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SUPERNOVA NEUTRINOS

AT FUTURE DETECTORS

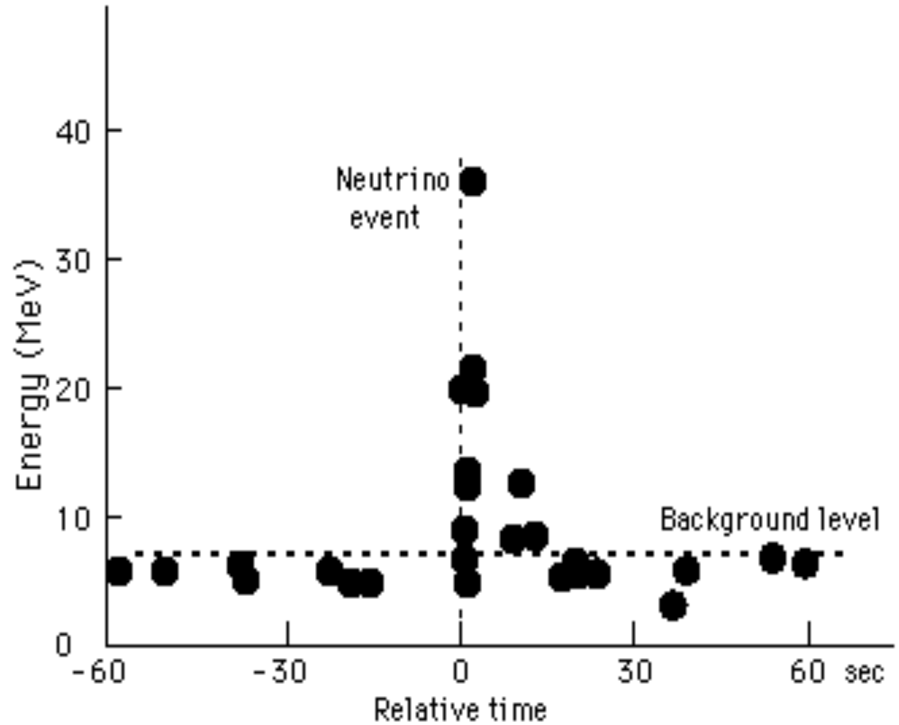
INT - Seattle, July 2011

20+ years back: the impact of SN1987A

What did we learn?

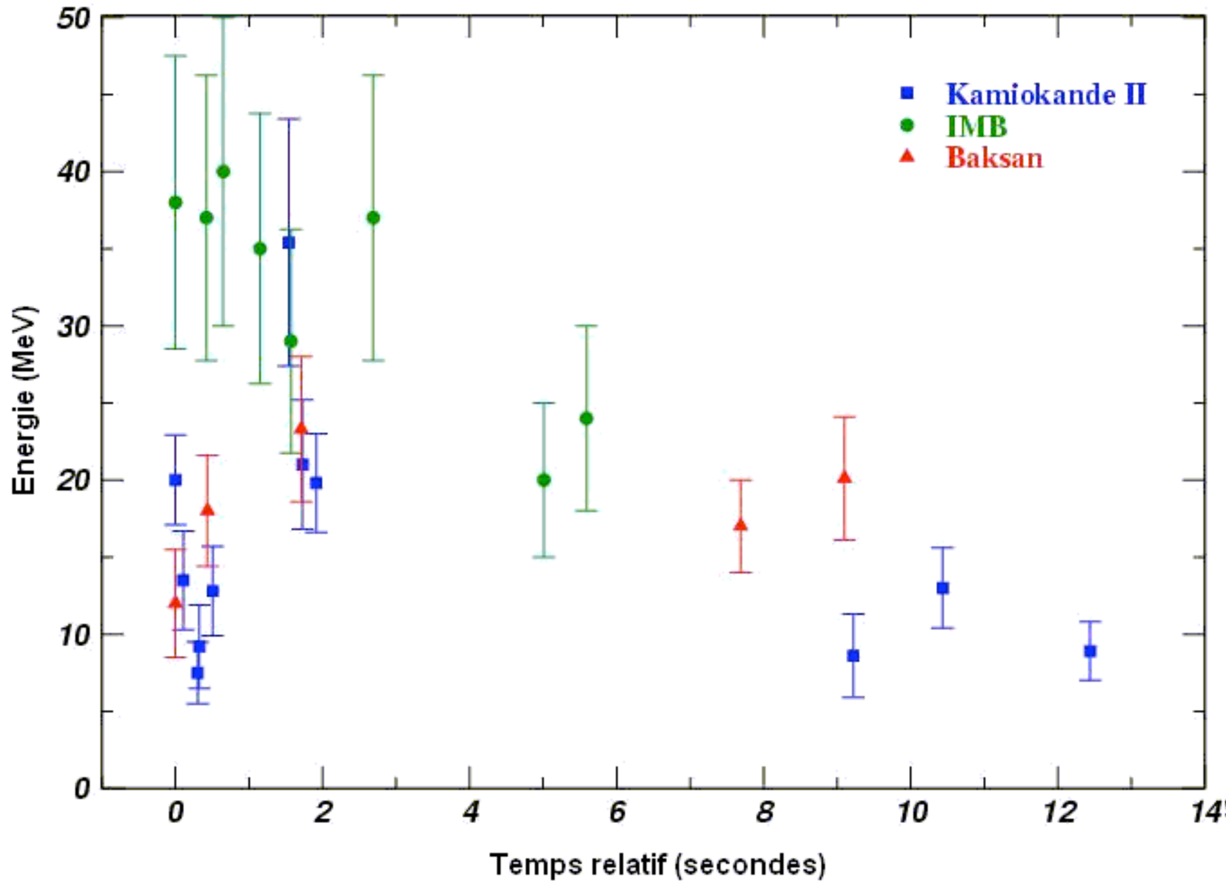
The *only* SN neutrino data

February 23, 1987: **SN1987A**



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

- ~ 1 Kt water/scintillator detectors
  - Inverse beta decay: anti-ν_e + p → n + e^+



Bionta et al., PRL 58,1987, Hirata et al., PRL 58,1987, Alekseev et al. JETP Lett. 45 (1987)

First confirmation of theory

- Luminosity ≈ total energy budget
  - Energy emitted is of *gravitational* nature:

    $L_\nu \approx G\, M^2_f/R_f - G\, M^2_i/R_i \sim 3\; 10^{53}$ ergs ✓ $(R_f \sim 10$ Km$)$

- Energy spectrum: ~ *Fermi Dirac (thermal)*
  - $E \approx 3.15\, T \sim$ 15-20 MeV ✓

- Duration of neutrino burst ~ diffusion time
  - Time ≈ (size^2)/(mean free path) ~ 10 s ✓

Open questions

- Precision?
  - Time structure (accretion, cooling,)
  - Oscillations (MSW, neutrino-neutrino,..)
  - Model discrimination (Eq. of state, neutrino transport,…)
  - New physics
- Total energy?
  - All neutrino species
- What is typical?

The situation now: opening a new phase

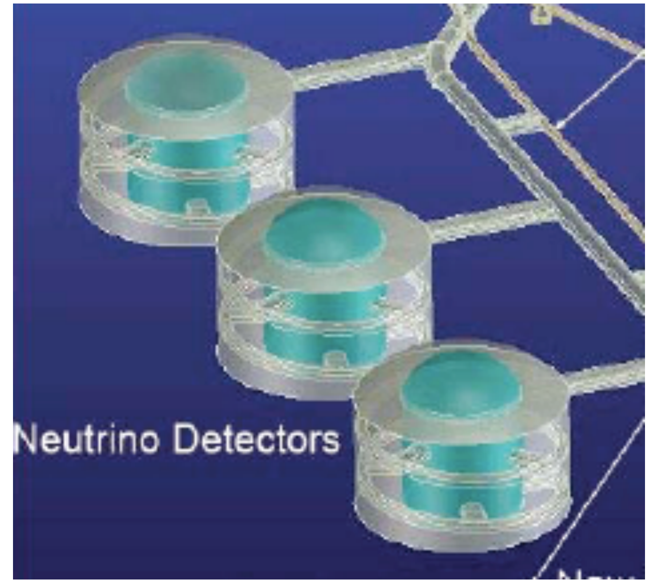
New focus on supernovae

- Solar, atmospheric fluxes down to precision phase (~10-40%)
  - Time to approach more distant, more complex sources: supernovae, GRBs, Dark Matter, …
    - *Solar/atmospheric become backgrounds!*

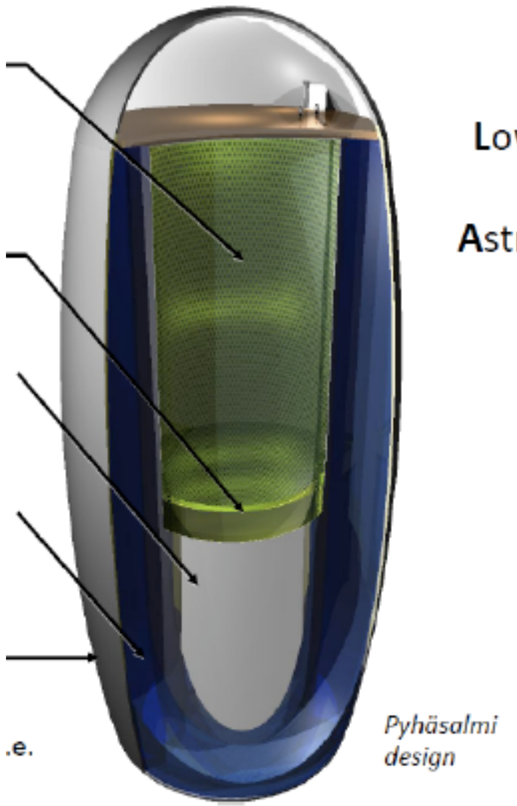
- New phase of detectors coming
  - Larger (0.1 – 1 Mt) & more sensitive

The next generation

DUSEL



Water Cherenkov,
0.3 -1 Mt
HyperK , UNO, MEMPHYS, DeepTITAND

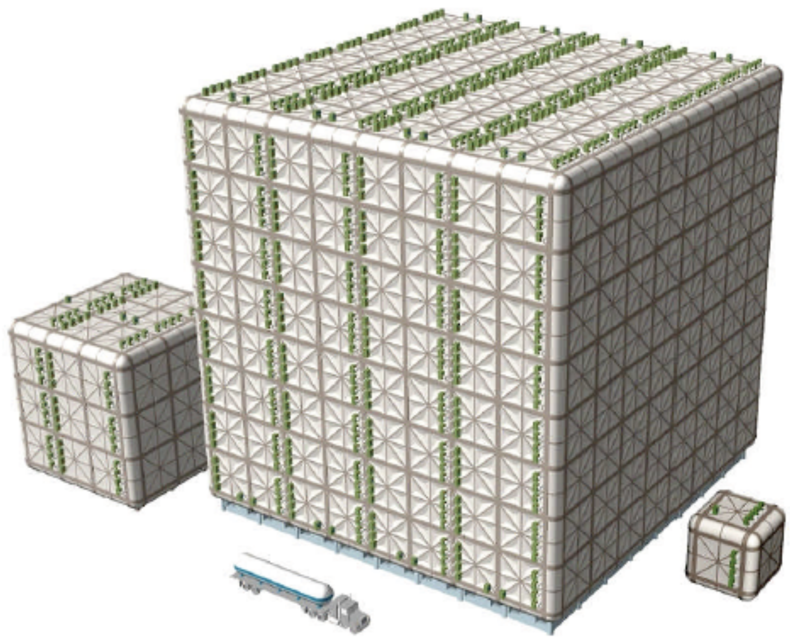


LENA

Low-Energy Neutrino Astrophysics

Liquid scintillator,
10-50 kt
LENA, Hano Hano

LANNDD



Liquid Argon,
10-100 kt
LANNDD, GLACIER

- Complementary designs:
  - For neutrino channel: He + Pb (HALO)

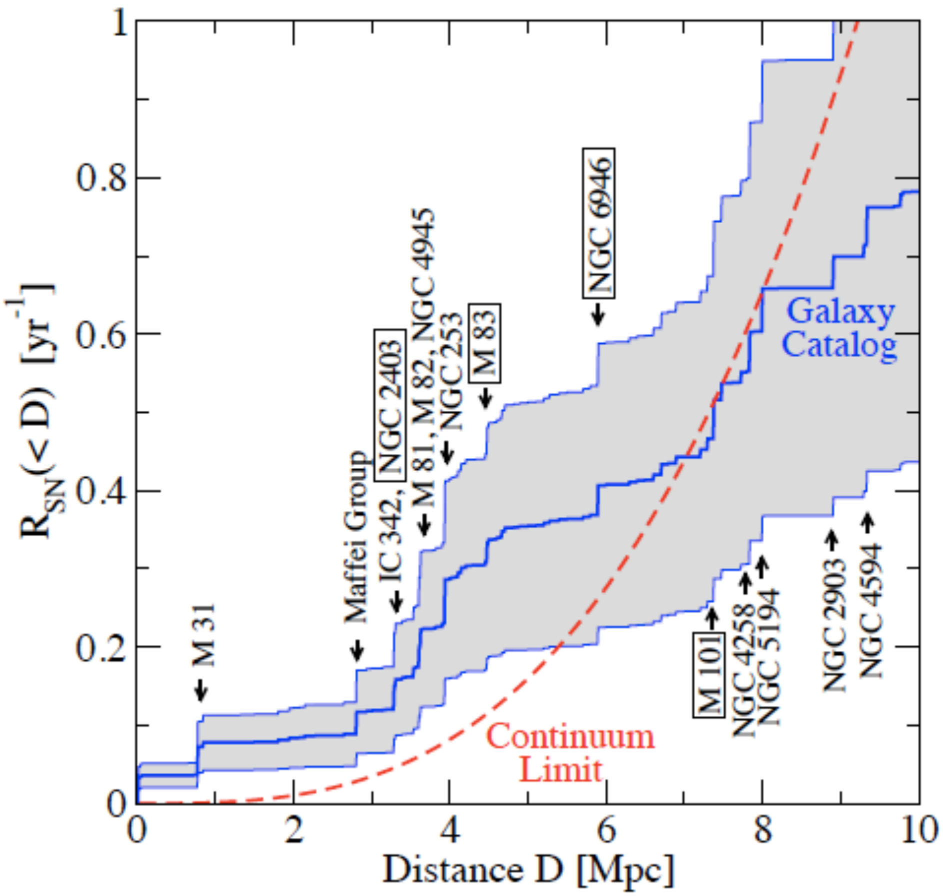
    http://www.snolab.ca/halo/detailedPhysics.html
  - For all-flavor: noble gas TPC (NOSTOS)

    Giomataris & Vergados, Phys.Lett.B634,2006
  - For luminosity: Km^3 ice/water (IceCUBE)

    IceCUBE coll. , arXiv:0908.0441

Looking farther…

- 1 -5 Mt mass
  - ~ few Mpc reach → ~ *1 SN every decade!*



Ando, Beacom & Yuksel, PRL95, 2005

… and in more detail

Events for Galactic SN (K. Scholberg, talk at Neutrino 2006, Sante Fe, NM)

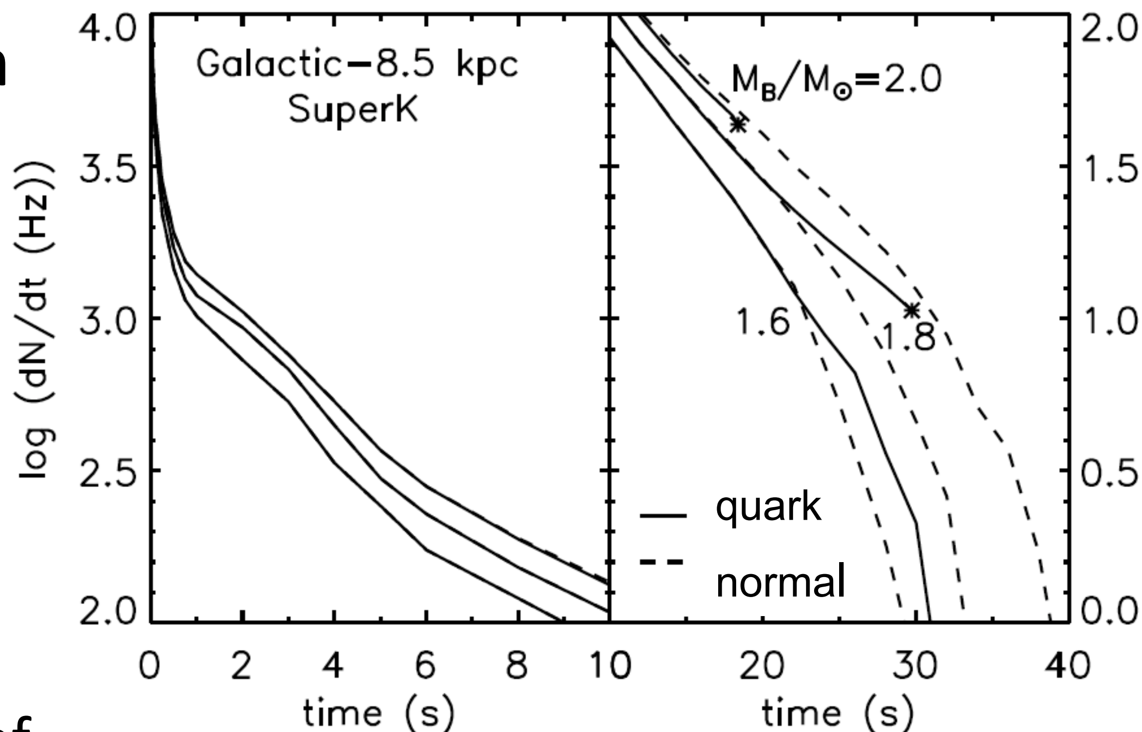
Detector	Type	Mass (kton)	Location	Events at 8.5 kpc	Status
Super-K[22]	H_2O	32	Japan	7000	Running
SNO[41]	D_2O	1 (D_2O)	Canada	400	Running until
		1.4 (H_2O)		450	end 2006
LVD[17]	C_nH_{2n}	1	Italy	200	Running
KamLAND[18]	C_nH_{2n}	1	Japan	300	Running
Borexino[20]	C_nH_{2n}	0.3	Italy	100	200x
Baksan[15]	C_nH_{2n}	0.33	Russia	50	Running
Mini-BooNE[12]	C_nH_{2n}	0.7	USA	200	Running
AMANDA/	Long string	0.4/PMT	South Pole	N/A	Running
IceCube[28]					Running
SAGE[42]	Ga	Russia	0.06	few	Running
Icarus[31]	LAr	2.4	Italy	200	200x
Daya Bay[43]	C_nH_{2n}	0.3	China	100	Proposed
SNO+[44]	C_nH_{2n}	1	Canada	300	Proposed
CLEAN[40]	Ne,Ar	0.01	Canada/USA?	30	Proposed
HALO[37]	Pb	0.1	Canada	40	Proposed
MOON[45]	^{100}Mo	0.03	?	20	Proposed
NOνA[46]	C_nH_{2n}	20	USA	4000	Proposed
OMNIS[29]	Pb	2-3	USA?	>1000	Proposed
LANNDD[32]	LAr	70	USA?	6000	Proposed
MEMPHYS[49]	H_2O	440	Europe	>100,000	Proposed
UNO[48]	H_2O	500	USA	>100,000	Proposed
Hyper-K[47]	H_2O	500	Japan	>100,000	Proposed
LENA[50]	C_nH_{2n}	60	Europe	18,000	Proposed
HSD[51]	C_nH_{2n}	100	USA	30,000	Proposed

Themes for the future: what will we learn?

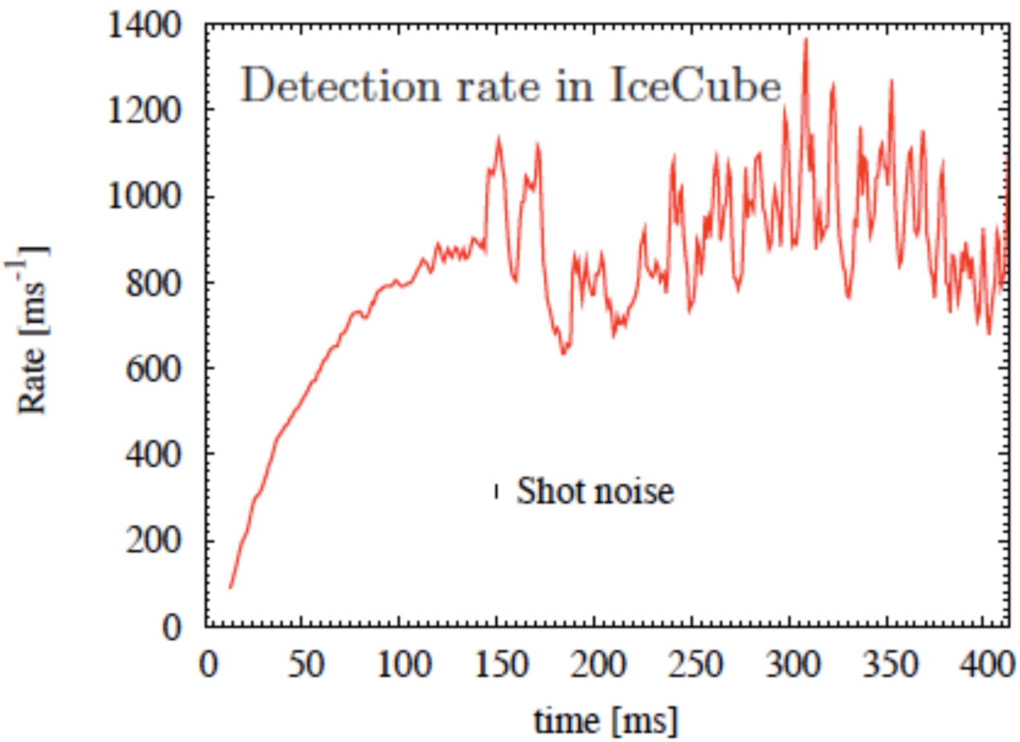
Timing

Pons et al., Phys.Rev.Lett.86,2001

- Late time evolution (> 10 s)
  - new phases of matter (quark matter, …)
  - Black hole formation
  - Transition to transparency (Eq. of state)



- < 1 s: SASI (Standing Accretion Shock Instability)
  - Oscillations of shock front modulates neutrino luminosity
  - Probes large scale convection



Blondin, Mezzacappa & DeMarino, ApJ 584
Marek, Janka & Mueller, Astron. Astrophys. 496, 475 (2009)
T. Lund, A. Marek. C.L., H.T. Janka & G. Raffelt, arXiv:1006.1889

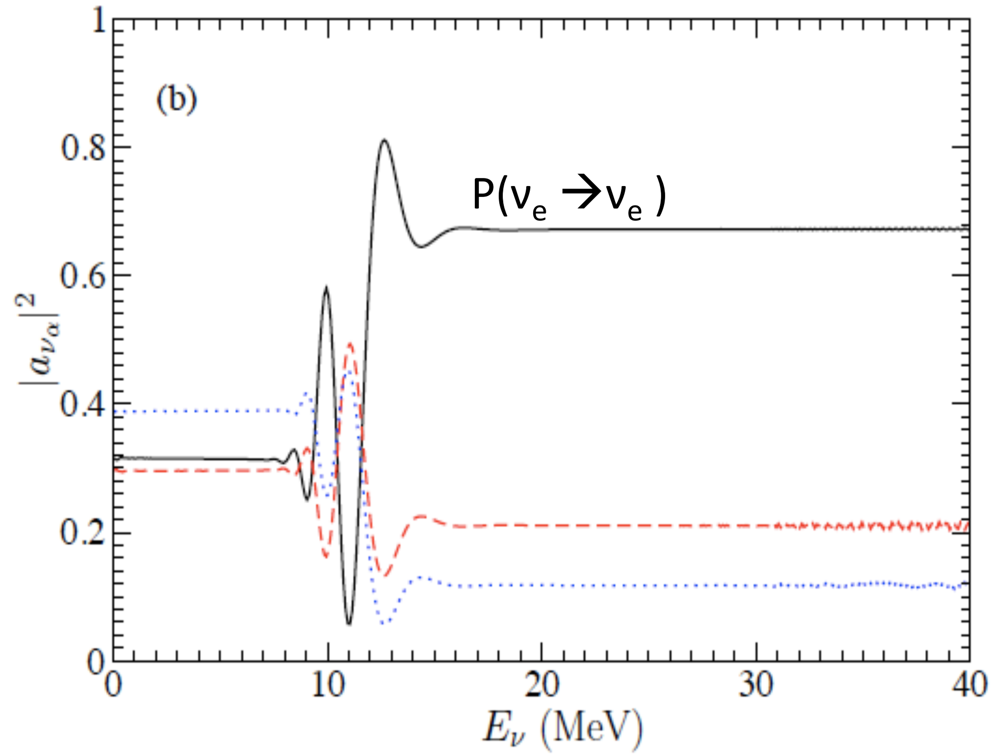
ν_e sensitivity

Detector type	process	Expected mass	Number of events (galactic SN)
Water Cherenkov	$\nu_e(^{16}O, ^{16}F)e^-$	~1 Mt	$O(10^3)$
Liquid Argon	$\nu_e(^{40}Ar, ^{40}K)e^-$	<100 Kt	$< O(10^3)$
Scintillator	$\nu_e(^{12}C, ^{12}B)e^-$	< 50 kt	$< O(10^2)$

Why are ν_e important?

- *Total* energy of SN
  - Eq. of state
- Neutronization/ deleptonization
  - e^- (p,n) ν_e
- Oscillation effects
  - Neutrino mass spectrum
  - flavor mixings
  - progenitor type

Survival of neutronization burst in ONeMg Sne!



Duan et al.,PRL.100,2008

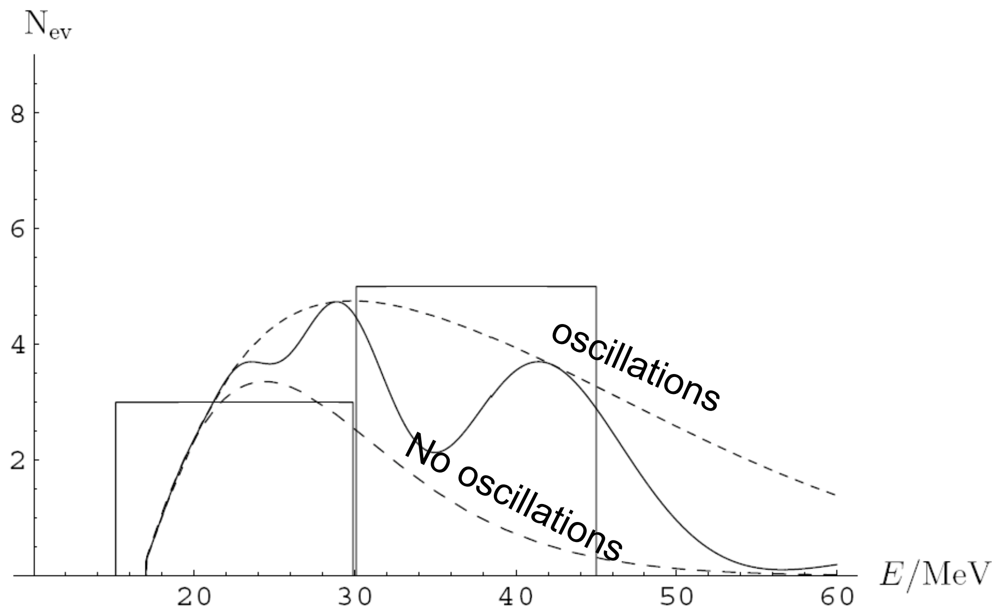
C.L., B. Mueller, H.T. Janka PRD, 2008

Oscillations: spectral distortions

p = survival probability

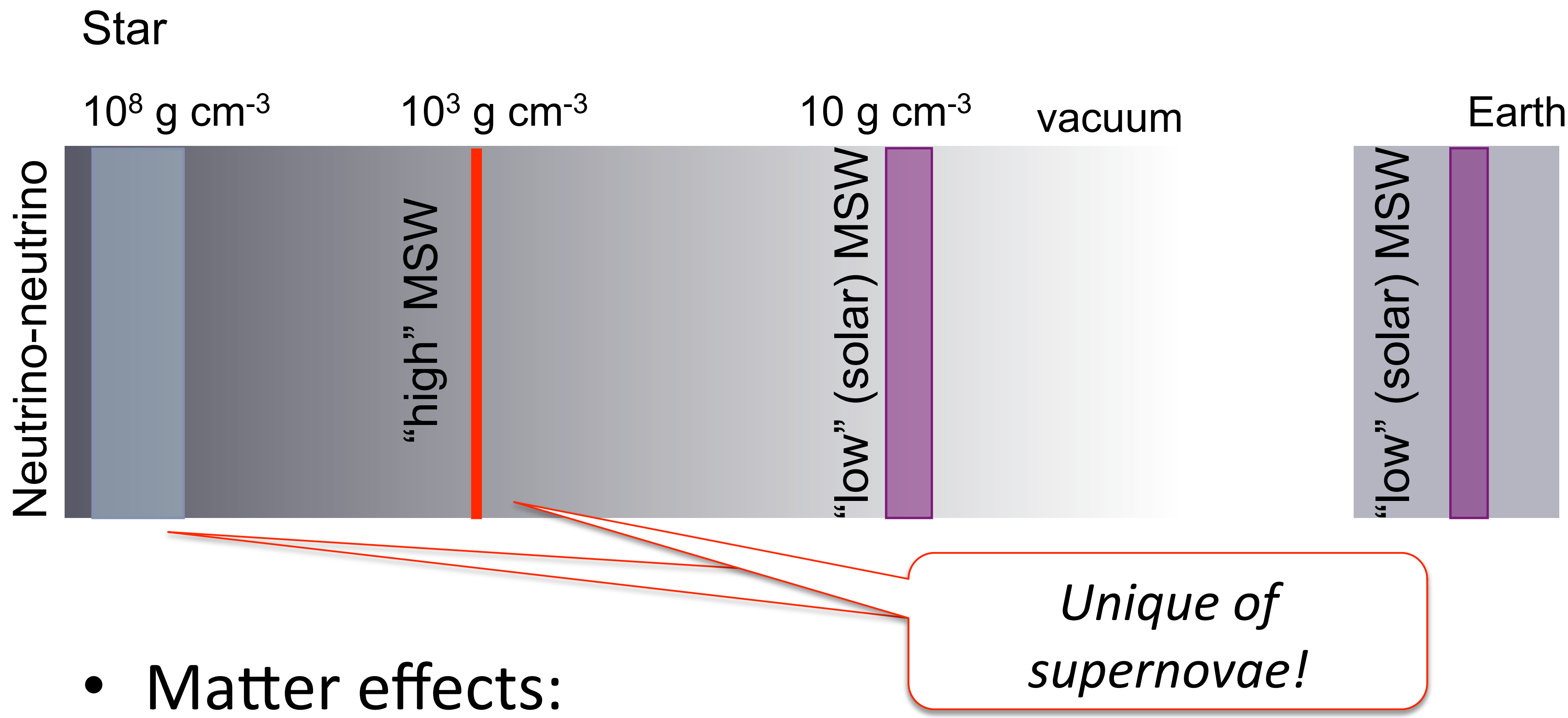
$$
\begin{aligned}
F_e &= pF_e^0 + (1-p)F_x^0 \\
F_{\bar{e}} &= \bar{p}F_{\bar{e}}^0 + (1-\bar{p})F_x^0
\end{aligned}
$$

x= μ, τ



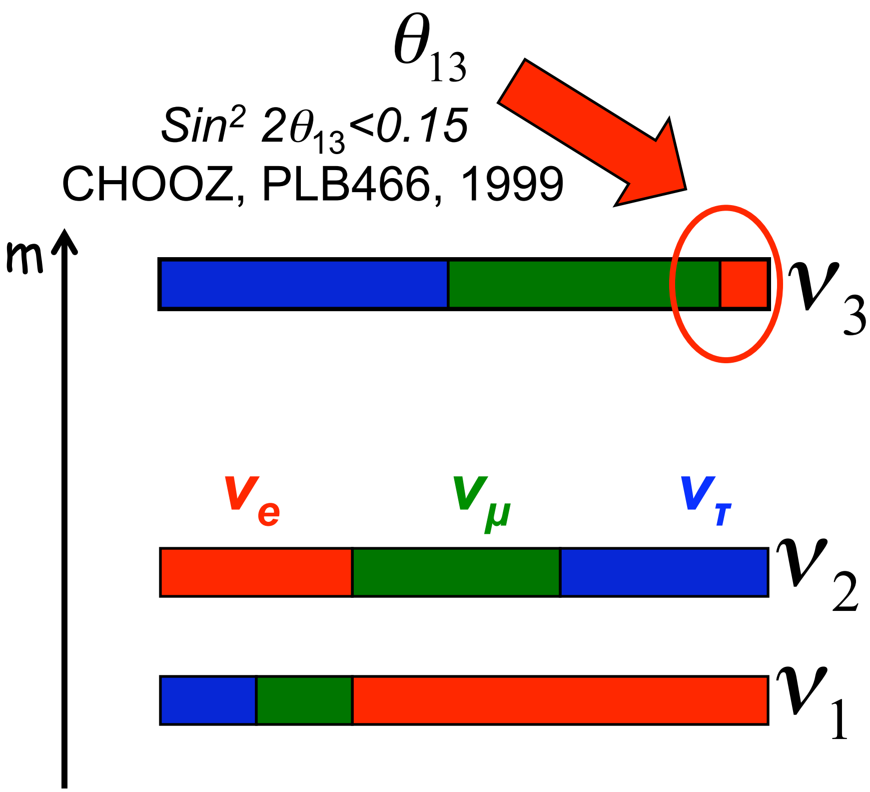
Harder spectrum!
Depends on masses, mixings

Neutrino oscillations



- Matter effects:
  - refraction frequency ≈ vacuum frequency
  - Neutrino-neutrino, neutrino-electron scattering

High MSW: θ_{13} *resonant* dependence



- Unique resonance:

  $\sin^2\theta_{13} \sim 1$ *in matter* ***if***:

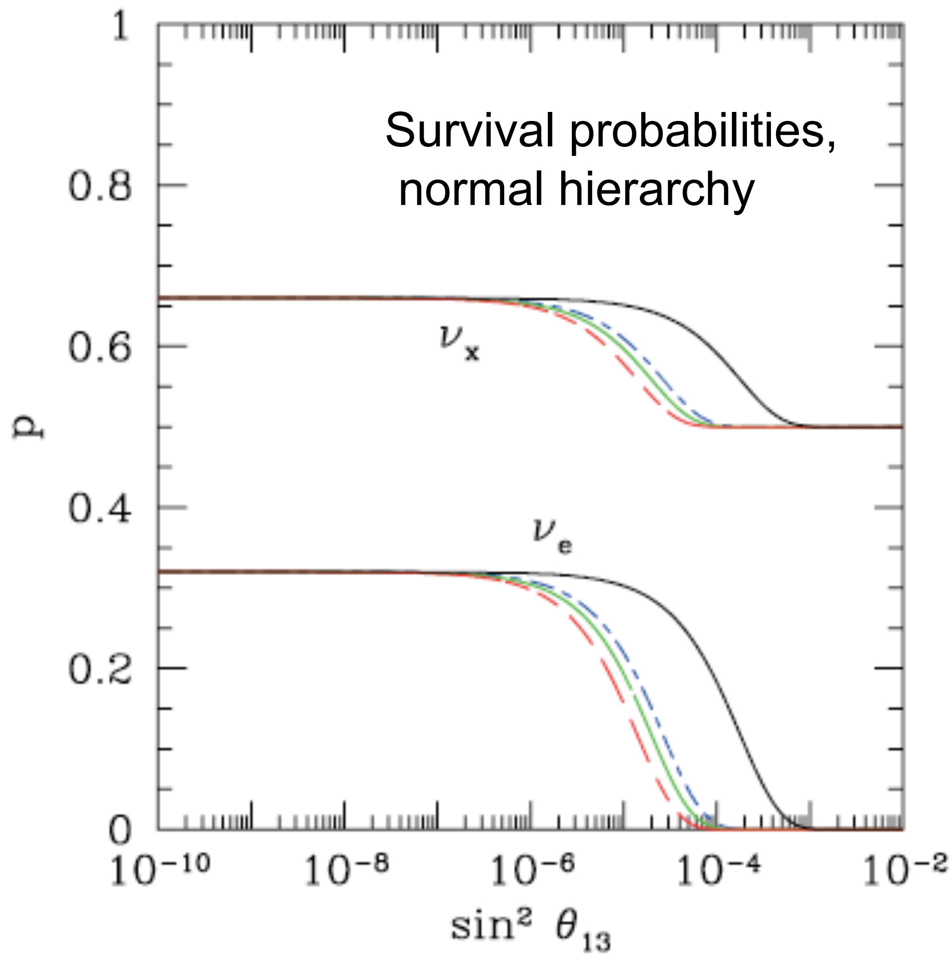
  $\Delta m^2_{31}/2E \sim 2^{1/2}\ G_F\ \rho/m_N$

- Realized for

  $\rho \sim 10^3\ g\ cm^{-3}$

Dighe and Smirnov, Phys. Rev. D62, 2000
C.L. & A. Y. Smirnov, JCAP 0306, 2003

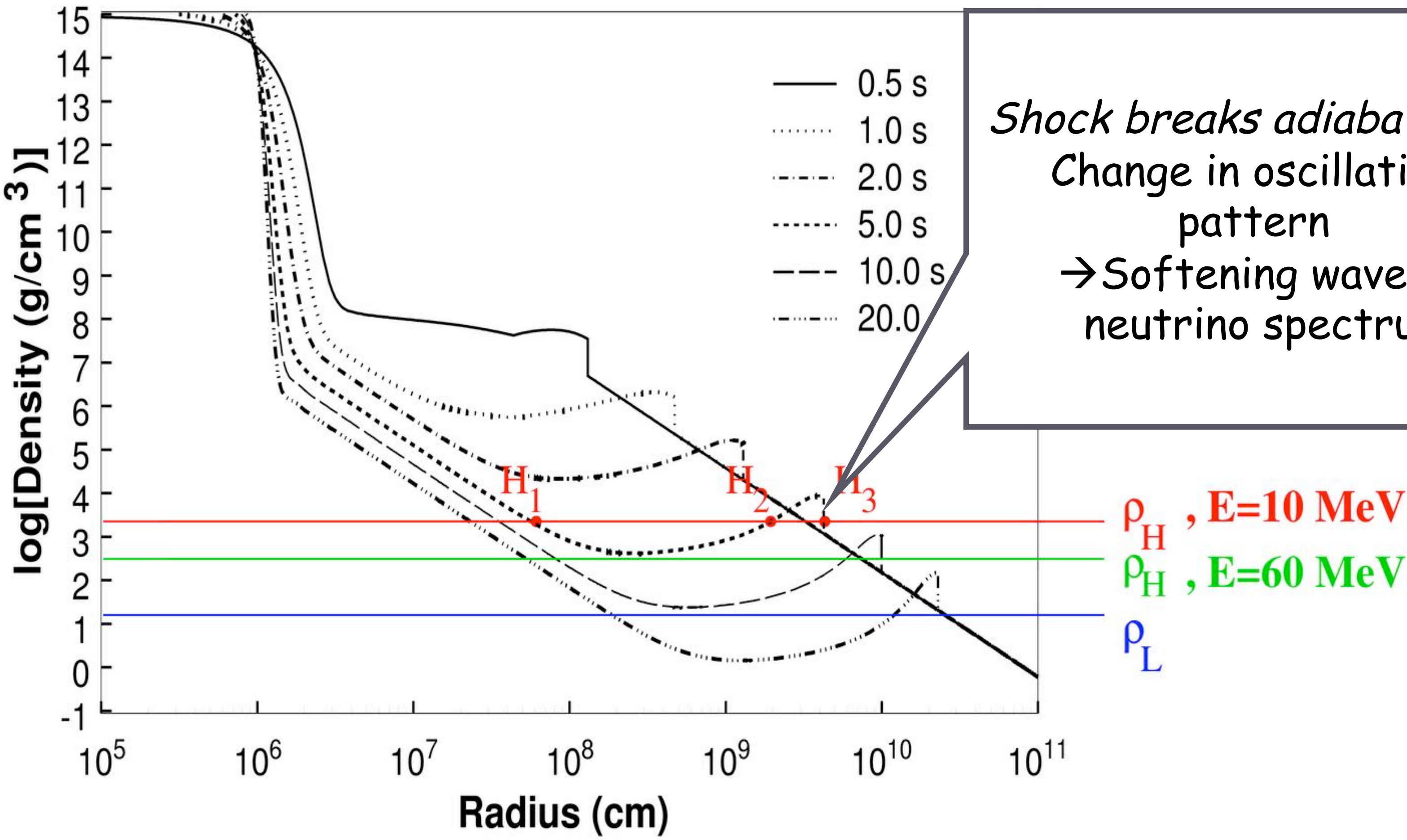
- Sensitivity down to $sin^2\ \theta_{13} \sim 10^{-5}$!



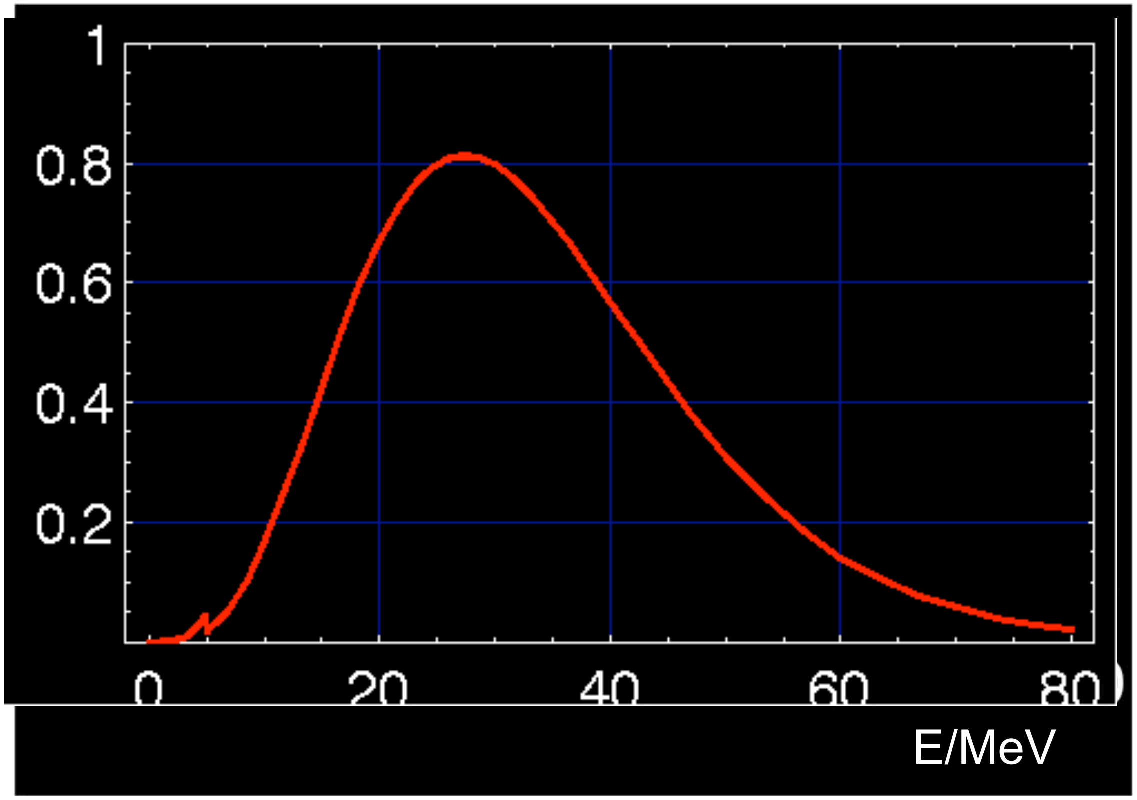
Plot from Nakazato et al., Phys.Rev.D7 , 2008

Monitor the shockwave

Schirato & Fuller, astro-ph/0205390



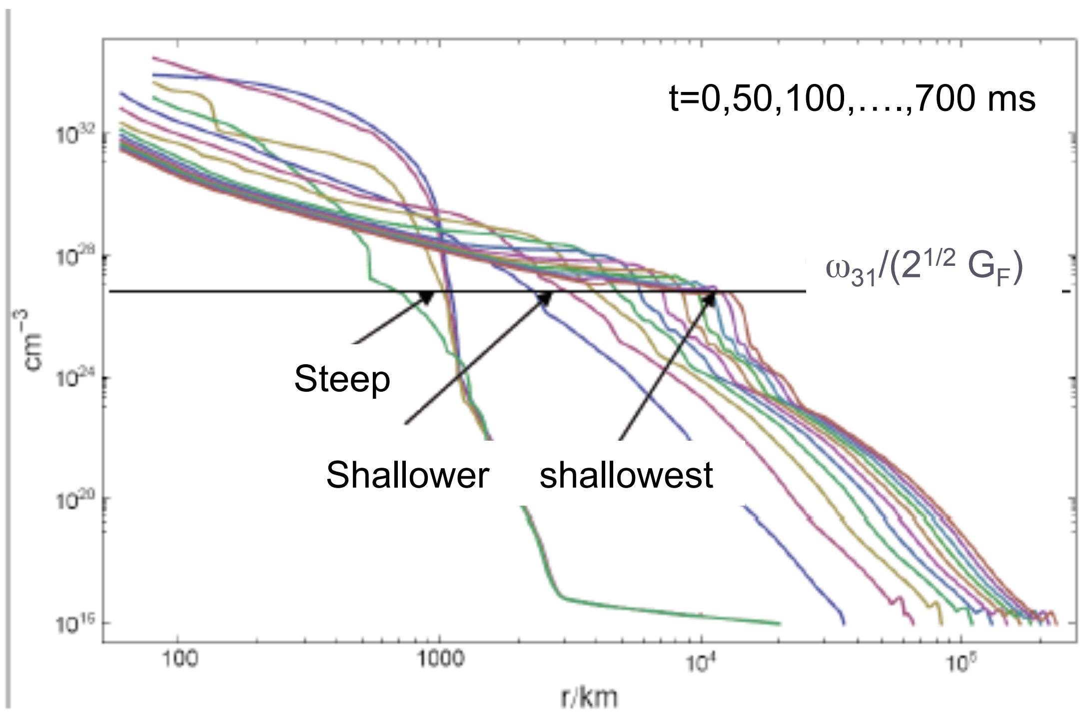
Shock breaks adiabaticity:
Change in oscillation pattern
→Softening wave in neutrino spectrum



E_{0e}=15 MeV
E_{0x}=21 MeV
L_e=L_x

ONeMg: revealing density step

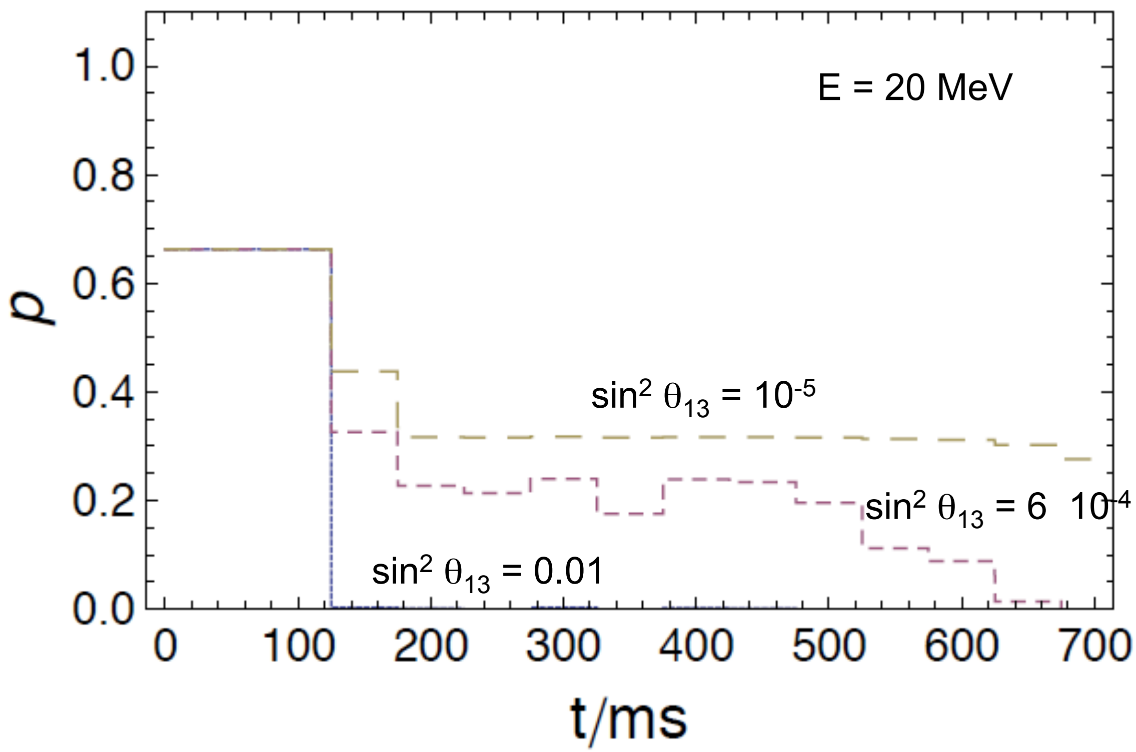
- *Profile becomes smoother: early (~1 s)* ***increase*** of conversion
  - Opposite of Fe-core supernovae! (decrease of conversion)



Lunardini, Muller and Janka, Phys. Rev. D 78, 023016 (2008)

ν_e survival probability

- *Reveals existence of density step and shock propagation*

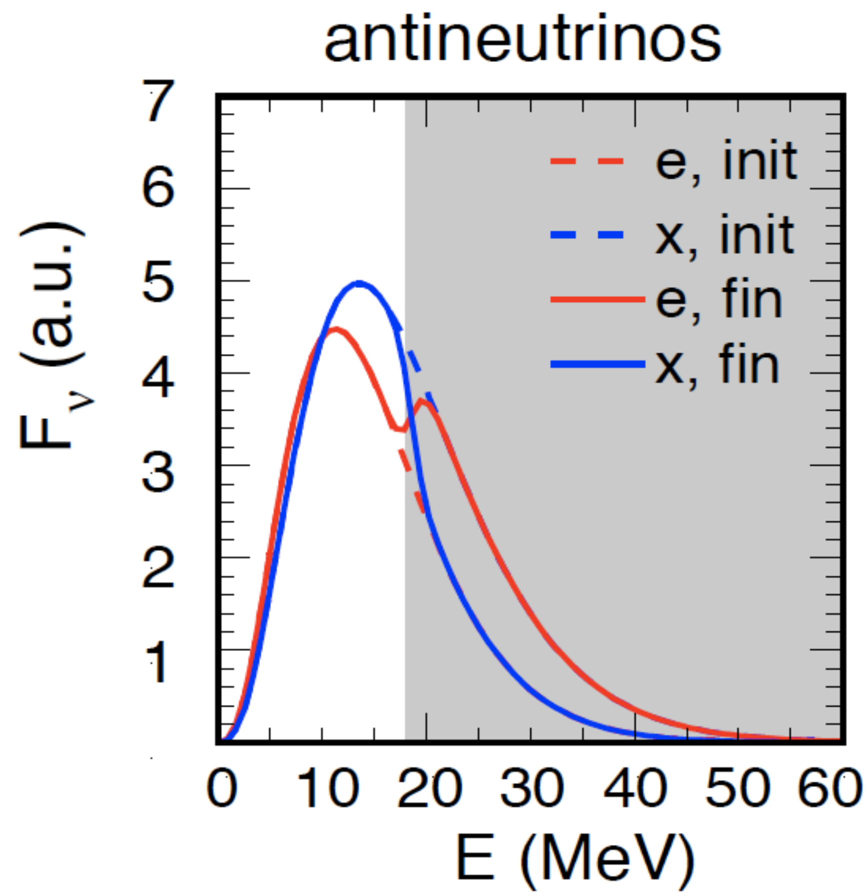


Neutrino-neutrino: spectral swaps

- Step-like probability as function of energy

- Work in progress

Groups: Munich, San Diego, LANL, North Carolina S., Trieste, Bari, Orsay, Tata Inst., New Mexico U., Minnesota U., …



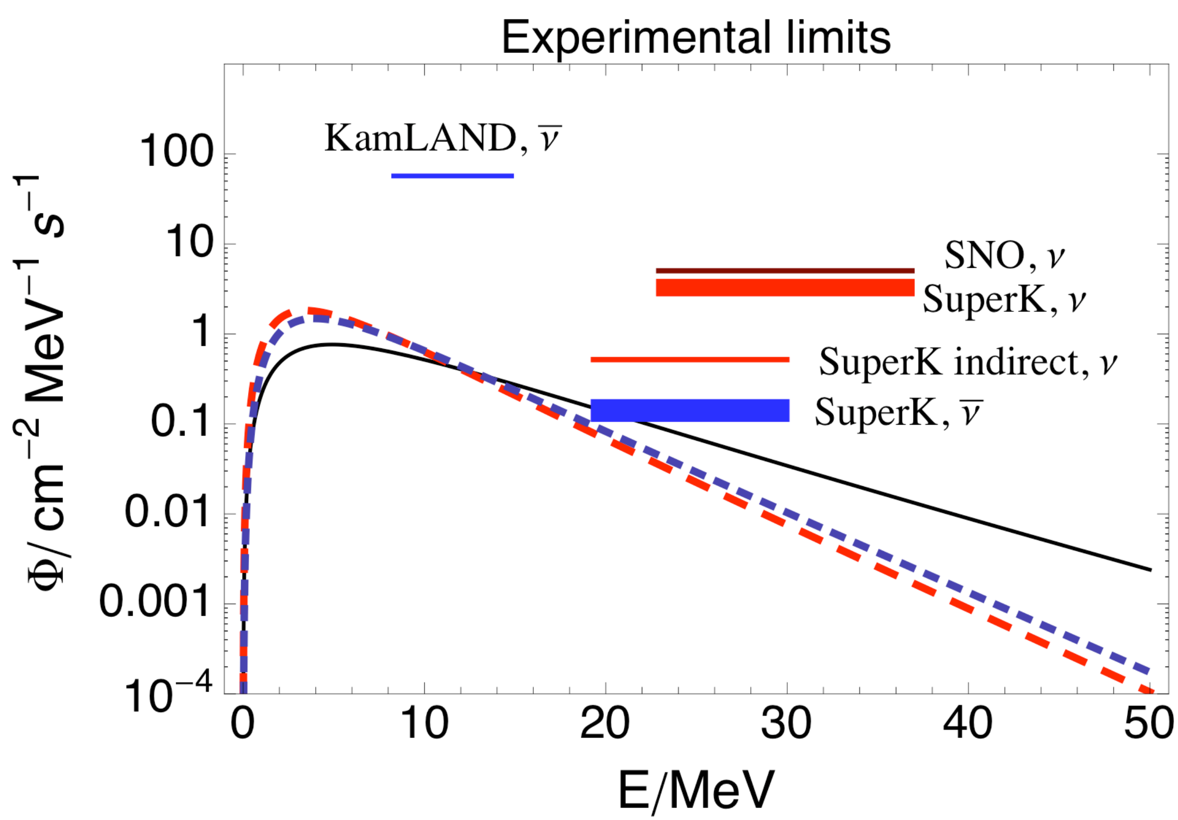
Plot from Dasgupta et al., arXiv:1002.2943

- Still, a galactic SN might take a while…

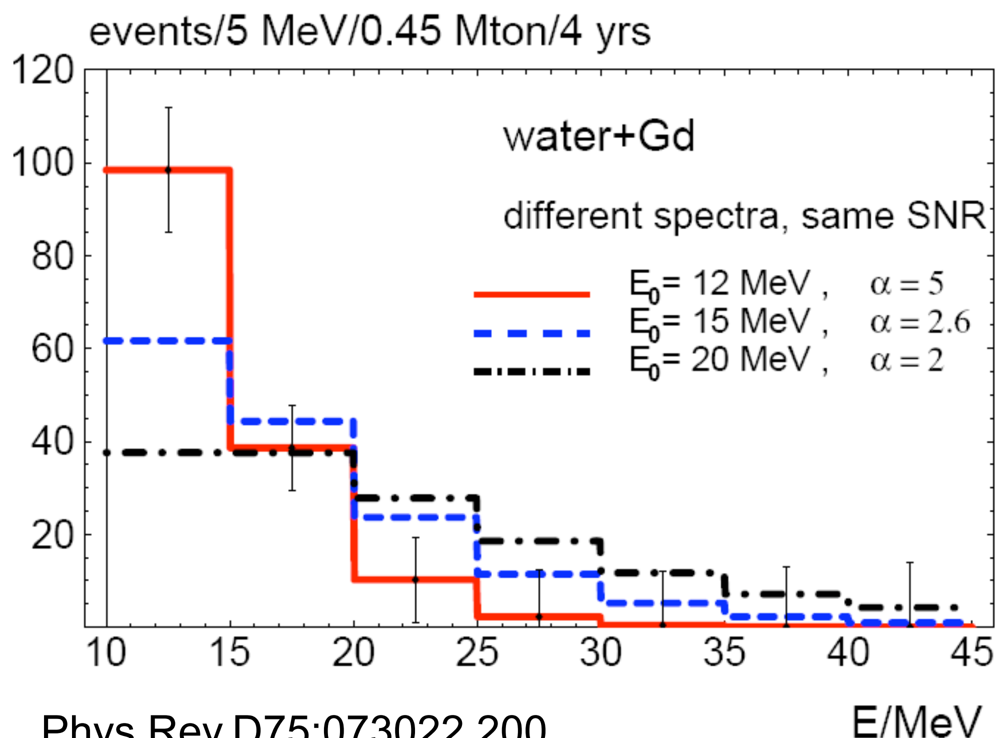
Clip art from
M. Vagins

Diffuse flux: everything and now

- *Sum over all SNe in the universe* $\sum_{\star} \Phi_{\nu}^{\star}$



- ***Now**: alternative to a galactic supernova!*
  - Continuous flux, *no waiting time*
  - might be everyday physics in future!
    - ~20 events/year at Mt water Cherenkov

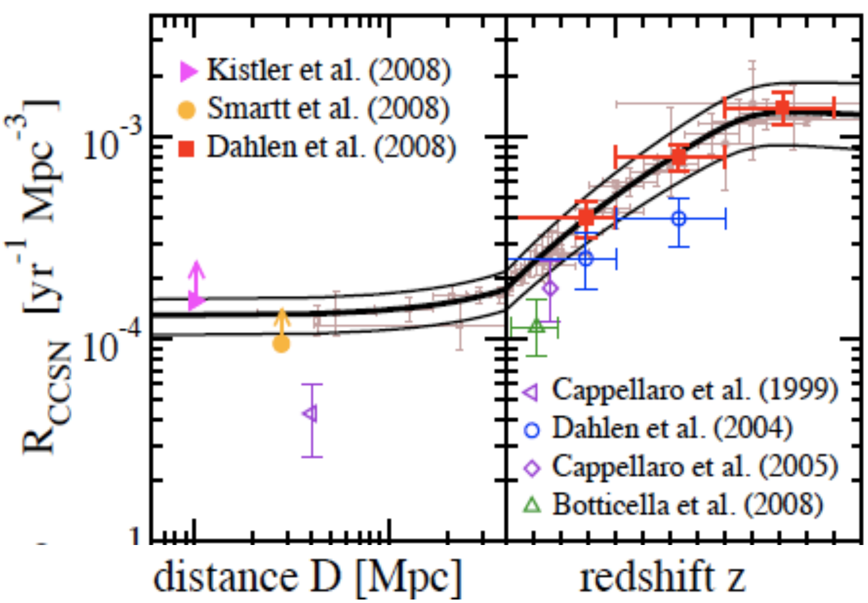


Plot from C.L., Phys.Rev.D75:073022,200

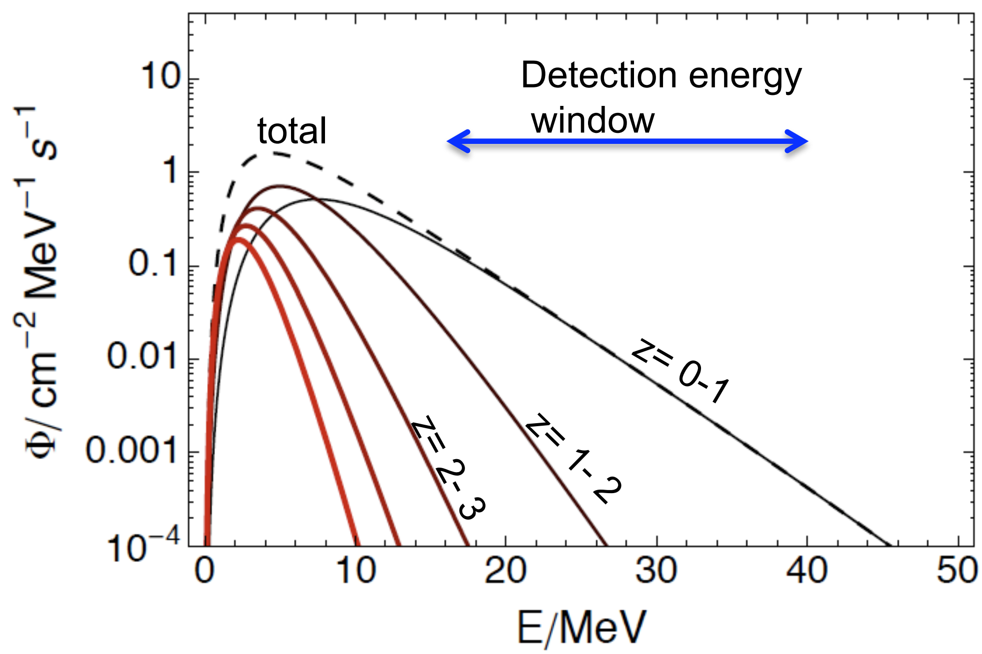
- ***Everything****: probes the whole supernova population of the universe*
  - What's typical?
  - Cosmological SNe
  - Diversity: Fe-core, ONeMg core, black hole core, …

Cosmological rate of SNe

- *increases* with z
  - ~ 40% of flux from z>0.5



Horiuchi, Beacom & Dwek, 2009



Ando and Sato, Phys. Lett. B559, 113, 2003
C.Lunardini, arXiv:1007.3252

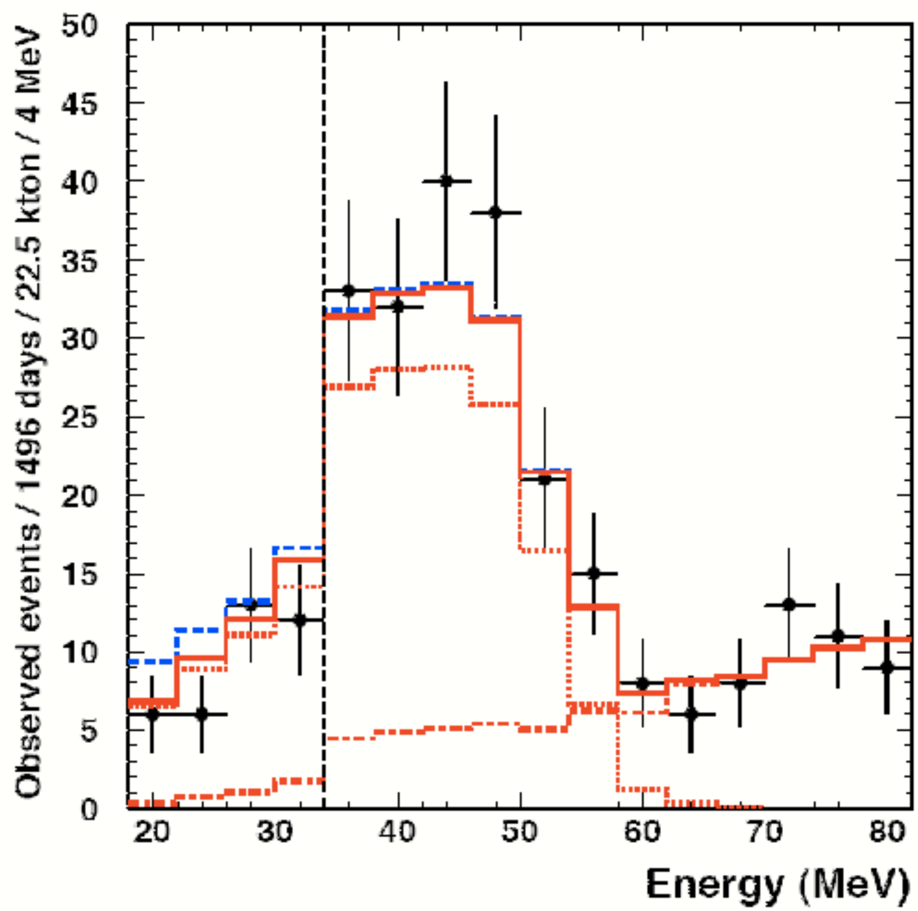
What can we learn? Rates only

- Model discrimination
  - E.g., distinguish combinations of spectra + SNR
  - Distinguish models of spectra if SNR is known
- Basic exclusion potential

Energy bins: testing spectra

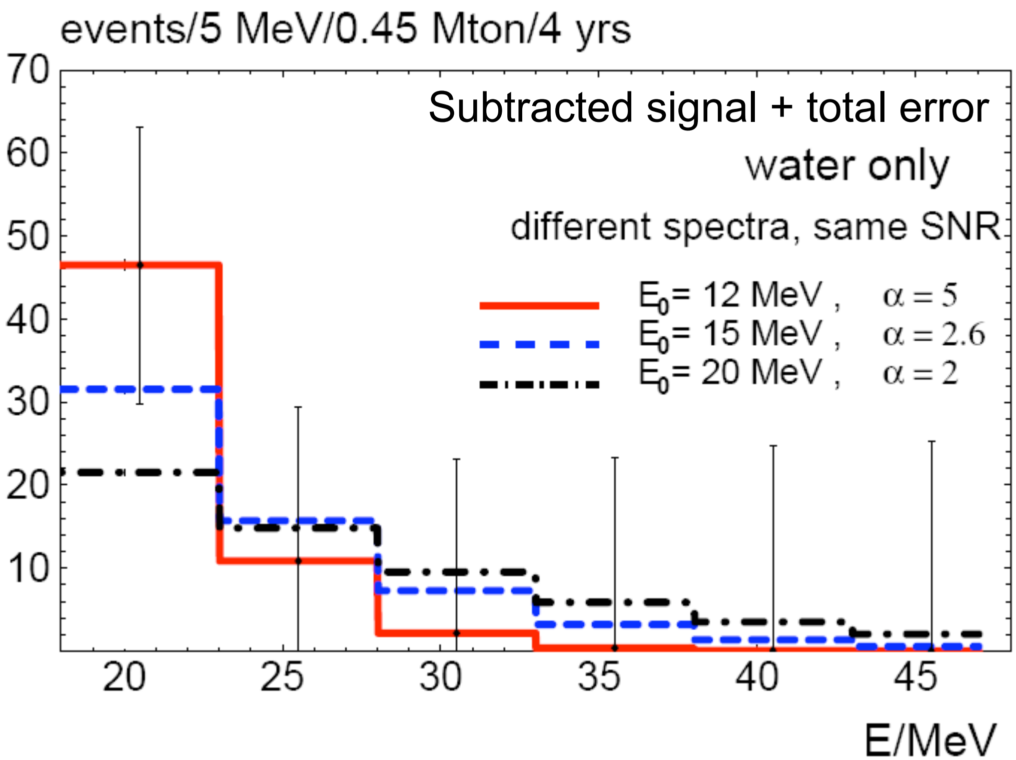
- Test spectral parameters E_0, α
  - Effective, after oscillations

- Background-limited



Spectral sensitivity: water only

Normalized to 60 events, β=3.28

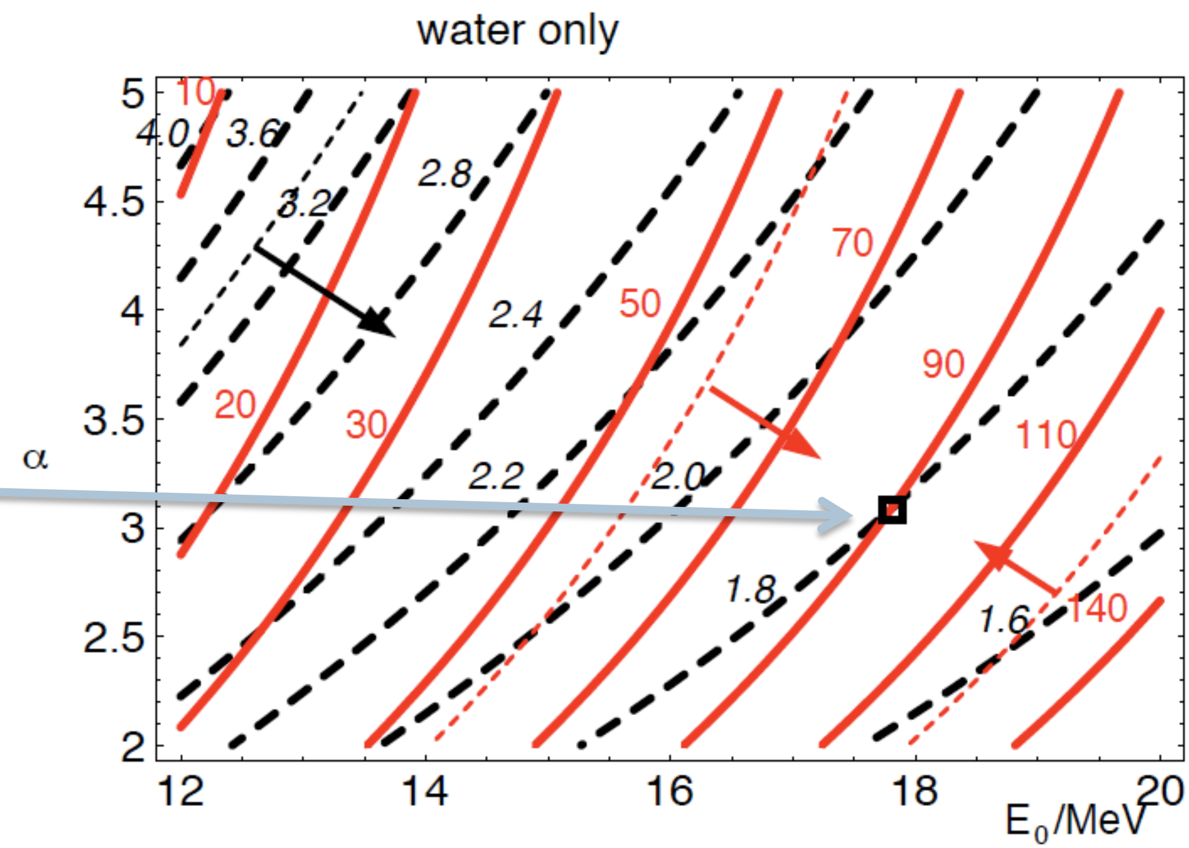


C.L., Phys.Rev.D75:073022,2007
Error bars from Fogli et al, JCAP 0504:002,2005

- needs N ~ 100-200
  - larger than typical, (incompatible with SN1987A)
- Ratio of bins:

$$\frac{N(18\text{-}23\ MeV)}{N(23\text{-}28\ MeV)} \sim 0.6 - 3$$

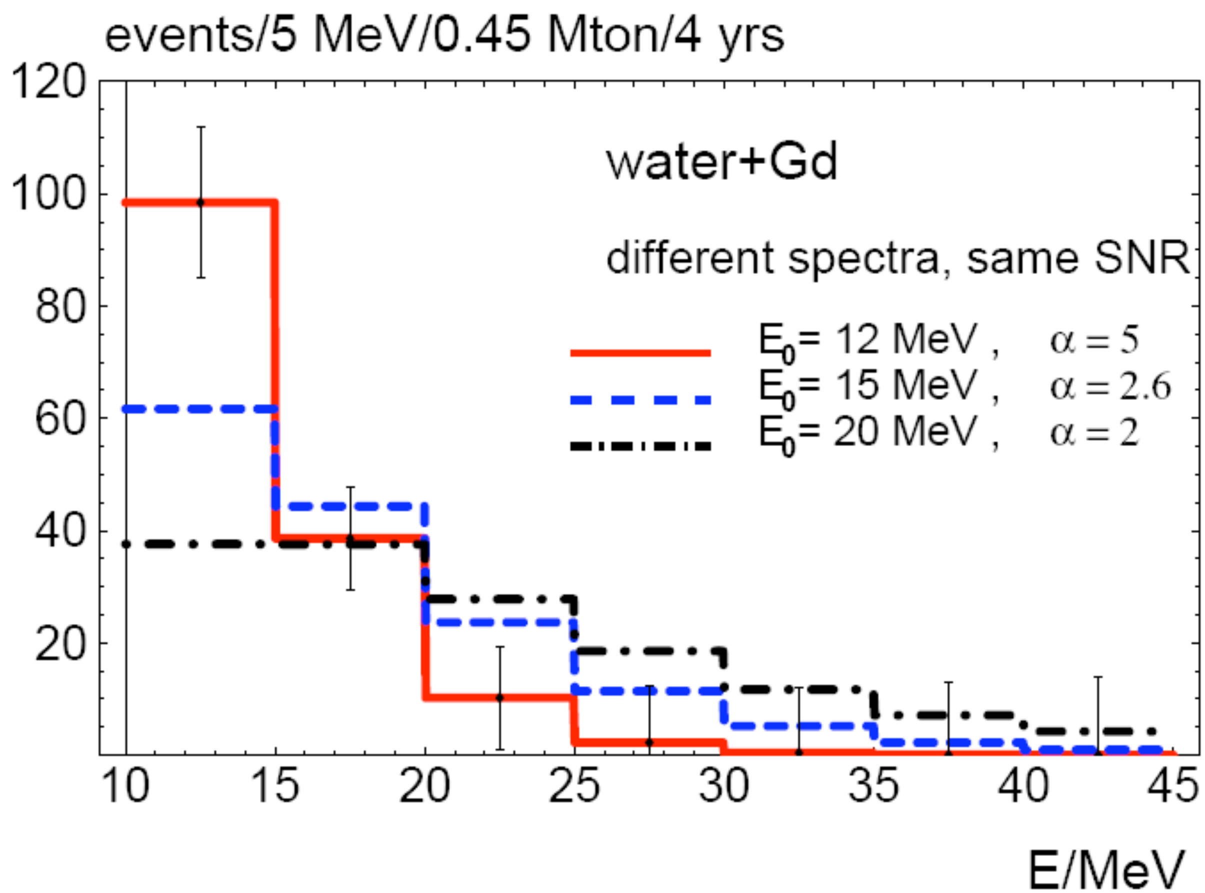
- Dashed : ratio of bins
- solid: number of events
  - Assume SNR known
- □ : Hypothetical measurement
  - Arrows indicate errors



C.L., Phys.Rev.D75:073022,200

Spectral sensitivity: Water+Gd
or liquid scintillator

Normalized to 150 events, β=3.28



- Dashed : ratio of bins
- solid: number of events
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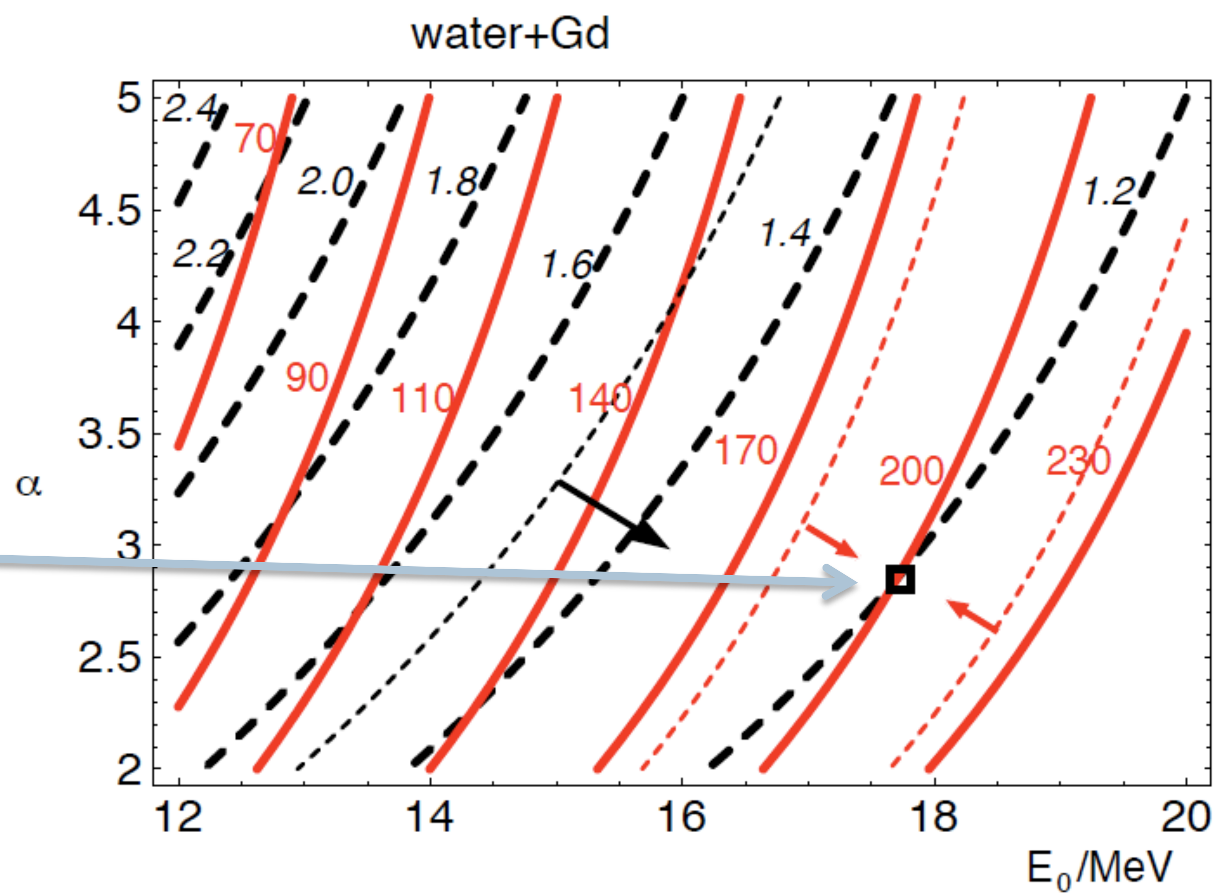


Probe oscillation probabilities

- water (anti-ν_e) / Ar (ν_e) rates:
  - $r_N = N_{H2O}(19.3 – 31.3\ \text{MeV})/N_{Ar}(19\text{-}39\ \text{MeV})$

($\bar{p}$, p)	**Θ_{13}, hierarchy**	**r_N**
(0.68, 0)	Large, any	2.7 – 4.5
(0.68,0.32)	Small, normal	3.8 – 5.8
(0.,0)	Small, inverted	5.0 – 6.0
(0,0.32)	Large, inverted, *No self-interactions*	7.2 – 7.8

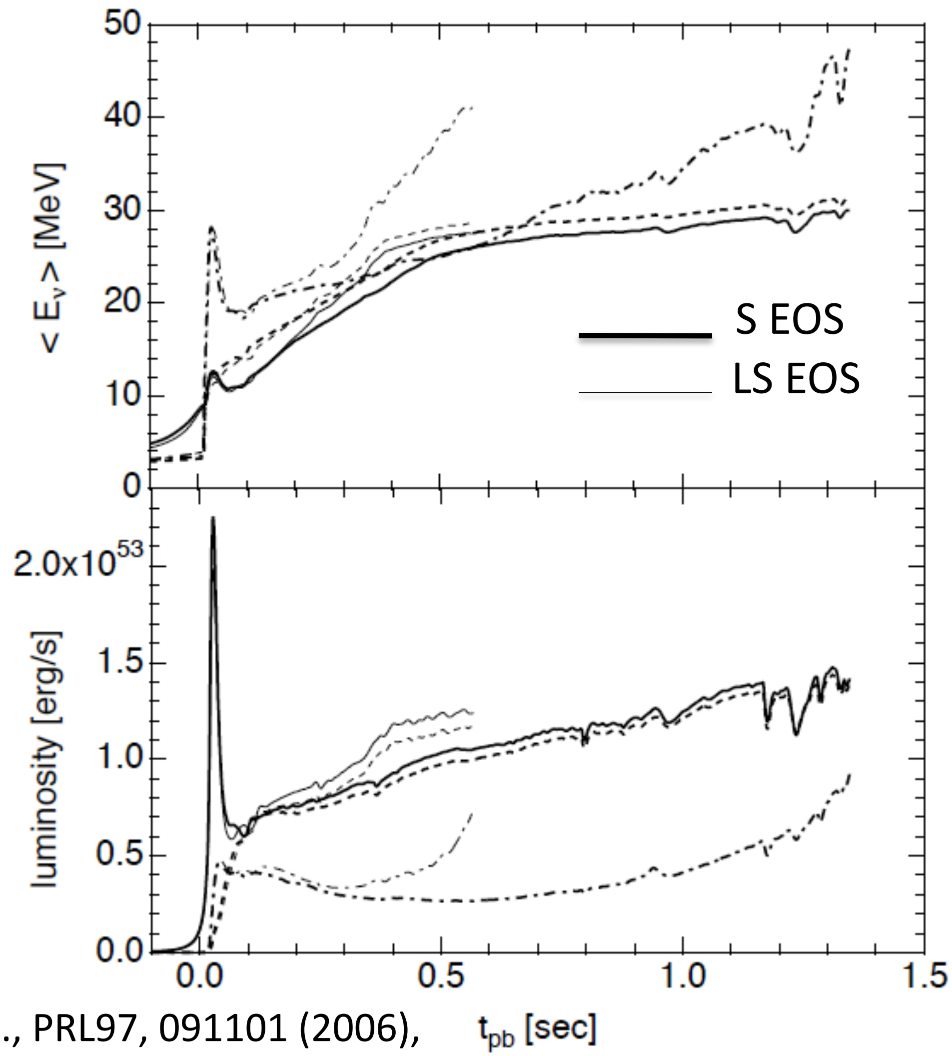
Variation with emission spectra

"small"= $\sin^2 \theta_{13} < 10^{-6}$,
"large" = $\sin^2 \theta_{13} > 10^{-4}$

C.L., in preparation

Reveal rare SN types: failed SNe

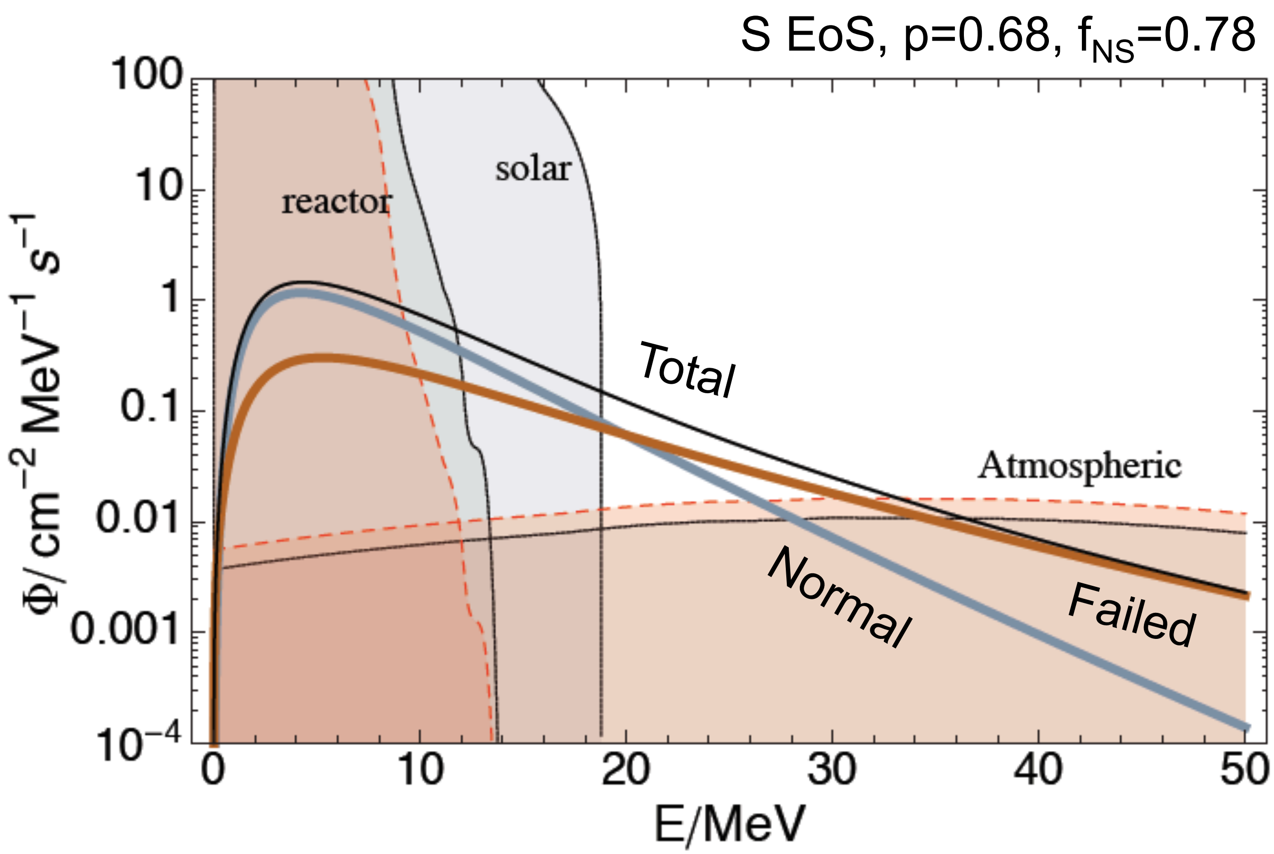
- M > 25-40 M_{sun} , 9-22% of collapses
  - *Too rare to expect a galactic one!*
- Collapse *directly* into black hole, no explosion
- *Neutrinos hotter and more luminous*
  - *<E> ≈ 20 MeV for all flavors*



Liebendörfer et al., ApJS, 150, 263, K. Sumiyoshi et al., PRL97, 091101 (2006),
T. Fischer et al., (2008), 0809.5129, K. Nakazato et al., PRD78, 083014 (2008)

failed SNe may dominate!

- *10-100% effect* on diffuse flux
  - Spectral distortion



C.L., Phys. Rev. Lett., 2009, J. Keehn & C.L., arXiv:1012.1274

Wrap up

The post-solar phase: supernovae, etc..

- **~2020 - …. : Discovery** *diffuse SN neutrino flux*
  - SN neutrinos become everyday physics
  - Complement SN1987A
  - Cosmological supernovae
  - Averaged over whole SN population
- *No precision!*

The post-solar phase: supernovae, etc..

- **~… - 2100: Precision**
  Galactic supernova
  – All flavor-detection
  – Model discrimination
  – Timing
  – Oscillation effects
  – New physics

- *Precision!*