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Reconstruction of Supernova Neutrino Spectra

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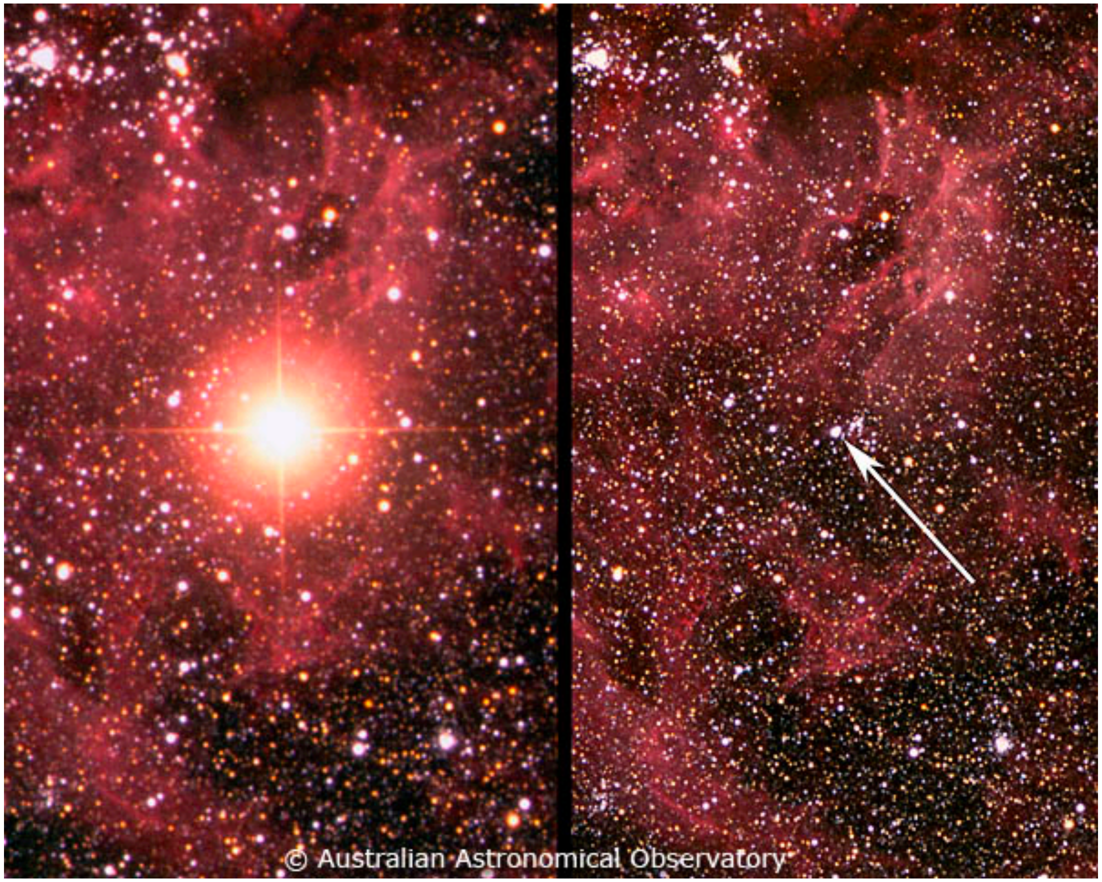
Neutrinos from Supernovae



The SN Neutrino Signal

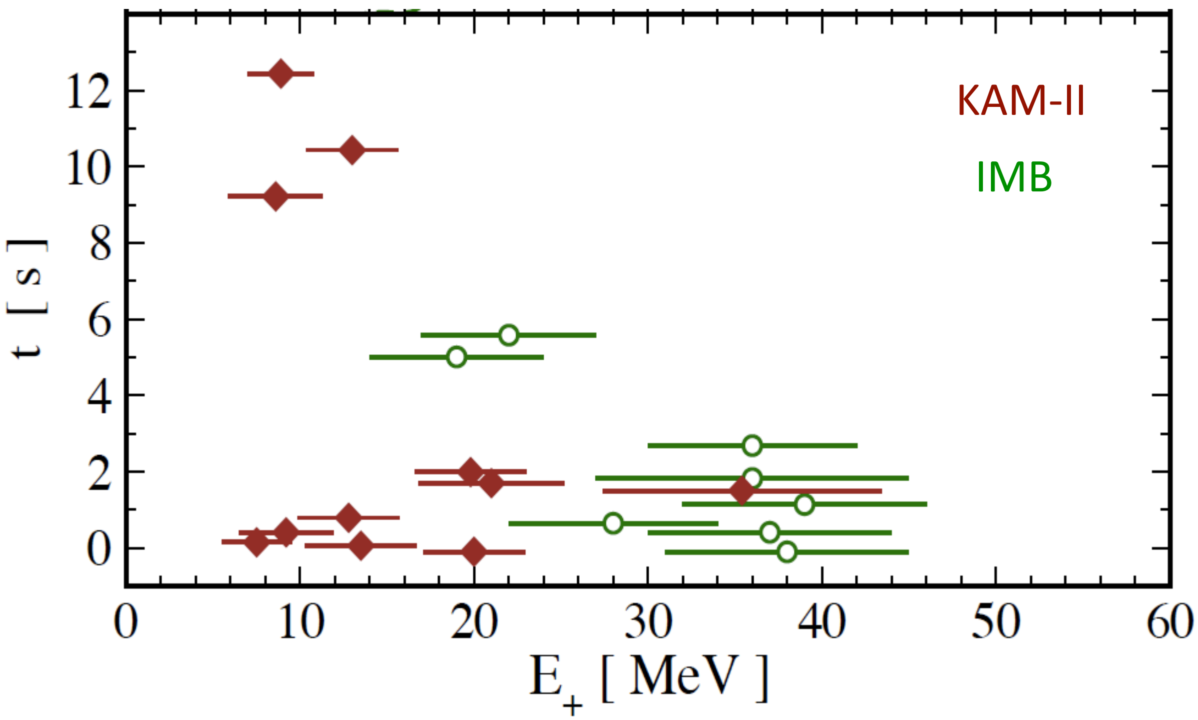


Figure adapted from Yuksel and Beacom

What did we learn ?

Our overall picture of SN explosions is correct

Limitations

- Mostly detected anti-ν_e
- Energy resolution limited
- Low statistics
- Background confusion

Need high-fidelity spectral measurements for all flavors

Detecting SN Neutrinos

- ν_e/anti-ν_e have charged current interactions
- What about the non-electron flavors?
- They have only neutral current interactions
- Elastic scattering with protons is the answer

Beacom, Farr, Vogel 2002

Detailed and updated status

Reconstruction of supernova ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$ neutrino spectra at scintillator detectors

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We present a new technique to directly reconstruct the spectra of ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$ from a supernova, using neutrino-proton elastic scattering events ($\nu + p \to \nu + p$) at scintillator detectors. These neutrinos, unlike ν_e and $\bar{\nu}_e$, have only neutral current interactions, which makes it very challenging, with any reaction, to detect them and measure their energies. With updated inputs from theory and experiments, we show that this channel provides a robust and sensitive measure of their spectra. Given the low yields and lack of spectral information in other neutral current channels, this is perhaps the only realistic way to extract such information. This will be indispensable for understanding flavor oscillations of SN neutrinos, as it is likely to be impossible to disentangle neutrino mixing from astrophysical uncertainties in a SN without adequate spectral coverage of all flavors. We emphasize that scintillator detectors, *e.g.,* Borexino, KamLAND, and SNO+, have the capability to observe these events, but they must be adequately prepared with a trigger for a burst of low-energy events. We also highlight the capabilities of a larger detector like LENA.

Published in PRD (2011)

ν-p elastic scattering

$$\nu + p \rightarrow \nu + p$$

$$\underbrace{\frac{dN}{dT'}}_{\substack{\text{Number of proton recoils}\\ \text{per visible energy}}} = \frac{N_p}{\underbrace{dT'/dT}_{\substack{\text{Visible energy as a}\\ \text{function of true recoil energy}}}} \int_{E_{\min}}^{\infty} dE \, \underbrace{\frac{dF}{dE}}_{\text{Neutrino spectrum at Earth}} \underbrace{\frac{d\sigma}{dT}}_{\text{Differential cross section}}(E)$$

Cross-Section

$$
\begin{aligned}
\frac{d\sigma}{dT} &= \frac{G_F^2 m_p}{\pi}\left[\left(1-\frac{m_p T}{2E^2}\right)c_v^2+\left(1+\frac{m_p T}{2E^2}\right)c_a^2\right] \\
&= \frac{4.83\times 10^{-42}\,\mathrm{cm}^2}{\mathrm{MeV}}\cdot\left(1+466\,\frac{T}{E^2}\right)\ ,
\end{aligned}
$$

- Standard model calculation
- Quite large (~1/4 inverse beta)
- Slightly prefers higher recoils

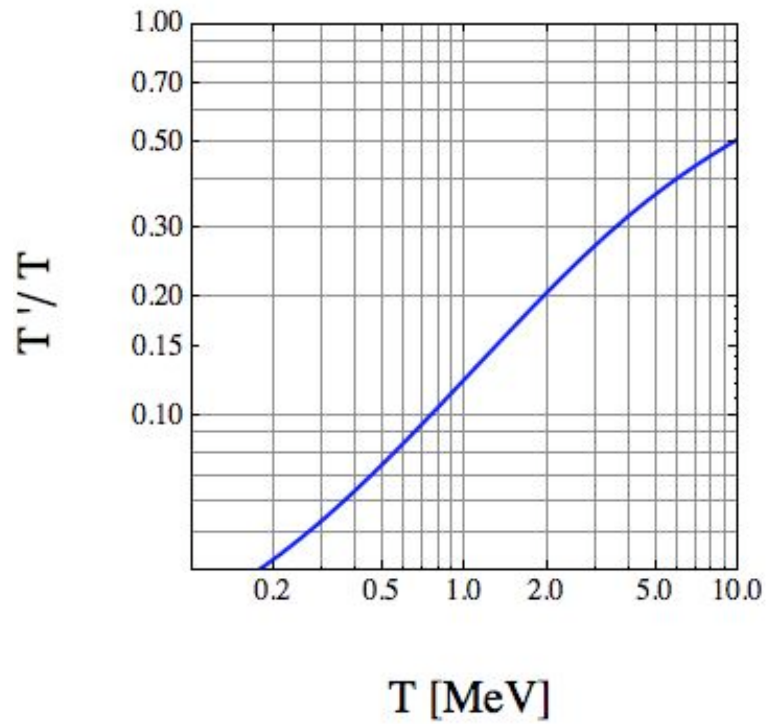
Quenching

$$T'(T) = \int_0^T \frac{dT}{1 + k_B \langle dT/dx \rangle}$$

- Heavier projectiles lose energy faster ~100-1000 MeV/cm
- Short tracks
- Total scintillation lower than that by electrons of same energy

Quenching at KamLAND

- Measured by Yoshida et al, NIM (2010)
- Not described by a simple 1/linear law
- Add quadratic corrections

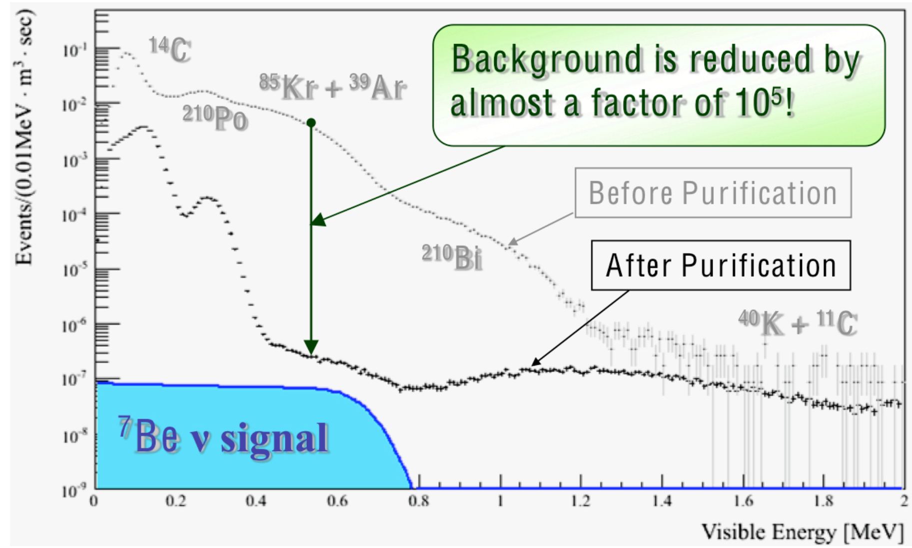


Energy resolution at KamLAND

- Number of photoelectrons proportional to visible energy
- Energy resolution is almost gaussian, determined by sqrt(Number of p.e.)
- $\Delta T'/T' \sim 6.9\%/\mathrm{sqrt}(T')$
- Almost negligible, <10% above 0.2 MeV

Backgrounds at KamLAND

- Radioactivity is the main background
- Below 0.2 MeV C-14
- At ~0.3 MeV Polonium peak
- Pulse-shape disc.
- Otherwise almost background free
- Made fiducial cuts



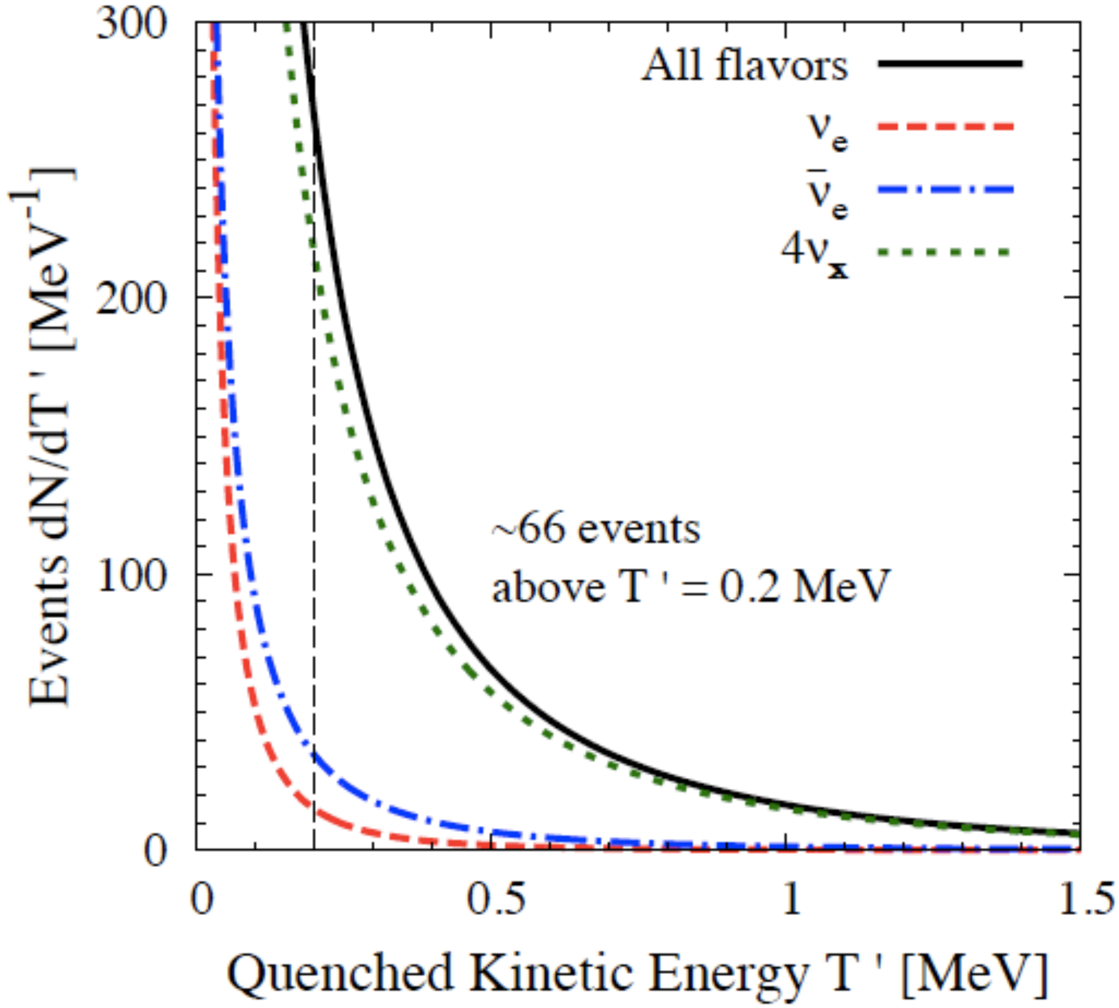
KamLAND after purification
Plot from Chris Grant's poster

Experimental Inputs

Detector	Mass [kton]	Chemical composition (rounded to nearest %)	N_p $[10^{31}]$	k_B [cm/MeV]	$\Delta T'/T'$ (T' in MeV)	Signal Yield (T' >0.2 MeV)
Borexino	0.278	C_9H_{12}	1.7	0.010	$4.5\%/\sqrt{T'}$	27
KamLAND	0.697	$C_{12}H_{26}$(80%v/v)+C_9H_{12}(20%v/v)	5.9	0.0100	$6.9\%/\sqrt{T'}$	66
SNO+	0.800	$C_6H_5C_{12}H_{25}$	5.9	0.0073	$5.0\%/\sqrt{T'}$	111

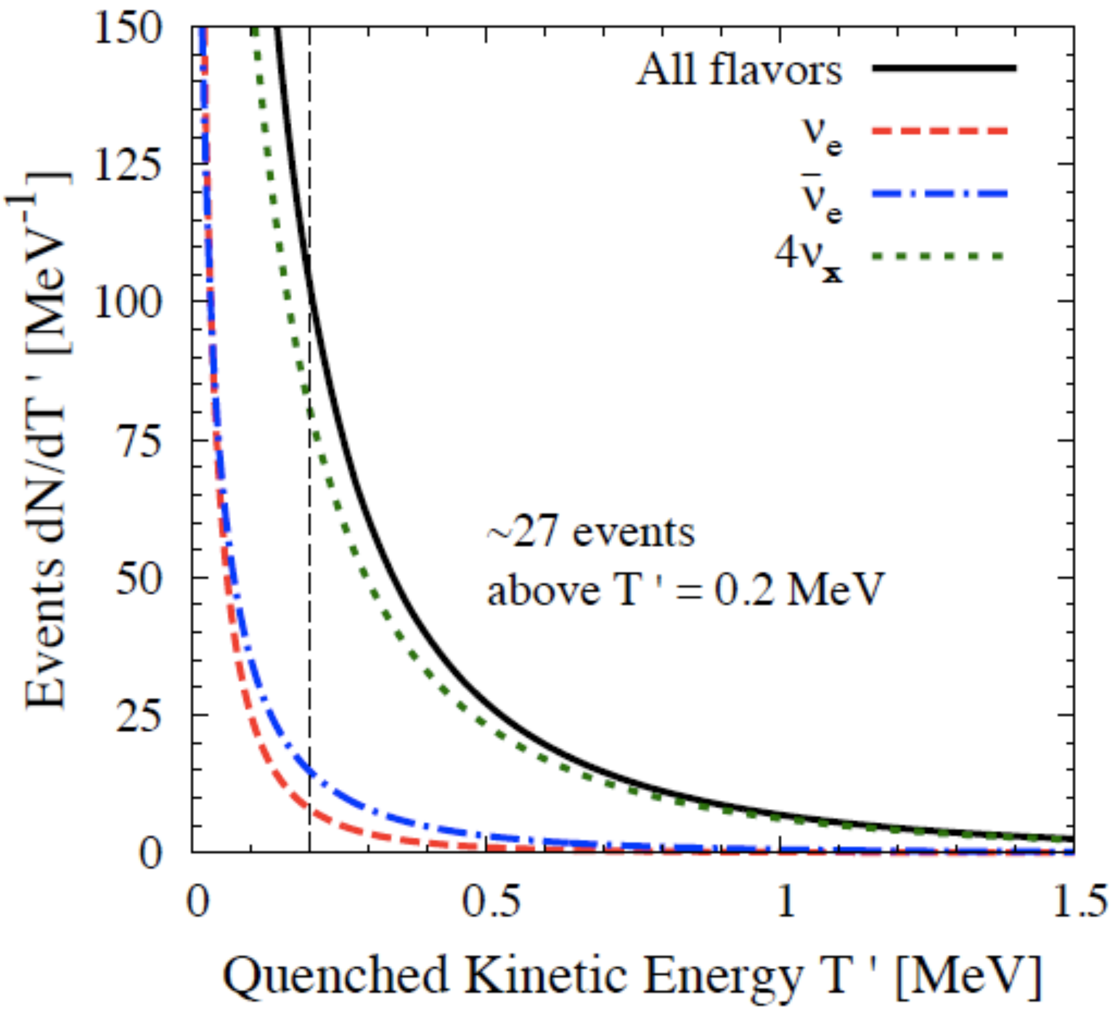
KamLAND has a quadratic correction C=2.73 10^-5 in quenching

KamLAND



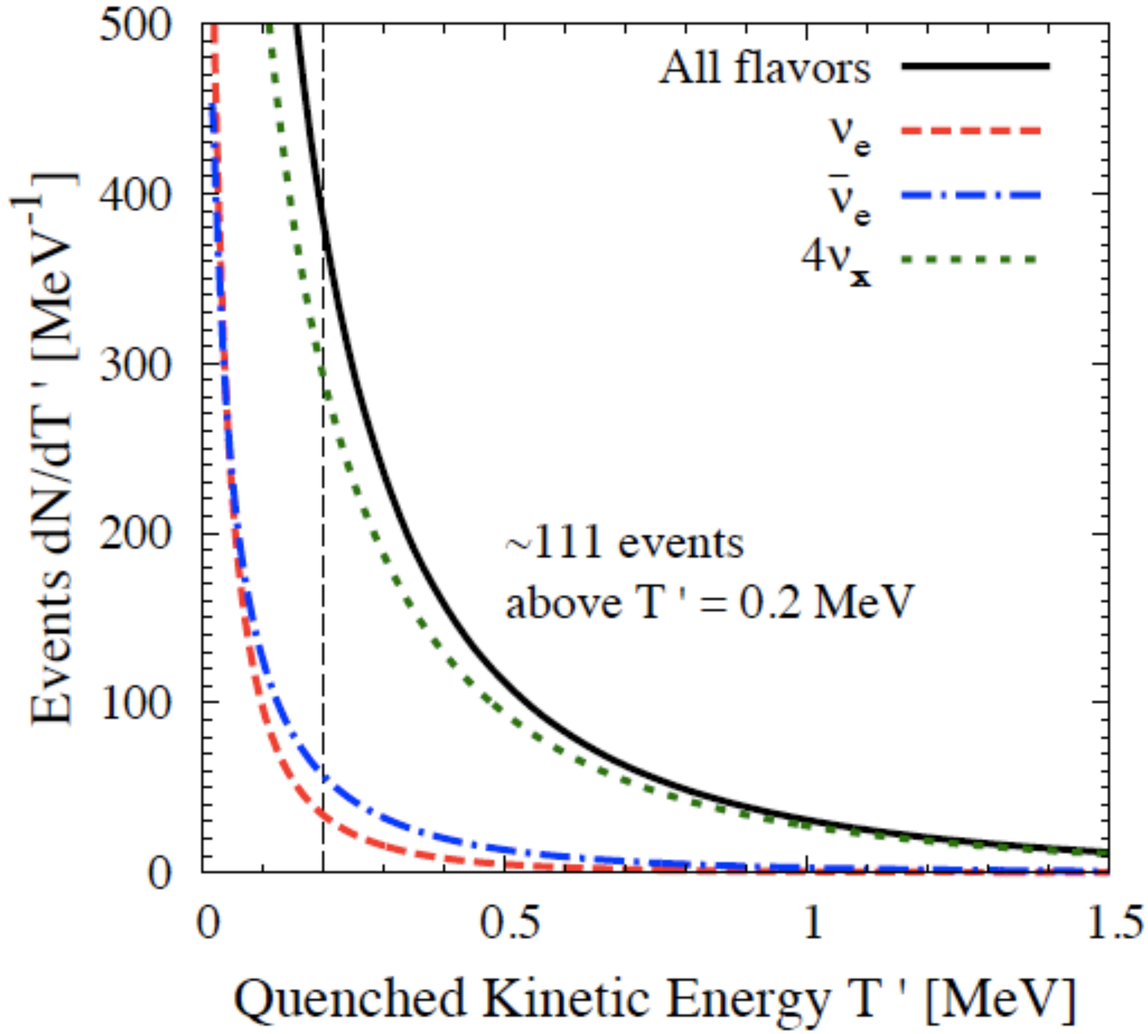
All flavors
ν_e
$\bar{\nu}_e$
$4\nu_x$
~66 events
above T ' = 0.2 MeV
Events dN/dT ' [MeV^{-1}]
Quenched Kinetic Energy T ' [MeV]
300
200
100
0
0.5
1
1.5

Borexino



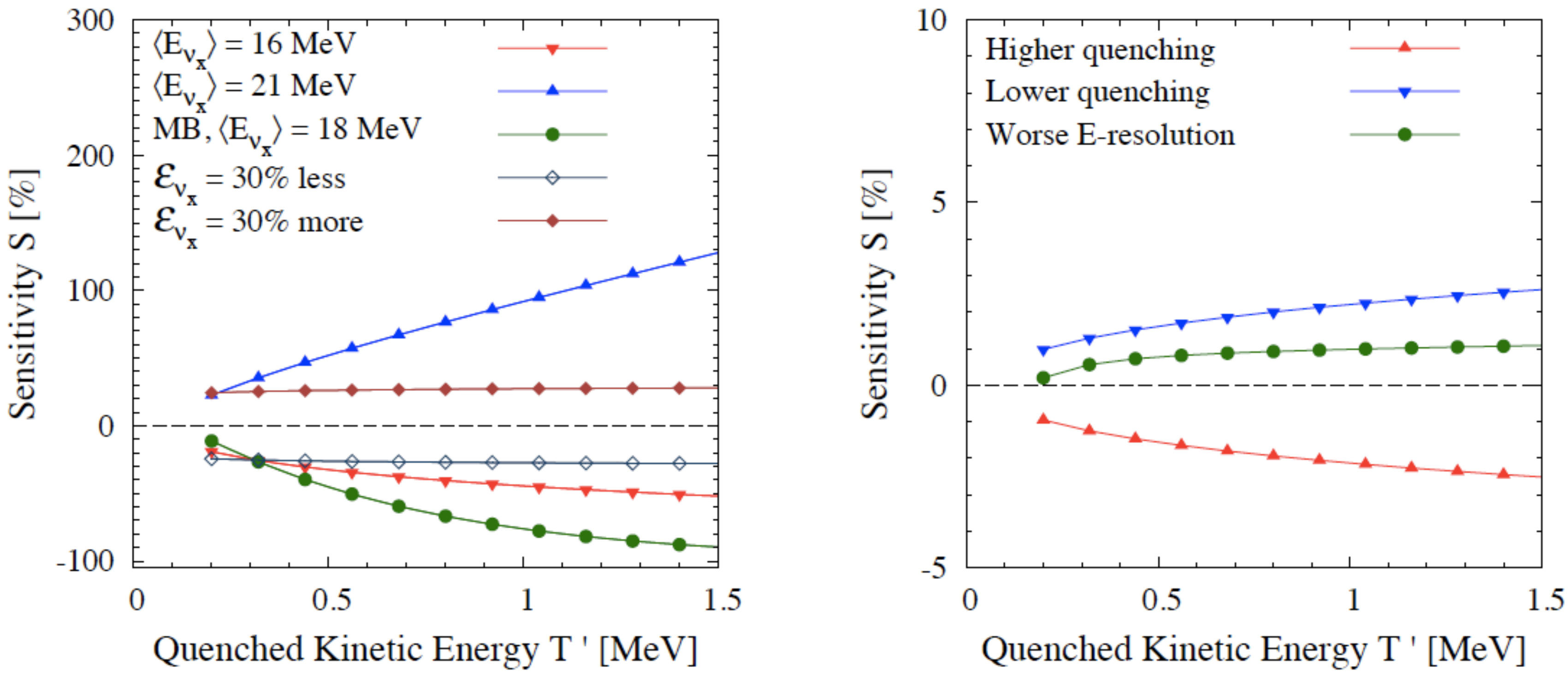
All flavors
ν_e
$\bar{\nu}_e$
$4\nu_x$
~27 events
above T ' = 0.2 MeV
Events dN/dT ' [MeV^{-1}]
Quenched Kinetic Energy T ' [MeV]
0
25
50
75
100
125
150
0
0.5
1
1.5

SNO+

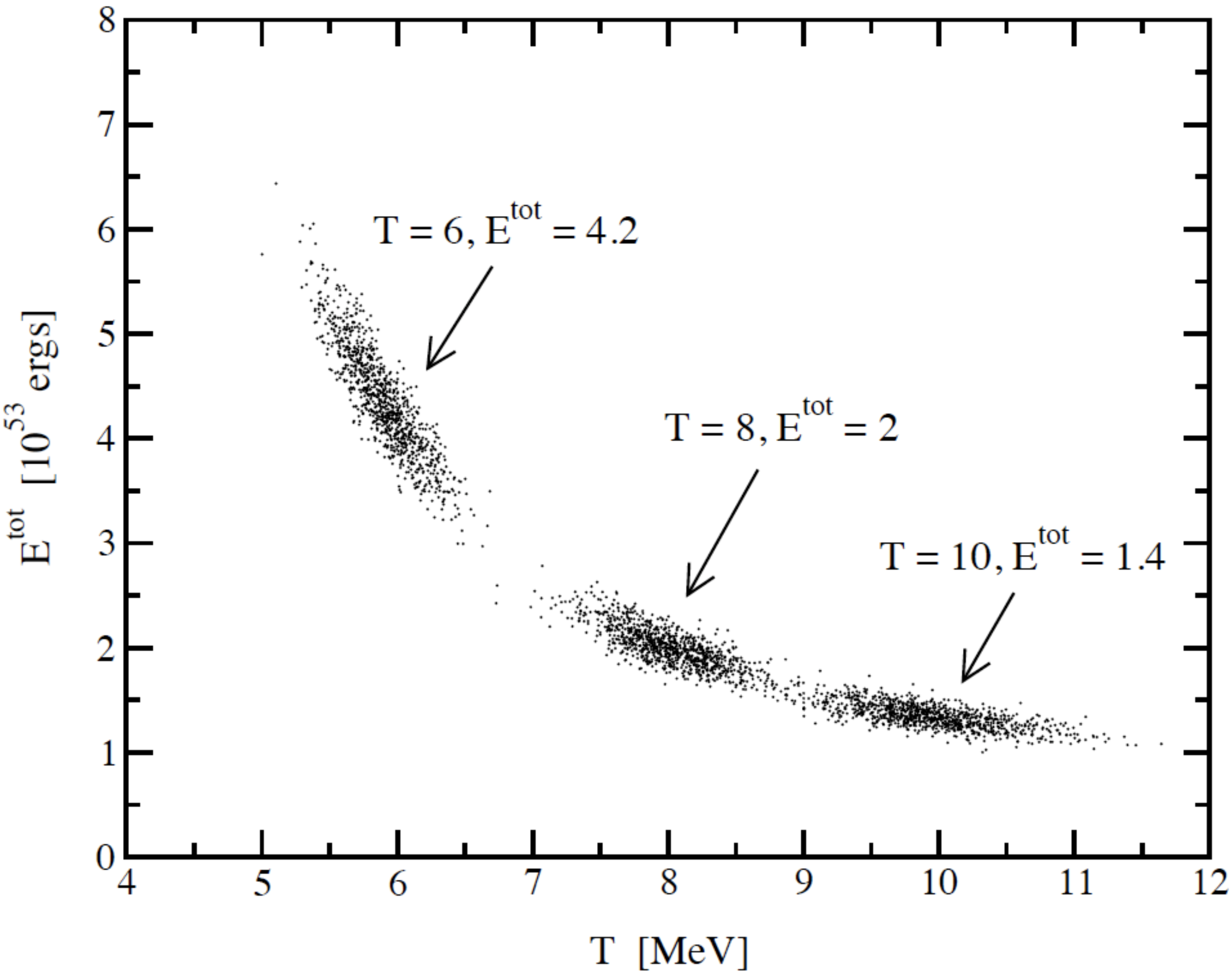


All flavors
ν_e
$\bar{\nu}_e$
$4\nu_x$
~111 events
above T ' = 0.2 MeV
Events dN/dT ' [MeV^{-1}]
Quenched Kinetic Energy T ' [MeV]
0
100
200
300
400
500
0
0.5
1
1.5

Flux Discrimination vs Systematics



Parametric Reconstruction



Beacom, Farr, Vogel, 2002

Nonparametric Reconstruction

$$N_i = \sum_{j=1}^{N_{\text{bin}}} K_{ij} F_j$$

$$\begin{aligned} F_j &= (dF/dE)_{E_j} \Delta E_j \,, \\ K_{ij} &= \begin{cases} N_p \Delta T'_i \left(\frac{dT}{dT'}\right)_{T'_i} \left(\frac{d\sigma}{dT}\right)_{T'_i, E_j} & \text{for } \; i \le j \\ 0 & \text{for } i > j \end{cases} \end{aligned}$$

If Nbin=3, for example,

$$\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix} = \begin{pmatrix} K_{11} & K_{12} & K_{13} \\ 0 & K_{22} & K_{23} \\ 0 & 0 & K_{33} \end{pmatrix} \begin{pmatrix} F_1 \\ F_2 \\ F_3 \end{pmatrix}$$

Nonparametric Reconstruction

$$F_j = \sum_{i=1}^{N_{\rm bin}} (K^{-1})_{ji}\, N_i$$

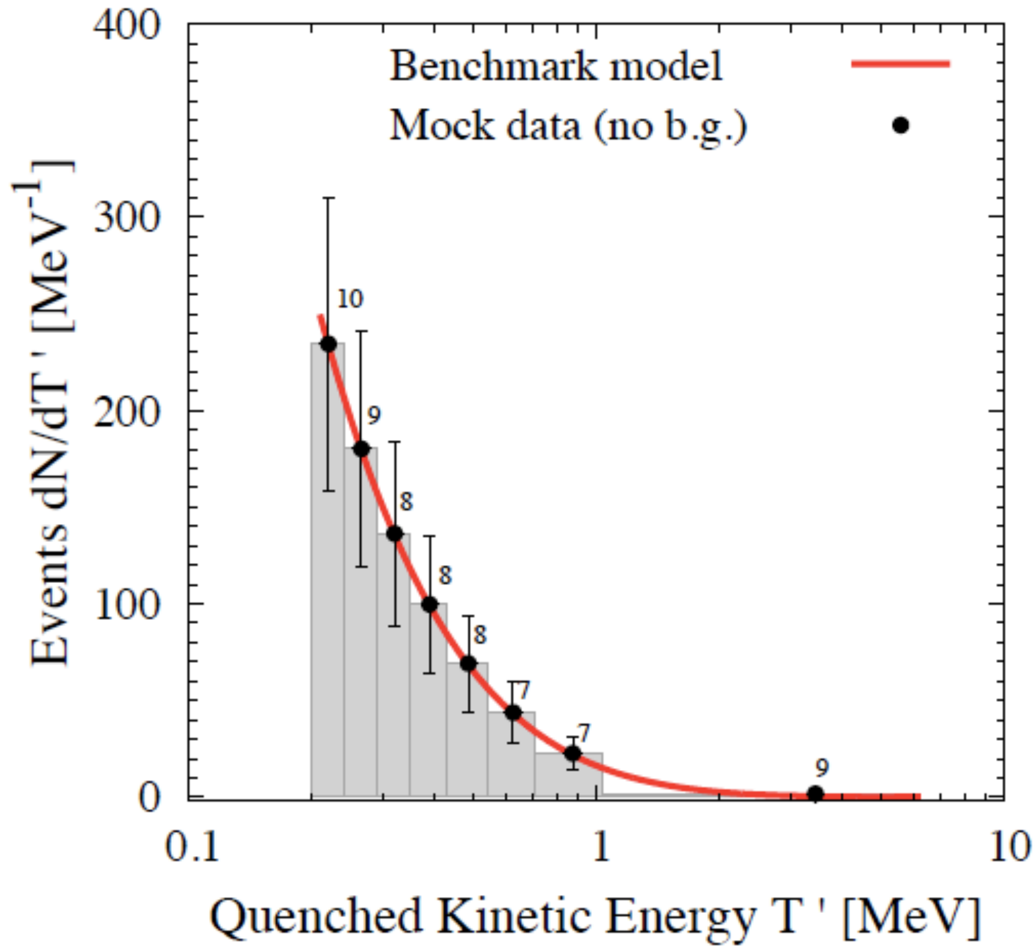
If Nbin=3, for example,

$$\begin{aligned}
F_3 &= N_3/K_{33} \;, \\
F_2 &= (N_2 - F_3 K_{23})\,/K_{22} \;, \\
F_1 &= (N_1 - F_2 K_{12} - F_3 K_{13})\,/K_{11}
\end{aligned}$$

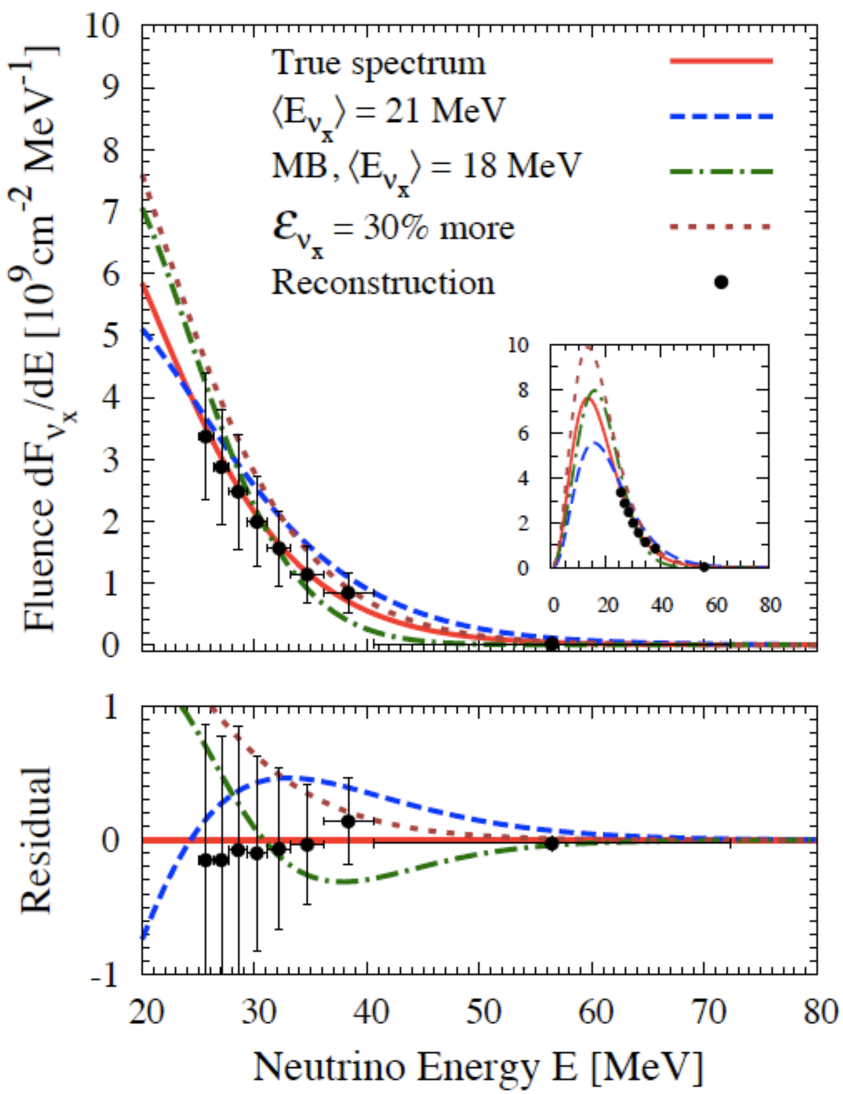
Regularization

- Need to add a regulator to avoid noisiness
- We typically add a penalty term such that the reconstruction is locally linear/quadratic
- Technically: Phillips-Twomey/Tikhonov

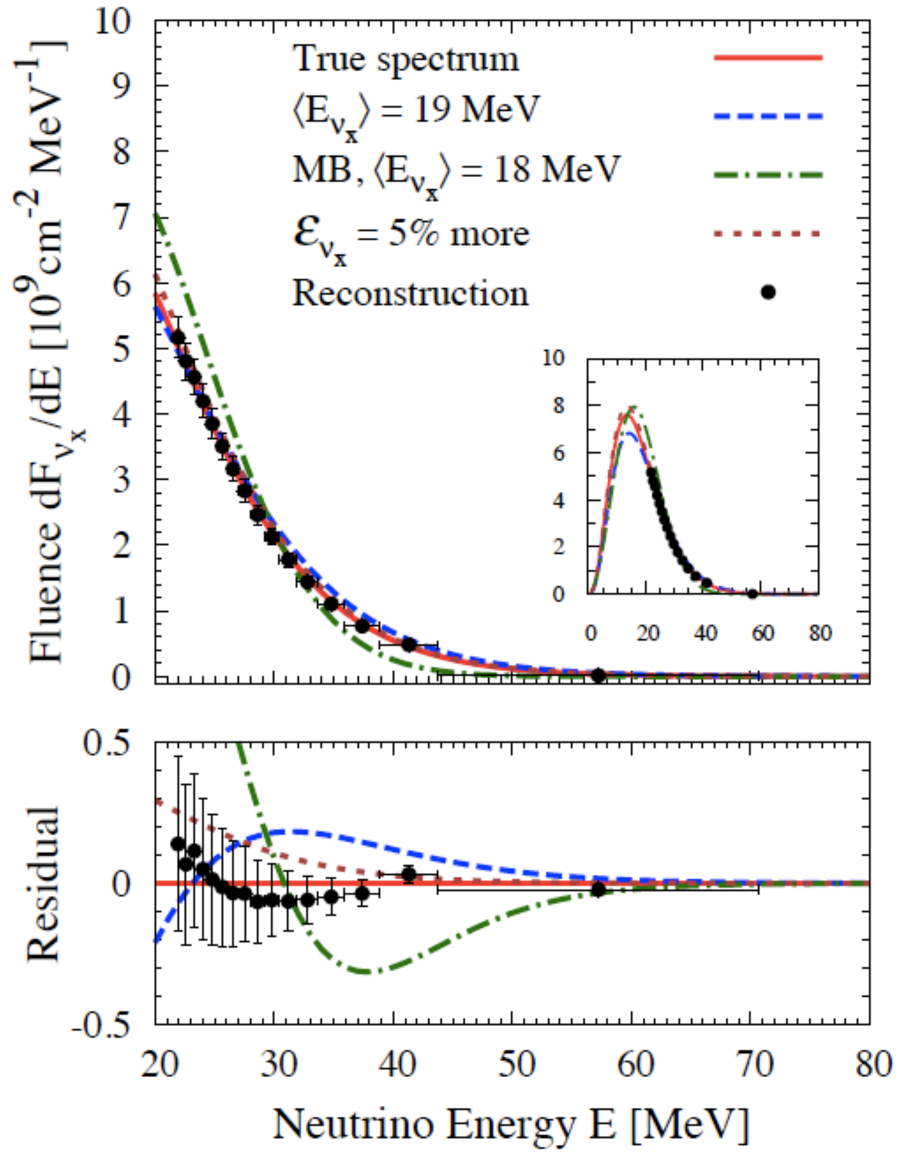
Generate Mock-data



Reconstruct Spectrum



LENA



True spectrum
$\langle E_{\nu_x} \rangle = 19$ MeV
MB, $\langle E_{\nu_x} \rangle = 18$ MeV
$\mathcal{E}_{\nu_x} = 5\%$ more
Reconstruction
Fluence dF_{ν_x}/dE [$10^9 cm^{-2} MeV^{-1}$]
Residual
Neutrino Energy E [MeV]

What do we learn?

- Observe all flavors
- Precision measurements in all flavors
- Better handle on total energy budget
- Disappearance and appearance