Diffuse SN Neutrino Background (DSNB)

What can we learn?

Ideas under construction

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- introduction: motivation and facts
- detection potential

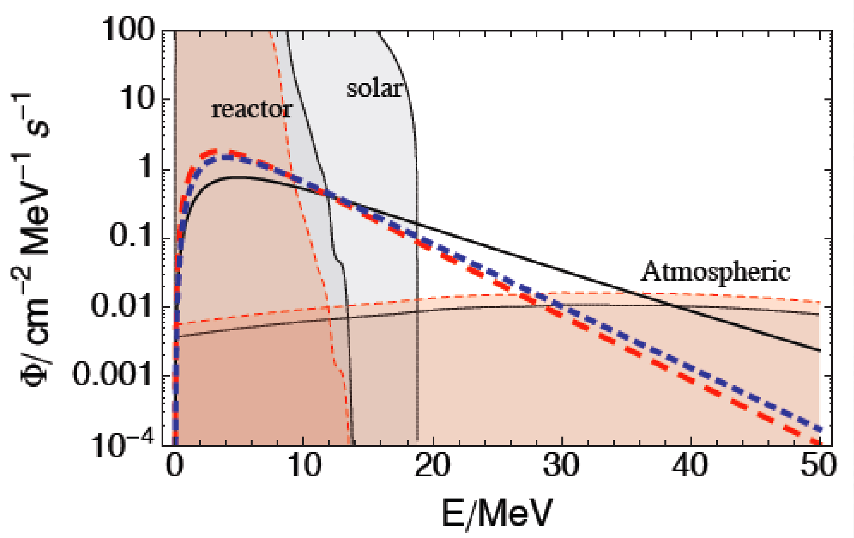
- What can we learn?
  - neutrino spectrum extraction
  - broadening the scope: miscellaneous ideas

- final remarks

Introduction

Neutrinos from cosmological SNe

- diffuse flux from all supernovae
  - ~ 40% cosmological contribution
- detectable above (irreducible) backgrounds



Different from a nearby SN

- *guaranteed* flux, no wait
- *cosmological* flux
  - longest propagation length
  - clean tracer of cosmological collapse rate (no extinction, no impostors …)
- image of SN *population*
  - What’s typical?
  - SN types, progenitor dependence, etc.

Main ingredients

$$\Phi(E) = \frac{c}{H_0}\int_0^{z_{max}} R_{SN}(z)\frac{dN(E')}{dE'}\frac{dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

Cosmological rate of supernovae

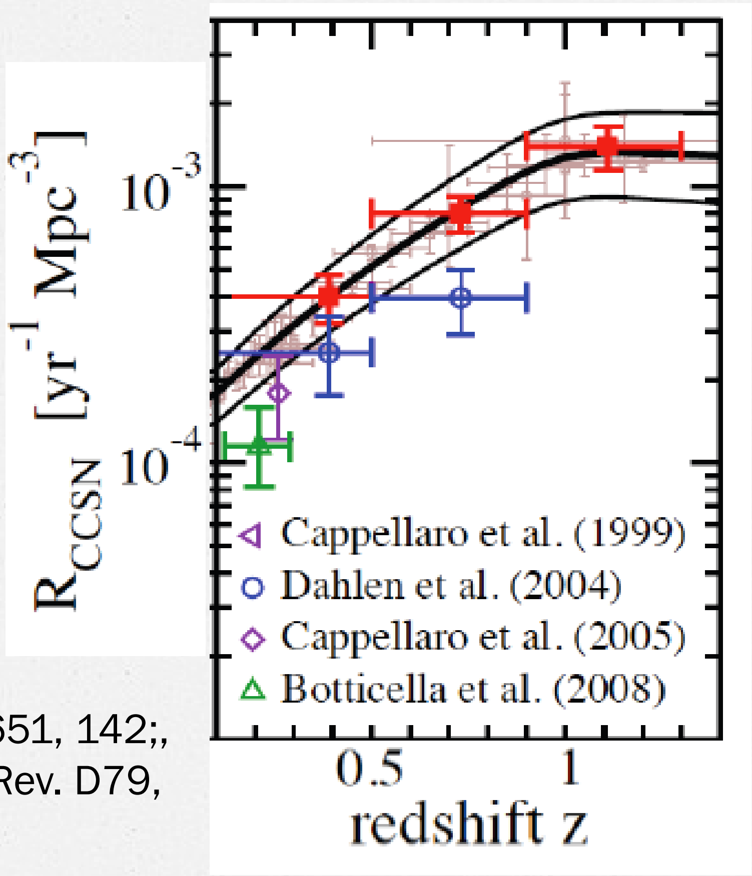
Neutrino flux at production
+
Oscillations
Redshift

Cosmology

Ando & Sato, 2004, New J. Phys. 6, 170 , Lunardini arXiv:1007.3252, Beacom Ann.Rev.Nucl.Part.Sci. 60 (2010)

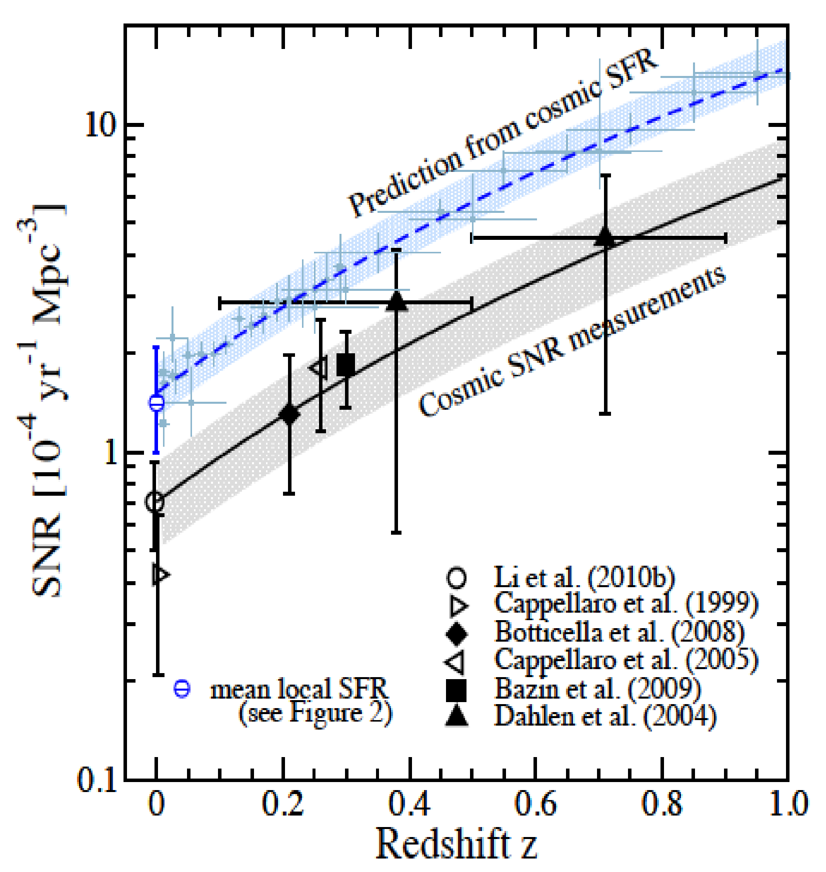
SN rate: grows with z

- proportional to ~ $(1+z)^{3.6}$ for z<1
  - flattens at z>1



Hopkins & Beacom, 2006, Astrophys. J. 651, 142;, Horiuchi, Beacom & Dwek, 2009, Phys. Rev. D79, 083013

- factor ~ 2 normalization uncertainty
  - direct counting vs star formation rate estimate



Hopkins & Beacom, 2006, Astrophys.
Horiuchi, Beacom & Dwek, 2009, Phy
083013

Flux at production

- alpha-spectrum:

$$\frac{dN}{dE} \simeq \frac{(1+\alpha)^{1+\alpha} L}{\Gamma(1+\alpha) {E_0}^2} \left(\frac{E}{E_0}\right)^{\alpha} e^{-(1+\alpha)E/E_0}$$

  - L ~ 0.5 10^{53} ergs

$$\alpha_w \sim 2 - 5$$

- hierarchy of spectra :

$$E_{0e} < E_{0\bar{e}} < E_{0x}$$

Keil, Raffelt & Janka, 2003, Astrophys. J. 590, 971

Oscillations

- spectrum swap (time-integrated):

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

- probabilities: matter (MSW) driven

	bar-p	p
$\Delta m^2_{31} > 0$	~ 0.68	0
$\Delta m^2_{31} < 0$	0	~ 0.32

C.L. & I. Tamborra,
JCAP 1207 (2012) 012

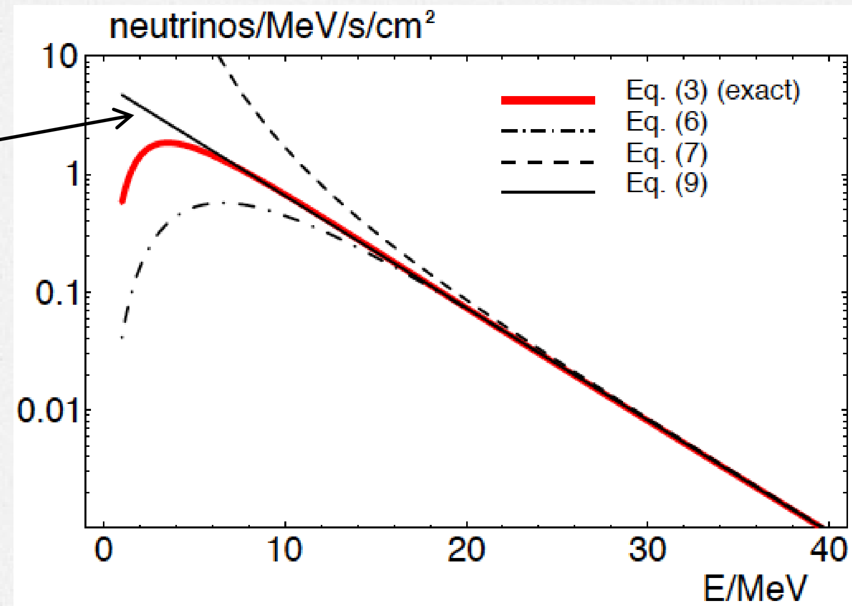
Uncertainties, degeneracies

	Large (~100% or more)	small (~ 10% or less)	Degenerate?
Avg. energy E_0	X		with α (quasi)
luminosity	X		With SNR norm.
α parameter	X		with E_0 (quasi)
mass hierarchy	X		with E_0 (quasi)
SNR power law		X	
SNR normaliz.	X		With luminosity
Prog. dependence		X (?)	
Collective oscill.		X	
Shock oscill. effect		X	

α - E_o quasi-degeneracy

- high E approximation:

$$\Phi_e = \Phi_e(0) e^{-E/\langle E \rangle}$$



- $\langle E \rangle \sim E_0/(1+\alpha)$
  - inherited from original α-spectrum

C.L., Phys.Rev. D75 (2007) 073022

Detection potential

Current: SuperKamiokande

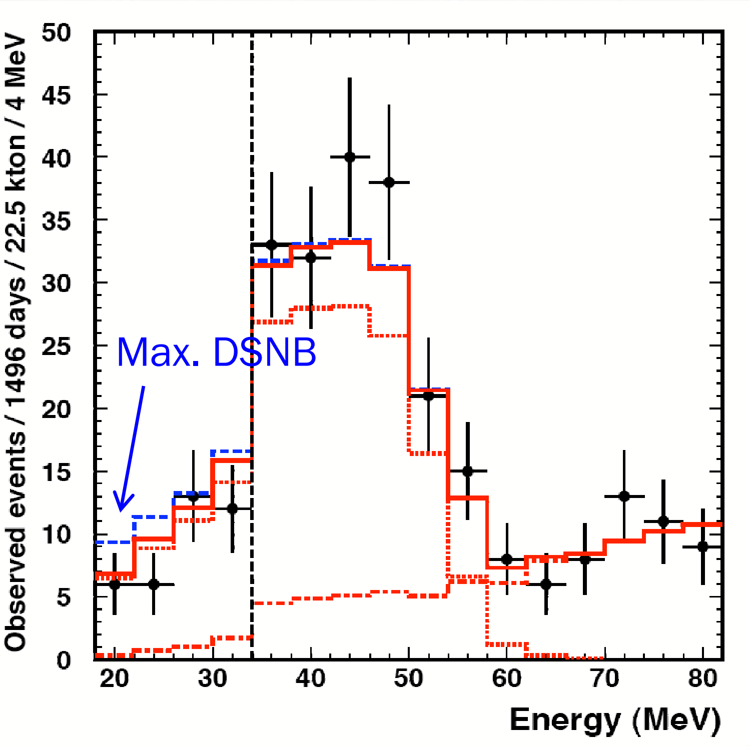
- 22.5 kt, water

  $\bar{\nu}_e + p \to e^+ + n$

  - high background

- anti-nu_e limit :

φ(E>17.3 MeV)< 2.8 - 3 cm^{-2} s^{-1} (90% C.L.)



Malek et al., Phys.Rev.Lett. 90 (2003) 061101
Bays et al., Phys.Rev. D85 (2012) 052007

Near future detectors

- small, low background, low threshold

technology	mass	Reaction	Energy window	Events/(5 yrs)
Water + Gadolinium (GADZOOKS)	22.5 kt	Anti-nue, inverse beta (90% eff.)	11 – 40 MeV	4 - 17
Liquid Scintillator (LENA)	50 kt	Anti-nue, inverse beta (100% eff.)	11 – 40 MeV	8 - 35

Future detectors

- large, high background, high threshold

technology	Mass	Reaction	Energy window	Events/(5 yrs)
Water Cherenkov (HyperK.,MemPHYS,DUSEL,..)	0.4 Mt	Anti-nue, inverse beta, (90% eff.)	19 – 40 MeV	27 - 227
Liquid Argon (LANDD, Glacier/Laguna)	0.1 Mt	nue + Ar, CC (100% eff.)	19 – 40 MeV	6 – 28

References

GADZOOKS: Beacom, J. F., and M. R. Vagins, 2004, Phys. Rev. Lett. 93, 171101.

LENA: Wurm, M., et al., 2007, Phys. Rev. D75, 023007.

HyperKamiokande: Nakamura, K., 2003, Int. J. Mod. Phys. A18, 4053.

MEMPHYS: Bellefon, A., et al., 2006, eprint hep-ex/0607026

LANDD : Cline, D. B., F. Raaelli, and F. Sergiampietri, 2006, JINST 1, T09001.

GLACIER: Ereditato, A., and A. Rubbia, 2006, Nucl. Phys. Proc. Suppl. 155, 233.

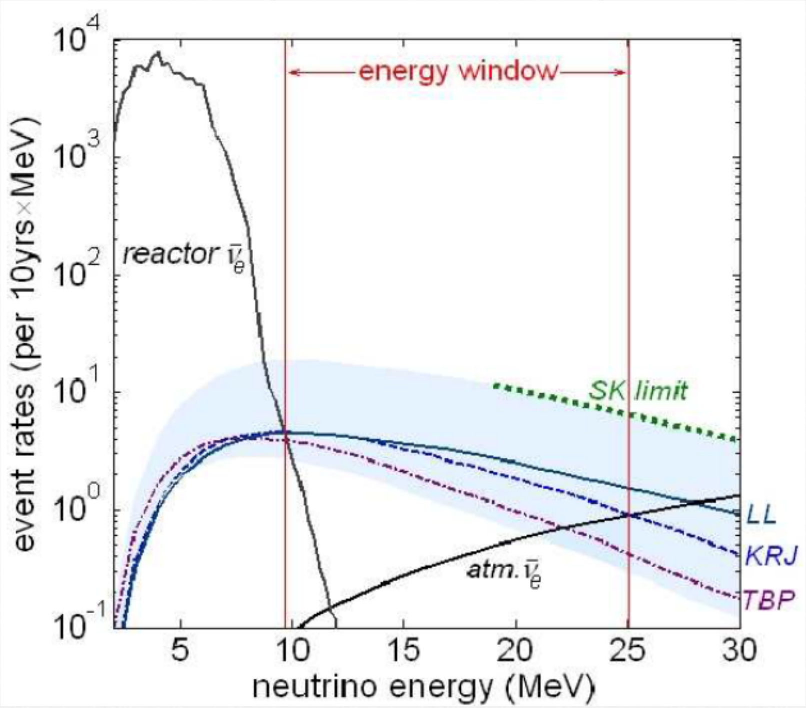
More on statistics

- inverse beta decay detectors : $\bar{\nu}_e + p \rightarrow e^+ + n$
  - liquid scintillator ≈ water + Gd (background reduction)

  - HyperK (pure) : SuperK ≈ 20 : 1
  - HyperK+Gd : LENA : GADZOOKS ≈ 20 : 2 : 1
  - 1 HyperK/year ≈ 10 LENA/year ≈ 20 GADZ./year

Background at LENA

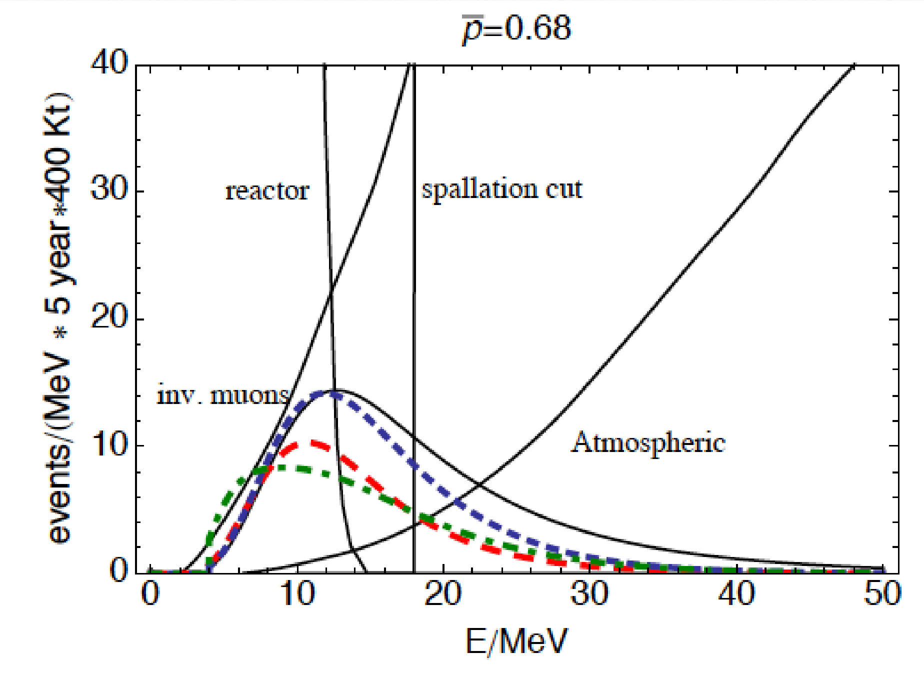
- reactor antineutrinos
- atmospheric antineutrinos
- energy window (S>B): ~ 10 - 30 MeV



Wurm et al., Phys.Rev. D75 (2007) 023007

Background in water

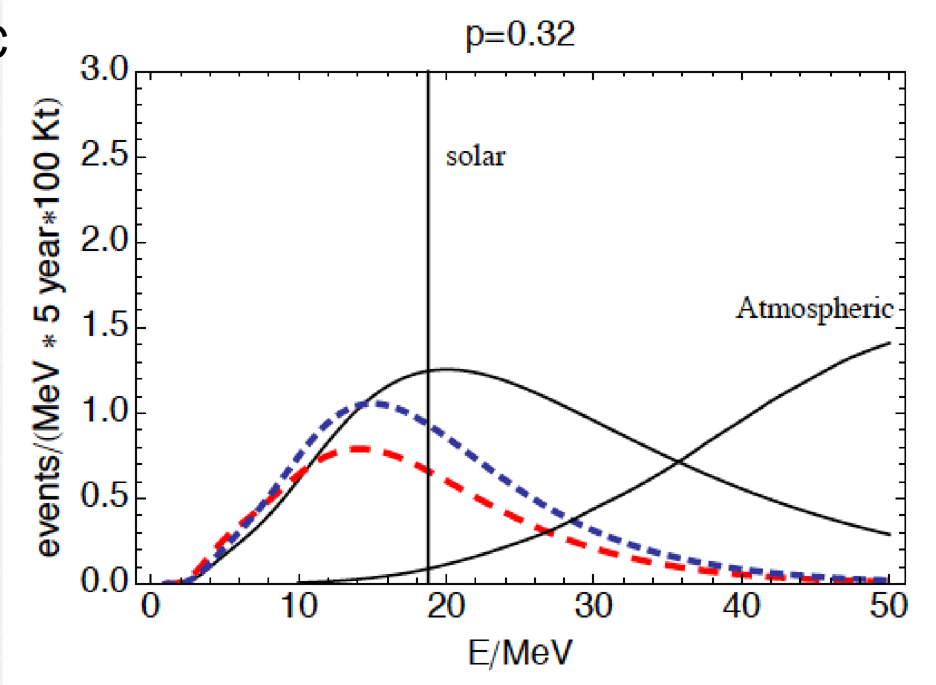
- spallation
  - cut E > 17.3 MeV
- invisible muons
- *Background-dominated!*



Fogli, et al., 2005, JCAP 0504, 002

Background at LAr

- solar, atmospheric neutrinos
- other..? Work in progress



Cocco et al., 2004, JCAP 0412, 002

What can we learn?

Neutrino spectrum extraction

Model discrimination at LENA

- probability of assignment to wrong model
  - number of events in 2 bins
  - fixed normalization
  - 30 years needed for 3 σ

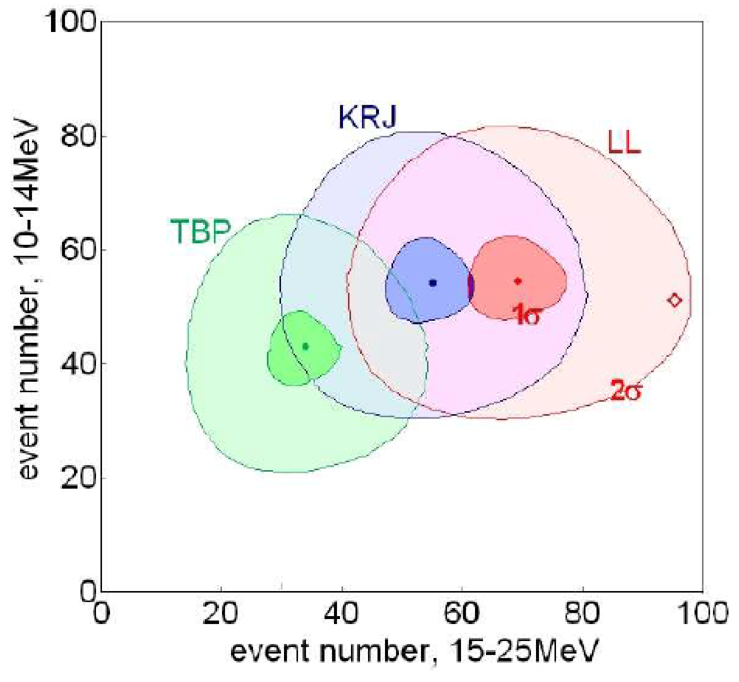


FIG. 8: Exclusion plot for the assignment of a simulated event spectrum in LENA to a wrong DSN model. A value of

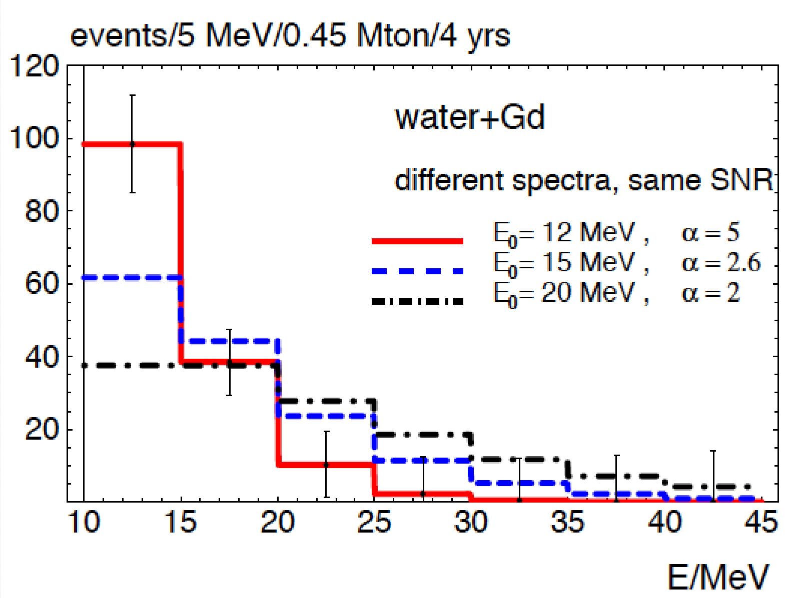
Wurm et al., Phys.Rev. D75 (2007) 023007

Extract spectrum

- Best case scenario: Mt water + Gd
  - low bkg + high stat.

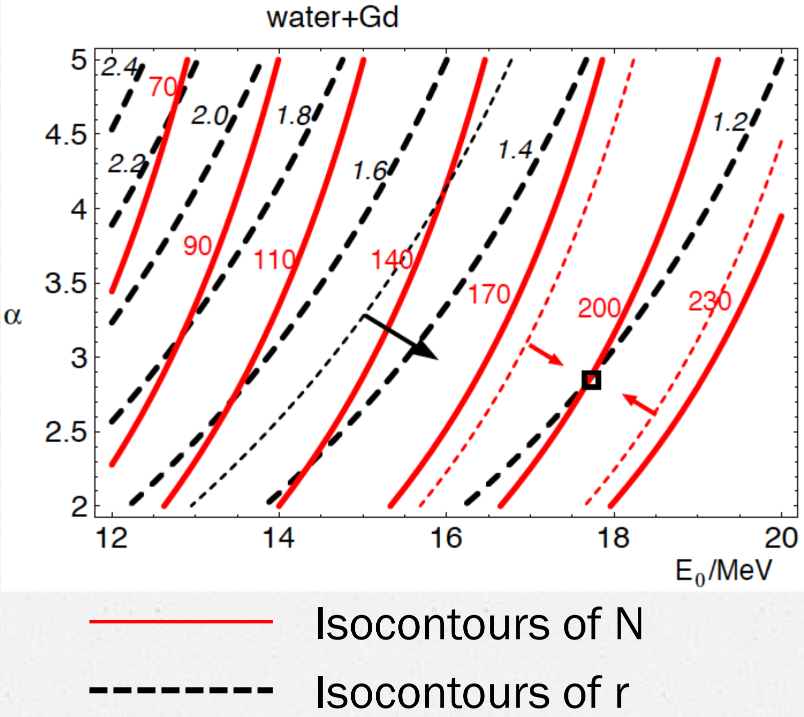
- spectral indicator :

$$r \equiv \frac{N(10 \leq E_{e^+}/\mathrm{MeV} < 15)}{N(15 \leq E_{e^+}/\mathrm{MeV} < 20)}$$

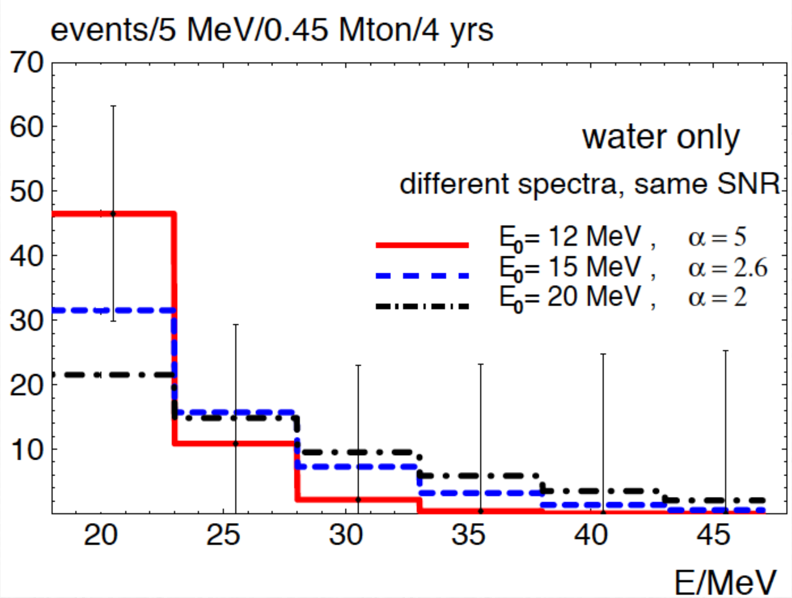


C.L., Phys.Rev. D75 (2007) 073022

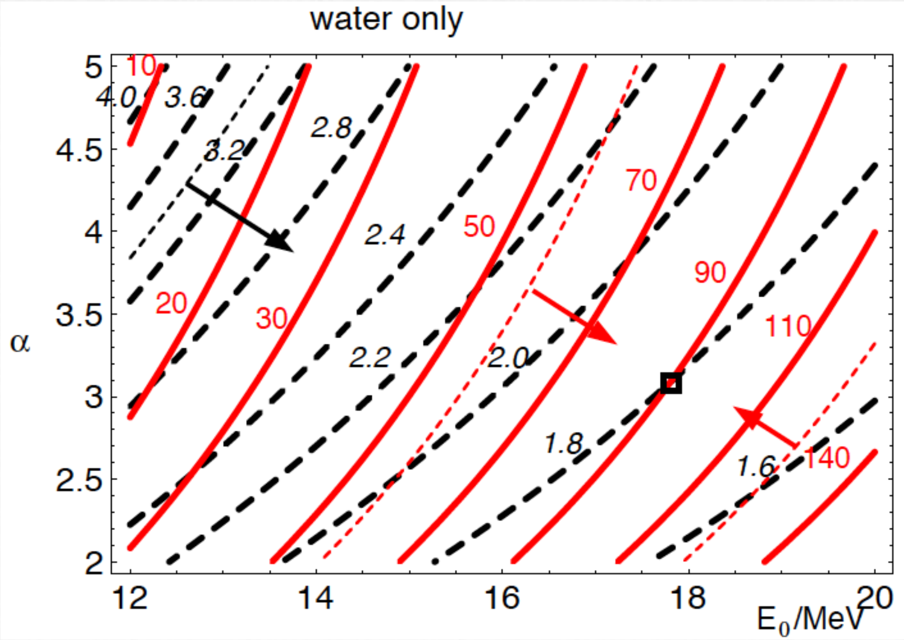
- probe effective (post-oscillations) spectral parameters
  - α , E_0 (degenerate)



- Mt mass, pure water
  - very limited by background!



- poor spectrum reconstruction

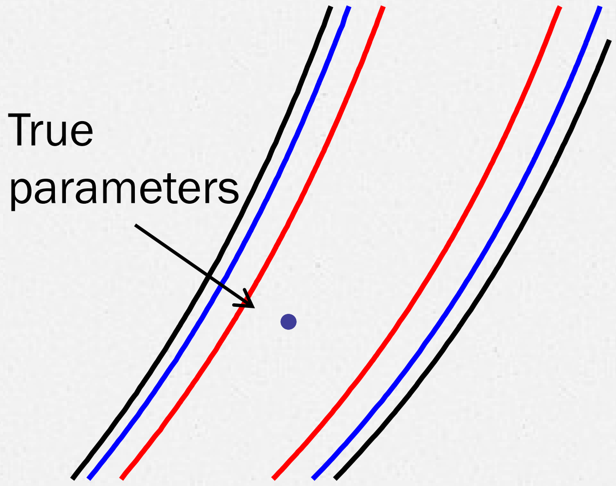


Example of data fit

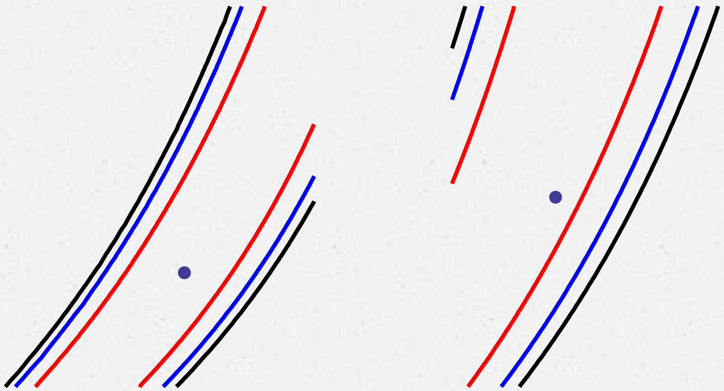
- Best case: Mt + Gd
  - E> 10 MeV, 10 yrs
  - assume known
    - Background
    - SN rate evolution
  - marginalized over normalization

- *α - E_0 degeneracy!*

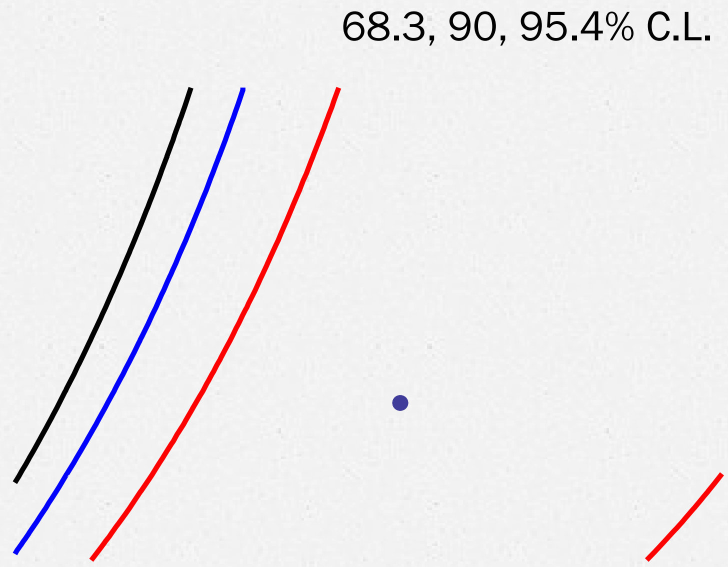
68.3, 90, 95.4% C.L.

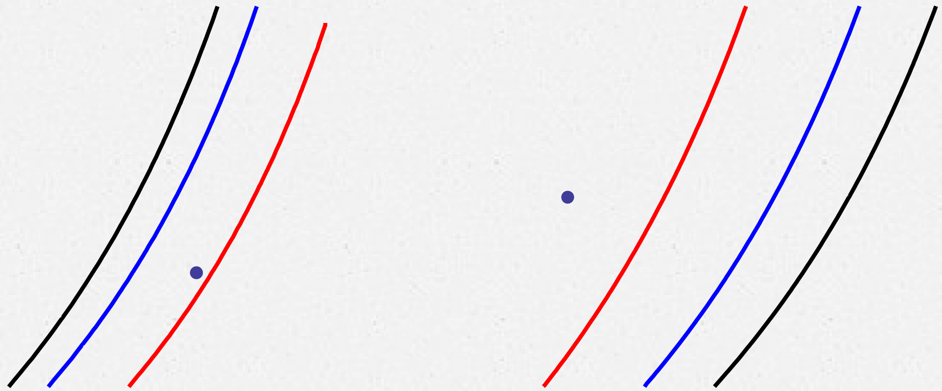


C.L., work in progress



- Realistic case: LENA
  - 10 MeV thresh. , 10 yrs running
  - assume known
    - Background
    - Supernova rate
  - marginalized over normalization





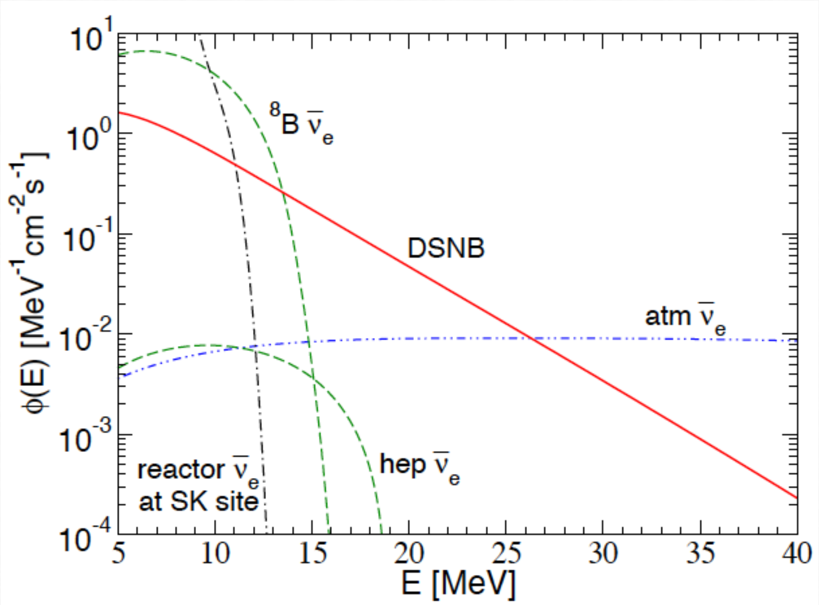
- background is severe limitation
  - high background level in widow
  - small energy window → α - E_0 *degeneracy*
- low threshold, low background detectors best
  - Liquid scintillator, Water+ Gd

What can we learn?

Broadening the scope: miscellaneous ideas

Is it SN or… ?

- what could an excess be?
  - Dark matter annihilation
  - Solar antineutrinos (resonant spin flavor oscillations)
  - …



Raffelt & Rashba, Phys.Atom.Nucl. 73 (2010) 609-613
Palomares Ruiz& Pascoli, Phys.Rev. D77 (2008) 025025

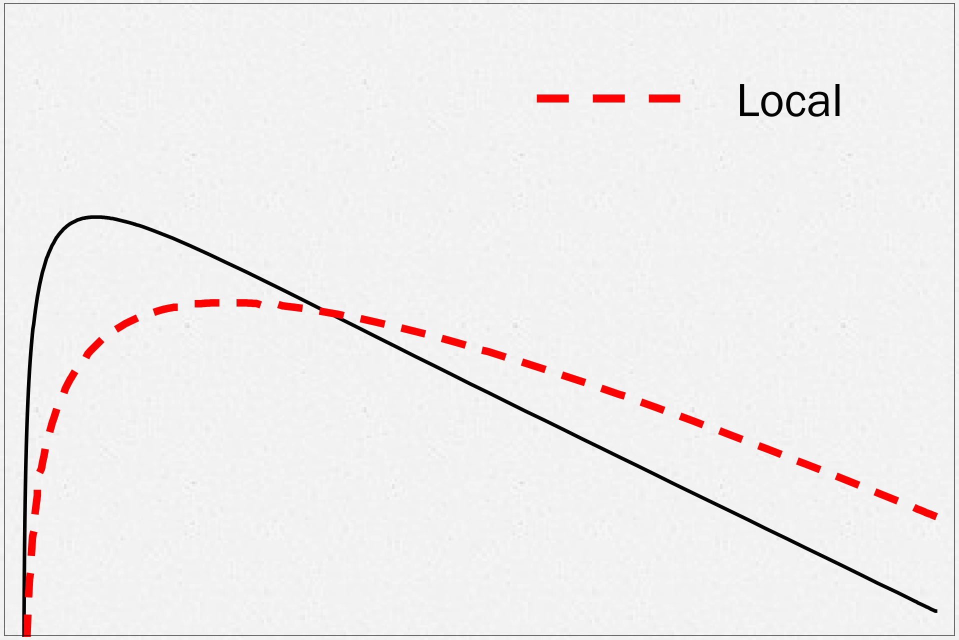
Do SNe emit neutrinos?

- only antineutrinos seen from SN1987A

- possible first nu_e detection with LAr
  - spectrum, luminosity, ..
  - comparison with anti-nue from 1987A : spectral hierarchy, lepton number, ..

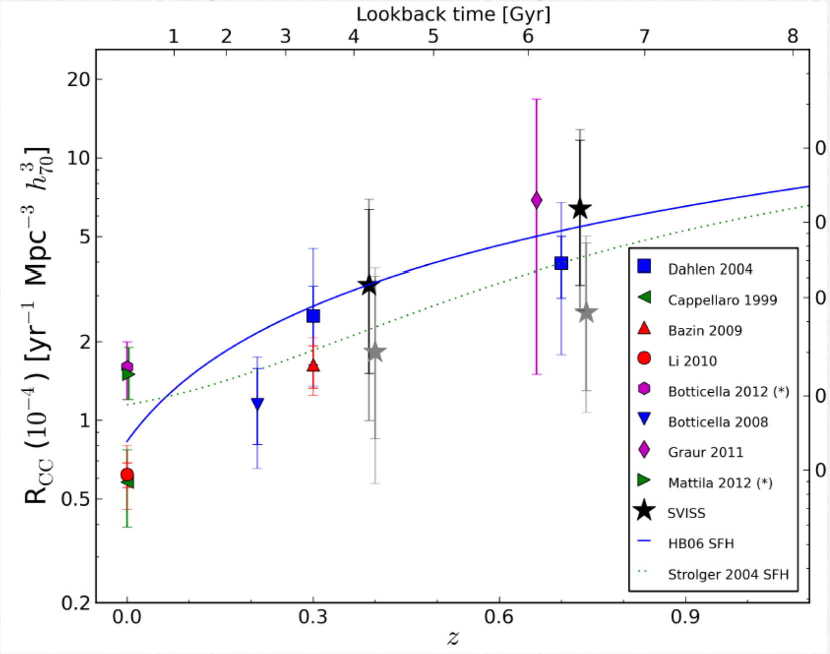
Is it local or cosmological?

- could be first observation :
  - of *cosmological* neutrinos
  - of *redshift* phenomenon on neutrinos

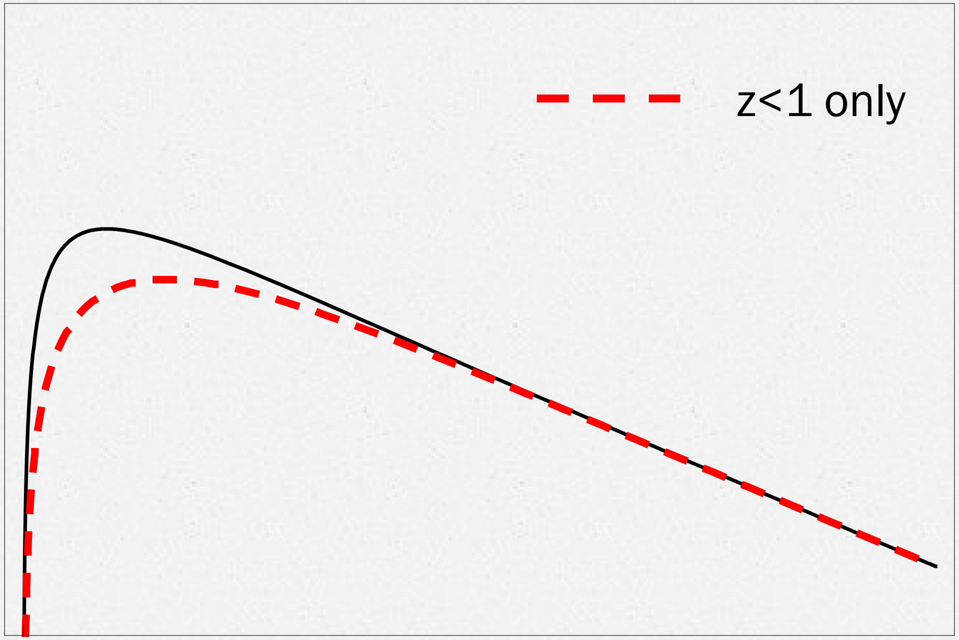

Local

Are there any SNe beyond z>1?

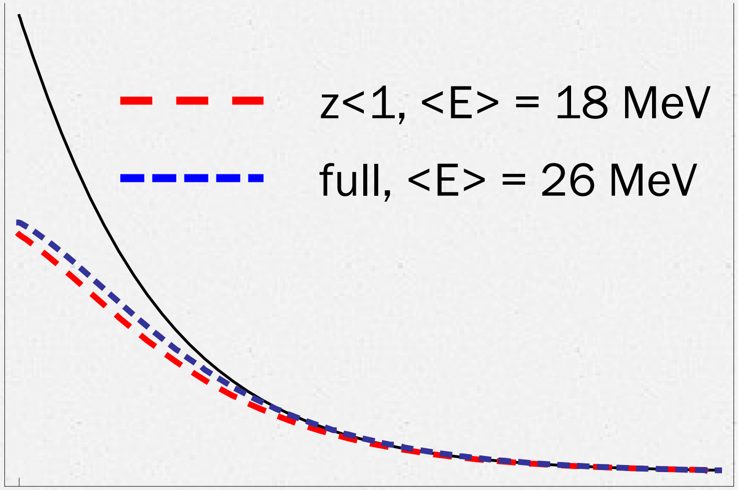
- SN counting reach z ~ 1
- possible direct test of *core collapse* at z > 1



Melinder et al., arXiv:1206.6897

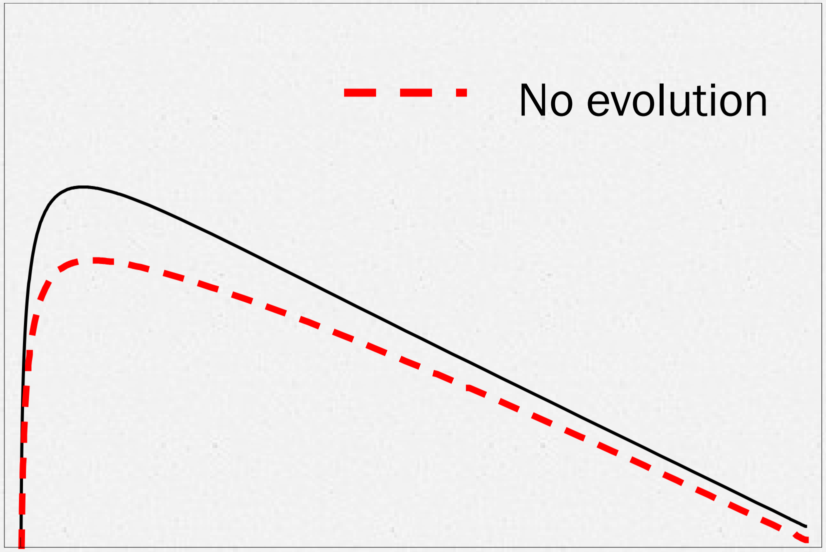

z<1 only

- can be mimicked by full population
  - with *extreme* spectral parameters



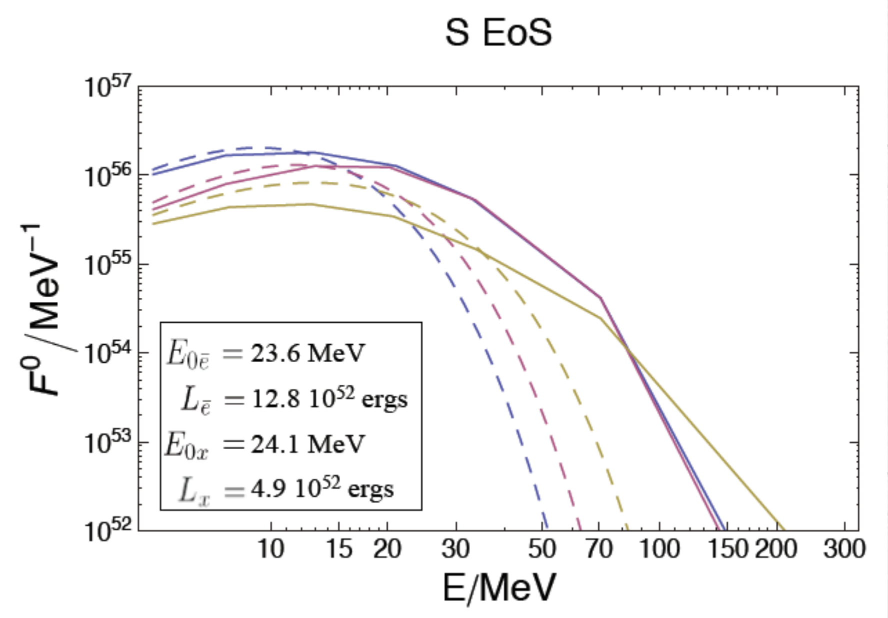
z-evolution of collapse rate?

- untested with neutrinos
  - complementary to resolve uncertainties



Failed Sne?

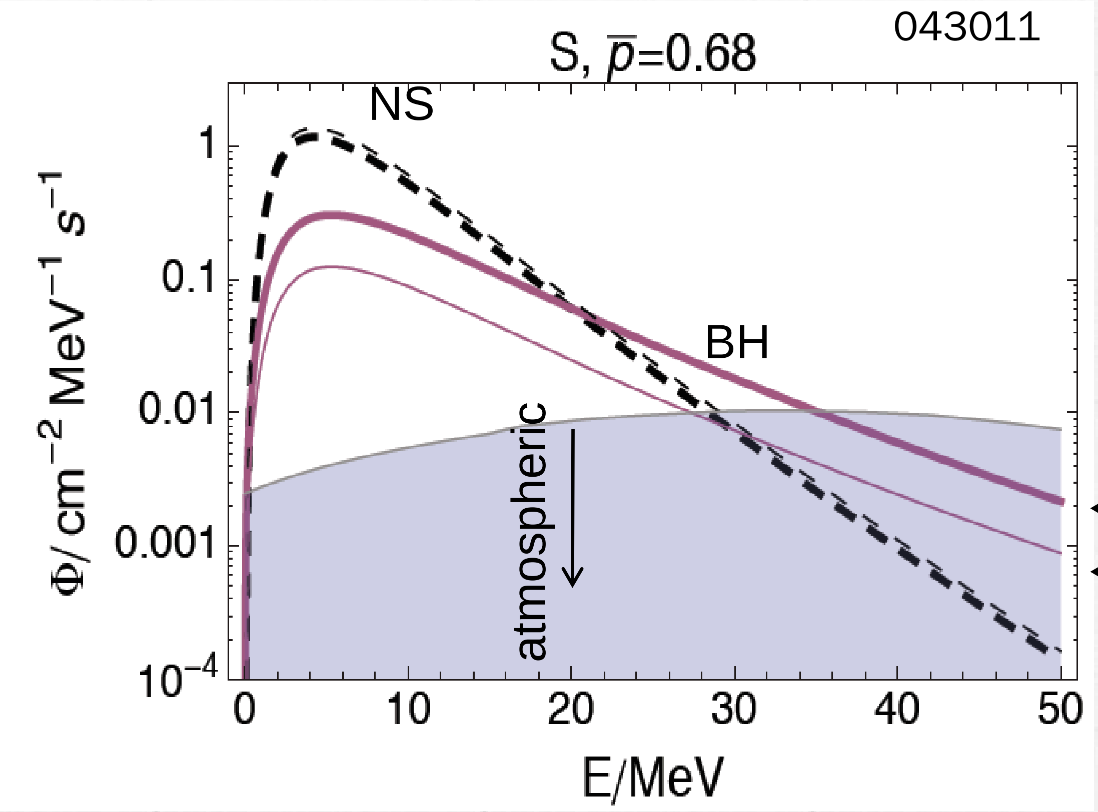
- direct collapse into black hole
  - 10-20% of all collapses
- more luminous, hotter



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)

- up to factor ~ 2 enhancement
- *spectral distortion*

CL, PRL 102, 231101, 1999
J. Keehn & CL, PRD85 (2012) 043011

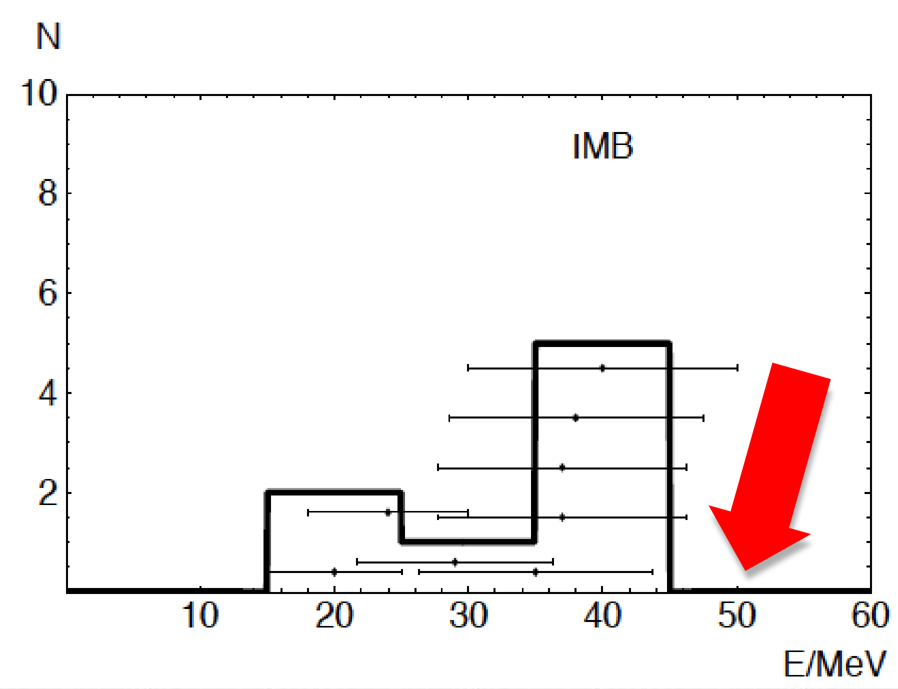


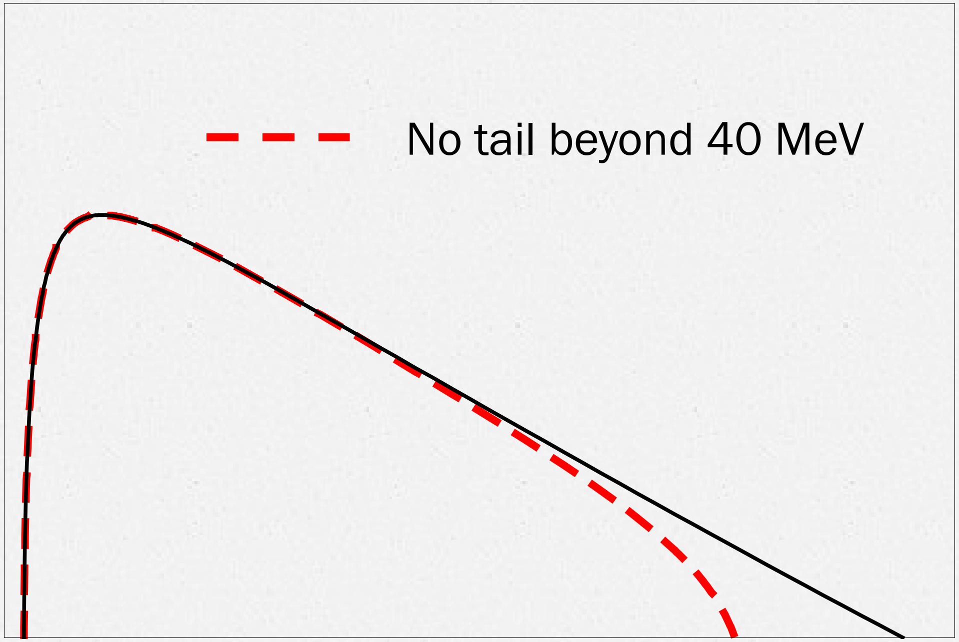
f_{NS}=0.78

f_{NS}=0.91

Spectrum tail ?

- no SN1987A data at E> 40 MeV




No tail beyond 40 MeV

Normalization

- degeneracies:
  - luminosity / SN rate (IMF, minimum mass, ..)
- extreme combinations of parameters might be excluded

Final remarks

Extraction of neutrino spectrum

- limited by backgrounds:
  - high background level in widow
  - small energy window → *α - E_0 degeneracy*

- low threshold, low background detectors best
  - Liquid scintillator, Water+ Gd

- external info needed to resolve degeneracy
  - theory priors

Think in other directions..

- Test theory that is usually taken for granted
  - *cosmological* neutrino propagation

- cosmological *population* of *collapsing* stars
  - different, rare SN types (failed SNe)
  - redshift evolution of rate
  - rate normalization (IMF, minimum mass, ..)
  - complementary to astronomy

- shift of perspective :
  - eventually we will have a Galactic supernova and fully consistent SN models
  - *enhance DSNB potential:*

Multi SN data - single SN data/models = SN population, history, etc.

Backup

Successful vs failed SNe

- NS-forming collapse
  - energetics:

$$E_{0\bar{e}} = 15 \text{ MeV} \quad E_{0x} = 18 \text{ MeV}$$

$$L_{\bar{e}} = L_x = 5 \cdot 10^{52} \text{ ergs} \qquad \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau = \nu_x$$

  - anti-ν_e survival probability:

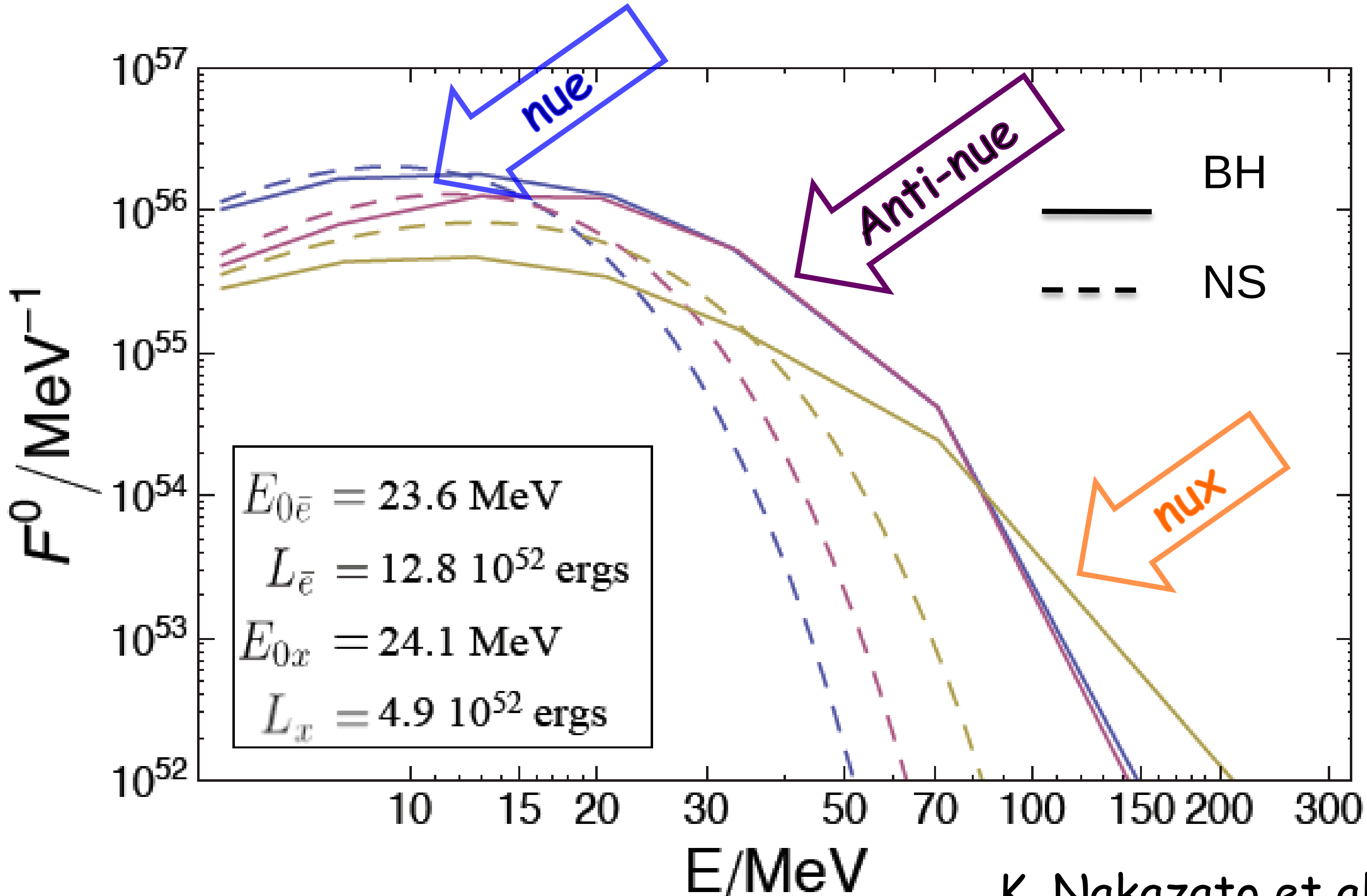
$$\bar{p} = 0 - \cos^2\theta_{12} \simeq 0 - 0.68$$

Keil, Raffelt, Janka, Astrophys. J. 590, 971 (2003)
S. Chakraborty, et al., JCAP 0809, 013 (2008)

- Direct BH-forming collapse:
  - *Higher energies:*
    - For all flavors $E_0 \sim 20 - 24\ \mathrm{MeV}$
    - Due to rapid contraction of protoneutron star before BH formation
  - *Electron flavors especially luminous*
    - (electron and positron captures)
  - Same interval of $\bar{p}$

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)

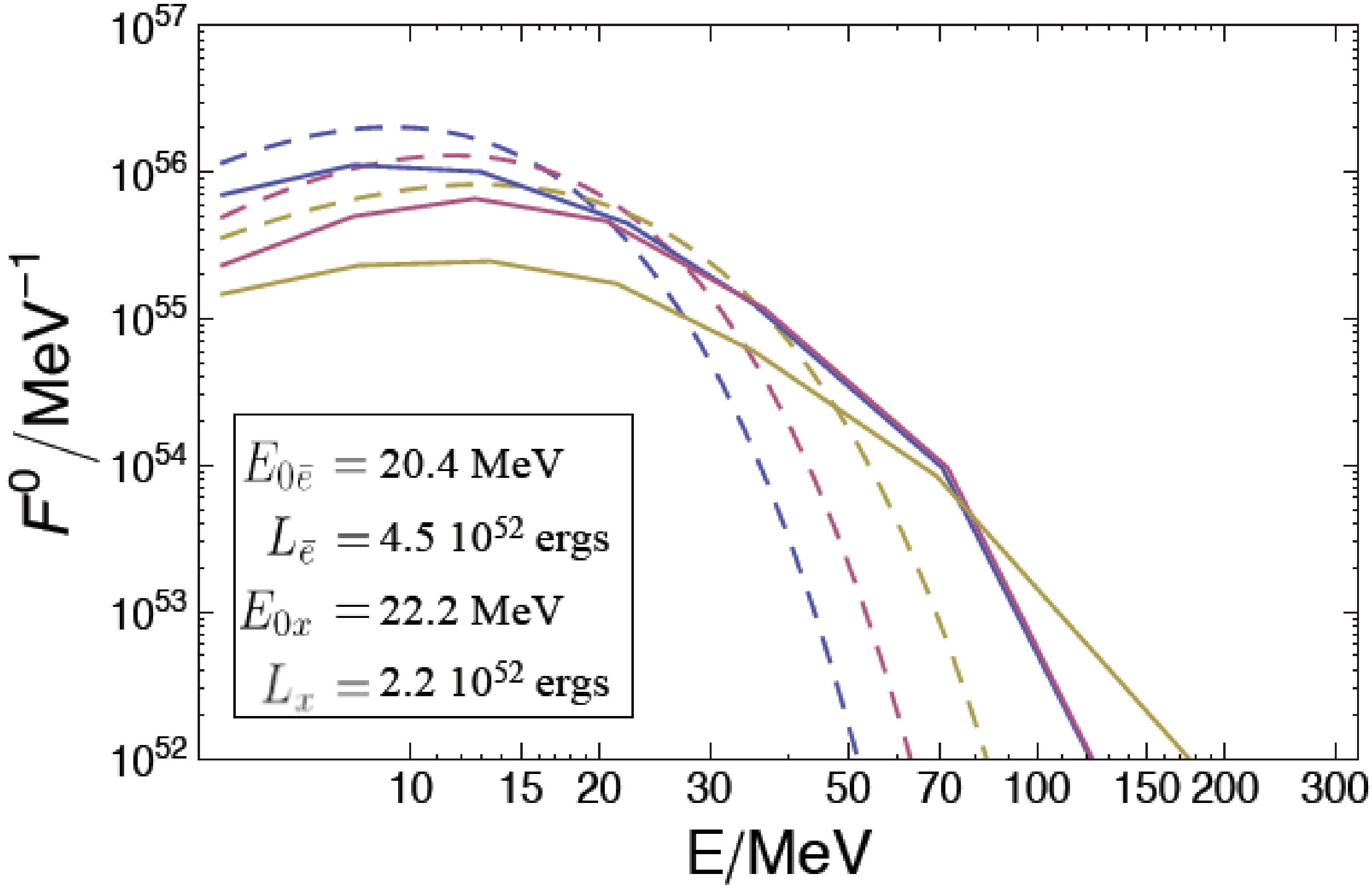
Shen et al. (S) EoS



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

- Progenitor: M=40 M_{sun}, from Woosley & Weaver, 1995
- "stiffer" eq. of state (EoS) → more energetic neutrinos

Lattimer-Swesty. (LS) EoS



A two population model: diffuse flux

C.L., arXiv:0901.0568, to appear in PRL

$$\Phi(E) = \frac{c}{H_0} \int_0^{z_{max}} R_{cc}(z) \left[f_{NS} F_{\bar{e}}^{NS}(E(1+z)) + (1 - f_{NS}) F_{\bar{e}}^{BH}(E(1+z)) \right] \times \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

$$f_{NS} = 0.78 - 0.91,$$

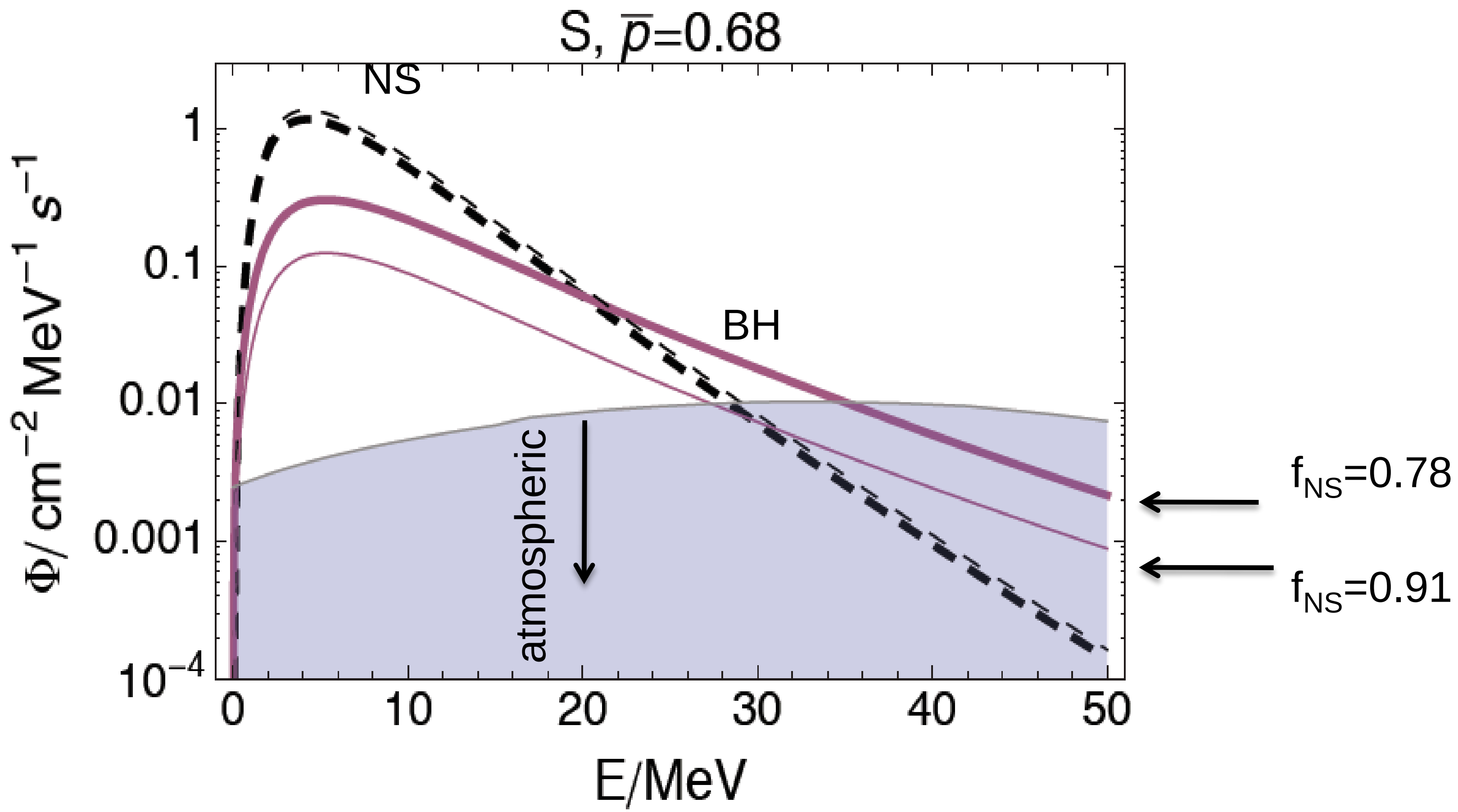
$\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$

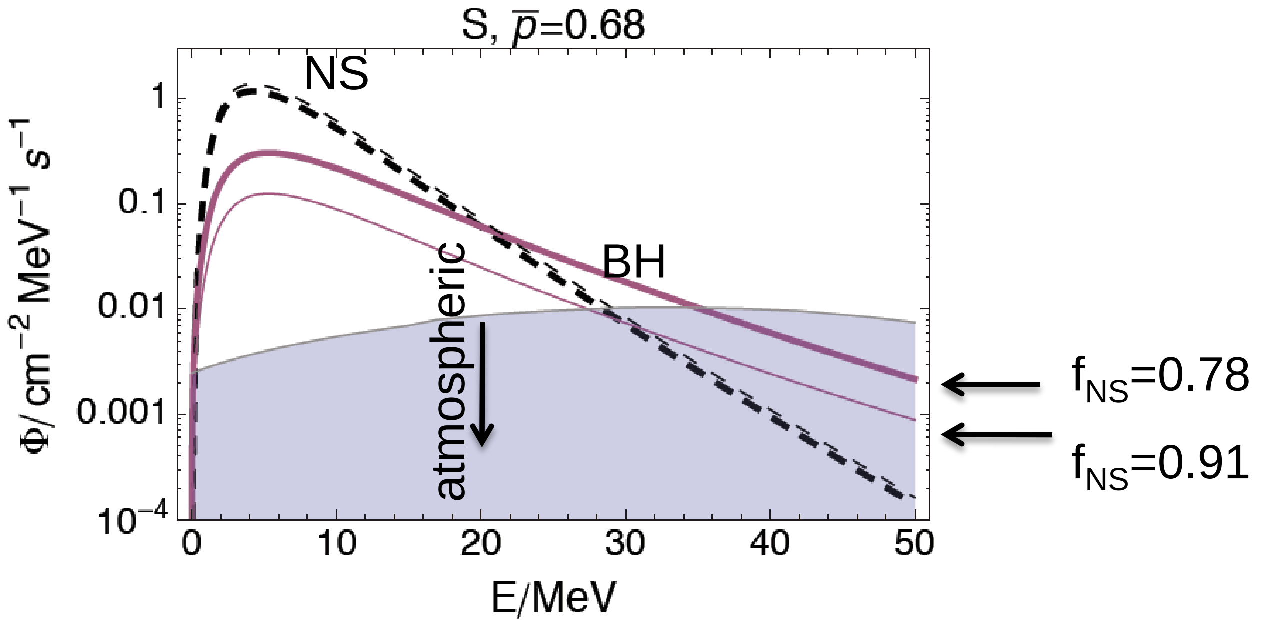
$$\bar{p} = 0 - \cos^2\theta_{12} \simeq 0 - 0.68$$

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

Results

- Best case: S EOS, maximum $\bar{p}$





Pure water:

SuperK : 19.3 – 35 MeV

fNS	flux NS	flux BH	flux total
0.78	0.32	0.46	0.78
0.91	0.37	0.19	0.56

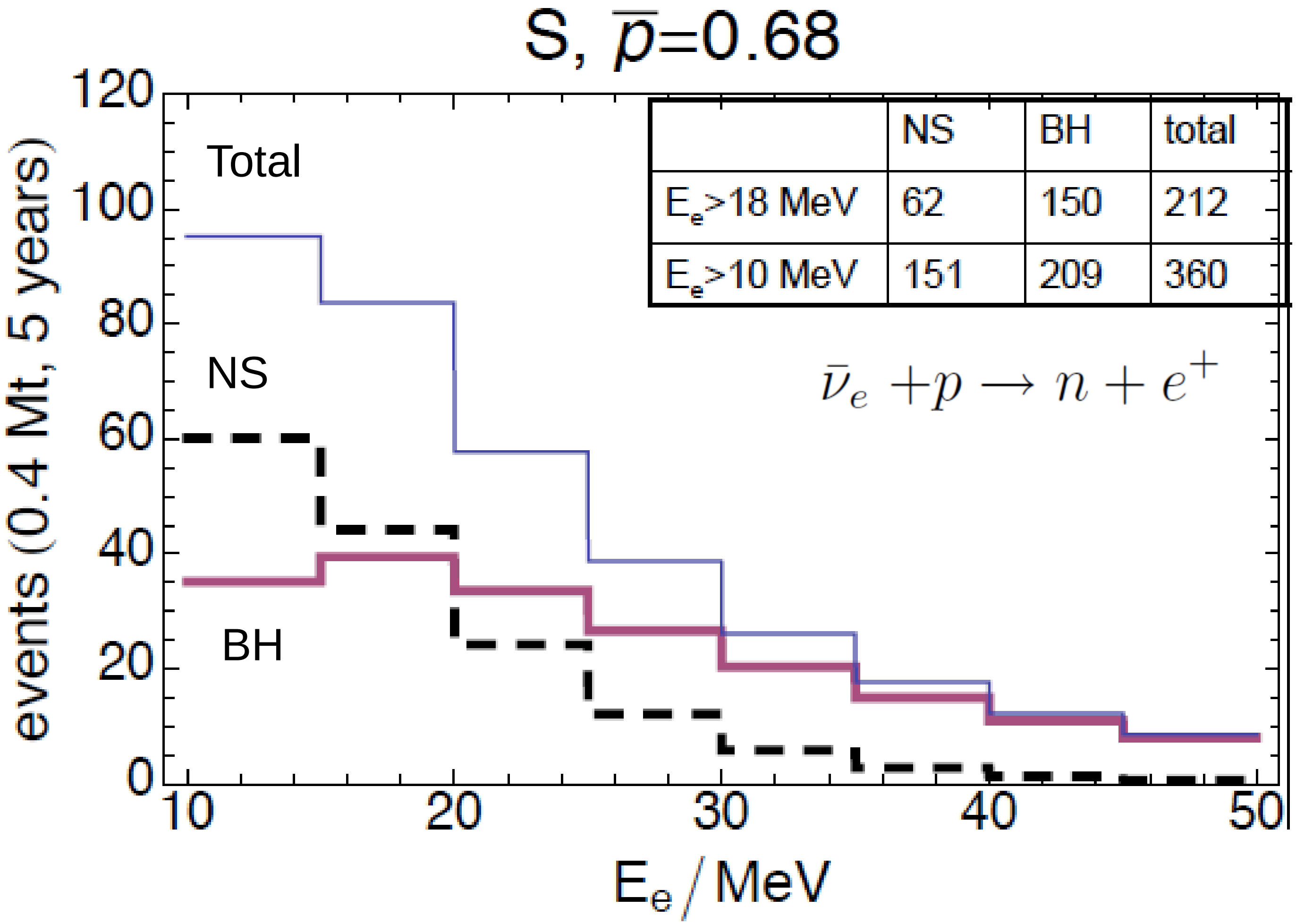
Close to SK limit!

Water + Gd:
(better bkg.reduction)
Beacom & Vagins,
PRL 93, 2004

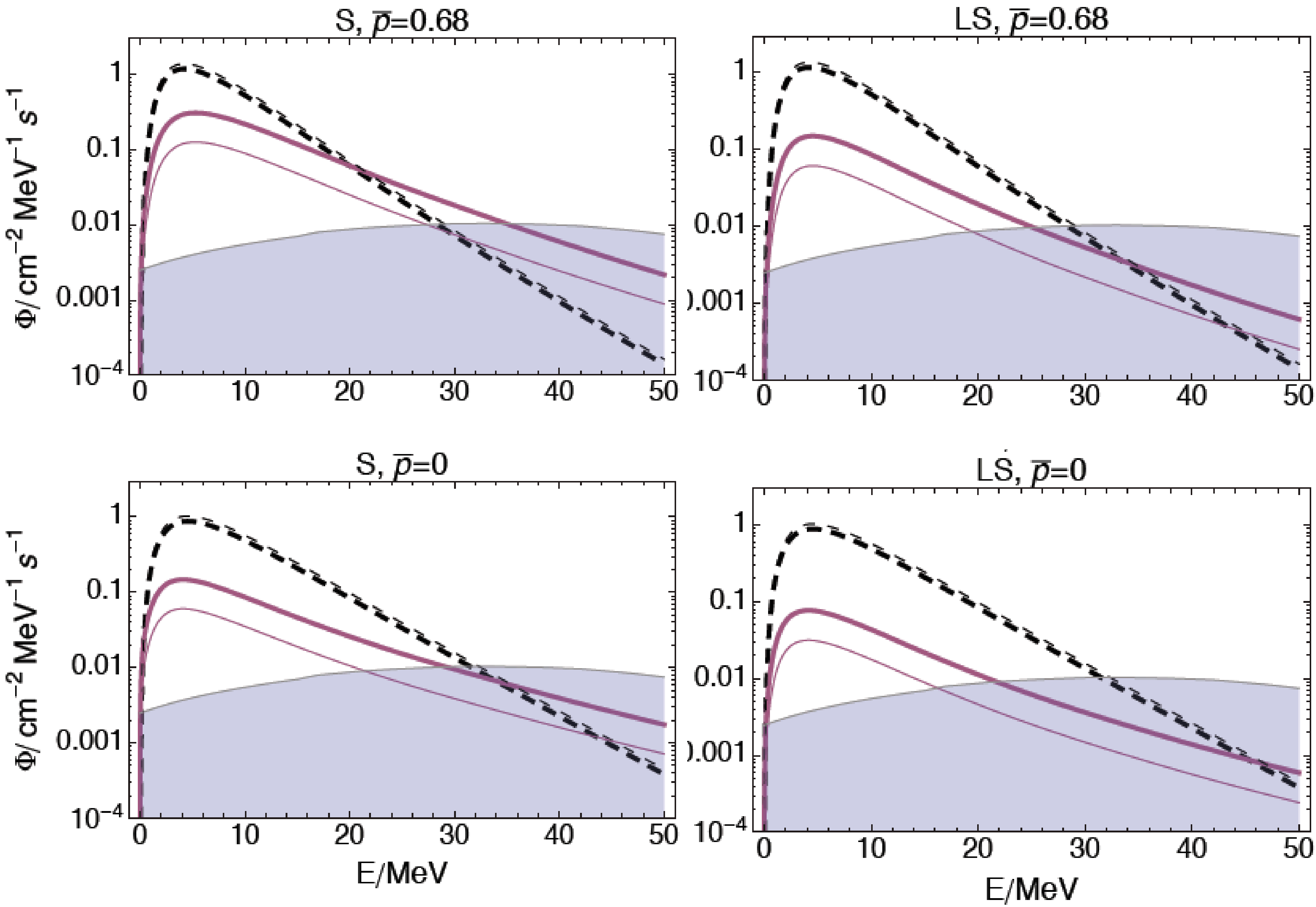
GADZOOKS: 11.3 – 35 MeV

fNS	flux NS	flux BH	flux total
0.78	1.84	1.4	3.24
0.91	2.15	0.57	2.72

Number of events in water



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



S, $\bar{p}$=0.68
LS, $\bar{p}$=0.68
S, $\bar{p}$=0
LS, $\bar{p}$=0
Φ/cm^{-2} MeV^{-1} s^{-1}
E/MeV

Significance above background?

- Typical case: 100% excess due to BH in 30-35 MeV bin
  - Water: buried by invisible muon bkg.

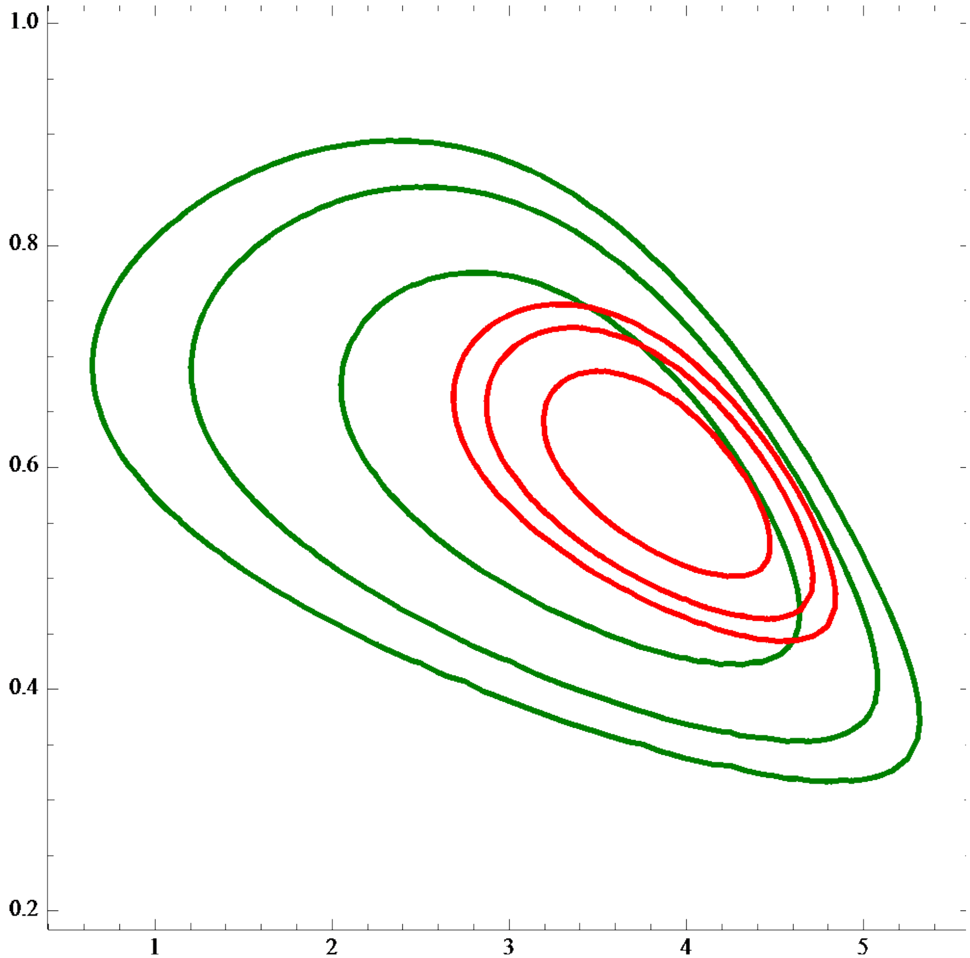
    G. L. Fogli et al., JCAP 0504, 002 (2005)

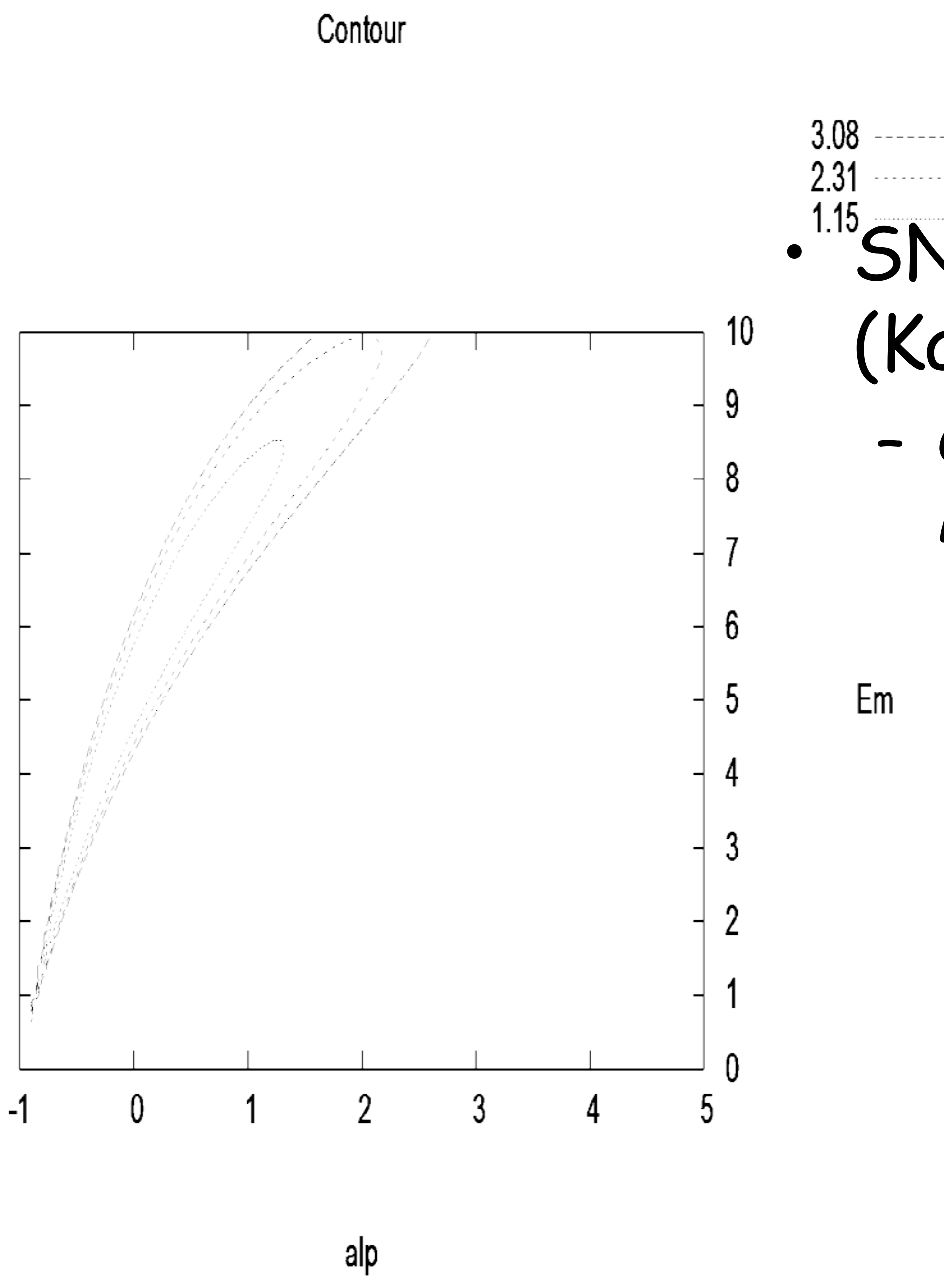
    - not statistically significant in single bin
    - Spectral fit might work
  - Water+Gd: invisible muons rejected
    - 12 Mt yr exposure needed for 3 sigma significance in single bin

FAQs

- Sensitivity to beta?
- Spallation, inv. Muons in Lar?
- SN1987A fit of spectrum?
- how solid is SNR evolution?
- How is SNR measured?
- How is SFR measured?
- Mini-burst from local Sne?

SNR fit (in prep.)





- SN1987A fit (Kamiokande only?)
  - Courtesy of A. Mirizzi