SUPERNOVA NEUTRINO DETECTION

with present & future detectors

Kate Scholberg
Boston University

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OUTLINE

- The Core Collapse ν Signal
- Supernova ν Detection with Current & Future Detectors
- What Can We Learn from a Galactic SN ν Signal?
  - → ν physics
  - → Core Collapse Physics
  - → Early Alert
- **SNEWS**: the Inter-Experiment Network
- Current Status & Future

SUMMARY OF THE SUPERNOVA NEUTRINO SIGNAL

$$\Delta E_B \sim \frac{G M_{core}^2}{R_{nstar}} \sim 2 \times 10^{53} \text{ ergs}$$

$\lesssim 1\%$ kinetic energy, em radiation
99% ν's of all flavors

ν_e from 'breakout' ~ 1%
$\nu\bar{\nu}$ from cooling 99%

NEUTRINO ENERGIES

$\langle E_{\nu_e} \rangle \sim 12$ MeV
$\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV
$\langle E_{\overset{(-)}{\nu}_{\mu,\tau}} \rangle \sim 18$ MeV

↓ deeper ν-sphere ∴ hotter ν's

TIMESCALE

$\Delta t \sim$ 10's of seconds
~ 50% in first second

PROMPT after core collapse

Possible sharp ν cutoff if BH forms

SUPERNOVA NEUTRINO DETECTORS

- Need $M \sim 1$ kton for ~ 100 interactions
- Must have bg rate $\ll$ rate in ν burst

Also want:
- timing
- energy resolution
- pointing
- flavor sensitivity (NC)

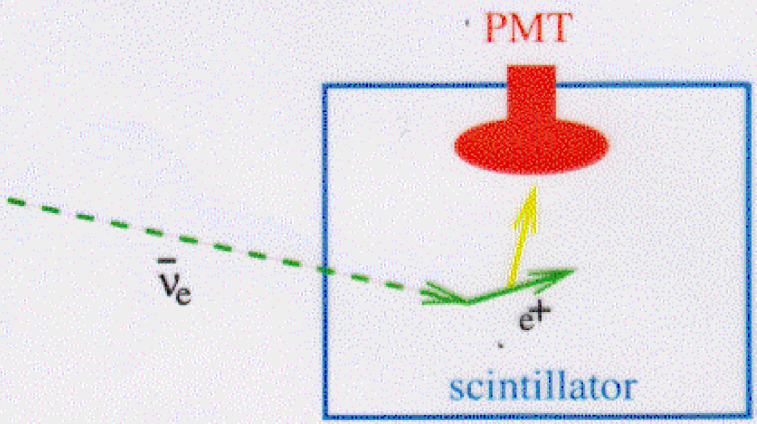
DETECTOR TYPES:

- scintillator	C_nH_{2n}
- water Cherenkov	H_2O
- heavy water	D_2O
- long string	H_2O
- "high Z"	Pb, Fe

⋮

SCINTILLATION DETECTORS

Liquid scintillator "$C_n H_{2n}$" volume viewed by PMTs



INVERSE BETA DECAY

CC $\quad \bar{\nu}_e + p \rightarrow \boxed{e^+} + n \qquad E_{e^+} = E_{\bar{\nu}_e} - 1.3\ \text{MeV}$

$\quad 180\ \mu s \hookrightarrow n + p \rightarrow d + \boxed{\gamma}\ \ 2.2\ \text{MeV}$

NC EXCITATION OF ^{12}C

NC $\quad \nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$

$\quad \hookrightarrow {}^{12}C + \boxed{\gamma}\ \ 15.1\ \text{MeV} \qquad \sim 5\%$

ELASTIC SCATTERING

NC, CC $\quad \nu_x + e^- \rightarrow \nu_x + \boxed{e^-} \qquad \sim$ few %

(Almost) NO POINTING (but: see Chooz hep-ex/9906011)

Examples: Mont Blanc, Baksan, Palo Verde, Chooz,

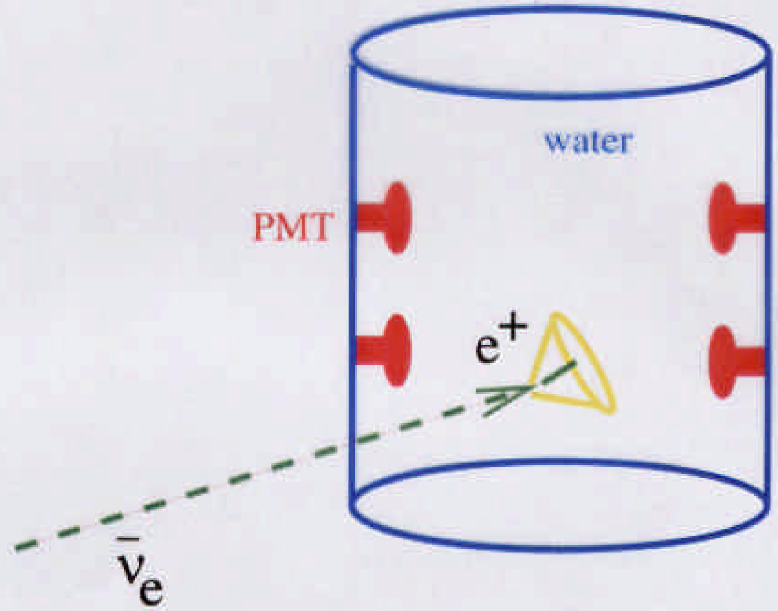
MACRO, LVD, Borexino, KamLAND

WATER CHERENKOV DETECTORS

Volume of clear water viewed by PMTs

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

Also: CC $\left\{ \begin{array}{l} \nu_e + {}^{16}O \rightarrow {}^{16}F + e^- \\ \nu_e + {}^{18}O \rightarrow {}^{18}F + e^- \\ \bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^- \end{array} \right\}$, NC $\nu_x + {}^{16}O \rightarrow \nu_x' + {}^{16}O^*$



NC, CC $\nu_x + e^- \rightarrow \nu_x + e^-$ few percent

POINTING $\Delta\theta \sim 25°$

$\nu_e \rightarrow e^-$ direction from Ch. cone $\delta\theta \gtrsim \frac{25°}{\sqrt{n}}$

Kamiokande, IMB, Super-Kamiokande, part of SNO

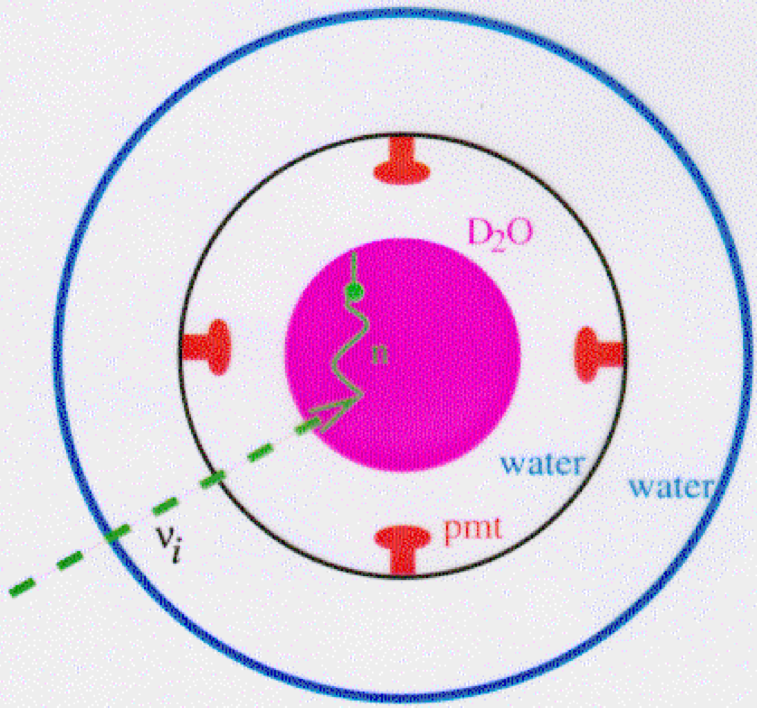
$\gtrsim 5000$ events @ 8.5 kpc

HEAVY WATER DETECTORS — SNO

D_2O viewed by PMTs + neutron detection

CC:
$$\nu_e + d \rightarrow p + p + e^-$$
$$\bar{\nu}_e + d \rightarrow n + n + e^+$$

NC:
$$\nu_x + d \rightarrow n + p + \nu_x$$
$$\bar{\nu}_x + d \rightarrow n + p + \bar{\nu}_x$$



VERY GOOD NC SENSITIVITY

⇒ sensitivity to ν mass, osc

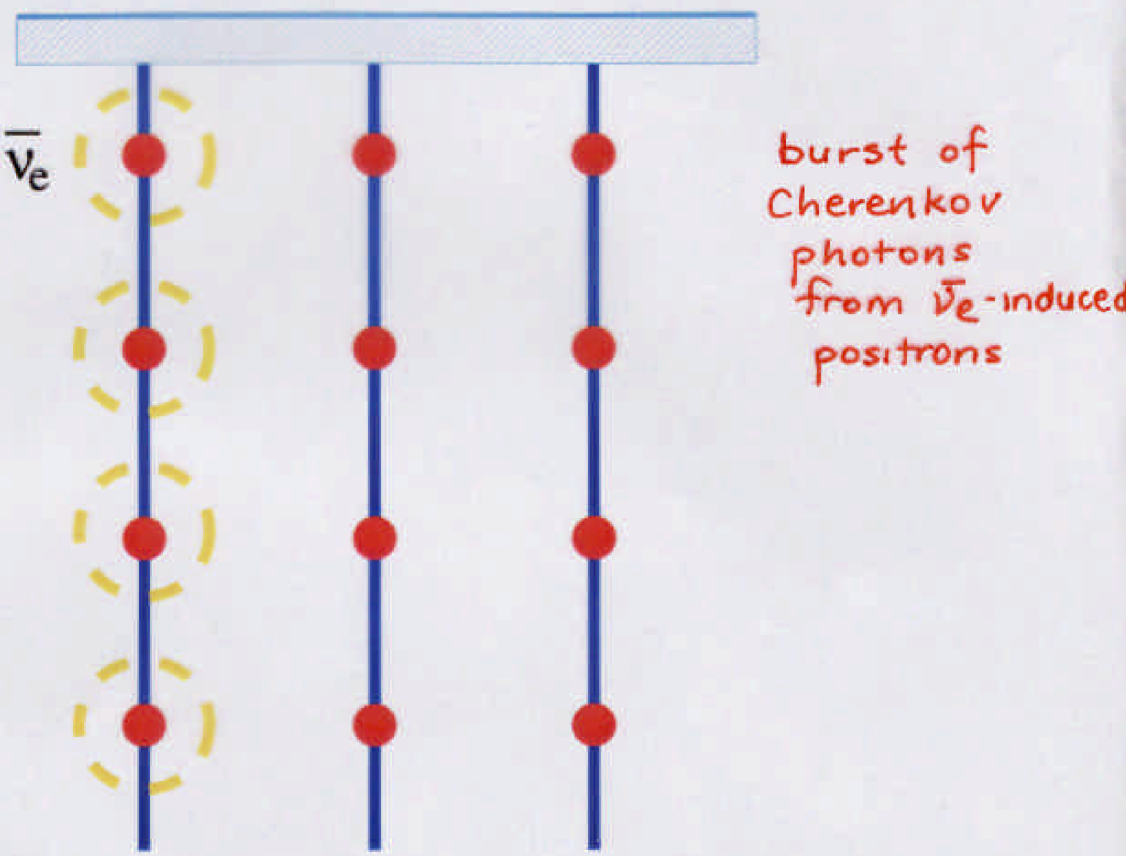
SNO: 1 kton D_2O, few hundred each of $\bar{\nu}_e p$, NC, CC breakup for collapse @ 8.5 kpc

1.4 kton H_2O

LONG STRING WATER CHERENKOV DETECTORS

~ km long strings of PMTs in very clear ice or water

Nominally multi-GeV energy threshold



BUT: may see burst of low energy $\bar{\nu}_e$'s (Halzen et al. PRD 53 7359)

as COINCIDENT INCREASE in PMT singles rates!

Meff ~ 0.4/PMT (No pointing, energy resolution)

AMANDA, Antares, Baikal, Nestor

→ low noise promising (~10 kpc sensitivity)

OTHER SN ν DETECTORS

• HIGH Z/NEUTRON DETECTORS

large quantity of high Z material + neutron counters

NC $\quad \nu_x + (A,Z) \rightarrow (A-1,Z) + \boxed{n} + \nu_x$

CC $\quad \begin{cases} \nu_e + (A,Z) \rightarrow (A-1,Z+1) + \boxed{n} + e^- \\ \bar{\nu}_e + (A,Z) \rightarrow (A-1,Z-1) + \boxed{n} + e^+ \end{cases}$

e.g. OMNIS (Fe/Pb), LAND (Pb)

• LIQUID ARGON

CC $\quad \nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + \boxed{e^-}$

e.g. Icanoe

• RADIOCHEMICAL

Homestake $\quad \nu_e + {}^{37}Cl \rightarrow \boxed{{}^{37}Ar} + e^-$

Gallium $\quad \nu_e + {}^{71}Ga \rightarrow \boxed{{}^{71}Ge} + e^-$

NOT REAL TIME, but may register counts

⇒ perform prompt extractions

\+ gravitational radiation from asymmetric explosions (~ unknown signal)

SUMMARY OF SN NEUTRINO DETECTOR TYPES

Detector type	Material	Energy	Time	Point	Flavor
scintillator	C,H	y	y	n	$\bar{\nu}_e$
water Čerenkov	H_20	y	y	y	$\bar{\nu}_e$
heavy water	D_20	NC: n	y	n	all
		CC: y	y	y	$\nu_e, \bar{\nu}_e$
long string water Čerenkov	H_2O	n	y	n	$\bar{\nu}_e$
liquid argon	Ar	y	y	y	ν_e
high Z/neutron	Fe Pb	n	y	n	all
radio-chemical	^{37}Cl ^{127}I ^{71}Ga	n	n	n	ν_e

- primary sensitivity to $\bar{\nu}_e$
- NC for heavy water, neutron
- pointing for water Ch., heavy water, argon
- all real-time except radiochemical
- all have energy resolution except { long string, neutron, radiochemical }

SUMMARY OF SPECIFIC SN NEUTRINO DETECTORS

± ~50%

Detector	Type	Mass (kton)	Location	No. of events @8.5 kpc	Status
Super-K	water Čeren.	32	Japan	5000	running
SNO	H_2O, D_2O	1.4 1	Canada	300 450	running
MACRO	scint.	0.6	Italy	150	running
LVD	scint.	0.7 (1 2001)	Italy	170	running
KamLAND	scint.	1	Japan	300	2001
Borexino	scint.	0.3	Italy	100	2000
Baksan	scint.	0.33	Russia	50	running
AMANDA	long string	Meff ~ 0.4/pmt	Antarctic		running
OMNIS	high Z Pb/Fe	10(Fe) +4(Pb)	USA	~1000	proposed
LAND	high Z Pb		Canada		proposed
Icanoe	liquid argon	9	Italy		2005

~ Galactic sensitivity

WHAT CAN WE LEARN FROM A GALACTIC SN ν SIGNAL?

- NEUTRINO PHYSICS
  - ν absolute mass from t.o.f. delay
  - ν oscillations from spectra

  ⋮

- CORE COLLAPSE PHYSICS
  - explosion mechanism
  - proto n star cooling
  - black hole formation

  } flavor, energy, time structure of burst

- ASTRONOMY FROM EARLY ALERT

  ~hours of warning before visible SN + some pointing w/ ν's

  - progenitor & environment info
  - unknown early effects?

NEUTRINO PHYSICS with SN NEUTRINOS

ν ABSOLUTE MASS : time of flight delay

Look for: { · energy-dependent time spread
· flavor-dependent delay

ν OSCILLATION (in core) : distortion of energy spectra (hot ν_e, $\bar{\nu}_e$)

Look for: NC vs. CC detected rates

e.g. { Fuller et al., astro-ph/9809164
Dighe & Smirnov, hep-ph/9907423
...

Also: ν lifetime

ν charge

No of ν flavors

ν magnetic moment

⋮

CAVEAT : Always at least some core-collapse model-dependence

MEASURING ABSOLUTE ν MASS WITH A SN BURST

Time of flight $\Delta t(E) = 0.515 \left(\frac{m}{E}\right)^2 D$

[m : eV, E : MeV, D : 10 kpc]

Spread in arrival time & correlation with energy

⇒ non-zero ν mass

BUT: due to finite emission Δt

⇒ only get upper limit on m_ν

SN1987A $m_{\bar{\nu}_e} \lesssim 20$ eV w/ reasonable assumptions

Next SN in Galaxy: will get $m_{\bar{\nu}_e} \lesssim 3$ eV

e.g. T. Totani astro-ph/980110

NOT BETTER THAN LAB!

PROMISING APPROACH FOR $\overset{(-)}{\nu}_{\mu,\tau}$

Use detectors with NC sensitivity

⇒ look for relative delay of $\overset{(-)}{\nu}_{\mu,\tau}$ wrt $\overset{(-)}{\nu}_e$

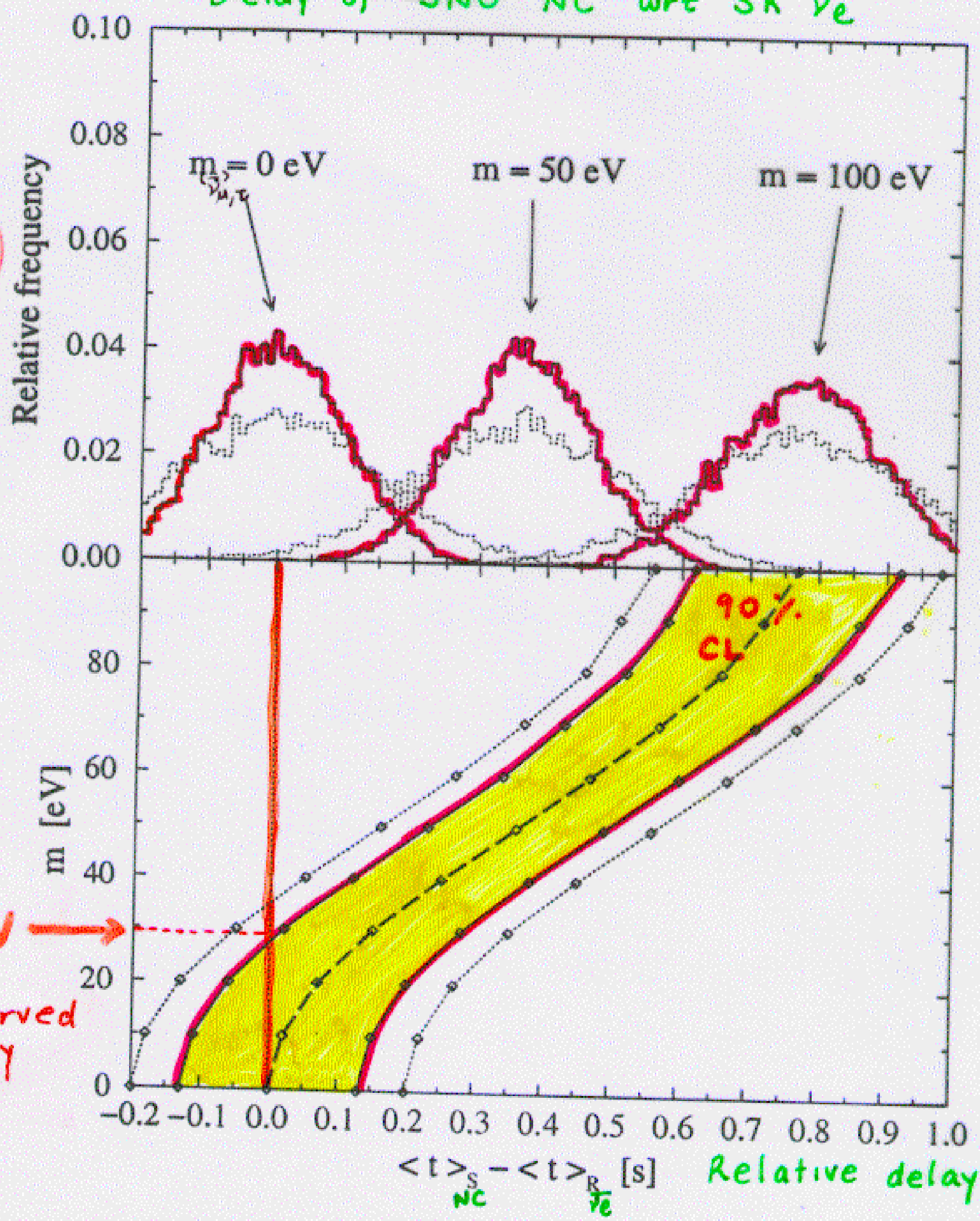
STRATEGY: tag NC & CC events and measure relative delay

e.g. Beacom & Vogel hep-ph/9806311

Delay of SNO NC wrt SK $\bar{\nu}_e$

MC simulation of 10^4 SN's

10 kpc



Limit **30 eV** for no observed delay

Relative delay

Get ~30 - 50 eV limits ($\overset{(-)}{\nu}_{\mu,\tau}$) with SK+SNO

Better than lab! $\left\{ \begin{array}{l} m_{\nu_\mu} < 0.17 \text{ MeV} \\ m_{\nu_\tau} < 18 \text{ MeV} \end{array} \right.$

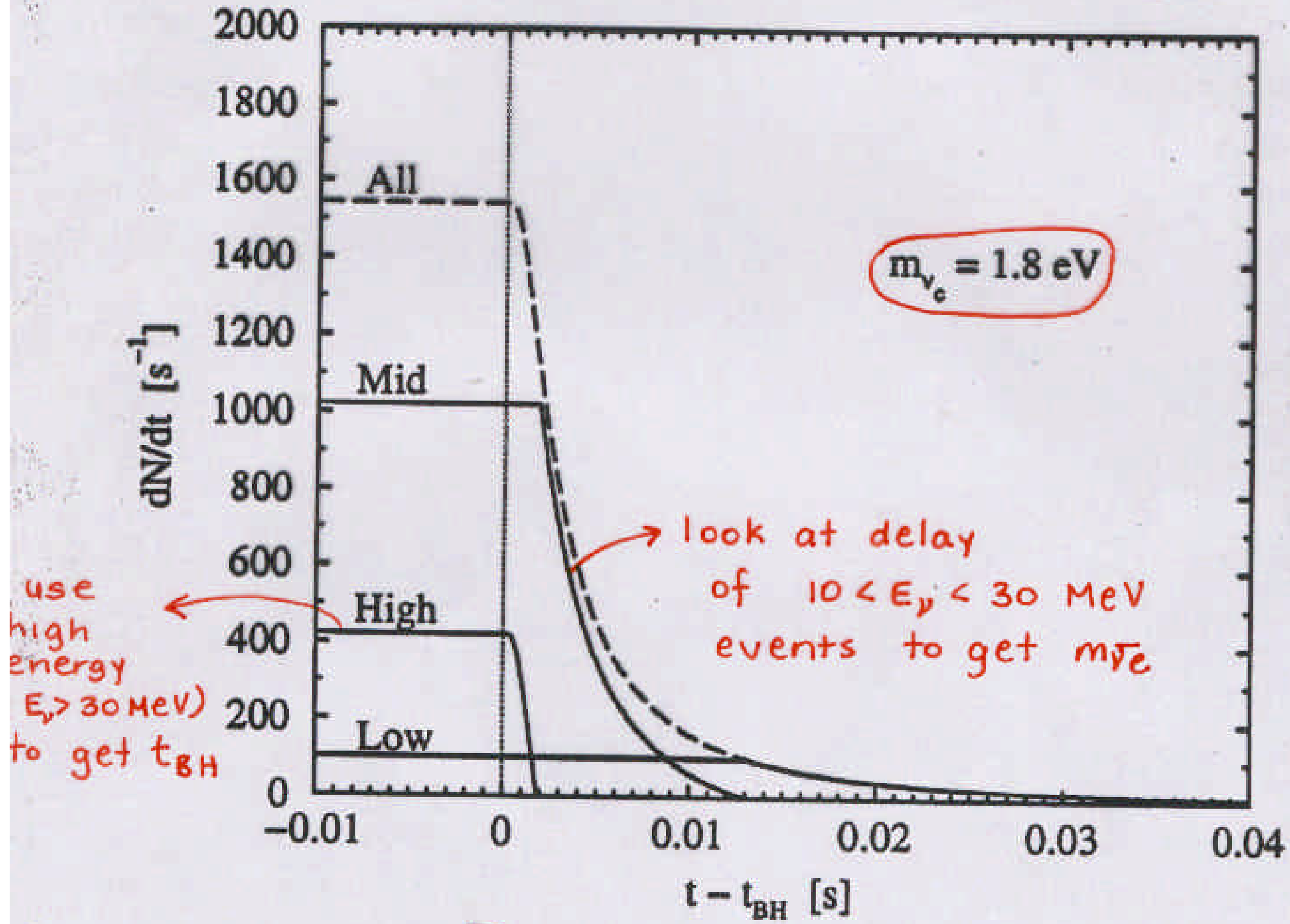
NEW : Beacom, Boyd & Mezzacappa hep-ph/0006015

Core collapse resulting in black hole formation (fraction : 50%?) ⇒ sharp cutoff of ν_x luminosity

⇓

t = 0 for tof delay measure

Use ν energy info e.g. SK $\bar{\nu}_e p$



⇒ limit on $\bar{\nu}_e$ mass : ~ 1.8 eV

Using NC in OMNIS-like detector:

~ 6 eV for $\overset{(-)}{\nu}_{\mu,\tau}$ mass limit

AN EARLY ALERT for astronomers

~hours of warning (depends on stellar envelope)

Early light actually not helpful for SN explosion theory (ν's are)

BUT:
- environment near progenitor probed by initial stages
- UV / soft x-ray flash @ shock breakout predicted

} info about progenitor from spectroscopy

\+ possible unknown early effects!

Early light observations very rare for extragalactic

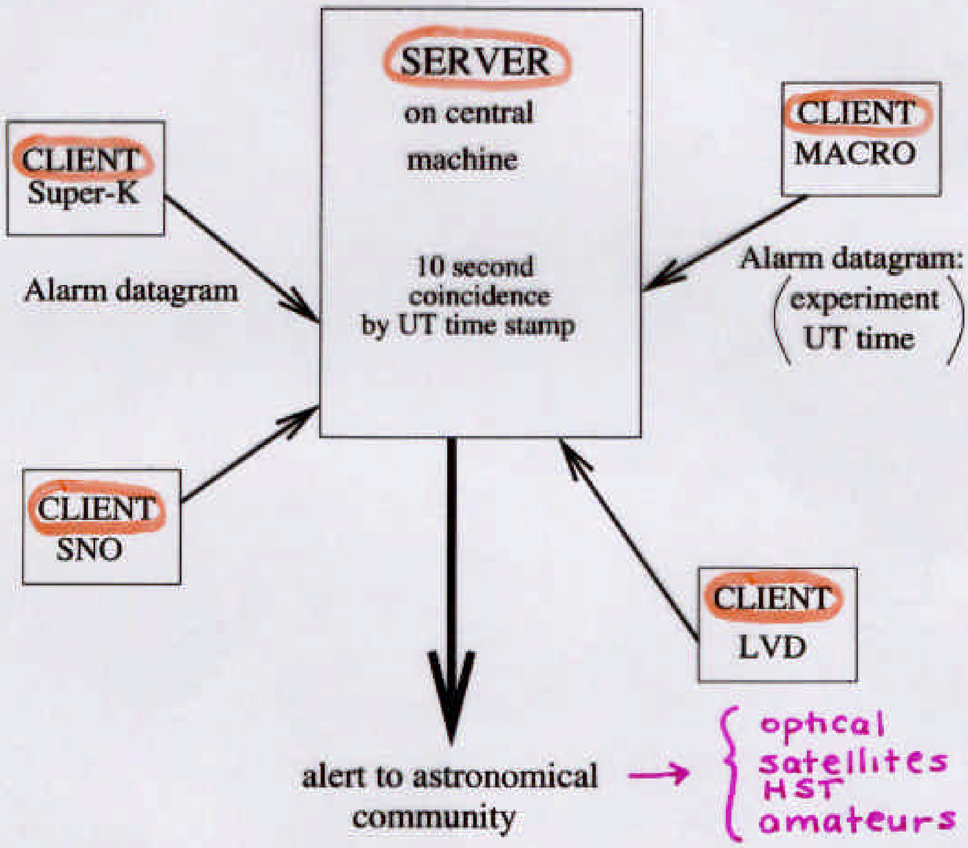
⇒ **S**uper**N**ova **E**arly **W**arning **S**ystem

Computer(s) receive 'blind' alert messages from ν detectors; automated alert if coincidence

SNEWS IMPLEMENTATION

Alarm datagrams sent by
individual experiments to server(s)

Now running @ Super-K site



MACRO, LVD, Super-K : automated alarms

Next : SNO, Amanda
New server @ LNGS

Automated alerts to astronomers
within the year

POINTING with ν's

Beacom & Vogel astro-ph/9811350

ASYMMETRIC REACTIONS

in a single detector may be the best bet

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

few % of SK events

$\Delta\theta \sim 25°$

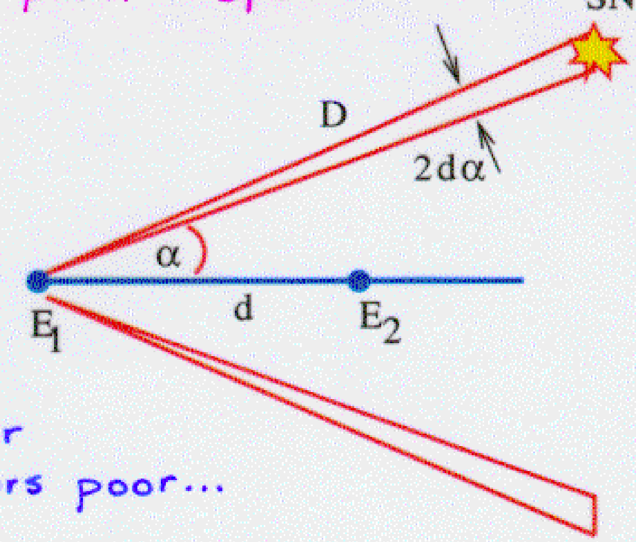
$\delta\theta \sim \frac{25°}{\sqrt{N}}$ } correction factor of ~2-4 due to centroiding on isotropic bg

SK ~ 5°, SNO ~ 20° for SN @ Galactic center

TRIANGULATION

using relative timing of signals

2 exp'ts : circle on sky
3 exp'ts : 2 blobs
4 exp'ts : point to spot



$\cos\alpha = \frac{c\Delta T}{d}$

$\delta(\cos\alpha) = \frac{c}{d}\delta(\Delta T)$ — registration error

Statistics for current detectors poor...

SK - SNO $\delta(\cos\alpha) \approx 0.5$ @ 10 kpc
for realistic pulse shapes
(+ practical problems for prompt answer)

Still worth a try...

SUMMARY

- Several ν detectors with Galactic sensitivity online now

  Super-K
  SNO
  MACRO
  LVD
  AMANDA
  Borexino
  KamLAND
  OMNIS
  ⋮

- Core collapse will yield a bonanza of information!

  → ν physics: • absolute mass limits

  $\bar{\nu}_e \lesssim 3$ eV
  $\overset{(-)}{\nu}_{\mu,\tau} \lesssim 30$ eV
  } better for BH collapse?

  • oscillation info

  etc.

  → Core collapse models

  → **SNEWS** : early alert from coincidence

Hoping for SN2XXX soon!