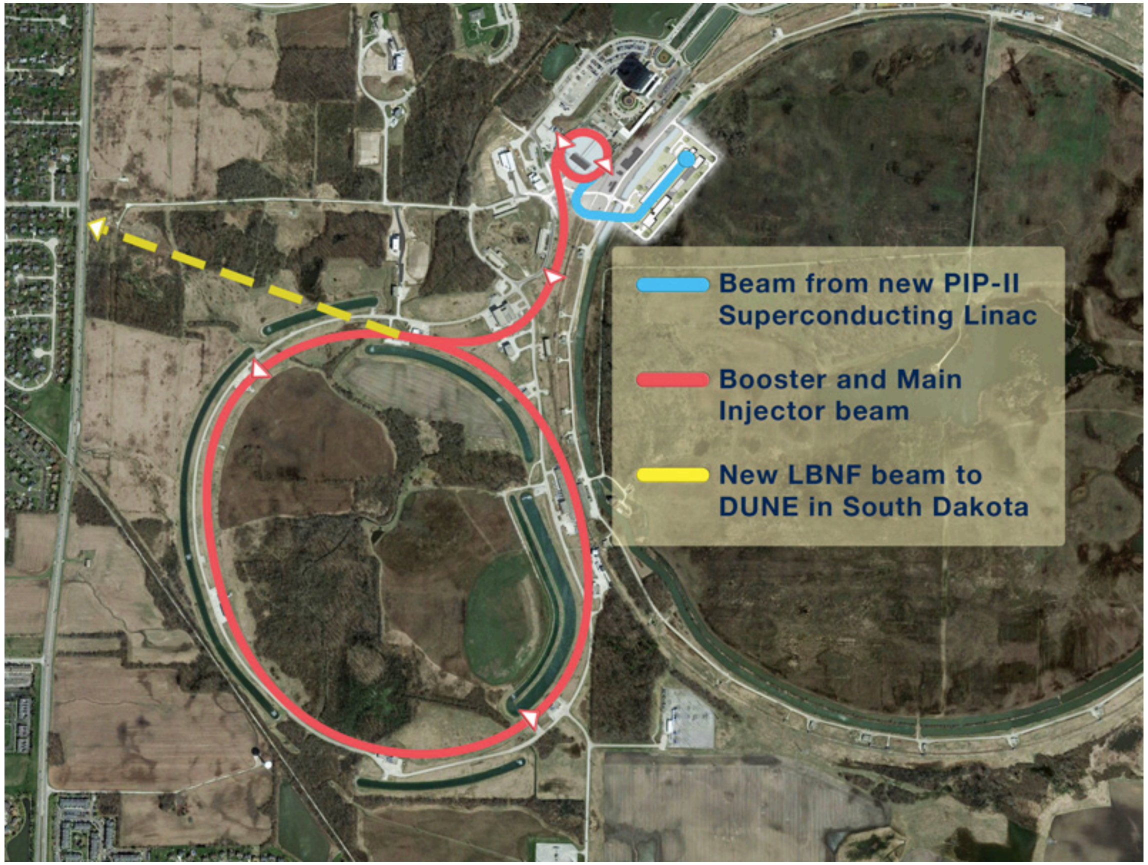
Stopped Pions @ FNAL

M. Toups

9/4/19

PIP-II will support a world-leading neutrino program @ FNAL

- Key high-level metrics for SC LINAC:
  - 2 mA (few μs average) @ 800 MeV
  - Injects 20 μA (average) into the Booster (1.1% duty factor)
    - Adequate for 1.2 MW @ 120 GeV (LBNF) + 80 kW @ 8 GeV
  - 1.6 MW @ 800 MeV with 20-100% duty factor (10 mA peak) additional beam available when upgraded to CW



Will be among the highest-power ~GeV proton beams in the world

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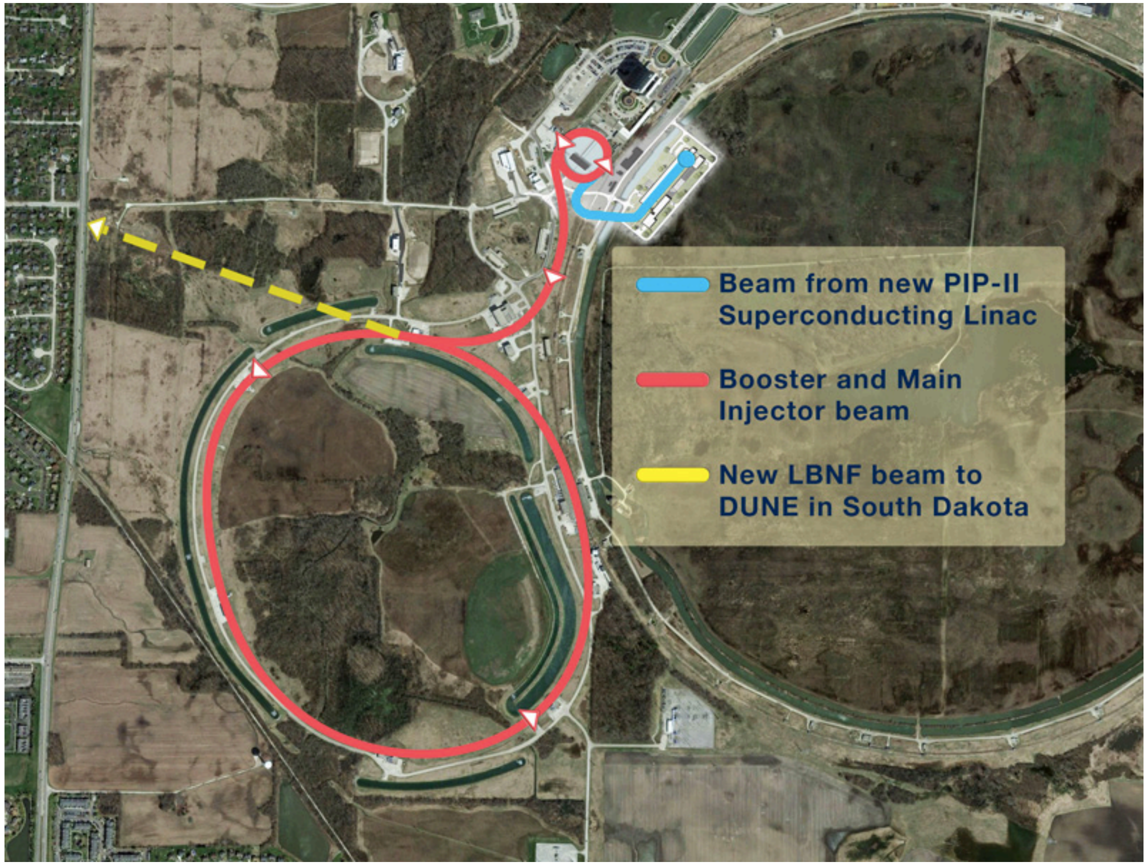


Will be among the highest-power ~GeV proton beams in the world

→ **What else can we do with all this beam?**

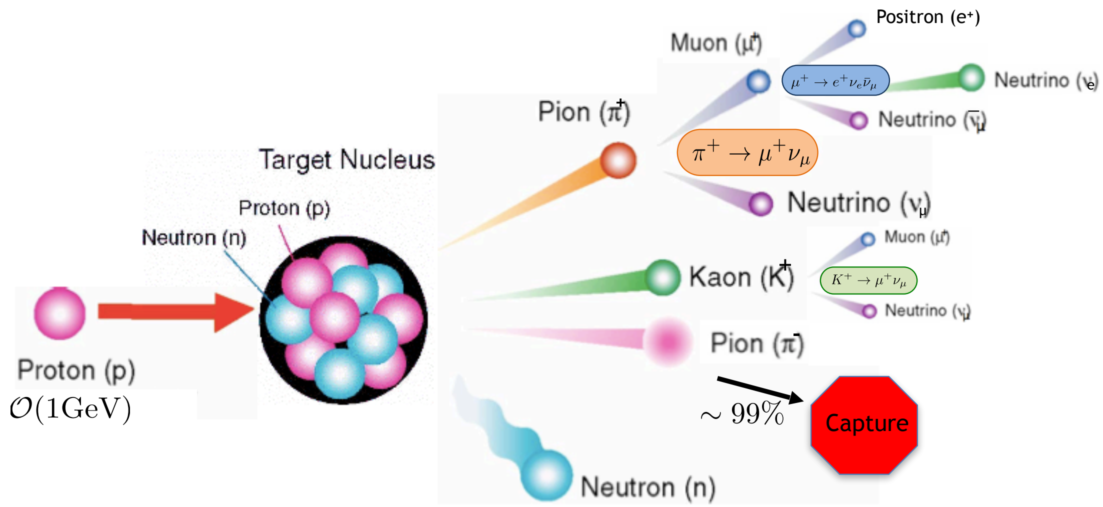
PIP-II stopped π source driven by 1.6 MW 800 MeV proton beam

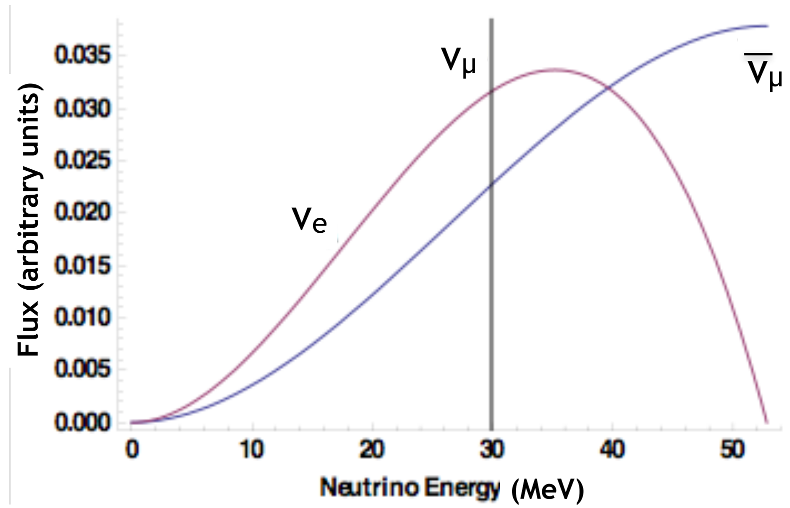
Extensive particle physics program:

- Sterile neutrino searches (ν_e appearance)
- Neutrino non-standard interactions, neutrino magnetic moment
- Standard Model tests (e.g. weak mixing angle)
- Charged current cross section measurements

Key source features for this physics:

- High flux (flux increases as $1/L^2$)
- Well understood ν energy spectrum, flavor content





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- Sterile neutrino searches (ν_e appearance)
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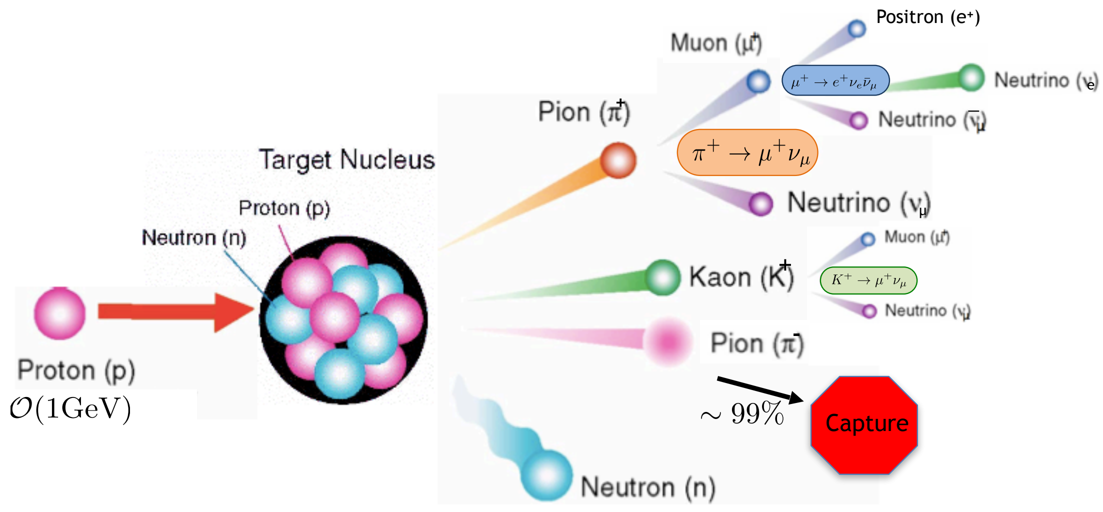
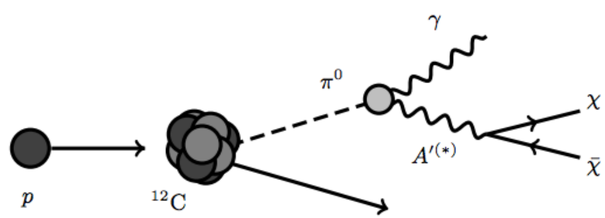
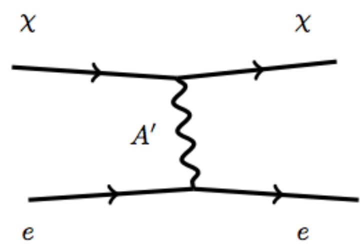
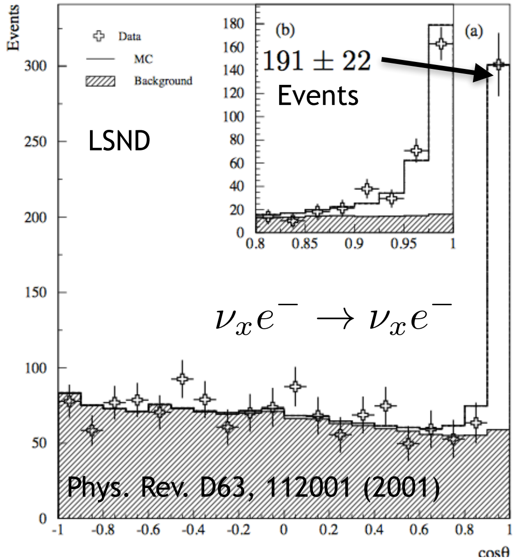
- Charged current cross section measurements
- Light Dark Matter Searches
- Coherent elastic neutrino-nucleus scattering

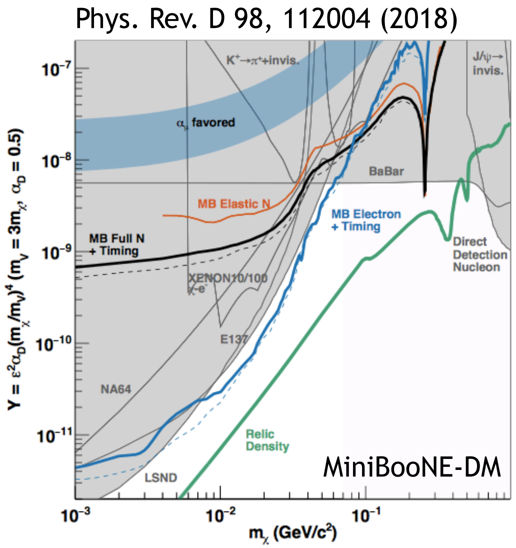


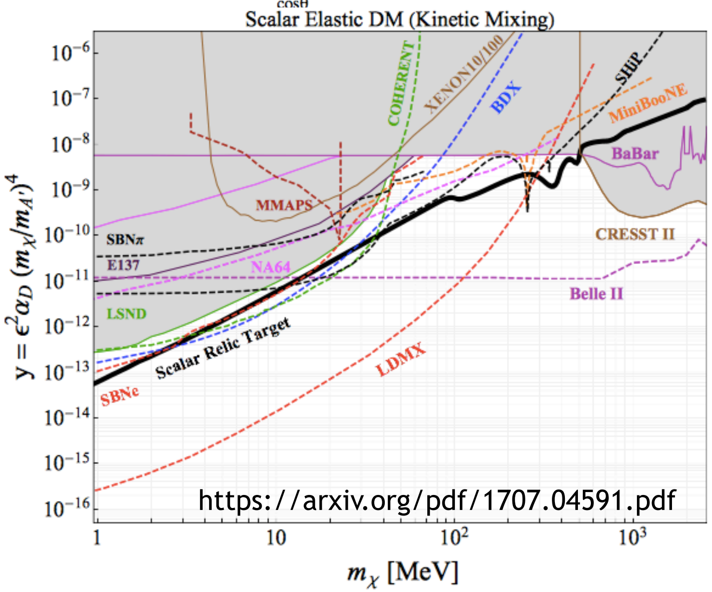




Stopped π experiments have best limits on light dark matter at low masses





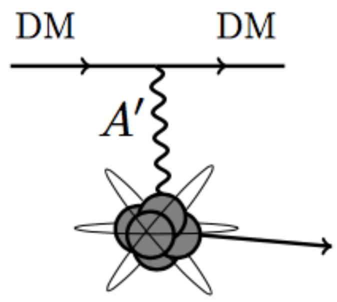


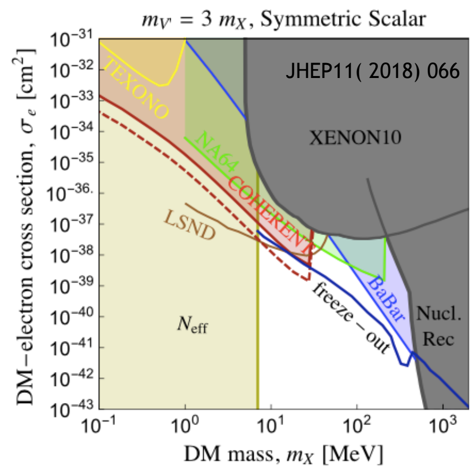
Can a PIP-II beam dump experiment with excellent cosmic rejection and angular resolution improve on LSND limits?

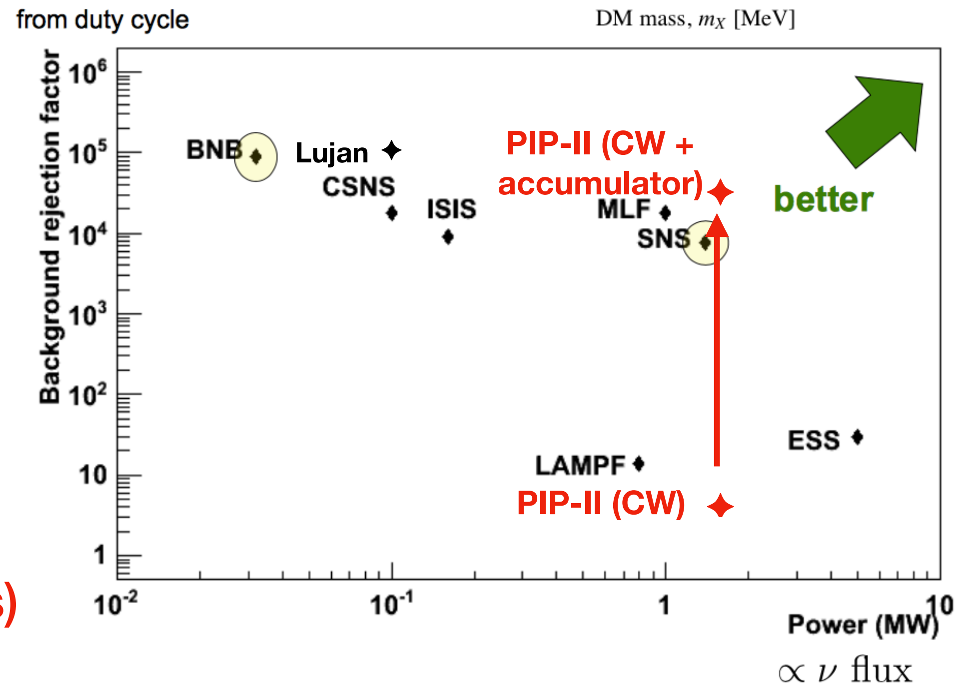
- PIP-II will have twice the power, but can only accommodate 20% duty factor vs. 7.2% at LAMPF/LSND
- Beam dump detector at PIP-II can be at ~arbitrary location and have large mass vs. LSND (100 tons @ 30 m downstream)
- Since y scales as the square root of the exposure, need at least a factor of 100 (3x more POT, 30x more mass/acceptance?) for same signal sensitivity at 10x lower y
- Improved sensitivity to light dark matter models via neutrino electron scattering also implies improved sensitivity to NSIs, neutrino magnetic moment, weak mixing angle, etc.

Accumulator Ring Extension of PIP-II Physics Program @ FNAL

- Coherent elastic neutrino-nucleus scattering (CEvNS) provides a rich particle physics program all by itself
  - Light dark matter searches
  - Sterile neutrino searches (ν_x disappearance)
  - Neutrino non-standard interaction (NSI) searches
  - Precision electroweak measurements
  - Neutrino magnetic moment searches
- Low threshold neutrino scattering experiments to detect CEvNS extremely difficult without small duty factor to reject backgrounds
- **Program fully realized only if protons are compressed into sub-μs pulses with duty factors $\in$ [10^{-5} - 10^{-4}]**



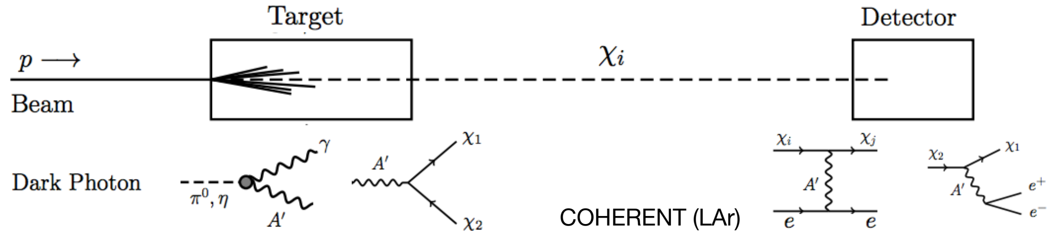




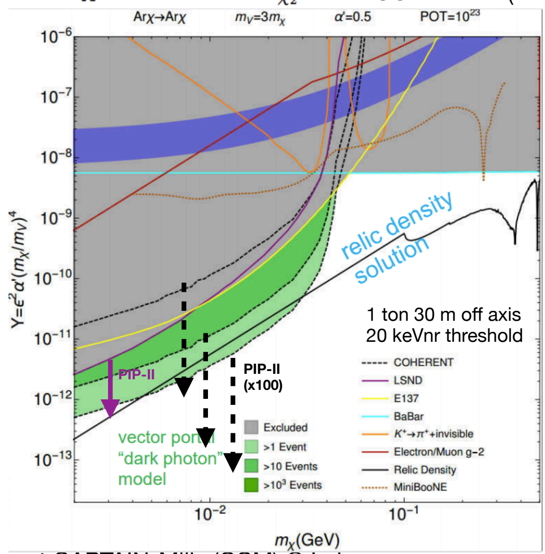
Can optimize source for particle physics (not neutrons)

Example: 100-ton LAr Detector @ 20-40 m

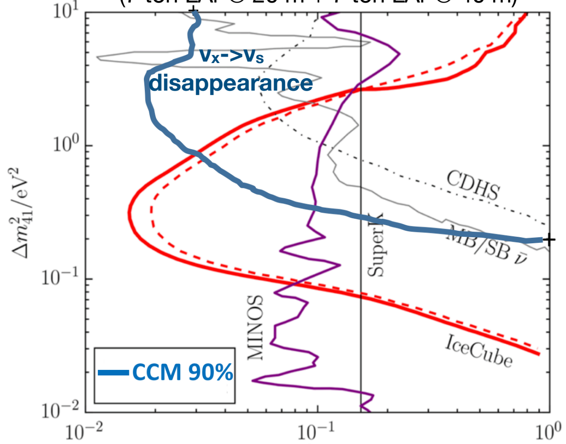
- **Sensitivity ($N_X \sim \alpha_D \epsilon^4/m_{A'}^4$) to benchmark light "vector portal" directly annihilating thermal dark matter model**
    - Assuming a threshold of 20 keVnr, expect 1000 nuclear recoil events in the 3-30 MeV range at relic density targets
    - Assuming LSND-like energy and angular resolutions for electron energies $E_e \in$ [18-50 MeV], electron scattering limits may probe relic density targets (x10 signal sensitivity)
        - Simultaneously allows sensitivity to NSIs, weak mixing angle, neutrino magnetic moments
    - Beam dump (unlike missing mass/momentum) experiments are sensitive to α_D and can also probe dark sector structure
- **O(1M) CEvNS events/year**
    - Allows smoking-gun neutral current sterile neutrino search ($\nu_x \to \nu_s$ disappearance)
    - Also measure NSIs, neutrino magnetic moments, etc.

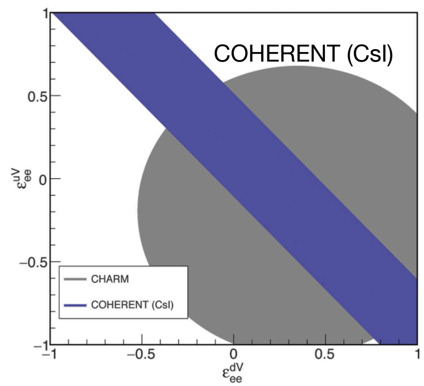


COHERENT (LAr)



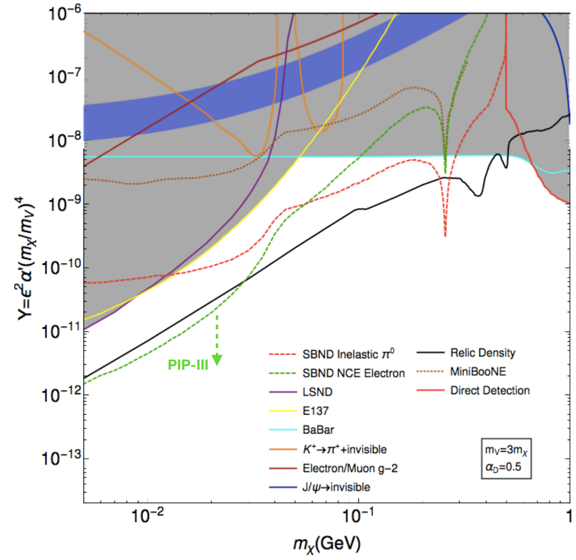
Coherent CAPTAIN-Mills (CCM) @ Lujan
(7 ton LAr @ 20 m + 7 ton LAr @ 40 m)

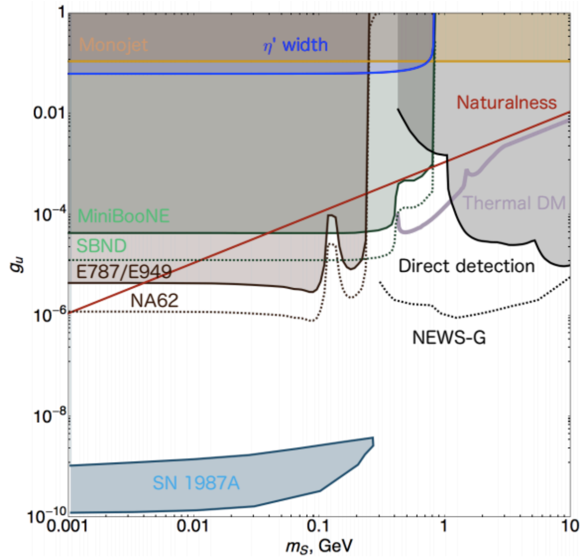




Light dark matter search driven by O(10) GeV PIP-III proton RCS

- Current BNB light dark matter search ideas propose adding a beam dump to reduce ν backgrounds seen in MiniBooNE's dark matter run
- PIP-II era Booster will increase 8 GeV beam power by factor of ~2, but PIP-III Rapid Cycling Synchrotron (RCS) replacement will be able to simultaneously support 2.3 MW @ 120 GeV for LBNF/DUNE and 0.4-1 MW @ 11 GeV for BNB
- Extends signal sensitivity to 5x lower values of y for vector portal dark matter models
- Also, improved sensitivity to e.g. hadrophilic dark sector





Concluding Remarks

- What set of facilities is Fermilab going to build after completing the program laid out in the 2014 P5 report?
- We need to think bigger than parasitic searches as we prepare for the next Snowmass in 2021
- PIP-II is upgradable to a 1.6 MW, 800 MeV CW proton beam, but needs a physics program
- PIP-II LINAC could support a beam dump experiment with a broad physics program including searches for light dark matter, NSIs, neutrino magnetic moments, sterile neutrinos, etc.
- In order to extend this program even further to include CEvNS, need to build a proton storage ring at FNAL to reduce beam duty cycle. Should FNAL push for this at the next Snowmass?

End

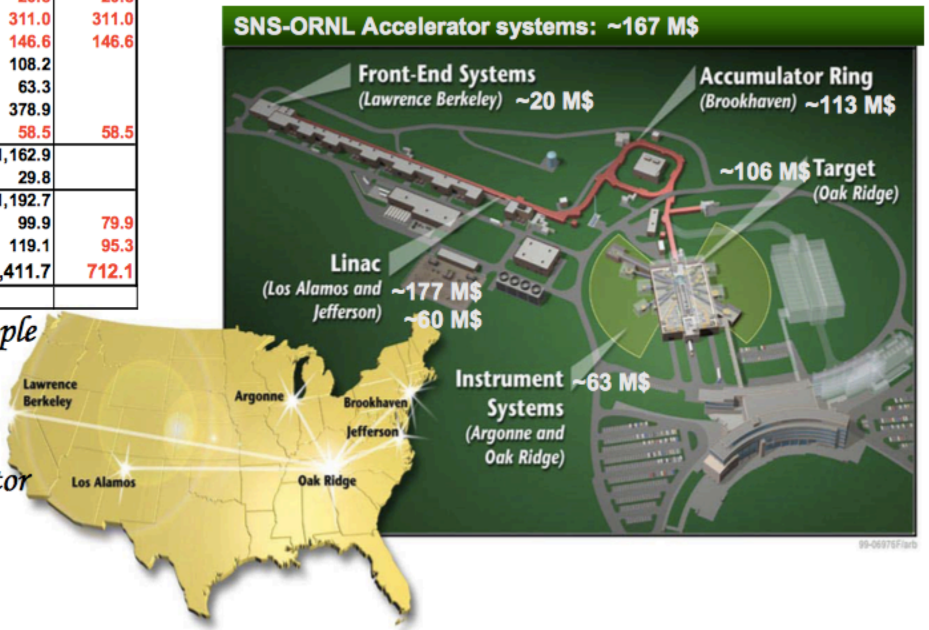
Estimated cost of PIP-II: ~$600 M in 2020 dollars

SNS Cost Breakdown

The Spallation Neutron Source Partnership

Description	Accelerator	
Project Support	75.6	
Front End Systems	20.8	20.8
Linac Systems	311.0	311.0
Ring & Transfer System	146.6	146.6
Target Systems	108.2	
Instrument Systems	63.3	
Conventional Facilities	378.9	
Integrated Control Syst	58.5	58.5
BAC	1,162.9	
Contingency	29.8	
TEC	1,192.7	
R&D	99.9	79.9
Pre-Operations	119.1	95.3
TPC	1,411.7	712.1

At peak: ~500 People worked on the construction of the SNS accelerator



The partners developed and built – SNS/ORNL integrated, installed + operated

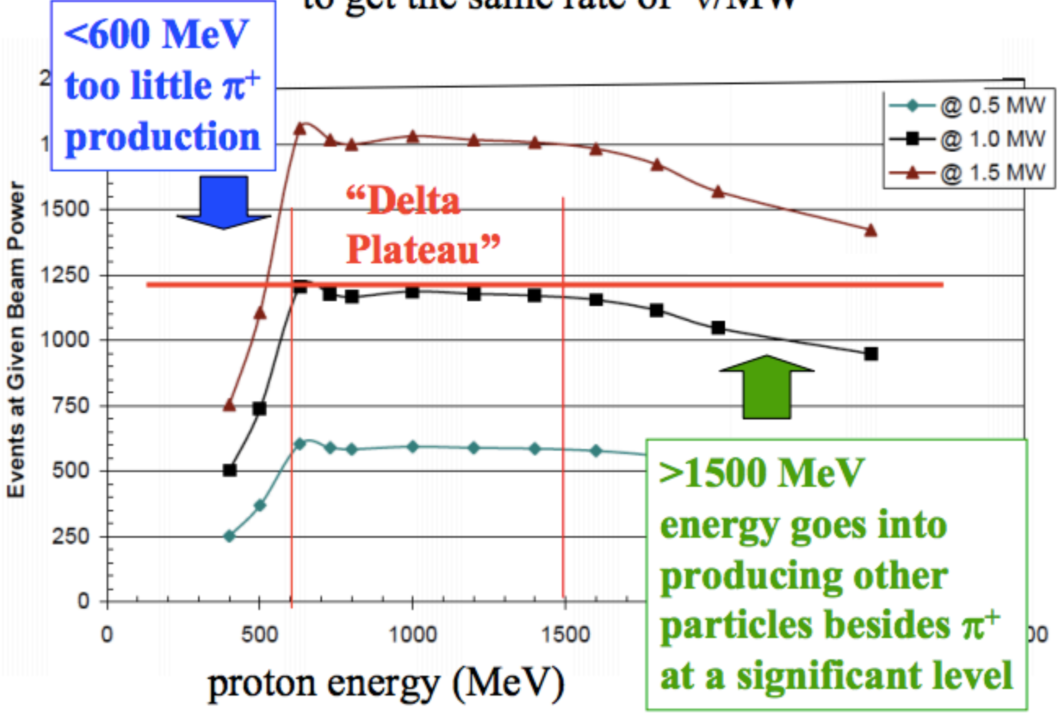
Cost Development between 2001 and 2006

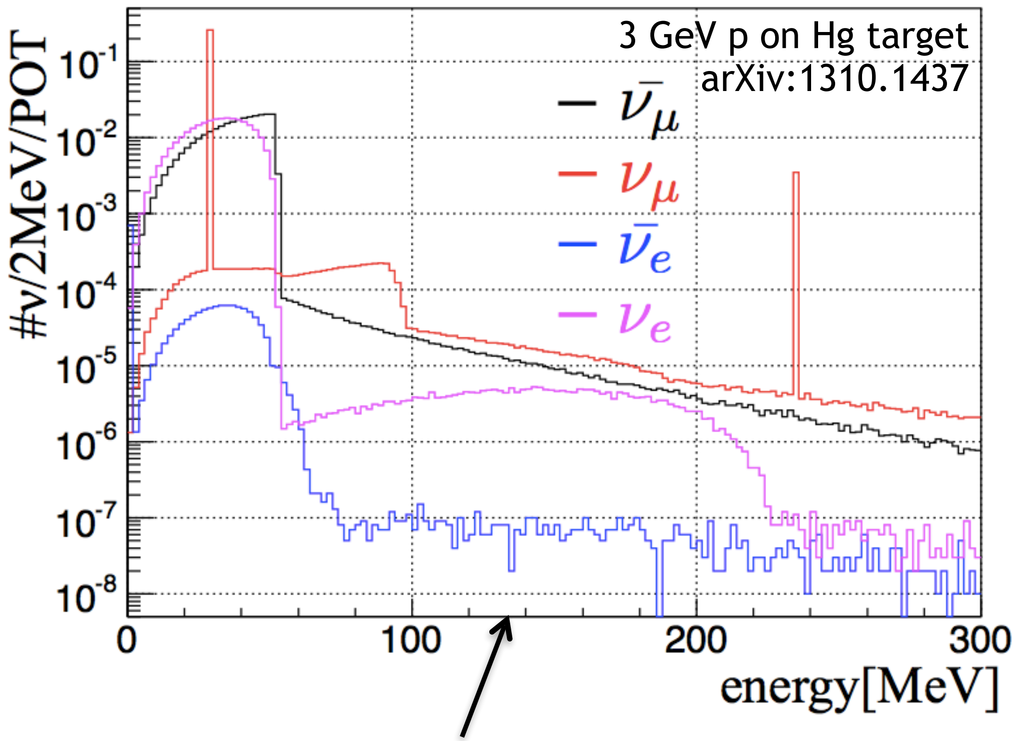
	Nov 2001 [$M]	May 2006 [$M]	Contingency
1.01 Research & Development	103.8	99.9	-3.8%
1.10 Operations	115.2	119.1	3.4%
Total OPC (Burdened, Escalated Dollars)	**219.0**	**219.0**	0.0%
1.02 Project Support	72.3	72.1	-0.3%
1.03 Front End Systems	19.3	20.8	7.9%
1.04 Linac Systems	272.4	311.0	14.2%
1.05 Ring & Transfer System	146.2	146.6	0.3%
1.06 Target Systems	95.3	114.9	20.5%
1.07 Instrument Systems	62.3	63.9	2.6%
1.08 Conventional Facilities	310.7	398.5	28.3%
1.09 Integrated Control Systems	58.6	58.5	-0.1%
Total Line Item (Burdened, Escalated Dollars)	**1037.0**	**1186.3**	14.4%

Norbert Holtkam, "The Spallation Neutron Source – Status and Applications"

Neutrino Production at Stopped π sources

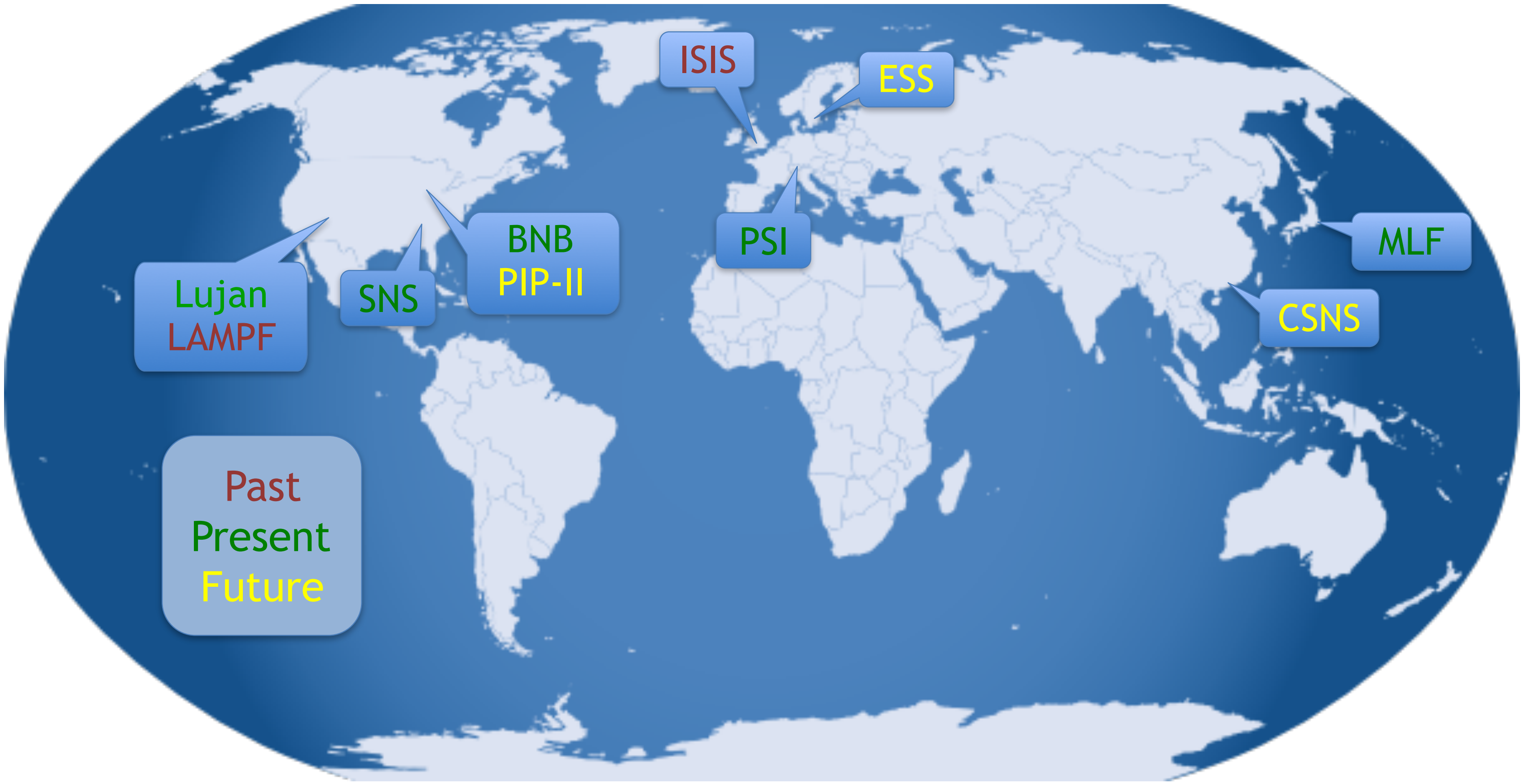
There is a "Delta plateau" where you can trade energy for current to get the same rate of ν/MW





For incident proton energies of $\gtrsim 3$ GeV, kaon production also becomes important

Locations of Decay-at-rest Neutrino “Beams”



Adapted from K. Scholberg

Stopped π Beam Figures of Merit

Facility	Proton Energy (GeV)	Power (MW)	Bunch Structure	Rate
LAMPF	0.8	0.8	600 μs	120 Hz
Lujan	0.8	0.08	290 ns	30 Hz
ISIS	0.8	0.16	2 x 100 ns	50 Hz
SNS	1.0	1.4	700 ns	60 Hz
MLF	3	1	2 x 100 ns (540 ns apart)	25 Hz
CSNS	1.6	0.1	<500 ns	25 Hz
ESS	2.5	5	2.86 ms (~1.3μs with PSR)	14 Hz
PSI	0.6	1.4	CW	CW
BNB	8	0.032	1.6 μs	5 Hz
PIP-II LINAC	0.8	1.6	CW	CW

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Higher power → Larger flux

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Adapted from K. Scholberg

- Small duty factors ⟶ reject cosmics
  - Also addressed by going underground or beam-off subtraction

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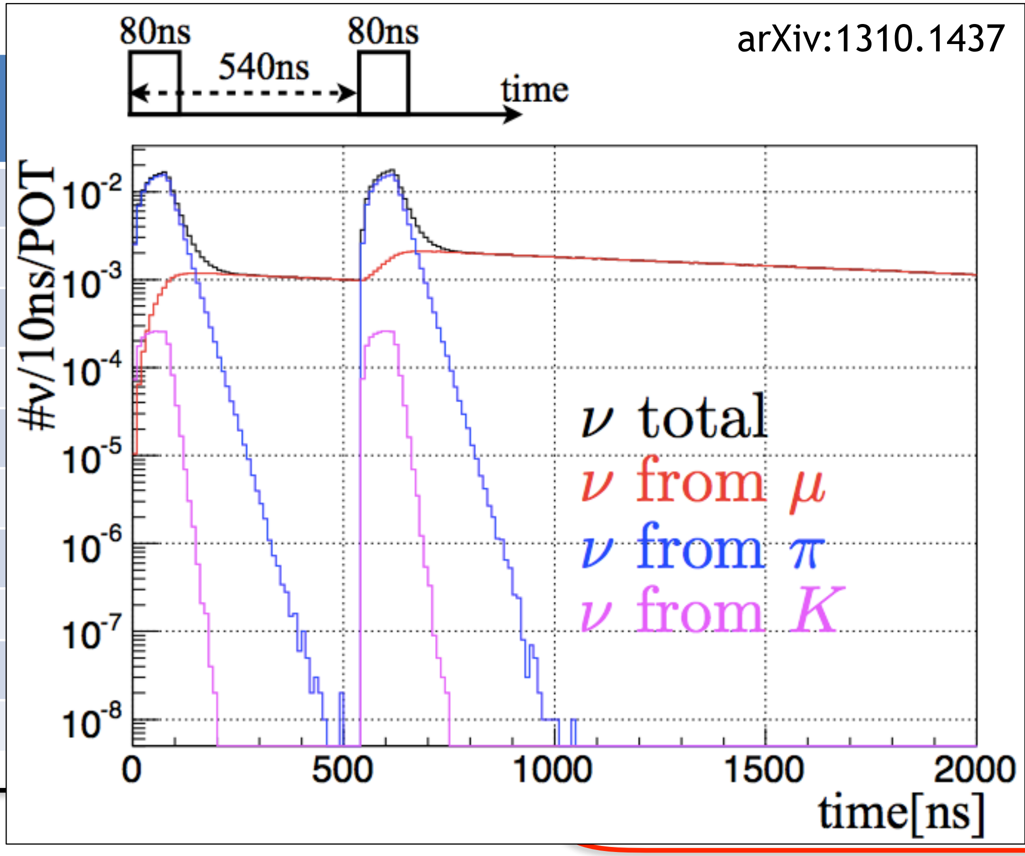

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$\lesssim 2.2\ \mu s$ bunch structure ⟶ π/μ DAR ν separation