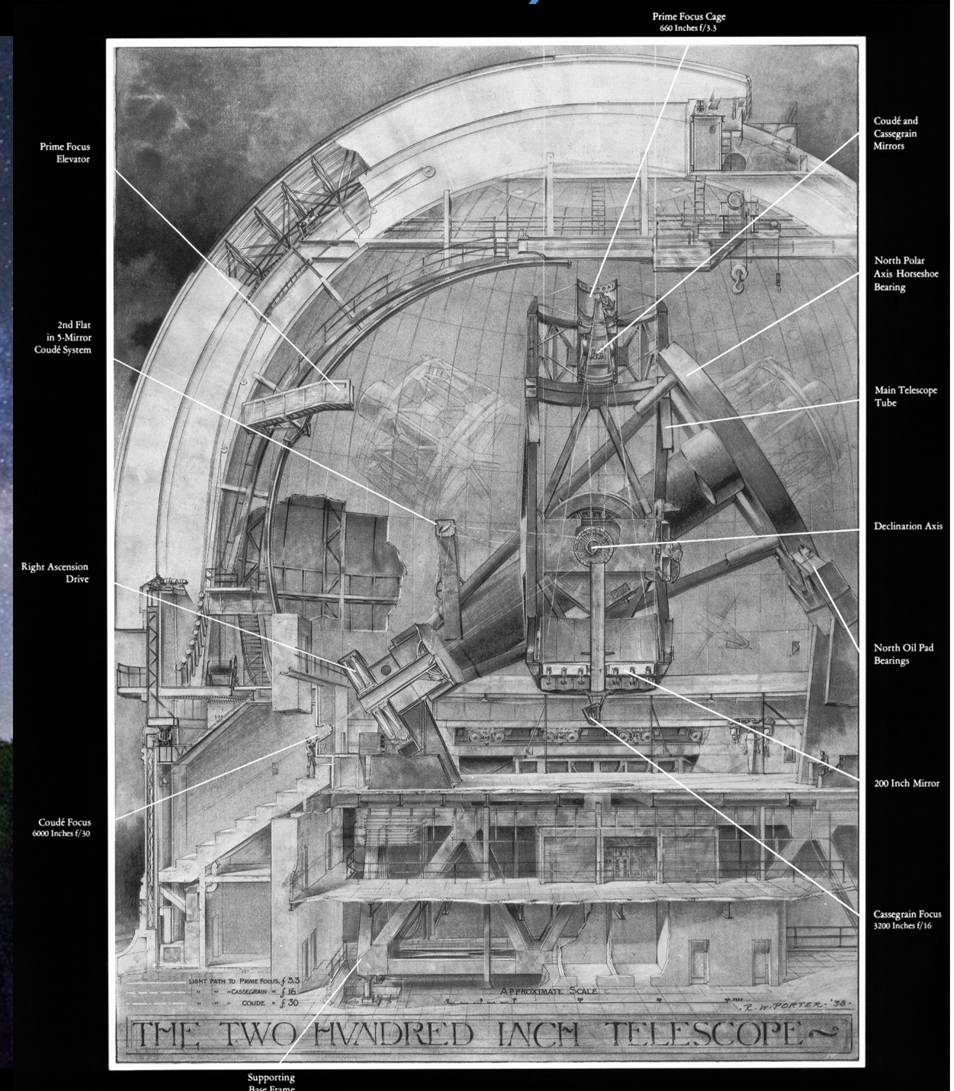
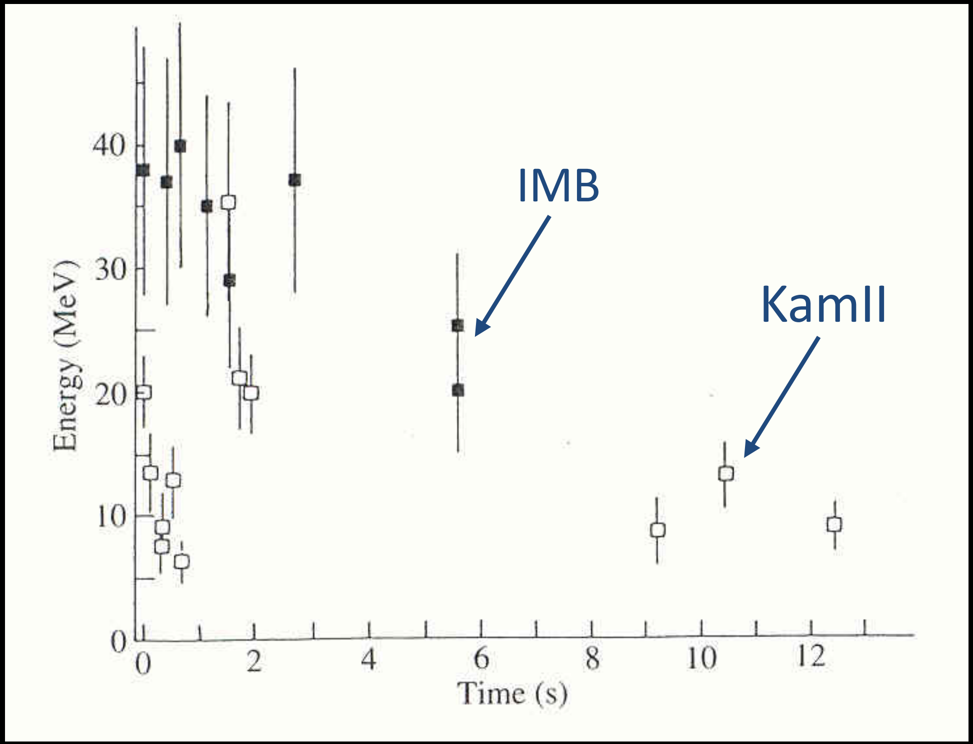
Neutrinos From Supernovae

John Beacom, The Ohio State University



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

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

What Does This Leave Unknown?

Total energy emitted in neutrinos?
Partition between flavors?
Emission in other particles?
Spectrum of neutrinos?
Neutrino mixing effects?
⋮
Supernova explosion mechanism?
Nucleosynthesis yields?
Neutron star or black hole?
Electromagnetic counterpart?
Gravitational wave counterpart?
⋮
and much more!

Plan of the Talk

Introduction: Three detection modes

Revolutionizing MeV neutrino astronomy

Milky Way burst

Nearby galaxy mini-burst

Diffuse Supernova Neutrino Background

Concluding perspectives

Introduction: Three Detection Modes

Basic Features of MeV Neutrino Detection

Detectors must be massive:

Effectiveness depends on volume, not area

Example signals:

$$\nu + e^- \to \nu + e^-$$

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

Detectors must be quiet:

Need low natural and induced radioactivities

Example background:

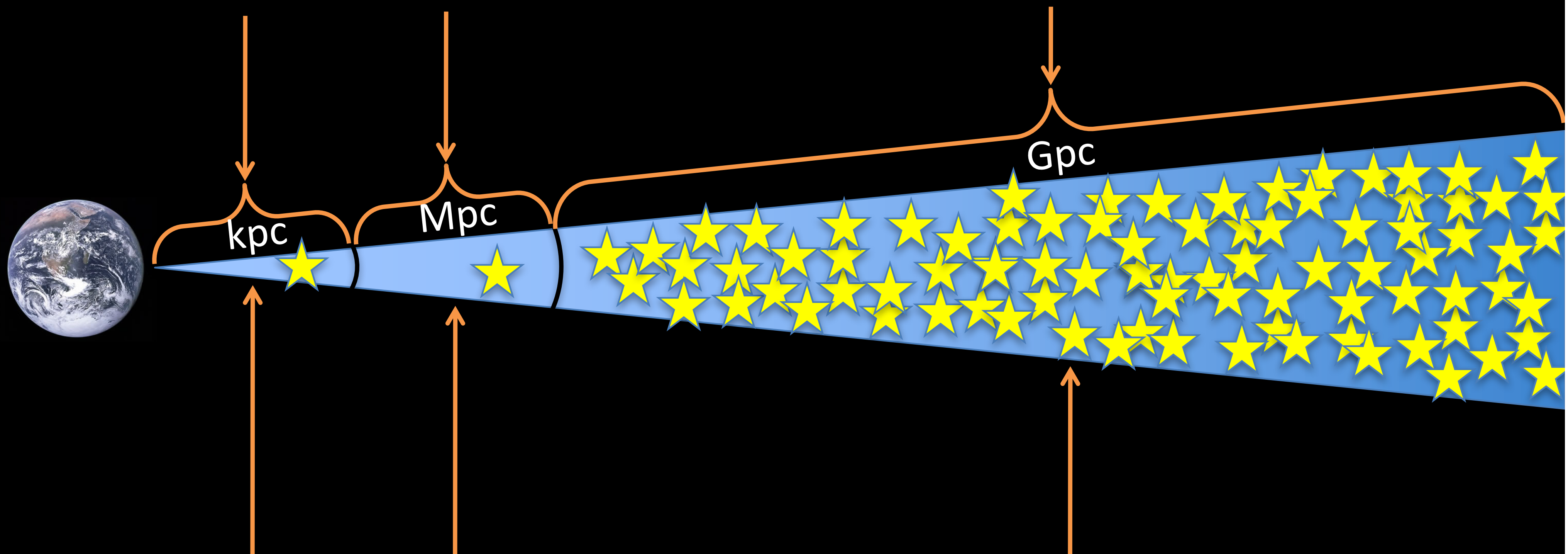
$$A(Z, N) \to A(Z+1, N-1) + e^- + \bar{\nu}_e$$

Distance Scales and Detection Strategies

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB



Rate ~ 0.01/yr

high statistics,
all flavors

Rate ~ 1/yr

object identity,
burst variety

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

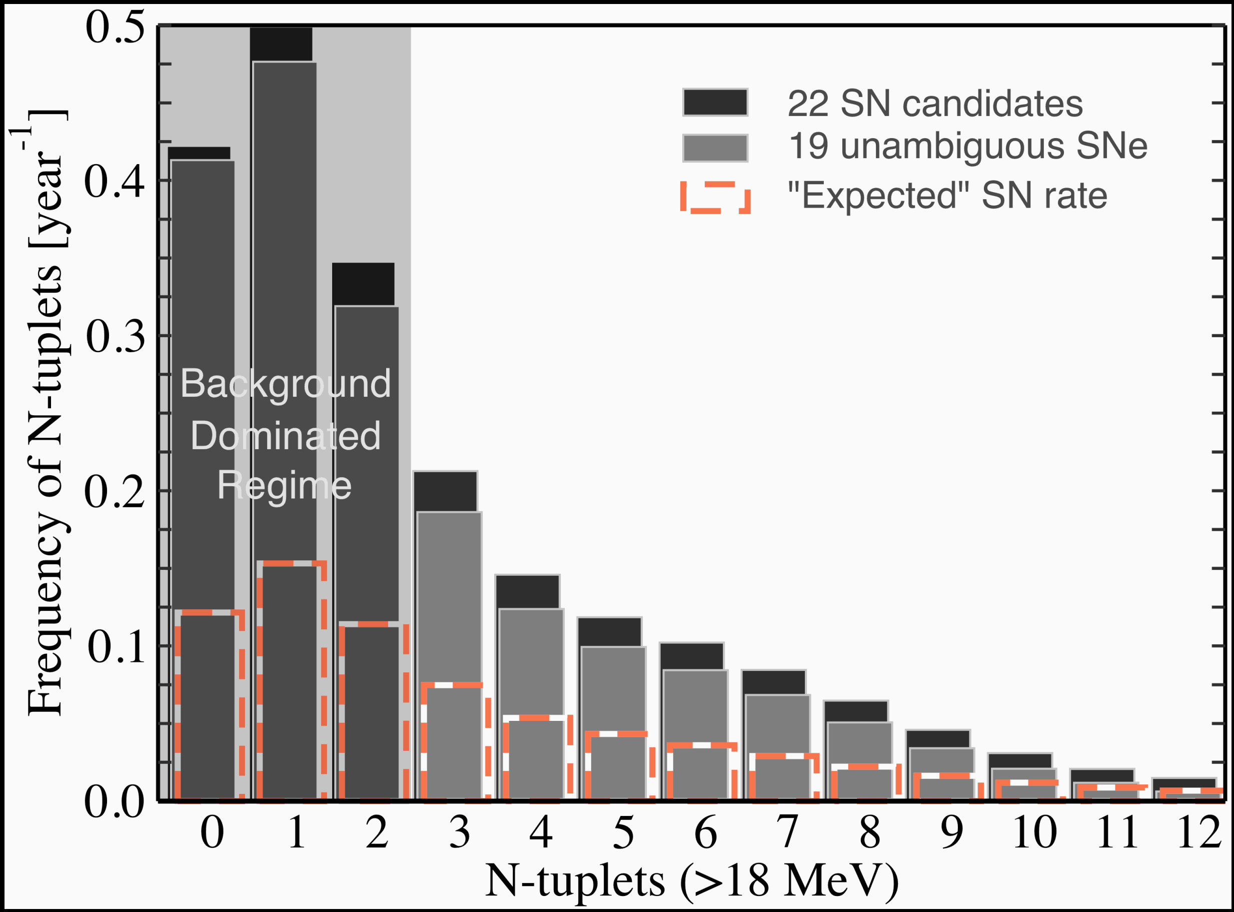
Much larger or better detectors are being proposed now

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

~ 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:

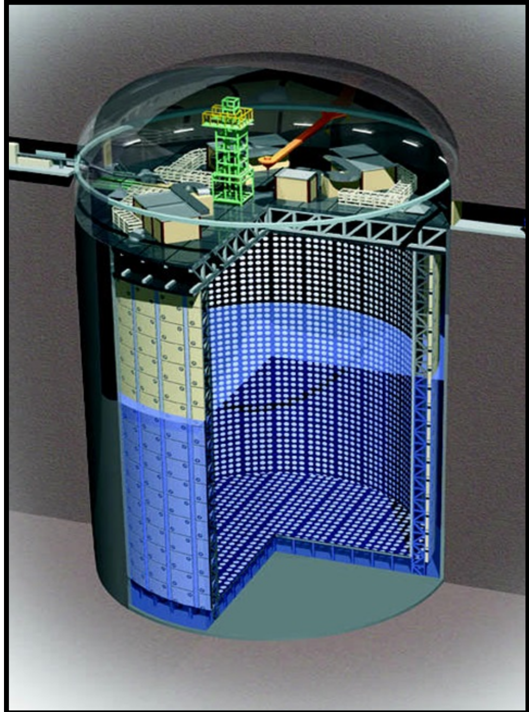
N_{SN} up by ~ 100 M_{det} up by ~ 10 $1/D^2$ down by ~ 10^{-10}

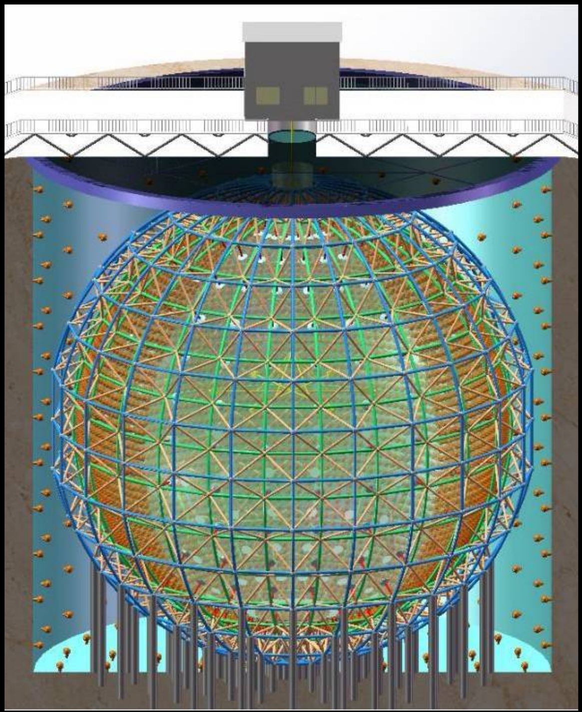
DSNB event rate in Super-Kamiokande is a few per year

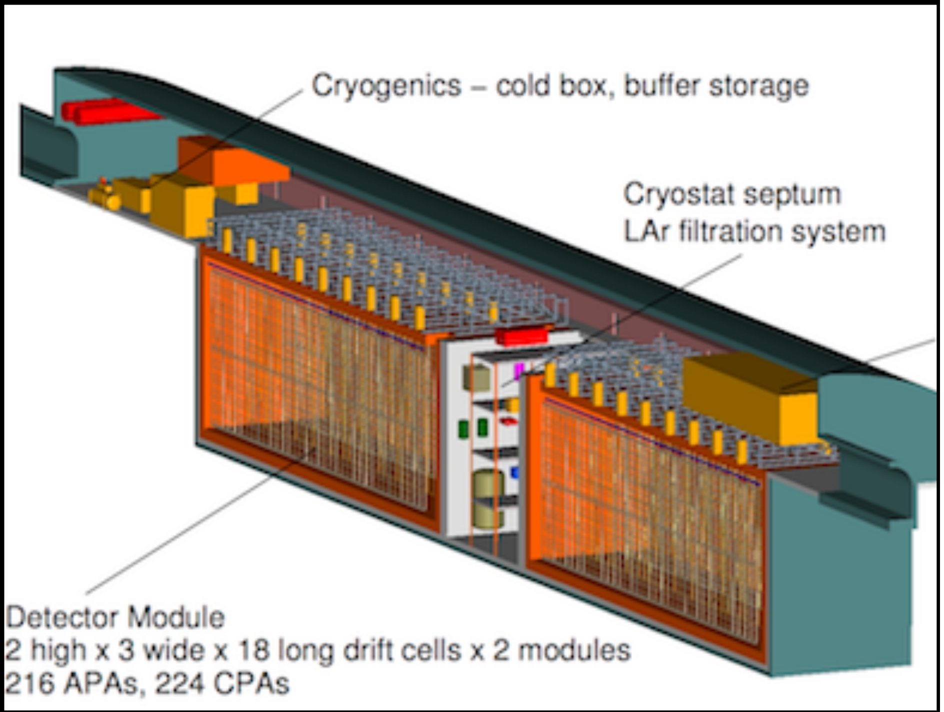
Revolutionizing MeV neutrino astronomy

First: Get Multi-kton-Scale Neutrino Detectors

Super-K	JUNO	DUNE







32 kton water	20 kton oil	34 kton liquid argon
Japan	China	United States
running	*building*	*proposing*

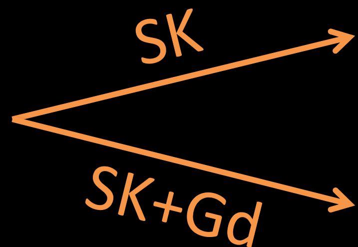
Excellent prospects for coverage of all neutrino flavors

Second: Enable Super-K Selection of Nuebar

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

Fate of the GADZOOKS! Proposal

For about 10 years:

Vagins and colleagues developed experimental aspects

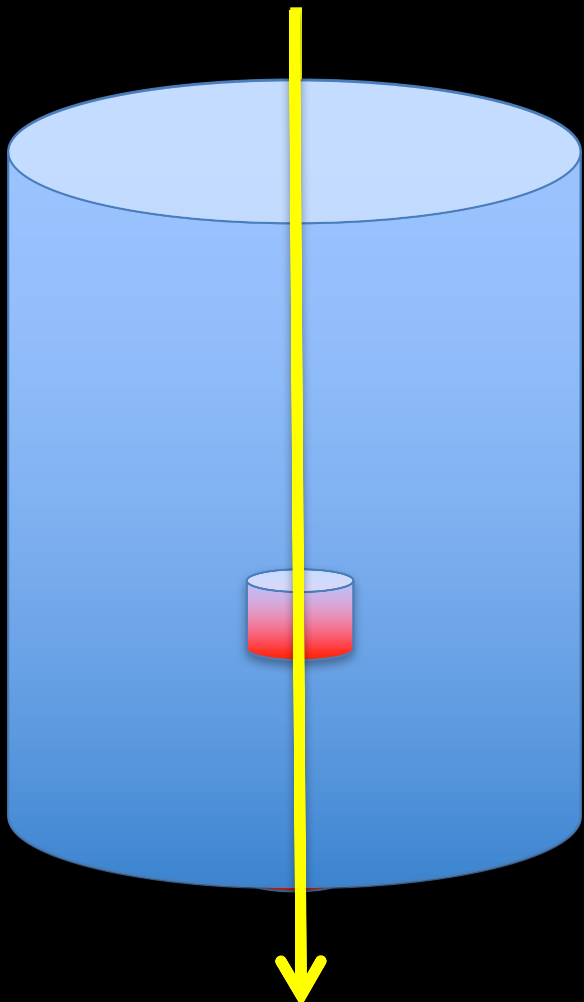
Beacom and colleagues developed theoretical aspects

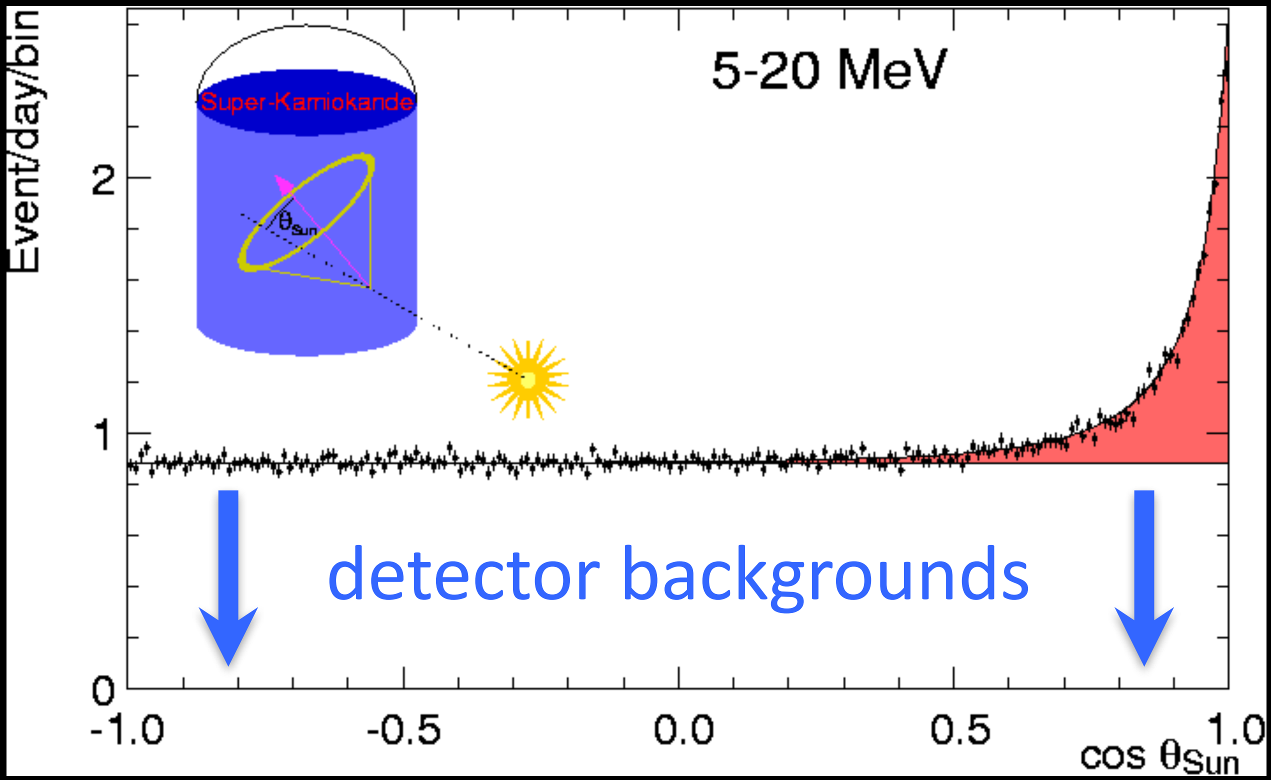
Super-K 2015: Yes

[41] Ref. [4] proposed adding a 0.2% gadolinium solution into the SK water. After exhaustive studies, on June 27, 2015, the SK Collaboration formally approved the concept, officially initiating the SuperK-Gd project, which will enhance anti-neutrino detectability (along with other physics capabilities) by dissolving 0.2% gadolinium sulfate by mass in the SK water.

Will greatly increase sensitivity for many studies

Third: Remove Spallation Backgrounds

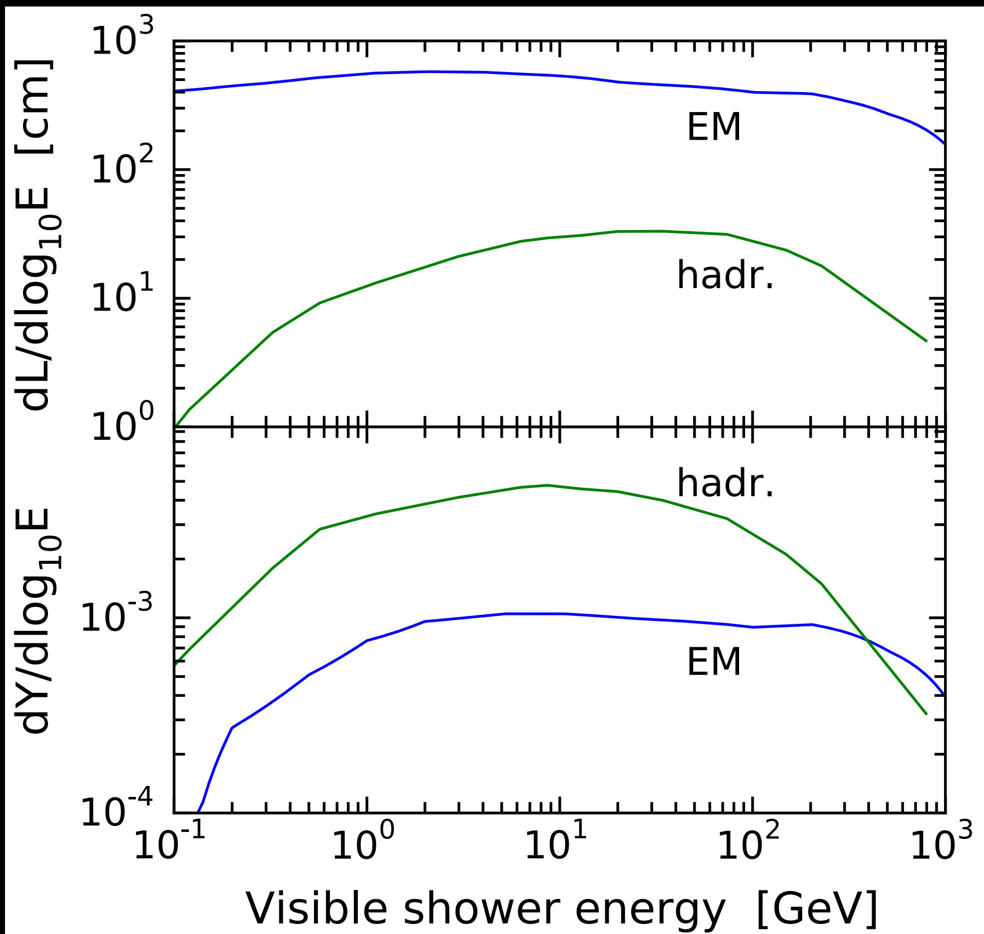


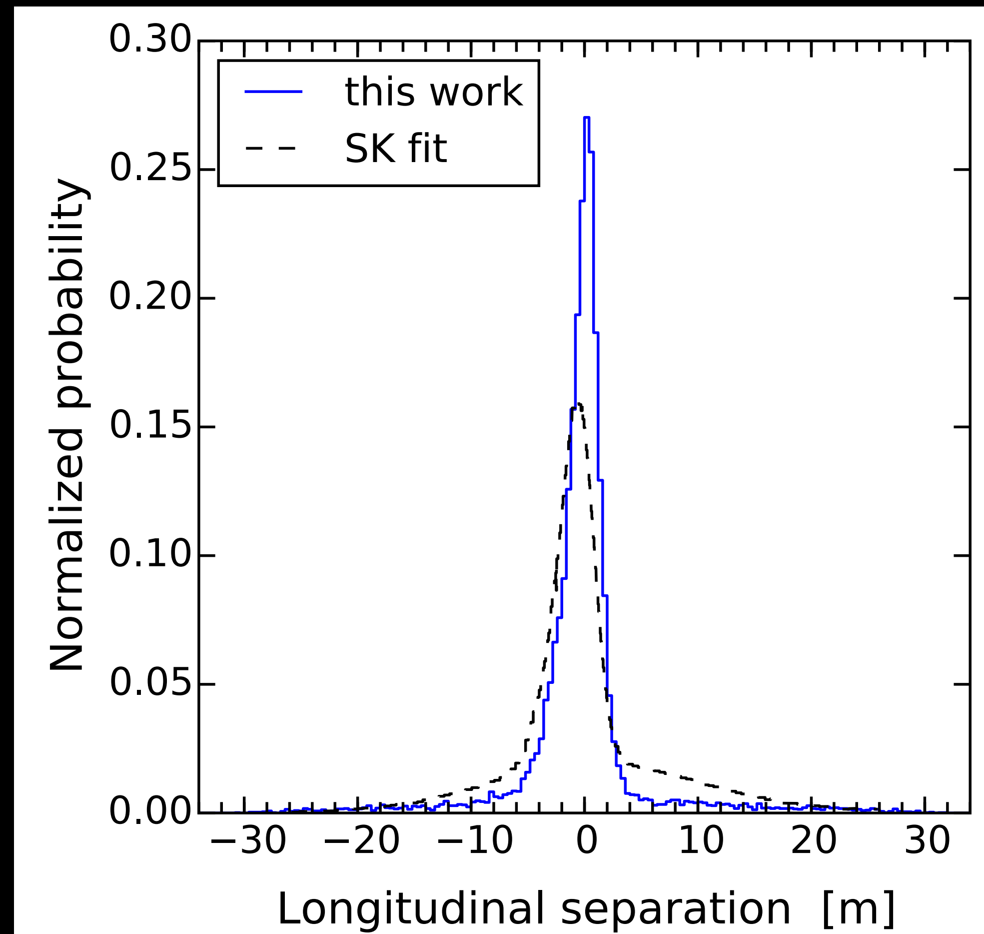


Super-K is already adopting Li-Beacom techniques

Expect to reduce backgrounds in all MeV detectors by ~ 10

Localizing Spallation Production





Li and Beacom 2015a,b

Almost all isotopes are produced in individual showers

These showers can be localized by their Cherenkov light

Milky Way Burst

The Flavor Problem

Need all flavors to measure the total emitted energy

Need all flavors to test effects of neutrino mixing

$\bar{\nu}_e$ Precise ($\sim 10^4$ events in Super-K)

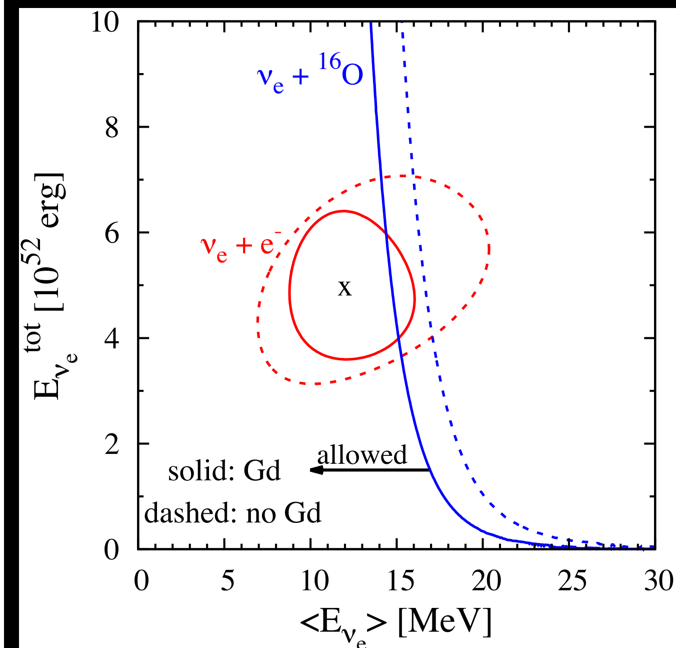
$\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$ Inadequate ($\sim 10^2$ events in oil)

ν_e Inadequate ($\sim 10^2$ events in Super-K)

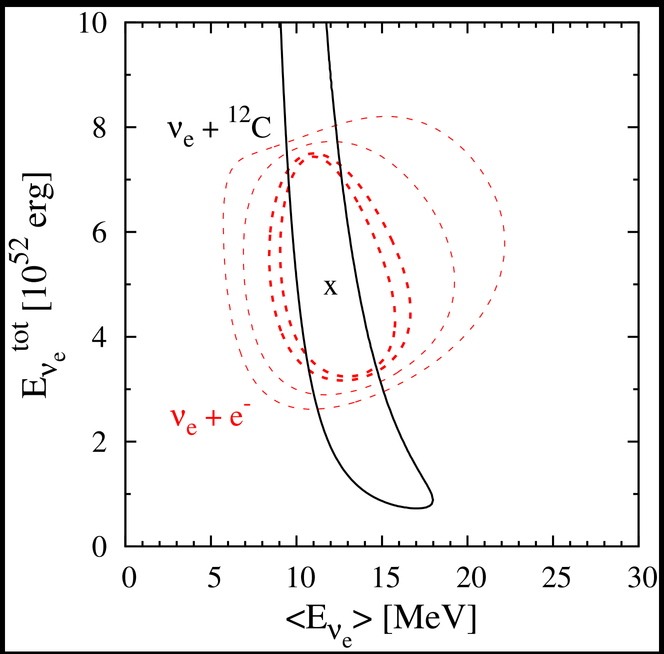
How will we ensure complete flavor coverage?

Focus on Measuring Nue

Super-K	JUNO	DUNE
~ 10^2 events	~ 10^2 events	~ 10^3 events



Laha and Beacom 2013



Laha and Beacom 2014

? ?

DUNE uncertain due to *cross section*, detector response

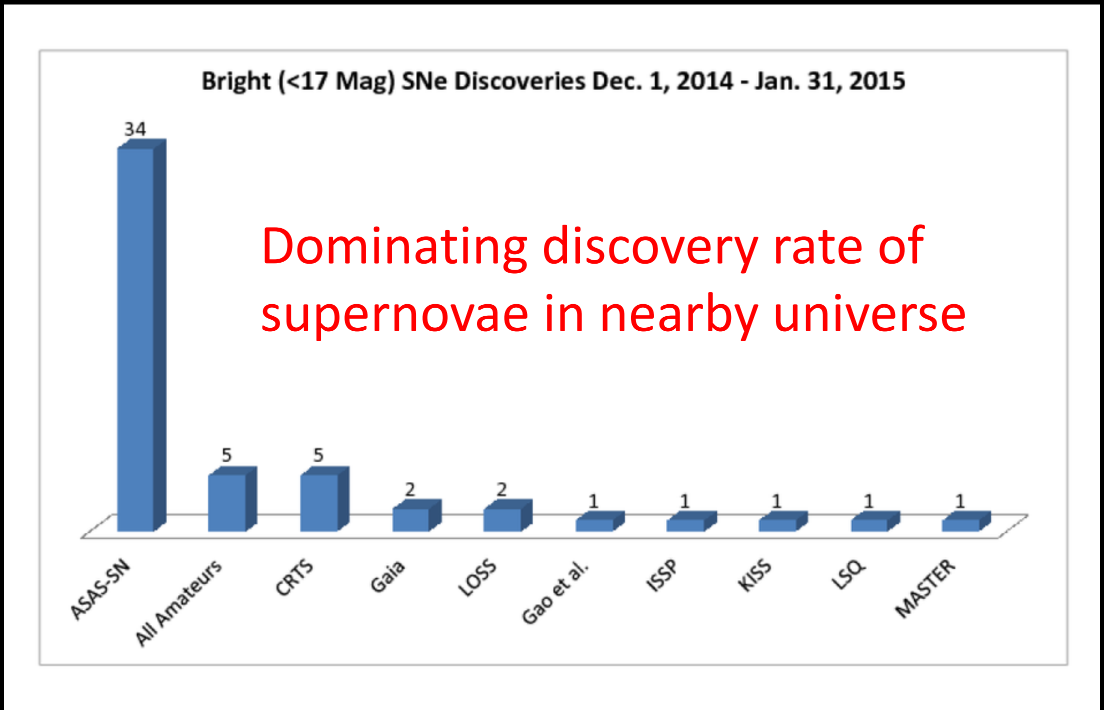
Need better understanding of neutrino+nucleus!

The Waiting Problem

Will we be ready to detect a Milky Way supernova?

All-Sky Optical Monitoring to Leverage

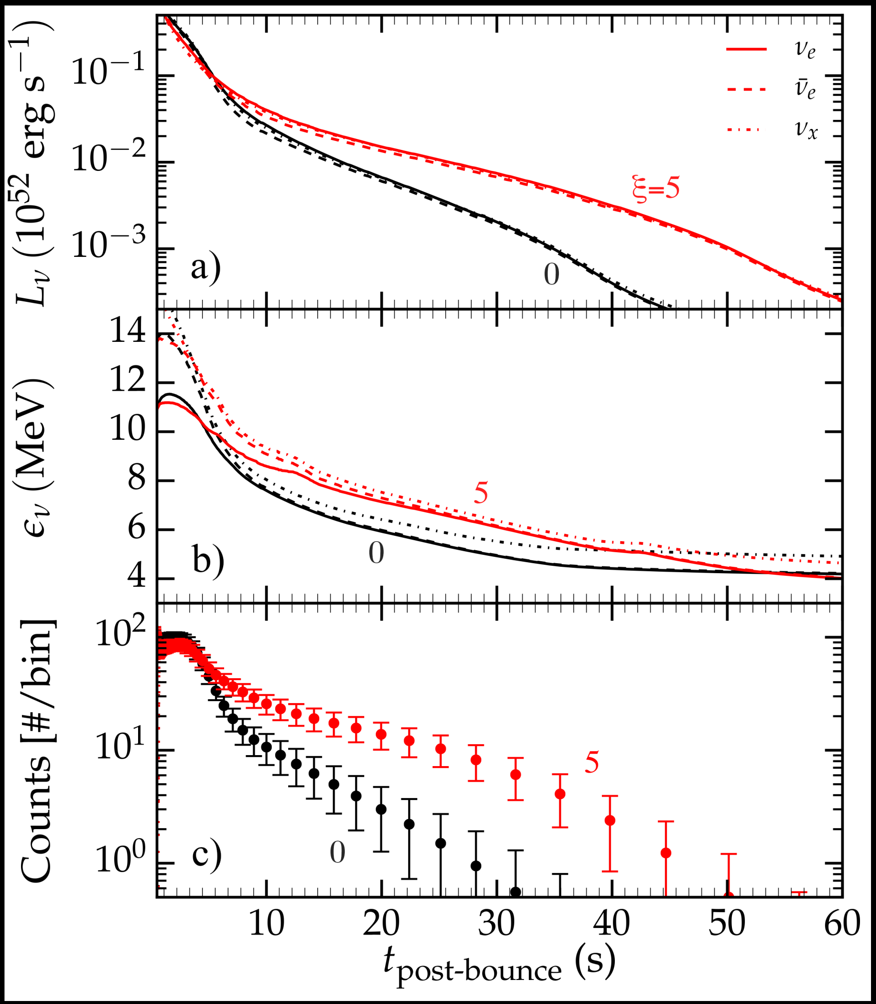
Connection to astronomy crucial, but optical data are lacking
Enter OSU's "Assassin" (All-Sky Automated Survey for SN)



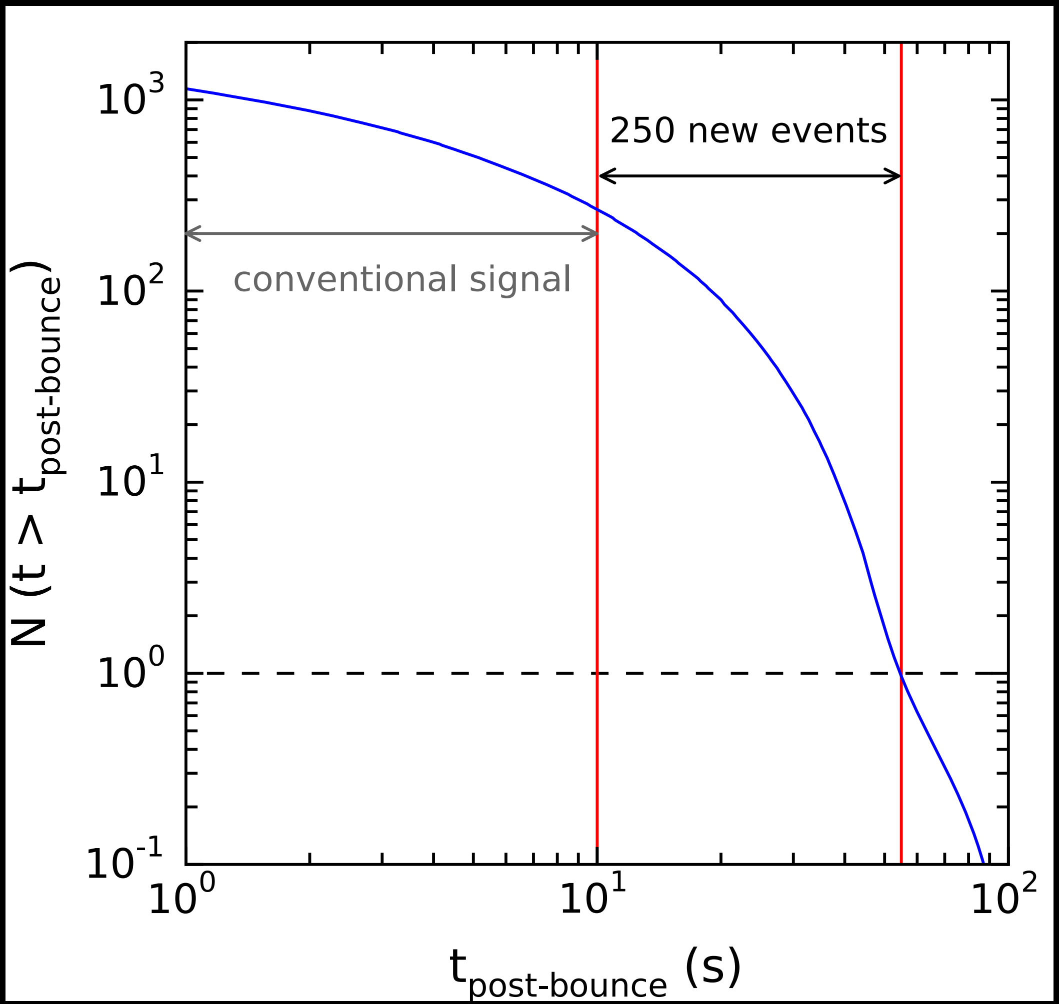
Discovering and monitoring optical transients to 17^{th} mag.
See also Adams, Kochanek, Beacom, Vagins, Stanek (2013)

The Aftermath

What are the conditions in the proto-neutron star?



Horowitz et al. (2017)

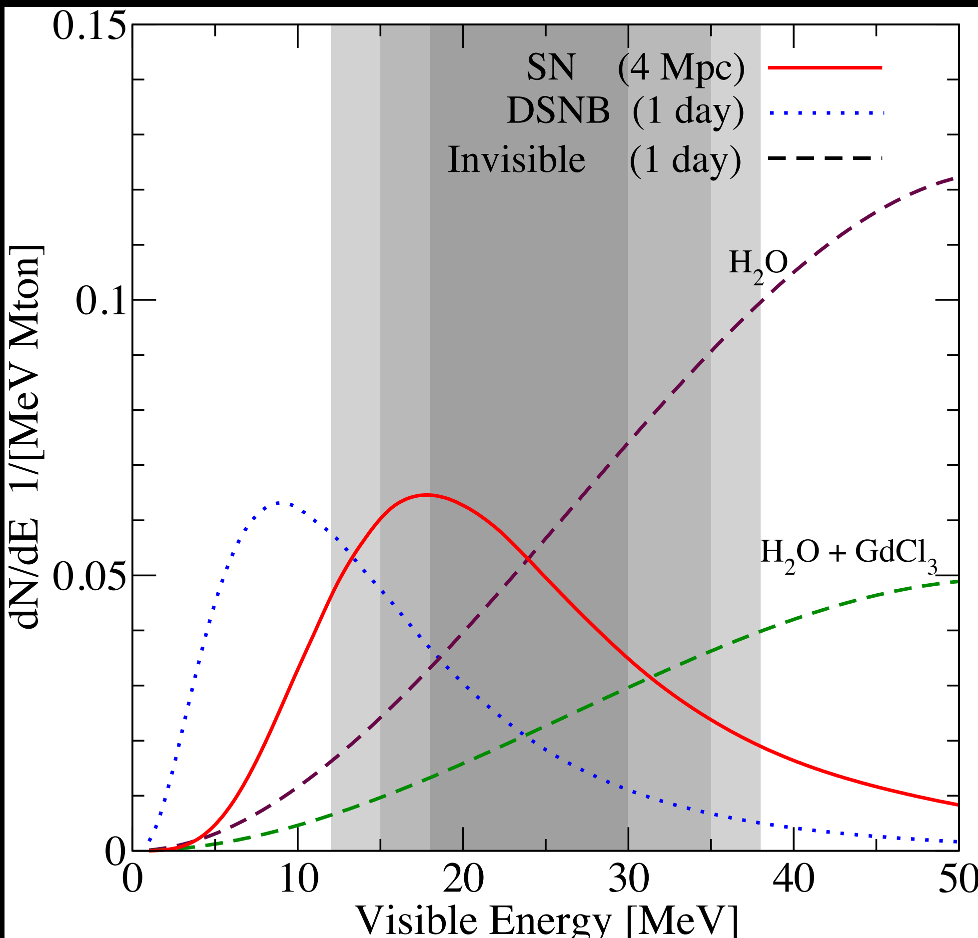


Li, Beacom, Roberts (in prep.)

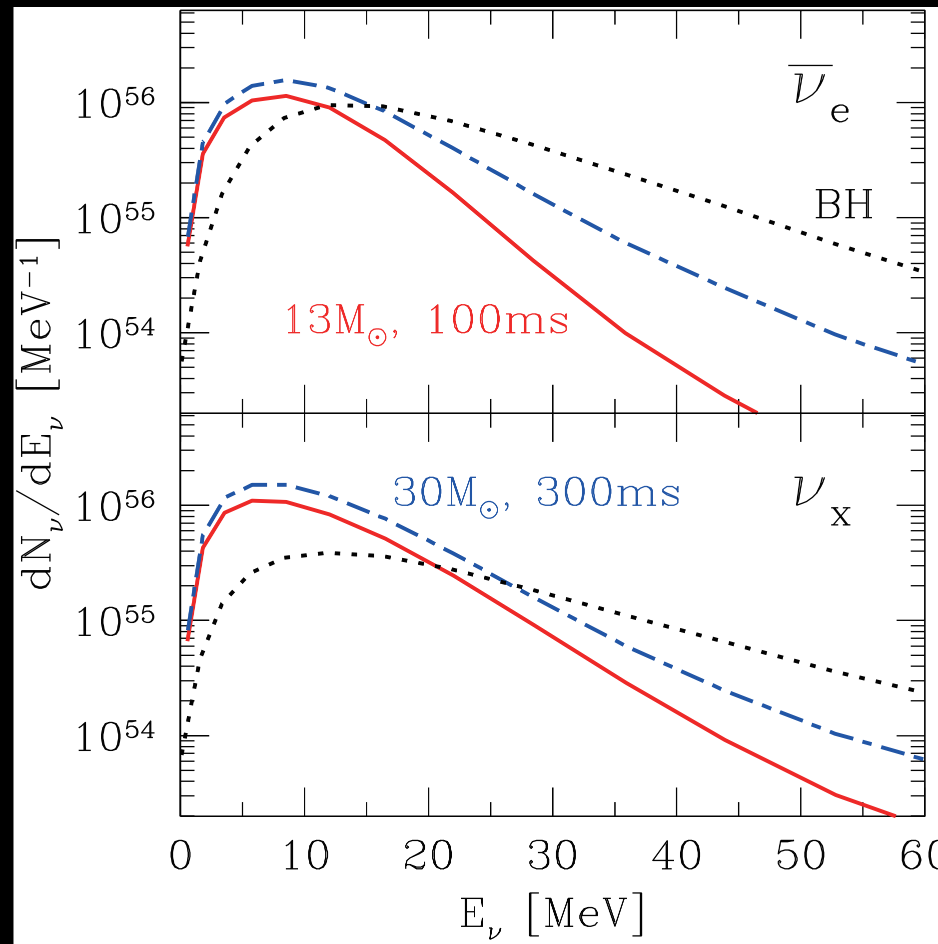
Nearby Galaxy Mini-Burst

The Variations

What are the properties of core collapse in extremes?



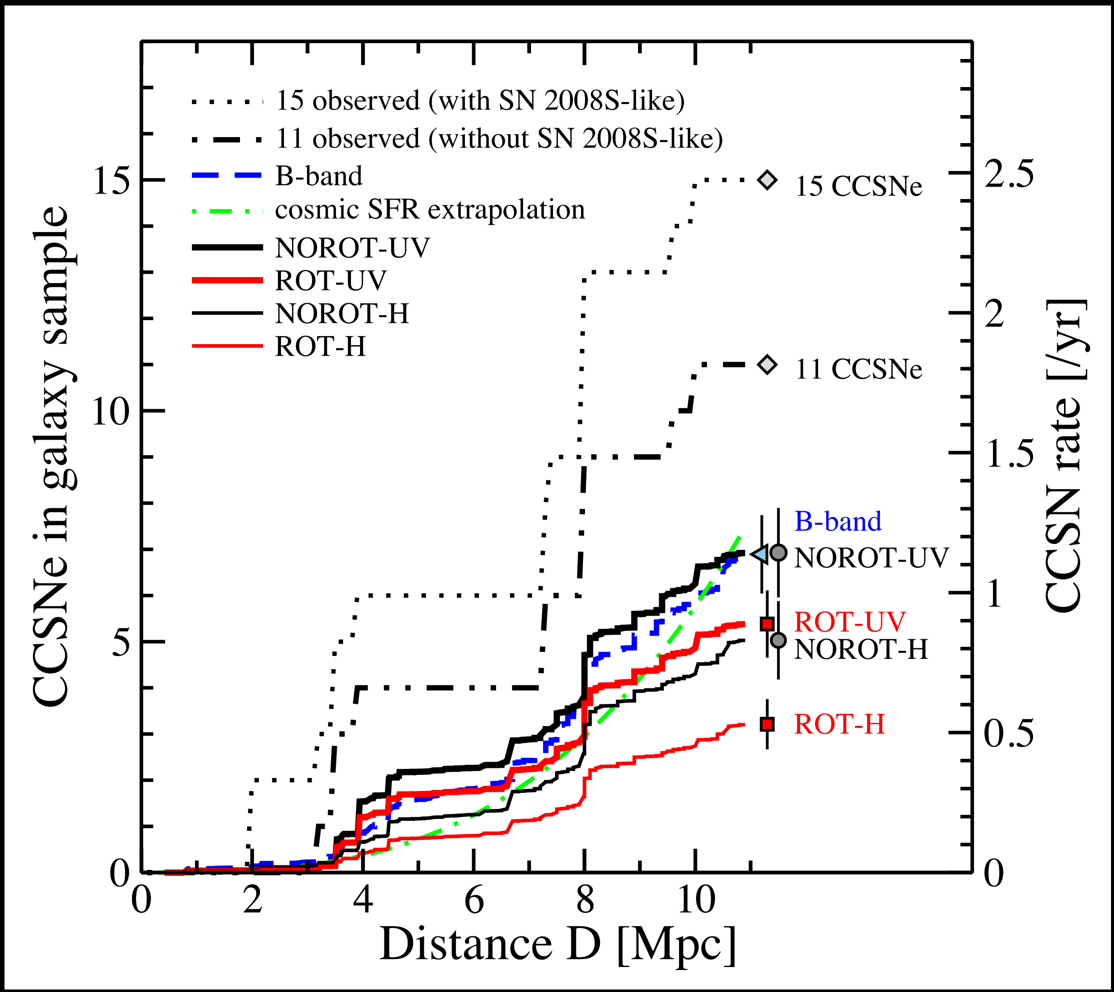
Idea from Ando, Beacom, Yuksel (2005)



Nakazato and collaborators

The Verifications

What are the varieties and rates of transients?



Horiuchi et al. (2013)

Neutrino bright, optically bright:
Core-collapse supernova

Neutrino bright, optically dim:
Core-collapse to black hole

Neutrino dim, optically bright:
Type Ia supernova
Supernova impostor

Neutrino dim, optically dim:
All the time!

Diffuse Supernova Neutrino Background

What Does Burst Detection Leave Unknown?

Average neutrino emission?
Variation between supernovae?
Surprise propagation effects?
⋮
Supernova rate of the universe?
Black hole formation probability?
Surprise sources?
⋮

Theoretical Framework

Signal rate spectrum in detector in terms of measured energy

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

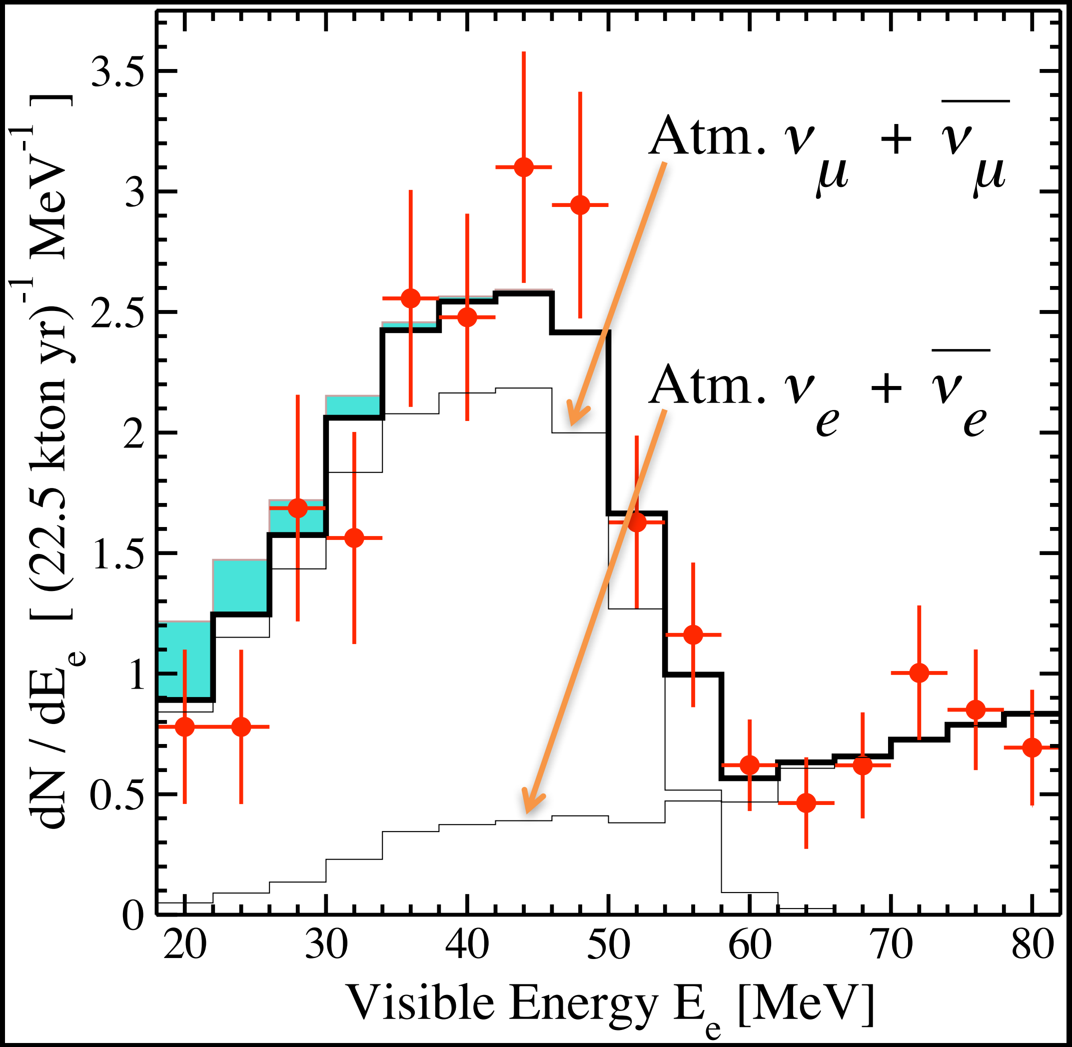
Third ingredient: Detector Capabilities (well understood)

Second ingredient: Core-collapse rate (formerly very uncertain, but now known with good precision)

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

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

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

Benefits of Neutron Tagging for DSNB

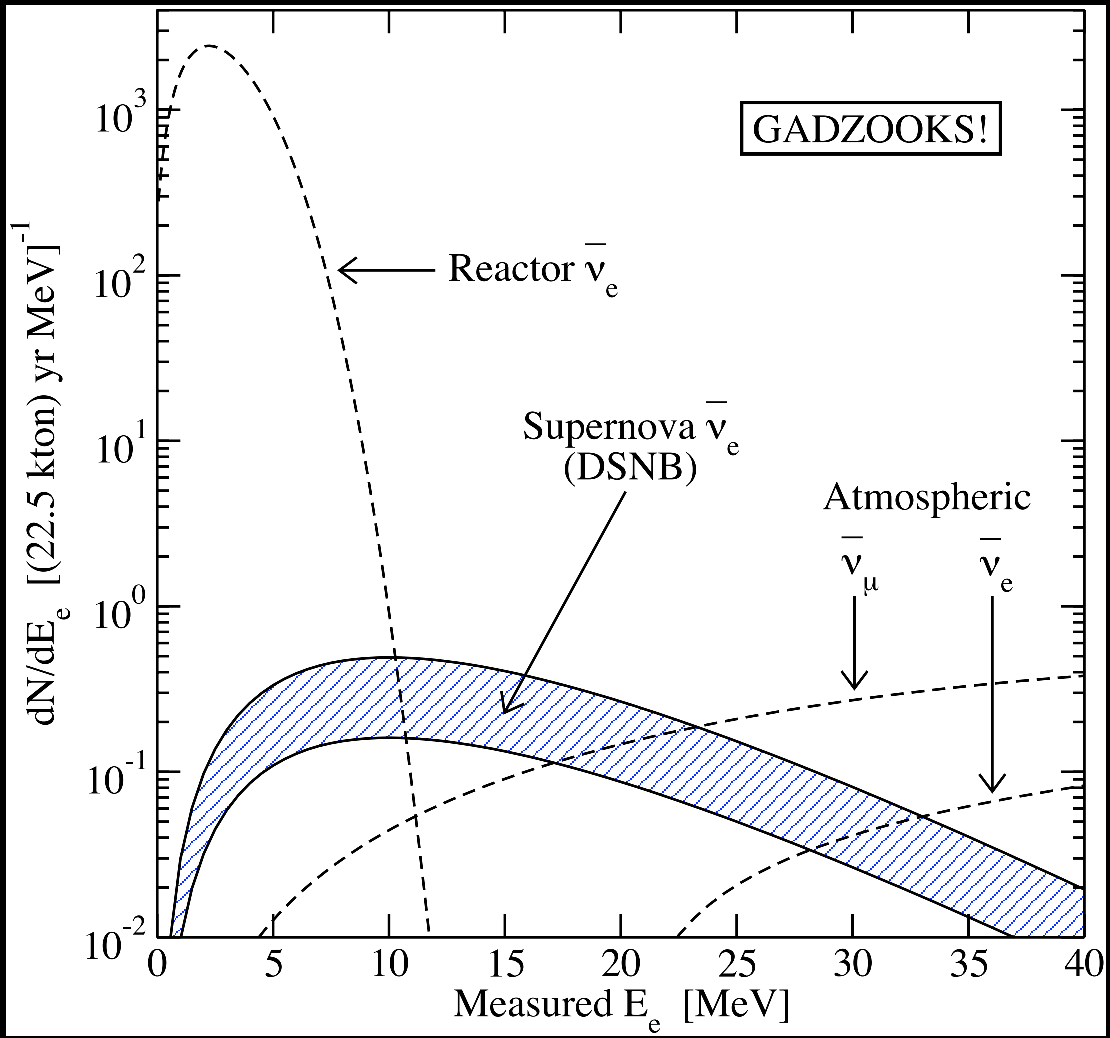
Solar neutrinos:
eliminated

Spallation daughter decays:
essentially eliminated

Reactor neutrinos:
now a visible signal

Atmospheric neutrinos:
significantly reduced

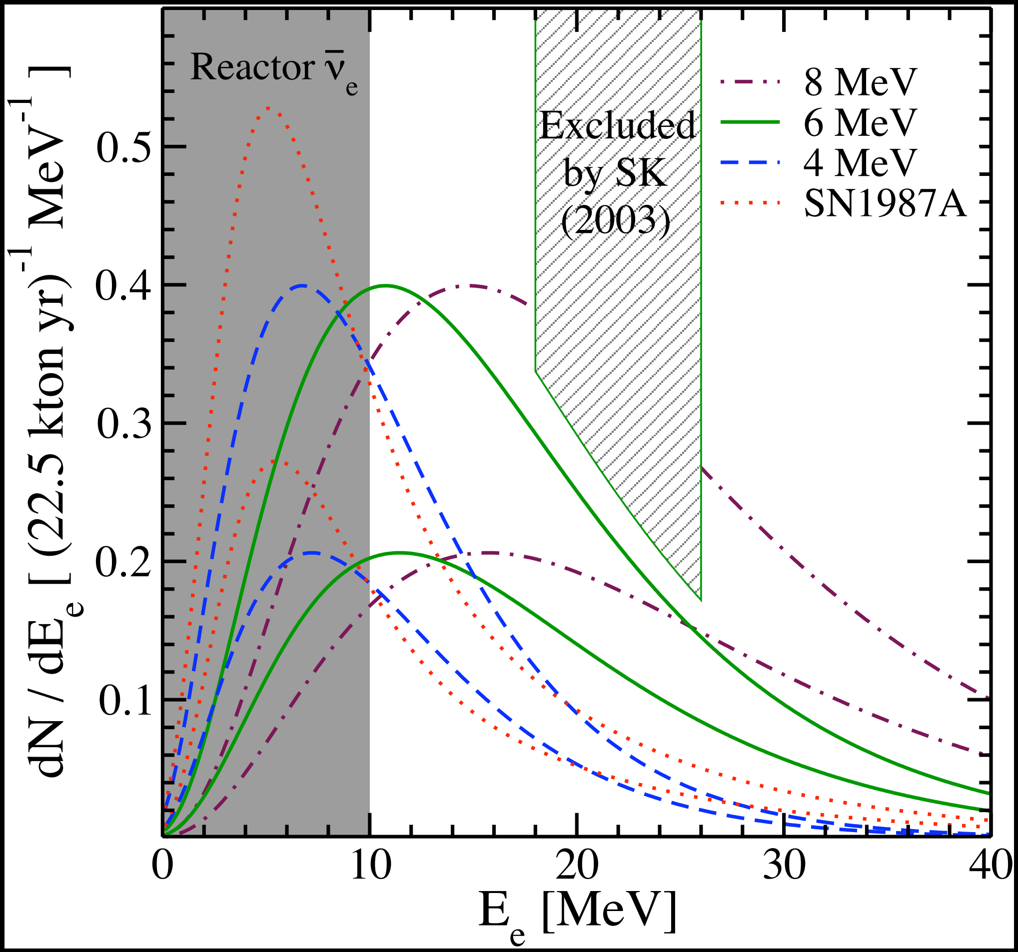
DSNB:
More signal, less background!



Beacom, Vagins (2004)

(DSNB predictions now at upper edge of band)

Super-K With Gd Can Detect the DSNB



Horiuchi , Beacom, Dwek (2009)

Success in Super-K would motivate case for Hyper-K with Gd

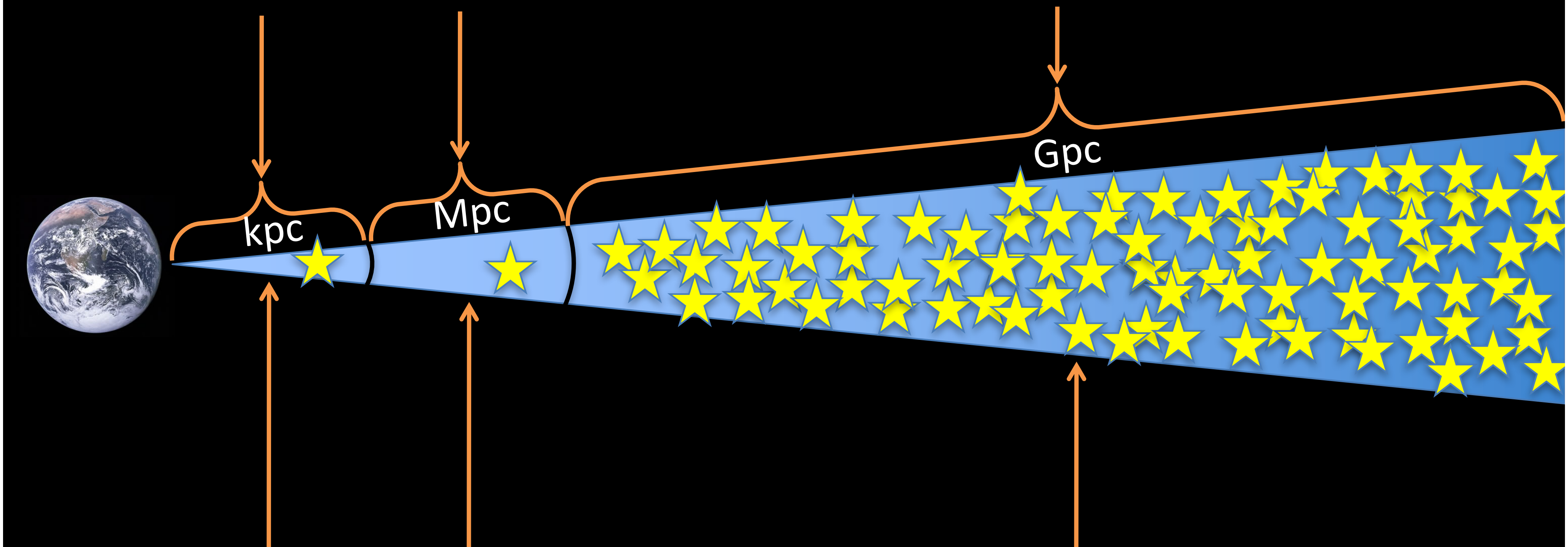
Concluding Perspectives

The Time for Supernova Neutrinos is Now

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

The Time for Neutrino Astronomy is Now

Neutrino Astronomy

MeV—GeV ν

Efforts:
HK and more

Targets:
Solar, SN, more
Surprises

TeV—PeV ν

Efforts:
IceCube and more

Targets:
GRBs, AGN, more
Surprises

EeV—ZeV ν

Efforts:
ANITA and more

Targets:
GZK process
Surprises

Neutrino astronomy must be broad

The Time for Neutrino Science is Now

Neutrino Science

Laboratory ν	Cosmology ν	Astronomy ν
Efforts: Fermilab and more	Efforts: CMB and more	Efforts: IceCube and more
Context: Precision Physics, BSM reach	Context: Precision Cosmology, BSM reach	Context: Transient Astronomy, Multi-messenger

Neutrinos are multi-frontier science

TeVPA 2017

tevpa2017.osu.edu

- August 7–11, Columbus, OH
- Registration and abstract submission are open
- Pre-meeting mini-workshops on Sunday, August 7