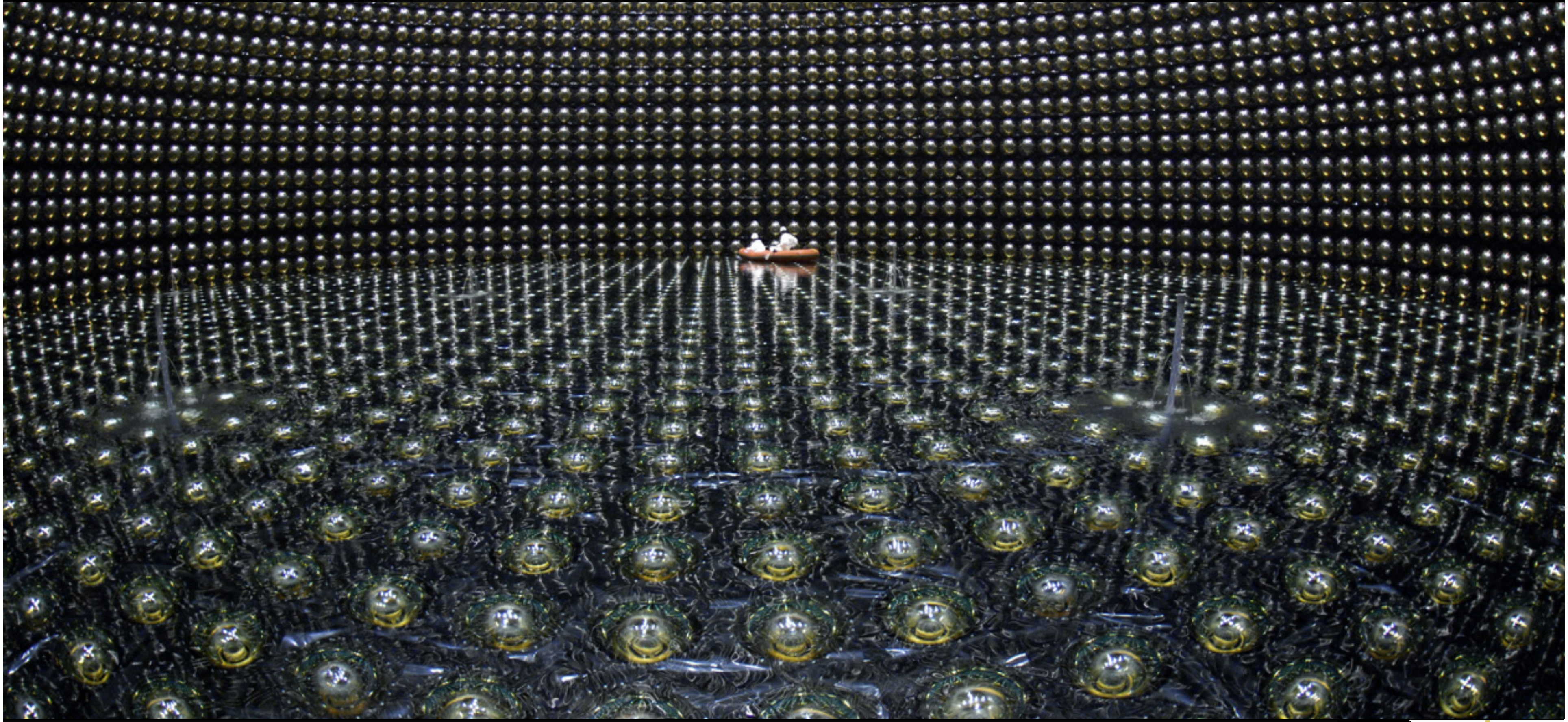
Particle and Nuclear Astrophysics with Supernova Neutrinos

John Beacom, Ohio State University



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

CCAPP

NSF

Why Is This Particle Different From All Other Particles?

Physics: Only weak interactions, so sensitive to feeble new forces
Astro/Cosmo: Probe great densities and distances without attenuation

Physics: Must accompany interconversions of protons and neutrons
Astro/Cosmo: Prodigious production in sources and the cosmos

Physics: Light masses are likely a clue about new physics
Astro/Cosmo: Low mass density preserves small-scale structure

Physics: Large quantum-mechanical mixing on macroscopic scales
Astro/Cosmo: Multiple flavors probe details of matter content

Status of Neutrino Research: Physics

Knowns	Unknowns
Three flavors: e, mu, tau	Are there sterile flavors?
Weak interactions only	What is the mass scale?
Large mixing angles	Dirac or Majorana masses?
Some masses nonzero	Exact angles, CP violation?
Masses at or below eV scale	Are there new interactions?
Lots of exotica ruled out	Big surprises?

Much of this is very recent

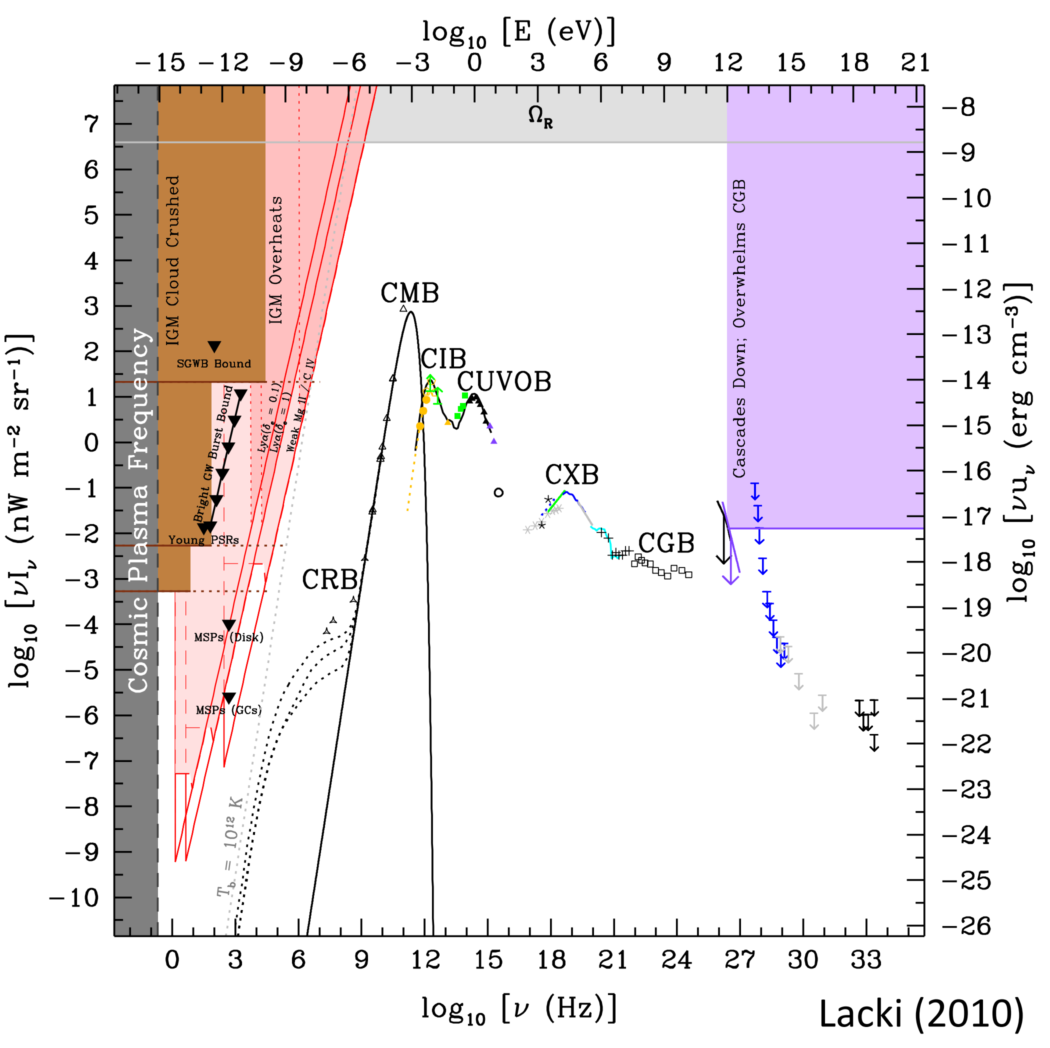
Great progress coming soon

Status of Neutrino Research: Astro/Cosmo

Knowns	Unknowns
Solar fusion neutrino emission	Are there sterile flavors?
SN 1987A neutrino emission	What is the mass scale?
BBN fit has N ~ 3 species	Cosmological effects?
CMB fit has N ~ 3 species	Astrophysical sources?
Dark matter is not neutrinos	Are there new interactions?
CMB+LSS fit has M < 1 eV	Big surprises?
Much of this is very recent	Great progress coming soon

Four Promising Neutrino Frontiers

Photons



Lacki (2010)

Neutrinos?

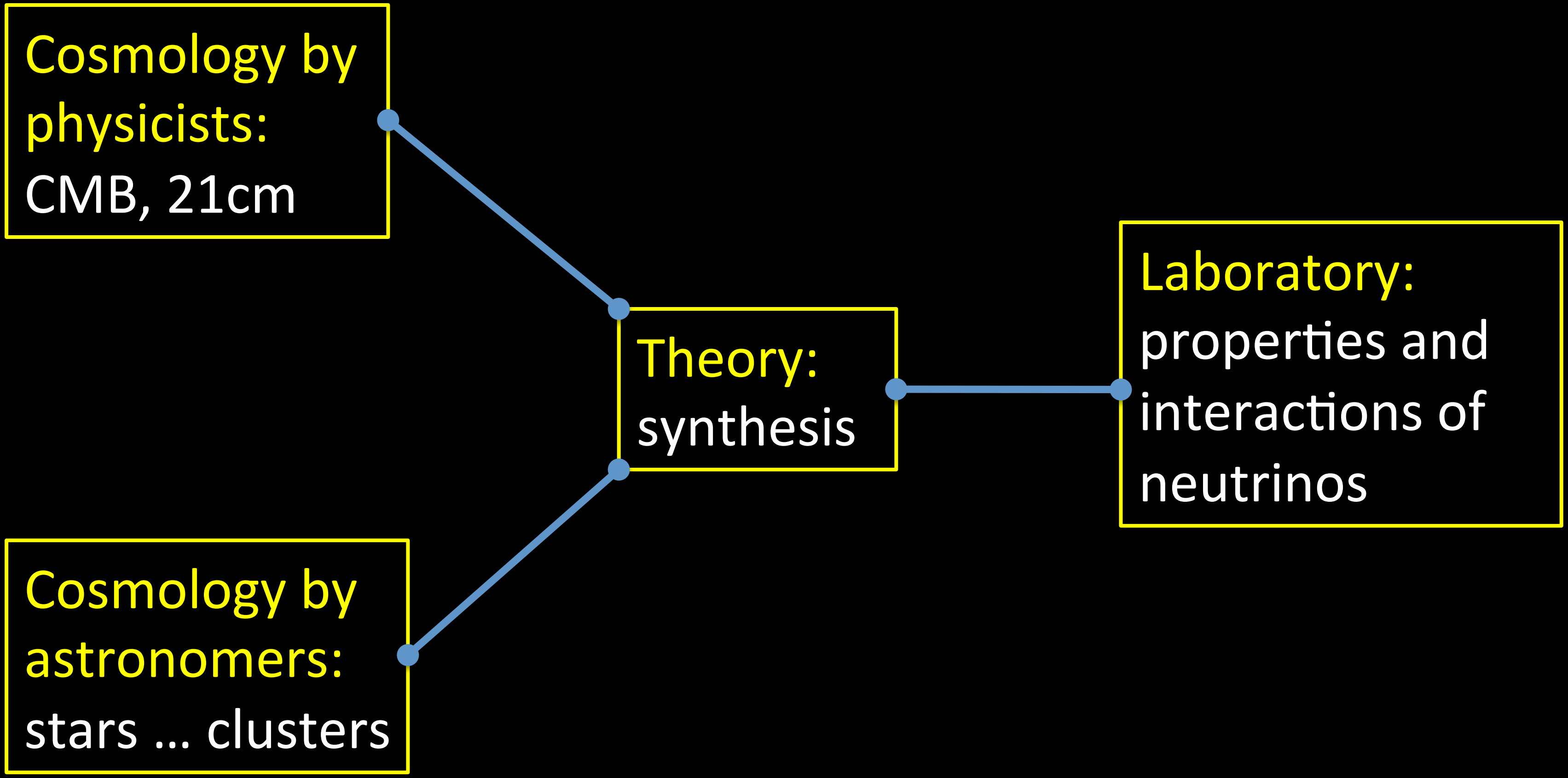
meV scale cosmo:
“detected” by BBN, CMB

MeV scale astro:
near detection in Super-K

TeV-PeV scale astro:
maybe detected by IceCube

EeV scale astro:
near detection in ANITA

Neutrino Cosmology: Next Steps



Cosmology by physicists:
CMB, 21cm

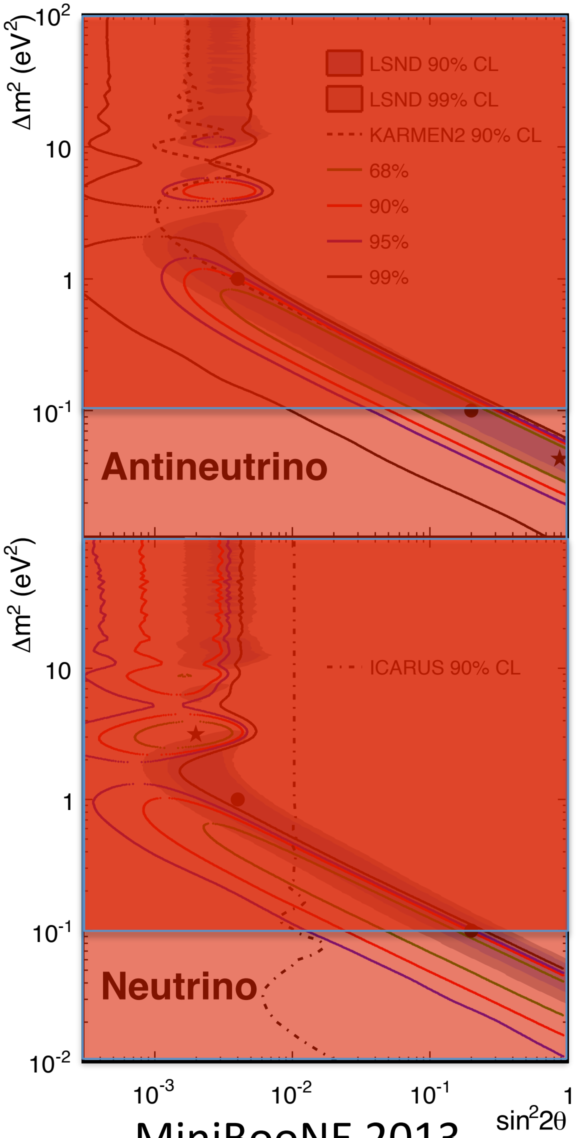
Theory:
synthesis

Laboratory:
properties and interactions of neutrinos

Cosmology by astronomers:
stars … clusters

Must reconcile N and M measurements – Are there sterile neutrinos?

Do Sterile Neutrinos Exist?



MiniBooNE 2013

LSND/MiniBooNE not active neutrino mixing

Mixing with new sterile neutrinos possible

Other anomalies suggest something similar

First issue: total flavors N

Default is that these increase cosmo N

Planck says $N < 3.3$

Nominally rules out all but tiny mixing

Second issue: total mass M

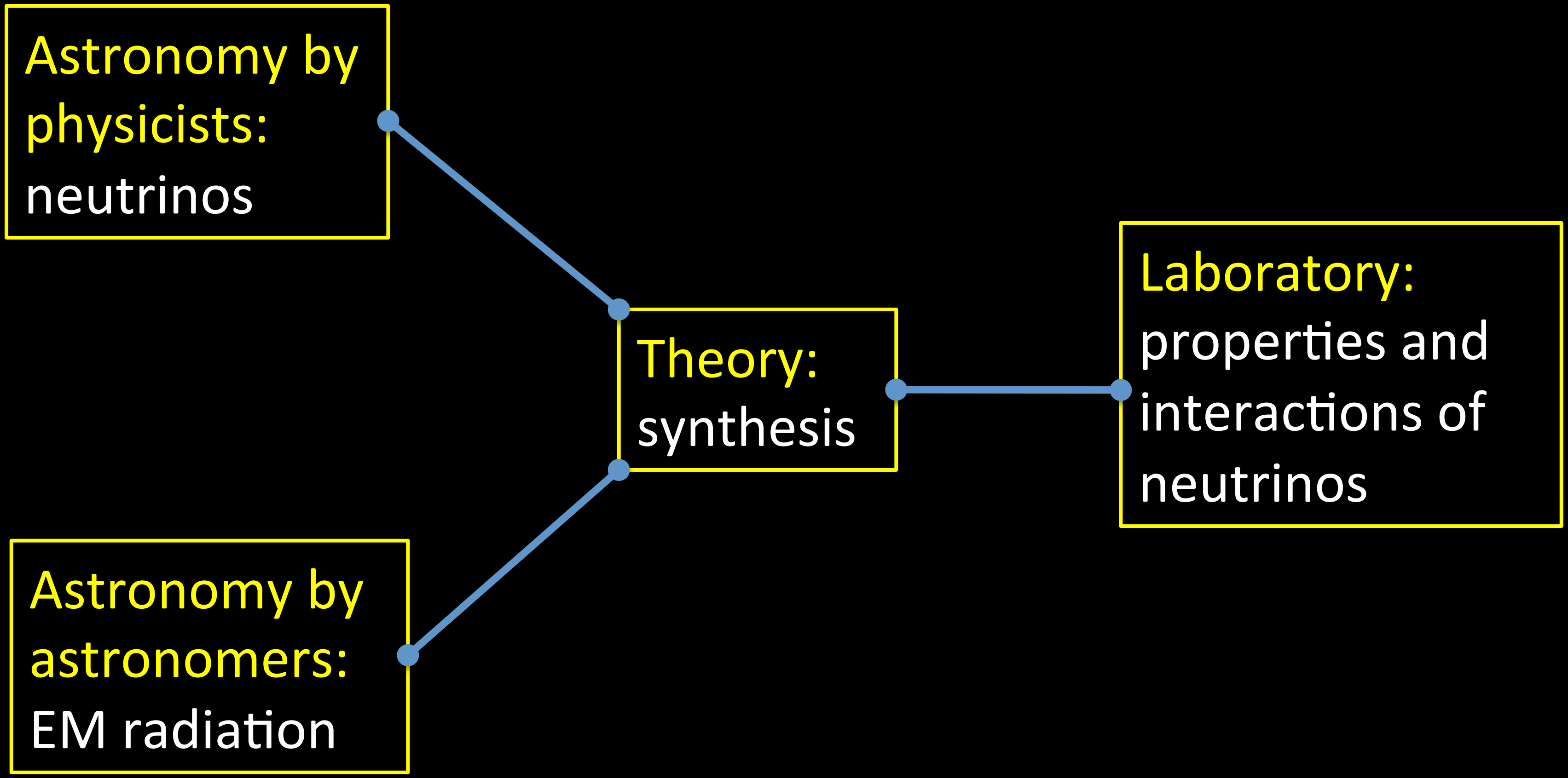
Default is that these increase cosmo M

Planck and others say $M < 0.3$ eV

Nominally rules out all but tiny masses

If we're lucky, there is a "big surprise" here

Neutrino Astrophysics: Next Steps



Astronomy by physicists:
neutrinos

Theory:
synthesis

Laboratory:
properties and interactions of neutrinos

Astronomy by astronomers:
EM radiation

Must find new sources – How can sensitivity be improved?

Do Astrophysical Neutrino Sources Exist?

Remaining 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

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?
….

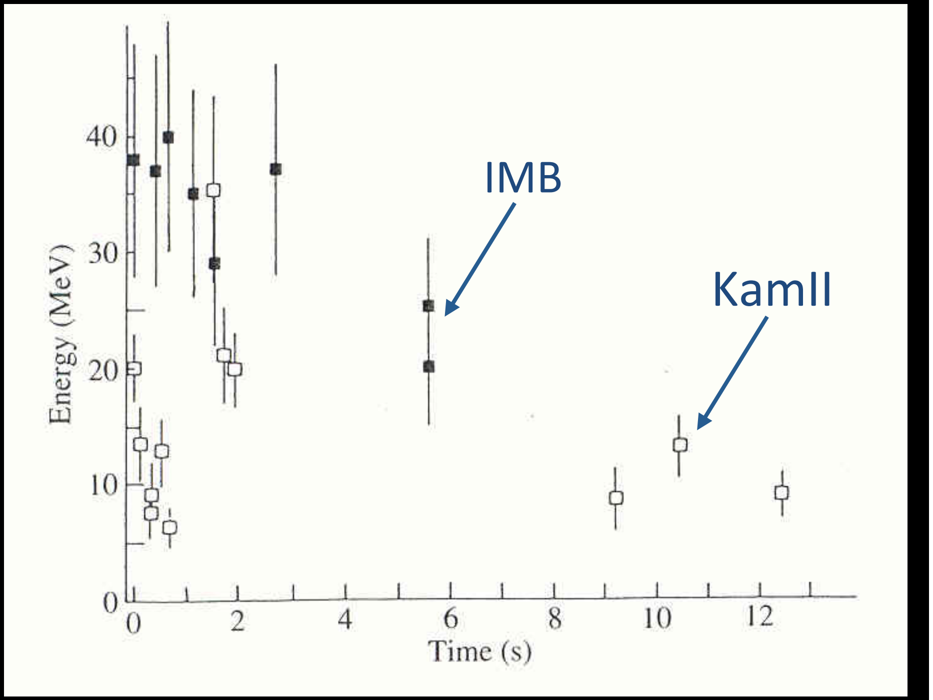
We cannot solve key problems without detecting supernova neutrinos

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



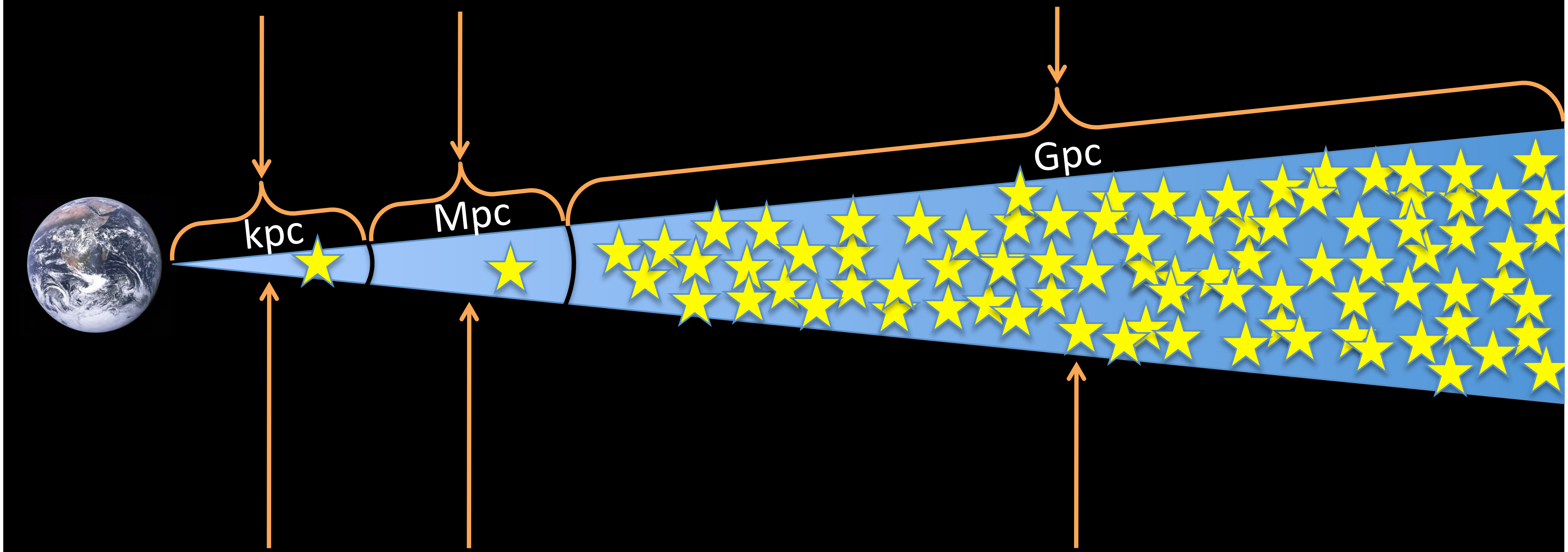
Observation: Type II supernova progenitors are massive stars

Observation: The neutrino precursor is very energetic

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

Introduction: Three Detection Modes

Distance Scales and Detection Strategies



N >> 1 : Burst

Rate ~ 0.01/yr

high statistics,
all flavors

N ~ 1 : Mini-Burst

Rate ~ 1/yr

object identity,
burst variety

N << 1 : DSNB

Rate ~ 10^8/yr

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

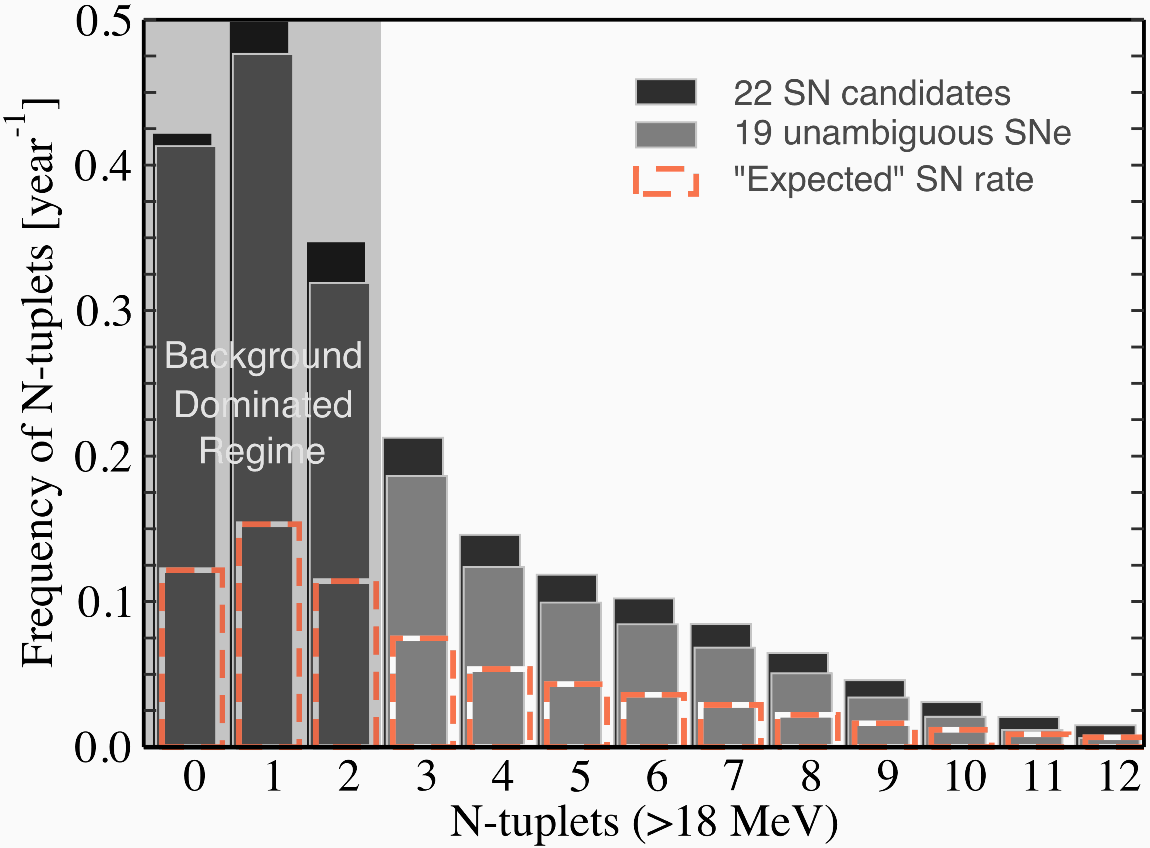
Much larger or better detectors are being proposed now

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

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

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

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

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

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

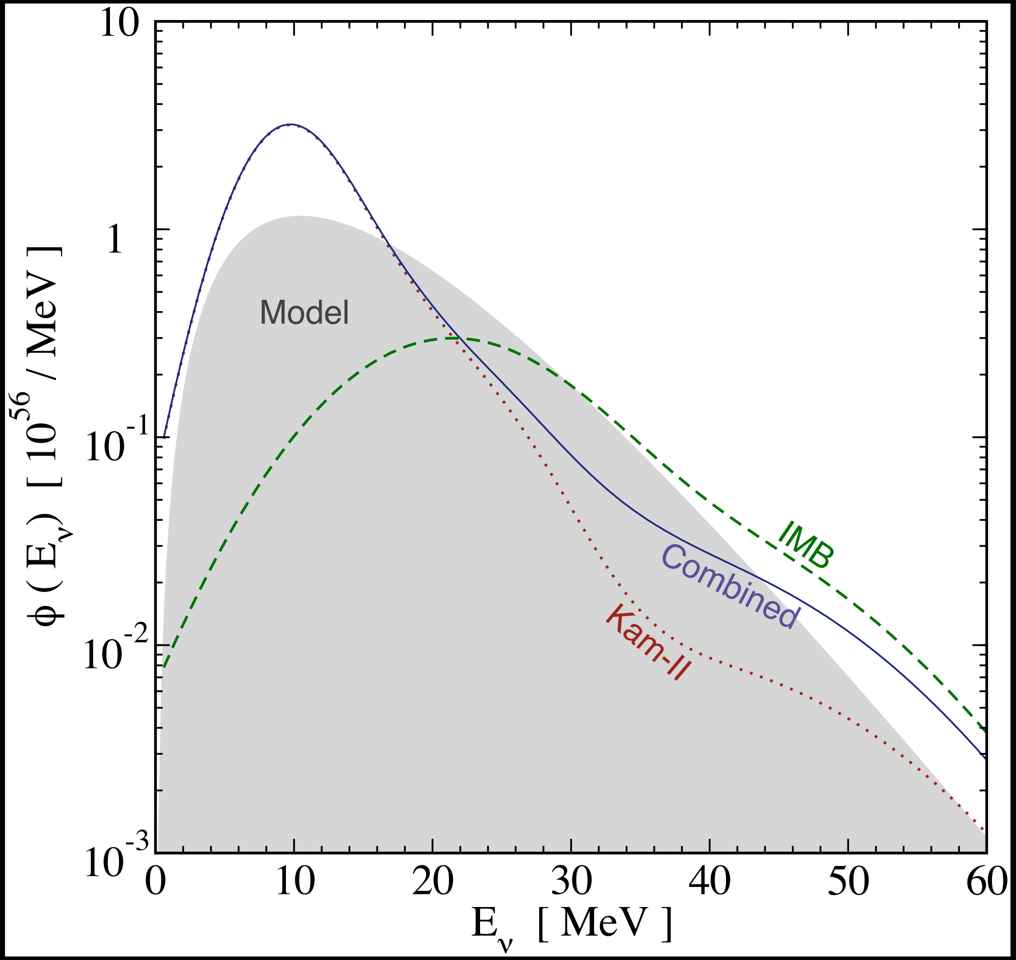
Core collapse releases ~ 3x10^{53} erg, shared by six flavors of neutrinos

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)

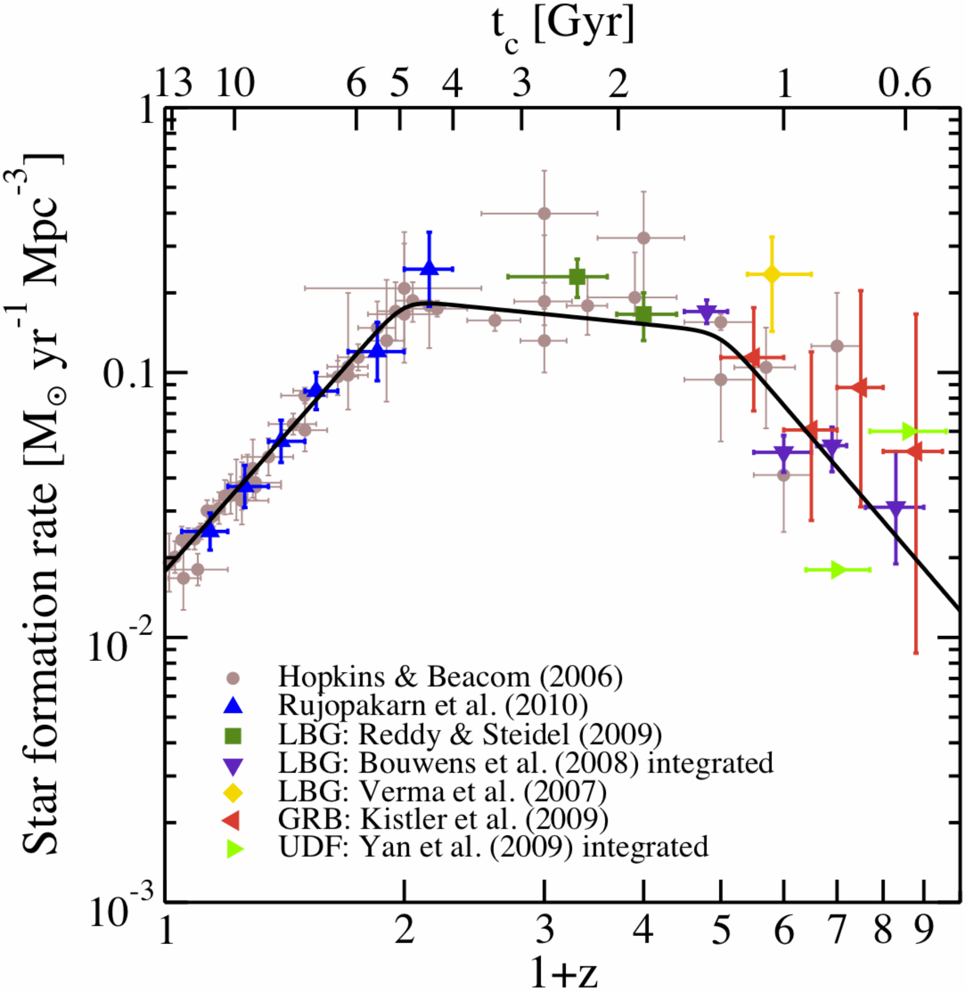
Measured from the core collapse supernova rate

(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

Third Ingredient: Neutrino Detection Capabilities

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

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

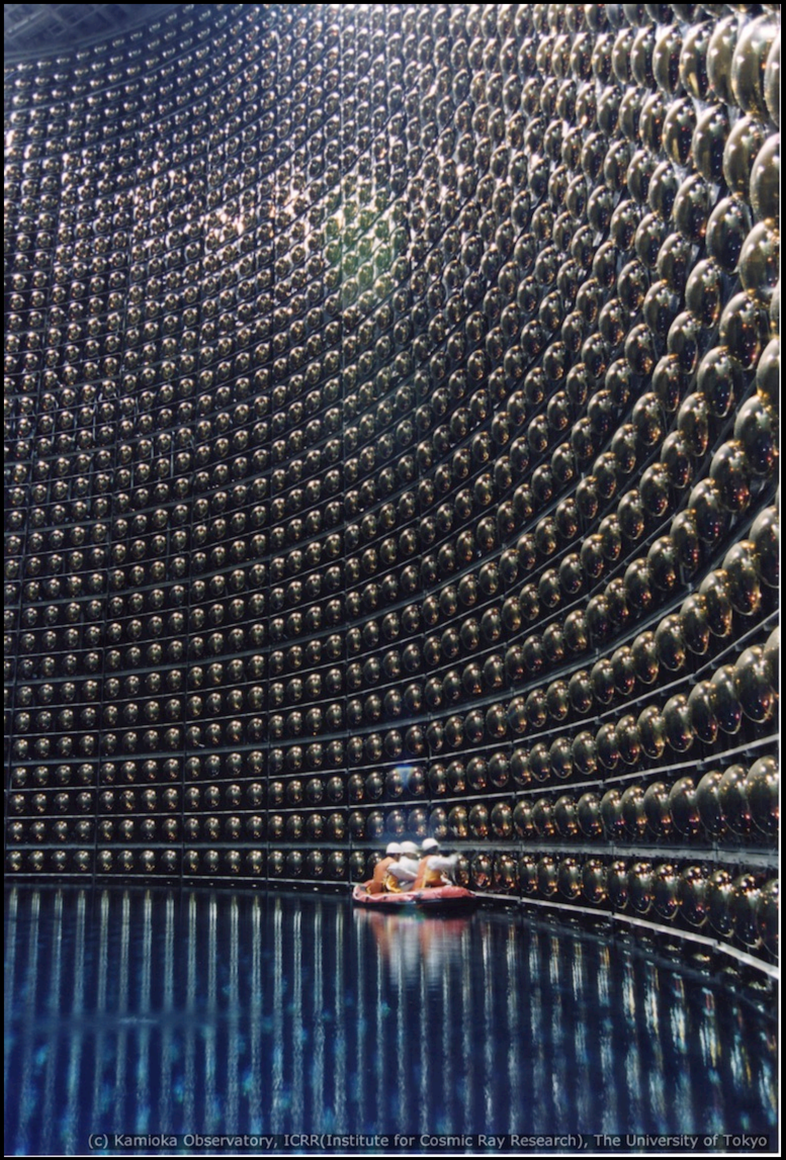
Free proton targets only

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

Kinematics good, $E_e \sim E_\nu$

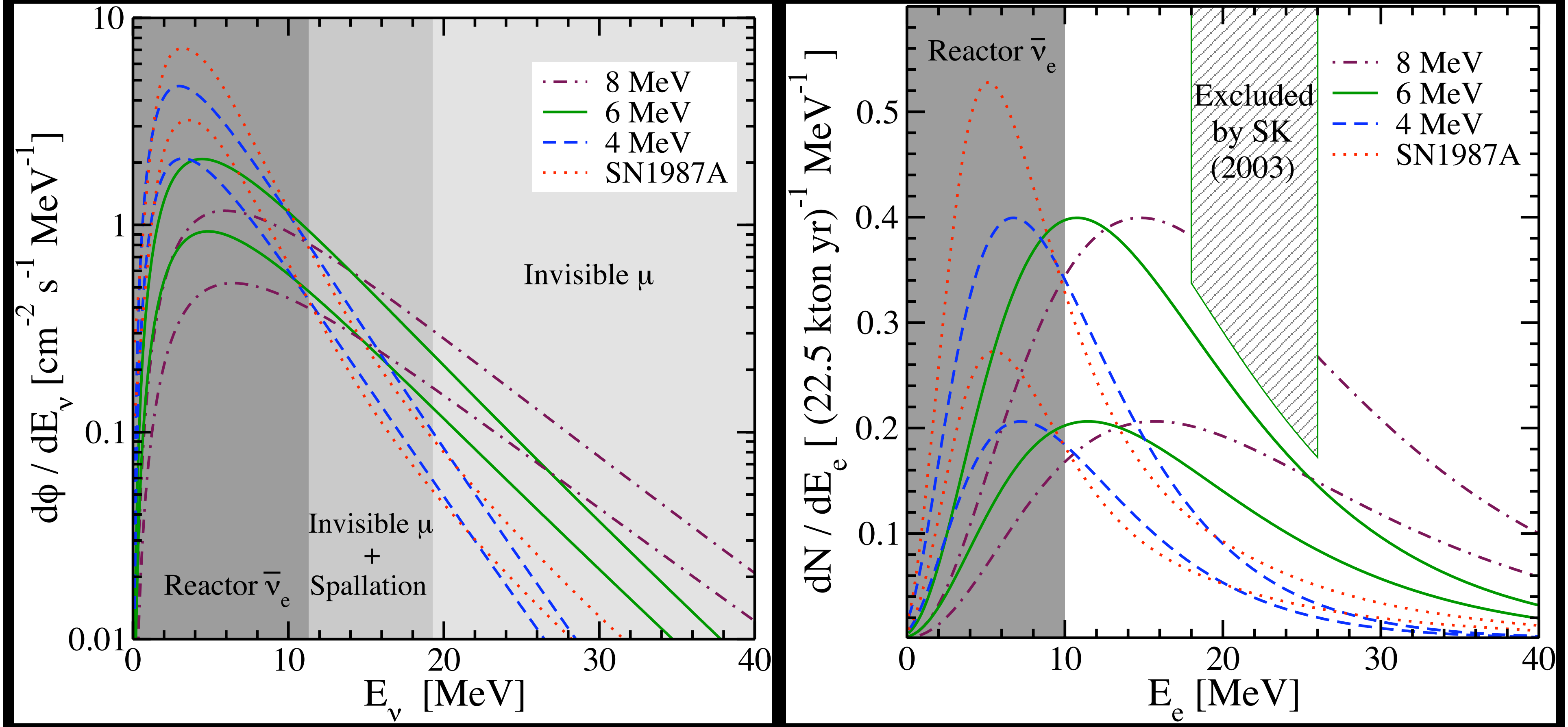
Directionality isotropic

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


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

Super-Kamiokande

Predicted Flux and Event Rate Spectra



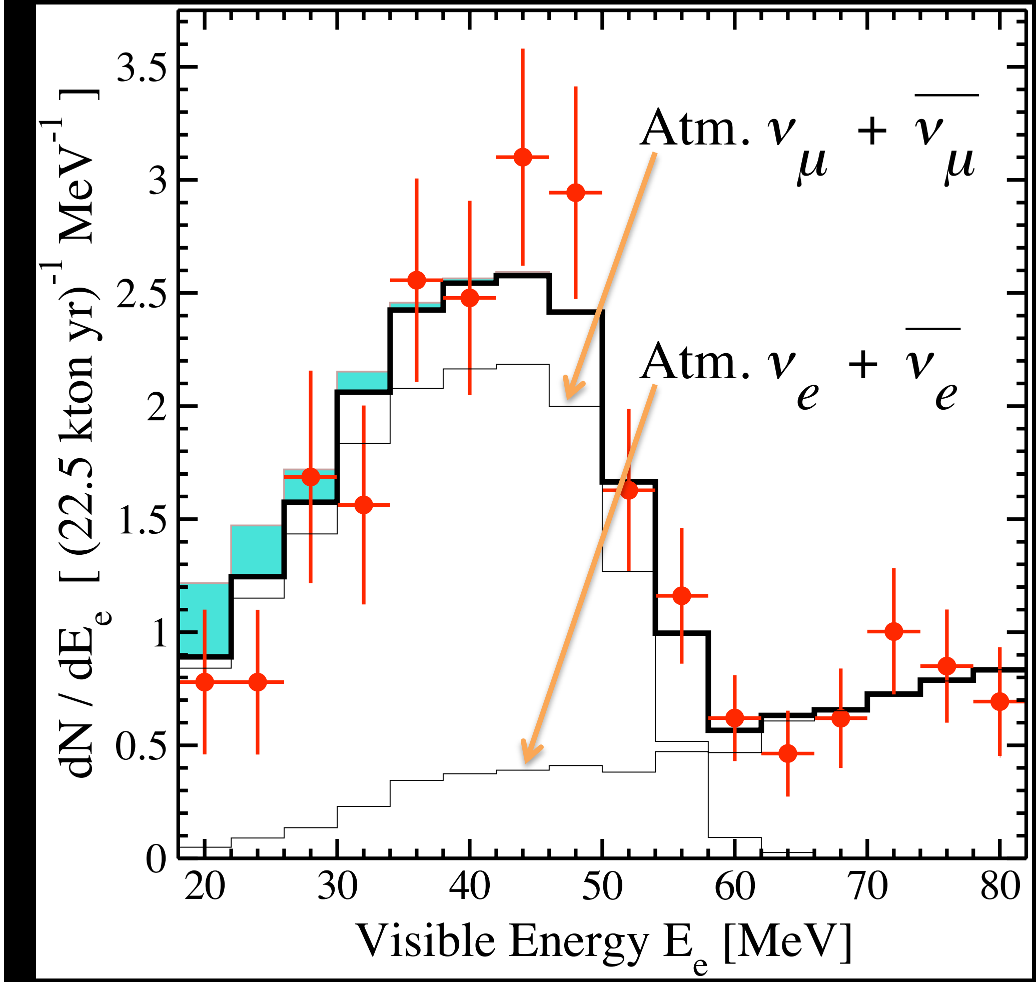
Horiuchi , Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate

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

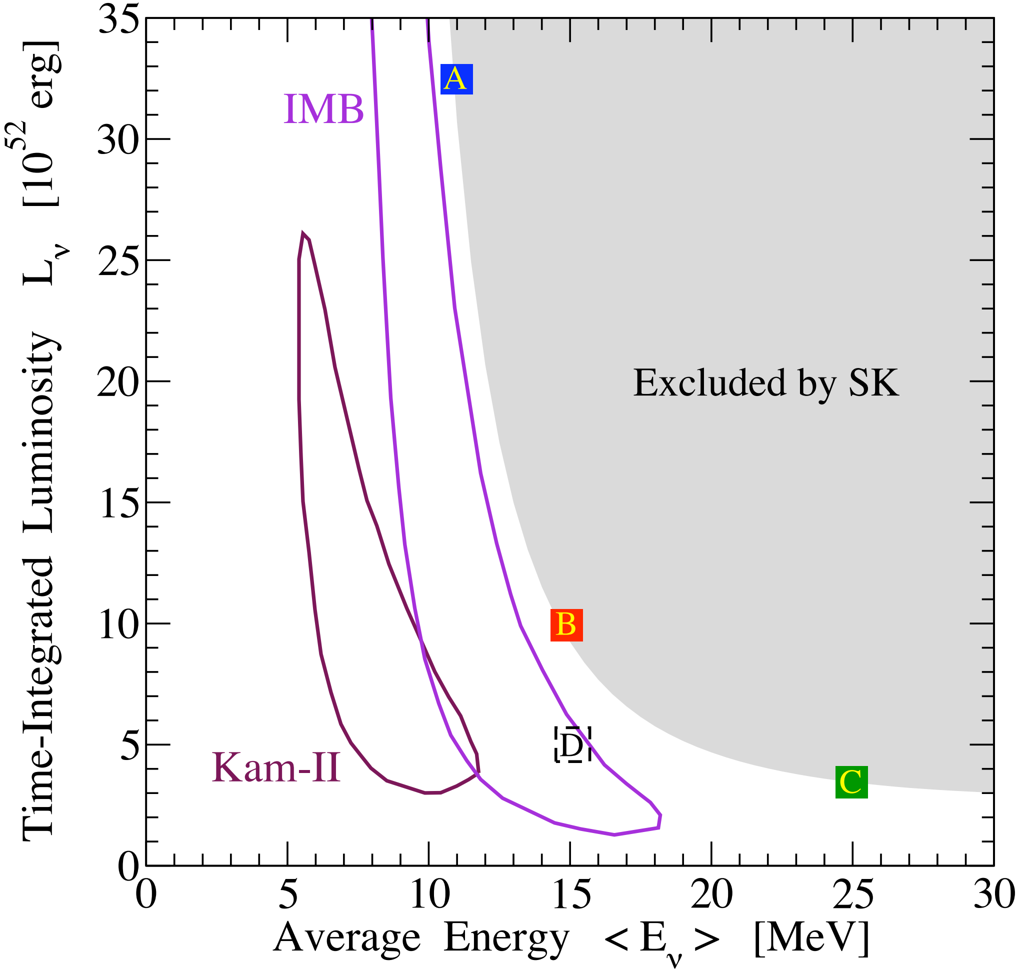
Limits on Supernova Neutrino Emission

2003 Super-Kamiokande limit:
$\Phi < 1.2\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (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)

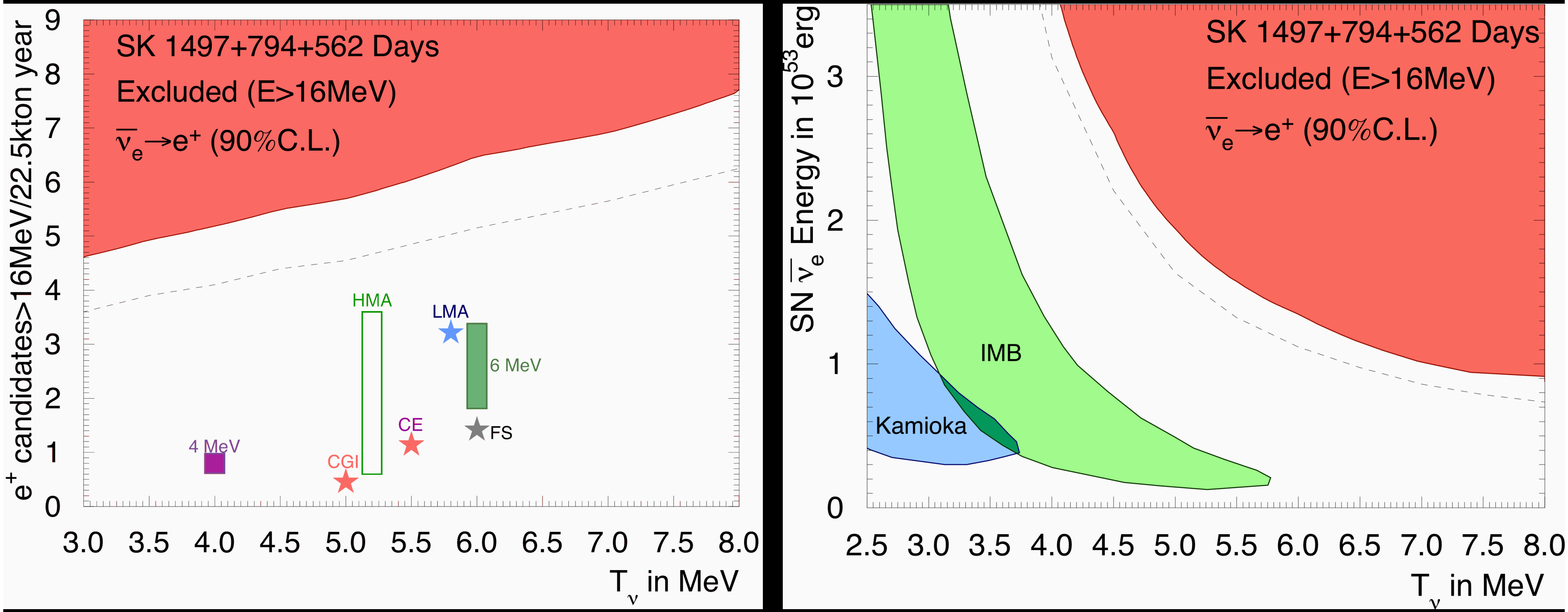


Yuksel, Ando, Beacom (2006);
SN 1987A fits from Jegerlehner, Neubig, Raffelt (1996)

New 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

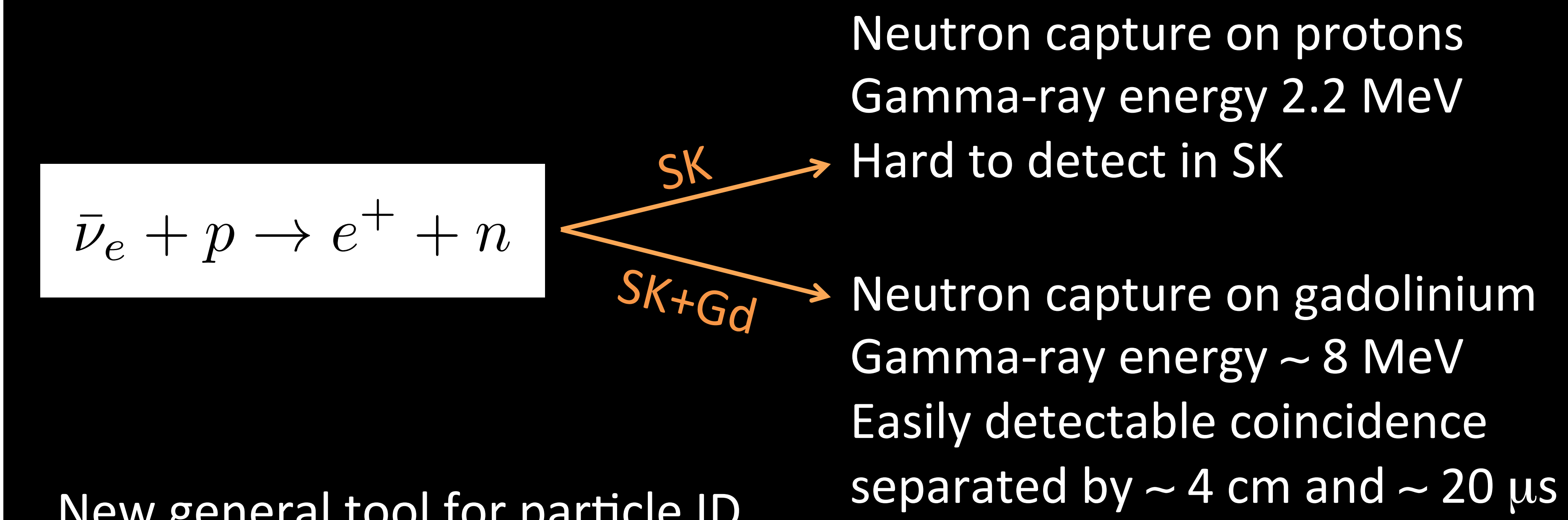
Emerging: Gadolinium in Super-Kamiokande?

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



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

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

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

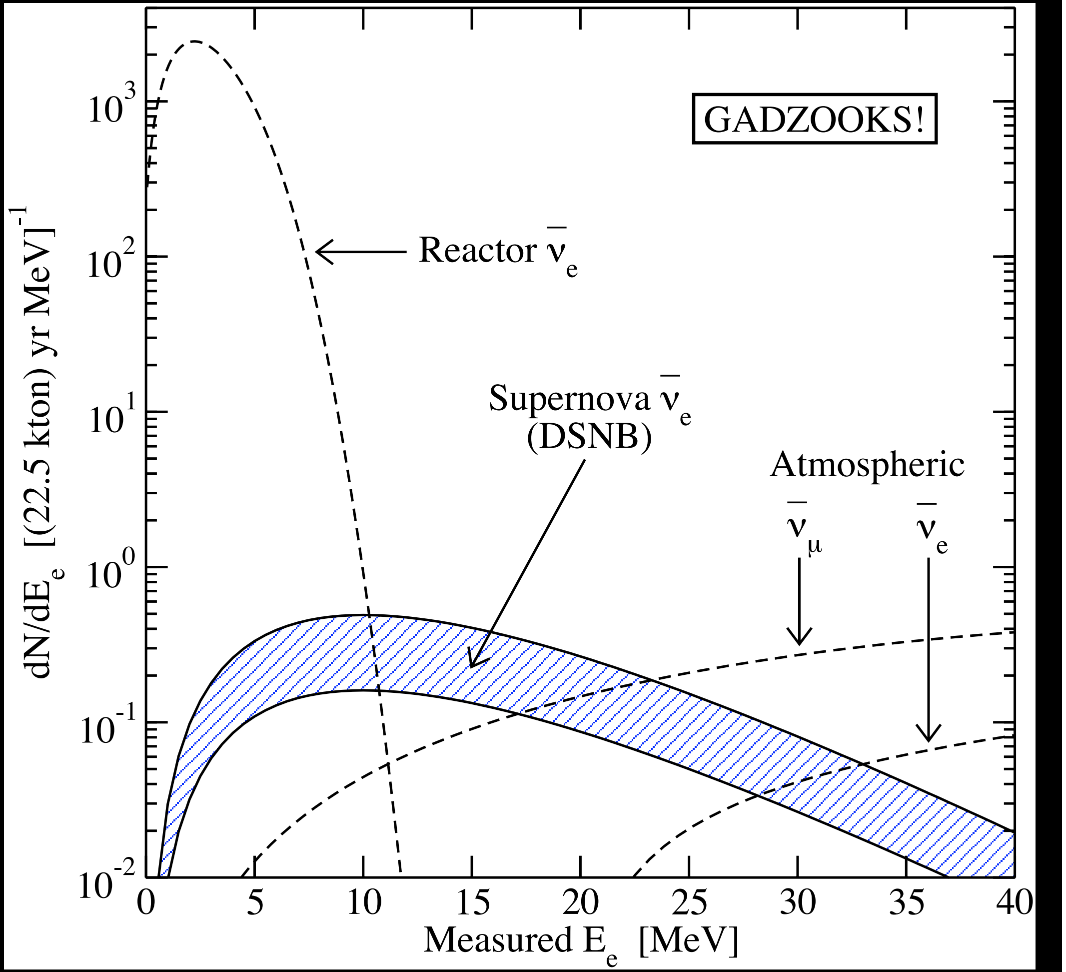
Solar neutrinos:
eliminated

Spallation daughter decays:
essentially eliminated

Reactor neutrinos:
now a visible signal

Atmospheric neutrinos:
significantly reduced

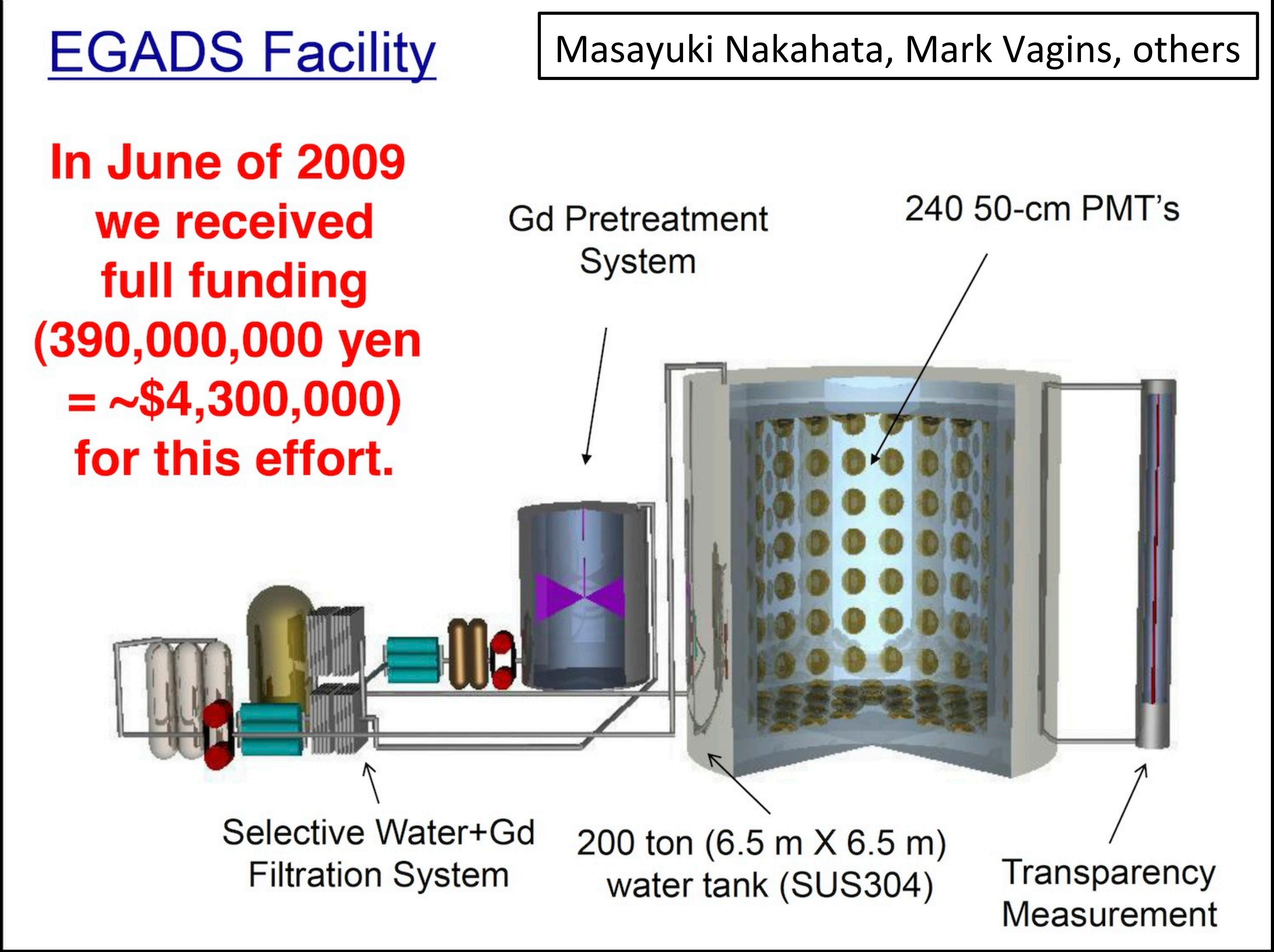
DSNB:
More signal, less background!



Beacom, Vagins (2004)

(DSNB predictions now at upper edge of band)

EGADS Proposal

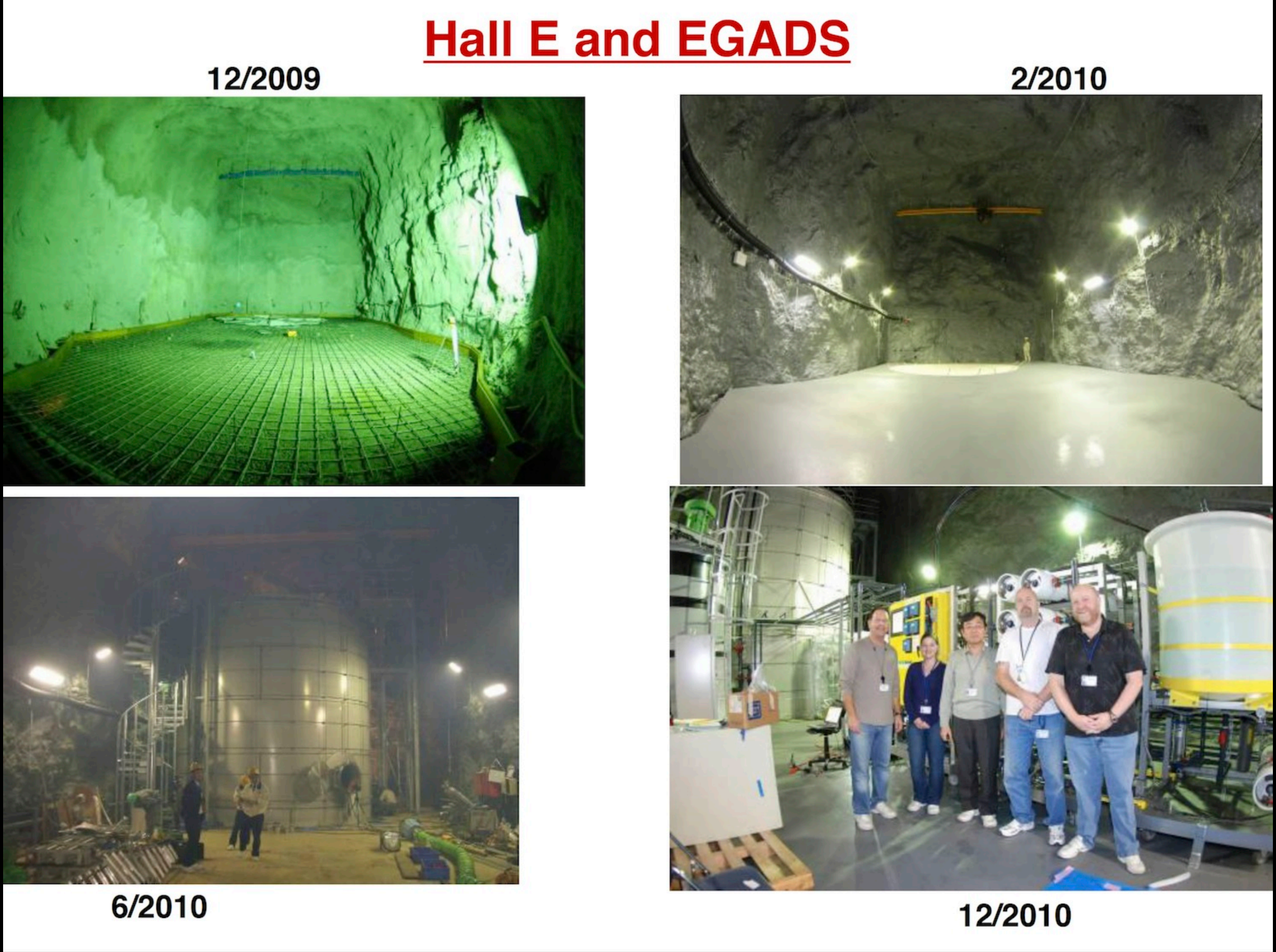


EGADS Facility

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

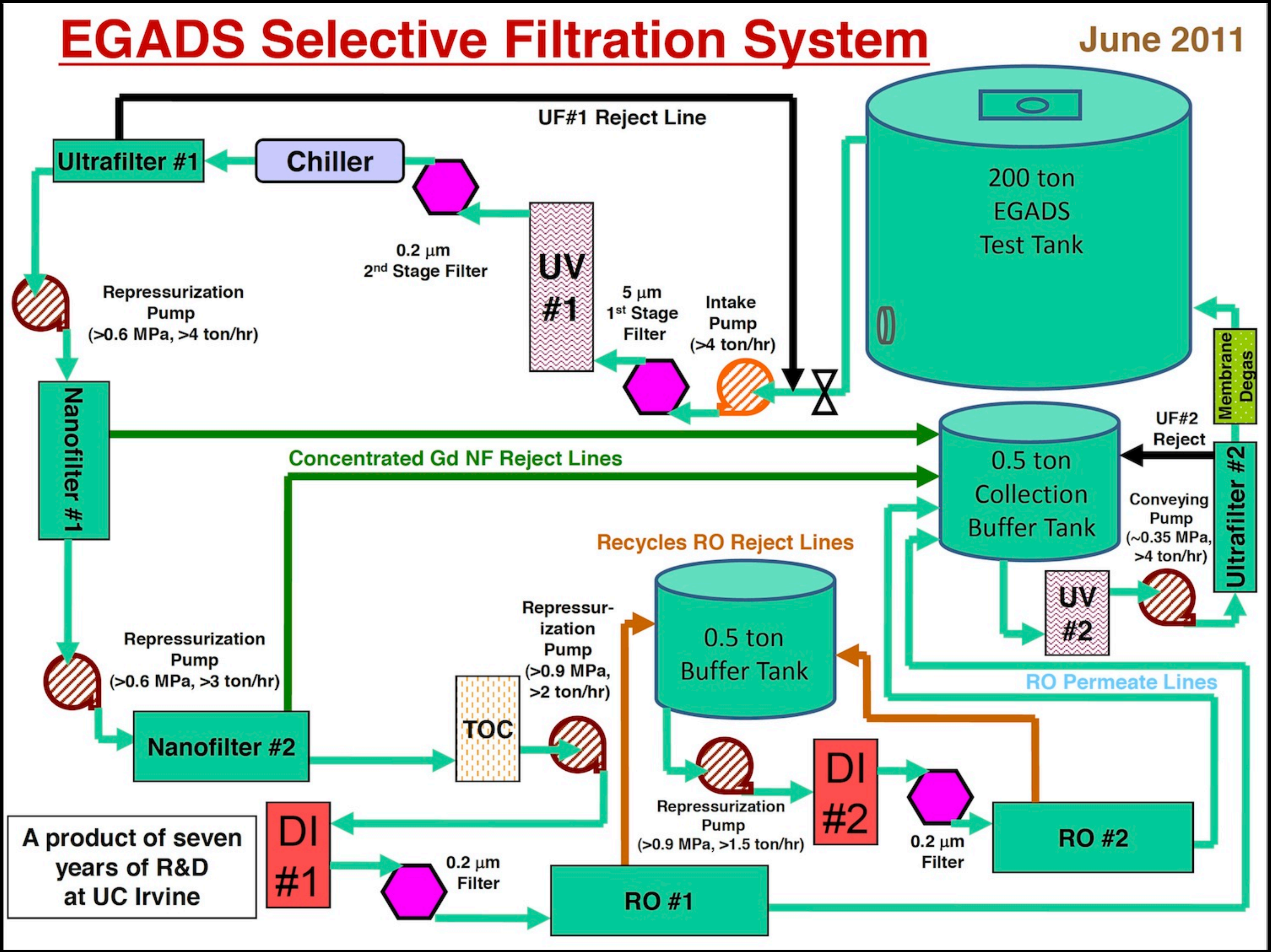
6/2010

12/2010

Mad Scientist at Work in Underground Lair

Adding 383 grams $Gd_2(SO_4)_3$ 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

On track for full test of EGADS with gadolinium water

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

Broader Vision

Understanding neutrino properties and interactions
is essential to nuclear and particle physics

Understanding neutrino production and presence
is essential to astrophysics and cosmology

Active synthesis and exploitation of extreme scales
will bring a new era of precision … *and discovery*

Center for Cosmology and AstroParticle Physics

CCAPP

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

New faculty 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