# Searches for Neutrino Magnetic Moment

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5th December 2016

Lancaster University

# Magnetic Moment

- Charged particles with spin have an intrinsic magnetic moment, $\mu_\mathrm{s}$, given by:

$$\mu_\mathrm{s} = g_\mathrm{s} \frac{q}{2m} \mathbf{S}$$

g-factor: $g_\mathrm{s}$ particle charge: $q$ particle mass: $m$
spin angular momentum: $\mathbf{S} = \hbar\sqrt{\mathbf{s}\left(\mathbf{s}+\mathbf{1}\right)}$

- For an electron, the Dirac equation predicts $g_\mathrm{s} = 2$.

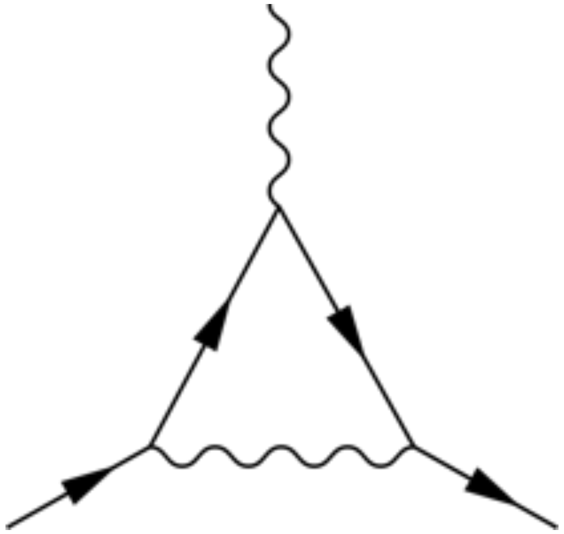
- Magnetic moments are frequently expressed in terms of Bohr magnetons, $\mu_\mathrm{B}$, given by:

$$\mu_\mathrm{B} = \frac{e\hbar}{2m_\mathrm{e}}$$

where $q = -e$

# Anomalous Magnetic Moment

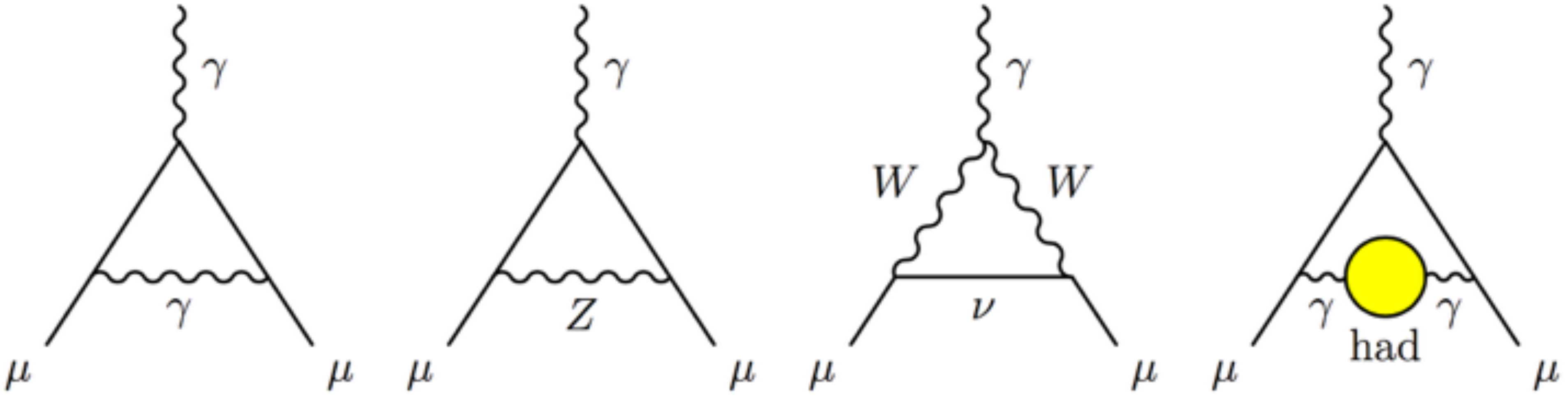
- Particle magnetic moments differ from those predicted by the Dirac equation due to corrections arising from virtual photon interactions.



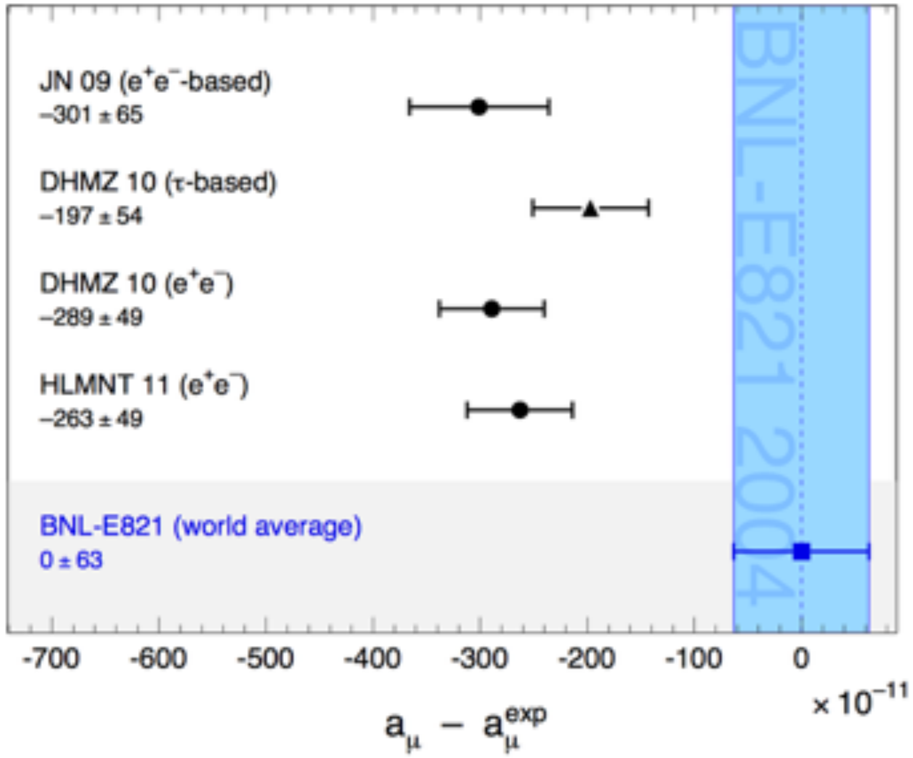
- The loop level contributions to a particle magnetic moment are known as the anomalous magnetic moment.
- For the electron the predicted anomalous magnetic moment, dominated by QED contributions, agrees with measurement to 11 significant figures.
  - (Arguably) The most accurately verified prediction in physics.

# Muon AMM

- For the muon, the anomalous magnetic moment has considerable contributions from EW and Hadronic interactions.



- Current measurements of the muon anomalous magnetic moment differ from theory by 3.6σ (2.4σ).
  - Hadronic loop contributions dominate theory uncertainty.



Muon Anomalous Magnetic Moment PDG Review Article

# Muon AMM

- The discrepancy between the predicted and measured anomalous magnetic moment for the muon is a potential signal of new (BSM) physics.

$$g_{\mathrm{s}}^{\mathrm{Tot}} = g_{\mathrm{s}}^{\mathrm{SM}}\left(g_{\mathrm{s}}^{\mathrm{QED}}, g_{\mathrm{s}}^{\mathrm{EW}}, g_{\mathrm{s}}^{\mathrm{Had}}\right) + g_{\mathrm{s}}^{\mathrm{New}}$$

  - New physics candidates include supersymmetry or a dark photon.

- The large errors on the theory and experimental values mean little can be read into the current discrepancy.

  - (Not that that has ever stopped theorists having a go).

# Muon AMM

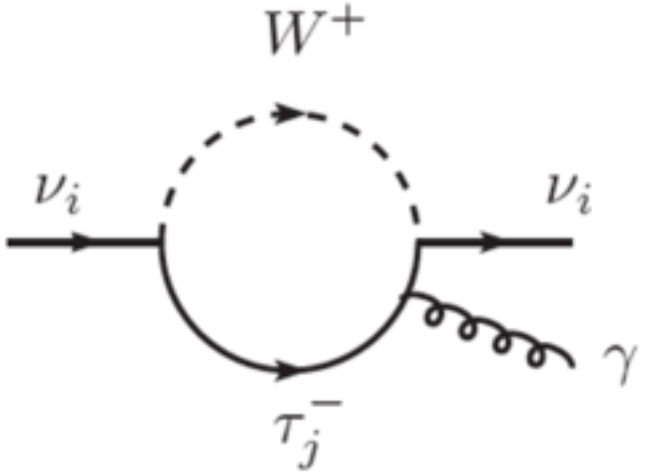
- Future improvements on the theory side, and results from the Muon g-2 experiment at Fermilab will change this situation.
  - Conservatively expect theory uncertainty to reduce by a factor of 2.
  - Muon g-2 will improve the experimental accuracy by a factor of 4.
- If the central values were to stay the same, expect difference between theory and experiment to gain a 5σ significance without theory improvements, and 7-8σ significance with theory improvements.

Muon g-2 TDR, arxiv.org/pdf/1501.06858v1.pdf

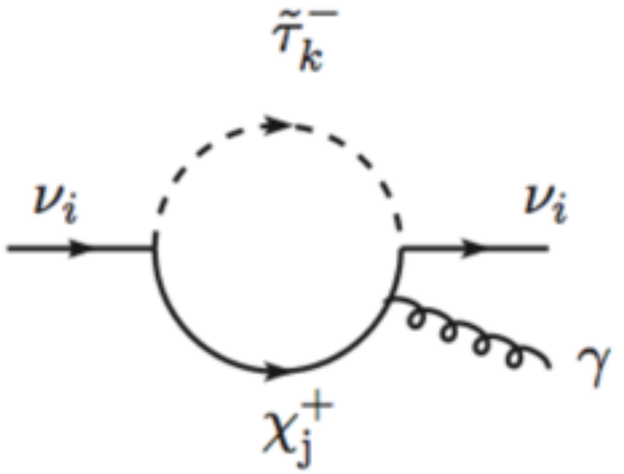
- But what can we learn from neutrinos?

# Neutrino MM

- Being a neutral particle the neutrino has no tree-level magnetic moment.
  - Only has an anomalous magnetic moment from loop level contributions.



- The SM coupling is incredibly small, and experimentally not measurable, $\mu_\nu \sim 3 \times 10^{-19} \mu_{\mathrm{B}} \, (m_\nu / 1\mathrm{eV})$.



- BSM physics contributions could enhance the neutrino magnetic moment to detectable levels.
  - MSSM extensions allow for magnetic moments as large as $\mu_\nu \approx 10^{-10} - 10^{-14} \mu_{\mathrm{B}}$.

Phys. Rev. D 89 055009 (2014)

# NMM Measurement Theory

- How do we search for the neutrino magnetic moment?

- The ν-electron elastic scattering differential cross section with respect to the kinetic energy of the recoil electron *T* in the Standard Model weak interactions is

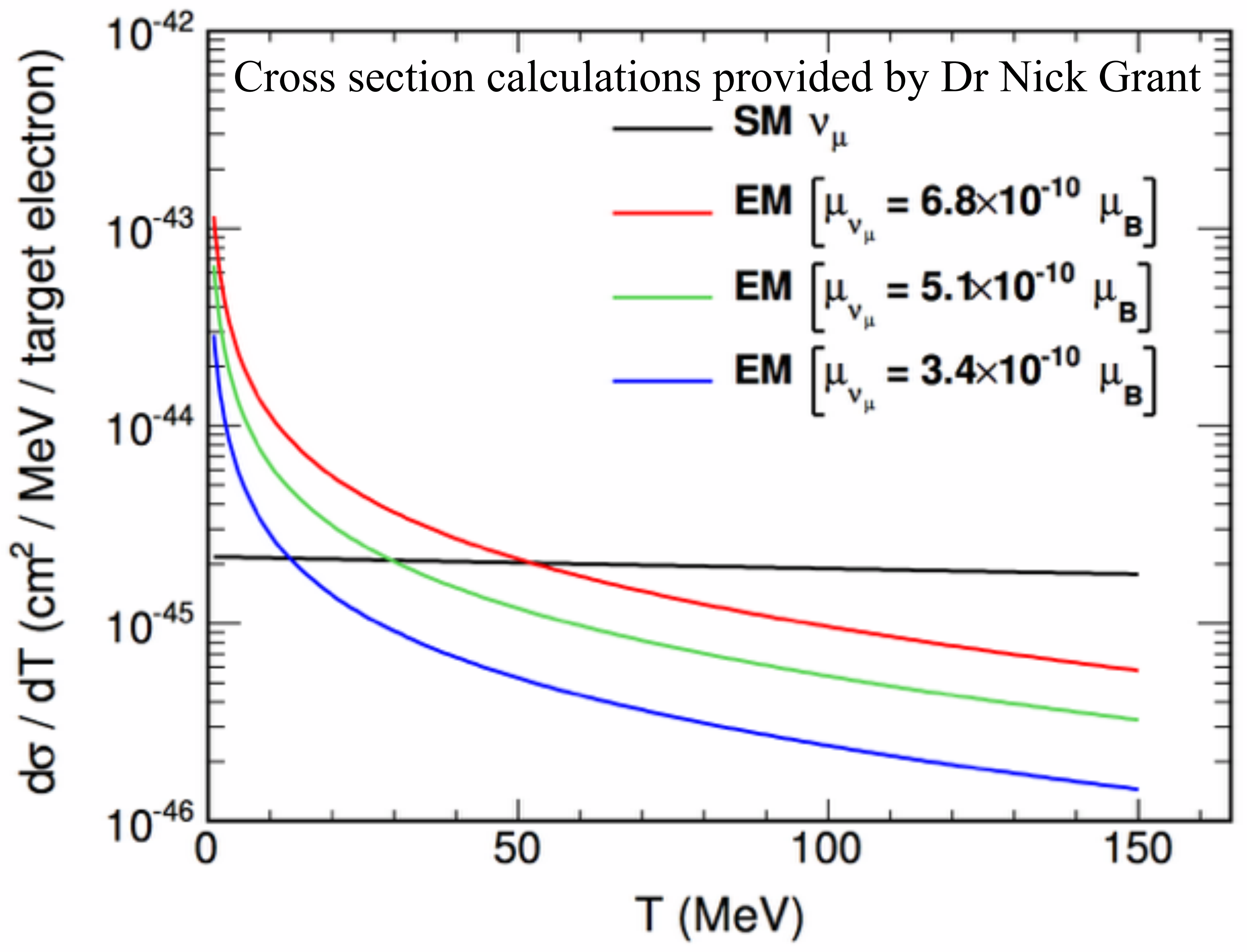
$$\frac{d\sigma}{dT} = \frac{G_F^2 m_{\mathrm{e}}}{2\pi}\left[(g_{\mathrm{V}}+g_{\mathrm{A}})^2 + (g_{\mathrm{V}}-g_{\mathrm{A}})^2\left(1-\frac{T}{E_\nu}\right)^2 + \left(g_{\mathrm{A}}^2+g_{\mathrm{V}}^2\right)\frac{m_{\mathrm{e}}T}{E_\nu^2}\right]$$

- The neutrino magnetic moment contributes an additional electromagnetic component to this cross section of

$$\frac{d\sigma}{dT} = \frac{\pi\alpha^2\mu_\nu^2}{m_{\mathrm{e}}^2}\left[\frac{1}{T}-\frac{1}{E_\nu}\right]$$

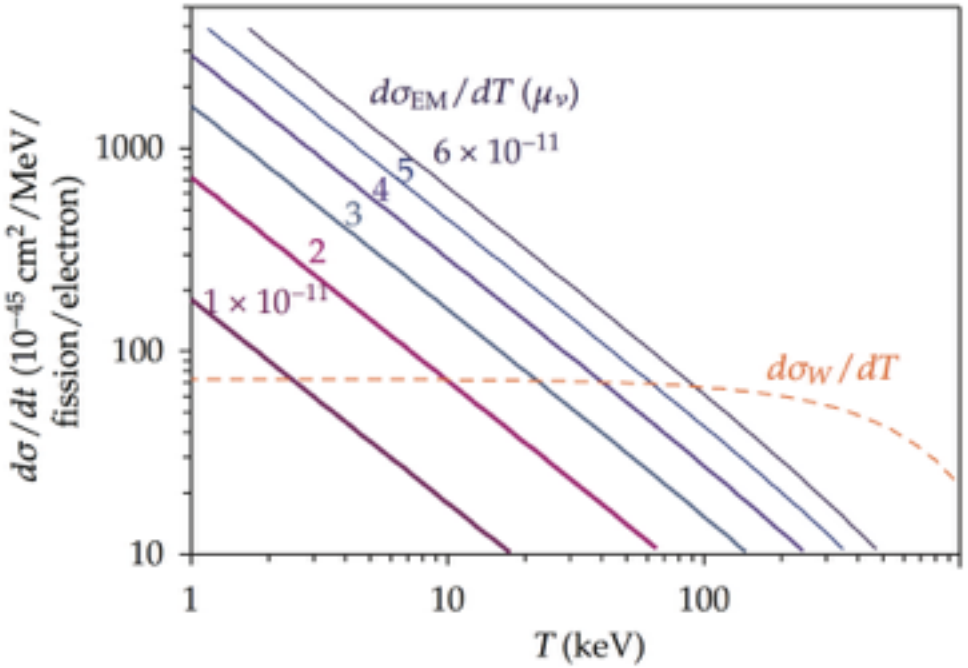
# NMM Measurement Theory

- At low values of *T*, the SM cross section is approximately constant, but the EM cross section decreases rapidly.



# NMM Measurement Theory

- Searching for the neutrino (anomalous) magnetic moment is then, in principle, straight forward.
  - The SM ν-e elastic scattering cross section is known to ~1% precision.
  - Require an experiment to measures a sample of ν-e elastic scattering interactions at a range of *T* values.
  - A ν-e elastic scattering spectrum can then be constructed.
  - This is searched for an enhancement of ν-e elastic scattering interactions at low *T* values above the SM expectation.
  - In the absence of a signal calculate new upper limit on the maximum NMM.



Adv. High Energy Phys. 2012, 350150 (2012)

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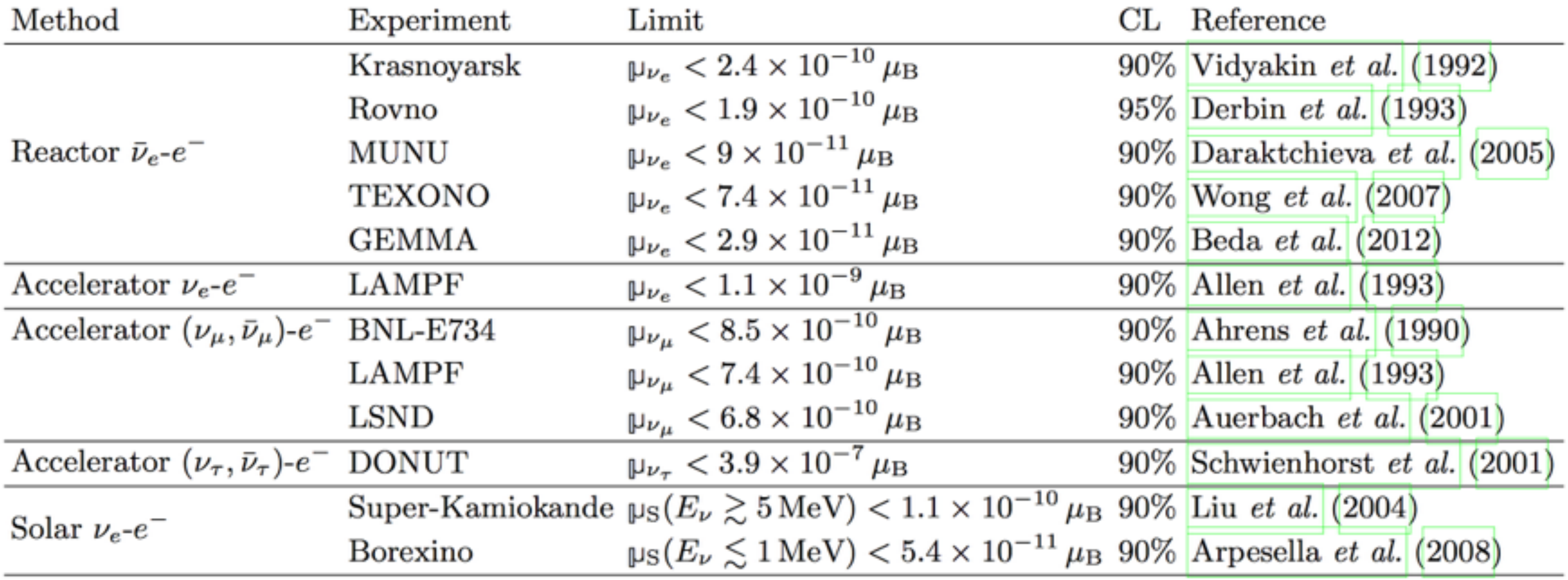
# Current Limits

- Current limits come from a range of different neutrino sources and experiments.
    - These are all significantly above the SM prediction, leaving plenty of scope for the emergence of new physics.



| Method | Experiment | Limit | CL | Reference |
|---|---|---|---|---|
| Reactor $\bar{\nu}_e$-$e^-$ | Krasnoyarsk | $\mu_{\nu_e} < 2.4 \times 10^{-10}\,\mu_B$ | 90% | Vidyakin *et al.* (1992) |
| | Rovno | $\mu_{\nu_e} < 1.9 \times 10^{-10}\,\mu_B$ | 95% | Derbin *et al.* (1993) |
| | MUNU | $\mu_{\nu_e} < 9 \times 10^{-11}\,\mu_B$ | 90% | Daraktchieva *et al.* (2005) |
| | TEXONO | $\mu_{\nu_e} < 7.4 \times 10^{-11}\,\mu_B$ | 90% | Wong *et al.* (2007) |
| | GEMMA | $\mu_{\nu_e} < 2.9 \times 10^{-11}\,\mu_B$ | 90% | Beda *et al.* (2012) |
| Accelerator $\nu_e$-$e^-$ | LAMPF | $\mu_{\nu_e} < 1.1 \times 10^{-9}\,\mu_B$ | 90% | Allen *et al.* (1993) |
| Accelerator $(\nu_\mu, \bar{\nu}_\mu)$-$e^-$ | BNL-E734 | $\mu_{\nu_\mu} < 8.5 \times 10^{-10}\,\mu_B$ | 90% | Ahrens *et al.* (1990) |
| | LAMPF | $\mu_{\nu_\mu} < 7.4 \times 10^{-10}\,\mu_B$ | 90% | Allen *et al.* (1993) |
| | LSND | $\mu_{\nu_\mu} < 6.8 \times 10^{-10}\,\mu_B$ | 90% | Auerbach *et al.* (2001) |
| Accelerator $(\nu_\tau, \bar{\nu}_\tau)$-$e^-$ | DONUT | $\mu_{\nu_\tau} < 3.9 \times 10^{-7}\,\mu_B$ | 90% | Schwienhorst *et al.* (2001) |
| Solar $\nu_e$-$e^-$ | Super-Kamiokande | $\mu_S(E_\nu \gtrsim 5\,\mathrm{MeV}) < 1.1 \times 10^{-10}\,\mu_B$ | 90% | Liu *et al.* (2004) |
| | Borexino | $\mu_S(E_\nu \lesssim 1\,\mathrm{MeV}) < 5.4 \times 10^{-11}\,\mu_B$ | 90% | Arpesella *et al.* (2008) |

Rev. Mod. Phys. 87 531 (2015)

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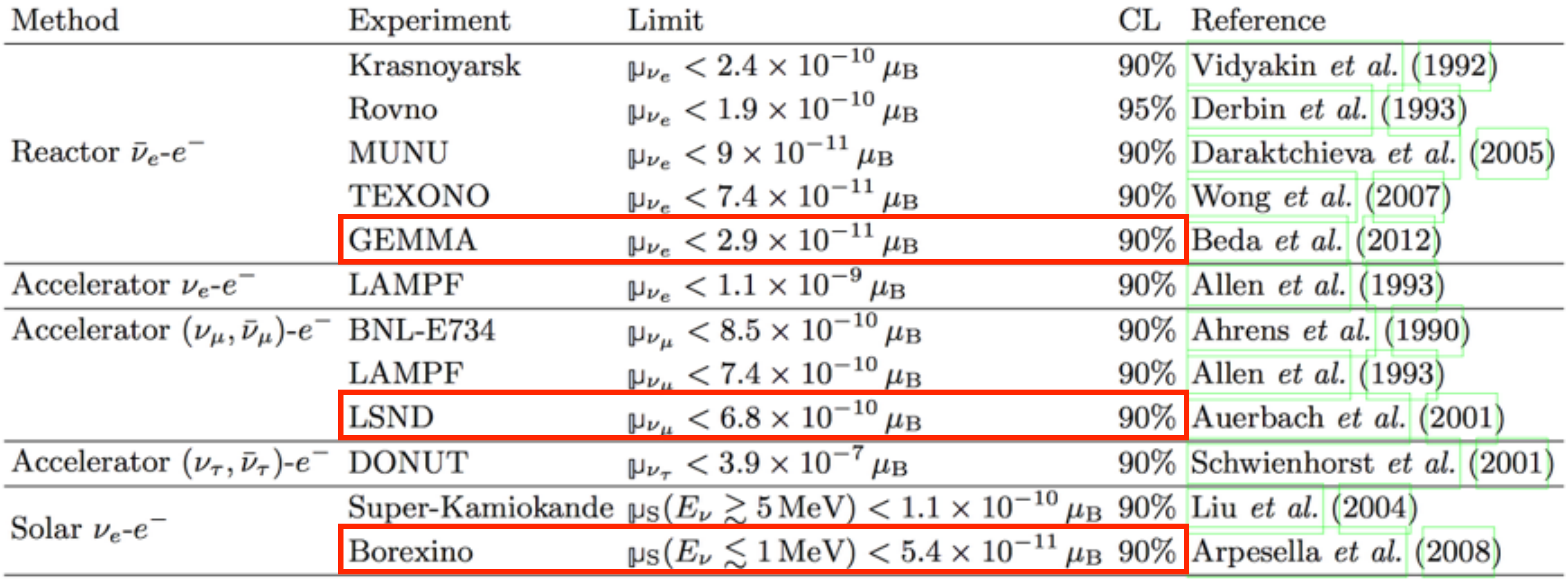

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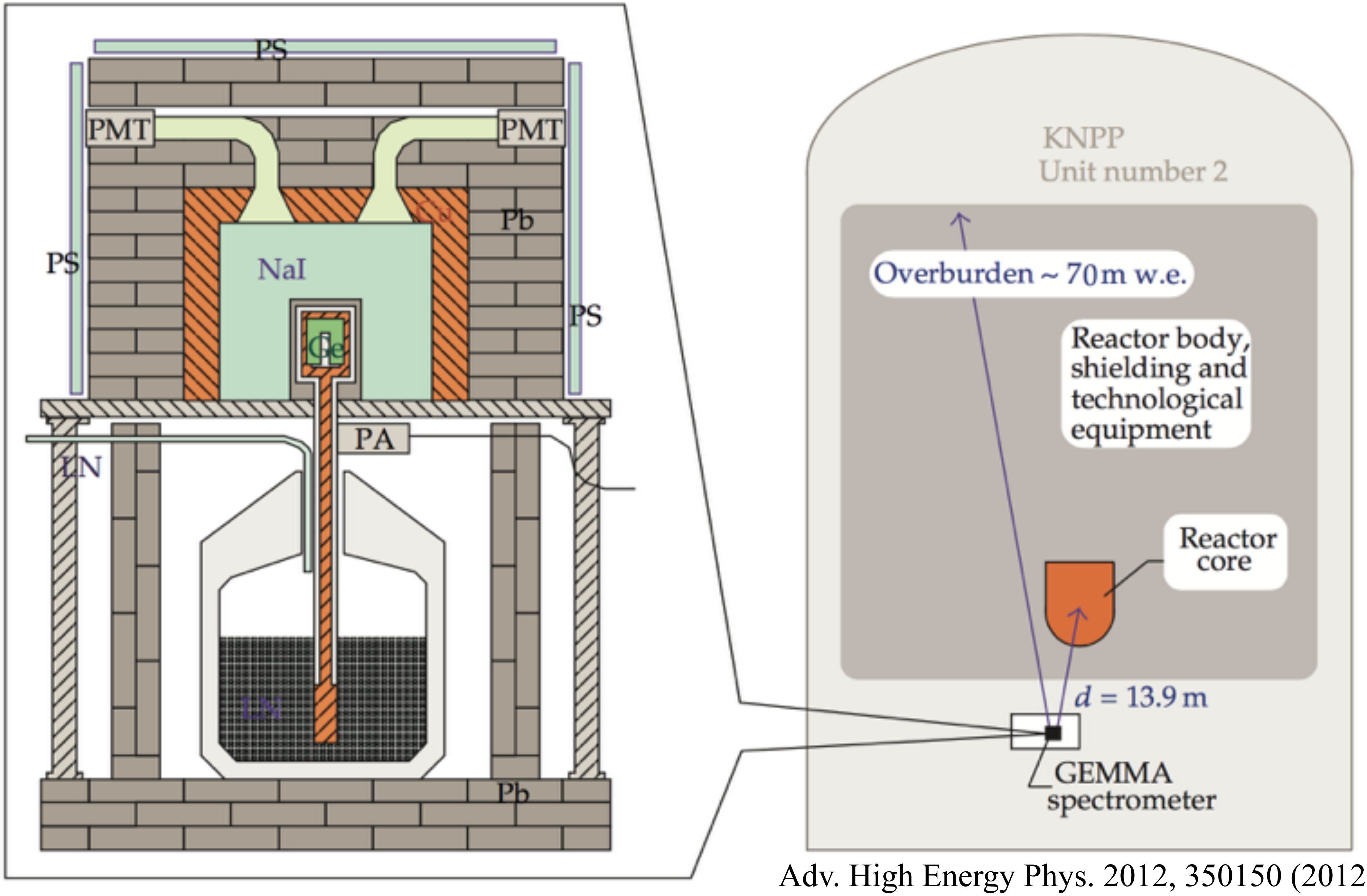
Rev. Mod. Phys. 87 531 (2015)

- Let's look at the details of a few of these methods.

# Reactor Limit

- Best experiment limit provided by the GEMMA spectrometer at the Kalinin Nuclear Power Plant, Russia.



Adv. High Energy Phys. 2012, 350150 (2012)

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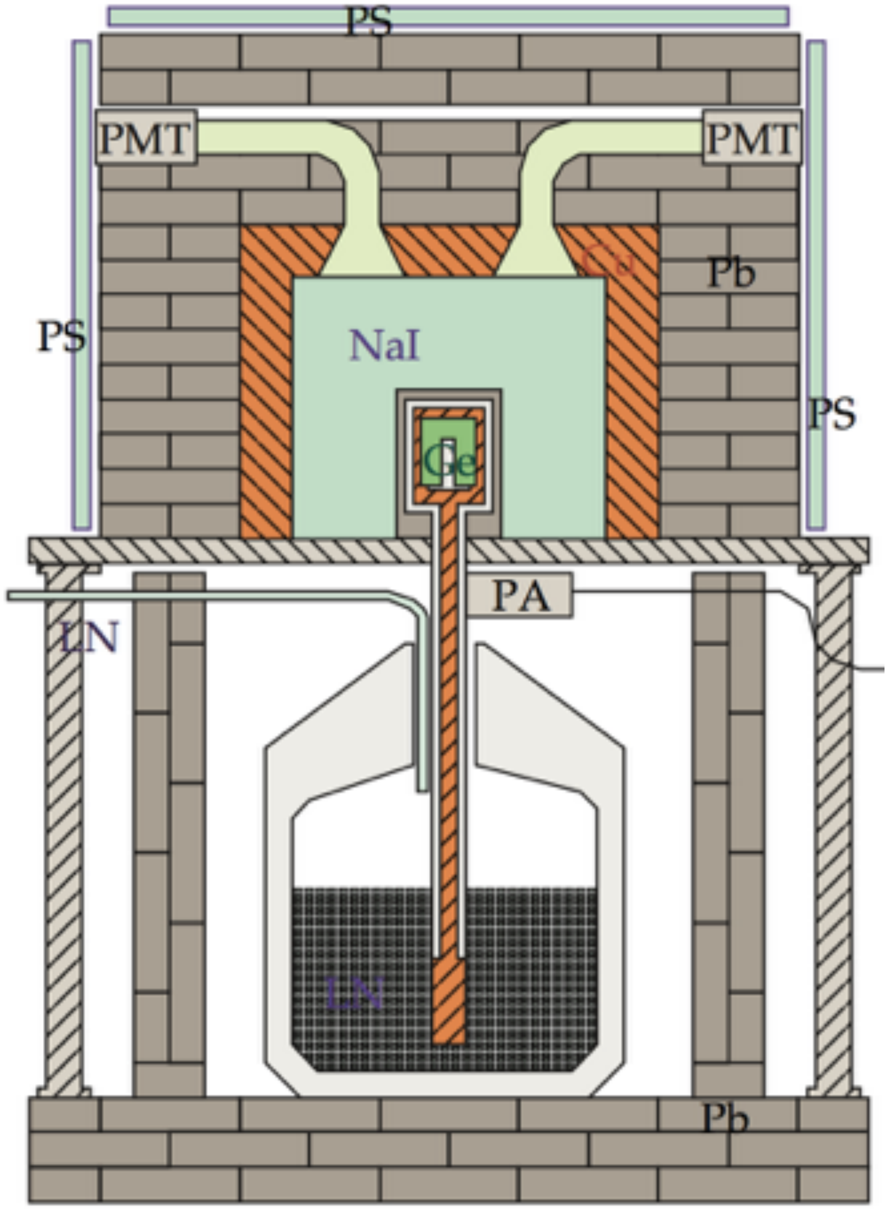
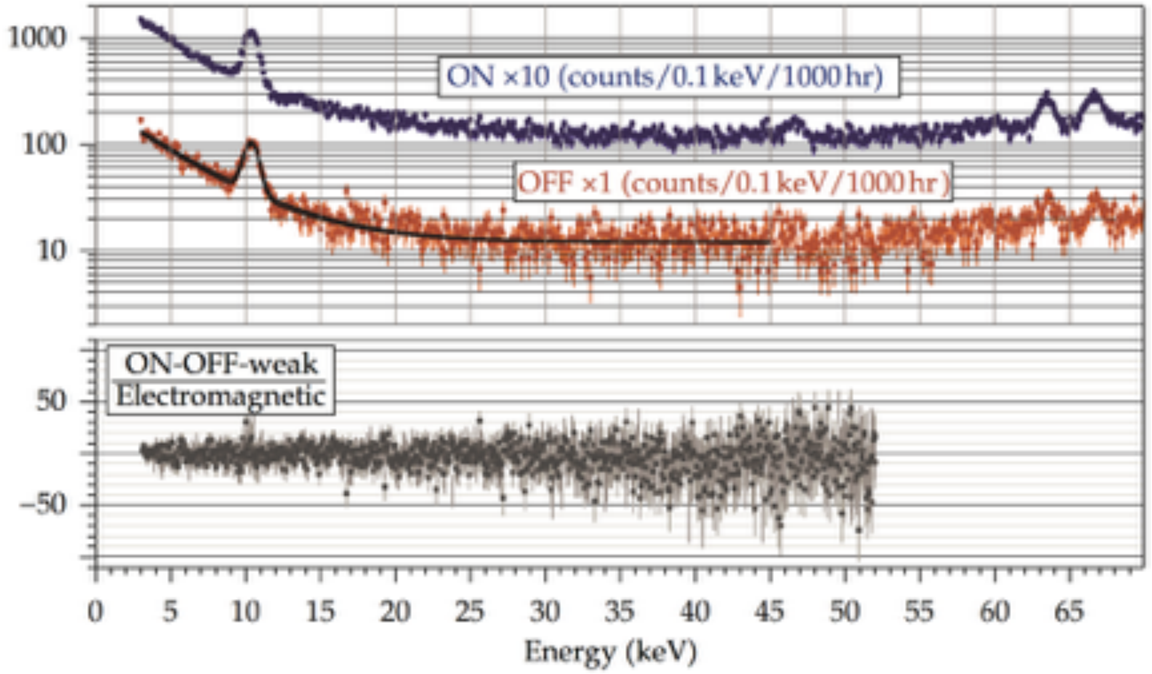


- 1.5 kg HPGe detector
- Passive and active shielding
- 2.8 keV energy threshold
- Reactor flux constraint from thermal power
- Reactor ON and OFF data for background subtraction

# Reactor Limit

- Build up a spectrum ON and OFF spectrum.
  - Fits are performed to the OFF data.
  - Channel-by-channel difference between calculated between fits and ON data.

Adv. High Energy Phys. 2012, 350150 (2012)



- Difference then renormalised to the known SM ν-e cross section and an upper limit on the contribution from the neutrino magnetic moment extracted.
  - Limit of $\mu_{\bar{\nu}_e} < 2.9 \times 10^{-11} \mu_B$ at 90% C.L.

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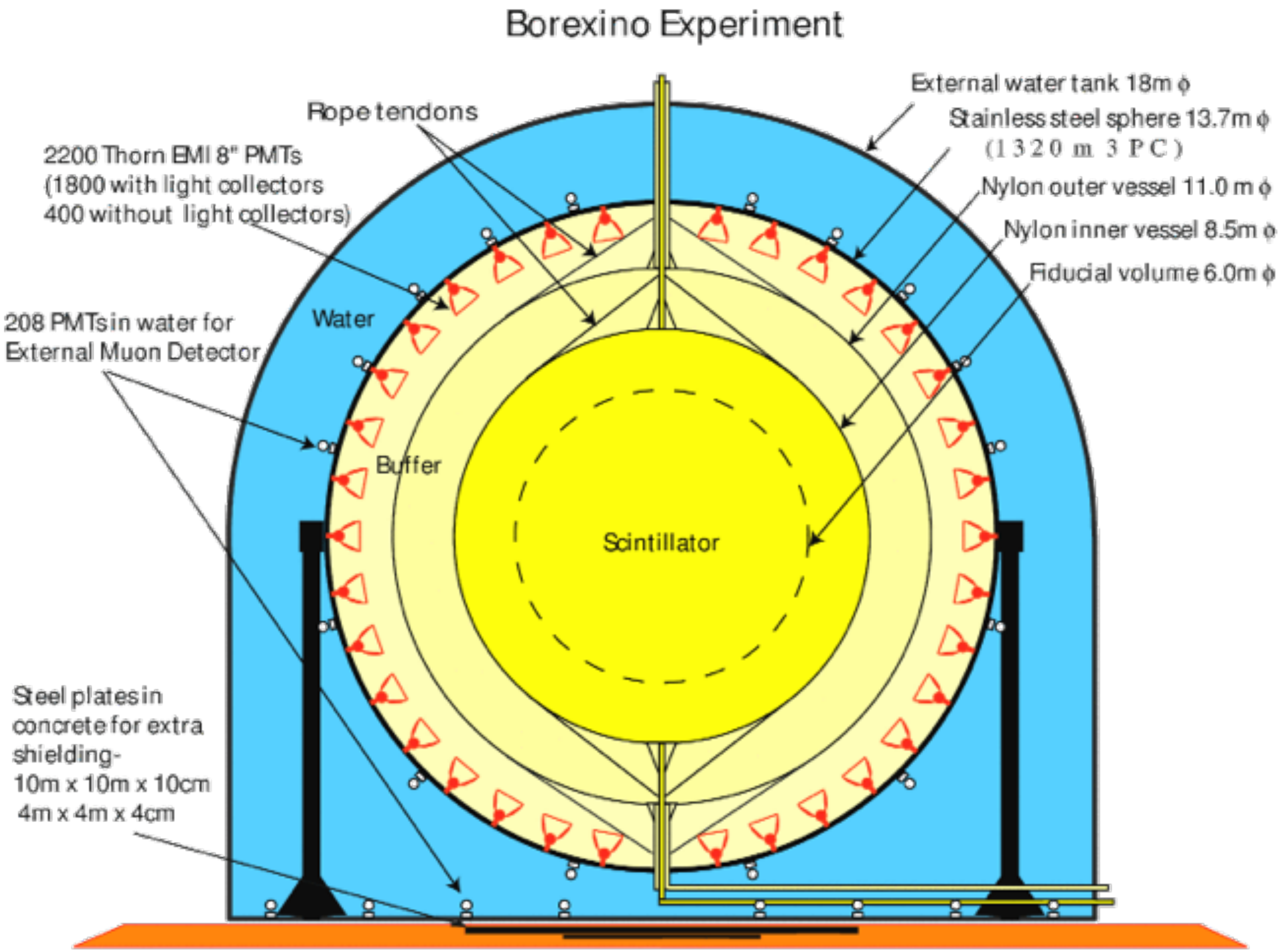
# Reactor Limit

- GEMMA-II will improve on the current limits, features:
  - Double the flux by moving to 10 m from unit 3 core.
  - 6 kg target mass (4x increase).
  - Reduced backgrounds.
  - 1.5 keV energy threshold
    - (GEMMA-III ~350 eV).
  - Separate flux monitoring detector (DANSS).
- Sensitive to $\mu_{\bar{\nu}_e} \approx 1 \times 10^{-11} \mu_B$.
  - (GEMMA-III $\mu_{\bar{\nu}_e} \approx 9 \times 10^{-12} \mu_B$).

# Solar Limit

- Best limit provided by the Borexino experiment at the Gran Sasso Underground Laboratory, Italy.

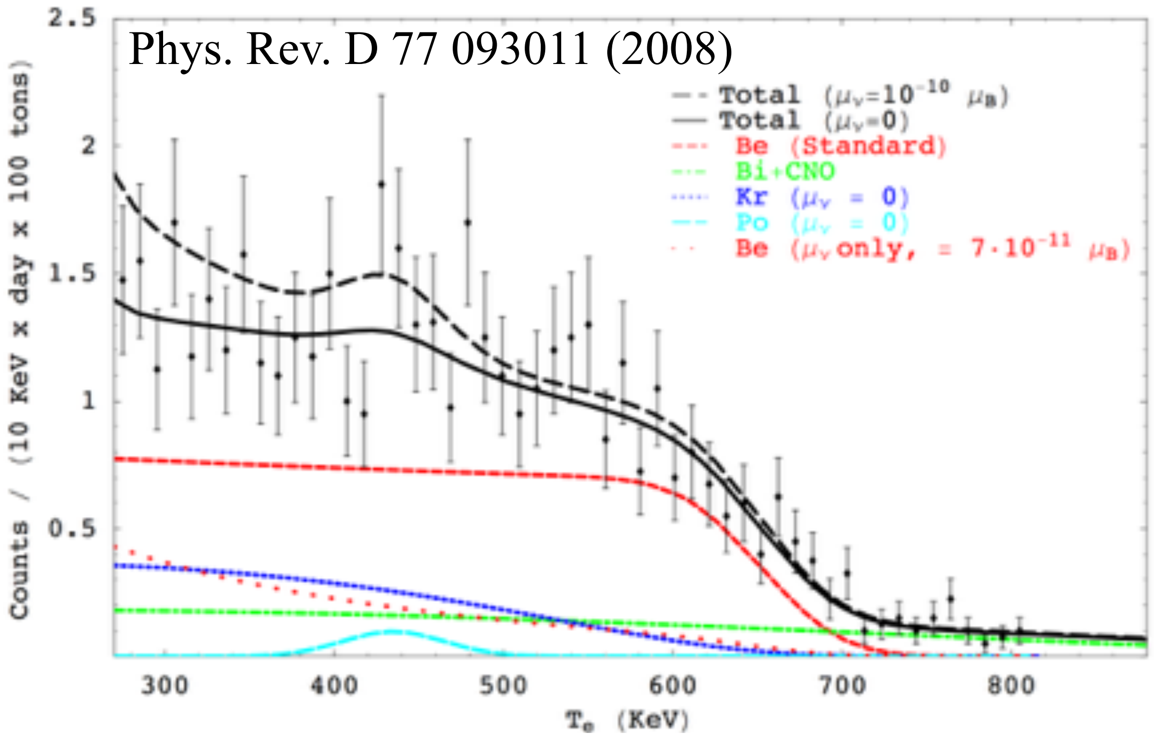


# Solar Limit

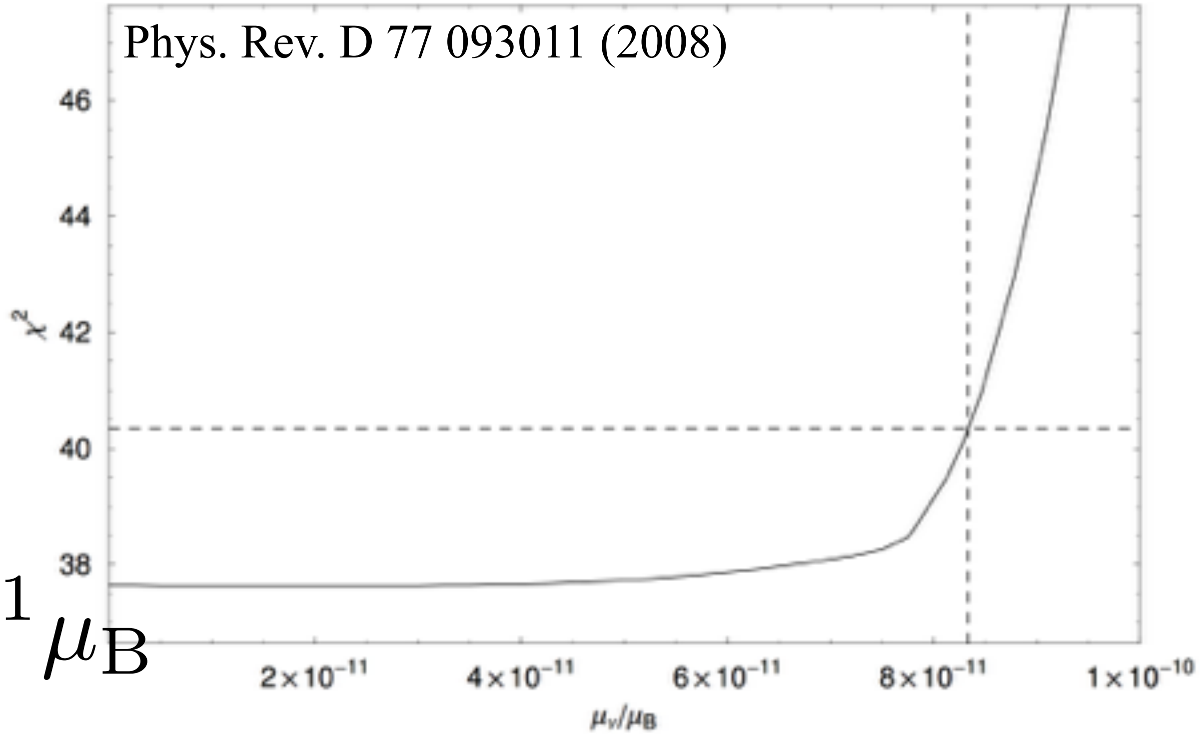
- Build up a spectrum of events with visible electron energy in the range $270 \leq T \leq 800\,\mathrm{keV}$.

- Parameterise different sources contributing to the spectrum at these energies.

- Perform a $\chi^2$ fit to the data as a function of $\mu_\nu$.
  - Limit of $\mu_\nu \leq 8.4 \times 10^{-11}\mu_{\mathrm{B}}$ at 90% C.L.



Phys. Rev. D 77 093011 (2008)



Phys. Rev. D 77 093011 (2008)

# Solar Limit

- The Borexino result, due to neutrino oscillations, is a combined result across all neutrino flavours.

- It is however possible to place conservative limits on the individual flavour contributions.

  - $\mu_{\nu_\mu} \leq 1.5 \times 10^{-11} \mu_\mathrm{B}$

  - $\mu_{\nu_\tau} \leq 1.9 \times 10^{-11} \mu_\mathrm{B}$

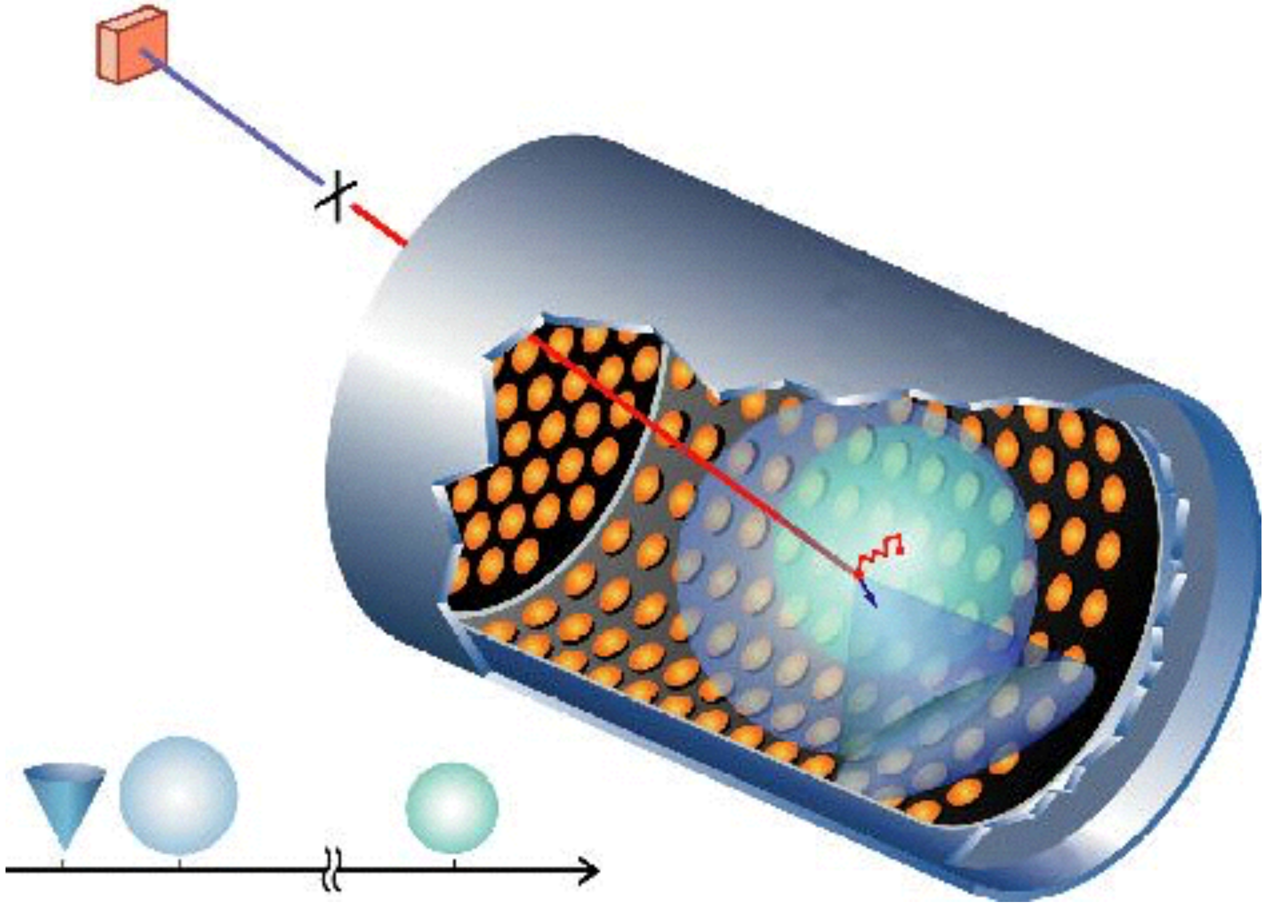
- Further possible improvements could include,

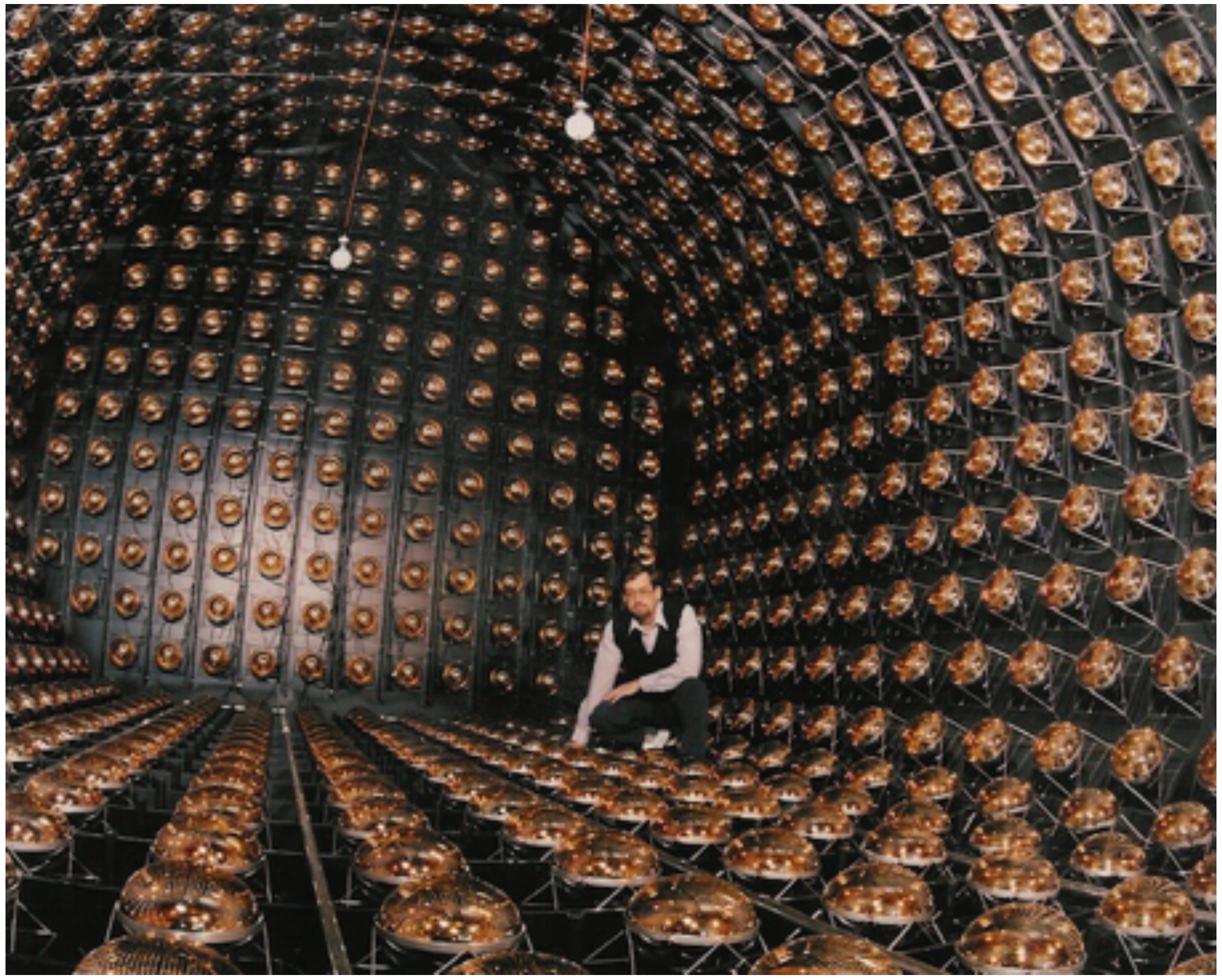
  - Reduced $^{85}$Kr background which mimics a NMM signal,

  - Increased exposure with temporal analysis.

# Accelerator Limit

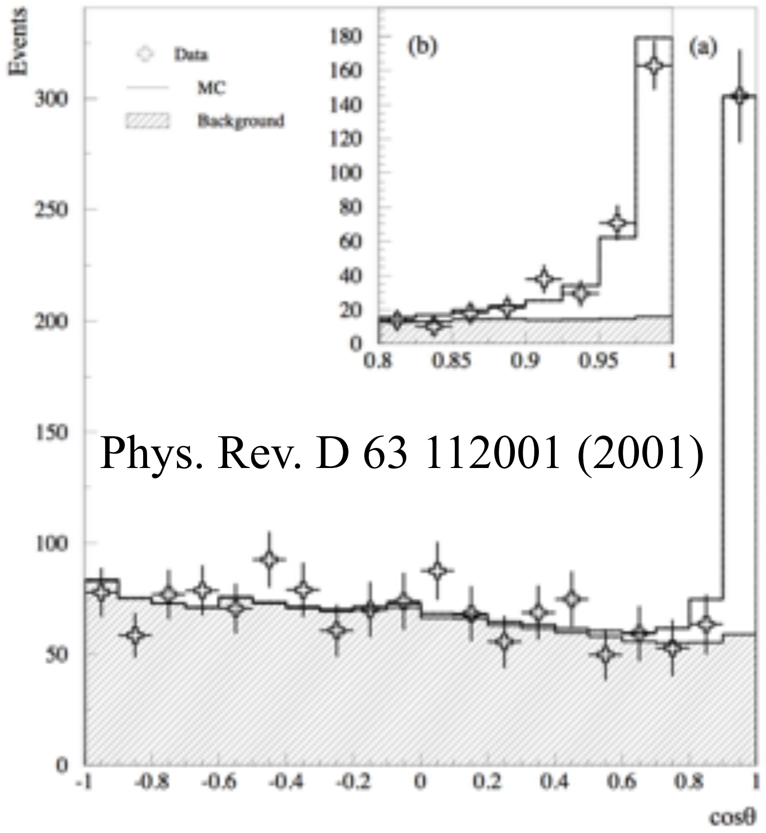
- Best limit provided by the LSND experiment at the Los Alamos National Laboratory, USA.



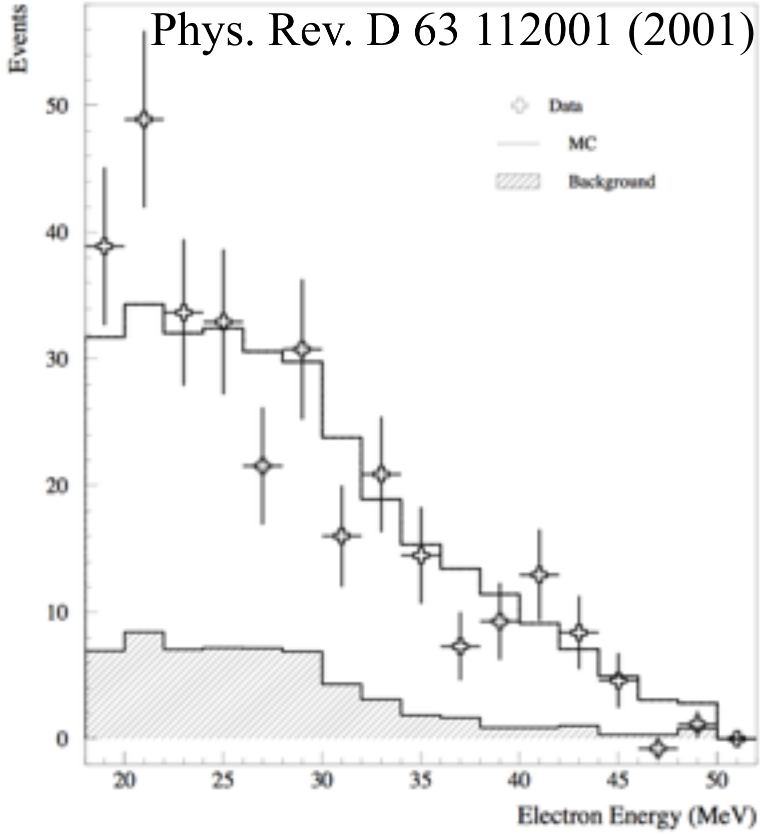


# Accelerator Limit

- Build up an inclusive spectrum of beam-excess electron events.
- Perform a fit as a function of $\cos\theta$ to parameterise the background.
    - Use this to estimate the background contribution in the signal enhanced region $\cos\theta > 0.9$.
- Compare the observed number of events to the SM prediction to extract limit on $\mu_\nu$.
    - Limit of $\mu_{\nu_\mu} < 6.8 \times 10^{-10} \mu_\mathrm{B}$ at 90% C.L.



Phys. Rev. D 63 112001 (2001)



Phys. Rev. D 63 112001 (2001)

# Accelerator Prospects

- Improvements on the $\mu_{\nu_\mu}$ limit should be possible with some of the current and planned near detectors for long-baseline neutrino oscillation experiments.

- These will crucially benefit from,

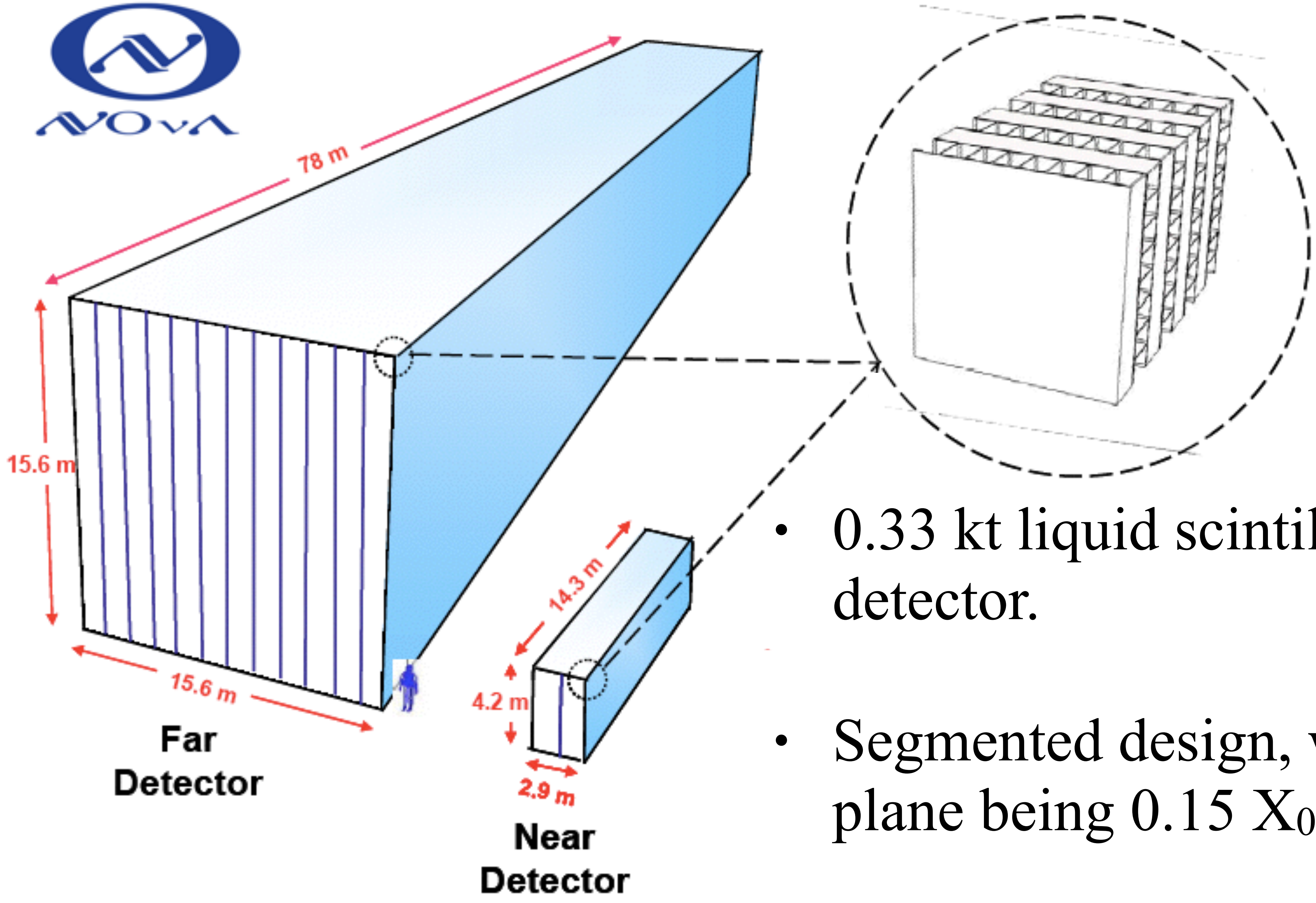
  - High intensity (~MW) neutrino beams,

  - Low energy thresholds,

  - Good angular reconstruction,

  - Near-fully active target materials.

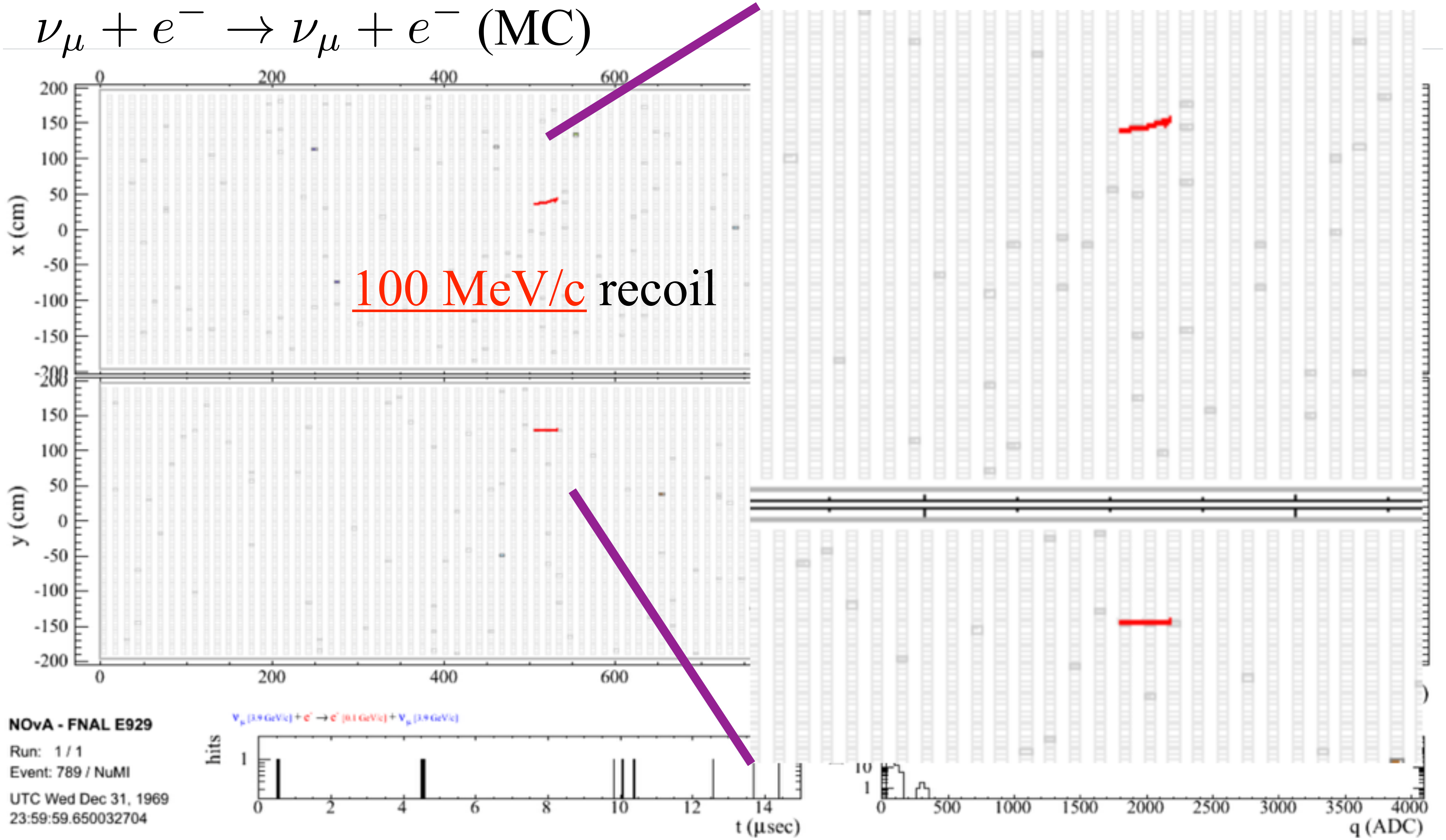
# Accelerator Prospects



- 0.33 kt liquid scintillator near detector.
- Segmented design, with each plane being 0.15 $X_0$.
- Excellent electron reconstruction at low energies.

# Accelerator Prospects

$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ (MC)



100 MeV/c recoil

Jarek Nowak Seminar: http://www.phys.virginia.edu/Files/fetch.asp?EXT=Seminars:2508:SlideShow

# Accelerator Prospects

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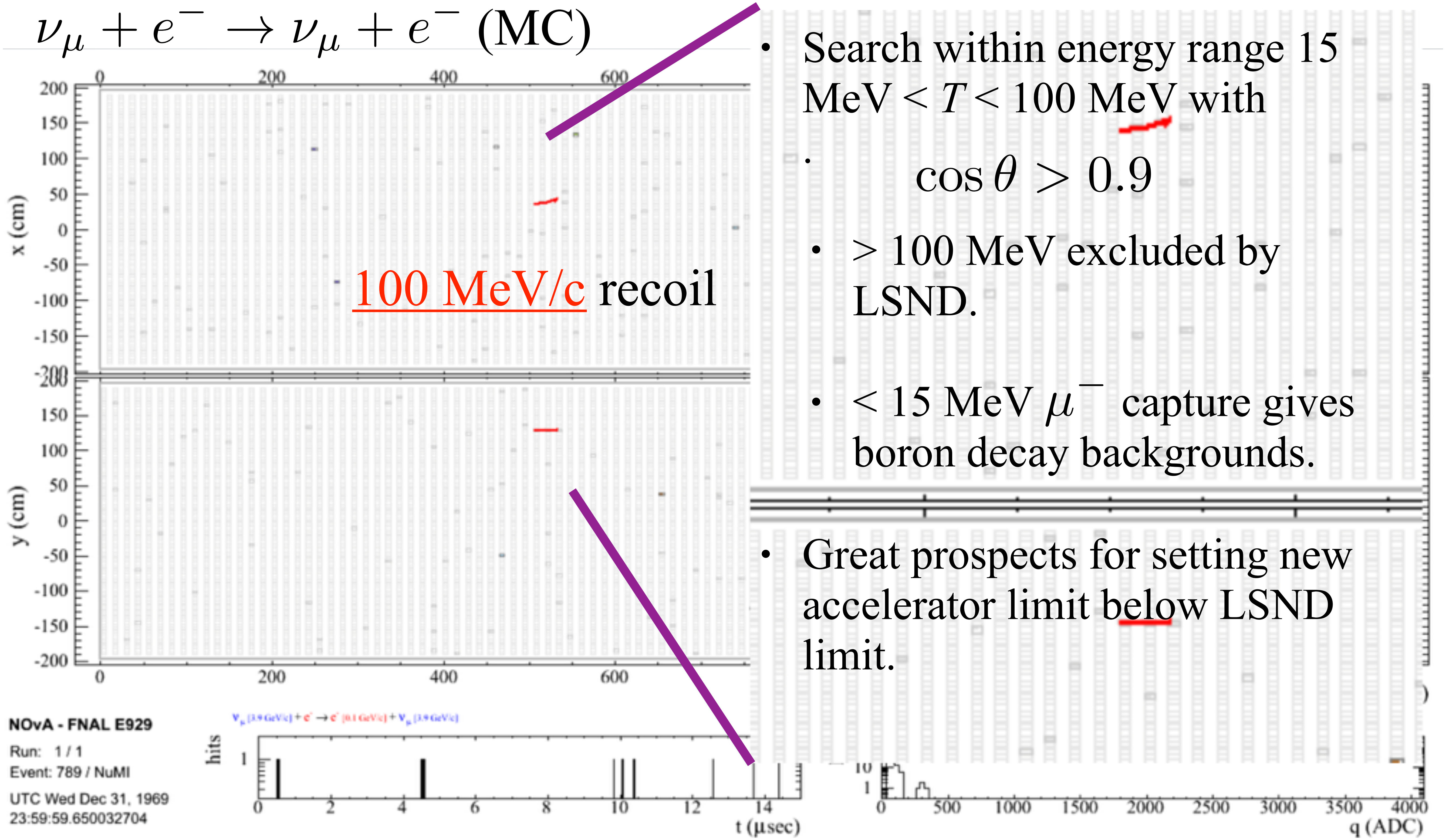


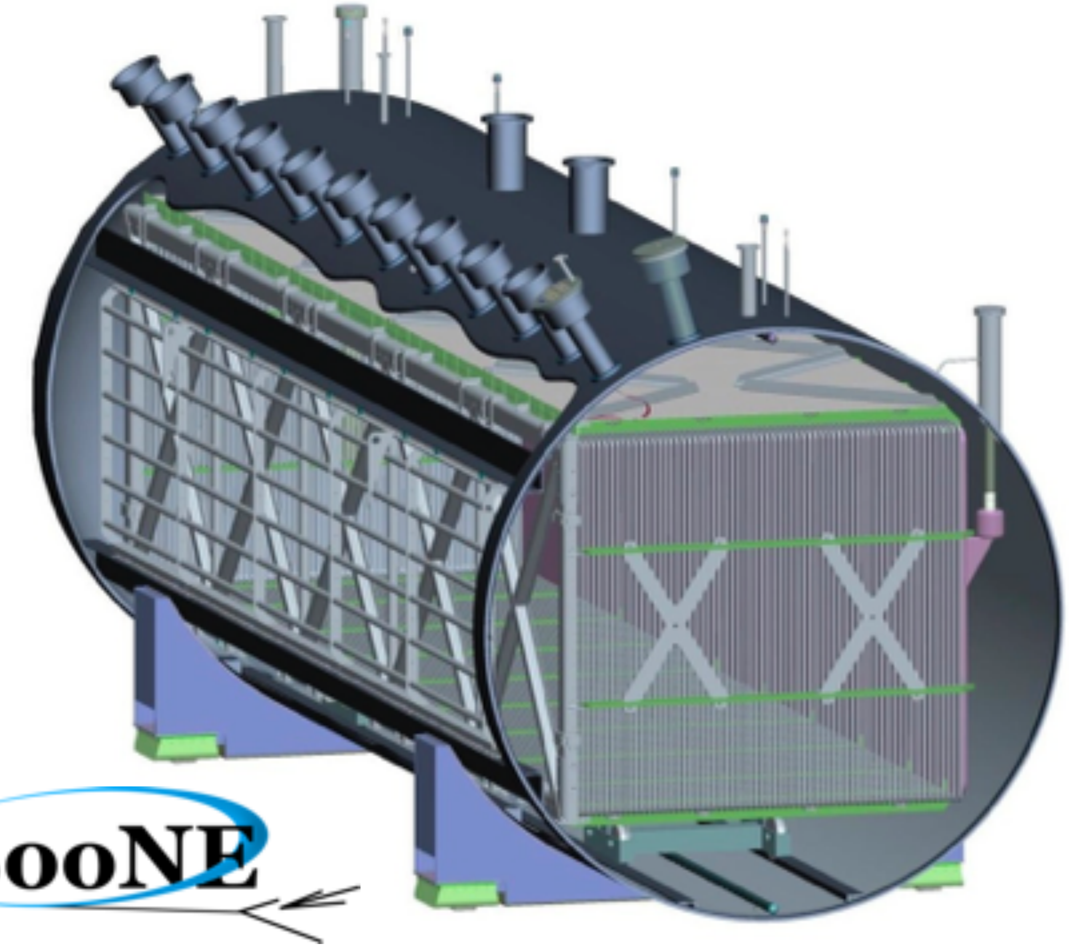
100 MeV/c recoil

- Search within energy range 15 MeV < $T$ < 100 MeV with
  - $\cos\theta > 0.9$
  - $>$ 100 MeV excluded by LSND.
  - $<$ 15 MeV $\mu^-$ capture gives boron decay backgrounds.
- Great prospects for setting new accelerator limit below LSND limit.

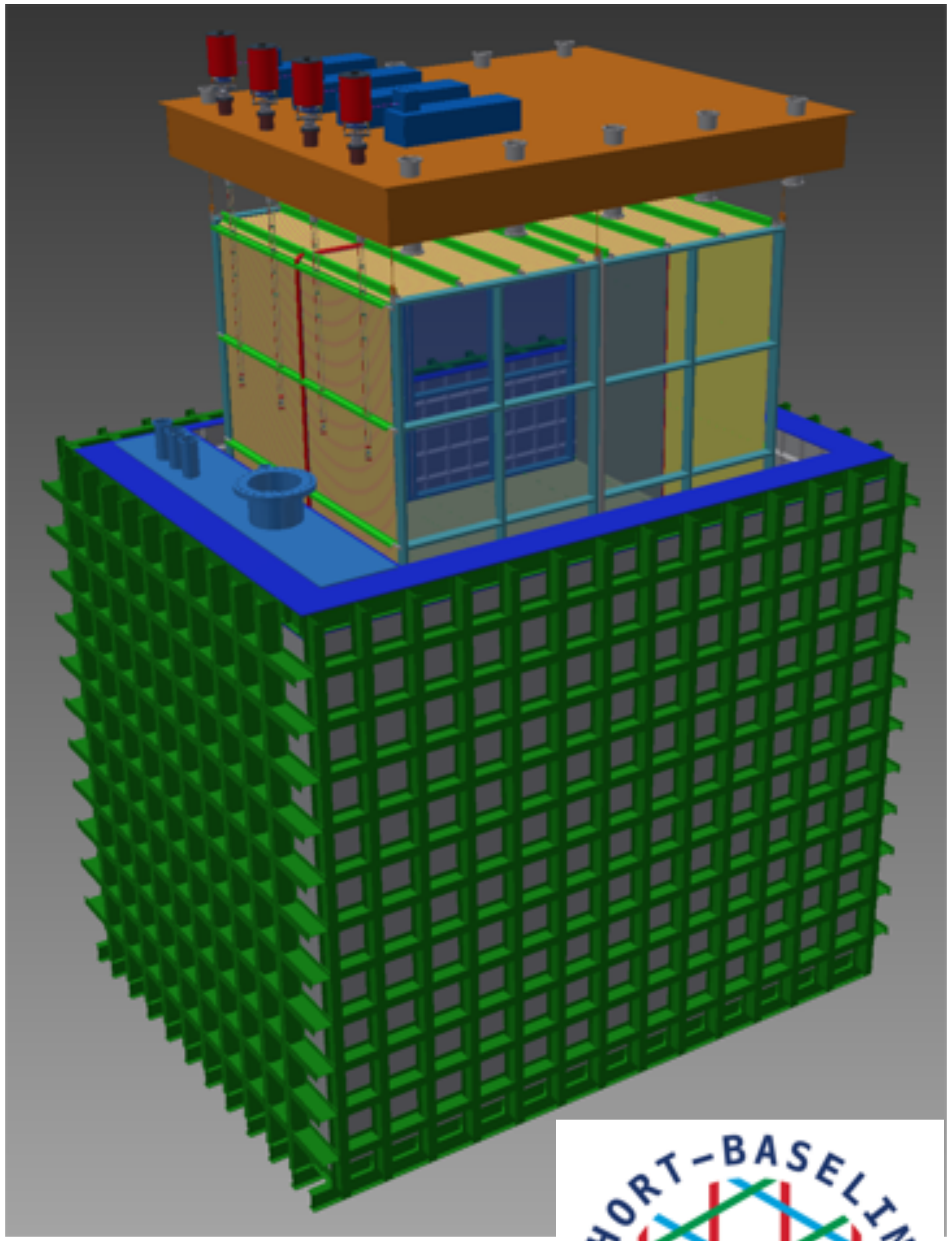
Jarek Nowak Seminar: http://www.phys.virginia.edu/Files/fetch.asp?EXT=Seminars:2508:SlideShow

# Accelerator Prospects

- Several liquid argon TPCs coming online in the next few years.
- High density, fully active detectors with excellent reconstruction.
- Expect even better limits from these types of detectors in the future.



µBooNE



SHORT-BASELINE
SBND
NEAR DETECTOR

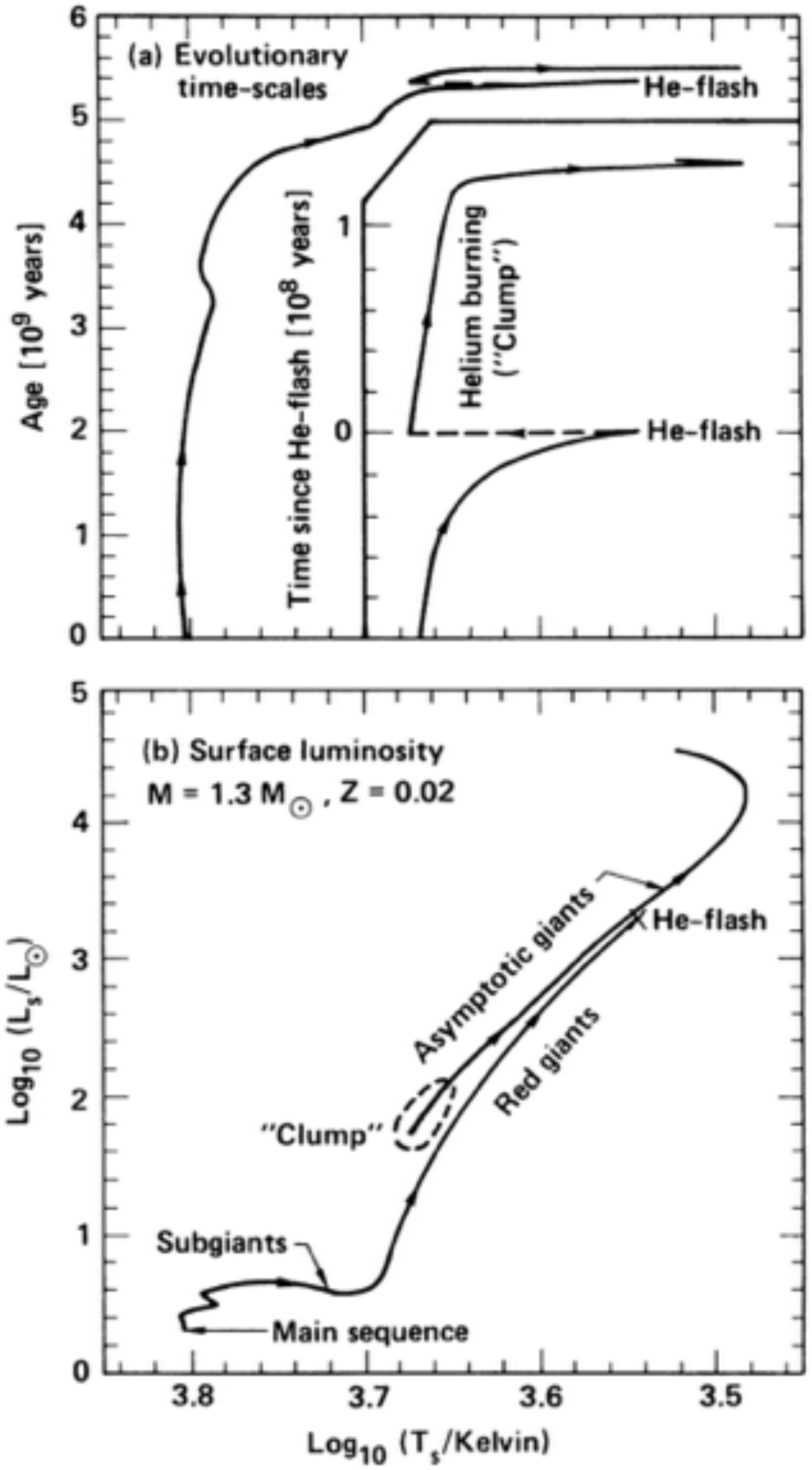
# Astrophysical Limits

- Additional limits can be derived from astrophysical processes which are affected by neutrino interactions.

- Observations of red giant stars from globular clusters can be used to set limits on the neutrino magnetic moment.

  - A large NMM enhances the plasmon decay rate, $\gamma \rightarrow \nu + \bar{\nu}$, increasing energy loses from the stellar core.

  - This reduces the core temperature, delaying the onset of the helium flash.



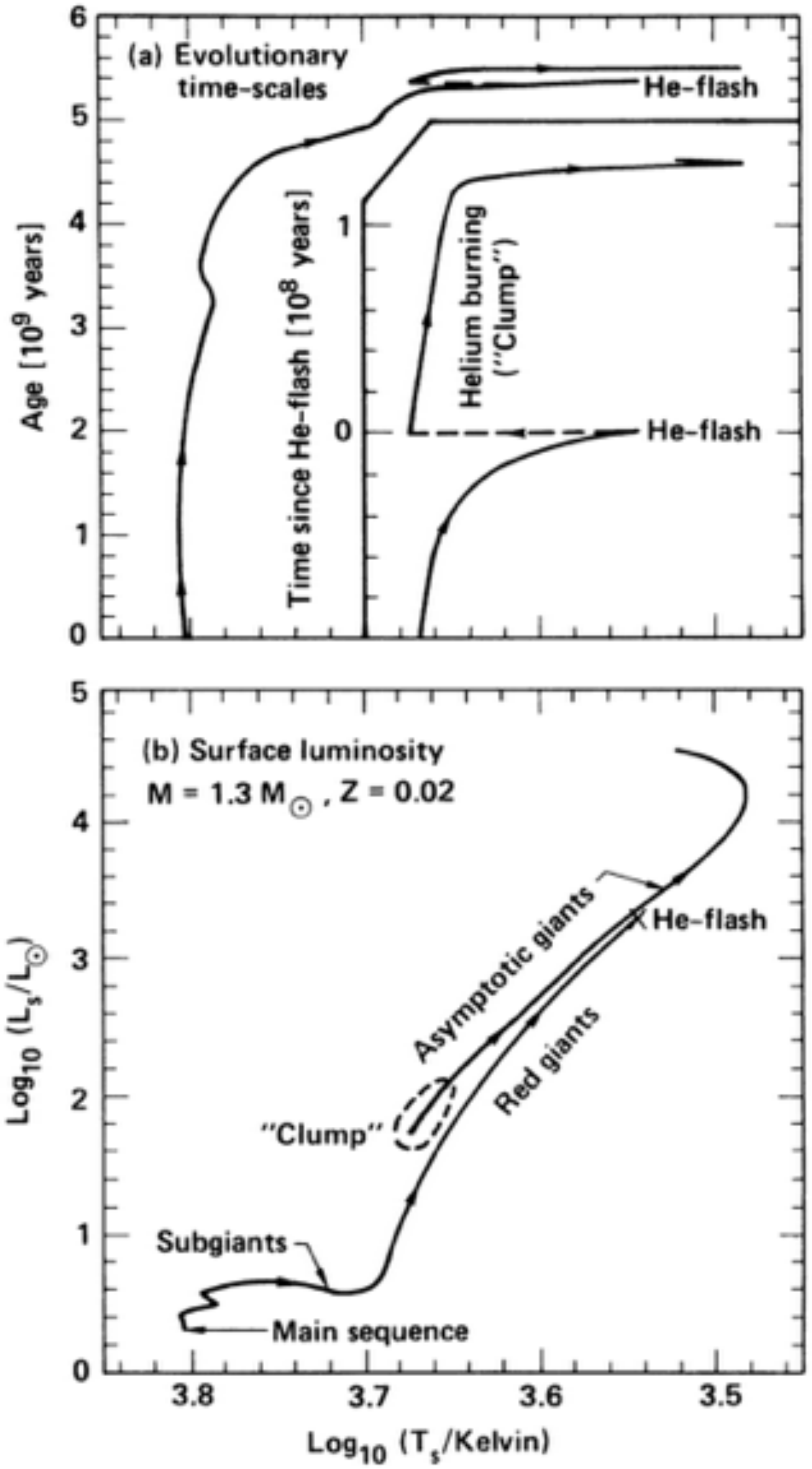
Phys. Rev. D 37 549 (1988)

# Astrophysical Limits

- Additional limits can be derived from astrophysical processes which are affected by neutrino interactions.

- Observations of red giant stars from globular clusters can be used to set limits on the neutrino magnetic moment.
  - Changes the maximum luminosity of stars at the tip of the red giant branch.
  - Can be used to infer a limit on the NMM.
  - Limit of $\mu_\nu < 3 \times 10^{-12} \mu_{\mathrm{B}}$.

Phys. Rev. Lett. 64 2856 (1990)



Phys. Rev. D 37 549 (1988)

# Astrophysical Limits

- Under the assumption that the neutrino is a Dirac particle, elastic scattering can lead to a chirality flip, $\nu_{\mathrm{L}} + e^- \to \nu_{\mathrm{R}} + e^-$.
  - $\nu_{\mathrm{R}}$ state is sterile with respect to the weak interaction.
- Within the high neutrino density of a supernova core, if there was a large NMM such interactions would carry away most of the supernova energy.
  - Because we observe neutrino explosions, we can set a limit on the energy escaping via sterile neutrino, and therefore the NMM.
  - Limit of $\mu_\nu < (1-4) \times 10^{-12} \mu_{\mathrm{B}}$.

Phys. Rev. D 59 111901 (1999)
Nucl. Phys. B 564, 204 (2000)

# Summary

- Searches for enhanced lepton anomalous magnetic moments are a potential signature of beyond the standard model physics.

- Currently an interesting anomaly between the theory and experimental results for the muon AMM.

    - Will be addressed by theoretical improvements and the g-2 experiment at Fermilab.

- Within the neutrino sector, current limits are many orders of magnitude above the SM expectation.

    - Significant scope for the emergence of new physics.

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# Summary

- Best experimental limits for $\mu_{\nu_e}$ currently from reactor experiments.
  - Next generation experiments coming online in the near future.
- Best experimental limits for $\mu_{\nu_\mu}$ currently from solar experiments.
  - Lots of new accelerator experiments will hopefully begin to challenge this in the coming years.
  - Accelerator results are direct flavour tests, not dependent on interpretation of neutrino oscillations.

# Summary

- Very best limits derived from astrophysical processes.
  - Limits are relatively old (1990), observationally limited currently.
  - Observation (optical + neutrino) of nearby supernova explosion would probably be the best way improve limits.
  - Results are general as it is difficult (impossible?) to disentangle results by different neutrino flavours.
- Hope that future results will begin to start ruling out BSM models, or perhaps reveal exciting new physics!

*Thank you for listening.*