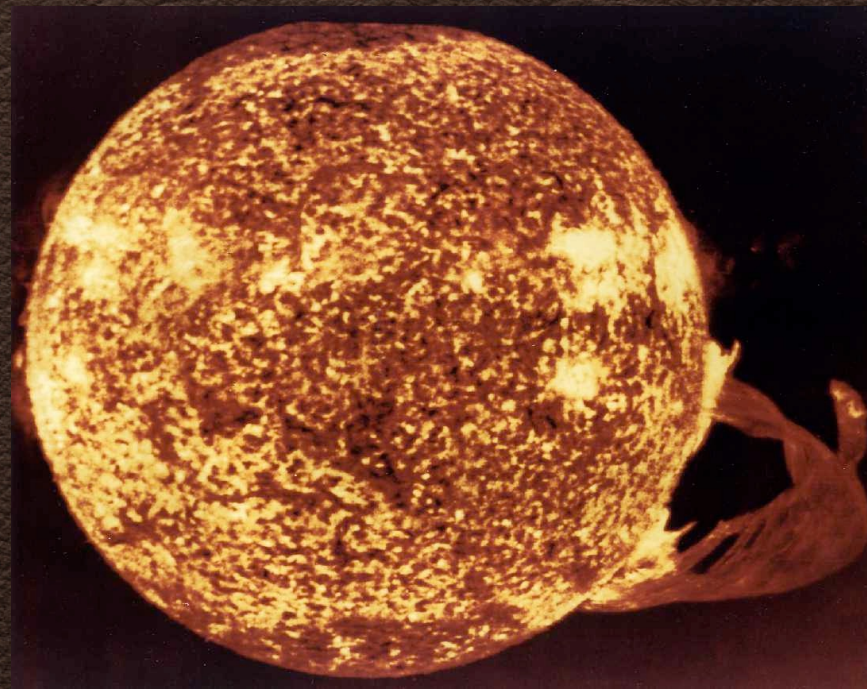


Solar Neutrinos



*PhyStat- ν Workshop on
Statistical Issues in
Experimental Neutrino
Physics May 30th, 2016
Michael Smy*



(Statistical) Techniques in Solar ν Physics

- ❖ take “statistical techniques” to also include combinatorial methods and discrimination variables, in particular:
 - ❖ triggering and reconstruction methods
 - ❖ discrimination methods
 - ❖ analysis methods
- ❖ SNO: Physical Review **C** 88, 025501 (2013)
- ❖ BOREXINO: Physical Review **D** 89, 112007 (2014)

Combined analysis of all three phases of solar neutrino data from the Sudbury Neutrino Observatory

B. Aharmim,⁶ S. N. Ahmed,¹⁴ A. E. Anthony,^{17,a} N. Barros,^{8,b} E. W. Beier,¹³ A. Bellerive,⁴ B. Beltran,¹ M. Bergevin,^{7,5,c} S. D. Biller,¹² K. Boudjemline,^{4,14} M. G. Boulay,¹⁴ B. Cai,¹⁴ Y. D. Chan,⁷ D. Chauhan,⁶ M. Chen,¹⁴ B. T. Cleveland,¹² G. A. Cox,^{19,d} X. Dai,^{14,12,4} H. Deng,¹³ J. A. Detwiler,⁷ M. DiMarco,¹⁴ P. J. Doe,¹⁹ G. Doucas,¹² P.-L. Drouin,⁴ F. A. Duncan,^{16,14} M. Dunford,^{13,e} E. D. Earle,¹⁴ S. R. Elliott,^{9,19} H. C. Evans,¹⁴ G. T. Ewan,¹⁴ J. Farine,^{6,4} H. Fergani,¹² F. Fleurot,⁶ R. J. Ford,^{16,14} J. A. Formaggio,^{11,19} N. Gagnon,^{19,9,7,12} J. T. M. Goon,¹⁰ K. Graham,^{4,14} E. Guillian,¹⁴ S. Habib,¹ R. L. Hahn,³ A. L. Hallin,¹ E. D. Hallman,⁶ P. J. Harvey,¹⁴ R. Hazama,^{19,f} W. J. Heintzelman,¹³ J. Heise,^{2,9,14,g} R. L. Helmer,¹ A. Hime,⁹ C. Howard,^{1,h} M. Huang,^{17,6,i} P. Jagam,⁵ B. Jamieson,² N. A. Jelley,¹² M. Jerkins,¹⁷ K. J. Keeter,^{14,j} J. R. Klein,^{17,13} L. L. Kormos,^{14,k} M. Kos,¹⁴ C. Kraus,^{14,6} C. B. Krauss,¹ A. Kruger,⁶ T. Kutter,¹⁰ C. C. M. Kyba,^{13,l} R. Lange,³ J. Law,⁵ I. T. Lawson,^{16,5} K. T. Lesko,⁷ J. R. Leslie,¹⁴ J. C. Loach,^{12,7} R. MacLellan,^{14,m} S. Majerus,¹² H. B. Mak,¹ J. Maneira,⁸ R. Martin,^{14,7} N. McCauley,^{13,12,n} A. B. McDonald,¹⁴ S. R. McGee,¹⁹ M. L. Miller,^{11,o} B. Monreal,^{11,p} J. Monroe,^{11,q} B. G. Nickel,⁵ A. J. Noble,^{14,4} H. M. O’Keeffe,¹² N. S. Oblath,^{19,11} R. W. Ollerhead,⁵ G. D. Orebi Gann,^{12,13,r} S. M. Oser,² R. A. Ott,¹¹ S. J. M. Peeters,^{12,s} A. W. P. Poon,⁷ G. Prior,^{7,e} S. D. Reitzner,⁵ K. Rielage,^{9,19} B. C. Robertson,¹⁴ R. G. H. Robertson,¹⁹ R. C. Rosten,¹⁹ M. H. Schwendener,⁶ J. A. Secrest,^{13,t} S. R. Seibert,^{17,9,13} O. Simard,^{4,u} J. J. Simpson,⁵ P. Skensved,¹⁴ T. J. Sonley,^{11,v} L. C. Stonehill,^{9,19} G. Tešić,^{4,w} N. Tolich,¹⁹ T. Tsui,² R. Van Berg,¹³ B. A. VanDevender,^{19,x} C. J. Virtue,⁶ H. Wan Chan Tseung,^{12,19} D. L. Wark,^{15,y} P. J. S. Watson,⁴ J. Wendland,² N. West,¹² J. F. Wilkerson,^{19,h} J. R. Wilson,^{12,z} J. M. Wouters,^{9,aa} A. Wright,^{14,bb} M. Yeh,³ F. Zhang,⁴ and K. Zuber^{12,b}

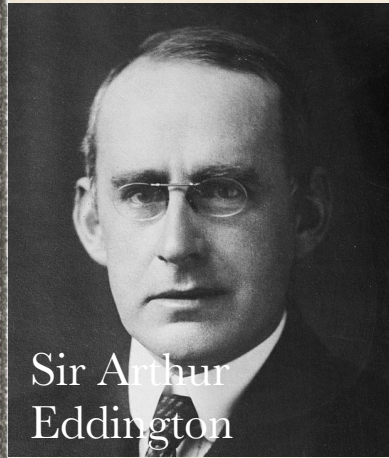
(SNO Collaboration)

Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy

G. Bellini,¹ J. Benziger,² D. Bick,³ G. Bonfini,⁴ D. Bravo,⁵ M. Buizza Avanzini,¹ B. Caccianiga,¹ L. Cadonati,⁶ F. Calaprice,² P. Cavalcante,⁴ A. Chavarria,² A. Chepurinov,⁷ D. D’Angelo,¹ S. Davini,⁸ A. Derbin,⁹ A. Empl,⁸ A. Etenko,¹⁰ K. Fomenko,^{11,4} D. Franco,¹² F. Gabriele,⁴ C. Galbiati,² S. Gazzana,⁴ C. Ghiano,¹² M. Giammarchi,¹ M. Göger-Neff,¹³ A. Goretti,² L. Grandi,² M. Gromov,⁷ C. Hagner,³ E. Hungerford,⁸ Aldo Ianni,⁴ Andrea Ianni,² V. Kobychiev,¹⁴ D. Korabiev,¹¹ G. Korga,⁸ D. Kryn,¹² M. Laubenstein,⁴ T. Lewke,¹³ E. Litvinovich,^{10,15} B. Loer,² F. Lombardi,⁴ P. Lombardi,¹ L. Ludhova,¹ G. Lukyanchenko,¹⁰ I. Machulin,^{10,15} S. Manecki,⁵ W. Maneschg,¹⁶ G. Manuzio,¹⁷ Q. Meindl,¹³ E. Meroni,¹ L. Miramonti,¹ M. Misiaszek,¹⁸ M. Montuschi,⁴ P. Mosteiro,² V. Muratova,⁹ L. Oberauer,¹³ M. Obolensky,¹² F. Ortica,¹⁹ K. Otis,⁶ M. Pallavicini,¹⁷ L. Papp,⁵ C. Pena-Garay,²⁰ L. Perasso,¹⁷ S. Perasso,¹⁷ A. Pocar,⁶ G. Ranucci,¹ A. Razeto,⁴ A. Re,¹ A. Romani,¹⁹ N. Rossi,²¹ R. Saldanha,² C. Salvo,¹⁷ S. Schönert,¹³ H. Simgen,¹⁶ M. Skorokhvatov,^{10,15} O. Smirnov,¹¹ A. Sotnikov,¹¹ S. Sukhotin,¹⁰ Y. Suvorov,^{21,10} R. Tartaglia,²¹ G. Testera,¹⁷ D. Vignaud,¹² R. B. Vogelaar,⁵ F. von Feilitzsch,¹³ J. Winter,¹³ M. Wojcik,¹⁸ A. Wright,² M. Wurm,³ J. Xu,² O. Zaimidoroga,¹¹ S. Zavatarelli,¹⁷ and G. Zuzel¹⁸

(Borexino Collaboration)

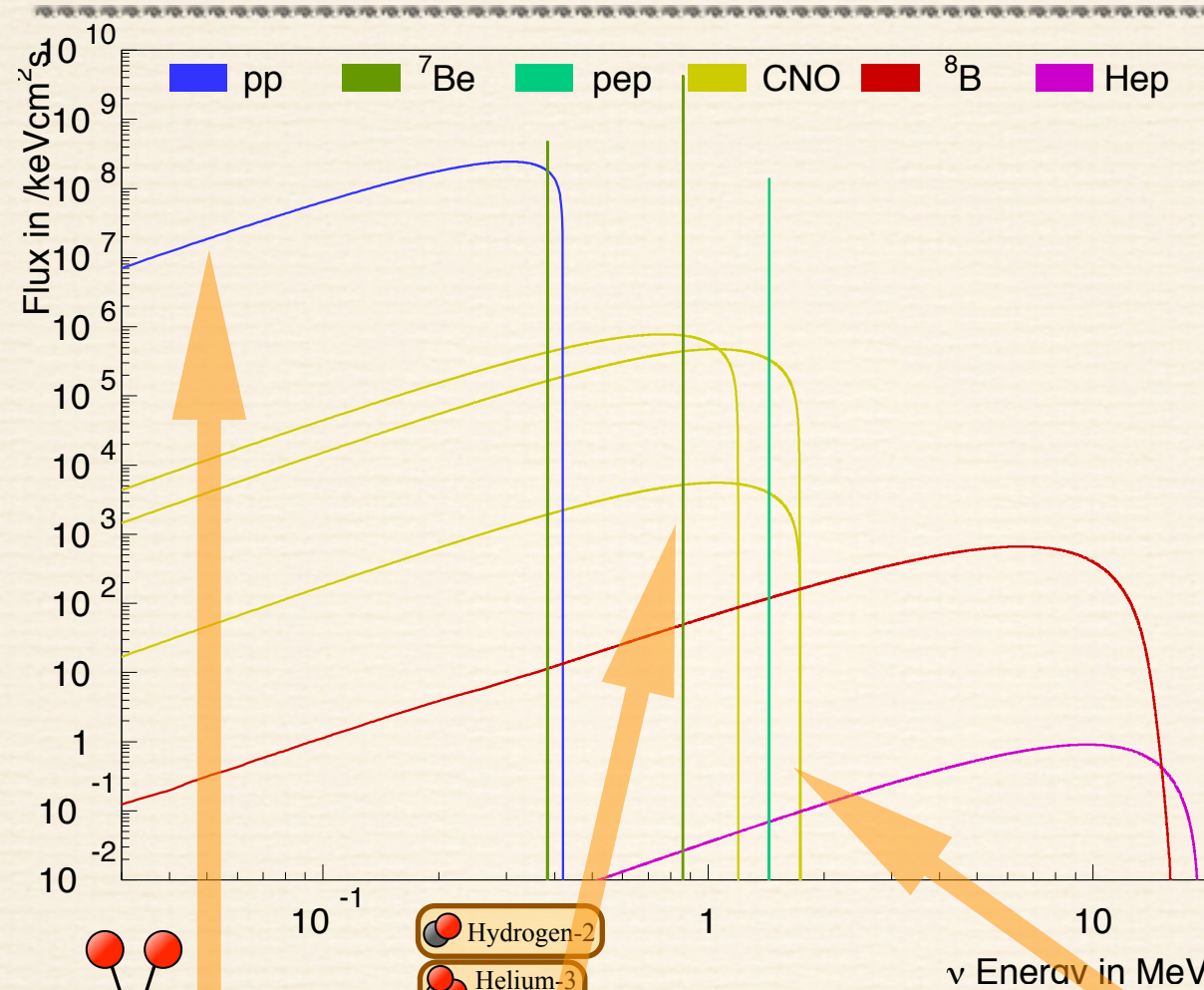
Solar Fusion and Solar Neutrinos



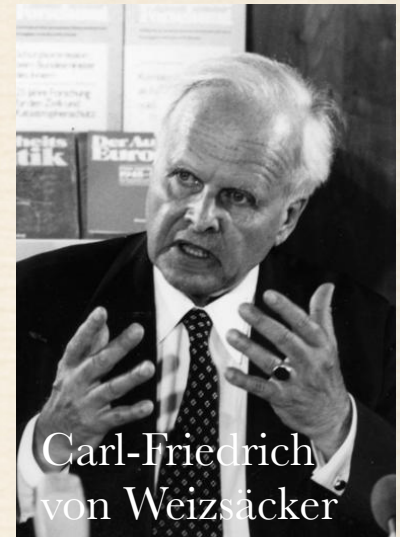
Sir Arthur Eddington



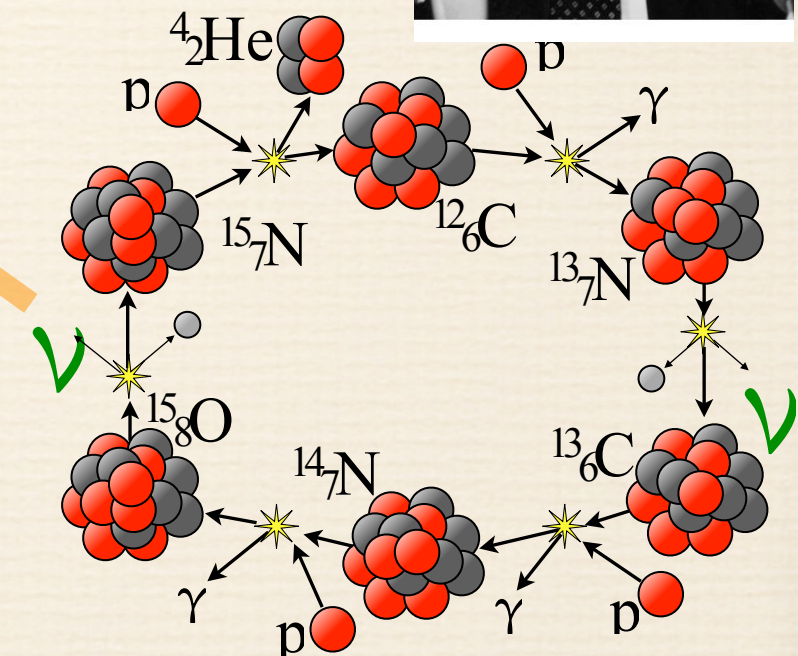
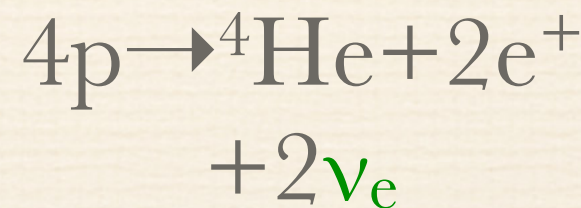
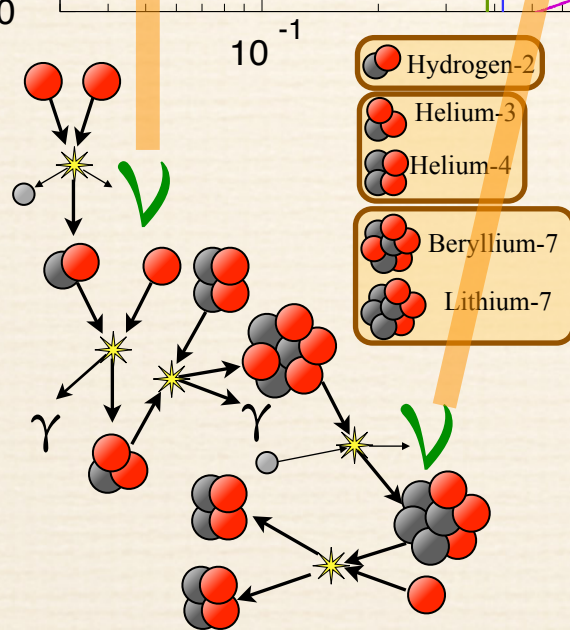
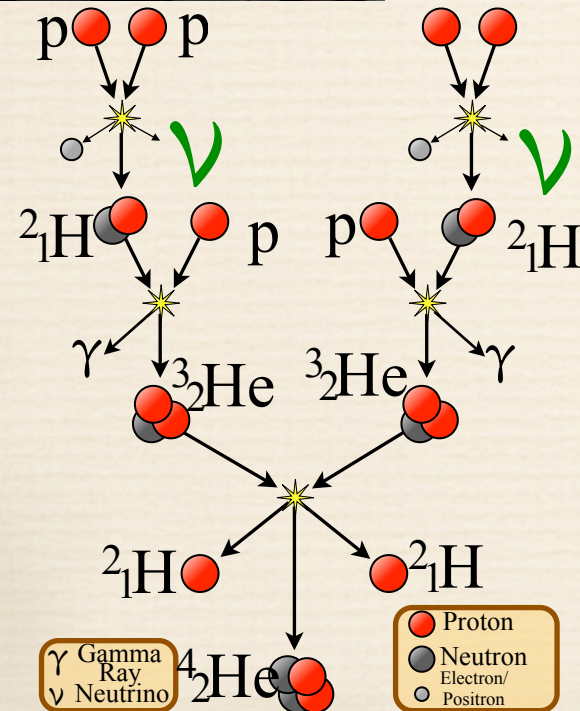
Hans Bethe



John Bahcall



Carl-Friedrich von Weizsäcker



Temperature of the Sun

Classical (Neyman) Confidence Intervals

Uses only $P(\text{data}|\text{theory})$

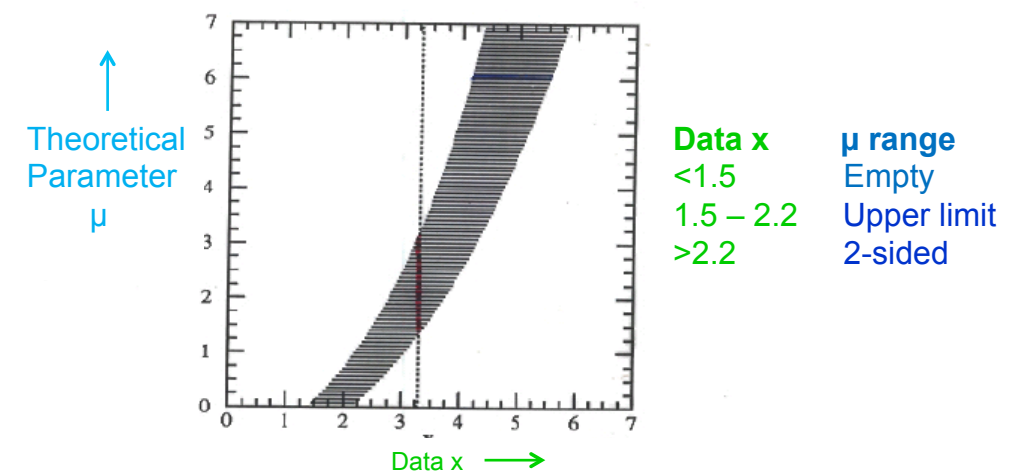


FIG. 1. A generic confidence belt construction and its use. For each value of μ , one draws a horizontal acceptance interval $[x_1, x_2]$ such that $P(x \in [x_1, x_2] | \mu) = \alpha$. Upon performing an experiment to measure x and obtaining the value x_0 , one draws the dashed vertical line through x_0 . The confidence interval $[\mu_1, \mu_2]$ is the union of all values of μ for which the corresponding acceptance interval is intercepted by the vertical line.

Example:

Param = Temp at centre of Sun

Data = est. flux of solar neutrinos

$\mu \geq 0$

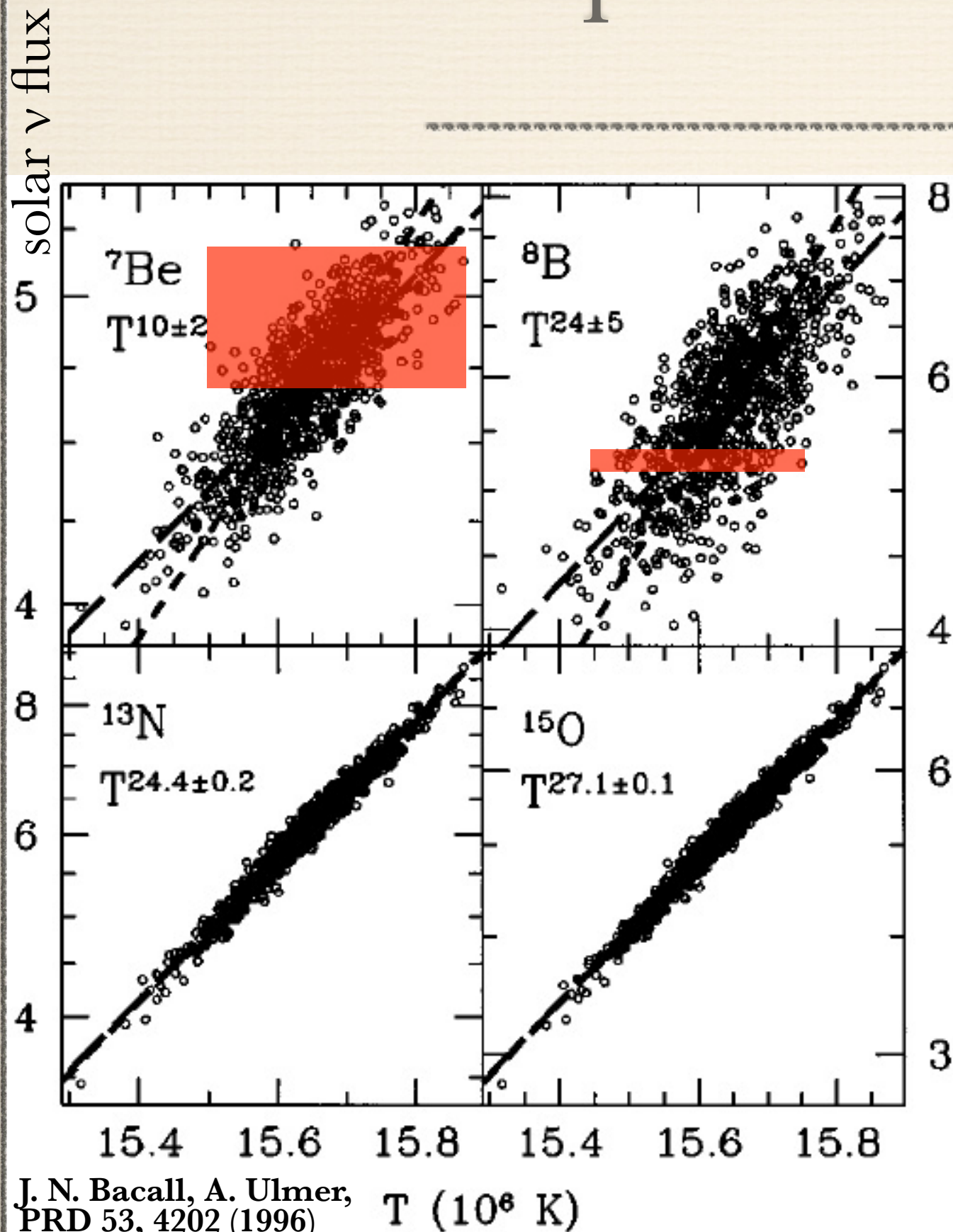
No prior for μ

Louis Lyons, this morning

- ❖ nice discussion this morning
- ❖ but: what IS the temperature of the sun?

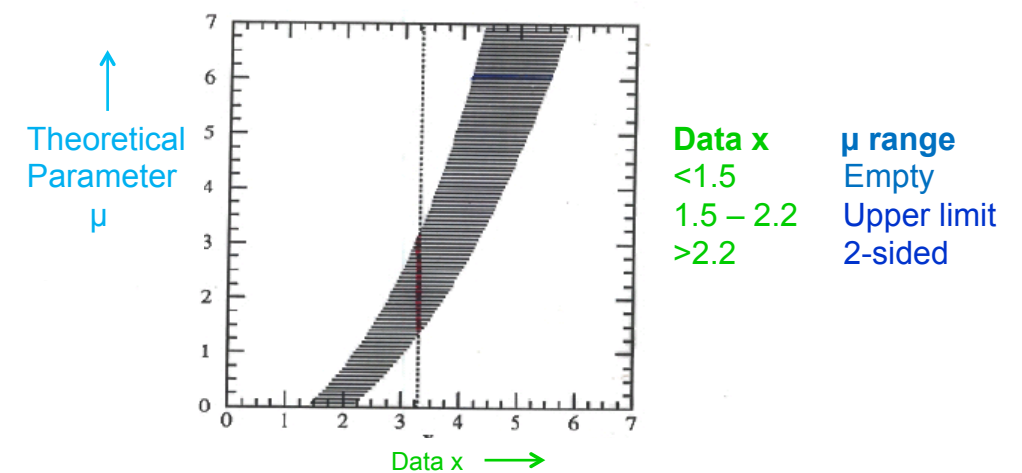
❖ a (frequentist?) answer...

Temperature of the Sun



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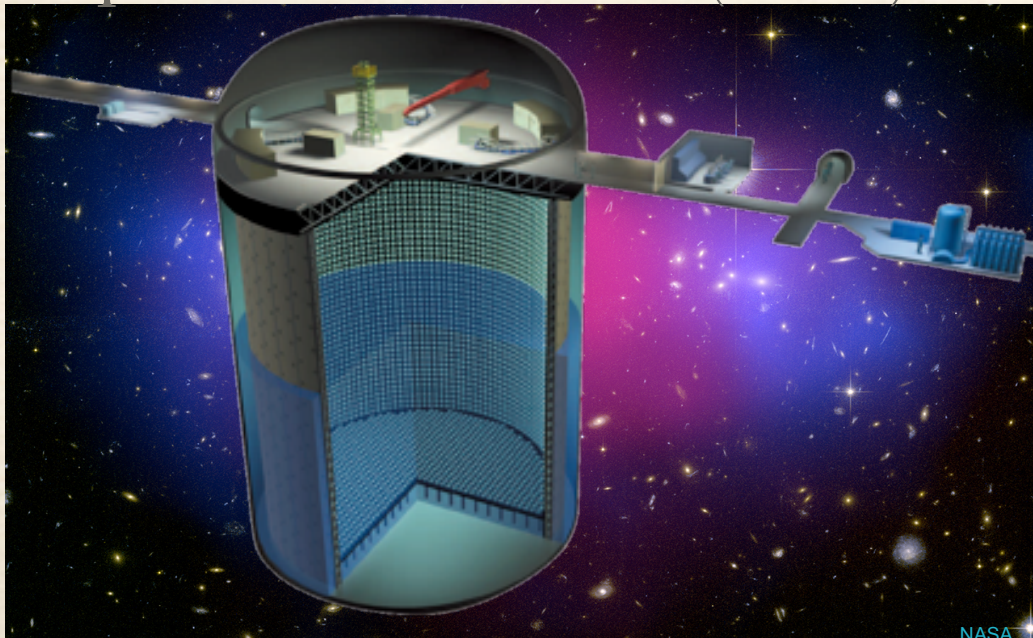
❖ but: what IS the temperature of the sun?

❖ a (frequentist?) answer...

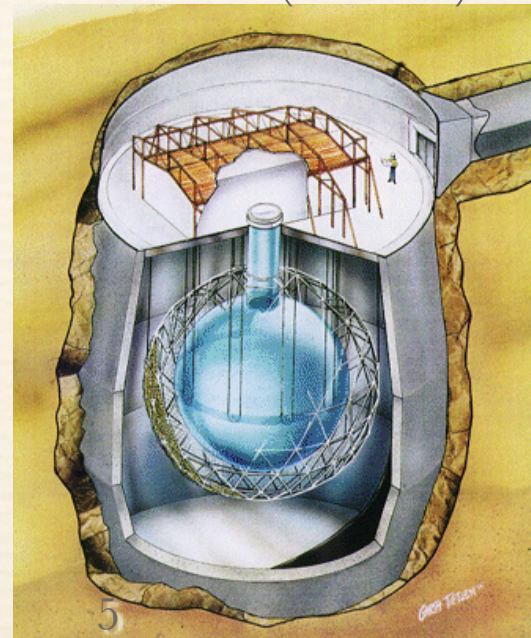
Solar Neutrino Analysis

- ❖ here: will ignore radiochemical experiments, since in those no event-by-event analysis is possible
- ❖ all other solar neutrino experiments detect neutrino interactions with light (either Cherenkov or scintillation)
- ❖ background are all-important in solar neutrino detection

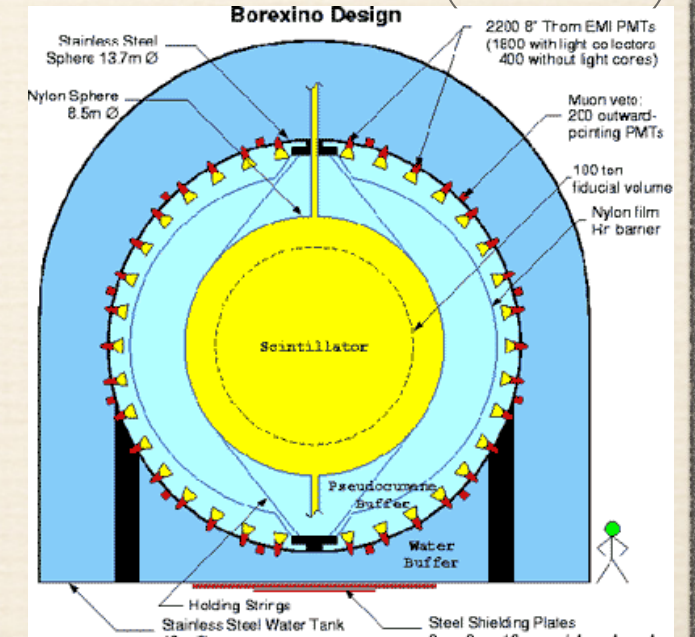
Super-Kamiokande (H_2O)



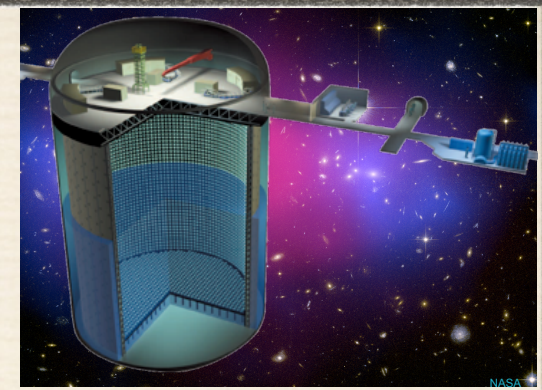
SNO (D_2O)



BOREXINO (Scint.)

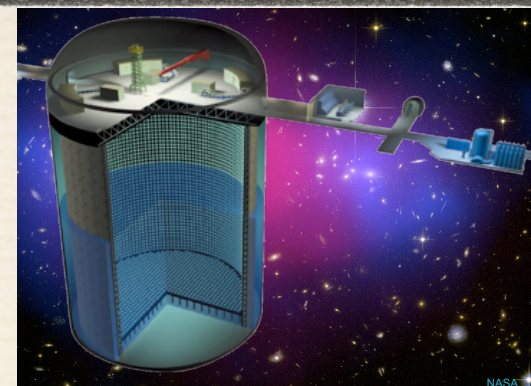


Super-Kamiokande



- ❖ 50,000 tons of water underground, cylindrical detector
- ❖ use innermost 22,500 tons to detect recoil electrons of solar ^8B neutrino-electron scattering by their Cherenkov light seen by 11,149 photomultiplier tubes (PMTs)
- ❖ **timing**: determine interaction **position**
- ❖ light pattern: determine electron **direction** (highly correlated with neutrino direction)
- ❖ **light intensity**: determine electron **energy** (lower limit on neutrino energy)

Triggering of Low-Light Interactions in Large Detectors

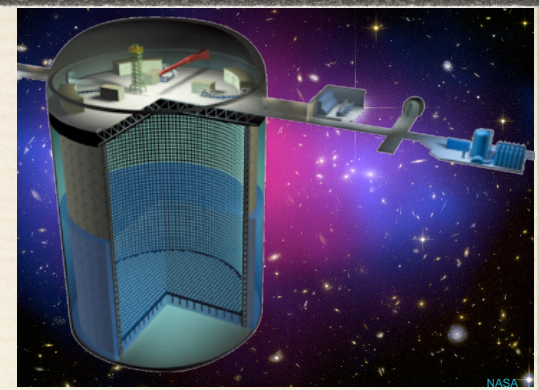


- ❖ usually look for PMT coincidence: time window depends on detector size)
- ❖ however, at low light levels, accidental trigger rate is too large
- ❖ solution: correct for time-of-flight from the interaction vertex to the PMT, and then demand a much tighter coincidence window which depends on PMT time resolution
- ❖ but the vertex is unknown...
- ❖ ...draw sets of four hits and solve vertex exactly: if $\underline{x}_i$ is the i^{th} PMT four-vector, and $\underline{v}$ the vertex four-vector, solve

$$(\underline{x}_i - \underline{v}) \cdot (\bar{\underline{x}}_i - \bar{\underline{v}}) = 0$$

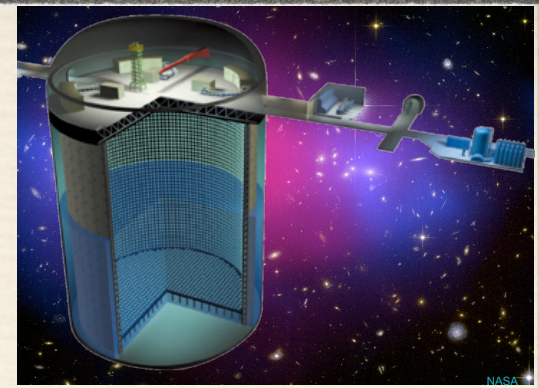
- ❖ by substituting $q = \underline{v} \cdot \bar{\underline{v}}$ and solving for five unknowns

BONSAI: Reconstruction of Low-Light Interactions



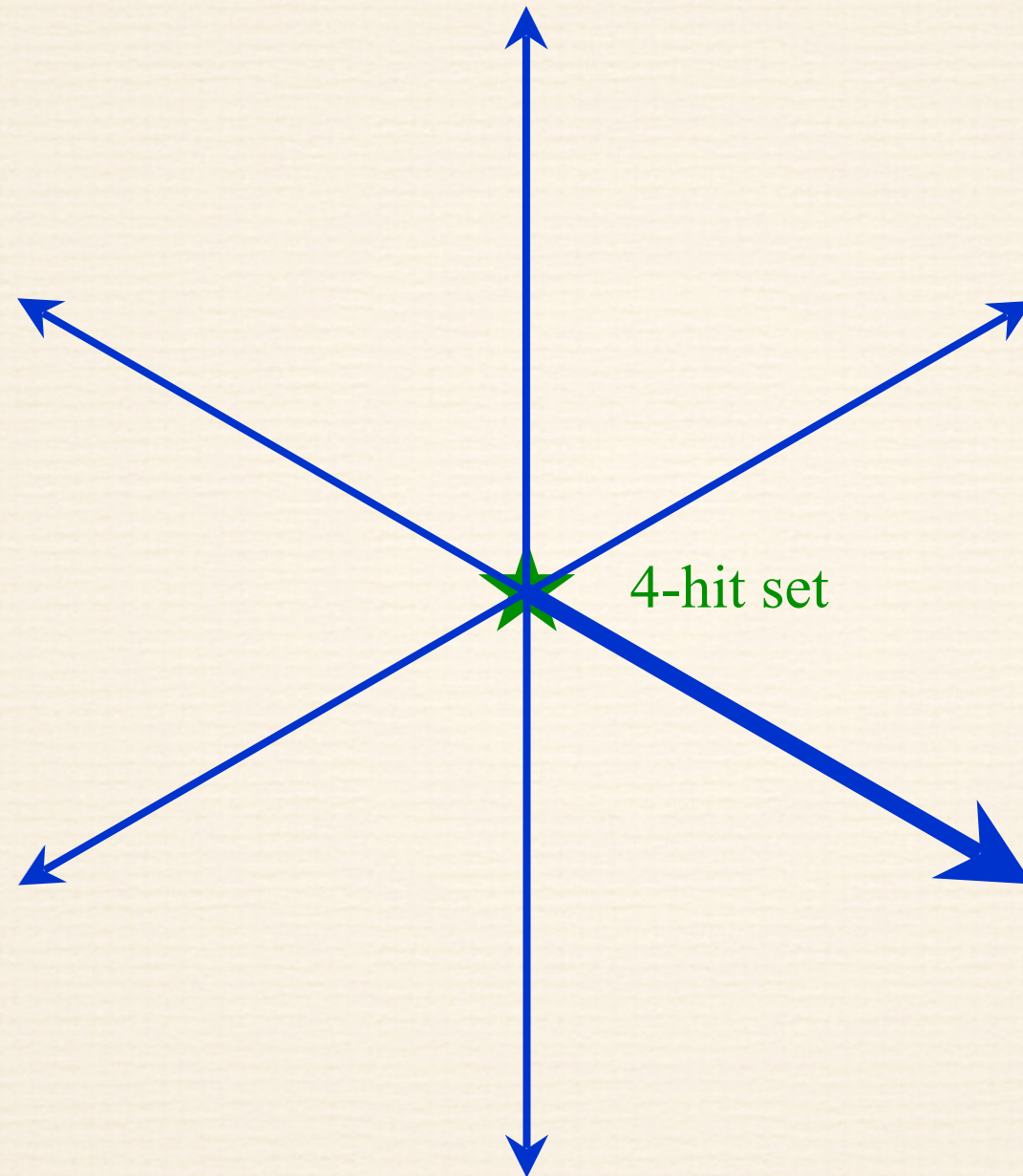
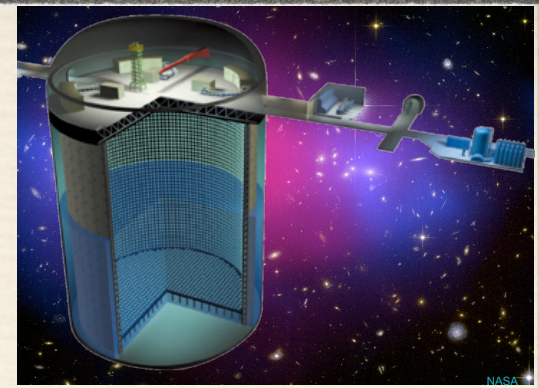
- ❖ Problem: local maxima of likelihood in finding the interaction vertex in a big detector with little light
- ❖ **B**Branch **O**ptimization **N**avigating **S**uccessive **A**nnealing **I**terations
- ❖ simple search tree at each grid point of the initial map to maximize a likelihood of the PMT time fit residuals
- ❖ trace ALL branches for a RANGE of likelihoods
- ❖ no randomness, but doesn't get stuck in local maxima
- ❖ growth and pruning is controlled by the allowed range of likelihood at each step

BONSAI Growth and Pruning

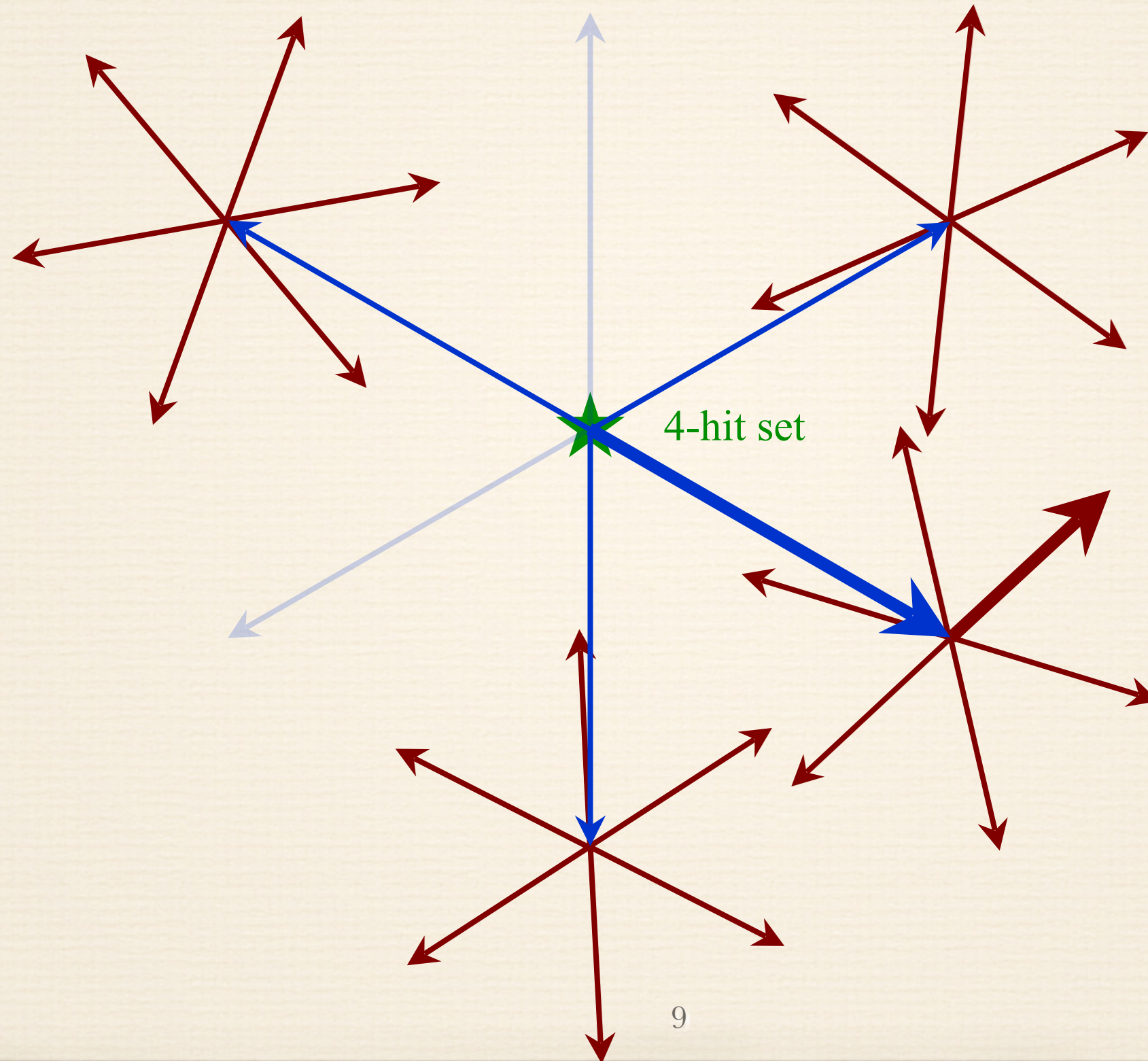
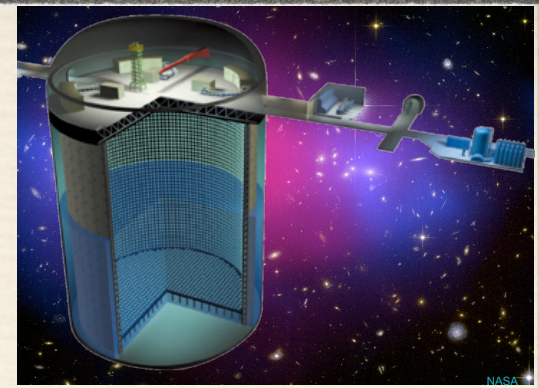


★ 4-hit set

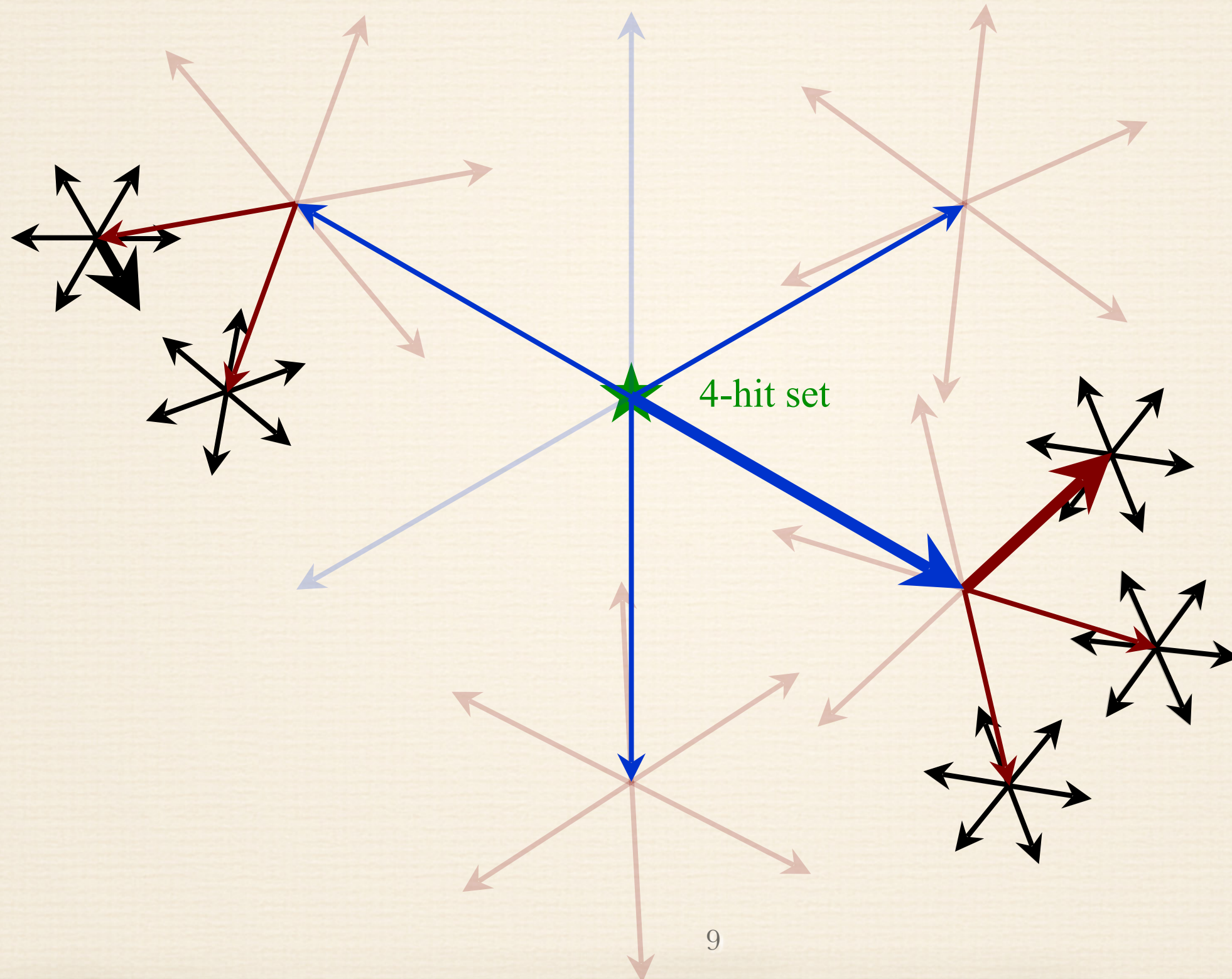
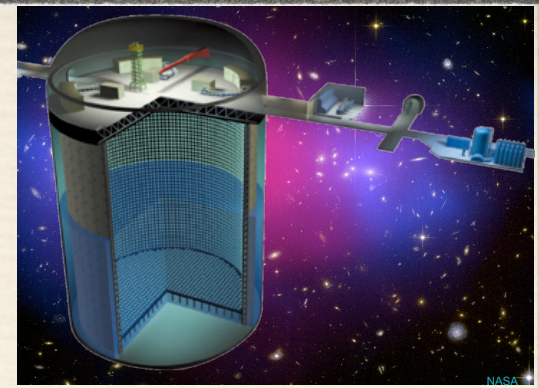
BONSAI Growth and Pruning



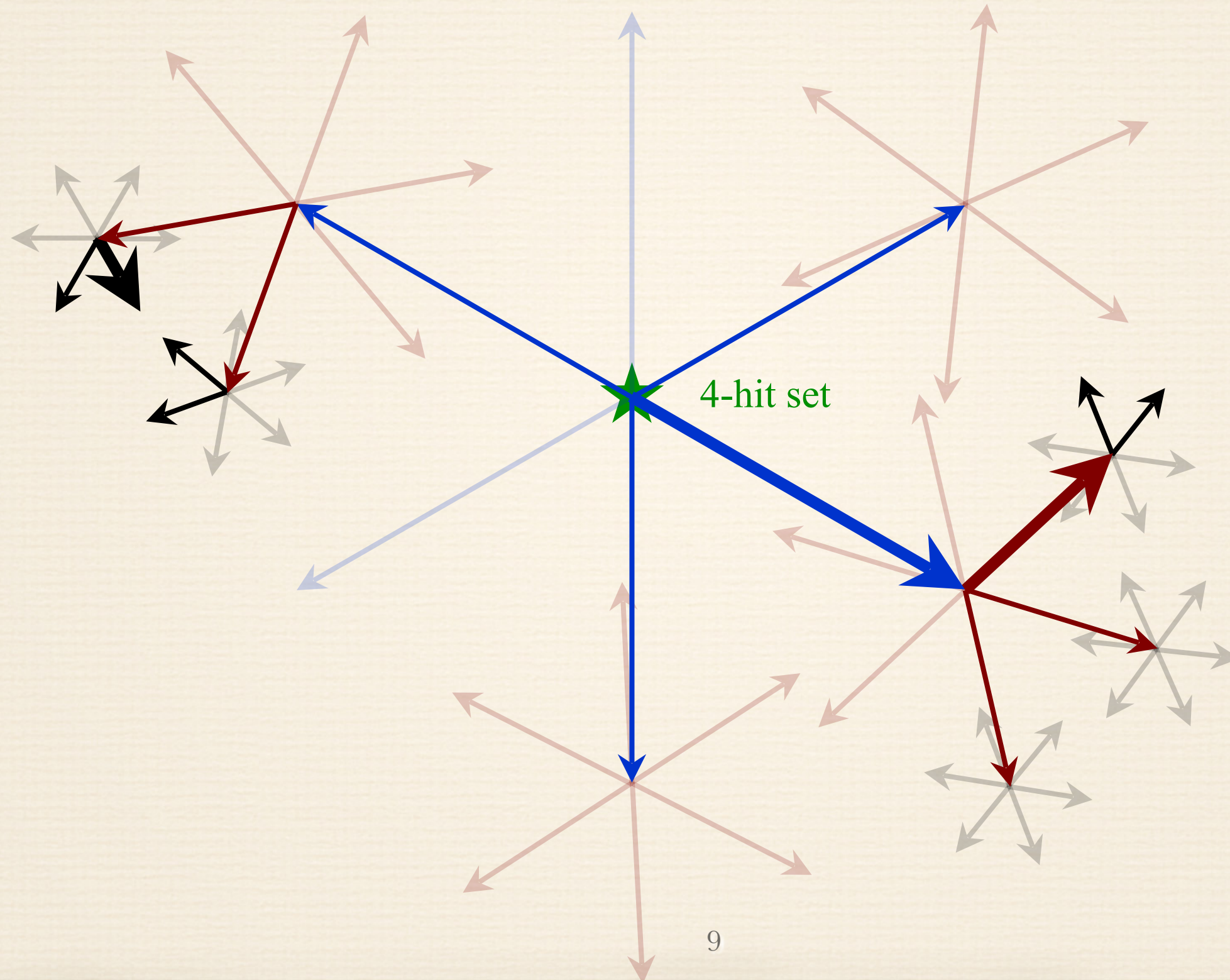
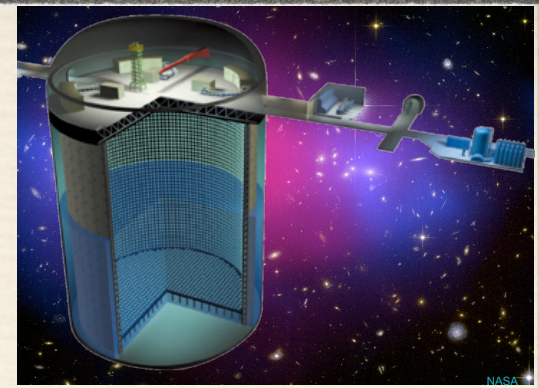
BONSAI Growth and Pruning



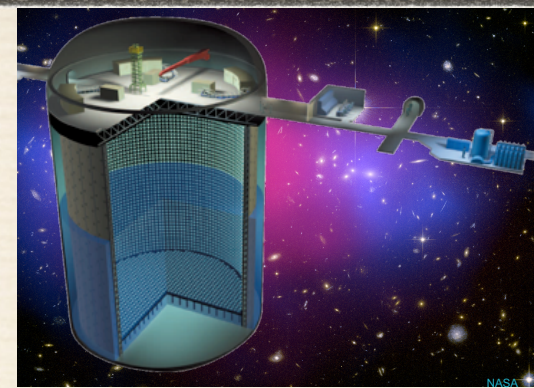
BONSAI Growth and Pruning



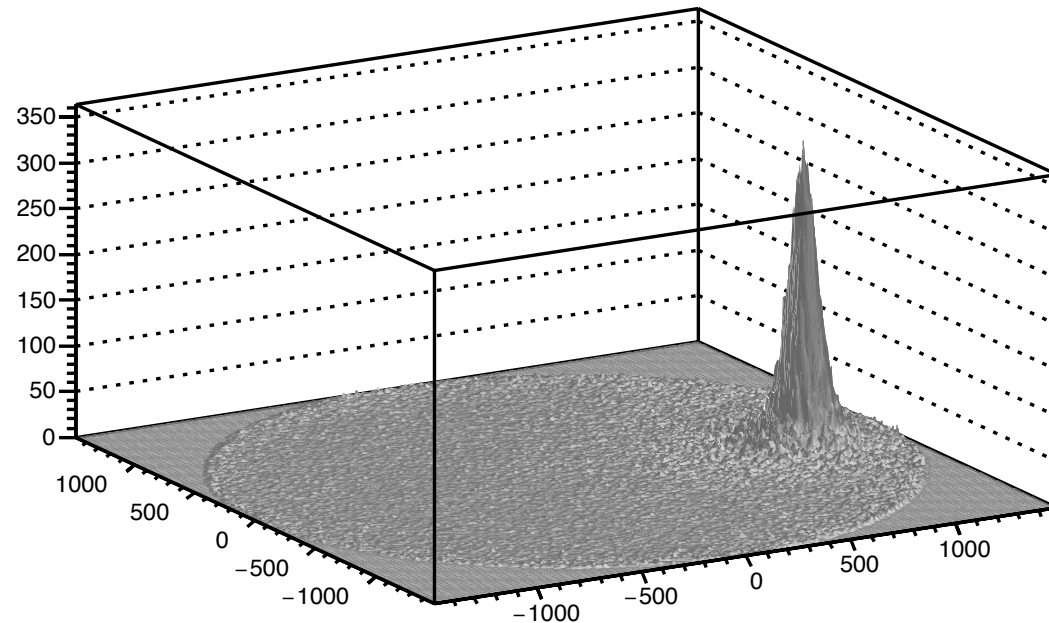
BONSAI Growth and Pruning



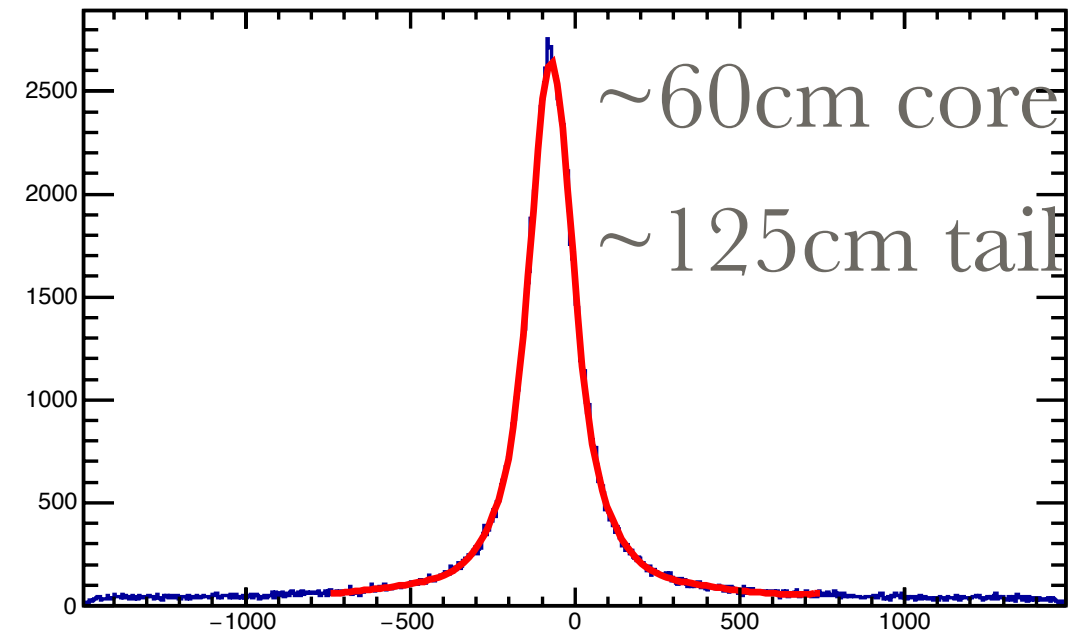
Ni-Cf Source Data (2.24-2.5 MeV: ~10 hits)



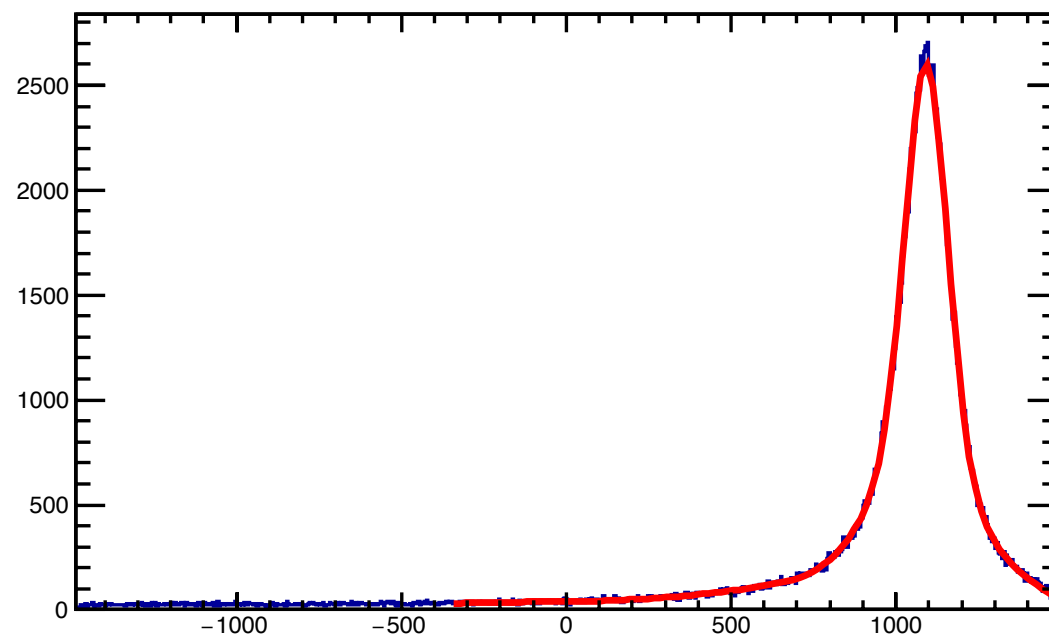
BONSAI x-y Distribution



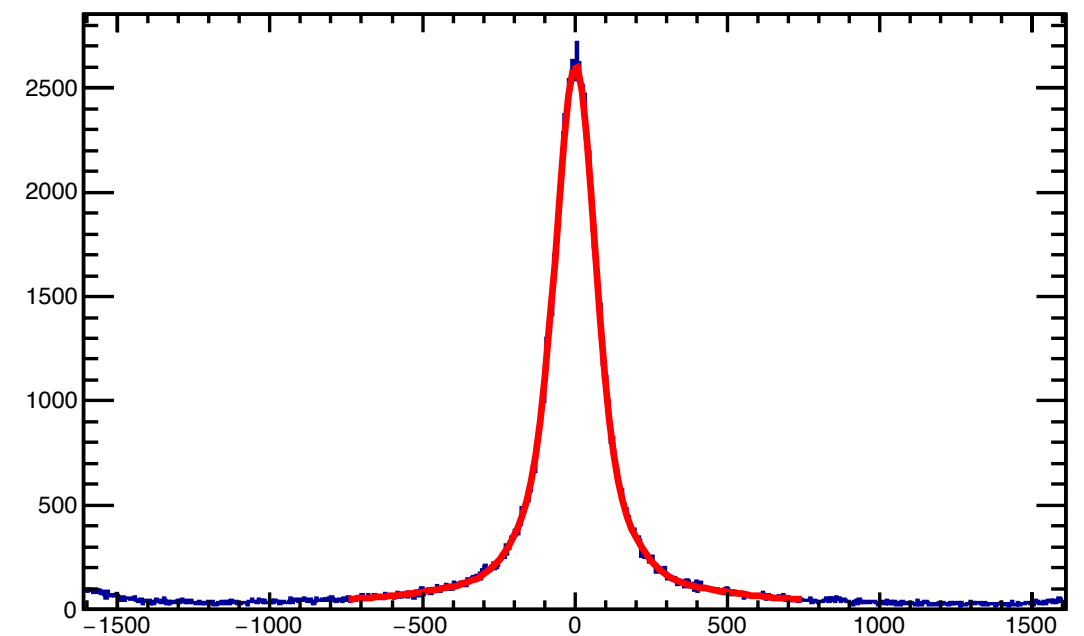
BONSAI y Distribution



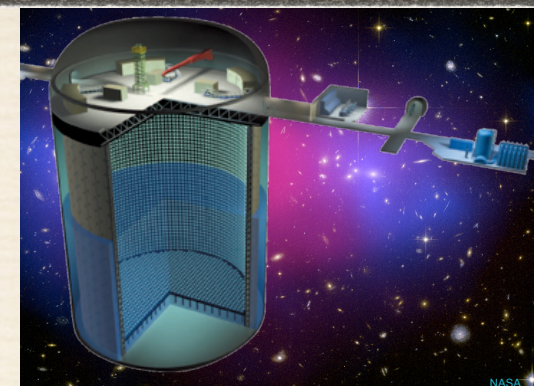
BONSAI x Distribution



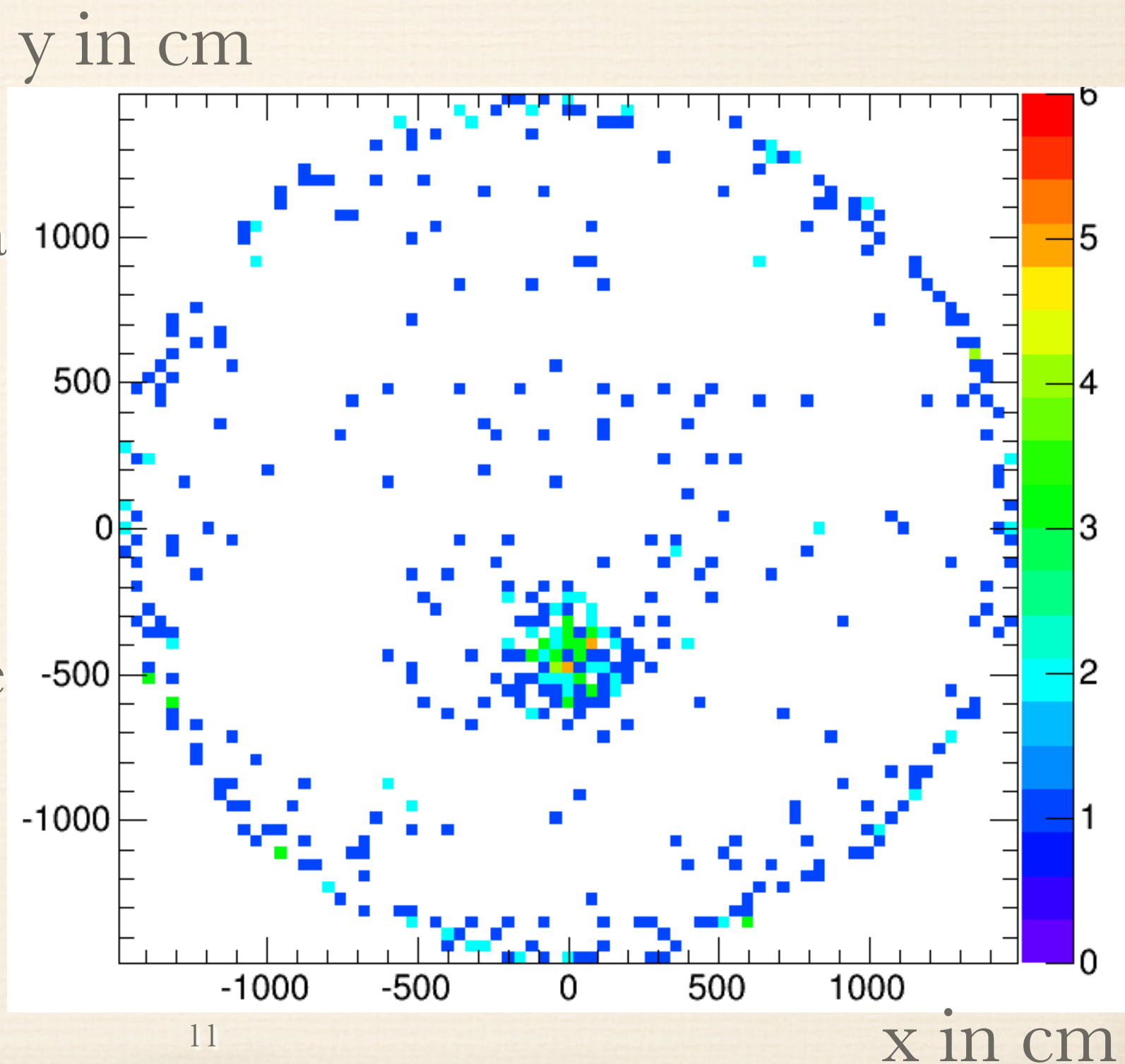
BONSAI z Distribution



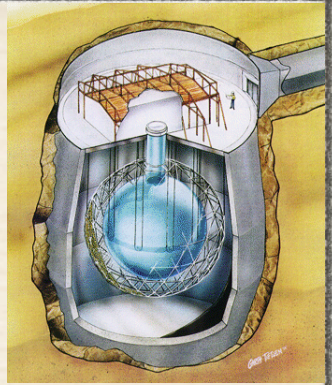
Triggering and Reconstruction of 2.5-5.5 MeV Electrons in SK



- ❖ one hour of low energy activity in SK just after injection of a bubble of Rn rich water
- ❖ slice in z : $|z| < 250\text{cm}$
- ❖ entering background from the detector edge
- ❖ the Rn bubble can be clearly seen

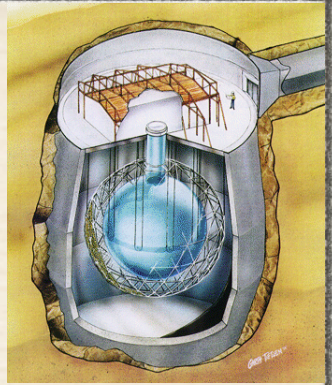


Sudbury Neutrino Observatory (SNO)



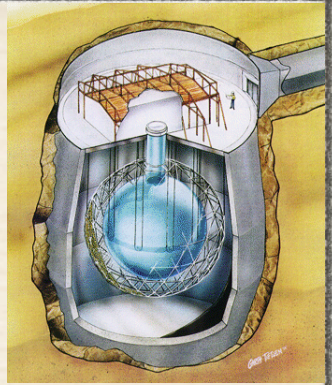
- ❖ SNO measured charged-current (CC) interactions of solar neutrinos on deuterium in heavy water, resulting electron energy is neutrino energy minus 1.4 MeV
- ❖ also: elastic scattering off electrons
- ❖ three ways to measure neutral-current (NC) break-up due to *any* type of active solar neutrino by detecting the neutron:
 - ❖ phase-I: pure D_2O (capture of n on deuterium)
 - ❖ phase-II: salted D_2O (capture of n on Chlorine)
 - ❖ phase-III: special 3He counters allow event-by event detection

SNO's Combined Oscillation Analysis



- ❖ SNO experimental variables:
 - ❖ energy distribution
 - ❖ radial vertex distribution
 - ❖ direction of events with respect to the sun
 - ❖ event hit pattern (distinguish electrons from γ cascades from neutron captures)
- ❖ different phases of SNO and three different interaction channels render a correct data analysis difficult to people outside the collaboration

SNO's Combined Oscillation Analysis



❖ therefore SNO defines and “measures” six generic variables of describing energy-dependent flavor changes:

❖ survival probability of electron-type solar neutrinos:

$$P_{ee}^{\text{day}}(E_\nu) = \mathbf{c_0} + \mathbf{c_1}(E_\nu[\text{MeV}] - 10) + \mathbf{c_2}(E_\nu[\text{MeV}] - 10)^2$$

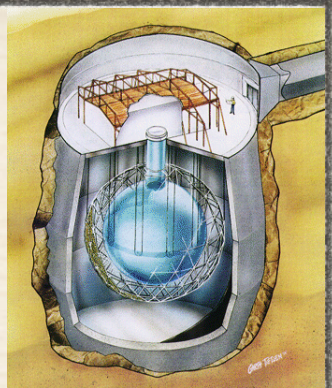
❖ energy-dependent day-night asymmetry:

$$A_{ee}(E_\nu) = 2 \frac{P_{ee}^{\text{night}}(E_\nu) - P_{ee}^{\text{day}}(E_\nu)}{P_{ee}^{\text{night}}(E_\nu) + P_{ee}^{\text{day}}(E_\nu)}$$

parameterized as $A_{ee}(E_\nu) = \mathbf{a_0} + \mathbf{a_1}(E_\nu[\text{MeV}] - 10)$

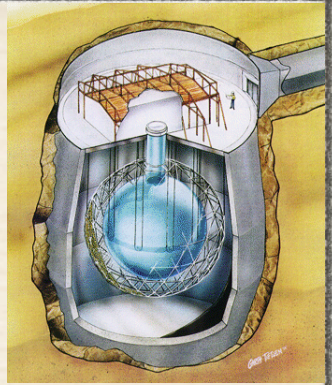
❖ total ^8B solar neutrino flux

SNO Variables



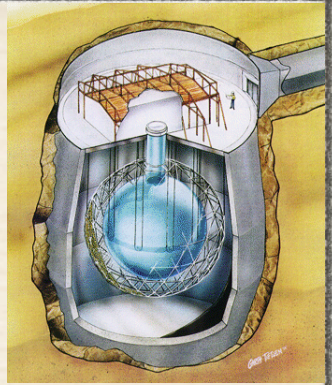
	Best fit	Stat.	Systematic Uncertainty			
			basic	D/N	MC	Total
ϕ_{8B}	5.25	± 0.16	$+0.11$ -0.12	± 0.01	$+0.01$ -0.03	$+0.11$ -0.13
c_0	0.317	± 0.016	$+0.008$ -0.010	± 0.002	$+0.002$ -0.001	± 0.009
c_1	0.0039	$+0.0065$ -0.0067	$+0.0047$ -0.0038	$+0.0012$ -0.0018	$+0.0004$ -0.0008	± 0.0045
c_2	-0.0010	± 0.029	$+0.0013$ -0.0016	$+0.0002$ -0.0003	$+0.0004$ -0.0002	$+0.0014$ -0.0016
a_0	0.046	± 0.031	$+0.007$ -0.005	± 0.012	$+0.002$ -0.003	$+0.014$ -0.013
a_1	-0.016	± 0.025	$+0.003$ -0.006	± 0.009	± 0.002	$+0.010$ -0.011

SNO Correlation Matrix

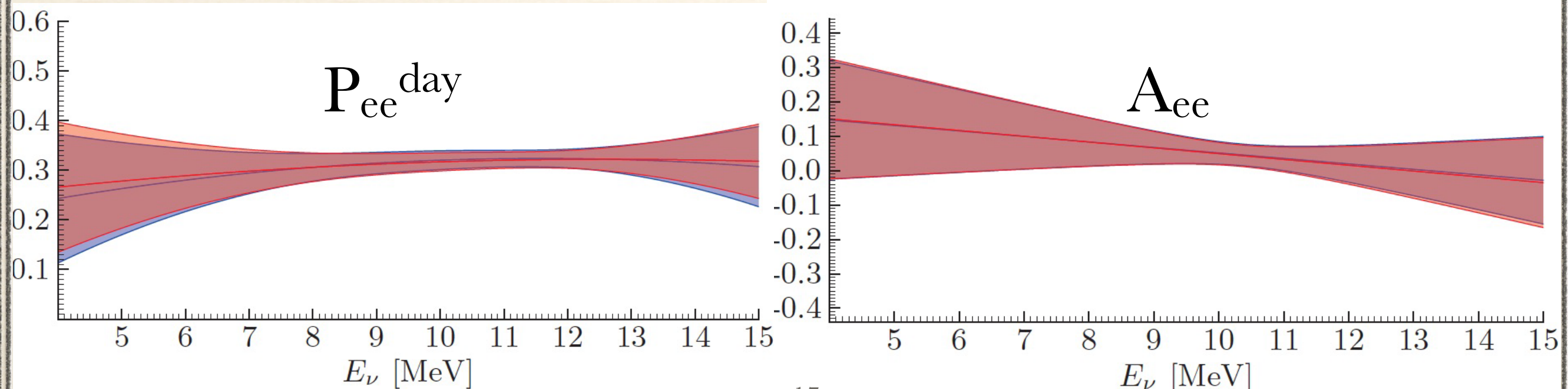


	ϕ_{8B}	c_0	c_1	c_2	a_0	a_1
ϕ_{8B}	1.000	-0.723	0.302	-0.168	0.028	-0.012
c_0	-0.723	1.000	-0.299	-0.366	-0.376	0.129
c_1	0.302	-0.299	1.000	-0.206	0.219	-0.677
c_2	-0.168	-0.366	-0.206	1.000	0.008	-0.035
a_0	0.028	-0.376	0.219	0.008	1.000	-0.297
a_1	-0.012	0.129	-0.677	-0.035	-0.297	1.000

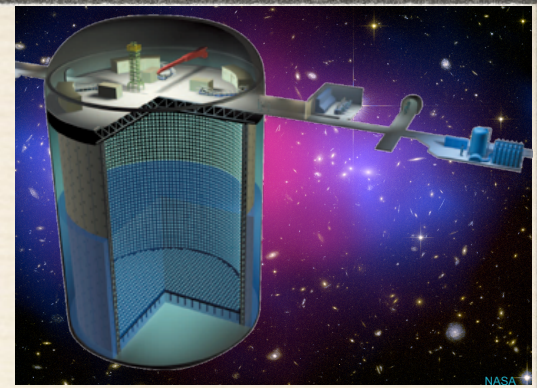
Using the SNO Variables



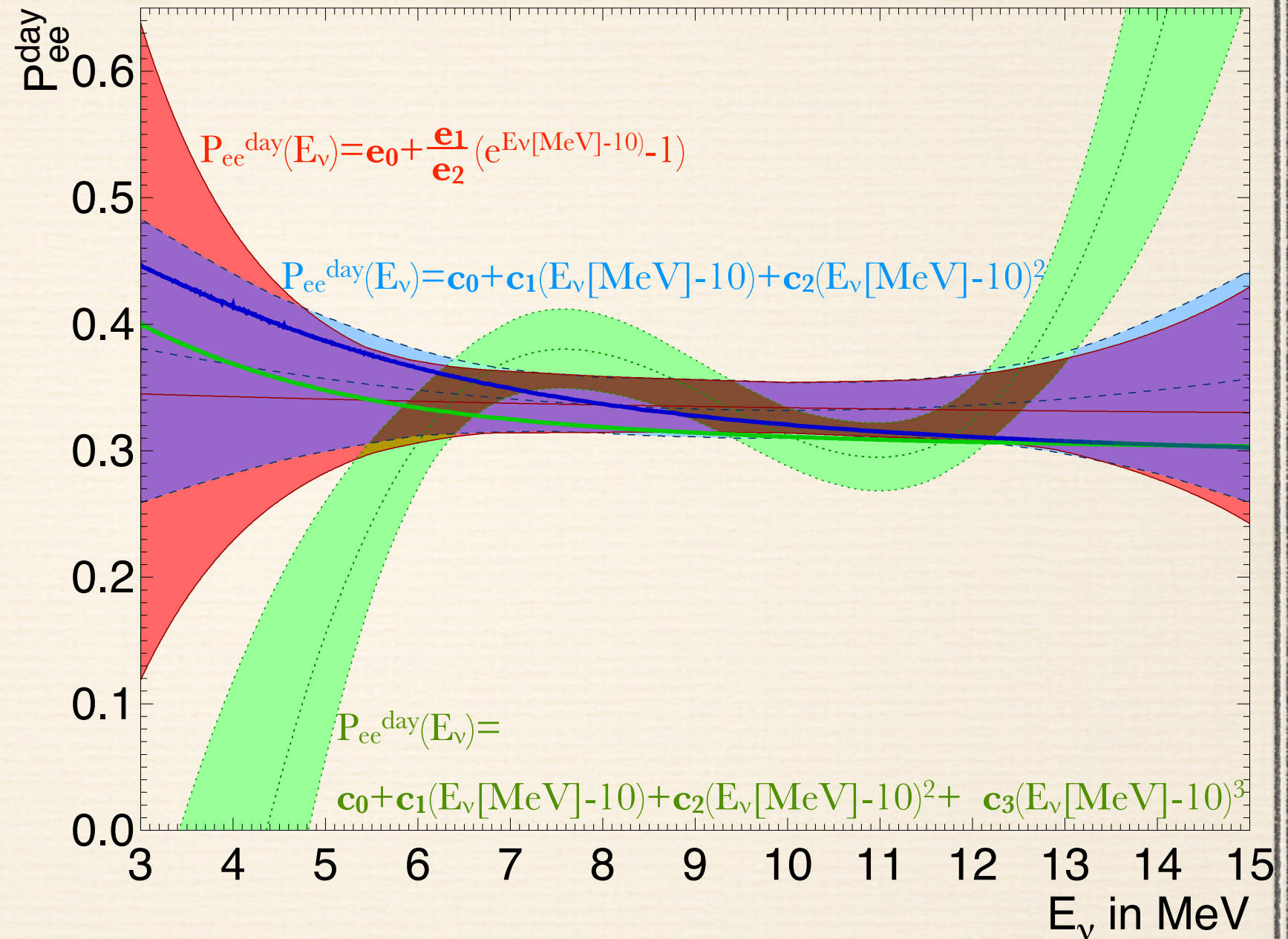
- ❖ fit P_{ee} parameters to MSW calculations of P_{ee} weighted by SNO sensitivity
- ❖ calculate a χ^2 value of the SNO “measurement” of these parameters using the SNO error matrix
- ❖ find best fit at minimum χ^2 and draw allowed region(s)
- ❖ coefficients also used to draw allowed 1σ bands



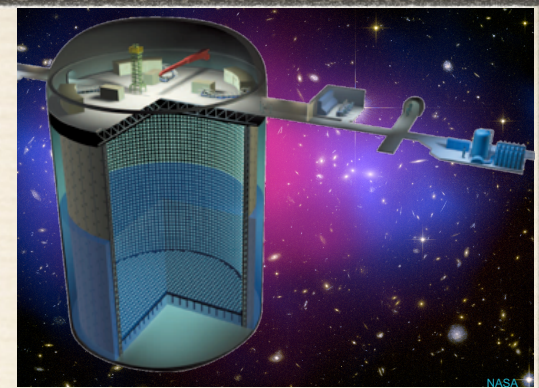
P_{ee} Analysis from SK



- ❖ SK does a similar analysis, but only for P_{ee} , not A_{ee} (standard A_{ee} assumed)
- ❖ use three different parameterizations
- ❖ lesson: only take these bands seriously in the sensitivity center



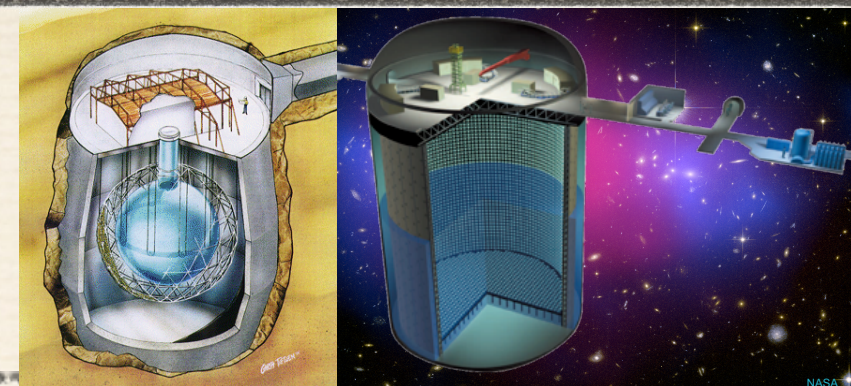
P_{ee} Analysis from SK



	e_0/c_0	e_1/c_1	e_2/c_2	C_3
expon.	0.336 ± 0.023	-0.0014 ± 0.0051	no constr.	
quadratic	0.334 ± 0.023	-0.0003 ± 0.0065	0.0008 ± 0.0029	
cubic	0.313 ± 0.024	-0.031 ± 0.016	0.0097 ± 0.0051	0.0044 ± 0.0020
SNO	0.315 ± 0.017	-0.0007 ± 0.0059	-0.0011 ± 0.0033	
SK+SNO	0.311 ± 0.015	-0.0034 ± 0.0036	0.0004 ± 0.0018	

- ❖ SNO (and SK+SNO) numbers are a reduction of their published results (taking out A_{ee})
- ❖ shape errors in SK+SNO reduced more than expected compared to SK, SNO

Correlations: SK+SNO



SNO

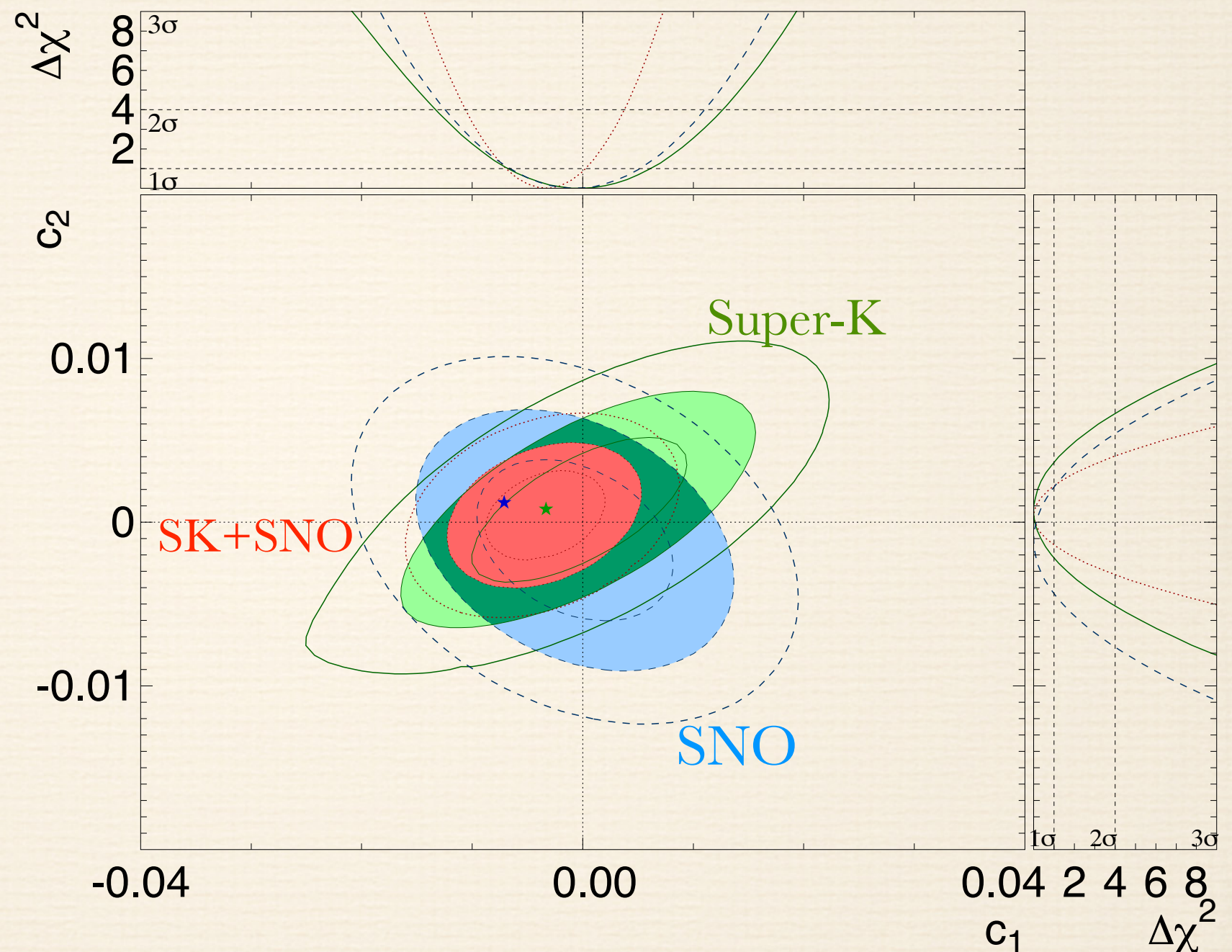
	c ₀	c ₁	c ₂
c ₀	1.000	-0.301	-0.391
c ₁	-0.301	1.000	-0.312
c ₂	-0.391	-0.312	1.000

Super-K

	c ₀	c ₁	c ₂
c ₀	1.000	-0.131	-0.345
c ₁	-0.131	1.000	0.649
c ₂	-0.345	0.649	1.000

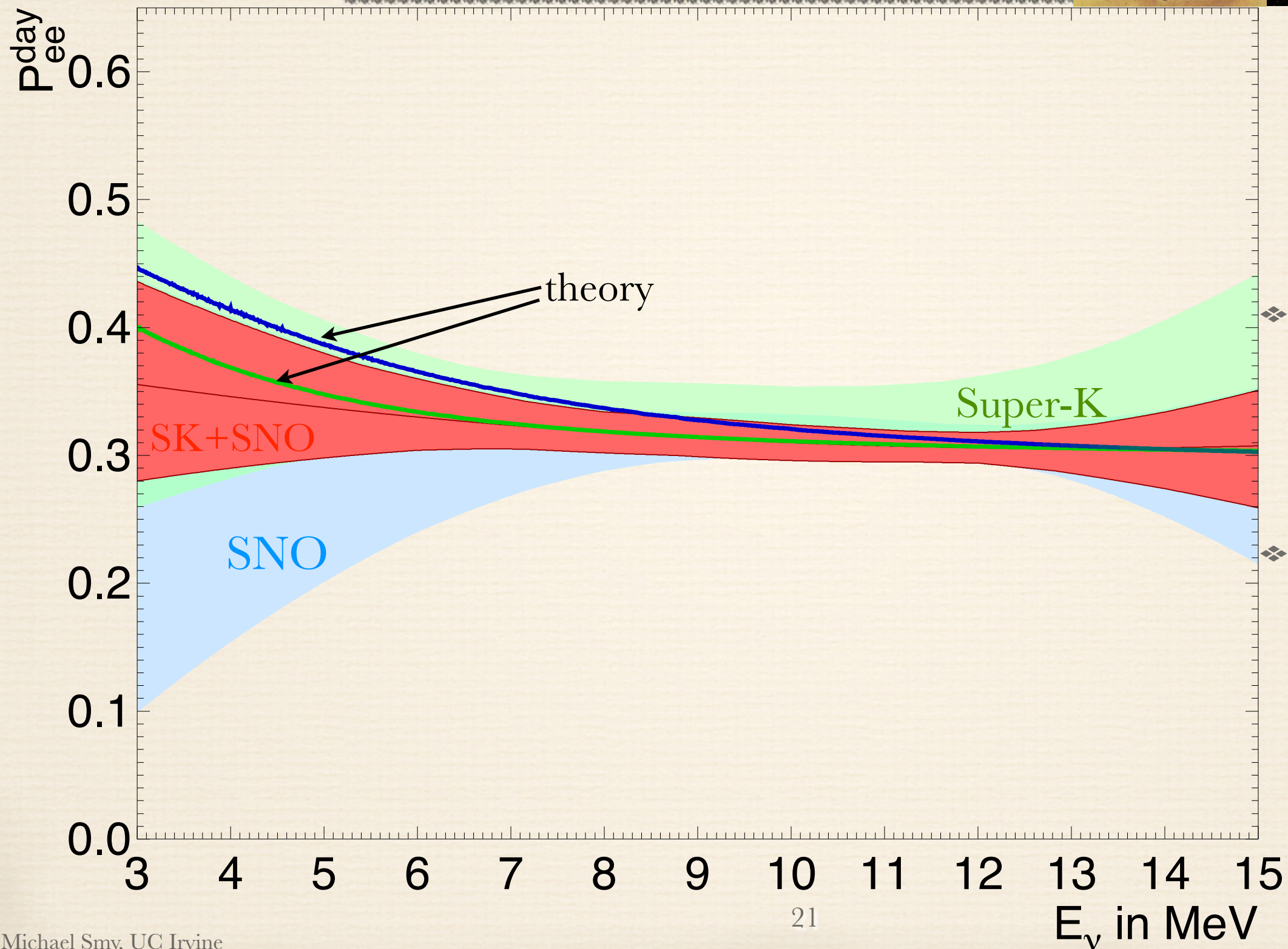
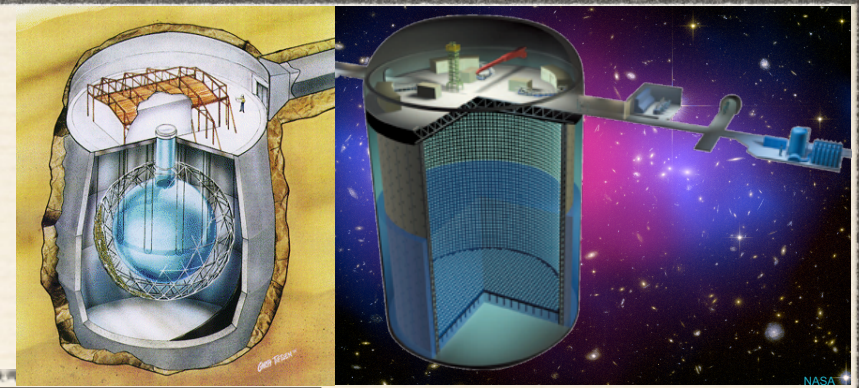
SK+SNO

	c ₀	c ₁	c ₂
c ₀	1.000	-0.453	-0.407
c ₁	-0.453	1.000	0.301
c ₂	-0.407	0.301	1.000



❖ shape correlations in SK, SNO
are opposite

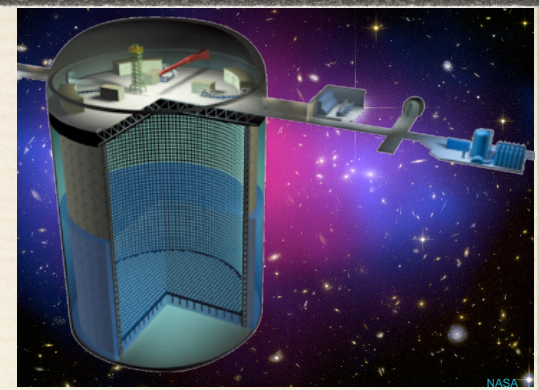
SK+SNO



◇ slightly less correlation of the coefficients

◇ large error reduction

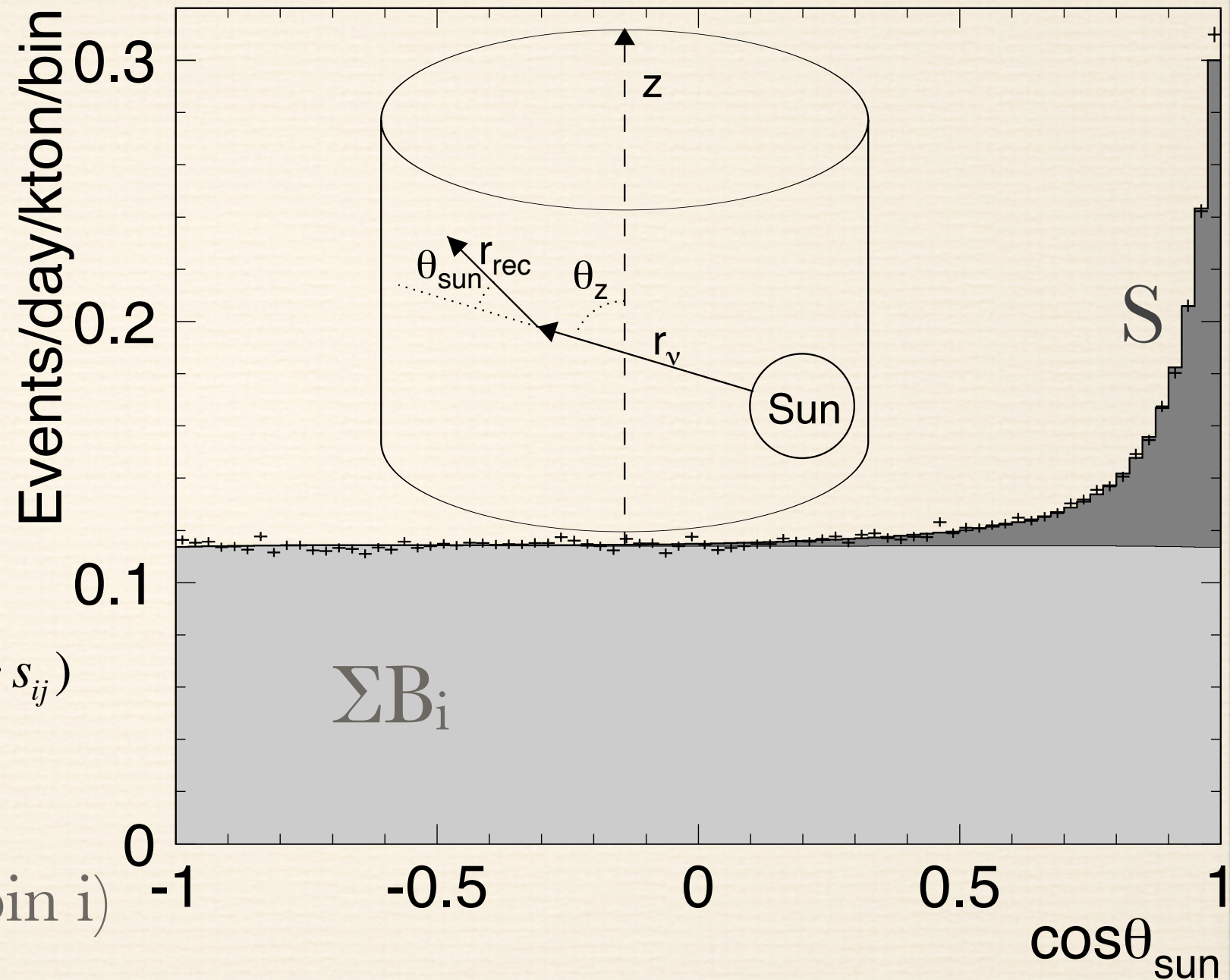
SK Oscillation Analysis: “Mixed Likelihood- χ^2 ”



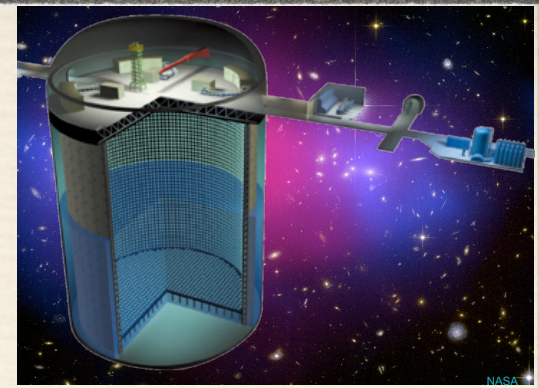
- ❖ SK measures elastic scattering off electrons; directionality is critical to the signal extraction
- ❖ use extended maximum likelihood fit in $N_{\text{bin}}=23$ energy regions i

$$L = e^{-\sum_i (B_i + S)} \prod_{i=1}^{N_{\text{bin}}} \prod_{j=1}^{n_i} (B_i \cdot b_{ij} + S \cdot Y_i \cdot s_{ij})$$

- ❖ S : signal events,
 B_i : background events (bin i)
 s_{ij} : signal pdf of event ij ,
 b_{ij} : background pdf of event ij ,
 Y_i : MC ratio of events in bin i



SK Oscillation Analysis: Mixed Likelihood- χ^2



- ❖ optimal analysis: add time-dependence of signal $z(t)$, and calculate $z(t)$ and Y_i for each oscillation parameter, include nuisance parameters for systematics like energy scale, ^8B ν spectrum, etc.

$$L = e^{-\sum_i (B_i + S)} \prod_{i=1}^{N_{bin}} \prod_{j=1}^{n_i} (B_i \cdot b_{ij} + S \cdot z(t) \cdot Y_i \cdot s_{ij})$$

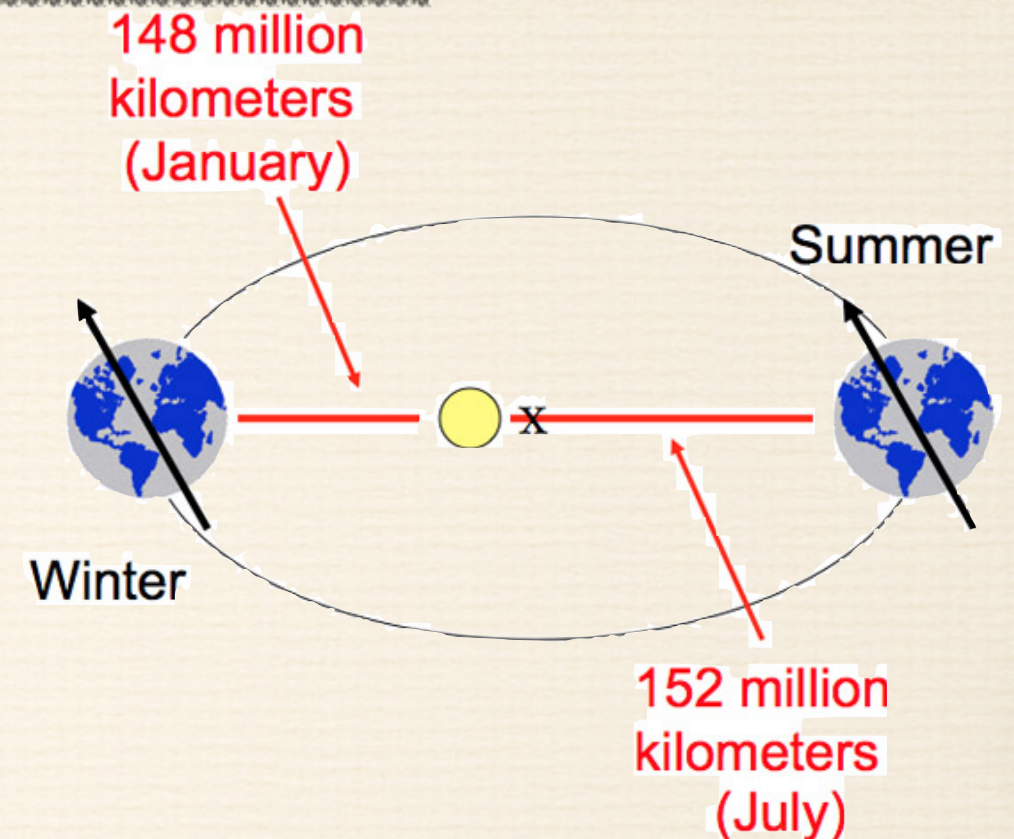
- ❖ but: $\sim 30,000$ solar neutrinos, and $\sim 400,000$ background events (takes a long time to fit for each possible oscillation parameter set)
- ❖ better to use binned χ^2 for spectrum, and likelihood for time dependence: $\log L = (\log L - \log L_{\text{no-tv}}) + \log L_{\text{no-tv}} = \Delta \log L_{\text{tv}} + \log L_{\text{no-tv}}$
- ❖ $L_{\text{no-tv}}$ is the likelihood for $z(t)=1$ (no time variation)

- ❖ $\Delta \log L_{\text{tv}}$ is the log of the likelihood ratio:
$$\frac{e^{-\sum_i (B_i + S)} \prod_{i=1}^{N_{bin}} \prod_{j=1}^{n_i} (B_i \cdot b_{ij} + S \cdot z(t) \cdot Y_i \cdot s_{ij})}{e^{-\sum_i (B_i + S)} \prod_{i=1}^{N_{bin}} \prod_{j=1}^{n_i} (B_i \cdot b_{ij} + S \cdot Y_i \cdot s_{ij})}$$

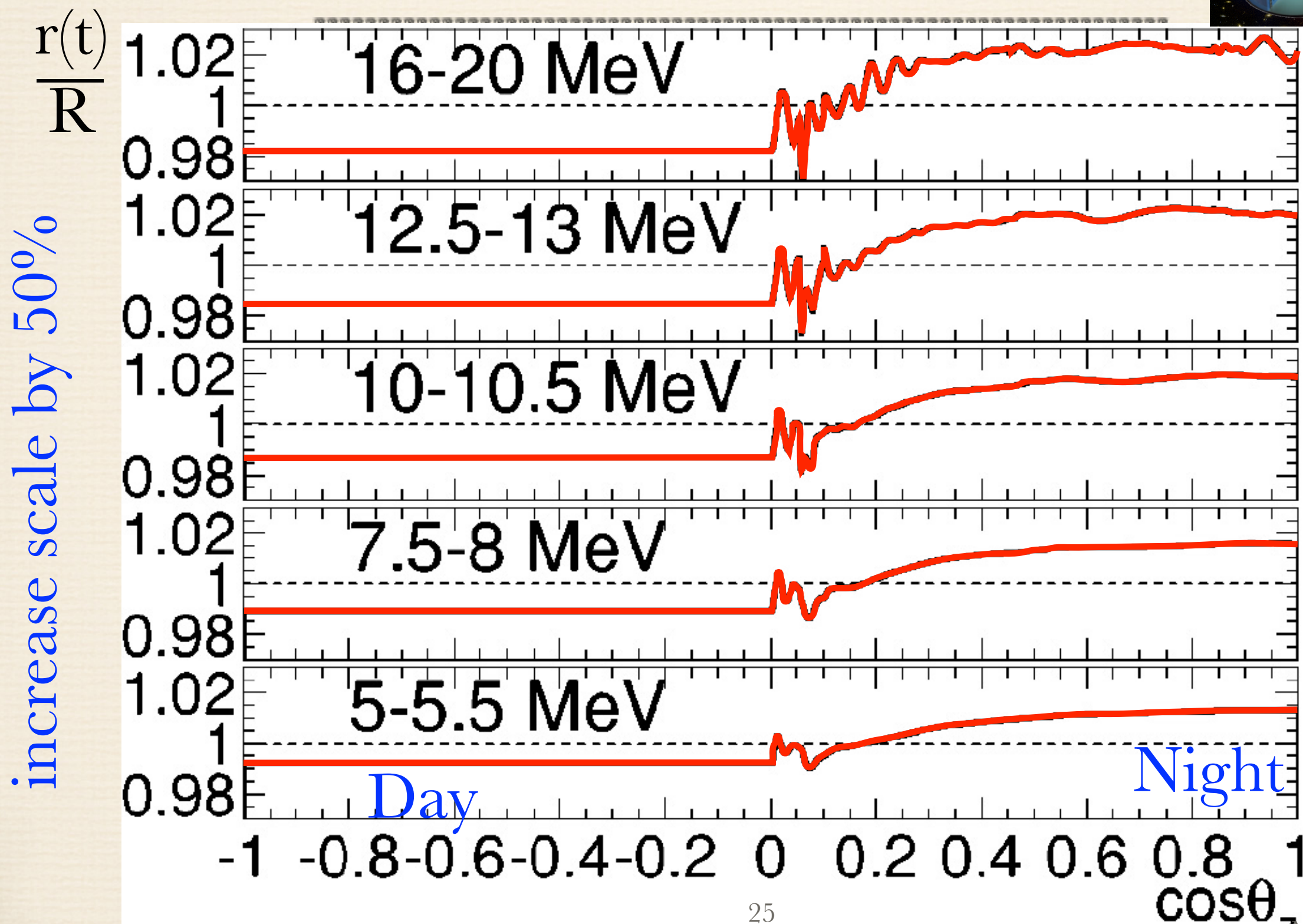
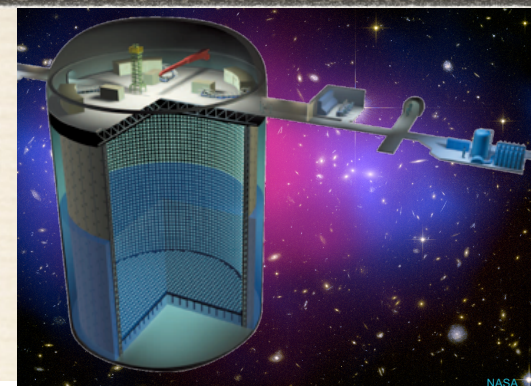
- ❖ approximate $\log L_{\text{no-tv}} = -1/2 \chi^2$

Solar Neutrino Time Variations

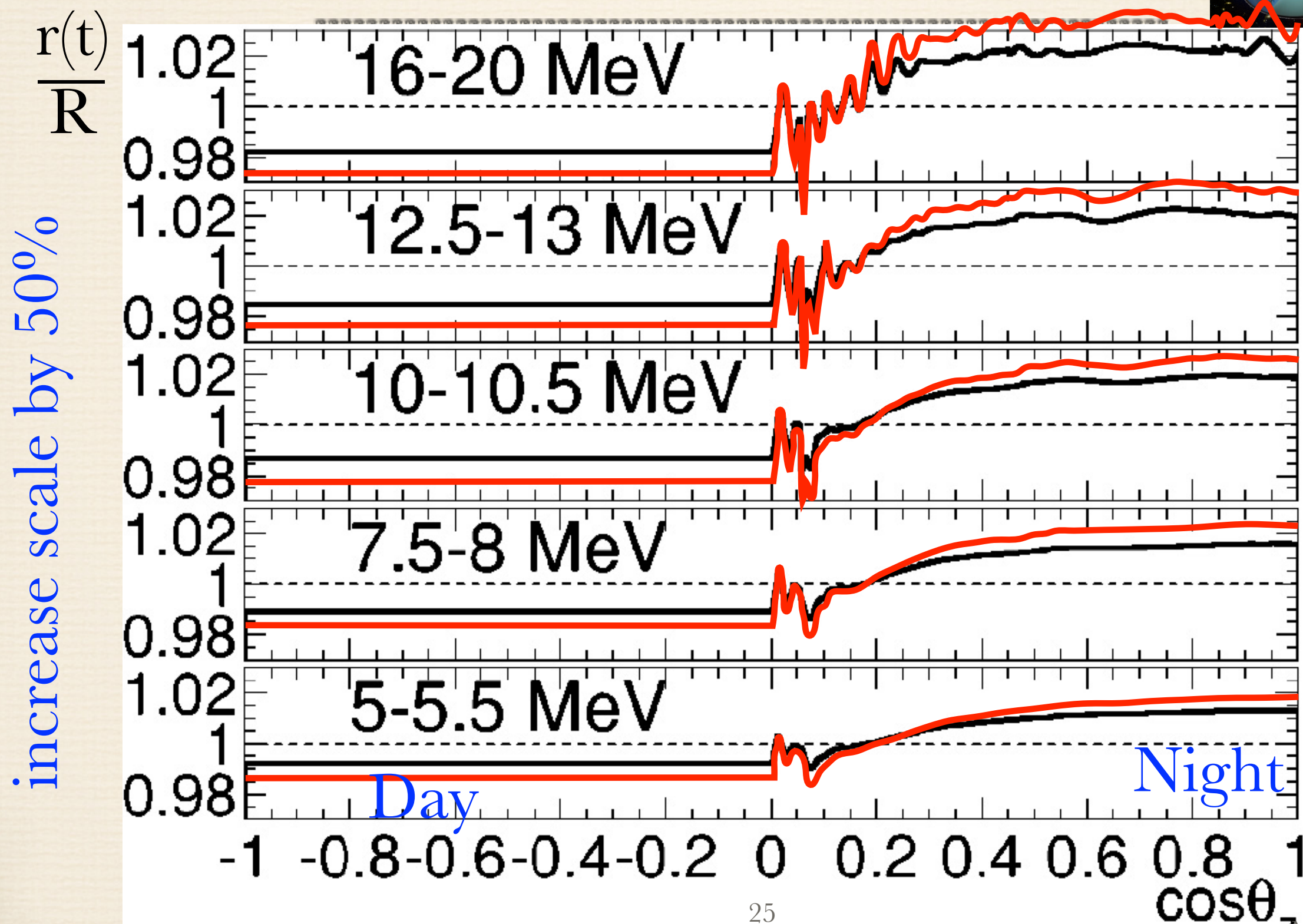
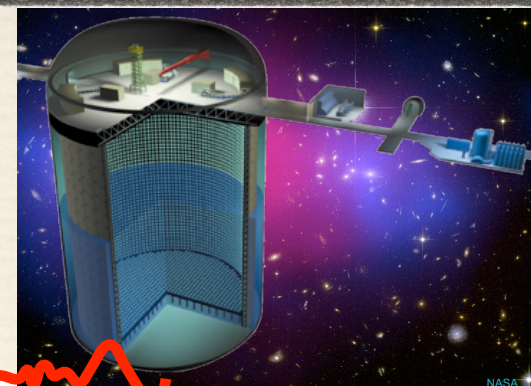
- ❖ $\pm 3.5\%$ flux variation between perihelion and aphelion (just $1/r^2$)
- ❖ possible change in solar neutrino luminosity
- ❖ possible change in solar neutrino flavor (e.g. resonant spin-flavor conversion)
- ❖ terrestrial matter effects: regeneration of ν_e flavor during the night (day/night effect)



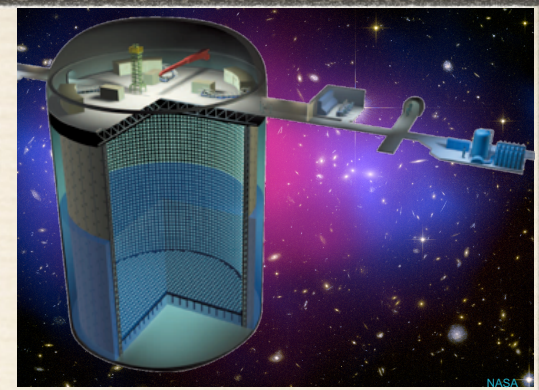
SK Time Variation Analysis



SK Time Variation Analysis



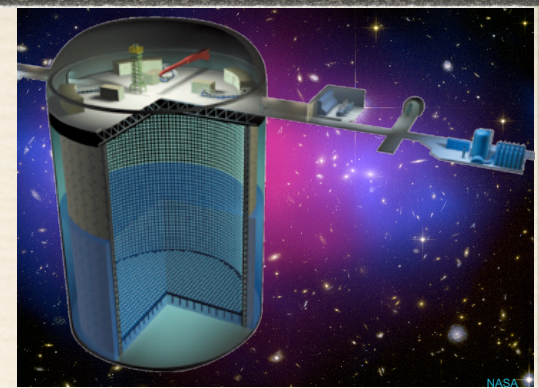
SK Time Variation Analysis



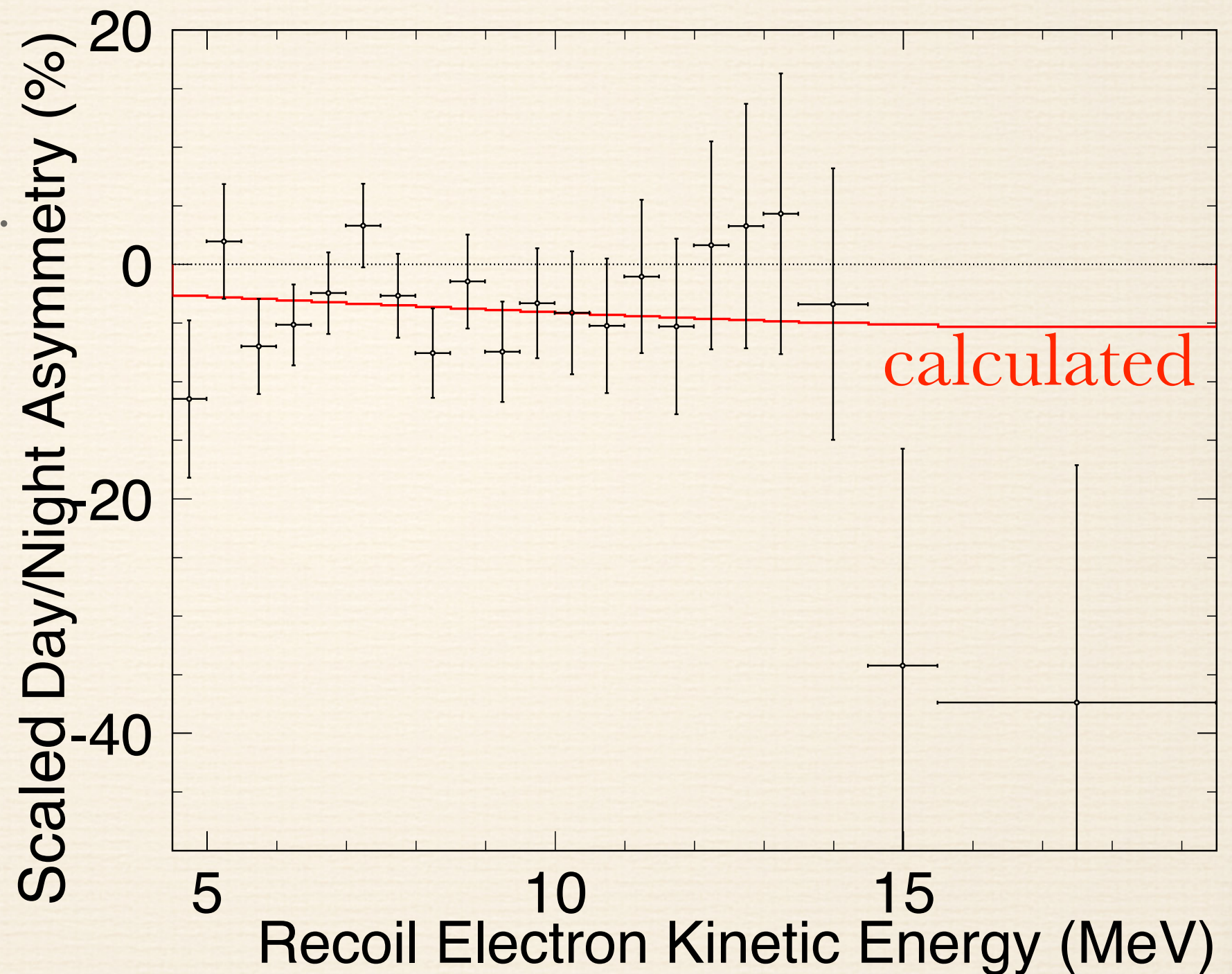
- ❖ expand likelihood fit to allow measuring the amplitude of the time variation independently of the average solar neutrino interaction rate $R=S/L$, where L is the detector lifetime
- ❖ time-dependent rate is then $r(t)=Rz(t)$
- ❖ define an amplitude scaling parameter α that increases/decreases the time variation, but leaves R unchanged
- ❖ day/night: measure diurnal variation by the asymmetry of the average day, night rate $R_{D,N}$
$$A_{DN} = \frac{R_D - R_N}{\frac{1}{2}(R_D + R_N)}$$
- ❖ if the “livetime” asymmetry is $L_{DN} = \frac{L_D - L_N}{\frac{1}{2}(L_D + L_N)}$, the desired scaling is

$$r(t, \alpha) = R \frac{1 + \alpha \left(\left[1 + \frac{1}{4} A_{DN} L_{DN} \right] \frac{r(t)}{R} - 1 \right)}{1 + \alpha \frac{1}{4} A_{DN} L_{DN}}$$

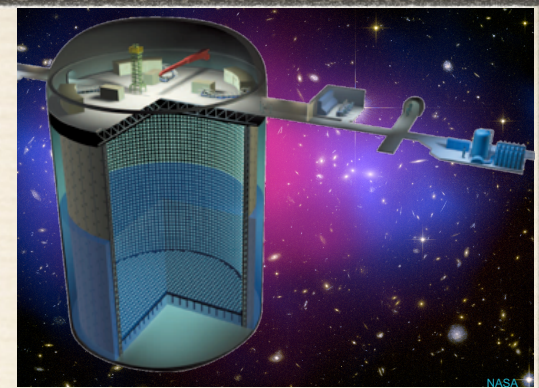
SK Time Variation Analysis



❖ result: scaled asym.
 $A_{DN} = -3.3 \pm 1.1\%$

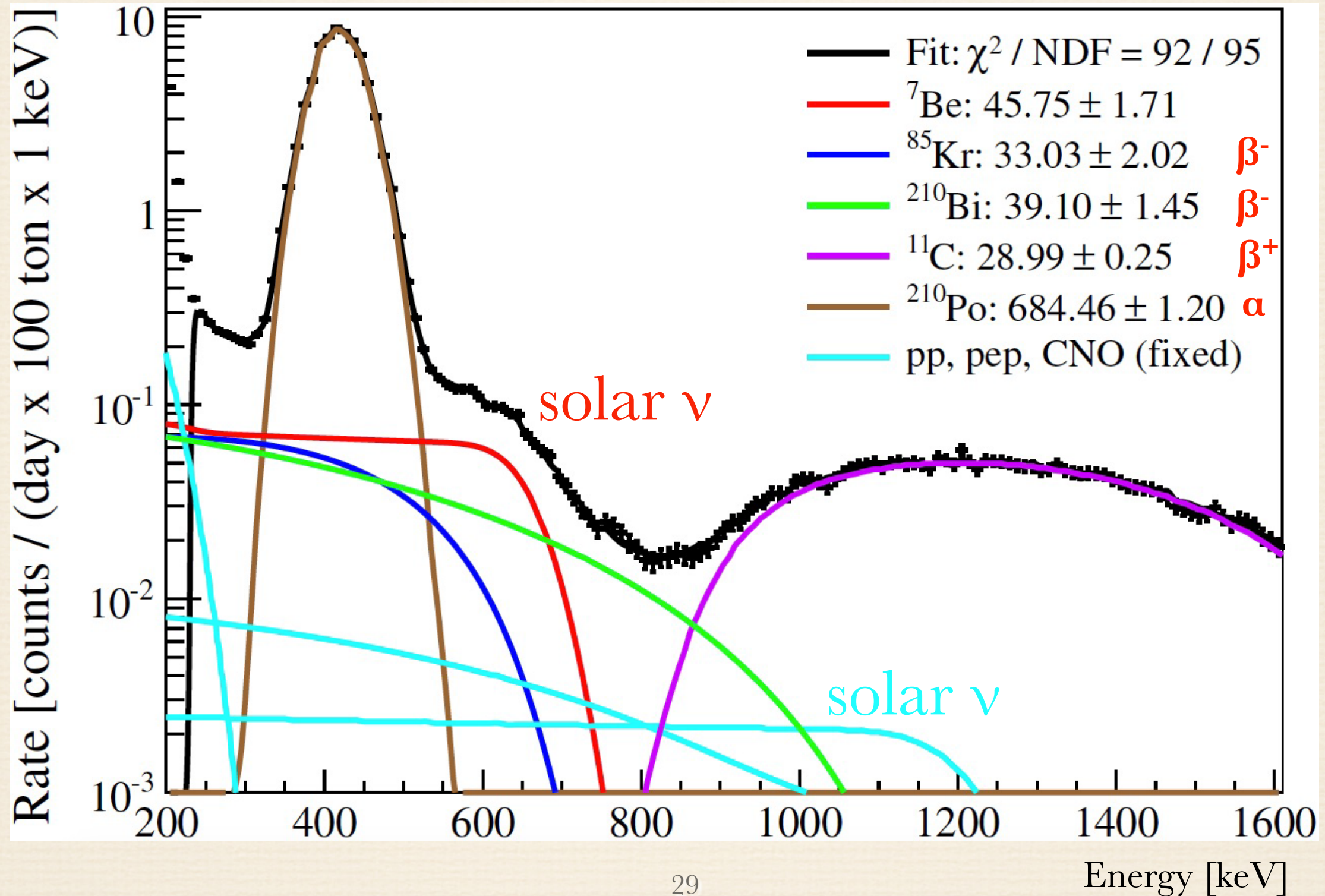
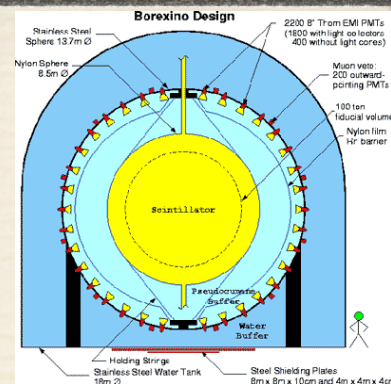


BOREXINO's D/N Analysis

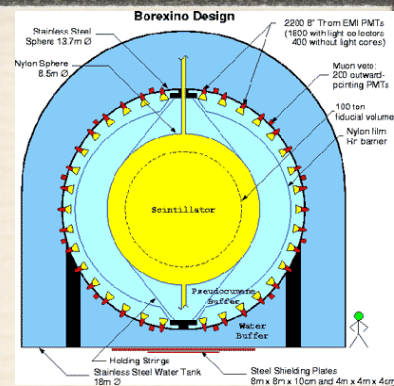


- ❖ fit the measured event rate spectrum to the (^7Be) solar neutrino rate various backgrounds
- ❖ subtract the measured day rate spectrum from the night rate spectrum: most backgrounds cancel, even in an enlarged fiducial volume
- ❖ fit this rate difference to the (^7Be) solar neutrino rate difference
- ❖ divide by the average rate obtained in the first step and obtain the day/night asymmetry
- ❖ correlations between numerator and denominator are not taken into account (but should be small)

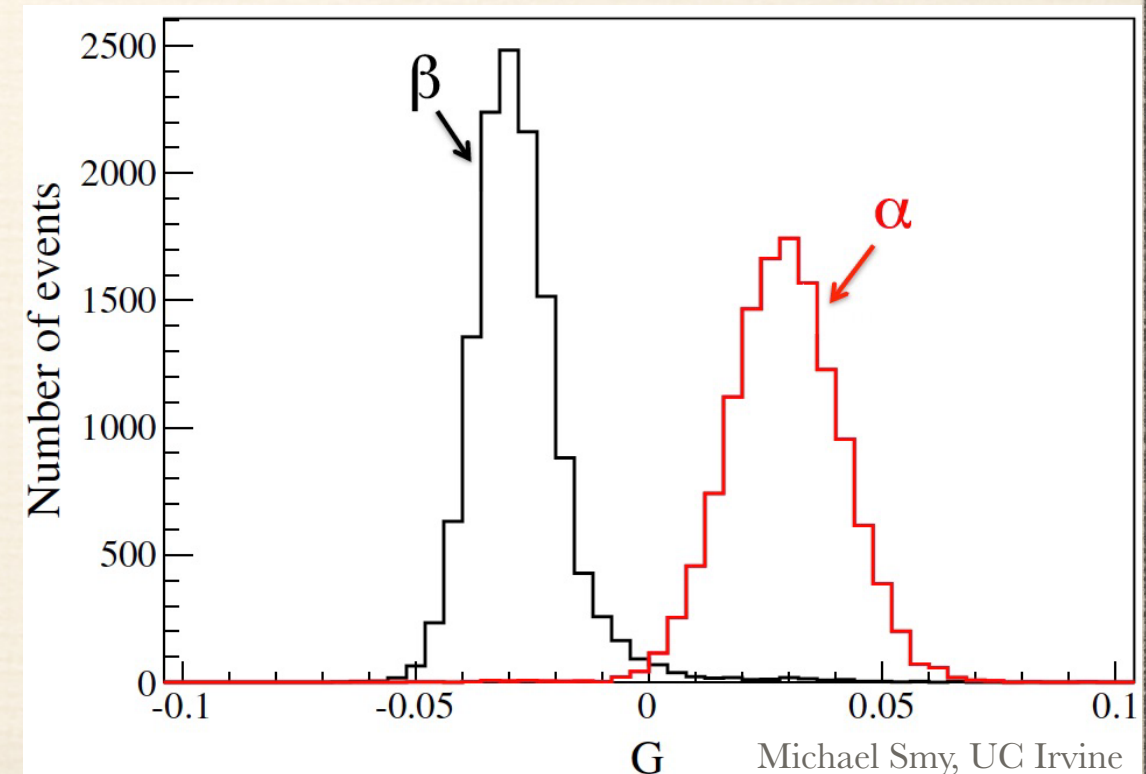
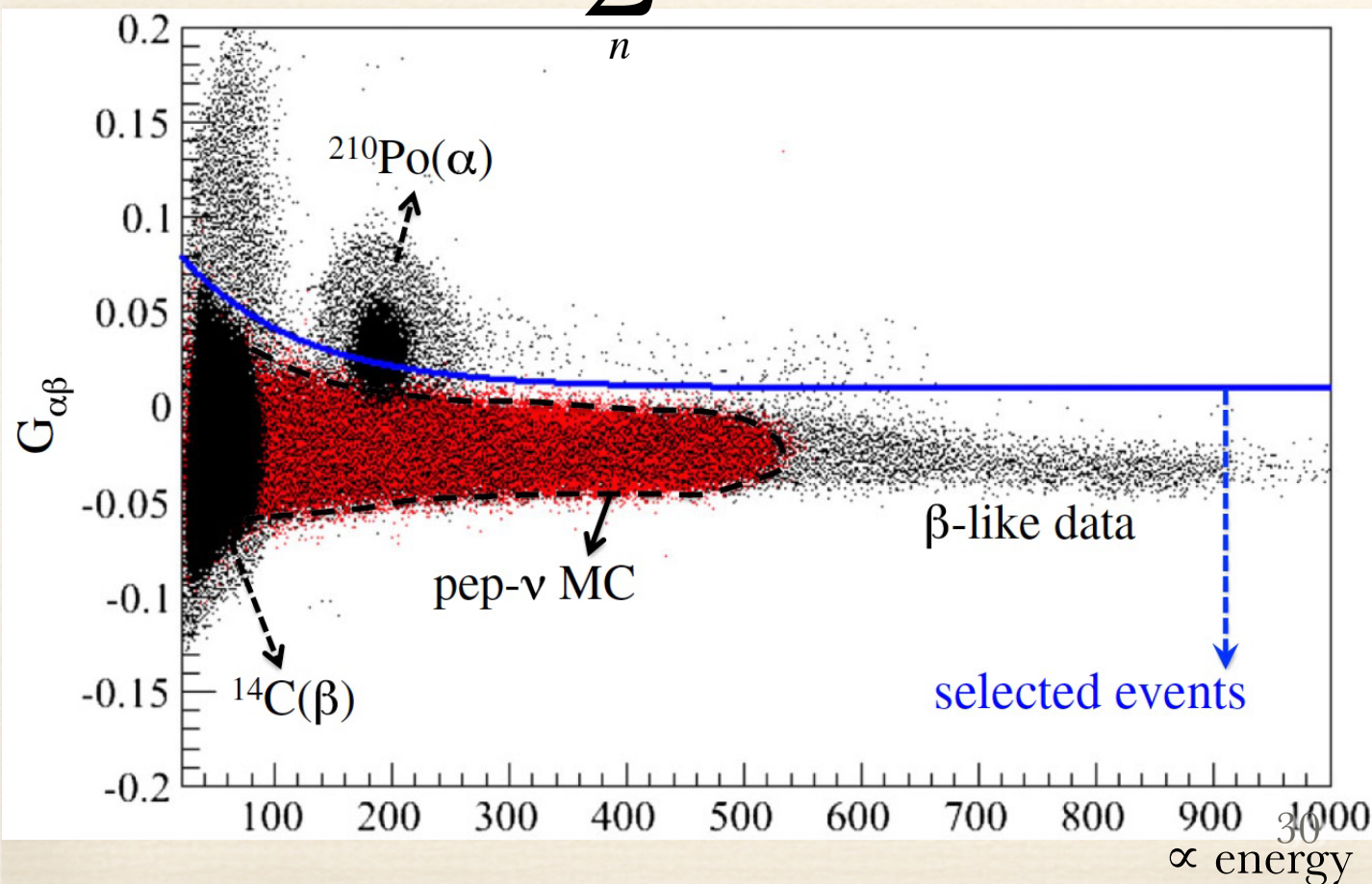
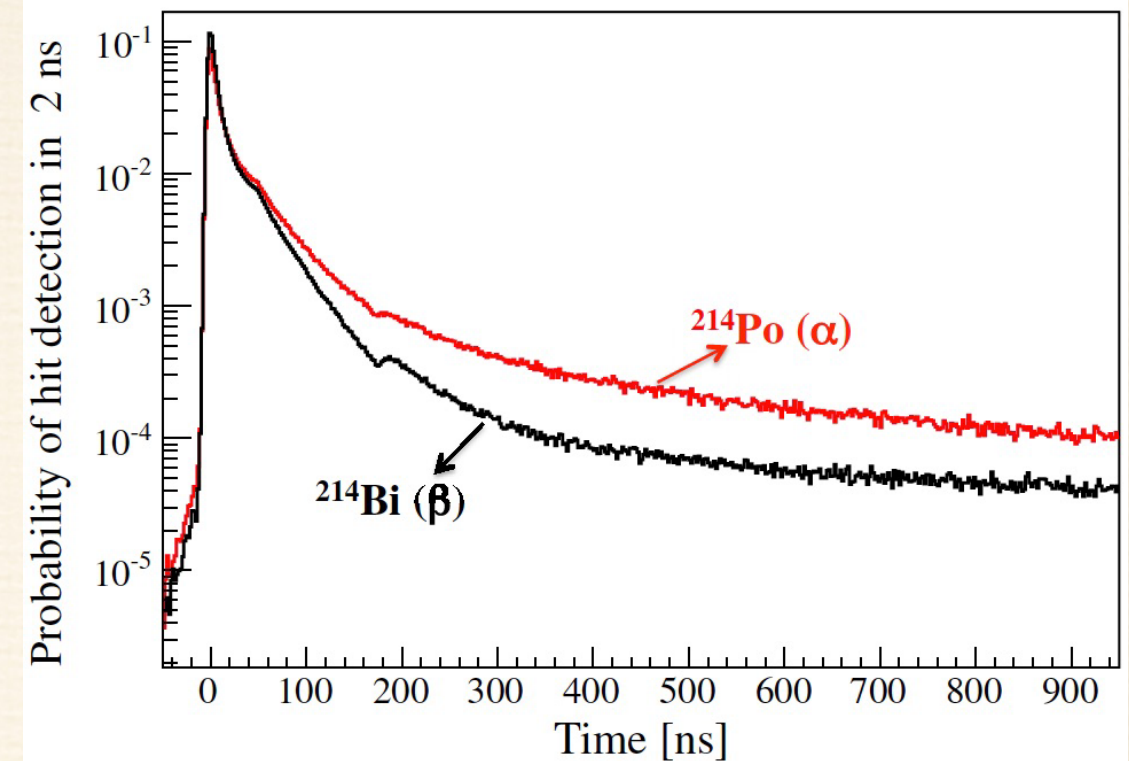
BOREXINO Rate Spectrum



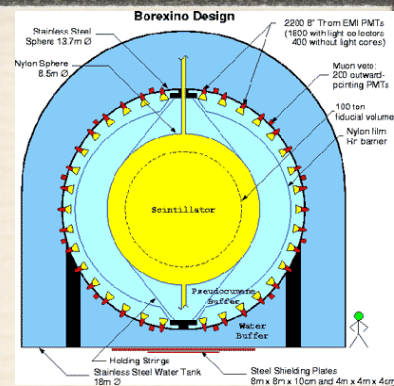
α - β Discrimination: Gatti Filter in BOREXINO



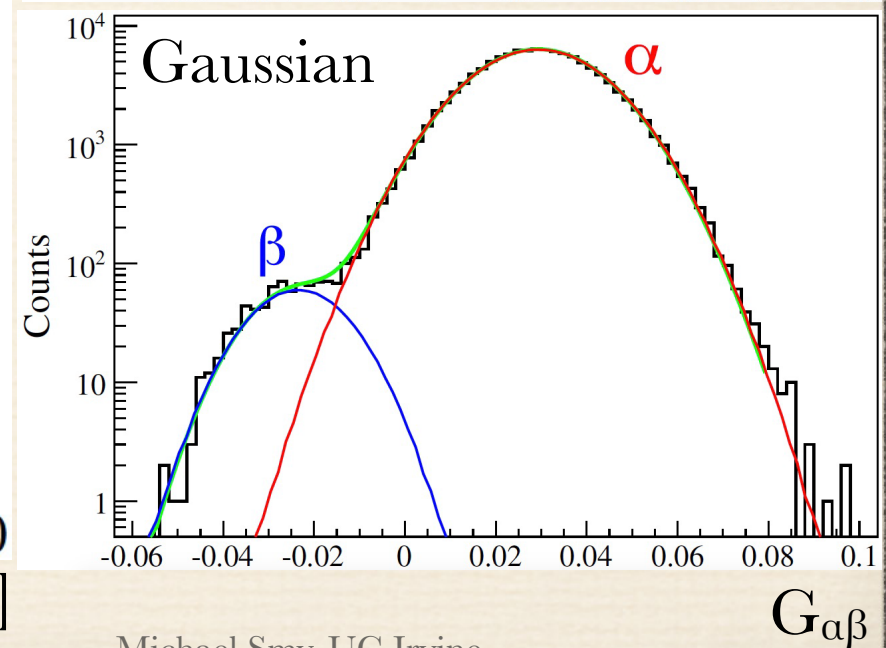
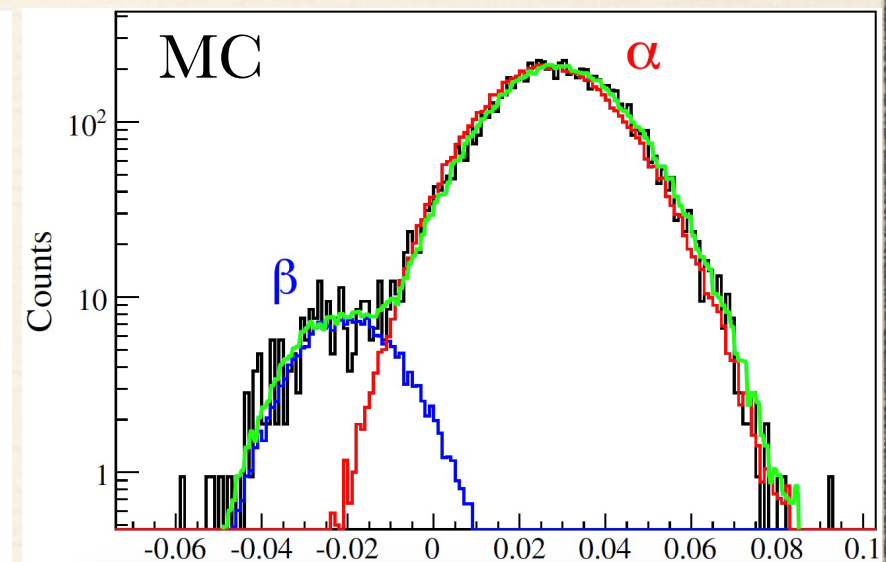
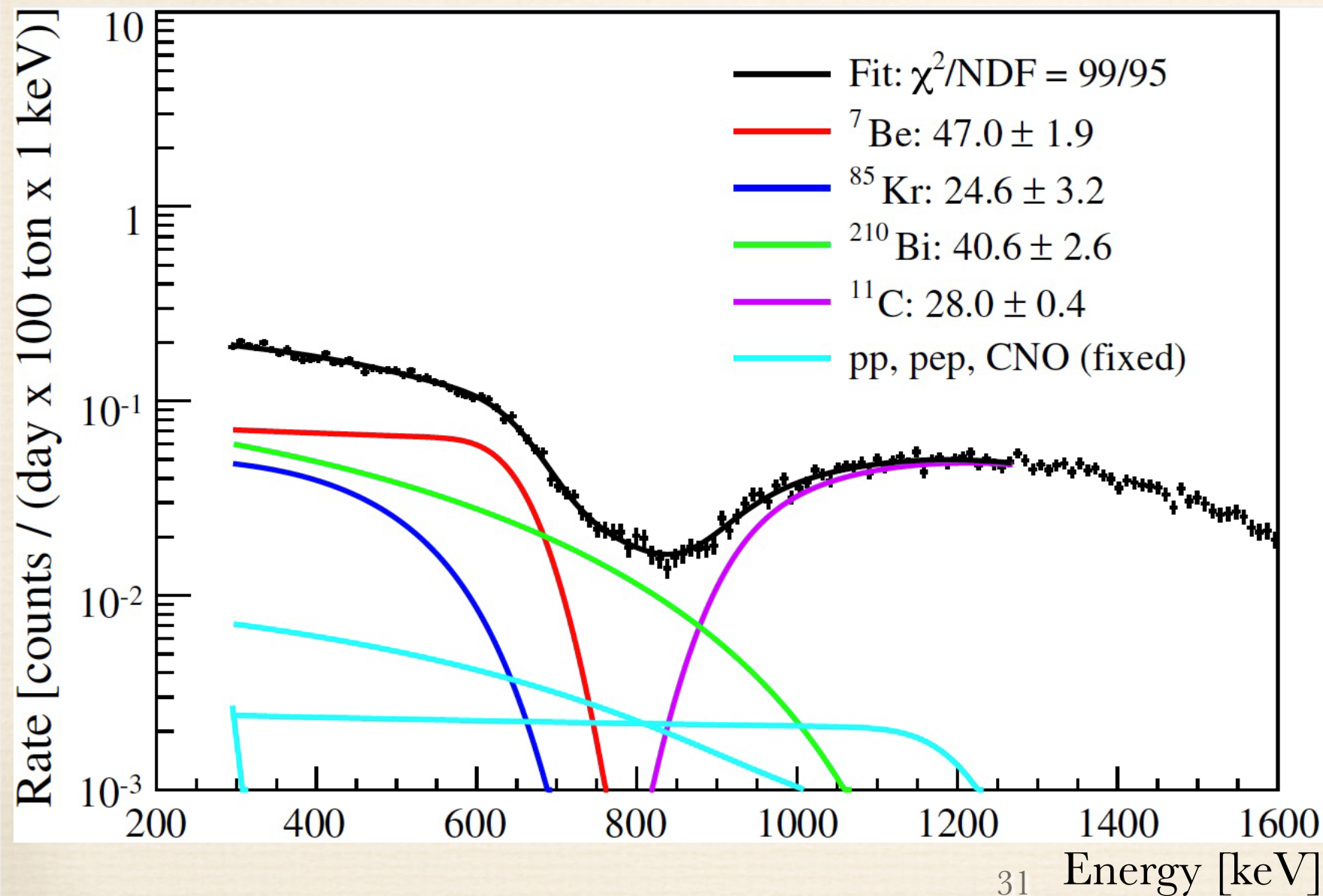
- ❖ have two binned time distributions (e.g. scintillation of α 's and β 's) r_1, r_2
- ❖ form asymmetries $w(t) = \frac{r_1(t) - r_2(t)}{r_1(t) + r_2(t)}$
- ❖ test data distributions $d(t)$ with Gatti variable $G = \sum_n d(t_n)w(t_n)$



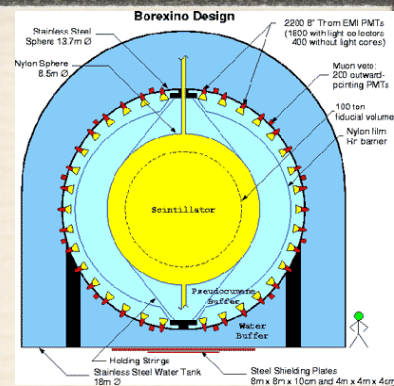
Statistically Remove Remaining α 's



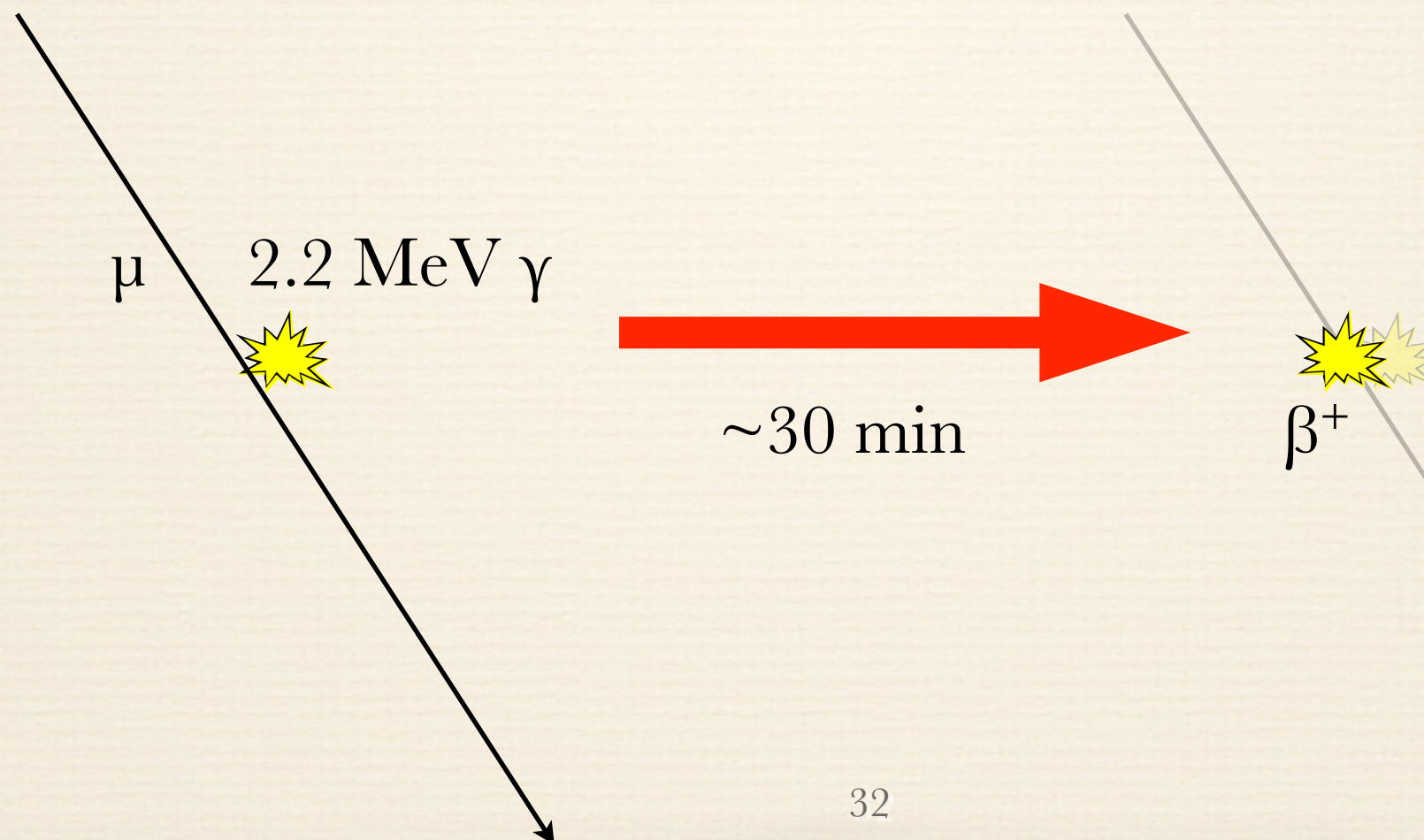
- ❖ make the Gatti distribution in each energy bin
- ❖ fit with either with MC distributions or Gaussians



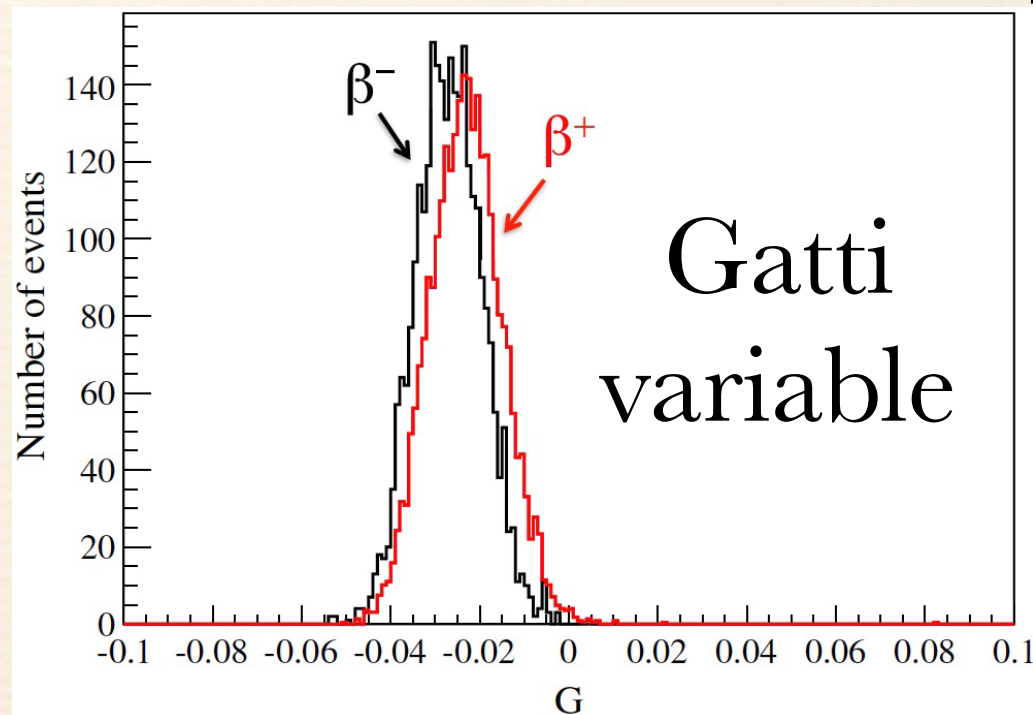
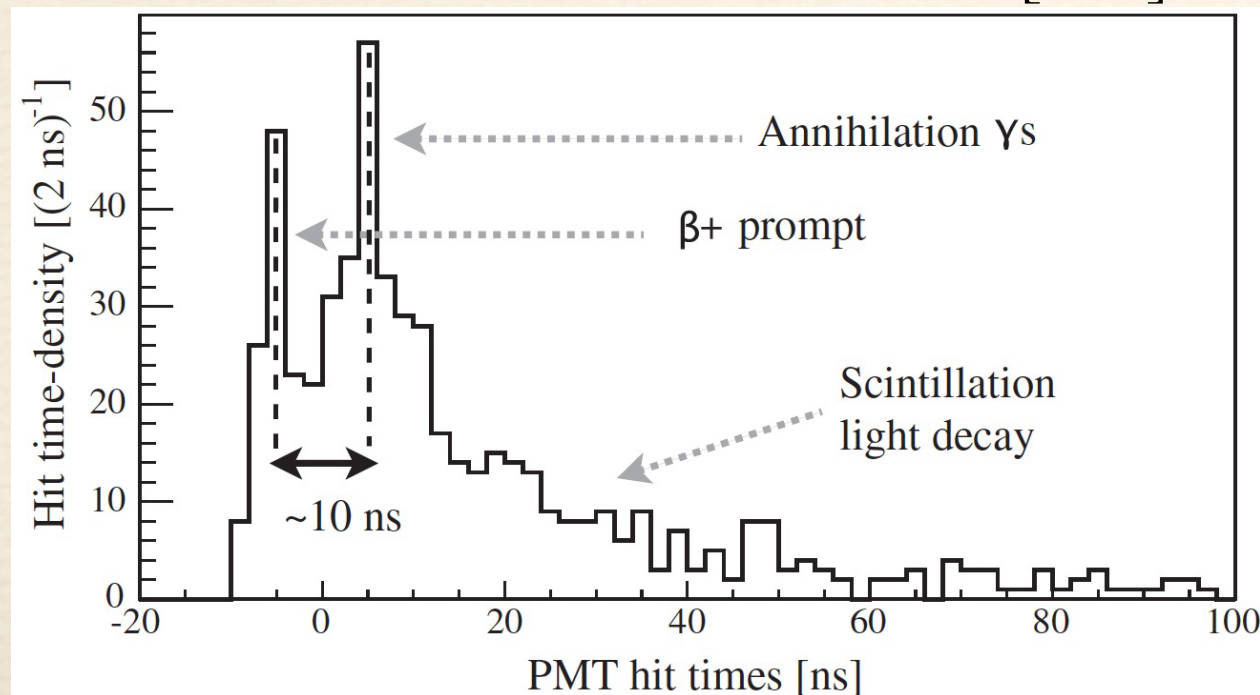
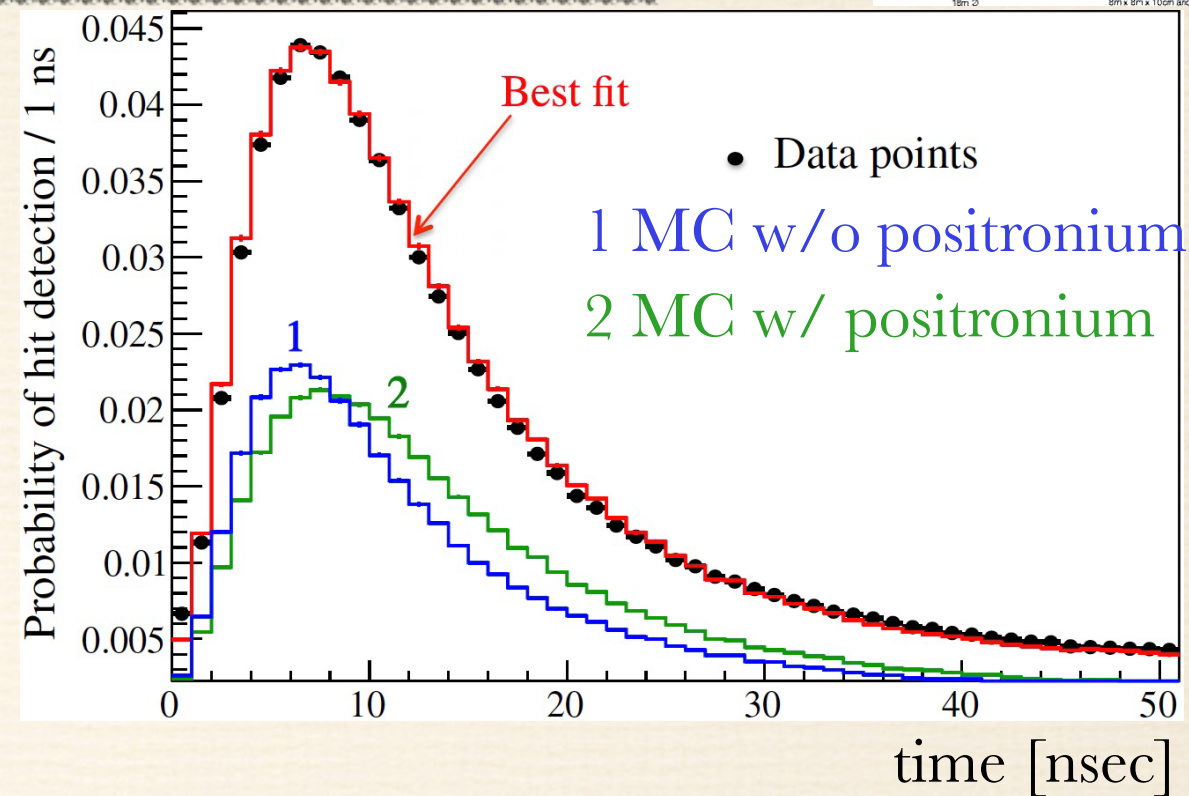
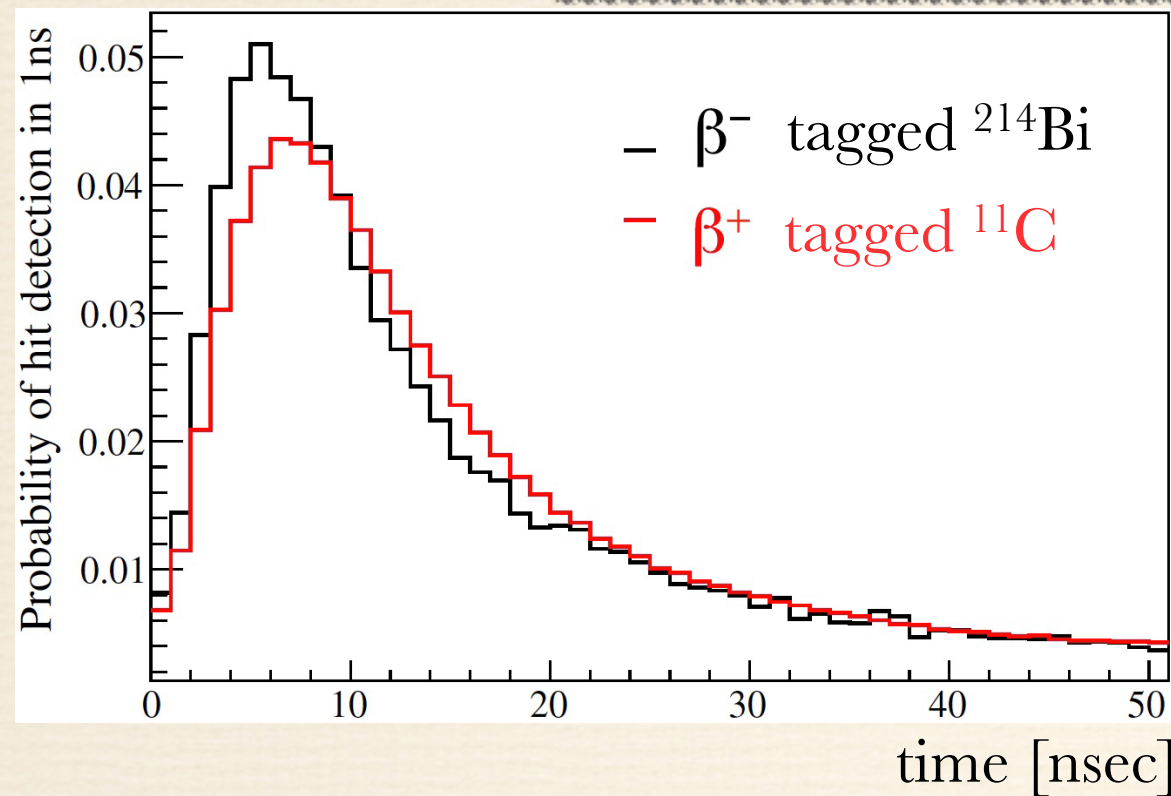
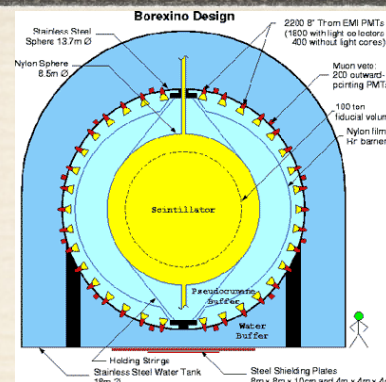
^{11}C β^+ Background



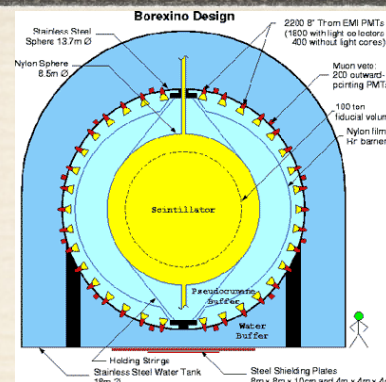
- ❖ ^{11}C is extremely long-lived: $\sim 30\text{min}$
- ❖ produced cosmogenically from ^{12}C by neutron emission
- ❖ tag β^+ decays to ^{11}B by spalling muon and n capture
- ❖ 50% efficient tag removes 90% of ^{11}C



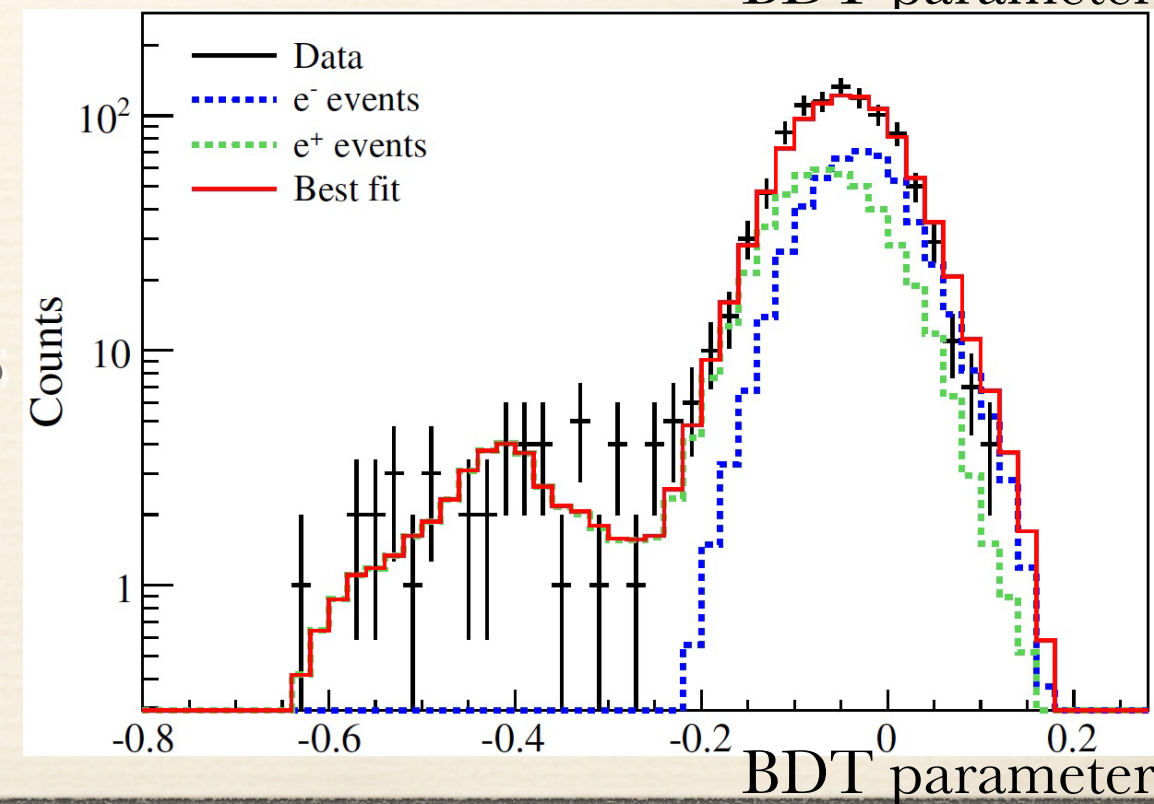
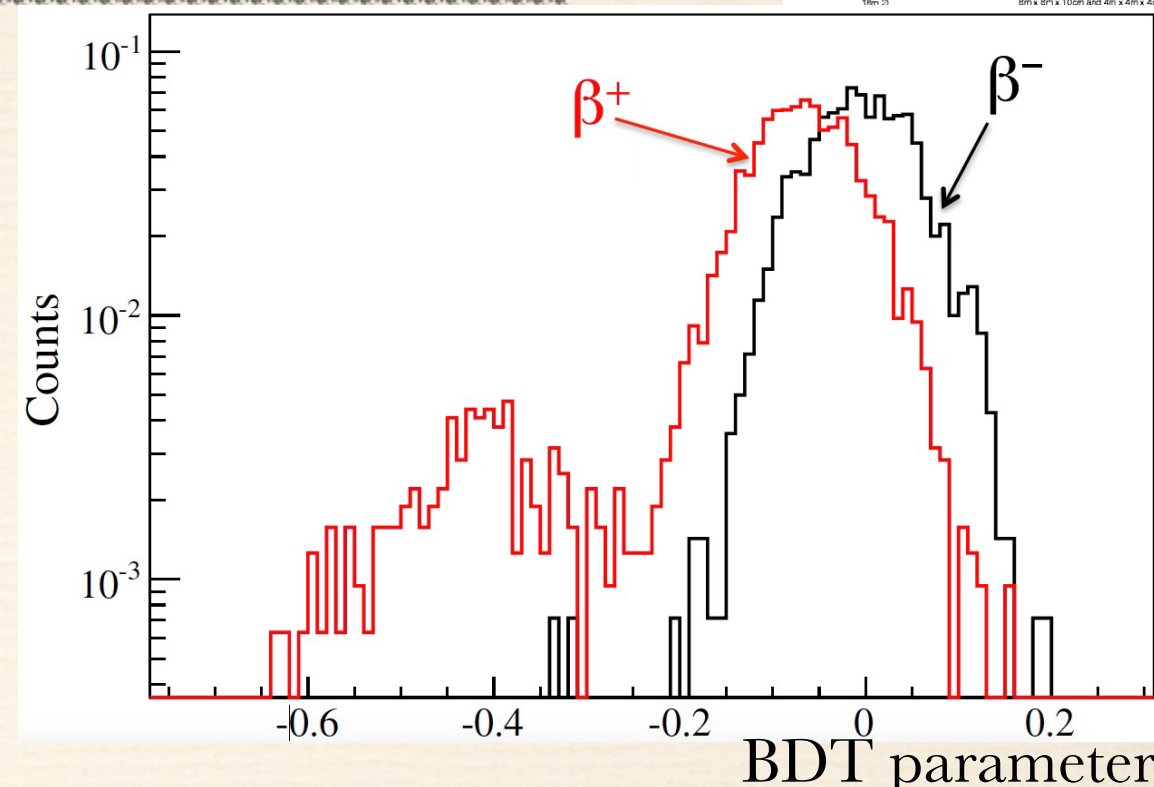
Distinguishing β^+



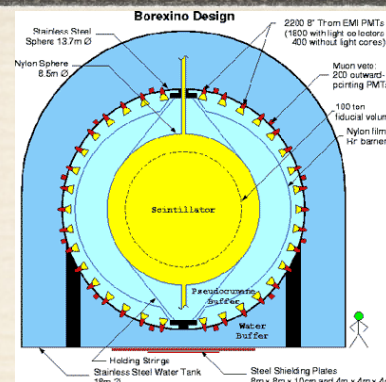
β^+ Boosted Decision Tree



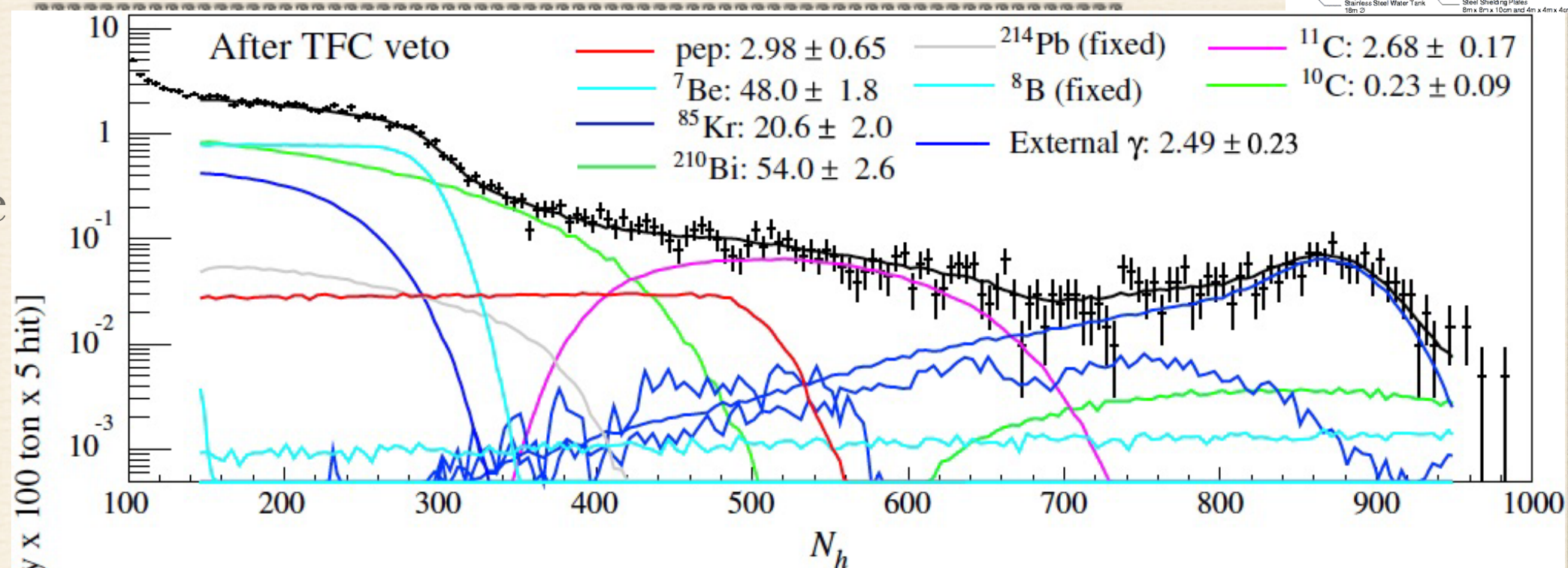
- ❖ use Gatti parameters for β^+/β^- , β^+ MC w/, w/o positronium, α/β
- ❖ use KS tests of time profiles
- ❖ first four moments of time profile
- ❖ “fraction of hits in tail” variables
- ❖ four Legendre polynomials of hit pair angles
- ❖ vertex reconstruction uncertainties
- ❖ determine remaining ^{11}C contamination ($\sim 10\%$ for a 50% signal efficiency)



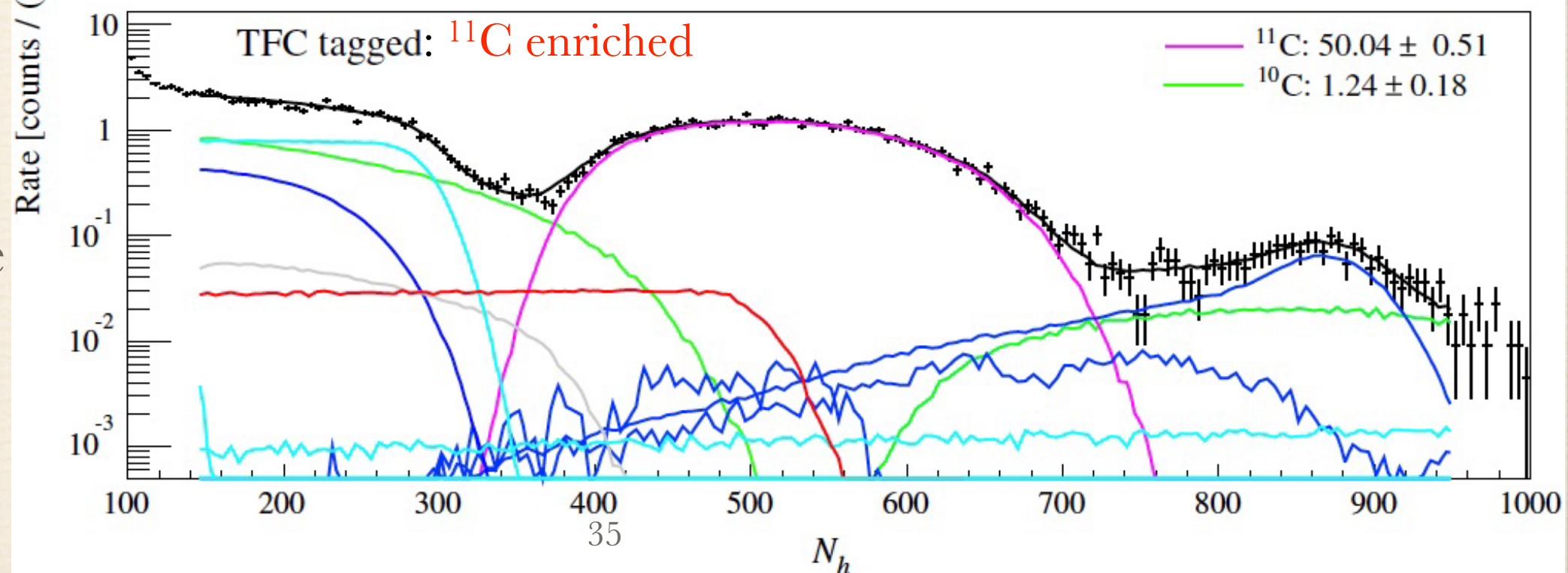
Separate out ^{11}C Background and Determine pep Rate



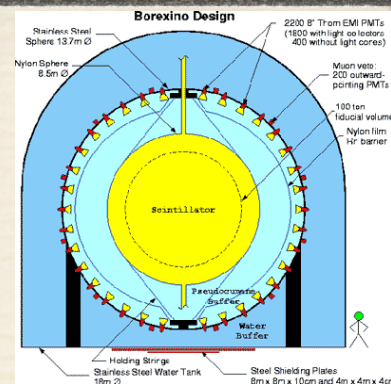
50% of exposure



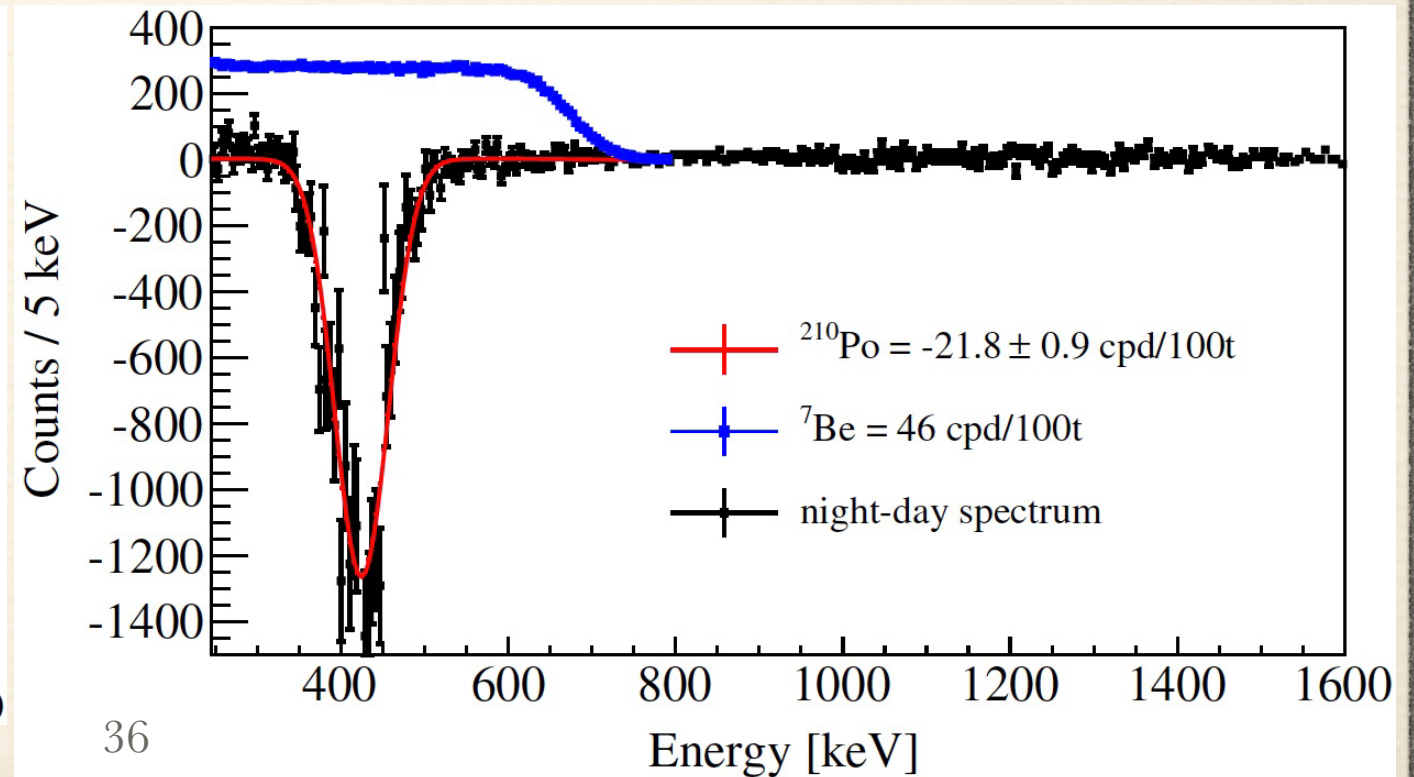
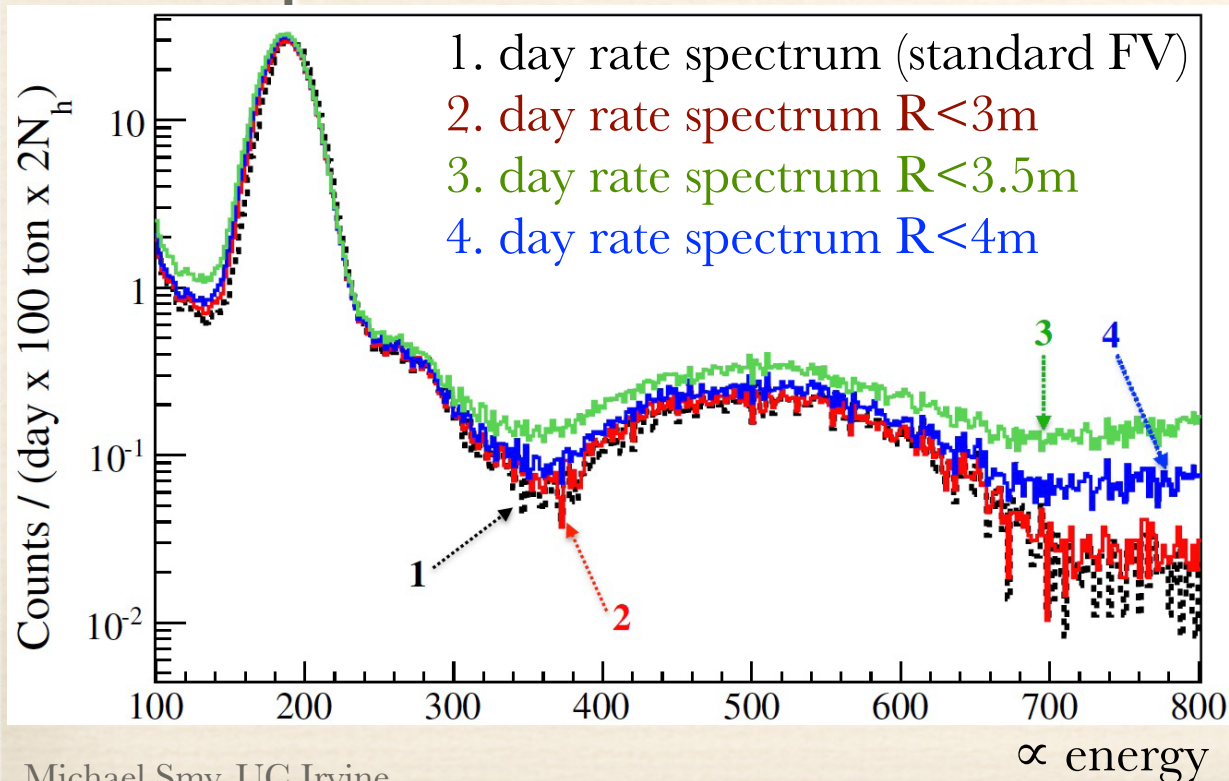
other
50% of exposure



Day/Night of ^7Be



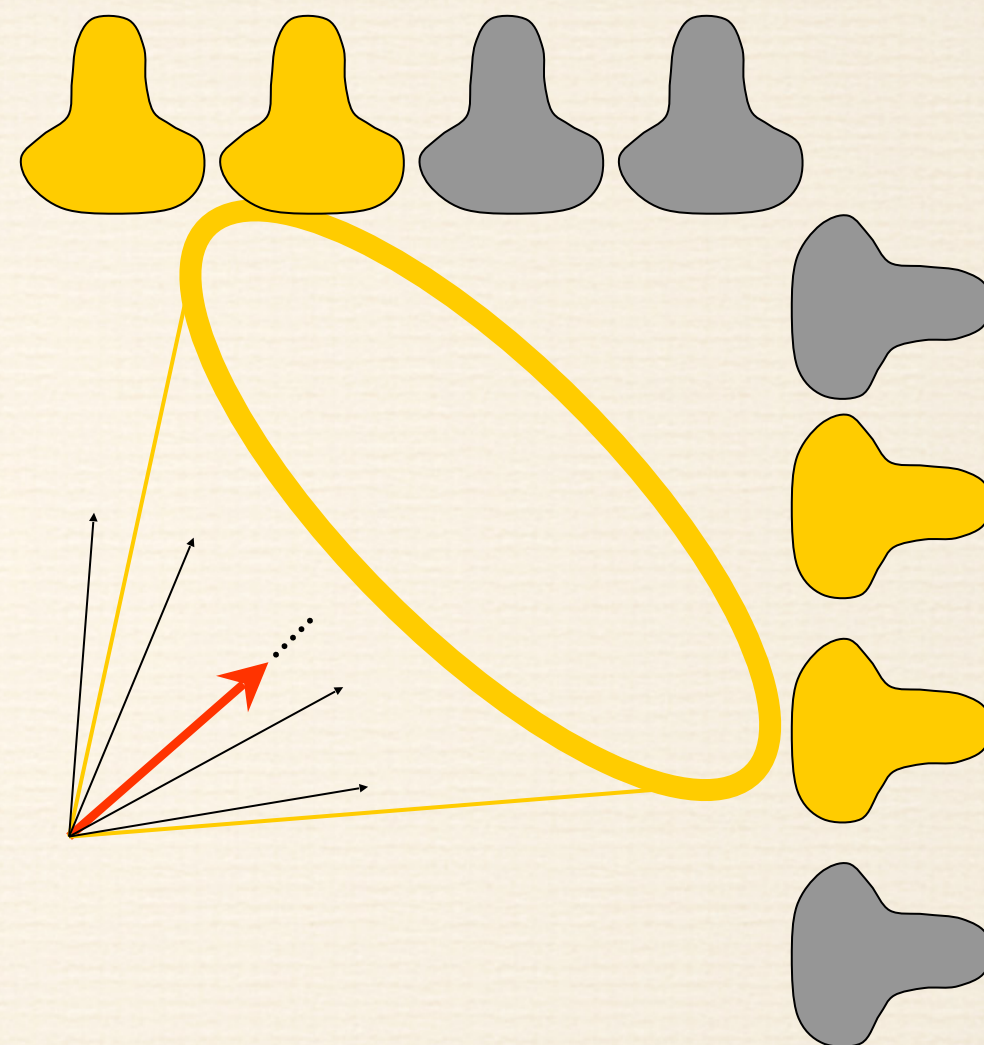
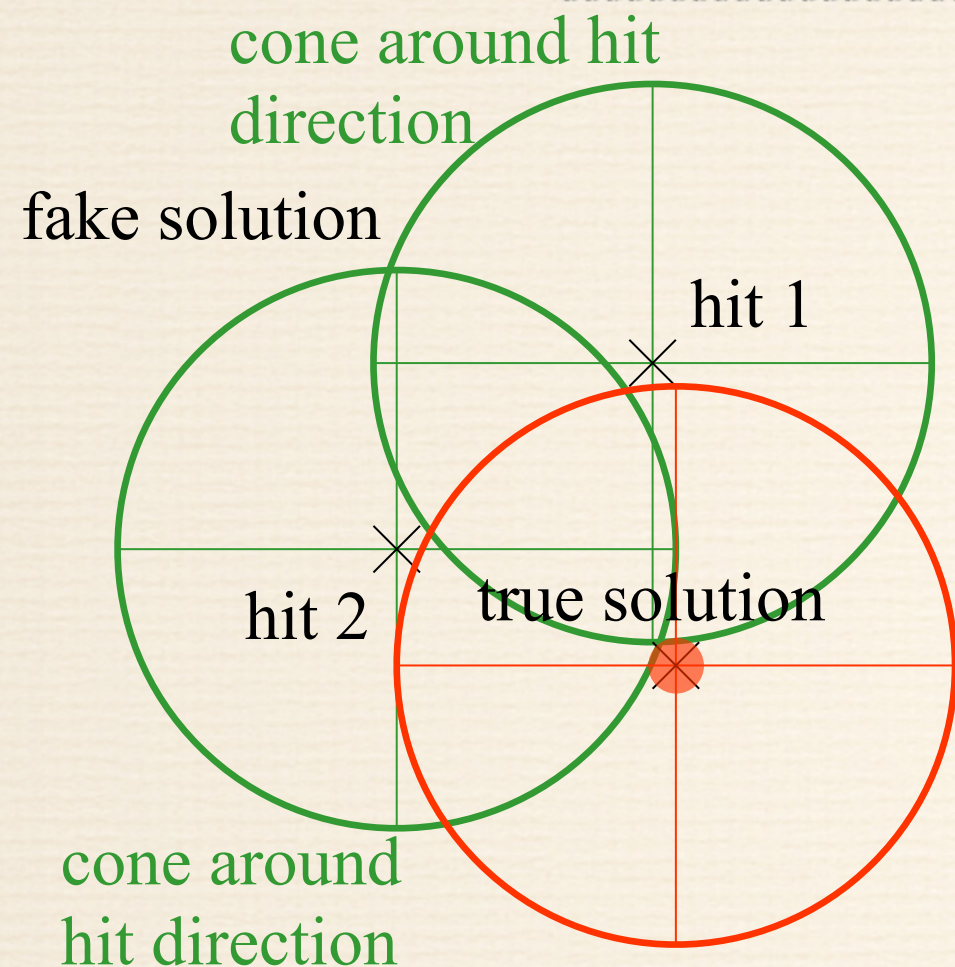
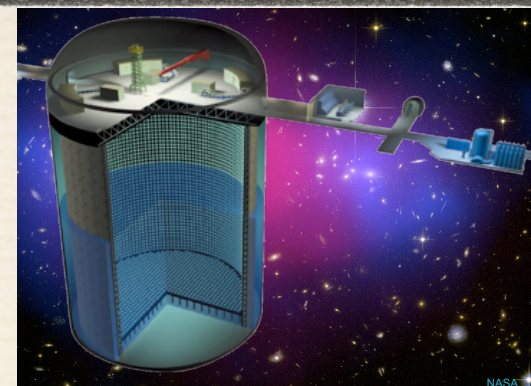
- ❖ find average rate $R = 46.0 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{sys})/\text{day}/100\text{t}$
- ❖ fit rate difference spectrum of enlarged volume to $R_N - R_D = 0.04 \pm 0.57(\text{stat})/\text{day}/100\text{t}$
- ❖ ratio is $A_{DN} = 0.001 \pm 0.012(\text{stat}) \pm 0.007(\text{sys})$
- ❖ “dip” is due to the finite lifetime of ^{210}P



Angular Hit Pattern

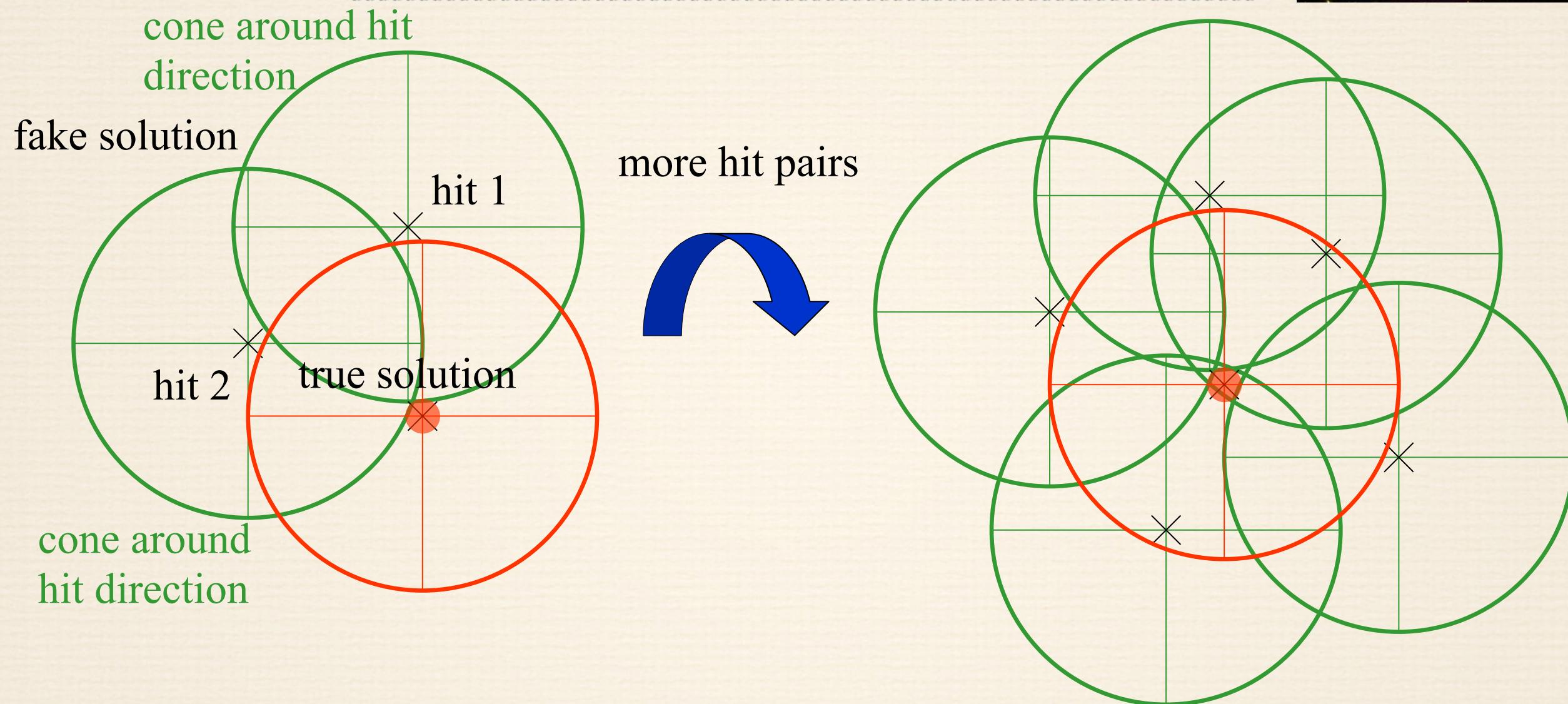
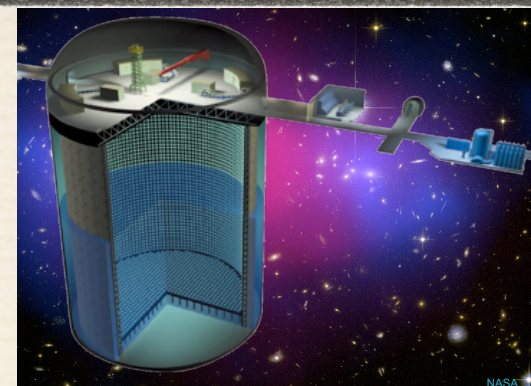
- ❖ mostly useful in water Cherenkov detectors
- ❖ obtains particle directions and velocity
- ❖ some limited sensitivity to energy (low energy electrons)

Direction fit: Hit-by-Hit Hough Transform



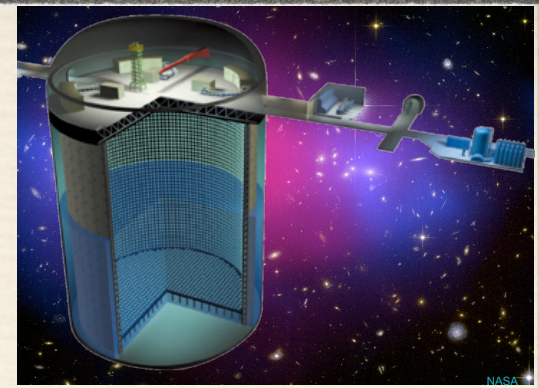
- ❖ event direction in region of “maximal overlap”
- ❖ find answer by combinatorial means from hit pairs

Direction fit: Hit-by-Hit Hough Transform

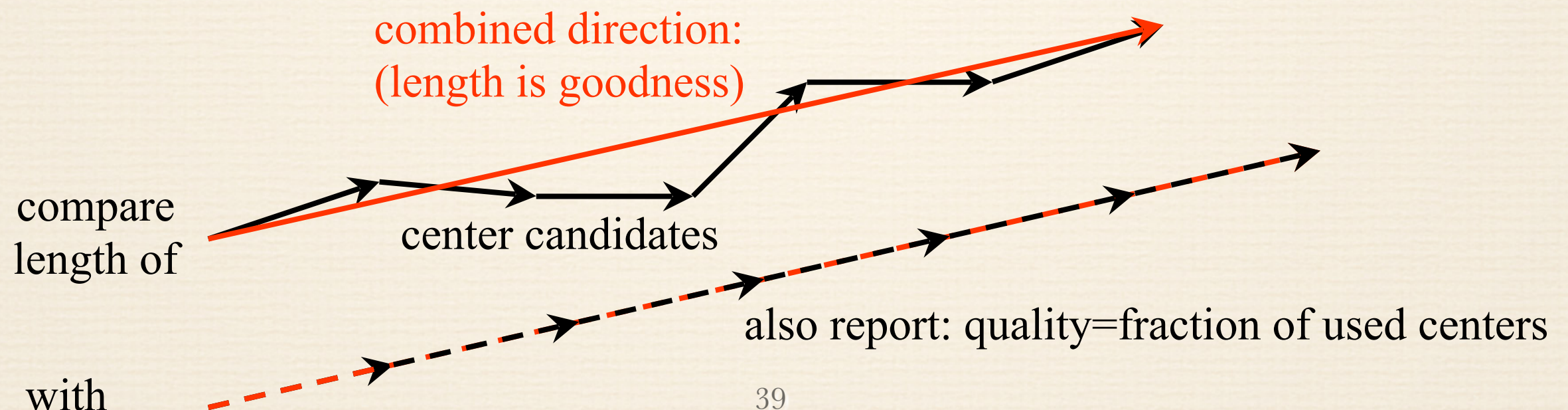


- ❖ event direction in region of “maximal overlap”
- ❖ find answer by combinatorial means from hit pairs

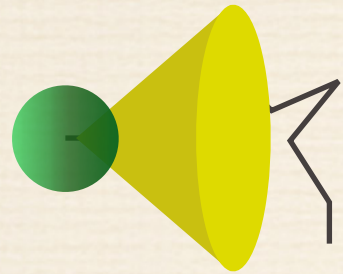
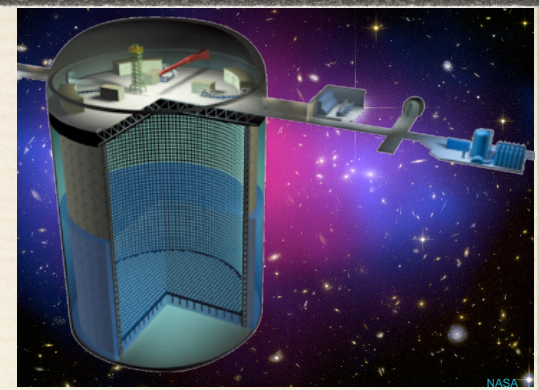
Estimate Multiple Coulomb Scattering



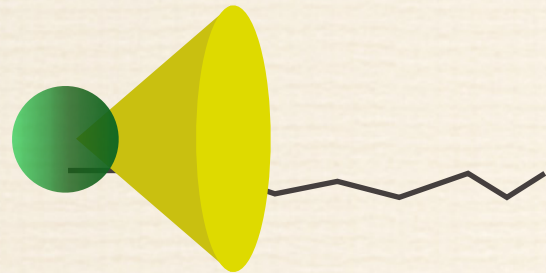
- ❖ scattering of hits transformed to scattering of direction center candidates
- ❖ combine “aligned” (within some maximum deviation angle) direction center candidates by vector sum
- ❖ find largest such sum
- ❖ goodness: length of vector divided by # centers



Use Multiple Coulomb Scattering to Separate Background from Solar ν 's

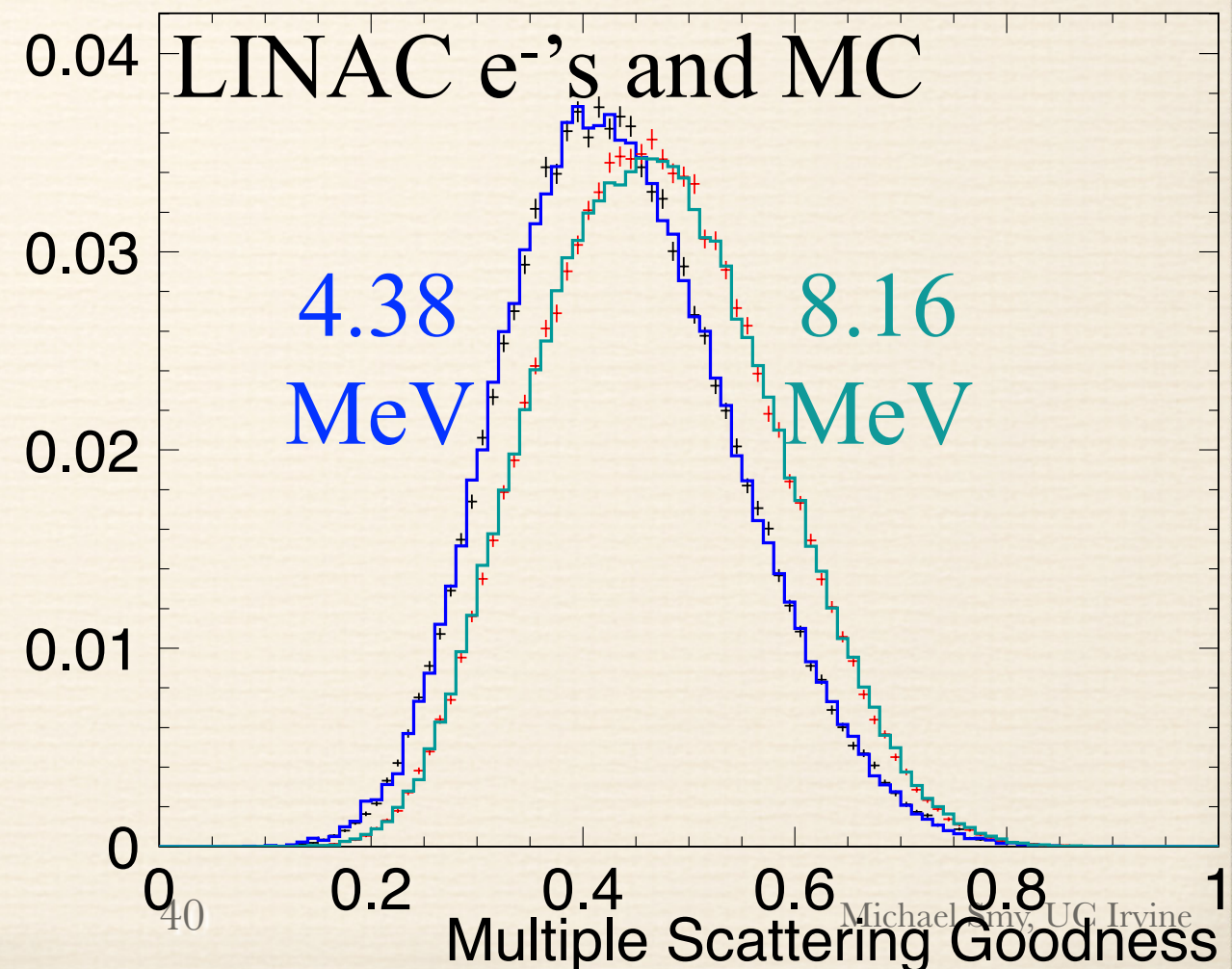


low energy more isotropic
electron: hit pattern

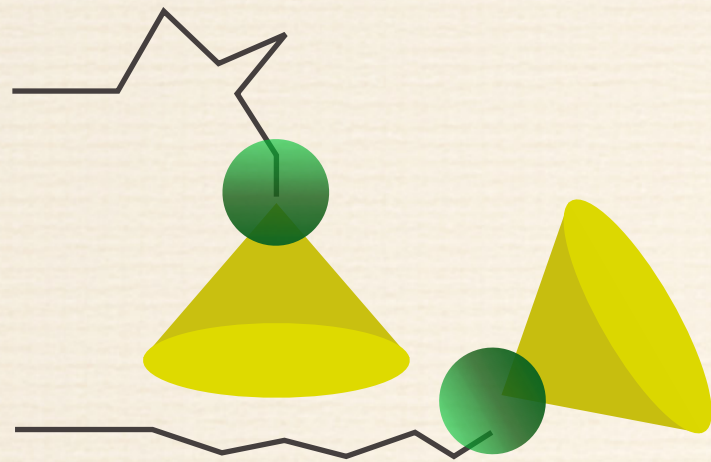
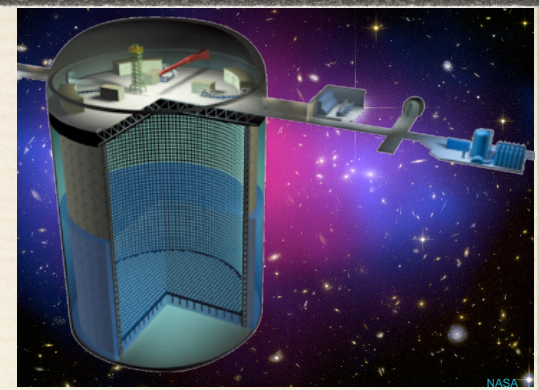


high energy more forward
electron: hit pattern

- ❖ true energy of many radioactive backgrounds is quite low (e.g. from Rn decay chain: 3.3 MeV endpoint)
- ❖ harder solar ν -induced electron spectrum
- ❖ use the “multiple scattering goodness” (MSG) to separate solar ν 's from background



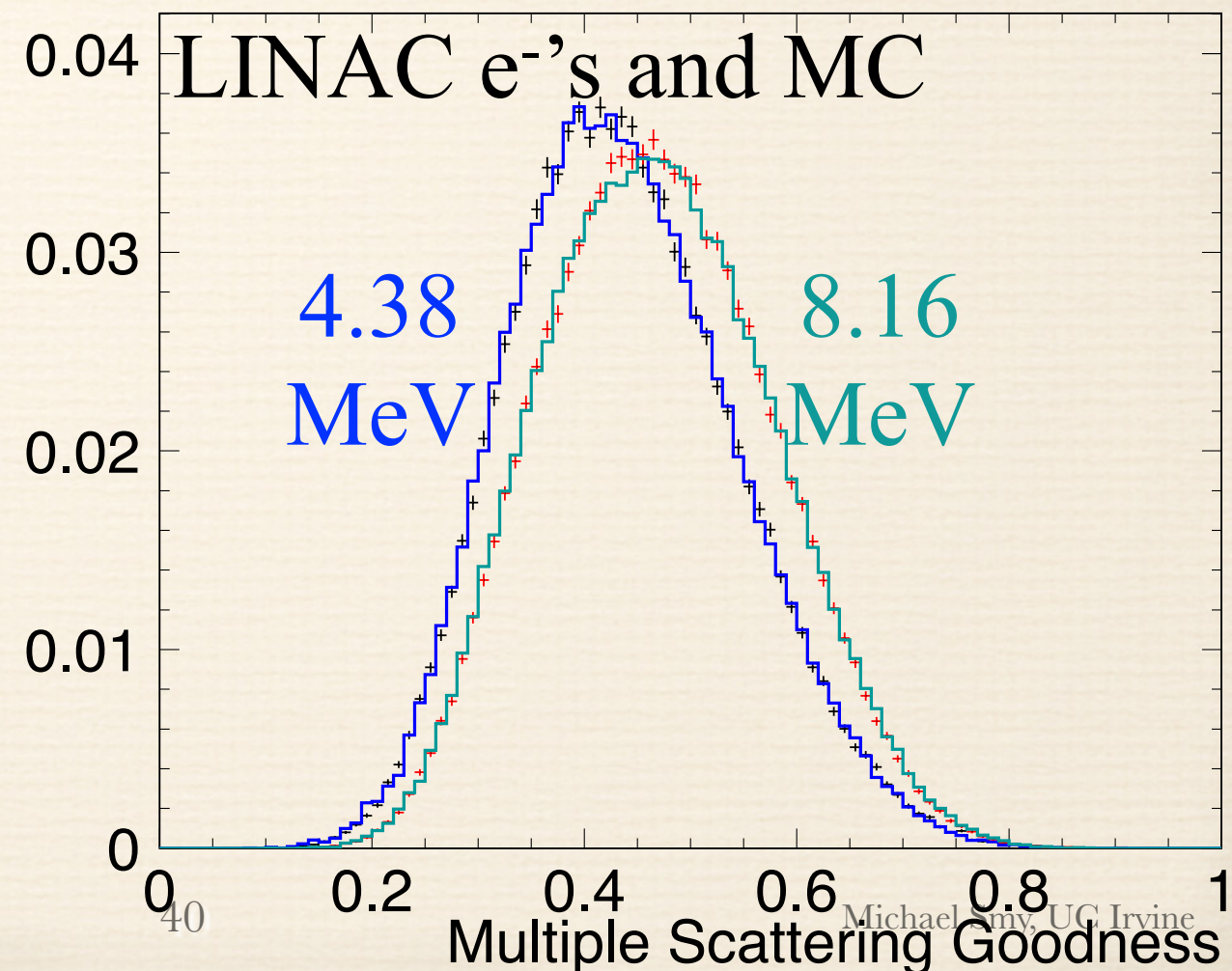
Use Multiple Coulomb Scattering to Separate Background from Solar ν 's



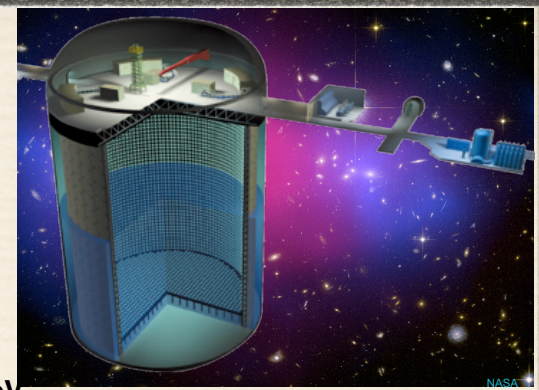
low energy electron: more isotropic hit pattern

high energy electron: more forward hit pattern

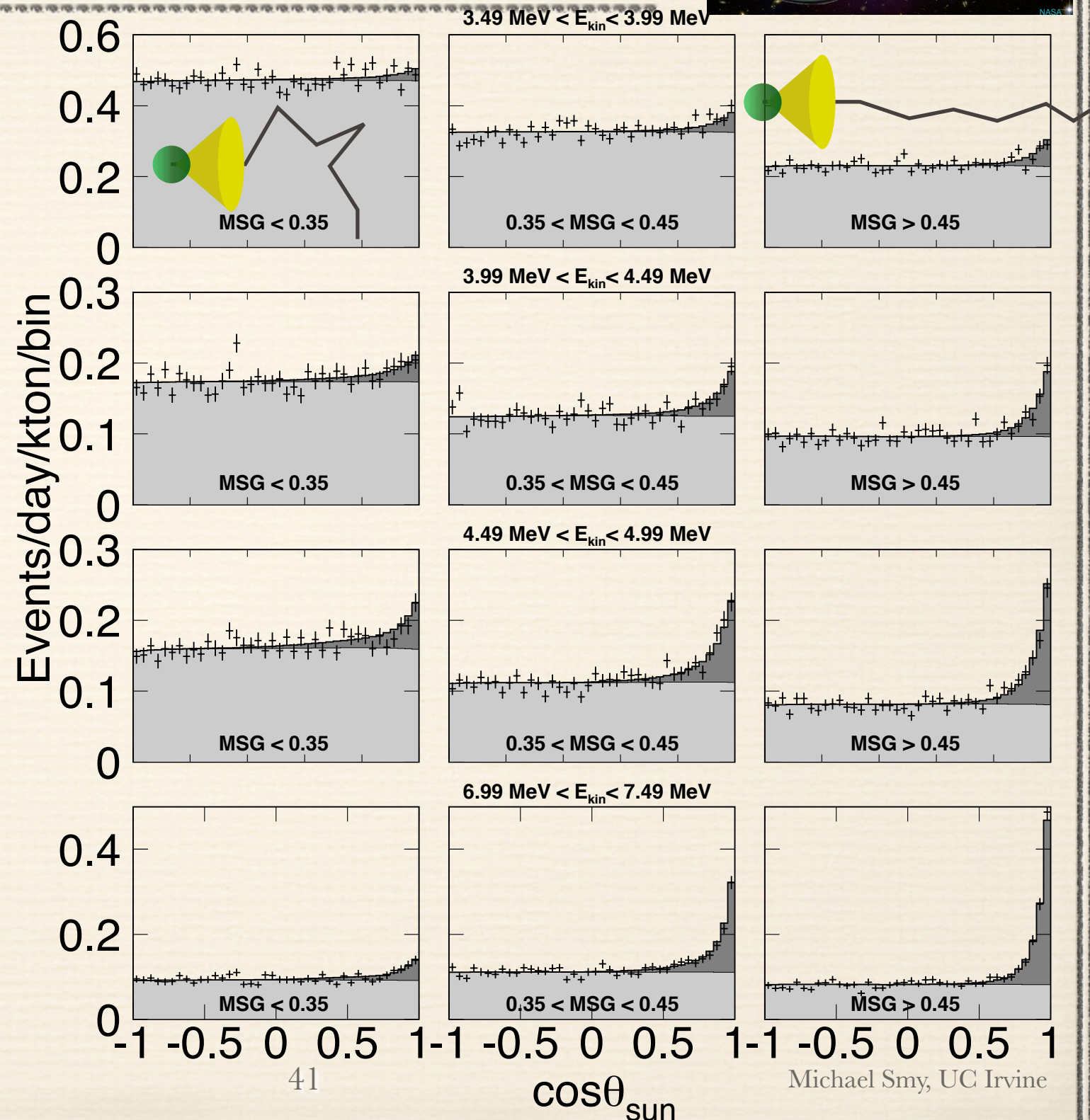
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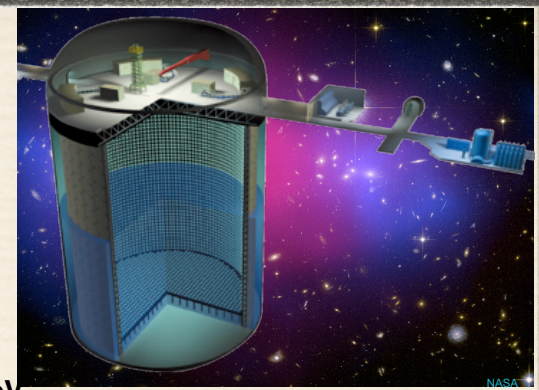
Use Multiple Coulomb Scattering to Separate Background from Solar ν 's



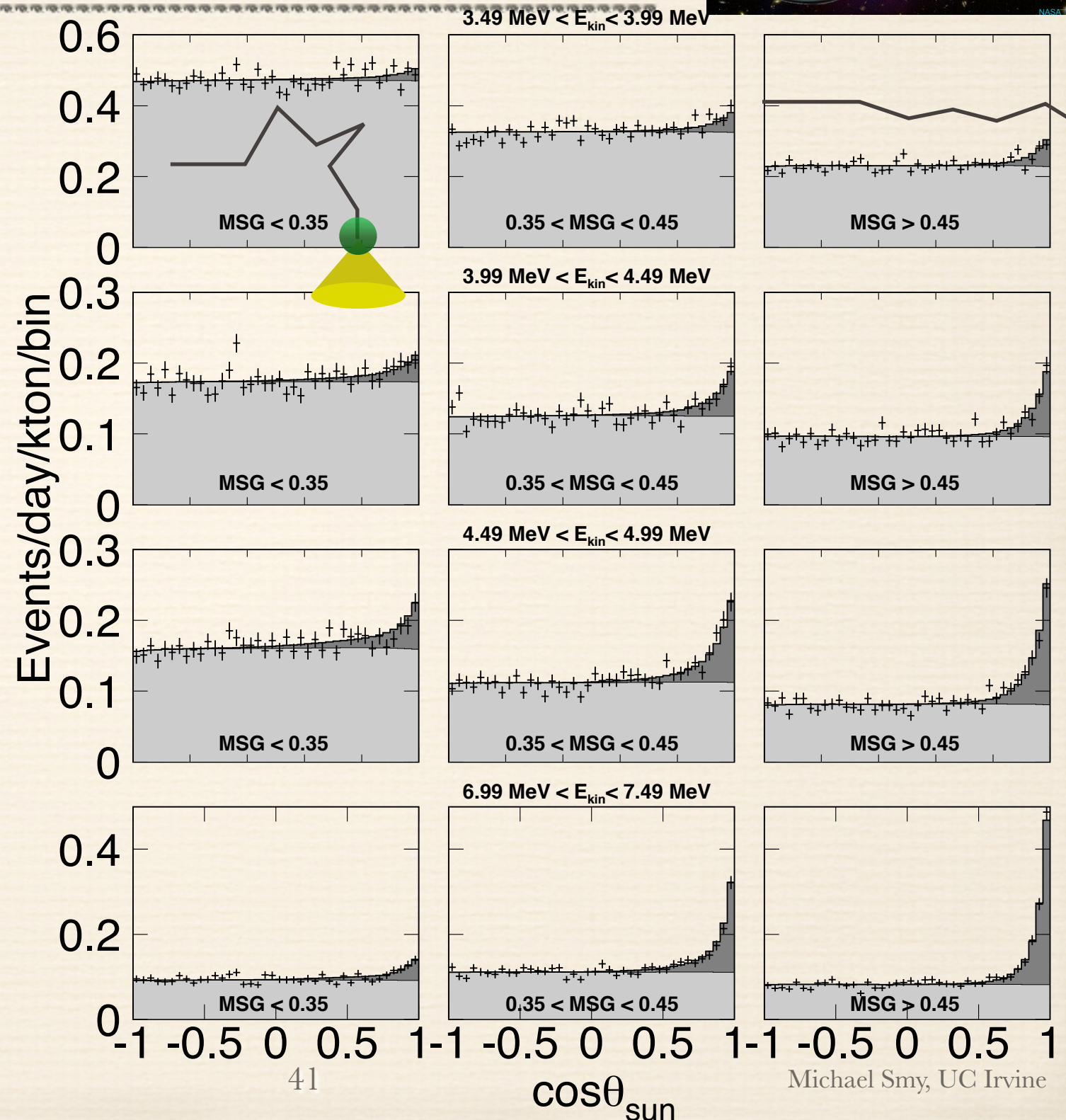
- ❖ background accumulates in left column (low MSG), solar signal in right column (high MSG)
- ❖ angular resolution gets better for higher MSG
- ❖ perform simultaneous fit to directional distribution in all three MSG bins
- ❖ gives a 10-15% smaller statistical uncertainties of signal rates at low energy



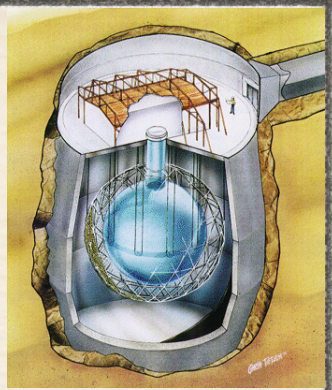
Use Multiple Coulomb Scattering to Separate Background from Solar ν 's



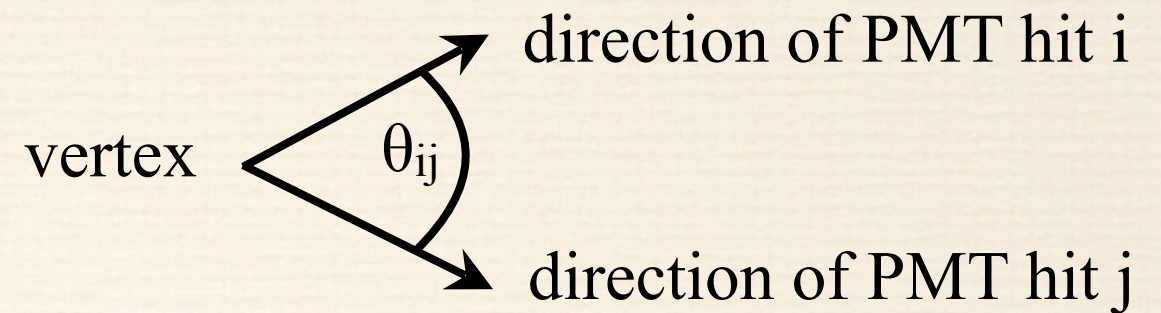
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- ❖ gives a 10-15% smaller statistical uncertainties of signal rates at low energy



SNO's ID of 8.6 MeV γ Cascade from n Capture on Cl



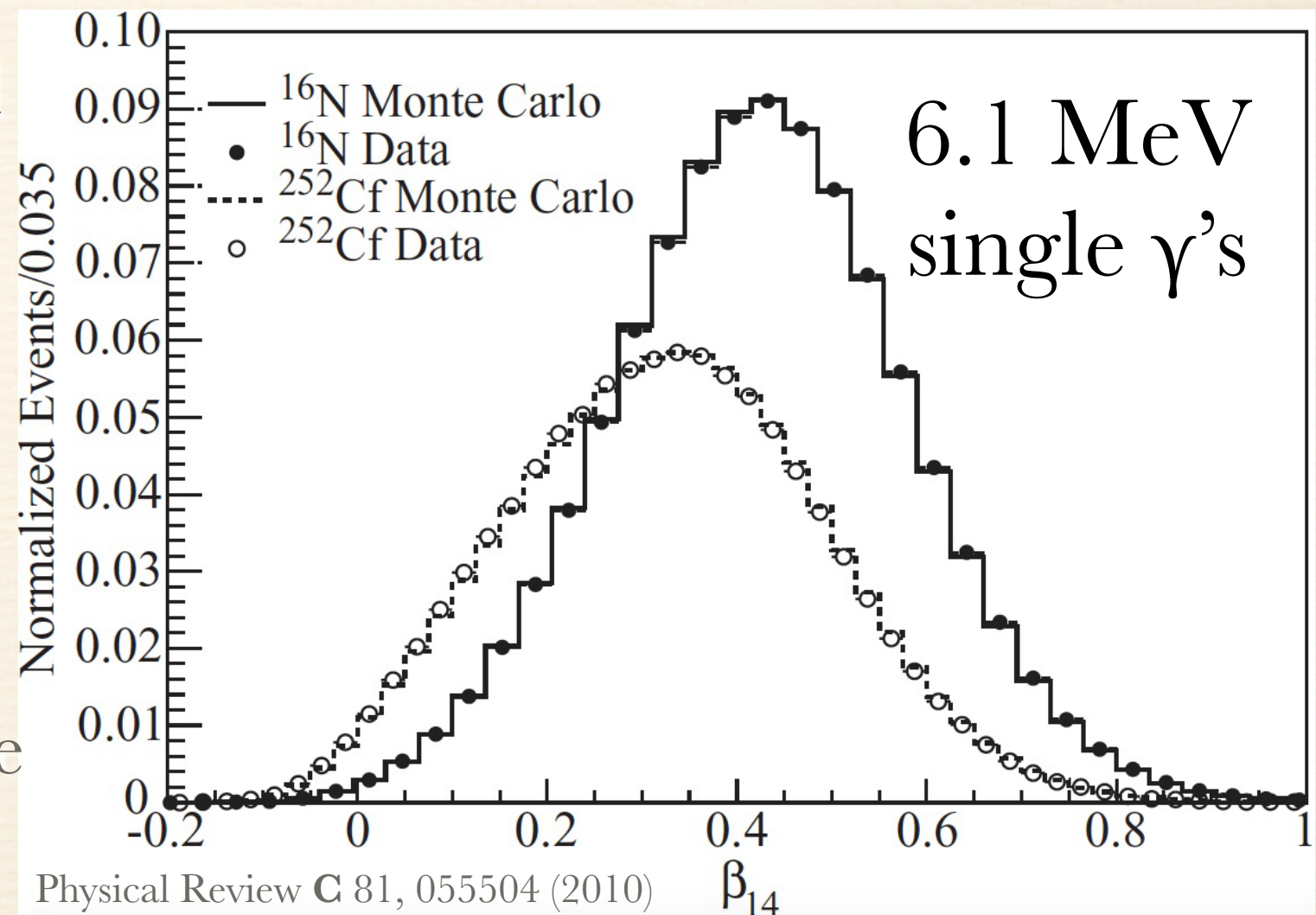
- ❖ get pairs of PMT hits and measure their relative angles θ_{ij} (seen from the vertex)



- ❖ using Legendre Polynomial P_l define

$$\beta_l = \frac{2}{N(N-1)} \sum_{i=1}^N \sum_{j=i+1}^N P_l(\cos \vartheta_{ij})$$

- ❖ $\beta_{14} = \beta_1 - 4\beta_4$ discriminates electrons from γ cascades
- ❖ used for the SNO salt phase data to distinguish NC events from CC events



Conclusion

- ❖ most statistical methods in solar neutrino physics are pretty straight-forward (perhaps even a bit out-dated)
- ❖ I hope you found some of the (non-statistical) analysis methods interesting and unique