Supernova Neutrino Detection with Future Large-Volume Detectors

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Plan of the Talk

Supernova astrophysics

Supernova neutrinos

SN 1987A

Neutrino detection

Diffuse supernova neutrino background

Conclusions

Understanding supernovae is essential for progress in astrophysics

Products of Stars and Supernovae

light

TeV-PeV-EeV neutrinos and gamma rays

winds

cosmic rays

gas, dust

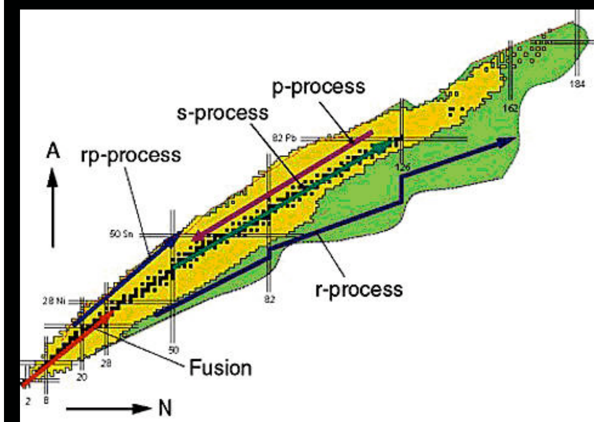
neutron stars, black holes (gravity waves?)

MeV neutrinos and gamma rays

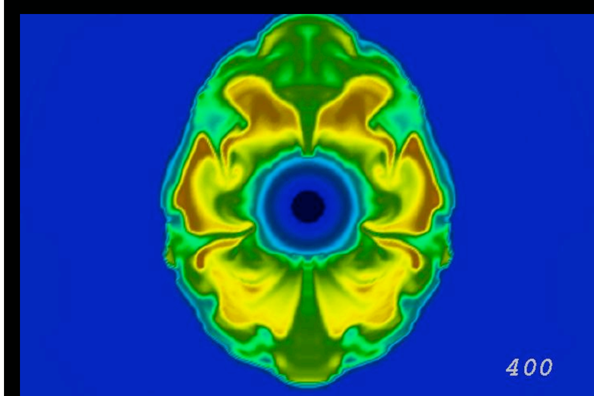
nucleosynthesis yields

Four Paths to Understanding Supernovae

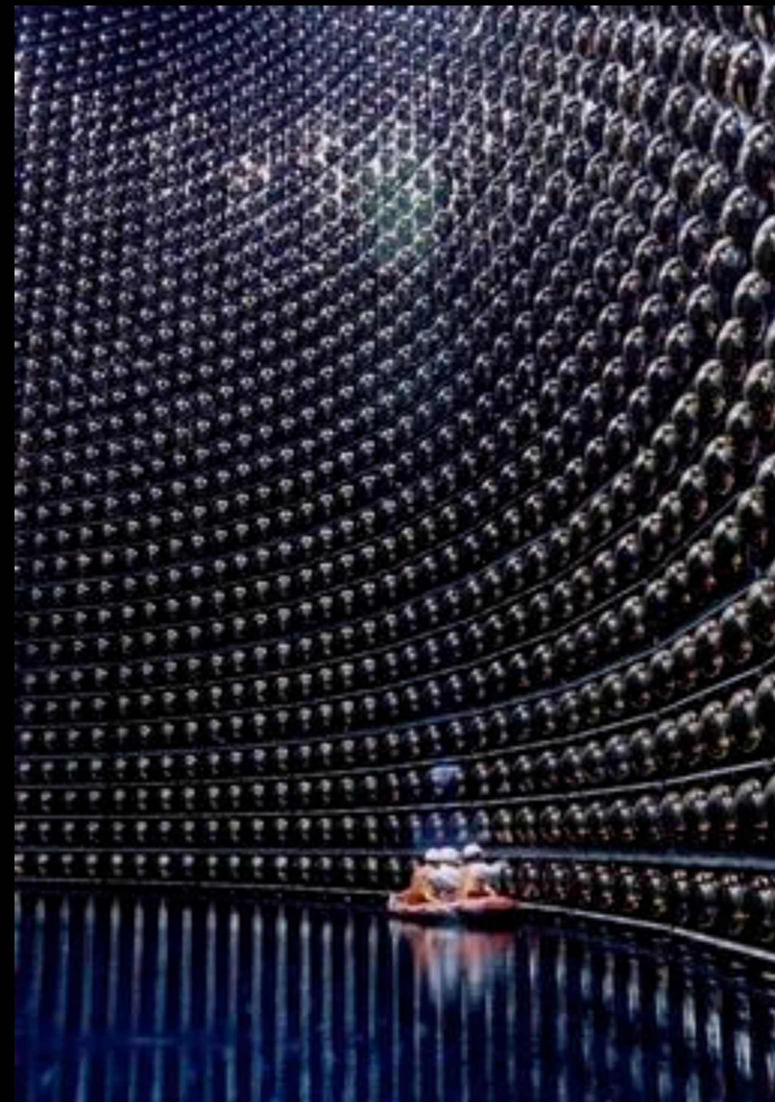
Astronomy



Nuclear Physics



Simulations



Direct Messengers

Mechanisms of Supernovae?

Thermonuclear supernova: type Ia (3 < M < 8)
runaway burning initiated by binary companion
MeV gamma rays from ^{56}Ni, ^{56}Co decays

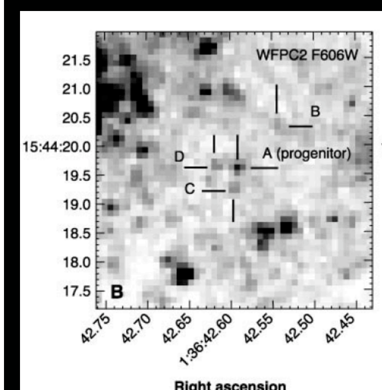
Core-collapse supernova: types II, Ib, Ic (M > 8)
collapse of iron core in a massive star
MeV neutrinos from proto-neutron star

Gamma-ray burst: long-duration type (M > 30?, spin)
collapse of iron core in a very massive star
significant angular momentum, jet formation
keV-MeV gamma rays from fireball

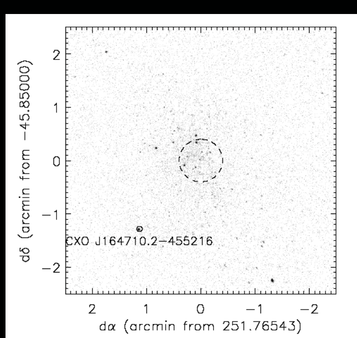
Which Progenitors Lead to Successful SNII?

From ~ 8 M_{sun} to ?

SN 1987A progenitor was ~ 20 M_{sun}
It clearly exploded and emitted neutrinos



SN 2005cs: initial mass 9 +3/-2 M_{sun}
initial mass 10 +3/-3 M_{sun}
SN 2003gd: initial mass 8 +4/-2 M_{sun}
initial mass ~ 8-9 M_{sun}
from the Smartt and Filippenko groups

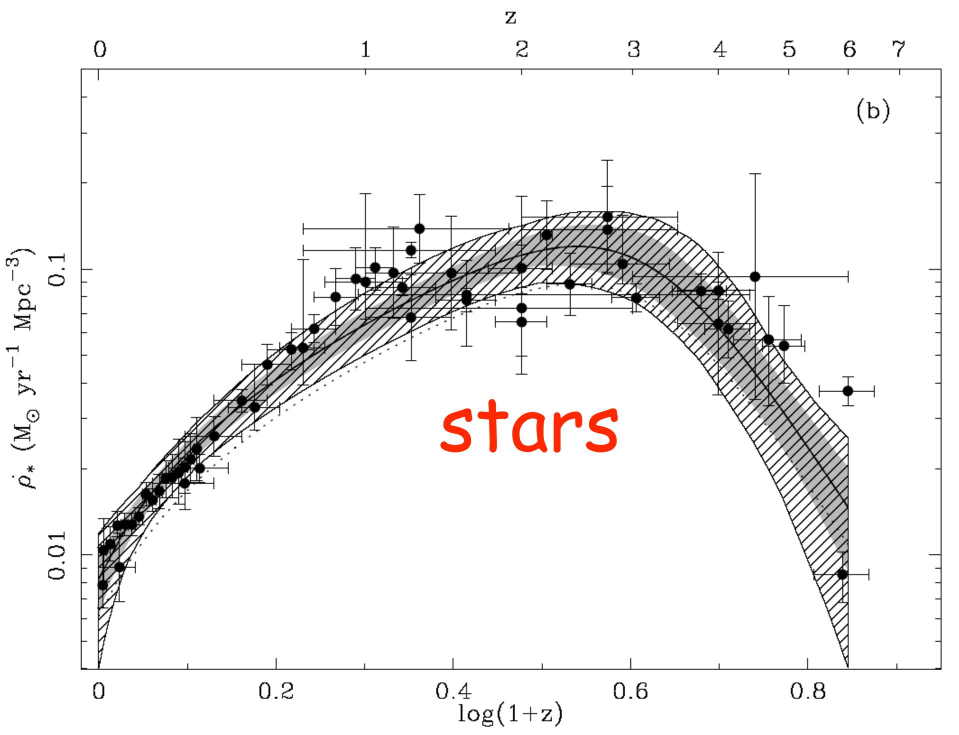


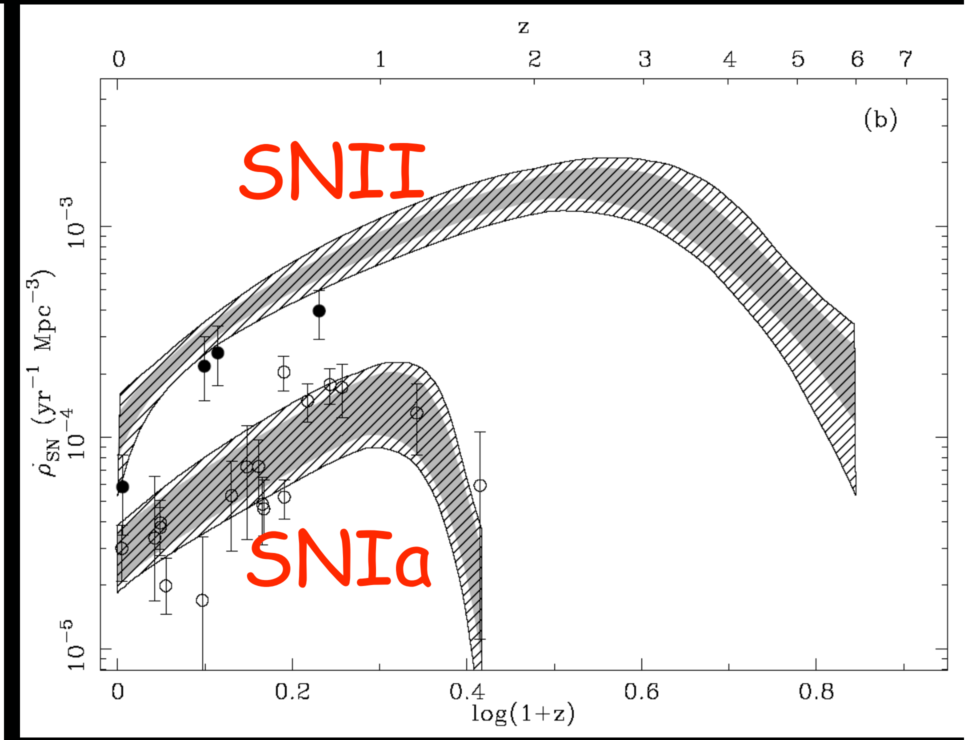
Muno et al. (2006) argue for a neutron star made by a ~ 40 M_{sun} progenitor

What is the Stellar Birth/Death History?

Birth

Death





Hopkins, Beacom, ApJ 651, 142 (2006)

Detecting neutrinos is essential for understanding supernovae (and more)

The Impossible Dream of Neutrino Astronomy

"If [there are no new forces] -- one can conclude that there is no practically possible way of observing the neutrino."

Bethe and Peierls, Nature (1934)

"Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star..."

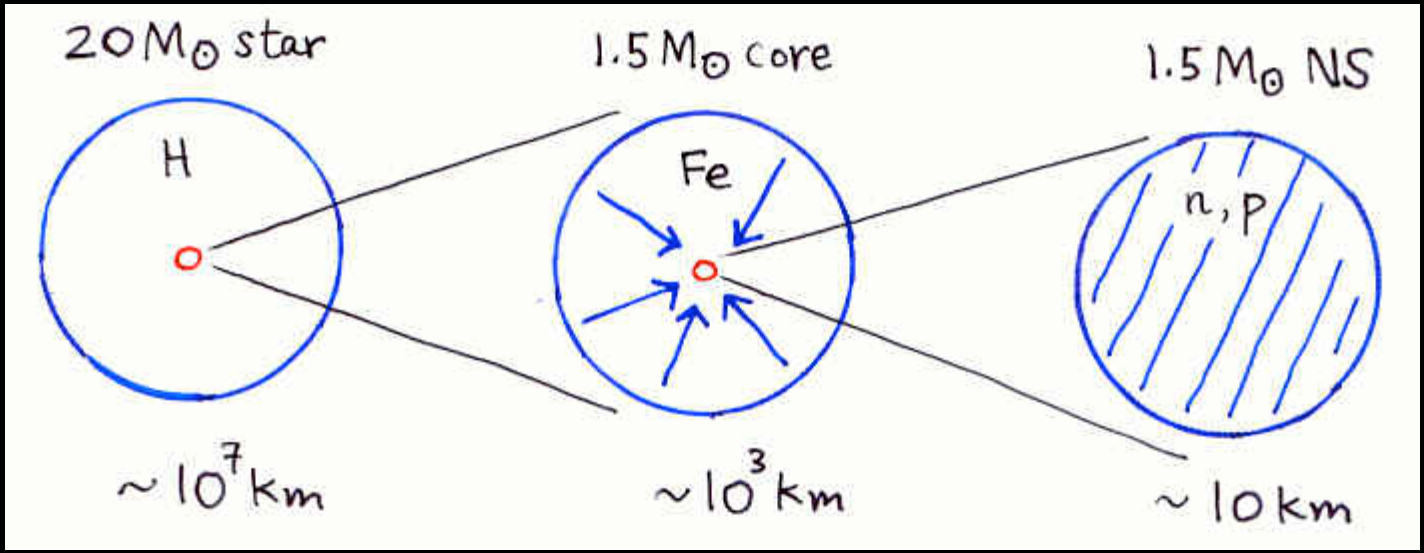
Bahcall, PRL (1964)

"The title 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."

Bahcall, <u>Neutrino Astrophysics</u> (1989)

Nobel Prizes: Reines (1995), Koshiba and Davis (2002)

Supernova Energetics



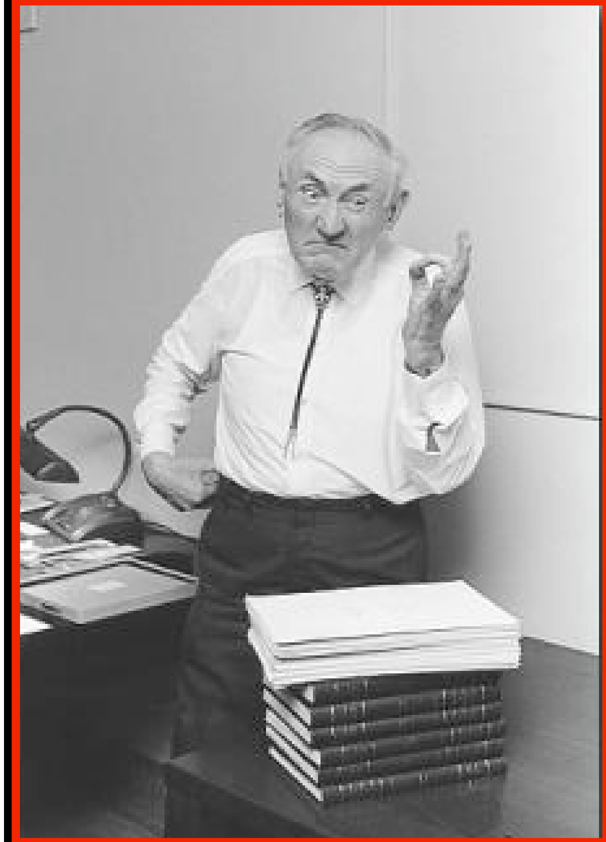
$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3 \times 10^{53} \text{ ergs} \simeq 2 \times 10^{59} \text{ MeV}$$

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

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

What Do We Want from Core-Collapse SNe?

A solid empirical description of the neutrino burst



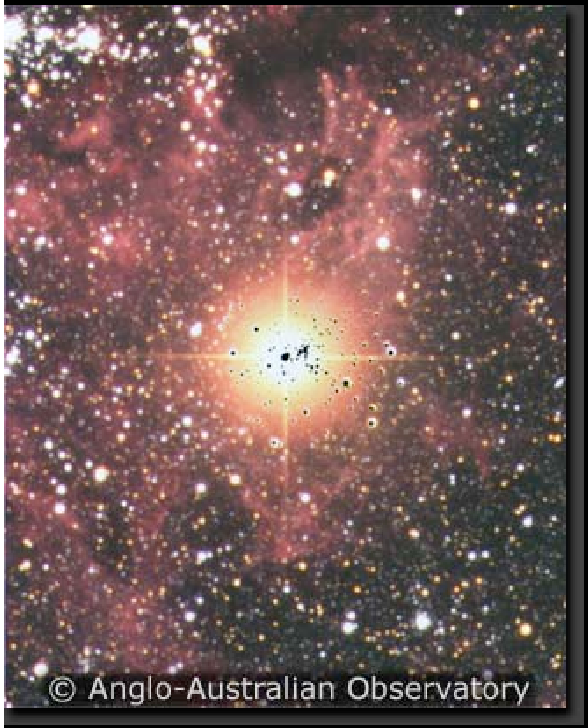
Primary science focus is the NS formation: binding energy, opacity to neutrinos, and timescales

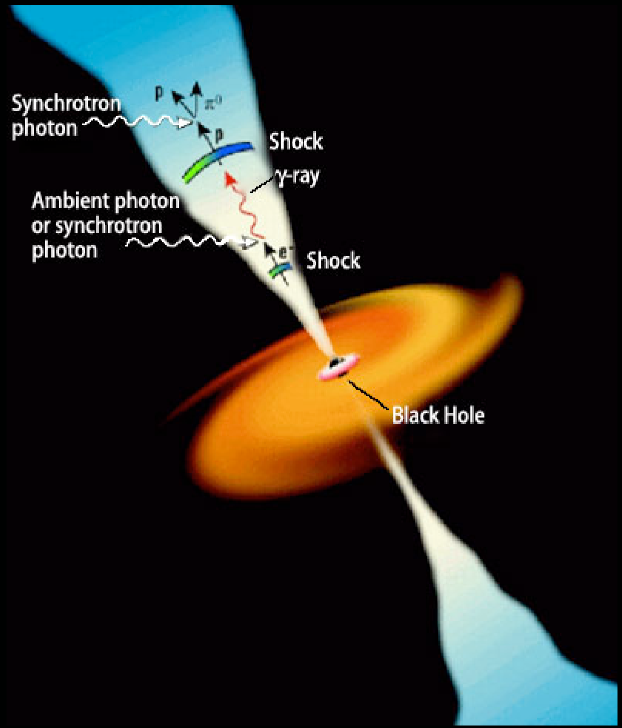
SN 1987A data was essential, but what do other supernovae do?

This is the key to testing standard and new physics in detail

Another phone call from Stockholm

Neutrino Astrophysics: The Race for Signals





MeV range	TeV range	EeV range
supernovae	AGN, SNR	GZK process
Super-K, etc	IceCube, etc	ANITA, etc

Every Supernova Neutrino is Sacred

• MeV neutrinos

Core-collapse supernovae

How are neutron stars and black holes formed?

• TeV neutrinos

Supernova remnants and GRBs

Hadronic or leptonic origin for TeV gamma rays?

• EeV neutrinos

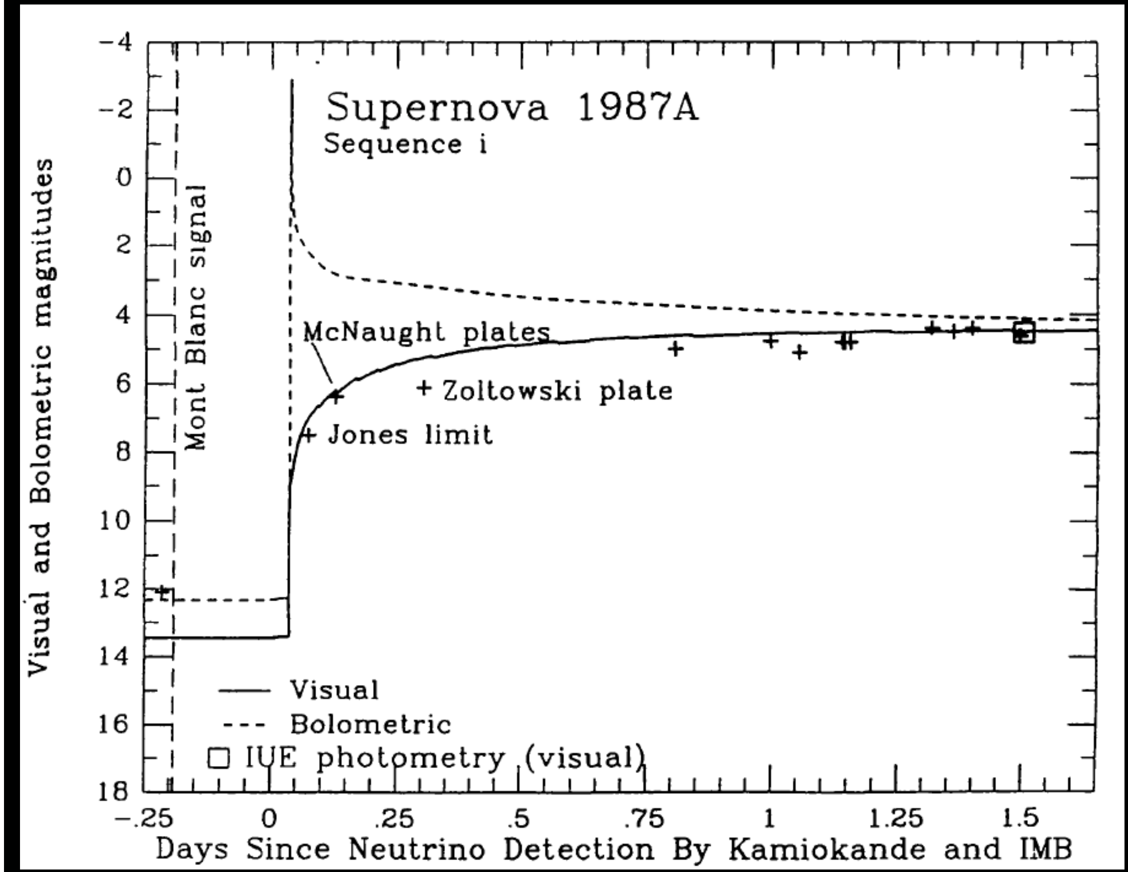
UHE cosmic rays (from GRBs?)

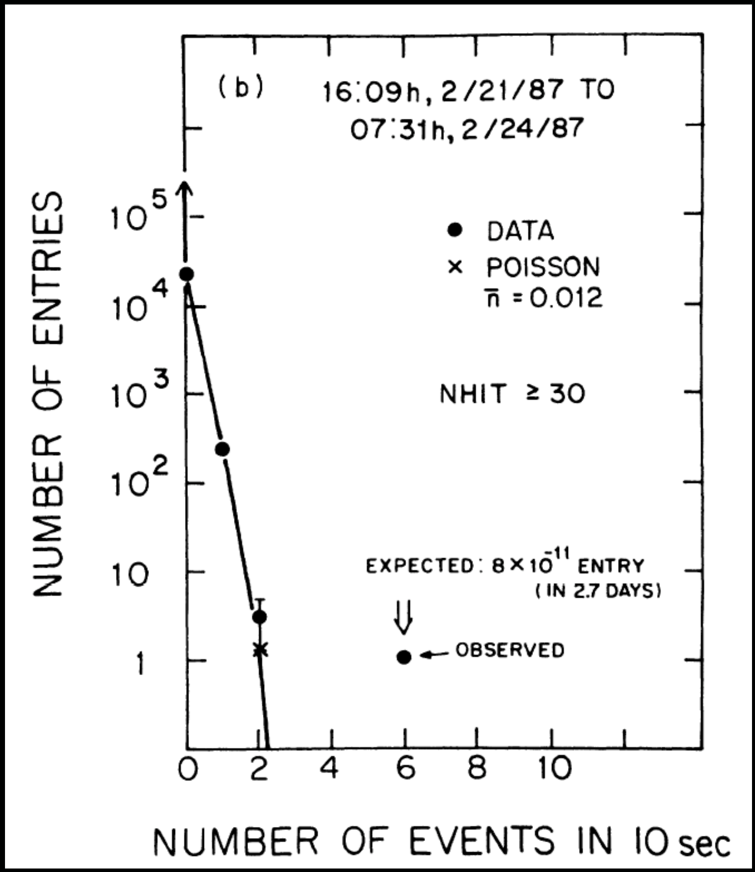
How are UHE cosmic rays accelerated?

What did we learn from SN 1987A?

Do Type-II Supernovae Emit Neutrinos?

Yes!





The neutrino burst arrived before the light

SN 1987A was briefly more detectable than the Sun!

How Are Supernova Neutrinos Detected?

from SN

hydrogen nucleus

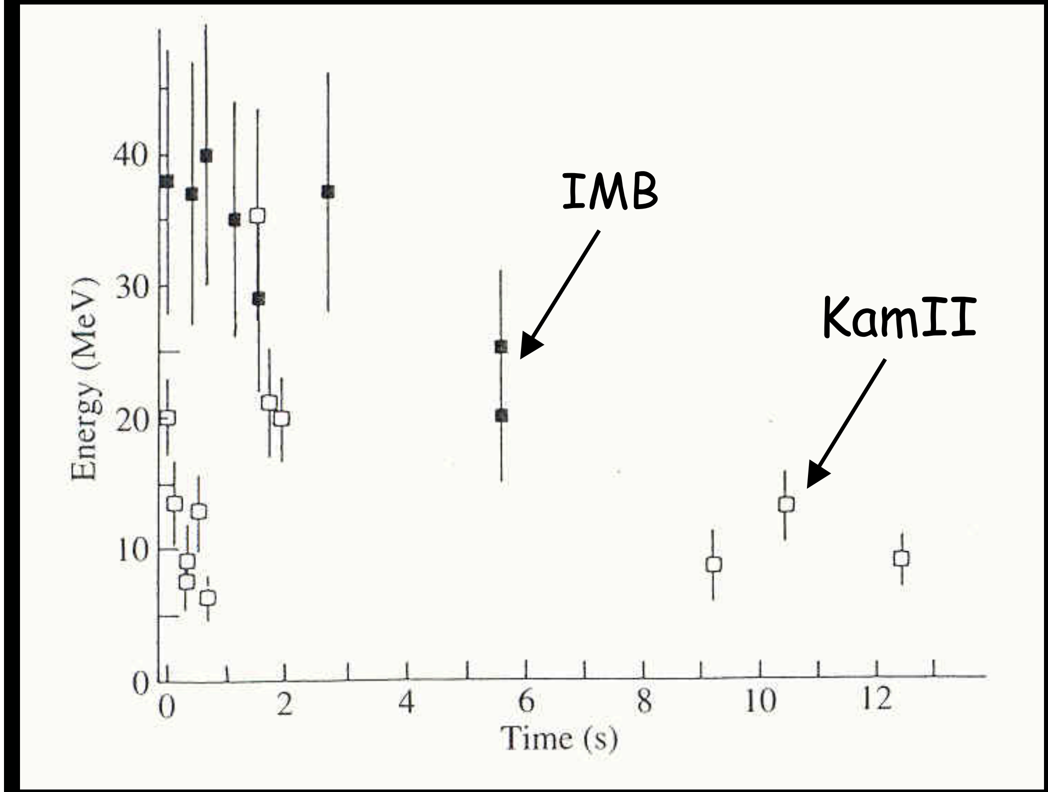
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

produces Cerenkov light

usually ignored (nota bene)

Neutrino Emission Due to NS/BH Formation?

Yes



Neutrinos before light

Huge energy release
$E_B \sim GM^2/R \sim 10^{53}$ erg

Low average energy
$E_\nu \sim 10$ MeV

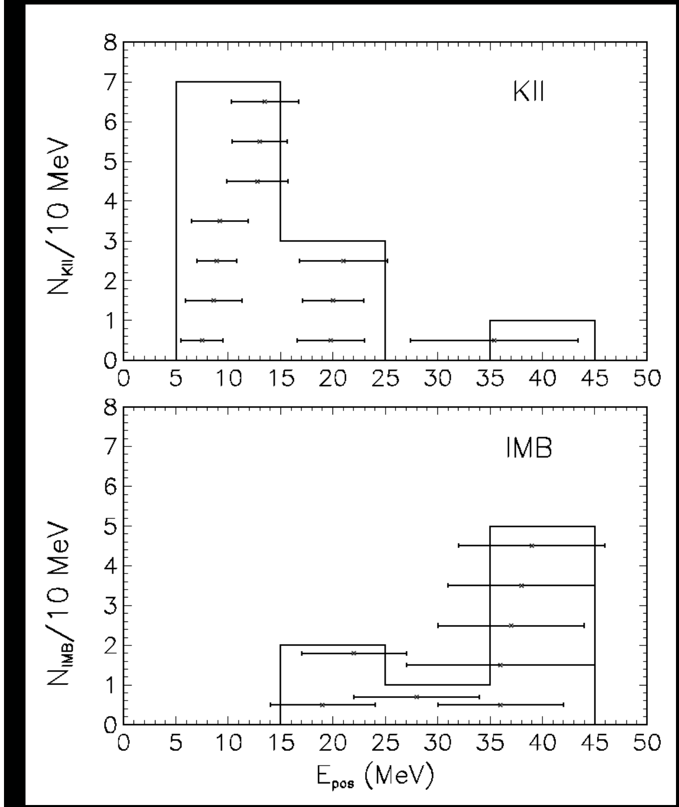
Very long timescale
$t \sim 10^4$ R/c

But still no direct observation of NS (or BH)

Do Data Agree with Each Other and Theory?

Yes? / No? / Maybe?

~ 20 events from $\bar{\nu}_e + p \longrightarrow e^+ + n$ in KamII, IMB



Mirizzi and Raffelt,
PRD 72, 063001 (2005)

Simplest fits consistent with

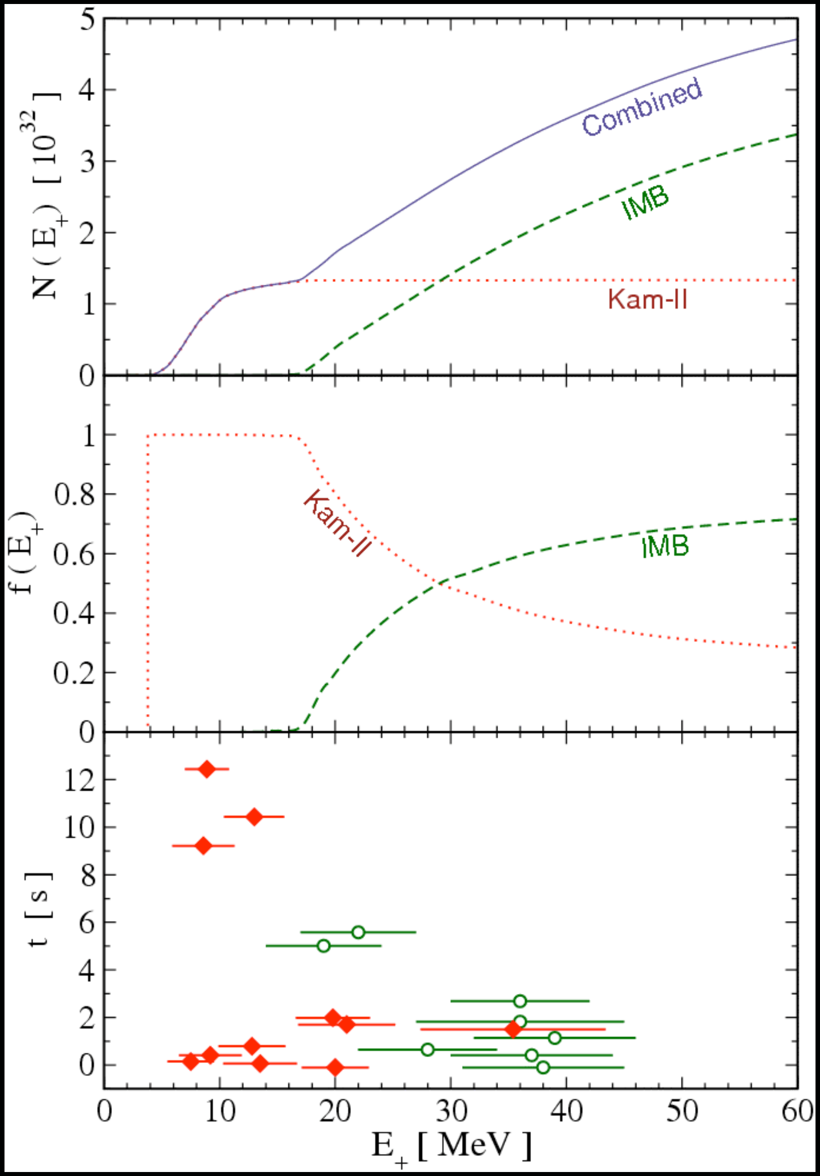
$E_{tot} \sim 5 \times 10^{52}$ erg

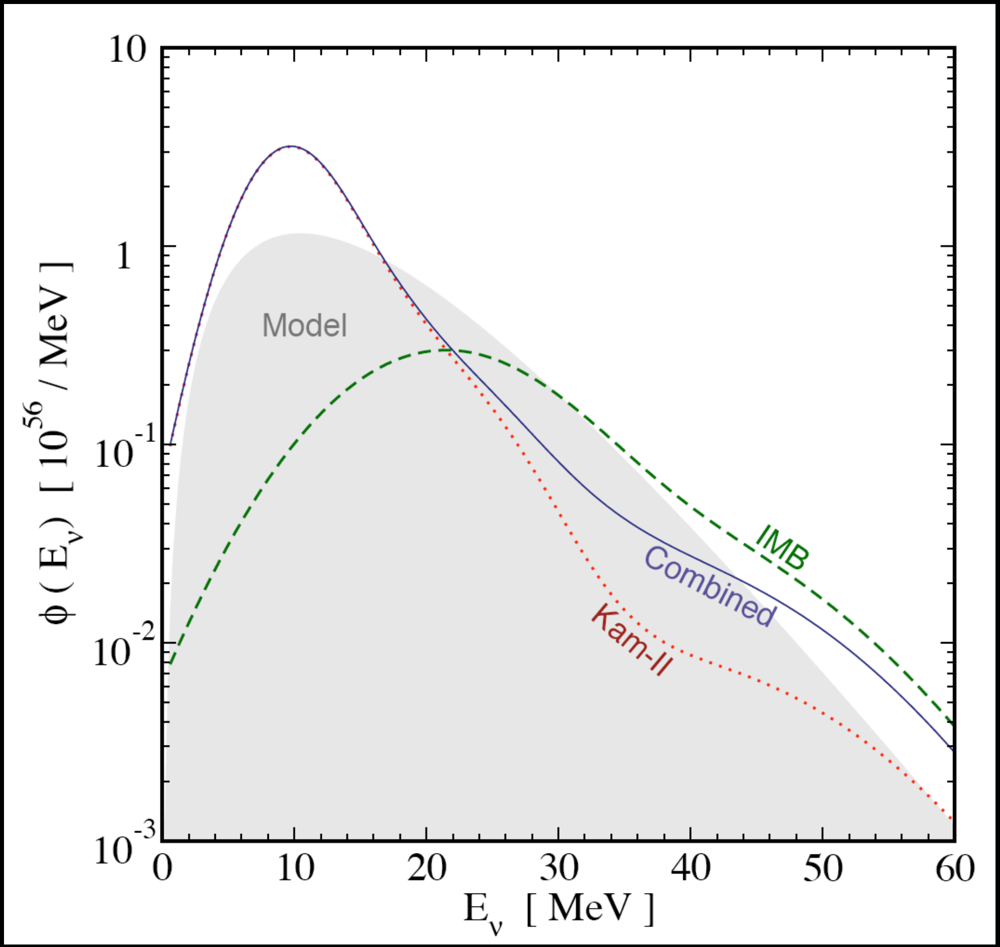
$T \sim$ few MeV

for the nuebar flavor

If the five unseen flavors were similar, then it fits expectations for NS formation in core collapse

A Fresh Look at the SN 1987A Data



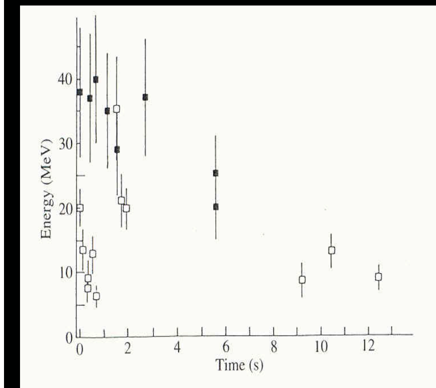


Data are consistent
Spectrum not thermal

Yuksel and Beacom, astro-ph/0702613

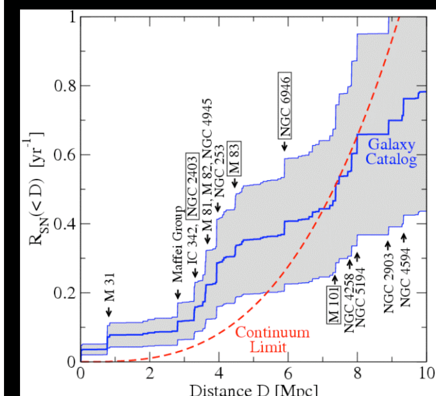
How to detect supernova neutrinos?

Supernova Neutrino Detection Frontiers



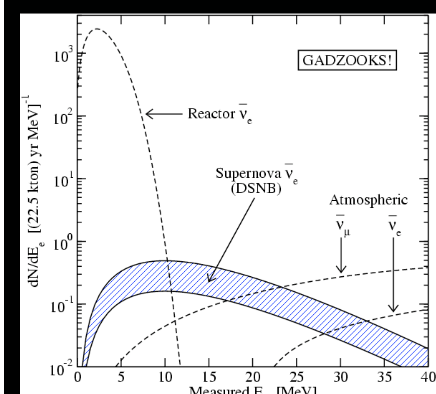
Milky Way

zero or at most one supernova
excellent sensitivity to details
one burst per ~ 30 years



Nearby Galaxies

one identified supernova at a time
direction known from astronomers
one "burst" per ~ 1 year



Diffuse Supernova Neutrino Background

average supernova neutrino emission
no timing or direction
(faint) signal is always there!

SNe in the Milky Way

talks on various detectors | Minakata's talk

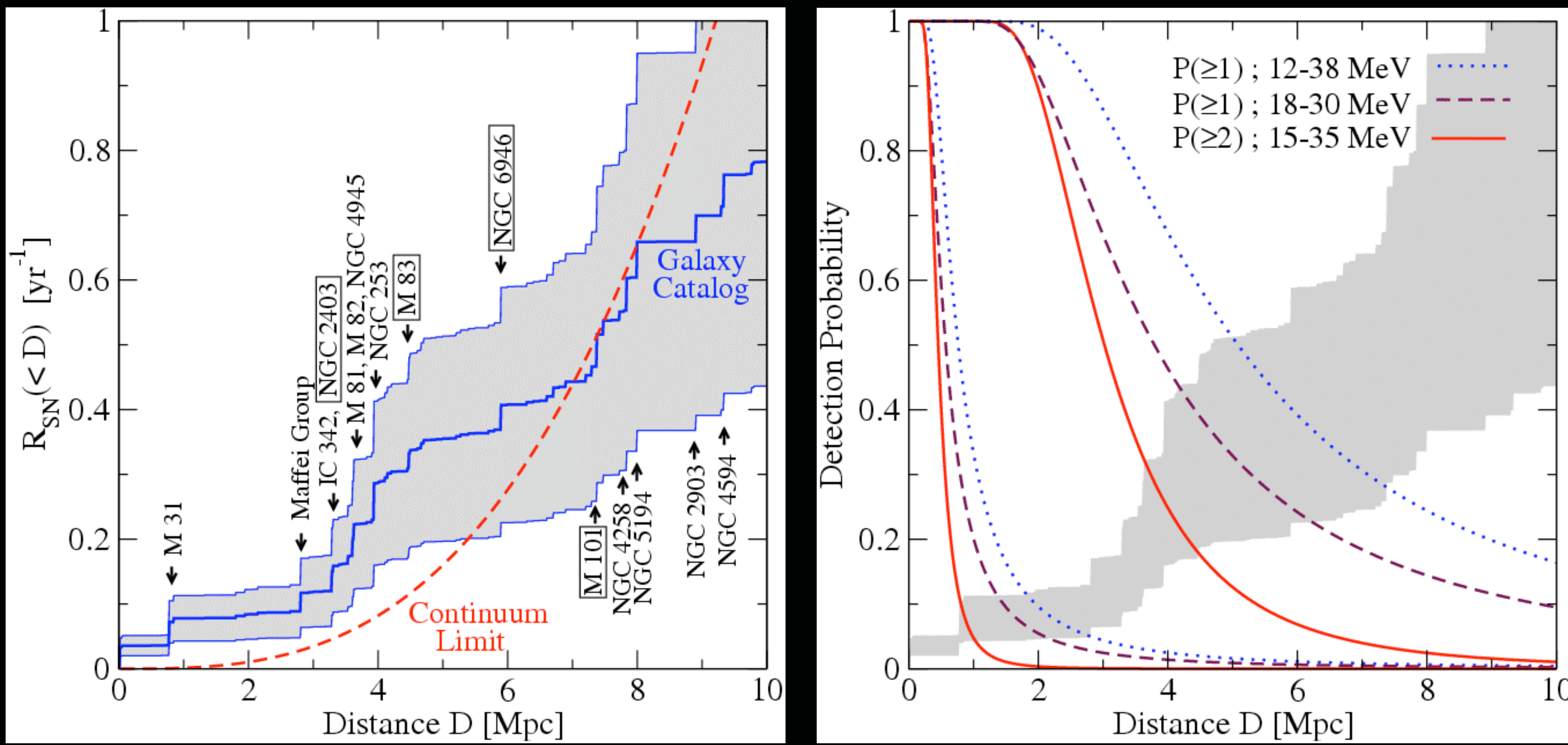
$\bar{\nu}_e$ Flagship is SK: largest with spectral data
Can measure flux, spectrum, and angular distribution vs. time; statistics at 1% scale

ν_e Crucial flavor, very poorly covered
SK may do with neutron tagging
Future large Argon detectors?

ν_μ, ν_τ Also crucial, hard to measure
SK may do with neutron tagging
KamLAND spectral technique could be key

SNe in Nearby Galaxies (Going Big)

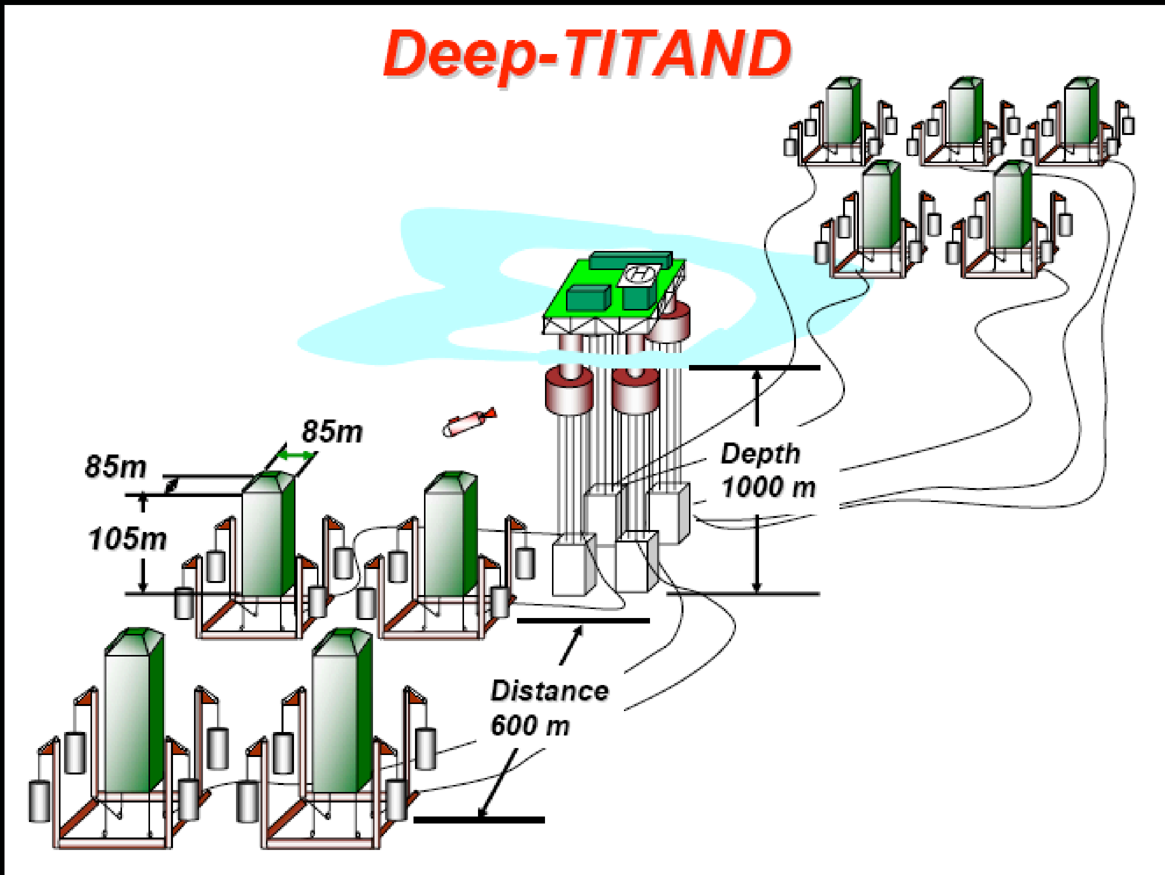
talks on various detectors



Ando, Beacom, Yuksel, PRL 95, 171101 (2005)

~ 1 Mton can collect ~ 1 nu/year in coincidence mode

SNe in Nearby Galaxies (Going Huge)



Suzuki's talk

~ 5 Mton is a magic size: yield like SN 1987A, every year, in burst mode!

Could test the average spectrum and time profile --
and could compare different supernovae!
Also use the time of collapse to test for gravity waves.
(Ando, Beacom, Yuksel, in preparation)

Diffuse supernova neutrino background

We could detect this soon!

What are the Ingredients of the DSNB?

detector capabilities

supernova rate history

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

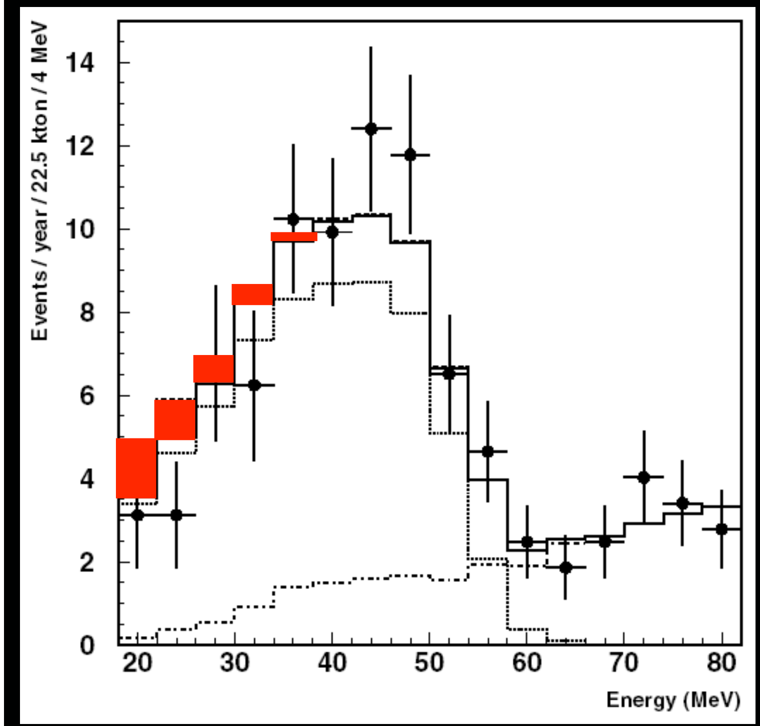
positron spectrum

neutrino spectrum per supernova

Might the DSNB be Detectable?

Yes!

~20 years ago: early theoretical predictions, and a weak limit from Kamiokande, Zhang et al. (1988)



Malek et al. (SK), PRL 90, 061101 (2003)

Kaplinghat, Steigman, Walker (2000)
flux < $2.2/cm^2/s$ above 19.3 MeV

SK limit is flux < $1.2/cm^2/s$

This might be possible!

Two serious problems:
Backgrounds daunting
Predictions uncertain

Now solved or solvable

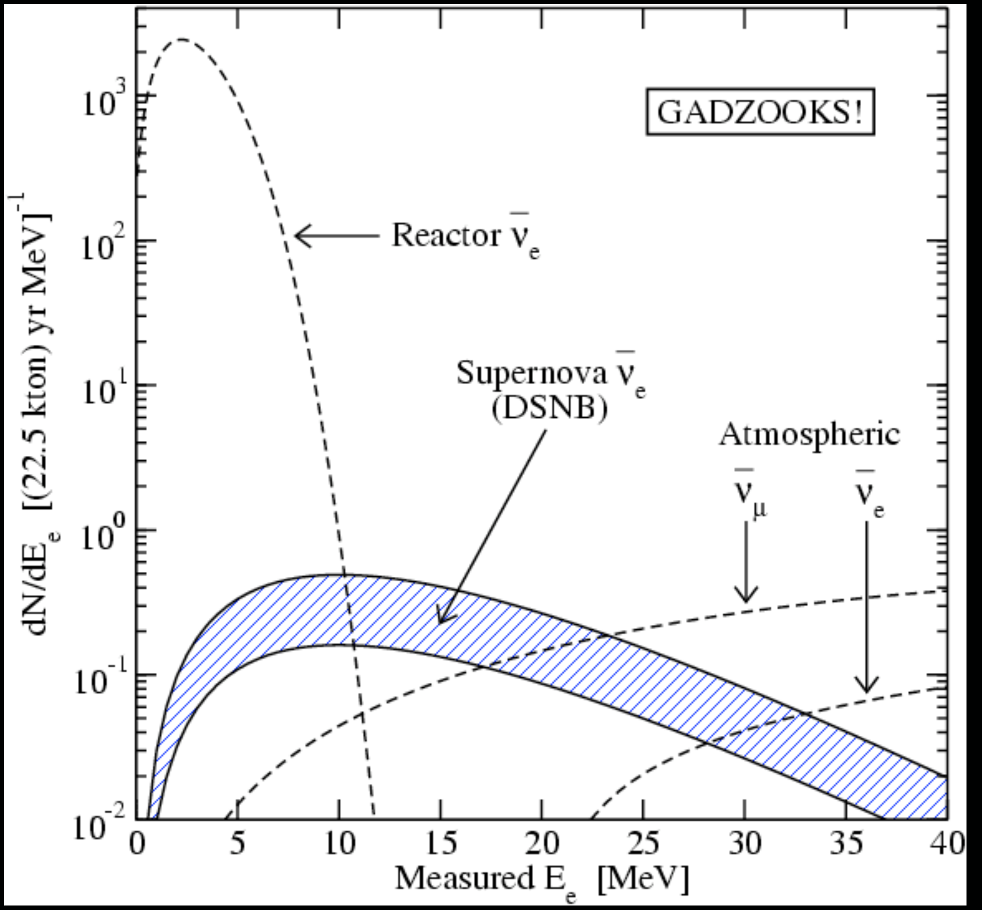
Can We Beat the Backgrounds?

Yes

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

Beacom, Vagins, PRL 93, 171101 (2004)

GADZOOKS!



At 0.2% $GdCl_3$:

Capture fraction = 90%

λ = 4 cm, τ = 20 μs

active R&D program in US and Japan

Neutron tagging means lower backgrounds, thresholds

But Will it Work?

Vagins' talk

- Beacom and Vagins demonstrated plausibility of many aspects based on available data and estimates

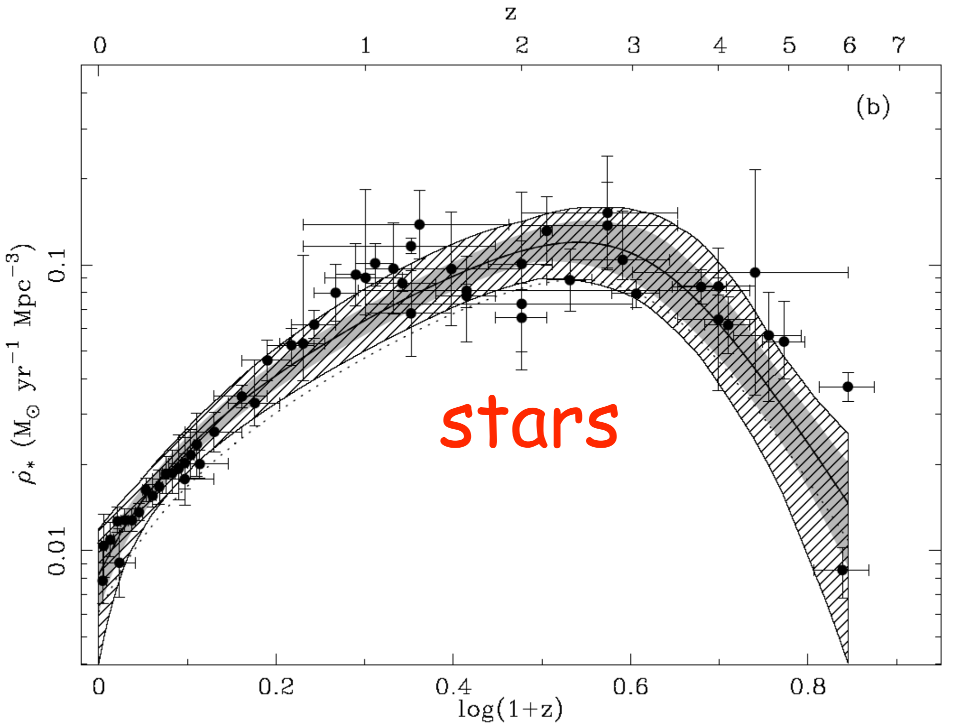
- Vagins is leading an intense R&D effort, funded by the DOE and Super-Kamiokande, to test all aspects ...and so far, so good

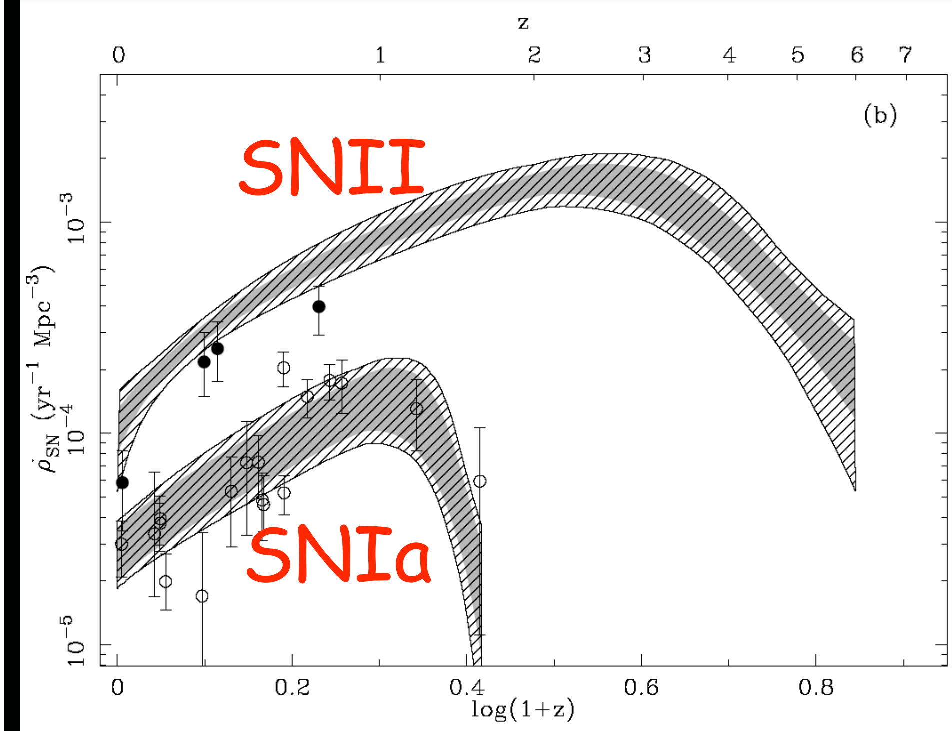
- Very high level of interest, based on the physics potential, for the DSNB, reactors, and more

- Super-Kamiokande gadolinium committee is now conducting a technical design review

Do We Know the Stellar Birth/Death History?

Yes



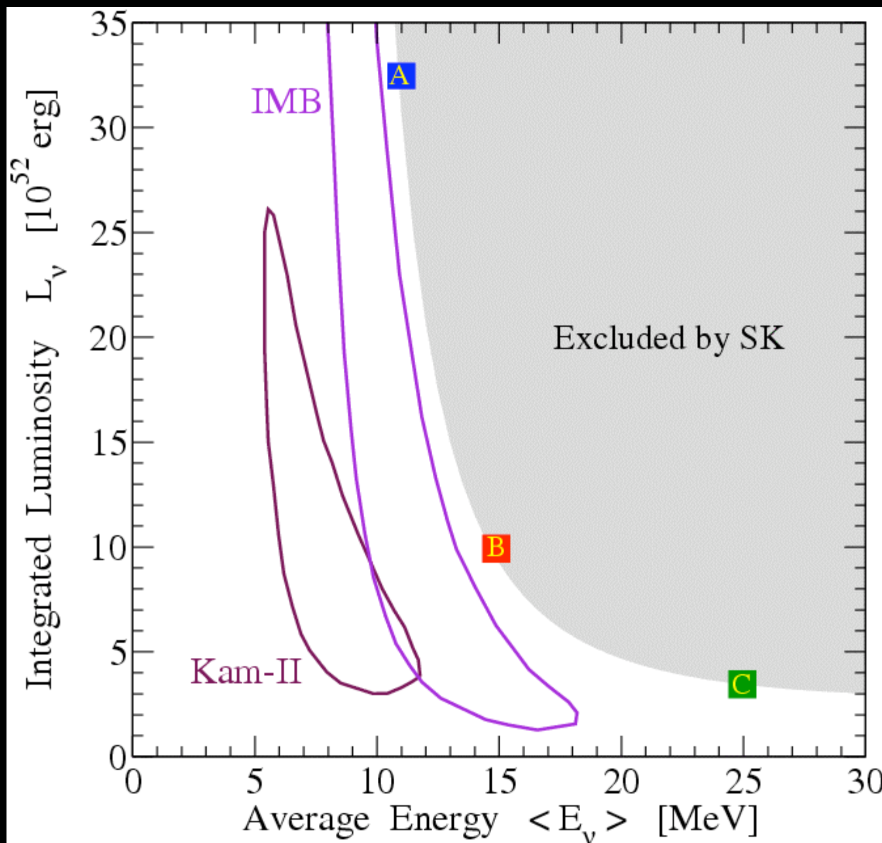


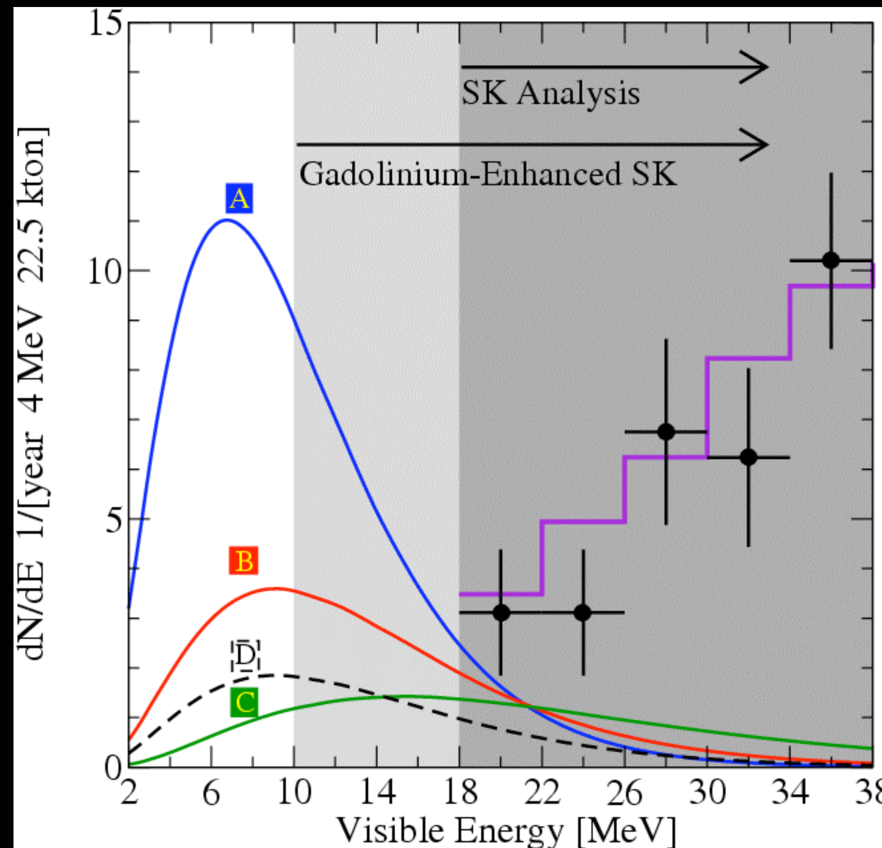
Hopkins, Beacom, ApJ 651, 142 (2006)

No longer a dominant uncertainty for the DSNB

What is the Neutrino Emission per Supernova?

We can find out

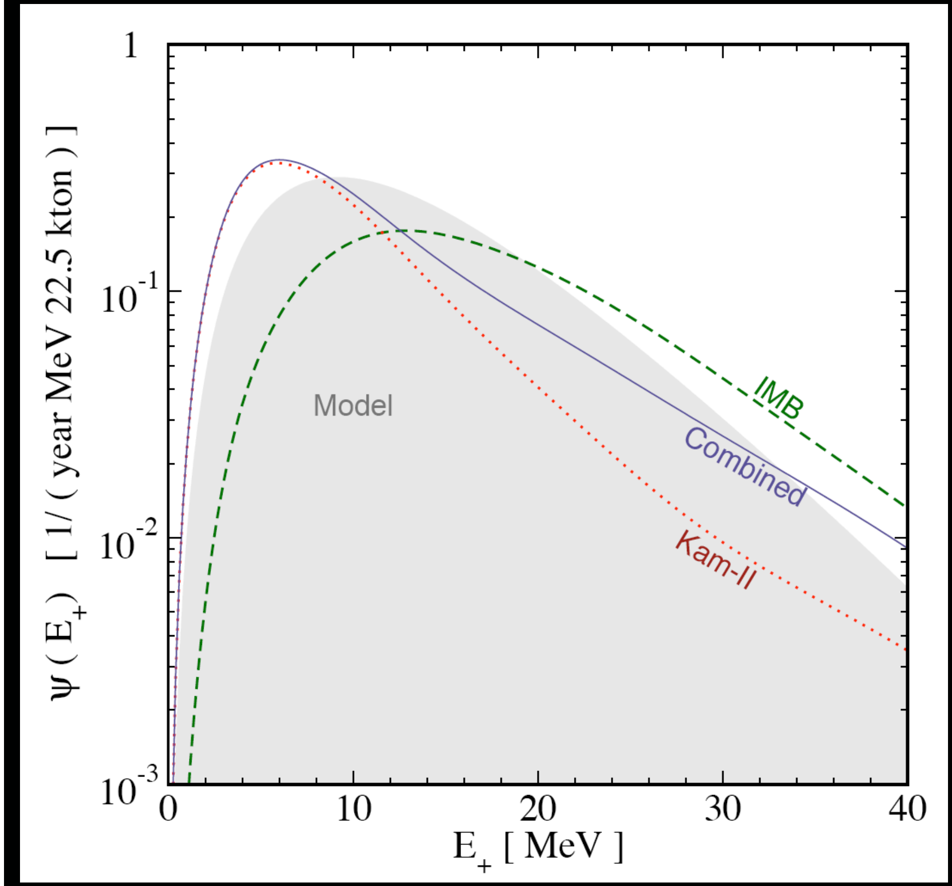


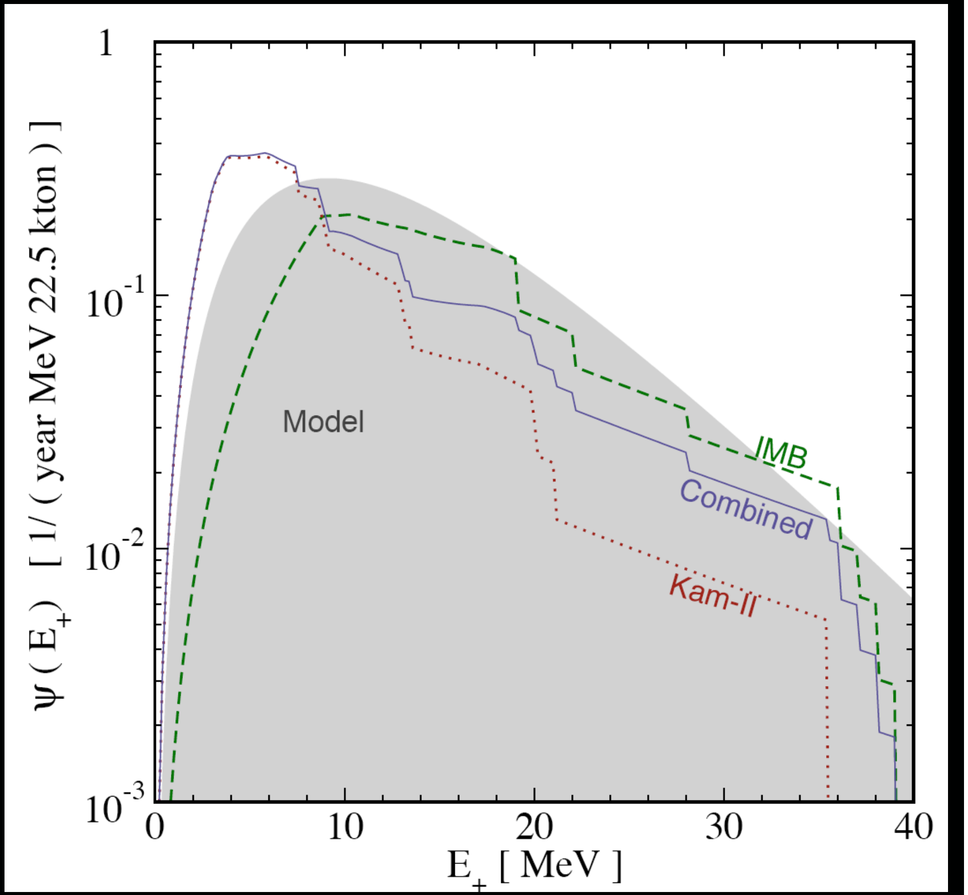


Yuksel, Ando, Beacom, PRC 74, 015803 (2006)

Mton prospects explored by Lunardini, astro-ph/0612701

DSNB Spectra Based on SN 1987A Data





Yuksel and Beacom, astro-ph/0702613

DSNB robust, primarily depends on IMB data

Concluding perspectives

Recommendations for the Future

Short-Term

- Plan to run Super-Kamiokande as long as possible
- Enhance the capabilities of all other detectors
- Implement neutron detection in Super-Kamiokande

Long-Term

- Develop detectors for the other neutrino flavors
- Go big to the ~ 1 Mton scale with SN capabilities
- Start dreaming about the ~ 5 Mton scale!

Conclusions

Understanding supernovae is crucial for astrophysics:
How do supernovae work and what do they do?
What is the history of stellar birth and death?

Detecting neutrinos is crucial for supernovae:
What is the neutrino emission per supernova?
How are neutron stars and black holes formed?

Neutrino astronomy has a very bright future:
Already big successes with the Sun and SN 1987A!
DSNB could be the first extragalactic detection!

Detection of the DSNB is very important:
Crucial data for understanding supernova explosions!
New tests of neutrino properties!