University of Virginia, HEP Seminar, April 21st 2015

Astroparticle physics with MeV neutrinos

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Image credit: NASA/ESA

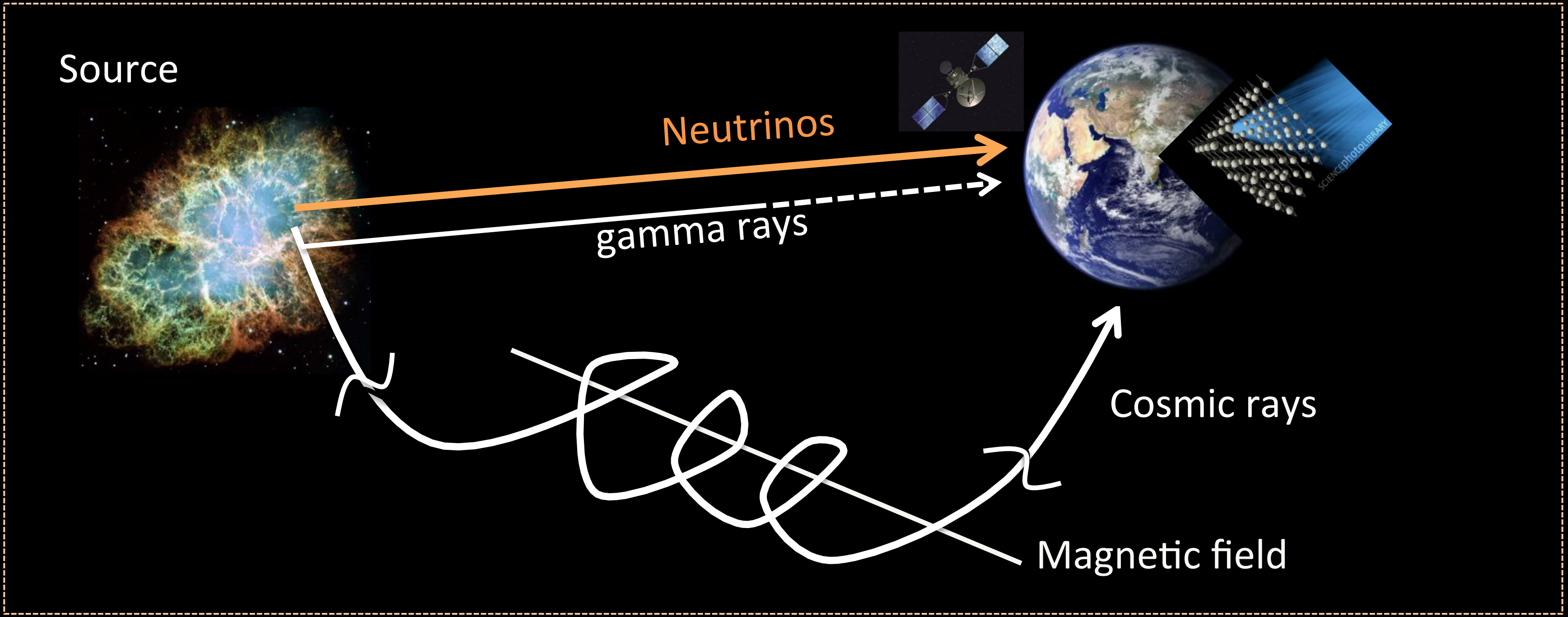
Contents

- Introduction: why astrophysical neutrinos now?
- Topic 1: Supernova neutrinos
  - Galactic events: rich physics and astronomy
  - Detectability beyond Galactic events
- Topic 2: Dark matter neutrinos
  - Two searches, two constraints
- Summary

Neutrinos as messenger particles

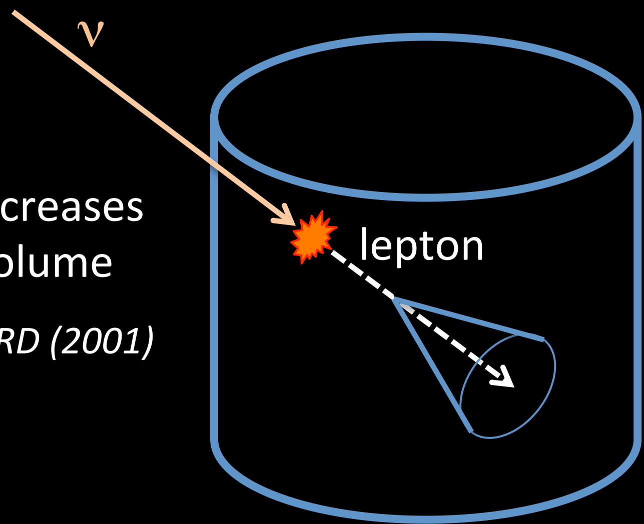
Neutrinos are great messenger particles:

- allow us to see optically thick (to photons) regions
- experience little attenuation through cosmic space
- travel in straight lines



Neutrino detection: Cherenkov

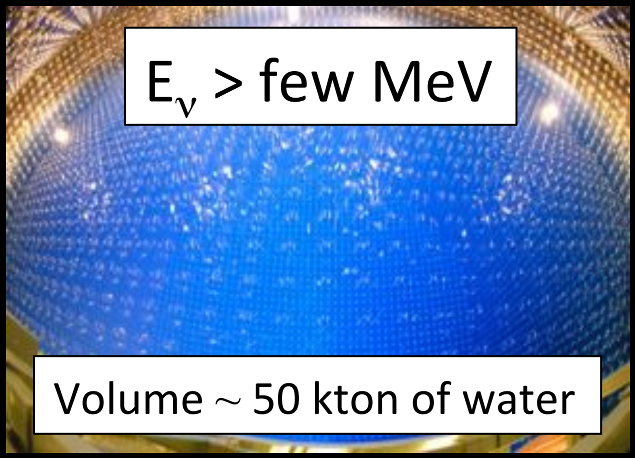
Use the Cherenkov light to reconstruct the original neutrino



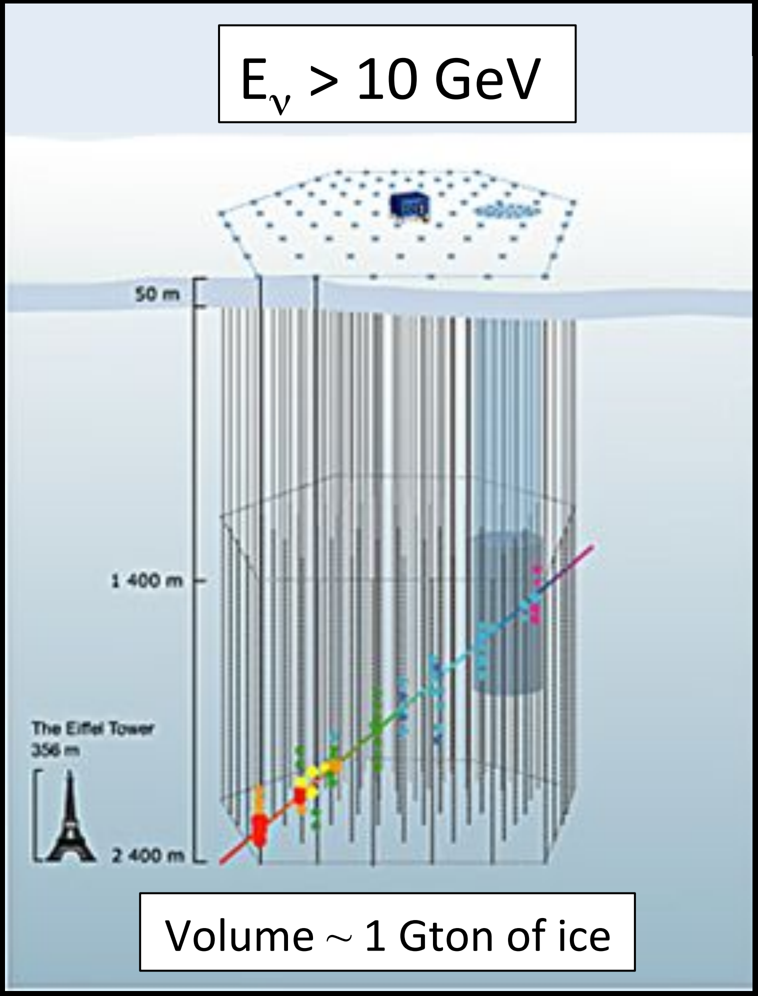
Muon range increases the effective volume

Dutta et al, PRD (2001)

Super-Kamiokande



IceCube



Neutrino sources

Radioactive decay

Sun (x1)

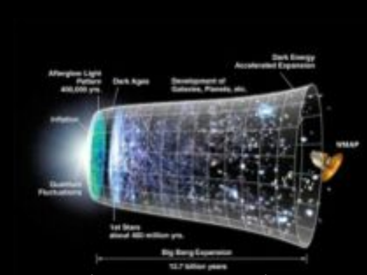
Nuclear reactors

Supernova (x1)

Particle accelerator

Astrophysical accelerator

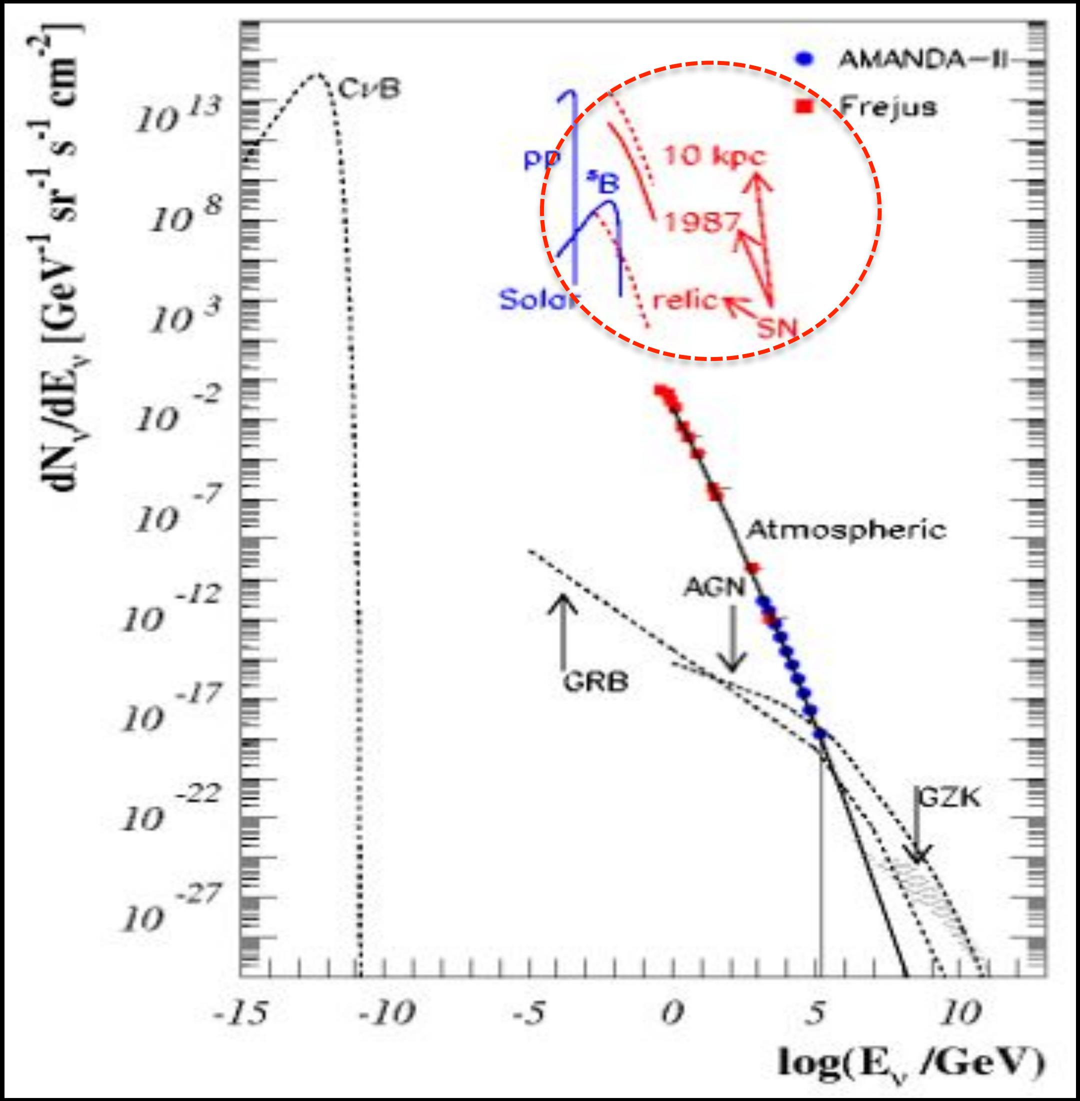
Atmospheric



Cosmic background

+ others?

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
- Reactor neutrinos
- Accelerator neutrinos

Some big questions

Neutrinos hold the key to solving many questions

I will talk about:

- *How to study the supernova explosion mechanism*
- *How to study the formation of black holes*
- *How to test the nature of uncertain transients*

- *How to test models of dark matter*

But there are many other important physics:

- *What are the properties of neutrinos?*
- *What is the physics at high temperature and density?*
- *Are there energy sinks due to new particles?*
- *Where are cosmic rays accelerated?*
- *Can we refine the Solar model?*
- *etc*

SUPERNOVA NEUTRINOS
- GALACTIC EVENTS -

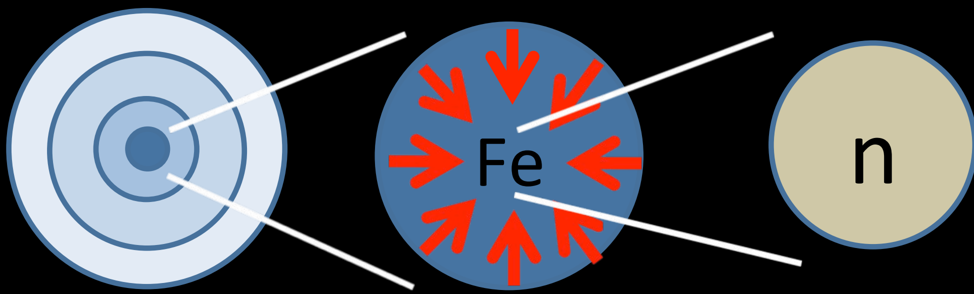
SN 1987A in the LMC

Sanduleak -69 202

SN 1987A 23 Feb 1987

SN 1987A in the LMC

Massive star — $\sim 1.4 M_{sun}$ core — Neutron Star



<u>Energy budget</u> $\sim 3 \times 10^{53}$ erg

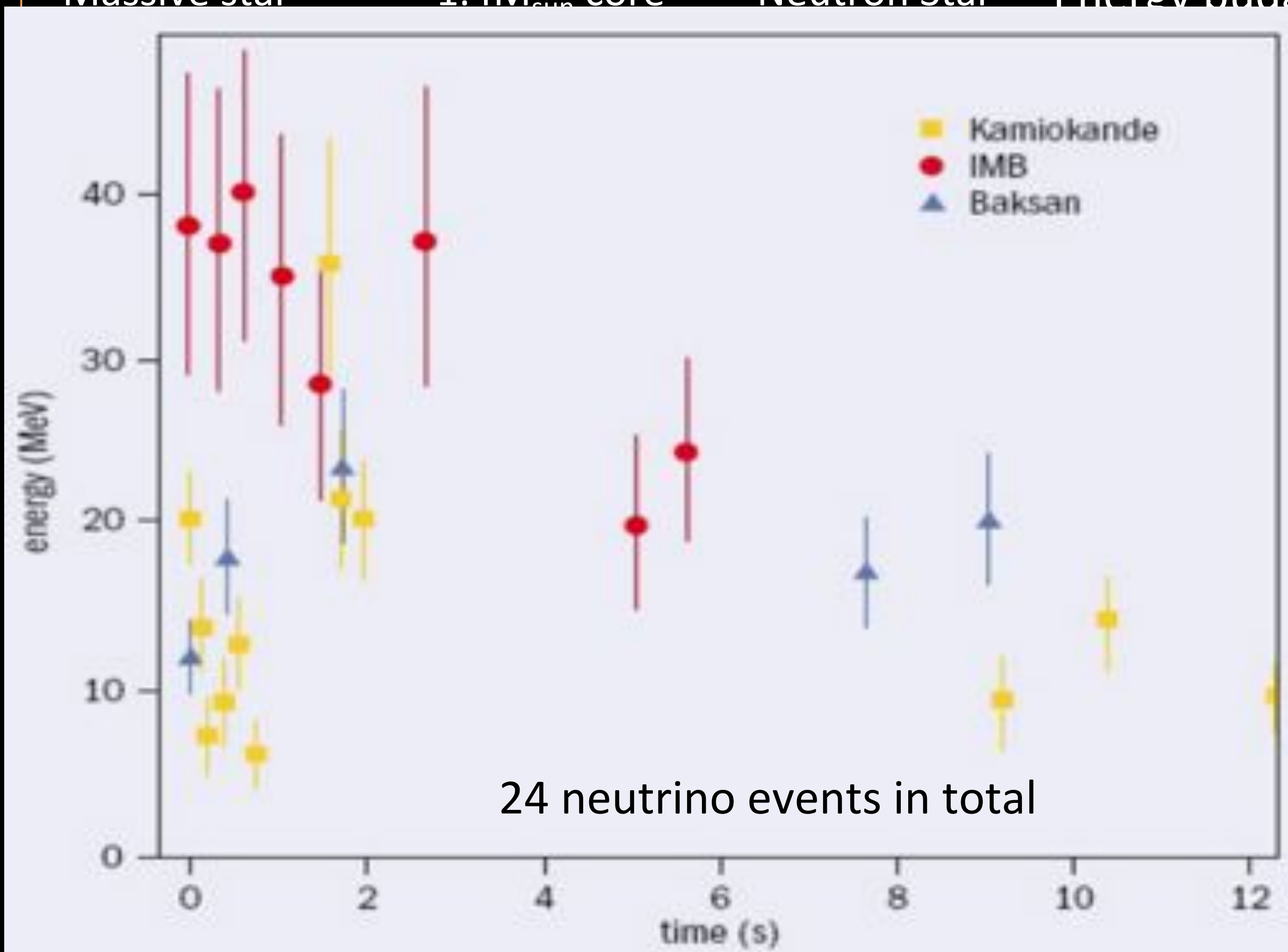
99%	into neutrinos
1%	into shock KE
0.01%	into photons

Sanduleak -69 202

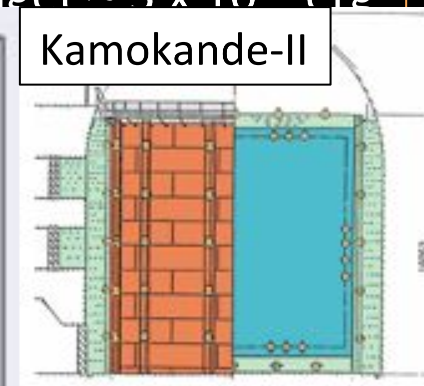
SN 1987A 23 Feb 1987

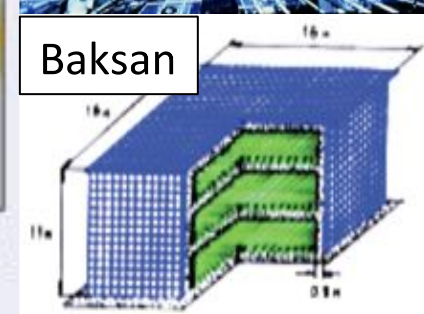
SN 1987A in the LMC

Massive star ~1.4M_{sun} core Neutron Star Energy budget ~ 3 x 10^{53} erg



24 neutrino events in total





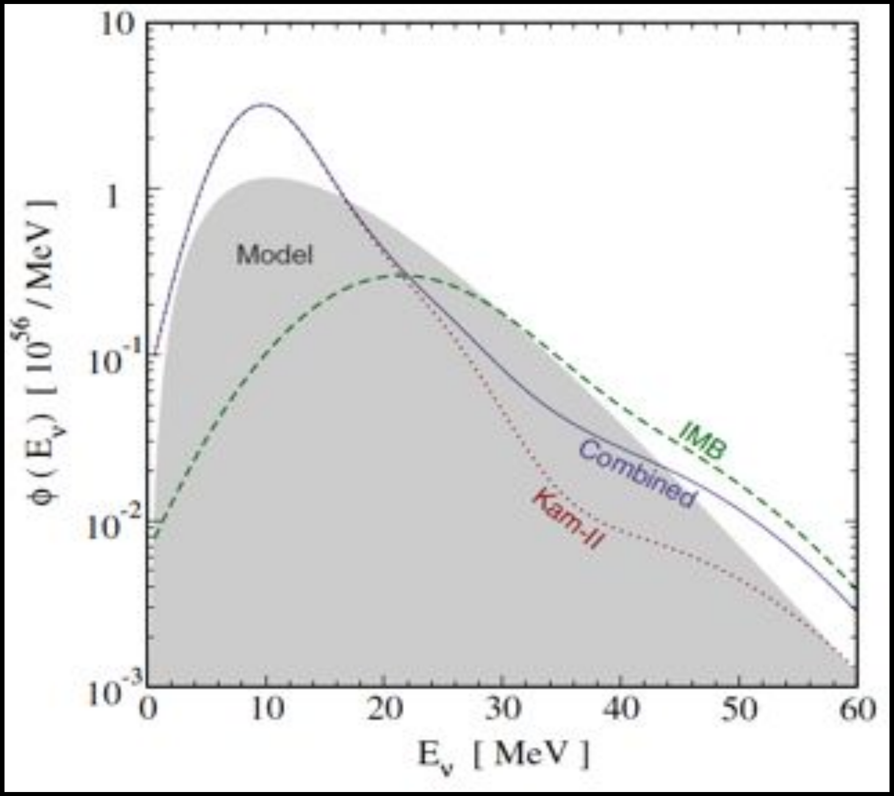
Feb 1987

Hirata et al, PRL (1987), Bionta et al (1987), Alekseev et al, PRL (1987)

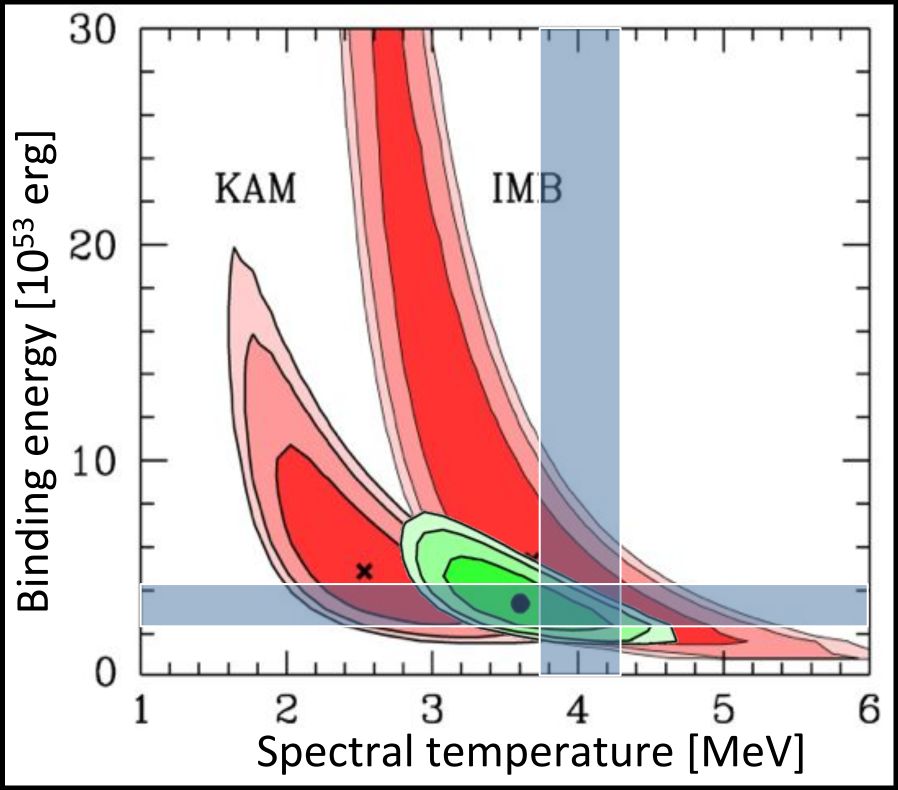
Lessons form SN 1987A neutrinos

Discovery of the key characteristics:

1. The thermal nature of neutrinos (spectrum & duration)
2. The neutrino temperature
3. The total binding energy



Yuksel & Beacom (2007)



Adapted from Jegerlehner, Neubig & Raffelt (1996)

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

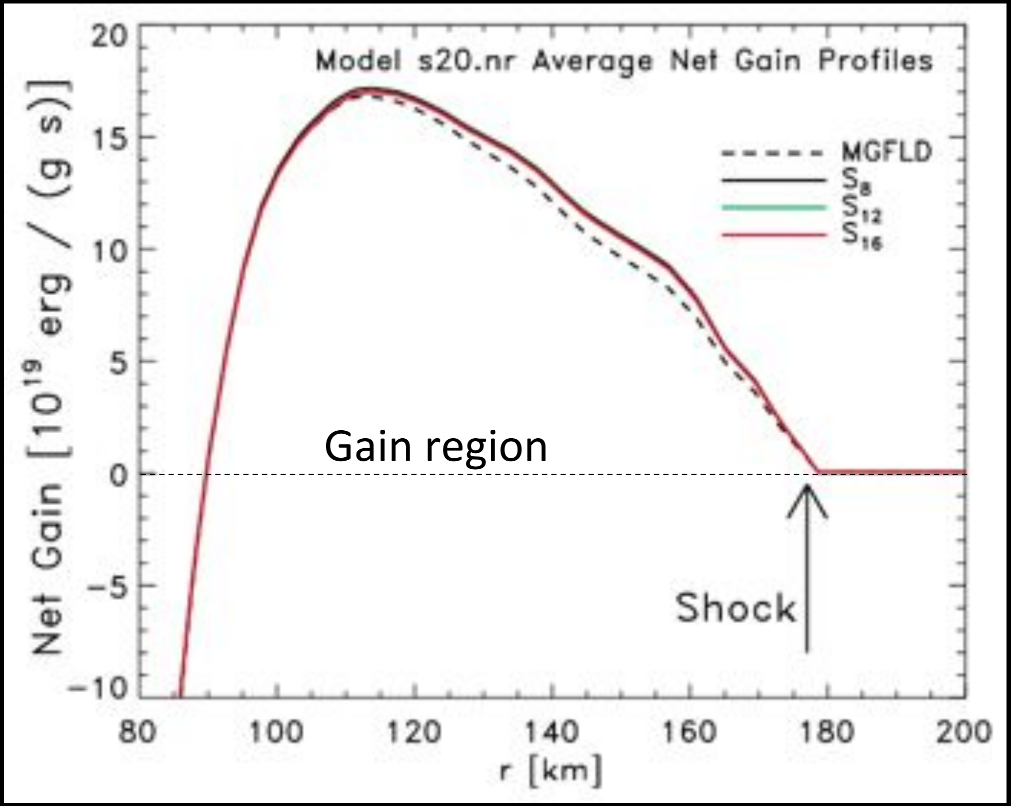
Wilson (1985), Bethe & Wilson (1985), ...

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.

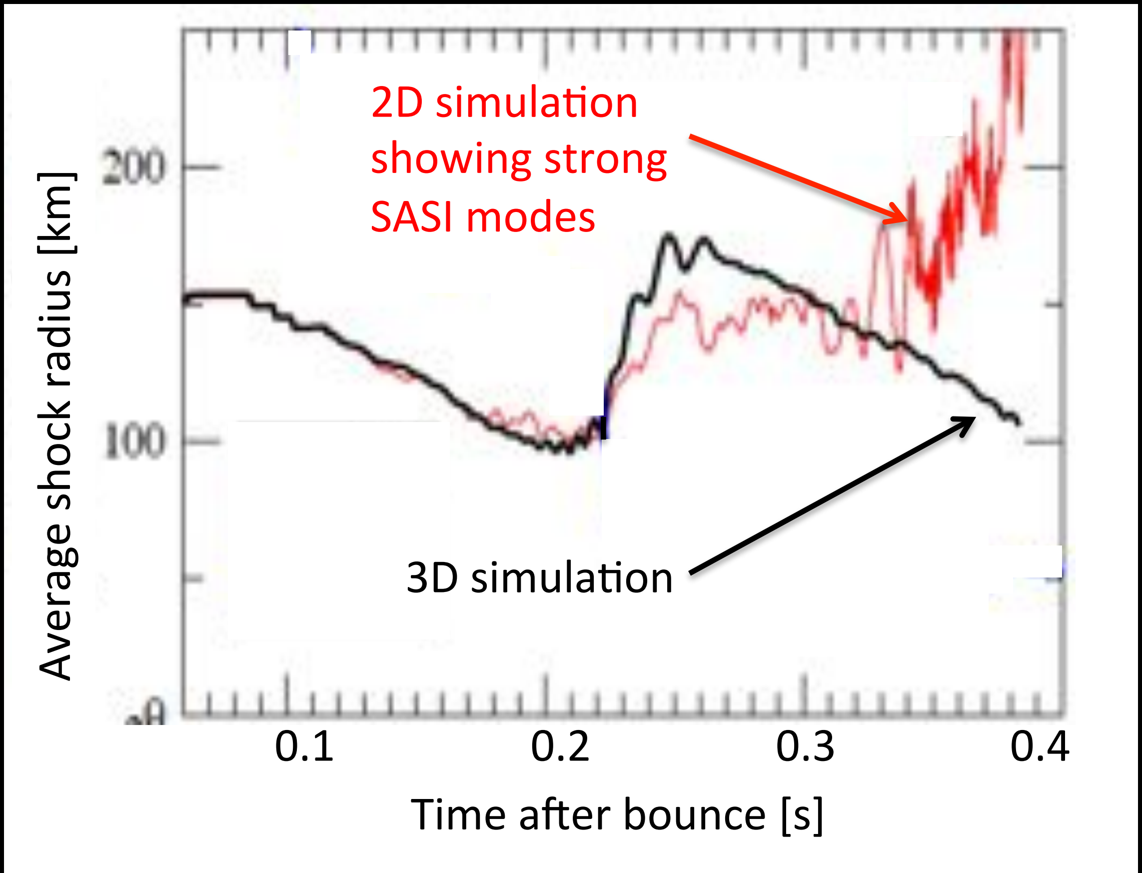


Ott, Burrow, Dessart & Livne (2008)

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



Hanke et al, ApJ (2014)

SASI in 2V vs 3D:
But 3D simulations show mixed results. Whether SASI really leads to explosions is sill unclear.

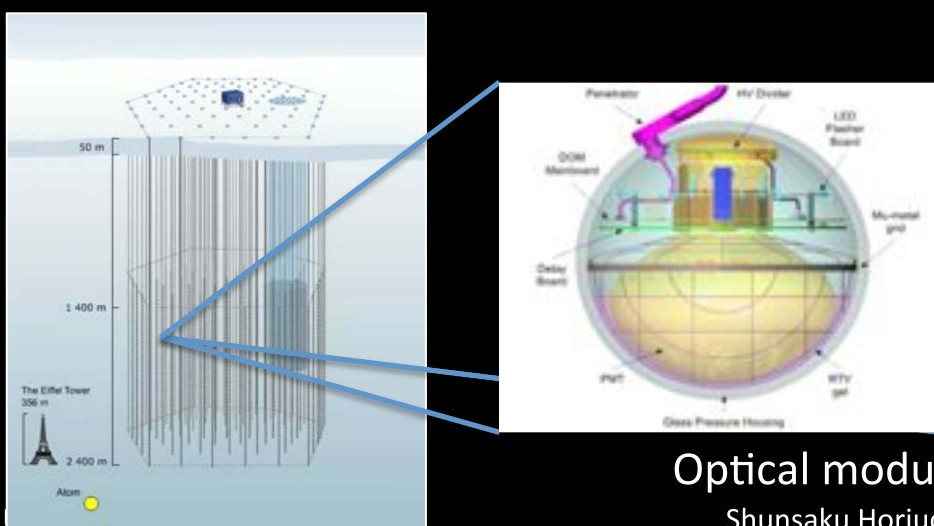
MeV transient detectors

Super-Kamiokande: (+ Hyper-K which will be x20 larger)

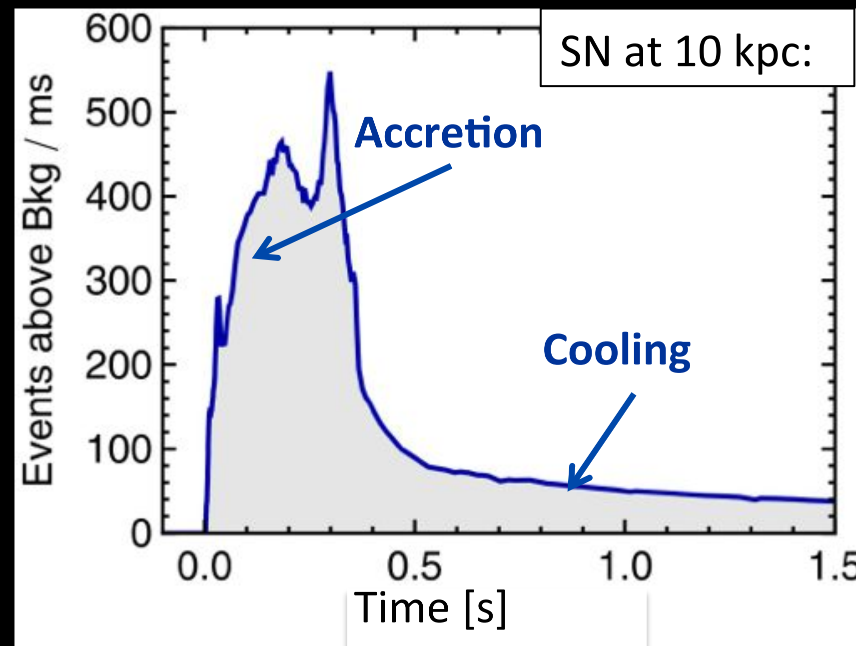
- IBD on free protons yields ~7000 events, good energy info
- Scattering on electrons yields ~300 events, good directional information
- O^{16} CC (-> e^- + F*) yields ~100 events

IceCube: "correlated noise"

- Each optical module has intrinsic noise
- Neutrinos from a supernova is seen as a rise in the noise level
- With 5160 modules, very well-sampled light curve can be obtained by IceCube



Optical module

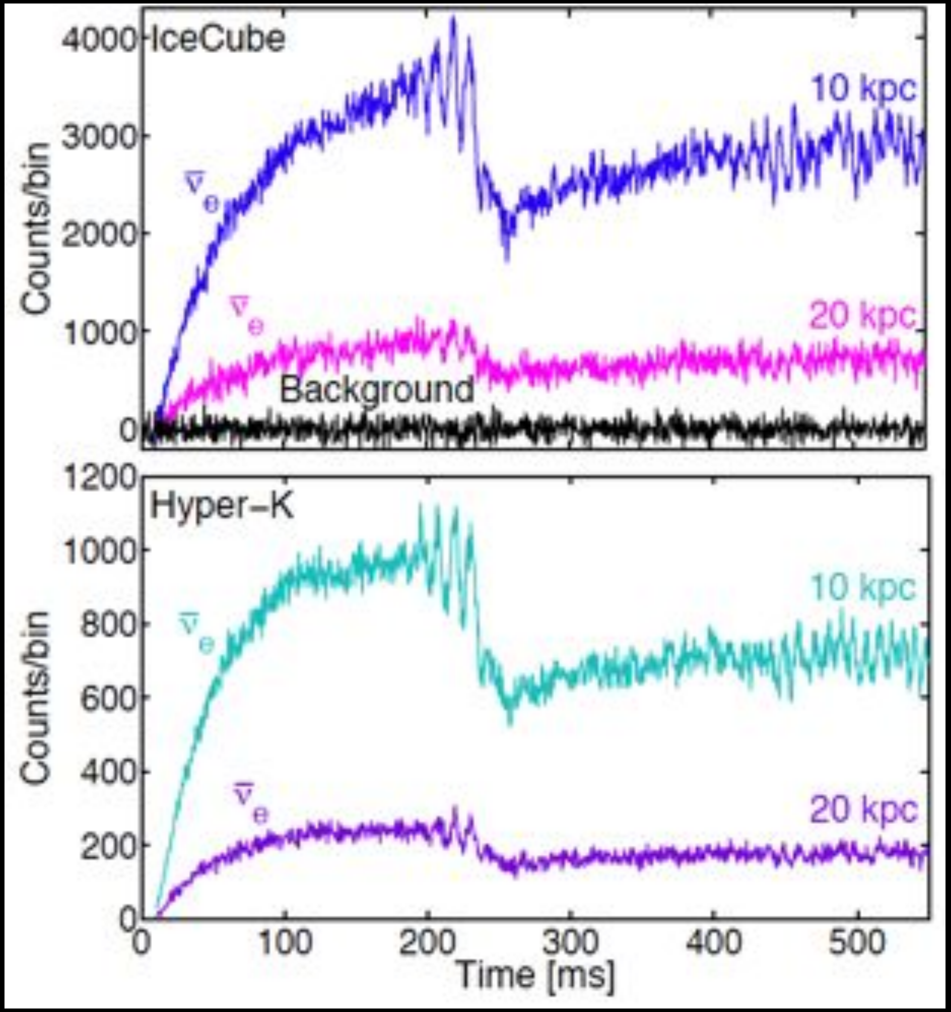


arXiv:0908.1871 Abbasi et al. (2011)

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*) →



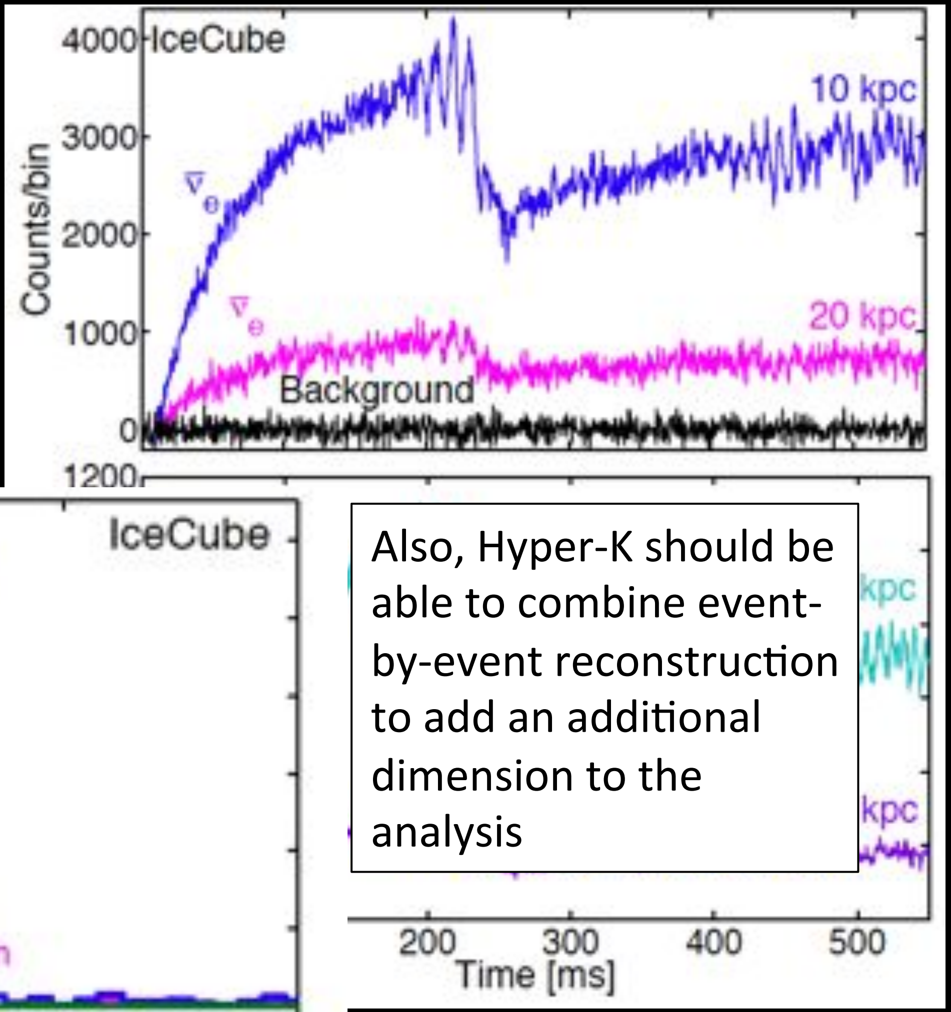
Tamborra et al (2013),
see also Lund et al (2010, 2012)

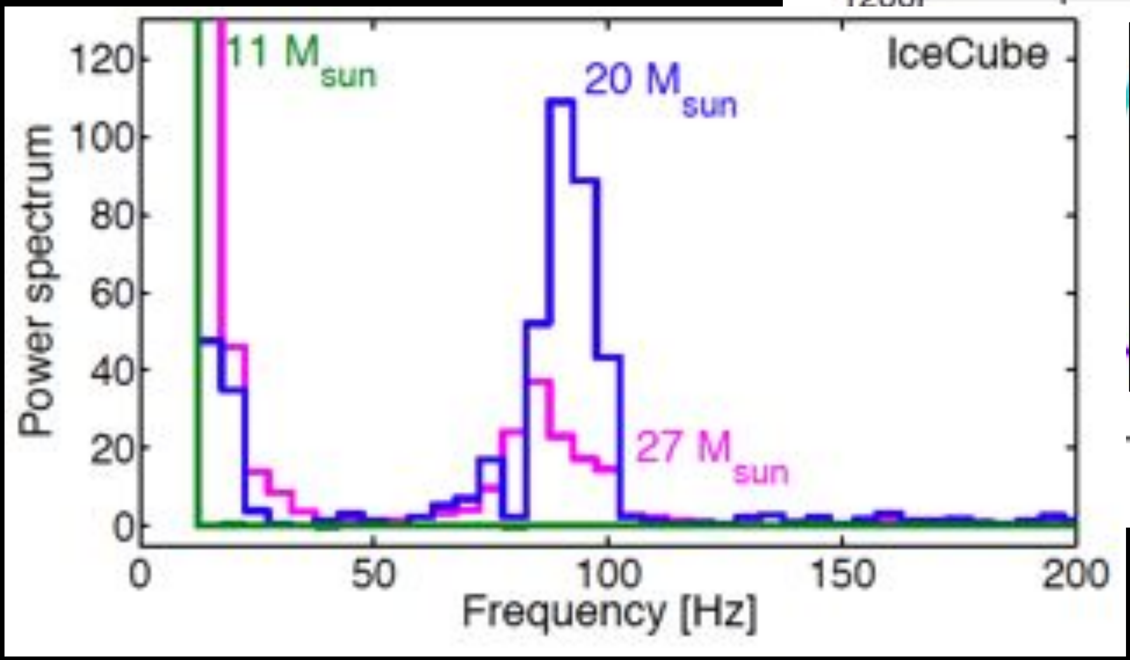
Observing the SASI mechanism

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





Also, 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 simulations

Sophisticated simulations

- 2D, 3D with neutrino transport
- A few progenitor models
- Address: explosibility, neutrino and gravitational wave signals

Mueller et al (2012, 2013, 2014), Hanke et al (2013), Takiwaki et al (2012, 2014), Bruenn et al (2013, 2014)

Two-dimensional systematic study

- 2D with simplified neutrino transport
- ~400 progenitor models
- Address: systematic study of progenitor dependence, SASI, other observables

Nakamura et al (2014)

One-dimensional systematic study

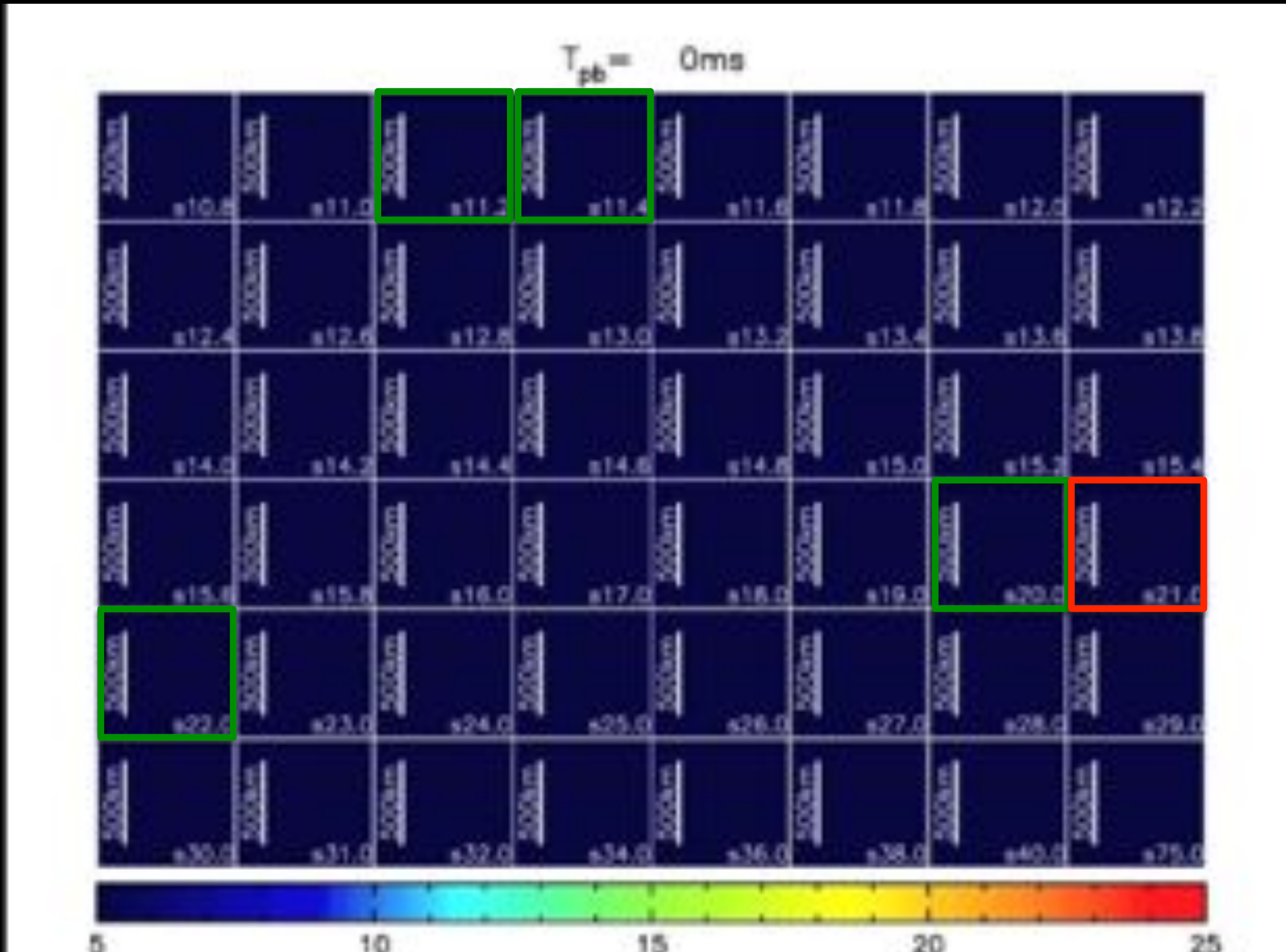
- 1D with parameterized neutrino heating
- Over 100 progenitor models
- Address: progenitor dependence, black hole formation

Ugliano et al (2012), O'Connor & Ott (2011, 2013)

Systematic simulations

48 solar-metallicity models
(10.8 to 75 Msun)

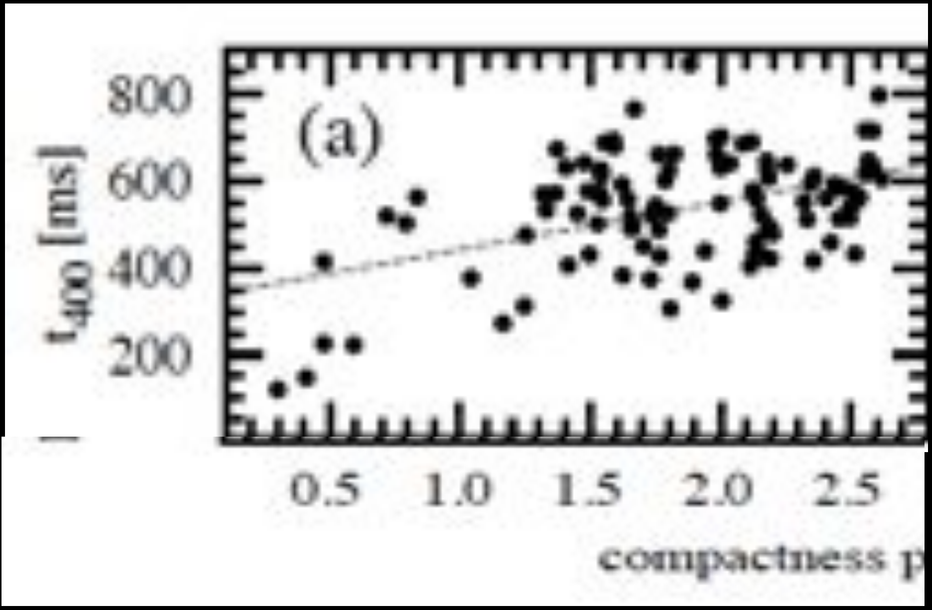
Nakamura et al (2014)



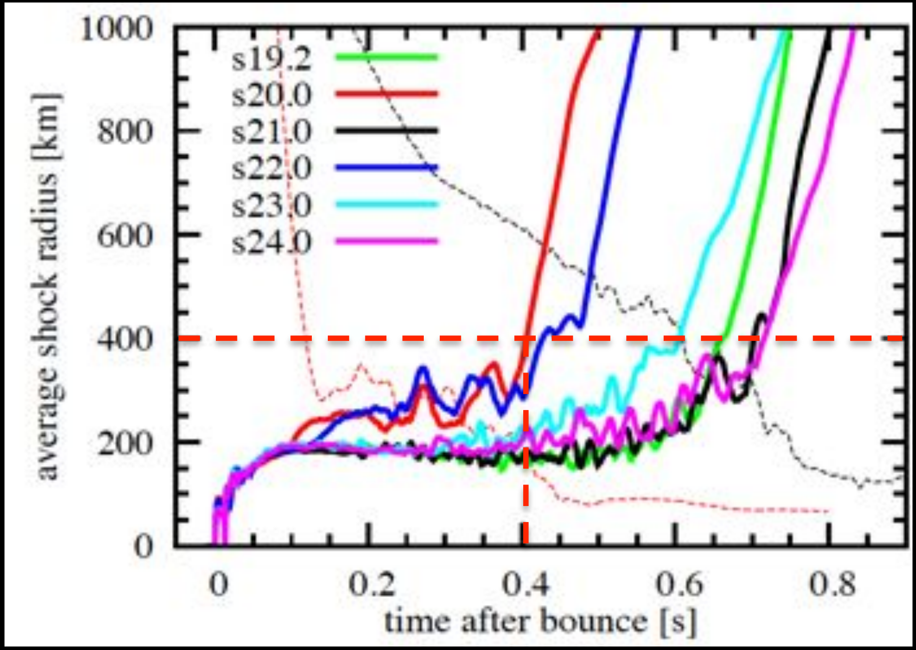
Entropy [k_B/baryon]

Importance of compactness

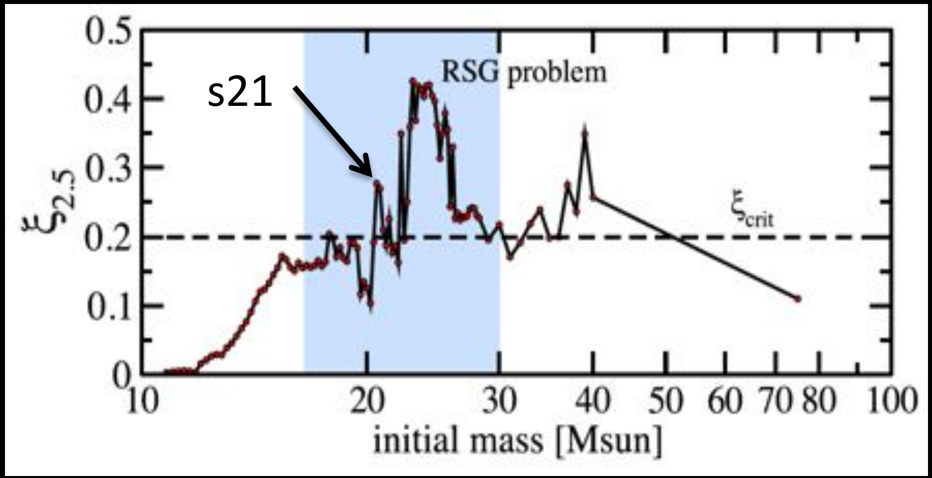
$$\xi = \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}}\Bigg|_t$$



🡫 Define t_{400} as the time taken for the supernova shock to reach 400 km



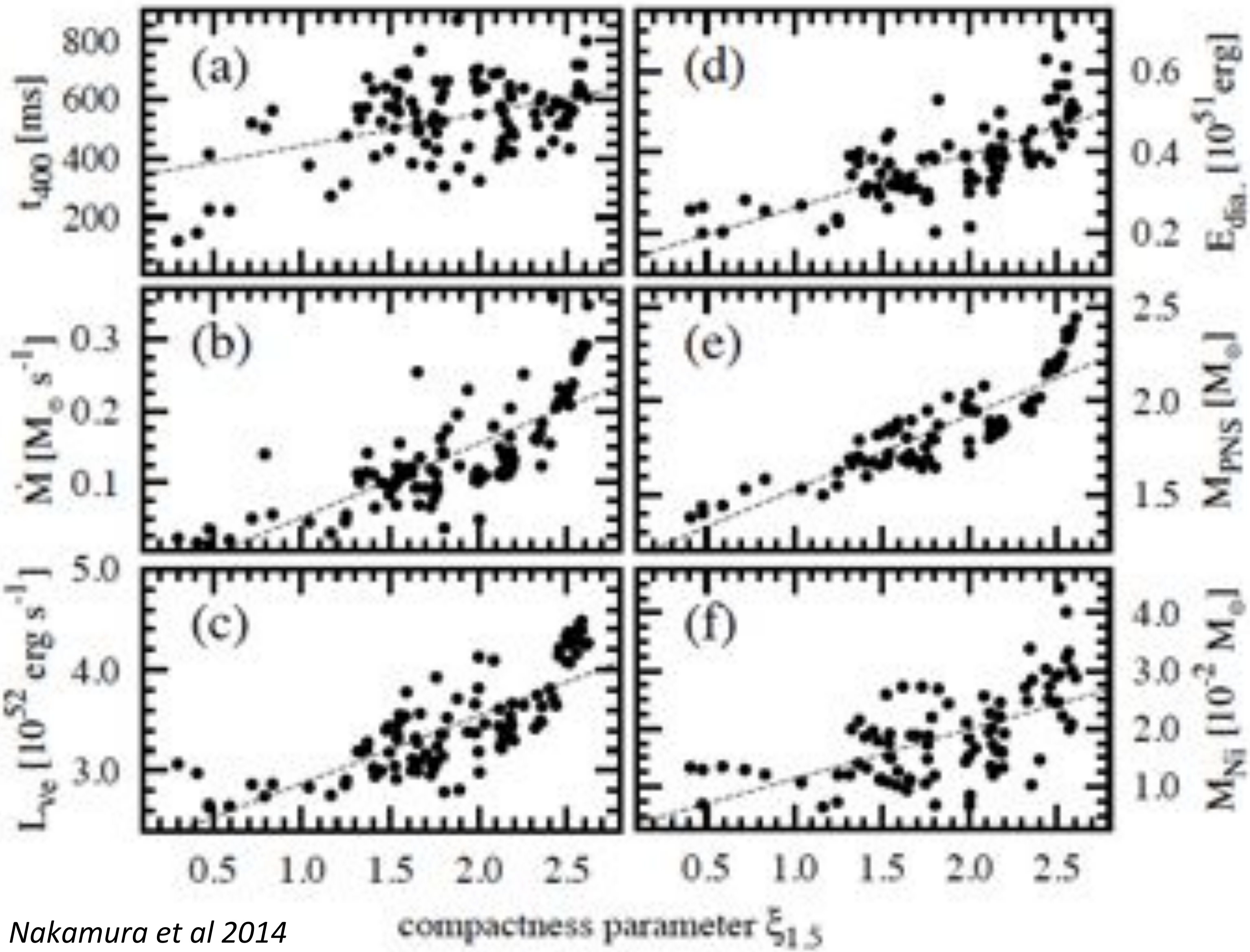
Nakamura et al (2014)



➔ Distribution of compactness in initial mass

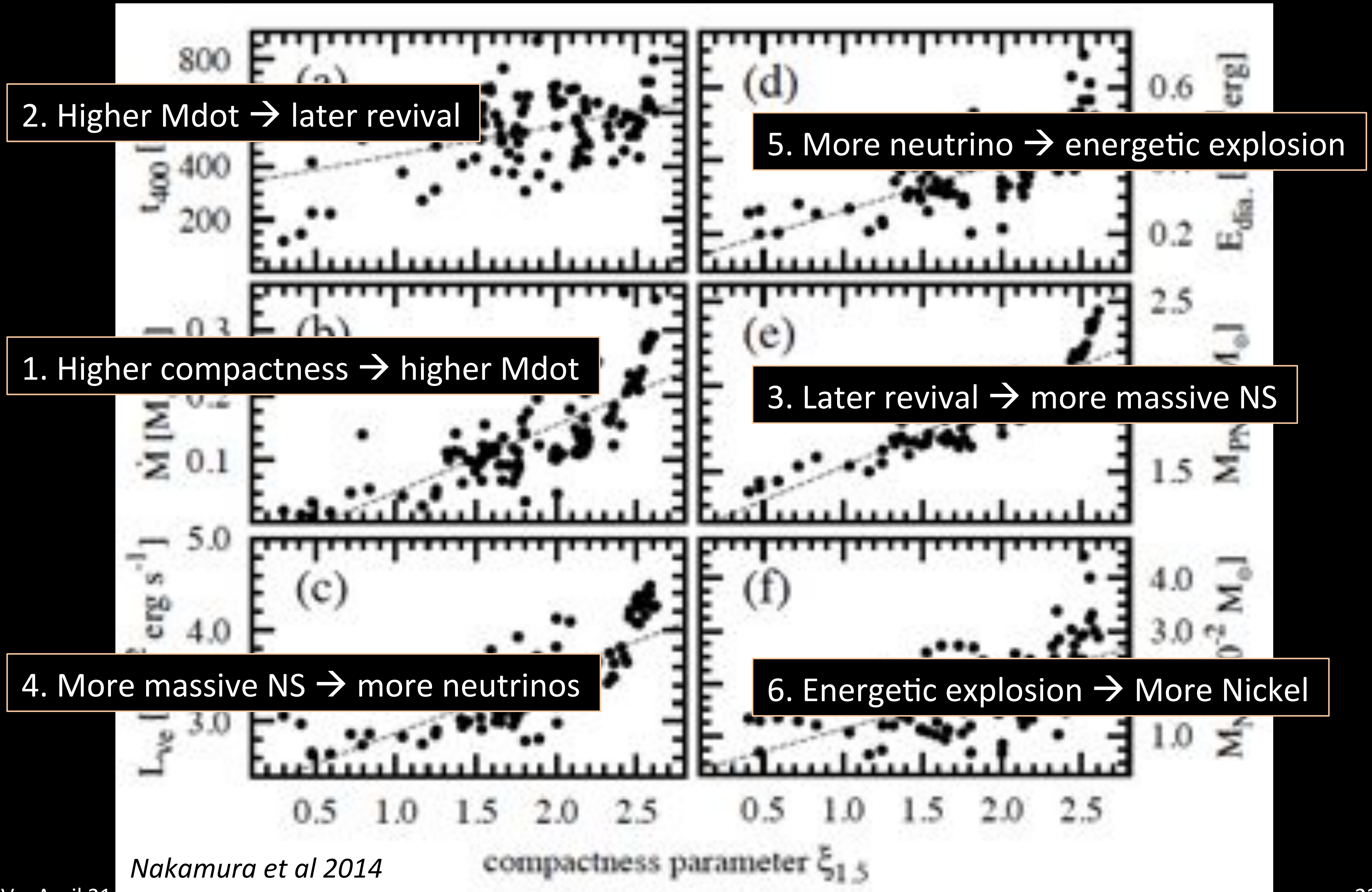
Horiuchi et al (2014), See also Sukhbold et al (2014)

Importance of compactness



Nakamura et al 2014

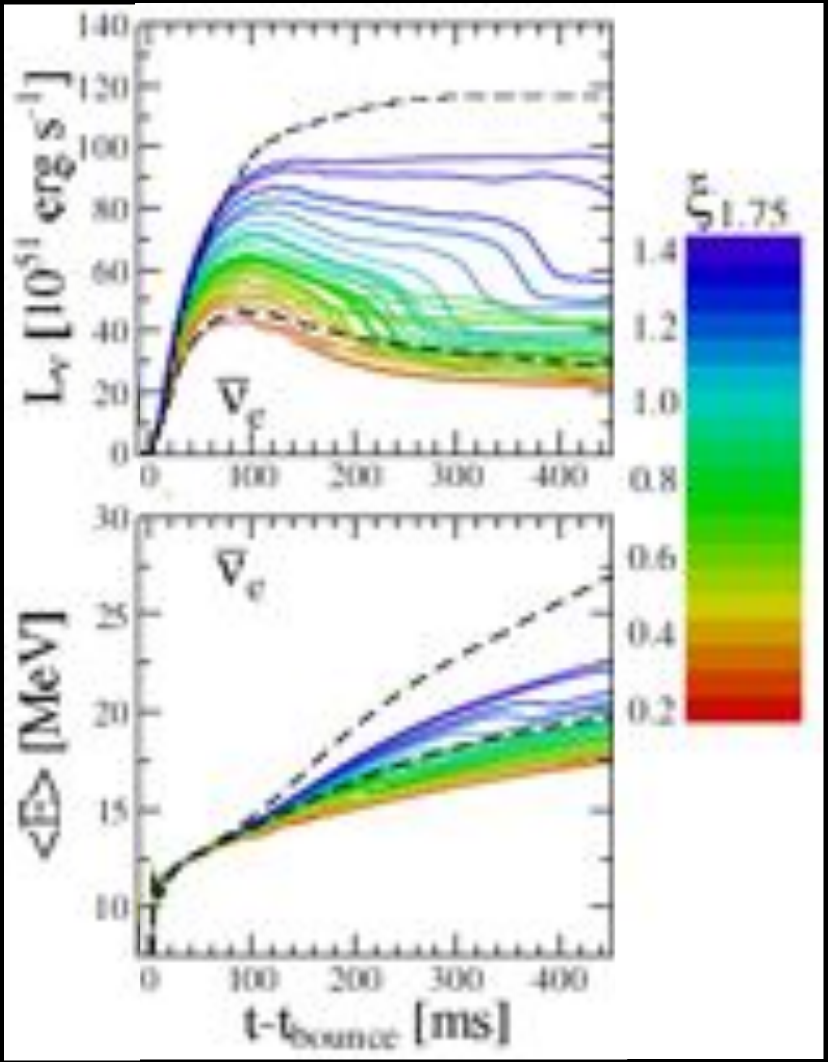
Importance of compactness



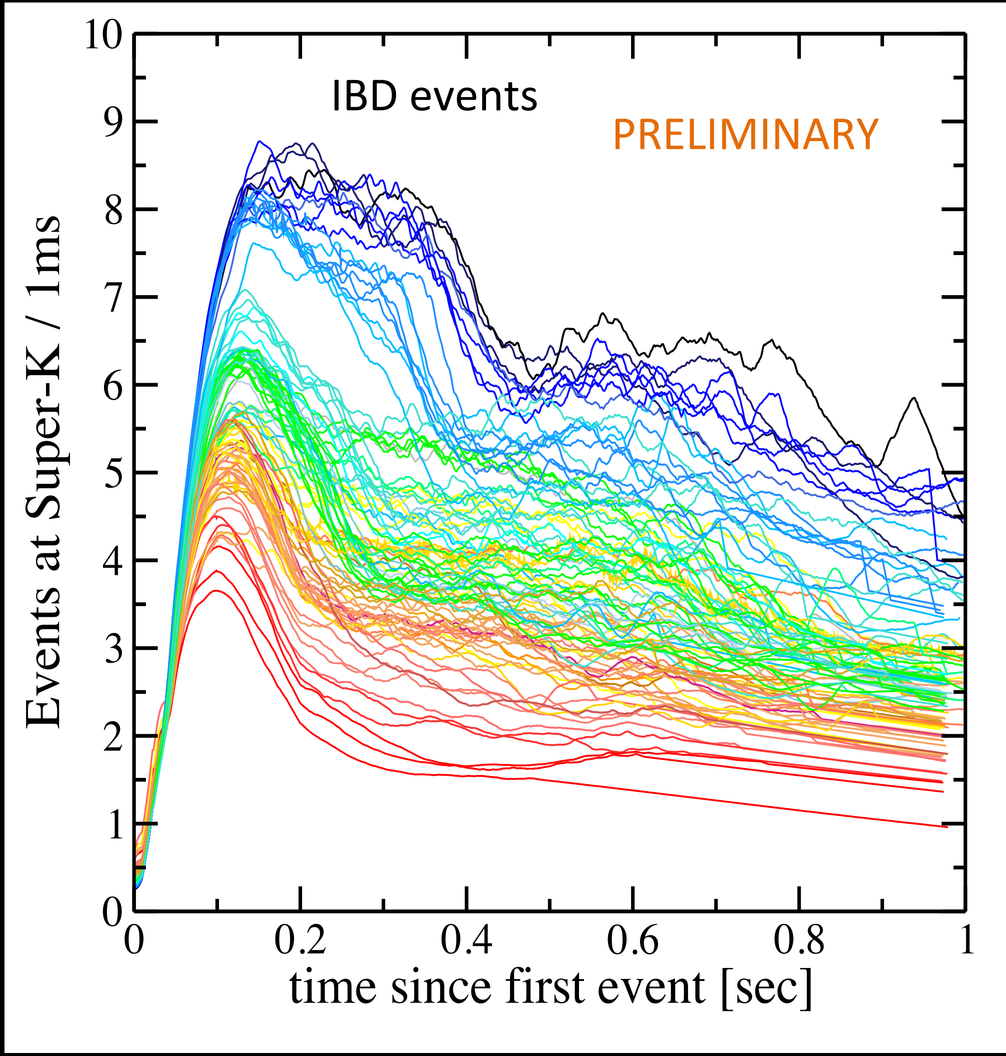
Nakamura et al 2014

Measuring the compactness

Use the fact that neutrino emission also depends on compactness



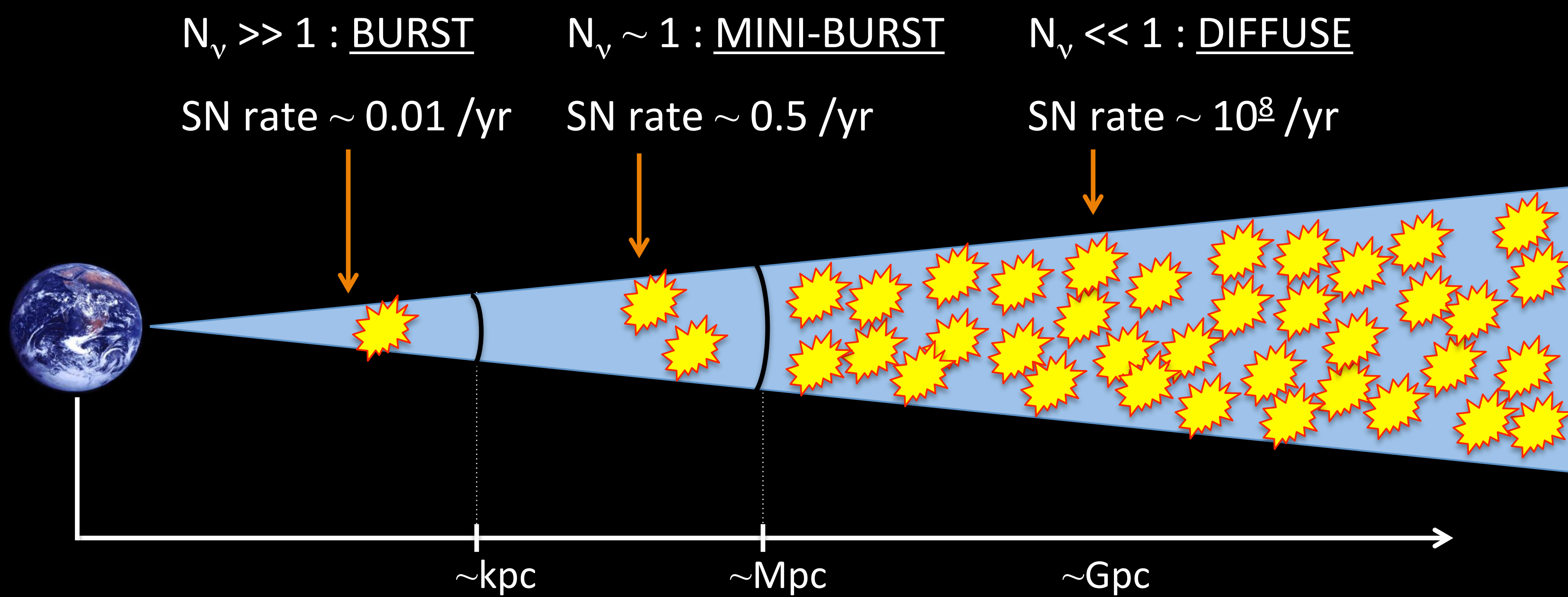
O'Connor & Ott (2013)



Horiuchi et al (in prep)

SUPERNOVA NEUTRINOS
- BEYOND GALACTIC EVENTS -

Distance scales and physics outcomes



	Galactic burst	Mini-bursts	Diffuse signal
Physics reach	Explosion mechanism, astronomy	supernova variety with individual ID	Average emission, multi-populations
Required detector	Basics are covered	Next generation	Current upgrades

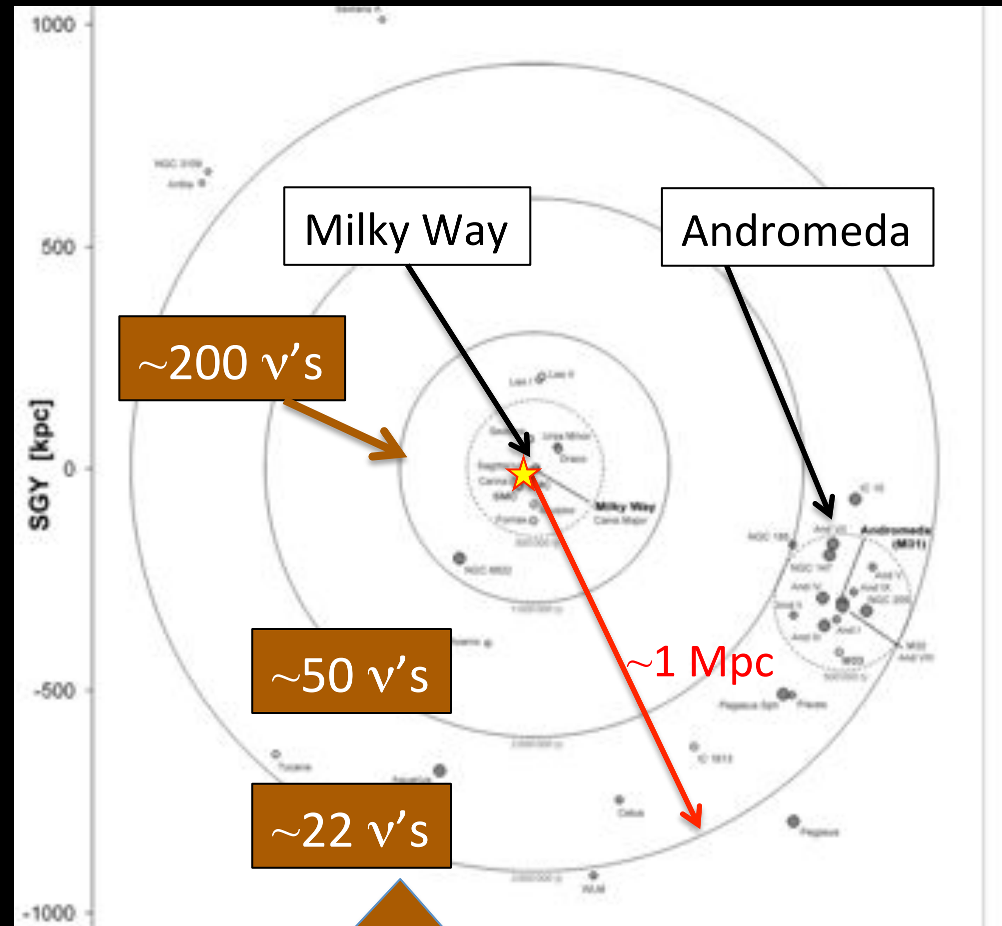
Reach to our neighbors

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



Supernova ν "horizon"

Super-Kamiokande and IceCube can reach to ~1 Mpc

Hyper-Kamiokande can reach ~4 Mpc

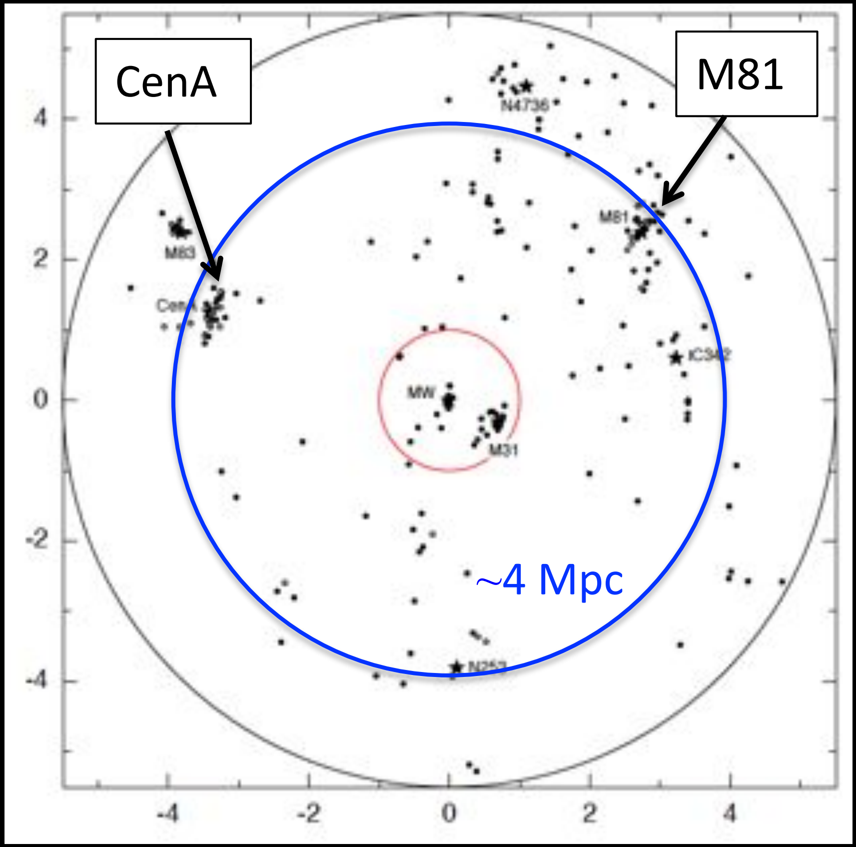
Ando et al, PRL (2004)

Events expected at Hyper-Kamiokande with ~20 times larger volume than Super-K

Nearby supernova rate

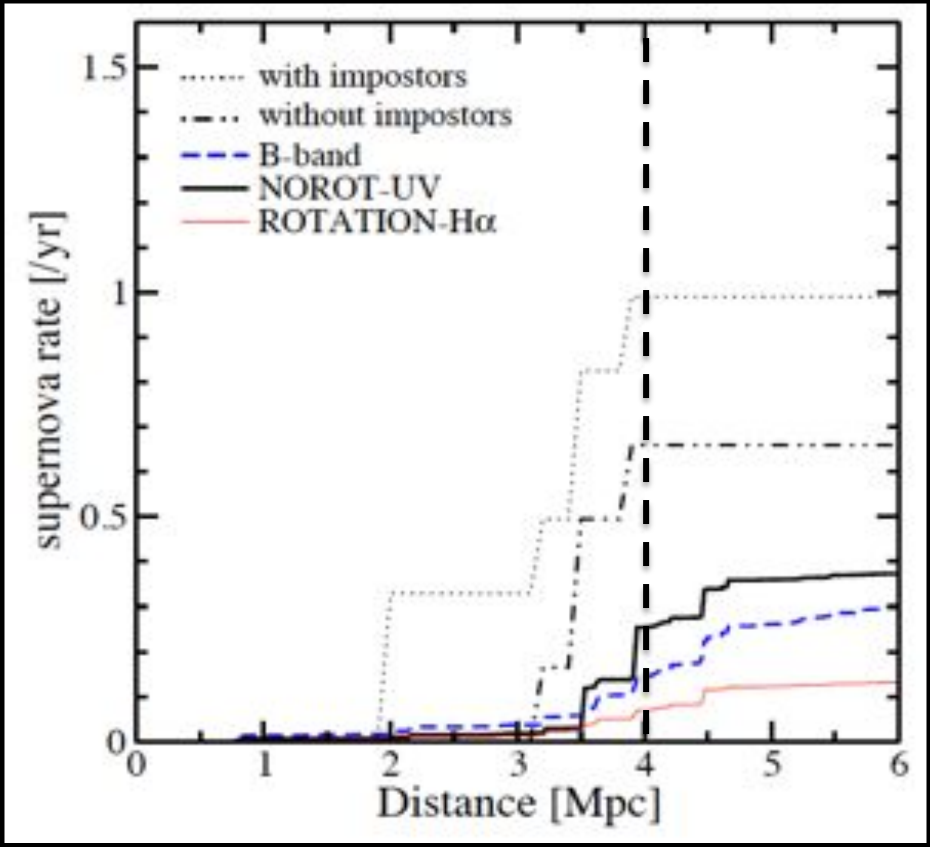
Looking nearby is advantageous due to the presence of structure

2D projection of nearby galaxies



Karachentsev et al, A&A (2002), ApJ (2013)

The cumulative supernova rate



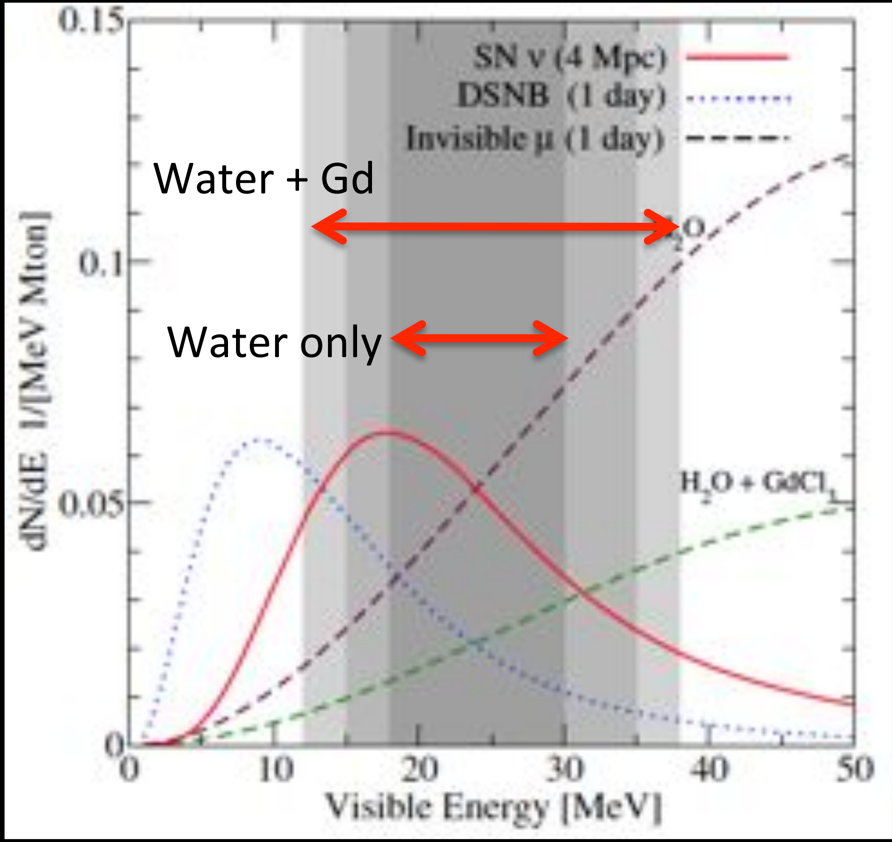
Adapted from HORIUCHI et al., ApJ (2013)

The Challenge: low statistic burst detection

Strategy:

Look for neutrino event doublets, triplets, etc (depending on the background rate: e.g., atmospheric neutrinos & spallation products at SK results in 0.7 doubles in 10 second per year – and Gadolinium will reduce these)

Or, use optical discovery of supernova to perform neutrino-optical coincidence detection.



Ando et al. (2005)

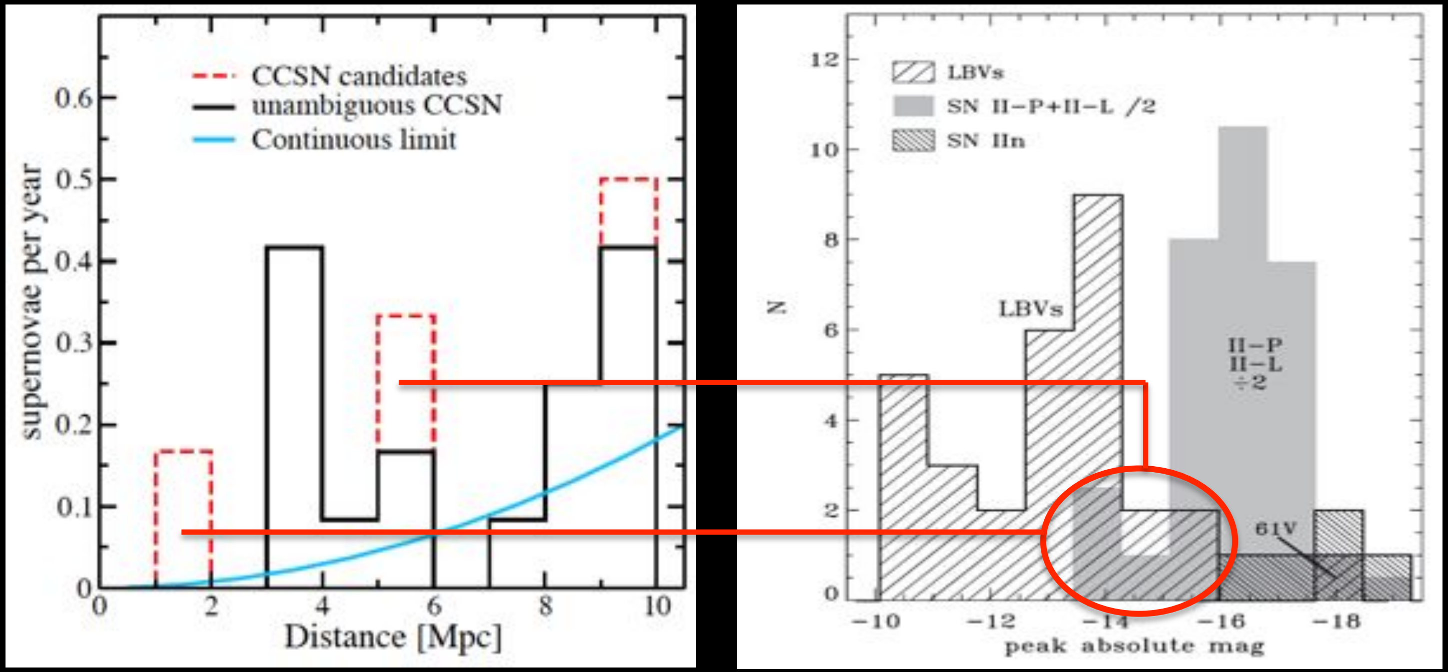
	H_2O only	H_2O + Gd
Energy range [MeV]	18-30	12-38
Signal ν (in ~10 sec for d = 1 Mpc)	~10	~20
Background ν (over 1 day)	~0.9	~1.2

➔ Can go to a few Mpc

Impostor or supernova?

There exist transient events whose nature continue to be debated: are they extreme luminous blue variables or dim supernovae? (SN2008S-like events)

Nearby potential impostors in red



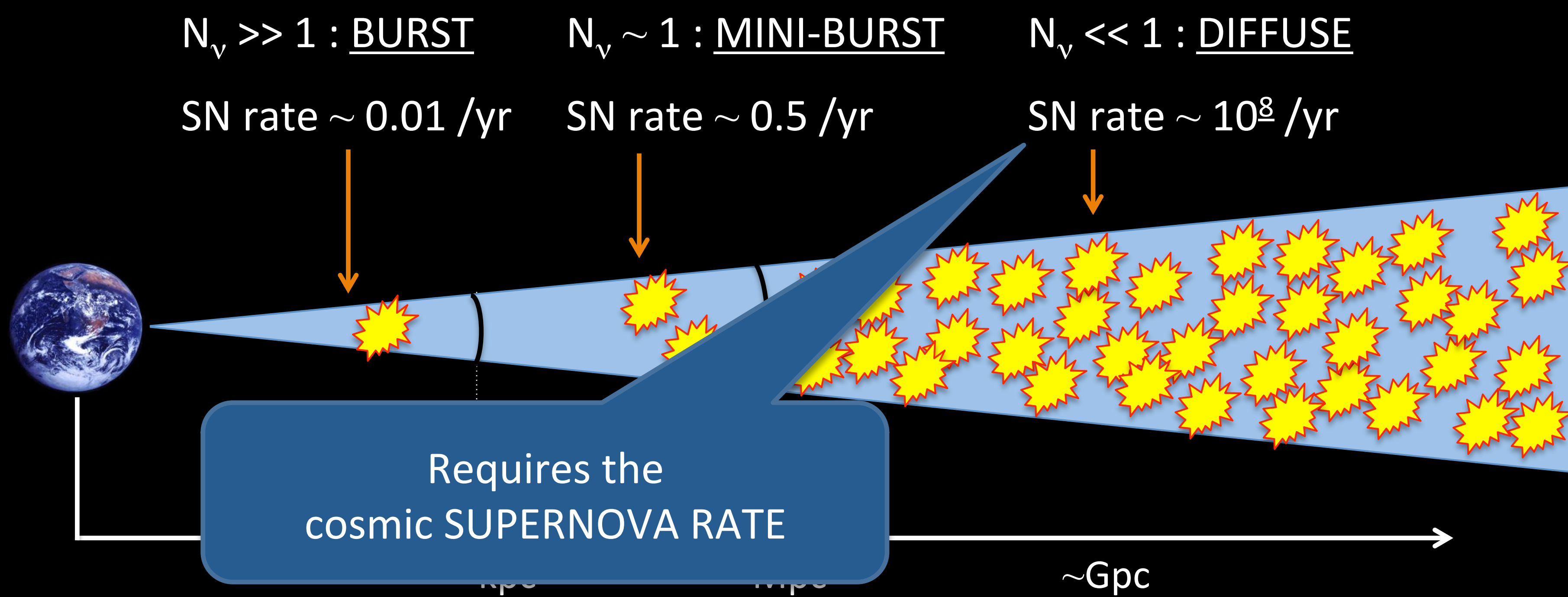
Smith et al. (2011)

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

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

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

Distance scales and physics outcomes



	Galactic burst	Mini-bursts	Diffuse signal
Physics reach	Explosion mechanism, astronomy	supernova variety with individual ID	Average emission, multi-populations
Required detector	Basics are covered	Next generation	Current upgrades

Theoretical DSNB Prediction

Observed positron spectrum

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

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

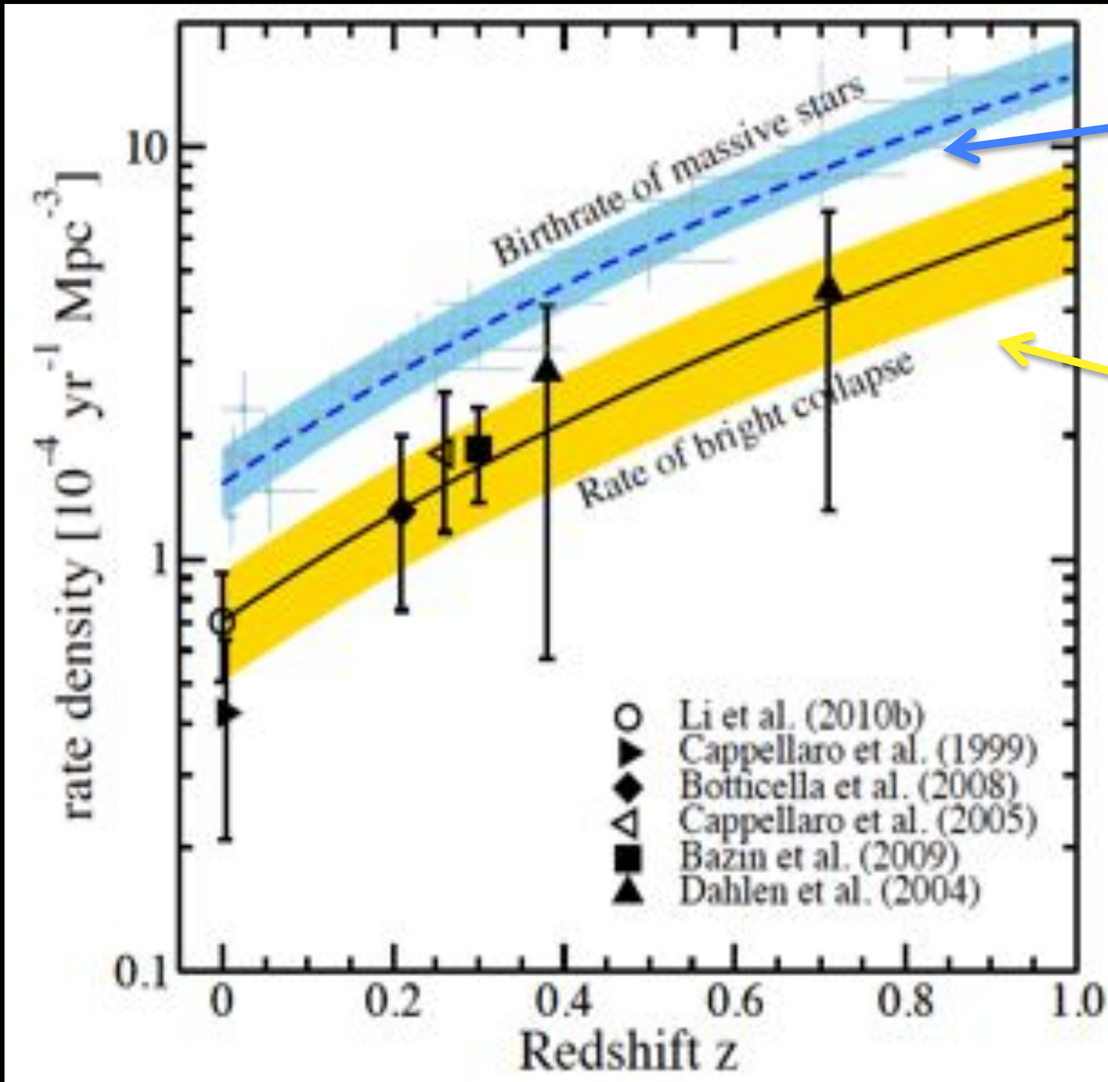
See, e.g., reviews by Beacom (2010), Lunardini (2010)

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

Input 3: neutrino detector capabilities well understood

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

Cosmic supernova rate



HORIUCHI et al, ApJ (2010)

Birthrate of massive stars that are expected to core collapse

Observed supernova rate derived from observations of *luminous* supernovae

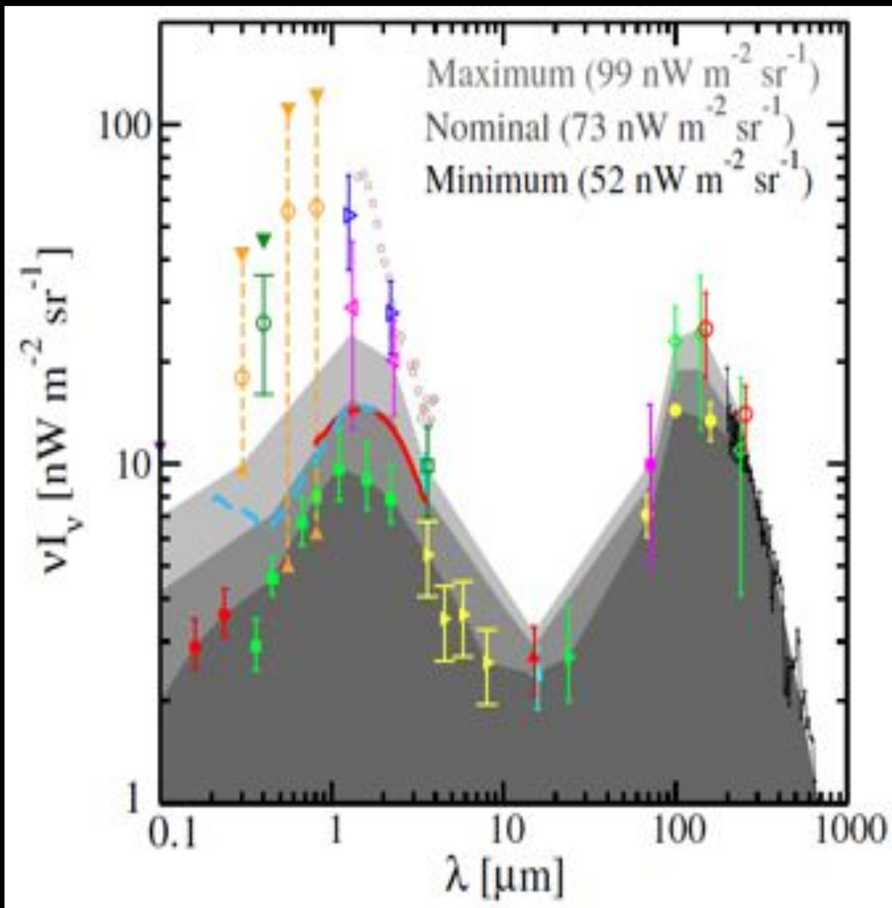
Astrophysical uncertainties exist, but the offset is not easily explained by systematics, e.g.,

- Initial mass function
- Star formation calibrations
- Dust affecting birthrate

HORIUCHI et al, PRD (2009)
HORIUCHI & Beacom, ApJ (2010)
HORIUCHI et al, ApJ (2013)

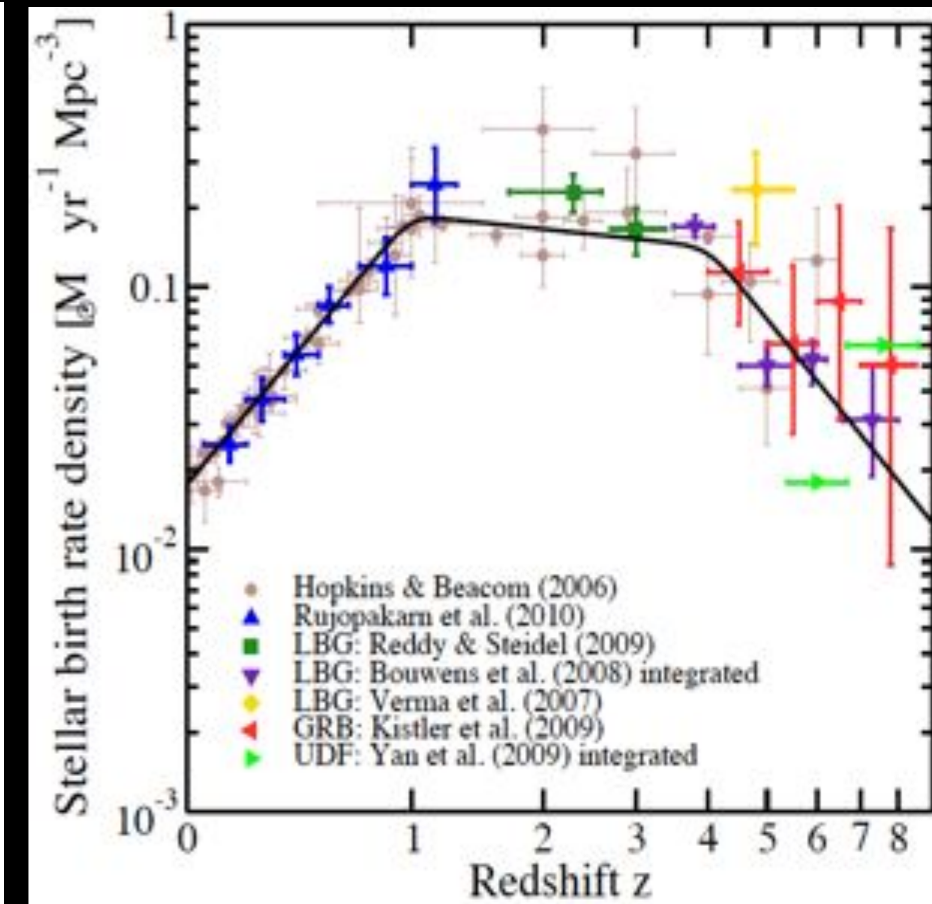
Useful observations

Extragalactic background Light (EBL)



HORIUCHI et al, PRD (2009)
Many updates, e.g., Gilmore et al, MNRAS (2012)

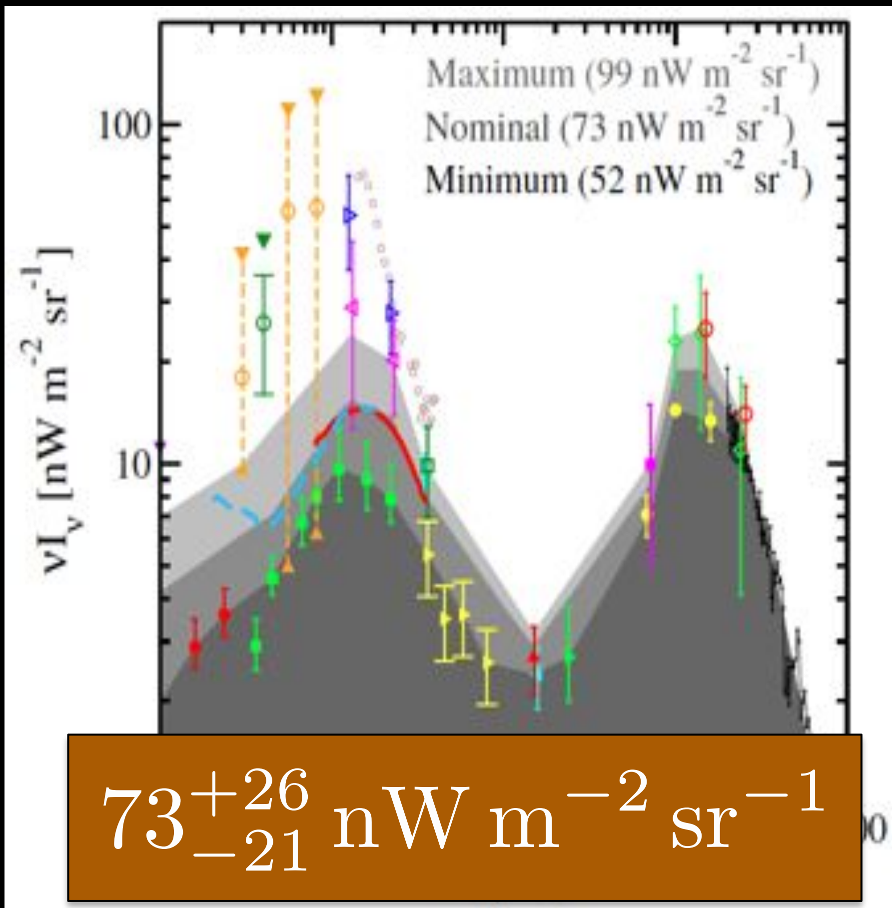
Cosmic stellar birth rate density



HORIUCHI & Beacom, ApJ (2010)
Many works, e.g., Yuksel et al, ApJ (2008)
Hopkins & Beacom, ApJ (2006)

Useful observations

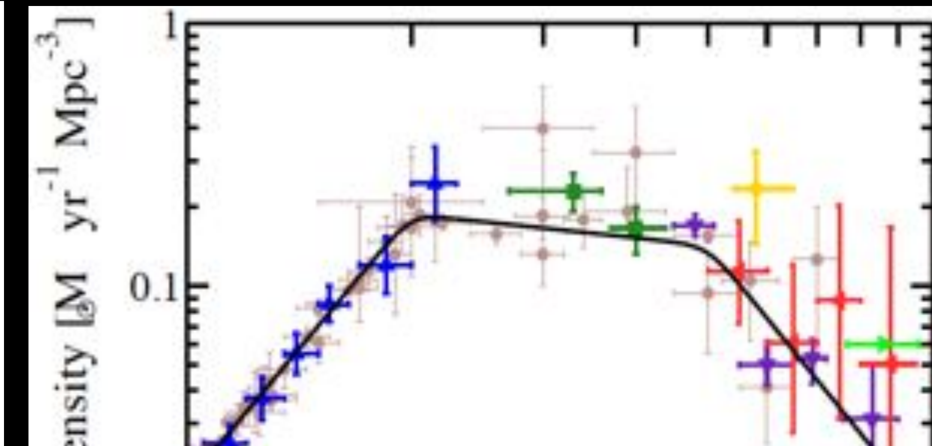
Extragalactic background Light (EBL)



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

HORIUCHI et al, PRD (2009)
Many updates, e.g., Gilmore et al, MNRAS (2012)

Cosmic stellar birth rate density



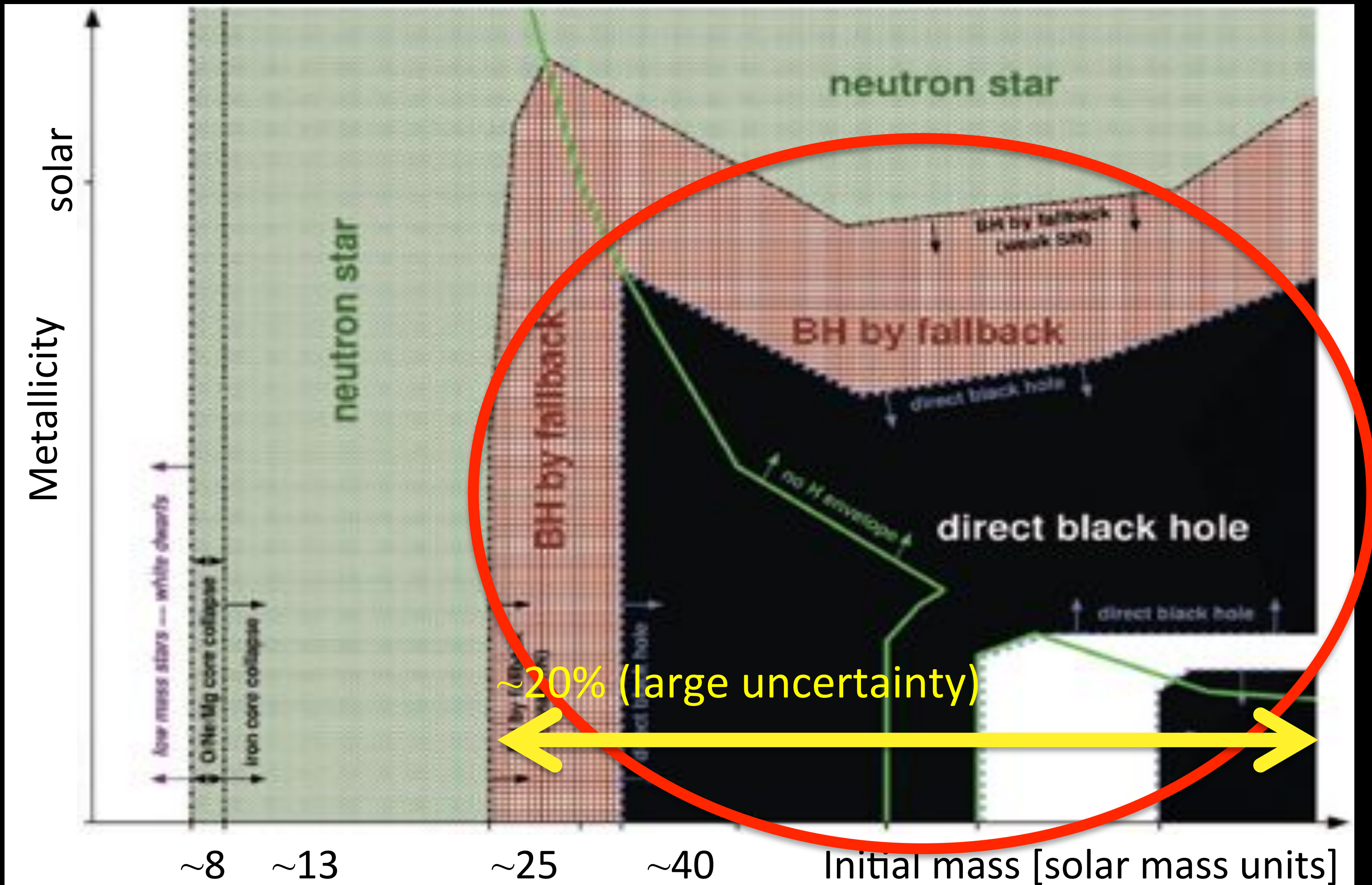
IMF	Total EBL intensity	Range
Salpeter '55	95 nW m^{-2} sr^{-1}	65–134
Kroupa '01	88 nW m^{-2} sr^{-1}	60–124
Baldy-Glazebrook '03	78 nW m^{-2} sr^{-1}	54–109

HORIUCHI & Beacom, ApJ (2010)
Many works, e.g., Yuksel et al, ApJ (2008)
Hopkins & Beacom, ApJ (2006)

What is the nature of missing supernovae?

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

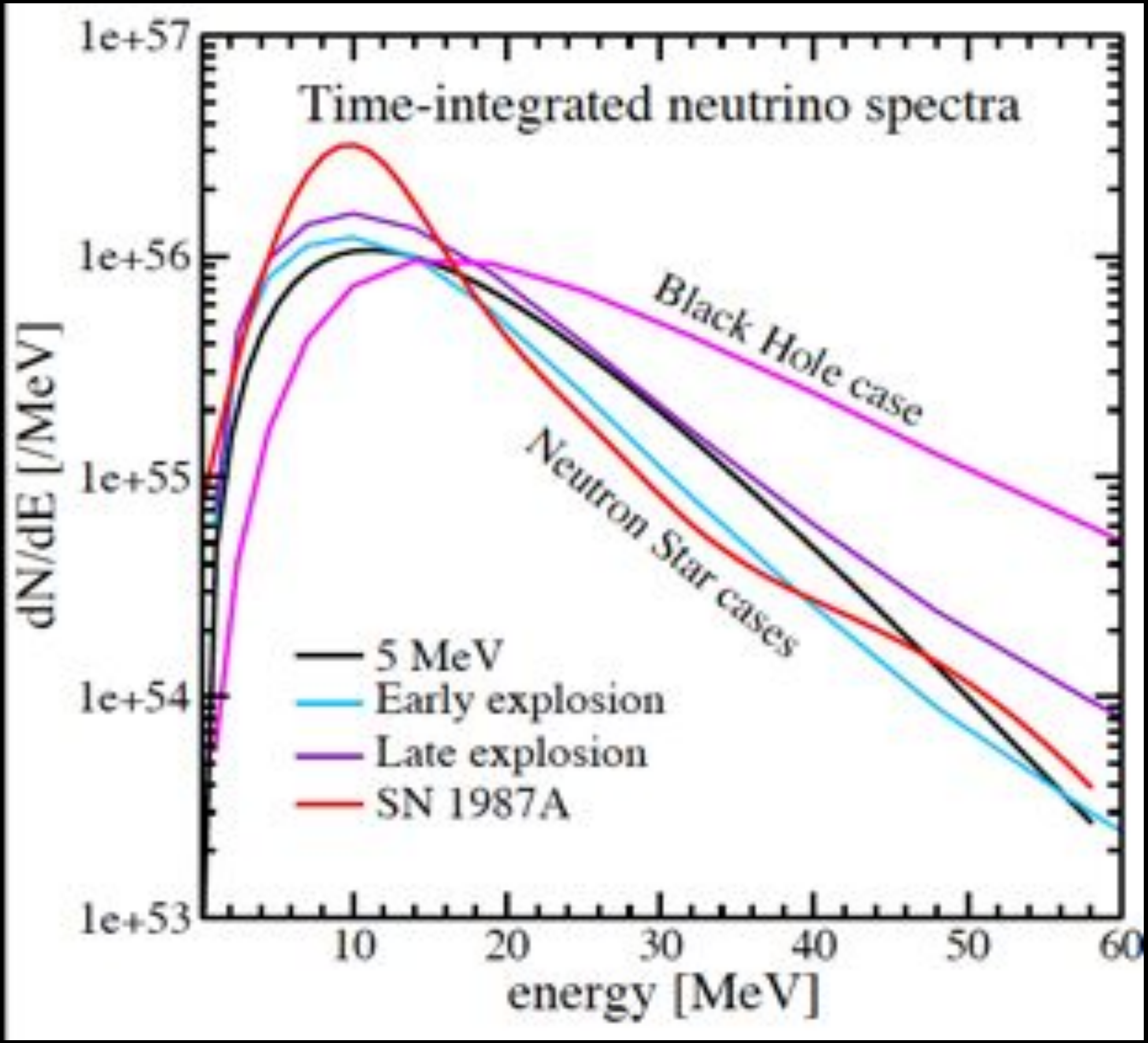
Massive stars that collapse `quietly' in photons are difficult to observe directly: "un-novae" or "failed supernovae" possible, e.g., due to collapse to Black holes.



Collapses to black holes are ν luminous

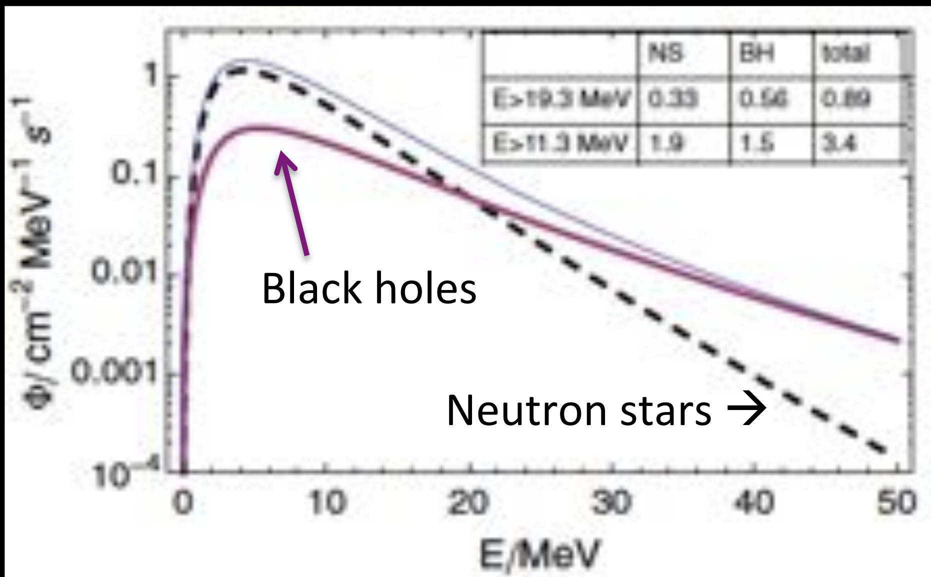
Neutrino emission:
Black hole necessarily goes through rapid mass accretion → ν emission is hotter & more luminous

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



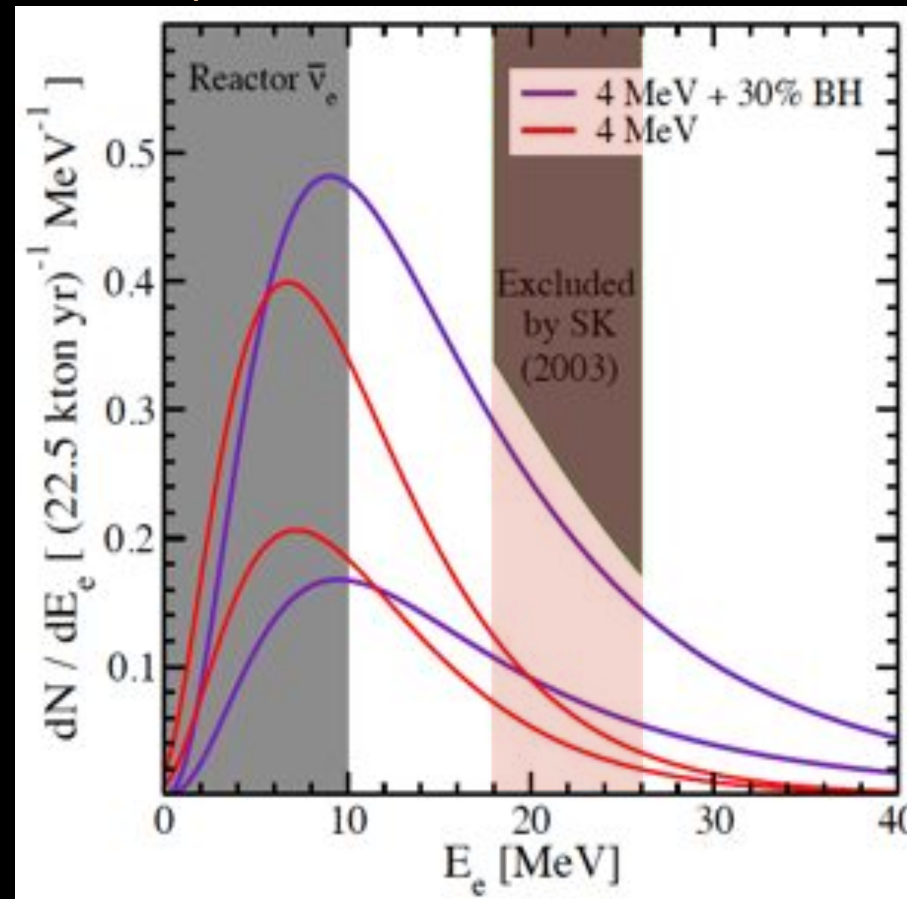
Event rates

Diffuse neutrino fluxes:



Lunardini PRL (2009); also Lien et al, PRD (2010), Keehn & Lunardini PRD (2010)

Event spectra with uncertainties:



Adapted from HORIUCHI et al, PRD (2009)

Event rate at Super-Kamiokande detector:

Spectrum	Current Super-K [/yr]
4 MeV	0.4 +/- 0.1
4 MeV+BH	1.1 +/- 0.3
SN1987A	0.5 +/- 0.1

Event rates

Use dissolved Gadolinium (Gd) for effective neutron-tagging *Beacom & Vagins, PRL (2004)*

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

current

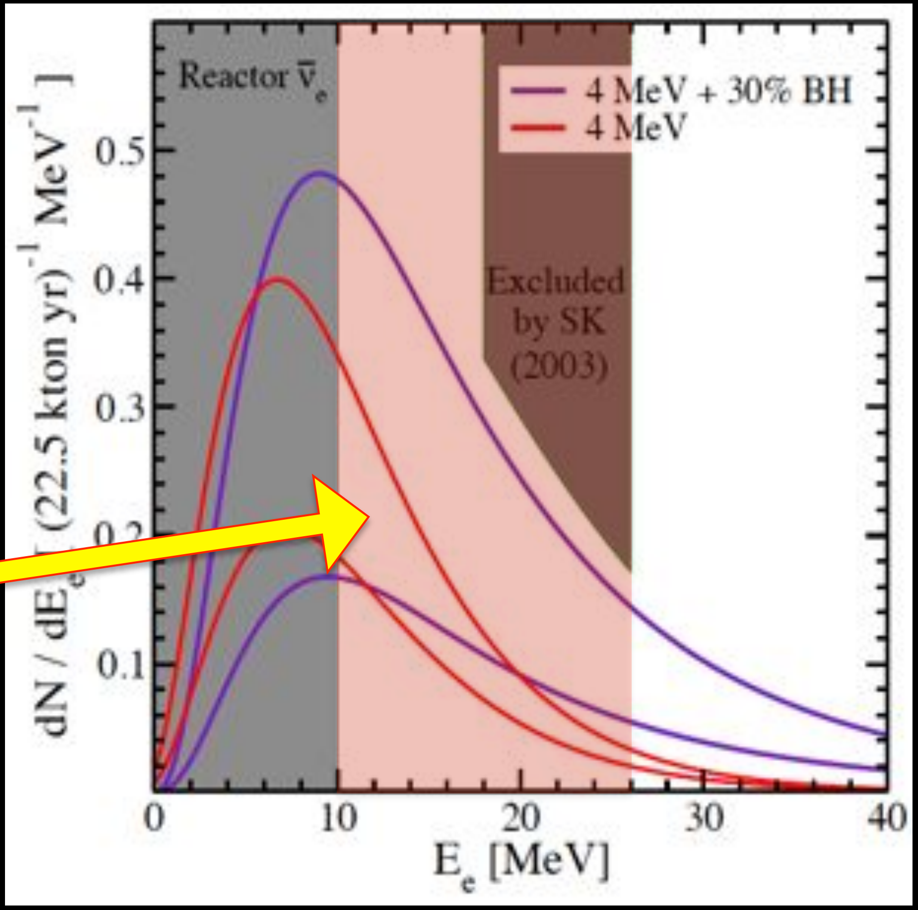
with Gd

Capture on protons, signal lost

Capture on Gd, provides a coincidence signal

→ Increased energy window
→ Opens an event limited search

Event spectra with uncertainties:



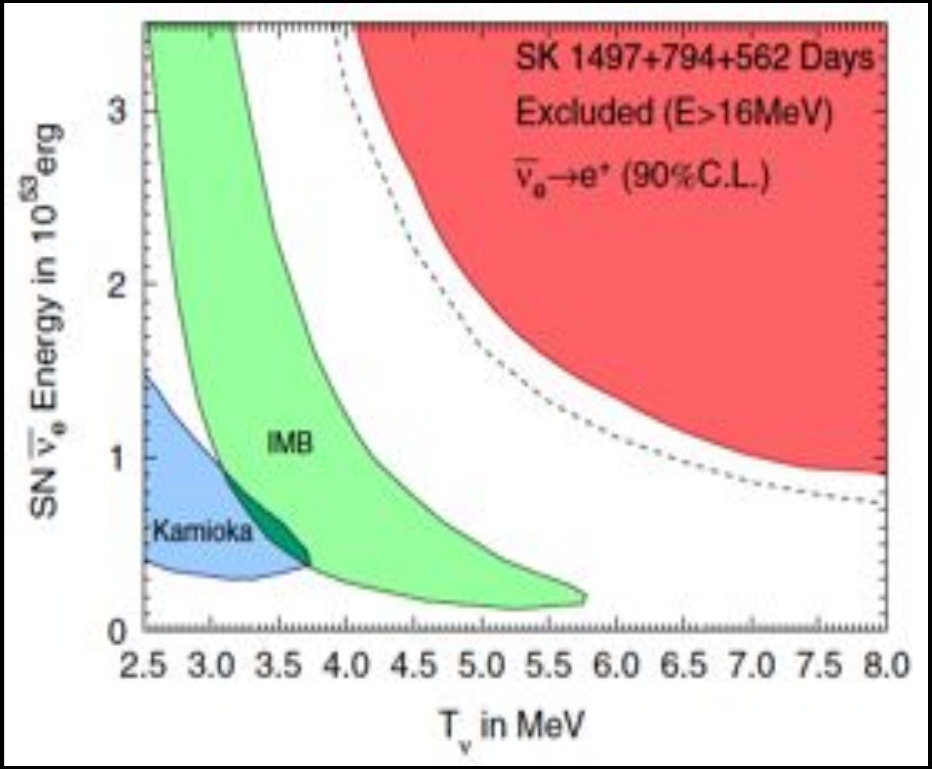
Adapted from HORIUCHI et al, PRD (2009)

Event rate at Super-Kamiokande detector:

Spectrum	Current Super-K [/yr]	With Gd upgrade [/yr]
4 MeV	0.4 +/- 0.1	1.8 +/- 0.5
4 MeV+BH	1.1 +/- 0.3	3.0 +/- 1.0
SN1987A	0.5 +/- 0.1	1.7 +/- 0.5

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

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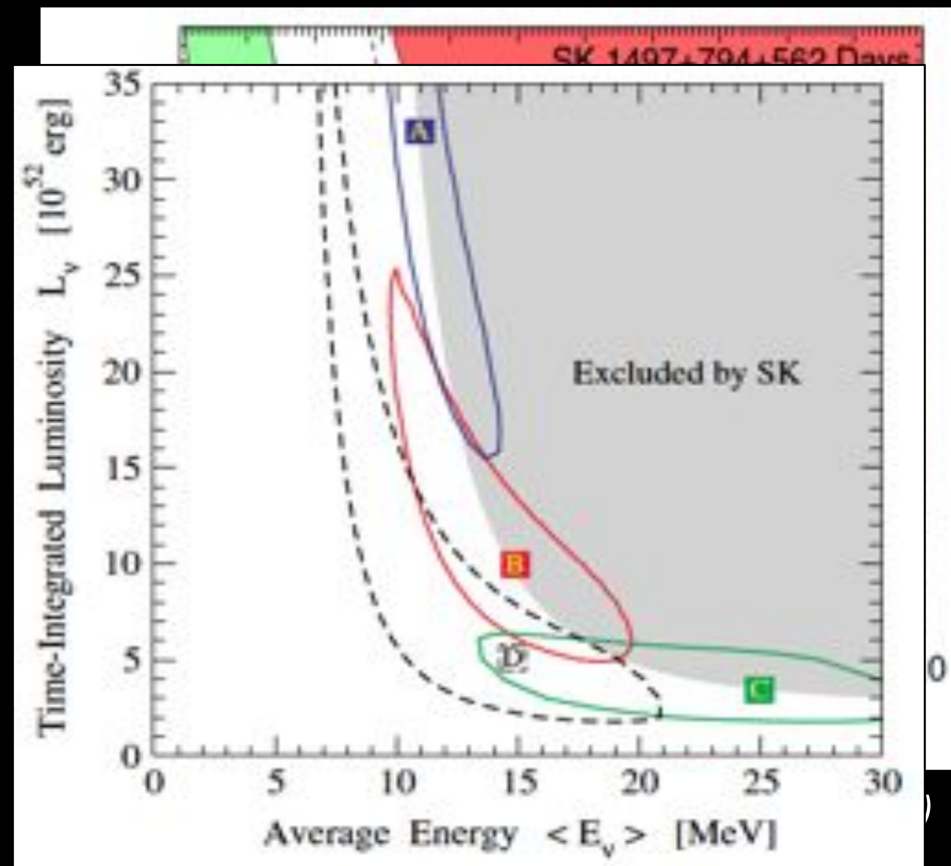
Super-K with Gd:

Removes the largest background sources and enables a signal dominated search



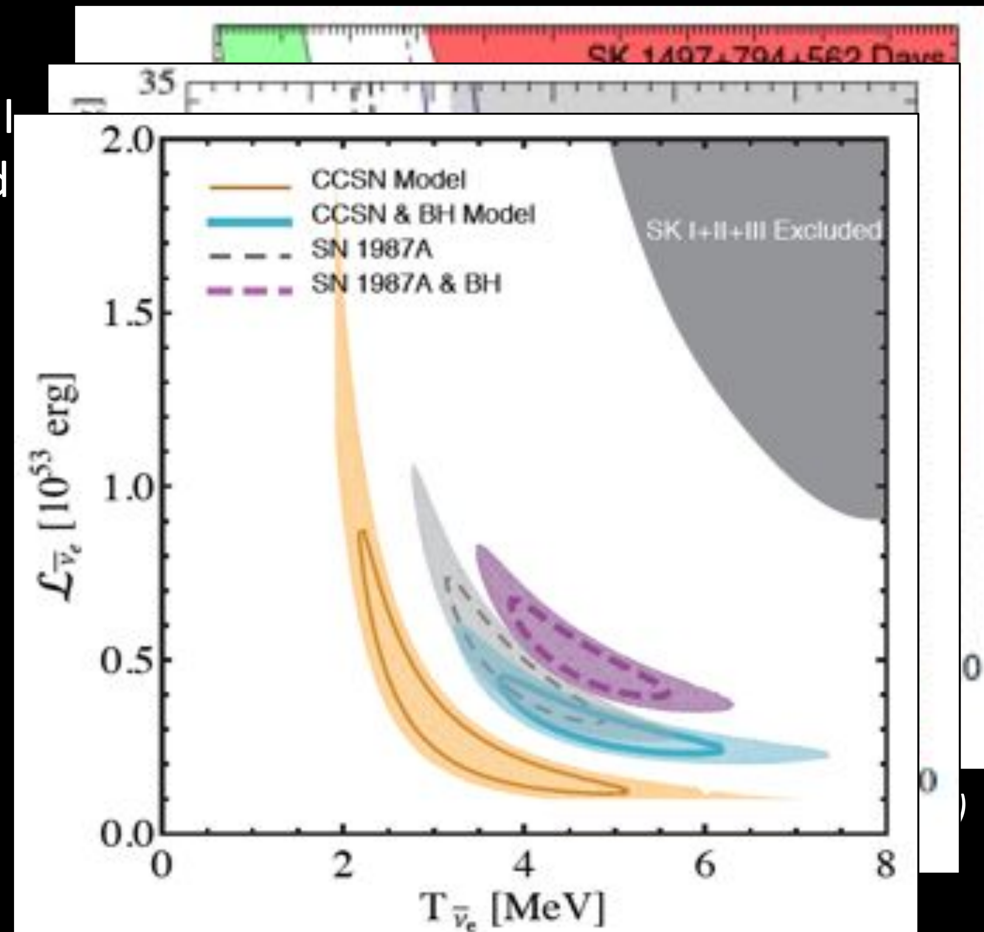
90% CL contours for 5 yr running Super-K with Gd,

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



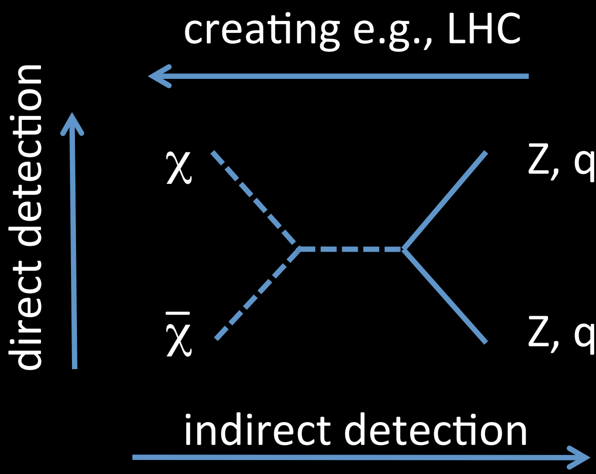
2σ and 5σ contours for 10 years runnng idealized Hyper-K with Gd [Yuksel & Kistler 2013]

NEUTRINOS FROM DARK MATTER

Particle dark matter

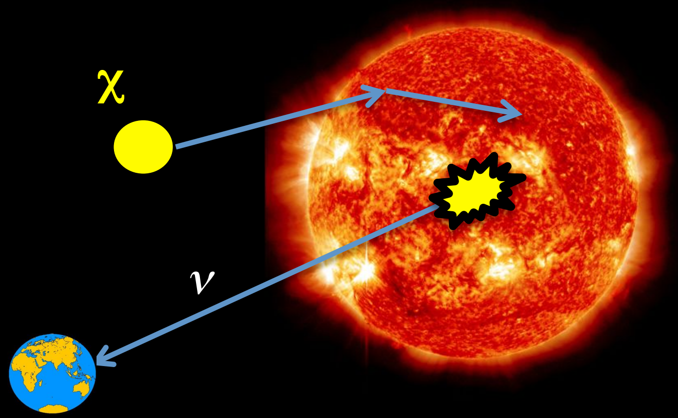
- What we know
  - Its existence
  - Their abundance
  - Is minimally interacting
  - Is highly clustered
    - Local density

- 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 (SD) scattering cross section
- Dark matter particles:
  1. Scatter in the sun
  2. Gravitationally captured
  3. Settle in the core
  4. Annihilate
  5. Neutrinos escape



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

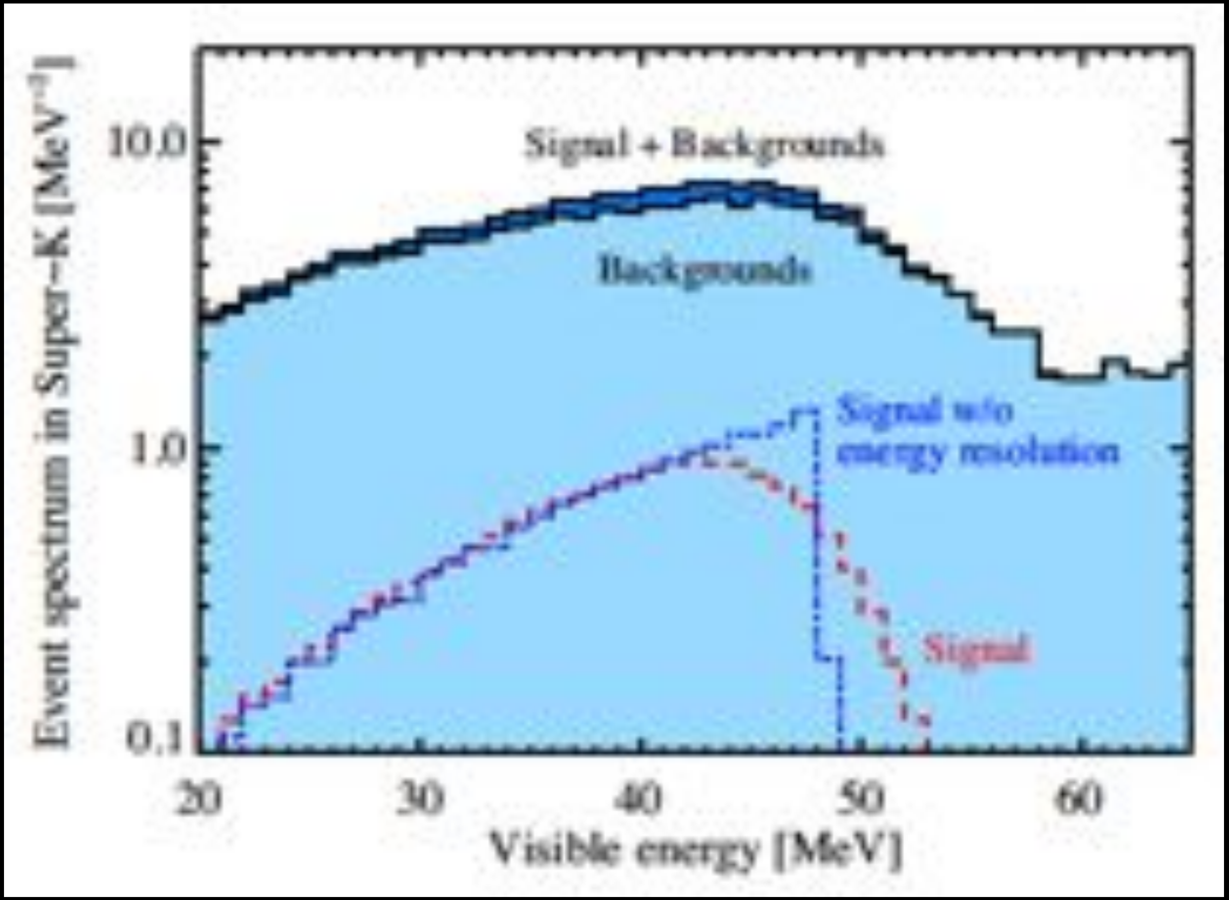
Limits on the scattering cross section

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



Rott et al. (2013), see also Bernal et al. (2013)

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

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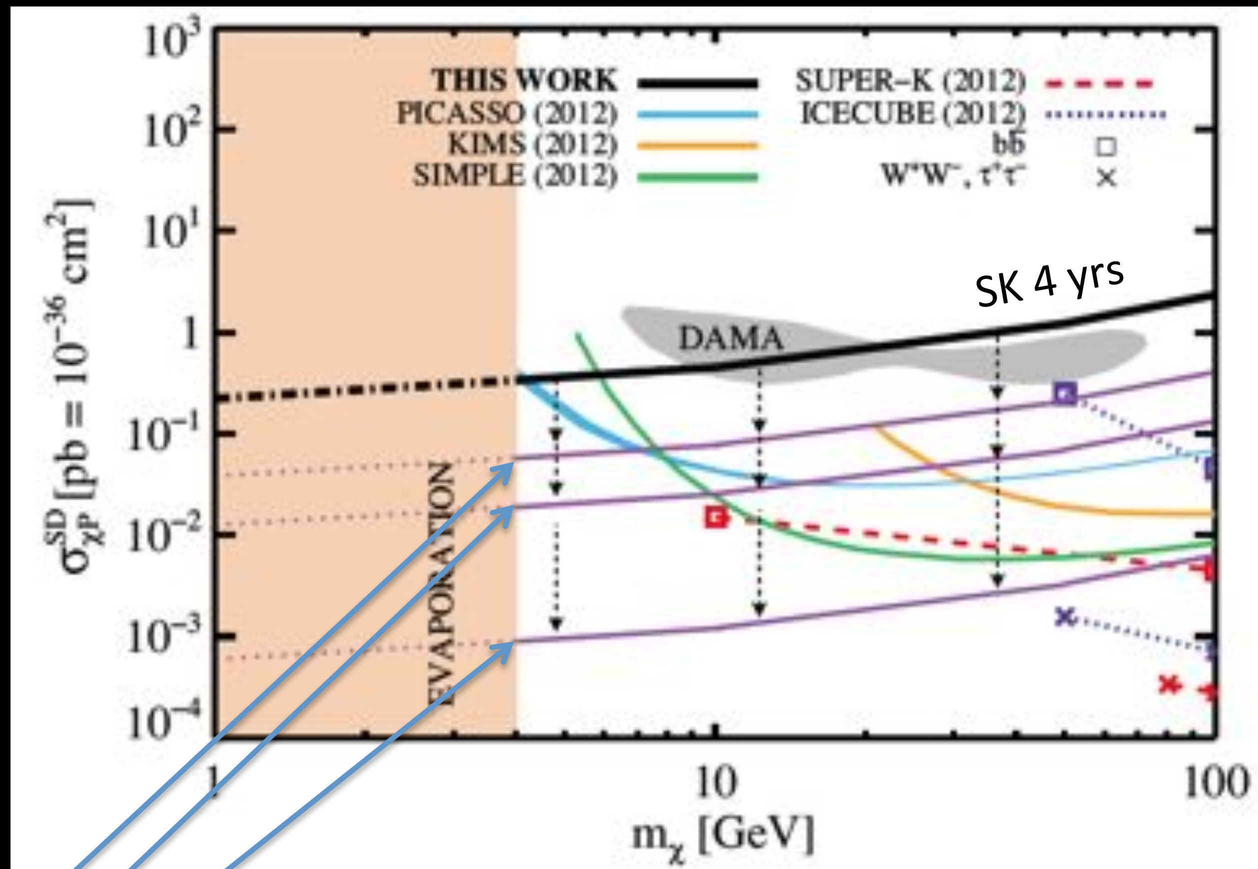


Future improvements:

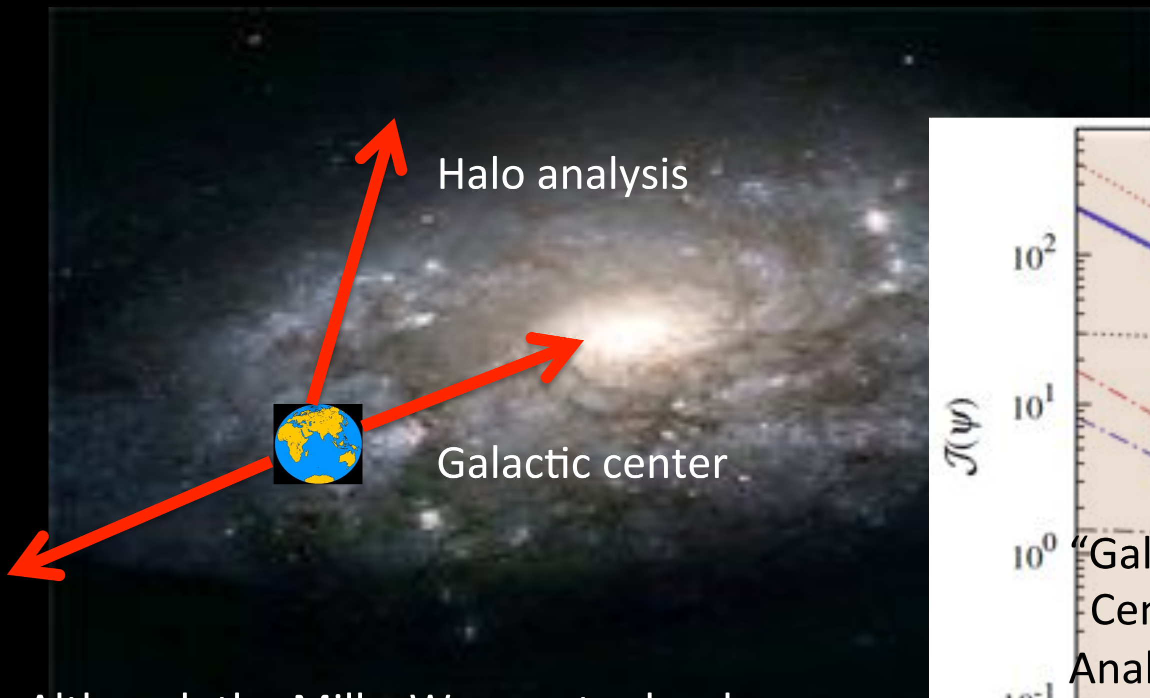
- Hyper-K 4 yrs................
- Super-K + Gd 4 yrs.......
- Hyper-K + Gd 4 yrs......

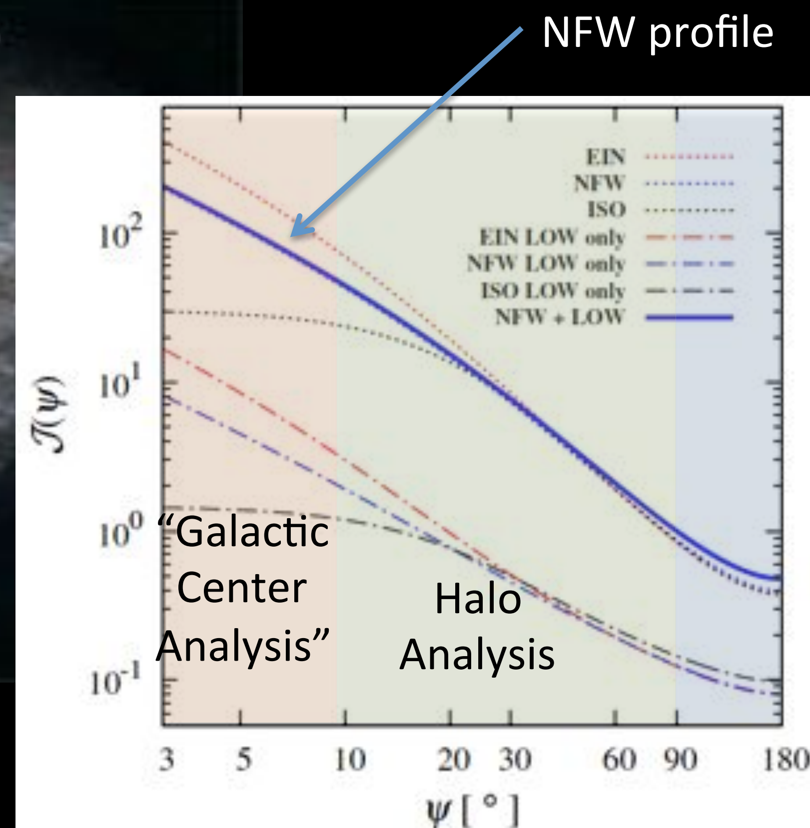
Rott et al. (2013), see also Bernal et al. (2013)
RED shows channel-differentiated Super-K limits

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

Limits on the annihilation cross section

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



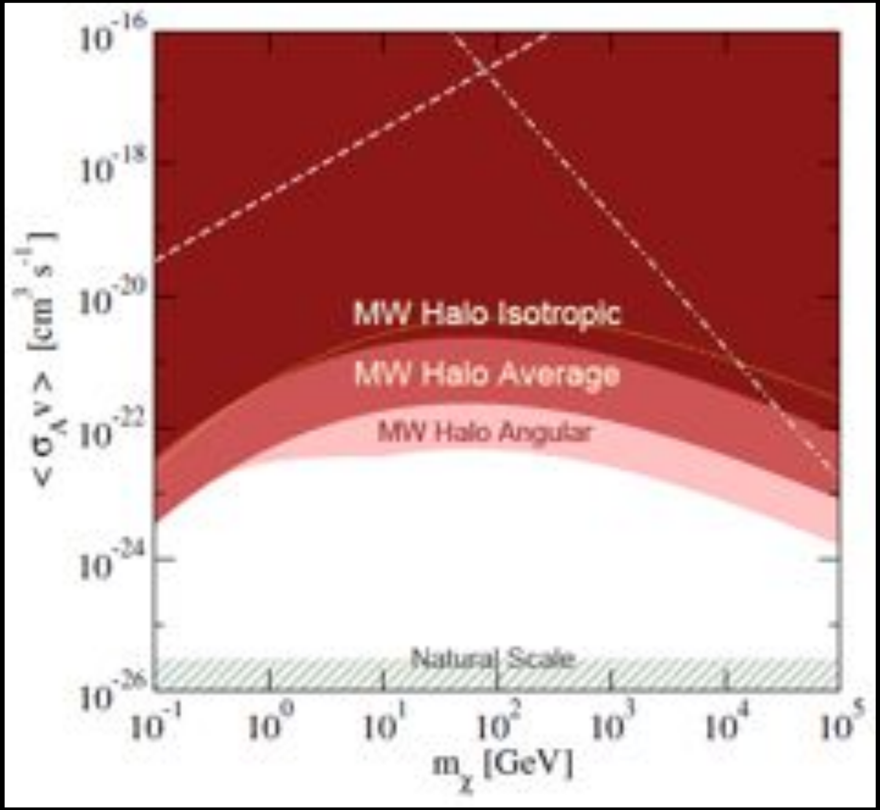


Although the Milky Way center has large expected signals, systematic uncertainty blows up due to unknown central density

Limits on the annihilation cross section

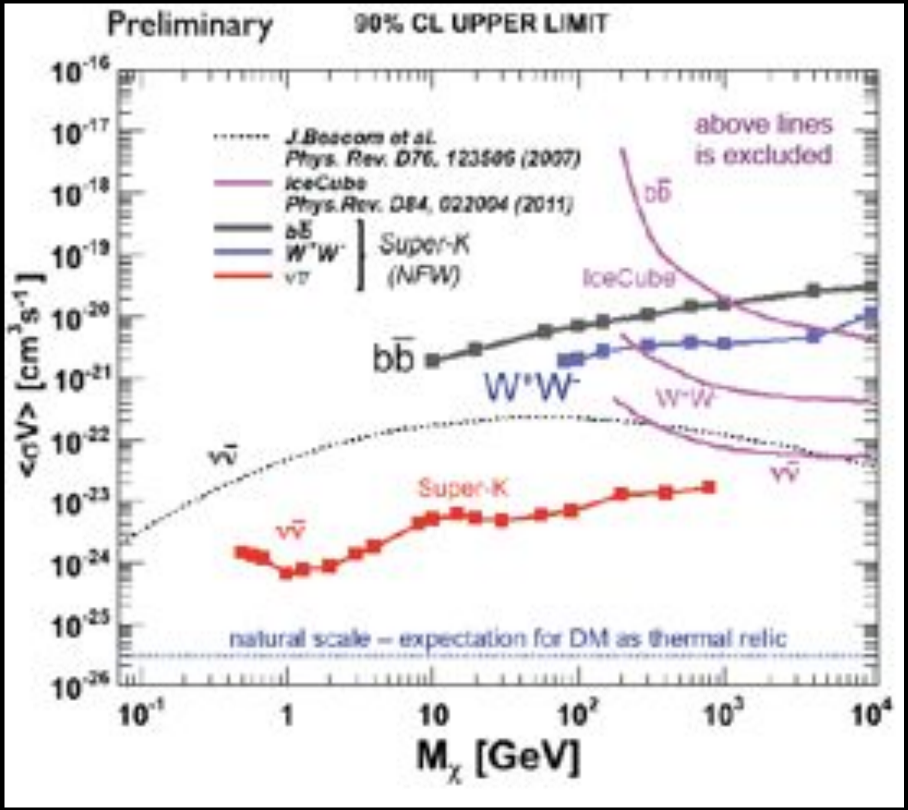
Halo analysis: look at the Milky Way halo at large and search for annihilation signal. Halo analysis benefits from signal and reduced profile uncertainty.

Simplified theorist (conservative) estimate:



Yuksel, Horiuchi, et al (2007)

Expert experimentalist analysis:



Rott, Neutrino 2012

Summary

Neutrinos are useful messenger particles, and current and next-generation neutrino detectors open the window to high-statistic astrophysical neutrino detections

Supernova neutrinos open valuable probes for many topics:

1. The supernova explosion mechanism
2. Black hole formation
3. Tests of debated transients

And a whole lot more…

There are now many operational and upcoming neutrino detectors

- Completion of IceCube
- Plans for larger versions of various ν experiments
- Upgrade of Super-Kamiokande
- Plans for Hyper-Kamiokande

When a new window is opened, we are confronted with new insights & surprises.

"The title [of the book] is more of an expression of hope than a description of the book's contents....the observational horizon of neutrino astrophysics may grow...perhaps in a time as short as one or two decades."

John Bahcall, Neutrino Astrophysics (1989)

Thank you!