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SUPERNOVA NEUTRINOS
AT FUTURE DETECTORS

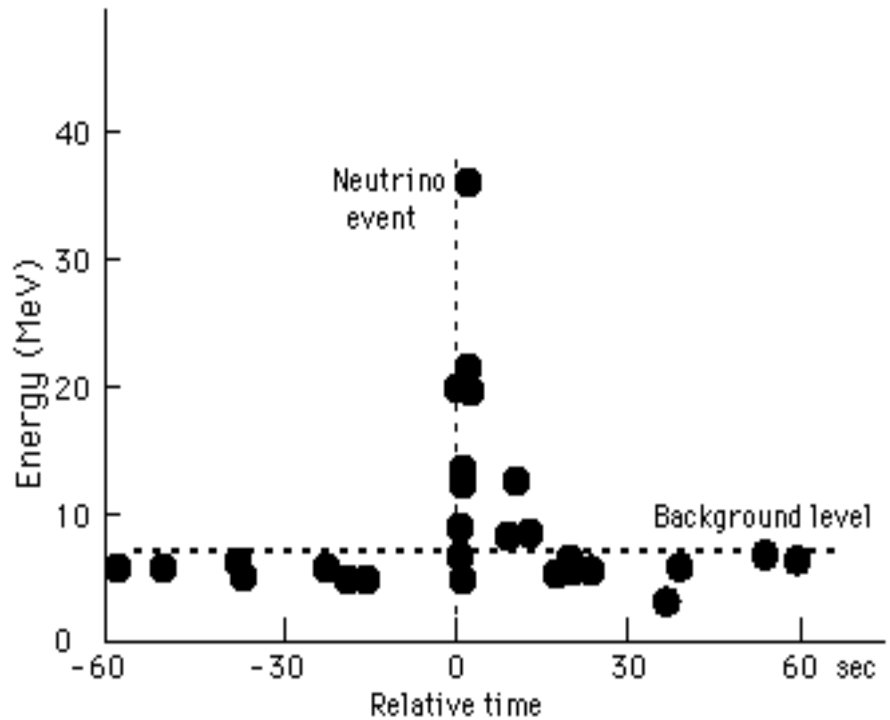
Recontres de Blois, June 2011

20+ years back: the impact of SN1987A

What did we learn?

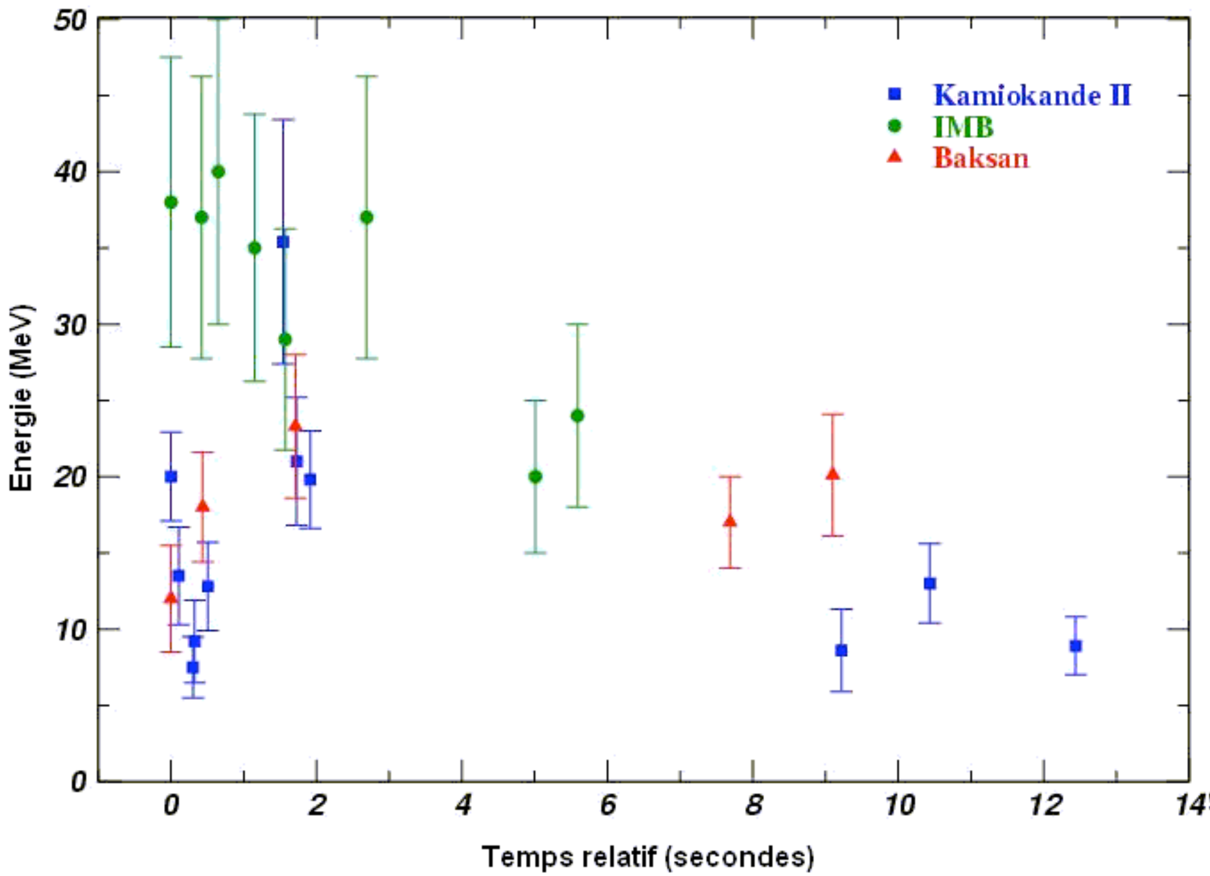
The *only* SN neutrino data

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:

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

- Energy spectrum: ~ *Fermi Dirac (thermal)*
  - E ≈ 3.15 T ~ 15-20 MeV ✓

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

Open questions

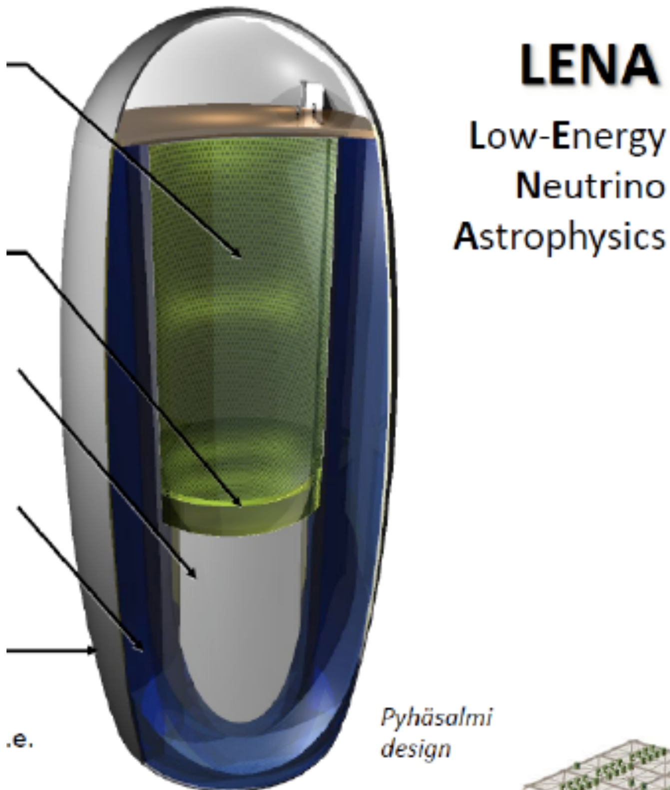
- Precision?
  - Time structure (accretion, cooling,)
  - Oscillations (MSW, neutrino-neutrino,..)
  - Model discrimination (Eq. of state, neutrino transport,…)
  - New physics
- Total energy?
  - All neutrino species
- What is typical?

The situation now: opening a new phase

New focus on supernovae

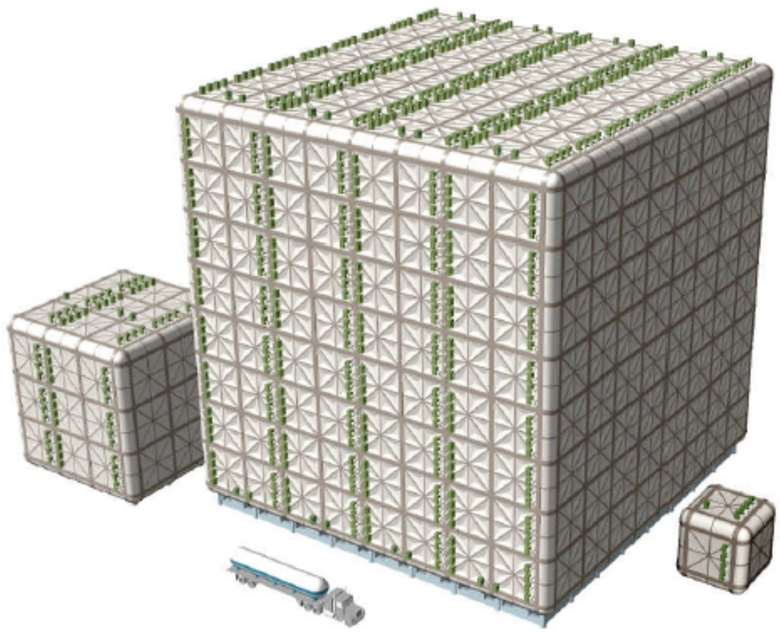
- Solar, atmospheric fluxes down to precision phase (~10-40%)
  - Time to approach more distant, more complex sources: supernovae, GRBs, Dark Matter, …
    - *Solar/atmospheric become backgrounds!*
- New phase of detectors coming
  - Larger (0.1 – 1 Mt) & more sensitive

The next generation



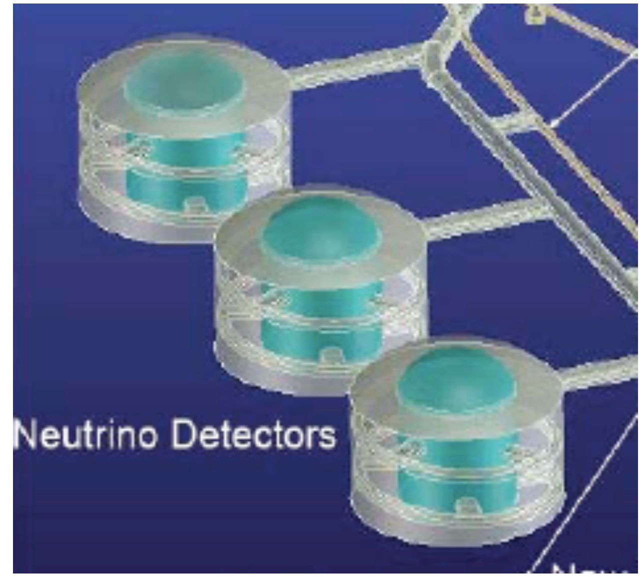
Liquid scintillator,
10-50 kt
LENA, Hano Hano

LANNDD



Liquid Argon,
10-100 kt
LANNDD, GLACIER

DUSEL



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

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

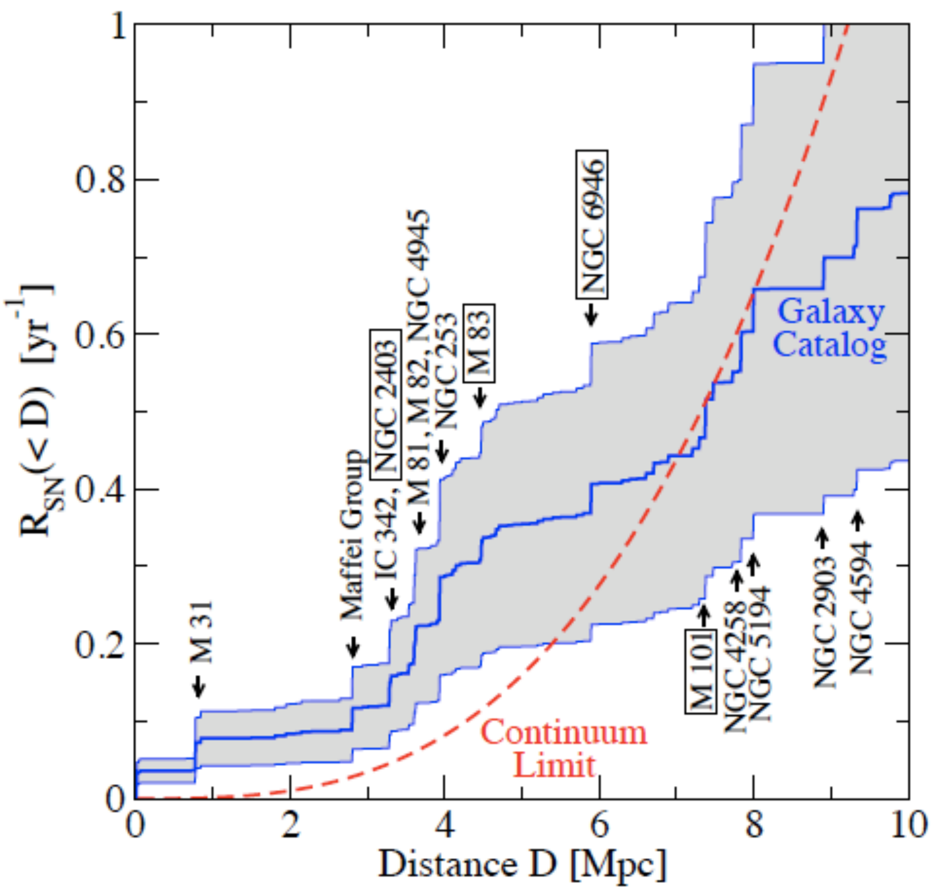
    http://www.snolab.ca/halo/detailedPhysics.html
  - For all-flavor: noble gas TPC (NOSTOS)

    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)

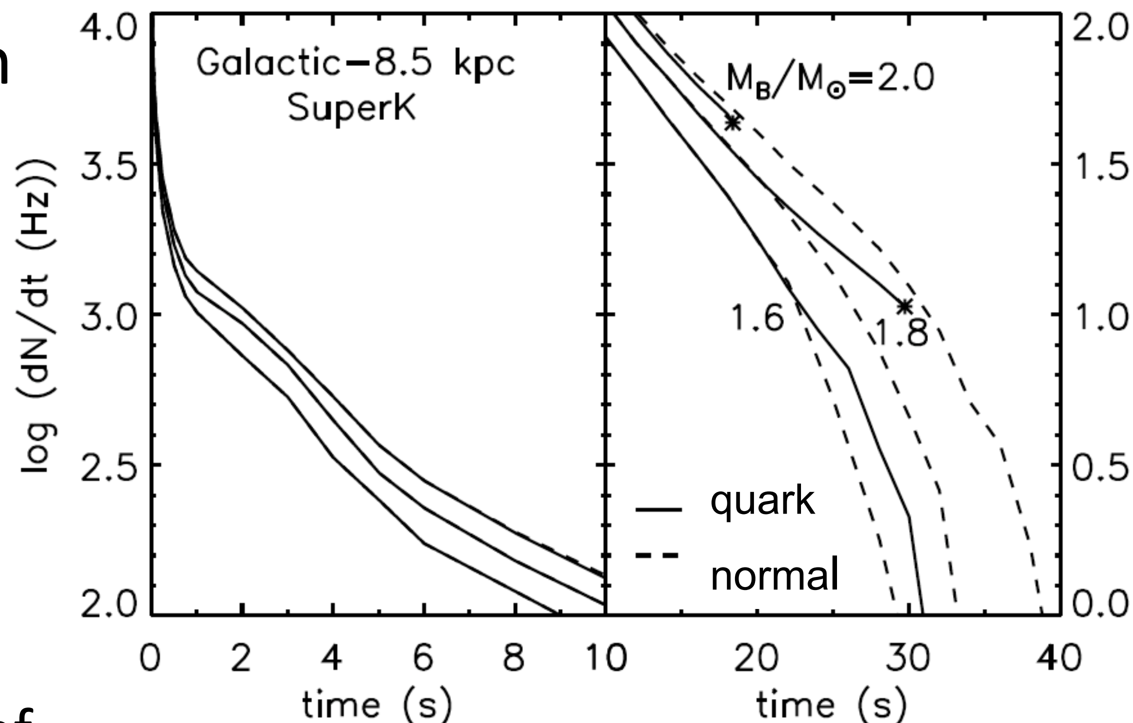
Detector	Type	Mass (kton)	Location	Events at 8.5 kpc	Status
Super-K[22]	H_2O	32	Japan	7000	Running
SNO[41]	D_2O	1 (D_2O) 1.4 (H_2O)	Canada	400 450	Running until end 2006
LVD[17]	C_nH_{2n}	1	Italy	200	Running
KamLAND[18]	C_nH_{2n}	1	Japan	300	Running
Borexino[20]	C_nH_{2n}	0.3	Italy	100	200x
Baksan[15]	C_nH_{2n}	0.33	Russia	50	Running
Mini-BooNE[12]	C_nH_{2n}	0.7	USA	200	Running
AMANDA/ IceCube[28]	Long string	0.4/PMT	South Pole	N/A	Running 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?

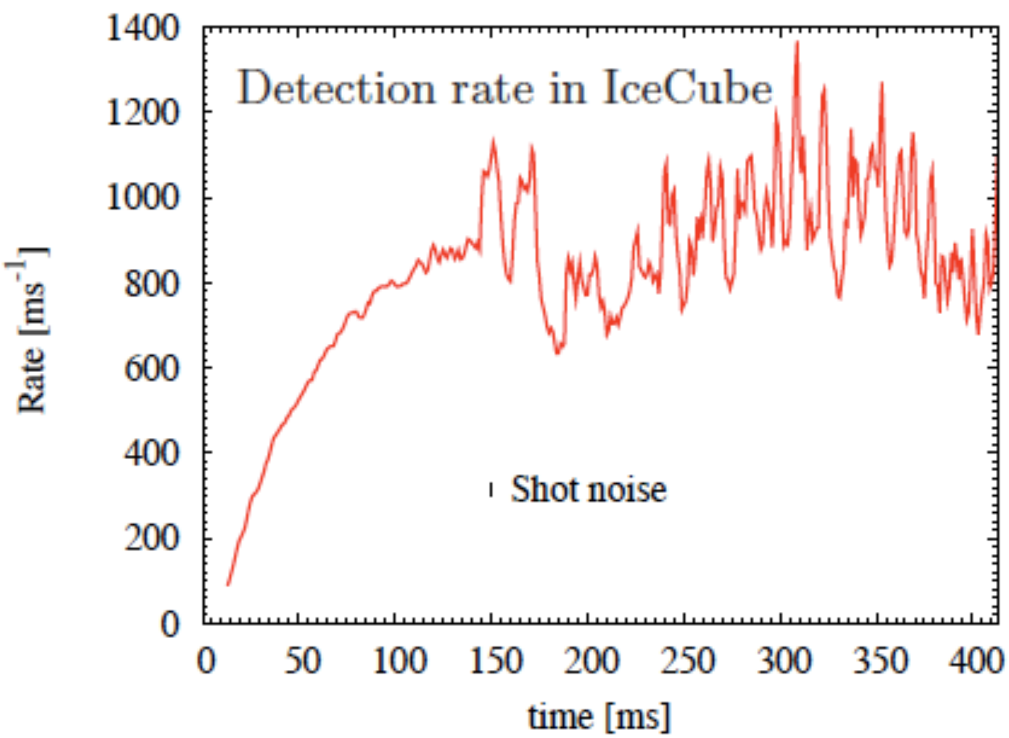
Timing

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

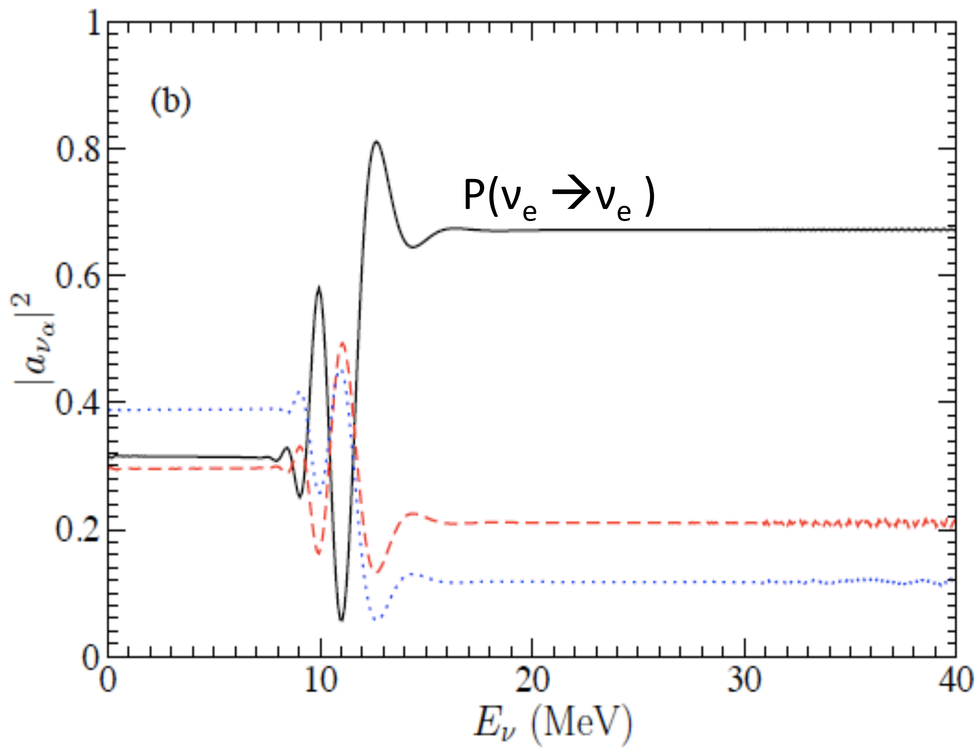
ν_e sensitivity

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
  - $e^- (p,n) \nu_e$
- 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

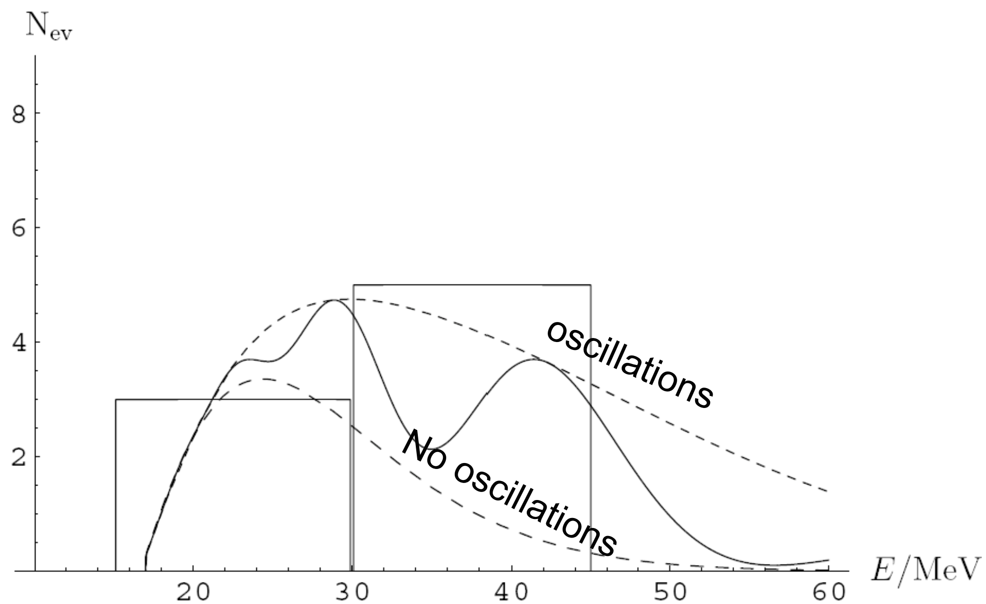
Oscillations: spectral distortions

p = survival probability

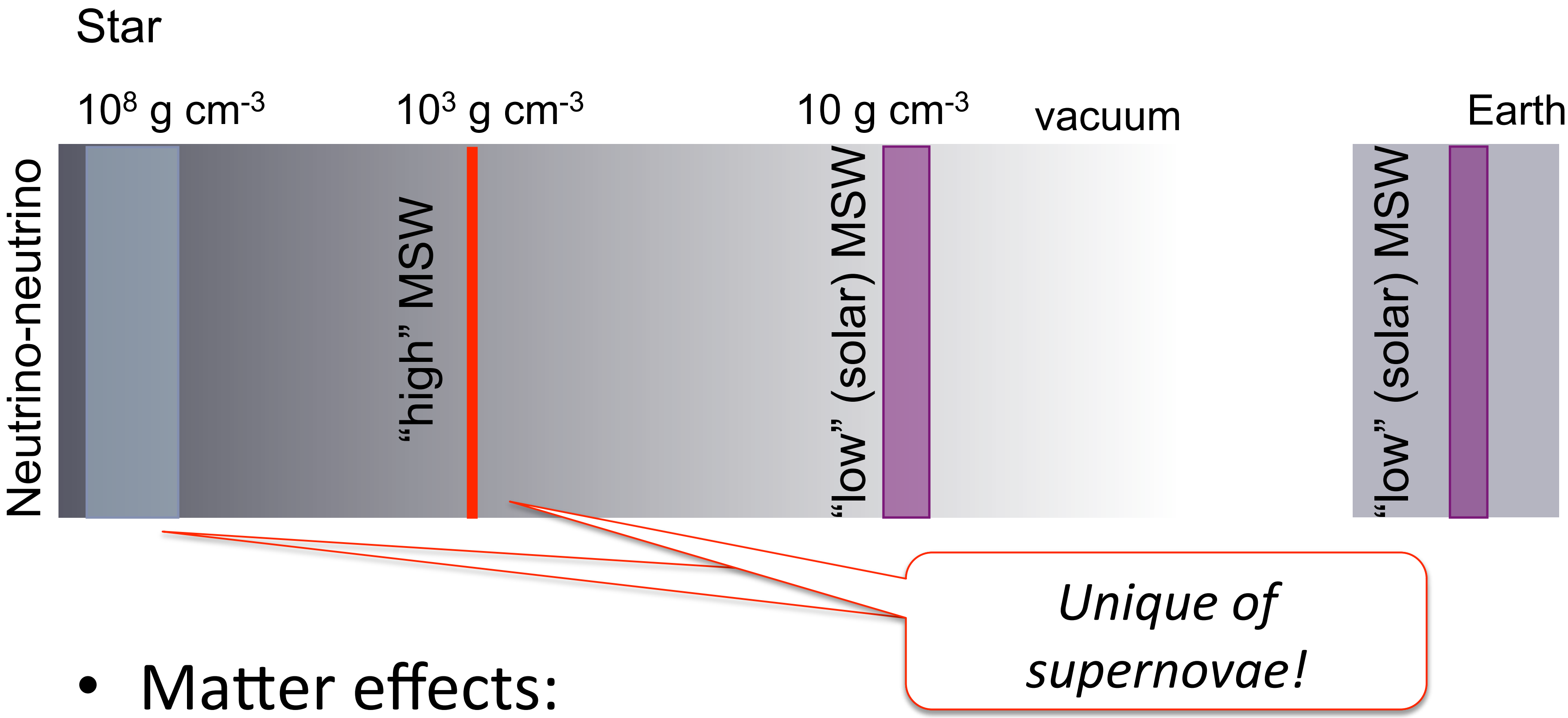
$$F_e = pF_e^0 + (1-p)F_x^0$$
$$F_{\bar{e}} = \bar{p}F_{\bar{e}}^0 + (1-\bar{p})F_x^0$$

x= μ, τ

Harder spectrum!
Depends on masses, mixings

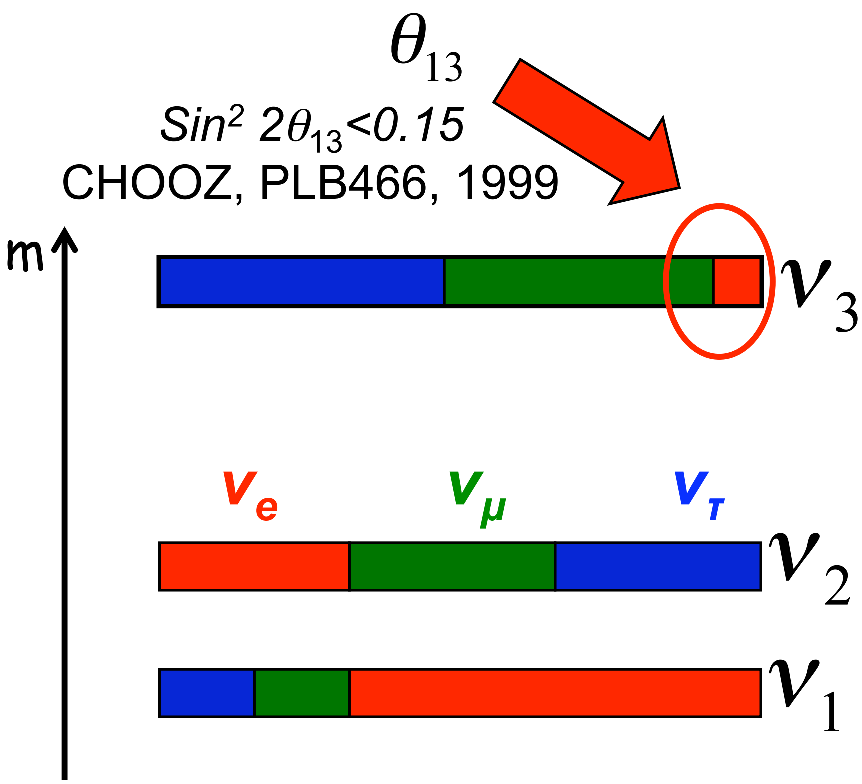


Neutrino oscillations



- 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**:*

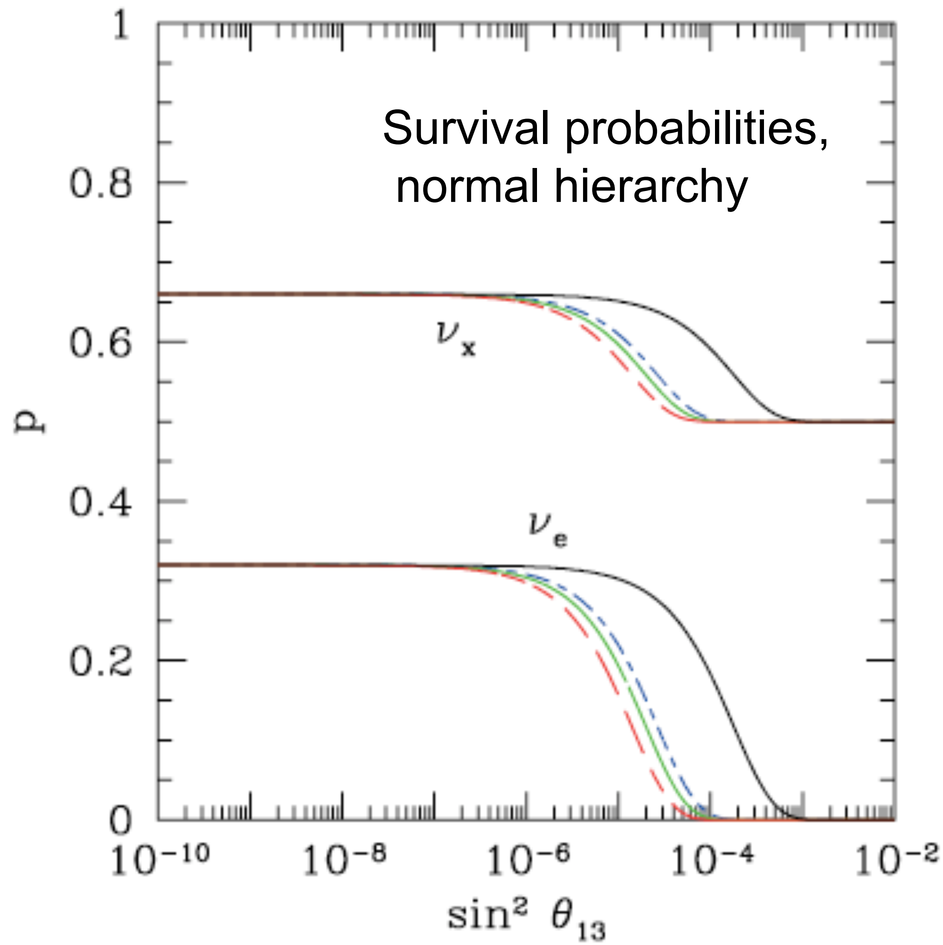
  $\Delta m^2_{31}/2E \sim 2^{1/2}\, G_F\, \rho/m_N$

- Realized for

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

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

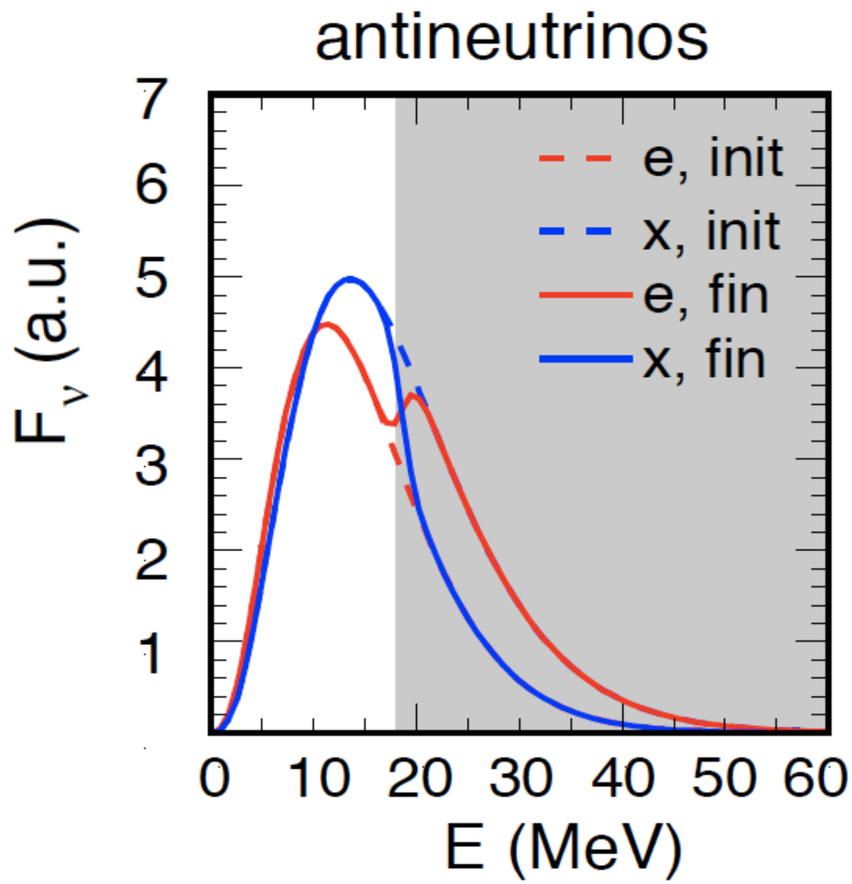
- Sensitivity down to $sin^2\ \theta_{13} \sim 10^{-5}$!



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

Neutrino-neutrino: spectral swaps

- Step-like probability as function of energy
- Work in progress



Plot from Dasgupta et al., arXiv:1002.2943

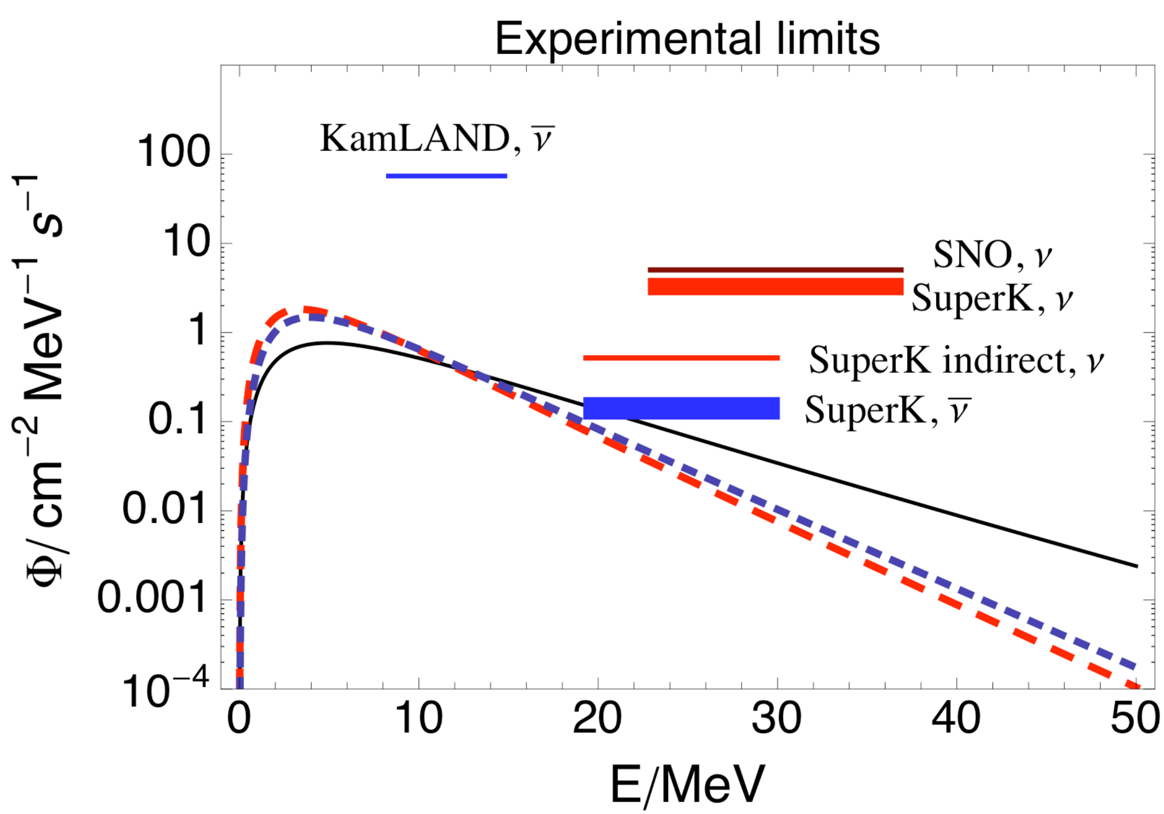
Groups: Munich, San Diego, LANL, North Carolina S., Trieste, Bari, Orsay, Tata Inst., New Mexico U., Minnesota U., …

- Still, a galactic SN might take a while…

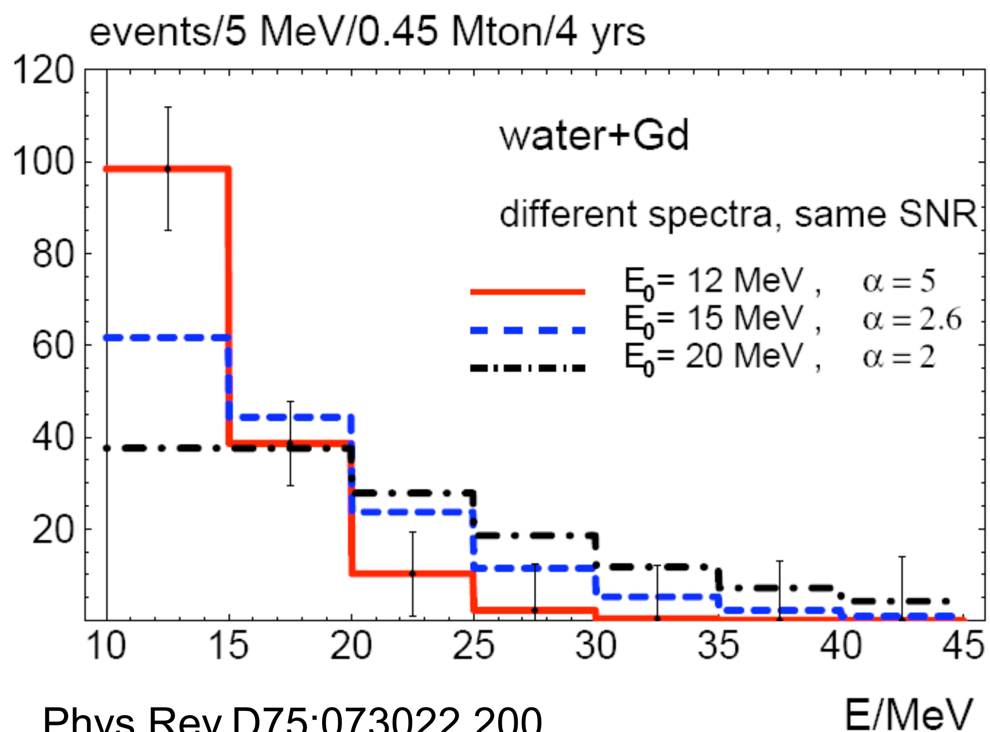
Clip art from
M. Vagins

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

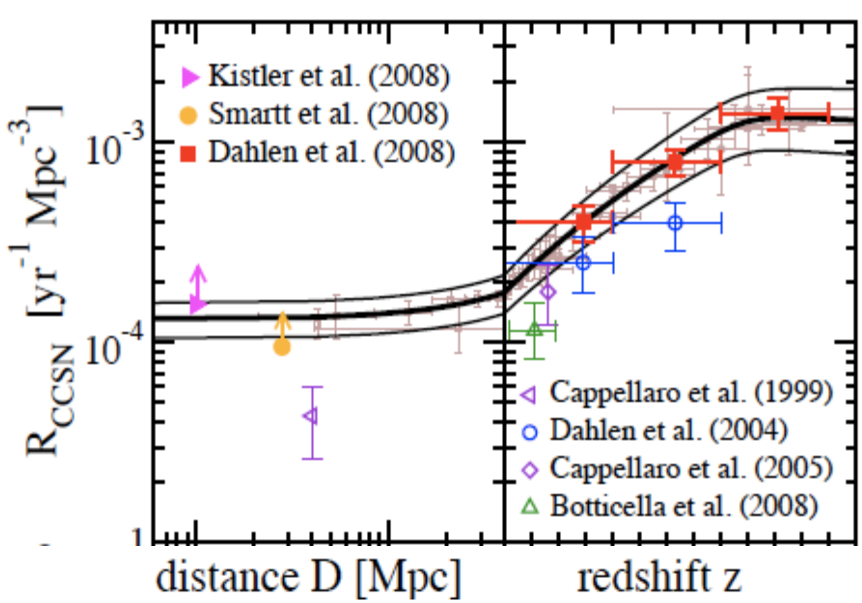


Plot from C.L., Phys.Rev.D75:073022,200

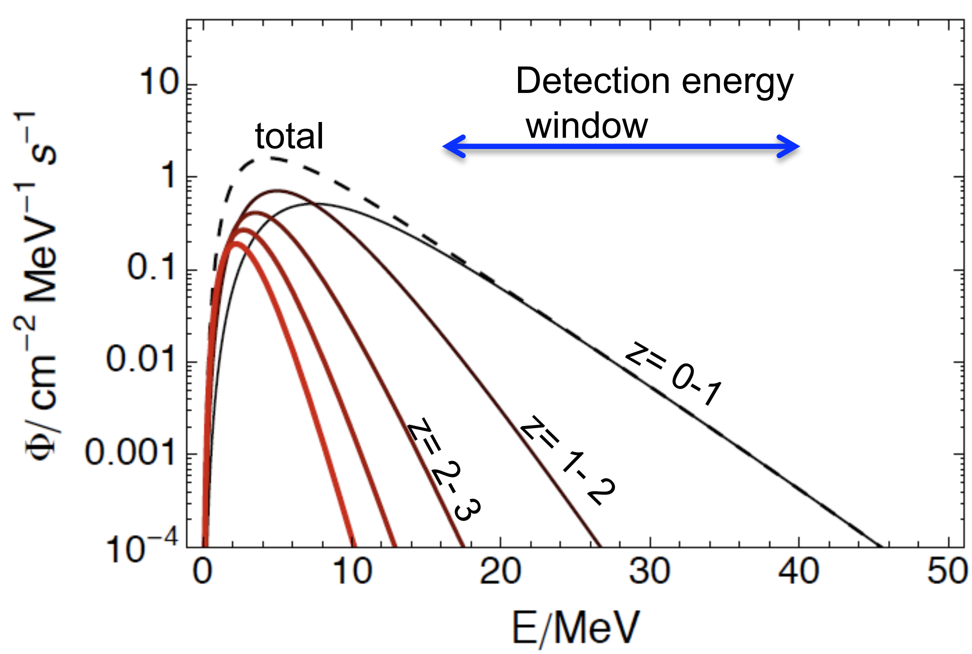
- ***Everything****: probes the whole supernova population of the universe*
  - What's typical?
  - Cosmological SNe
  - Diversity: Fe-core, ONeMg core, black hole core, …

Cosmological rate of SNe

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



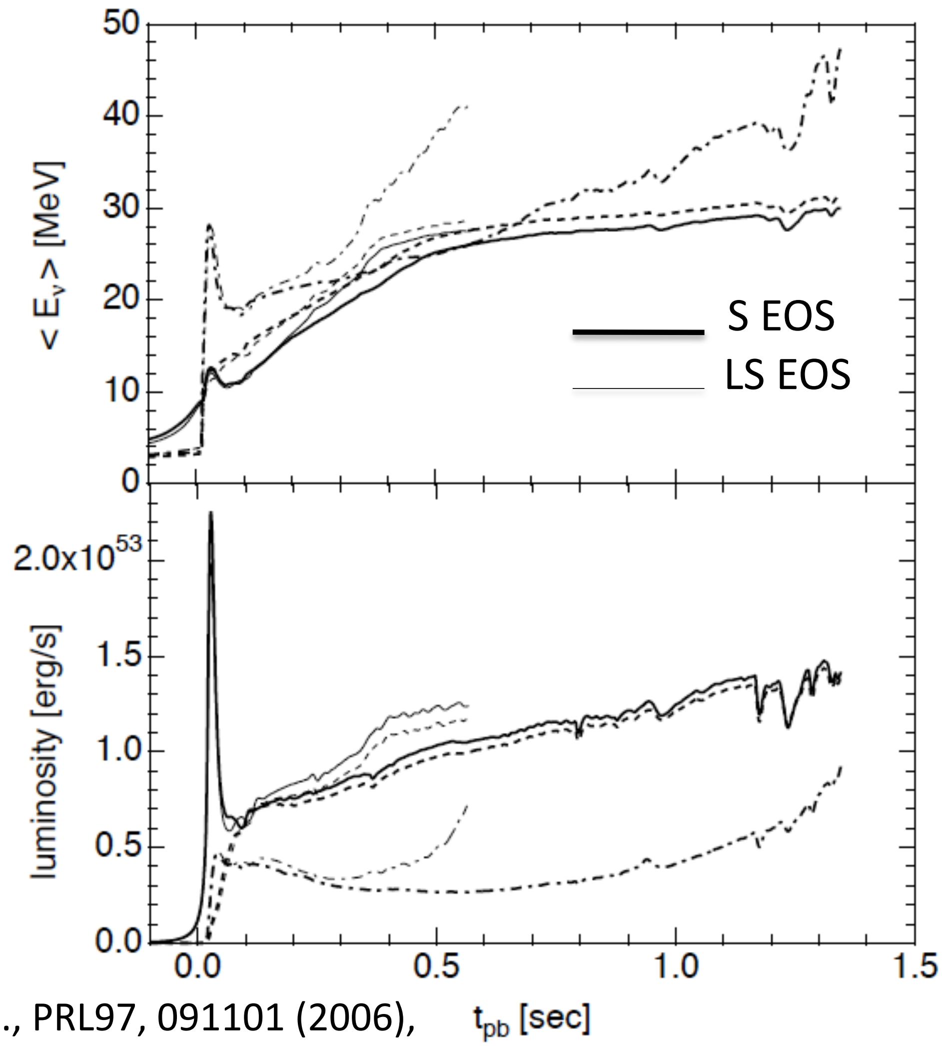
Horiuchi, Beacom & Dwek, 2009



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

Example: failed SNe

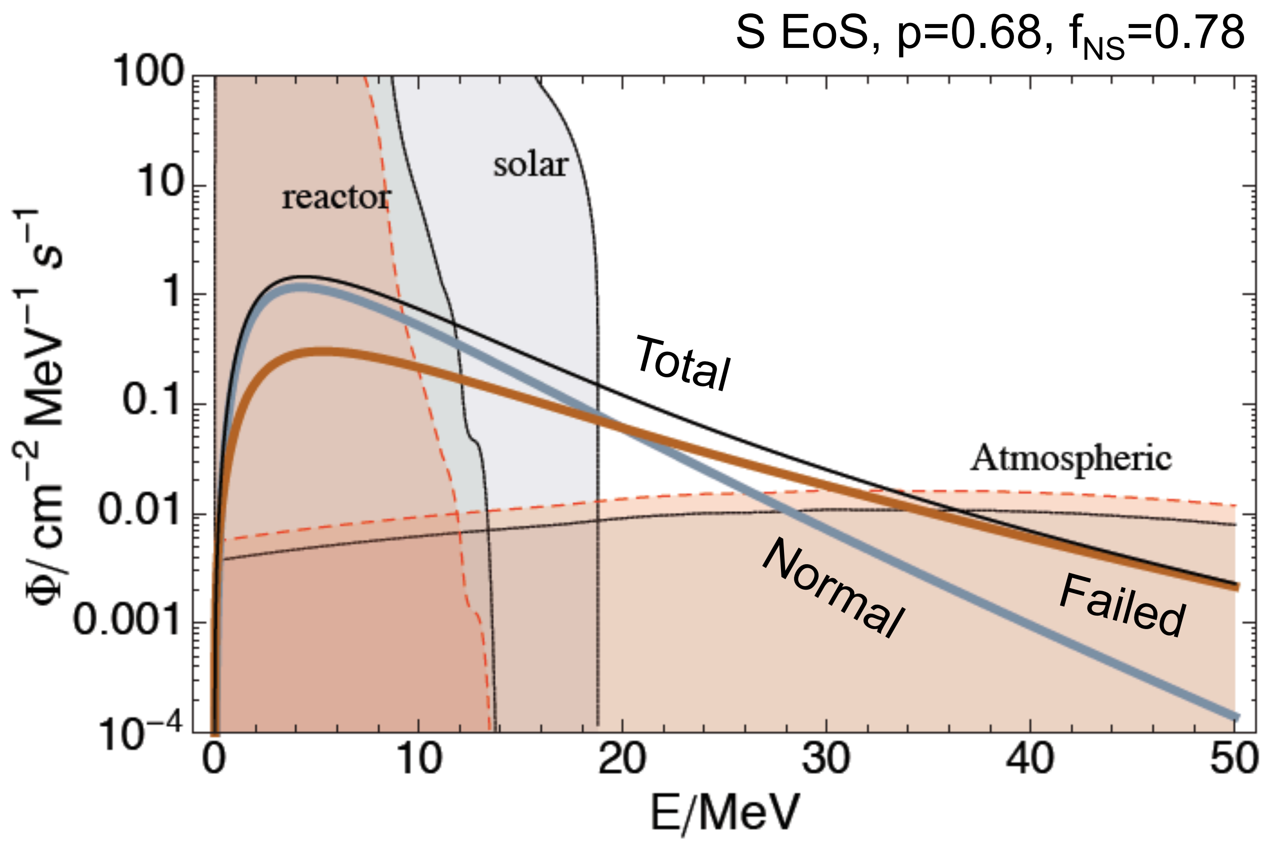
- M > 25-40 M_{sun} , 9-22% of collapses
  - *Too rare to expect a galactic one!*
- Collapse *directly* into black hole, no explosion
- *Neutrinos hotter and more luminous*
  - *<E> ≈ 20 MeV for all flavors*



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

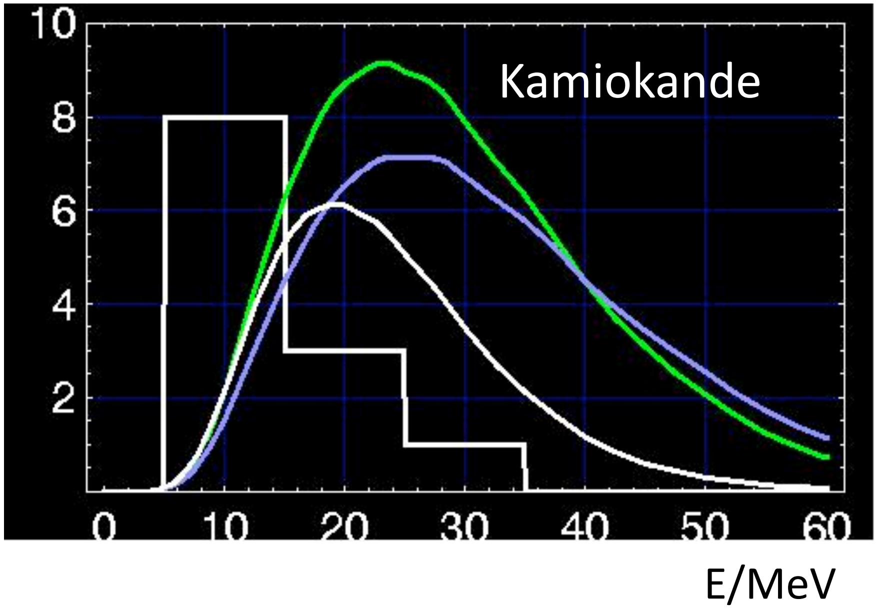
- *Precision!*

backup

Data (sparse) vs theory..

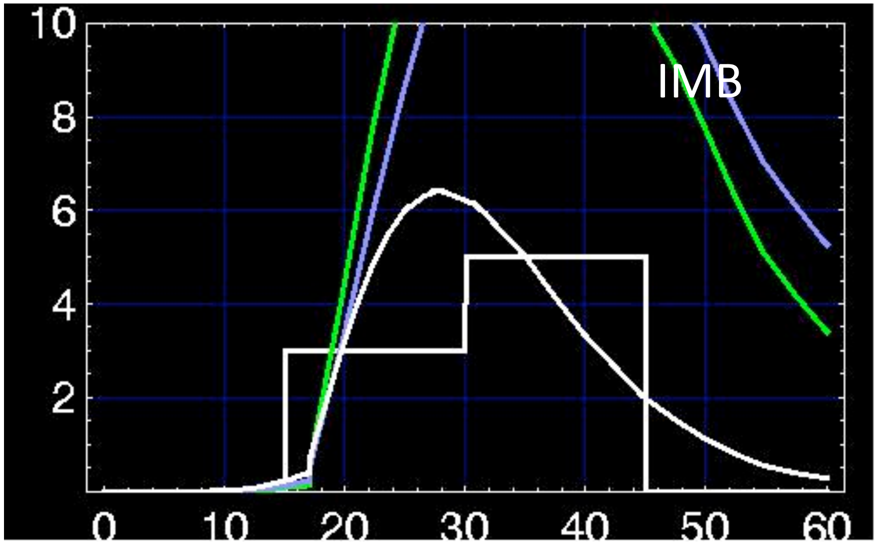
- ~ 1 Kt water detectors

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

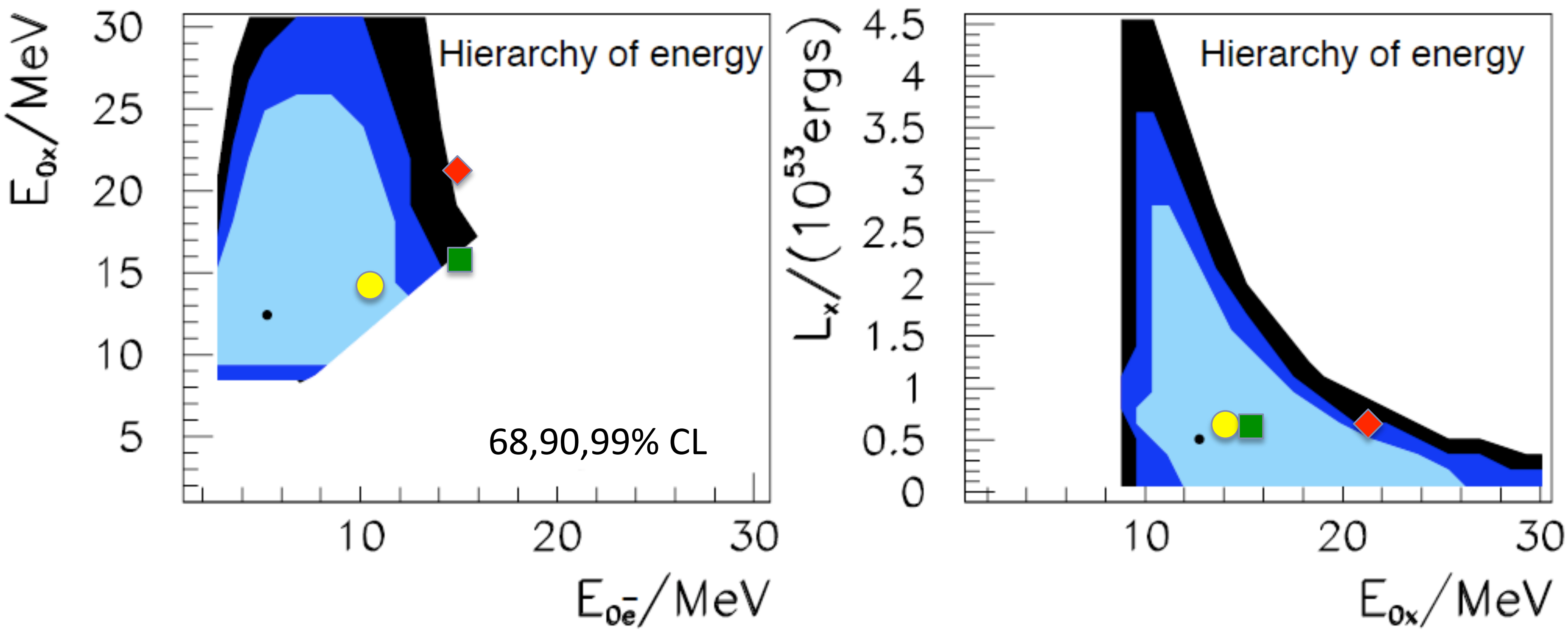


$\sin^2\theta_{13}=10^{-4}$

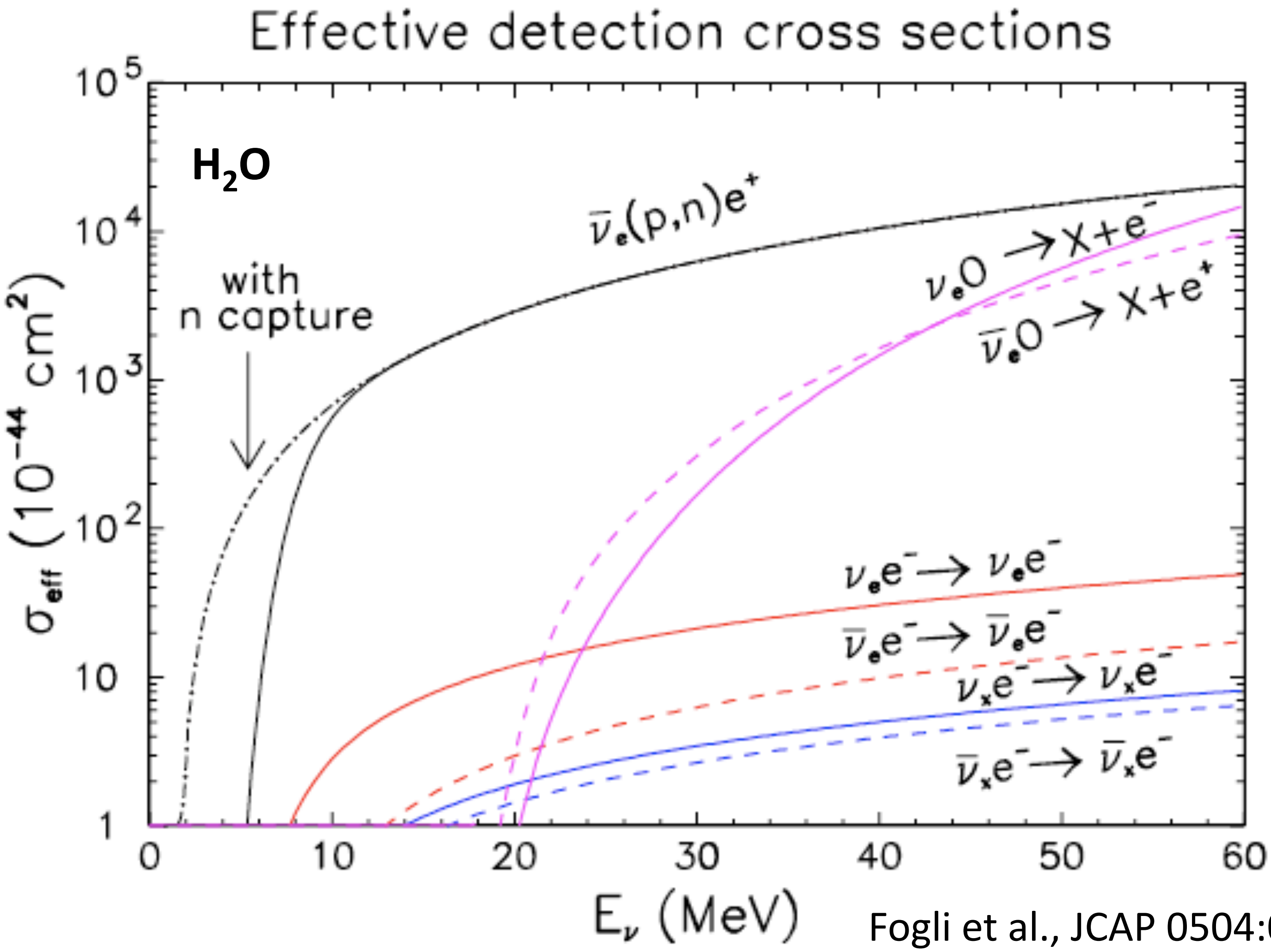
- Garching/ORNL
- Lawrence Livermore
- Arizona



5 parameters fit, with oscillations, marginalized (C.L., Astropart.Phys.,2006.)



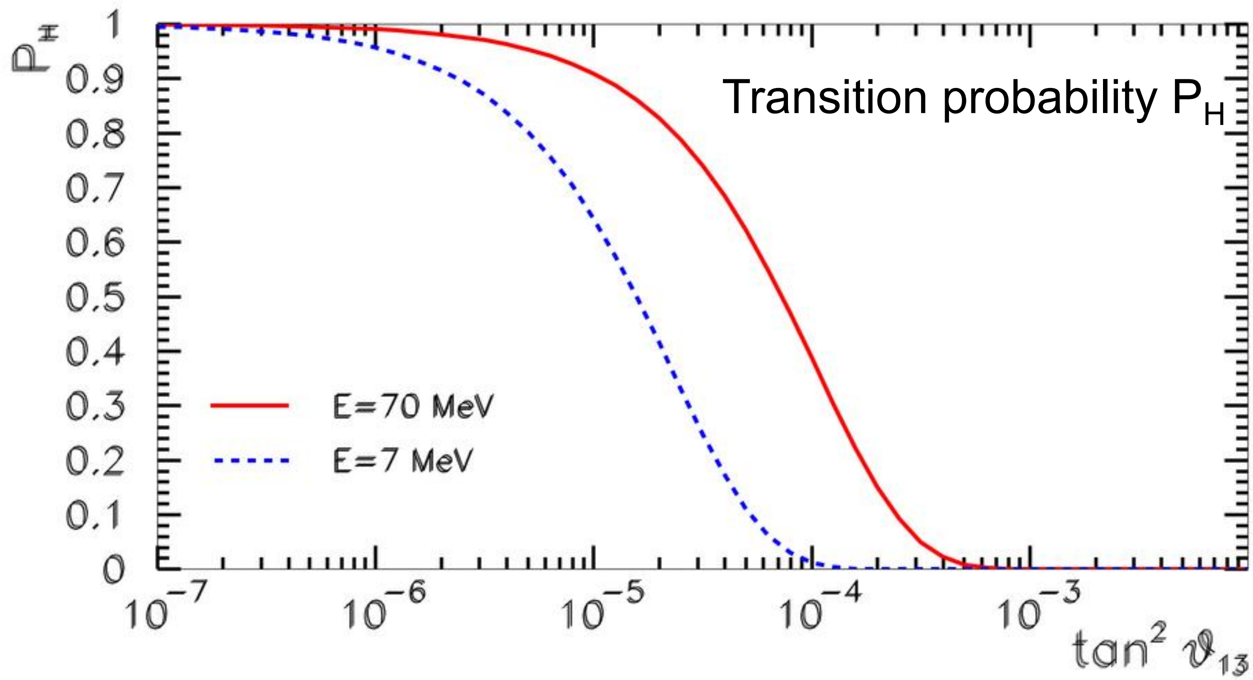
Lawrence Livermore	Totani et al., Astrophys. J. 496 (1998)
Arizona	Thompson, Burrows & Pinto, Astrophys. J. 592 (2003)
Garching	Keil, Raffelt & Janka, Astrophys. J. 590 (2003)



Fogli et al., JCAP 0504:002,2005

High MSW: θ_{13} *resonant* dependence

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



C. L. and A. Y. Smirnov, Nucl. Phys. B 616, 307 (2001), JCAP 0306, 009(2003);

A two population model: diffuse flux

C.L., arXiv:0901.0568, Phys. Rev. Lett., 2009

$$\Phi(E) = \frac{c}{H_0} \int_0^{z_{max}} R_{cc}(z) \left[f_{NS} F_{\bar{e}}^{NS}(E(1+z)) + (1 - f_{NS}) F_{\bar{e}}^{BH}(E(1+z)) \right]$$

$$\times \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

$f_{NS} = 0.78 - 0.91,$ $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$

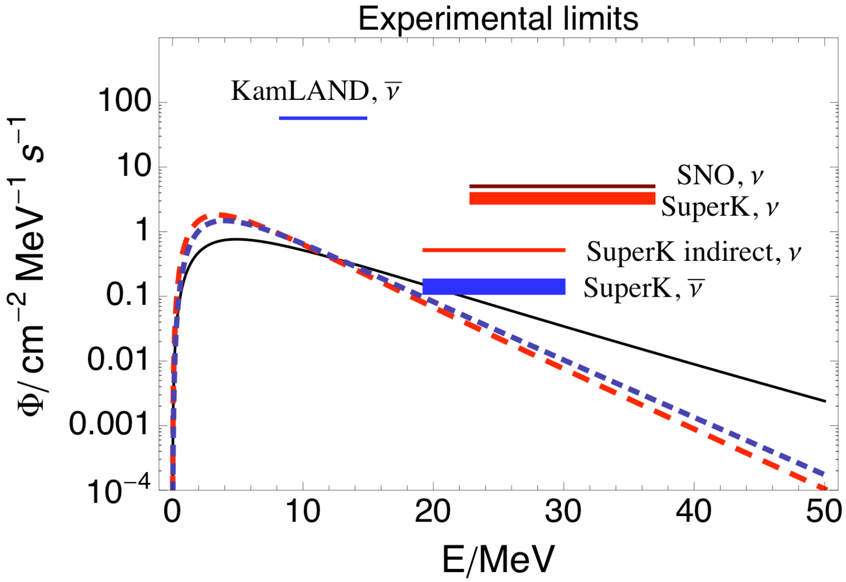
$\bar{p} = 0 - \cos^2 \theta_{12} \simeq 0 - 0.68$

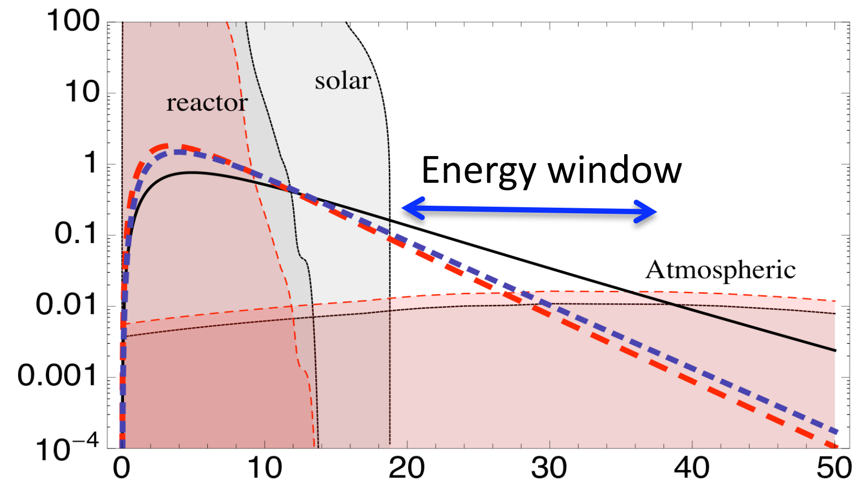
anti-ν_e survival probability
(time averaged, constant in energy)

Upper limits and backgrounds

SuperKamiokande (Malek et al., PRL, 2003):

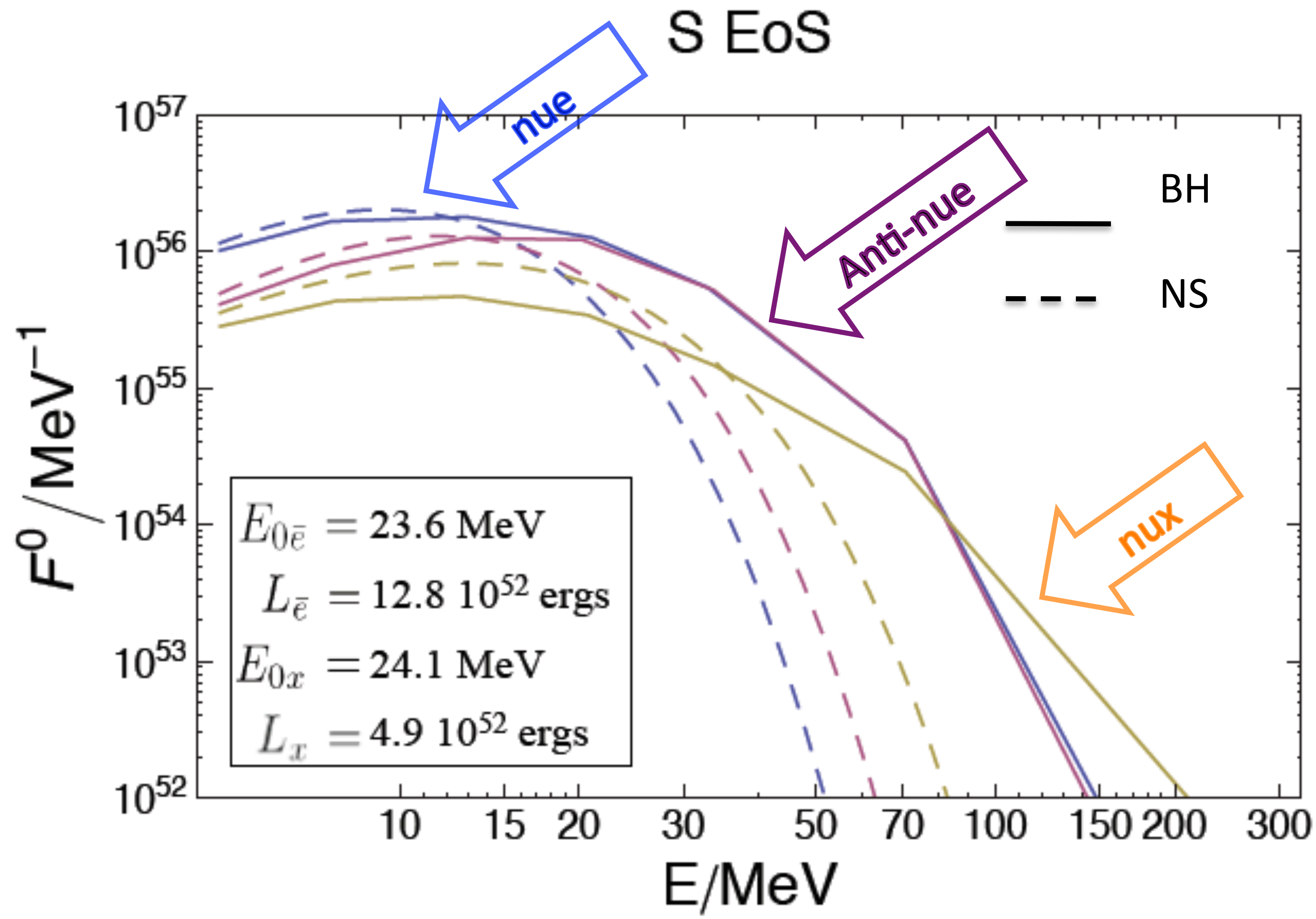
$$\Phi_{\bar{\nu}_e}(E > 19.3\ \mathrm{MeV}) < 1.4 - 1.9\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \quad \text{at } 90\%\mathrm{C.L.}$$





Red dashed: Homestake
Solid, grey: Kamioka

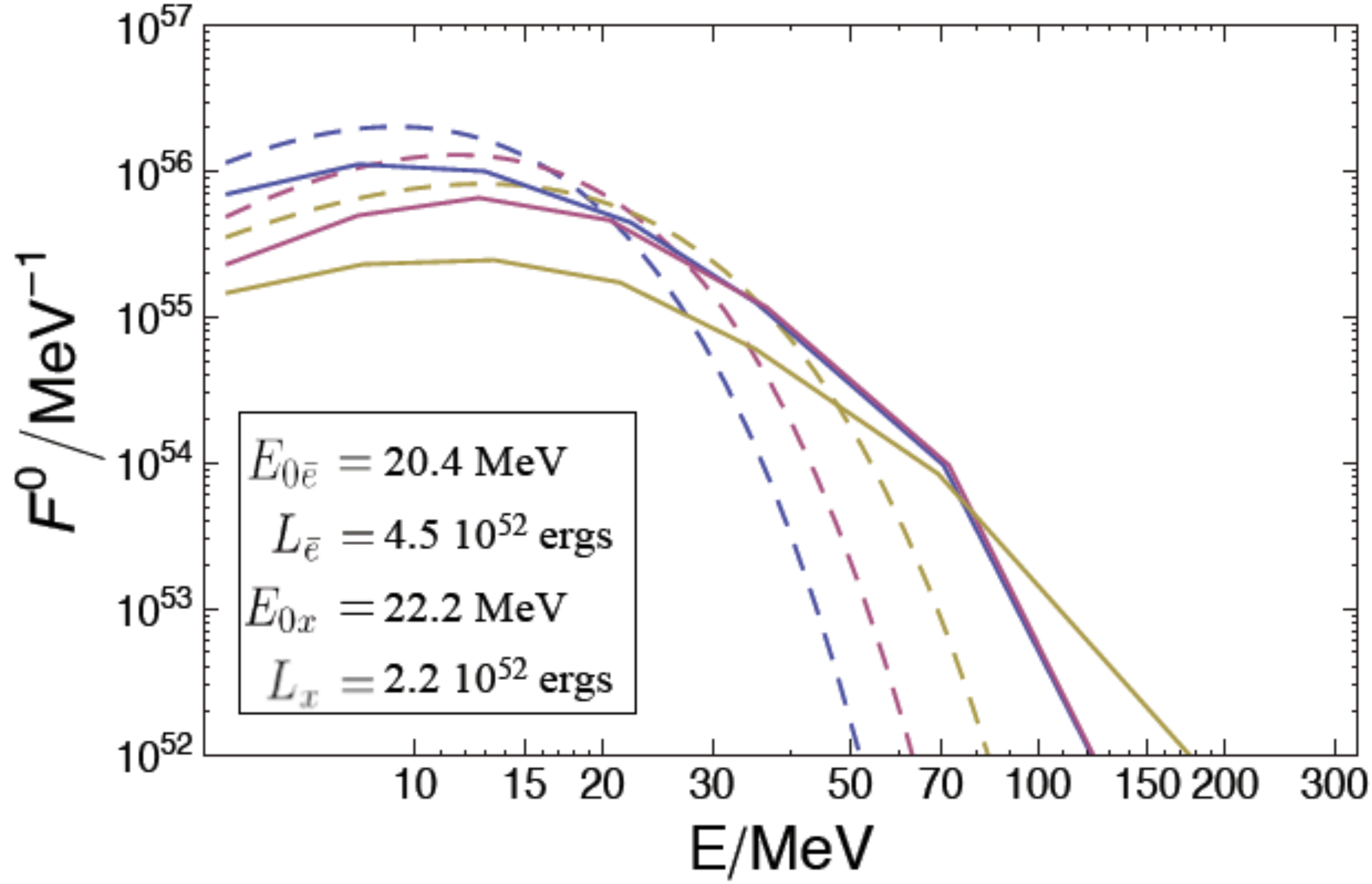
Time-integrated fluxes



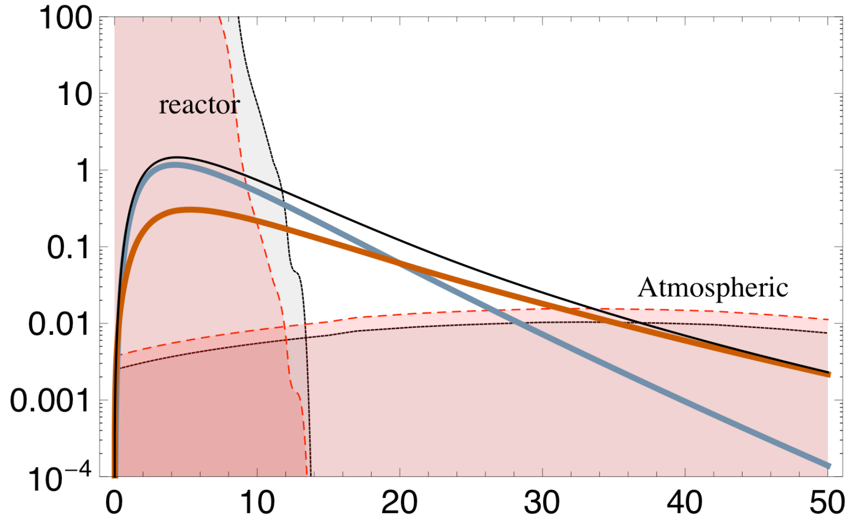
– Progenitor: M=40 M_{sun}, from Woosley & Weaver, 1995

K. Nakazato et al., PRD78, 083014 (2008)

Lattimer-Swesty. (LS) EoS



Larger energy window

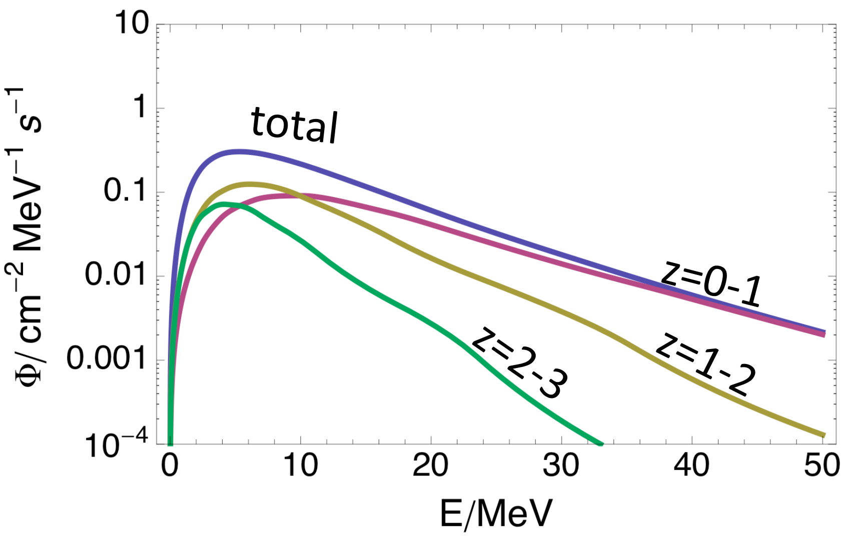


Red dashed: Homestake
Solid, grey: Kamioka

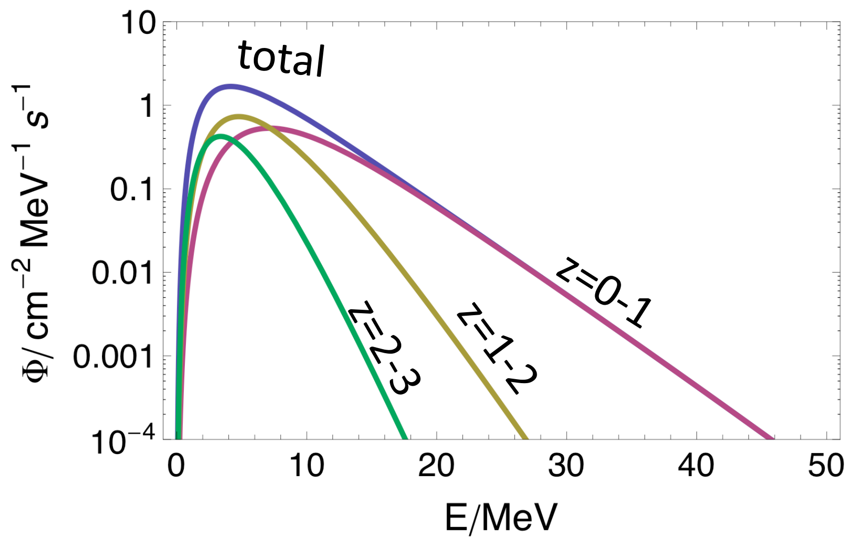
- NS only:
  - 12-29 MeV @Kamioka
  - 10 – 27 MeV @Homestake
- NS+BH:
  - 12-36 MeV @Kamioka
  - 10-32 MeV @Homestake

Stronger cosmological (z>1) contribution

Black hole forming:
58% (32%) above 10 MeV (20 MeV)

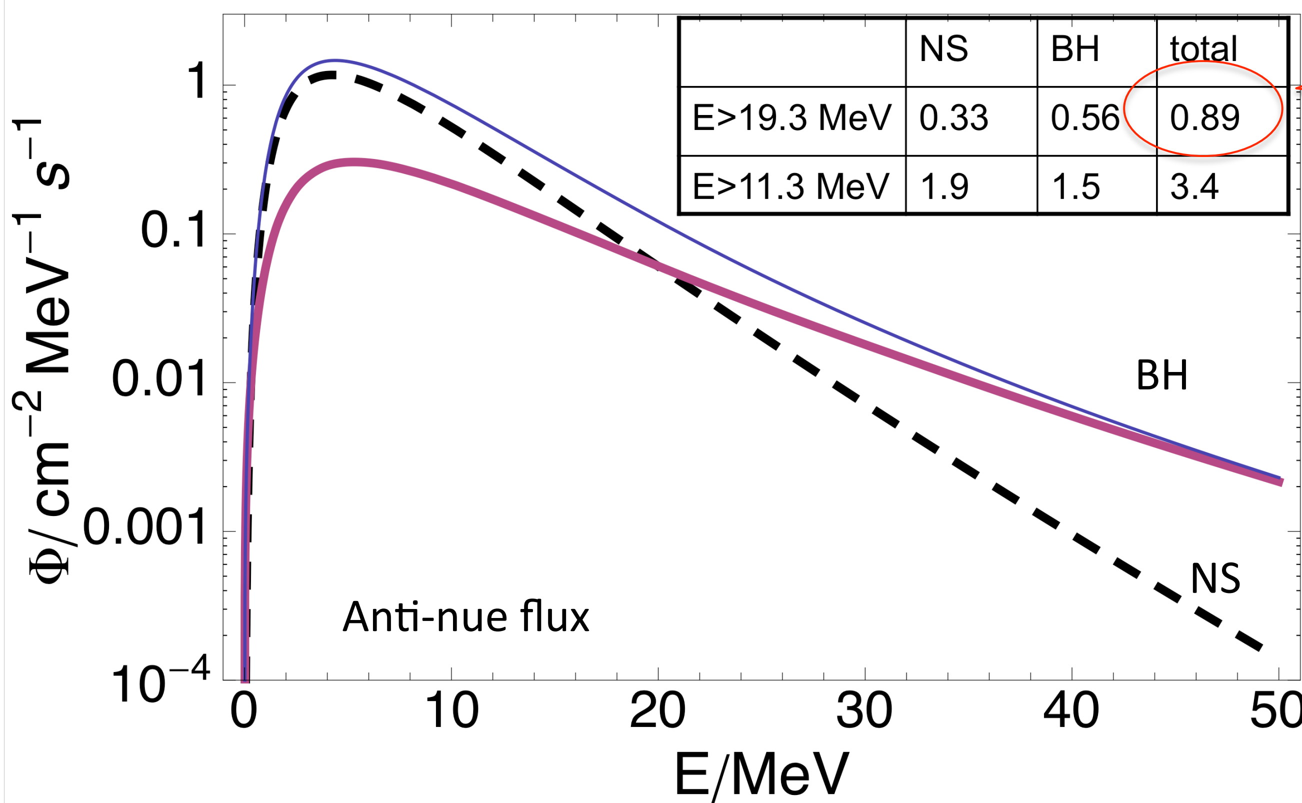


Neutron-star forming:
<30% (<15%) above 10 MeV (20 MeV)



failed SNe may dominate!

- Best case: "stiff" EoS, 22% failed SNe, *maximum* $\bar{p}$

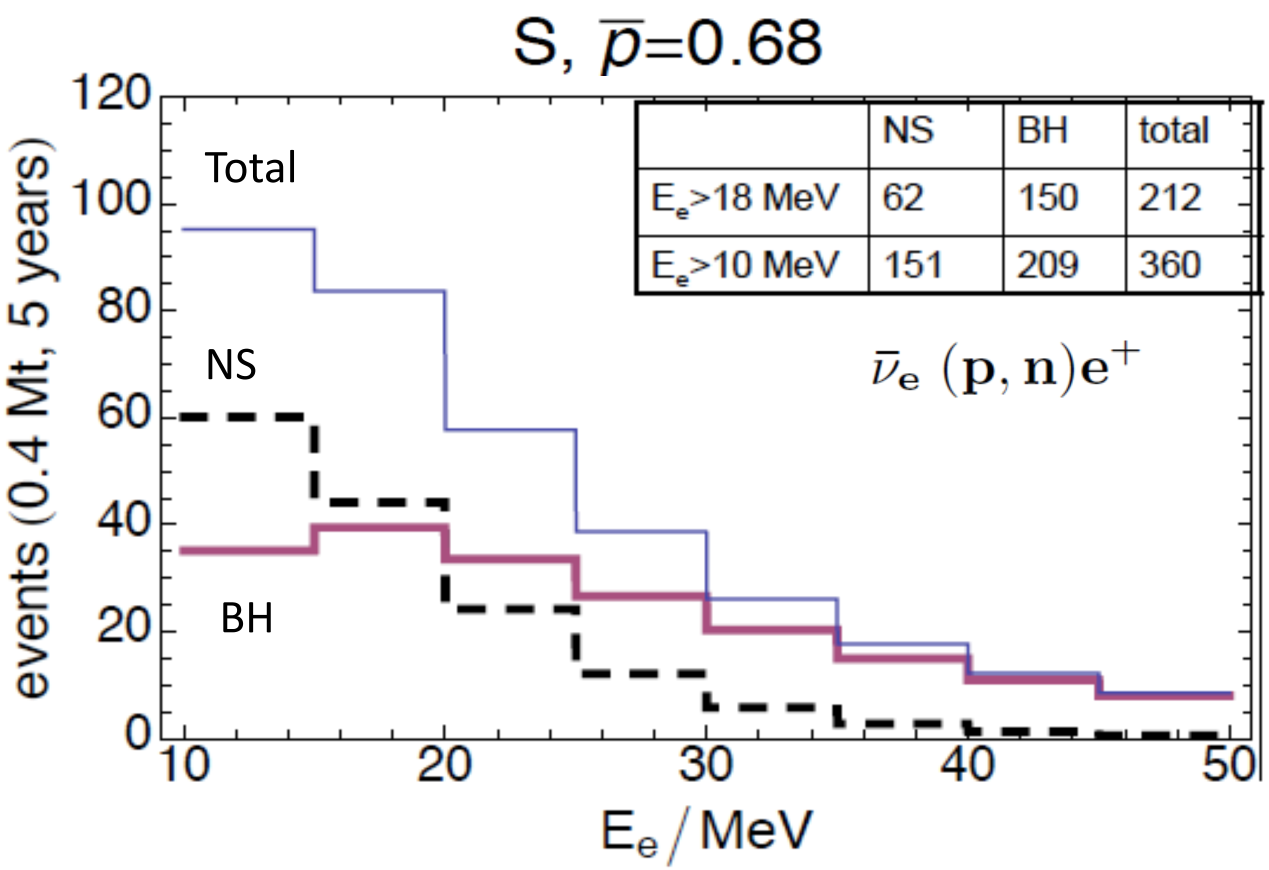


	NS	BH	total
E>19.3 MeV	0.33	0.56	0.89
E>11.3 MeV	1.9	1.5	3.4

Close to SK limit!

C.L., arXiv:0901.0568, Phys. Rev. Lett., 2009, J. G. Keehn and C.L., in preparation

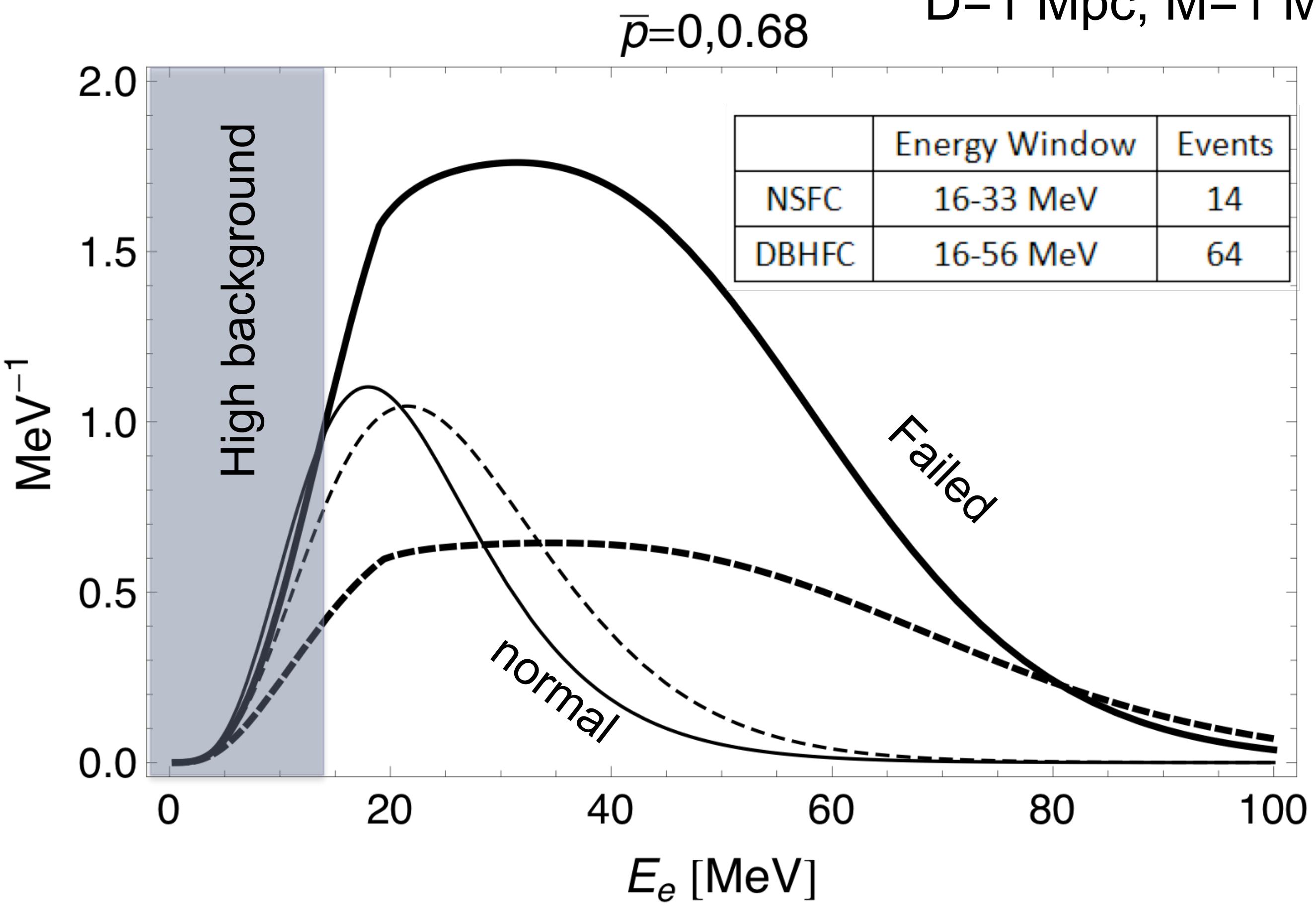
- Best: ~ 100% enhancement



	NS	BH	total
E_e>18 MeV	62	150	212
E_e>10 MeV	151	209	360

What about nearby failed SNe?

D=1 Mpc, M=1 Mt, S EoS

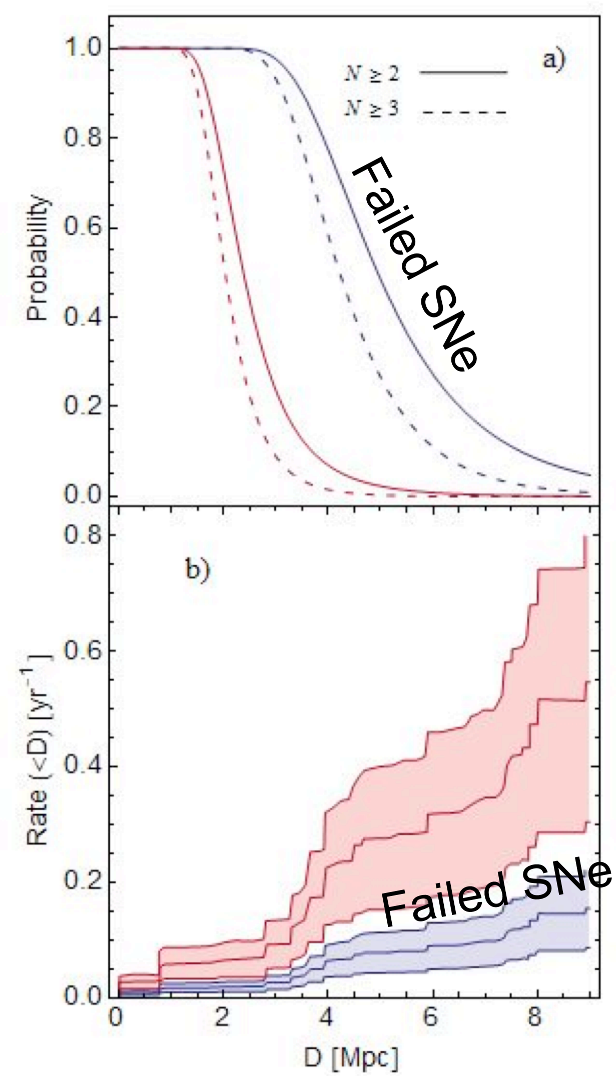


	Energy Window	Events
NSFC	16-33 MeV	14
DBHFC	16-56 MeV	64

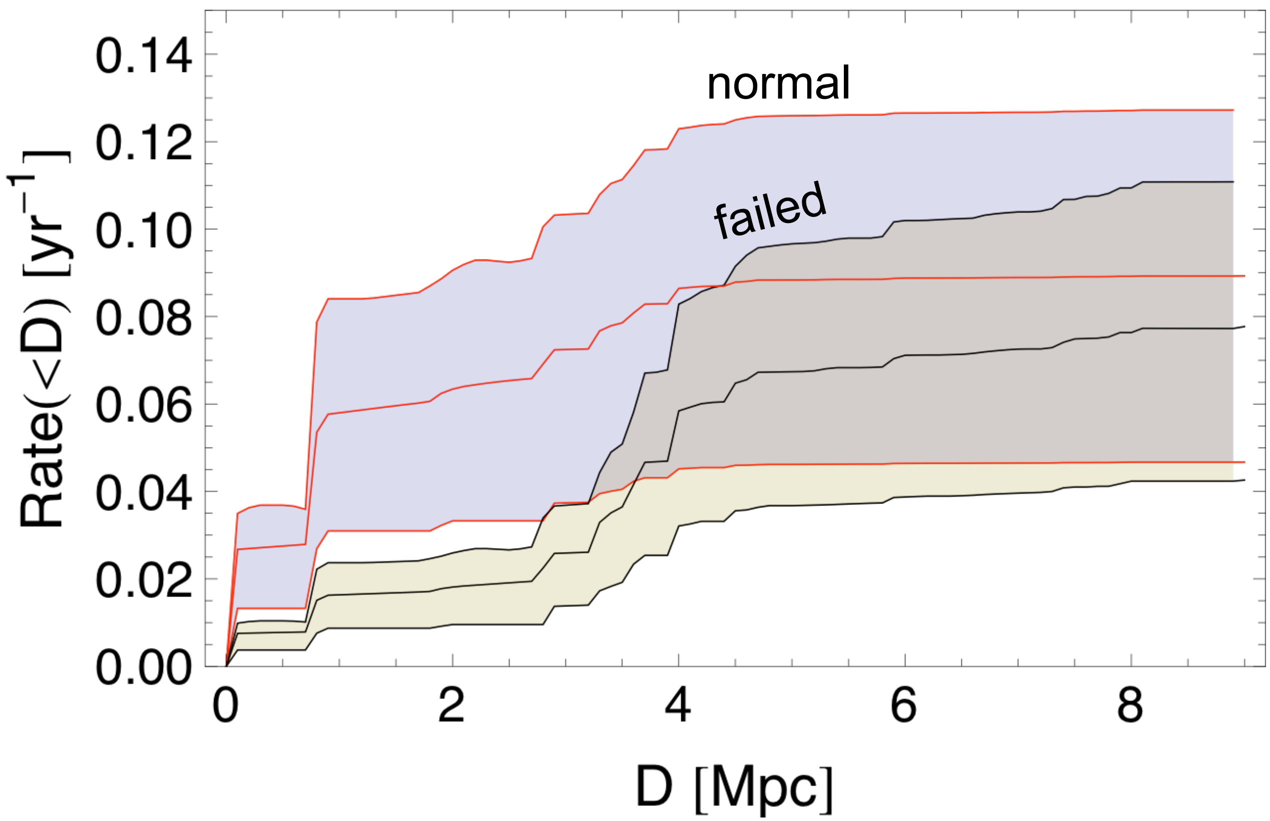
Extragalactic failed SNe at Mt detectors

L. Yang & C.L., arXiv:1103.4628

- 2-3 events from ~4-5 Mpc
  - S EoS, 20% failed SNe
- up to 1 per decade expected!
  - Comparable to normal SNe



Local rate from S. Ando, J. F. Beacom, and H. Yuksel (2005).



- Up to ~ 0.1 yr^{-1} bursts (N≥2) can be detected
- Comparable to rate of normal SNe!

Background: N≥ 2 ok

- Invisible muons, atmospheric neutrinos
  - λ=1855 yr^{-1} (failed), λ=680 yr^{-1} (normal)

- Accidental coincidence in Δt
  - $\omega_2=\lambda^2\,\Delta t$, $\omega_3=\lambda^3\,\Delta t^2$ (Δt=1 s, 10s for failed, normal)

	DBHFC yr^{-1}	NSFC yr^{-1}
ω_2	0.10 yr^{-1}	0.15
ω_3	$6.4\cdot 10^{-6}$	$3.1\cdot 10^{-5}$

Concept	energy window (MeV)	detection processes	experiment (location)	fiducial mass (kt)
H_2O	19.3 - 30	$\bar{\nu}_\mathbf{e}\ (\mathbf{p},\mathbf{n})\mathbf{e}^+$	**SK (Japan)**	22.5
	$[17.3 - 30]$	$\nu_e\ (^{16}O, X)e^-$	DUSEL WC (USA)	300
		$\bar{\nu}_e\ (^{16}O, X)e^+$	MEMPHYS (Europe)	440
		$\nu_w(e^-, e^-)\nu_w$	Hyper-K (Japan)	500
		$\nu_w(p,p)\nu_w$	Deep-TITAND (Japan)	$5\ 10^3$
		$\nu_w(^{16}O, X)\nu_w$		
$H_2O + Gd$	11.3 - 30	same as H_2O	GADZOOKS (Japan)	22.5
			DUSEL WC+Gd	300
			MEMPHYS+Gd	440
			Hyper-K+Gd	500
Scintillator	$\sim 8 - 30$	$\bar{\nu}_\mathbf{e}\ (\mathbf{p},\mathbf{n})\mathbf{e}^+$	LENA (Europe)	50
		$\nu_e\ (^{12}C, X)e^-$	Hano Hano (USA)	10
		$\bar{\nu}_e\ (^{12}C, X)e^+$		
		$\nu_w(e^-, e^-)\nu_w$		
		$\nu_w(p,p)\nu_w$		
		$\nu_w(^{12}C, X)\nu_w$		
Argon	$\sim 18 - 30$	$\nu_\mathbf{e}\ (^{\mathbf{40}}\mathbf{Ar}, \mathbf{X})\mathbf{e}^-$	DUSEL LAr (USA)	< 100
		$\bar{\nu}_e\ (^{40}Ar, X)e^+$	GLACIER (Europe)	100
		$\nu_w(e^-, e^-)\nu_w$		
		$\nu_w(^{40}Ar, X)\nu_w$		