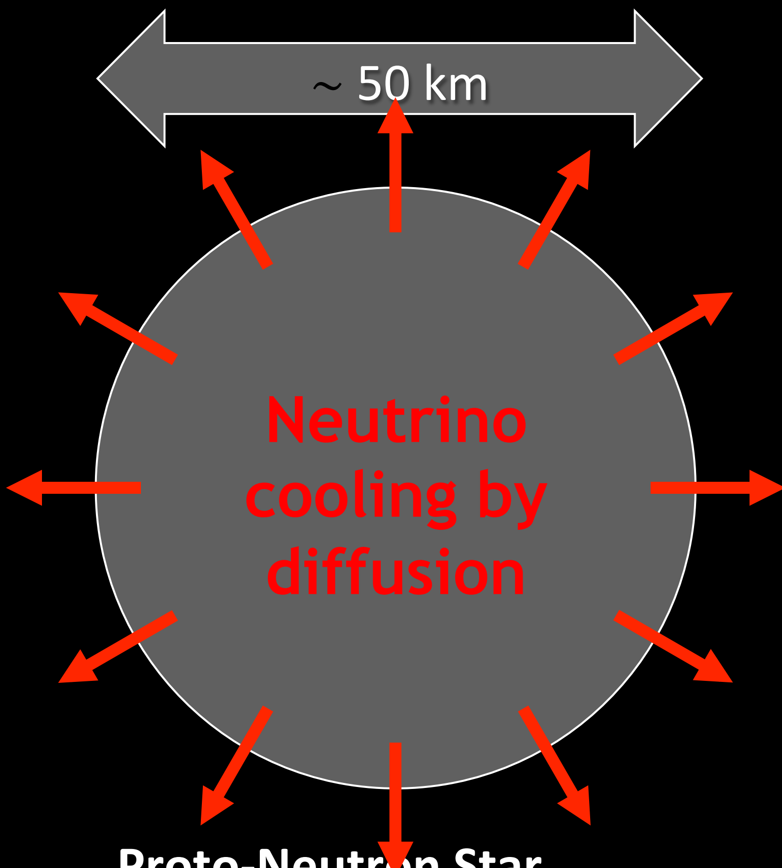
Low Energy Neutrino Measurements with CAPTAIN

R.Svoboda, Santa Fe 2014


Future Potential for
Supernova Neutrino
Detection with LBNE

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \quad \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

T 10 MeV

Gravitational binding energy

$$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{SUN}\, c^2$$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion

0.01% Photons, outshine host galaxy

Neutrino luminosity

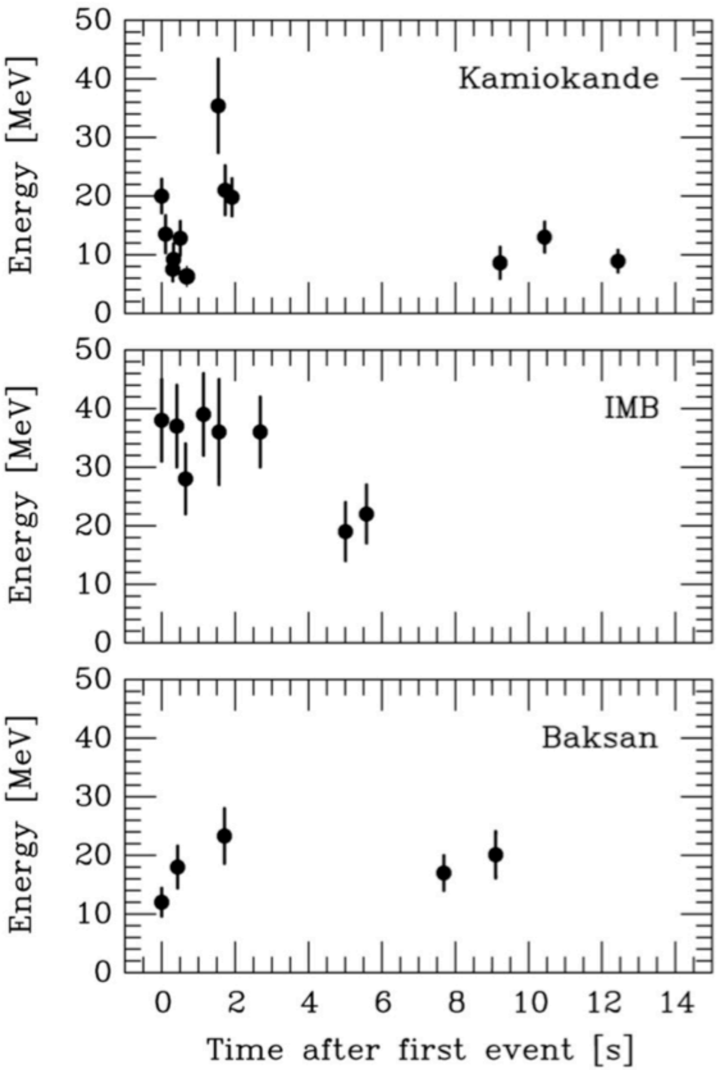
$L_\nu \quad 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

$3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

Physics from the 1987A Supernova

- SN1987A, average of **one citation every ten days for last 26 years** – only 20 events total!
- Most precise straightforward test of weak equivalence
- Direct neutrino TOF with 10^5 LY baseline (could be enhanced by LIGO signal)
- Limits on neutrino decay over 10^5 years
- Energy loss to generic "sterile" particles in Type-II collapse
- **Type II/Ib SN thought to happen every ~15 years**



The Galactic Supernova Rate from COMPTEL ^{44}Ti γ-line Observations

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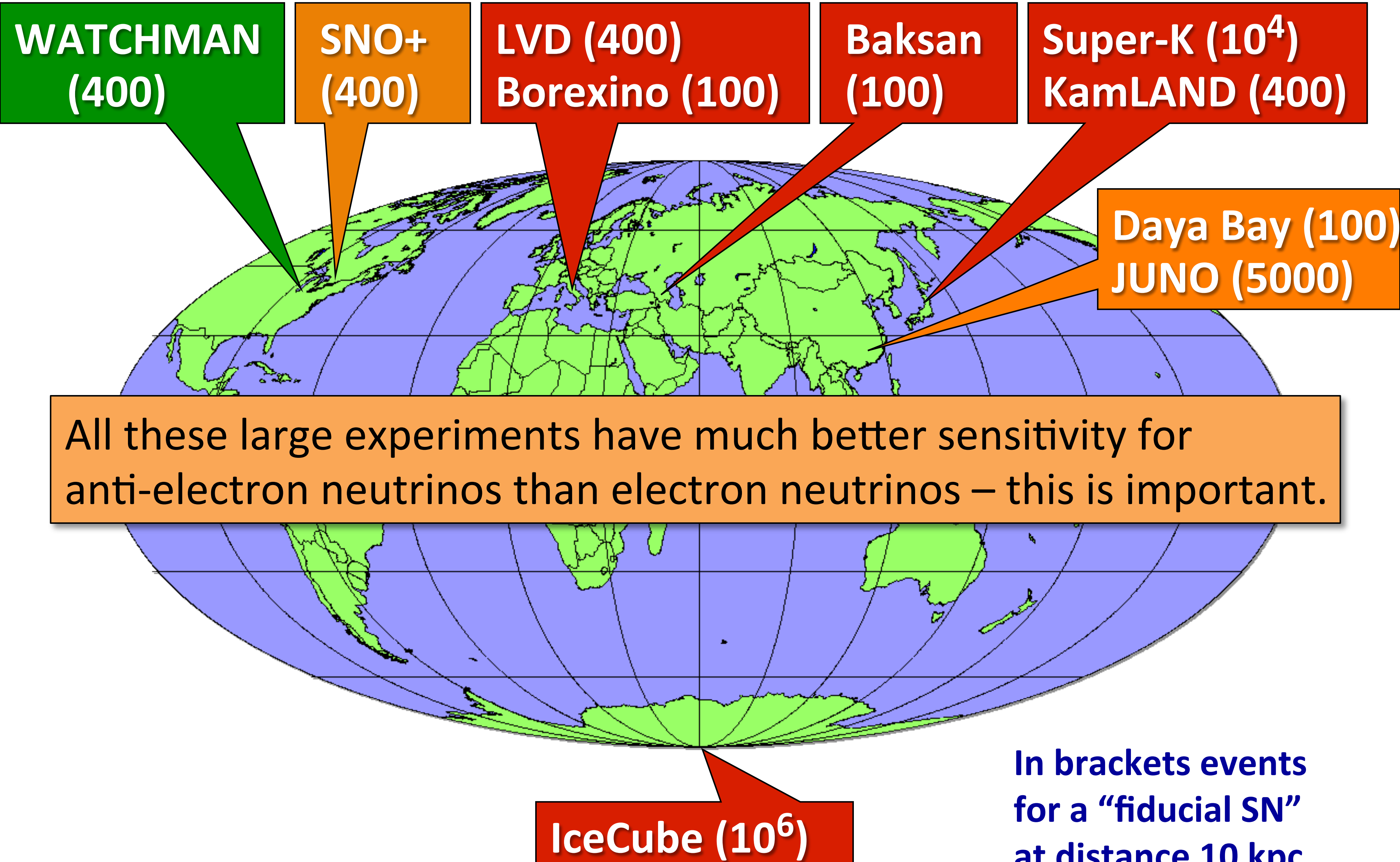
This is considered one of the most reliable methods for estimating SN rate in our galaxy

^{44}Ti has a half life of 63 years and comes from nucleosynthesis in Type-Ib and Type-II SN.

Measuring the amount of ^{44}Ti gives a good estimate of the rate over the last few 100 years, since gamma rays have much less attenuation than optical photons.

This gives a rate of 1 every 13-17 years, depending on assumed distribution in galaxy. ~50% chance for LBNE to see a SN.

Large Underground Detectors for Supernova Neutrinos

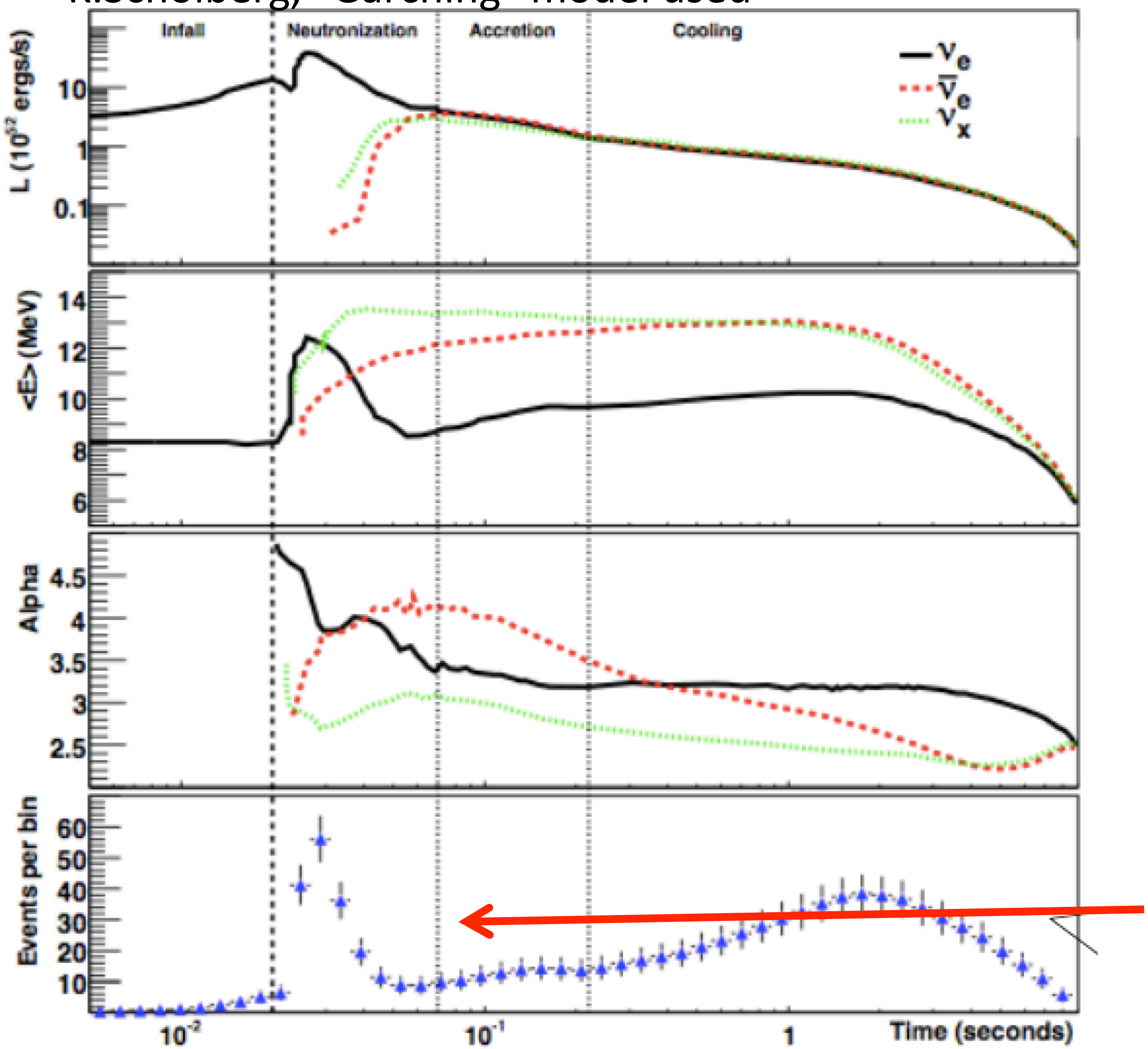


All these large experiments have much better sensitivity for anti-electron neutrinos than electron neutrinos – this is important.

In brackets events for a "fiducial SN" at distance 10 kpc

Detection of a SN neutronization burst requires ν_e sensitivity.

K.Scholberg, "Garching" model used



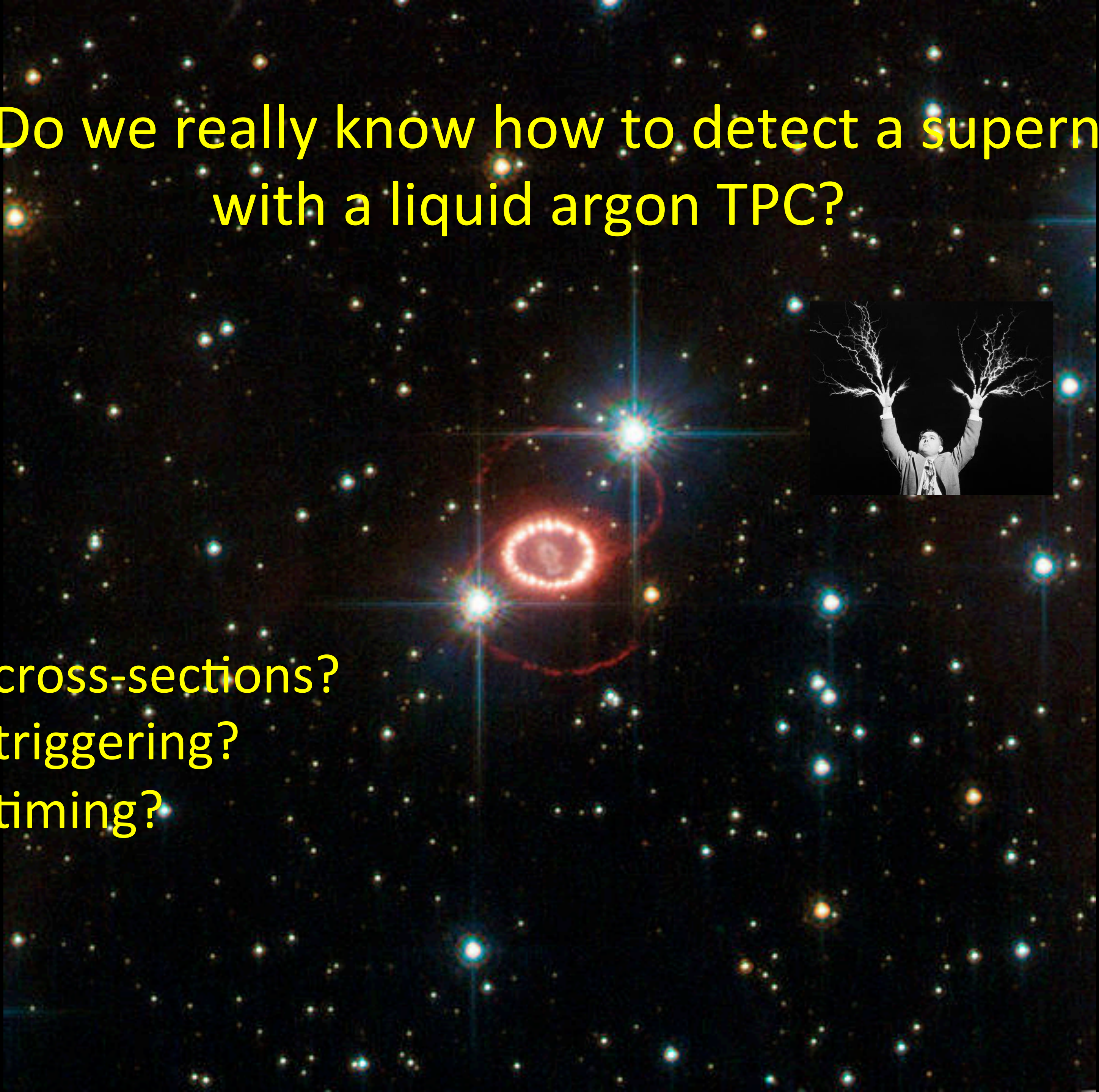
Burst is only 20 ms long and is essentially all ν_e

Mean energy of events is low, 10-12 MeV

IMB/Kamiokande detected higher energy cooling neutrinos, not neutrinos from the neutronization process

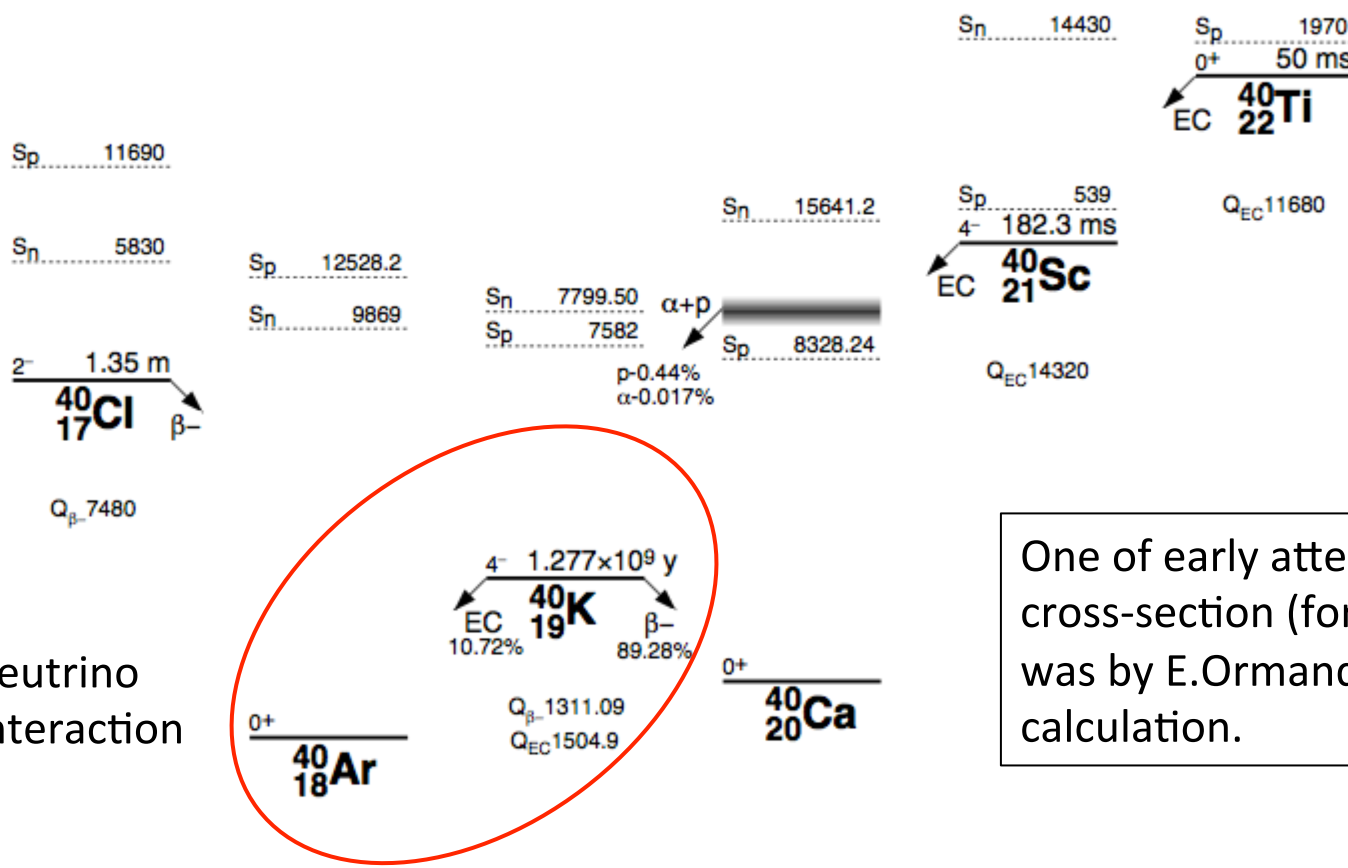
Potential for ν_e detection in liquid argon by LBNE

Do we really know how to detect a supernova with a liquid argon TPC?



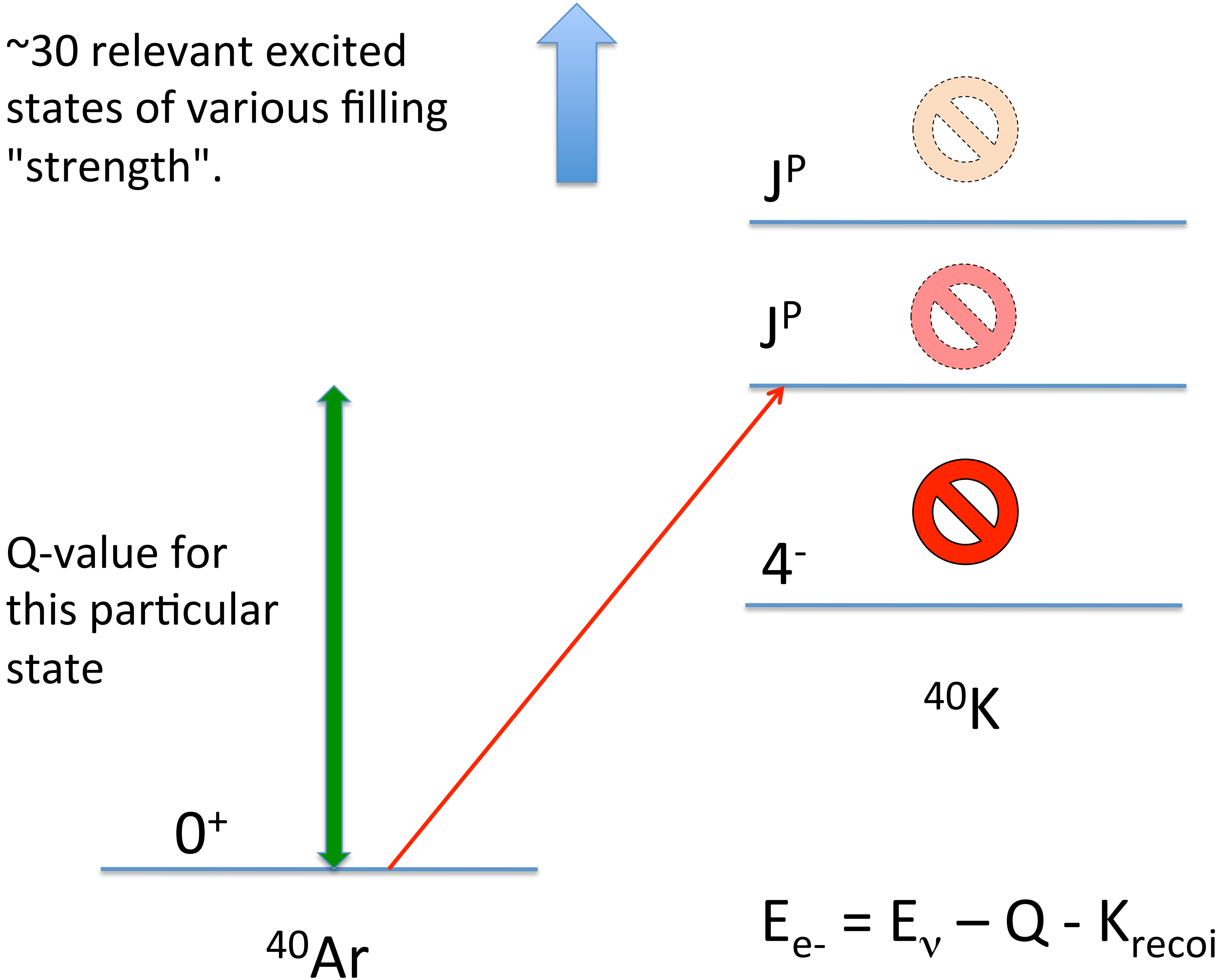
cross-sections?
triggering?
timing?

$\nu_e + {}^{40}Ar \rightarrow {}^{40}K_{g.s.} + e^-$ has a low threshold, but rarely occurs due to $0^+ \rightarrow 4^-$ (3rd forbidden) transition. Most all of the cross section is into excited states of ^{40}K.

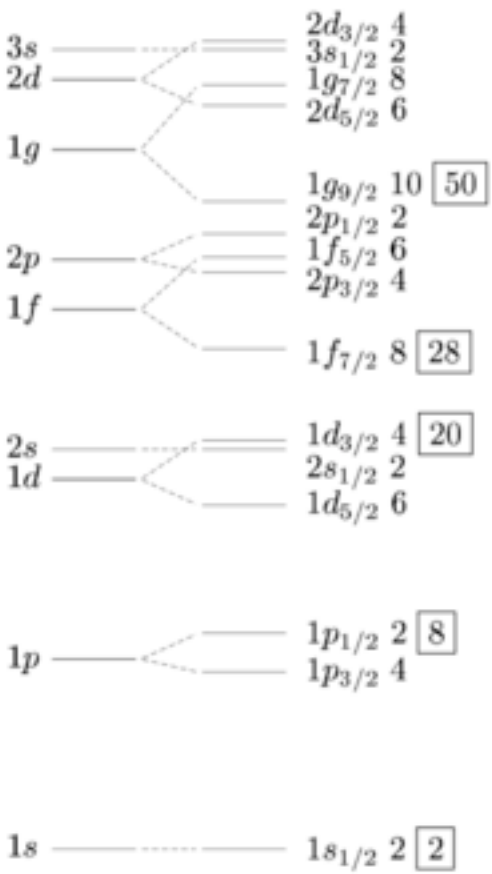


neutrino interaction

One of early attempts to calculate cross-section (for solar neutrinos) was by E.Ormand using shell model calculation.


~30 relevant excited states of various filling "strength".
Q-value for this particular state
0^+
^{40}Ar
J^P
J^P
4^-
^{40}K
$E_{e-} = E_\nu - Q - K_{recoil}$

How to get the "strengths"



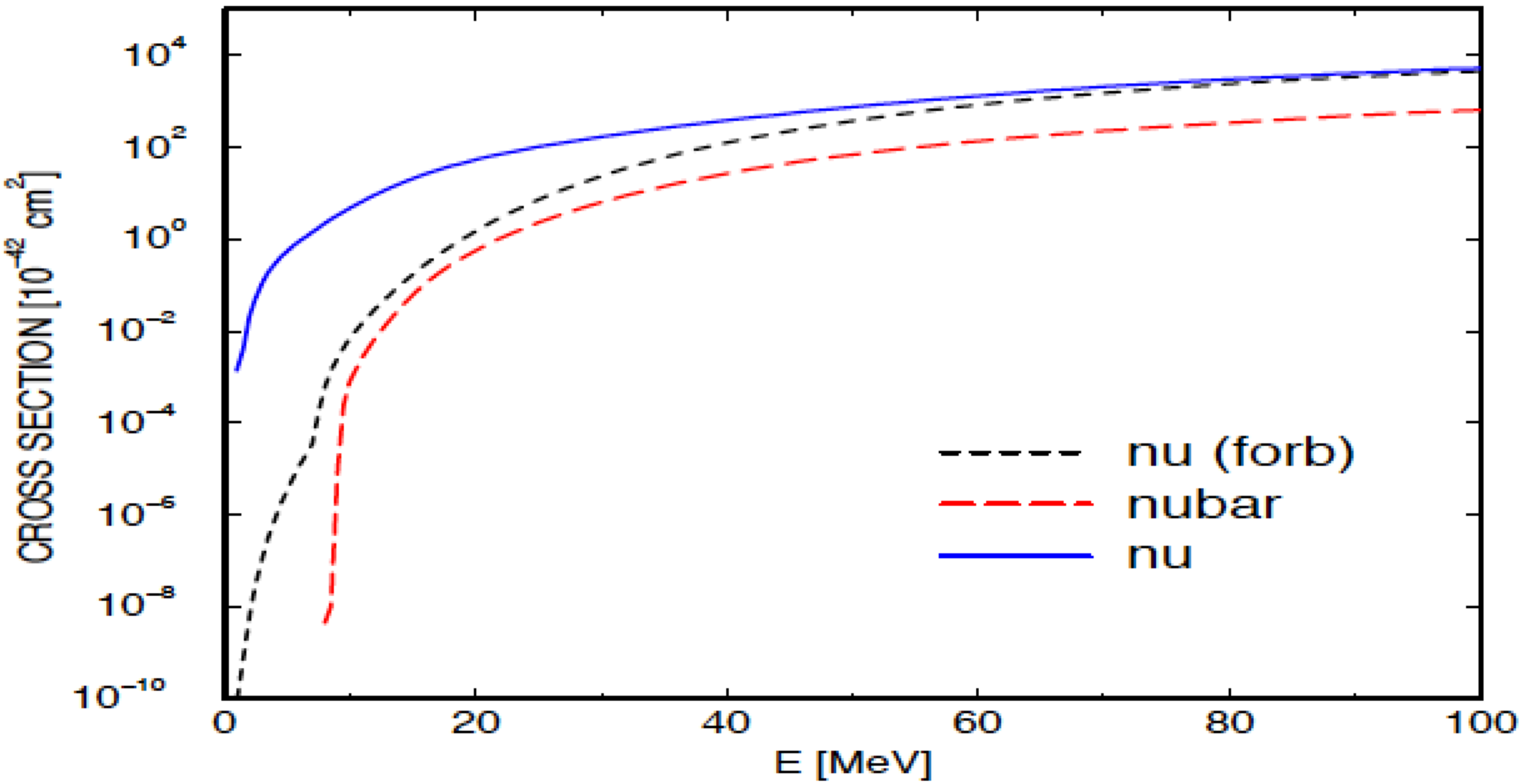
Vanilla shell model best at lower energies <12 MeV

40-Ar is Z=18 (2 proton holes) and N=22 (2 neutron partial shell). This makes a shell model calculation difficult and uncertain.

The Ormand et al. calculation used only the IAS Fermi transition plus the lowest six GT excited states lying below the IAS. Did not consider higher energy excited states relevant for SN.

RPA calculations have been done that are relavent to higher energies.

Transition from allowed to forbidden state strength in RPA calculation



RPA calculation, E.Kolbe, K.Langanke, G.Martinez-Pinedo, P.Vogel

J.Phys.G29:2569-2596,2003

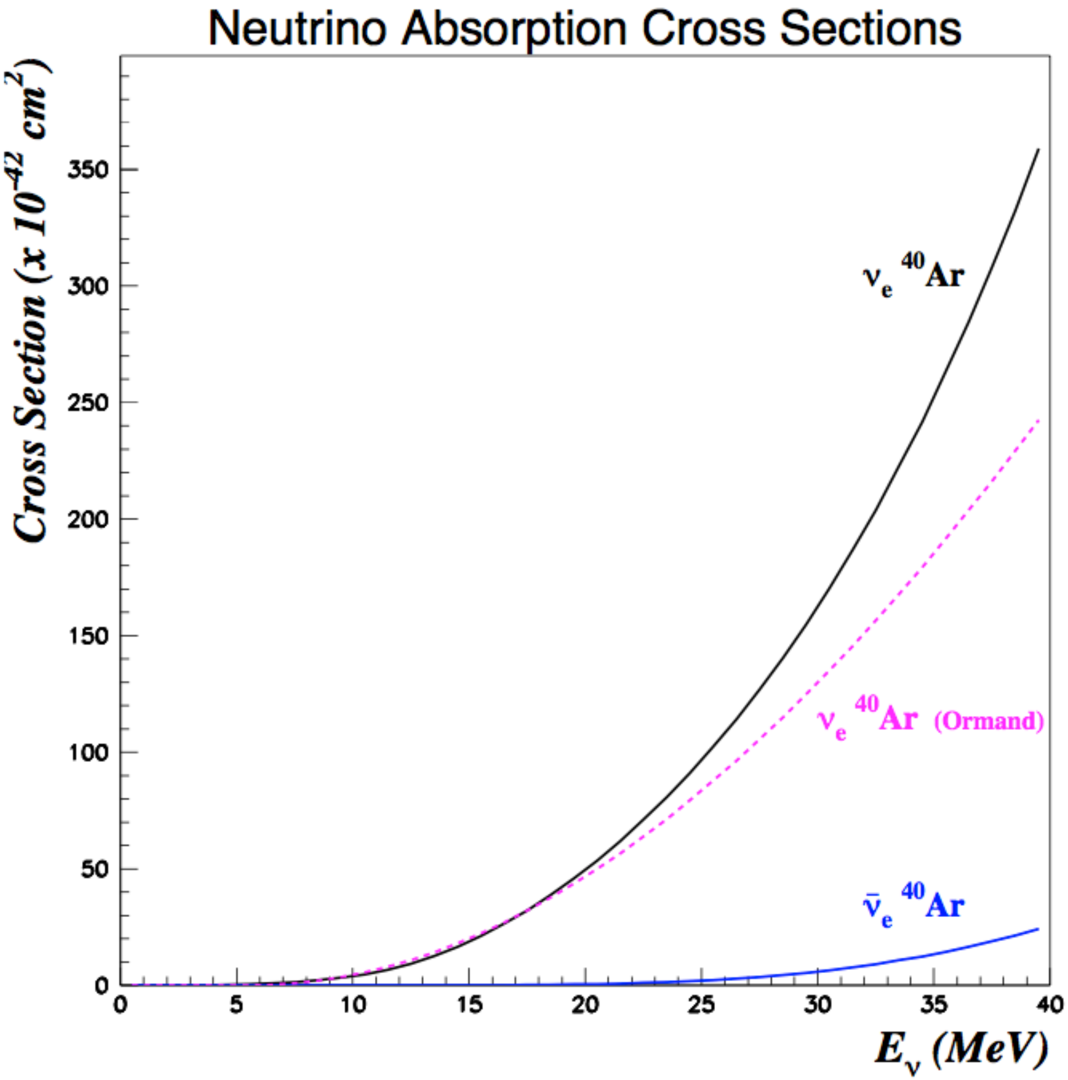


Figure 3: Cross sections as a function of neutrino energy for ν_e and $\bar{\nu}_e$ absorption reactions. We compare the results from shell model calculations [16] considering only Fermi and Gamow–Teller transitions with those from RPA calculations including all the multipoles [10].

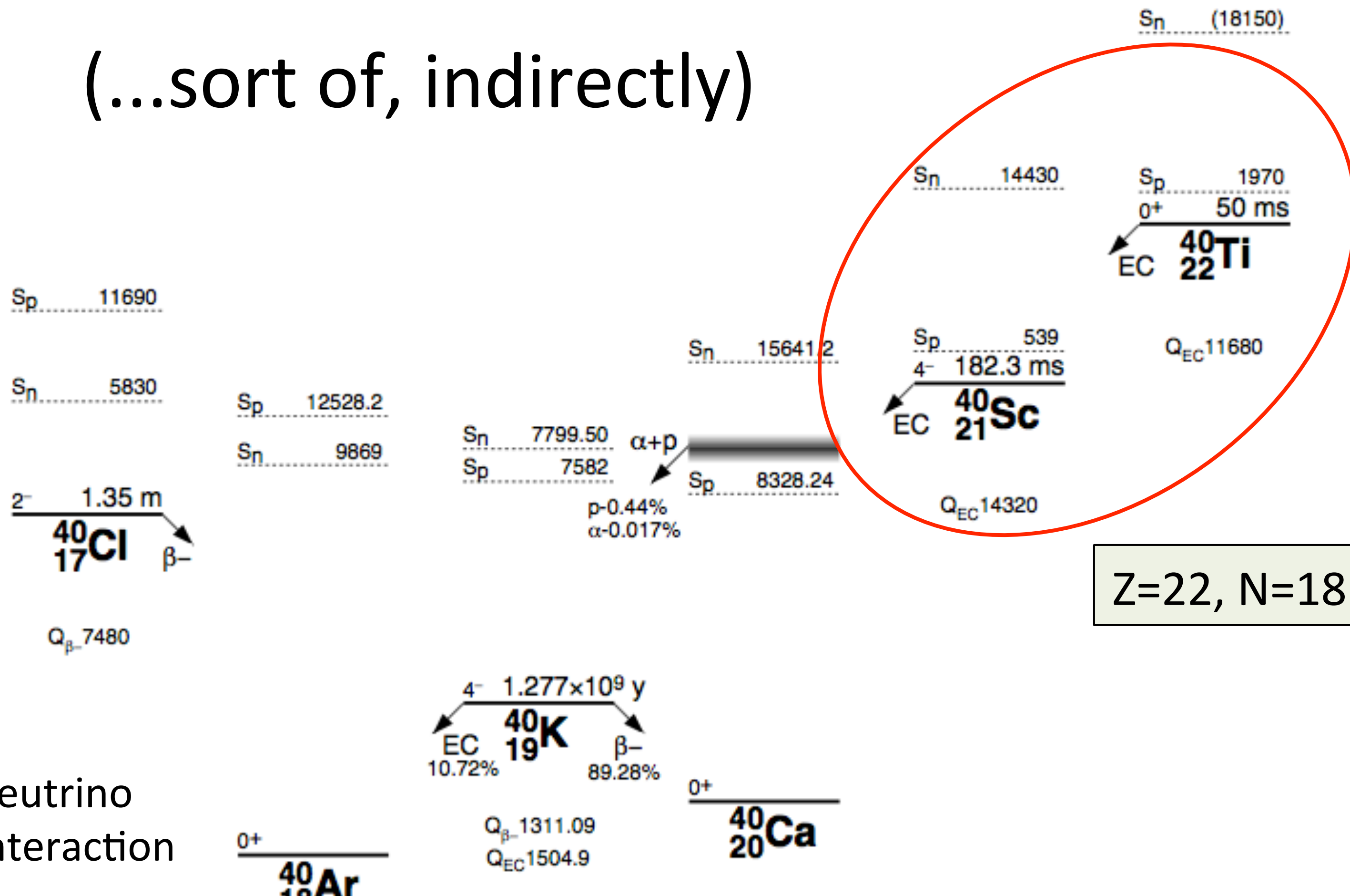
This is the RPA calculation used in a 2003 paper by Bueno, Gil-Botella, and Rubbia [hep-th/0307222]. This
Is used in many SN sensitivity Studies.

No error bars?

Can we just measure the strengths?

A=40
NP A521, 1(1990)

(...sort of, indirectly)



Z=22, N=18 to Z=21, N=19

neutrino interaction

Z=18, N=22 to Z=19, N=21

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

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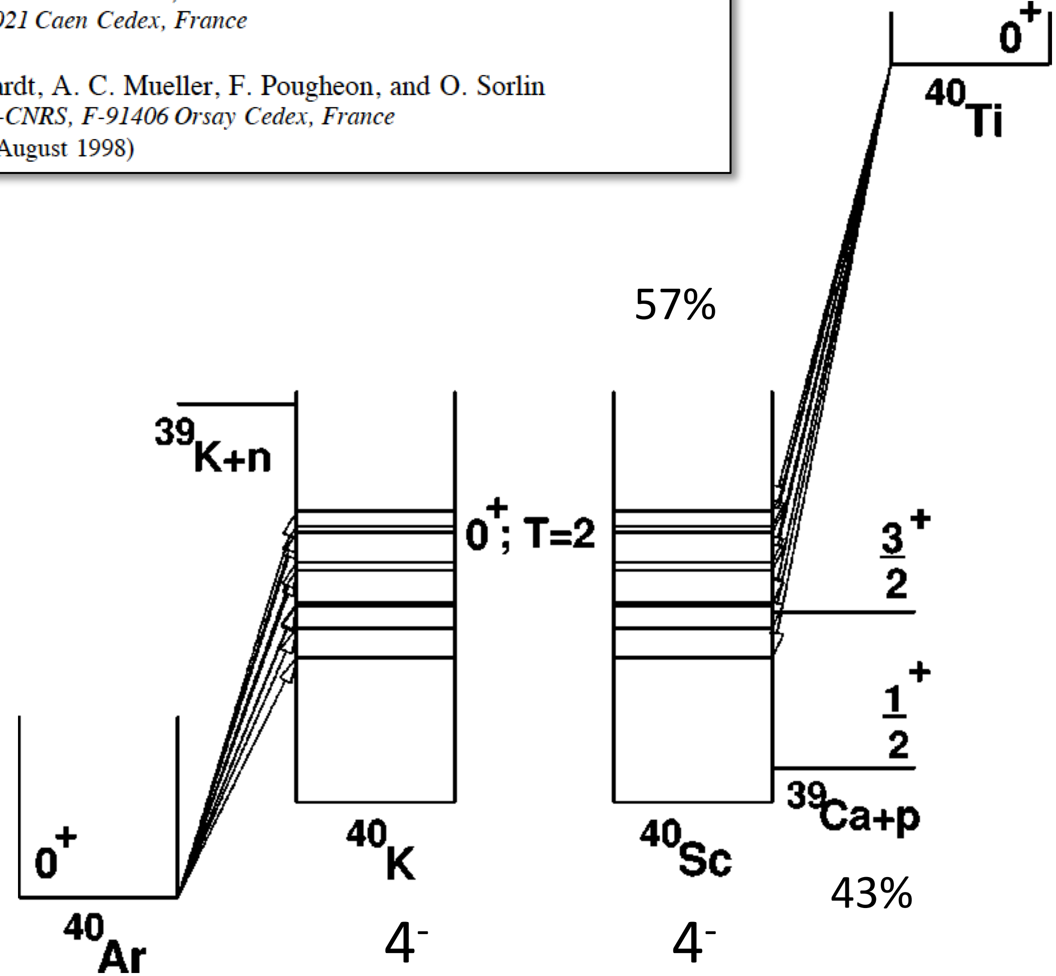
(Received 4 August 1998)

Make 40-Ti via heavy ions on a thin, heavy target (e.g. Cr on Ni). Embed ions in silicon detector.

Use TOF and dE/dx to separate 40-Ti out from ion "soup"

Observe beta decay to 40-Sc excited states, which decay via delayed proton emission



This work		Liu *et al.*[a] [11]	
E_x(keV)	B(%)	E_x(keV)	B(%)
		1750±20[c]	1.1±0.6
2281±8	23.78±0.61	2300±10	26.0±3.0
		2570±20[c]	0.6±0.3
2752±8	29.82±0.69	2770±10	32.0±3.0
2937±13	1.95±0.41		
3143±20	0.91±0.21	3100±20	1.3±0.7
3334±19	0.58±0.17	3350±20	1.0±0.5
(3569±56)	(0.11±0.11)		
3652±10	1.73±0.20		
3786±10[b]	2.58±0.29	3760±10	4.7±0.5
(3861±49)	(0.11±0.11)		
4067±24	0.43±0.14		
4111±30[b]	0.86±0.19		
4267±10	2.05±0.22		
4364±8[b]	25.32±0.82	4370±10	31.0±3.0
4522±12	1.85±0.28		
4655±12[b]	1.97±0.29		
4825±21[b]	2.14±0.36	4780±20	0.9±0.5
5017±27[b]	1.39±0.35		
5080±35[b]	0.86±0.26	5070±20	1.1±0.6
(5223±32)	(0.11±0.11)	(5360±20)	(0.4±0.2))
5696±23	0.24±0.09	>5500	0.7±0.2
6006±21	0.21±0.07		
Total	99.00±1.59		100.8±5.4

[a]Listed simply in order of increasing excitation energy.
[b]Daughter state decaying to both the ground and first excited states of ^{39}Ca. The remaining transitions fed only the ^{39}Ca ground state.
[c]Ref. [11] assigned these groups to p_0 decays. We believe this is incorrect; we assign our corresponding groups to p_1 decays.

28 delayed proton states identified (ones in parenthesis are tentative). 21 associated with 40-Sc decay.

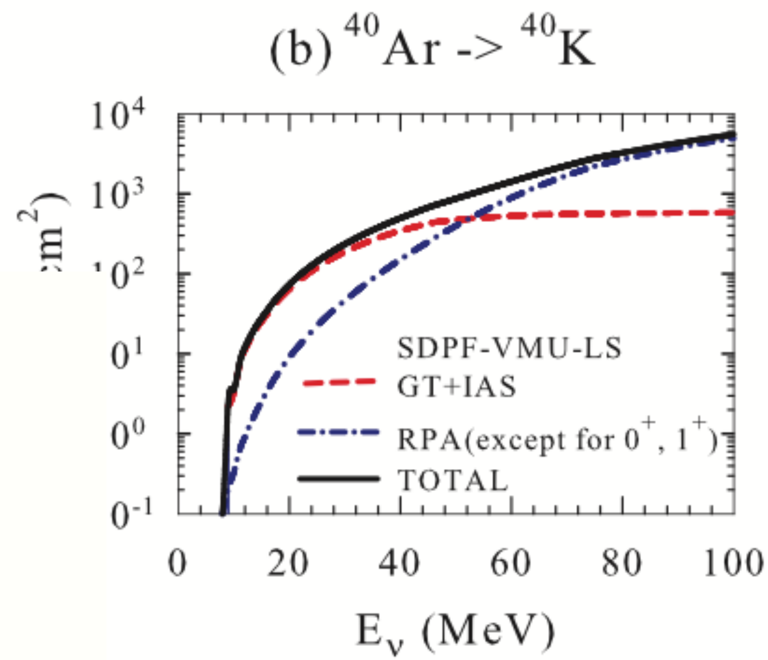
Branching ratios deduced from area of proton detection peak in Si detector.

Statistical error is very small. Hard to deduce systematic uncertainties after many corrections made for detection efficiency, event isolation corrections, etc. Many deduced from Monte Carlo. Also, 40-K becomes unbound at 8 MeV (40-Ti at 6 MeV) – what is the effect of that?

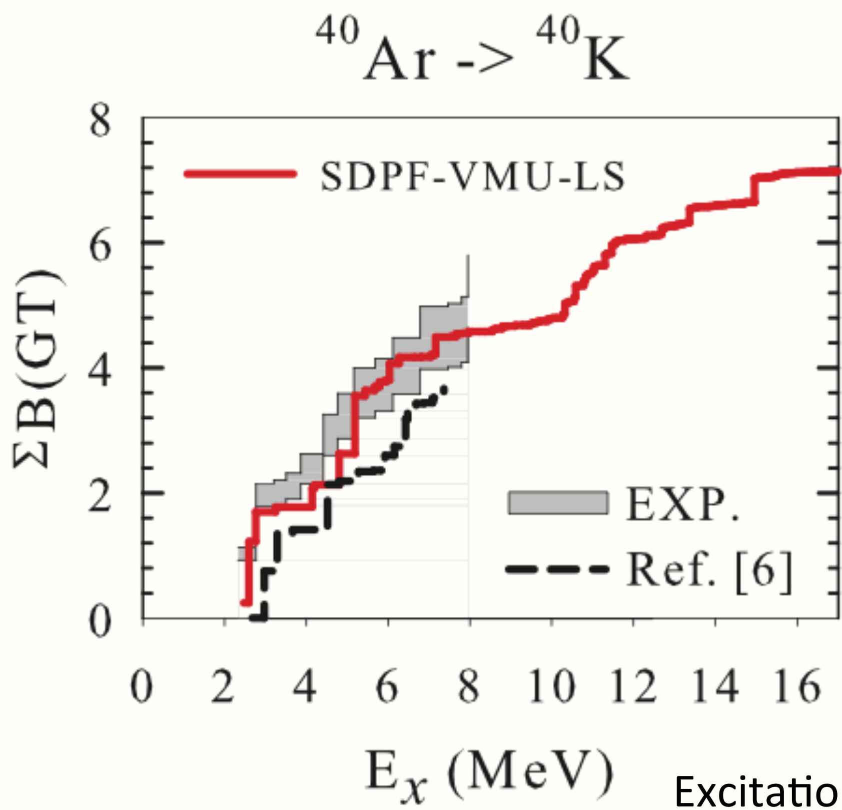
Question: How well can the analog decay be trusted to give the neutrino strengths given theoretical uncertainties?

Calculation of this cross-section has recently been revisited by Suzuki and Honma [arXiv:1211.4078]

They cut off 40-Ti data at 8 MeV and use hybrid Shell Model at low energy and RPA at higher energy.

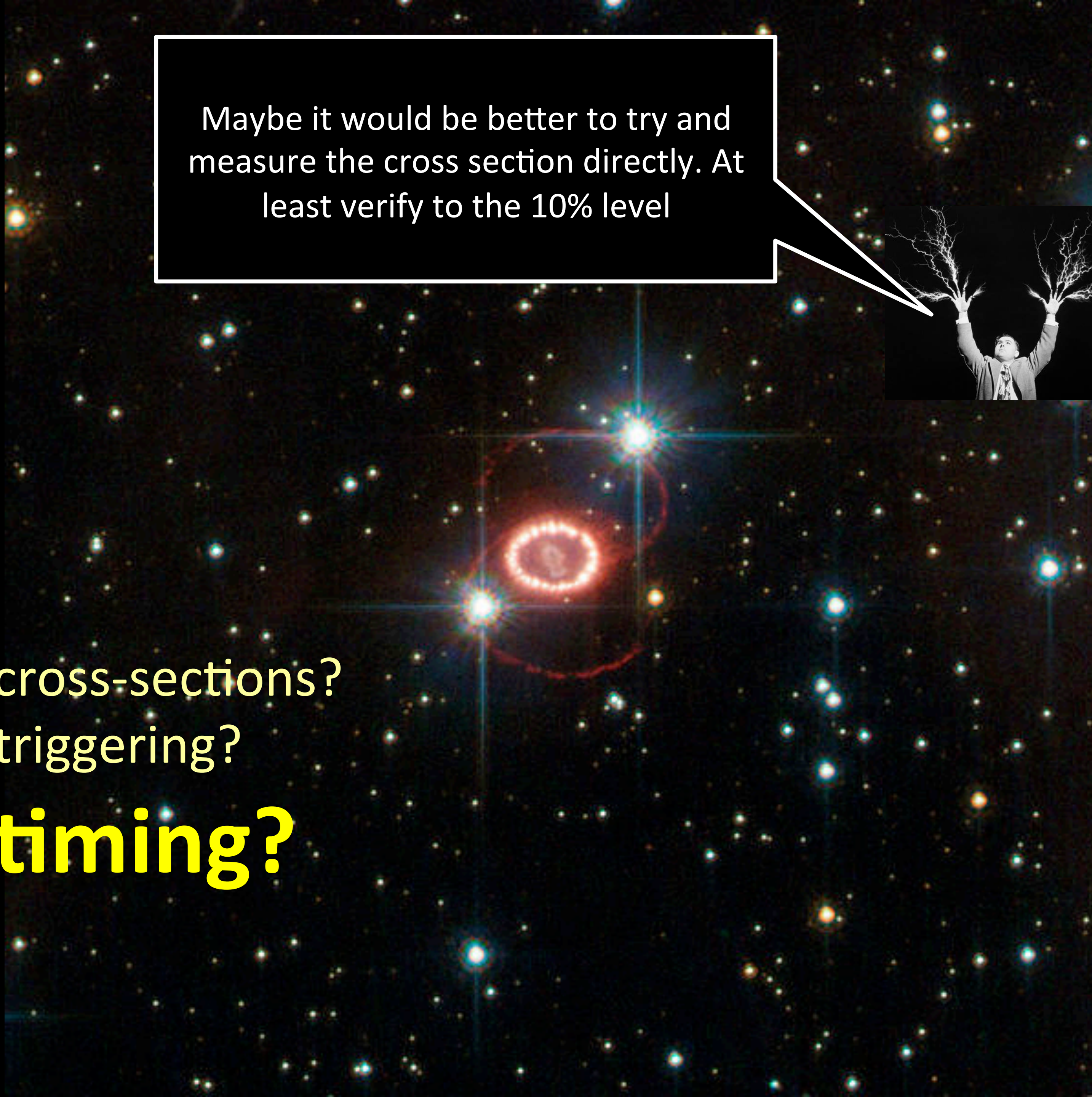


Neutrino Energy



Ormand calculation

Excitation Energy



Maybe it would be better to try and measure the cross section directly. At least verify to the 10% level

cross-sections?

triggering?

timing?

Timing dispersion at 10 kpc

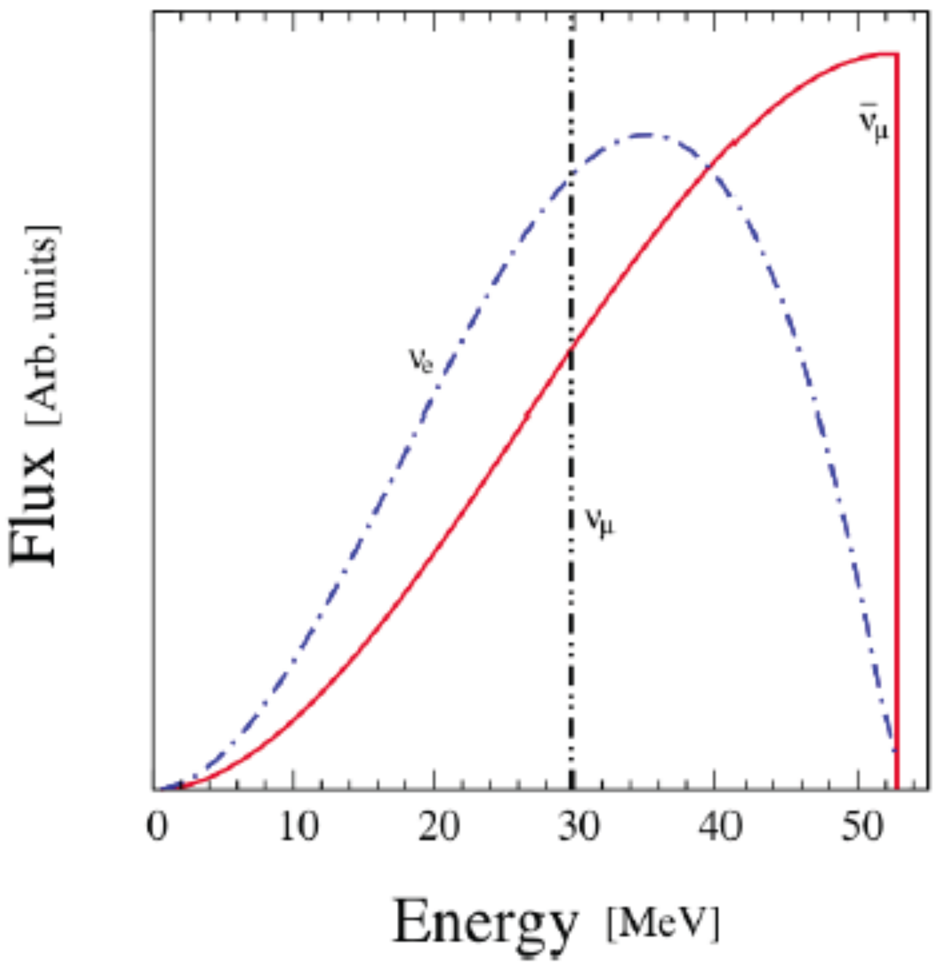
distance (kp)	**m1 (meV)**	**m2 (meV)**	
10	2	200	
E (MeV)	T2 (usec)	T1 (usec)	Dt
5	757.4	0.1	757.3
6	526.0	0.1	525.9
7	386.4	0.0	386.4
8	295.9	0.0	295.8
9	233.8	0.0	233.7
10	189.3	0.0	189.3
12	131.5	0.0	131.5
13	112.0	0.0	112.0
14	96.6	0.0	96.6
15	84.2	0.0	84.1
16	74.0	0.0	74.0
17	65.5	0.0	65.5
18	58.4	0.0	58.4
19	52.5	0.0	52.4
20	47.3	0.0	47.3

Questions

- Light yield of low energy events?
- Can we tell neutrino events from background?
- Is interaction rate consistent with calculated cross section?
- What kind of light collection would we need to get time of individual events?
- How to trigger on a SN?

Energy Spectrum for π Decay-at-Rest Beam

(No uncertainty in energy spectrum)

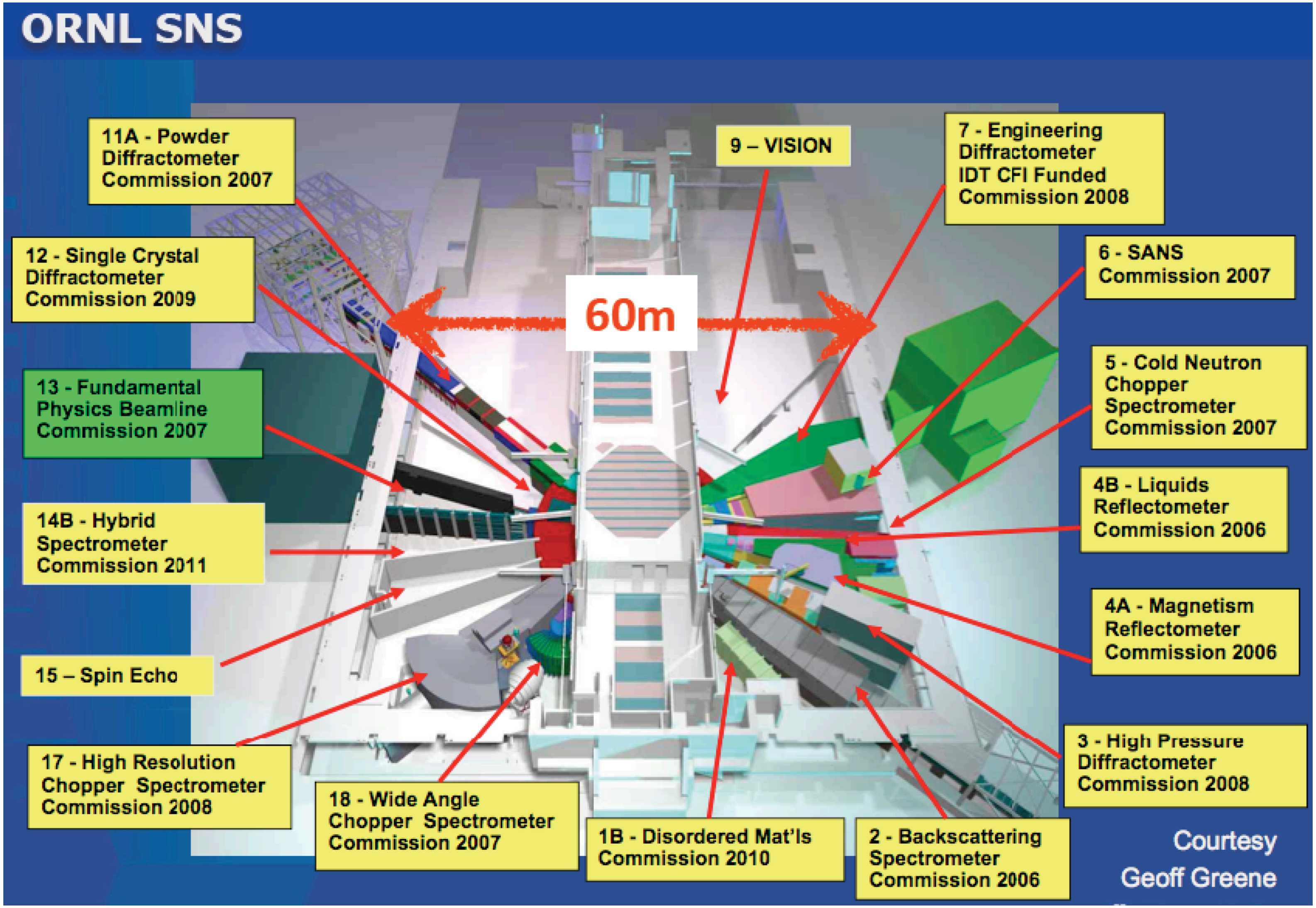


Can use neutrinos from a stopped pion beam as a low energy source of neutrinos

Well-defined electron neutrino spectrum

Good duty cycle (limited by muon lifetime)

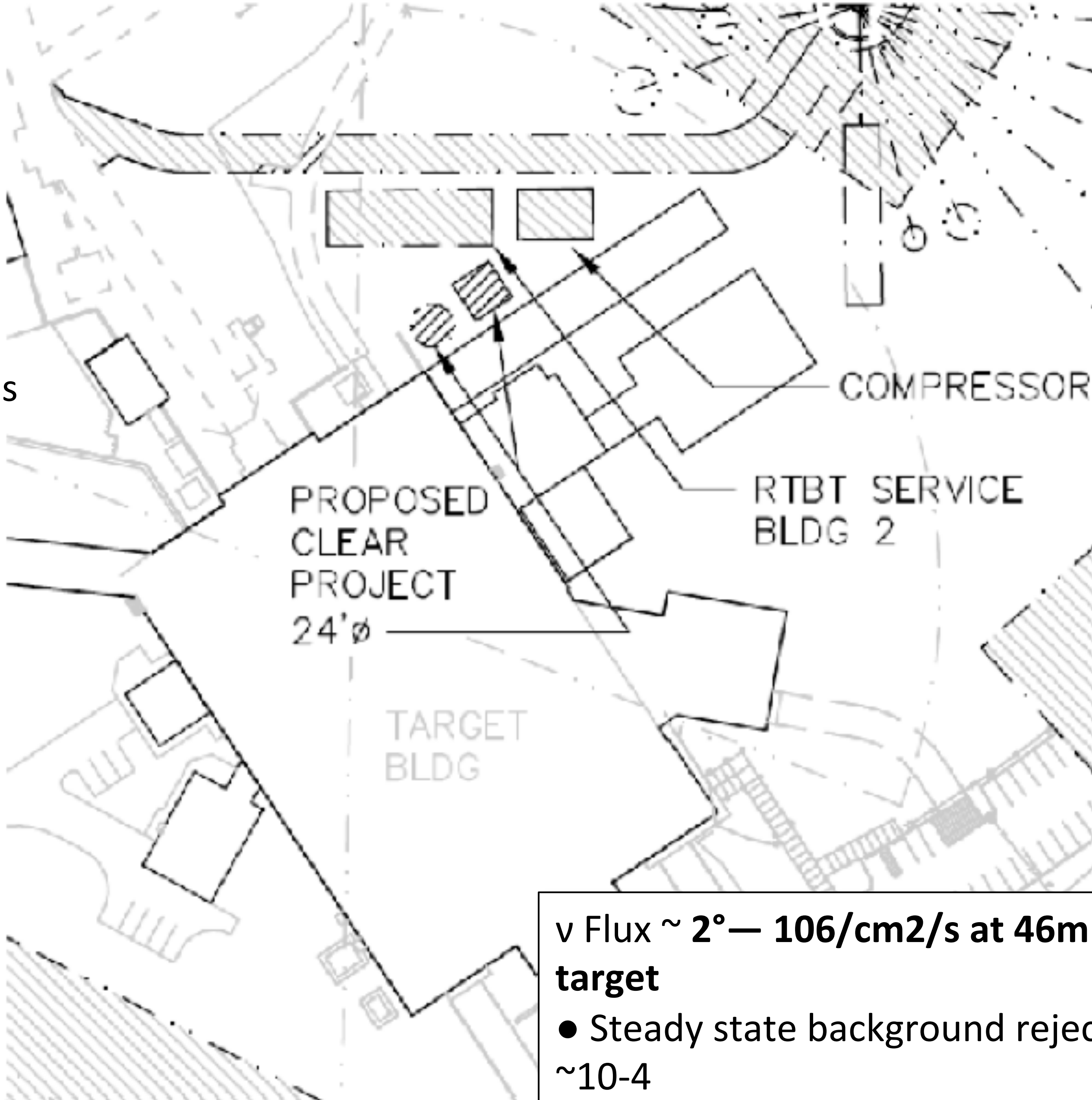
SNS: 1 MW 1000 Gev



Detector site 46 meters from the SNS target

1.4 MW
1000 MeV
0.12 neutrinos per POT on Hg target

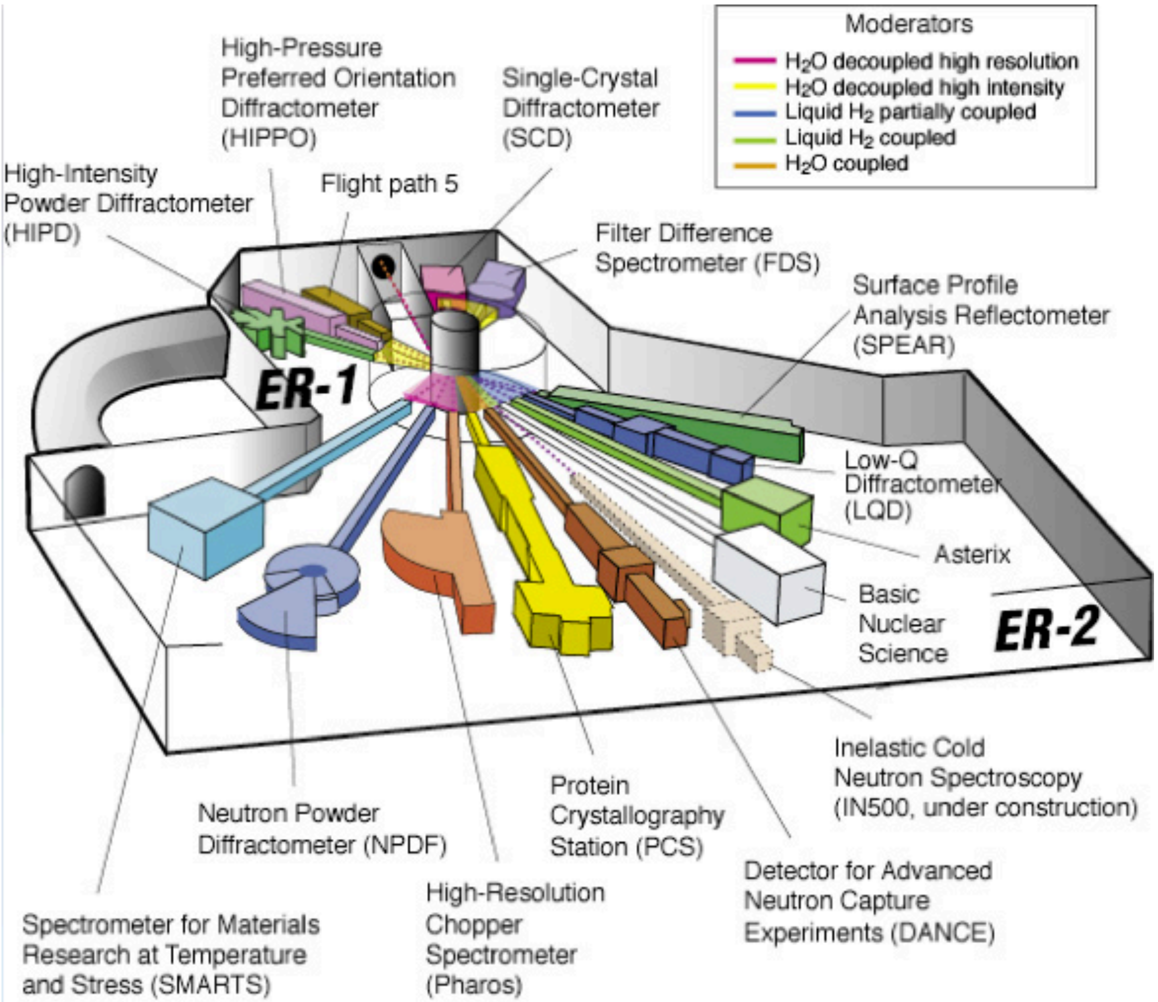
but need to go far away



ν Flux ~ **2°— 106/cm2/s at 46m from the target**

- Steady state background rejection factor ~10-4

Lujan: 800 MeV 100 kW



0.04 neutrinos/POT on tungsten target

Likely have to move far away

Fermilab:

- The only national laboratory in US dedicated to the particle physics
- Strong support on neutrino physics programs

Neutrino Signal at BNB calculated by MC from MB by Steve Brice. About 1 neutrino per POT (versus 0.12/0.04 for SNS/Lujan)

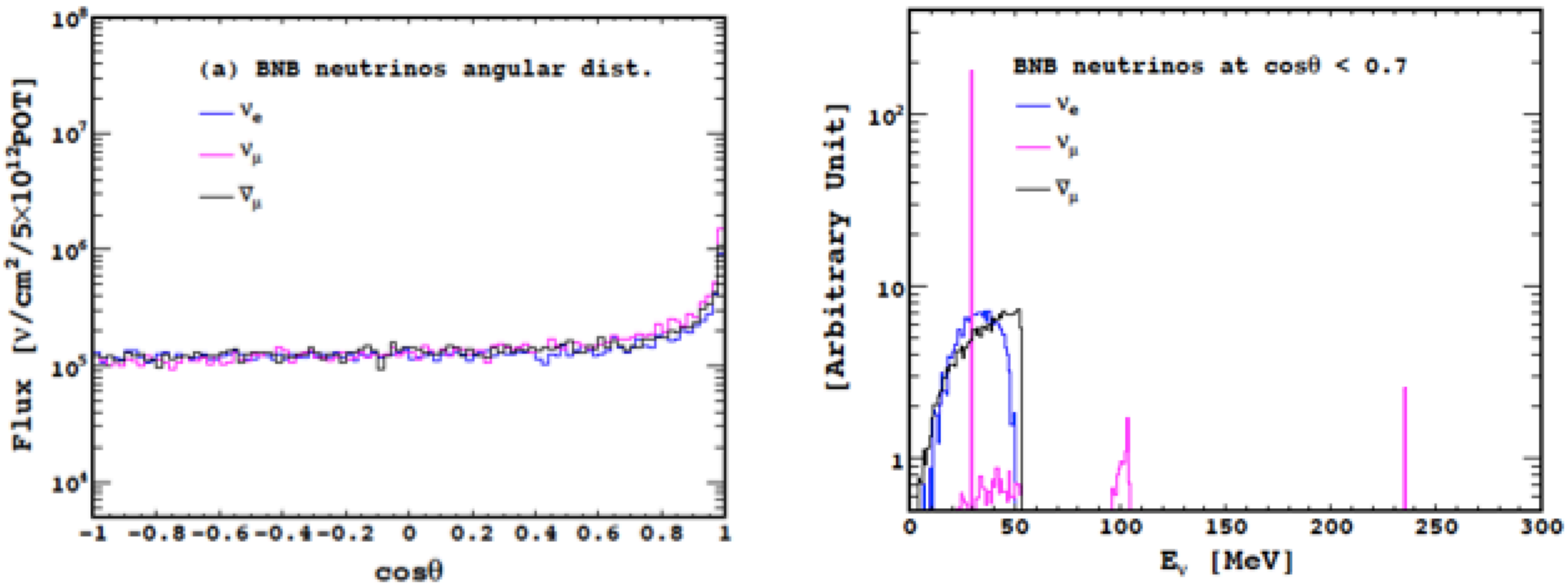


Figure 4 The flux of neutrinos at a point 20 meters from a reference point near the upstream end of the decay pipe (left). The spectrum of neutrinos from the BNB simulation program (right). Both from reference [XX]

location	d (m)	PPP	E(MeV)	KW	POT/year	nu/p	nu per sec	flux/flavor	events/year
SNS at CLEAR	30	1.5E+14	1000	1440	1.8E+23	0.12	1.08E+15	9.55E+06	1366
SNS at OscSNS	46	1.5E+14	1000	1440	1.8E+23	0.12	1.08E+15	4.06E+06	581
Lujan in Hall	10	4.0E+13	800	102	1.6E+22	0.04	3.2E+13	2.55E+06	364
Lujan Outside	40	4.0E+13	800	102	1.6E+22	0.04	3.2E+13	1.59E+05	23
BNB C	20	5.0E+12	8000	13	2.0E+20	1	1E+13	1.99E+05	28
BNB A or B	8	5.0E+12	8000	13	2.0E+20	1	1E+13	1.24E+06	178

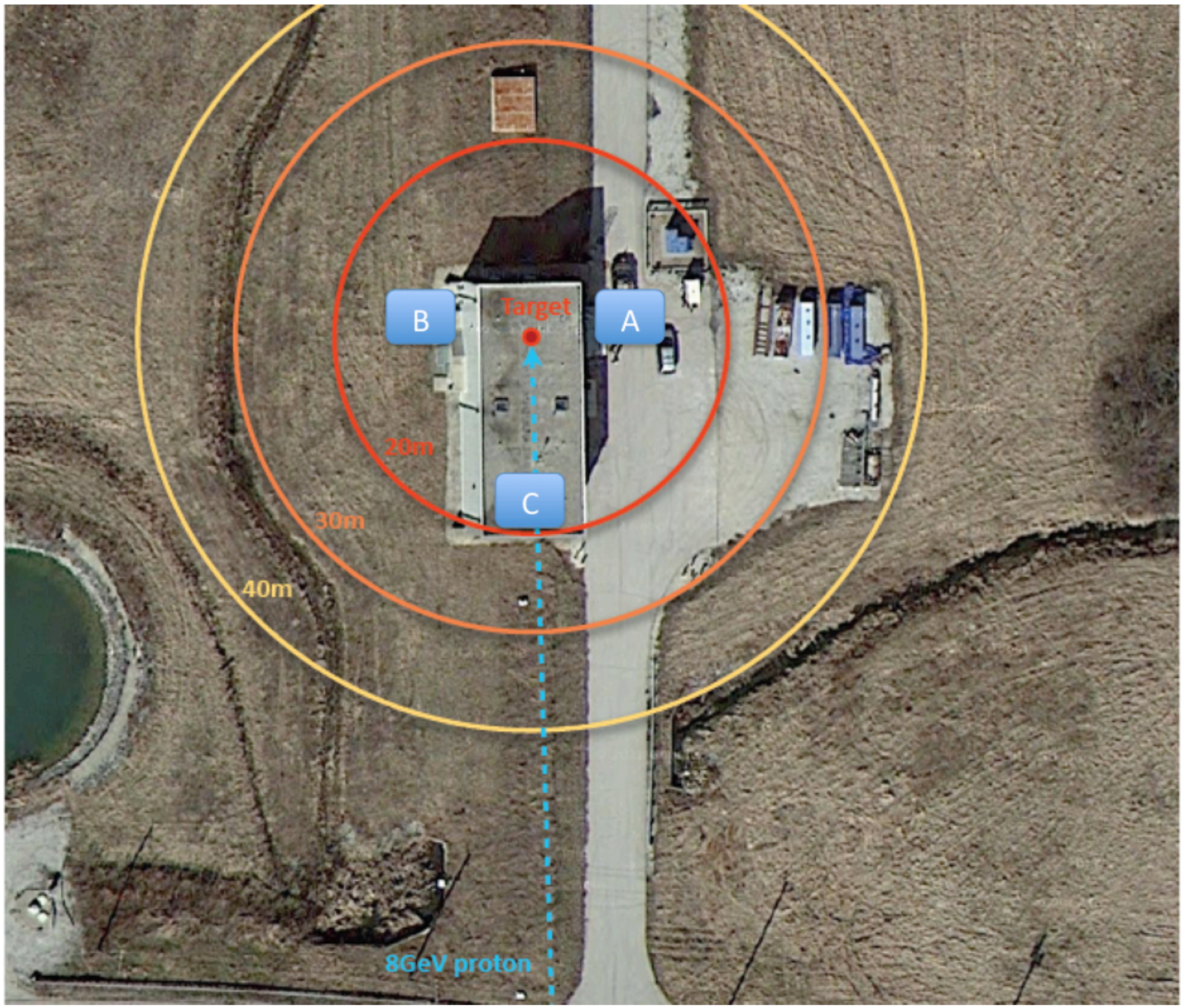
Note: these rates are still preliminary

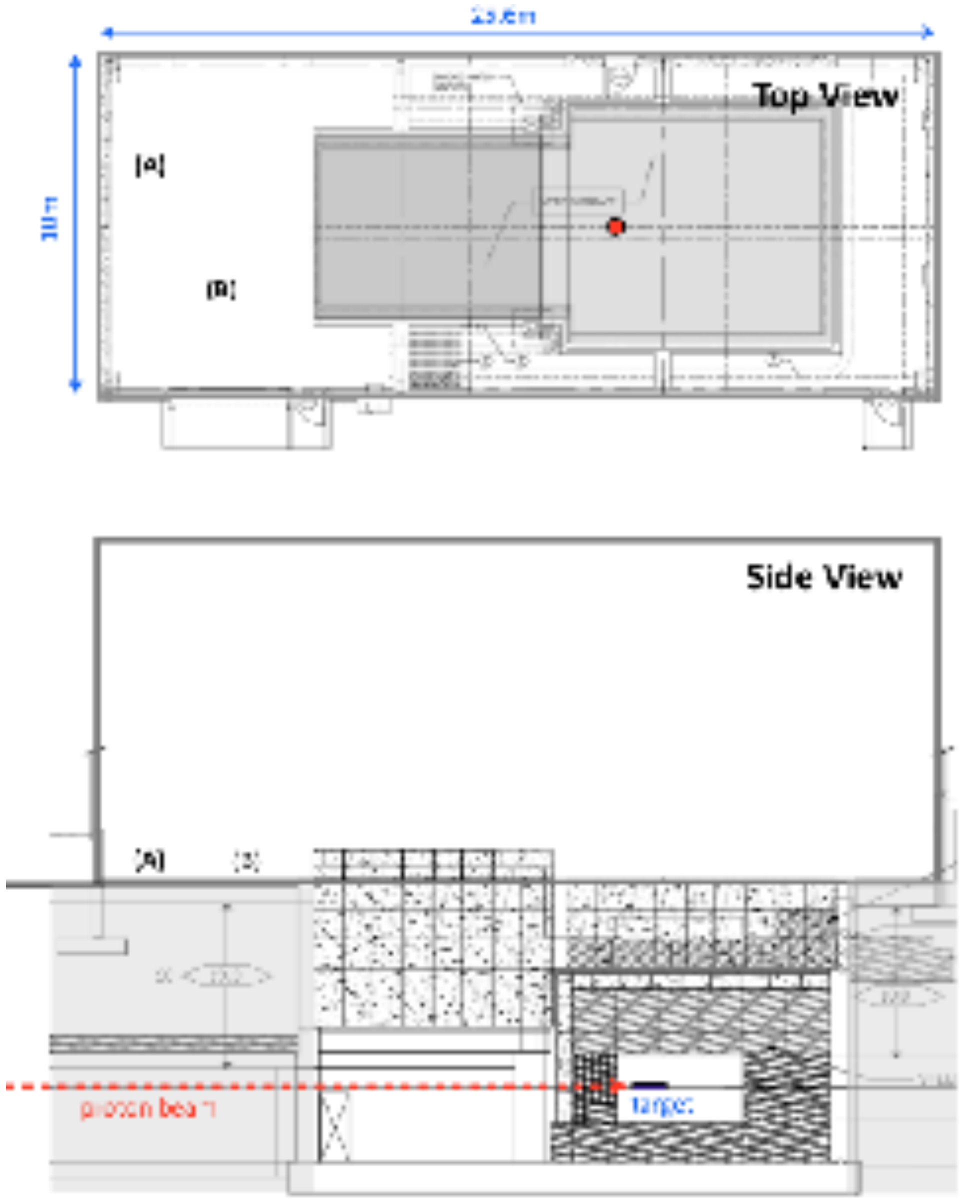
SNS would give the best event rate by far, but there is no facility readily available.

Lujan gives an very low event rate if we have to go outside the hall.

BNB is low, but a facility exists.

Locations near the BNB



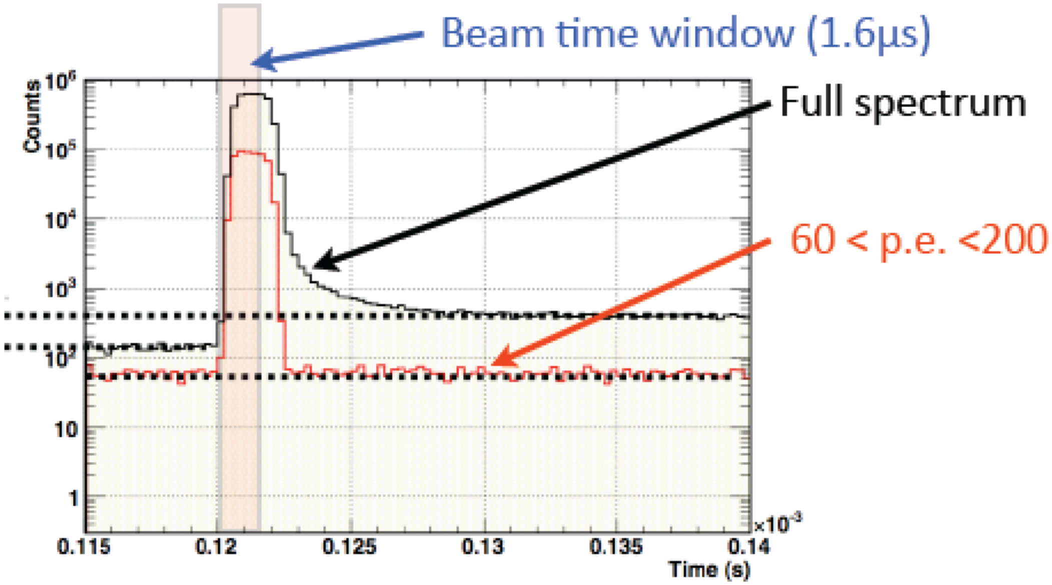


Location inside would be preferred, but issues with space and neutron background

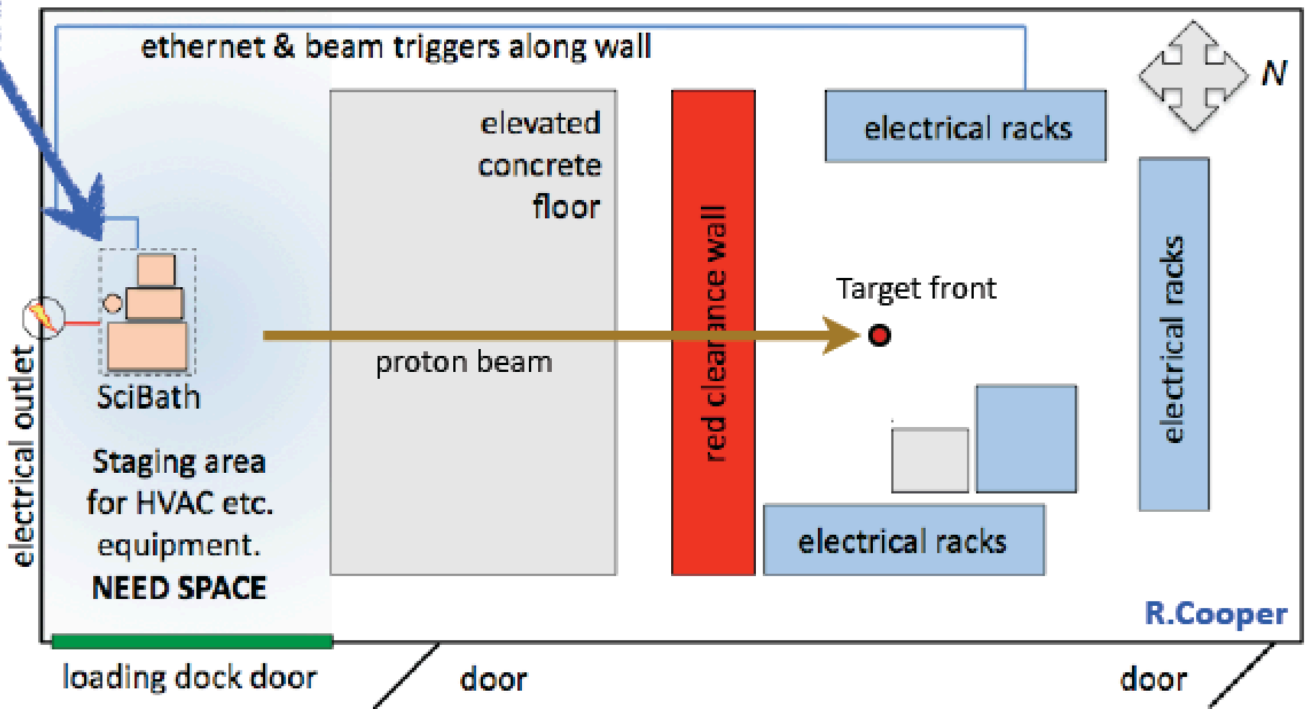
Outside is possible with moving some A/C plants

Neutrons may be a serious problem

SciBath at BNB Target Building (2012)

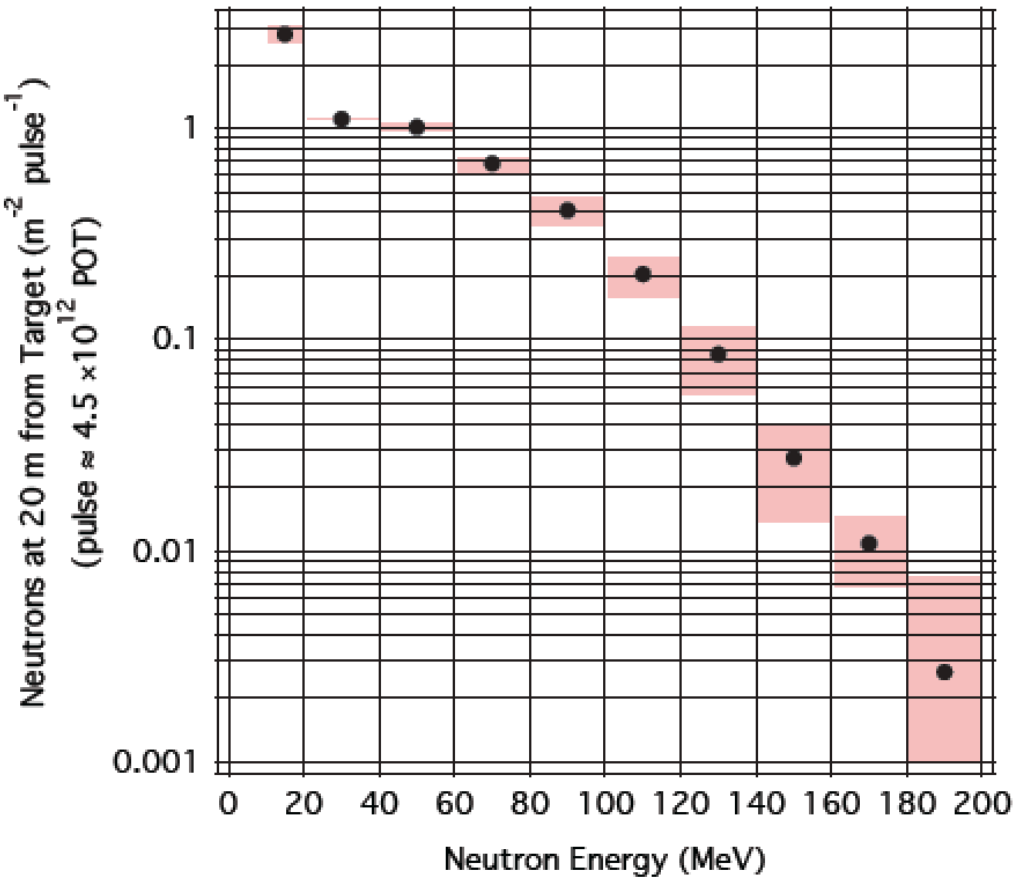


- Detector located in the target building (MI-12 @20m away from the target)
- Pre-beam, in-beam, off-beam backgrounds measurements
- Data taking: Feb~Apr 2012



Neutron Flux and Energy Spectrum

Measured neutron spectrum at MI-12



Estimate 10-20 neutrons per pulse through CAPTAIN at this position

The experiment doesn't have to be zero background: trade offs between neutrino flux, background rate and live time

Fast Neutrons

- meters of shielding needed
- often counterintuitive
- need for different layers (steel, concrete, water, poly ...)

Neutron Shielding

Best way is to measure the neutron shielding effects at the experimental site.

BNB Plans for Operations in FY16 and beyond

Using the Booster

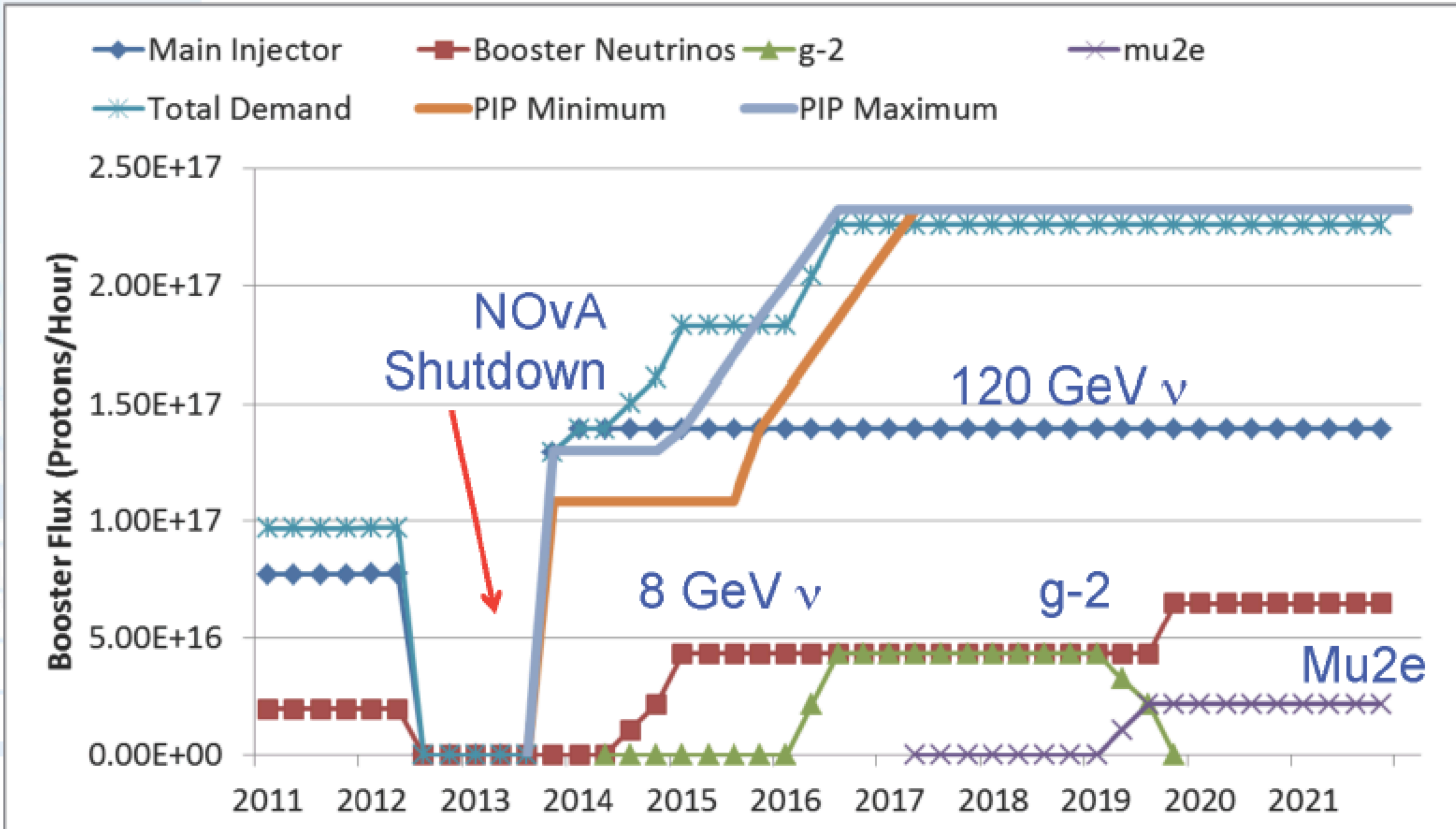
- Booster is a resonant machine at 15 Hz
- RF is pulsed on cycles with beam, limits us to ~7.5 Hz
    - at higher frequencies the cavities spark
    - at higher frequencies the tuners overheat
    - Refurbishment plan as part of PIP
- There is an RF pre-pulse associated with beam cycles

Metrics: BNB

FY2014	Total Design	Total Base	Total Metric
October	0.00E+00	0.00E+00	0
November	0.00E+00	0.00E+00	0
December	0.00E+00	0.00E+00	0
January	0.00E+00	0.00E+00	0
February	0.00E+00	0.00E+00	0
March	0.00E+00	0.00E+00	0
April	0.00E+00	0.00E+00	0
May	2.27E+18	1.59E+18	1.82E+18
June	4.47E+18	3.13E+18	3.57E+18
July	4.69E+18	3.28E+18	3.75E+18
August	7.07E+18	4.95E+18	5.65E+18
September	1.51E+19	1.06E+19	1.21E+19
FY2015			
October	9.08E+18	6.36E+18	7.27E+18
November	8.79E+18	6.15E+18	7.03E+18
December	1.79E+19	1.25E+19	1.43E+19
January	2.70E+19	1.89E+19	2.16E+19
February	3.52E+19	2.46E+19	2.81E+19
March	4.42E+19	3.10E+19	3.54E+19
April	5.30E+19	3.71E+19	4.24E+19
May	6.21E+19	4.35E+19	4.97E+19
June	7.09E+19	4.96E+19	5.67E+19
July	7.36E+19	5.15E+19	5.89E+19
August	8.07E+19	5.65E+19	6.46E+19
September	1.05E+20	7.33E+19	8.38E+19

Plan for FY16 and beyond is 2E20 POT/year for BNB. This is much smaller than what they COULD deliver due to sharing with NOVA

Proton Improvement Plan Projection



Conclusions

- The detection of SN ν_e is scientifically very interesting and has never been done.
- The cross-section for ν_e on argon has uncertainties that are hard to quantify. Depends on believing isospin symmetry and pure theoretical calculations. The actual cross section has **never** been measured.
- Low energy events have not really been systematically studied in a liquid argon TPC, timing and triggering are uncertain . Need to investigate
- A low energy neutrino run is possible at BNB, but depends on details of neutron backgrounds critically. It may be that significant neutron shielding will be needed.

BACKUP SLIDES

Flux Averaged Cross Section: I get 0.95E-40