Supernova Shock Waves and Sterile Neutrinos

Sandhya Choubey

Harish-Chandra Research Institute, Allahabad, India

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S.C., Nicholas Harries and Graham Ross

Phys. Rev. **D74**, *053010 (2006) and hep-ph/0702xxx*

Flavor Oscillations of Supernova Neutrinos

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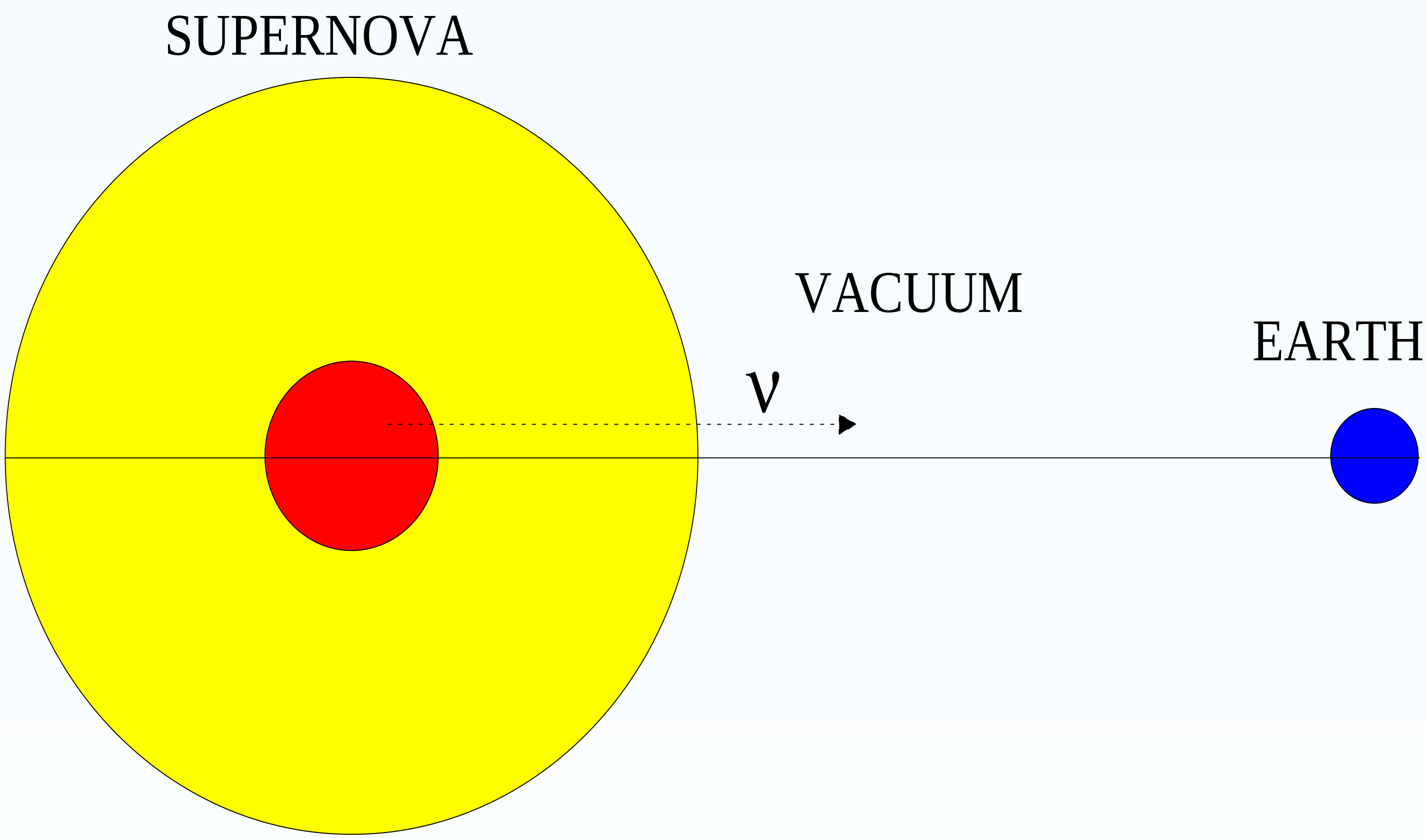

√Neutrino cross the mantle and envelope of the SN
√Neutrino might cross the earth
√Matter effects are crucial
√In this talk we will assume that they do not cross the earth

Neutrino Flavor Oscillations in Matter

√Evolution equation of neutrinos in matter is given by:

$$i\frac{d}{dt}\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix} = \frac{1}{4E}\mathcal{M}_F^m\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix}$$

√For oscillations between active neutrinos:

$$\mathcal{M}_F^m = \begin{pmatrix}-\Delta m^2\cos 2\theta + 2\sqrt{2}G_F N_e E & \Delta m^2 \sin 2\theta\\ \Delta m^2 \sin 2\theta & \Delta m^2\cos 2\theta - 2\sqrt{2}G_F N_e E\end{pmatrix}$$

√Mixing angle in matter changes to:

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2\cos 2\theta - 2\sqrt{2}G_F N_e E}$$

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$\longrightarrow$ MSW Matter Enhanced Resonance

L. Wolfenstein, Phys. Rev. D **17**, 1978

S.P.Mikhyev, A.Yu.Smirnov, SJNP **42** 1985

√Resonance condition possible *only* for $\boxed{\Delta m^2 > 0}$

Neutrino Flavor Oscillations in Matter

$\surd$For oscillations between active anti-neutrinos:

$$\mathcal{M}_F^m = \begin{pmatrix} -\Delta m^2 \cos 2\theta - 2\sqrt{2}G_F N_e E & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta + 2\sqrt{2}G_F N_e E \end{pmatrix}$$

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Neutrino Flavor Oscillations in Matter

$\surd$For oscillations between ν_μ and $\nu_{sterile}$:

$$\mathcal{M}_F^m = \begin{pmatrix} -\Delta m^2 \cos 2\theta - \sqrt{2} G_F N_n E & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta + \sqrt{2} G_F N_n E \end{pmatrix}$$

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√Resonance condition possible *only* for $\boxed{\Delta m^2 > 0}$

Neutrino Flavor Oscillations in Matter

√For oscillations between $\bar{\nu}_e$ and $\bar{\nu}_{sterile}$

$$\mathcal{M}_F^m = \begin{pmatrix} -\Delta m^2 \cos 2\theta - 2\sqrt{2} G_F N_e E + \sqrt{2} G_F N_n E & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta + 2\sqrt{2} G_F N_e E - \sqrt{2} G_F N_n E \end{pmatrix}$$

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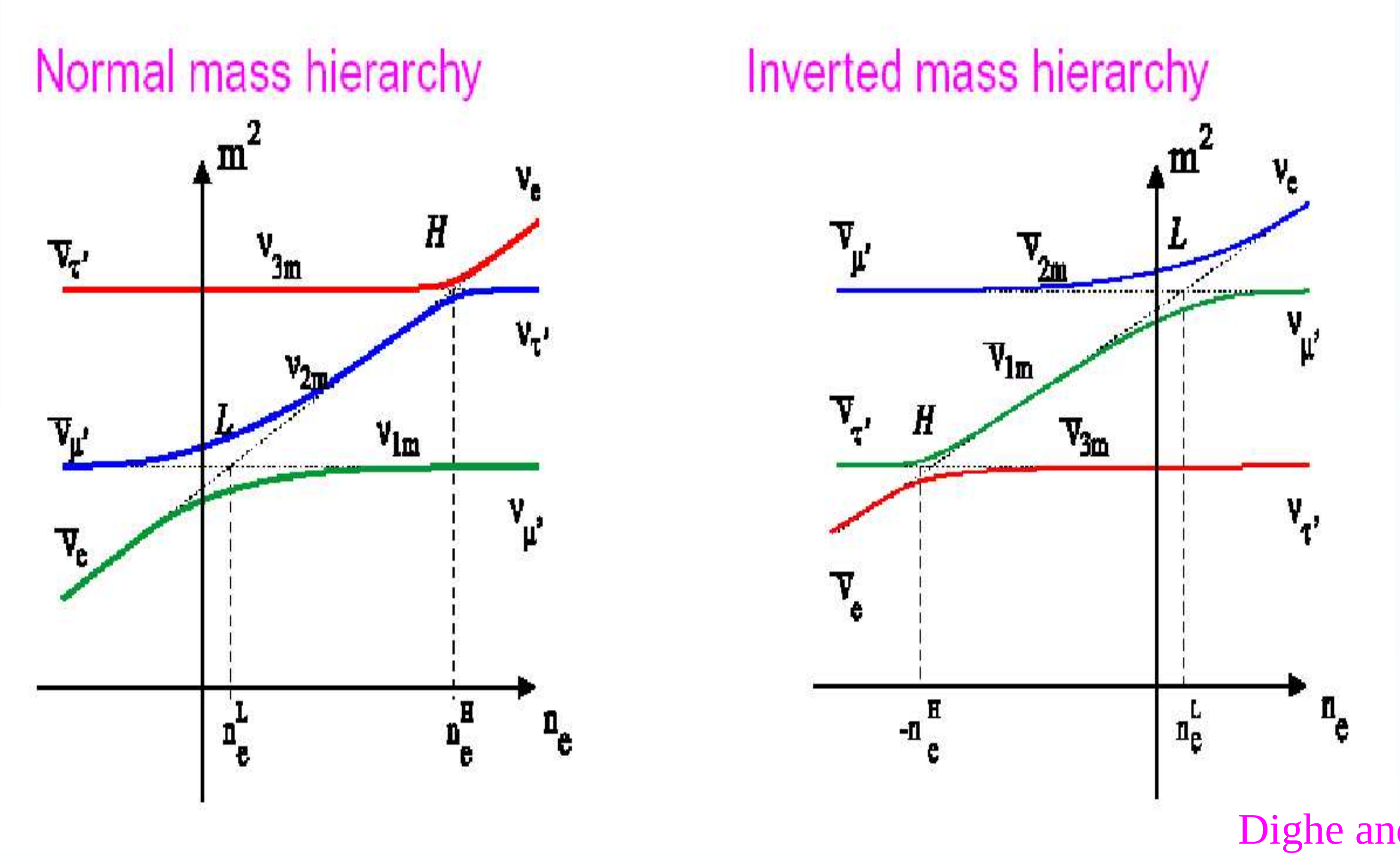
Flavor Oscillations of Supernova Neutrinos

$\surd$Three flavor scenario



Dighe and Smirnov (2000)

$\surd$ L always lies in the neutrino channel

$\surd$ H will be in the (anti)neutrino channel for $\Delta m^2_{31}(<)>0$

$\surd$Net flavor conversion depends on the "jump probability" P_J

Flavor Oscillations of Supernova Neutrinos

$$P_J \approx \exp(-\gamma\ \sin^2\theta); \quad \gamma = \pi \frac{\Delta m^2}{E} \left| \frac{dln\ N_e}{dx} \right|^{-1}_{x=x_{\rm res}}$$

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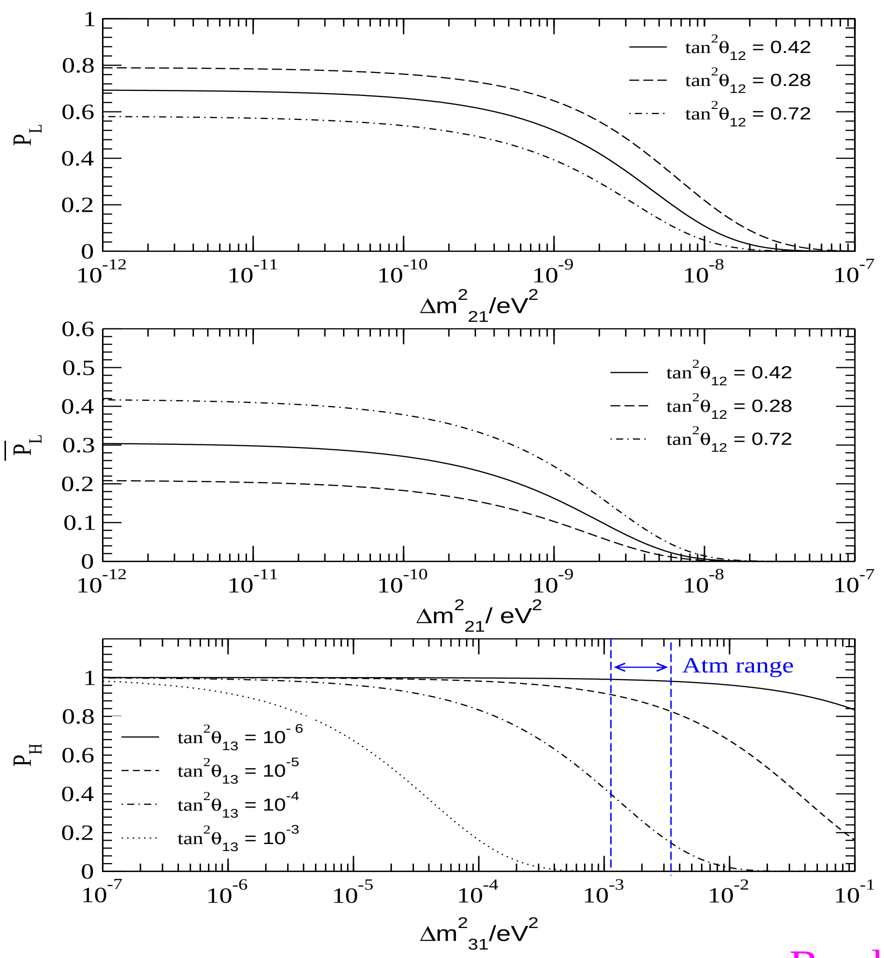

Bandyopadhyay,S.C.,Goswami,Kar,hep-ph/0312315

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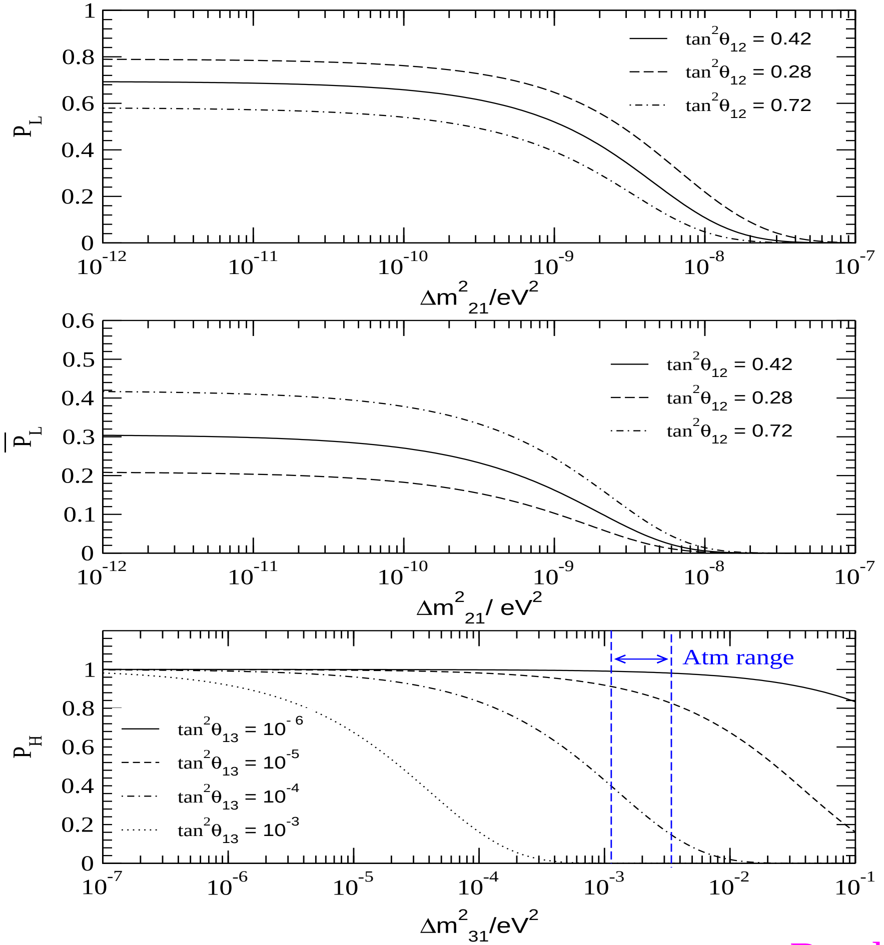

$\surd P_L = 0$ and $\bar{P}_L = 0$ always

$\surd P_H$ depends on $\sin^2\theta_{13}$

Bandyopadhyay,S.C.,Goswami,Kar,hep-ph/0312315

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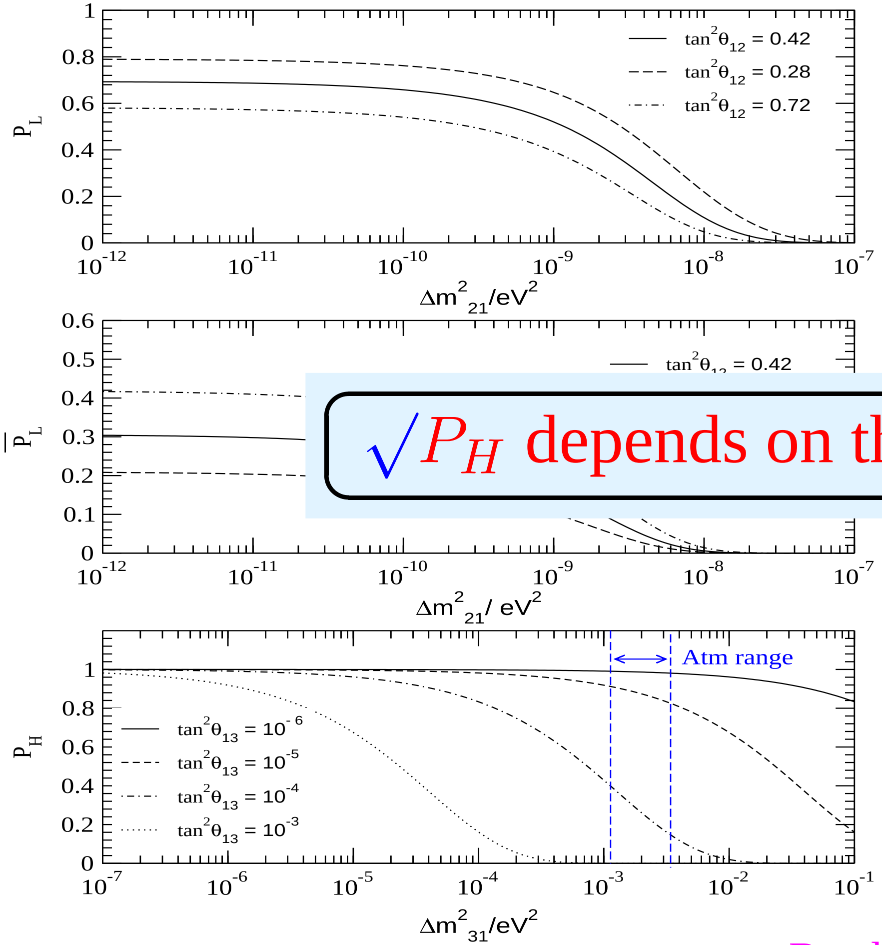

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$\surd P_H$ depends on the SN density profile

Bandyopadhyay,S.C.,Goswami,Kar,hep-ph/0312315

Explaining LSND

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$\surd$Is there an evidence for oscillations on very short length scales? $\Rightarrow \Delta m^2 \sim \mathrm{eV}^2$

$\surd$Can it be accommodated with the solar and atm data?

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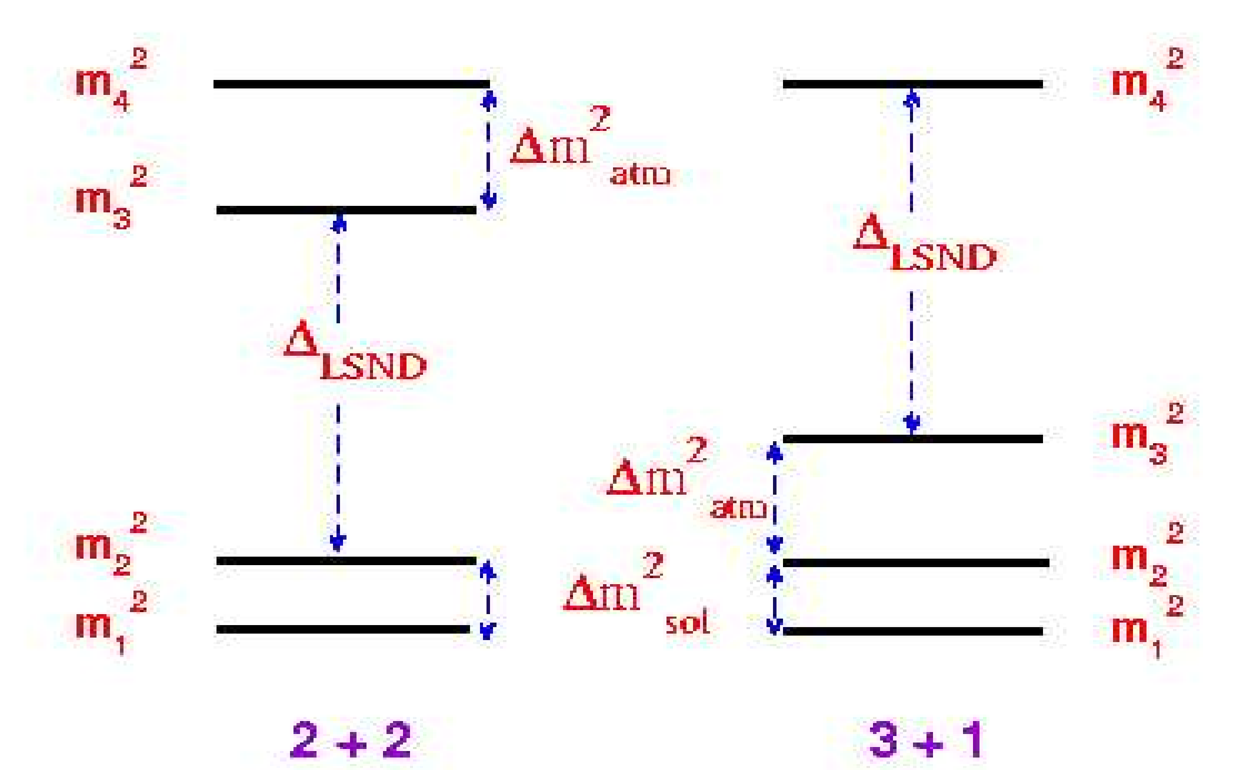
√Is there an evidence for oscillations on very short length scales? $\Rightarrow \Delta m^2 \sim \mathrm{eV}^2$

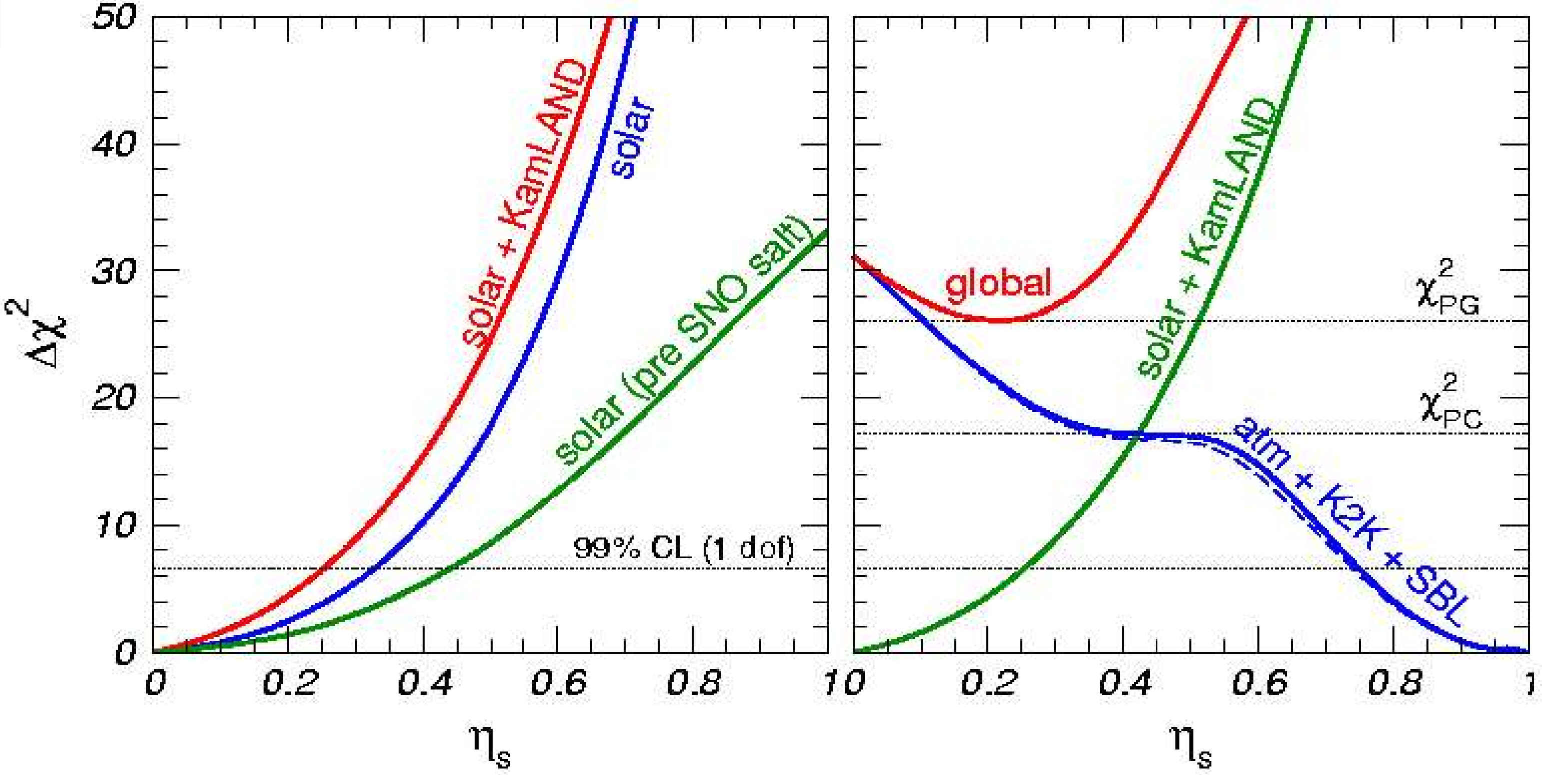
√Can it be accommodated with the solar and atm data?

√Add one sterile neutrino – 2+2 and 3+1 mass schemes



Explaining LSND

√ The 2+2 scheme is ruled out by the solar and atm data

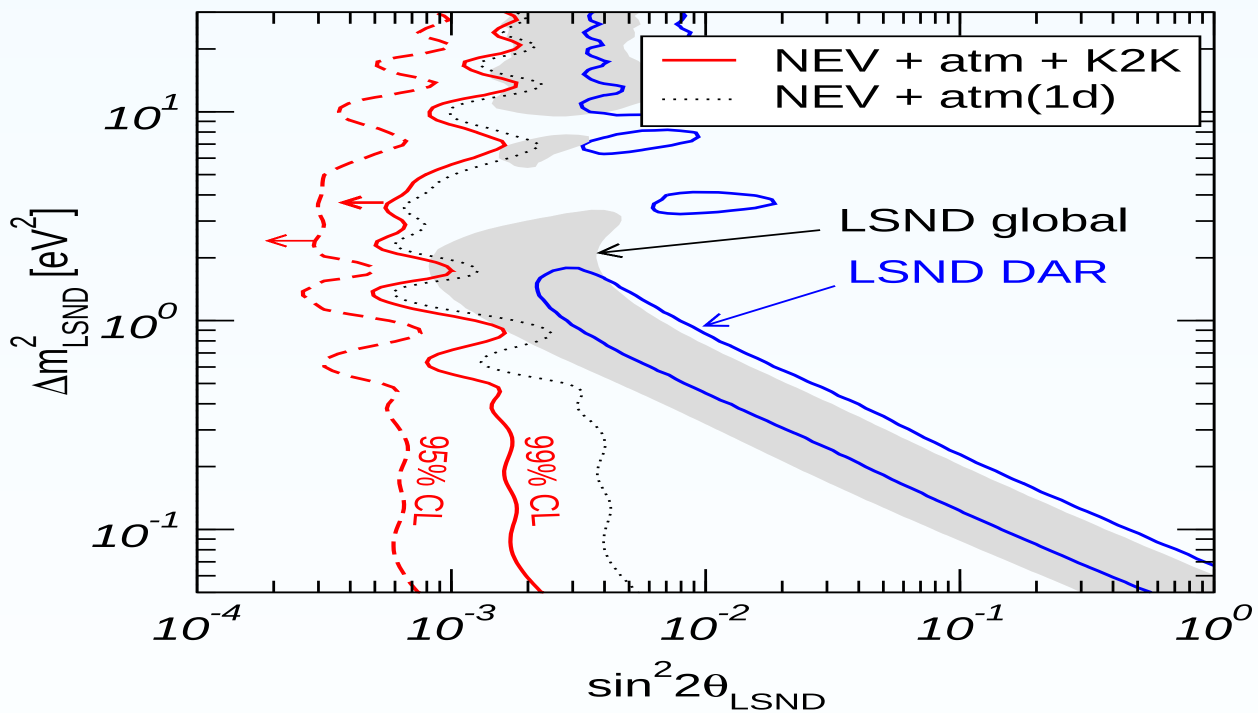


Maltoni et al, hep-ph/0405172

√ Oscillations to pure sterile states is strongly disfavored by both the solar and atmospheric data

Explaining LSND

√ The 3+1 scheme is strongly disfavored by the SBL data

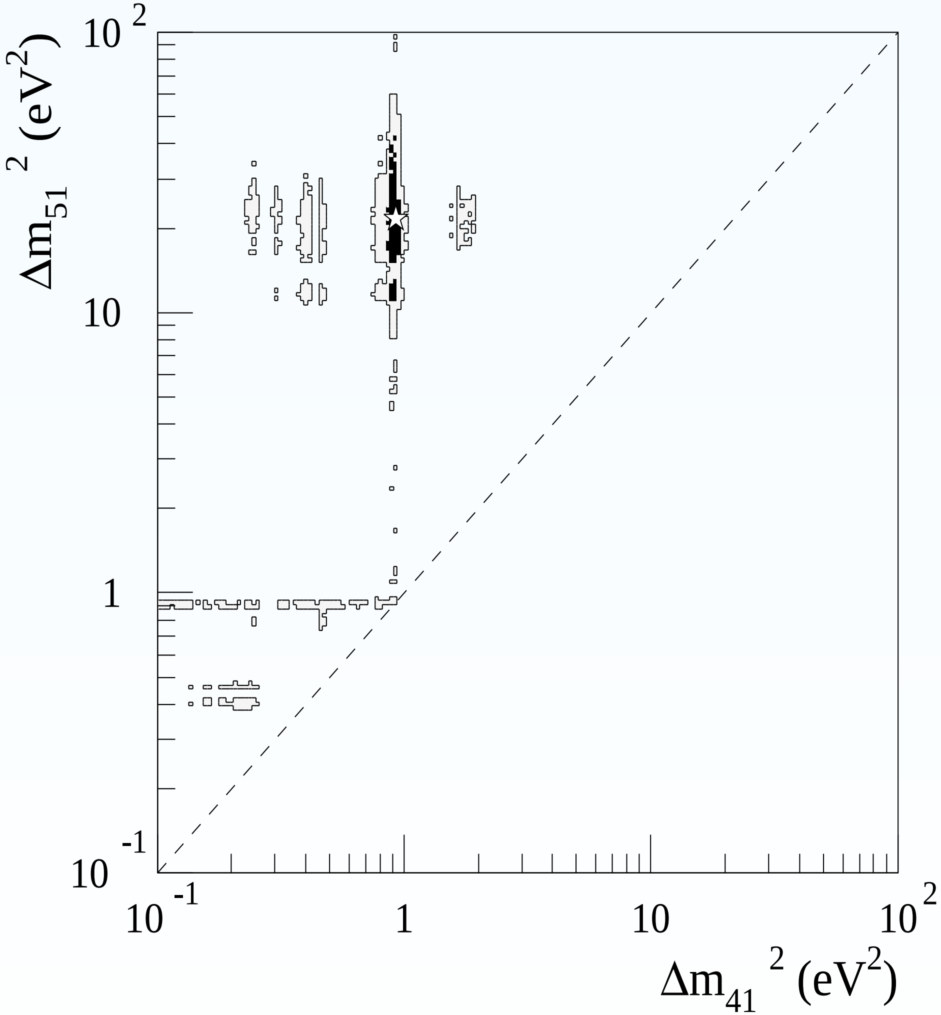


Maltoni et al, hep-ph/0405172

√ Very small area allowed at the 99% C.L.

The (3+2) Scenario to Explain LSND

√Addition of a 2nd sterile ν state reduces the tension



√Best-Fit:	√BF2:
$\Delta m^2_{41} = 0.92$ eV^2,	0.46 eV^2
$\Delta m^2_{51} = 22$ eV^2,	0.89 eV^2
$U_{e4} = 0.121$,	0.090
$U_{\mu 4} = 0.204$,	0.226
$U_{e5} = 0.036$,	0.125
$U_{\mu 5} = 0.224$	0.160

Sorel, Conrad, Shaevitz, hep-ph/0305255

Survival Probability of SN $\bar{\nu}_e$ in (3+2) Scenario

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√Mass Spectra Possible within (3+2)

$$\begin{aligned}
\mathrm{N2+N3}: &\quad \Delta m^2_{31} > 0 \quad, \Delta m^2_{41} > 0 \text{ and } \Delta m^2_{51} > 0\,,\\
\mathrm{N2+I3}: &\quad \Delta m^2_{31} < 0 \quad, \Delta m^2_{41} > 0 \text{ and } \Delta m^2_{51} > 0\,,\\
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\end{aligned}$$

√$\Delta m^2_{21} > 0$ at more than 6σ from solar neutrino data

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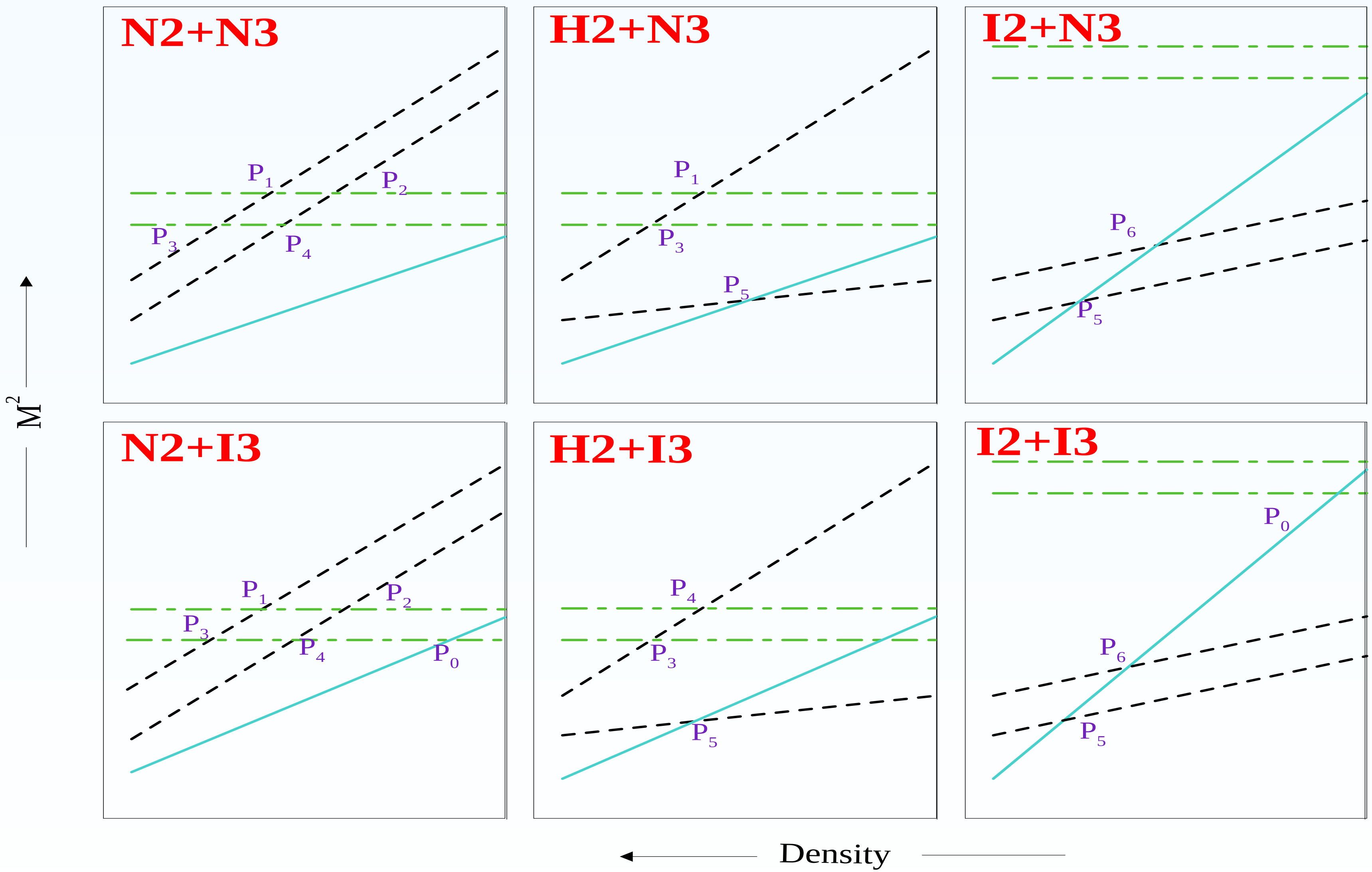

√Multiple resonances involving the steriles

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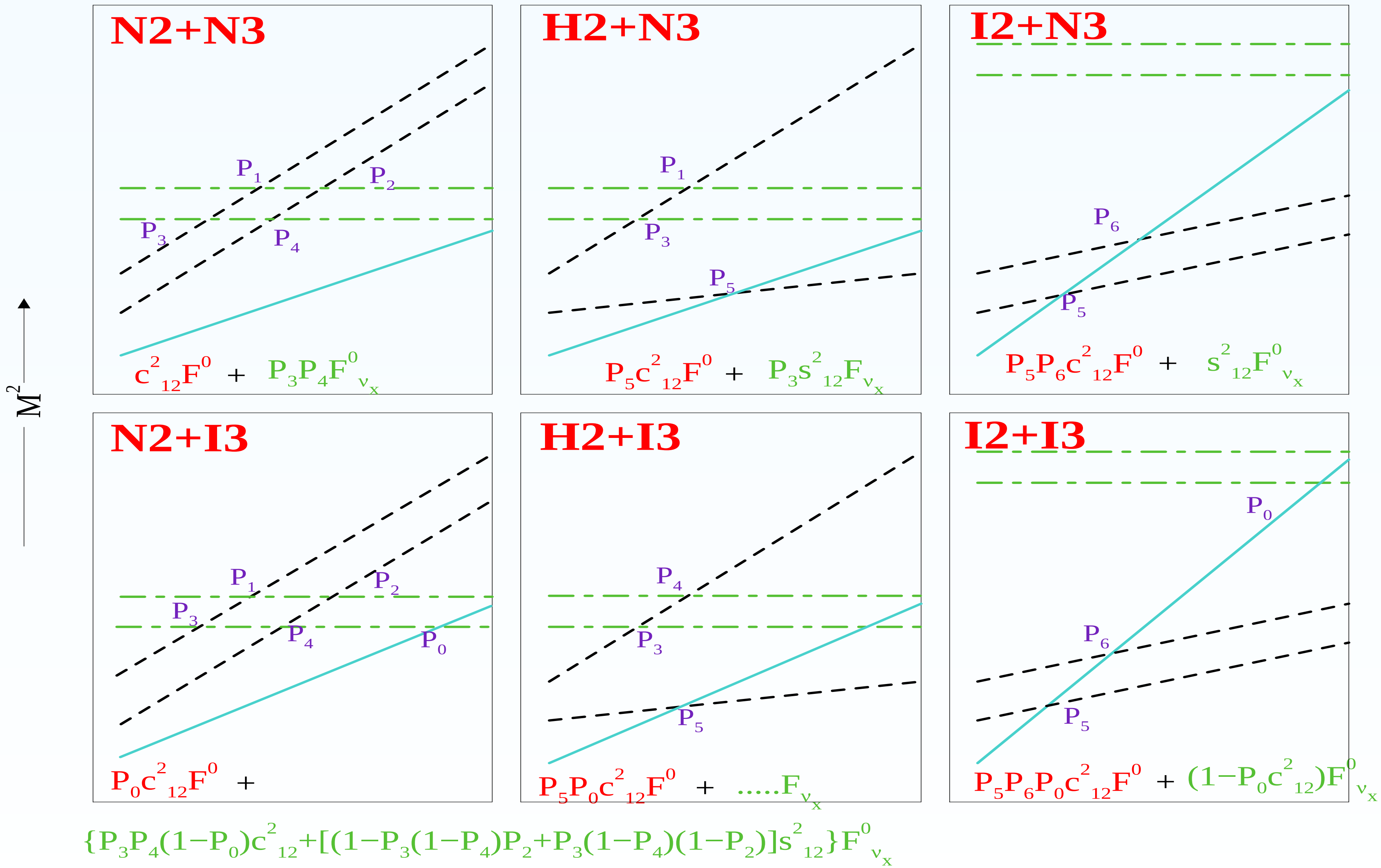

√Two terms in F_e: (i) remainder of $\bar{\nu}_e$ (ii) conversion from ν_x

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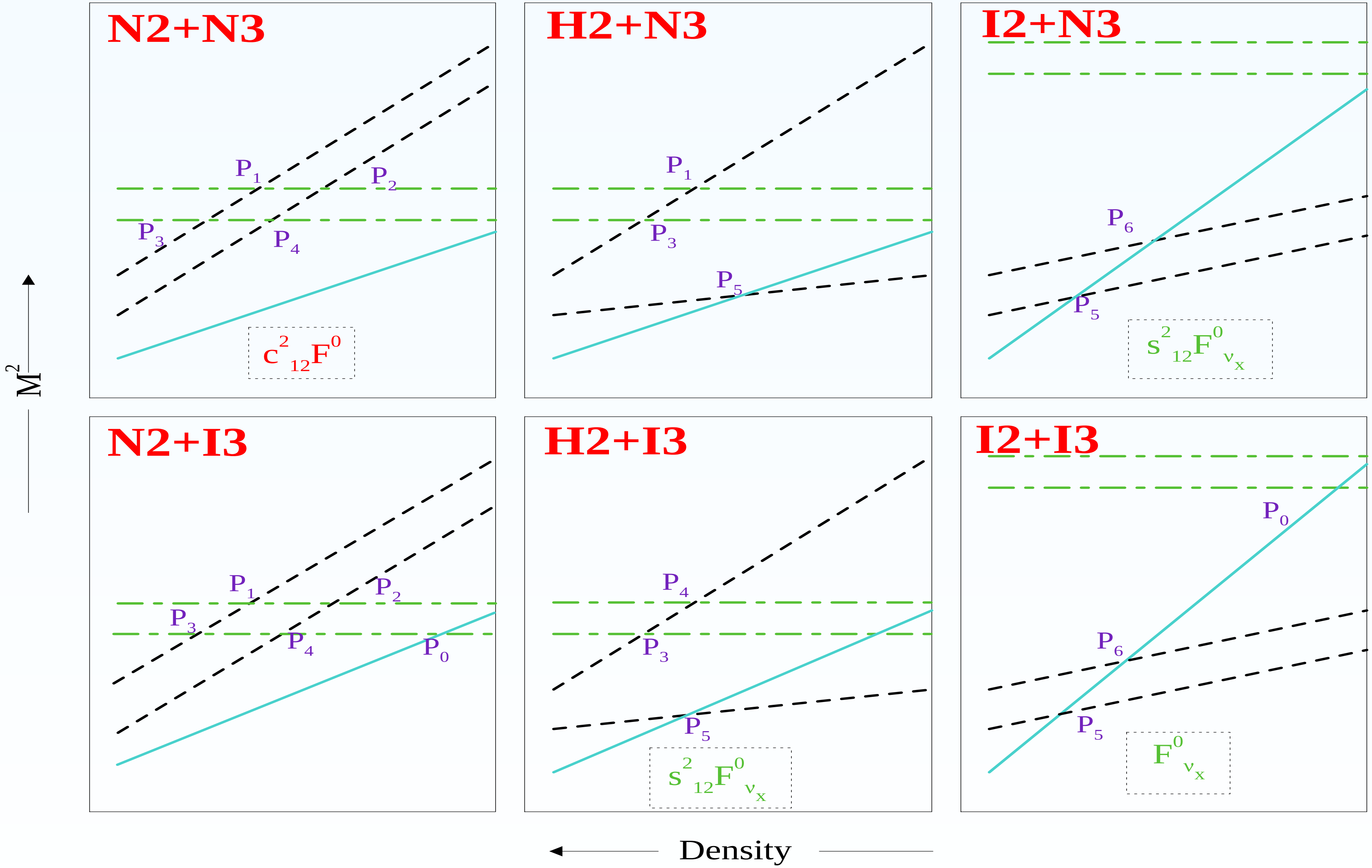

√The resonances are all adiabatic

Shock Wave and Level Crossing

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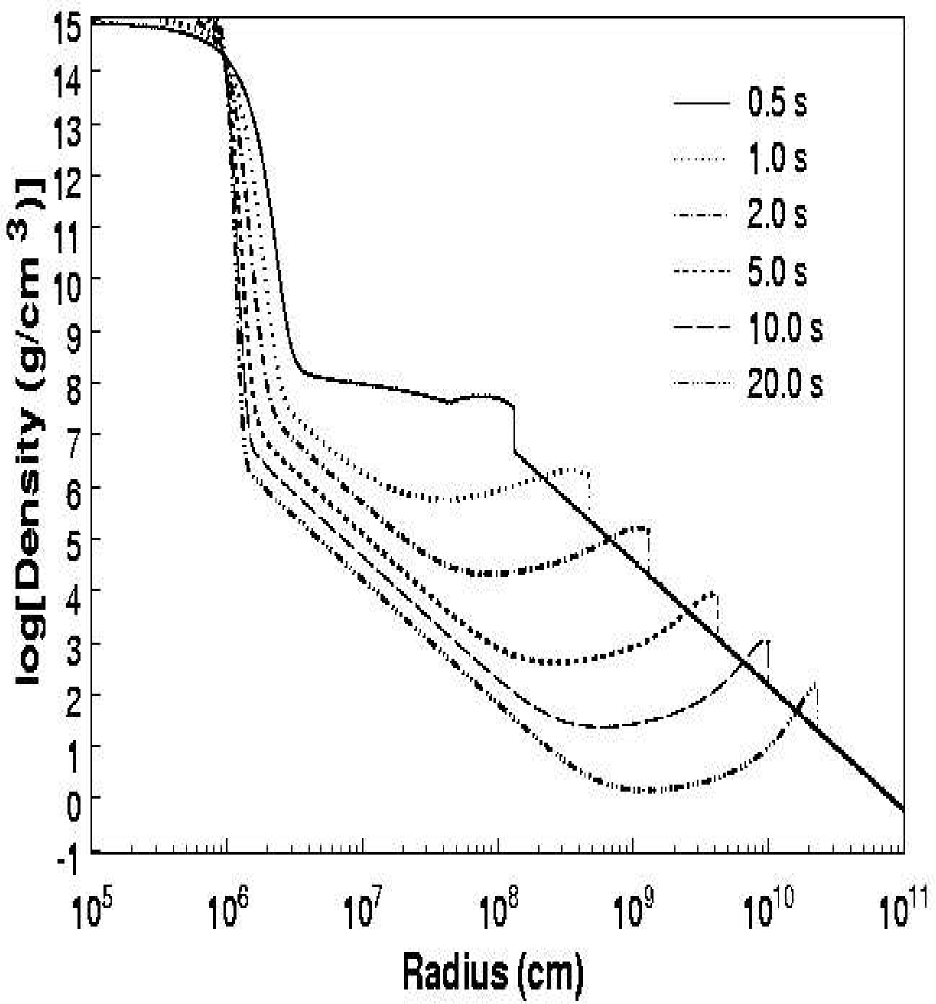
FORWARD SHOCK

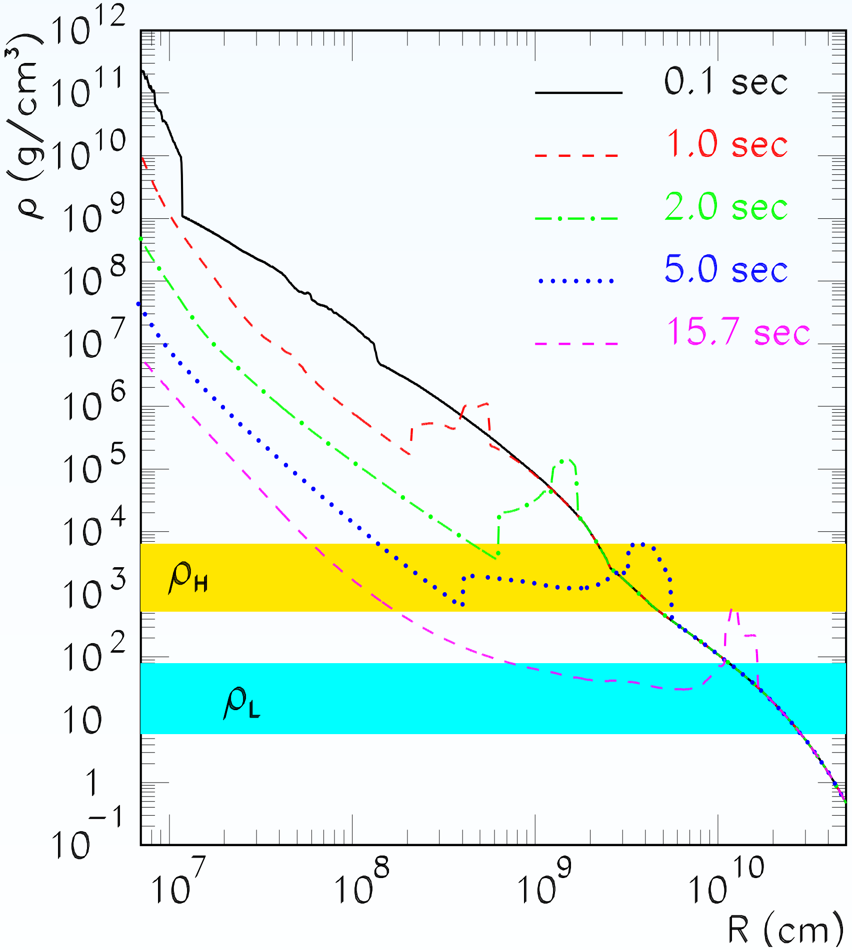


- √Density profile shows a sharp jump at the shock front
- √This sharp change in density causes:
- √More than 1 resonance driven for a given Δm^2
- √The additional resonances are non-adiabatic

Schirato and Fuller, astro-ph/0205390

Shock Wave and Level Crossing

REVERSE SHOCK



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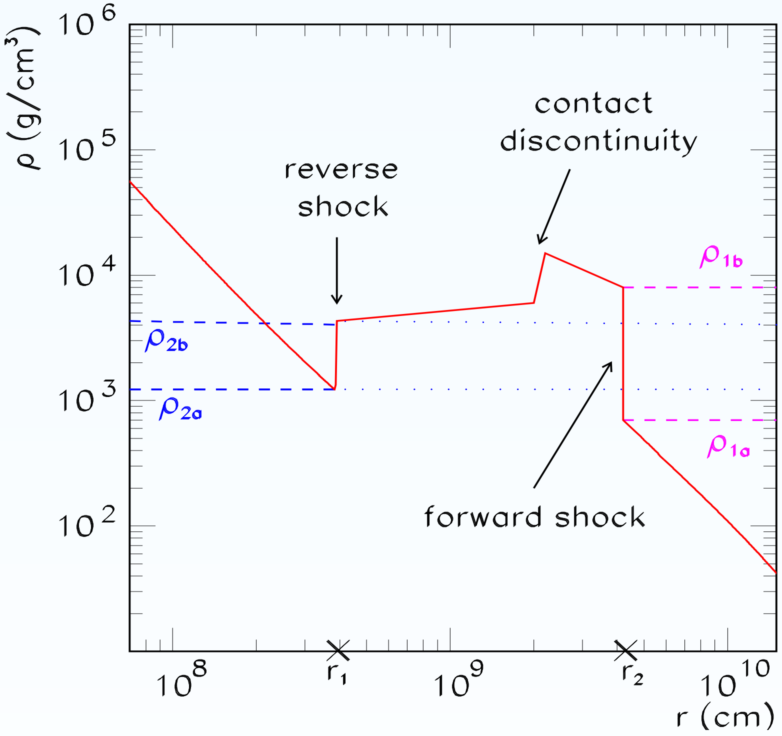
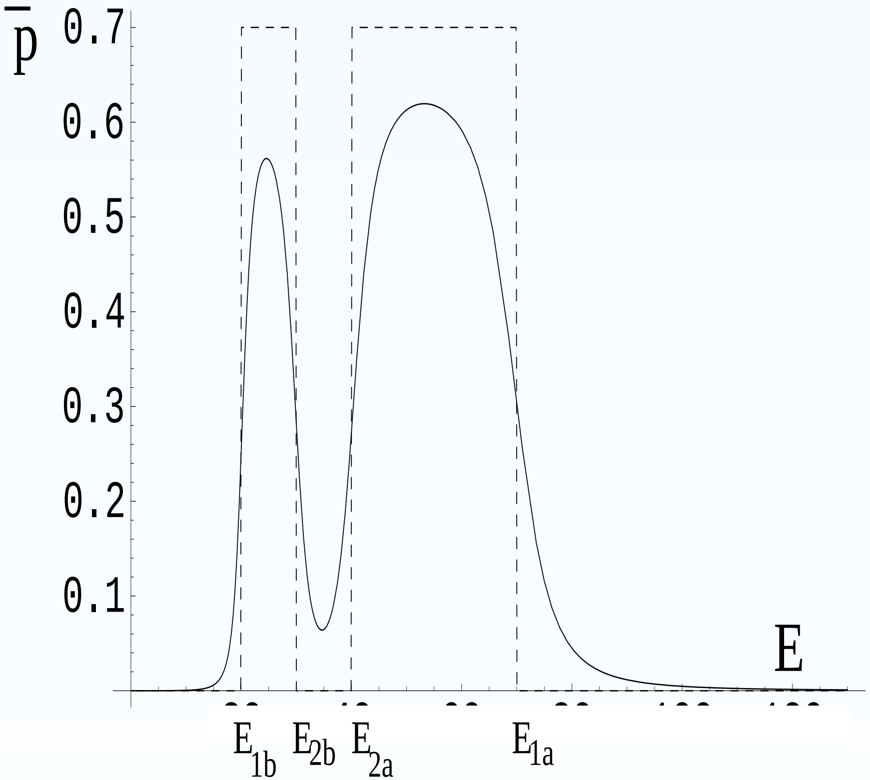
Tomas,Kachelriess,Raffelt,Dighe,Janka,Scheck, hep-ph/0407132

√Reverse Shock is a generic feature of all SN models

Impact of Shock on the Survival Probability





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$$P_J \approx \exp\left(-\pi \frac{\Delta m^2 \sin^2\theta}{E} \left|\frac{dln\ N_e}{dx}\right|^{-1}_{x=x_{\rm res}}\right)$$

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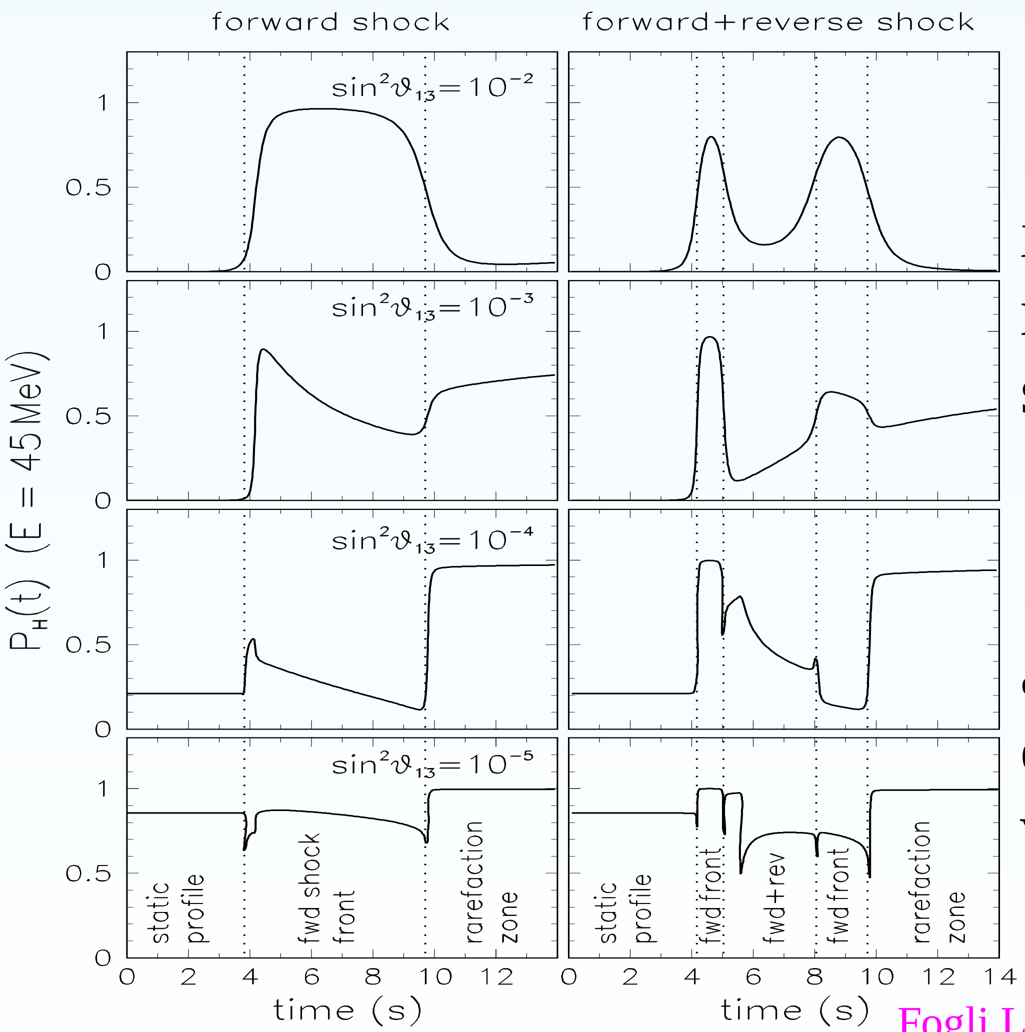


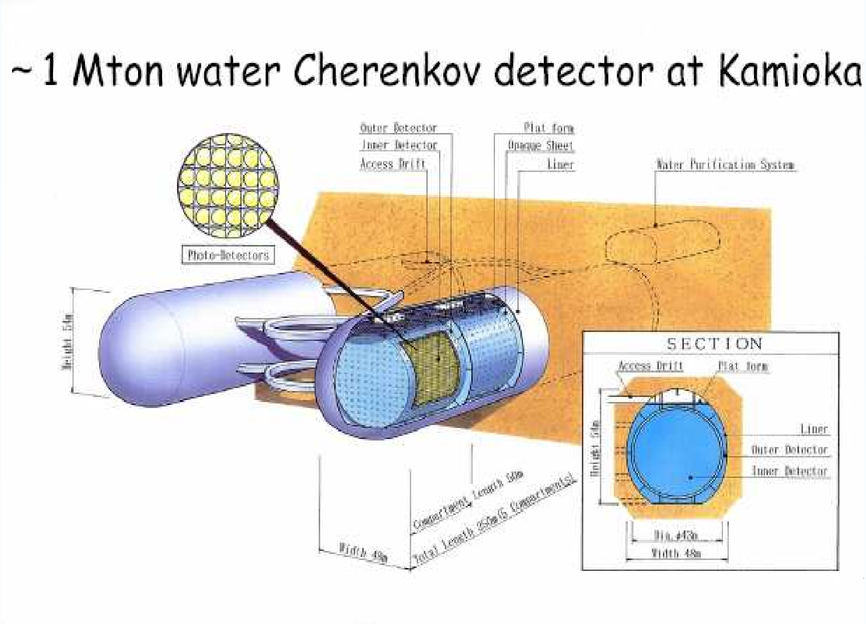
Fogli,Lisi,Mirizzi,Montanino, hep-ph/0412046

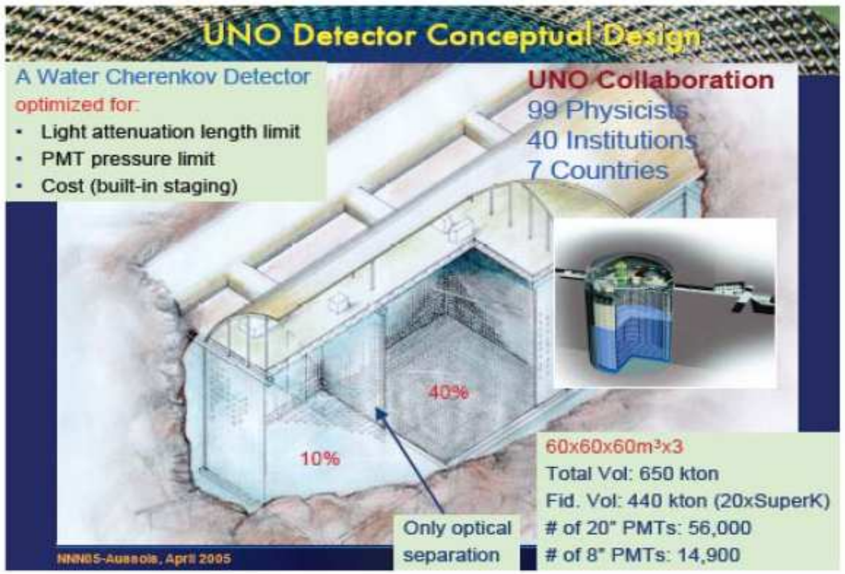
√Sudden broad "dip" in E and t is the signature of the forward shock

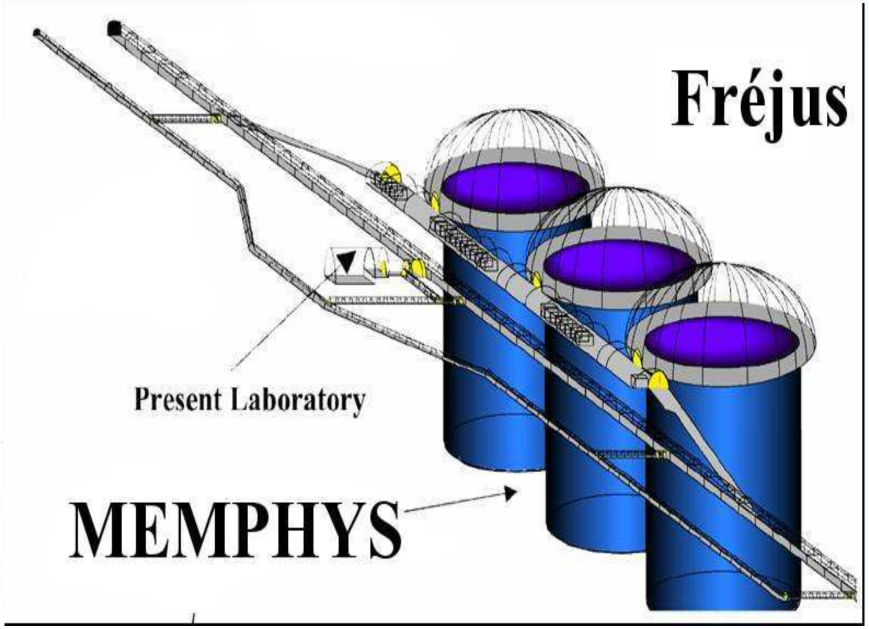
√"Double Dip" in E and t is the signature of the forward and reverse shock

√In principle, position of the dips can be mapped to the density profile of the SN and hence to its shock dynamics

SN Neutrinos in Megaton Water Detectors

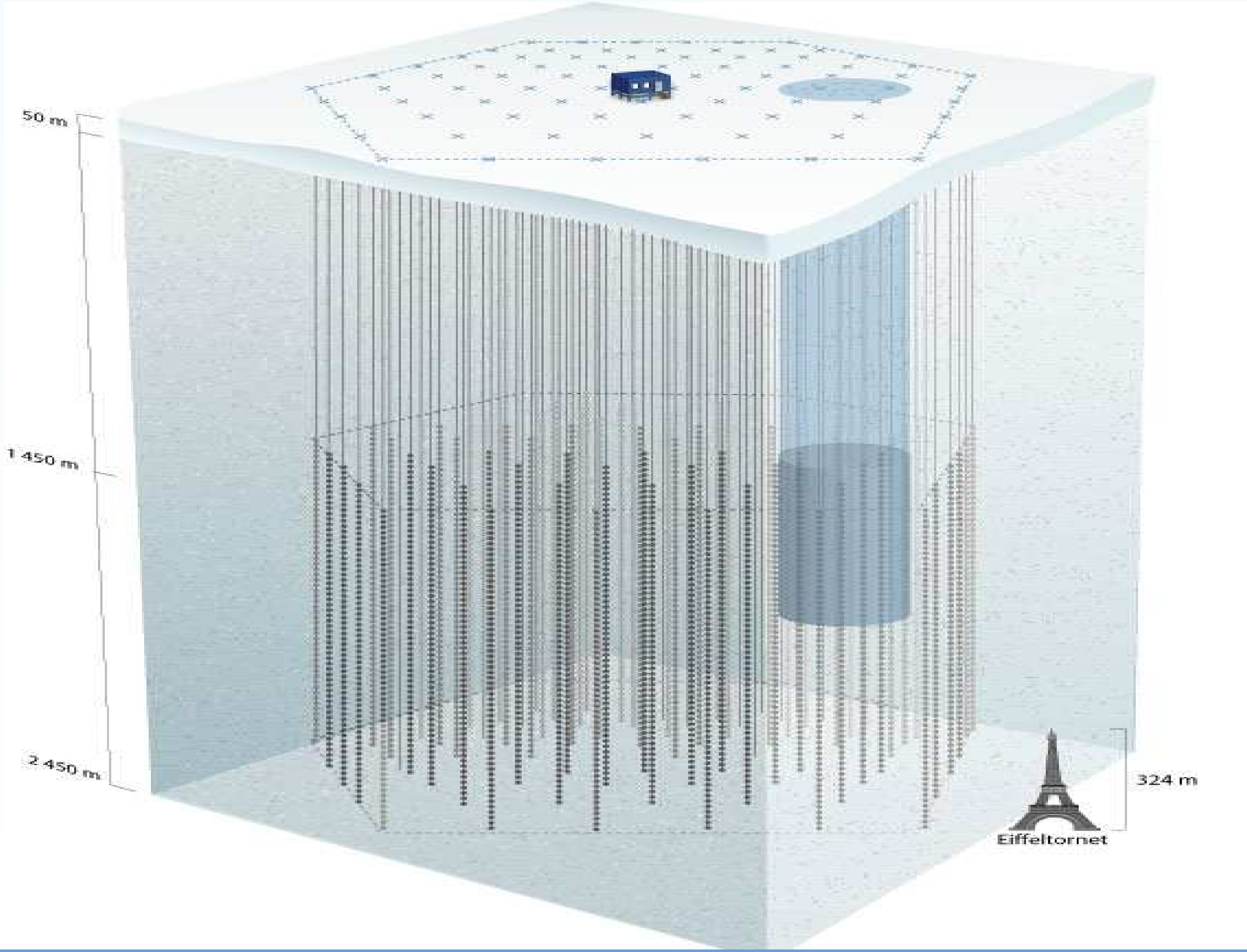






√Will measure both E and time

IceCube as a Supernova Detector



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Halzen, Jacobson, Zas (1995)

Dighe, Keil, Raffelt (2003)

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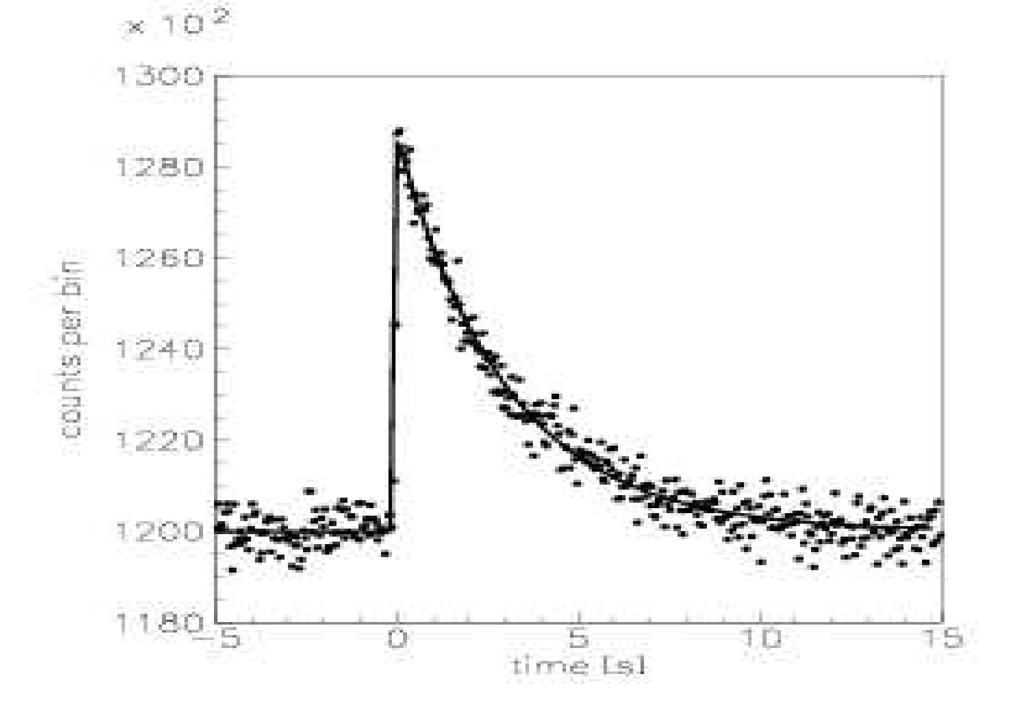
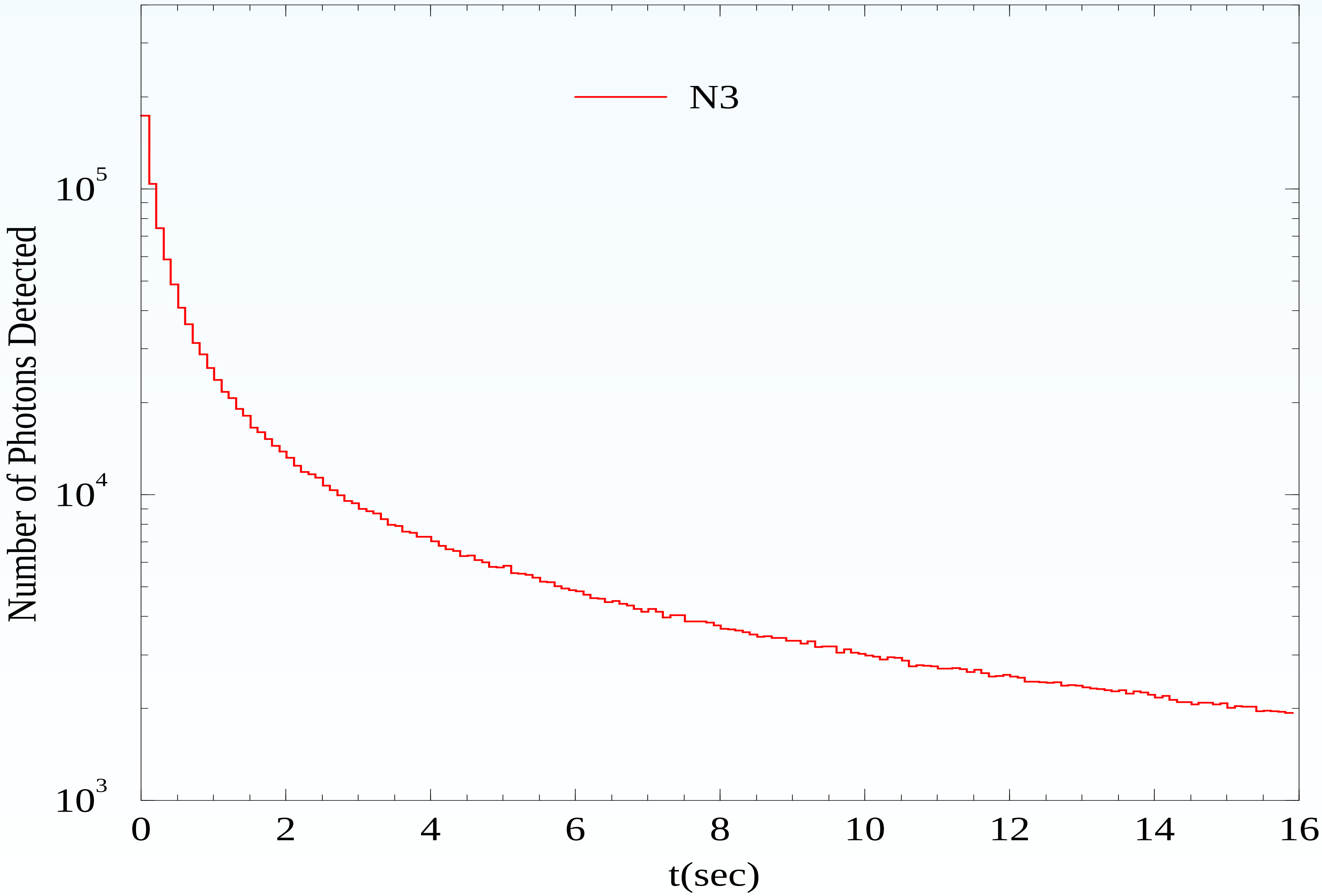


IceCube Collaboration

SN ν Signature in IceCube for Three Neutrinos



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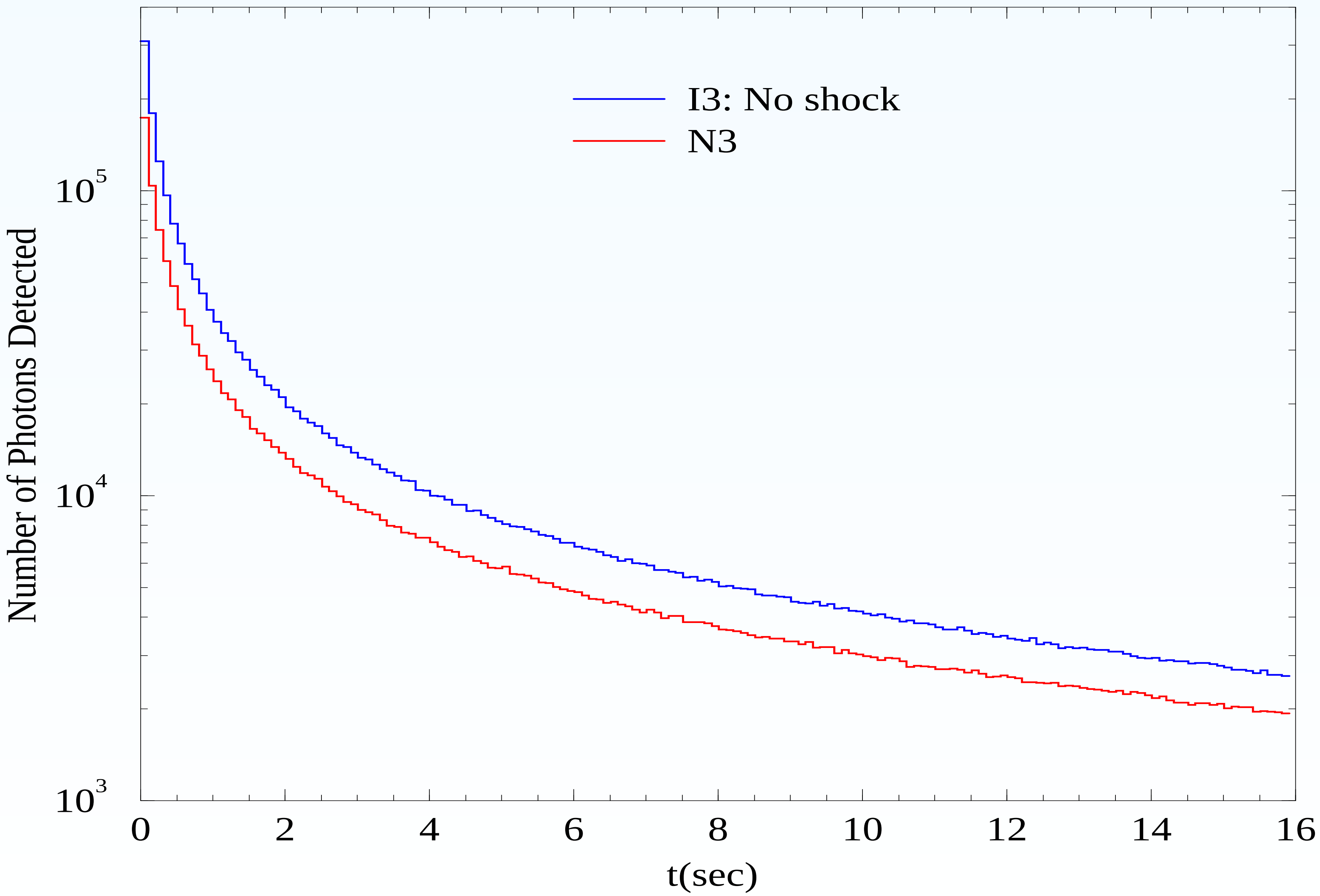

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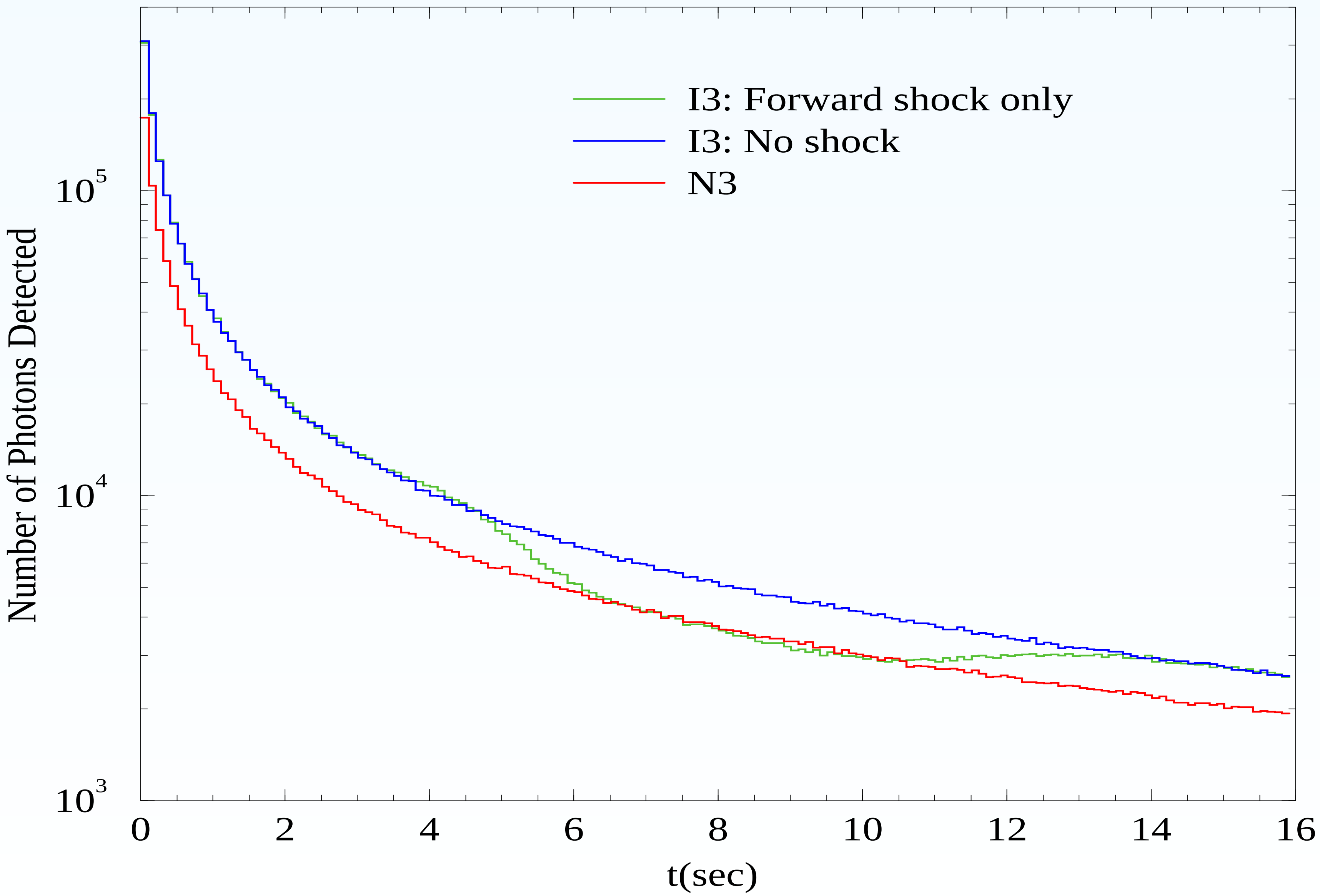

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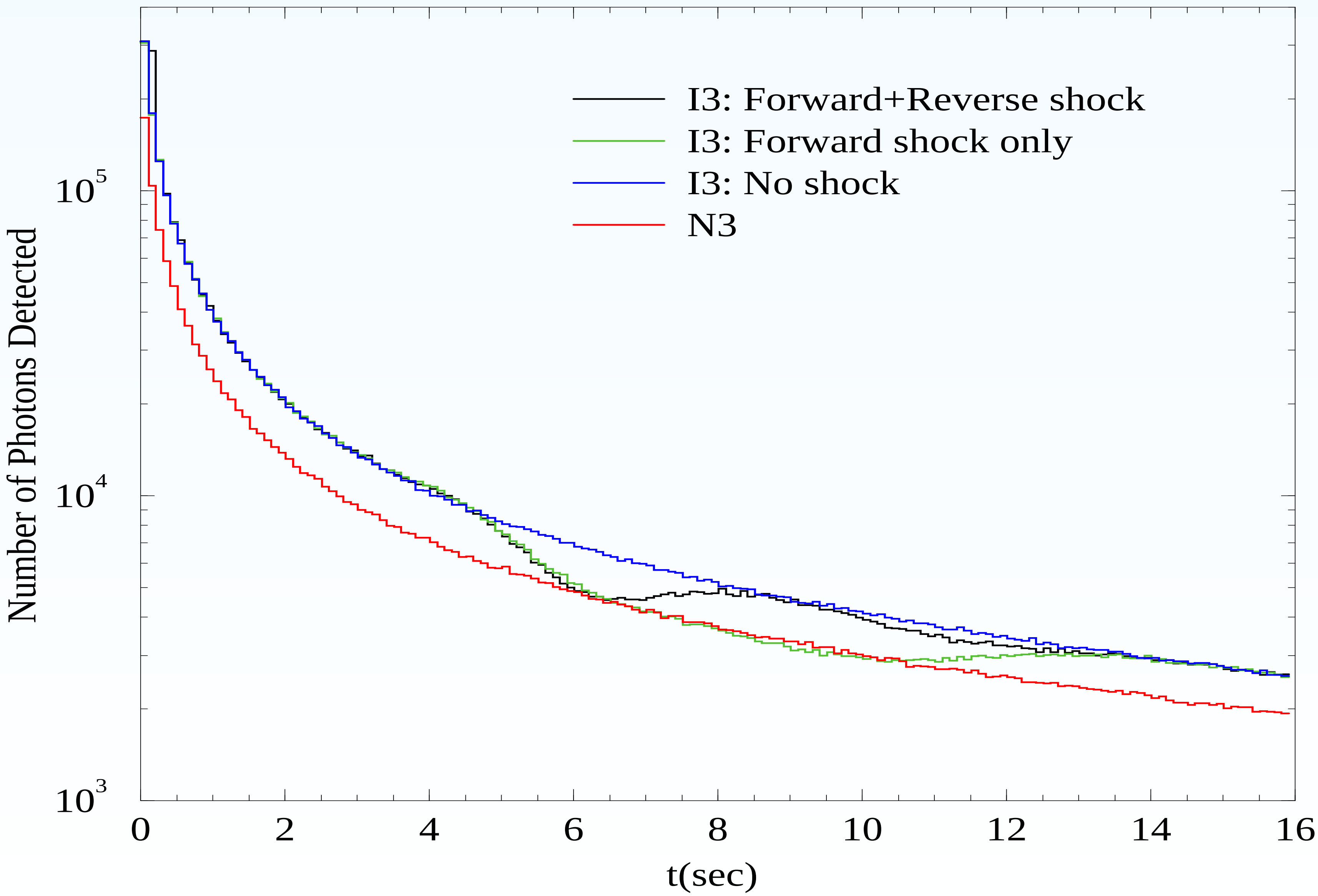

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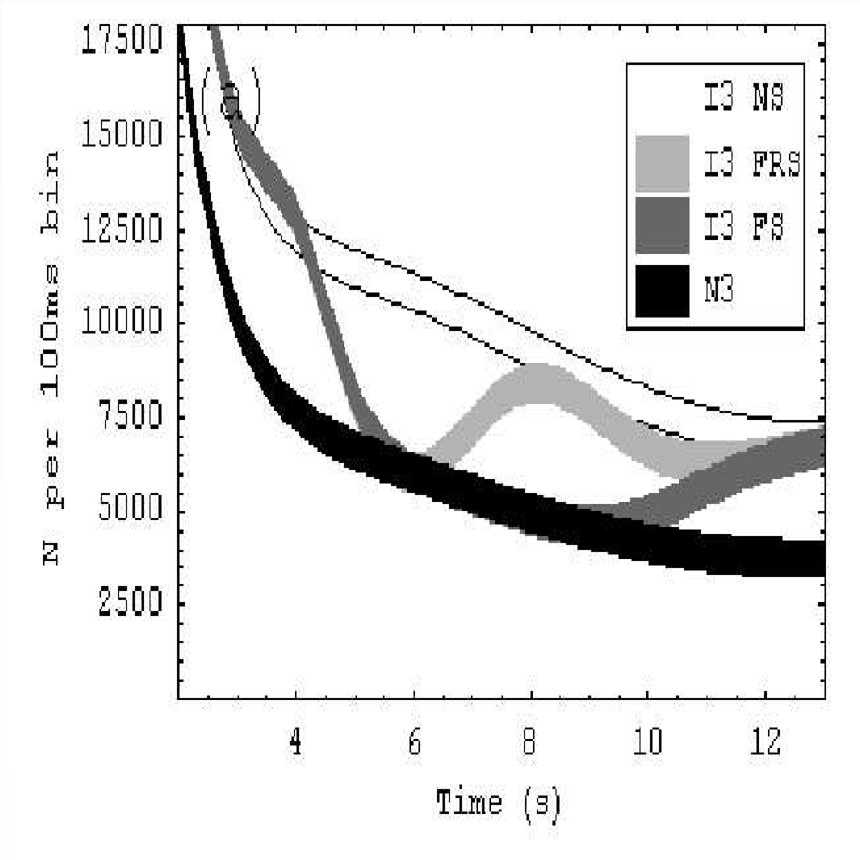
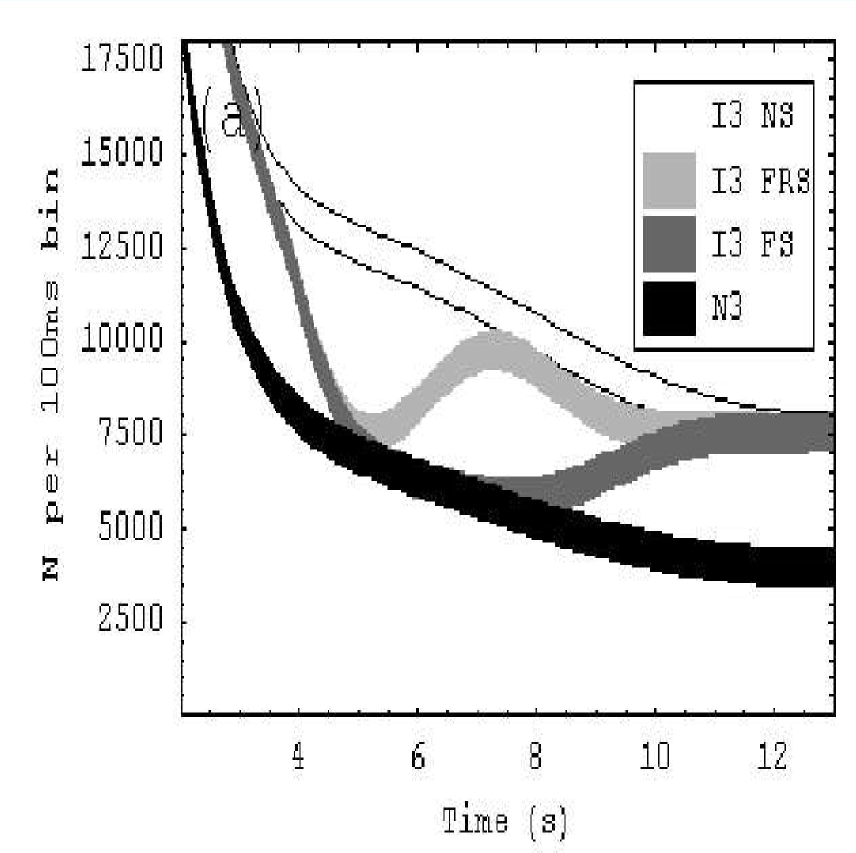




$\surd \langle E_{\bar{\nu}_e} \rangle = 15, \langle E_{\nu_x} \rangle = 24$

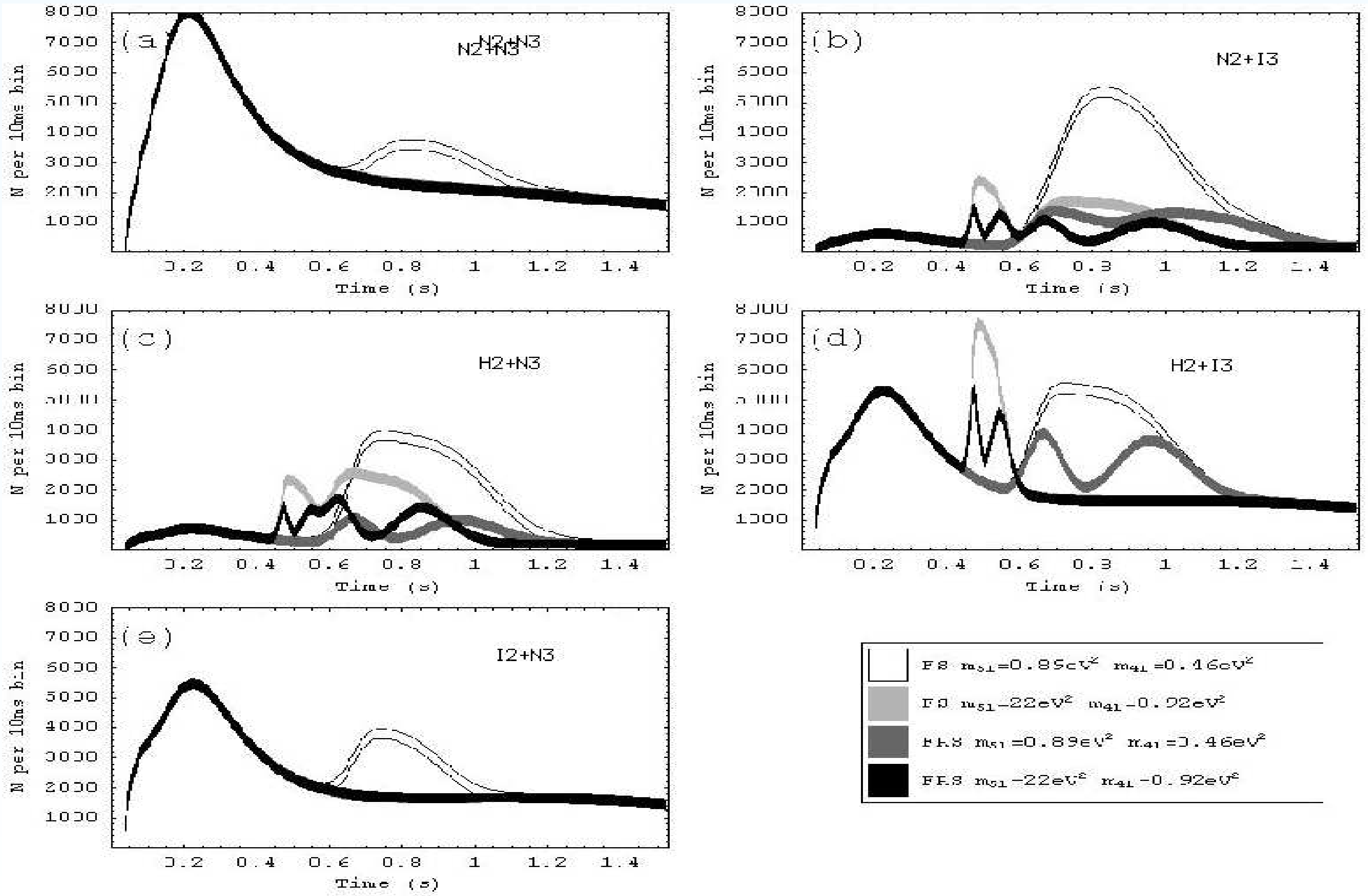
$\surd \frac{\Phi^0_{\bar{\nu}_e}}{\Phi^0_{\nu_x}} = 1.6$

$\surd \langle E_{\bar{\nu}_e} \rangle = 15, \langle E_{\nu_x} \rangle = 18$

$\surd \frac{\Phi^0_{\bar{\nu}_e}}{\Phi^0_{\nu_x}} = 0.8$

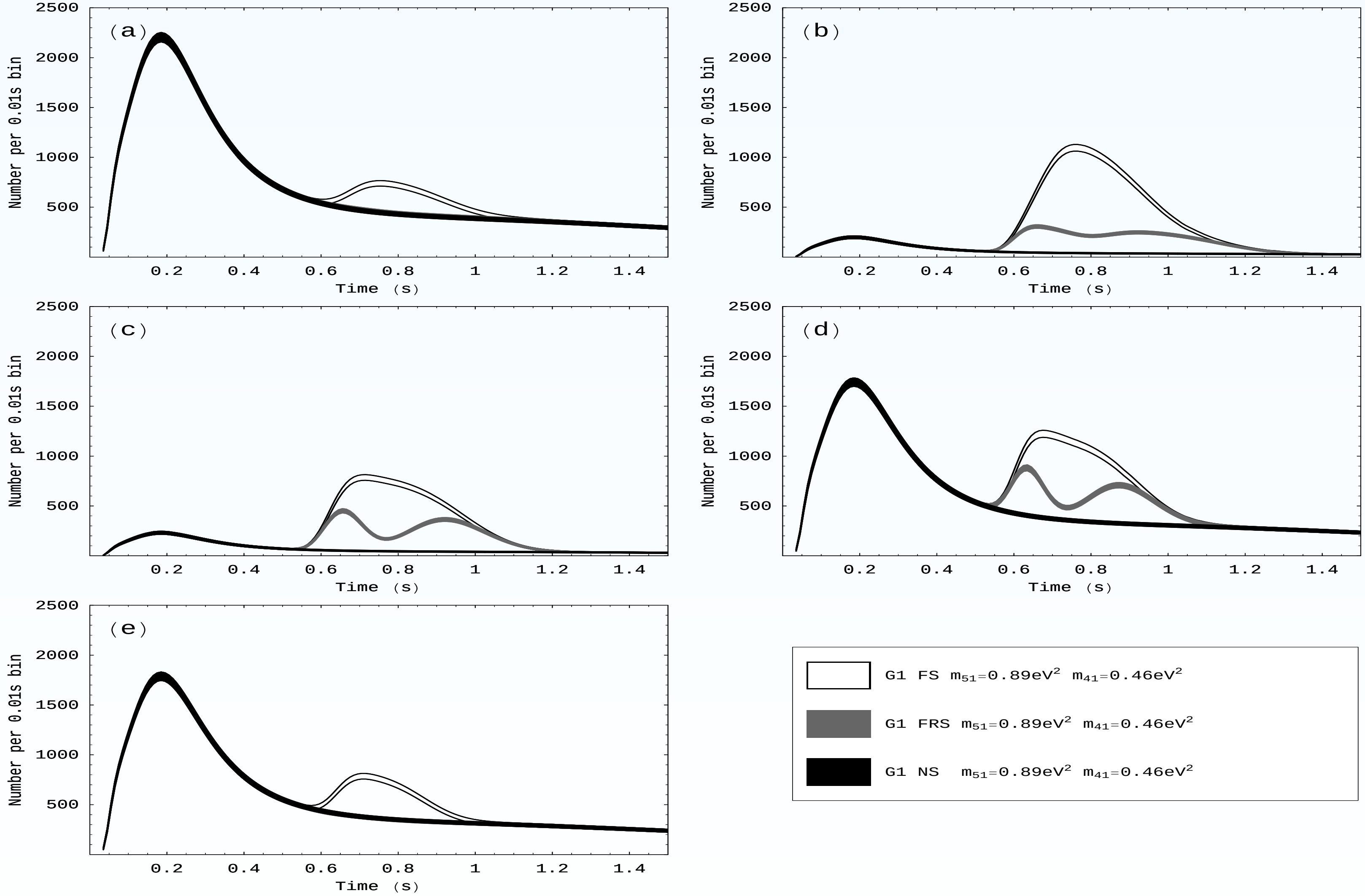
SC, Harries, Ross, hep-ph/0605255

SN ν Signature in IceCube for Five Neutrinos



$\surd$Shock effects at very early times signal sterile neutrinos

SN ν Signature in "Hyper-K" for Five Neutrinos



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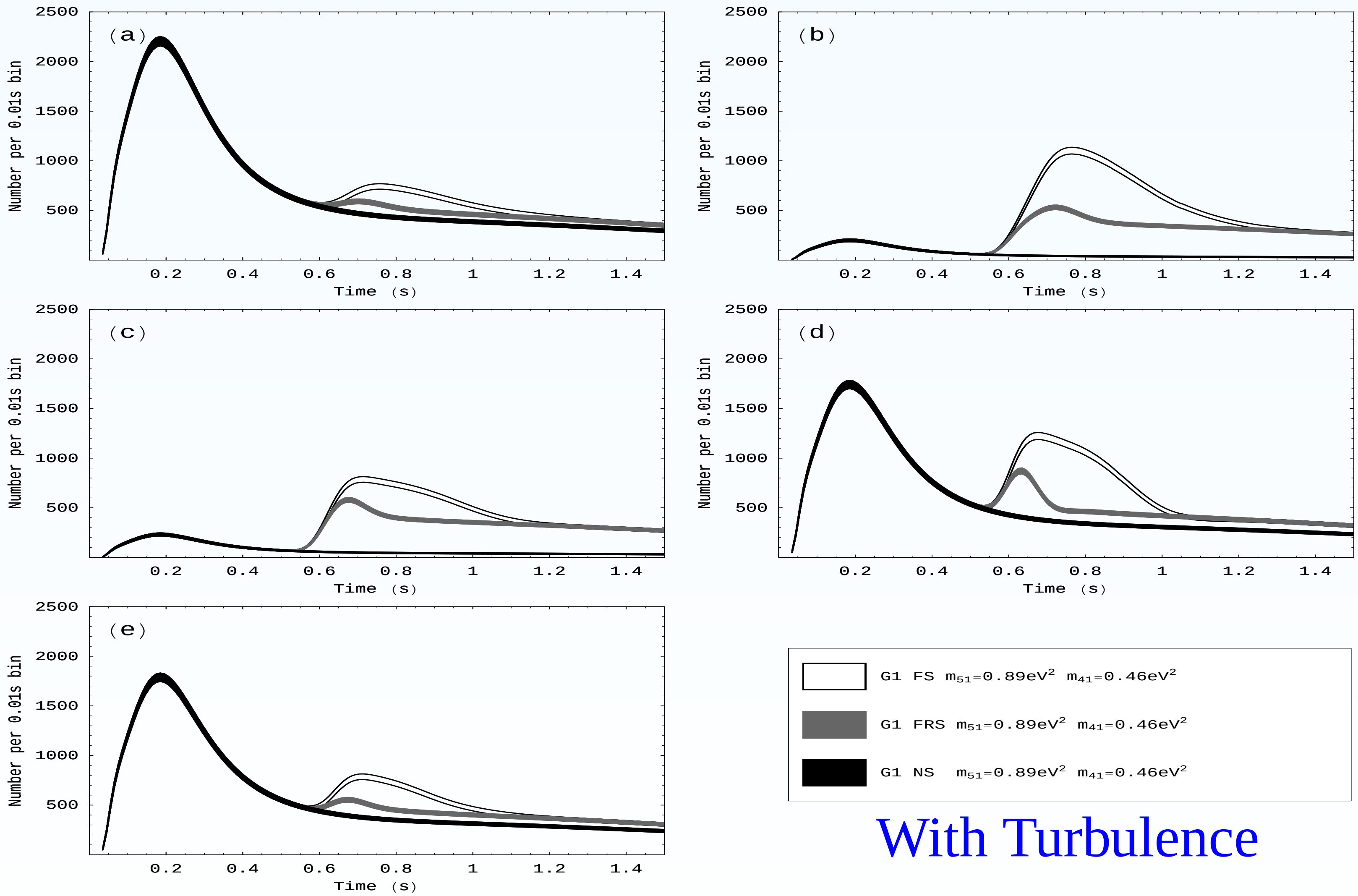

With Turbulence

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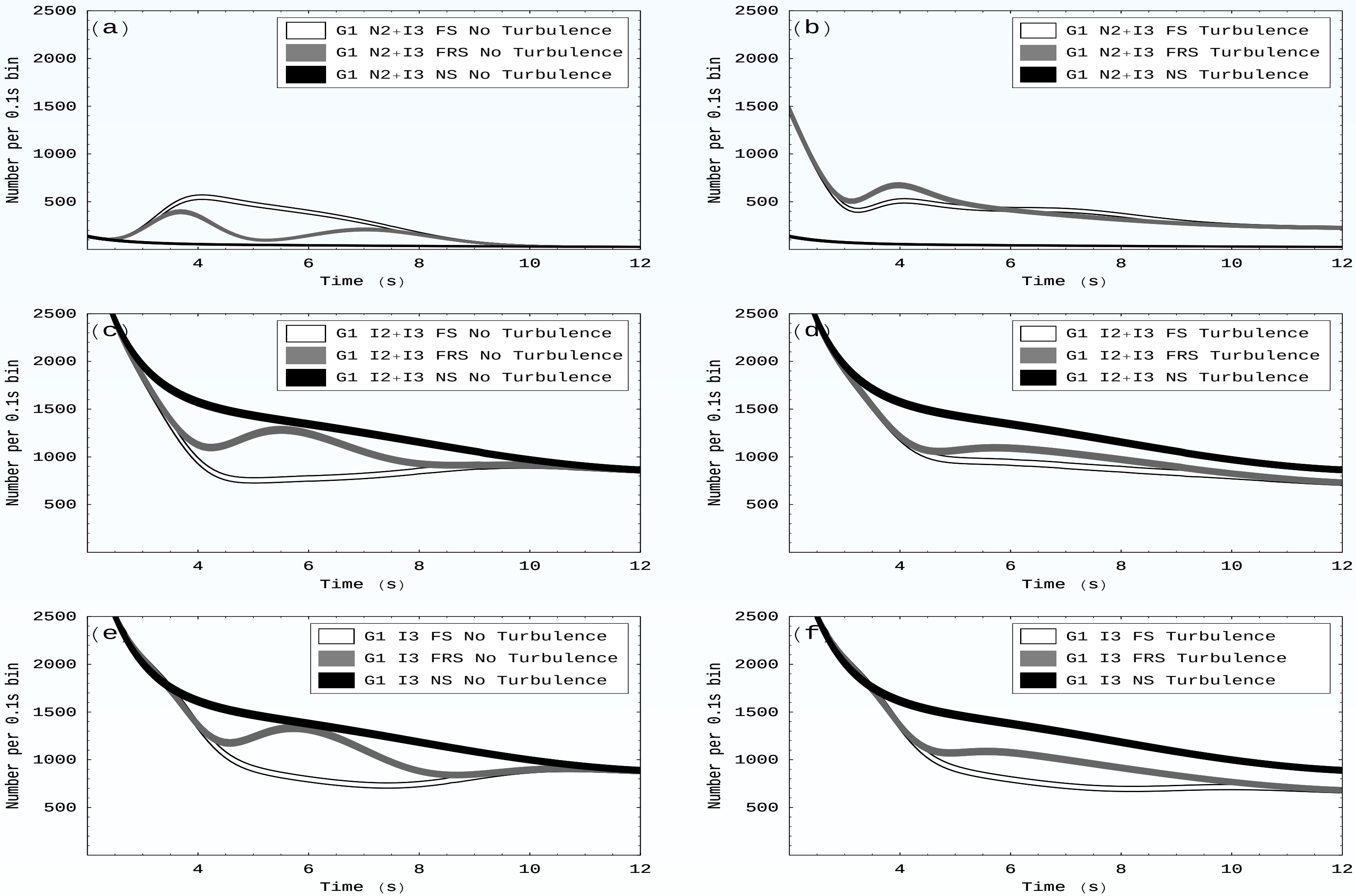

$\surd$Shock effects at late times

Comparing early and late time signal

Spectrum	Early Times		Late Times	
	Events	Shock Effect	Events	Shock Effects
N3	L	χ	L	χ
I3	L	χ	L	$\surd$
N2+N3	L	$\surd$	S	χ
N2+I3	S	$\surd$	S	$\surd$
H2+N3	S	$\surd$	S	χ
H2+I3	L	$\surd$	S	χ
I2+N3	L	$\surd$	S	χ
I2+I3	L	χ	L	$\surd$

$\surd$ L$\Rightarrow$ Large events; S$\Rightarrow$ Small events

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H2+I3	L	$\surd$	S	χ
I2+N3	L	$\surd$	S	χ
I2+I3	L	χ	L	$\surd$

$\surd$All sterile cases (except I2+I3) have shock effects at early times

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H2+N3	S	$\surd$	S	χ
H2+I3	L	$\surd$	S	χ
I2+N3	L	$\surd$	S	χ
I2+I3	L	χ	L	$\surd$

$\surd$ N3 has a unique signature and hence can be identified

Comparing early and late time signal

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H2+N3	S	$\surd$	S	χ
H2+I3	L	$\surd$	S	χ
I2+N3	L	$\surd$	S	χ
I2+I3	L	χ	L	$\surd$

$\surd$N2+I3 has a unique signature and hence can be identified

Comparing early and late time signal

Spectrum	Early Times		Late Times	
	Events	Shock Effect	Events	Shock Effects
N3	L	χ	L	χ
I3	L	χ	L	$\surd$
N2+N3	L	$\surd$	S	χ
N2+I3	S	$\surd$	S	$\surd$
H2+N3	S	$\surd$	S	χ
H2+I3	L	$\surd$	S	χ
I2+N3	L	$\surd$	S	χ
I2+I3	L	χ	L	$\surd$

$\surd$H2+N3 has a unique signature and hence can be identified

Comparing early and late time signal

Spectrum	Early Times		Late Times	
	Events	Shock Effect	Events	Shock Effects
N3	L	χ	L	χ
I3	L	χ	L	$\surd$
N2+N3	L	$\surd$	S	χ
N2+I3	S	$\surd$	S	$\surd$
H2+N3	S	$\surd$	S	χ
H2+I3	L	$\surd$	S	χ
I2+N3	L	$\surd$	S	χ
I2+I3	L	χ	L	$\surd$

$\surd$(I3, I2+I3) are similar & (N2+N3, H2+I3, I2+N3) are similar

$\surd$Model dependent analysis can differentiate between them

Conclusions

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- √ Supernova neutrinos are free

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- ✓ Different possible mass/mixing schemes can be tested
- ✓ Supernova neutrinos are free
- ✓ Built the detectors and be patient!

Thankyou!