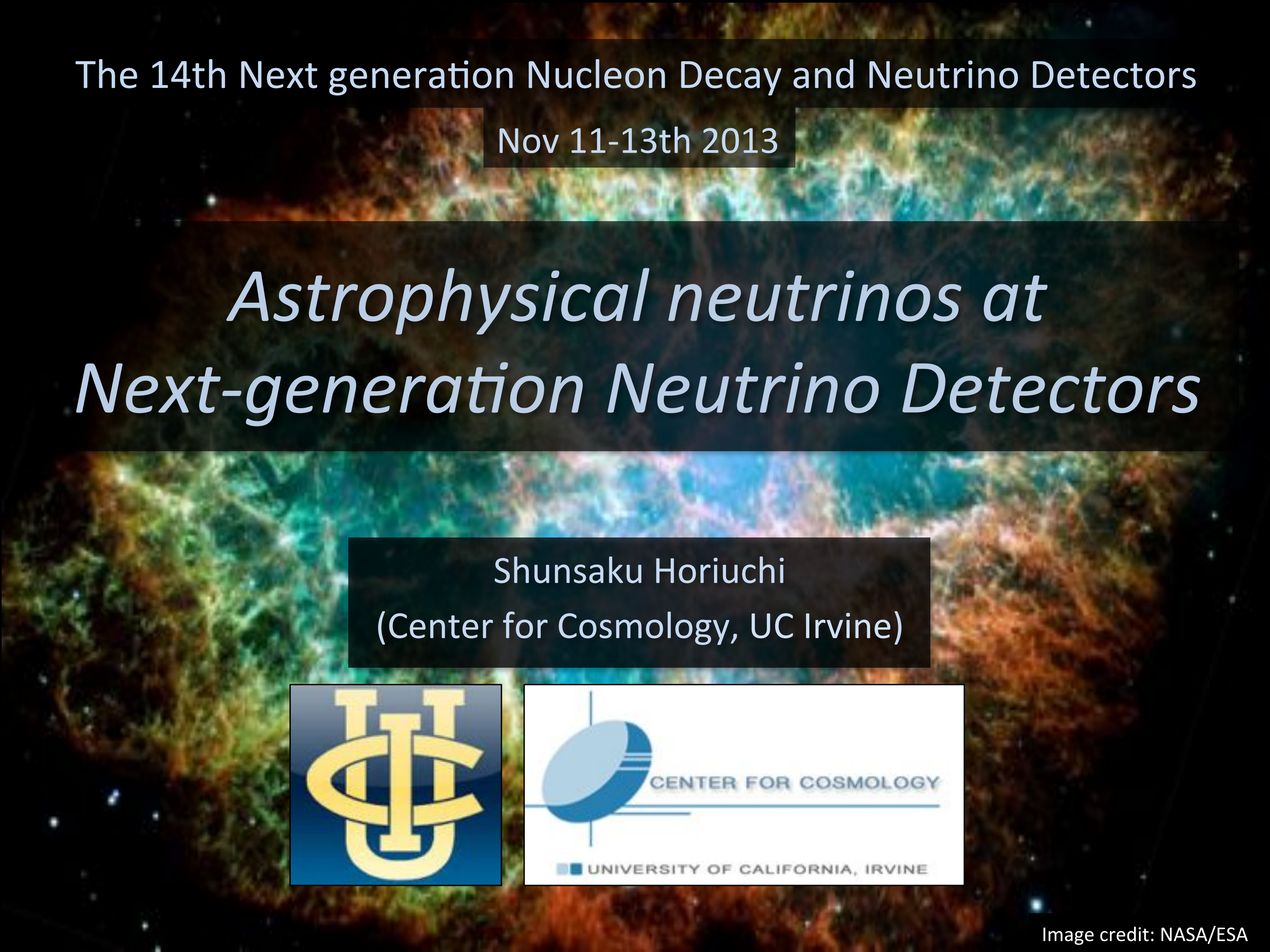


The 14th Next generation Nucleon Decay and Neutrino Detectors

Nov 11-13th 2013

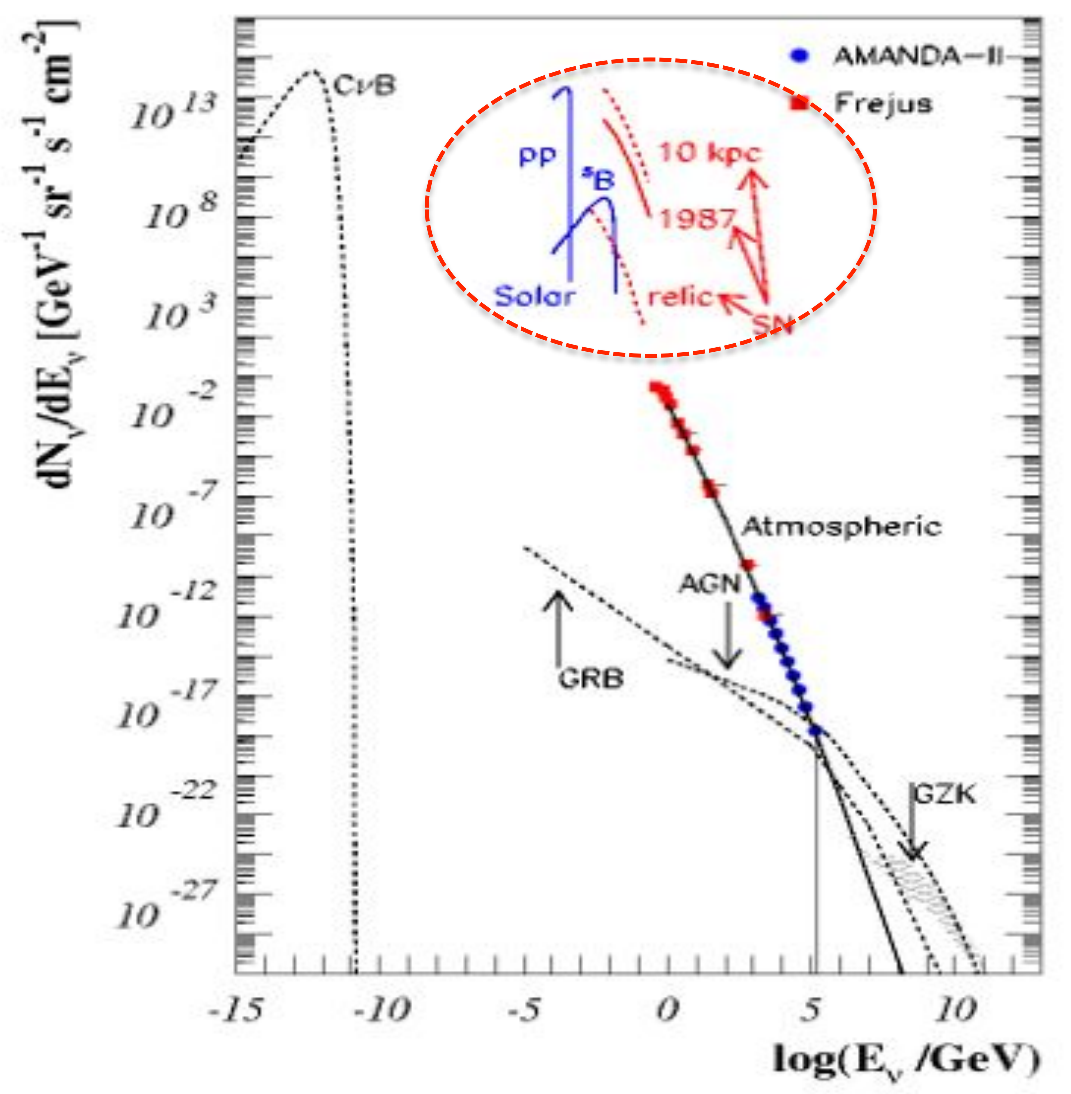
Astrophysical neutrinos at Next-generation Neutrino Detectors

Shunsaku Horiuchi
(Center for Cosmology, UC Irvine)

CENTER FOR COSMOLOGY
UNIVERSITY OF CALIFORNIA, IRVINE

Image credit: NASA/ESA

The neutrino sky



Extra-terrestrial Sources:

- Big bang relics (~10^{-4} eV)
- Solar neutrinos (~1 MeV)
- Core-collapse supernova neutrinos (~10 MeV)
- Atmospheric neutrinos
- Neutrinos from cosmic-ray sources (GRBs, AGNs)
- Cosmogenic neutrinos (~10^{15}-10^{20} eV)

Terrestrial sources

- Geothermal neutrinos

The big questions

- Neutrinos probes of astrophysics
  - *What makes a core collapse explode?*
  - *Can we refine the Solar model?*
  - *Where are cosmic rays accelerated?*
  - *What is the nature of dark matter?*
- Neutrinos probes of fundamental physics
  - *What are the properties of neutrinos?*
  - *What is the physics beyond the Standard Model?*
  - *What is the physics at high temperature and density?*
  - *What is the nature of physics at very high neutrino density?*
- Surprising physics? New sources?

νs dominate the energy budget and offer a view of the interior

νs offer a view of the solar interior and fusion

High-energy νs as smoking guns of hadronic interactions

Dark matter search requires multi-messenger

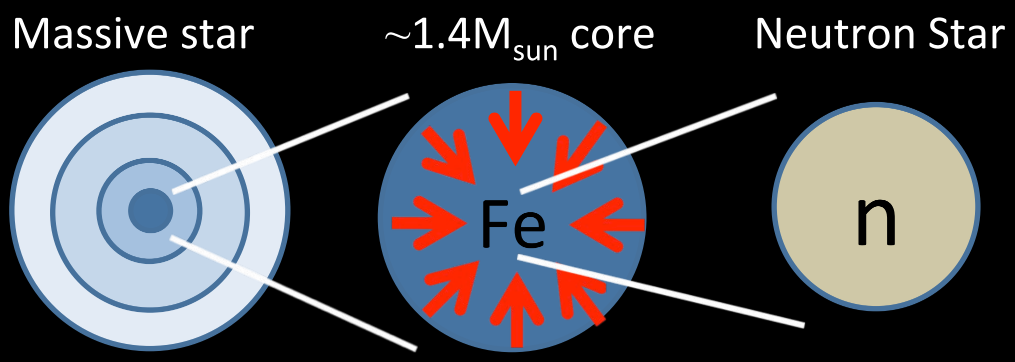
GALACTIC SUPERNOVA NEUTRINOS

SN 1987A in the LMC

Sanduleak -69 202

SN 1987A 23 Feb 1987

SN 1987A in the LMC



Energy budget $\sim 3 \times 10^{53}$ erg

99%	into neutrinos
1%	into shock KE
0.01%	into photons

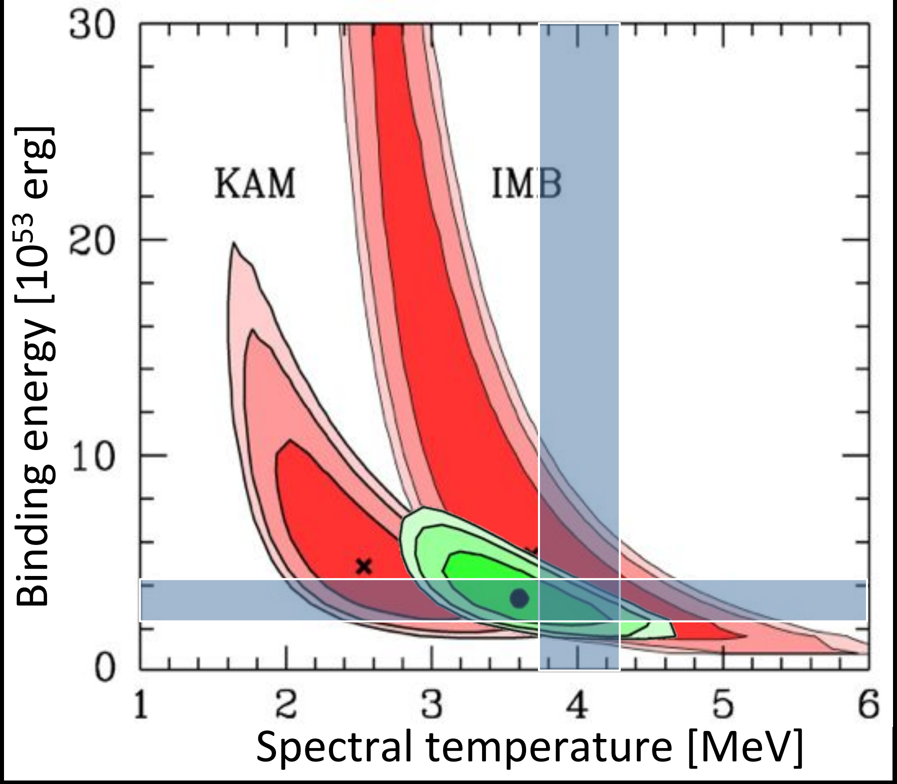
Sanduleak -69 202

SN 1987A 23 Feb 1987

Interpreting SN 1987A Neutrinos

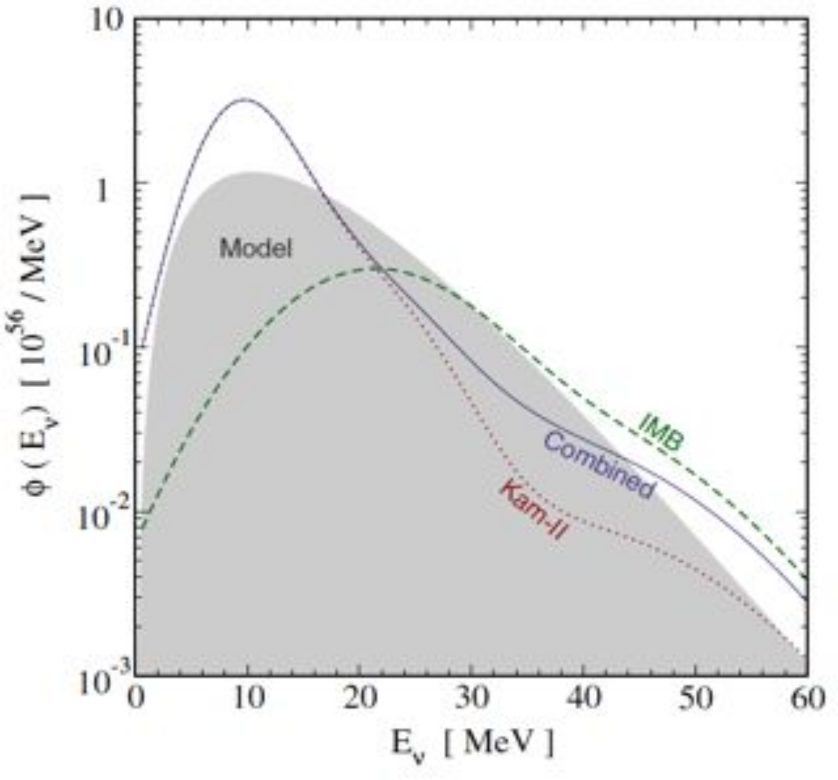
Confirmations: of the typical time-integrated neutrino emission, and the neutrino spectrum.

Adapted from Jegerlehner, Neubig & Raffelt (1996)



Blue: recent long-term simulations (Basel, Garching). Contours show CL of 68.3%, 90% and 95.4%

Yuksel & Beacom (2007)



Grey region shows a simple Fermi-Dirac spectrum.

Supernova mechanism

The problem: the bounce shock stalls at ~150 km. How is this stalled shock revived? This is the "supernova mechanism"

The neutrino mechanism:
net energy deposition in the gain region behind the shock

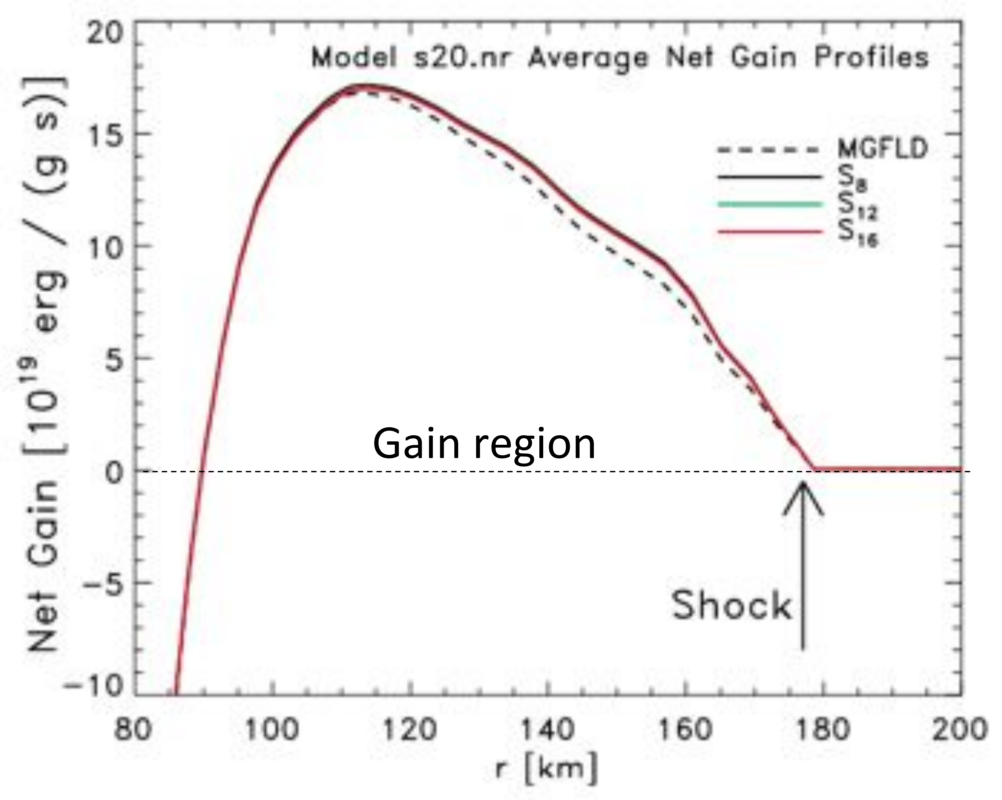
Wilson (1985), Bethe & Wilson (1985, …

Cooling: $Q_\nu^- \propto T^6$

Heating: $Q_\nu^+ \propto L_\nu r^{-2} \bar{\epsilon}_\nu^2$

But this (mostly) fails in 1D (the exception is small mass stars with O-Ne-Mg cores)

Multi-dimensionality and fluid instabilities likely play a central role



Ott, Burrow, Dessart & Livne (2008)

Standing Accretion Shock Instability (SASI)

Non-radial oscillatory shock-deformation mainly of l = 1, 2 modes (*Blondin et al 2003*)
Many subsequent 2D studies obtained robust explosions with SASI

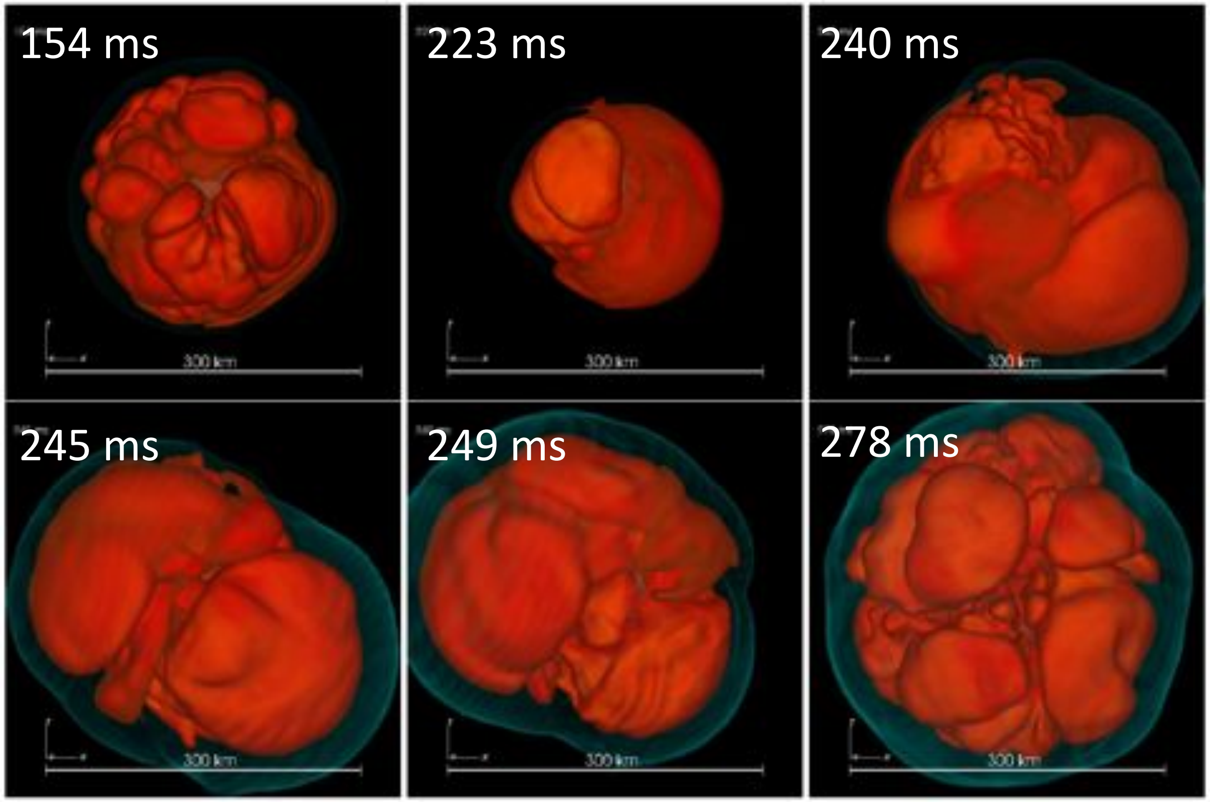
Foglizzo et al (2006, 2007), Suwa et al (2010),
Takiwaki et al (2013), Bruen et al (2013), etc

SASI in 3D:

Initial simulations showed mixed results: easier explosions, to considerably reduced SASI activity…

More recent 3D simulations with detailed neutrino transport shows strong SASI activity

But whether they lead to explosions sill unclear

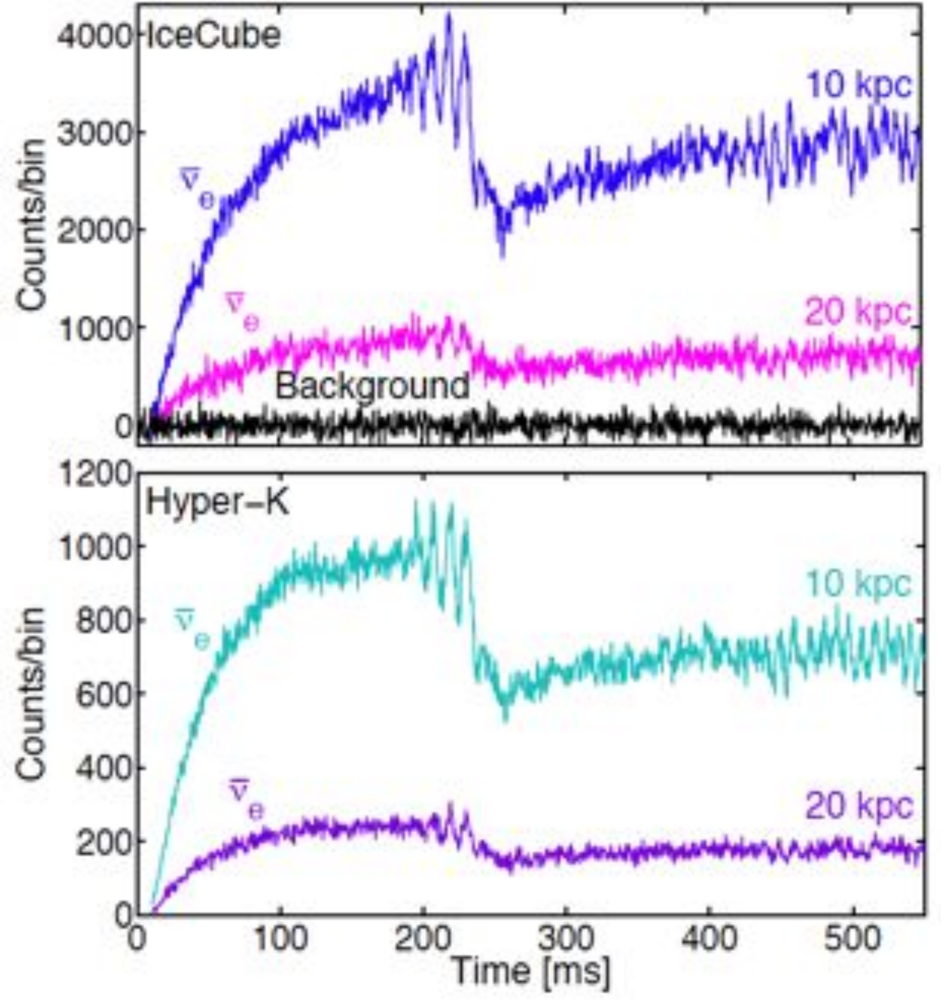


Hanke et al (2013)

Observing the SASI mechanism

SASI imprints fast variations in luminosity and energy which can be measured.

For example, using the 3D simulation by the Garching group (Hanke et al 2013) →



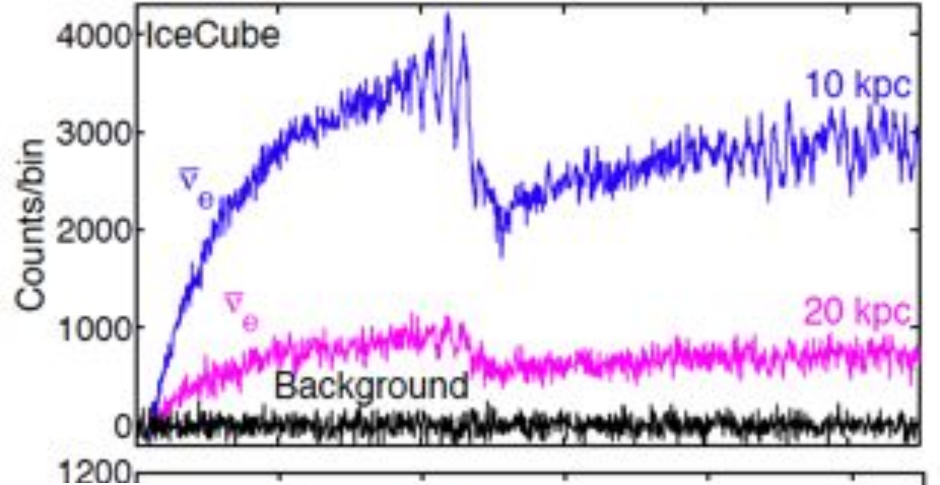
Tamborra et al (2013),
see also Lund et al (2010, 2012)

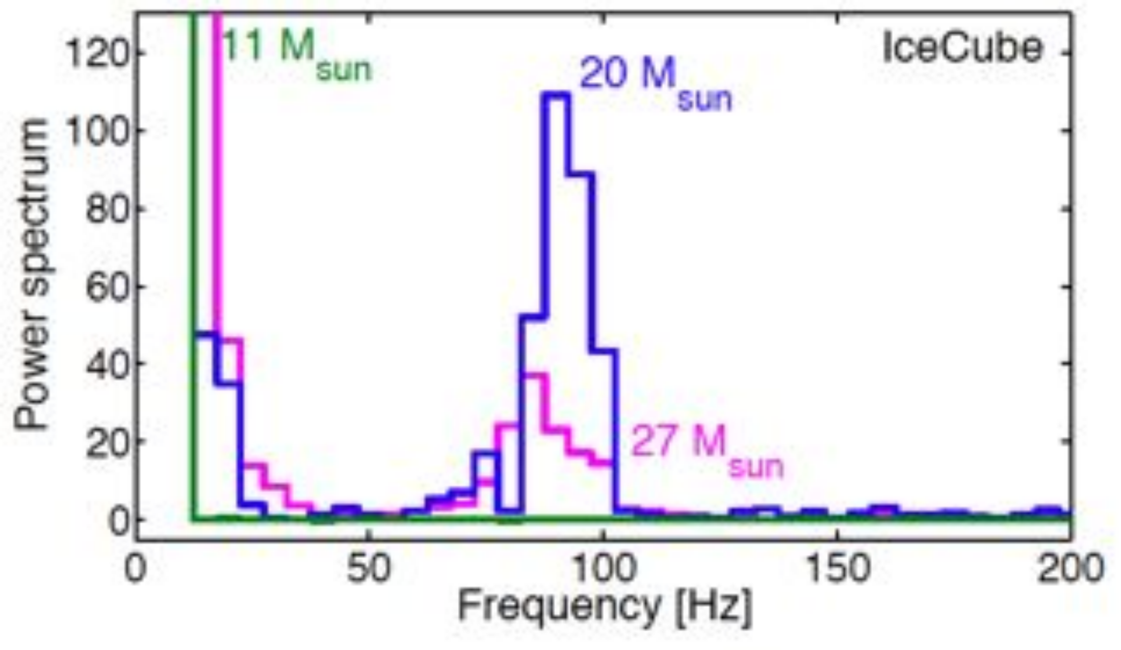
Observing the SASI mechanism

SASI imprints fast variations in luminosity and energy which can be measured.

For example, using the 3D simulation by the Garching group (Hanke et al 2013) →

Great prospects to reveal characteristic oscillations via counts power spectrum





Hyper-K should be able to combine event-by-event reconstruction to add an additional dimension to the analysis

Tamborra et al (2013),
see also Lund et al (2010, 2012)

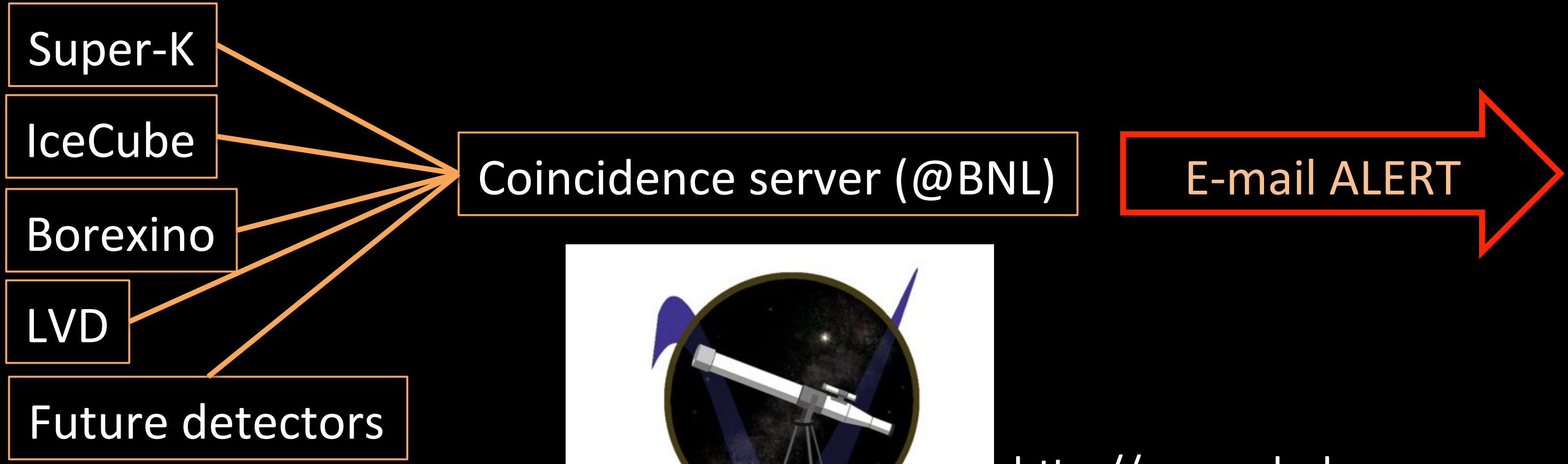
Supernova astronomy with neutrinos

Observables with νs:

1. Early warning
2. Pointing
3. Distance determination

➔ Warns astronomers when and where to look*

*not always a simple problem in e.g., the optical, due to dust and resources


Super-K

IceCube

Borexino

LVD

Future detectors

Coincidence server (@BNL)

E-mail ALERT

SNEWS

http://snews.bnl.gov
astro-ph/0406214

EGADS

For EGADS updates, see Adams et al 2013 (arXiv:1306.0559)

Supernova pointing

Triangulation:

Can give pointing, but depends on where, and the "leading edge" must be observed and modeled

	Super-K	**Hyper-K**
Water only	8 deg	1.4 deg
Water + Gd (95% tag)	3 deg	0.6 deg

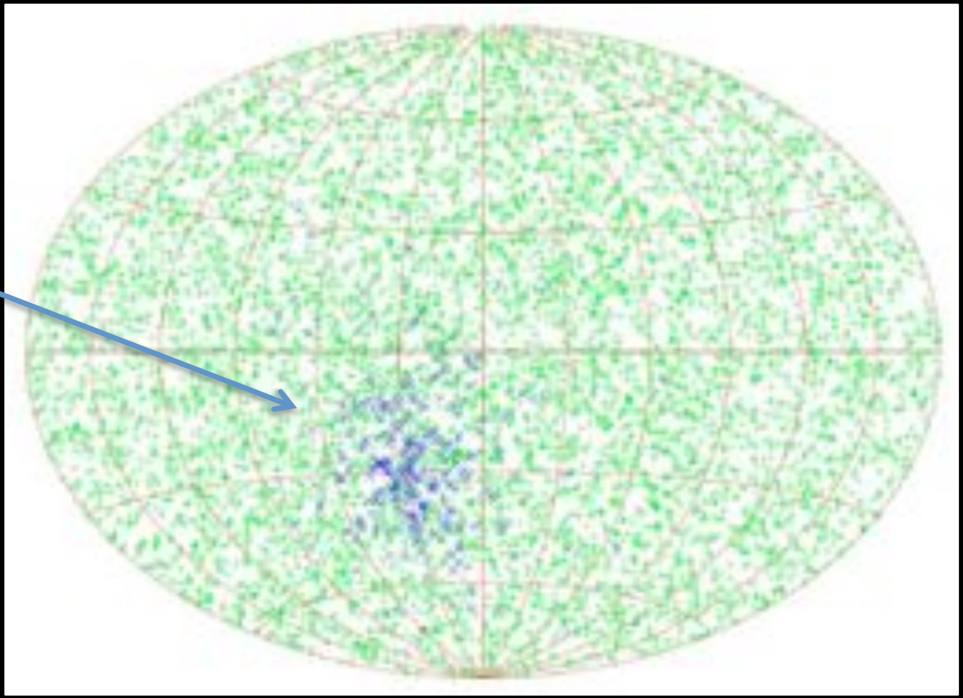
Gadolinium strategy: *Beacom & Vagins (2004)*

See more on Tuesday's talk by Renshaw

Use directional neutrinos:

νe scattering has the ideal kinematics

$\nu e \rightarrow \nu e$

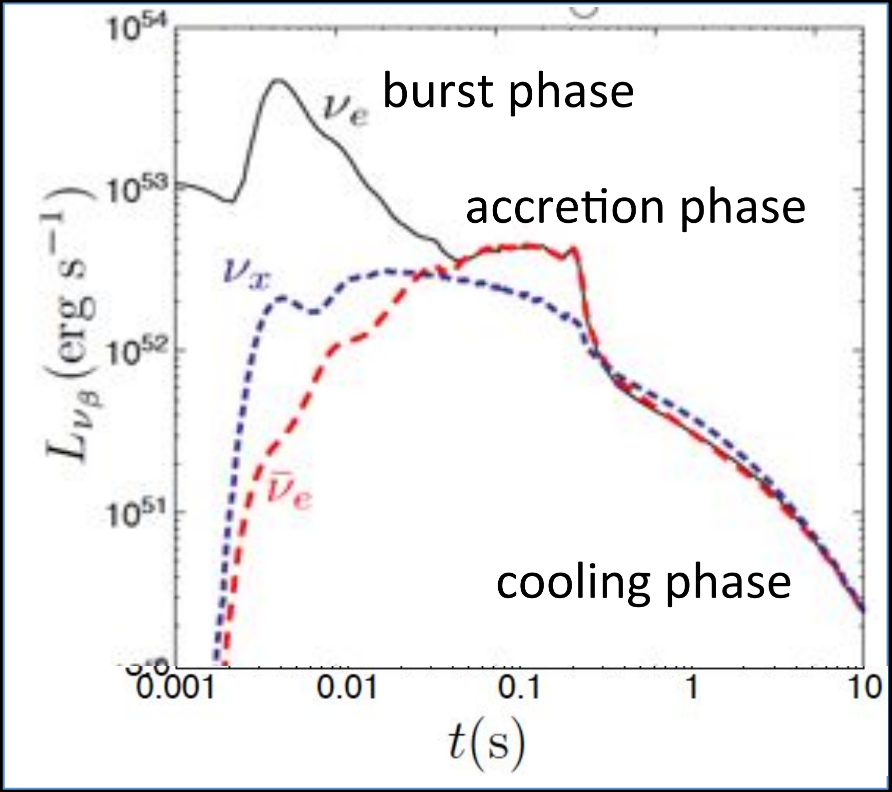


Beacom & Vogel (1999), Tomas et al. (2003)

νe absorption on ^{16}O is isotropic and degrades the angular resolution to ~3 deg at SK

$$\nu_e + {}^{16}\mathrm{O} \rightarrow X + e-$$

Supernova distance



burst phase

accretion phase

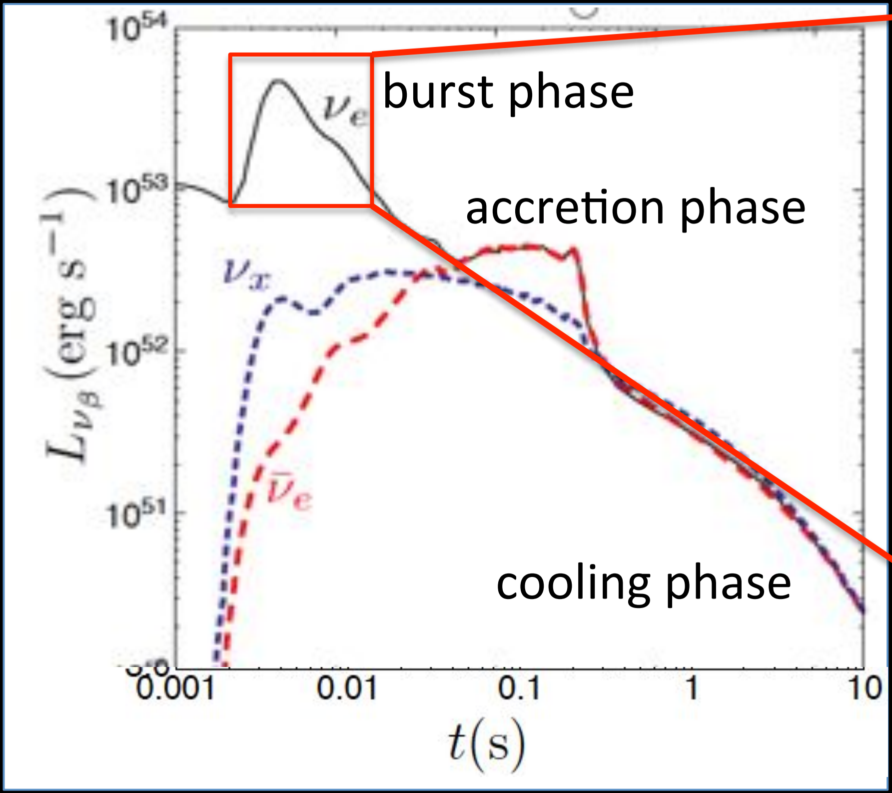
cooling phase

Long-term simulation of Fischer et al (2010)

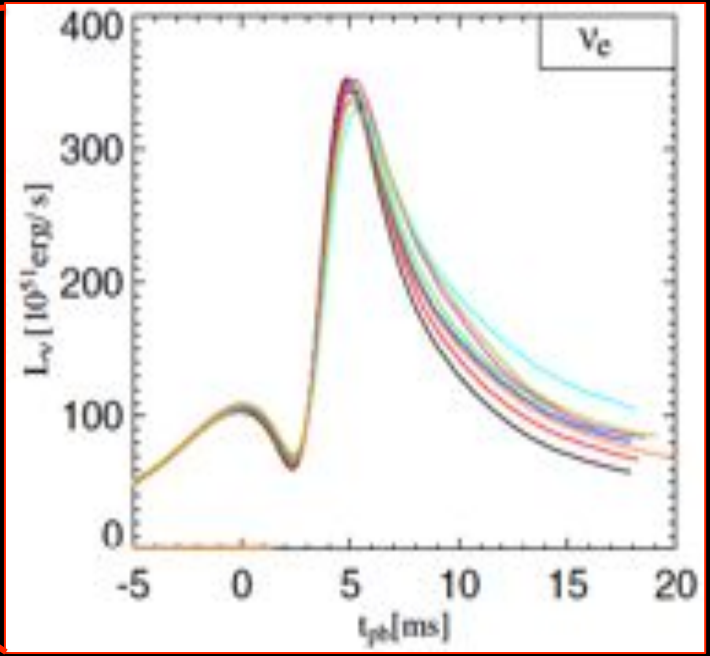
Total events:

Subject to modeling and oscillation uncertainties

Supernova distance



Long-term simulation of Fischer et al (2010)



Kachelreiss et al. (2005)

Total events:

Subject to modeling and oscillation uncertainties

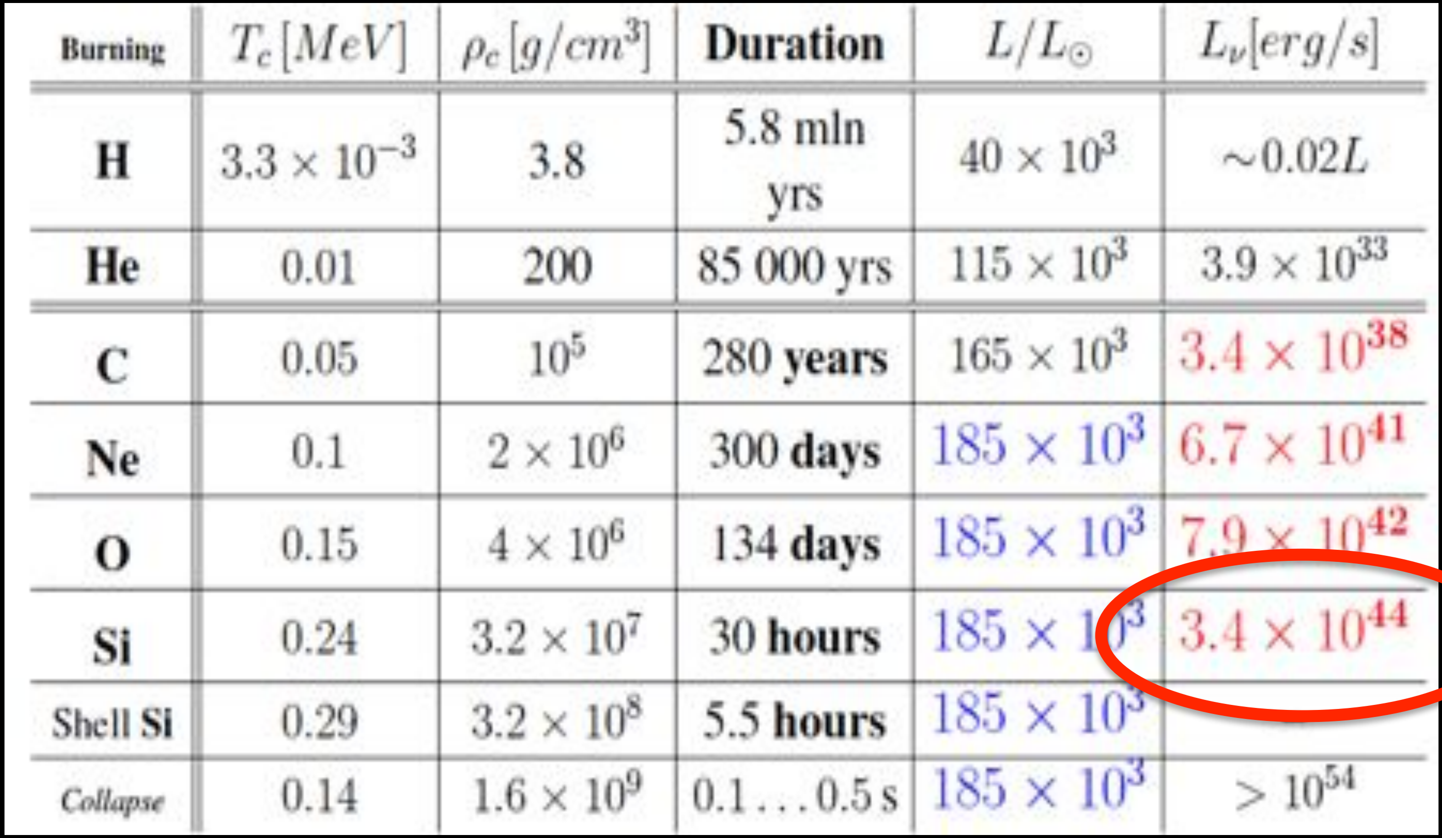
Burst events:

The neutronization (νe) burst is more robustly predicted with ~10% variation. Needs inverted mass hierarchy.

→ The distance can be measured to ~0(10)% accuracy by Hyper-K

Early early warning signal

Neutrinos: The ν luminosity rapidly rises at the late stages of stellar nucleosynthesis, which gives an early-early warning for a supernova



Burning	$T_c\,[MeV]$	$\rho_c\,[g/cm^3]$	**Duration**	$L/L_\odot$	$L_\nu[erg/s]$
H	3.3×10^{-3}	3.8	5.8 mln yrs	40×10^3	$\sim 0.02L$
He	0.01	200	85 000 yrs	115×10^3	3.9×10^{33}
C	0.05	10^5	**280 years**	165×10^3	3.4×10^{38}
Ne	0.1	2×10^6	**300 days**	185×10^3	6.7×10^{41}
O	0.15	4×10^6	**134 days**	185×10^3	7.9×10^{42}
Si	0.24	3.2×10^7	**30 hours**	185×10^3	3.4×10^{44}
Shell Si	0.29	3.2×10^8	**5.5 hours**	185×10^3	
Collapse	0.14	1.6×10^9	$0.1 \ldots 0.5$ s	185×10^3	$> 10^{54}$

Early early warning signal

Neutrinos: The ν luminosity rapidly rises at the late stages of stellar nucleosynthesis, which gives an early-early warning for a supernova

Burning	$T_c\,[MeV]$	$\rho_c\,[g/cm^3]$	Duration	$L/L_\odot$	$L_\nu[erg/s]$
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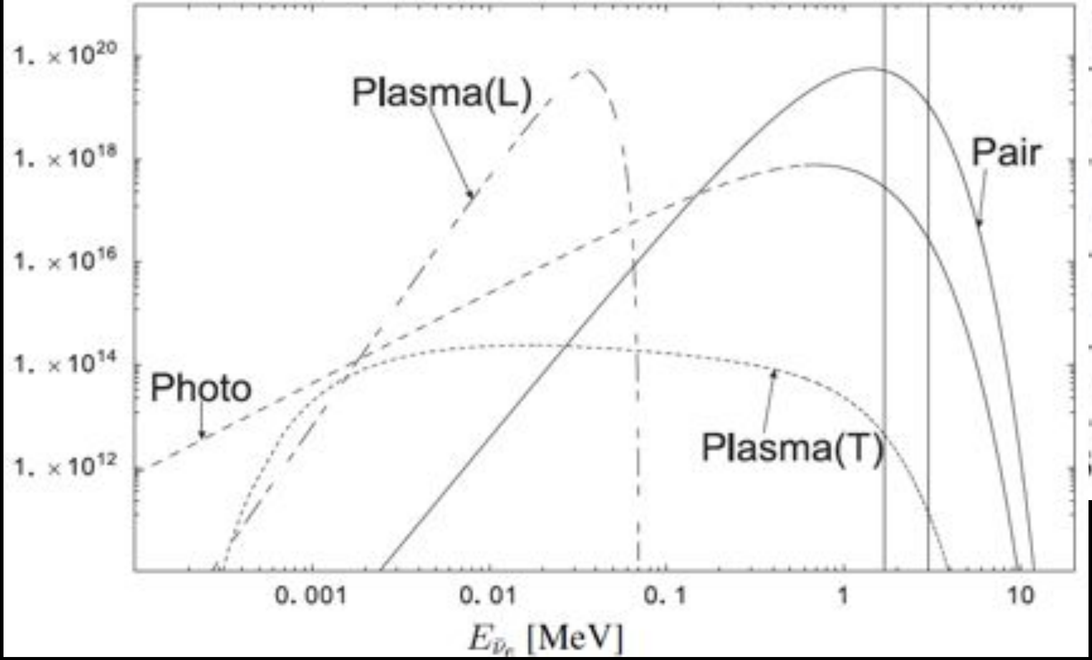
				185×10^3	



Odrzywolek (2004)

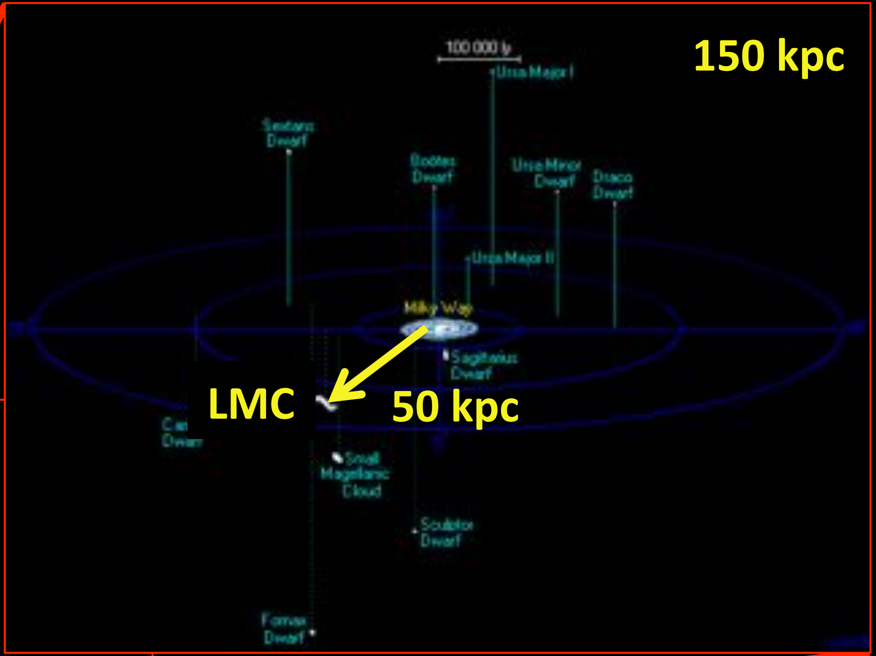
	Range [kpc]
Super-K + Gd	0.5
Hyper-K +Gd	2

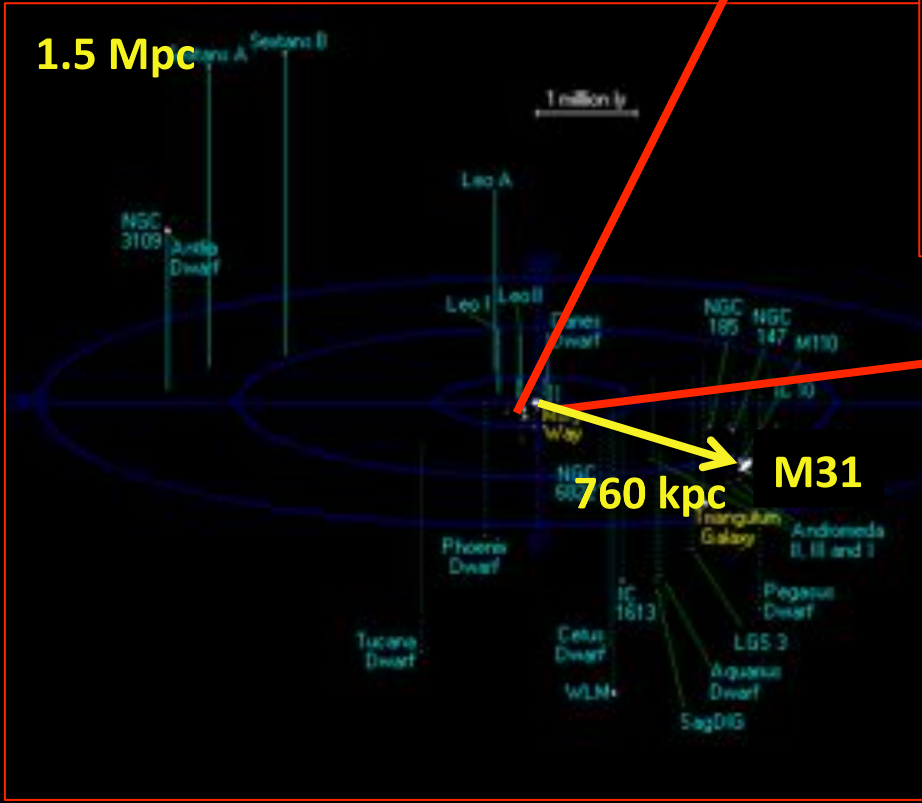
SUPERNOVA NEUTRINOS FROM NEARBY GALAXIES

Reach to our neighbors

With Super-Kamiokande:

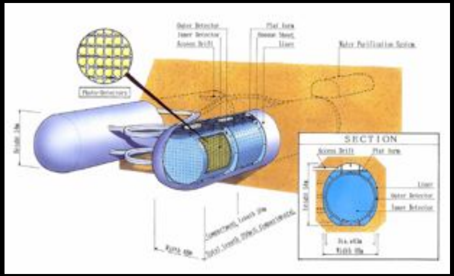
- $\sim 10^4$ events from GC
- $\sim$400 events from LMC
- $\sim$1 event from M 31





With Hyper-Kamiokande:

- $\sim$10 event from M 31



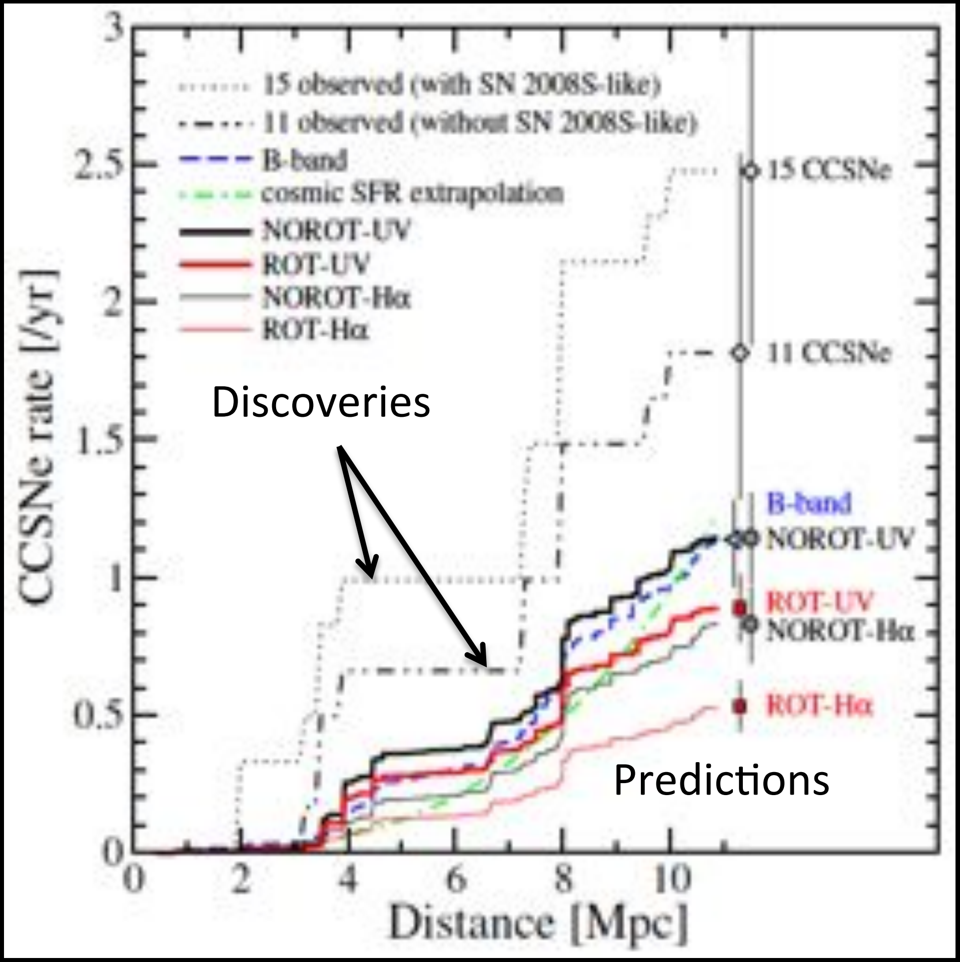
The nearby supernova rate

M 83 (4.5 Mpc)

1923A, 1945B, 1950B,
1957D, 1968L, 1983N

NGC 6946 (5.9 Mpc)

1917A, 1939C, 1948D,
1968D, 1969P, 1980K,
2002hh, 2004et, 2008S



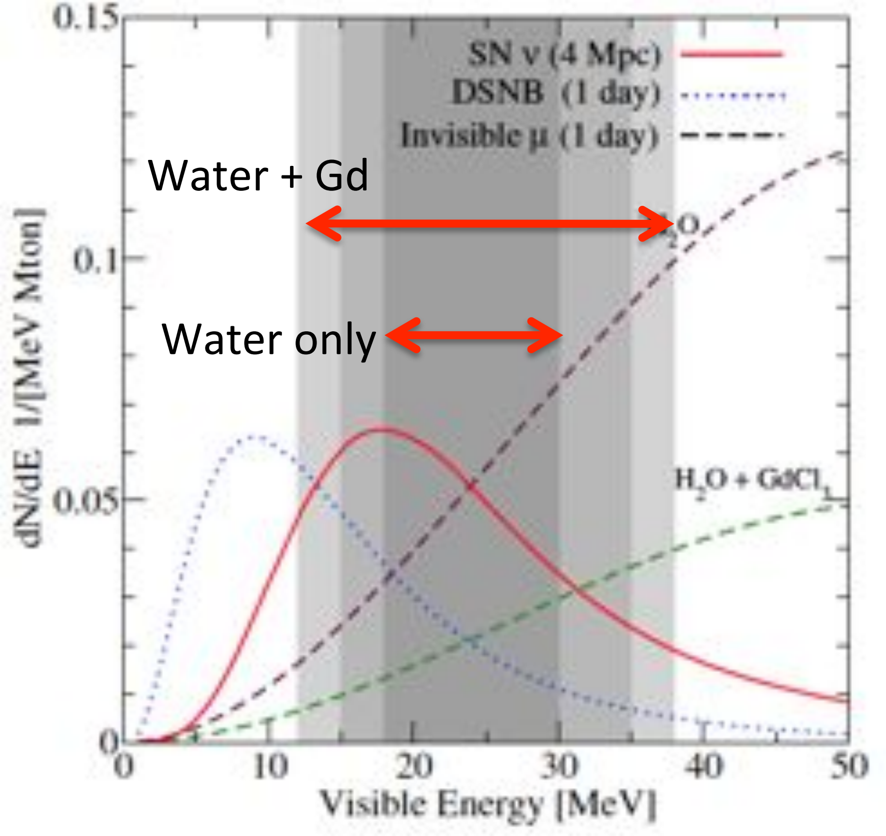
Horiuchi et al. (2013)
Also Ando et al (2005)

- Lower-limit: these are not full-sky systematic surveys, so many supernovae, but also galaxies, are likely missed
- High impact of systematic searches, e.g., Lick Observatory SN Search

The Challenge: low statistic burst detection

Signal: look for doublets, triplets, etc depending on background rate

- Backgrounds:
  - Reactor neutrinos
  - Atmospheric neutrinos
  - Invisible muons decays
- Gadolinium removes backgrounds, allowing a larger energy range to be searched



Ando et al. (2005)

	H_2O only	H_2O + Gd
Energy range [MeV]	18-30	12-38
Signal ν (in ~10 sec for d = 1 Mpc)	5	10
Background ν (over 1 day)	0.5	0.6

➔ Can go to a few Mpc

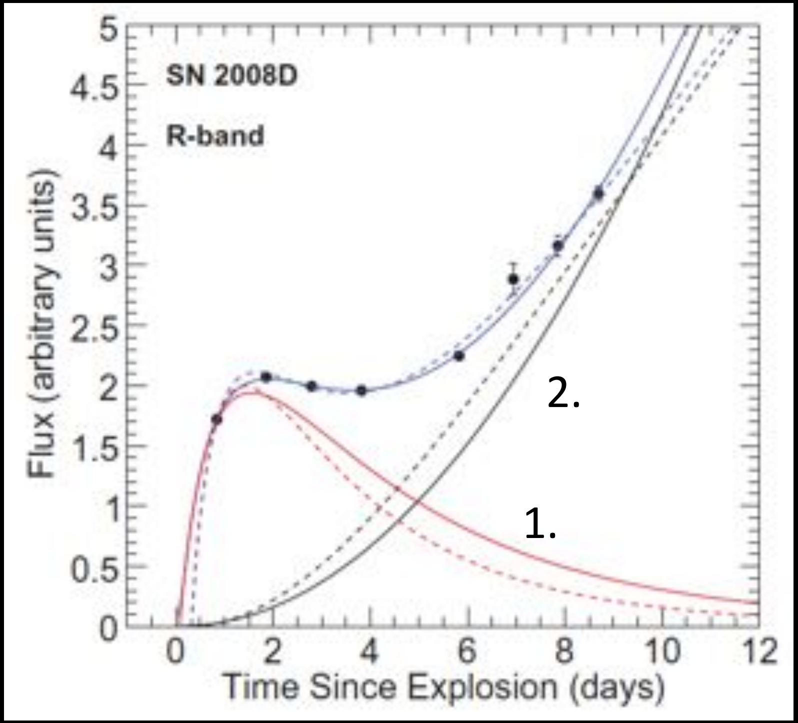
How far can we probe?

Signal: or, look for events coinciding with an observed optical supernova

Reduce the time window using light curve fitting.

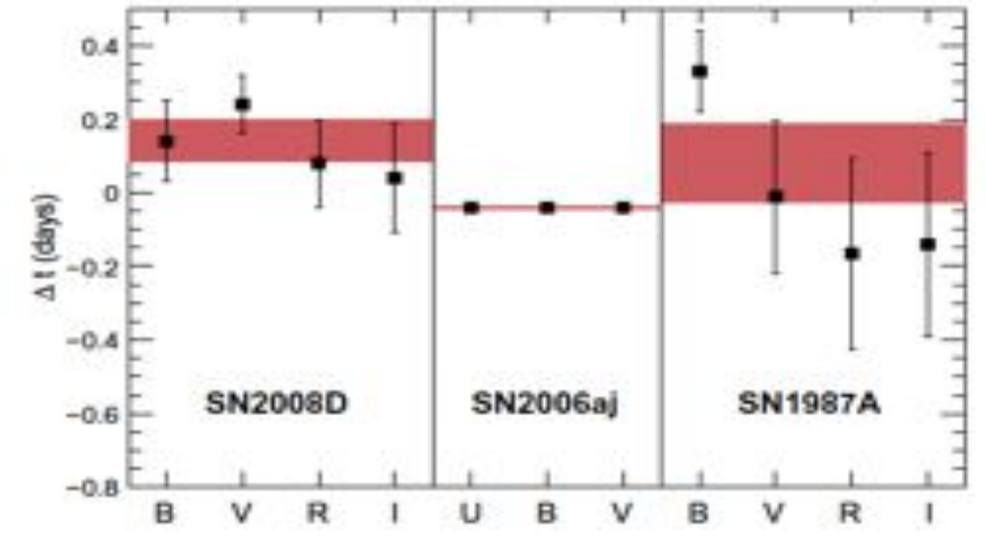
Model as the sum of:

1. Thermal shock breakout phase
2. Expanding photosphere phase



Cowen et al. (2009)

If a few hours is possible → we can probe ν out to ~3 Mpc



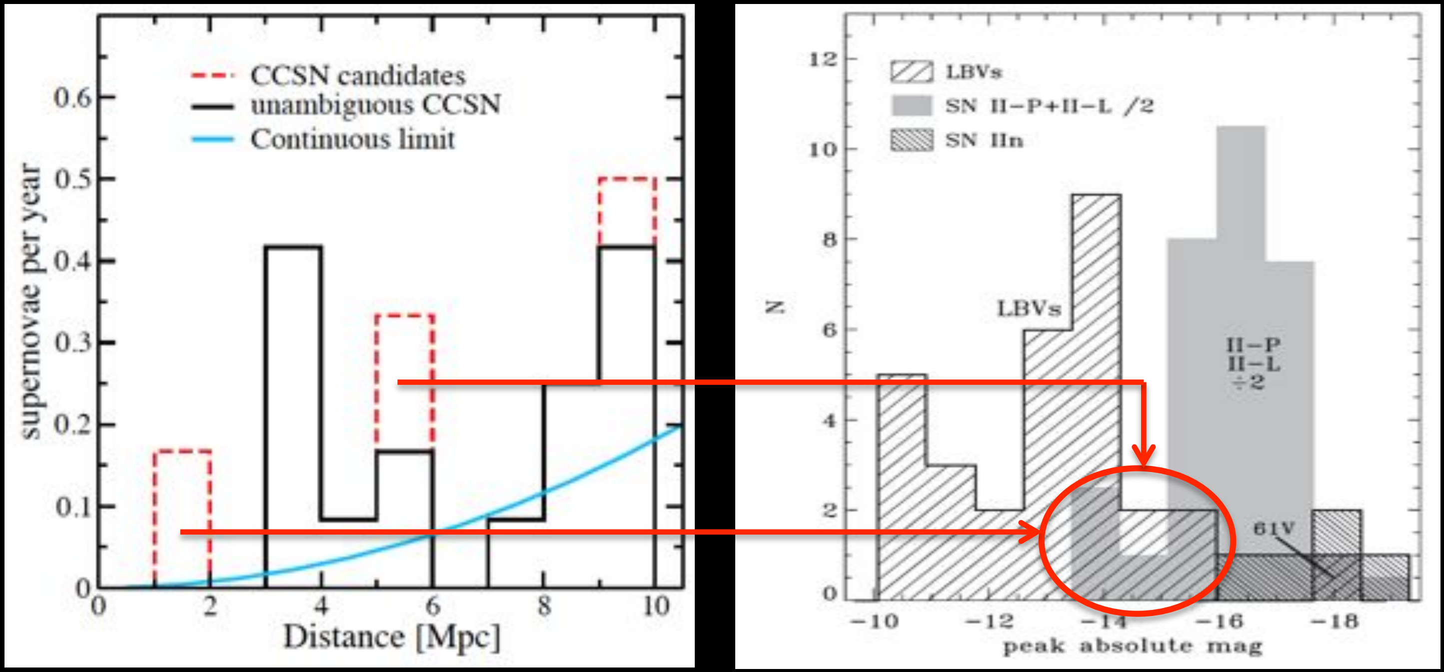
	H_2O only	H_2O + Gd
Energy range [MeV]	18-30	12-38
ν counts (for 3 Mpc)	0.5	1
Bkg counts (in 5 hrs)	0.1	0.13

Impostor or supernova?

SN2008S-like events:

Are they extreme luminous blue variables or dim supernovae?

Nearby potential impostors in red



Smith et al. (2011)

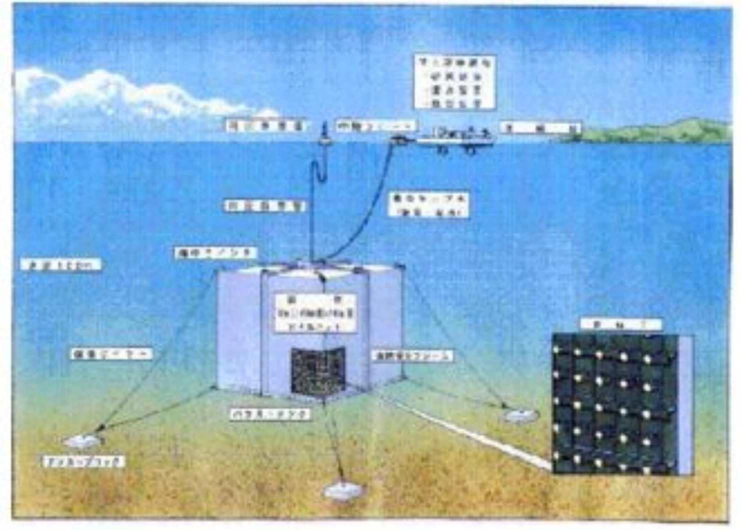
Lots of recent interest in the community: 181 abstracts on "SN2008S" as of Nov 2013 using the NASA-ADS object search. *Smith et al. (2009), Bond et al. (2009), Berger et al. (2009), Botticella et al. (2009), Pumo et al. (2009), Thompson et al. (2009), etc etc etc*

Even a few MeV neutrinos will be an indisputable signal to settle the debate.

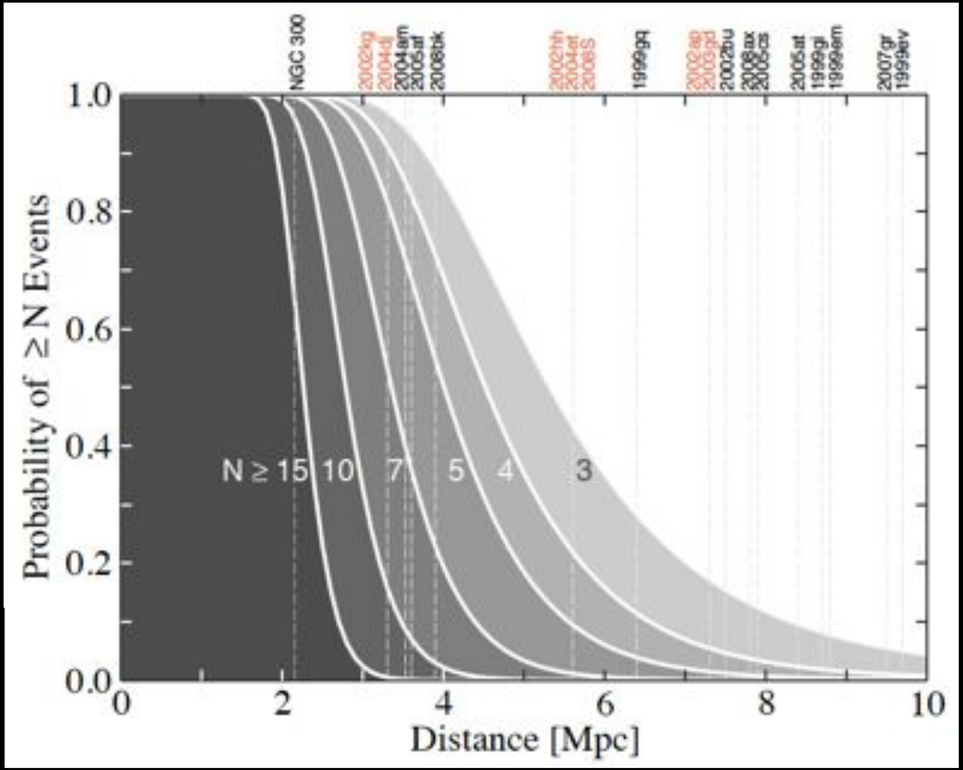
Mton detectors are well-placed to make significant & unique contributions

Looking further to a ~5 Mton detector

$N_\nu > 3$ \`mini-bursts' from nearby (almost annual) supernovae possible with Deep-TITAND



Suzuki (2001)



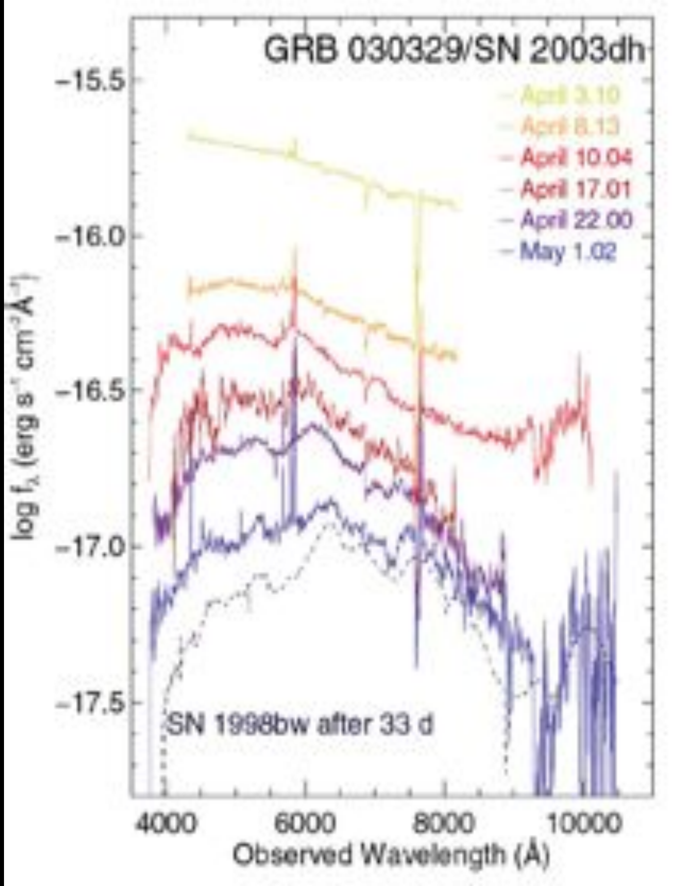
Kistler et al. (2008)

Higher backgrounds (less depth and no n-tagging), but $N_\nu = 3$ is expected to occur once every ~5 years so triplets can be used.

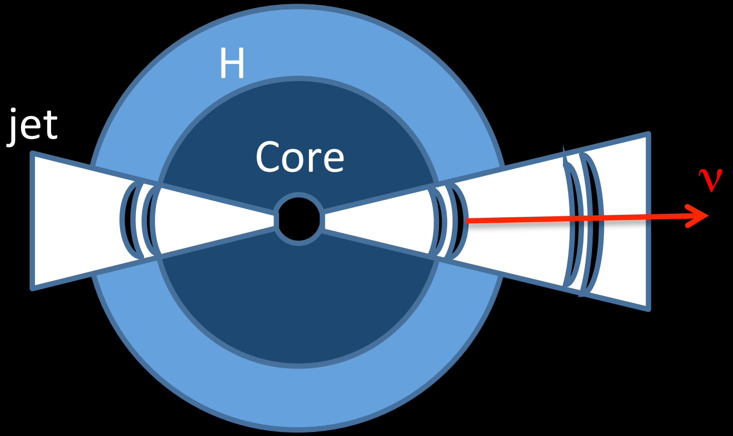
Weighed by the supernova rate yields an expected total ν rate of ~50 events per year from all nearby supernovae!

Higher-energy neutrino transients

Supernova/long-GRB connection established that some supernovae have powerful jets



Hjorth et al (2003), Stanek et al (2003)



$$p + \gamma \rightarrow N\pi + X$$

Various ν emission scenarios investigated:

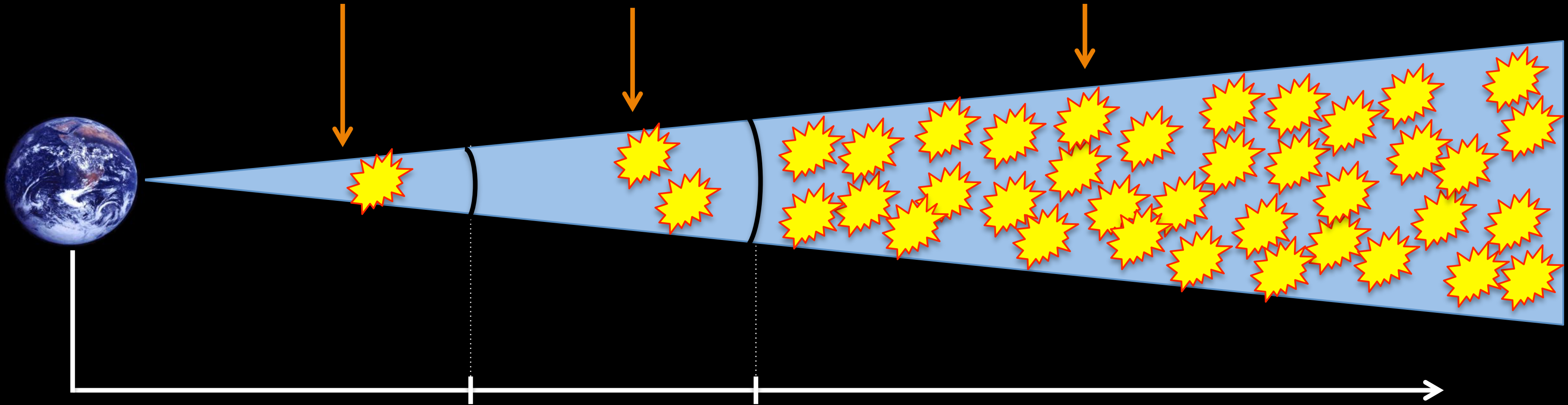
- Quasi-thermal 0.1 – 1 GeV emission
- Non-thermal > 1 GeV emission from choked/hidden/weak jets

Model-dependent → provide information on jet and proto-neutron star properties. Can typically be probed out to ~10 Mpc by Hyper-K or IceCube.

Meszaros & Waxman (2001), Razzaque et al (2003,2004, 2005), Ando & Beacom (2005), Horiuchi & Ando (2008), Murase et al (2013), Murase & Ioka (2013), etc…

DIFFUSE BACKGROUND OF SUPERNOVA NEUTRINOS

Distance scales and physics outcomes



$N_\nu >> 1$: BURST

SN rate ~ 0.01 /yr

$N_\nu \sim 1$: MINI-BURST

SN rate ~ 1 /yr

$N_\nu << 1$: DIFFUSE

SN rate ~ 10^8 /yr

~kpc

~Mpc

~Gpc

Galactic burst:
Explosion mechanism, astronomy

Basics are covered, and future detectors

Mini-bursts:
Transient ID, can probe burst variety

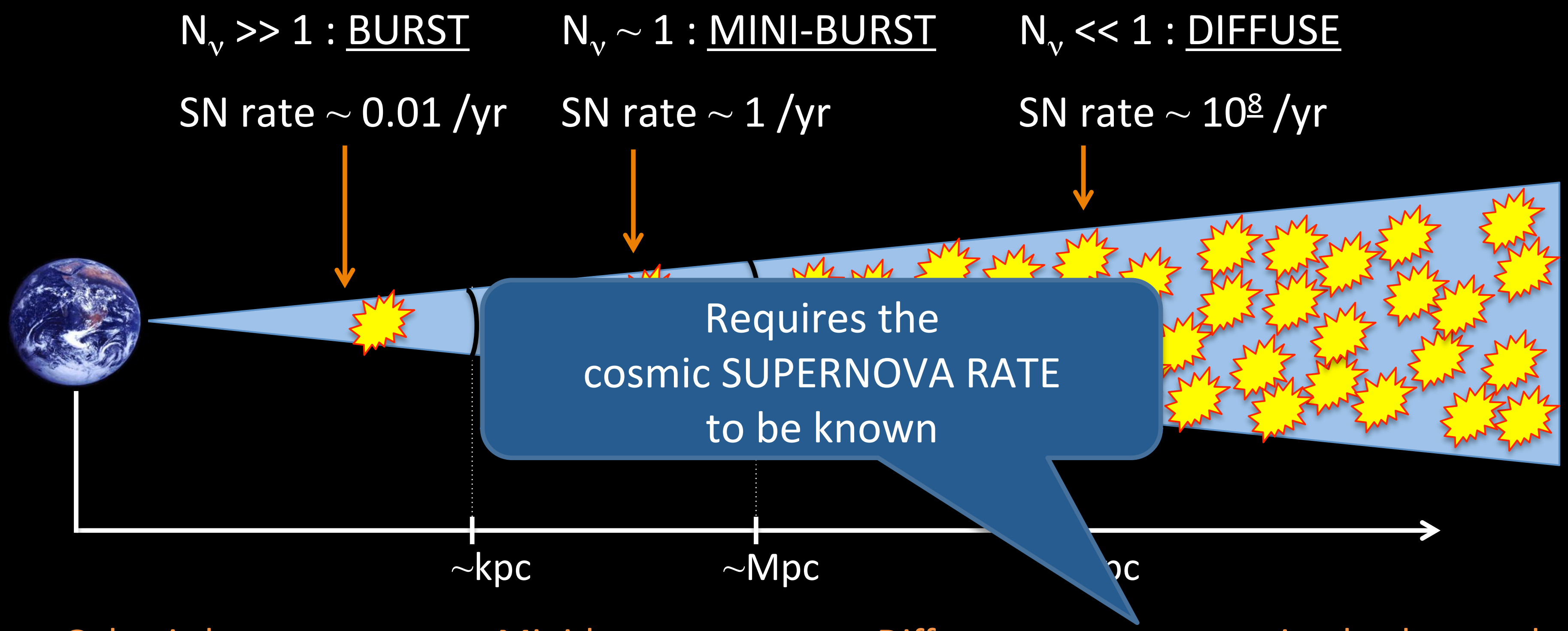
Next generation, e.g., Hyper-K

Diffuse supernova neutrino background:
average emission, multi-populations

Near future, i.e., SuperK with Gadolinium, and future detectors

(adapted from Beacom@Nu2012)

Distance scales and physics outcomes



$N_\nu >> 1$: <u>BURST</u>

SN rate ~ 0.01 /yr

$N_\nu \sim 1$: <u>MINI-BURST</u>

SN rate ~ 1 /yr

$N_\nu << 1$: <u>DIFFUSE</u>

SN rate ~ 10^8 /yr

Requires the
cosmic SUPERNOVA RATE
to be known

Galactic burst:
Explosion mechanism, astronomy

Basics are covered, and future detectors

Mini-bursts:
Transient ID, can probe burst variety

Next generation, e.g., Hyper-K

Diffuse supernova neutrino background:
average emission, multi-populations

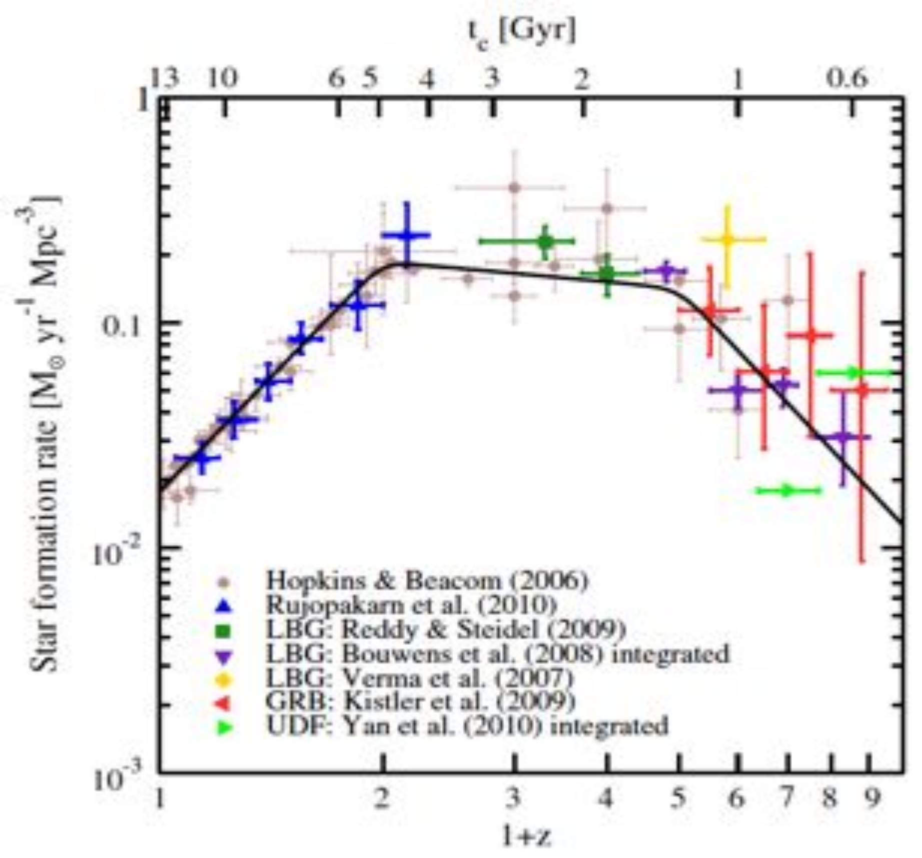
Near future, i.e., SuperK with Gadolinium, and future detectors

(adapted from Beacom@Nu2012)

Core-collapse rate

Core collapse rate = Birth rate of massive stars

*because lifetime of massive stars are cosmologically short



Horiuchi & Beacom (2010) see also Hopkins & Beacom (2006)

The star formation rate:

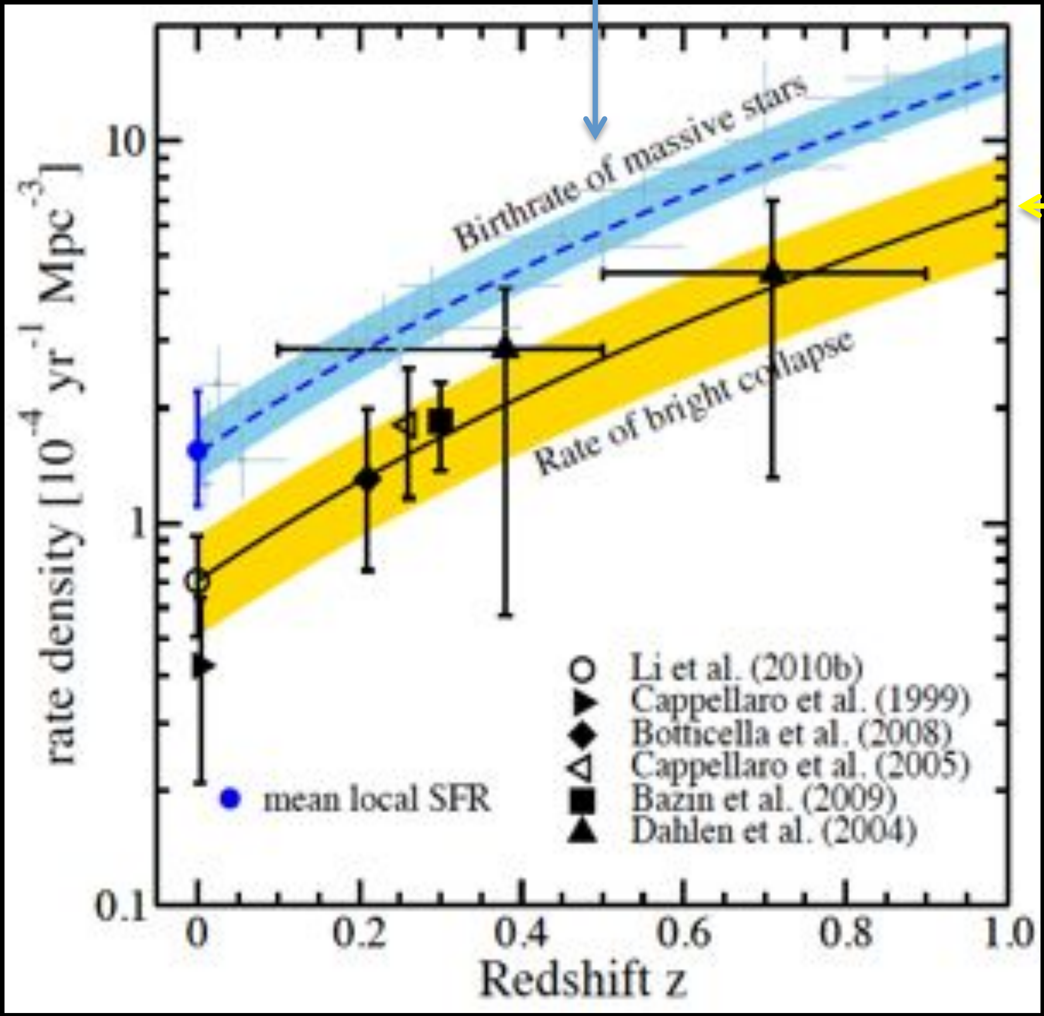
Has been measured by many groups, using many wavebands (radio, FIR, MIR, NIR, $H\alpha$, UV, X rays) and many data sets

Uncertainties are mostly systematic

SFR data have rapidly increased and the uncertainty is now mainly:

- dust correction
- SFR calibration factors
- (Initial mass function is import for SFR but not so for core-collapse rate)

Birthrate & supernova rate



Adapted from Horiuchi et al (2011)

Birthrate of massive stars

The birth rate of 8 – 100 Msun stars

Observed supernova rate

Gives the observed core-collapse rate, probed by observations of *luminous* supernovae.

(Birth rate) – (supernova rate) = DIM or DARK collapse

Massive stars that collapse `quietly' in photons are difficult to observe directly: "un-novae".

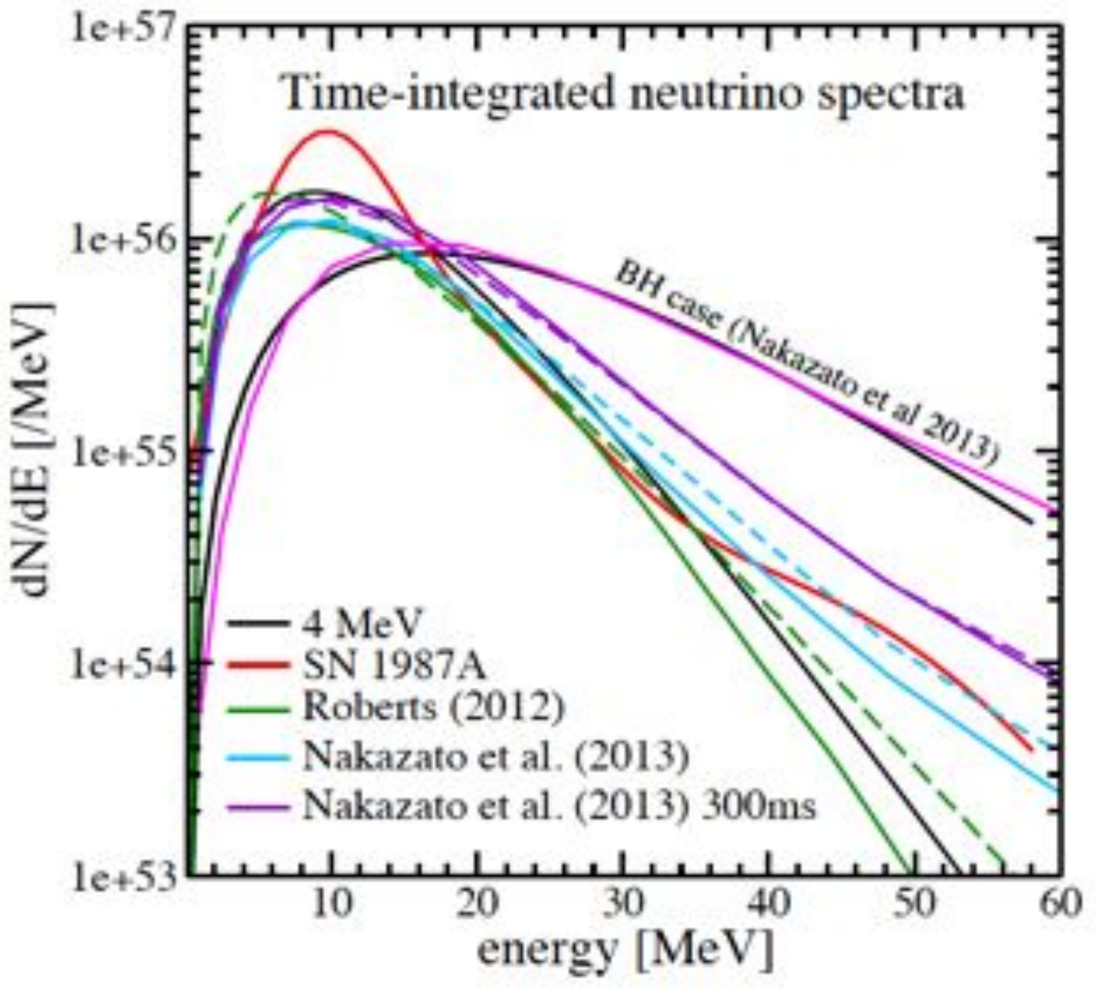
How dark are un-novae?

Neutrino emission: Black hole necessarily goes through a (even if brief) PNS phase.

Rapid mass accretion leads to ν emission that is hotter & more luminous

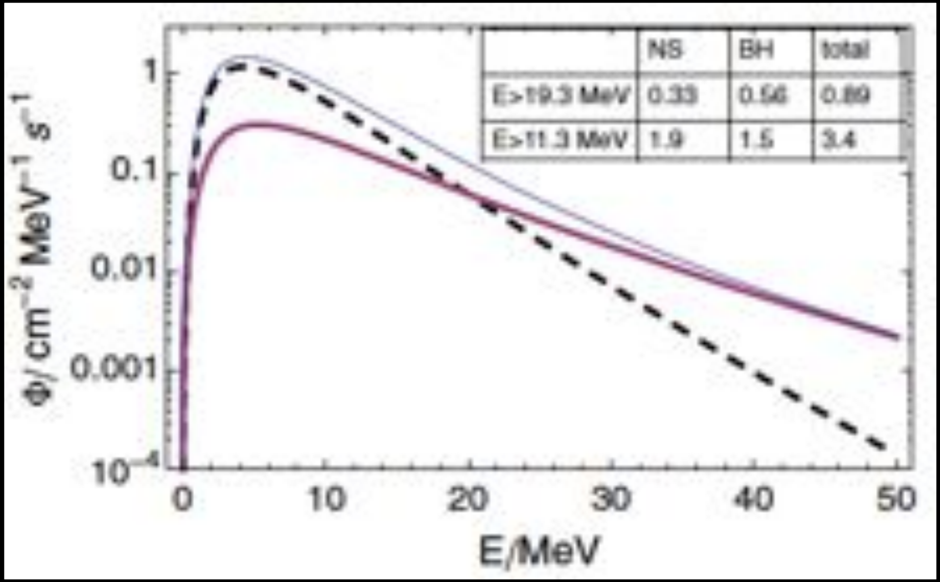
Details: dependent on the progenitor core structure (→ mass accretion) and nuclear equation of state (→ maximum proto-NS mass)

Sumiyoshi et al 2006, 2007, 2008, 2009, Nakazato et al 2008, 2010, Fischer et al 2009, O'Connor & Ott 2011



Event rate

Diffuse neutrino with collapse to BH:



	NS	BH	total
E>19.3 MeV	0.33	0.56	0.89
E>11.3 MeV	1.9	1.5	3.4

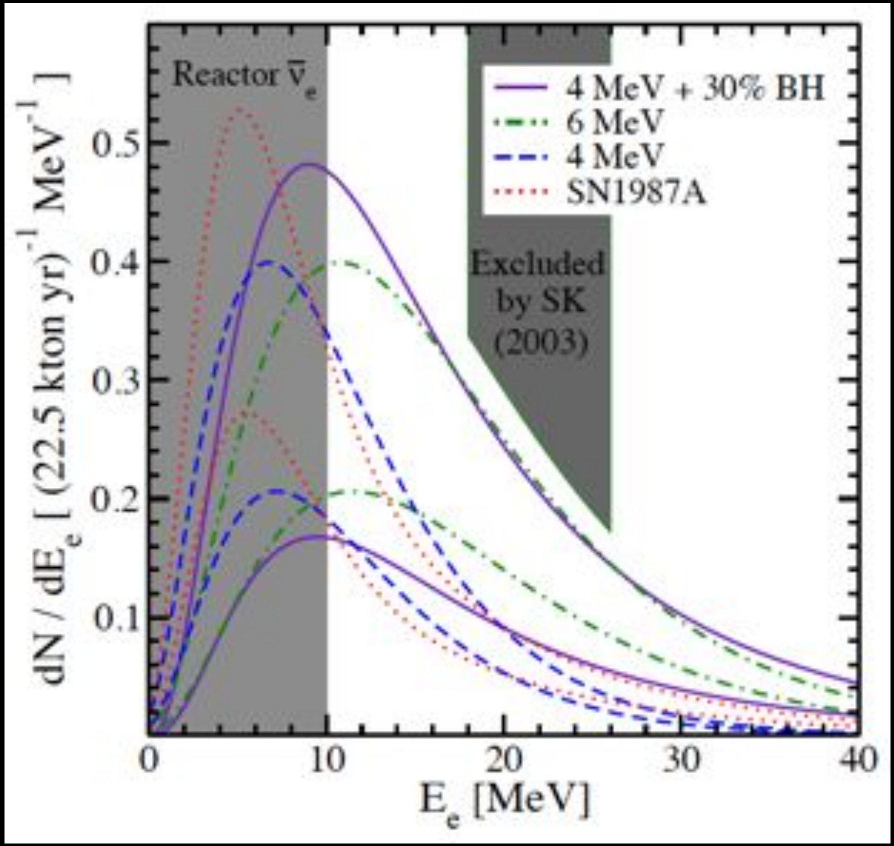
Lunardini (2009)

See also Lien et al. (2010), Keehn & Lunardini (2010)

Event rates: note various assumptions

spectrum	H_2O [/yr]	H_2O+Gd [/yr]	HK+Gd [/yr]
4 MeV	0.4 +/- 0.1	1.8 +/- 0.5	20 +/- 5
4 MeV+BH	1.1 +/- 0.3	3.0 +/- 1.0	30 +/- 10
SN1987A	0.5 +/- 0.1	1.7 +/- 0.5	20 +/- 5

With uncertainties:



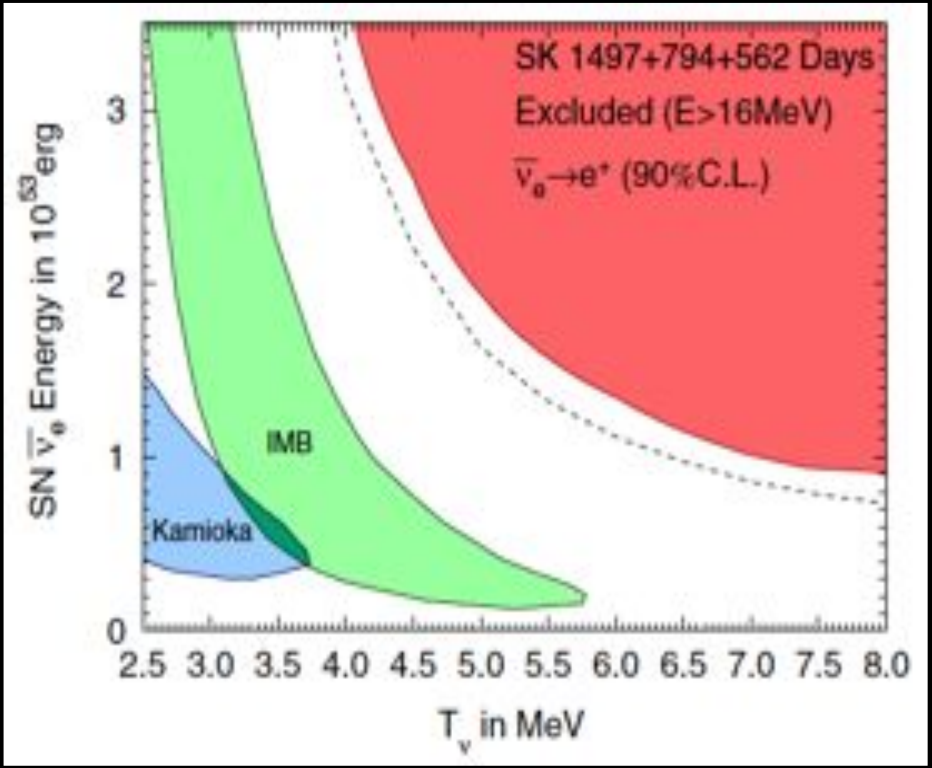
Adapted from Horiuchi et al. (2009)

The uncertainty due to supernova rate is getting competitively small, and will further decrease as more data is collected.

Limits and future reach

Super-K limits:

state-of-the-art limits with SK-I, SK-II, and SK-III data, employing improved background modeling power and statistics treatment.



Bays et al. (2012)

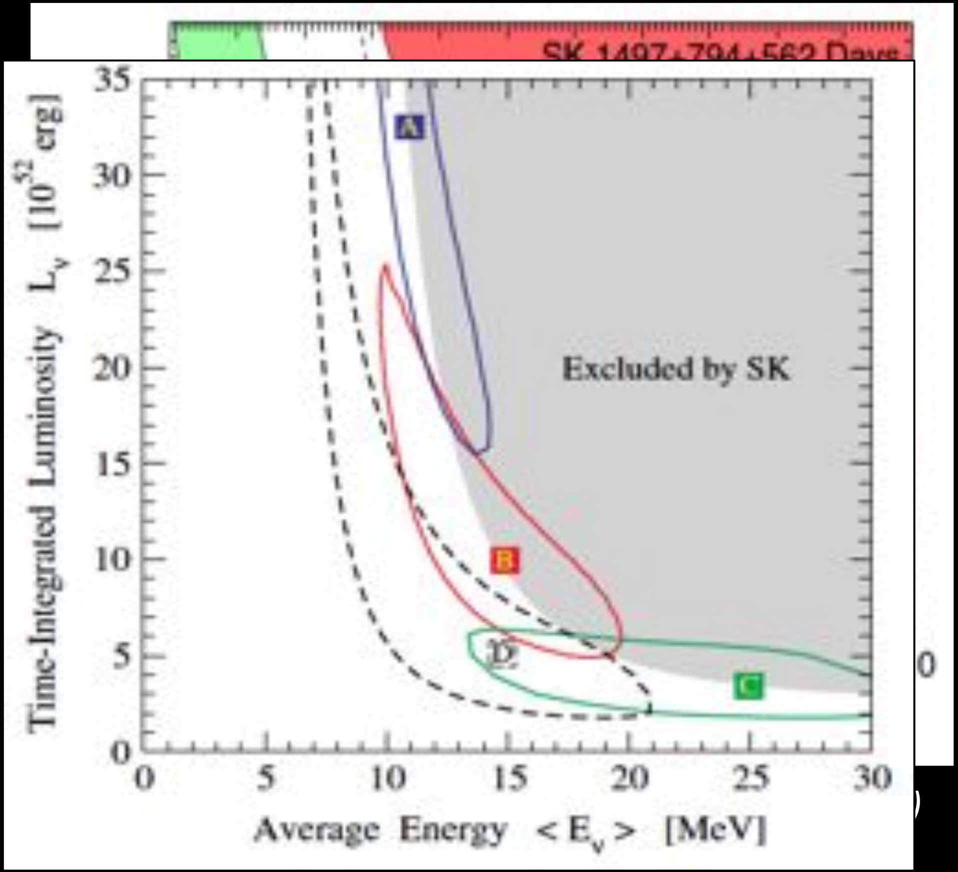
Limits and future reach

Super-K limits:

state-of-the-art limits with SK-I, SK-II, and SK-III data, employing improved background modeling power and statistics treatment.

Super-K with Gd:

Removes the largest background sources and enables a signal dominated search



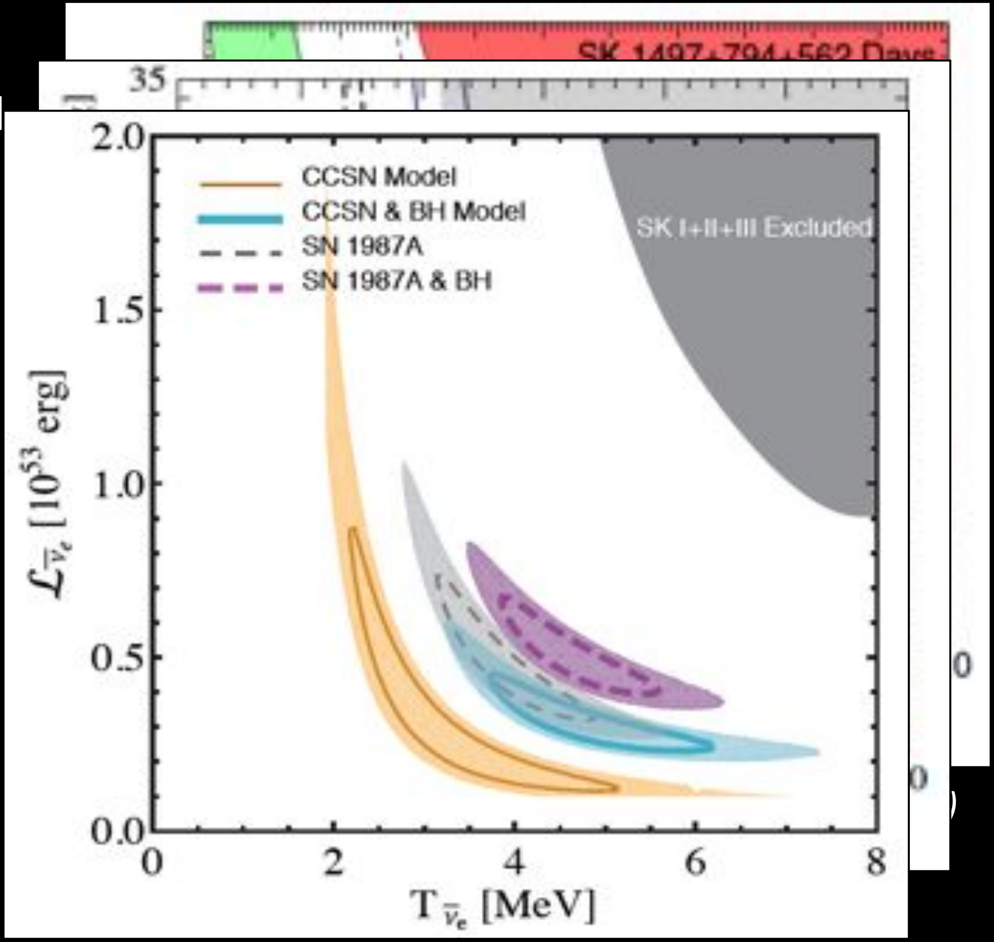
90% CL contours for 5 yr running Super-K with Gd,

Limits and future reach

Super-K limits:
state-of-the-art limits with SK-I, SK-II and SK-III data, employing improved background modeling power and statistics treatment.

Super-K with Gd:
Removes the largest background sources and enables a signal dominated search

Hyper-K with Gd:
The second component from black hole forming collapses may be studied

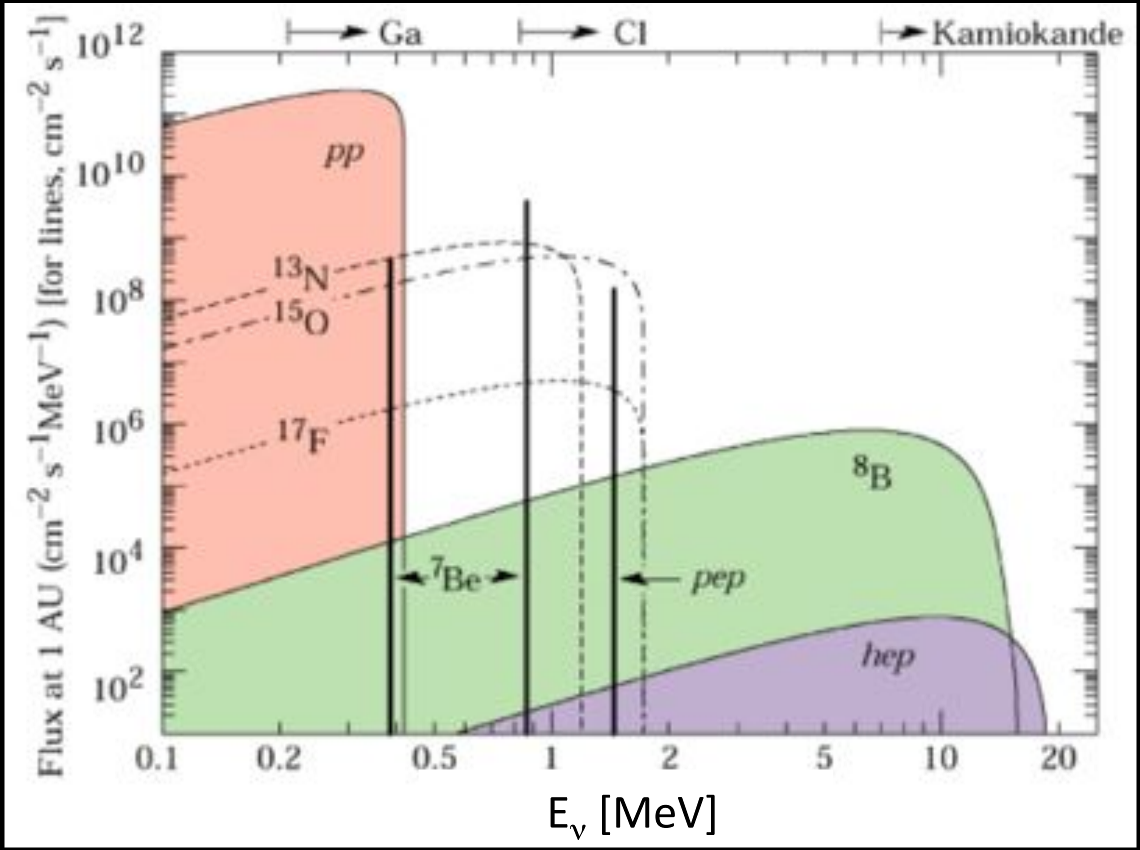


2σ and 5σ contours for 10 years runnng idealized Hyper-K with Gd [Yuksel & Kistler 2013]

SOLAR NEUTRINOS

Solar neutrinos

The Standard Solar Model ν



Standard Solar Model (SSM) is tested and agree with observations → what next?

There are several inconsistencies and topics to be probed:

1. Studies of core CNO fusion rate and tests of the solar abundance problem
2. Studies of time modulations
3. Probes of $P_{ee}(E)$ in the vacuum-matter transition region and tests of non-standard ν interactions

Solar abundance problem

Solar photospheric abundance:

Updated measurements are low:

- Z/X ~ 0.0229 [*Grevesse & Sauval 1998*]
- Z/X ~ 0.0165 [*Asplund et al. 2005*]
- Z/X ~ 0.0178 [Asplung et al 2009]

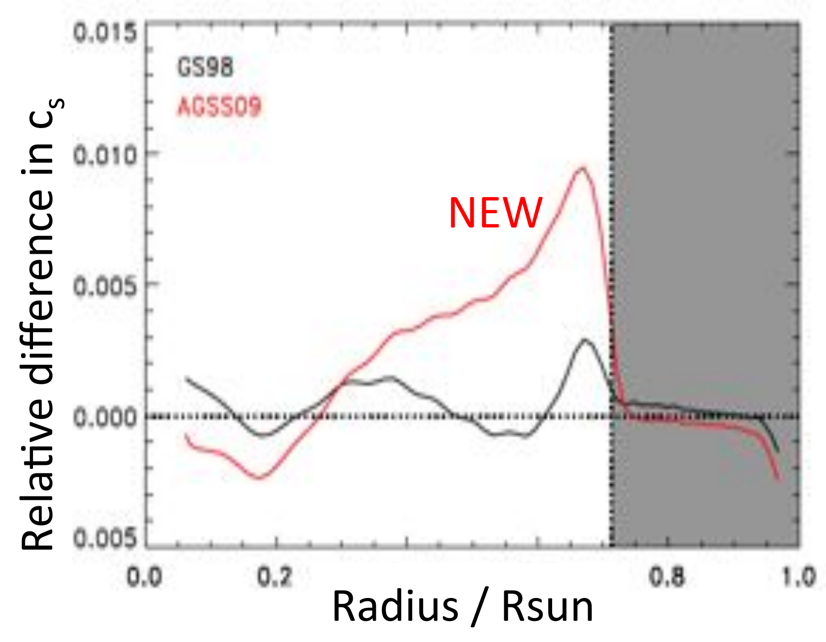
(but, see *Caffau et al 2010*: Z/X ~ 0.0211)

→ Leads to inconsistencies between the SSM and helioseismology

[e.g., Bahcall et al 2005, *Serenelli et al 2010*]

→ Change opacities?

→ homogenous zero-age Sun is incorrect?



Haxton et al 2013

CNO-ν flux:

Sensitive to metallicity (flux is reduced by ~30%) and can test the inhomogeneous solar model

→ Prospects for SNO+, LENA

	GS98	AGSS09
N-ν	2.96 (1 +/- 0.14)	2.17 (1 +/- 0.14)
O-ν	2.23 (1 +/- 0.15)	1.56 (1 +/- 0.15)

Fluxes from Haxton et al 2013

^{7}Be-ν and ^{8}B-ν

Search for time-modulations

$$N(t) = N_0(1 + A\sin(t/T + \psi))$$

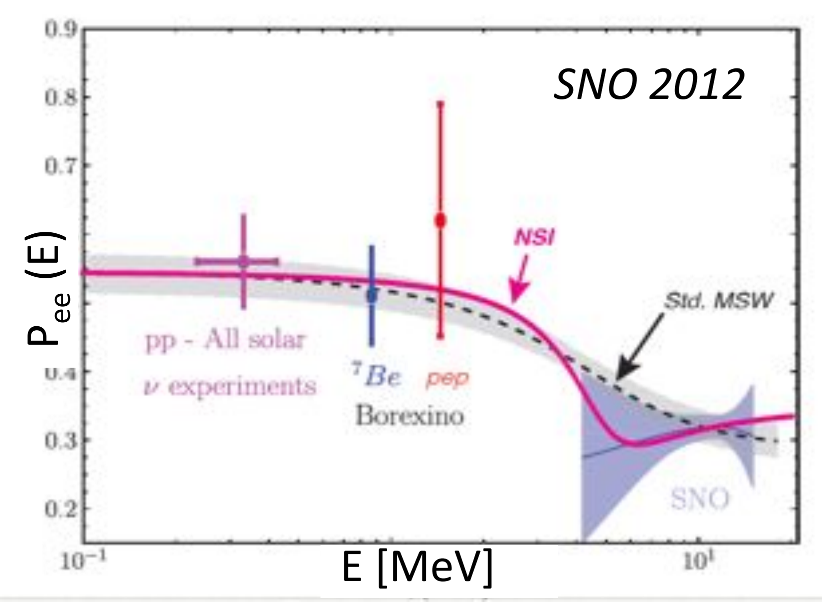
- Current limits exclude *A* greater than $\sim 10\%$ with ^{8}B-ν [SuperK, SNO]
- Smaller *A* modulation studies facilitated by vast statistics (e.g., ^{8}B-ν at Hyper-K, ^{7}Be-ν at LENA)
- Possible causes to look for:
  - Day/night effects?
  - Correlation to solar cycle
  - Helioseismic g-modes
  - Annual
  - Any other?

P_{ee}(E) in the transition region

- Non-standard interaction (NSI) predict different P_{ee}(E)

Friedland et al (2004)

- Data consistent with MSW-LMA, but few data in the important transition region



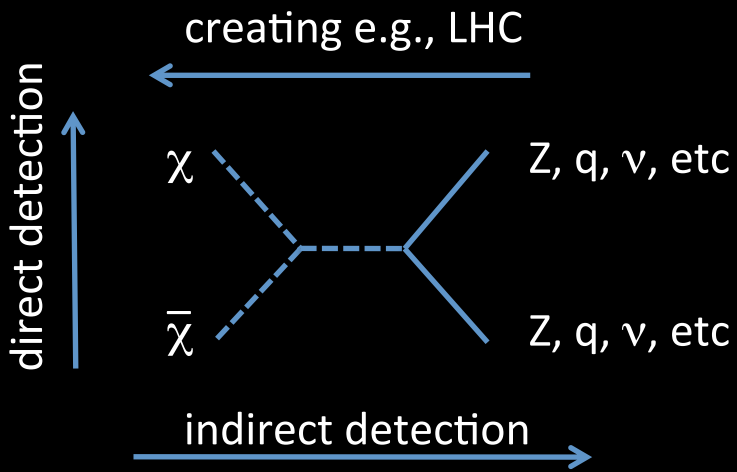
SNO 2012

NEUTRINOS FROM DARK MATTER

Particle dark matter

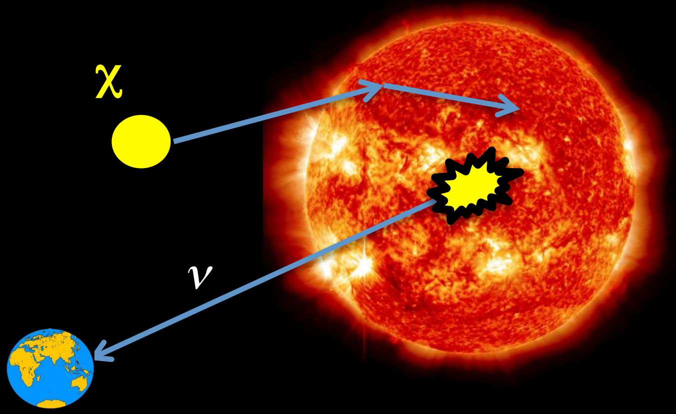
- What we know
  - Its existence
  - Their abundance
  - Is minimally interacting
  - Is highly clustered
    - Local density

- What we do not know
  - Its mass
  - Its interactions
    - Cross section
  - Whether they annihilate
    - If they do, the branching ratios to final states
  - Is it a WIMP?



Two profoundly different neutrino probes

- Solar dark matter neutrinos as probes of the scattering cross section
- Dark matter particles:
  1. Scatters in the sun
  2. Gravitationally captured
  3. Settles in the core
  4. Annihilates
  5. Neutrinos escape



- Milky Way halo neutrinos as probes of the annihilation cross section
- Dark matter particles:
  1. Clump in the early universe
  2. Merge, etc, and host the Milky Way galaxy
  3. Settles in a distribution
  4. Annihilates
  5. Many particles get to us (ν, γ, even some charged CRs)

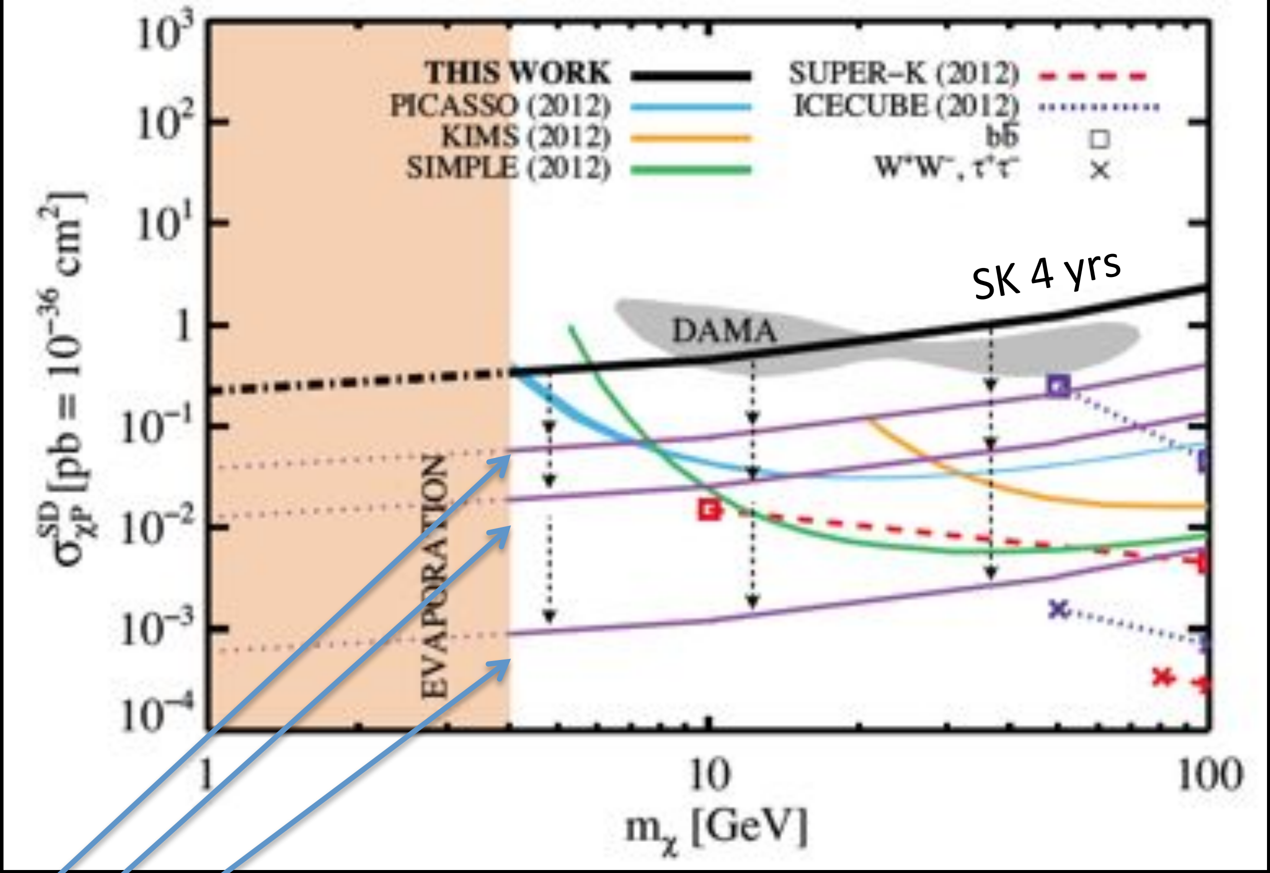
Limits on the scattering cross section

Signals:

- HE neutrinos from prompt decays (the normal focus)
- LE neutrinos from π^+ decay at rest (recently worked out), < 53 MeV

LE neutrinos:

- Must model shower development in the sun: production and energy loss/capture
- Include mixing



Future improvements:

- Hyper-K 4 yrs…………….
- Super-K + Gd 4 yrs…….
- Hyper-K + GD 4 yrs……

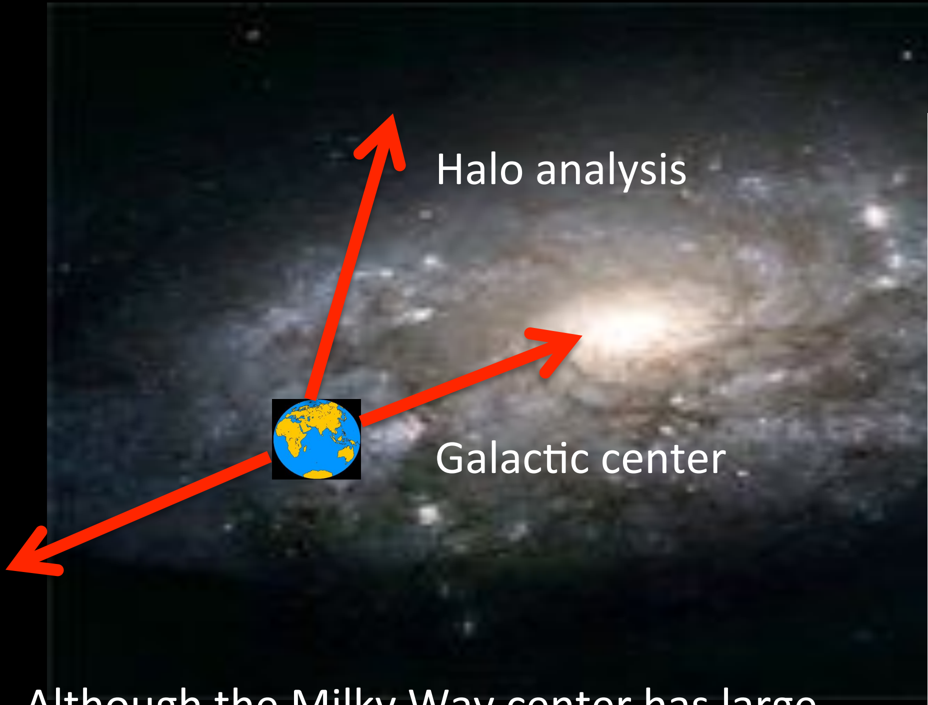
Rott et al. (2013), see also Bernal et al. (2013)
RED shows channel-differentiated Super-K limits

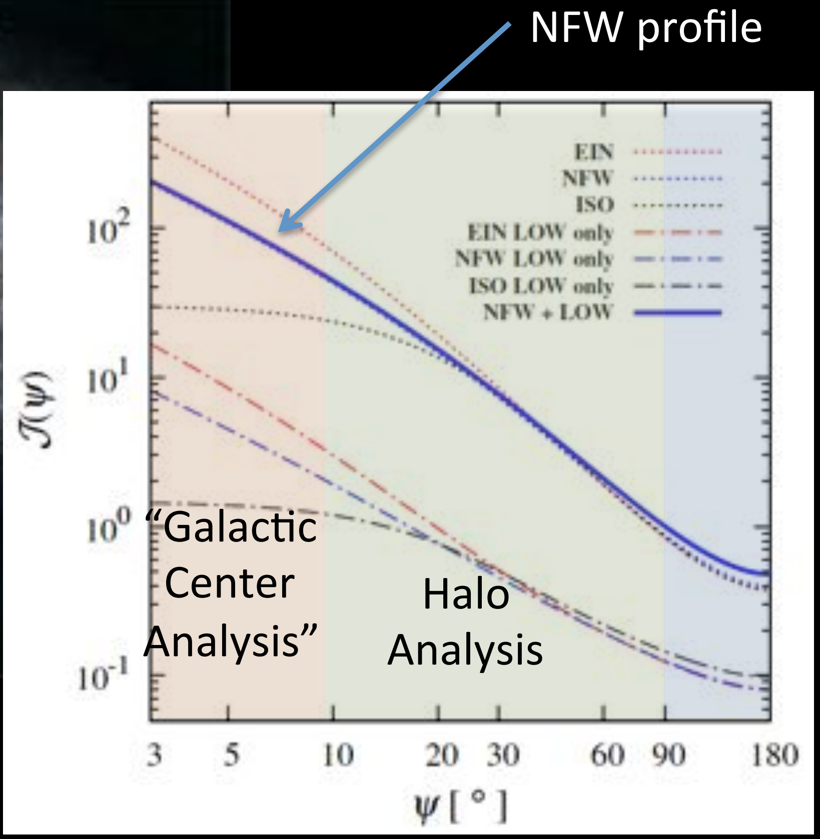
$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Limits on the annihilation cross section

Possible sources:

Cosmic diffuse from all galaxy halos, as well as our Milky Way halo



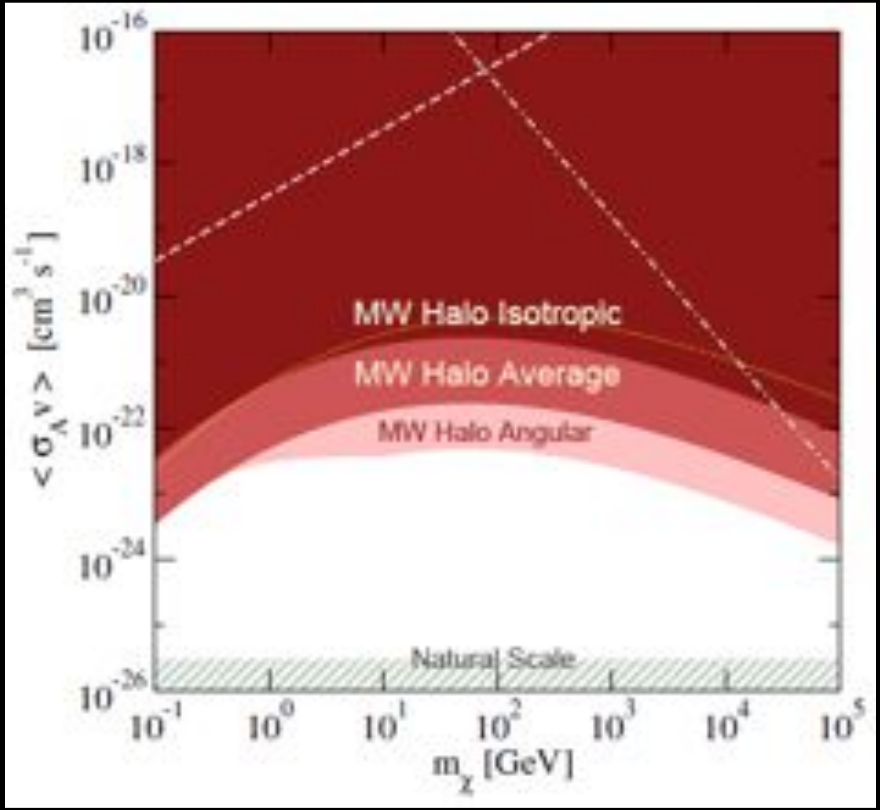


Although the Milky Way center has large expected signals, systematic uncertainty blows up due to unknown central density

Limits on the annihilation cross section

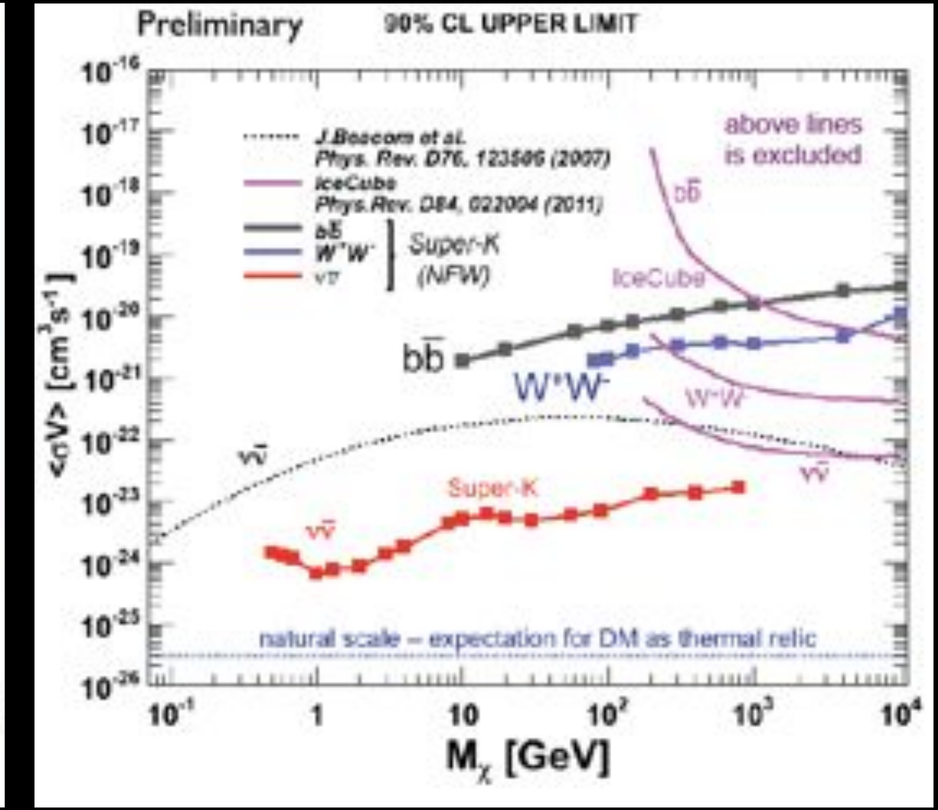
Halo analysis: look at the Milky Way halo at large and search for annihilation signal. Halo analysis benefits from signal and reduced profile uncertainty.

Simplified theorist (conservative) estimate:



Yuksel et al (2007)

Expert experimentalist analysis:



Rott, Neutrino 2012

Summary

- *Next generation ν detectors opens the window to high-statistic astrophysical neutrino detections that have high potential impact for many astrophysical topics:*

1. Supernova neutrino
   - The big question: explosion mechanism
   - Neutrino astronomy: eagerly anticipated
   - Neutrinos from many supernovae
2. Solar neutrino
   - Refining the standard solar model
3. Dark matter probes
   - Discovery potential; competitive and complementary to other searches

Thank you!

Back-up slides

Event identification with Gd

Beacom & Vagins (2004): use dissolved Gadolinium (Gd) for effective neutron-tagging

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

H_2O

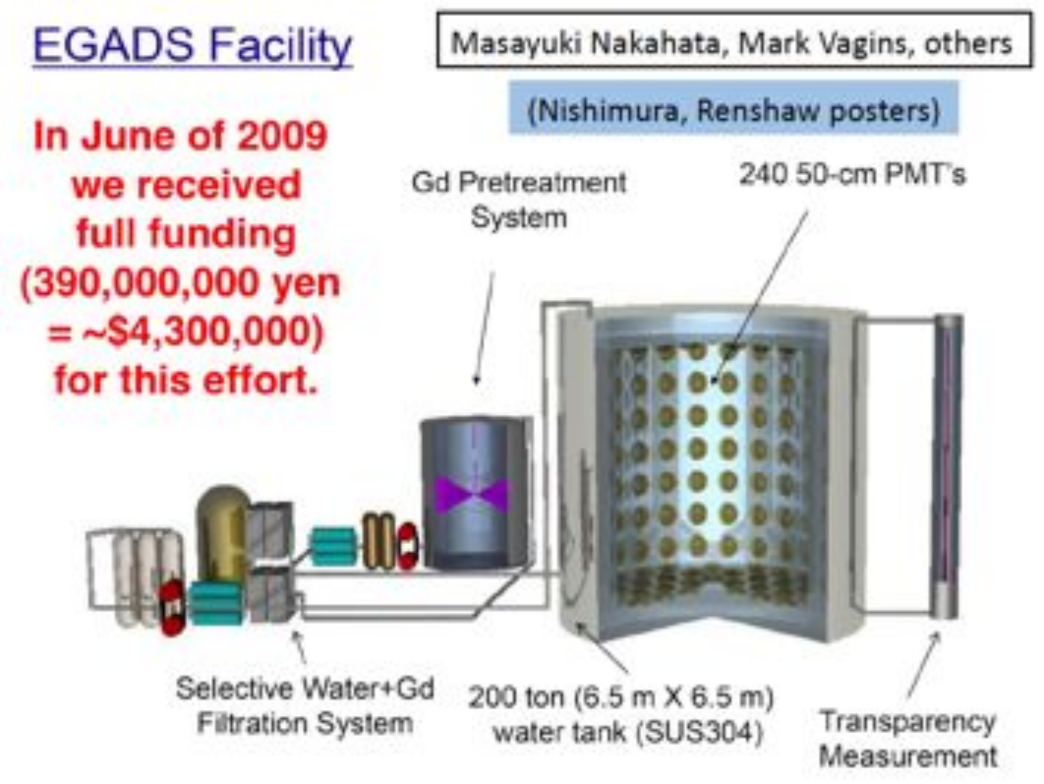
Capture on protons, 2.2 MeV gamma (below threshold)

H_2O + Gd

Capture on Gd, ~8 MeV gamma, easily detectable coincidence signal

EGADS = Evaluating Gadolinium's Action on Detector Systems

dissolving, material corrosion, water transparency, Gd removal, filtration system, etc



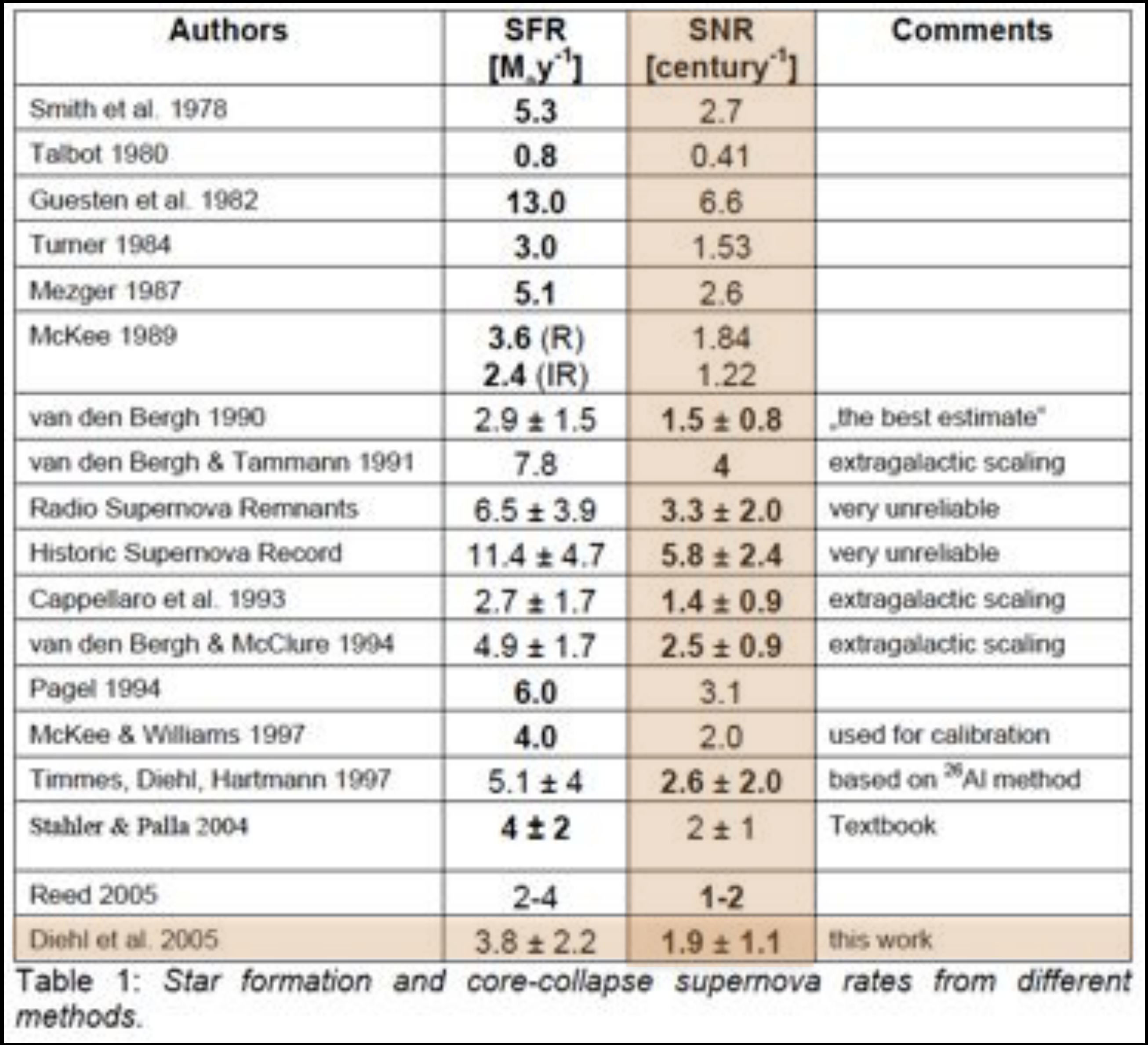
EGADS Facility

Masayuki Nakahata, Mark Vagins, others

(Nishimura, Renshaw posters)

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

Galactic supernova rate



Authors	SFR $[M_\odot y^{-1}]$	SNR $[\text{century}^{-1}]$	Comments
Smith et al. 1978	**5.3**	2.7	
Talbot 1980	**0.8**	0.41	
Guesten et al. 1982	**13.0**	6.6	
Turner 1984	**3.0**	1.53	
Mezger 1987	**5.1**	2.6	
McKee 1989	**3.6** (R) **2.4** (IR)	1.84 1.22	
van den Bergh 1990	2.9 ± 1.5	**1.5 ± 0.8**	„the best estimate"
van den Bergh & Tammann 1991	7.8	**4**	extragalactic scaling
Radio Supernova Remnants	6.5 ± 3.9	**3.3 ± 2.0**	very unreliable
Historic Supernova Record	11.4 ± 4.7	**5.8 ± 2.4**	very unreliable
Cappellaro et al. 1993	2.7 ± 1.7	**1.4 ± 0.9**	extragalactic scaling
van den Bergh & McClure 1994	4.9 ± 1.7	**2.5 ± 0.9**	extragalactic scaling
Pagel 1994	**6.0**	3.1	
McKee & Williams 1997	**4.0**	2.0	used for calibration
Timmes, Diehl, Hartmann 1997	5.1 ± 4	**2.6 ± 2.0**	based on ^{26}Al method
Stahler & Palla 2004	**4 ± 2**	2 ± 1	Textbook
Reed 2005	2-4	**1-2**	
Diehl et al. 2005	3.8 ± 2.2	**1.9 ± 1.1**	this work

Table 1: *Star formation and core-collapse supernova rates from different methods.*

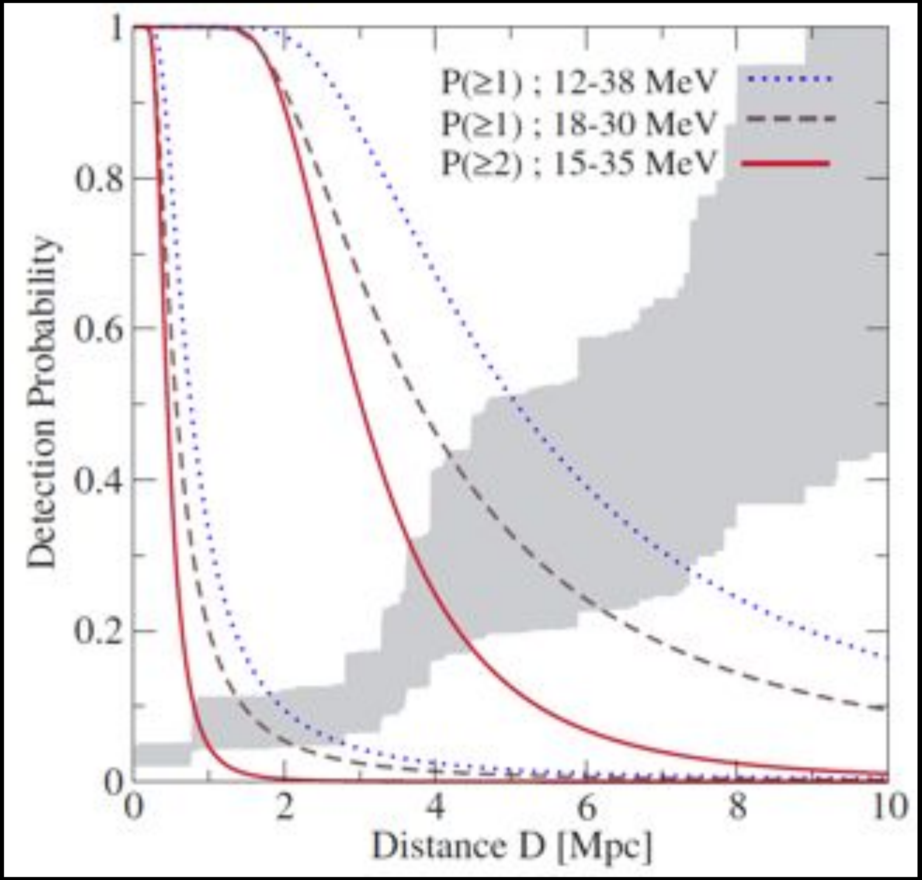
Generally a few per century

Observed Galactic SN yields a latest rate estimate of ~4.6 per century (Adams et al 2013)

Null observation of neutrino bursts yields a consistent < 9 SN (90% CL)

Diehl et al 2006

Distances probed



Ando et al (2005)

Yields in Hyper-K without/with Gd:

$$N_{e^+}(18 < E_{e^+} < 30) \approx 5 \left(\frac{d}{1\,\mathrm{Mpc}}\right)^{-2}$$

(water only)

$$N_{e^+}(12 < E_{e^+} < 38) \approx 9 \left(\frac{d}{1\,\mathrm{Mpc}}\right)^{-2}$$

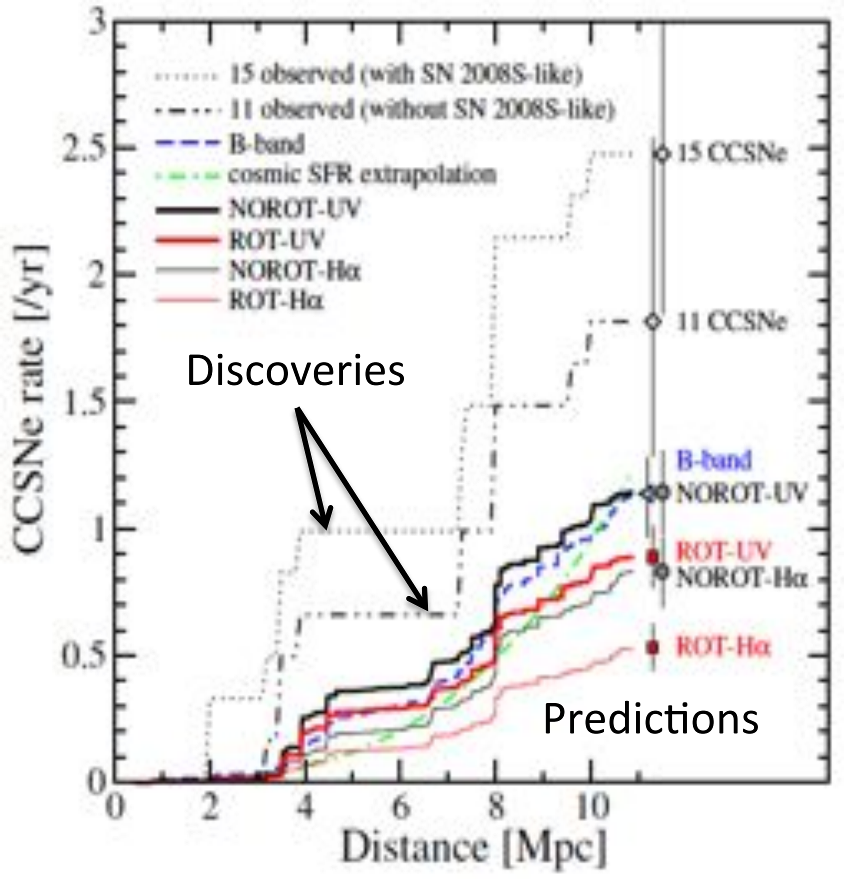
(water + Gd)

Singles: out to several Mpc
Doubles: out to few Mpc

Expected yields from burst searches

Nearby supernova rate:
Determined from discoveries as well as predictions based on star formation rate

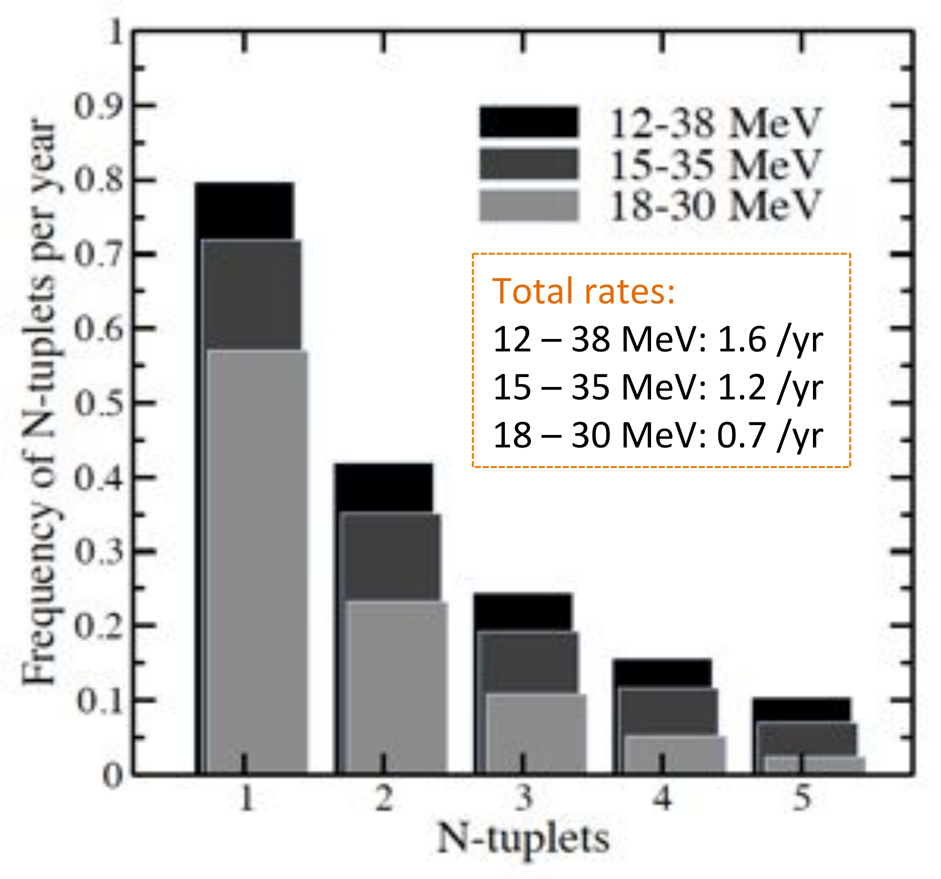
Rate of N-tuplets:
The frequency of obtaining a N-tuplet in Hyper-K, assuming the nearby supernova rate



Discoveries

Predictions

Horiuchi et al. (2013)



Total rates:
12 – 38 MeV: 1.6 /yr
15 – 35 MeV: 1.2 /yr
18 – 30 MeV: 0.7 /yr

Adapted from *Kistler et al. (2011)*

Theoretical DSNB Prediction

Observed positron spectrum

Input 1: supernova neutrino spectrum (intensely studied by simulations, quantity *waiting to be observed*)

$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu)\int R_{\mathrm{CCSN}}(z)\left|\frac{cdt}{dz}\right|(1+z)\frac{dN_\nu}{dE_\nu}\left[E_\nu(1+z)\right]dz$$

See, e.g., reviews by Beacom (2010), Lunardini (2010)

Input 2: core-collapse rate (intensely studied by astronomers using photons, *rapidly improving*)

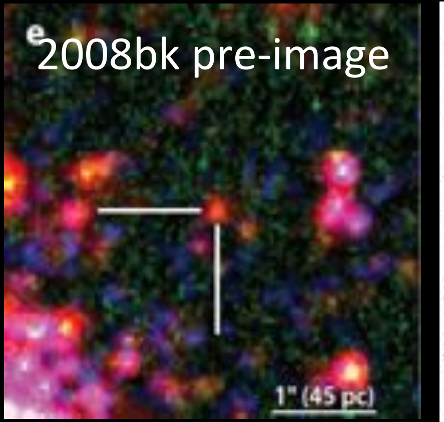
Input 3: neutrino detector capabilities well understood

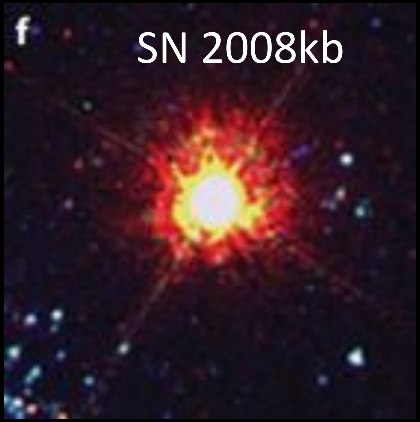
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

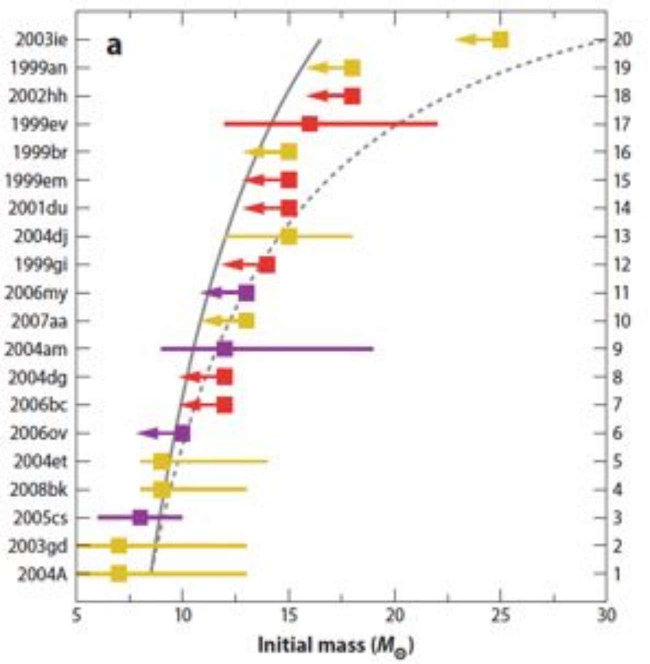
Star formation → supernova

$$R_{\rm SN}(z) = \dot{\rho}_*(z)\,\frac{\int_{M_{\rm min}}^{M_{\rm max}} \psi(M)\,dM}{\int_{0.1}^{100} M\,\psi(M)\,dM}$$

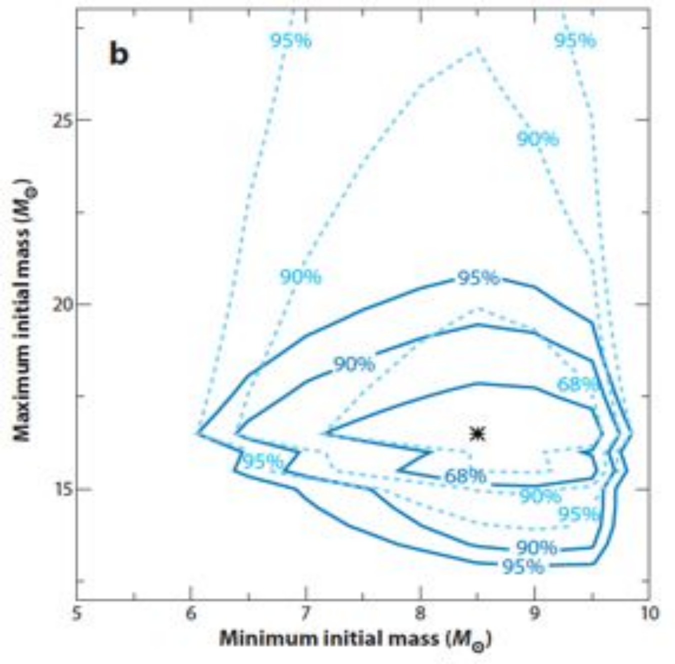
M_{min} and M_{max} could be obtained from pre-supernova imaging studies of nearby supernovae







Solid: Salpeter IMF with M_{max} = 16.5 Msun; dashed with M_{max} = 30 Msun.



$M_{min} \approx 8.5^{+1}_{-1.5}$ Msun to $M_{max} \approx 16.5 \pm 1.5$ Msun.

Smartt et al. (2009), Smartt (2009)

Extragalactic background light (EBL)

Observed EBL:

Various constraints, with lower limits from summing observed galaxies, and direct measurements

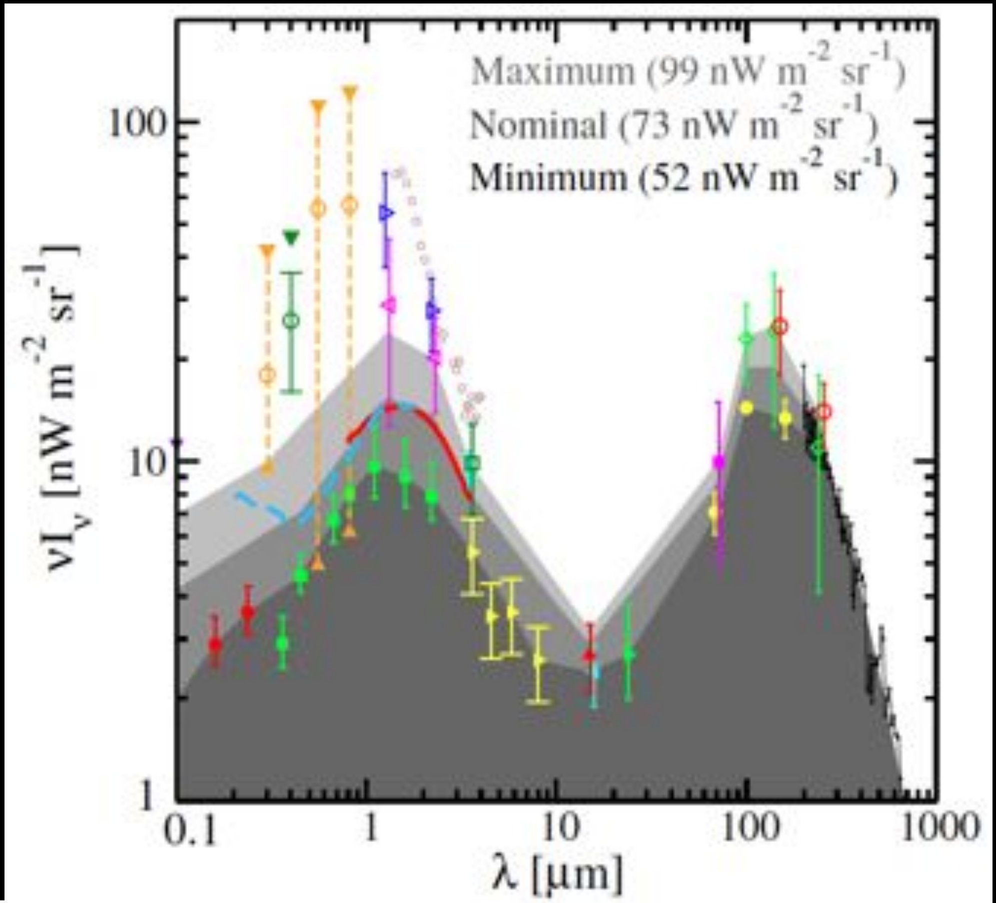
Hauser & Dwek (2001)

With recent constraints from distant TeV blazar observations, the nominal total EBL is:

$$73^{+26}_{-21}\,\mathrm{nW\,m^{-2}\,sr^{-1}}$$

Calculated EBL from stars:

Depends on the IMF to some degree but modern shapes provide good consistency with observed



Horiuchi et al. (2009)

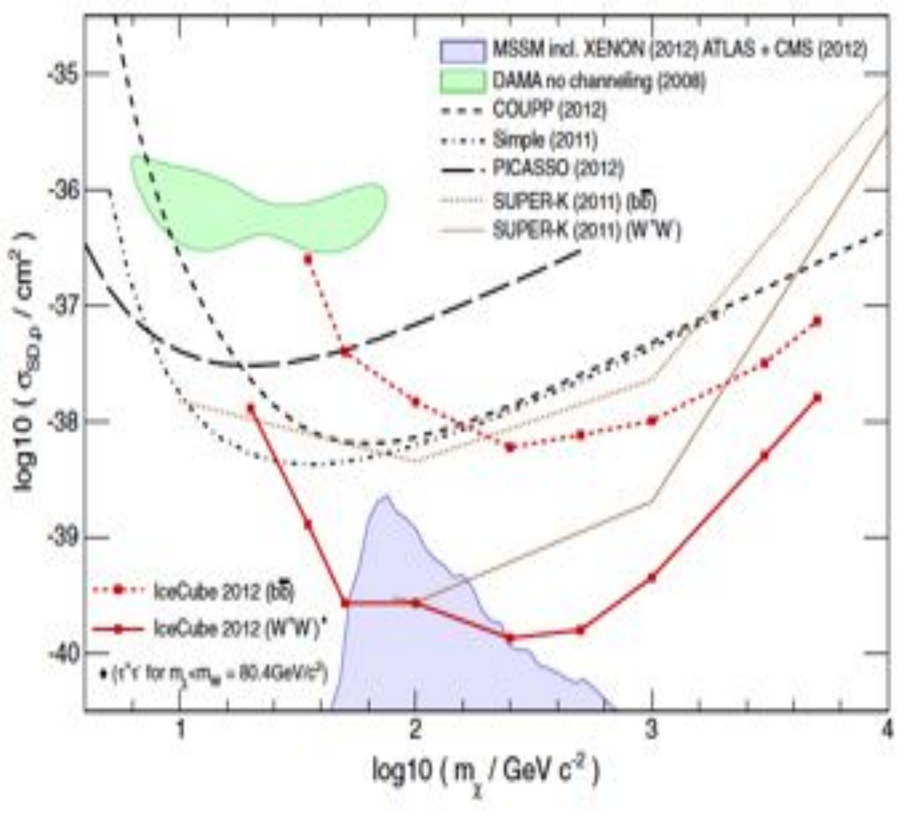
IMF	Total EBL intensity	Range
Salpeter (1955)	95 nW m^{-2} sr^{-1}	65–134
Kroupa (2001)	88 nW m^{-2} sr^{-1}	60–124
Baldy-Glazebrook (2003)	78 nW m^{-2} sr^{-1}	54–109

Note, other contributions e.g., AGN contributes only few % to the observed EBL

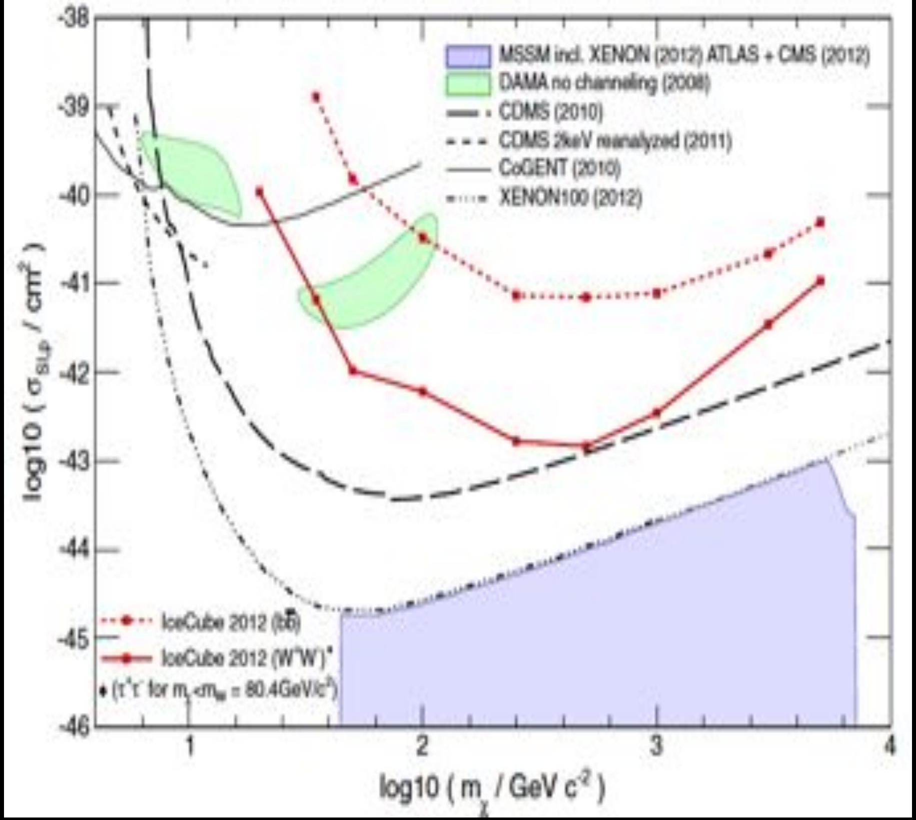
e.g., Hopkins et al. (2006)

Scattering cross section limits

Spin-dependent



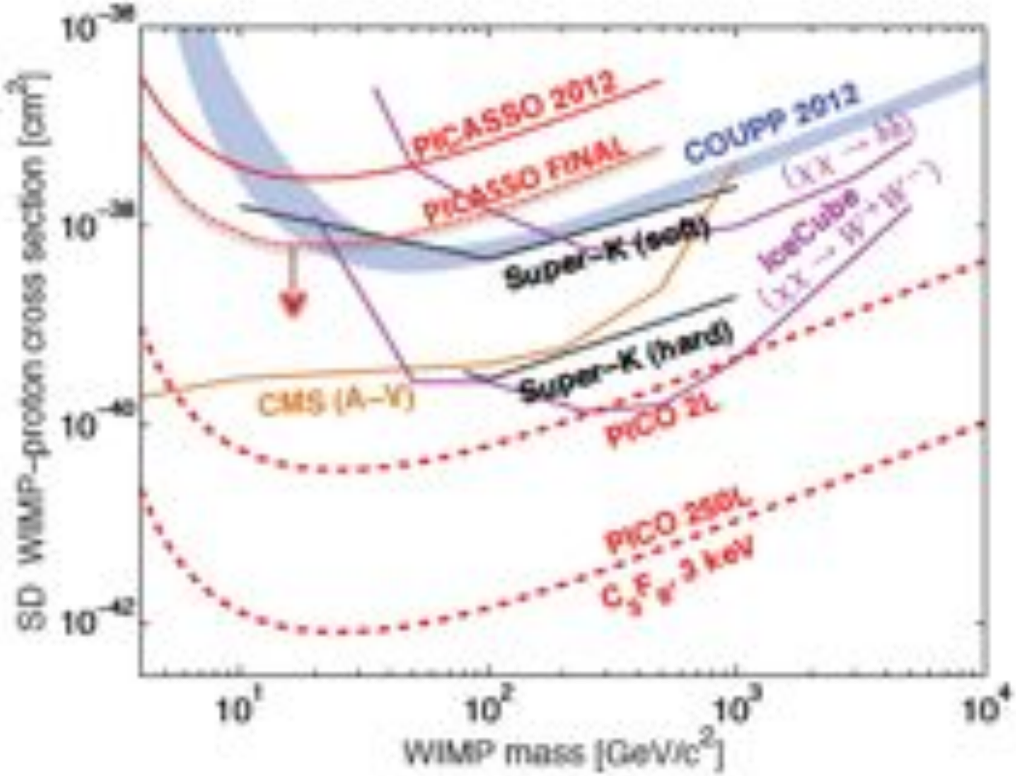
Spin-independent



IceCube 2013

Direct detection future

- The PICASSO and COUPP collaborations have joined to explore large scale superheated detector options as PICO.
- PICO-lite
  - 2L C_3F_8 chamber using COUPP compression chamber technology.
  - Low energy threshold and excellent alpha discrimination.
  - Large sensitivity in spin dependent sector.
  - Starts running Fall 2013.
  - See talk by Russell Neilson.
- PICO 250L
  - Large detector research and development.
  - Choice of compression chamber or geyser technology.



From Jackson, TAUP 2013