Core-Collapse Astrophysics
with
Multi Megaton Neutrino Detectors

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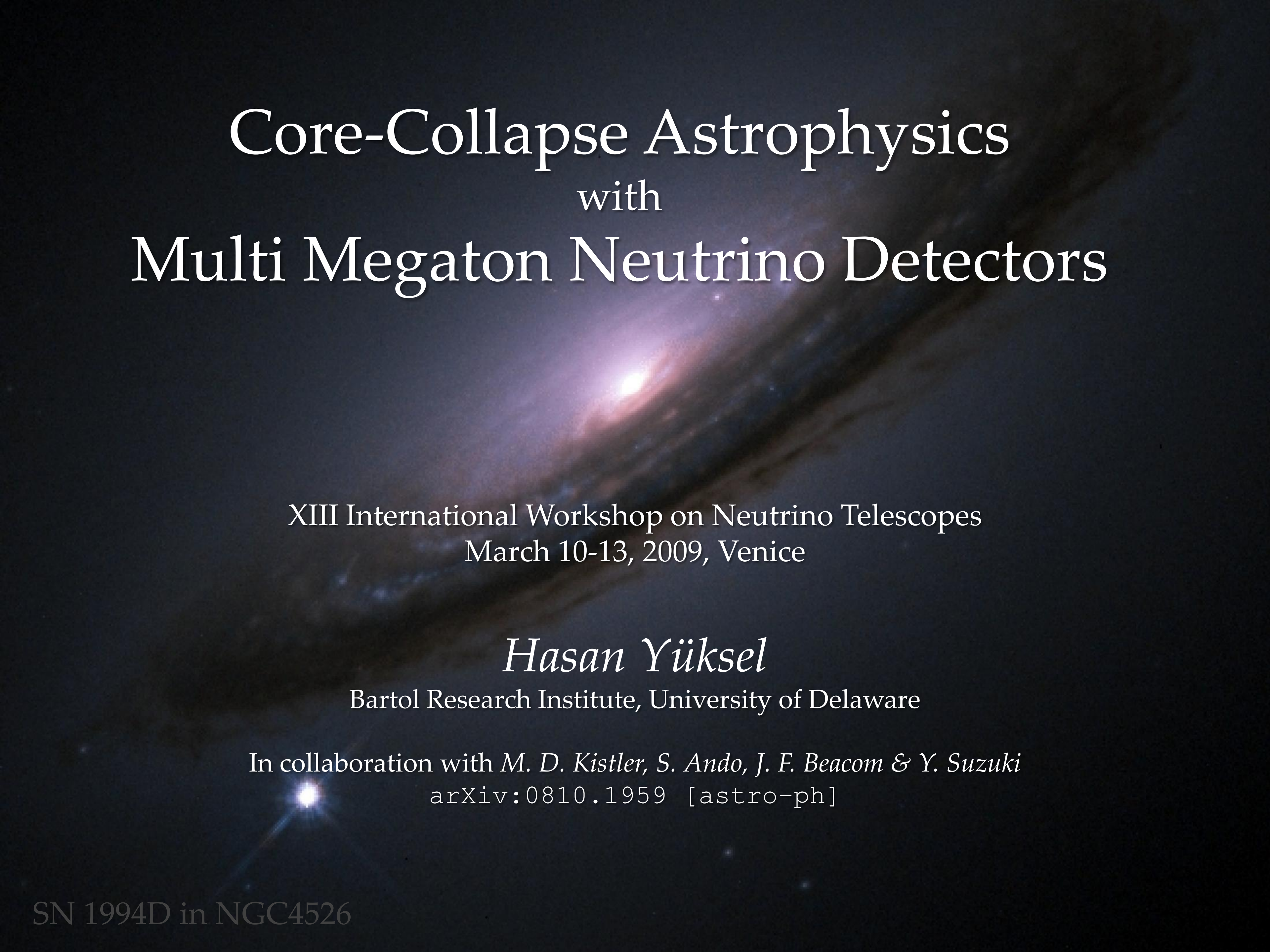
In collaboration with *M. D. Kistler, S. Ando, J. F. Beacom & Y. Suzuki*
`arXiv:0810.1959 [astro-ph]`



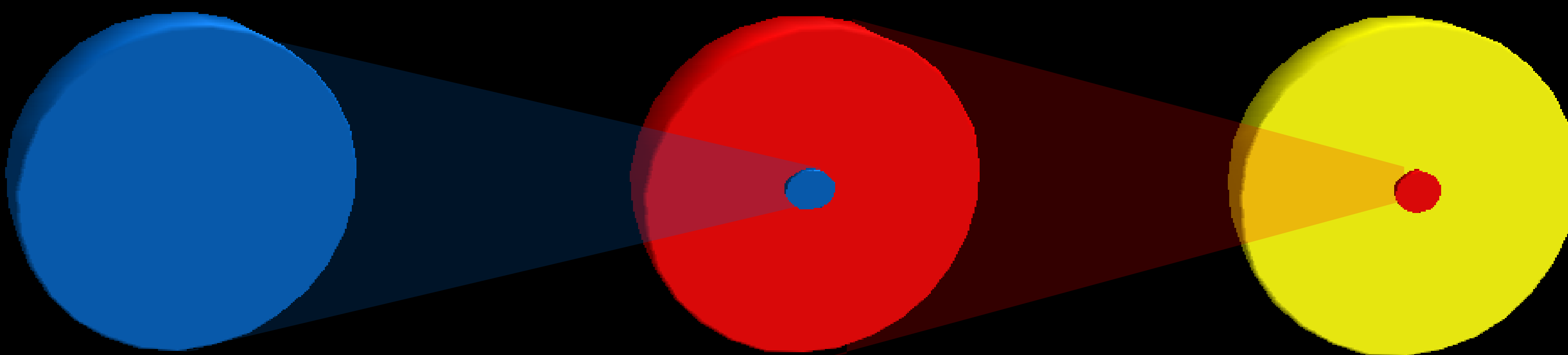
SN 1994D in NGC4526

Core-collapse SN & Neutrinos

proto-neutron star
~ 10 km $\sim 1.4\ m_\odot$

iron core
$\sim 10^3$ km $\sim 1.4\ m_\odot$

massive star
$\sim 10^8$ km $\sim 10\ m_\odot$

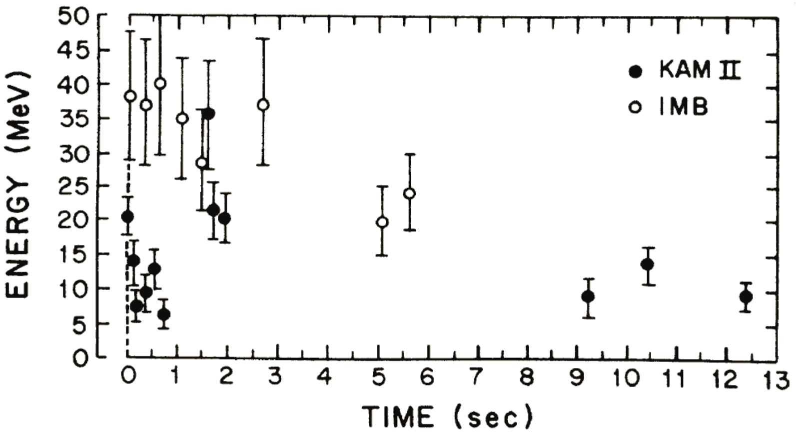


$$\frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} \approx 3 \times 10^{53}\text{ergs}\,\frac{(M_{NS}/1.4M_\odot)^2}{R_{NS}/10\text{km}}$$

~ 1/6th rest mass of the Sun

neutrinos ~ %99 K.E. of the explosion ~1% radiation ~ 0.01%

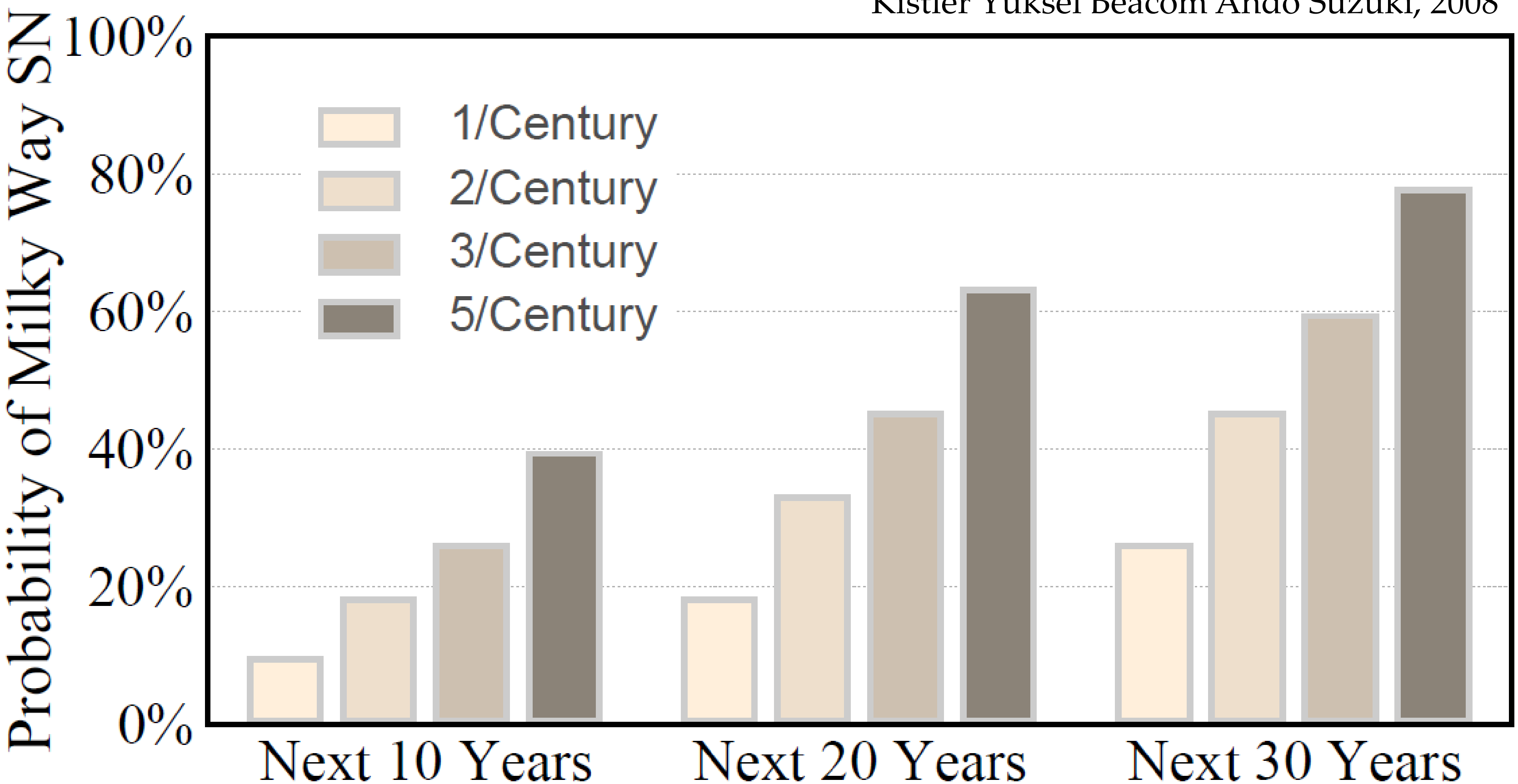
SN 1987A



ENERGY (MeV)
TIME (sec)
KAM II
IMB
0
5
10
15
20
25
30
35
40
45
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13

How Long to Wait for Next Milky Way SN?

Kistler Yüksel Beacom Ando Suzuki, 2008



While waiting for the next Milky Way Supernova: Diffuse Supernova Neutrino Background

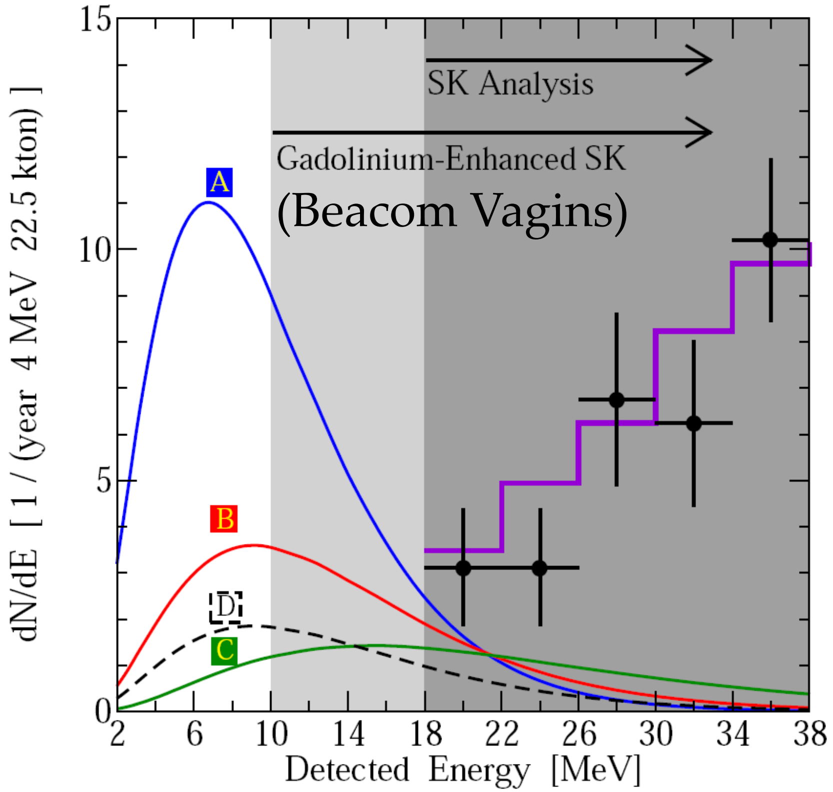
Diffuse Supernova Neutrino Background

History of Star Formation in the Universe	Neutrino Emission per Supernova	Detection	Standard Cosmological Assumptions
• Core Collapse SN Rate per unit star formation	• Average energy of a given flavor • Total Luminosity emitted in each flavor • Oscillations between flavors	• Detector Size • Neutrino Cross Sections • Competing Backgrounds	• Hubble Constant • Omega Matter • Omega Lambda

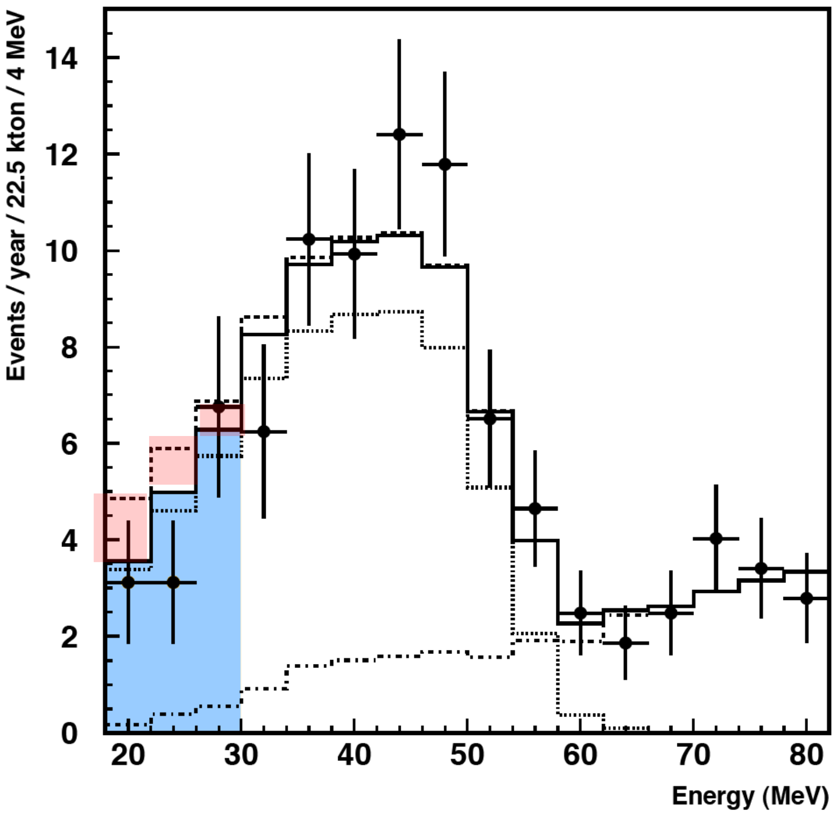
$$\psi(E_+) = \frac{c}{H_0}\sigma(E_\nu)N_t \int_0^{z_{max}} \phi(E_\nu[1+z])\frac{R_{SN}(z)}{h(z)}dz$$

Upper Limits on the DSNB

Yüksel Ando Beacom



Malek et al., (Super-K Coll.)

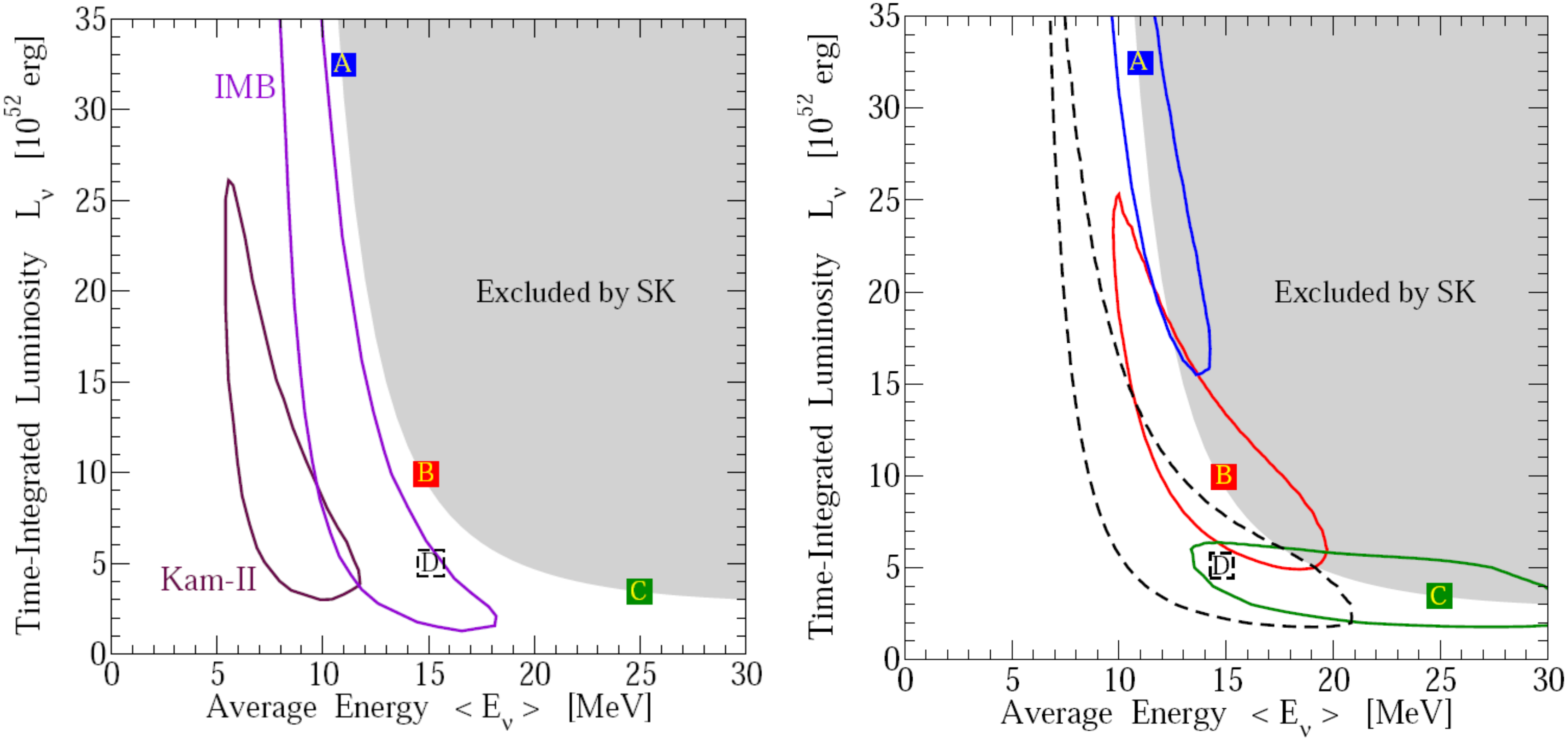


Super-K Limit on $\bar{\nu}_e$: 1.2 cm^{-2} s^{-1} (>18 MeV)

SNO limit on ν_e : < 70 cm^{-2} s^{-1} at 90% (Aharmin et al.)

Potential of Gd Enhanced Super-K

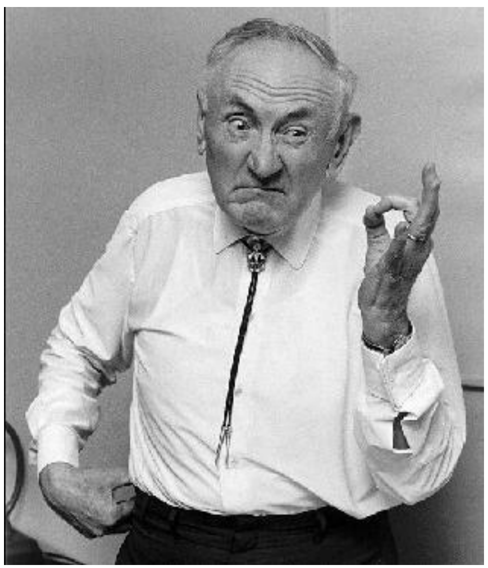
Yüksel Ando Beacom

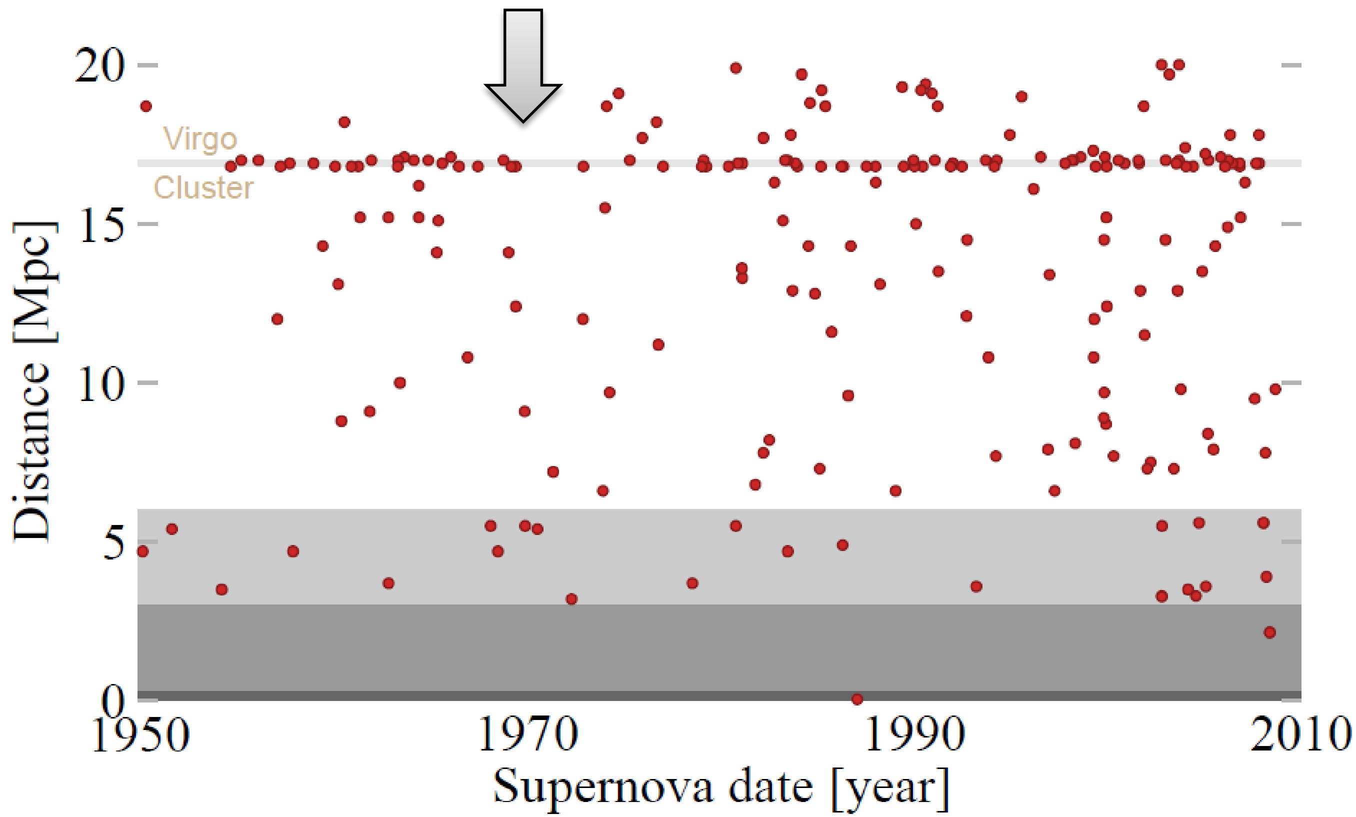


- the time-integrated luminosity and average energy may also constrain the explosion energy and protoneutron star opacity

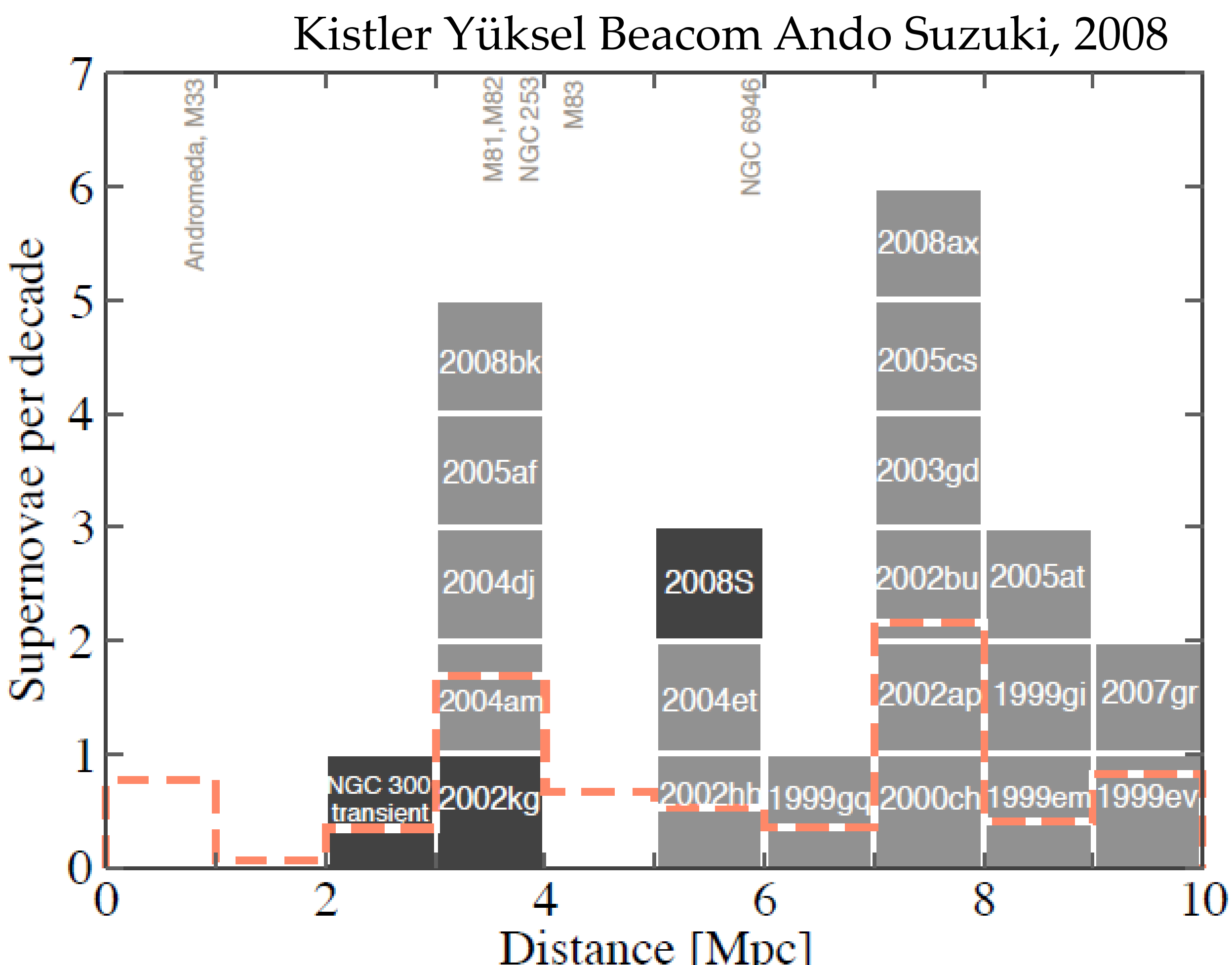
If we had a Multi-Megaton detector in the last decade…

Supernovae Discoveries in the Neighbourhood



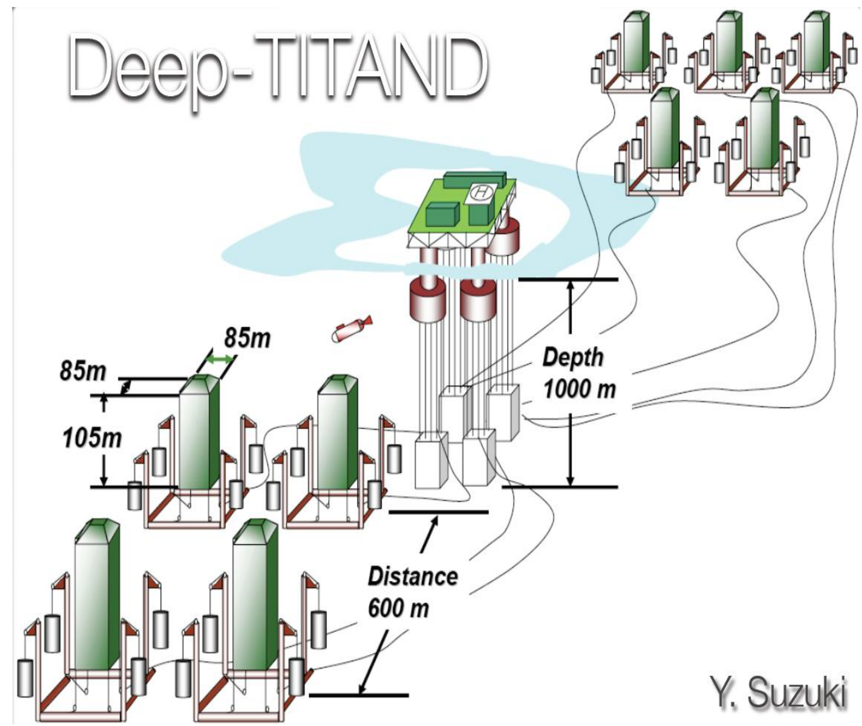


Almost 20 Supernovae since 1999 within 10 Mpc



A Case Study: Deep-TITAND

- A modular 5 Mton detector
- Key motivations:
  - proton decay
  - long-baseline neutrinos
  - atmospheric neutrinos
- going underwater bypasses the need to move mountains
- shallower depth & lower photomultiplier coverage to lower costs



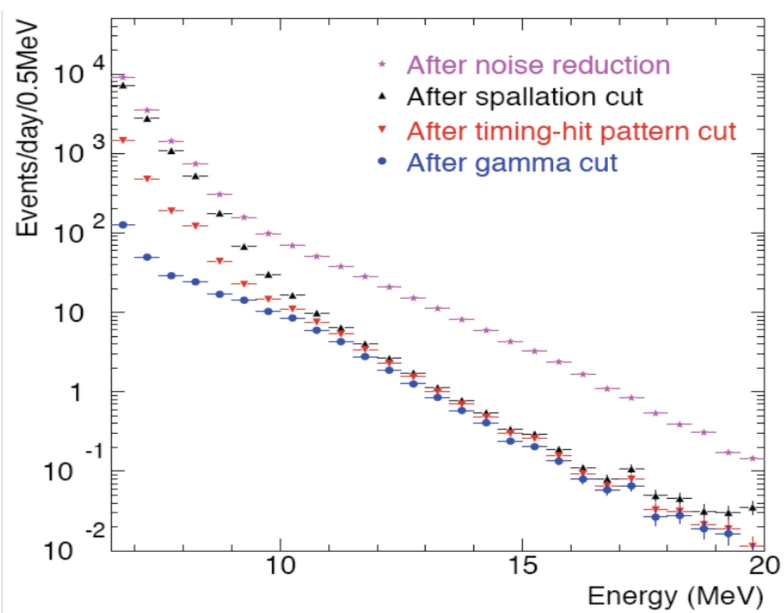
Such decisions would sacrifice the low-energy capabilities for all but burst detection

Limiting Backgrounds are Well Characterized

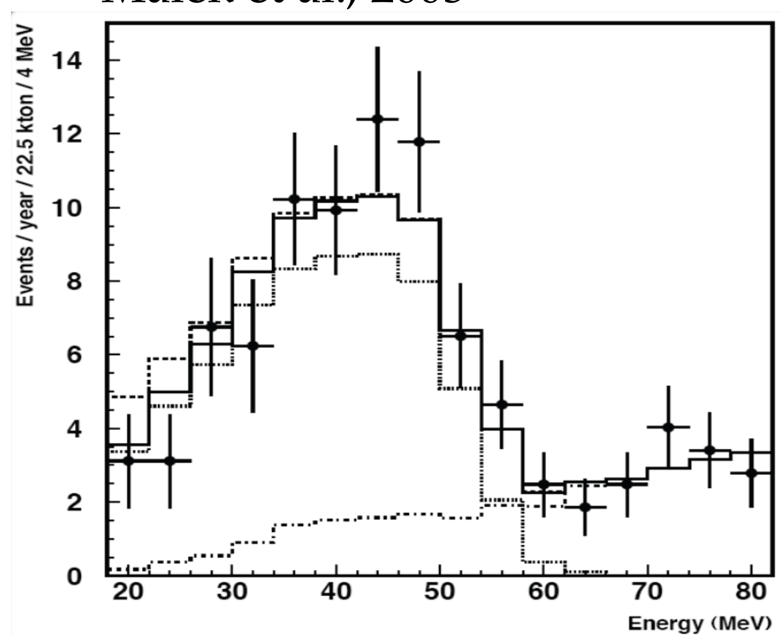
Low-energy: include natural radioactivities, solar neutrinos, photomultiplier noise, and beta decays from nuclei produced following spallation by cosmic ray muons

High-energy: dominanted by the decays of non-relativistic muons produced by atmospheric neutrinos in the detector (invisible muons)

Cravens et al., 2008



Malek et al., 2003



A Window of Opportunity

Background rate in 18–60 MeV in SK: ~ 0.2 events/day
Scaling this to a 5 Mton detector mass : $\sim 5 \times 10^{-4}\ s^{-1}$

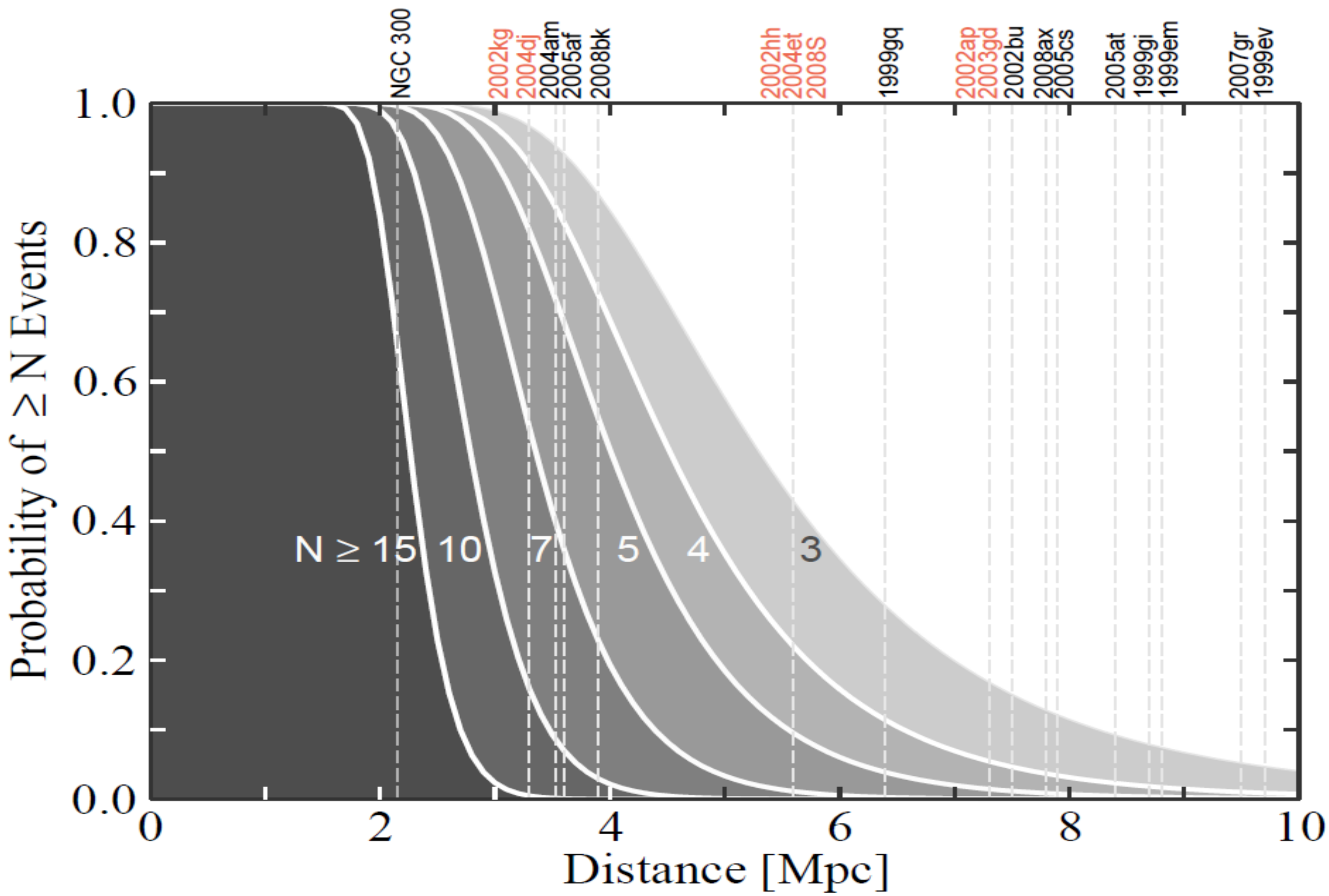
Consider an analysis window of 10 sec duration
(comparable to the SN 1987A)

Rate of accidental coincidences.:

$N \geq 4$: exceedingly rare (~1 per 3000 years)
$N = 3$: only once every five years

Examination of the energy and timing of the events
will allow further discrimination from backgrounds

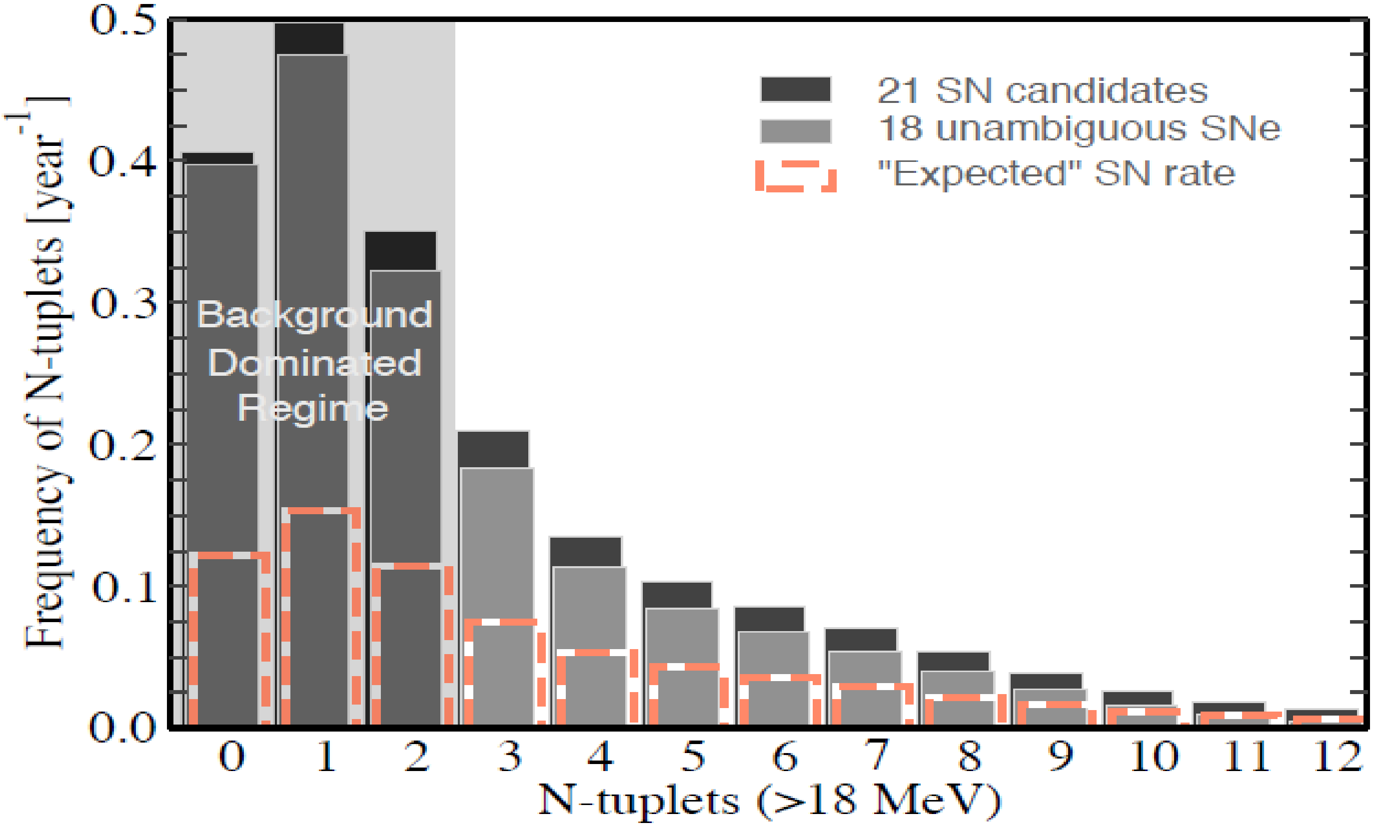
Probability of N Events vs. Distance



a Fermi-Dirac neutrino spectrum with an average energy of 15 MeV and a total energy of 5×10^{52} erg

“Mini-Bursts” of Neutrinos could be detected Occasionally

Kistler Yüksel Beacom Ando Suzuki, 2008



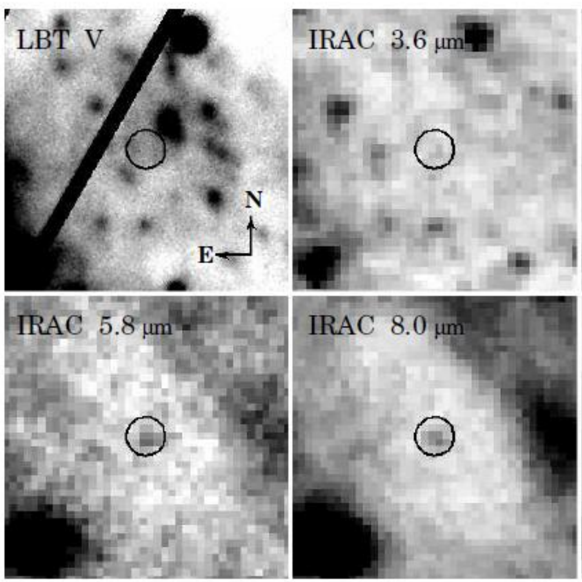
If we had this kind of detector in the last 10 years, neutrino yield could have been between 20-40

Detecting “Mini-Bursts” would allow a continuous “death watch” of all stars within ~5 Mpc, making previously impossible tasks practical:

Probing the Core Collapse

Great diversity of optical signals reflect the wide range of masses and other properties of supernova progenitors while neutrino signals mainly depend on the formation of a ~ 1.4M⊙ neutron star (needs to be tested)

An example: SN 2008S in NGC 6946



Is this an O-Ne-Mg Supernova produced by ~10 solar mass progenitor or even an LBV outburst?

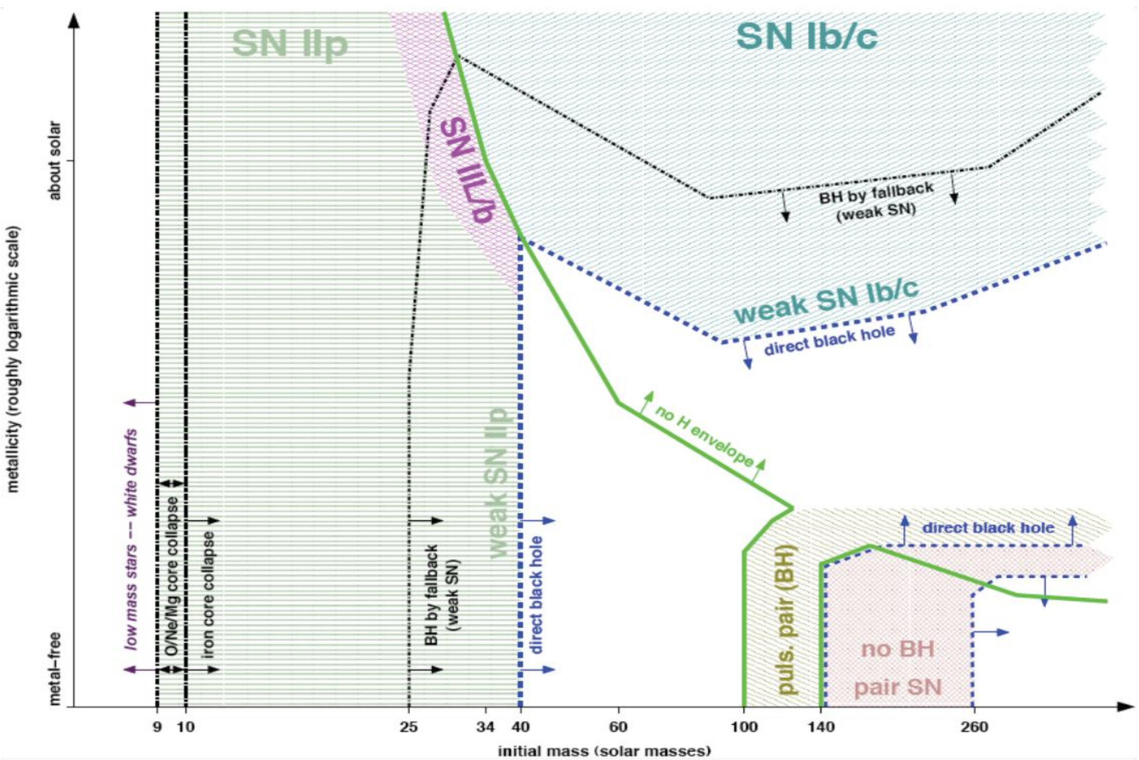
Only νs can tell for sure..

DISCOVERY OF THE DUST-ENSHROUDED PROGENITOR OF SN 2008S WITH *SPITZER*

José L. Prieto[2,4], Matthew D. Kistler[3,4], Todd A. Thompson[2,4], Hasan Yüksel[3,4], Christopher S. Kochanek[2,4], Krzysztof Z. Stanek[2,4], John F. Beacom[2,3,4], Paul Martini[2,4], Anna Pasquali[5], and Jill Bechtold[6]

Probing the Black Hole Formation

Woosley, Heger, and Weaver: Evolution and explosion of massive stars

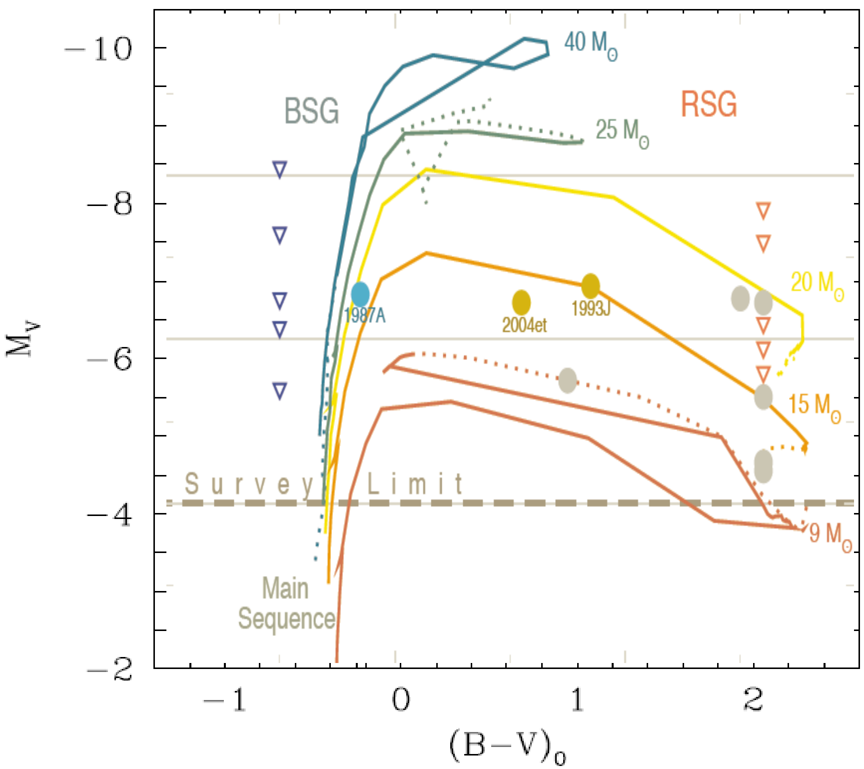


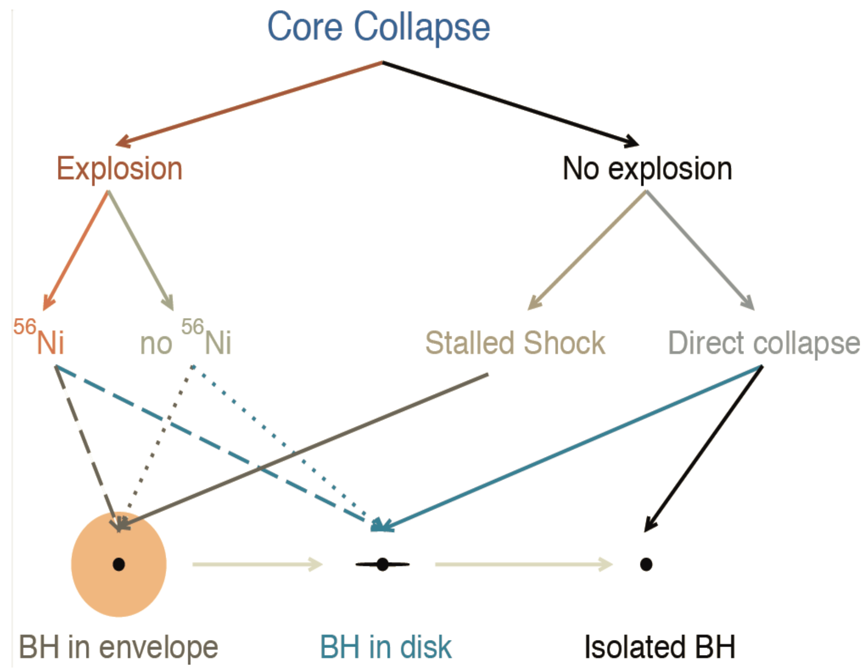
Of course in the absence of rotation, and without an outgoing shock produced by neutrino energy deposition, there is no supernova. The star simply disappears.

A burst of neutrinos should still be emitted before the black hole forms

A SURVEY ABOUT NOTHING: MONITORING A MILLION SUPERGIANTS FOR FAILED SUPERNOVAE

Christopher S. Kochanek[1,3], John F. Beacom[1,2,3], Matthew D. Kistler[2,3], José L. Prieto[1,3], Krzysztof Z. Stanek[1,3], Todd A. Thompson[1,3], and Hasan Yüksel[2,3]





- ~10 meter class telescope can watch most of the massive stars (in 30 galaxies) within 10 Mpc
- look for disappearing Stars which may directly go to black hole
- plus all other potentially surprising discoveries

Core Collapse Timer

Detection of a neutrino burst allow the determination of the instant of a core collapse with a precision of ~ a few seconds

Much smaller time window allow to search for more speculative signals such as gravitational waves or high-energy neutrinos from choked jets

Advance warning that photons should soon be on the way, allowing searches to commence for the elusive UV/X-ray signal of supernova shock breakout and also the early supernova light curve

Testing the Neutrino Signal

For SN 1987A, the Kamiokande-II and IMB detectors collected only ~ 10 events each which strictly restricts the details of the collapsed core

By measuring neutrinos from many supernovae, the deduced energy spectra and time profiles could be compared to each other and to theory

Supernova Neutrino Frontier

- Milky Way Supernova: long wait but big payoff

- Diffuse Supernova Neutrino Background
  [neutrino emission per SN] x [star formation (supernova) rate]

  - DSNB predictions are fairly close to Super-K upper limit
  - Steady source and imminent detection in the near term
  - Astronomers will measure star formation rate better eventually
  - DSNB can test neutrino emission per supernova

- Nearby Galaxies:
  frequent supernova but requires Mton-scale detectors

  - New telescopes, optical and neutrino, may allow a complete characterization of stellar final states
  - Crucial tests of neutrino signal even if there is a Galactic SN
  - Exact timing for more speculative signals (TeV neutrinos, GW)

Concluding Remarks

- SN 1987A showed the possibility of neutrino astronomy
- Until more supernovae are detected by neutrinos, many fundamental questions will never be decisively answered:
  - Probe core-collapse mechanism
  - Total rate of core collapses in the local universe
  - Early warning of SN in the neighborhood
  - Tests of neutrino signal
- Unique capabilities and science prospects of a Multi Megaton detector will remain important even after the discovery of the DSNB or a galactic SN