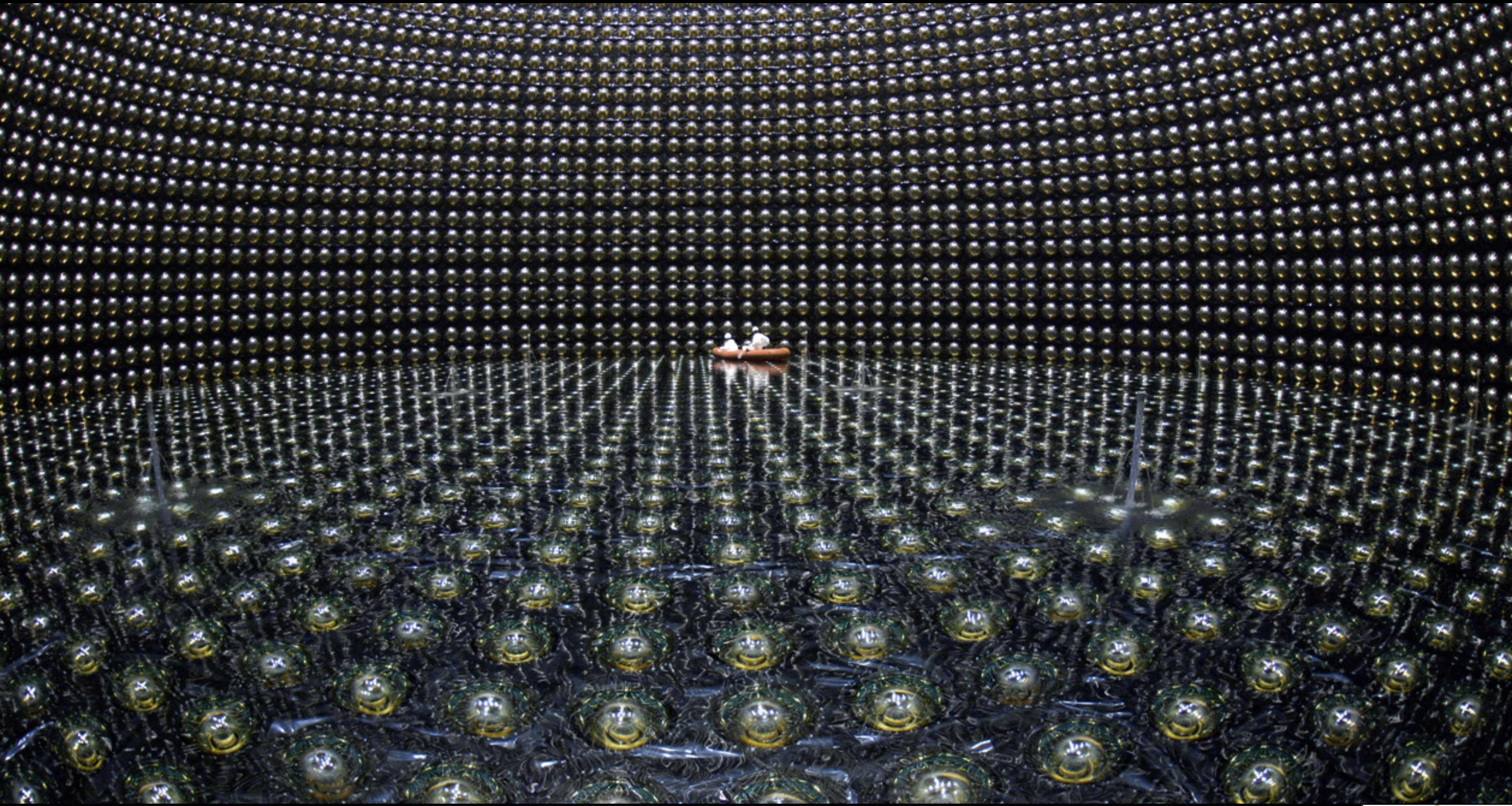
Supernova Neutrinos

John Beacom, Ohio State University



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

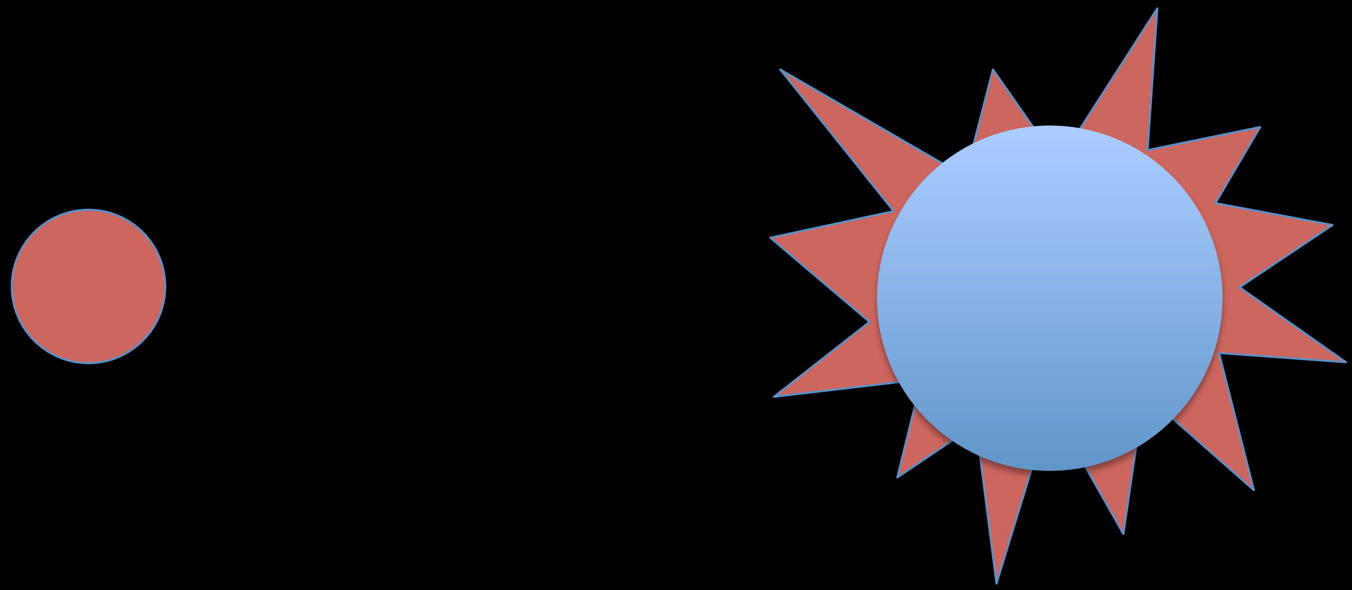
CCAPP

NSF

Why are Supernovae Special Stars?

Stars
Slow release of energy
Gravity > Pressure: *contraction*

Supernovae
Fast release of energy
Pressure >> Gravity: *explosion*



Can only reveal the interior conditions of collapsing stars with neutrinos

Why are Neutrinos Special Particles?

Charged leptons

$\tau^{\pm}$

$\mu^{\pm}$

$e^{\pm}$

decay ↓

Neutral leptons

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

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

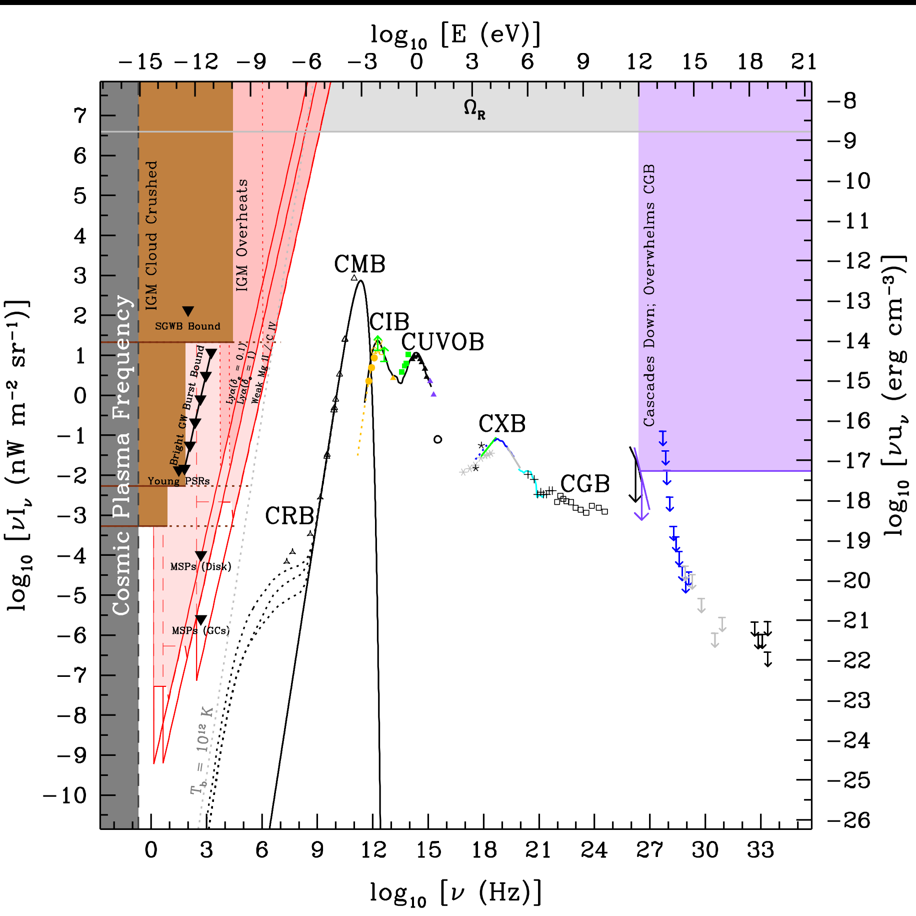
$\nu_e, \bar{\nu}_e$

mixing ↕

Can only probe all neutrino properties with extremes of astrophysics

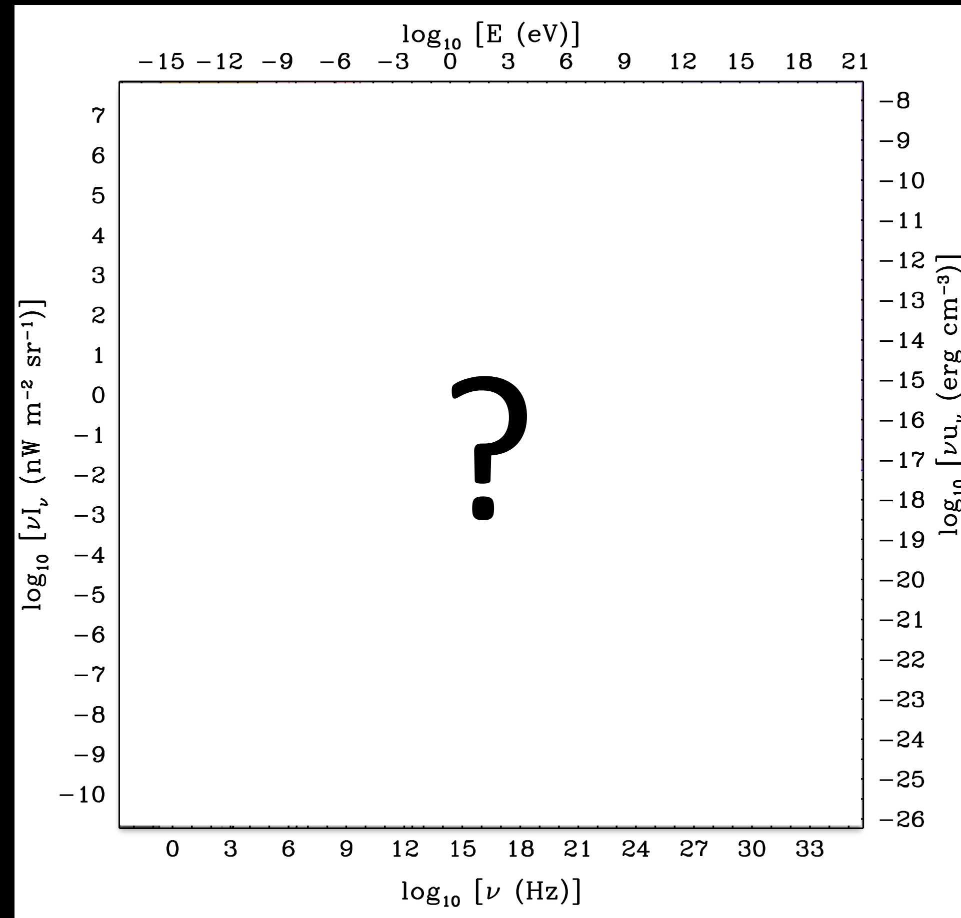
Why are Cosmic Backgrounds Special Data?

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

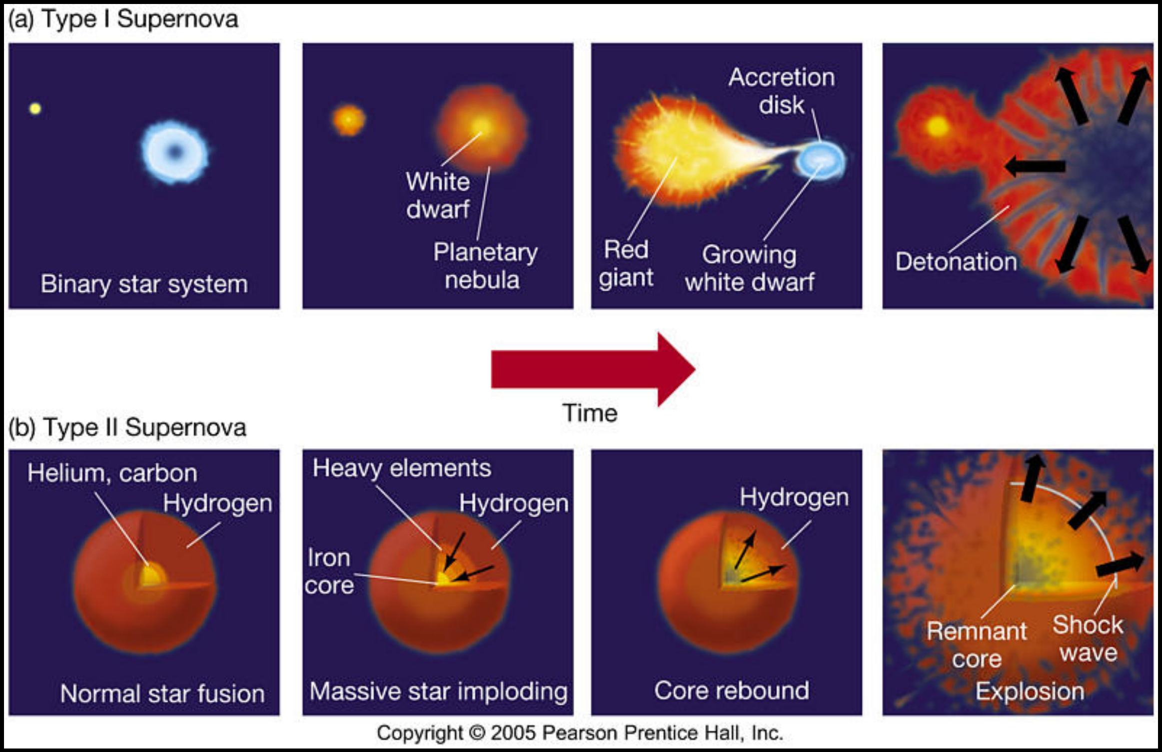
(DSNB = Diffuse Supernova Neutrino Background)

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

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

approximately shared among all six flavors

Neutrinos are trapped by scattering interactions and diffuse out

quasi-thermal with <E> ~ 15 MeV

τ ~ 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?

....

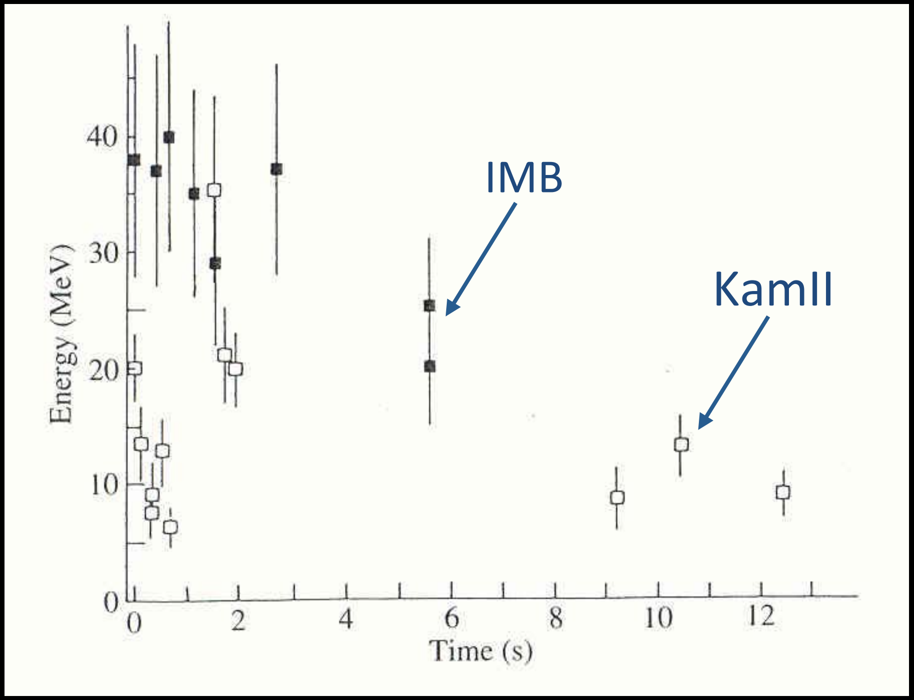
We cannot solve key problems without detecting supernova neutrinos

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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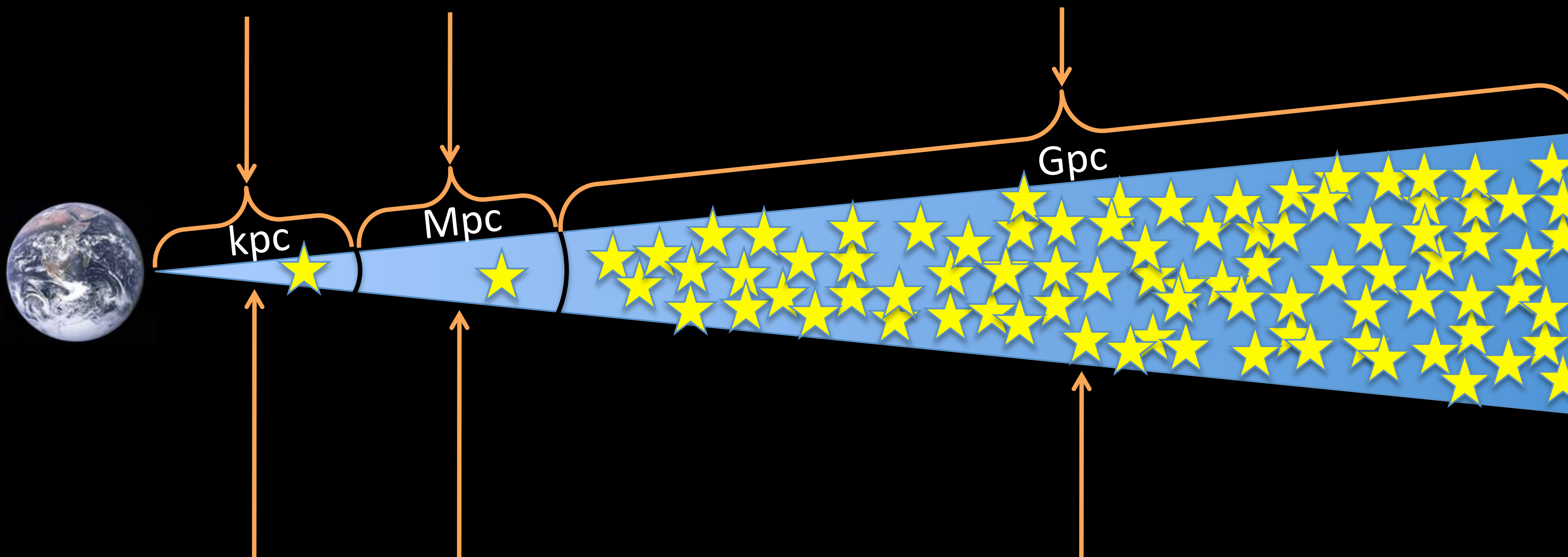
Introduction: Three Detection Modes

Distance Scales and Detection Strategies

N >> 1 : Burst   N ~ 1 : Mini-Burst   N << 1 : DSNB



Rate ~ 0.01/yr   Rate ~ 1/yr   Rate ~ 10^8/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

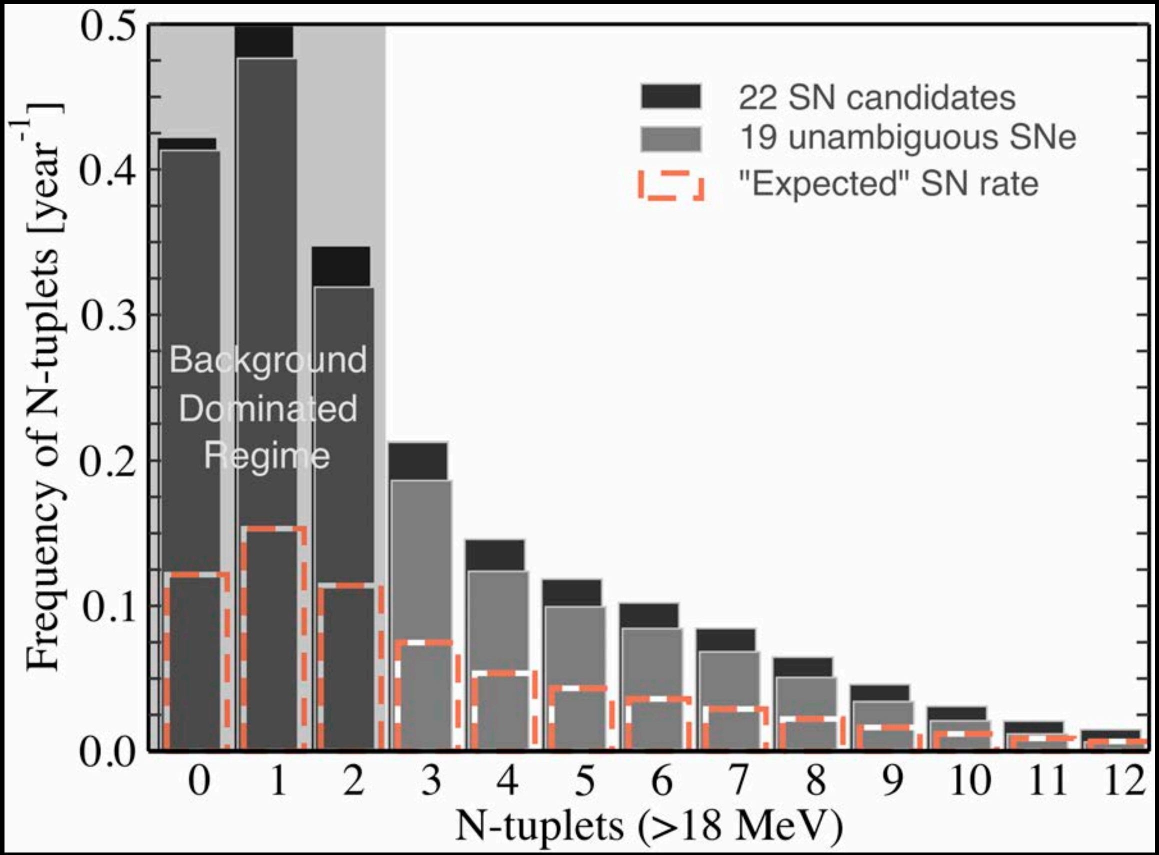
Much larger or better detectors are being proposed now

Simple Estimate: Extragalactic Mini-Burst Yields

Yield in Super-Kamiokande ~ 1 (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

~ 1 s^{-1}

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

For the DSNB relative to SN 1987A:

N_{SN} up by ~ 100 M_{det} up by ~ 10 $1/D^2$ down by ~ 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

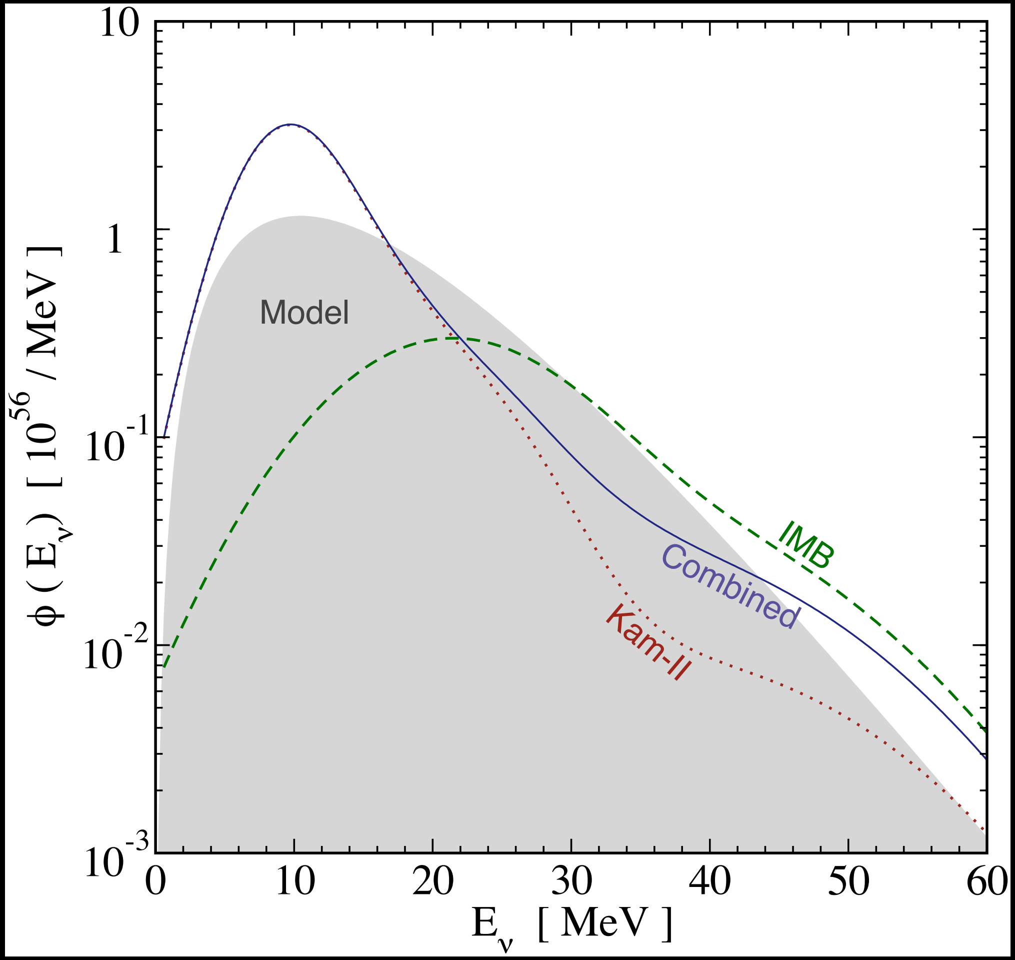
Core collapse releases ~ 3x10^{53} erg, shared by six flavors of neutrinos

Spectra quasi-thermal with average energies of ~ 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

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

Measured from N/τ using luminosity and spectrum of galaxies

(now high precision)

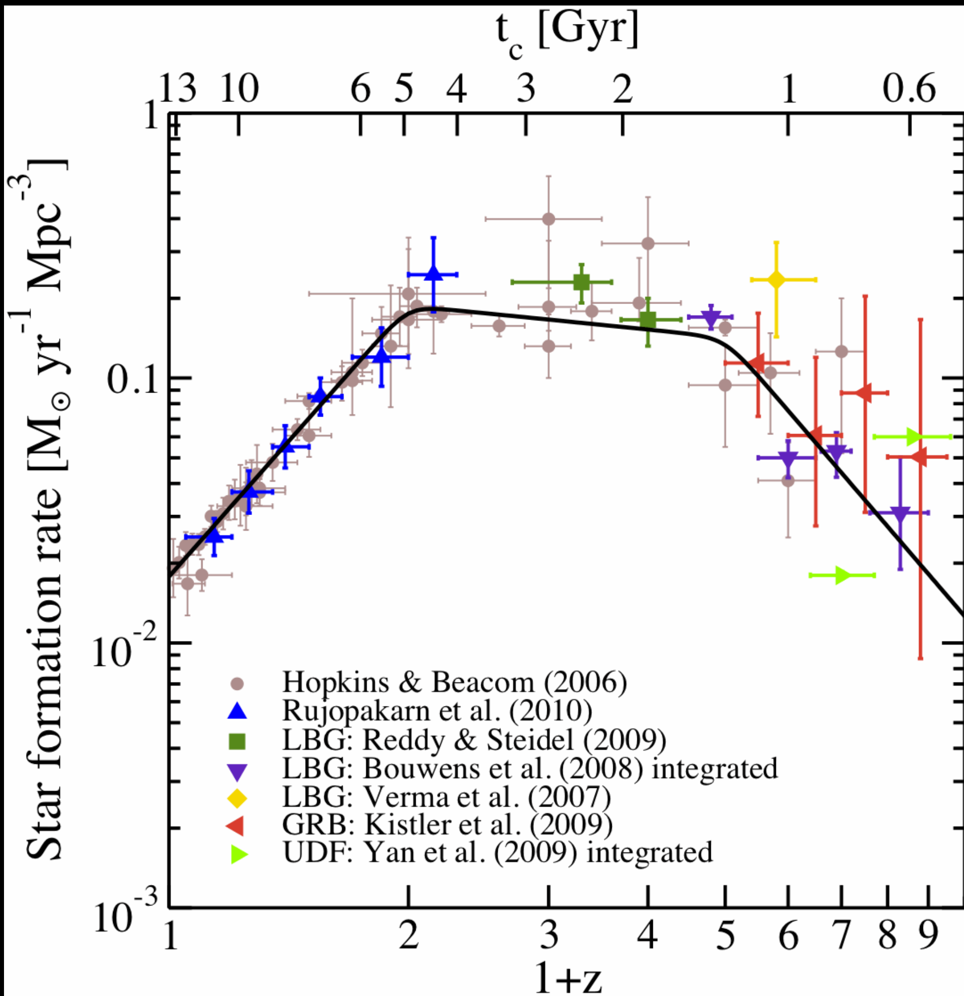
Measured from the core collapse supernova rate

(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)

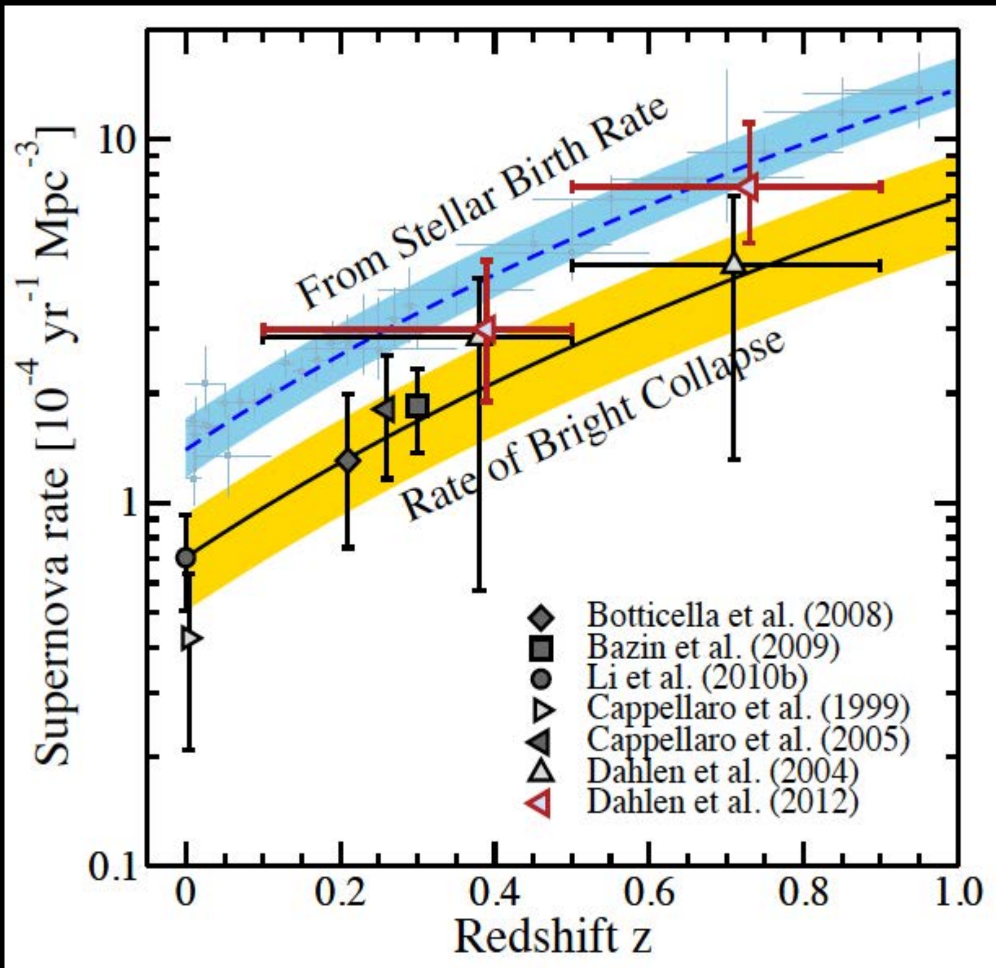
Impressive agreement among results from different groups, techniques, and wavelengths

Integral of R_{SF} agrees with EBL

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

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)

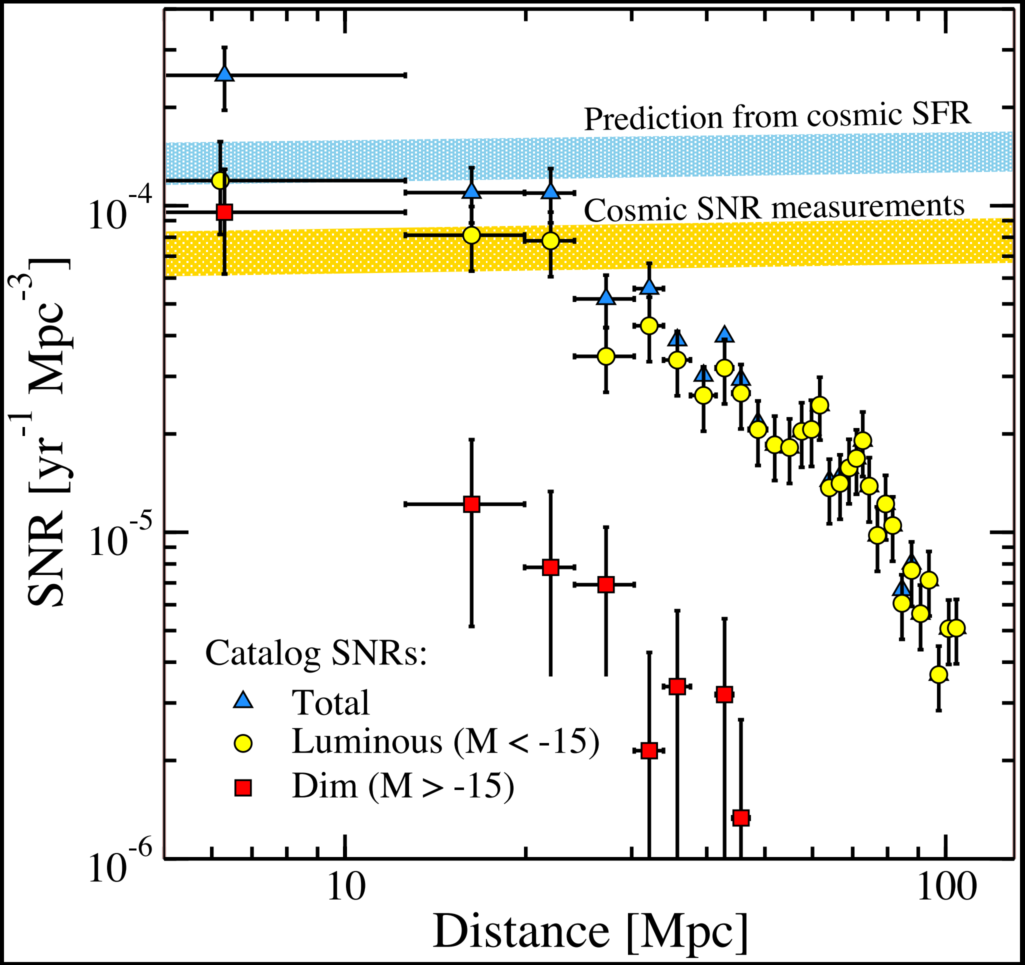
Some measured cosmic supernova rates are half as big as expected, a greater deviation than allowed by uncertainties

Why?

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

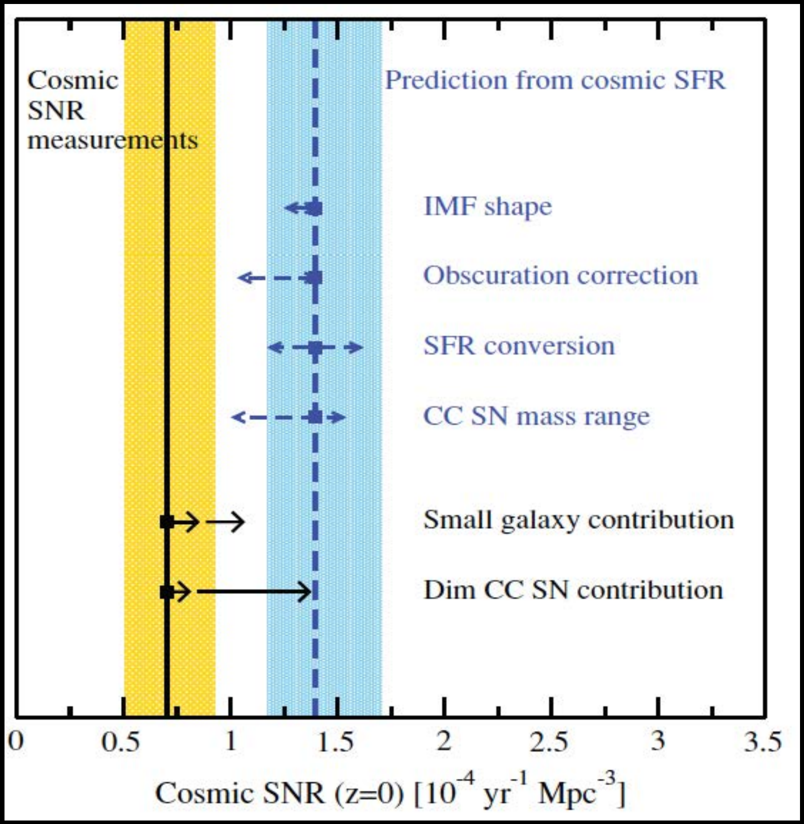
What About the Supernova Rate Nearby?

Within ~ 10 Mpc, *more* supernovae than expected are found



Horiuchi et al. (2011)

Lots of faint supernovae



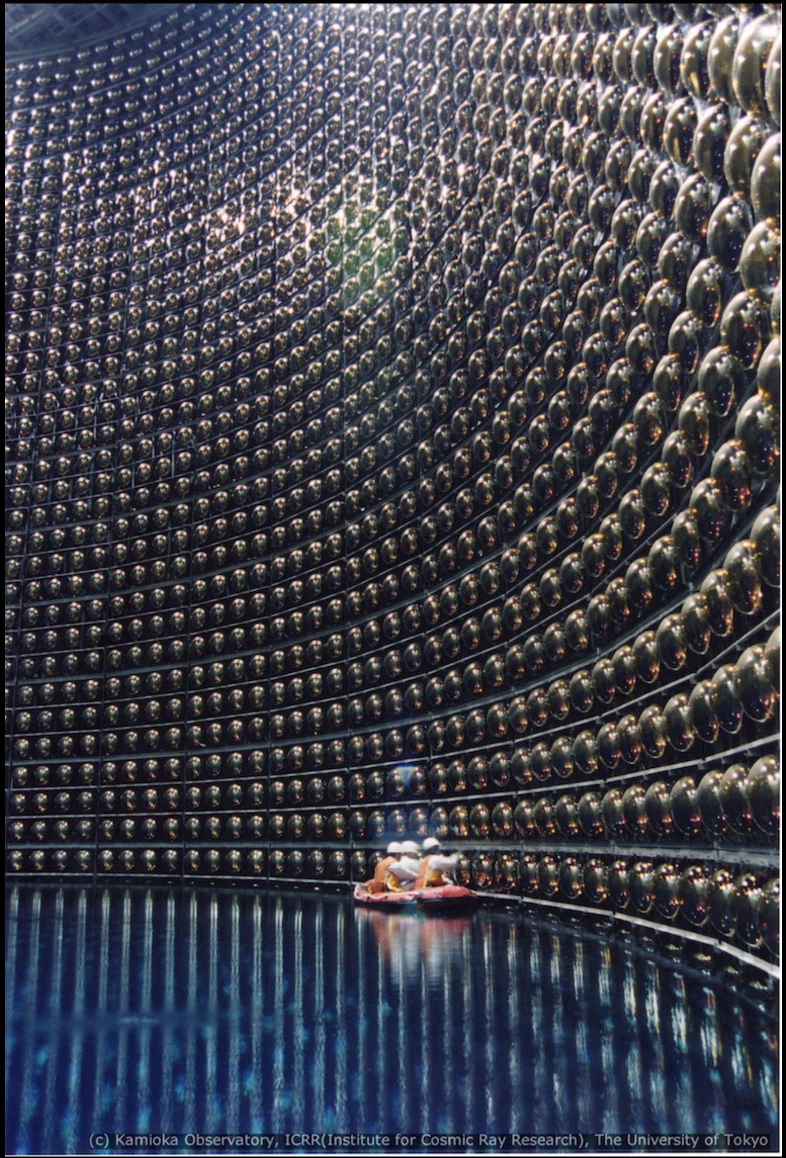
Third Ingredient: Neutrino Detection Capabilities

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

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

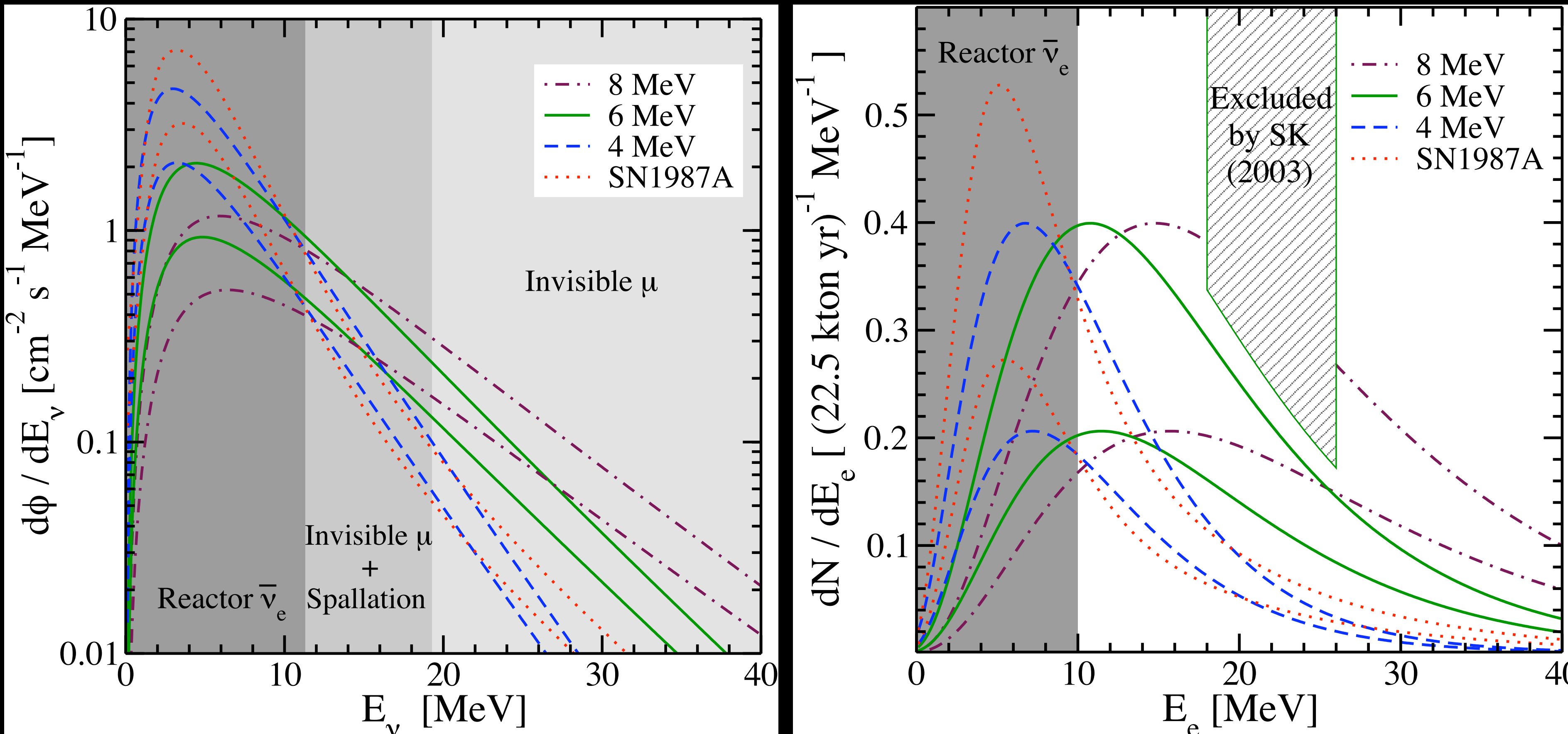
Free proton targets only
Cross section grows as $\sigma \sim E_\nu^2$
Kinematics good, $E_e \sim E_\nu$
Directionality isotropic

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



Super-Kamiokande

Predicted Flux and Event Rate Spectra



Horiuchi , Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate

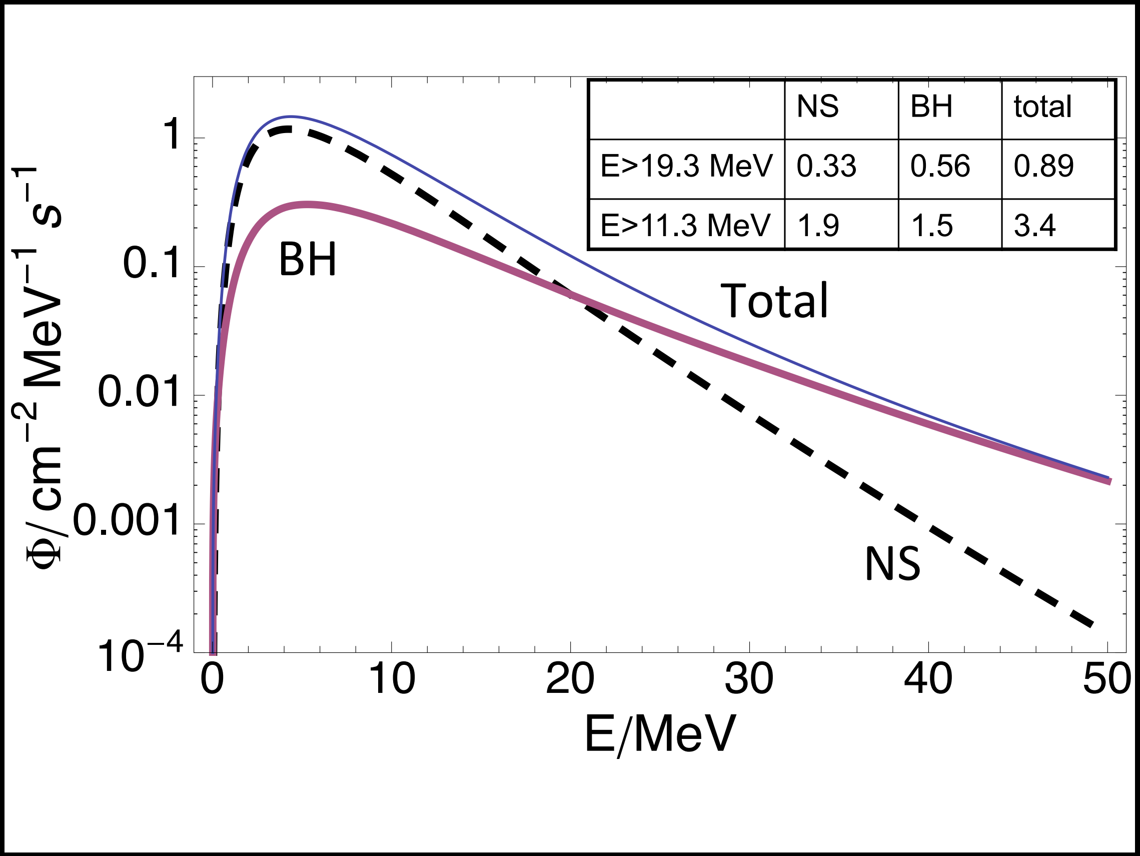
Neutrino Emission with Black Hole Formation

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

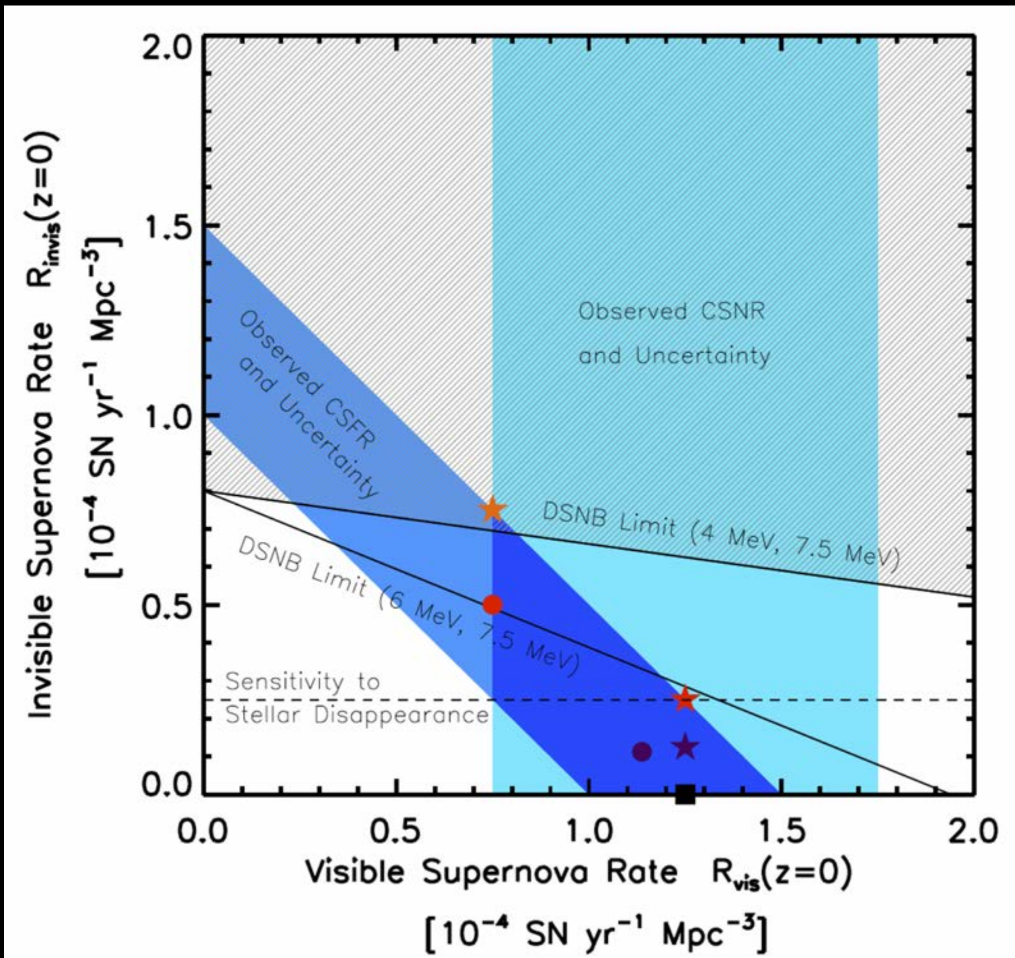
Sumiyoshi et al. (2007)
Nakazato et al. (2008)
Fischer et al. (2008)
O'Connor, Ott (2011)
….

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 ~ 50%

Standard models predict at least ~ 10% black holes

This can be resolved

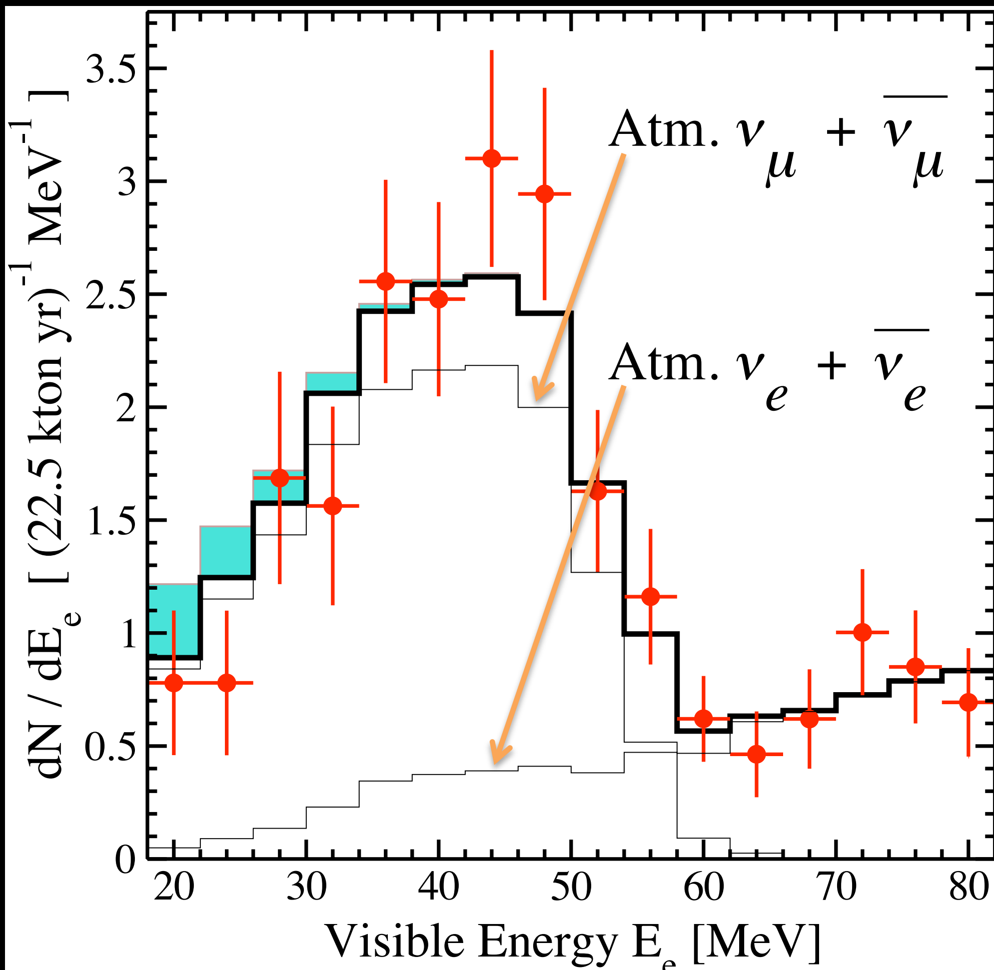
"Survey About Nothing" (Kochanek et al., 2008) can see massive stars disappear; ASAS-SN for nearby SN rate

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

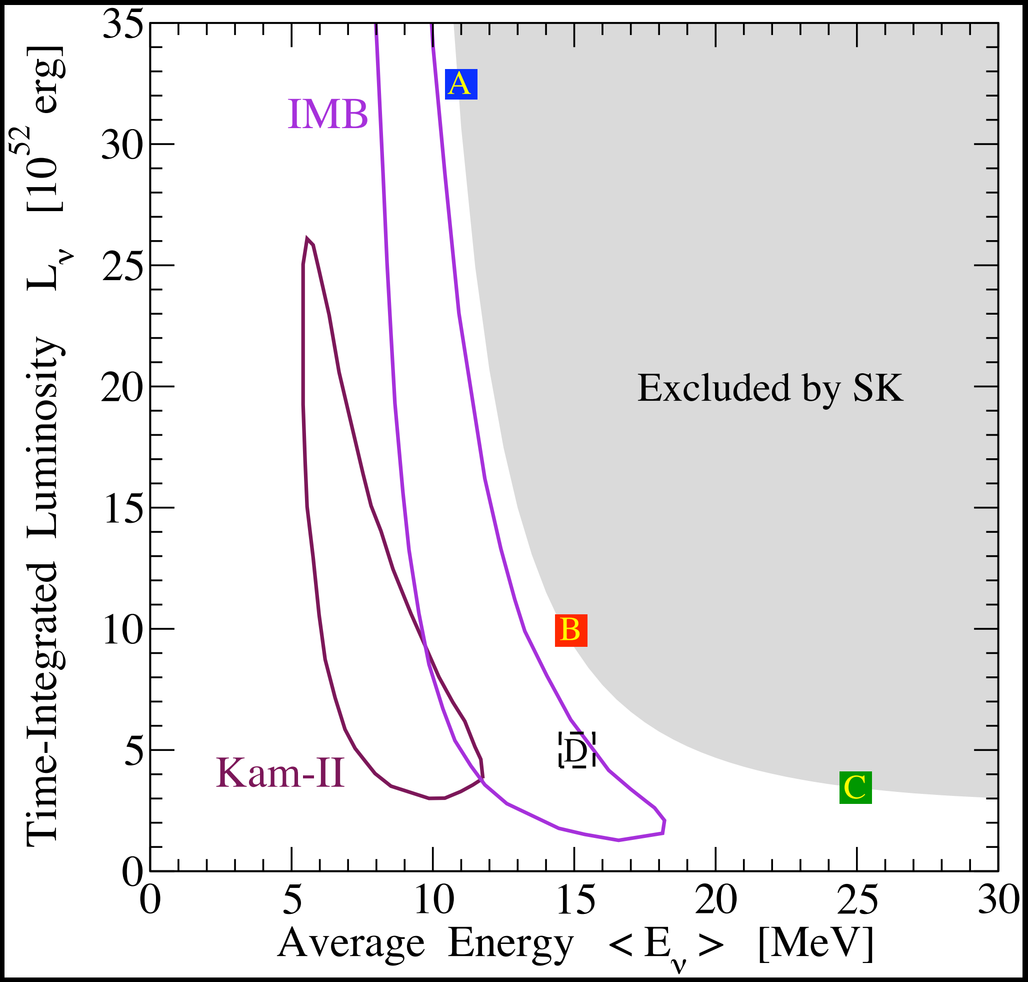
Limits on Supernova Neutrino Emission

2003 Super-Kamiokande limit:
$\Phi < 1.2\ cm^{-2}\ s^{-1}$ (90% CL)
for nuebar with $E_\nu > 19.3$ 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 ~ 100 improvement over Kamiokande-II limit

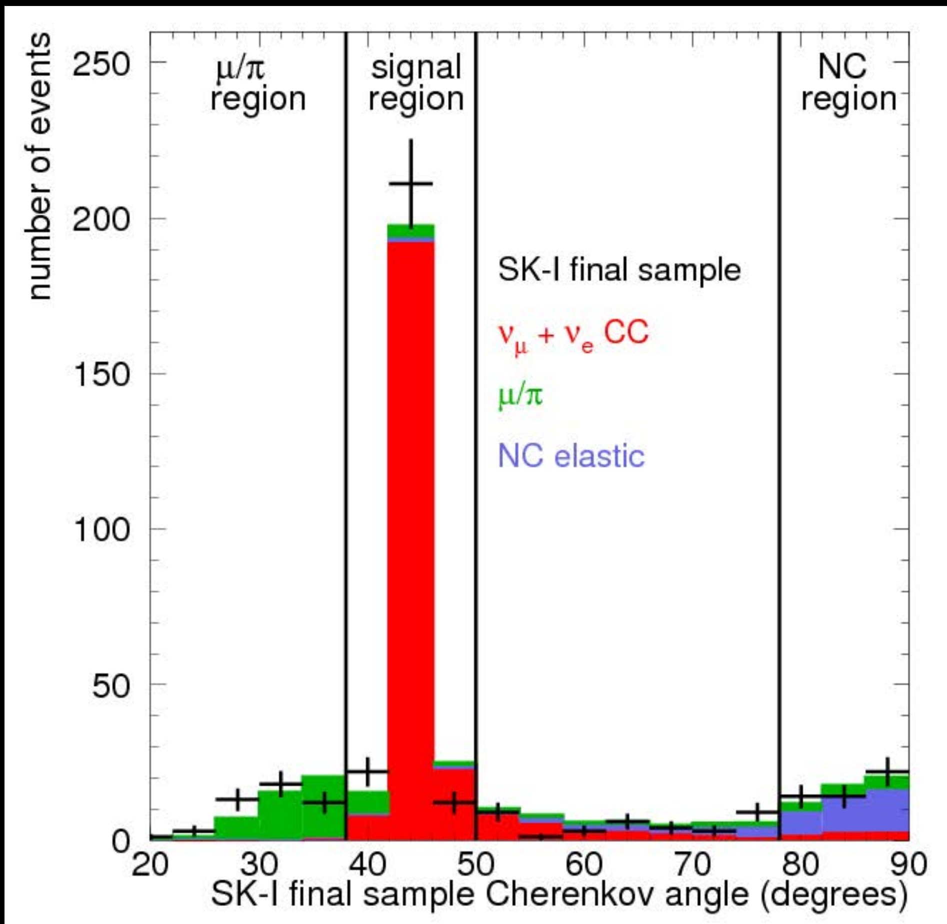
2012: all details down to ~ 10%

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
....

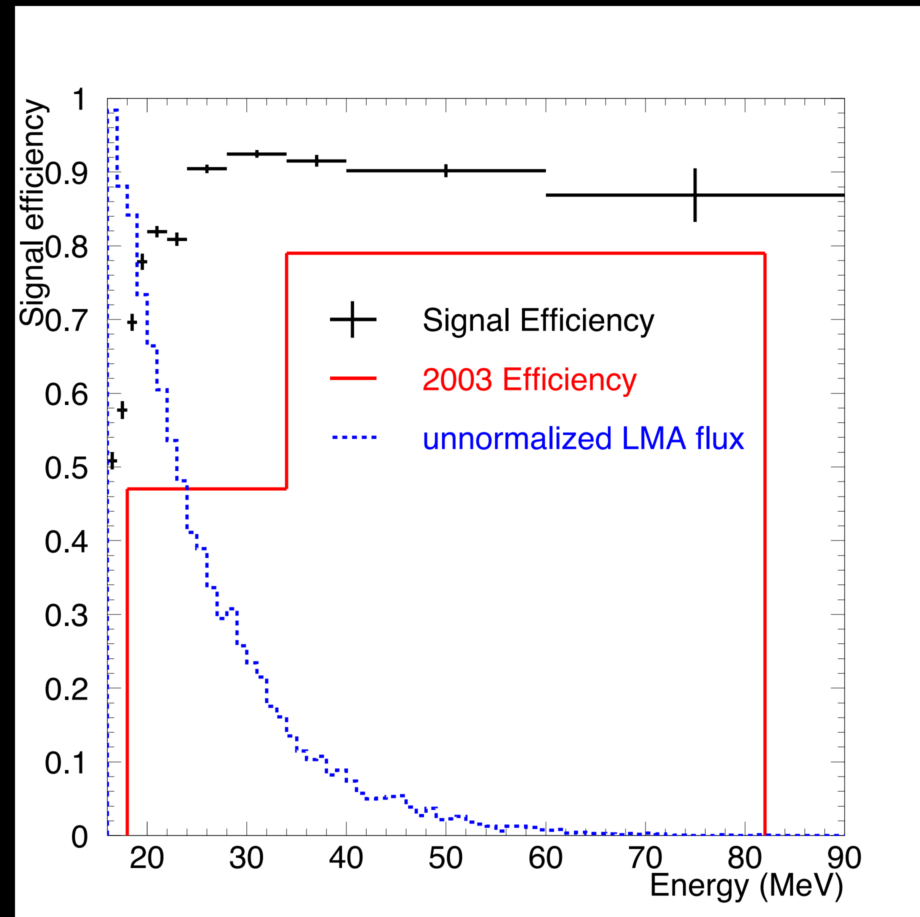
Who got the better Ph.D. thesis project?

Examples of the New Work on Details

Background separation by topology:

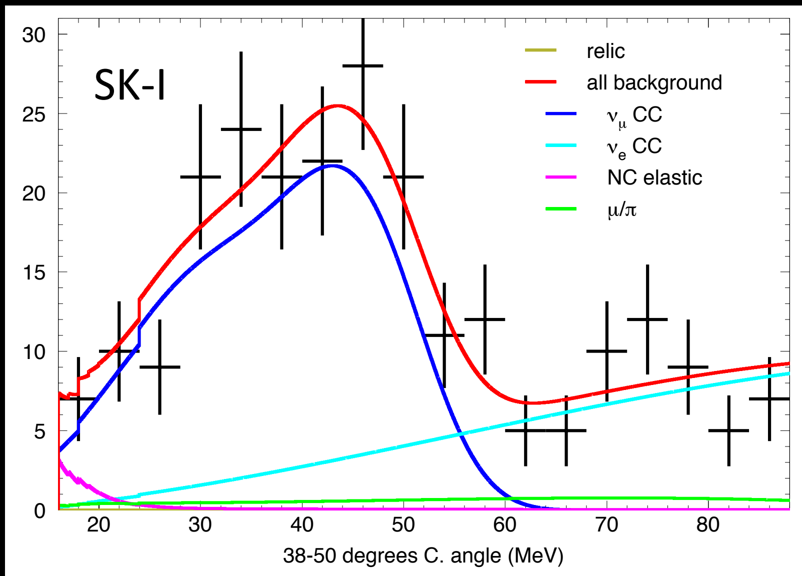


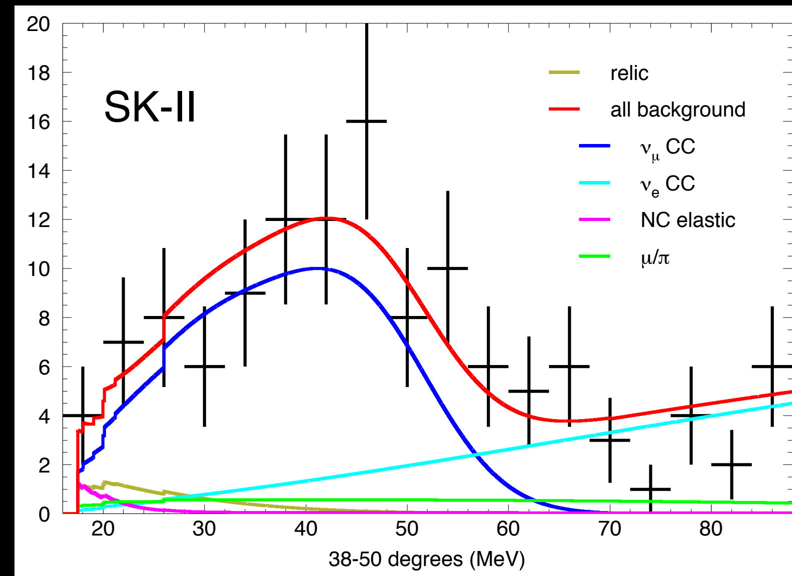
Improvement in SK-I Efficiency:

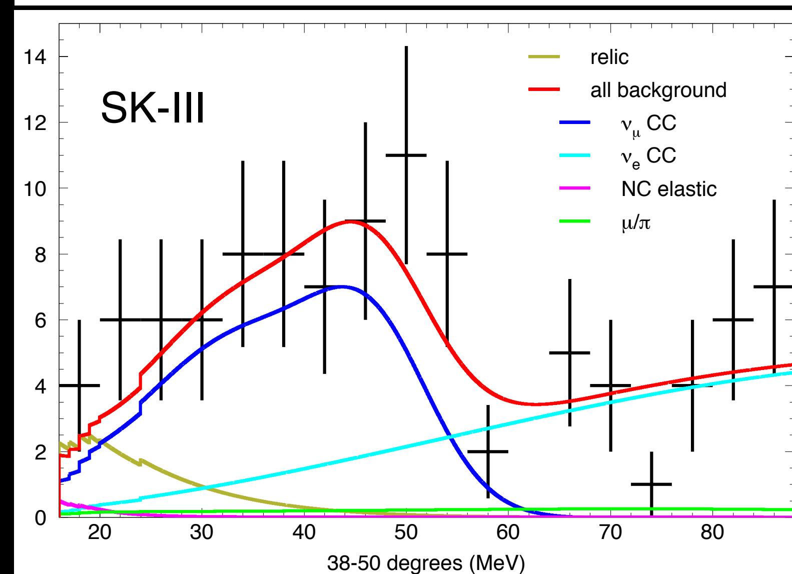


Bays et al. [Super-Kamiokande] (2012)

Energy Spectrum Fits







SK-I:

Best fit is *slightly negative* DSNB

SK-II and SK-III:

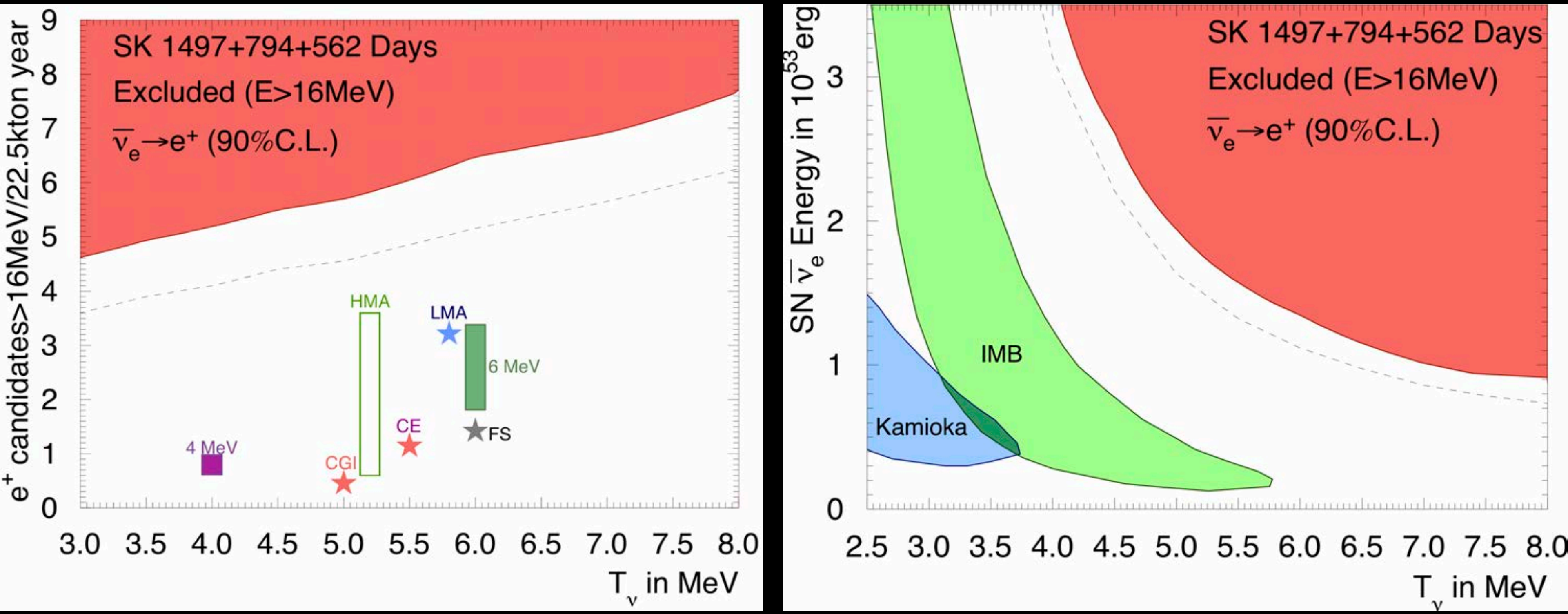
Best fit is *slightly positive* DSNB

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

New Super-Kamiokande Limits

Much improved analysis and more data

To be *conservative*, new limits are a factor ~ 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 HAνSE 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

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

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 ~ 8 MeV
Easily detectable coincidence
separated by ~ 4 cm and ~ 20 μs

New general tool for particle ID
Rich new physics program

Benefits of Neutron Tagging for DSNB

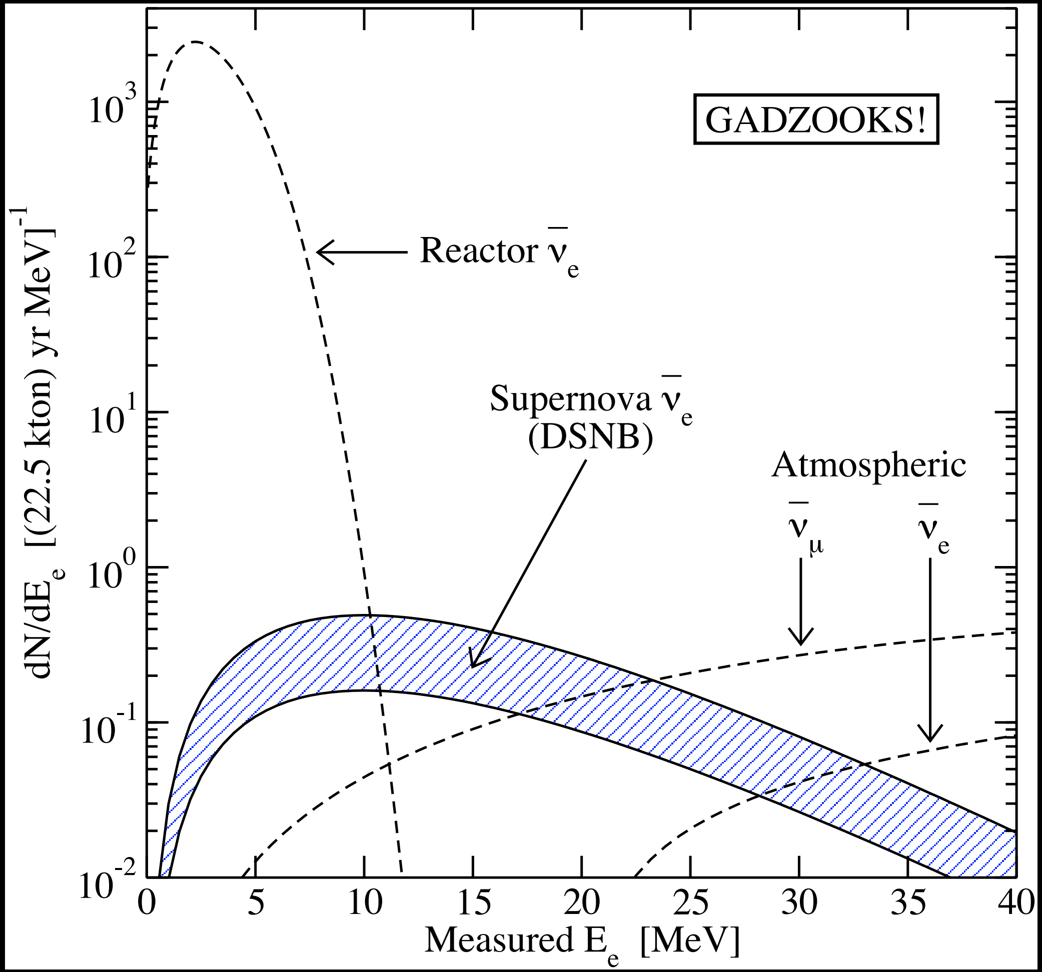
Solar neutrinos:
eliminated

Spallation daughter decays:
essentially eliminated

Reactor neutrinos:
now a visible signal

Atmospheric neutrinos:
significantly reduced

DSNB:
More signal, less background!

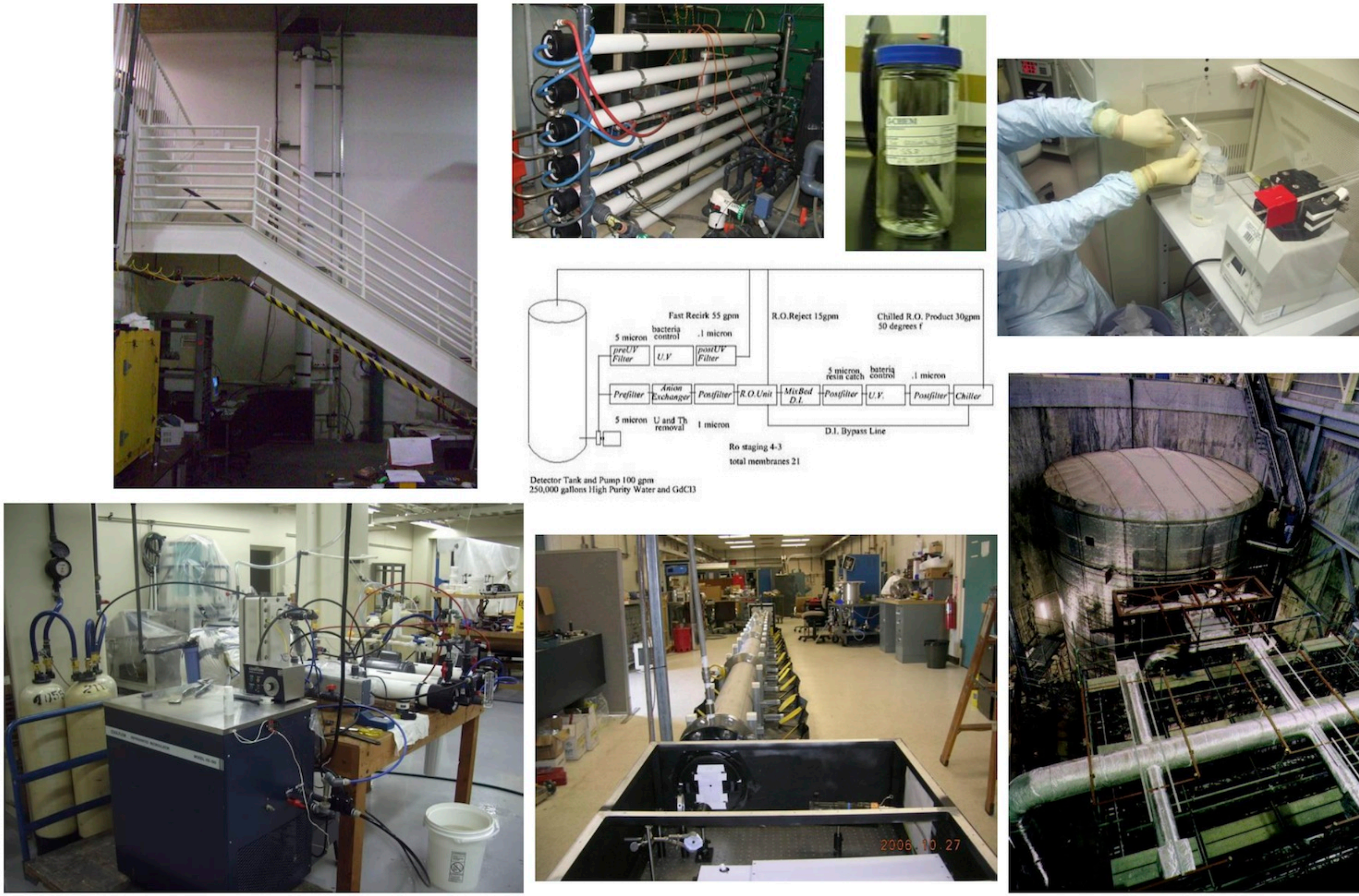


Beacom, Vagins (2004)

(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:

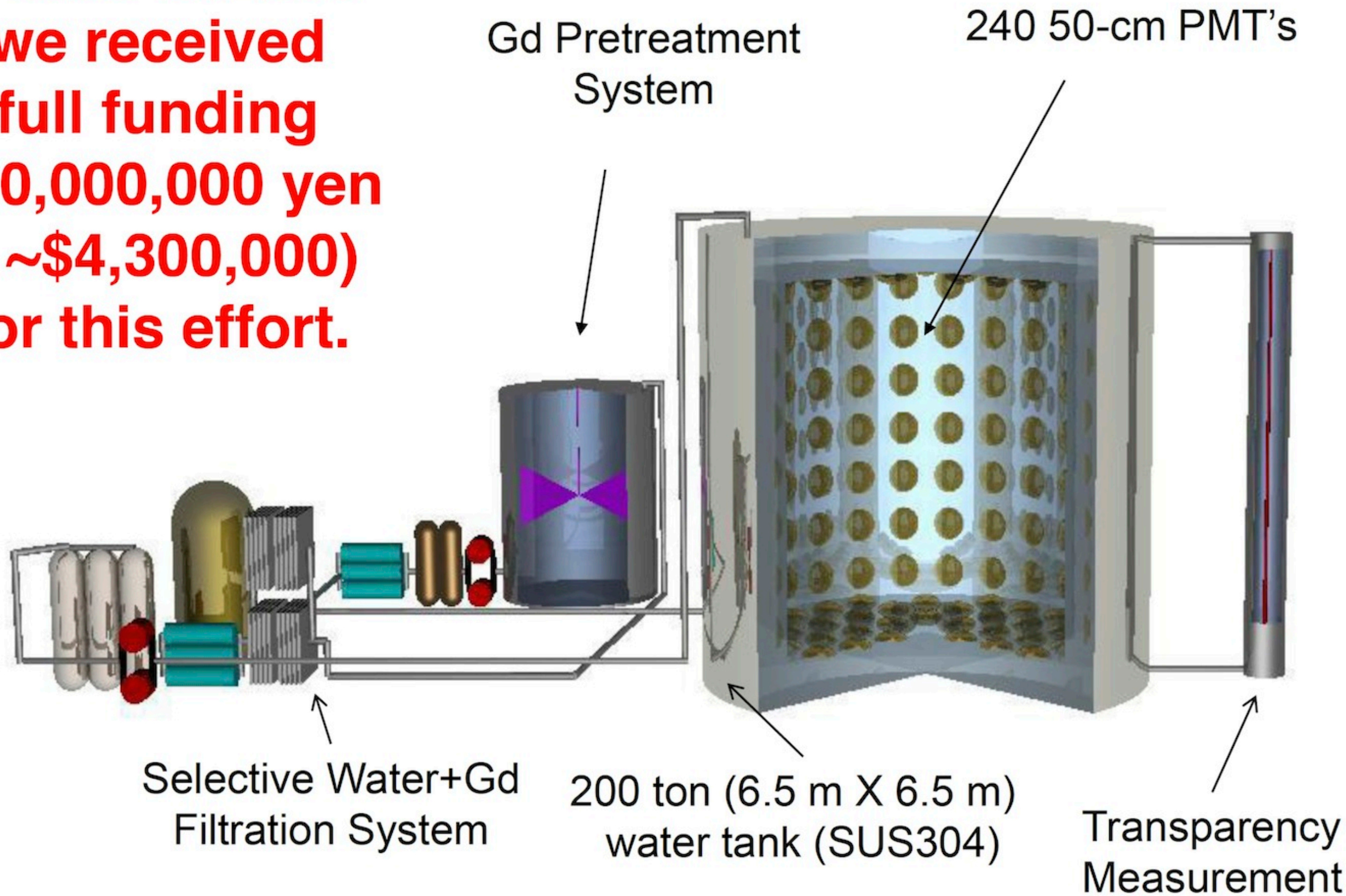


EGADS Proposal

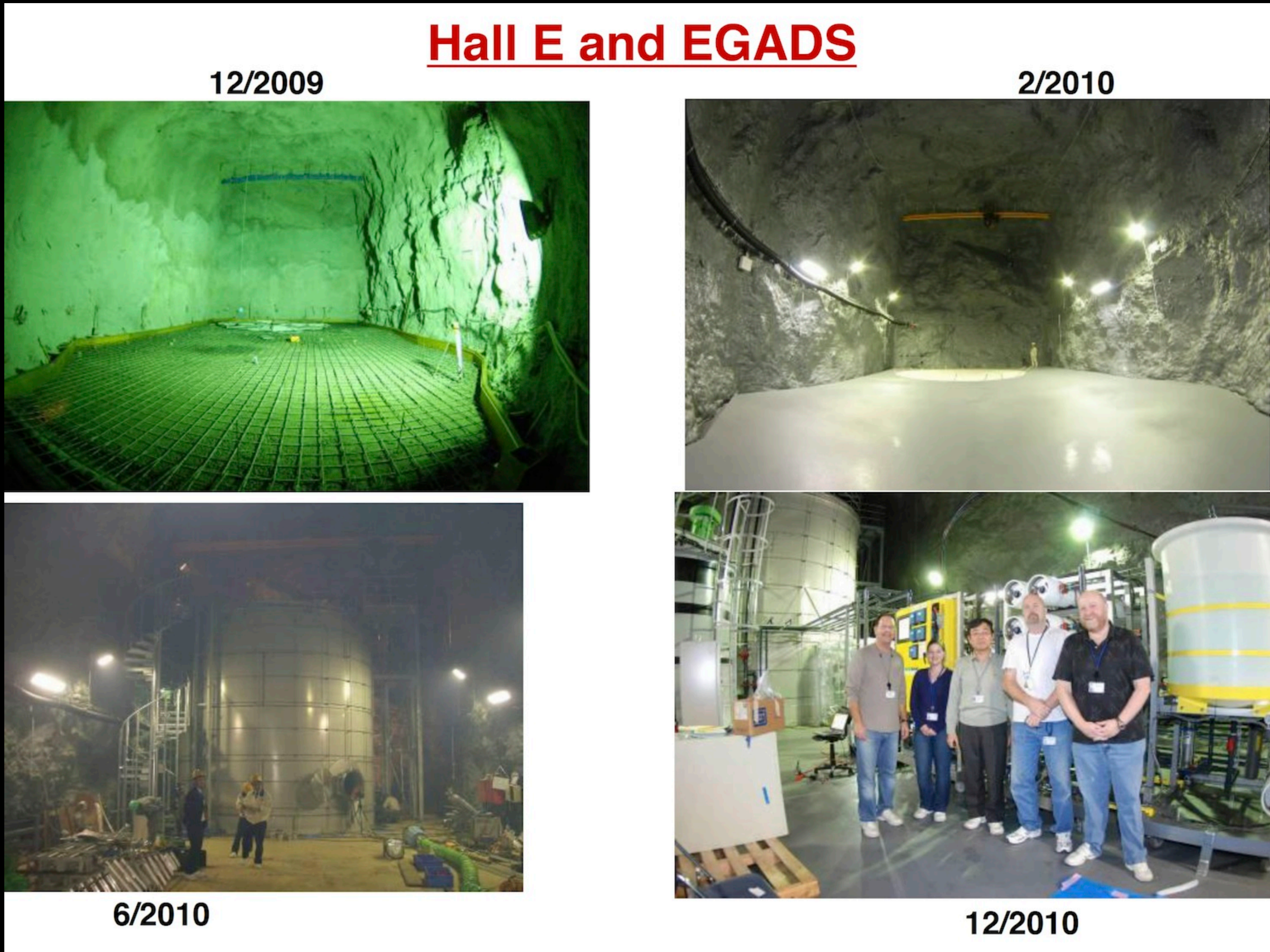
EGADS Facility

Masayuki Nakahata, Mark Vagins, others

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



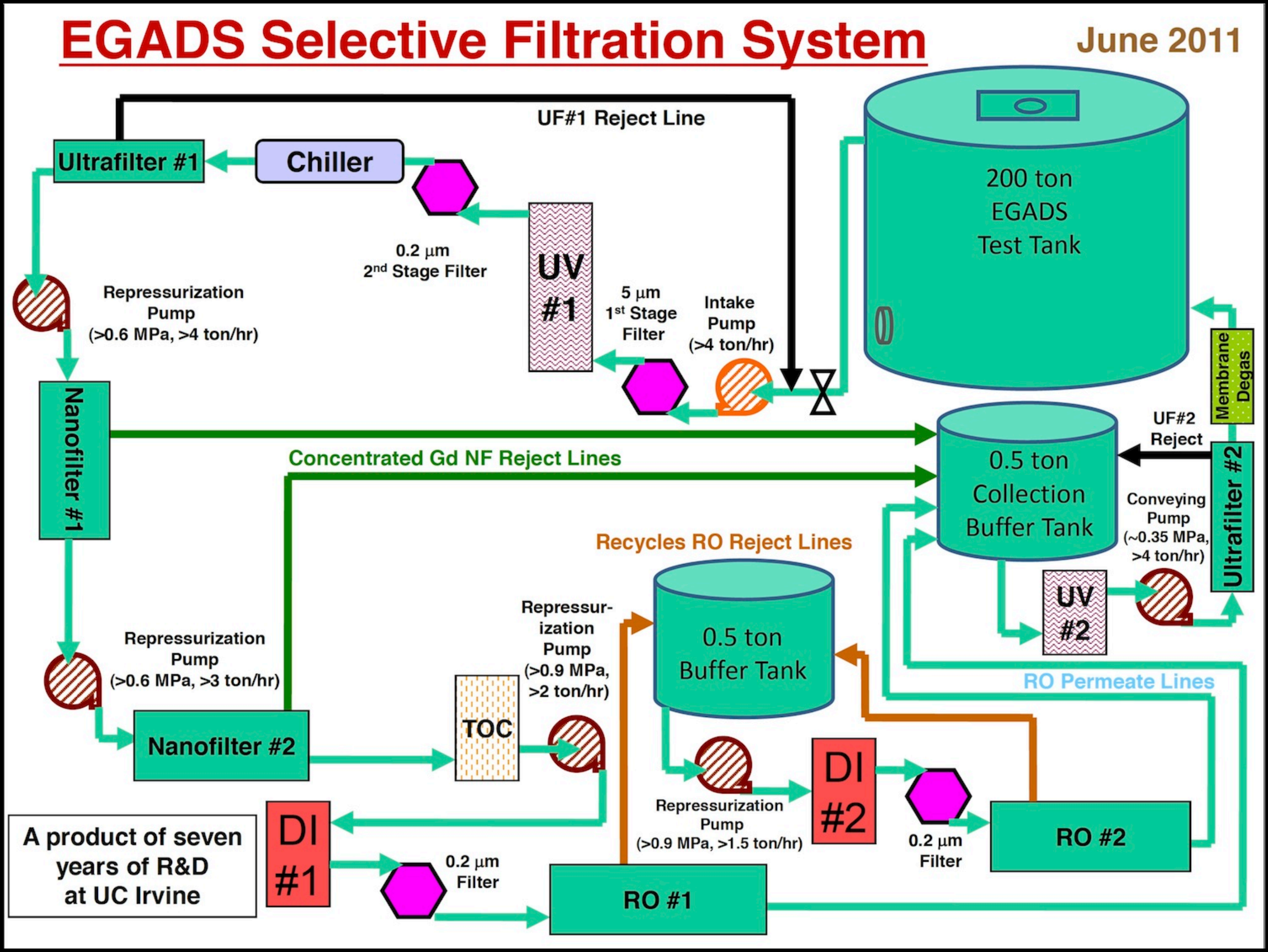
EGADS Detector



Mad Scientist at Work in Underground Lair

Adding 383 grams $Gd_2(SO_4)_3$ to 191 liters of H_2O; January 5th, 2011

Water and Gadolinium Filtration System



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:

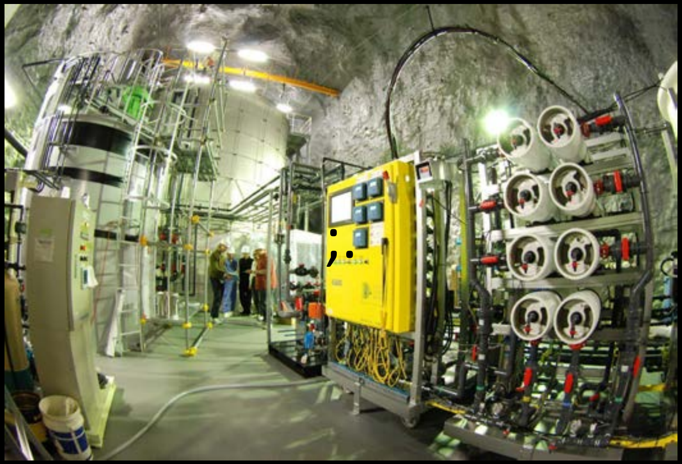
Gadolinium water circulation already has 99.97% efficient return

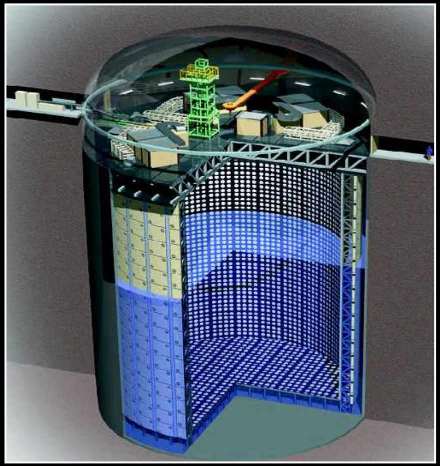
Gadolinium Water Transparency:

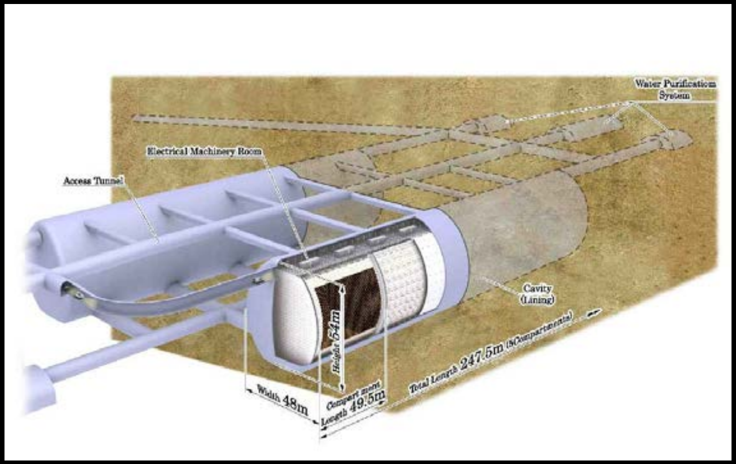
Transparency for filtered gadolinium water is already very high

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	Nearby Galaxies	DSNB
Mostly ready	Need new detectors	Need an upgrade
Lifetime events	Annual events	Steady detections
Only way to measure precise details, time structure, all flavors, etc.	Only way to check neutrino presence, burst variation, isolate dark bursts, etc.	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

Multiple SN neutrino detection modes

←	→
Core-collapse paradigm	Optical supernova types
Core-collapse simulations	Supernova explosions
Failed collapses	Disappearing stars
Extreme stellar outbursts	Supernova "impostors"
Exact collapse time	Gravitational wave searches
Nuclear matter theory	Neutron star properties
Conditions above core	Nucleosynthesis yields
Massive star fates	Missing supernova problem
Variety in collapse	Variety in neutron stars
New particle physics	Extreme conditions

Center for Cosmology and AstroParticle Physics

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

CCAPP

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

Postdoctoral Fellowship applications welcomed in Fall

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