Supernova neutrino signal at Helium And Lead Observatory:

Learning about the primary neutrino fluxes and neutrino properties

D. Väänänen, C. Volpe, arXiv: 1105.6225

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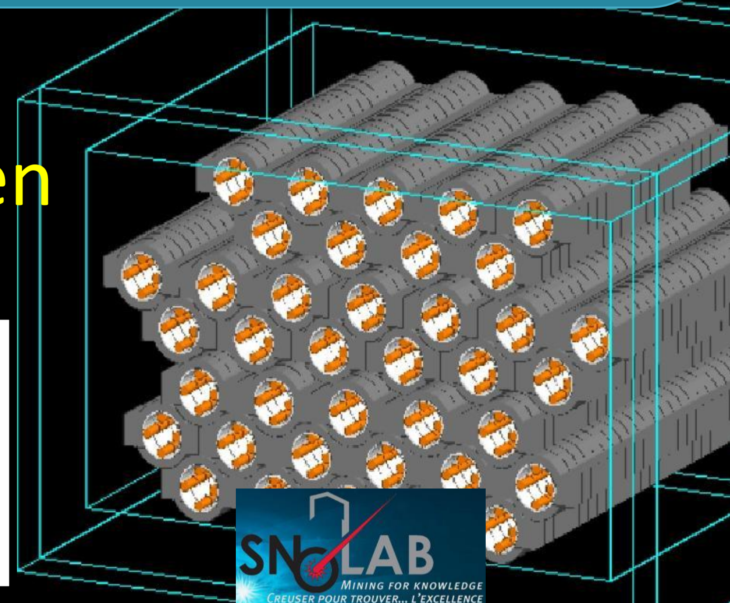
ORSAY



SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

HAνSE 2011
Hamburg Neutrinos from Supernova Explosions

DESY, Hamburg Site/Germany
19-23 July 2011

Motivation

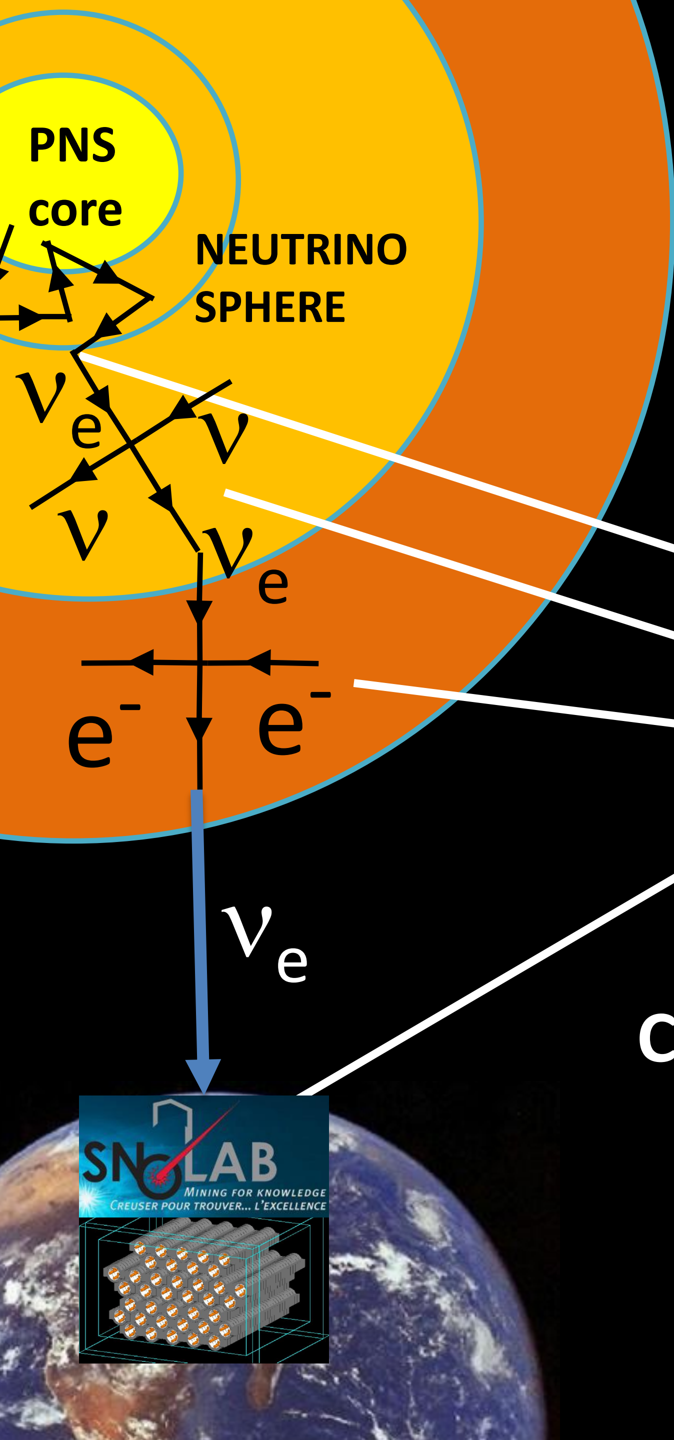
- Helium And Lead Observatory (HALO), a dedicated supernova (SN) neutrino detector **under construction** at SNOLAB
- Most of the existing and proposed detectors mainly sensitive to electron antineutrinos
  - **Pb detector sensitive to electron neutrinos**
- Previous works* emphasized the interest of Pb based neutrino detector, however:

  1) recent SN simulations suggest different neutrino fluxes

  2) νν – interactions were not included

* e.g. **[Fuller, Haxton, McLaughlin, PRD59, 085005 (1999)], [Kolbe, Langanke, PRC63, 025802 (2001)], [Engel, McLaughlin, Volpe, PRD67, 013005 (2003)]**

➢ **New predictions for HALO necessary!**



THE EVOLUTION OF THE TALK

A. Open Questions:

1) Unknown neutrino properties
2) Neutrino fluxes at neutrino sphere

B. Neutrino Evolution: The Formalism

1) *Primary* neutrino fluxes
2) $\nu\nu$ -interactions
3) MSW Effects
4) Final Fluxes at Earth

C. Neutrino Signal at HALO

- Can we extract information on the open questions?

1) Unknown neutrino properties:

- θ_{13} < 0.2 (PDG), non-zero [Fogli *et al.* arXiv:1106.6028]?
- **Neutrino mass hierarchy**:

Normal (NMH) or Inverted (IMH)?

1) Unknown neutrino properties:

- $\theta_{13} < 0.2$ (PDG), non-zero [Fogli *et al.* arXiv:1106.6028]?
- **Neutrino mass hierarchy**:

Normal (NMH) or Inverted (IMH)?

2) Neutrino fluxes at the neutrino spheres -

the *primary* fluxes: $F^0_\nu(E_\nu) \propto \frac{L_\nu}{\langle E_\nu \rangle}\phi(E_\nu,\ldots)$

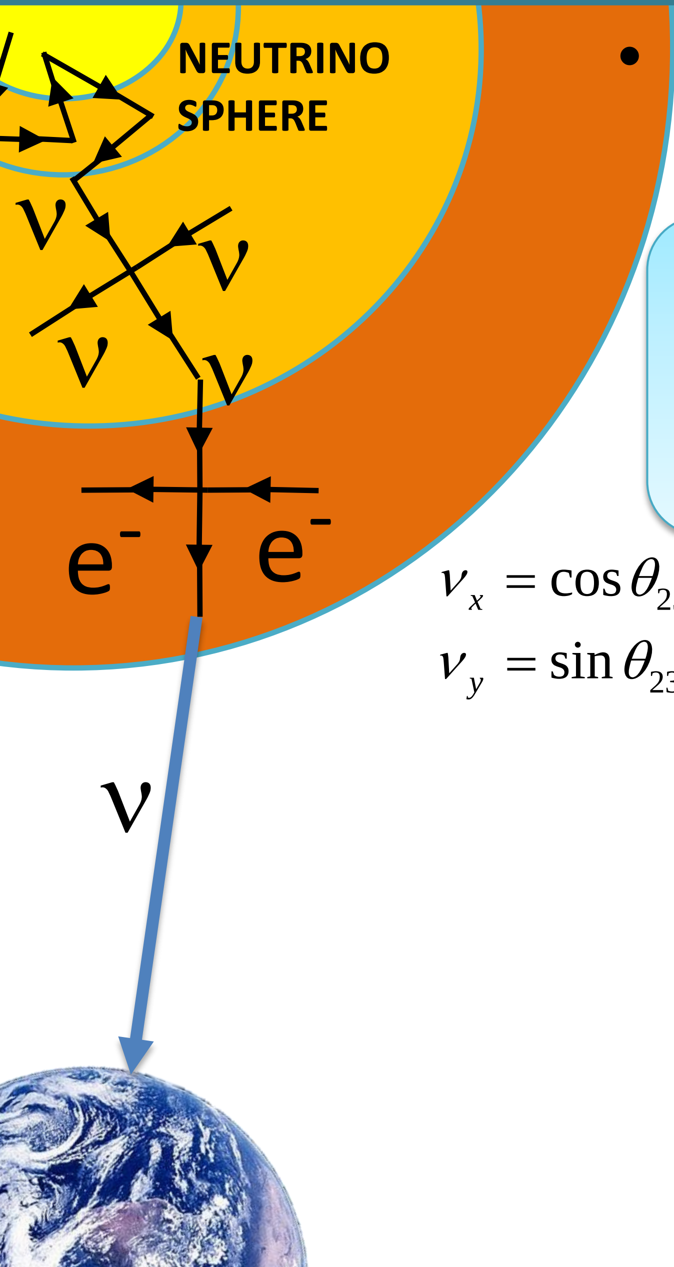
- Luminosities, average energies and energy spectrum?

From SN simulations:
e.g. [Keil, Raffelt, Janka, Astrop.J. 590, 971], [Ficher *et al*. 0908.1871]

$$\begin{cases} 0.5 \le \frac{L_{\nu_x}}{L_{\nu_e}} \le 2,\; L_{\bar{\nu}_e} \approx L_{\nu_e} \\ \left(L_{\nu_x} \equiv L_{\nu_\mu} = L_{\bar{\nu}_\mu} = L_{\nu_\tau} = L_{\bar{\nu}_\tau}\right) \\ \int \mathrm{d}t \sum_\ell L_{\nu_\ell} \sim 3\cdot 10^{53}\ \mathrm{erg} \end{cases}$$

$$\langle E^0_{\nu_e} \rangle \approx 10-12\ \mathrm{MeV}$$
$$\langle E^0_{\bar{\nu}_e} \rangle \approx 13-16\ \mathrm{MeV}$$
$$\langle E^0_{\nu_x} \rangle \approx 15-25\ \mathrm{MeV}$$

The Formalism and Assumptions



- We consider iron core-collapse SNe
  - **Factorized dynamics:**

$$\begin{pmatrix} F(\nu_e) \\ F(\nu_\mu) \\ F(\nu_\tau) \end{pmatrix} = A P_{\mathrm{MSW}} P_{\nu\nu} \begin{pmatrix} F^0(\nu_e) \\ F^0(\nu_x) \\ F^0(\nu_y) \end{pmatrix}$$

$$\nu_x = \cos\theta_{23}\nu_\mu - \sin\theta_{23}\nu_\tau$$
$$\nu_y = \sin\theta_{23}\nu_\mu + \cos\theta_{23}\nu_\tau$$

$$F^0(\nu_x) = F^0(\nu_y) = F^0(\nu_\mu) = F^0(\nu_\tau)$$

1) Primary fluxes

2) Effects due to $\nu\nu$ – interactions

3) MSW effects

4) Decoherence of the wave packets

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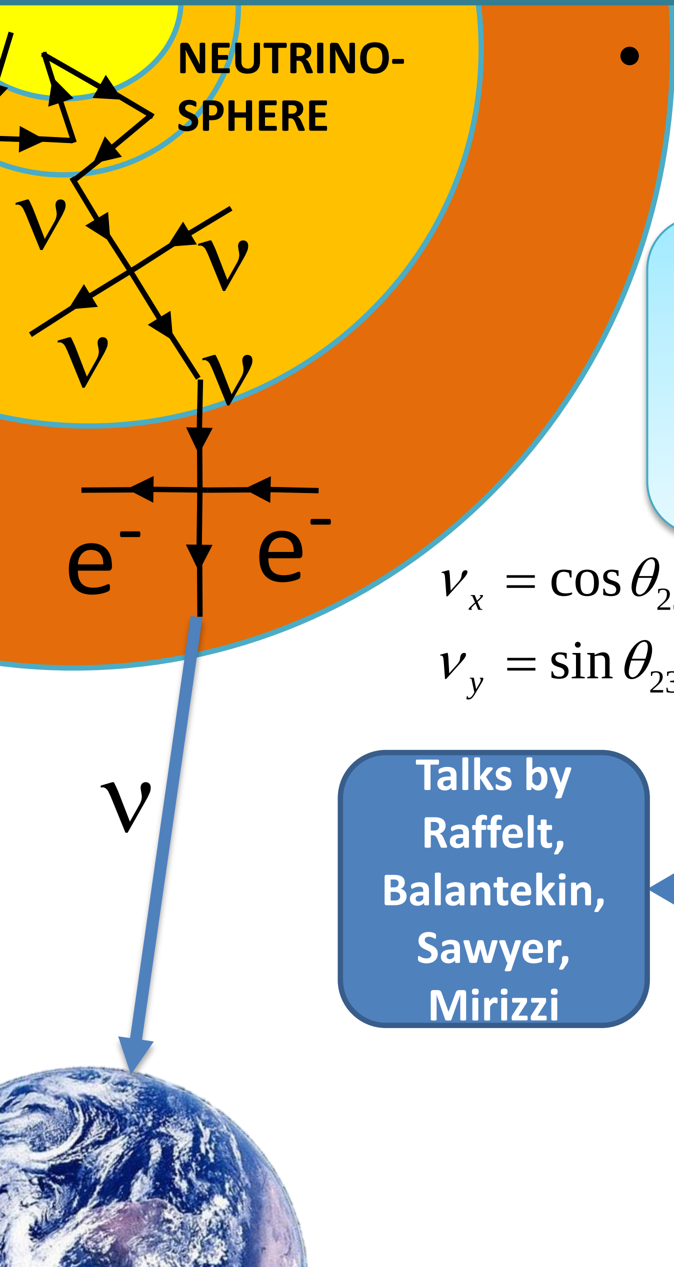

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Talks by Raffelt, Balantekin, Sawyer, Mirizzi

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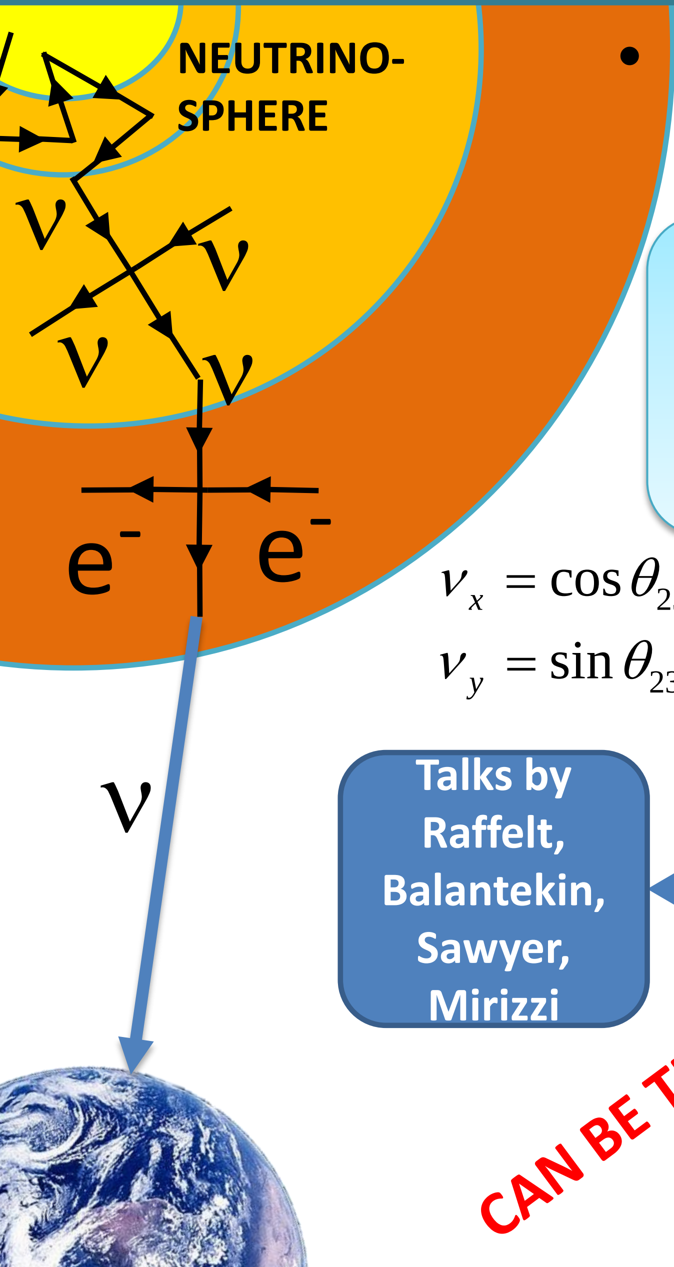

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1) Primary fluxes

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4) Decoherence of the wave packets

Talks by Raffelt, Balantekin, Sawyer, Mirizzi

CAN BE TREATED INDEPENDENTLY!

1) Neutrino fluxes at the neutrino shpere

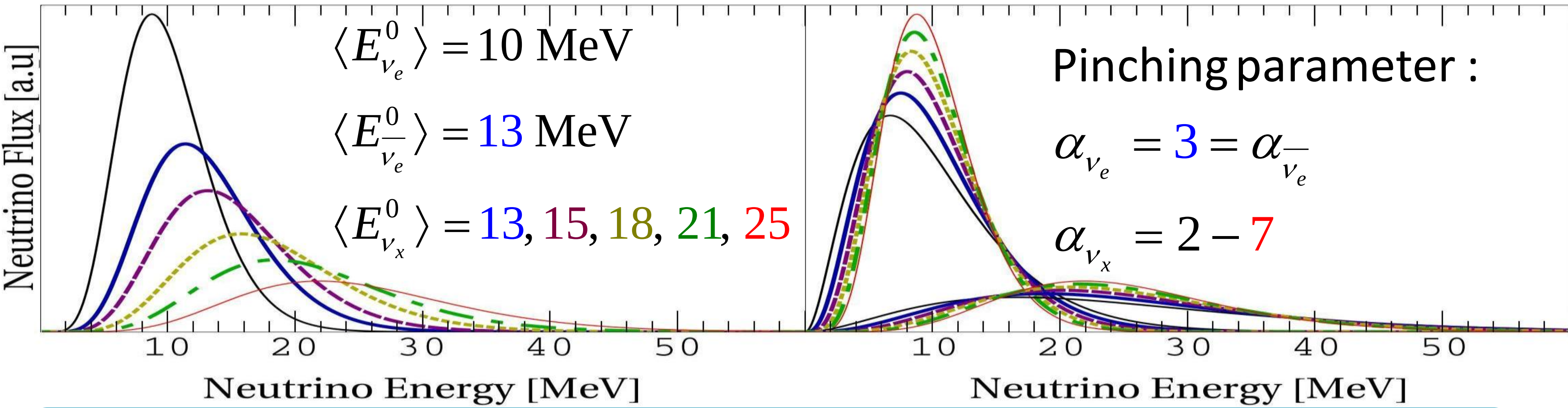
$$\begin{pmatrix} F(\nu_e) \\ F(\nu_\mu) \\ F(\nu_\tau) \end{pmatrix} = AP_{\mathrm{MSW}} P_{\nu\nu} \begin{pmatrix} F^0(\nu_e) \\ F^0(\nu_x) \\ F^0(\nu_y) \end{pmatrix}$$

We assume:

$$F_\nu^0(E_\nu) \propto \frac{L_\nu}{\langle E_\nu \rangle} \times E_\nu^{\alpha_\nu} \exp\left[-(\alpha_\nu + 1) \frac{E_\nu}{\langle E_\nu \rangle} \right]$$

Power Law energy distribution

- Equal luminosities or $L_{\nu_x} = 2L_{\nu_e}$ $(L_{\bar{\nu}_e} = L_{\nu_e}, L_{\nu_x} \equiv L_{\nu_\mu} = L_{\nu_\tau})$ and



Important information on neutrino transport in SN core

2) Fluxes after the $\nu\nu$ -interactions

$$\begin{pmatrix} F(\nu_e) \\ F(\nu_\mu) \\ F(\nu_\tau) \end{pmatrix} = A P_{\mathrm{MSW}} P_{\nu\nu} \begin{pmatrix} F^0(\nu_e) \\ F^0(\nu_x) \\ F^0(\nu_y) \end{pmatrix}$$

$$P_{\nu\nu} = \begin{pmatrix} P_{ll} & P_{ex} & P_{ey} \\ P_{ex} & 1-P_{ex} & 0 \\ P_{ey} & 0 & 1-P_{ey} \end{pmatrix}, \qquad \begin{aligned} P_{ll} &= 1 - P_{ex} - P_{ey} \\ P_{\alpha\beta} &\equiv P(\nu_\alpha \leftrightarrow \nu_\beta) \end{aligned}$$

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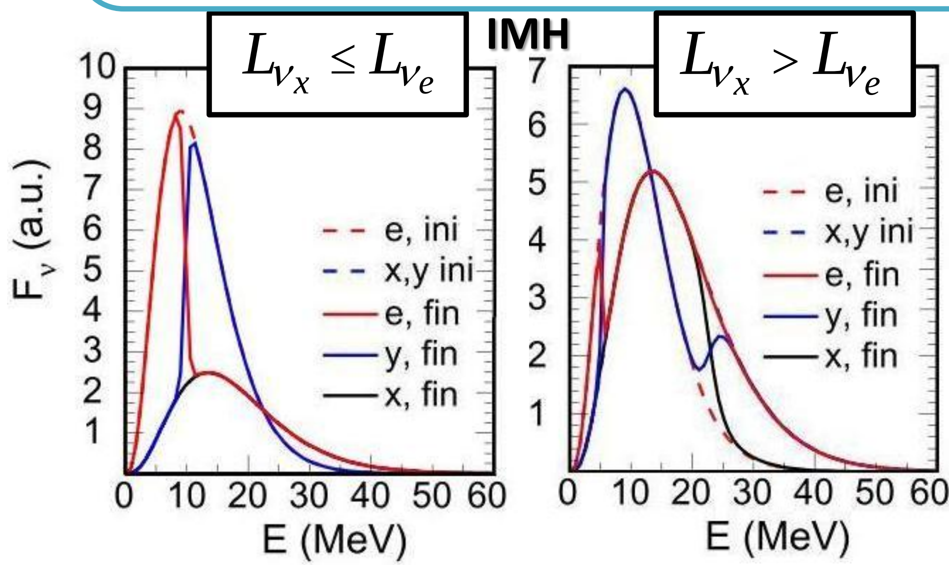

A. Mirizzi, R. Tomàs, arXiv:1012.1339 (2010)

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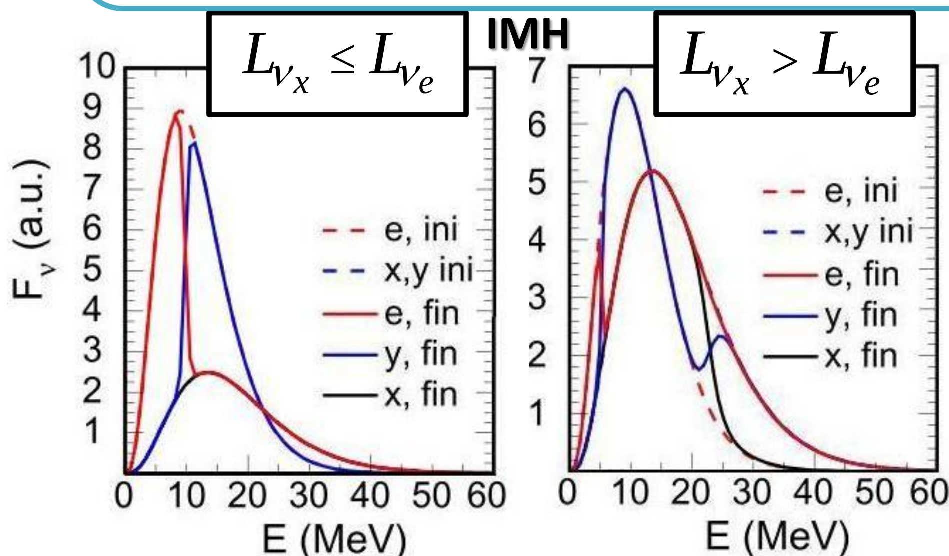

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We assume:

- 0, 1 or 2 splits in energy

$$P_{ey} = \begin{cases} 1, & \text{if } E_{\text{low}}^{\text{split}} < E < E_{\text{high}}^{\text{split}} \\ 0, & \text{otherwise} \end{cases}$$

$$P_{ex} = \begin{cases} 1, & \text{if } E > E_{\text{high}}^{\text{split}} \\ 0, & \text{otherwise} \end{cases}$$

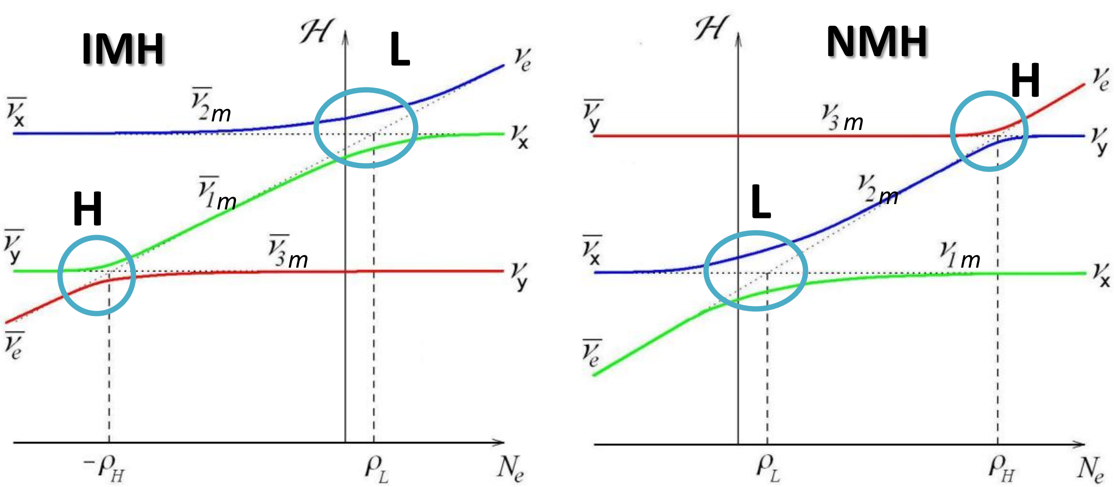
Large dependence on luminosity and mass hierarchy

3) Fluxes after the MSW region

$$\begin{pmatrix} F(\nu_e) \\ F(\nu_\mu) \\ F(\nu_\tau) \end{pmatrix} = A P_{\mathrm{MSW}} P_{\nu\nu} \begin{pmatrix} F^0(\nu_e) \\ F^0(\nu_x) \\ F^0(\nu_y) \end{pmatrix}$$

$$P_{\mathrm{MSW}} \equiv \begin{pmatrix} P_H P_L & 1-P_L & (1-P_H)P_L \\ P_H(1-P_L) & P_L & (1-P_H)(1-P_L) \\ 1-P_H & 0 & P_H \end{pmatrix}, \quad \begin{matrix} P_{L,H} \equiv P_{\mathrm{R}}(\nu_{im} \leftrightarrow \nu_{jm}) \\ i, j = 1, 2, 3 \end{matrix}$$

A. Dighe, A. Smirnov, PRD 62, 033007 (2000)



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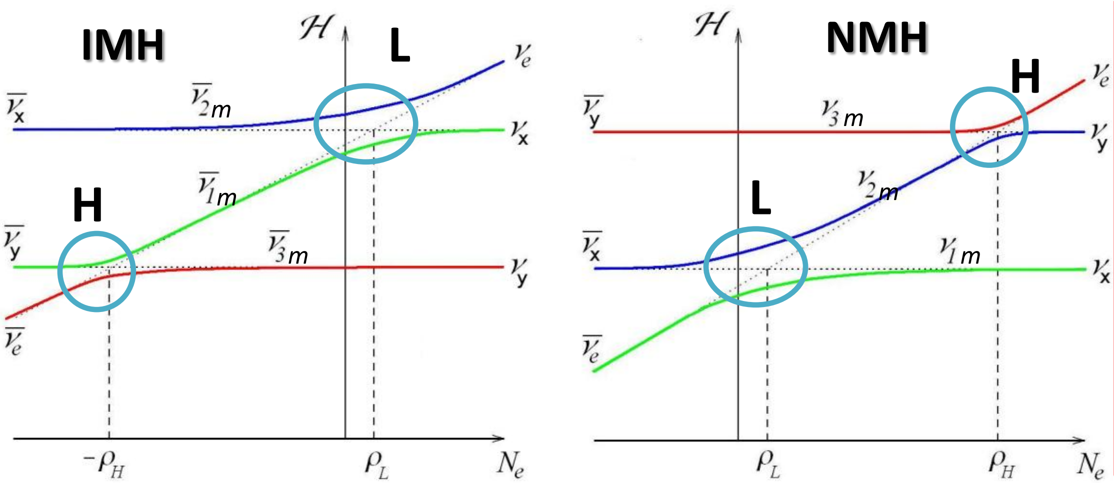


We assume:

- at H-resonance:

$$\begin{cases} \theta_{13} = 0.1 \quad \Leftrightarrow P_H \approx 0 \\ \theta_{13} = 0.001 \Leftrightarrow P_H \approx 1 \end{cases}$$

- at L-res: $P_L \approx 0$ always

➢ Neutrinos exit the star as pure mass eigenstates

4) Final neutrino fluxes

$$\begin{pmatrix} F(\nu_e) \\ F(\nu_\mu) \\ F(\nu_\tau) \end{pmatrix} = A P_{\text{MSW}} P_{\nu\nu} \begin{pmatrix} F^0(\nu_e) \\ F^0(\nu_x) \\ F^0(\nu_y) \end{pmatrix}$$

$$A = \begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu 1}|^2 & |U_{\mu 2}|^2 & |U_{\mu 3}|^2 \\ |U_{\tau 1}|^2 & |U_{\tau 2}|^2 & |U_{\tau 3}|^2 \end{pmatrix} \qquad |U_{\ell i}|^2 = |\langle \nu_\ell | \nu_i \rangle|^2$$

$$(\ell = e, \mu, \tau;\ i = 1, 2, 3)$$

- Final (flavor) fluxes incoherent sums of massive fluxes

E.g. :

$$F(\nu_e) = |U_{e1}|^2 F_1 + |U_{e2}|^2 F_2 + |U_{e3}|^2 F_3$$

$$|U_{e1}|^2 \approx 0.68, |U_{e2}|^2 \approx 0.31, |U_{e3}|^2 = \sin^2\theta_{13}$$

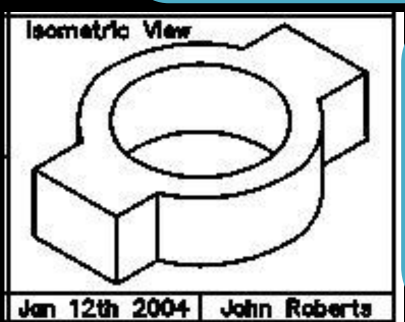
Helium And Lead Observatory (HALO)

- A dedicated SN neutrino detector under construction
  - 76t of Pb (HALO-2: 1kt)

See also talk by Virtue!

$$\mathrm{CC}: \begin{cases} \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n} + \mathrm{e}^- \\ \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n} + \mathrm{e}^- \end{cases}$$

$$\mathrm{NC}: \begin{cases} \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n} \\ \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n} \end{cases}$$

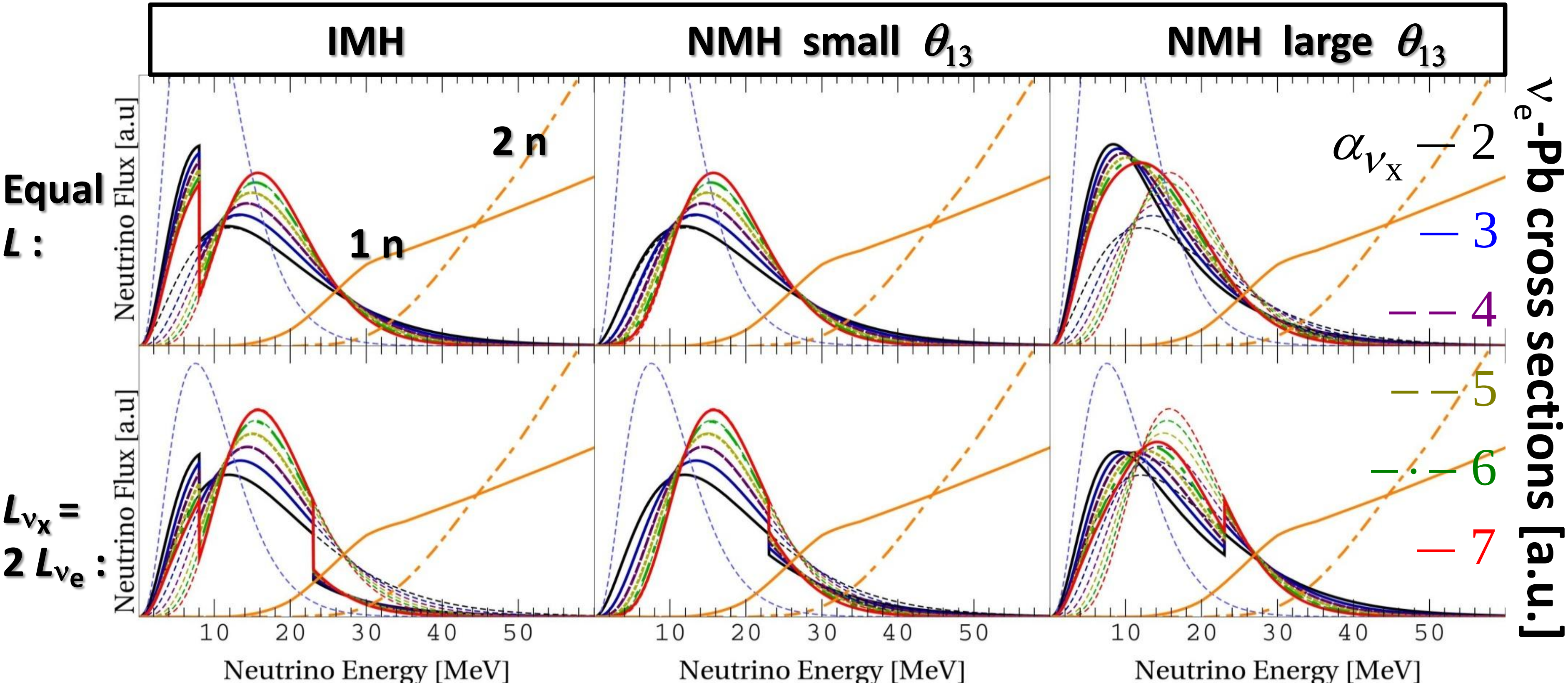


Inside ^{3}He gas detectors for neutron detection

- ✓ Detection efficiency: ~ 50% (electrons not detected)
- ✓ Good time resolution: ~ 30 ms

ν_e flux at Earth

Dependence on α_{ν_x} and neutron emission cross sections:

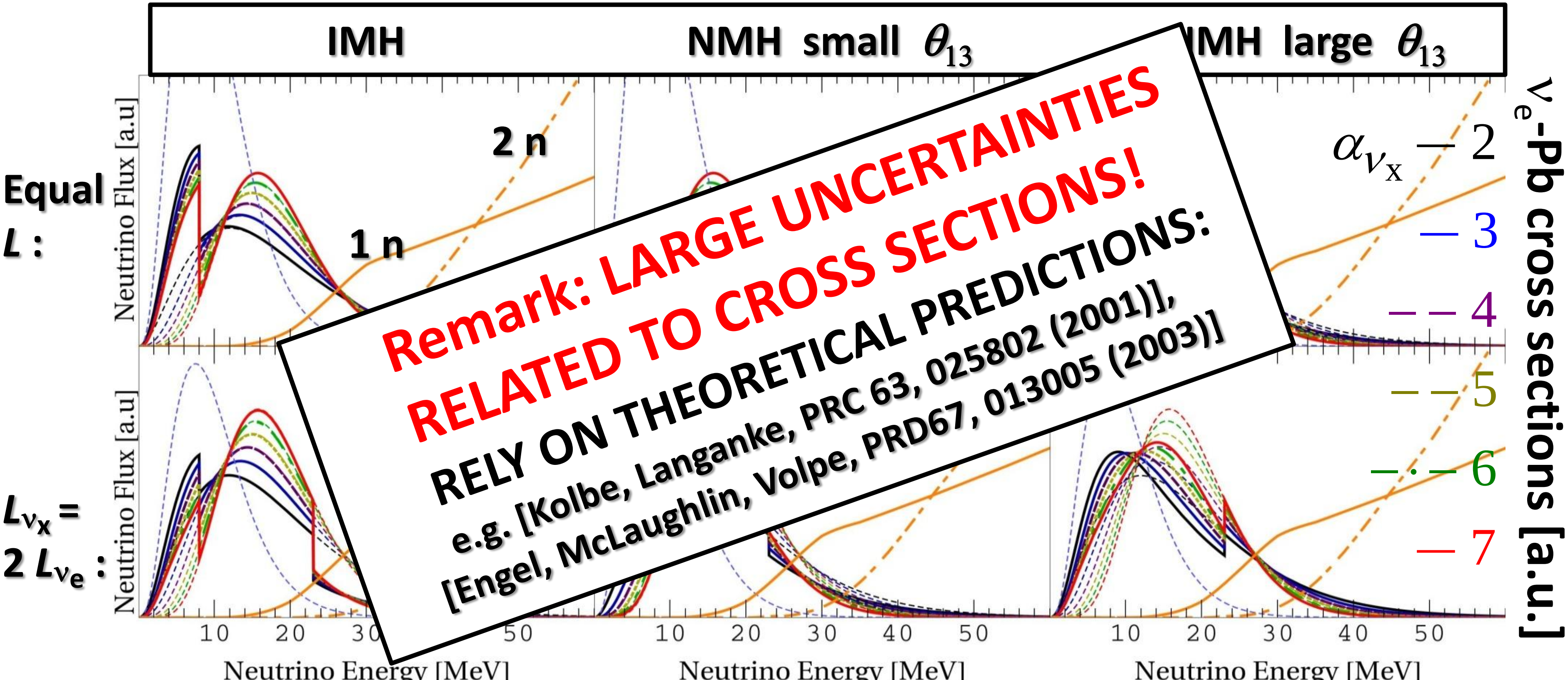


Dashed : initial $F^0(\nu_e)$ $\left(\langle E^0_{\nu_e}\rangle = 10\ \text{MeV}\right)$ and $F^0(\nu_x)$ $\left(\langle E^0_{\nu_x}\rangle = 18\ \text{MeV}\right)$, Solid : final $F^0(\nu_e)$

- ✓ Sensitive to the tail of the energy spectrum
- ➢ Can we learn about primary ν-fluxes and ν-properties?

ν_e flux at Earth

Dependence on α_{ν_x} and neutron emission cross sections:



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Remark: LARGE UNCERTAINTIES RELATED TO CROSS SECTIONS!

RELY ON THEORETICAL PREDICTIONS:

e.g. [Kolbe, Langanke, PRC 63, 025802 (2001)], [Engel, McLaughlin, Volpe, PRD67, 013005 (2003)]

- ✓ Sensitive to the tail of the energy spectrum
- ➢ Can we learn about primary ν-fluxes and ν-properties?

THE RESULTS

1) Total numbers of 1n- (N_{1n}) and 2n-events (N_{2n}) during the whole explosion
2) 1n- and 2n-event rates
3) Ratio of 1n- and 2n-events (N_{1n} / N_{2n})
4) Summary

We consider:

- **1 kt of Pb (HALO - 2)**
- **Galactic supernova at 10 kpc**
- **100% detection efficiency**
- **NC + CC events**

1) Total numbers of events

- Assuming **equal luminosities** during the whole explosion with total time-integrated luminosity $\int dt \sum_\ell L_{\nu_\ell} = 3\times10^{53}$ erg

$\langle E^0_{\nu_x}\rangle$ [MeV]	13	18				25
MH (and θ_{13})	NMH small θ_{13}	IMH		NMH small θ_{13}		IMH
α_{ν_x}	7	2	7	2	7	2
N_{1n}	90	390	285	300	225	570
N_{2n}	< 3	150	30	105	24	390
neutrons emitted	~ 90	690	345	510	273	1350

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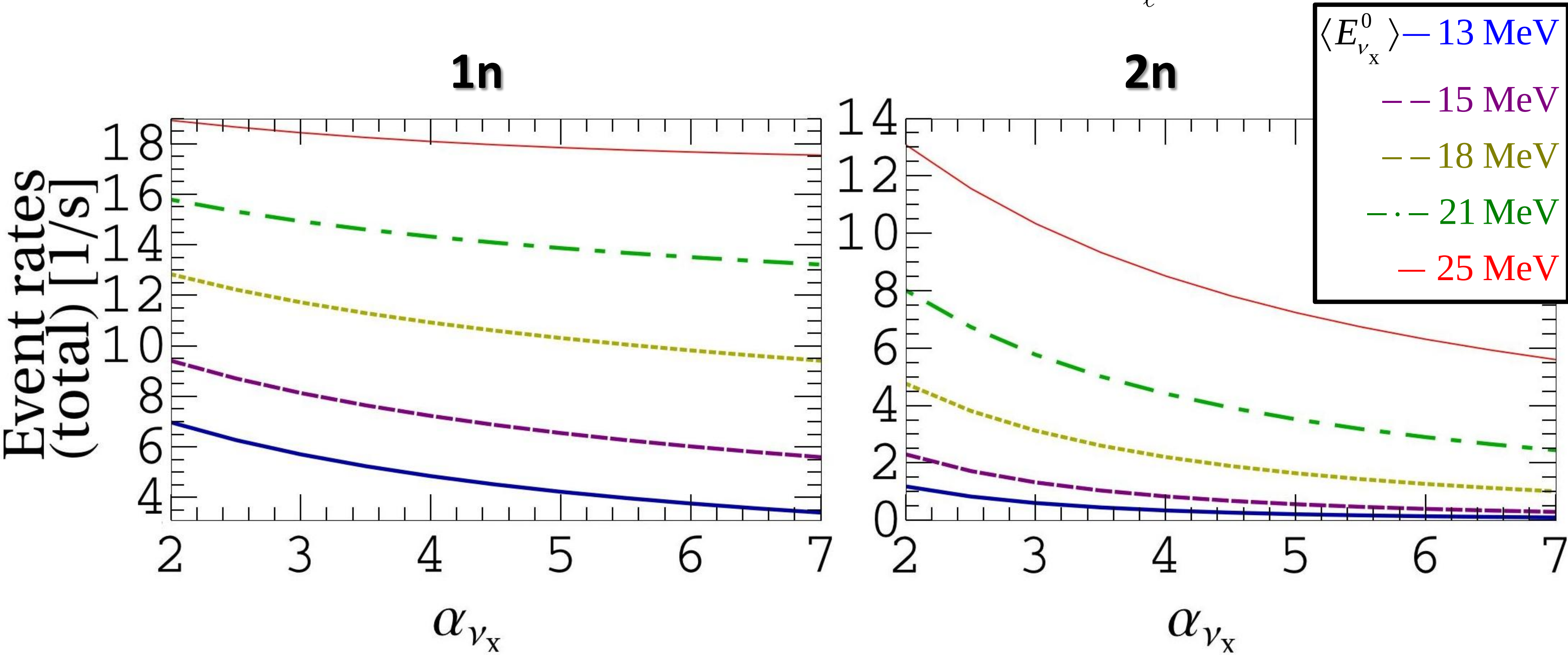
✓ For HALO – I, multiply by 0.076

- ➢ higher average energies appreciated (or SN closer!)

2) 1n- and 2n-emission event rates

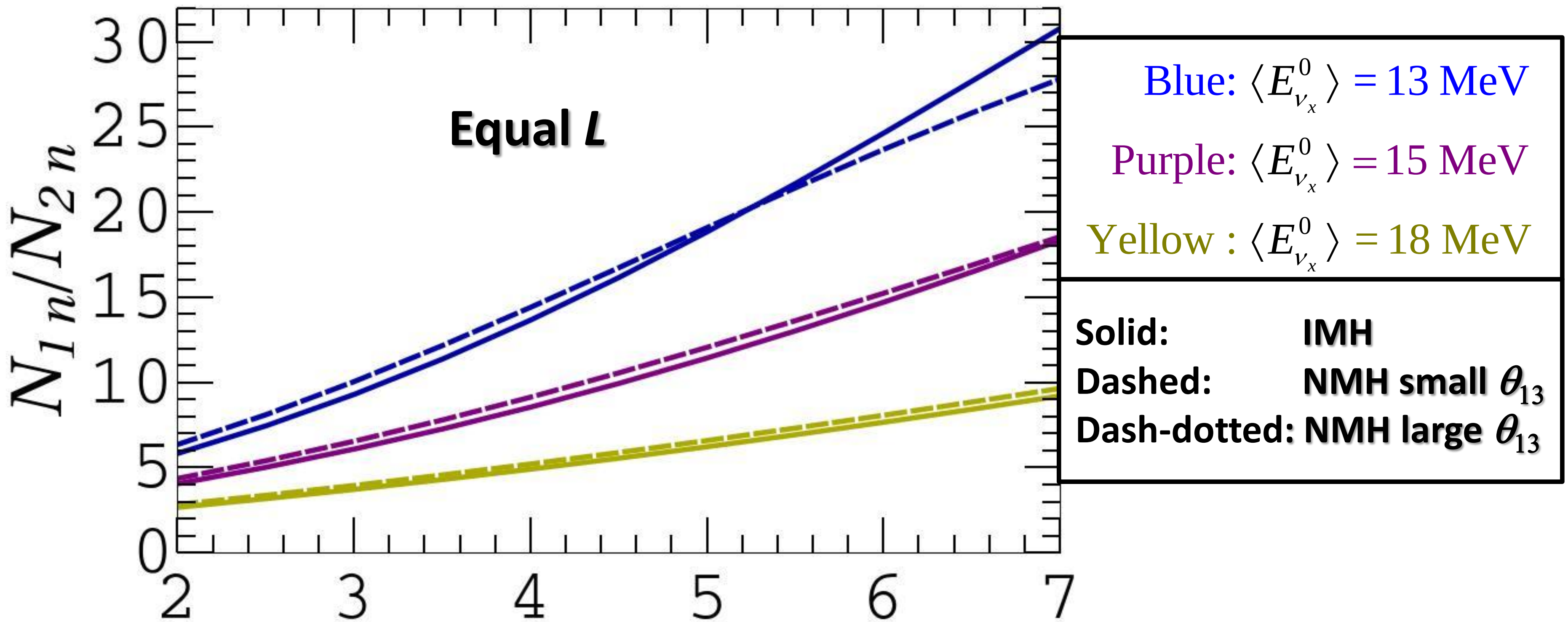
- Assuming **IMH** and **equal luminosities:** $\sum_{\ell} L_{\nu_\ell} = 10^{52}$ erg s^{-1}



➢ Complementary: 1n events more sensitive to pinching for lower average energies while opposite true for 2n events

3) Ratio of 1n- and 2n- events

- Independent of common flux parameters



- ➢ Allows to identify the degenerate combinations of α_{ν_x} and $\langle E^0_{\nu_x} \rangle$
- ➢ Sensitivity to pinching has small dependence on unknown neutrino properties and flux parameters

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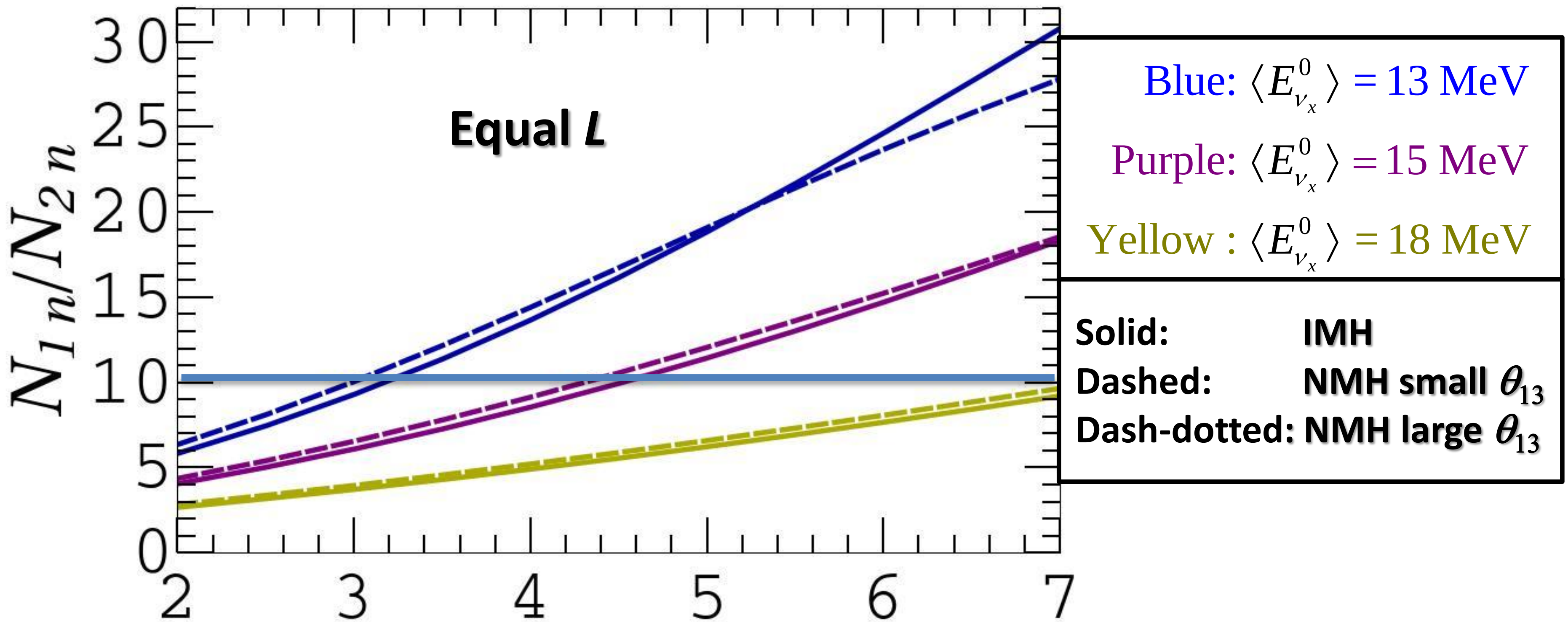

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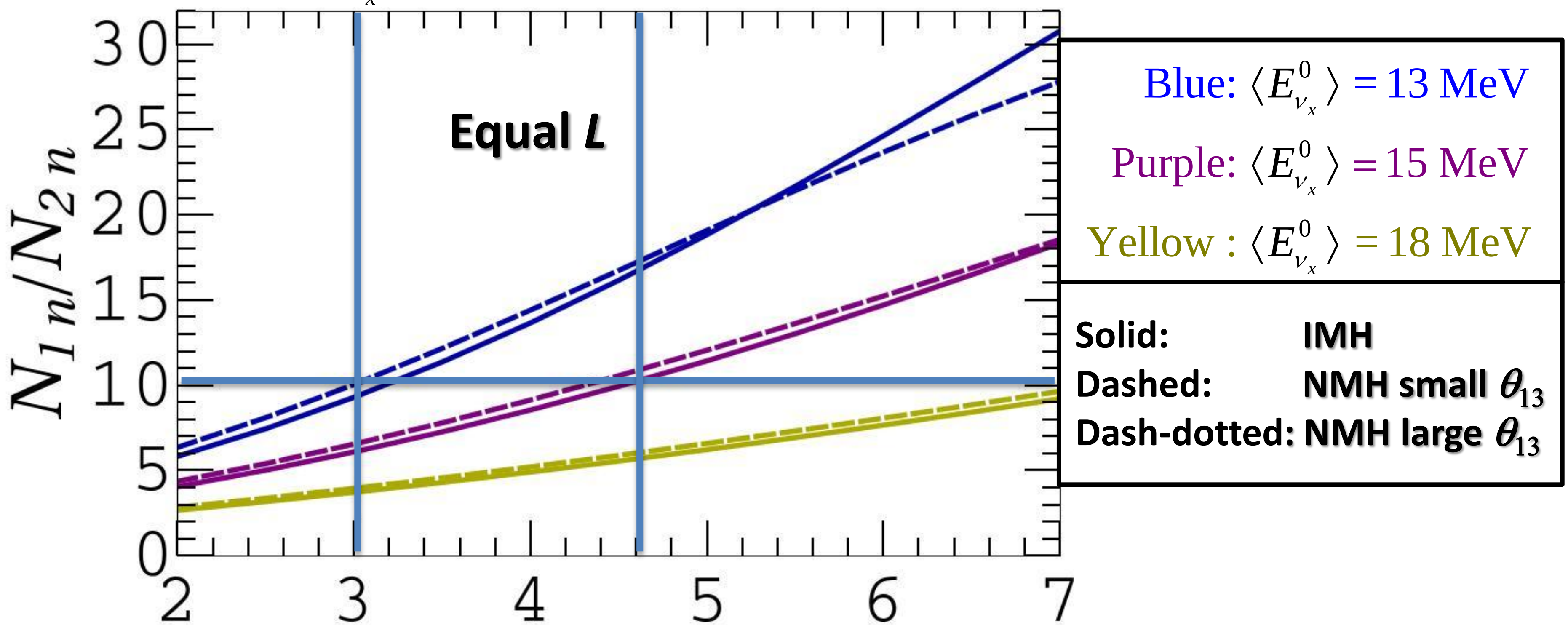
e.g. $\langle E^0_{\nu_x} \rangle = 13 - 15$ MeV



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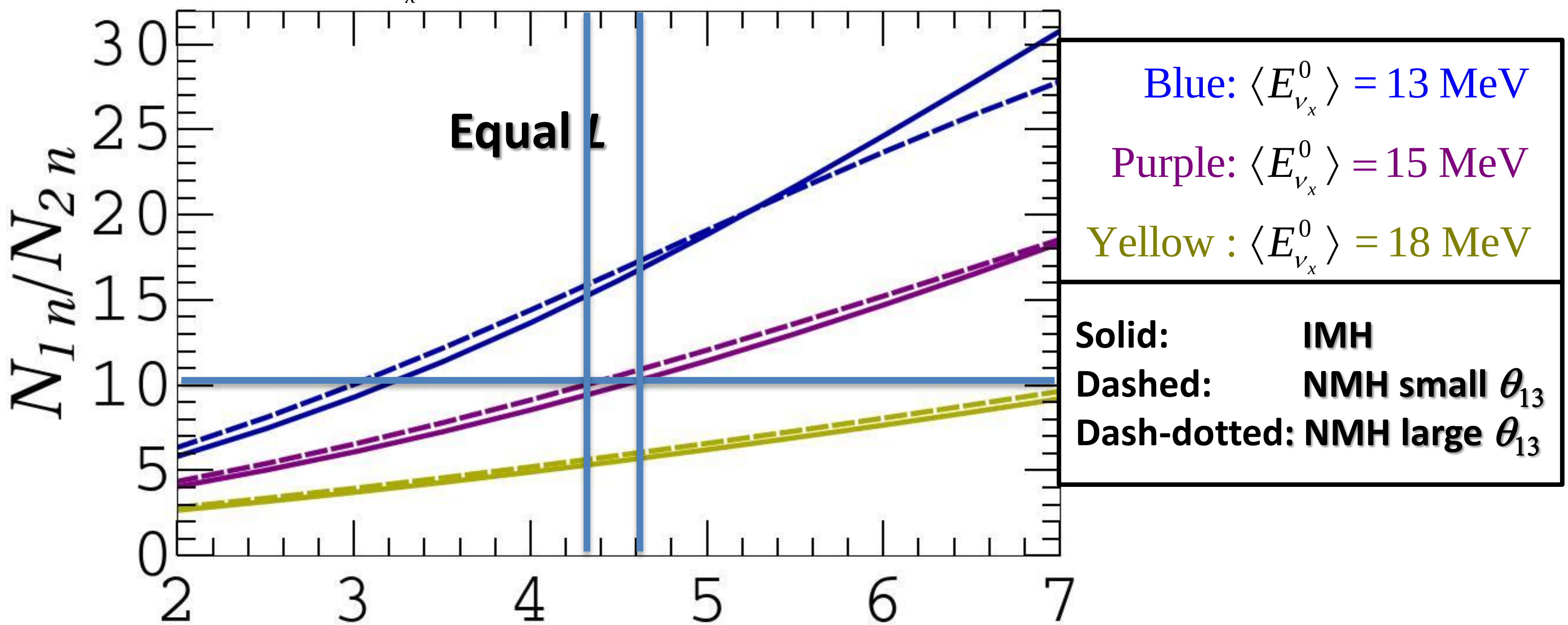
- Independent of common flux parameters

e.g. $\langle E^0_{\nu_x} \rangle \approx 15$ MeV



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4) Summary of the Results

- For $\int dt \sum_{\ell} L_{\nu_\ell} = 10^{53}$ erg

$\langle E^0_{\nu_x} \rangle$ — 13 MeV

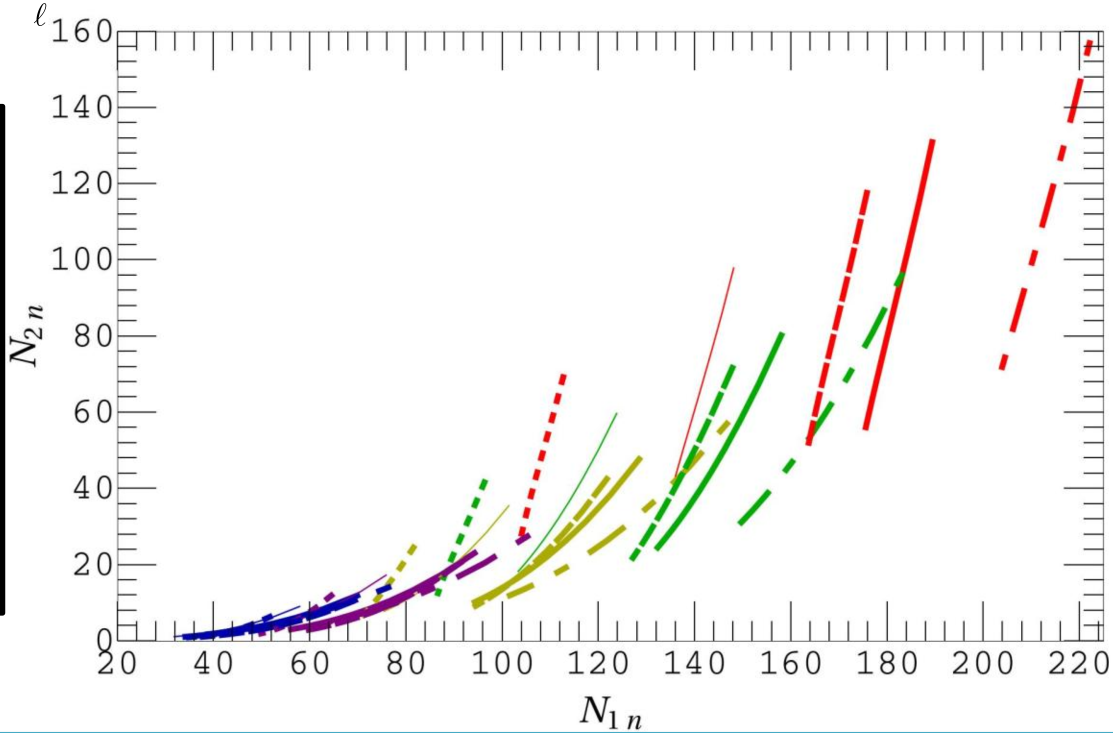
– – 15 MeV

– – 18 MeV

– · – 21 MeV

— 25 MeV

$\langle E^0_{\nu_e} \rangle = 10$ MeV



$\alpha_{\nu_x} = 2 - 7$,
less events
with larger α_x

equal L: solid lines:
- thick: IMH,
- thin: NMH small θ_{13}

$L_{\nu_x} = 2 L_{\nu_e}$:
- dotted: IMH,
- dashed: NMH large θ_{13}
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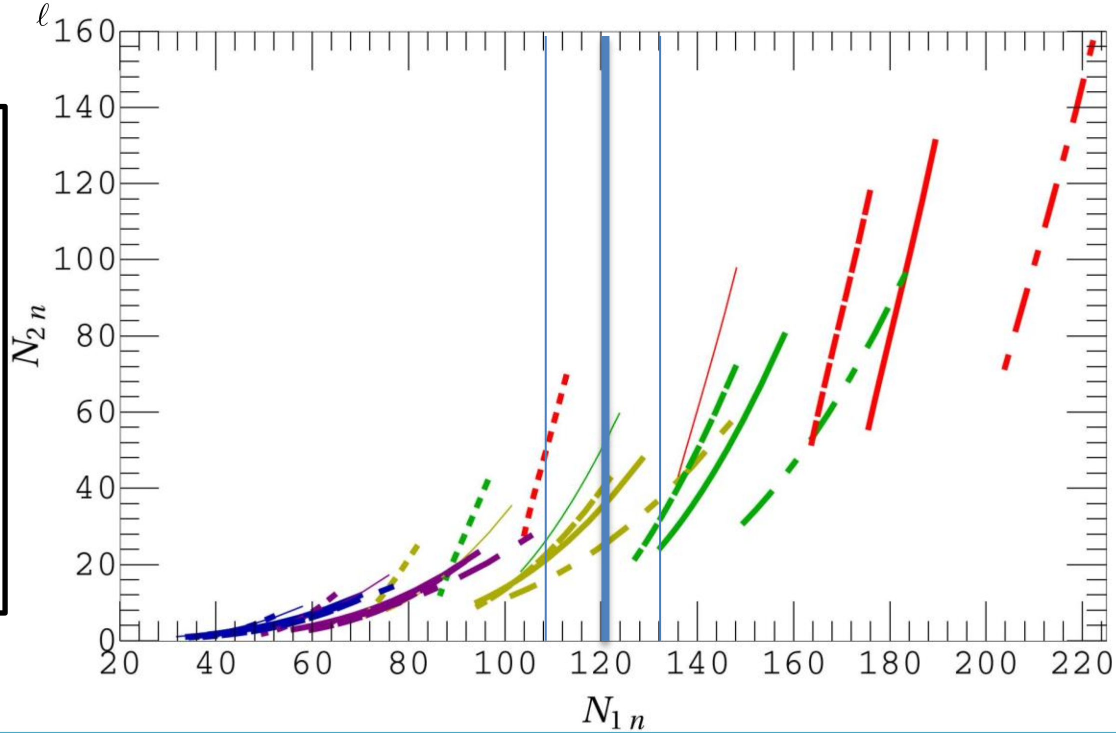

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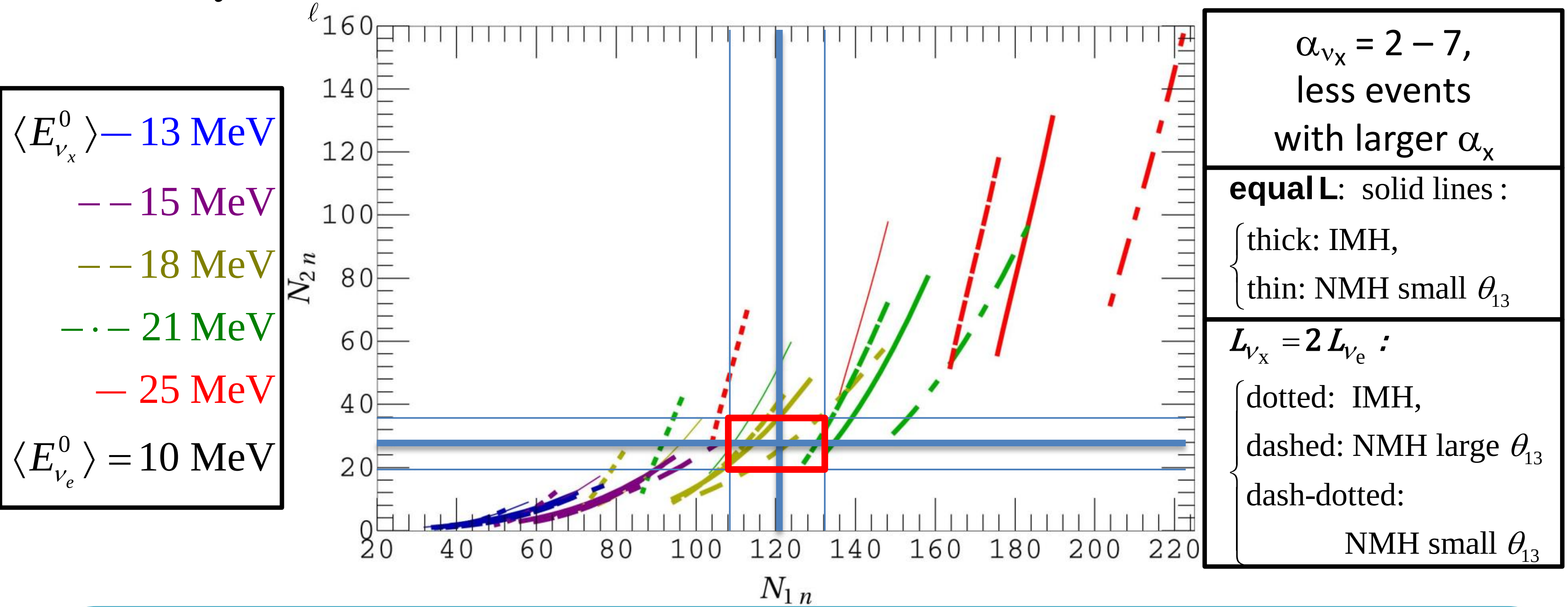

Combination of 1n- and 2n-events provides:

- Constraints on α_{ν_x} and $\langle E^0_{\nu_x} \rangle$

4) Summary of the Results

- For $\int \mathrm{d}t \sum_{\ell} L_{\nu_\ell} = 10^{53}$ erg

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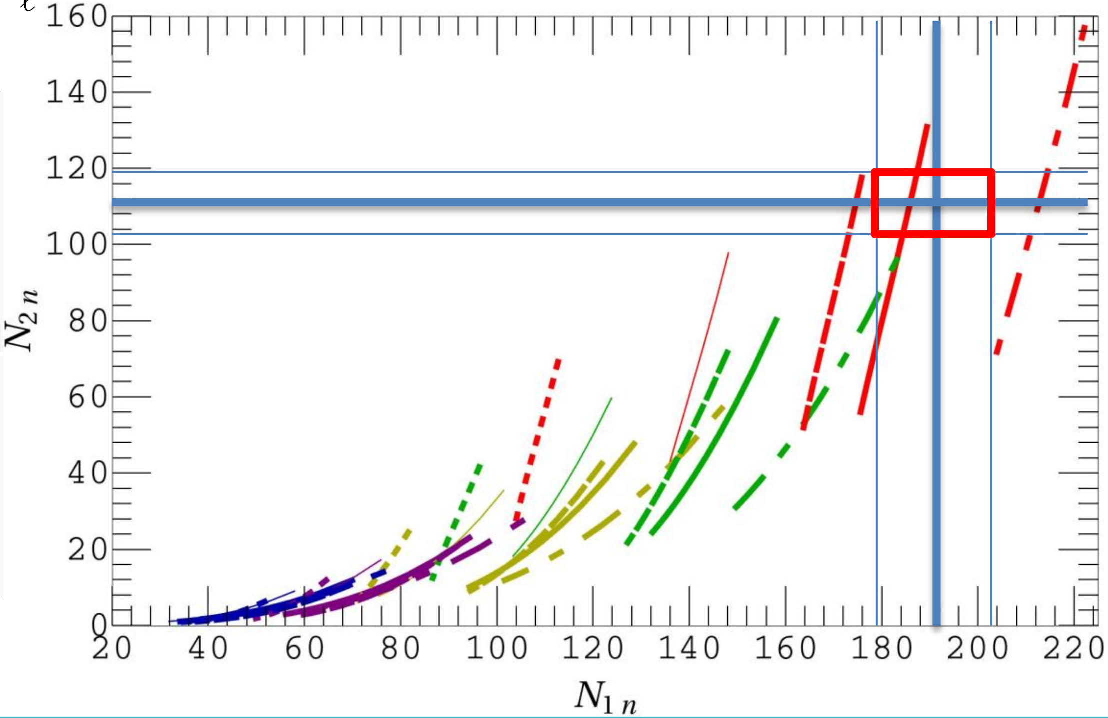
$\langle E^0_{\nu_e} \rangle = 10$ MeV



$\alpha_{\nu_x} = 2 - 7$, less events with larger α_x

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- dash-dotted: NMH small θ_{13}

Combination of 1n- and 2n-events provides:

- Constraints on α_{ν_x} and $\langle E^0_{\nu_x} \rangle$
- Possibility to indicate other unknowns depending on how much the primary neutrino fluxes differ

Conclusions

We have provided:

- ✓ Compact analytical way to calculate neutrino flavor evolution in SNe and final neutrino fluxes at Earth

We have shown that SN neutrino signal at HALO provides:

- ✓ Possibility to identify degenerate solutions of **primary non-electron-type neutrino average energy** and **pinching values**
- ✓ Better constraints and possible indication on **luminosity and mass hierarchy and** θ_{13} in conjunction with other detectors

Future prospects:

- ✓ Better understanding of $\nu\nu$ – interaction effects
- ✓ Include other possible effects (Earth matter, shock wave, turbulence)

D. Väänänen, C. Volpe, arXiv: 1105.6225

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Talk by Kneller after coffee!

D. Väänänen, C. Volpe, arXiv: 1105.6225

Conclusions

Our study emphasizes the importance of having:

- ✓ More information on the **high-energy component of the primary neutrino spectra** from SN simulations

- ✓ **Measurement** of neutrino – lead cross sections!
  - ➢ spallation sources (e.g SNS at Los Alamos, ESS at Lund) or
  - ➢ Low energy beta beams [C. Volpe, J. Phys. G 30, L1-L6 (2004)]

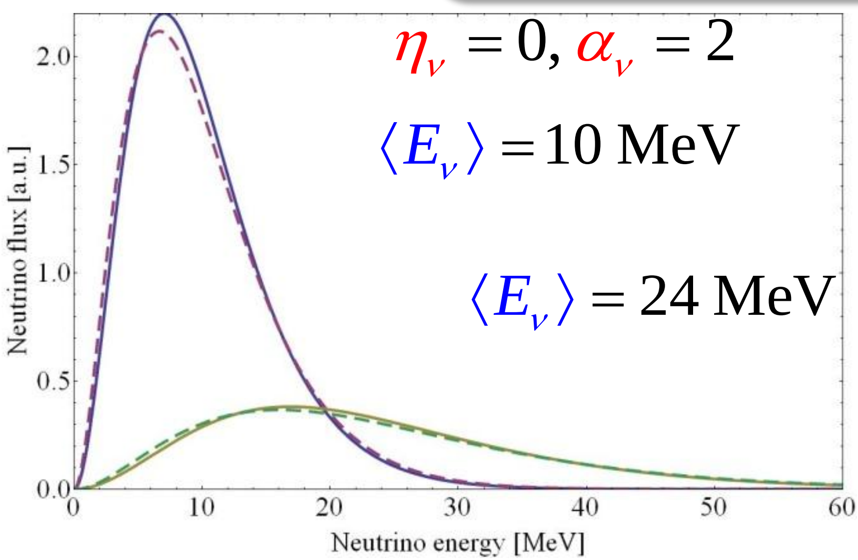
- ✓ A worldwide network of supernova neutrino detectors with **complementary detection channels** and **energy thresholds**

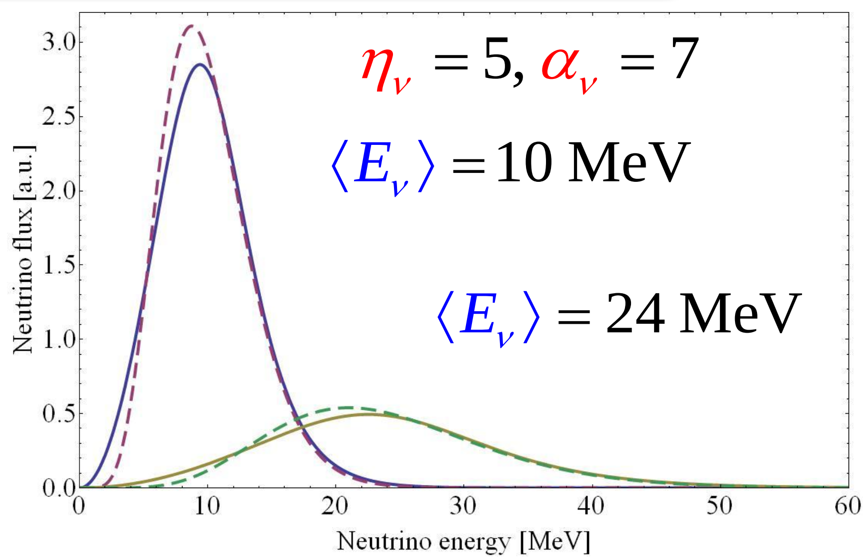
D. Väänänen, C. Volpe, arXiv: 1105.6225

Parameterization of primary ν – fluxes

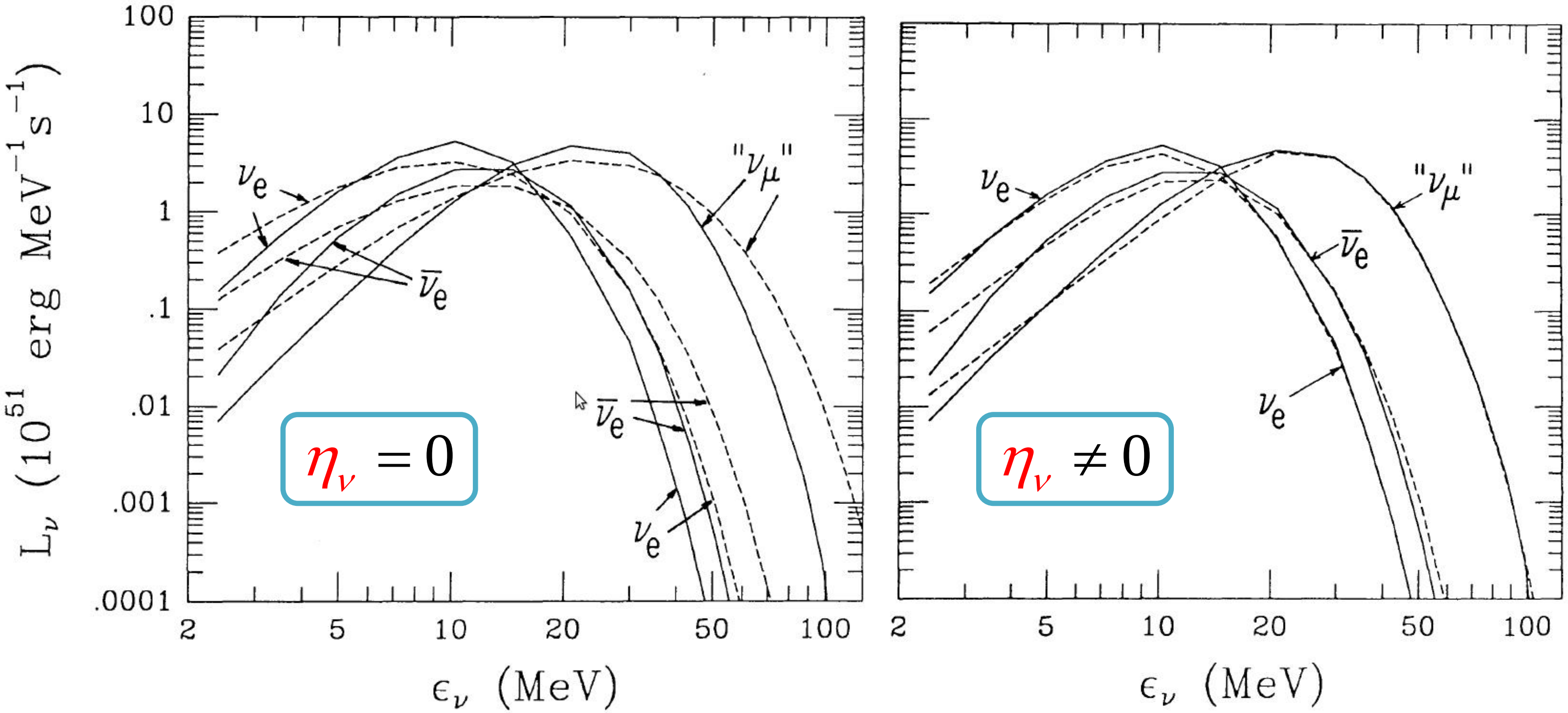
$$F_\nu^0(E_\nu) \equiv \frac{L_\nu}{\langle E_\nu \rangle}\phi(E_\nu,\ldots)$$

- Pinched Fermi-Dirac: $\phi(E_\nu,T_\nu,\eta_\nu) \sim \dfrac{E_\nu^2}{\exp\left(E_\nu/T_\nu-\eta_\nu\right)+1}, \quad \langle E_\nu \rangle = T_\nu \dfrac{F_3(\eta_\nu)}{F_2(\eta_\nu)}$
- Modified Power Law: $\phi(E_\nu,\langle E_\nu\rangle,\alpha_\nu) \sim E_\nu^{\alpha_\nu}\exp\left[-\left(\alpha_\nu+1\right)\dfrac{E_\nu}{\langle E_\nu\rangle}\right]$





Why pinched primary neutrino fluxes?

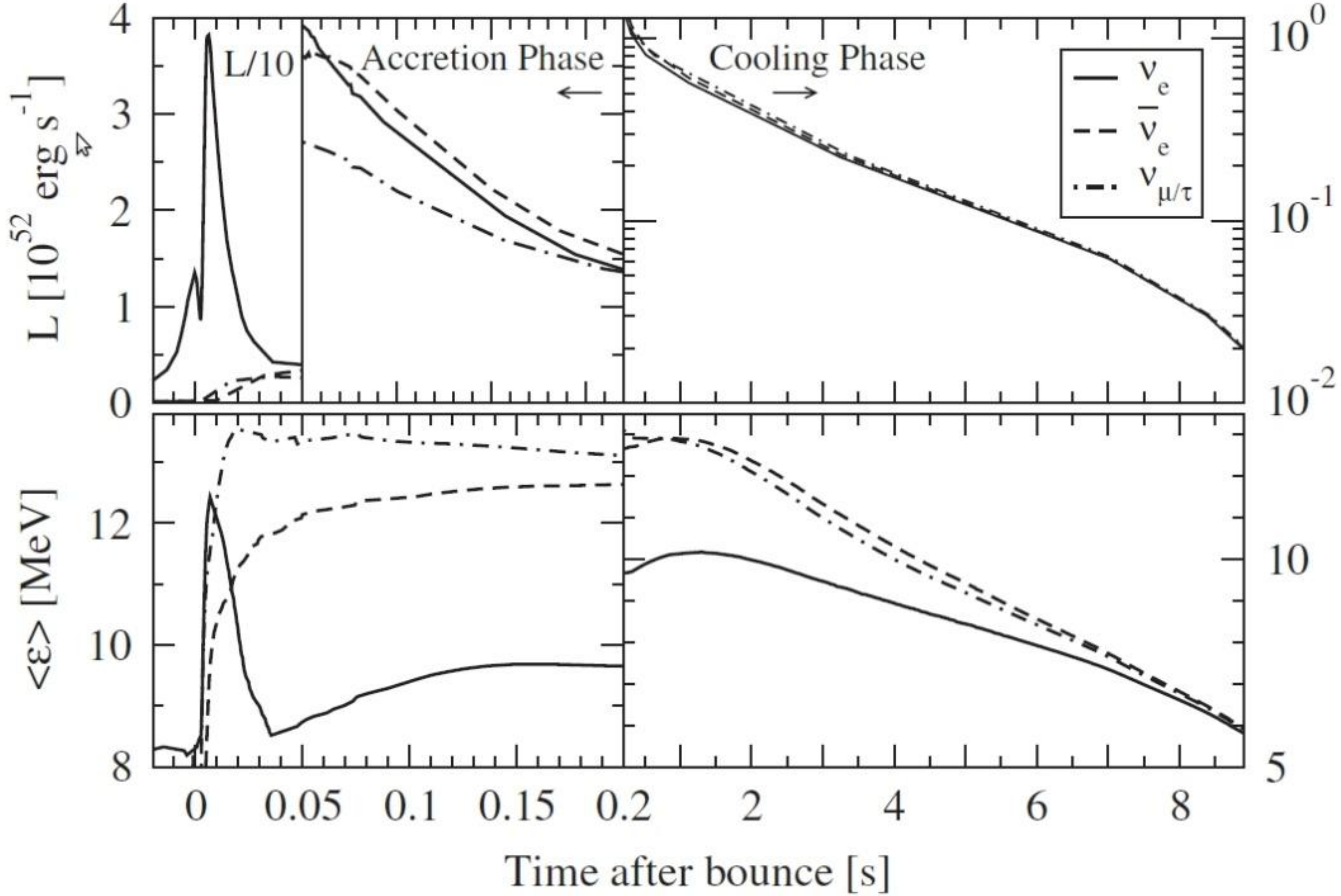


Burrows et al. ASTROPHYS. J., 364, 222 (1990)

- Solid: simulation, Dashed: FD fit

$$(\text{N.B.} \quad F^0_{\nu_\mu} = F^0_{\nu_\tau} = F^0_{\bar{\nu}_\mu} = F^0_{\bar{\nu}_\tau} \equiv F^0_x)$$

Luminosities and average energies



Hüdepohl *et al.*
PRL 104, 251101 (2010)

Luminosities and average energies

[Keil, Raffelt, Janka, Astrophys. J. 590, 971 (2003)]

-> aveE_e = 9.4 MeV,

aveE_ae = 13 MeV

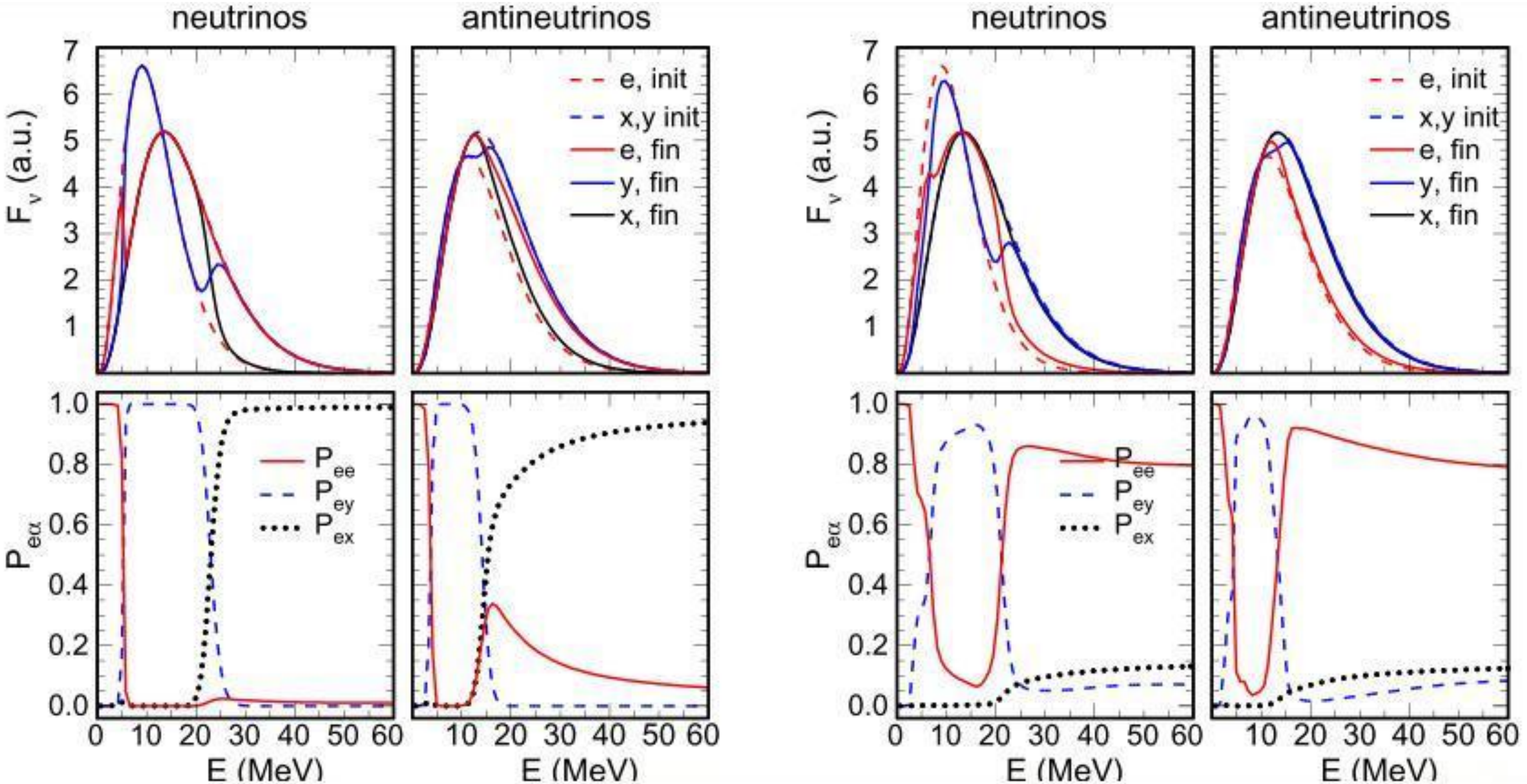
aveE_x = 15.8 MeV,

Le = Lae = 4.1x10^51 erg s^-1,

Lx = 7.9x10^51 erg s^-1

Single-angle vs. multi-angle

Phi_e : Phi_ae : Phi_x = 0.85 : 0.75 : 1.00 (Phi = L/<E>)



Single-angle

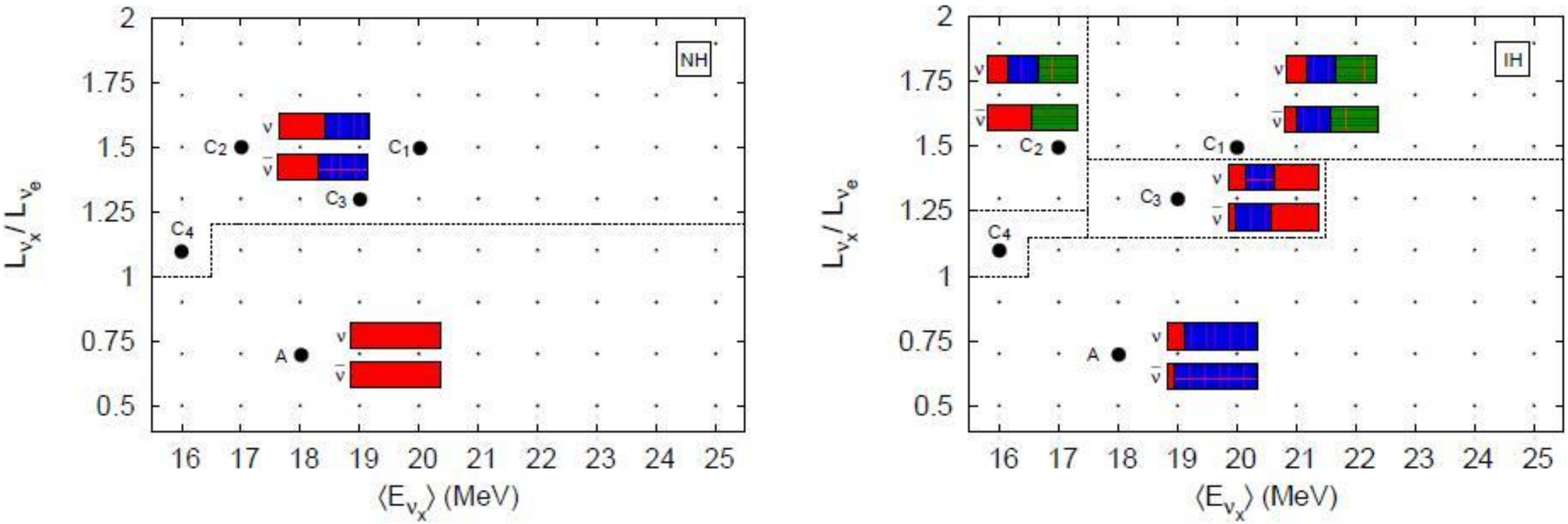
Multi-angle

Number fluxes

Phi = L/<E>,
<E_e> = 10 MeV, <E_ae> = 13 MeV

Phi_e : Phi_ae : Phi_x		
< E^0_x >	Equal L	Lx = 2 Le (Lae = Le)
13	1.30 : 1.00 : 1.00	0.65 : 0.50 : 1.00
15	1.50 : 1.15 : 1.00	0.75 : 0.58 : 1.00
18	1.80 : 1.38 : 1.00	0.90 : 0.69 : 1.00
21	2.10 : 1.62 : 1.00	1.05 : 0.81 : 1.00
25	2.50 : 1.92 : 1.00	1.25 : 0.96 : 1.00

Split dependence on luminosity and mass hierarchy



Phi = L/<E>,

<E_e> = 12 MeV, <E_ae> = 13 MeV, <E_x> = 18 MeV

Phi_e : Phi_ae : Phi_x
2.40 : 1.60 : 1.00
0.85 : 0.75 : 1.00
0.81 :0.79 : 1.00

ν_e signal at a detector

$$N_{CC} = \int dE F_{\nu_e}(E) \sigma_\nu^{CC}(E)$$

$$F_{\nu_e} = |U_{e1}|^2 F_1 + |U_{e2}|^2 F_2 + |U_{e3}|^2 F_3$$

- In our example (for neutrinos in IMH with $L_{\nu_x} = 2\, L_{\nu_e}$):

E range	(F_1, F_2, F_3)
$E < E_L$	$(F^0(\nu_x), F^0(\nu_e), F^0(\nu_y))$
$E_L < E < E_H$	$(F^0(\nu_x), F^0(\nu_y), F^0(\nu_e))$
$E > E_H$	$(F^0(\nu_e), F^0(\nu_x), F^0(\nu_y))$

High energy split visible due to low MSW resonance!

C. Massive neutrino fluxes which exit the star

- Equal luminosities:

Energy ranges	$F = (F_1, F_2, F_3)$		
	IMH	NMH	
		Small θ_{13}	Large θ_{13}
$0 - E_L$	$(F^0(\nu_x), F^0(\nu_e), F^0(\nu_y))$	$(F^0(\nu_x), F^0(\nu_y), F^0(\nu_e))$	$(F^0(\nu_x), F^0(\nu_e), F^0(\nu_y))$
E_L - E_H	$(F^0(\nu_x), F^0(\nu_y), F^0(\nu_e))$	-	-
E_H – infty	-	-	-
Split E values	$E_L = 8$ MeV, $E_H \mapsto$ infty	E_L, $E_H \mapsto$ infinity	

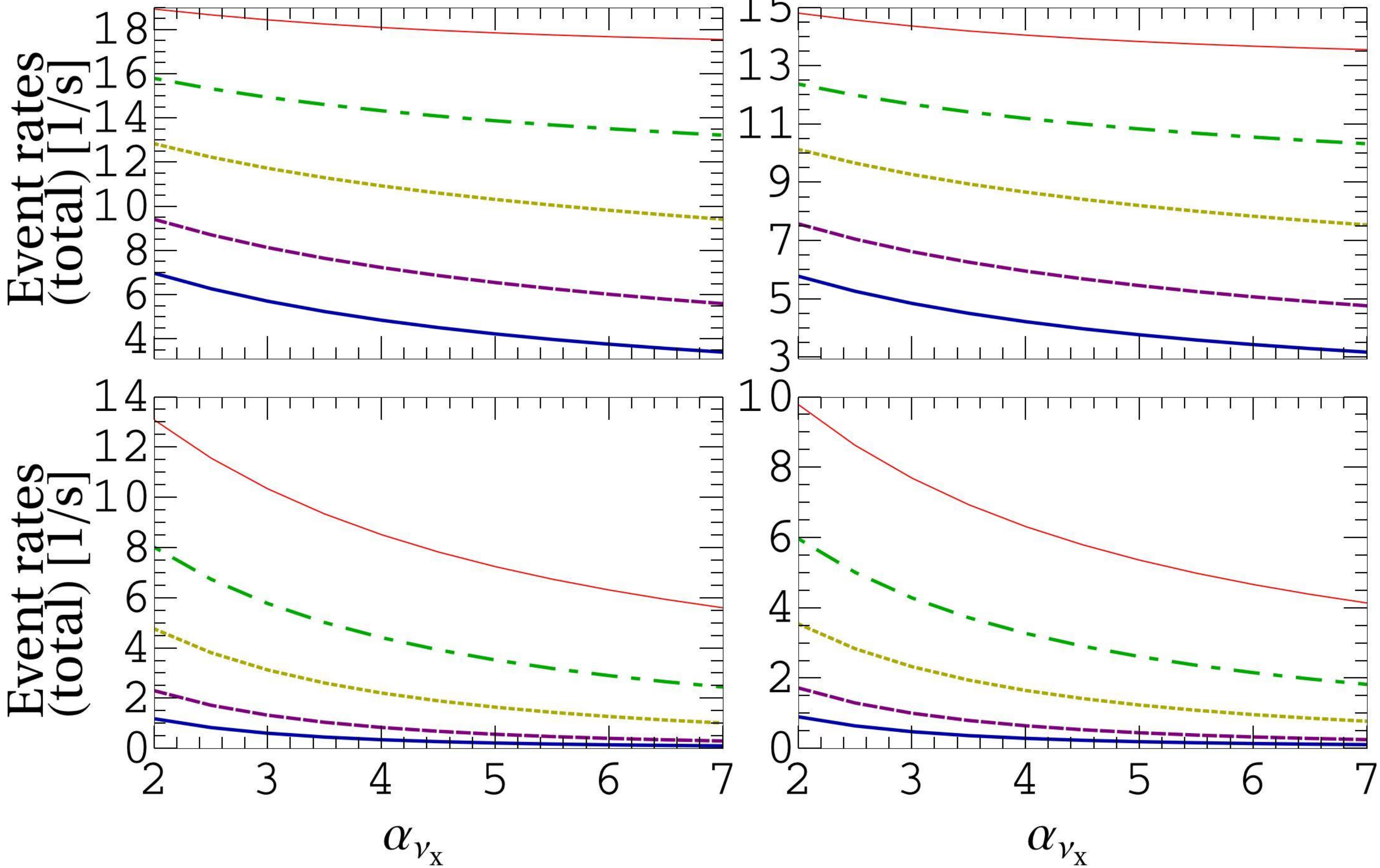
C. Massive neutrino fluxes which exit the star

- $L_{\nu_x} = 2\ L_{\nu_e}$:

Energy ranges	$F = (F_1,\ F_2,\ F_3)$		
	IMH	NMH	
		Small θ_{13}	Large θ_{13}
$0 - E_L$	$(F^0(\nu_x), F^0(\nu_e), F^0(\nu_y))$	$(F^0(\nu_x), F^0(\nu_e), F^0(\nu_y))$	$(F^0(\nu_x), F^0(\nu_y), F^0(\nu_e))$
E_L - E_H	$(F^0(\nu_x), F^0(\nu_y), F^0(\nu_e))$	$(F^0(\nu_x), F^0(\nu_y), F^0(\nu_e))$	$(F^0(\nu_x), F^0(\nu_e), F^0(\nu_y))$
E_H – infty	$(F^0(\nu_e), F^0(\nu_x), F^0(\nu_y))$	-	-
Split E values	$E_L = 8$ MeV, $E_H = 23$ MeV	E_L= 23 MeV, $E_H \longmapsto$ infinity	

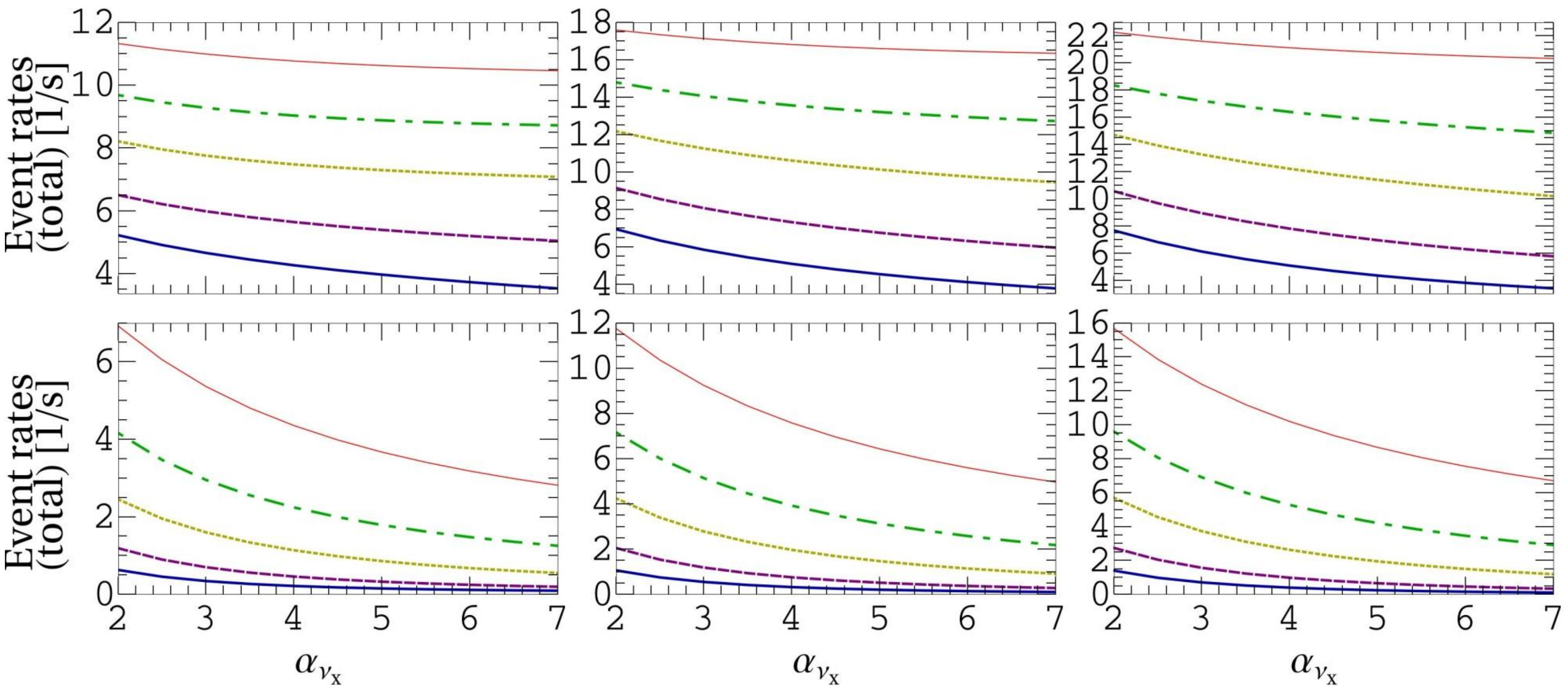
Neutron emission event rates

- Equal L = 1.67x10^51 erg s^(-1)



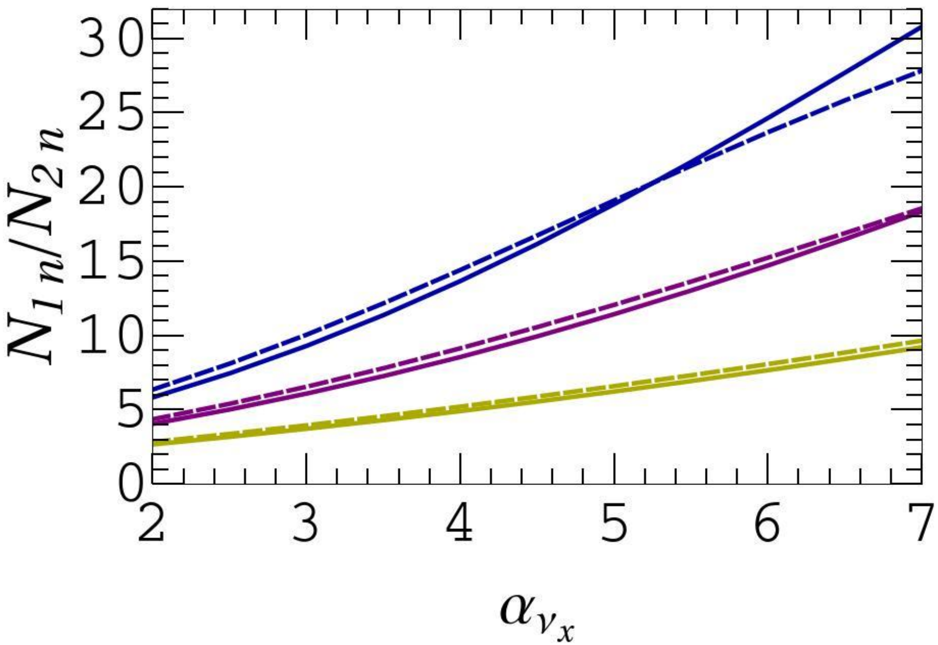
Neutron emission event rates

- Lx = 2 Le, Le = 10^51 erg s^(-1)

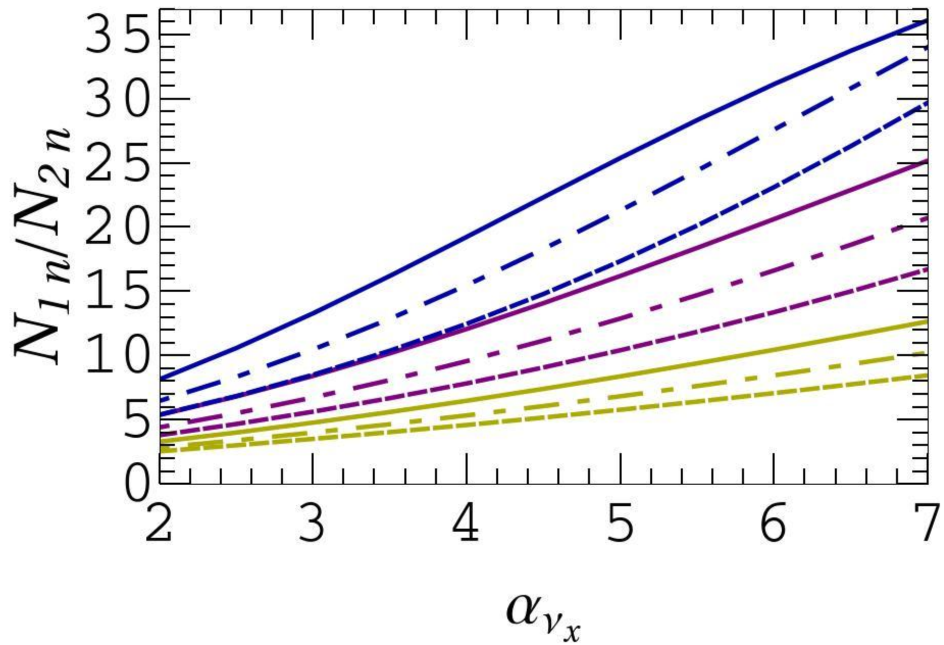


Ratios:
Dependence on luminosity hierarchy

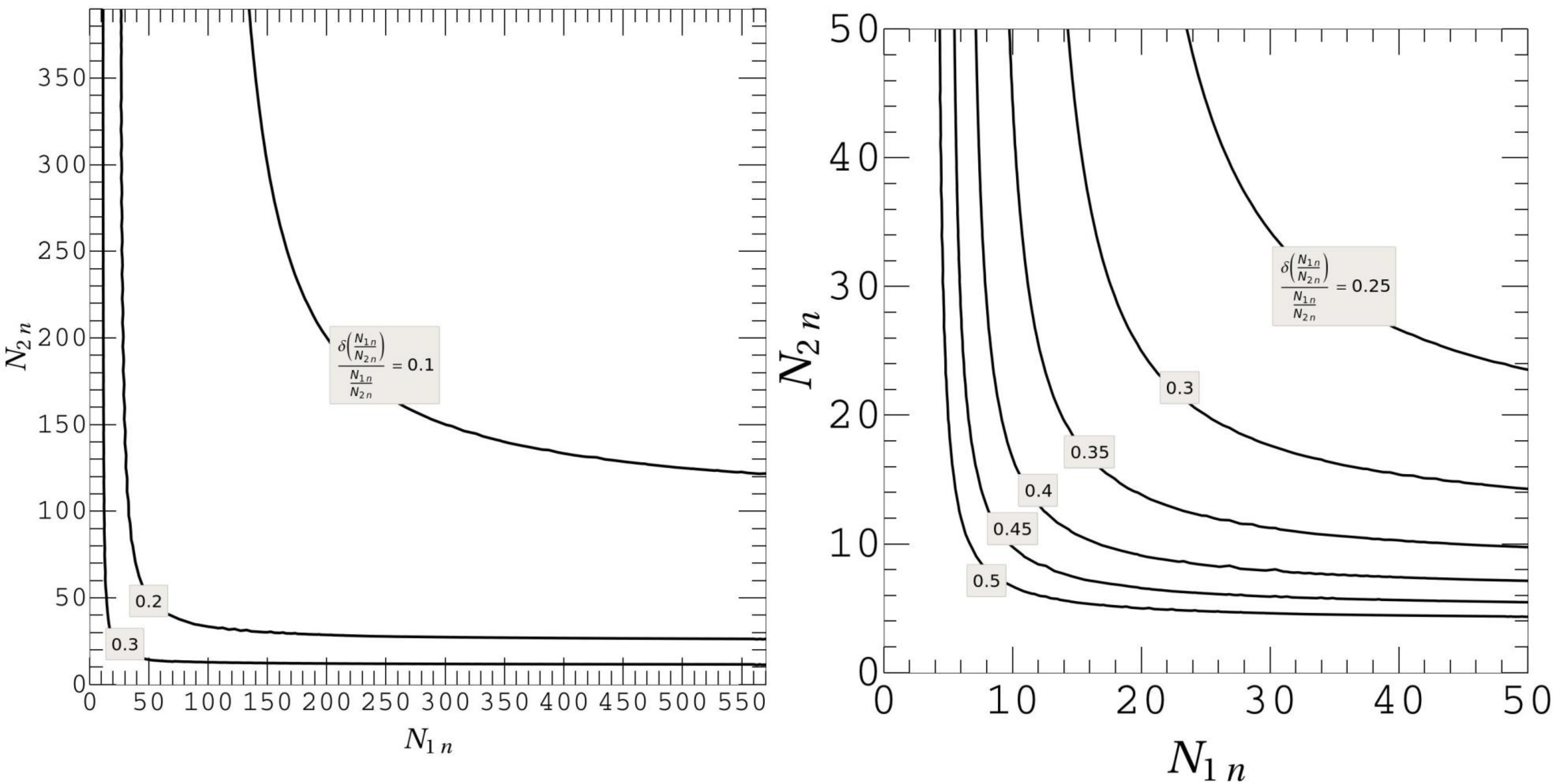
Equal luminosities



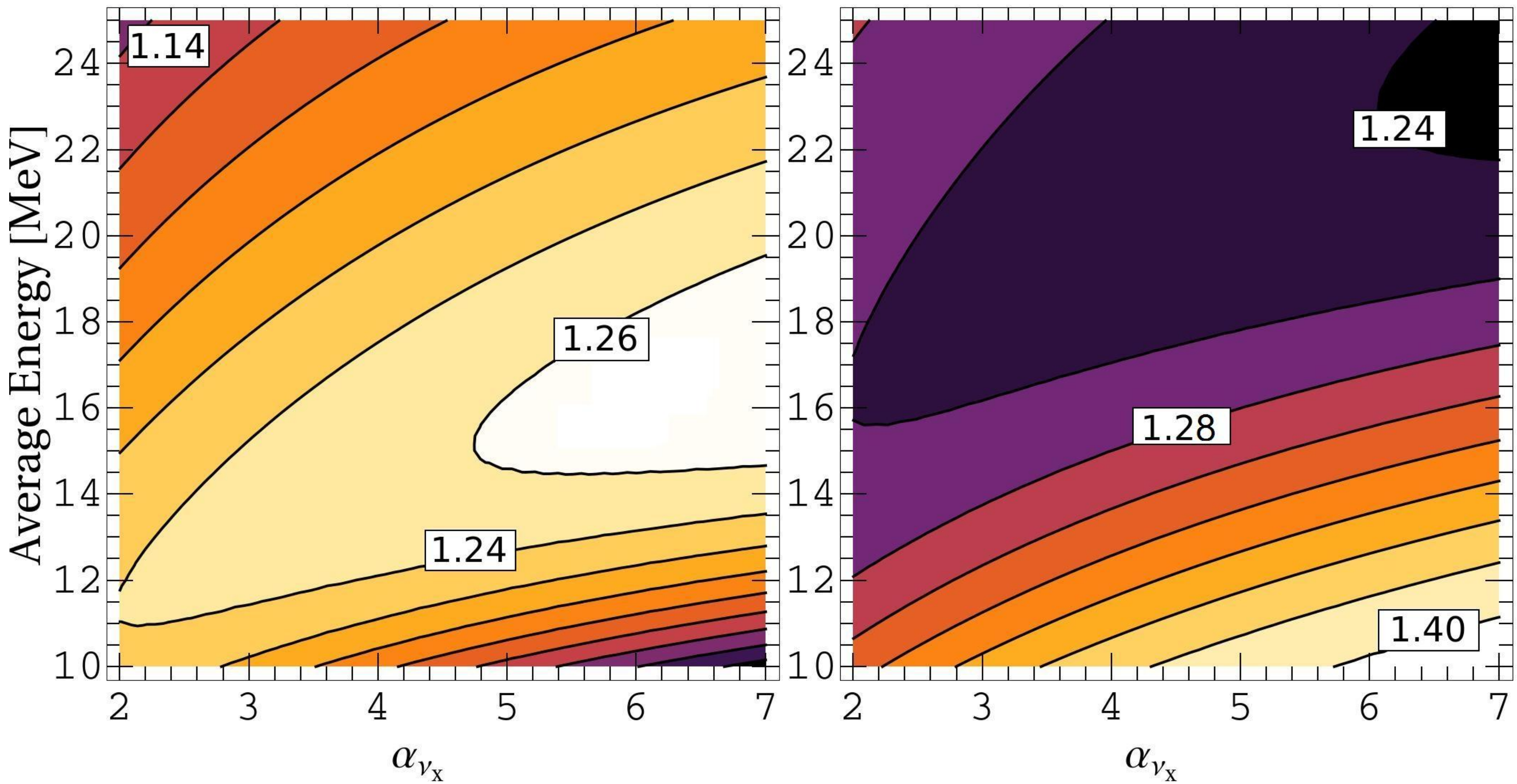
$L_x = 2\ L_e$



errors on ratio



Flux averaged cross sections

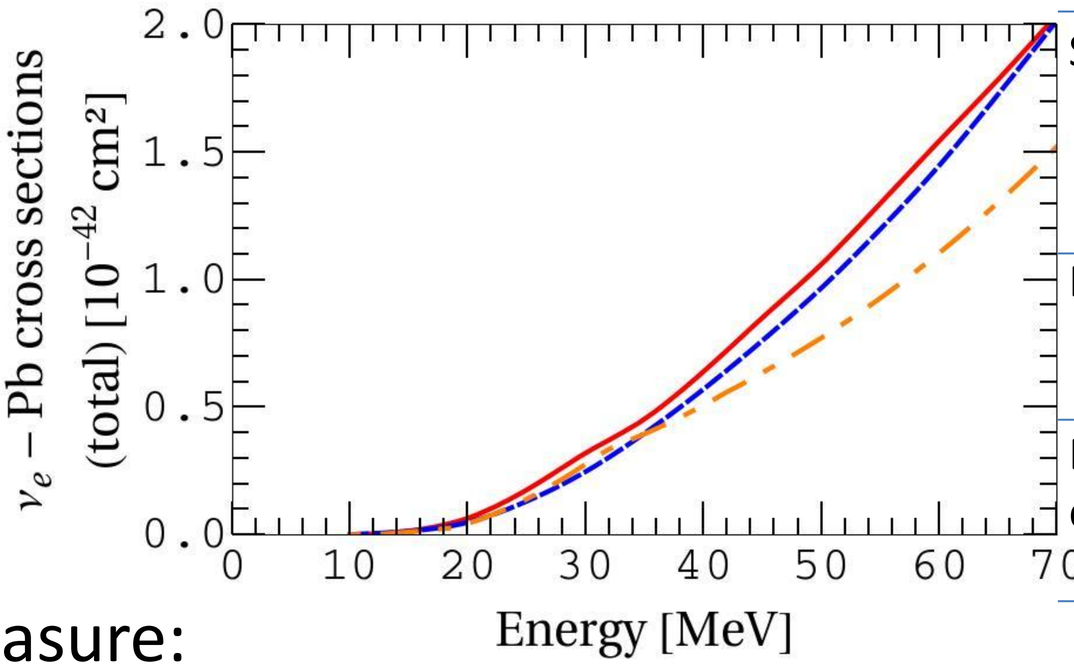


RPA/QRPA

RPA/RRPA

Remark: uncertainties on cross sections

- Cross sections rely on theoretical predictions:



Solid:	**J. Engel, G. McLaughlin, C. Volpe, PRD 67, 013005 (2003)**
Dashed:	**E. Kolbe *et al.*, PRC 63, 025802 (2001)**
Dashed-dotted:	**N. Paar** (private communication)

- To measure:
  – spallation sources (e.g SNS at Los Alamos, ESS at Lund) or
  – Low energy beta-beams **C. Volpe, J. Phys. G 30, L1-L6 (2004)**

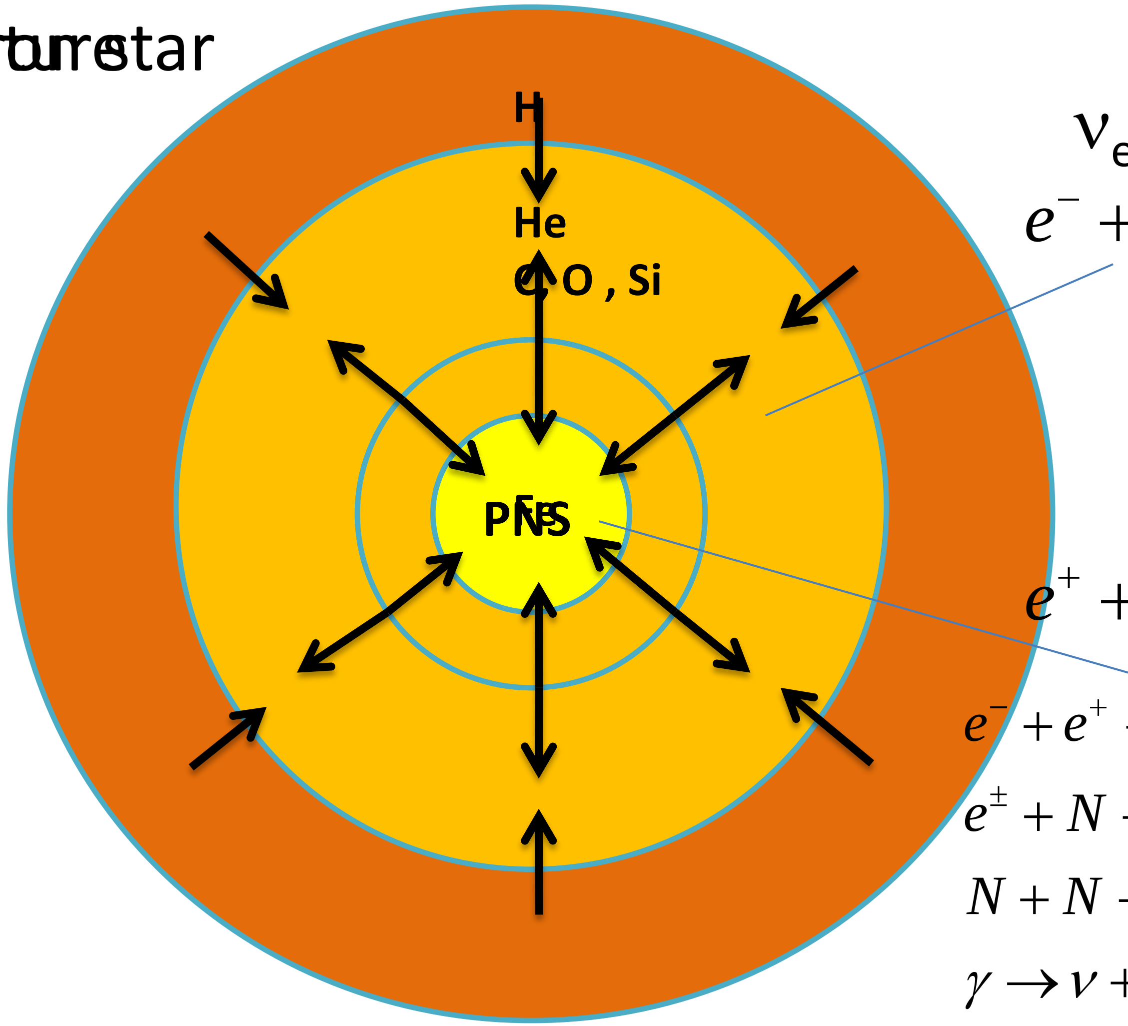
In order to extract as much information as possible from SN ν fluxes, the ν – Pb cross sections should be measured!

Iron core-collapse supernovae

Massive stars, $M > 8 M_{sol}$

Onion structure

Proto-neutron star formation



ν_e burst

$$e^- + p \rightarrow n + \nu_e$$

$$e^+ + n \rightarrow p + \bar{\nu}_e$$

$$e^- + e^+ \rightarrow \nu + \bar{\nu}$$

$$e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu}$$

$$N + N \rightarrow N + N + \nu + \bar{\nu}$$

$$\gamma \rightarrow \nu + \bar{\nu}$$

$$\gamma + e^\pm \rightarrow e^\pm + \nu + \bar{\nu}$$

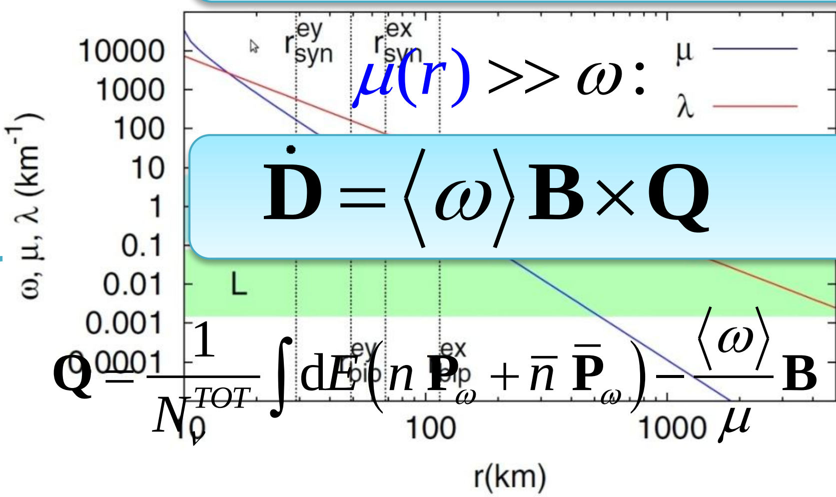
Flavor evolution

- Polarization vector formalism (2f):

$$\rho = \begin{pmatrix} |a_{\upsilon_e}|^2 & a_{\upsilon_e} a^*_{\upsilon_{x,y}} \\ a^*_{\upsilon_e} a_{\upsilon_{x,y}} & |a_{\upsilon_{x,y}}|^2 \end{pmatrix} = \frac{1}{2}\left(1 + \vec{\mathrm{P}} \cdot \vec{\sigma}\right)$$

$$\vec{\mathrm{P}} = \begin{pmatrix} 2\Re\mathrm{e}\left(a^*_{\upsilon_e} a_{\upsilon_{x,y}}\right) \\ 2\Im\mathrm{m}\left(a^*_{\upsilon_e} a_{\upsilon_{x,y}}\right) \\ |a_{\upsilon_e}|^2 - |a_{\upsilon_{x,y}}|^2 \end{pmatrix}$$

- EOM: $\dot{\mathbf{P}}_\omega = \left(\pm\omega\mathbf{B} + \lambda(r)\mathbf{z} + \mu(r)\mathbf{D}\right) \times \mathbf{P}_\omega$



$\mu(r) >> \omega$:

$$\dot{\mathbf{D}} = \langle\omega\rangle \mathbf{B} \times \mathbf{Q}$$

$$\mathbf{Q} = \frac{1}{N_\nu^{TOT}} \int \mathrm{d}E \left(n\,\mathbf{P}_\omega + \bar{n}\,\bar{\mathbf{P}}_\omega\right) - \frac{\langle\omega\rangle}{\mu}\mathbf{B}$$

$$\mathbf{B} = \sin(2\theta_{13})\mathbf{x} \mp \cos(2\theta_{13})\mathbf{z}$$

$$\mathbf{D} = \frac{1}{N_\nu^{TOT}} \int \mathrm{d}E \left(n\,\mathbf{P}_\omega - \bar{n}\,\bar{\mathbf{P}}_\omega\right)$$

$$\omega = \frac{\Delta m^2}{2E}, \quad \lambda(r) = \sqrt{2} G_F N_e(r),$$

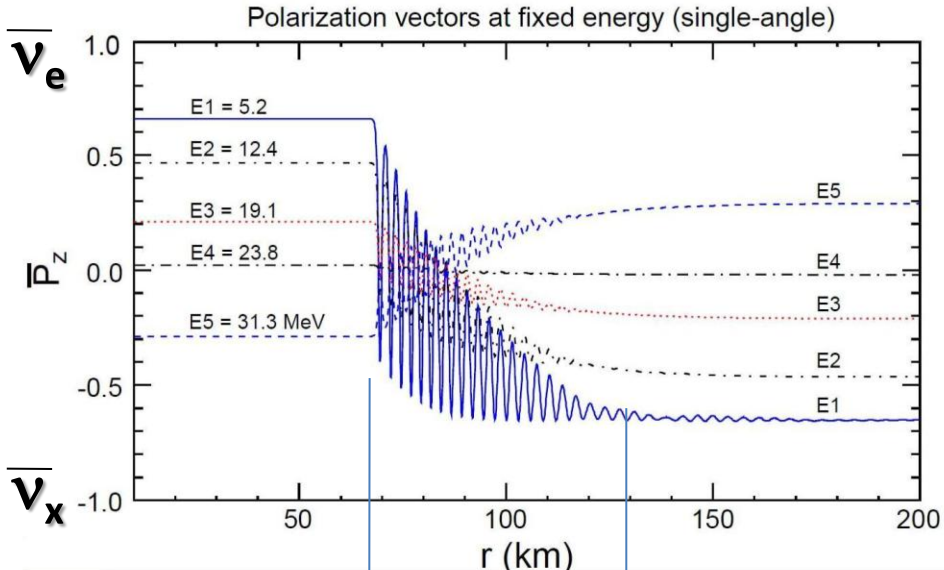
$$\mu(r) = \sqrt{2} G_F N_\nu^{TOT}(r), \quad N_\alpha = \int \mathrm{d}E\, n_\alpha$$

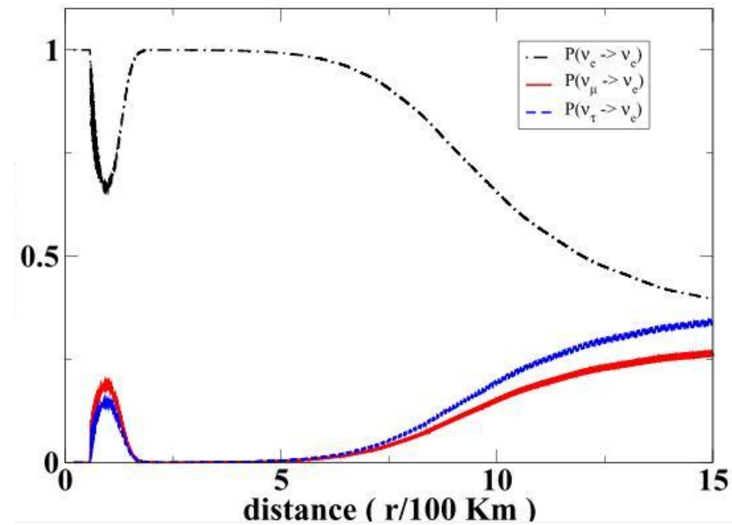
Dasgupta *et al.*, PRD 77, 113002(2008)

Collective effects!

Collective flavor conversion effects

G. Fogli *et al* JCAP 12:010 (2007)





Gava *et al.*, PRD 78, 083007 (2008)

Synchronized oscillations | Bipolar oscillations | Spectral split

- “gyroscopic flavor pendulum”:

$$\mathbf{L} = m\,\mathbf{r}\times\dot{\mathbf{r}} + \sigma\mathbf{r}$$
$$\dot{\mathbf{L}} = m\,\mathbf{r}\times\mathbf{g}$$

$$\mathbf{L} = \mathbf{D},$$
$$m = \mu^{-1}, \quad \mathbf{r} = \mathbf{Q}/|\mathbf{Q}|,$$
$$\sigma = \mathbf{D}\cdot\mathbf{r}, \quad \mathbf{g} = \langle\omega\rangle\,\mu\,|\mathbf{Q}|\,\mathbf{B}$$

$$\mathbf{Q} = \frac{1}{N_\nu^{TOT}}\int \mathrm{d}E\left(n\,\mathbf{P}_\omega + \bar{n}\,\bar{\mathbf{P}}_\omega\right) - \frac{\langle\omega\rangle}{\mu}\mathbf{B}$$