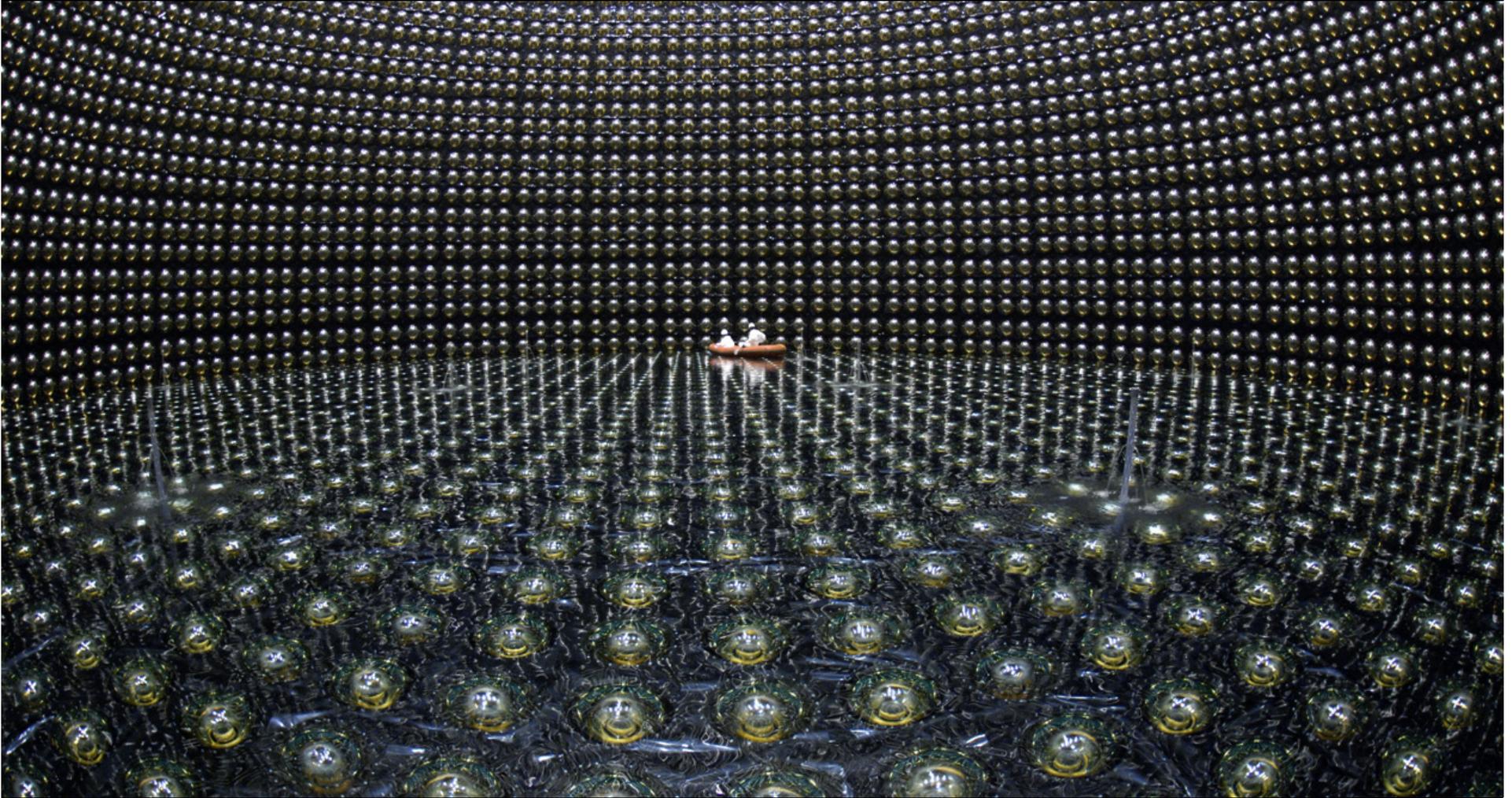


# *Supernova Neutrinos*

*John Beacom, Ohio State University*



The Ohio State University's Center for Cosmology and AstroParticle Physics

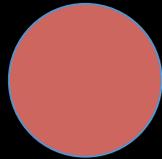


# Why are Supernovae Special Stars?

## Stars

Slow release of energy

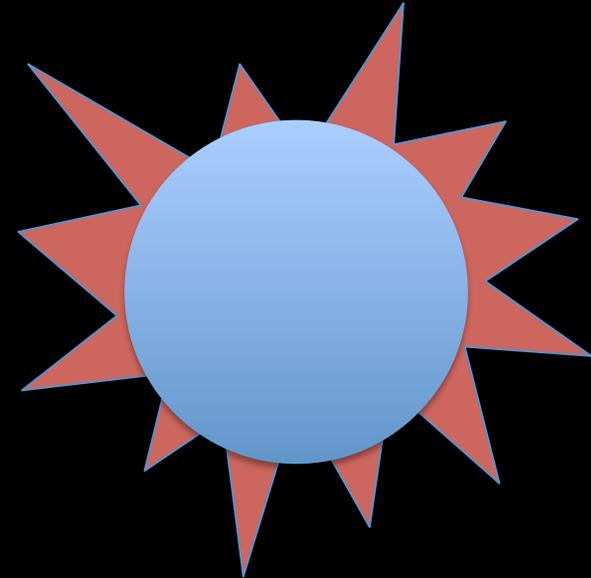
Gravity > Pressure: *contraction*



## Supernovae

Fast release of energy

Pressure  $\gg$  Gravity: *explosion*



Can only reveal the interior conditions of collapsing stars with neutrinos

# Why are Neutrinos Special Particles?

Charged leptons

$$\tau^{\pm}$$

$$\mu^{\pm}$$

$$e^{\pm}$$



Neutral leptons

$$\nu_{\tau}, \bar{\nu}_{\tau}$$

$$\nu_{\mu}, \bar{\nu}_{\mu}$$

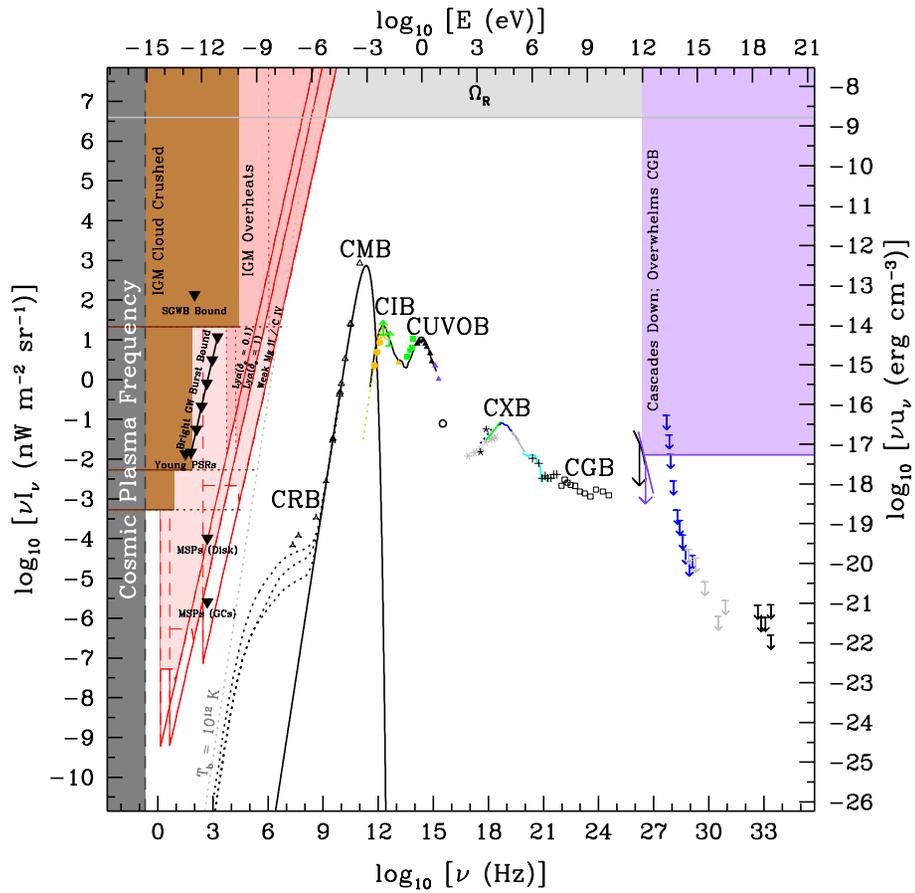
$$\nu_{e}, \bar{\nu}_{e}$$



Can only probe all neutrino properties with extremes of astrophysics

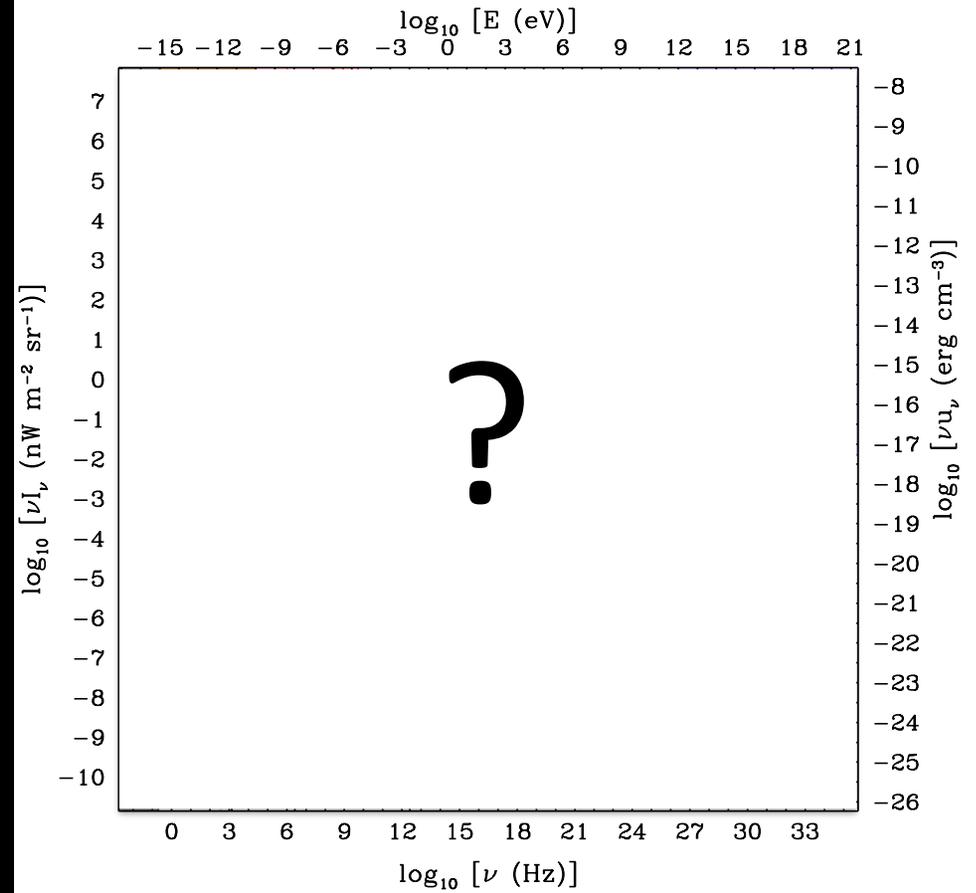
# Why are Cosmic Backgrounds Special Data?

Photons



Lacki (2010)

Neutrinos



Can only detail energy budget of the universe with cosmic backgrounds

# *Talk Outline*

Introduction: Basics and Motivations

Introduction: Detection Modes

**DSNB: Theoretical Predictions**

**DSNB: Experimental Limits**

**DSNB: Detection Strategy**

Concluding Perspectives

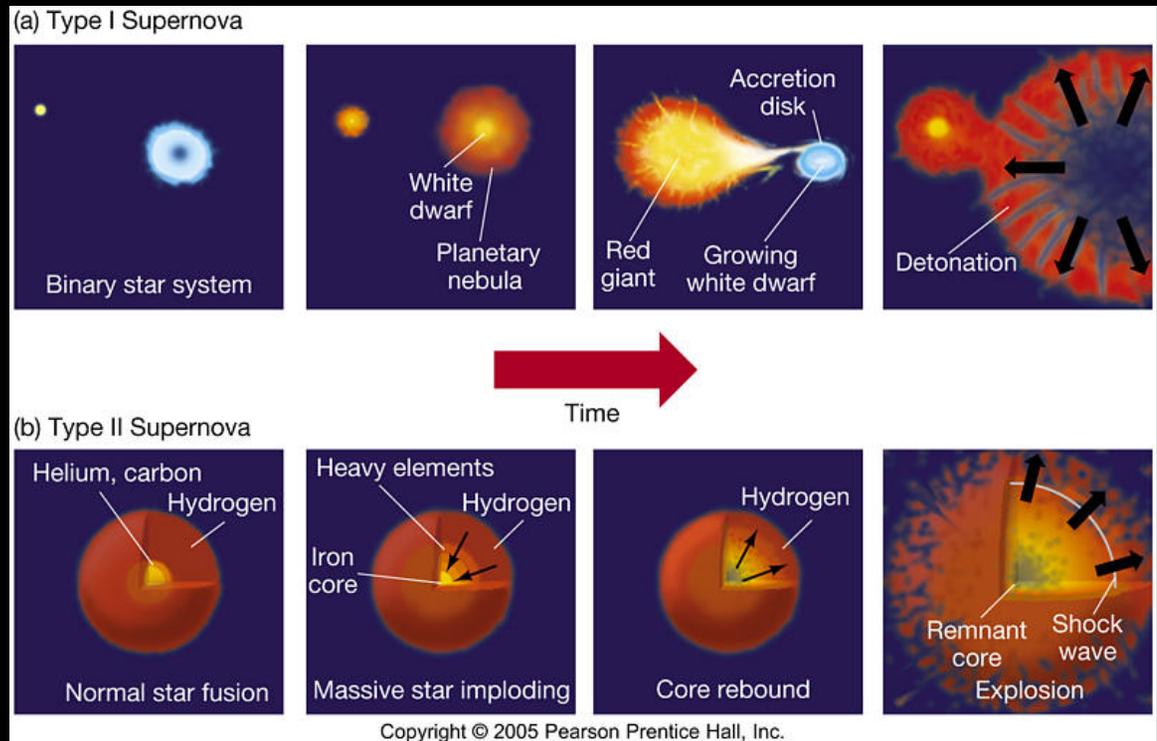
*(DSNB = Diffuse Supernova Neutrino Background)*

# Introduction: Basics and Motivations

# Core-Collapse Supernova Basics



**Type Ia**  
(thermonuclear,  
few neutrinos)



**Type II**  
(core collapse,  
many neutrinos)

Neutrinos carry away the change in gravitational potential energy

$$\Delta(\text{P.E.}) \sim (-GM^2/R)_{\text{neutron-star}} - (-GM^2/R)_{\text{stellar-core}} \sim -3 \times 10^{53} \text{ erg}$$

approximately shared among all six flavors

Neutrinos are trapped by scattering interactions and diffuse out

quasi-thermal with  $\langle E \rangle \sim 15 \text{ MeV}$

$\tau \sim \text{few seconds}$

# *Importance of Supernova Neutrino Detection*

How do core-collapse supernovae explode?

How do they form neutron stars and black holes?

What are the nucleosynthesis products of supernovae?

What are the actions and properties of neutrinos?

What is the cosmic rate of black hole formation?

Which supernova-like events make neutrinos?

What else is out there that makes neutrinos?

....

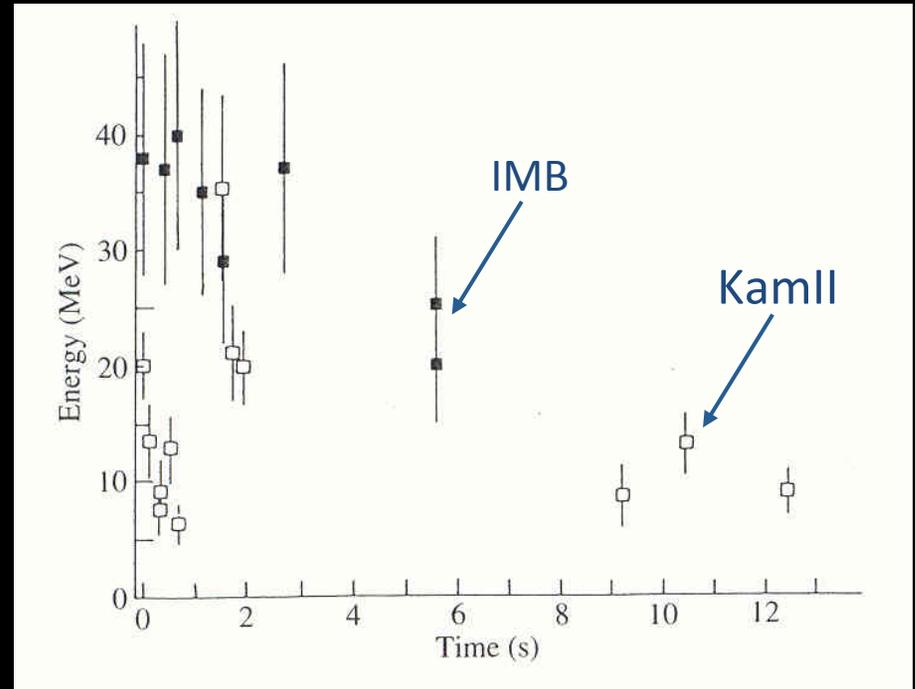
**We cannot solve key problems without detecting supernova neutrinos**

The required detections are – surprisingly – within our reach

Detecting even a few neutrinos could often give decisive answers

Will open new frontiers in observational neutrino astrophysics

# SN 1987A: Our Rosetta Stone



**Observation:** Type II supernova progenitors are massive stars

**Observation:** The neutrino precursor is very energetic

**Theory:** Core collapse makes a proto-neutron star and neutrinos

# *Supernova Neutrino Detections Since 1987*

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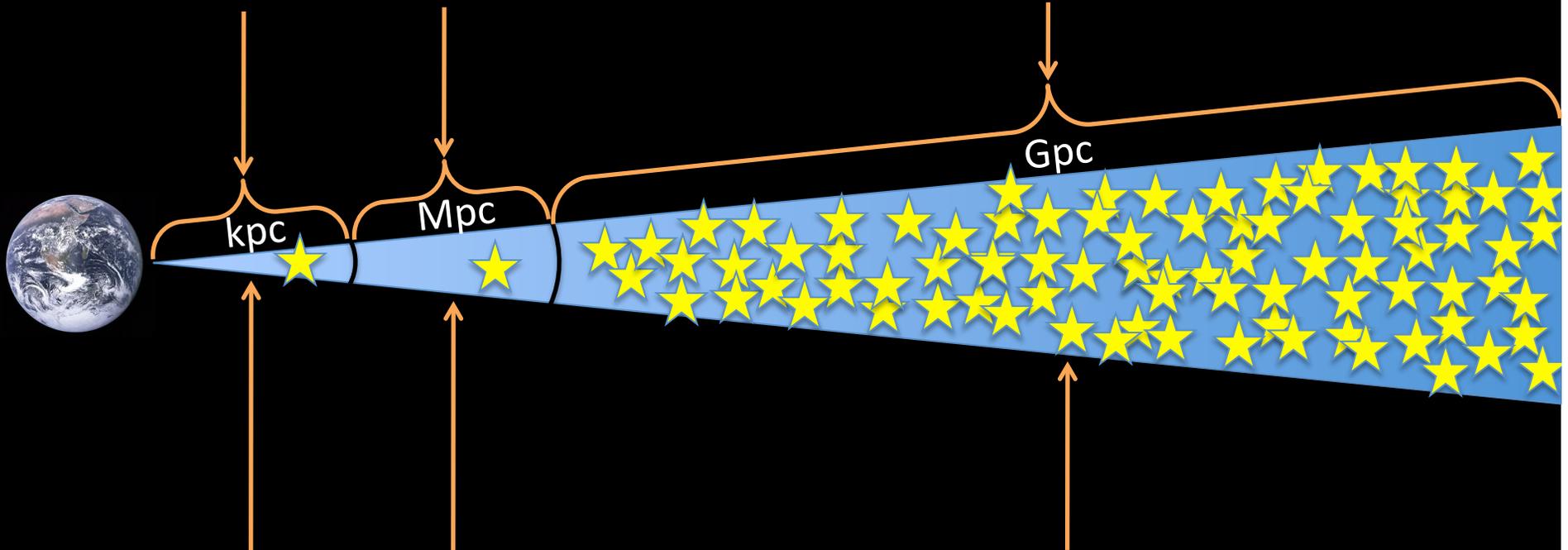
# Introduction: Three Detection Modes

# Distance Scales and Detection Strategies

$N \gg 1$  : **Burst**

$N \sim 1$  : **Mini-Burst**

$N \ll 1$  : **DSNB**



Rate  $\sim 0.01/\text{yr}$

Rate  $\sim 1/\text{yr}$

Rate  $\sim 10^8/\text{yr}$

high statistics,  
all flavors

object identity,  
burst variety

cosmic rate,  
average emission

# Simple Estimate: Milky Way Burst Yields

## Super-Kamiokande (32 kton water)

- ~  $10^4$  inverse beta decay on free protons
- ~  $10^2 - 10^3$  CC and NC with oxygen nuclei
- ~  $10^2$  neutrino-electron elastic scattering (*crude directionality*)

## KamLAND, MiniBooNE, Borexino, SNO+, etc (~ 1 kton oil)

- ~  $10^2$  inverse beta decay on free protons
- ~  $10^2$  neutron-proton elastic scattering
- ~  $10 - 10^2$  CC and NC with carbon nuclei
- ~ 10 neutrino-electron elastic scattering

## IceCube ( $10^6$ kton water)

- Burst is significant increase over background rate
- Possibility of precise timing information

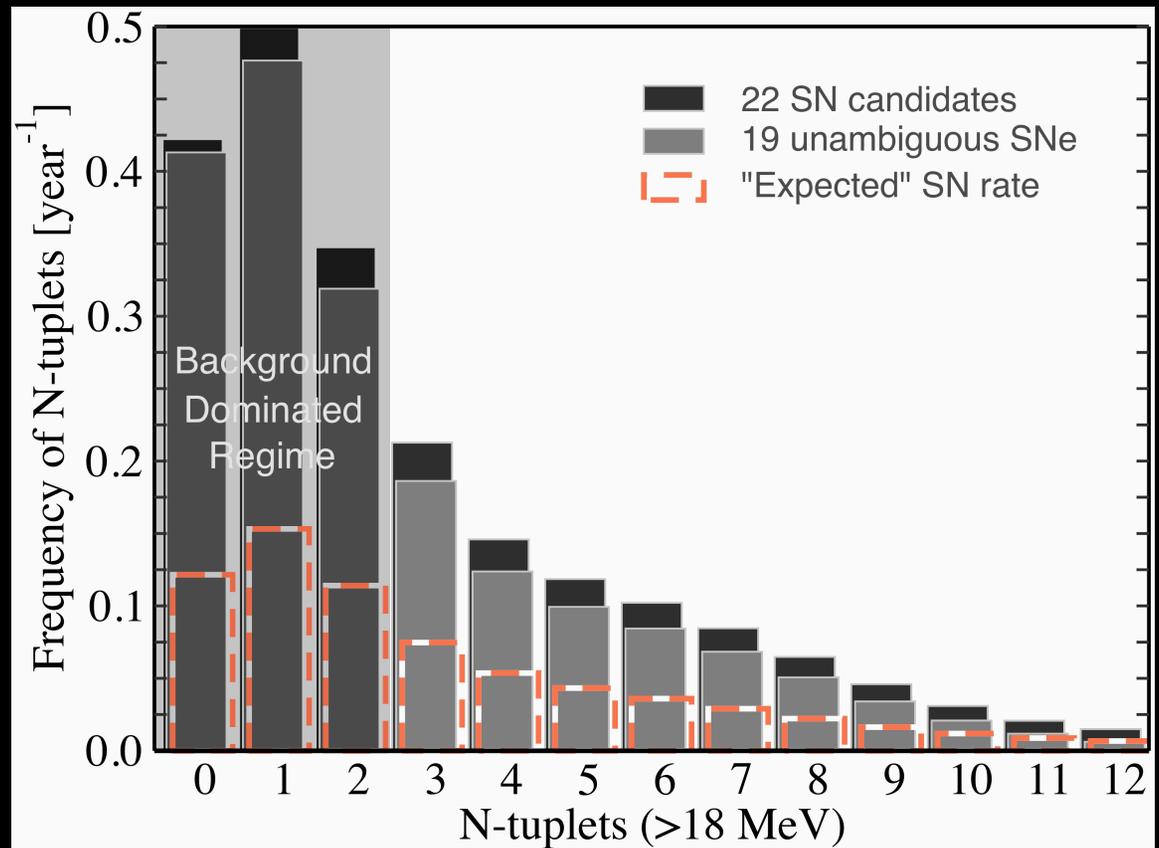
Much larger or better detectors are being proposed now

# Simple Estimate: Extragalactic Mini-Burst Yields

Yield in Super-Kamiokande  $\sim 1 \text{ (Mpc/D)}^2$

A 5000-kton detector could see mini-bursts from galaxies within several Mpc, where the supernova rate is above one per year

New considerations for such a detector as a dense infill for IceCube!



Kistler, Ando, Yuksel, Beacom, Suzuki (2011);  
builds on Yoichiro Suzuki's ideas for Deep-TITAND

# Simple Estimate: DSNB Event Rate

Super-Kamiokande rate in  
every 10 second interval

Kamiokande-II rate in a  
special 10 second interval

$$\sim 1 \text{ s}^{-1}$$

$$\left[ \frac{dN_\nu}{dt} \right]_{\text{DSNB}} \sim \left[ \frac{dN_\nu}{dt} \right]_{87A} * \frac{\left[ \frac{N_{SN} M_{det}}{4\pi D^2} \right]_{\text{DSNB}}}{\left[ \frac{N_{SN} M_{det}}{4\pi D^2} \right]_{87A}}$$

For the DSNB relative to SN 1987A:

$N_{SN}$  up by  $\sim 100$

$M_{det}$  up by  $\sim 10$

$1/D^2$  down by  $\sim 10^{-10}$



**DSNB event rate in Super-Kamiokande is a few per year**

Present: Standard Model of Predicted DSNB

See my 2010 article in Annual Reviews of Nuclear and Particle Science

# Theoretical Framework

Signal rate spectrum in detector in terms of measured energy

$$\frac{dN_e}{dE_e}(E_e) = N_p \sigma(E_\nu) \int_0^\infty \left[ (1+z) \varphi[E_\nu(1+z)] \right] \left[ R_{SN}(z) \right] \left[ \left| \frac{c dt}{dz} \right| dz \right]$$

Third ingredient: Detector Capabilities  
(well understood)

Second ingredient: Supernova  
Rate  
(formerly very uncertain, but now  
known with good precision)

First ingredient: Neutrino spectrum  
(this is now the unknown)

Cosmology? Solved. Oscillations? Included. Backgrounds? See below.

# First Ingredient: Supernova Neutrino Emission

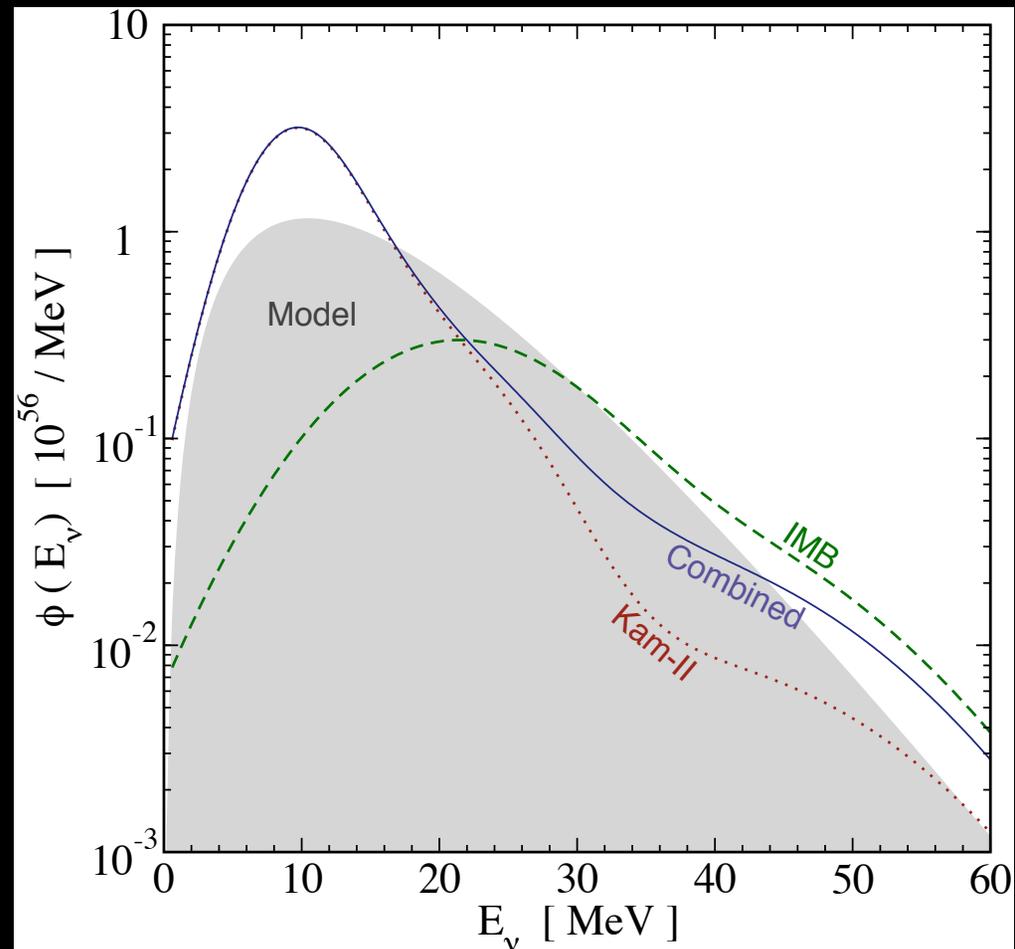
Core collapse releases  
 $\sim 3 \times 10^{53}$  erg, shared by  
six flavors of neutrinos

Spectra quasi-thermal  
with average energies of  
 $\sim 15$  MeV

Neutrino mixing surely  
important but actual  
effects unknown

**Goal is to measure the  
received spectrum**

Nonparametric reconstruction from SN 1987A data



Yuksel, Beacom (2007)

# Importance of the Neutrino Spectrum

Experiment

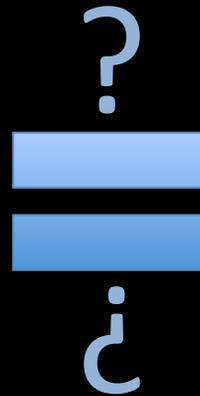
SN 1987A data

Experiment

DSNB data

Experiment

SN 2012? data



Theory

Supernova simulations  
(*initial spectra*)

+

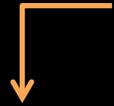
Neutrino flavor change  
(*effects of mixing*)

+

Nucleosynthesis yields  
(*neutrino interactions*)

# Second Ingredient: Cosmic Supernova Rate

Number of massive stars unchanging due to short lifetimes



$$\left(\frac{dN}{dt}\right) = 0 = + \left(\frac{dN}{dt}\right)_{\text{star birth}} - \left(\frac{dN}{dt}\right)_{\text{bright collapse}} - \left(\frac{dN}{dt}\right)_{\text{dark collapse}}$$

Measured from  $N/\tau$  using luminosity and spectrum of galaxies

(now high precision)

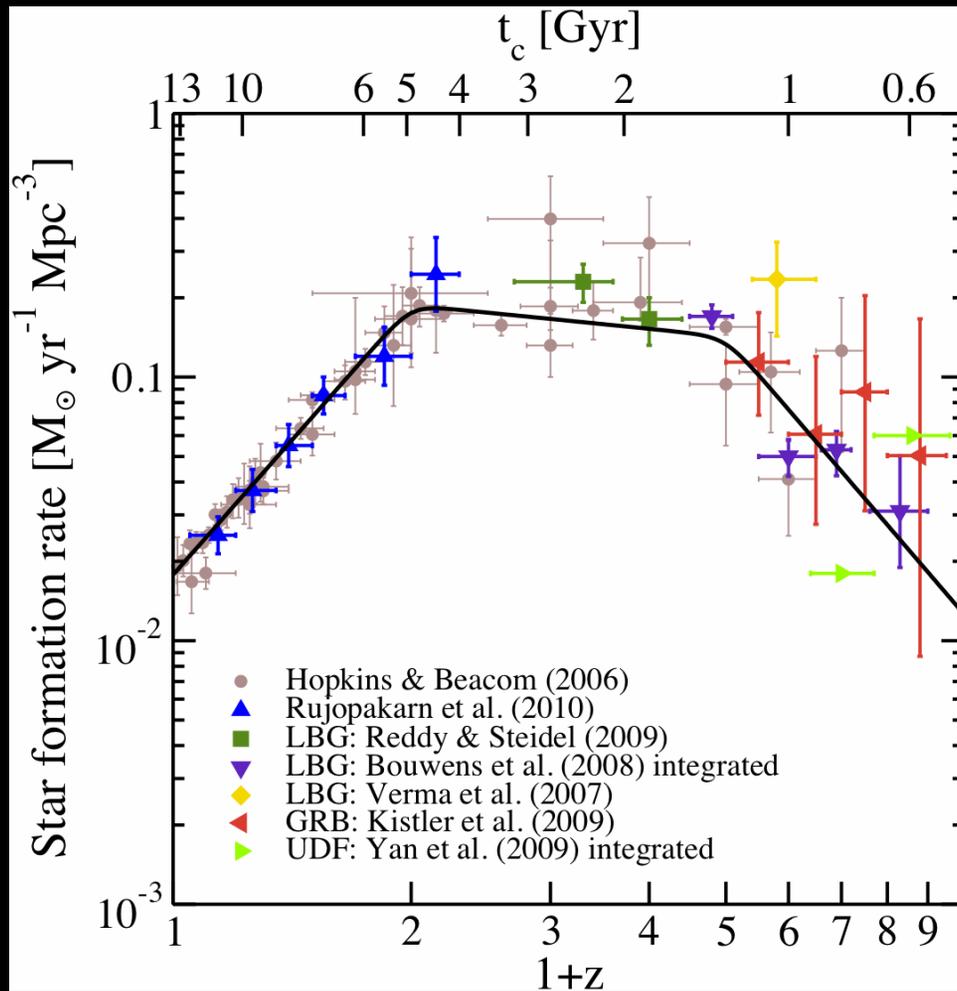
Measured from the core collapse supernova rate

(precision will improve rapidly)

Inferred from mismatch; can be measured by star disappearance; can be **measured by DSNB**

(frontier research area)

# Predictions from Cosmic Star Formation Rate



Horiuchi, Beacom (2010);  
see also Hopkins, Beacom (2006)

Total star formation rate  
deduced from massive stars  
using initial mass function (IMF)

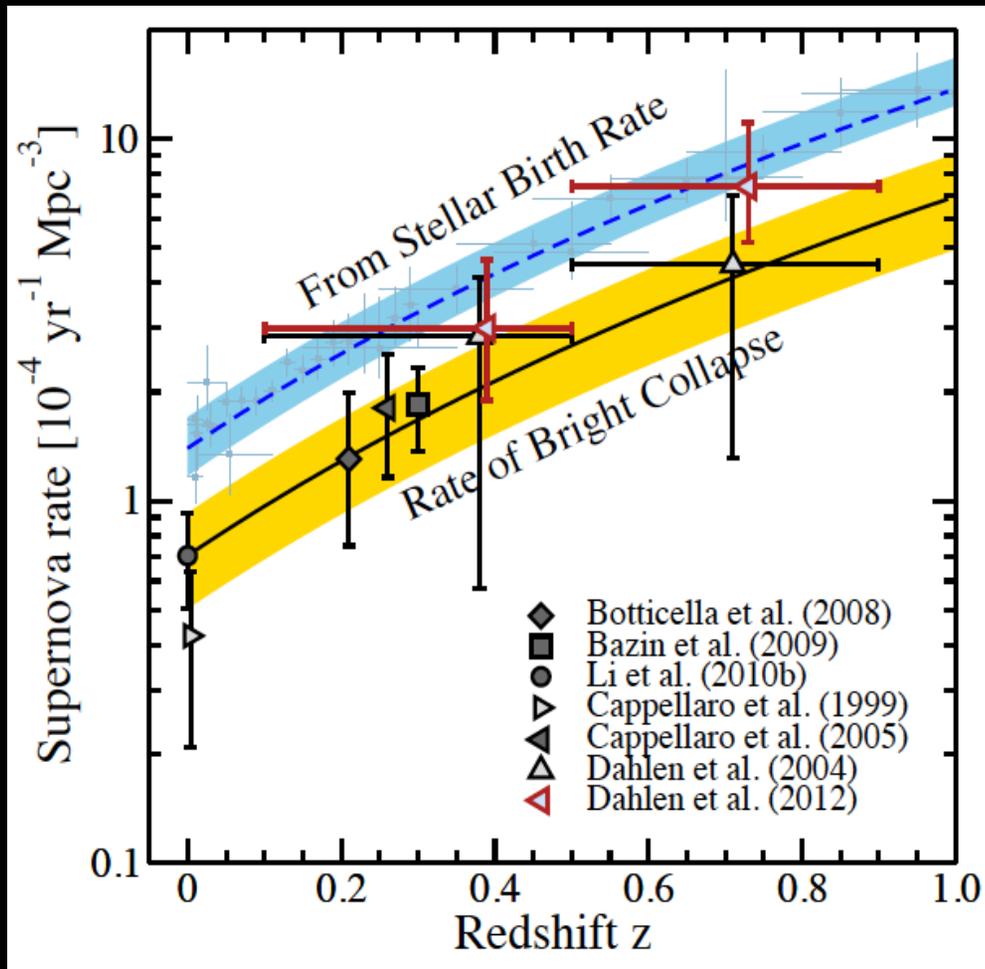
Impressive agreement among  
results from different groups,  
techniques, and wavelengths

Integral of  $R_{SF}$  agrees with EBL

$$R_{SN}(z) \simeq \frac{R_{SF}(z)}{143M_{\odot}}$$

IMF uncertainty on  $R_{SN}$  small

# Measured Cosmic Supernova Rate



Horiuchi et al. (2011) plus updates;  
see also Hopkins, Beacom (2006),  
Botticella et al. (2008),  
Mattila et al. (2012)

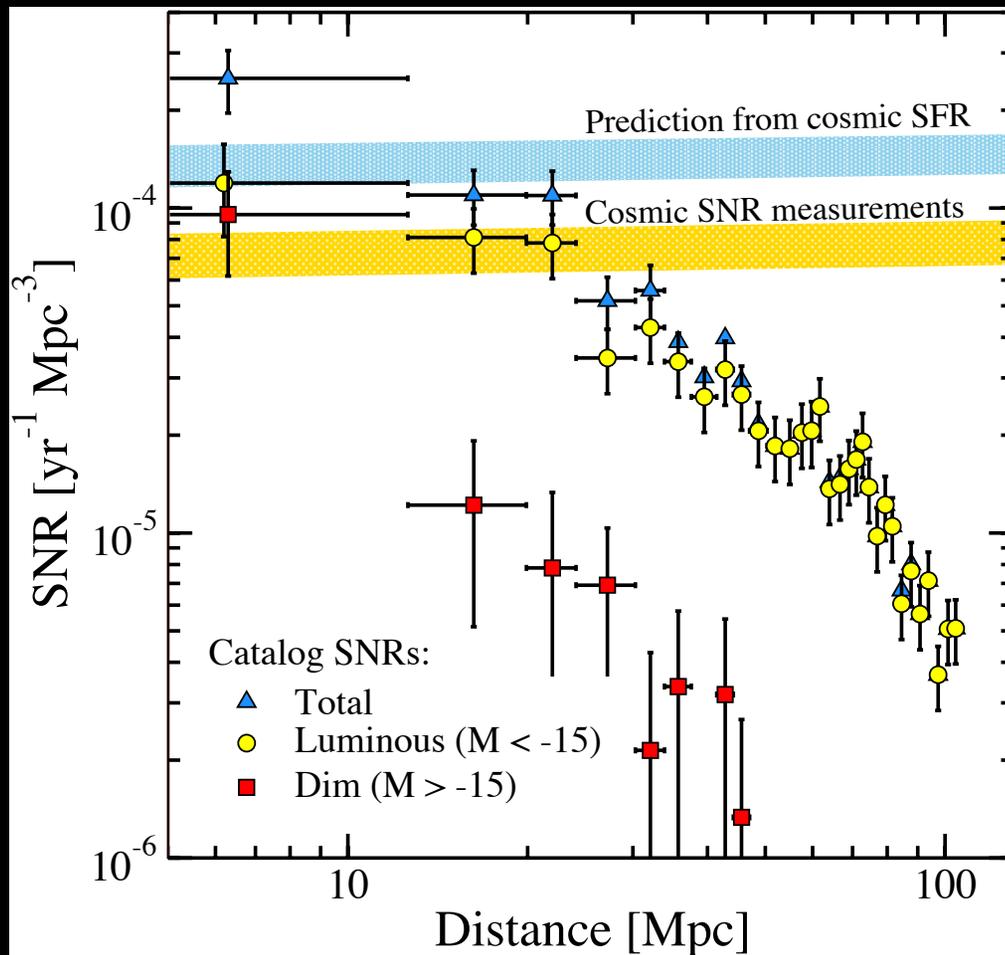
Some measured cosmic supernova rates are **half as big as expected**, a greater deviation than allowed by uncertainties

Why?

There must be missing supernovae – are they faint, obscured, or truly dark?

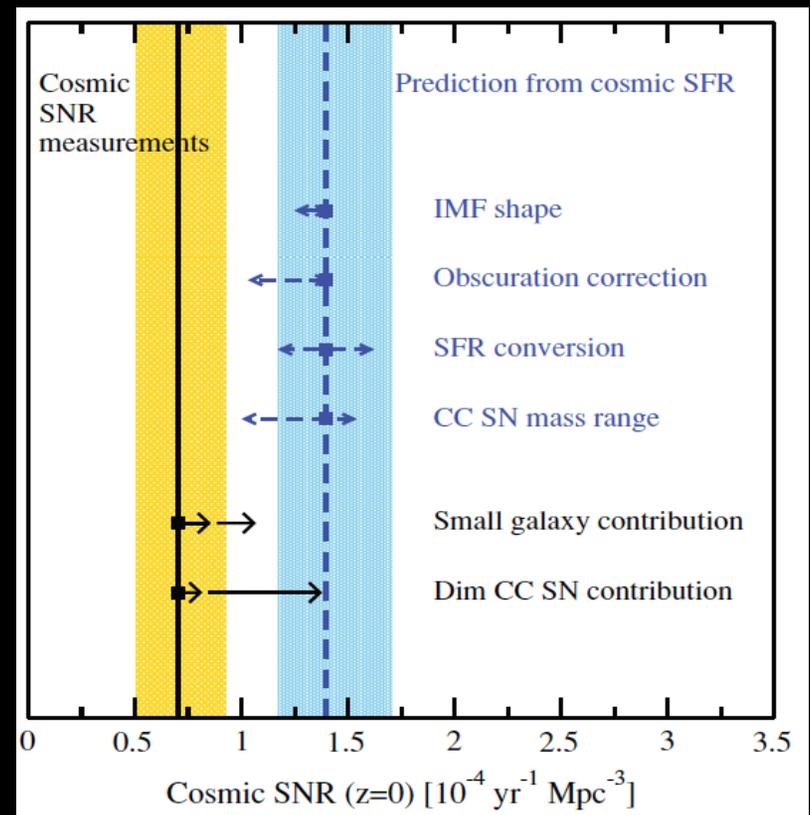
# What About the Supernova Rate Nearby?

Within  $\sim 10$  Mpc, more supernovae than expected are found



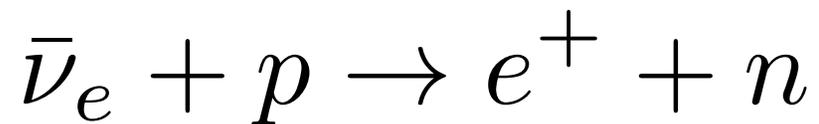
Horiuchi et al. (2011)

← Lots of faint supernovae



# Third Ingredient: Neutrino Detection Capabilities

Only Super-Kamiokande has  
large enough mass AND  
(nearly) low enough backgrounds



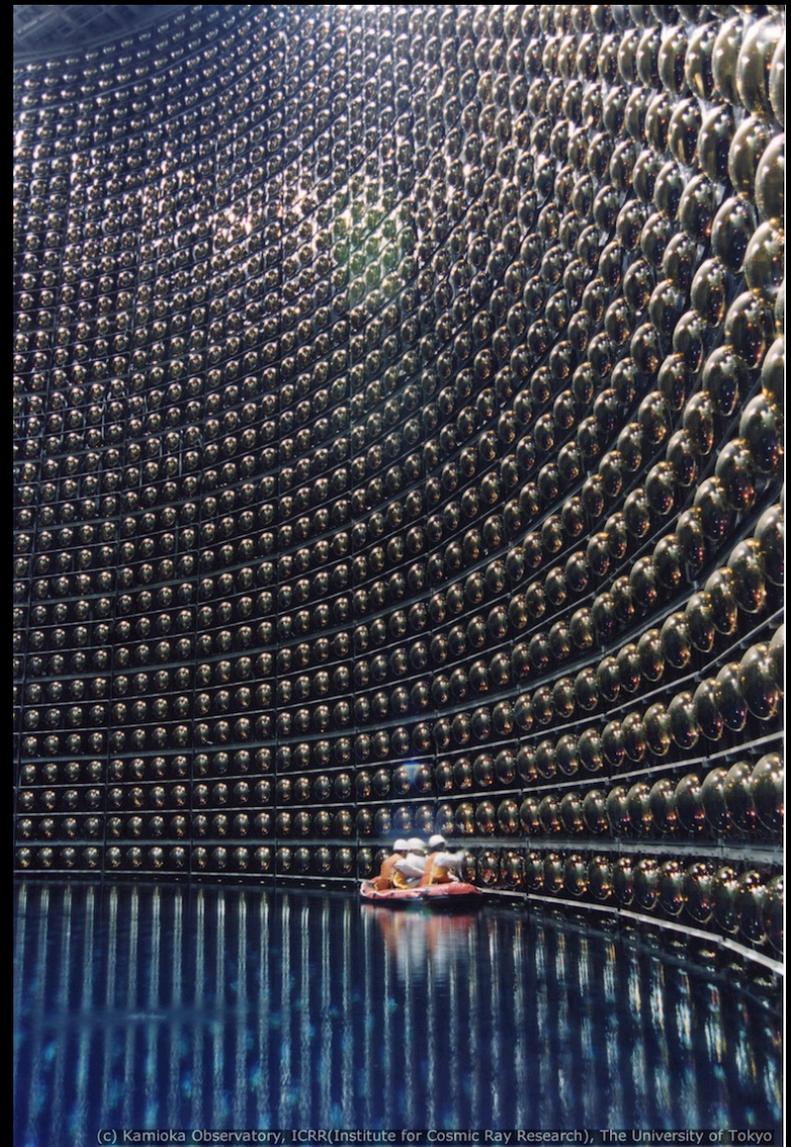
Free proton targets only

Cross section grows as  $\sigma \sim E_\nu^2$

Kinematics good,  $E_e \sim E_\nu$

Directionality isotropic

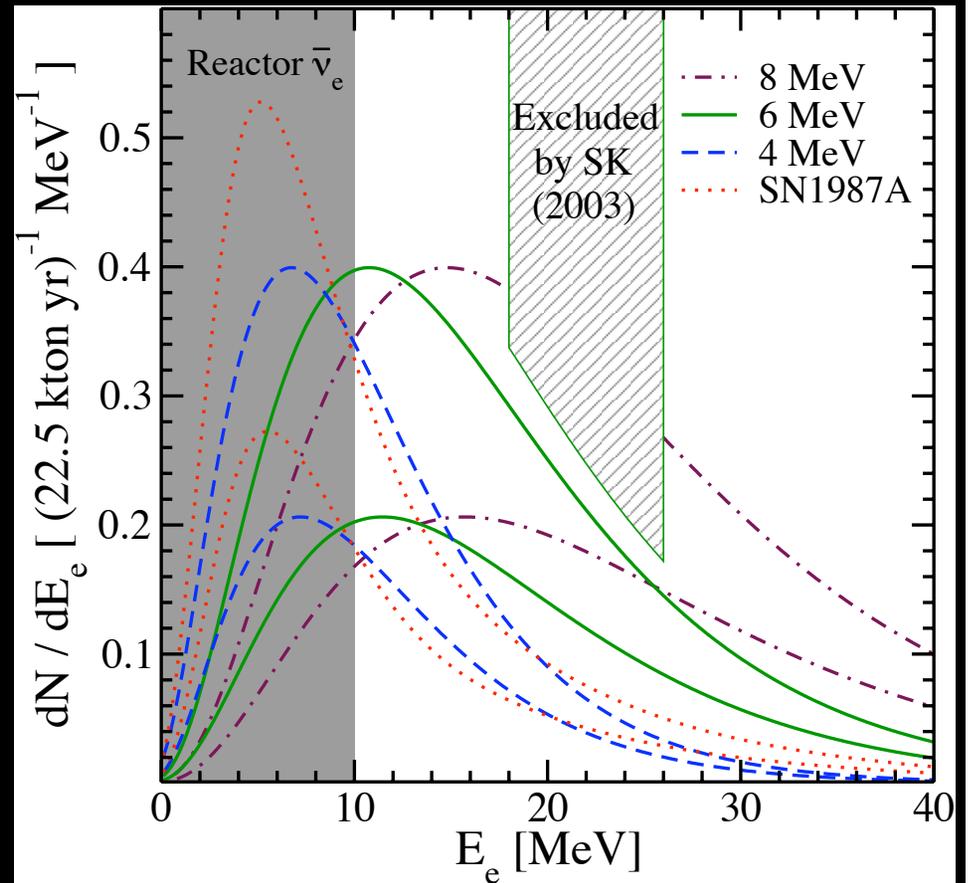
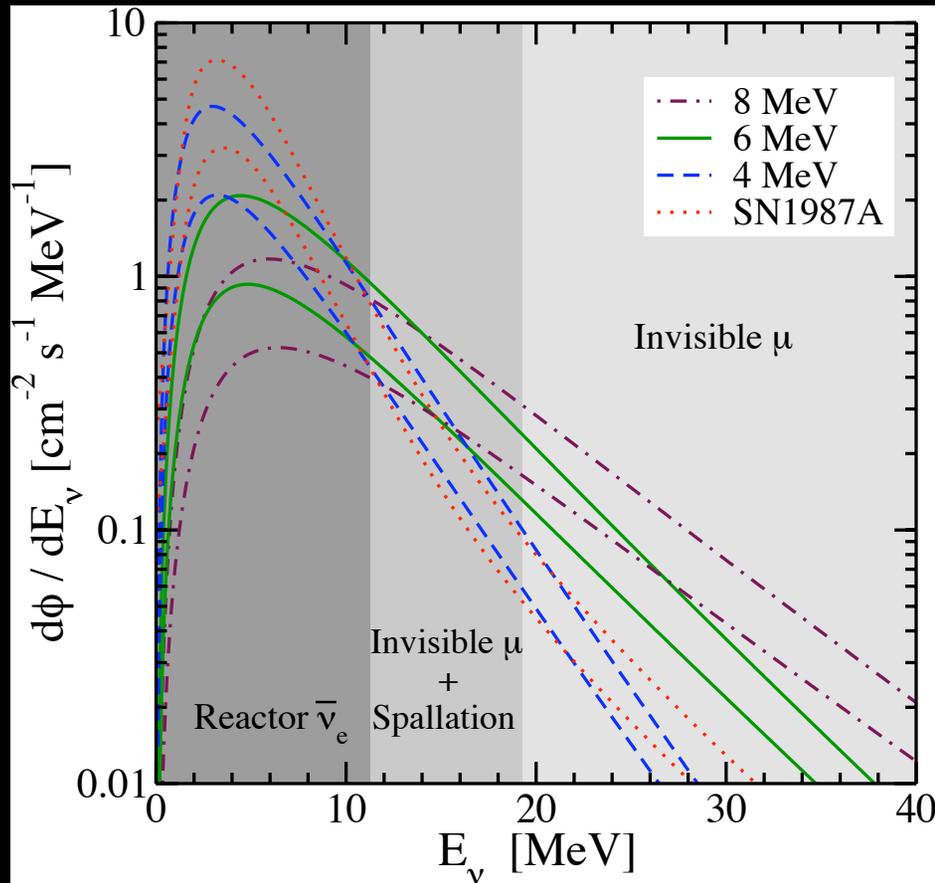
Vogel, Beacom (1999); Strumia, Vissani (2003)



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Super-Kamiokande

# Predicted Flux and Event Rate Spectra



Horiuchi, Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate

# Neutrino Emission with Black Hole Formation

When core collapse fails (no optical supernova), the neutrino emission can be *larger* in total and average energy

The collapse goes *farther* and *faster*, but must shed much thermal energy by neutrino emission

Sumiyoshi et al. (2007)

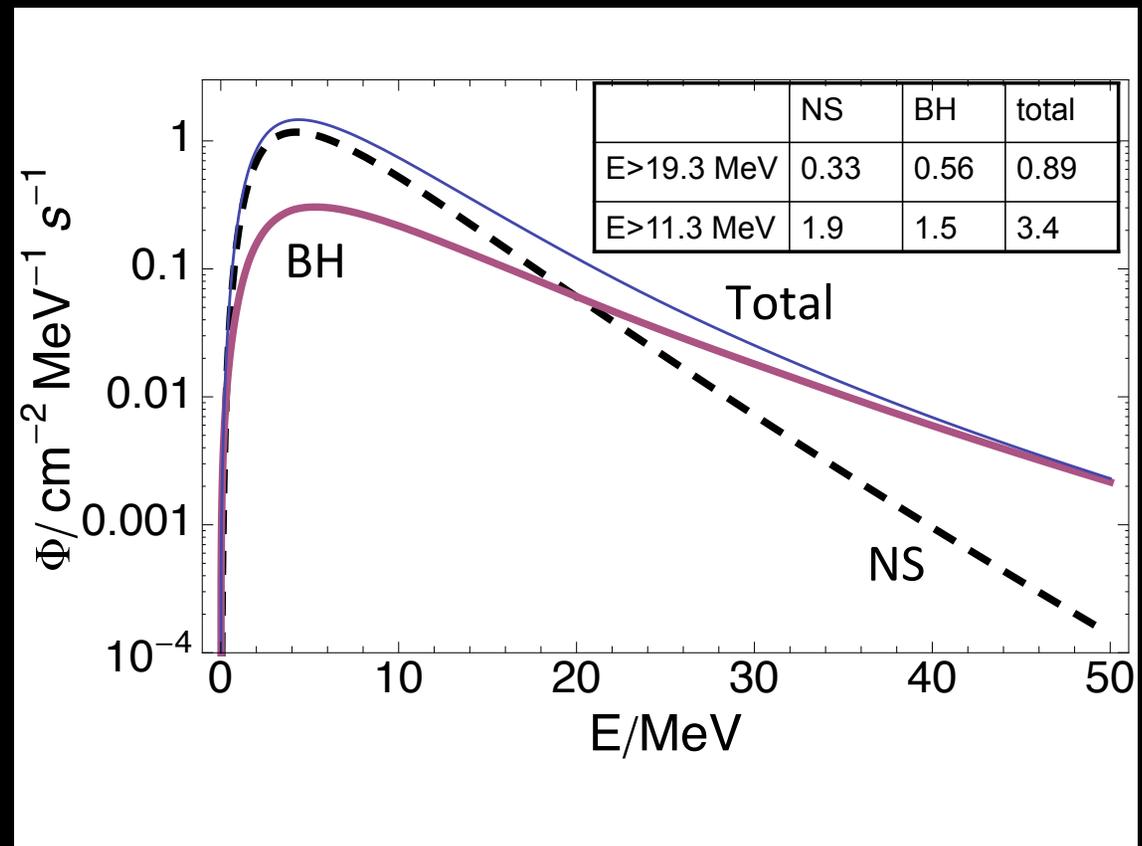
Nakazato et al. (2008)

Fischer et al. (2008)

O'Connor, Ott (2011)

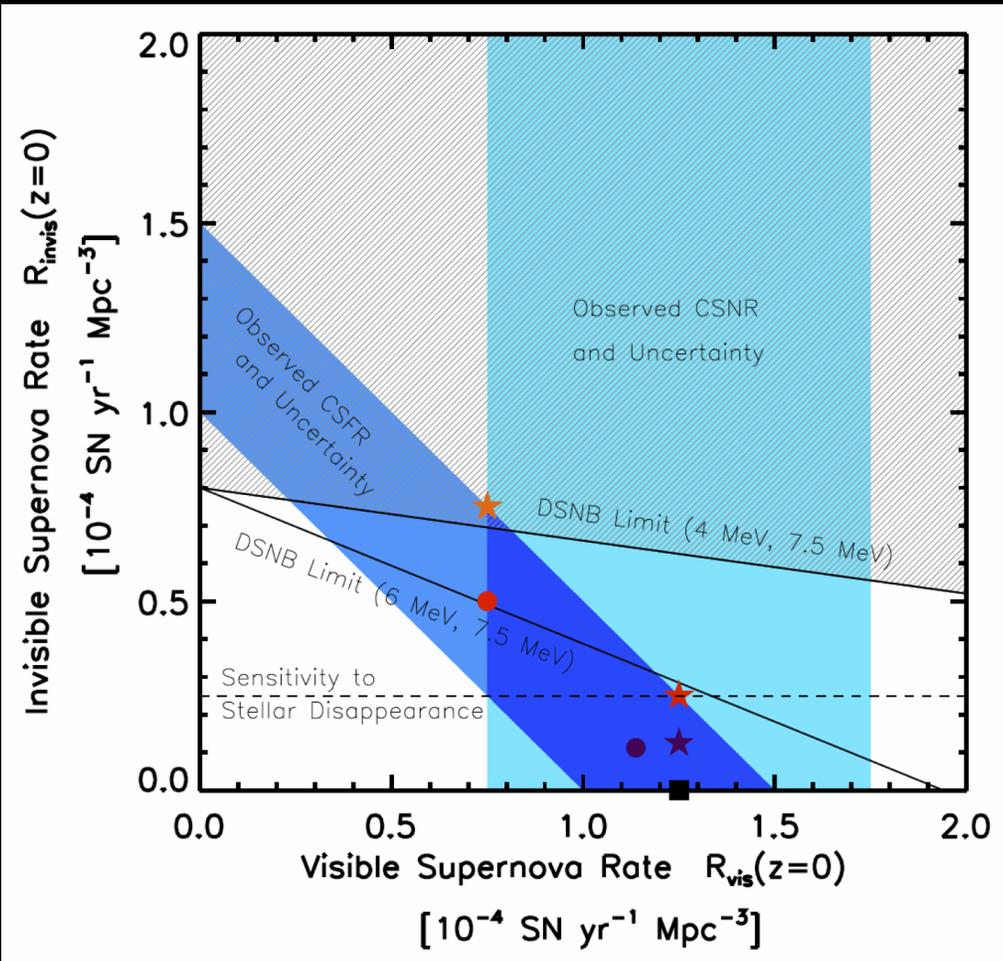
....

DSNB spectrum could be *more detectable*



Lunardini (2009)

# Limits on the Black Hole Formation Rate



Lien, Fields, Beacom (2010)

Low visible supernova rate would require large black hole fraction, up to  $\sim 50\%$

Standard models predict at least  $\sim 10\%$  black holes

This can be resolved

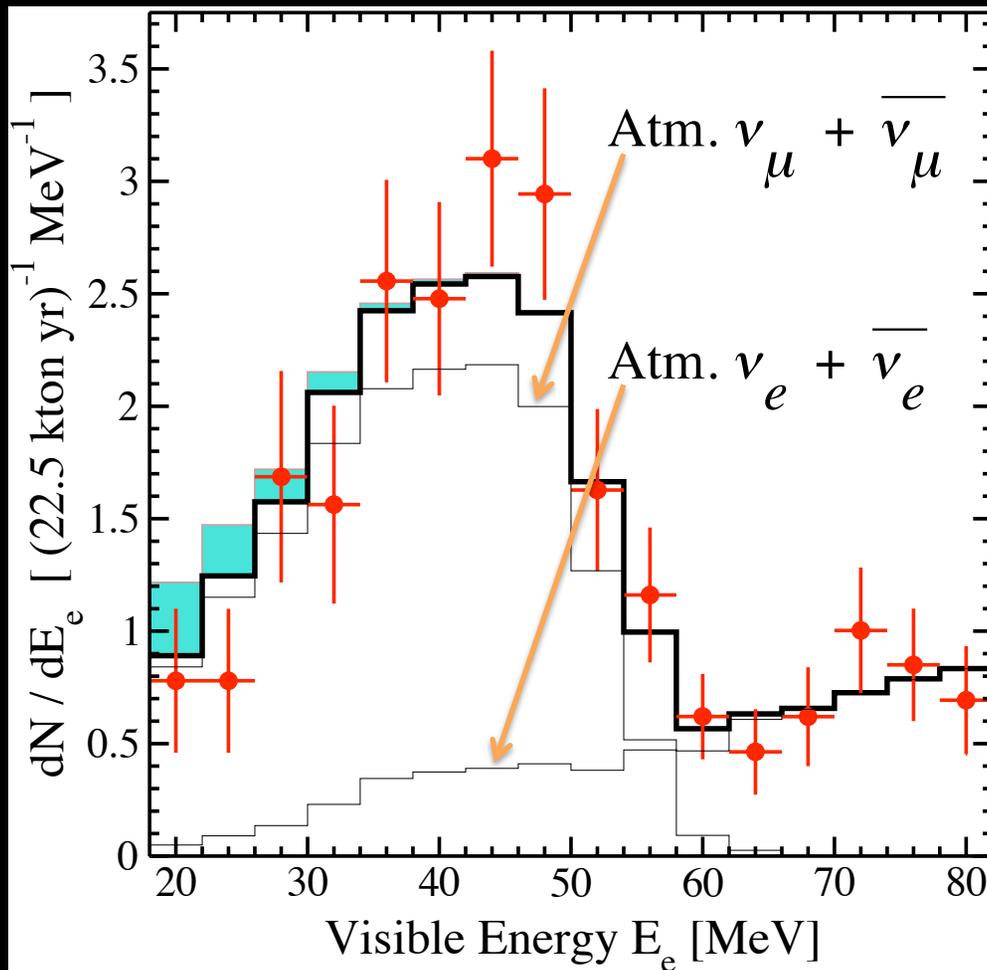
“Survey About Nothing” (Kochanek et al., 2008) can see massive stars disappear; ASAS-SN for nearby SN rate

Large DSNB a crucial test

# Present: Limits from Super-Kamiokande

See Bays et al. [Super-Kamiokande] (2012)

# Measured Spectrum Including Backgrounds



Malek et al. [Super-Kamiokande] (2003);  
energy units changed in Beacom (2011) – use with care

Amazing background rejection:  
nothing but neutrinos despite  
huge ambient backgrounds

Amazing sensitivity: factor  
~100 over Kamiokande-II limit  
and first in realistic DSNB range

No terrible surprises

**Challenges: *Decrease*  
backgrounds and energy  
threshold and *increase*  
efficiency and particle ID**

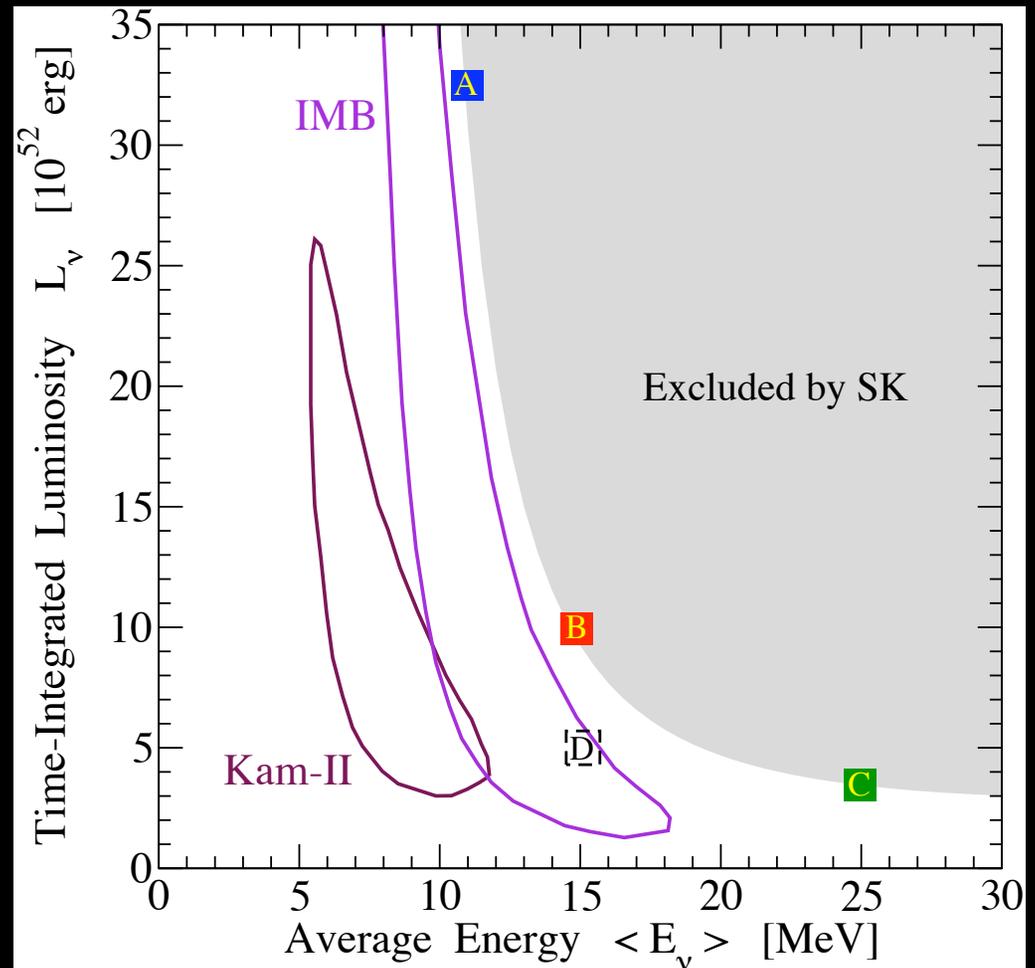
# Limits on Supernova Neutrino Emission

2003 Super-Kamiokande limit:  
 $\Phi < 1.2 \text{ cm}^{-2} \text{ s}^{-1}$  (90% CL)  
for nuebar with  $E_\nu > 19.3 \text{ MeV}$

Supernova rate uncertainty is now subdominant; this limits the effective nuebar spectrum that includes mixing effects

Within range of expectations from theory and SN 1987A!

Also limits from KamLAND (lower energy) and SNO (nue)



Yuksel, Ando, Beacom (2006);  
SN 1987A fits from Jegerlehner, Neubig, Raffelt (1996)

# *New Analysis of Super-Kamiokande Data*

**2003:** factor  $\sim 100$  improvement  
over Kamiokande-II limit

**2012:** all details down to  $\sim 10\%$

More data

Full reanalysis

Three detector periods

Backgrounds in more detail

New backgrounds included

Lowered energy threshold

Improved efficiency

Detailed systematics

Better treatment of statistics

Improved cross section

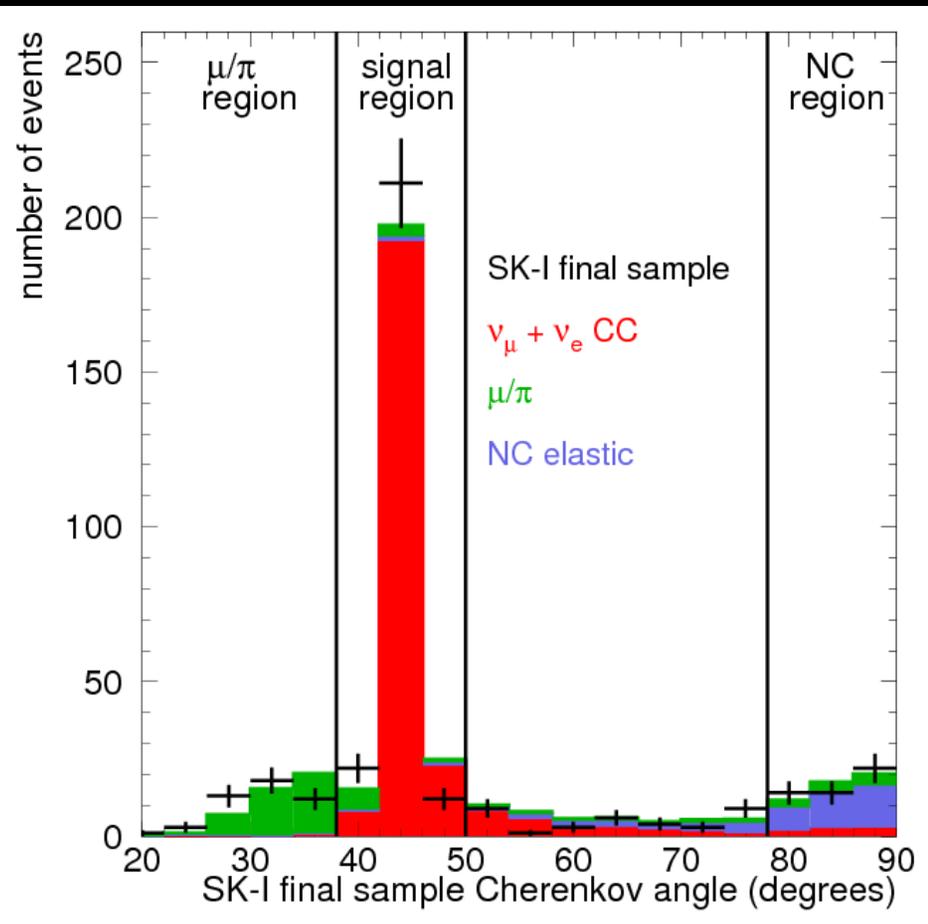
Conservative choices

....

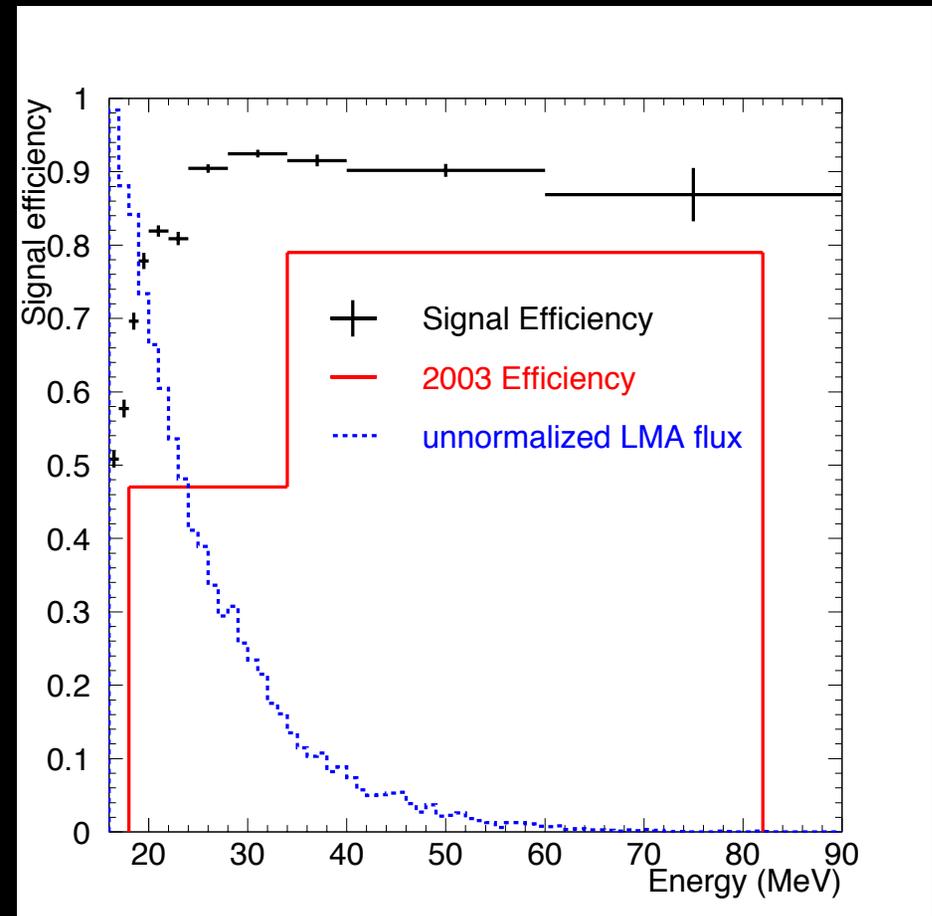
**Who got the better Ph.D. thesis project?**

# Examples of the New Work on Details

Background separation by topology:

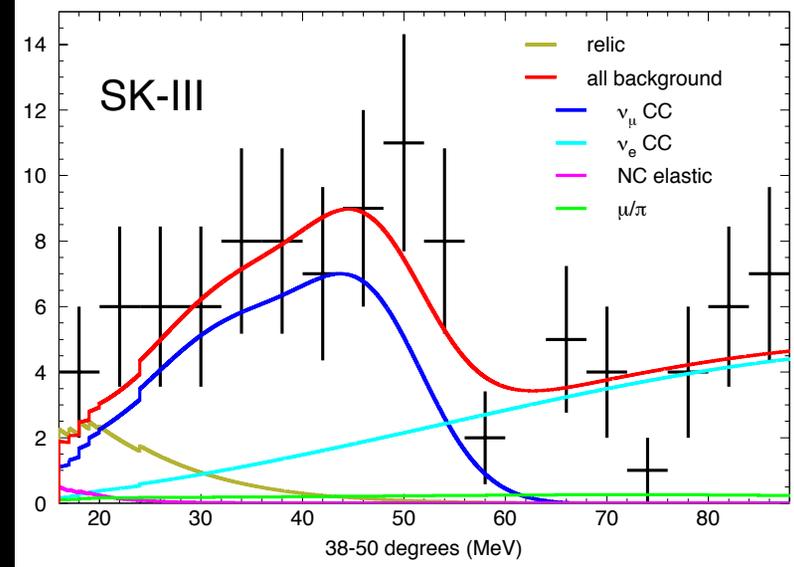
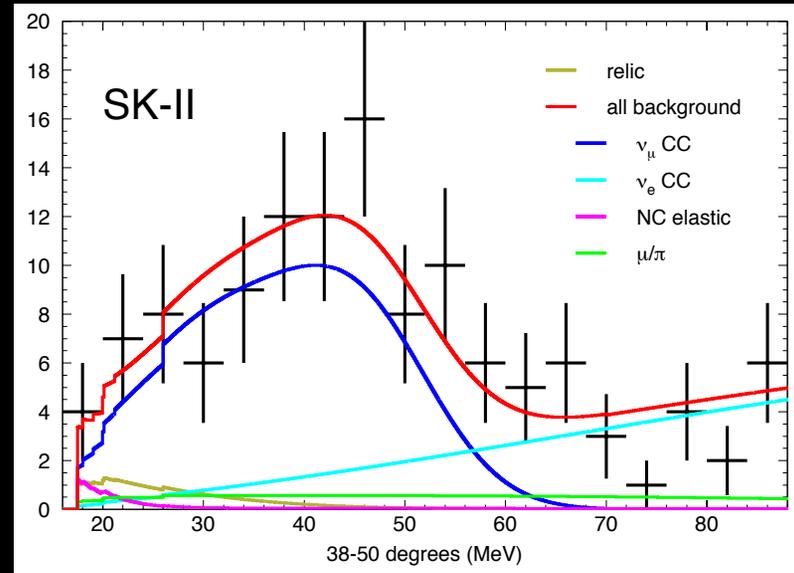
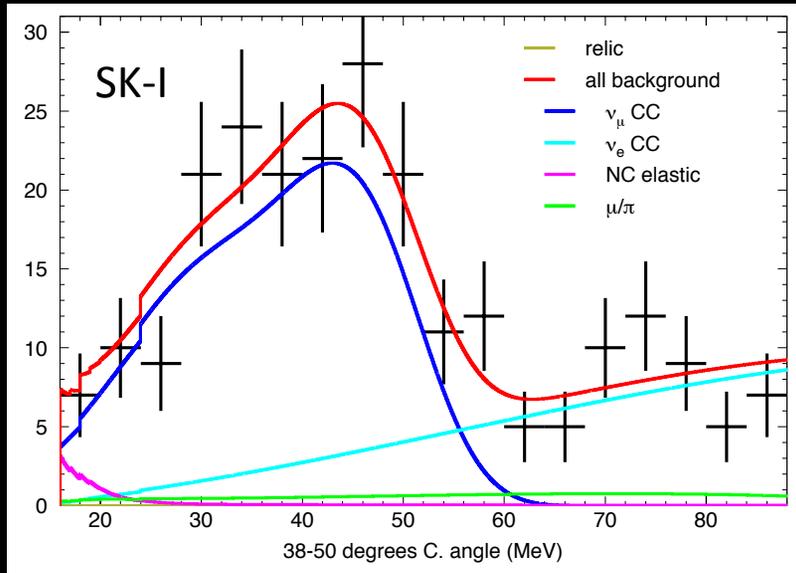


Improvement in SK-I Efficiency:



Bays et al. [Super-Kamiokande] (2012)

# Energy Spectrum Fits



SK-I:

Best fit is *slightly negative* DSNB

SK-II and SK-III:

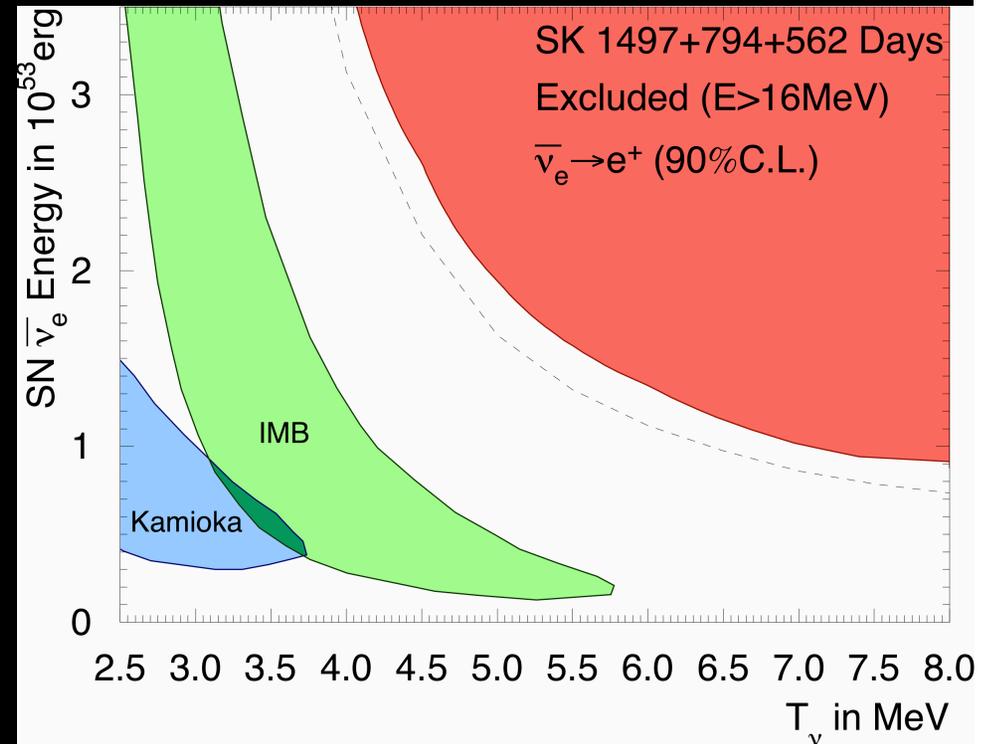
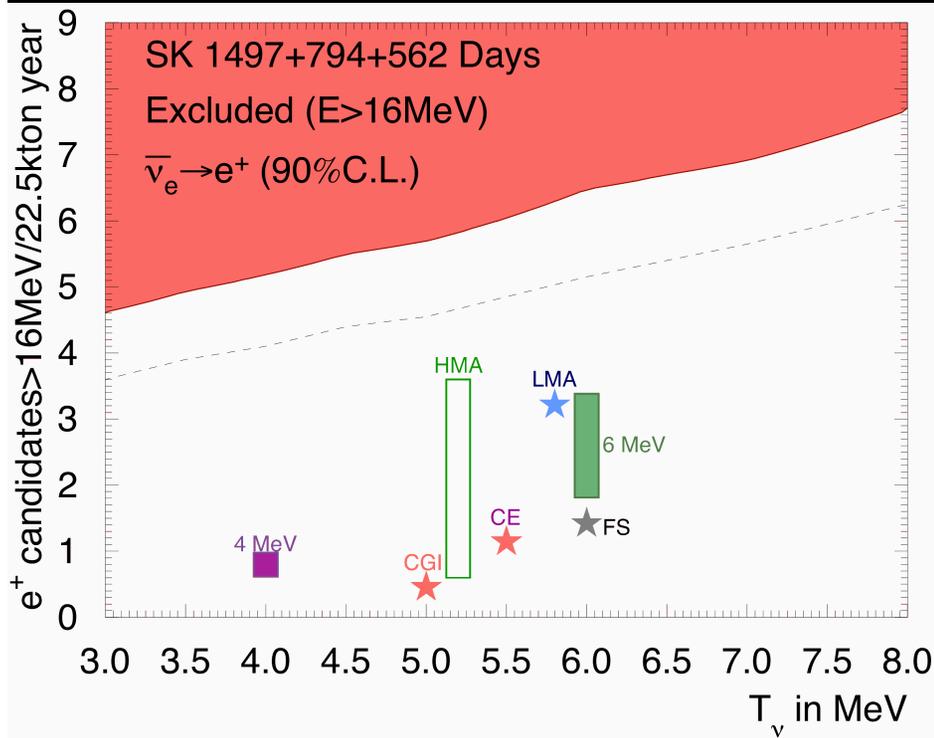
Best fit is *slightly positive* DSNB

Bays et al. [Super-Kamiokande] (2012)

# New Super-Kamiokande Limits

Much improved analysis and more data

To be *conservative*, new limits are a factor  $\sim 2$  worse than before



Bays et al. [Super-Kamiokande] (2012)

**Must further decrease detector backgrounds and energy threshold**

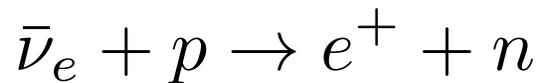
Emerging: Gadolinium in Super-Kamiokande?

See talks by Mark Vagins at HAvSE 2011 and LowNu 2011

# GADZOOKS! Proposal

The signal reaction produces a neutron, but most backgrounds do not

Beacom and Vagins (2004): First proposal to use dissolved gadolinium in large light water detectors showing it could be practical and effective



SK

Neutron capture on protons  
Gamma-ray energy 2.2 MeV  
Hard to detect in SK

SK+Gd

Neutron capture on gadolinium  
Gamma-ray energy  $\sim 8$  MeV  
Easily detectable coincidence  
separated by  $\sim 4$  cm and  $\sim 20$   $\mu$ s

New general tool for particle ID  
Rich new physics program

# Benefits of Neutron Tagging for DSNB

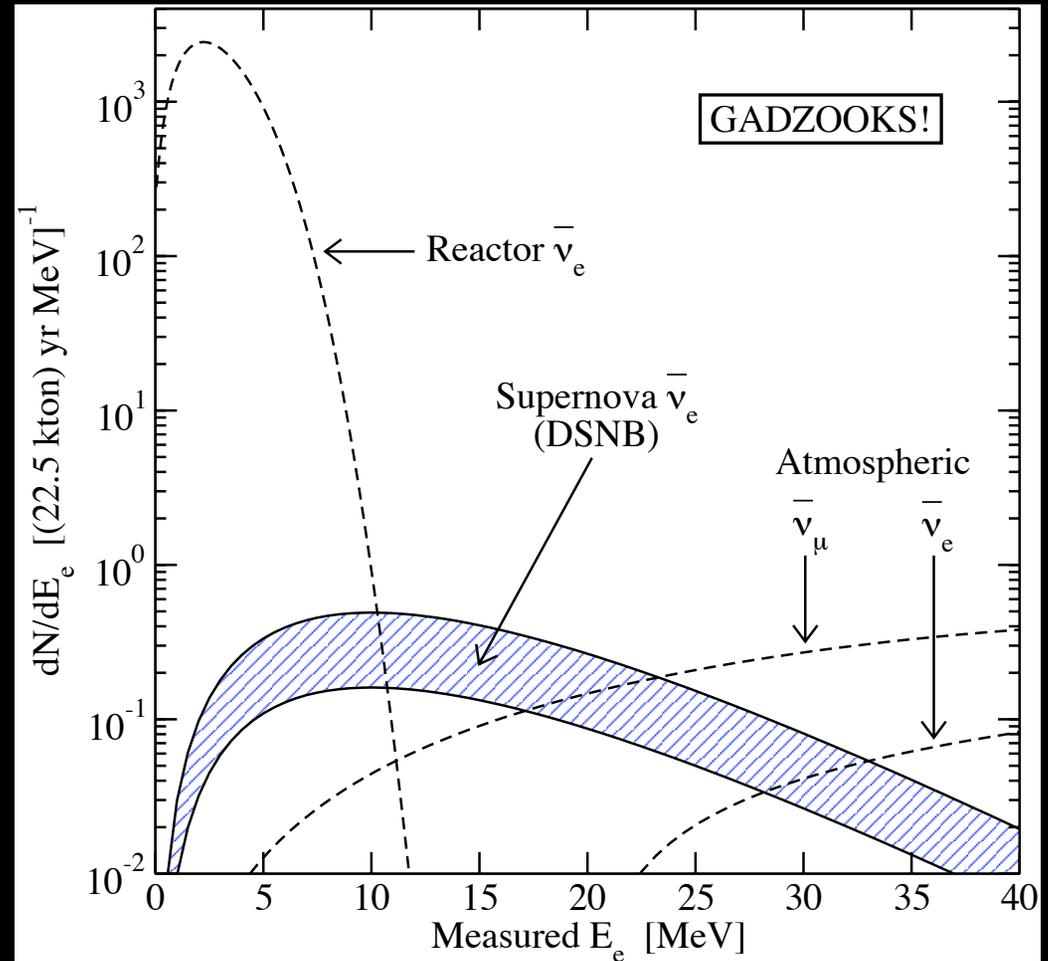
**Solar neutrinos:**  
eliminated

**Spallation daughter decays:**  
essentially eliminated

**Reactor neutrinos:**  
now a visible signal

**Atmospheric neutrinos:**  
significantly reduced

**DSNB:**  
*More signal, less background!*

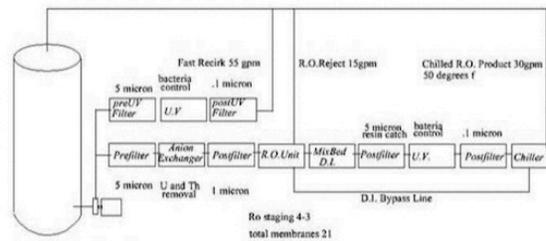


Beacom, Vagins (2004)

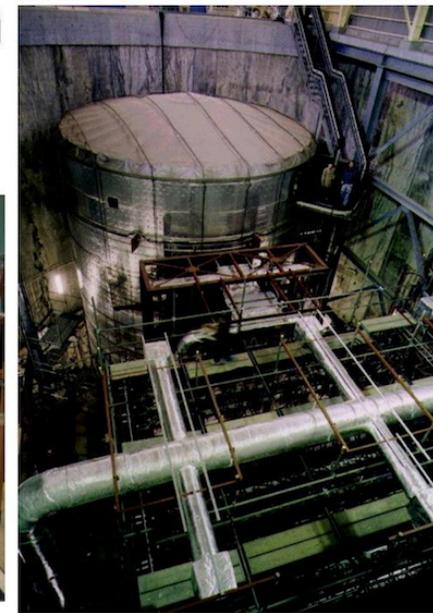
**(DSNB predictions now at upper edge of band)**

# Research and Development Efforts

Over the last seven years there have been a large number of Gd-related R&D studies carried out in the US and Japan:



Detector Tank and Pump 100 gpm  
250,000 gallons High Purity Water and GdCl3

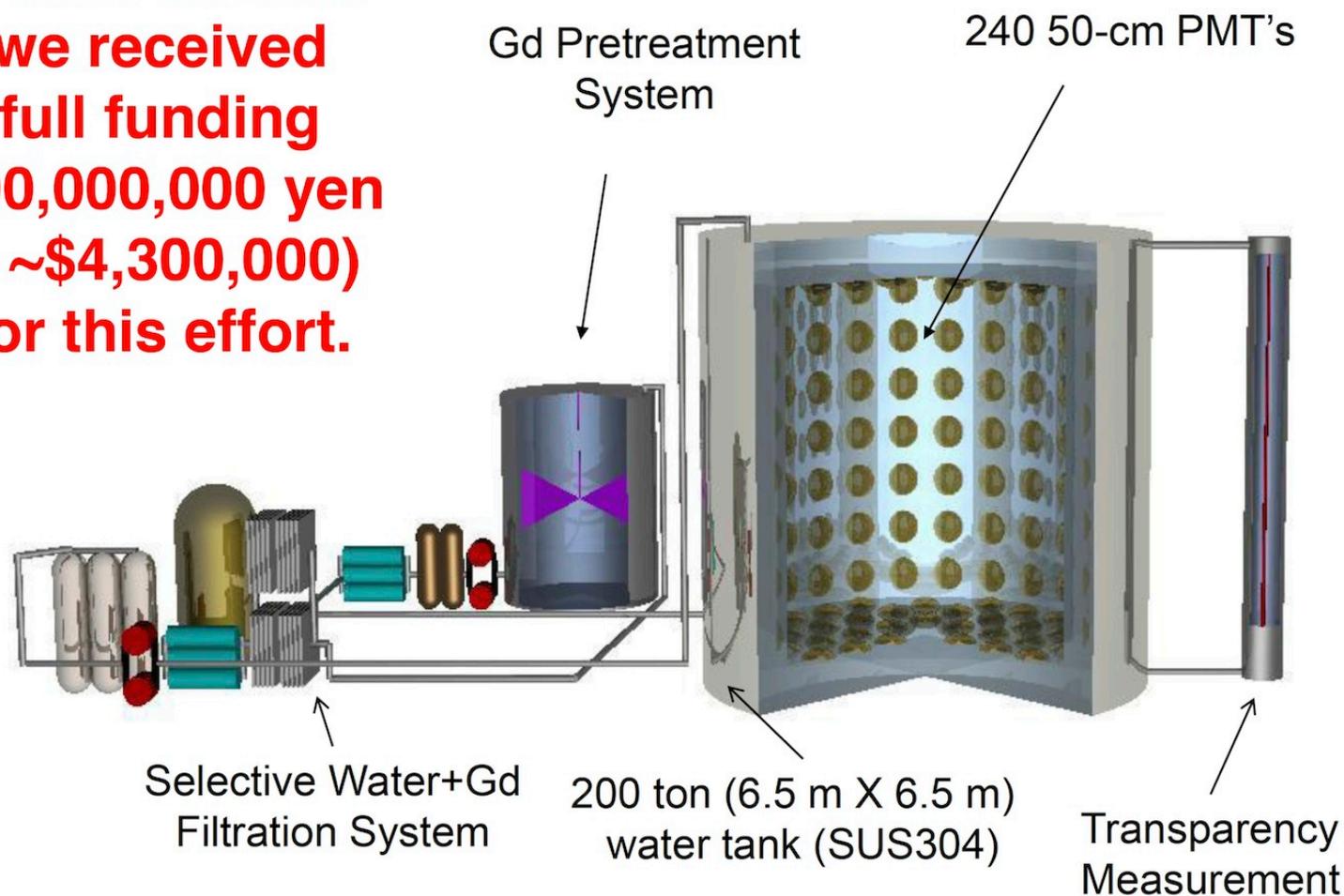


# EGADS Proposal

## EGADS Facility

Masayuki Nakahata, Mark Vagins, others

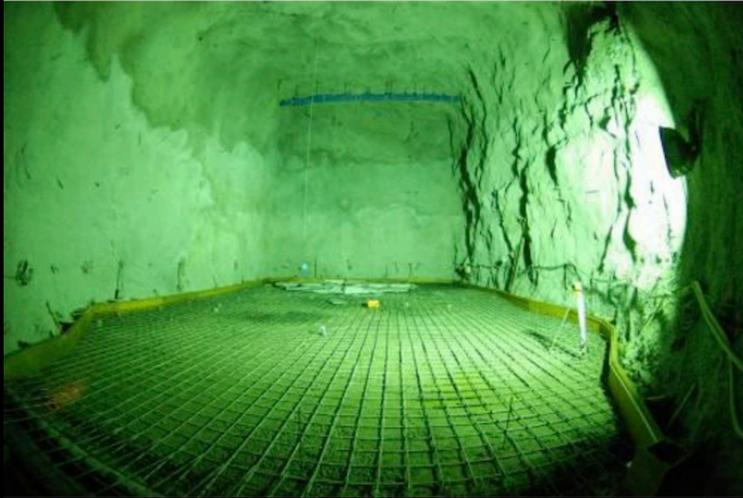
**In June of 2009  
we received  
full funding  
(390,000,000 yen  
= ~\$4,300,000)  
for this effort.**



# EGADS Detector

## Hall E and EGADS

12/2009



2/2010



6/2010



12/2010

# *Mad Scientist at Work in Underground Lair*

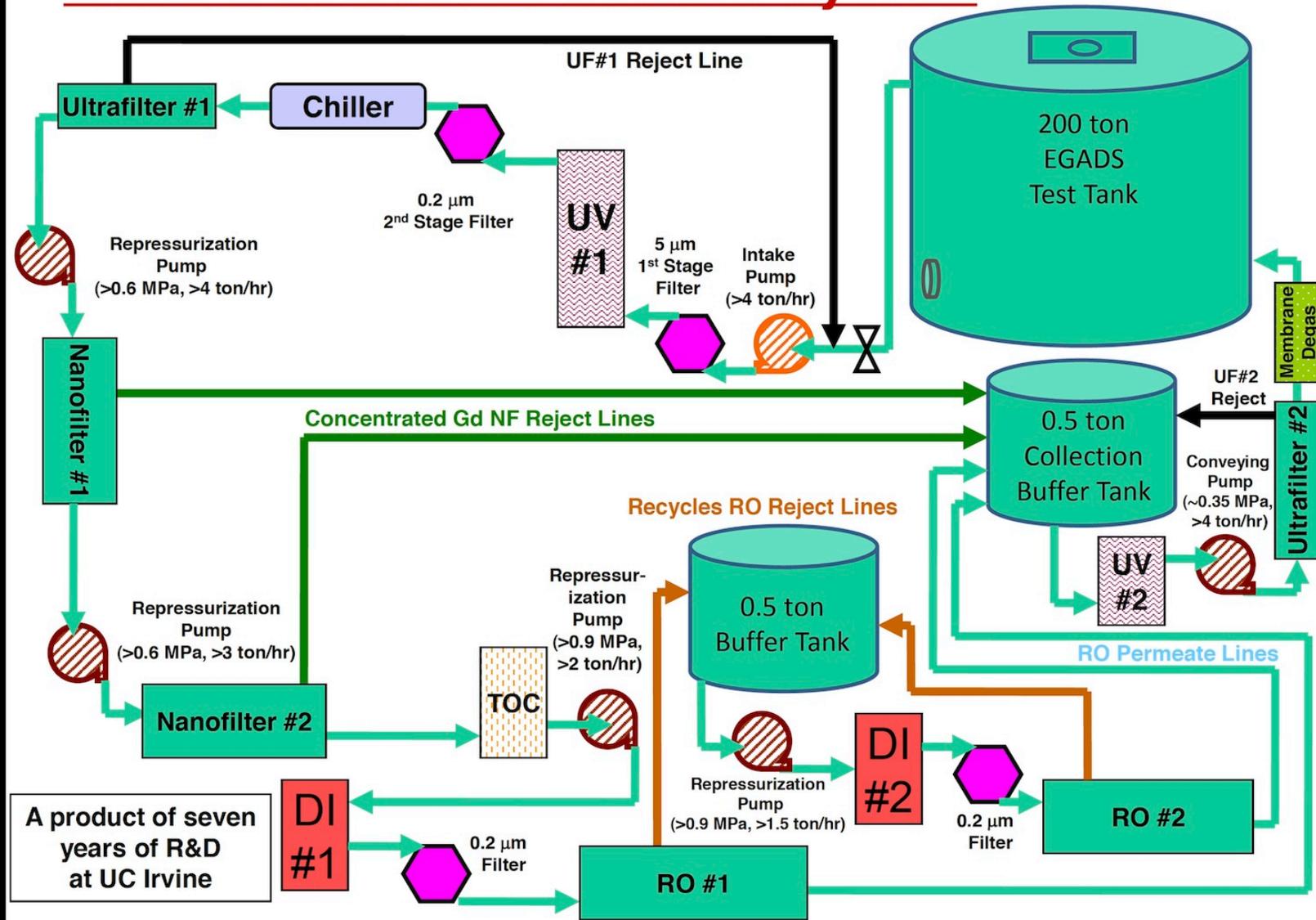


Adding 383 grams  $\text{Gd}_2(\text{SO}_4)_3$  to 191 liters of  $\text{H}_2\text{O}$ ; January 5<sup>th</sup>, 2011

# Water and Gadolinium Filtration System

## EGADS Selective Filtration System

June 2011



# *Recent News from Vagins*

## **Filtration System – Pure Water:**

Transparency of filtered pure water in EGADS equivalent to SK

## **Gadolinium Water Small-Batch Brew System:**

Gadolinium dissolved with no problems in 15-ton holding tank

## **Gadolinium Removal System:**

Demonstrated factor  $10^6$  removal of gadolinium in a single pass

## **Filtration System – Gadolinium Water:**

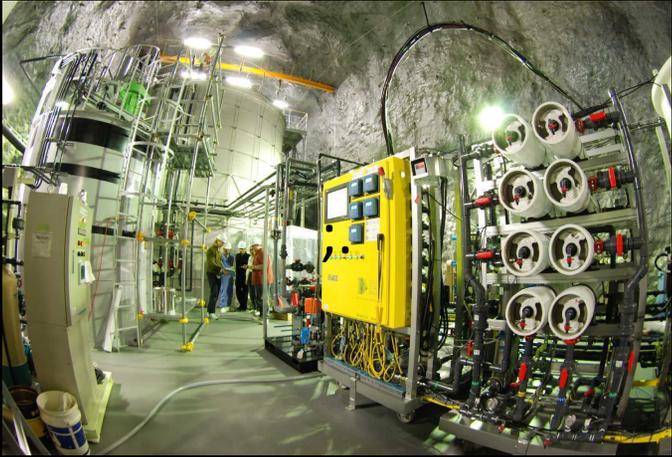
Gadolinium water circulation already has **99.97%** efficient return

## **Gadolinium Water Transparency:**

Transparency for filtered gadolinium water is already very high

**Now testing EGADS with gadolinium-loaded water**

# Possible Future for Water + Gd Detectors

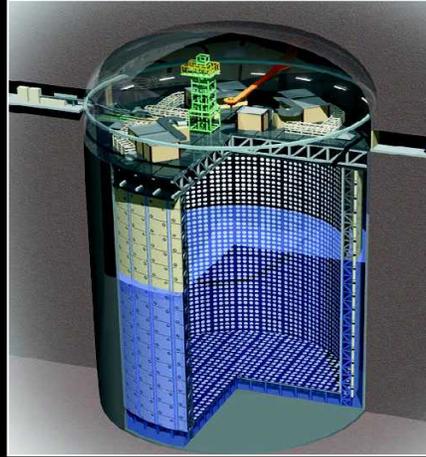


## EGADS:

0.2 kton total

Almost completed

Gd addition soon

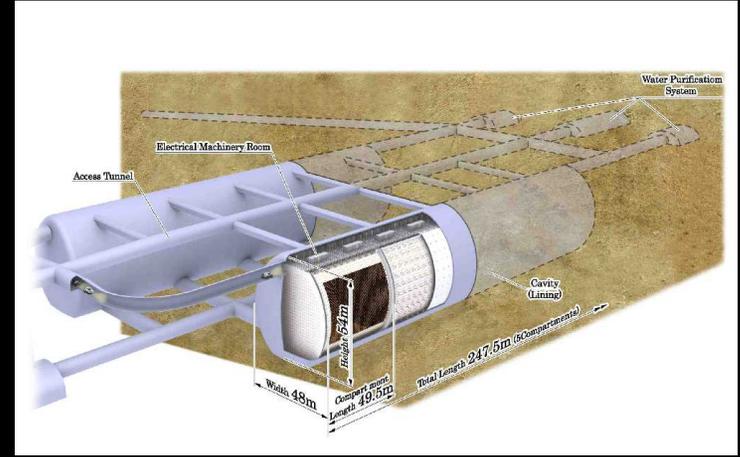


## Super-K:

22.5 kton fiducial

Working well

Gd decision soon



## Hyper-K:

560 kton fiducial

LOI submitted

Gd discussed

**Dramatically increased reach for many physics topics with Gd**

# Concluding Perspectives

# *Prospects for First Detection of the DSNB*

## **Guaranteed signal:**

SK has a few DSNB nuebar signal interactions per year  
Astrophysical uncertainties are small and shrinking quickly

## **Super-Kamiokande upgrade:**

Possibility of adding gadolinium is seriously considered  
Research and development work very promising so far

## **Supernova implications:**

New measurement of cosmic core-collapse rate (and more?)  
Direct test of the average neutrino emission per supernova

## **Broader context:**

Possible first detections besides Sun and SN 1987A  
Non-observation of a signal would require a big surprise

# Summary of Three Detection Modes

## Milky Way

Mostly ready

Lifetime events

Only way to measure precise details, time structure, all flavors, etc.

## Nearby Galaxies

Need new detectors

Annual events

Only way to check neutrino presence, burst variation, isolate dark bursts, etc.

## DSNB

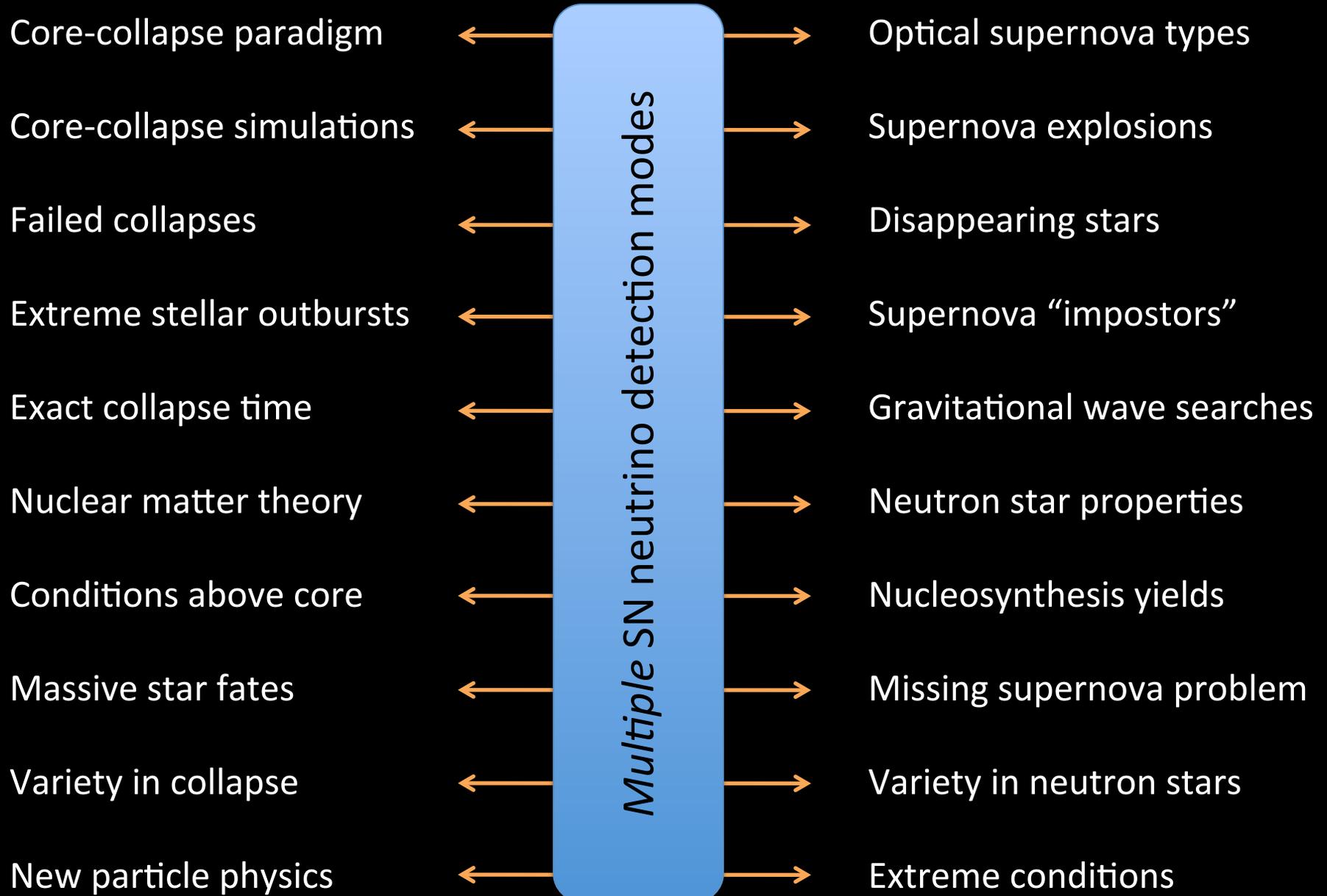
Need an upgrade

Steady detections

Only way to measure average emission, cosmic emissivity, new sources, etc.

**We cannot solve key problems without detecting supernova neutrinos**

# Broader Vision for Core-Collapse Science



# Center for Cosmology and AstroParticle Physics

The Ohio State University's Center for Cosmology and AstroParticle Physics



New faculty hires Linda Carpenter, Chris Hirata, and Annika Peter

Postdoctoral Fellowship applications welcomed in Fall

[ccapp.osu.edu](http://ccapp.osu.edu)

Some (rough) statistics that may surprise

**Columbus, Ohio:** 0.8 million people (city), 1.8 million people (metro)

**Ohio State University:** 56,000 students on Columbus campus

**Physics:** 55 faculty, **Astronomy:** 20 faculty

**CCAPP:** 20 faculty, 10 postdocs from both departments