Low Energy Neutrino Scattering: Supernovae Neutrino Energies

J. Carlson

- Introduction
- Why is this interesting ?
  - Decoupling regime
  - Coherent Scattering
  - Detection
- Scattering from nuclei
  - Deuteron
  - 4He (theory)
  - Data and theory for 12C
- Conclusion

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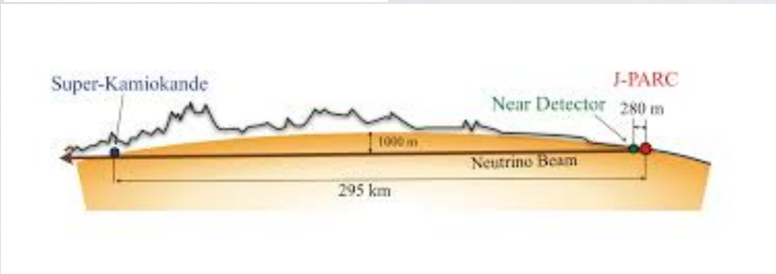
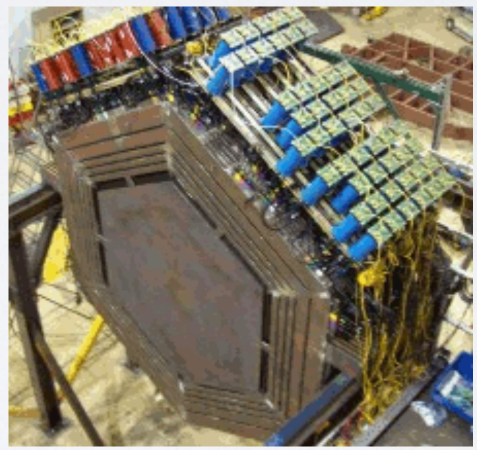
Accelerator Neutrinos

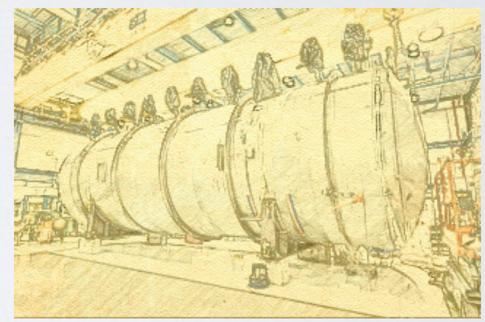


MINOS

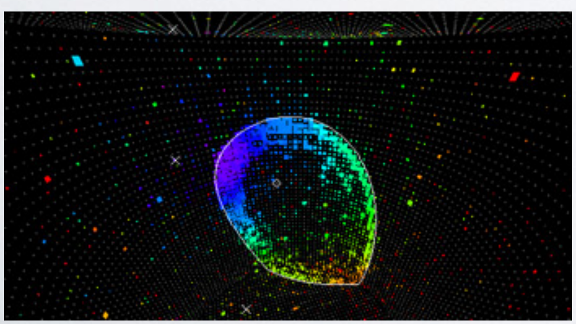
SuperK



MINERva



MicroBooNE



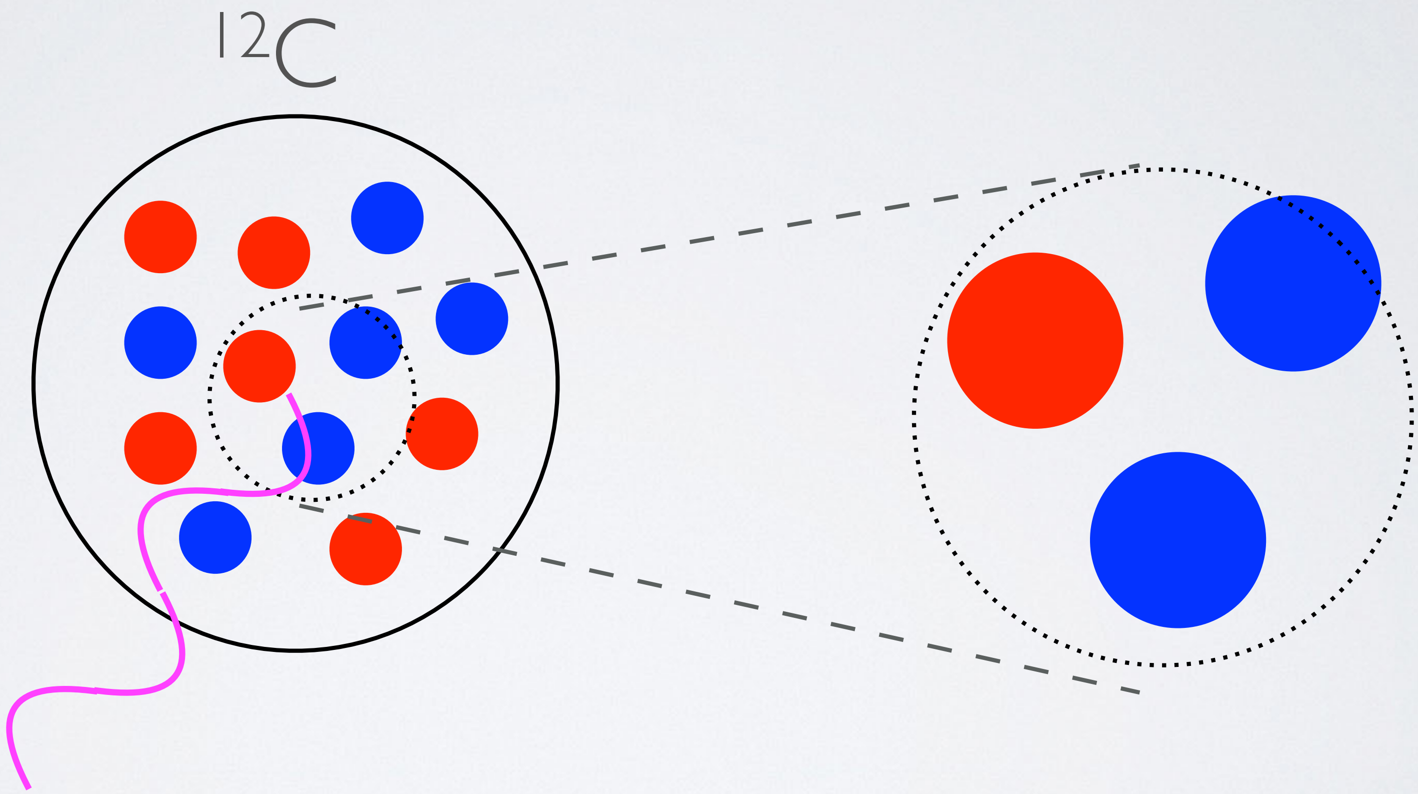
Advantages: Control over Energy, flux

neutrino 'beams' can be sent over long distances

Energies ~ 1 GeV

Contributions to Sum Rules

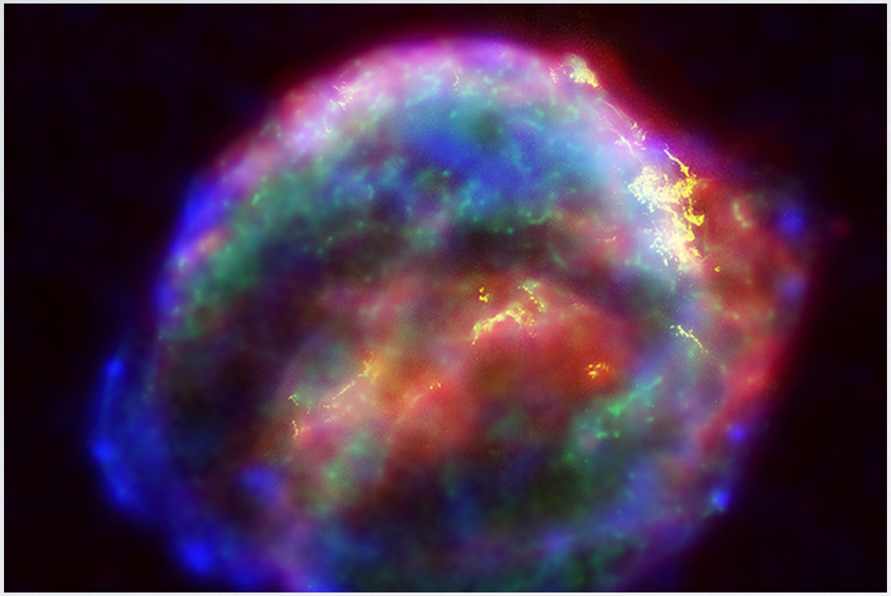
Ground State (low-momentum piece):
external momentum is large (≧ Fermi momentum)

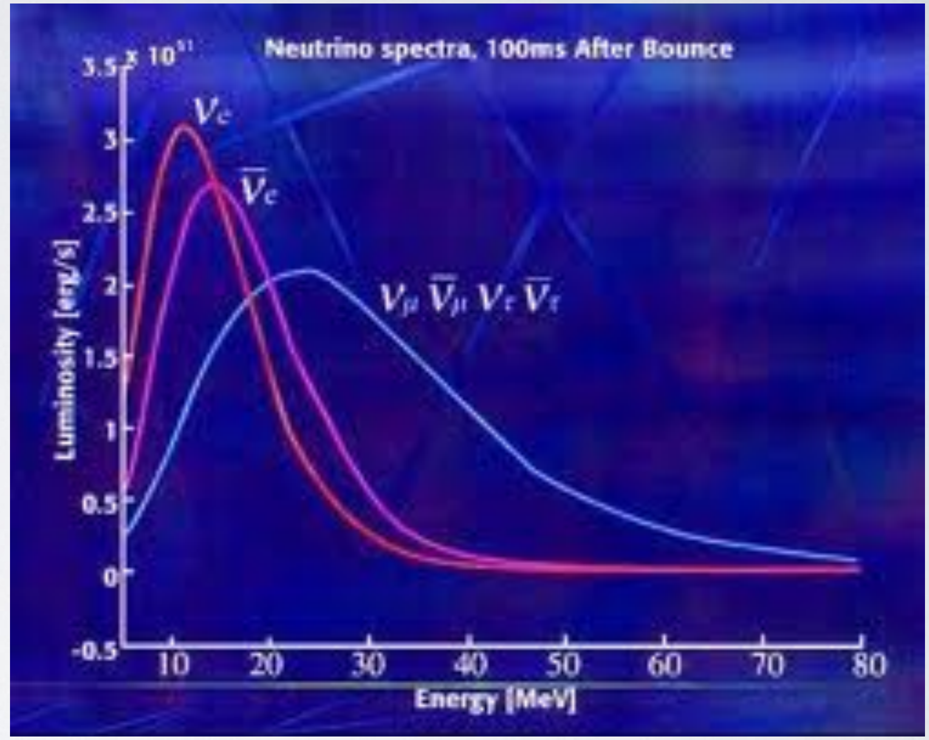


For a large momentum transfer to have an important matrix element,
need contribution from pion-exchange interaction (correlations) or currents

Supernovae and Astrophysical Neutrinos

Different Sources, time dependence, different epochs





Kepler Supernova

Can we make r-process nuclei in supernovae; and/or neutron-star mergers ?

Need to understand low energy neutrinos in matter

Supernova Neutrino Spectra and Nucleosynthesis

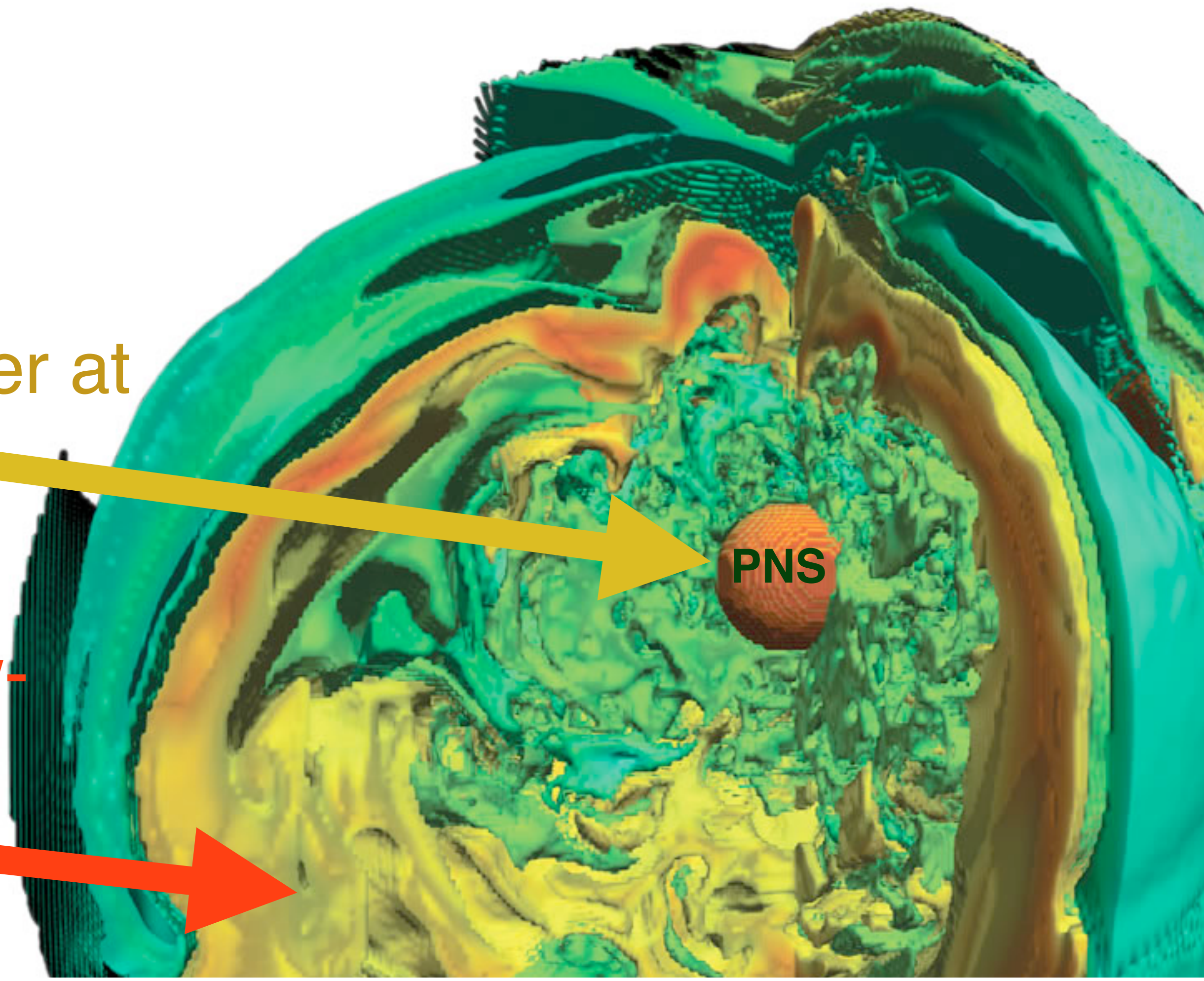
Electron and anti-electron neutrinos play a crucial role in supernova. Their energy spectrum impacts:

1. Explosion mechanism
2. Nucleosynthesis
3. Detection

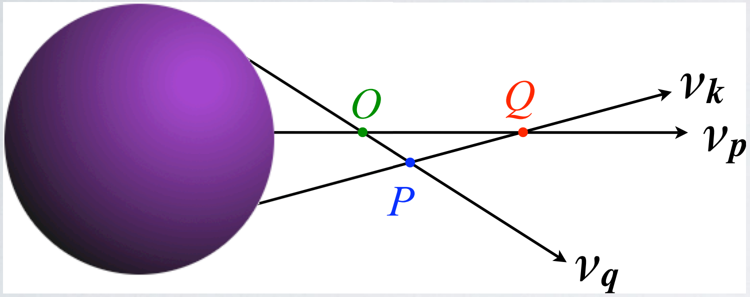
$$\begin{cases} \bar{\nu}_e + p \rightarrow n + e^+ \\ \nu_e + n \rightarrow p + e^- \end{cases}$$

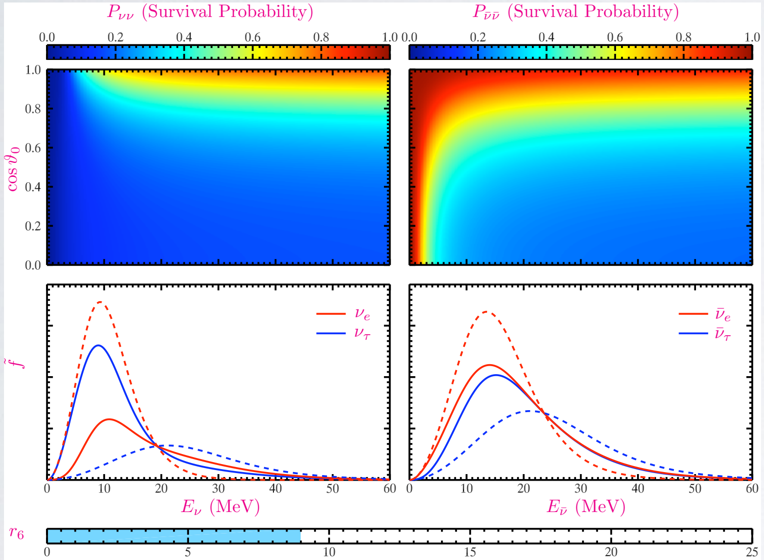
Neutrino-sphere at high density. Neutron-rich matter at moderate entropy.
R ~ 10-20 km

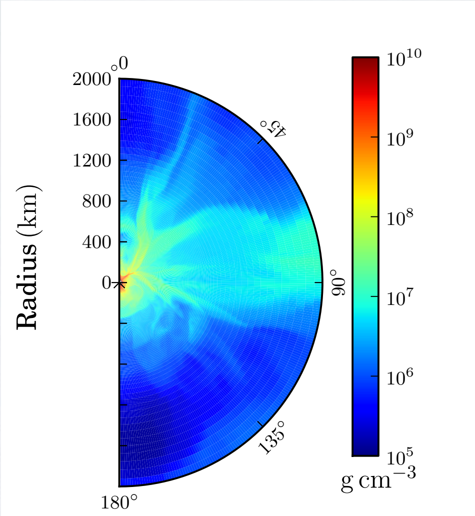
Neutrino driven wind at low-density and high entropy.
R ~ 10^3-10^4 km



After emission from the proto-neutron star surface
Very few neutrinos scatter from e, n, p, ….;
but collective oscillations may be important







Cherry, Carlson, Friedland, Fuller, Vlasenko PRL 2012

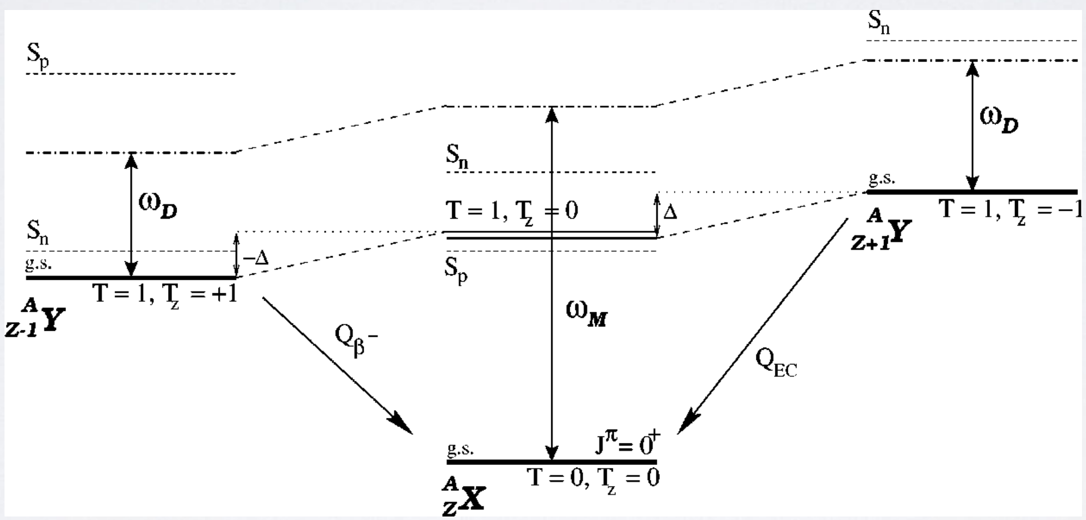
Duan, Fuller, Carlson, Qian, PRD 2006 and many more

Different epochs and neutrino hierarchies can produce spectral swaps,…
Much is unknown (scattering from nucleons and nuclei, …)
Can also have lepton flavor violation (Vlasenko, Cirigliano, Fuller, 2014)

Neutrino Scattering from Nuclei

Impacts explosion mechanism, r-proces, ….
Necessary for interpreting neutrino observations
How well do we understand it?

Energies 50 MeV
Typically going to excited states or low in the continuum

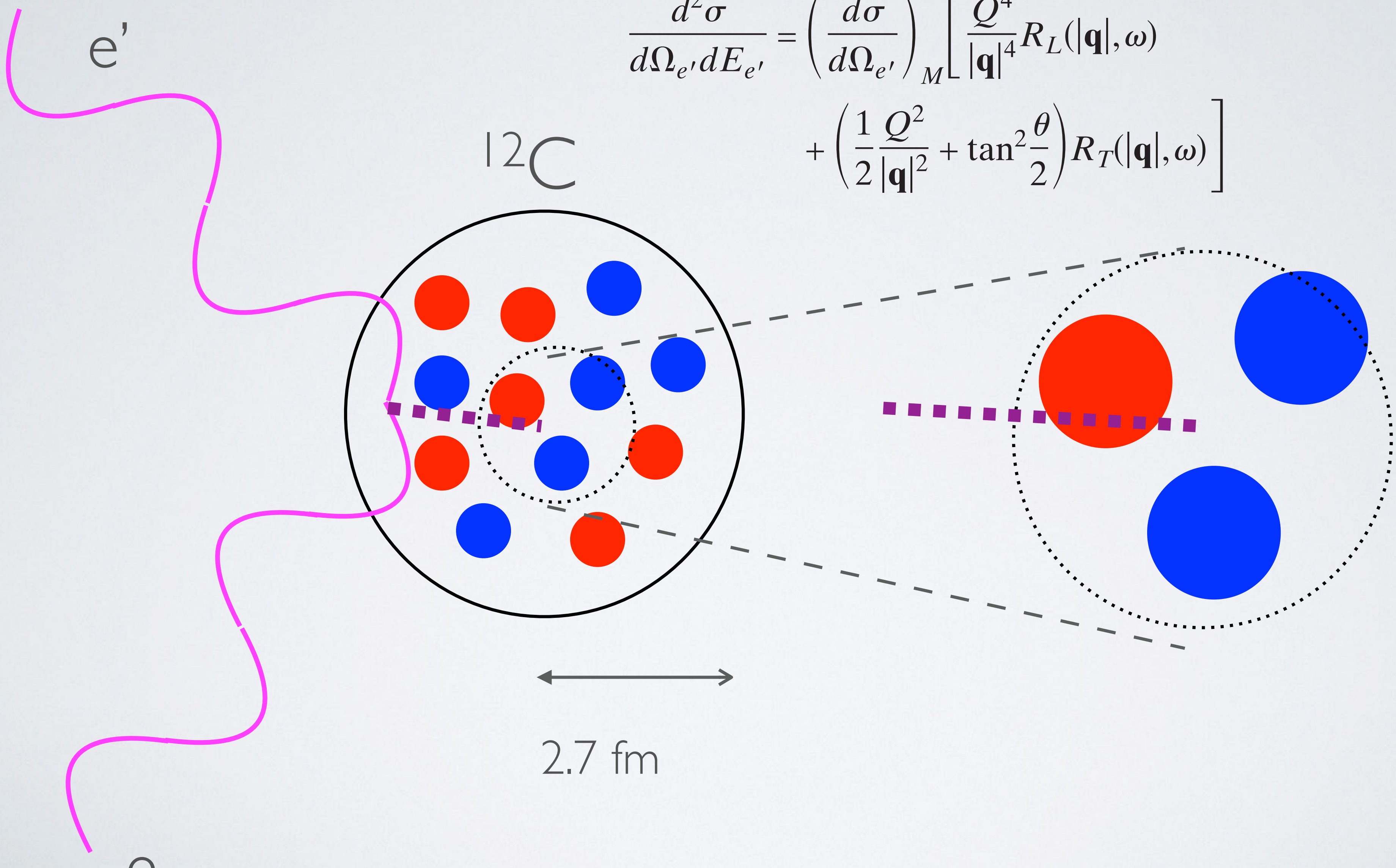


Generic Neutral and Charged-Current Processes
Momenta ~ 50-100 MeV/c = 0.25 - 0.5 fm^{-1}

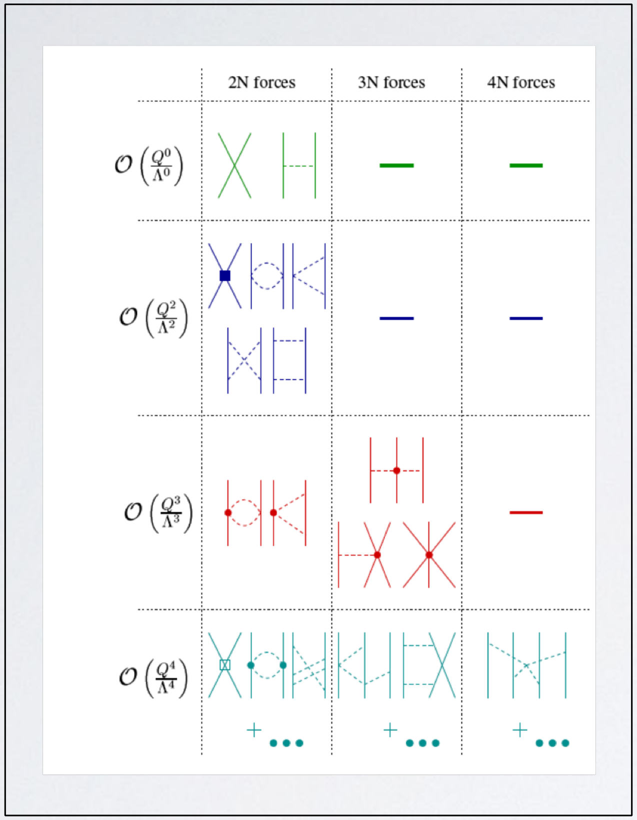
Inclusive electron scattering,

measure electron kinematics only

$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega)\right]$$

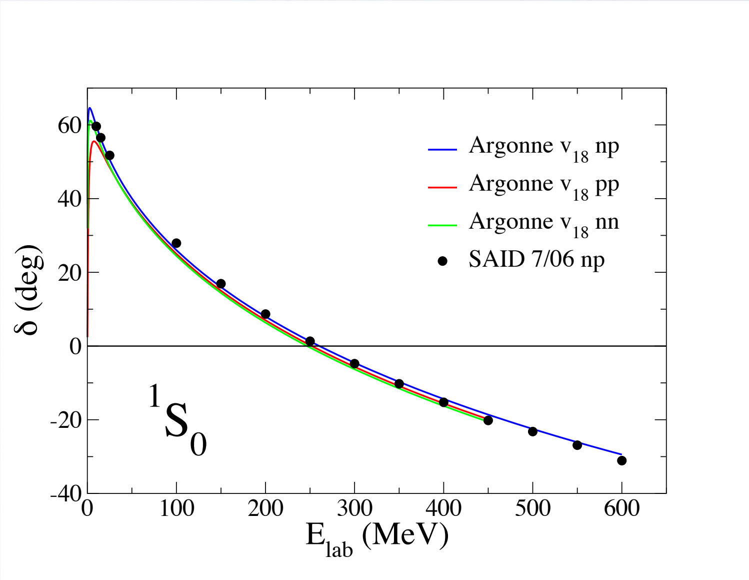


Nuclear Interactions



Chiral EFT
and Phenomenological models

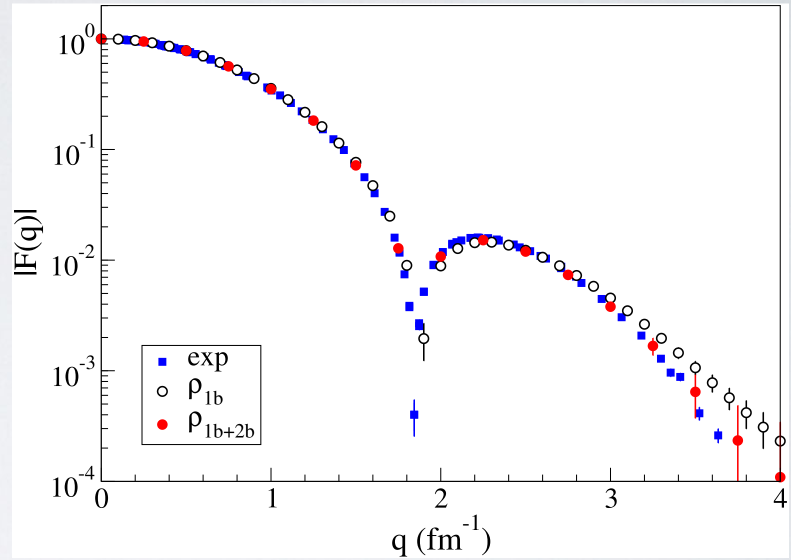
investigating/improving
predictive power



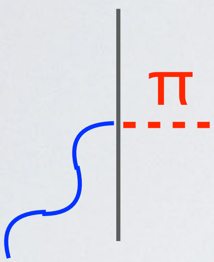
NN interactions fit to huge database
3N interactions fit to nuclei

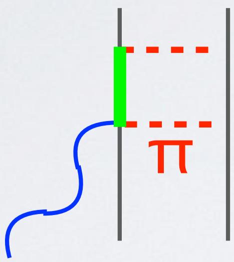
Higher Momenta: Form Factors

^{12}C elastic form factor

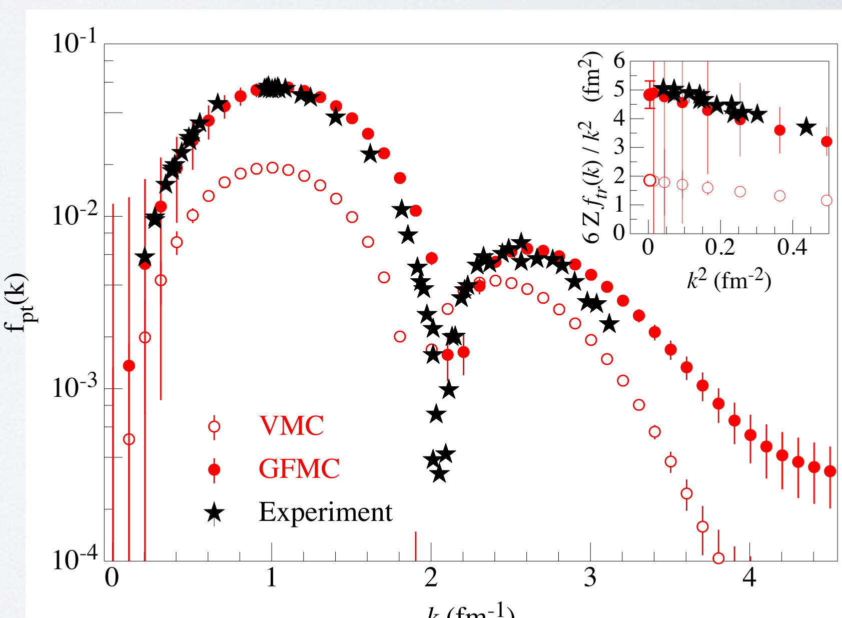


Currents: 1 + 2-nucleon currents + …

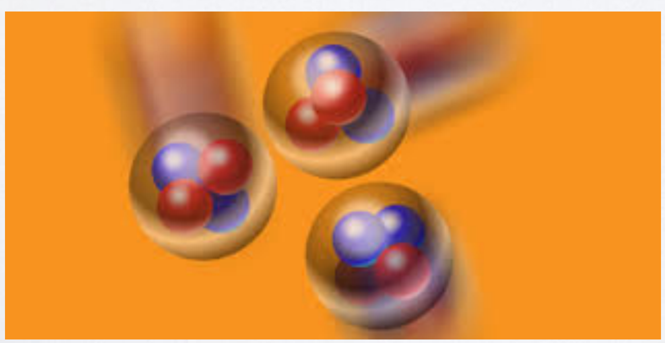




virtual pions, deltas, …



Elastic Processes and Low-Energy Transitions
Quasi-Elastic Inclusive Scattering

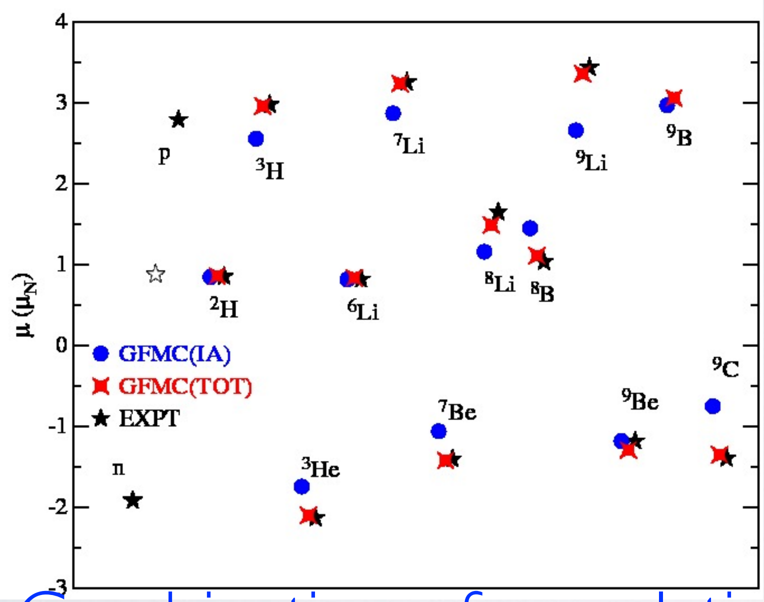


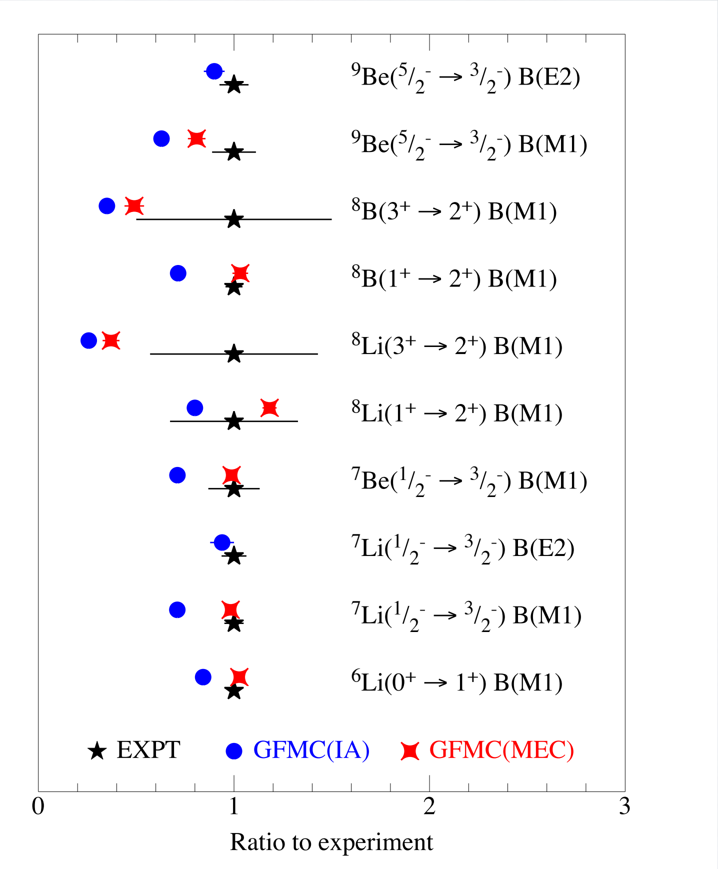
2-Nucleon Currents and Low-Energy Transitions

Magnetic Moments

A < 10

EM transitions





Combination of correlations and currents

p = 2.792 n = -1.913

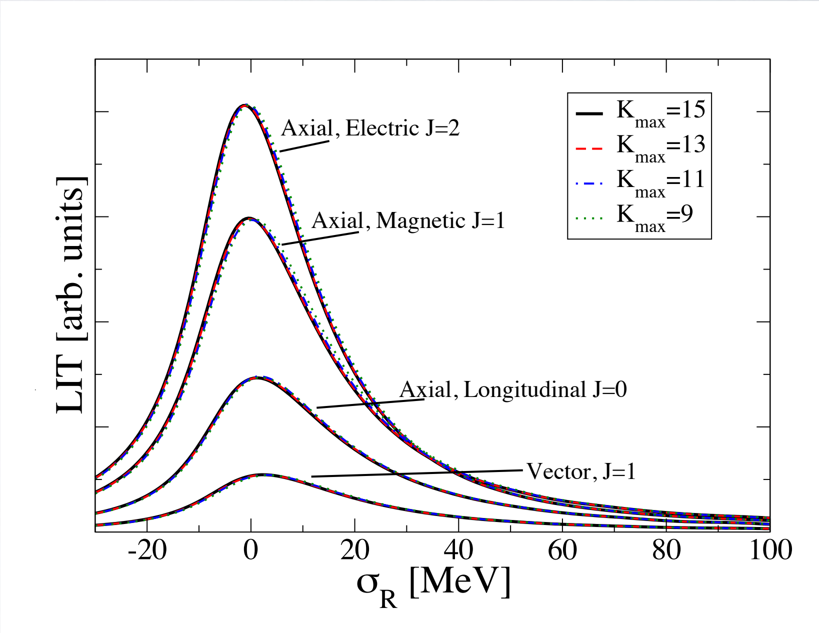
^{3}H = 2.979 ^{3}He = -2.128

Pastore, Pieper, Schiavilla, Wiringa: arXiv 1406.2343, 1302.5091

Inelastic Neutrino Scattering on ^{4}He

Gazit and Barnea, PRL 2007

Multipole Expansion



AV18; AV18+UIX interaction
Currents from chiral theory, continuity eq

T [MeV]	$\langle\sigma_x^0\rangle_T = \frac{1}{2}\frac{1}{A}\langle\sigma_{\nu_x}^0 + \sigma_{\bar{\nu}_x}^0\rangle_T$ $[10^{-42} cm^2]$			
	AV8' [3]	AV18	AV18+UIX	AV18+UIX+MEC
4	2.09(-3)	2.31(-3)	1.63(-3)	1.66(-3)
6	3.84(-2)	4.30(-2)	3.17(-2)	3.20(-2)
8	2.25(-1)	2.52(-1)	1.91(-1)	1.92(-1)
10	7.85(-1)	8.81(-1)	6.77(-1)	6.82(-1)
12	2.05	2.29	1.79	1.80
14	4.45	4.53	3.91	3.93

TABLE I: Temperature averaged neutral current inclusive inelastic cross-section per nucleon (in $10^{-42} cm^2$) as a function of neutrino temperature (in MeV).

Integrated Cross section versus neutrino T
Some effect from interaction (A=4 binding)
Very little effect from 2-body currents (!?)

Neutrino Scattering from ^{12}C

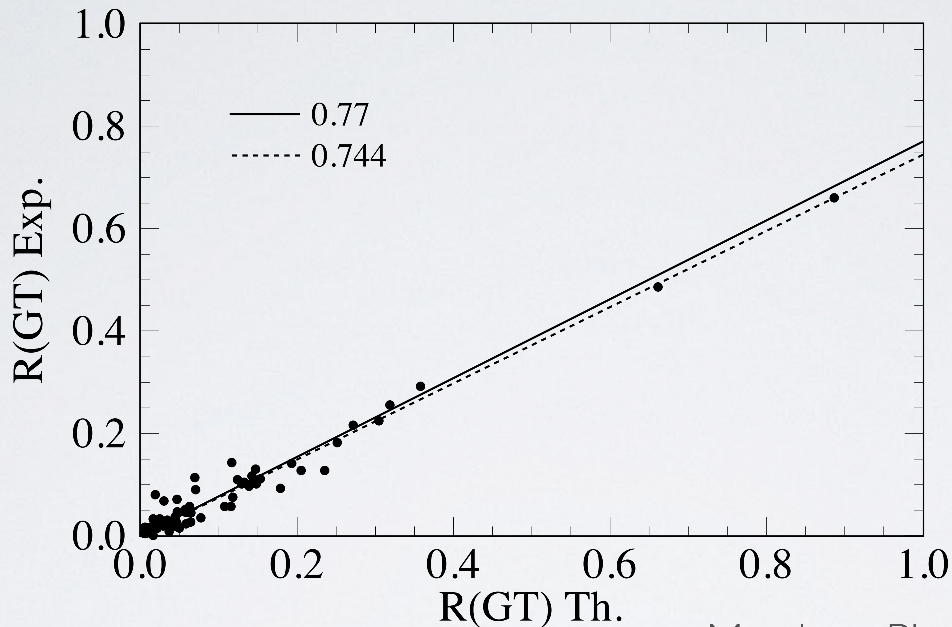
Hayes and Towner, PRC, 1999

	Muon neutrino DIF	Electron neutrino DAR	Muon Capture	Photo-absorption
Closed shell RPA	18.2	21.9	45.4	
+2p-2h	16.7	20.4	44.1	21.6
CRPA	17.6	14.4	38.0	
Shell Model	13.8	12.5	42.2	23.6
Experiment	12.4(2)	14.4(4)	39.0(1)	21(2)

At best ~10% uncertainty; no 2-body currents

Weak Processes in Larger Nuclei:

Gamow-Teller Matrix Elements in Beta Decay



Martinez-Pinedo and Poves, PRC 1996

Shell Model Calculations of Beta Decay typically require a quenching (reduction) of g_A by ~ 0.75 to reproduce experimental rates

Not yet understood at a `microscopic' level

Neutrino Detection from a Galactic Supernovae

Scholberg 2012

TABLE II: Summary of neutrino detectors with supernova sensitivity. Neutrino event estimates are approximate for 10 kpc; note that there is significant variation by model. Not included are smaller detectors (e.g., reactor neutrino scintillator experiments) and detectors sensitive primarily to coherent elastic neutrino-nucleus scattering (e.g., WIMP dark matter search detectors). The entries marked with an asterisk are surface or near-surface detectors and will have larger backgrounds.

Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980-present
LVD	C_nH_{2n}	1	Italy	300	1992-present
Super-Kamiokande	H_2O	32	Japan	7,000	1996-present
KamLAND	C_nH_{2n}	1	Japan	300	2002-present
MiniBooNE*	C_nH_{2n}	0.7	USA	200	2002-present
Borexino	C_nH_{2n}	0.3	Italy	100	2005-present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007-present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE*	Ar	0.17	USA	17	Near future
NOνA*	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

Conclusions/Outlook

- Supernovae neutrinos can teach us a lot about both neutrinos and supernovae
- Microscopic theory important for decoupling and propagation in the supernovae; and hence for energy deposition and potentially r-process
- Basic Theory ingredients understood
- More data essential - very limited at present
- Advances in many-body theory and computing essential
- Close relationship with many important issues
  - Quasi-Elastic neutrino scattering
  - Double-beta decay (Majorana neutrinos)
  - Astrophysical Sources (neutron star mergers,…)