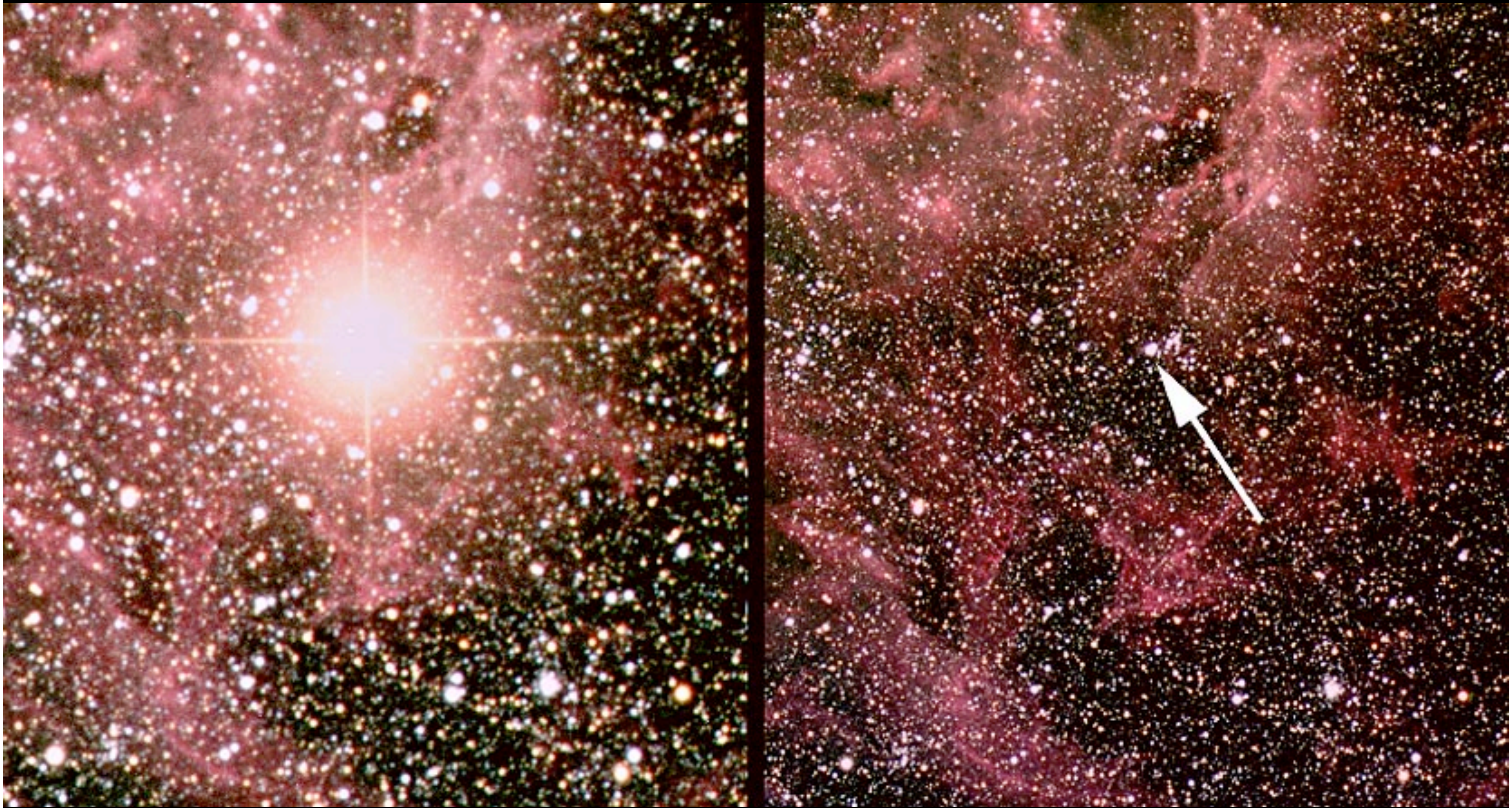
# Direct Measurements of Supernova Neutrino Emission Parameters



John Beacom, The Ohio State University

# Plan of the Talk

Taste of neutrinos from SN 1987A

So what about supernovae?

Supernovae in the Milky Way

Supernovae in nearby galaxies

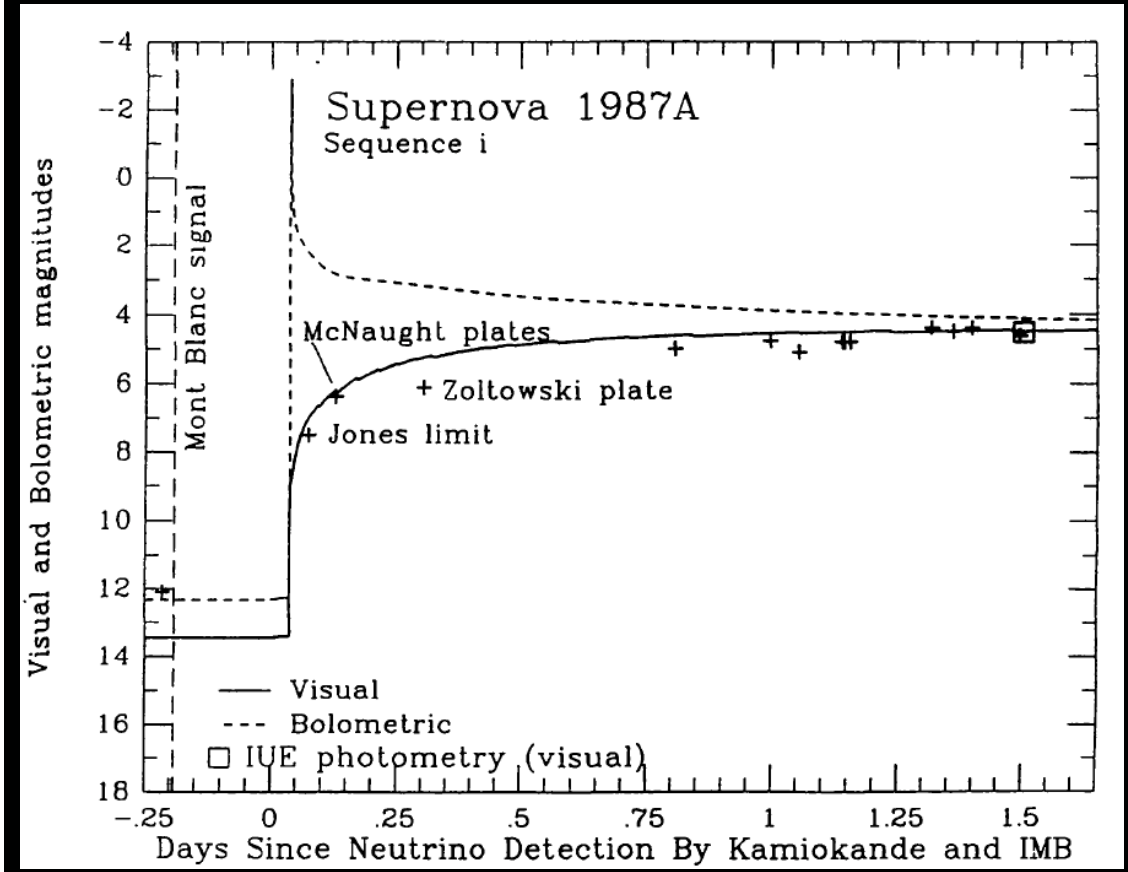
Diffuse supernova neutrino background

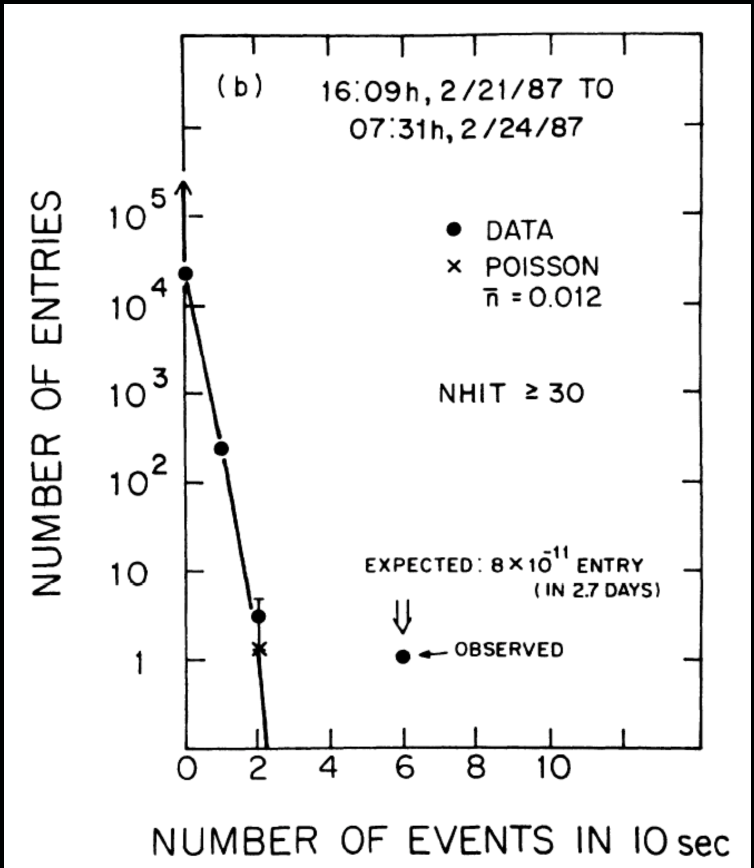
Concluding perspectives

# Taste of Neutrinos from SN 1987A

# Do Type-II Supernovae Emit Neutrinos?

**Yes!**



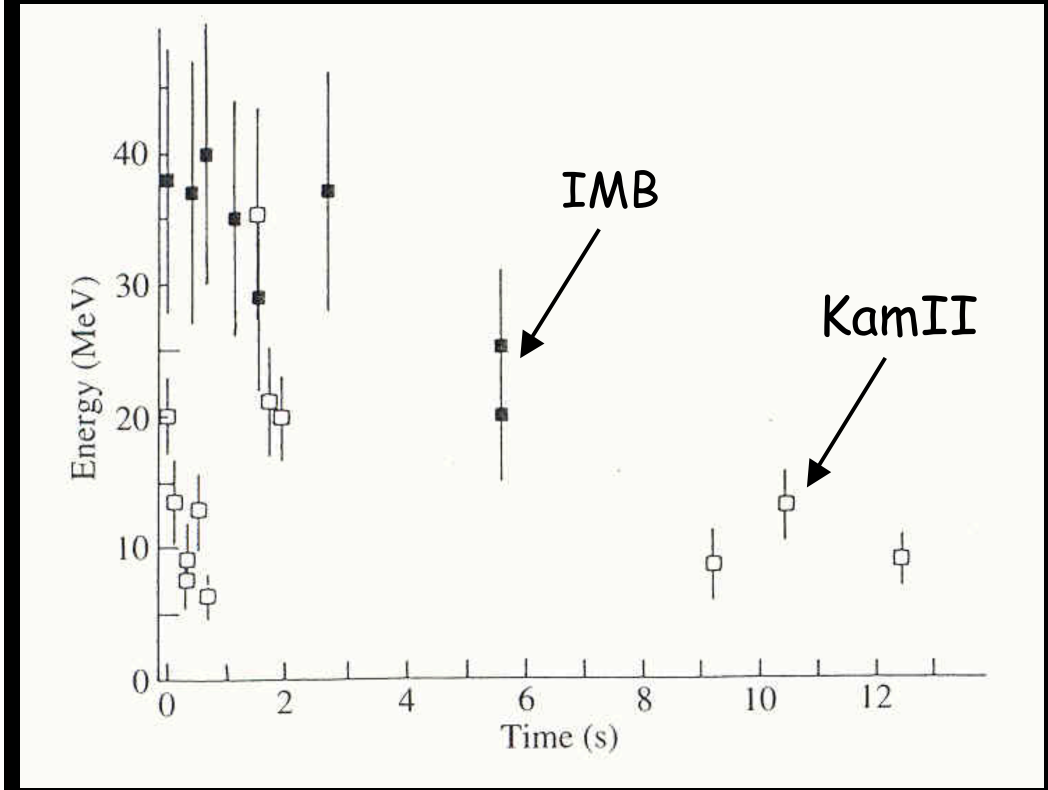




The neutrino burst arrived before the light

SN 1987A was briefly more detectable than the Sun!

# 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

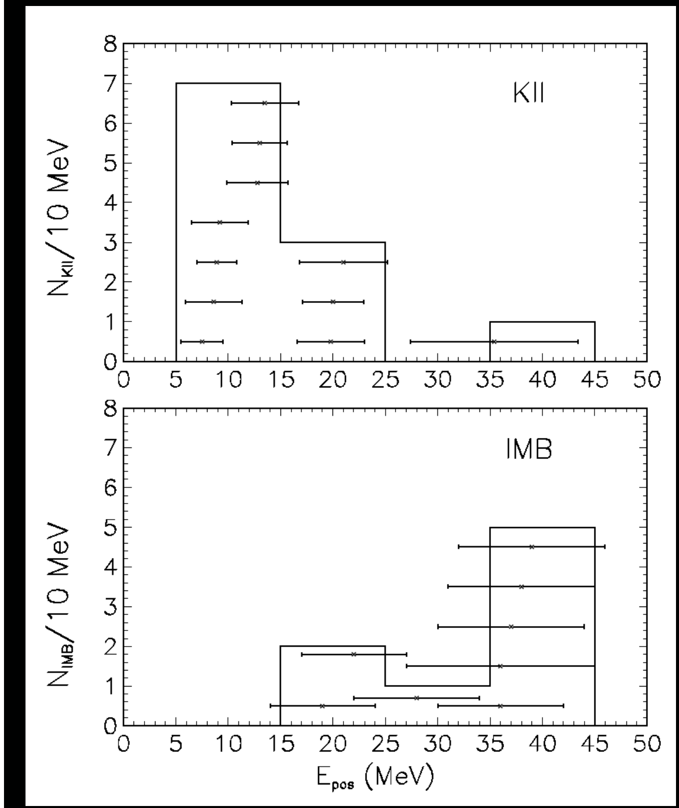
Very long timescale
$t \sim 10^4$ R/c

But still no direct observation of NS (or BH)

# Do Data Agree with Each Other and Theory?

Yes

~ 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

# Do Data Agree with Each Other and Theory?

No?

- Kam-II, IMB, and theory spectra disagree?
- Same for the angular distributions?
- Was the first Kam-II event really pointing?
- What about Baksan and Mont Blanc?

Small statistics, and detectors pushed to limits

But we theorists have no other data to fight about!

# So What About Supernovae?

# Products of Stars and Supernovae

light

TeV-PeV-EeV neutrinos and gamma rays

winds


cosmic rays

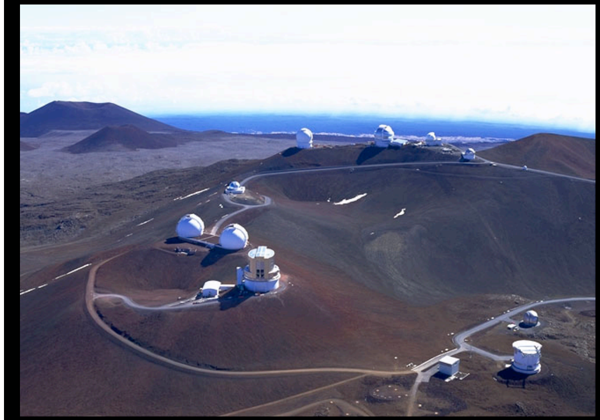
gas, dust

neutron stars, black holes

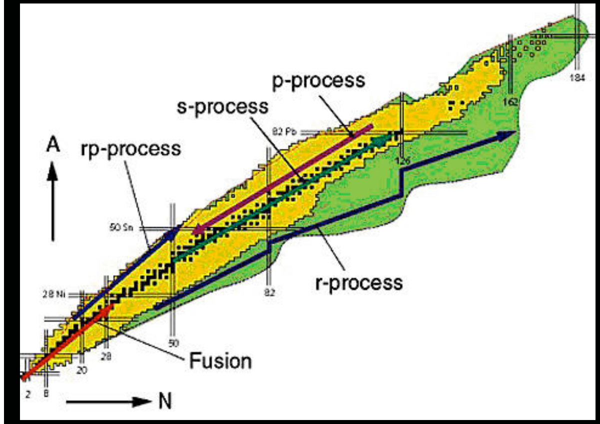
MeV neutrinos and gamma rays

nucleosynthesis yields

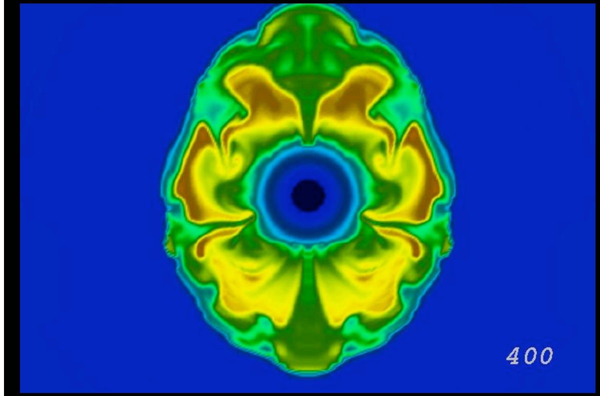
# Four Paths to Understanding Supernovae



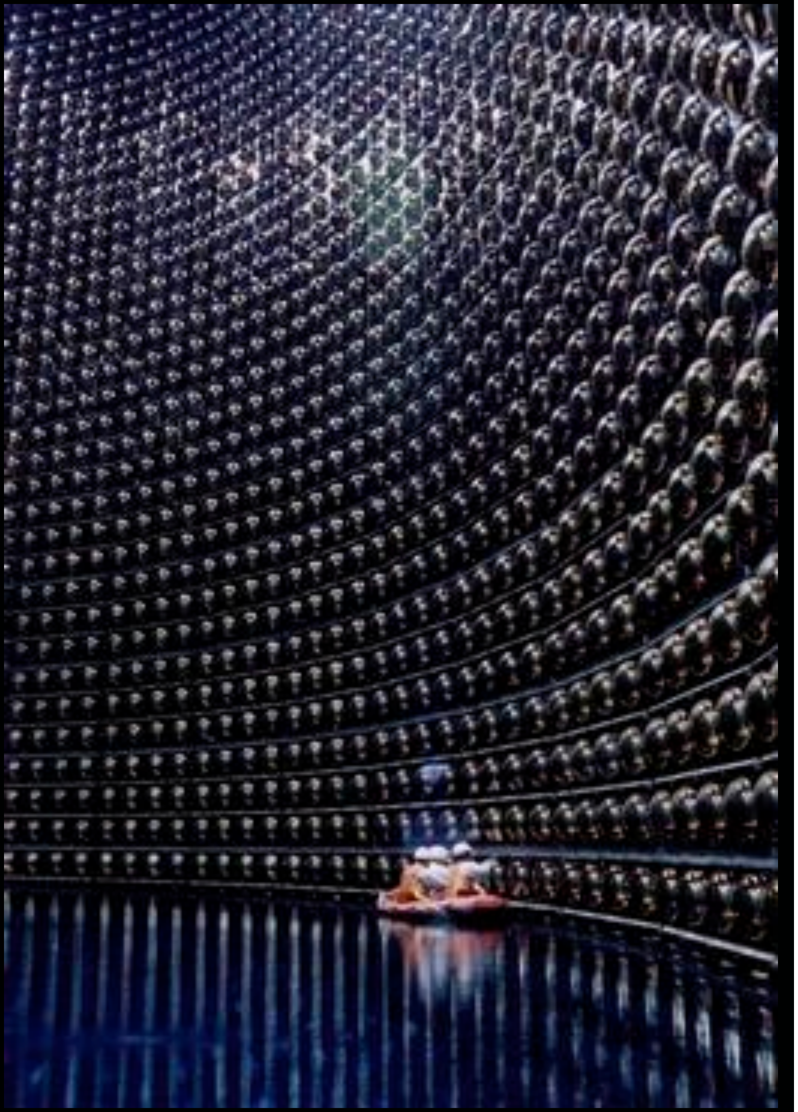
Astronomy




Nuclear Physics




Simulations



Direct Messengers

# Mechanisms of Supernovae

Thermonuclear supernova: type Ia

runaway burning initiated by binary companion

MeV gamma rays from $^{56}$Ni, $^{56}$Co decays

Core-collapse supernova: types II, Ib, Ic

collapse of iron core in a massive star

MeV neutrinos from proto-neutron star

Gamma-ray burst: long-duration type

collapse of iron core in a very massive star

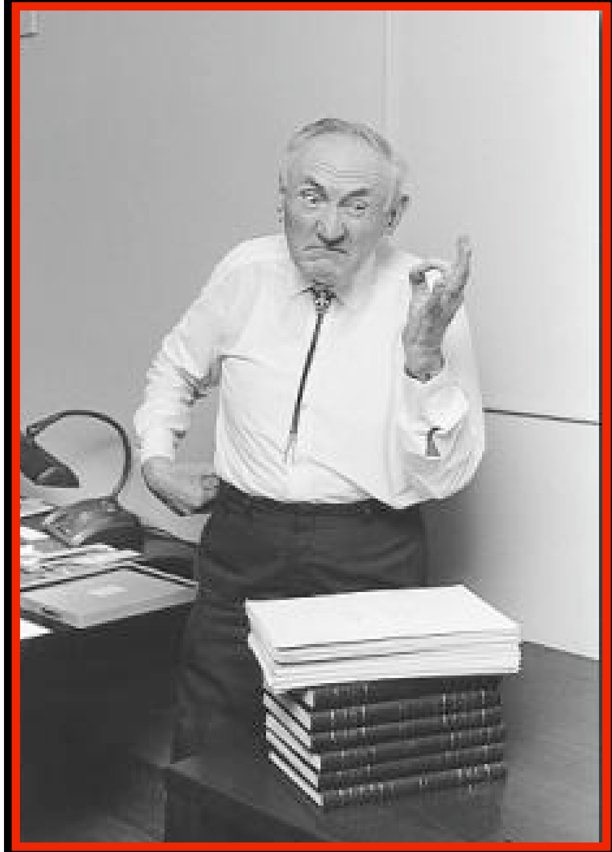
significant angular momentum, jet formation

keV gamma rays from fireball

very high energy gamma rays and neutrinos?

# What Do We Want from Core-Collapse SNe?

**A solid empirical description of the neutrino burst**



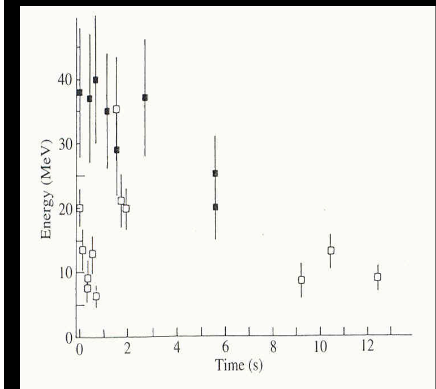
Primary science focus is the NS formation: binding energy, opacity to neutrinos, and timescales

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

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

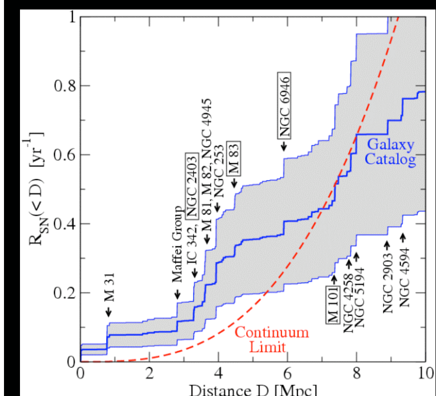
**To know how a Swedish accent sounds on the phone**

# Supernova Neutrino Detection Frontiers



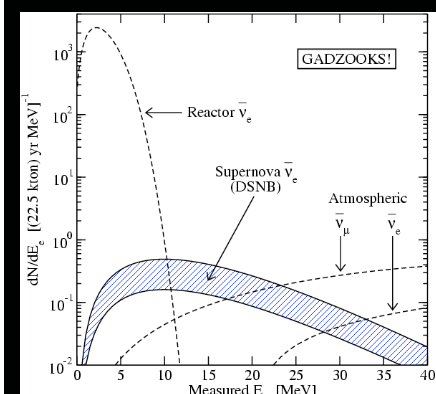

## Milky Way

zero or at most one supernova
excellent sensitivity to details




## Nearby Galaxies

one identified supernova at a time
direction known from astronomers




## Diffuse Supernova Neutrino Background

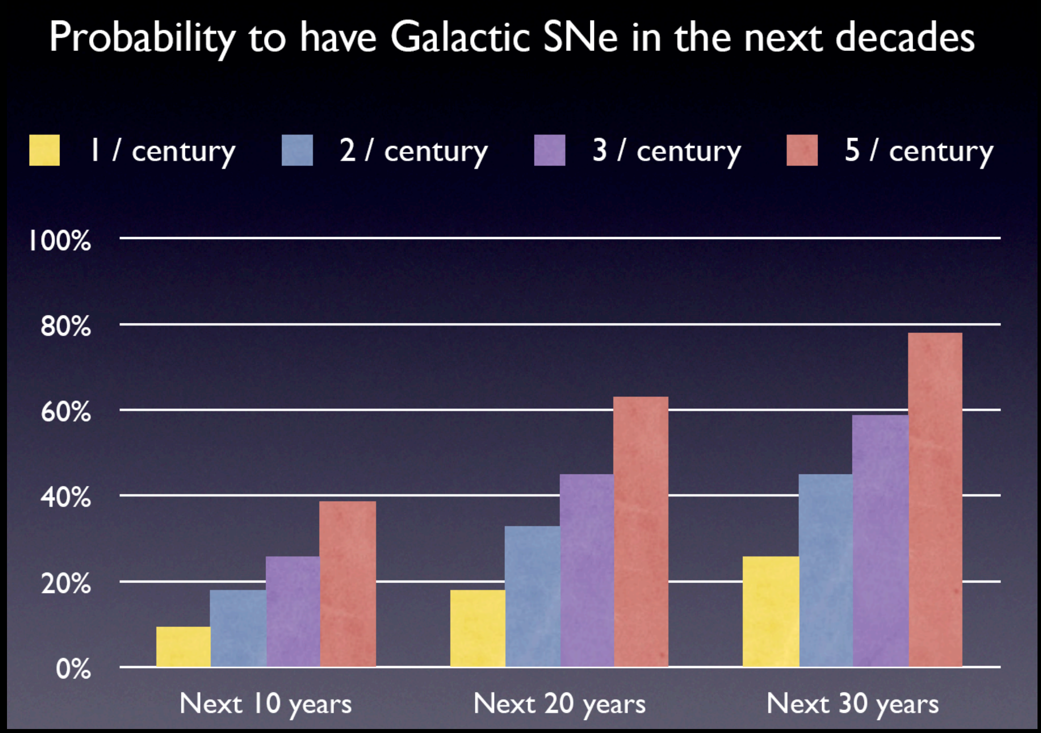
average supernova neutrino emission
no timing or direction

# Supernovae in the Milky Way

# How Long to Wait for Next Milky Way SN?

Until we get one

Very good chances if we can wait for decades




Ando

What else can we do while we wait?

# Are We Ready for Next Milky Way SN?

**Yes, if we are**

~ $10^4$ events in Super-Kamiokande
~ $10^3$ events in other detectors combined
significant background excess in IceCube
can point with SK, cross-check with SNEWS

**NOOOO!!!!, if we aren't**

It would be a tragedy if a burst is missed

**Early warning system?**

Maybe detect pre-supernova signal! (Odrzywolek et al.)

# Adequate Detectors for Next Milky Way SN?

Yes, No, and Maybe

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

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

$\nu_\mu, \nu_\tau$ Also crucial, hard to measure
SK may do with neutron tagging
KamLAND spectral technique could be key

see papers by Lisi et al., Minakata et al., others

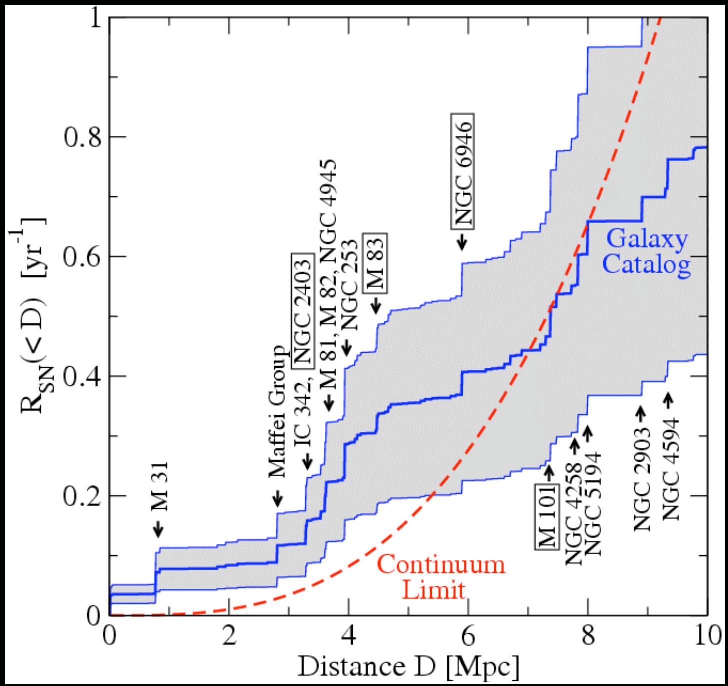
# Waiting is Boring

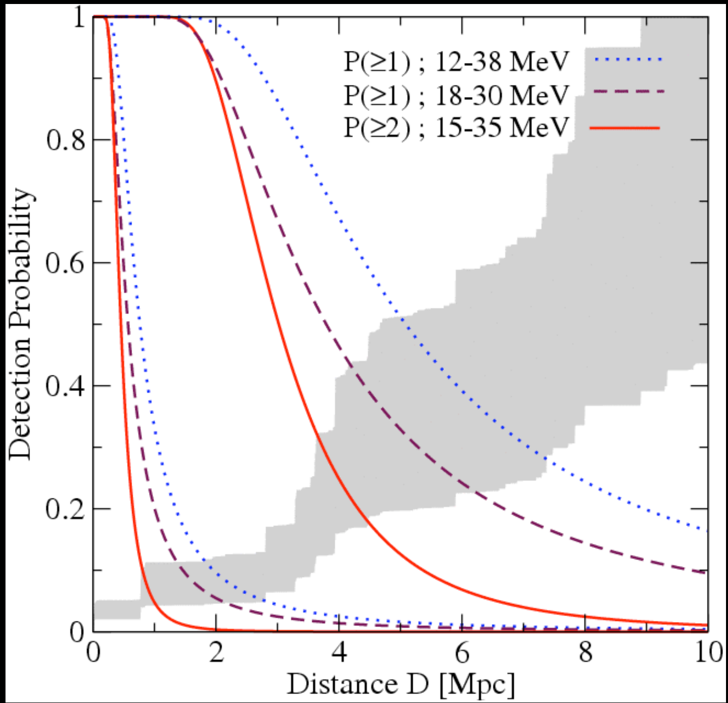
"Everybody complains about the supernova rate, but nobody does anything about it."

# Supernovae in Nearby Galaxies

# Can We Detect SNe in Nearby Galaxies?

**Yes, if we go big**




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

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

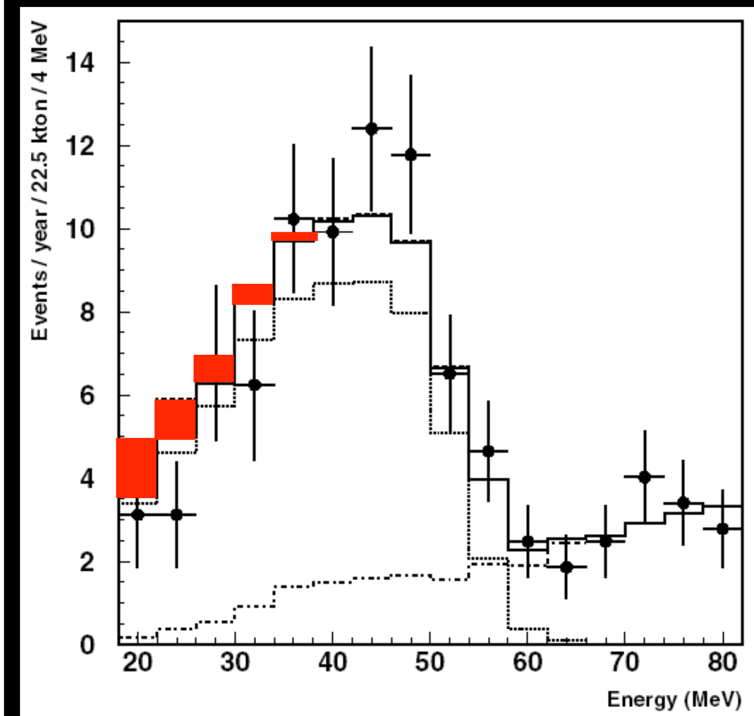
But ~ 5 Mton is a magic size: better yield than SN 1987A, every year, in burst mode

# Diffuse Supernova Neutrino Background

# Might the DSNB be Detectable?

Yes!

~20 years ago: early theoretical predictions
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:
Predictions uncertain
Backgrounds daunting

Now solved or solvable

# What are the Ingredients of the DSNB?

detector capabilities

supernova rate history

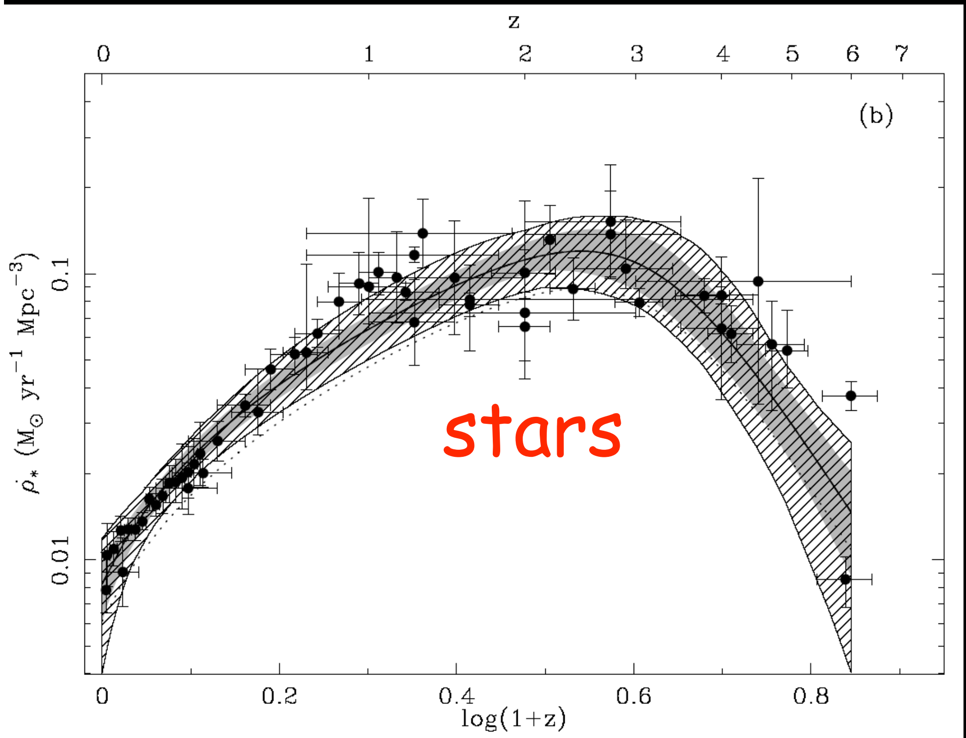
$$\psi(E_+) = \frac{c}{H_0}\,\sigma(E_\nu)N_t \int_0^{z_{max}} \phi(E_\nu[1+z])\,\frac{R_{SN}(z)}{h(z)}\,dz\,,$$

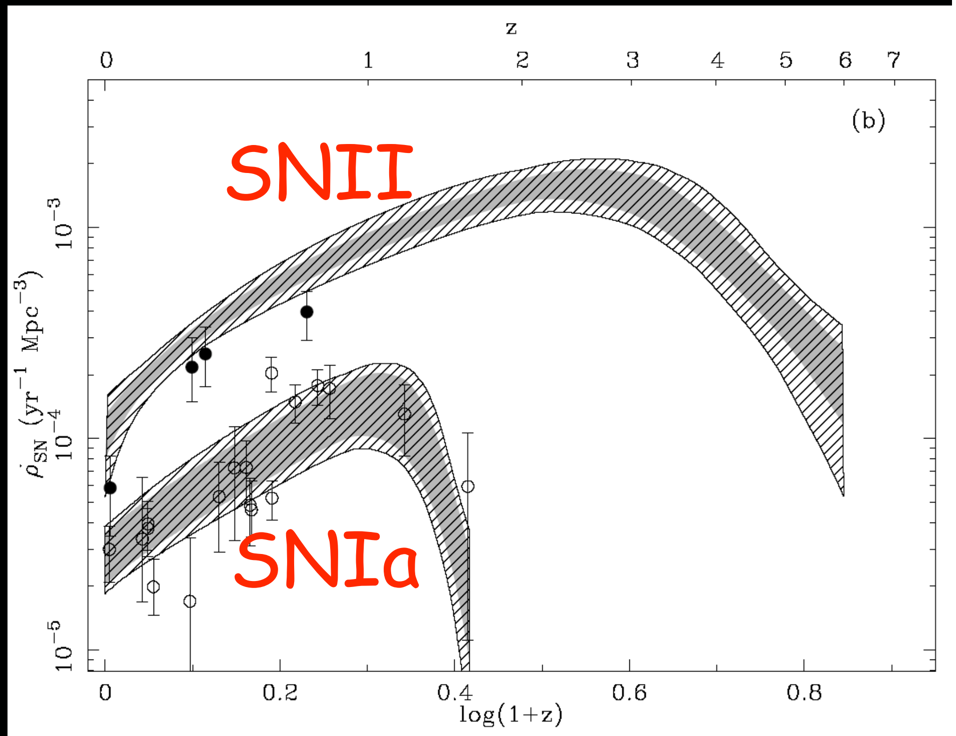
positron spectrum

neutrino spectrum per supernova

# Do We Know the Stellar Birth/Death History?

Yes




Hopkins, Beacom, ApJ 651, 142 (2006)

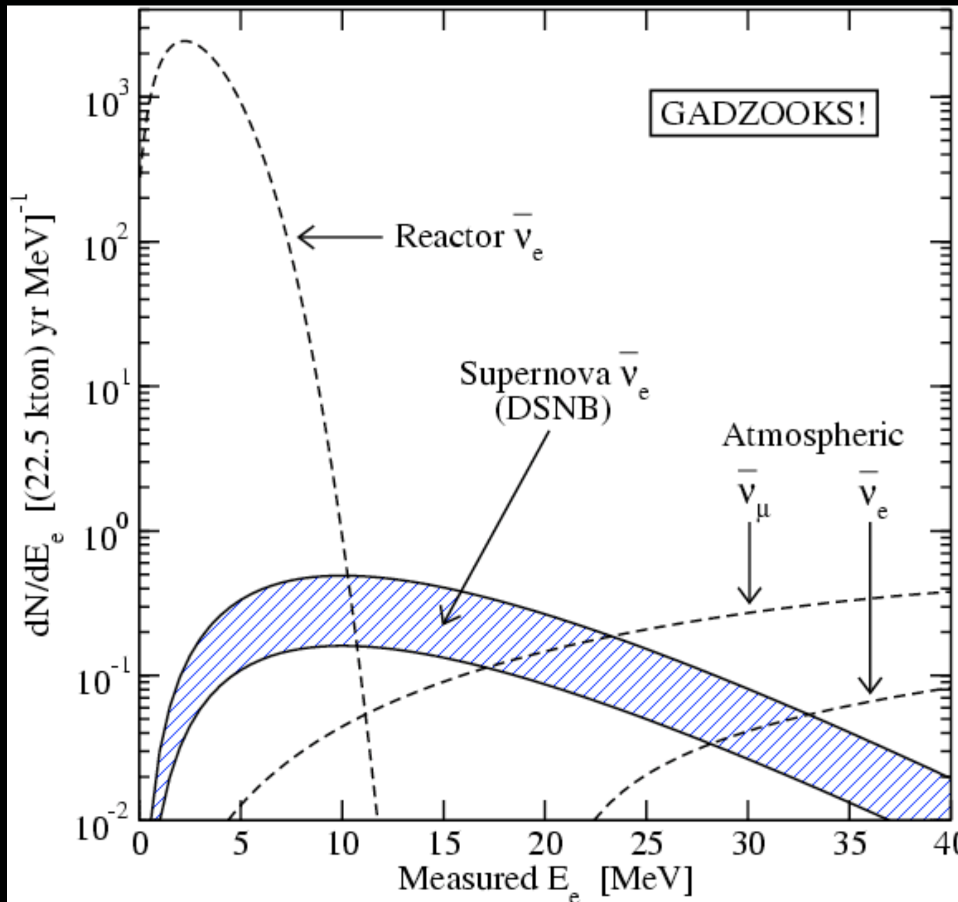
No longer a dominant uncertainty for the DSNB

# Can We Beat the Backgrounds?

Yes

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

Beacom, Vagins, PRL 93, 171101 (2004)


At 0.2% $GdCl_3$:

Capture fraction = 90%

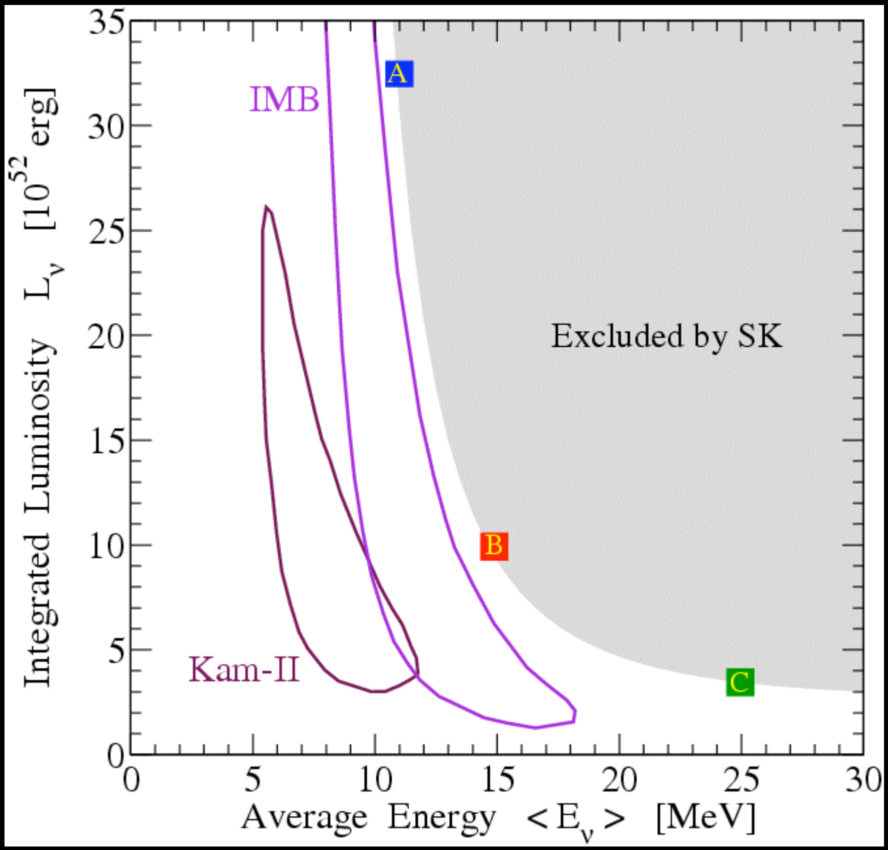
$\lambda$ = 4 cm, $\tau$ = 20 $\mu$s

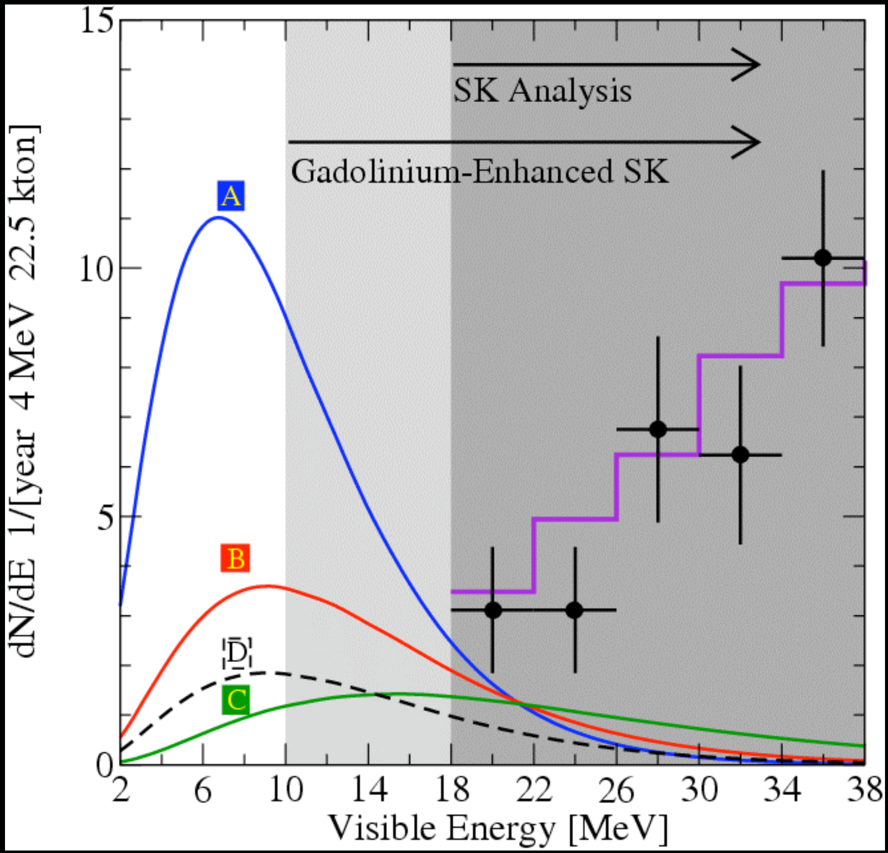
active R&D program in US and Japan

Neutron tagging means lower backgrounds, thresholds

# What is the Neutrino Emission per Supernova?

We can find out



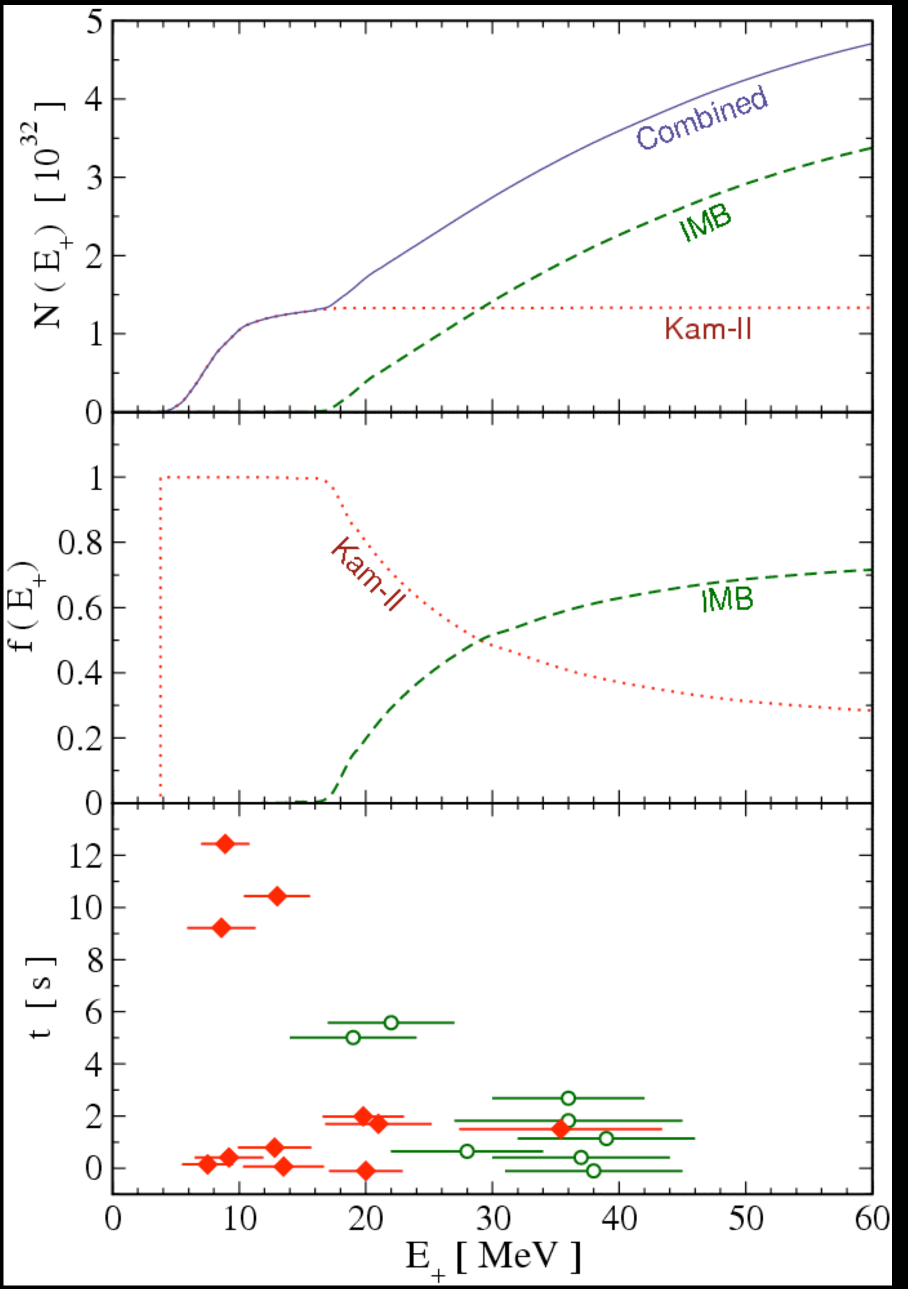

Yuksel, Ando, Beacom, PRC 74, 015803 (2006)

Mton prospects explored by Lunardini, astro-ph/0612701

# An Anniversary Present for SN 1987A

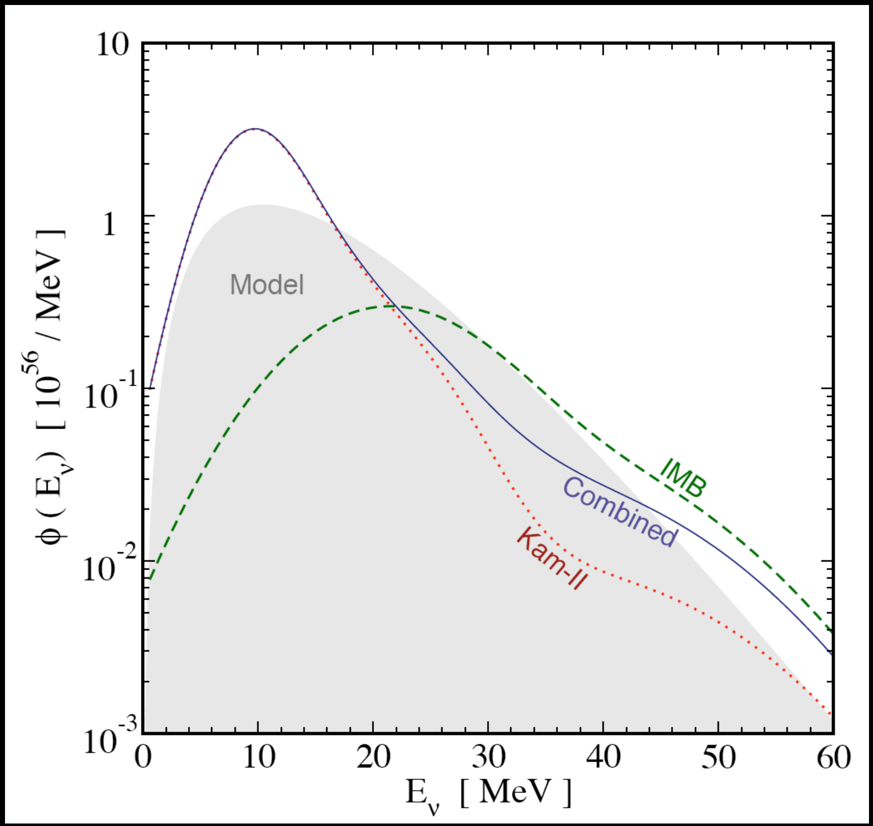
Kam-II, IMB results inconsistent with each other, theory?

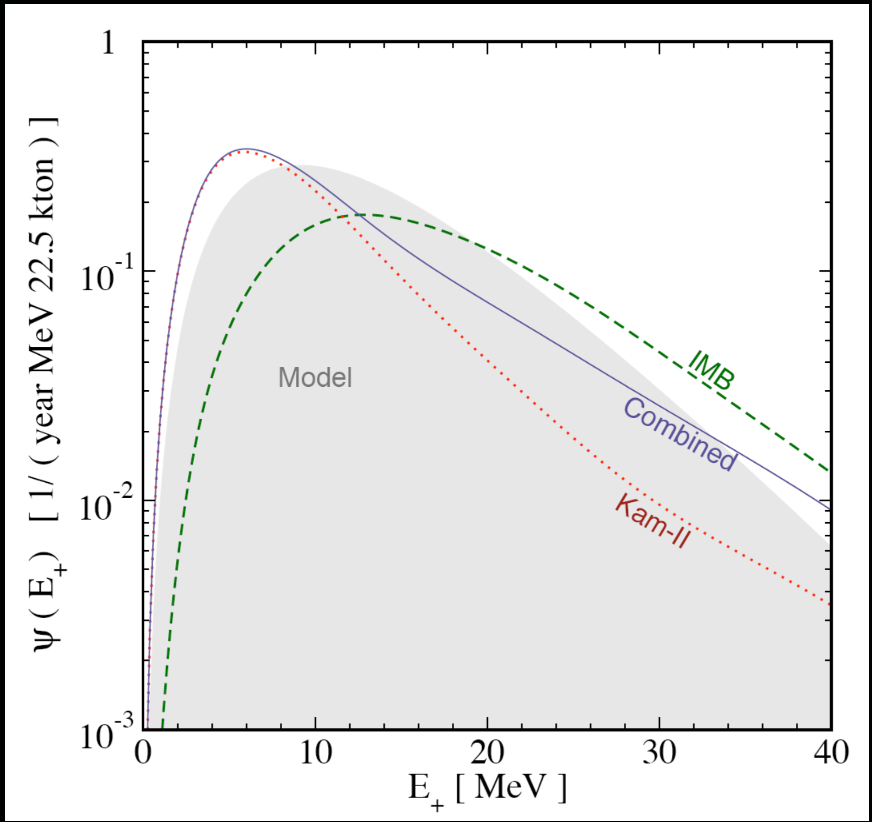
DSNB very uncertain? (Lunardini)




Yuksel and Beacom, astro-ph/0702613

# An Anniversary Present for SN 1987A

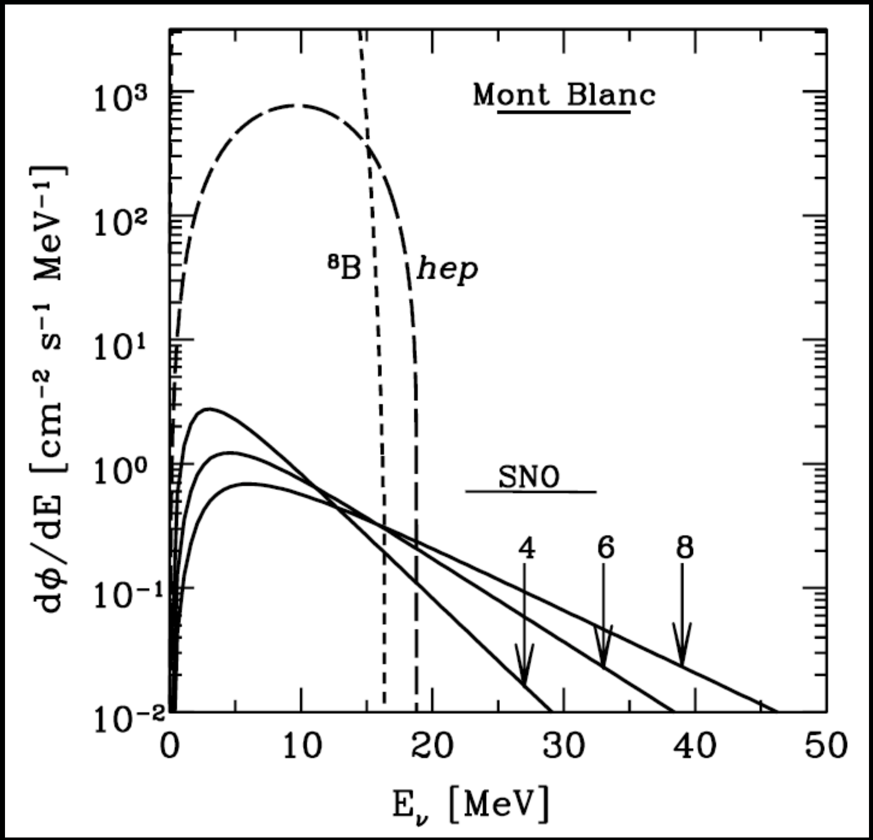


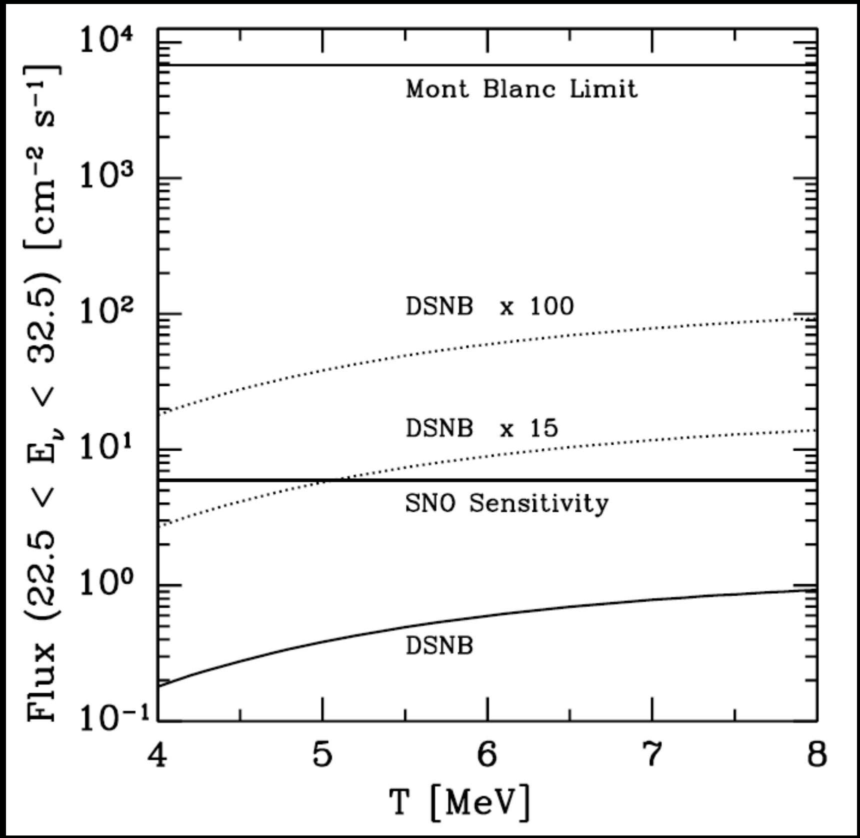




Yuksel and Beacom, astro-ph/0702613

Data consistent
Spectrum nonthermal
DSNB robust, primarily depends on IMB data

# Electron Neutrino DSNB



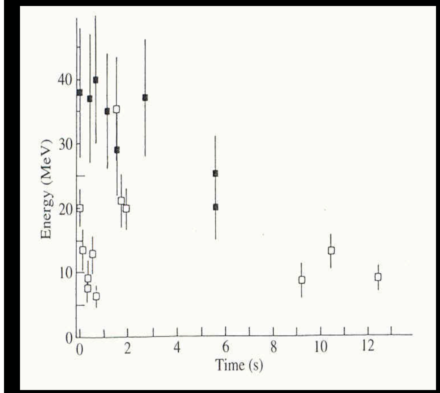

Beacom, Strigari, PRC 73, 035807 (2006)

If there was a large electron neutrino flux in 87A
--> SNO can detect the electron neutrino DSNB

This flux can be enhanced [Lunardini, PRD 73, 083009 (2006)]

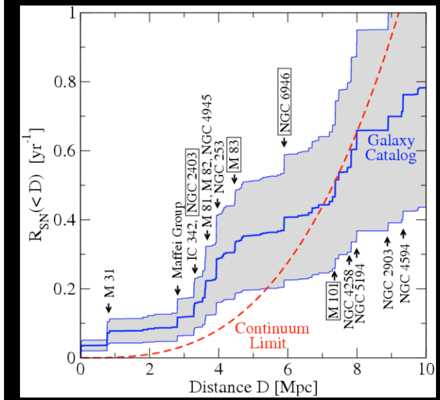
# Concluding Perspectives

# Supernova Neutrino Detection Frontiers



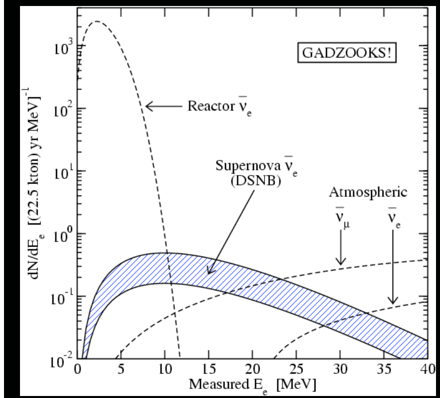

## Milky Way

long wait, big payoff




## Nearby Galaxies

frequent, but needs Mton scale




## Diffuse Supernova Neutrino Background

steady source, needs neutron tagging (Super-Kamiokande with gadolinium)

# Conclusions

The discovery of neutrinos from SN 1987A was of monumental importance:

Confirmation of type-II supernovae physics

Neutrino astronomy is possible and has unique power

Twenty years of further study have revealed:

More neutrino data are essential for understanding

It's hard! Sun and SN 1987A are the only sources

New supernova sources are within reach, and bold actions will quickly lead to fantastic discoveries

# grazie