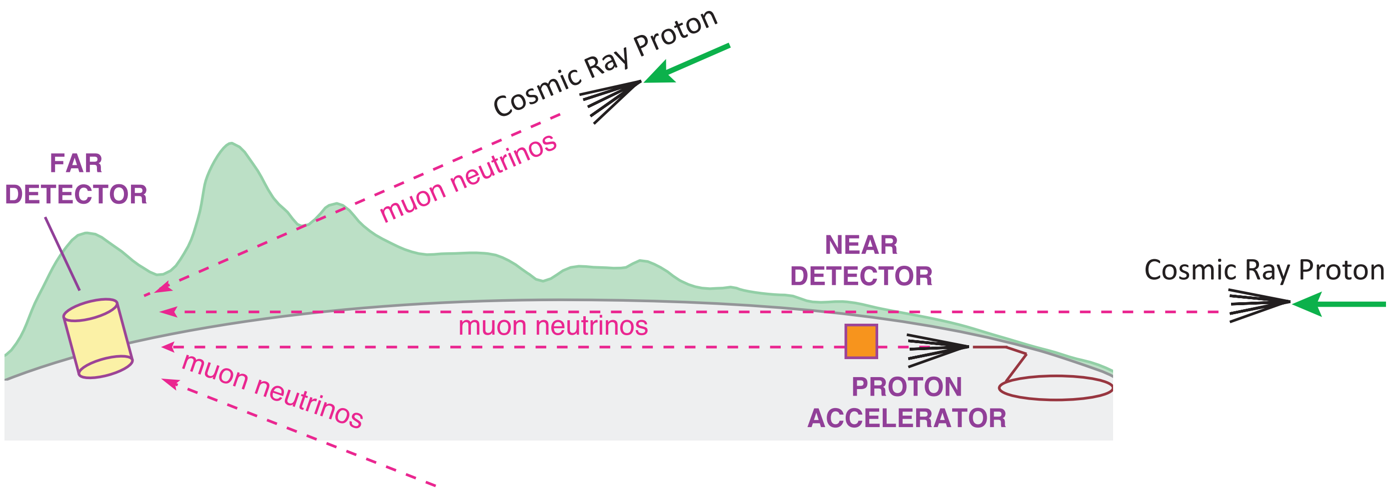
(5) Atmospheric Neutrinos



- ★ 5 decades of energy
- ★ 4 decades of path length
- ★ matter effects
- ★ up-down symmetric flux (Multi-GeV)
- ★ mixed flux of ν_e, ν_μ, anti-ν_e, anti-ν_μ



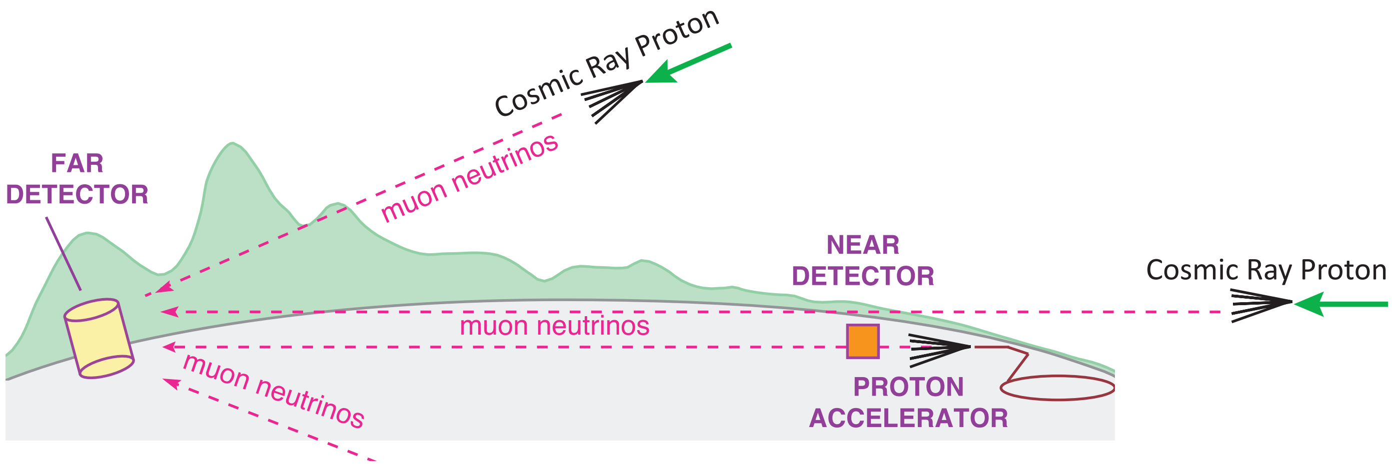
(5) Atmospheric Neutrinos

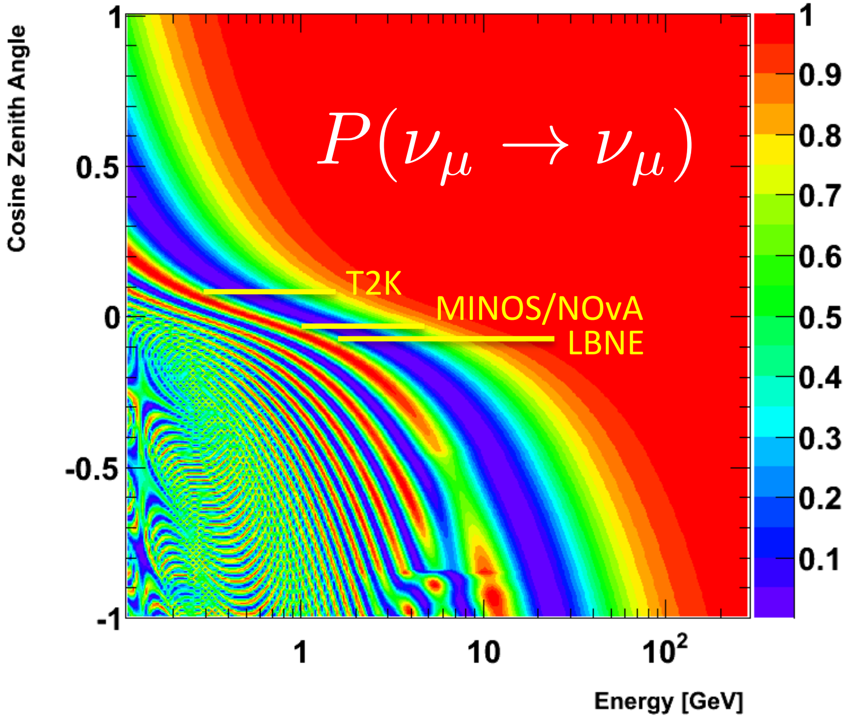


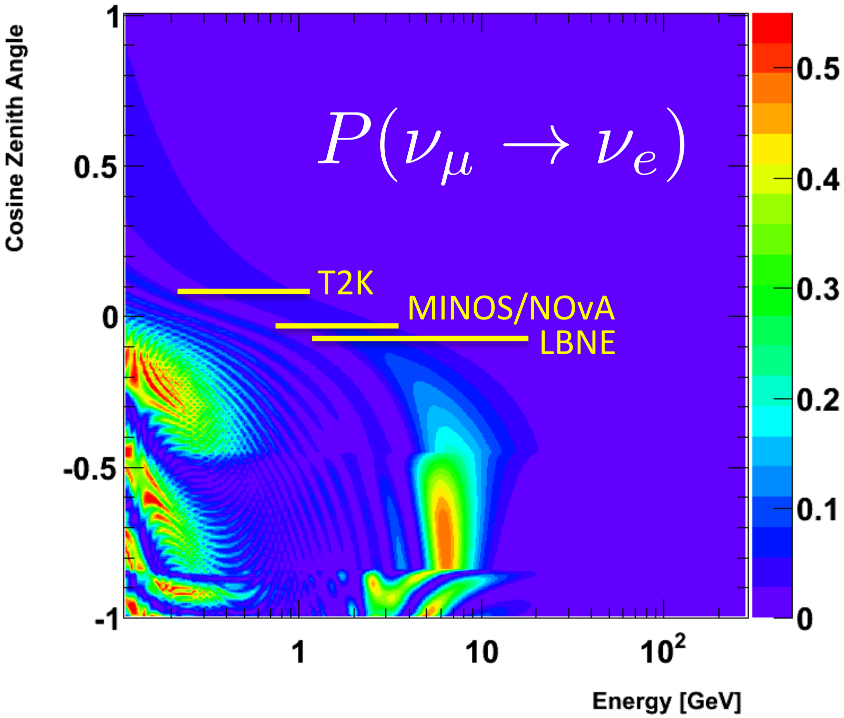
- ★ 5 decades of energy
- ★ 4 decades of path length
- ★ matter effects
- ★ up-down symmetric flux (Multi-GeV)
- ★ mixed flux of ν_e, ν_μ, anti-ν_e, anti-ν_μ

- ★ Mass hierarchy
- ★ Octant of θ23
- ★ 3-flavor oscillation with different L, E, matter than beam experiment
- ★ subdominant / exotic physics

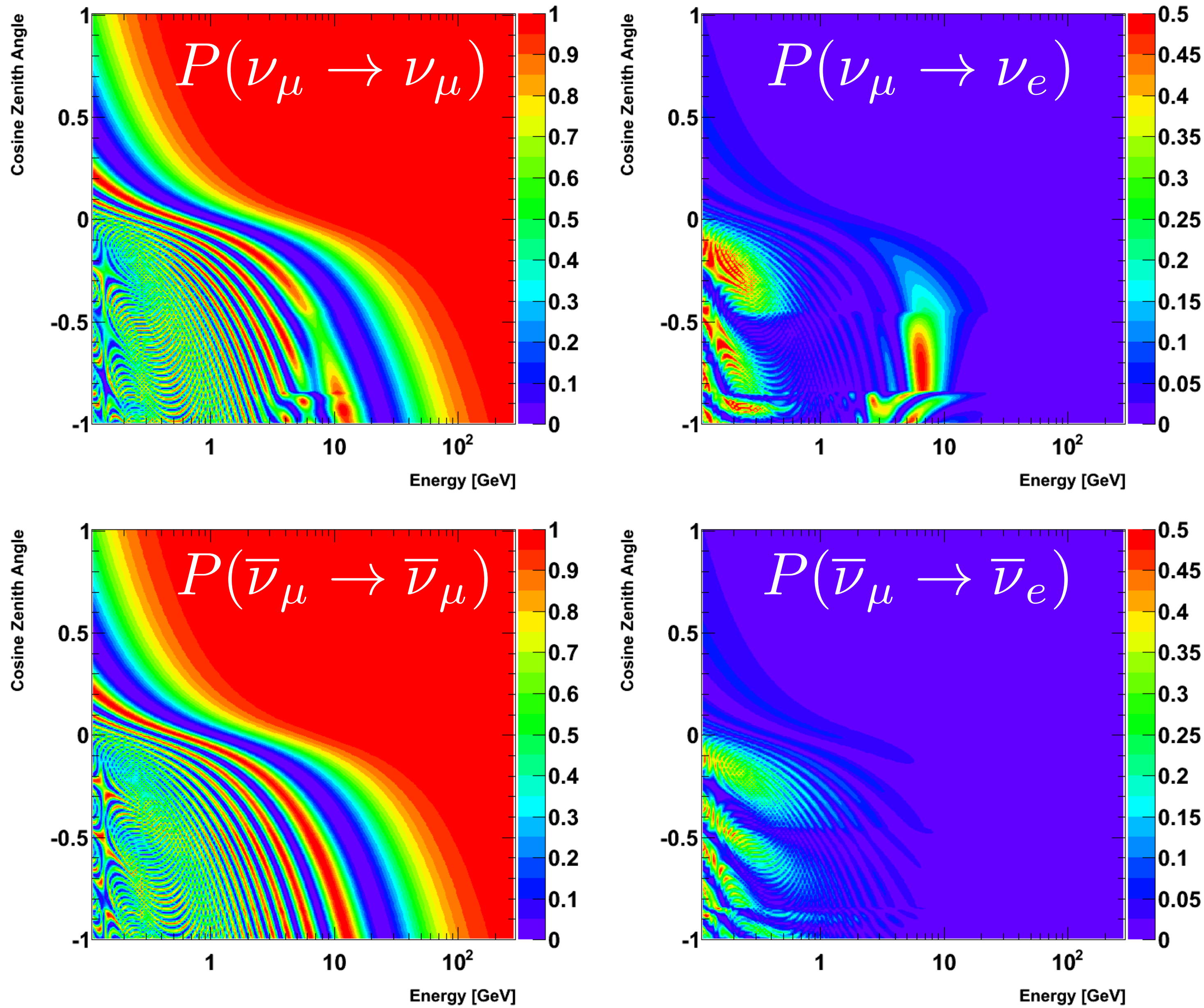
(5) Atmospheric Neutrinos







Oscillograms: Graphical representations of ν mixing probability

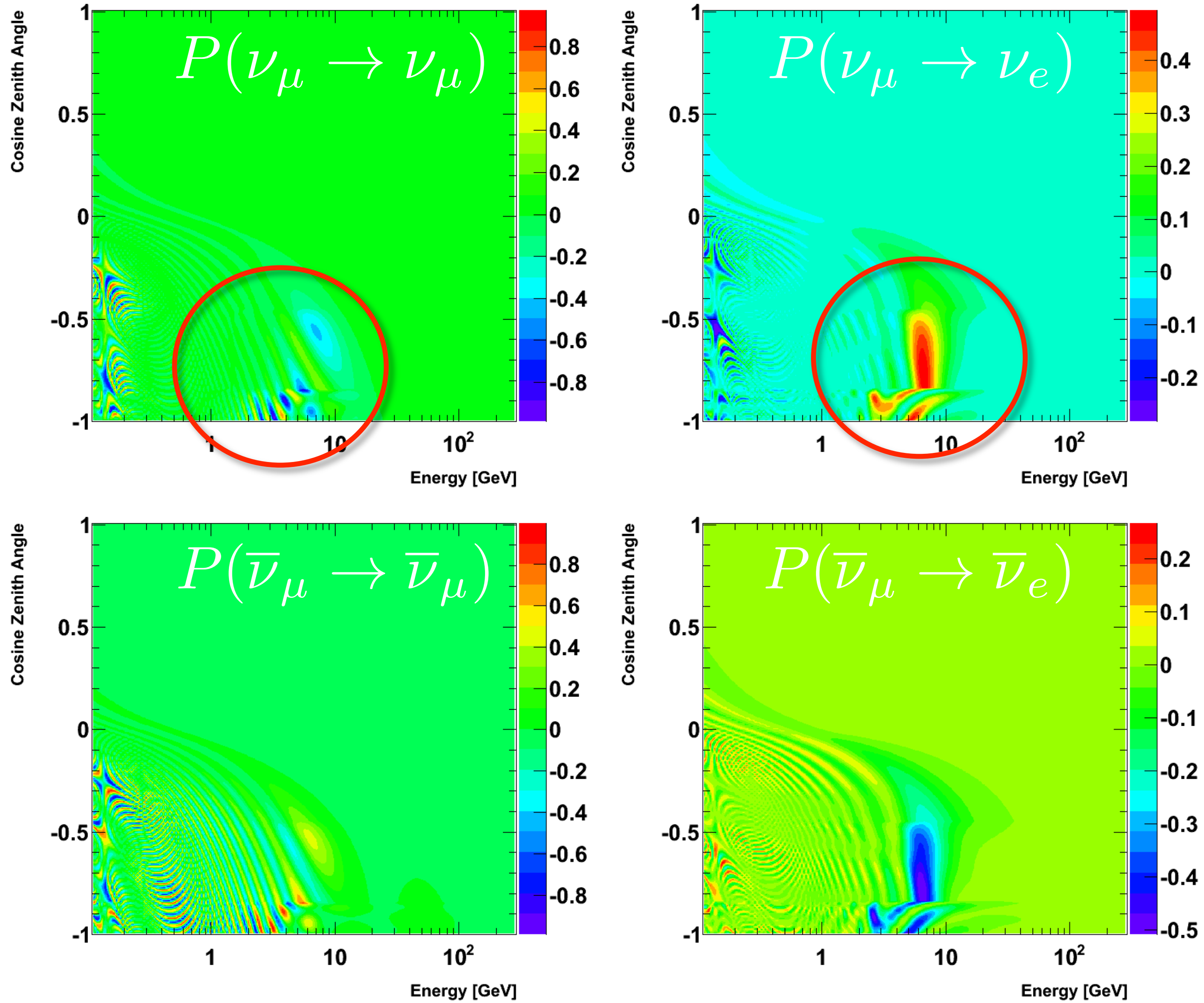


Resonance in $\nu_\mu - \nu_e$ for NH

…

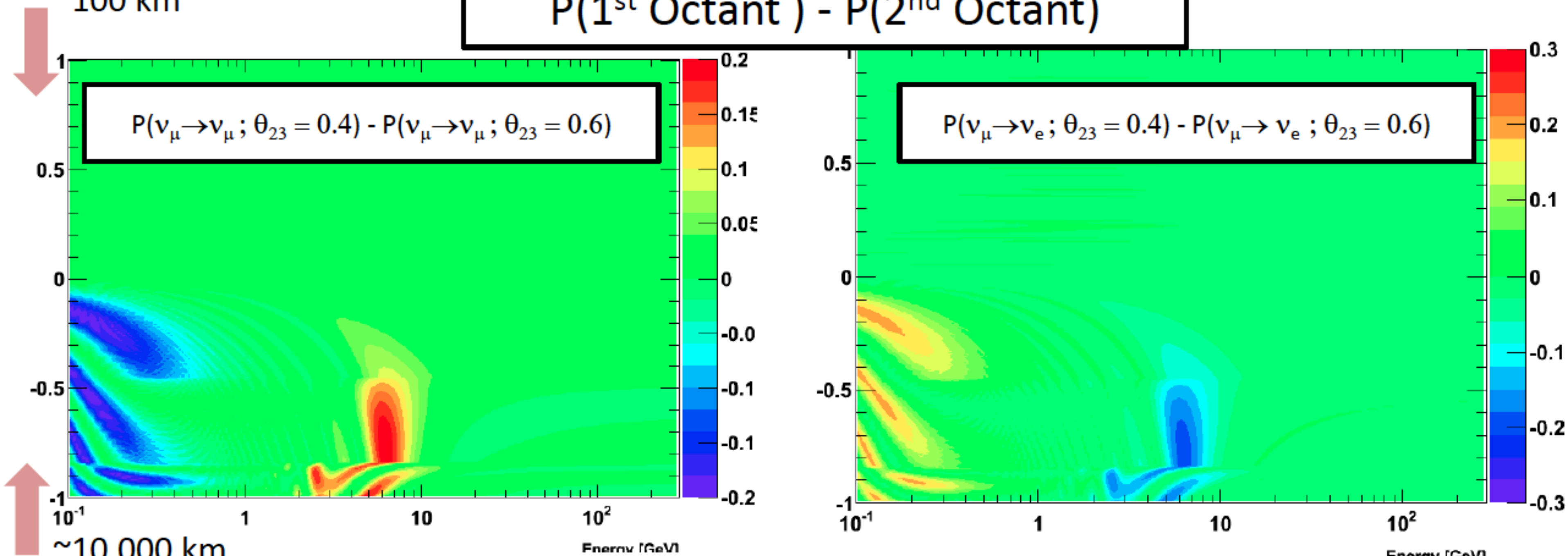
(in antinu for IH)

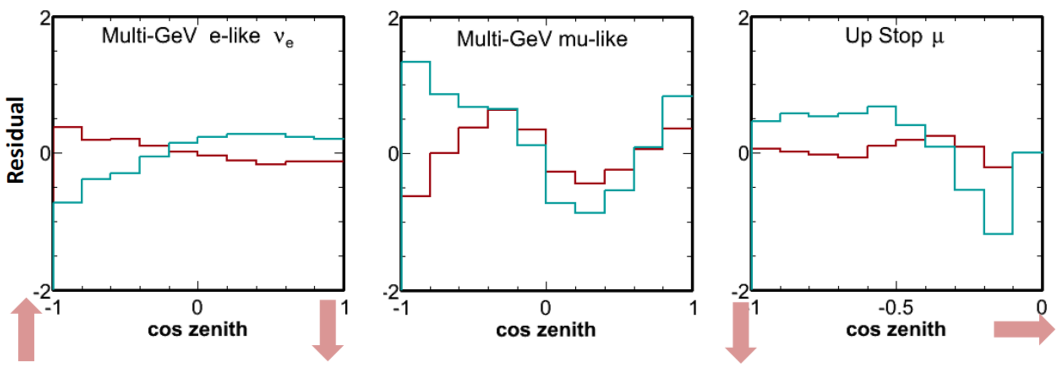
Normal Hierarchy minus **Inverted Hierarchy**



First Octant minus Second Octant

P(1st Octant) - P(2nd Octant)



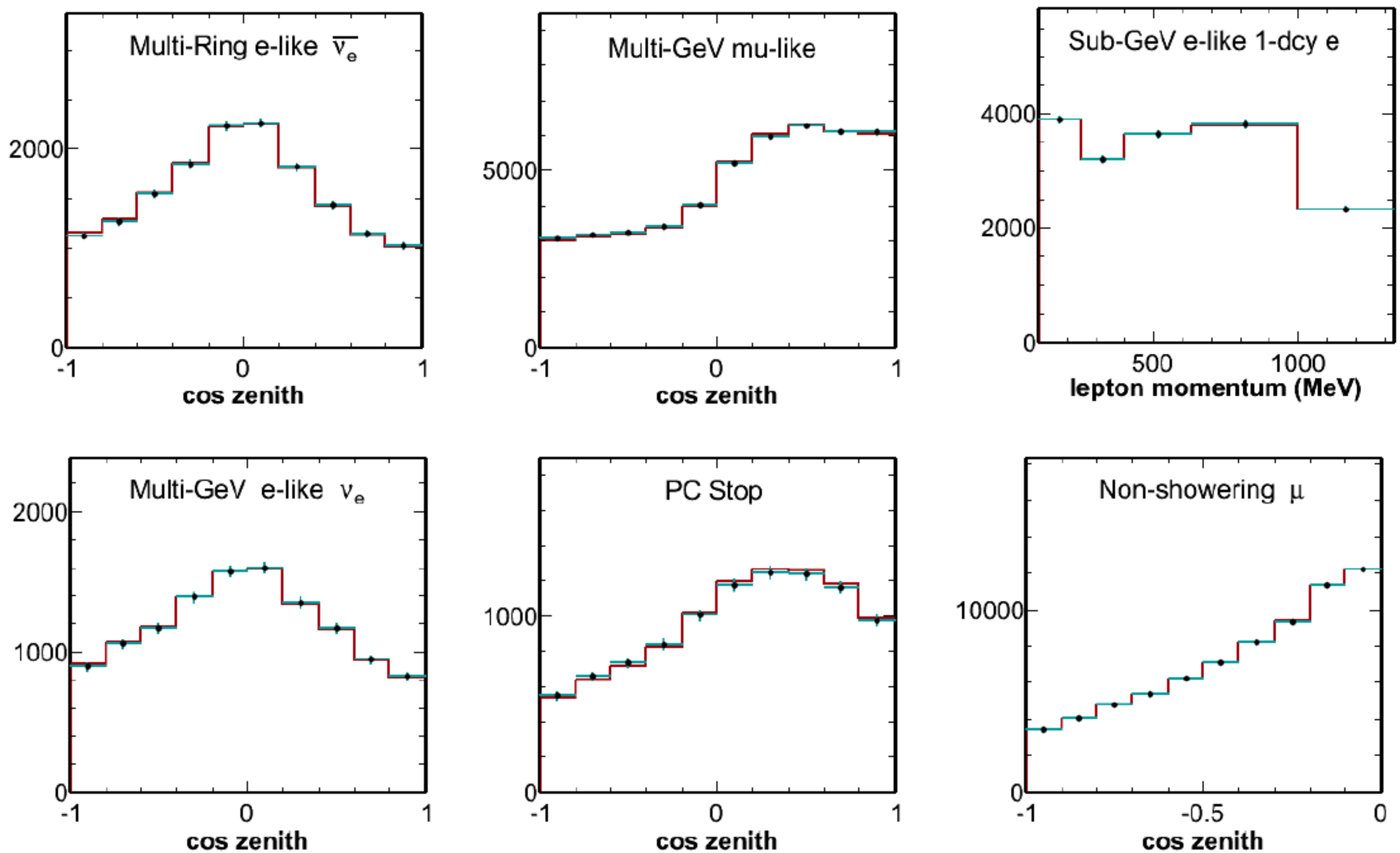


θ_{23} = **0.4** vs. θ_{23} = 0.5

θ_{23} = **0.6** vs. θ_{23} = 0.5

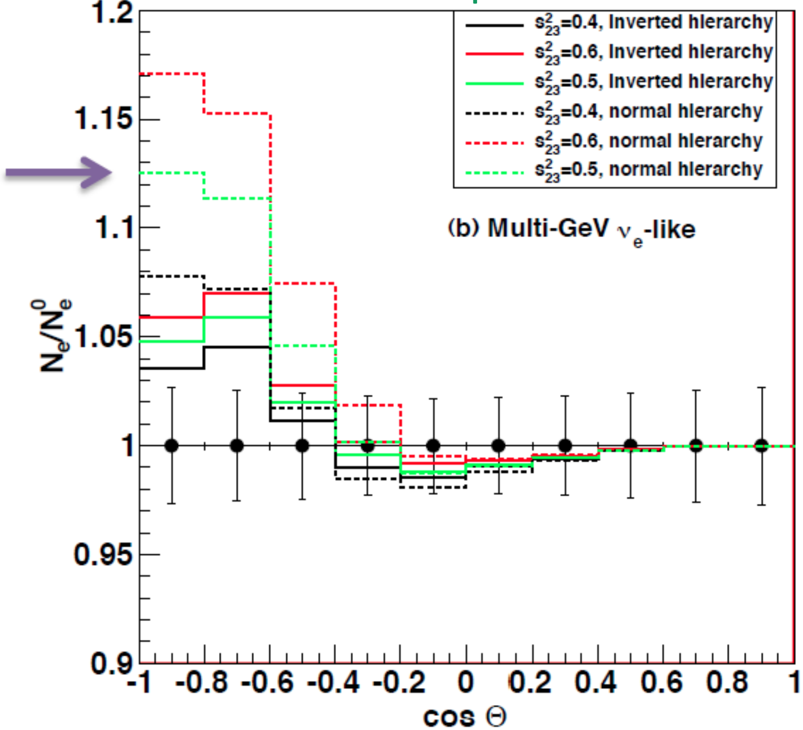
In 1st Octant:
More multi-GeV muon survival
Less electron appearance

Example Zenith Distributions (10 yr HK)

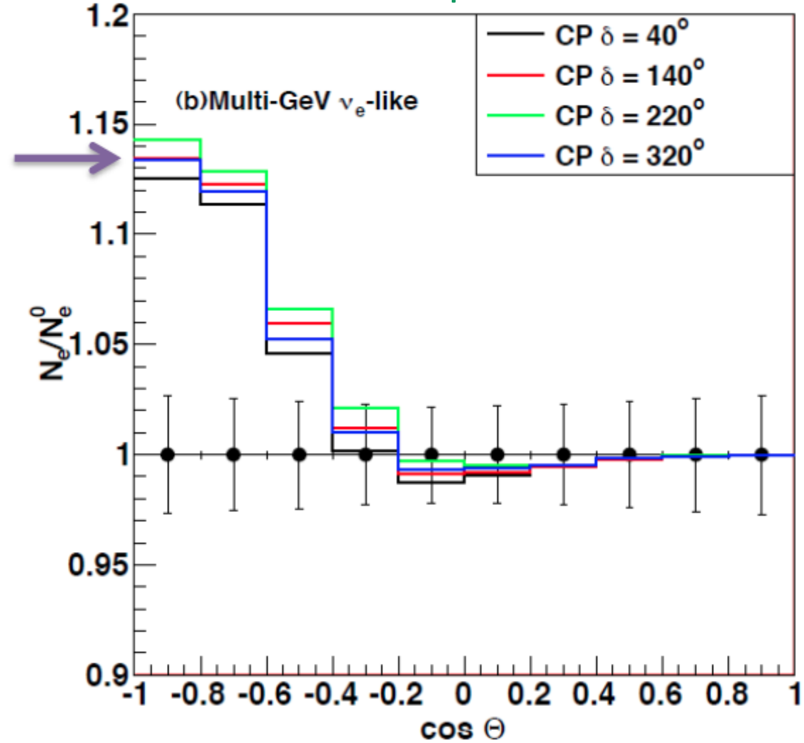


Multi-GeV ν_e-like and anti ν_e-like samples

Octant dependence

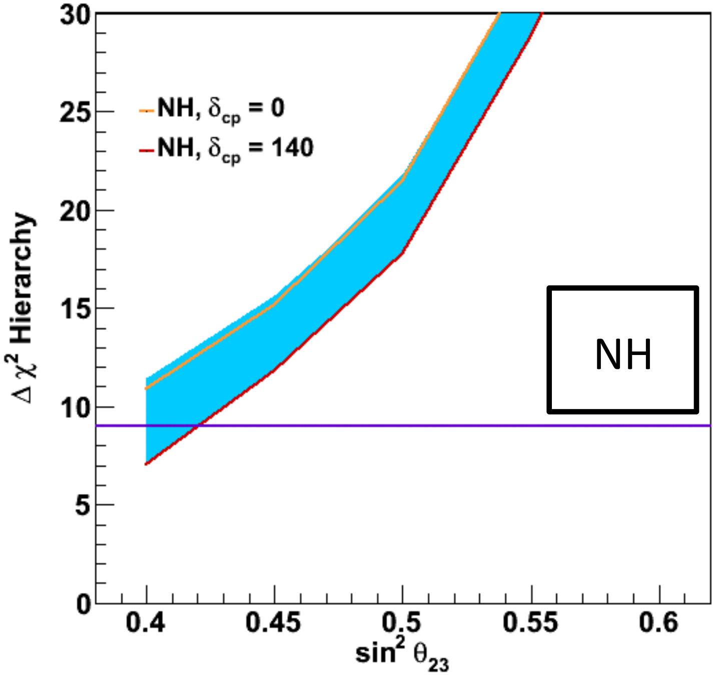


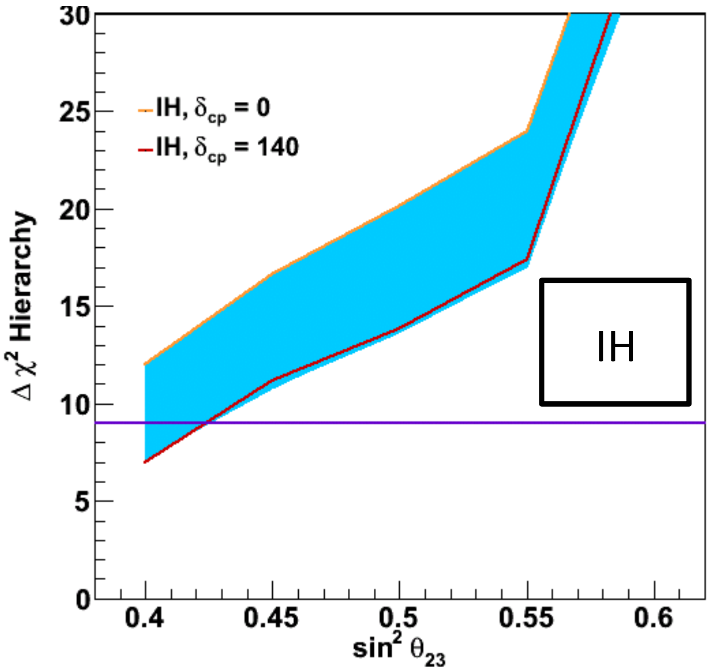
CP-δ dependence

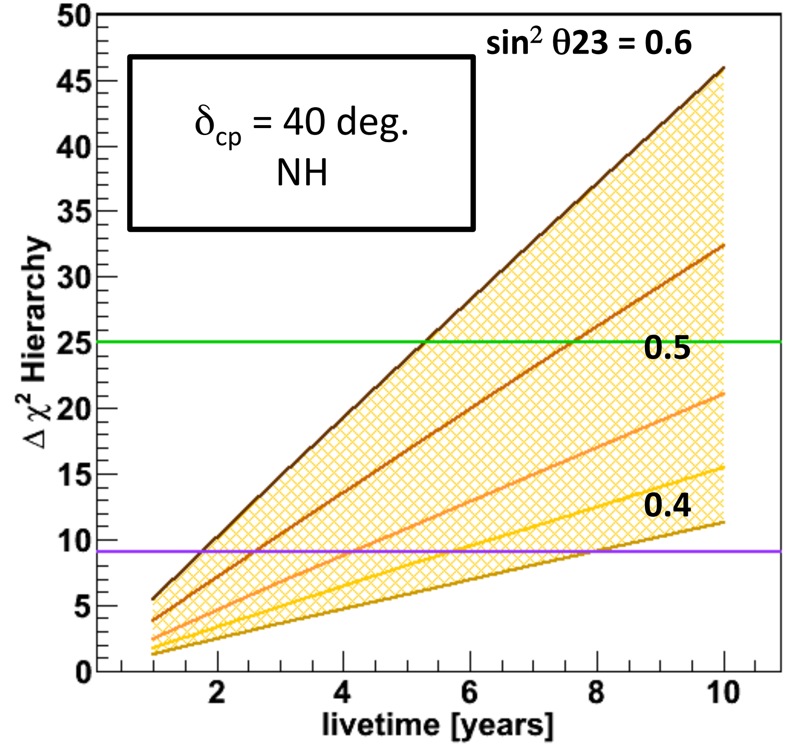


Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_e like	1R	60.2	10.6	13.5	14.8
	MR	57.5	17.4	10.7	13.7
Anti-ν_e like	1R	55.7	36.6	1.1	6.4
	MR	51.9	20.7	8.2	19.7

Hierarchy Sensitivity including CP-δ Dependence

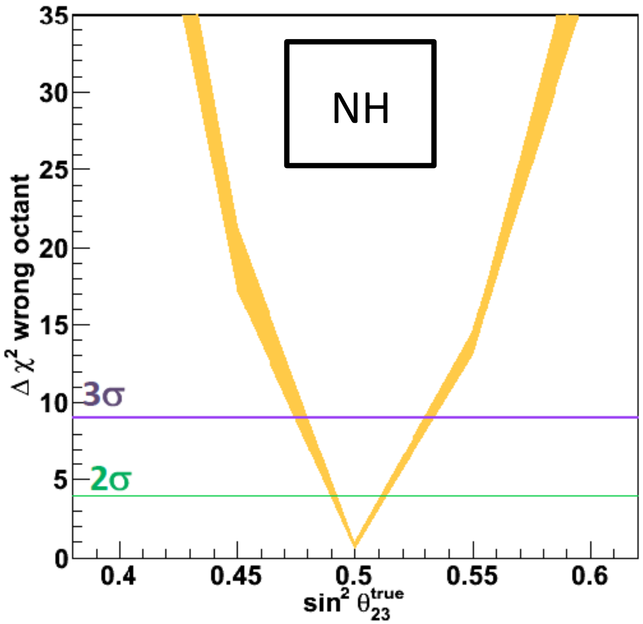


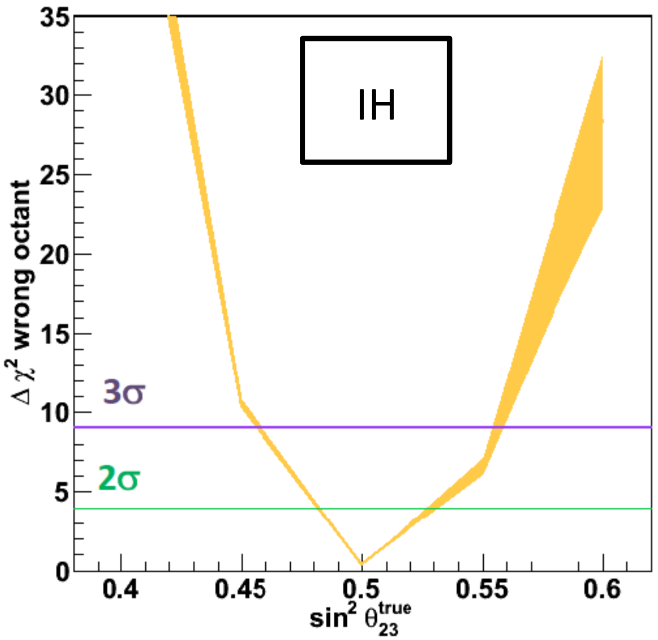




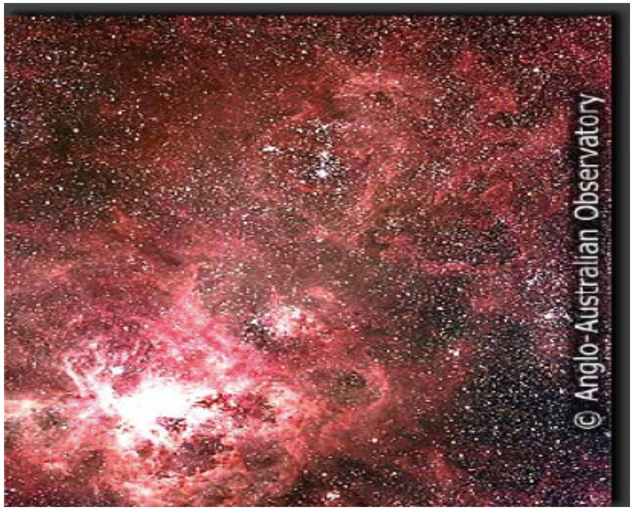
Octant Sensitivity

Band = CP-δ uncertainty



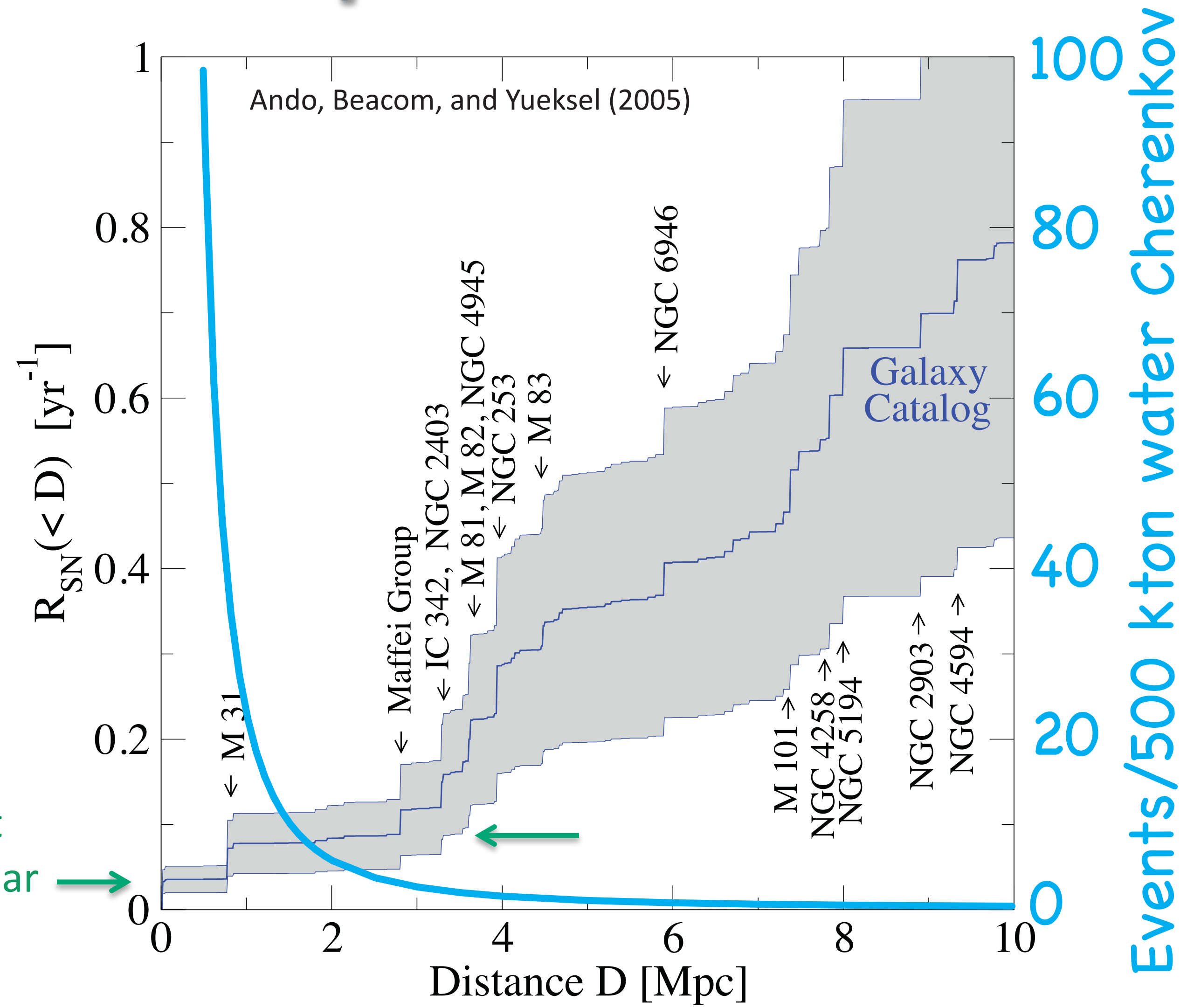


(3) Supernova Neutrino Burst



- ★ Guaranteed signal – if you run long enough.
- ★ Enormous statistics in a megaton-scale detector.
- ★ Time profile and spectra of great astrophysical interest. Possibilities such as Si-burning and black hole formation.
- ★ Standard picture: Initial burst of ν_e and cooling tail of equal flavors
- ★ Matter effects in SN and in earth may be revealed.
- ★ May reveal fundamental neutrino physics as well.

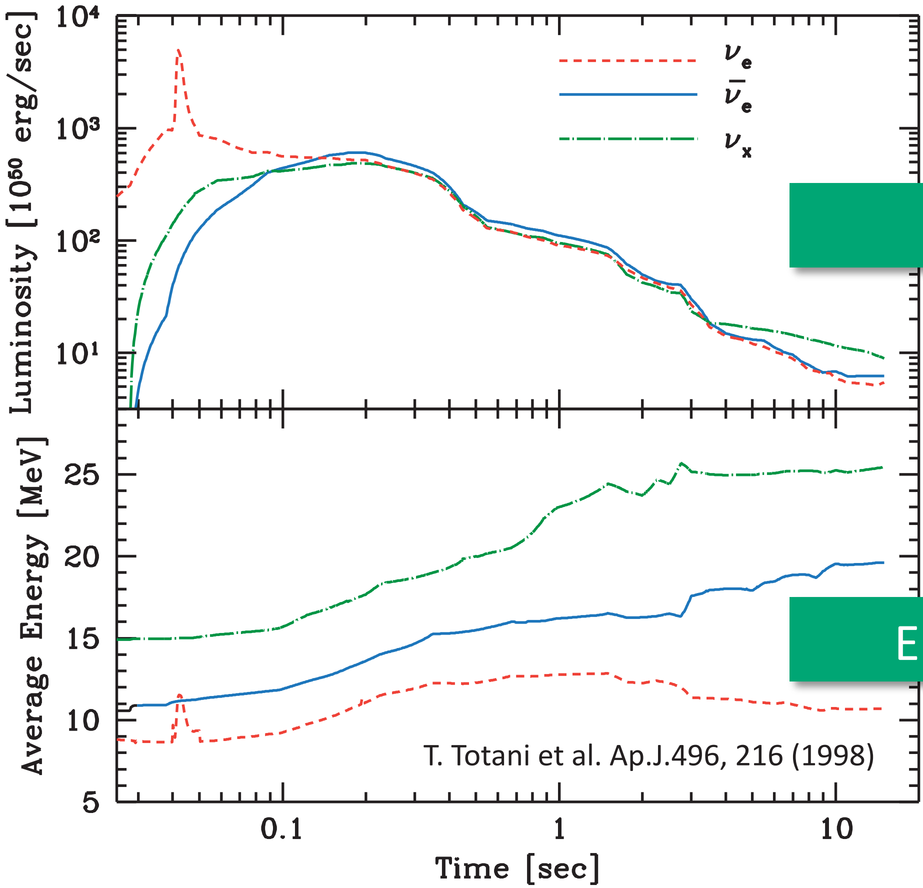
Supernova Rate



Milky Way: few percent chance per year

500 kton detector adds few-event coincidence from Andromeda

Supernova Observables

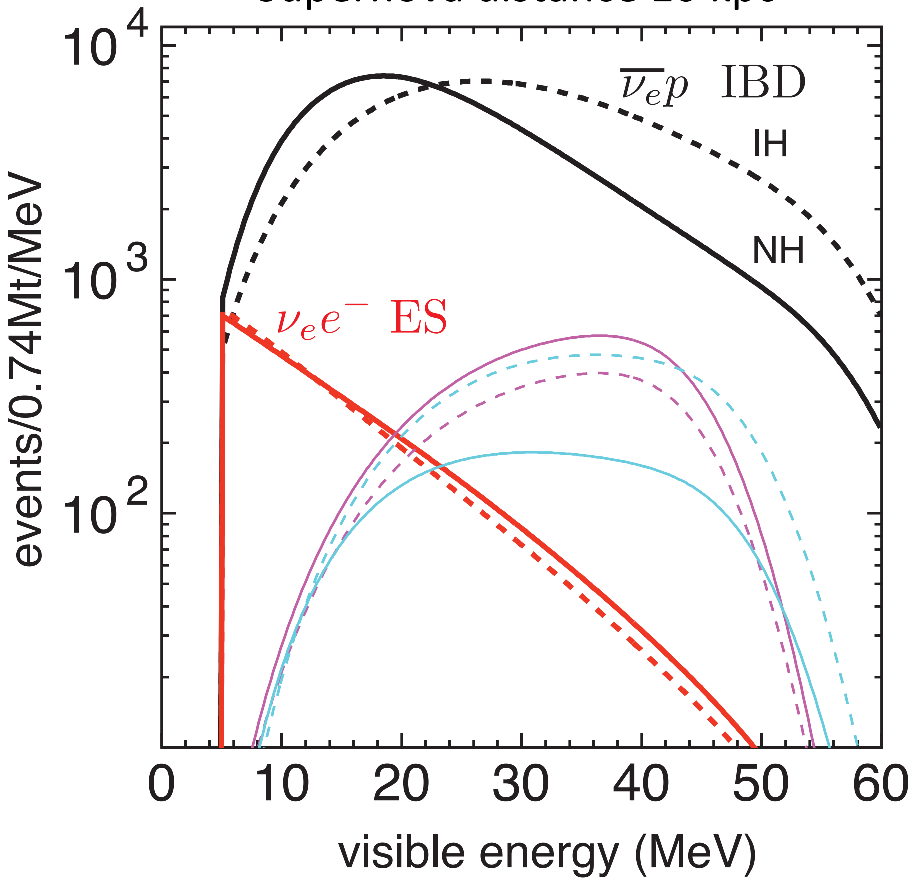


Time profile

Energy Spectrum

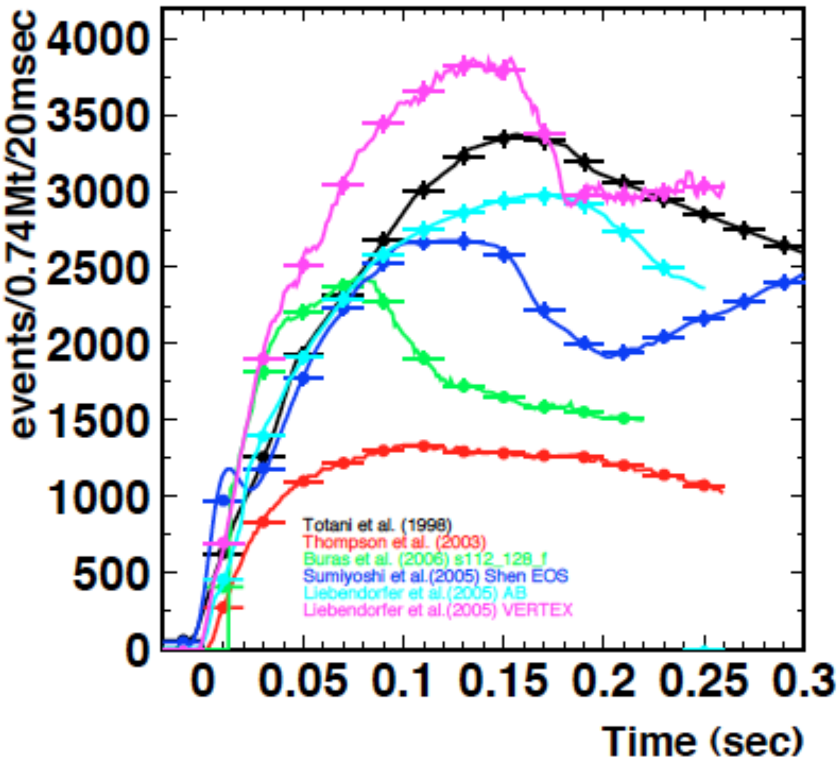
Event Rates in Hyper-K

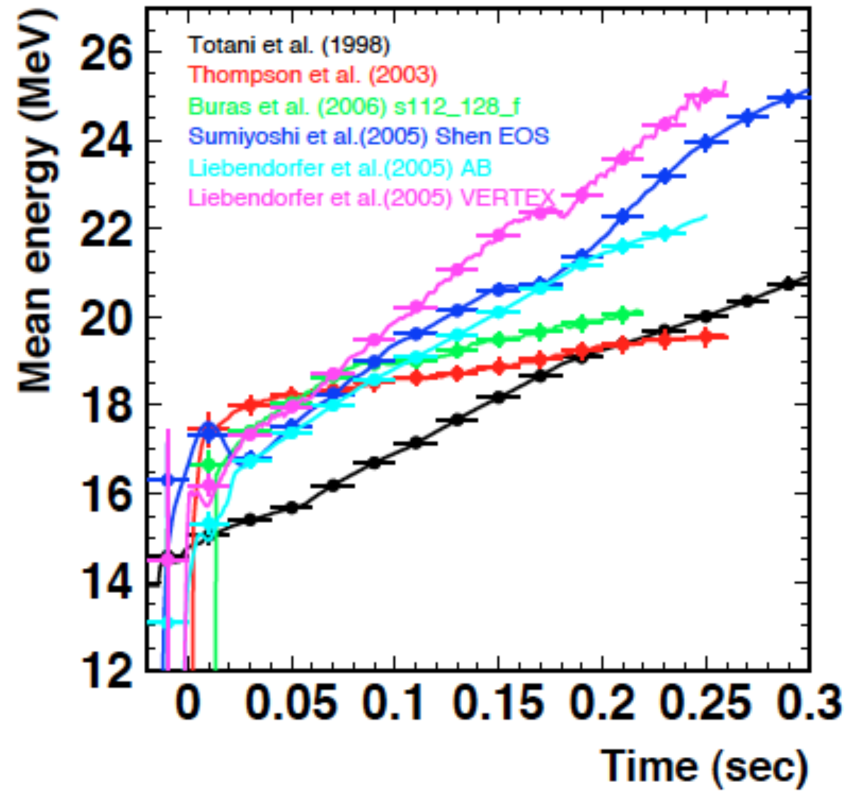
Supernova distance 10 kpc



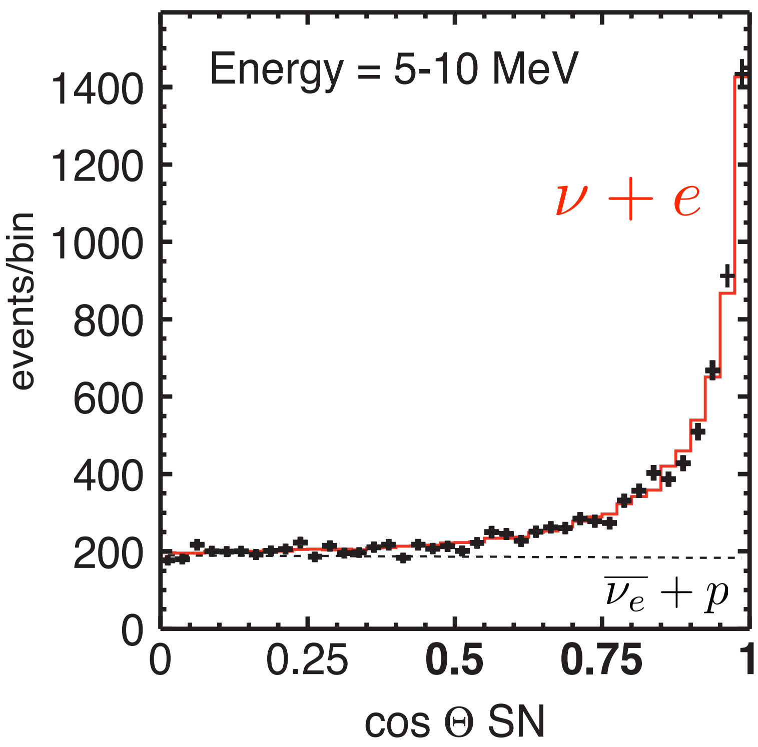
Entire inner volume (0.74 Mton) should be useable for SN burst.

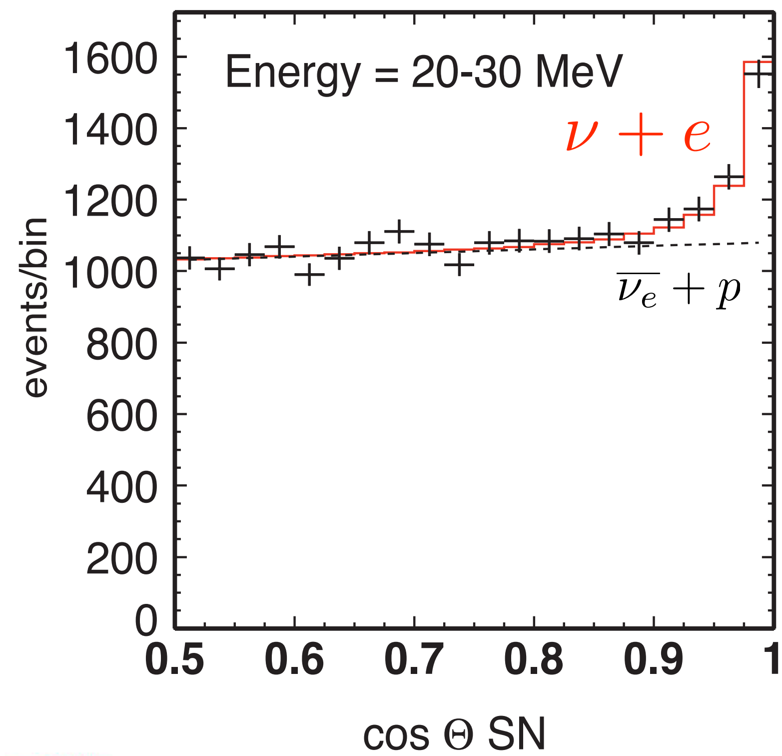
Enough Statistics to Distinguish SN Models

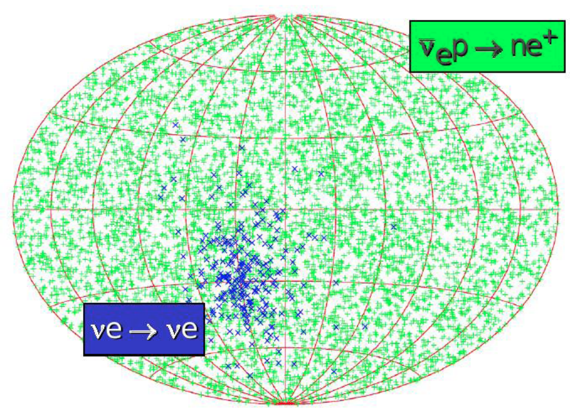




Directional Pointing



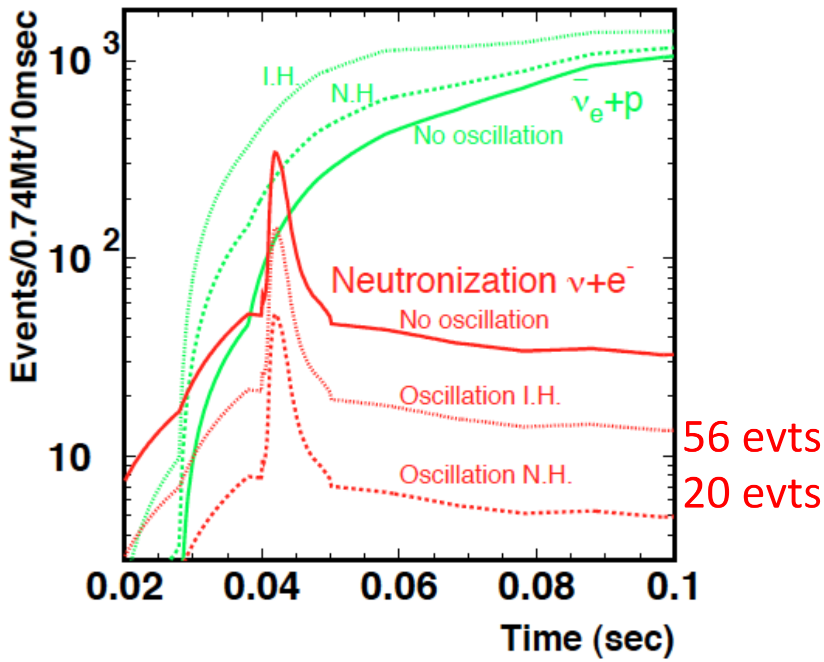




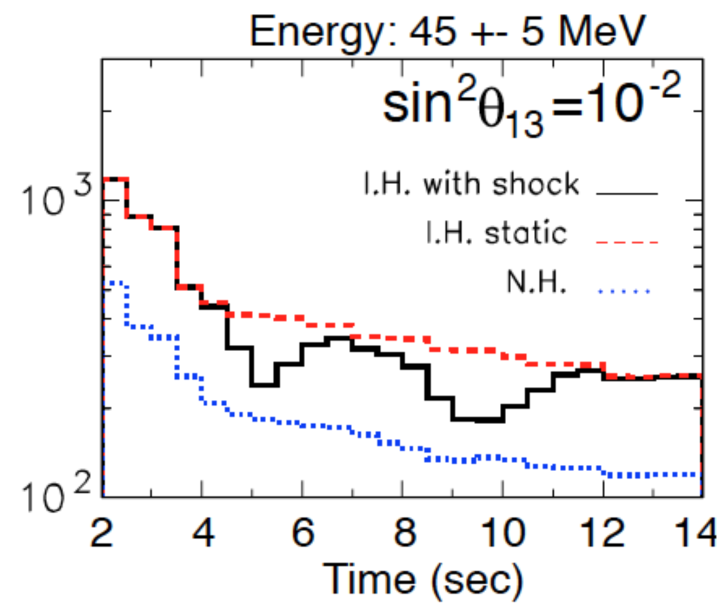
Accuracy of
1-2 degrees

Mass Hierarchy Determination

Neutrino – antineutrino matter resonance swaps with Normal – Inverted Hierarchy

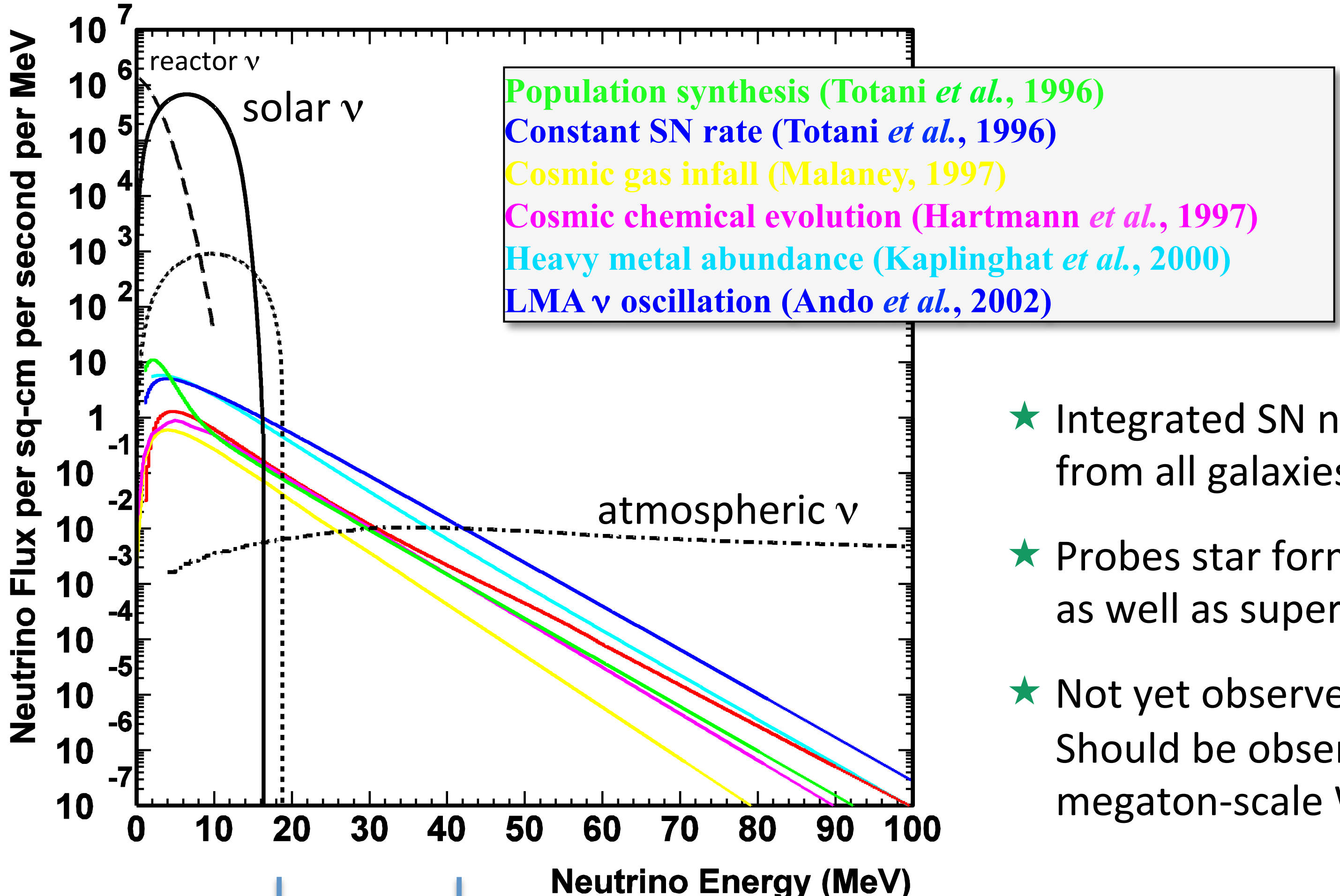


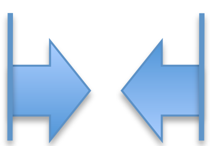
Size of neutronization burst may suggest hierarchy



Observation of shock wave in IBD events favors IH

(4) Diffuse Relic Supernova Neutrinos

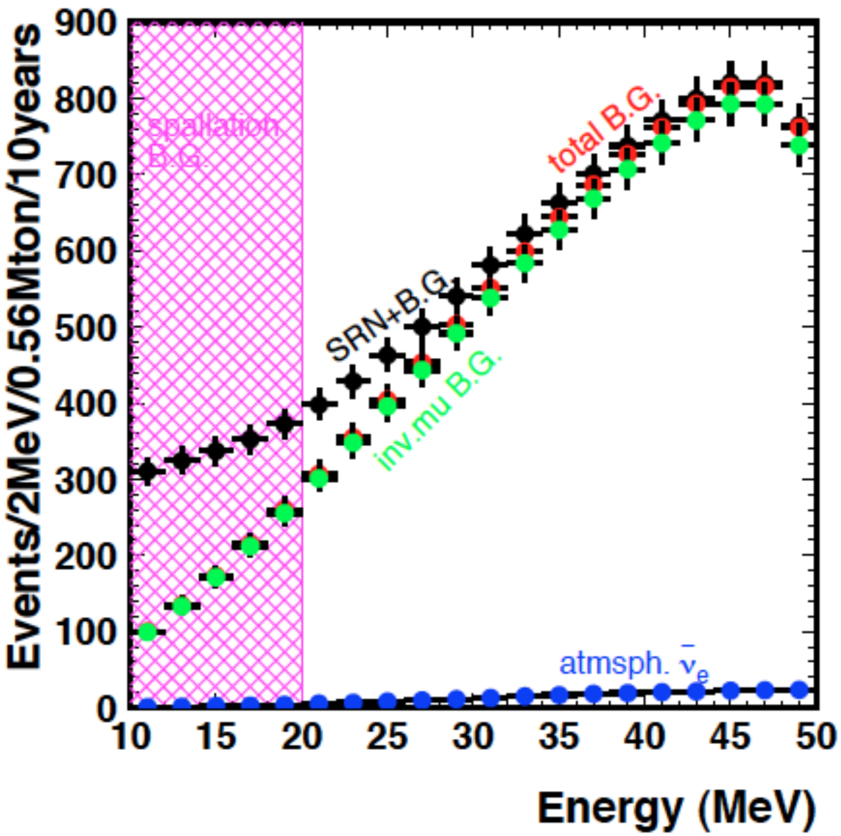


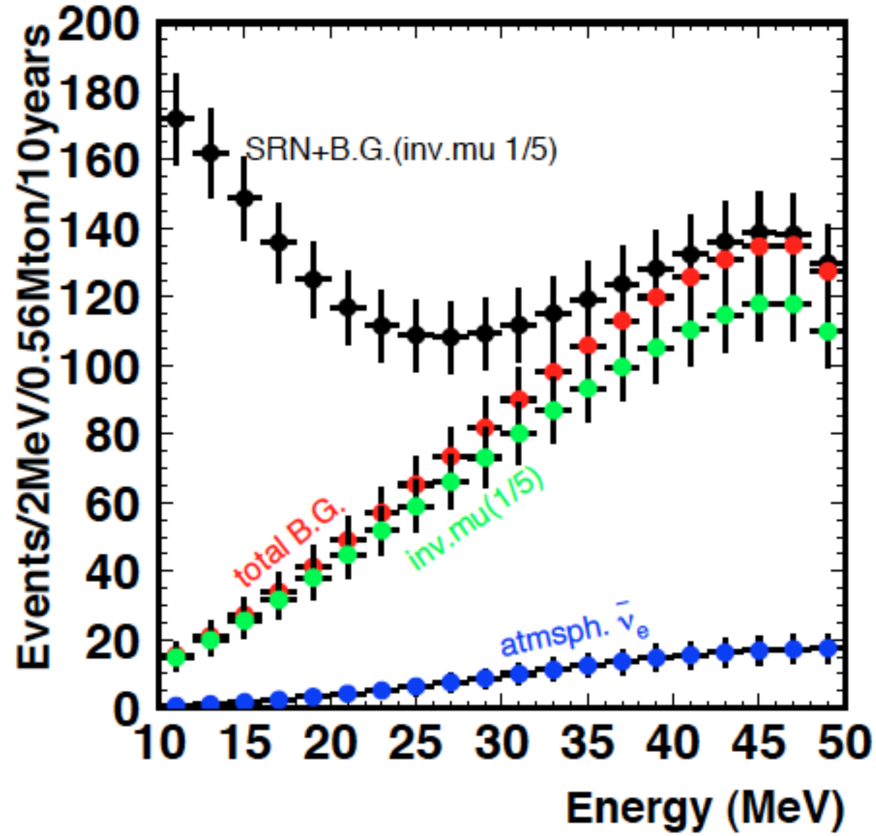


search in this energy range

- ★ Integrated SN neutrino flux from all galaxies (to z≈1)
- ★ Probes star formation models as well as supernova models.
- ★ Not yet observed! Should be observable by megaton-scale WC detector.

DRSN Event Rates (Hyper-K)





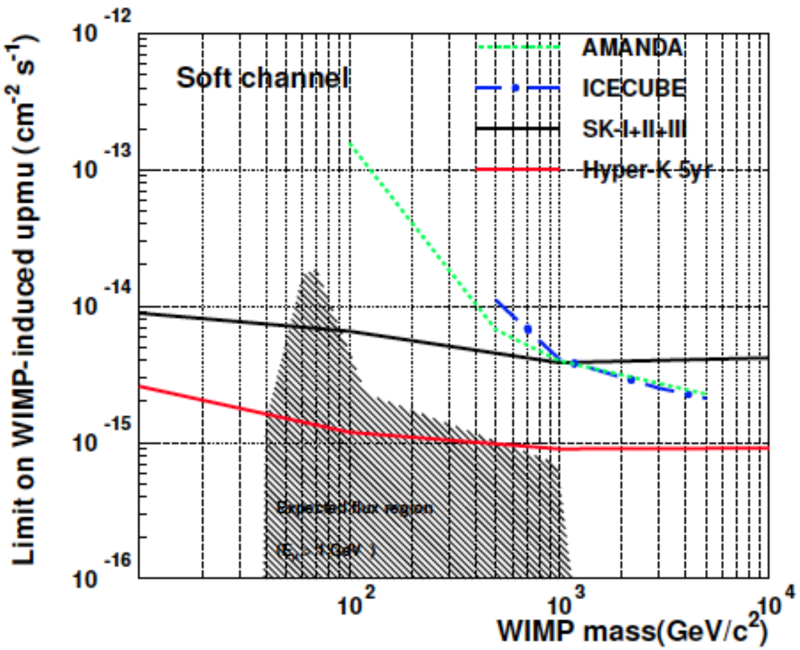
Remarkable improvement with Gd tagging of neutron. See A. Renshaw talk.

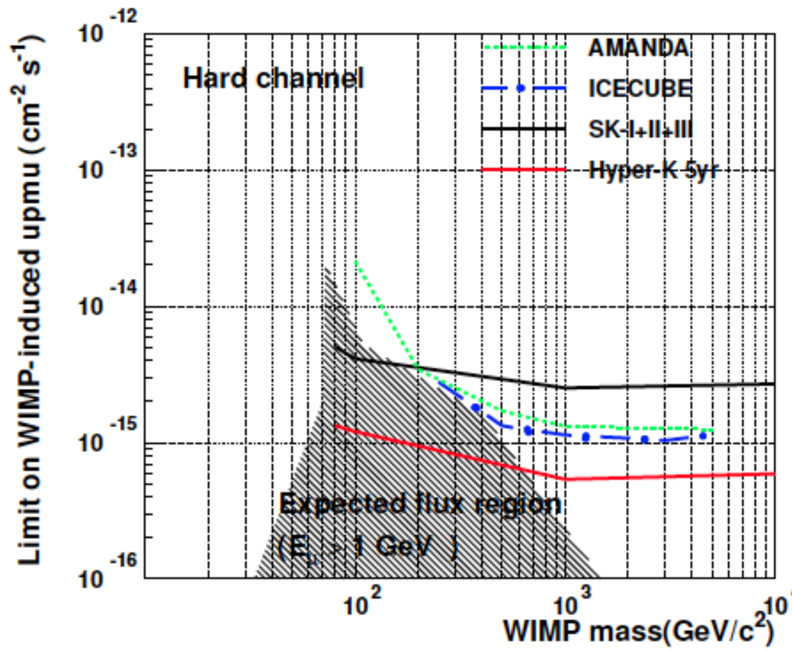
(6) Indirect Dark Matter

★ High energy neutrinos from dark matter decay or annihilation in the:

Sun
Earth
Galactic Center plus Halo

★ Competitive with colliders, nu telescopes and direct detection at low mass (10s of GeV)





Summary

1. Nucleon Decay
2. Long-Baseline Neutrino Oscillation
3. Supernova Neutrino Burst
4. Diffuse Relic Supernova Neutrinos
5. Atmospheric Neutrinos
6. Indirect Dark Matter Neutrinos
7. Solar Neutrinos

A broad physics program makes a compelling case for a next generation massive Water Cherenkov experiment.

In most cases, the physics opportunities are really complementary to that of a massive LArTPC.

But that's another talk …