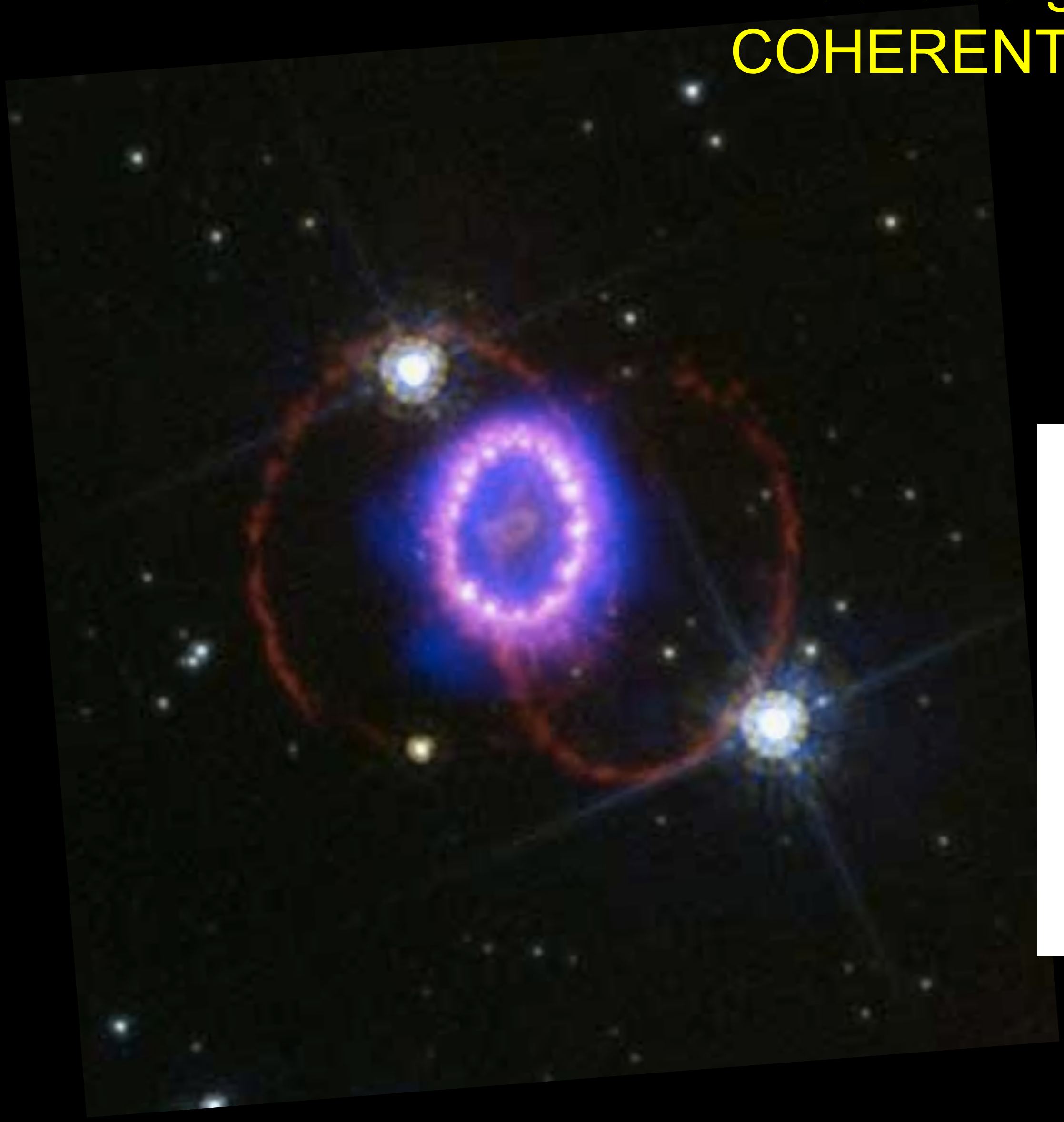
The Helium and Lead Observatory

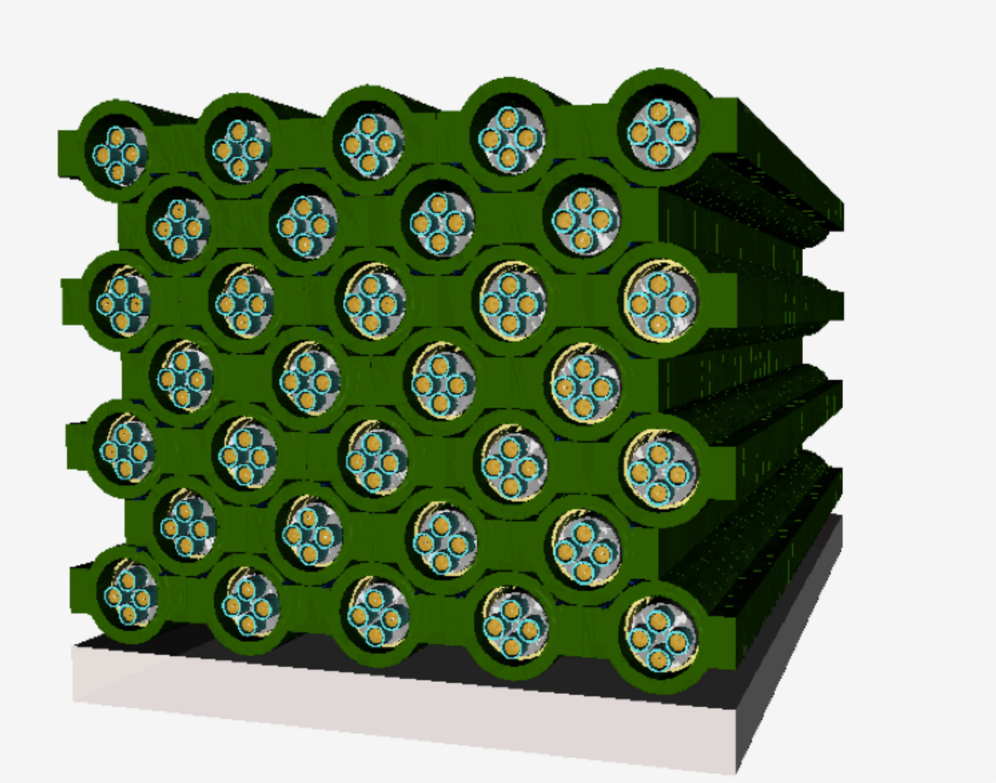
K. Scholberg, Duke University
COHERENT Theory workshop

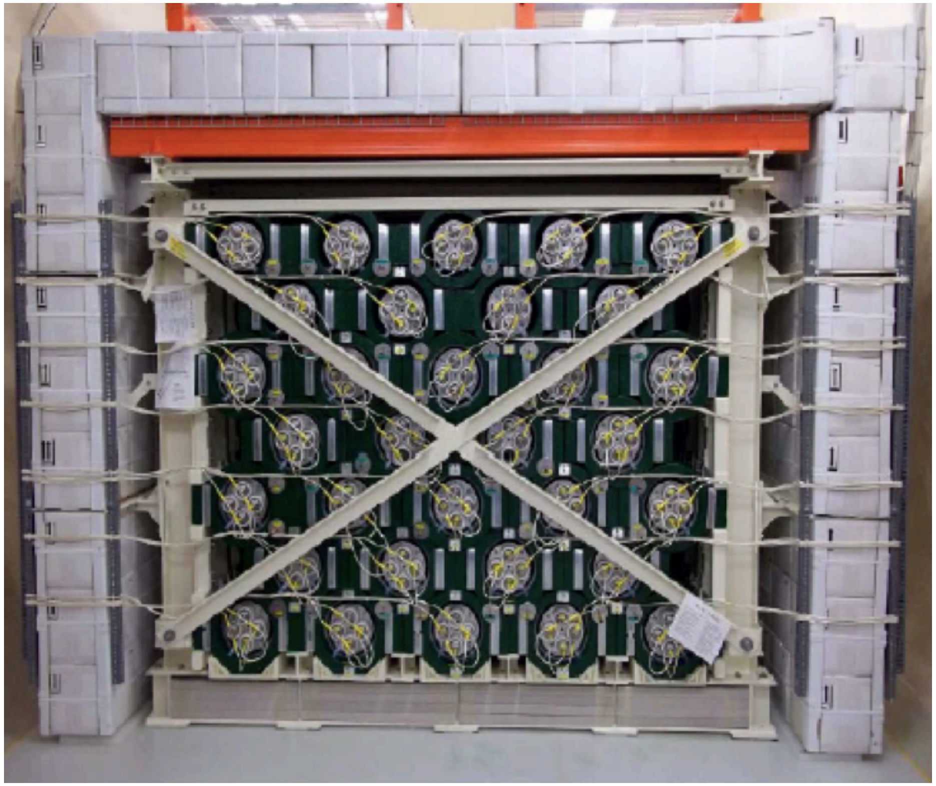


HALO at SNOLAB

-79 tonnes of lead instrumented with old
SNO ^{3}He neutron counters, w/HPDE moderator
+ water shield

- dedicated for supernova neutrino detection





- taking data since 2013
- very low maintenance

Interactions of supernova neutrinos on lead

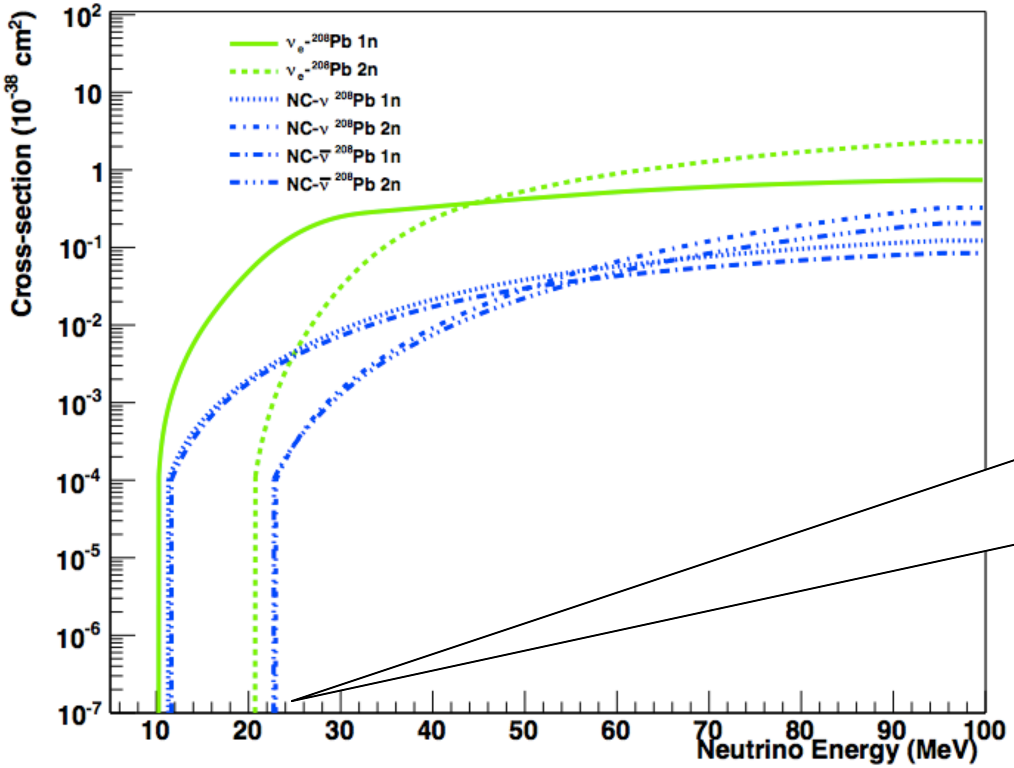
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^- \quad \mathrm{CC}$$

$\searrow$ 1n, 2n emission

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x \quad \mathrm{NC}$$

$\searrow$ 1n, 2n, γ emission

Observe single and double ~few MeV neutron events in the ^{3}He counters



sharp thresholds, so 1n/2n relative rates are strongly dependent on the neutrino spectrum

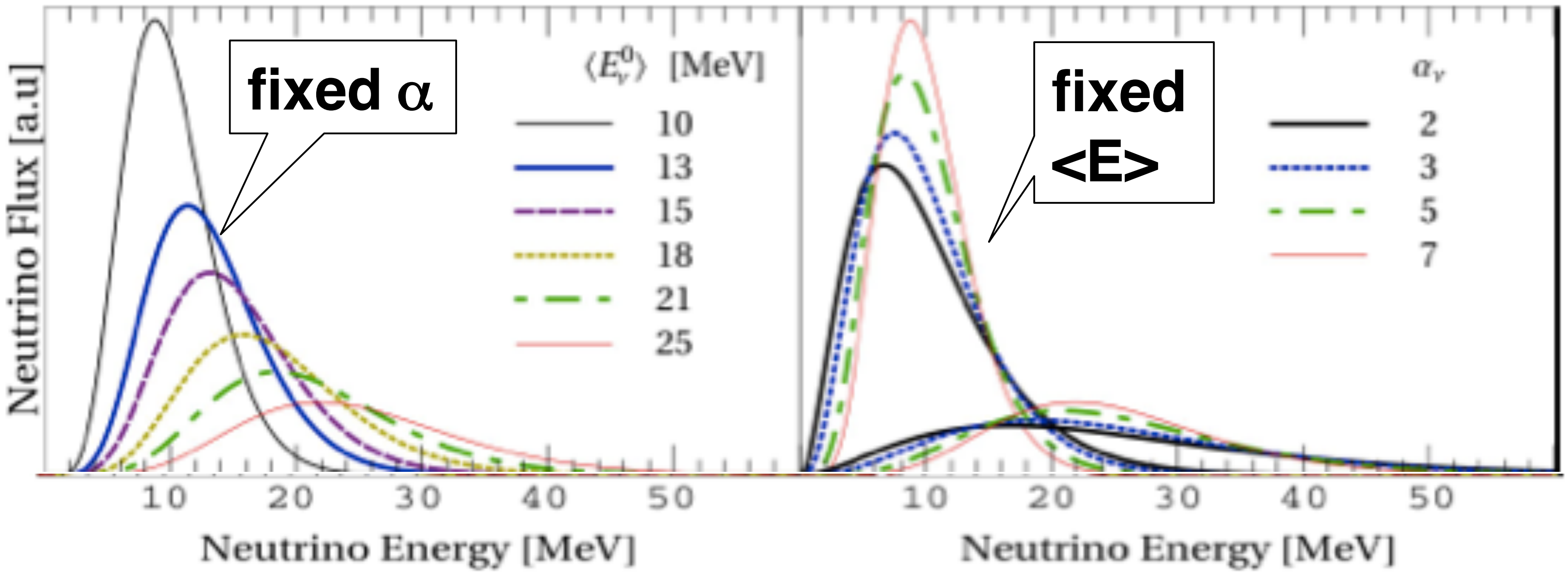
(similar for other lead isotopes)

Expected supernova neutrino spectra

Vaananen & Volpe JCAP 1110:019, 2011, arXiv:1105.6225

Modified power law is a decent approximation;
different α, <E> parameters for different flavors

$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right] \qquad \mathcal{N} = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}$$

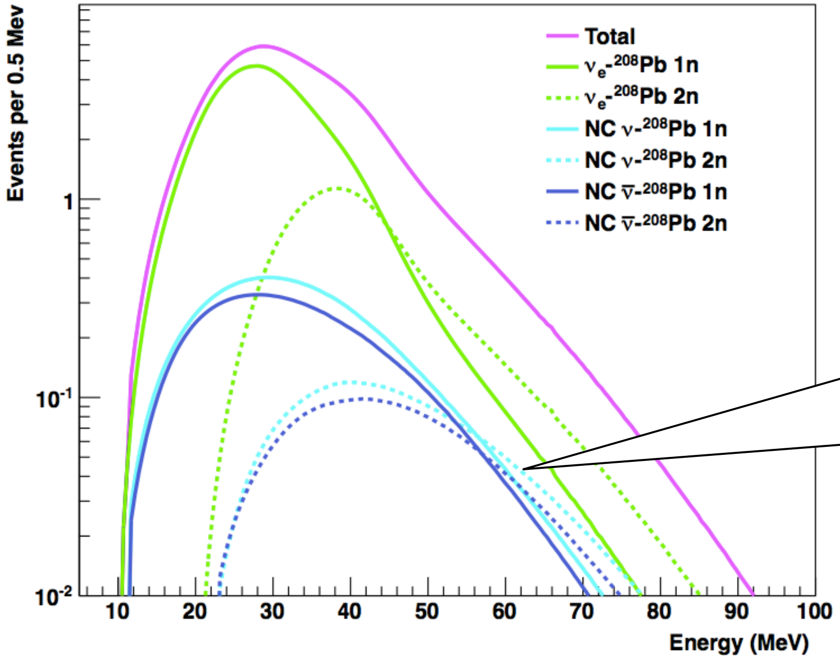

fixed α

fixed <E>

The larger the “pinching” parameter α,
the more suppressed the high energy tail

Example of event rates for particular models

`http://www.phy.duke.edu/~schol/snowglobes`



2n events sample higher neutrino energies

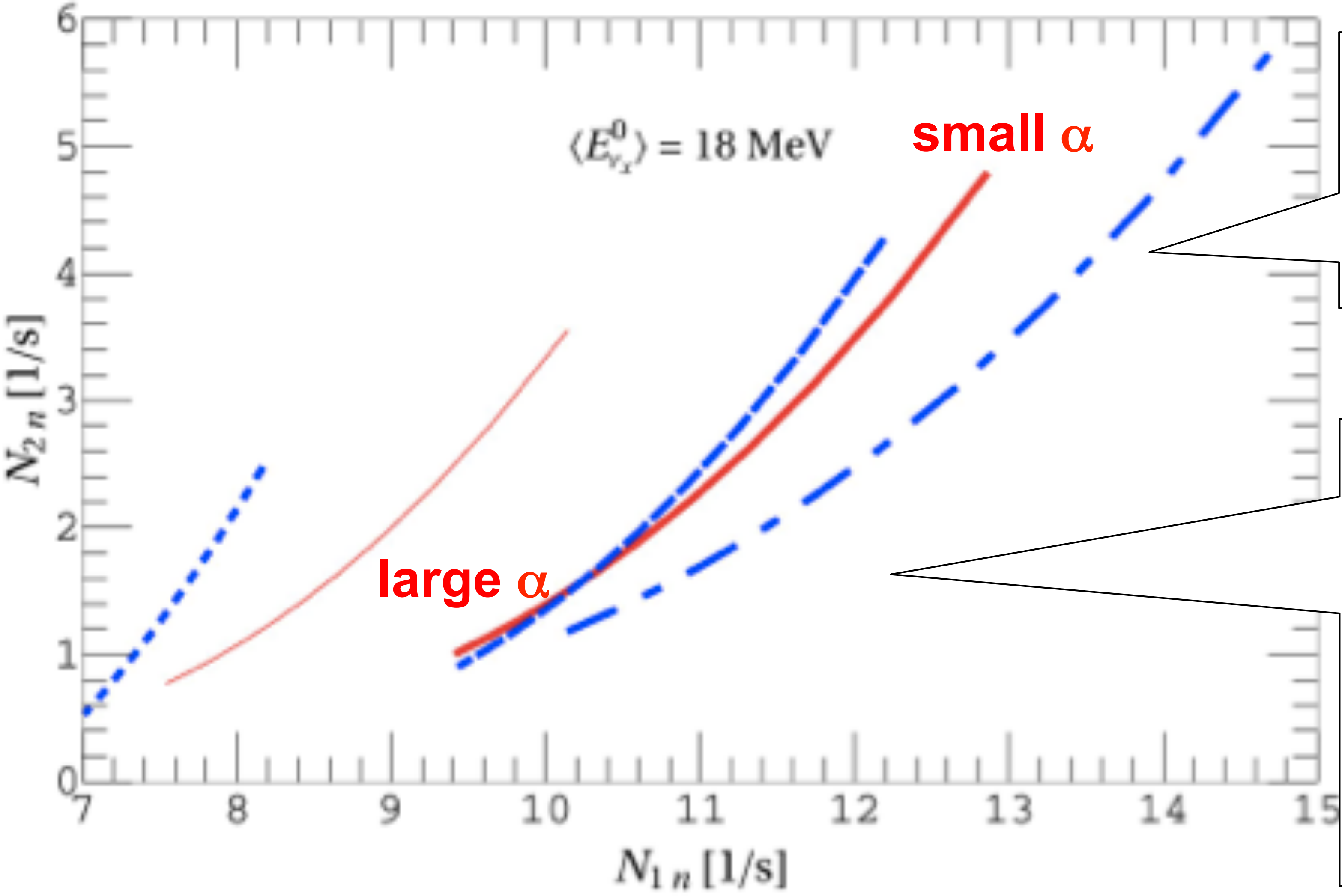
Channel	Events, "Livermore" model	Events, "GKVM" model
$\nu_e + ^{208}\mathrm{Pb} \rightarrow e^- + ^{207}\mathrm{Bi} + n$	124	173
$\nu_e + ^{208}\mathrm{Pb} \rightarrow e^- + ^{206}\mathrm{Bi} + 2n$	14	45
$\nu_x + ^{208}\mathrm{Pb} \rightarrow \nu_x + ^{207}\mathrm{Pb} + n$	53	23
$\nu_x + ^{208}\mathrm{Pb} \rightarrow \nu_x + ^{206}\mathrm{Pb} + 2n$	27	7
$\bar{\nu}_x + ^{208}\mathrm{Pb} \rightarrow \bar{\nu}_x + ^{207}\mathrm{Pb} + n$	48	19
$\bar{\nu}_x + ^{208}\mathrm{Pb} \rightarrow \bar{\nu}_x + ^{206}\mathrm{Pb} + 2n$	23	6
Total 1n events	225	215
Total 2n events	64	58
Total events	289	272

expect a few hundred events per kton @ 10 kpc

For a given (<E>, α), predict a (N_{1n}, N_{2n}) measurement

Range of predictions for range of models:

Vaananen & Volpe JCAP 1110:019, 2011, arXiv:1105.6225

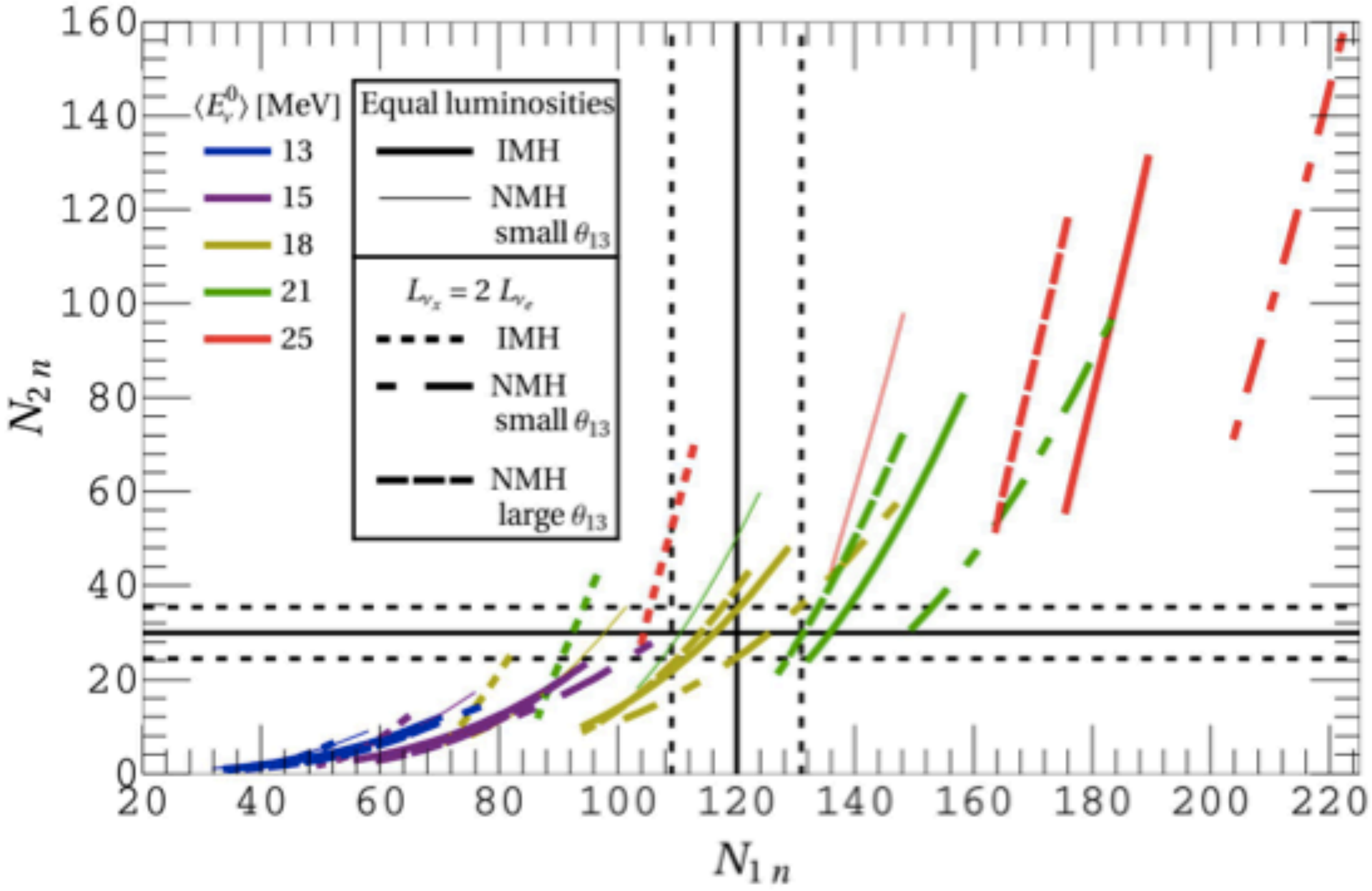


each line tracks values of α for a given model

different lines represent different mass hierarchy and flavor luminosity models

Comparing (N_{1n}, N_{2n}) measurement to prediction

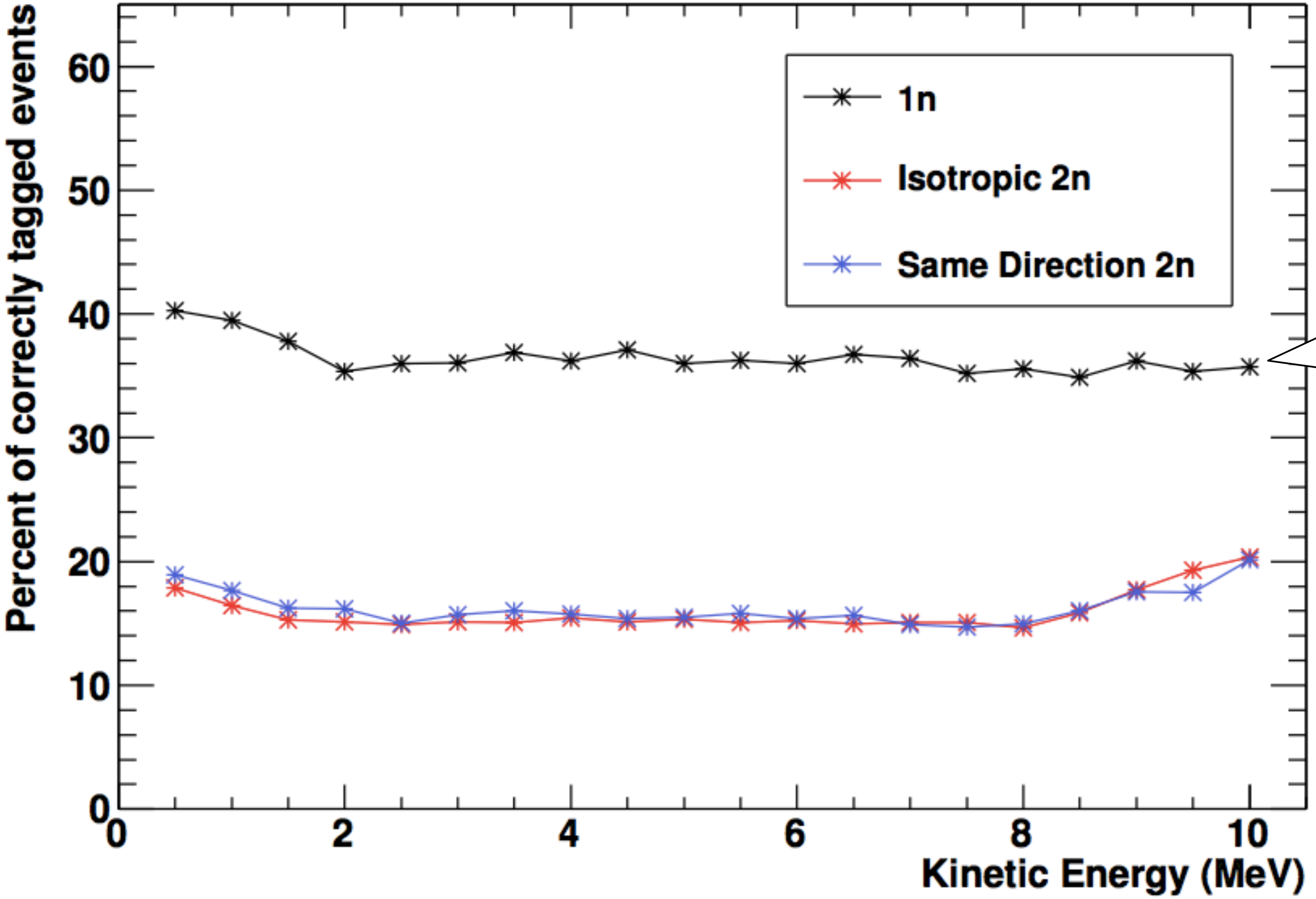
Vaananen & Volpe JCAP 1110:019, 2011, arXiv:1105.6225



One can constrain models by measuring a (N_{1n}, N_{2n}) point in this space

How well can we do with realistic HALO parameters?

In practice, neutron detection efficiency is not perfect...



Efficiency ~independent of energy

HALO Geant4 simulation study
Leigh Schaefer, TUNL REU, summer 2011

Caveat: worse efficiency in latest HALO G4 sim... not yet final

1n and 2n efficiencies estimated from MC:

$$\begin{pmatrix} N_{\text{1n observed}} \\ N_{\text{2n observed}} \end{pmatrix} = A(E_n) \begin{pmatrix} N_{\text{1n true}} \\ N_{\text{2n true}} \end{pmatrix}$$

$$A(E_n) = \begin{pmatrix} \text{1n measured as 1n} & \text{2n measured as 1n} \\ \text{1n measured as 2n} & \text{2n measured as 2n} \end{pmatrix}$$

One can infer the true numbers of 1n & 2n events from observed ones:

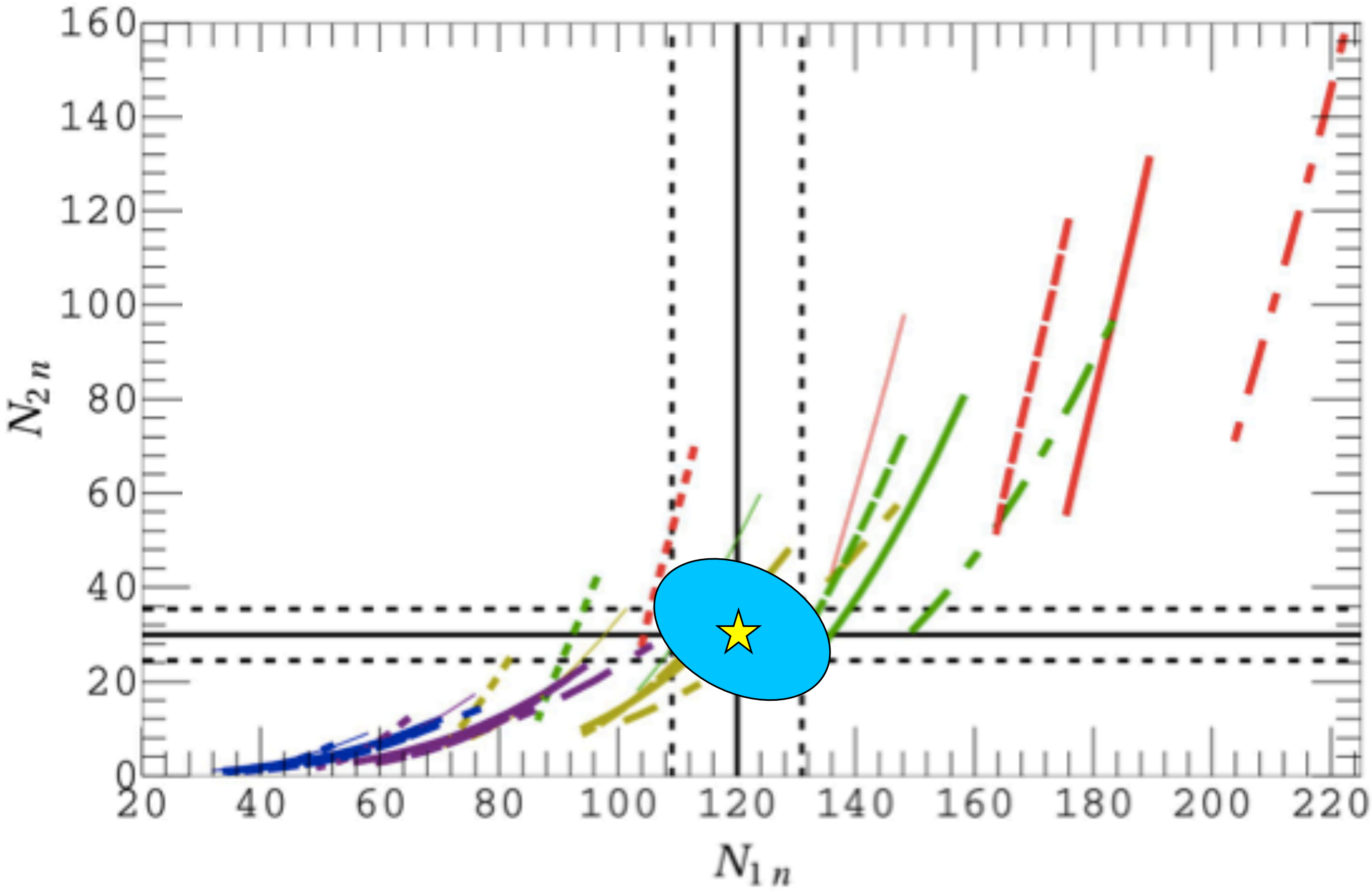
$$\begin{pmatrix} N_{\text{1n inferred}} \\ N_{\text{2n inferred}} \end{pmatrix} = A^{-1}(E_n) \begin{pmatrix} N_{\text{1n observed}} \\ N_{\text{2n observed}} \end{pmatrix}$$

Matrix estimated from MC: $A = \begin{pmatrix} 0.38 & 0.41 \\ 0.0002 & 0.15 \end{pmatrix}$

is reasonably well modeled by $A = \begin{pmatrix} \epsilon & 2\epsilon(1-\epsilon) \\ 0 & \epsilon^2 \end{pmatrix}$

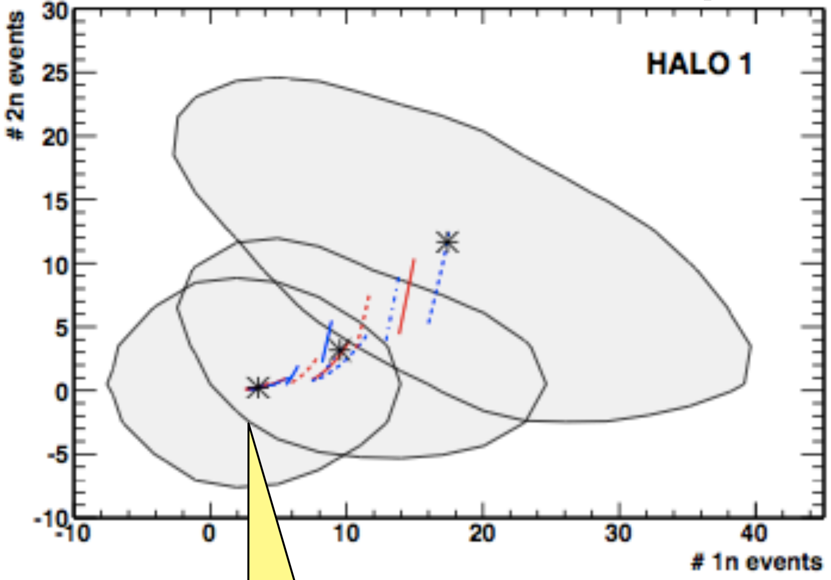
which assumes ~independent n detections

Sensitivity estimate: for given true (N_{1n},N_{2n}) mean values, use simple Poisson MC to determine range of inferred ($N_{1n\ obs}$,$N_{2n\ obs}$) values

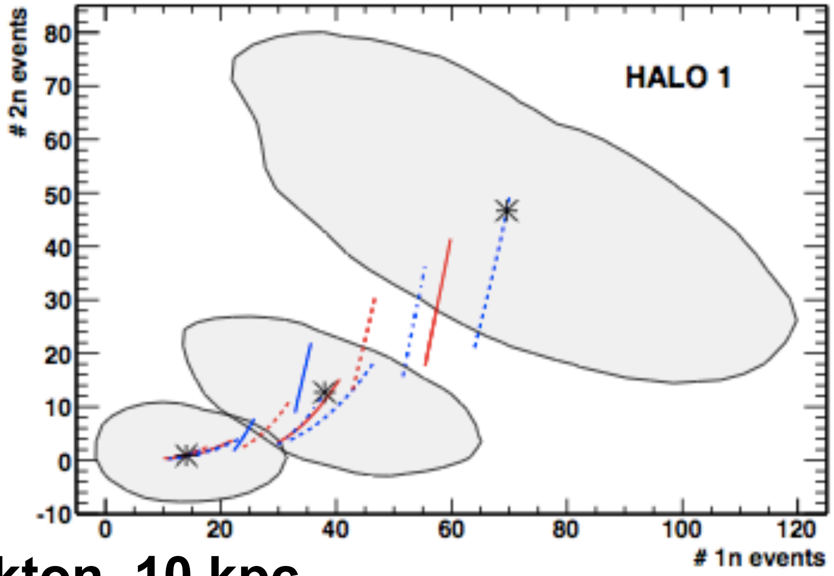


Results for different detector masses & SN distances

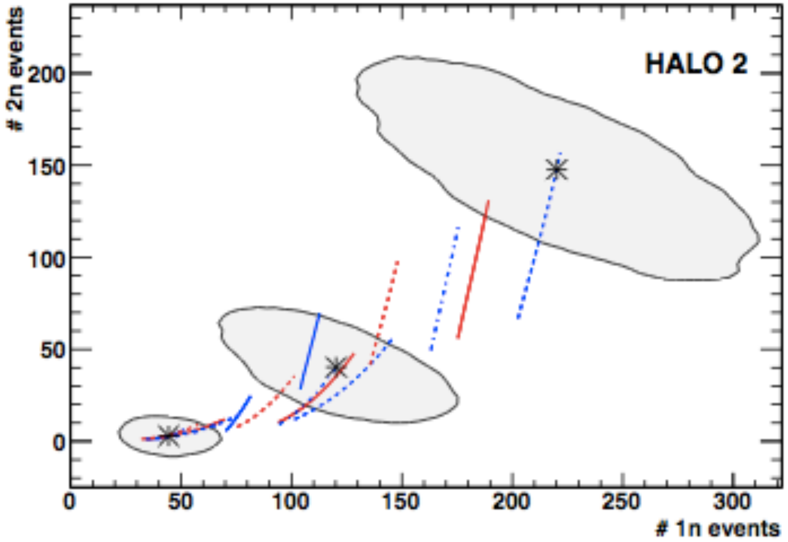
79 tons, 10 kpc



79 tons, 5 kpc



1kton, 10 kpc



Note that measuring few events will give significant information

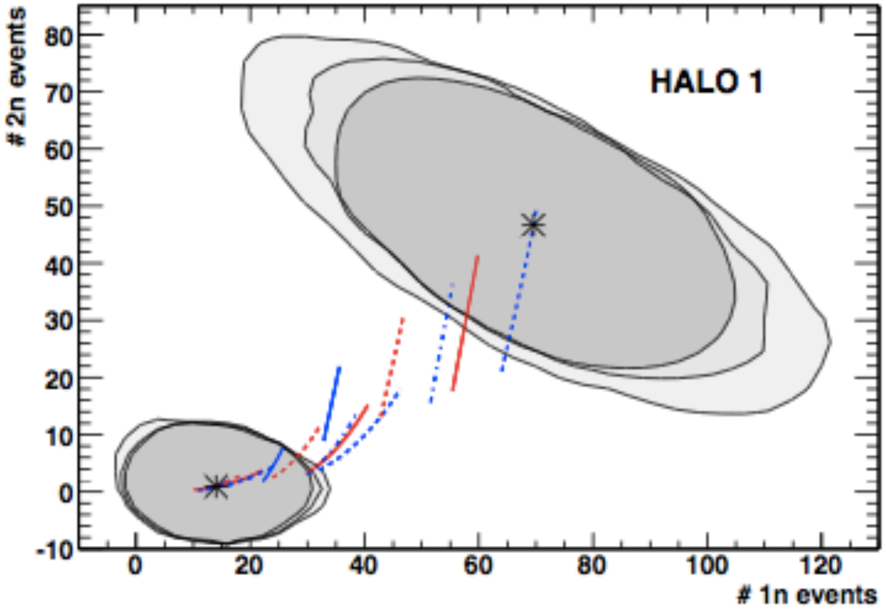
Nicolas Kaiser,
DAAD exchange student,
summer 2011

- Curves represent predictions for a range of models with different fluxes and oscillation parameters, from Vaananen & Volpe JCAP 1110:019, 2011
- Shaded regions enclose 90% of HALO inferred values for given true values

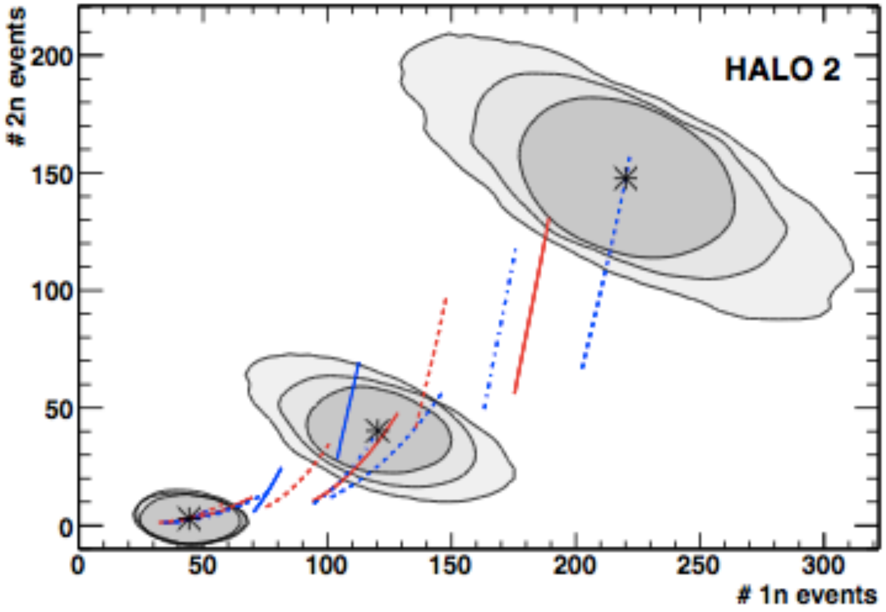
How much better could one do with improved detector efficiency?

$$A = \begin{pmatrix} \epsilon & 2\epsilon(1-\epsilon) \\ 0 & \epsilon^2 \end{pmatrix}$$

5 kpc



10 kpc



ε = 40%,50%,60%

ε = 40%,60%,80%

Future

- Simulation improvement
- Calibration with ^{252}Cf source
- Fast alert and integration into SNEWS
- Possible graphite reflector to improve efficiency
- ~ kt of lead from OPERA...?
- Measurements and theory needed... different isotopes?

Summary

- SN neutrino spectra for different flavors carry information about supernova physics & neutrino oscillation phenomena

- The observed numbers of 1n and 2n events in lead is sensitive to neutrino spectral information

- HALO1, with 79 tonnes of lead, is ready to observe SN neutrinos via double & single n emission

- HALO1 has some ability to constrain models for a Galactic SN (observation of only a few events carries information!)

- HALO2, an envisioned upgrade to ~1 kton, will have significant sensitivity

- Measurements and theory very useful...

Backups

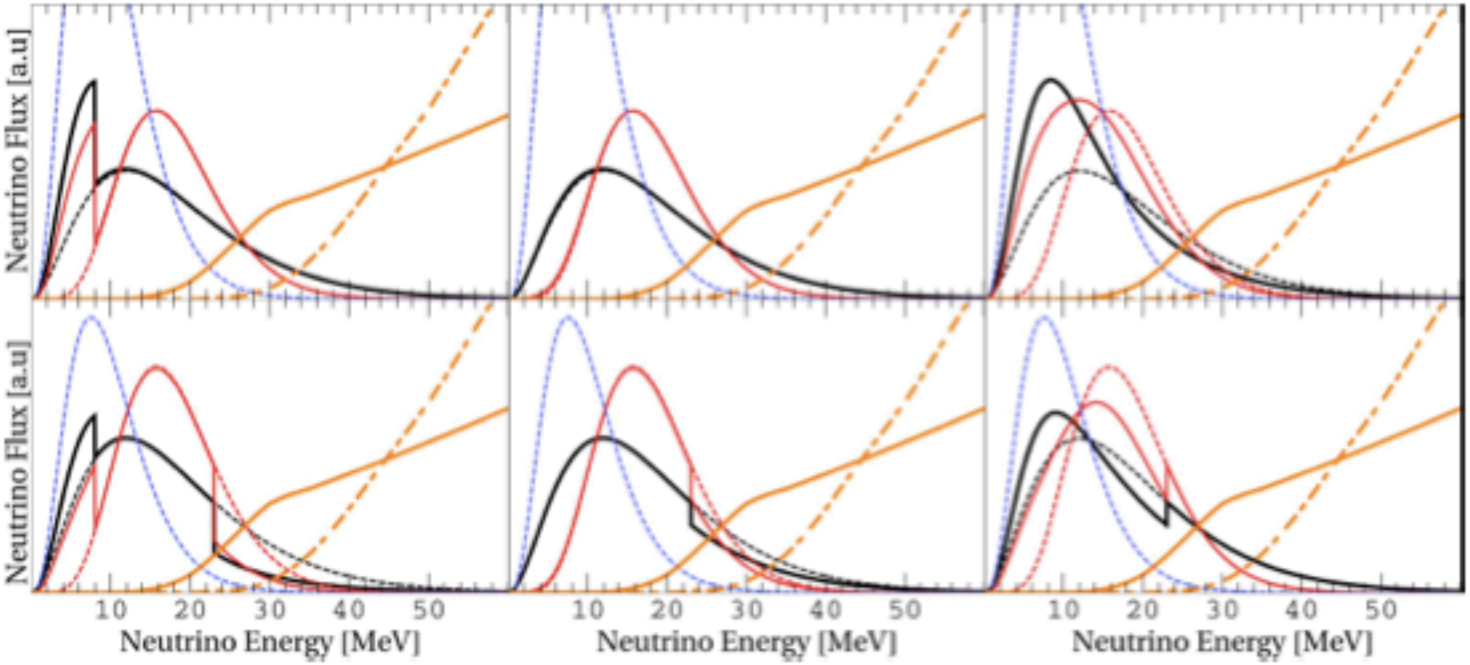
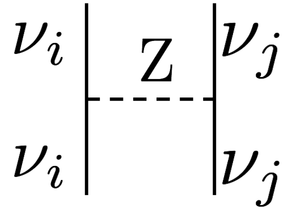


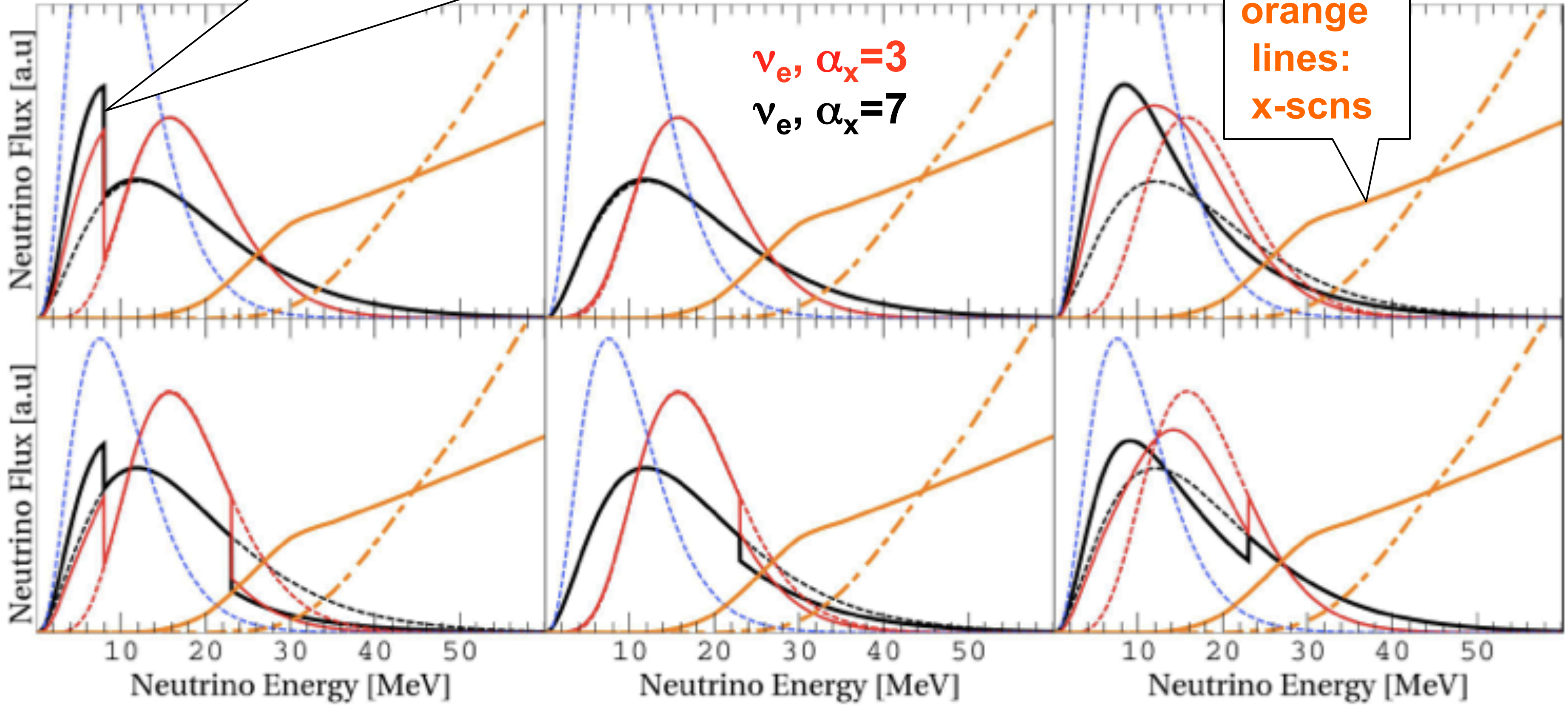
Figure 3. (Color online) Electron neutrino fluxes at Earth, eq. (3.9), (solid lines) as a function of energy including $\nu - \nu$ interactions, the MSW effect and decoherence. The primary ν_e (blue thin dashed) and ν_x (black and red thin dashed) fluxes at the neutrinosphere, eqs. (2.6) and (2.10), are also shown. Black (red) lines correspond to pinching parameter $\alpha_{\nu_x} = 2$ (7). For the primary ν_e flux $\alpha_{\nu_e} = 3$. In this figure the primary average energies are fixed as $\langle E^0_{\nu_e} \rangle = 10$ MeV, $\langle E^0_{\nu_x} \rangle = 18$ MeV. Upper row: equal luminosities, lower row: $L_{\nu_x} = 2L_{\nu_e}$. Left panel: inverted mass hierarchy (IMH), middle panel: normal mass hierarchy (NMH) with large θ_{13}, right panel: NMH with small θ_{13}. Additionally, the charge current $\nu_e -$ Pb one-(thick, solid, orange) and two-neutron (thick, dash-dotted, orange) emission cross sections (from ref. [51]) are also shown.

Examples of SN neutrino spectra modified by collective effects from *neutrino-neutrino* interactions

Vaananen & Volpe JCAP 1110:019, 2011, arXiv:1105.6225

“spectral swap” features modify ν spectra for different ν mass hierarchy, θ_{13}, flavor luminosity ratio





ν_e, α_x=3

ν_e, α_x=7

orange lines: x-scns

Measuring spectral information for different flavors will help constrain models (astrophysics & mass hierarchy)