Neutrino Beams and Instrumentation

- Beams
- Instrumentation

Please see AF2, NF09, and NF10 reports!

Emphasis will be on future, pre-TDR instruments

Josh Klein , U. Penn
Snowmass
July 20, 2022

Neutrino Beams

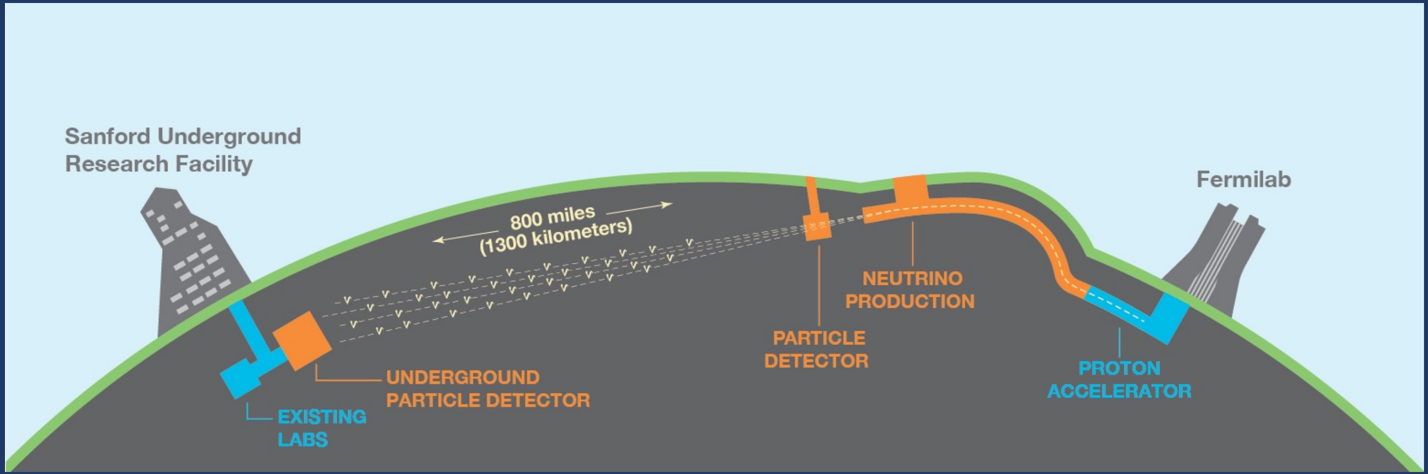
Neutrino Beams

BEAMS of *NEUTRINOS*!

Neutrino Beams

BEAMS of *NEUTRINOS*!

- You can't focus them
- You can't even collimate them
- And with σ ~ 0.1-10 fb, you need huge number of them
- To get even to ~1 event/day 1000 km away or more



Free Neutrino Beams

- Solar neutrinos
- Atmospheric neutrinos
- Extragalactic neutrinos
- Cosmic background neutrinos
- Diffuse supernova background neutrino
- Supernova burst neutrinos But working hard to turn this one on

Funding agencies not turning these off in next decade

Additional Advantages:

- In some cases (e.g., solar) flavor content well known
- Sources are intrinsically interesting

Disadvantages:

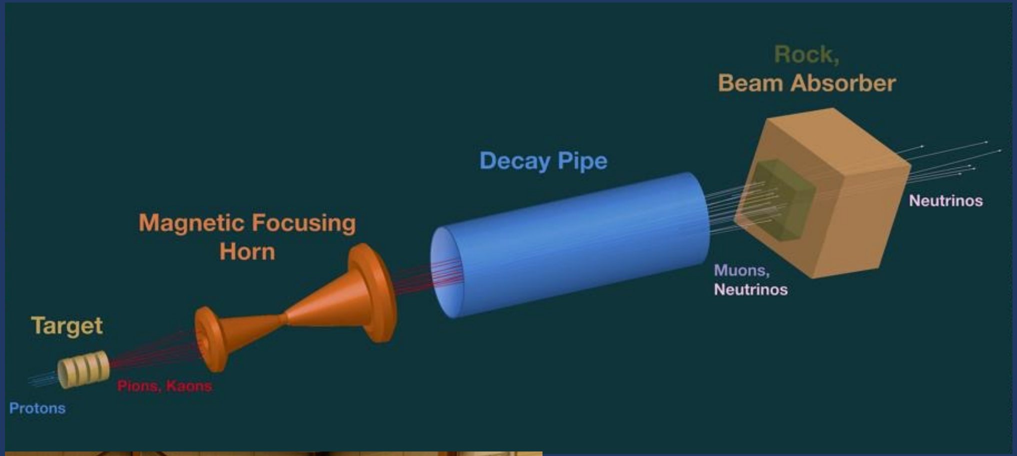
- Can't turn them off (or on…)
- Can't change flavor content
- Can't change spectrum

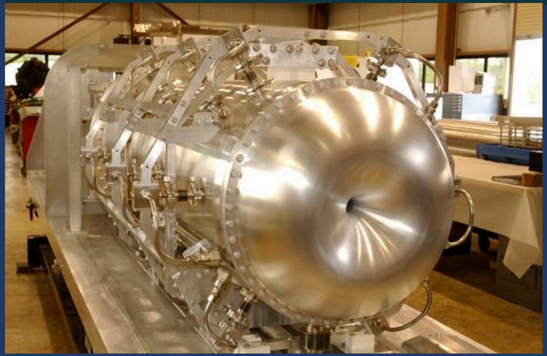
Controllable Neutrino Beams

Many options!

- Horn beams --- "focused" high-energy beams with selection of flavor/antiflavor
- Spallation neutron sources --- high ν flux (typ. stopped π) in pulsed time structure
- Beam dump beams --- Enhanced high-energy ν (and exotic state) source
- Reactor neutrinos --- pure, low-energy anti-ν_e flux, free to funding agencies
- Cyclotron/source beams --- pure flavor content with well-known spectrum
- Beta beams --- pure flavor content, known spectrum, at high energies
- Stored muon beams --- very well-known flavor content and spectrum, high flux
- Collider beams --- very high energy, pretty good tracking at production vertex

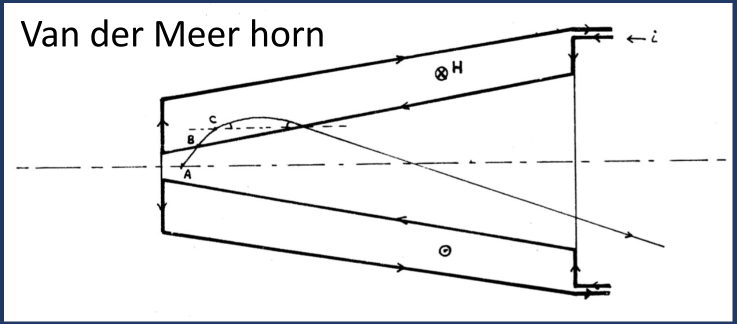
"Horn" Beams





FNAL Booster Horn

You can't focus the neutrinos, but you *can* focus the mesons

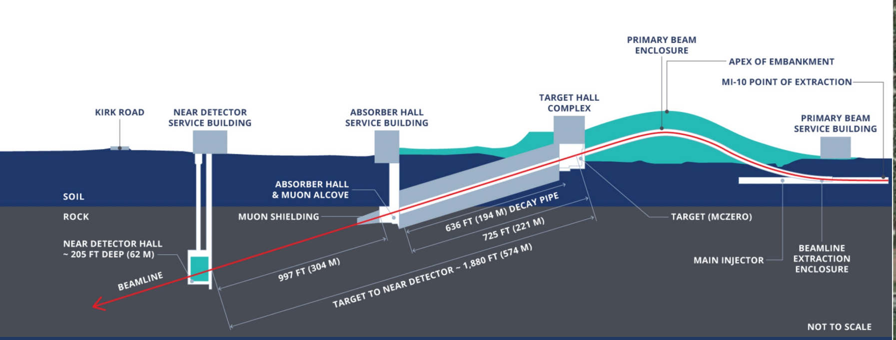


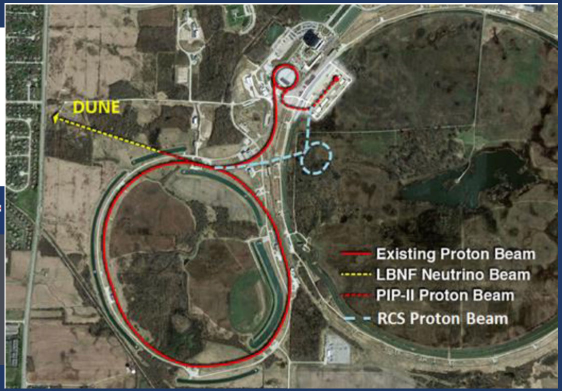
"Horn" shape acts as magnetic total internal reflector

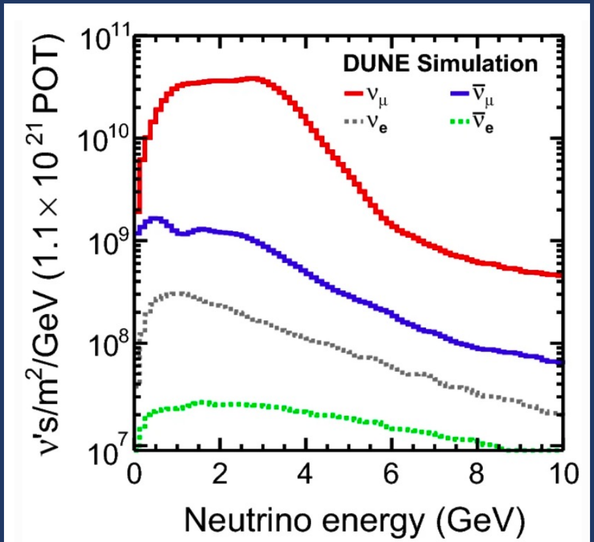
Magnetic focusing allows for flavor/antiflavor selection by reversing current---
focusing π^- rather than π^+

LBNF Beam

World's most intense neutrino beam





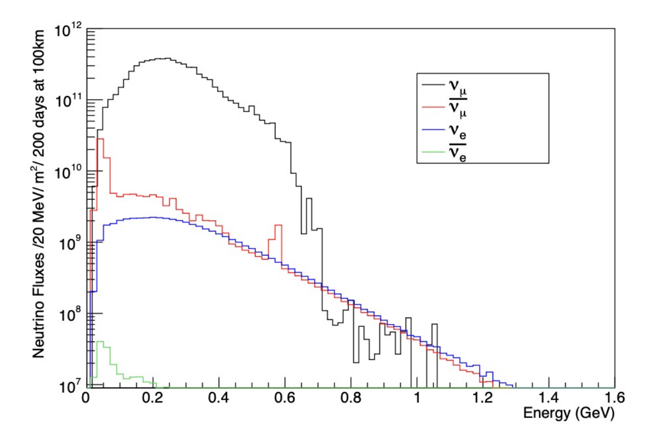


- Current beam design uses 3 serial horns
- Proton Improvement Plan II ("PIP II") gets beam up to 1.2 MW for 120 GeV p
  - 800 MeV superconducting linac will replaced current 400 MeV linac
- Critical DUNE Phase II physics needs 2.4 MW
  - Linac will go to 2 GeV
  - 50-year-old Booster replaced with rapid-cycling synchrotron or linac up to 8 GeV
  - Rest of design is already done to accommodate 2.4 MW
  - Lots of other physics leveraged by these upgrades— 2-4x10^{21} POT/year

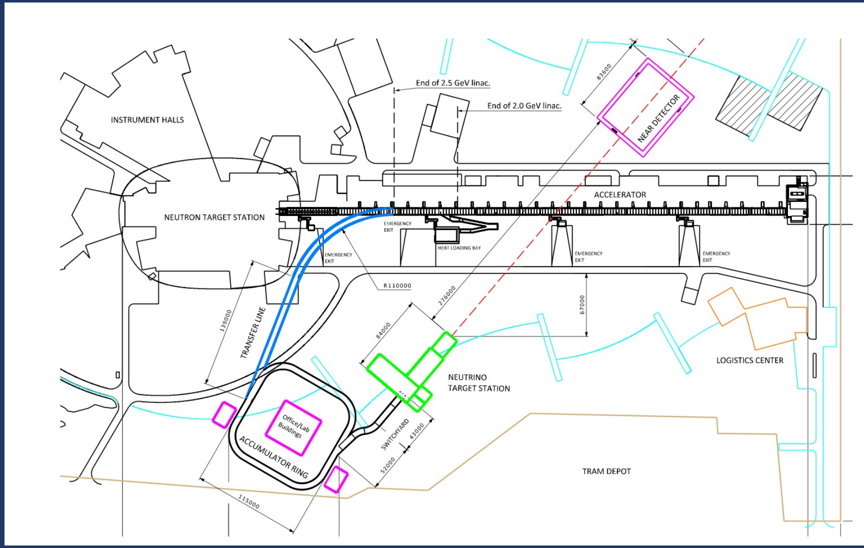
Major challenges: How many νs, what flavors, what spectrum, and how do they interact…?

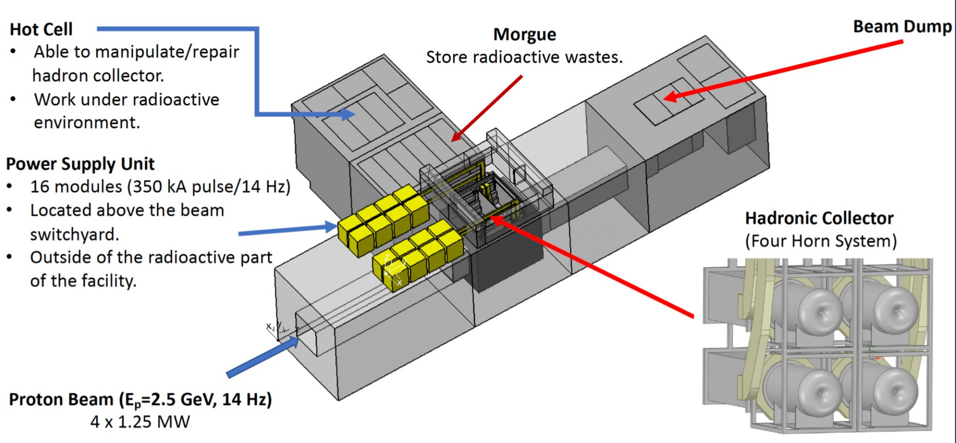
“Spallation” Beams

- Oak Ridge (COHERENT) pioneered “parasitic” ν program
- Japanese Spallation Neutron Source will allow K decay at rest ν physics



Next-generation is hybrid spallation source+horn beam:
European Spallation Source ν Super Beam (ESSνSB)





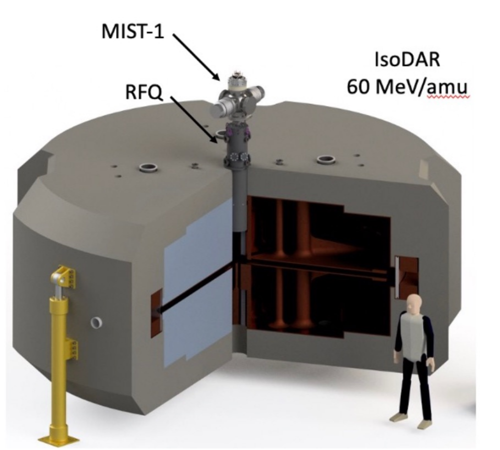
Four parallel horns so 5/4=1.25 MW per target

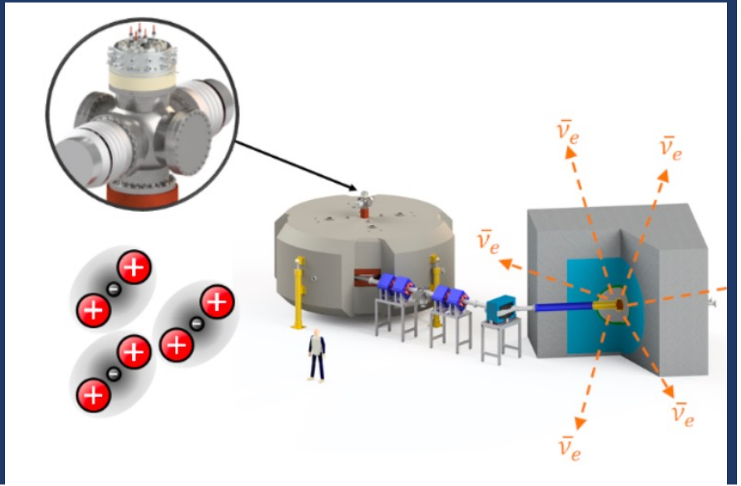
Cyclotron/Source Beams

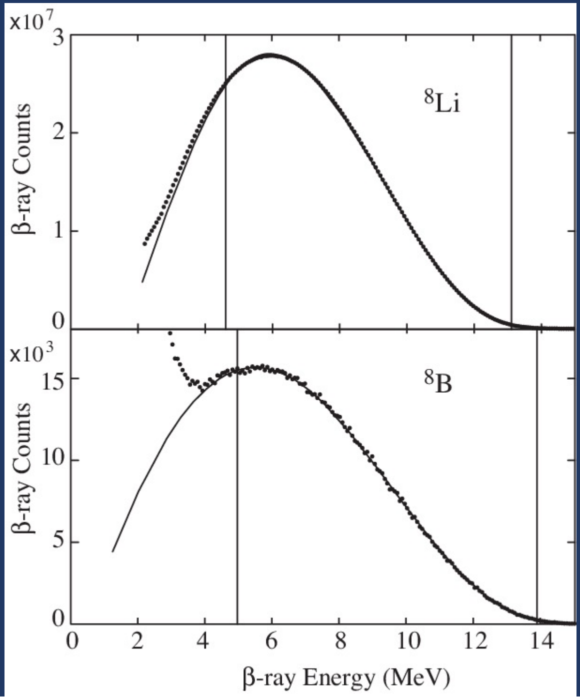
- Standard β sources can be made very hot but energies tend to be very low
- Higher-energy β sources are short-lived; hard to bring to a detector
- But if you can make the source right there, can get both!

IsoDAR---high current (10 mA of protons at 60 MeV) cyclotron to make ^{8}Li off of ^{7}Li via neutron capture

Order-of-magnitude higher power than existing cyclotrons



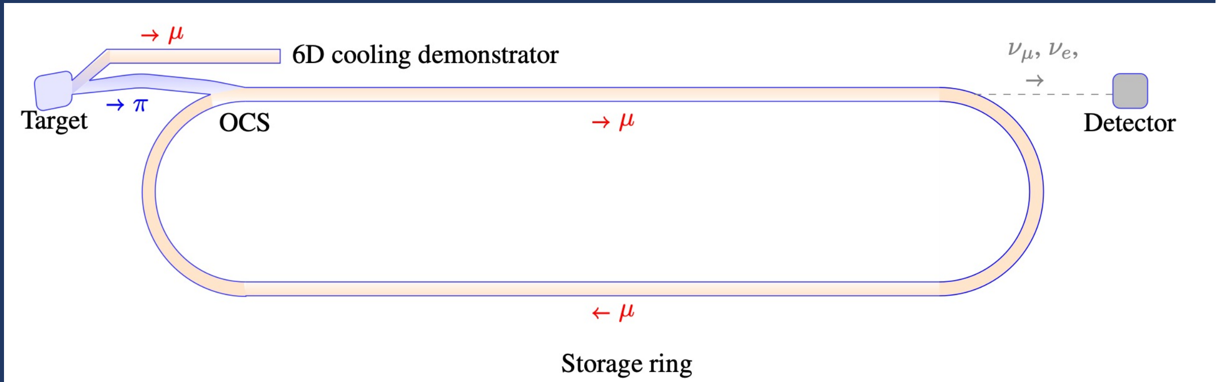




Stored Muon Beams

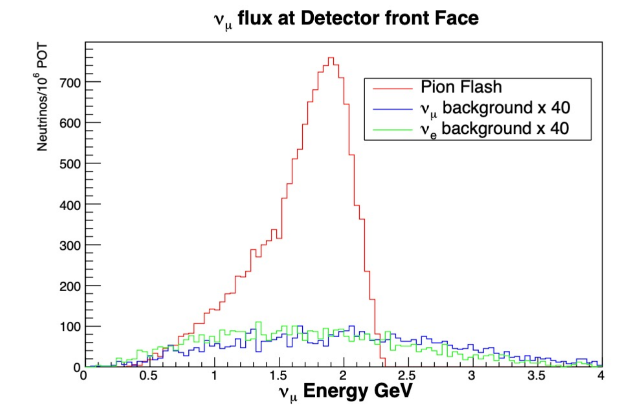
- High flux
- Very well known flavor+energy
- And all at 3-5 GeV
- Important demonstration on the road to a muon collider
- While also making precise (1%) ν+A measurements and other physics

nuSTORM

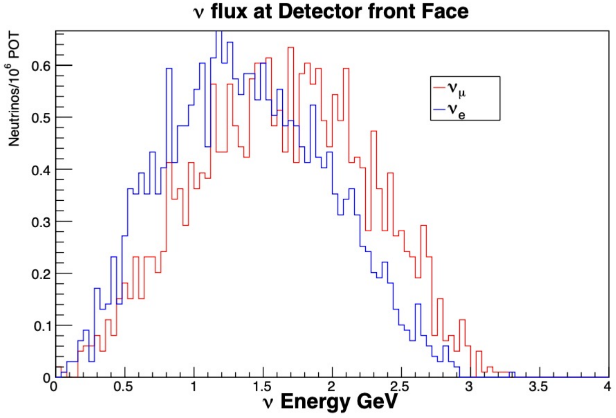


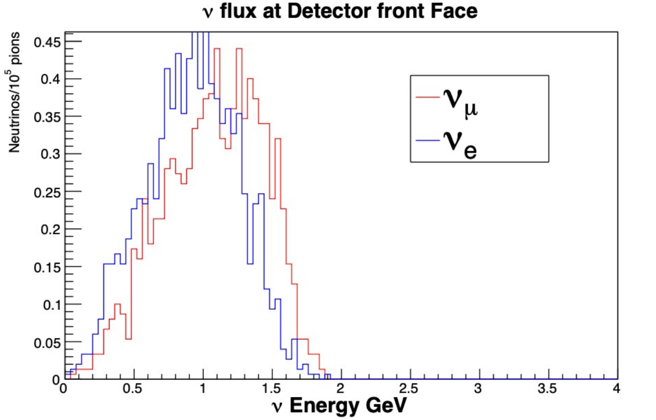
At FNAL or CERN

5 GeV “pion flash” neutrinos



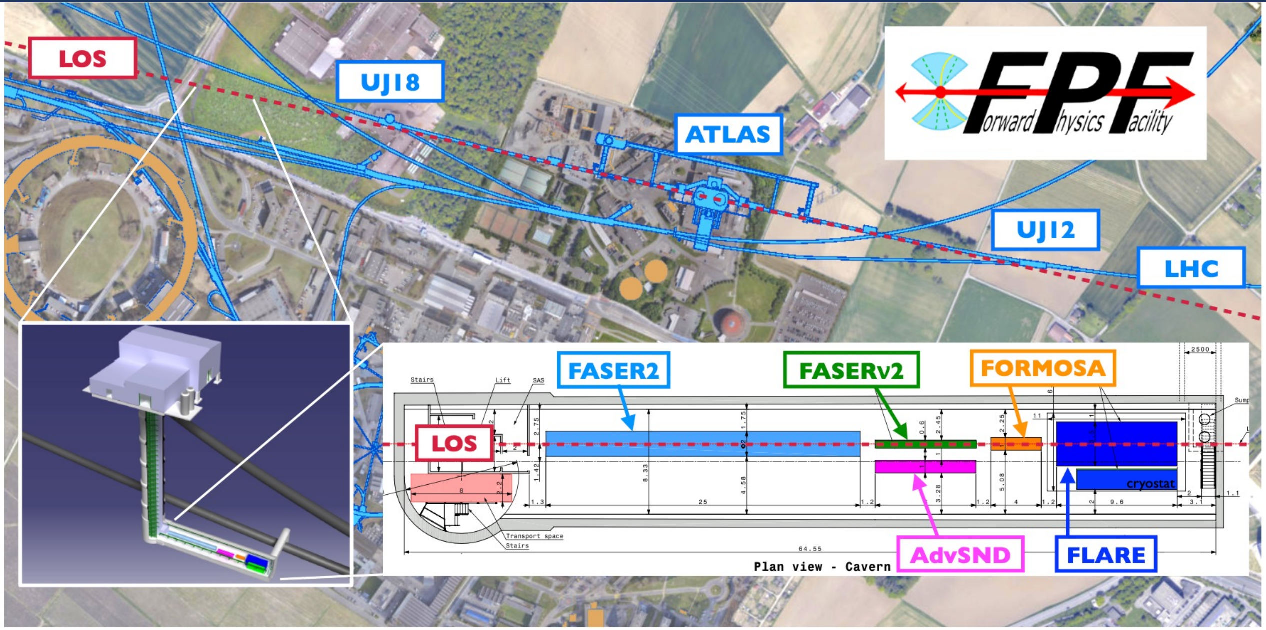
Neutrinos from μ decay

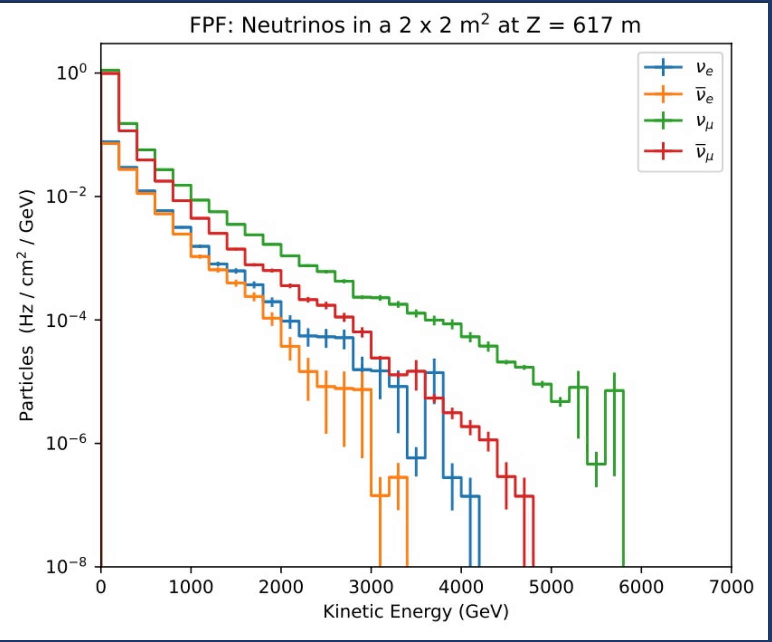




Collider "Beams"

Neutrinos at TeV energies!

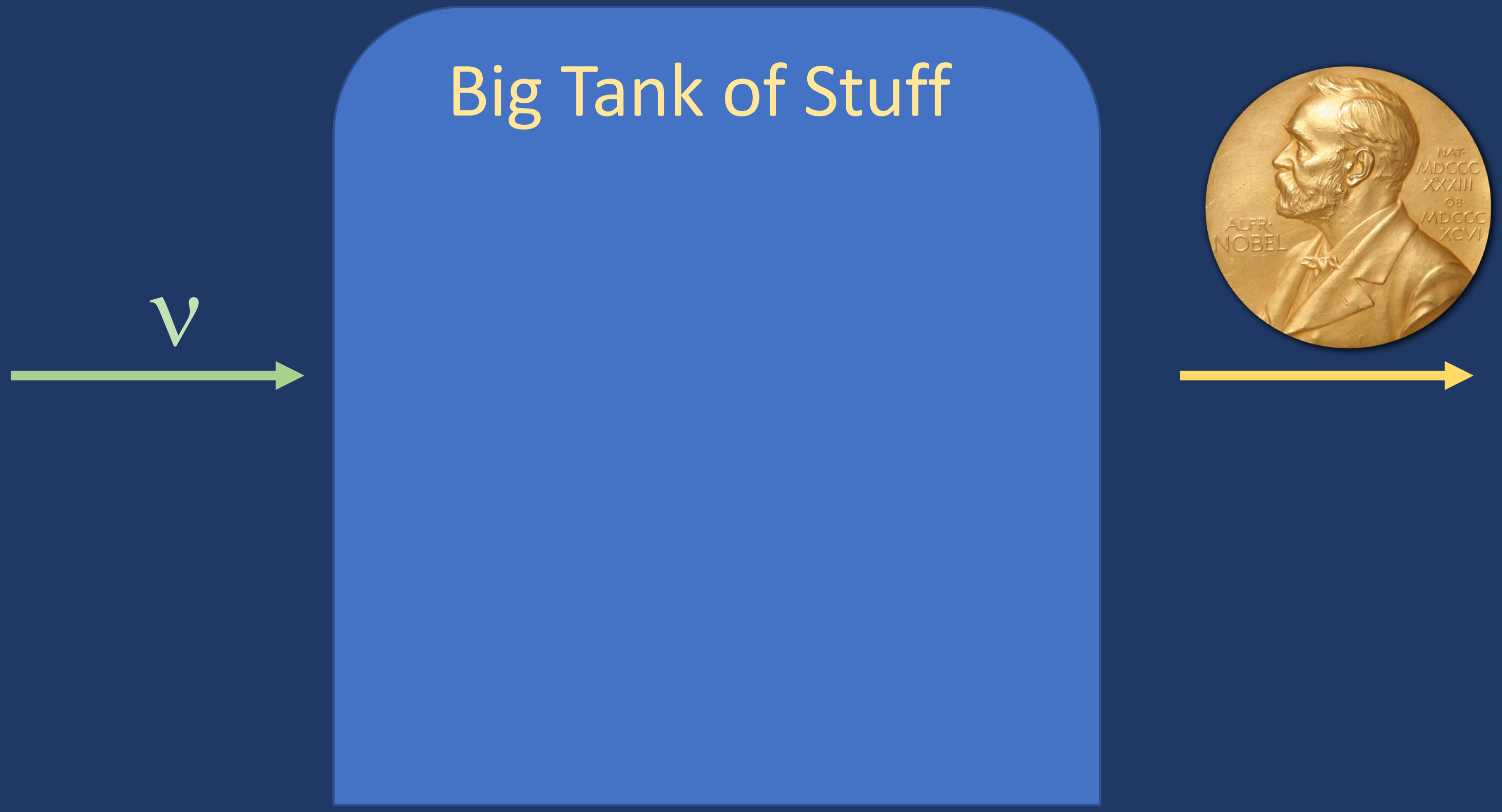




Possibility (with good enough timing) to tag ν at the production point…

Neutrino Instrumentation

The Colloquial View…



Neutrino Instrumentation

The Game Has Changed

Success has raised the bar---three primary areas of interest:

- Resolution Frontier
- Precision Frontier
- Energy Frontier

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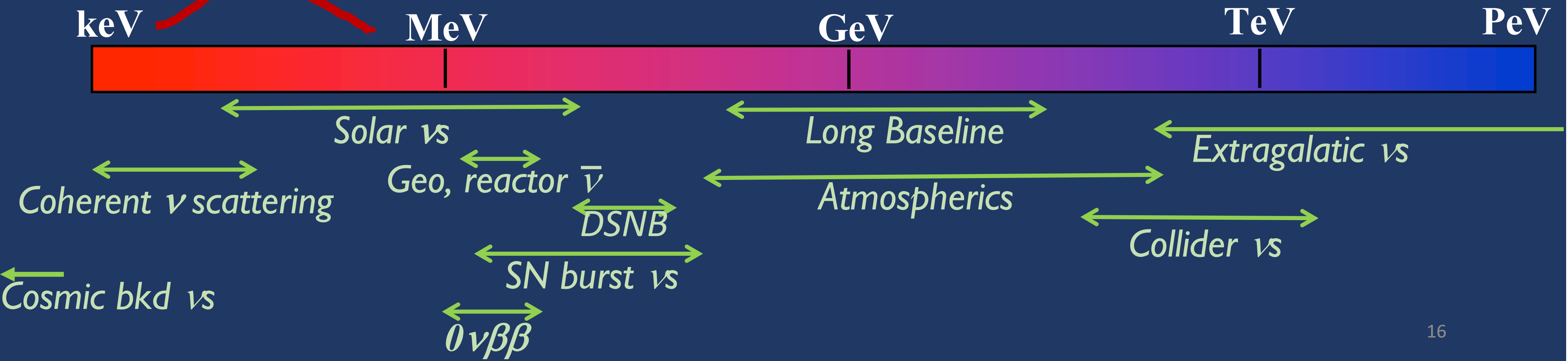
- ~~Energy Frontier~~

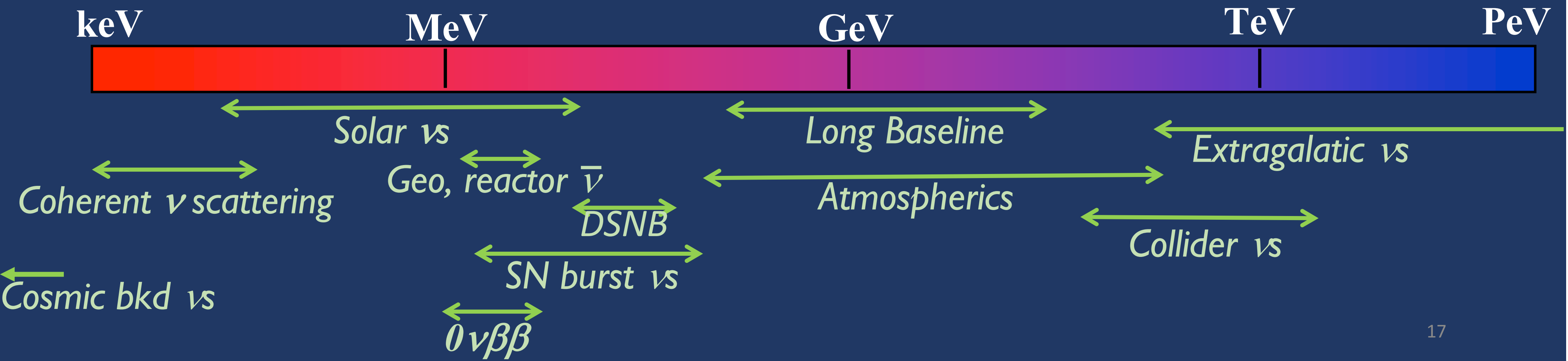


Neutrino Instrumentation

The Game Has Changed

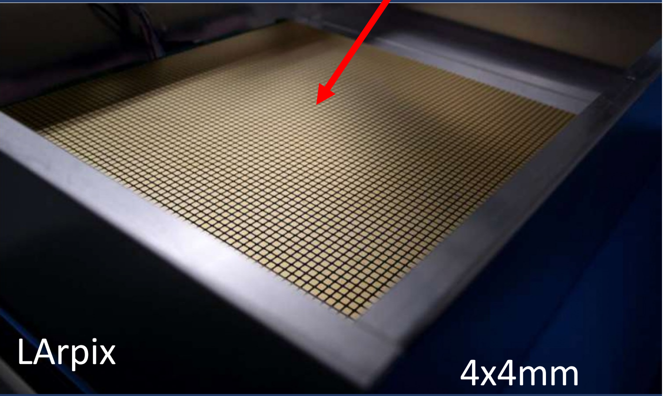
Success has raised the bar---three primary areas of interest:

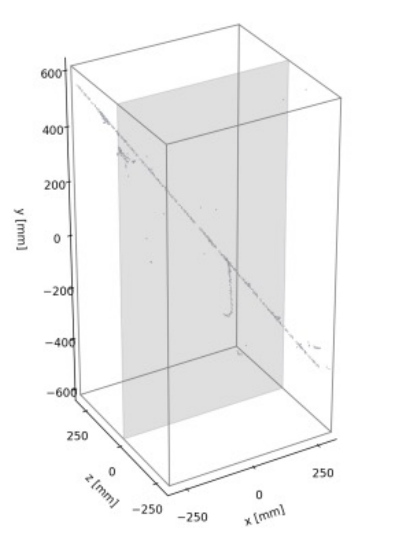
- Resolution Frontier
- Precision Frontier
- Breadth Frontier --- optimizing physics from eV to EeV



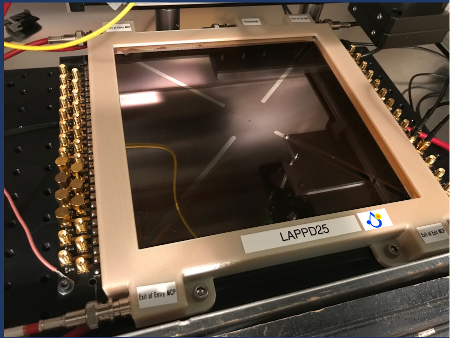
Resolution

Need better position resolution to resolve neutrino pileup at DUNE Near Detector site

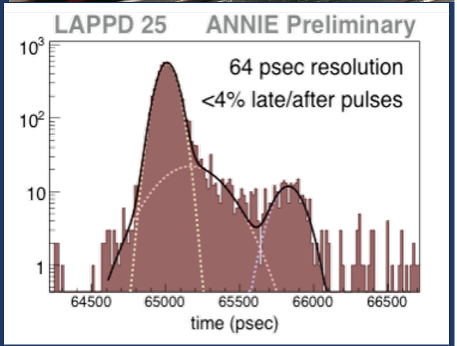




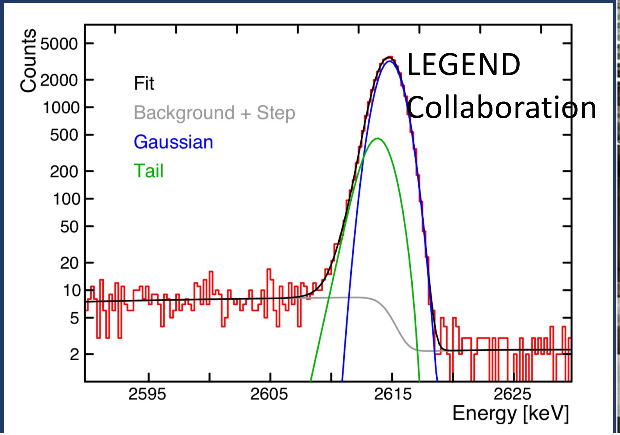
”Qpix” pixels may be viable to cover an entire DUNE-sized module (~ 10e6)



Narrowing timing resolution for better reconstruction in photon-based experiments



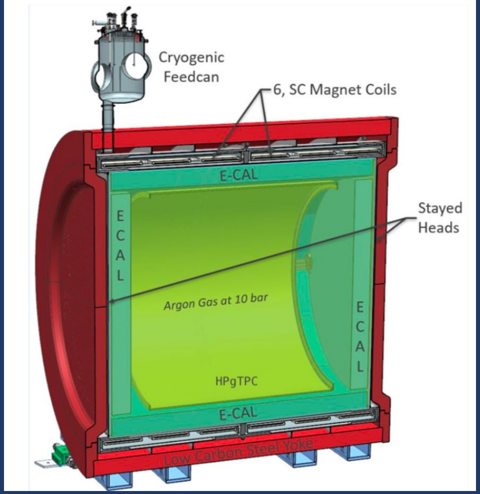
High Purity GE detectors σ_E~0.1%

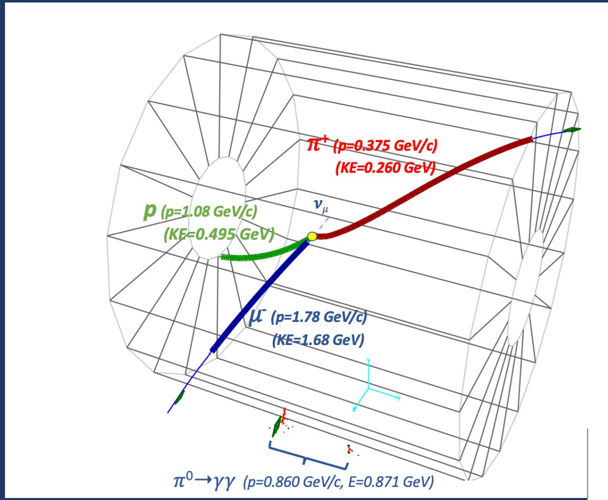


Narrowing energy resolution in low-energy detectors reduces backgrounds

Precision

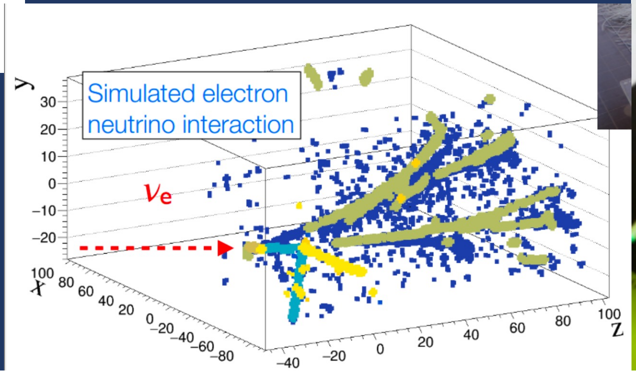
- Horn beams have a complex mixture of flavors and fluxes
- And neutrino interactions are not well understood
- Need new instruments to constrain fluxes, spectra, and cross sections

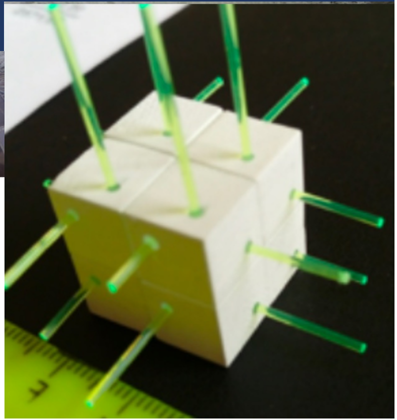




- DUNE Near Detector (“ND-GAr”)
- High-pressure gaseous argon TPC
- Precision reconstruction of final states

- T2K Near Detector (“SFGD”)
- 3D reconstruction with scintillator cubes+fibers
- Precision reconstruction of final states





Breadth

Low-E ν physics at DUNE can be leveraged by underground argon+shielding

Underground Ar significantly reduces radiogenic backgrounds

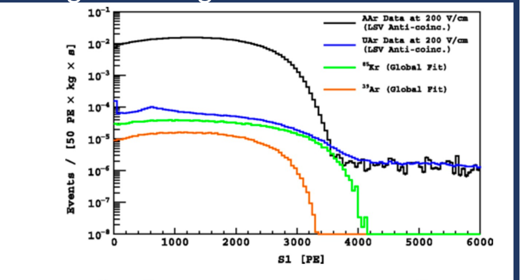
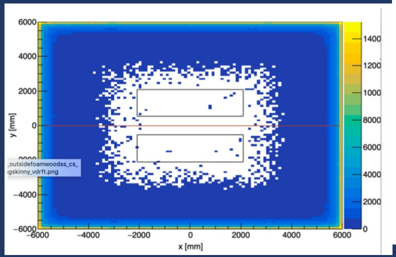
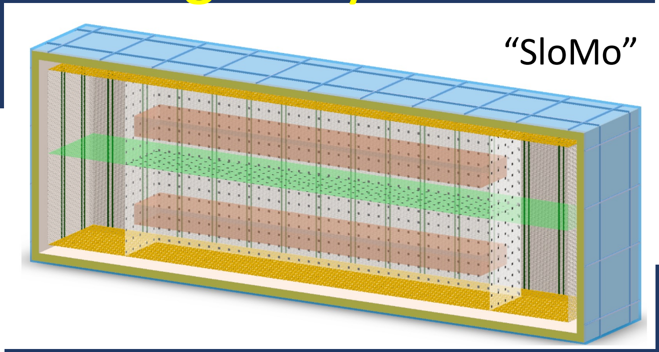


Figure 5: ^{39}Ar and ^{85}Kr from DarkSide-50 showing a x1400 reduction in ^{39}Ar for UAr. [20]

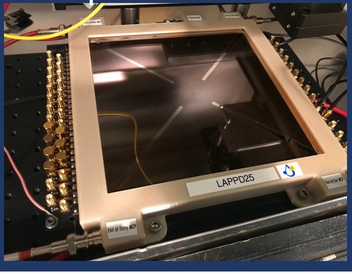
Neutron shield reduces scatters in fiducial volume

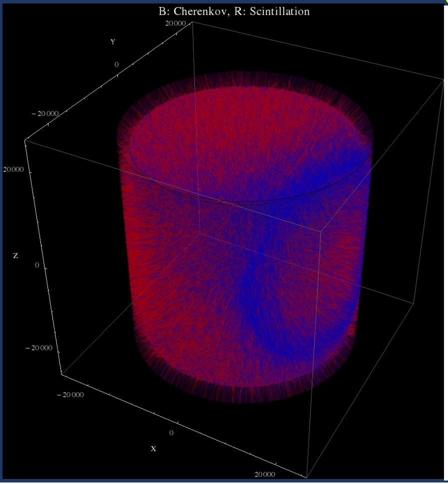


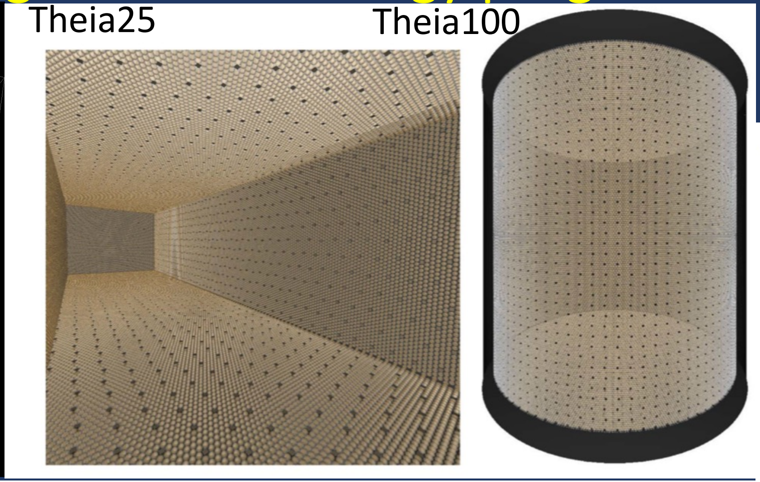


Hybrid Cherenkov/scintillation detectors would have “best of both worlds”---high and low-energy programs

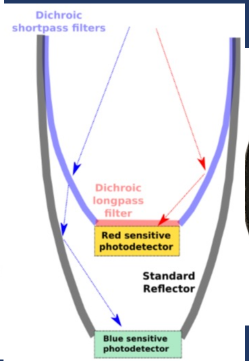
LAPPD picosecond timing

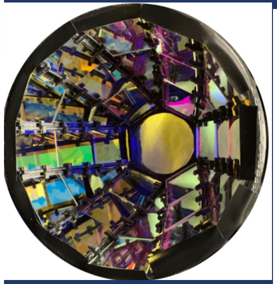


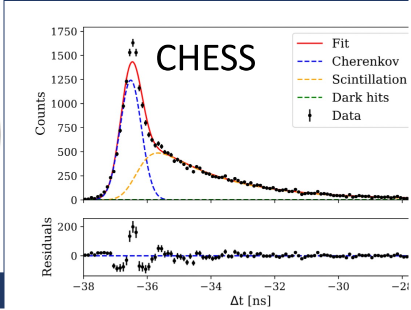




Spectral sorting--Dichroicons

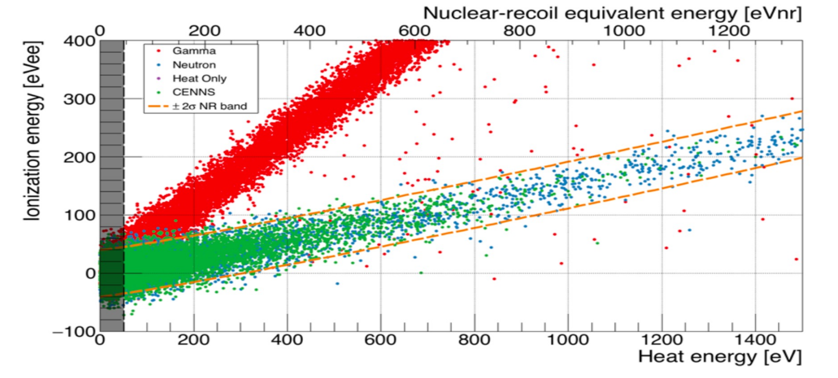


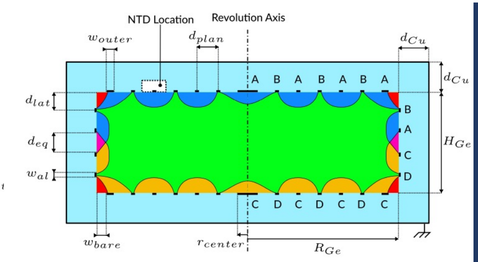


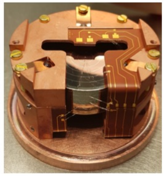


Breadth

Example of pushing energy thresholds down to 50 eV







Cryocube for Ricochet NTD-Ge

Example of pushing energy thresholds up to EeV

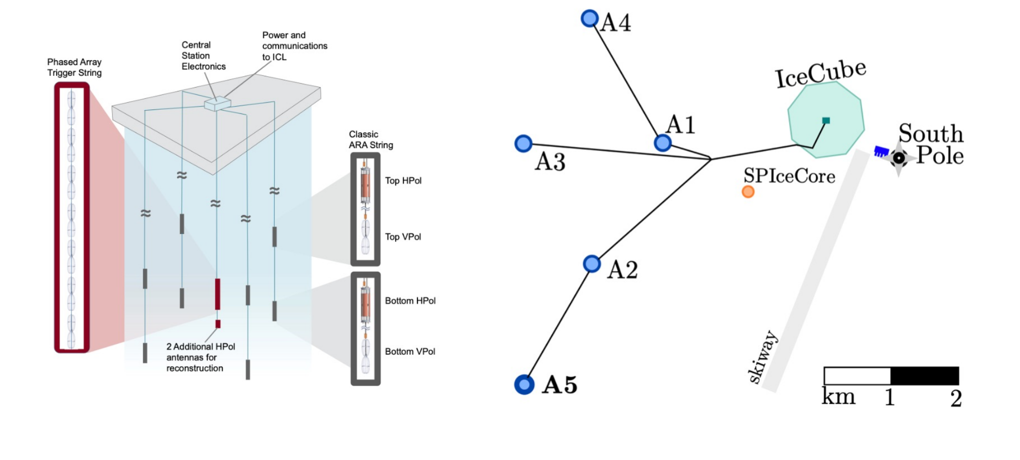


Figure 28. Schematic and map ARA stations at the South Pole. Figure reproduced from Ref. [661]

ARA radio detection

Breadth

Solar+reactor+supernova+0νββ+beam+atmospherics

Experiment	Basic Approach	Enabling Technology
SloMo	LArTPC	10 ktonne underground argon neutron shield
SoLAr	LArTPC	charge+light pixels
Theia	Hybrid Cherenkov/scintillator	WbLS fast timing dichroicons
LiquidO	Scintillator tracking	"Milky scintillator" fiber readout
LArXe	LArTPC+Xe	photo-ionizing dopants xenon loading

Extragalactic sources

Proposed Detector	Basic Approach	Energy Range	Enabling Technology
P-ONE	Water Cherenkov	> TeV	Scale, telecomm fibers
ICECUBE-Gen2 (optical)	Ice Cherenkov	TeV-PeV	Scale, multi-PMTs
Trinity	Air-shower Cherenkov	10-1000 PeV	60° FOV optics
RET	Radar reflection off ionization	> 10 PeV	In-ice radar reflection
TAMBO	(Air-shower) water Cherenkov tanks	1-100 PeV	Mountain/valley geography
RNO-G	Askaryan emission in ice	> PeV	Greenland ice, solar+wind power autonomous radio detectors
ICECUBE-Gen2 (radio)	Radio array	PeV-EeV	Omni-directional cylindrical antennas
BEACON	Radio air-shower detection	100 PeV–EeV	Mountain geometry, interferometric phased arrays
GRAND	Geomagnetic air-shower radio	> PeV	Very large-scale radio array
POEMMA	Space-based optical air-shower	10 PeV-40 EeV	Wide-FOV Schmidt telescopes, Cherenkov camera
PUEO	Balloon-based radio in ice and air	> EeV	Realtime interfermetric beamforming, Xilinx RFSoC
GCOS	Nested water Cherenkov tanks +radio	> 10 EeV	TBD

Table 4: Proposed detectors and enabling technologies for high-energy and ultra-high-energy neutrino detection. Only those experiments not yet past the technical design phase are included.

Coherent ν+A scatttering

Experiment	Enabling technology	E_{th}(NR)	target material	mass	status	ν source
MINER [105]	phonon detectors	$\mathcal{O}$(100eV)	Ge, Al_2O_3	$\mathcal{O}$(100g)	D/C	R
NUCLEUS [106–108]	phonon detectors	$\mathcal{O}$(10eV)	$CaWO_4$,Al_2O_3	$\mathcal{O}$(10g)	D/C	R
RICOCHET [109]	phonon detectors	$\mathcal{O}$(10eV)	Ge, Zn	$\mathcal{O}$(1kg)	D/C	R
BULLKID [110]	phonon detectors	$\mathcal{O}$(10eV)	Si	$\mathcal{O}$(10g)	R&D	-
CONNIE [111]	CCD sensors	$\mathcal{O}$(100eV)	Si	$\mathcal{O}$(100g)	run	R
COHERENT [112]	cryog. scintillator	$\mathcal{O}$(1keV)	CsI	$\mathcal{O}$(10kg)	D/C	S
COHERENT [112]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(10kg)	D/C	S
COHERENT [112]	scintillator	$\mathcal{O}$(1keV)	NaI	$\mathcal{O}$(1ton)	D/C	S
CONUS [113]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(1kg)	run	R
Dresden [114]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(1kg)	run	R
nuGen [115]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(1kg)	run	R
TEXONO [116]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(1kg)	run	R
NEON [117]	scintillator	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(10kg)	run	R
SBC [118]	bubble	$\mathcal{O}$(100eV)	lAr(Xe)	$\mathcal{O}$(10kg)	R&D	R
NEWS-G [119]	gaseous	$\mathcal{O}$(100eV)	Ne,CH_4	$\mathcal{O}$(100g)	run	-
COHERENT [120]	liquid noble	$\mathcal{O}$(1keV)	lAr	$\mathcal{O}$(10kg)	run	S
RED100 [121]	liquid noble	$\mathcal{O}$(1keV)	lXe	$\mathcal{O}$(100kg)	run	R
CHILLAX [122]	liquid noble	$\mathcal{O}$(100eV)	lAr,lXe	$\mathcal{O}$(10kg)	R&D	R/S
NUXE [123]	liquid noble	$\mathcal{O}$(100eV)	lAr,lXe	$\mathcal{O}$(10kg)	R&D	R

(Not included here many dedicated 0νββ experiments!)

Collider Neutrinos

Technology	FASER2	FASERnu2	Adv-SND	FLArE	FORMOSA
Large aperture SC magnet	x				
High resolution tracking	x		x	x	
Large scale emulsion		x			
Silicon tracking			x		
High purity noble liquids				x	
Low noise cold electronics				x	
Scintillation				x	x
Optical materials				x	x
Cold SiPM				x	
Picosec synchronization			x	x	x
Intelligent Trigger	x		x	x	x

Table 5: Enabling technologies for the detectors and systems of the far forward physics facility.

Summary

- New era in development of high-flux neutrino beams
- Many creative ideas for new instrumentation and detectors
- Advancing detector resolution, precision, and breadth
- Very exciting time for future neutrino experiments!