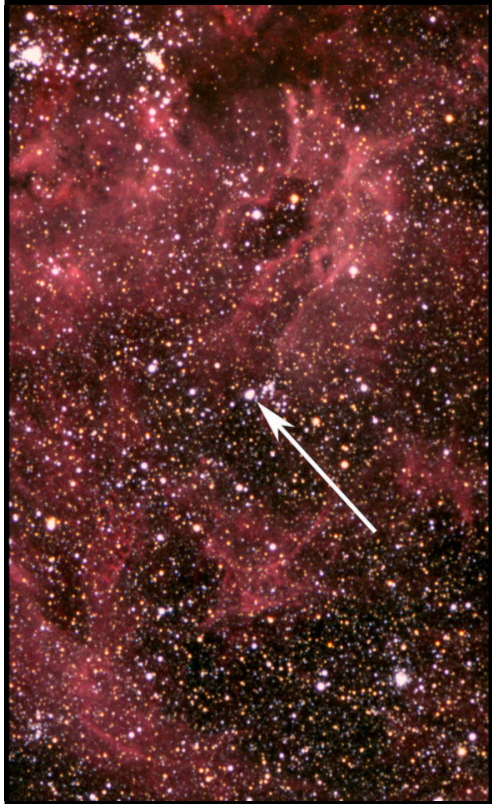
Supernovae and Neutrinos: The Crossroads

John Beacom, The Ohio State University



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

CCAPP

NSF

Gateway: Astrophysics

Neutron stars
Black holes
GW sources
Cosmic rays
Chemical elements
Galaxy feedback

Supernovae

Gateway: Particle Physics

Origin of mass
Mixing, CP violation
Collective effects
Dark matter
New forces
New particles

Neutrinos

Crossroads

Origin of mass
Mixing, CP violation
Collective effects
Dark matter
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New particles

Neutron stars
Black holes
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Supernovae X Neutrinos

Why a Crossroads?

To understand supernovae

only neutrinos can reveal these extreme conditions

To understand neutrinos

only these extreme conditions can reveal particle properties

Crossroads: Past Versus Future

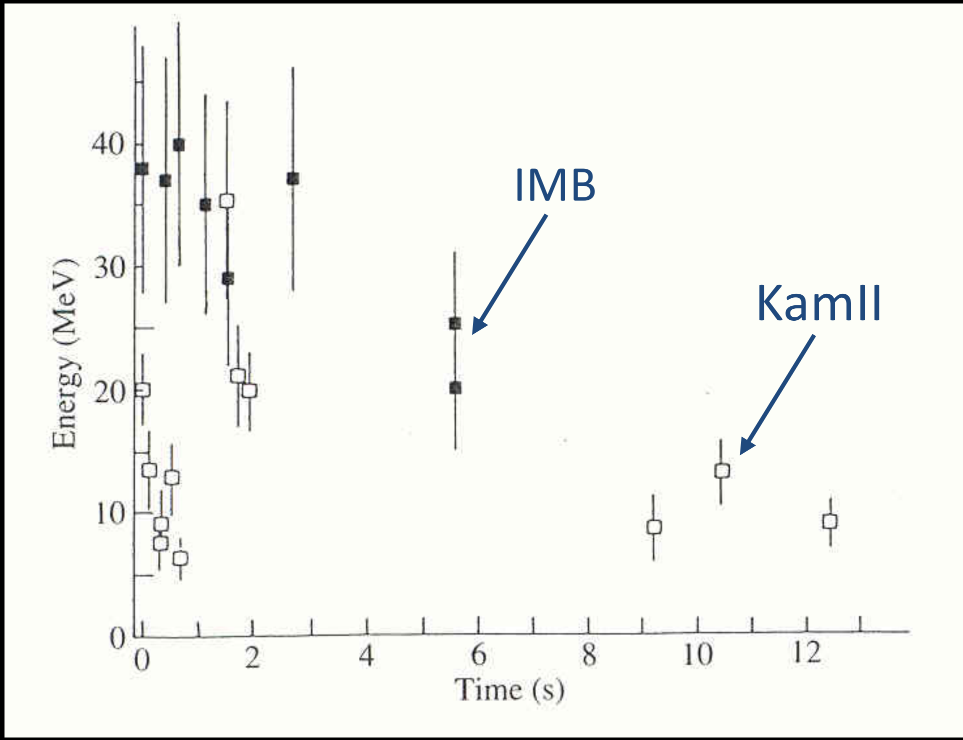
Are we ready?

For Milky Way burst detection?
To precisely detect the DSNB?
To detect extragalactic minibursts?

To advance multimessenger astrophysics?
To probe physics beyond the standard model?
To make neutrino astronomy real?

What should we do differently?

SN 1987A: Our Rosetta Stone



Observation: Type II supernova progenitors are massive stars

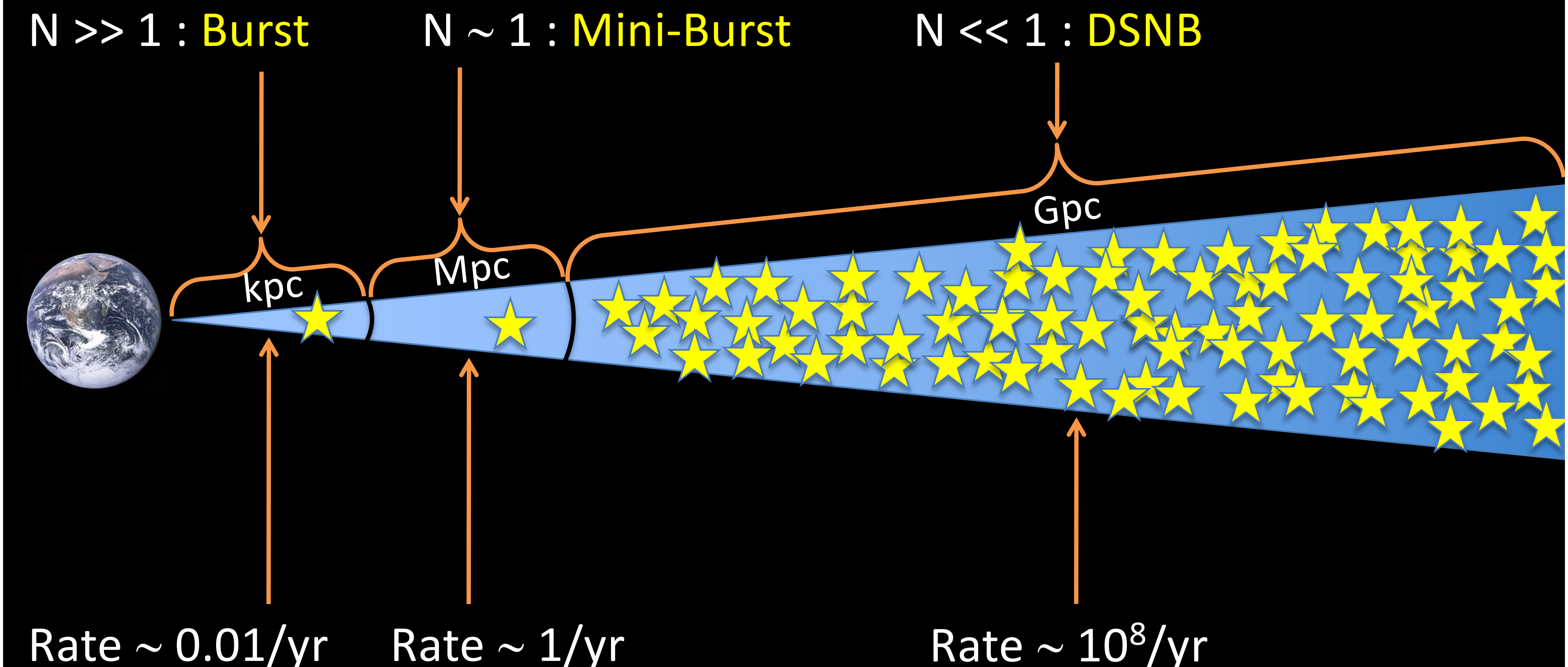
Observation: The neutrino precursor is very energetic

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!

Distance Scales and Detection Strategies



high statistics,
all flavors

object identity,
burst variety

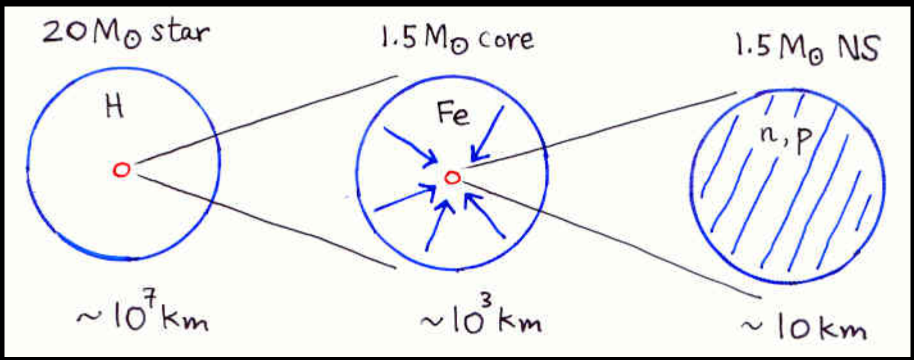
cosmic rate,
average emission

Scientific Opportunities: MW Burst

Question 1: The Source

What are the mechanisms of core collapse?

Idealized; simple

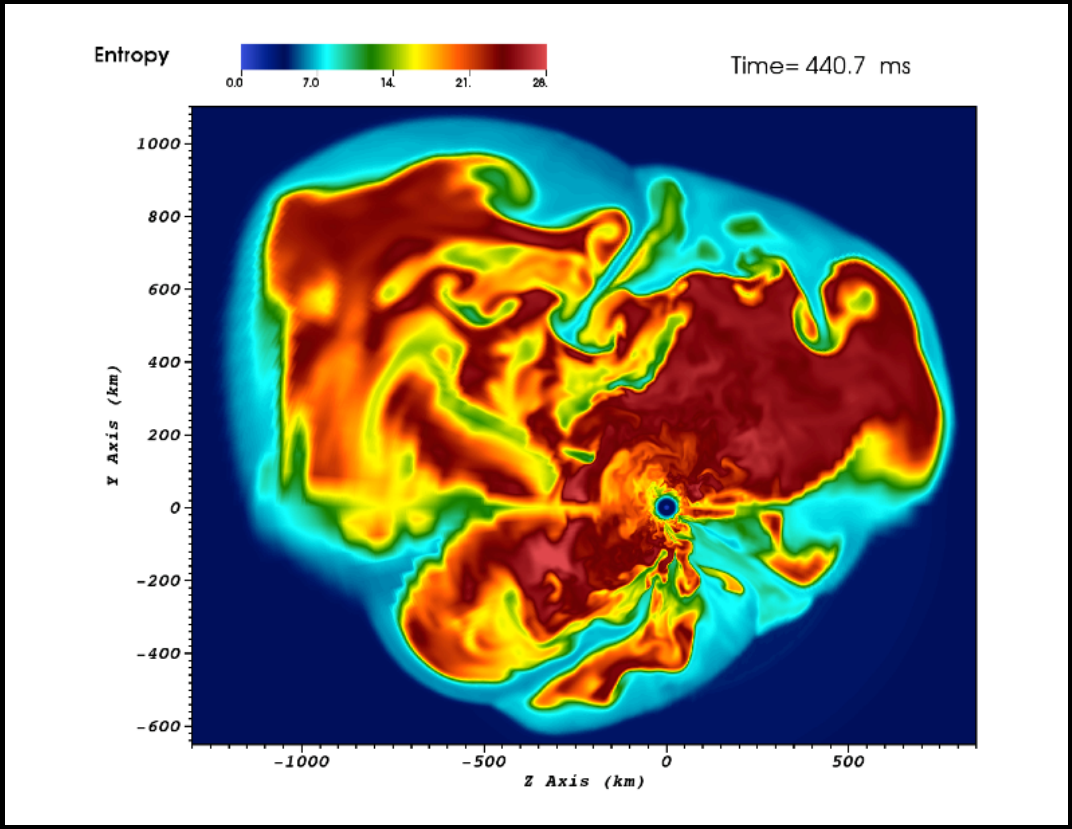


$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3 \times 10^{53}\ \text{ergs} \simeq 2 \times 10^{59}\ \text{MeV}$$

K.E. of explosion $\simeq 10^{-2}\ \Delta E_B$

E.M. radiation $\simeq 10^{-4}\ \Delta E_B$

Realistic; complex



Oak Ridge group (2015)

Question 2: The Messengers

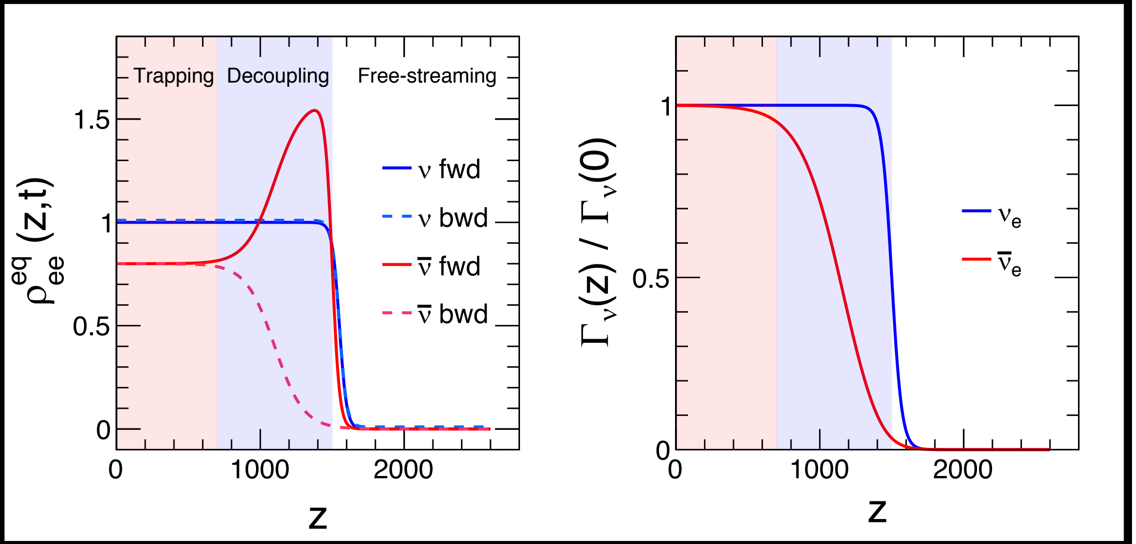
How do neutrinos mix in core collapse?

Idealized; simple

	Mass ordering	
	Normal (NH)	Inverted (IH)
ν_e survival prob.	0	$\sin^2\theta_{12} \approx 0.3$
$\bar{\nu}_e$ survival prob.	$\cos^2\theta_{12} \approx 0.7$	0
$\bar{\nu}_e$ Earth effects	Yes	No

Dighe and Smirnov (1999); Raffelt slide

Realistic; complex



Capozzi, Dasgupta, Mirizzi, Sen, Sigl (2019)

The Flavor Problem: Experiment

Need all flavors to measure the total emitted energy

Need all flavors to test effects of neutrino mixing

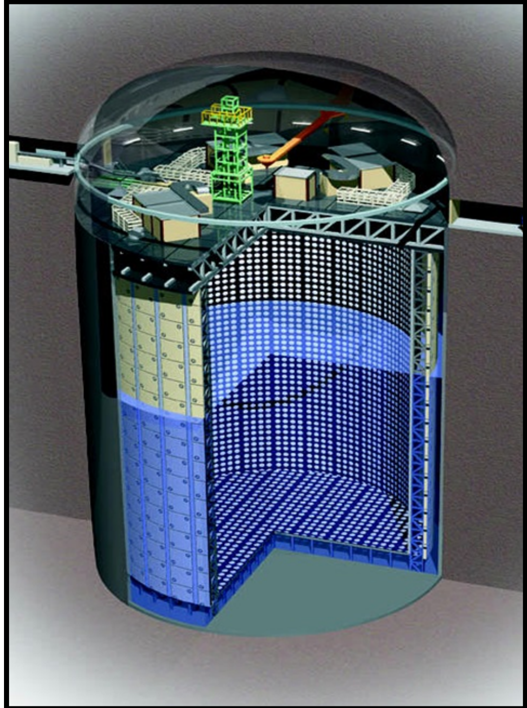
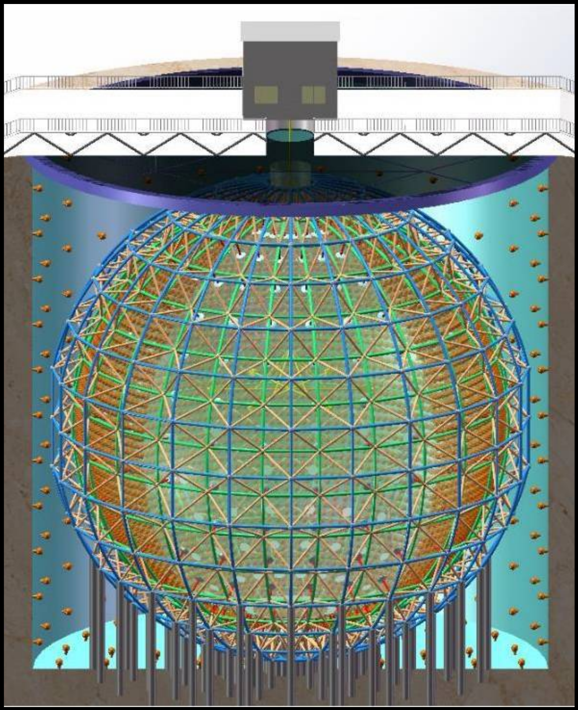
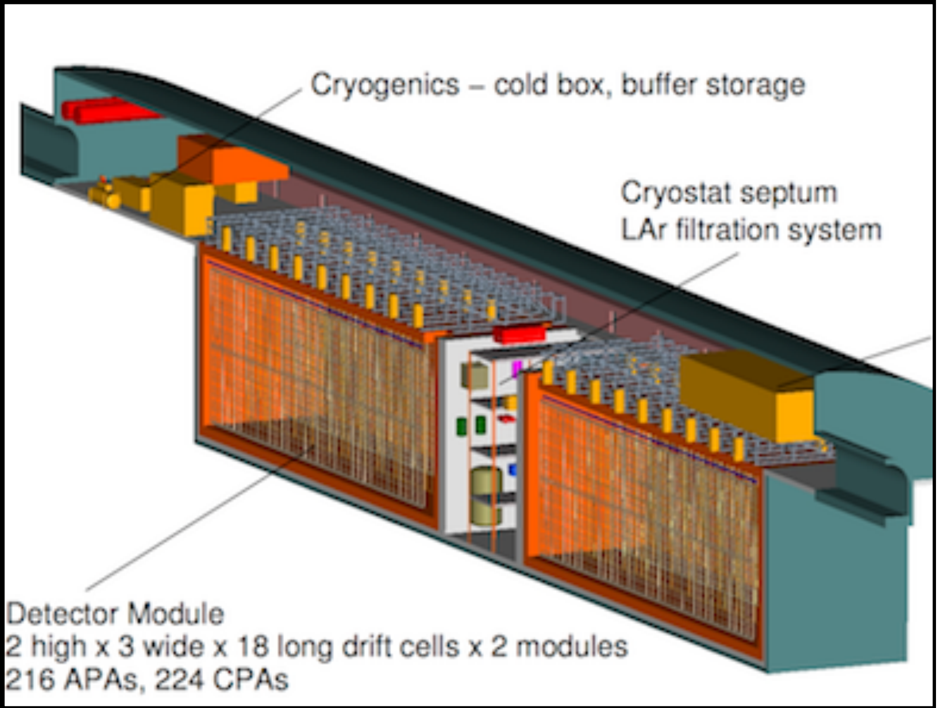
$\bar{\nu}_e$ Precise (~ 10^4 events in Super-K)

$\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$ Inadequate (~ 10^2 events in KL+)

ν_e Inadequate (~ 10^2 events in Super-K)

How will we ensure complete flavor coverage?

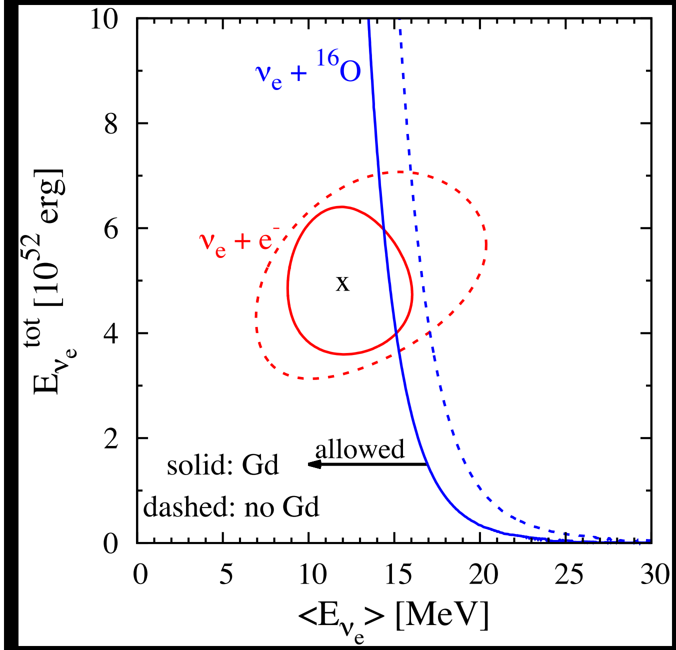
Multi-kton-Scale Neutrino Detectors

Super-K	JUNO	DUNE
		
32 kton water	20 kton oil	40 kton liquid argon
Japan	China	United States
running	*building*	*preparing*

Together, **excellent potential for MeV neutrino astronomy**

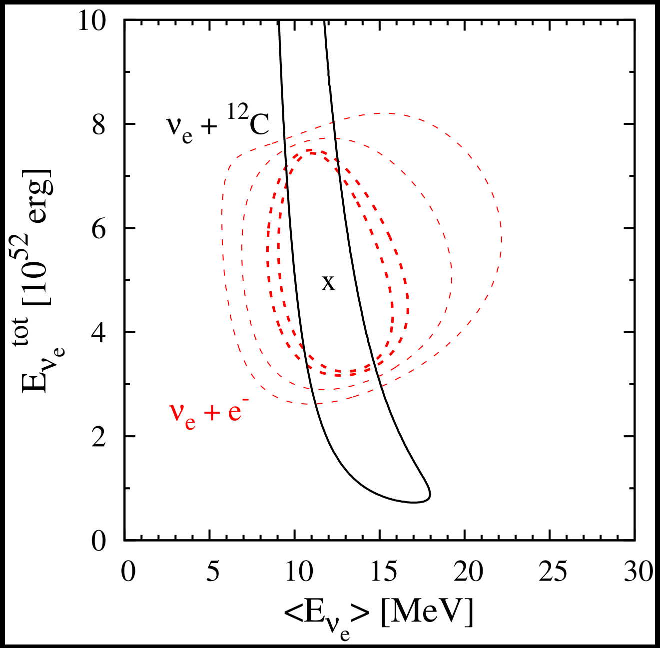
Focus on Measuring Nue

Super-K ~ 10^2 events



Laha and Beacom 2013

JUNO ~ 10^2 events



Laha and Beacom 2014

DUNE ~ 10^3 events

? ?

DUNE uncertain due to *cross section, detector response*

Need better understanding of neutrino+nucleus!

The Timeline Problem

present and near future | beyond that

→ time

large detectors used to measure neutrino mixing | maybe not anymore

Who will build detectors for supernova neutrinos?

What is Needed?

Interactions: Understand neutrino-nucleus cross sections

This should include differential cross sections, particle emission, etc.

Detectors: Understand detection response, especially DUNE

Coordination: Ensure full coverage, especially flavors

Simulations: Robust predictions to at least 10 seconds

Theory: Solution of flavor mixing problem

Costs and benefits of "flavor censorship"

Question 3: The Consequences

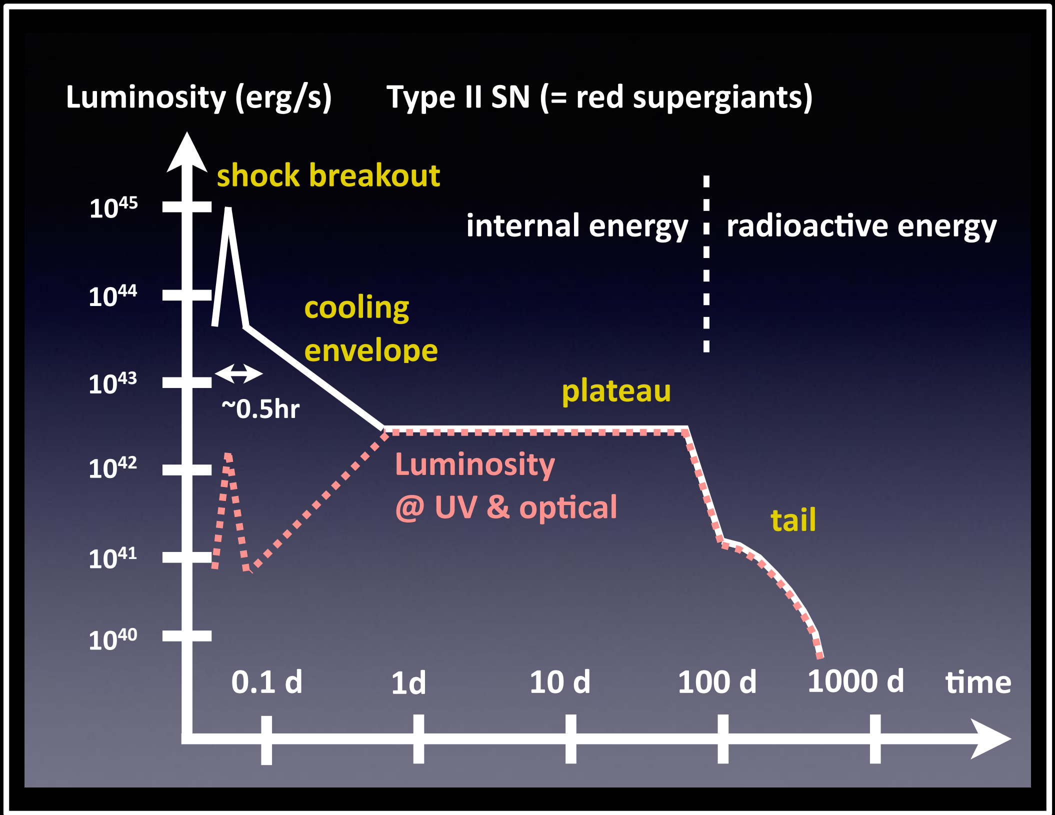
What are the dynamics of the supernova?

Idealized; simple

Core collapse leads to an outgoing shock of total energy ~ 10^{51} erg

Light signal has total energy ~ 10^{49} erg

Realistic; complex



Tanaka (2017)

Question 4: The Multimessengers

How do these signals reveal the dynamics?

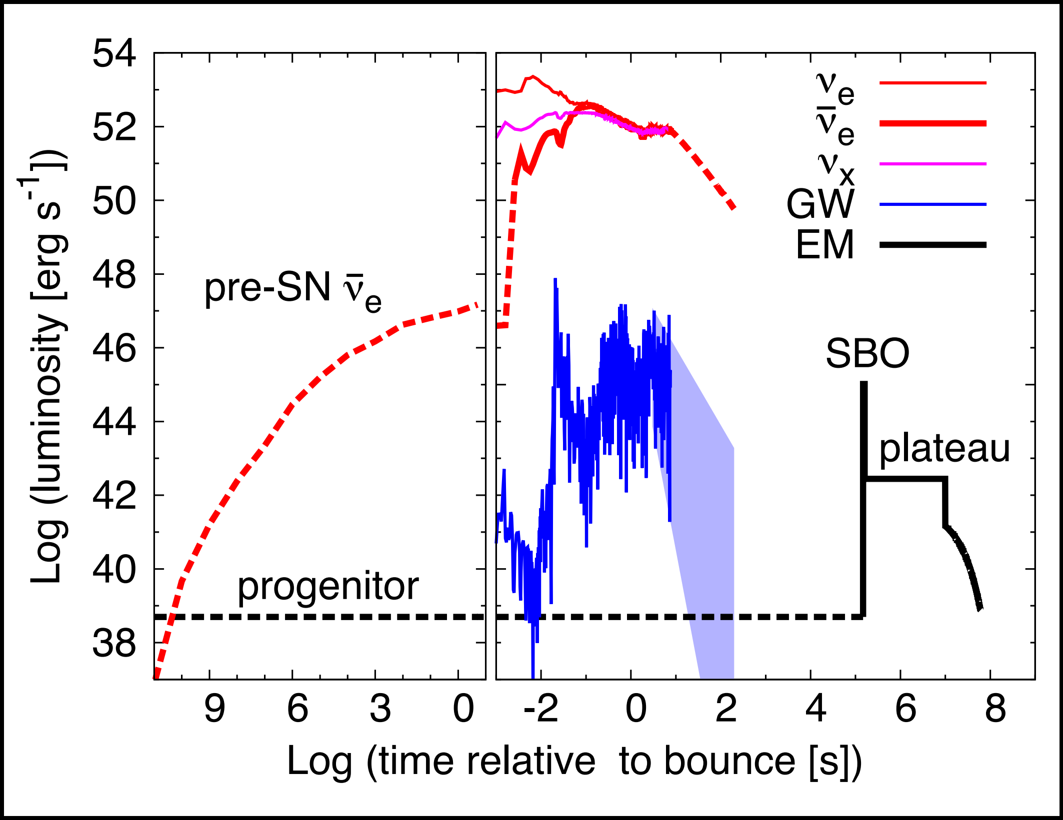
Idealized; simple

Astronomers detect the optical light

Physicists detect the neutrinos

Nobody detects anything else

Realistic; complex



Nakamura et al. (2016)

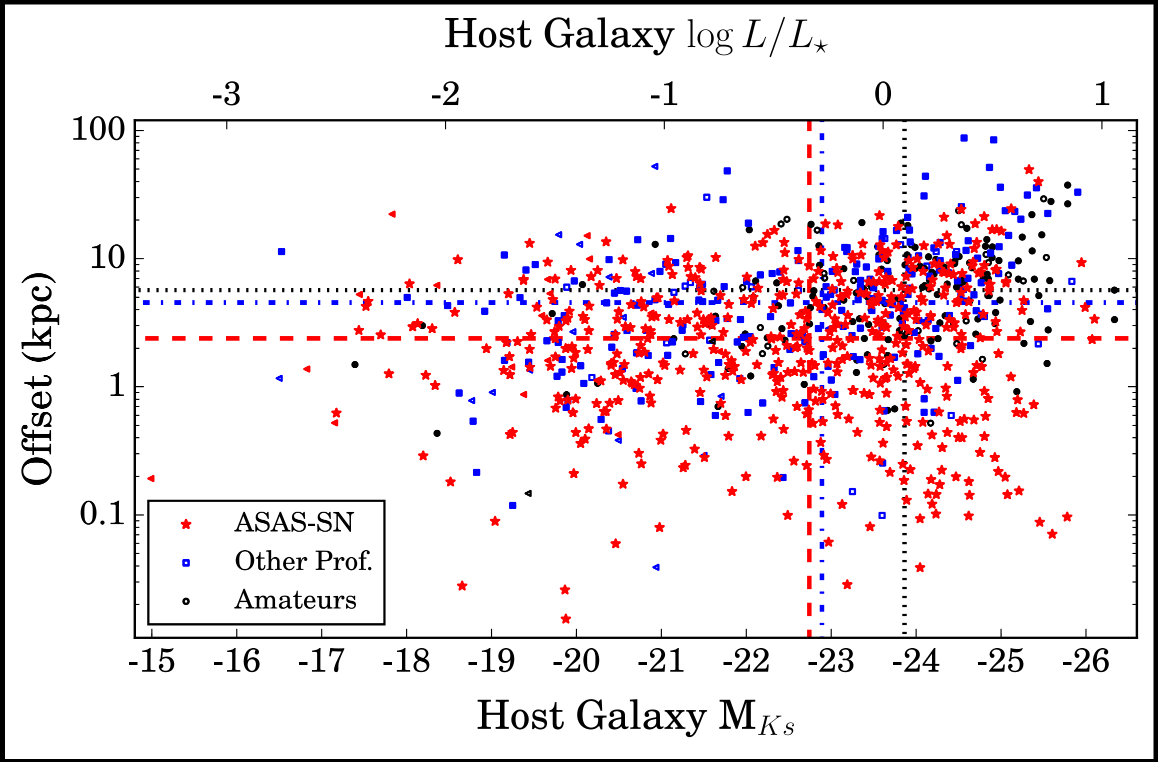
The Waiting Problem

Will we be ready to detect a supernova neutrino burst?

How Will We See the Supernova?

Connection to astronomy crucial, but optical data are lacking

Enter OSU's "ASAS-SN" (All-Sky Automated Survey for SN)



Discovering and monitoring optical transients to 18th mag.

What is Needed?

Detectors: Ensure readiness with practiced alarms

Coordination: Test procedure with practiced alarms, alerts

Pointing: Decide if triangulation works or not

This needs a new paper to check Beacom and Vogel (1999) versus Brdar, Lindner, Xu (2018)

Theory: Clear predictions for possible signals

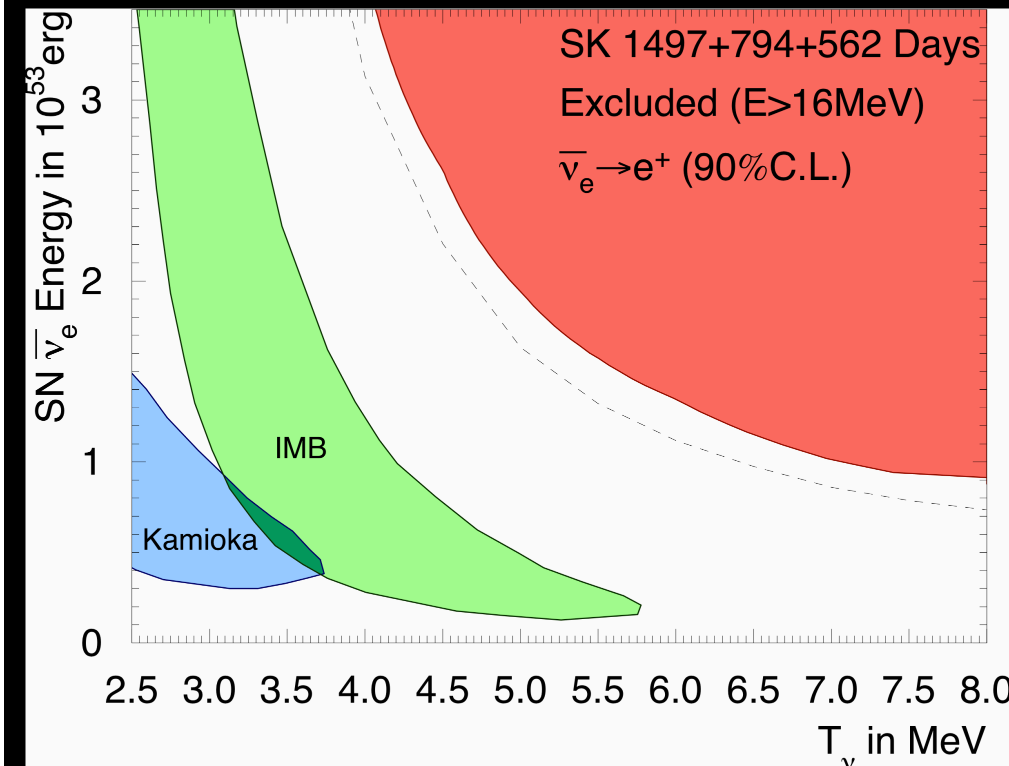
Observers: New facilities for full Milky Way coverage

Build on Adams, Kochanek, Beacom, Vagins, Stanek (2013), Nakamura et al. (2016)

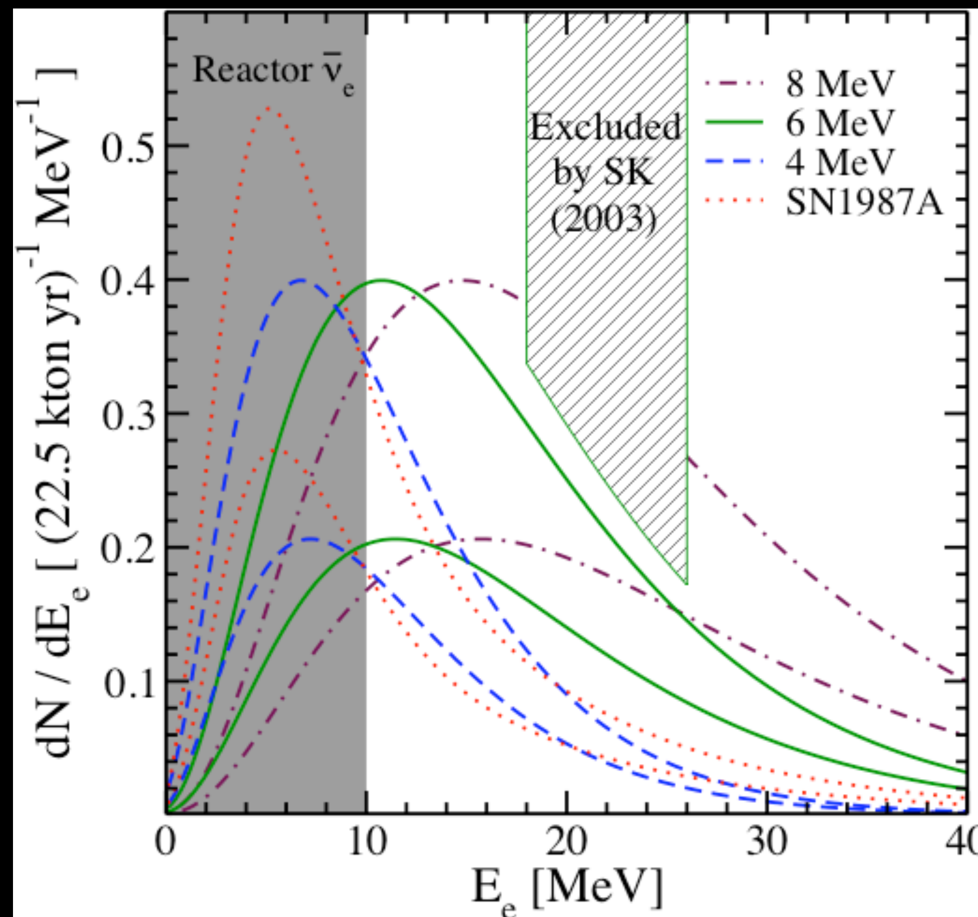
Scientific Opportunities: DSNB

Question 1: The Template

What are the properties of core collapse on average?



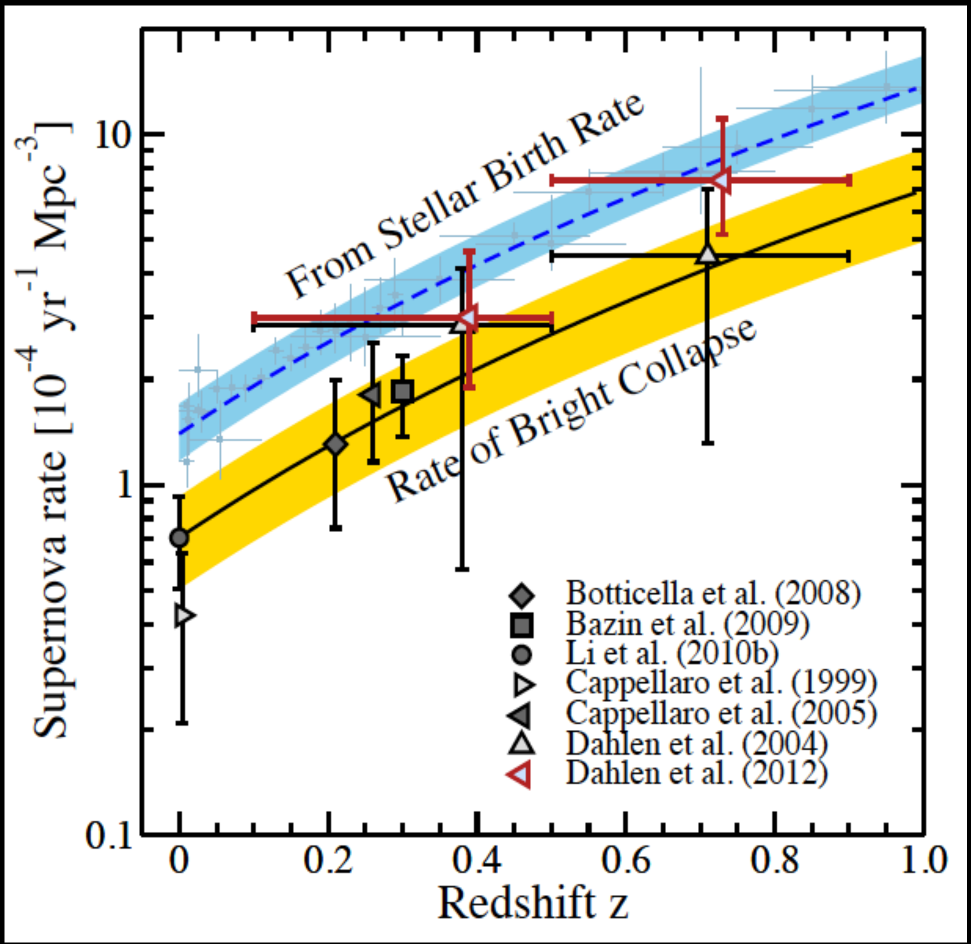
Bays et al. [Super-Kamiokande] (2012)



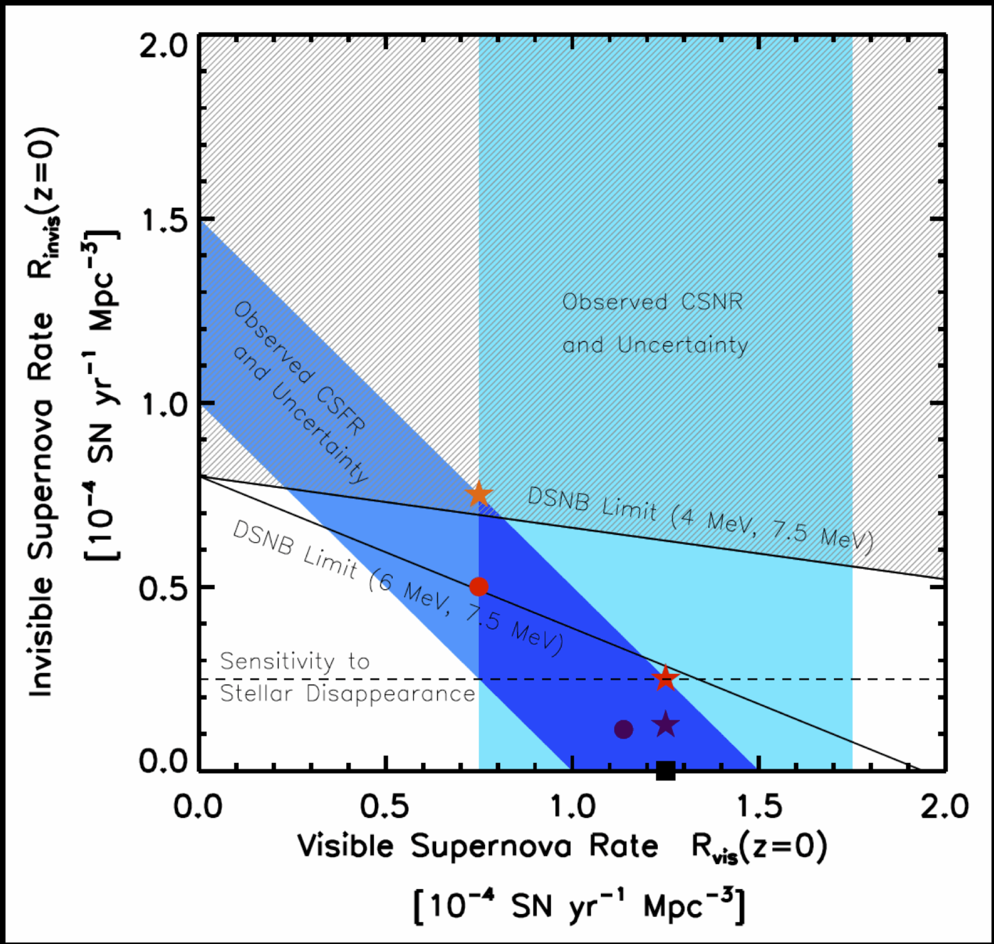
Horiuchi , Beacom, Dwek (2009)

Question 2: The Multitude

What is the cosmic rate of core collapses?

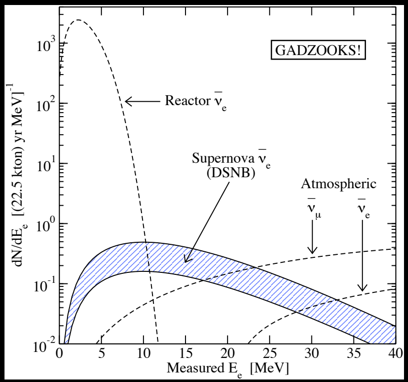


Horiuchi et al. (2011)



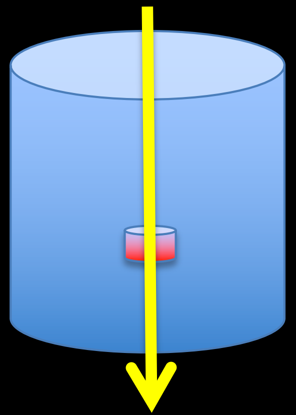
Lien, Fields, Beacom (2010)

What is Needed?



Full deployment of Gd in Super-K
Full plans for Gd in Hyper-K

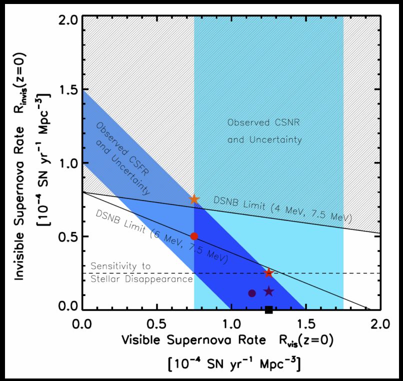
See Vagins talk



New ways to reduce backgrounds further

Spallation backgrounds: Li and Beacom, 2014+

Atmospheric Backgrounds: Zhou and Beacom, 2019+



Advance, update astrophysical constraints

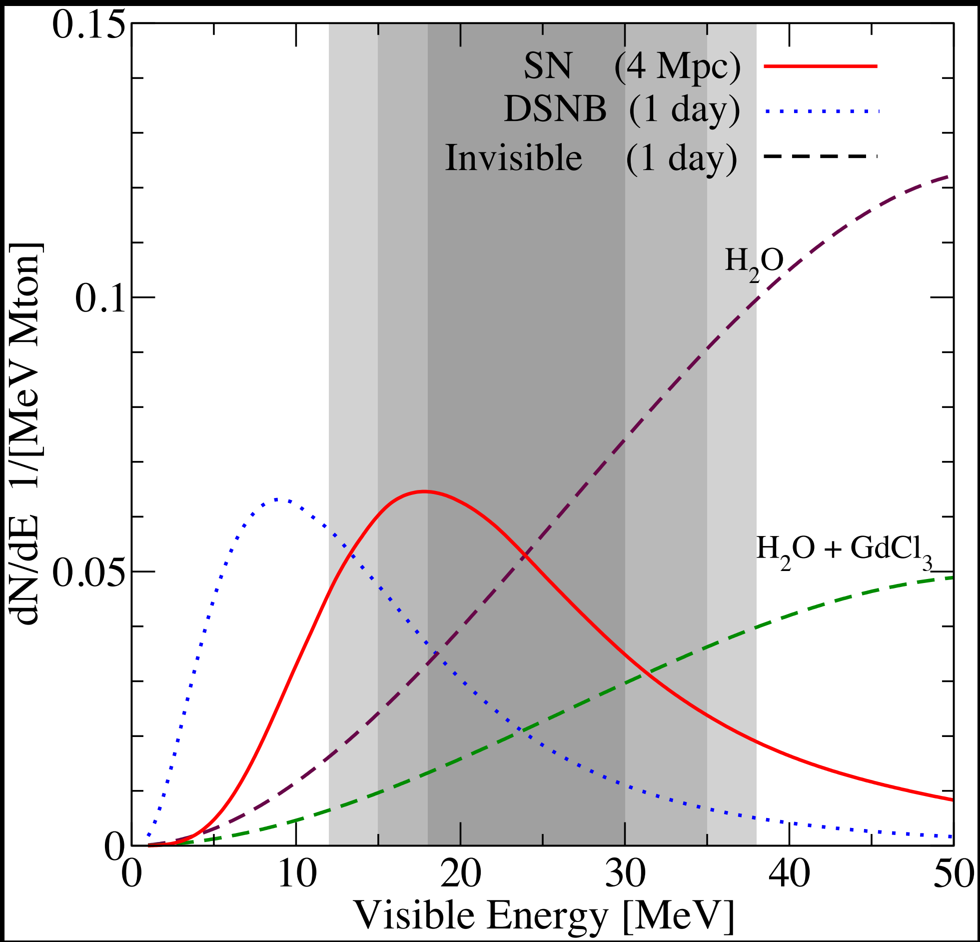
ASAS-SN nearby supernova rate forthcoming

Other new data on SFR, direct BH detection, etc.

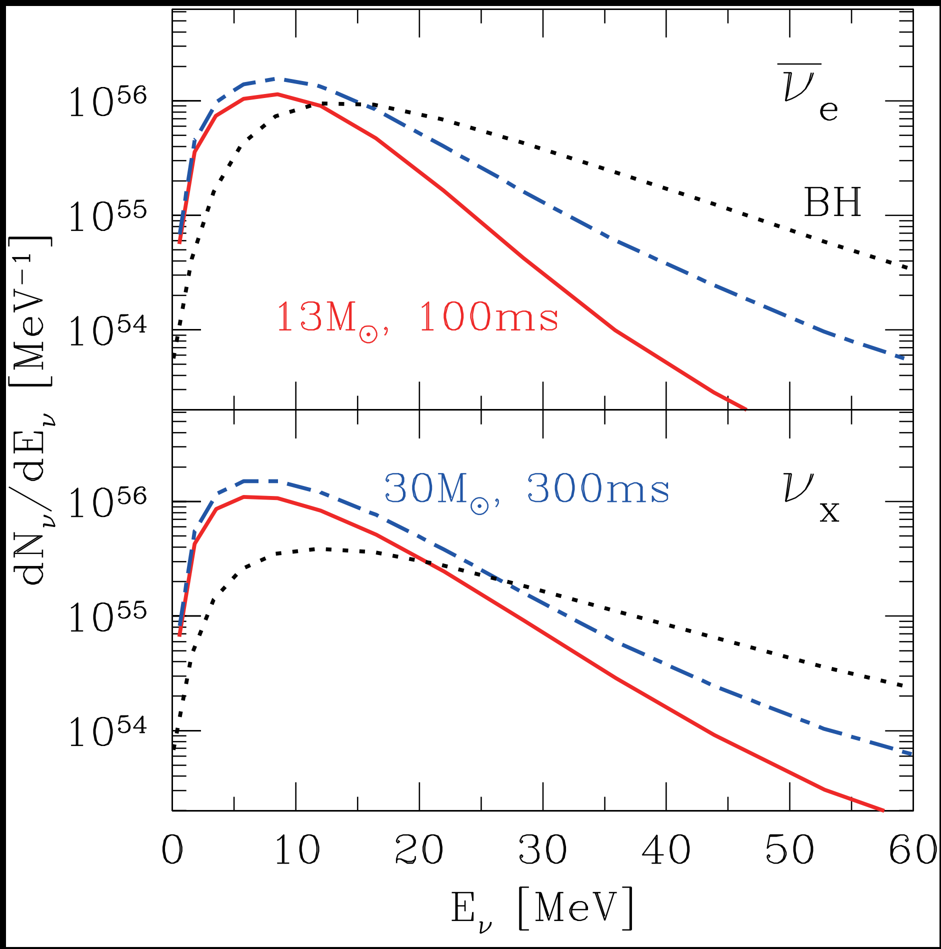
Scientific Opportunities: Nearby Galaxies

Question 1: The Variations

What are the properties of core collapse in extremes?



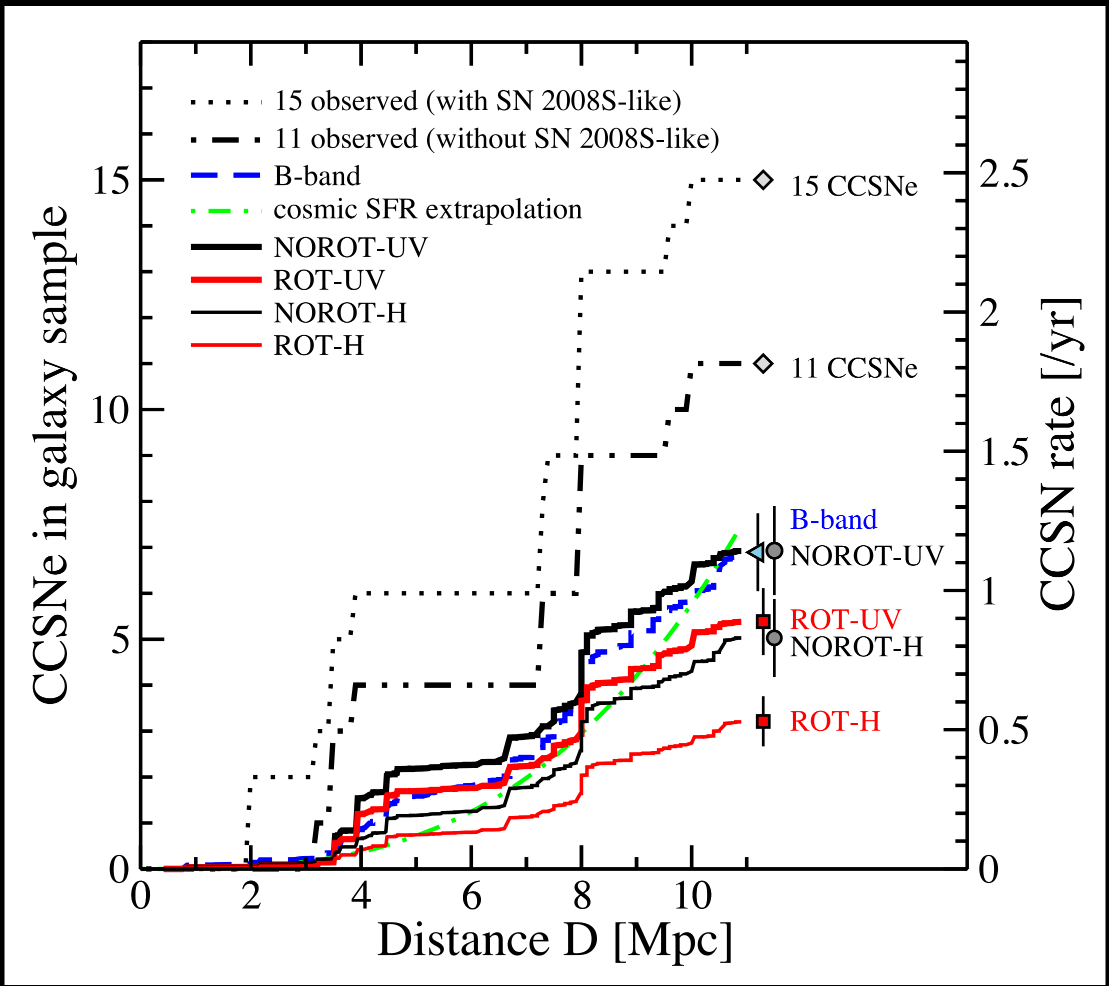
Idea from Ando, Beacom, Yuksel (2005)



Nakazato and collaborators

Question 2: The Verifications

What are the varieties and rates of transients?



Horiuchi et al. (2013)

Neutrino bright, optically bright:
Core-collapse supernova

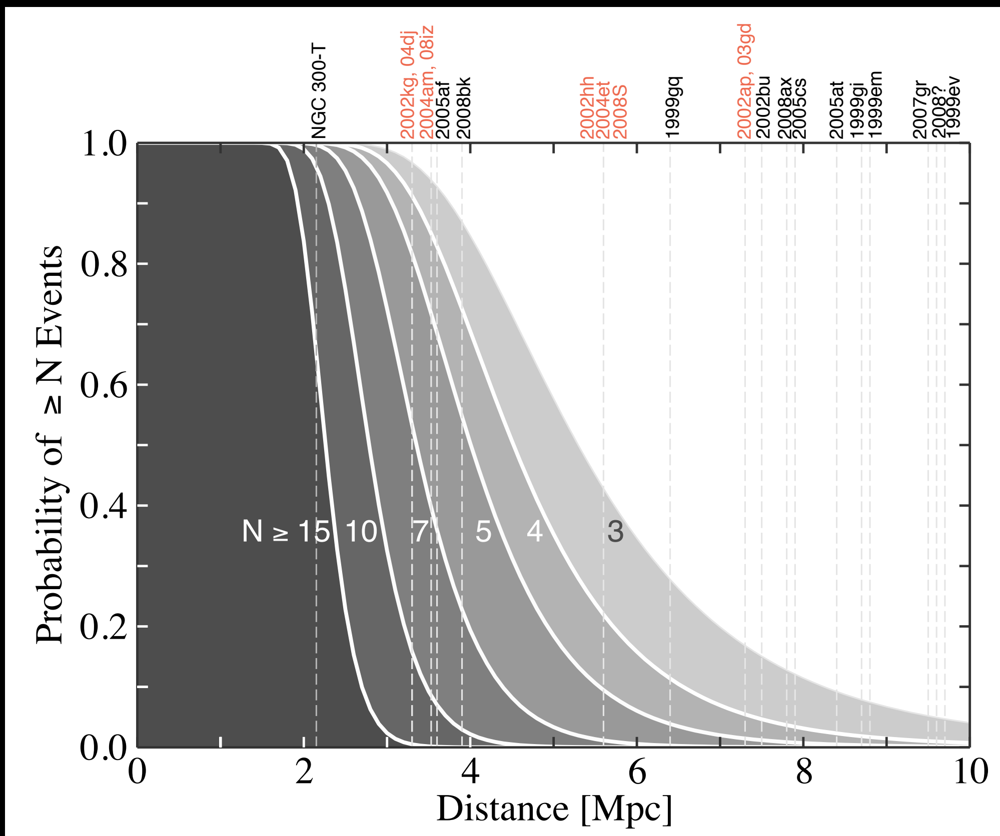
Neutrino bright, optically dim:
Core-collapse to black hole

Neutrino dim, optically bright:
Type Ia supernova
Supernova impostor

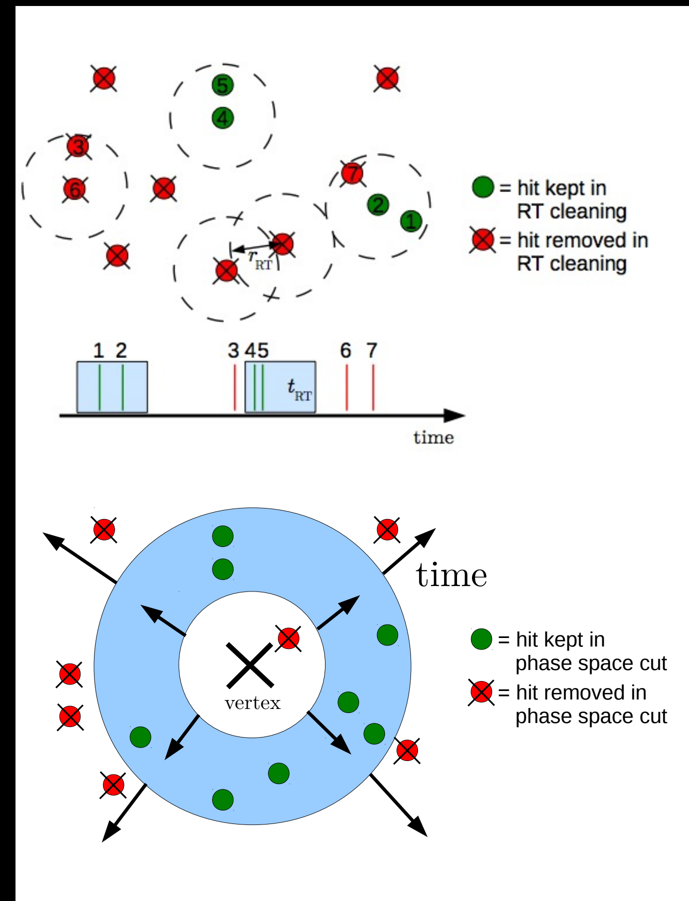
Neutrino dim, optically dim:
All the time!

What is Needed?

Detector of mass > 5 Megaton



Kistler et al. (2011)



Boser et al. (2014)

Best hope is a *dedicated* modification of IceCube

Concluding Perspectives

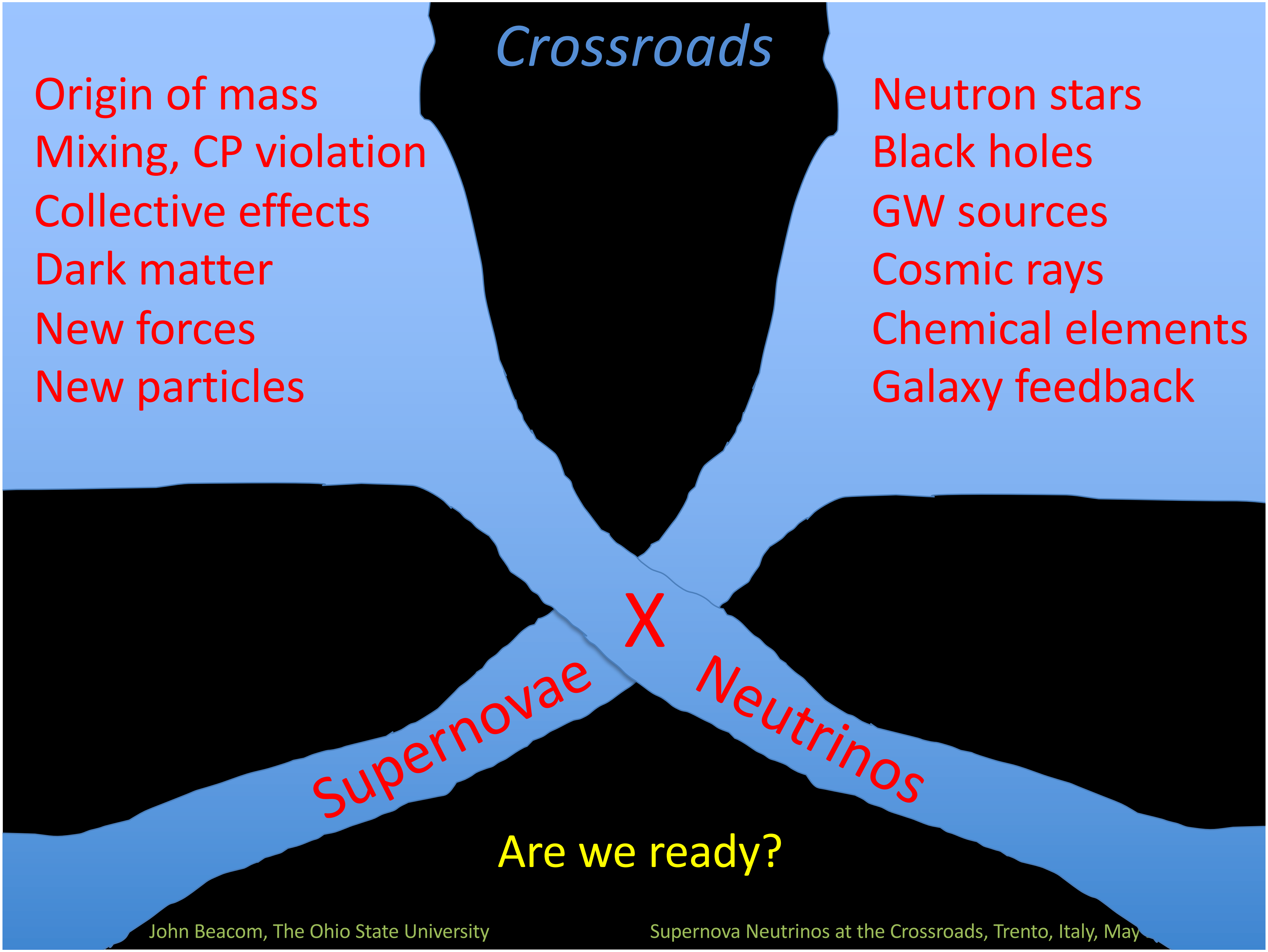
Take-Away Messages

Profound physics questions depend on MeV neutrinos
Extreme conditions, neutrino properties, surprises

Need better detectors, signal ID, and backgrounds
With theoretical help, can leverage other investments

Next discovery may be the DSNB in Super-K with Gd
Construction is already underway

Rich prospects, rich context
Interpretation will be complicated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Supernovae
X
Neutrinos
Are we ready?
John Beacom, The Ohio State University
Supernova Neutrinos at the Crossroads, Trento, Italy, May

How to Advance our Goals?

We’re going to need a bigger boat

The Time for Neutrino Astronomy is Now

Neutrino Astronomy

MeV—GeV ν	TeV—PeV ν	EeV—ZeV ν
Efforts: SK, HK and more	Efforts: IceCube and more	Efforts: ANITA and more
Targets: Solar, SN, more Surprises	Targets: GRBs, AGN, more Surprises	Targets: GZK process Surprises

Neutrino astronomy must be broad

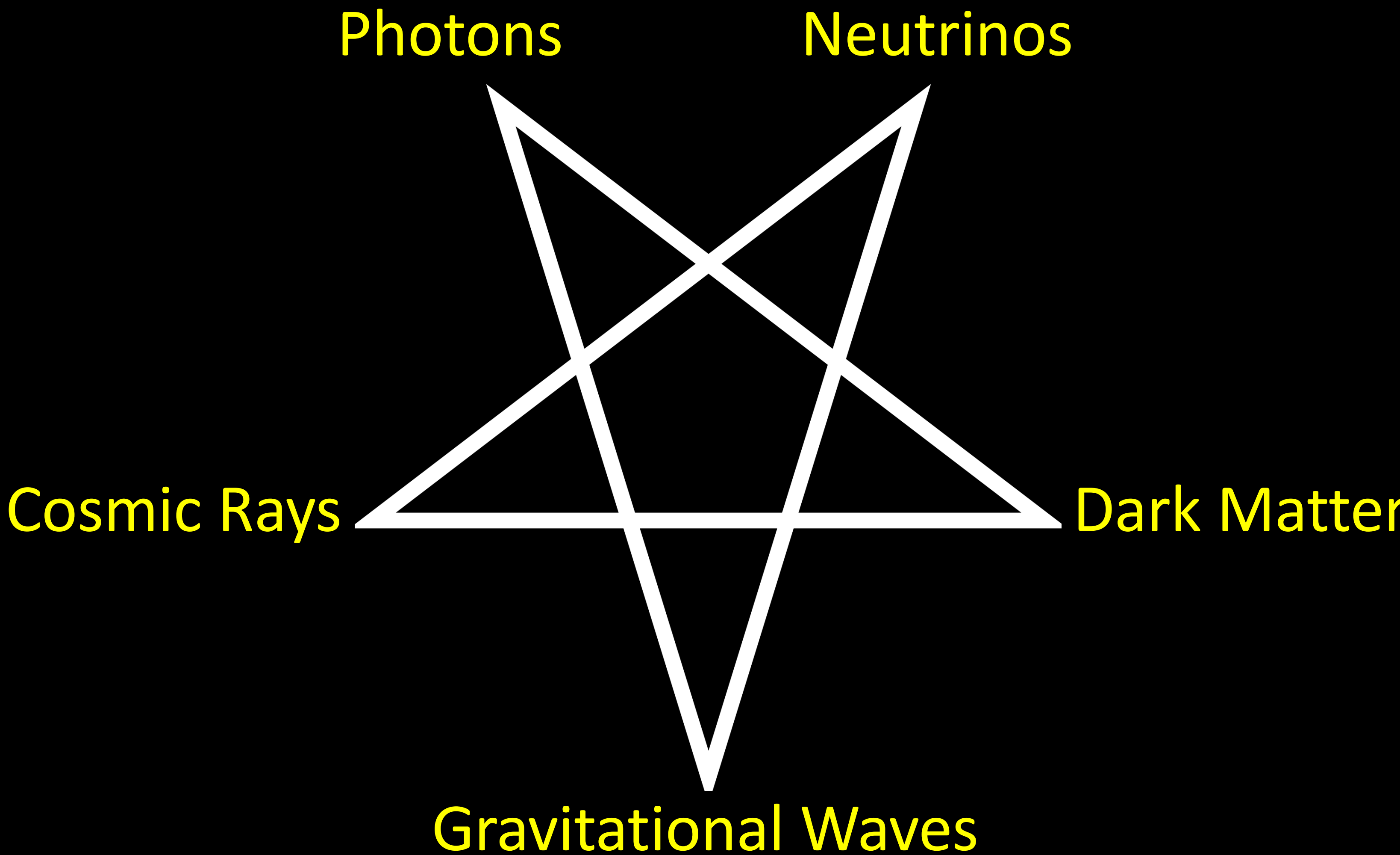
The Time for Neutrino Science is Now

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

Summoning the Multi-Messenger



Careful what we wish for!