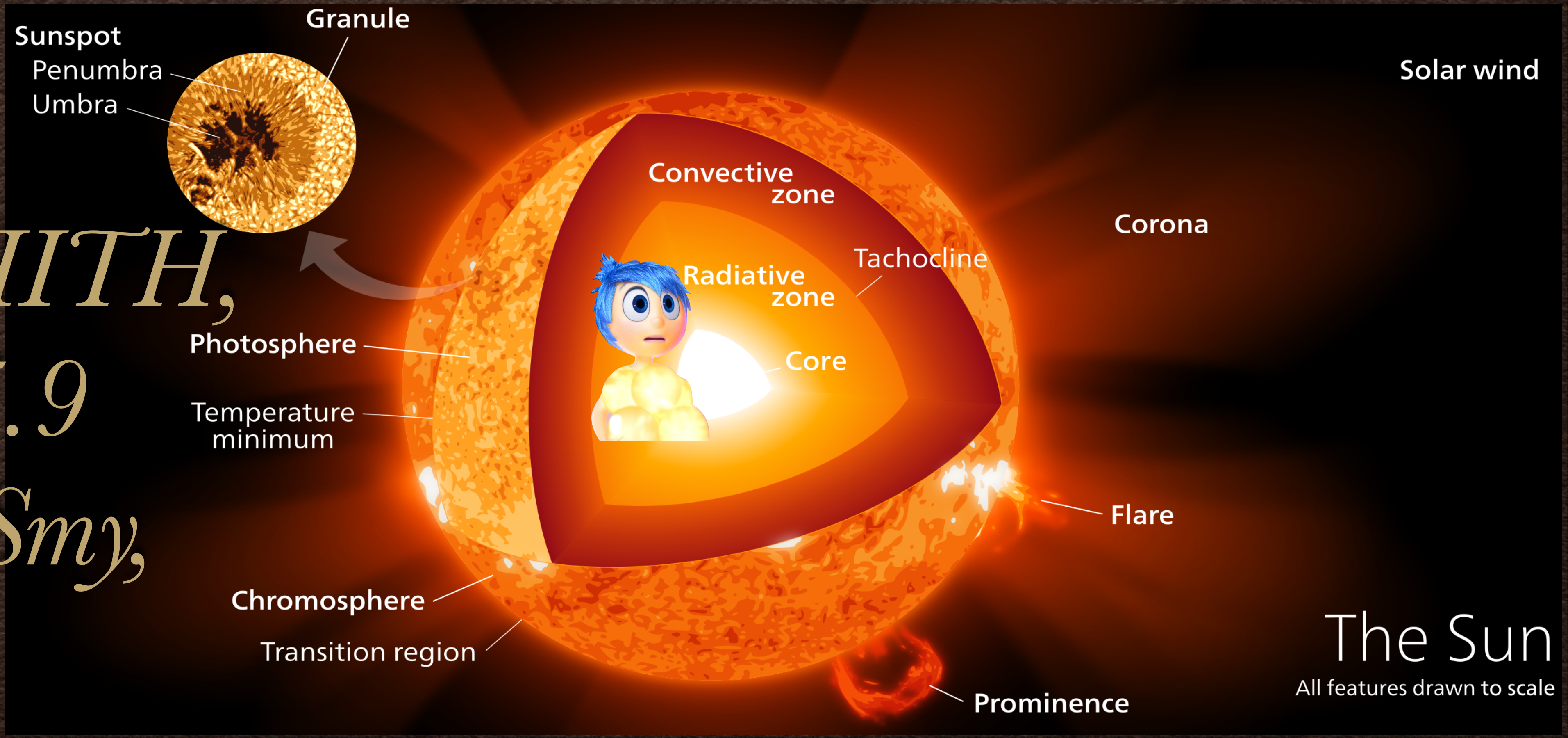
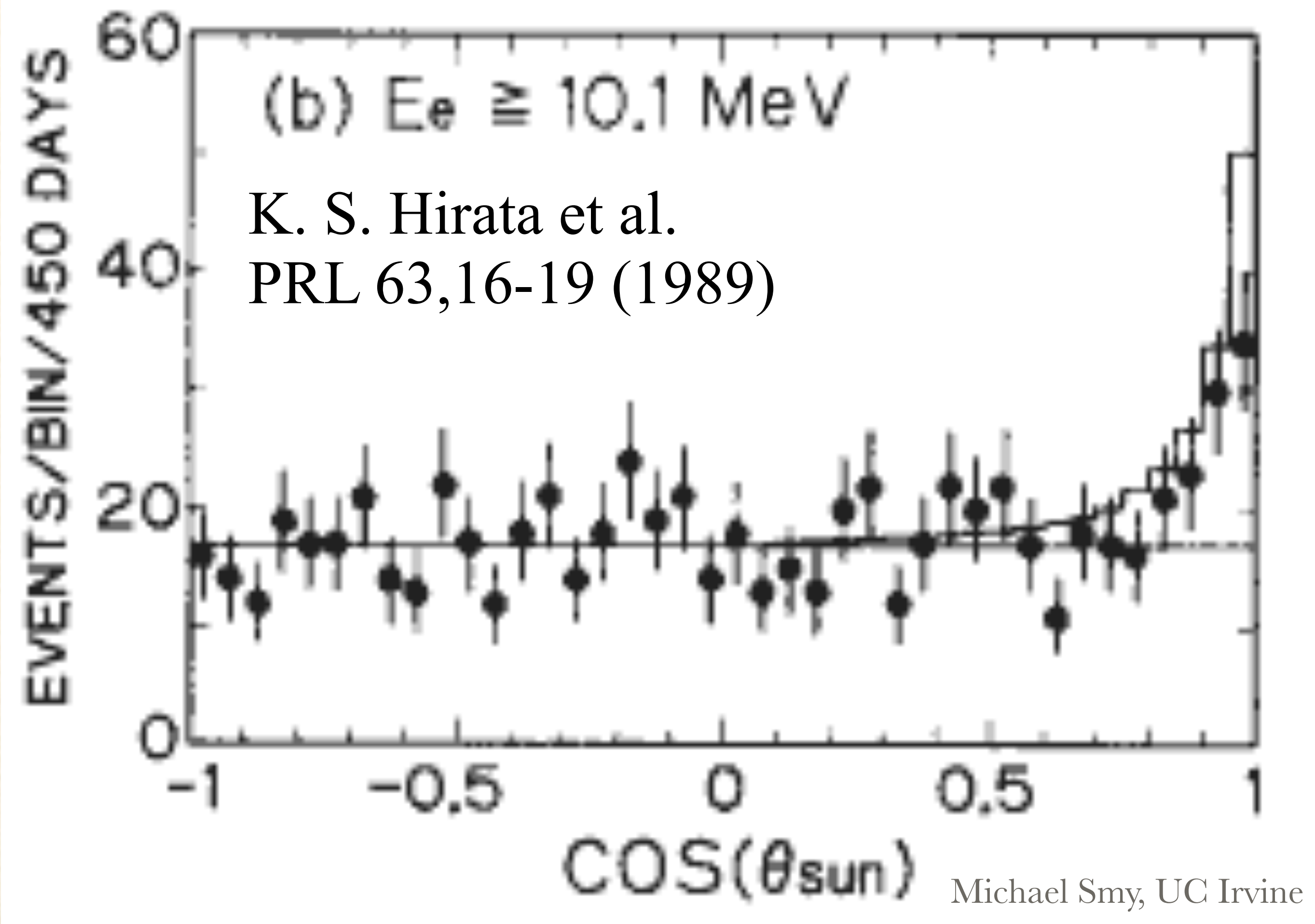
Stars and Matter Inside Out: Low Energy Neutrinos at Super-Kamiokande



Seminar at IITH, 2018.5.9
Michael Smy, UCI

1987: Birth of ν Astronomy

- Sanduleak -69⁰ 202 (dist. ~50kpc) turned supernova in 1987 and 24 ν interactions were observed within 13 seconds of each other: 11 by Kamiokande-II, 8 by IMB and 5 by Baksan (BNO)
- Kamiokande observed an excess of events in the solar direction due to solar neutrino-electron elastic scattering



Michael Smy, UC Irvine

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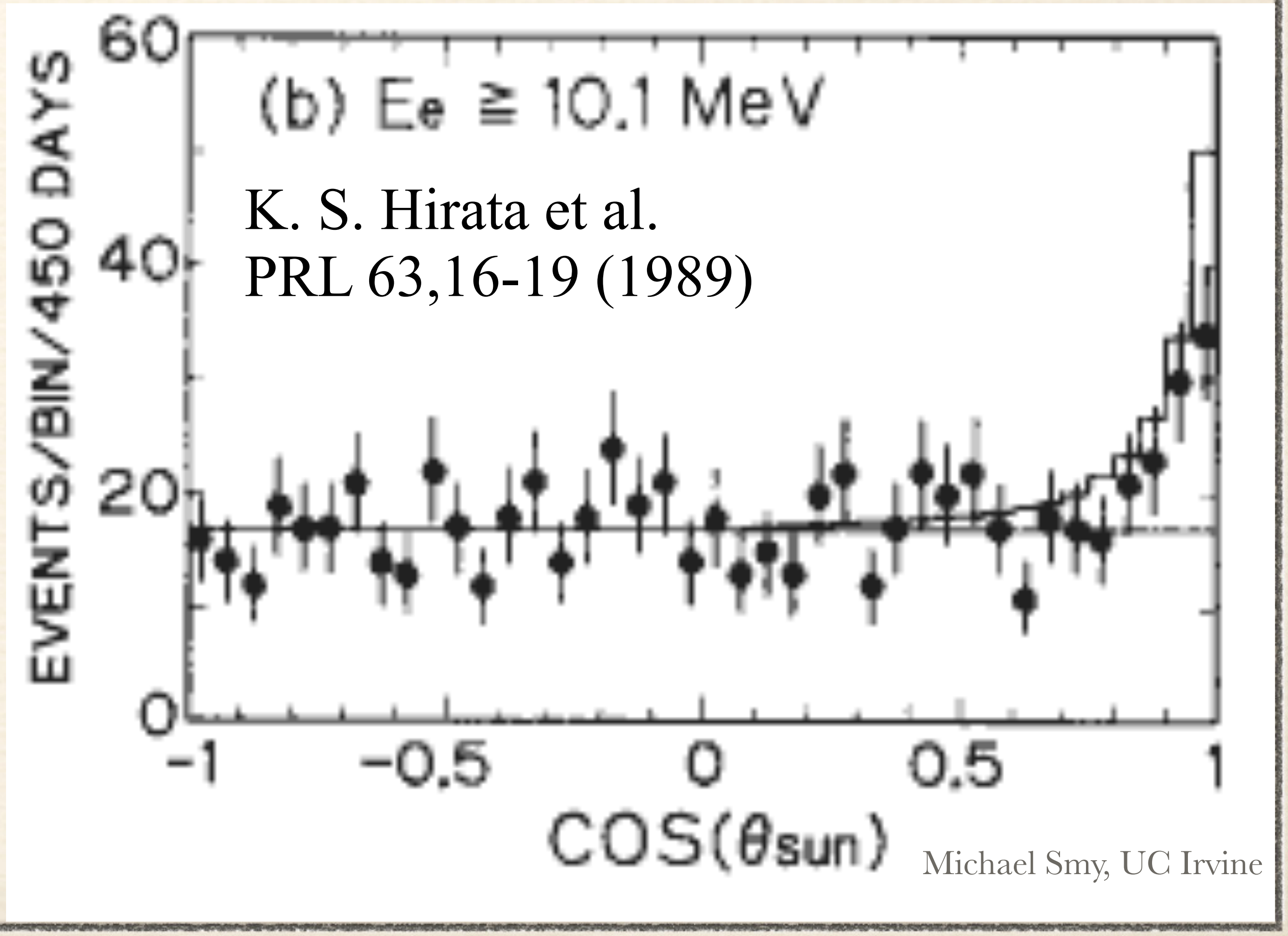
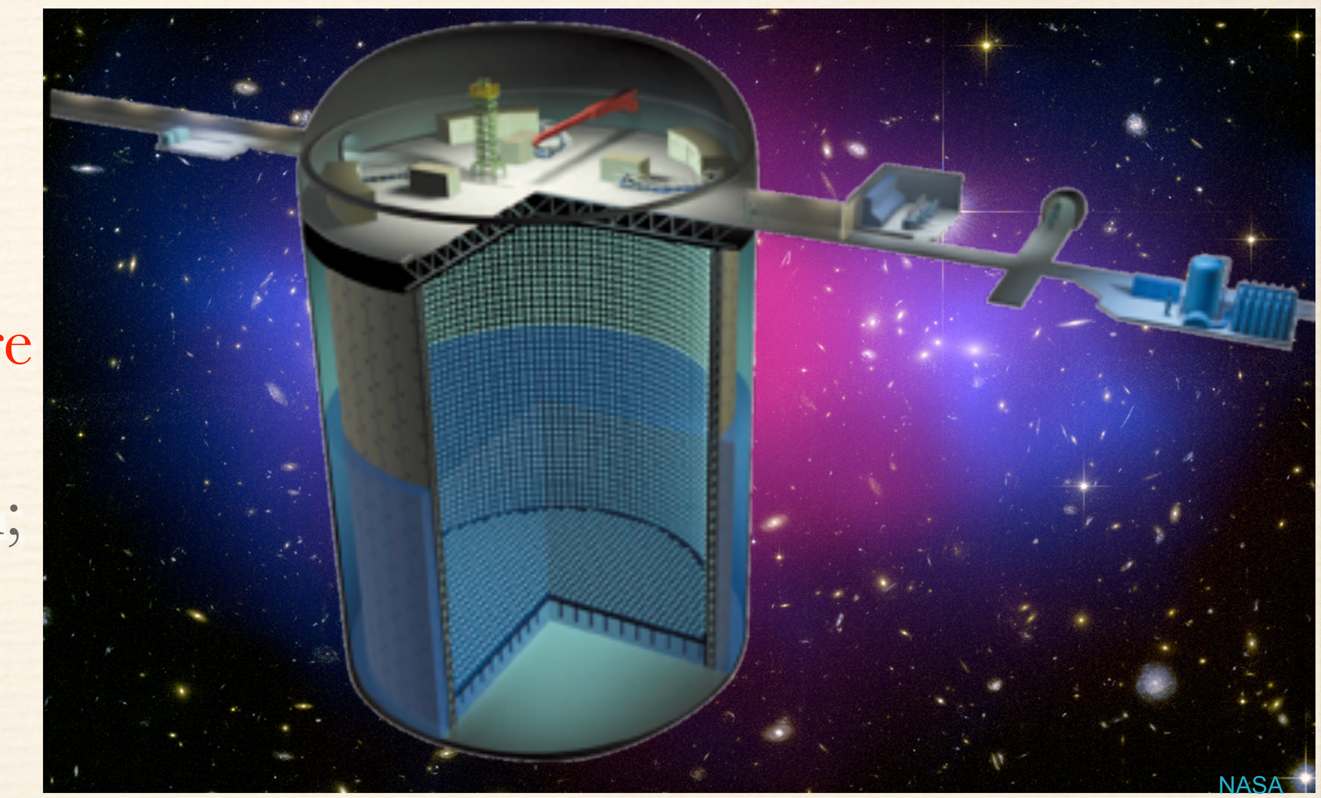


22 Years of Super-Kamiokande!

- 1998: discovery of atmospheric neutrino flavor transformation and neutrino mass
- 2000: solar mixing angle is large
- 2001: discovery of solar neutrino flavor transformation with SNO; uniquely measure oscillation parameters (with all solar data)
- 2004: discovery of atmospheric ν oscillation; confirmation from K2K with ν_μ beam
- 2011: first indication of positive θ_{13} from T2K with ν_μ neutrino beam
- 2012: first evidence for τ appearance
- 2013: first direct indication of matter effects on ν oscillations (solar ν day/night effect)
- 2013: first observation of $\nu_\mu \rightarrow \nu_e$ appearance
- 2017: first hint of CP violation in ν oscillations

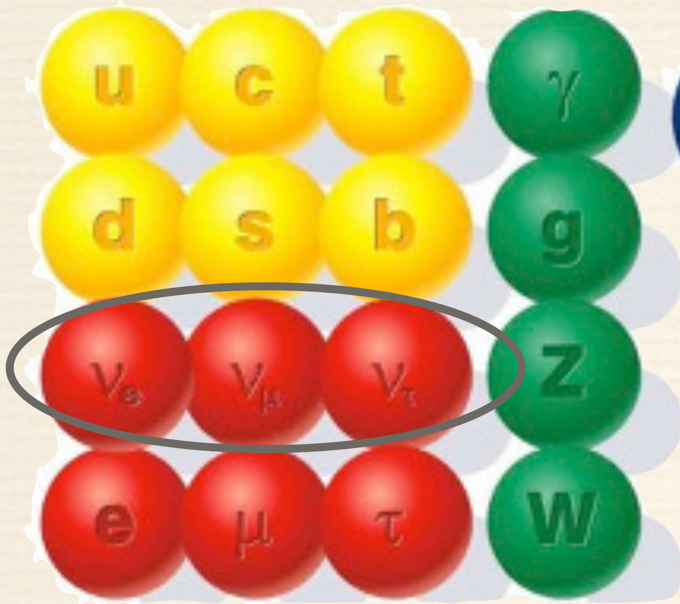


- 50,000 ton water Cherenkov detector
  - ID: 32,000 tons (FV 22,500 tons); 11,129 PMTs (SK-I 11,146 PMTs)
  - OD: 18,000 tons; 1,885 PMTs

layout by Y. Suzuki, ICRR (Michael Smy, UC Irvine)

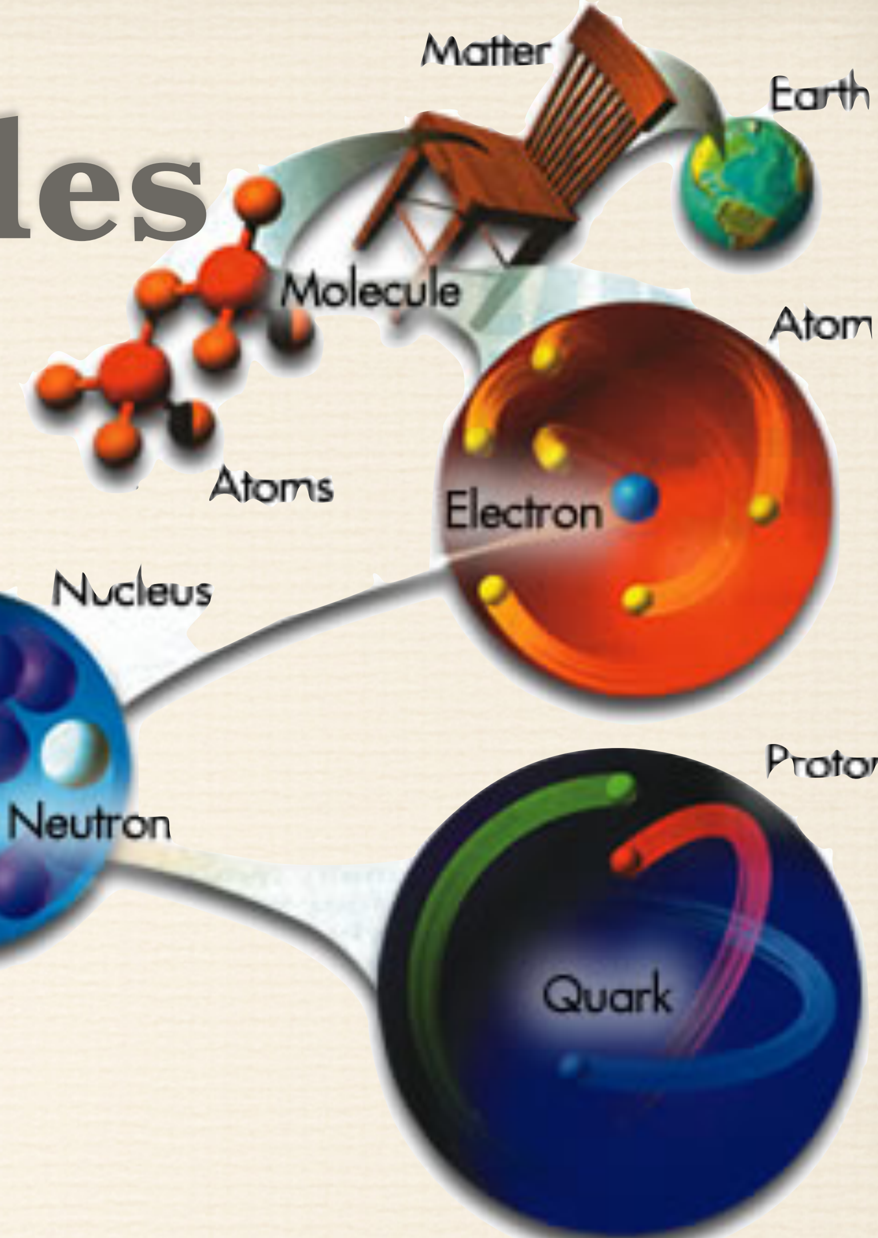
Fundamental Particles

Modern "Periodic Table"



Higgs boson gives mass to other particles

- quarks
- leptons
- force carriers



Forces

- γ: electromagnetic force holds atoms and molecules together
- g: strong force binds quarks into protons/neutrons, nucleons into nuclei
- W: weak force changes leptons (quarks) into other leptons (quarks)
- Z: weak force interactions without affecting lepton/quark "type"
- (gravity holds solar system and galaxy together)

Michael Smy, UC Irvine

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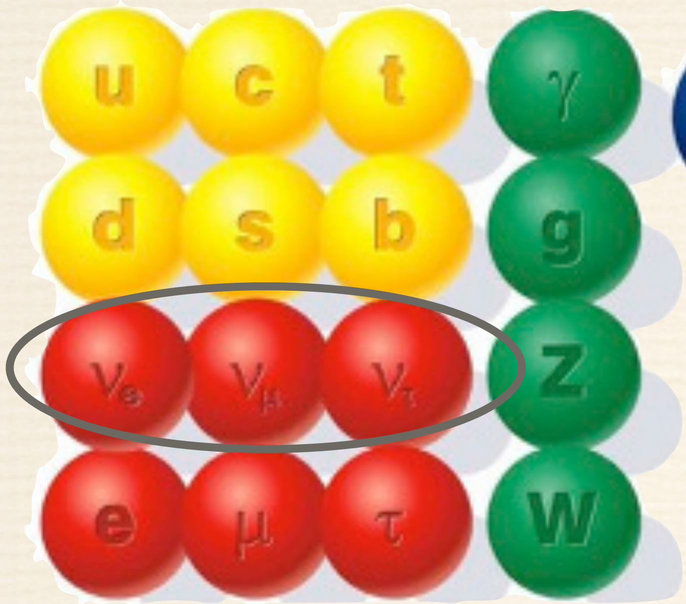

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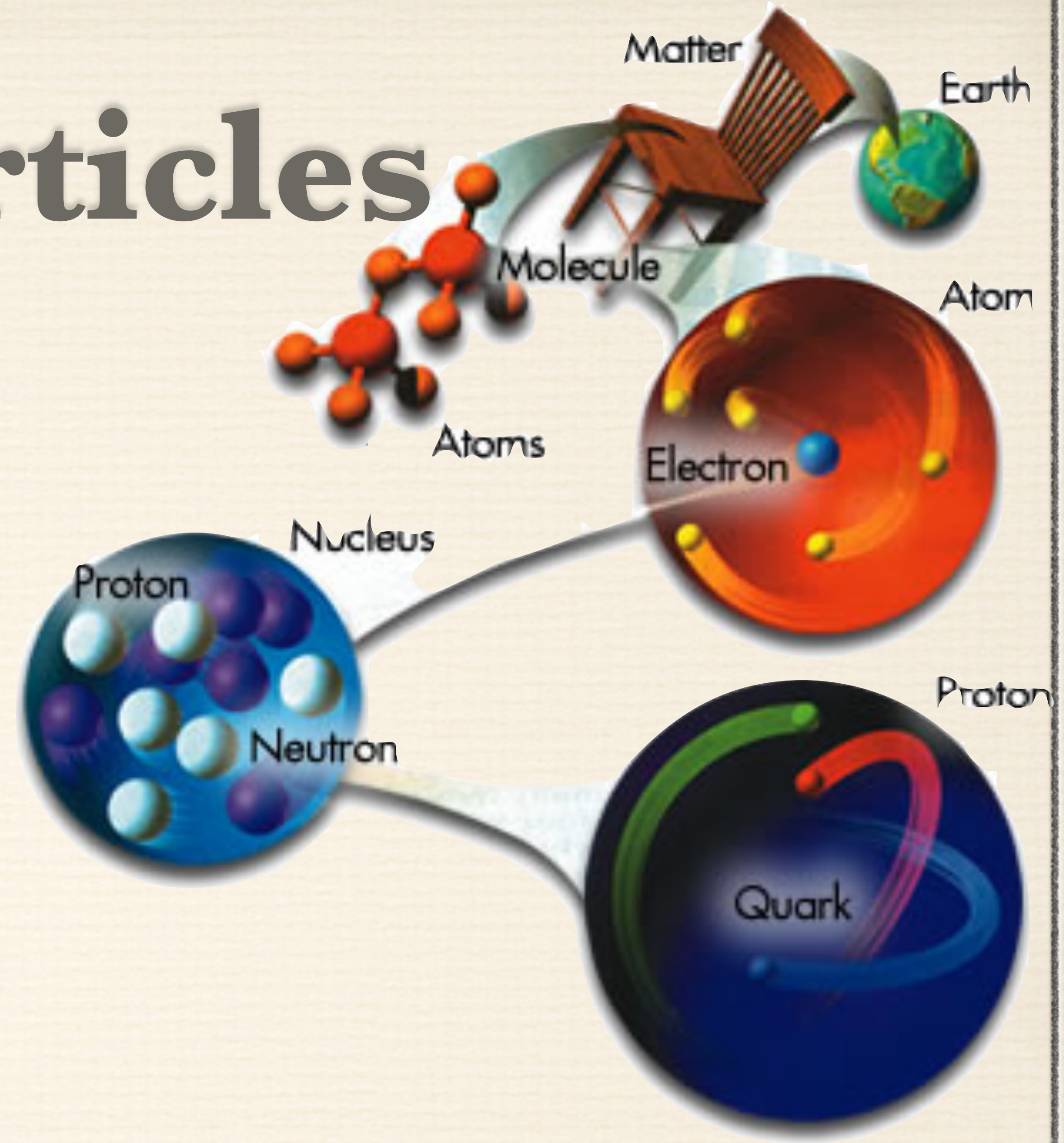


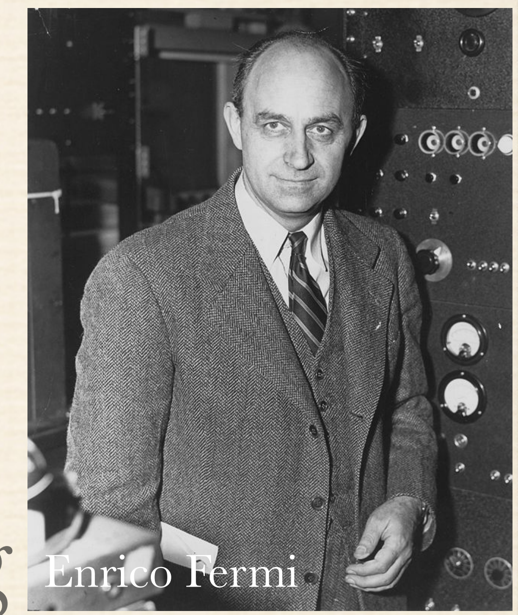
Forces required to make the stars shine:

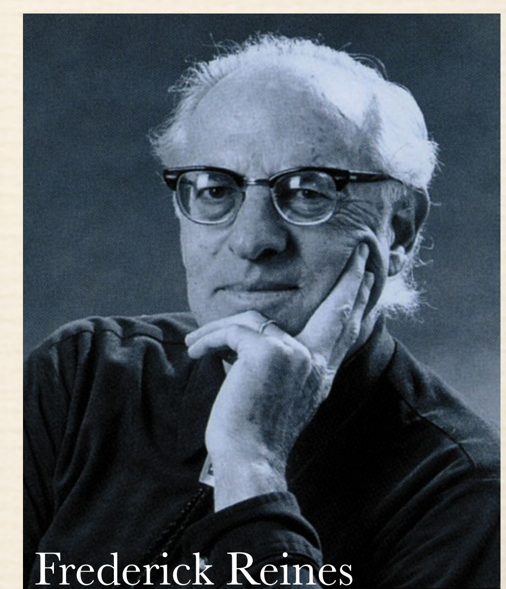
- γ: transports energy from stellar nuclear fusion
- g: strong force fuses light nuclei into heavier ones in stars releasing energy
- W: weak force produces neutrons from protons in stars
- gravity confines stellar plasma

Neutrinos

- invented in 1930 as electrically neutral fundamental particles to rescue conservation of energy in nuclear β decay
- interactions described in 1933
- discovered in 1956
- weak interactions (W's) may change "left-handed" leptons $e^-/\mu^-/\tau^-$ into corresponding neutrino states ($\nu_e/\nu_\mu/\nu_\tau$) and vice versa
- neutrinos also scatter of quarks and leptons by "neutral current" weak interactions (Z's) independent of the type ("flavor")

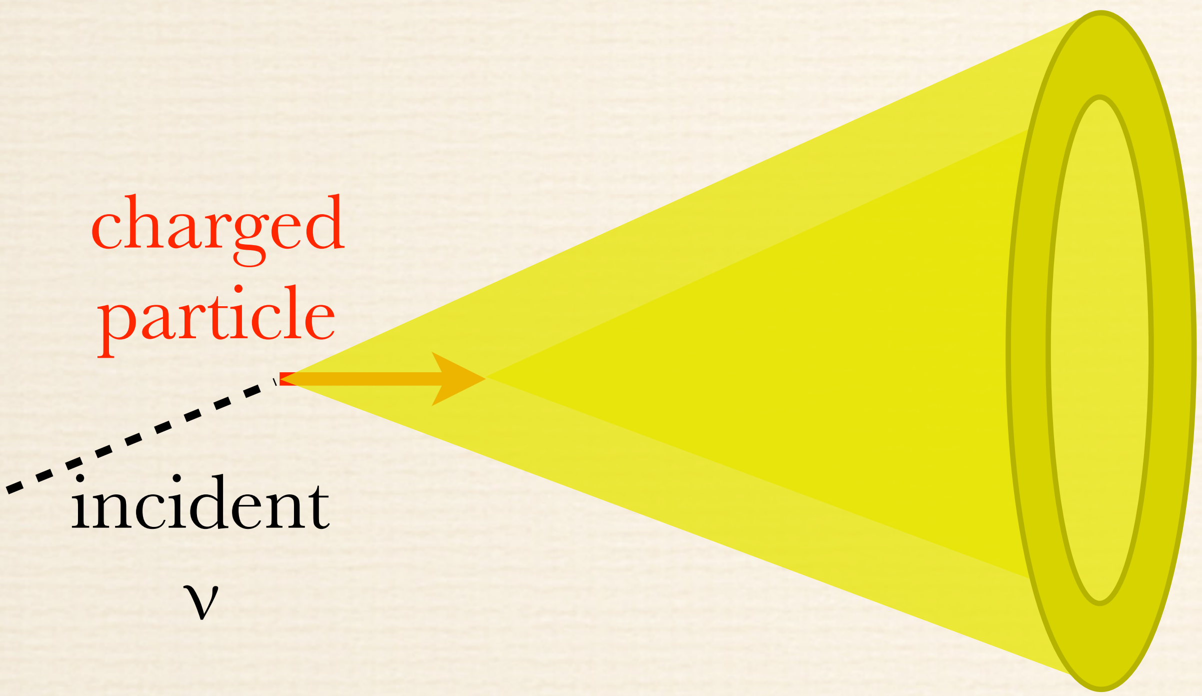

Wolfgang Pauli

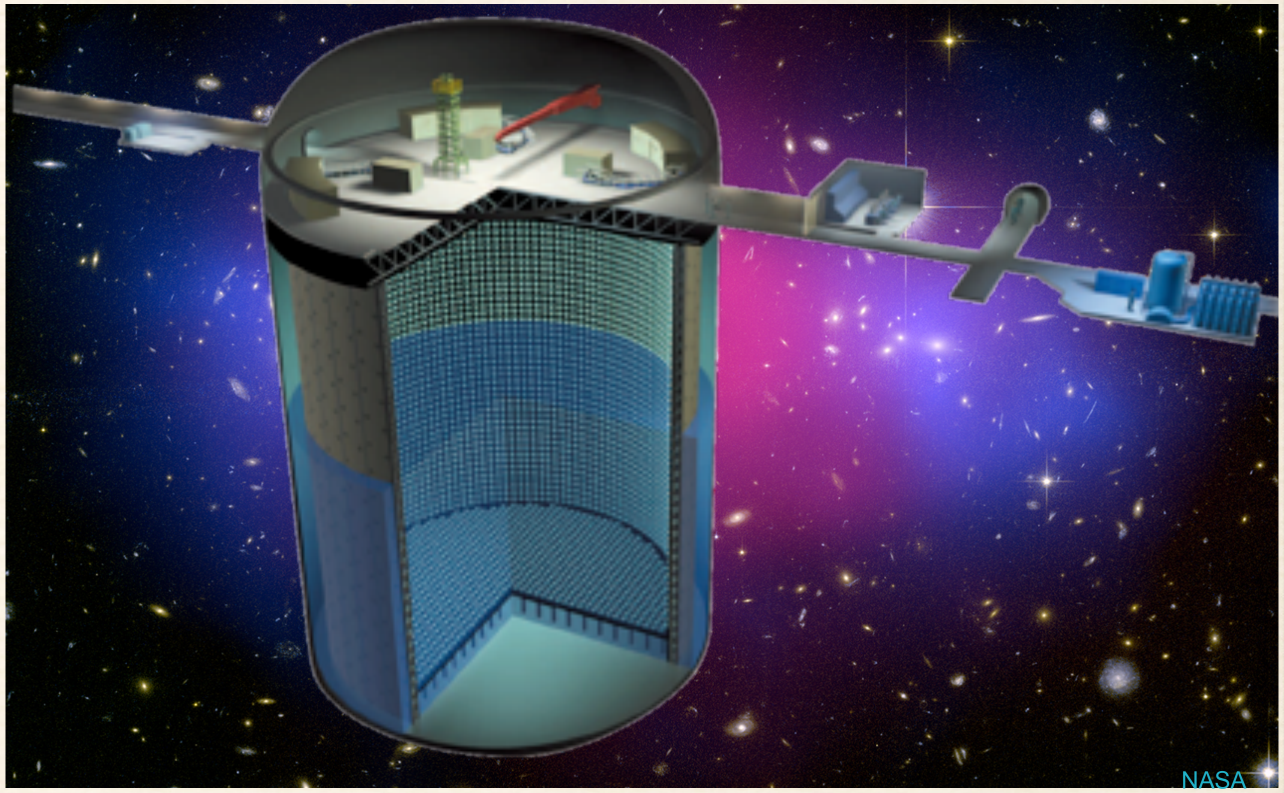

Enrico Fermi


Frederick Reines

Neutrinos in Cherenkov Detectors

- Cherenkov-Det.: transparent medium surrounded by light sensors
- neutrinos produce charged particles moving faster than the speed of light in the medium (e.g. water)



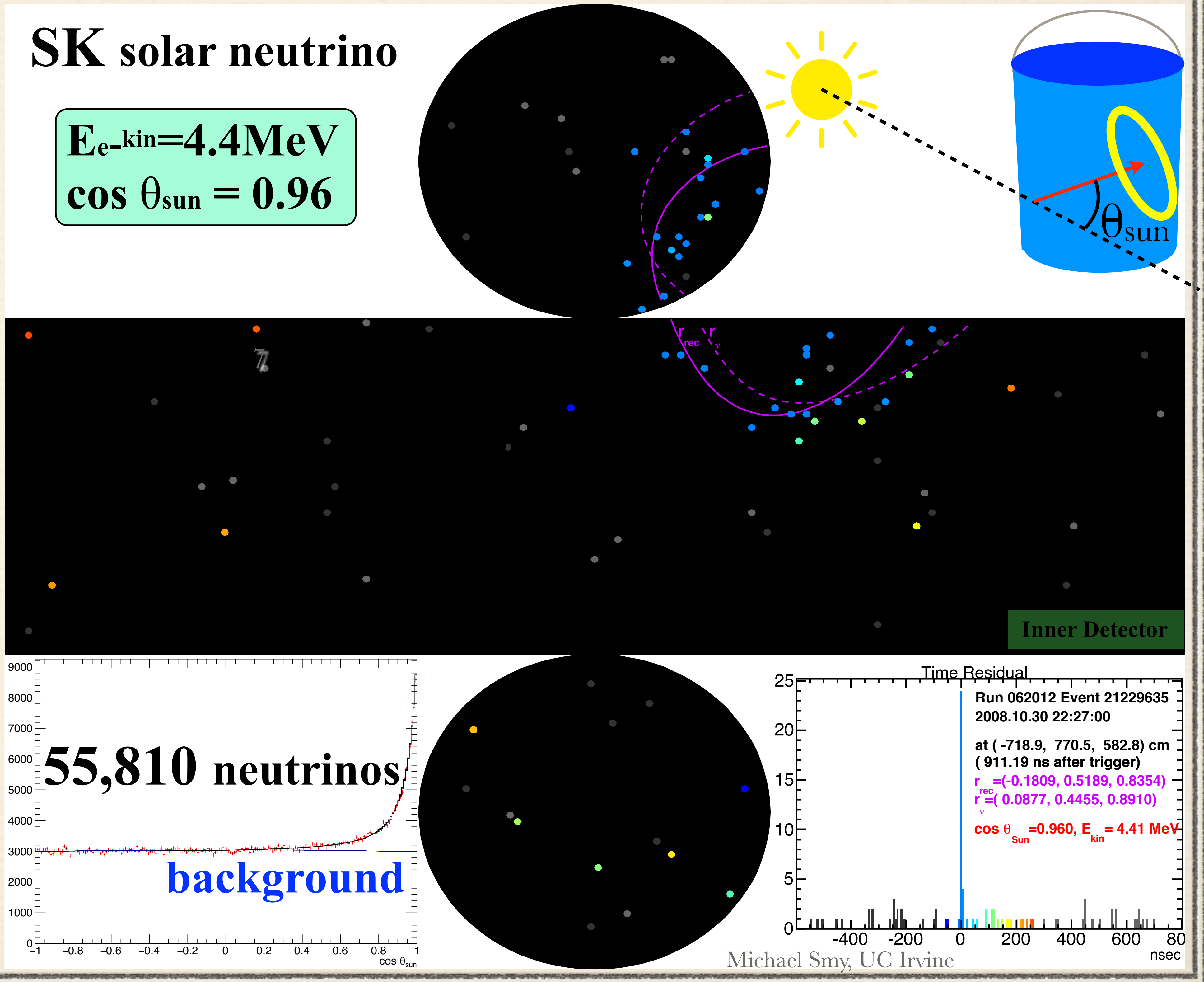


- charged particles emit Cherenkov light in a cone
- light sensors record time and intensity of the Cherenkov light
- reconstruct track(s) of charged particle(s) from timing & intensity

Michael Smy, UC Irvine

Solar Neutrinos in Super-K: Recoil e⁻ from Elastic Scattering

- PMT timing ➛ location of interaction: **~60cm error**
- hit pattern ➛ particle direction: **~30⁰ error**
- brightness ➛ energy: **14% @ 10 MeV error** (≈6 hits/MeV above threshold)



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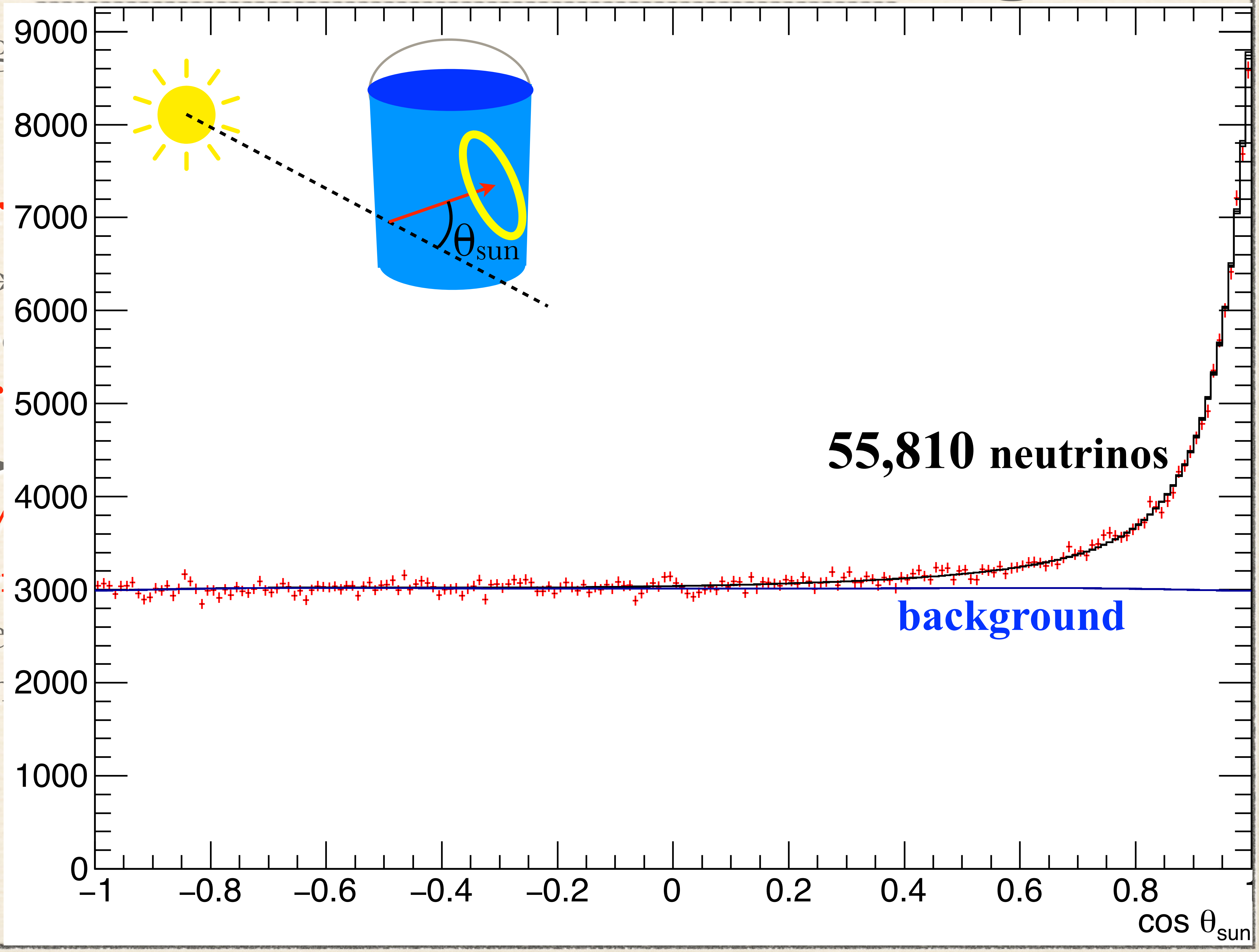
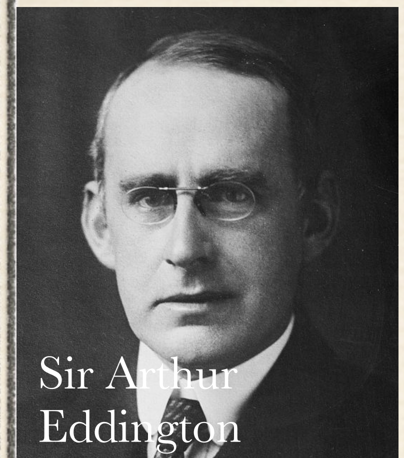
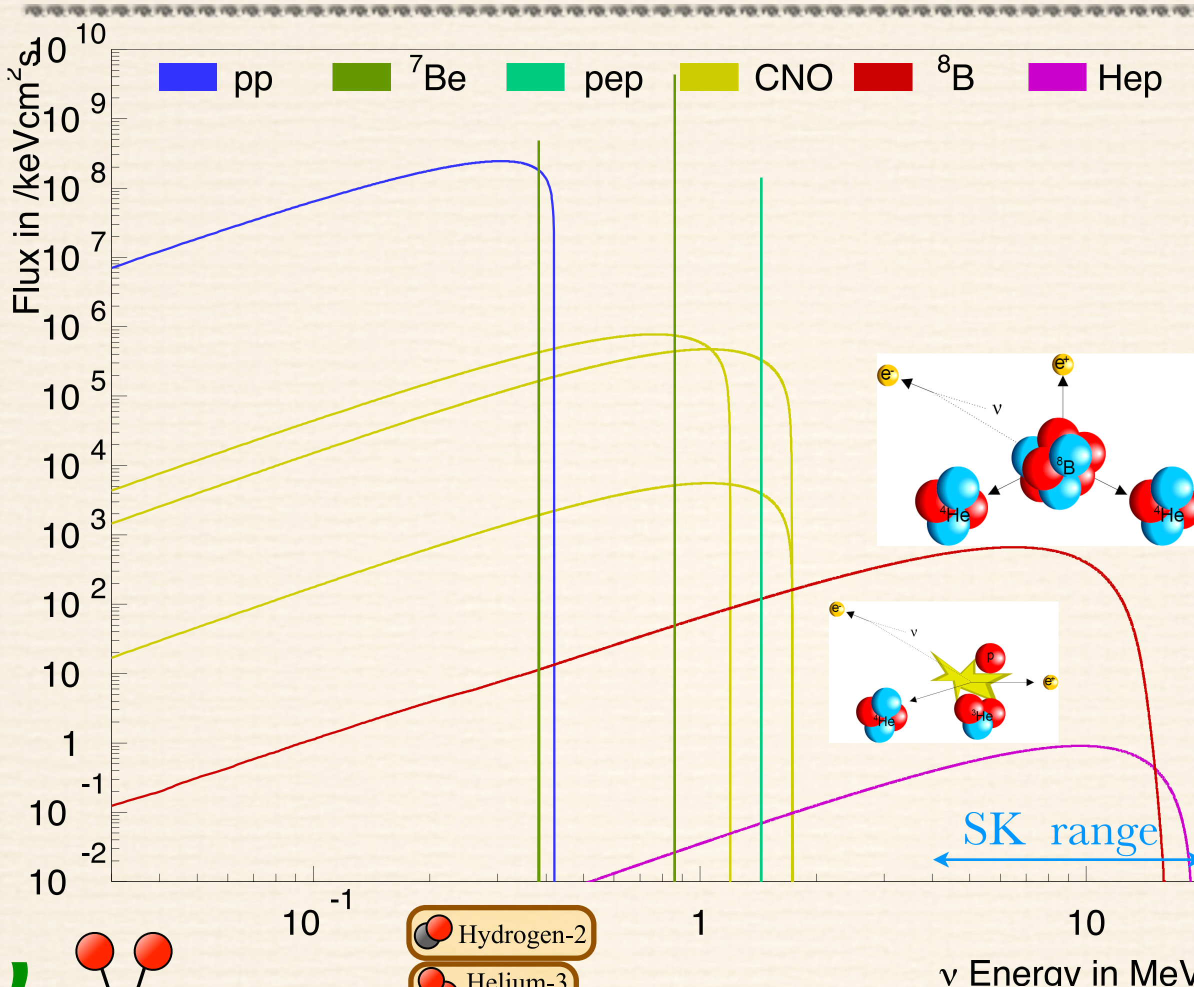
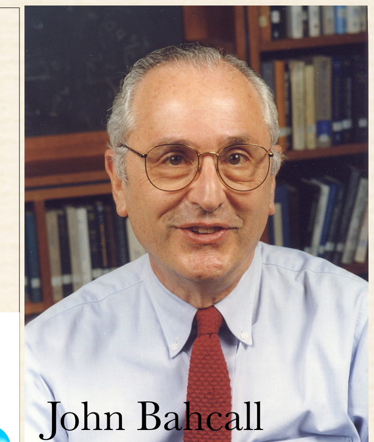
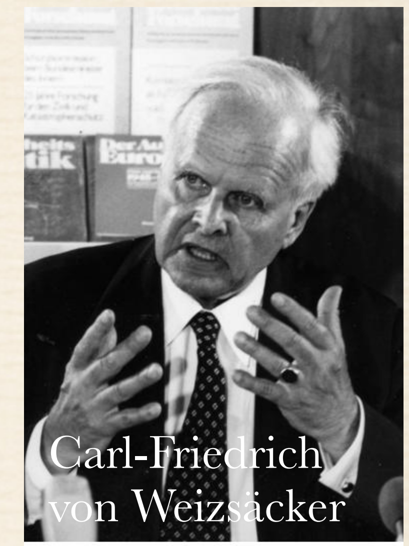


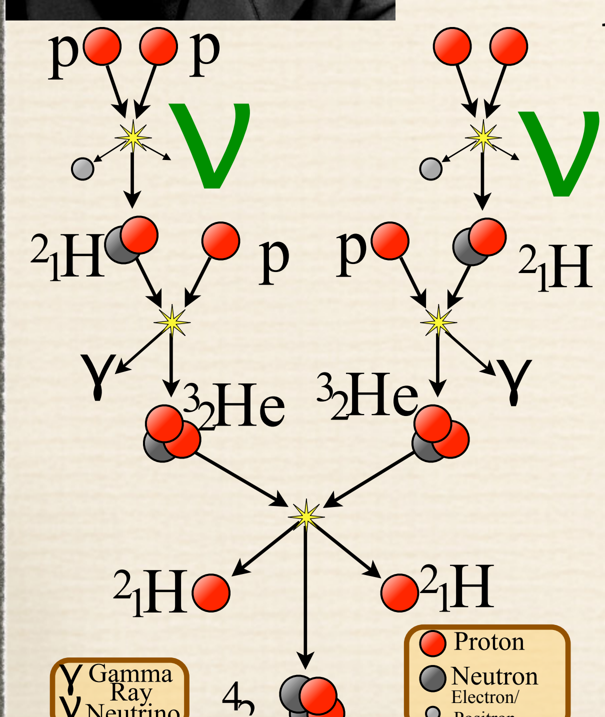
Stellar Fusion and Neutrinos

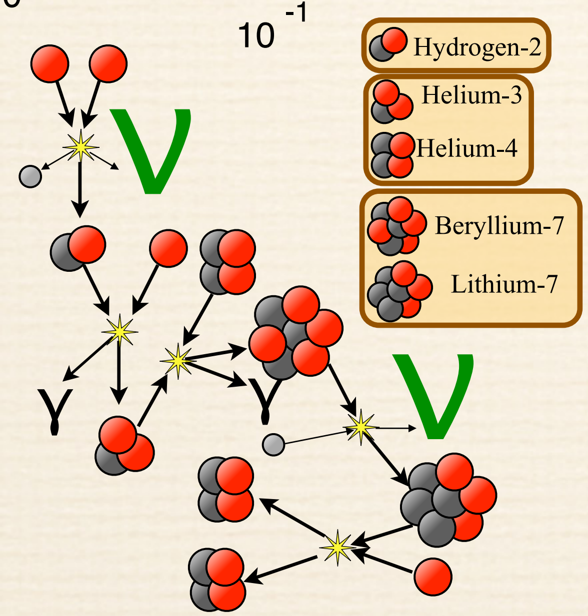




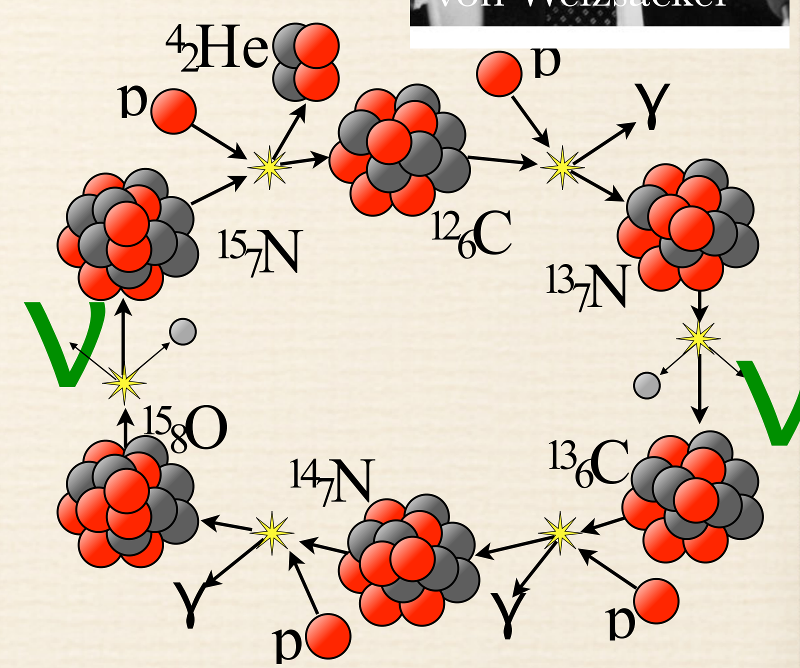








$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$



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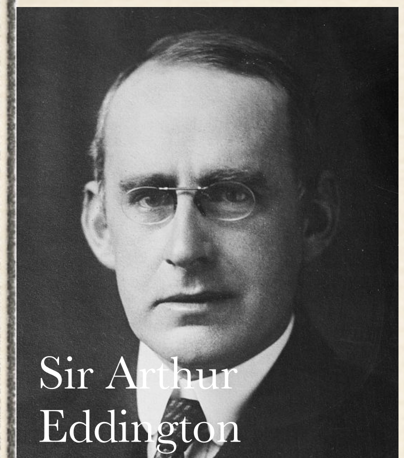
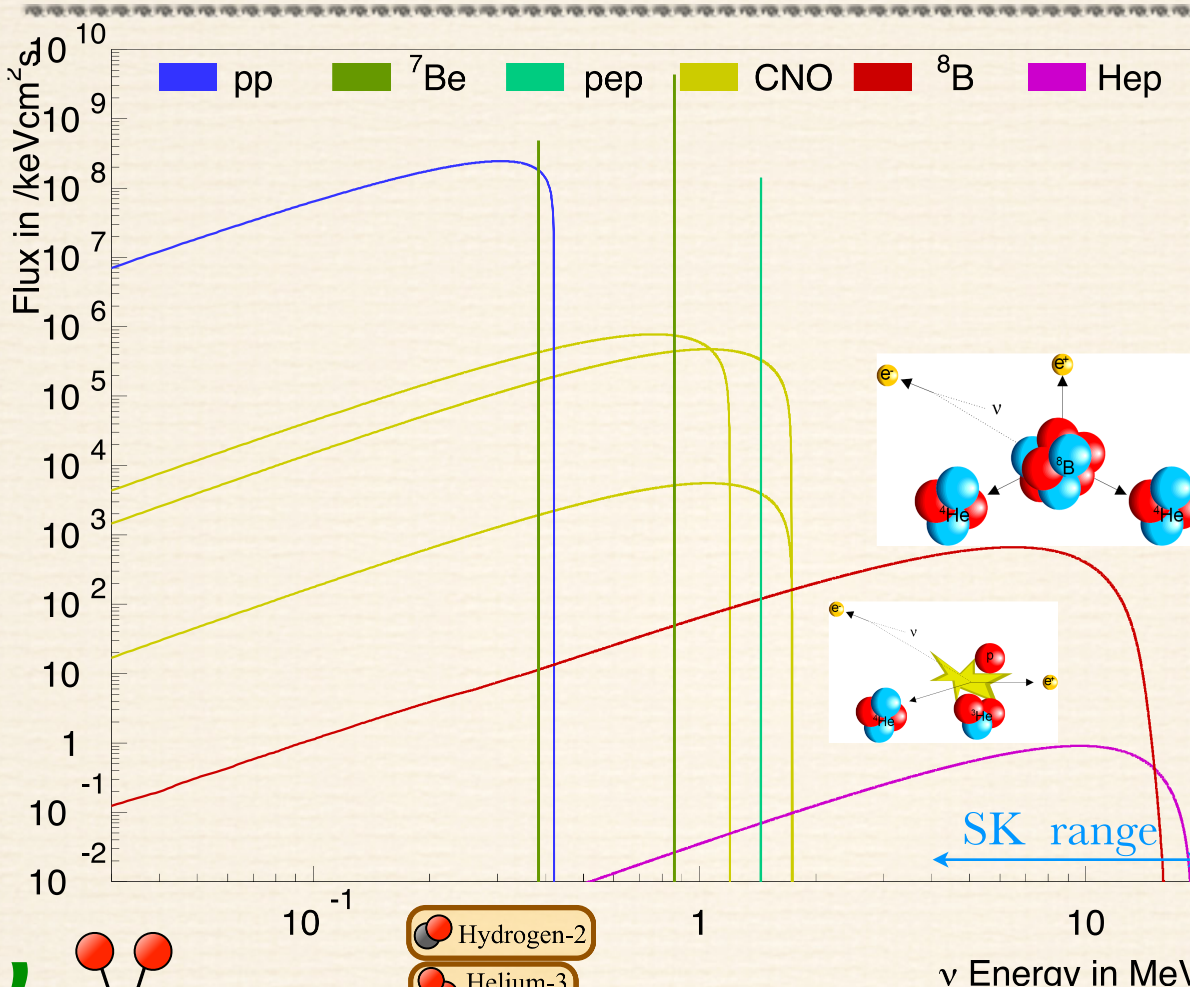
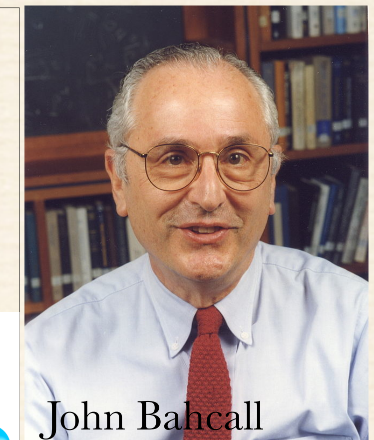
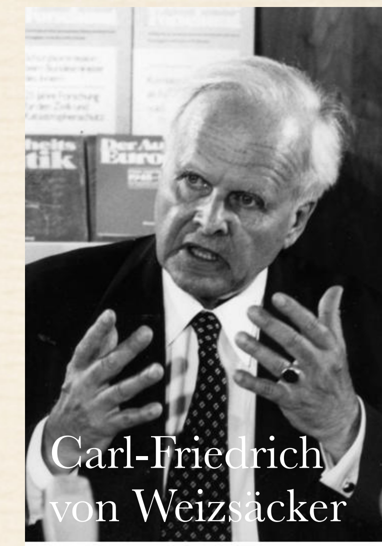
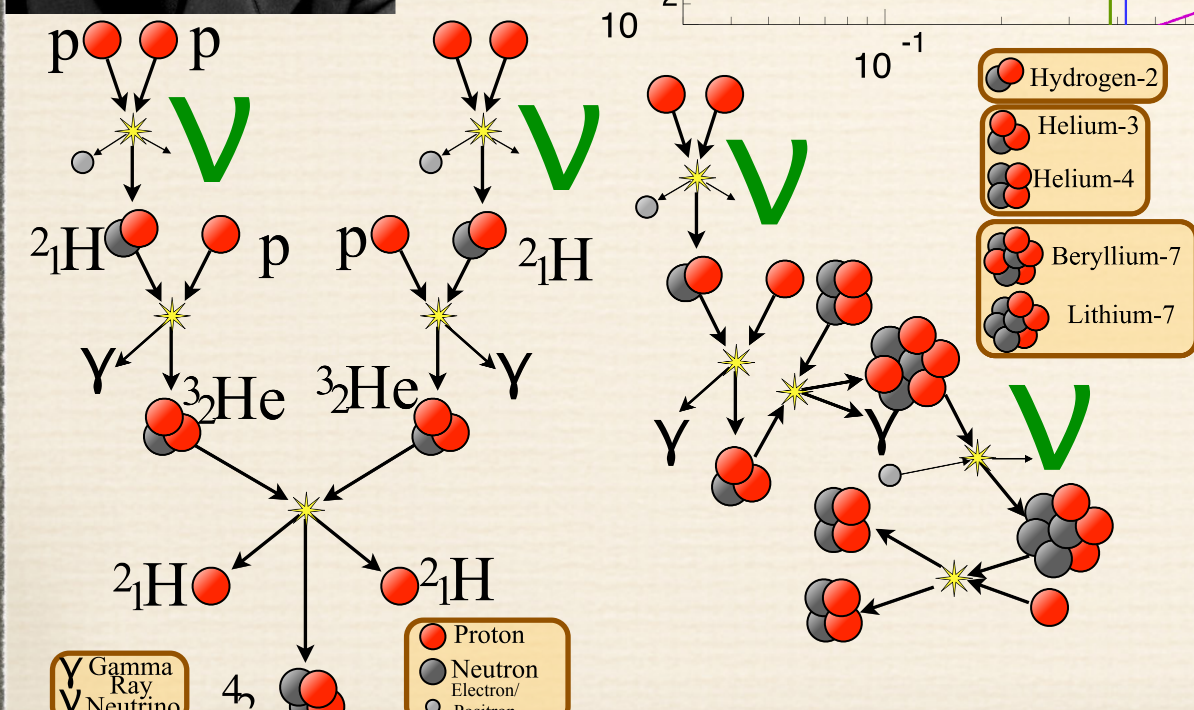
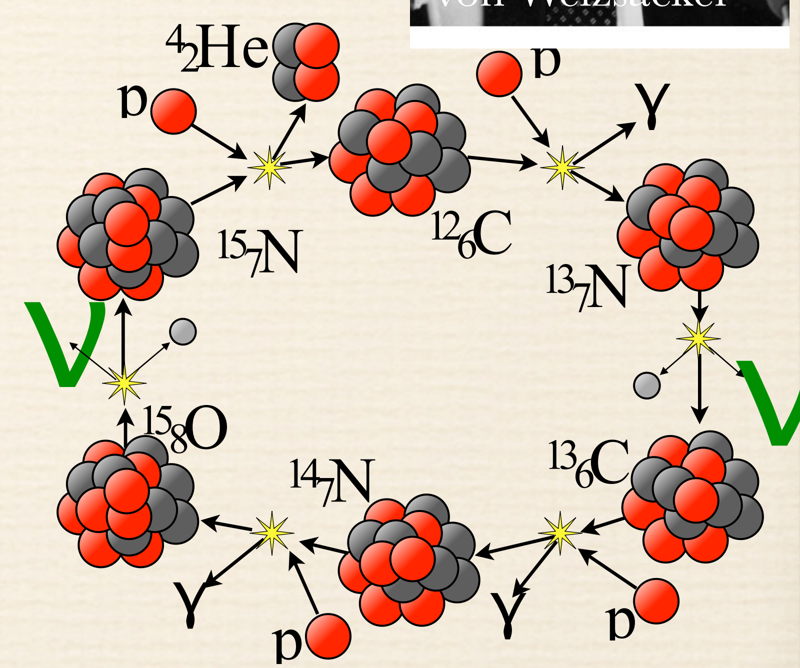








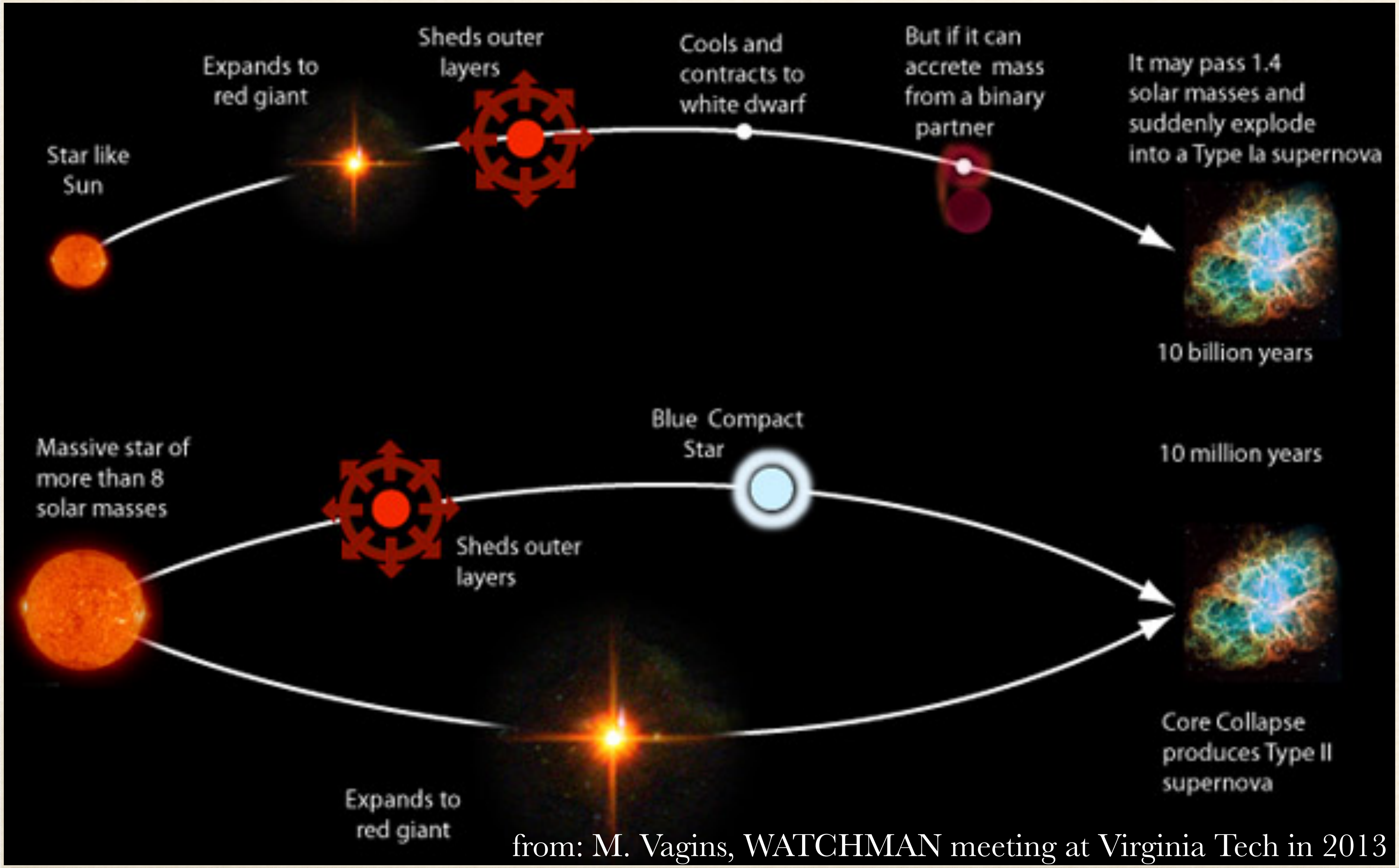




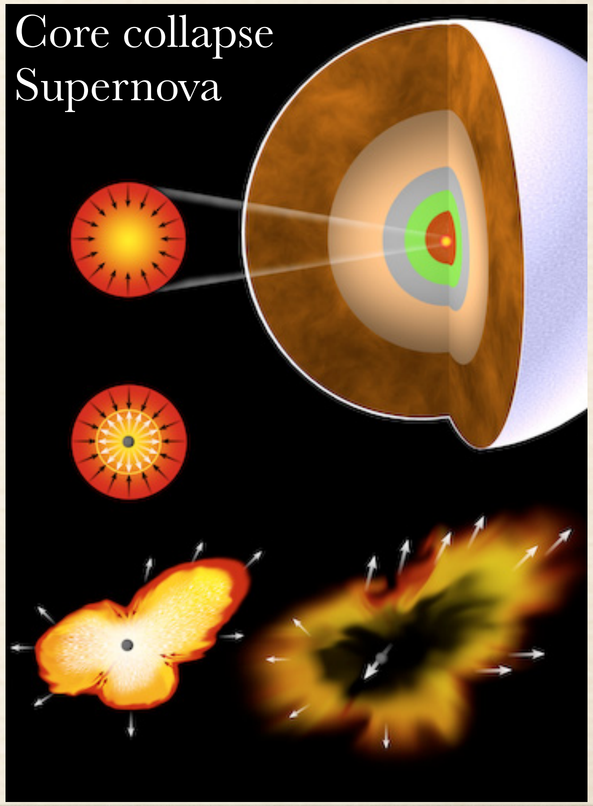
$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$

Supernova Explosions

- origin of heavy elements >He (or stars would just keep theirs)
- production of elements heavier than Fe (also: n star mergers)
- very energetic, interesting events: core collapse supernovae release about three sextillion Yottawatts for ~10 seconds!

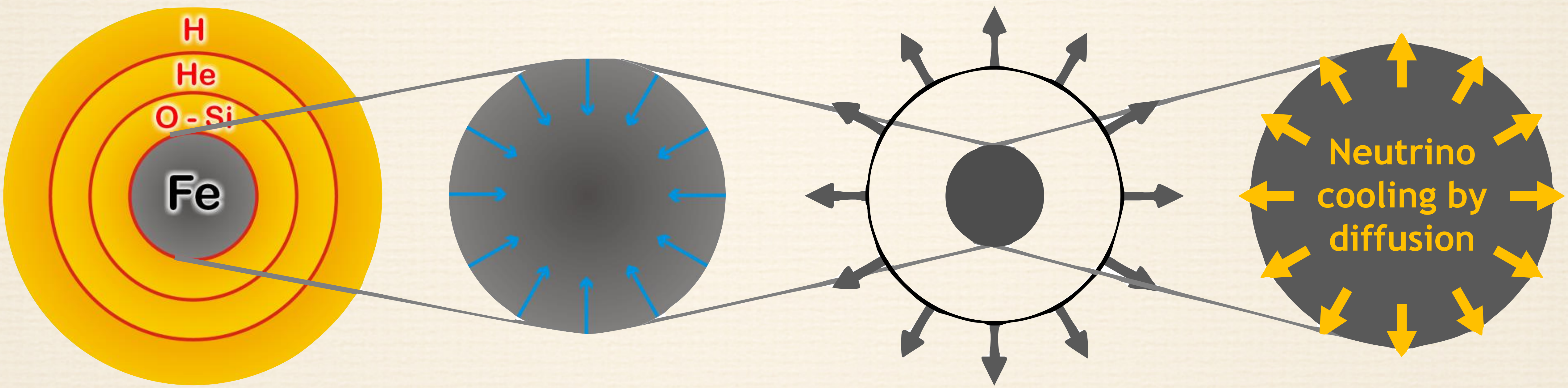


from: M. Vagins, WATCHMAN meeting at Virginia Tech in 2013



Core-Collapse Supernova Explosion: The ν Bomb!

End state of a massive star $M \gtrsim 6\text{–}8\ M_\odot$	Collapse of degenerate core	Bounce at ρ_{nuc} Shock wave forms explodes the star	Grav. binding E $\sim 3 \times 10^{53}$ erg emitted as nus of all flavors



- ~99% of energy released into neutrinos
- ~0.01% goes into light emission!
- must understand neutrinos to understand these events!

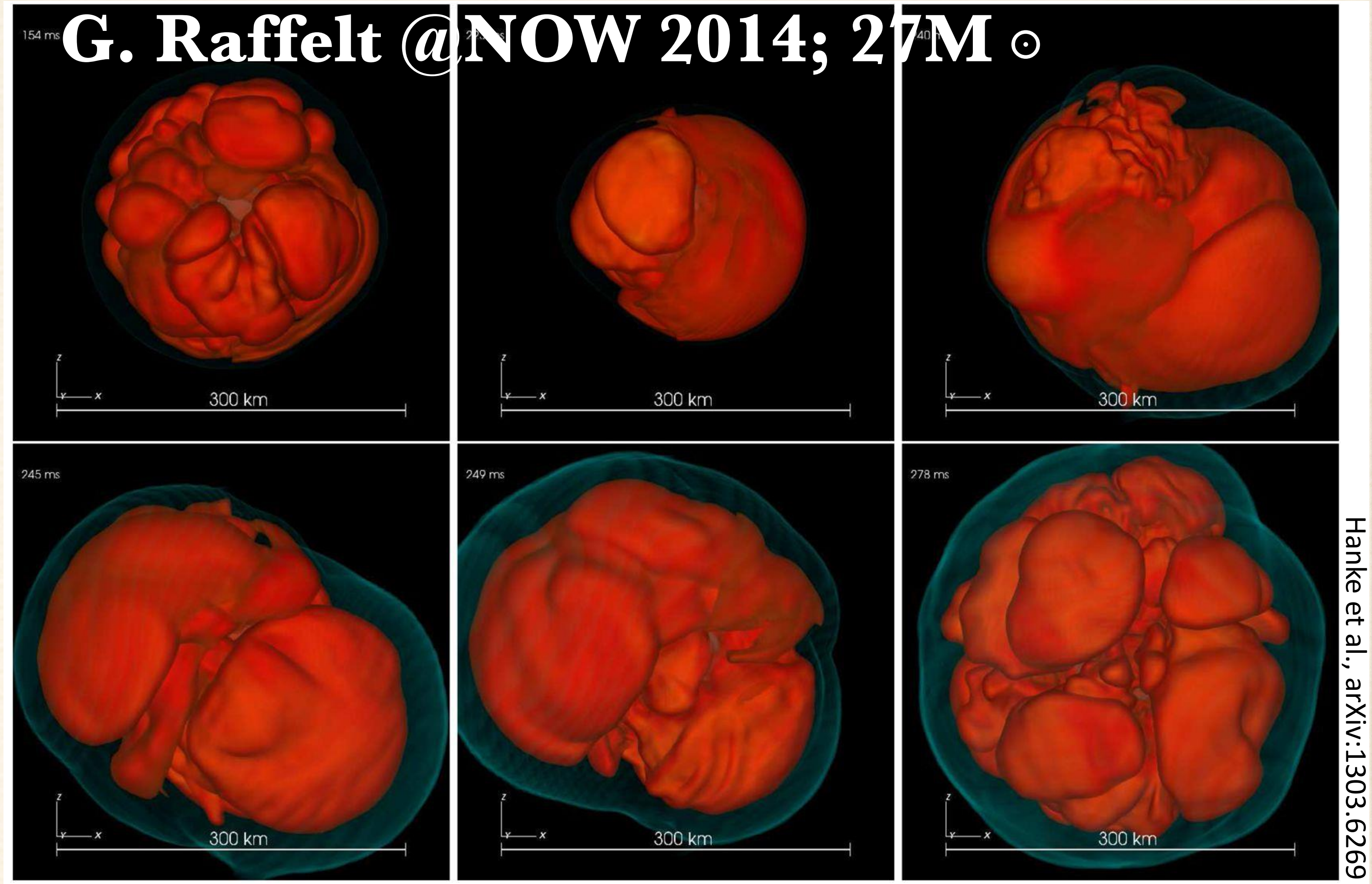
Courtesy G. Raffelt @ NOW 2014

Neutrinos Power the Explosion

- simulations: shock rebound stalls after about 600ms
- stalled shock wave needs energy to start re-expansion against ram pressure of infalling stellar matter
- neutrinos can supply fresh energy!
- SASI is 3D "sloshing" of shock wave

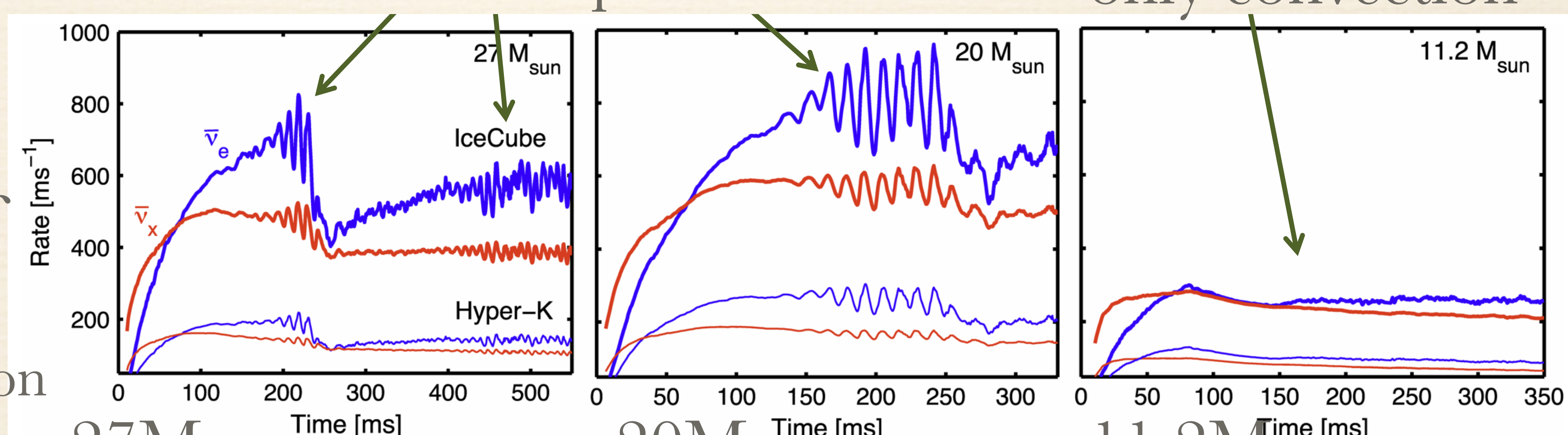
(=standing accretion shock instability)

G. Raffelt @NOW 2014; 27M$_\odot$



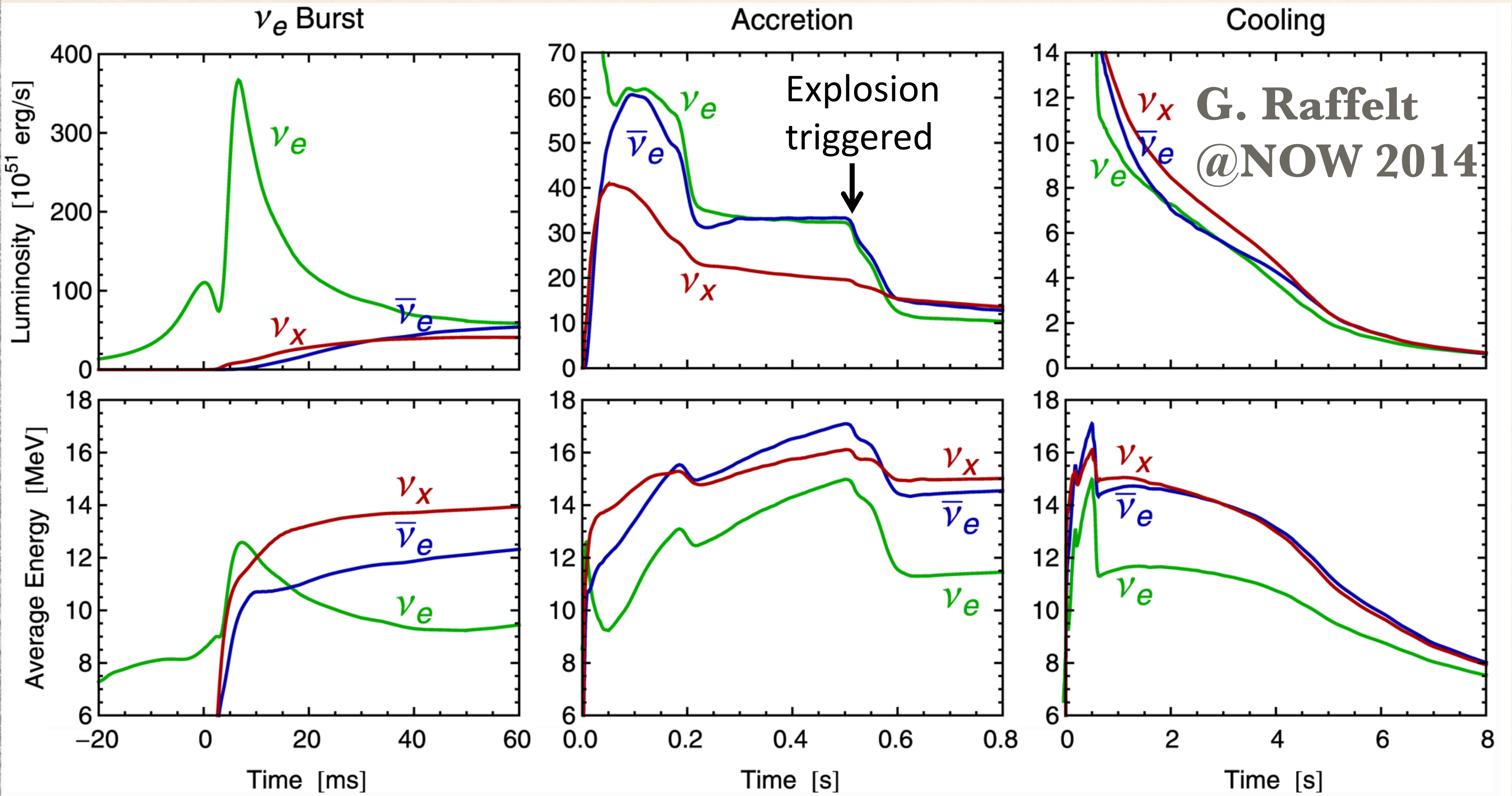
SASI episodes

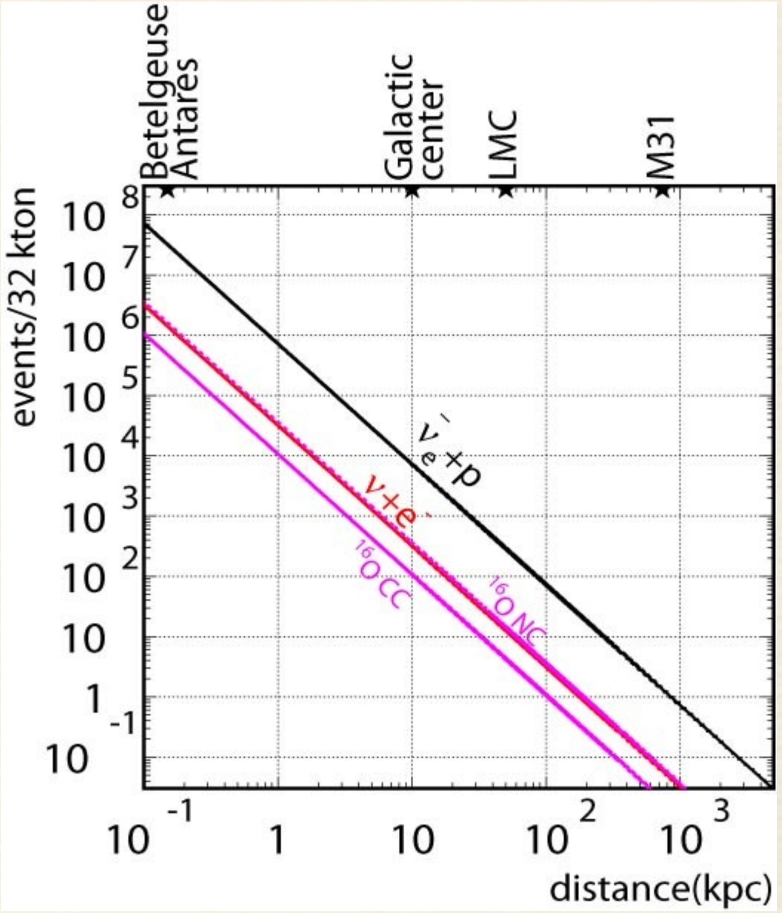
only convection



27M$_\odot$ 20M$_\odot$ 11.2M$_\odot$

Supernova ν Emission





shock breakout; outer core de-leptonization

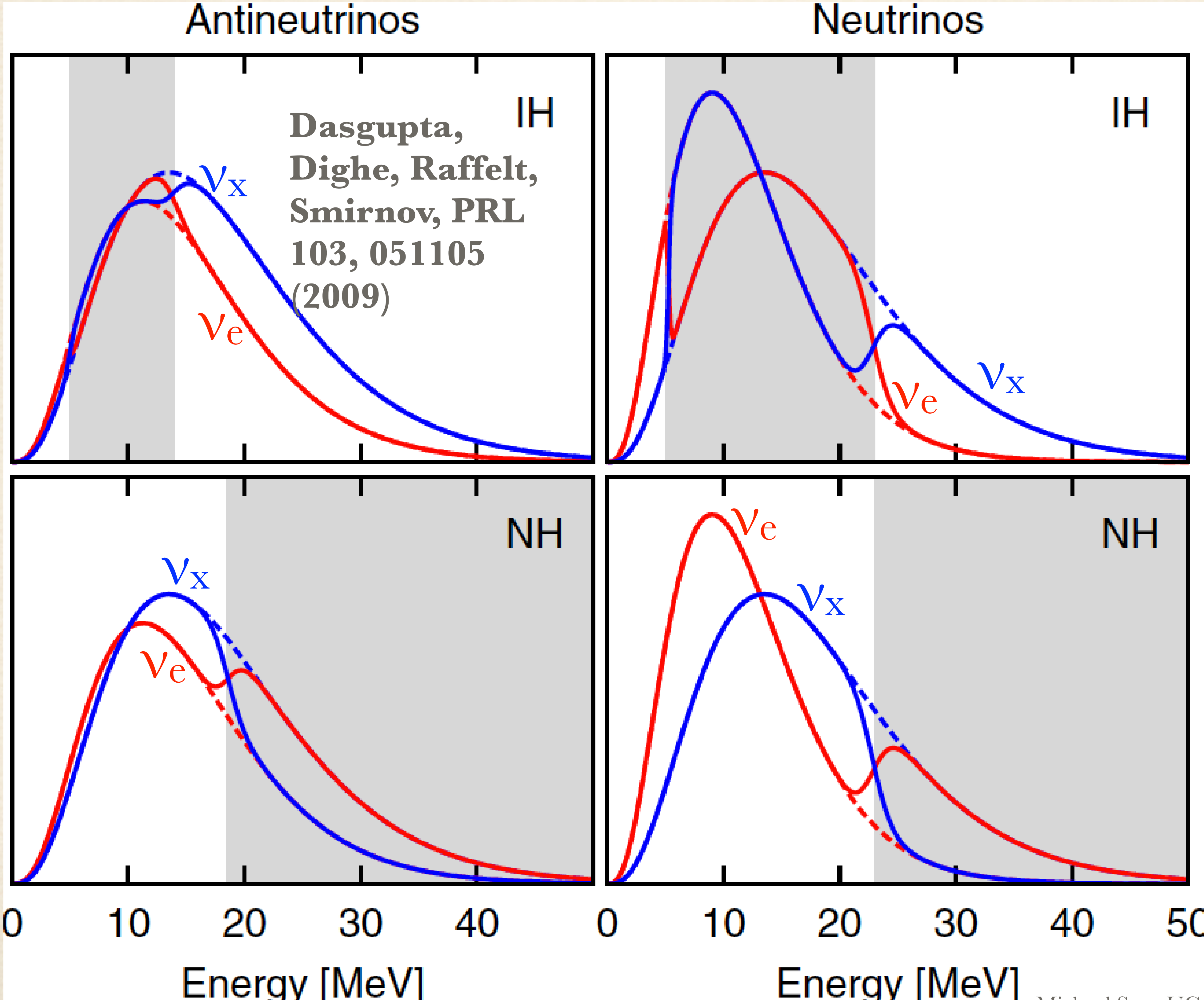
shock stalls ~150km; in-falling matter powers ν's

cooling on neutrino diffusion time scale

SN ν events in Super-K

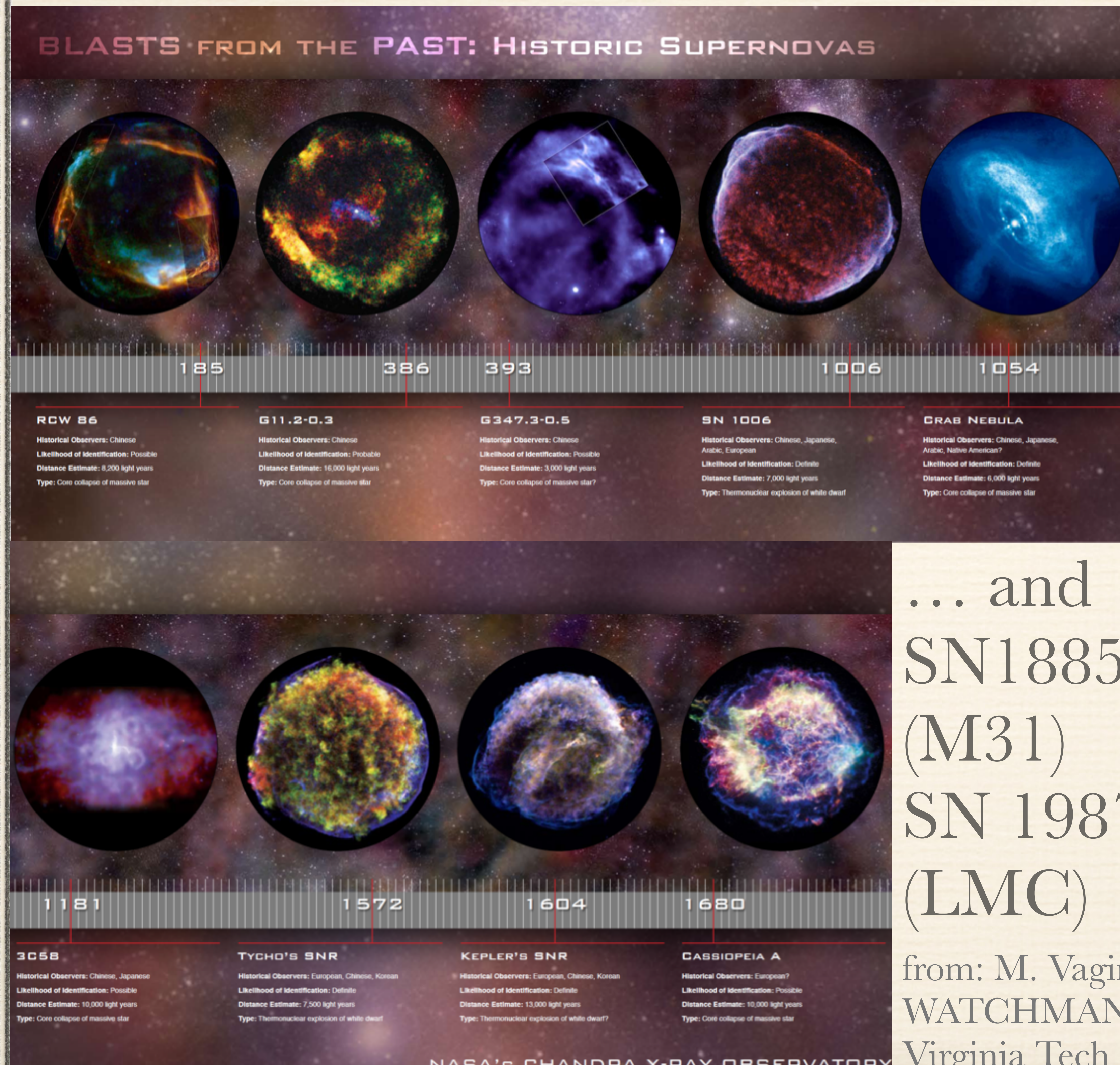
- water detectors: mostly $\overline{\nu}_e$'s; liquid Argon TPCs (DUNE) ν_e's
- see ν_e burst with LArTPC, cooling with water detector
- develop larger water detectors; enhance with Gd (Hyper-K)

ν-ν Interaction: Only in SN!



- neutrinos trapped by dense PNS
- ν_x escape earlier (at higher T)
- non-linear ν self-interaction “swaps” the spectra
- depends on mass ordering

Supernovae in our Backyard



- 3/9 remnants: not core collapse SN
- six observed core collapse explosions in ~1800 years
- see only ~20%: ~2 CCSN/century

… and SN1885a (M31) SN 1987a (LMC)

from: M. Vagins, WATCHMAN meeting at Virginia Tech in 2013

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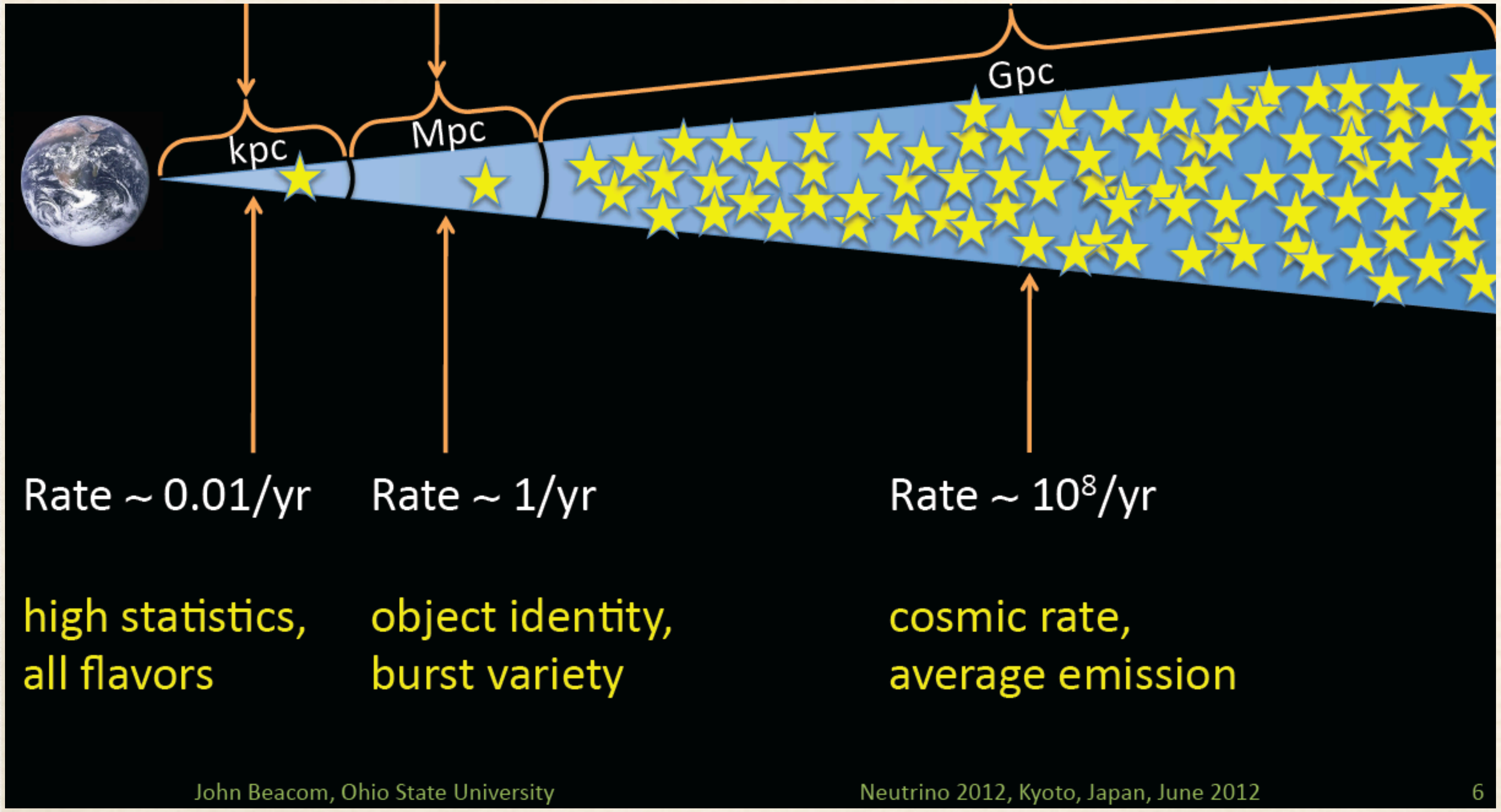
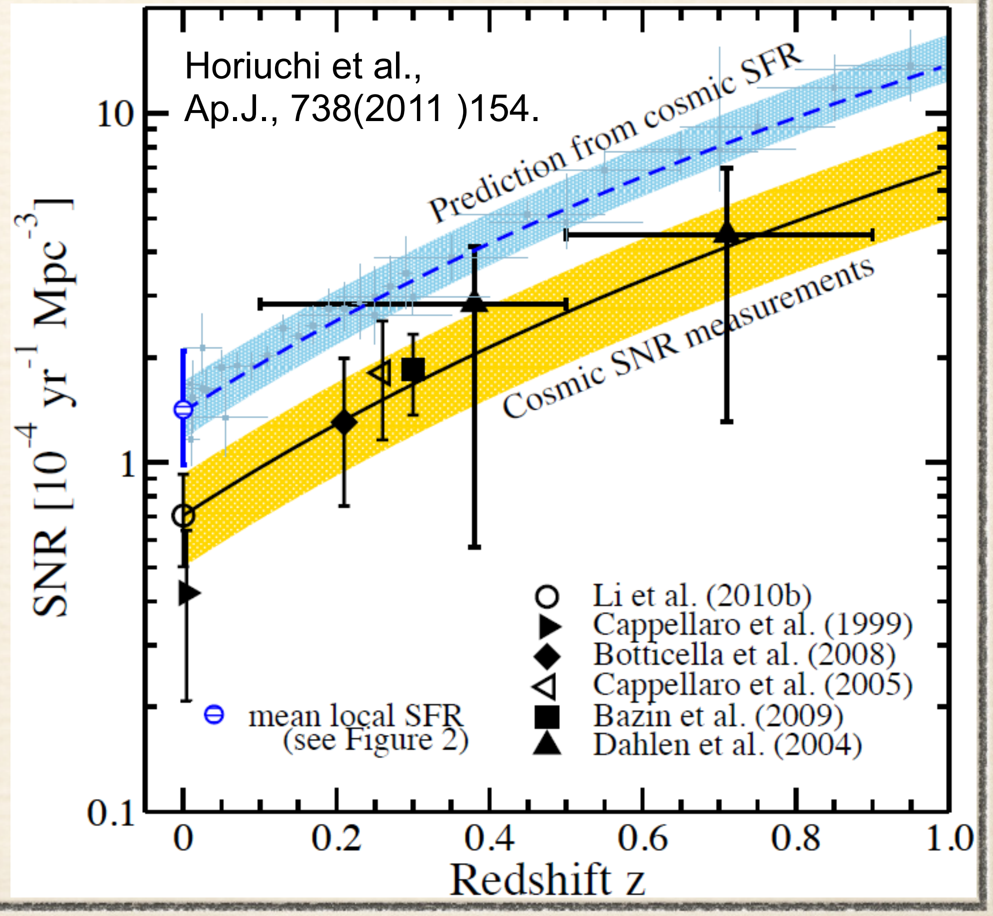
Diffuse, Distant SN Flux

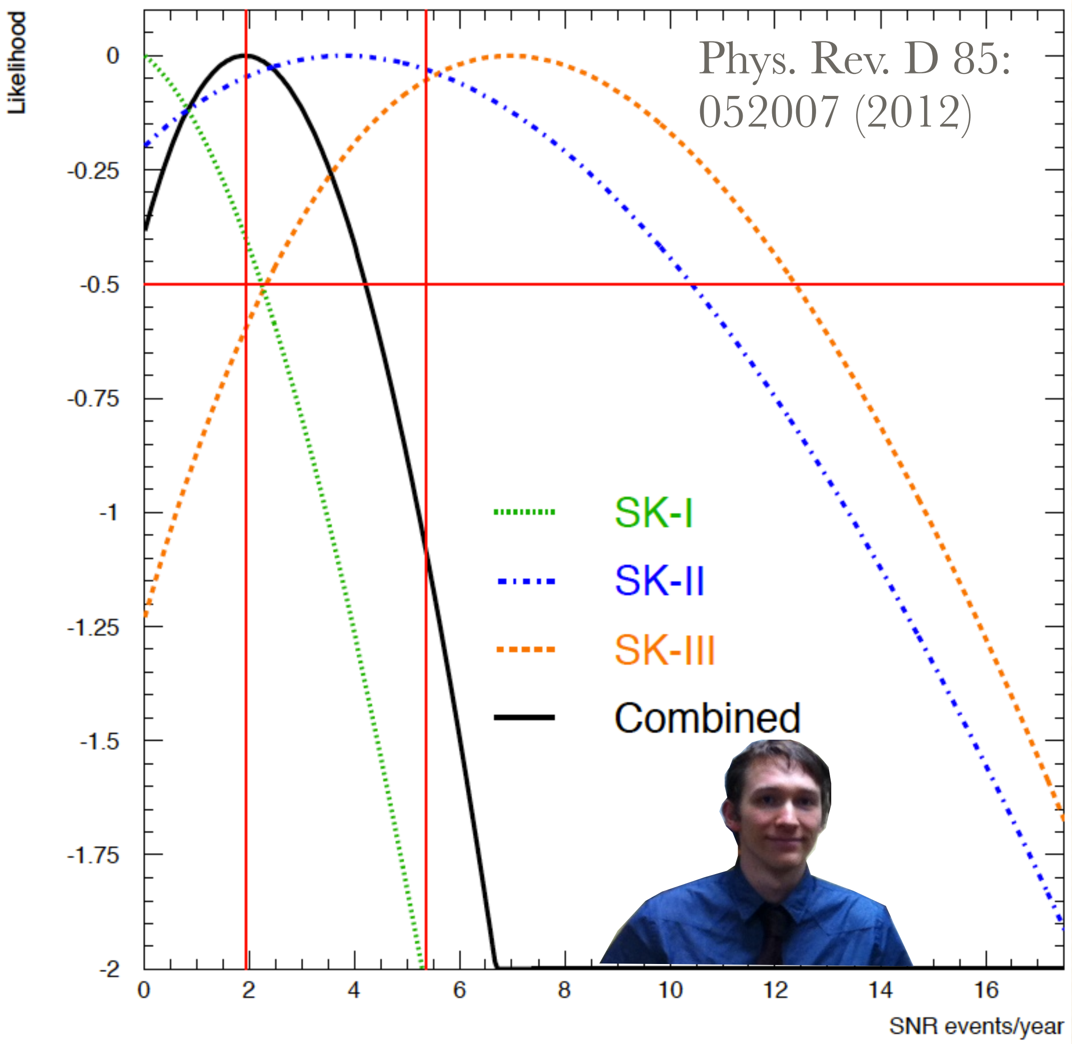
- galactic core collapse supernova neutrinos: a long journey, a long wait! (PhD students should finish <50yr)
- … so look beyond our galaxy: CC SN rate about 1 Hz!
- resulting neutrino interaction rate is a few per year in Super-K
- **observed SN rate** only ~half of **prediction from star formation**
- a problem with the observation? or the prediction? neutrinos would tell!





Super-K's Diffuse, Distant SN ν Search Using IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$

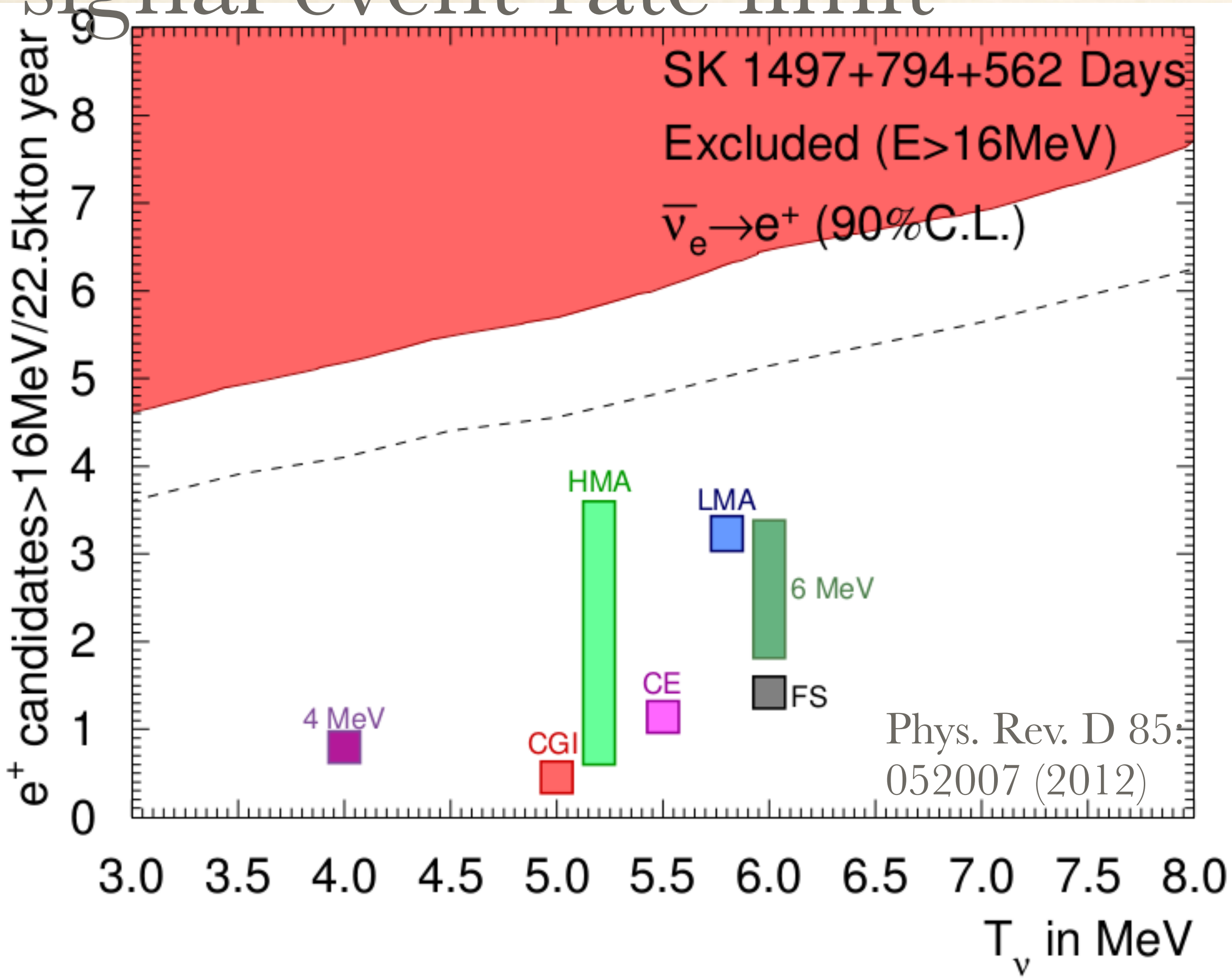
- PhD thesis of Kirk Bays (now at CalTech working on Nova)
- analysis has backgrounds from atmospheric ν interactions
- world's best sensitivity for distant supernova ν's



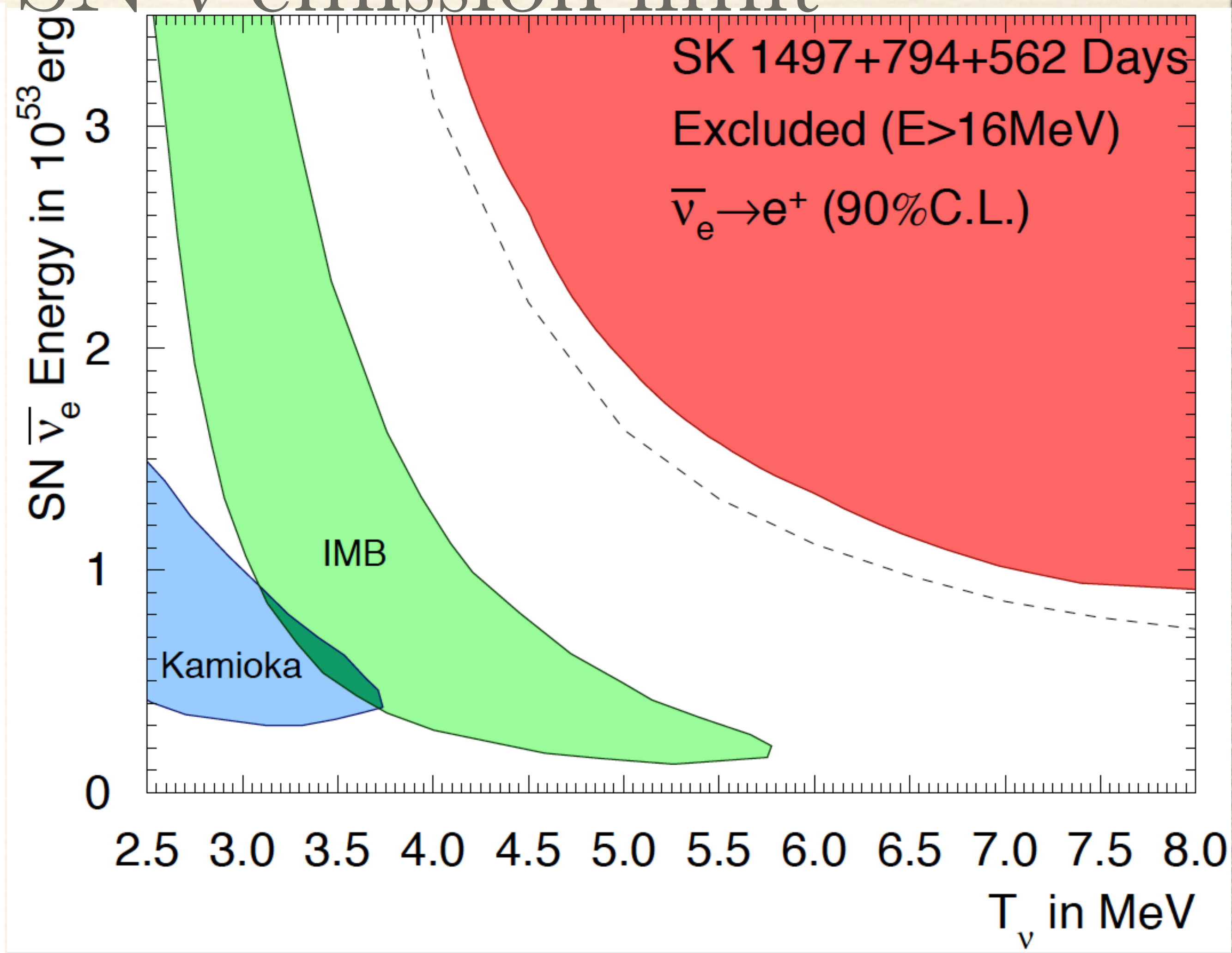
- SK-I: -0.3±2.3/yr, (1497d)
- SK-II: 4±6.5/yr, (794d)
- SK-III: 7±5/yr, (562d)
- SK I-III: 2±2 events/yr
- SK IV: ~2860 days of data

Super-K's Diffuse, Distant SN Search

signal event rate limit



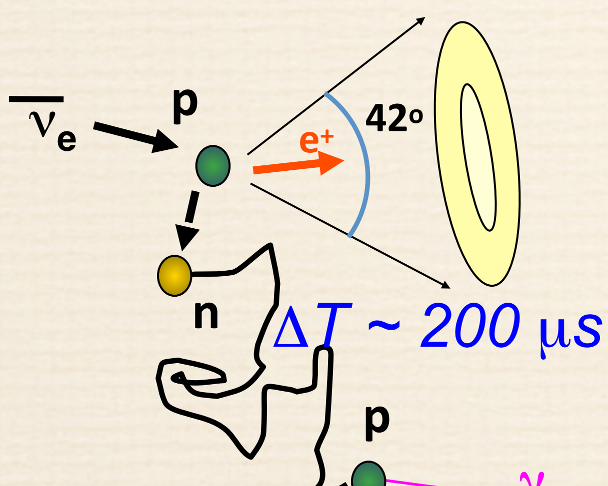
SN ν emission limit

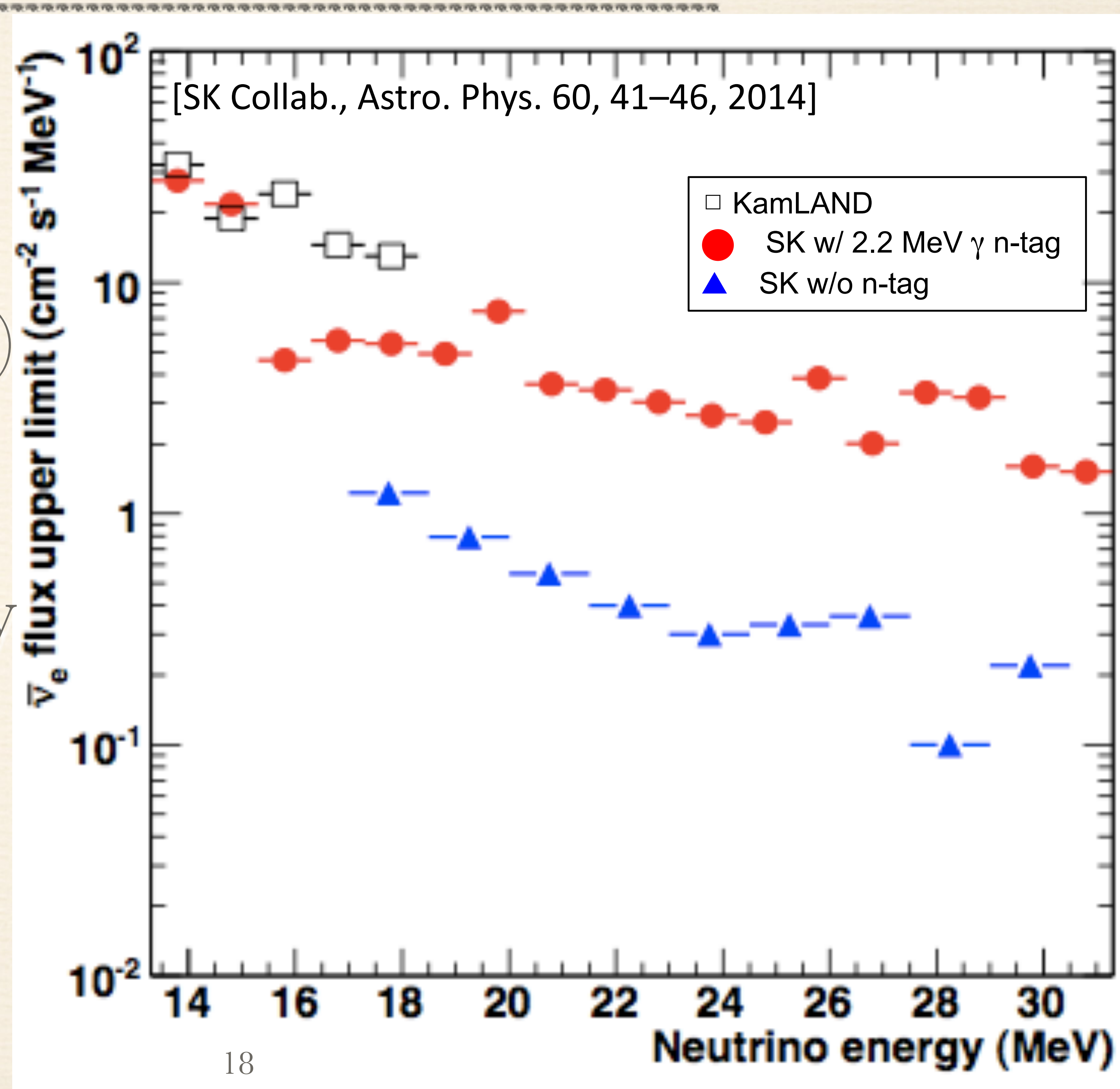


- event rate limits are close to theoretical predictions
- neutrino emission limits are close to expectations based on SN 1987a
- must reduce background for discovery!

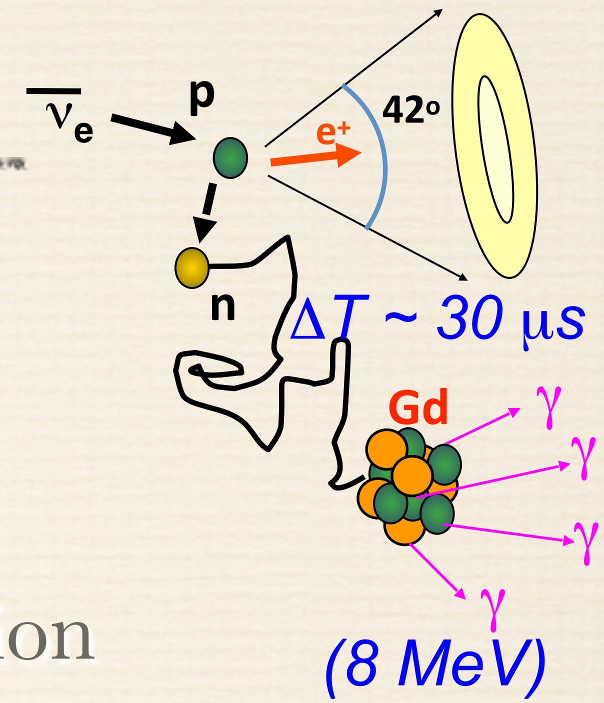
Detect IBD Neutron by 2.2 MeV γ

- n+p→d+γ
- efficiency only 10-15% (recently improved to ~20%)
- limit gets worse due to poor tagging efficiency

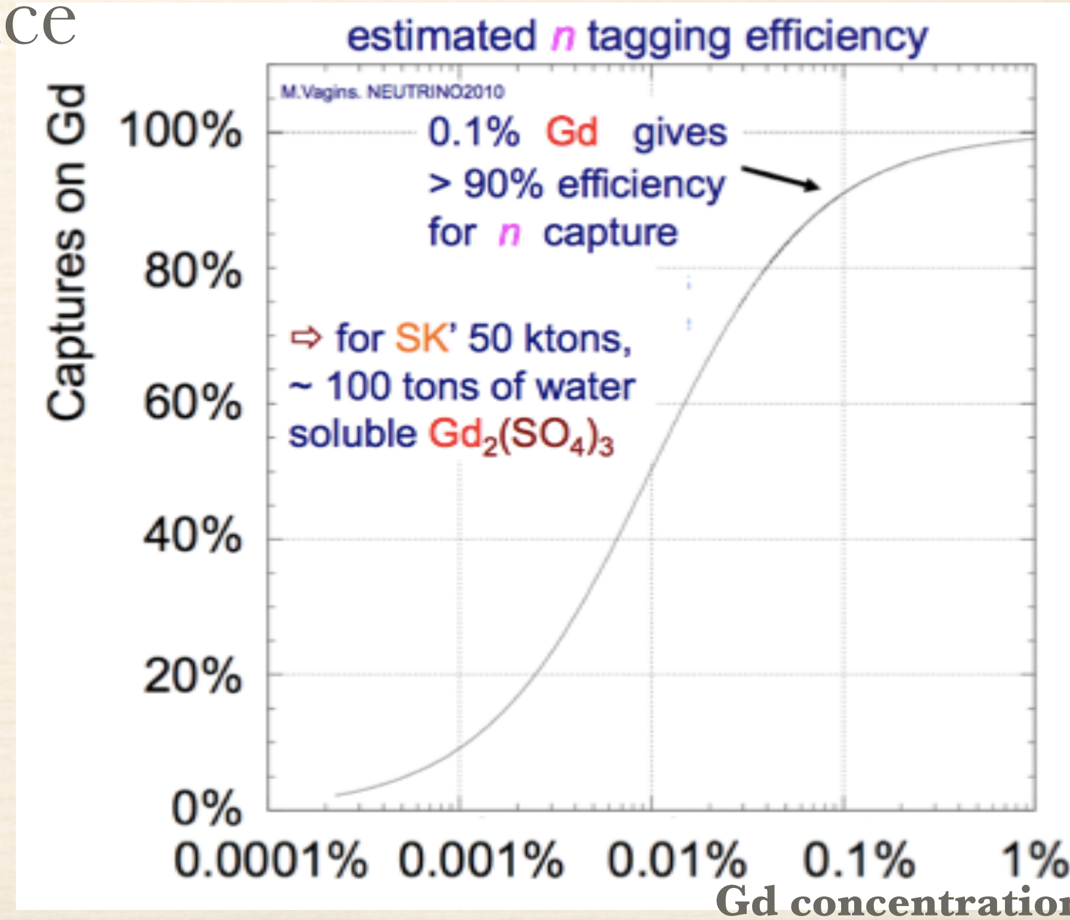




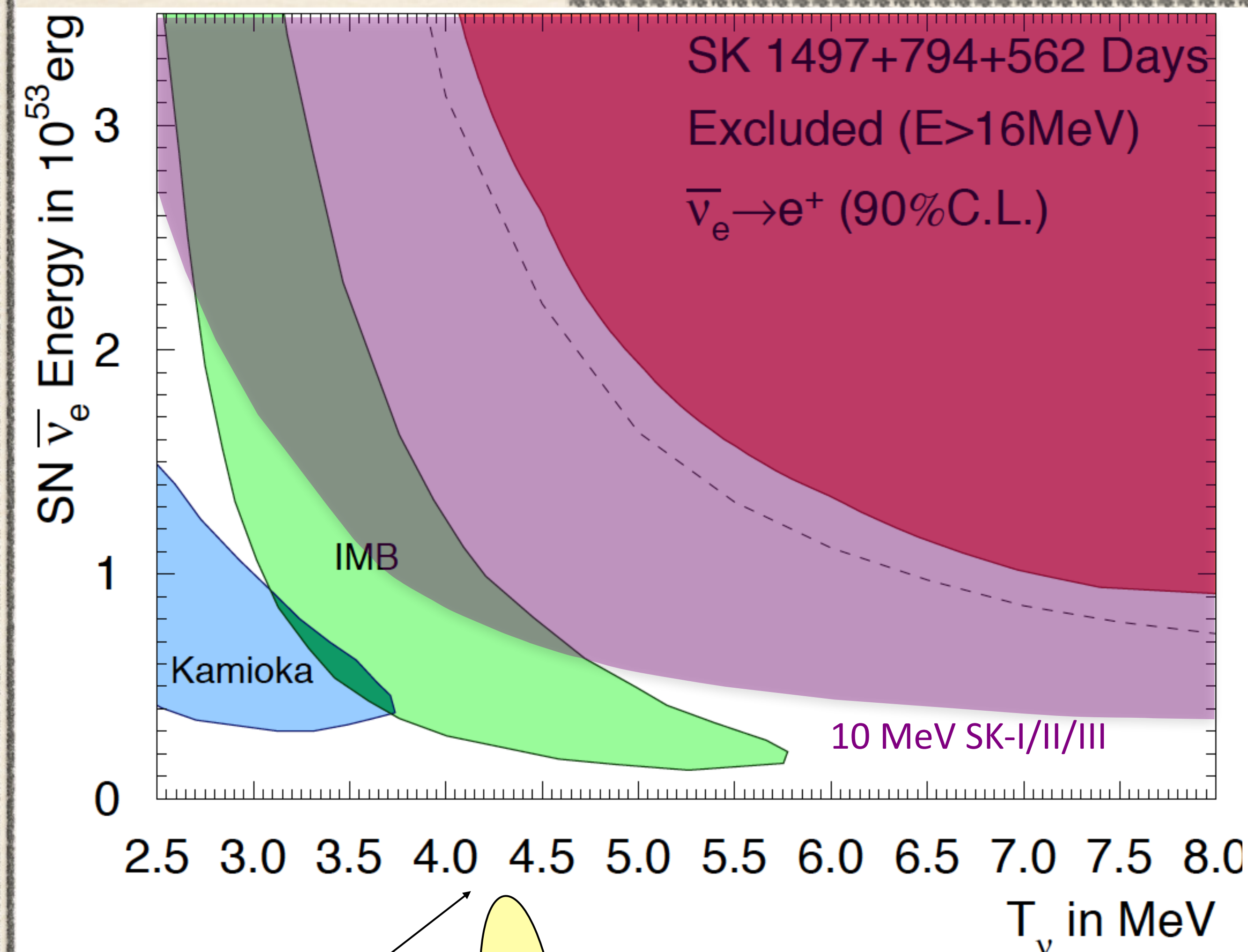
Detect Neutron from IBD with Gd

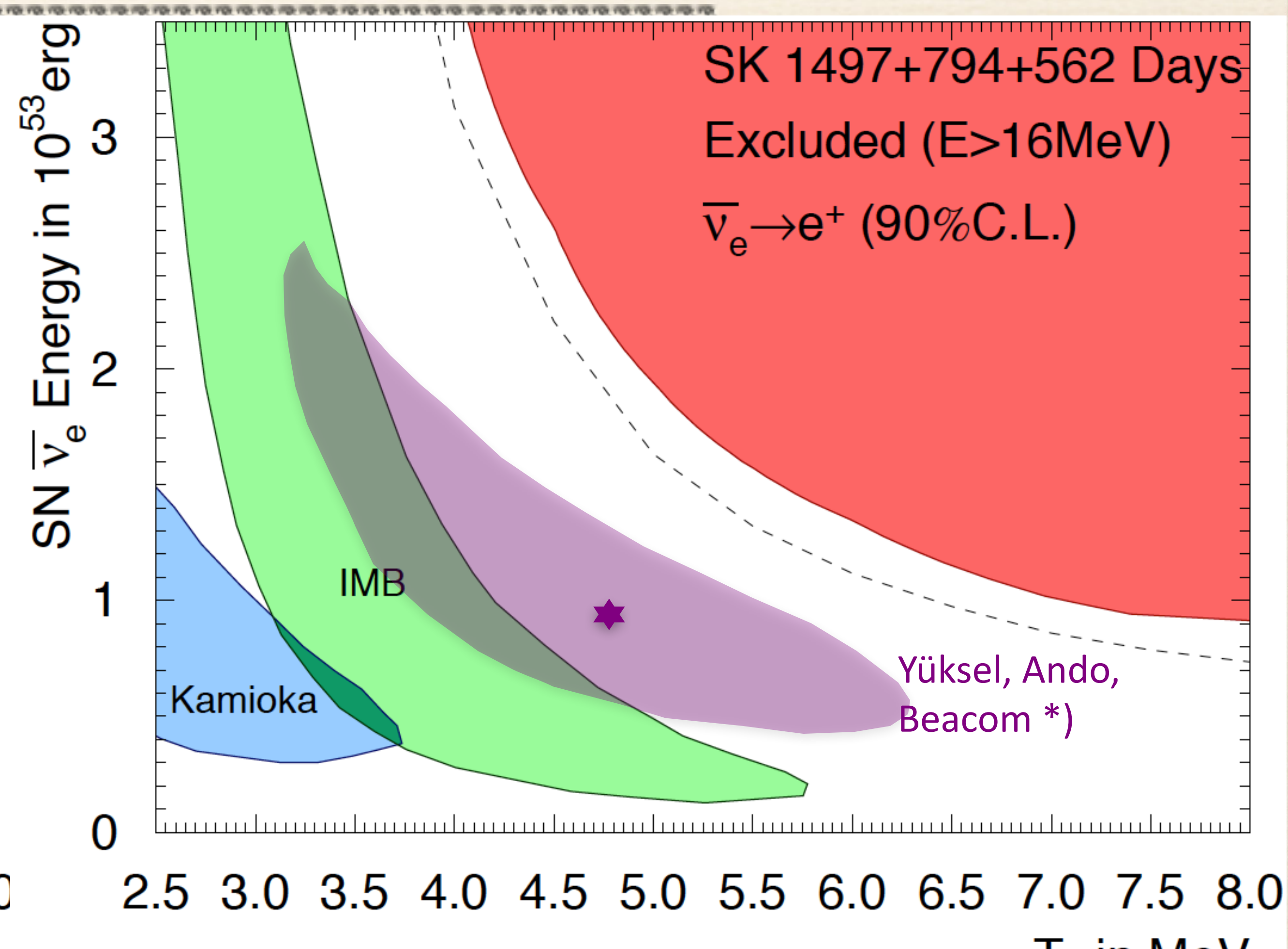


- idea from J. Beacom and M. Vagins: dissolve 0.1% Gd ions to capture neutrons (GADZOOKS!) ***Phys. Rev. Lett.*, 93:171101, 2004**
- idea studied and developed at UCI
- giant cross section (49000barn): tighter time correlation (30 μsec), higher multiplicity (3-4 γ's), higher energy (8 MeV): more distinct signature! (reduce accidental coincidences by >100)
- use $Gd_2(SO_4)_3$ for
  - small light attenuation
  - compatibility with Super-K detector (not corrosive)
  - high solubility

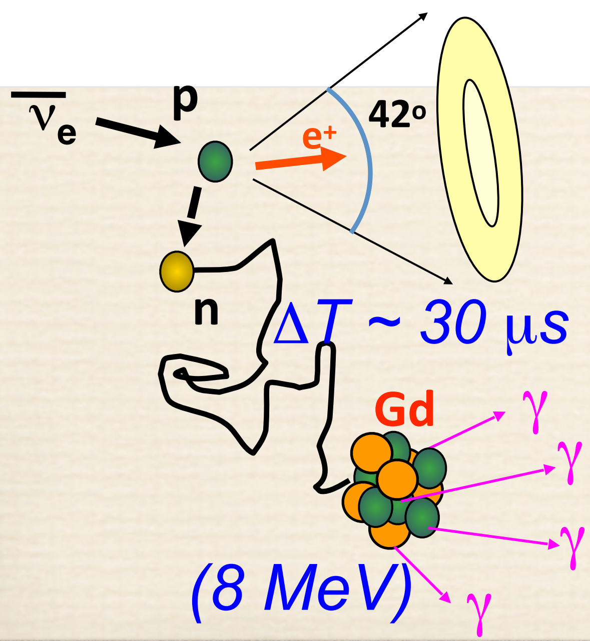


IBD with Gd-n Tag: Sensitivity Estimates



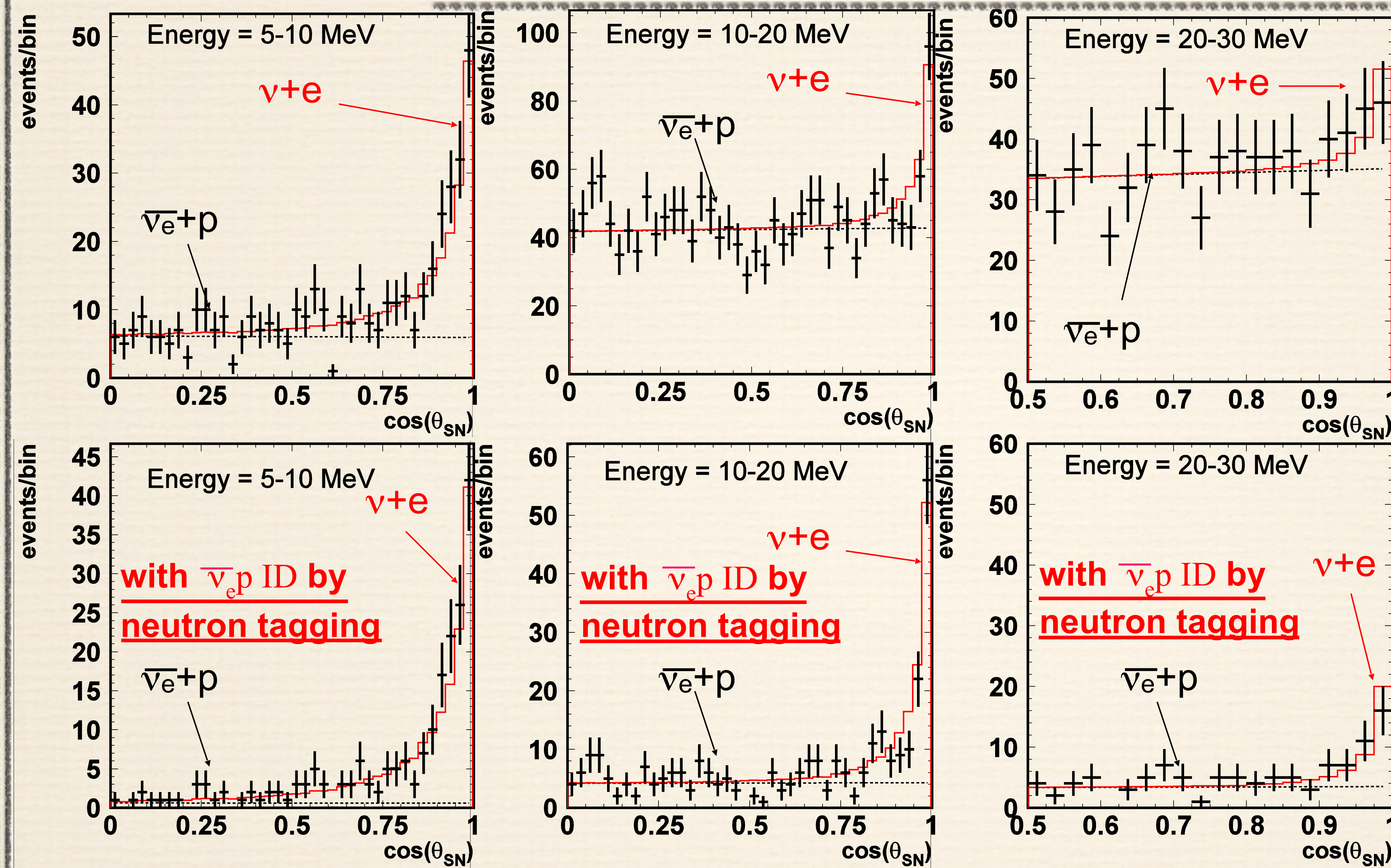


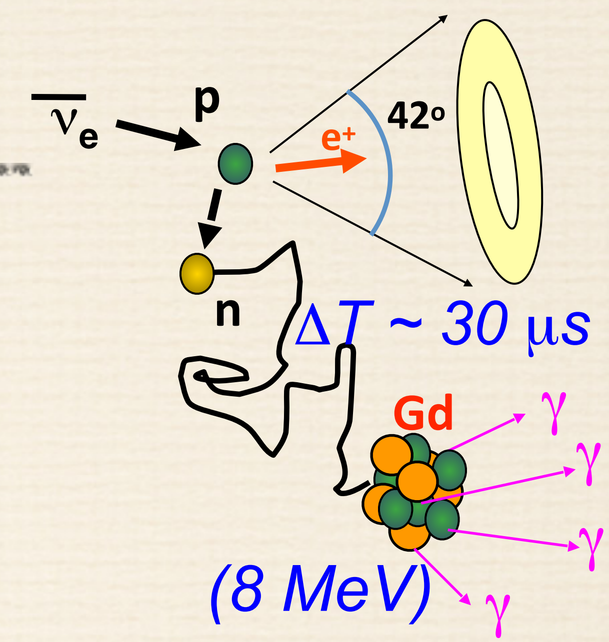
*) Phys. Rev. C 74 015803 (2006)

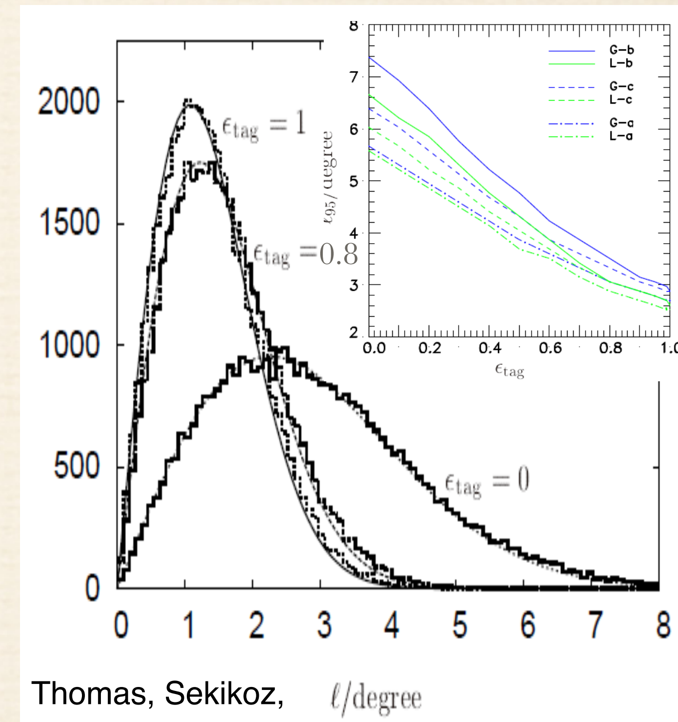


- gain sensitivity from lower threshold!
- discovery, if best models are correct!
- exclude wide range of models, if no signal

Flavor Decomposition and Pointing with n Tagging







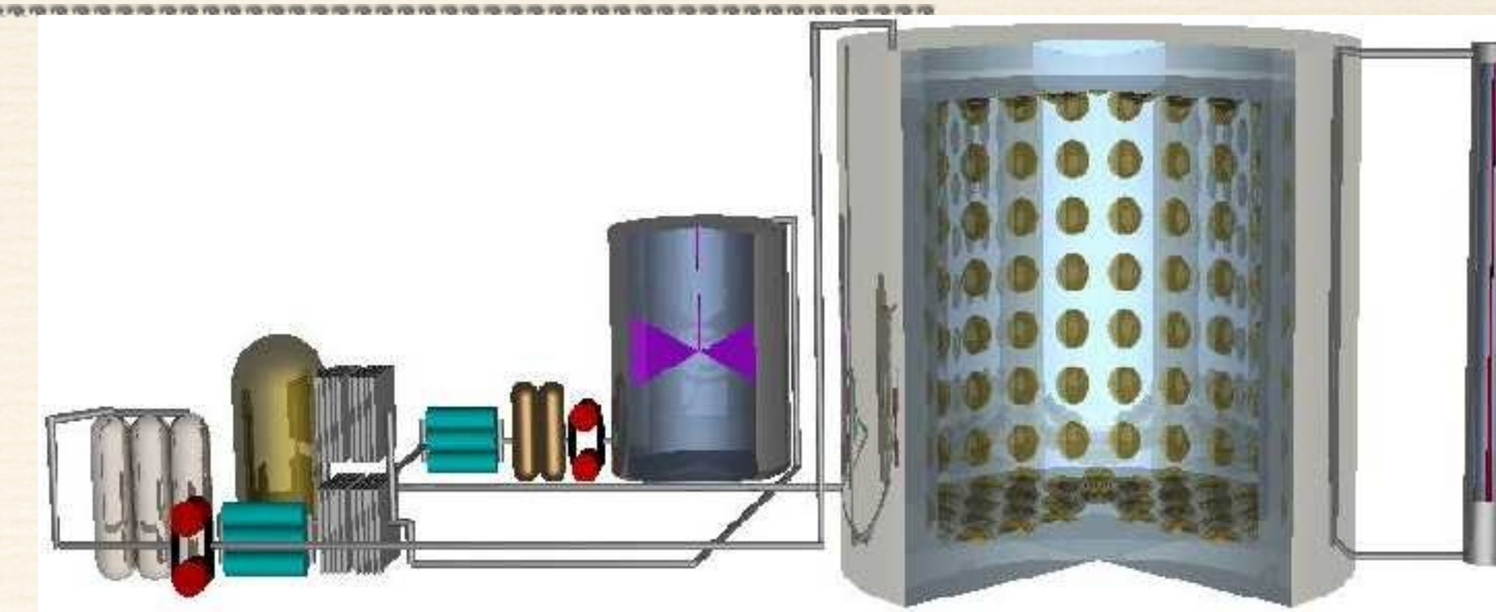
Thomas, Sekikoz, Raffelt, Kachelriess, Dighe hep-ph/0307050v2

- improve ES signal and flavor decomposition of galactic SN ν burst
- improve angular resolution by factor of two!

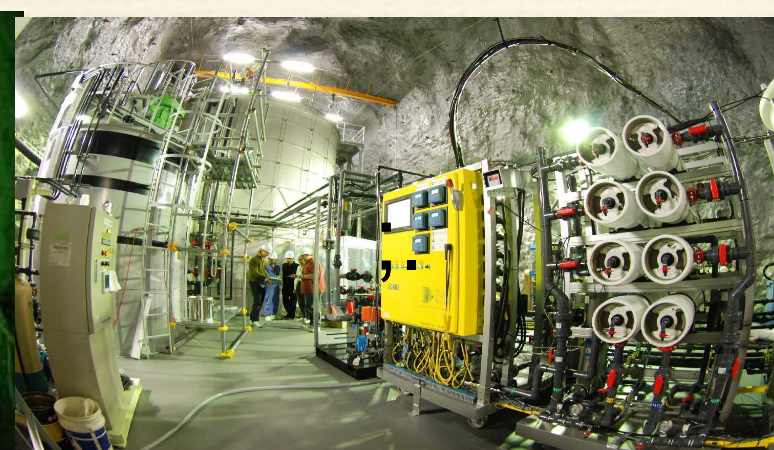
Courtesy M. Nakahata, ICRR

EGADS

- 200t test detector
- proof of principle
- check compatibility
- check light attenuation
- measure Gd concentration
- develop Gd solution and removal technology
- develop calibration techniques

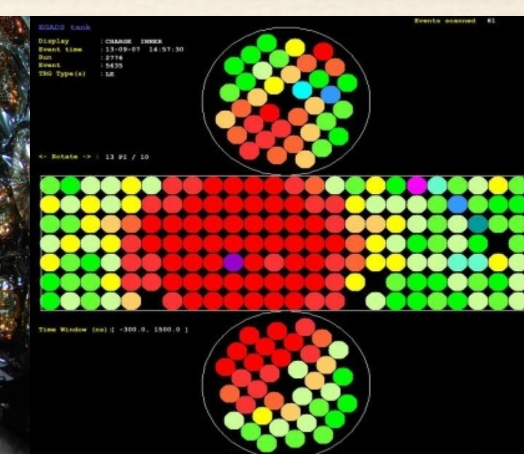


12/2009



11/2011

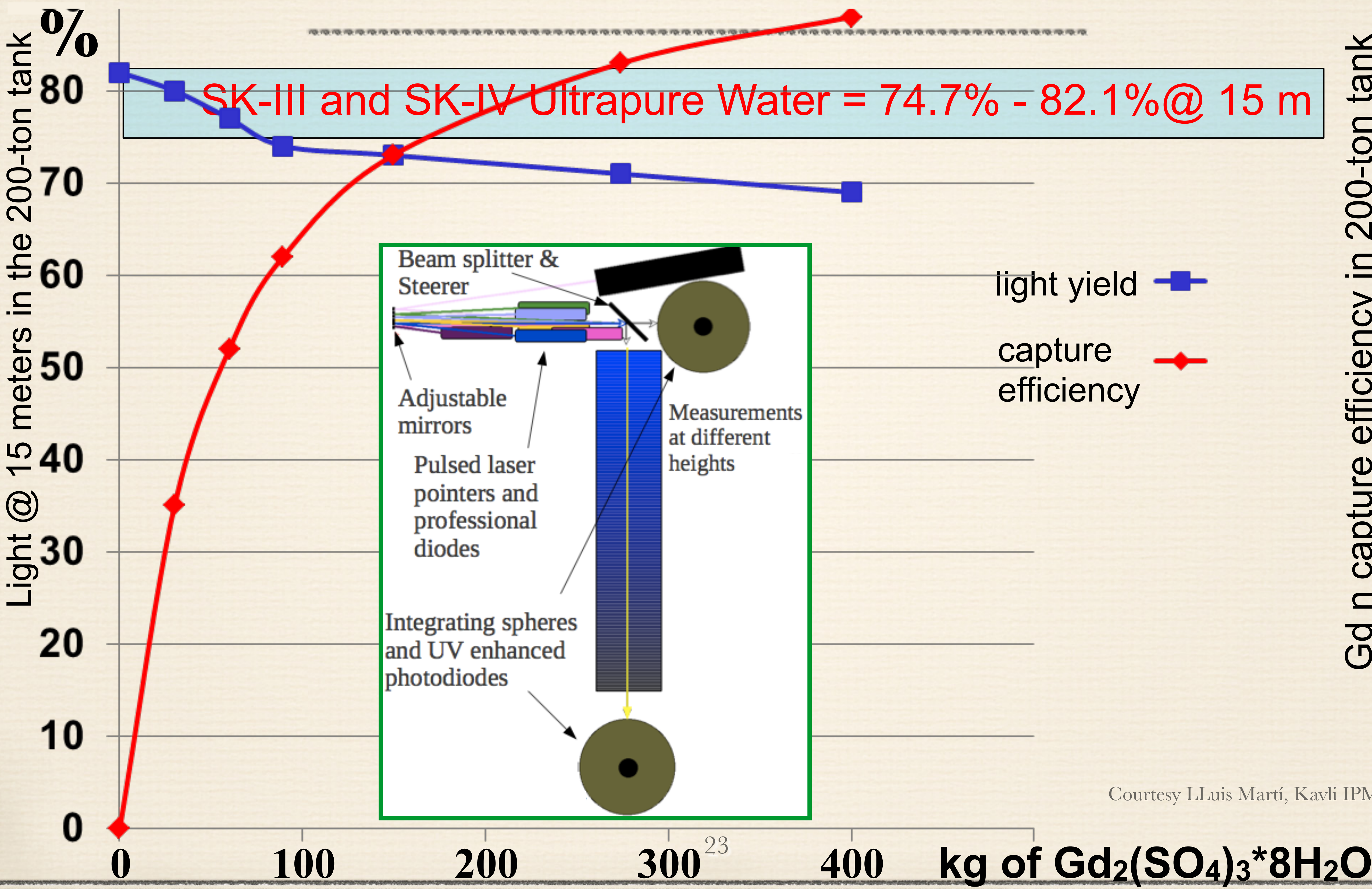
8/2013



9/2013

Courtesy Mark Vagins, UC Irvine

Just Tank: Smooth Behavior as Gd is Added

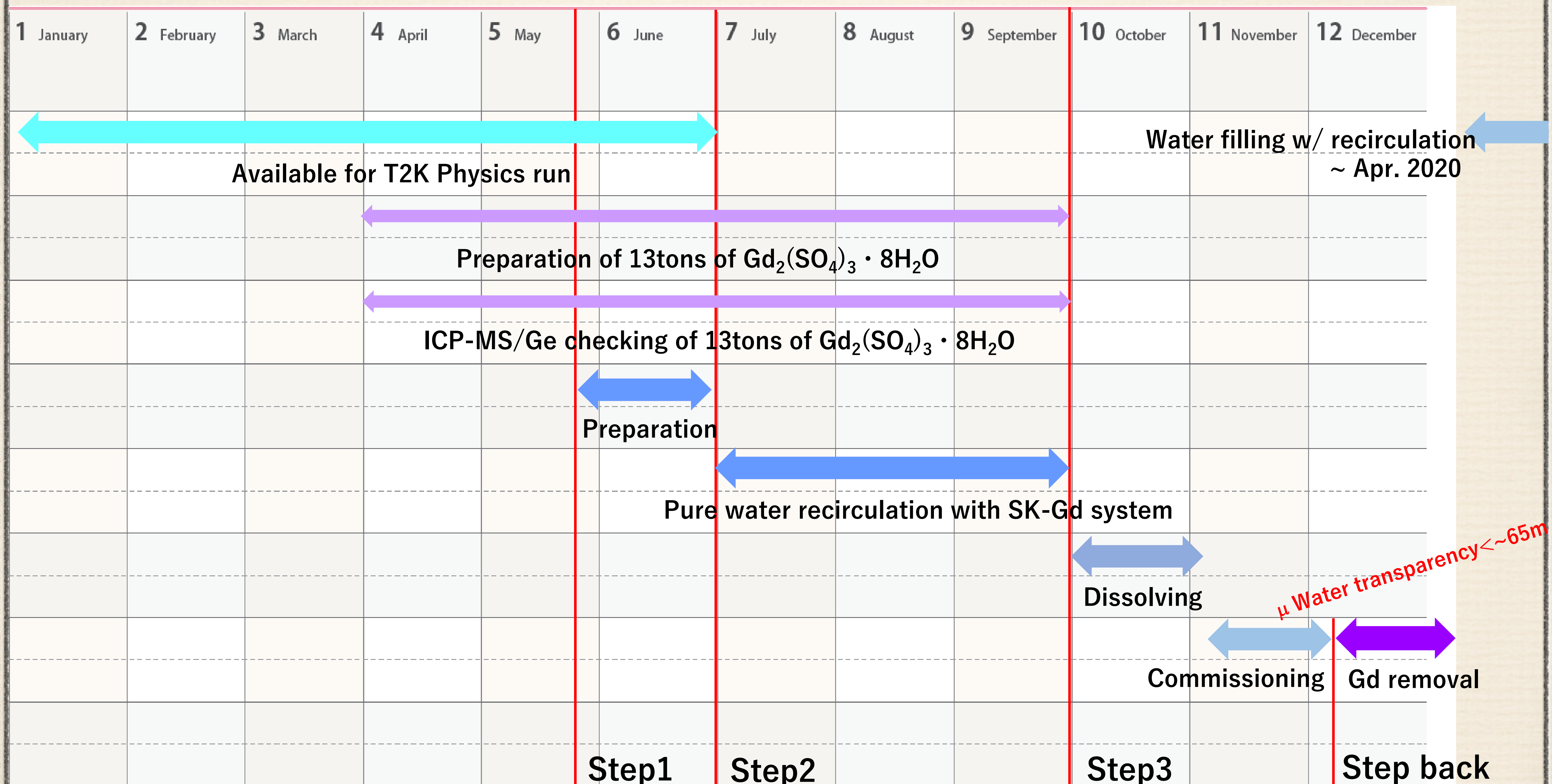


Courtesy LLuis Martí, Kavli IPMU

Schedule to add $Gd_2(SO_4)_3$

- June 2018-September 2018: prepare Super-K for Gd phase
  - replace dead PMTs
  - add pipes for better water flow control of inner and outer detector
  - the tank leaks: seal possible places where leak might occur
- 2019: start dissolving 13 tons of $Gd_2(SO_4)_3*8H_2O$
  - agreed plan of Super-K collaboration
  - subject to approval by other stake holders, in particular T2K

Schedule to add $Gd_2(SO_4)_3$



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Solar Neutrinos

- nuclear physics/astrophysics
  - sun shines via nuclear fusion
  - solar core temperature and stability
  - test (evolutionary) solar models (and some of the assumptions)
- particle physics:
  - neutrino "oscillations" (periodic change of neutrino type): solar neutrino data started this idea
  - "flavor" transformation: test Mikheyev-Smirnov-Wolfenstein effect (compare low and high energy solar neutrinos)
  - directly test matter effects on neutrino oscillations (in the earth) by comparing day- and night-time interaction rates
  - neutrino magnetic moment

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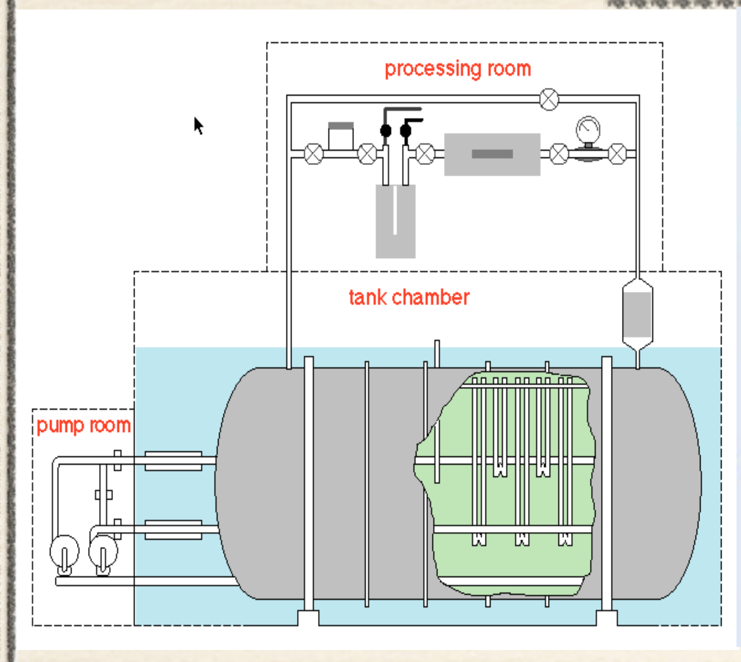
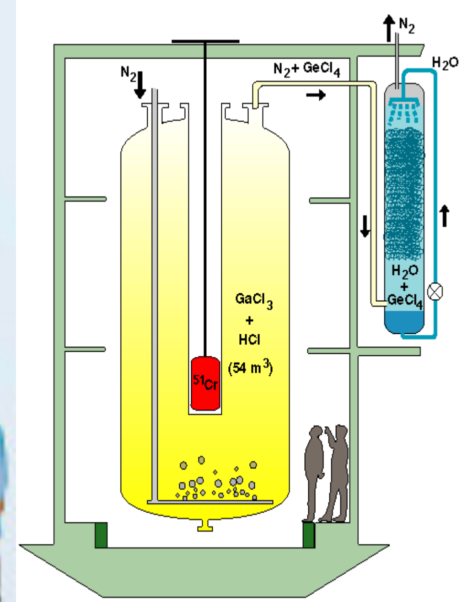
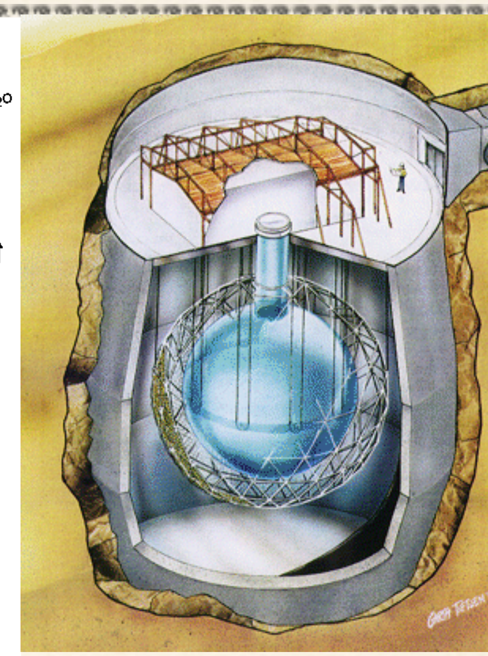
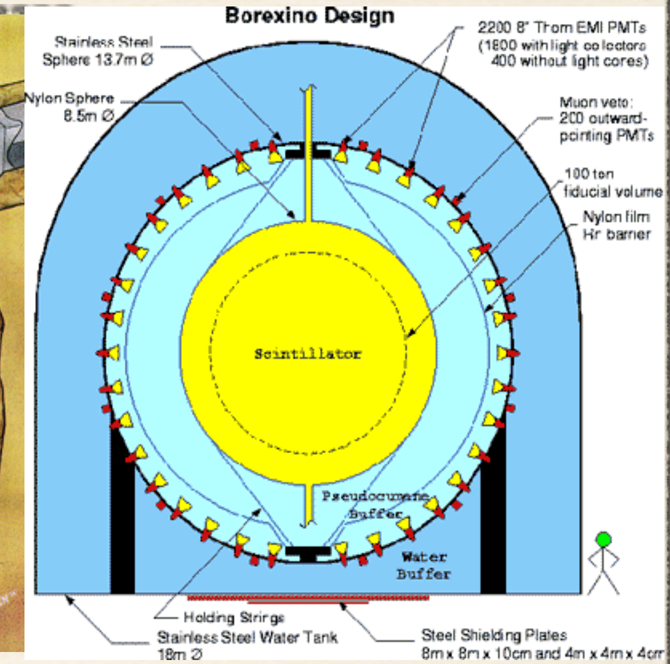
Other Solar Neutrino Experiments









Homestake (Cl) SAGE (Ga) GALLEX(Ga) SNO (D_2O) BOREXINO (Scint.)

- Cl➛Ar (>800keV) and Ga➛Ge (>200keV) when ν_e➛e^-: count Ar/Ge atoms! (radiochemical detection)
- water-Cherenkov (>few MeV) e^- elastic scattering (all active ν), d➛p+p when ν_e➛e^- and d➛p+n (all active ν)
- scintillator (>few 100 keV) e^- elastic scattering (all active ν)

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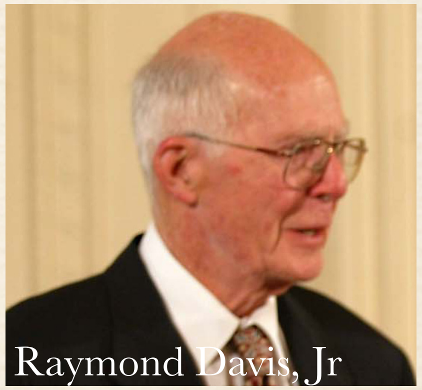
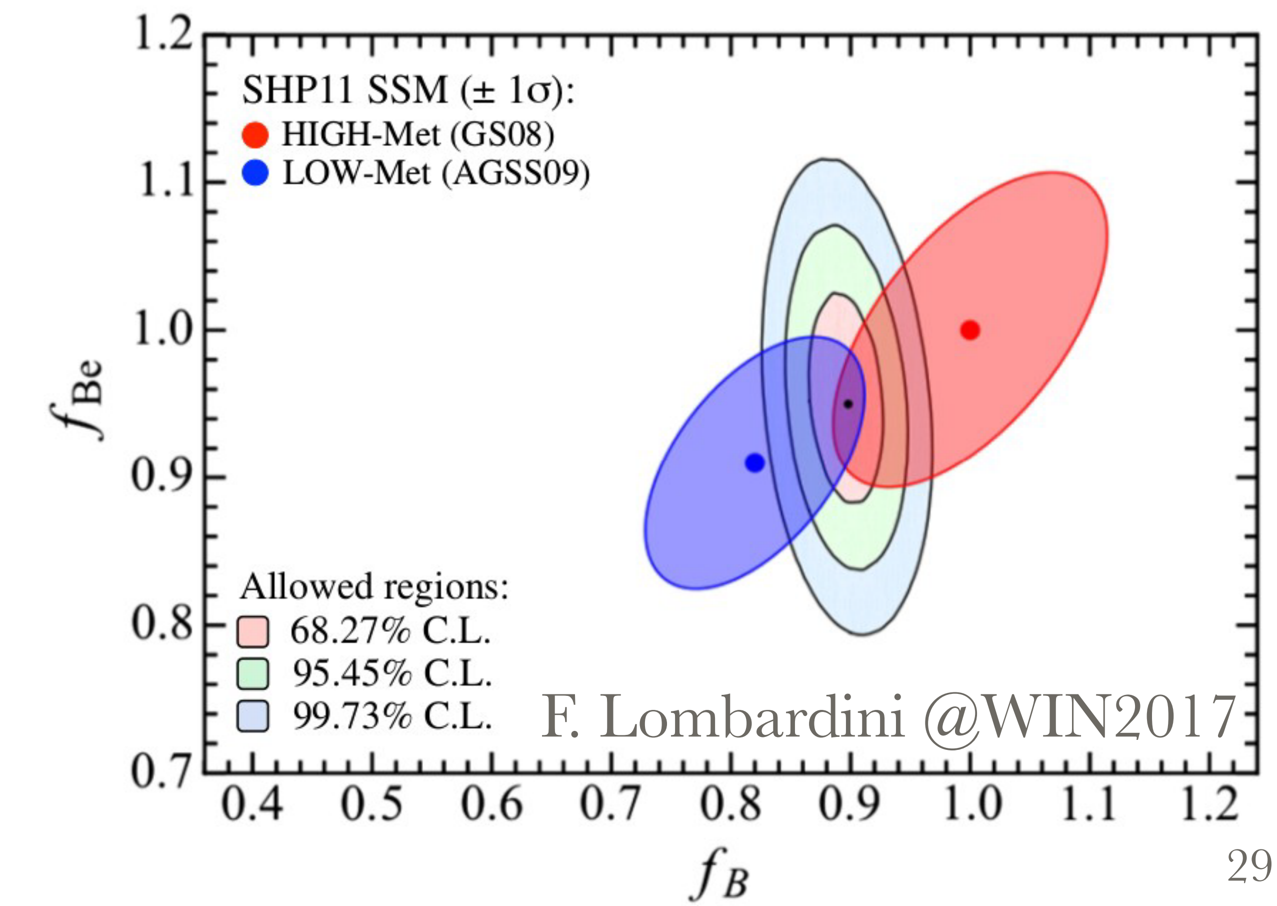
Solar Model and Solar ν Data

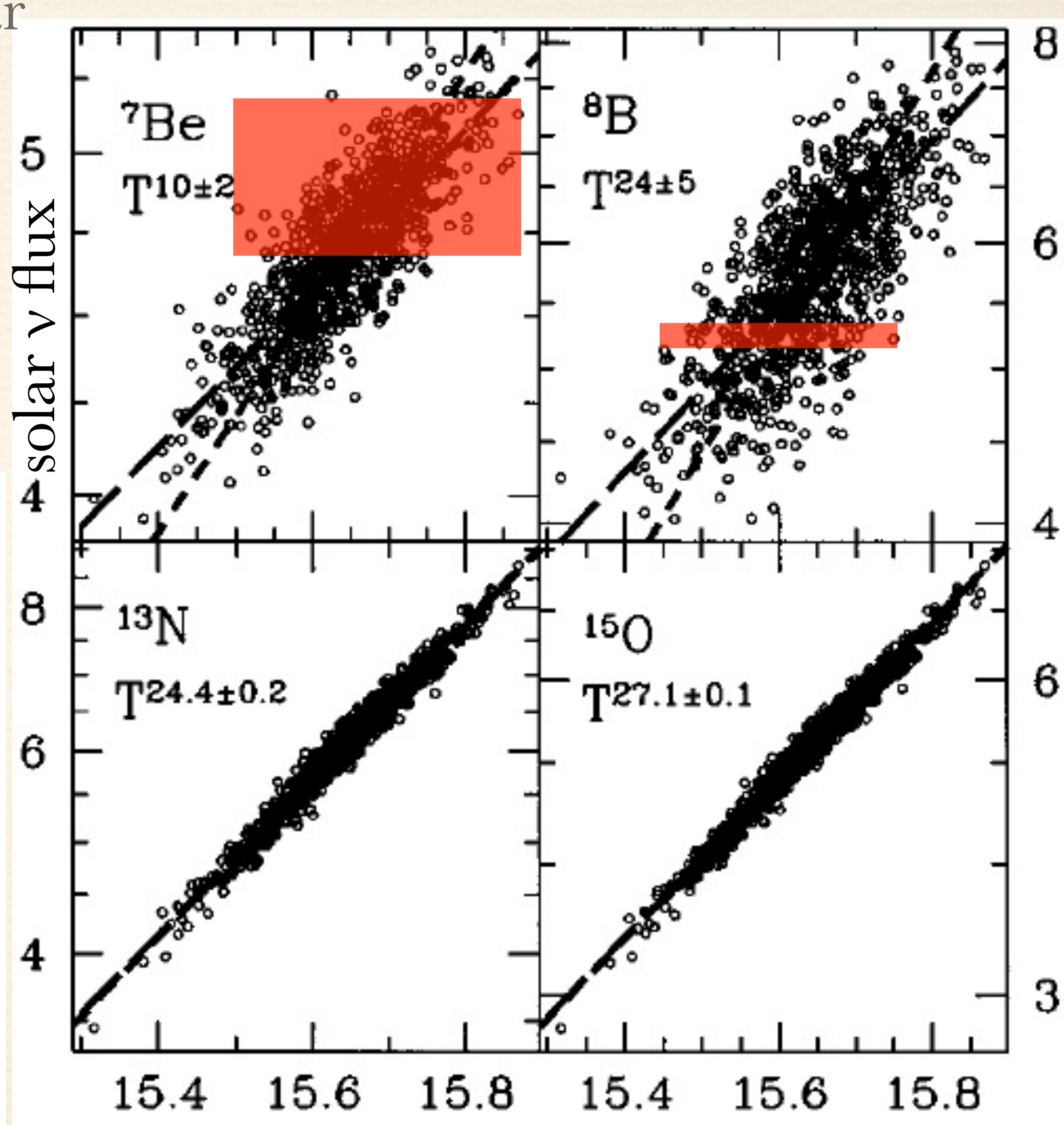


- solar ν detection: evidence for nuclear fusion
- ^{8}B solar ν's: measure of core temperature
- today: two (evolutionary) solar models based on different element abundance data: Grevesse & Sauval (1998; GS98) and Asplund et al. (2009; AGSS09)
- newer AGSS09 doesn't fit as well with helio-seismology data
- AGSS09 reduces CNO flux by ~30%
- changes opacity and core temperature

Solar ^{8}B ν's and Solar Models

- measure value and stability) of solar core temperature
- can't discriminate between high- and low-metallicity models
- CNO value could select one class and break degeneracy with opacity





J. N. Bacall, A. Ulmer, PRD 53, 4202 (1996)

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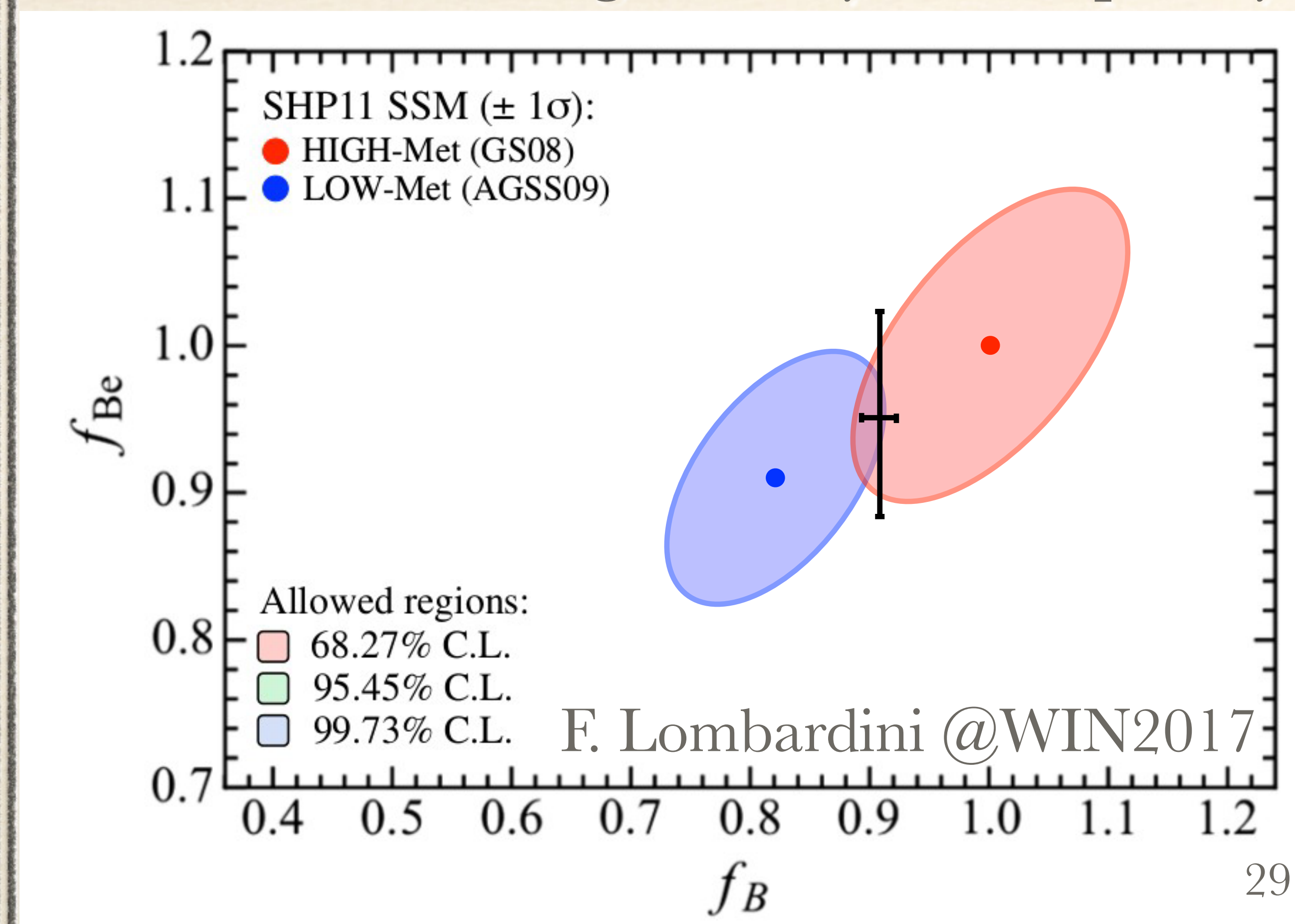

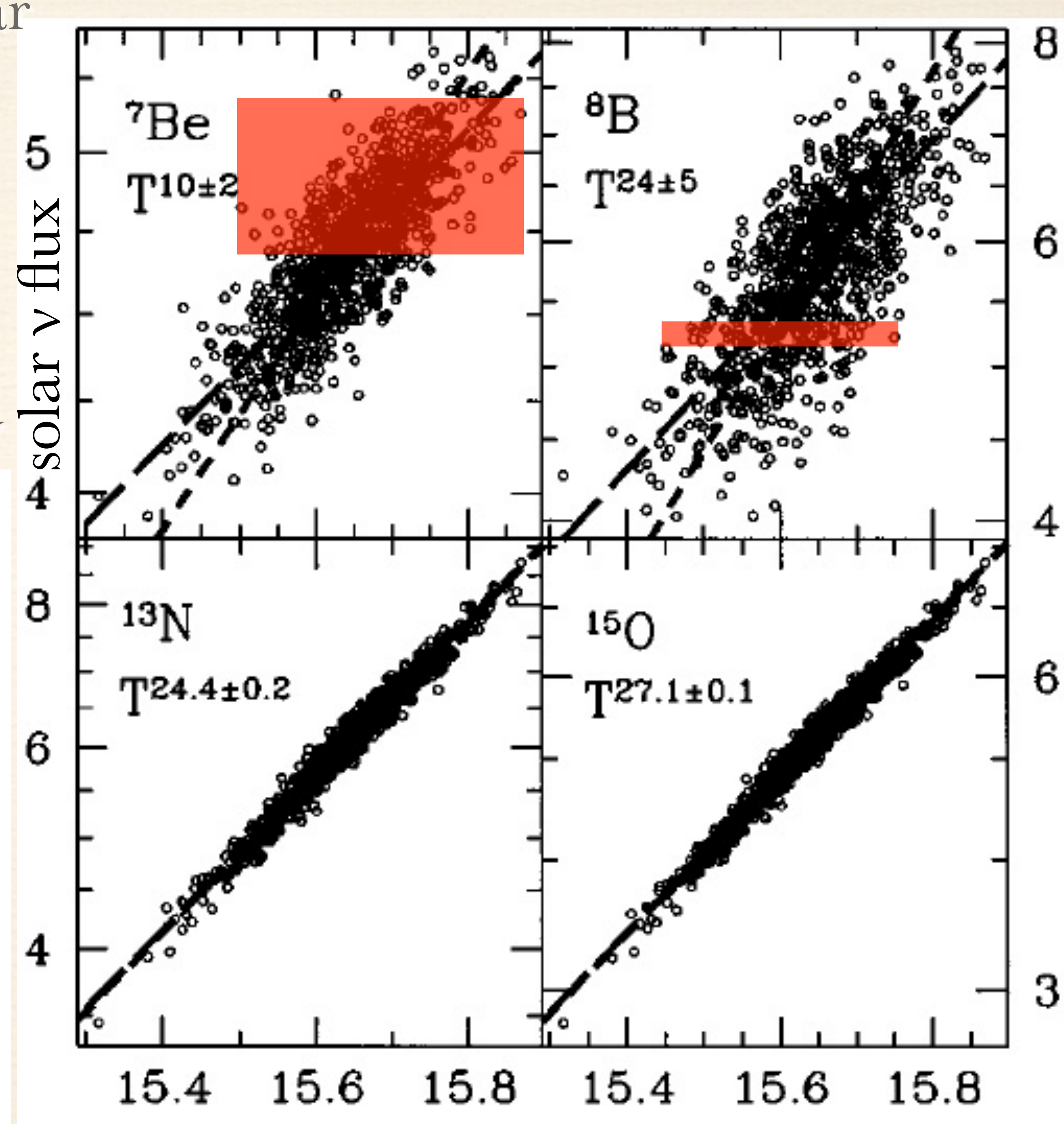

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Mass and Weak Eigenstates

- weak or flavor eigenstate if ν's created by W's (e.g. β^+ decay: ν_e's)
- linear comb. of mass eigenstates (neutrinos with definite mass): e.g. $|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$
- ν's propagate as mass eigenstates, (usual plane wave $e^{i(\vec{p}\cdot\vec{r}-Et)/\hbar}$) $E^2=m^2c^4+p^2c^2$: $p \approx E/c - m^2c^3/(2E)$
- component phases of $|\nu_e\rangle$ shift with time/distance: ν oscillations

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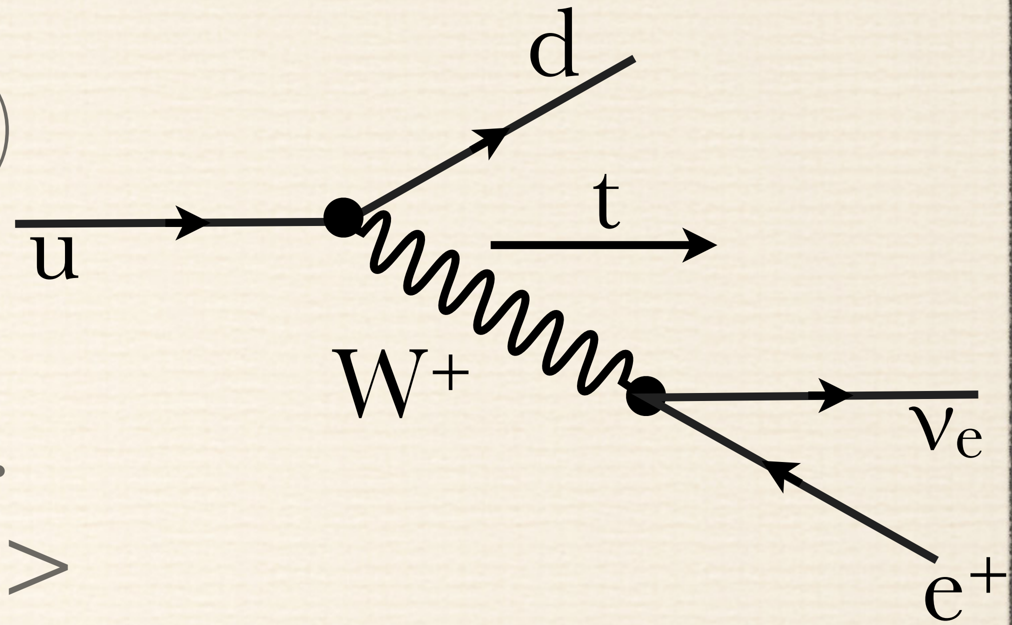

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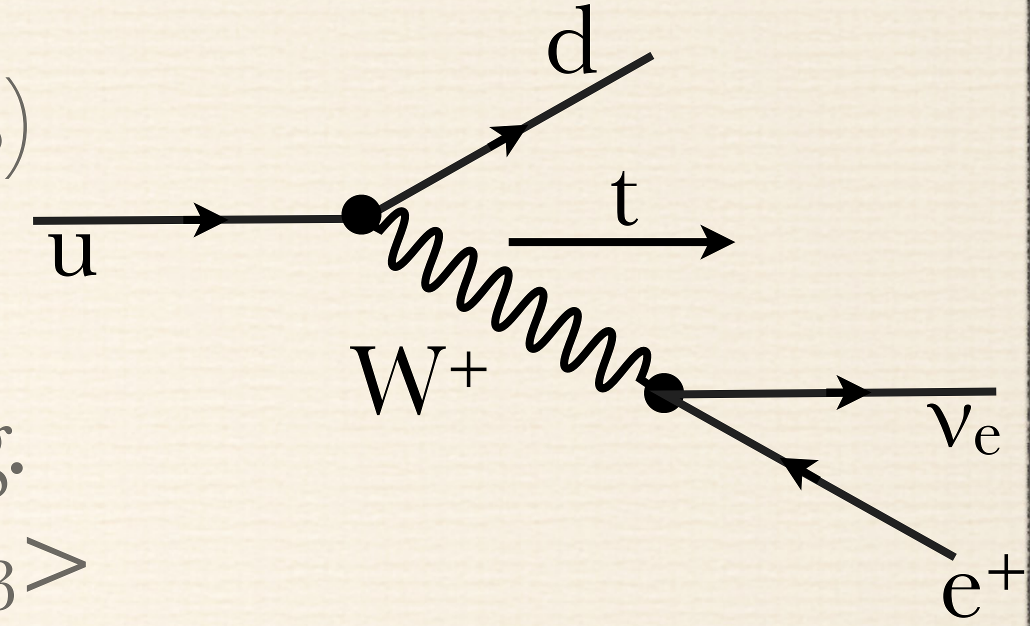

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PMNS Matrix

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1> \\ |\nu_2> \\ |\nu_3> \end{pmatrix}$$

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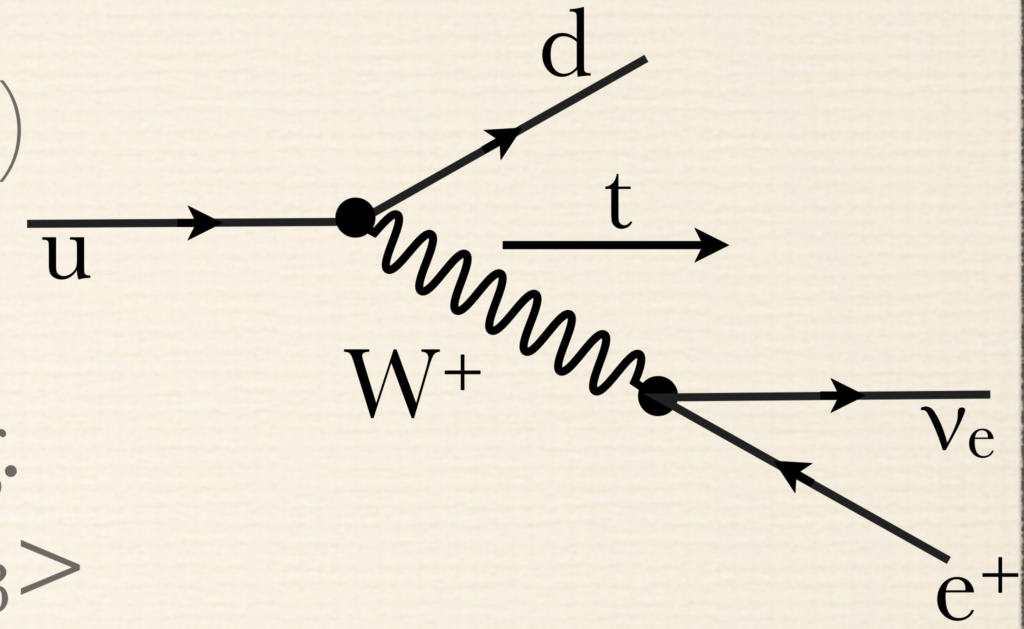

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phase shift after distance L

$$\Delta\varphi_{ij}(L) = \frac{m_i^2 - m_j^2}{2E}\frac{c^3}{\hbar}L = \frac{\Delta m_{ij}^2 c^3}{2E\hbar}L$$

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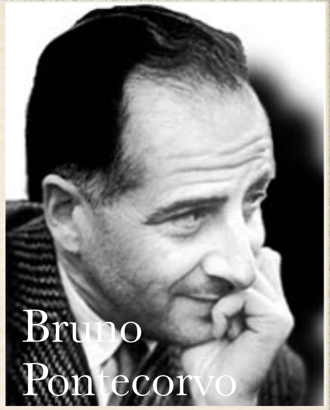
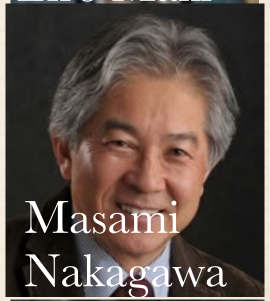
PMNS Matrix
(Pontecorvo-Maki-Nakagawa-Sakata)



- parametrize: three angles, one phase:
  - solar angle θ_{12} governing solar ν oscillation
  - reactor angle θ_{13} governing reactor ν oscillation
  - atmospheric angle θ_{23} governing atm. ν oscillation
  - oscillation CP-violating phase δ (ν beams)
- (two more CP phases α_1, α_2 if ν's are Majorana-particles)
- use $c_{ij}=\cos\theta_{ij}$ and $s_{ij}=\sin\theta_{ij}$,

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

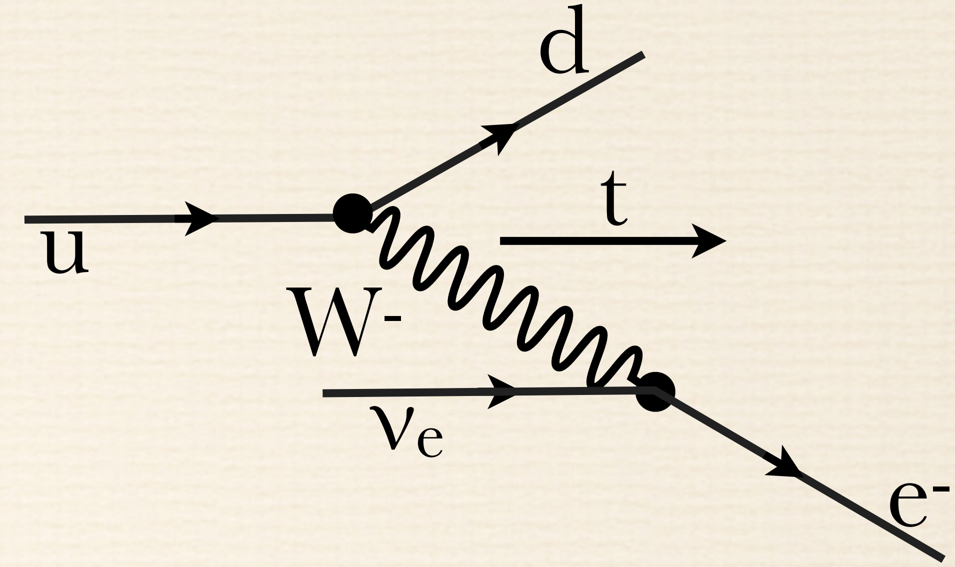


- approximate numerical values:

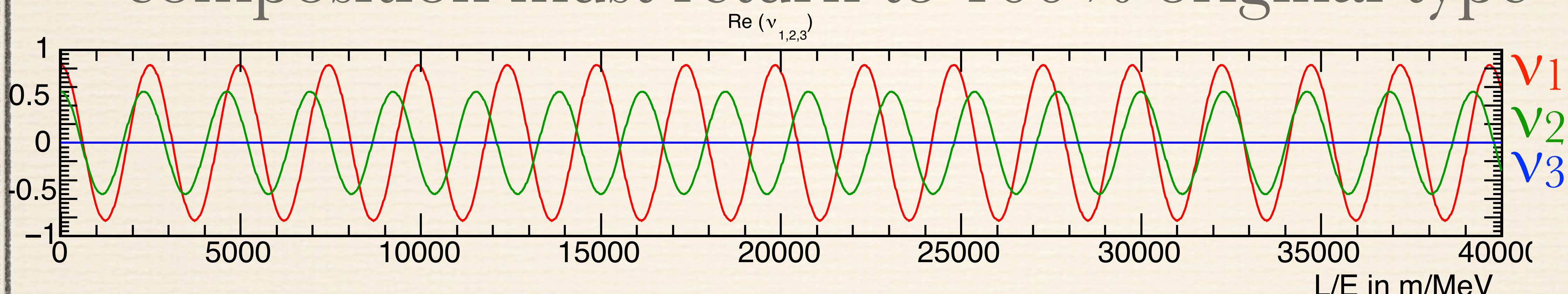
$$\begin{pmatrix} 0.826 & 0.544 & 0.075+i0.130 \\ -0.462+i0.070 & 0.613+i0.046 & 0.635 \\ 0.305+i0.083 & -0.569+i0.055 & 0.757 \end{pmatrix}$$

Neutrino Flavor Oscillation

- when neutrinos are detected by conversion to lepton (W's): after distance L there probability of detecting a different type



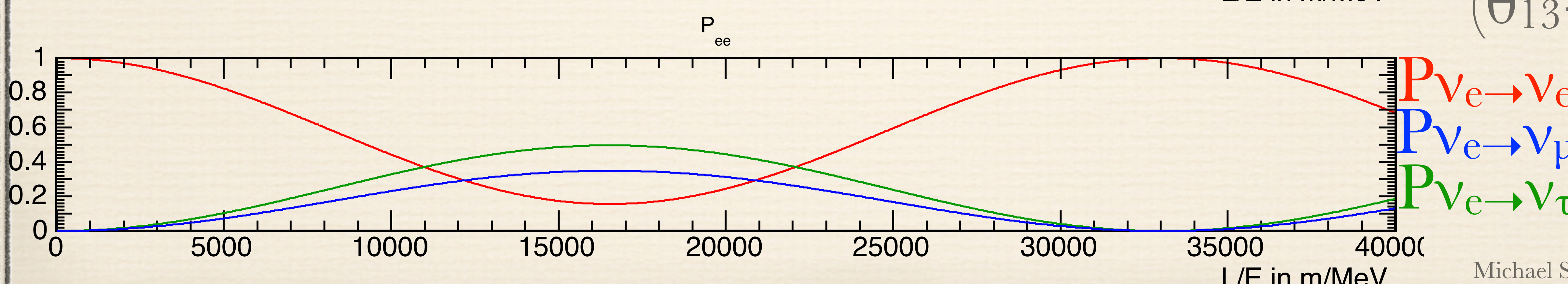
- "disappearance" of production type may not be complete at any L, but composition must return to 100% original type



ν_e: $\nu_1+\nu_2$

$\nu_{\mu/\tau}$: $\nu_1-\nu_2$

($\theta_{13}=0$)



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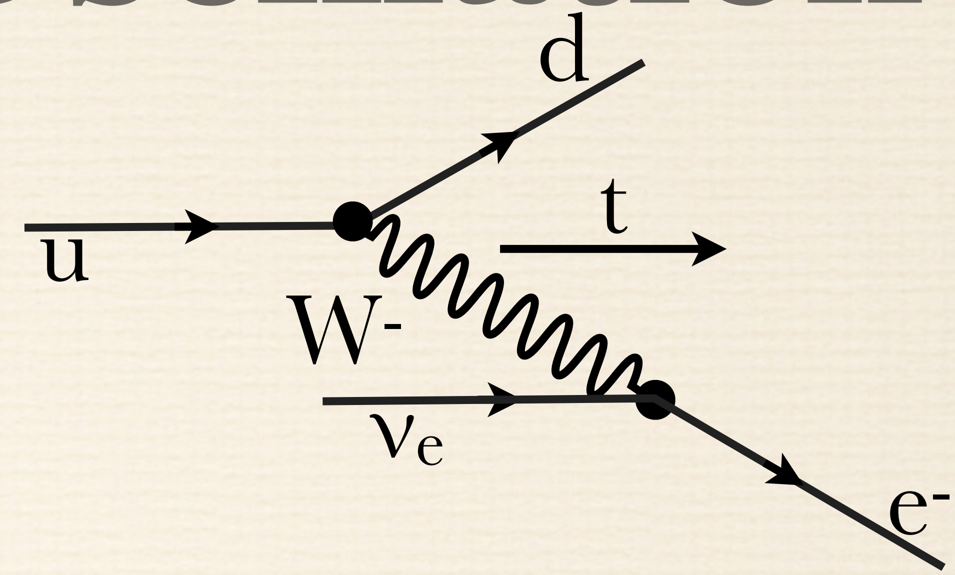

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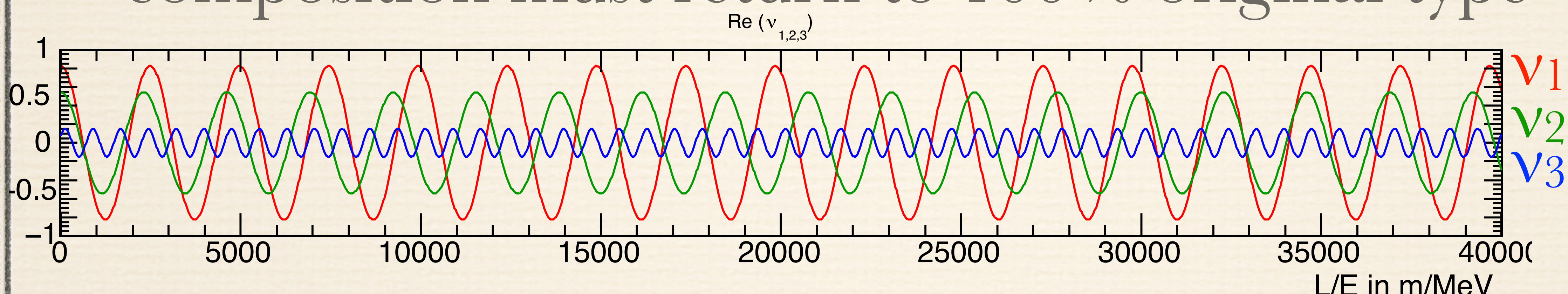

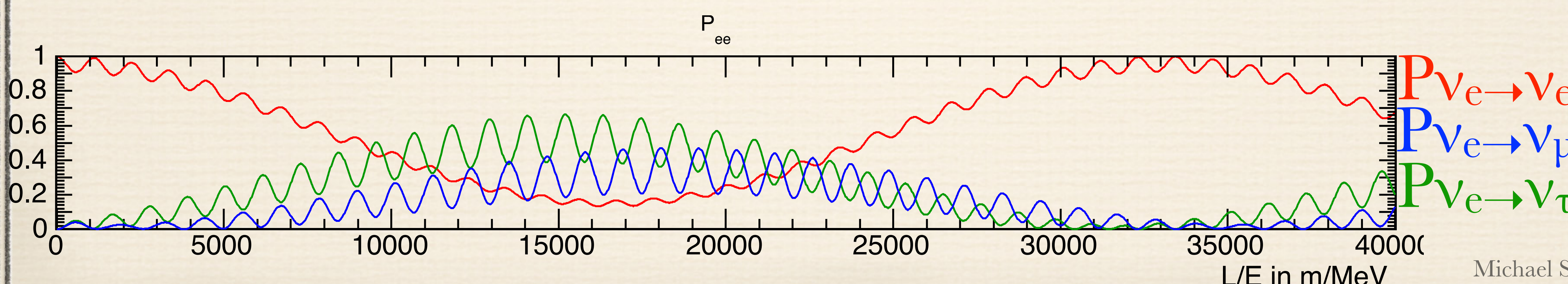

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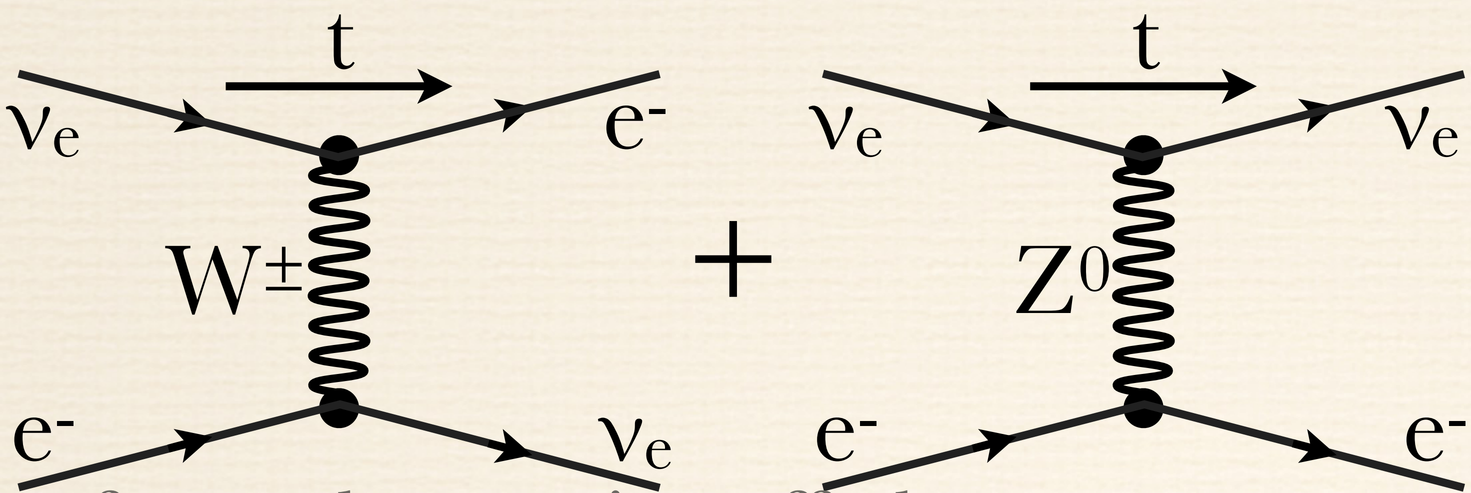
Quark and Lepton Mixing

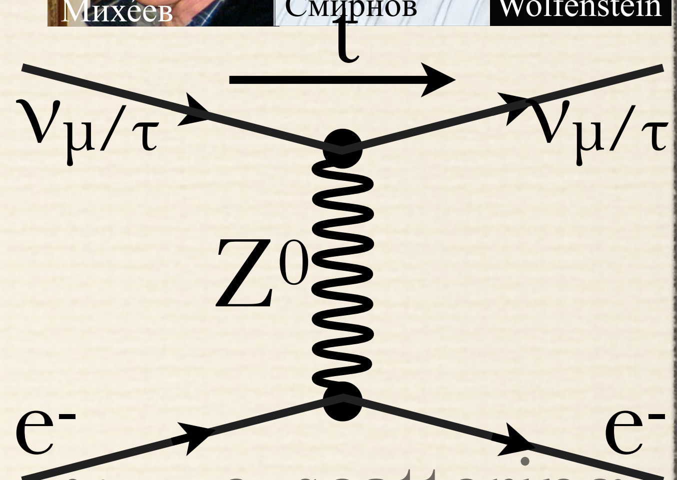
- in weak interactions, down-type quarks mix just as ν's
- quark mixing angles are small; biggest is Cabibbo Angle
- big neutrino mixing angles: first discovered by Super-K in 1998 (θ_{23} from atm. ν), 2000 (θ_{12} from solar ν) and Super-K/T2K in 2011 (θ_{13} from an intense ν-beam)
- now: θ_{12} from Super-K/SNO, θ_{13} from Daya-Bay/ Reno/Double Chooz, θ_{23} from Super-K/T2K

	θ_{12}	θ_{13}	θ_{23}	δ
quarks	13.04	0.201	2.38	69
leptons	33.36	8.66	40.0 or 50.4	300

MSW Effect



ν_e forward-scattering off electrons

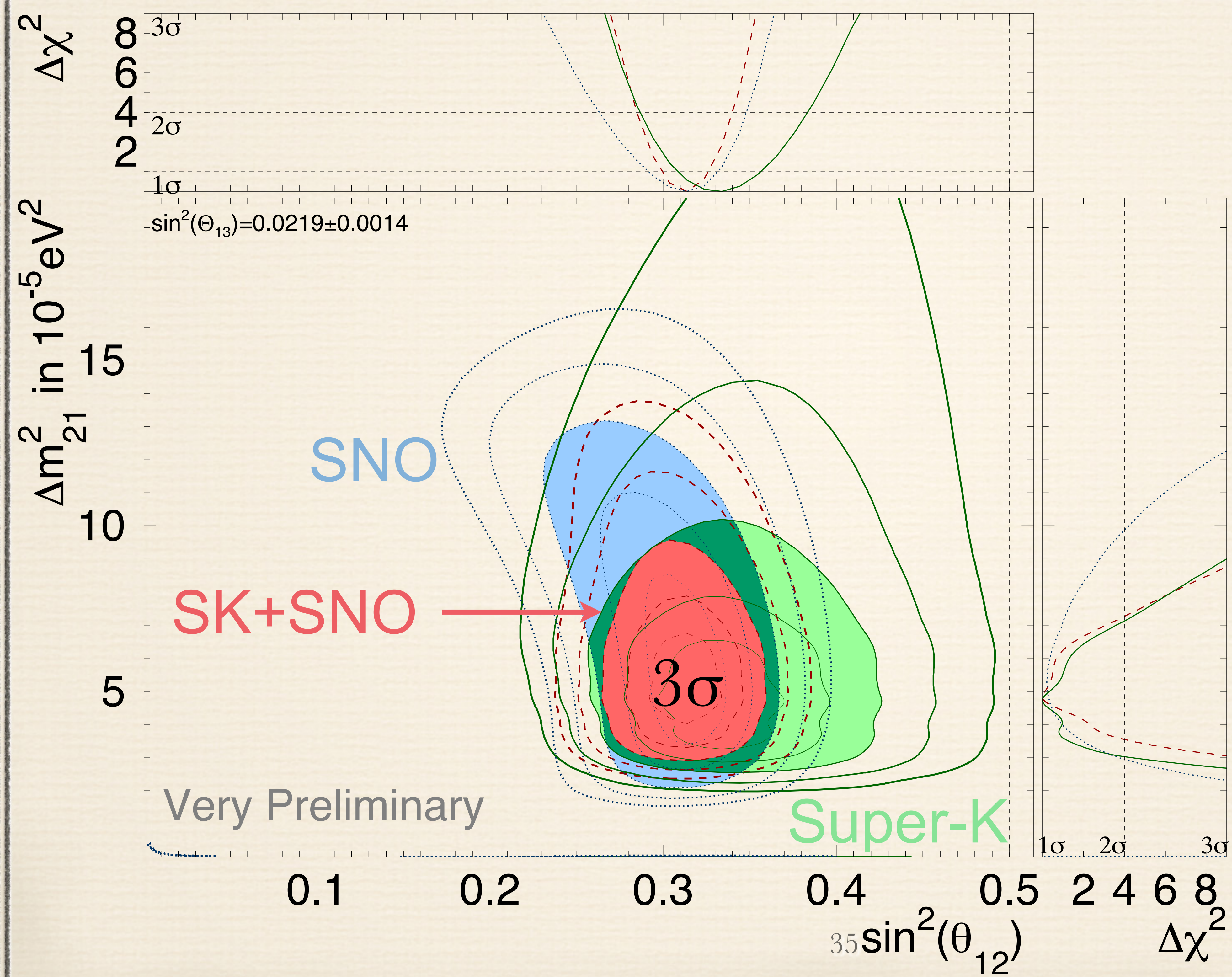


$\nu_{\mu/\tau}$-e^- scattering

- matter interactions: phase shifts affecting ν oscillations
- resonant conversion to ν_2 if ρ_e changes adiabatic adiabatically
- extra "potential" of ν_e (compared to $\nu_{\mu/\tau}$) in a "Hamiltonian"
- similar to light propagation in medium ("index of refraction"), use effective mixing angle and Δm^2

$$H_{matter} = \kappa\rho_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \frac{1}{2E} U^\dagger_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U_{PMNS} \qquad \kappa = \sqrt{2} G_F$$

Solar ν Angle θ_{12} & Mass² Difference



- Super-K data best constrains Δm^2_{21}
- SNO data best constrains $\sin^2\theta_{12}$
- correlation via ^{8}B flux adds to complementarity

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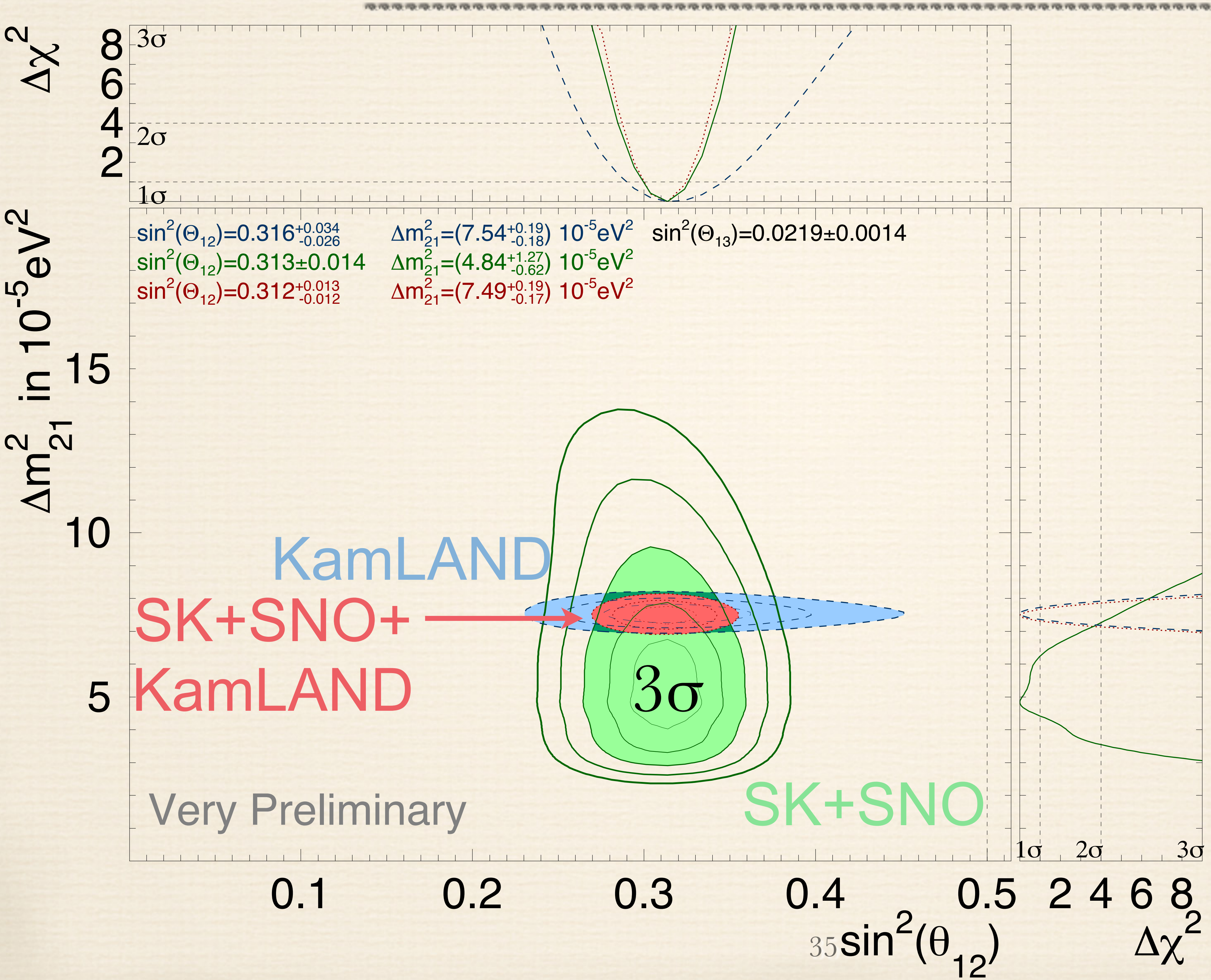

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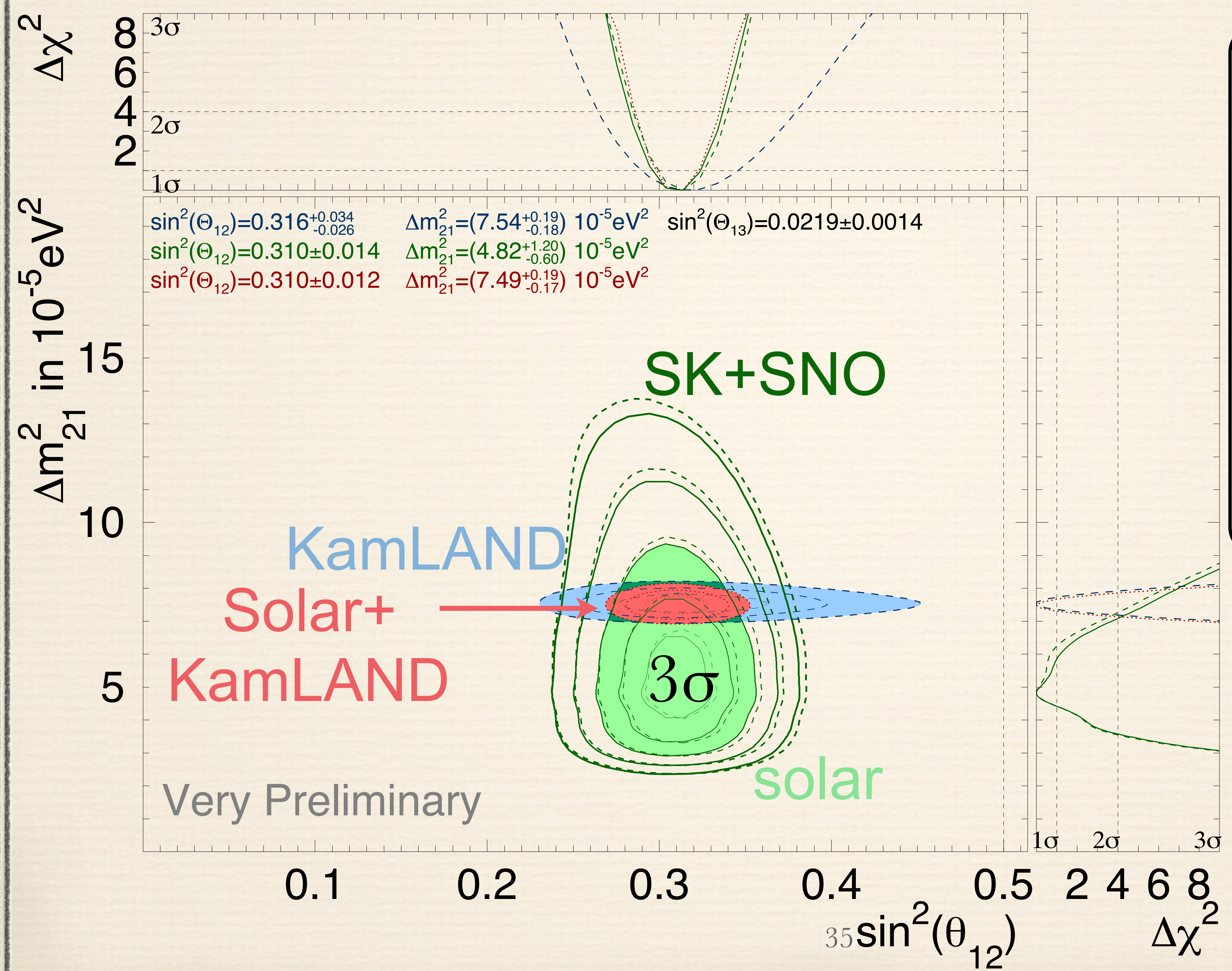

$\sin^2\theta_{12} = 0.310\pm0.014$
$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60} \times10^{-5}eV^2$

$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times10^{-5}eV^2$

$\sin^2\theta_{12} = 0.310\pm0.012$
$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times10^{-5}eV^2$

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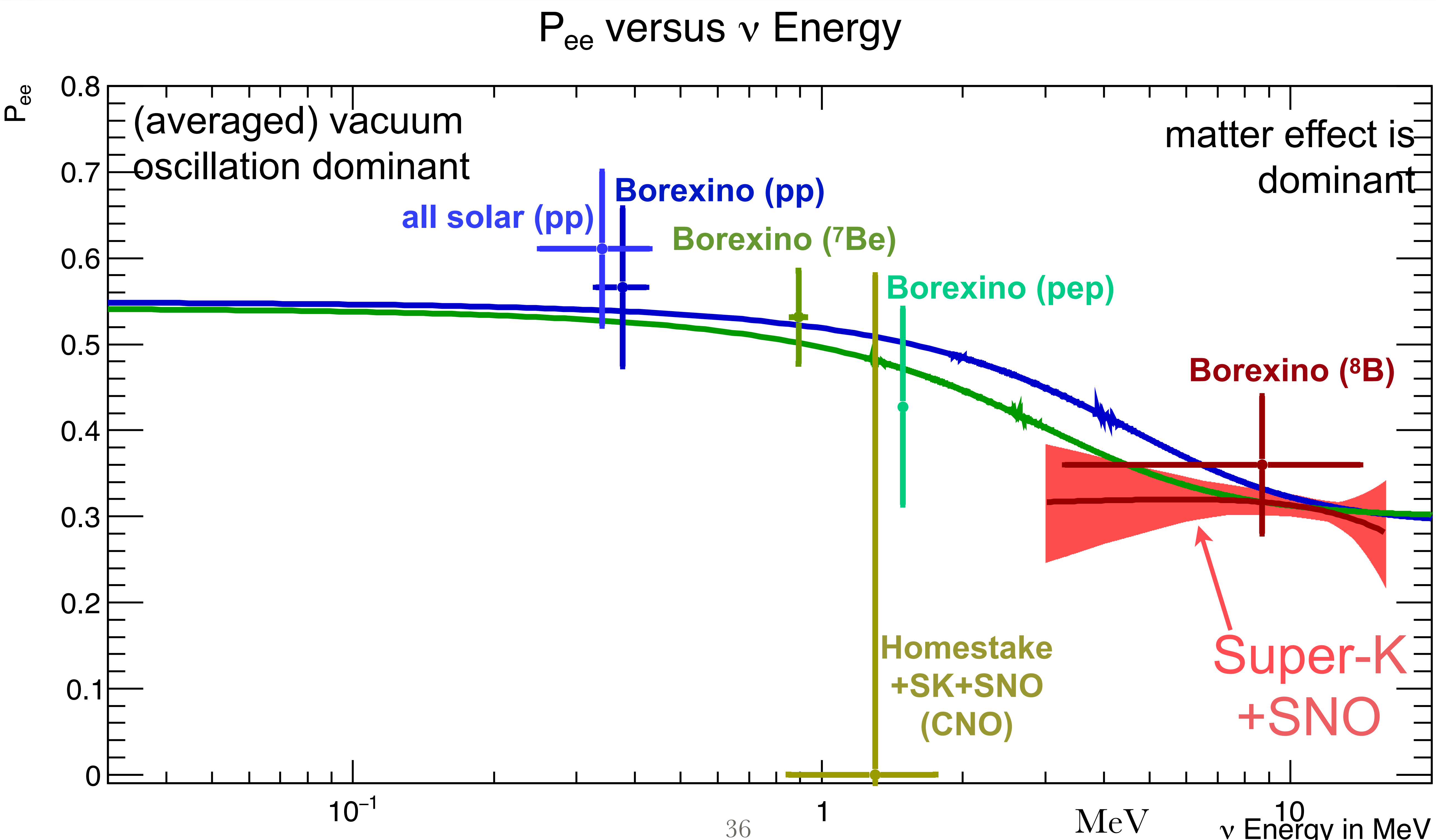
Solar Neutrino Flavor Conversion



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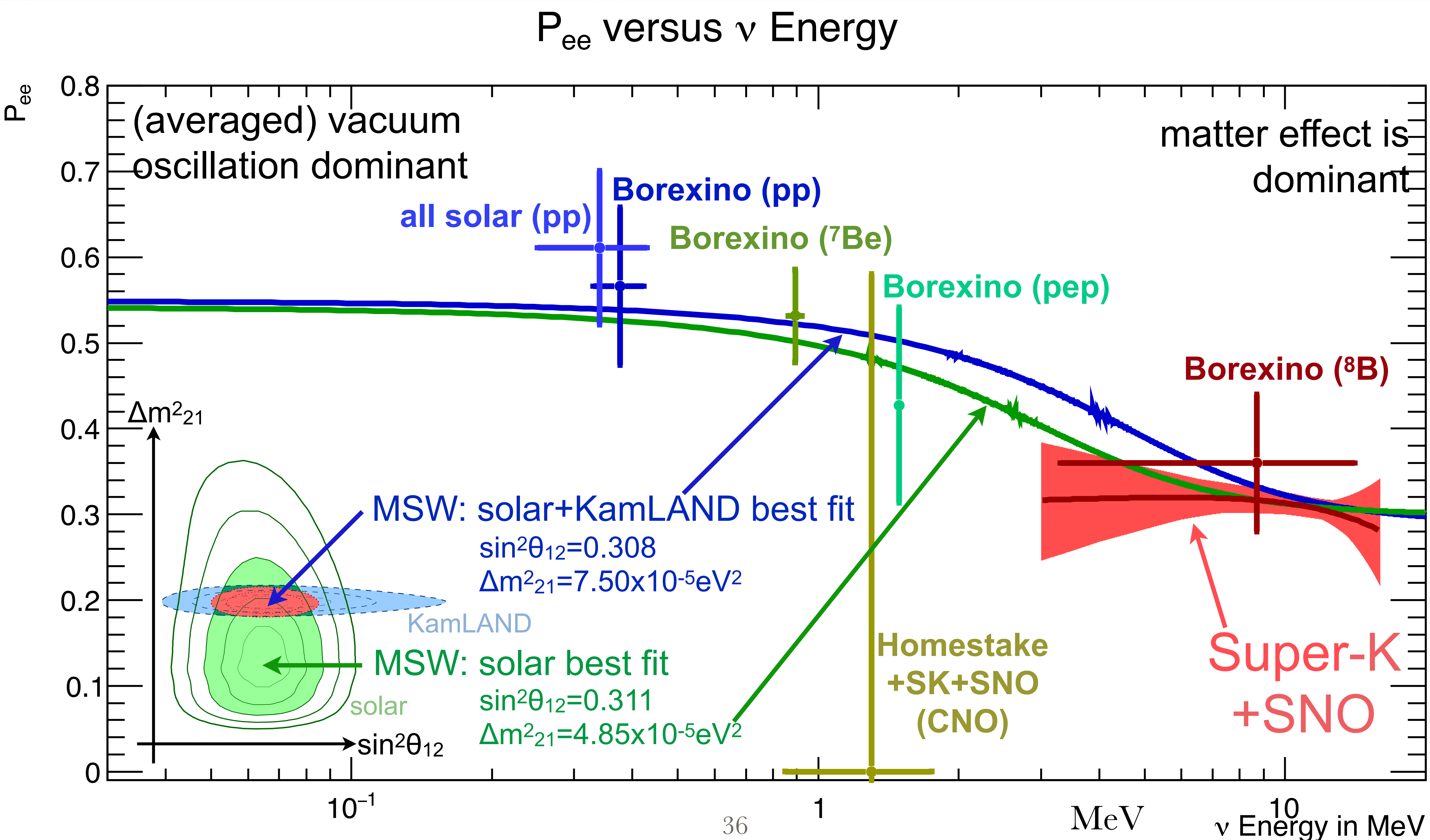

MeV

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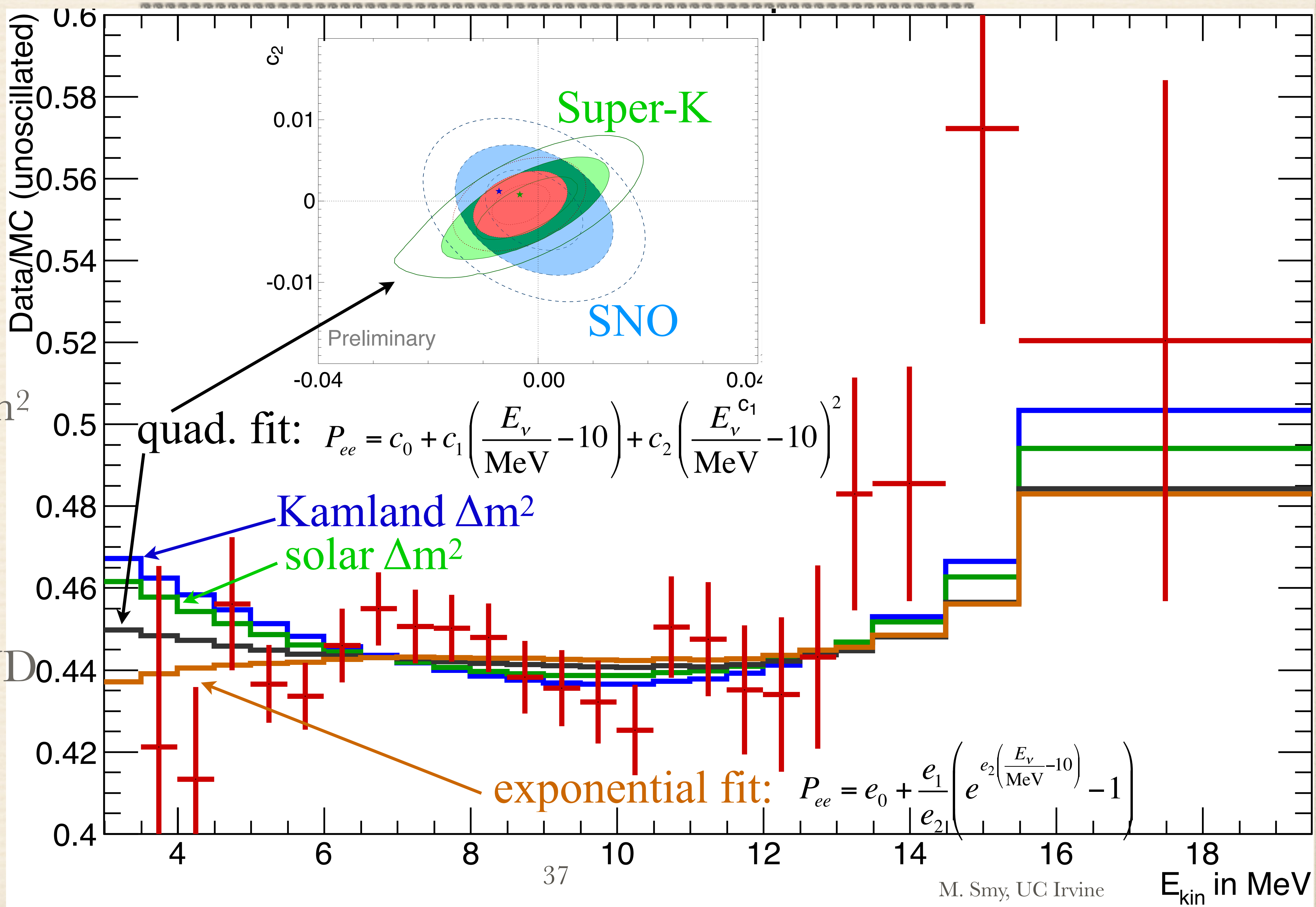
Test Resonant Conversion in the Sun (MSW)

latest Super-K recoil e- spectral data: consistent with solar best fit Δm^2 within 1σ, but ~2σ tension with KamLAND measure-ment



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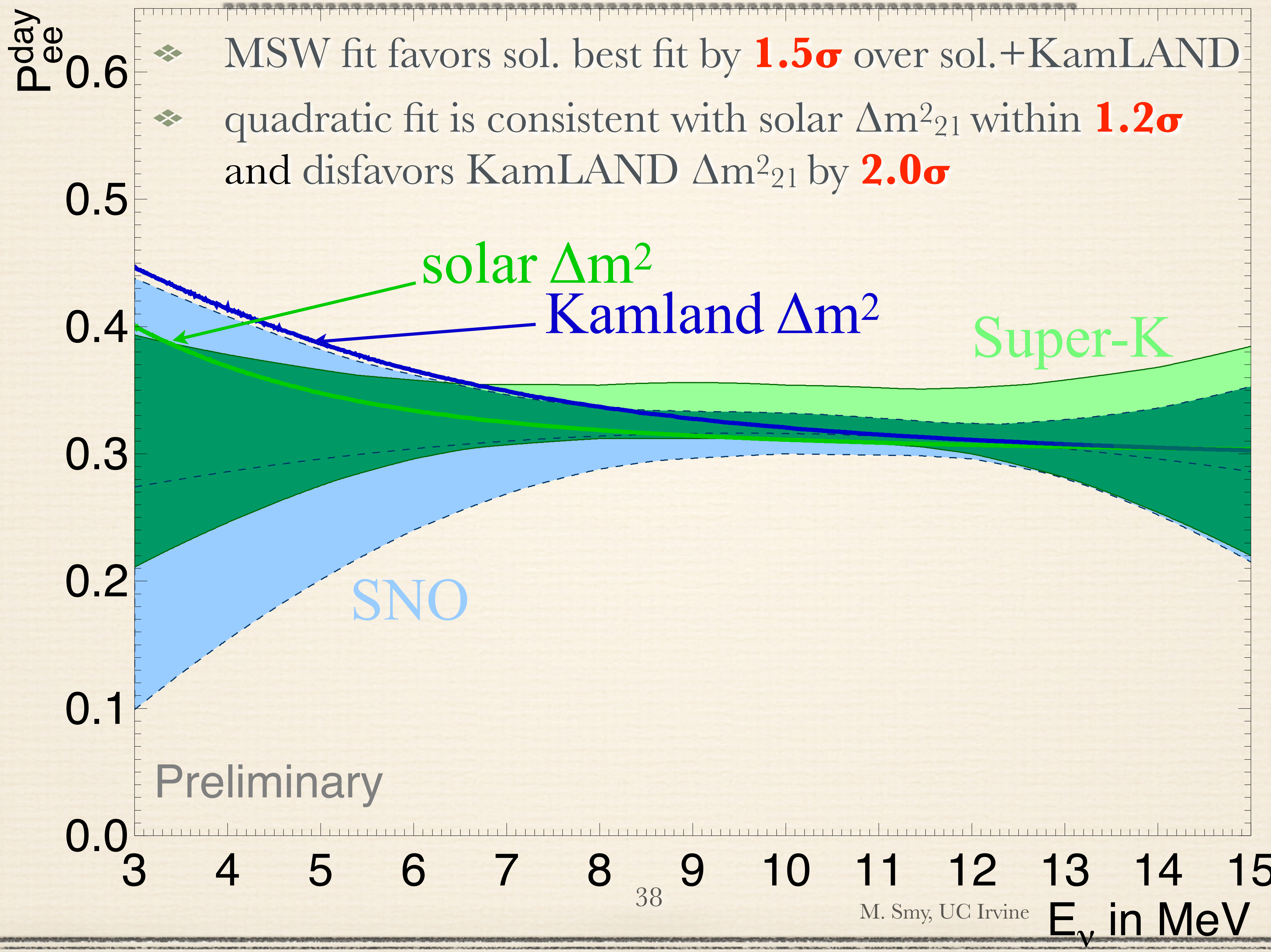
Super-K and SNO: resulting P_{ee}

- MSW fit favors sol. best fit by **1.5σ** over sol.+KamLAND
- quadratic fit is consistent with solar Δm^2_{21} within **1.2σ** and disfavors KamLAND Δm^2_{21} by **2.0σ**



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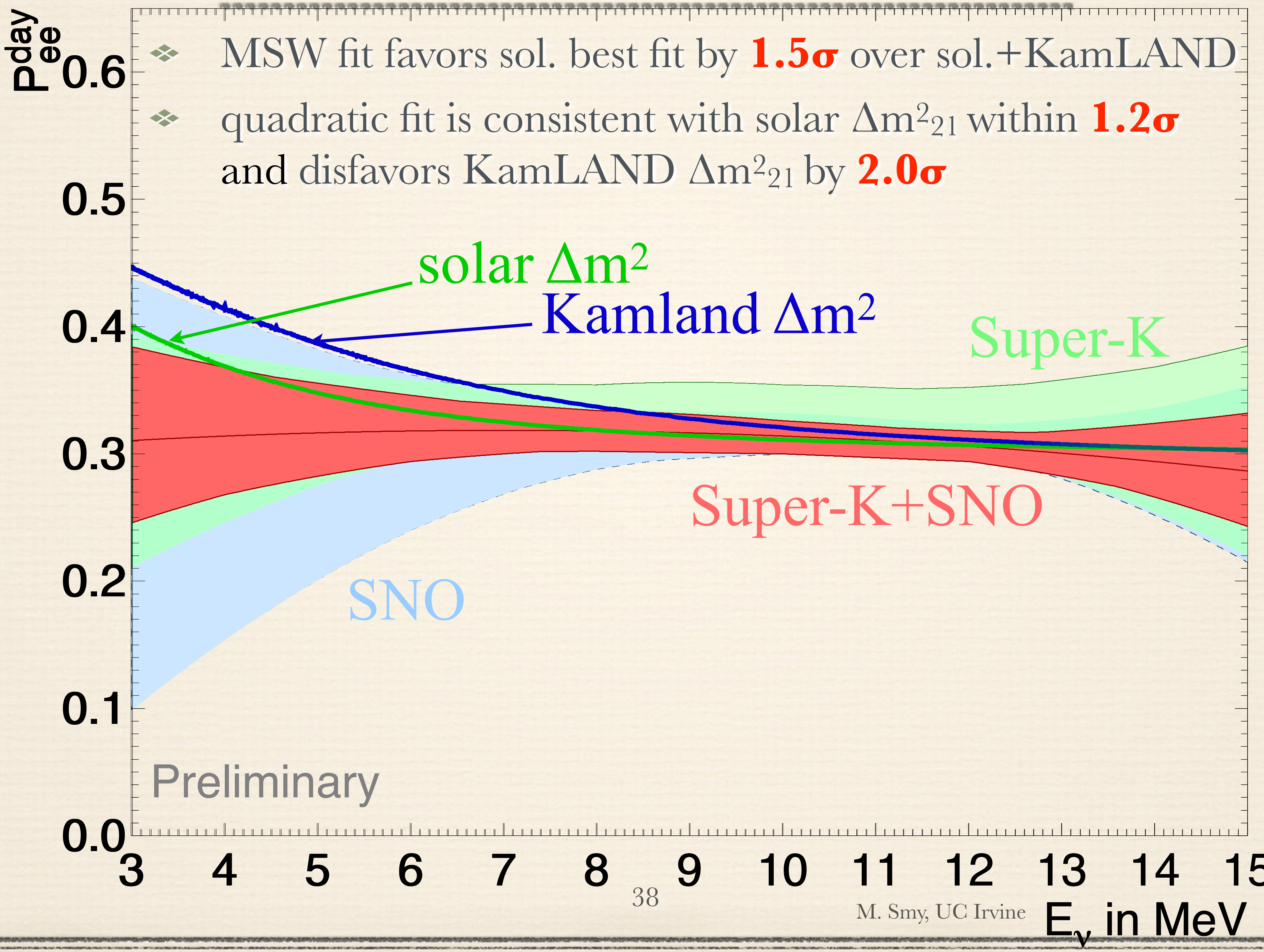

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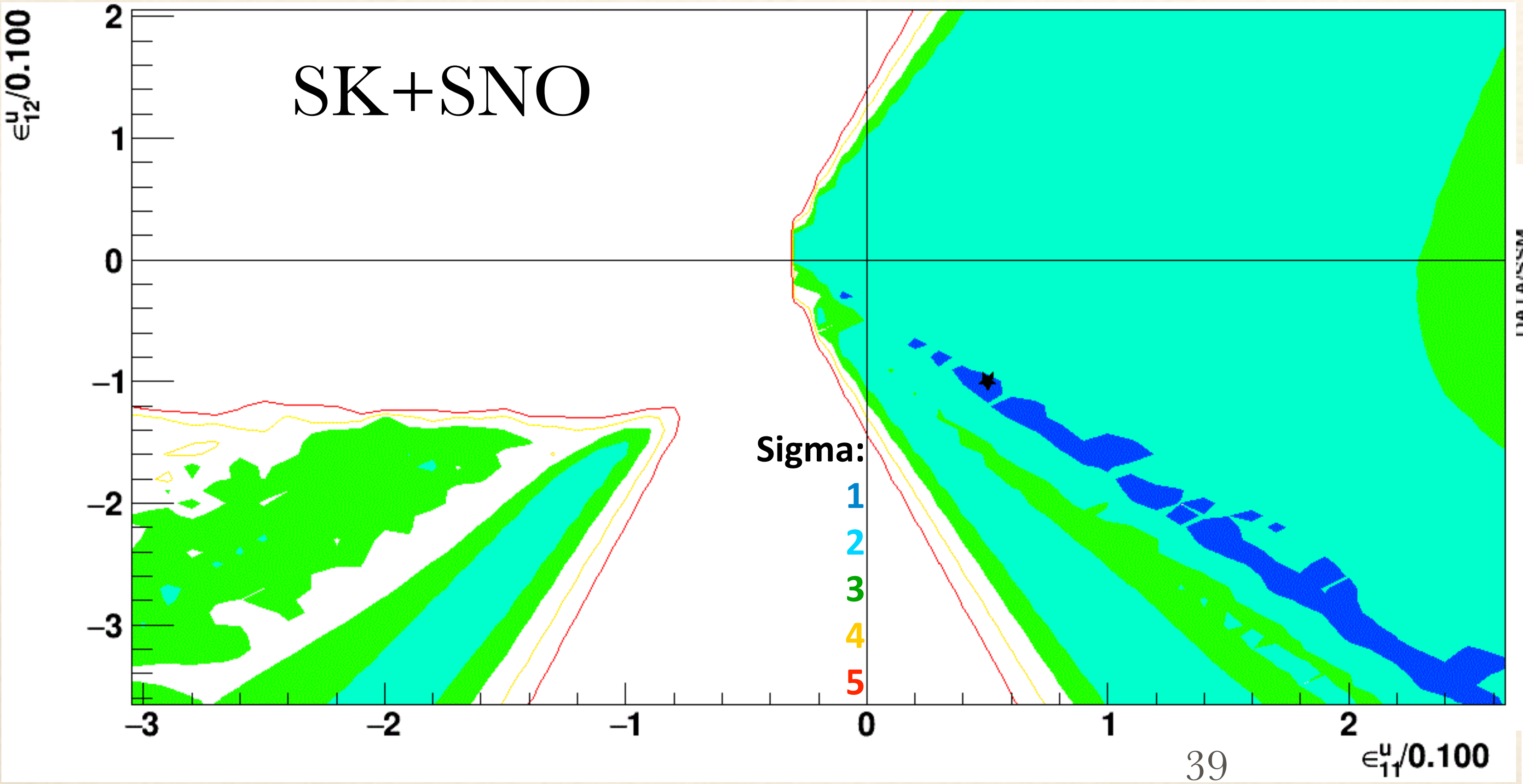
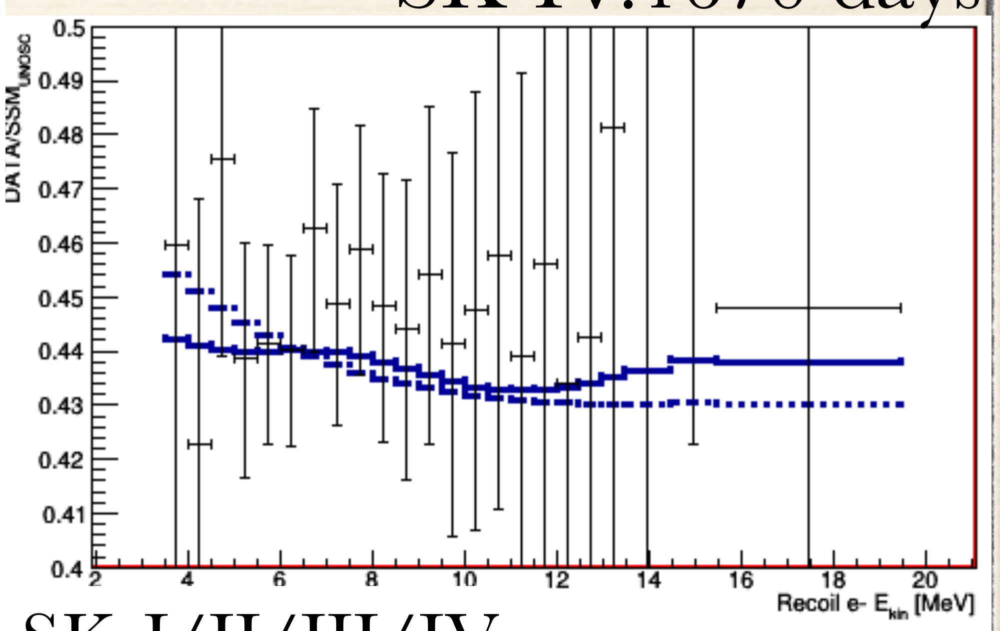
Non-Standard Neutrino Interactions

- extend Hamiltonian $H_{matter} = \kappa\rho_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \frac{1}{2E} U^\dagger_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U_{PMNS}$
- is able to explain the lack of spectral distortion
- to reduce # of parameters, use ε_{11}, and ε_{12} (mass basis) instead of ε_{ee}, $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$
- one ε_{ij} is sum of electron-, up-quark, down-quark terms; turn each on by itself



up-quark

SK-IV:1670 days



SK-I/II/III/IV

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Non-Standard Neutrino Interactions

- extend Hamiltonian $H_{matter} = \kappa\rho_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon^*_{e\mu} & \varepsilon^*_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon^*_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix} + \frac{1}{2E} U^\dagger_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U_{PMNS}$
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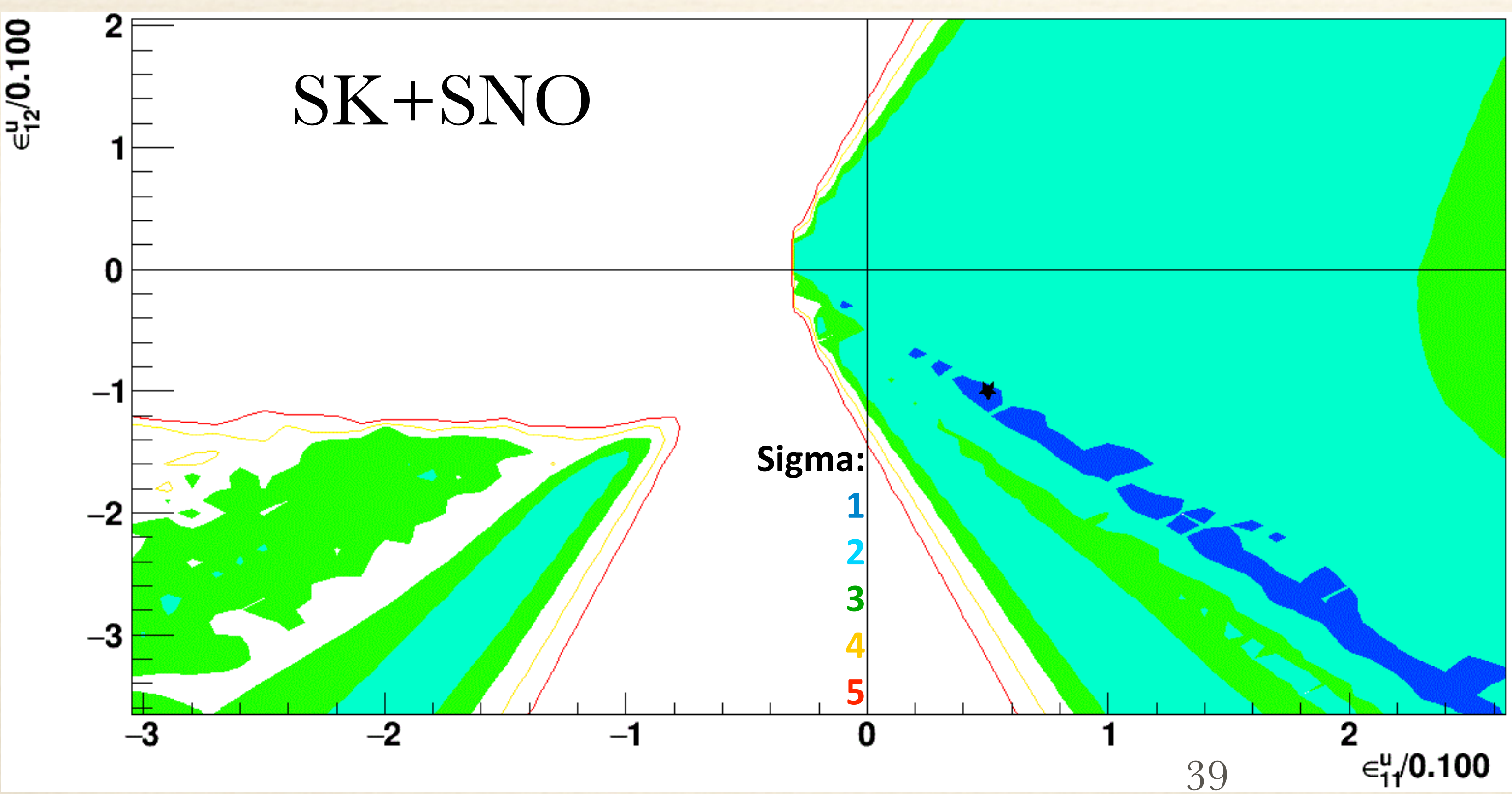
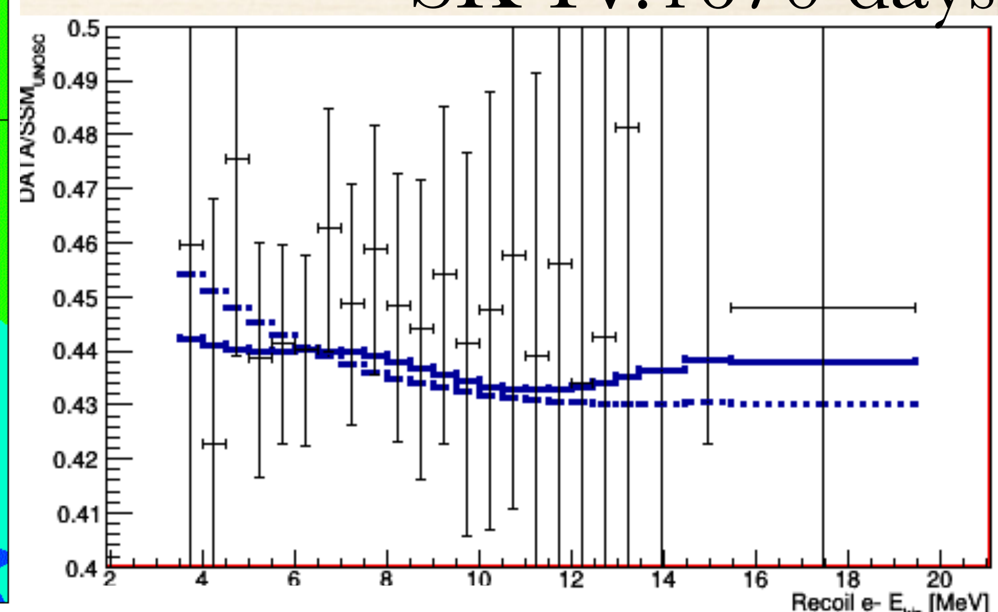


up-quark

SK-IV:1670 days



SK-I/II/III/IV

Non-Standard Neutrino Interactions

- extend Hamiltonian $H_{matter} = \kappa\rho_e \begin{pmatrix} 1+\varepsilon_{ee} & 0 & \varepsilon_{e\tau}^{*} \\ 0 & 0 & 0 \\ \varepsilon_{e\tau} & 0 & \varepsilon_{\tau\tau} \end{pmatrix} + \frac{1}{2E} U_{PMNS}^{\dagger} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U_{PMNS}$
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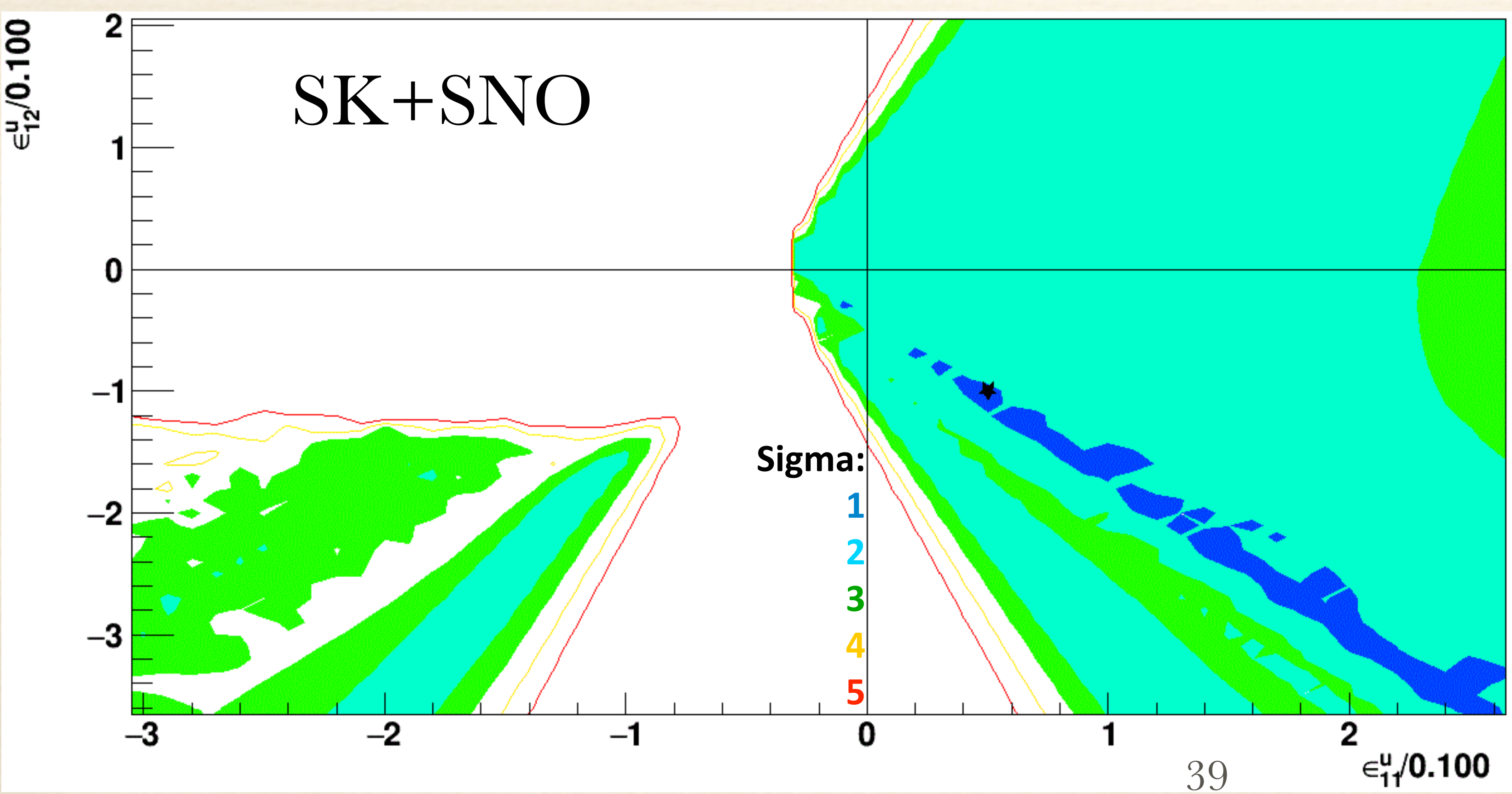
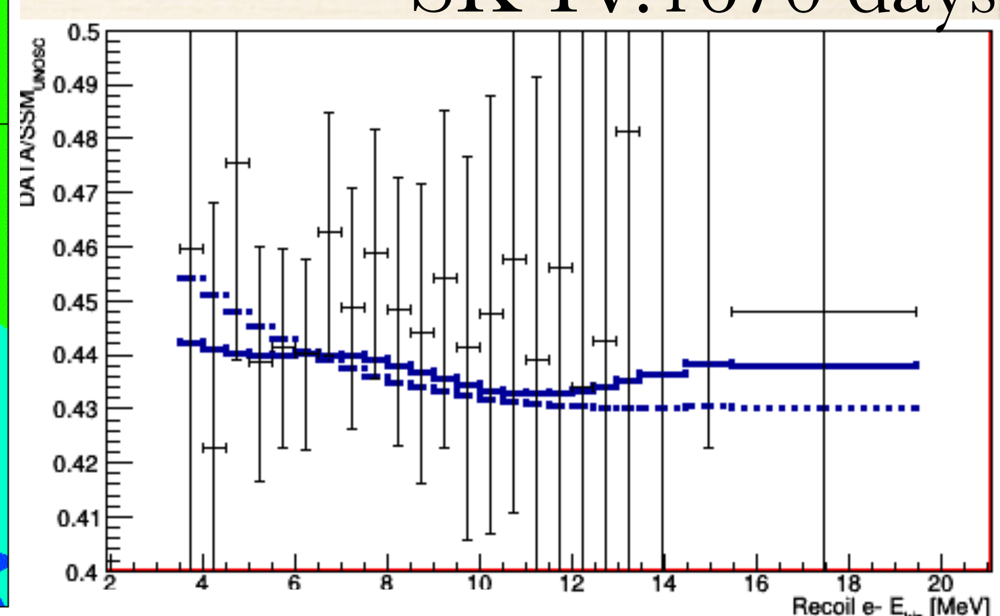


up-quark

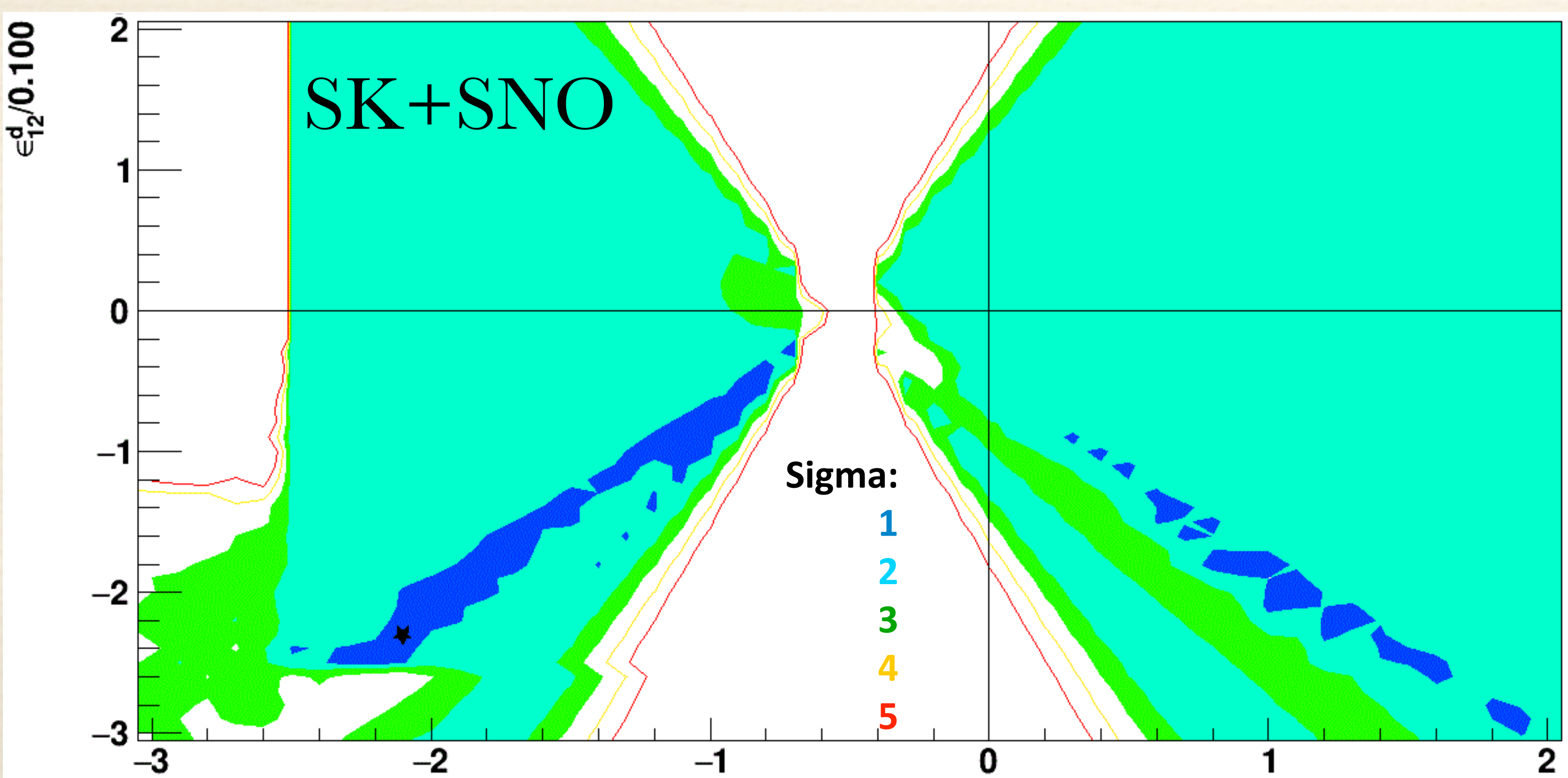
SK-IV:1670 days



SK-I/II/III/IV

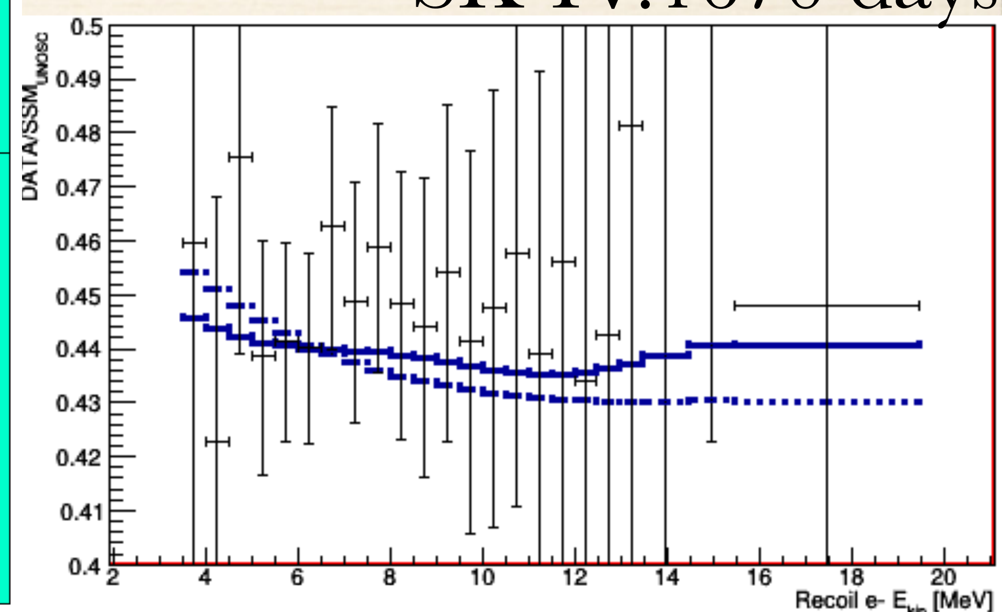
Non-Standard Neutrino Interactions

- extend Hamiltonian $H_{matter} = \kappa\rho_e \begin{pmatrix} 1+\varepsilon_{ee} & 0 & \varepsilon^*_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon_{e\tau} & 0 & \varepsilon_{\tau\tau} \end{pmatrix} + \frac{1}{2E} U^\dagger_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U_{PMNS}$
- is able to explain the lack of spectral distortion
- to reduce # of parameters, use ε_{11}, and ε_{12} (mass basis) instead of ε_{ee}, $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$
- one ε_{ij} is sum of electron-, up-quark, down-quark terms; turn each on by itself



down-quark

SK-IV:1670 days

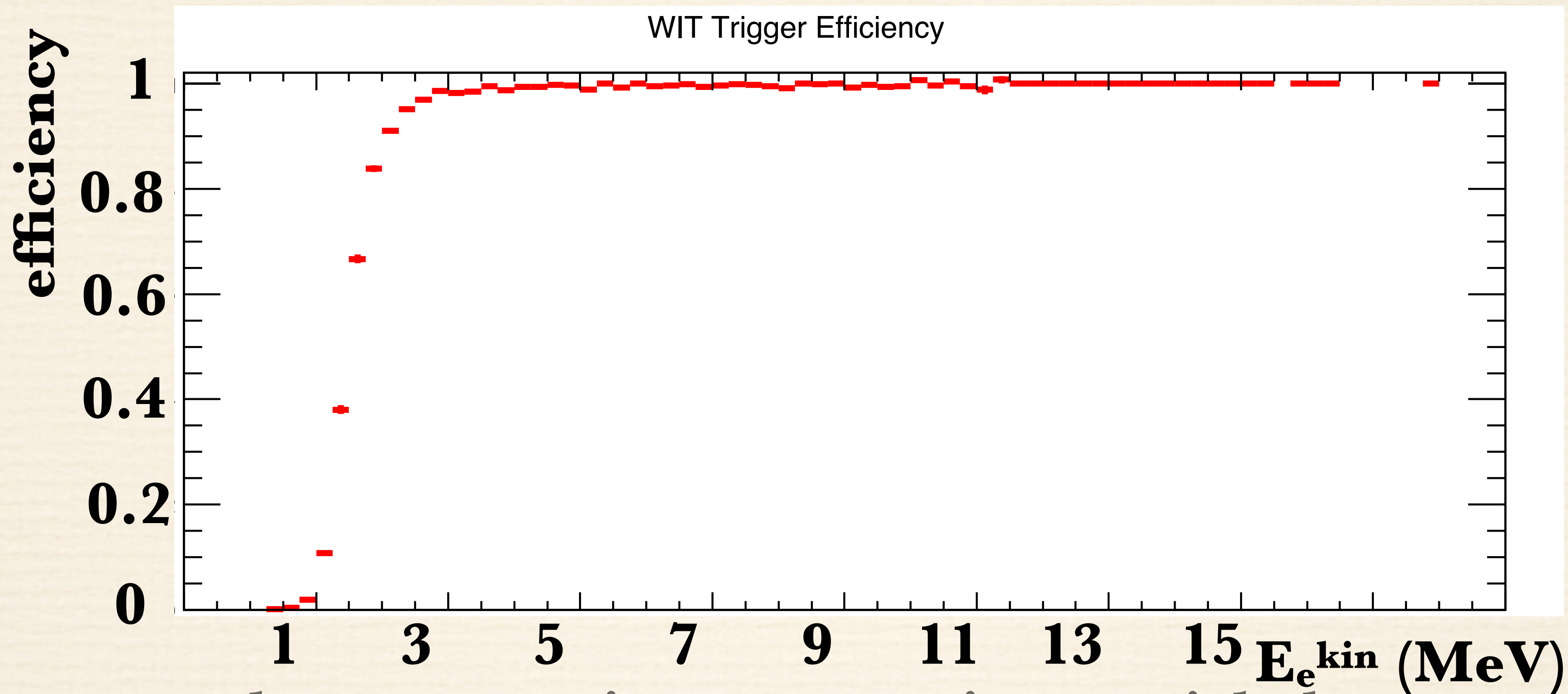


SK-I/II/III/IV

M. Smy, UC Irvine

Probe MSW: Future Improvements

- lower threshold: Wideband Intelligent Trigger has >90% efficiency for kinetic energies >2.5 MeV



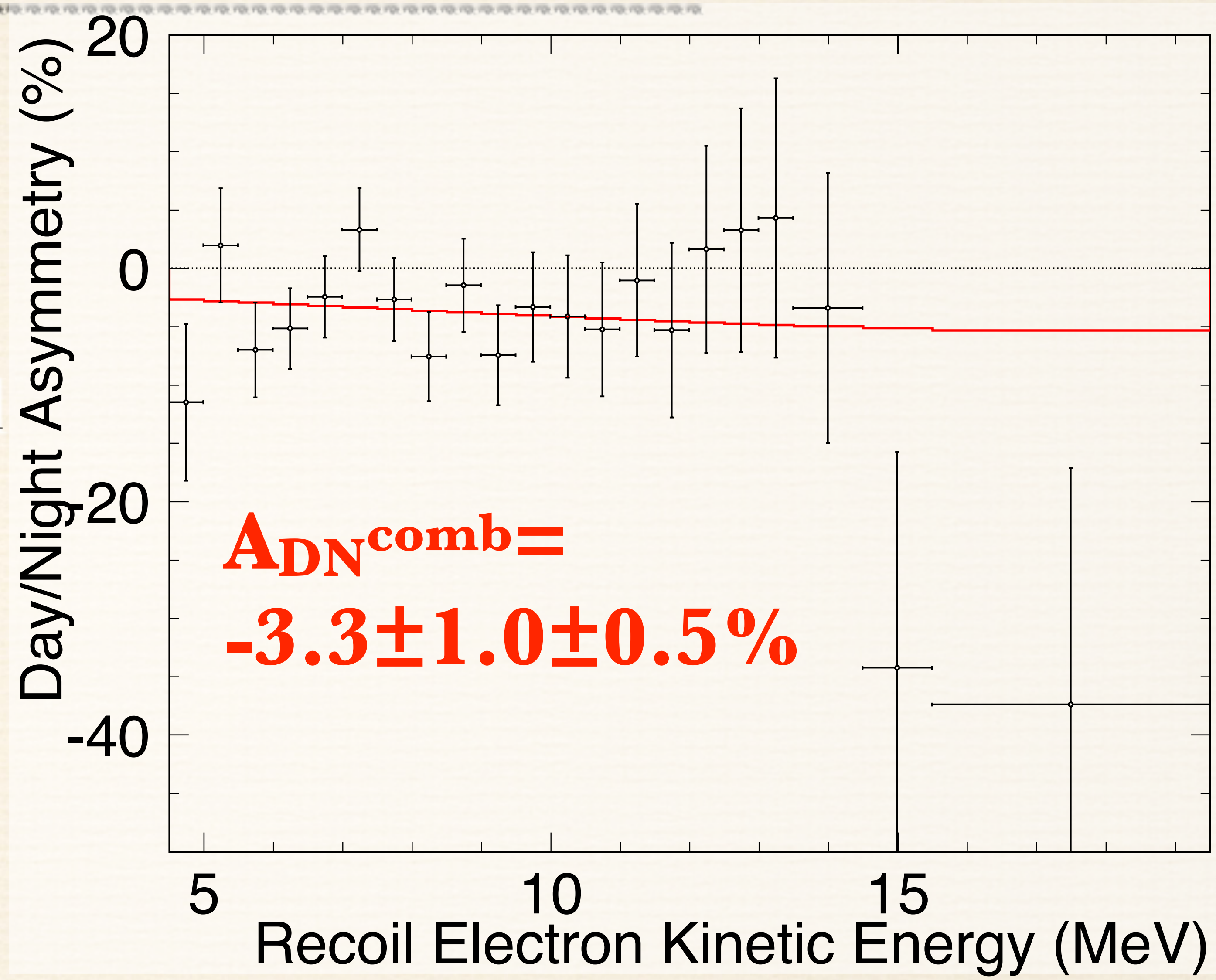
- smaller spectral systematic uncertainty with better calibration:
  - linear accelerator injecting single electrons with E=5-18 MeV
  - Deuterium-Tritium generator to make ^{16}N with 14 MeV n's
  - Cosmic μ Spallation products

Earth Matter Effects

- direct test: compare flavor content of the same "beam" with and without matter being present
- with current parameters: no effect below few MeV; large effect near ~50 MeV, a few % for ^{8}B neutrinos
- form asym. $A_{DN}=2(D-N)/(D+N)$
- mostly a "regeneration" effect: $P_{ee}^{night}>P_{ee}^{day}$ $(A<0)$
- searched for by Super-K, SNO (E_ν>few MeV) and BOREXINO (E_ν=0.86 MeV)
- no significant non-zero A_{DN} from SNO or BOREXINO
- 2.8σ indication from Super-K

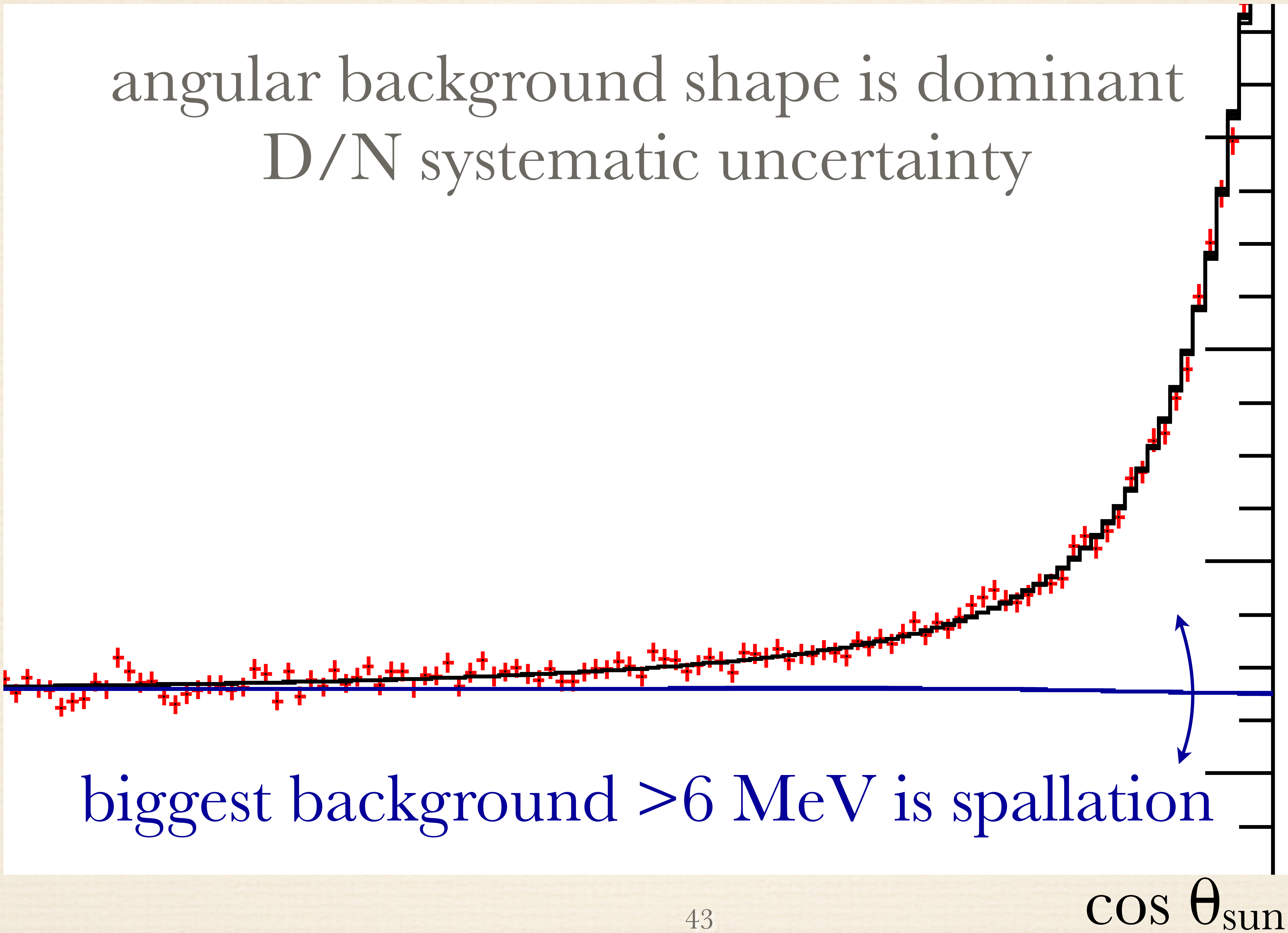
Super-K Result and its Future

- currently ~3σ significance for $A_{DN}\neq 0$
- Super-K-IV uncertainty by itself is ±1.6±0.6%, with full data set (60% more data), it should reach ±1.3±0.4%
- combined $\sigma_{A_{DN}}$=0.9±0.4%
- expect ~3.4σ significance, if same central value



to reach >5σ in reasonable time, need larger event rate, reduction in systematic uncertainty, better control of spallation background will achieve both

D/N Systematic Uncertainty



Michael Smy, UC Irvine

Nuclear Spallation Background in Water

- mechanism: muon occasionally starts showers,
- some showers contain hadrons; e.g. neutrons or, $\pi^{\pm}$
- these break up the oxygen nucleus and change them to radioactive elements: ^{16}N, ^{12}B, and many others
- after some msec's to sec's, these elements $\beta\gamma$ decay and make background
- the decay locations are close to the muon tracks, but directly correlate with the volume covered by the shower

★^{16}O

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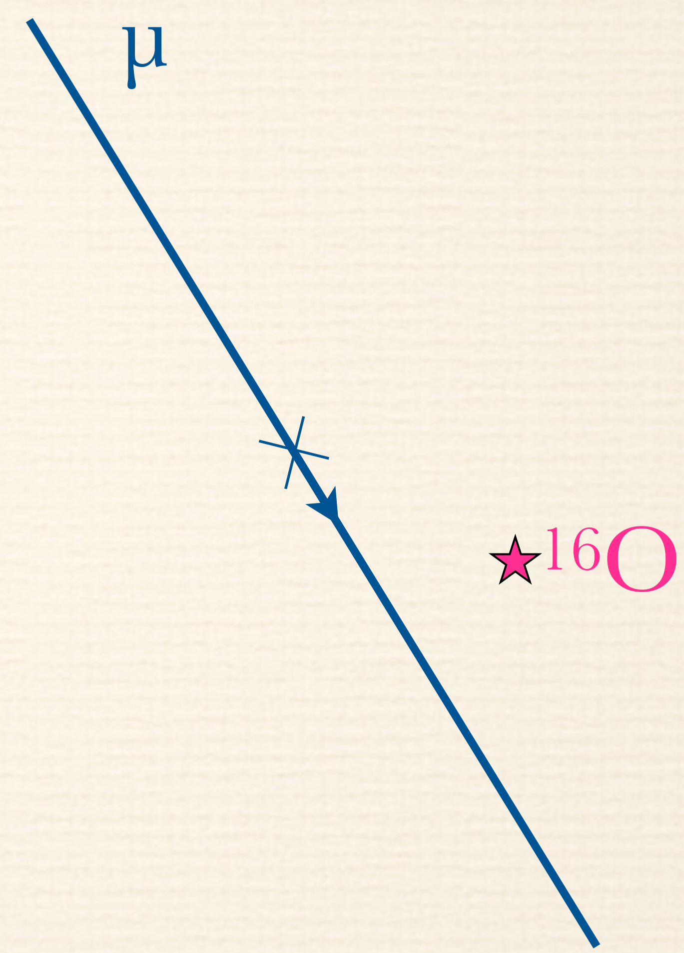

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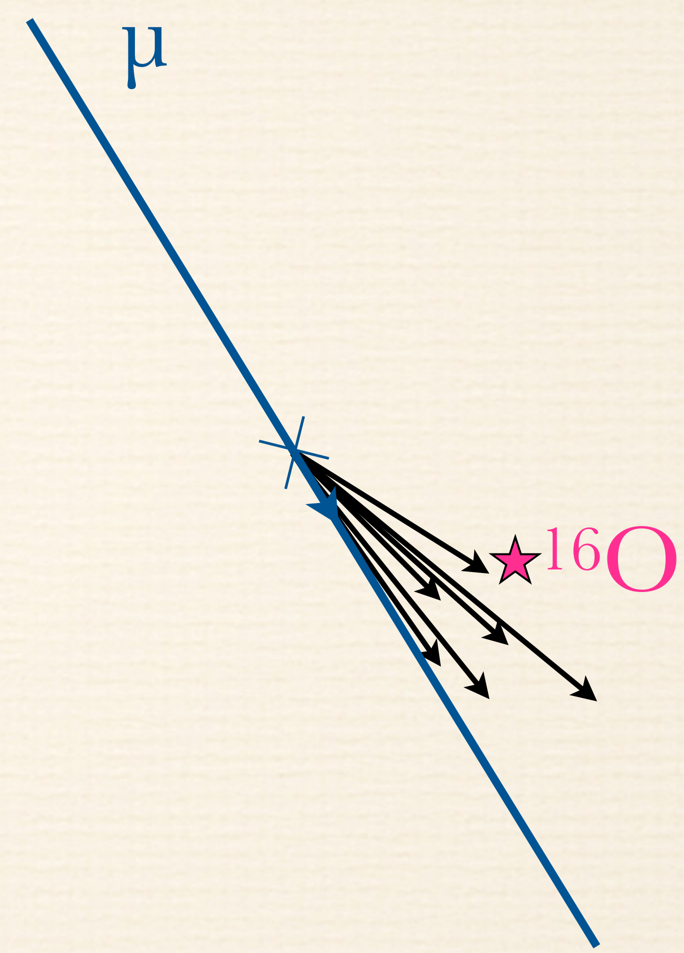

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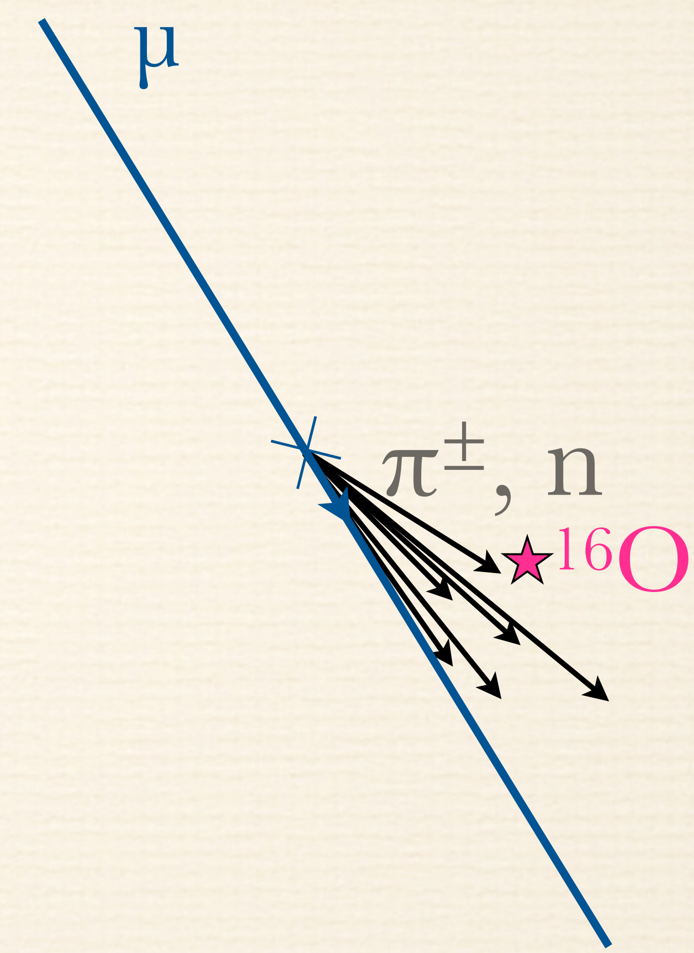

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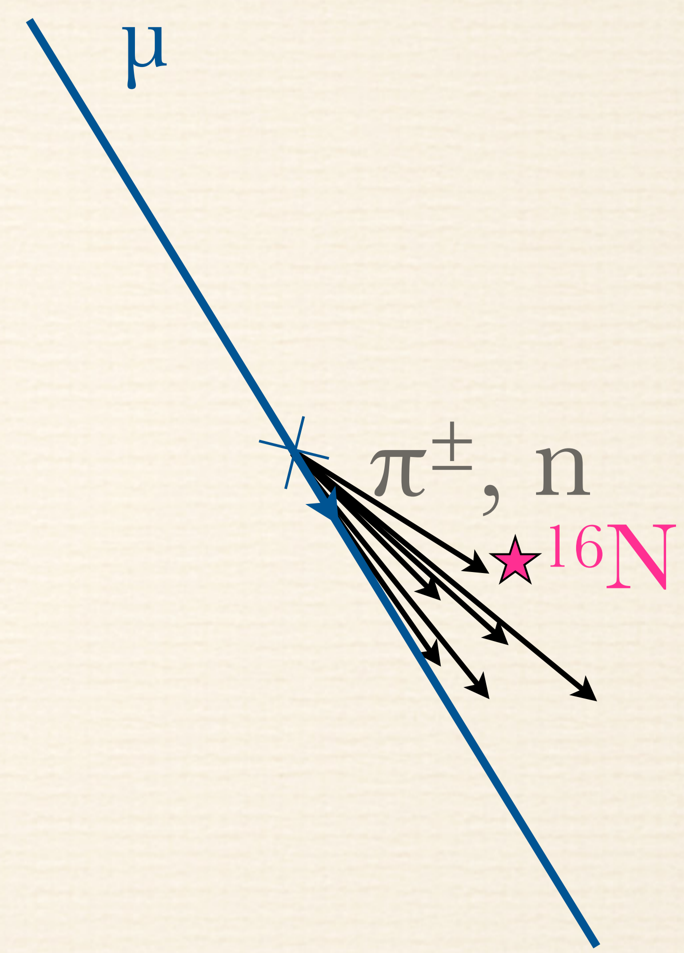

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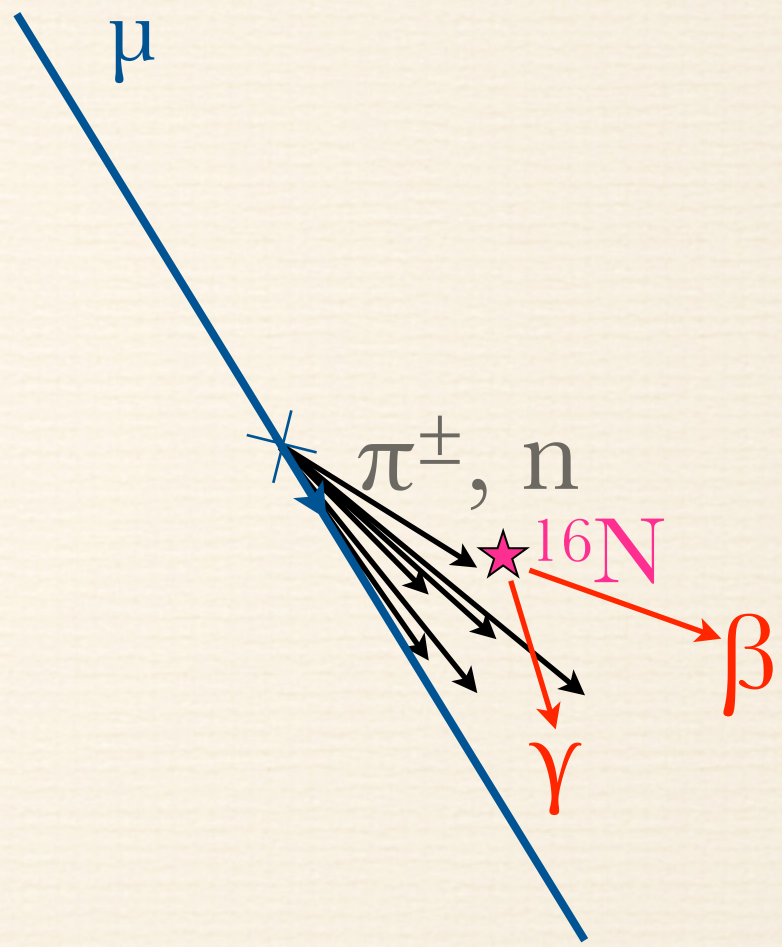
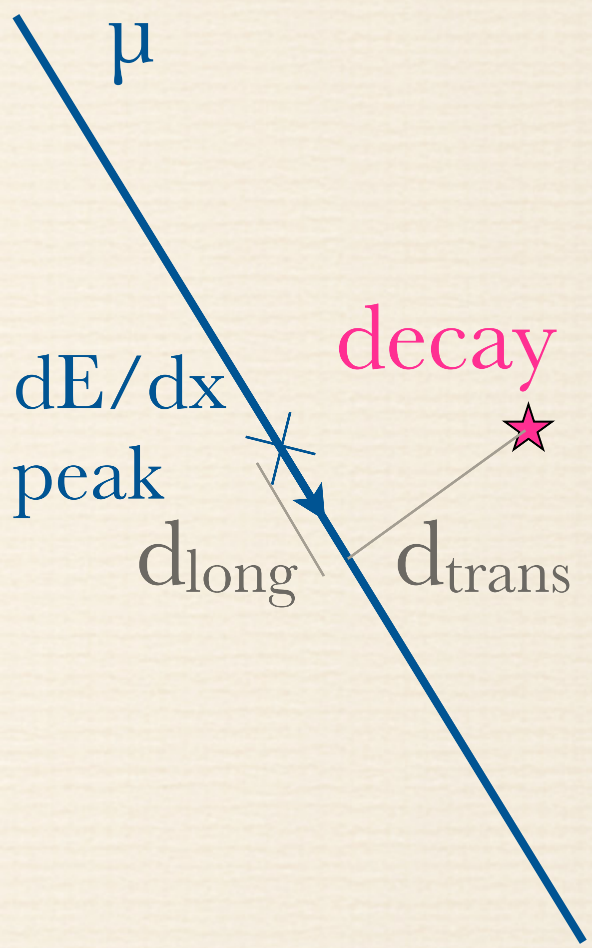


Nuclear Spallation Tagging

- traditionally, form likelihood based on time difference to muon, distance to muon track, and excess light of the muon above the MIP expectation (from electromagnetic component of the showers)
- in 2012, we invented a new method for the distant supernova neutrino search: the muon dE/dx profile (using water Cherenkov detectors as a TPC) points out the spallation location



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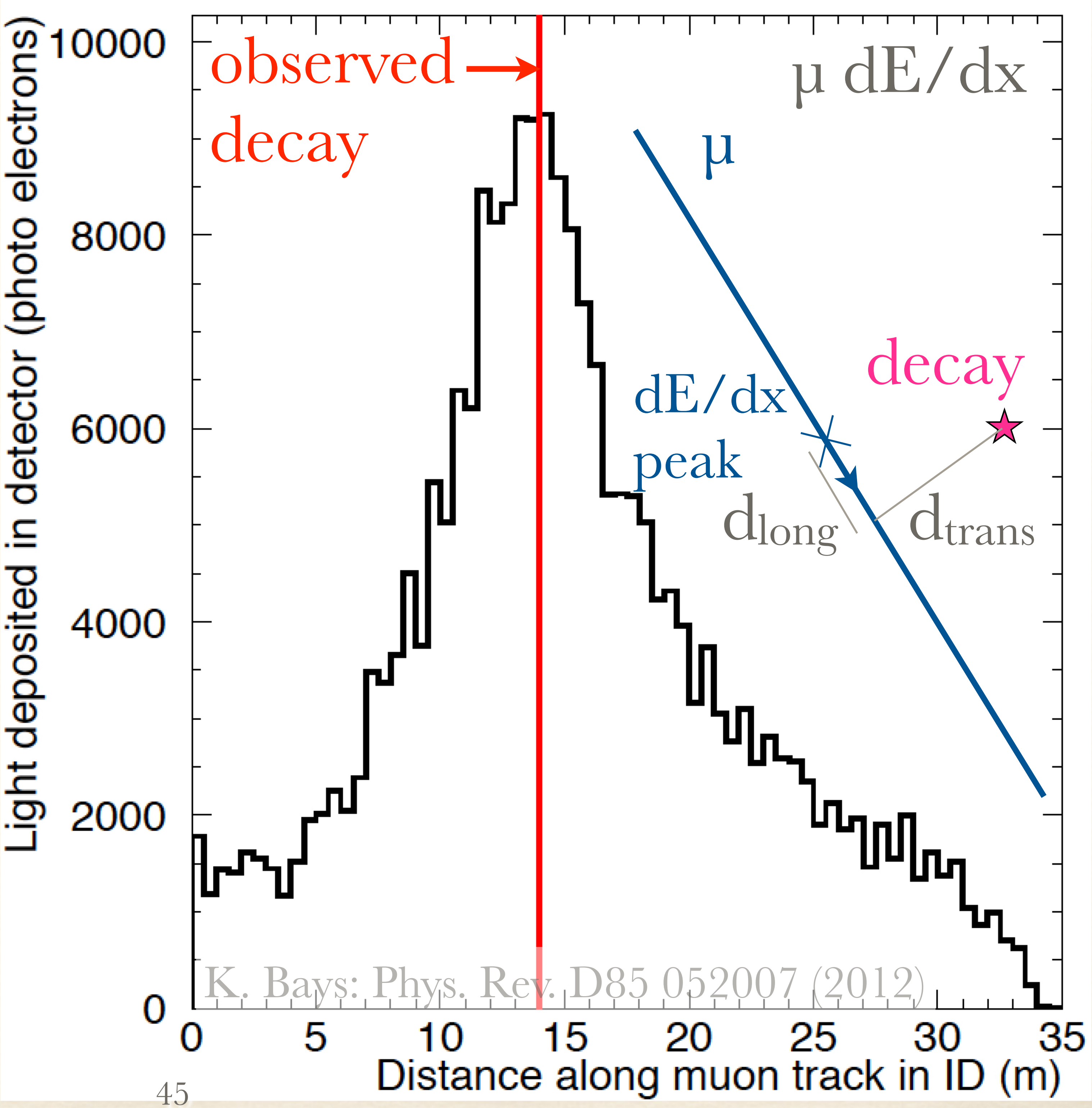
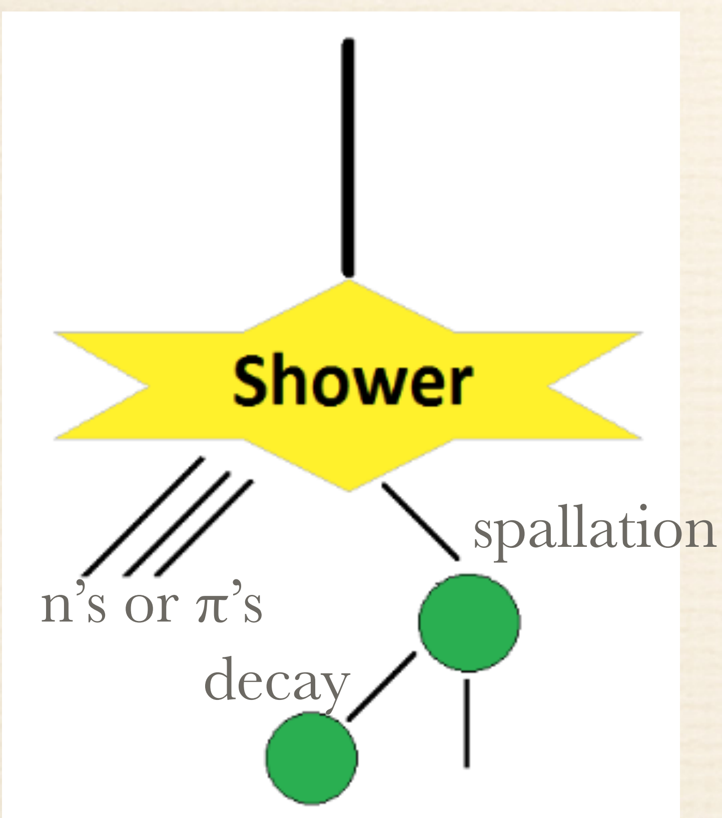
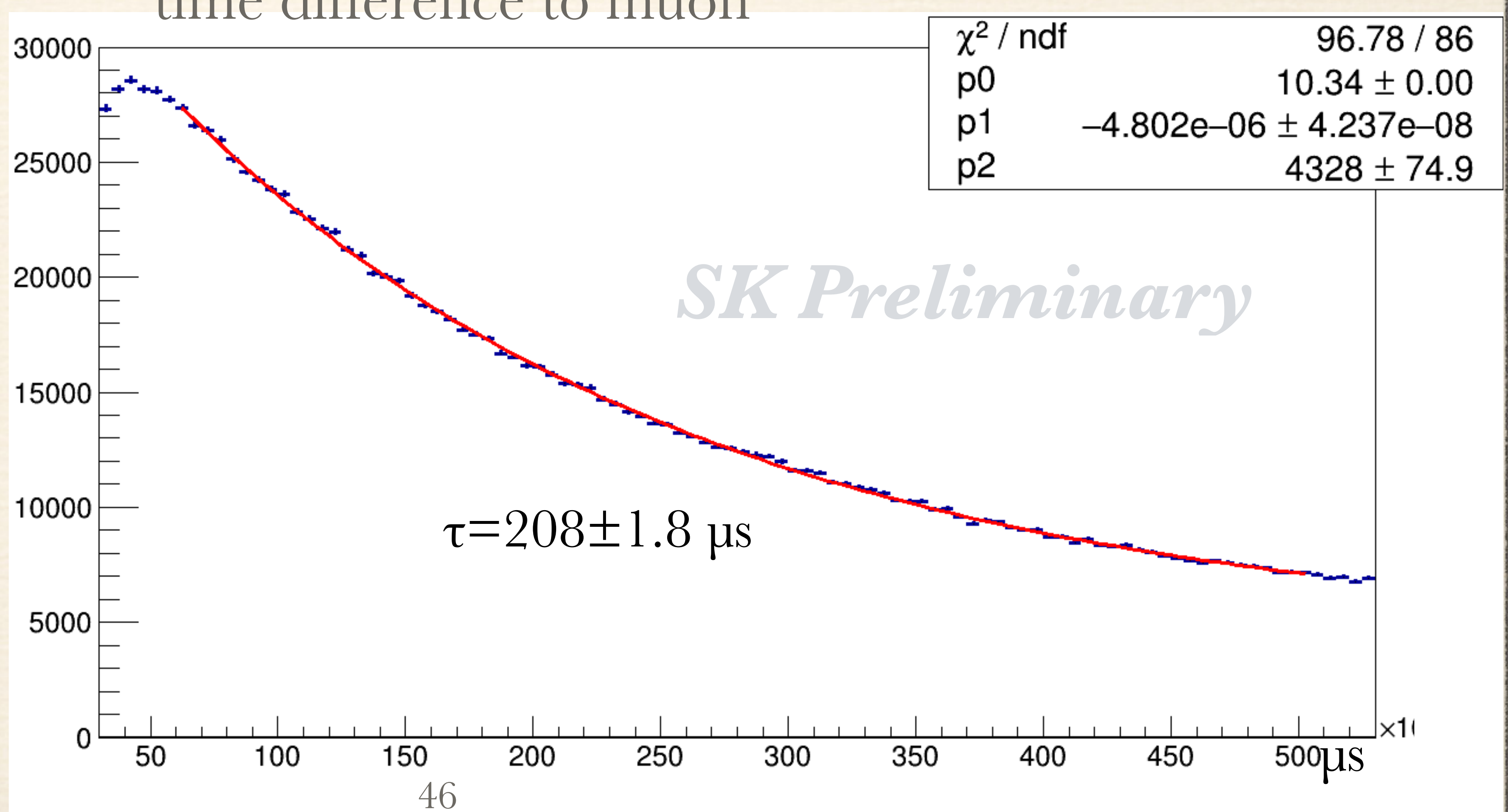


Detecting Hadronic Showers

- J. Beacom, S. Li (Phys. Rev. C 89, 045801, 2014): investigate how spallation nuclei are produced in hadronic showers
- S. Locke (TeVPA 2017): observed 2.2 MeV γ's from many neutron captures on hydrogen after muons using Super-K's new software trigger (threshold ~2.5 MeV kinetic electron energy; 2.2 MeV γ efficiency ~13%)



time difference to muon



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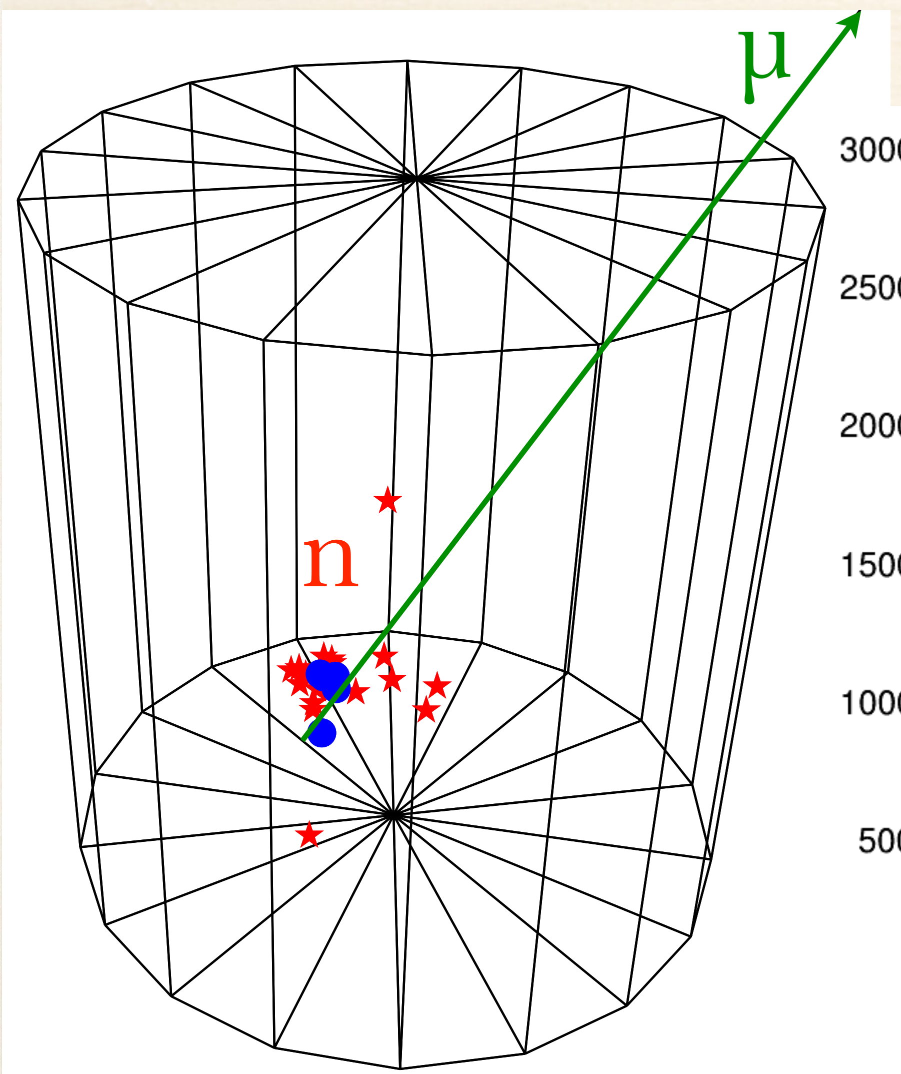
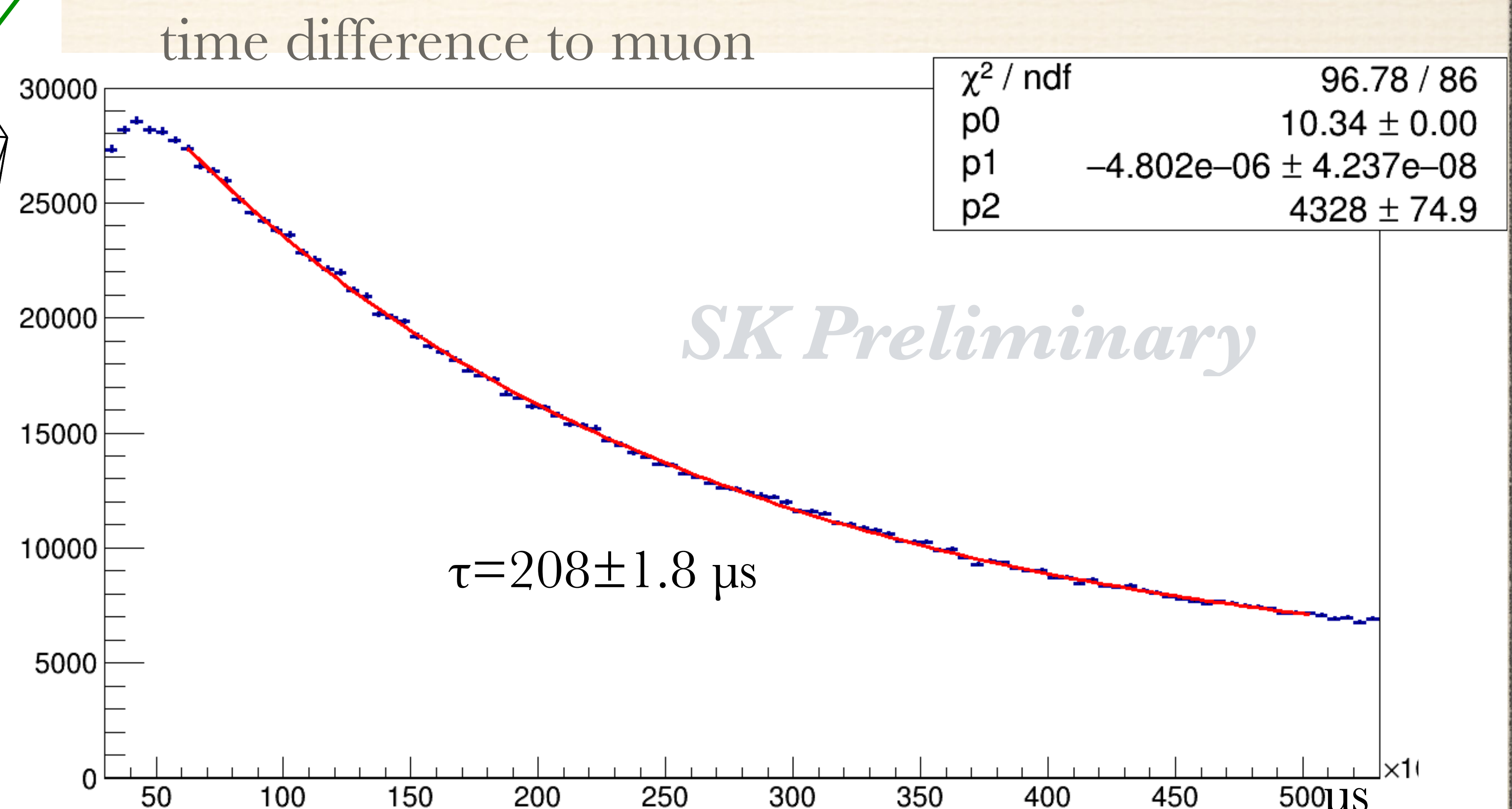
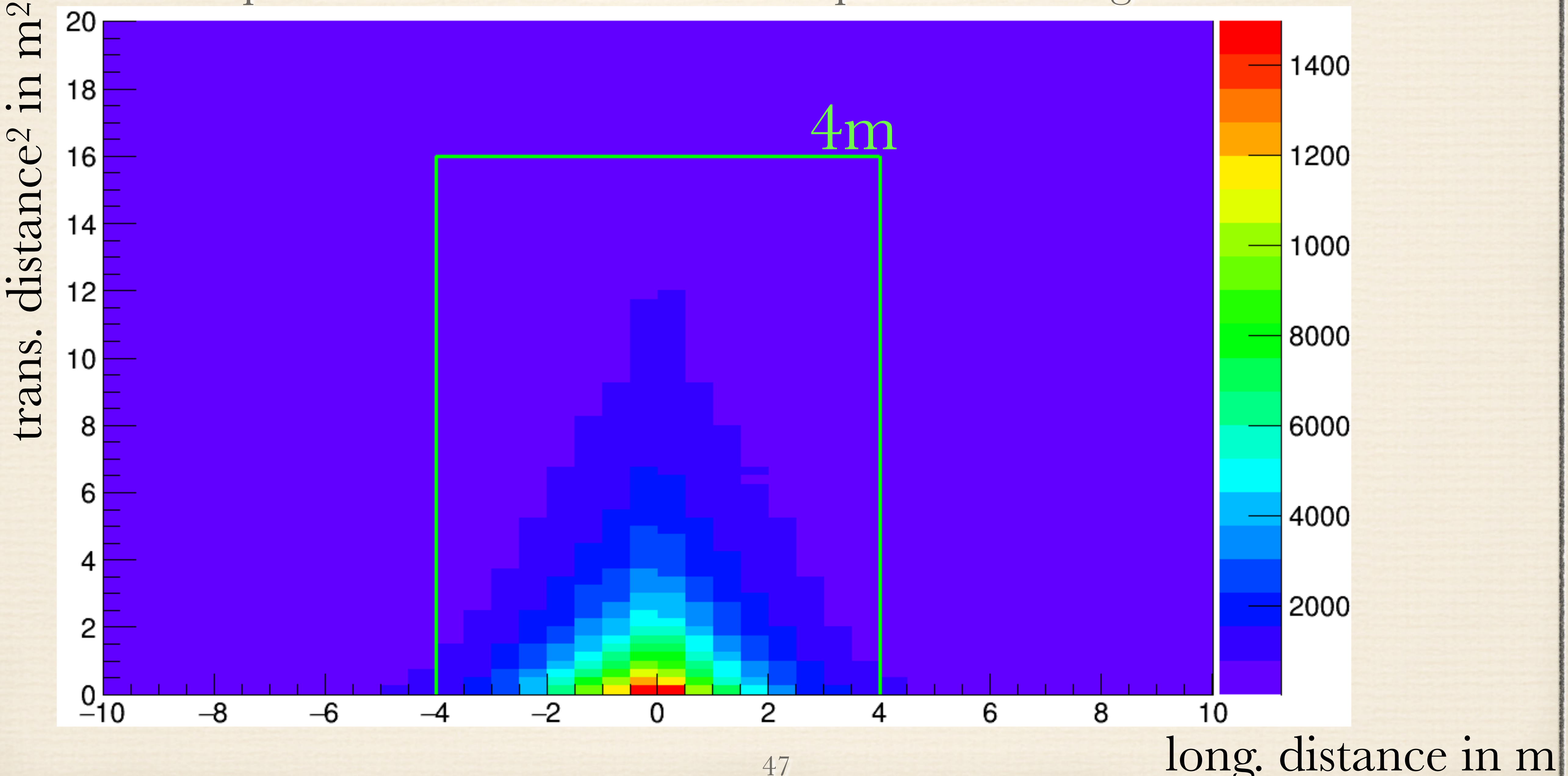




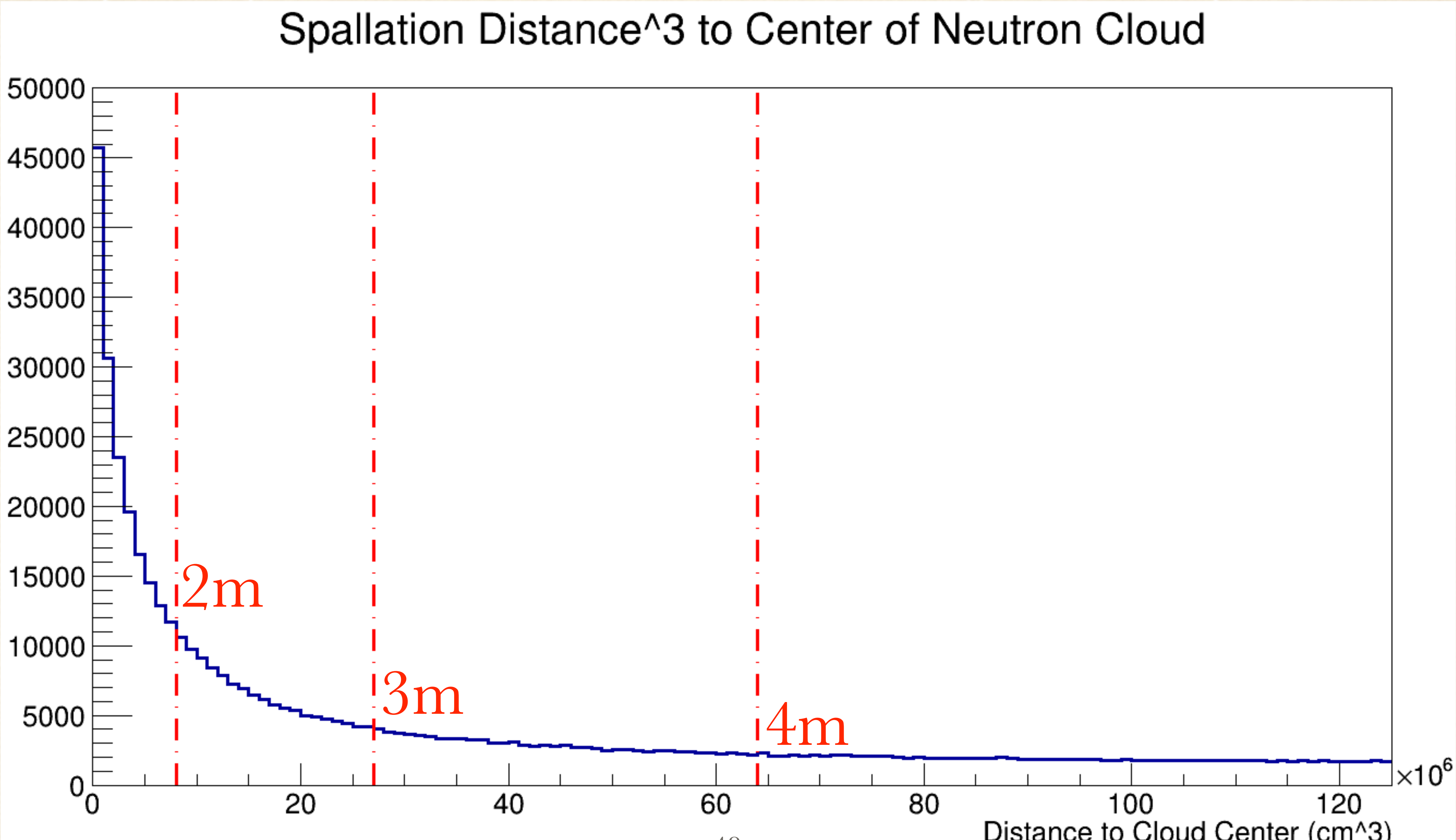
Hadronic Showers

- neutrons after muons are spatially correlated with neutrons and each other: neutrons tag ^{16}N production as well as indicate the 3D location of the decay
- reduce Super-Kamiokande's dominant spallation background



Finding Spallation Decays

- simplest way: events within 1 minute near the average neutron capture vertices



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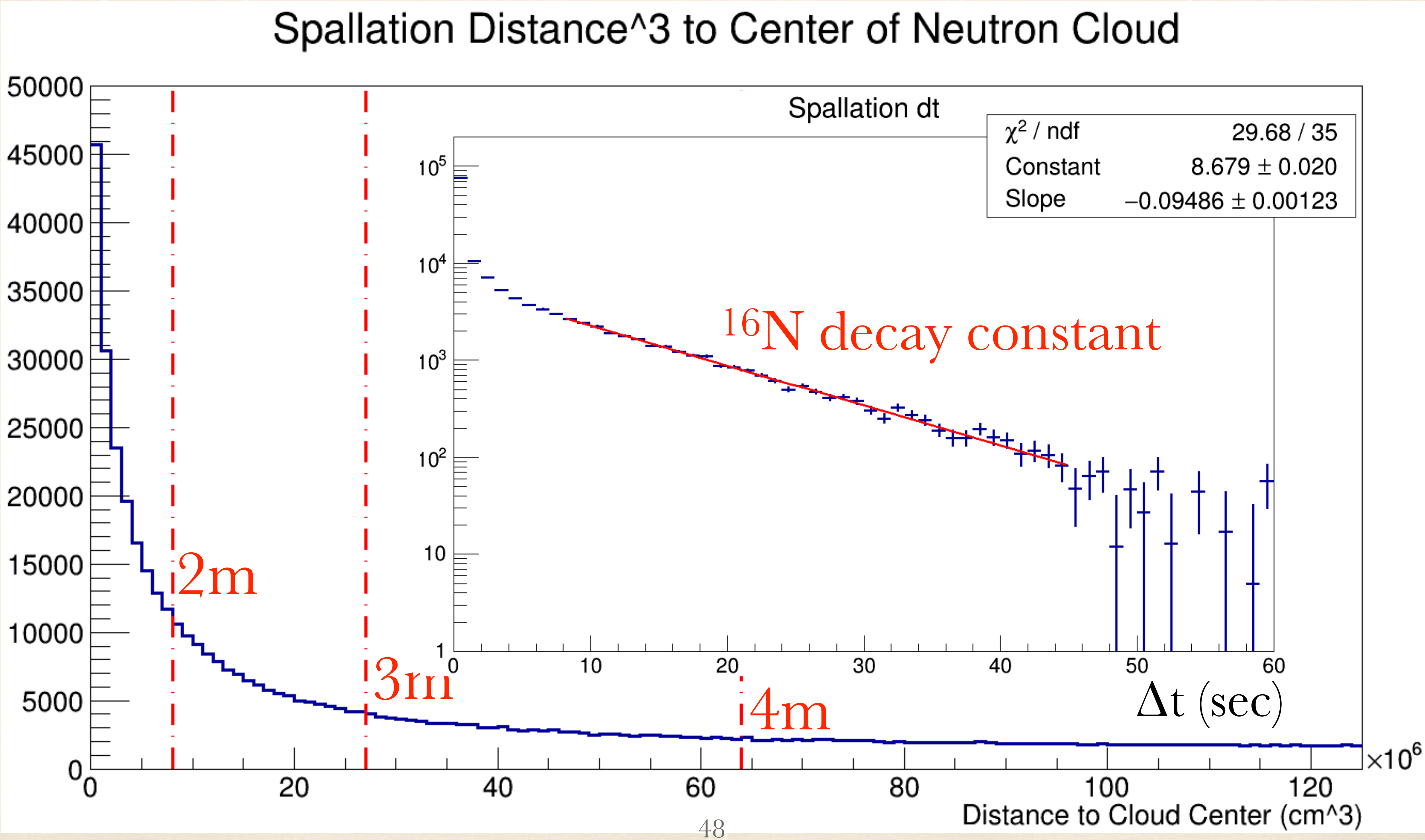
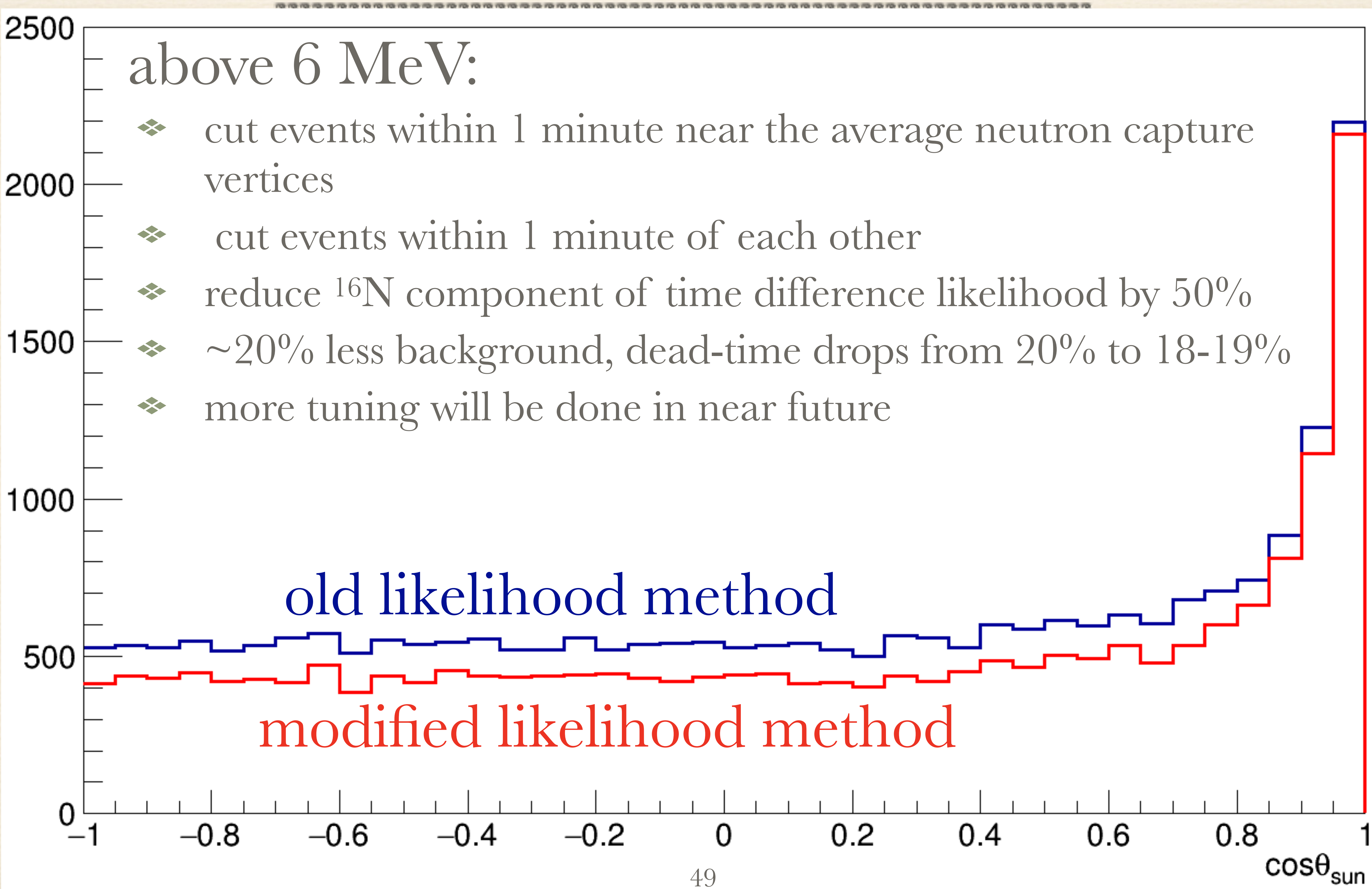


Finding Spallation Decays

above 6 MeV:

- cut events within 1 minute near the average neutron capture vertices
- cut events within 1 minute of each other
- reduce ^{16}N component of time difference likelihood by 50%
- ~20% less background, dead-time drops from 20% to 18-19%
- more tuning will be done in near future



Outlook

- still many interesting questions in solar neutrino land
  - particle physics: solar MSW effect, terrestrial matter effects, CPT invariance (compare KamLAND/JUNO oscillation parameters governing $\overline{\nu}_e$'s with solar fit)
  - solar and astrophysics: metallicity, solar models
  - terrestrial physics: reconstruct electron density and earth's chemical composition (by comparison with matter density from seismic measurements)
- can still learn a lot from Super-K data
- galactic core-collapse supernova will have large impact, if one shows up in the next few years
- hope to discover distant supernova neutrinos in the next decade