CEvNS and Inelastic Neutrino-Nucleus Scattering at Stopped-Pion Sources

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U.S. DEPARTMENT OF ENERGY | Office of Science

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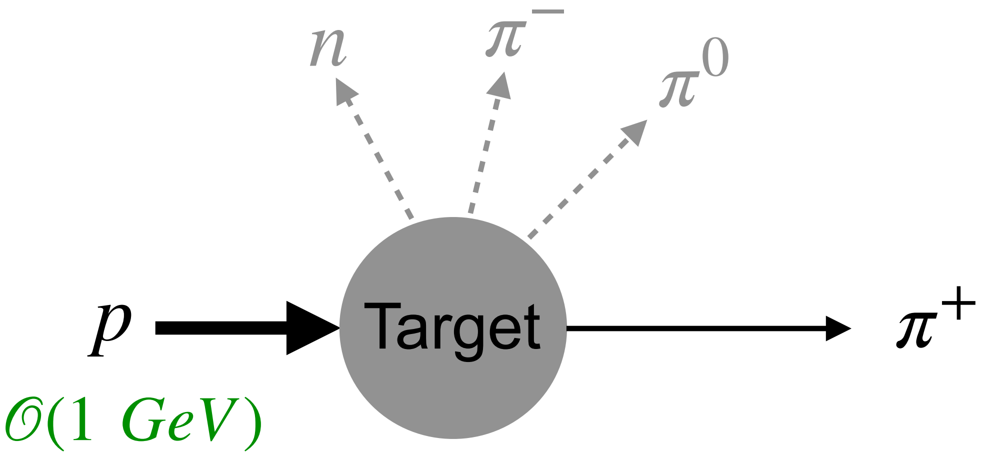
CEvNS and Inelastic Neutrino-Nucleus Scattering at Stopped-Pion Sources

- Outline
  - A bit of background and status of the field
  - Snowmass activities: LOIs, White Papers, Workshops

Stopped-Pion Sources



- **Proton energy**:

  - Sufficient energy (~1 GeV) to produce pions
    [SNS at ORNL, Lujan at LANL]

  - Higher energies lead to heavier mesons: kaons (> 3GeV), eta
    [JPARC-MLF]

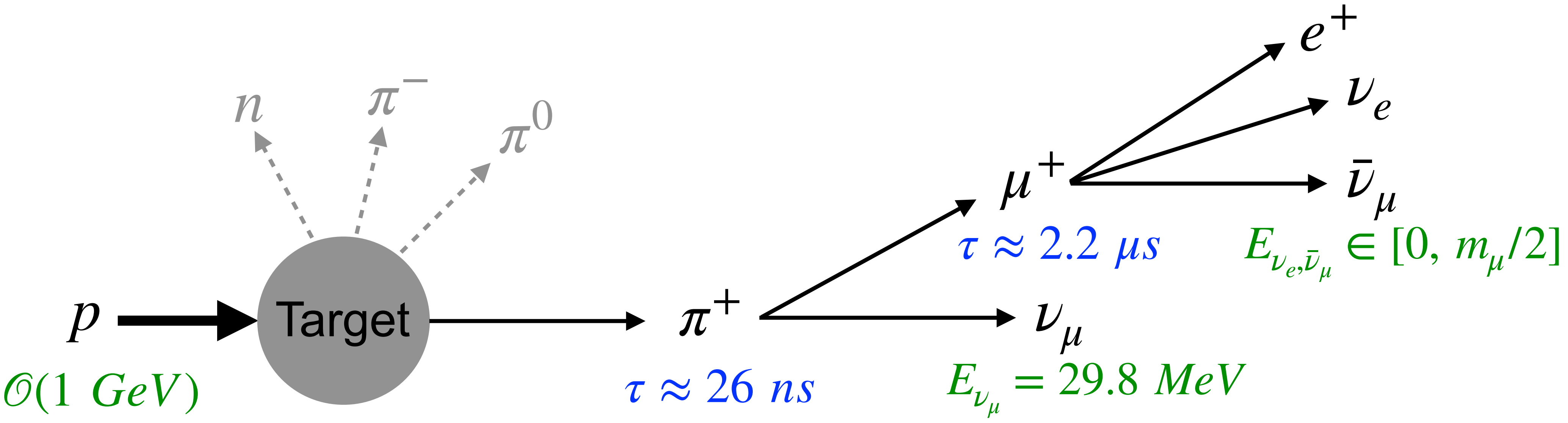
- **Target**:

  - Heavier targets at spallation sources massively produce neutrons (primary motive)
    [Hg at SNS at ORNL and JPARC-MLF, W at Lujan at LANL]

  - For a dedicated hep facility lighter targets would be preferred (low neutrons from beam)

  - Neutrons mimic the same signature as CEvNS

Stopped-Pion Sources



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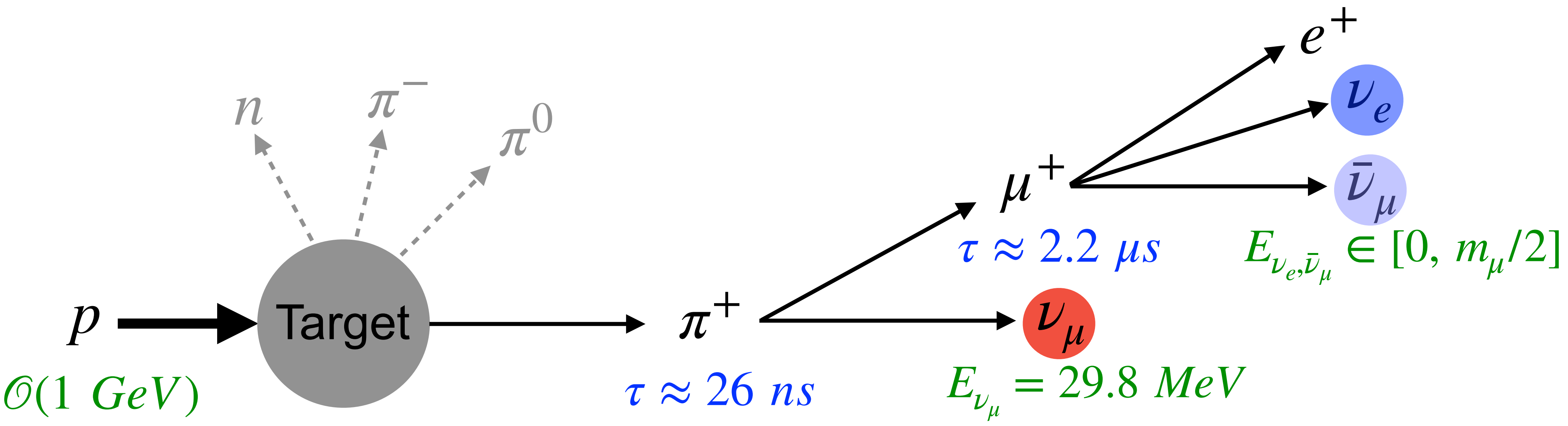


p $\mathcal{O}(1\ GeV)$

Target

n π^- π^0

π^+ $\tau \approx 26\ ns$

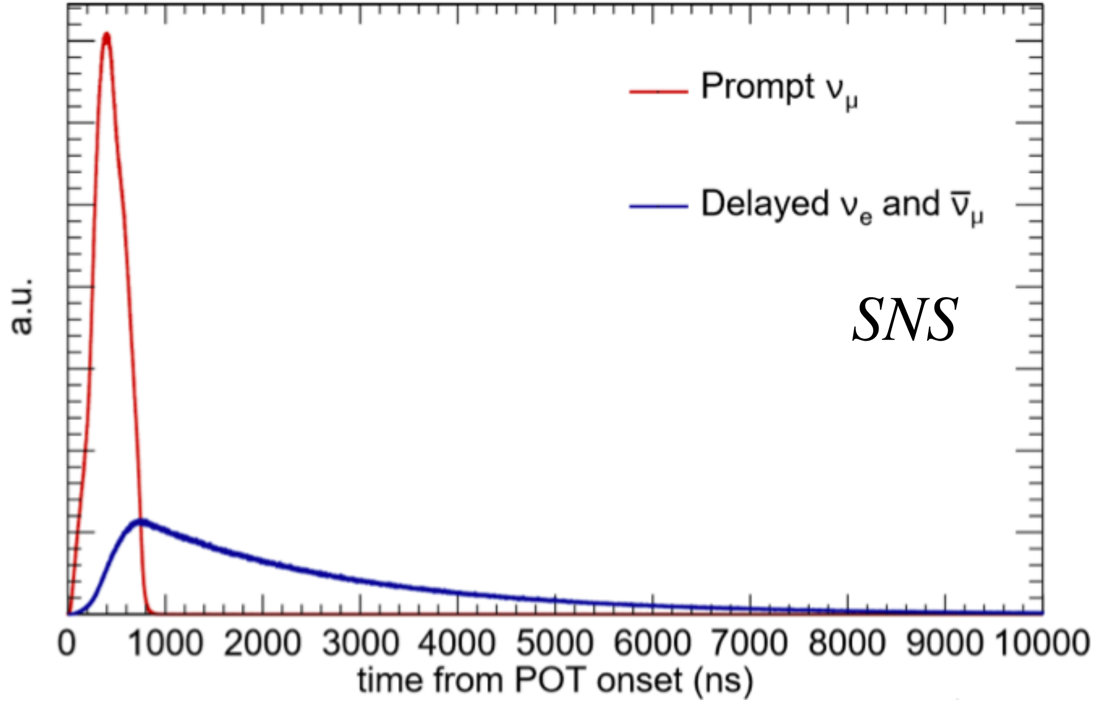
ν_μ $E_{\nu_\mu} = 29.8\ MeV$

μ^+ $\tau \approx 2.2\ \mu s$

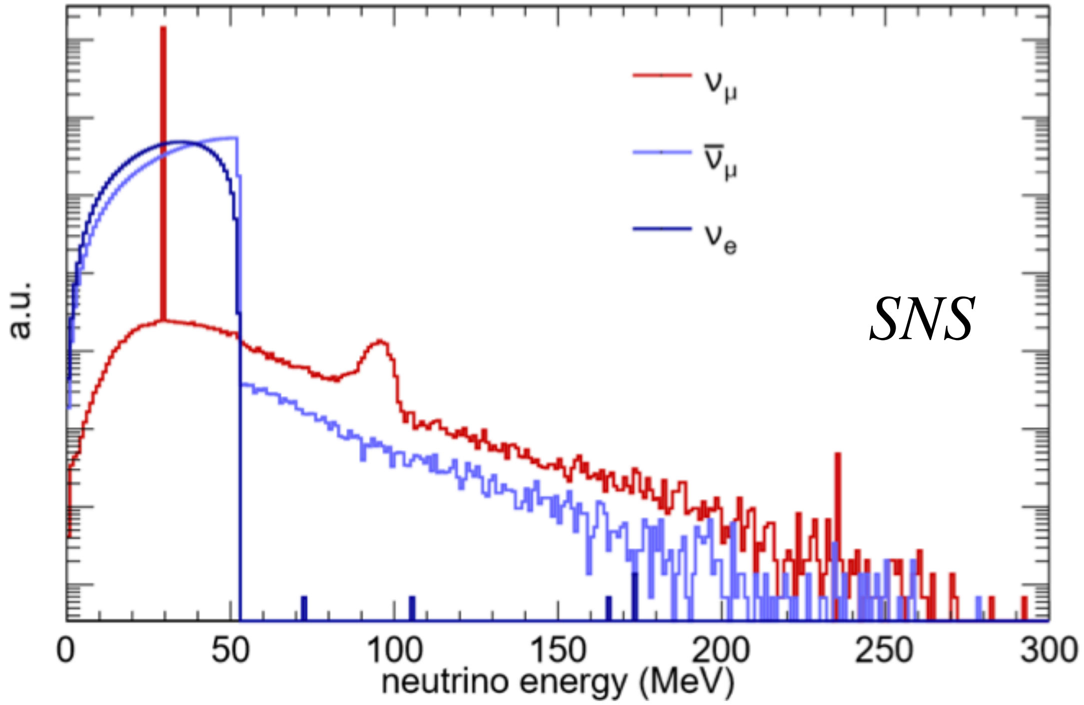
e^+ ν_e $\bar{\nu}_\mu$

$E_{\nu_e,\bar{\nu}_\mu} \in [0,\ m_\mu/2]$

Timing Profile

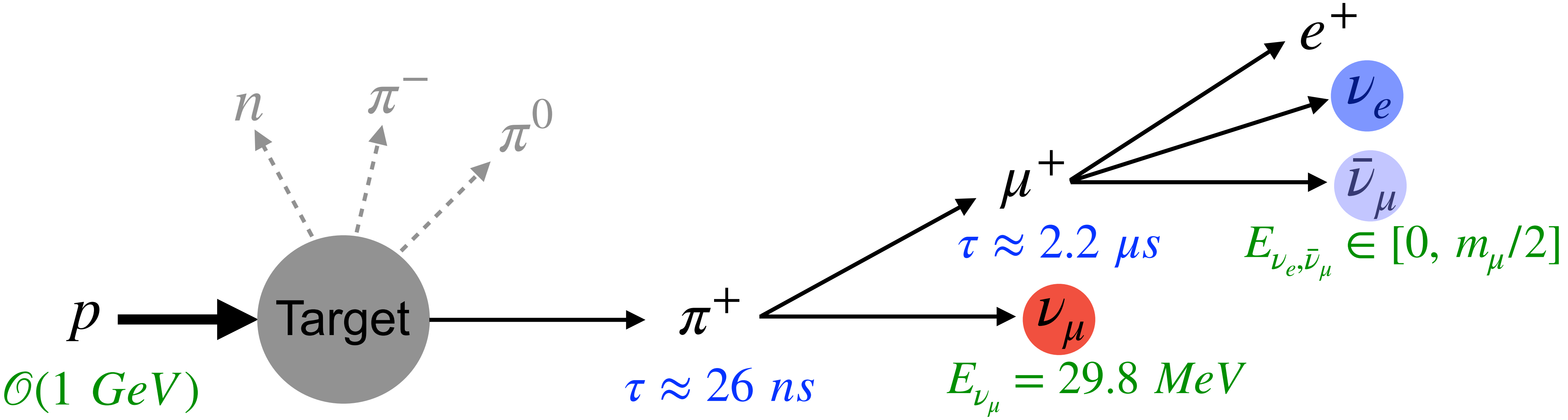


Energy Profile



D. Akimov et al. [COHERENT], Science 357, 6356, 1123-1126 (2017)

Stopped-Pion Sources



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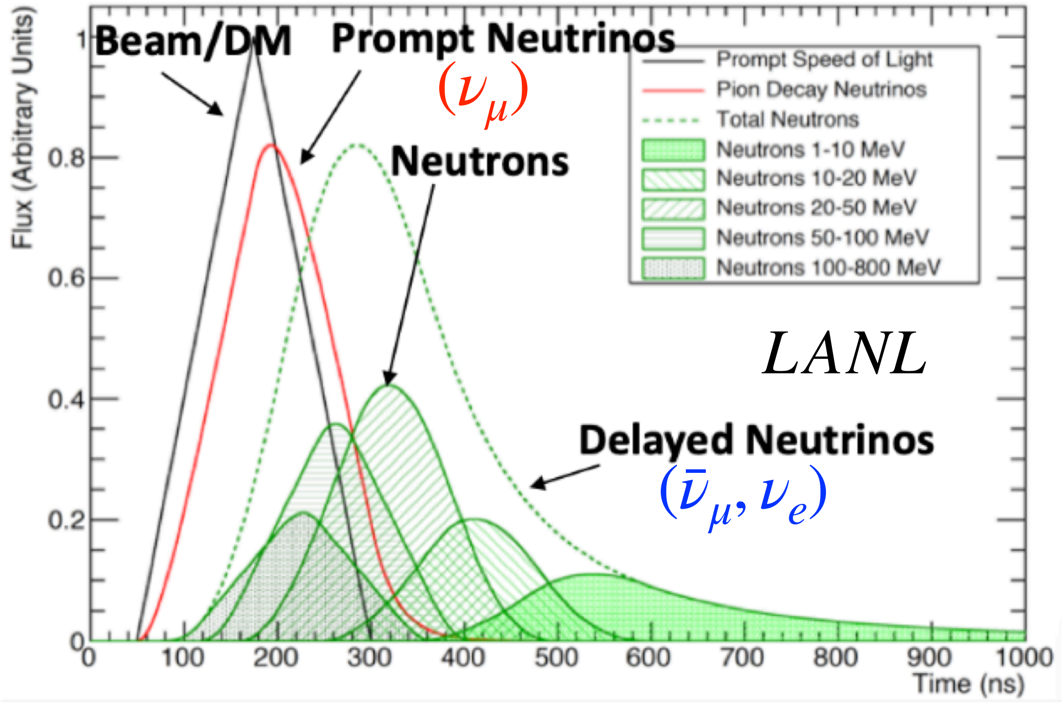

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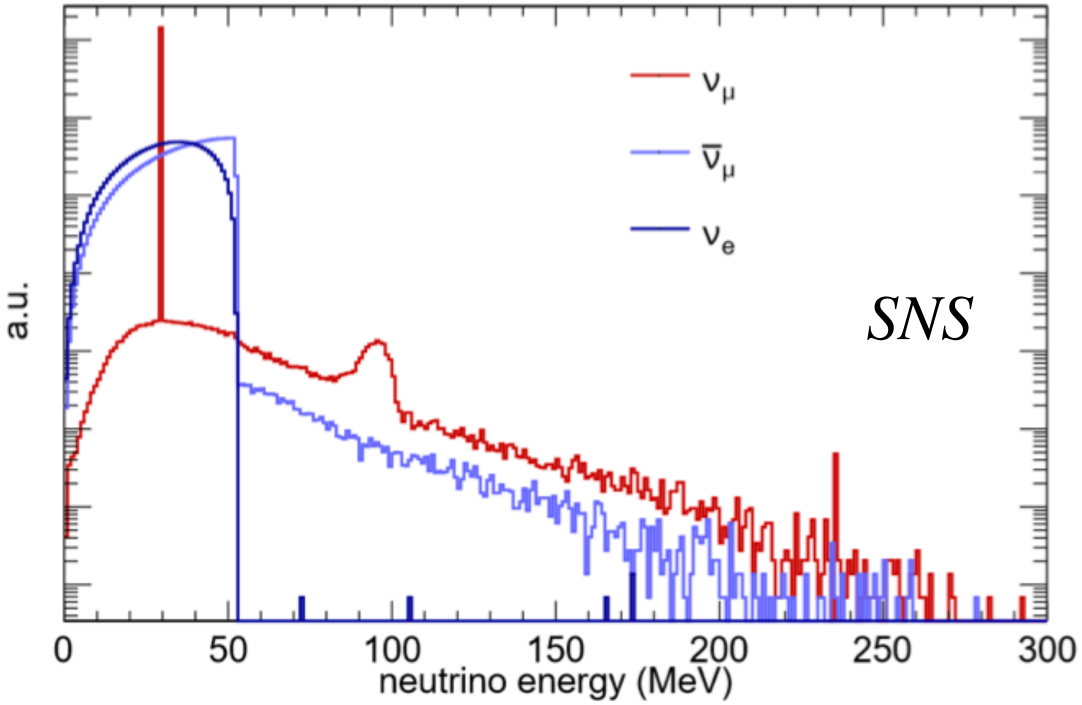
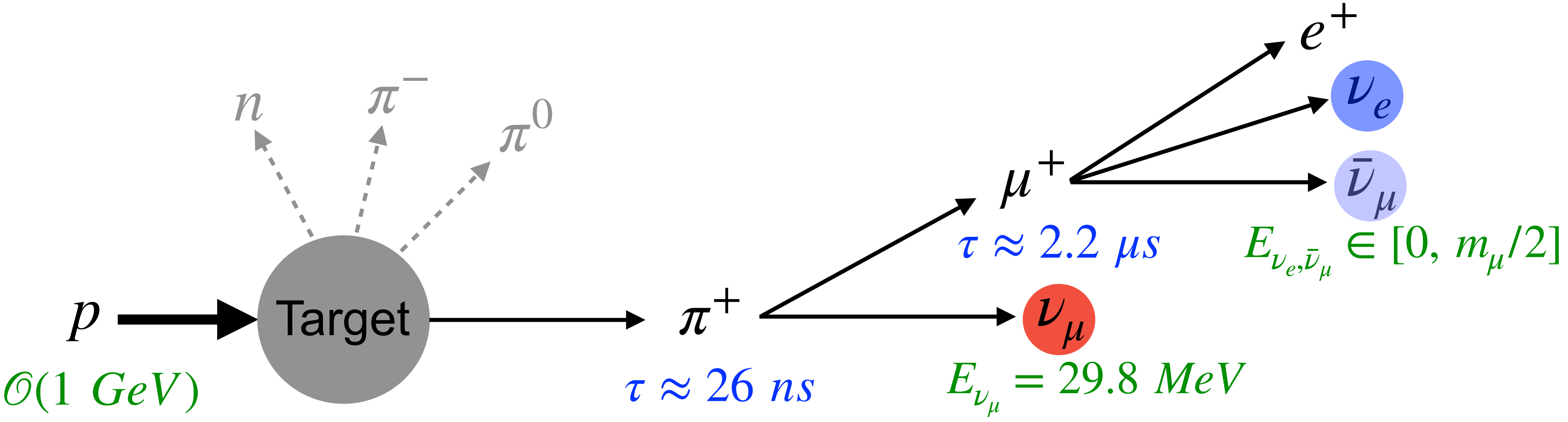
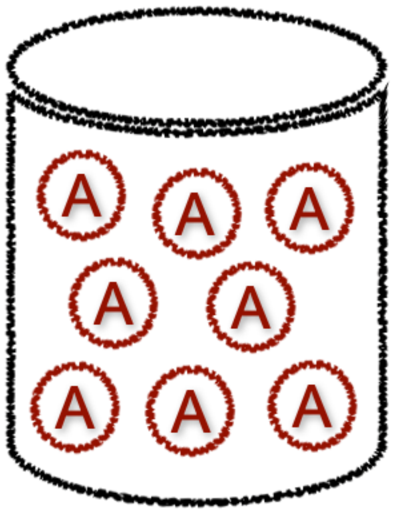


- Proton pulse duration and time between different pulses are key factors

  - For beam spills < μ^+ lifetime: can separate piDAR and muDAR neutrinos
  - For beam spills < π^+ lifetime: can separate light dark matter production (from π^0, η) from neutrino production

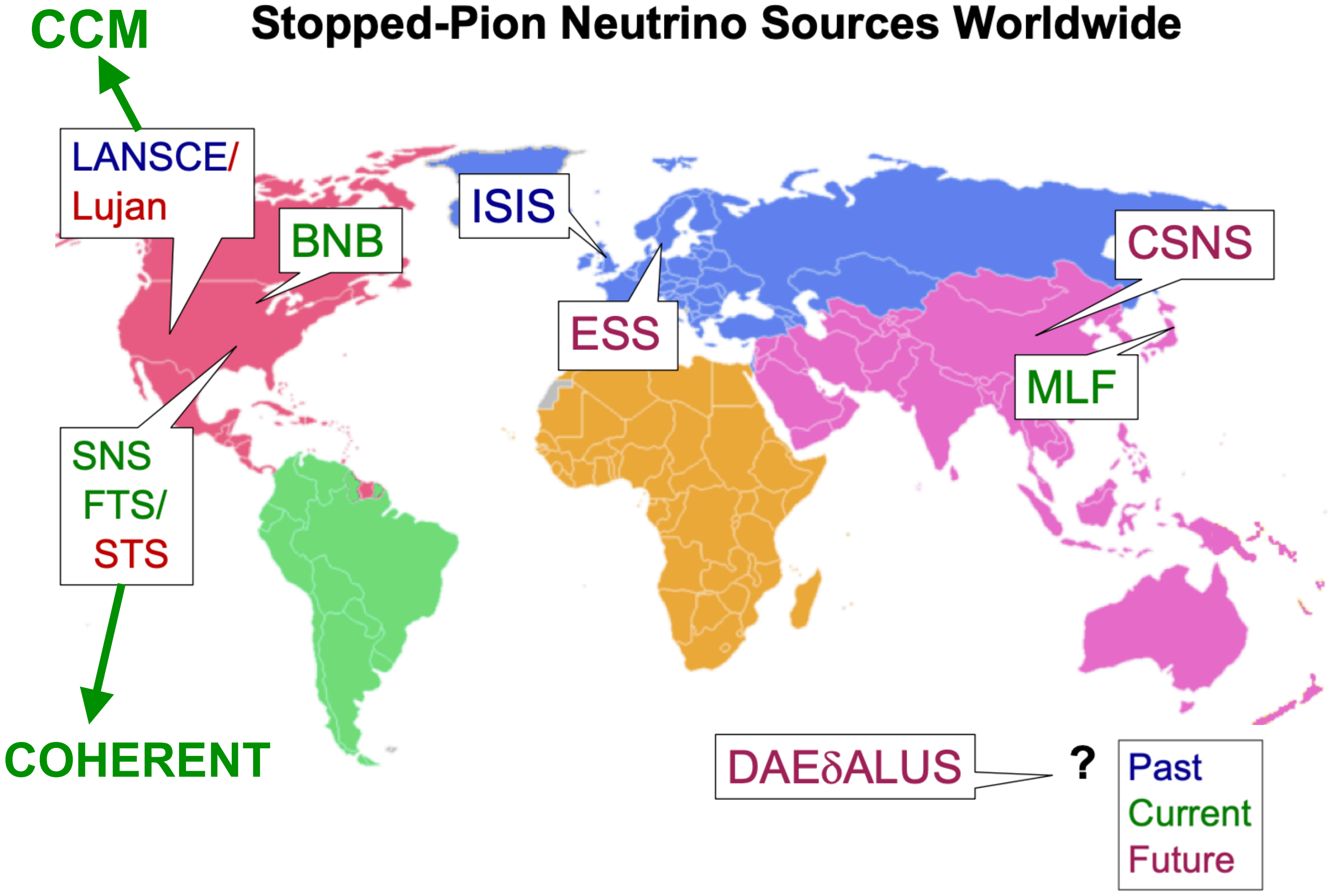
Stopped-Pion Sources



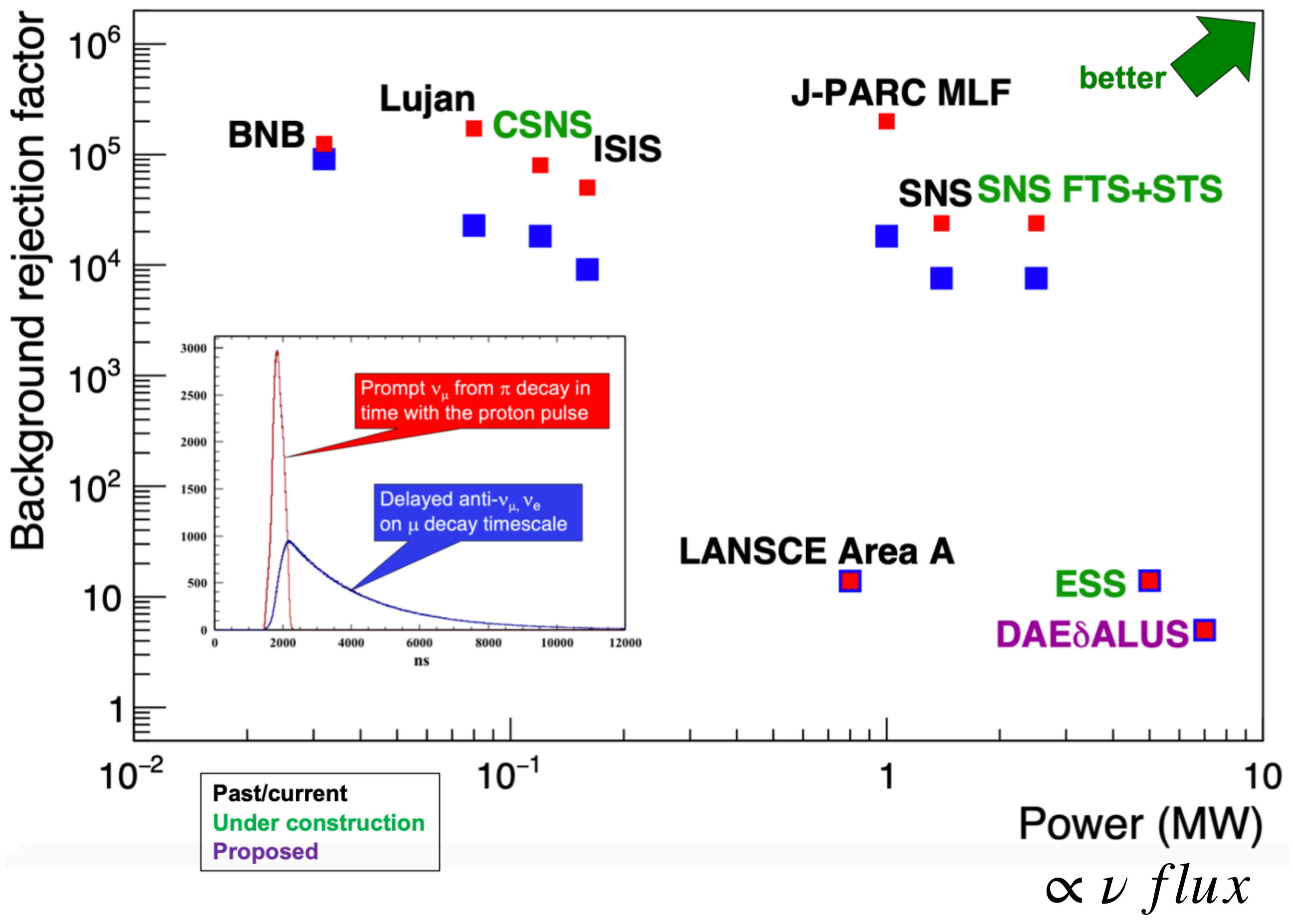


Low threshold (~keV) detector

Stopped-Pion Neutrino Sources Worldwide

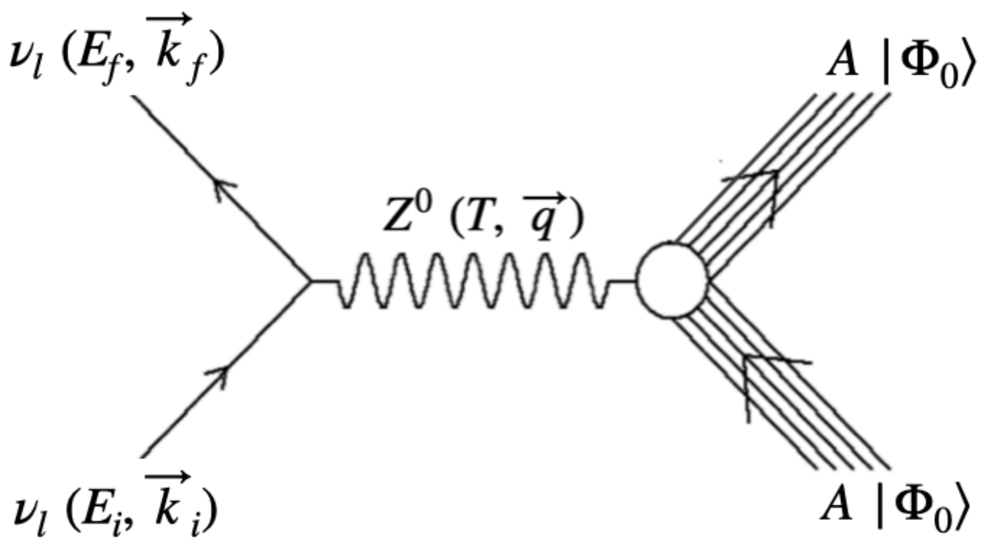


Flavor separation with beam timing can be helpful!



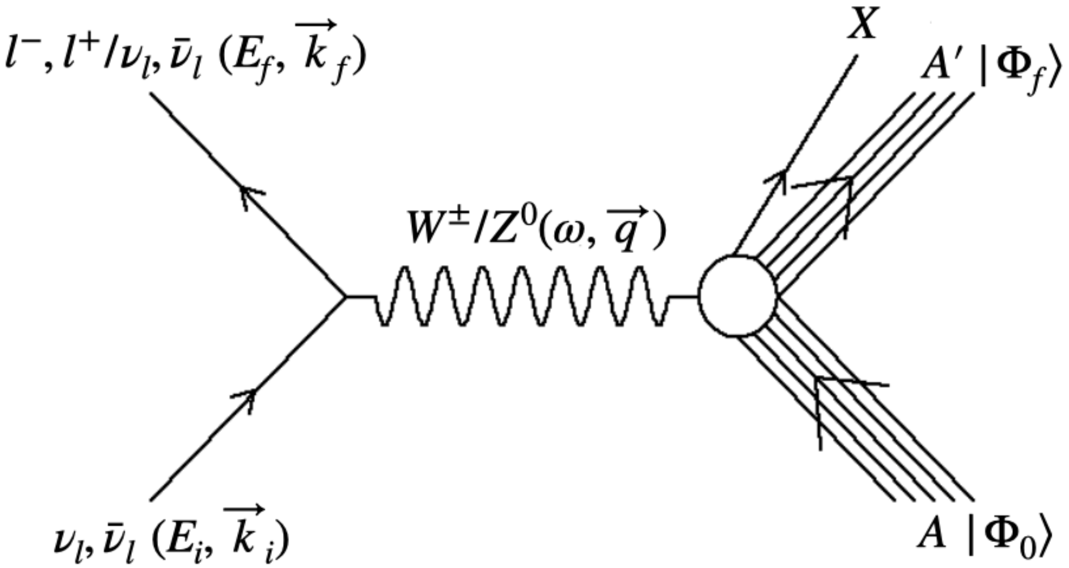
Coherent Elastic and Inelastic Neutrino-Nucleus Scattering

Coherent elastic



- Tiny recoil energy
- Final state nucleus stays in its ground state
- Signal: keV energy nuclear recoil (gamma)

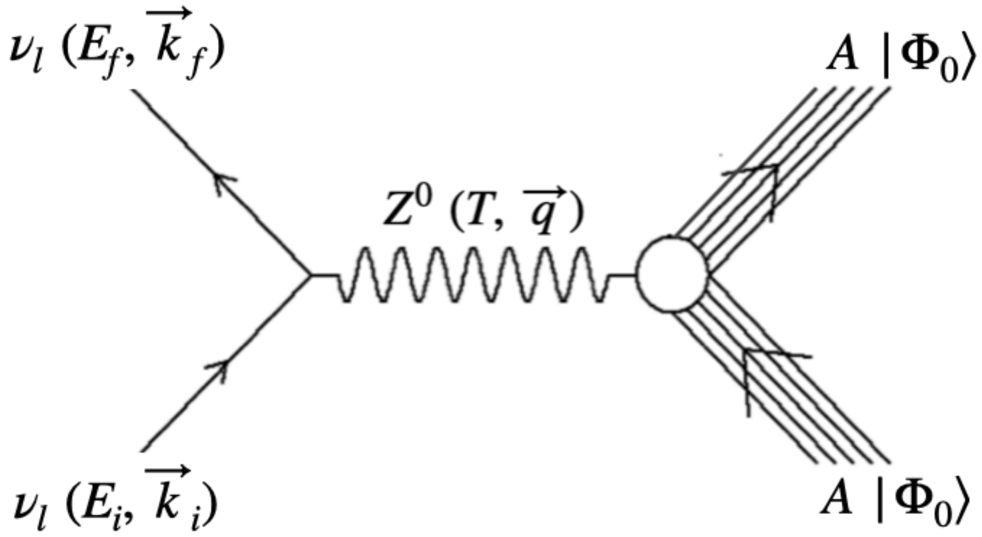
Inelastic CC/NC



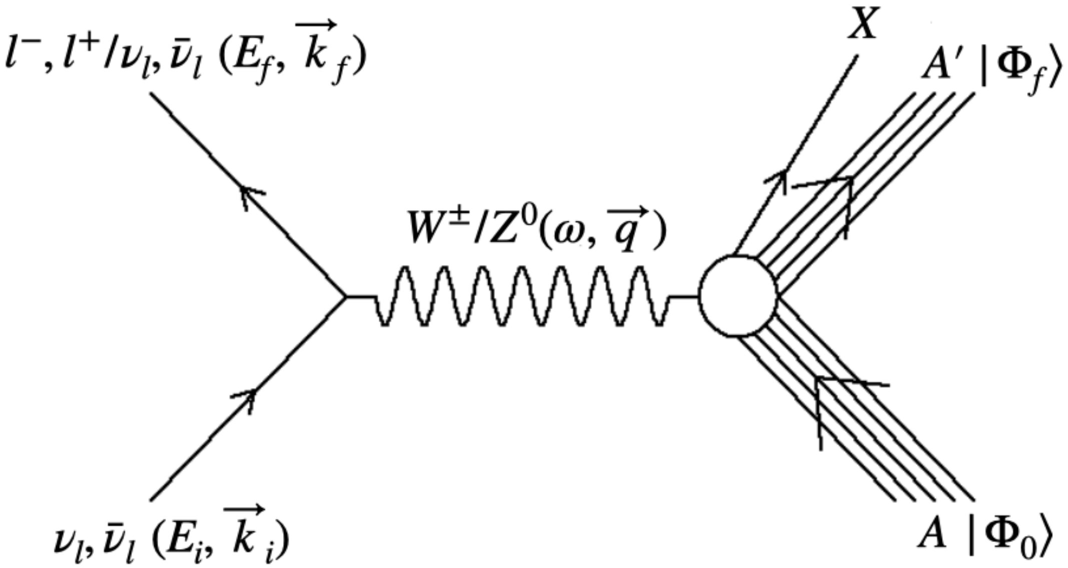
- Small energy transferred to the nucleus
- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π).
  Followed by nuclear de-excitation into gammas, p, n, nuclear fragmentations.
- ν_e CC Signal: e^-, de-excitation gamma rays (~ 1 to ~ 10 MeV), n or p emission
- ν NC Signal: de-excitation gamma rays (~ 1 to ~ 10 MeV), n or p emission

Coherent Elastic and Inelastic Neutrino-Nucleus Scattering

Coherent elastic



Inelastic CC/NC



$$\sum_{fi} |\mathscr{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$

Leptonic Tensor: $L_{\mu\nu} = \sum_{fi} (\mathscr{J}_{l,\mu})^\dagger \mathscr{J}_{l,\nu}$

Hadronic Tensor: $W^{\mu\nu} = \sum_{fi} (\mathscr{J}_n^\mu)^\dagger \mathscr{J}_n^\nu$

Transition Amplitude: $\mathscr{J}_n^\mu = \langle \Phi_0 | \hat{J}_n^\mu(q) | \Phi_0 \rangle$

Cross Section:

$$\boxed{d\sigma \propto \frac{G_F^2}{4\pi} Q_W^2 F_W^2(q)}$$

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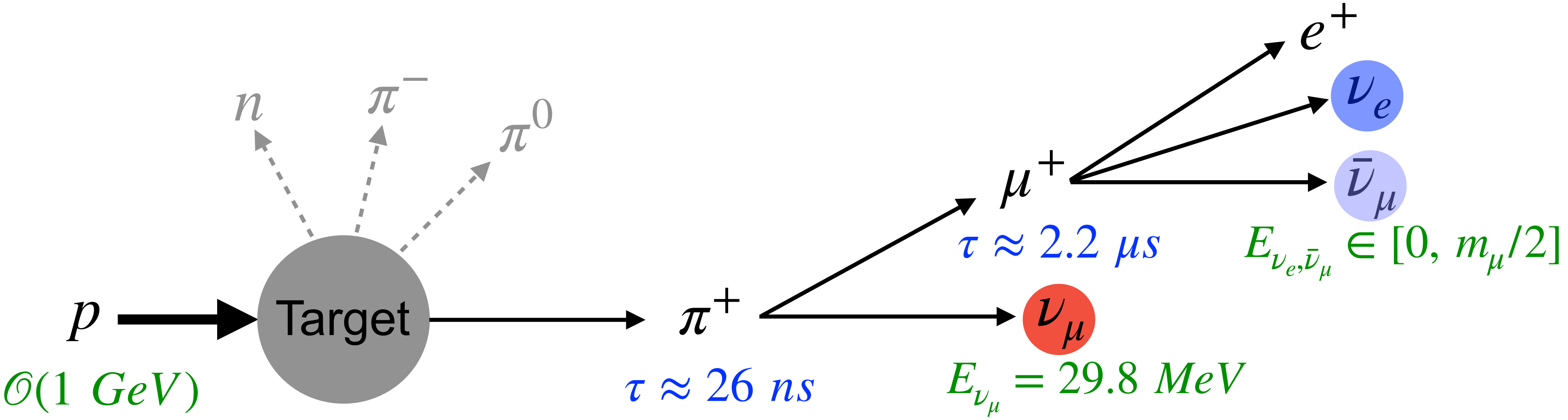
Cross Section:

$$\boxed{d\sigma \propto \frac{G_F^2}{4\pi} \sum_{J^\pi} [v_{CC} W_{CC} + v_{CL} W_{CL} + v_{LL} W_{LL} + v_T W_T \pm v_{T'} W_{T'}]}$$

Stopped-Pion Sources and CEvNS



n π^- π^0

p → Target → π^+

$\mathcal{O}(1\ GeV)$

$\tau \approx 26\ ns$

μ^+ → e^+, ν_e, $\bar{\nu}_\mu$

$\tau \approx 2.2\ \mu s$

$E_{\nu_e,\bar{\nu}_\mu} \in [0,\ m_\mu/2]$

ν_μ

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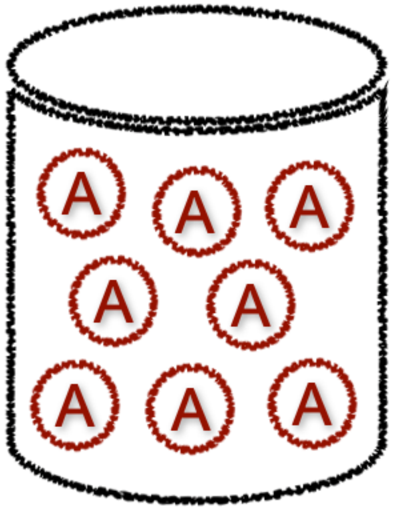
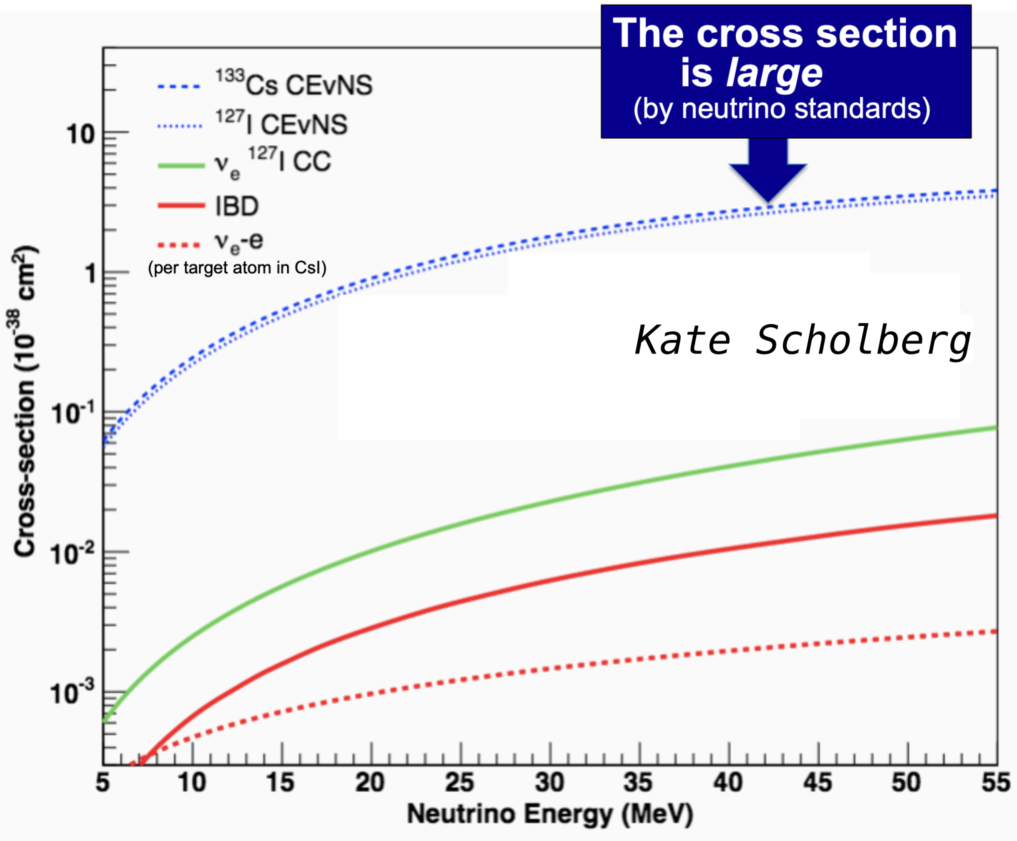


Low threshold (~keV) detector

Coherent elastic neutrino-nucleus scattering (CEvNS):

- Large cross section but tiny recoil
- Only experimental signature: keV energy deposited by nuclear recoil in the target material
- Recent R&D in dark matter and $0\nu\beta\beta$ detector technologies helped overcoming long standing (> 40 years) hurdle

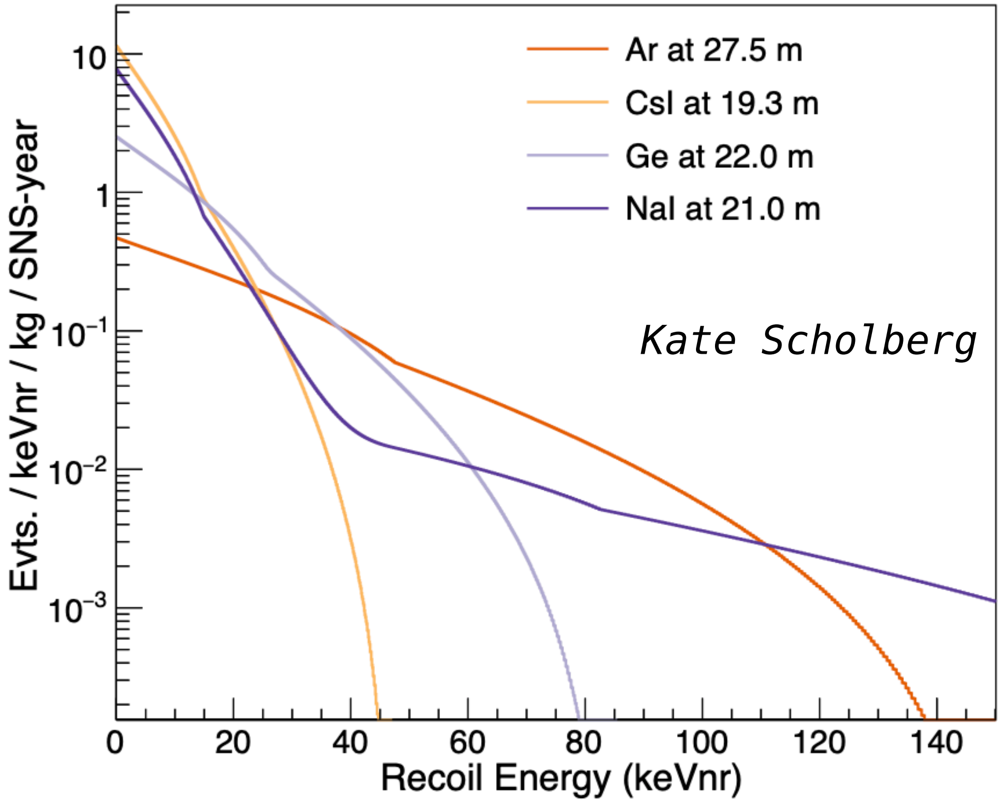
Large cross section



The cross section is *large*
(by neutrino standards)

Kate Scholberg

Tiny nuclear recoil



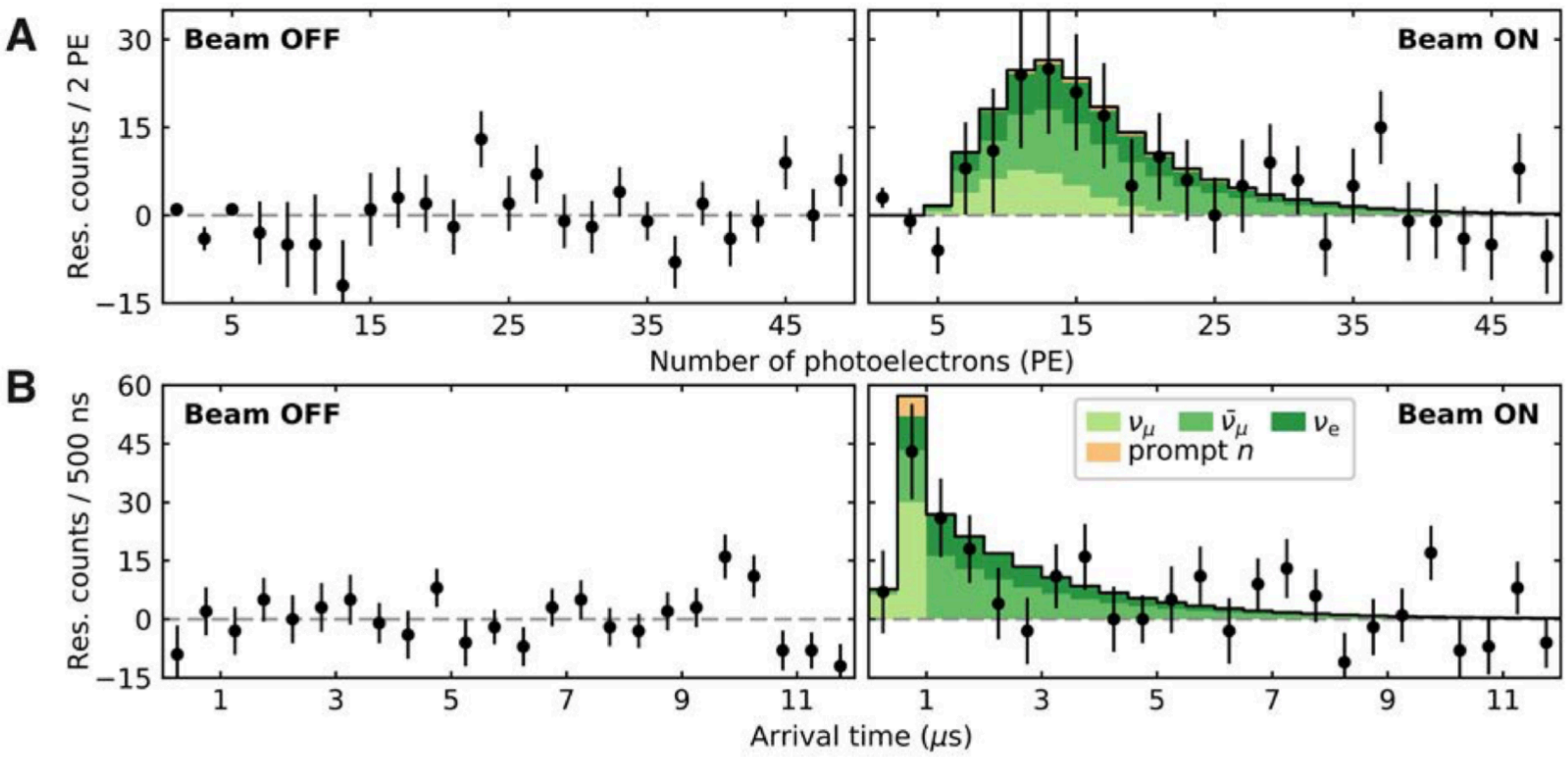
Kate Scholberg

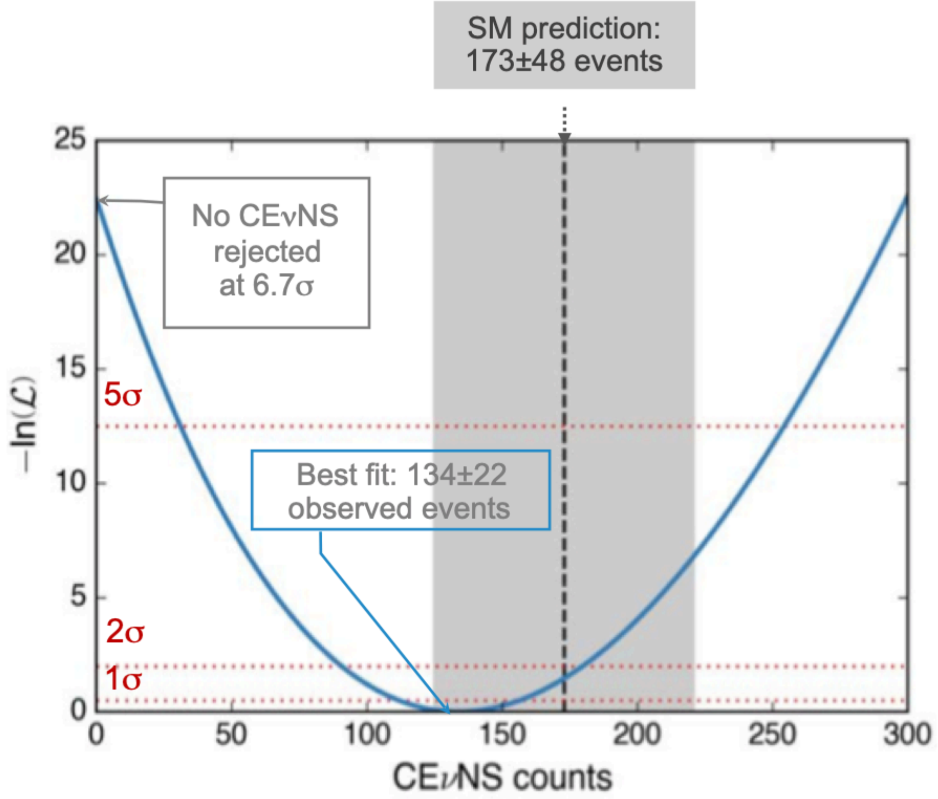
Observing CEvNS

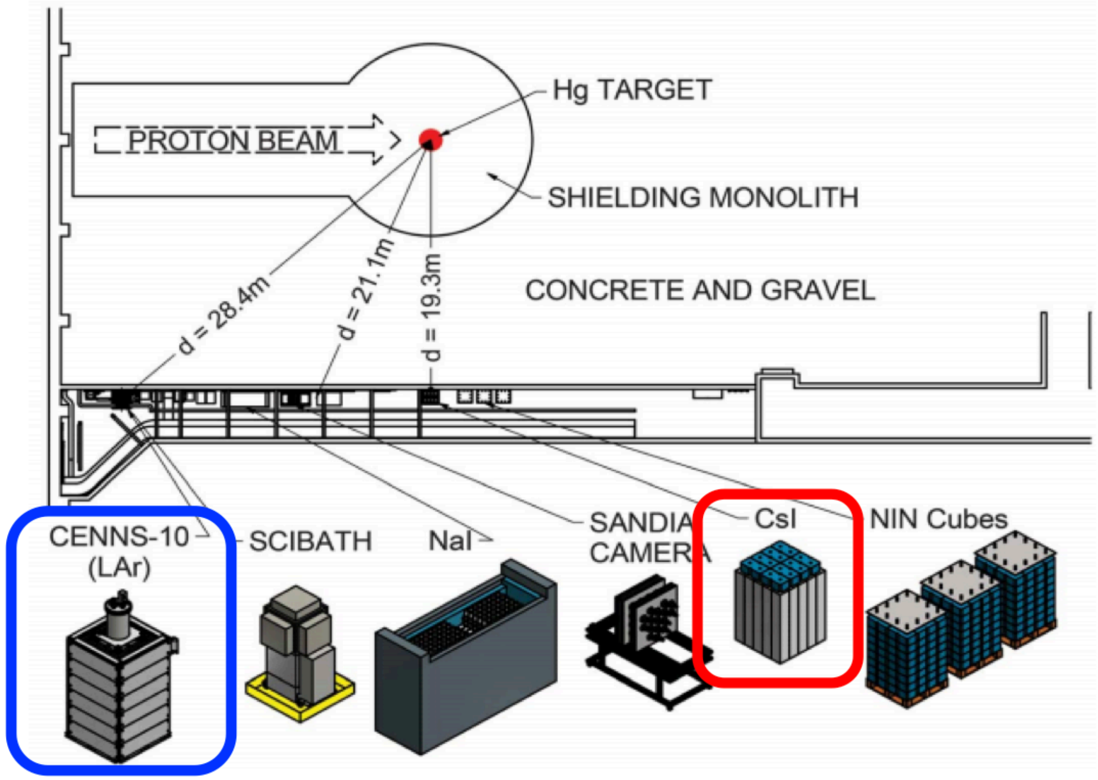
COHERENT Collaboration at SNS at ORNL

- **14 kg CSI detector**

D. Akimov et al. [COHERENT], Science 357, 6356, 1123–1126 (2017)







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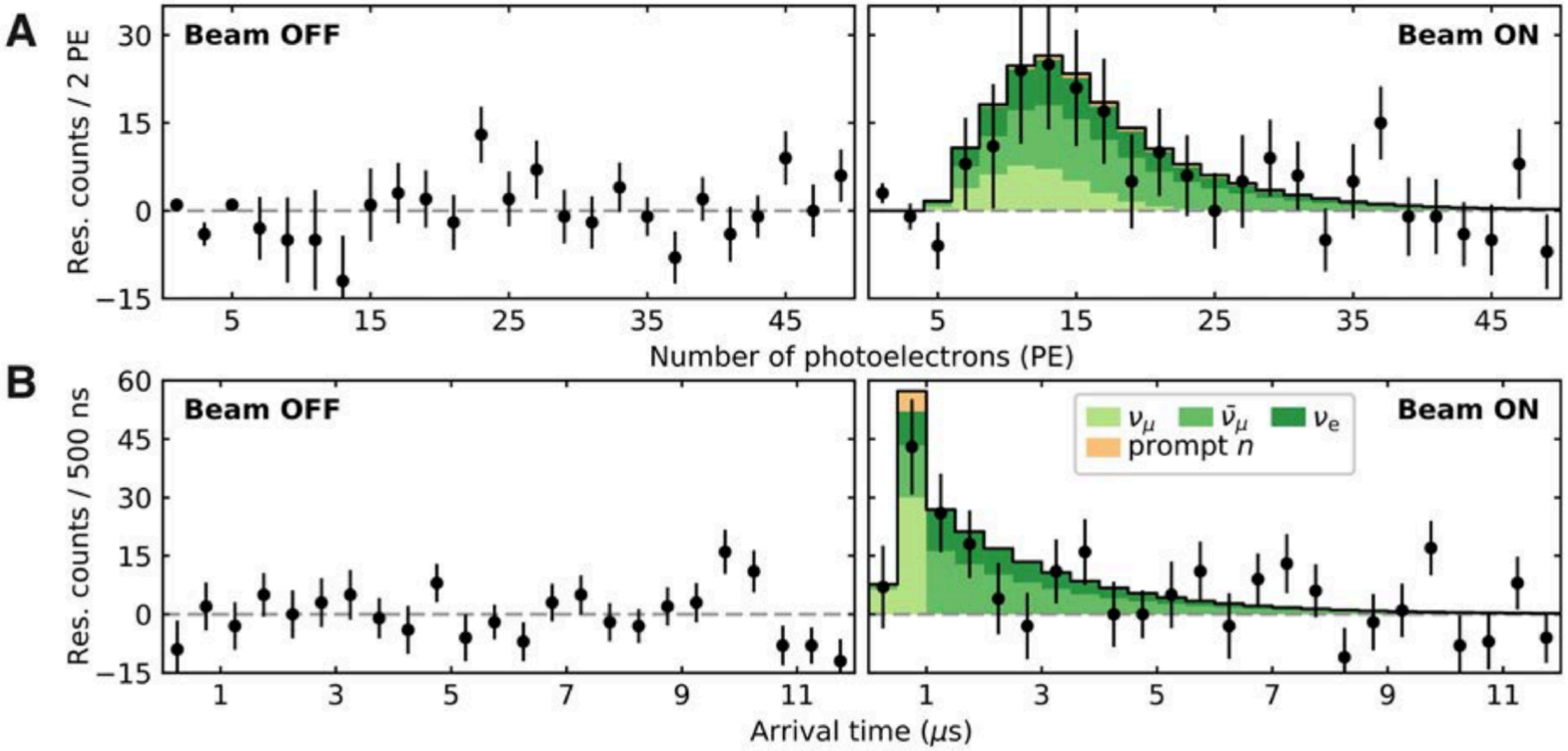
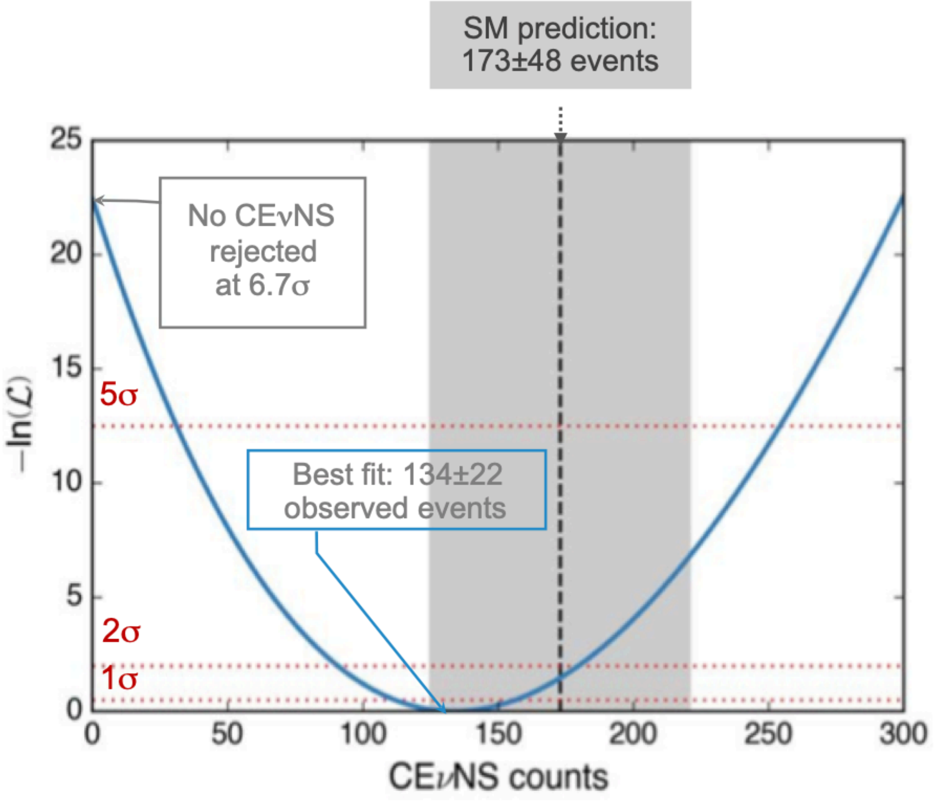
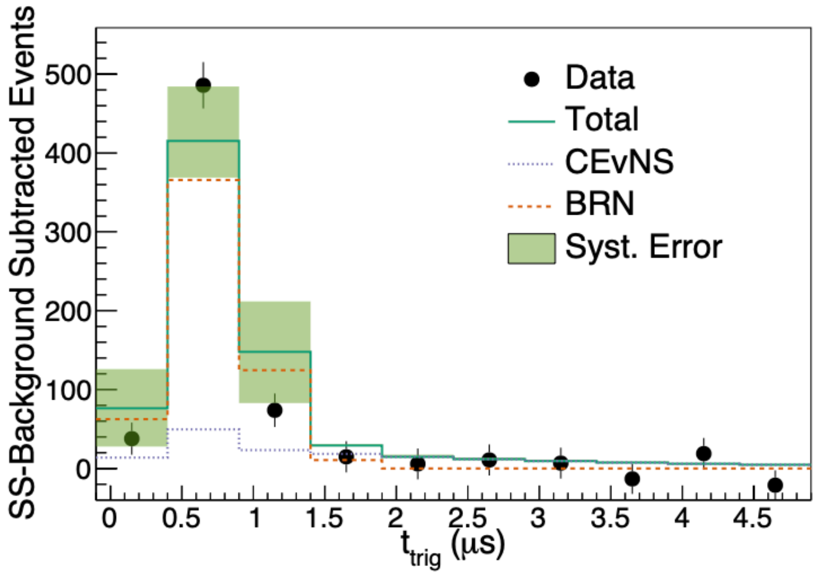
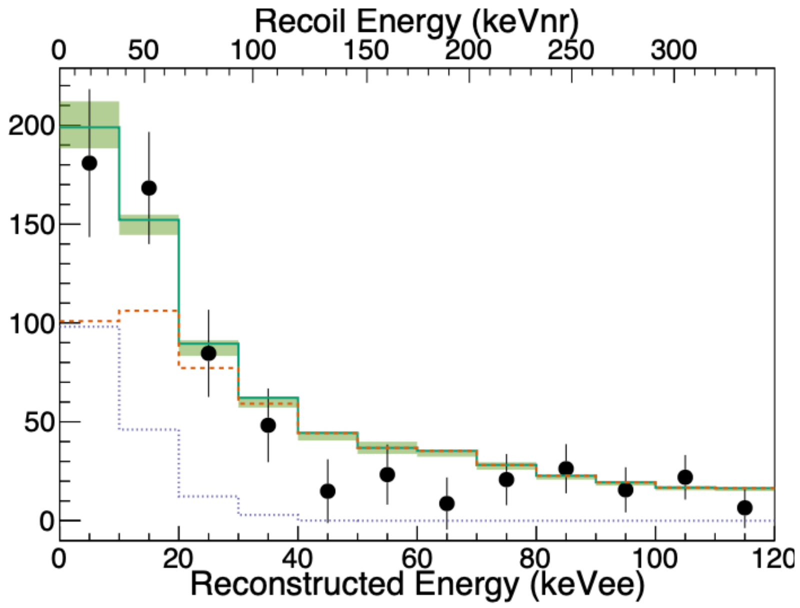
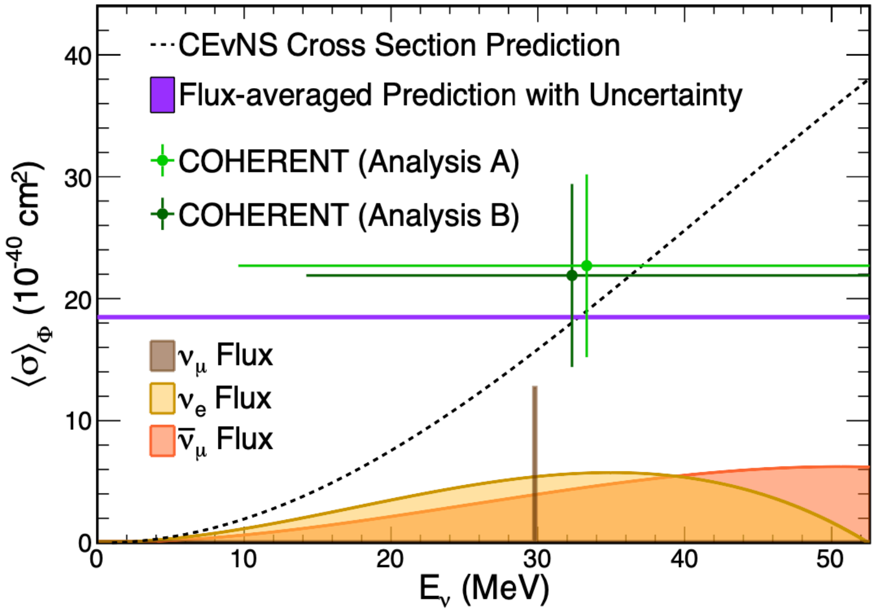




- **24 kg LAr (CENNS-10) detector** *D. Akimov et al. [COHERENT], arXiv:2003.10630 [nucl-ex]*

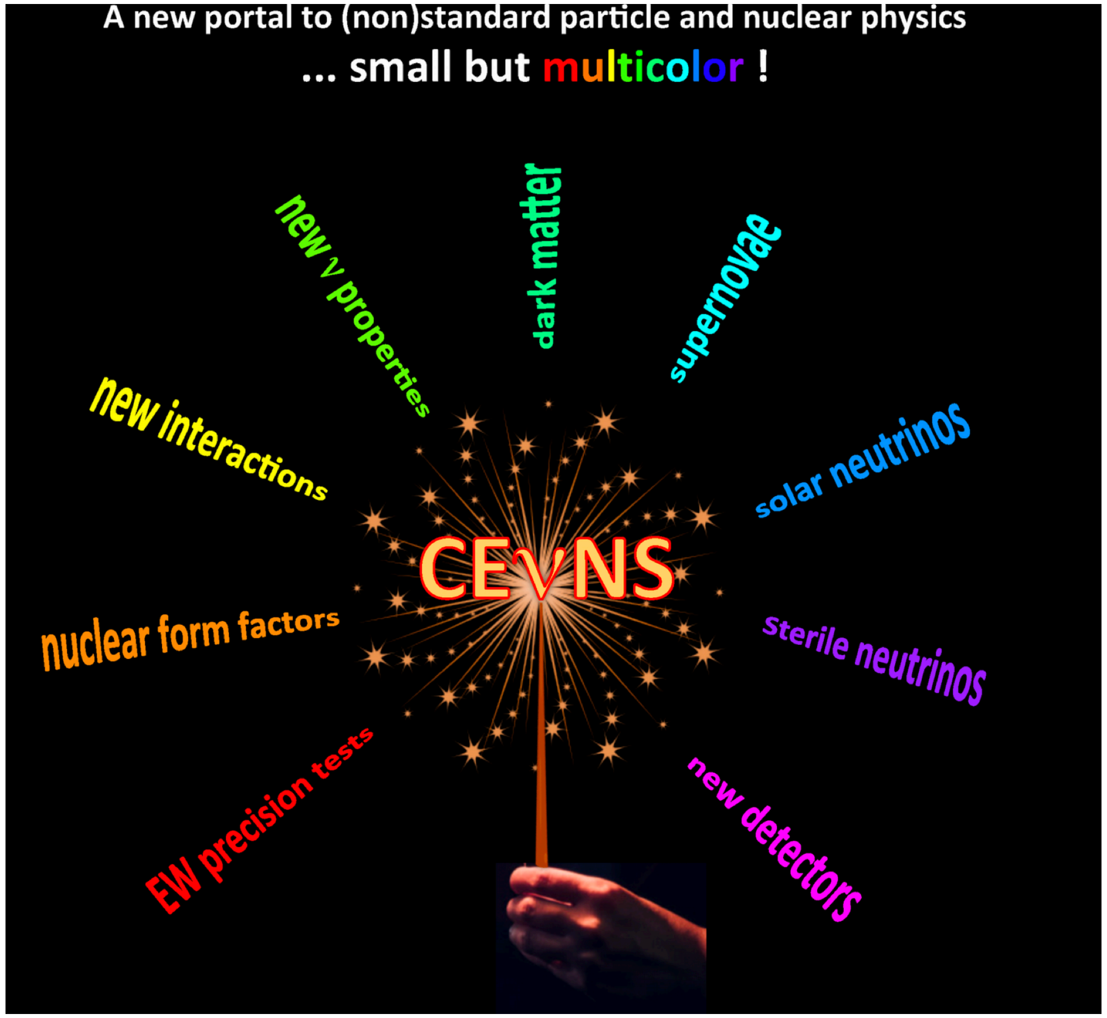






CEvNS: A New Portal to Standard and Non-Standard Physics

- New physics may be weakly interacting and hiding at low energies
- Any deviation from the SM expectation → new physics
- SM expectation of CEvNS cross section have to be know at a precision that allows resolving degeneracies in the standard and non-standard physics observables



Eligio Lisi, NuINT 2018

Matteo Cadeddu, Magnificent CEvNS 2020

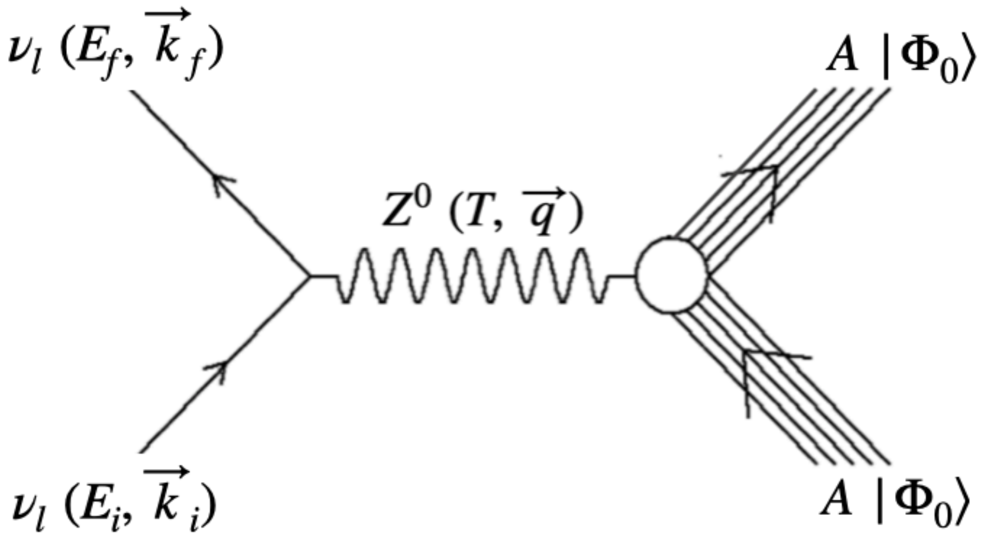
CEvNS Cross Section and Form Factors

- **Cross section**:

$$\frac{d\sigma}{dT} = \frac{G_F^2}{\pi} M_A \left[1 - \frac{T}{E_i} - \frac{M_A T}{2E_i^2}\right] \frac{Q_W^2}{4} F_W^2(q)$$

  - Weak Form Factor:

$$\begin{aligned} Q_W\ F_W(q) &\approx \langle \Phi_0 | \hat{J}_0(q) | \Phi_0 \rangle \\ &\approx \left(1 - 4\sin^2\theta_W\right) Z\, F_p(q) - \ N\ F_n(q) \\ &\approx 2\pi \int d^3r\ \left[(1 - 4\sin^2\theta_W)\rho_p(r) - \rho_n(r)\ \right] j_0(qr) \end{aligned}$$



Nuclear recoil: $T \in \left[0, \frac{2E_i^2}{(M_A + 2E_i)}\right]$

$$Q_W^2 = [g_n^V N + g_p^V Z]^2$$

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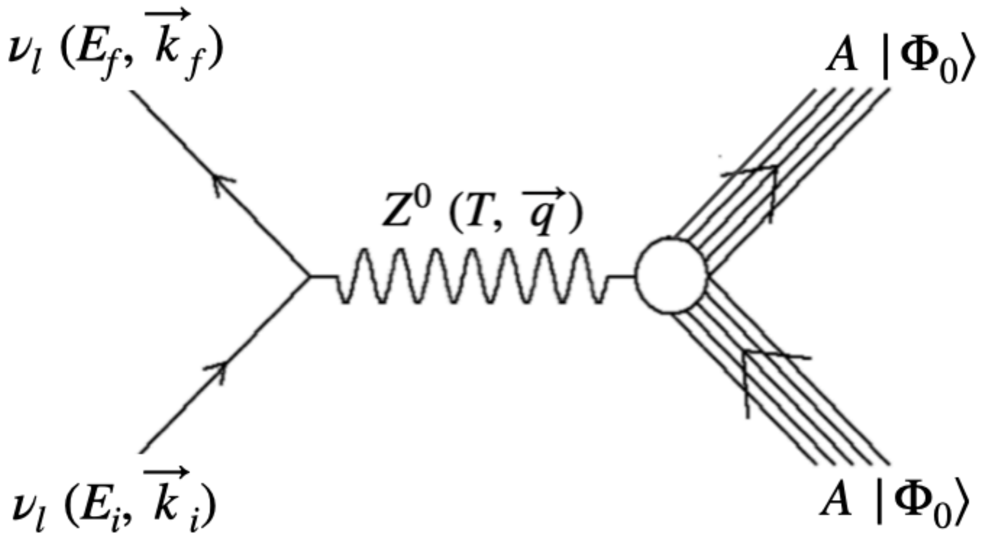

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Charge density and charge form factor: proton densities and charge form factors are well know through decades of elastic electron scattering experiments.

Neutron densities and neutron form factor: neutron densities and form factors are poorly known. Note that CEvNS is primarily sensitive to neutron density distributions.

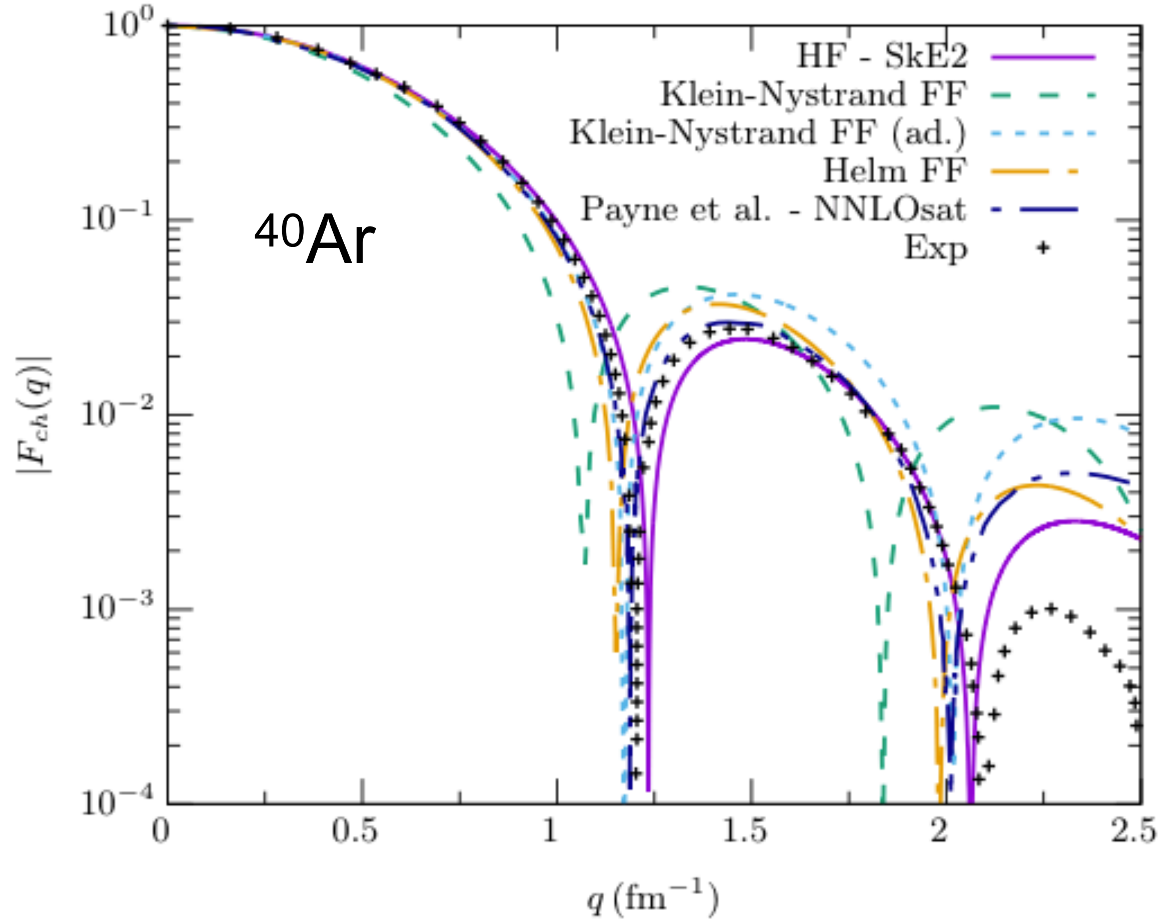
- **Electroweak probes** such as parity–violating electron scattering (**PVES**) and **CEvNS** provide relatively model-independent ways of determining weak form factor and neutron distributions.

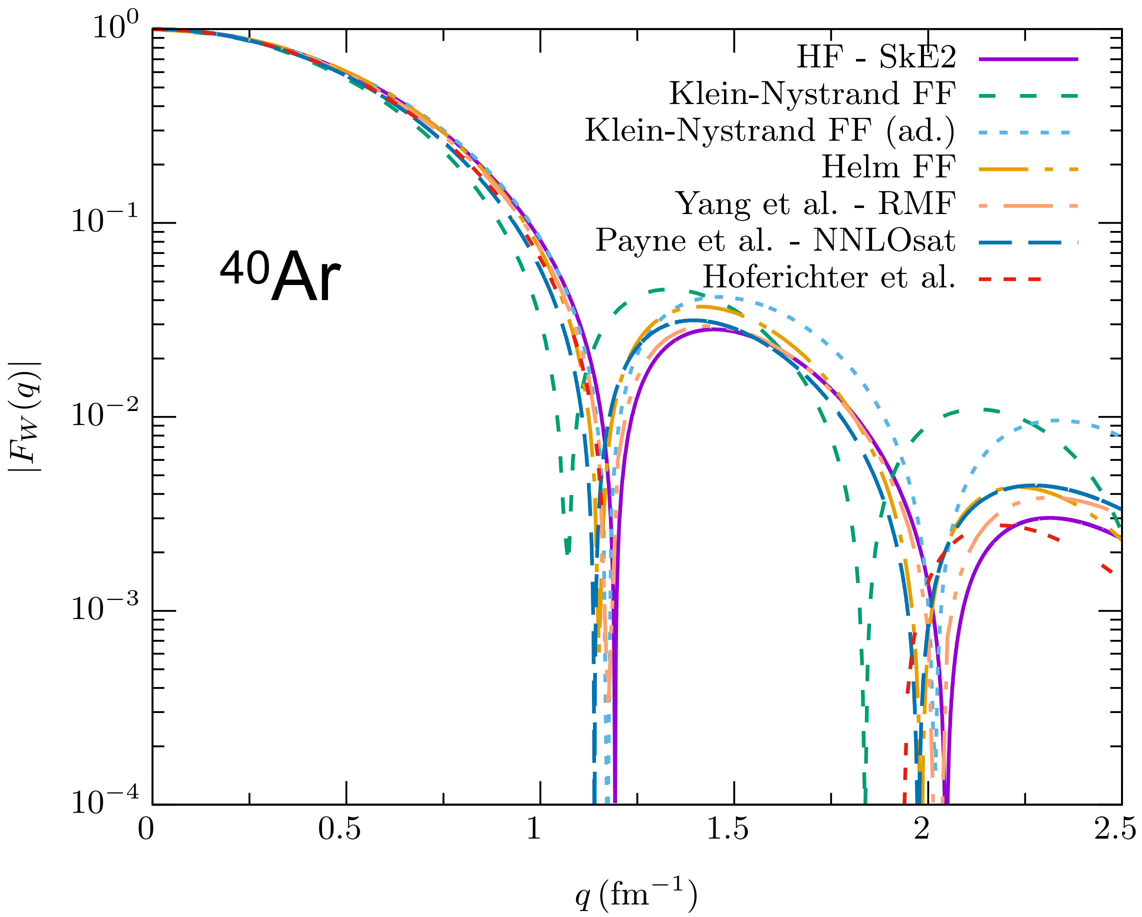
PVES experiment, PREX, at Jefferson lab has measured the weak charge of ^{208}Pb at a single value of momentum transfer.

$$A_{PV}(q^2) = \frac{G_F q^2}{4\pi\alpha\sqrt{2}} \; \frac{Q_W F_W(q^2)}{Z F_{ch}(q^2)}$$

CEvNS Cross Section: Theory Status

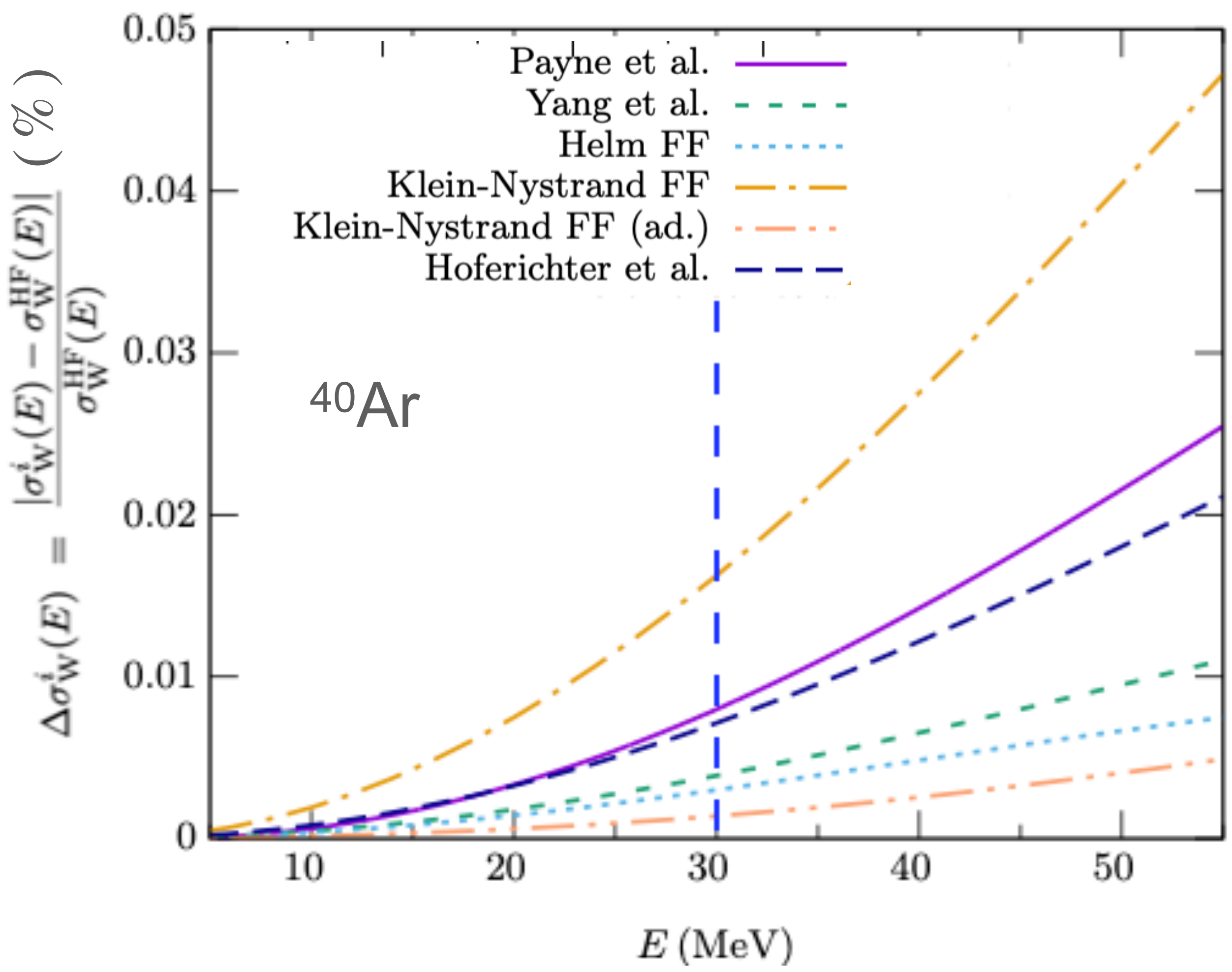
- A simplistic Helm and Klein-Nystrand type form factor is heavily used in experiments. More involved calculation are being reported now.
- A coupled-cluster theory from first principles using a chiral NNLO$_{sat}$ interaction: *[C. G. Payne, S. Bacca, G. Hagen, W. Jiang, T. Papenbrock, arXiv:1908.09739]*
- Relativistic mean–field approach *[J. Yang, J. A. Hernandez, J. Piekarewicz, arXiv:1908.10939]*
- Hartree-Fock SkE2 approach: *[N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658]*
- Effective field theory and large-scale nuclear shell model: *[M. Hoferichter, J. Menendez, A. Schwenk, arXiv:2007.08529]*
- Four-fermion effective filed theory and radiative corrections: *[O. Tomalak, P. Machado, V. Pandey and R. Plestid, arXiv:2011.05960]*
- …..





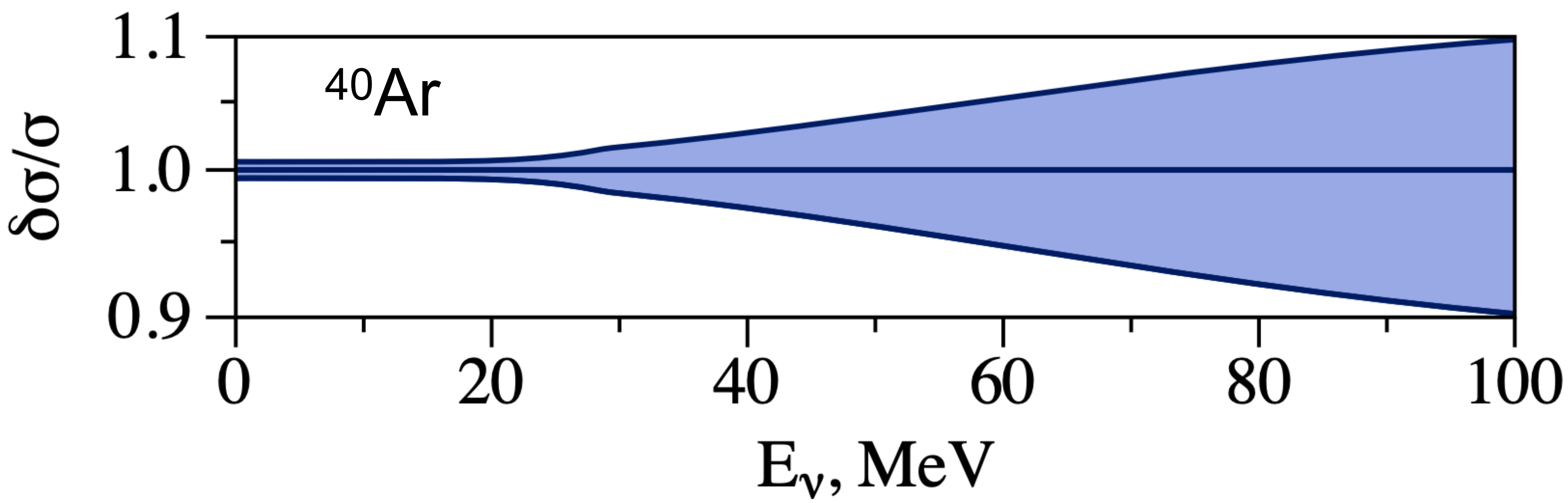
CEvNS Cross Section: Theory Status

- Relative CEvNS cross section differences between the results of different calculations:



N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]

- Relative CEvNS cross section theoretical uncertainty (includes nuclear, nucleonic, hadronic, quark levels as well as perturbative errors):



O. Tomalak, P. Machado, V. Pandey, R. Plestid, arXiv:2011.05960 [hep-ph]

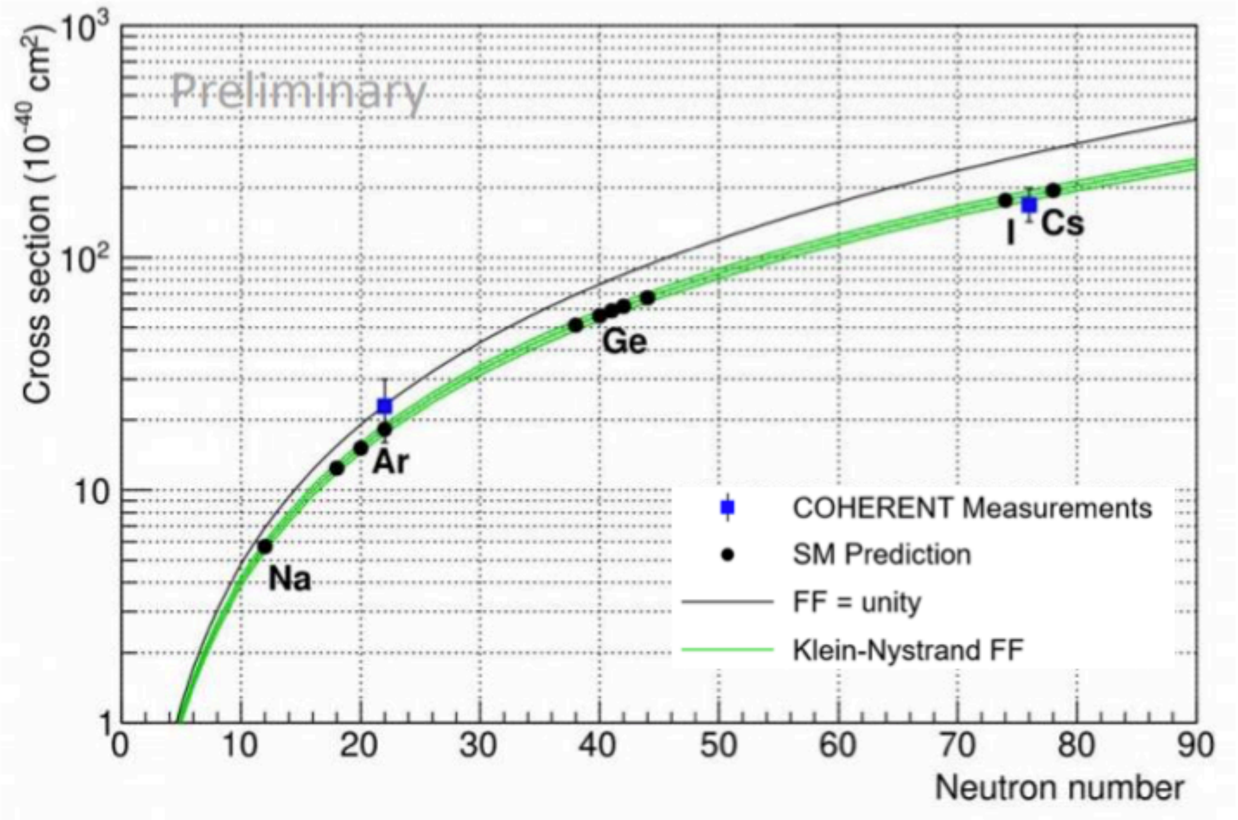
CEvNS Cross Section: Experimental Status

COHERENT Collaboration at SNS at ORNL

- **CsI:14.6 kg**
  - Flux averaged cross section extracted

CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

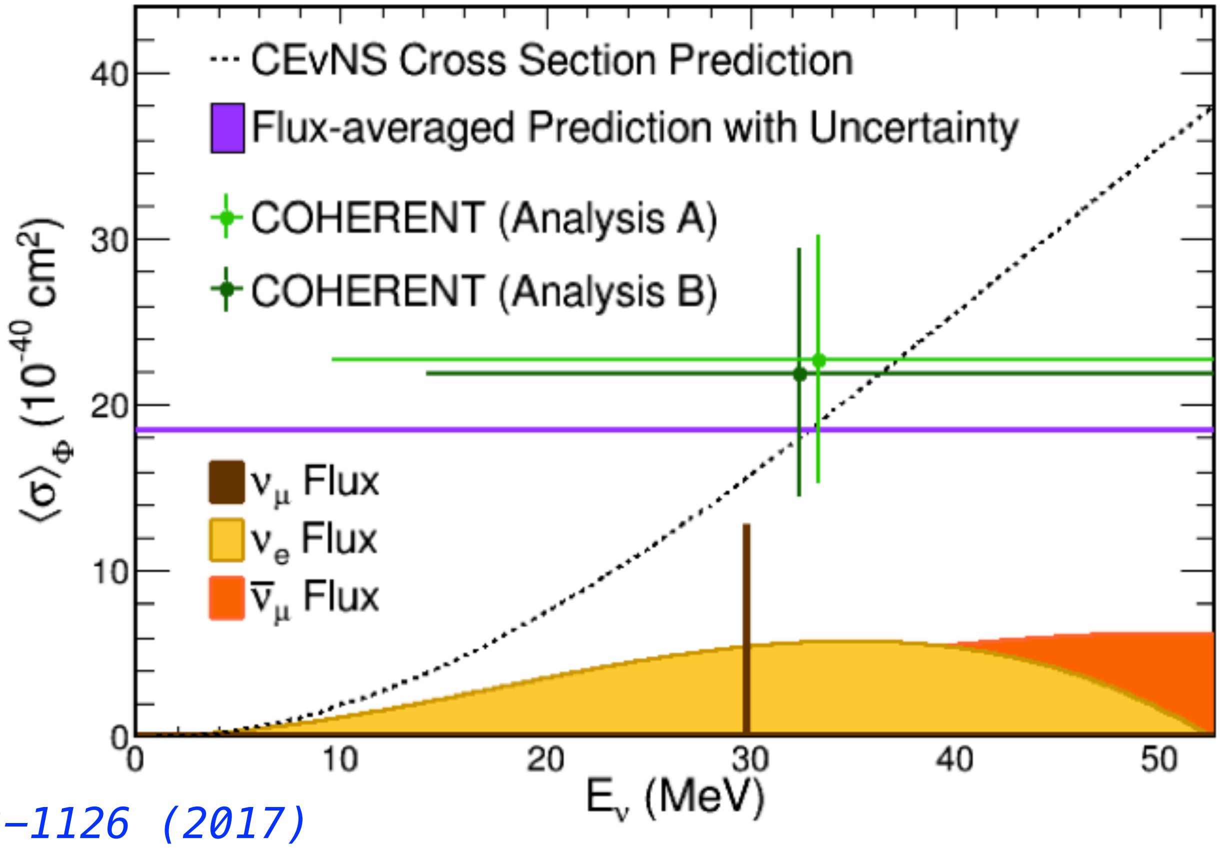
  - Systematic uncertainty reduced from 28% (2017 results) to 13% (2020 results in M7 workshop)
  - Detector decommissioned



- **^{40}Ar: CENNS-10, 24 kg**
  - Flux averaged cross section extracted

$$(2.3 \pm 0.7) \times 10^{-39}\ cm^2$$

  - Collecting more data



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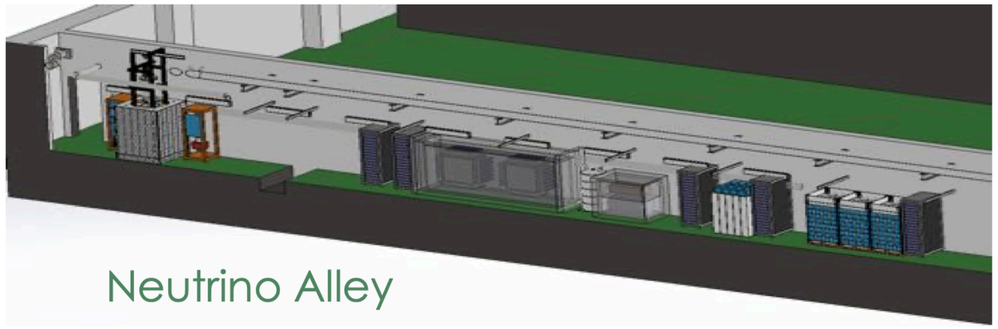
CEvNS: Ton-Scale LAr Detectors

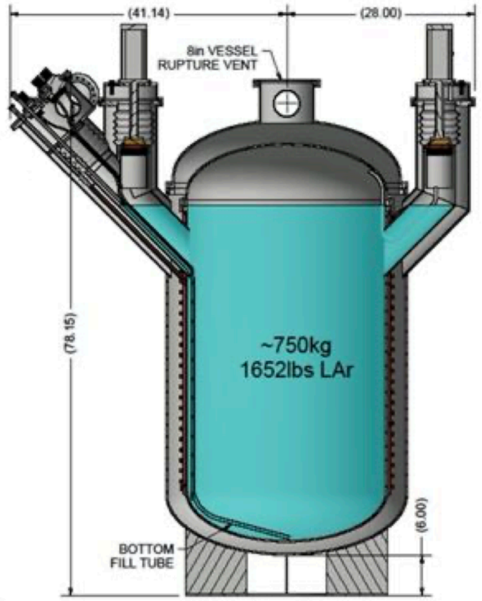
COHERENT

750kg LAr detector at SNS at ORNL

- In R&D phase.



High Statistics CEvNS



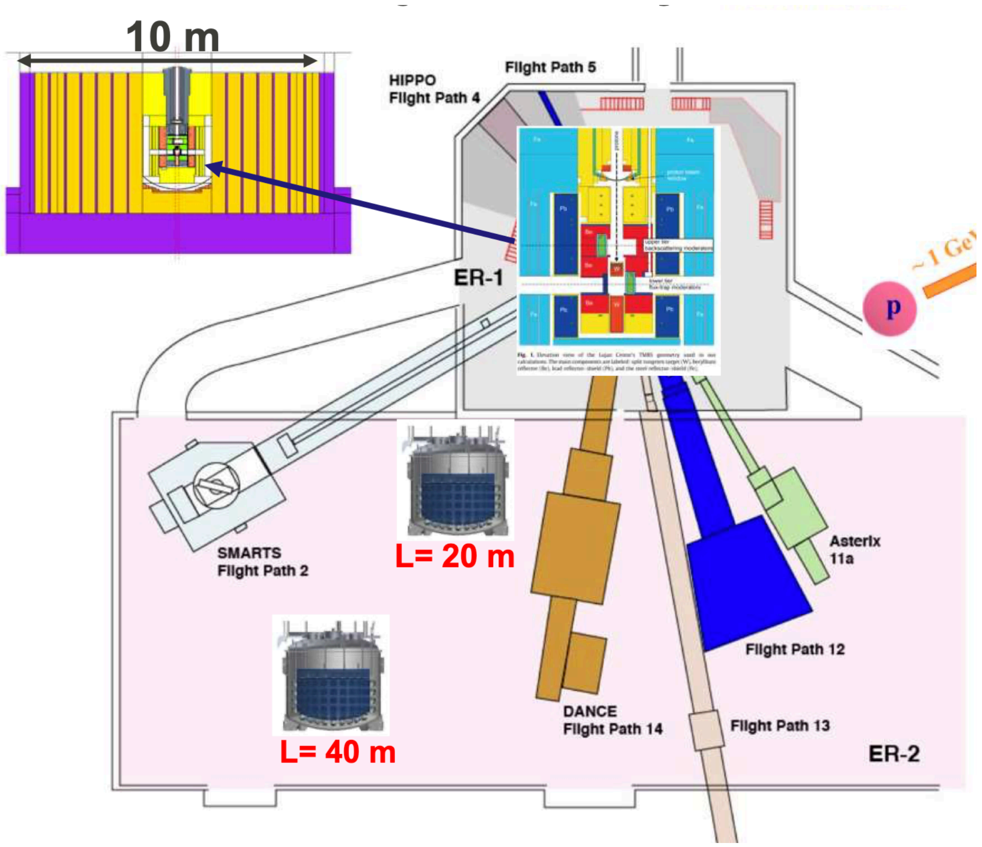
Walt Fox, IU

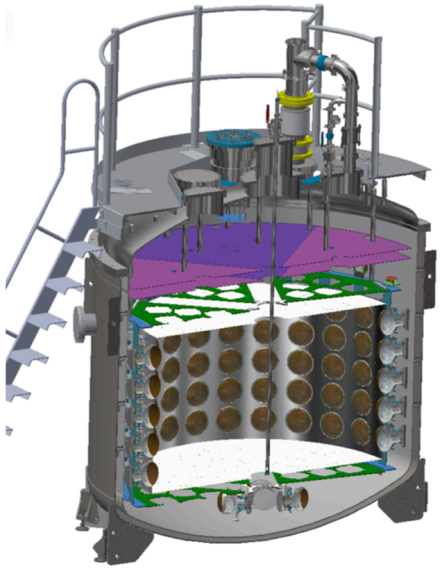
- 750kg LAr
- Single phase
- Light Collection Options
  - 3” PMT TPB
  - SiPM, Xenon Doping, …
- ~3000 CEvNS/yr

Coherent CAPTAIN-Mills (CCM)

10 ton LAr detector at Lujan center at LANL

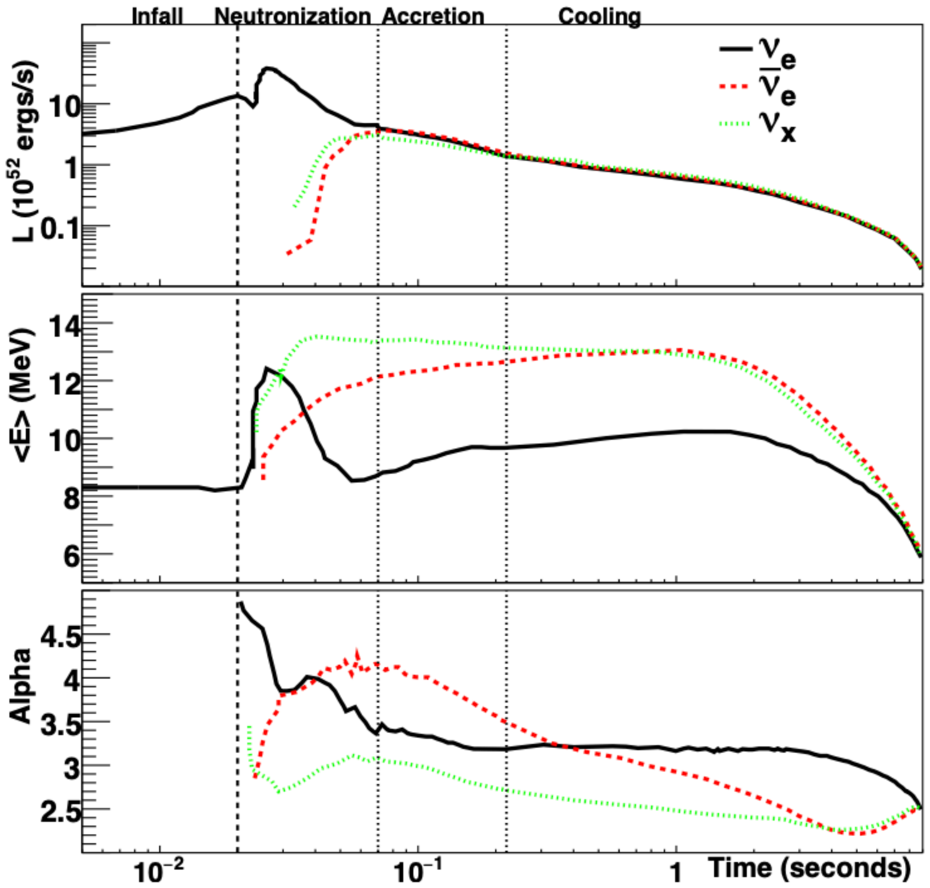
- Collected data in 2019, analysis ongoing
- Detector is being upgraded, will collect more data in summer 2021





10s of MeV Inelastic Neutrino-Nucleus Scattering

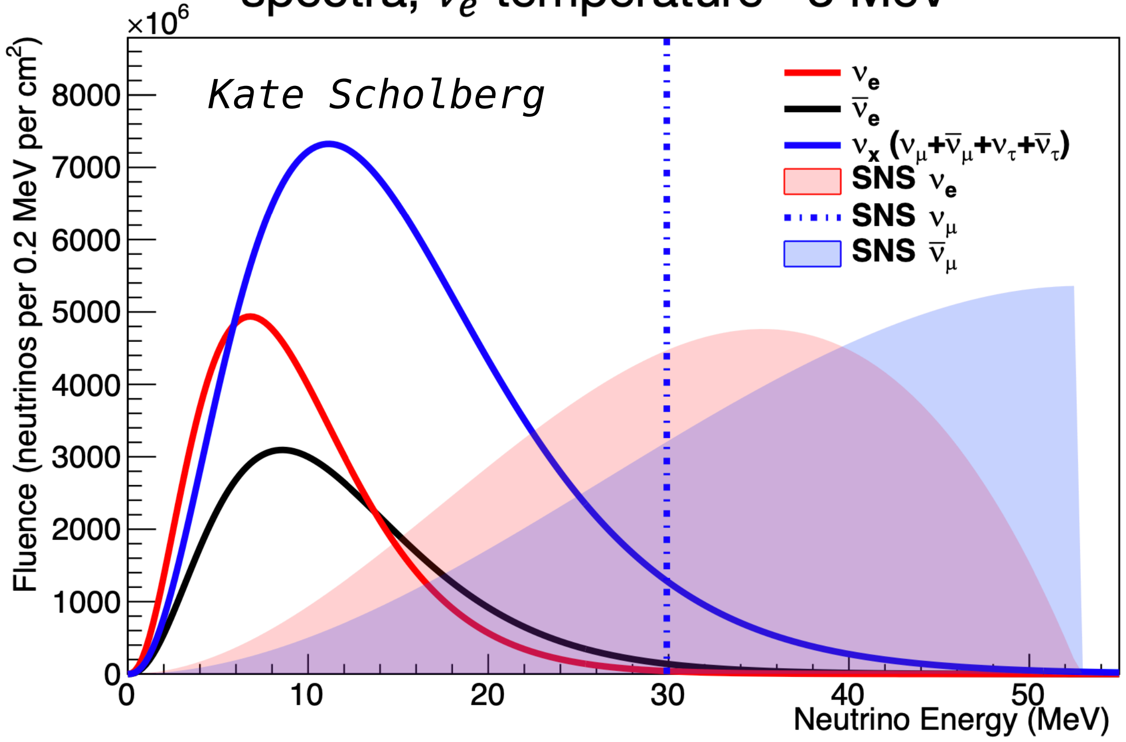
- CEvNS experiments at **stopped-pion sources** are also powerful avenues to measure **10s of MeV** **inelastic CC and NC** cross sections subject to detailed underlying nuclear structure and dynamics.
  - These are vital in understanding of core-collapse supernovae, but are almost completely unexplored experimentally so far
  - These measurement will greatly enhance the prospects of detecting neutrinos from a core-collapse supernova in future neutrino experiments such as DUNE.



arXiv:2008.06647 [hep-ex] [DUNE Collaboration]

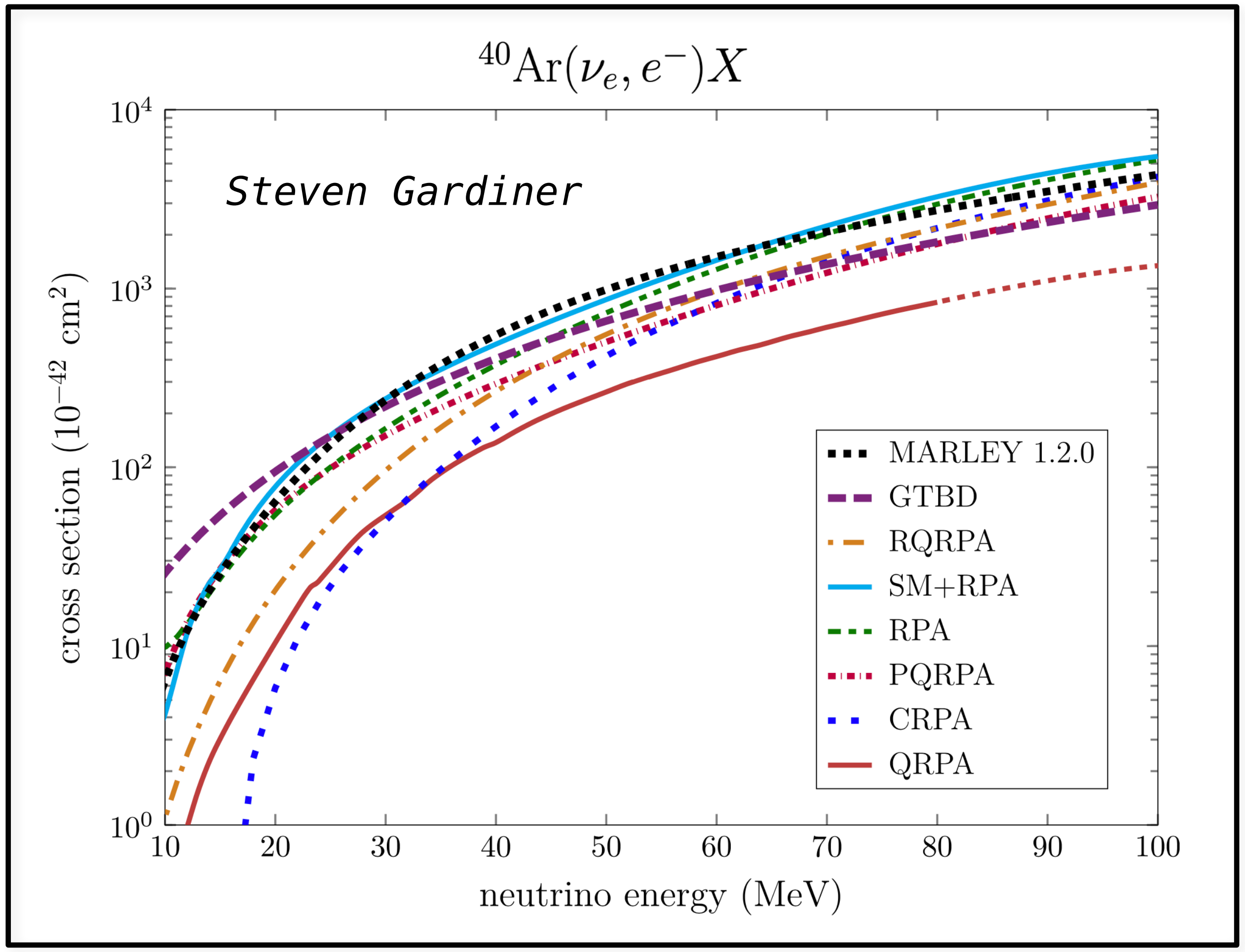
Neutrino signal from the core-collapse supernova starts with a short, sharp “neutronization” (or “breakout”) burst primarily composed of ν_e from $e^- + p \to \nu_e + n$.

Supernova flux (10 kpc): pinched spectra; ν_e temperature ~3 MeV



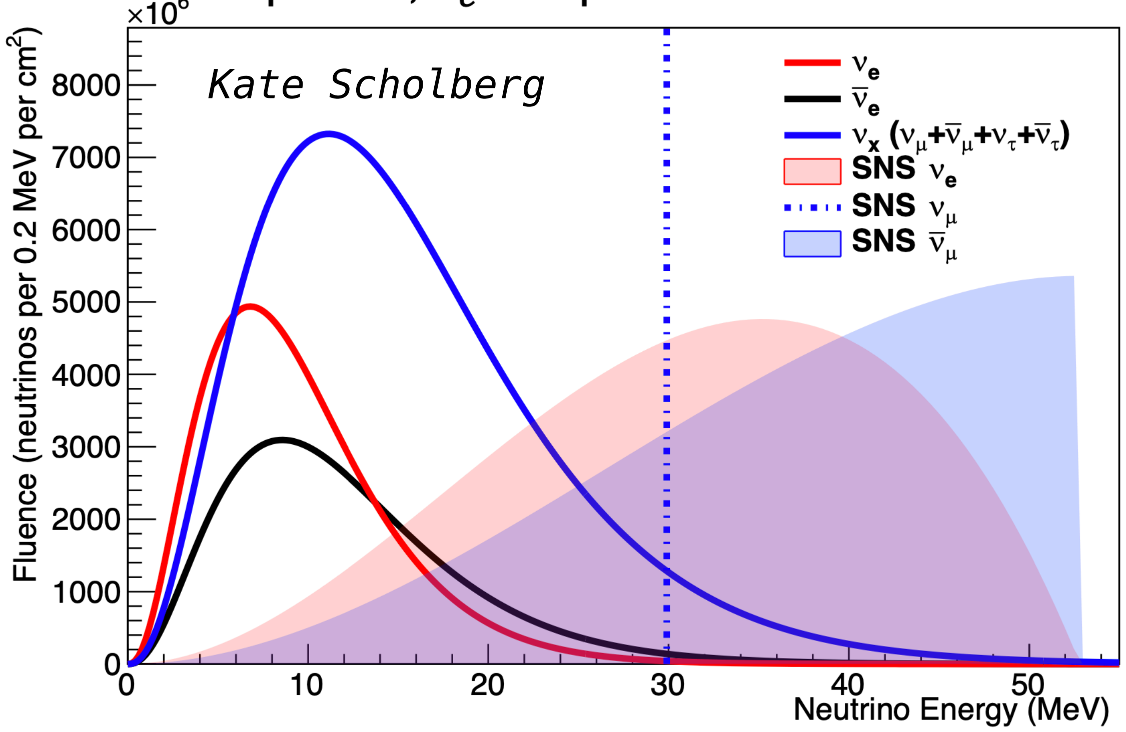
10s of MeV Inelastic Neutrino-Nucleus Scattering

- CEvNS experiments at **stopped-pion sources** are also powerful avenues to measure **10s of MeV inelastic CC and NC** cross sections subject to detailed underlying nuclear structure and dynamics.
  - These are vital in understanding of core-collapse supernovae, but are almost completely unexplored experimentally so far
  - These measurement will greatly enhance the prospects of detecting neutrinos from a core-collapse supernova in future neutrino experiments such as DUNE.



Need Measurements!

Supernova flux (10 kpc): pinched spectra; ν_e temperature ~3 MeV



CEvNS and Inelastic Neutrino-Nucleus Scattering at Stopped Pion Sources

- Outline
  - A bit of background and status of the field
  - Snowmass activities: LOIs, White Papers, Workshops
    - With my Snowmass hat on, as Snowmass Early Career liaison to NF06 and TF11

LOIs: CEvNS and Inelastic Neutrino-Nucleus Interactions

LOIs: CEvNS at Stopped Pion Sources

Mainly focused on BSM searches:

- ✦ Upgrade and future plans at SNS at ORNL: LOI - 67, LOI - 95, LOI - 161, LOI - 141
- ✦ Upgrade plans at Los Alamos National Lab: LOI - 215
- ✦ Upgrade plans at Fermilab: LOI - 99
- ✦ Directional CEvNS detectors: LOI - 141, LOI - 150

LOIs: Inelastic Neutrino-Nucleus Interactions at Stopped Pion Sources

✦ LOI - 194

Low-energy Inelastic Neutrino Cross Sections

J. Barrow,[1,2] P.S. Barbeau,[3,4] E. Conley,[3] S. Gardiner,[2] S. Hedges,[3,4] A. Mastbaum,[5] V. Pandey,[6] and K. Scholberg[3]

Contact Information:
Steven Gardiner, Fermilab

✦ LOI - 139

COHERENT LOI 4: Inelastic Neutrino-Nucleus Interaction Measurements with COHERENT

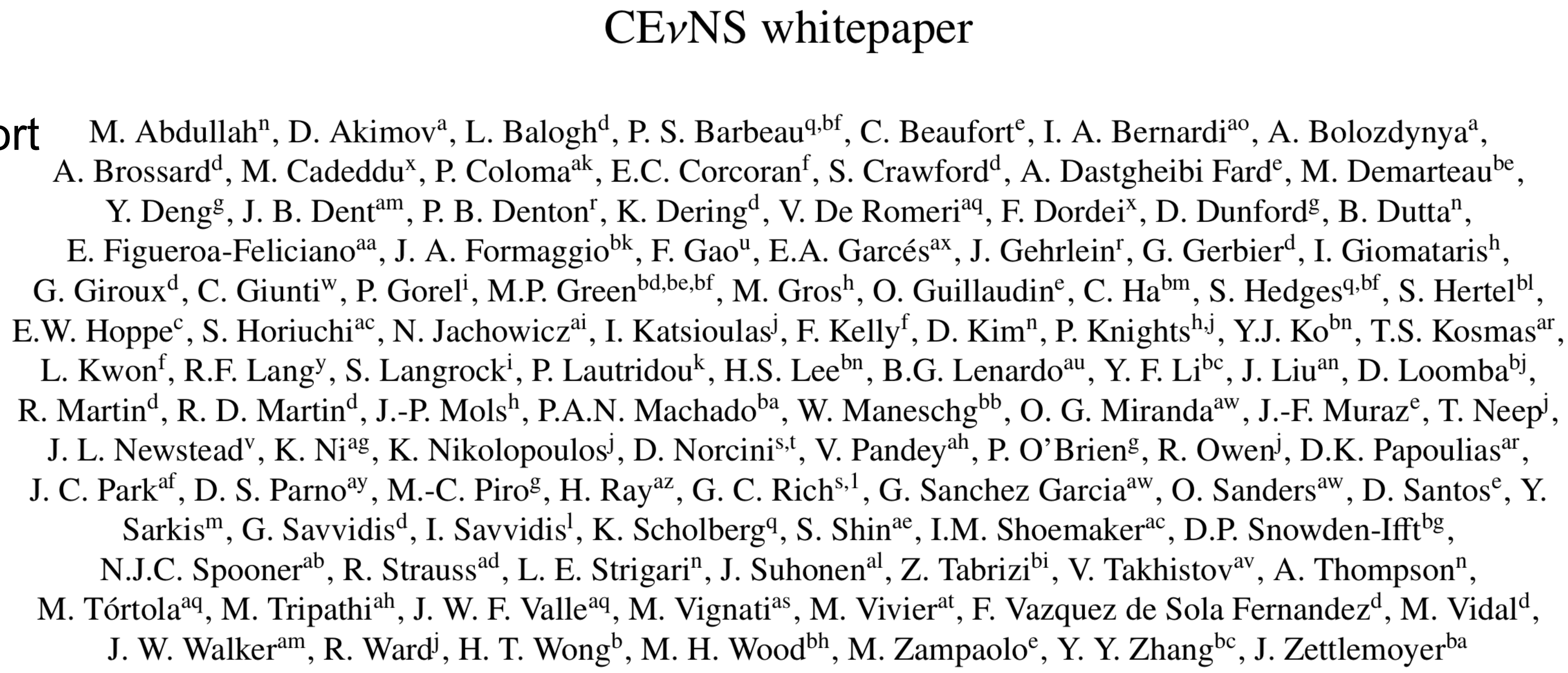
Contact Information:
Kate Scholberg (Duke University),

COHERENT Collaboration

White Paper Efforts: CEvNS and Inelastic Neutrino-Nucleus Interactions

✦ **CEvNS White Paper:**

Broad CEvNS Community Effort
Co-ordinated by:
Louis Strigari (TAMU)



CEνNS whitepaper

M. Abdullah[n], D. Akimov[a], L. Balogh[d], P. S. Barbeau[q,bf], C. Beaufort[e], I. A. Bernardi[ao], A. Bolozdynya[a],
A. Brossard[d], M. Cadeddu[x], P. Coloma[ak], E.C. Corcoran[f], S. Crawford[d], A. Dastgheibi Fard[e], M. Demarteau[be],
Y. Deng[g], J. B. Dent[am], P. B. Denton[r], K. Dering[d], V. De Romeri[aq], F. Dordei[x], D. Dunford[g], B. Dutta[n],
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E.W. Hoppe[c], S. Horiuchi[ac], N. Jachowicz[ai], I. Katsioulas[j], F. Kelly[f], D. Kim[n], P. Knights[h,j], Y.J. Ko[bn], T.S. Kosmas[ar],
L. Kwon[f], R.F. Lang[y], S. Langrock[i], P. Lautridou[k], H.S. Lee[bn], B.G. Lenardo[au], Y. F. Li[bc], J. Liu[an], D. Loomba[bj],
R. Martin[d], R. D. Martin[d], J.-P. Mols[h], P.A.N. Machado[ba], W. Maneschg[bb], O. G. Miranda[aw], J.-F. Muraz[e], T. Neep[j],
J. L. Newstead[v], K. Ni[ag], K. Nikolopoulos[j], D. Norcini[s,t], V. Pandey[ah], P. O'Brien[g], R. Owen[j], D.K. Papoulias[ar],
J. C. Park[af], D. S. Parno[ay], M.-C. Piro[g], H. Ray[az], G. C. Rich[s,1], G. Sanchez Garcia[aw], O. Sanders[aw], D. Santos[e], Y.
Sarkis[m], G. Savvidis[d], I. Savvidis[l], K. Scholberg[q], S. Shin[ae], I.M. Shoemaker[ac], D.P. Snowden-Ifft[bg],
N.J.C. Spooner[ab], R. Strauss[ad], L. E. Strigari[n], J. Suhonen[al], Z. Tabrizi[bi], V. Takhistov[av], A. Thompson[n],
M. Tórtola[aq], M. Tripathi[ah], J. W. F. Valle[aq], M. Vignati[as], M. Vivier[at], F. Vazquez de Sola Fernandez[d], M. Vidal[d],
J. W. Walker[am], R. Ward[j], H. T. Wong[b], M. H. Wood[bh], M. Zampaolo[e], Y. Y. Zhang[bc], J. Zettlemoyer[ba]

✦ **NF06 co-ordinated Electron Scattering White Paper:** We are planning to have a broad electron scattering white paper focusing on connections between
- CEvNS and PVES
- Low energy inelastic scattering and potential low-energy electron experiments
- GeV scale electron scattering and neutrino oscillation physics

More community feedback and involvement will be solicited in the workshop next Monday (more info on the next slide).

✦ **Snowmass White Paper from the LEPLAr Workshop:** A Low Energy Physics in LAr (LEPLAr) workshop was organized recently, primarily by DUNE folks, focusing on low energy physics in LAr experiments. A dedicated session was organized on the low energy inelastic scatterings. A Snowmass white paper is planned to be prepared with likely a dedicated section on low energy inelastic neutrino-nucleus physics.

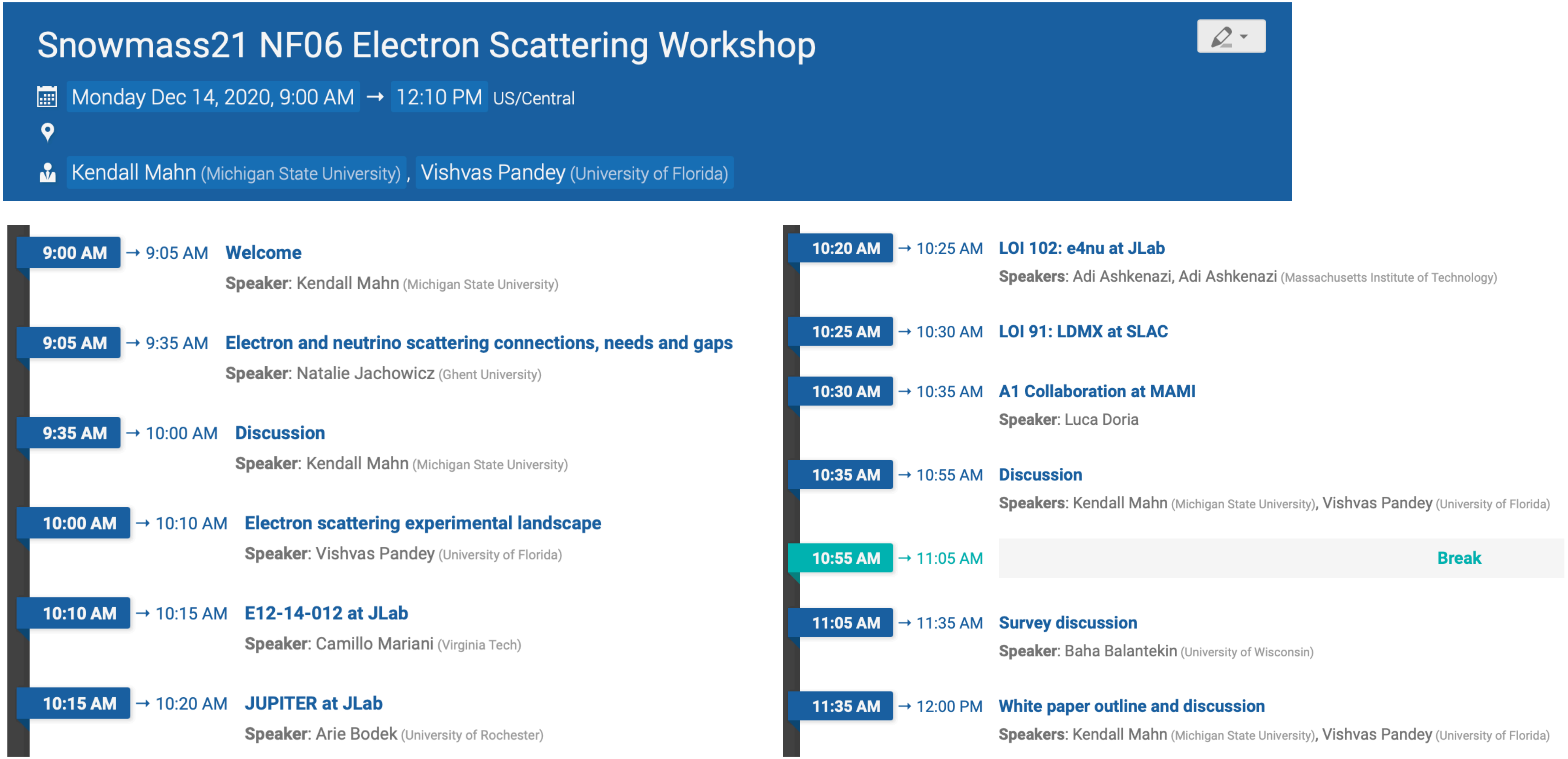
NF06 Snowmass Workshops

- **NF06 Low Energy Neutrinos and Electron Scattering Workshop**: focusing on connections between CEvNS and PVES, and low energy inelastic scattering and potential low-energy electron experiments. We were planning for January 2021 but now with potential delay in Snowmass, will move to a bit later in the year.

NF06 Snowmass Workshops

✦ **NF06 Low Energy Neutrinos and Electron Scattering Workshop**: focusing on connections between CEvNS and PVES, and low energy inelastic scattering and potential low-energy electron experiments. We were planning for January 2021 but now with potential delay in Snowmass, will move to a bit later in the year.

✦ **NF06 Electron Scattering Workshop [Mon, Dec 14]:** https://indico.fnal.gov/event/46620/



Snowmass21 NF06 Electron Scattering Workshop

Monday Dec 14, 2020, 9:00 AM → 12:10 PM US/Central

Kendall Mahn (Michigan State University), Vishvas Pandey (University of Florida)

9:00 AM	→ 9:05 AM	**Welcome**	**Speaker**: Kendall Mahn (Michigan State University)
9:05 AM	→ 9:35 AM	**Electron and neutrino scattering connections, needs and gaps**	**Speaker**: Natalie Jachowicz (Ghent University)
9:35 AM	→ 10:00 AM	**Discussion**	**Speaker**: Kendall Mahn (Michigan State University)
10:00 AM	→ 10:10 AM	**Electron scattering experimental landscape**	**Speaker**: Vishvas Pandey (University of Florida)
10:10 AM	→ 10:15 AM	**E12-14-012 at JLab**	**Speaker**: Camillo Mariani (Virginia Tech)
10:15 AM	→ 10:20 AM	**JUPITER at JLab**	**Speaker**: Arie Bodek (University of Rochester)
10:20 AM	→ 10:25 AM	**LOI 102: e4nu at JLab**	**Speakers**: Adi Ashkenazi, Adi Ashkenazi (Massachusetts Institute of Technology)
10:25 AM	→ 10:30 AM	**LOI 91: LDMX at SLAC**	
10:30 AM	→ 10:35 AM	**A1 Collaboration at MAMI**	**Speaker**: Luca Doria
10:35 AM	→ 10:55 AM	**Discussion**	**Speakers**: Kendall Mahn (Michigan State University), Vishvas Pandey (University of Florida)
10:55 AM	→ 11:05 AM	**Break**	
11:05 AM	→ 11:35 AM	**Survey discussion**	**Speaker**: Baha Balantekin (University of Wisconsin)
11:35 AM	→ 12:00 PM	**White paper outline and discussion**	**Speakers**: Kendall Mahn (Michigan State University), Vishvas Pandey (University of Florida)