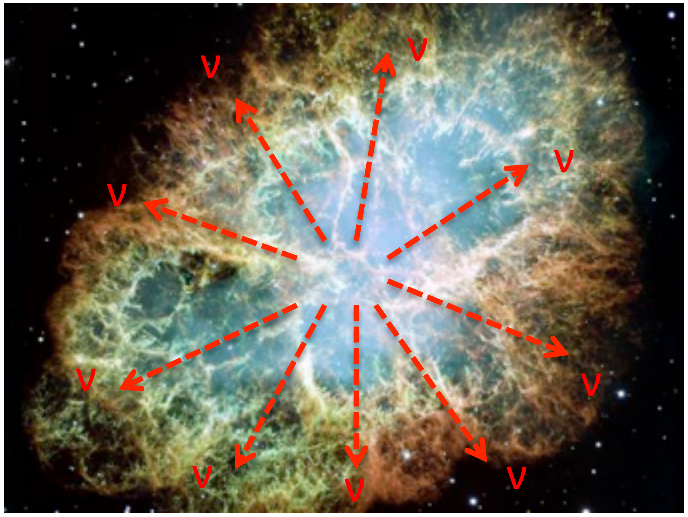
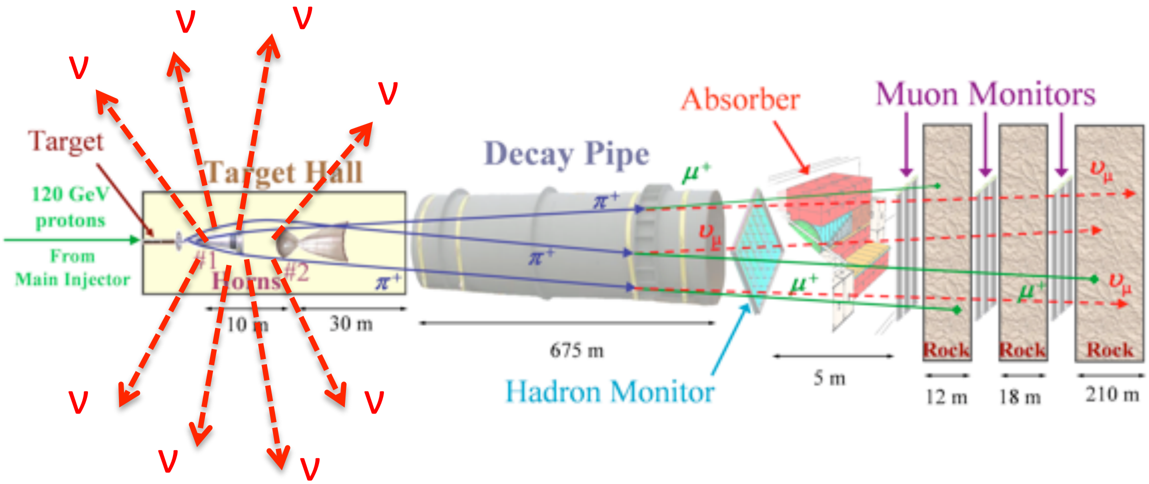




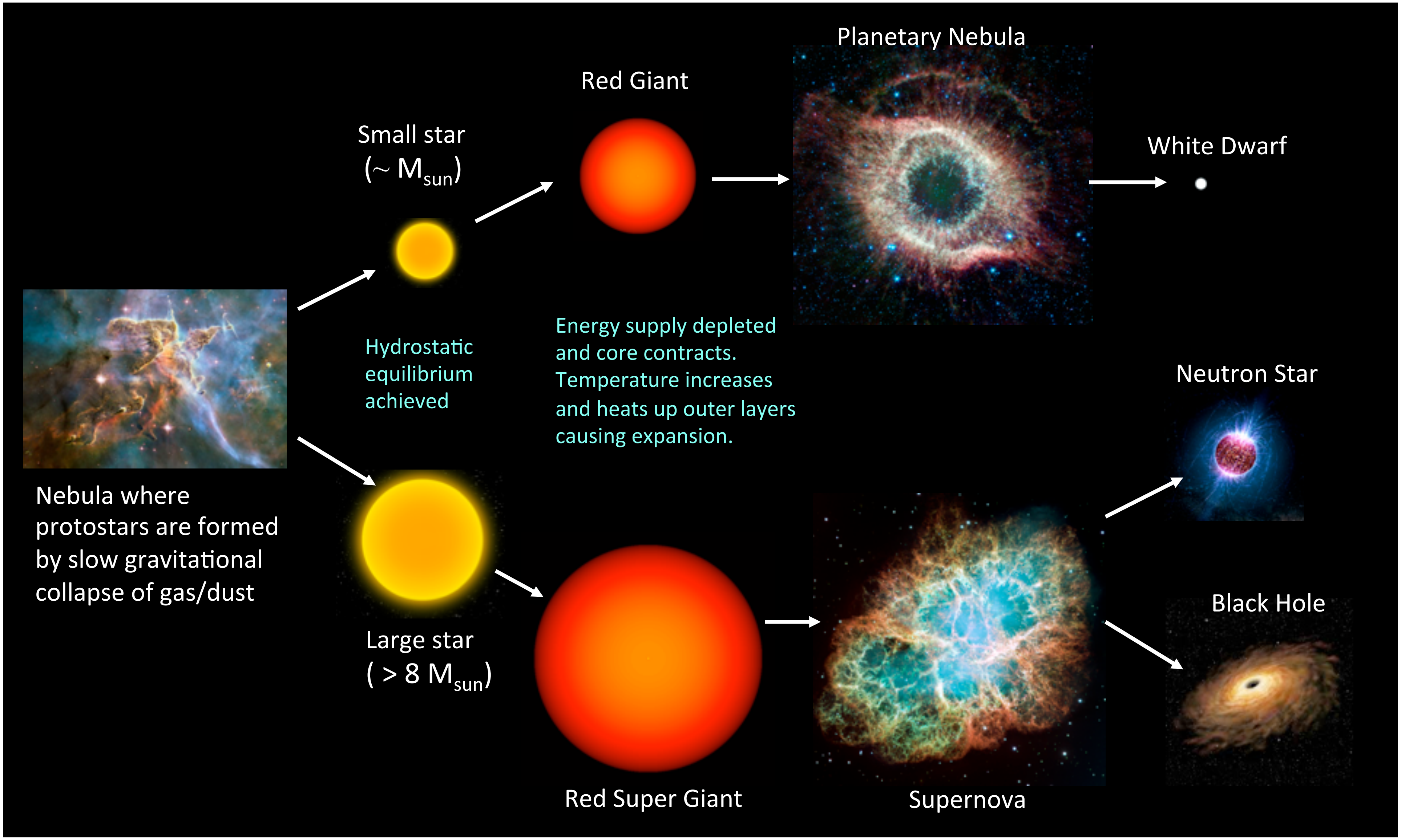
# Unlocking the Secrets of Exploding Stars with Terrestrial Neutrino Beams

Christopher Grant

UC Davis HEP Seminar

November 10, 2015

# Stellar evolution in a nutshell



Nebula where protostars are formed by slow gravitational collapse of gas/dust

Small star

$(\sim M_{sun})$

Hydrostatic equilibrium achieved

Large star

$( > 8\ M_{sun})$

Red Giant

Energy supply depleted and core contracts. Temperature increases and heats up outer layers causing expansion.

Red Super Giant

Planetary Nebula

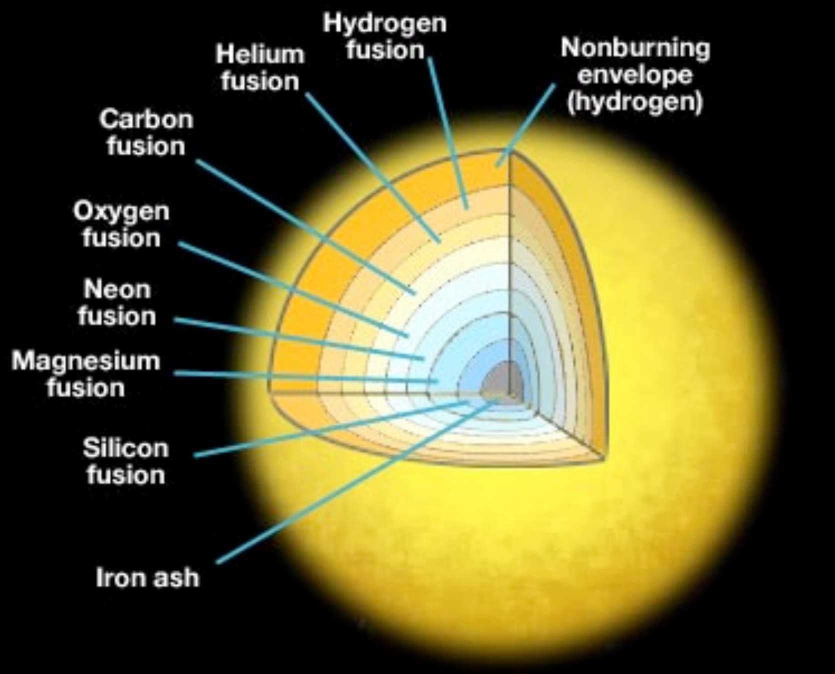
White Dwarf

Supernova

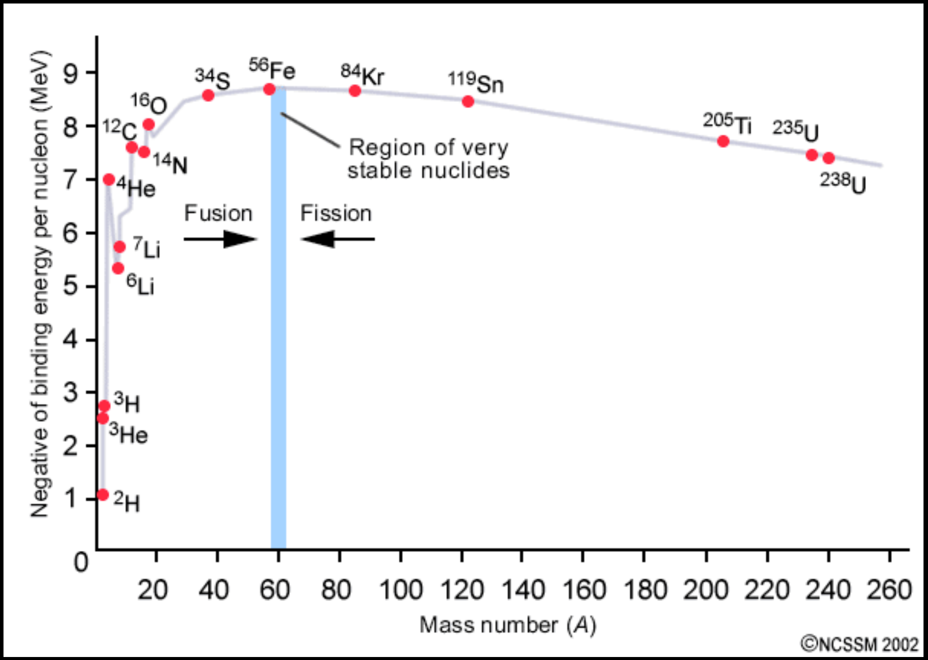
Neutron Star

Black Hole

# The death of very massive stars



https://www.e-education.psu.edu/astro801/content/l6_p5.html

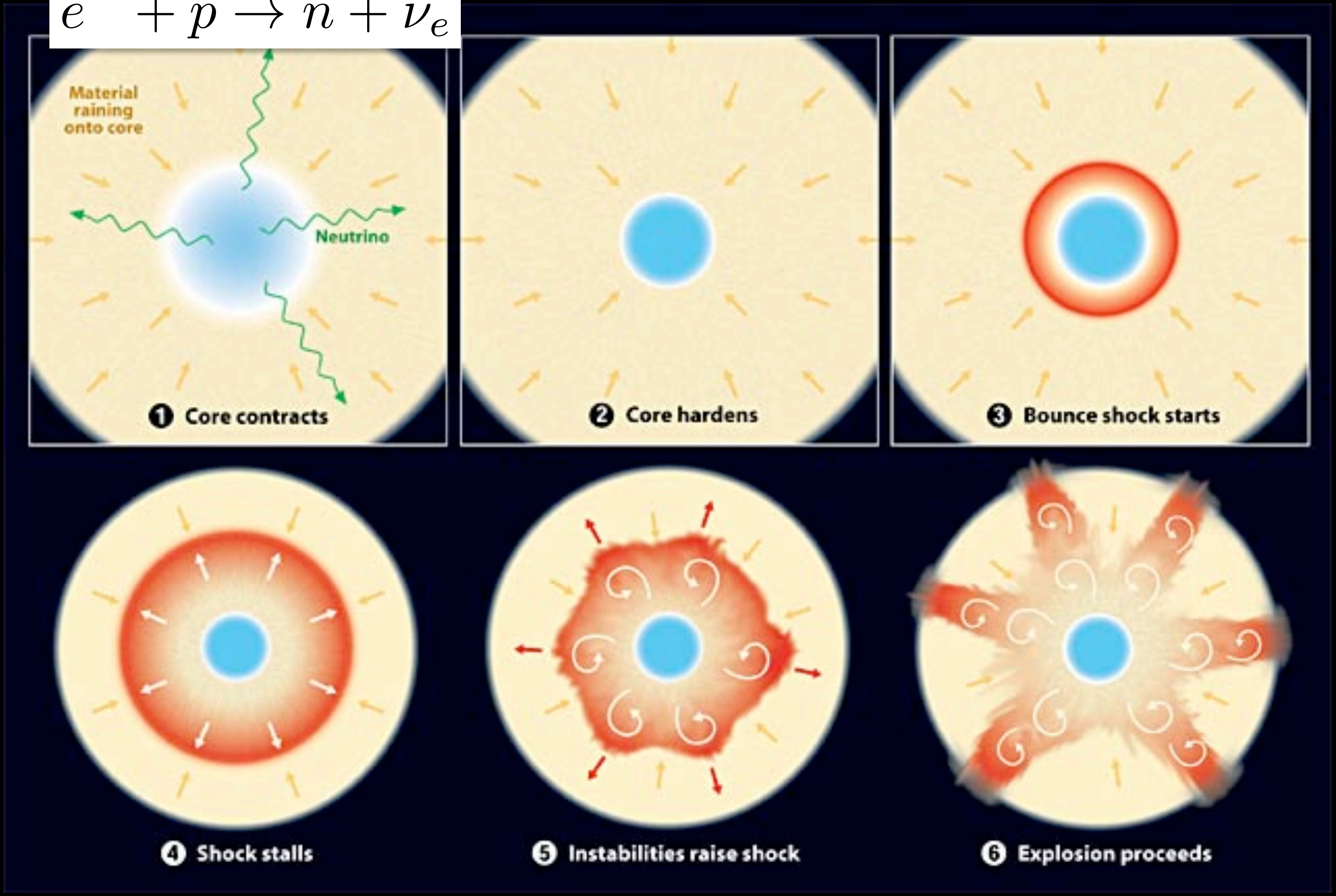


An iron core will grow inside of very massive stars until it reaches a mass where electron degeneracy can no longer support it (1.44 $M_{sun}$), called the Chandrasekhar Mass.

The core continues to collapse and the excitement begins…

# Core collapse

$$e^- + p \to n + \nu_e$$



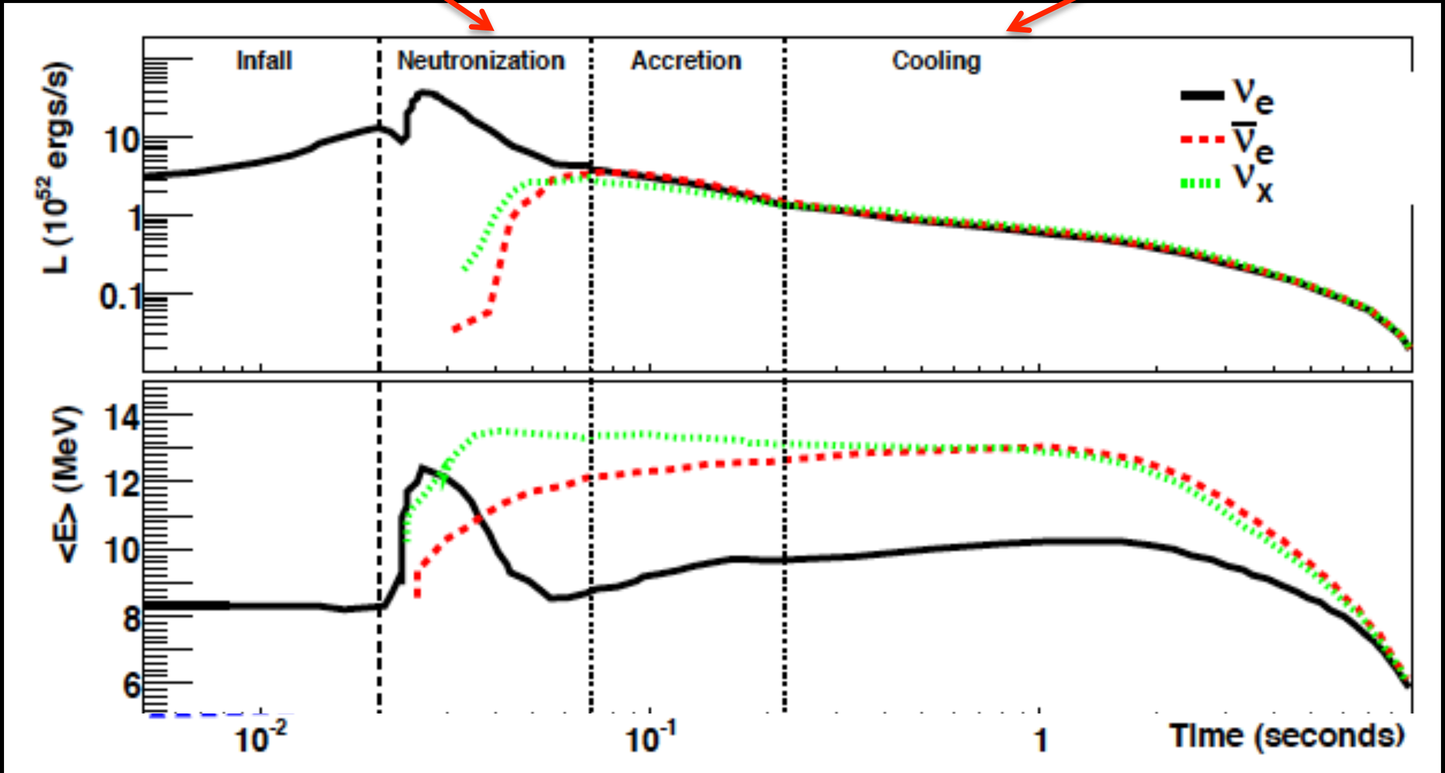
www.skyandtelescope.com

# Spectacular Explosion

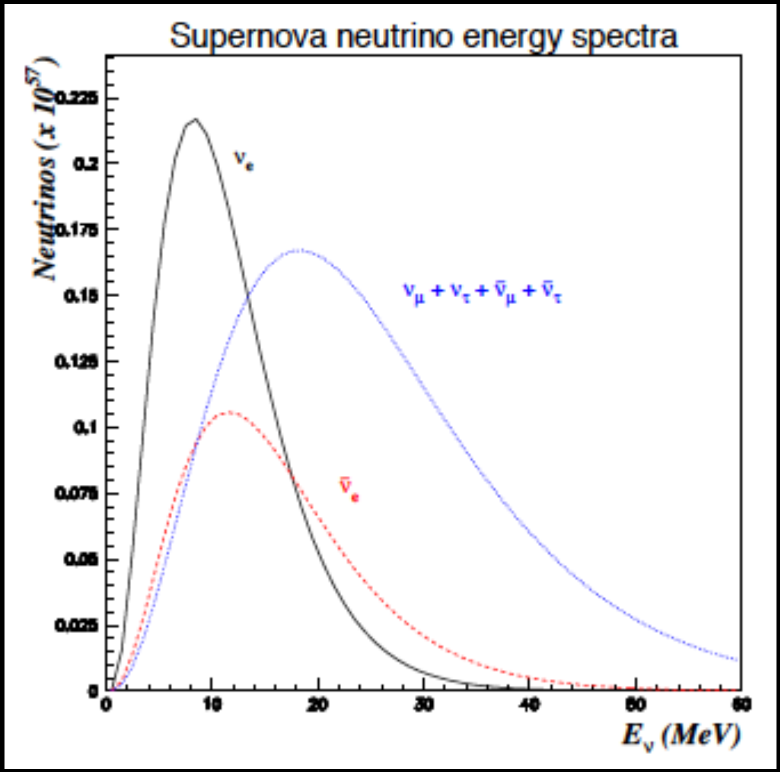
# Neutrino production from a supernova

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

$e^+ + e^- \rightarrow Z^0 \rightarrow \nu_x + \overline{\nu}_x$



# Neutrino production from a supernova



Fun facts:

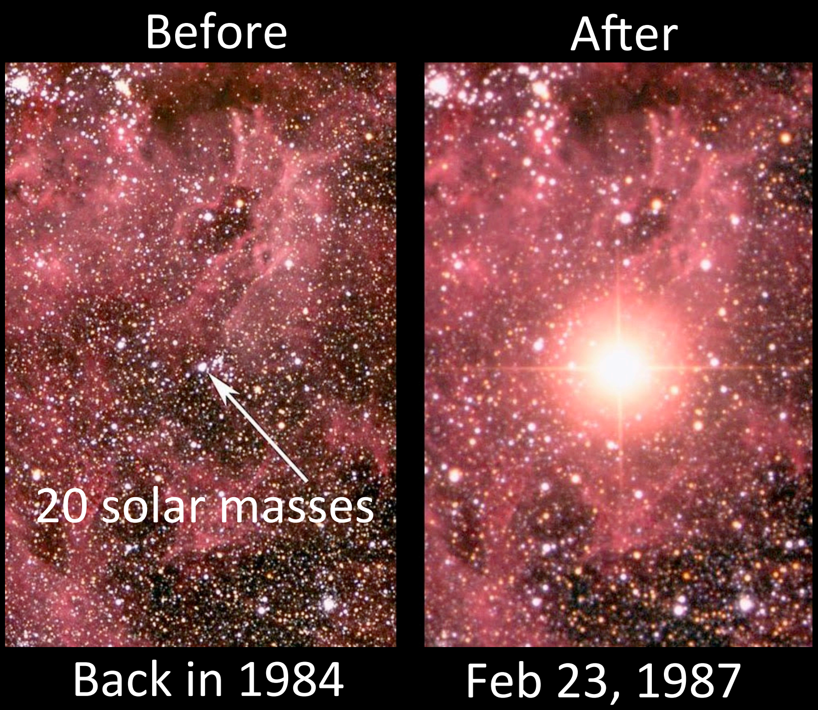
99% of the total binding energy of the star is carried away by neutrinos. This corresponds to a neutrino luminosity of $\sim 10^{53}$ ergs

Only 0.01% of this energy goes into light $\sim 10^{49}$ ergs

Our Sun only emits $10^{33}$ ergs / s so this is still like $10^{16}$ Suns

It is estimated that supernova occur in our galaxy with a frequency of about 1/25 years. Not always optically observable due to interstellar dust which absorbs light. Neutrinos will always be there! …(unless a black hole forms!)

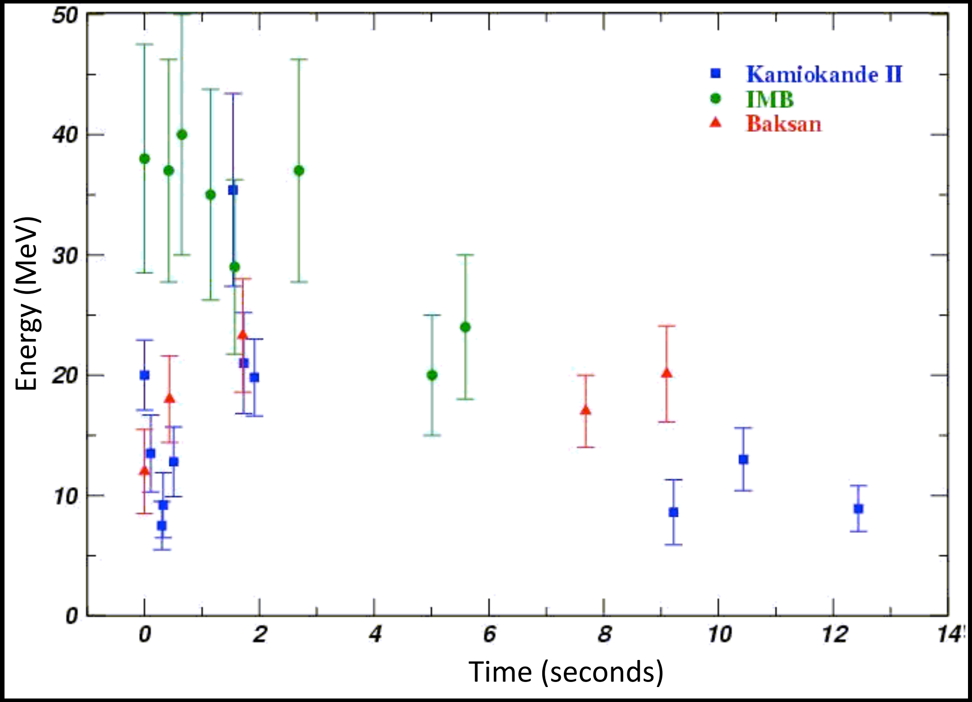
# First and only observation of supernova neutrinos



Supernova was optically observed in the Large Magellanic Cloud 170,000 light years from Earth (50 kpc). Two experiments searching for proton decay were running at the time, including another neutrino experiment in Russia…they found a signal 4 hours prior to the observation of light!

# SN 1987A neutrinos

Kamiokande = 12 events IMB = 8 events Baksan = 5 events



Kamiokande and Irvine-Michigan-Brookhaven experiments were using large water Cherenkov detectors. Baksan was a liquid scintillator detector.

Primary signal:

$$\overline{\nu}_e + p \rightarrow n + e^+$$

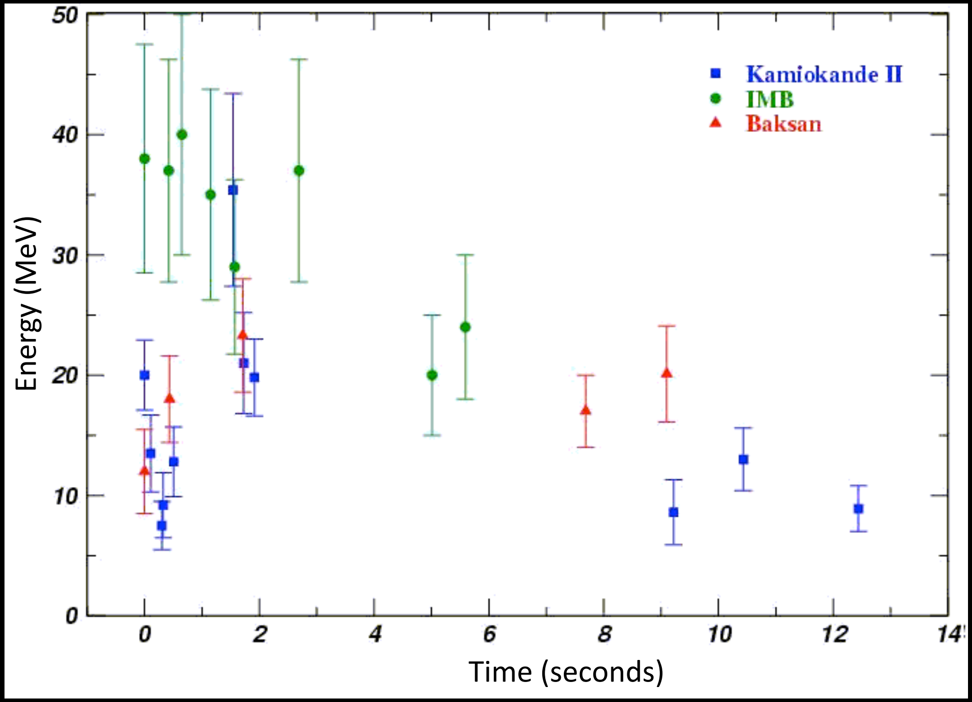
These experiments were only sensitive to the cooling neutrinos at later times during the burst.

# SN 1987A neutrinos

Kamiokande = 12 events

IMB = 8 events

Baksan = 5 events



For neutrinos of energies $E_1$ and $E_2$:

$$m^2 \approx \frac{\Delta t}{D\left(\frac{1}{E_1^2} + \frac{1}{E_2^2}\right)}$$

SN1987A events provided an upper limit on the neutrino mass:

$$m(\overline{\nu}_e) < 11 \text{ eV}$$

## Neutrino production from a supernova

These 25 events confirmed some of our basic theories behind core collapse and resulting explosion.

It would be even better to have much higher statistics and have sensitivity to early-time phenomena like the neutronization burst.

Future neutrino experiments are trying to prepare for the next one…

# About those neutrinos

QUARKS

**UP QUARK**
A teeny little point inside the proton and neutron, it is friends forever with the down quark.

**CHARM QUARK**
A second generation quark, it is charmed, indeed.

**TOP QUARK**
This heavyweight champion doesn't live long enough to make friends with anyone.

**DOWN QUARK**
A tiny little point inside the proton and neutron, it is friends forever with the up quark.

**STRANGE QUARK**
Why is this second generation quark so strange?

**BOTTOM QUARK**
This third generation quark is puttin' on the pounds.

LEPTONS

**ELECTRON-NEUTRINO**
These miniscule bandits like to steal away energy and escape detection.

**MUON-NEUTRINO**
A slightly heavier bandit than its sibling to the left.

**TAU-NEUTRINO**
Wily and sneaky, this bandit is the newest particle to arrive at the Zoo.

**ELECTRON**
A familiar friend, this negatively charged, busy l'il guy likes to bond.

**MUON**
A "heavy electron" who lives fast and dies young.

**TAU**
A "heavy muon" who could stand to lose a little weight.

FORCE CARRIERS

**PHOTON**
The massless wavicle we know and love.

**GLUON**
The "glue" of the strong nuclear force.

**W BOSON**
**Z BOSON**
As the carrier particles of the weak nuclear force, they're downright obese.

THEORETICALS

**HIGGS BOSON**
It's the one everyone wants to meet, but for now it's playing hard to get. You'd be smiling too if everyone was looking to interview *you*.

**GRAVITON**
Still unobserved, yet theoretically *everywhere*.

**TACHYON**
Can this devious and clever particle really travel faster than light?

**DARK MATTER**
The mysterious missing mass. Difficult to see because it's so *dark*.

NUCLEONS

**PROTON**
We would not be here without her positivity.

**NEUTRON**
He insists on remaining neutral.

# About those neutrinos

They come in three lovable flavors:

($10.49 each plus shipping and handling)

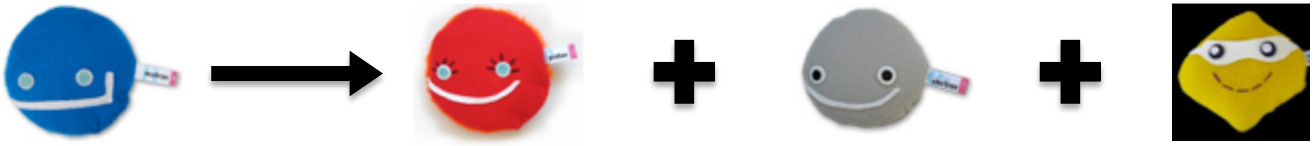
http://particlezoo.net/shop.html

electron neutrino

muon neutrino

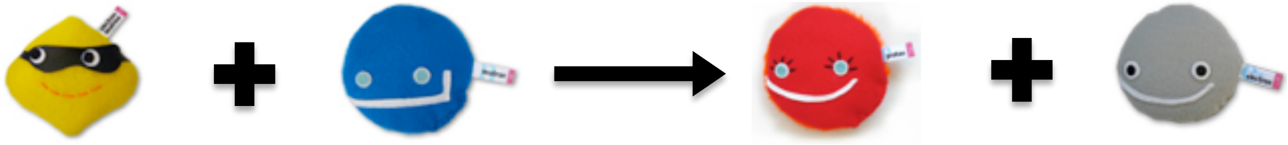
tau neutrino

Produced in pairs with their lepton partners:



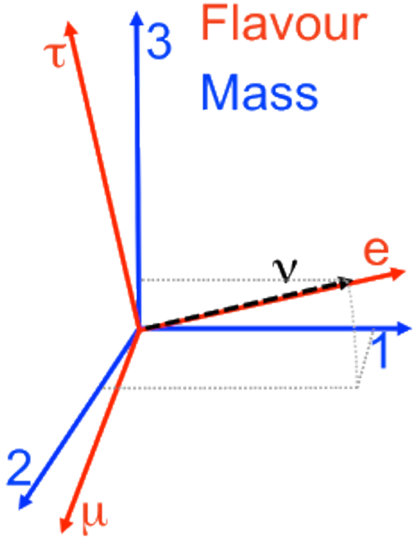
$$n \longrightarrow p + e^- + \bar{\nu}_e$$

Or they produce a lepton partner when they interact with matter:

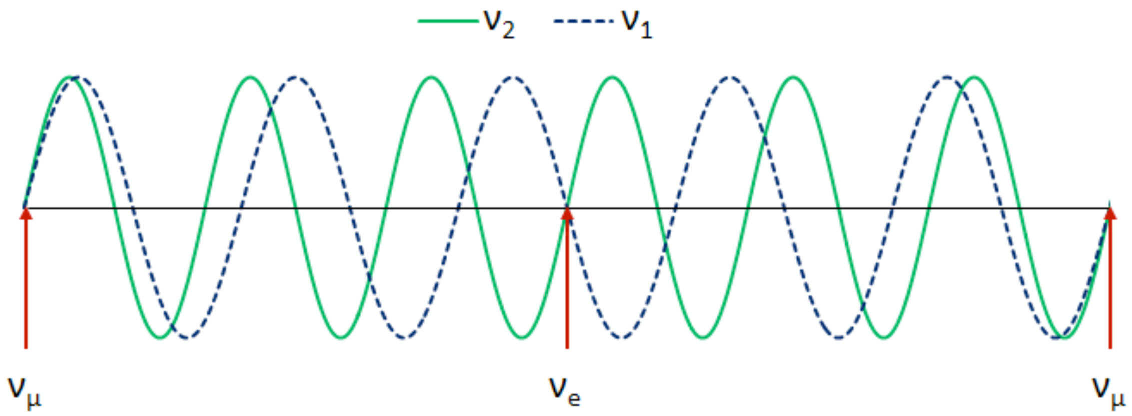


$$\nu_e + n \longrightarrow p + e^-$$

# About those neutrinos



Mismatch of mass eigenstates causes flavor oscillations:



Neutrinos oscillations:

Distance

$$P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(1.27\,\frac{\Delta m^2[\mathrm{eV}^2]\;L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

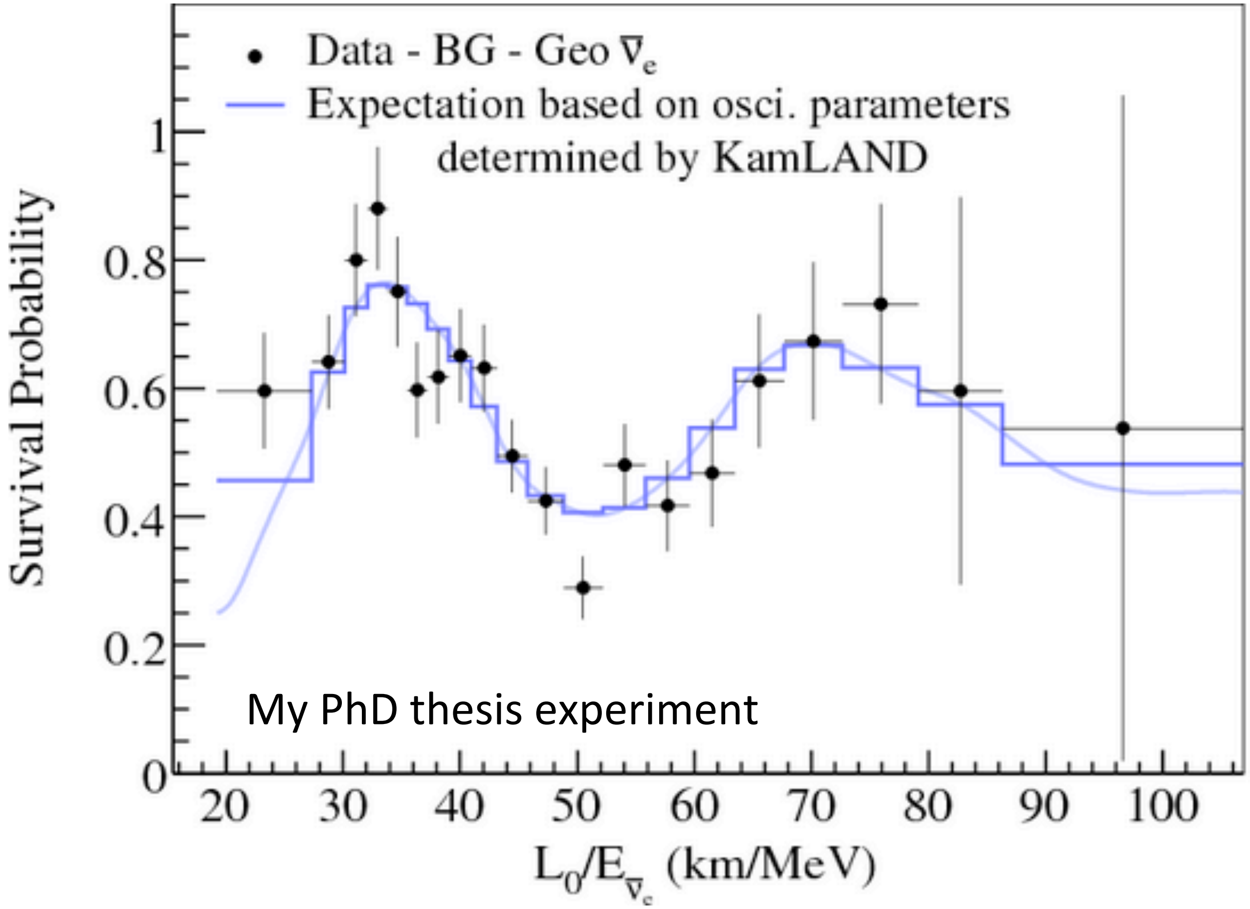
Energy

Non-zero squared-mass difference

$$\Delta m^2 = m_2^2 - m_1^2$$

# About those neutrinos

$$P_{\alpha\to\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\Delta m^2[\mathrm{eV}^2]\;L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

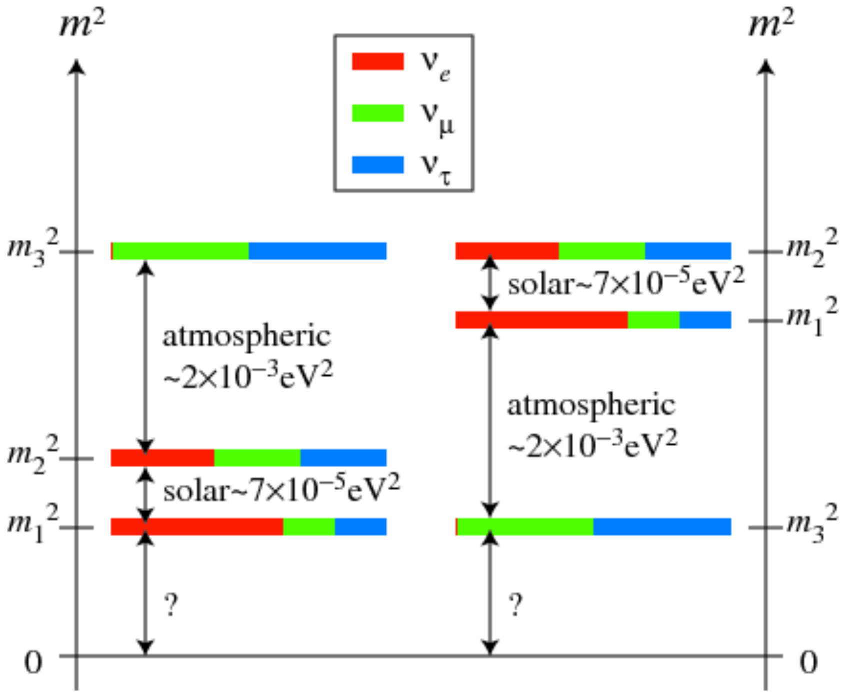


My PhD thesis experiment

# Big questions in the neutrino oscillation puzzle

Oscillation measurements are explained fairly well by three flavor picture.

$$\theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{21}, \Delta m^2_{32} (\approx \Delta m^2_{31})$$

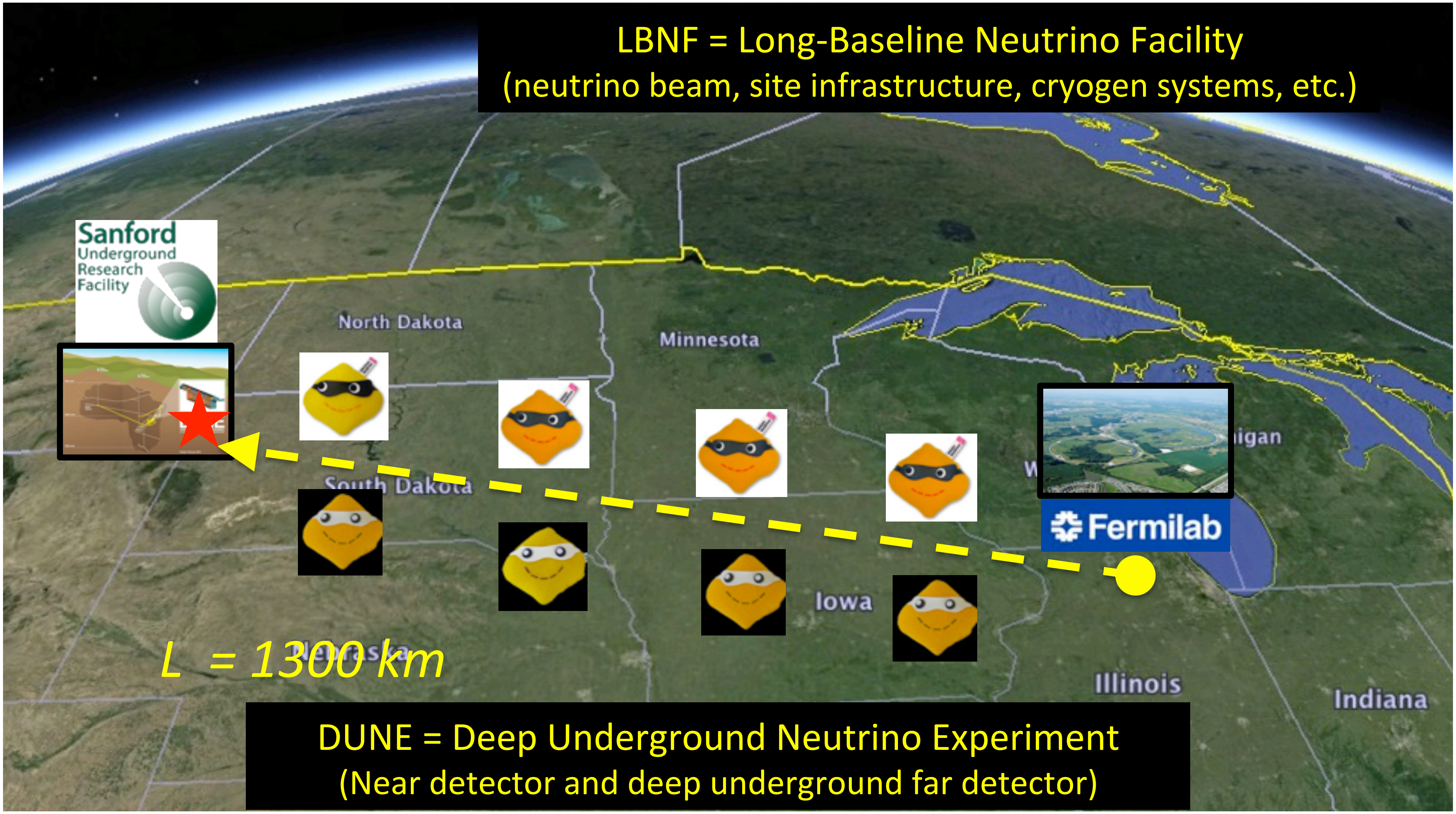


$$P(\nu_\alpha \rightarrow \nu_\beta) \overset{?}{=} P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta)$$

**Do neutrinos and anti-neutrinos oscillate differently?**

**What are the ordering of the mass states?**
**What is the overall scale?**

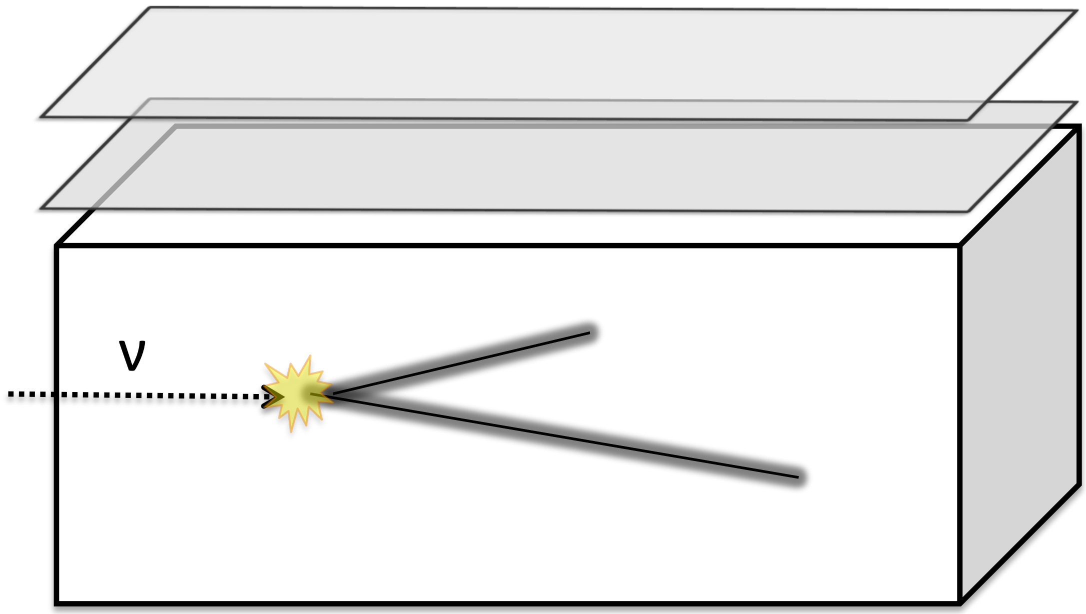
# DUNE and LBNF



LBNF = Long-Baseline Neutrino Facility
(neutrino beam, site infrastructure, cryogen systems, etc.)

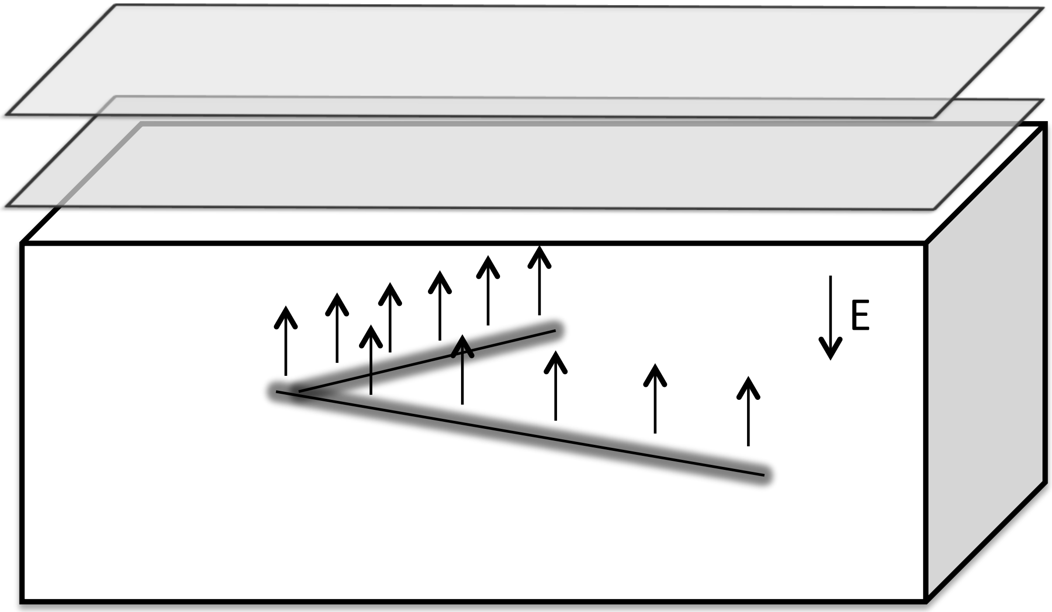
DUNE = Deep Underground Neutrino Experiment
(Near detector and deep underground far detector)

# DUNE Liquid Argon Time Projection Chamber



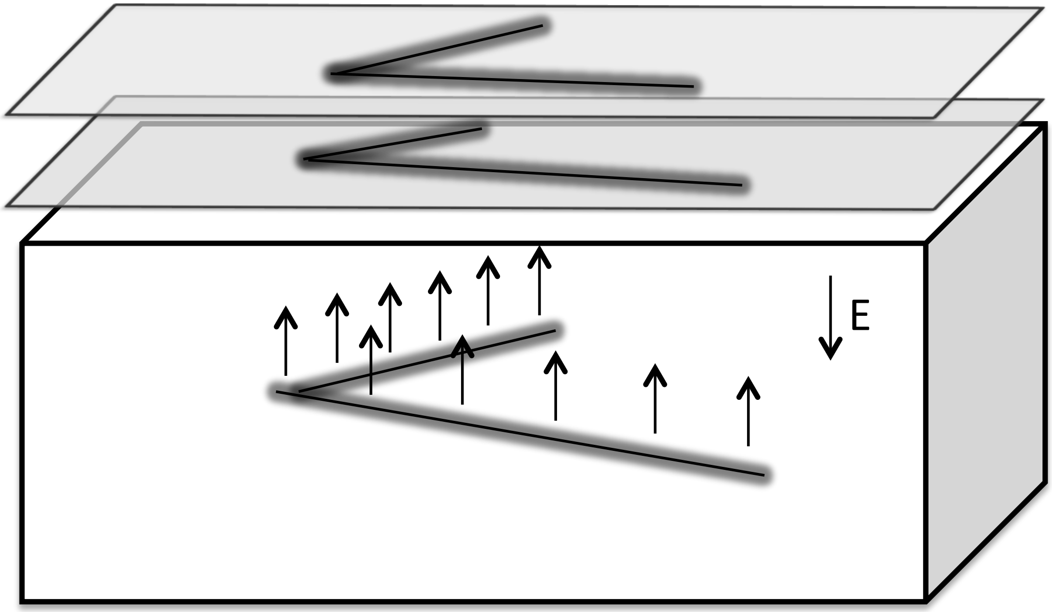
Neutrino interacts with argon to create charged particles which create ionization tracks

# DUNE Liquid Argon Time Projection Chamber



Electric field applied across the region drifts ionization charge to a series of wire planes

# DUNE Liquid Argon Time Projection Chamber



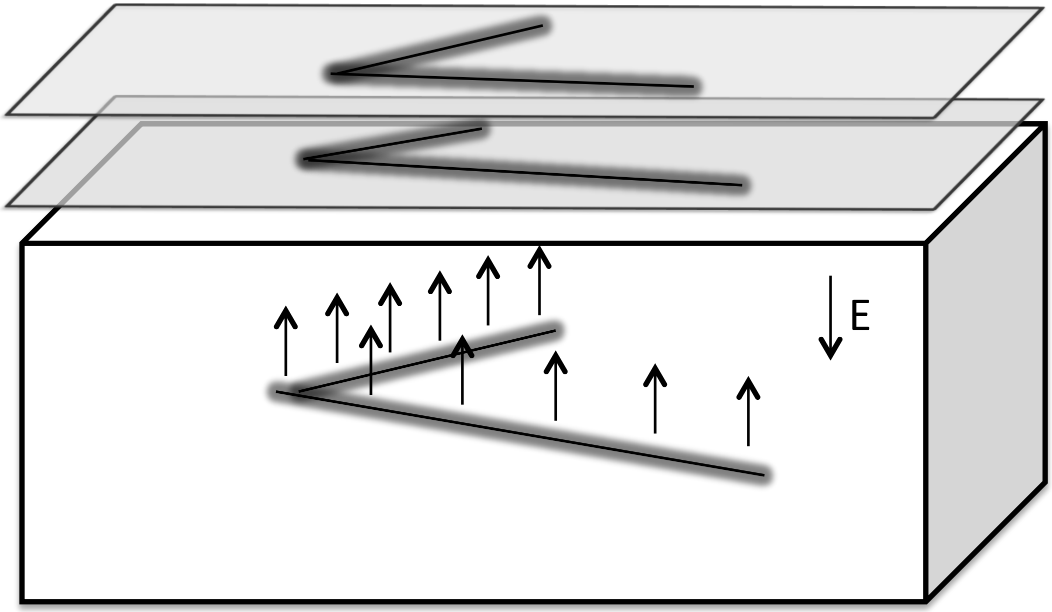
Charge collection = energy

Induction signal = position

+ time = 3D image of event

Electric field applied across the region drifts ionization charge to a series of wire planes

# DUNE Liquid Argon Time Projection Chamber



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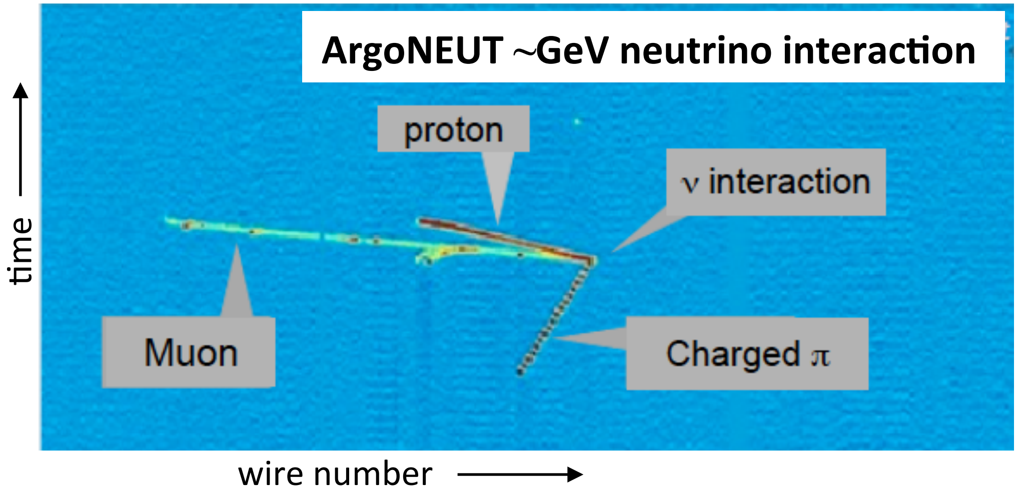
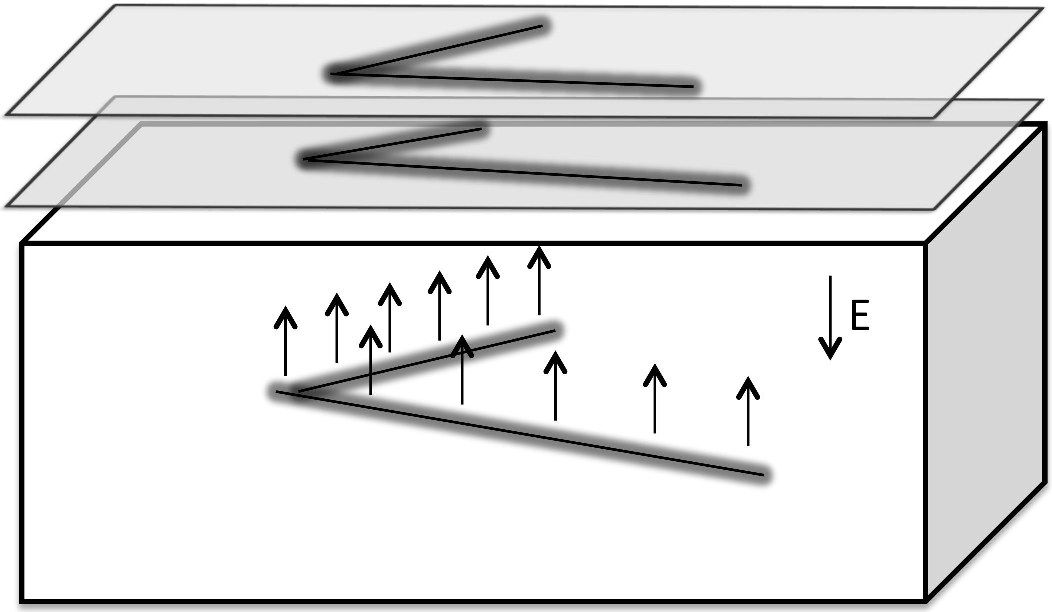

ArgoNEUT ~GeV neutrino interaction

# DUNE Liquid Argon Time Projection Chamber



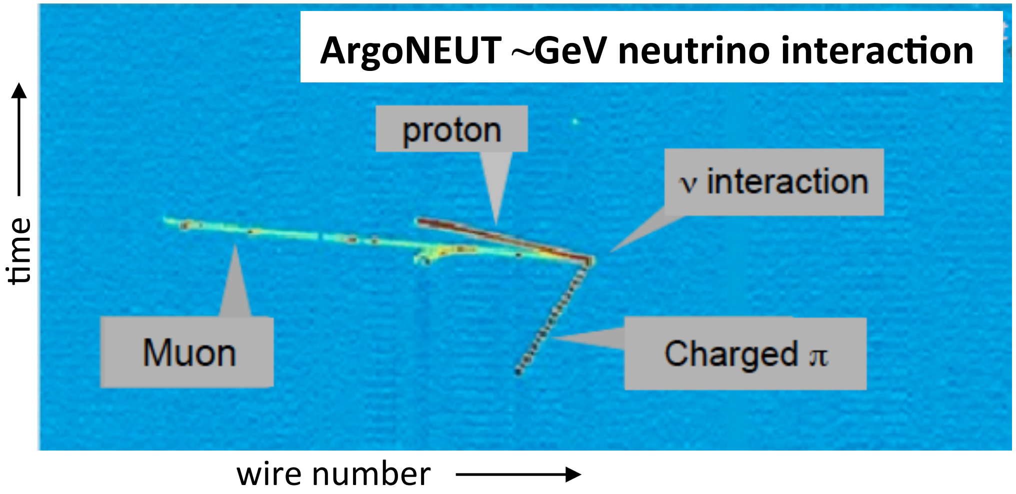
Charge collection = energy

Induction signal = position

+ time = 3D image of event

Scintillation light can be used for better timing precision:

Ionizing charge is slow (~ms timing)
Scintillation light is fast (~ns timing)


ArgoNEUT ~GeV neutrino interaction

# Major physics goals of DUNE:

1. Determine CP-violating phase
2. Neutrino mass hierarchy
3. Detect supernova neutrinos if one occurs

# DUNE supernova neutrino detection potential

Supernova at 10 kpc – outer edge of our galaxy, opposite our solar system

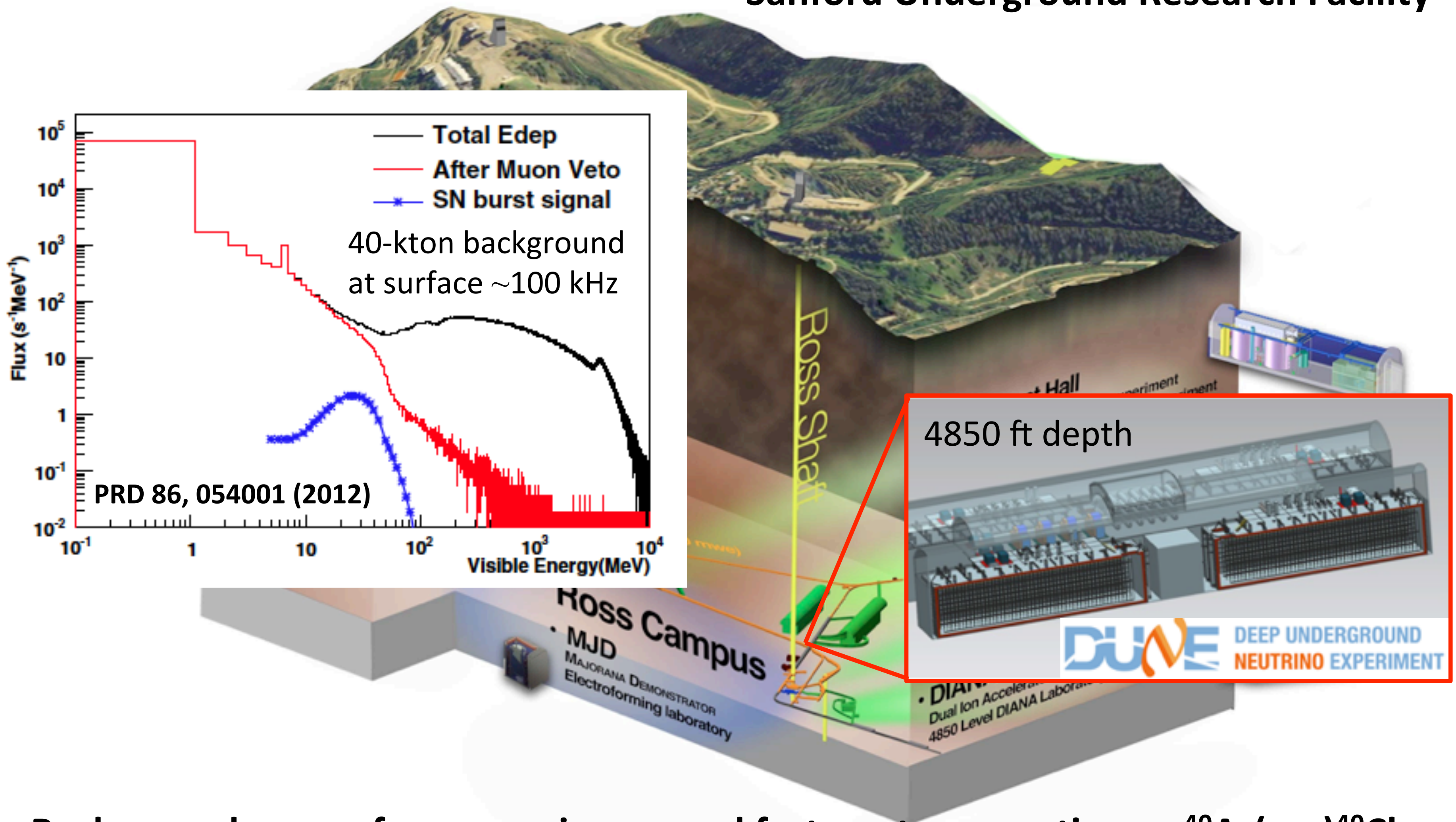
| Reaction Type | Events / 40 kt |
|---|---|
| (CC) $\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$ | ~2800 |
| (CC) $\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Cl}^* + e^+$ | ~240 |
| (ES) $\nu + e^- \rightarrow \nu + e^-$ | ~340 |
| (NC) $\nu + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ar}^* + \nu'$ | ~360 |

**DUNE would have unique sensitivity to electron flavored SN neutrinos – can probe the neutronization at the onset of the burst**

Remember: water and scintillator detectors (inverse beta decay) are mainly sensitive to cooling $\bar{\nu}_e$.

# Backgrounds at SURF 4850 ft level

**Sanford Underground Research Facility**



40-kton background at surface ~100 kHz

PRD 86, 054001 (2012)

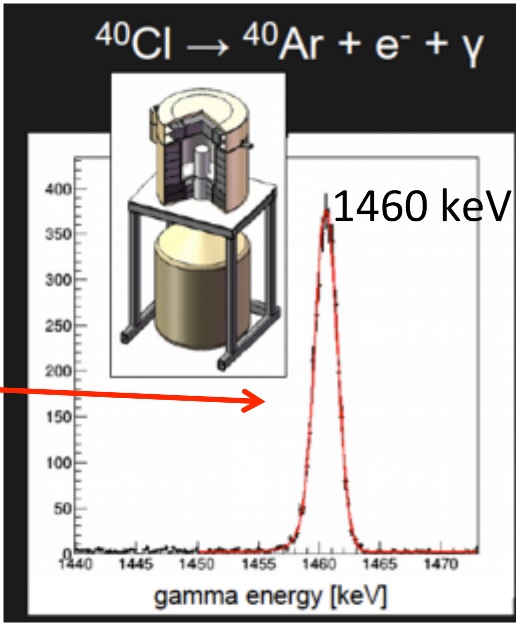
4850 ft depth

**Backgrounds come from cosmic rays and fast neutron reactions – $^{40}$Ar(n,p)$^{40}$Cl**

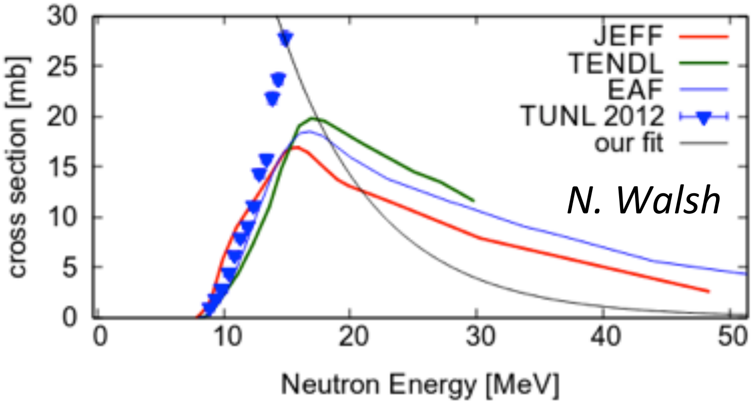
# Constraining (n,p) backgrounds at 4850 ft level

*C. Grant, N. Walsh, A. Manalaysay, E. Pantic, R. Svoboda*

**BACON**
**(Bucket of Argon COunting Neutrons)**



Designed a neutron target at the Crocker Cyclotron and measure the $^{40}$Ar(n,p)$^{40}$Cl cross-section up to 50 MeV – originally measured only up to 15 MeV.



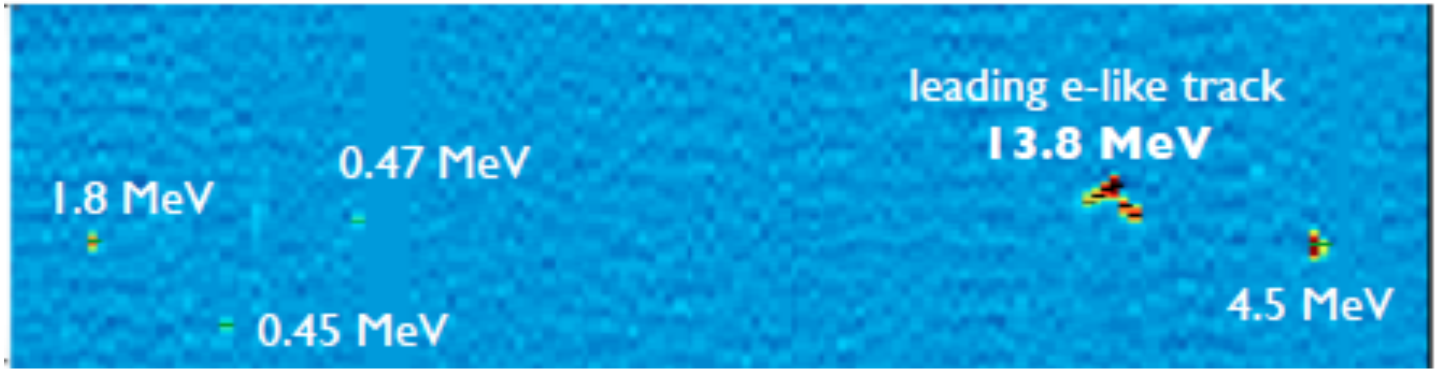
**~50 background events per day inside 40-kton at 4850 ft depth**

# Low-energy electrons and gammas in a liquid argon TPC

Charged-current absorption:

$$\nu_e + {}^{40}\text{Ar} \to {}^{40}\text{K}^* + e^-$$

Looking for possible “blips” and “dots” of neutrino-induced *radioactivity*



(simulated low-energy electron and gamma data from C. Adams)

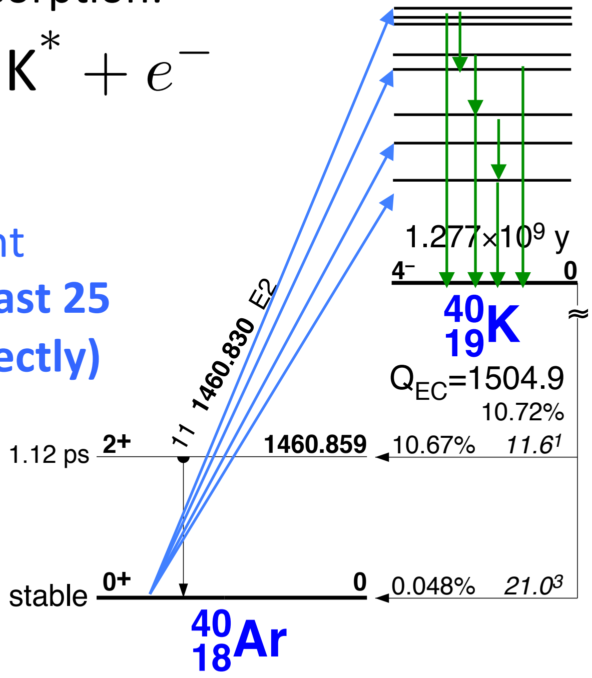
**This is what we think we’re looking for…but it’s not very obvious!**

# Low-energy neutrino interactions on argon

Charged-current absorption:

$$\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$$

We need to know dominant transition intensities **(at least 25 transitions observed indirectly)**



This also means knowing all the de-excitation gammas/ nucleons **(sparse data for gammas and NO DATA FOR NUCLEON EMISSION)**

# Low-energy neutrino interactions on argon

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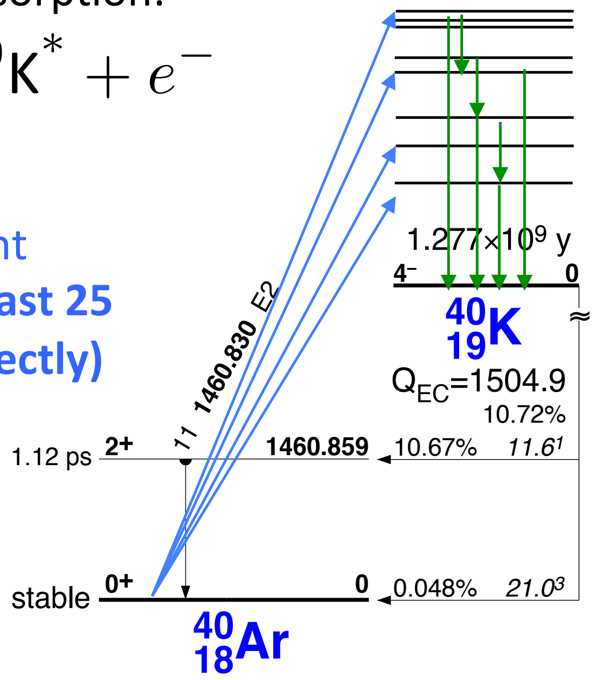


This also means knowing all the de-excitation gammas/ nucleons **(sparse data for gammas and NO DATA FOR NUCLEON EMISSION)**

Recoil Energy of Nucleus (negligible)

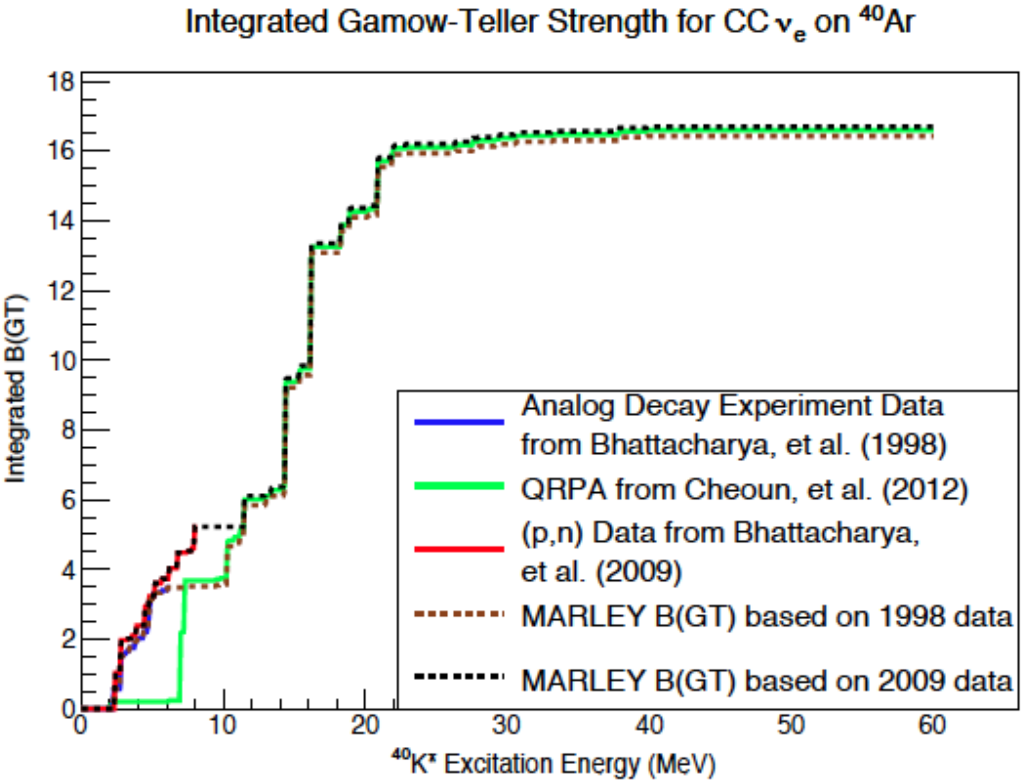
**Reconstructing true neutrino energy:** $E_\nu = E_e + Q + K_{\text{recoil}}$

Outgoing Electron Energy

Energy donated to transition

# MARLEY (Model of Argon Reaction Low-Energy Yields)

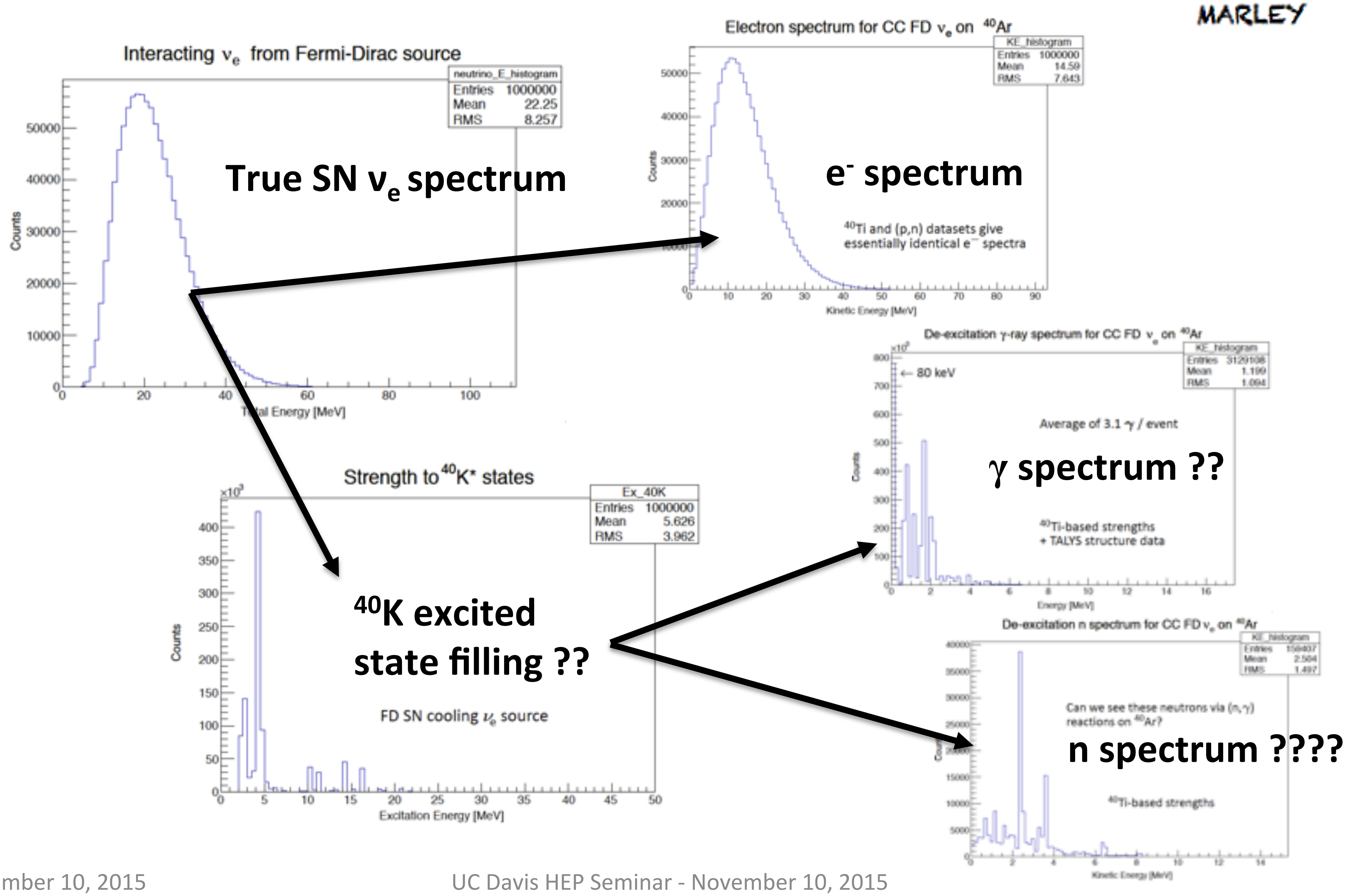
*S. Gardiner, K. Bilton, C. Grant, E. Pantic, R. Svoboda*



***MARLEY tries to model argon reactions to the best of our knowledge, but it needs to be tuned with real data***

# MARLEY (Model of Argon Reaction Low-Energy Yields)

*S. Gardiner, K. Bilton, C. Grant, E. Pantić, R. Svoboda*



**True SN $\nu_e$ spectrum**

**$e^-$ spectrum**

$^{40}$Ti and (p,n) datasets give essentially identical $e^-$ spectra

Average of 3.1 γ / event

**γ spectrum ??**

$^{40}$Ti-based strengths
+ TALYS structure data

**$^{40}$K excited state filling ??**

FD SN cooling $\nu_e$ source

Can we see these neutrons via (n,γ) reactions on $^{40}$Ar?

**n spectrum ????**

$^{40}$Ti-based strengths

# MARLEY (Model of Argon Reaction Low-Energy Yields)

*S. Gardiner, K. Bilton, C. Grant, E. Pantic, R. Svoboda*

MARLEY modeling uncertainties come from the following:

1. Only indirect measurements of the $^{40}K$ state filling are available, and different measurements have poor agreement
2. Sparse data for de-excitation gammas
3. No data whatsoever for nucleon emission (big issue for neutrinos above 12 MeV)

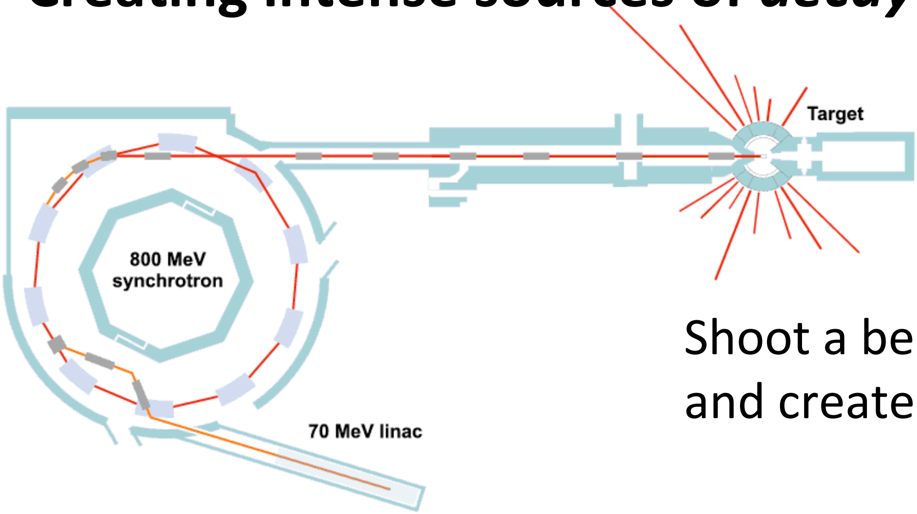
**We really don't know exactly what we're looking for in DUNE!**

**Two challenges to address:**

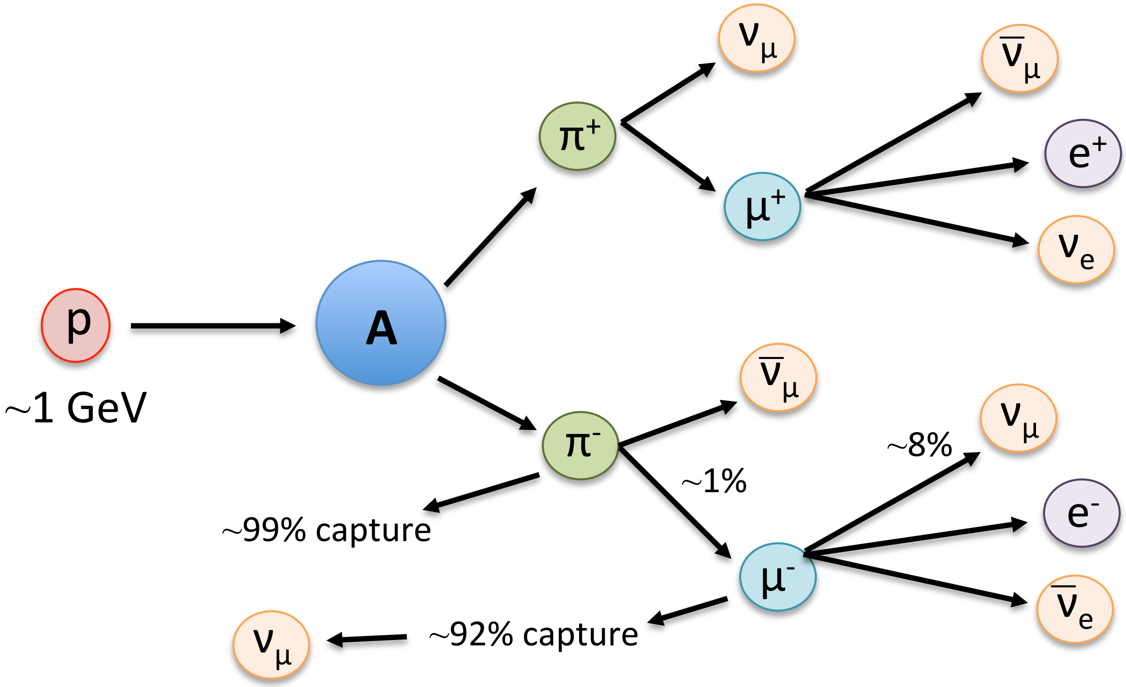
1. Physics of low-energy argon-nucleus reactions
2. 10-kiloton detector operation and design

**Can't we just directly measure low-energy neutrino reactions in argon? Best to try with a small detector.**

# Creating intense sources of *decay-at-rest* neutrinos



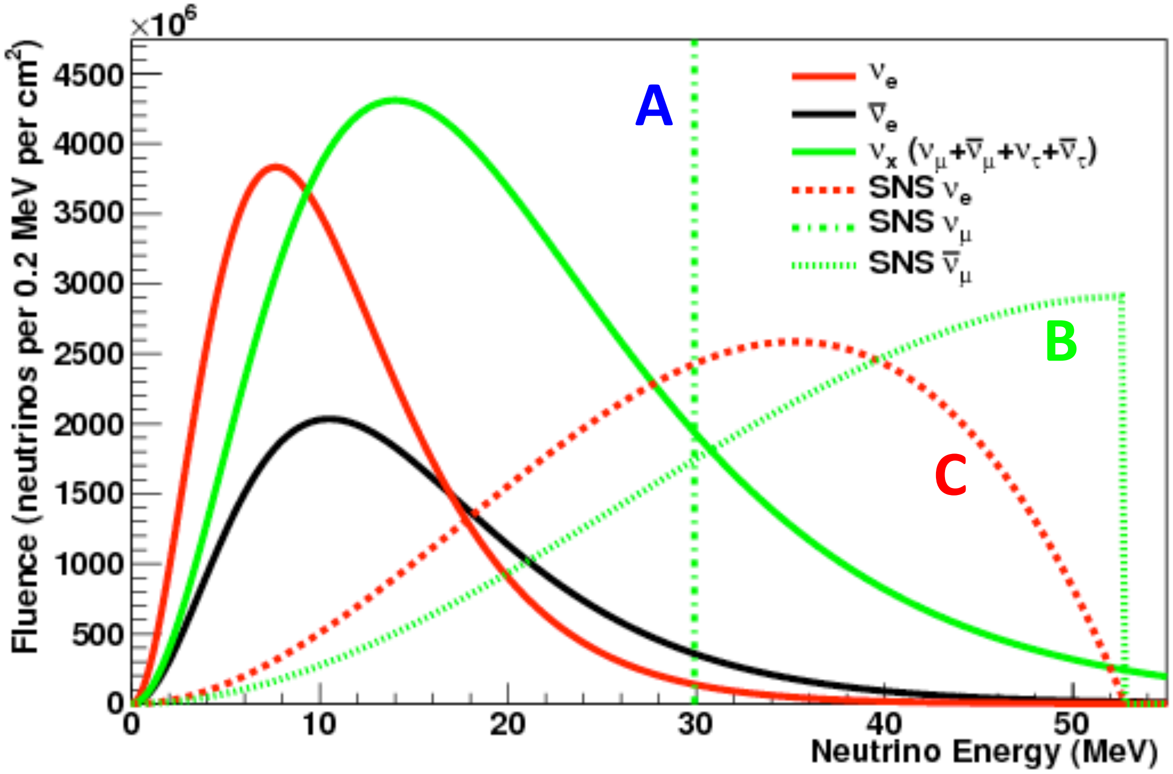
Shoot a beam of ~1 GeV protons onto a target and create lots of stopped pions:

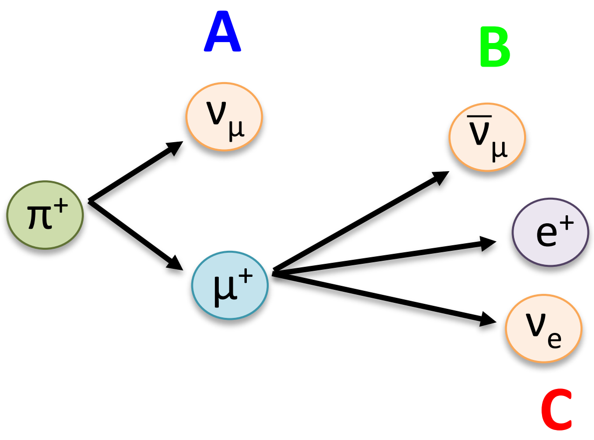


Isotropic emission of mainly:

$\nu_\mu$ $\bar{\nu}_\mu$ $\nu_e$

# Pion and muon decay-at-rest spectra



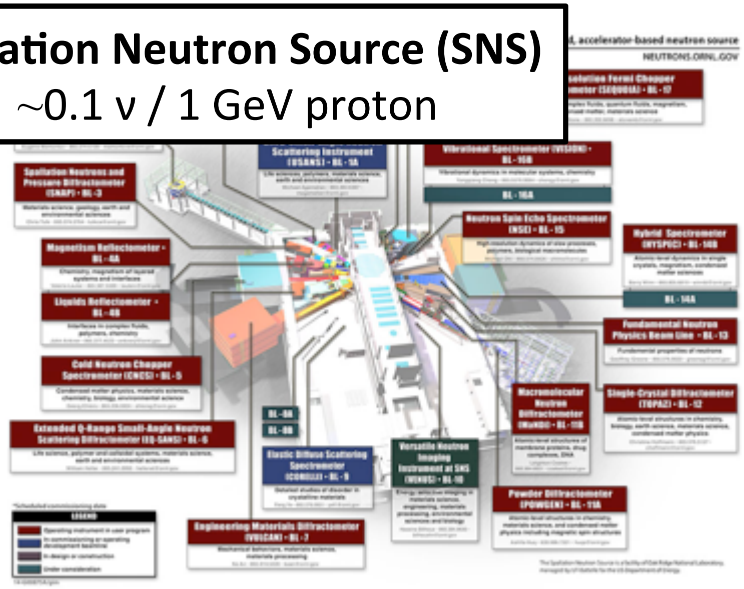


# Modern beam-stop facilities

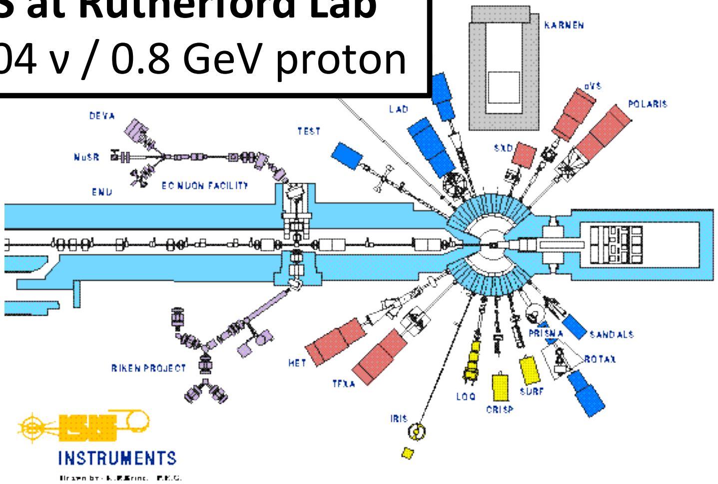
There are several beam stop facilities currently available around the world.

Beam powers are 160 kW – 1.4 MW

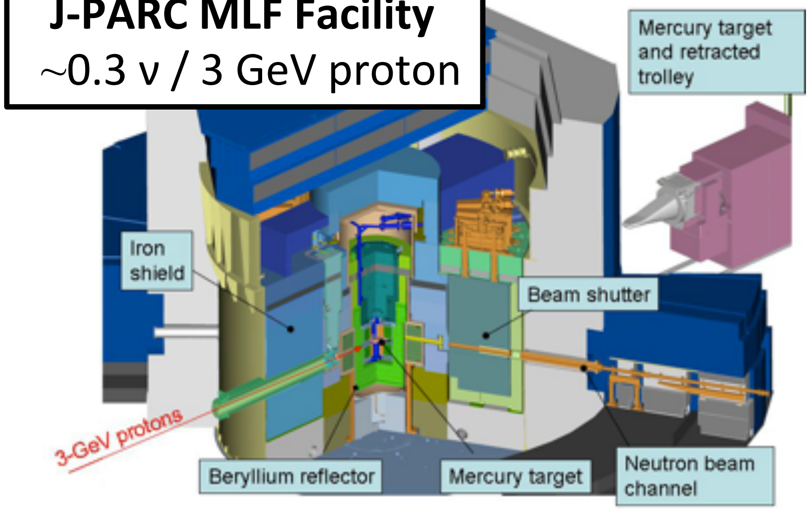
**Spallation Neutron Source (SNS)**
~0.1 ν / 1 GeV proton



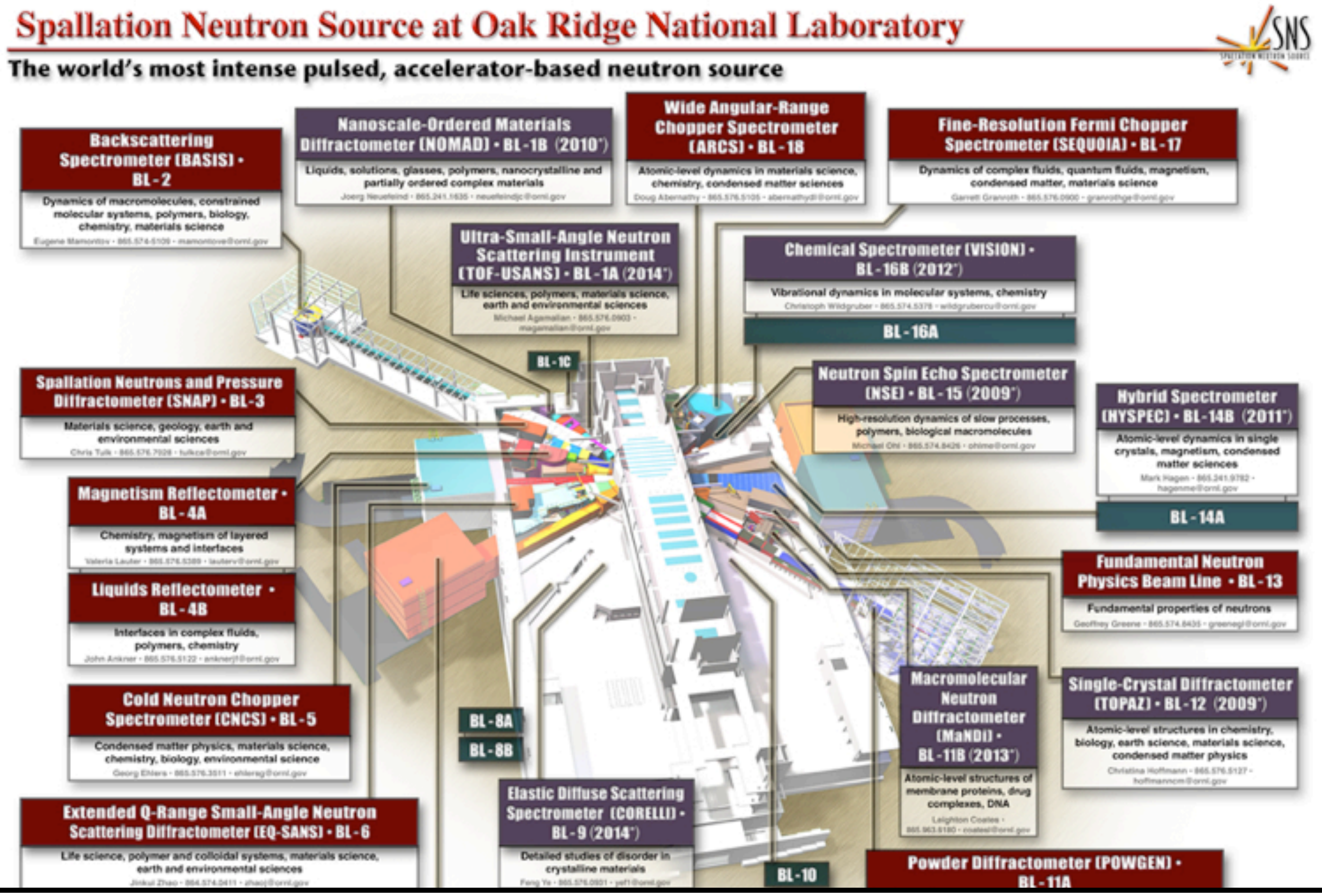
**ISIS at Rutherford Lab**
~0.04 ν / 0.8 GeV proton



**J-PARC MLF Facility**
~0.3 ν / 3 GeV proton



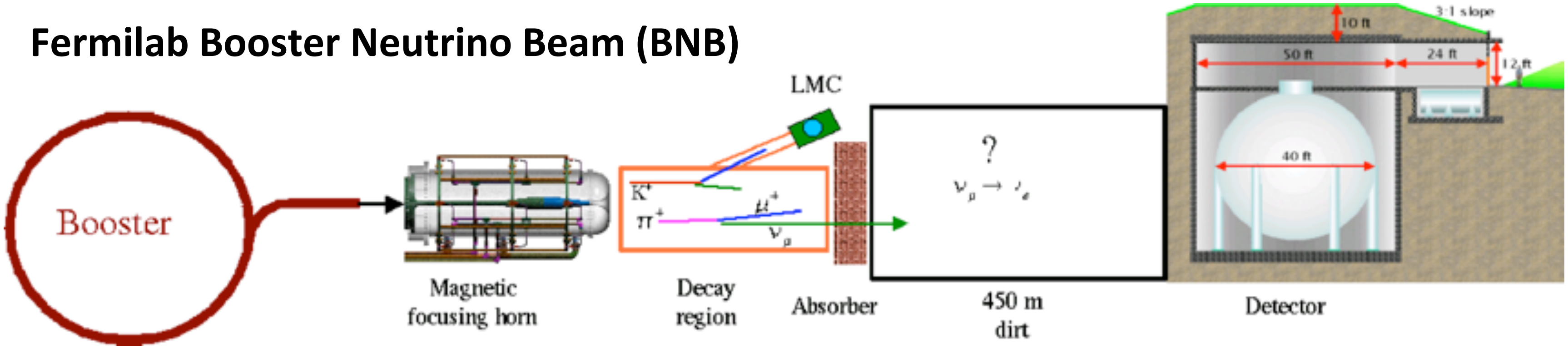
## Modern beam-stop facilities



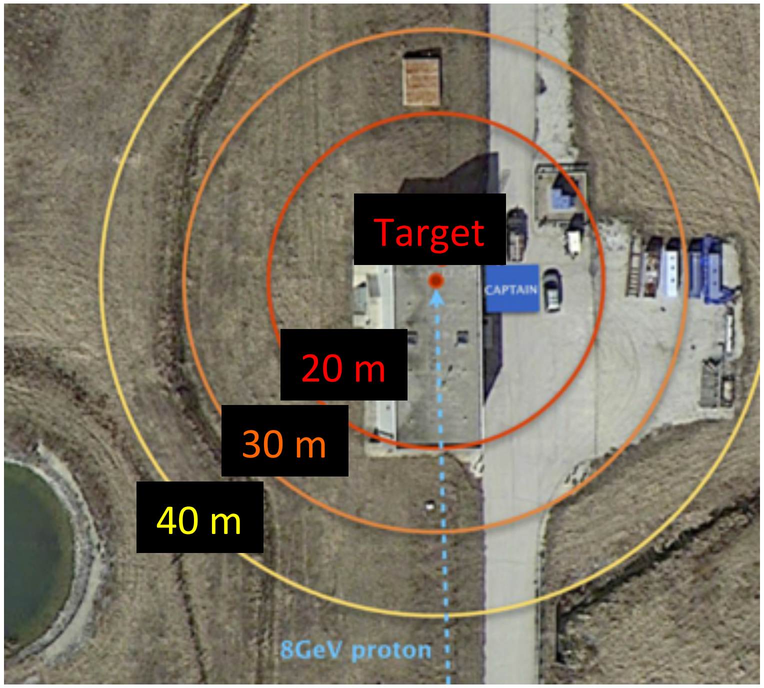
The real estate near the source is taken up by many other experiments.
Closest proximity ~60 meters away from source.

# Decay-in-flight facilities

**Fermilab Booster Neutrino Beam (BNB)**



*8 GeV protons onto beryllium target*
*Typically running at 16 kW beam power*



Decay-at-rest neutrino production occurs for pions and kaons that stop in the shielding near the target.

Can get within ~12 m proximity, but the beam power is much lower.

# Neutrino event rate comparison

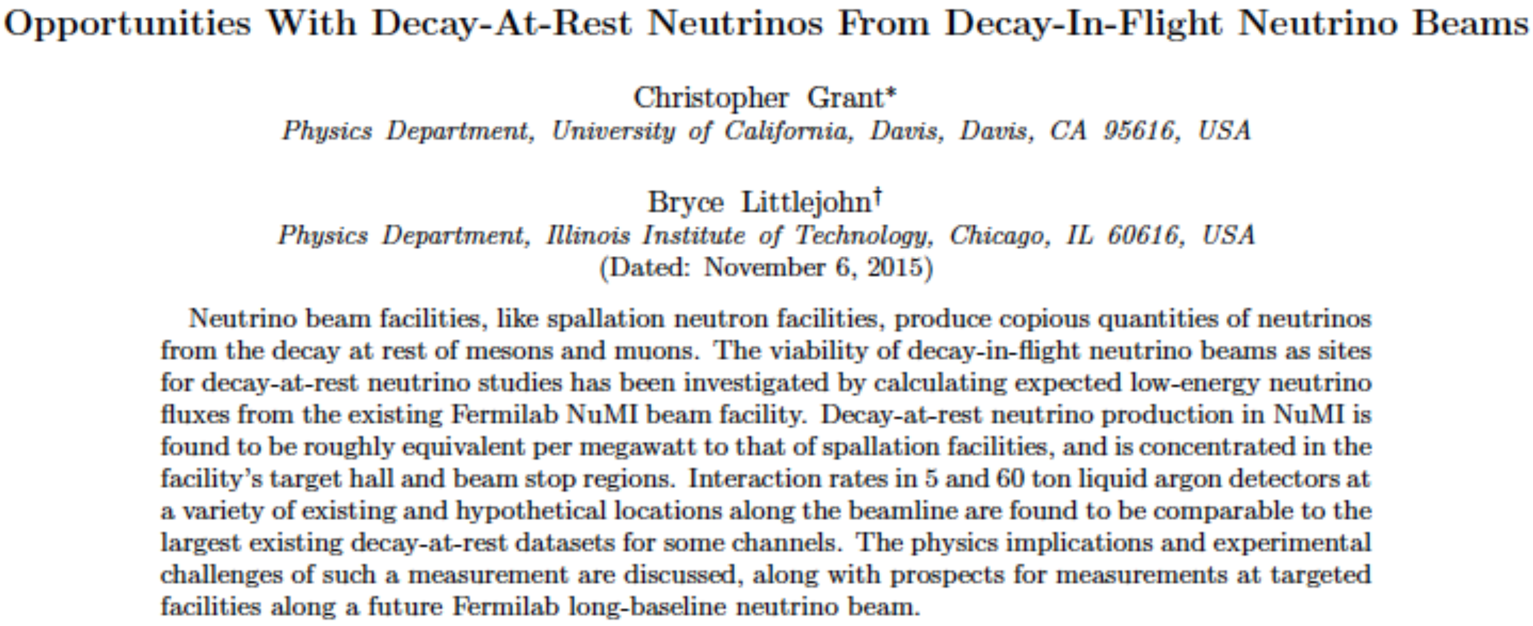
| | | |
|---|---|---|
| **Facility:** | **Spallation Neutron Source** | **Booster Neutrino Beam** |
| **Source:** | 1 GeV and 1.4 MW beam | 8 GeV and 16 kW beam |
| **Closest Proximity:** | ~60 meters | ~12 meters |
| **CC $\nu_e$ interaction rate in 5-ton liquid argon:** | 340 events / year | 350 events / year |

*No assumptions about detection efficiencies have been made*

**The source-detector distance from SNS makes the BNB event rate look good**

**Is this the best we can do? It would take a long time to accumulate thousands of events.**

# But there’s more…



## Opportunities With Decay-At-Rest Neutrinos From Decay-In-Flight Neutrino Beams

Christopher Grant*
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Bryce Littlejohn†
*Physics Department, Illinois Institute of Technology, Chicago, IL 60616, USA*

(Dated: November 6, 2015)

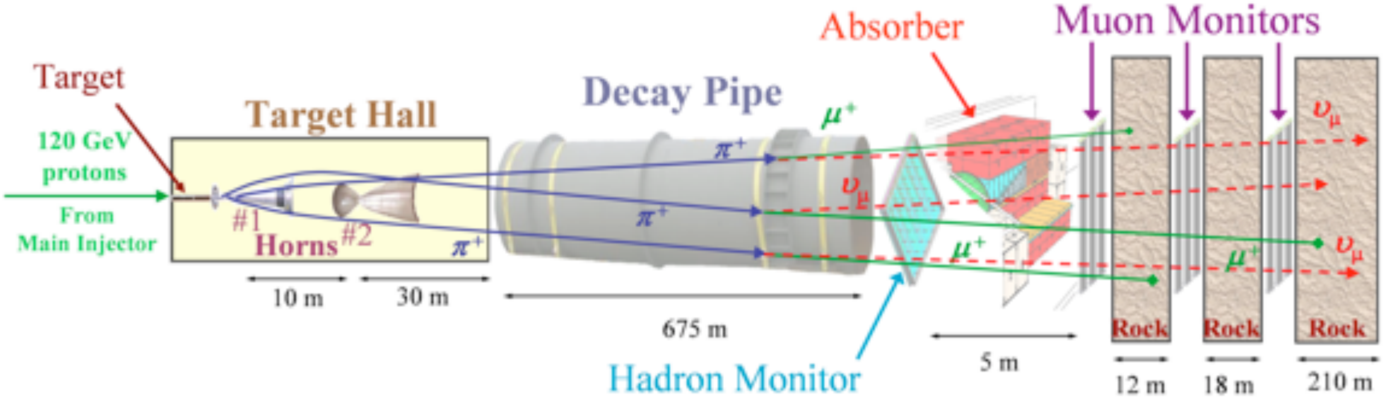
Neutrino beam facilities, like spallation neutron facilities, produce copious quantities of neutrinos from the decay at rest of mesons and muons. The viability of decay-in-flight neutrino beams as sites for decay-at-rest neutrino studies has been investigated by calculating expected low-energy neutrino fluxes from the existing Fermilab NuMI beam facility. Decay-at-rest neutrino production in NuMI is found to be roughly equivalent per megawatt to that of spallation facilities, and is concentrated in the facility’s target hall and beam stop regions. Interaction rates in 5 and 60 ton liquid argon detectors at a variety of existing and hypothetical locations along the beamline are found to be comparable to the largest existing decay-at-rest datasets for some channels. The physics implications and experimental challenges of such a measurement are discussed, along with prospects for measurements at targeted facilities along a future Fermilab long-baseline neutrino beam.

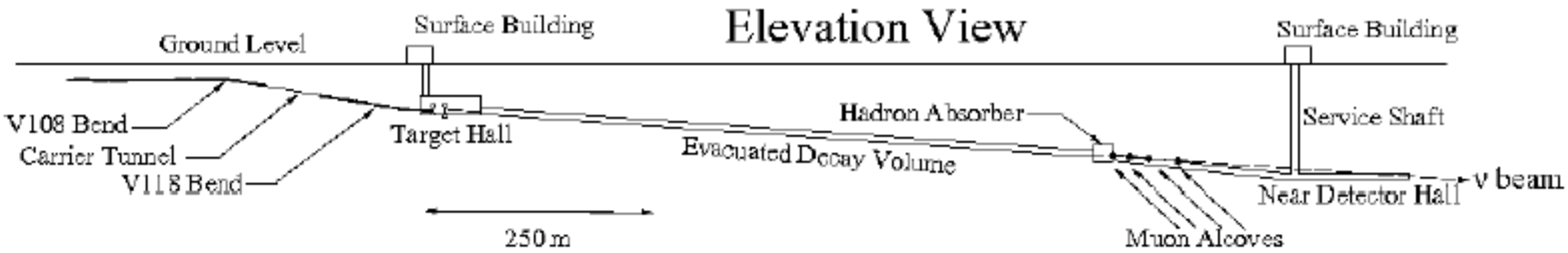
**C. Grant and B. Littlejohn, arXiv:1510.08431**

*Being submitted to Phys. Rev. Lett.*

# NuMI beamline decay-at-rest production

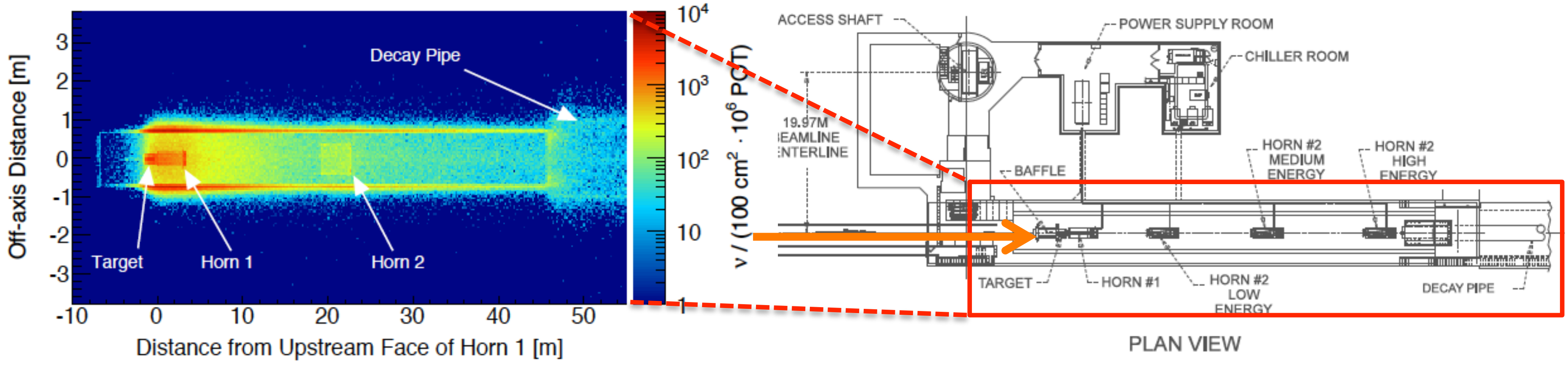
*120 GeV protons on carbon target*
*Upgrade to 700 kW expected in at the end of 2016*

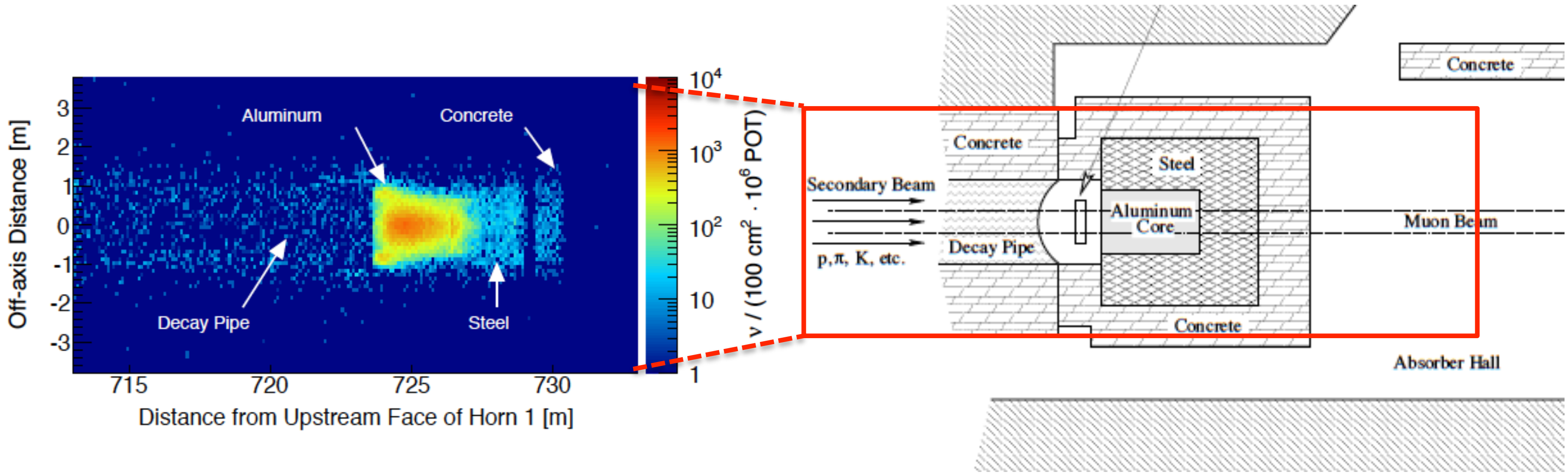




Target is at ~40 m depth Absorber is at ~80 m depth

# Neutrino production along the beam line

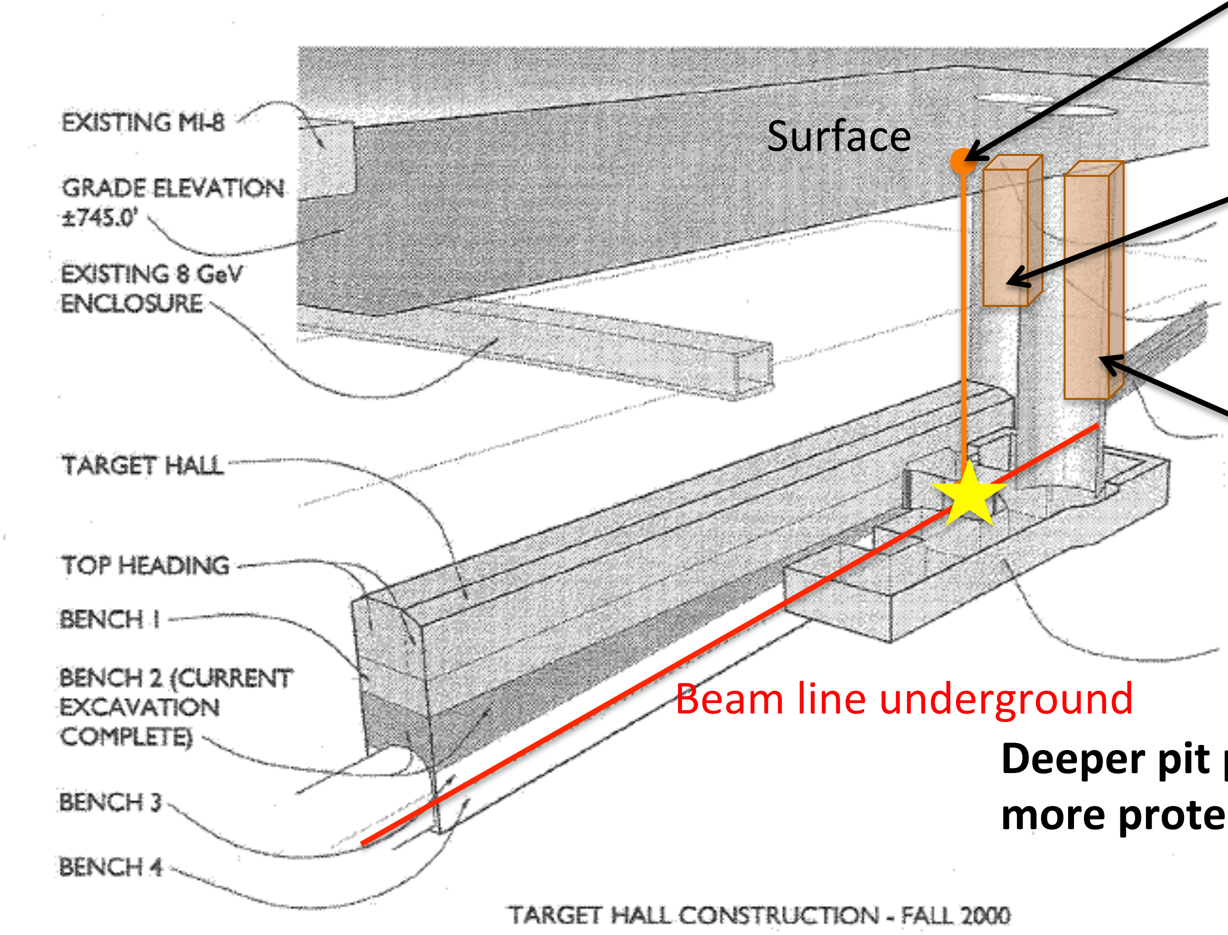




**C. Grant and B. Littlejohn, arXiv:1510.08431**

***41 stopped ν per proton on target!***

# Potential detector positions near the NuMI target



TARGET HALL CONSTRUCTION - FALL 2000

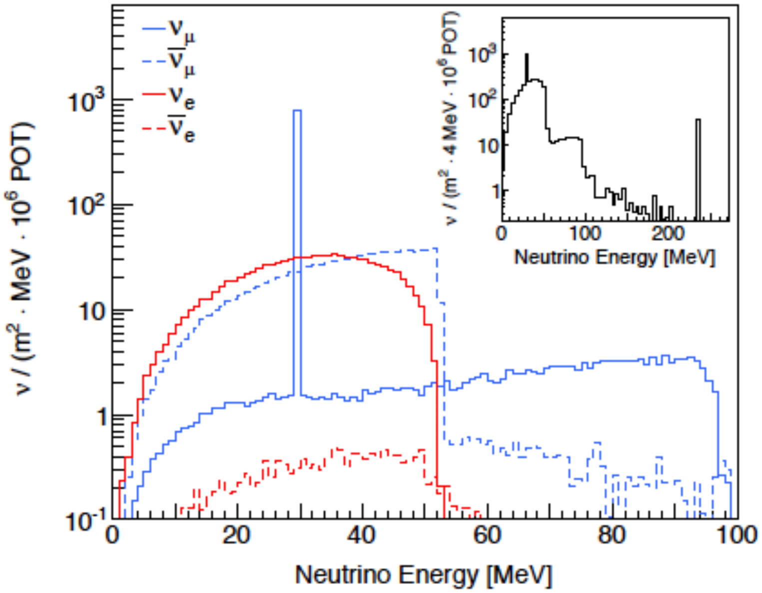
~40 m away from target (no excavation)

~30 m away from target (minor excavation)

~25 m away from target (moderate excavation)

**Deeper pit provides better flux and more protection from cosmic rays**

# NuMI event rate comparison with other facilities



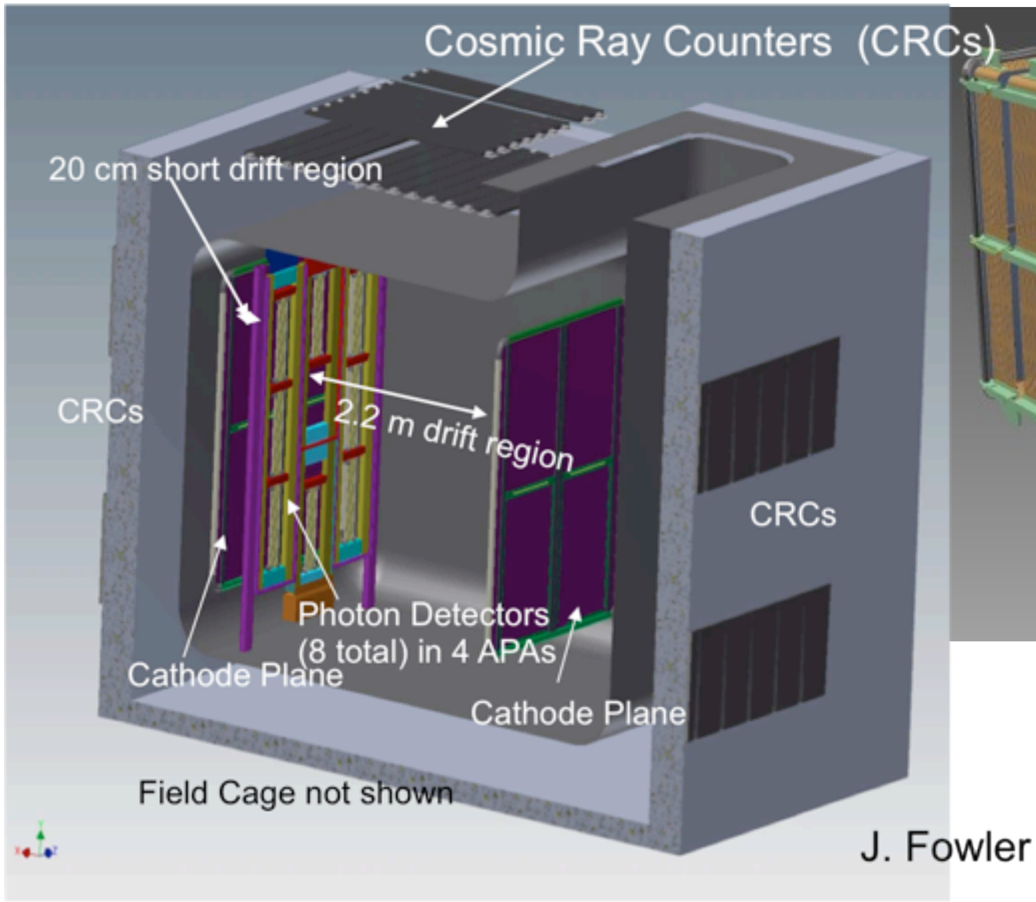
**More than a factor of 3x increase in event rate compared to SNS and BNB can be obtained at 25 meters from the NuMI target**

**C. Grant and B. Littlejohn, arXiv:1510.08431**

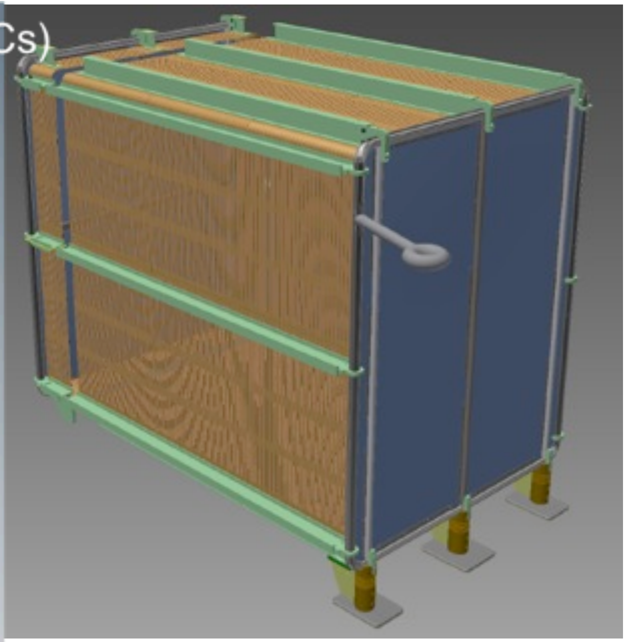
| | |
|---|---|
| **Facility:** | **NuMI** |
| **Source:** | 120 GeV and 700 kW beam |
| **CC $\nu_e$ interaction rate in 5 t liquid argon:** | 490 events / year @ 40 meters<br>810 events / year @ 30 meters<br>1,100 events / year @ 25 meters |

# Thinking bigger…

**DUNE 35-ton prototype**



**10-ton instrumented TPC**

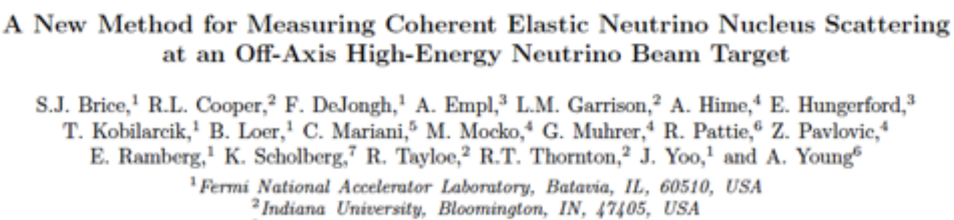


*Currently operating and taking data at Fermilab*

**2,200 CC $\nu_e$ events per year at 25 meters from the NuMI target!**

# Additional physics opportunities - CENNS

**Phys. Rev. D 89, 072004**



A New Method for Measuring Coherent Elastic Neutrino Nucleus Scattering
at an Off-Axis High-Energy Neutrino Beam Target

S.J. Brice,[1] R.L. Cooper,[2] F. DeJongh,[1] A. Empl,[3] L.M. Garrison,[2] A. Hime,[4] E. Hungerford,[3]
T. Kobilarcik,[1] B. Loer,[1] C. Mariani,[5] M. Mocko,[4] G. Muhrer,[4] R. Pattie,[6] Z. Pavlovic,[4]
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[5] *Virginia Tech, Blacksburg, VA 24061, USA*
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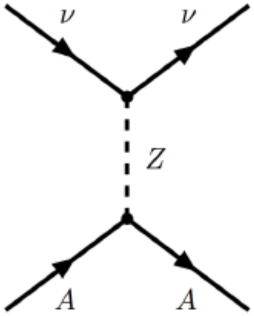
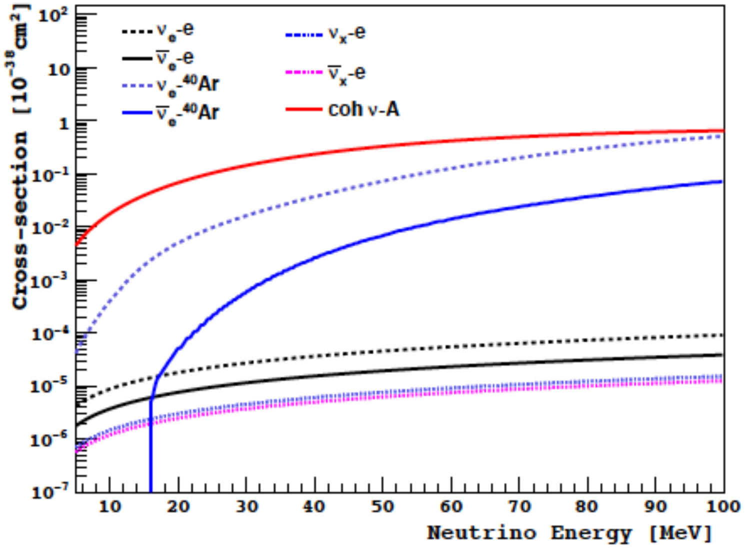


$\sigma \sim (\#\ \text{neutrons})^2$



Proposed a ton-scale liquid argon detector at BNB to measure coherent elastic neutrino-nucleus scattering – **predicted by Standard Model but has never been directly observed**

CENNS could play a major role in the explosion of a core-collapse SN, as predicted by numerical simulations - **Ann. Rev. Nucl. Sci. 27, 167 (1977)**

**At least a factor 3 boost in sensitivity for this detector near NuMI (300 events per year to 900 events per year)**

# Additional physics opportunities – Sterile Neutrinos

PHYSICAL REVIEW D 85, 093020 (2012)

**Sterile neutrino search with kaon decay at rest**

J. Spitz

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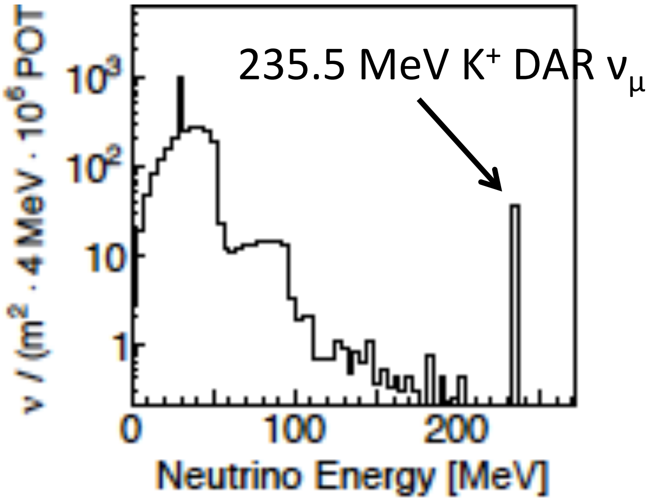
(Received 2 April 2012; published 31 May 2012)



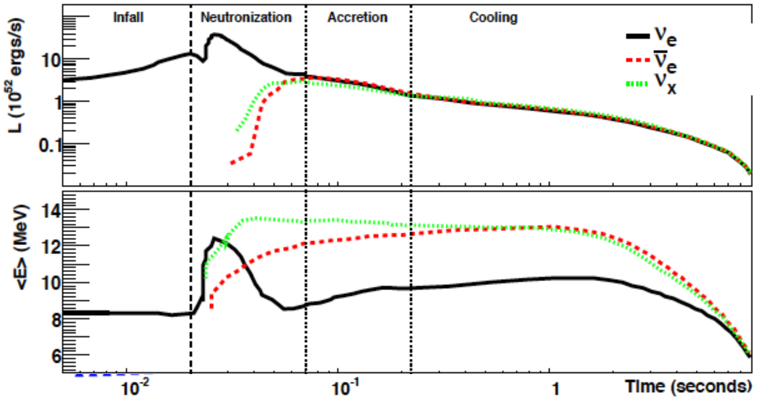
**C. Grant and B. Littlejohn, arXiv:1510.08431**

Probe conflicting results by an experiment called LSND that observed a 3.8σ excess of $\bar{\nu}_e$ events from a decay-at-rest $\bar{\nu}_\mu$ source.

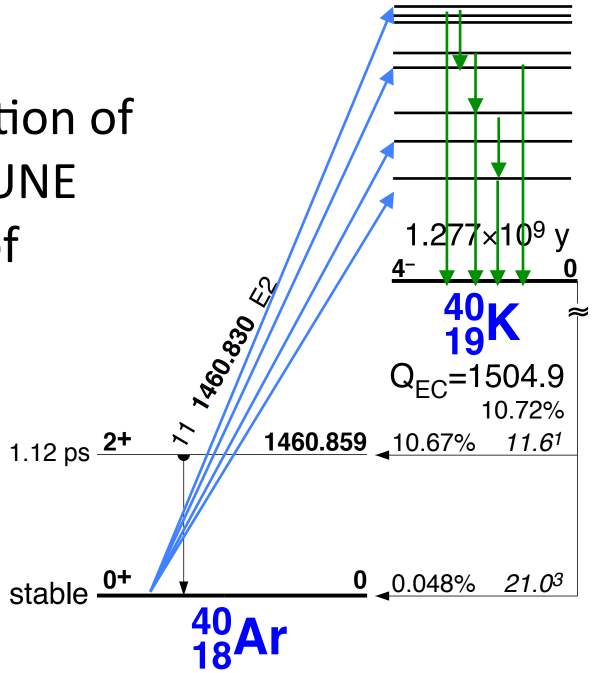
Proposal to use a **2-kton liquid argon TPC** at 160 meters from the BNB target to confirm or refute the existence of sterile neutrinos.

**Instead, a similar sensitivity could be obtained from a ~600 ton liquid argon detector 160 meters away from NuMI (existing ICARUS detector is 600 tons)**

# Summary and Conclusions

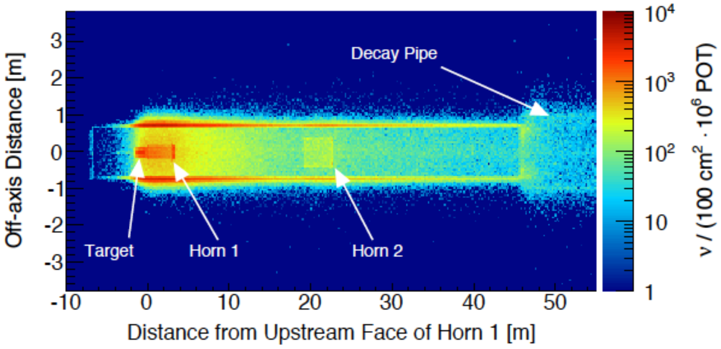


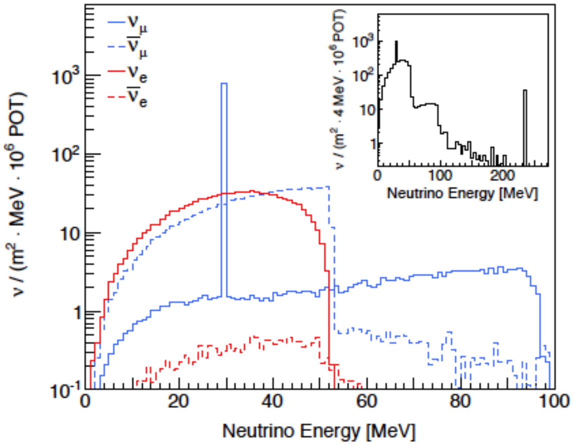
Supernova neutrinos carry a wealth of information about the onset of the burst.



Successful detection and interpretation of the data from an experiment like DUNE relies on a detailed understanding of neutrino-Argon reactions.

# Summary and Conclusions





A 10-ton demonstrator near the NuMI target at Fermilab would provide thousands of low-energy interactions to study for the very first time.

Future facilities should be considered near intense decay-in-flight beams, instead of allowing these wonderful source of decay-at-rest neutrinos to simply evaporate up into the cosmos!

**2.4 MW beam, similar to NuMI is being designed for DUNE!**

Let’s not miss the next one!