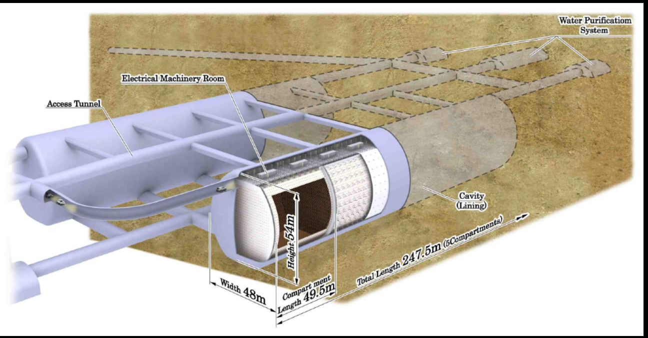


Open Meeting for the Hyper-Kamiokande Project
Kavli IPMU, Aug 21-23 2012

Supernova neutrino astronomy with Hyper-Kamiokande

Shunsaku Horiuchi (CCAPP, OSU → UC Irvine)
John Beacom (CCAPP, OSU)
Eli Dwek (NASA)

CCAPP

THE OHIO STATE UNIVERSITY

Why supernova neutrinos?

> *Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star...*
>
> John N. Bahcall, *Phys. Rev. Lett.* 12, 303 (1964)

Supernovae are an intriguing mix of particle, nuclear, astro, and astronomy

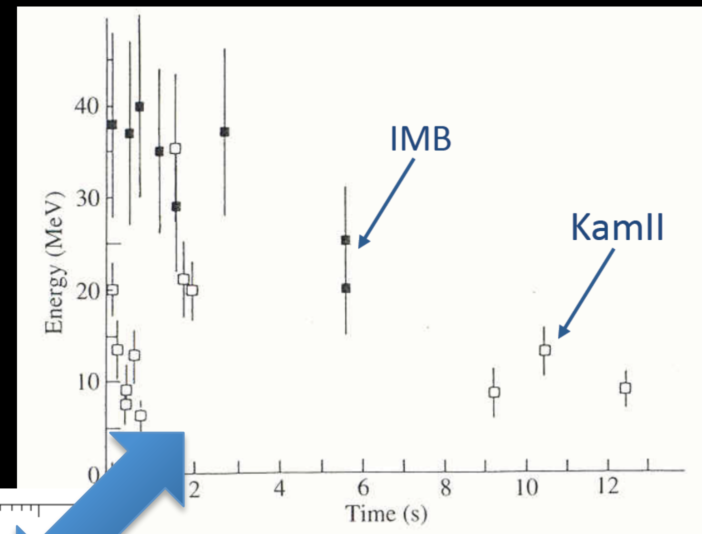
And, neutrinos hold the key to solving many outstanding questions:

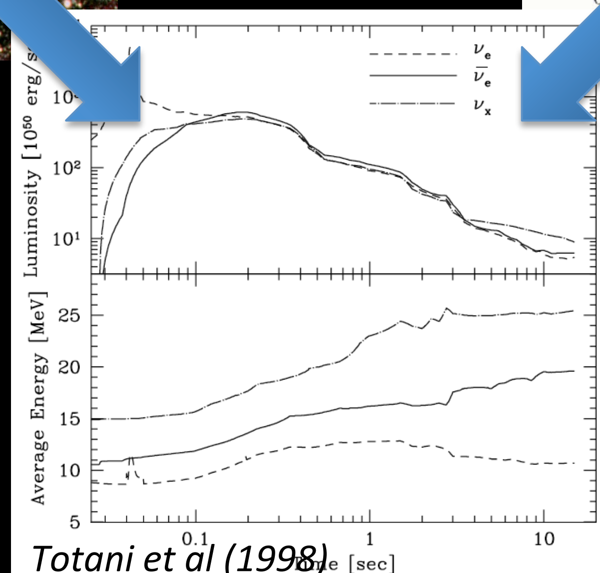
- *What is the supernova explosion mechanism?*
- *What is the physics at high temperature and density?*
- *Do black holes form? How and when?*
- *What is the interior environment like?*
- *Was there a jet? An accretion disk?*
- *What nucleosynthesis products are made?*
- *What is the nature of physics at very high neutrino density?*
- *What are the properties of neutrinos?*
- *Which explosions are indeed core collapse?*
- *…etc…*

SN1987A as a guide

Observation: Type II supernova associated with massive star

Observation: MeV neutrino precursor very energetic for ~10s



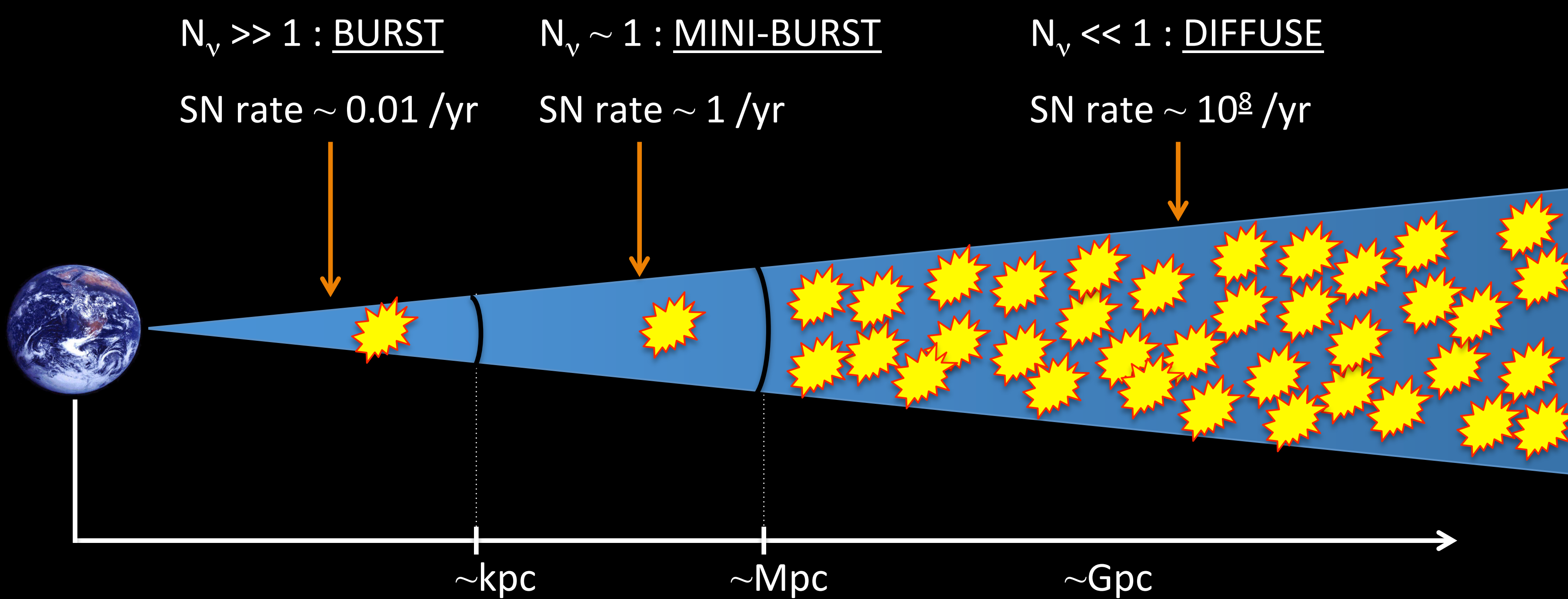


Totani et al (1998)

SN1987A gave us the introduction. The next aim is to obtain the whole script!

Theory: core-collapse makes neutrinos and supernova

Distance scales and physics outcomes



Galactic burst:
high ν statistics, much nuclear, particle, physics & astronomy

Basics are covered, now improvements [Koshio-san's talk]

Mini-bursts:
Transient ID, can probe burst variety

Next generation, i.e., Hyper-K with Gadolinium

Diffuse supernova neutrino background (supernova relic neutrinos): average emission, cosmic core-collapse rate, multi-populations

Near future, i.e., SuperK with Gadolinium

(slide adapted from Beacom@Nu2012)

Theoretical DSNB Prediction

Observed positron spectrum

Input 1: supernova neutrino spectrum (intensely studied by theorists, unknown quantity *waiting to be observed*)

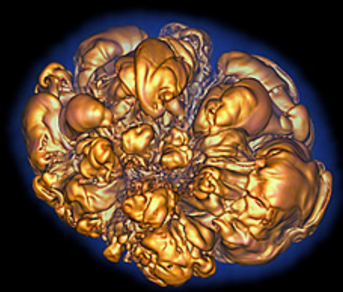
$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu) \int R_{\mathrm{CCSN}}(z) \left|\frac{cdt}{dz}\right| (1+z) \frac{dN_\nu}{dE_\nu}\left[E_\nu(1+z)\right] dz$$

See, e.g., reviews by Beacom (2010), Lunardini (2010)

Input 2: core-collapse rate (intensely studied by astronomers using photons, *rapidly improving*)

Input 3: neutrino detector capabilities *well understood* (great idea GADZOOKS! and larger volume offered by Hyper-Kamiokande)

Input 1: supernova neutrino emission



$E_\nu \sim 3 \times 10^{53}$ erg

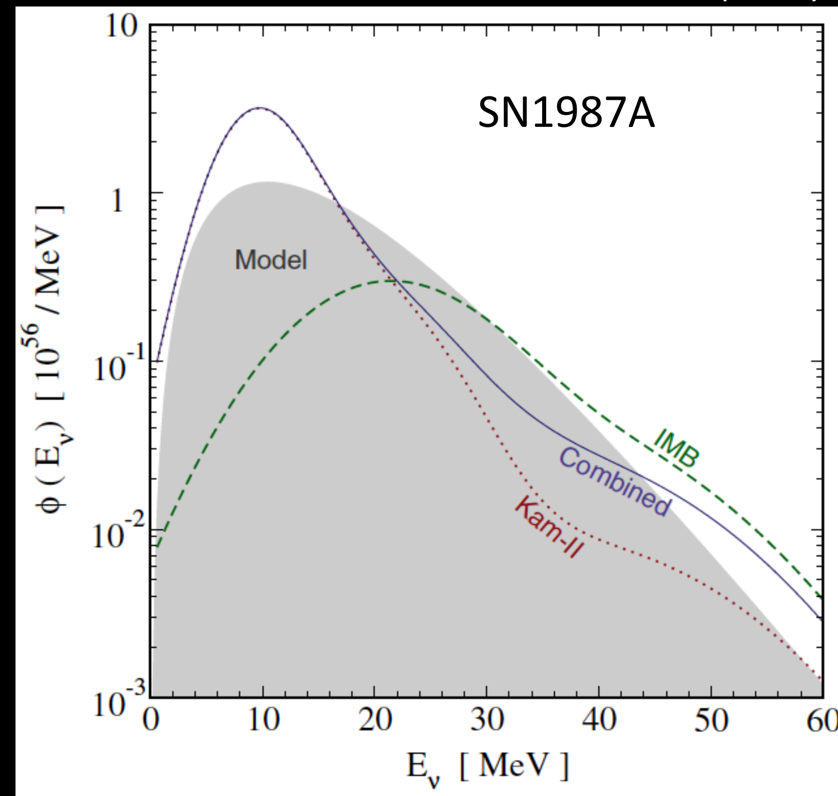
$\varepsilon_\nu \sim 15$ MeV

Core-collapse simulations:
Complex multi-dimensional general relativistic (magneto-) hydrodynamics with neutrino transport

$$
\begin{aligned}
F_{\nu_e}^{\rm NH} &= \sin^2\theta_{12}[1 - P_c(F_{\nu_e}^c, F_{\bar\nu_e}^c, E)](F_{\nu_e}^0 - F_{\nu_y}^0) + F_{\nu_y}^0 \\
F_{\bar\nu_e}^{\rm NH} &= \cos^2\theta_{12}\bar P_c(F_{\nu_e}^c, F_{\bar\nu_e}^c, E)(F_{\bar\nu_e}^0 - F_{\nu_y}^0) + F_{\nu_y}^0 \ , \\
F_{\nu_e}^{\rm IH} &= \sin^2\theta_{12}P_c(F_{\nu_e}^c, F_{\bar\nu_e}^c, E)(F_{\nu_e}^0 - F_{\nu_y}^0) + F_{\nu_y}^0 \ , \\
F_{\bar\nu_e}^{\rm IH} &= \cos^2\theta_{12}[1 - \bar P_c(F_{\nu_e}^c, F_{\bar\nu_e}^c, E)](F_{\bar\nu_e}^0 - F_{\nu_y}^0) + F_{\nu_y}^0
\end{aligned}
$$

Neutrino Mixing:
Collective effects, well-known MSW, shock effects

Yuksel & Beacom (2007)



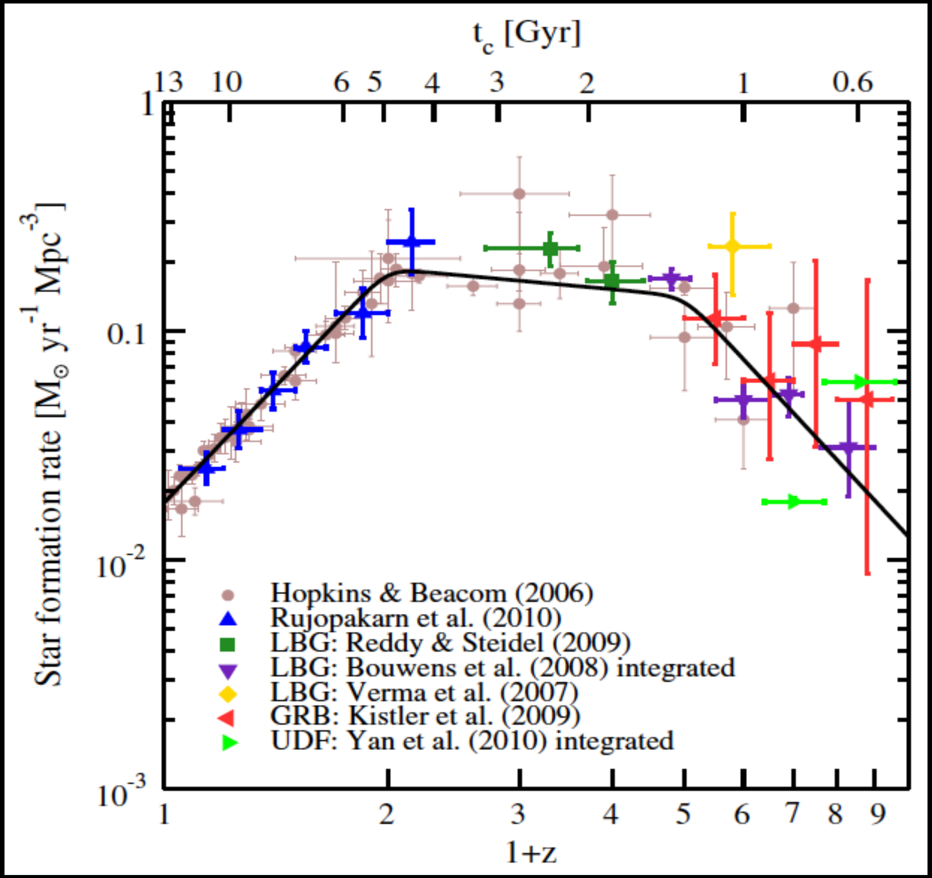
Observed spectrum:
e.g., reconstruction of SN1987A

One of the GOALS is to use the DSNB to measure the average neutrino spectra

Input 2: core-collapse rate

Core-collapse rate = Birth rate of massive stars

*because lifetime of massive stars are cosmologically short



The star formation rate:

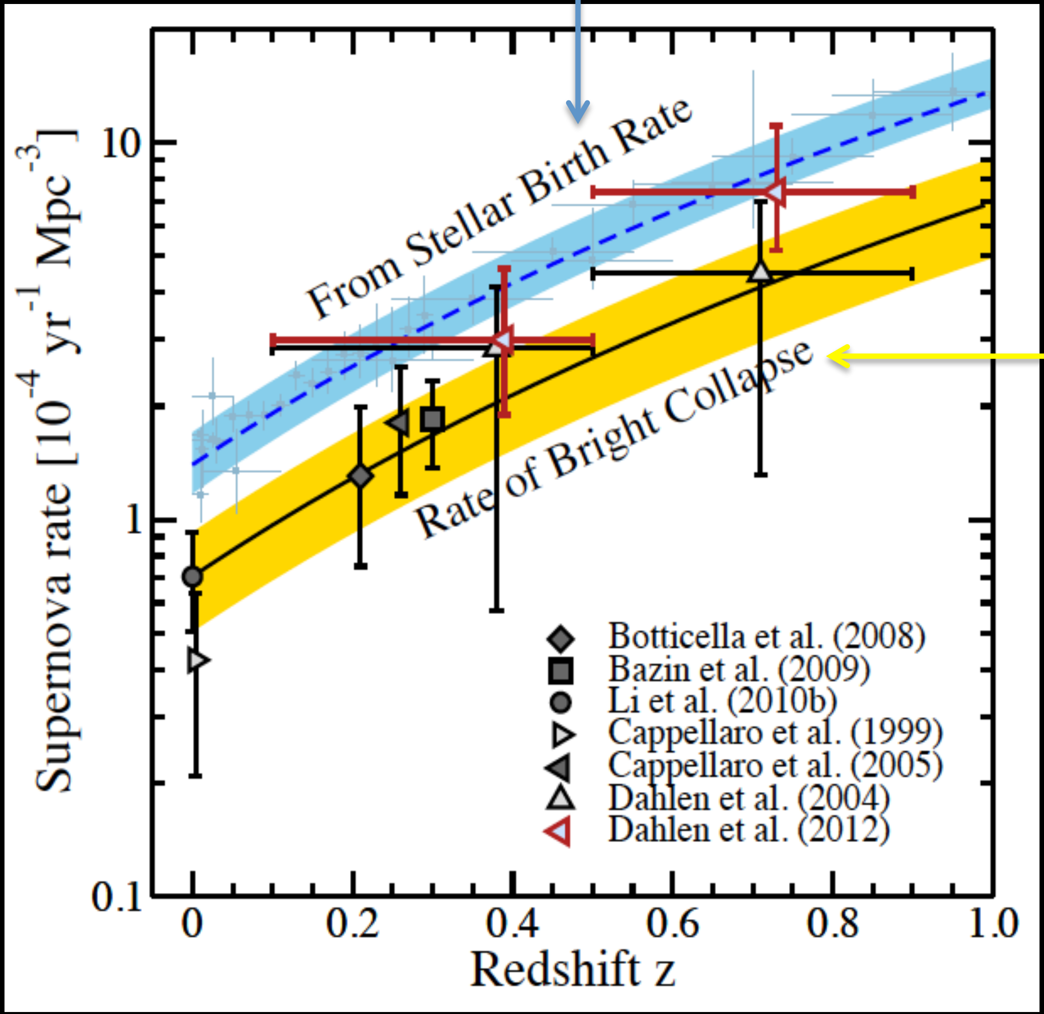
Has been measured by many groups, using many wavebands and many sources. The uncertainties have rapidly decreased (now mainly systematic)

Integral consistency checks:

Comparison with, e.g., the background light, stellar mass density, and metal mass density confirm the integral of the star formation rate

Horiuchi & Beacom (2010)
see also Hopkins & Beacom (2006)

Input 2: core-collapse rate



Horiuchi et al. (2011) with latest data from Dahlen et al. (2012)

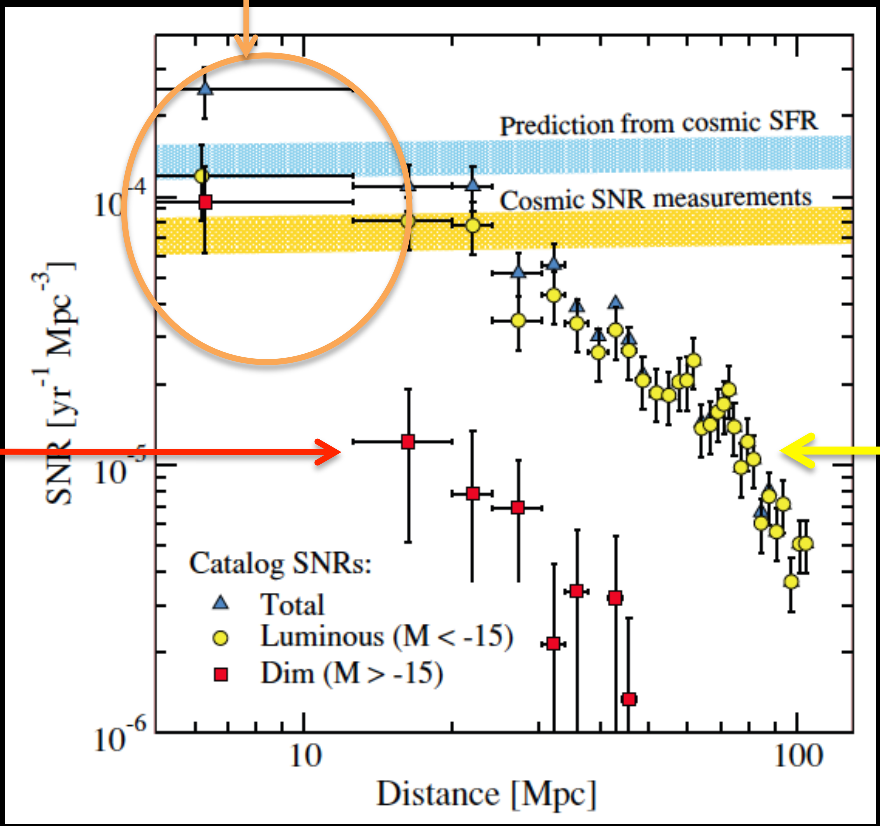
From birth of massive stars:
Gives the *total* normalization for the core-collapse rate, known to within a few tens of percent at low-z

Rate of bright collapse:
Gives the observed core-collapse rate, probed by observations of *luminous* supernovae. Recent rapid increase in measurements

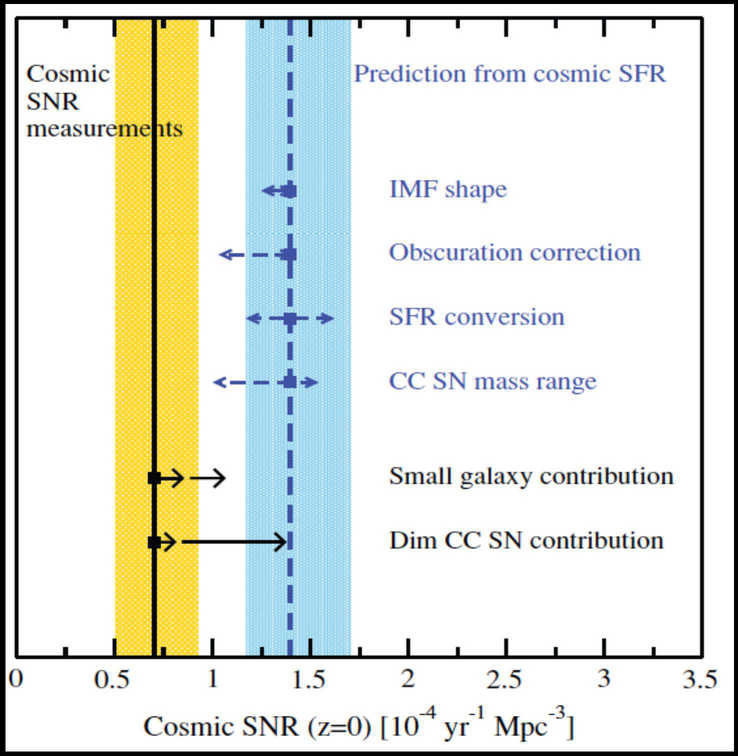
(Birth rate) – (bright collapse)
= DIM or DARK collapse
Massive stars that collapse \`quietly’ are difficult to observe directly (but can be probed by neutrinos!)

Are there enough dim supernova? Yes

There are many dim supernovae nearby!
The fraction of dim / bright is almost 40% and is sufficient to explain the offset



Horiuchi et al. (2011)



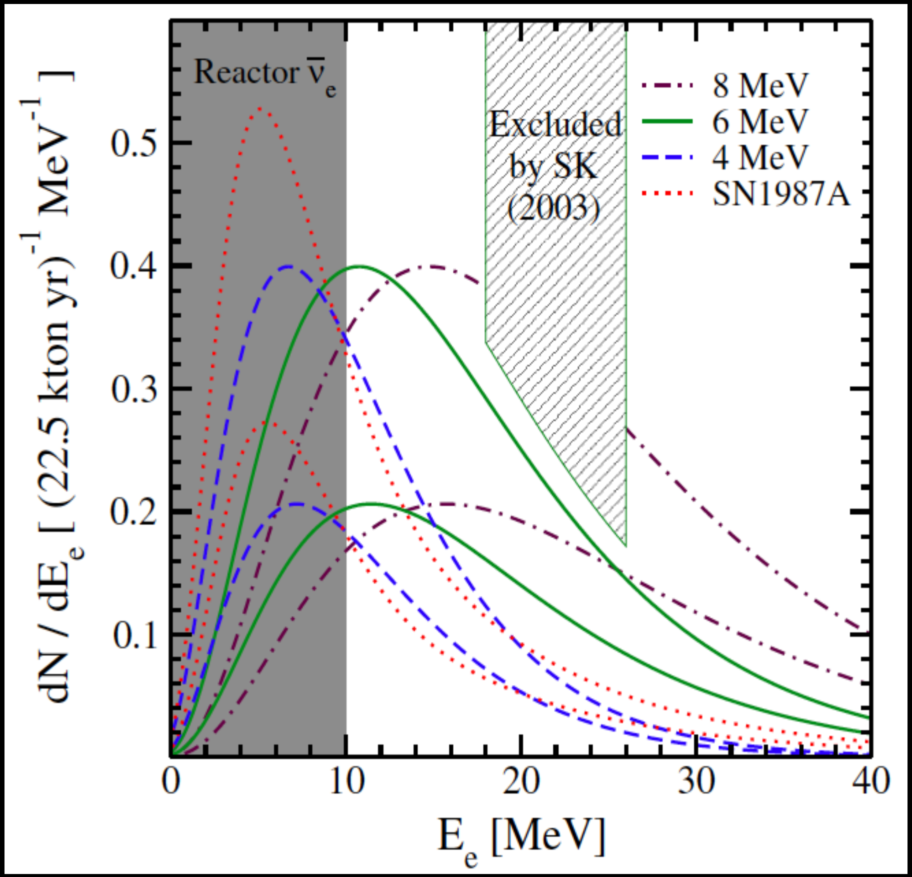
see also Mattila et al (2012)

"Dim" supernovae:
Those that fall below the "bright" ones

"Bright" supernovae:
That are typically targeted and successfully observed

Event rate

$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu)\int R_{\rm CCSN}(z)\left|\frac{cdt}{dz}\right|(1+z)\frac{dN_\nu}{dE_\nu}\left[E_\nu(1+z)\right]dz$$



Horiuchi, Beacom, Dwek (2009)

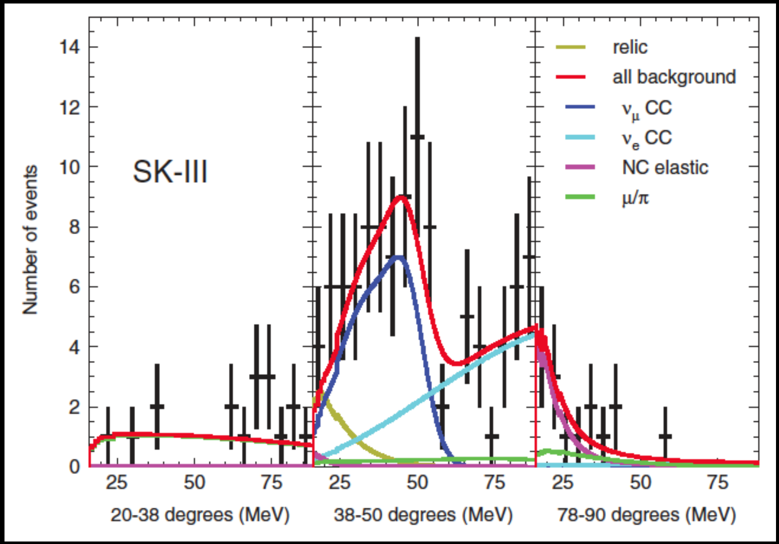
Event spectrum:

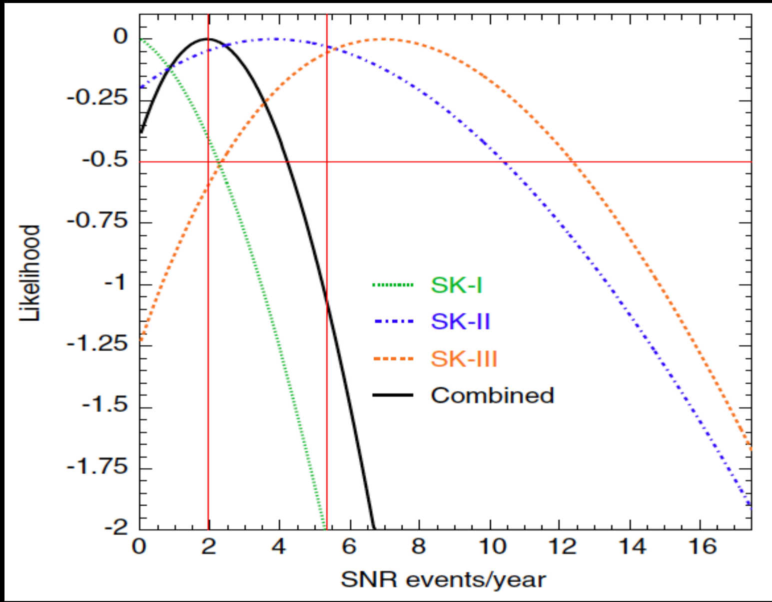
Four ν spectra are shown (here, *T* refers to the effective ν temperature after mixing). For each, two curves show the uncertainty due to the supernova rate.

The uncertainty due to supernova rate is already competitively small compared to the range of plausible neutrino spectra

The SN rate uncertainty should further decrease with time

Exciting limits: Super-Kamiokande





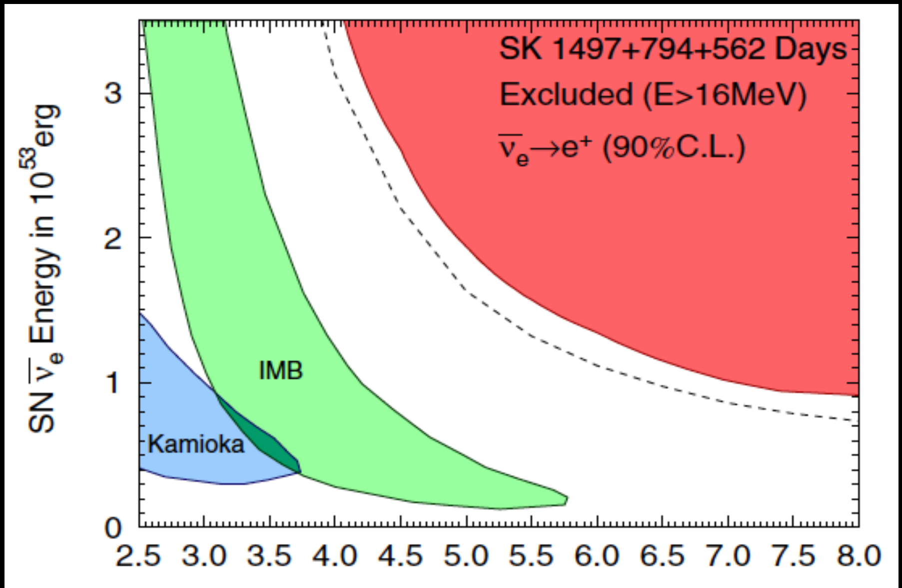
Super-K limit: *Bays et al. (2012)*

Currently background dominated search.

SK-II & SK-III best-fits prefer a slightly positive DSNB!

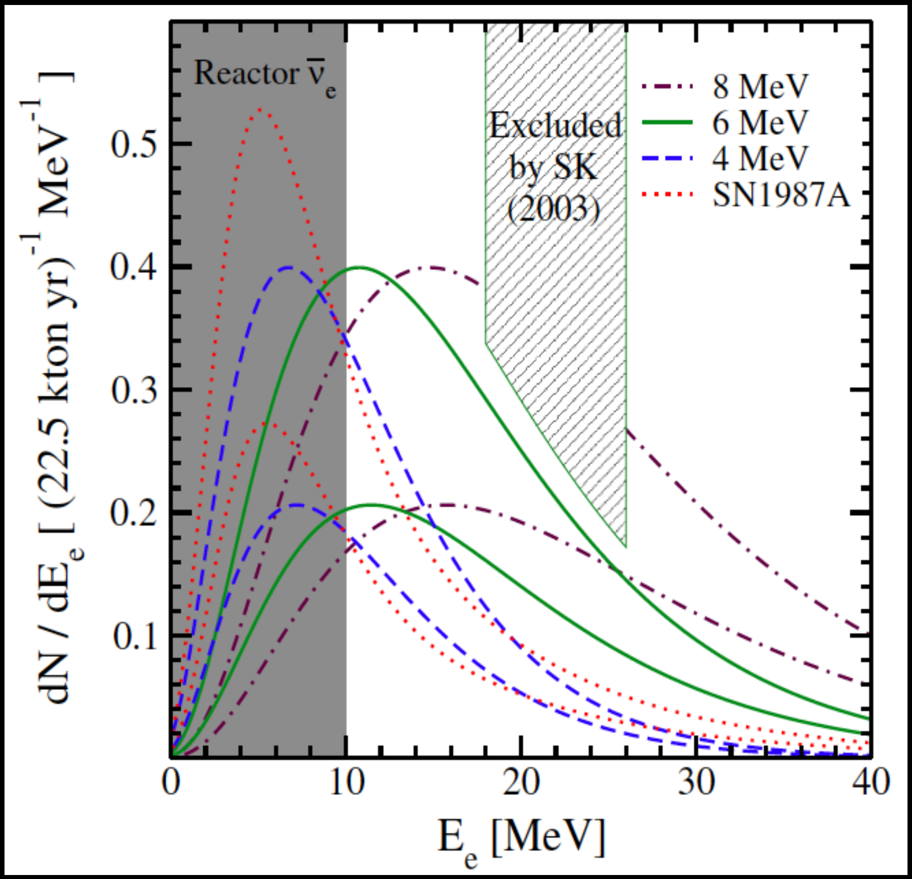
Upper limit:

Conservative limits on the average supernova neutrino parameters



Bays et al. (2012)

Event rate predictions at Hyper-K



Horiuchi, Beacom, Dwek (2009)

Event rates at Hyper-K:
Gd improves rates by a factor > 2

(18-30 MeV range without Gd,
10-30 MeV range with Gd,
0.5 Mton fiducial volume,
Strumia & Vissani 2003 cross section,
signal efficiency 100%)

	Without Gd [/yr]	With Gd [/yr]
SN1987A	13 +/- 4	40 +/- 12
6 MeV	37 +/-10	86 +/- 25
5 MeV	23 +/- 6	65 +/- 20
4 MeV	11 +/- 3	40 +/- 12

Detected over invisible muon background

Background vastly reduced (factor ~5)

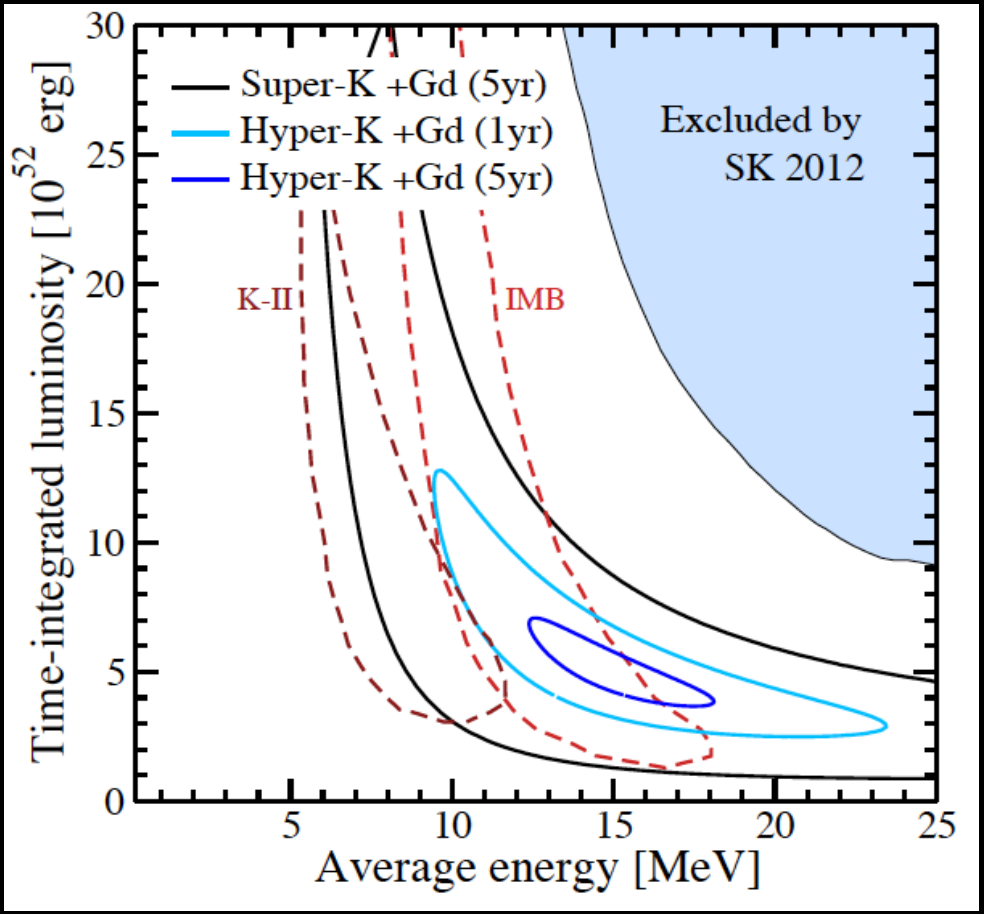
Studying the neutrino emission parameters

Gd will be very powerful indeed:
It gives an excellent probe of the average νebar energy and the time-integrated νebar luminosity

Why do we need to pin these down so well?

- One reason is the marginal inconsistency between the IMB and Kamiokande-II best-fits
- A related question is: was SN1987A typical or rare? (also for any future Galactic supernovae)
- The DSNB is expected to be composed of multiple components

SN rate uncertainty should be small enough (and declining)



90% contours for E_ν = 5 x 10^{52} erg and ε_ν = 15 MeV (Caution very simplified: idealized detector with all spallation removed, invisible muon reduced by factor 5, only Poisson errors)

Recent interest: failed supernovae

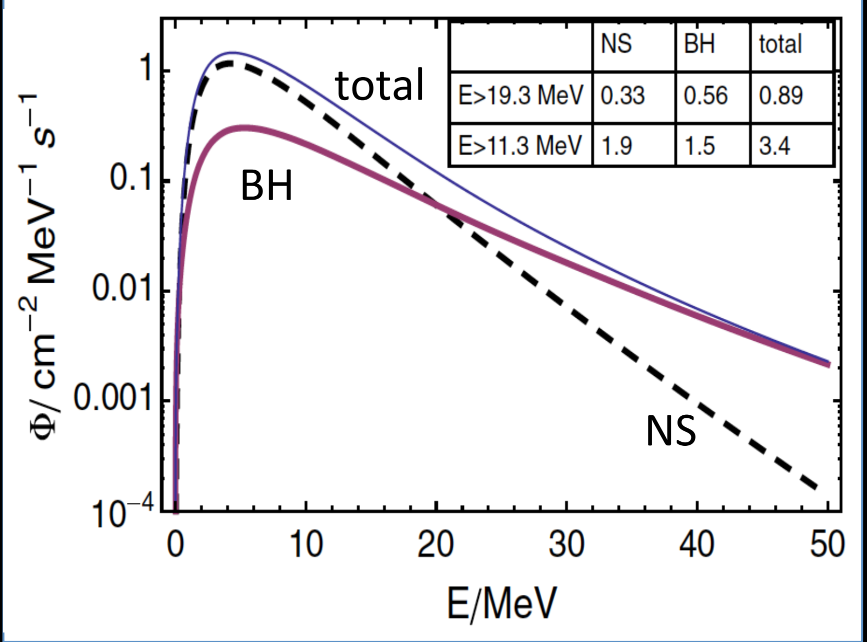
Neutrino emission in failed supernovae:

The ν-ebar emission may be larger in *both* total energy and average energy, with the precise value depending on the EoS

$E_\nu \sim$ 5 x 10^{52} erg → (5 – 13) x 10^{52} erg

$\varepsilon_\nu \sim$ 15 MeV → 20 – 24 MeV

Sumiyoshi et al. (2007,2008), Fischer et al. (2008), neutrino detection in Galactic supernova discussed by Nakazato et al. (2008)



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

Lunardini (2009)

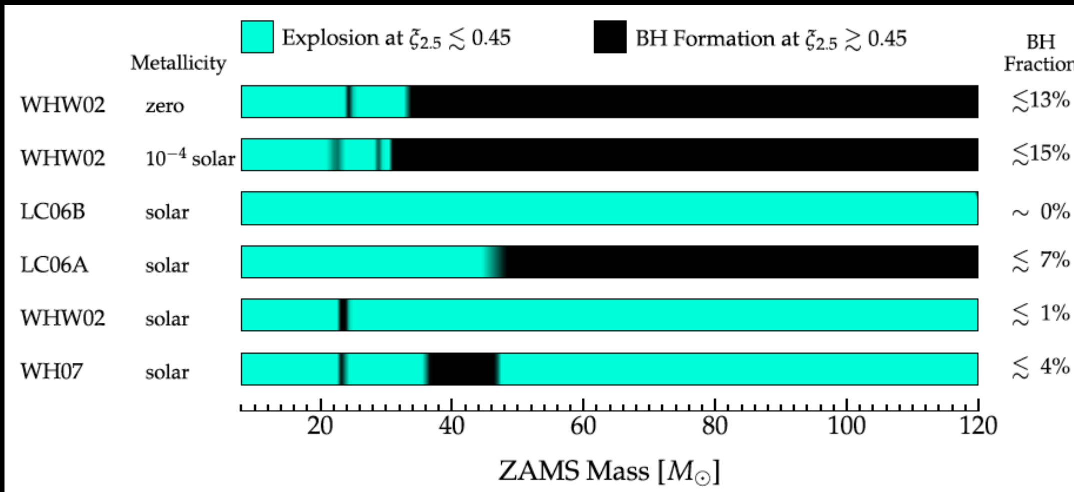
Interesting second component to the DSNB:

What is the neutrino emission from failed supernovae? Also, what is the fraction of such collapses? To study these with the DSNB, one can investigate

1. Increase in event rates
2. Spectral distortion ← measuring the high-energy portion becomes important

Fraction of failed supernovae

O'Connor & Ott (2011)



Theory:

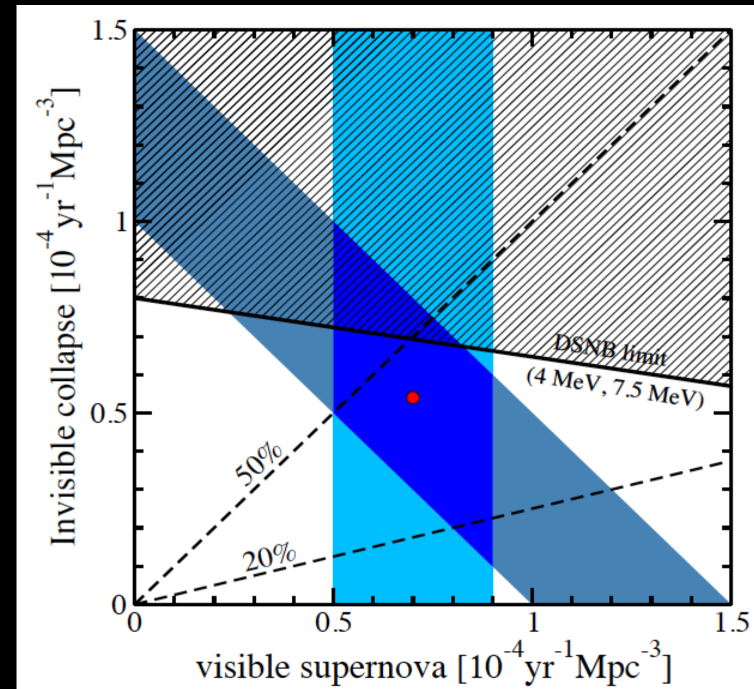
Predicts 0 – 15%, depending on pre-supernova model, nuclear EoS, rotation, metallicity, and mass loss prescription.

Survey about nothing:

In progress! Monitor 10^6 massive stars (few times per year) and look for disappearing stars. So far, in 5 years running, 2 luminous supernovae observed.

Kochanek et al. (2008)

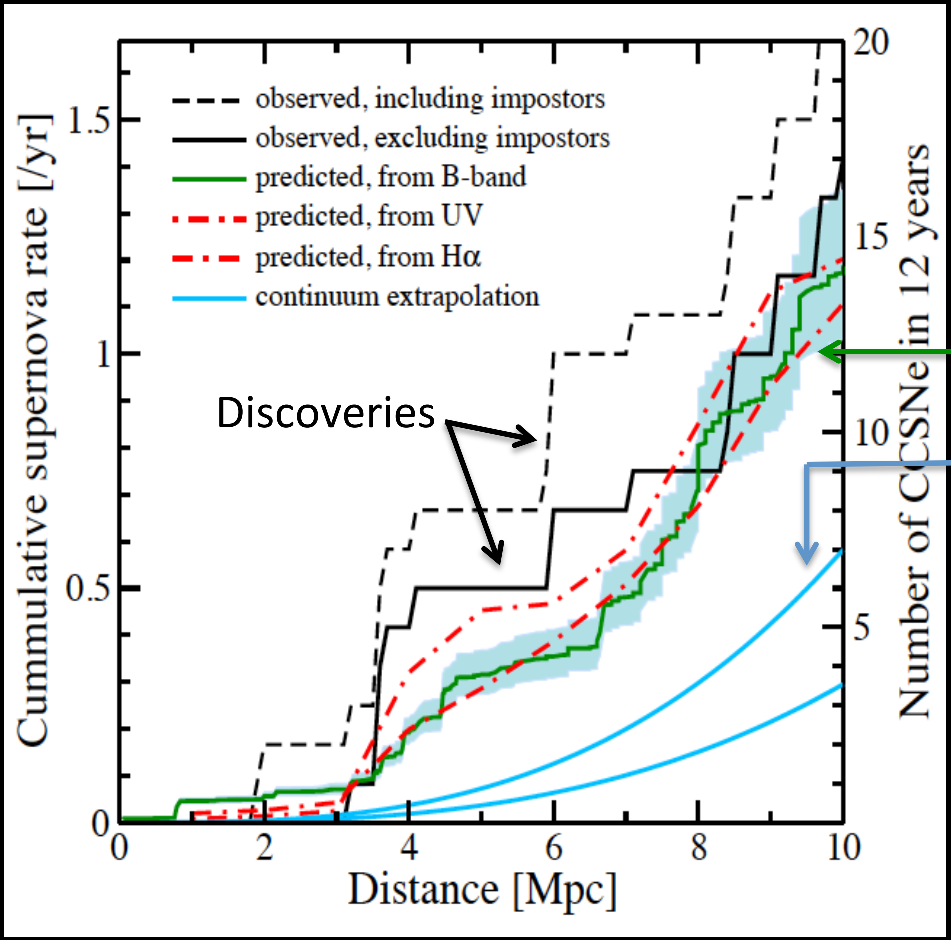
Adapted from Lien, Fields & Beacom (2010)



"Observations":

Core-collapse rate (inferred from star formation rate) and supernova rate can be used to estimate the failed supernova rate, but complicated by astro effects

Mini-bursts: reach into our neighbors



Horiuchi et al. (in prep); see also Ando et al. (2005)

High nearby supernova rates:
Both observations and predictions show that our neighborhood has an *enhancement* of supernovae wrt the smooth limit

Predictions

Smooth limit

Yields in Hyper-K without/with Gd:

$$N_{e^+}(18 < E_{e^+} < 30) \approx 5 \left(\frac{d}{1\,\mathrm{Mpc}}\right)^{-2}$$

$$N_{e^+}(12 < E_{e^+} < 38) \approx 9 \left(\frac{d}{1\,\mathrm{Mpc}}\right)^{-2}$$

Can probe out to a few Mpc

Mini-burst Prediction

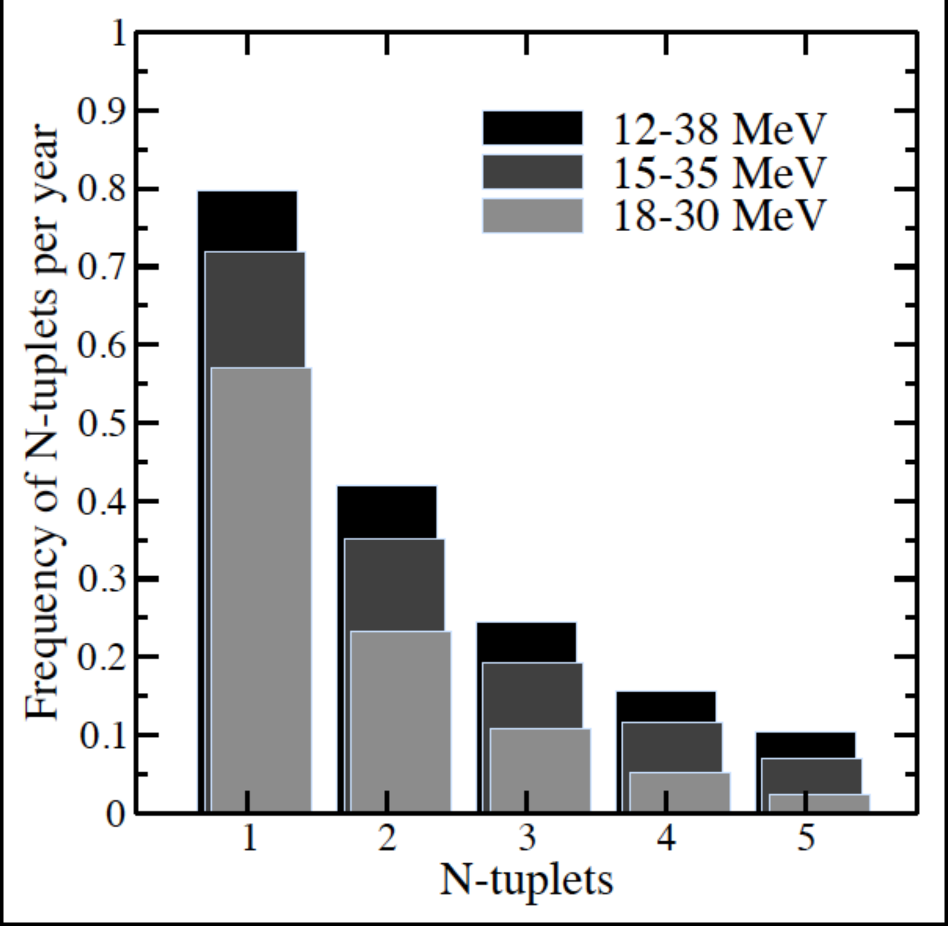
Targets:
Coincidence with nearby supernovae and also failed supernovae (Survey about Nothing)

Backgrounds:
The usual suspects: reactor and atmospheric neutrinos, spallation daughter decays, invisible muon decays

Background control:
Narrow the time window helps reduce accidental signals caused by backgrounds

Rate of neutrinos (total):
12 – 38 MeV: 1.6 per yr
15 – 35 MeV: 1.2 per yr
18 – 30 MeV: 0.7 per yr

Adapted from *Kistler et al. (2011)*

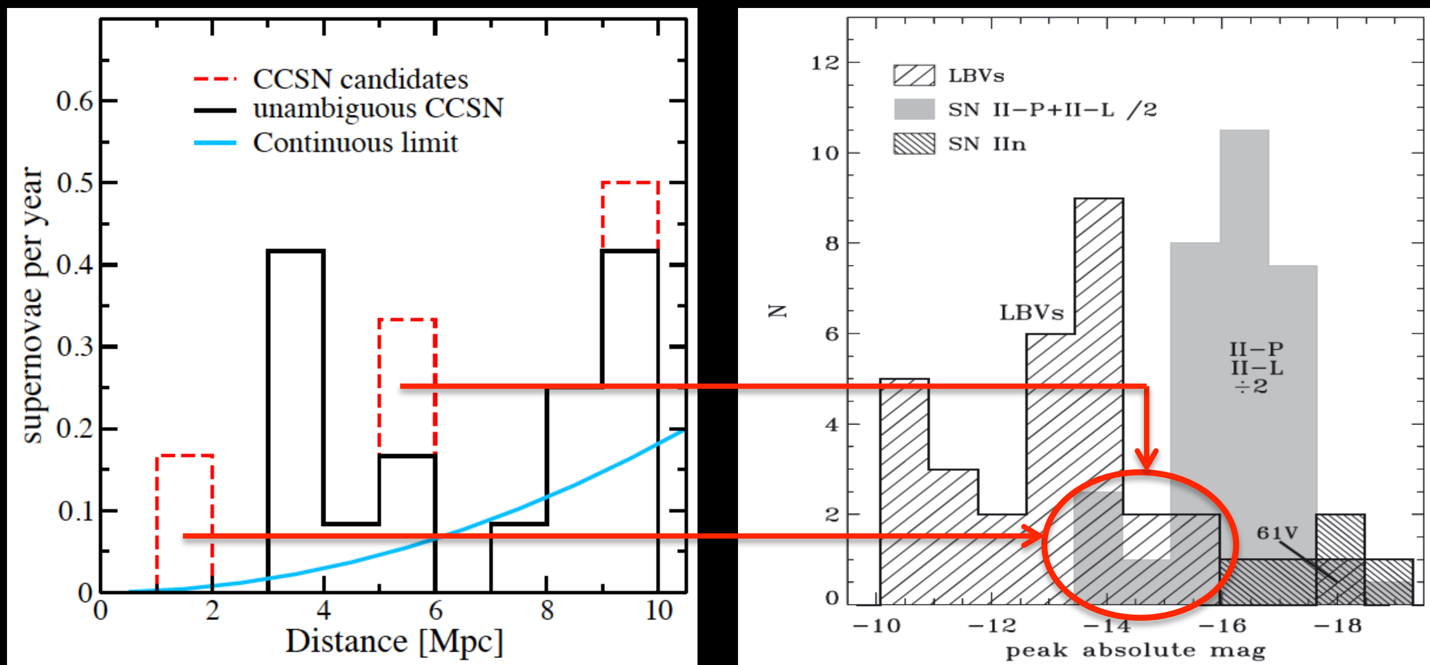


Rate of N-tuplets:
The frequency of obtaining a N-tuplet in Hyper-K, assuming the nearby supernova rate

Recent interest: impostor or supernova?

Recently discovered transients (SN2008S-like events):
Are they extreme LBVs or dim supernovae (e.g., electron-capture core-collapses)?

Nearby potential impostors in red



Smith et al. (2011)

Even a few MeV neutrinos will be an indisputable signal to settle the debate.

Hyper-K is well-placed to make significant & unique contributions

Lots of recent interest in the community: 98 abstracts on "SN2008S" as of Aug 2012: *Smith et al. (2009), Bond et al. (2009), Berger et al. (2009), Botticella et al. (2009), Pumo et al. (2009), Thompson et al. (2009), Kashti et al. (2010), Khan et al. (2010), Smith et al. (2011), Kochanek (2010, 2011), Prieto et al. (2012), …*

Summary: supernova neutrinos

- HISTORICAL *discovery of neutrinos* from SN1987A [past]

- EXCITING *limits on diffuse* with Super-K, and *Gadolinium* potential [present]

- GREAT physics prospects with Hyper-K [future]
  - DSNB is a *guaranteed* signal
  - Provides *physics benefits* for supernova, supernova rates, and populations like black-hole forming collapses
  - Potential to open a *completely new window* into our nearby galaxies: major contributions to astrophysics & astronomy
  - New, unexpected, exciting, signals

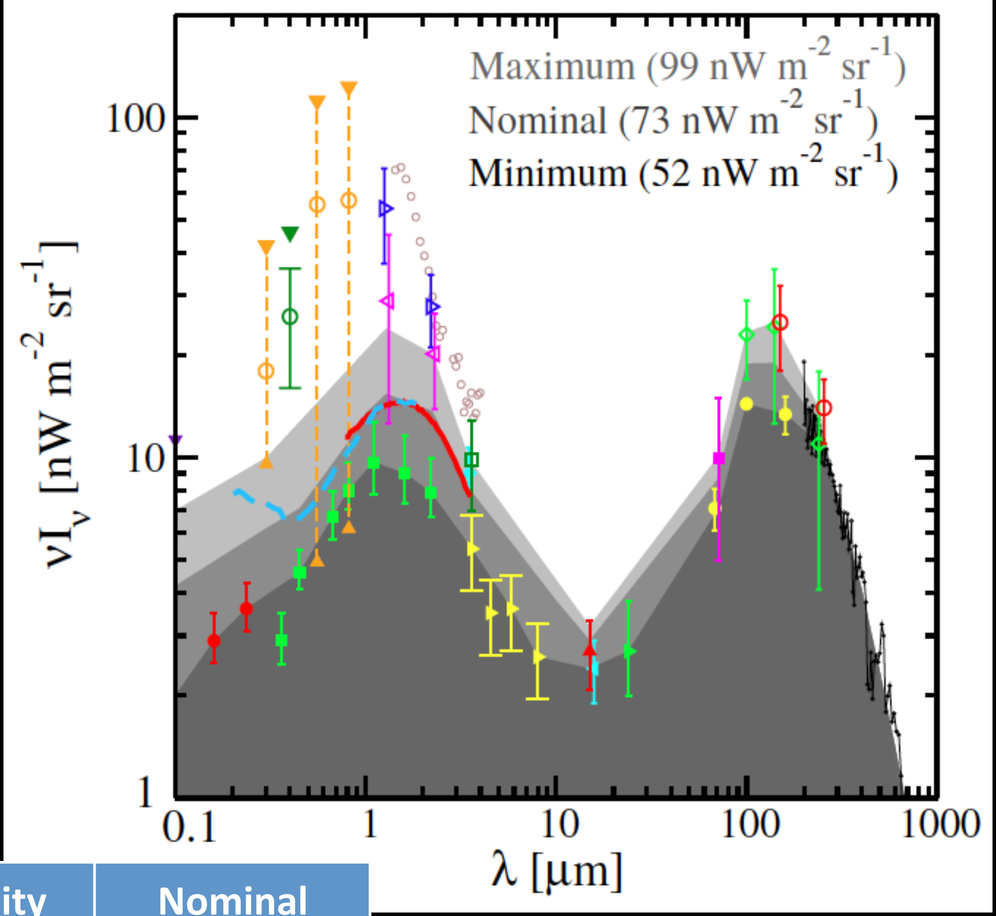
Back-up slides

Integrated constraints: EBL

Observed EBL:
Various constraints, with lower limits from summing observed galaxies, upper limits that has foreground concerns, and recent constraints from distant TeV blazar observations. Nominal total EBL is

$$73^{+26}_{-21}\,\mathrm{nW\,m^{-2}\,sr^{-1}}$$

Calculated EBL from stars:
Depends on the IMF to some degree but modern shapes provide good consistency with observed



IMF	Total EBL intensity	Nominal
Salpeter (1955)	**65–134 nW m^{-2} sr^{-1}**	95
Kroupa (2001)	**60–124 nW m^{-2} sr^{-1}**	88
Baldy-Glazebrook (2003)	**54–109 nW m^{-2} sr^{-1}**	78

Note other contributions:
Minimal, e.g., AGN contributes only few % to the observed EBL

e.g., Hopkins et al. (2006)

Star formation to supernova conversion

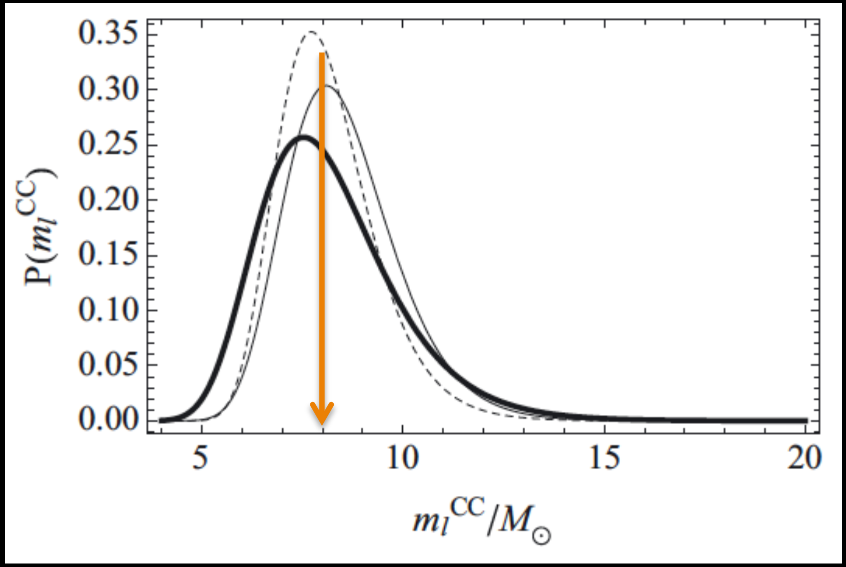
$$R_{SN}(z) = \dot{\rho}_*(z) \frac{\int_{M_{min}}^{M_{max}} \psi(M)\, dM}{\int_{0.1}^{100} M \psi(M)\, dM}$$

What are M_{min} and M_{max}? They are obtained from pre-supernova imaging studies of nearby supernovae

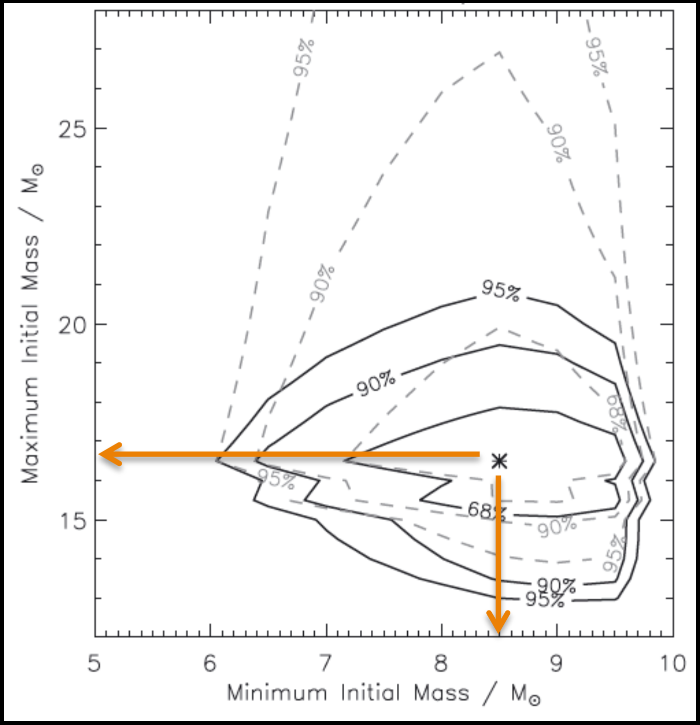
Using nearby supernovae:

$M_{min} \sim 8$ Msun

$M_{max} \sim 16$ Msun

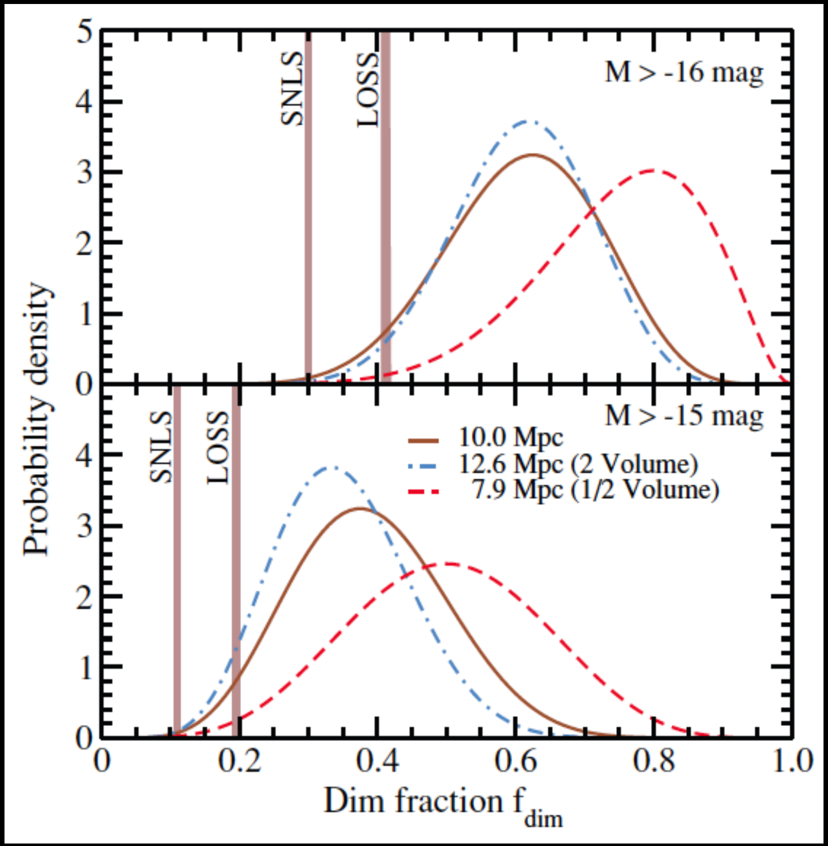


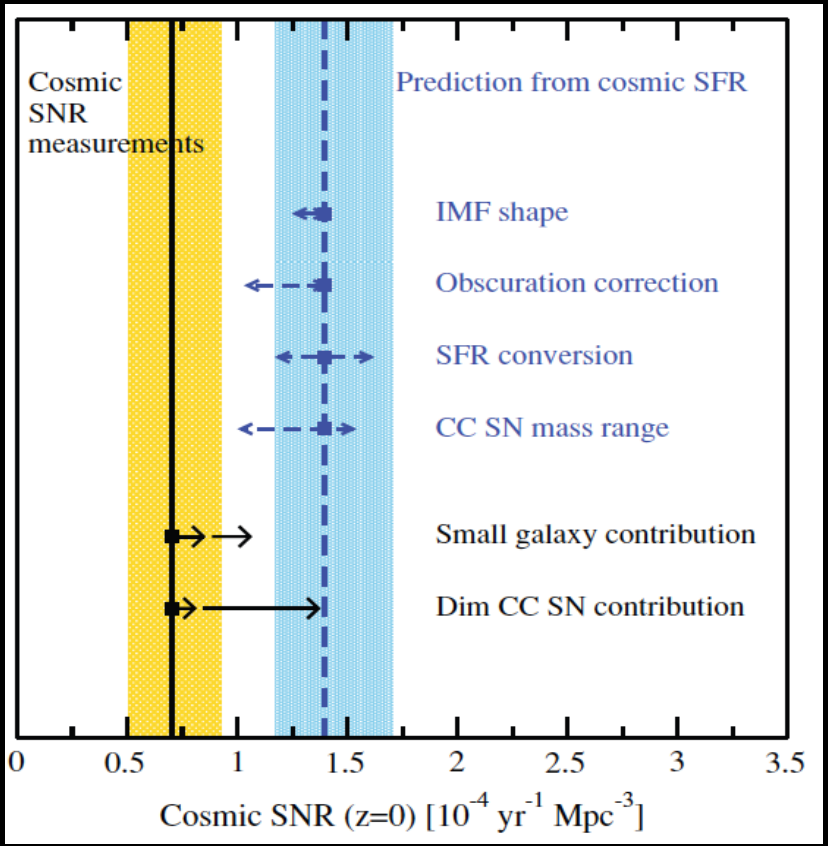
Botticella et al. (2012)



Smartt et al. (2009)

Uncertainties



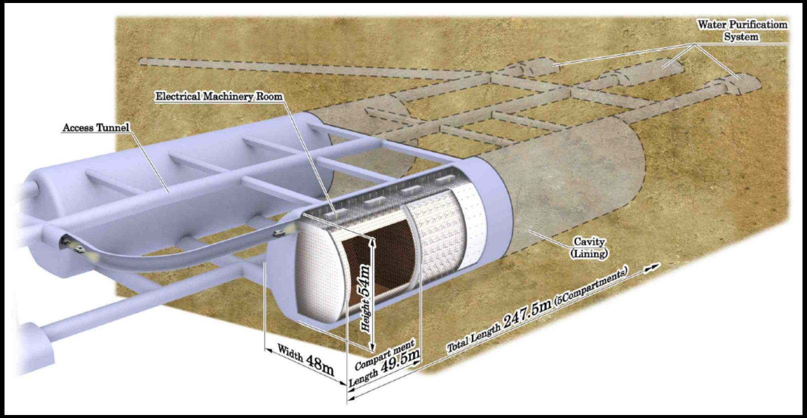


Horiuchi et al. (2011)

Apart from dim supernova, other variations of inputs cannot easily explain the normalization discrepancy (it would imply there is some conspiracy of all effects going in the same direction).

Input 3: detector capabilities

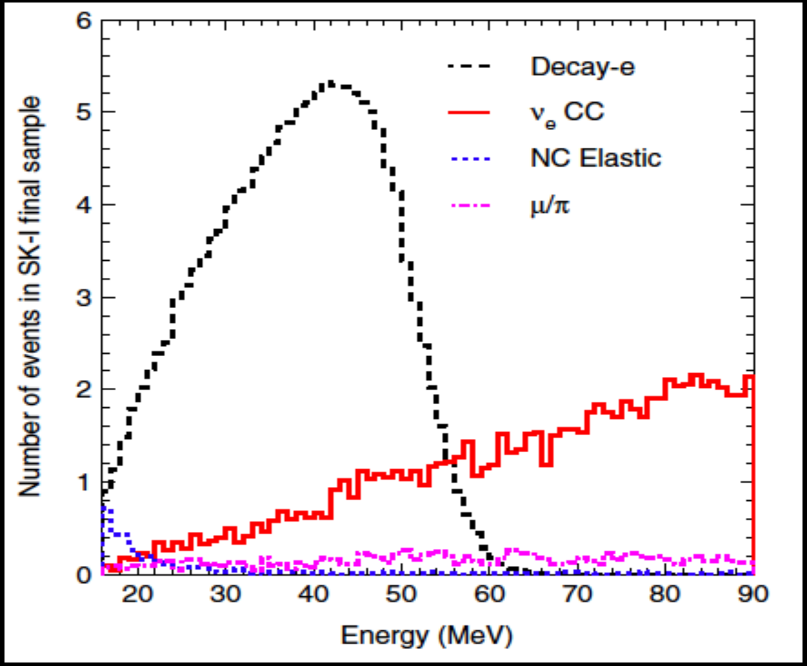
Hyper-K; Abe et al. (2011)



Detection channel:

- Inverse-beta decay on free protons
  - Super-K: 22.5 kton
  - Hyper-K: 0.5 Mton
- Cross-section known
- Kinematics good
- No directionality (but that's okay)

Vogel & Beacom (1999), Strumia & Vissani (2003)



Competing backgrounds:

- Neutrino backgrounds
  - Atmospheric
  - Reactor
- Invisible muon decays
- Spallation daughter decays

Bays et al. (2012)