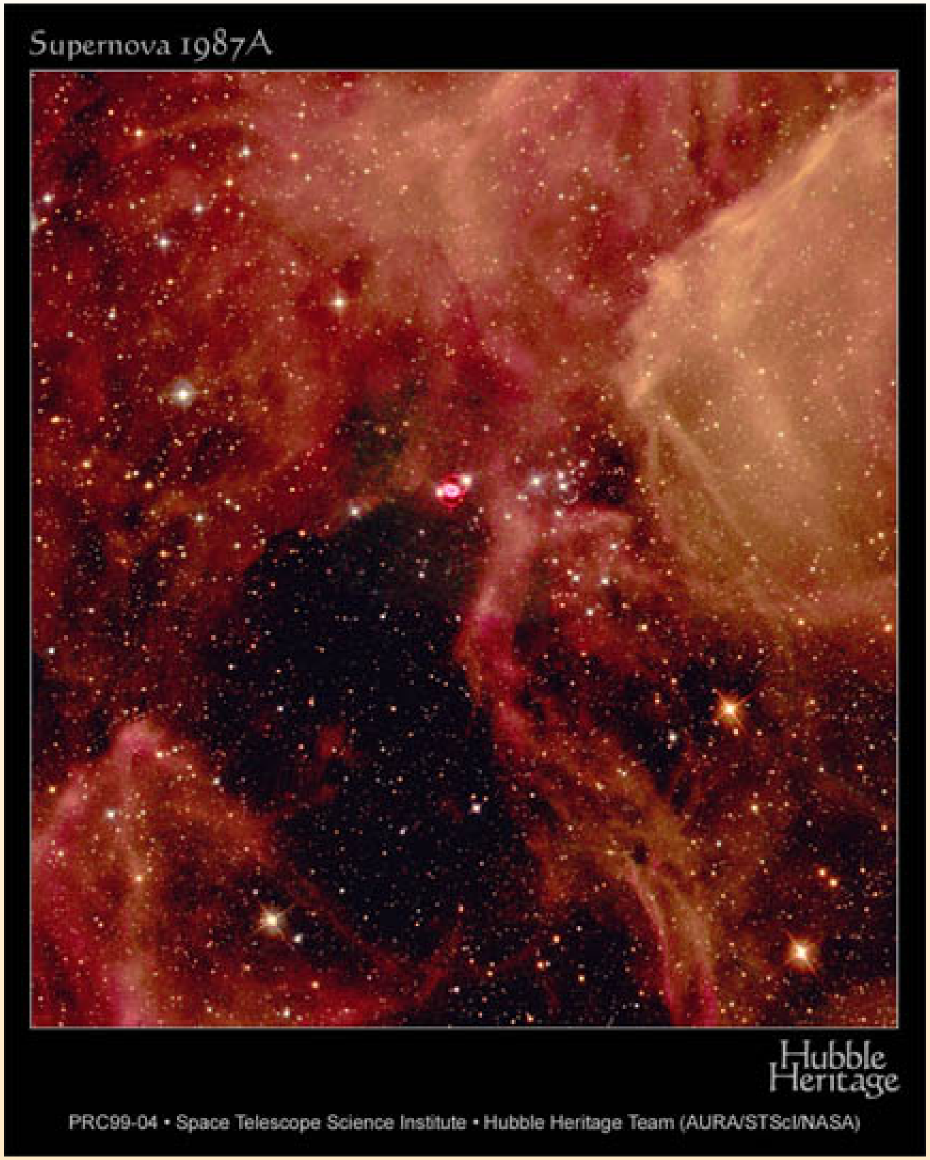
Supernova Neutrinos, LSND and MiniBooNE

- Constraints on neutrino oscillations from supernovæ
- MiniBooNE as a supernova neutrino detector
- MiniBooNE status

Michel Sorel
Columbia U./MiniBooNE

Moriond EW 2002



Three good reasons to look for supernova (SN) neutrinos

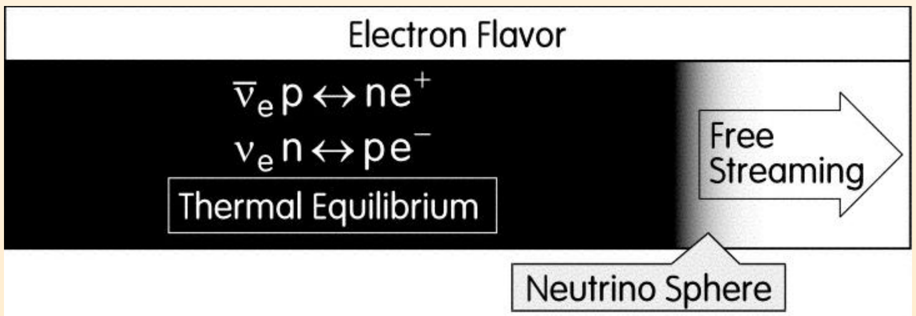
1. High-energy astrophysicists can learn much about core-collapse SN explosion mechanism from neutrinos
   $\Rightarrow$ 99% of SN energy is released in neutrinos

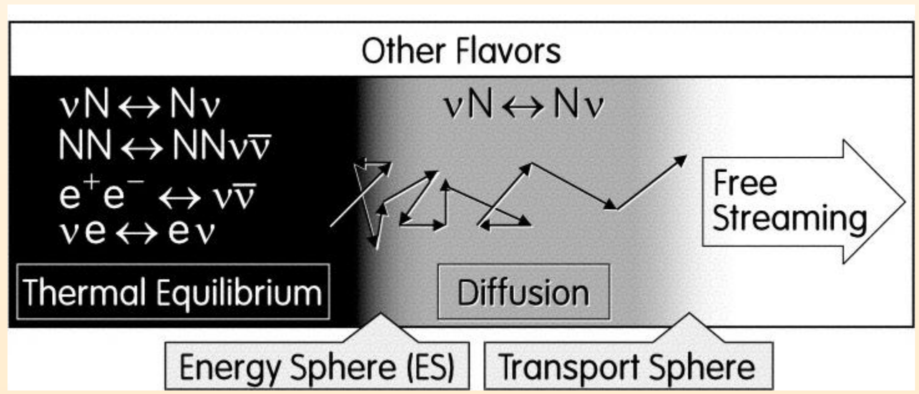
2. Particle physicists can learn much about neutrino masses and mixings

3. Astronomers want to have advanced warning so they can see early stages of a SN
   $\Rightarrow$ Neutrinos arrive before photons

Neutrinos in supernova explosions

- Neutrinos and antineutrinos of all flavors are produced via: $NN \longrightarrow NN\nu\bar{\nu}$, $e^+e^- \longrightarrow \nu\bar{\nu}$,...
- Neutrinos get trapped for some time and reach thermal equilibrium
- Neutrinos eventually escape, each flavor taking away same fraction of energy
- Different neutrino temperatures due to different allowed neutrino interactions:



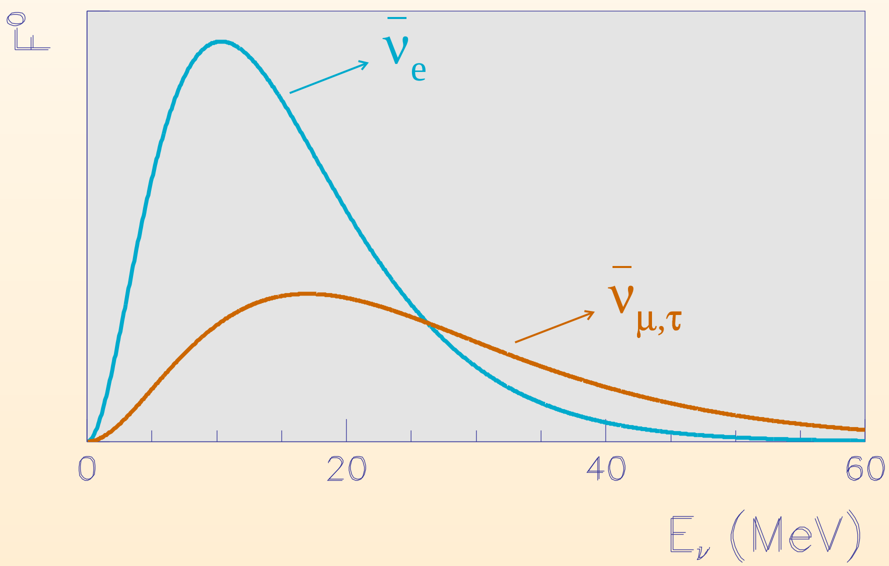


- More interactions ⇔ larger trapping radius ⇔ lower temperature
- Duration of neutrino burst: 1-10s

SN neutrino energy spectra as a probe for neutrino oscillations

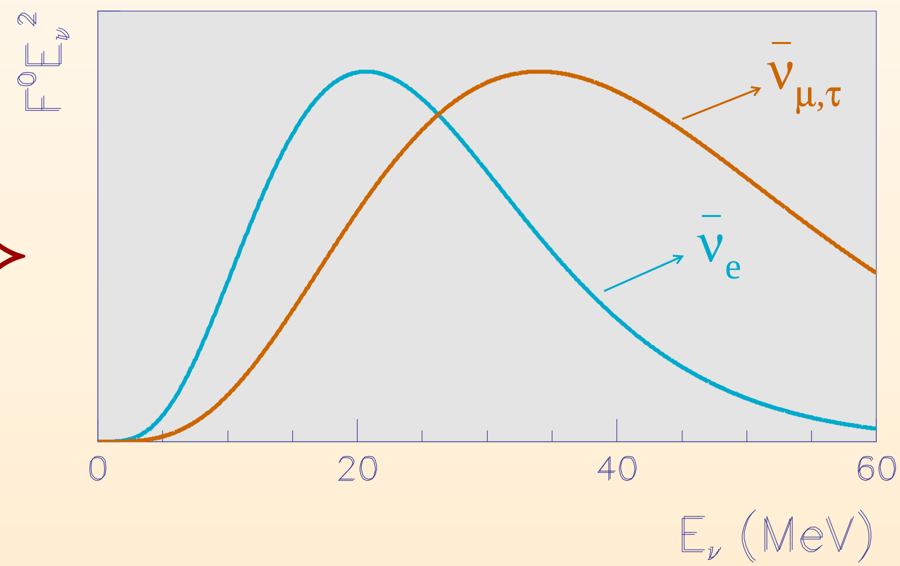
- At last scattering surface, $\bar{\nu}_e$'s are on average less energetic than $\bar{\nu}_\mu$'s and $\bar{\nu}_\tau$'s:

Flux at neutrinosphere



$\Longrightarrow$

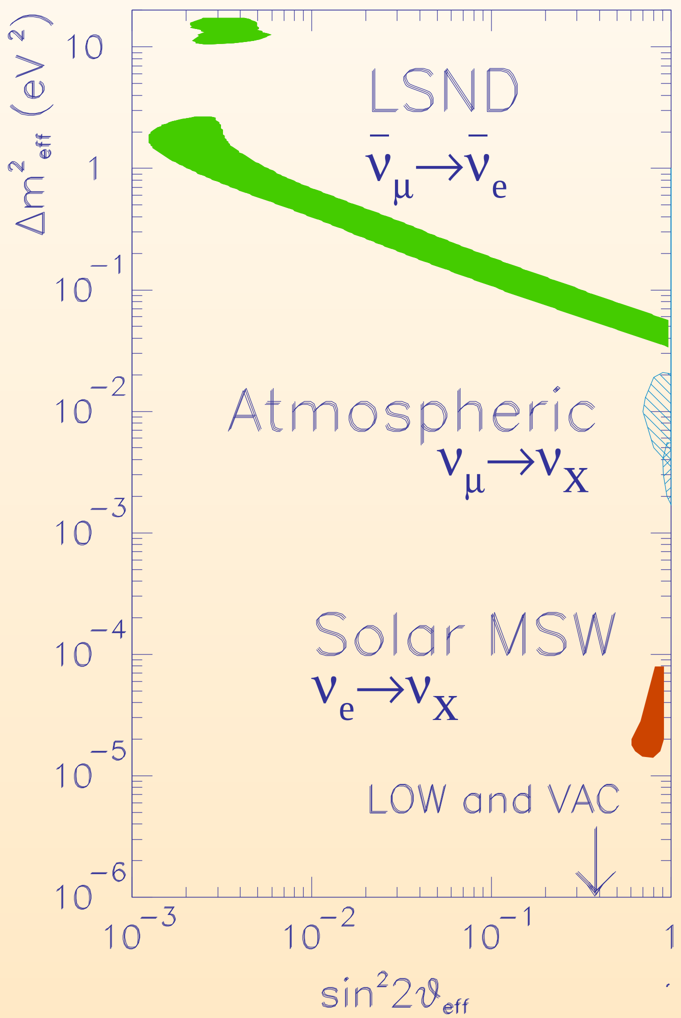
Flux times cross-section



- At a $\bar{\nu}_e$ detector on Earth, the observed average neutrino energy is higher than that predicted by the primary $\bar{\nu}_e$ spectrum, if $\bar{\nu}_{\mu,\tau} \longrightarrow \bar{\nu}_e$ oscillations occur

Parameter space for neutrino oscillations

- There are three experimental hints pointing toward neutrino oscillations:



- ϑ_{eff}: effective mixing angle
- Δm^2_{eff}: leading Δm^2 responsible for oscillations
- For two-flavor (α, β) oscillations:

$$\begin{cases} \vartheta_{eff} = \vartheta \\ \Delta m^2_{eff} = m_2^2 - m_1^2 \end{cases}$$

$$\begin{pmatrix} \bar{\nu}_\alpha \\ \bar{\nu}_\beta \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} \bar{\nu}_1 \\ \bar{\nu}_2 \end{pmatrix}$$

- To explain all of the data with oscillations, (at least) four neutrinos are needed

Popular 4-neutrino models

- In these models, a *sterile* neutrino with no standard weak coupling is added
- Popular models:

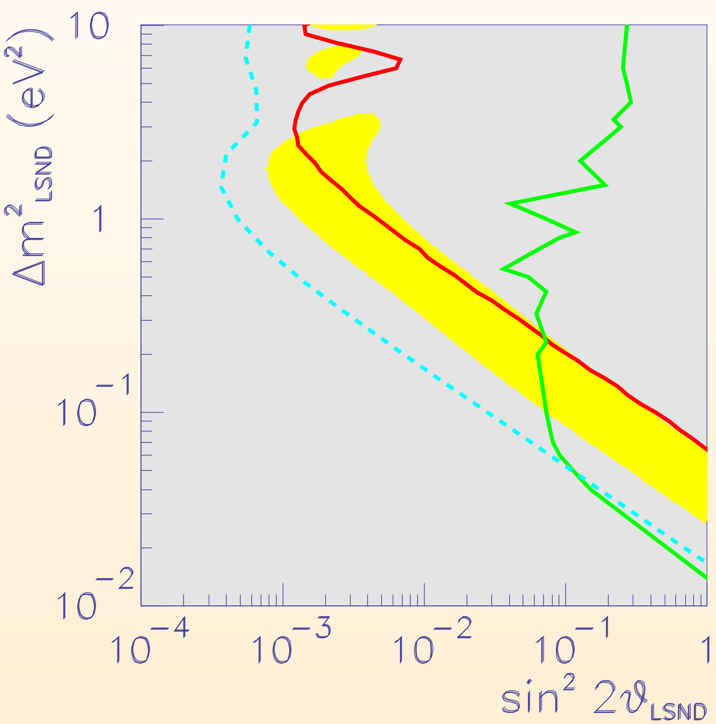
2+2 Models | 1+3 Models

Normal hierarchy | "LSND-inverted" hierarchy | Normal hierarchy | "LSND-inverted" hierarchy

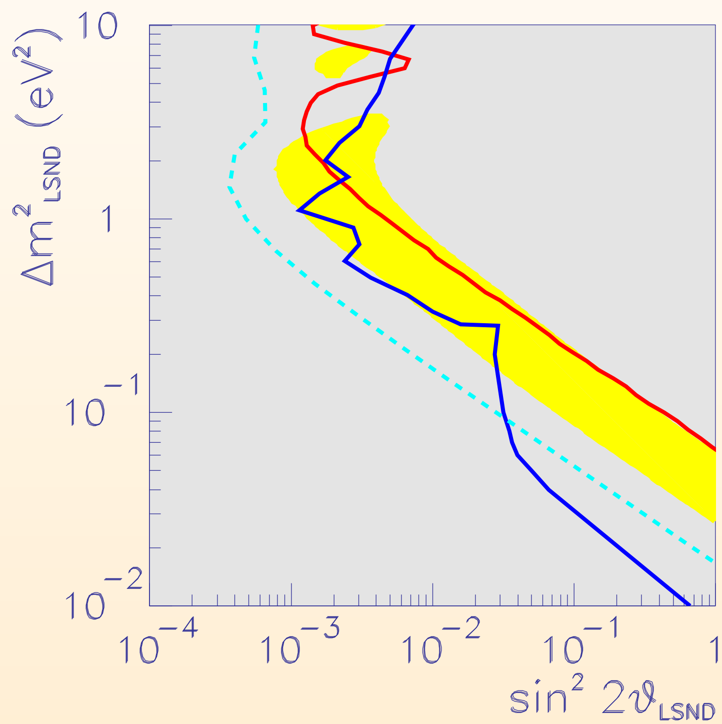
- Flavor content: $\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$ $\bar{\nu}_s$

Constraints on LSND-oscillations (not from supernovæ)

2+2 Models



1+3 Models



- LSND allowed region (99% CL)
- Regions to the right of lines are excluded at 99% CL by: Karmen (2000), Bugey, Bugey+CDHS+SuperK
- MiniBooNE projected sensitivity at 90% CL

Matter effects on neutrino propagation

- In matter:
  - $\bar{\nu}_e$'s undergo CC forward-scattering from electrons
  - All active flavor $\bar{\nu}$'s undergo NC forward-scattering from electrons, protons, neutrons
- Hamiltonian in the flavor basis:

$$(H)_{\alpha\beta} = (H_0 + V)_{\alpha\beta} = U^*_{\alpha i} U_{\beta i} \frac{m_i^2}{2p} + A_\alpha \frac{G_F \rho}{m_N} \delta_{\alpha\beta}$$

Mixing matrix ($U^*_{\alpha i}$)

Neutrino mass (m_i^2)

Density (ρ)

flavor index (α)

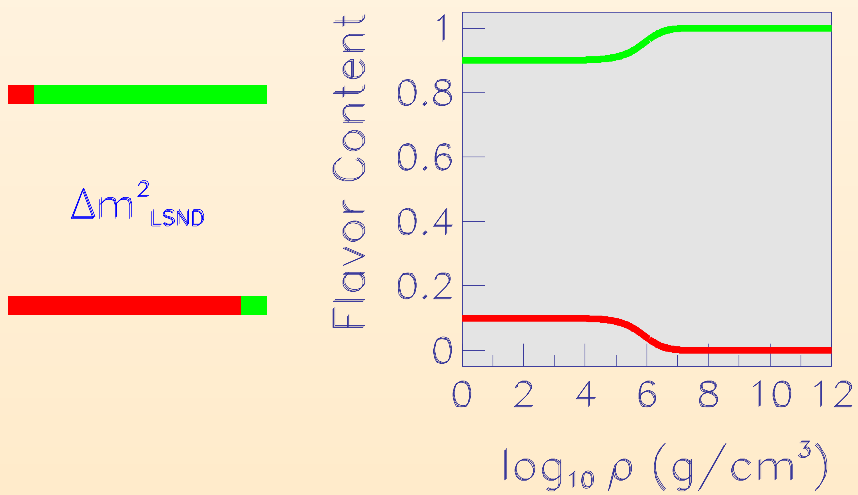
mass index (i)

flavor-dependent numerical coefficient (A_α)

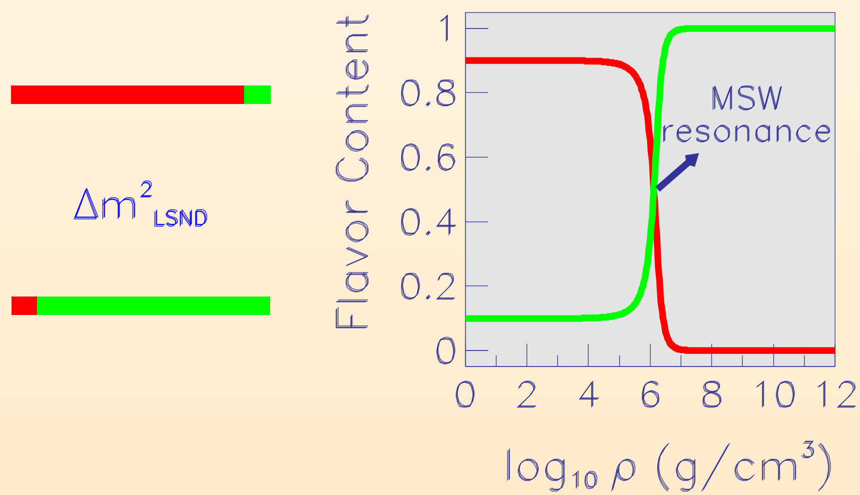
Adiabatic approximation

- Matter density varies slowly enough so that transitions between local Hamiltonian eigenstates are suppressed
- Oscillations occur because the eigenstates' flavor content changes with density
- Simple two-neutrino example ($\bar{\nu}_e$ $\bar{\nu}_\mu$):

Normal hierarchy



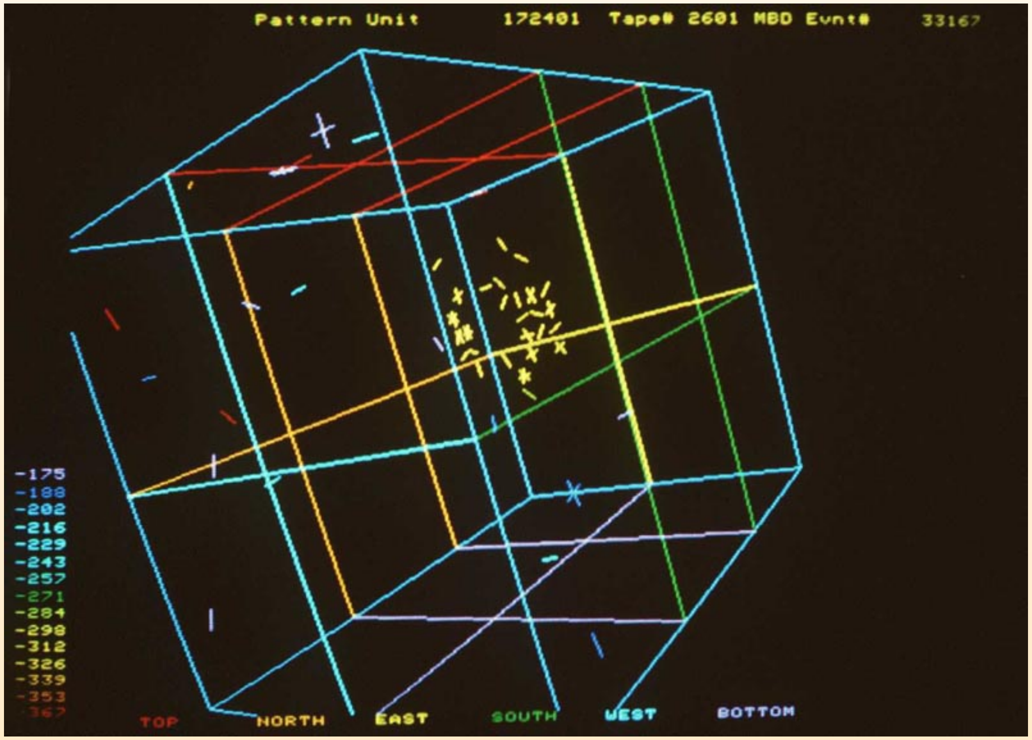
Inverted hierarchy



- Inverted hierarchy $\Leftrightarrow$ large $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ conversion

SN1987A

- On Feb 23rd, 1987, a supernova exploded in the Large Magellanic Cloud
- Its neutrino emission was detected by Kamiokande (Japan) and IMB (US)



SN1987A neutrino signal

- Overall, twenty neutrinos detected
- All neutrinos interpreted as $\bar{\nu}_e$'s
- From the measured energy spectrum, a low-energy flux $F_{\bar{\nu}_e}$ was inferred, consistent with no oscillations
- Smirnov *et al.*, PRD 49 (1994) 1389:

$$p \leq 0.35 \text{ @ } 99\% \text{ CL}$$

where the permutation factor p is defined as:

$$F_{\bar{\nu}_e}(E) \propto pF^0_{\bar{\nu}_\mu}(E) + (1-p)F^0_{\bar{\nu}_e}(E)$$

Event no.	Time (UT) on Feb 23	E_{det} (MeV)	ϑ_{LMC} (deg)
Kam-2			
K-1	7:35:35.00	20.0 ± 2.9	18 ± 18
K-2	35.11	13.5 ± 3.2	40 ± 27
K-3	35.30	7.5 ± 2.0	108 ± 32
K-4	35.32	9.2 ± 2.7	70 ± 30
K-5	35.51	12.8 ± 2.9	135 ± 23
K-6	35.69	6.3 ± 1.7	68 ± 77
K-7	36.54	35.4 ± 8.0	32 ± 16
K-8	36.73	21.0 ± 4.2	30 ± 18
K-9	36.92	19.8 ± 3.2	38 ± 22
K-10	44.22	8.6 ± 2.7	122 ± 30
K-11	45.43	13.0 ± 2.6	49 ± 26
K-12	47.44	8.9 ± 1.9	91 ± 39
IMB			
I-1	7:35:41.37	38 ± 7	80 ± 10
I-2	41.79	37 ± 7	44 ± 15
I-3	42.02	28 ± 6	56 ± 20
I-4	42.52	39 ± 7	65 ± 20
I-5	42.92	36 ± 9	33 ± 15
I-6	44.06	36 ± 6	52 ± 10
I-7	46.38	19 ± 5	42 ± 20
I-8	46.96	22 ± 5	104 ± 20

Constraints on neutrino oscillations from SN1987A

- LSND-inverted hierarchies are excluded ($\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$ $\bar{\nu}_s$):

2+2 Models

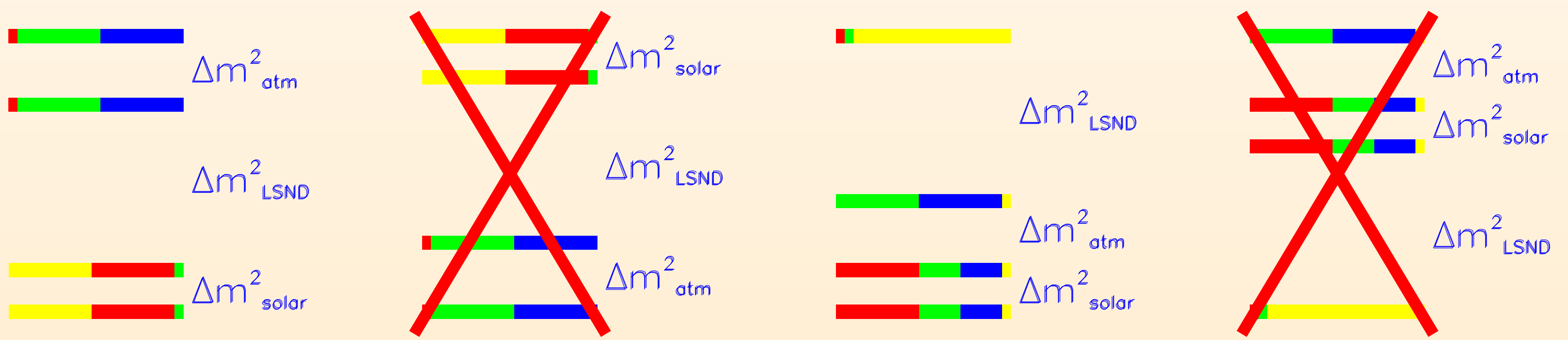
Normal hierarchy

"LSND-inverted" hierarchy

1+3 Models

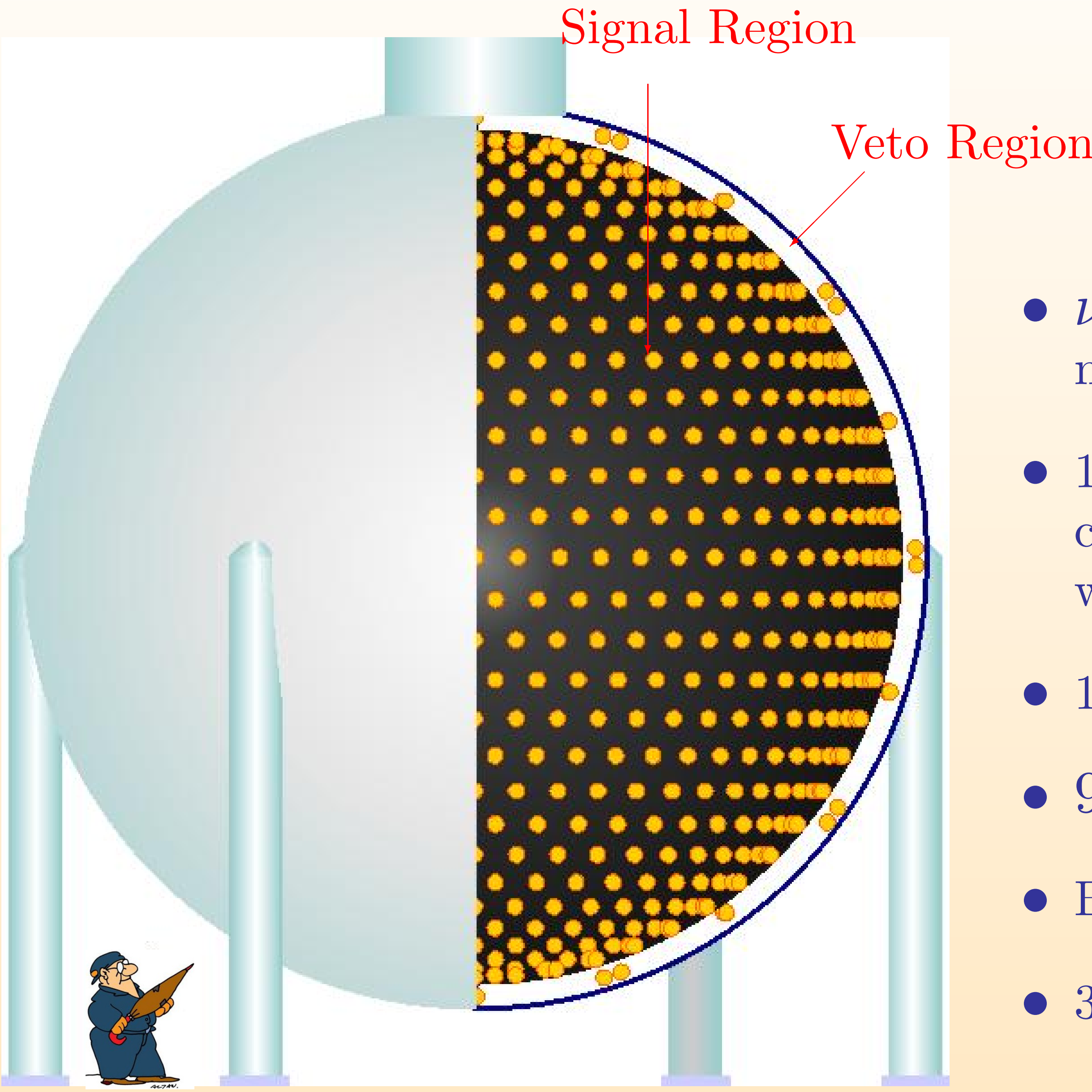
Normal hierarchy

"LSND-inverted" hierarchy



- For the normal mass hierarchy schemes, SN1987A data do not provide competitive constraints
- A future SN neutrino detection will help in further constraining neutrino mass & mixing models

MiniBooNE



- $\nu_\mu \longrightarrow \nu_e$ oscillation experiment at Fermilab
- 12m in diameter spherical Cherenkov detector filled with 800t of mineral oil
- 1280 PMTs (10% coverage)
- 99% efficient veto shield
- Beam duty factor: $8 \cdot 10^{-6}$
- 3m dirt overburden

BooNE collaboration & SN team

- I. Stancu, **University of Alabama**
- S. Koutsoliotas, **Bucknell University**
- E. Church, G. J. VanDalen, **University of California, Riverside**
- E. Hawker, R. A. Johnson, J. L. Raaf, N. Suwonjandee, **University of Cincinnati**
- T. Hart, E. D. Zimmerman, **University of Colorado**
- L. Bugel, J. M. Conrad, J. Formaggio, J. M. Link, J. Monroe, M. H. Shaevitz, M. Sorel, G. P. Zeller, **Columbia University**
- D. Smith, **Embry Riddle Aeronautical University**
- C. Bhat, S. J. Brice, B. C. Brown, B. T. Fleming, R. Ford, F. G. Garcia, P. Kasper, T. Kobilarcik. I. Kourbanis, A. Malensek, W. Marsh, P. Martin, F. Mills, C. Moore, E. Prebys, A. D. Russell, P. Spentzouris, R. Stefanski, T. Williams, **Fermi National Accelerator Laboratory**
- P. J. Nienaber, **College of the Holy Cross**
- D. C. Cox, A. Green, H.-O. Meyer, R. Tayloe, **Indiana University**
- G. T. Garvey, W. C. Louis, G. B. Mills, E. Quealy, V. Sandberg, B. Sapp, R. Schirato, R. Van de Water, D. H. White, **Los Alamos National Laboratory**
- R. Imlay, W. Metcalf, M. Sung, M. O. Wascko, **Louisiana State University**
- J. Cao, Y. Liu, B. P. Roe, **University of Michigan**
- A. O. Bazarko, M. Leung, P. D. Meyers, R. Patterson, F. C. Shoemaker, **Princeton University**

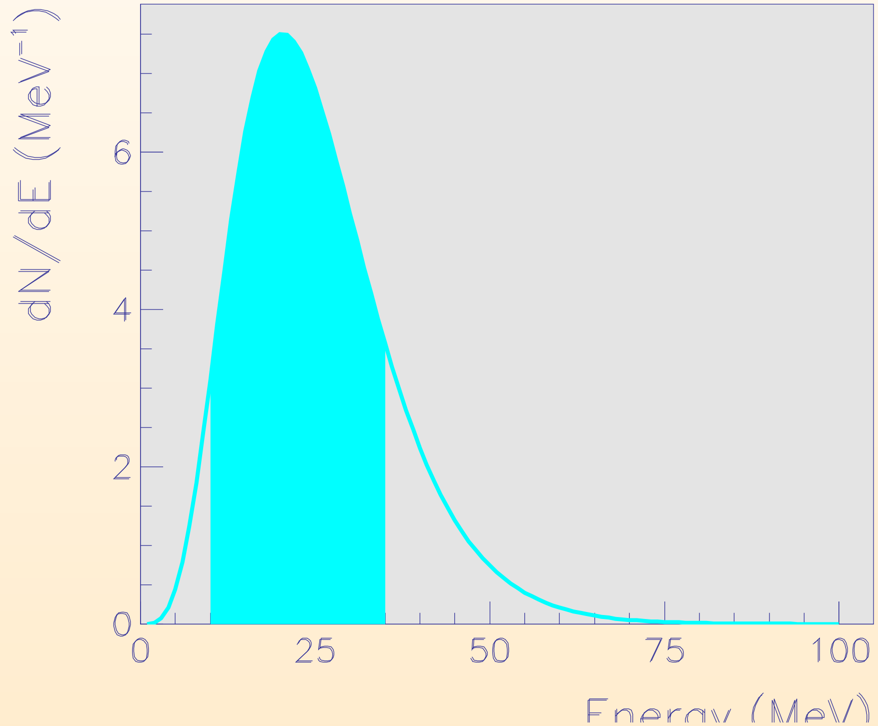
MiniBooNE SN team:

- John Beacom
- Matthew Sharp
- Joe Formaggio
- Richard Schirato
- Janet Conrad
- Michel Sorel

SN signal in MiniBooNE

- For a SN explosion in the center of our Galaxy, we expect ~ 200 neutrino interactions in MiniBooNE, mostly from the CC reaction: $\bar{\nu}_e + p \longrightarrow e^+ + n$

  - Half of the detected positrons have an energy in the range $10\text{MeV} < E < 35\text{MeV}$

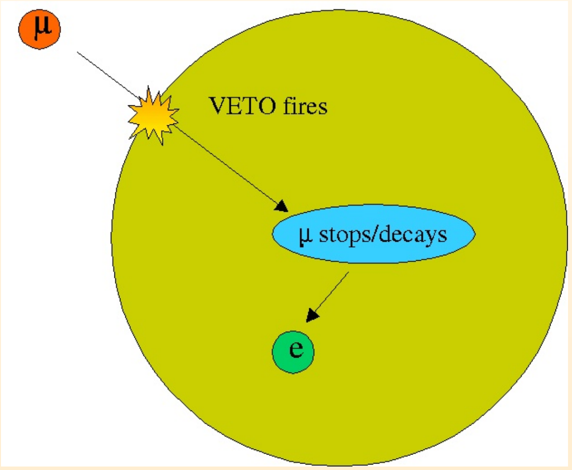


- The NC reaction: $^{12}C + \nu \longrightarrow ^{12}C^* + \nu$
  $\hookrightarrow ^{12}C + \gamma(15.1\text{MeV})$

  is expected to give 20-30 interactions

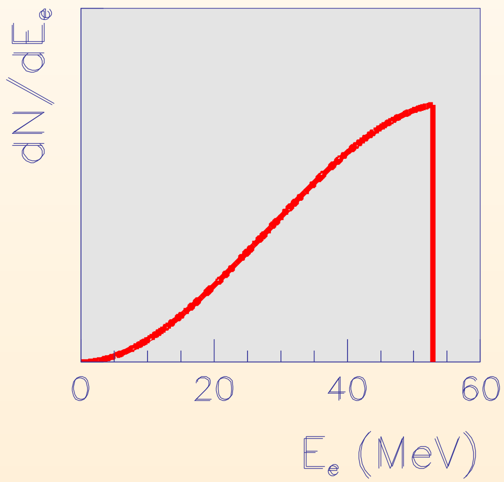
Backgrounds to SN events

- Background due to 10kHz rate of cosmic ray muons entering the detector, 2kHz of which stop inside. Muons typically tagged by veto shield.



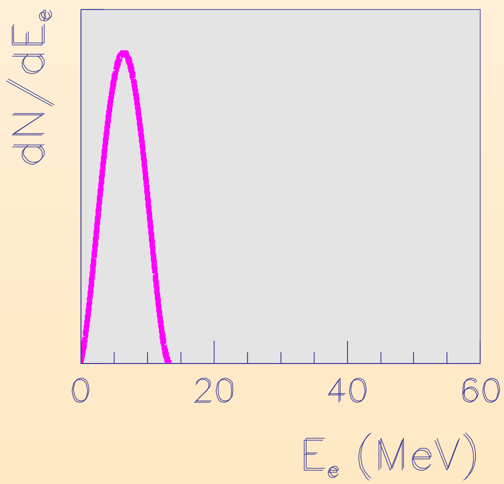
1. Muons decaying

   Signature: "high-energy", Michel electrons



2. Muons capturing on C atoms

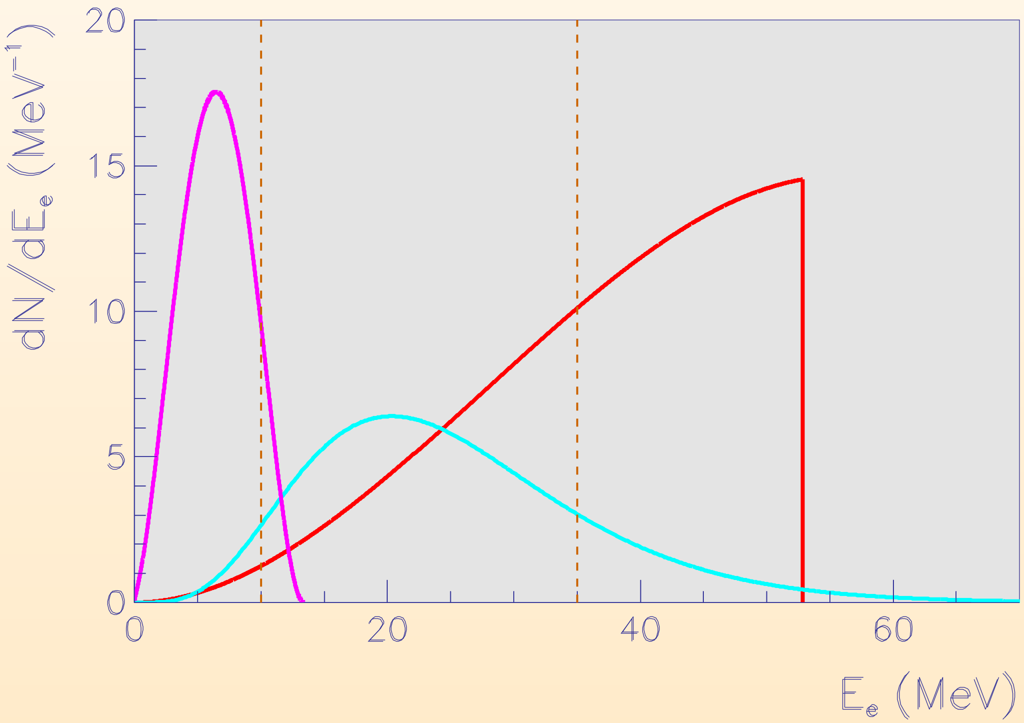
   ^{12}B atoms created, which β-decay (long half-life)
   Signature: low-energy, β-decay electrons



Background reduction

- Excluding events within $10\mu s$ of a 99% efficient veto tag, left with:
  - 90% of SN signal
  - 40Hz of background Michel electrons, 15Hz of background ^{12}B β-decay electrons

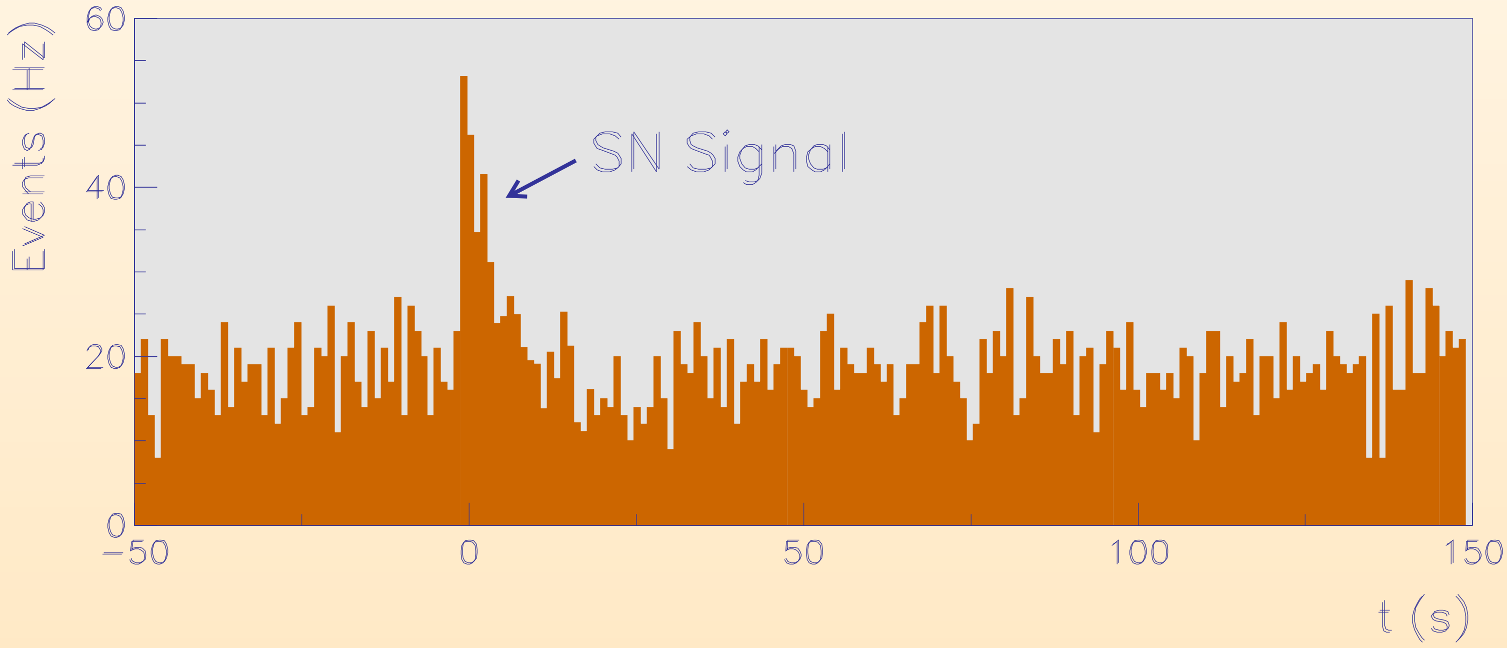
- Integrating over the $10s$ of a typical SN neutrino burst:



- We will measure the energy spectrum of the backgrounds very accurately

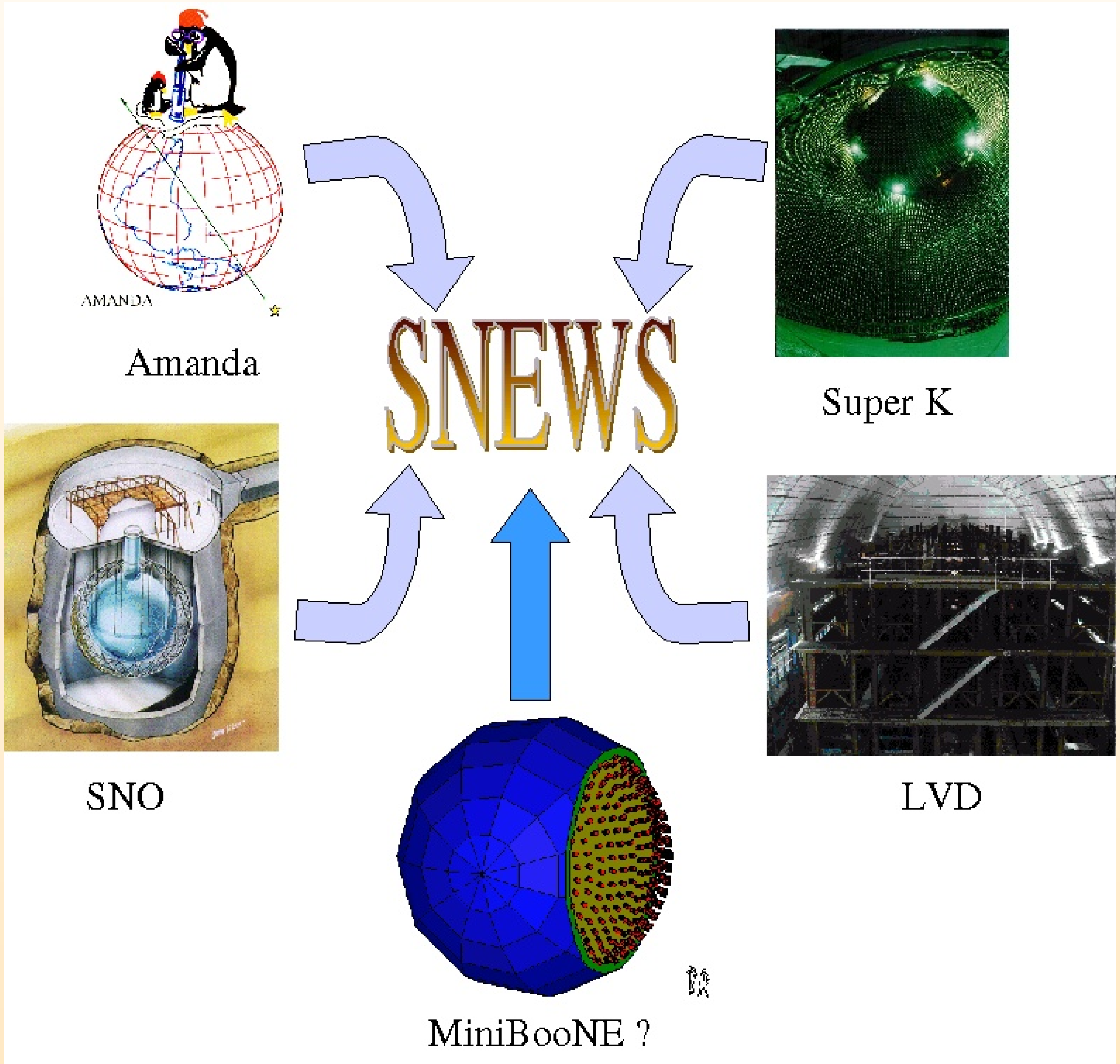
Triggering on a SN

- Selecting only events in the 10MeV $<$ E $<$ 35MeV energy range:
  - 45% of SN signal
  - 20Hz of background Michel electrons, 1-2Hz of background ^{12}B β-decay electrons
- Easy to catch a real SN trigger, while keeping false trigger rate reasonably low
- For a typical, galactic SN signal (sharp rise with τ=3s exponential decay):



SNEWS

SuperNova Early Warning System



- Many ν detectors watching for SN
- If the network sees a SN, an alert is sent to astronomers
- More nodes reduce drastically false alarm rates

MiniBooNE detector

General status of MiniBooNE

The detector:

- PMT's and calibration systems installed
- 1/2 filled with oil
- DAQ works
- Starting to look at cosmic ray events!

The beamline (for main $\nu_\mu \to \nu_e$ search):

- Magnets are being installed in tunnel
- Magnetic focusing horn tested to >10 million pulses
- First bit of beam in April!

We have much to learn!

- "Learning Curve" in late spring/early summer
- Last fixes during "July shutdown"
- and then...*we run!*

MiniBooNE's first Cherenkov ring!