Opportunities with 10s-0f-MeV Neutrinos

- ❑ Overview of the development of neutrino physics
- ❑ Motivations for the study of low-energy neutrinos:
  - Solar neutrinos
  - Supernova neutrinos
  - Accelerator neutrinos
- ❑ If time: some current Berkeley interests: BEST and DUNE

Wick Haxton, UC Berkeley

Neutrino Scattering… @ MITP

June 26 2023

N3AS Network in Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER

Conceptual development of neutrino physics and the Standard Model

- 1914: Chadwick and others observed a continuous β decay spectrum
  - emission of "unobserved radiation" as a potential explanation suggested by Chadwick, supported by C. D. Ellis, disputed by Meitner
  - work done in Geiger's lab: Chadwick interned when WWI broke out

- 1927 and 1930: Calorimetry experiments by Ellis and Wooster, γ -ray measurements of Meitner
  - no significant electron scattering in target or accompanying conventional radiation

- 1930: Pauli's suggestion of a light neutrino, including apologies for its lack of observability
  - emission in β decay as an explanation for Chadwick's spectrum
  - identification as a spin-1/2 nuclear constituent explained even spin of Z=7 ^{14}N

- 1932: Chadwick's discovery of the neutron

- 1934: Fermi's formulation of a effective theory of weak interactions — particle creation

$$n_{\mathrm{bound}} \rightarrow p_{\mathrm{bound}} + e^- + \bar{\nu}_e$$

modeled through analogy with electrodynamics, charge-charge but no analog of electric field: contact interaction

- Fermi later recognized covariance implied currents

$$\rho \rightarrow j^\mu = (\rho, \vec{j})$$

contains SM's CVC and isospin structure

$$j^{E\&M} = j_\mu^{V;S} + j_\mu^{V;V(0)} \qquad \Leftrightarrow \qquad j^{Weak} = j_\mu^{V;V(\pm)}$$

- 1936: Gamow and Teller identify an axial current contribution

Pauli

Chadwick

Fermi

- One of the most remarkable papers in physics for what it did and did not contain

"… *the two components* [vector, axial vector] *in the linear combination have the same order of magnitude, then all transitions* [satisfying the selection rules] *would now* [be strong allowed ones]"

THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 49, No. 12 JUNE 15, 1936 SECOND SERIES

Selection Rules for the β-Disintegration

G. GAMOW AND E. TELLER, *George Washington University, Washington D. C.*

(Received March 28, 1936)

§1. The selection rules for β-transformations are stated on the basis of the neutrino theory outlined by Fermi. If it is assumed that the spins of the heavy particles have a direct effect on the disintegration these rules are modified. §2. It is shown that whereas the original selection rules of Fermi lead to difficulties if one tries to assign spins to the members of the thorium family the modified selection rules are in agreement with the available experimental evidence.

The rate they deduced $\omega \sim |\langle 1\rangle|^2 + g_A^2|\langle\vec{\sigma}\rangle|^2$ can be obtained by adding probabilities

$$j_\mu^{lep\ V;\mp} j_\mu^{nucl\ V;\pm} \Leftrightarrow j_\mu^{lep\ V;\mp} j_\mu^{nucl\ V;\pm} + j_\mu^{lep\ A;\mp} j_\mu^{nucl\ A;\pm}$$

or by adding amplitudes $H_{\text{weak}} \sim \frac{G_F}{\sqrt{2}} \left(j_\mu^{lep\ V;\mp} - j_\mu^{lep\ A;\mp}\right)\left(j_\mu^{nucl\ V;\pm} - j_\mu^{nucl\ A;\pm}\right)$

yielding PNC. But the paper makes no comment on this.

- 1937: Majorana observes the neutrino may or may not carry an additively conserved charge: $\nu_e \equiv \bar{\nu}_e$

Basically by 1937 all of the ingredients of the SM were in hand, though the prejudice for parity conservation kept distant both the possibility of a V-A weak theory and a Majorana neutrino (as by 1950 neutrinoless beta decay limits appeared to rule out a Majorana neutrino)

	$\mu = 0$	$\mu = 1,2,3$
$j_\mu^{weak} = j_\mu^{V;V_\pm}$	$1 \;\; \tau_\pm$	$\vec{p}/m_N \;\; \tau_\pm$
$+ j_\mu^{A;V_\pm}$	$\vec{\sigma} \cdot \vec{p}/m_N \;\; \tau_\pm$	$\vec{\sigma} \;\; \tau_\pm$

But the neutrino remained a bit abstract to physicists: not mentioned by Bethe, Critchfield as they developed the theory of stellar hydrogen burning

1956: Cowan and Reines discover the anti-neutrino using a reactor source and a scintillator doped with the neutron absorber Cd: $\bar{\nu}_e + p \rightarrow n + e^+$

1957: The discovery of PNC

1958: The V-A theory was formulated

Feynman and Gell-Mann "Theory of the Fermi Interaction"
Sudarshan and Marshak "Chiral Noninvariance and the Universal Fermi Interaction"

1960s: Experimental neutrino physics expands at both high and low energies

CERN PS experiments, bubble chamber detectors
First efforts on solar neutrinos (ν_e s) — later

1967: Weinberg’s electroweak unification paper published, in which both a neutral partner Z to the W was introduced, yielding neutral currents

1971: Veltman/’t Hooft completion of the Standard Model, led theorists to advocate
- NC event searches at the CERN PS
- and at FermiLab

1972: Gargamelle detector completed at CERN, exposed to there CERN PS neutrino beam line

1972: FermiLab starts operations, at 10 times CERN’s energy

Gargamelle

Class A events: charge-current reactions producing a muon

Class B events: events with charged hadrons, attributed to neutrons produced upstream interacting in the target

1972: An isolated electron track was found in the antineutrino Class B event set

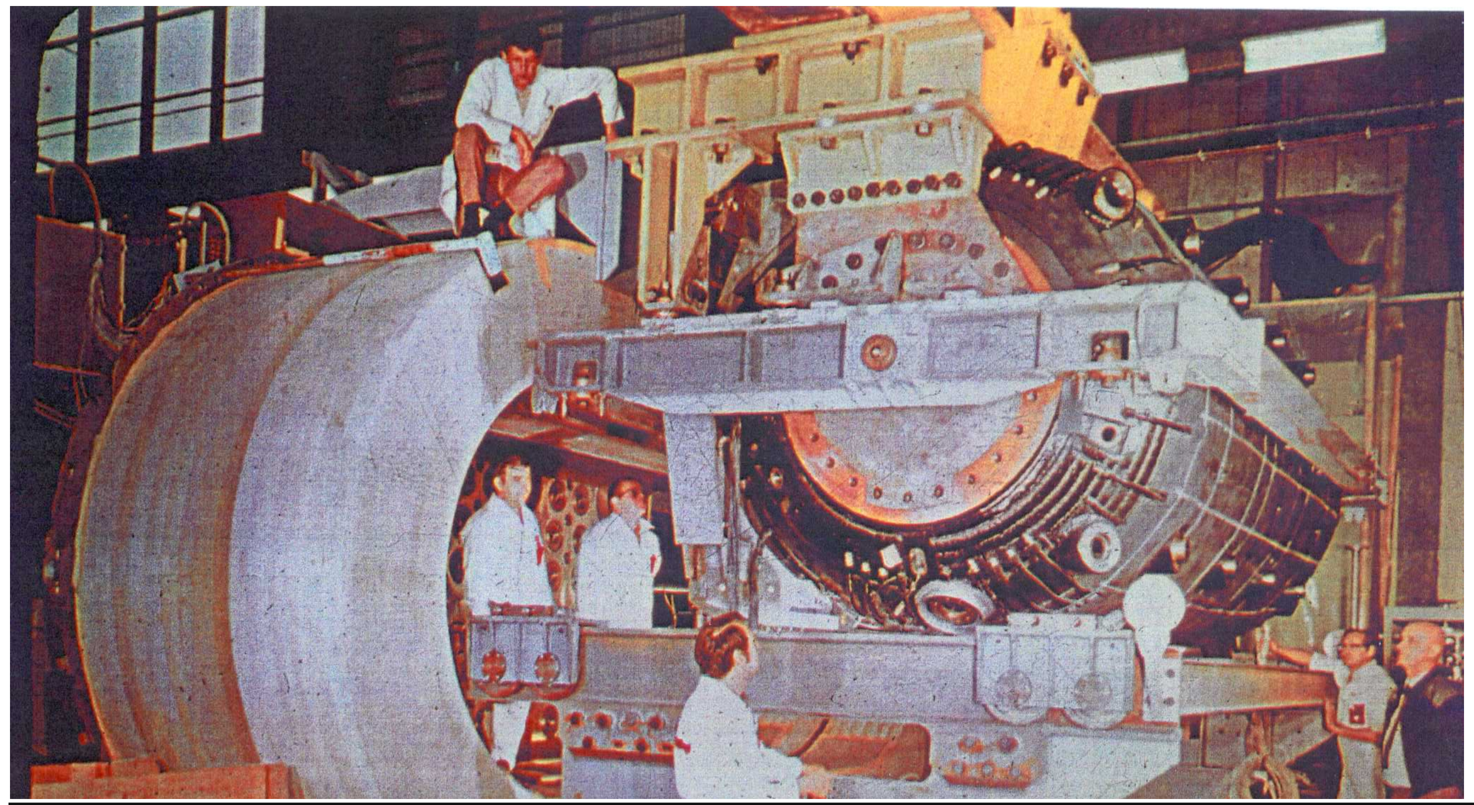
attributed to an entirely leptonic neutral process

1973:   Announced discovery of neutral currents

$$\nu_e\ (\bar{\nu}_e) + e^- \to \nu_e\ (\bar{\nu}_e) + e^-$$

$$\nu_e\ (\bar{\nu}_e) + p \to \nu_e\ (\bar{\nu}_e) + p$$

$$\nu_e\ (\bar{\nu}_e) + n \to \nu_e\ (\bar{\nu}_e) + p + \pi^-$$



First neutral current event

1972: Harvard/Penn/Wisconsin experiment begins operations at Fermilab

- revised its trigger to search for NC events, e.g., $\mu^- + p$
- submits a discovery paper
- re-enforced Gargamelle's decision to publish
- HPW mid-1973 data set showed fewer events: decision to withdraw
- drafted a no-NC paper
- but later found that detector modifications had increased their punch-thru neutrons, enhancing their CC signal, driving the NC signal downward
- "alternating neutral currents"

1974: HPW publishes a discovery paper with a NC/CC event ratio in agreement with Gargamelle

Experimentally confirmed structure of the SM weak current

$$J_\mu^+ = \cos\theta_C \;\bar{u}\gamma_\mu(1-\gamma_5)d + \sin\theta_C \;\bar{u}\gamma_\mu(1-\gamma_5)s$$

$$J_\mu^0 = \bar{u}\gamma_\mu(1-\gamma_5)u - \;\bar{d}\gamma_\mu(1-\gamma_5)d - 4\sin^2\theta_W J_\mu^{em}$$

which contains an isoscalar vector interaction $\sim -4\sin^2\theta_W \;\frac{1}{2}$

and an isovector vector interaction $\sim \left(2-4\sin^2\theta_W\right)\;\frac{\tau_3}{2}$

which implies a coherent <u>neutral</u> vector charge contribution at low enrergy

$$\sim -4\sin^2\theta_W \frac{Z+N}{2} + \left(2-4\sin^2\theta_W\right)\frac{Z-N}{2} \quad \sim -N + (1-4\sin^2\theta_W)Z \sim -N$$

while incorporating the interactions of Fermi and Gamow-Teller

Thus was established the light quark/gluon/photon Hamiltonian from which we do NP

- Reduction of the interaction to the non-relativistic nucleon level, where most nuclear physics is done

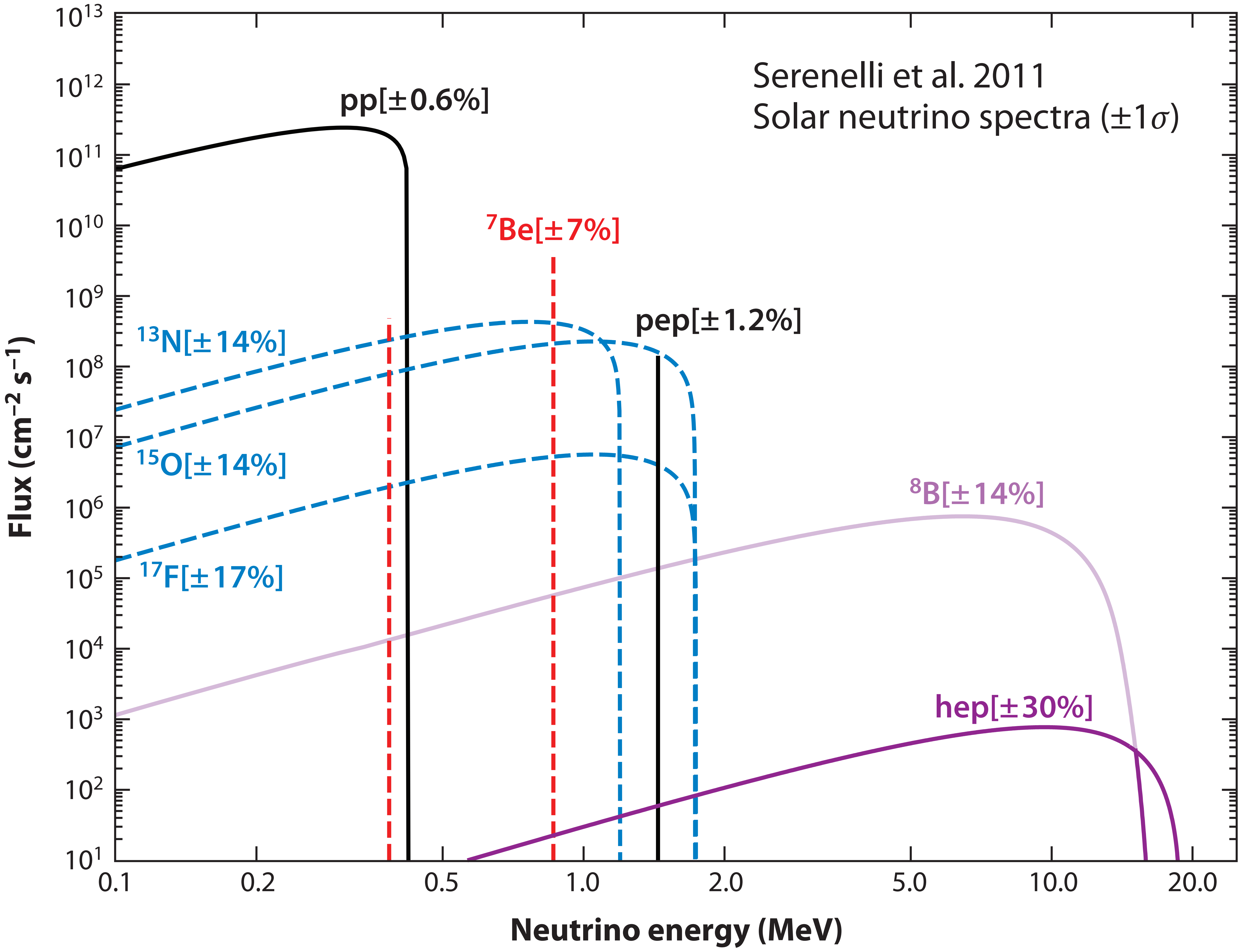
- The renormalization of this interaction to allow its embedding in a finite nucleon-level Hilbert space
    - — should be independent of the cutoffs used (apart from the rate of convergence)
    - — in practice, what we do in NP is typically quite approximate

- The numerical solution of the resulting many-body problem

We should hear this week about progress in each of these steps, made possible by advances in both computation and theory

Low-energy neutrinos #1: Solar neutrinos

- Our best-understood source of low-energy neutrinos, with spectra that are precisely known and fluxes determined with precisions ranging upward from 1.5%



Also provided an early example of the power of Multi-Messenger Astrophysics

<u>Observations:</u>
Sun's age, physical parameters
photon luminosity
solar neutrinos
helioseismology
metallicity: photo absorption lines

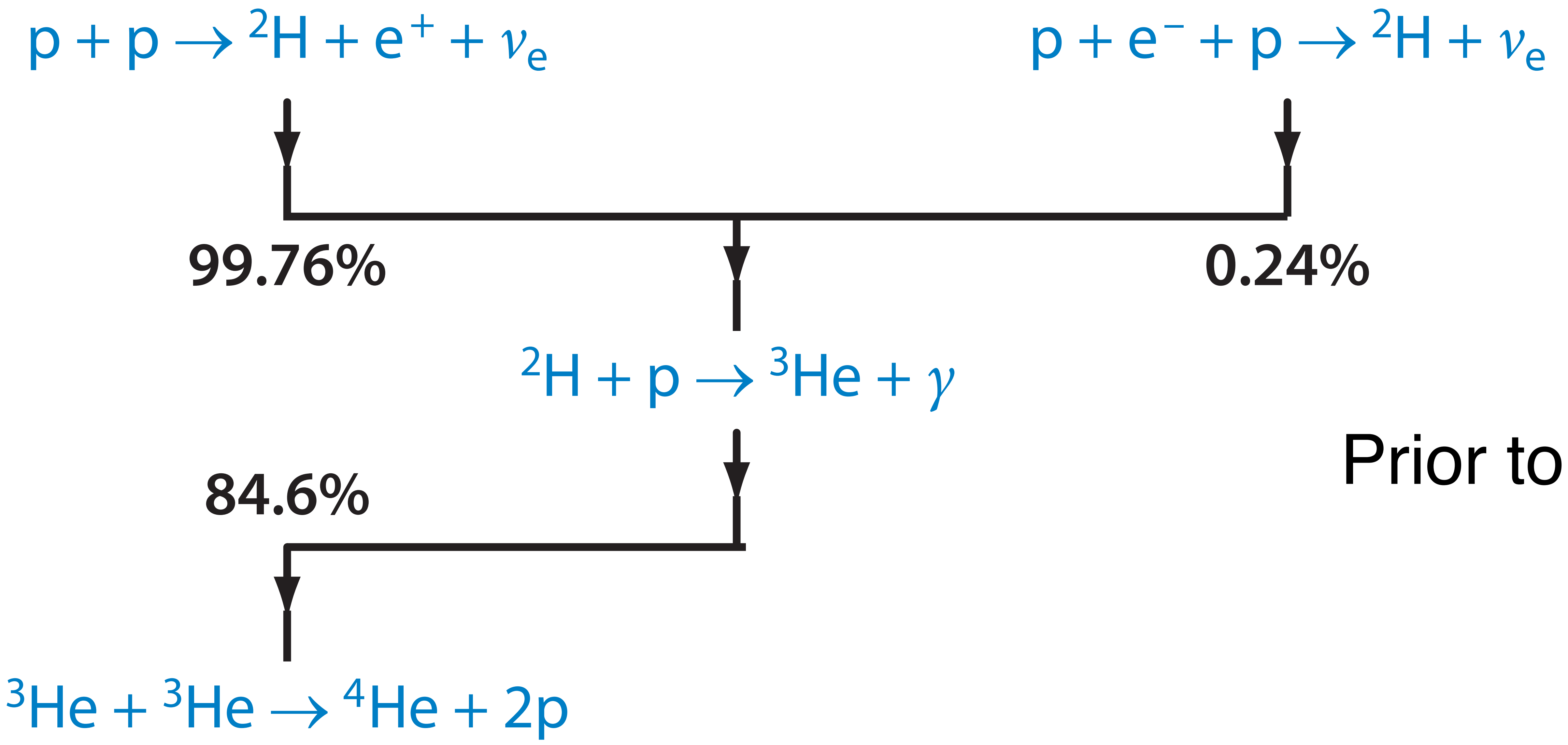
<u>Input Microphysics:</u>
nuclear reaction rates
opacities
EoS and corrections
diffusion coefficient

<u>Modeling:</u>
boundary conditions
physics: hydrostatic equilibrium
energy production
energy transport: rad. & convect.

<u>leading to the discovery of new fundamental physics</u>

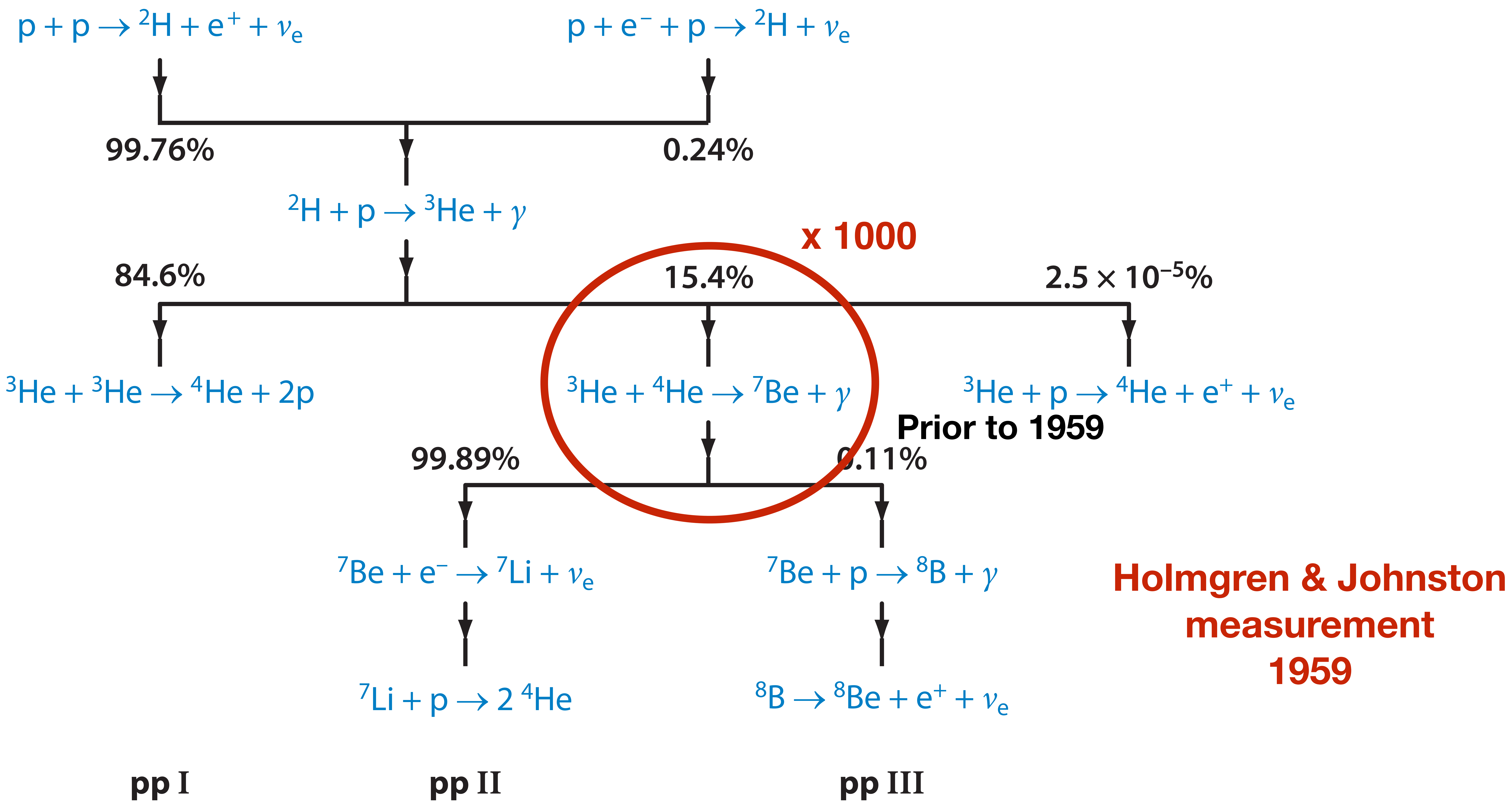
- The radiochemical Cl neutrino detector was proposed by Pontecorvo in 1946, developed as a practical experiment by Alvarez in 1949, and implemented by Davis in the 1950s, who did both prototype solar and reactor experiments

$$4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}$$

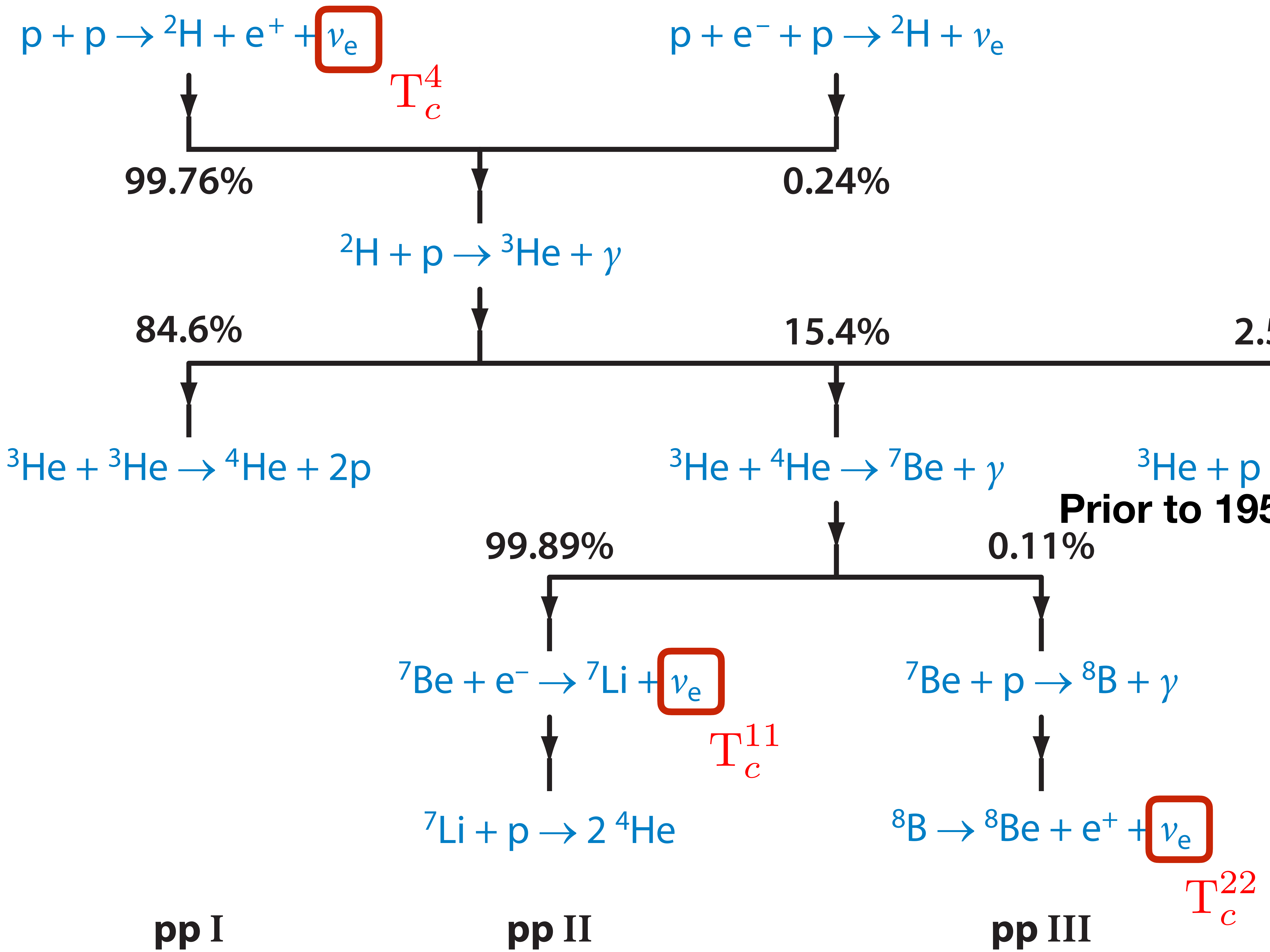


Prior to 1959: solar neutrinos though to be too low in energy for detection in the chlorine detector

$$4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}$$



$$4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}$$



dependence on the core temperature

Have a neutrino thermometer capable of measuring the solar core temperature to 1%

- So both the experimental opportunity to measure solar neutrinos and the astrophysical motivation for doing so fell into place

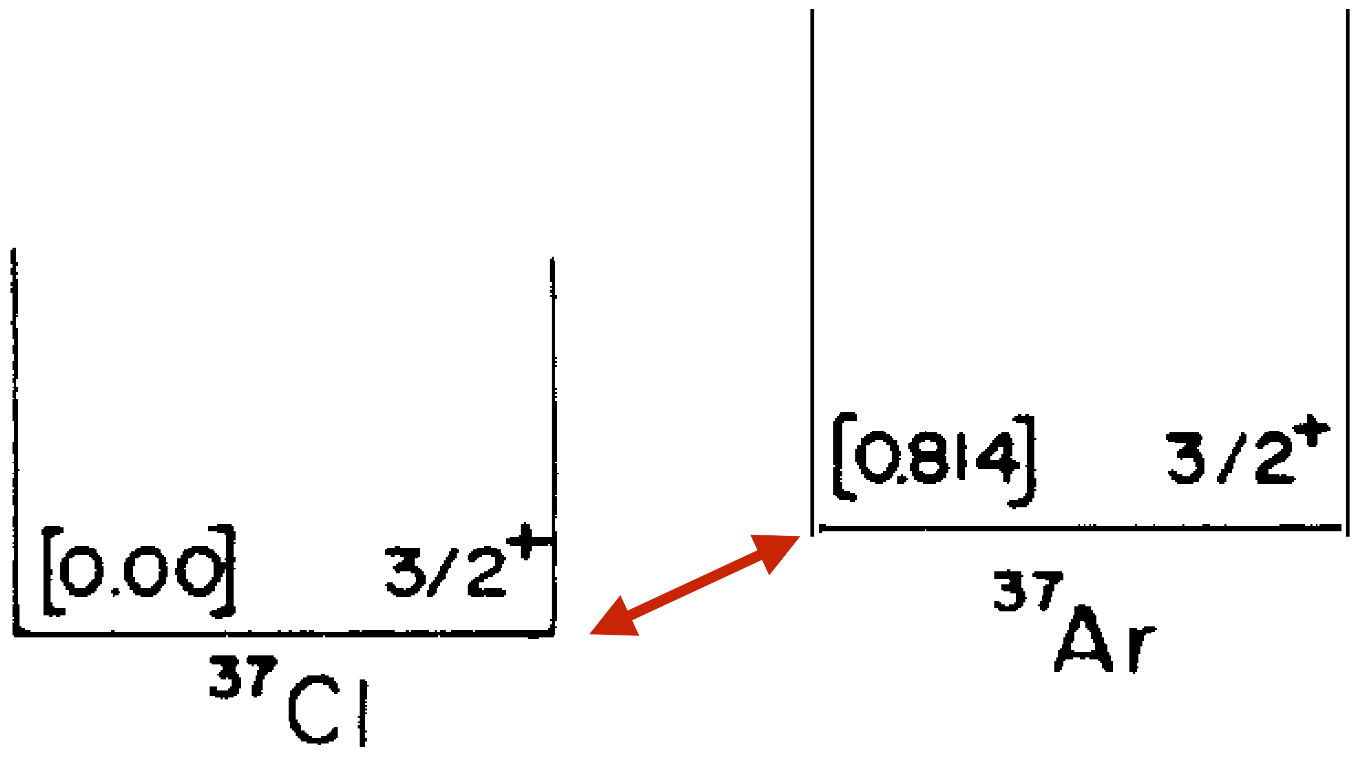
- Fowler recognized the opportunity, recruited postdoc John Bahcall (weak interactions) to join a Caltech group that included stellar modelers Iben and Sears
  - resulting model solar temperature profile folded off-line with weak rates, to make the first quantitative estimate of solar neutrino fluxes

- First quantitative estimate of the core temperature, folded with what little information existed on the Gamow-Teller EC and β decay reactions producing the neutrinos
  - — weak interactions in stellar environments: plasmas, screening, …
  - — utilization of laboratory measurements: theory needed to extrapolate measured weak rates to the lower energies of the solar Gamow peak
  - — selected use of theory: $p + p \rightarrow \nu_e + e^+ + D$

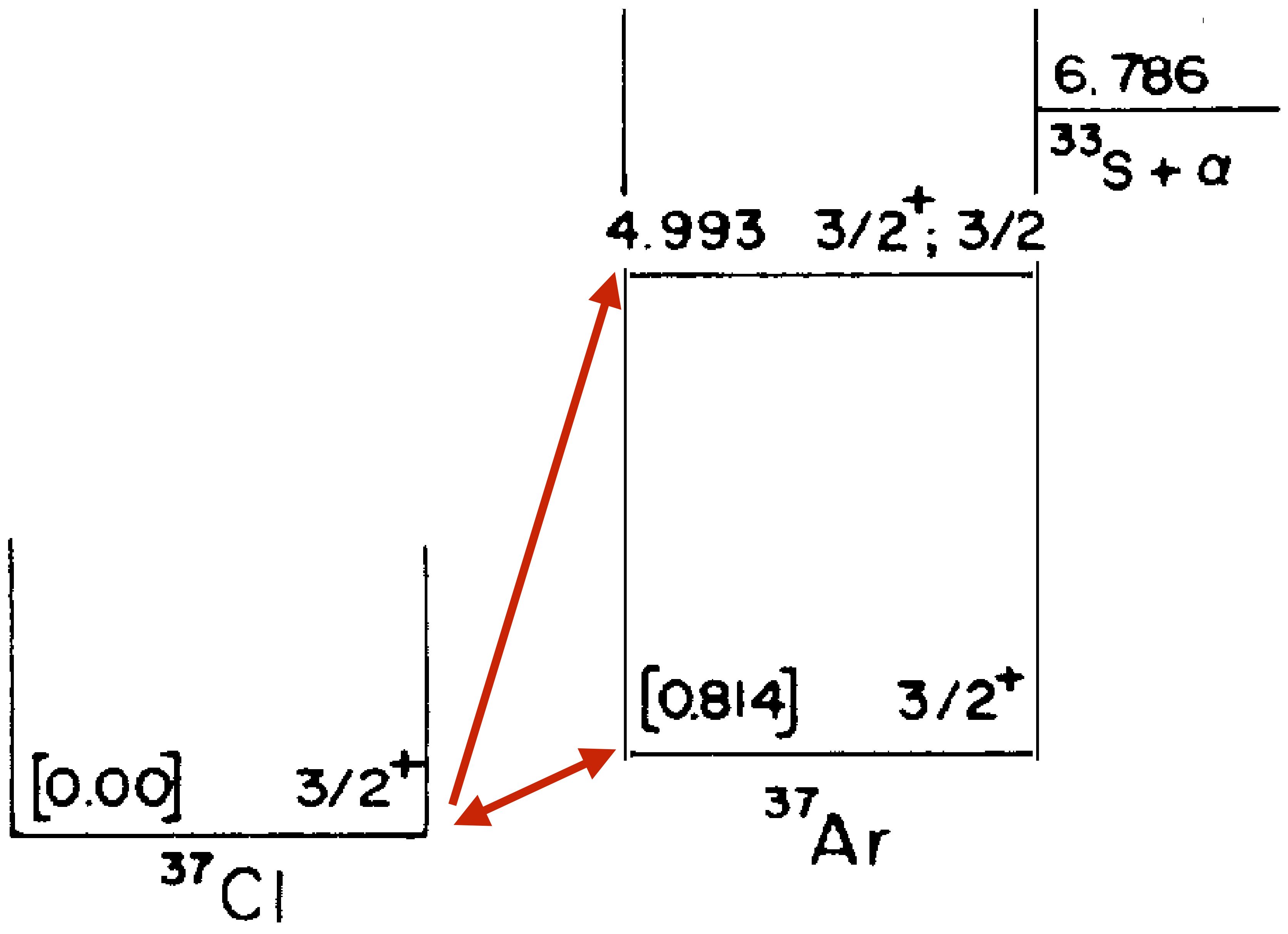
- One also had to develop a quantitative understanding of neutrino absorption on Cl, to demonstrated that any experimental result could be interpreted

The Learning Curve

Bahcall's initial estimate of cross section based on EC rate and detailed balance



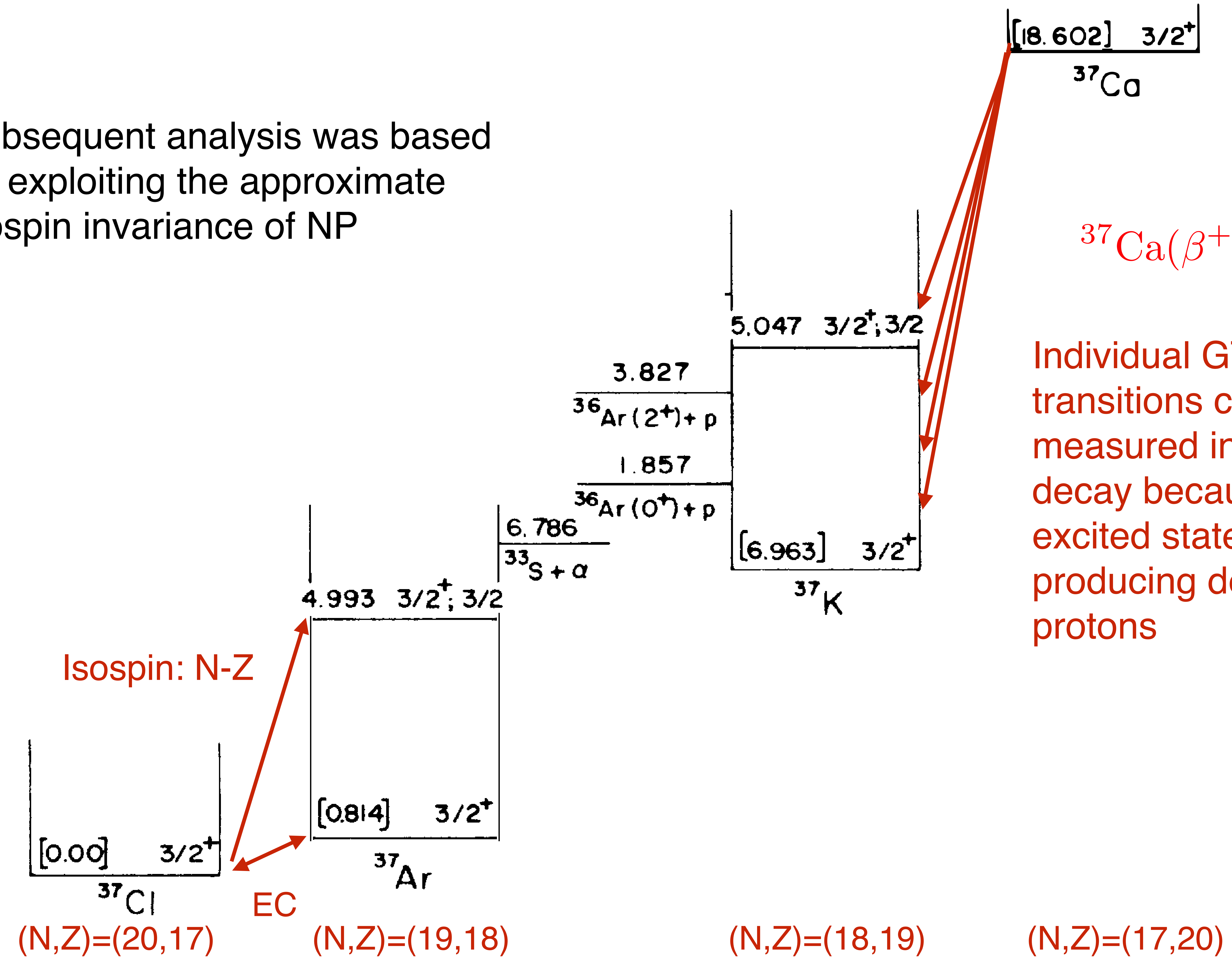
Bahcall's initial estimate of cross section based on EC rate and detailed balance



During a seminar at NBI, Mottelson pointed out to Bahcall the importance of excited states, including the analog Fermi transition

Their subsequent inclusion increased the cross section by a <u>critical factor of 20</u>

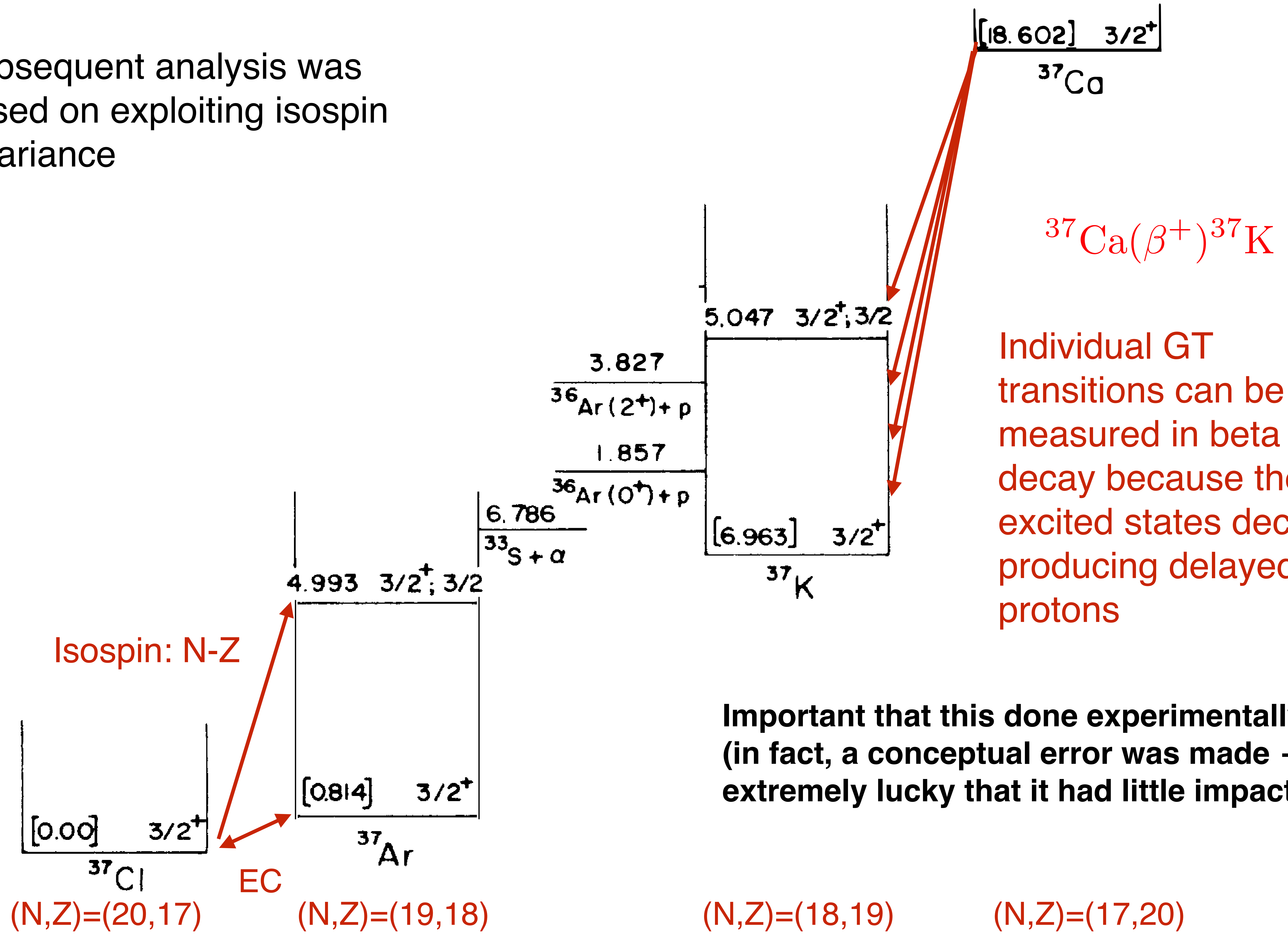
Subsequent analysis was based on exploiting the approximate isospin invariance of NP



$^{37}\mathrm{Ca}(\beta^{+})^{37}\mathrm{K}$

Individual GT transitions can be measured in beta decay because the excited states decay, producing delayed protons

Subsequent analysis was based on exploiting isospin invariance



Individual GT transitions can be measured in beta decay because the excited states decay, producing delayed protons

Important that this done experimentally (in fact, a conceptual error was made — extremely lucky that it had little impact)

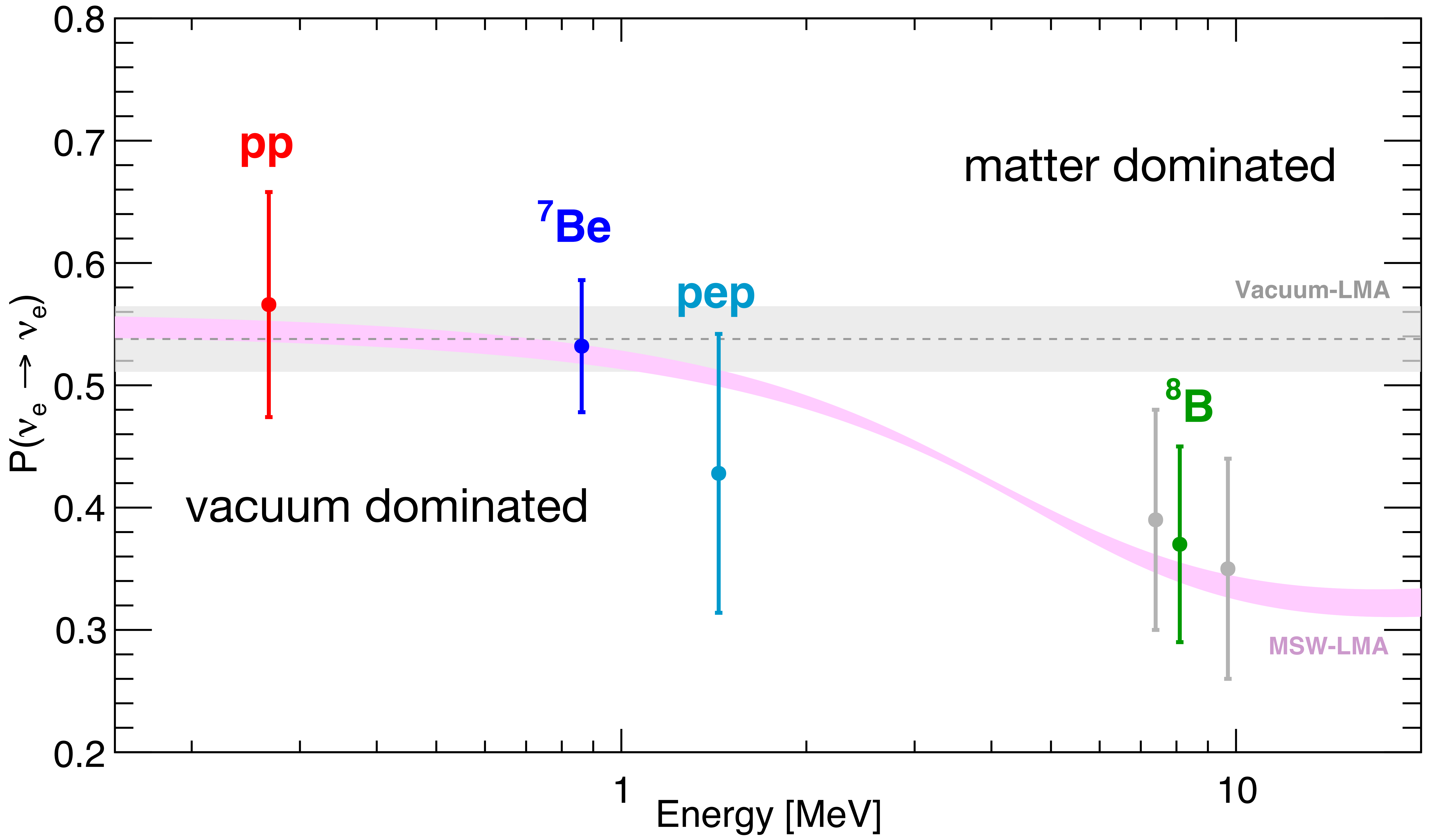
- Similar nuclear physics issues later arose in the Ga and SNO experiments

  $^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$ strong g.s. transition (EC) + neutrino source experiments

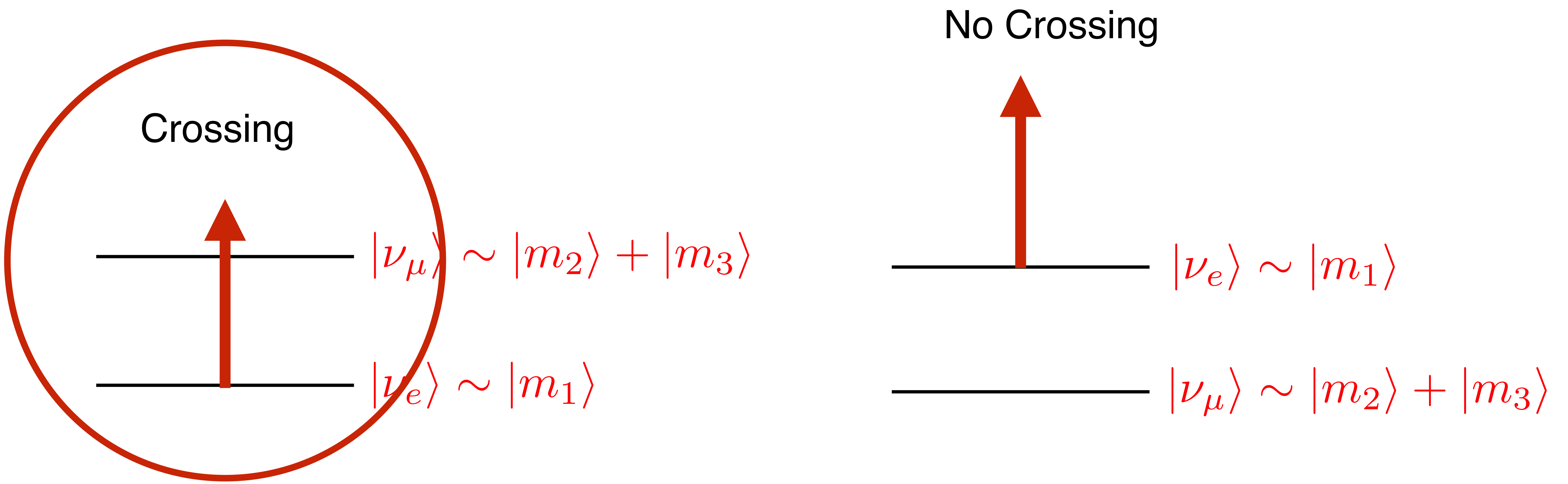
  $\mathrm{d}(\nu_e, e^-)p + p, \quad \mathrm{d}(\nu, \nu')n + p$ calculated with potentials and in EFT, remaining uncertainties estimated at 1.5%

- Our ability to determine quantitatively — through a combination of laboratory experiment and theory — the nuclear microphysics of the sun and the detector responses of Cl, Ga, SNO yielded fundamental physics
  — the discovery of neutrino mass and flavor oscillations
  — the observation of matter effects, determining the ordering of two eigenstates

Borexino's mapping of the vacuum → matter oscillation transition



This good fortunate — the solar neutrino spectrum spanning the level crossing — then was leveraged to determine the ordering of the mass eigenstates



mass difference decreased:
oscillation length increased

mass difference increased:
oscillation length decreased

- One would think this kind of success would inspire continued investment in a solar neutrino program and low-energy neutrino physics — but no

- Among the unanswered question are two that address fundamental assumptions of our theory of the sun and main-sequence stellar evolution

  — the SSM's assumption of hydrostatic equilibrium: the equivalence of the sun's weak (neutrino) and E&M (photon) luminosities. Theory (p+p fusion) has positioned us to test this equivalence at 1-2%, but experiment stands at 10%

  — the SSM's assumption of a uniform ZAMS star — now called into question by the solar metallicity problem and by direct observations of how planetary disks alter the composition of gas accreting onto young suns: CNO neutrinos

- But we dropped the ball on this low-energy neutrino program — even while the astrophysical theory we test is crucial to major new missions like Plato's study of asteroseismology of main-sequence stars in the Milky Way

Low-energy neutrinos #2: Supernova neutrinos

- Goal is to understand the neutrino physics well enough that we can use the explosion characteristics, neutrino emission, and nucleosynthesis to constrain the explosion mechanism, and its underlying physics (e.g., the EoS)

- Colgate and White (1966) proposed the first hydrodynamically plausible mechanism for a Type-II supernova explosion, aided by an intense fluence of neutrinos. Proposed that a “gale” of hot neutrinos would deposit sufficient energy and momentum in the mantel to drive its ejection

- The discovery in 1973 of neutral currents radically changed the model: neutrinos leak out, and are relatively cool because they decouple at low density ($10^{12}\ \mathrm{g/cm}^3$) over a time (3 sec) much larger than the dynamical time of a prompt explosion

- Typical temperatures are 4-7 MeV, with $\langle E \rangle \sim 3T_\nu \sim 12-21\ \mathrm{MeV}$, with flavor differences in neutrino opacities yielding a weak hierarchy $T_{\nu_e} \lesssim T_{\bar{\nu}_e} \lesssim T_{\nu_{\mathrm{heavy}}}$

- Neutrinos are the primary drivers of transport in the explosion: energy, entropy, lepton number. Account for 99% of energy emitted

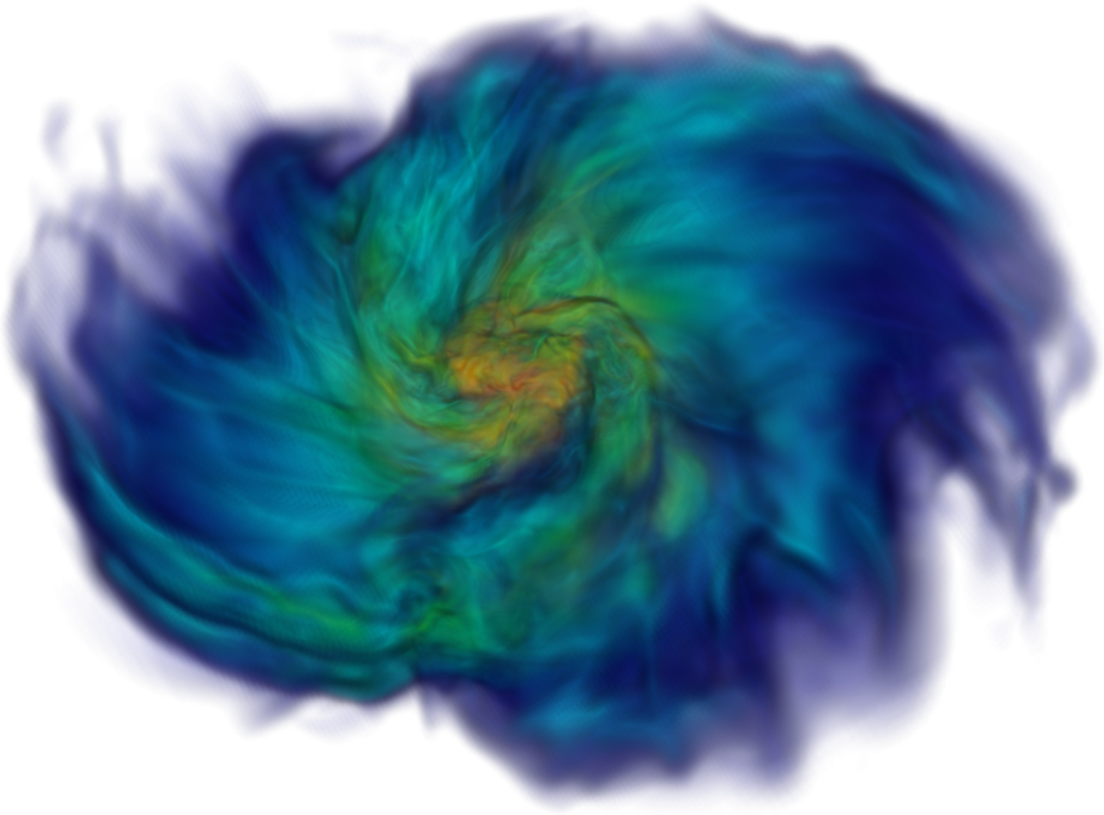
- They also set the initial conditions prior to the explosion, cooling the collapsing core and controlling its lepton fraction, influencing the rebound and shock wave generation
  — electrons convert to $\nu_e\mathrm{s}$ via EC
  — neutrino opacities vary as $E_{\nu_e}^2$: the lowest energy neutrinos escape rapidly
  — inelastic down scattering refills the emptying states, driven by neutrino reactions on electrons and nuclei, which together maximize loss of lepton number

- The result is a smaller core mass, and a weakened shock that stalls, after progressing only part way through the iron core, but boiling the Fe through which it passes to n/p

- The delayed mechanism: neutrino heating of the nucleon soup left in the shock's wake generates pressure, regenerating the shock wave, which moves outward

- Convection and a low mass progenitor increases the prospects of a successful explosion

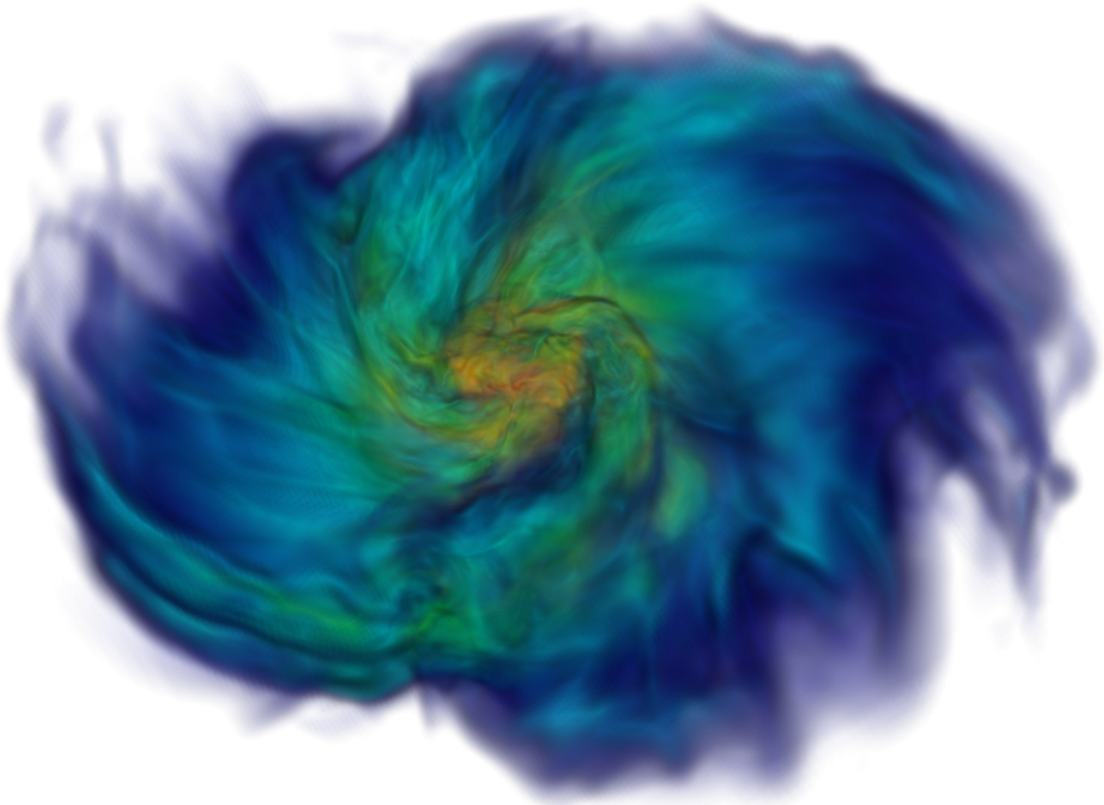
Demonstrating an understanding of SNe and their neutrinos is of broad importance



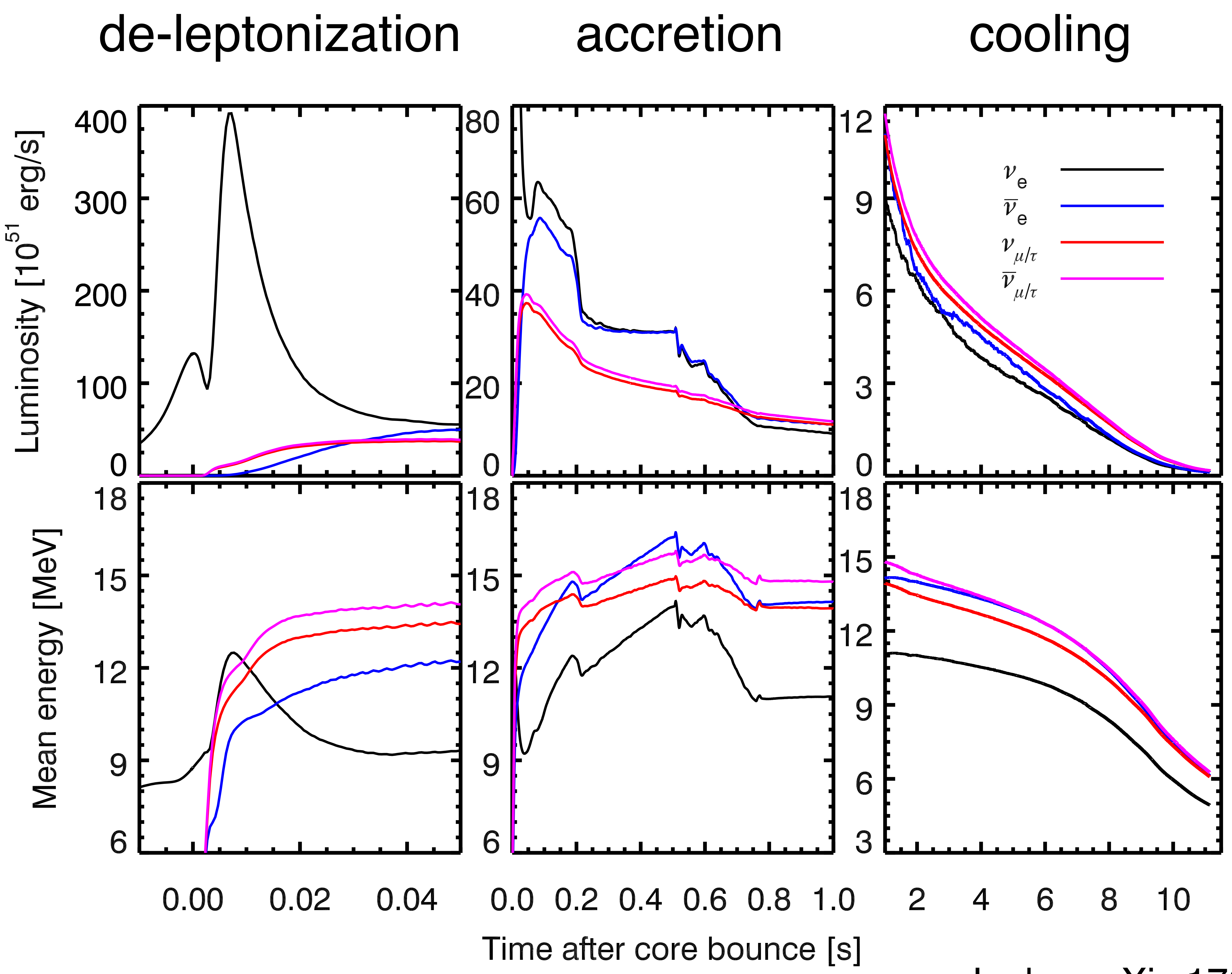
- While we have come to understand that the flavor physics of SNe is complex, there are “clean" opportunities to do fundamental physics, given a nearby (galactic) SN neutrinos

- To get more value out of multi-messenger physics of gravitational waves, kilonovae, and associated forensics of nucleosynthesis, we need to have confidence in our understanding of NS mergers: opportunities to observe these neutrinos will be extremely rare, but the similarities of these explosions to SNe make the latter a surrogate

Neutrino basics of SNe and NS mergers

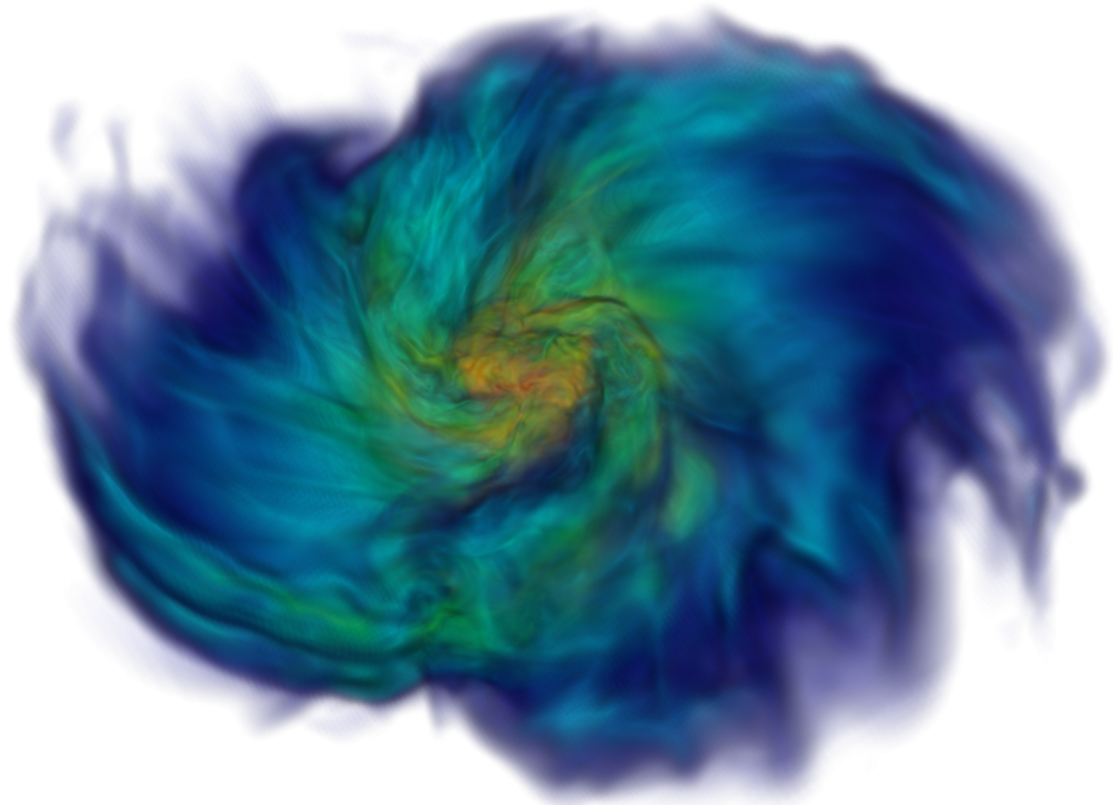


SN Neutrinos

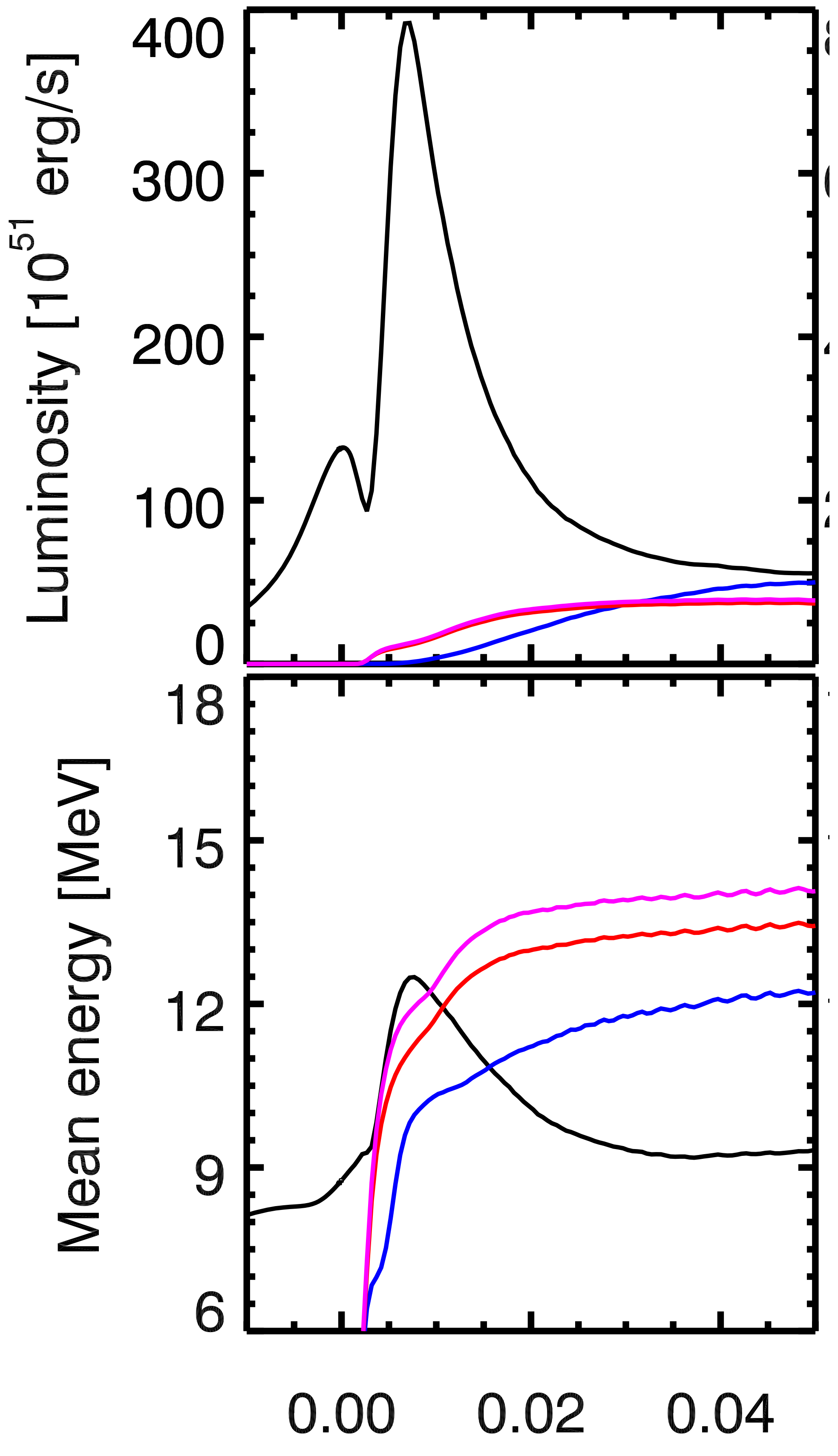


Janka arXiv:1702.08713

Neutrino basics of SNe and NS mergers



de-leptonization



- high flux, modest fluency (1% of the neutrino emission)
- mean energy of about 12 MeV — readily detectable
- flavor purity quite good
- most important, created outside the SN's dynamical core — what we know about neutrinos today is adequate to model this source

- Neutrino-nucleus physics
  - — we understand trapping: coherent scattering
  - — heating, lepton number loss: more complex, involving inelastic reactions, where allowed and first-forbidden responses make significant contributions

- Nucleosynthesis
  - — charge-current reactions off nucleons control p/n chemistry: resulting small neutron excesses and proliferation of seeds makes conditions for a robust r-process difficult to achieve — well understood
  - — nucleosynthesis in the mantle: largely driven by NC inelastic reactions that excite C, Ne, and other major isotopes above particle breakup
    - — includes the production of p, n that then react
    - — sensitive to T_ν, oscillations in mantle, neutrino self interactions in core

- Post processing: elements produced in the explosion are processed by the intense neutrino flux: smooths productions by spalling

- Almost all of this physics requires the calculation of inclusive responses
  — in the SM, Lanczos methods are of great power
  — recursive mapping of the full Hamiltonian H into effective Hamiltonians H_n which have the same first $2n+1$ energy moments
  — allowed inclusive response functions can be evaluated by using as the Lanczos pivot, e.g.,

$$\sum_{i=1}^{A} \vec{\sigma}(i)\tau_+(i)|O_{g.s.}\rangle$$

  — extraordinary numerical progress: successful implementation on leadership class machines, can handle matrices of dimension $\sim 10^{11}$

  — first-forbidden contributions often treated with less sophistication: QRPA and related methods that make compromises in the degree of correlation, but can more readily be applied to momentum-dependent operators

$$\sum_{i=1}^{A} [\vec{\sigma}(i) \otimes q\vec{r}(i)]_{J=0,1,2}\, \tau_+(i)|O_{gs}\rangle$$

- The future of experiment is brighter than is currently the case for solar neutrinos

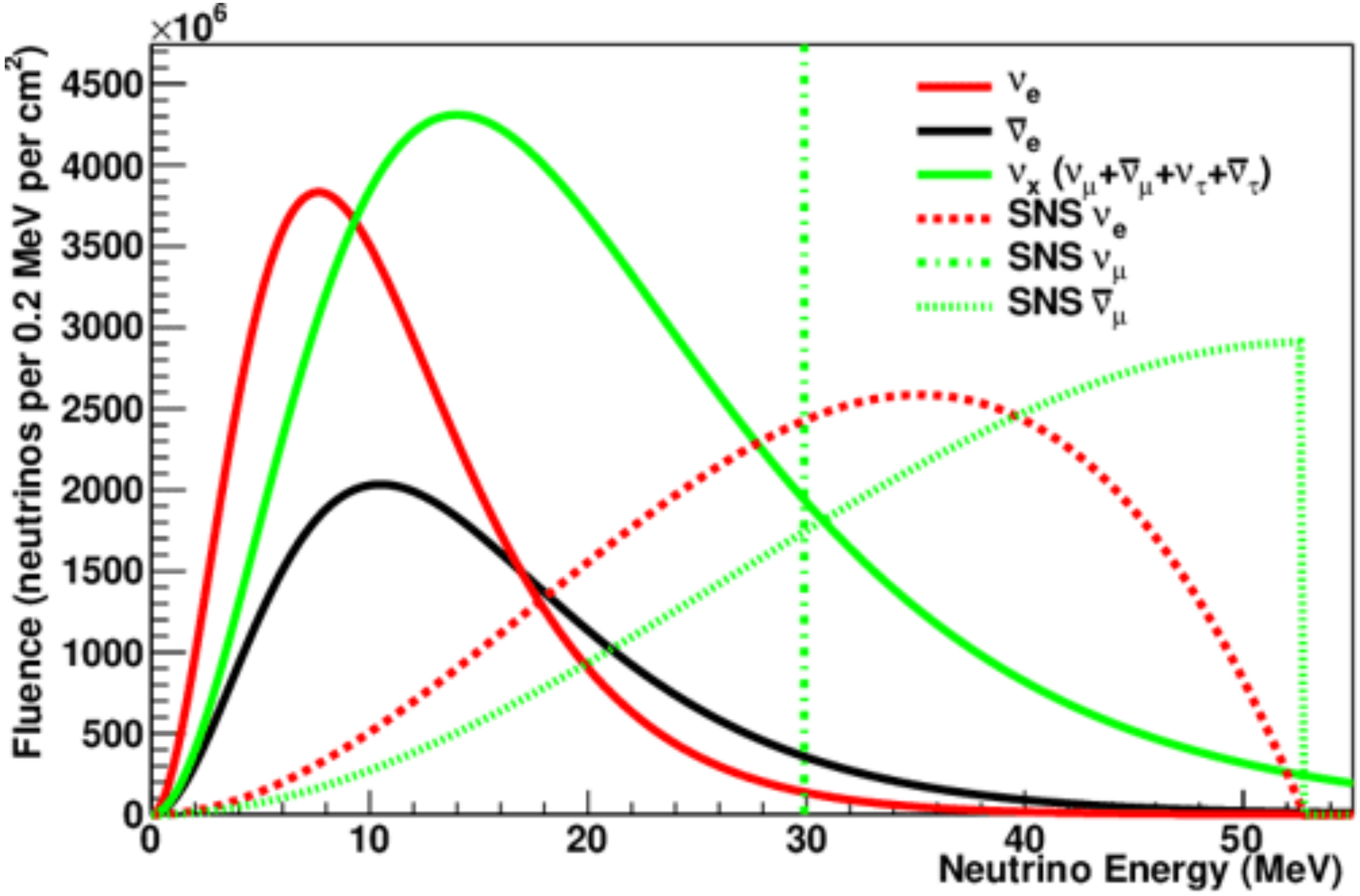
  — SuperK is now operating with Gd, results expected soon: a primary motivation for neutron tagging to help isolate the relic supernova flux

  — HyperKamiokande and DUNE will be able to map out the supernova neutrino light curve to times on the order of 100s in a nearly background-free way: will follow the evolution of the core as it cools and radiates its lepton number

  — the large number of events could provide detailed angular distributions that could be disentangled to provide additional flavor physics information

  — advent of multi-messenger astrophysics and fast-slewing telescopes: possibility of gaining more information on the progenitor, through observation of the shock breakout following neutrino detection

- Potentially, connections to the laboratory — including electron scattering to test our theory and experiments with stopped pion neutrinos



$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

So a modest step up in energy

Low energy accelerator neutrinos: We once had a significant program at LAMPF

- Produced the world's then most intense muon and neutrino beams

E225, led by Herb Chen, 1975-93:

— probed the interference between neutral and charge-changing weak currents

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

— measured: $\nu_e + {}^{12}\mathrm{C} \rightarrow \nu_e + {}^{12}\mathrm{C}^*$ 1^+1 15.1 MeV

E645, E764, 1980-92: oscillation experiments using p, ${}^{12}\mathrm{C}$ targets

$\nu_e,\ \bar{\nu}_e$ appearance in $\nu_\mu,\ \bar{\nu}_\mu$ beams

E31, 1975-1980: charged current reactions $\bar{\nu}_e + p,\ \nu_e + D$

test of family number conservation

E1173, 1989-1999: the LSND experiment $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance, …

- Kate will tell us about the coherent scattering program now underway at the SNS

- In fact, the SNS beam structure is ideal for a more robust NP program
    — pions delivered in short bursts, 695 ns in width at 60 Hz

$$\pi^+ \to \mu^+ + \nu_\mu, \quad \tau = 26 \text{ ns}$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e, \quad \tau = 2.2 \ \mu\text{s}$$

    — effective duty cycle for delivering ν_μs is 0.004%
      and for delivering $\bar{\nu}_\mu$s, ν_es is 0.02%

    — low effective backgrounds

    — timing: flavor separation, a tool for probing oscillations

    — SNS upgrade from 1.4 MW to 2.8 MW

- An opportunity to create a needed low-energy program in neutrino-nucleus physics

This was meant to provide high-level motivation for this workshop

I will conclude with the two contemporary neutrino NP problems we have worked on at Berkeley this past year

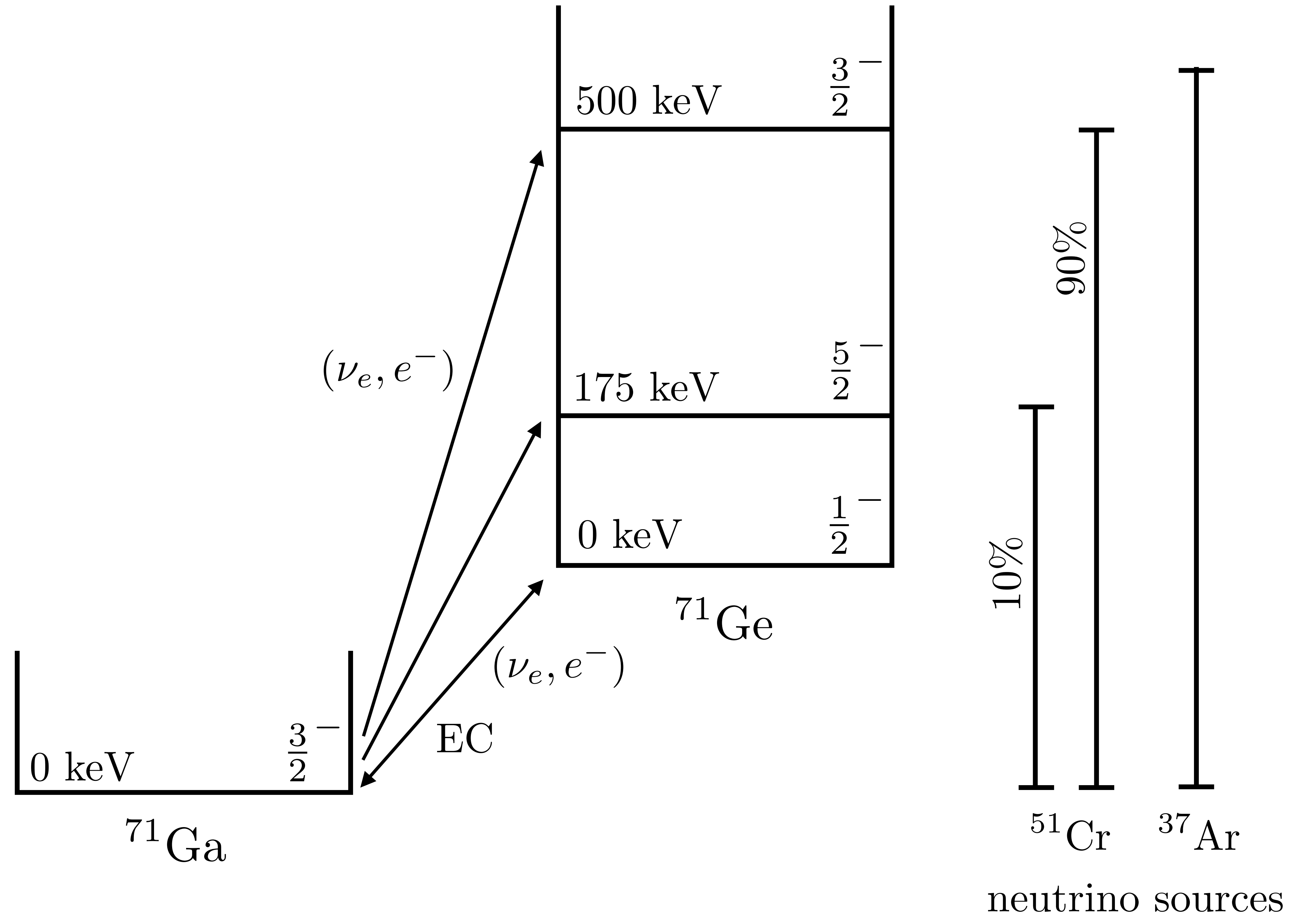
— Baksan Experiment on Sterile Neutrinos

— The axial response of the DUNE detector

BEST

- The Ga solar neutrino experiments SAGE and GALLEX/GNO each performed two neutrino source experiments to check overall efficiencies, and particularly the cross section for absorbing low-energy solar neutrinos
  - — radiochemical detectors, like Cl
  - — high sensitivity to the pp and ^{7}Be neutrino sources
  - — provided an early indication of new physics: minimum astronomical value
  - — meticulous Ge tracer experiments performed in each run, to verify the high efficiency of Ge recovery

$$^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$$



- Precisely known EC rate determines the pp neutrino cross section to 1%
- ^{7}Be neutrino absorption also occurs through two excited-state transitions
- Theory predicts these to be relatively weak, and thus uncertain
- Each collaboration performed two calibrations using intense (MCi) EC line neutrino sources chosen because they mimic the ^{7}Be line neutrinos
- Source intensities measured to 0.3%

The calibration experiments gave rates lower than expected

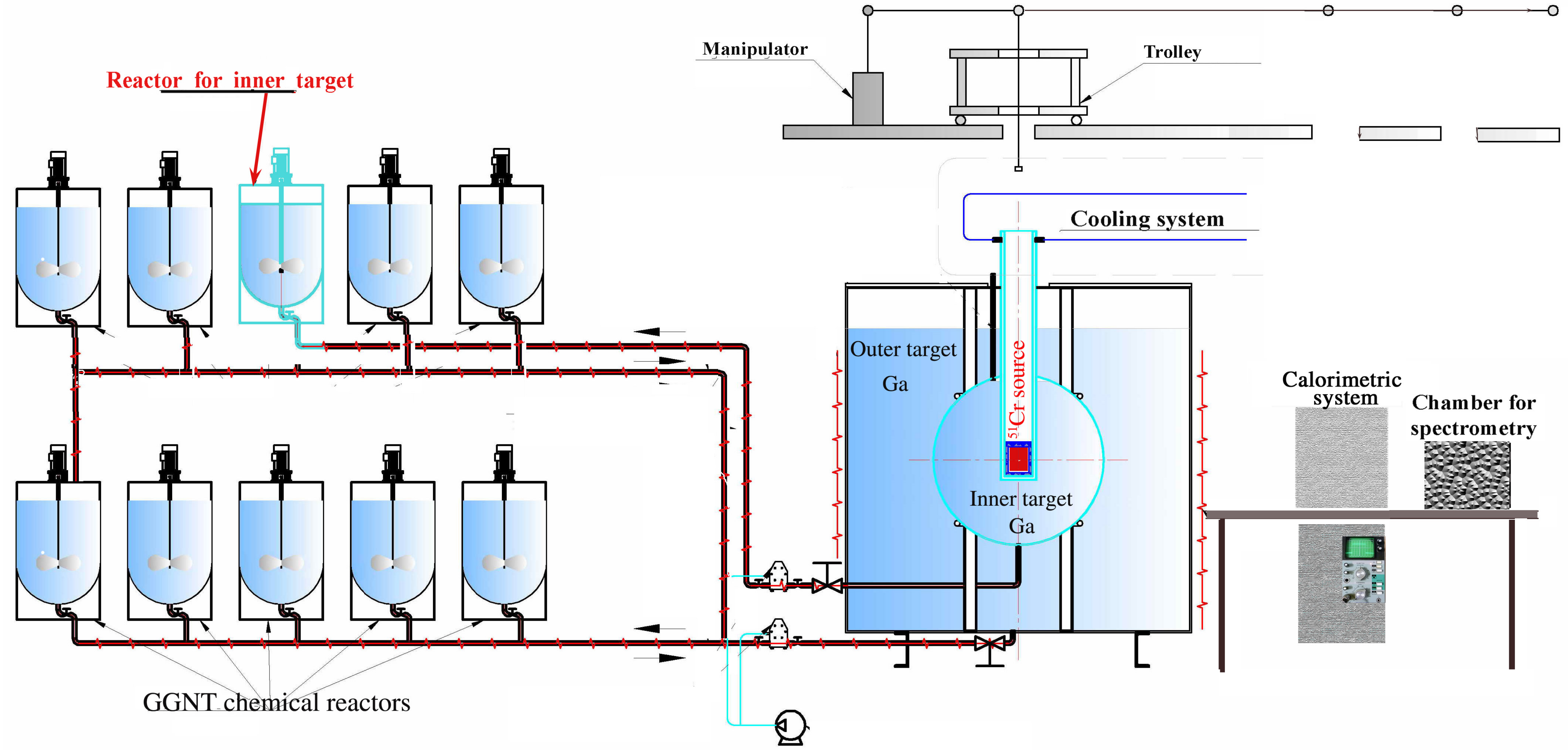
$$\frac{R_{\text{measured}}}{R_{\text{expected}}} = 0.866 \pm 0.54$$

which came to be known as the Ga anomaly, and is frequently cited as possible evidence for oscillations into a 4th sterile neutrino state with $\delta m^2 \gtrsim 1\ \mathrm{eV}^2$

BEST is a recently completed experiment to test this ansatz in a detector specially designed to provide baseline information, using a low-energy ^{51}Cr neutrino source of unprecedented intensity, 3.4 MCi

SAGE Collaboration, PRL 128 (2022) 232501

SAGE Collaboration, PRC 105 (2022) 065502



No sign of oscillations was found in the comparison of rates in the inner and outer detector, but the anomaly persisted and in fact increased in significance

$$\frac{R_{\text{experiment}}}{R_{\text{measured}}}\bigg|_{\text{combined}} = 0.81 \pm 0.05$$

This is an example of a precision experiment where the cross section is a common systematic, whose value can influence the significance of the anomaly, though not remove it.

Extract the g.s. transition strength from the precisely measured EC rate

$$\omega = \frac{\ln[2]}{\tau_{\frac{1}{2}}} = \frac{G_F^2 \cos^2 \theta_C}{2\pi} \; |\phi_{1s}|^2_{\text{avg}} \; E^2_{\nu,1s} \; \left[2(1+\epsilon_o^{1s})(1+\tfrac{P_L+P_M}{P_K})\right] \; g_A^2 \; [2 \; \mathrm{B}_{\mathrm{GT}}^{(\nu,\mathrm{e})}(\mathrm{gs})] \; [1+g_{v,b}]_{\mathrm{EC}} \; [1+\epsilon_q]$$

No sign of oscillations was found in the comparison of rates in the inner and outer detector, but the anomaly persisted and in fact increased in significance

$$\frac{R_{\text{experiment}}}{R_{\text{measured}}}\bigg|_{\text{combined}} = 0.81 \pm 0.05$$

This is an example of a precision experiment where the cross section is a common systematic, whose value can influence the significance of the anomaly, though not remove it.

Extract the g.s. transition strength from the precisely measured EC rate

$$\omega = \frac{\ln[2]}{\tau_{\frac{1}{2}}} = \frac{G_F^2 \cos^2\theta_C}{2\pi} \; |\phi_{1s}|^2_{\text{avg}} \; E^2_{\nu,1s} \left[2(1+\epsilon_o^{1s})(1+\frac{P_L+P_M}{P_K})\right] \; g_A^2 \; [2\ \mathrm{B}^{(\nu,\mathrm{e})}_{\mathrm{GT}}(\mathrm{gs})] \; [1+g_{v,b}]_{\mathrm{EC}} \; [1+\epsilon_q]$$

EC rate known experimentally to 0.3%: a dozen high-precision experiments

No sign of oscillations was found in the comparison of rates in the inner and outer detector, but the anomaly persisted and in fact increased in significance

$$\left.\frac{R_{\text{experiment}}}{R_{\text{measured}}}\right|_{\text{combined}} = 0.81 \pm 0.05$$

This is an example of a precision experiment where the cross section is a common systematic, whose value can influence the significance of the anomaly, though not remove it.

Extract the g.s. transition strength from the precisely measured EC rate

$$\omega = \frac{\ln[2]}{\tau_{\frac{1}{2}}} = \frac{G_F^2 \cos^2\theta_C}{2\pi} \; |\phi_{1s}|^2_{\text{avg}} \; E^2_{\nu,1s} \left[2(1+\epsilon_o^{1s})(1+\tfrac{P_L+P_M}{P_K})\right] \; g_A^2 \; [2\ \mathrm{B}^{(\nu,\mathrm{e})}_{\mathrm{GT}}(\mathrm{gs})] \; [1+g_{v,b}]_{\mathrm{EC}} \; [1+\epsilon_q]$$

PDG and Perkeo III results, 0.05% accuracy

No sign of oscillations was found in the comparison of rates in the inner and outer detector, but the anomaly persisted and in fact increased in significance

$$\left.\frac{R_{\mathrm{experiment}}}{R_{\mathrm{measured}}}\right|_{\mathrm{combined}} = 0.81 \pm 0.05$$

This is an example of a precision experiment where the cross section is a common systematic, whose value can influence the significance of the anomaly, though not remove it.

Extract the g.s. transition strength from the precisely measured EC rate

$$\omega = \frac{\ln[2]}{\tau_{\frac{1}{2}}} = \frac{G_F^2 \cos^2\theta_C}{2\pi} \; |\phi_{1s}|^2_{\mathrm{avg}} \; E^2_{\nu,1s} \left[2(1+\epsilon_o^{1s})(1+\tfrac{P_L+P_M}{P_K})\right] \; g_A^2 \; [2\ \mathrm{B}^{(\nu,\mathrm{e})}_{\mathrm{GT}}(\mathrm{gs})] \; [1+g_{v,b}]_{\mathrm{EC}} \; [1+\epsilon_q]$$

Atomic 1s density averaged over the nucleus: 0.5% agreement among three relativistic HF calculations

No sign of oscillations was found in the comparison of rates in the inner and outer detector, but the anomaly persisted and in fact increased in significance

$$\left.\frac{R_{\text{experiment}}}{R_{\text{measured}}}\right|_{\text{combined}} = 0.81 \pm 0.05$$

This is an example of a precision experiment where the cross section is a common systematic, whose value can influence the significance of the anomaly, though not remove it.

Extract the g.s. transition strength from the precisely measured EC rate

$$\omega = \frac{\ln[2]}{\tau_{\frac{1}{2}}} = \frac{G_F^2 \cos^2\theta_C}{2\pi} \; |\phi_{1s}|^2_{\text{avg}} \; E^2_{\nu,1s} \left[2(1+\epsilon_o^{1s})(1+\frac{P_L+P_M}{P_K})\right] \; g_A^2 \; [2 \; \mathrm{B}^{(\nu,\mathrm{e})}_{\mathrm{GT}}(\mathrm{gs})] \; [1+g_{v,b}]_{\mathrm{EC}} \; [1+\epsilon_q]$$

experimentally known branching ratio of L and M capture to K capture

No sign of oscillations was found in the comparison of rates in the inner and outer detector, but the anomaly persisted and in fact increased in significance

$$\left.\frac{R_{\mathrm{experiment}}}{R_{\mathrm{measured}}}\right|_{\mathrm{combined}} = 0.81 \pm 0.05$$

This is an example of a precision experiment where the cross section is a common systematic, whose value can influence the significance of the anomaly, though not remove it.

Extract the g.s. transition strength from the precisely measured EC rate

$$\omega = \frac{\ln[2]}{\tau_{\frac{1}{2}}} = \frac{G_F^2 \cos^2\theta_C}{2\pi} \, |\phi_{1s}|^2_{\mathrm{avg}} \, E^2_{\nu,1s} \left[2(1+\epsilon_o^{1s})(1+\tfrac{P_L+P_M}{P_K})\right] \, g_A^2 \, [2 \, \mathrm{B}_{\mathrm{GT}}^{(\nu,\mathrm{e})}(\mathrm{gs})] \, [1+g_{v,b}]_{\mathrm{EC}} \, [1+\epsilon_q]$$

atomic exchange and overlap corrections need to relate instantaneous
EC branching ratios to experimental K, L, M probabilities

No sign of oscillations was found in the comparison of rates in the inner and outer detector, but the anomaly persisted and in fact increased in significance

$$\left.\frac{R_{\text{experiment}}}{R_{\text{measured}}}\right|_{\text{combined}} = 0.81 \pm 0.05$$

This is an example of a precision experiment where the cross section is a common systematic, whose value can influence the significance of the anomaly, though not remove it.

Extract the g.s. transition strength from the precisely measured EC rate

$$\omega = \frac{\ln[2]}{\tau_{\frac{1}{2}}} = \frac{G_F^2 \cos^2\theta_C}{2\pi}\ |\phi_{1s}|^2_{\text{avg}}\ E^2_{\nu,1s}\ \left[2(1+\epsilon_o^{1s})(1+\tfrac{P_L+P_M}{P_K})\right]\ g_A^2\ [2\ \mathrm{B}_{\mathrm{GT}}^{(\nu,\mathrm{e})}(\mathrm{gs})]\ [1+g_{v,b}]_{\mathrm{EC}}\ [1+\epsilon_q]$$

radiative corrections (net significant e 0.5%)

No sign of oscillations was found in the comparison of rates in the inner and outer detector, but the anomaly persisted and in fact increased in significance

$$\frac{R_{\text{experiment}}}{R_{\text{measured}}}\Bigg|_{\text{combined}} = 0.81 \pm 0.05$$

This is an example of a precision experiment where the cross section is a common systematic, whose value can influence the significance of the anomaly, though not remove it.

Extract the g.s. transition strength from the precisely measured EC rate

$$\omega = \frac{\ln[2]}{\tau_{\frac{1}{2}}} = \frac{G_F^2 \cos^2\theta_C}{2\pi}\ |\phi_{1s}|^2_{\text{avg}}\ E^2_{\nu,1s}\ \left[2(1+\epsilon_o^{1s})(1+\tfrac{P_L+P_M}{P_K})\right]\ g_A^2\ [2\ \mathrm{B}^{(\nu,\mathrm{e})}_{\mathrm{GT}}(\mathrm{gs})]\ [1+g_{v,b}]_{\mathrm{EC}}\ [1+\epsilon_q]$$

corrections to allowed approx: weak magnetism (0.5%)

No sign of oscillations was found in the comparison of rates in the inner and outer detector, but the anomaly persisted and in fact increased in significance

$$\left.\frac{R_{\text{experiment}}}{R_{\text{measured}}}\right|_{\text{combined}} = 0.81 \pm 0.05$$

This is an example of a precision experiment where the cross section is a common systematic, whose value can influence the significance of the anomaly, though not remove it.

Extract the g.s. transition strength from the precisely measured EC rate

$$\omega = \frac{\ln[2]}{\tau_{\frac{1}{2}}} = \frac{G_F^2 \cos^2\theta_C}{2\pi} \, |\phi_{1s}|^2_{\text{avg}} \, E^2_{\nu,1s} \left[2(1+\epsilon_o^{1s})(1+\tfrac{P_L+P_M}{P_K})\right] \; g_A^2 \; [2 \; \mathrm{B}^{(\nu,\mathrm{e})}_{\mathrm{GT}}(\mathrm{gs})] \; [1+g_{v,b}]_{\mathrm{EC}} \; [1+\epsilon_q]$$

extracted transition density for the (ν, e) direction

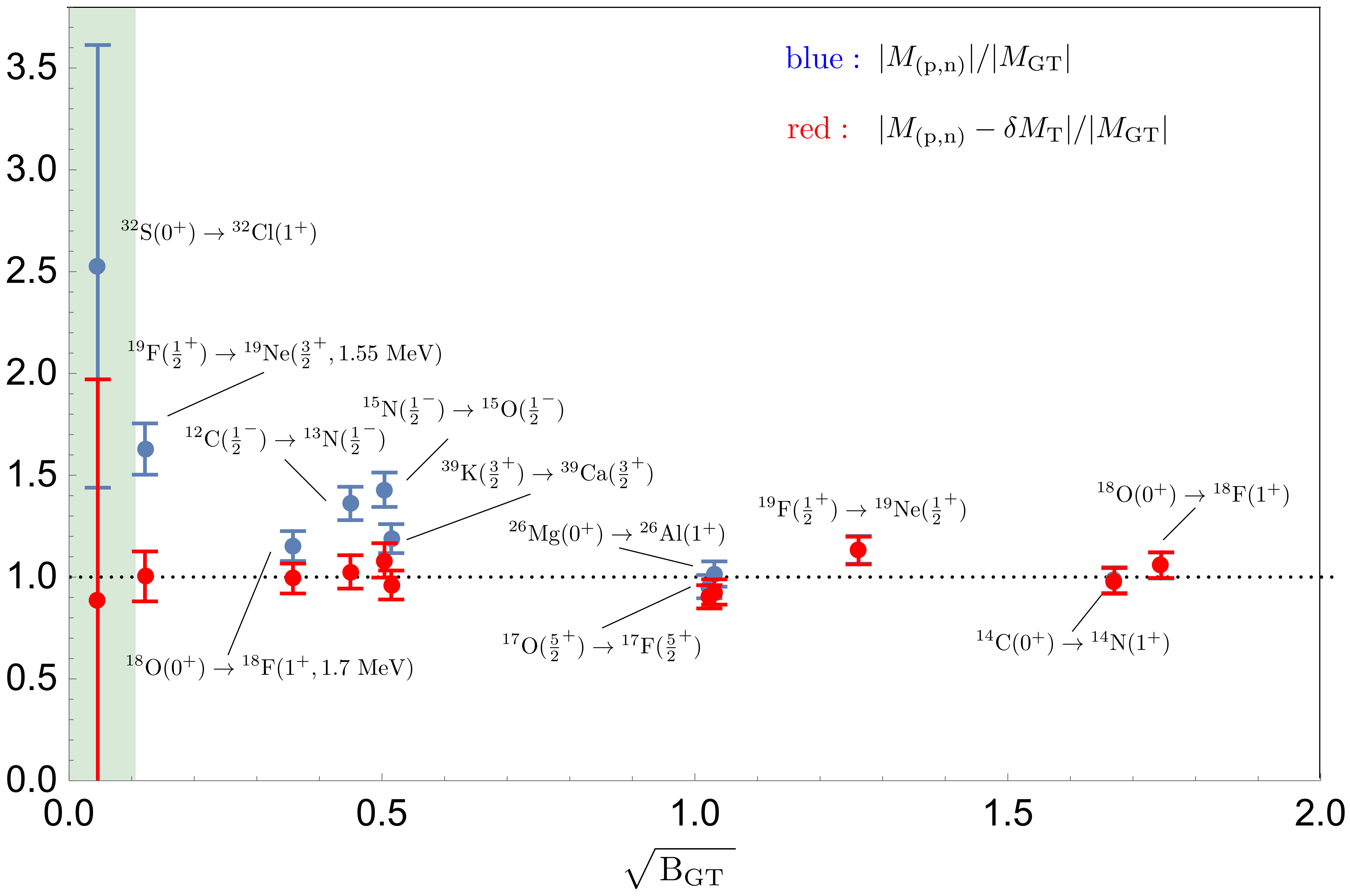
A tedious business where at each step, all relevant information from experiment is fed in, and experimental and theoretical errors are propagated. The same steps are needed in the (ν, e) direction …

$$\sigma_{\rm gs} = \begin{cases} (5.39 \pm 0.08) \times 10^{-45}\ \mathrm{cm}^2 & {}^{51}\mathrm{Cr} \\ (6.45 \pm 0.10) \times 10^{-45}\ \mathrm{cm}^2 & {}^{37}\mathrm{Ar} \end{cases}$$

The excited-state contributions — which if set to 0 remove 6% of the 19% anomaly — can be extracted from (p,n) forward scattering data, but only if the usual relationship takes into account the tensor contribution expected due to long-range pion exchange

$$M_{(p,n)} \propto M_{GT} + \delta M_T, \quad \delta \sim 0.08$$

Correction important when M_{GT} is weak and M_T is strong: this relationship is empirical and can be tested against EC transitions of known strength



blue : $|M_{(\mathrm{p,n})}|/|M_{\mathrm{GT}}|$
red : $|M_{(\mathrm{p,n})} - \delta M_{\mathrm{T}}|/|M_{\mathrm{GT}}|$
$^{32}\mathrm{S}(0^+) \to {}^{32}\mathrm{Cl}(1^+)$
$^{19}\mathrm{F}(\frac{1}{2}^+) \to {}^{19}\mathrm{Ne}(\frac{3}{2}^+, 1.55\ \mathrm{MeV})$
$^{15}\mathrm{N}(\frac{1}{2}^-) \to {}^{15}\mathrm{O}(\frac{1}{2}^-)$
$^{12}\mathrm{C}(\frac{1}{2}^-) \to {}^{13}\mathrm{N}(\frac{1}{2}^-)$
$^{39}\mathrm{K}(\frac{3}{2}^+) \to {}^{39}\mathrm{Ca}(\frac{3}{2}^+)$
$^{19}\mathrm{F}(\frac{1}{2}^+) \to {}^{19}\mathrm{Ne}(\frac{1}{2}^+)$
$^{18}\mathrm{O}(0^+) \to {}^{18}\mathrm{F}(1^+)$
$^{26}\mathrm{Mg}(0^+) \to {}^{26}\mathrm{Al}(1^+)$
$^{17}\mathrm{O}(\frac{5}{2}^+) \to {}^{17}\mathrm{F}(\frac{5}{2}^+)$
$^{14}\mathrm{C}(0^+) \to {}^{14}\mathrm{N}(1^+)$
$^{18}\mathrm{O}(0^+) \to {}^{18}\mathrm{F}(1^+, 1.7\ \mathrm{MeV})$
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
$\sqrt{\mathrm{B_{GT}}}$

BEST is puzzled by the result

- Precisely understood neutrino source, cross section highly constrained by a known EC rate

- Two decades of experimental experience with the same technique: consistent measurements of the pp flux by SAGE, GALLEX, and Borexino

- Tracer experiments using both hot and cold chemistry verifying Ge recovery at the 1-2% LEVEL

- But a result that requires a large mixing to a fourth neutrino, in conflict with some null sterile neutrino searches

Higher energies: CalLat result on $g_A(q^2)$

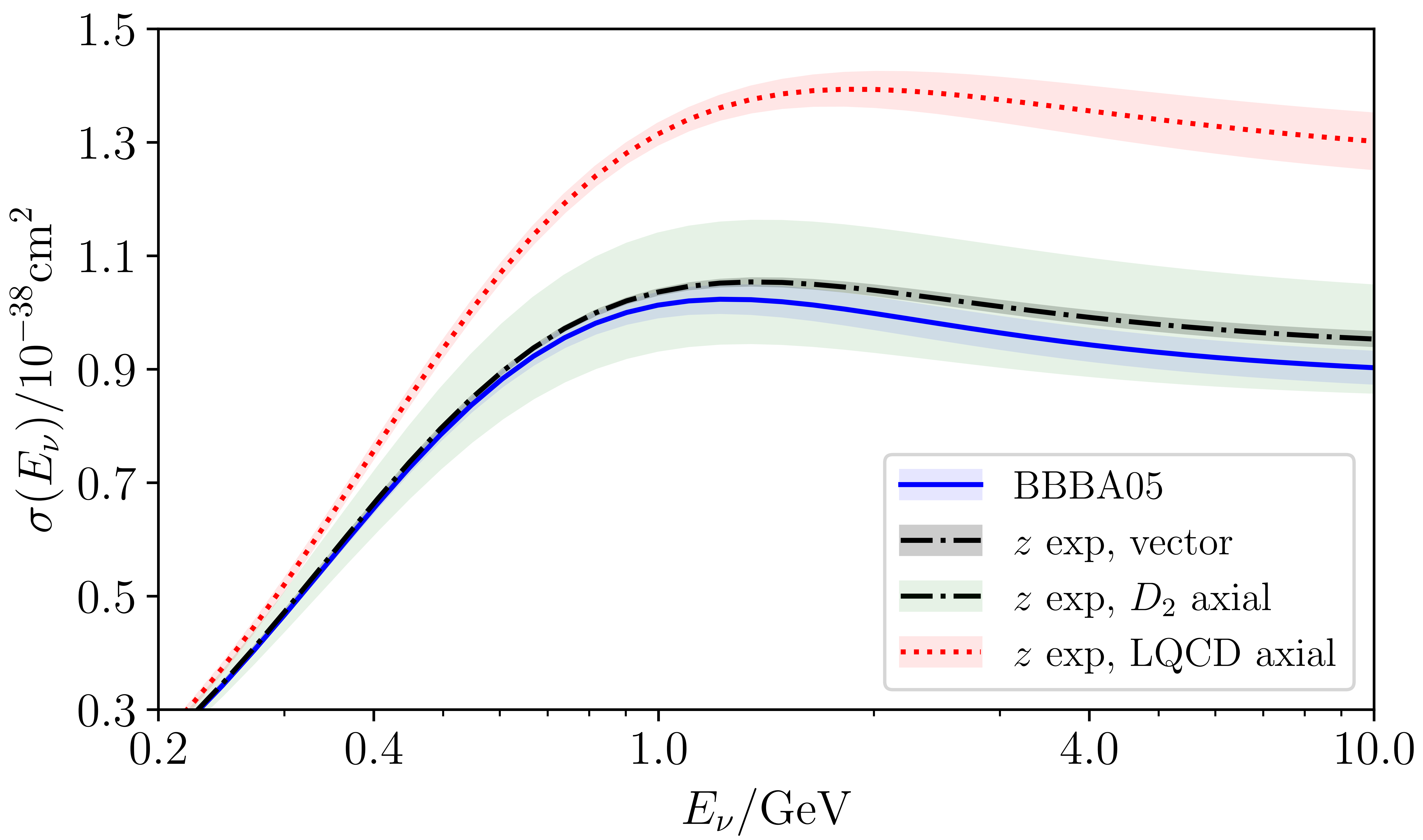
- The DUNE detector response with need to be understood at the $\sim$ 5% level

- Analysis franework is based on event generators that take as much input as possible from experiment, supplemented by theory

- Arguably the simplest nuclear input is $g_A(q^2)$, which governs the single-nucleon axial contribution to the quasi-elastic response, which DUNE hopes to isolate

- CalLat's lattice QCD calculation of gA(0) achieved a precision of 0.7%

- This work has now been extended to the form factor



Andrte Walker-Loud,
Aaron Meyer, et al.

- The LQCD axial response is 30% larger and better determined than experiment, calling into question the older bubble chamber data use by GENIE and others

- Program will be extended to resonance production, pion production

Conclusions: none — just looking forward to a week in which I can learn about the work being done by others