PHYSICS POTENTIAL OF NEUTRINOS FROM SUPERNOVAE

Introduction to physics of supernova neutrinos

What can we learn from a future observation?

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Collapsing stars and neutrinos

1−3 times / century in our galaxy a large mass star $(M > 8 M_\odot)$ dies....

- ***gravitational instability*:**

  C, O, Si burned into Fe −> end of nuclear fusion

  self−gravitation overcomes the pressure of degenerate electron gas

- ***collapse* begins:**

  a core with nuclear density $(\rho \simeq 10^{14}\ g \cdot cm^{-3})$ and ~ 20 Km radius is formed

  neutrinos are trapped in the neutrinosphere (thermal equilibrium)

- **material bounces back: *shock−wave* is formed.**

  Neutron−star cooling by neutrino emission;

  explosion

Order of magnitude estimates:

Thermal production of $\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$ **:**

$$e^+e^- \to \nu\bar{\nu} \quad NN \to NN\nu\bar{\nu}$$

Duration of neutrino burst ~ diffusion time:

(random walk)

$$\tau \sim t_{diff} \sim R^2/\lambda = \mathcal{O}(10)\ s$$

Total energy released ~ core binding energy:

$$E_b \sim \frac{3}{5}\frac{G_N M^2}{R} \simeq 1.6 \cdot 10^{53} ergs \left(\frac{M}{M_\odot}\right)^2 \left(\frac{10Km}{R}\right)$$

comparable to the whole universe!

Typical kinetic energy of nucleons:

virial theorem:

$$\langle E_{kin} \rangle \sim \frac{G_N M m_N}{2R} \approx 20\ \mathrm{MeV}$$

neutrino energy spectra and luminosities:
a naive argument..

- **emission from a thermal sphere (neutrinosphere):**

  → **thermal spectra**

- **different flavors have different interactions with the medium:** → **"hierarchy" of the spectra**

$\nu_e + n$ | $\bar{\nu}_e + p$ | NC only

$$\langle E_e \rangle \quad < \quad \langle E_{\bar{e}} \rangle \quad < \quad \langle E_{\mu,\tau,\bar{\mu},\bar{\tau}} \rangle$$

$\sim 9 - 11$ MeV $\qquad \sim 14 - 17$ MeV $\qquad \sim 21 - 24$ MeV

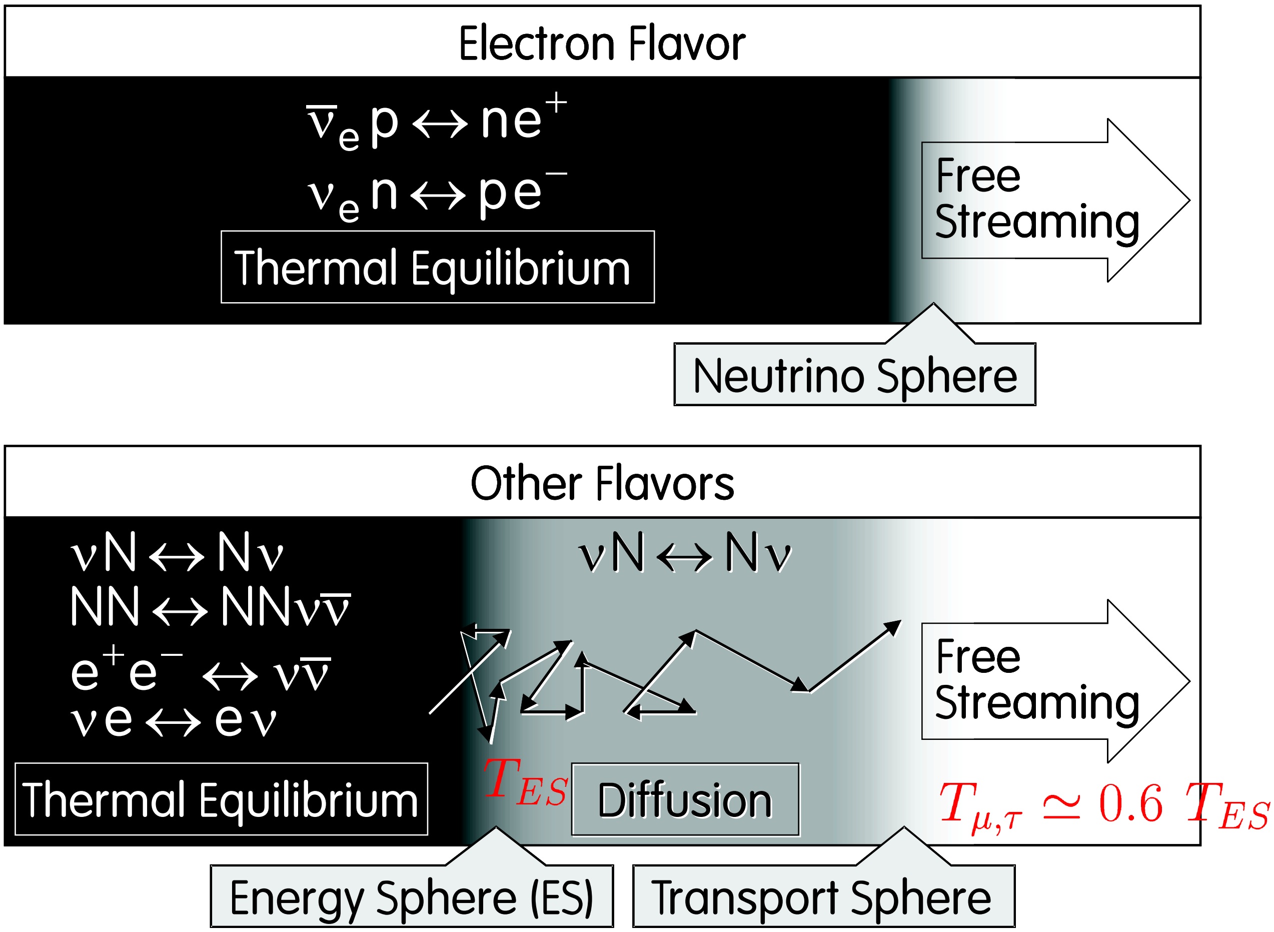
- **"equipartition" of luminosities between flavors:**

$$L_e \simeq L_{\bar{e}} \simeq L_{\mu,\tau,\bar{\mu},\bar{\tau}}$$

however, physics is more complicated...

the non−electron energy sphere is more internal,

but diffusion must be taken into account....



effective **thermal spectra, smaller differences in energies:**

$$\langle E_e \rangle < \langle E_{\bar{e}} \rangle < \langle E_{\mu,\tau} \rangle$$

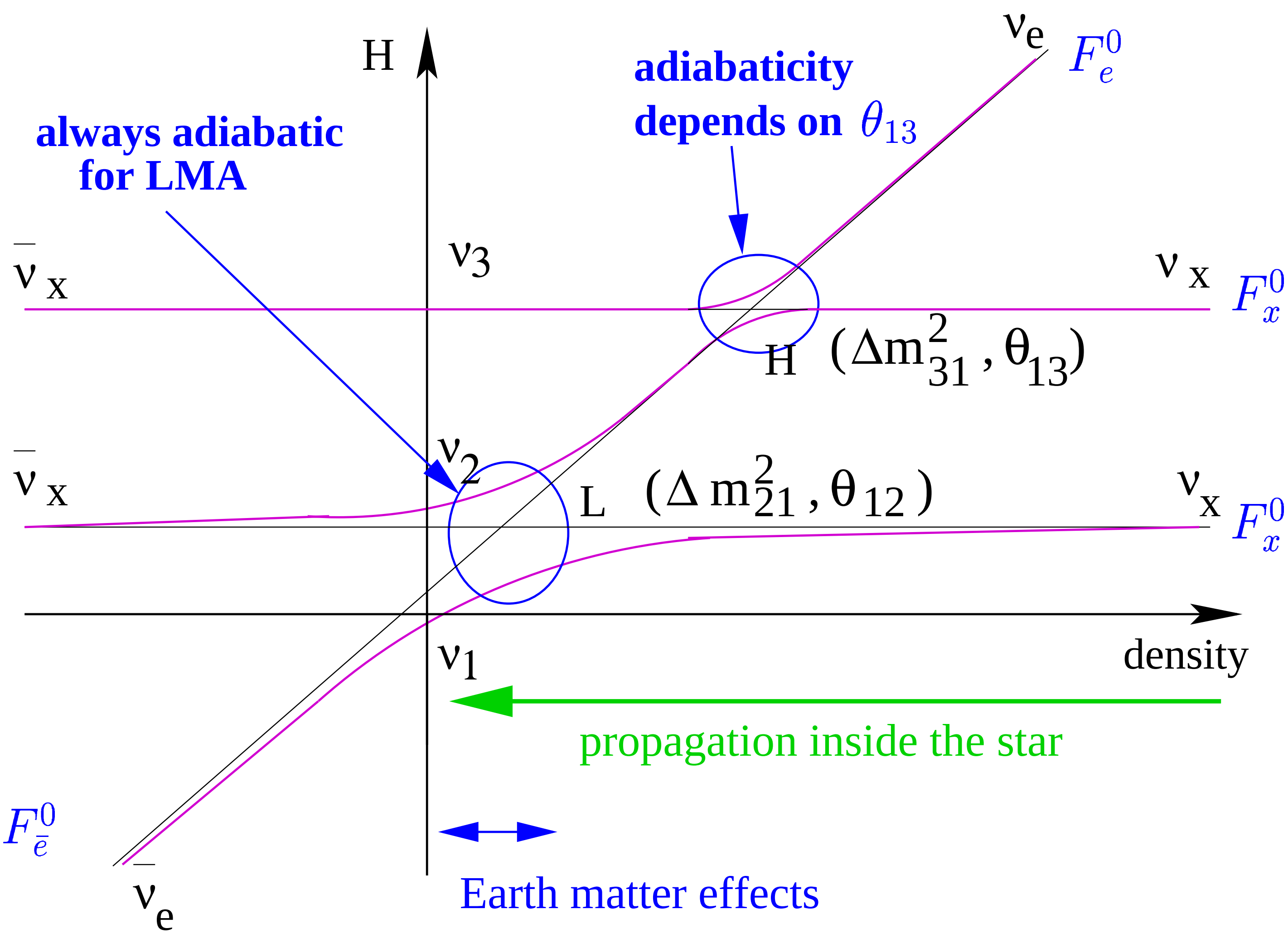
$$0.8 \quad : \quad 1 \quad : \quad 1.1$$

Similar luminosities (~ factor of 2)

[G.Raffelt, astro−ph/0105250]

conversion effects: swap of fluxes

for normal hierarchy:



Permutation: (LMA parameters taken)

P_H jump probability

$$F_e = P_H P_{2e} F_e^0 + (1 - P_H P_{2e}) F_x^0 \qquad P_{2e} \equiv P(\nu_2 \to \nu_e)$$

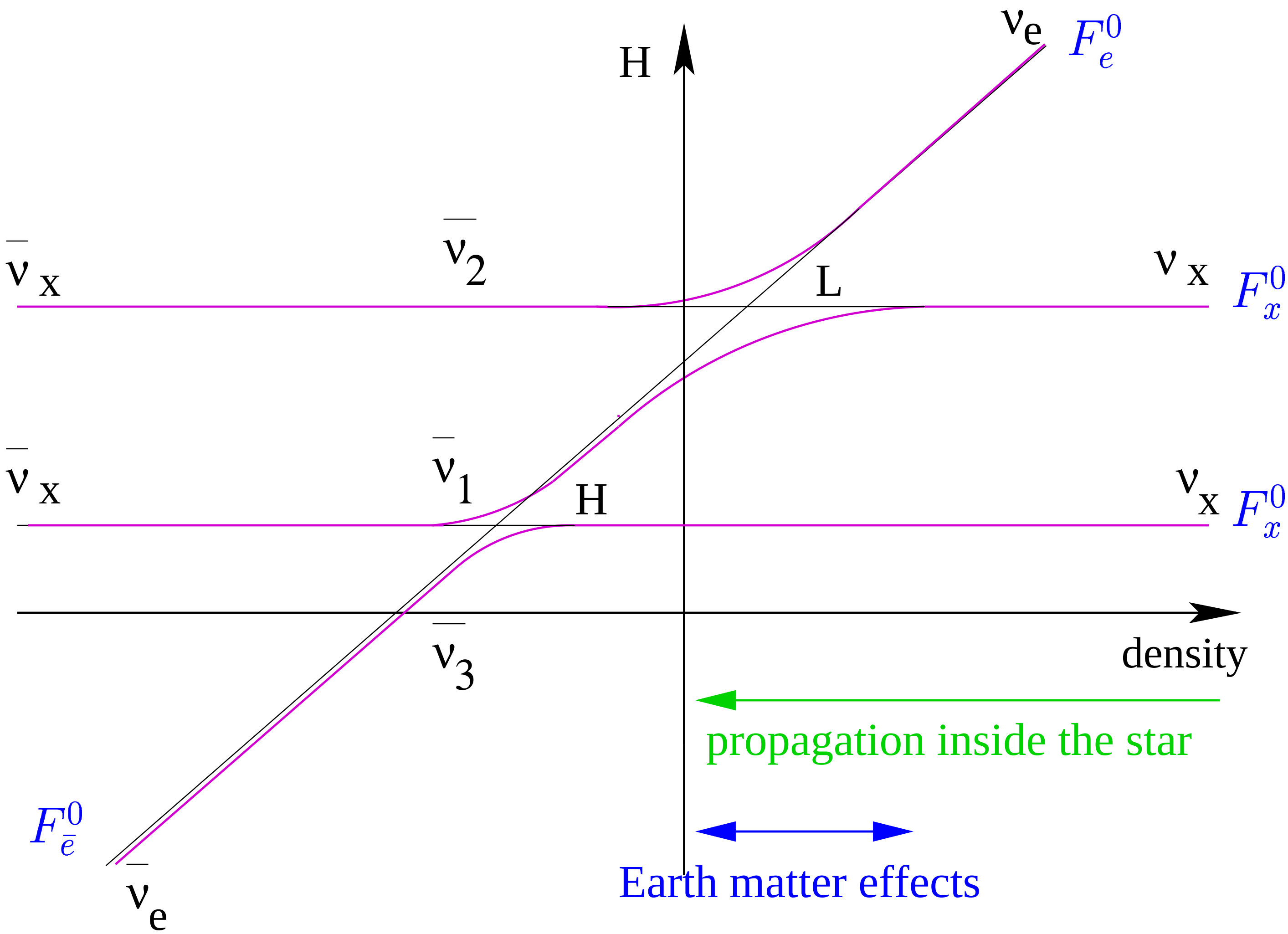
$$F_{\bar{e}} = P_{1\bar{e}} F_{\bar{e}}^0 + (1 - P_{1\bar{e}}) F_{\bar{x}}^0$$

hardening of spectra

with no Earth crossing:

$$P_{2e} = \sin^2 \theta_{12} \qquad P_{1\bar{e}} = \cos^2 \theta_{12}$$

for inverted hierarchy:



$$F_e = P_{2e} F_e^0 + (1 - P_{2e}) F_x^0$$

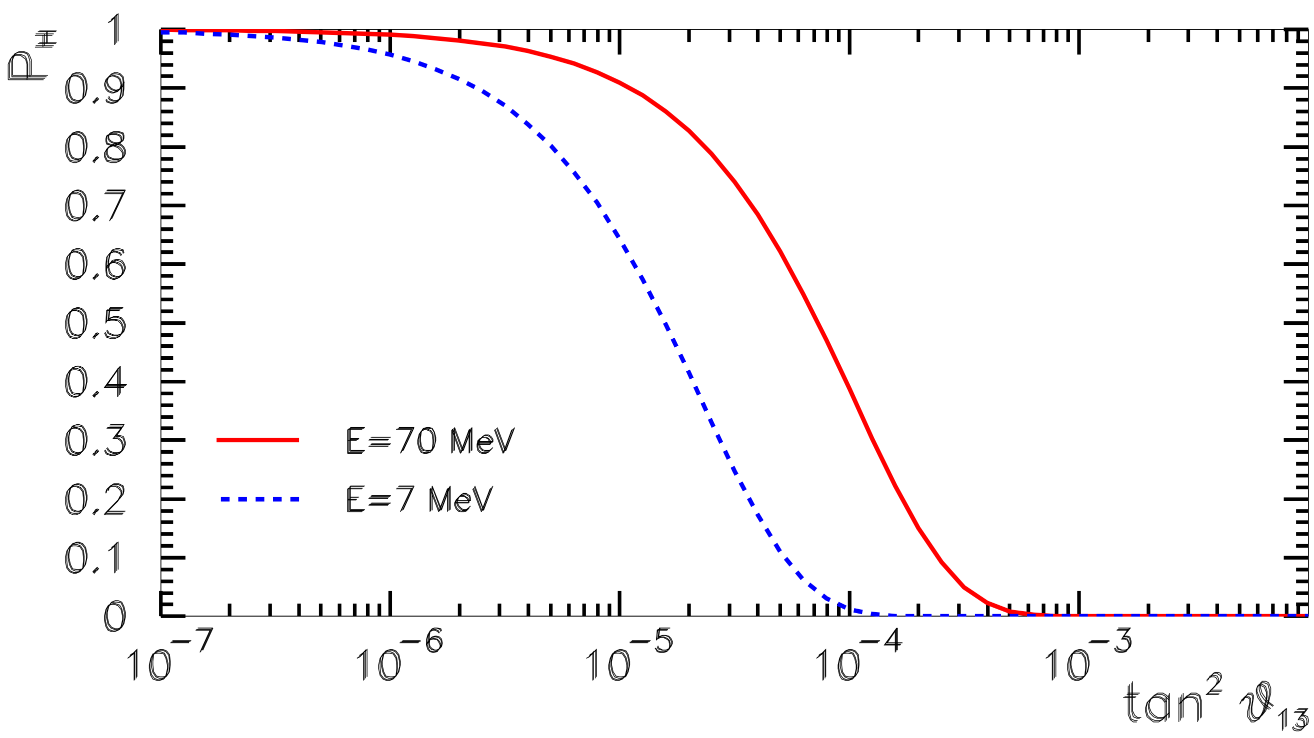
$$F_{\bar{e}} = P_H P_{1\bar{e}} F_{\bar{e}}^0 + (1 - P_H P_{1\bar{e}}) F_{\bar{x}}^0$$

Jump probability and θ_{13}

taking the density profile of the progenitor star,
$\rho(r) \propto r^{-3}$, the jump probability in the high density resonance has the form:

$$P_H \propto exp\left[-\sin^2\theta_{13}\left(\frac{|\Delta m^2_{31}|}{E}\right)^{2/3} const\right]$$

(Δm^2_{31} atmospheric mass splitting)



Detection of supernova neutrinos:

what is needed? high statistics, energy resolution, timing, flavor sensitivity, $\nu - \bar{\nu}$ sensitivity, directionality, low energy threshold....

what is feasible? examples...

WATER: SUPERKAMIOKANDE [Japan, 32kt volume]
(UNO, HyperK..)

$\bar{\nu}_e \; p \rightarrow e^+ \; n$ ~8000 events (D=10kpc)

$\nu_{e,\mu,\tau} \; e^- \rightarrow \nu_{e,\mu,\tau} \; e^-$ (ES) ~200+60+60 events

$\bar{\nu}_e \; O \rightarrow N \; e^+$

$\nu_e \; O \rightarrow F \; e^-$

HEAVY WATER: SNO [Sudbury, Ontario, 1kt volume]

$\nu_e \; d \rightarrow p \; p \; e^-$ ~240 events

$\bar{\nu}_e \; d \rightarrow n \; n \; e^+$ ~120 events

$\nu_{e,\nu,\tau} \; d \rightarrow p \; n \; \nu_{e,\mu,\tau}$ ~490 events

SCINTILLATOR: KamLAND [Japan, 1kt]
(Borexino, LVD...)

$\bar{\nu}_e \; p \rightarrow e^+ \; n$ ~330 events

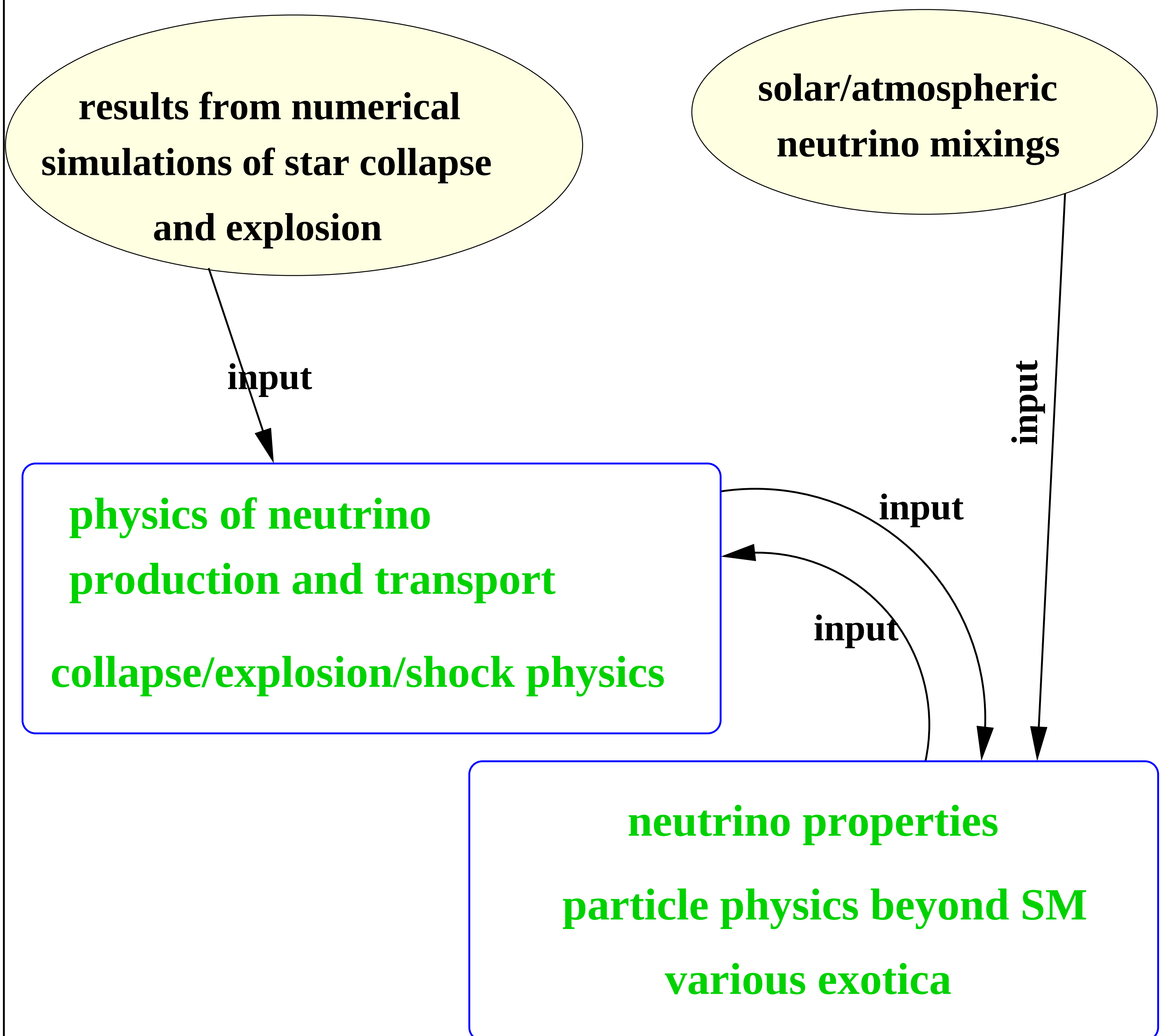
$\nu \; p \rightarrow \nu \; p$ ~300 events above 150 keV

$\nu_e \; ^{12}C \rightarrow ^{12}N \; e^-$

WHAT CAN WE LEARN FROM A FUTURE GALACTIC SUPERNOVA?

what is interesting? **what is feasible?**

ASTROPHYSICS **PARTICLE PHYSICS**

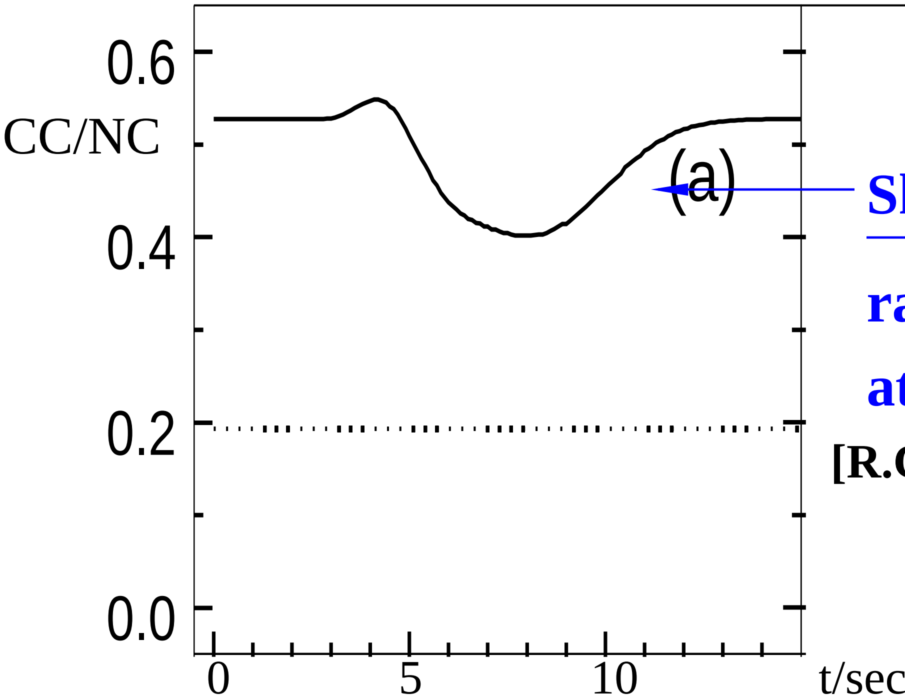


Astrophysical properties:

- **physics of collapse/shock wave propagation (time distribution of signal)**
- **physics of neutrino spectra formation and transport (spectra and luminosities of observed signal)**
- **early alert (SNEWS network)**

  pointing to the supernova $(\nu + e^- \rightarrow \nu + e^-)$

  physics of black−hole formation



Shock−effects:

ratios of CC/NC rates

at SNO

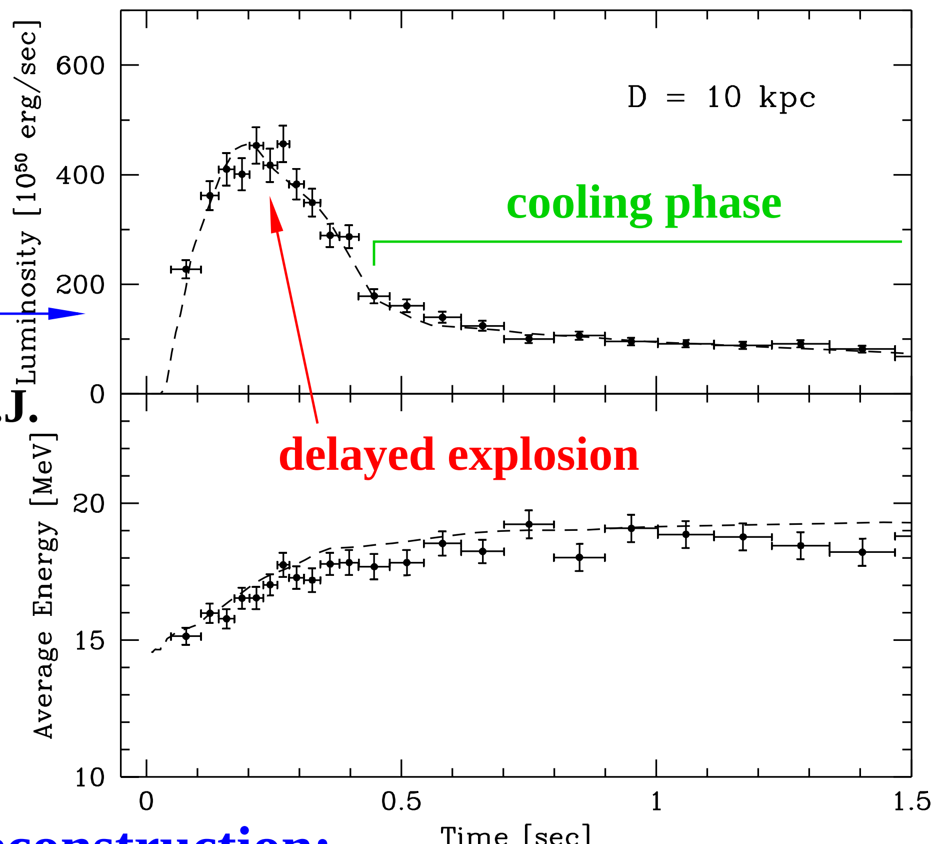
[R.C.Schirato and G.M.Fuller, astro−ph/0205390]

Time structure

of neutrino burst

seen at SuperK:

[T.Totani et al,Astrophys.J. 496:216−225,1998]



Energy/luminosity reconstruction:

fits of simulated data from SK and SNO show determination of average energies and luminosities with 10−20% accuracy

[Barger at al,hep−ph/0112125, Minakata et al, Phys.Lett.B542:239−244,2002]

Particle physics information:

- **Oscillation parameters: mass spectrum, (observed spectra) U_{e3} mixing**

- **absolute scale of neutrino mass (time delay)**

- **neutrino−induced refraction**

- **neutrino magnetic/transition moment,**
  non−standard interactions (FCNC)
  violation of equivalence principle (VEP)
  effects of CPT violation...
  sterile neutrinos, axions, ...
  physics of extra dimensions (KK−induced energy loss)

Probing oscillation parameters:

observed fluxes: (F_α^0 original fluxes)

ν_e**:** $$F_e = pF_e^0 + (1-p)F_x^0$$

$\bar{\nu}_e$**:** $$F_{\bar{e}} = \bar{p}F_{\bar{e}}^0 + (1-\bar{p})F_{\bar{x}}^0$$

No conversion effects if $F_e^0 = F_x^0, \; F_{\bar{e}}^0 = F_{\bar{x}}^0$ ***!***

different energy spectra for

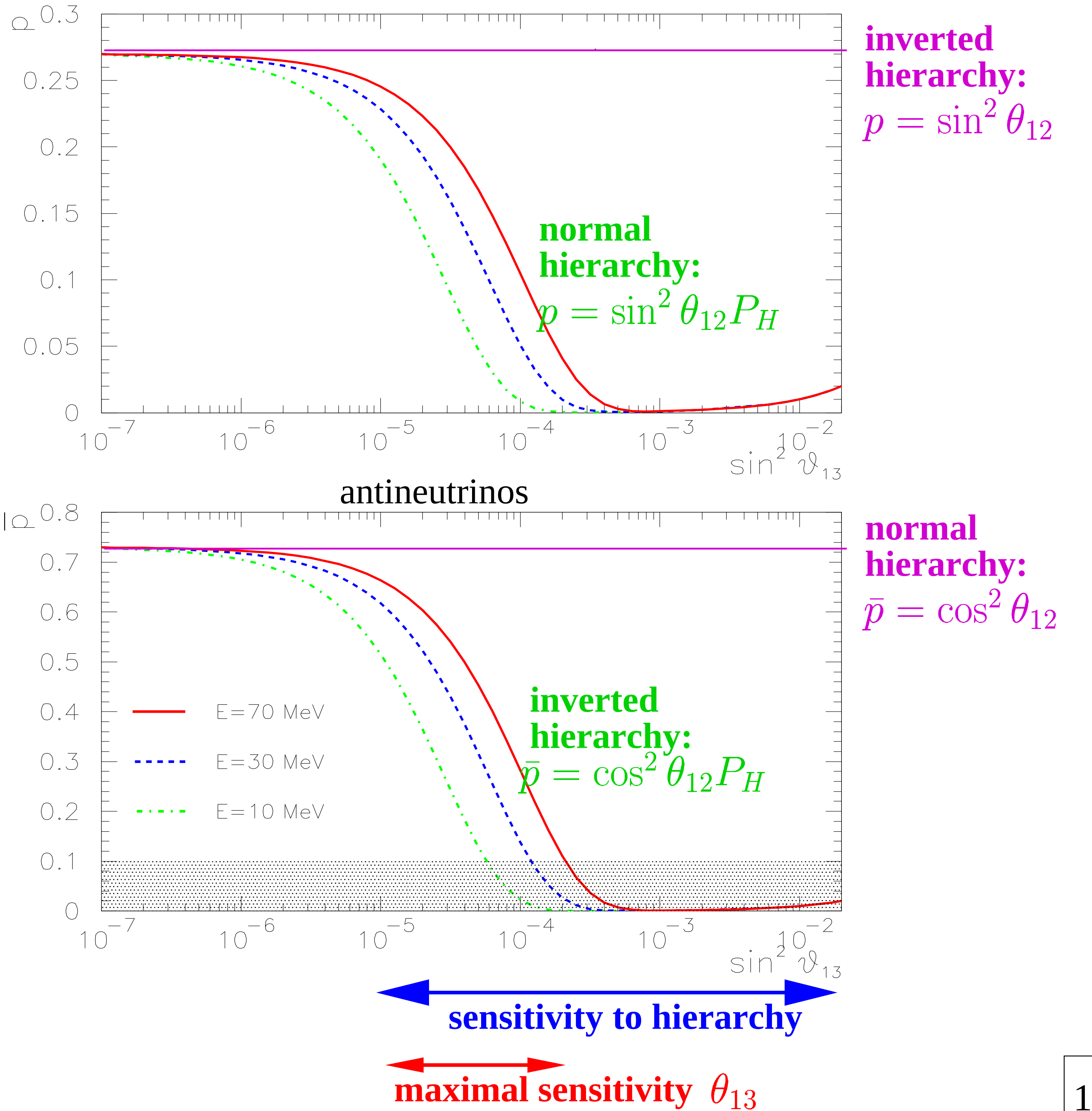
electron and non−electron flavors

is a necessary condition!

If the energy spectra are different,

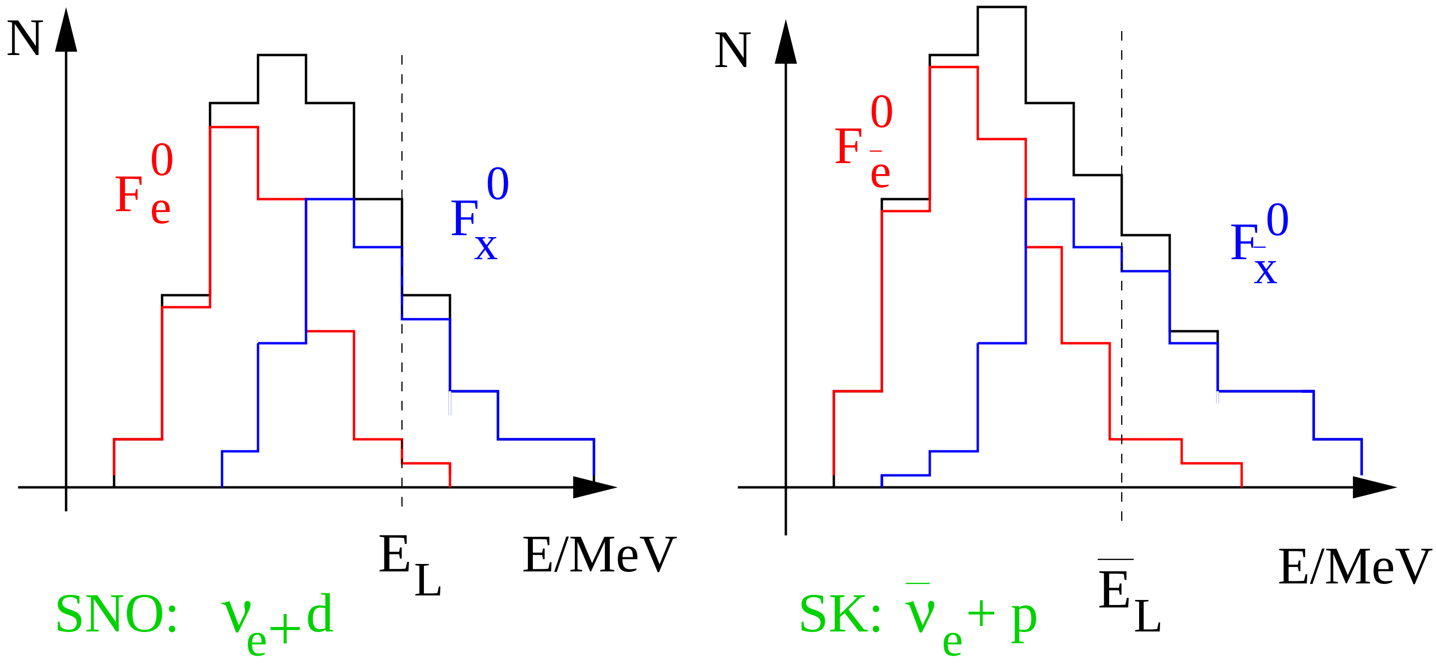
the mass hierarchy and the θ_{13} angle can be probed:

permutation parameters: neutrinos



good indicators are the high−energy tails of events collected in the first 3−5 seconds:

[C.L., A.Yu.Smirnov, in preparation]



effects of poor knowledge of original spectra are reduced

effects of poor knowledge of shock−wave physics are eliminated.

simple analytical description is possible.

$$R \equiv N^{SNO}(E > E_L)/N^{SK}(E > \bar{E}_L)$$

$$\simeq Q\mathcal{F}(\theta_{12}, \theta_{13}, hierarchy, \alpha, \bar{\alpha})$$

Q is precisely calculable for suitably chosen thresholds

$\alpha \equiv N_e^0/N_x^0, \;\; \bar{\alpha} \equiv N_{\bar{e}}^0/N_{\bar{x}}^0$ **measure overlap of spectra**

another approach: global fit of data.

global fit of the SuperKamiokande and SNO data can be performed with both astrophysical and oscillation parameters (the 13 angle) as fitting parameters. Certain a priori assumptions on the original energy spectra are needed.

[Barger et al., hep−ph/0112125]

Results:

Results strongly depend on assumptions on the original energy spectra (hierarchical or not)

If $T_{\bar{e}}/T_x \geq 1.1$ **is allowed,**

the mass hierarchy is very hard to determine.

Conditional bounds can be put on the θ_{13} **angle if:**

$\sin^2\theta_{13} \leq few \cdot 10^{-5}$ ⟶ $\sin^2\theta_{13} \leq few \cdot 10^{-4}$ **upper bound**

$\sin^2\theta_{13} \geq few \cdot 10^{-3}$ ⟶ $\sin^2\theta_{13} \geq few \cdot 10^{-5}$ **lower bound**

Conclusions:

The detection of neutrinos from a supernova in the (near? far?) future will produce a great excitement in the scientific community

The physics potential of the study of these neutrinos is enormous for both particle physics and astrophysics.

The models of core collapse and shock−wave propagation will undergo a crucial test

Among the many studies of physics beyond the Standard Model of particle physics, the missing pieces of the neutrino mass spectrum and mixing matrix will be probed.

Let us be patient... it is worth waiting!