

# Supernova neutrinos (SN $\nu$ )

Cecilia Lunardini  
Institute for Nuclear Theory  
and Physics Department  
University of Washington, Seattle  
[lunardi@u.washington.edu](mailto:lunardi@u.washington.edu)

Moving soon to *Arizona State University*

# What every (neutrino) physicist should know on SN $\nu$

- What is a supernova: exploding stars
  - Why certain stars explode
- Supernovae emit neutrinos
  - Why; Features of the emitted flux
- SN  $\nu$  were detected: SN1987A
- The future: the next SN  $\nu$  detection
- We can learn a lot from SN  $\nu$ 
  - Oscillations
  - Physics of core collapse
  - ...

# References

- These slides only for feeling/motivation
- Serious references:
  - The "bible":

*Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles.*  
G.G. Raffelt, 1996. Chicago, USA: Univ. Pr. (1996) 664 p.
  - On SN  $\nu$  oscillations:

Dighe and Smirnov, Phys.Rev.D62:033007,2000.  
e-Print: hep-ph/9907423
  - Reviews of current status of affairs:

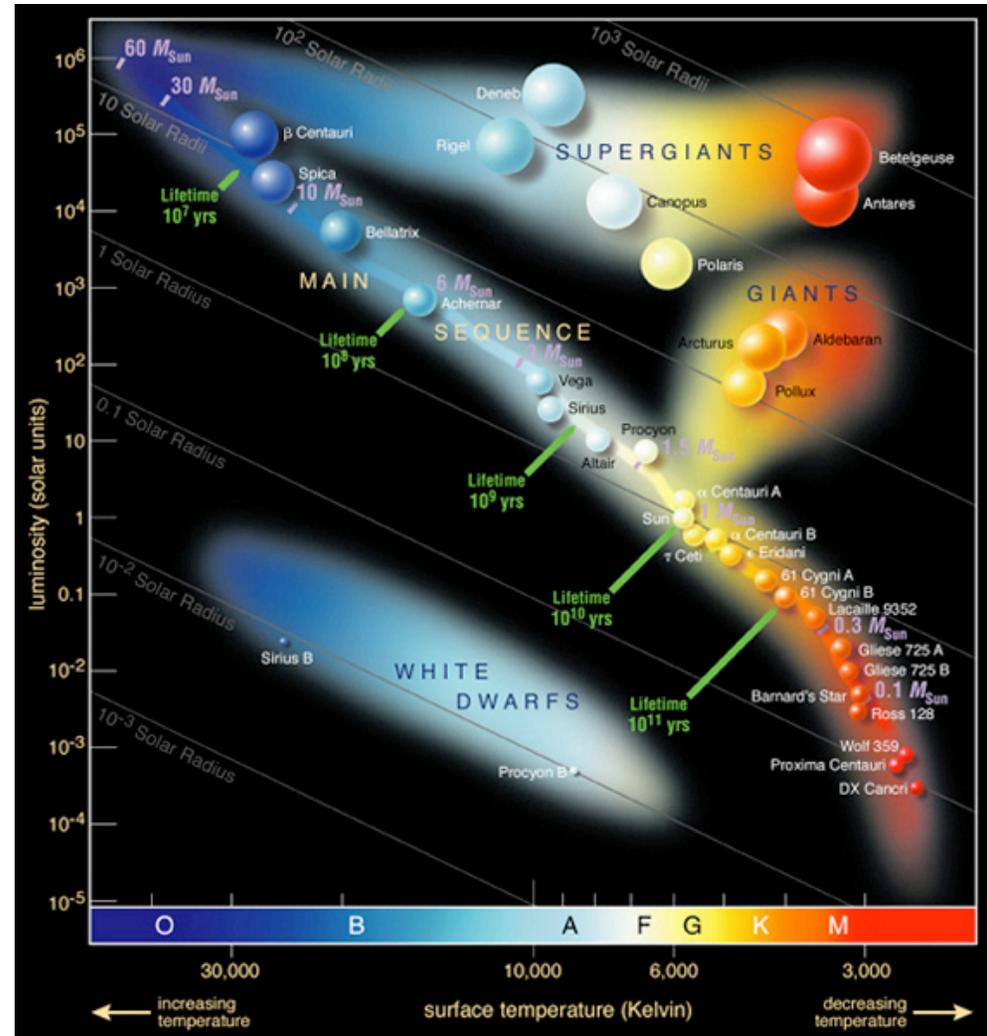
Neutrino 2006 conference: <http://neutrinosantafe06.com/>
  - More on SPIRES, arXiv  
(names in random order: Smirnov, Raffelt, Ando, Sato, Lunardini, Beacom, McLaughlin, Nunokawa, Minakata, Lisi, Janka, Fukugita, Fuller, Qian, Goswami, Dighe, Pastor, Kahelriess, Mangano, ...)

# What is a supernova?

Core collapse supernovae  
(type II, Ib, Ic, not Ia)

# Stars lifecycles

- Different mass, different fate

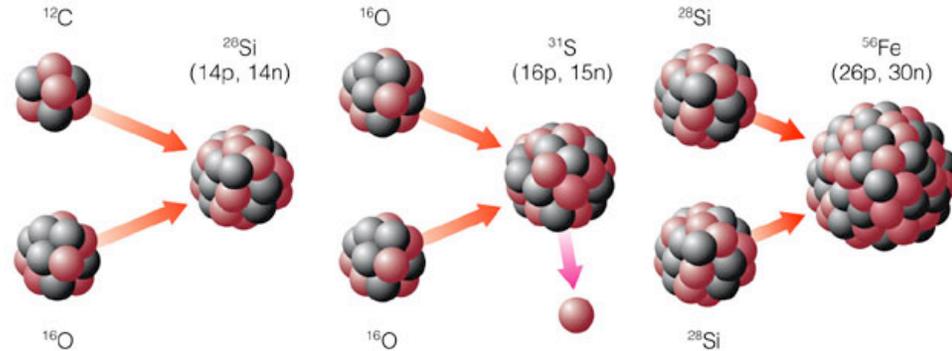


- A *supernova* is the final act of the life of large mass stars ( $M > 8 M_{\text{sun}}$ ): explosion!
- Why: gravity + nuclear physics (Fe)



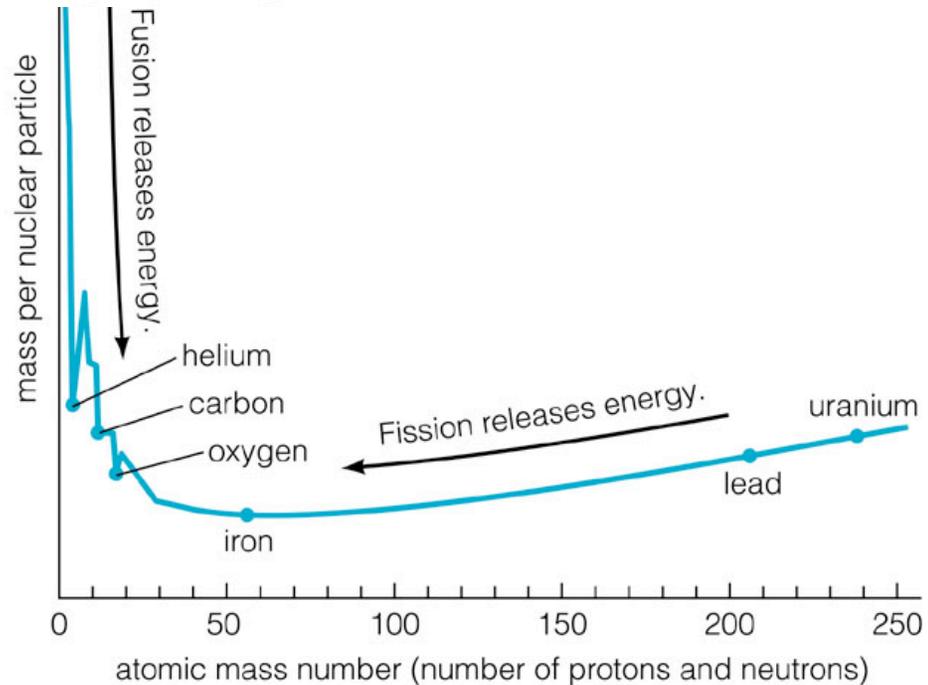
# Fusion chain: iron is the end

- Iron can not be fused
  - Highest binding energy



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- Iron mass is inert: no energy, no pressure



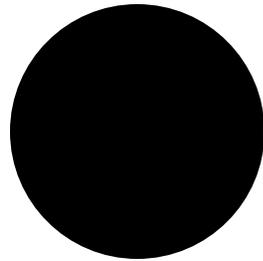
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# *The collapse*

- *Equilibrium in stars*: balance of gravity and pressure from nuclear fusion
- Iron core → less mass for fusion
  - loss of pressure
  - gravity wins
  - *collapse*

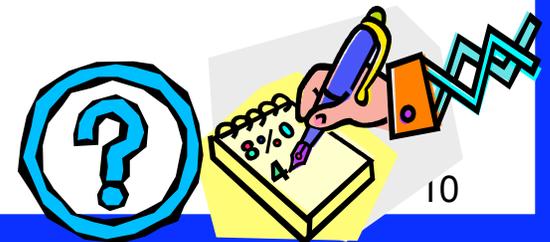
1. Nuclear fusion ends with Fe
2. Gravity wins: collapse into core of *nuclear density*  
( $\rho \sim 10^{14} \text{ g cm}^{-2}$ ,  $R \sim 20 \text{ Km}$ )
3. Bounce back, shock, explosion
4. Energy emitted (light, neutrinos, explosion)
5. Small, cold neutron star remains,  $M \sim (1.35 - 2.1) M_{\text{sun}}$

Neutron star



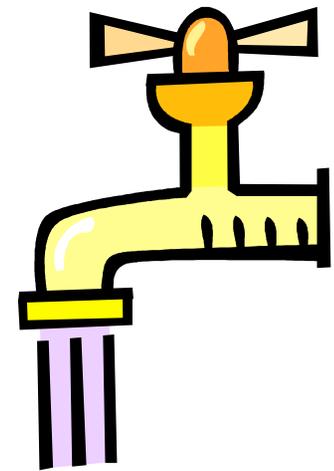
# Why the shock?

- The collapsed core has a very "stiff" equation of state (pressure-volume relation)= is virtually incompressible
- Matter falls on the core *supersonically*, i.e. faster than mechanic waves arriving from the core
  - The outer layers "don't know" that the core has become stiff
  - no time to adapt to the stiffening

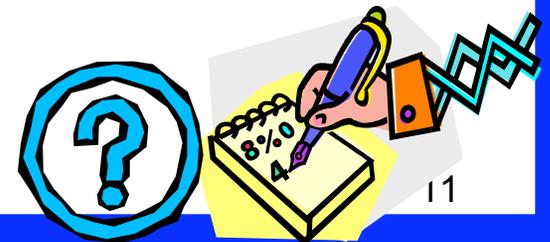


# A domestic shockwave: the water hammer

- If you close the faucet suddenly, a shockwave hits the pipe
  - Acoustic bang
  - Danger of hydraulic disaster



Don't try this at home!



# *Supernovae emit neutrinos*

.. why, how, ...

# Why do SN emit neutrinos?

- Physical conditions are right for *neutrino thermal equilibrium*:
  - Hot and dense:  $T \sim 5-30 \text{ MeV}$  ,  $\rho \sim 10^8 - 10^{14} \text{ g cm}^{-3}$
  - $\rightarrow$  m.f.p.  $\sim m_n / (G_F^2 E^2 \rho) \sim 10 \text{ cm} - 100 \text{ Km}$   
 $\ll$  size of star
  - Produced neutrinos ( $Z \rightarrow \nu$  , anti- $\nu$ ) stay trapped and a thermal gas of neutrinos builds up (*Fermi Dirac* population)

- Neutrino radiation is the most *efficient* mechanism of energy emission
  - Rule of thumb: the most weakly coupled particle is the best cooling channel (least absorbed)
  - Neutrinos are the most weakly coupled
  - → most energy must be emitted in  $\nu$  : star becomes colder by neutrino cooling

# Features of neutrino emission

- Luminosity  $\sim$  total energy budget
  - Energy emitted is of *gravitational* nature:  
 $L_\nu \sim G M_f/R_f - G M_i/R_i \sim 3 \cdot 10^{53} \text{ ergs}$   
( $R_f \sim 10 \text{ Km}$ )
- Duration of neutrino burst  $\sim$  diffusion time
  - Time  $\sim (\text{size}^2)/(\text{mean free path}) \sim 10 \text{ s}$

- Flavor composition: almost "democratic" ( $\nu_e, \nu_\mu, \nu_\tau, \text{anti-}\nu_e, \text{anti-}\nu_\mu, \text{anti-}\nu_\tau$  in similar amount)
  - Production and scattering rates similar for different species
- Energy spectrum:  $\sim$  Fermi Dirac

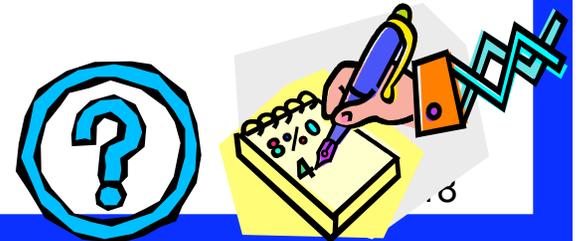
$$F_\alpha^0(E, T_\alpha, L_\alpha, D) = \frac{L_\alpha}{4\pi D^2 T_\alpha^4 F_3} \frac{E^2}{e^{E/T_\alpha} + 1}$$

- ferm. surface of decoupling,  $R \sim O(100)\text{Km}$
- $E \sim 3.15 T \sim 15\text{-}20 \text{ MeV}$

- Important deviation from flavor-democracy:  
*different energy spectra*
  - $\langle E_e \rangle < \langle E_{\text{anti-}e} \rangle < \langle E_x \rangle$   $x = \mu, \tau, \text{anti-}\mu, \text{anti-}\tau$
- Explanation:
  - Rule of thumb: the most strongly coupled particle decouples at lower density, where matter is colder --> colder spectrum
  - $\nu_x$  have neutral current only:  $\nu_x + n, p \rightarrow \nu_x + n, p$
  - $\nu_e$  and anti- $\nu_e$  couple via neutral current and charged current :  $\nu_e + n \rightarrow e^- + p$
  - There are more n than p  $\rightarrow \nu_e$  more strongly coupled than anti- $\nu_e$

# Interesting facts

- A supernova is the only place in the *modern* universe with thermal neutrinos
  - Other places are not dense enough (m.f.p.  $\sim 1$  light year of lead)
  - All other neutrino emitters are powered by different physics (fusion, fission, etc.)
- Overwhelming luminosity:
  - $3 \times 10^{53}$  ergs/10 s  $\sim 10^{18} L_{\text{sun}}$
  - Optical SN luminosity is minor ( $10^{-2} L_{\nu}$ ), a SN is essentially a *neutrino event*

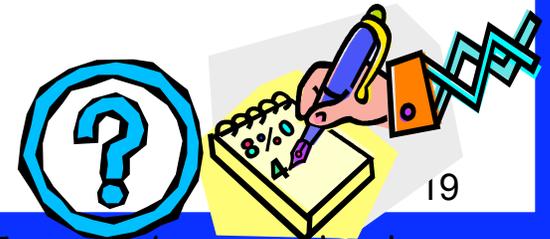


# Explosion or not explosion?



Mini-review: Woosley & Janka, Nature Physics 1 (2005) 147, astro-ph/0601261

- Simulations fail to produce explosion naturally (i.e., in a self consistent way, without adjusting parameters)
- It is important, but not worrisome, because:
  - Only part of the relevant physics is included (CPU reasons)
  - High precision required: only 1% of total energy budget goes into the shock!
- Feeling is that we are close to success

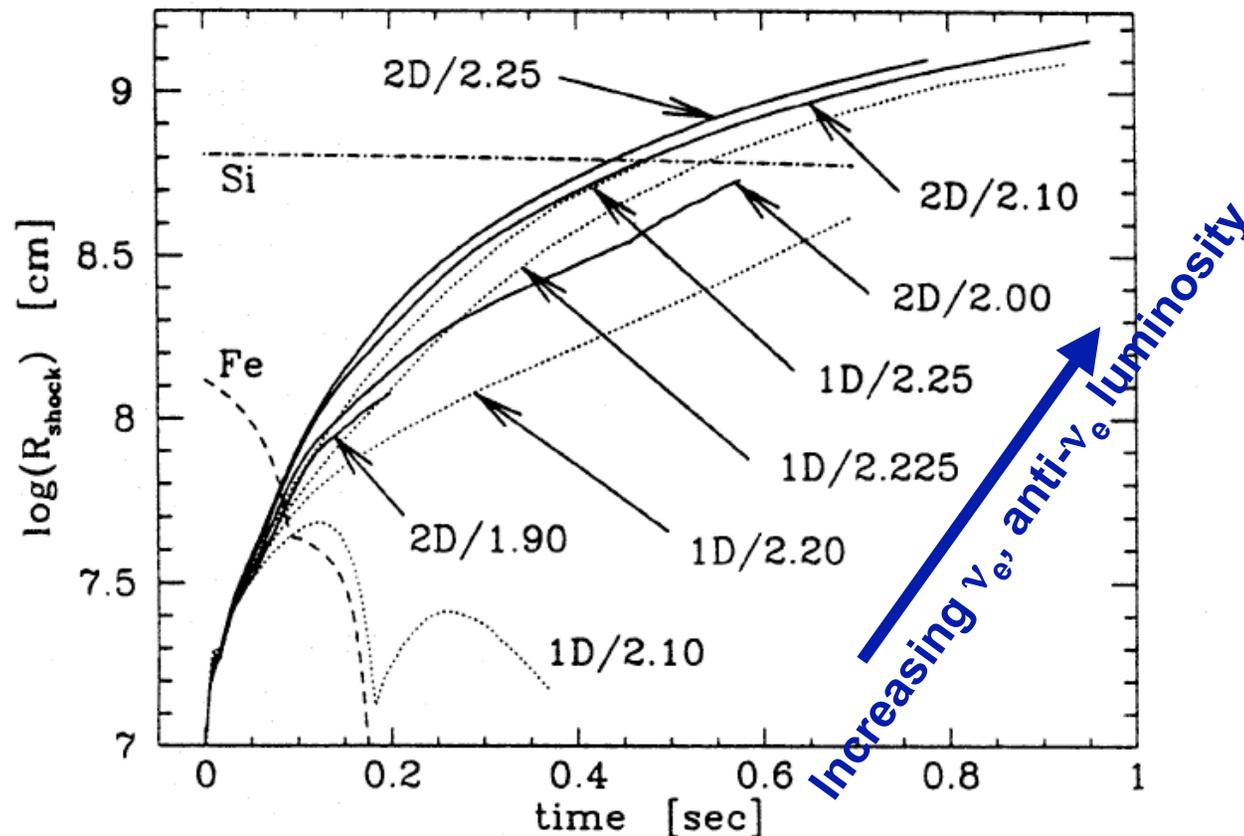


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# *$\nu$ help revive a stalled shock*

Colgate and White, *Astrophys. J.*, **143** (1966).

- Shock loses energy into dissociating iron
  - $\nu$  energy deposition into the shock



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Figure from Janka & Mueller, *Astron. Astrophys.* 306, 1996

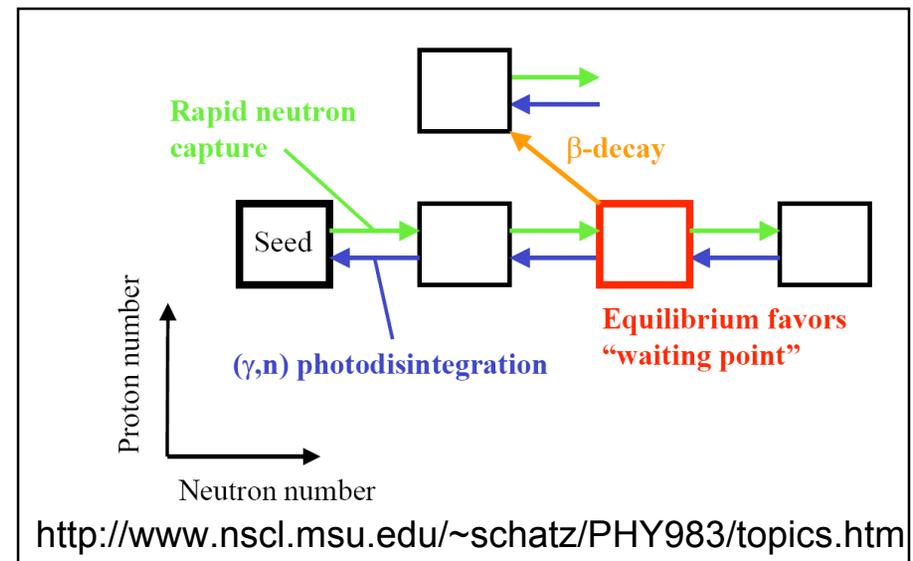
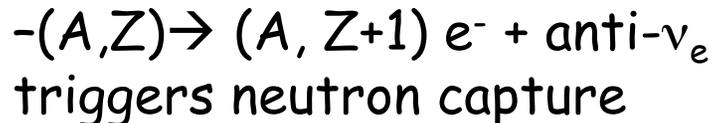
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# *$\nu$ influence synthesis of heavy elements*

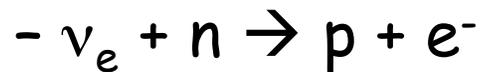
- Supernovae as elemental factories
  - Neutron-rich medium
- “rapid” neutron capture

## *(r-process)*

-Equilibrium:



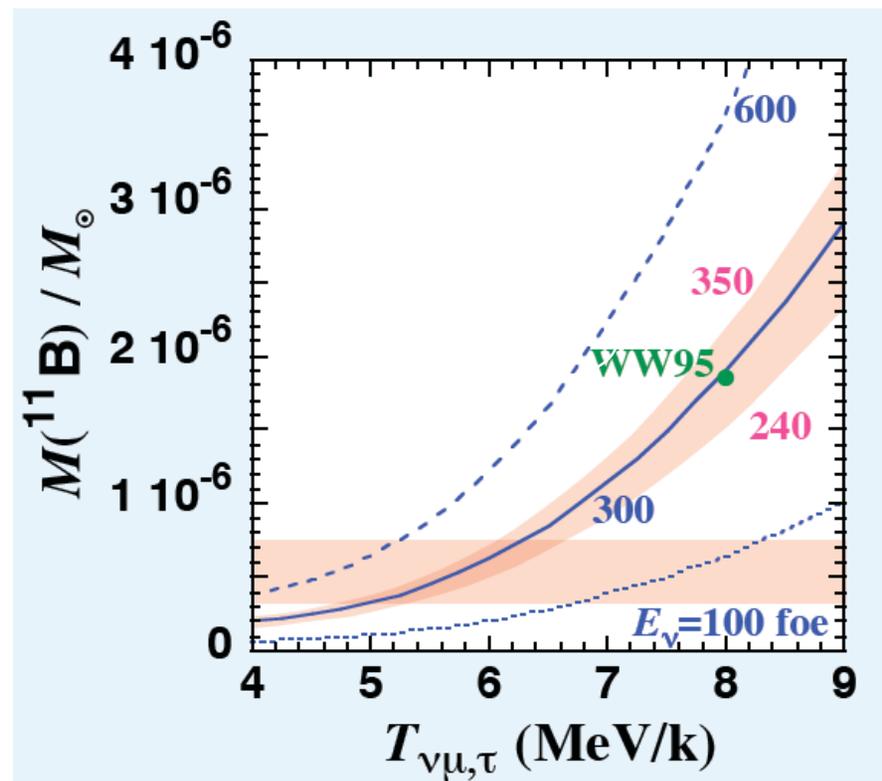
- Neutrino and r-process: determine n to p relative abundances



- Neutrino processes



*Strongly spectrum-dependent!*



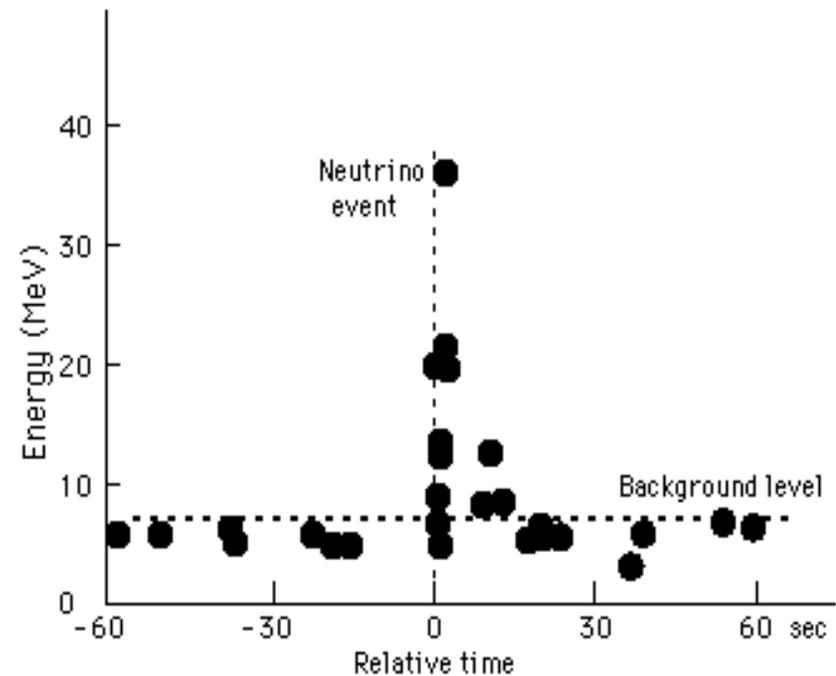
Yoshida, Kajino & Hartmann, PRL94, 2005;  
plot from talk by Yoshida & Kajino

*SN v were detected:*  
*SN1987A*

- February 23<sup>rd</sup> 1987: the closest SN of the modern era: Sanduleak -69 202 (Blue SuperGiant) in the Magellanic Cloud ( $5 \cdot 10^4$  pc) exploded, thus becoming **SN1987A**

Plot from: <http://astro.berkeley.edu/~bmetzger/sn1987a.html>

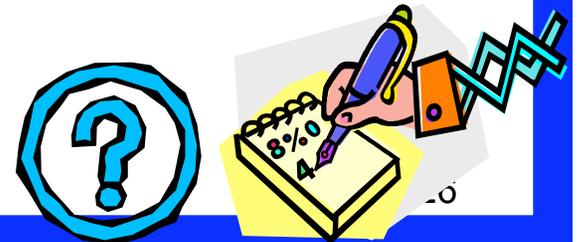
- Several hours *earlier*, at the solar neutrino detector *Kamiokande*, an unmistakable flash was received...
- The water of Kamiokande detected anti- $\nu_e$  from SN1987A :  
$$\text{anti-}\nu_e + p \rightarrow n + e^+$$



Observed by  
Cerenkov effect

# Neutrinos come first

- Neutrinos escape a SN in  $\sim 10$  s after collapse
- The explosion happens after few *hours* from collapse
  - Several hours is the time it takes for the shockwave to break through the surface of the star.
- Neutrino detector can give early alert to the astro community
  - SNEWS network of neutrino detectors



# *The first (and only, so far) test of core collapse theory*

- Data recorded by Kamiokande (Japan), IMB (USA) and Baksan (USSR)
- *Data agreed with theory*
  - "order of magnitude" level, low statistics
  - *Great success, birth of neutrino astrophysics!*

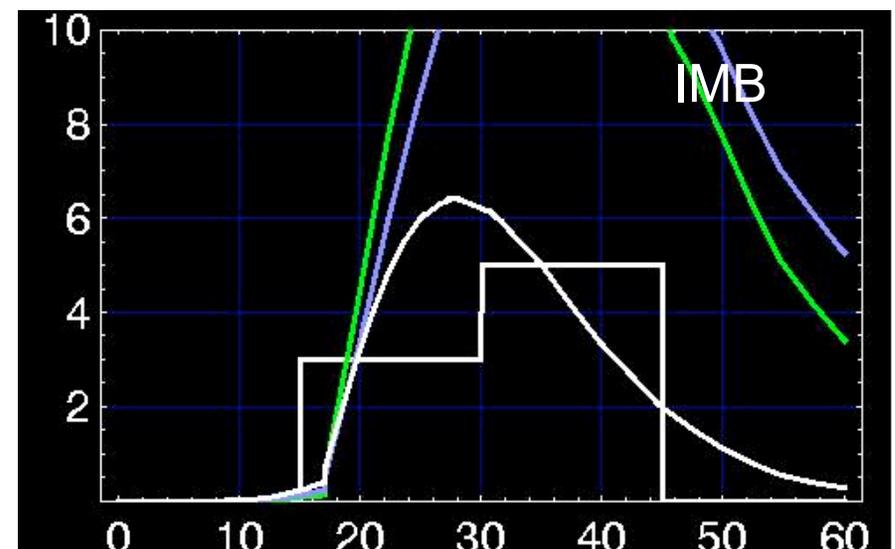
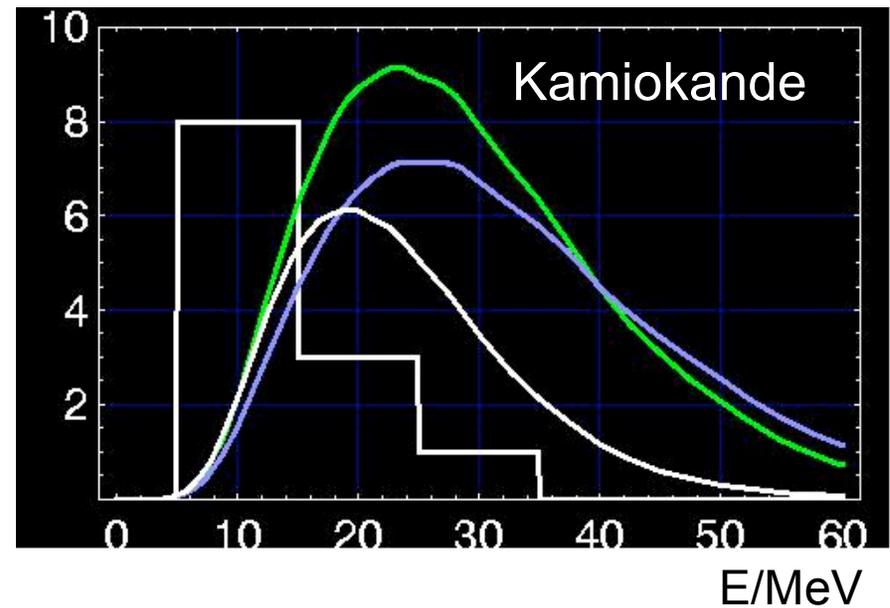
# Agreement is acceptable...

Bionta et al., PRL 58,1987,  
Hirata et al., PRL 58,1987,  
PRD 38,1988

$$\sin^2\theta_{13}=10^{-4}$$

- Garching/ORNL
- Lawrence Livermore
- Arizona

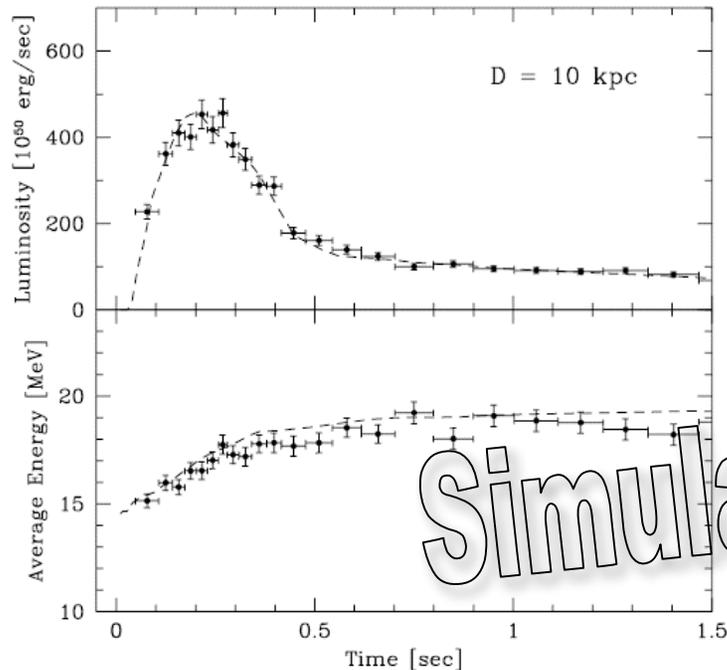
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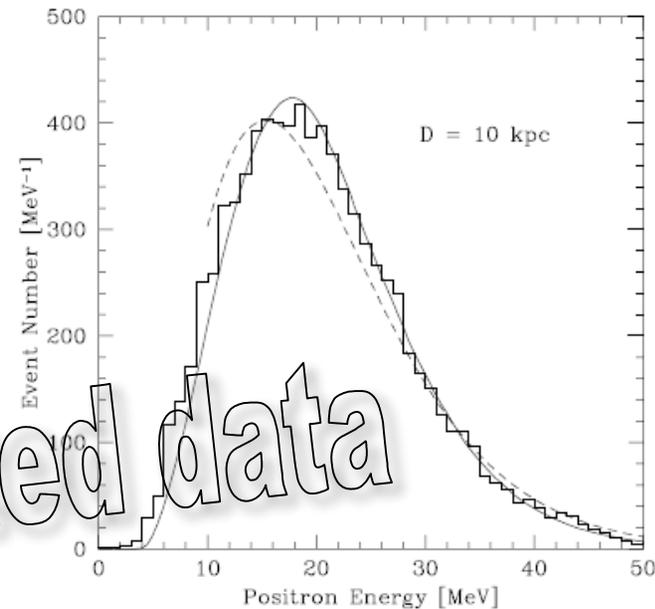
*The future: the next SN  $\nu$*   
*detection*

# 20 years later, better detectors

- SuperKamiokande wins for statistics:
  - $\sim 10^4$  anti- $\nu_e$  events for typical galactic distance  $d \sim 8-10$  kpc  $\rightarrow$  *precision!*
  - Few  $10^2$   $\nu_e$  events from  $\nu_e + O \rightarrow e^- + F$



Simulated data

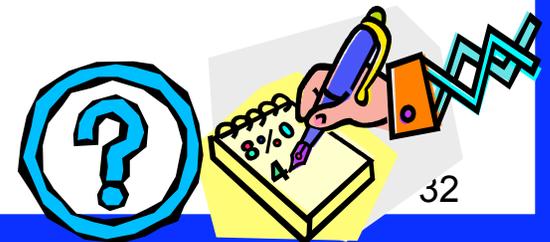


# Future detectors

- Liquid scintillator best for energy resolution  
anti- $\nu_e + p \rightarrow n + e^+$  , LENA (EU project)
- Liquid Argon best for  $\nu_e$  detection
  - $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}$  , LANDD, ...
- Size is crucial:
  - Megaton water Cherenkov (UNO, HyperKamiokande,  $\sim 20 \text{ } \text{£ SK}$ ) will open new era: more precision, look farther out in the Universe

# Why don't we detect SN $\nu$ all the time?

- Only SN nearby give detectable flux
  - SuperKamiokande can see only as far as 1 Mpc ( $\sim 1$  event in SK)
- SN are relatively rare
  - Need very massive star (1% of all stars)
  - $\sim 1-4$ /century within 1 Mpc radius



# Will we ever advance enough to see SN $\nu$ continuously?

- With Megaton size, we will see the *diffuse flux* of SN  $\nu$ 
  - Sum of all  $\nu$  from all SN in the universe
  - $\sim$  constant in time  $\rightarrow$  transition from rare event to routine detection (just like solar  $\nu$ , atmospheric  $\nu$ , etc..)



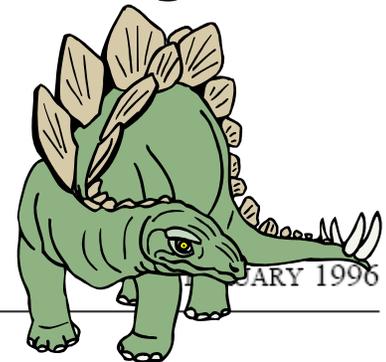
*The last SN seen in the galaxy  
was in the 1600's. Isn't a galactic  
SN overdue by now?*

- No reason to worry:
  - Statistics is statistics
  - We most likely have missed some
    - Obscuration
    - No telescopes available in suitable observation points (southern emisphere...)
    - No neutrino detectors available until ~ 30 years ago



# Are $\nu$ from a nearby SN dangerous?

- Only if you stand really close (few pc)
  - $\nu$  produce Atom recoil  $\rightarrow$  DNA damage
  - Did neutrinos kill the dinosaurs?



VOLUME 76, NUMBER 6

PHYSICAL REVIEW LETTERS

JANUARY 1996

## Biological Effects of Stellar Collapse Neutrinos

J. I. Collar\*

*Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208*  
(Received 13 April 1995)

Massive stars in their final stages of collapse radiate most of their binding energy in the form of MeV neutrinos. The recoil atoms that they produce in elastic scattering off nuclei in organic tissue create radiation damage which is highly effective in the production of irreparable DNA harm, leading to cellular mutation, neoplasia, and oncogenesis. Using a conventional model of the galaxy and of the collapse mechanism, the periodicity of nearby stellar collapses and the radiation dose are calculated. The possible contribution of this process to the paleontological record of mass extinctions is examined.



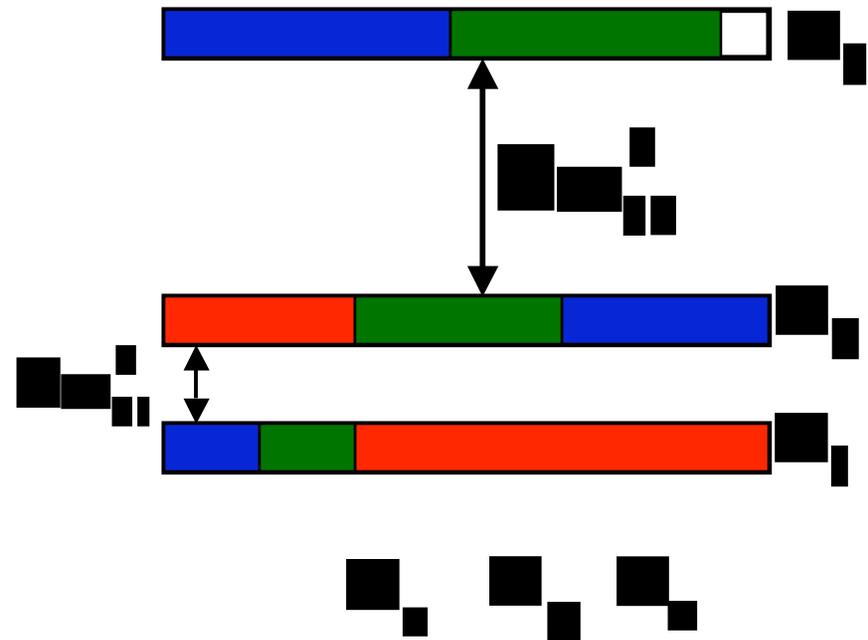
*We can learn a lot from SN  $\nu$*

Oscillations  
Physics of core collapse

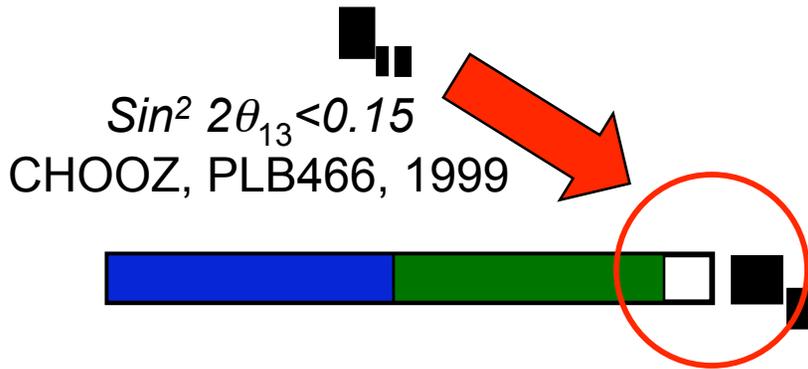
# Oscillations

# Masses and mixings

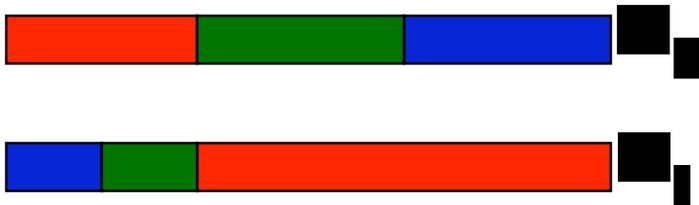
- *solar* :  $\nu_e$ 
  - $\Delta m^2_{21} \sim 8 \cdot 10^{-5} \text{ eV}^2$  ,
  - $\tan^2 \theta_{12} \sim 0.3$
- *atmospheric*:  $\nu_\mu - \nu_\tau$ 
  - $|\Delta m^2_{32}| \sim 3 \cdot 10^{-3} \text{ eV}^2$
  - $\tan^2 \theta_{23} \sim 1.0$



# The (unknown) supernova angle, $\theta_{13}$



Commonly called *reactor angle*



Normal  
 hierarchy,  
 $\Delta m^2_{32} > 0$



Inverted  
 hierarchy,  
 $\Delta m^2_{32} < 0$

## Why "supernova" angle?

- $\theta_{13}$  drives conversion inside a SN, via the *MSW effect*
- The *super-dense matter* inside the SN satisfies the MSW resonance condition:  
$$2^{1/2} G_f n_e = \cos 2\theta_{13} \Delta m_{31}^2 / (2E) \rightarrow \sin 2\theta_{13}(\text{matter}) \sim 1 !!$$

- Resonance density: 
$$\rho_{res} \approx \frac{1}{2\sqrt{2}G_F} \frac{\Delta m^2}{E} \frac{m_N}{Y_e} \cos 2\theta$$

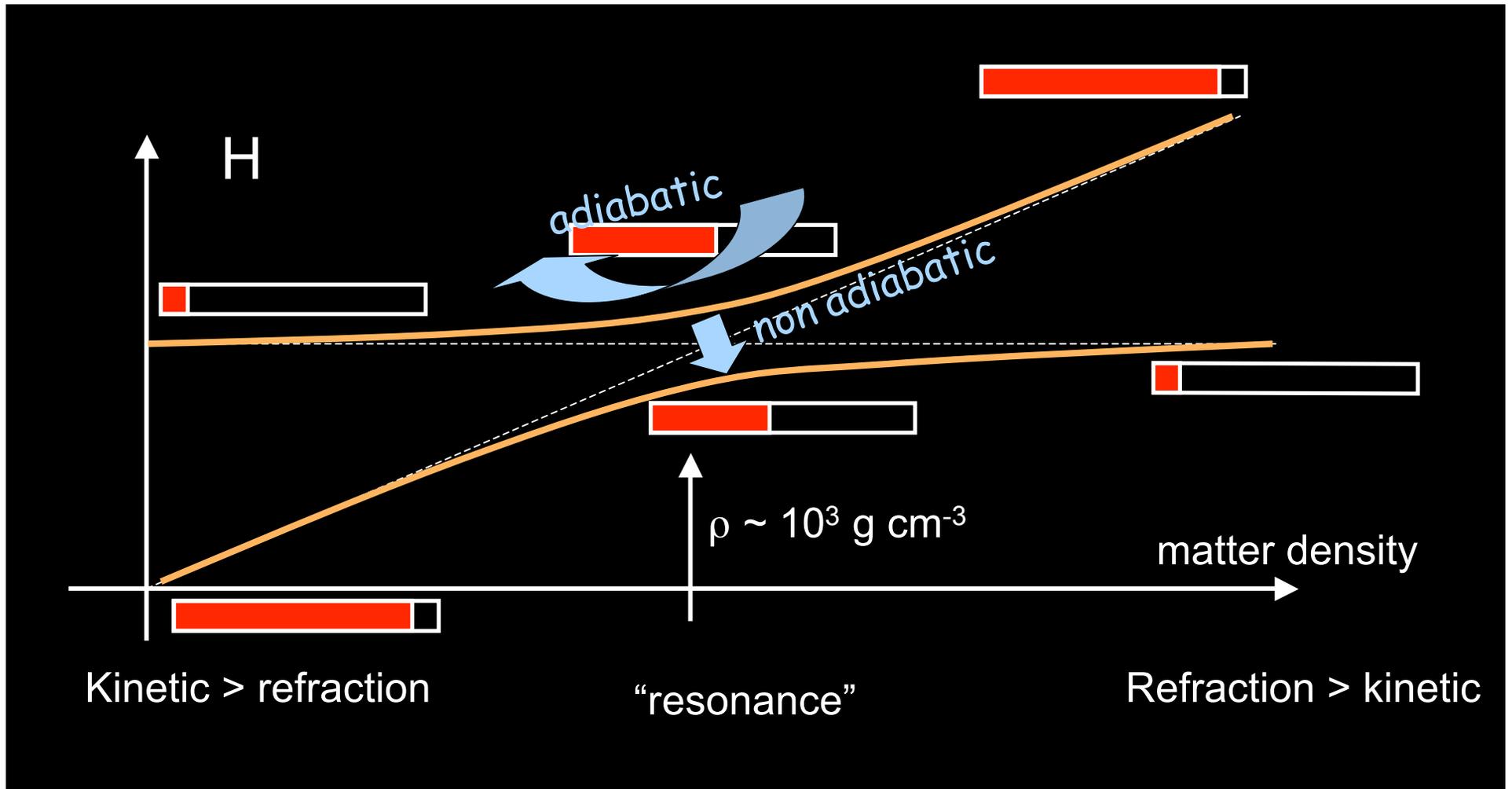
$$\sim 1.4 \times 10^6 \text{ g/cc} \left( \frac{\Delta m^2}{1 \text{ eV}^2} \right) \left( \frac{10 \text{ MeV}}{E} \right) \left( \frac{0.5}{Y_e} \right) \cos 2\theta$$

- Two resonances :

1.  $\Delta m^2_{31} \sim 3 \cdot 10^{-3} \text{ eV}^2 \rightarrow \rho_{res} \sim \text{few } 10^3 \text{ g cm}^{-3}$   
*Unique of supernova*

2.  $\Delta m^2_{21} \sim 7 \cdot 10^{-5} \text{ eV}^2 \rightarrow \rho_{res} \sim \text{few } 10 \text{ g cm}^{-3}$   
 star and Earth

# Basics of MSW resonance



Mikheev, Smirnov, Wolfenstein (1985,1978)

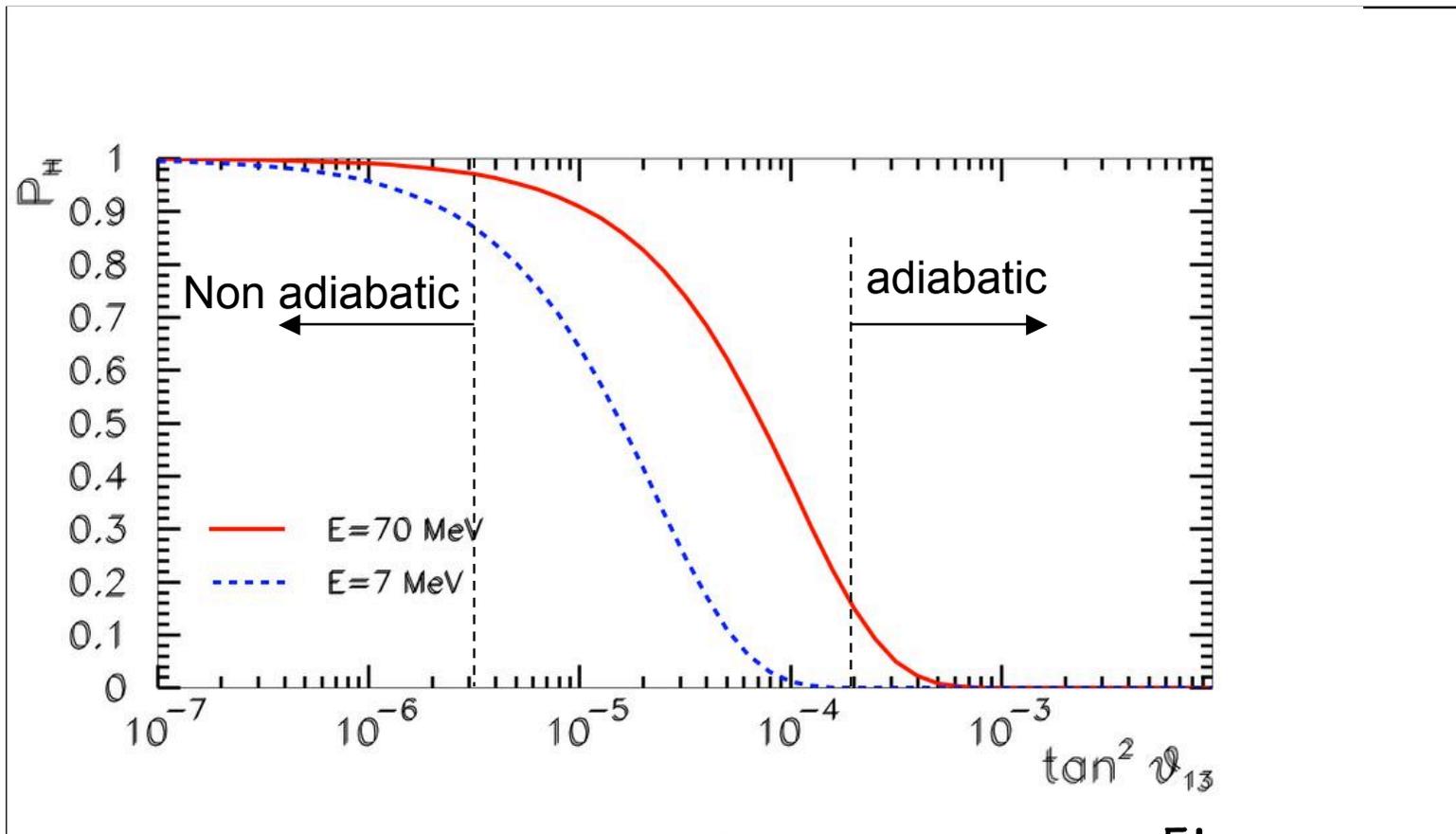
# Transition ("jumping") probability

- Depends on density profile:

$$P_f = \exp\left(-\frac{\pi}{2}\gamma\right)$$
$$\gamma \equiv \frac{\Delta m^2 \sin^2 2\theta}{2E \cos 2\theta} \frac{1}{(1/n_e)(dn_e/dr)}$$

- In a SN:  $\rho / r^{-3}$

$$P_H = \exp\left[-\left(\frac{E_{na}}{E}\right)^{2/3}\right],$$
$$E_{na} \simeq 1.08 \cdot 10^7 \text{ MeV} \left(\frac{|\Delta m_{32}^2|}{10^{-3} \text{ eV}^2}\right) C^{1/2} \sin^3 \theta_{13}$$

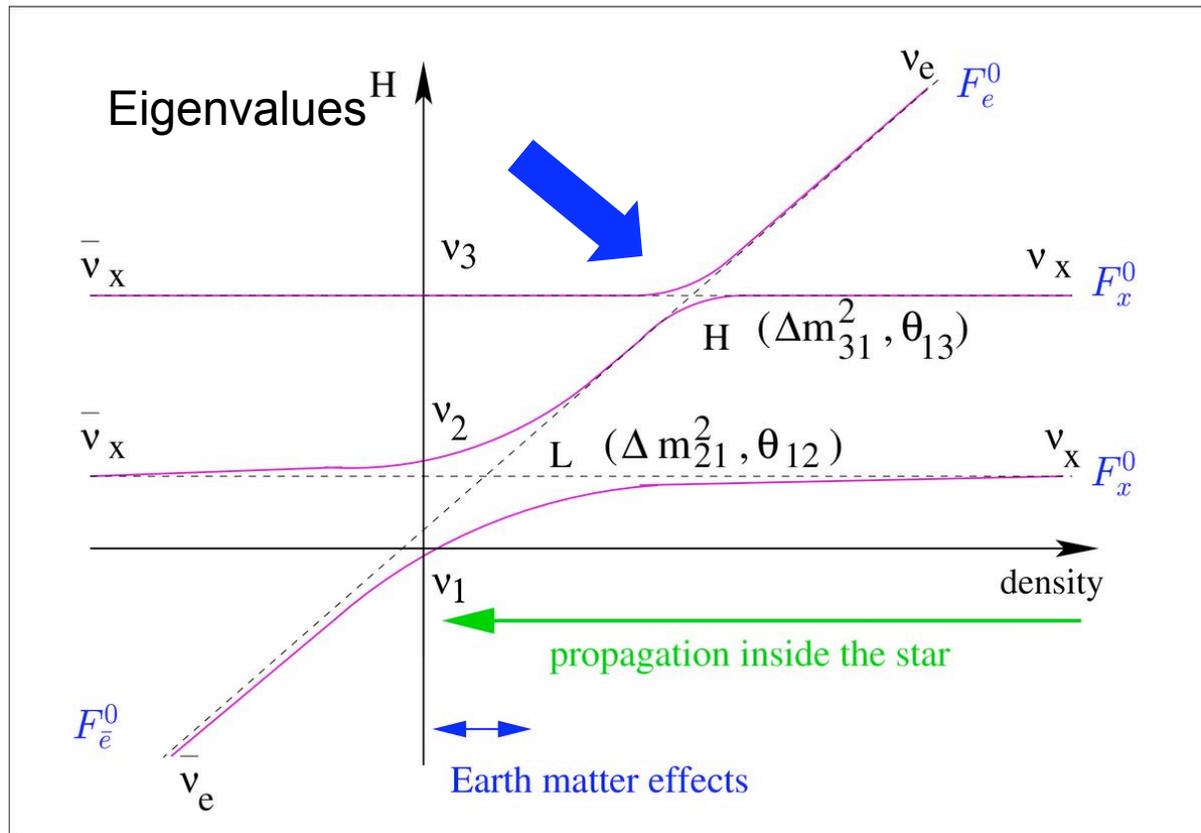


- Measure  $P_H \rightarrow$  test  $\tan^2 \theta_{13}$  down to  $10^{-5}$ !

# $\theta_{13}$ as switch

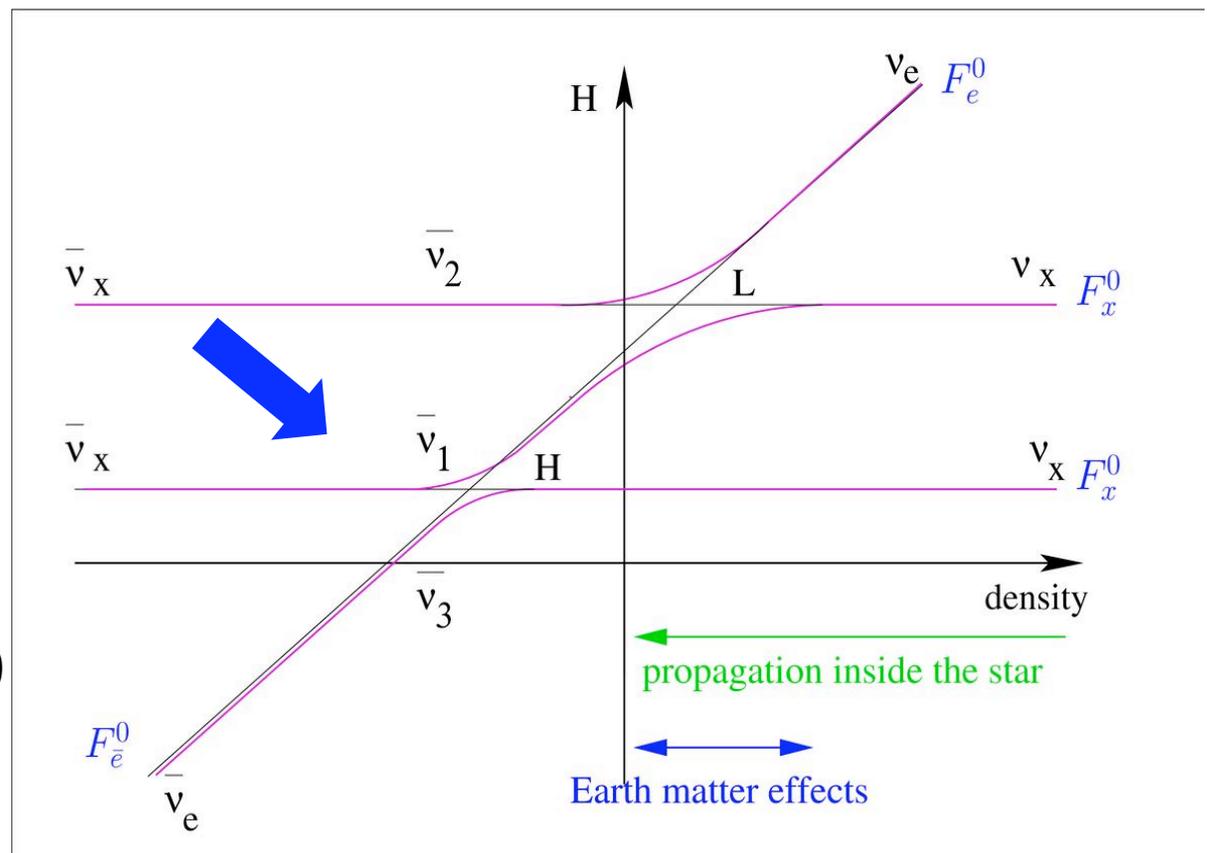
## Normal hierarchy:

- Adiabatic,  
 $\nu_e \rightarrow \nu_3 \sim \nu_\mu$
- Non adiabatic,  $\nu_e$   
 $\rightarrow \nu_2 \sim \sin \theta \nu_e +$   
 $\cos \theta \nu_\mu$



## Inverted hierarchy:

- Adiabatic  
 $\text{anti-}\nu_e \rightarrow \text{anti-}\nu_3 \sim \text{anti-}\nu_\mu$
- Non adiabatic  
 $\text{anti-}\nu_e \rightarrow \text{anti-}\nu_1 \sim \cos \theta \text{ anti-}\nu_e + \sin \theta \text{ anti-}\nu_\mu$



# Oscillated fluxes: hardening of spectra!

$$F_e = p F_e^0 + (1-p) F_x^0$$

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

*Harder spectrum!*

Normal hierarchy:

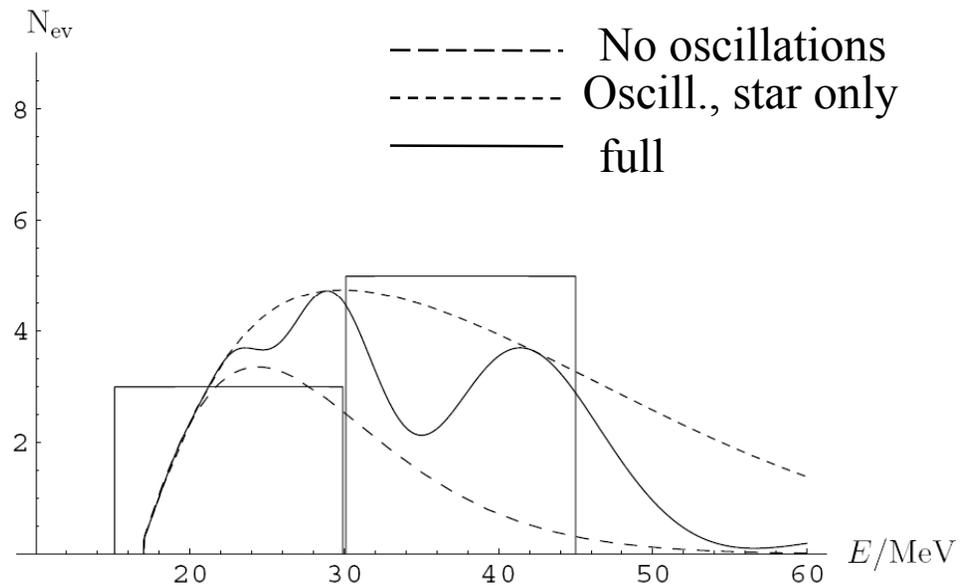
$$p = P_H \sin^2 \theta_{12}$$

$$\bar{p} = \cos^2 \theta_{12}$$

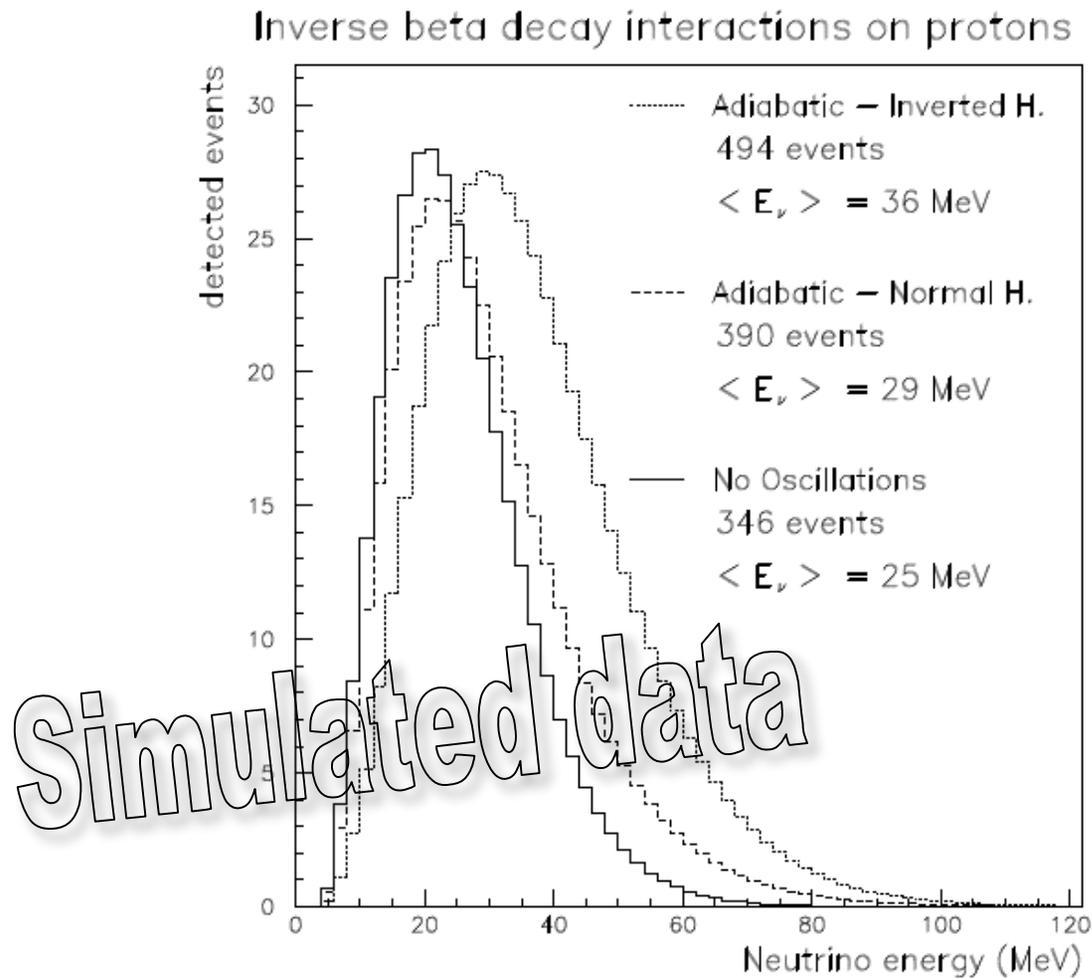
Inverted hierarchy:

$$p = \sin^2 \theta_{12}$$

$$\bar{p} = P_H \cos^2 \theta_{12}$$



# Spectra will tell about $\theta_{13}$ and hierarchy

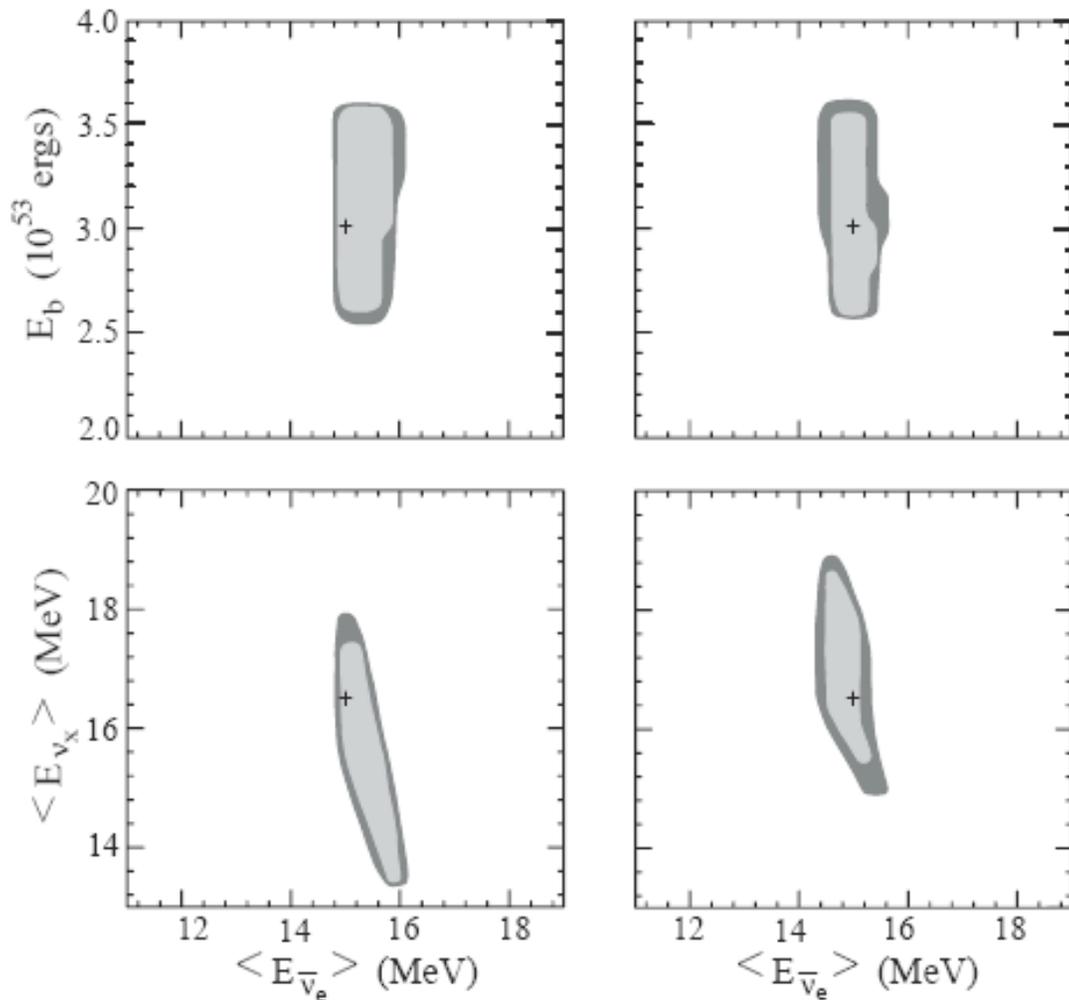


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Plot from LVD experiment, *Astropart.Phys.*27:254-270,2007

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- A fit to data will give *precise* energies and luminosities



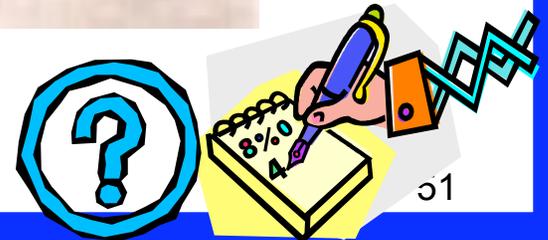
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From: Barger, Marfatia and Wood, Phys.Lett.B547:37-42,2002

# Physics of core collapse

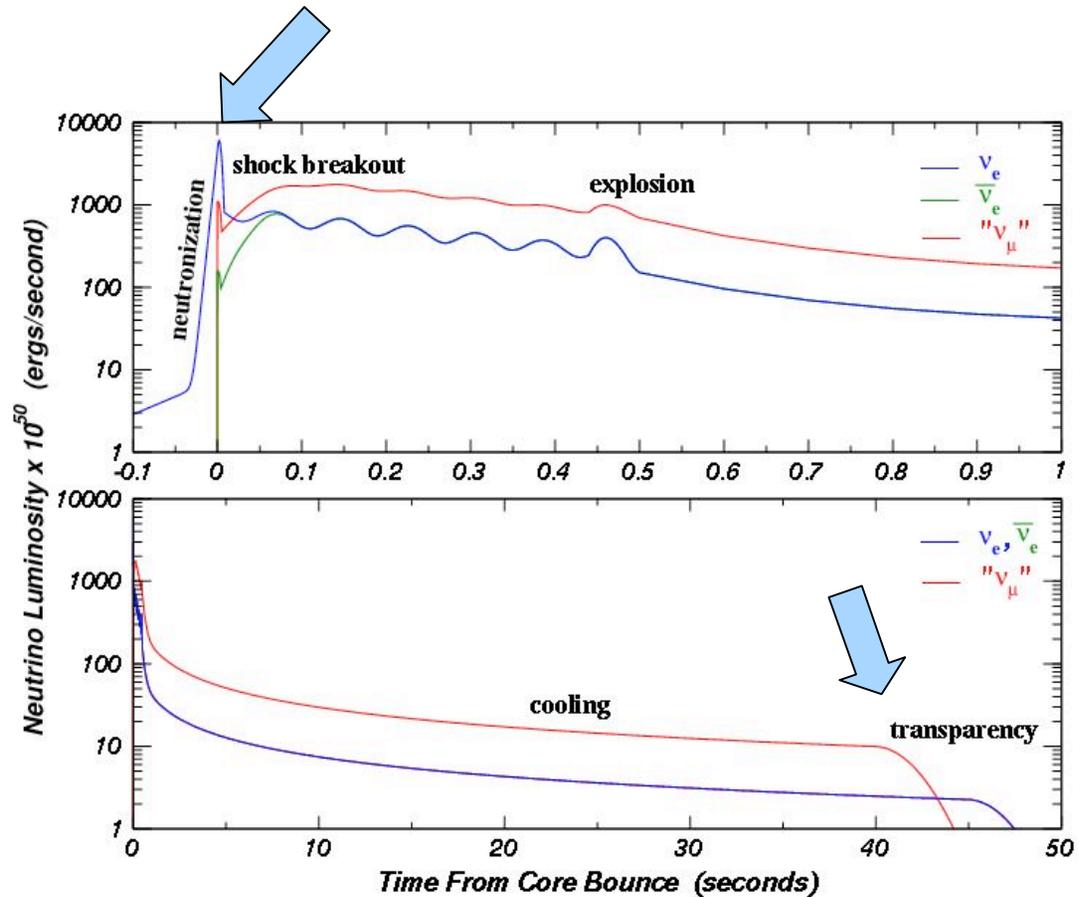
# Looking inside a SN

- Neutrinos are the only radiation coming out from near the collapsed core
  - *Only way to image the interior of the star!*
  - Similar to taking a radiography of an object



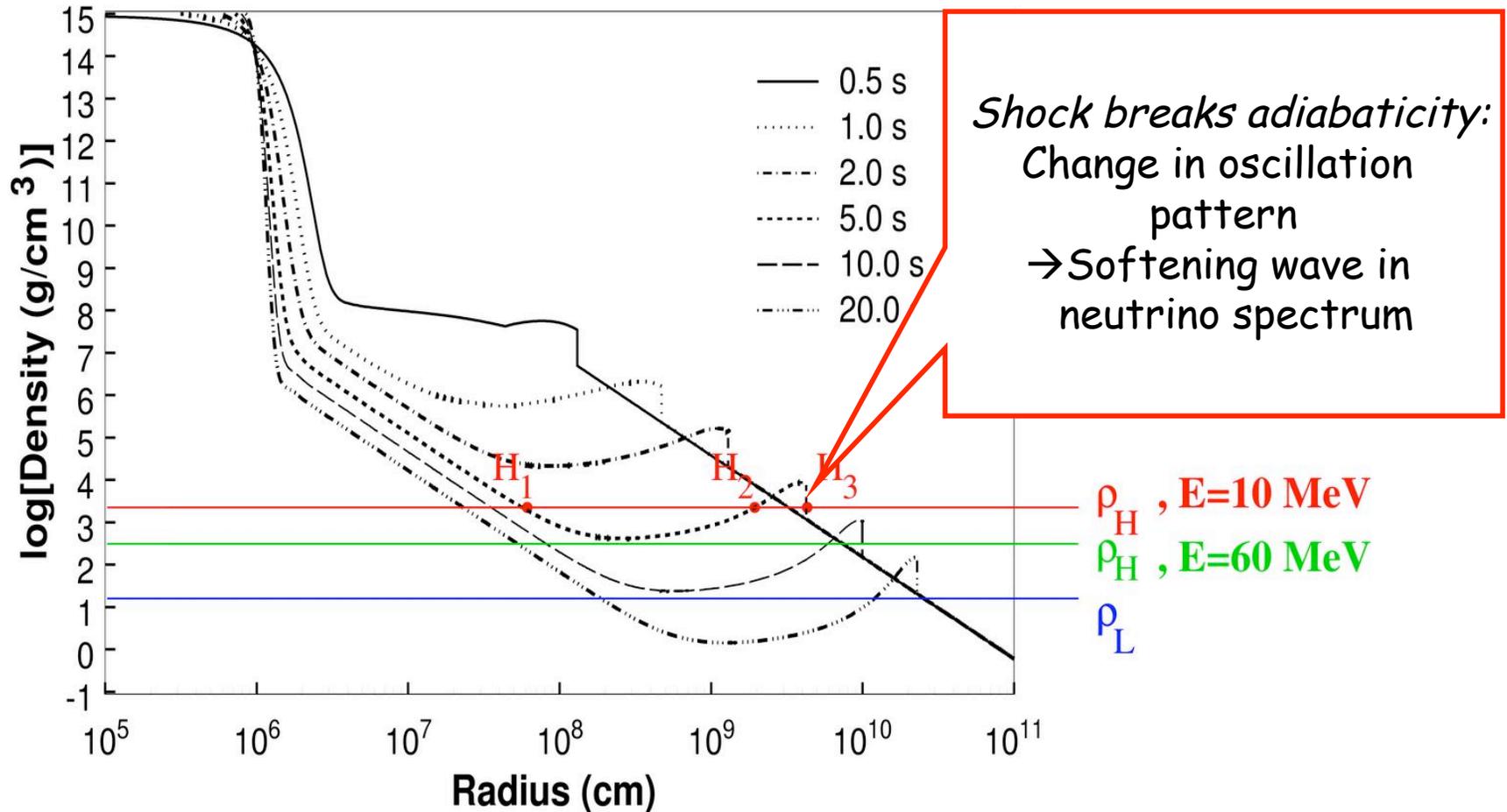
# Watch the collapse happening!

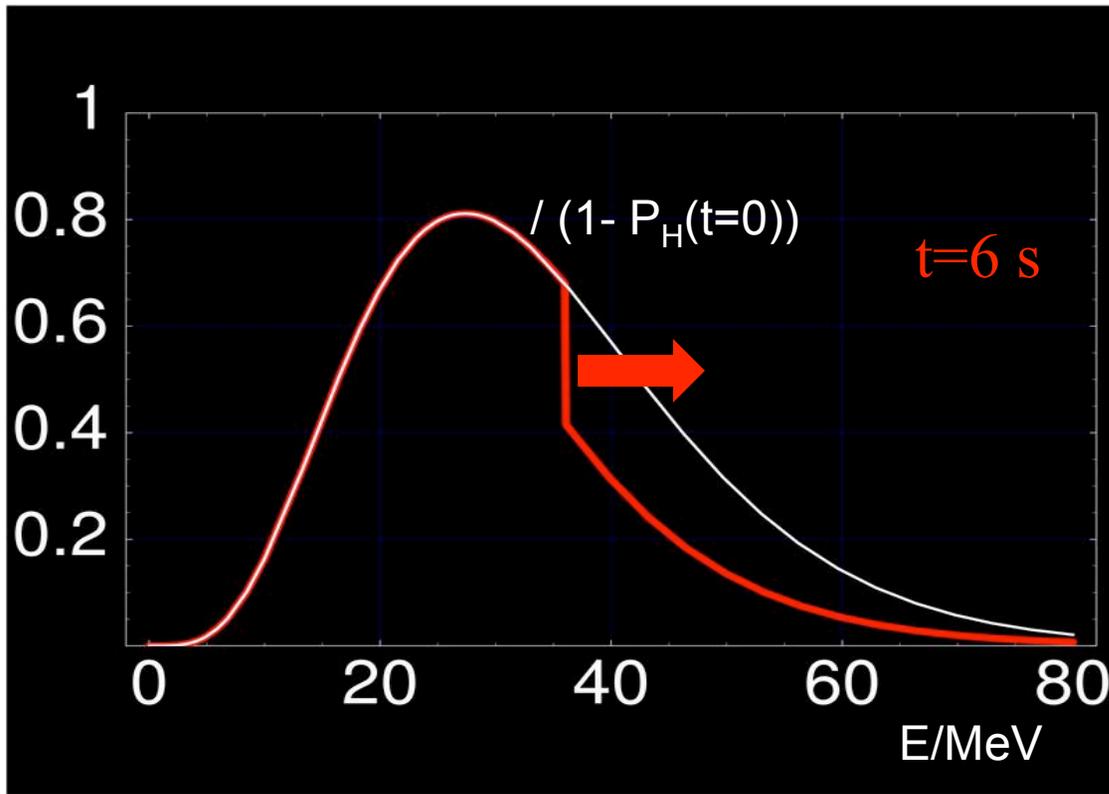
- *Neutronization*: pressure makes atoms "swallow" their own electrons
  - $e^- + p \rightarrow n + \nu_e$
- *Transparency*



# Monitor the shockwave

Schirato & Fuller, astro-ph/0205390





$$E_{0e} = 15 \text{ MeV}$$

$$E_{0x} = 21 \text{ MeV}$$

$$L_e = L_x$$



Miscellanea...

# Neutrinos can locate a SN

- $\nu + e^- \rightarrow \nu + e^-$  carries angular information
  - 5 degrees sensitivity at SuperKamiokande
  - Guidance for astronomers, unique if SN is obscured

## Looking for exotic particles: the energy loss argument

- If a particle is more weakly interacting than  $\nu$  and can be produced in a SN, it contributes to cooling
  - faster cooling and less luminous  $\nu$  burst
  - Can reveal (or constrain) axions, sterile neutrinos, ...

# *The lecture in one slide*

- Massive stars explode as supernovae due to gravity and nuclear physics
- A supernova is mostly a neutrino phenomenon: 99% of total energy
- The next galactic supernova will give a high statistics signal in detectors
  - Precision physics
- We will :
  - Test theory of core collapse
  - Learn about missing neutrino mixing and masses
  - Constrain/reveal exotica
  - ...