Recent Results from Neutrino and Dark Matter Experiments

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XVIII Mexican School of Particles and Fields

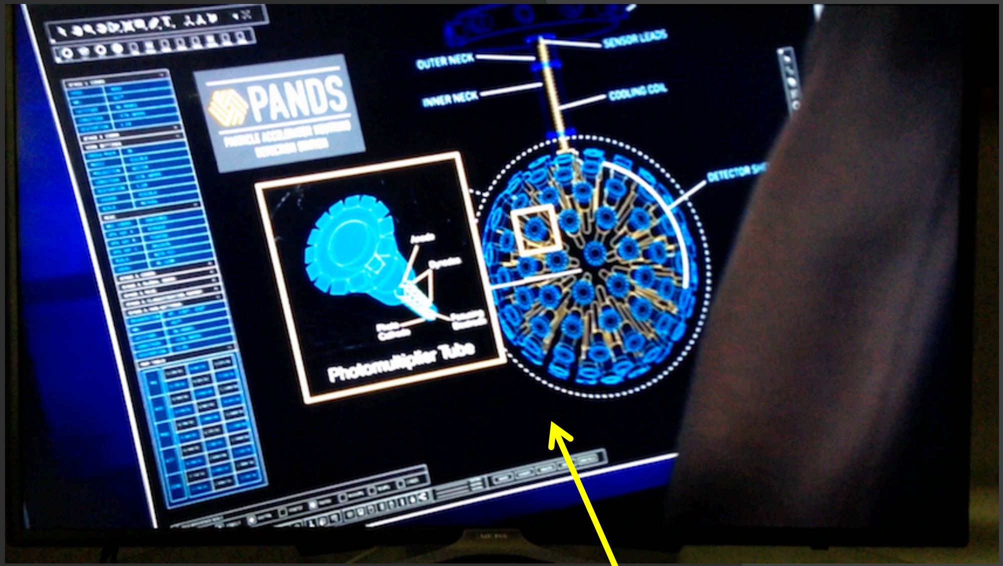
October 23, 2018

Neutrino Physics is a big field now!

- Neutrino oscillations
    - Long baseline
    - Short baseline
    - Accelerator
    - Reactor
    - Atmospheric
- Neutrino mass
    - Direct mass measurements
    - Double beta decay
    - Neutrino mass theory (and mixing matrix theory)
- Neutrino sources from nature
    - Solar
    - Geo
    - Supernova
    - Astrophysical energetic sources (e.g. AGN blazars)

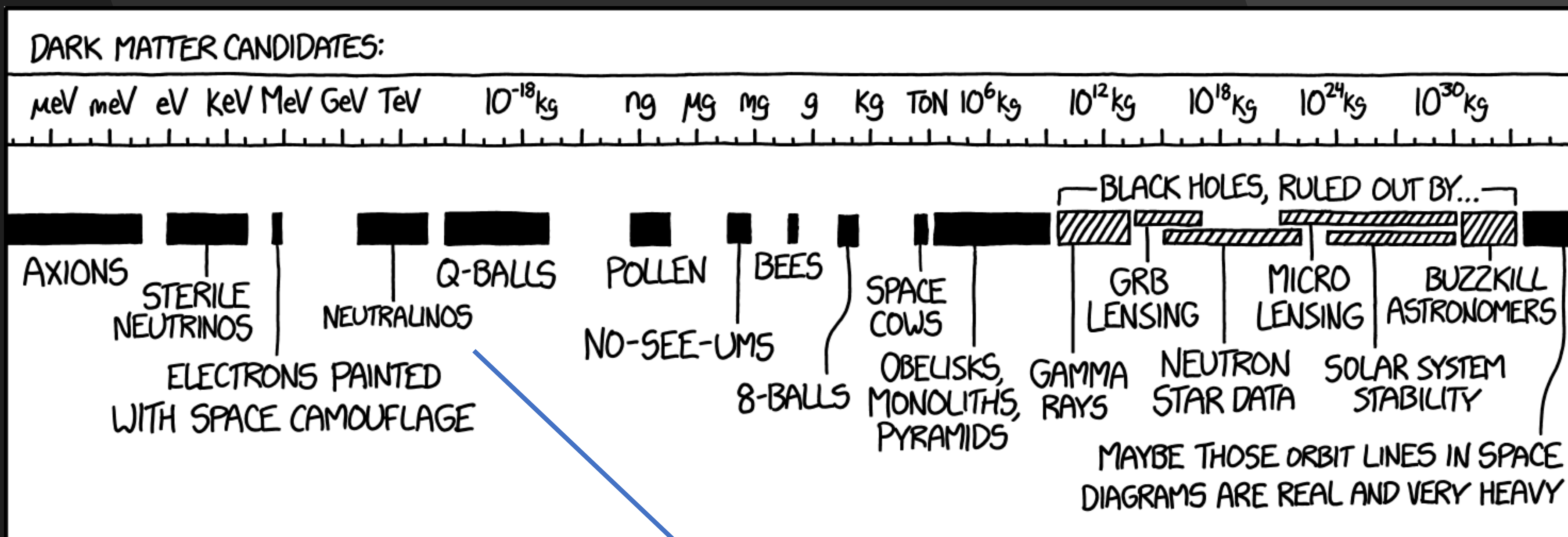
Dark Matter Experimental Searches

- Direct Detection
  - Spin-independent
  - Spin-dependent
  - WIMPs
  - Axions
  - Light WIMP candidates
  - Hidden sector particles
- Indirect Detection (γ, ν, cosmic ray antimatter)
- Production at Colliders
- Fixed target DM production-detection

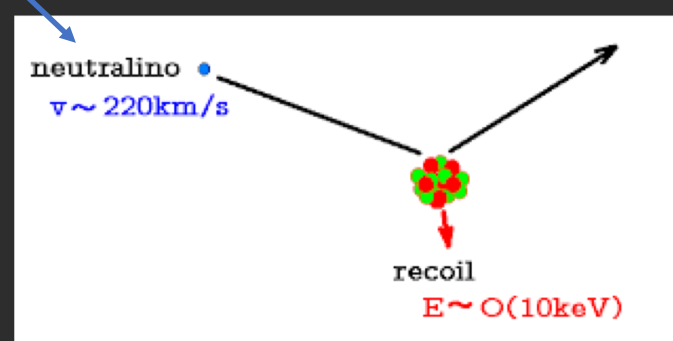


Scorpion S4E17
TV show copying
the DEAP-3600
detector schematic

Dark Matter Candidates



Neutralinos from supersymmetry are a candidate DM Weakly Interacting Massive Particle (WIMP)



Direct detection by observing nuclear recoils

PICO

PICO is a bubble chamber DM detector at SNOLAB with world-leading sensitivity to ***spin-dependent*** WIMP-nucleon couplings

How does PICO work?

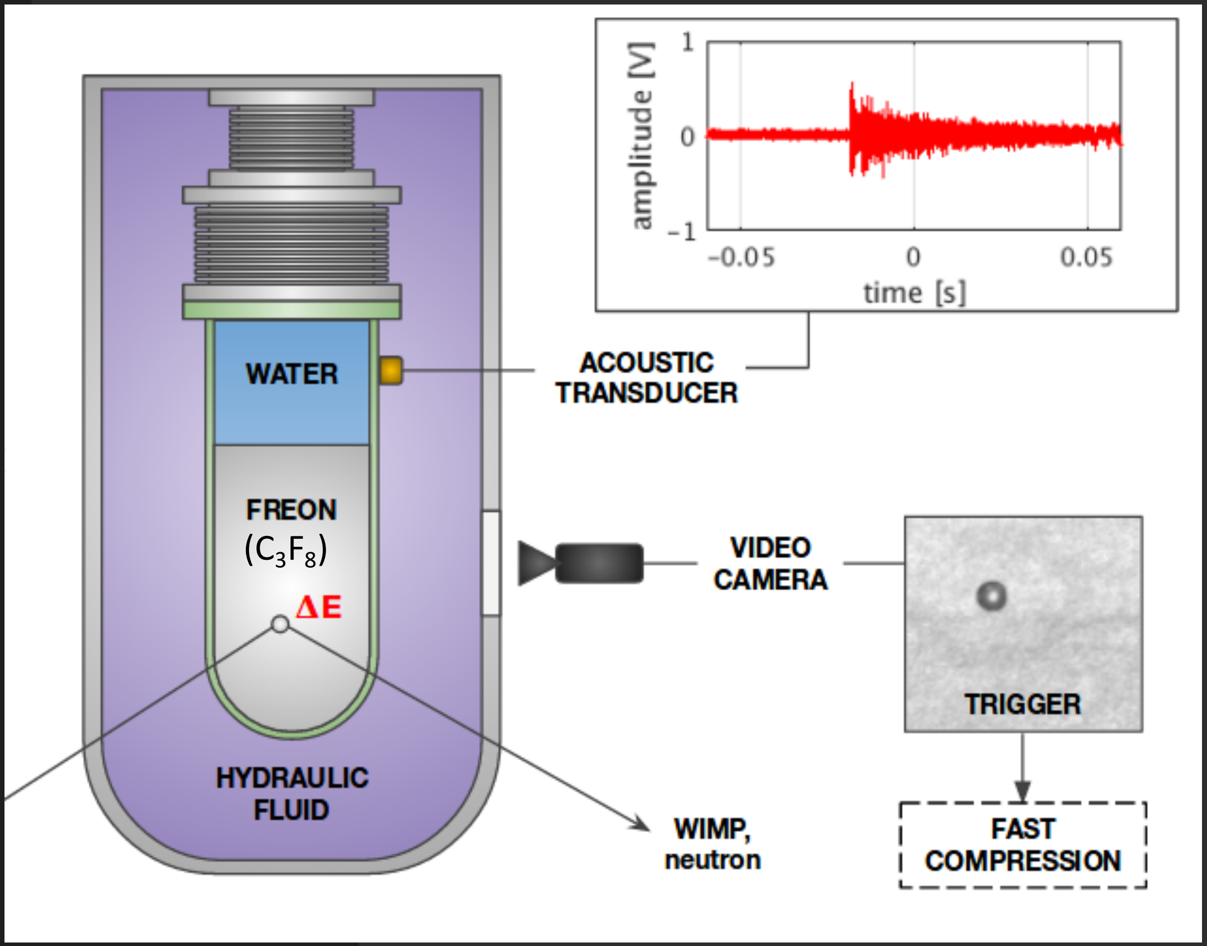
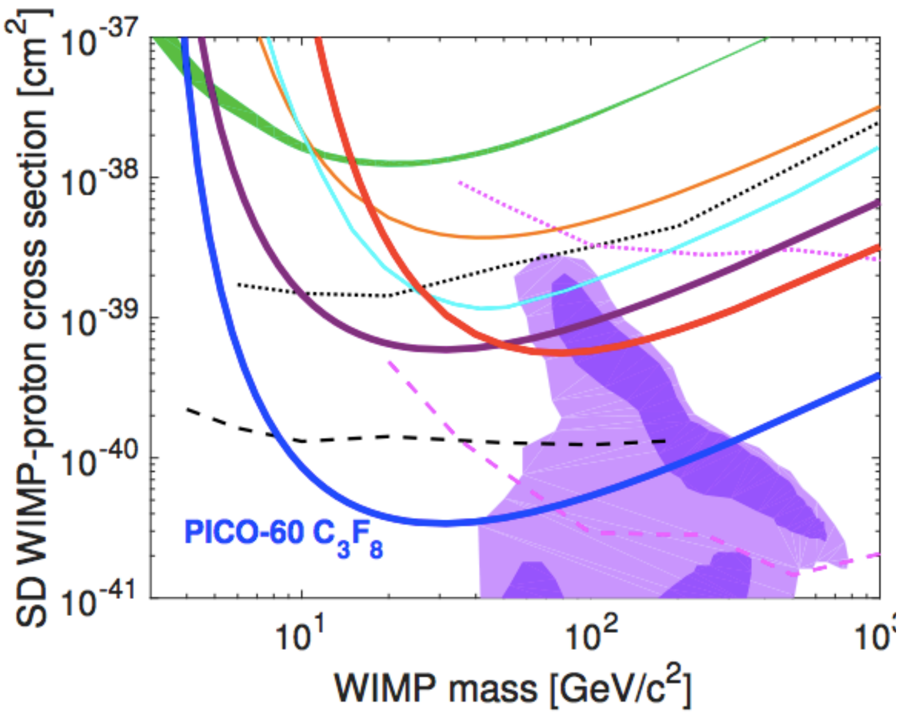


figure from G. Giroux

PICO-60 Results from 2017

- 52.2 kg of C_3F_8 (45.7 kg fiducial volume)
- Most sensitive spin-dependent DM search
- Dashed exclusion curves are indirect detection limits (model-dependent)
- PandaX-II uses xenon that also has spin-dependent sensitivity…but not as good as fluorine



PICO-60 CF3I
PICO-2L
PICASSO
SIMPLE
PandaX-II
IceCube
SuperK

C. Amole et al., Phys. Rev. Lett. 118, 251301 (2017) from R. Neilson, IDM2018, July 2018

PICO-60 Recent Results

- Lower energy threshod from 3.29 keV to 2.45 keV
- Measure/calibrate lower threshold nucleation efficiency and acoustic parameter using neutrons
- Slightly larger fiducial volume, other small analysis improvements

Combined PICO-60 C_3F_8 results

	2.45keV	3.29keV	Total
Exposure (kg-d)	1404.2	1167.0	2571.2
WIMP candidates	**3**	**0**	**3**
Multiple bubble events*	2	3	5

Background prediction			
Neutron background from multiples**	0.8	0.5	1.3
Neutron background from simulation	0.38	0.25	0.63
Gamma background	0.13	0.03	0.16
^{8}B CEVNS background	0.10	0.06	0.16

Rough (2-sigma) agreement between observation and background simulation, but we choose not to make use of the background prediction in setting exclusion limits.

*Multiples exposure is larger than WIMP search exposure due to fewer cuts.
**Expect 3.8 multiples per single bubble from neutron backgrounds.

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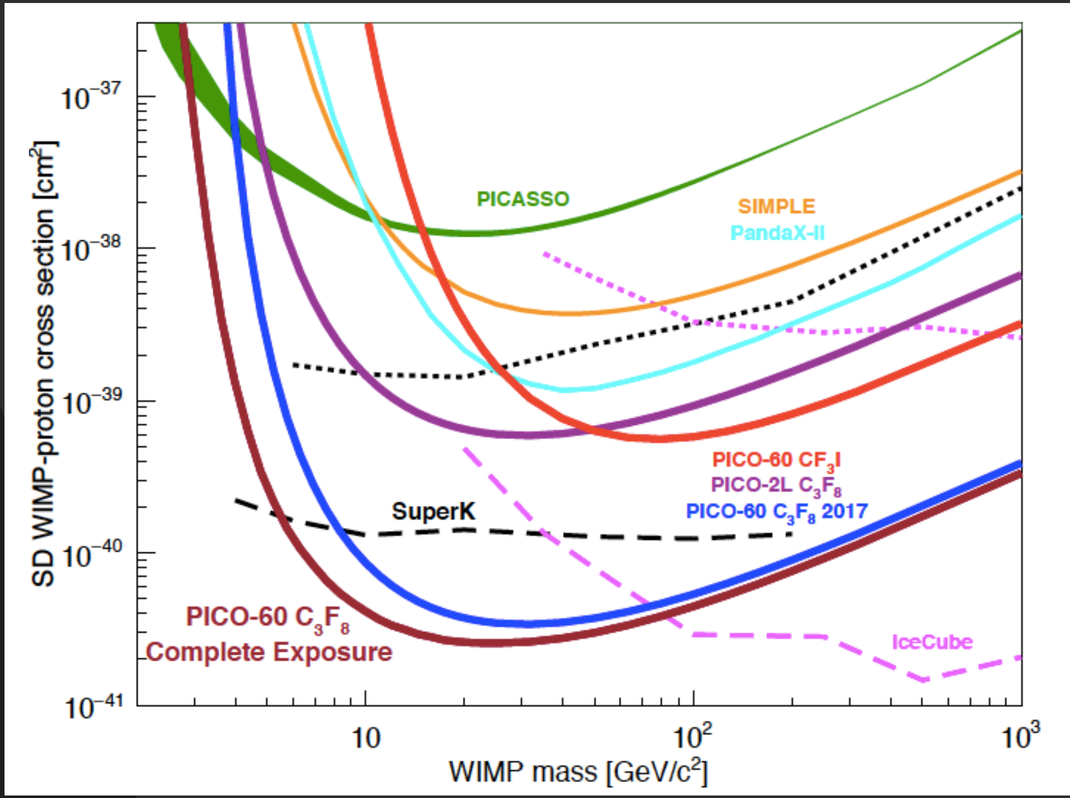
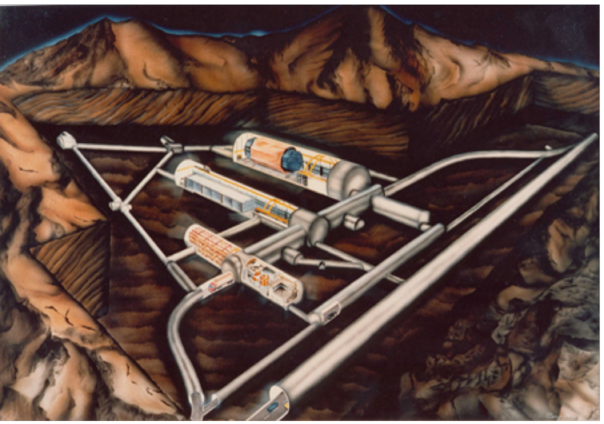
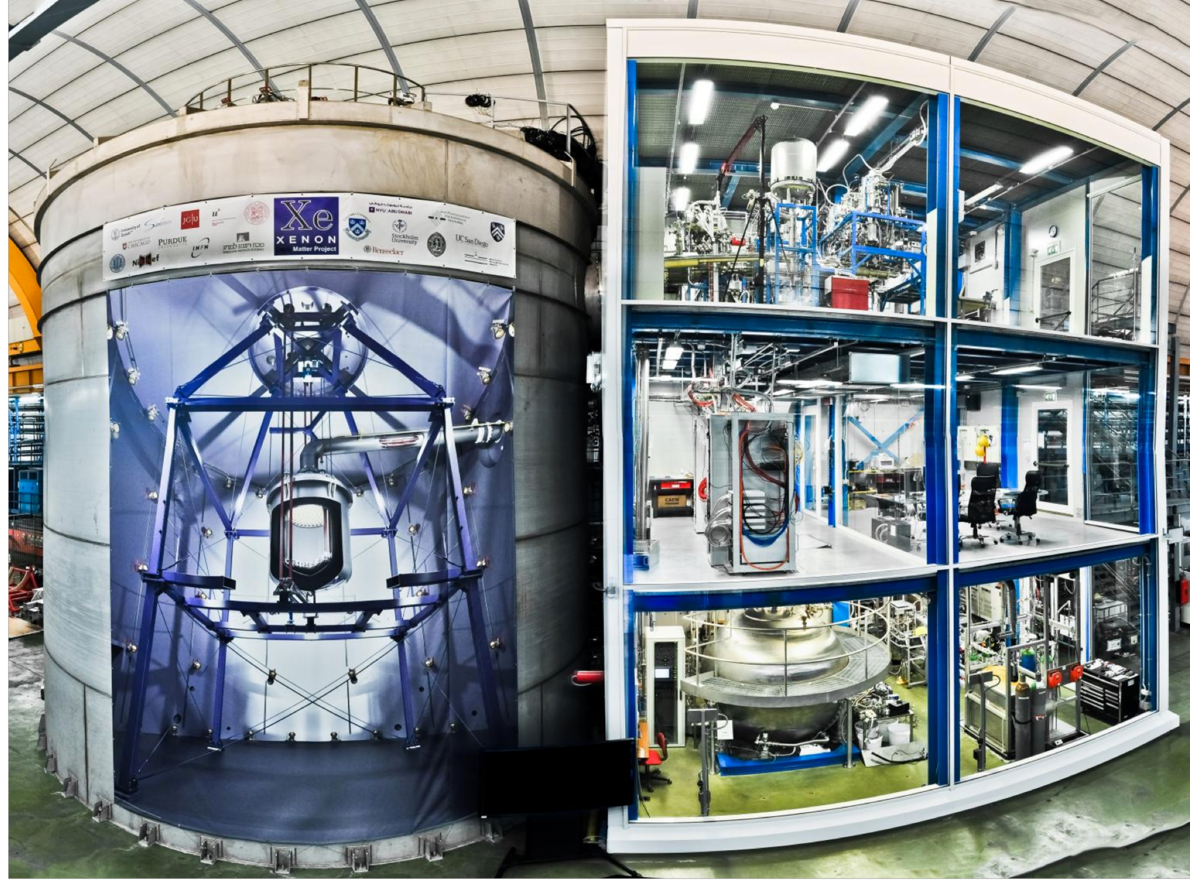


Xe
XENON
Dark Matter Project

INFN Laboratori Nazionali del Gran Sasso

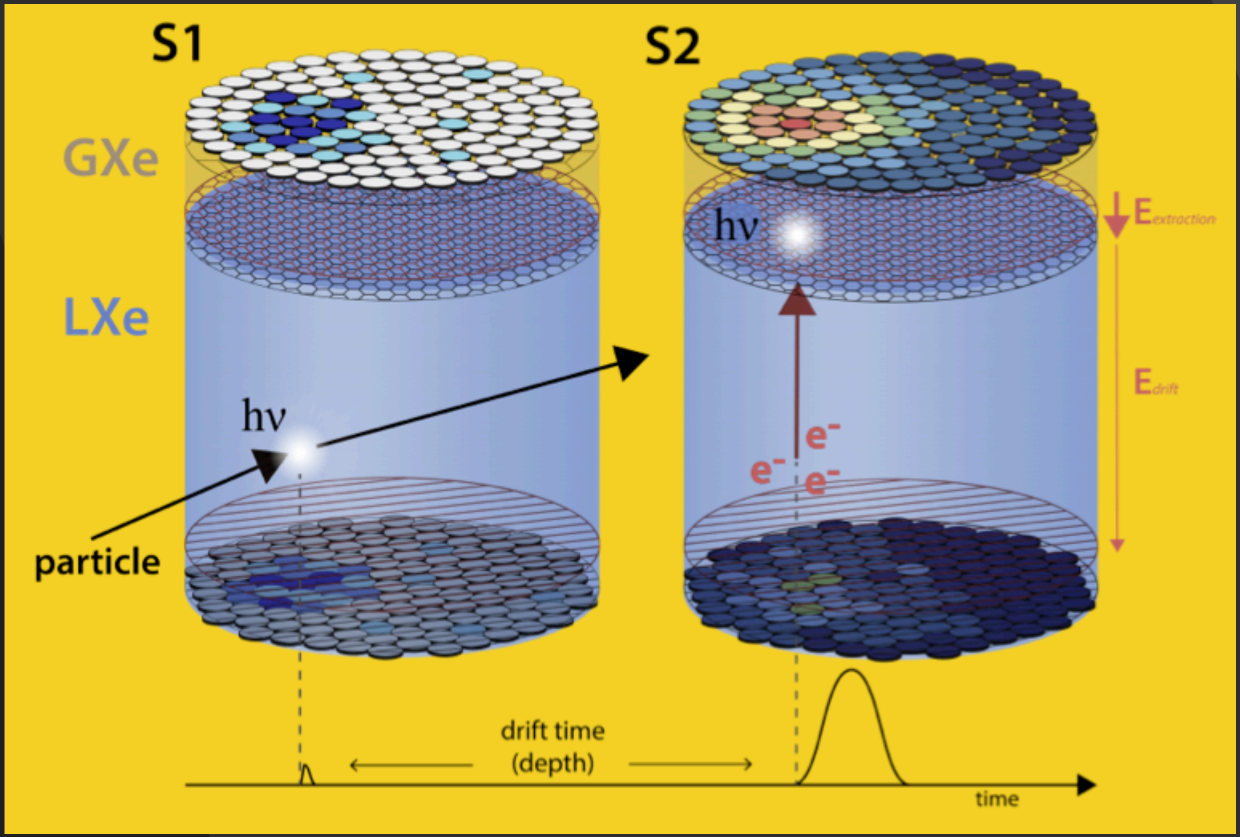




XENON1T is a two-phase LXe TPC DM detector at Gran Sasso lab in Italy with world-leading sensitivity to ***spin-independent*** WIMP-nucleon couplings

How does XENON1T work?

- 2 tonne active liquid xenon volume (3.2 T total); 1.3 T fiducial volume
- S2:S1 ratio discriminates between nuclear recoils (WIMP, neutron) and electron recoils (gamma-ray backgrounds)



from L. Grandi, IDM2018, July 2018

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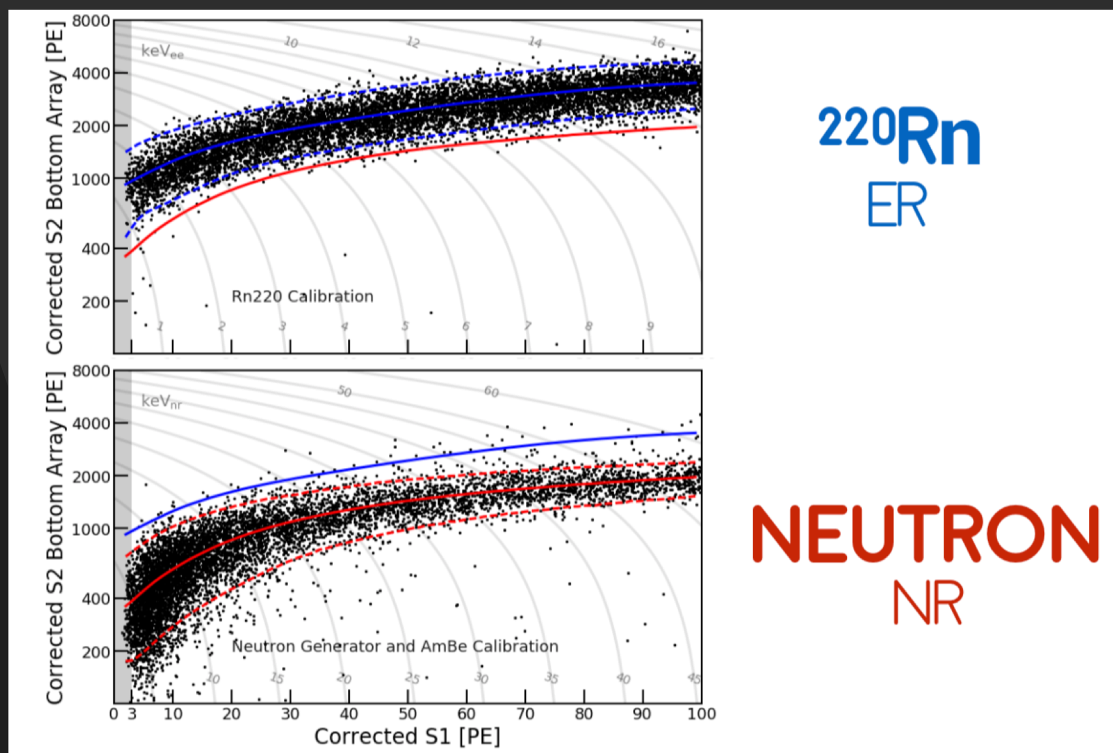
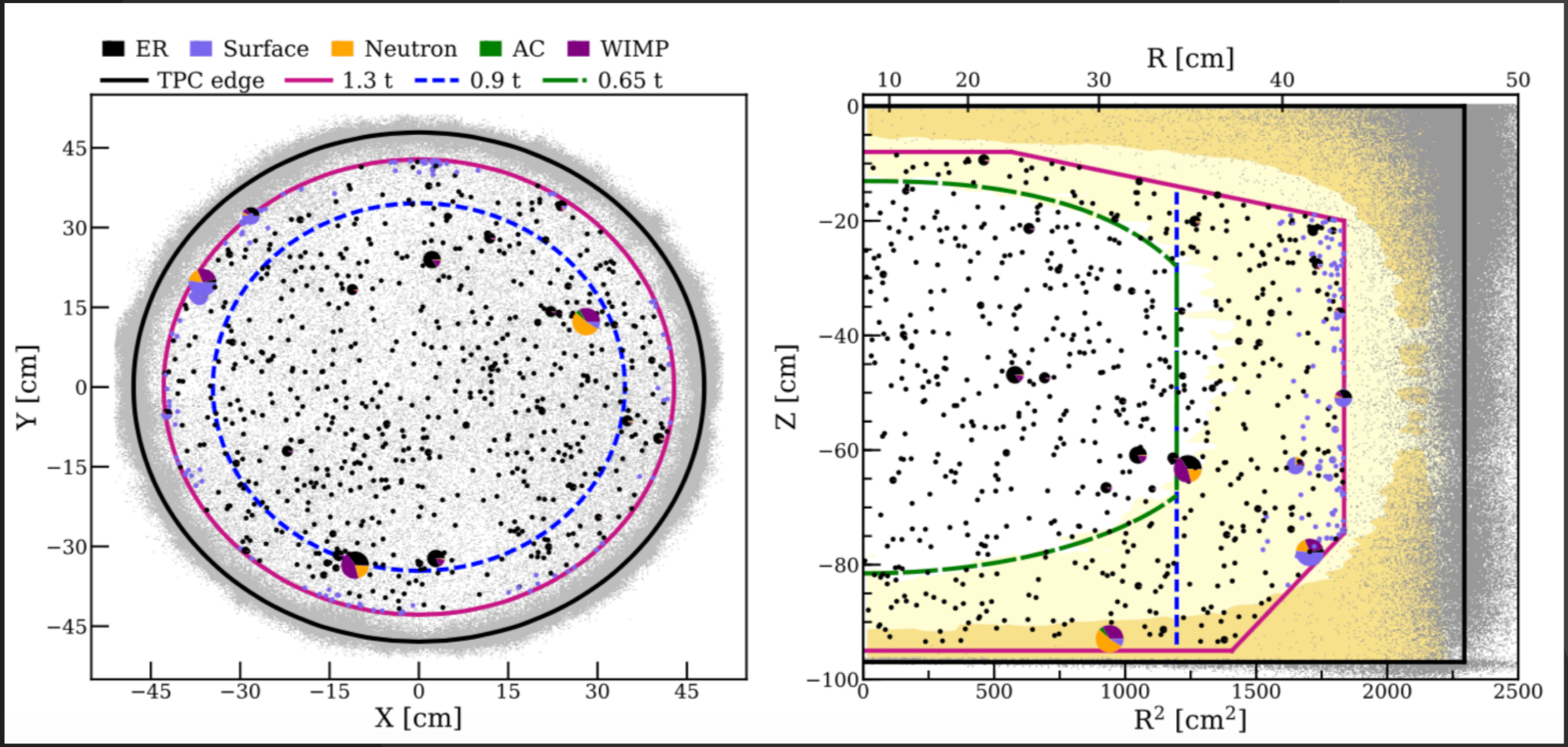


from E. Aprile *et al.*, PRL 121, 111302 (2018)

XENON1T Recent Results

- 1 tonne-year exposure
- 1.4-10.6 keV_{ee} equivalent to 4.9-40.9 keV_{nr}



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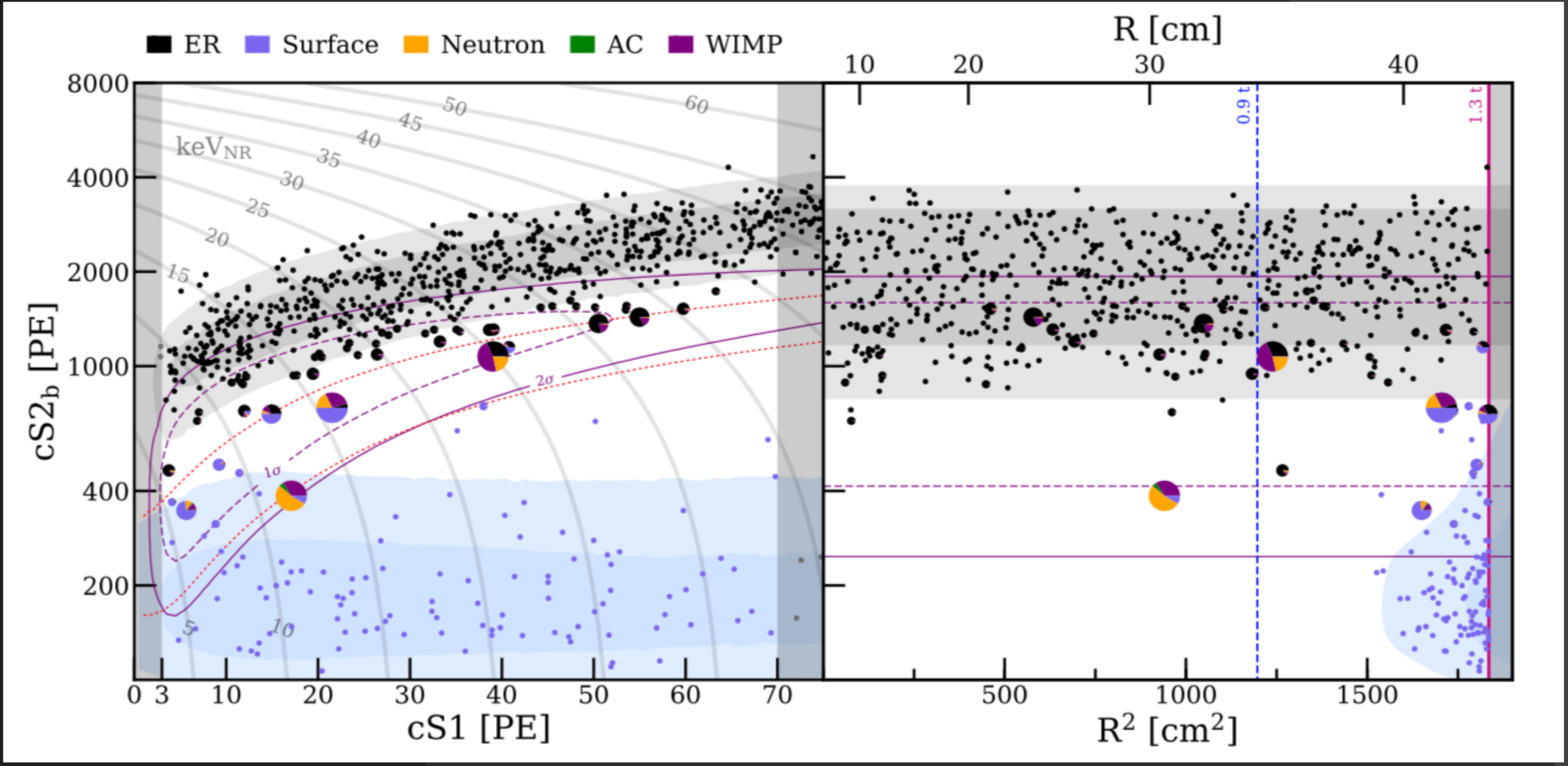
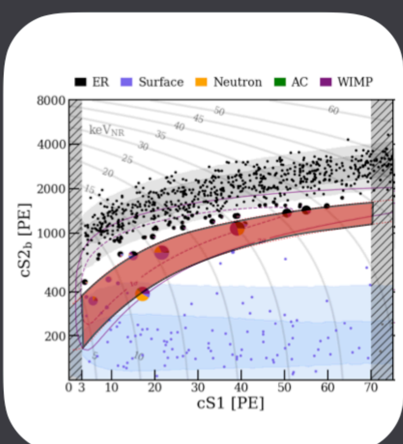


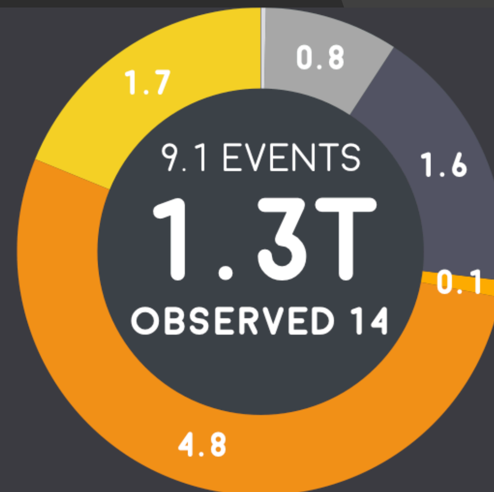
from L. Grandi, IDM2018, July 2018

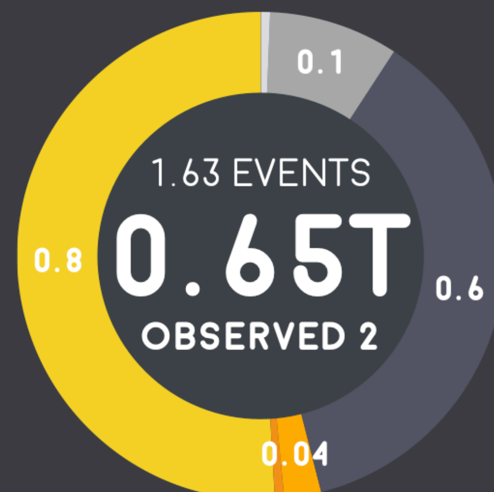
XENON1T Recent Results

INSIDE WIMP BOX @BEST FIT VALUES FOR 200 GEV WIMP



- CESνN
- NEUTRON
- ER (RN DOMINATED)
- SURFACE
- ACCIDENTALS
- WIMP

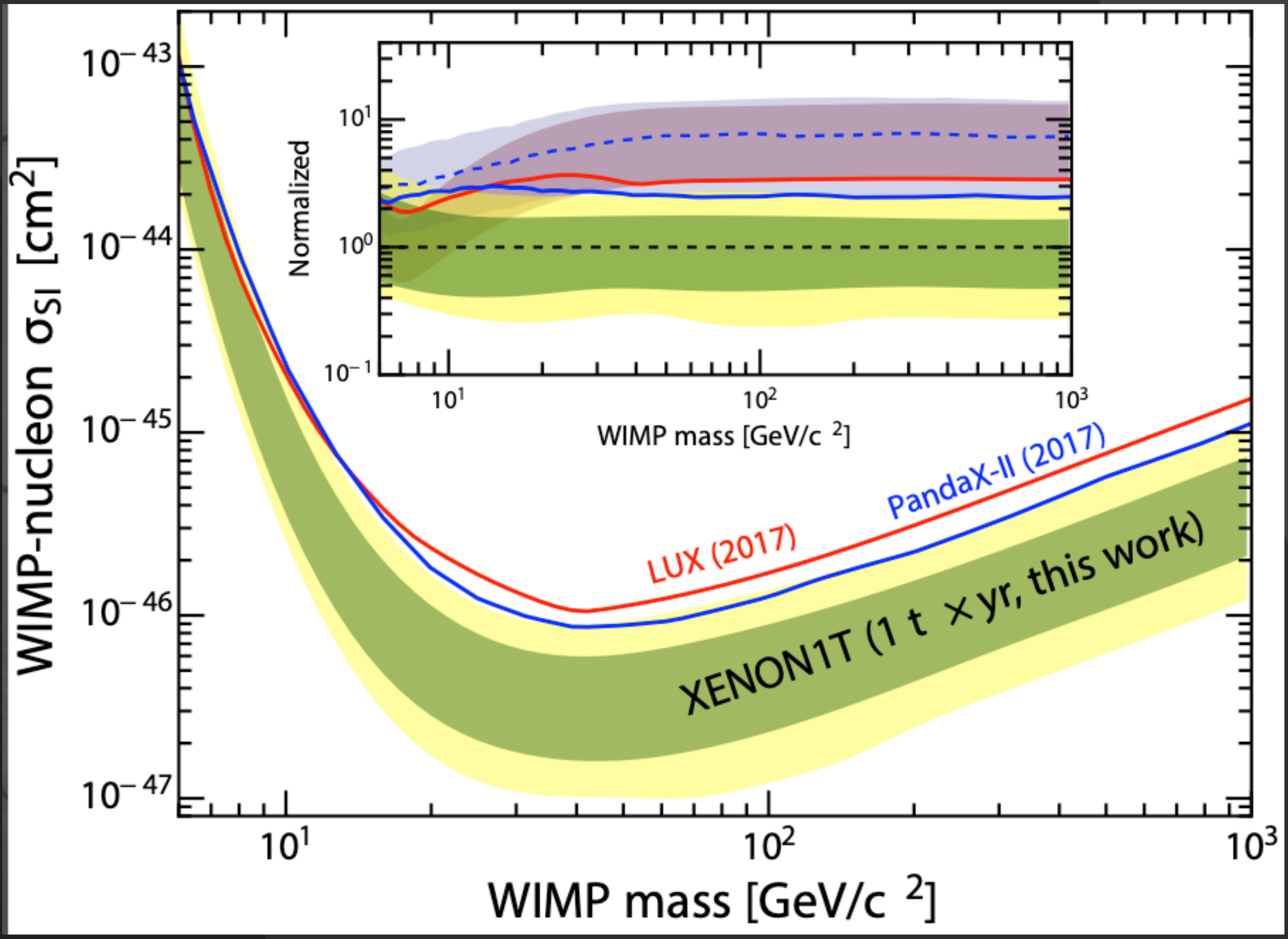




INSIDE WIMP BOX

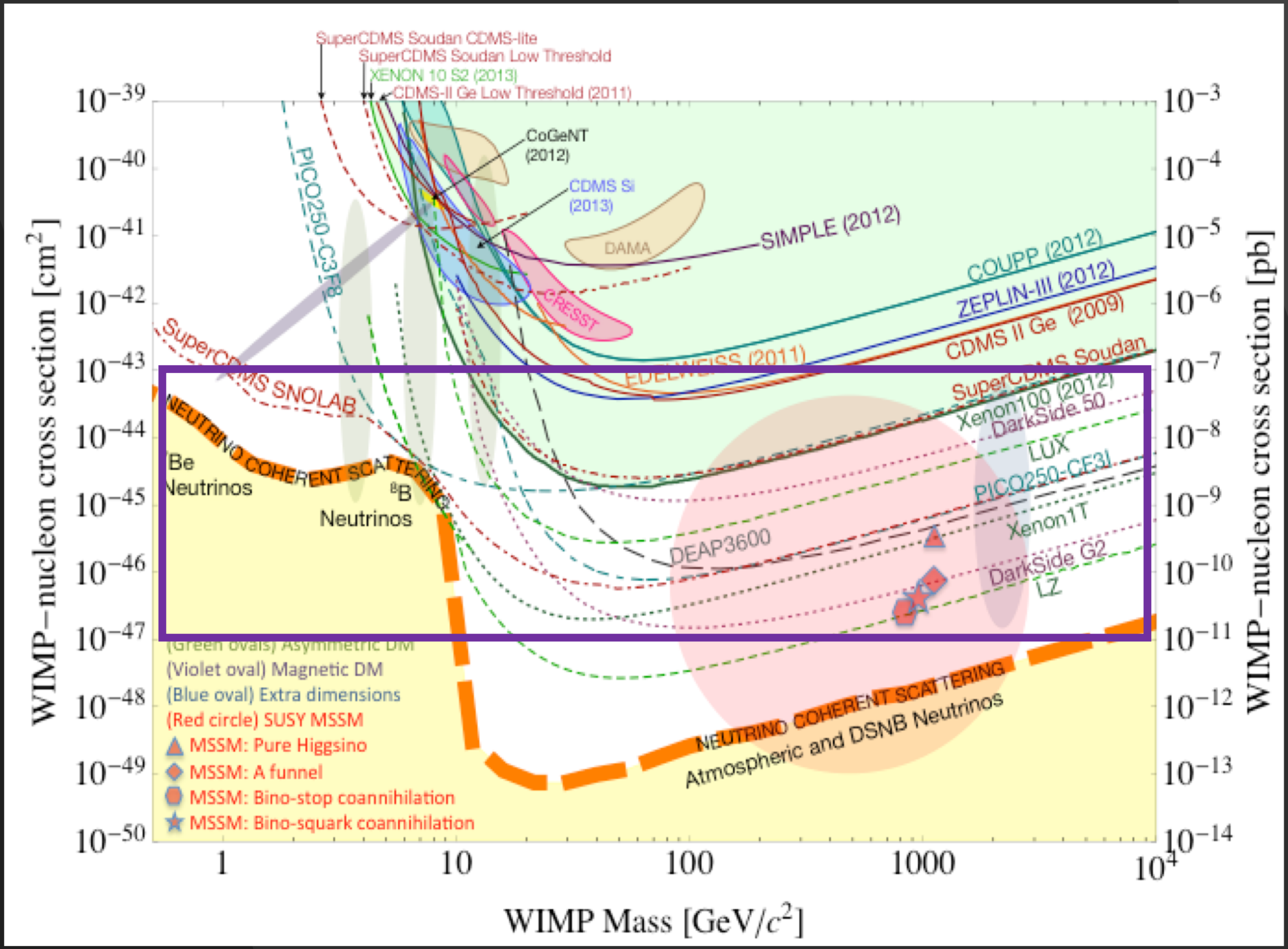
from E. Aprile *et al.*, PRL 121 111302 (2018)

XENON1T Recent Results



from *Snowmass “P5 G2DM” study arXiv:1310.8327*

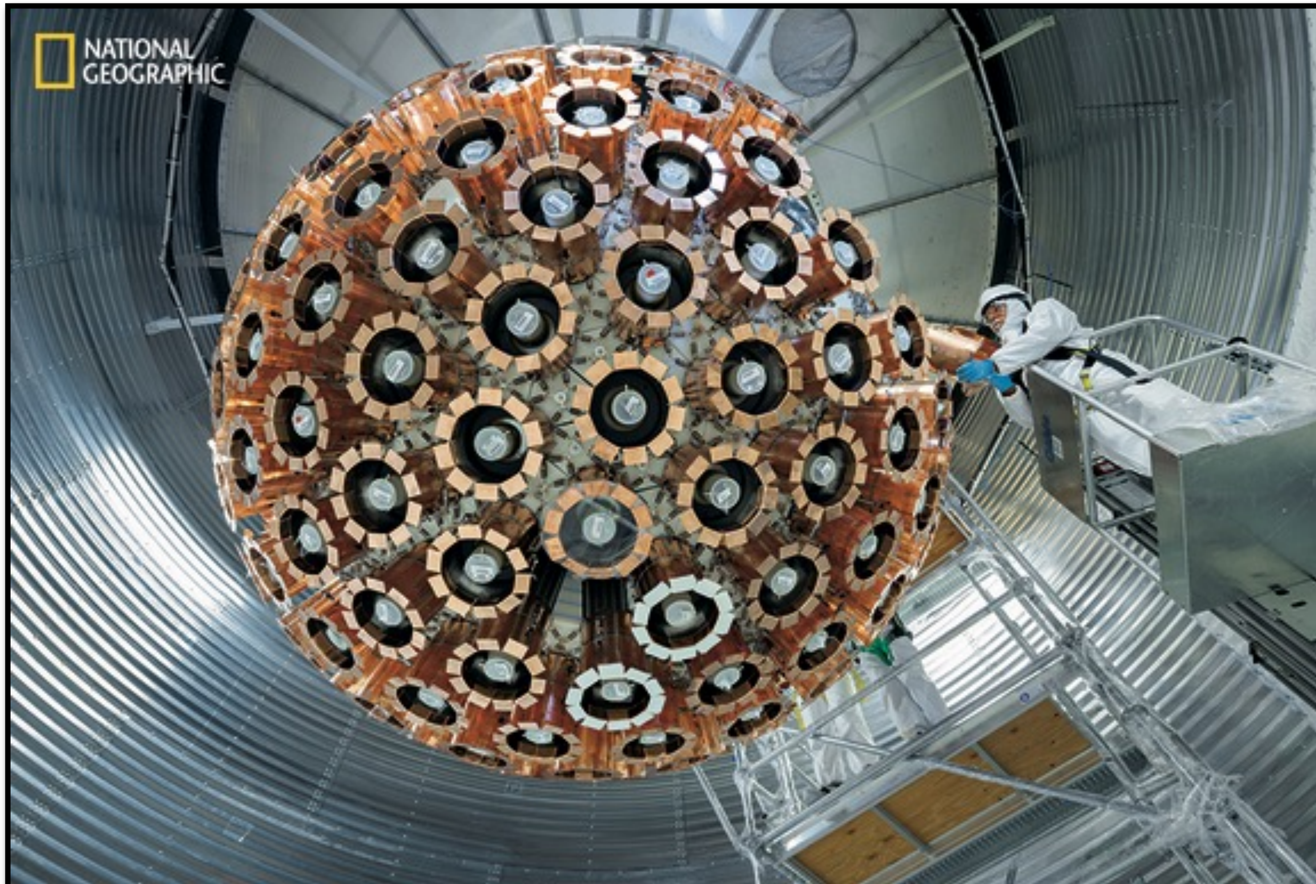
XENON1T Recent Results



DEAP 3600

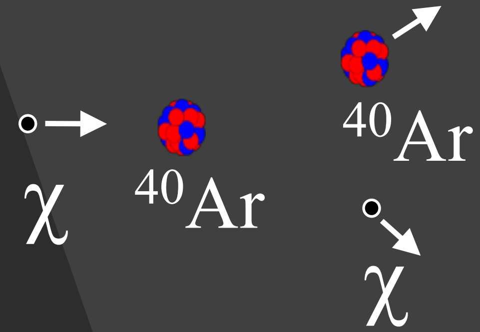
SNOLAB

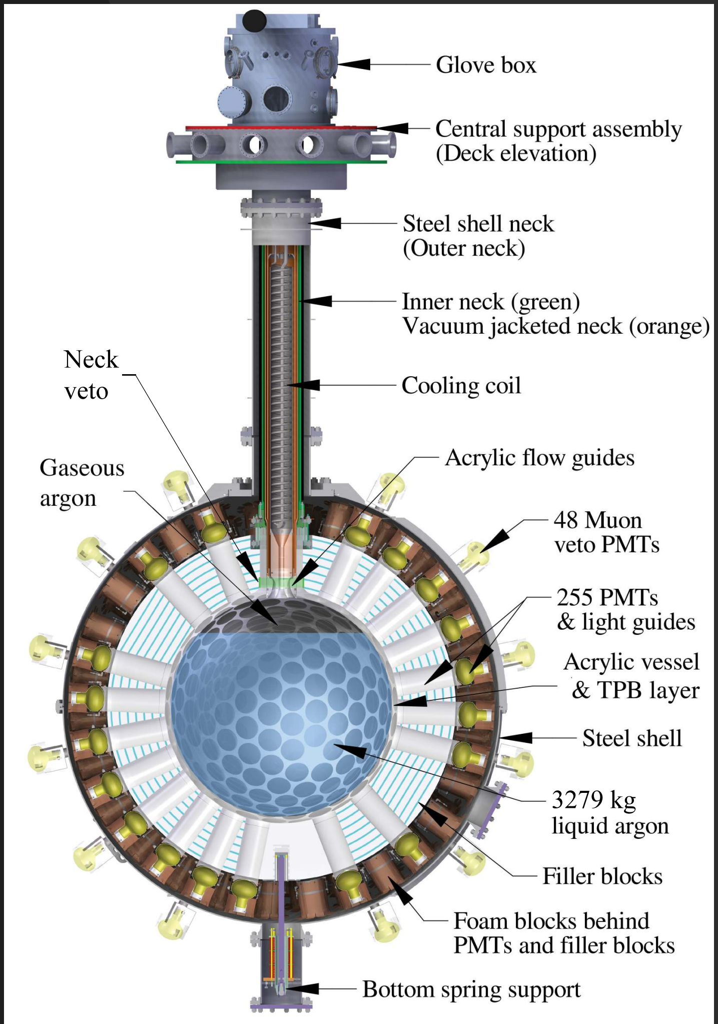
Instituto de Física



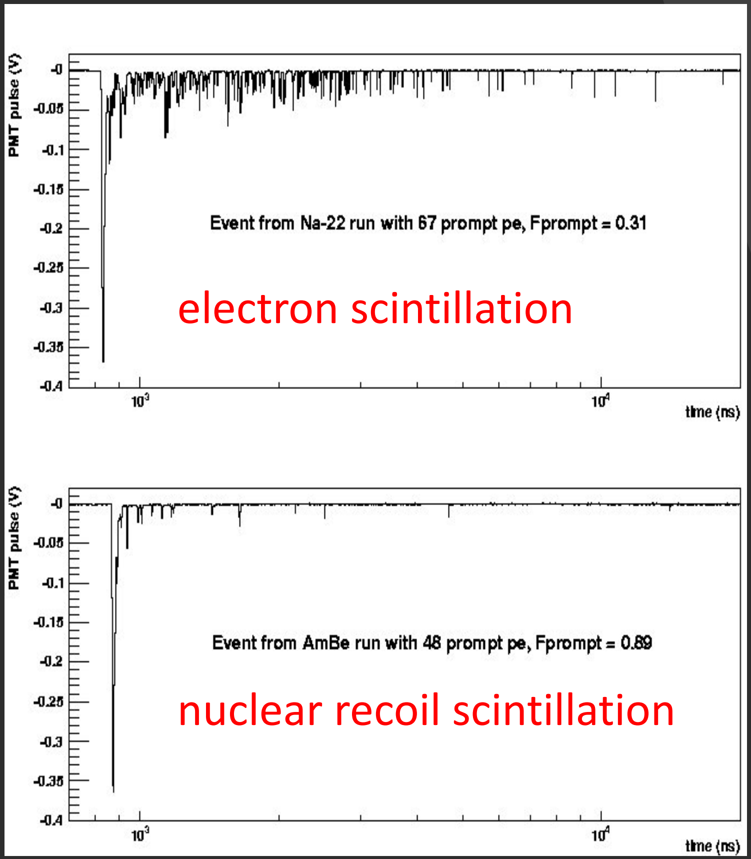
DEAP-3600 is a LAr scintillating DM detector at SNOLAB – it's the DM detector with the ***largest fiducial mass*** (2.2 tonnes) and has leading spin-independent WIMP *sensitivity with Ar*, especially at high mass >200 GeV

How does DEAP work?



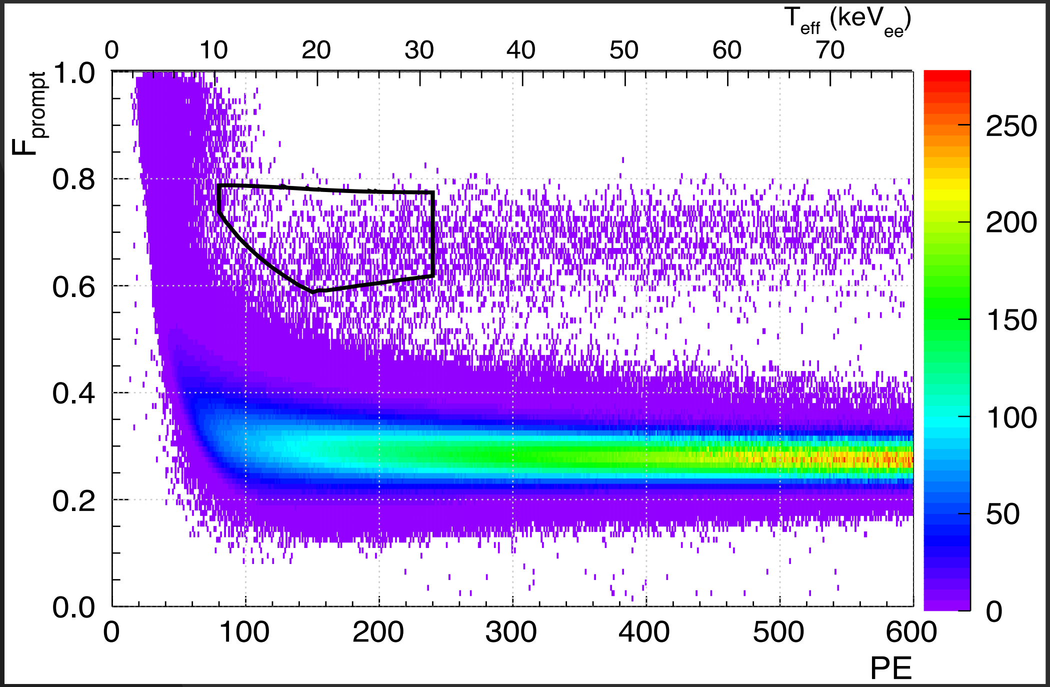


LAr scintillation time profile



DEAP-3600 Recent Results

- 9.87 tonne-day exposure – soon, new results with 2.2 tonne-year exposure
- 10-31 keV_{ee} equivalent to 37-105 keV_{nr}



Neutron-source nuclear recoil band

Electron band mostly from ^{39}Ar beta decay

Calibration: nuclear recoil discrimination using deployed gamma and neutron sources

DEAP-3600 Recent Results

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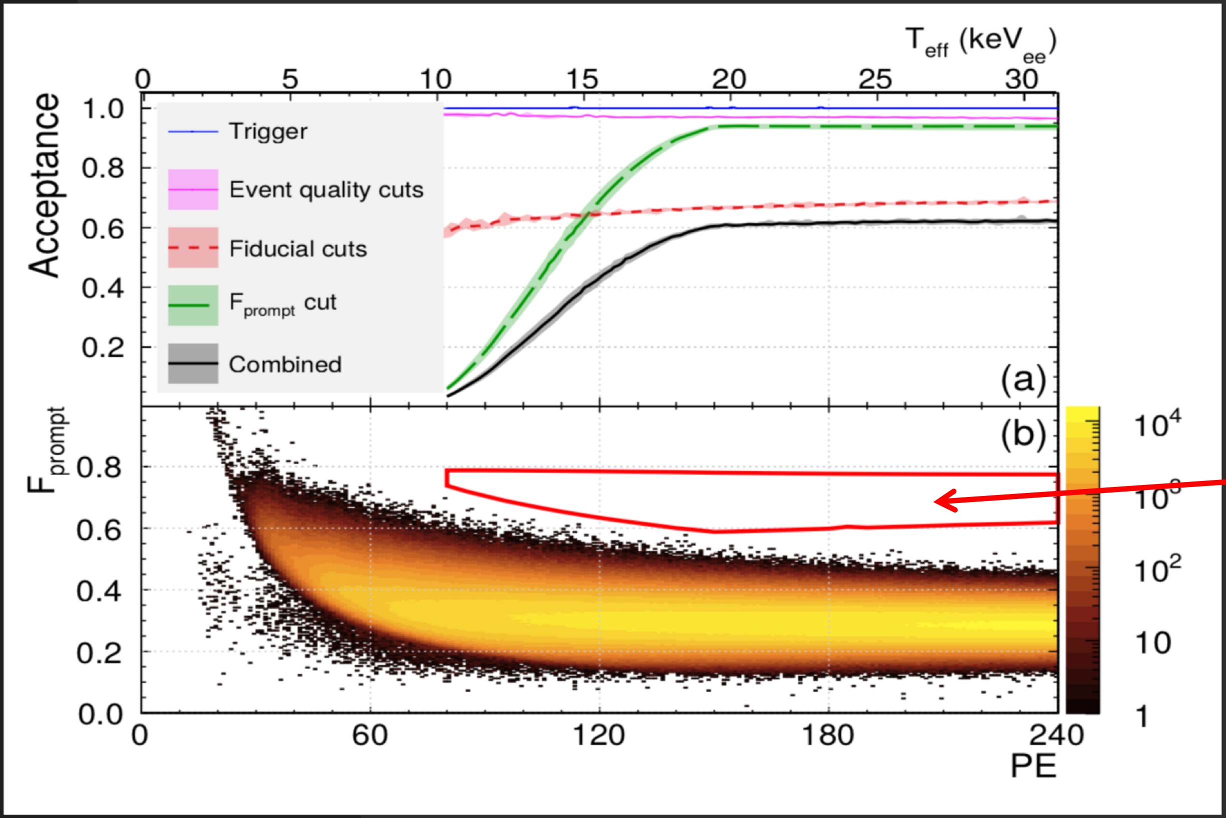

No events in the nuclear recoil band

DEAP-3600 Recent Results

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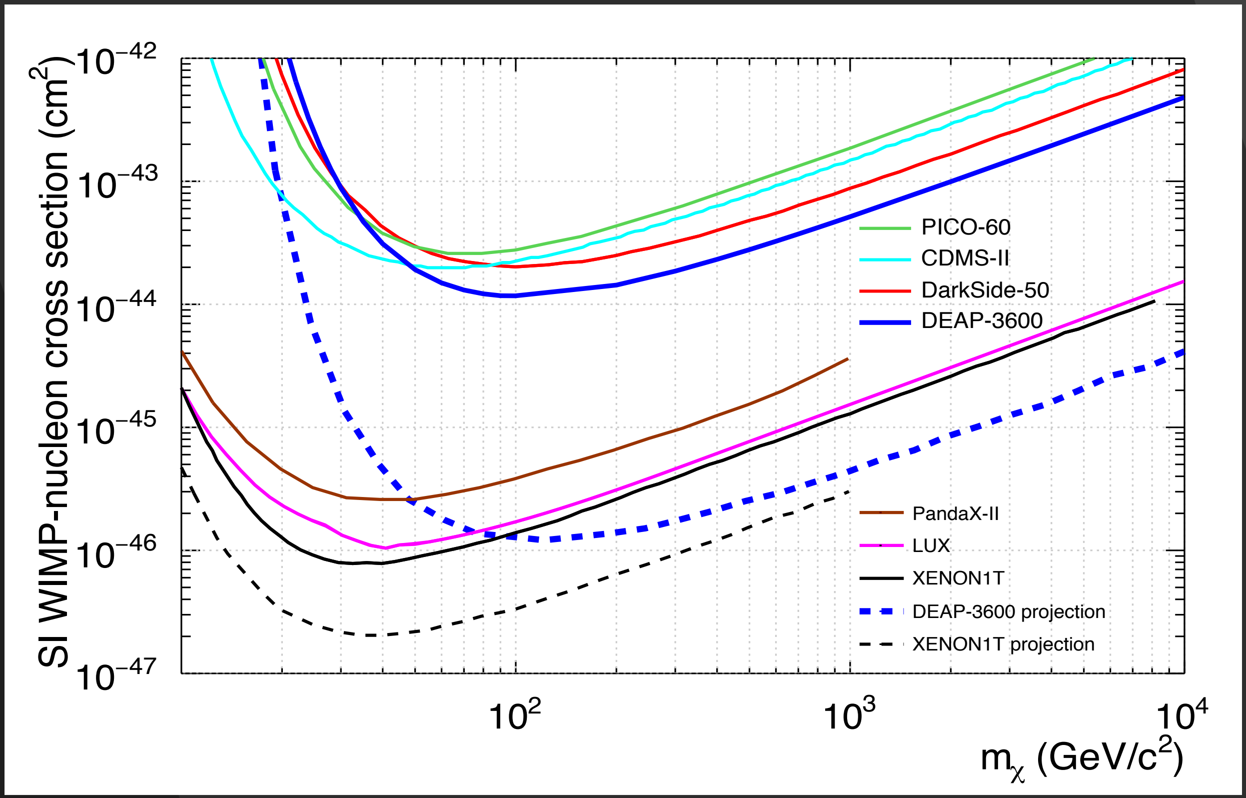
- 10-31 keV_{ee} equivalent to 37-105 keV_{nr}



Concluding Remarks: Dark Matter Searches

- Searches for WIMP (neutralino) dark matter are excluding lots of parameter space
- Will supersymmetry be found at the LHC?
- Is supersymetric DM alive?
- All of the leading dark matter experiments are seeing... signals in excess of background!
  - Does that mean the signal is just around the corner?
  - Does that mean we need a better handle on backgrounds (estimation and reducing)?
  - Just low statistics and nothing to get excited about? Yeah, probably…
- Searches for particle dark matter are branching out to test other DM candidates/models

Neutrino Physics is a big field now!

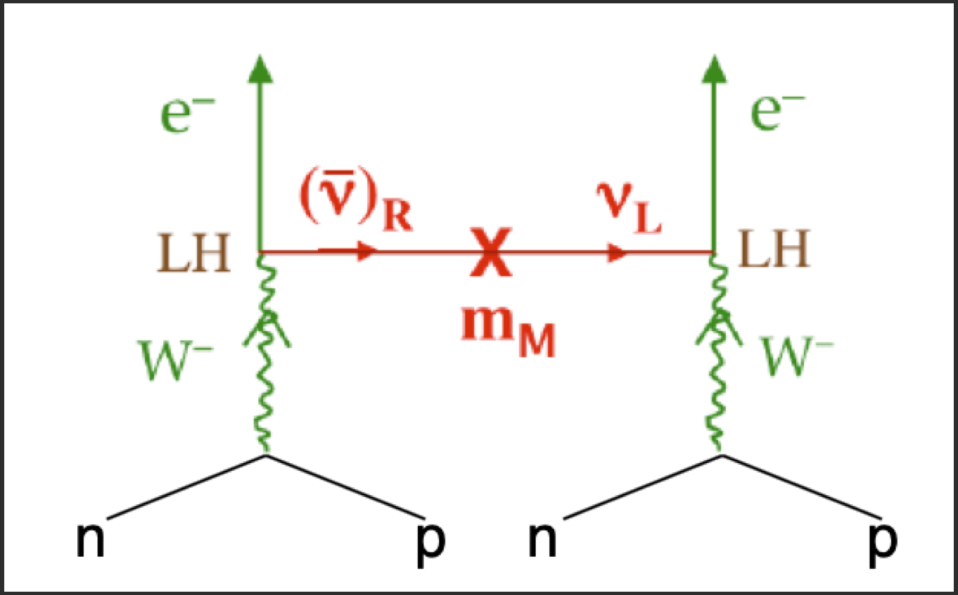
- Neutrino oscillations
  - Long baseline
  - Short baseline
    - Accelerator
    - Reactor
    - Atmospheric
- Neutrino mass
  - Direct mass measurements
  - Double beta decay
  - Neutrino mass theory (and mixing matrix theory)
- Neutrino sources from nature
  - Solar
  - Geo
  - Supernova
  - Astrophysical energetic sources (e.g. AGN blazars)

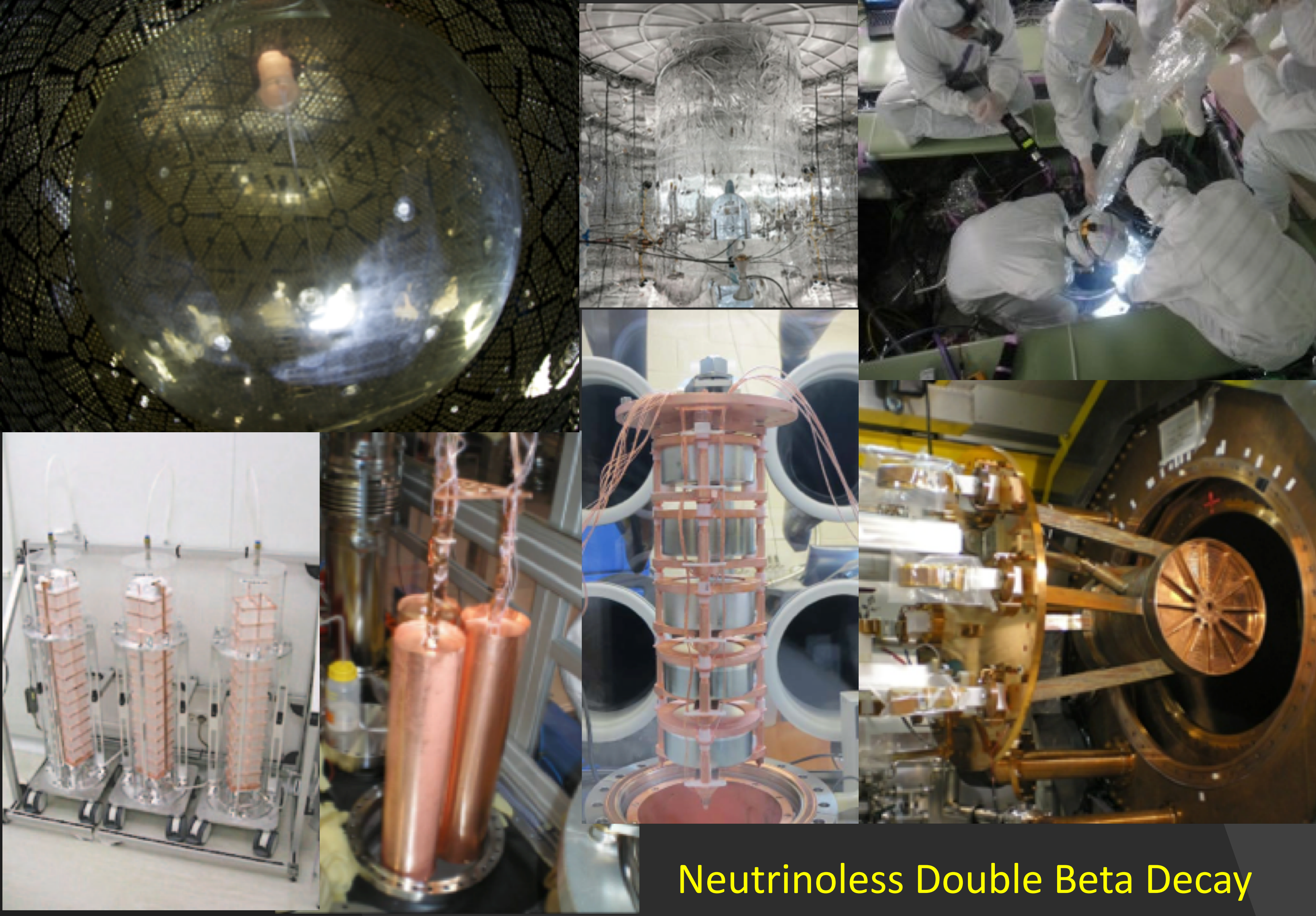
Double Beta Decay

$$m\overline{\psi}_L^{\,C}\psi_L$$

Majorana neutrino mass has this term in the Lagrangian

It’s precisely this term that is responsible for the process below, neutrinoless double beta decay





Neutrinoless Double Beta Decay Experiments

Photo Gallery

Summary of Recent Double Beta Decay Results

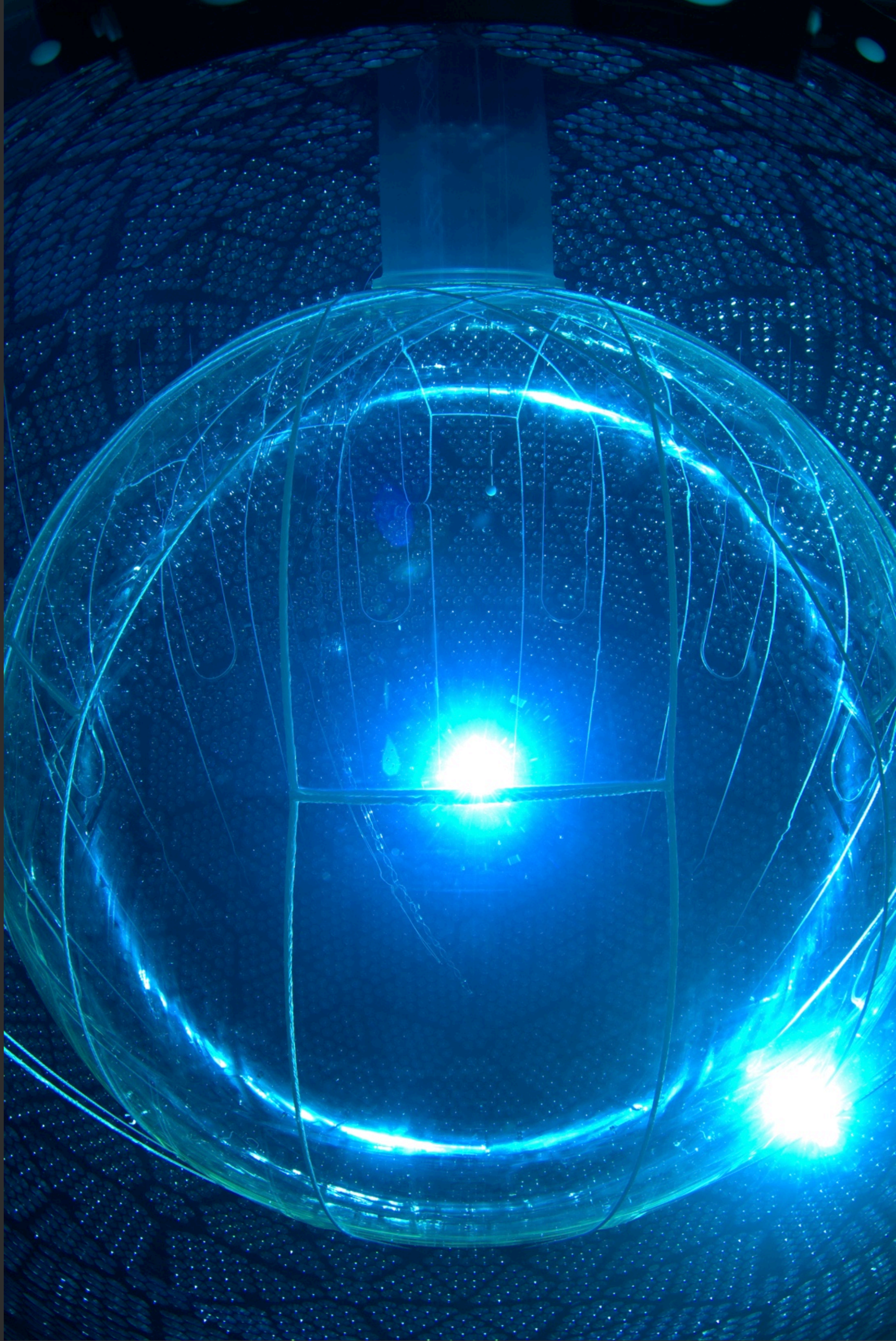
Experiment	Isotope	$T_{1/2}$ lower limit [yr]	$m_{\beta\beta}$ upper limit range [meV]
EXO-200	^{136}Xe	1.8×10^{25}	150-400
KamLAND-Zen	^{136}Xe	1.1×10^{26}	60-160
GERDA	^{76}Ge	8.0×10^{25}	120-260
Majorana Demonstrator	^{76}Ge	1.9×10^{25}	240-520
CUORE	^{130}Te	1.5×10^{25}	110-500

$$\left[T_{1/2}\right]^{-1} = G_{0\nu}\frac{\left\langle m_{\beta\beta}\right\rangle^2}{m_e^2}\left|M_{0\nu}\right|^2$$

$$\left|\sum_i m_i U_{ei}^2\right| \equiv \left\langle m_{\beta\beta}\right\rangle$$

SNO+

- Is the upgraded Sudbury Neutrino Observatory
- 3.9 tonnes of tellurium in 780 tonnes of liquid scintillator
- Search for double beta decay of ^{130}Te
- Te loading starts in 2019



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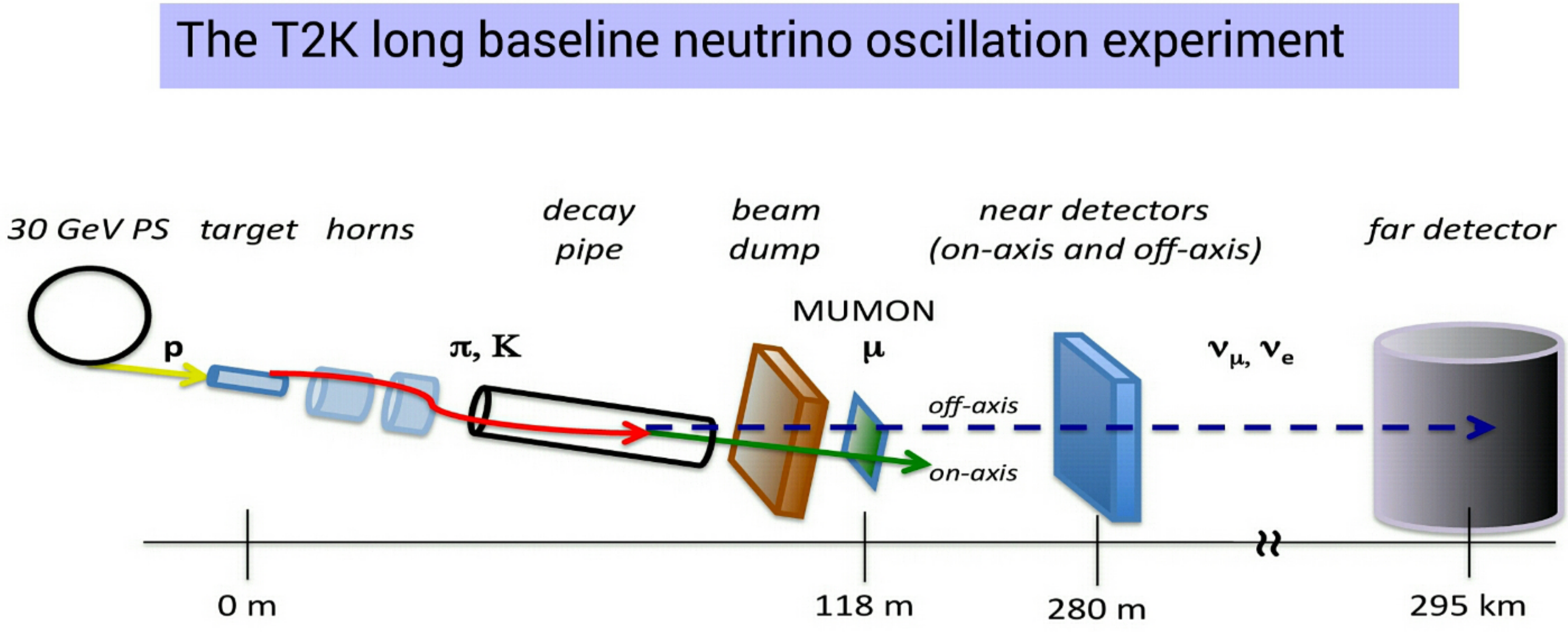
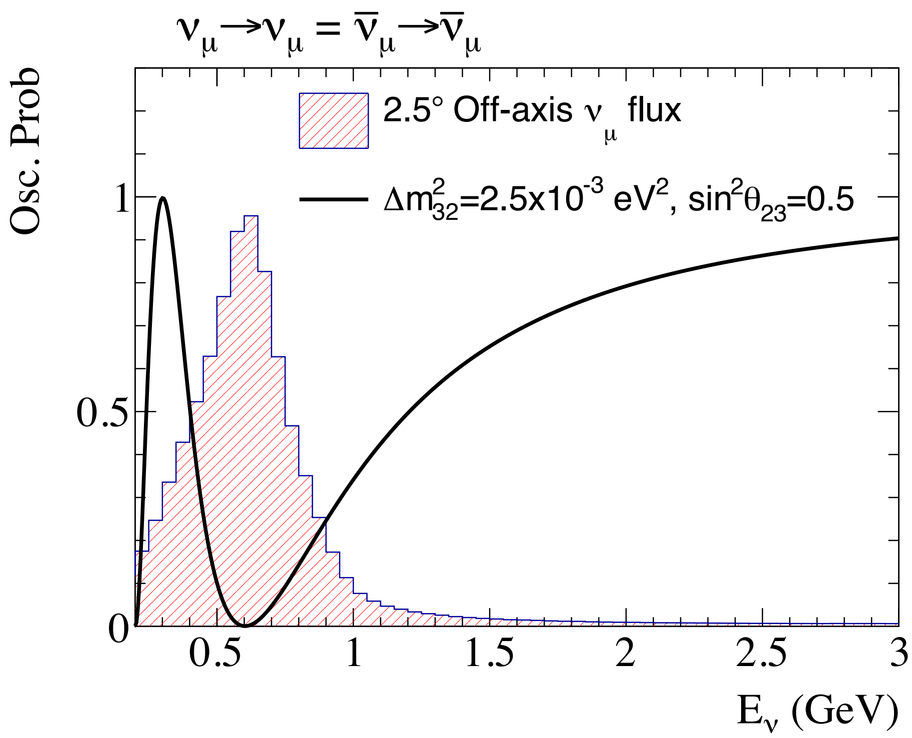
Long Baseline Experiments

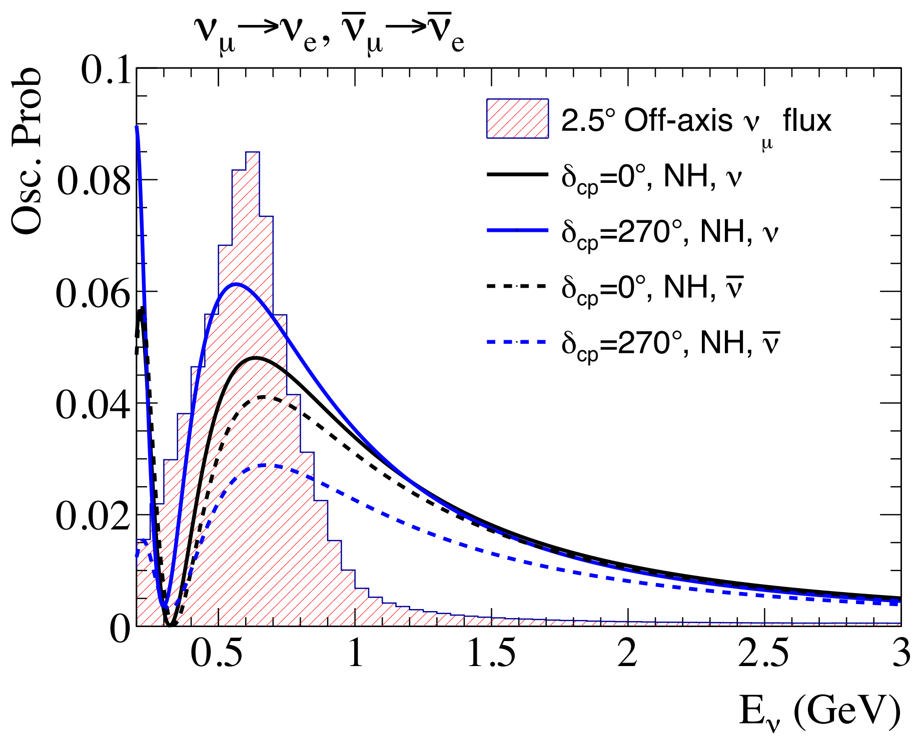
Long Baseline Experiments

How to make a neutrino beam



What is measured in an accelerator neutrino oscillation experiment?





ν_μ disappearance

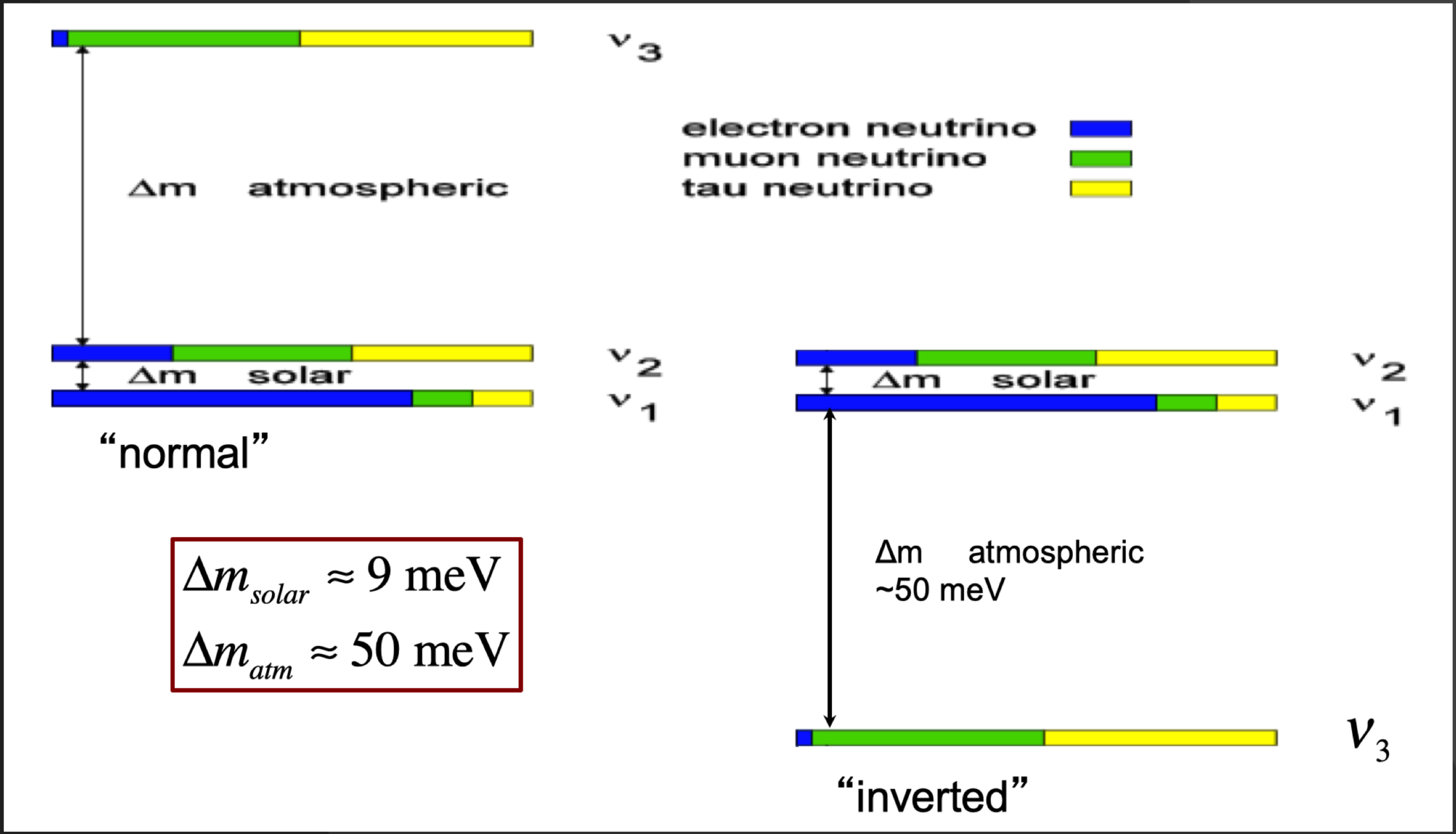
ν_e appearance

What is measured in an accelerator neutrino oscillation experiment?

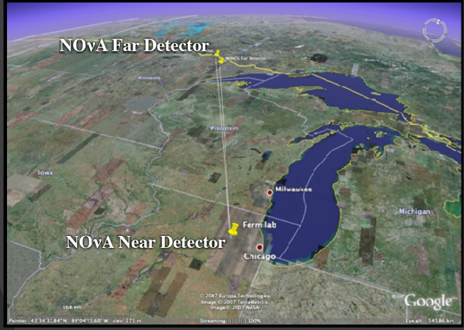
- Δm^2_{32}
- $\sin^2\theta_{23}$
- $\sin^2\theta_{13}$
- Neutrino mass hierarchy (normal or inverted)
- δ_{CP}

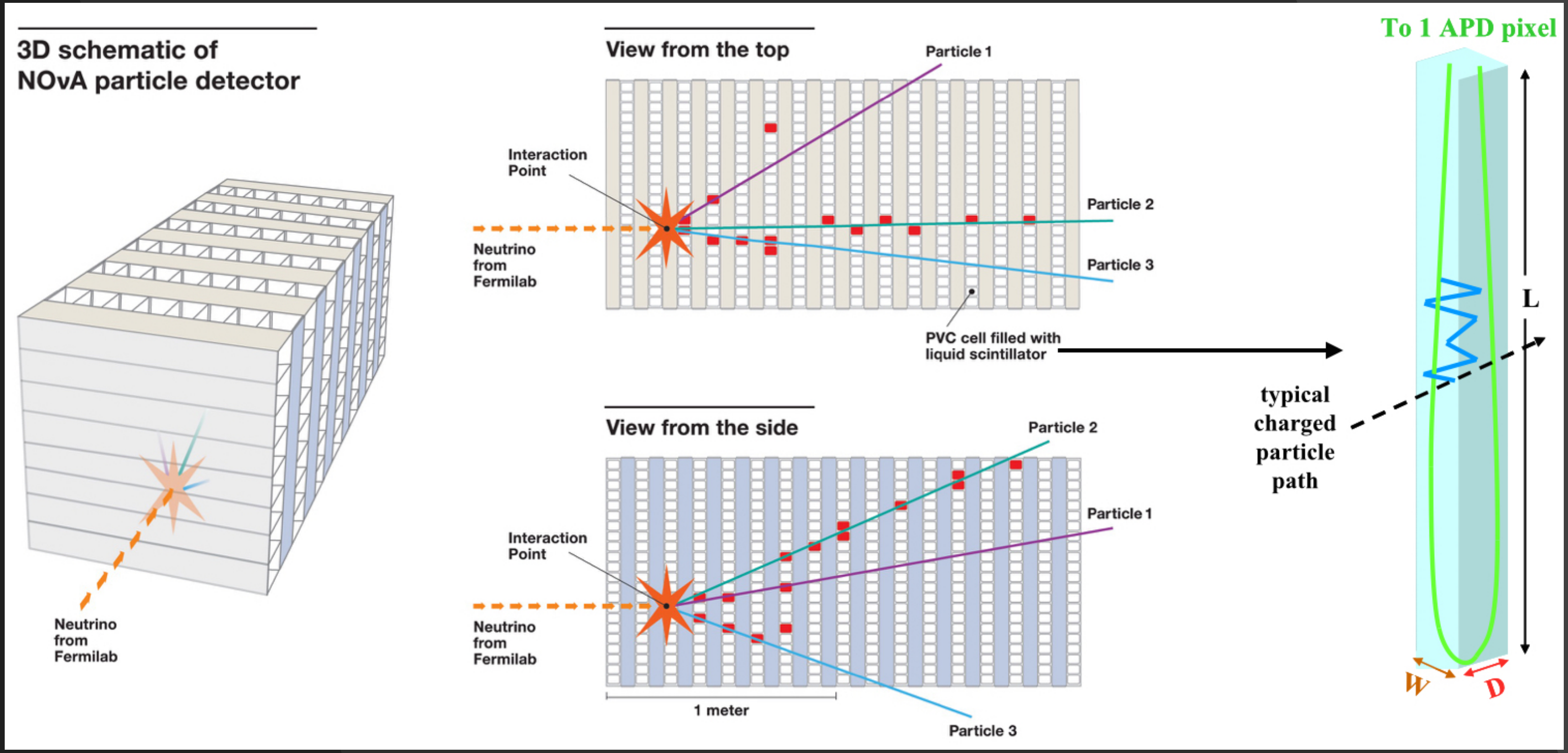
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

On the neutrino mass hierarchy…



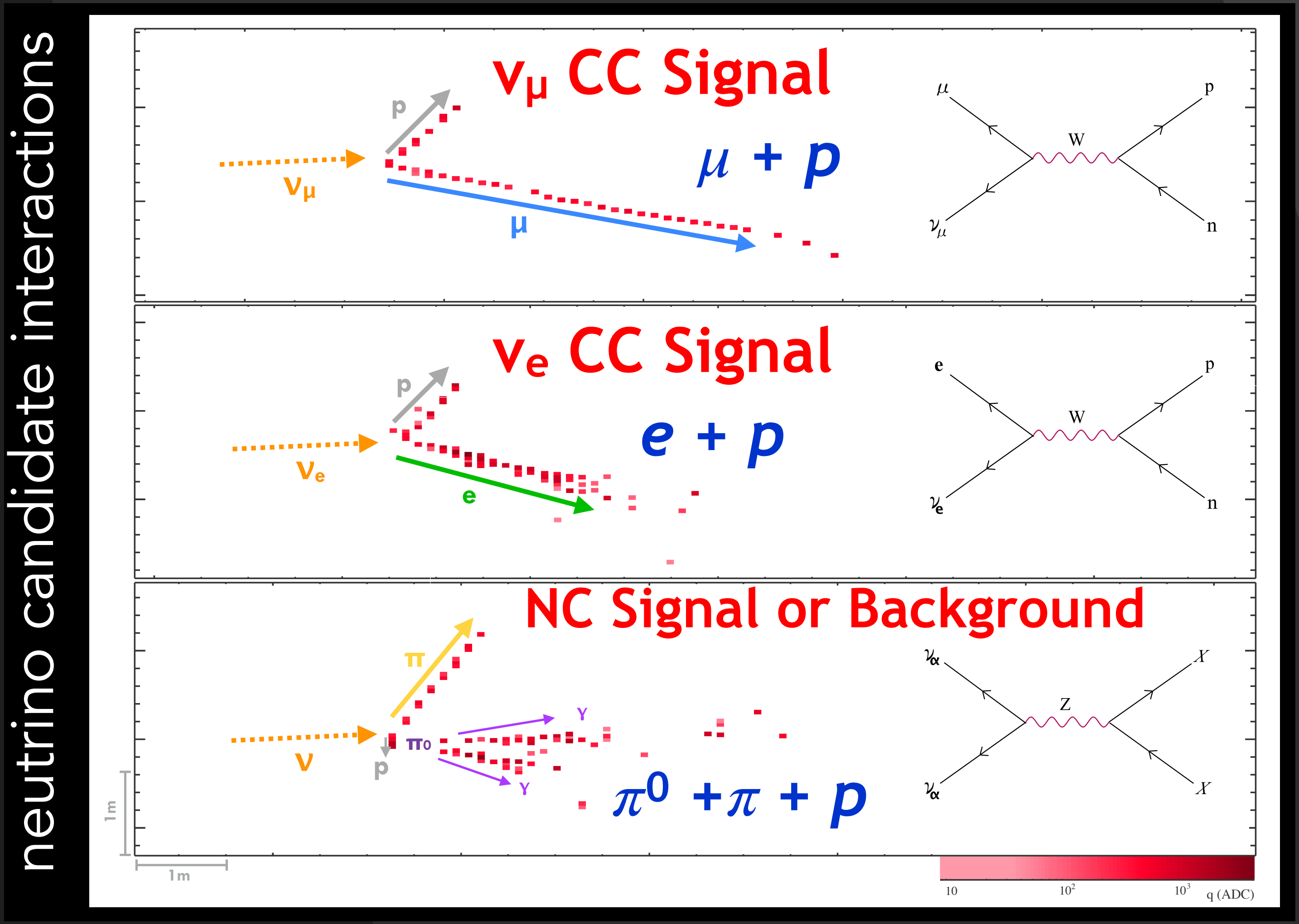
NOνA





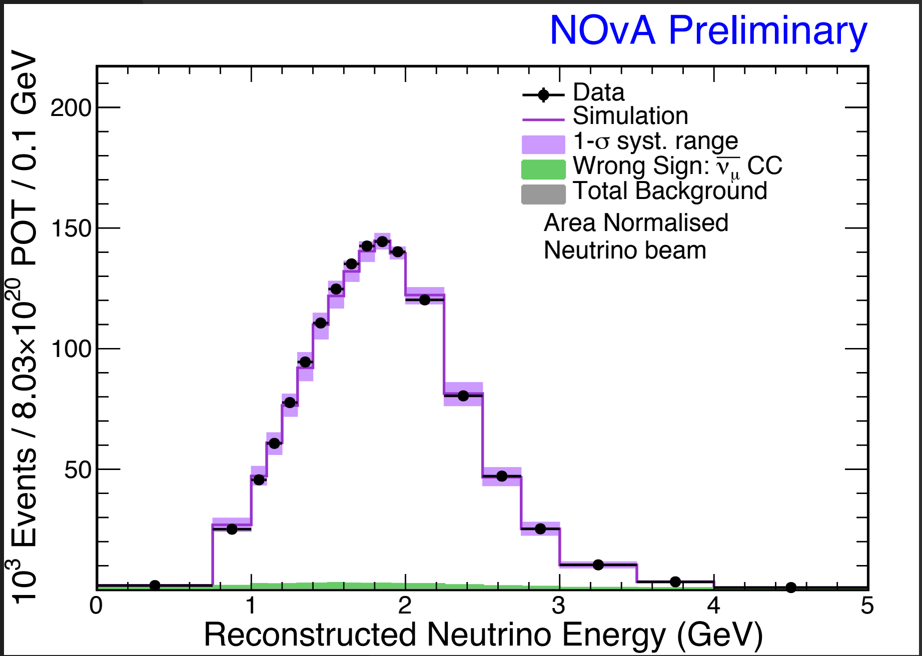
NOνA content from M. Sanchez, Neutrino 2018, June 2018

NOvA Detector Signals

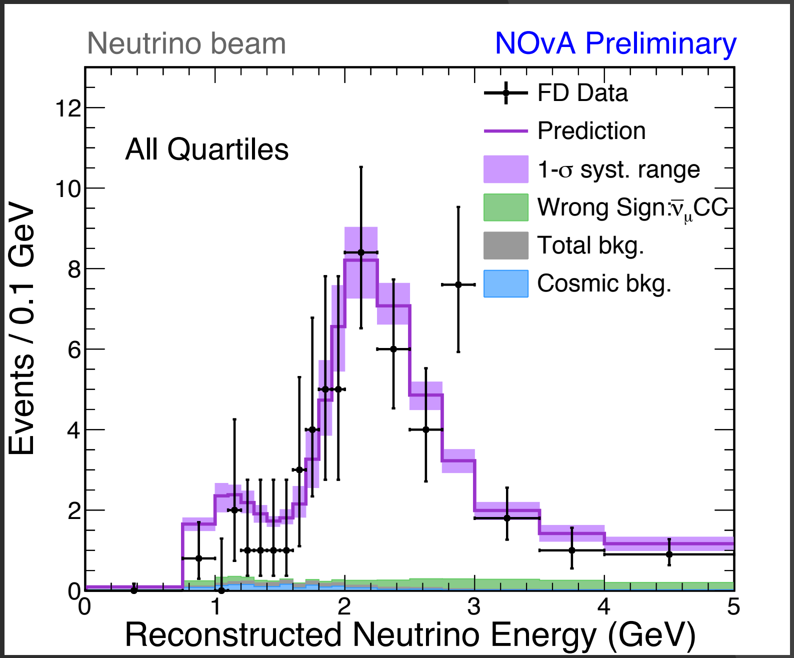


NOvA ν_μ disappearance

Near Detector



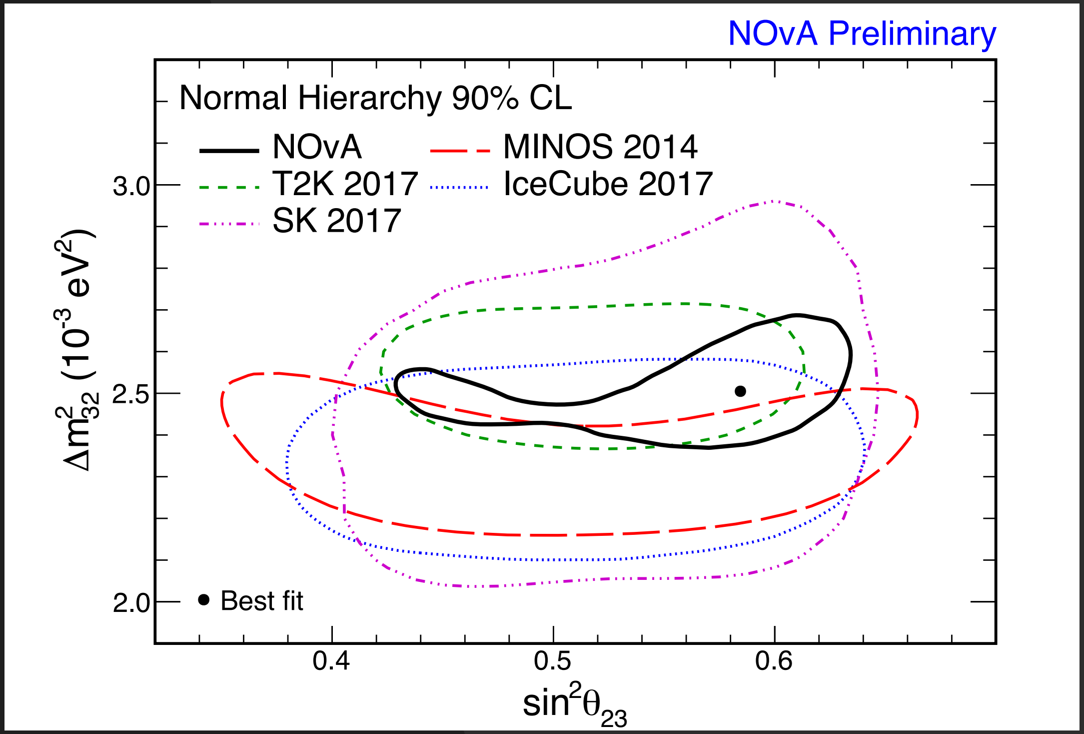
Far Detector
(note: spectrum distorted by oscillations)

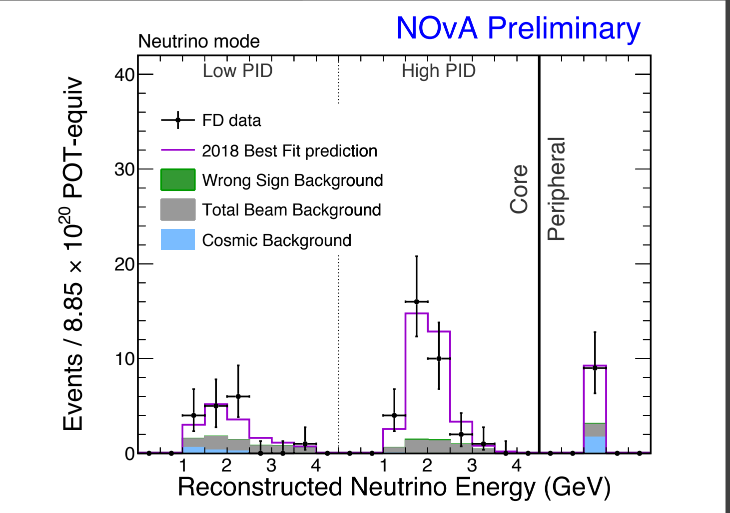


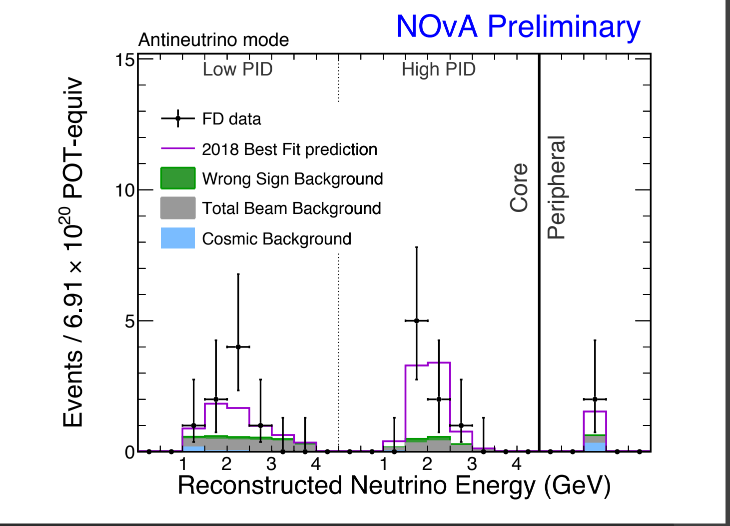
113 events observed in FD, 730 events expected if no oscillations

NOvA ν_e appearance

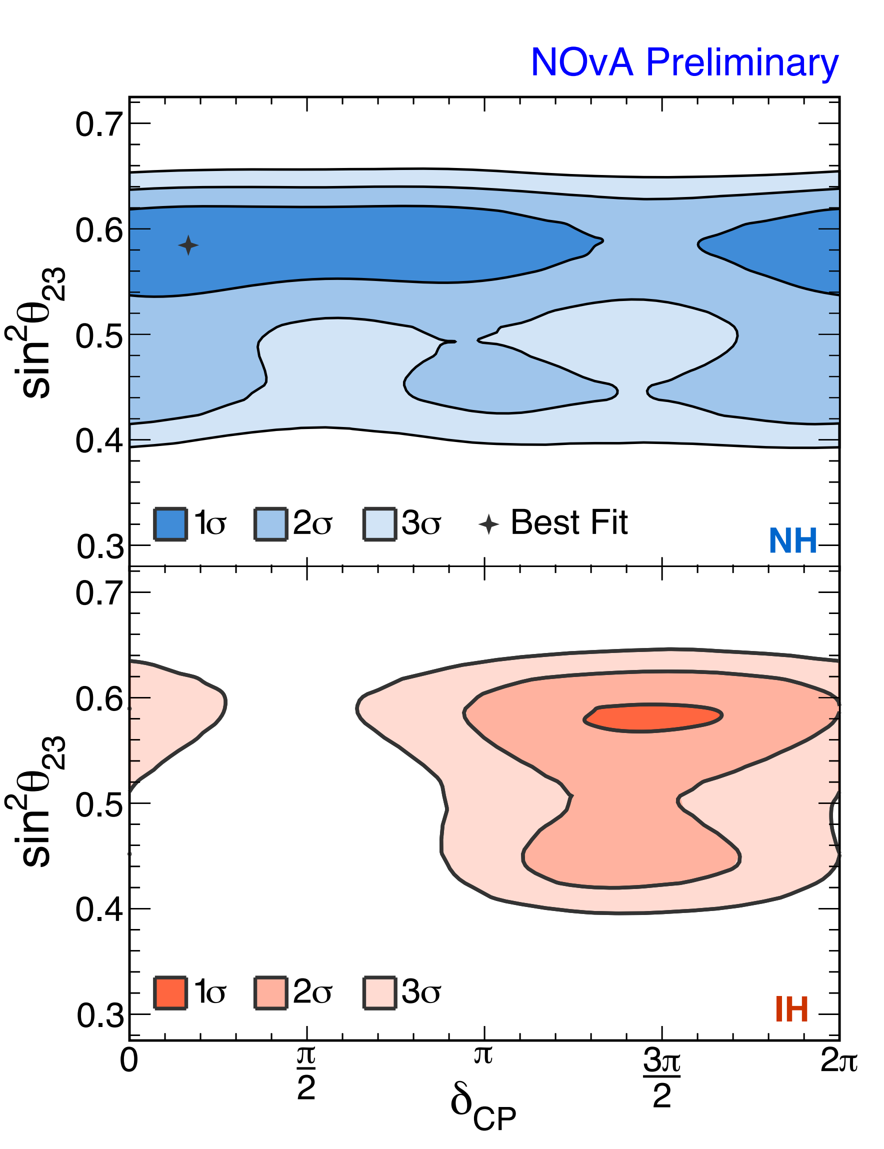
- 58 events for neutrino with 15 background
- 18 events for antineutrino with 5.3 background

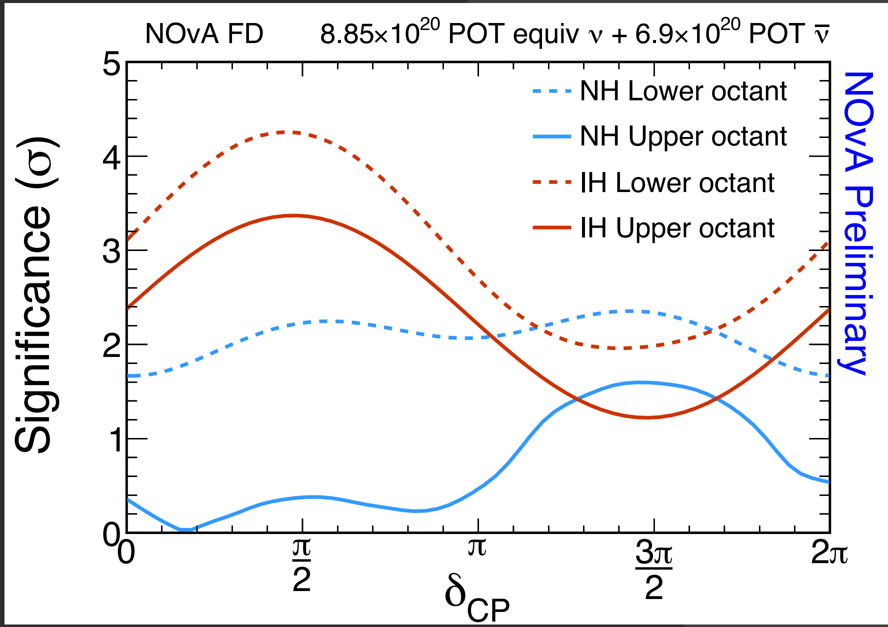






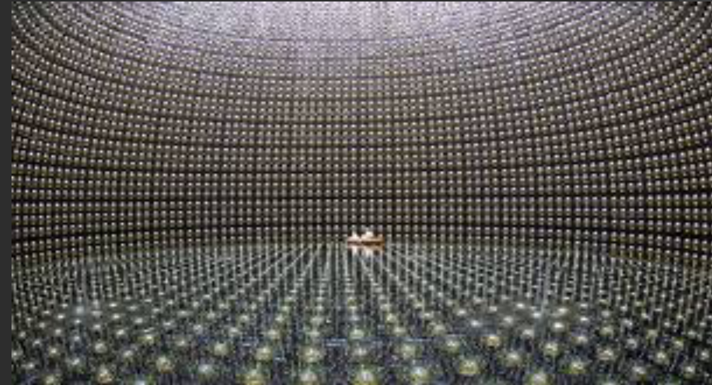
NOvA CP violation

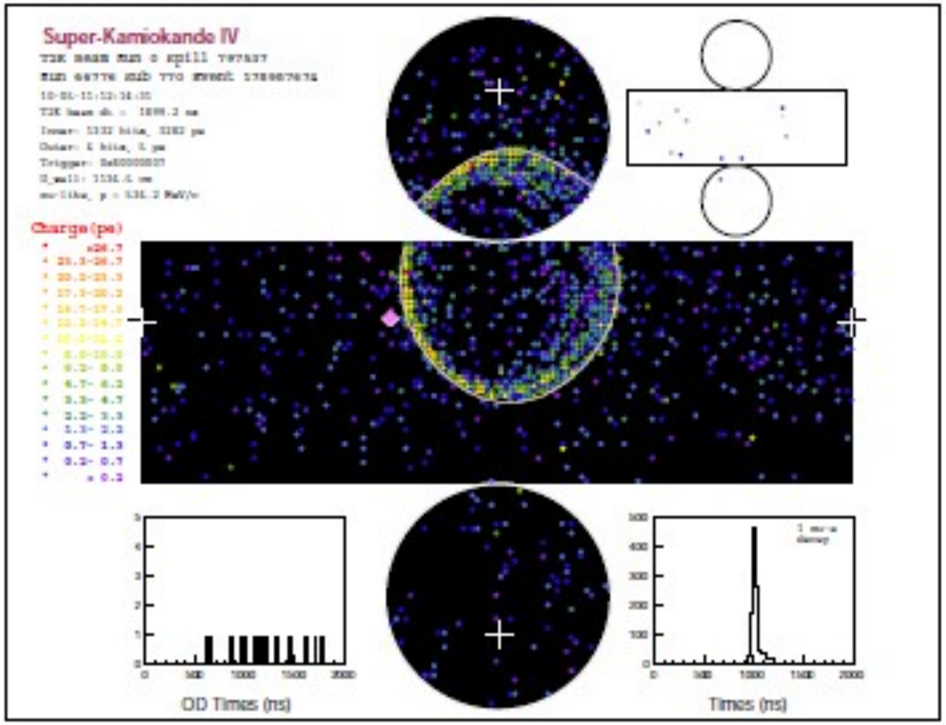


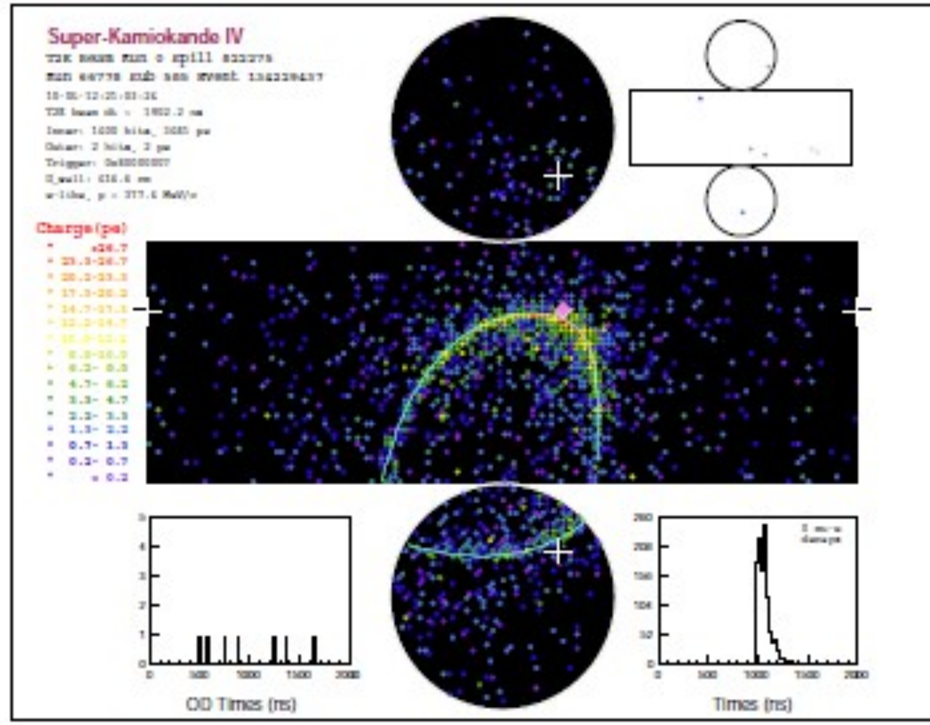


Normal hierarchy preferred: 1.8σ
Some ability to start to constrain δ_{CP}

T2K

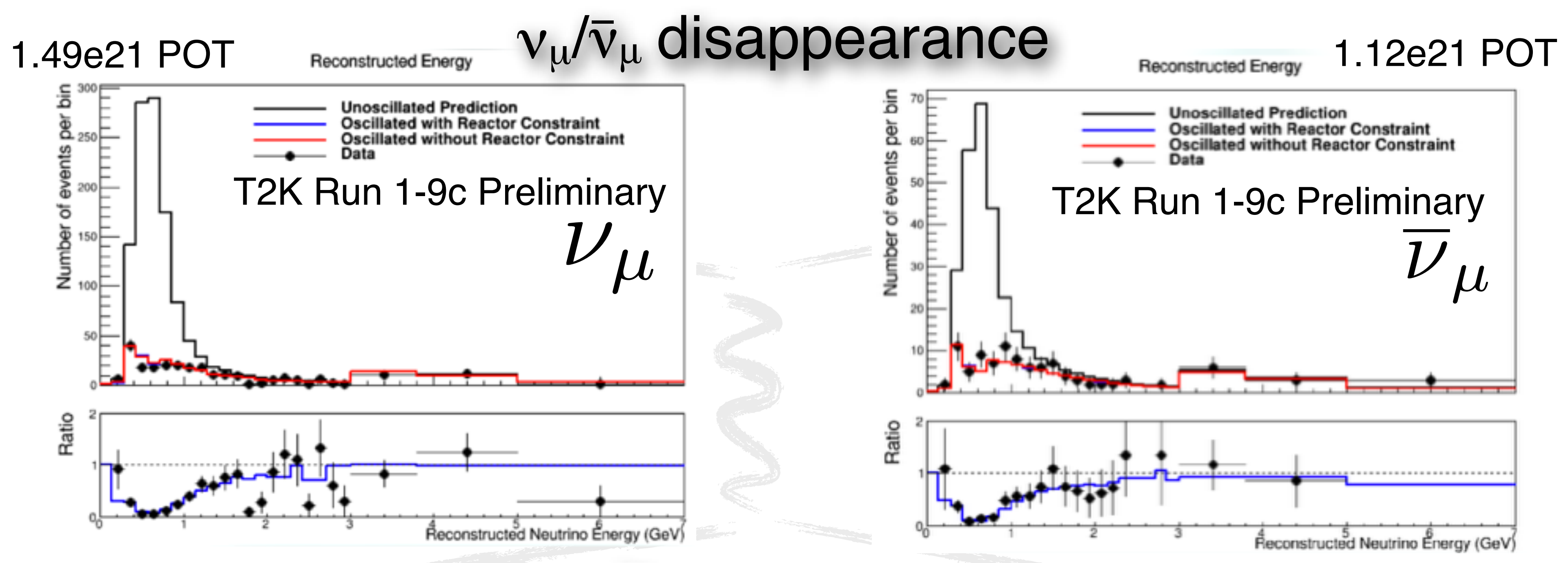




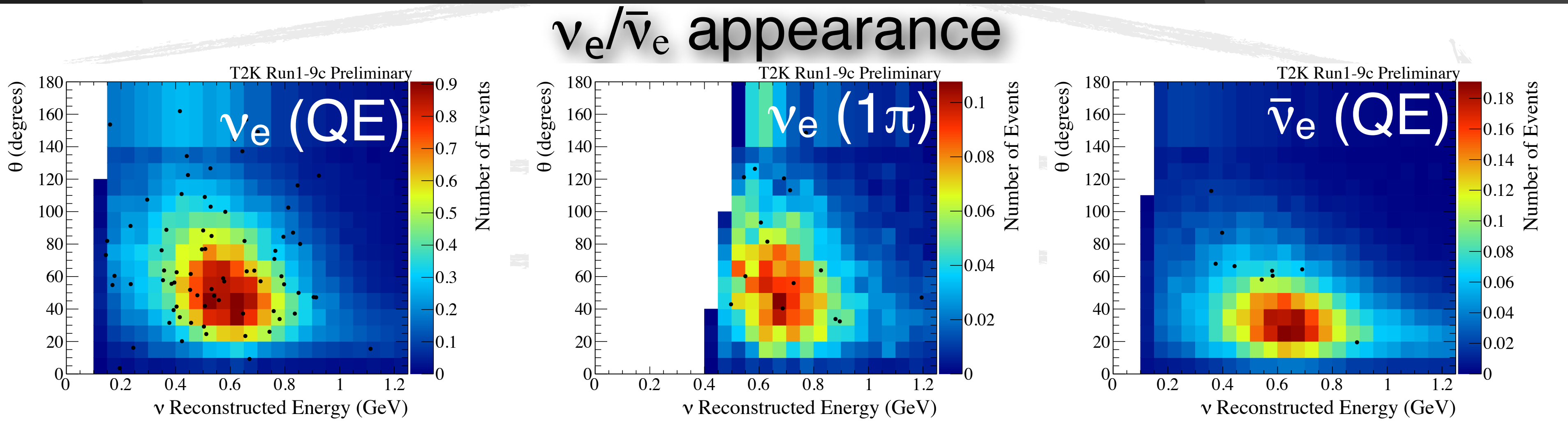


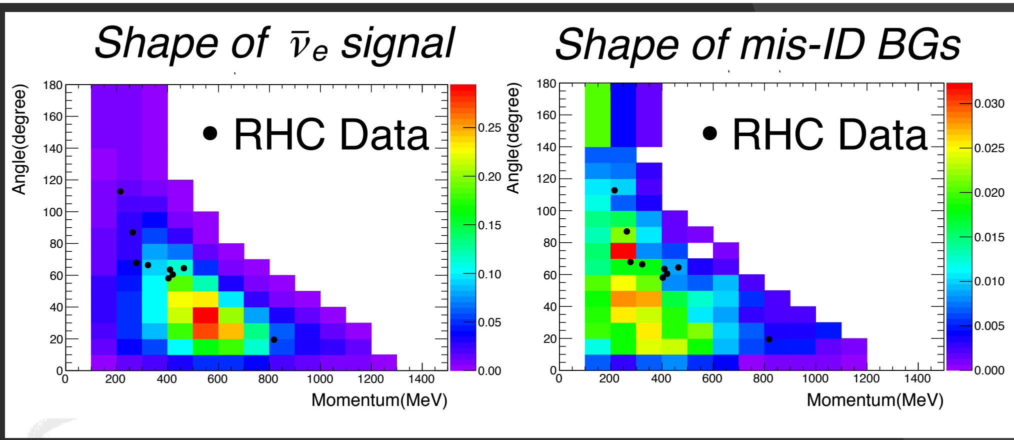
T2K content from M. Wascko, Neutrino 2018, June 2018

T2K ν_μ disappearance



T2K ν_e appearance

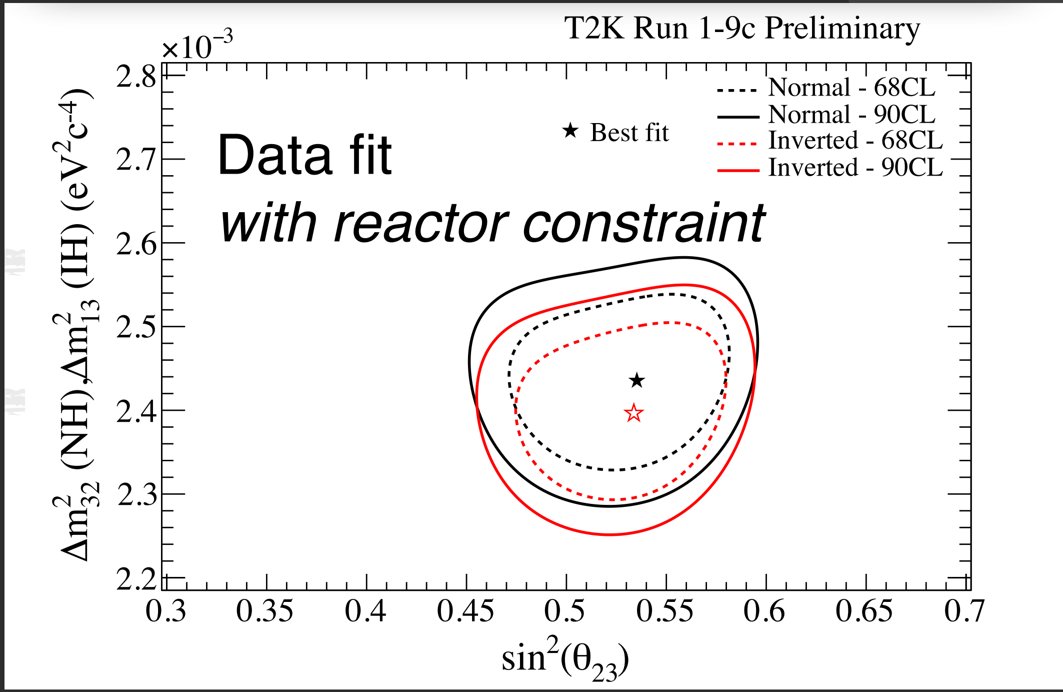




Neutrino appearance:
- 75 events observed
- 73.8 events predicted best-fit oscillations

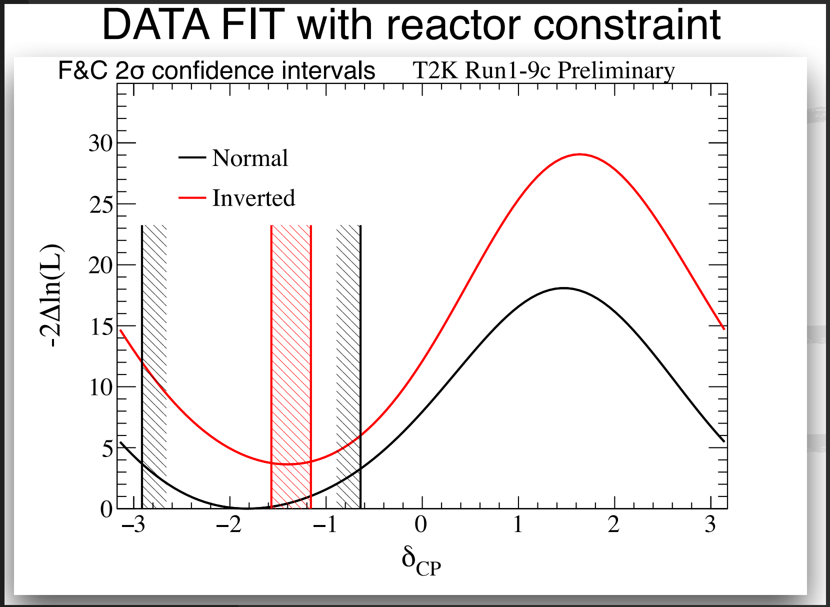
Antineutrino appearance:
- 9 events observed
- 6.5 if no oscillation
- 11.8 with oscillations

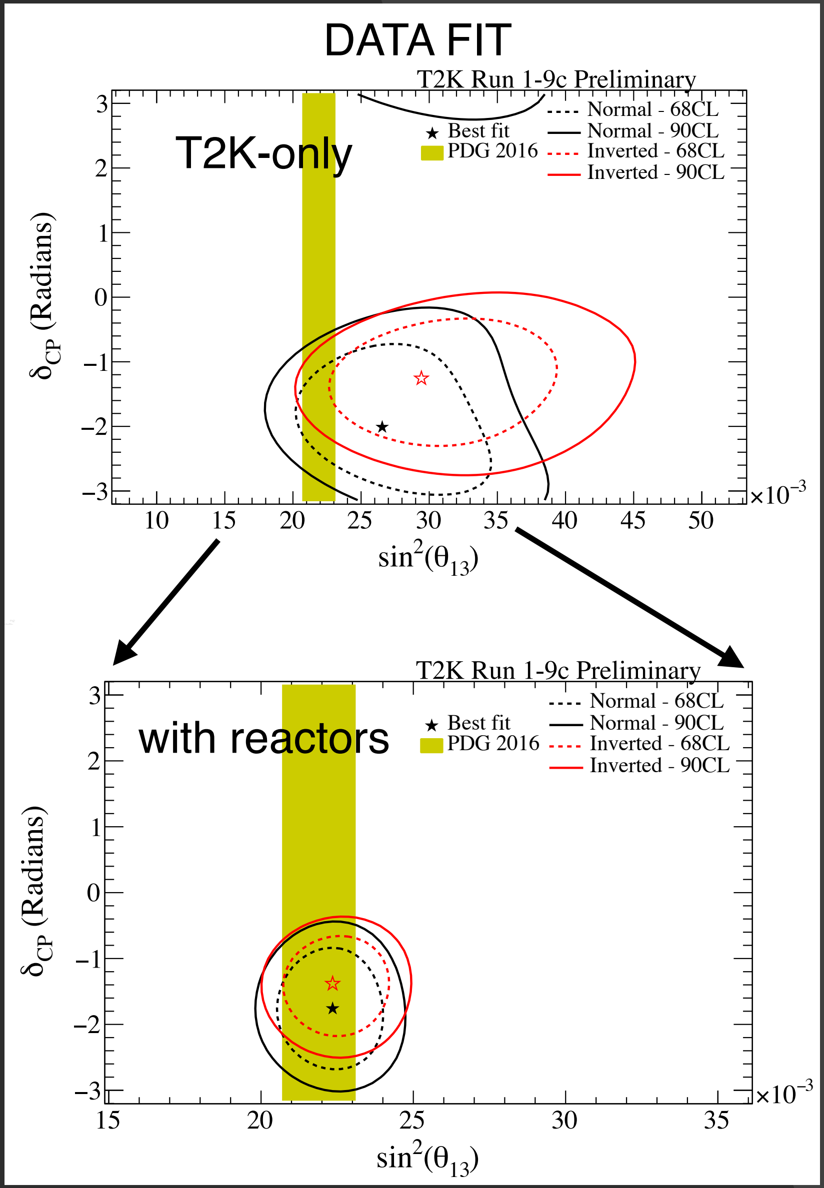
T2K Latest Results
oscillation parameters



	NH	IH
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\lvert\Delta m^2\rvert$	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

T2K CP violation



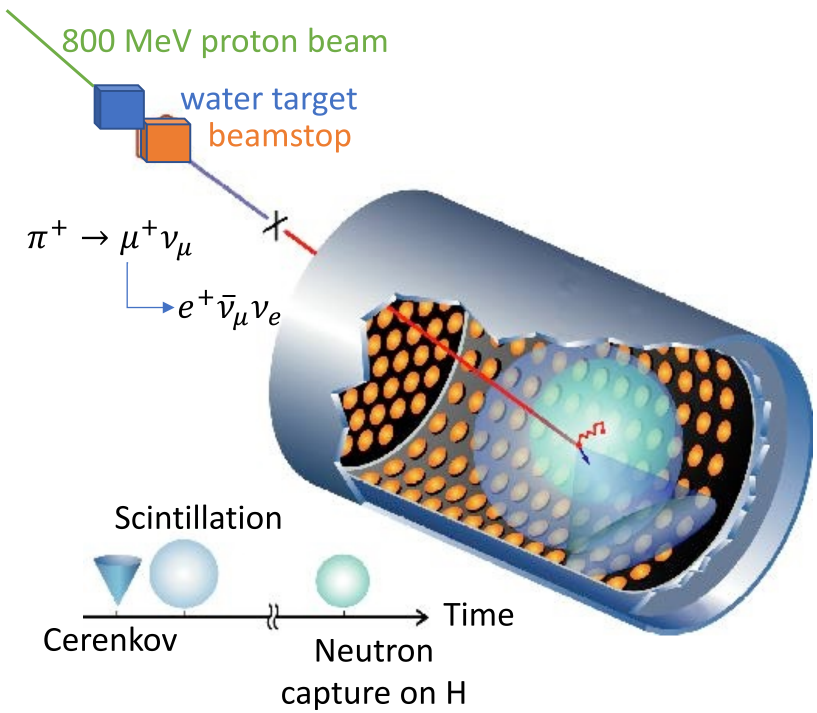


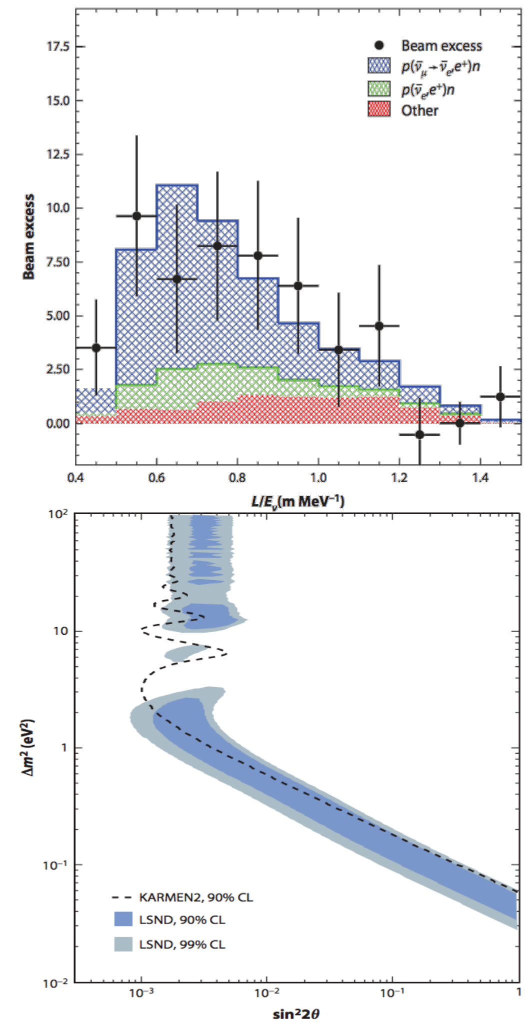
Normal hierarchy preferred @ 88.8%

CP-conserving δ_{CP} lie outside 2σ region

Is the 3-flavor oscillation picture complete?

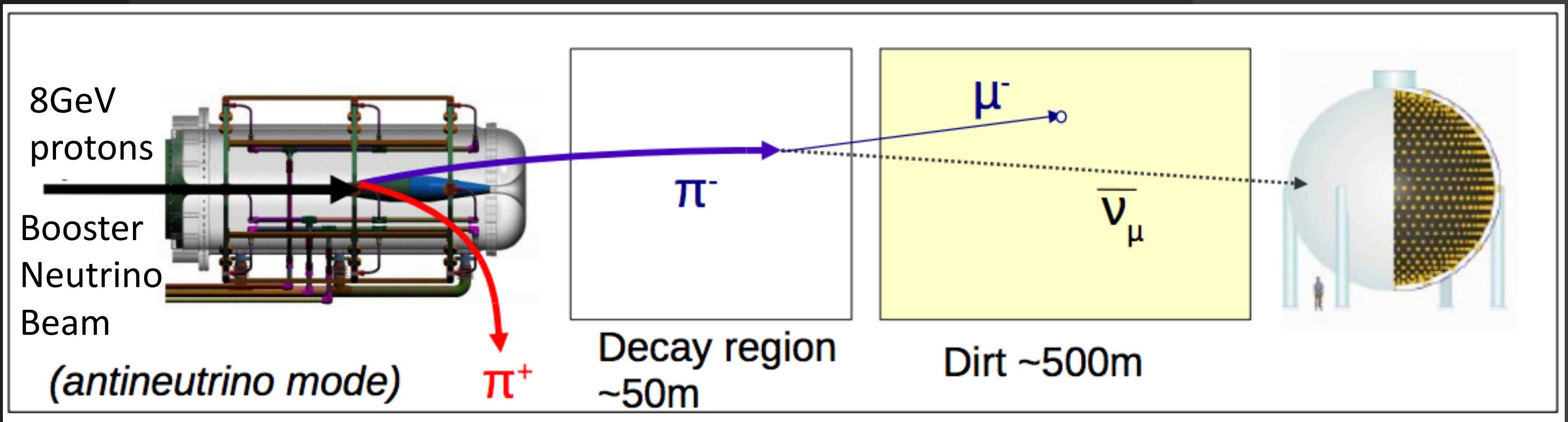
LSND Anomaly





LSND observed a 3.8σ excess

MiniBooNE



- Built at Fermilab to test/resolve the LSND anomaly

MiniBooNE L/E ~500 m/500 MeV

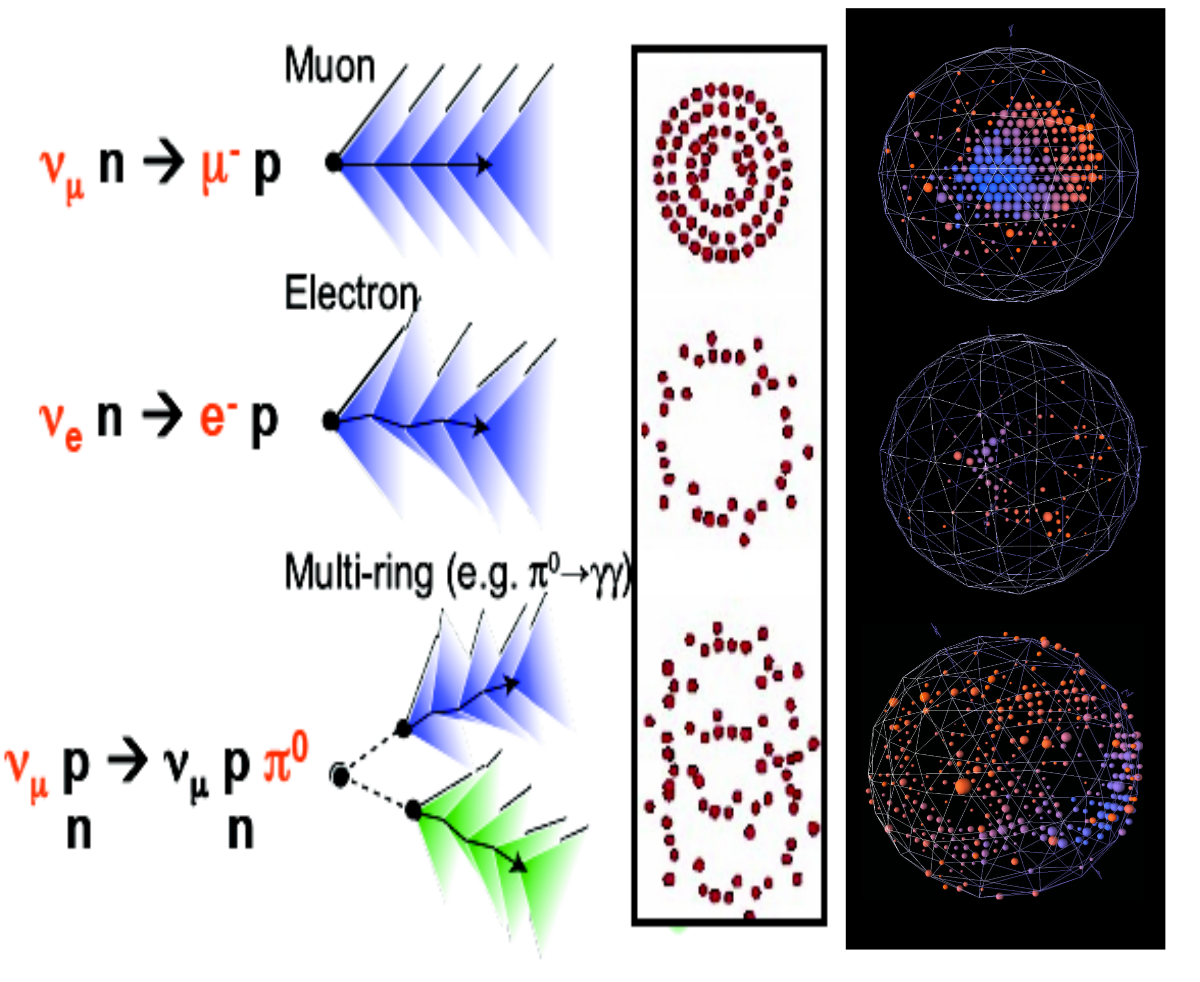
LSND L/E ~30 m/30 MeV

- Different backgrounds, different systematics, different (similar) detector

- However, MiniBooNE saw its own low-energy “background” excess…

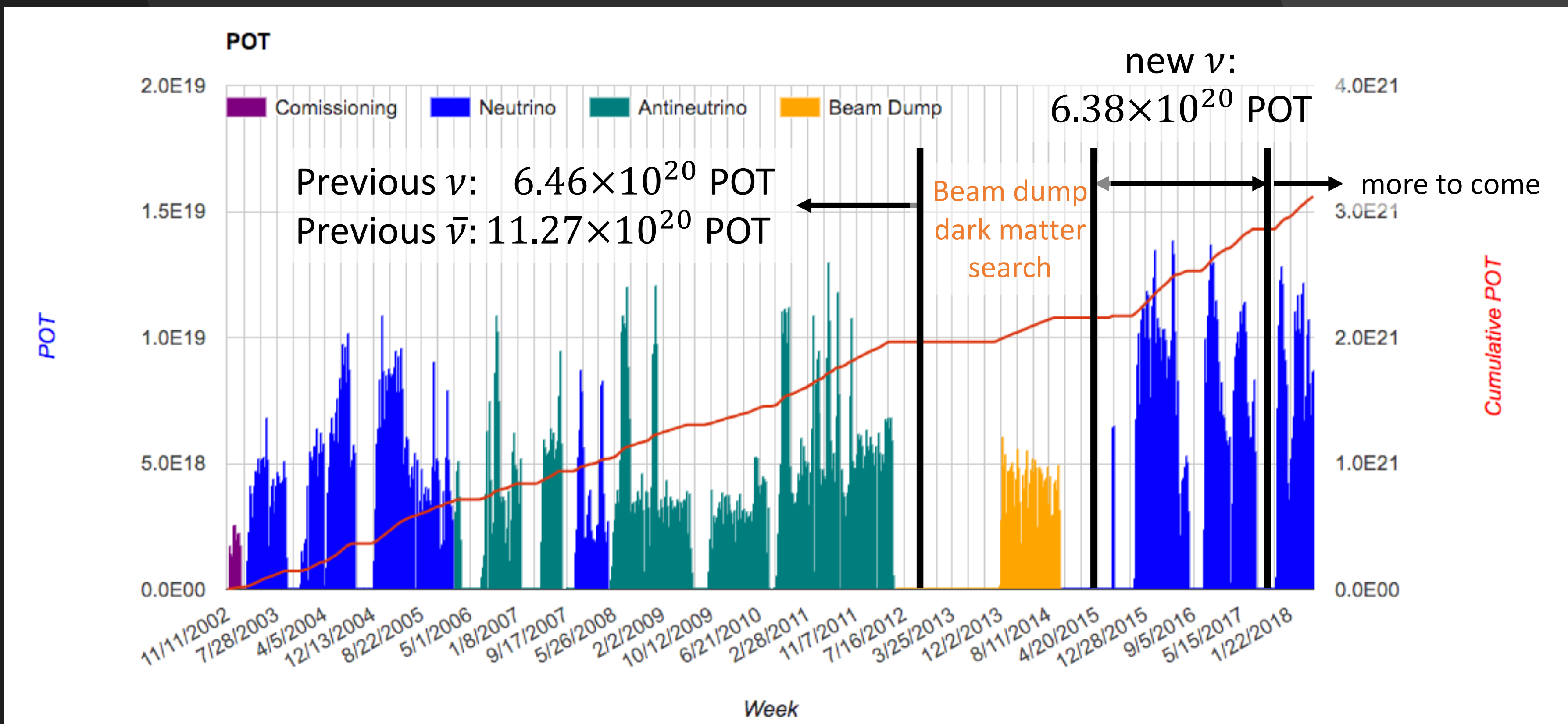
MiniBooNE content from E.-C. Huang, Neutrino 2018, June 2018

MiniBooNE: Mineral Oil Cherenkov/Scintillator Detector



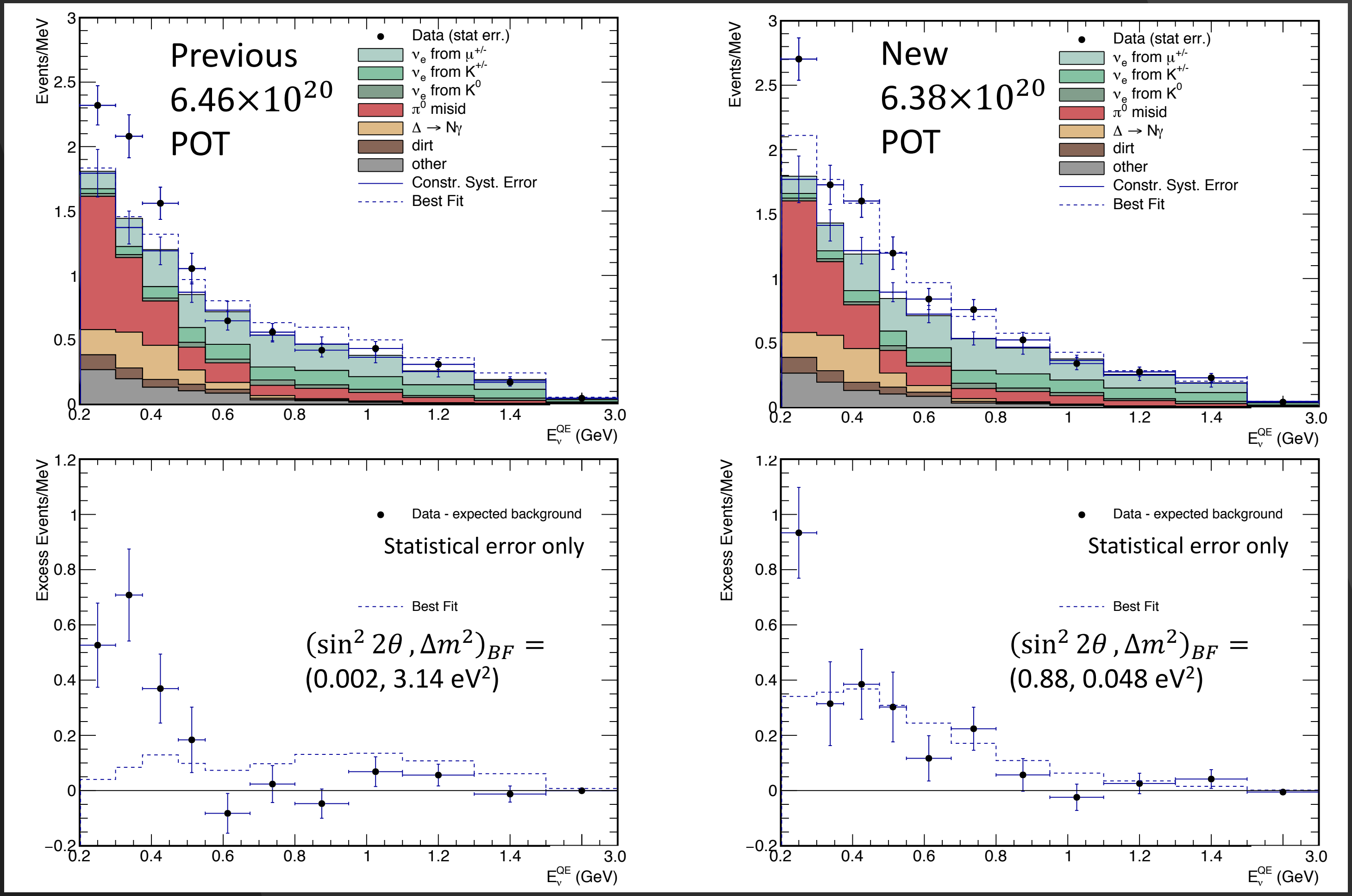
MiniBooNE Recent Results

- Double the neutrino data set, consistency checks, improved background estimates



A.A. Aguilar-Arevalo *et al.*, arXiv:1805.12028

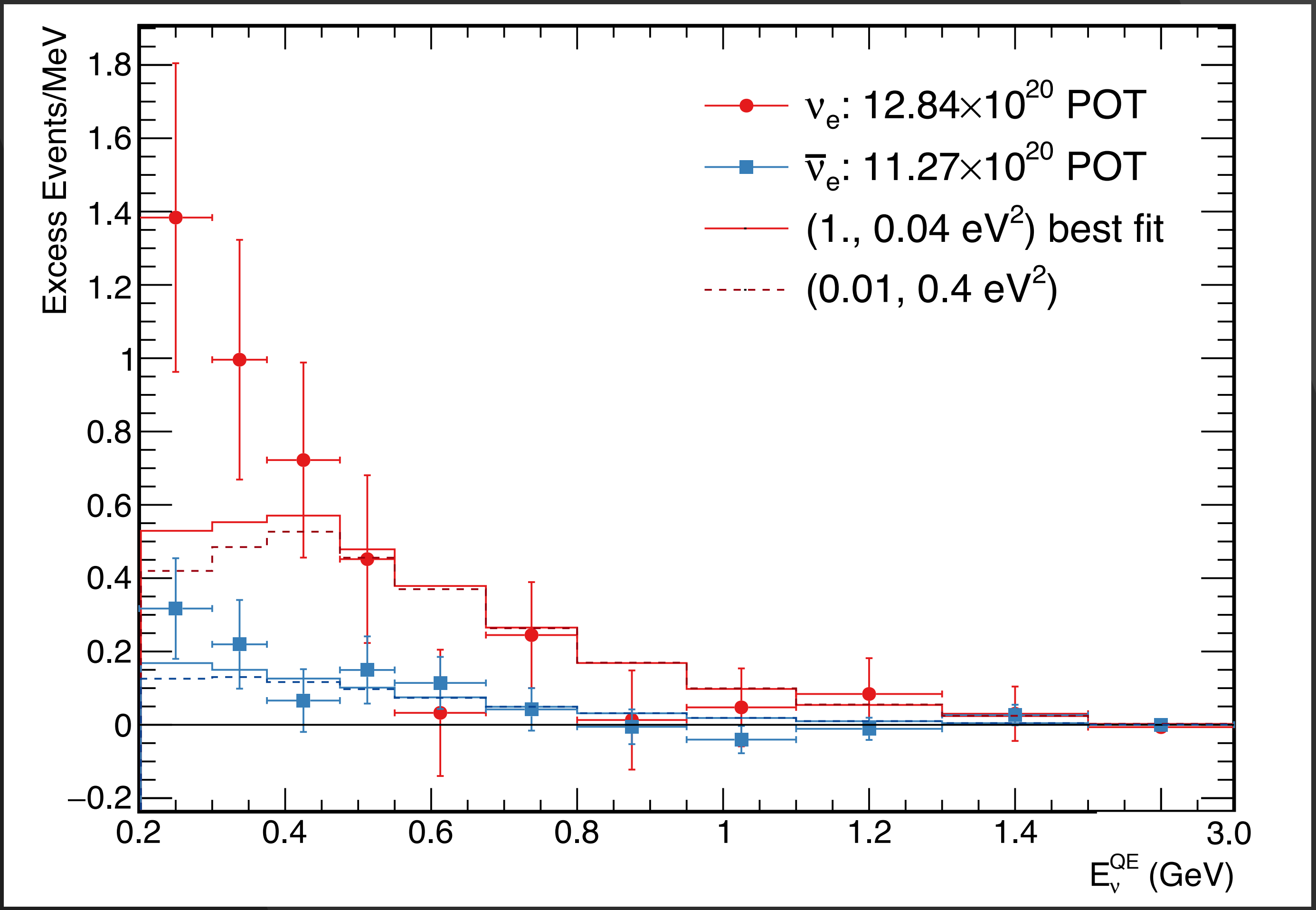
MiniBooNE Recent Results



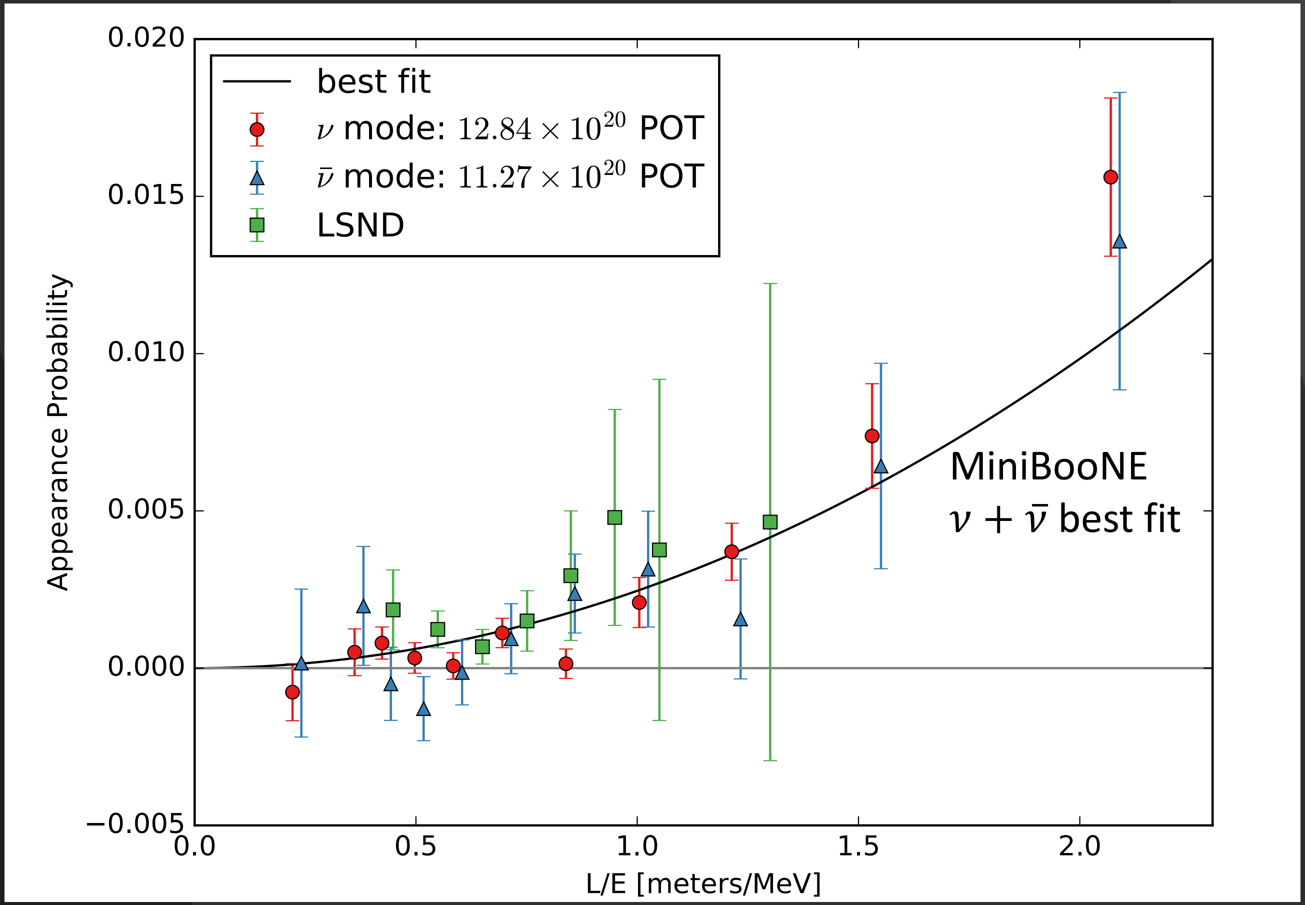
Previously MiniBooNE had a low-energy excess in neutrino mode inconsistent with oscillations

Now with double the data, the low-energy data fits the oscillation hypothesis

MiniBooNE Recent Results



MiniBooNE Recent Results

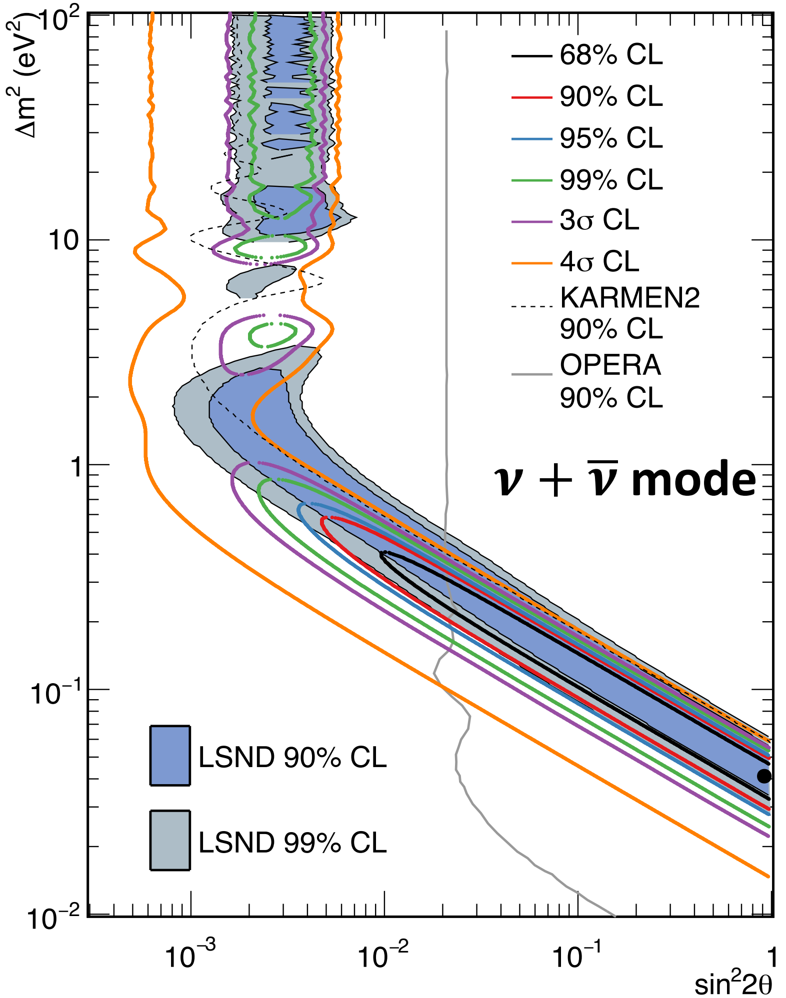


MiniBooNE+LSND Oscillation Results

Simple 2-neutrino oscillation model

Δm^2 is large: ~0.1-1.0 eV^2
inconsistent with 3-neutrino model

Confirms LSND at 4.8σ



$$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$$
$$\chi^2/ndf = 19.5/15.4\ (\text{prob} = 20.1\%)$$

Concluding Remarks: Neutrino Physics Recent Results

- We've learned a lot since the discovery of neutrino oscillations 20 years ago!
- We're closing in on the mass hierarchy and the CP violating phase
- We still need to understand neutrino mass – are neutrinos Majorana fermions? $\Longrightarrow$ double beta decay
- What's going on with LSND and MiniBooNE? Maybe more surprises? Mixing with sterile neutrinos?

Our work here is not done!