Neutrino Physics at the J-PARC MLF

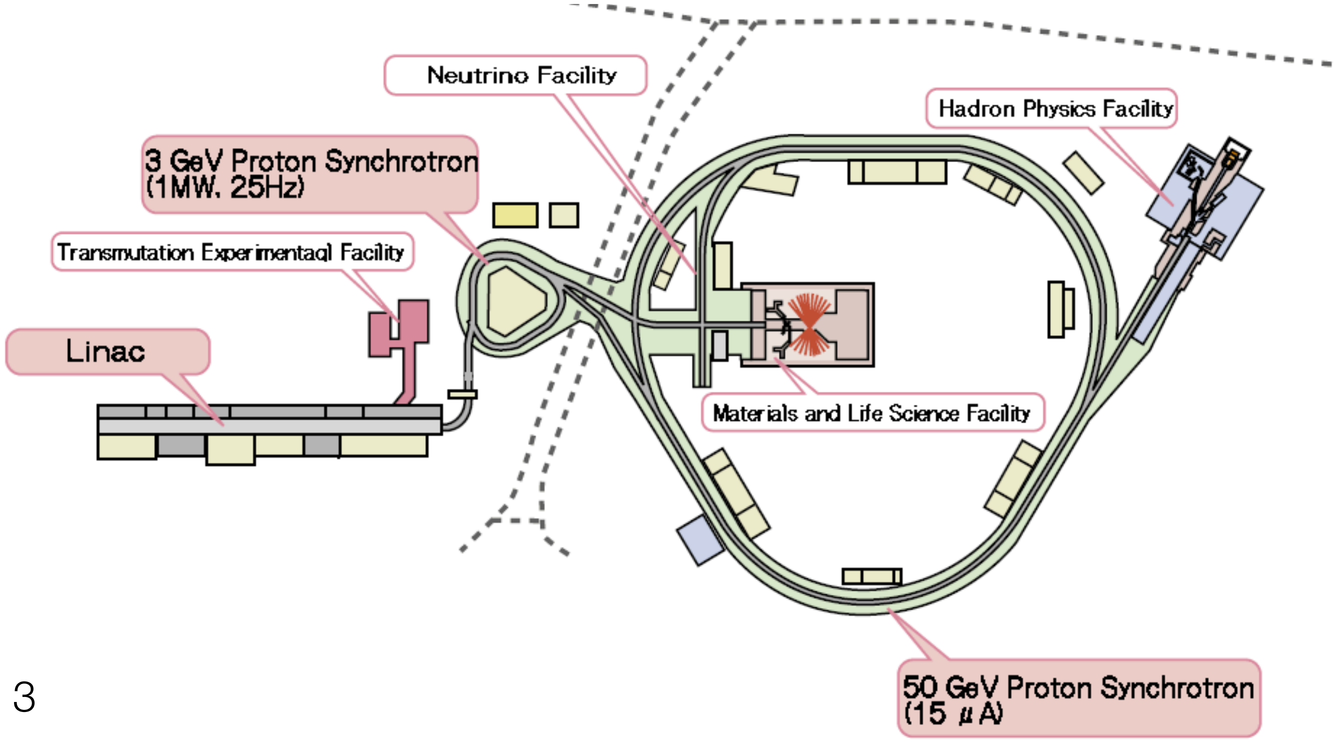
Johnathon Jordan
Magnificent CEvNS 2019
November 11, 2019

The J-PARC MLF

J-PARC

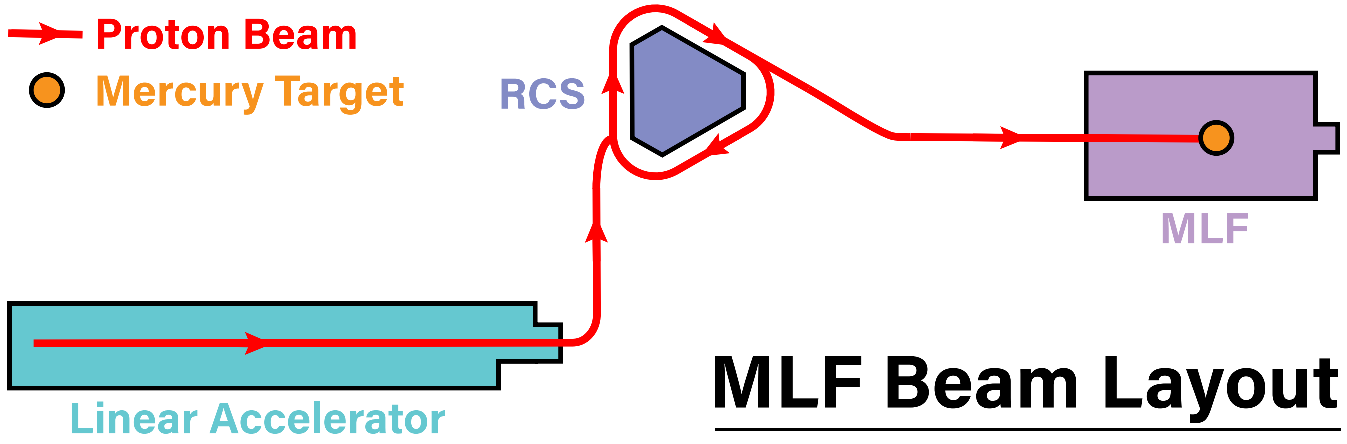
J-PARC = Japan Proton Accelerator Research Complex

J-PARC is in Tokai on the eastern coast of Japan



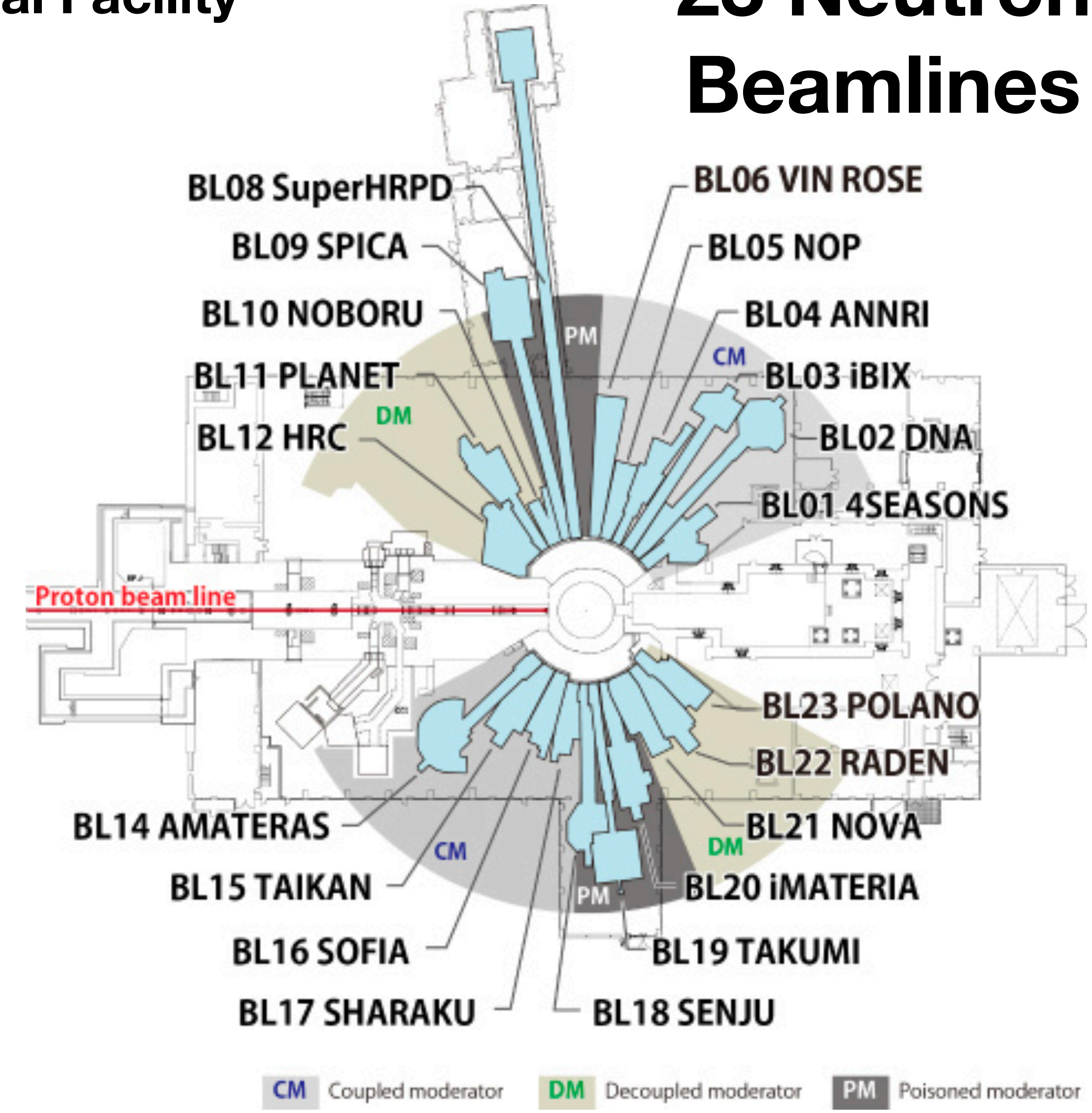
The J-PARC MLF

MLF = Material and Life Science Experimental Facility



MLF Beam Layout

23 Neutron Beamlines



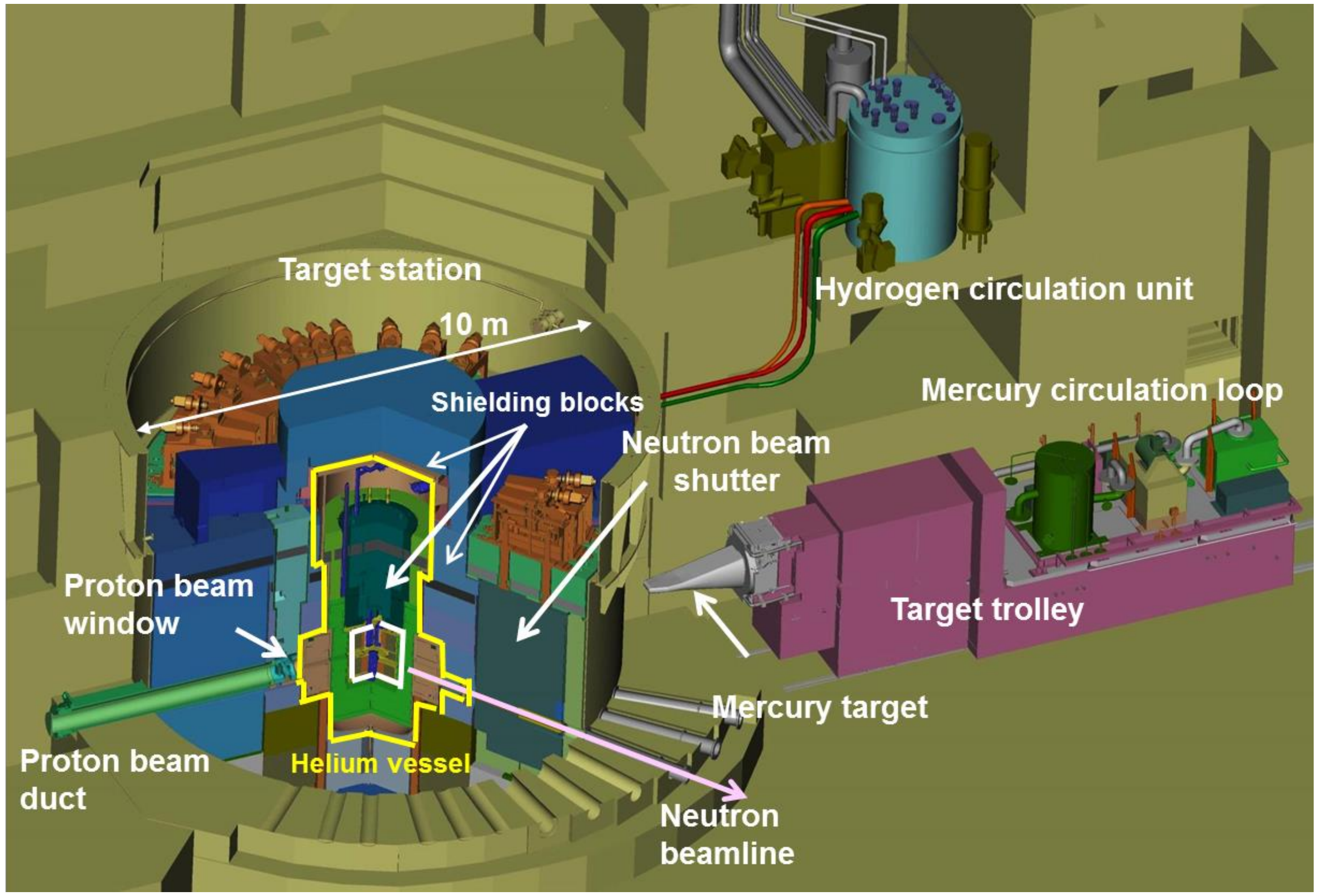
MLF Basics:

- Home of the Japan Spallation Neutron Source (JSNS)
- 23 neutron beamlines
- 3 GeV proton beam incident on a mercury target
- Design power: 1 MW (latest: 535 kW)
- In operation since May 2008

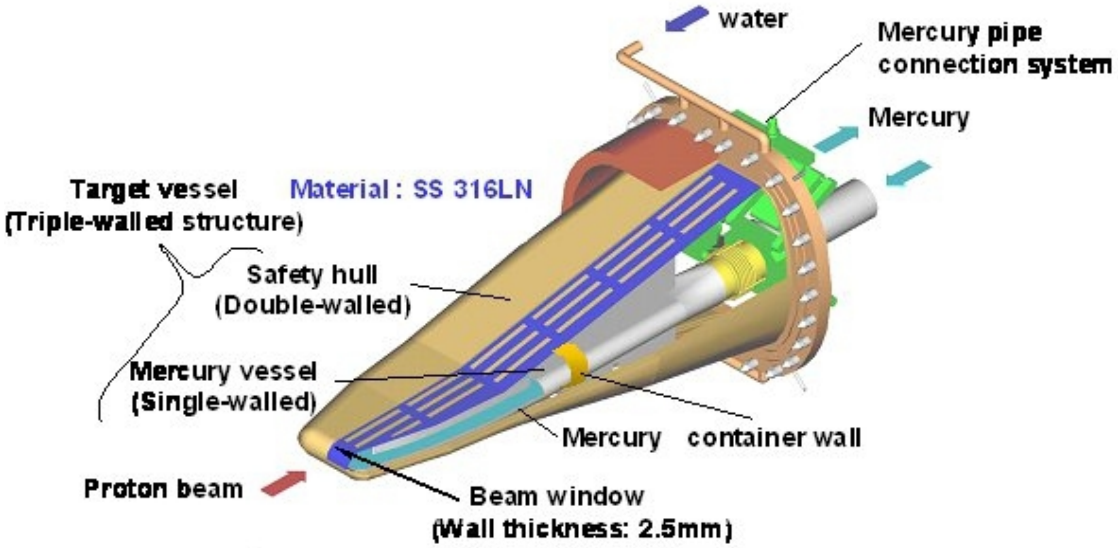
JSNS vs. Oak Ridge SNS

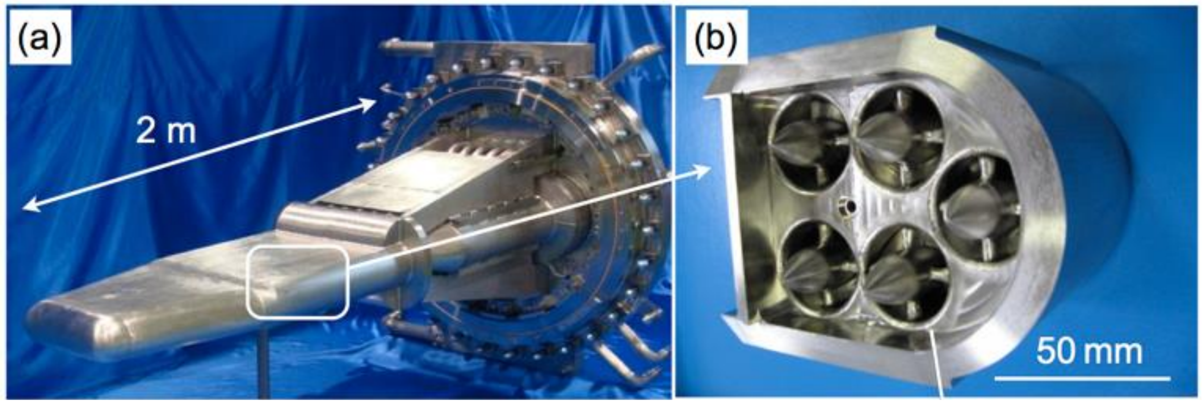
Property	JSNS	SNS
Beam Power	1 MW (~500 kW)	1.4 MW
Proton Energy	3 GeV	1 GeV
Repetition Rate	25 Hz	60 Hz
Beam Timing	Two 100 ns pulses separated by 540 ns	350 ns FWHM
Target	Mercury	Mercury
POT/day	~1.8×10^{20} (1 MW)	~5.0×10^{20}
π^+/μ^+ Decays/POT	~0.3	~0.08
K^+ Decays/POT	~0.006	~0

MLF Target



Mercury is circulated at 154 kg/s!

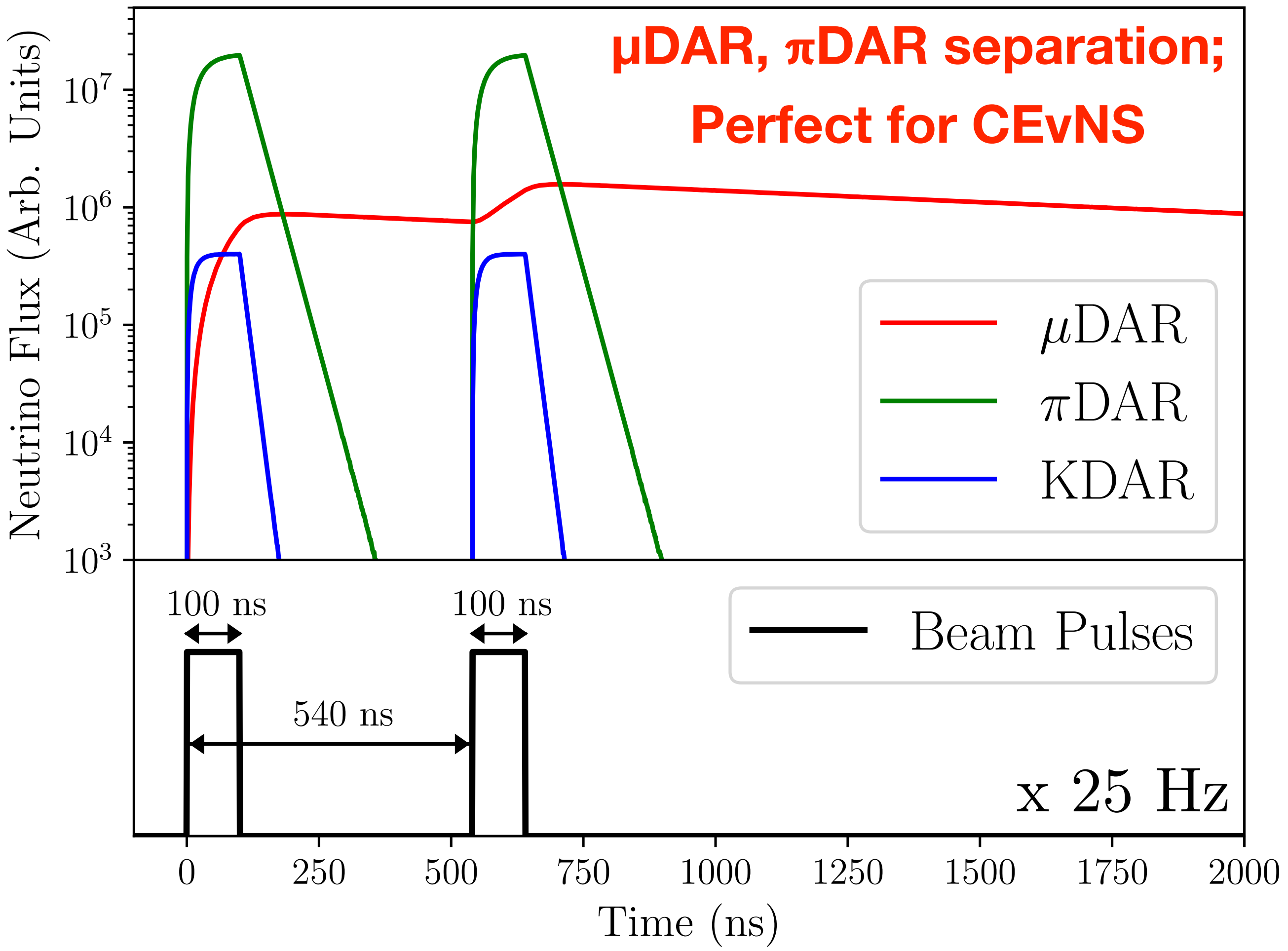


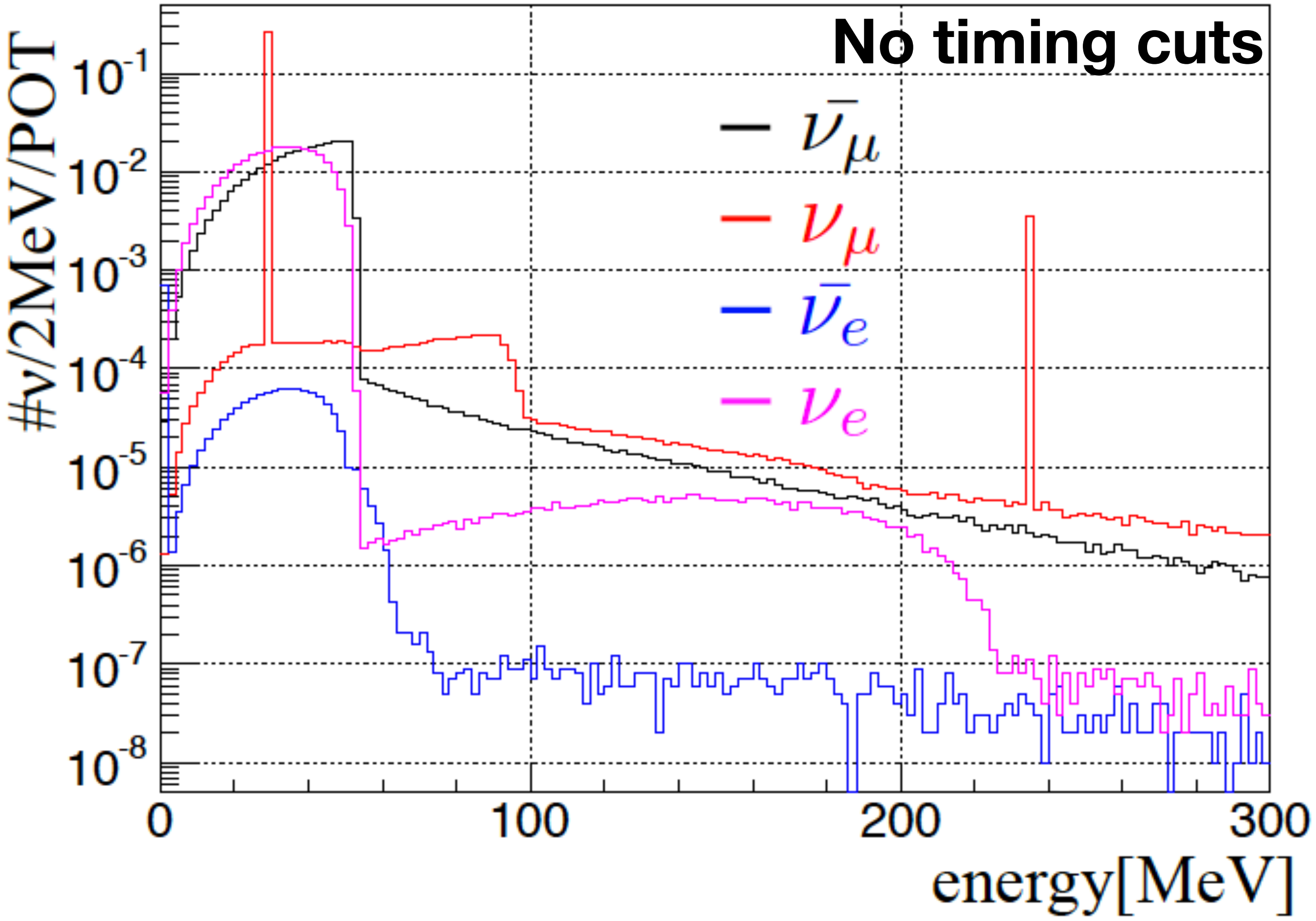


The neutron production target is a double-walled stainless steel vessel with circulating mercury.

The heavy target material and shielding ensure an almost entirely DAR neutrino source.

Neutrino Production

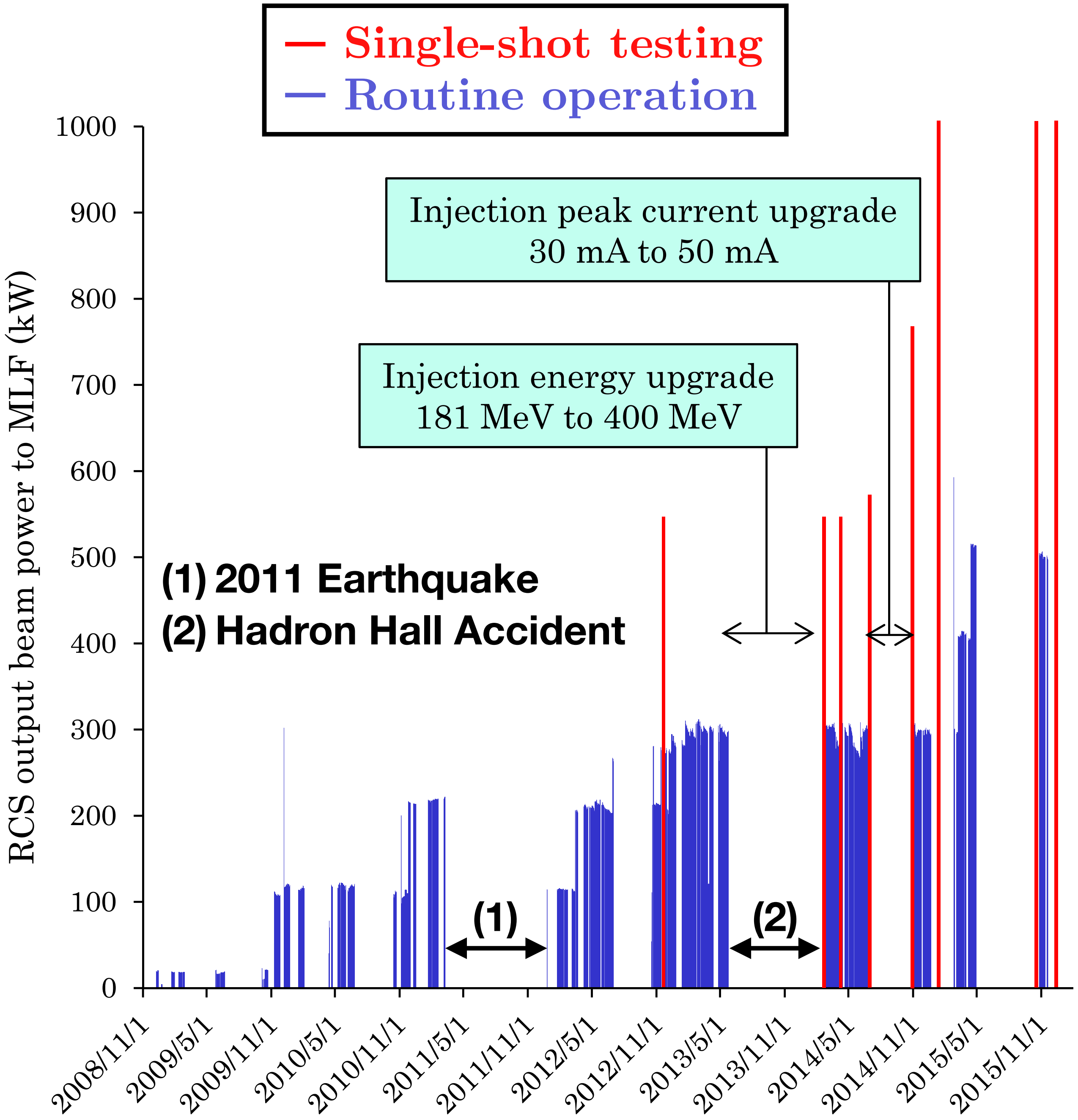

μDAR, πDAR separation;
Perfect for CEvNS


No timing cuts

The MLF beam is delivered in two close bunches at 25 Hz producing prompt and delayed neutrinos.

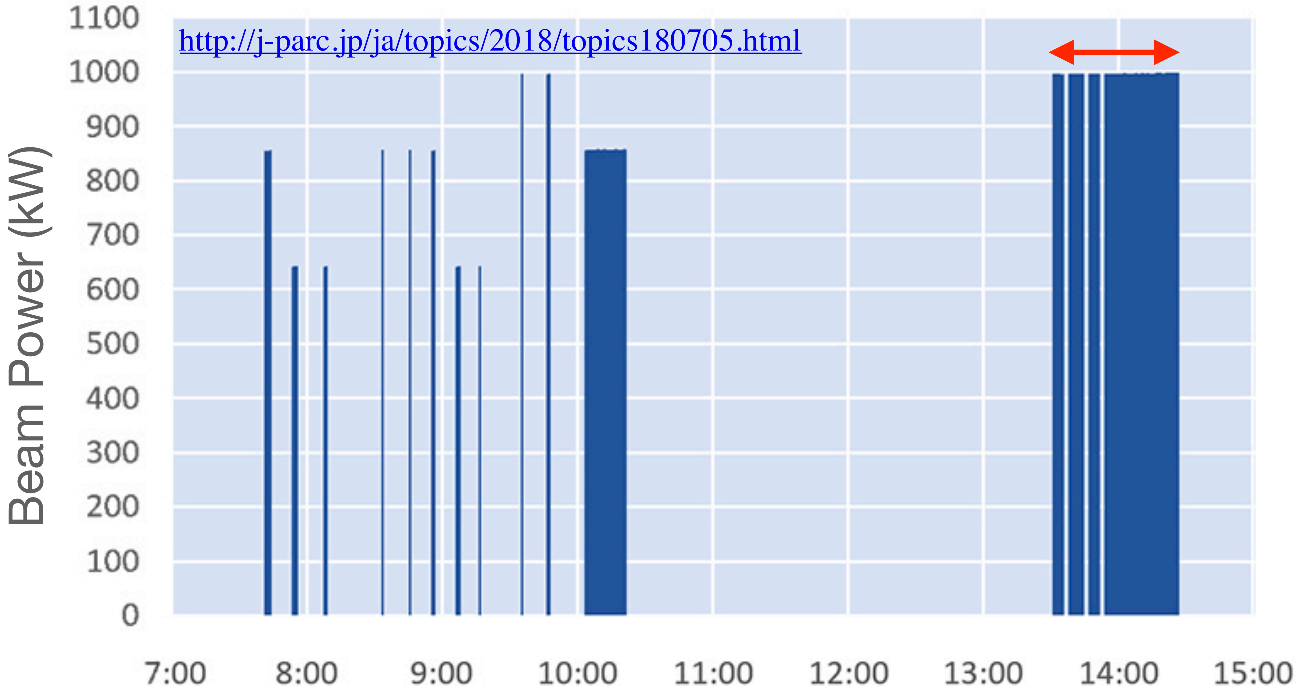
The neutrino fluxes are well-understood because they come predominantly from decay at rest.

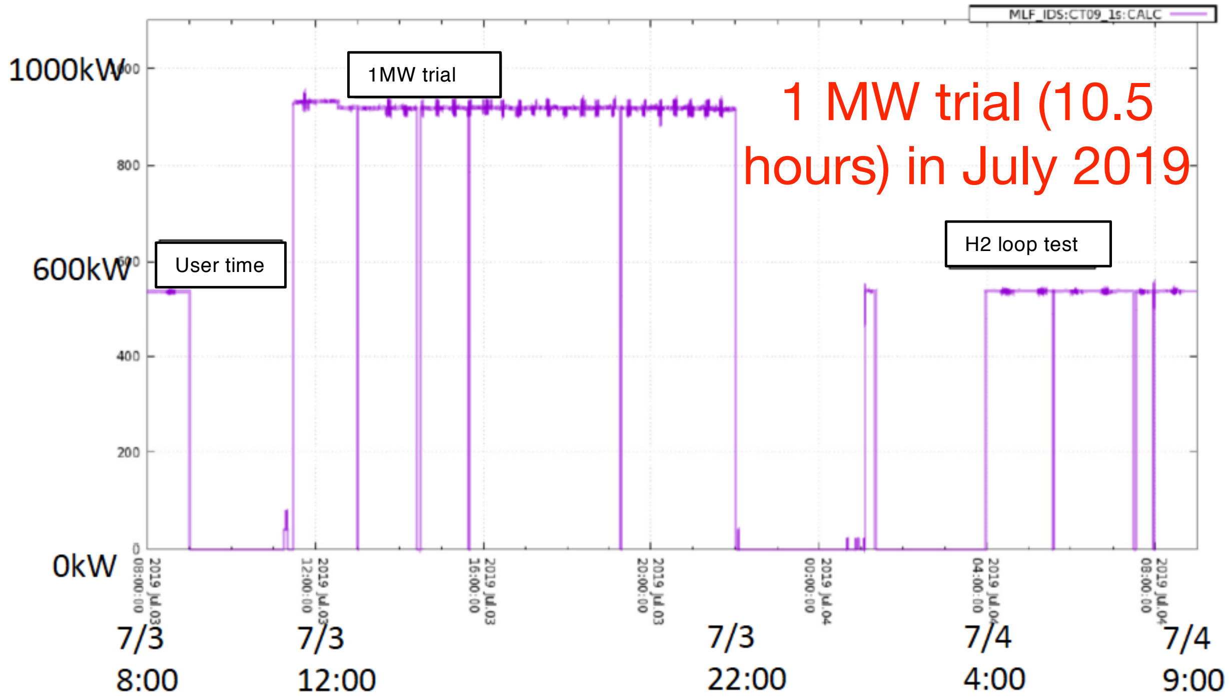
MLF Status



H. Hotchi, et. al., Achievement of a low-loss 1-MW beam operation in the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex, Phys. Rev. Accel. Beams 20, 060402 (June 2017)

1 MW trial (1 hour) in July 2018





1 MW trial (10.5 hours) in July 2019

MLF Status

- The MLF has been providing stable operation at a beam power of ~500 kW
    - In fiscal year 2018, 94% availability was achieved corresponding to 4129 hours of beam time for users
- Several trials at 1 MW beam power have been performed to iron out potential issues and do target studies
    - 1 hour in July 2018
    - 10.5 hours in July 2019
- Significant effort is going towards target improvements to achieve stable 1 MW operation
- The tentative plan is to gradually increase the beam power over the next year during normal user periods

JSNS^2

J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source

Short-Baseline Anomalies

Experiment	Source	Oscillation Channel	Significance
LSND	Pion and muon decay-at-rest (DAR)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ
MiniBooNE	Pion and kaon decay-in-flight (DIF)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ
MiniBooNE	Pion and kaon decay-in-flight (DIF)	$\nu_\mu \rightarrow \nu_e$	4.5σ
Reactors	Beta Decay	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	Varies
GALLEX/SAGE	Radioactive Source (Electron Capture)	$\nu_e \rightarrow \nu_e$	2.8σ

4.8σ

New experiments are required to address the anomalies at short baseline.

Tension With Other Data

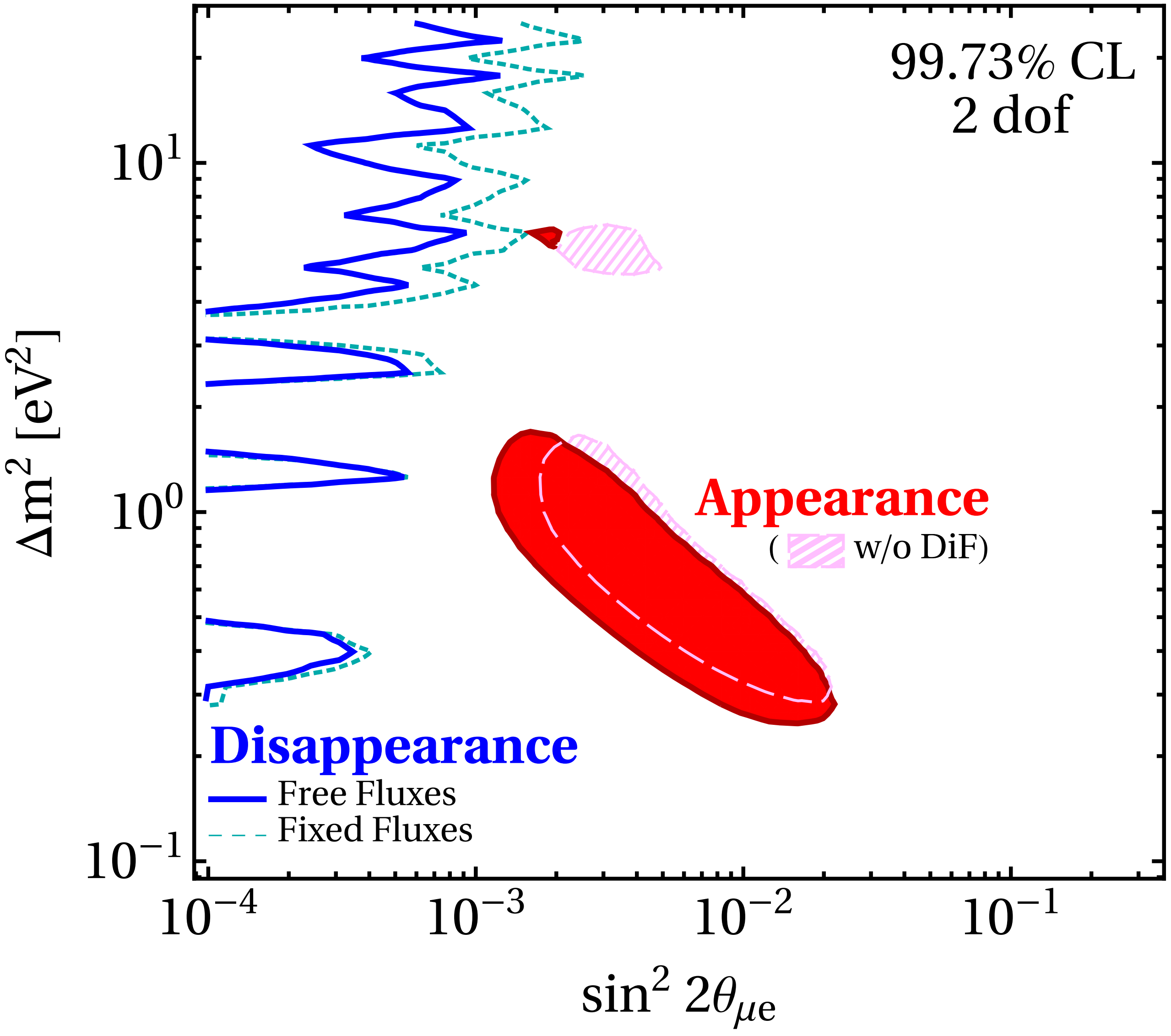
- There is tension between $\nu_\mu \rightarrow \nu_e$ appearance and ν_μ/ν_e disappearance
- In the short-baseline limit:

$$P_{ee} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P_{\mu\mu} = 1 - 4|U_{\mu4}|^2(1 - |U_{\mu4}|^2)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P_{\mu e} = 4|U_{\mu4}|^2|U_{e4}|^2\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

This tension motivates new experiments to definitively address the anomalies.



$$\sin^2 2\theta_{\mu e} = 4|U_{\mu4}|^2|U_{e4}|^2$$

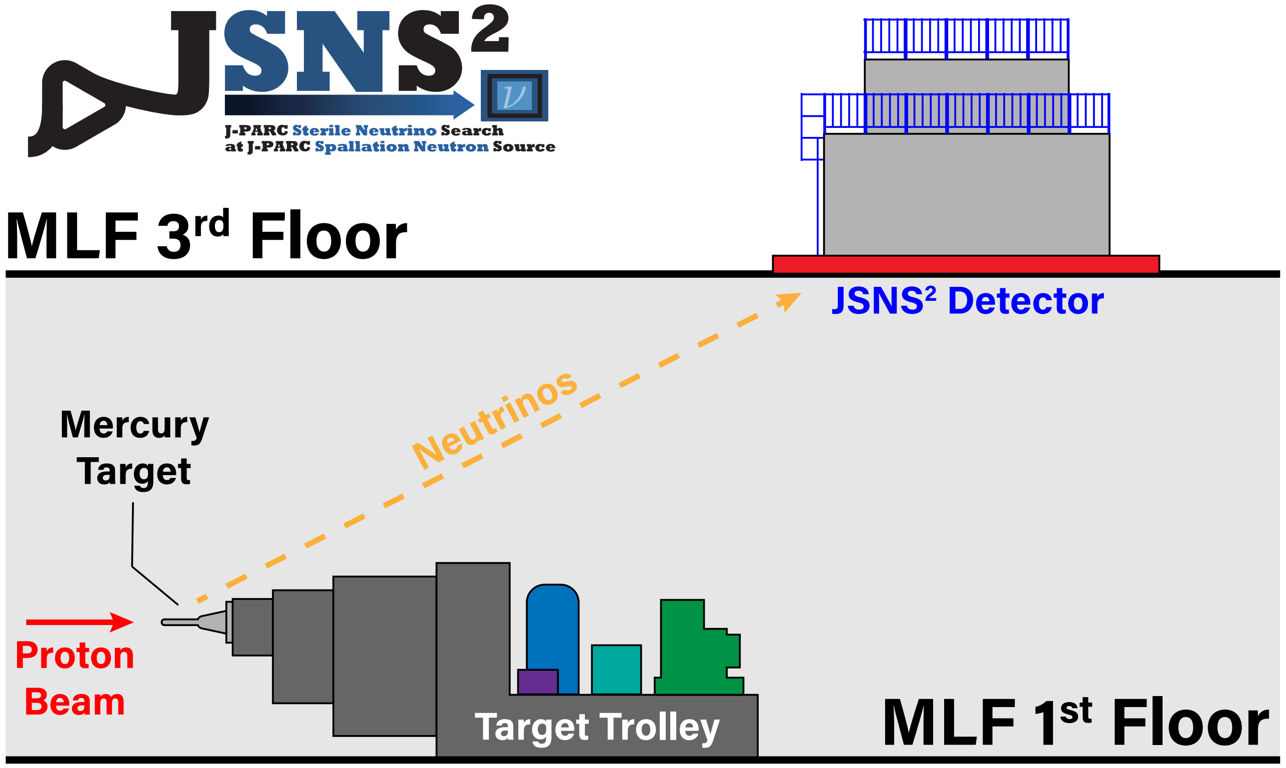
M. Dentler et al., JHEP **08**, 010 (2018), 1803.10661

JSNS^2

J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source

- Direct test of LSND
  - Same neutrino source (muon decay at rest)
  - Same interaction mechanism (Inverse Beta Decay)
  - Similar baseline (24 m vs. 30 m)
- Target volume filled with Gd-doped liquid scintillator
  - Phase 0: 17 tons
  - Future Phases: Multiple detectors/baselines
- First data in early 2020 (Phase 0)

Detector location on the MLF 3rd Floor



JSNS^2 TDR arXiv:1705.08629

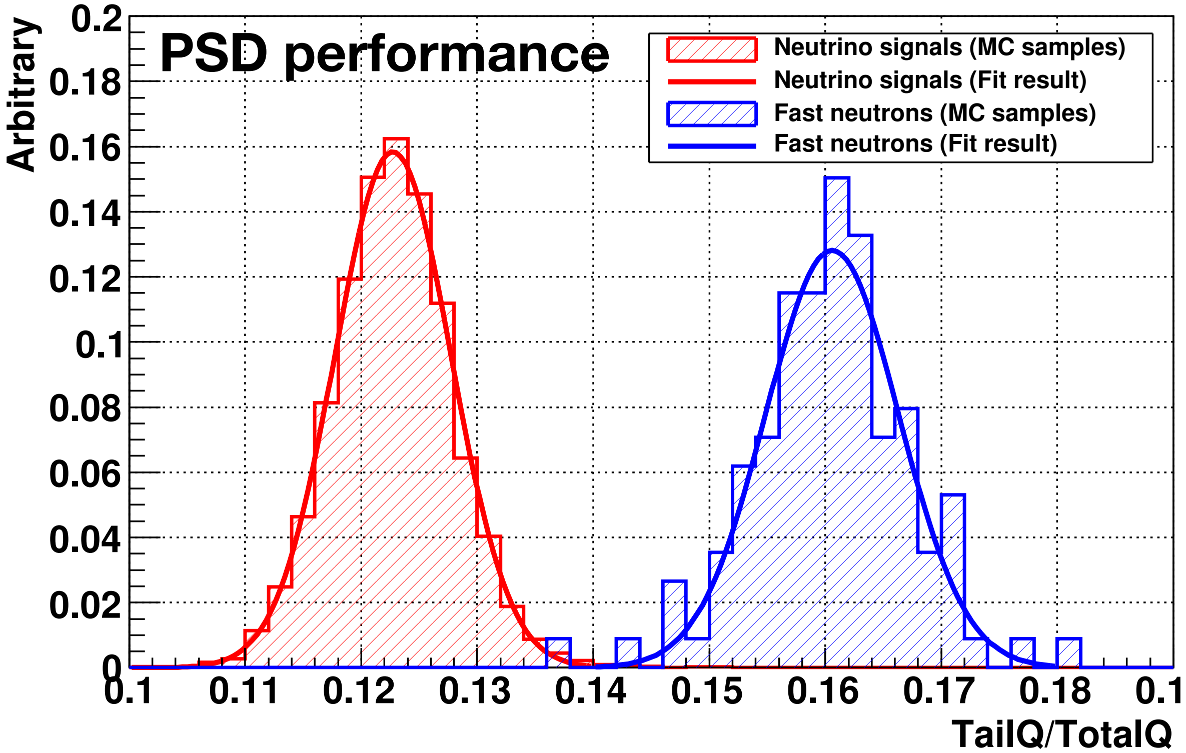
JSNS^2 Collaboration

July 2019 Collaboration Meeting

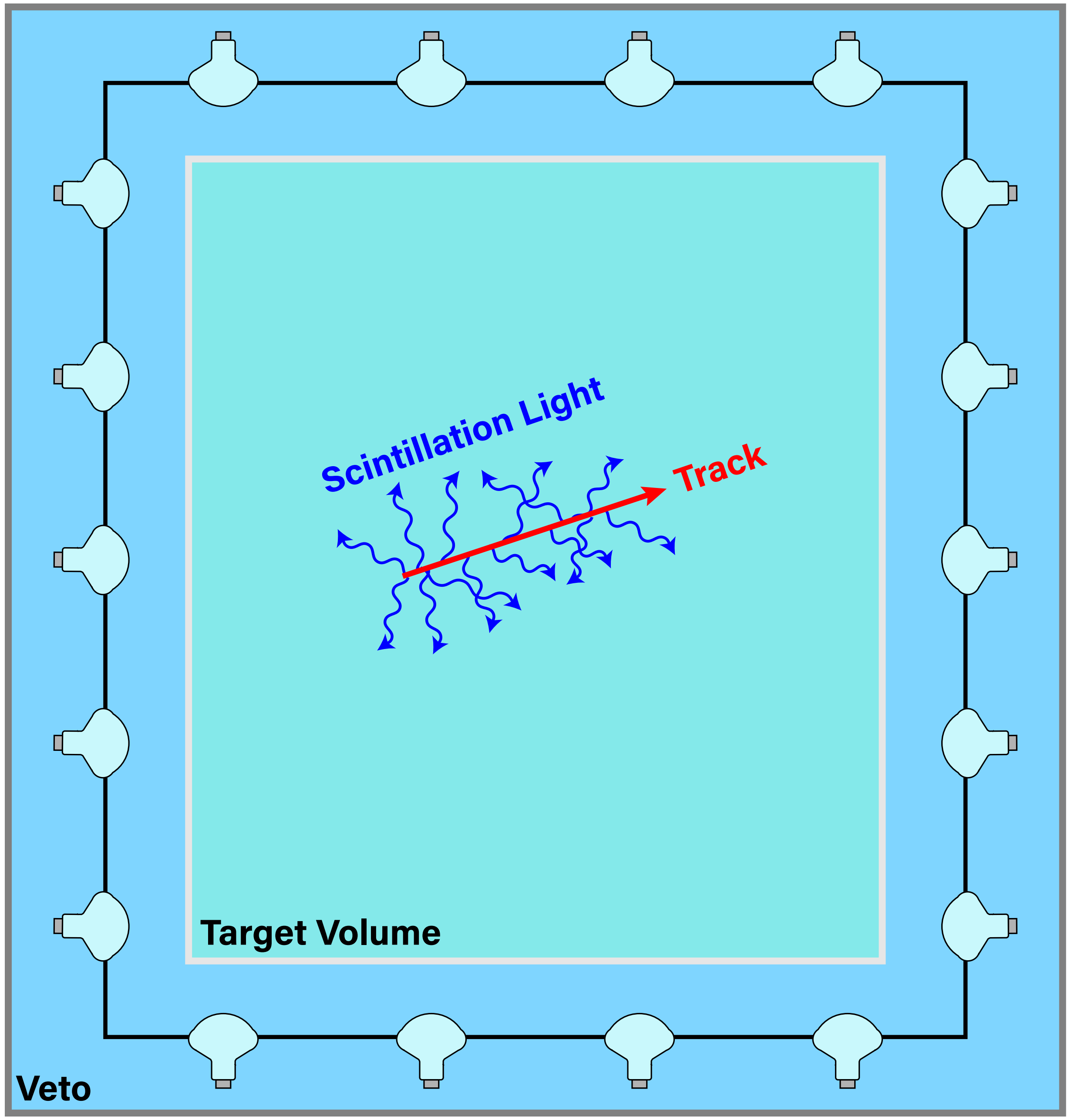
~50 members from Japan, Korea, the US, and the UK

JSNS^2 Detector

- JSNS^2 uses a liquid scintillator detector
  - 17 tons of Gd-loaded scintillator
  - ~50 total tons of scintillator
- Oscillation candidates are identified using the standard IBD signature
  - Prompt positron
  - Delayed neutron capture on Gd
- Pulse shape discrimination (PSD) is used to reject fast neutron backgrounds

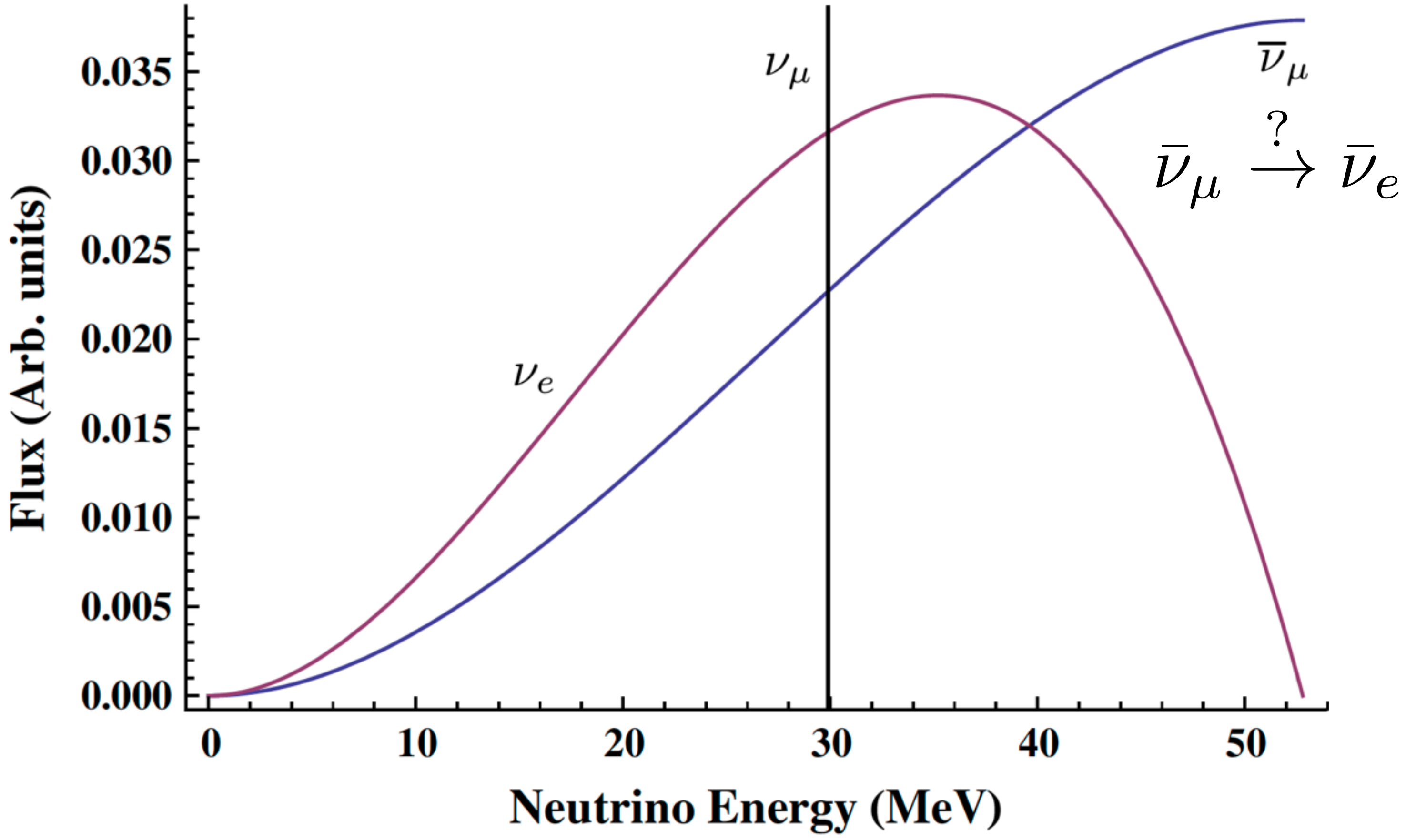


JSNS^2 Detector



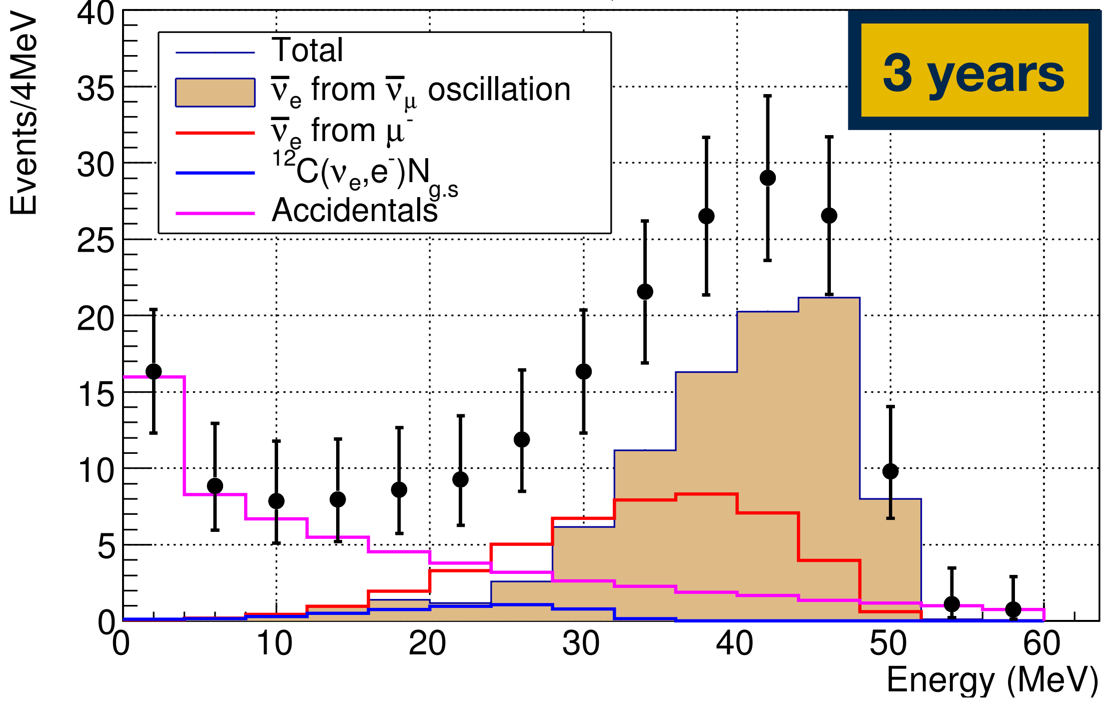
Oscillation Signatures

$$\pi^+ \rightarrow \mu^+\nu_\mu \qquad \mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$

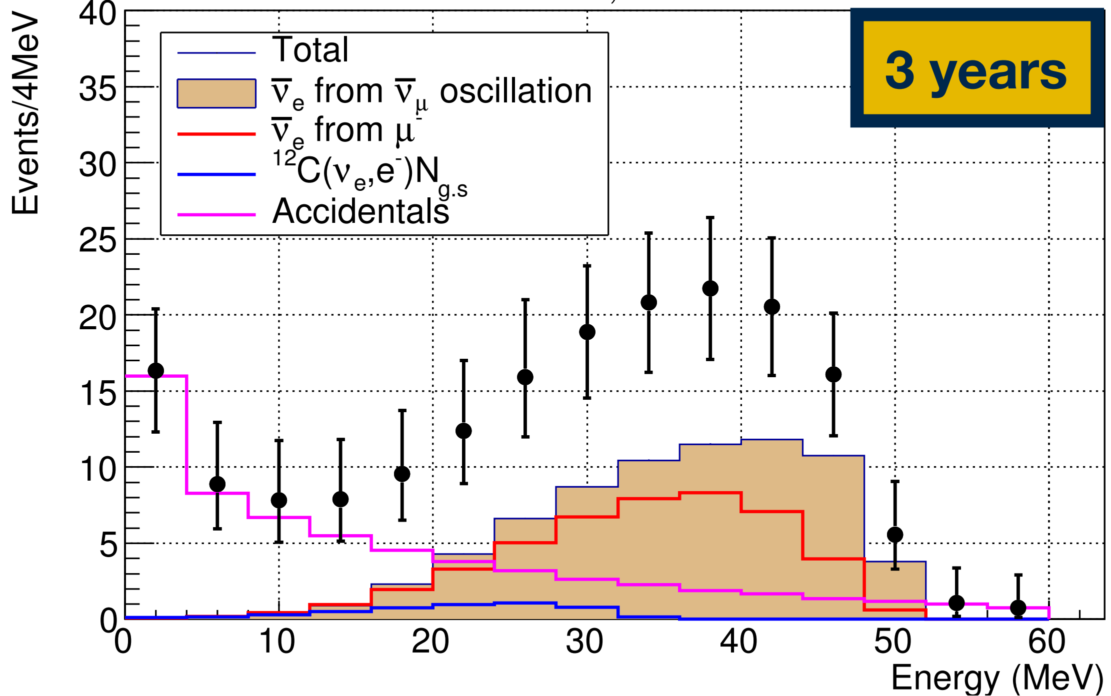


Search for electron antineutrino appearance using the IBD signature

$\Delta m^2 = 2.5\ \mathrm{eV}^2,\ \sin^2 2\theta = 0.003$

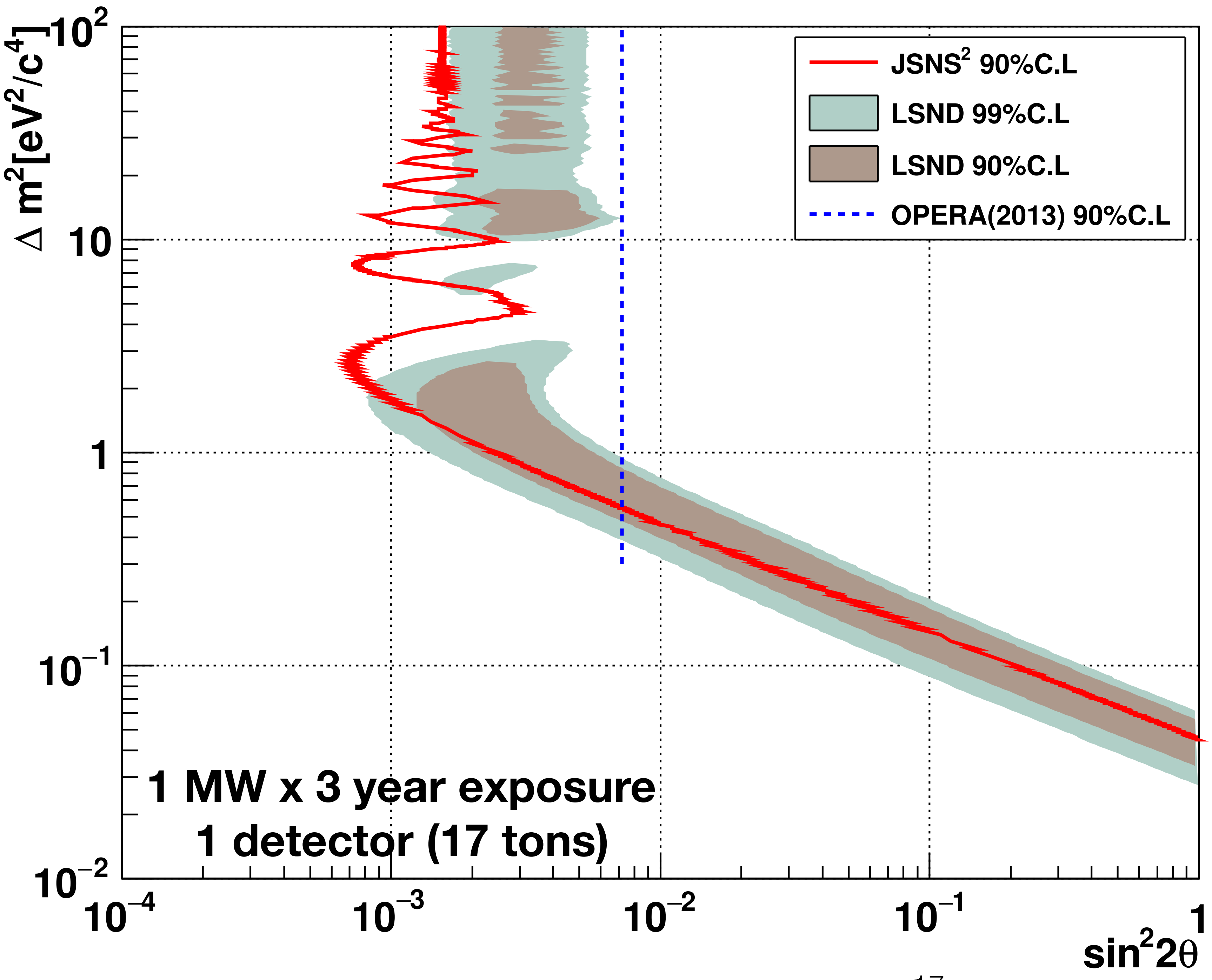


$\Delta m^2 = 1.2\ \mathrm{eV}^2,\ \sin^2 2\theta = 0.003$



JSNS^2 TDR arXiv:1705.08629

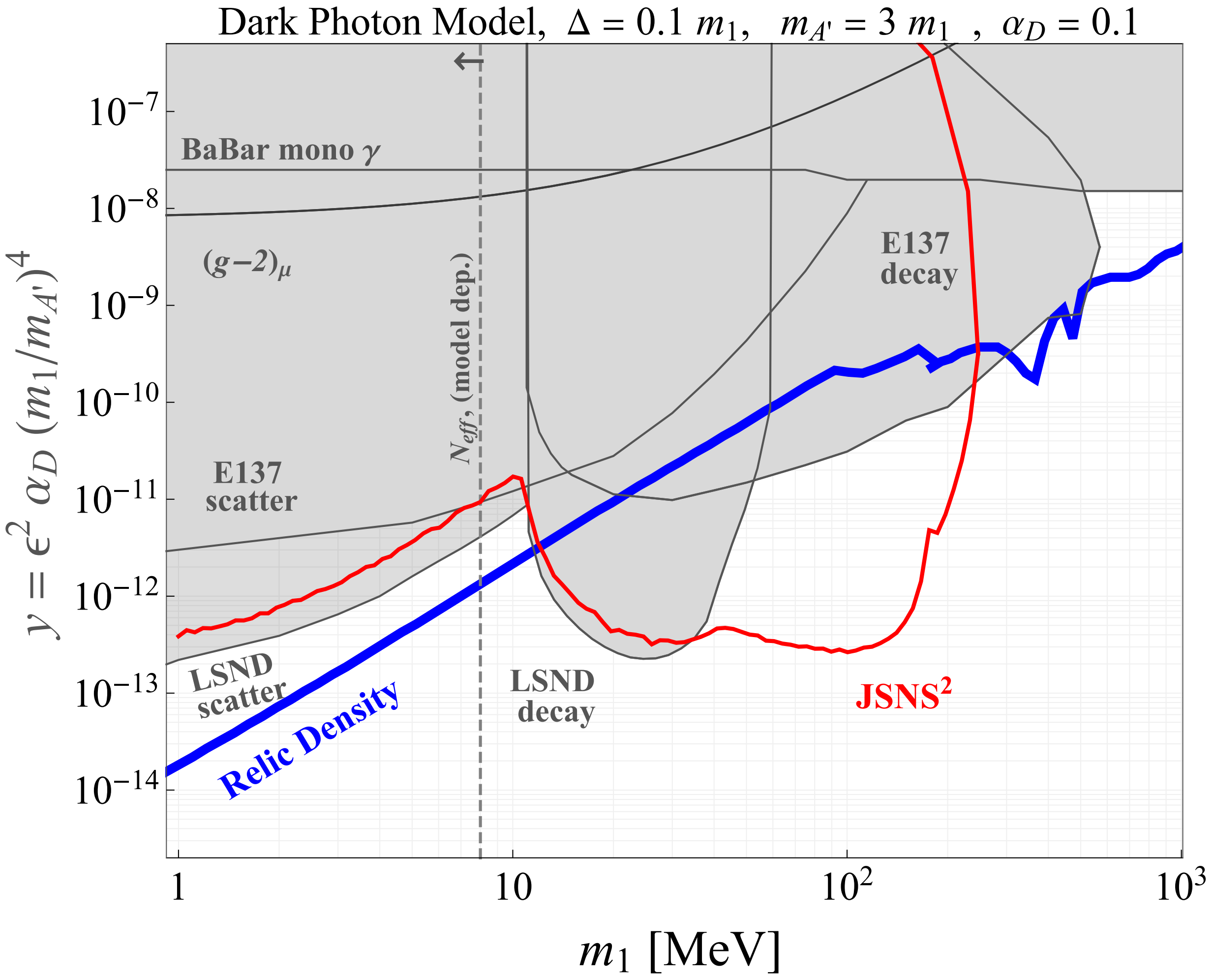
JSNS^2 Sensitivity



JSNS2 will be able to directly test large parts of the LSND parameter space in Phase 0!

Other Physics with JSNS^2

- Beyond the Standard Model physics searches
  - Sensitive to hidden sector models (e.g. vector portal or Higgs portal models)
  - Intermediate energy and high beam power give competitive sensitivity
- Neutrino cross section measurements
  - Low energy neutrino cross sections relevant for supernova modeling
  - Cross section measurements using monoenergetic neutrinos from KDAR



Sensitivity of JSNS2 to coannihilating vector portal dark matter with future detector improvements (shielding)

JJ, Y. Kahn, G. Krnjaic, M. Moschella, J. Spitz
arXiv:1806.05185, Phys. Rev. D 98, 075020

Other Physics with JSNS^2

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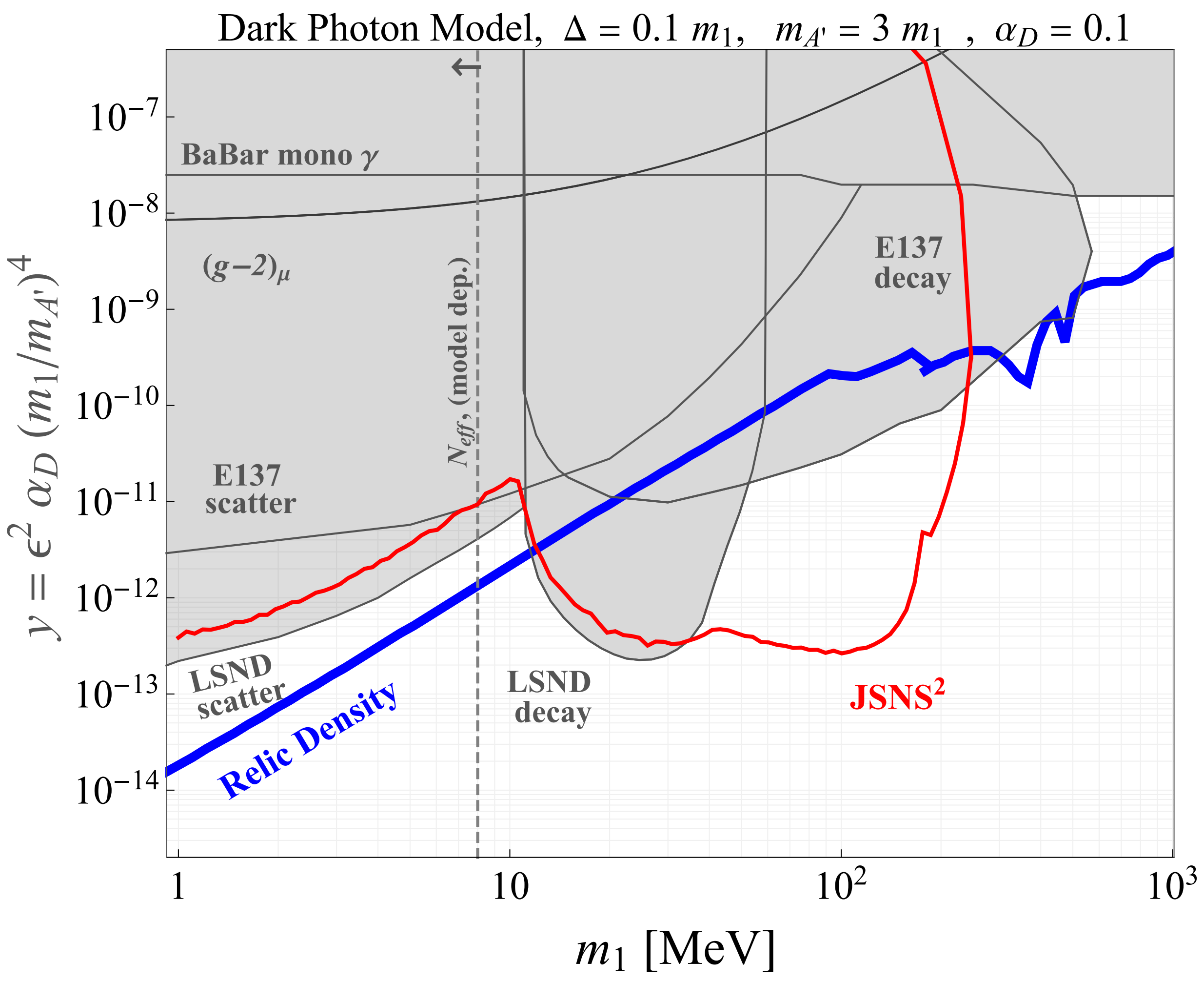

Dark Photon Model, $\Delta = 0.1\, m_1$, $m_{A'} = 3\, m_1$, $\alpha_D = 0.1$

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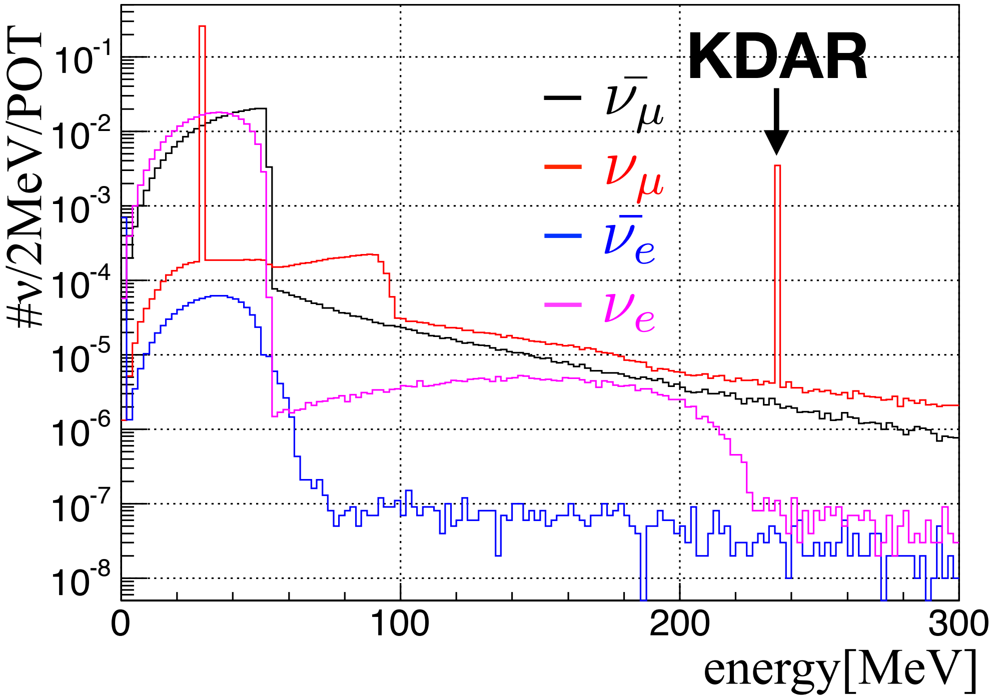
KDAR in JSNS^2

KDAR: $K^+ \rightarrow \mu^+ \nu_\mu \quad [BR = 63.6\%]$
$E_\nu = 236\ \mathrm{MeV}$ if K^+ is at rest



The MLF is the best place in the world to measure KDAR neutrinos

High statistics

3 years of data will yield between 30,000 and 60,000 KDAR interactions

Excellent energy resolution

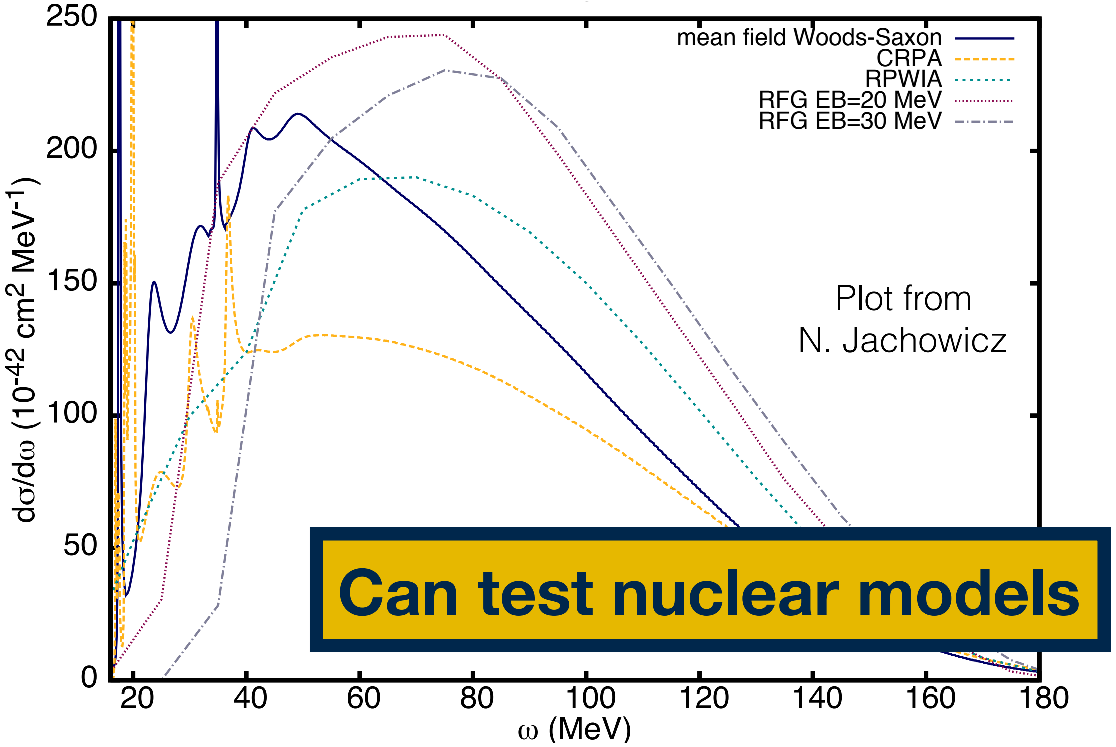
The energy resolution of JSNS^2 will be a few percent at these energies

Low backgrounds

The KDAR measurement in JSNS^2 is essentially background free

Neutron counting

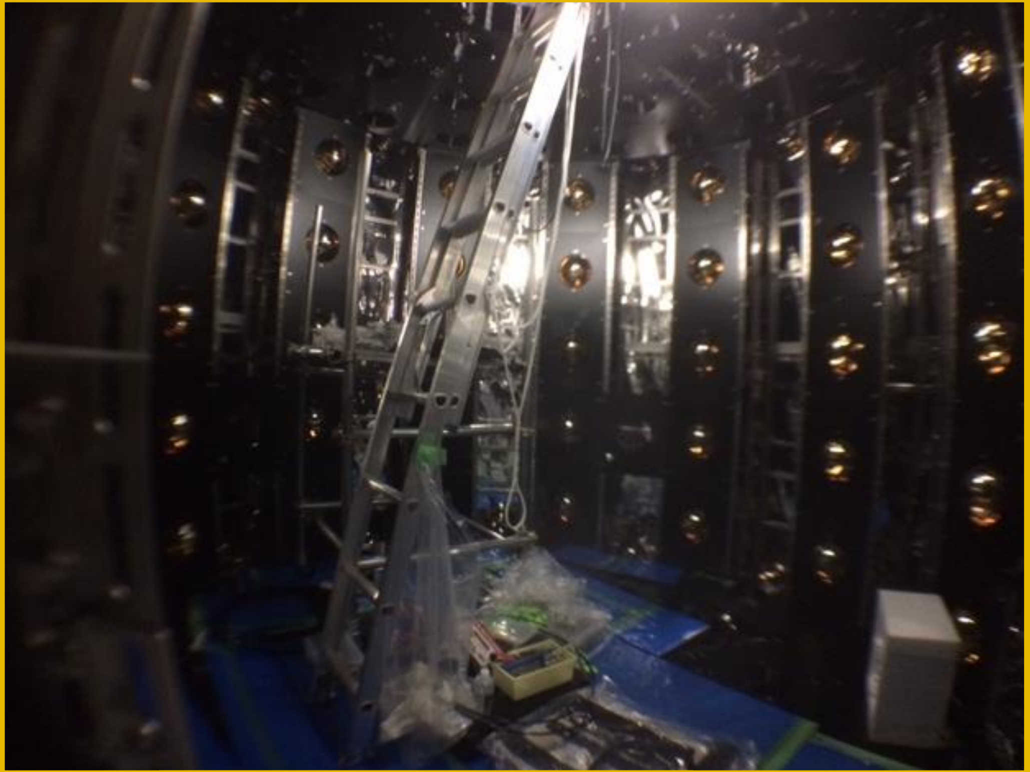
JSNS^2 can tag final state neutrons from the neutrino interactions



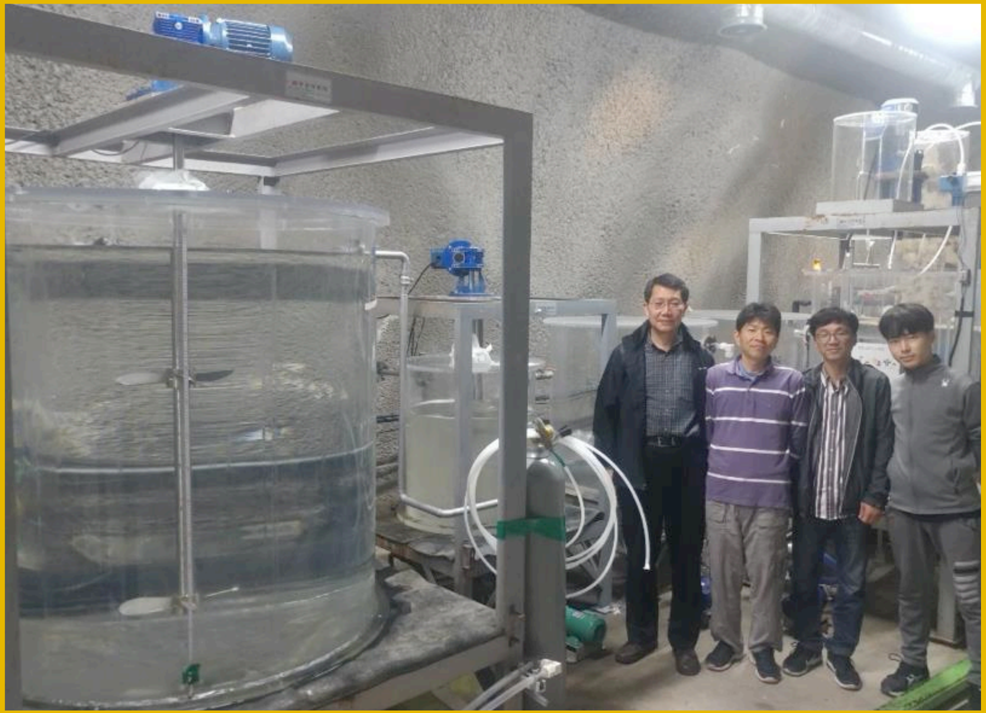
Plot from
N. Jachowicz

Can test nuclear models

JSNS^2 Construction



Detector construction is nearing completion. Expect to be finished early next year with data soon after!



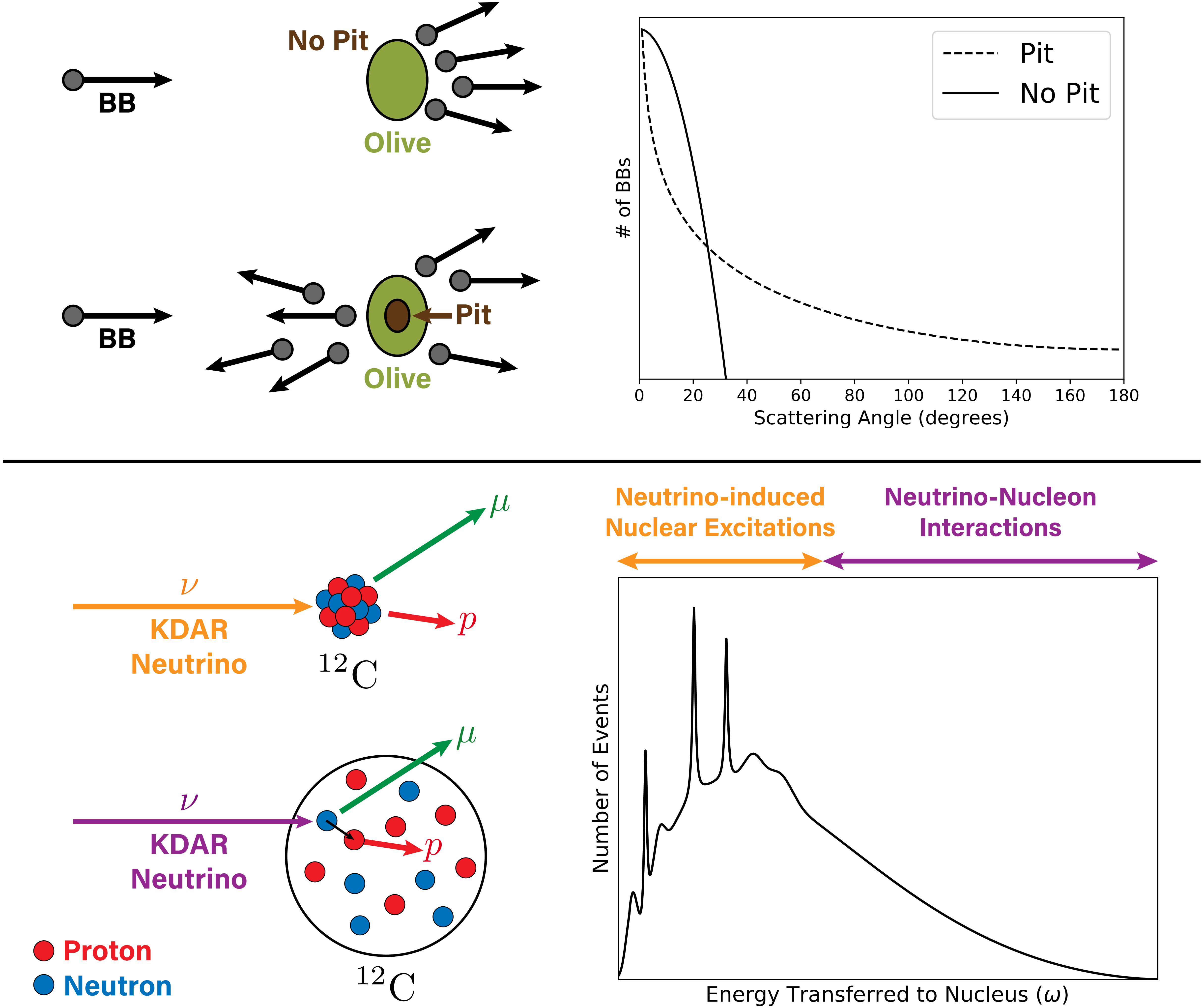
Conclusion

- The J-PARC MLF is a world-class pulsed neutron/neutrino source
  - Prompt neutrinos from pion and kaon decay can be separated from delayed neutrinos from muon decay
  - The beam power continues to increase with target upgrades; working towards the design power of 1 MW
- JSNS^2 will use the MLF neutrino source to test the LSND anomaly directly
  - JSNS^2 is sensitive to large portions of the LSND parameter space in Phase 0; additional detectors can improve the sensitivity
  - In addition, JSNS^2 will pursue various cross section measurements and new physics searches

Backup

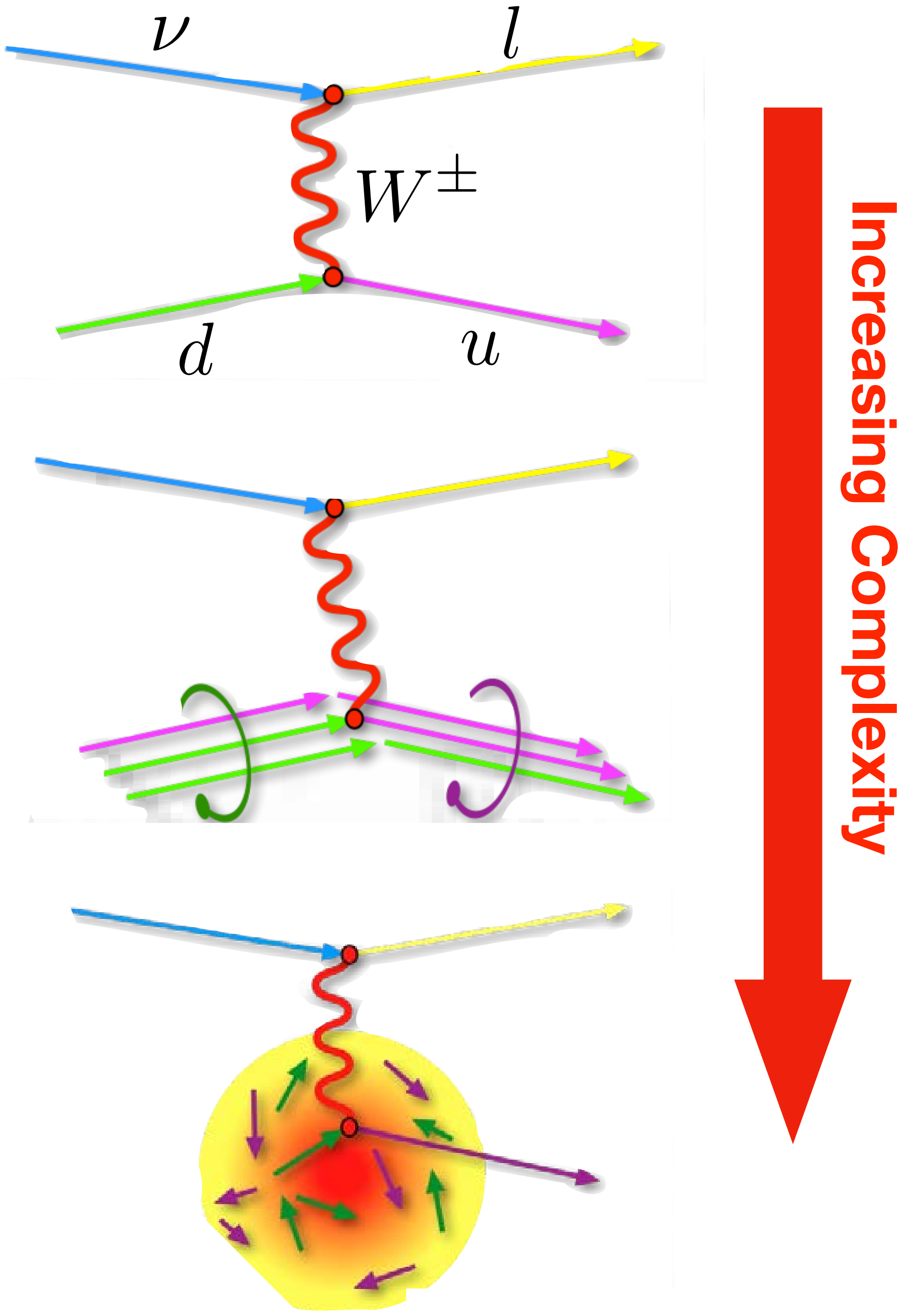
JSNS^2 vs. LSND

	LSND	JSNS^2	Advantage of JSNS^2
Detector Mass	167 Tons	17 Tons	
Baseline	30 m	24 m	
Beam Kinetic Energy	0.8 GeV	3.0 GeV	Allows for KDAR measurements.
Beam Power	0.056 MW	1.0 MW	Much more intense beam
Beam Pulse	600 μs, 120 Hz	80 ns (x2), 25 Hz	300 times less steady state background for IBD.
Capture Nucleus	H (2.2 MeV)	Gd (~8 MeV)	Shorter capture time, higher signal to noise ratio.


BB
No Pit
Olive
BB
Pit
Olive
Pit
No Pit
# of BBs
0
20
40
60
80
100
120
140
160
180
Scattering Angle (degrees)
ν
KDAR
Neutrino
μ
p
^{12}C
ν
KDAR
Neutrino
μ
p
^{12}C
Proton
Neutron
Neutrino-induced
Nuclear Excitations
Neutrino-Nucleon
Interactions
Number of Events
Energy Transferred to Nucleus (ω)

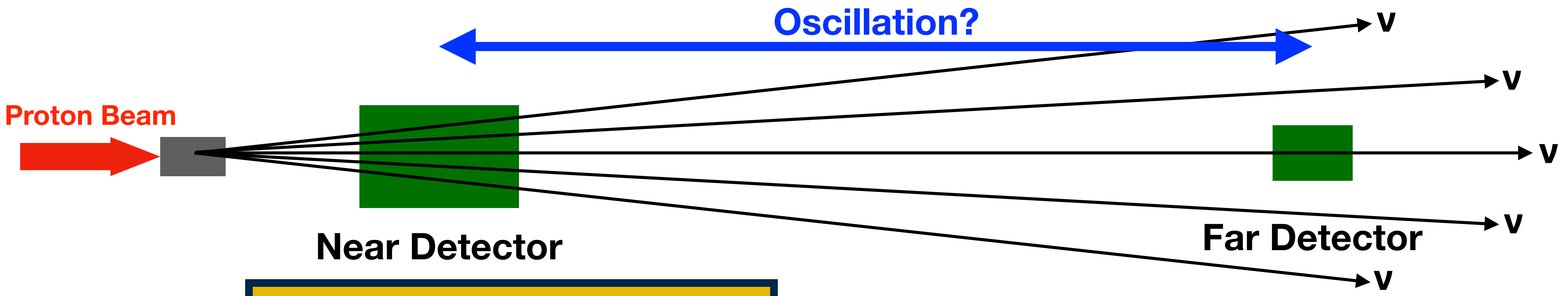
Probing the Nucleus

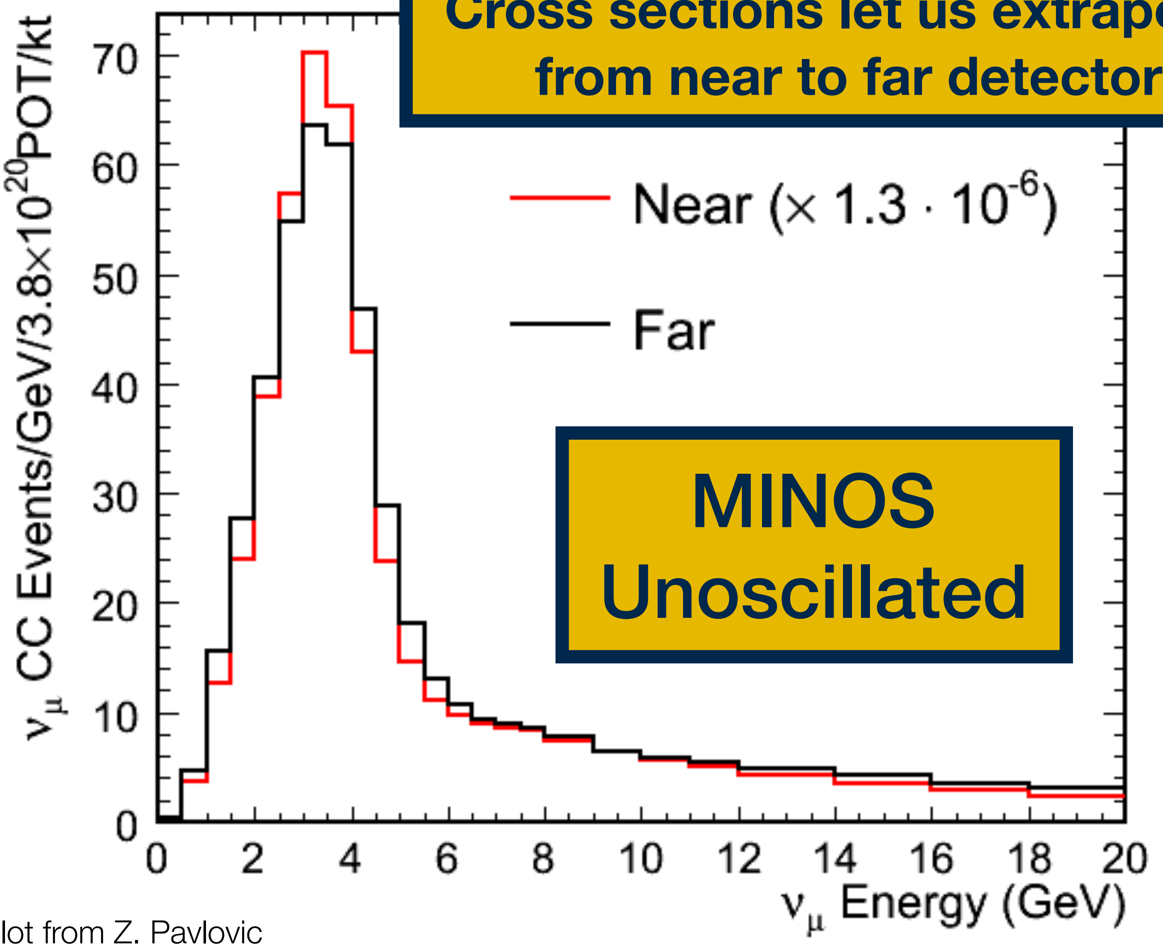
- Calculations are difficult:
  - Fermi motion
  - Correlated nucleon pairs
  - Final state interactions
- Measurements are difficult:
  - Energy resolution
  - Event classification issues
  - Cherenkov threshold/invisible particles (neutrons)



Adapted from K. McFarland

Cross Sections

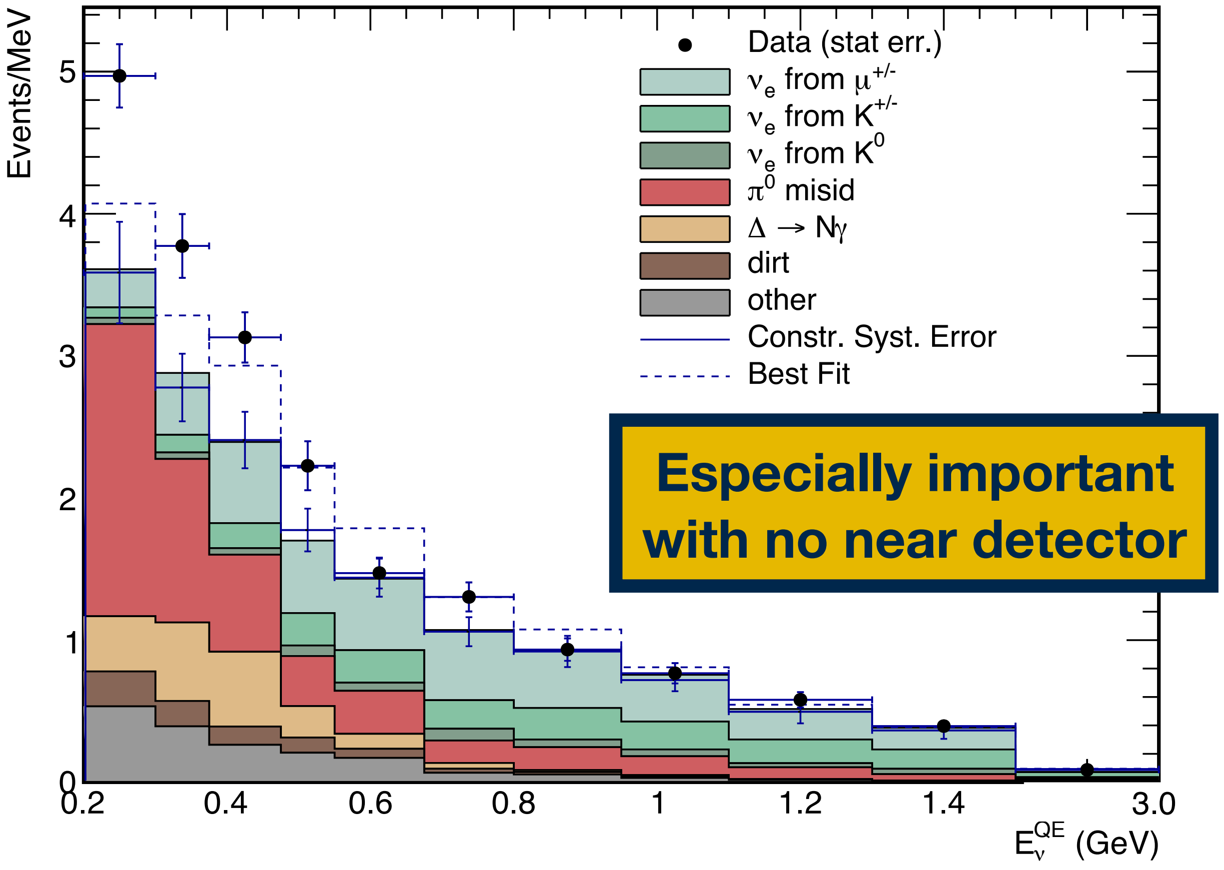




Cross sections let us extrapolate from near to far detectors

MINOS Unoscillated

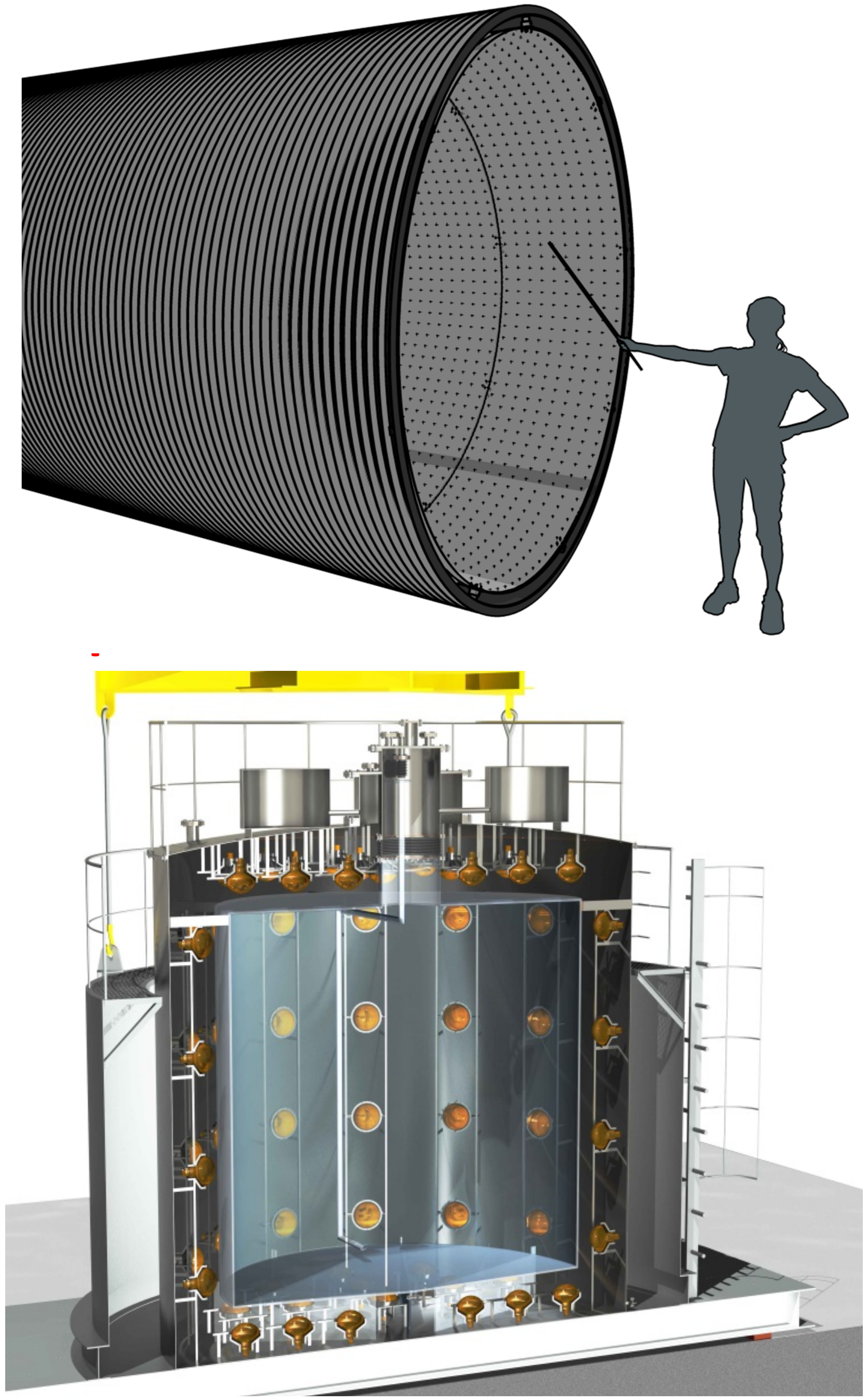
Plot from Z. Pavlovic



Especially important with no near detector

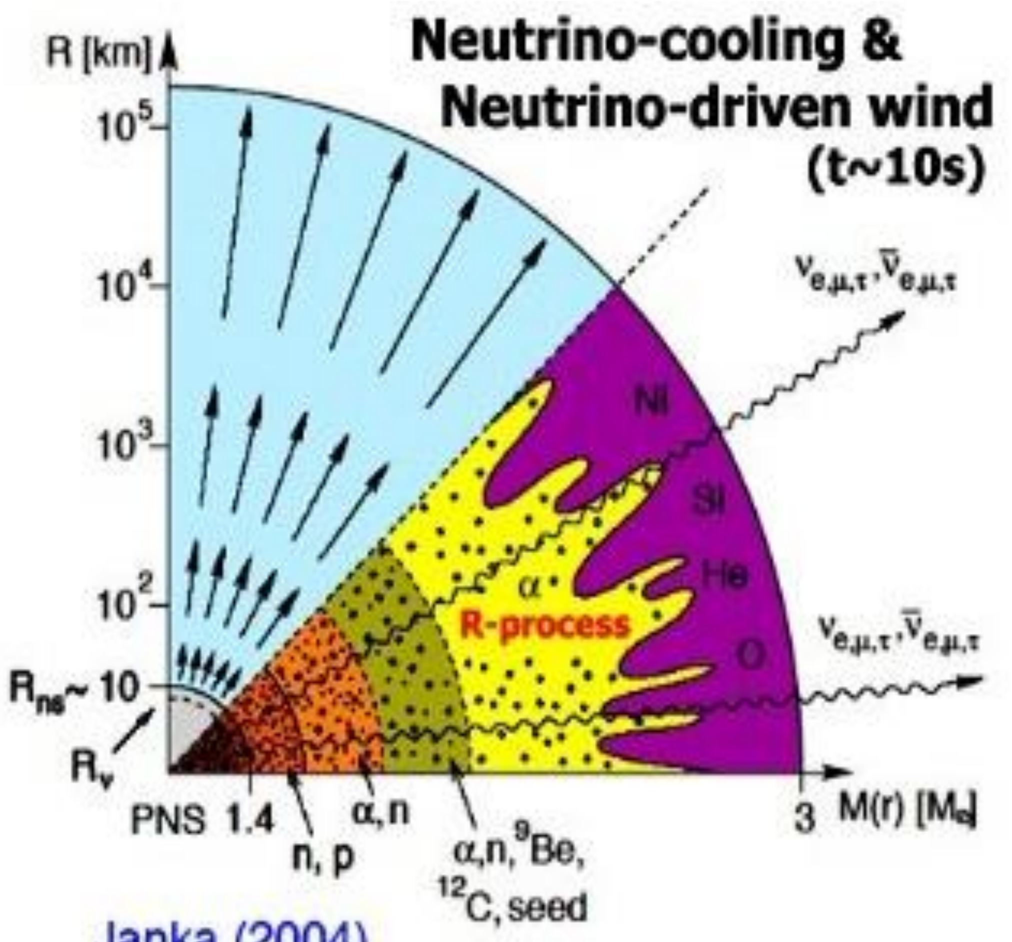
Other KDAR Physics

- KDAR neutrinos open up many other physics measurements:
    - Oscillation search for sterile neutrinos at short baseline
    - Measure Δs for nucleon spin
    - Look for dark matter annihilation in the sun
    - Measure the CC neutron yield



J. Spitz, Phys. Rev. D 85 093020 (2012).
S. Axani, et. al., Phys. Rev. D 92 092010 (2015).
C. Rott, et. al., J. of Cosmol. and Astropart. Phys. 11 039 (2015).
C. Rott, et. al., arXiv:1710.03822 [hep-ph].

Neutrino-nucleus interaction in Type-II SN



Janka (2004)

ν-A interactions are important in

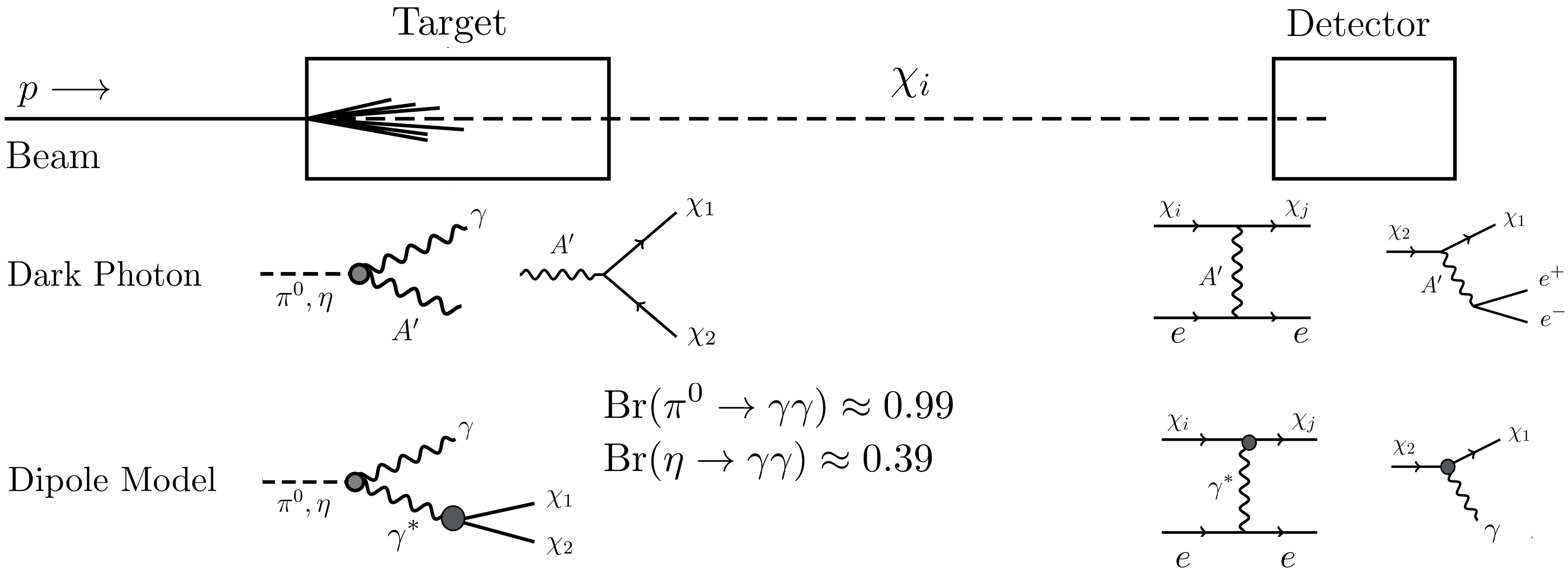
- core-cooling by ν-emission
- ν-heating on shock wave
- ν-process of nucleosynthesis
- efficiency of neutrino detectors

Reaction rates are to be known with accuracy better than ~10%!

Experiment	$\sigma(^{12}C(\nu_e,e^-)^{12}N_{g.s.})$ (10^{-42} cm^2)
KARMEN (PLB332, 251 (1994))	9.1±0.5±0.8 (10.4%)
LSND (PRC64, 065501 (2001))	8.9±0.3±0.9 (10.7%)
JSNS^2 (arXiv:1601.01046)	(~3%(stat.) expected in 5yrs)

Production and Detection of Dark Matter

High Luminosity Proton Beam (100's of MeV to 10's of GeV)



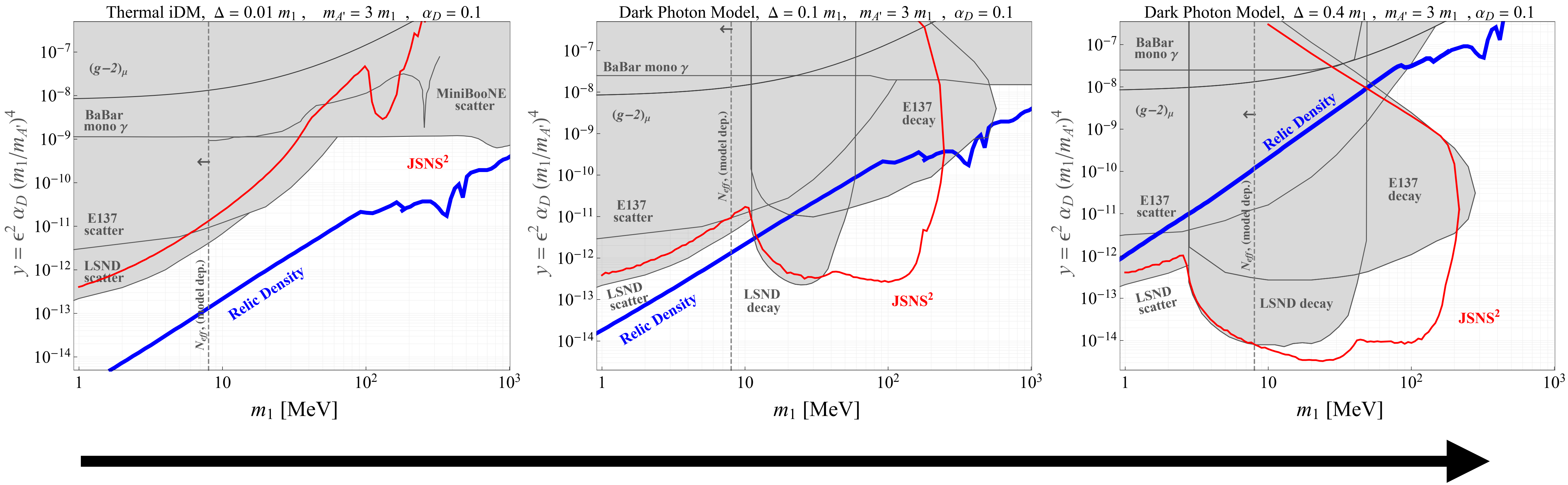
$$\mathrm{Br}(\pi^0 \to \gamma\gamma) \approx 0.99$$
$$\mathrm{Br}(\eta \to \gamma\gamma) \approx 0.39$$

Large boosts mean there are no kinematic constraints on the scattering like in traditional direct dark matter searches.

Dark Photon Constraints

$$\sigma v \propto \left(\epsilon^2 \alpha_D \frac{m_1^4}{m_{A'}^4}\right)\frac{1}{m_1^2} \equiv \frac{y}{m_1^2}$$

Cast constraints/sensitivity in terms of y and m₁ which govern the relic density.



Increasing Δ

Dipole Model Constraints

- We present newly computed constraints on the preferred parameter space for this model
- Existing LSND data constrains the dipole model as an explanation for the 3.5 keV GCE