The wide world of **Neutrino Experiments**
TRISEP 2019 summer school

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TRIUMF
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Office of Science
U.S. Department of Energy

Disclaimer

- I speak (too) fast in English… sorry…
- Please! ask me to repeat or slow down
- It is OK to raise your hand or interrupt with a question

Feedback? Comments? *mahn@pa.msu.edu*

Outline

Is our understanding of neutrino mixing complete?

What do we know about neutrino mass?

Neutrinos as probes: neutrino astrophysics, coherent neutrino scattering

Outline

Is our understanding of neutrino mixing complete?

What do we know about neutrino mass?

Neutrinos as probes: neutrino astrophysics, coherent neutrino scattering

Encore from lecture 1

Outline

Is our understanding of neutrino mixing complete?

Sterile neutrinos

What do we know about neutrino mass?

The enigma of neutrino mass

- Neutrinos are massive because we observe oscillation

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right) + \ldots$$

The enigma of neutrino mass

- Neutrinos are massive because we observe oscillation
- Dirac mass terms imply a right handed particle…
- … which doesn't interact via the weak force ***- sterile***

$$\mathcal{L}_D = -m_D \left(\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L \right)$$

Sterile neutrino oscillation

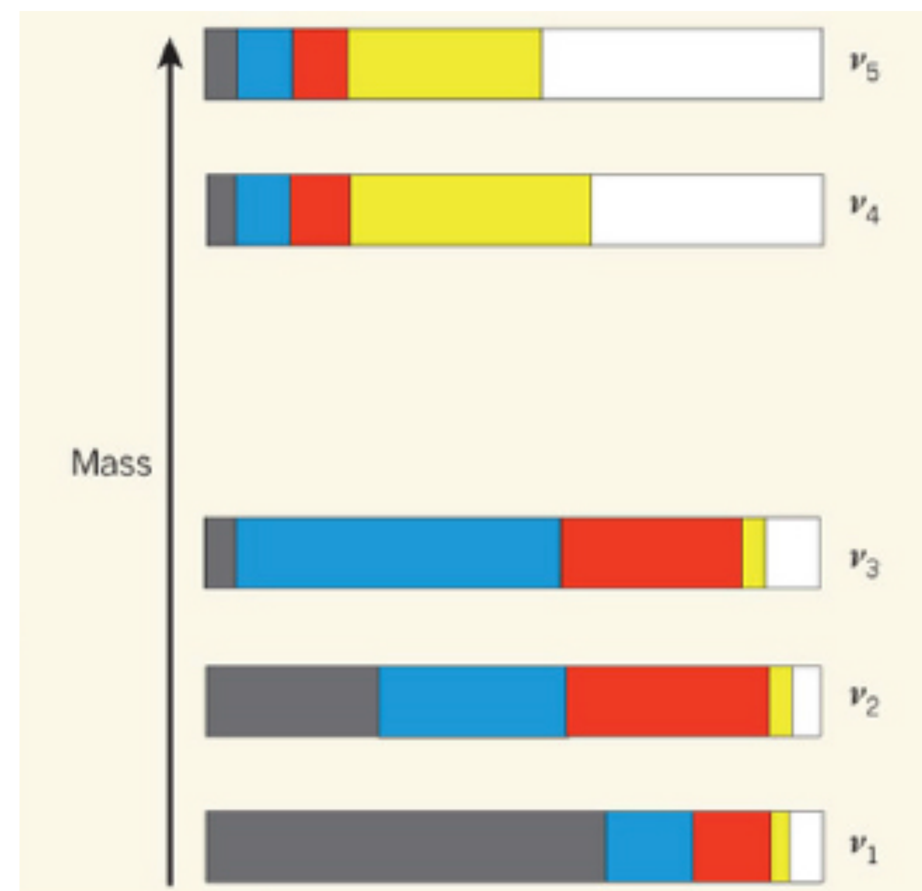
- Neutrinos are massive because we observe oscillation
- Dirac mass terms imply a right handed particle…
- … which doesn't interact via the weak force ***- sterile***
- Mixing matrix would be modified:

$$U_{\alpha i} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 1} & \cdots & U_{\mu N} \\ \vdots & \vdots & \ddots & \vdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_N \end{pmatrix}$$

Sterile neutrino oscillation

- Neutrinos are massive because we observe oscillation
- Dirac mass terms imply a right handed particle…
- … which doesn't interact via the weak force ***- sterile***
- Mixing matrix would be modified:
- Additional mass splittings would be observed

$$U_{\alpha i} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 1} & \cdots & U_{\mu N} \\ \vdots & \vdots & \ddots & \vdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_N \end{pmatrix}$$



W.C. Louis,
Nature, Volume: 478,
Pages: 328–329

Sterile neutrino oscillation

- “3+1” oscillation looks much like regular two flavor oscillation

disappearance appearance

$$P(\nu_\mu \to \nu_e) = 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\left(\frac{1.27\,\Delta m_{41}^2 L}{E}\right)$$

$$P(\nu_\mu \to \nu_x) = 1 - 4\,|U_{\mu 4}|^2 \,(1 - |U_{\mu 4}|^2) \sin^2\left(\frac{1.27\,\Delta m_{41}^2 L}{E}\right)$$

Evidence

For steriles!

Reactor antineutrino anomaly

Gallium anomaly

LSND appearance

MiniBooNE appearance

What steriles?

Reactor disappearance, flux modelling

MINOS, T2K NC

MiniBooNE, SciBooNE, IceCube disappearance

Cosmology

Evidence

For steriles!

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MiniBooNE, SciBooNE, IceCube disappearance

Cosmology

Above list is eV scale sterile
keV sterile neutrino // dark matter candidate:
White paper: *arxiv1602.04816*
and new measurements: *Phys. Rev. D 95, 123002 (2017)*

Evidence

For steriles!	What steriles?
Reactor antineutrino anomaly	Reactor disappearance, flux modelling
Gallium anomaly	
LSND appearance	MINOS, T2K NC
MiniBooNE appearance	MiniBooNE, SciBooNE, IceCube disappearance
	Cosmology

More steriles == heavy neutral leptons

Often tested at collider or fixed target experiments

No confluence, nor tension

T2K exotics: Heavy Neutral Lepton search

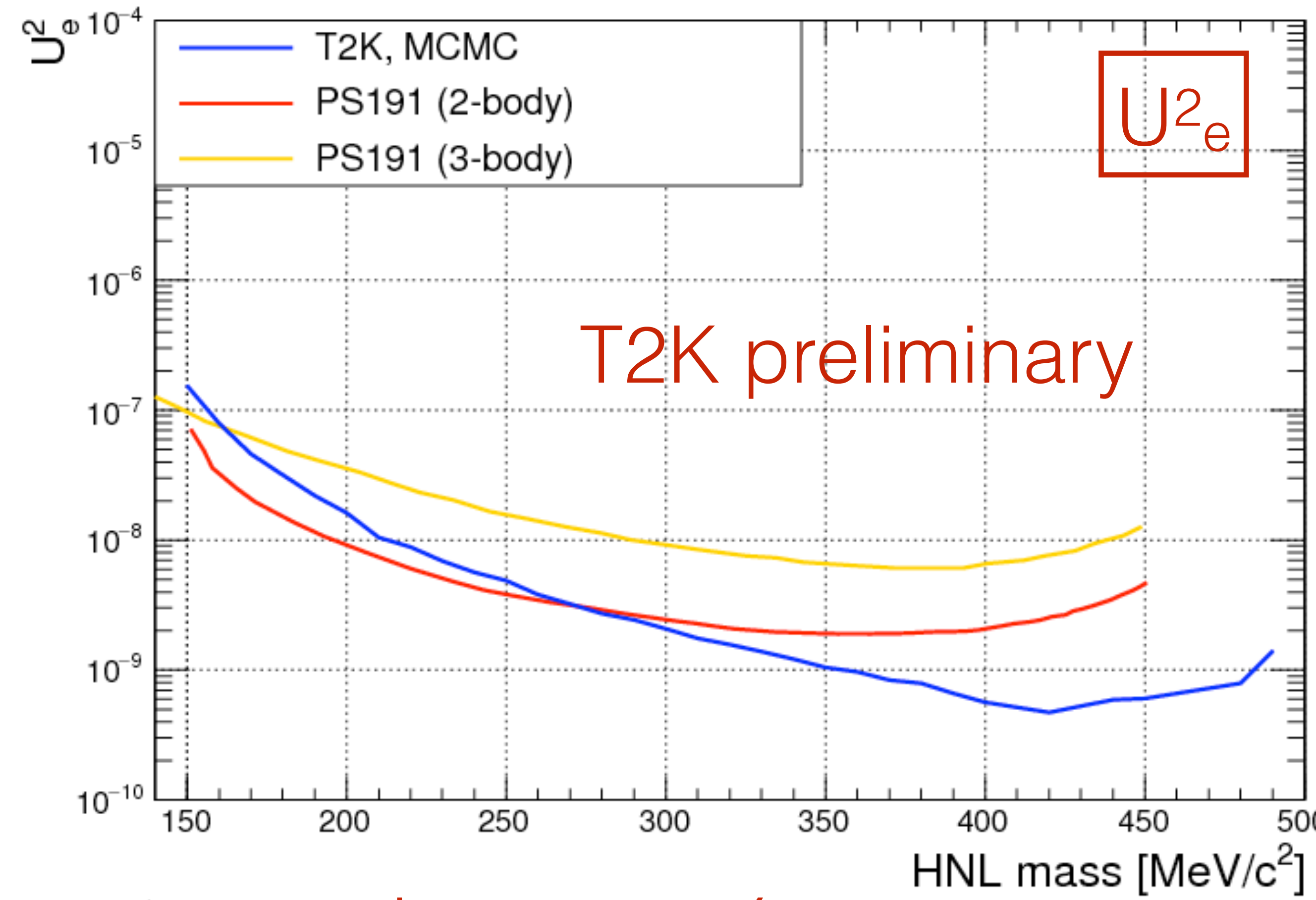
$K^+ \to \ell^+ N$

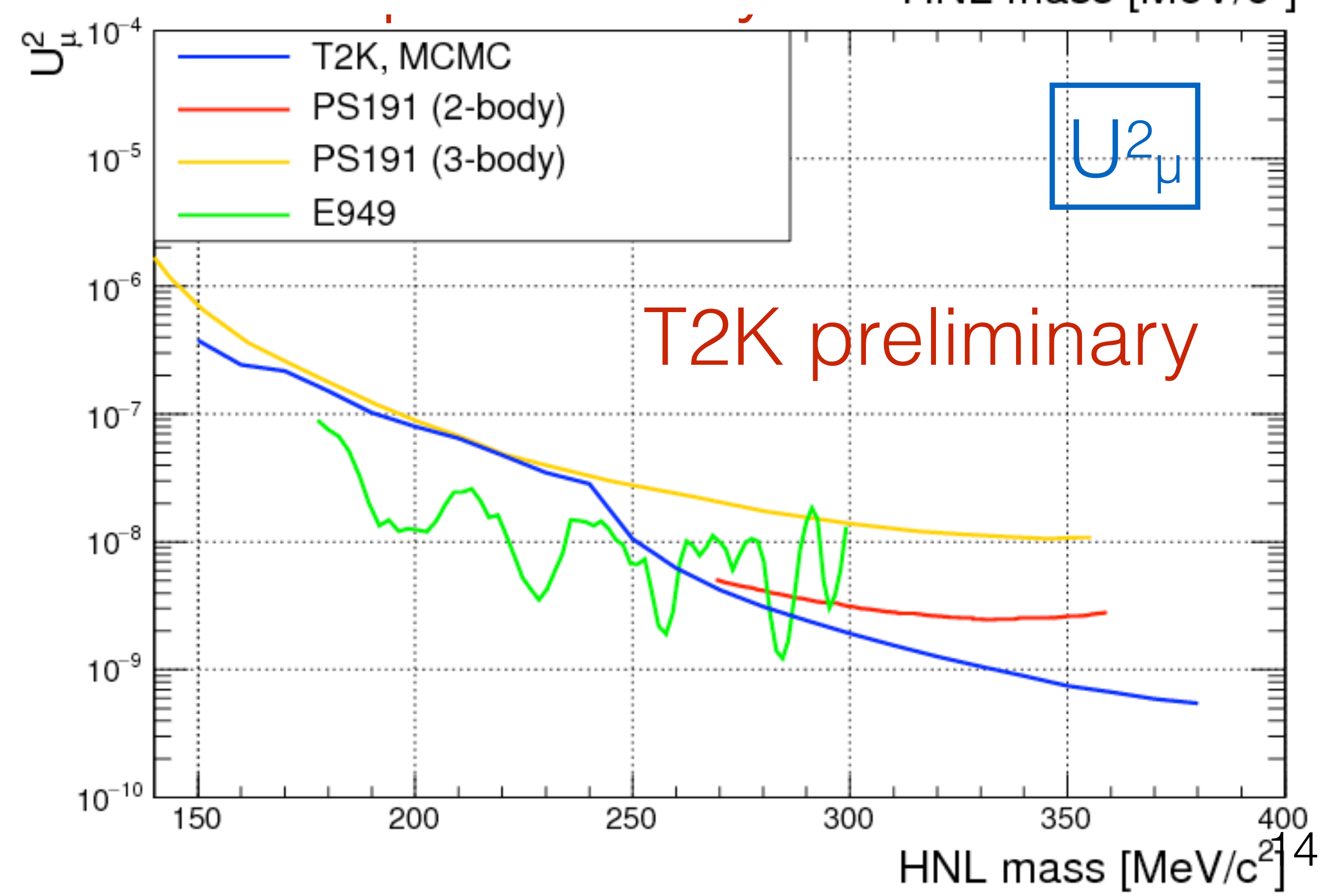
$N \to \ell^\pm \pi^\mp, \ell^\pm \ell^\mp \nu$

Production of heavy neutral leptons (N) from kaon decay

- Uses large volume, low mass TPCs for signal selection
- Best high-mass limits on coupling to N to μ, e

https://arxiv.org/abs/1902.07598



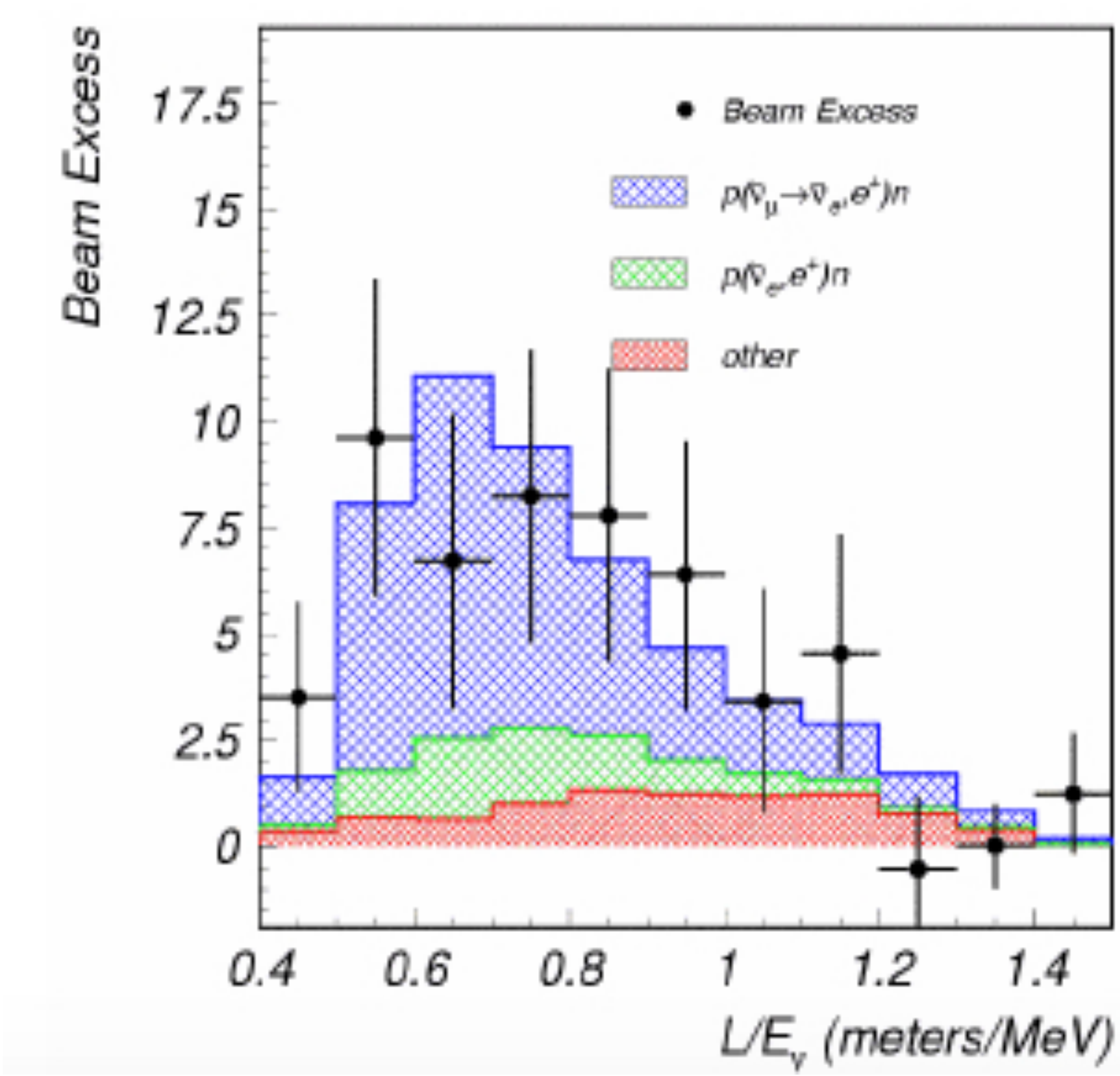


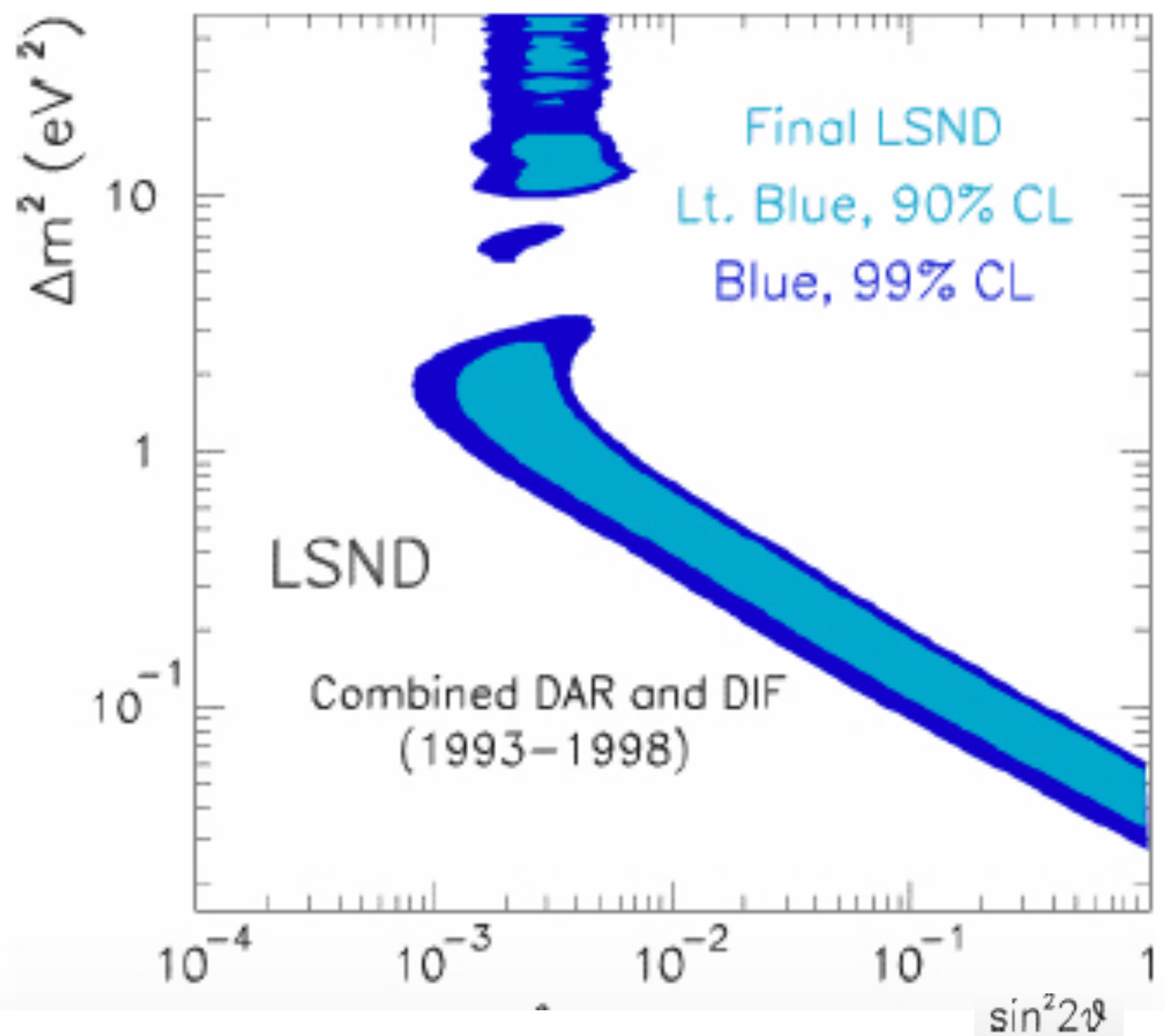
LSND Experiment: observation of 3.8σ excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam

For steriles!

"Short baseline": E_ν ~30 MeV, L~30m

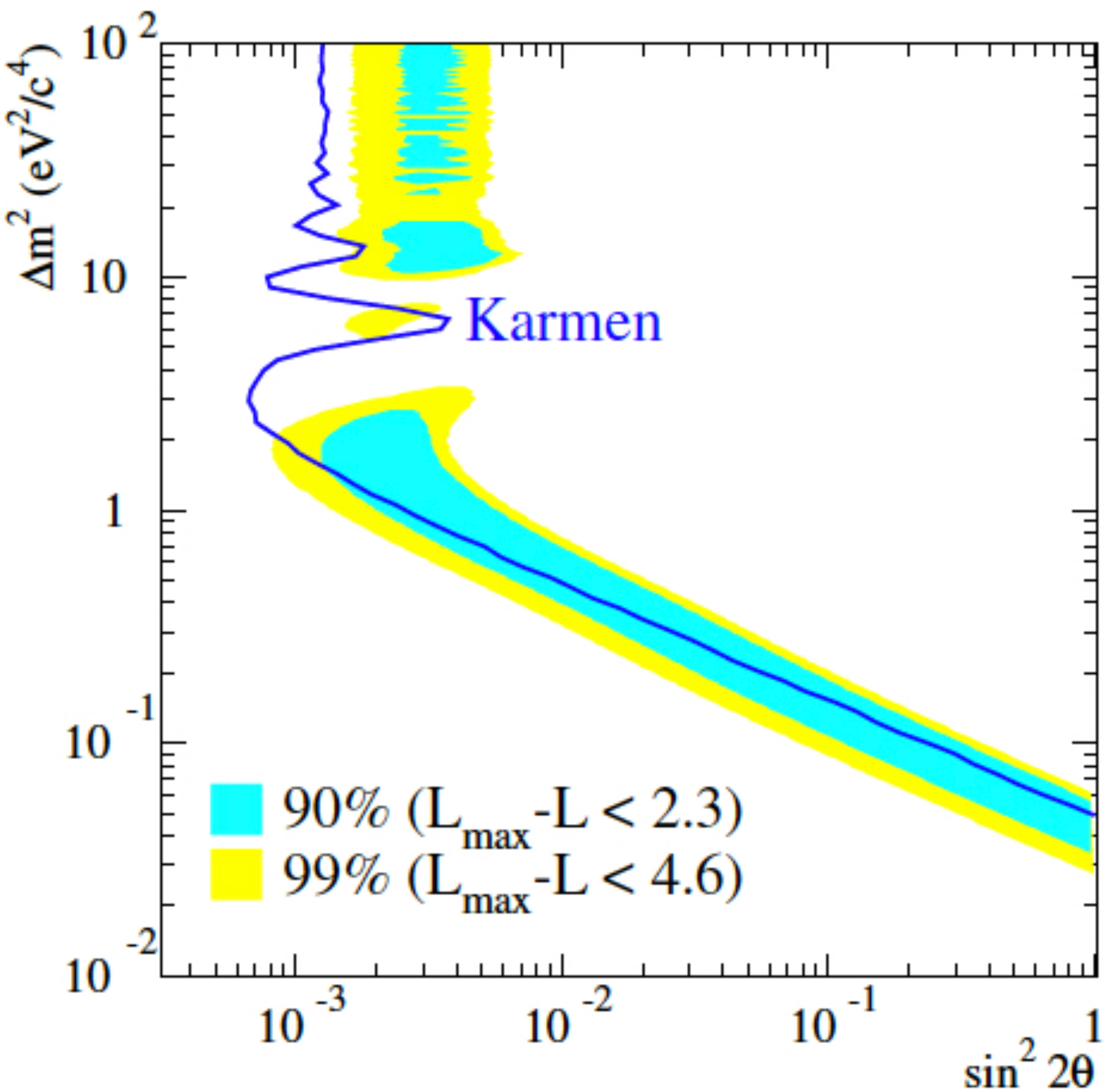
$\overline{\nu}_e$ detected with inverse beta decay and delayed n capture



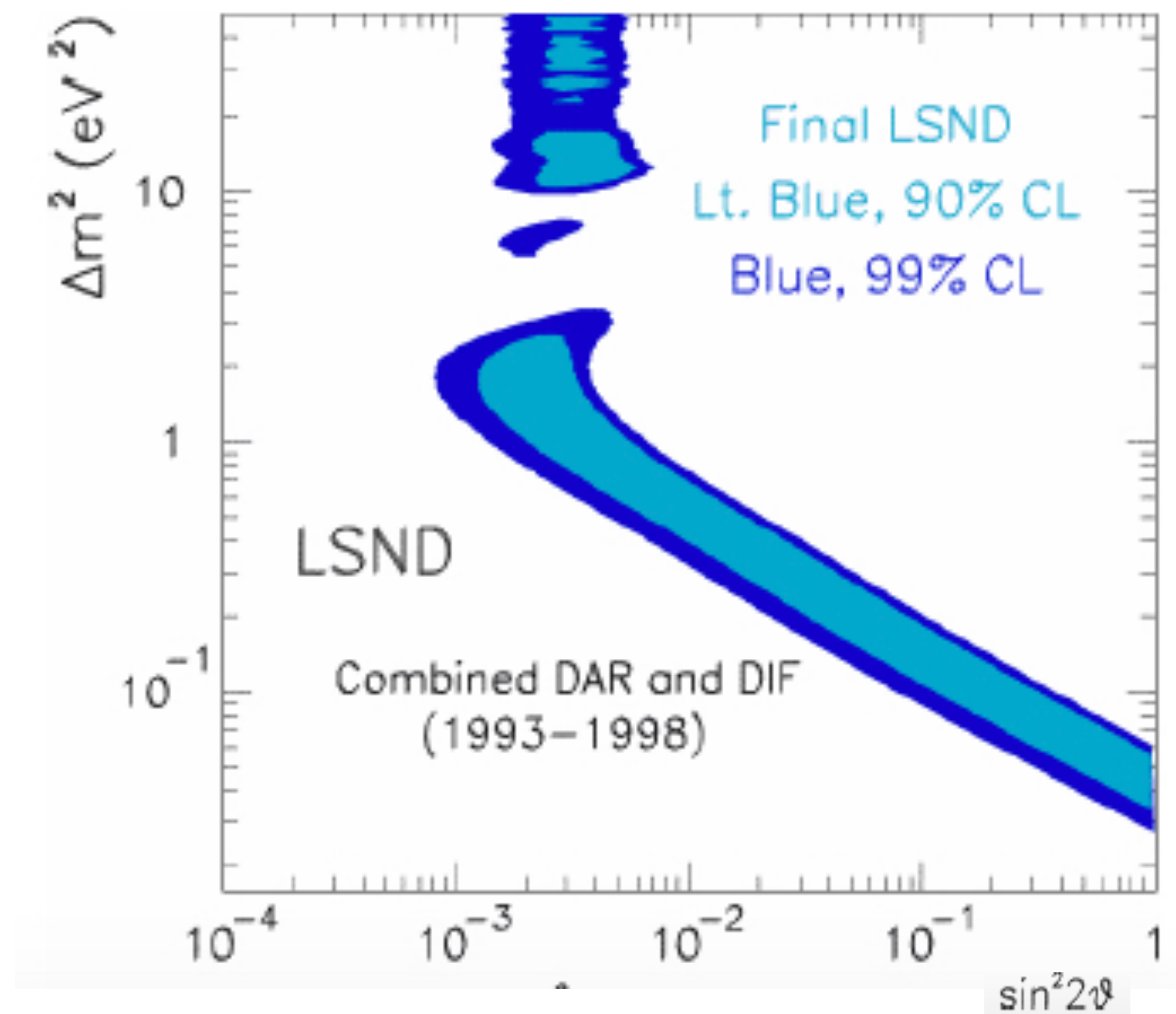


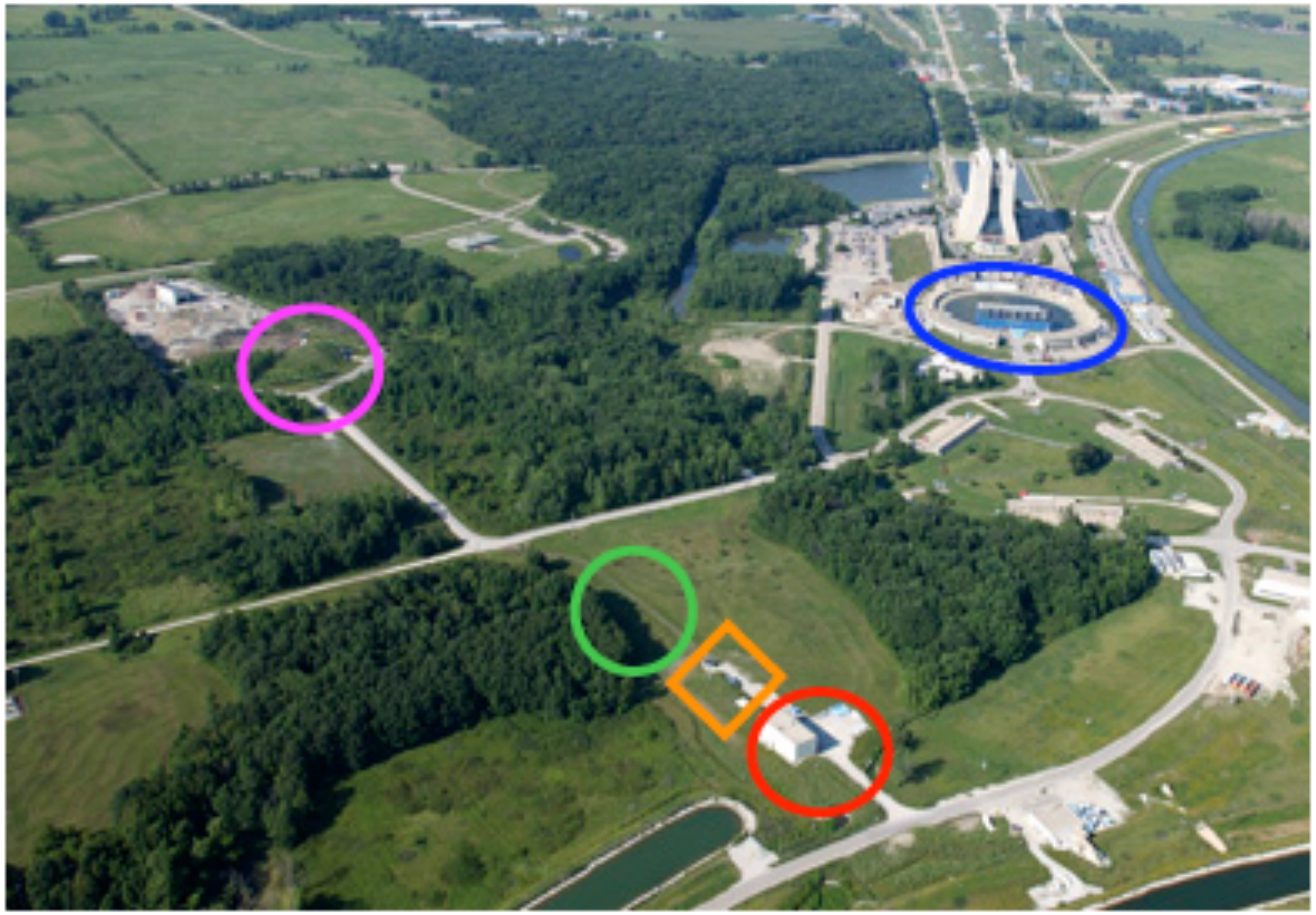
Phys. Rev. D 64 (2001) 112007

Similar Karmen experiment saw no evidence; but not fully excluded



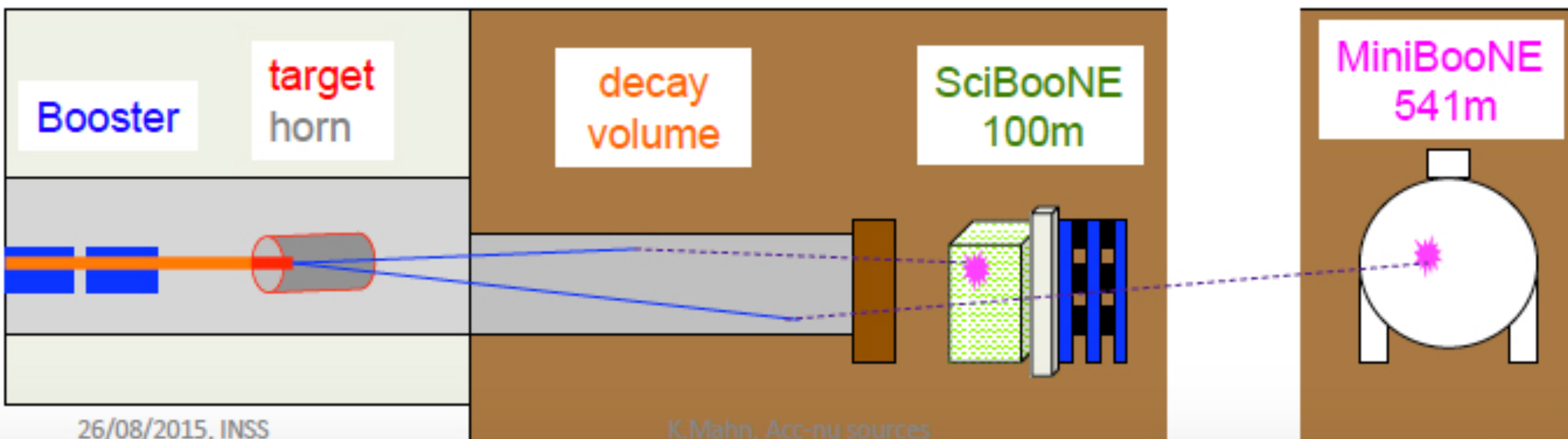
Phys. Rev. D 65 (2002) 112001





- MiniBooNE placed for maximal LSND oscillation (541 m at 1 GeV; $\Delta m^2 \sim 1 eV^2$)
- Different signal identification, systematics
- SciBooNE reused from earlier experiments

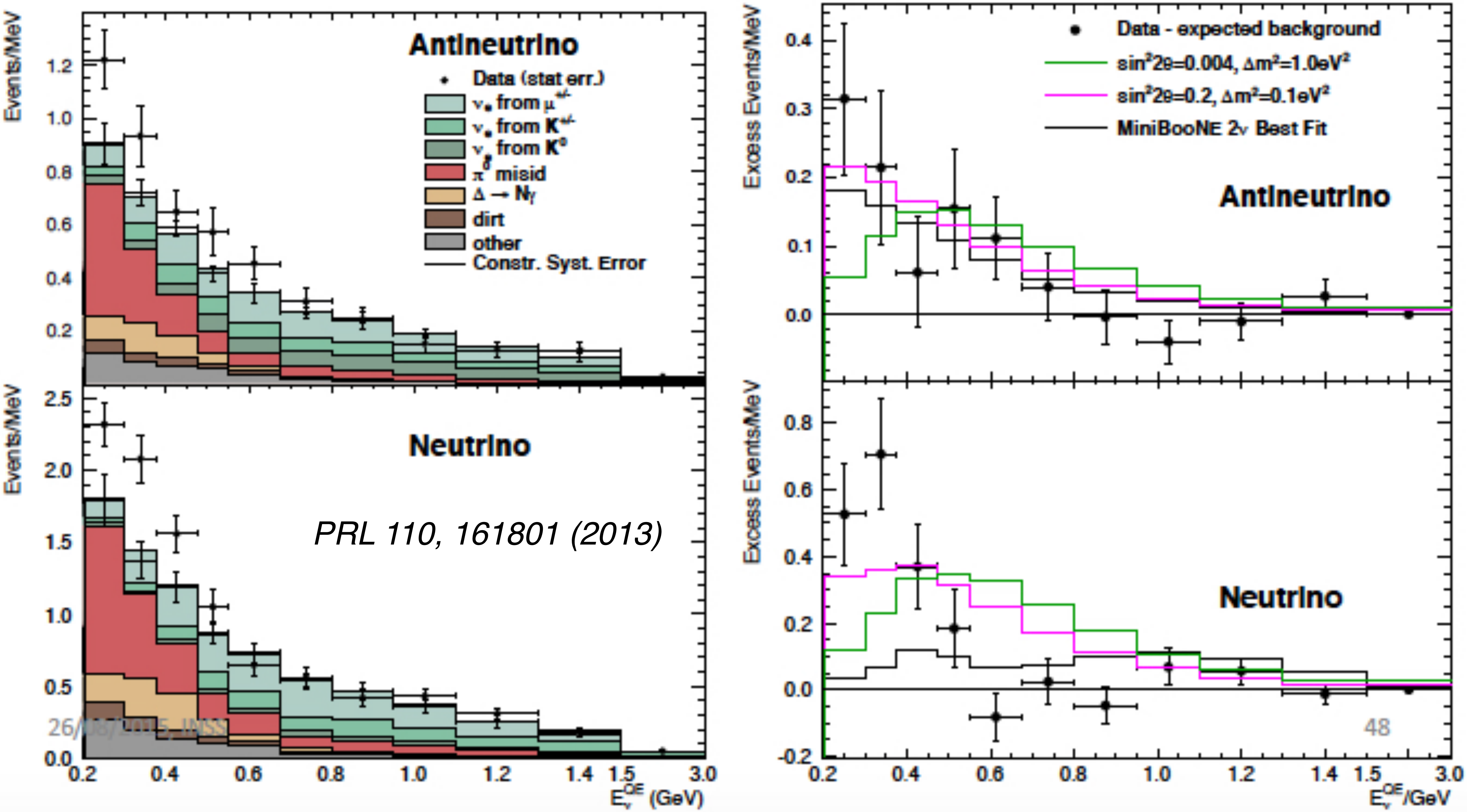
Beamline now to be used for short baseline neutrino program (SBN)



What steriles? Circa 2013

Lack of $\nu_\mu \rightarrow \nu_e$ appearance but observation of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

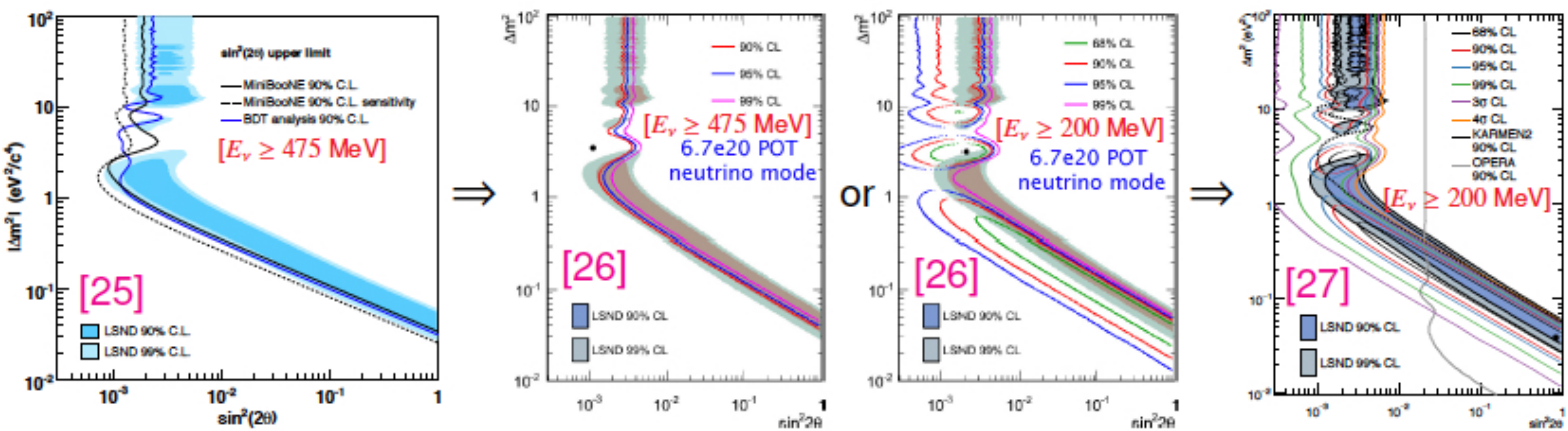
- Low energy excess drives tension in neutrinos, not well mapped to 3+1 signal
- Photon background? MicroBooNE to test



For sterile s!

MiniBooNE neutrino data

- Statistics: 5.58 (2007) $\to$ 6.46 (2008) $\to$ 12.84 (2018) $\times 10^{20}$ POT;
- is ν signal compatible with 2ν oscillations? 2007: $P_{\text{osc}} \simeq 1\%$ $\Rightarrow$ no it isn't [25]; 2012: $P_{\text{osc}} \simeq 6\%$ $\Rightarrow$ maybe it is [26]; 2018: $P_{\text{osc}} \simeq 15\%$ $\Rightarrow$ yes it is [27];
- do MB-ν rule out LSND-$\bar{\nu}$ signal? 2007: yes [25]; 2012: not really [26]; 2018: no [27].



[25] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], Phys. Rev. Lett. **98** (2007) 231801 [arXiv:0704.1500].

[26] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

[27] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], arXiv:1805.12028.

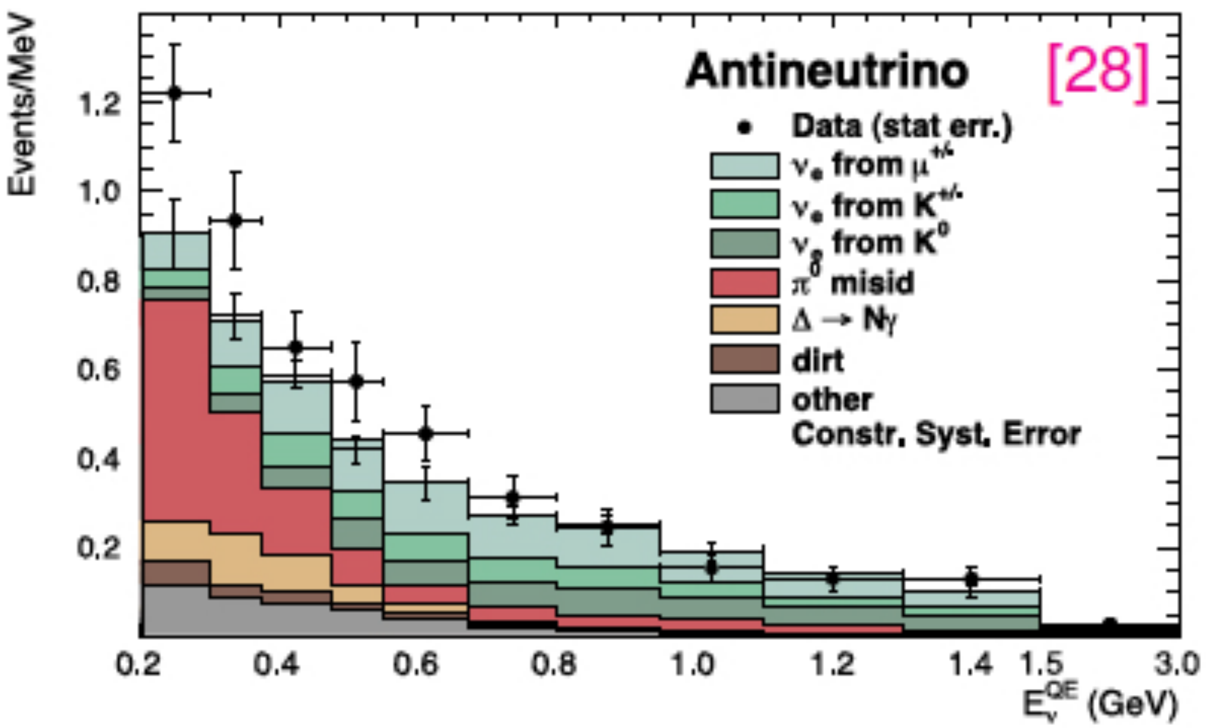
⇒ Talk: Huang

M. Maltoni, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI:10.5281/zenodo.1287014

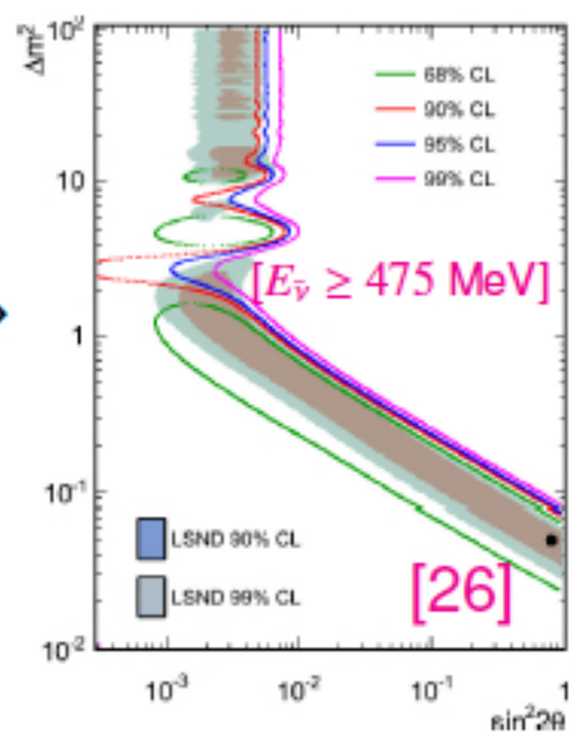
For steriles!

MiniBooNE antineutrino data

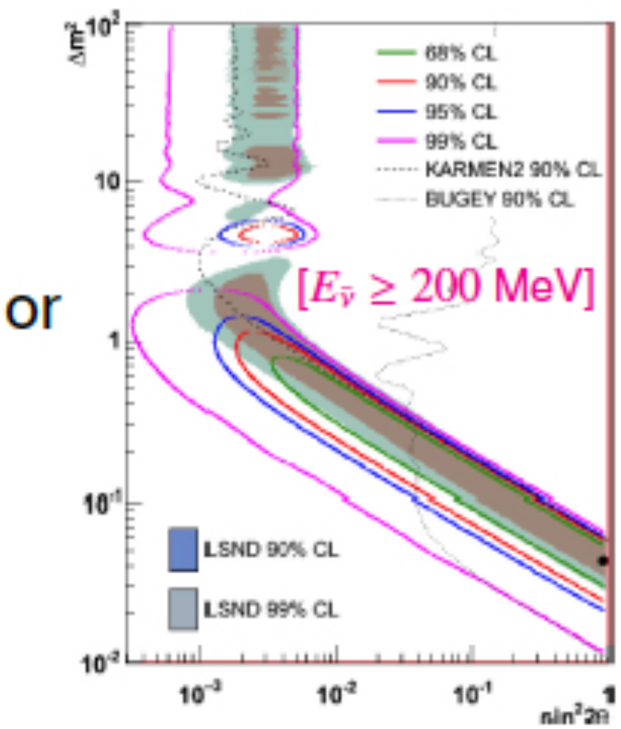
- New data presented at Neutrino 2012, statistics doubled ($\rightarrow 11.27 \times 10^{20}$ POT) [26];
- compatibility with ν data: { low-energy excess increased $\Rightarrow$ better agreement; mid-energy excess reduced $\Rightarrow$ better agreement;
- is $\bar{\nu}$ signal compatible with 2ν oscillations? $P_{osc} = 66\%$ $\Rightarrow$ definitely yes [28];
- is MB-$\bar{\nu}$ signal compatible with LSND? Yes, irrespective of the energy threshold.



$\Rightarrow$



or



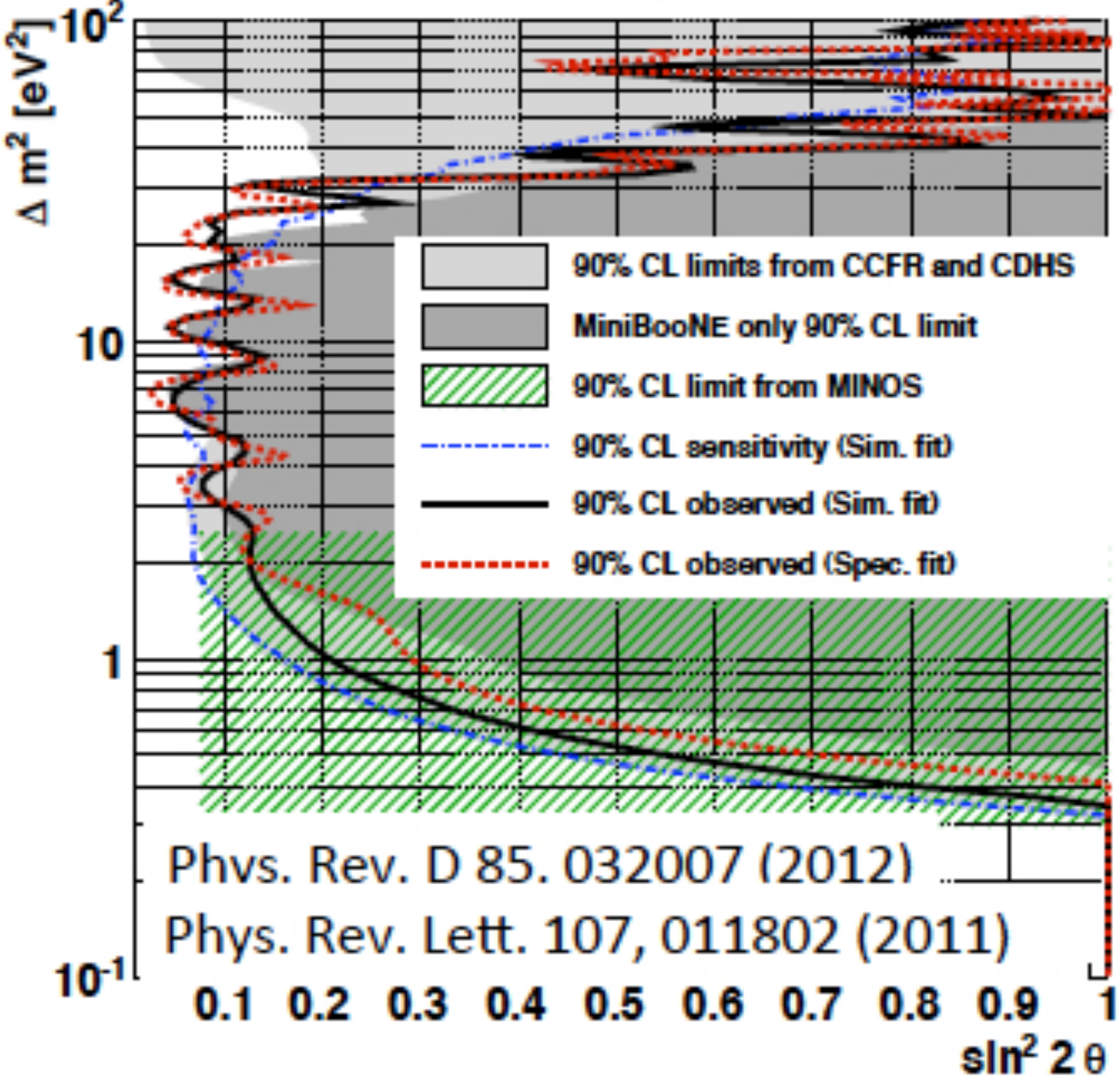
[26] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

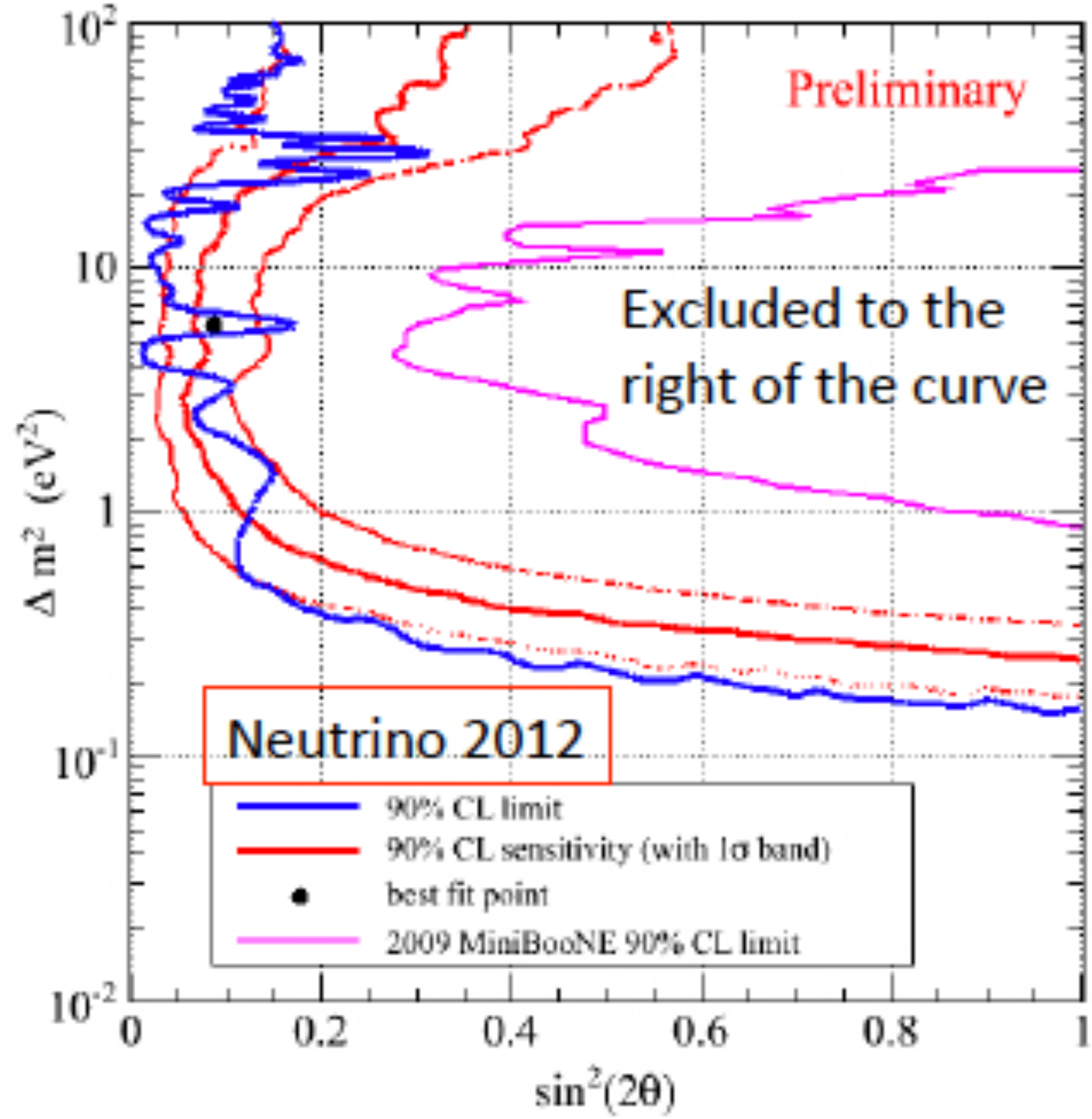
[28] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], PRL **110** (2013) 161801 [arXiv:1303.2588].

M. Maltoni, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI:10.5281/zenodo.1287014

What steriles? Circa 2012

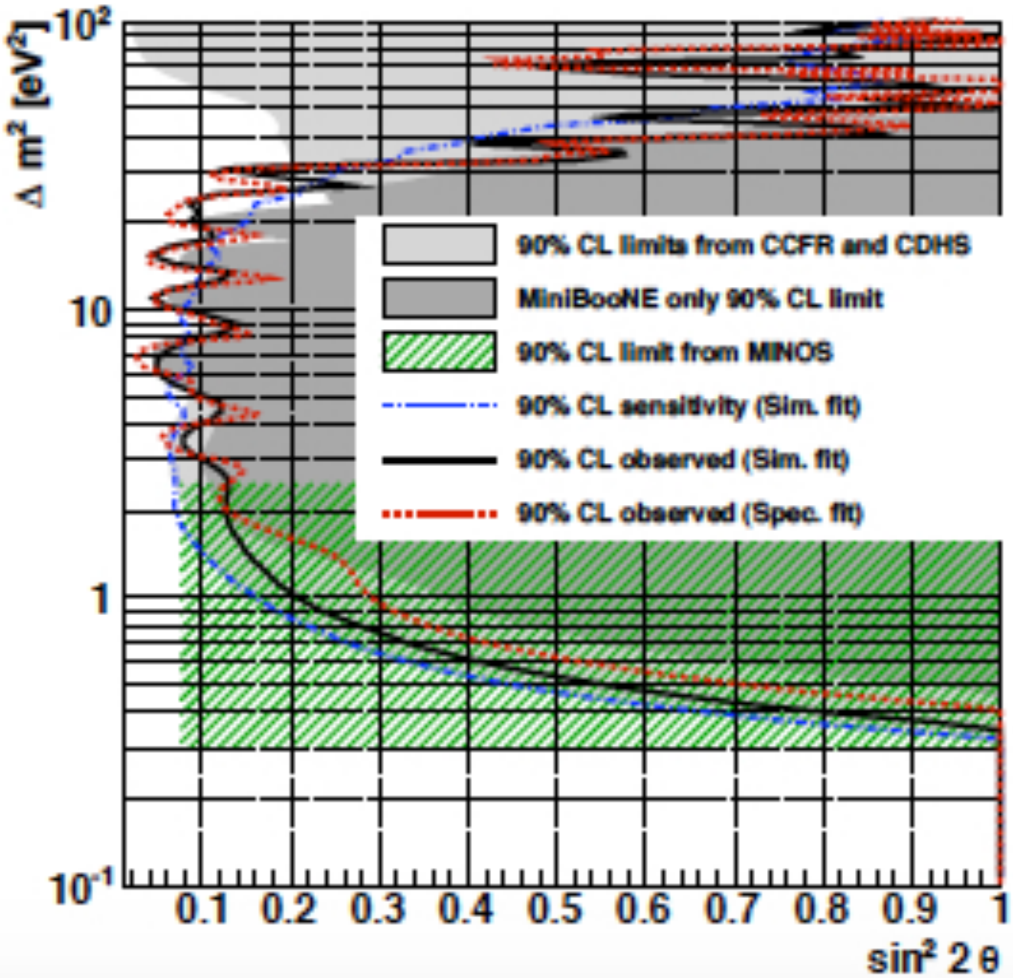
Joint search for non standard disappearance with MiniBooNE and SciBooNE data is consistent with no ν_μ or $\bar{\nu}_\mu$ disappearance at 90%CL

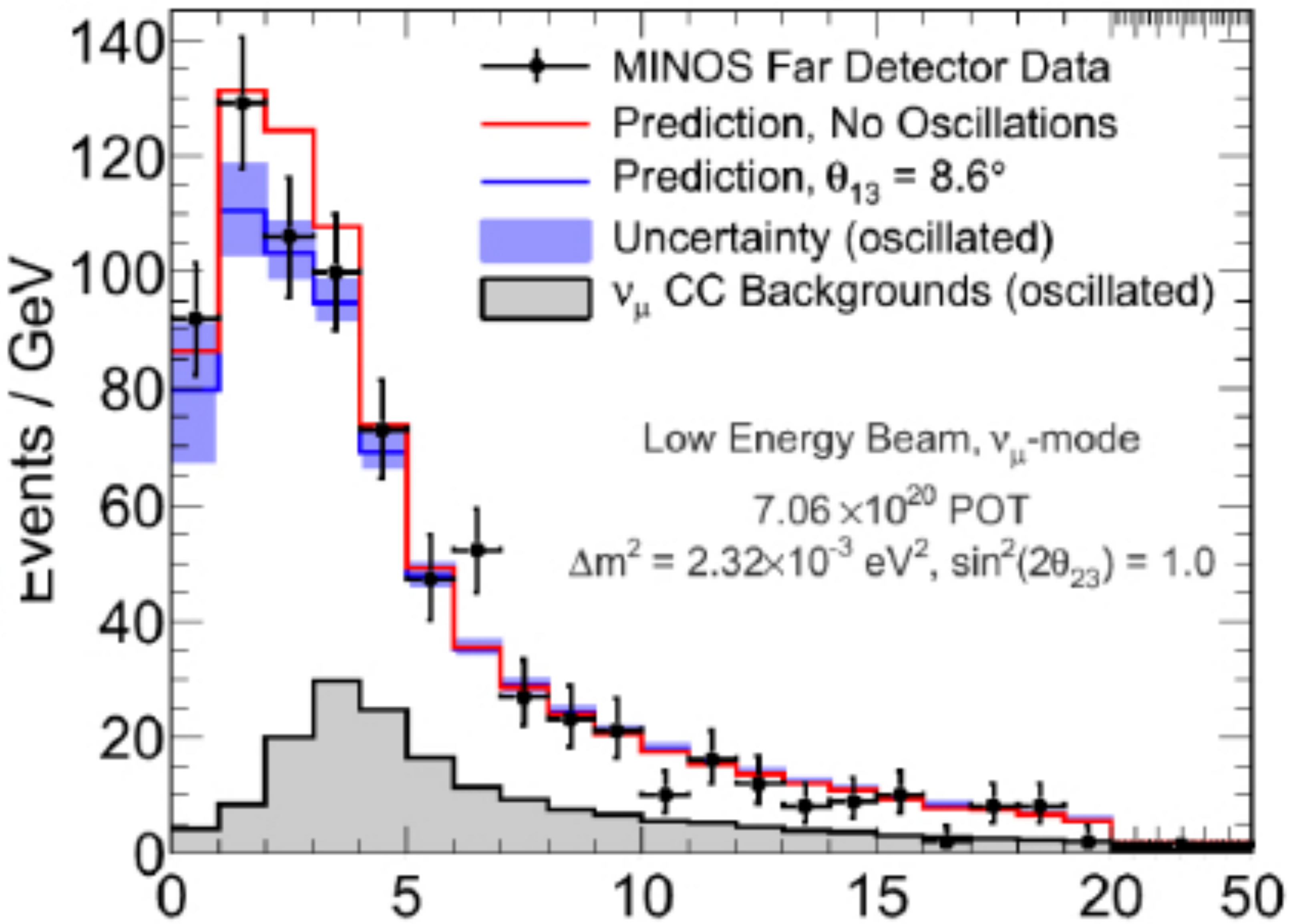




What steriles? Circa 2012

The presence of a sterile neutrino would produce a deficit of active flavors at the far detector (NC deficit)





Green limit from MINOS NC far detector events

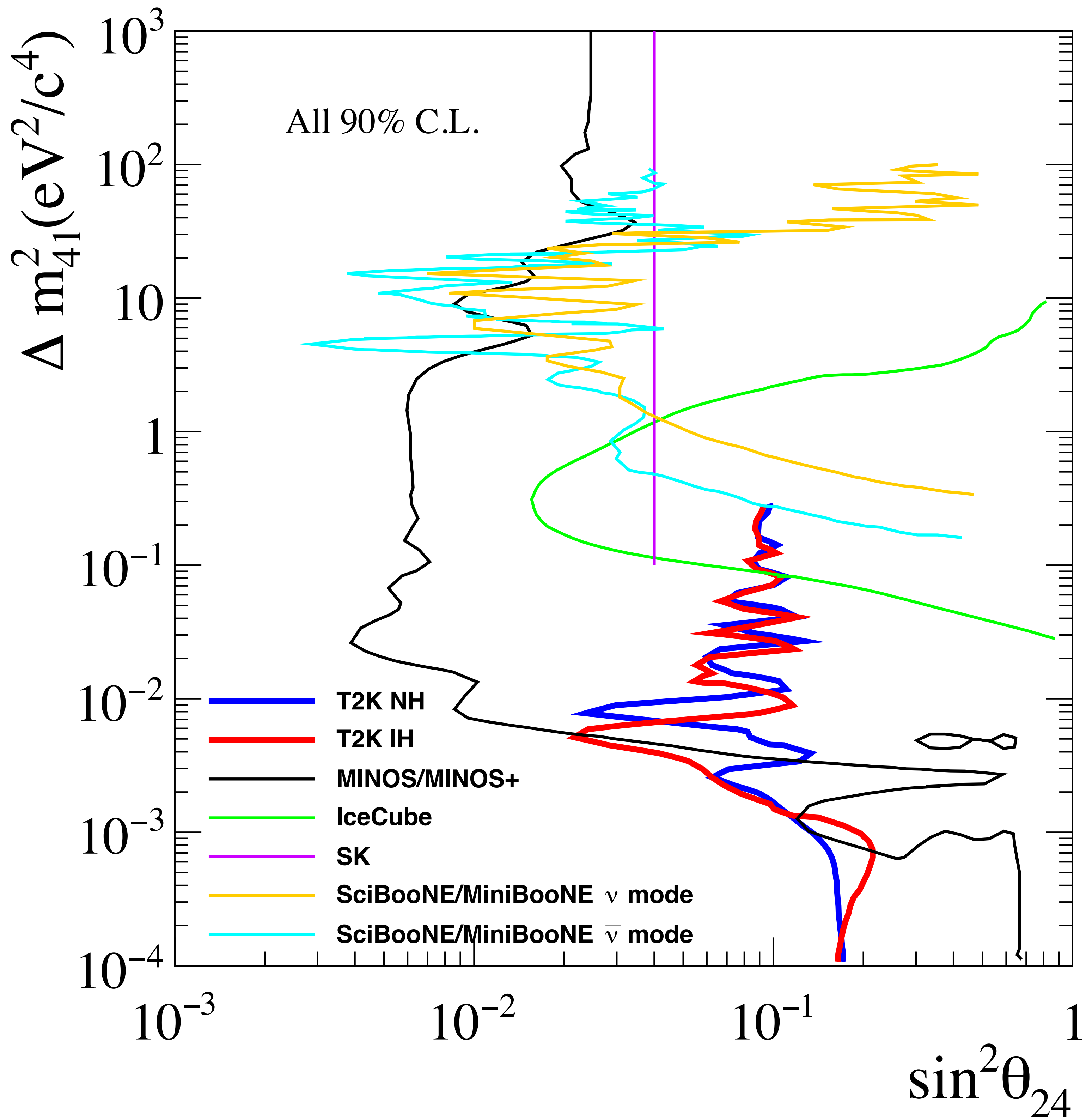
- Consistent with expected flux, and no sterile mixing

What steriles?

Search for sterile neutrinos… with the T2K far detector

- 3+1 model including muon, electron and neutral current samples

Phys. Rev. D 99, 071103 (2019)



What steriles?

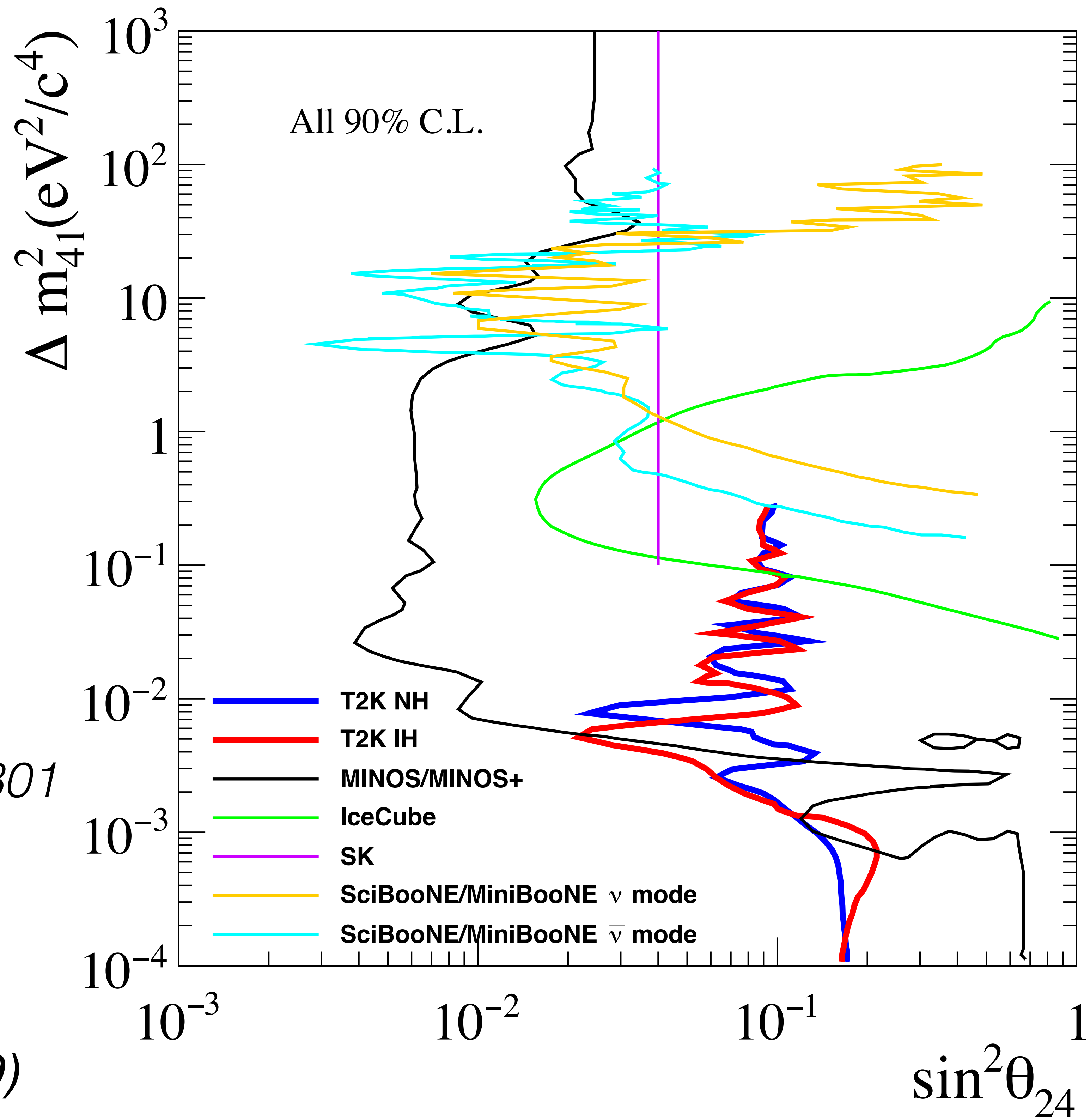
Search for sterile neutrinos…
with the T2K far detector

No steriles in IceCube data either…

Phys.Rev.Lett. 117 (2016) no.7, 071801

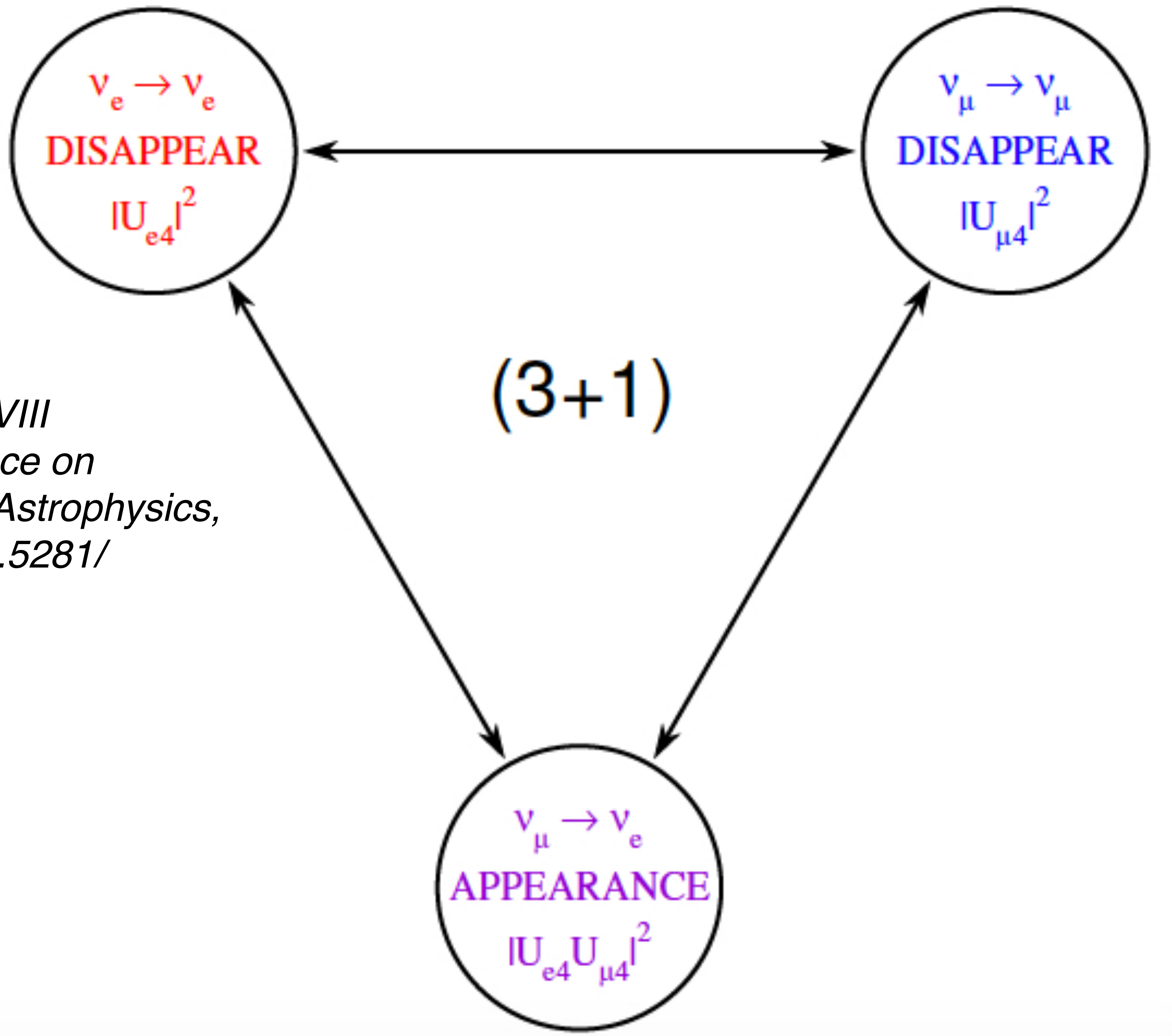
Nor MINOS/MINOS+ improved analyses

Phys. Rev. Lett. 122, 091803 (2019)



Sterile neutrino oscillation

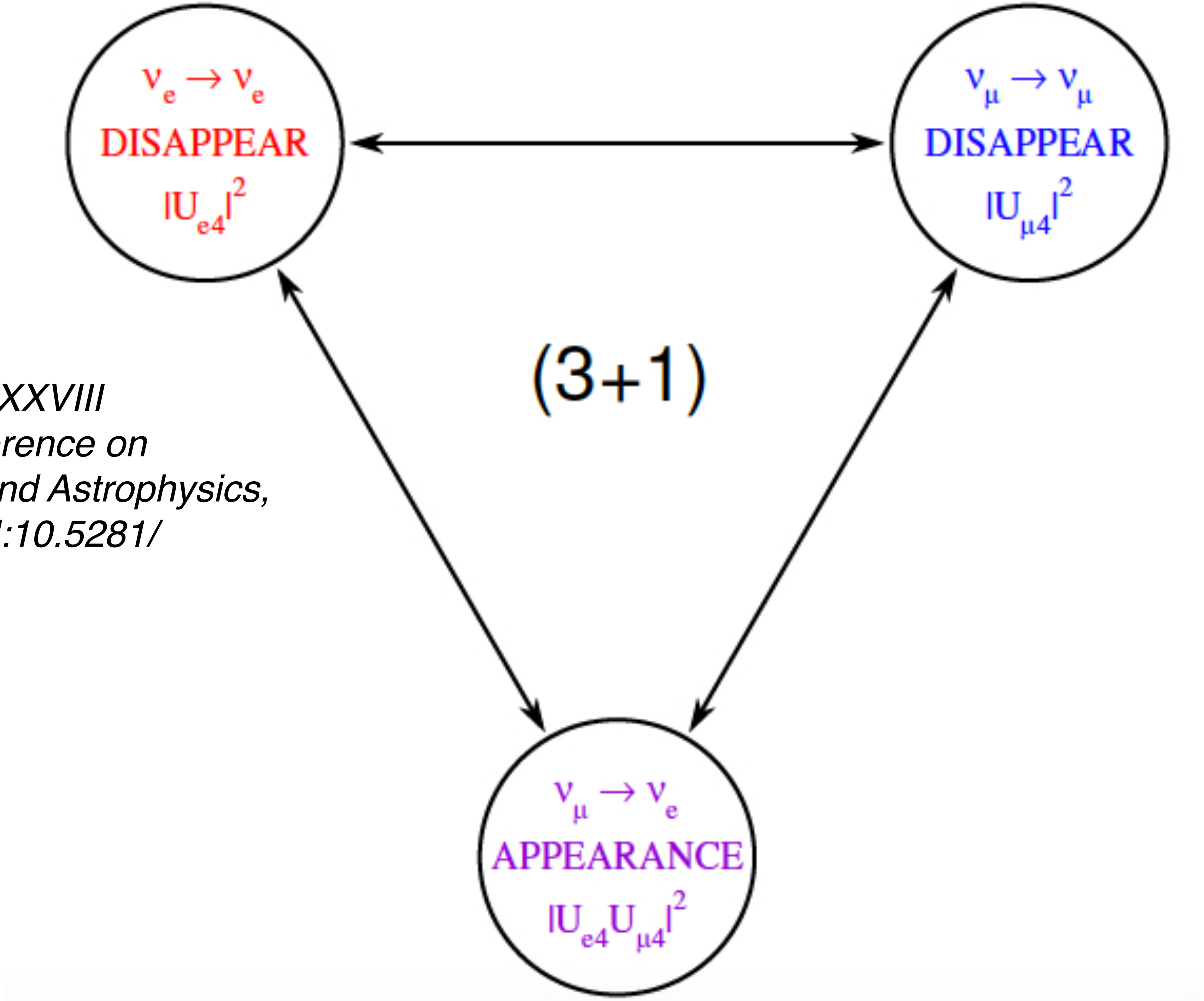
- ν_μ disappearance (and neutral current) is at odds with ν_e appearance
- Doesn't improve with 3+2 models



M. Maltoni, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI:10.5281/zenodo.1287014

Sterile neutrino oscillation

- What about ν_e disappearance?



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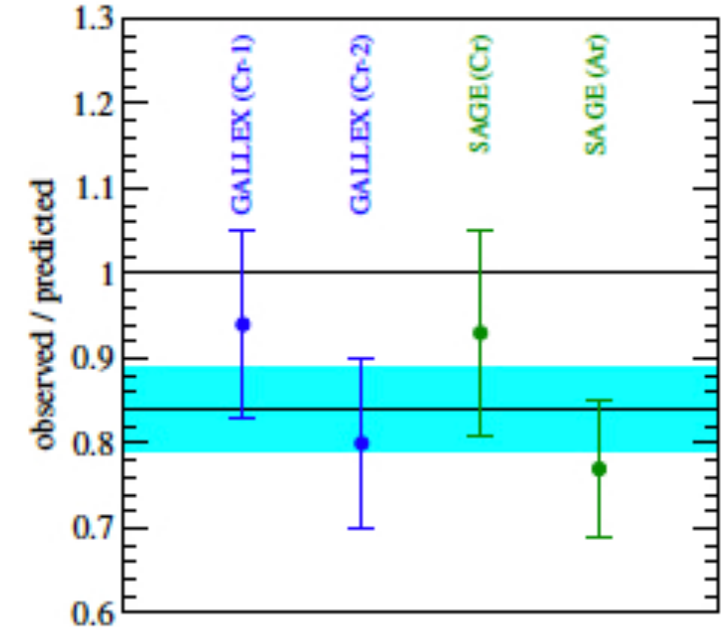
For steriles!

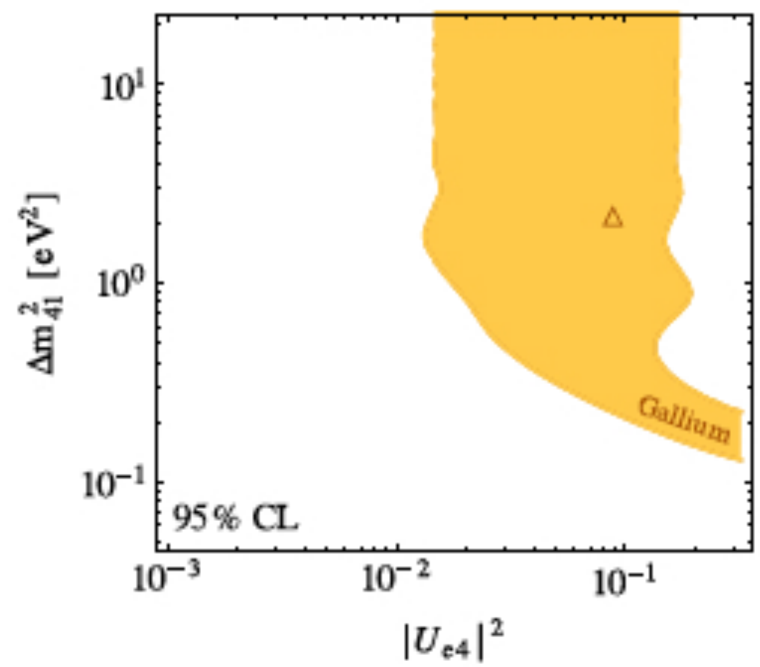
ν_e disappearance: the gallium anomaly

- The $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}$ neutrino capture cross-section, relevant for the GALLEX and SAGE solar neutrino experiments, was calibrated with intense $^{51}\mathrm{Cr}$ and $^{37}\mathrm{Ar}$ neutrino sources;
- these measurements show a significant deficit with respect to the predicted values:

$$\left.\begin{array}{l}\text{GALLEX:}\begin{cases} R_1(\mathrm{Cr}) = 0.94 \pm 0.11 \text{ [18]} \\ R_2(\mathrm{Cr}) = 0.80 \pm 0.10 \text{ [18]} \end{cases} \\ \text{SAGE:}\begin{cases} R_3(\mathrm{Cr}) = 0.93 \pm 0.12 \text{ [19]} \\ R_4(\mathrm{Ar}) = 0.77 \pm 0.08 \text{ [20]} \end{cases}\end{array}\right\} \Longrightarrow \boxed{0.84 \pm 0.05}$$

- such 3σ deficit can be interpreted in terms of ν oscillations;
- once again, data suggests $\Delta m^2 \gtrsim 1$ eV^2.





[18] F. Kaether *et al.*, Phys. Lett. **B685** (2010) 47–54 [arXiv:1001.2731].
[19] J. Abdurashitov *et al.* [SAGE collab], Phys. Rev. **C59** (1999) 2246–2263 [hep-ph/9803418].
[20] J. Abdurashitov *et al.* [SAGE collab], Phys. Rev. **C73** (2006) 045805 [nucl-ex/0512041].

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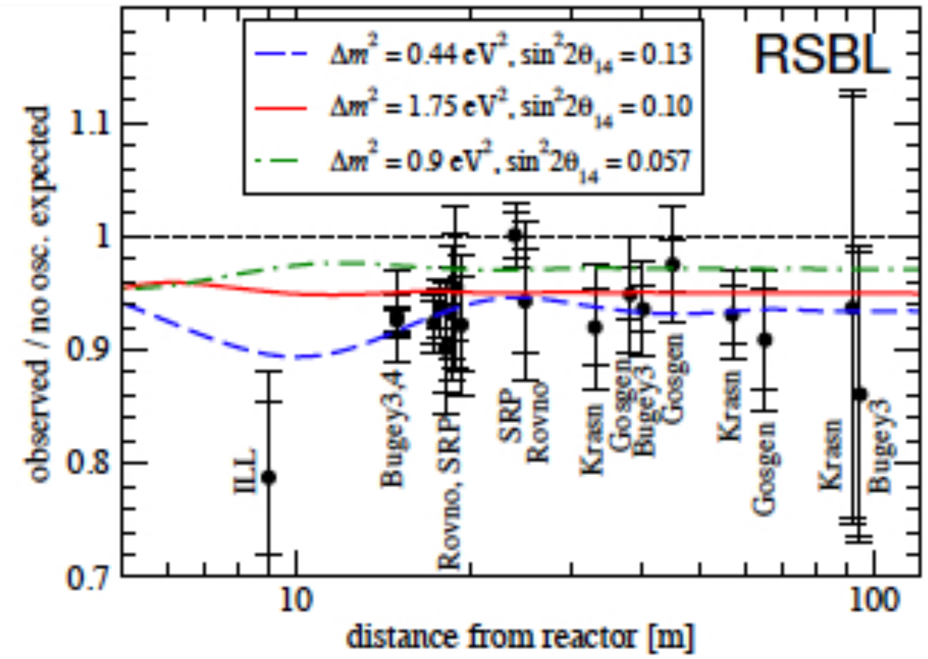
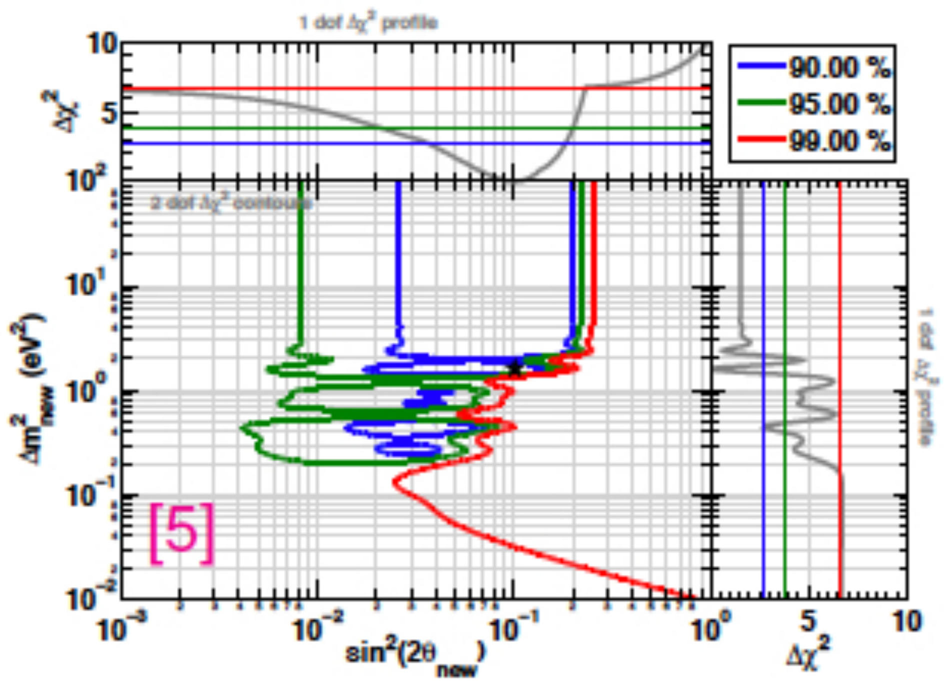
For steriles!

$\bar{\nu}_e$ disappearance: the reactor anomaly

- In [3, 4] the reactor $\bar{\nu}$ fluxes was reevaluated;
- the new calculations result in a small increase of the flux by about **3.5%**;
- hence, **all** reactor short-baseline (RSBL) finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to SBL neutrino oscillations;
- no visible dependence on $L \Rightarrow \Delta m^2 \gtrsim 1$ eV^2;
- global data (3σ): $\begin{cases} \Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5} \text{ eV}^2, \\ |\Delta m^2_{\text{ATM}}| \simeq [2.4 \to 2.6] \times 10^{-3} \text{ eV}^2; \end{cases}$

$\Rightarrow$ solutions: **add new neutrinos** or **revise fluxes**.





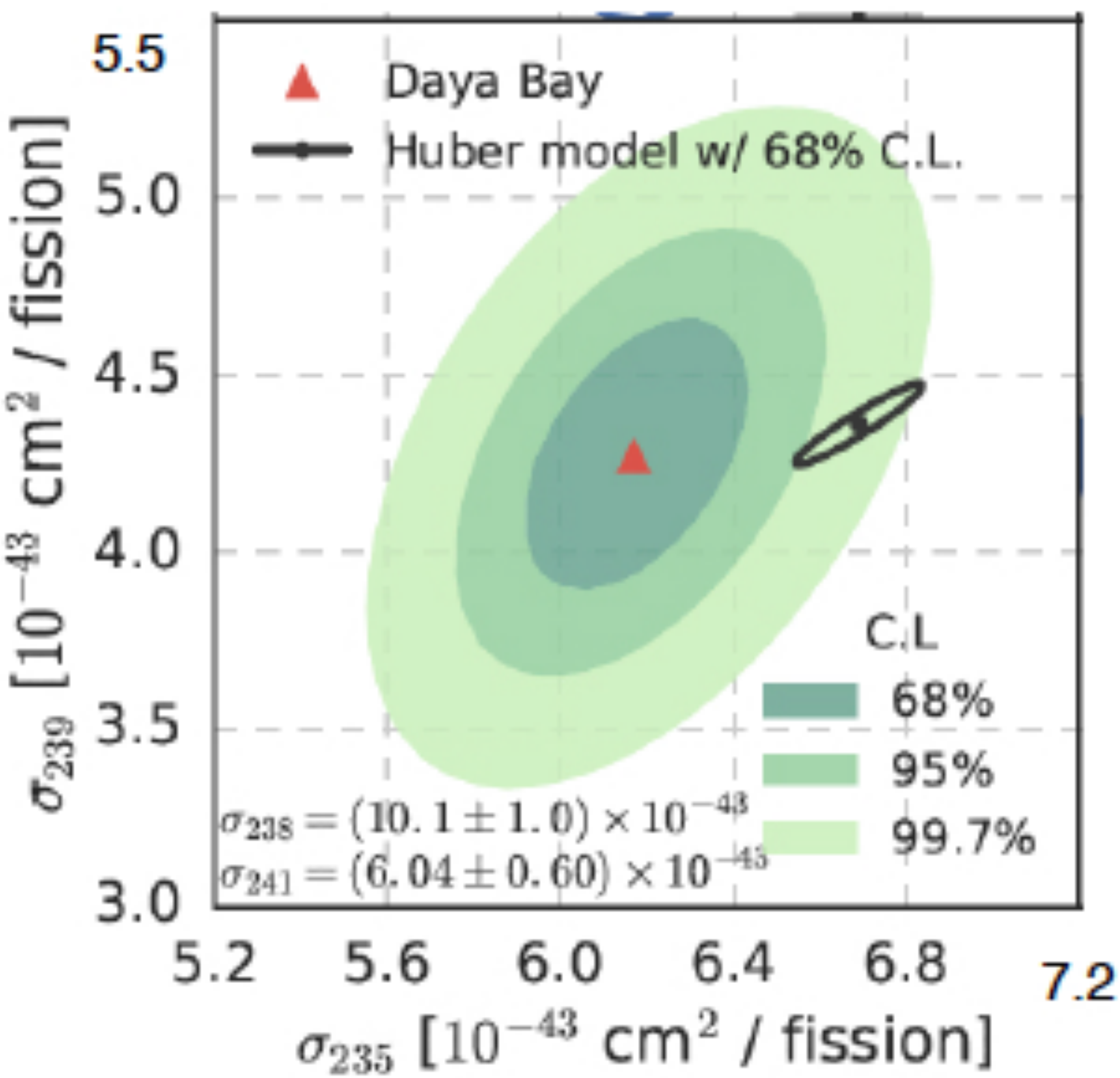
[3] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663].
[4] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687].
[5] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755].

$\Rightarrow$ Talk: Hayes

$\Rightarrow$ Talk: Suhonen

M. Maltoni, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI:10.5281/zenodo.1287014

What steriles?



Daya Bay results call into question flux modeling

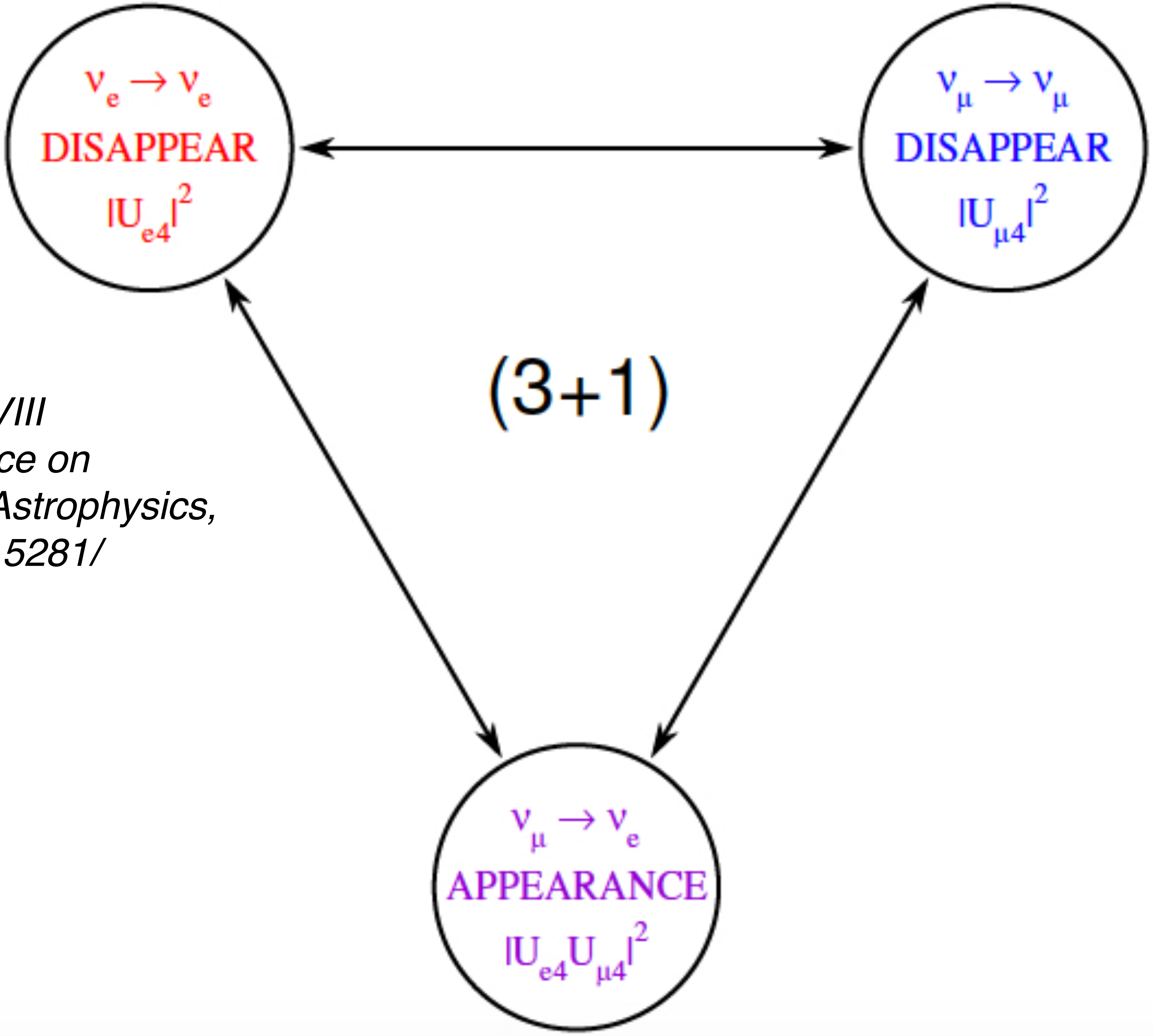
Phys. Rev. Lett. 118 251801 (2017)

As do nuclear theory groups

Phys. Rev. Lett. 120, 022503 (2018)

Sterile neutrino oscillation

- ν_μ disappearance (and neutral current) is at odds with ν_e appearance
- And, ν_e disappearance needs more study



M. Maltoni, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI:10.5281/zenodo.1287014

Ongoing sterile searches

Reactor

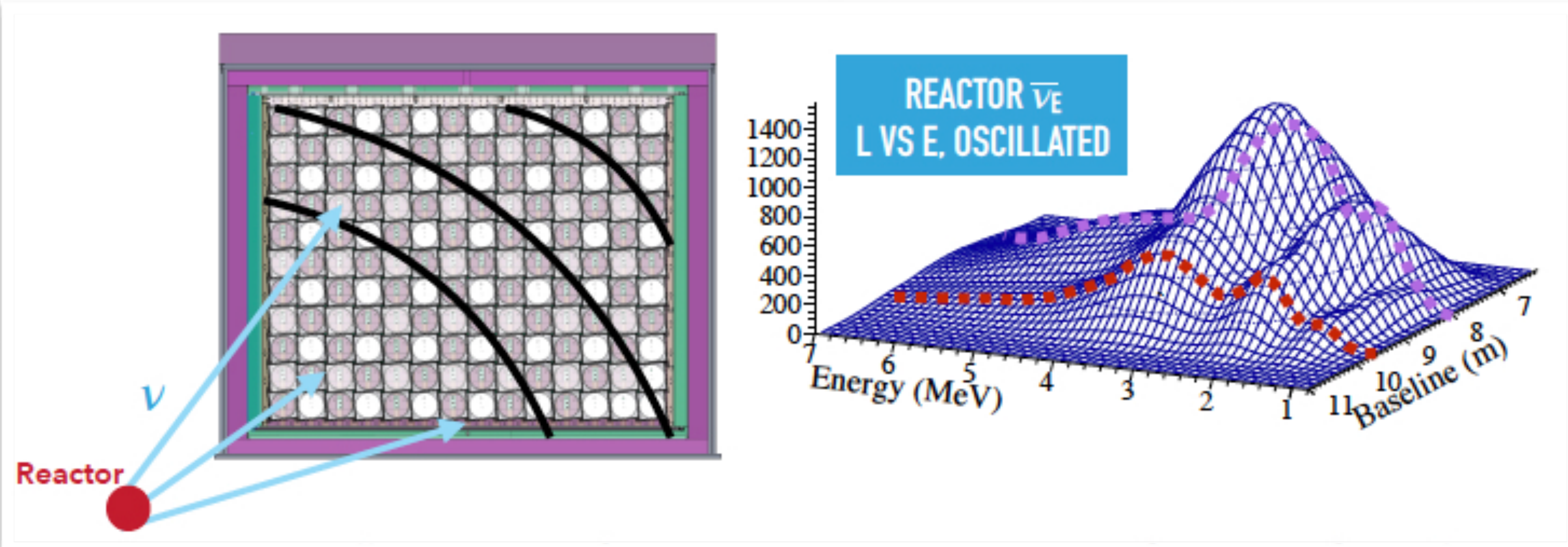
Experiment	Power	Core Size	Mass	n Tag	Baseline	Country
DANSS	3 GW	3.7 m	1 ton	Gd	10.7-12.7 m	Russia
NEOS	2.8 GW	3.1 m	1.75 tons	Gd	23.7 m	Korea
Neutrino-4	90 MW	42 cm	0.4 tons	Gd	6-12 m	Russia
Stereo	58 MW	40 cm	2 tons	Gd	9 m	France
Prospect	85 MW	50 cm	2.5 tons	^{6}Li	7 m	USA
SoLid/CHANDLER	60 MW	50 cm	3.1 tons	^{6}Li/ZnS	5.5 m	Belgium

J. Link, INSS2017

~~Source-based~~

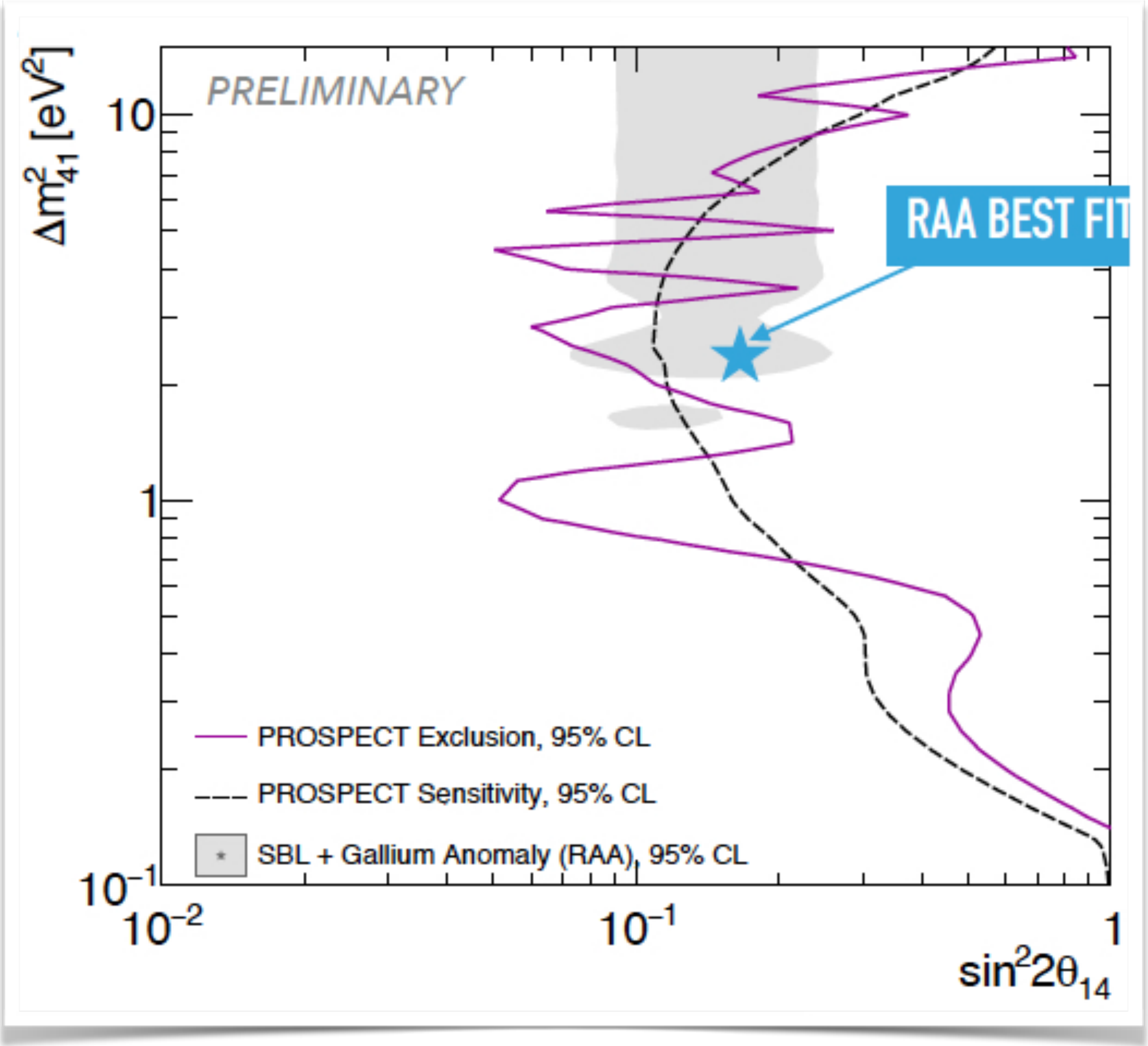
Accelerator-based SBN

PROSPECT experiment



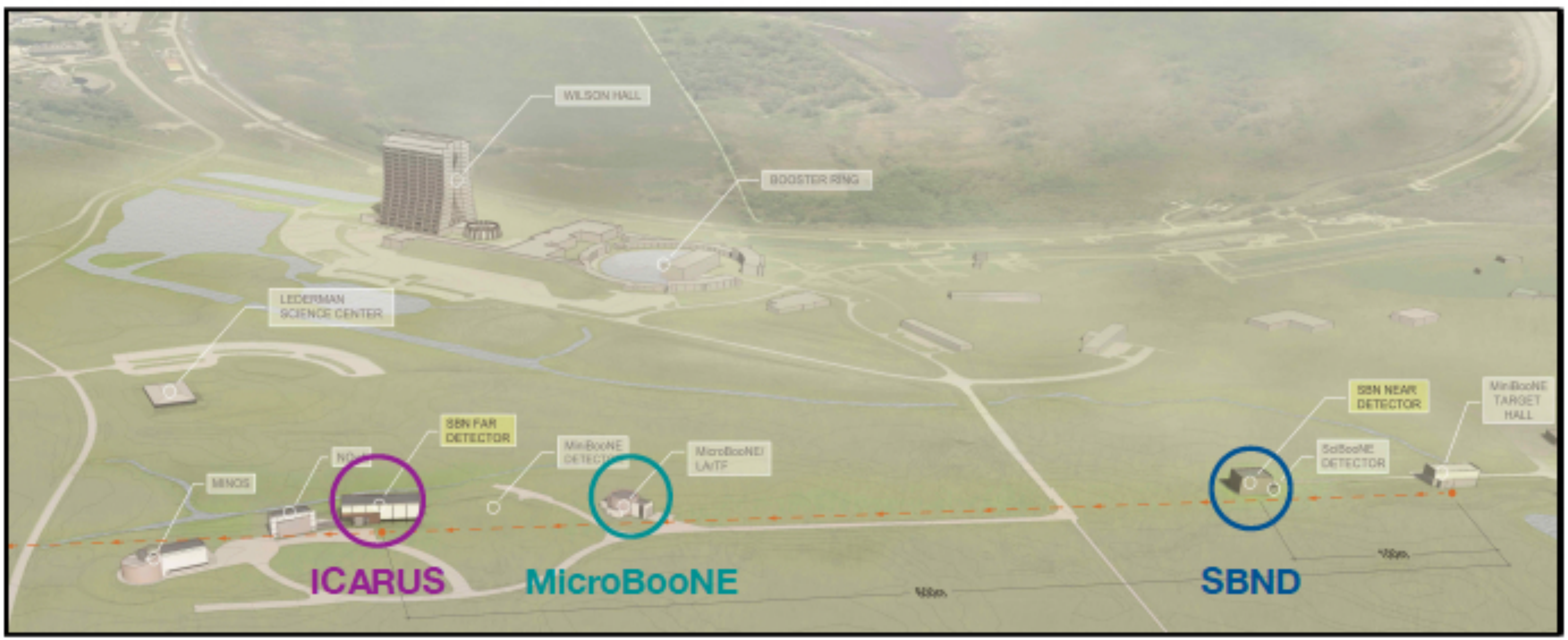
T. Langford, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI:10.5281/zenodo.1286999

PROSPECT experiment



Phys. Rev. Lett. 121, 251802 (2018)

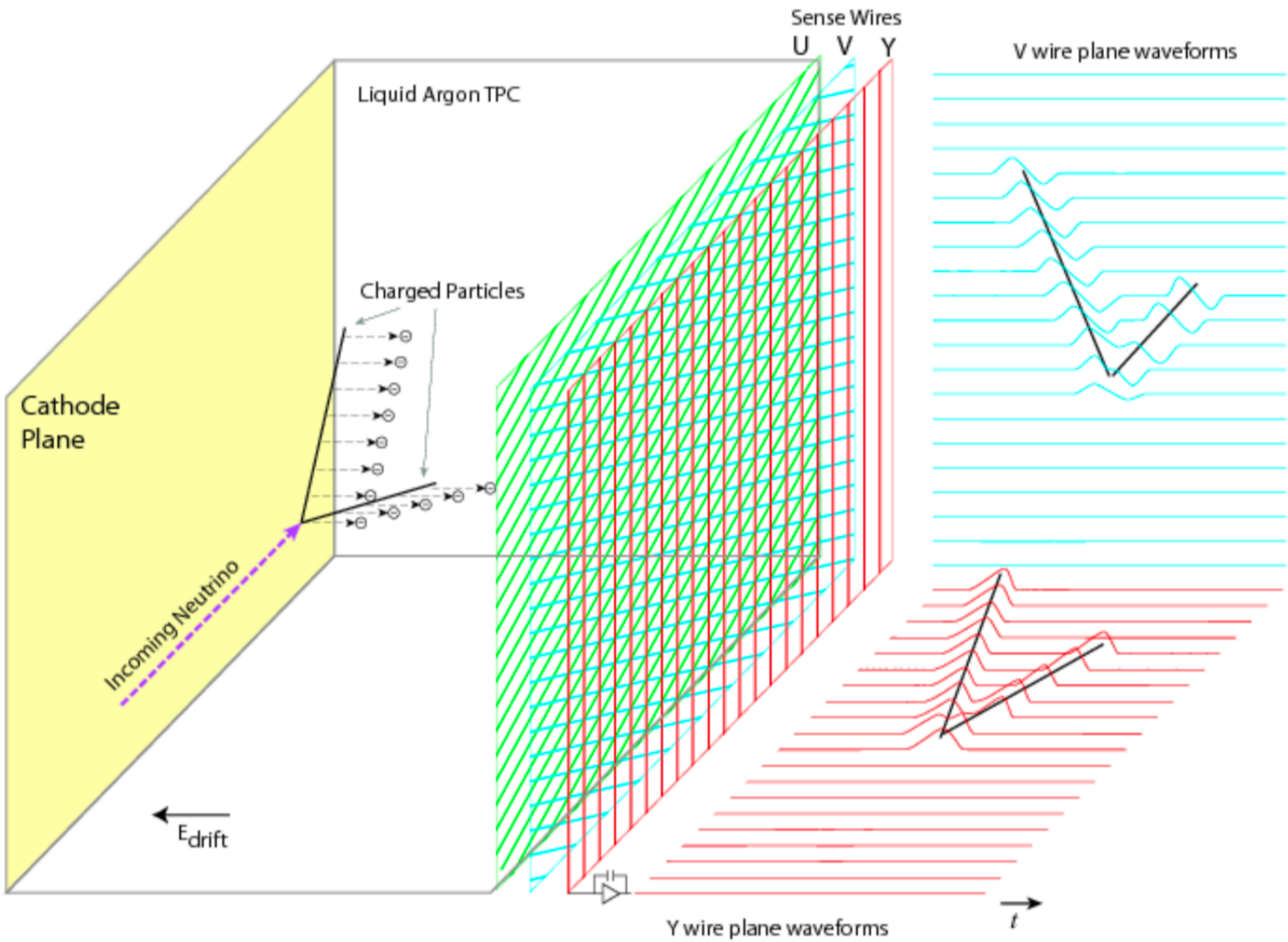
Short Baseline Neutrino Program (SBN)



SBN proposal: https://arxiv.org/abs/1503.01520

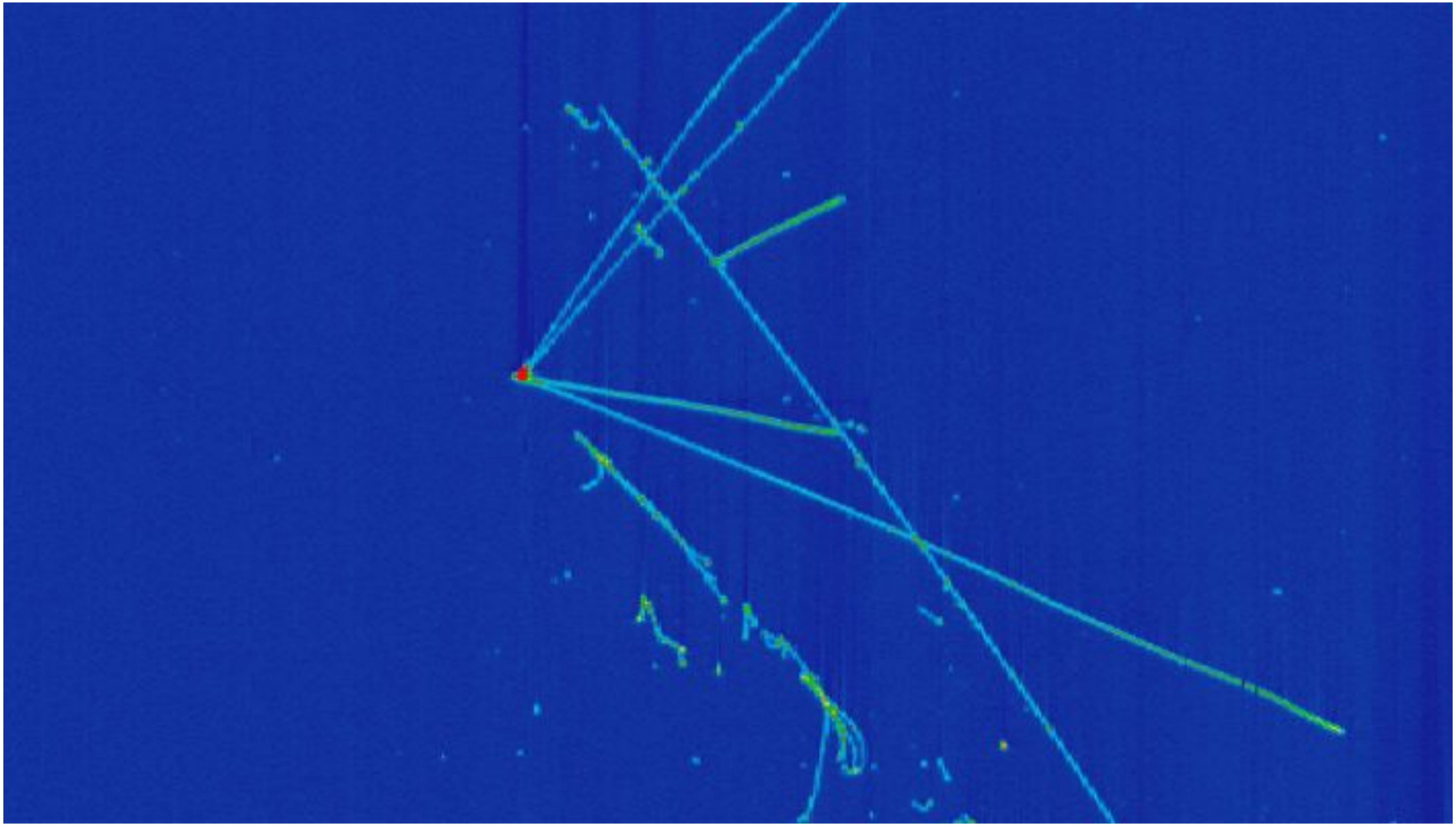
R. Guenette, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: 10.5281/zenodo.1294113

Liquid Argon TPCs



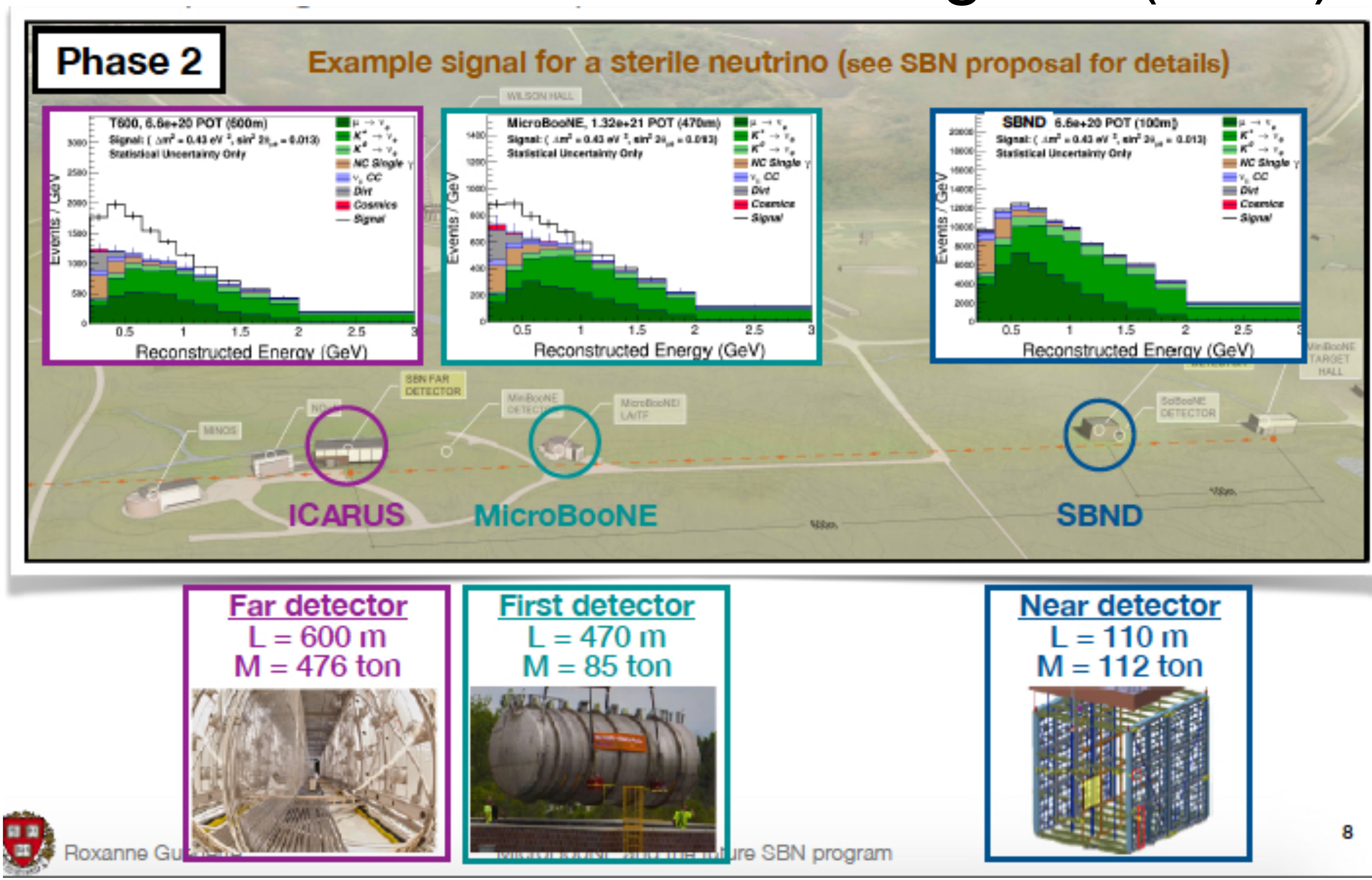
credit: B. Yu, y2u.be/lH88L5nVvmY

Liquid Argon TPCs



https://microboone.fnal.gov/

Short Baseline Neutrino Program (SBN)



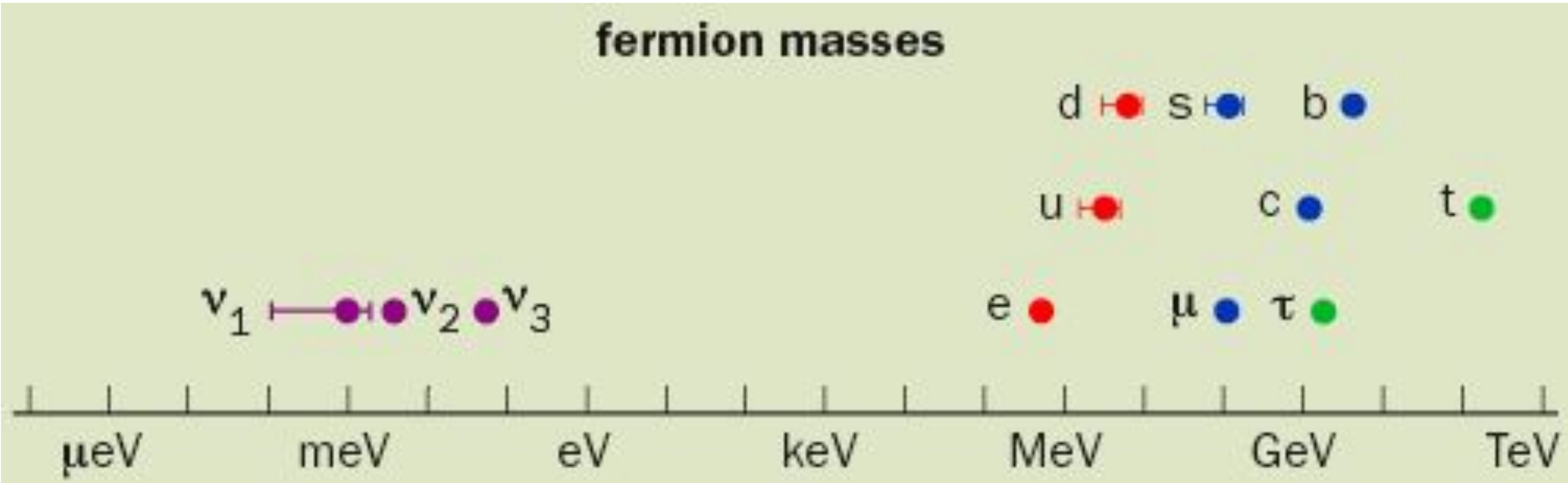
R. Guenette, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: 10.5281/zenodo.1294113

Outline

What do we know about neutrino mass?

Direct mass searches
Neutrino-less double beta decay

Neutrino mass

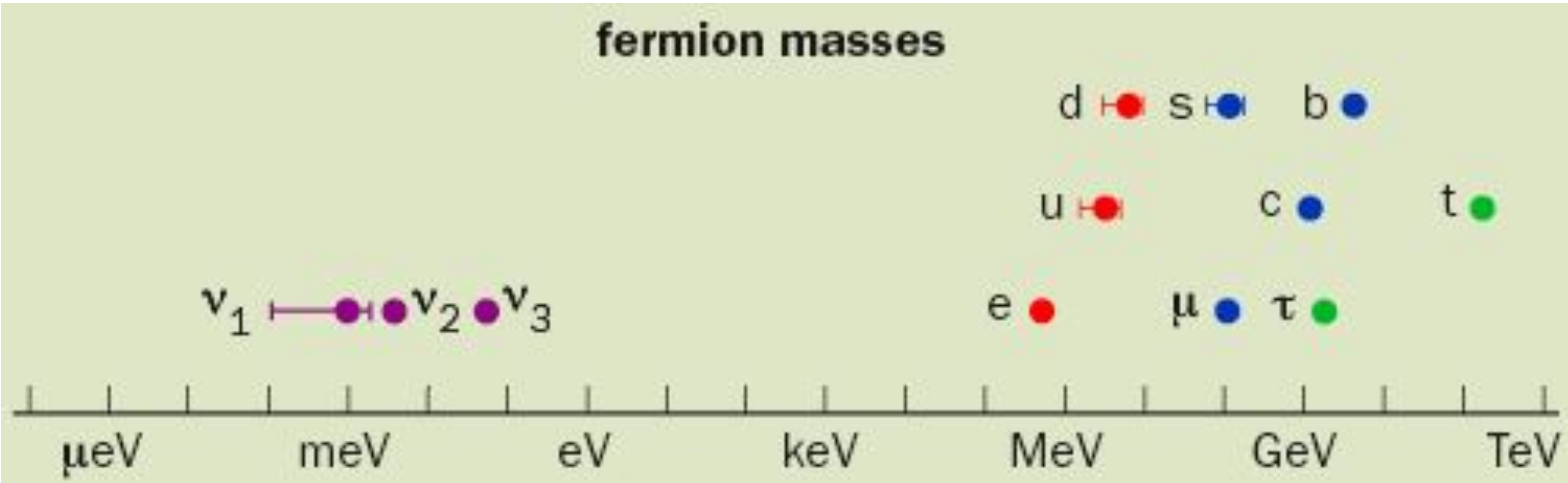


Credit: H. Murayama

Neutrinos have mass unlike the other particles

- Neutral lepton - *Majorana particle?*

Neutrino mass

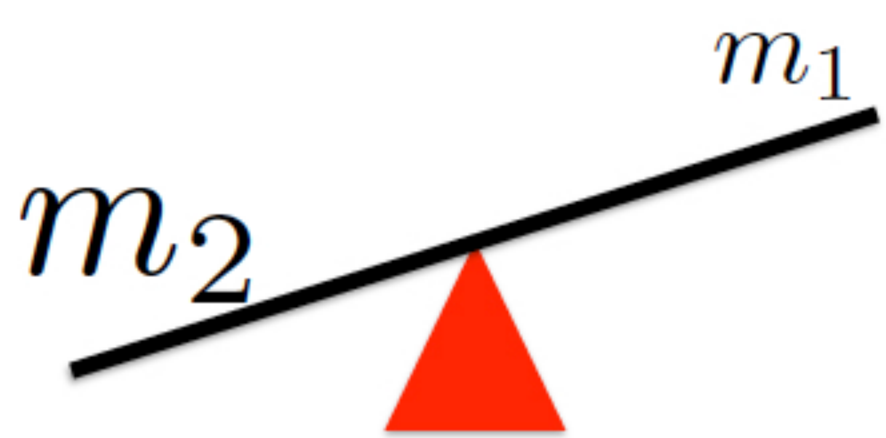


Credit: H. Murayama

See-saw mechanism *(Gell-Mann, Ramond, Slansky and Yanagida, 1979)*

$$m_1 \simeq \frac{(m_\mathrm{D})^2}{m_R} \ll m_\mathrm{D} \, ,$$

$$m_2 \simeq m_R \, ,$$



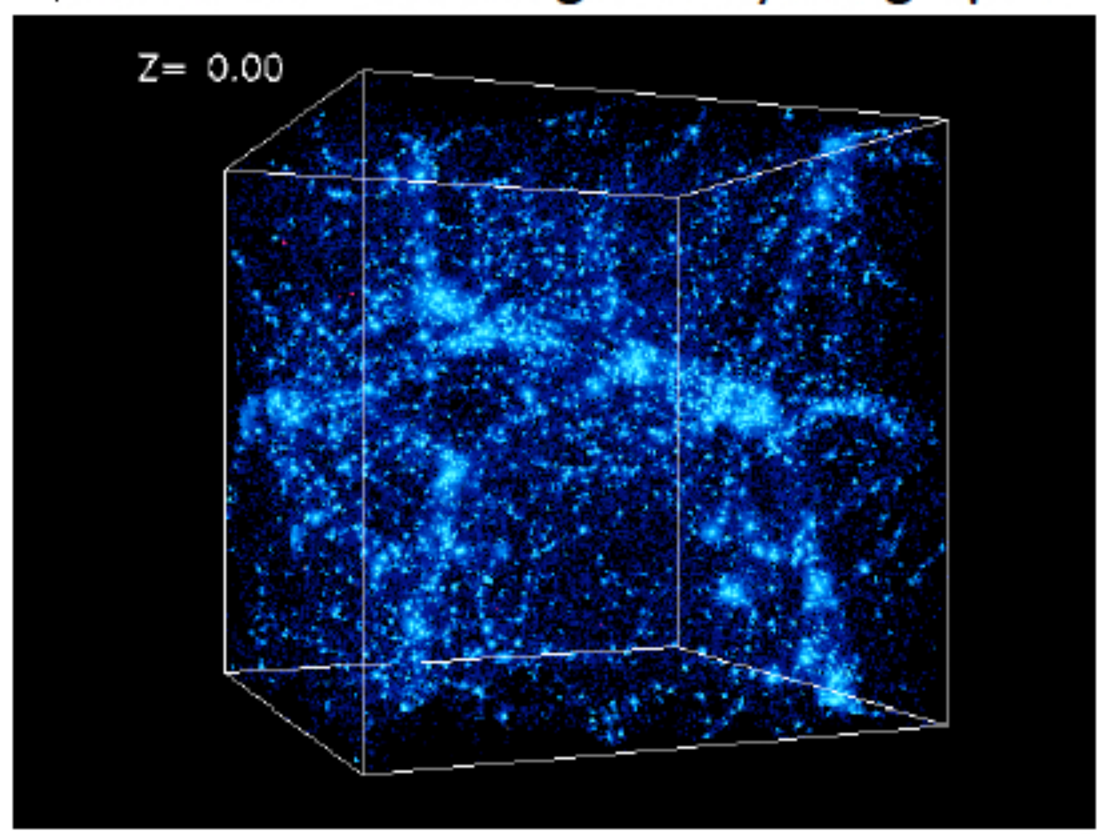
How do we measure neutrino mass?

www.istockphoto.com

Constraints from:

- Cosmology - large scale structure evolution (CMB, galaxy surveys)

Center for Cosmological Physics graphic



How do we measure neutrino mass?

Effective density parameters	Planck 2015 (TT+lowP+lensing) + BAO
ΔN_{eff} (extra contribution to density *before* NR transition)	<0.7 (95%CL)
m_{eff} (extra contribution to density *after* NR transition)	< 400 meV (95%CL)

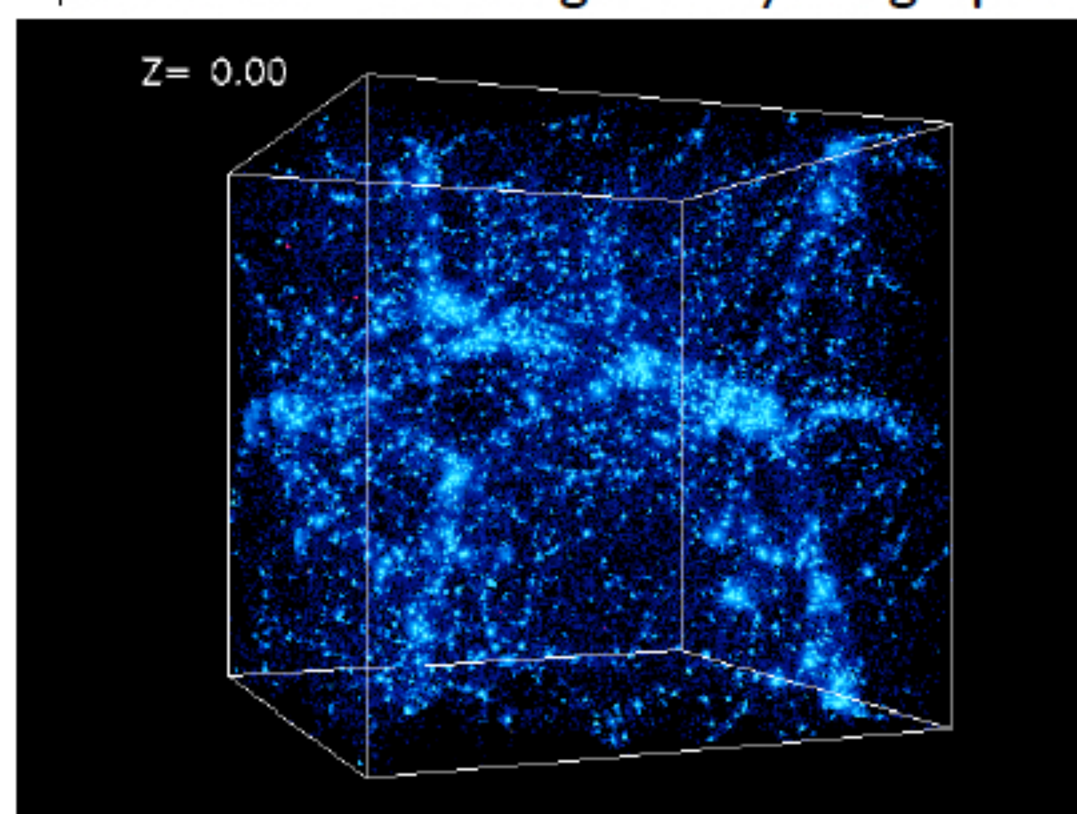
What steriles?

.com

C

• e

Center for Cosmological Physics graphic



J. Lesgourgues, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018
DOI: 10.5281/zenodo.1287028

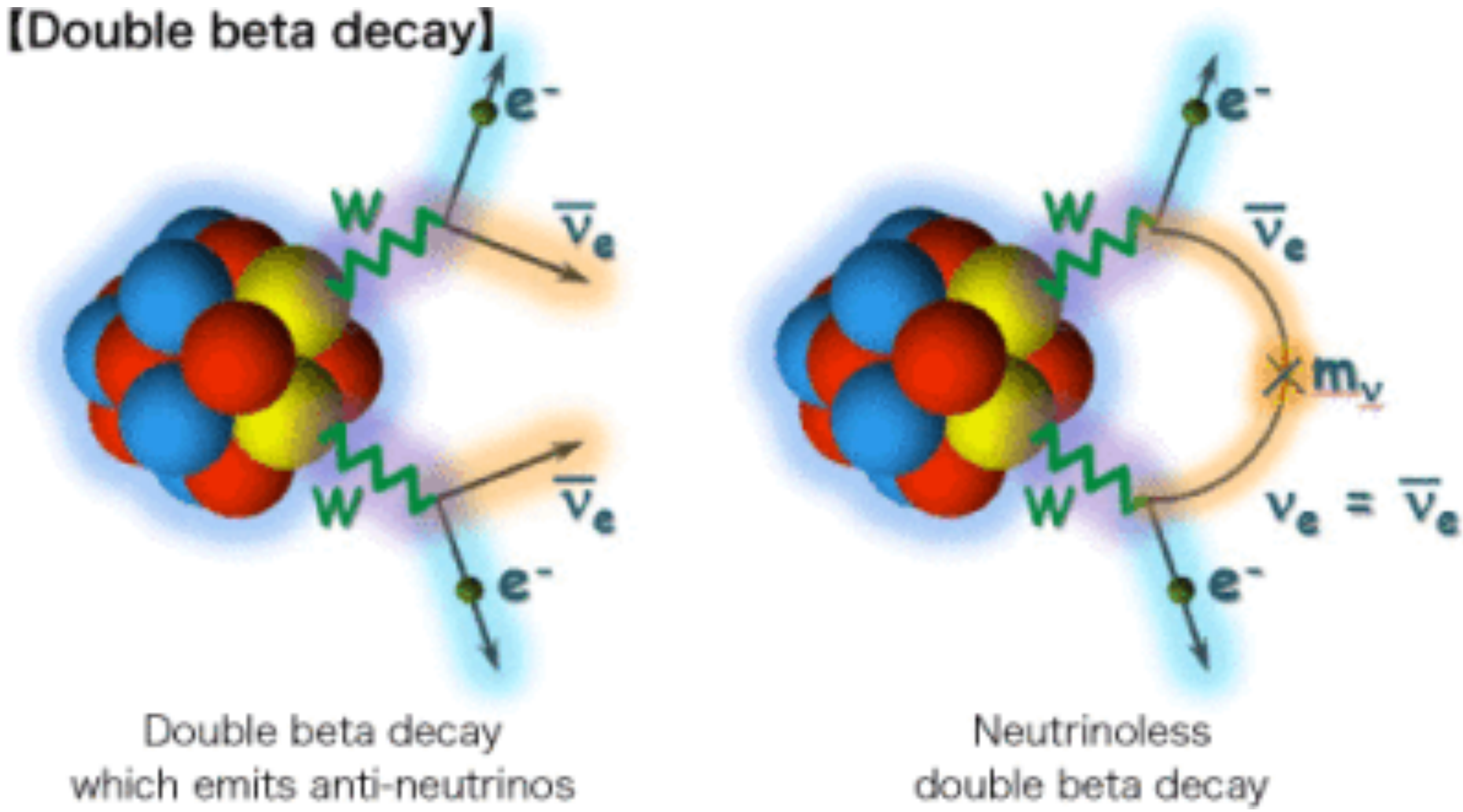
How do we measure neutrino mass?

www.istockphoto.com

Constraints from:

- Cosmology
- Searches for neutrino-less double beta decay (rare process)
- Kinematics of beta decay

Neutrino-less and double beta decay

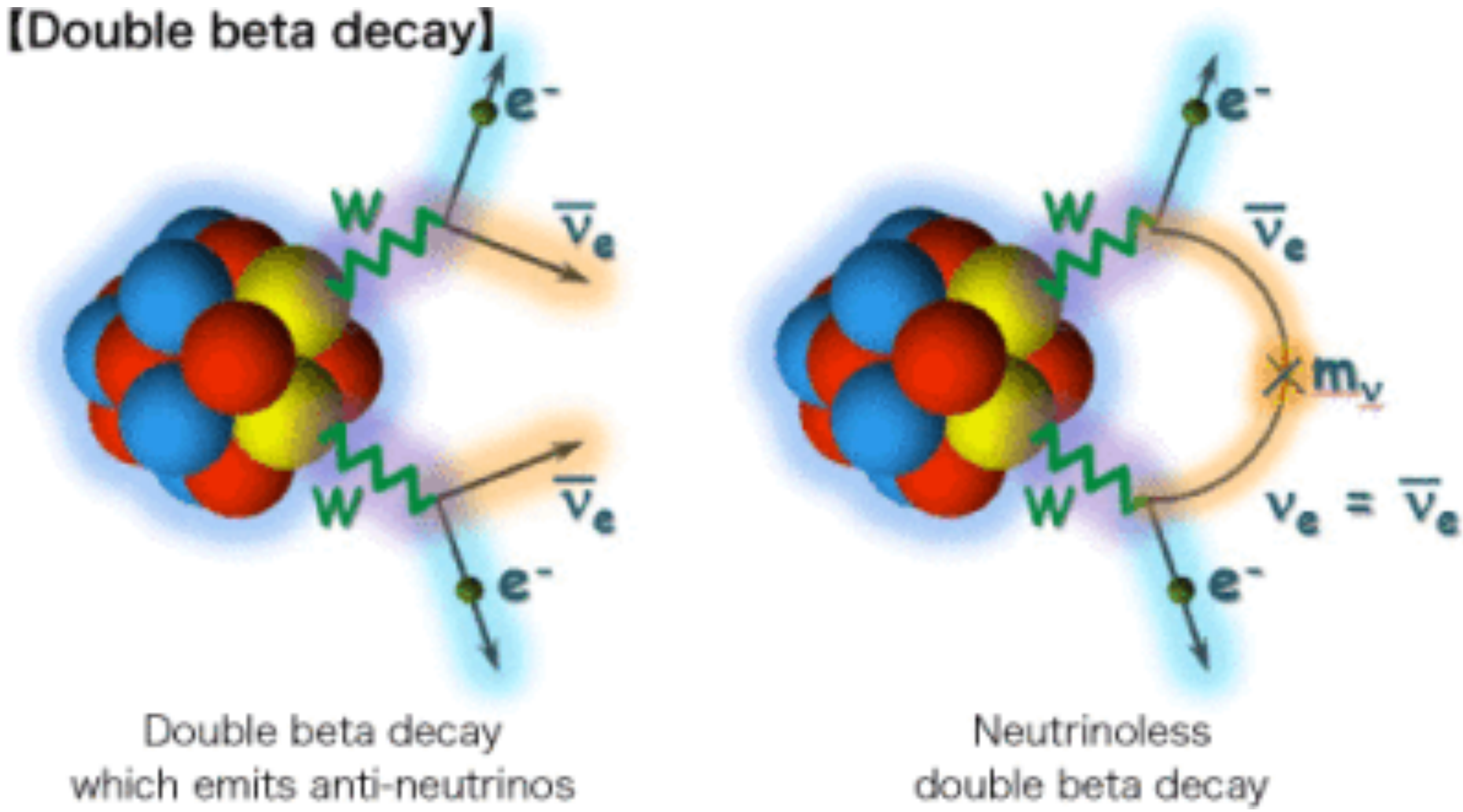


credit: CANDLES experiment

This process can only occur if neutrinos are Majorana particles*

- Only possible in certain nuclei

Neutrino-less and double beta decay



credit: CANDLES experiment

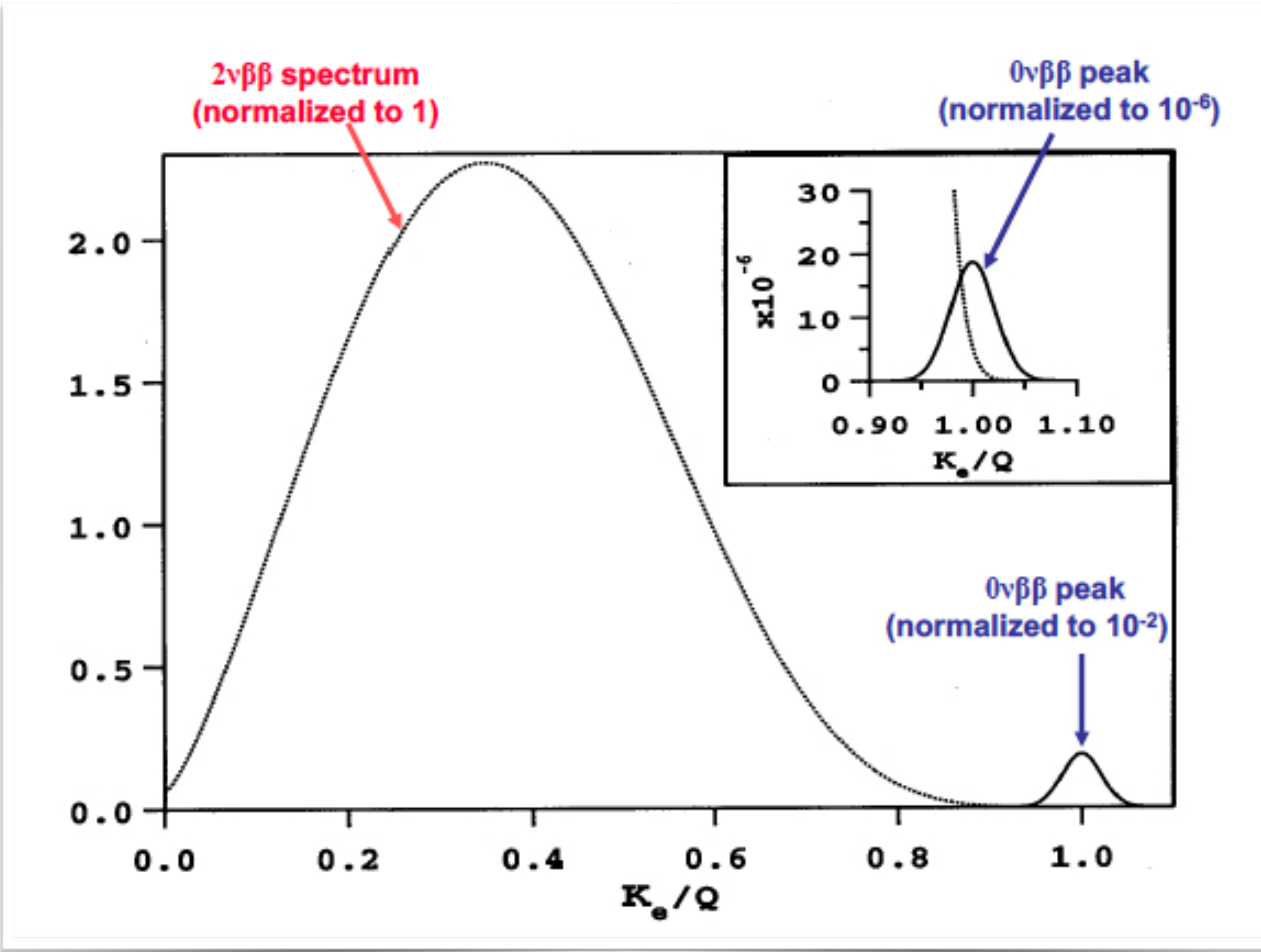
This process can only occur if neutrinos are Majorana particles*

- Only possible in certain nuclei

May be other mechanisms? Example: JHEP 1106:091, 2011

How do you measure neutrino less double beta decay? **0νββ**

How do you measure neutrino less double beta decay?



credit: M. Dolinkski, INSS2017

How do you measure neutrino less double beta decay?

Phase space factor ~Q^5 — Effective Majorana mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \langle m_\nu \rangle^2$$

Nuclear matrix element

Measured half-life corresponds to a measurement of neutrino mass

- Needs: nuclear theory
- Needs: Suitable nuclei

credit: M. Dolinkski, INSS2017

How do you measure neutrino less double beta decay?

Phase space factor ~Q^5 → $G^{0\nu}$

Effective Majorana mass → $\langle m_\nu \rangle$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \langle m_\nu \rangle^2$$

Nuclear matrix element → $M^{0\nu}$

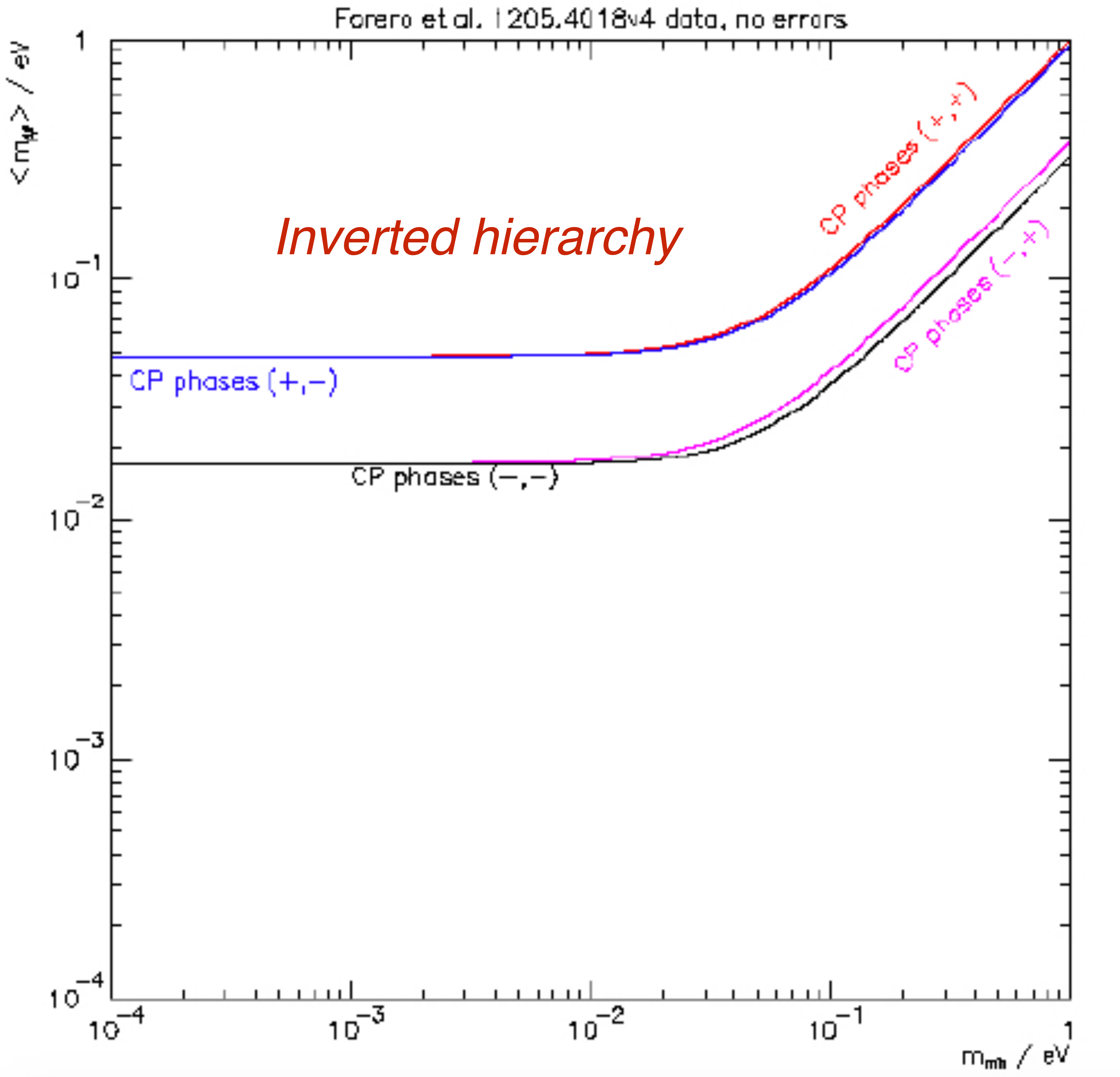
Measured half-life corresponds to a measurement of neutrino mass

- Needs: nuclear theory
- Needs: Suitable nuclei
- Needs: oscillation parameters

$$\langle m_{\beta\beta} \rangle = \Big| m_1 \cdot (1-\sin^2\theta_{12}) \cdot (1-\sin^2\theta_{13}) + m_2 \cdot \sin^2\theta_{12} \cdot (1-\sin^2\theta_{13}) \cdot e^{i\cdot(\alpha_2-\alpha_1)} + m_3 \cdot \sin^2\theta_{13} \cdot e^{-i\cdot\alpha_3} \Big|$$

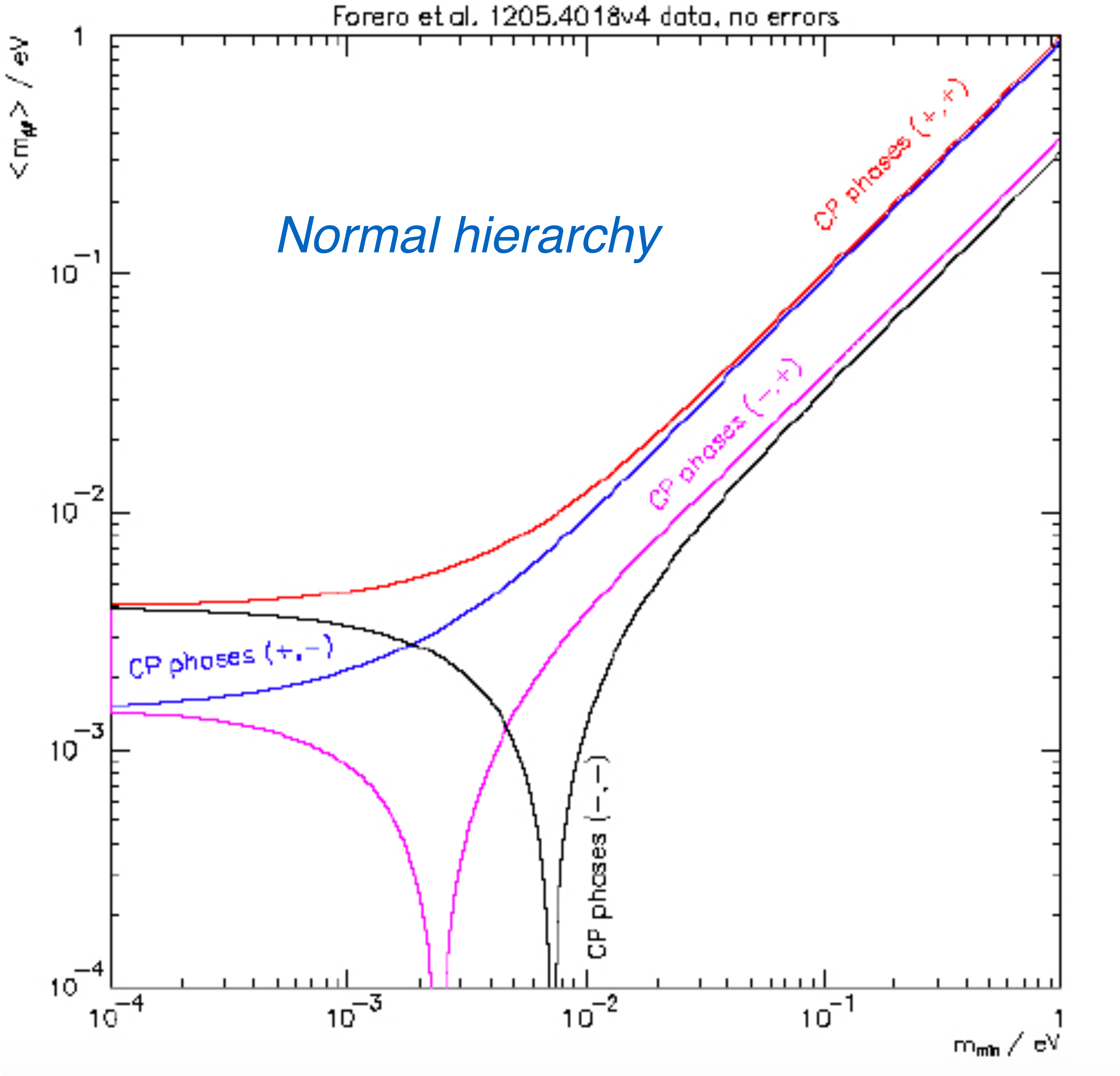
credit: M. Dolinkski, INSS2017

How do you measure neutrino less double beta decay?



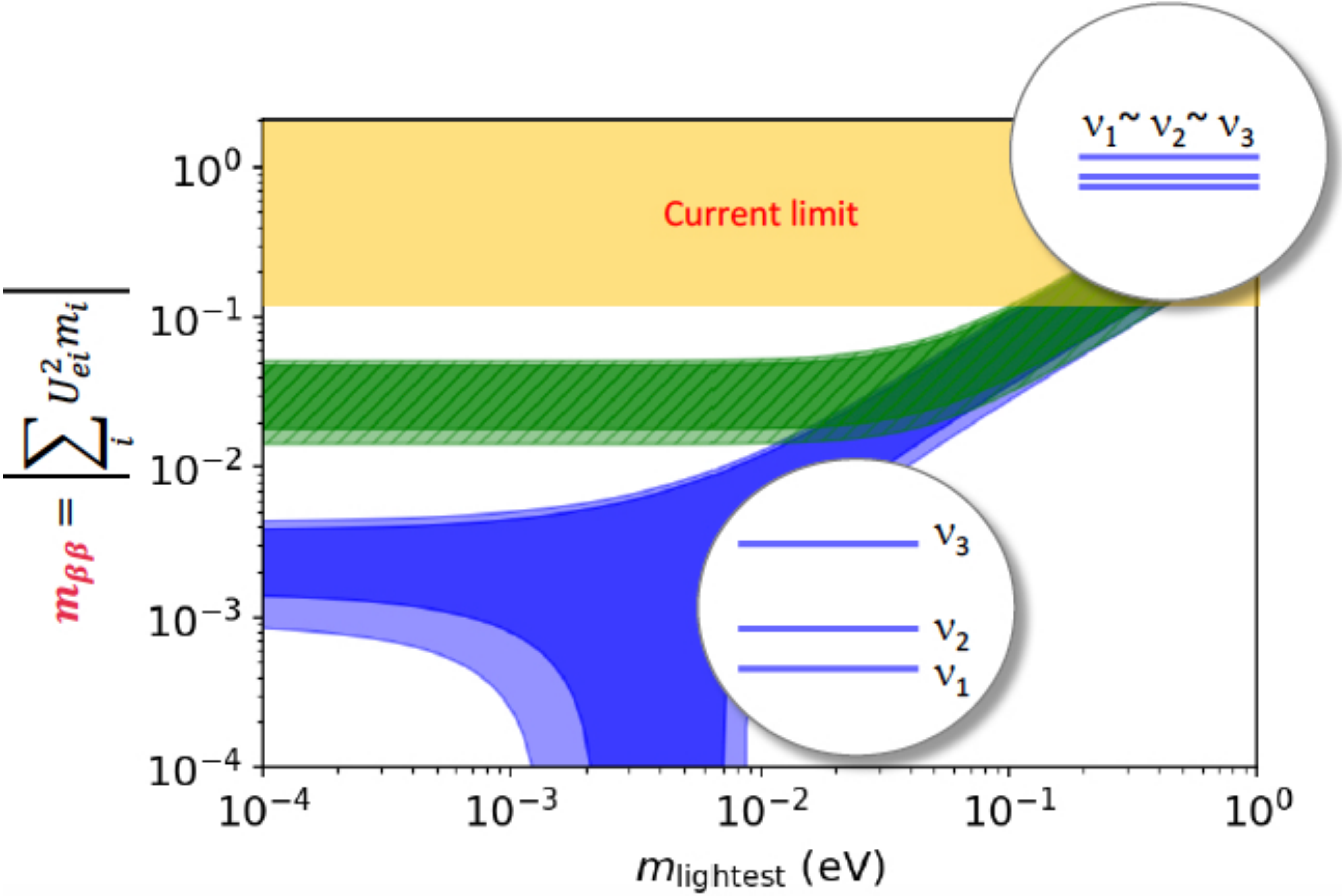
credit: M. Dolinkski, INSS2017
credit: Andreas Piepke

How do you measure neutrino less double beta decay?



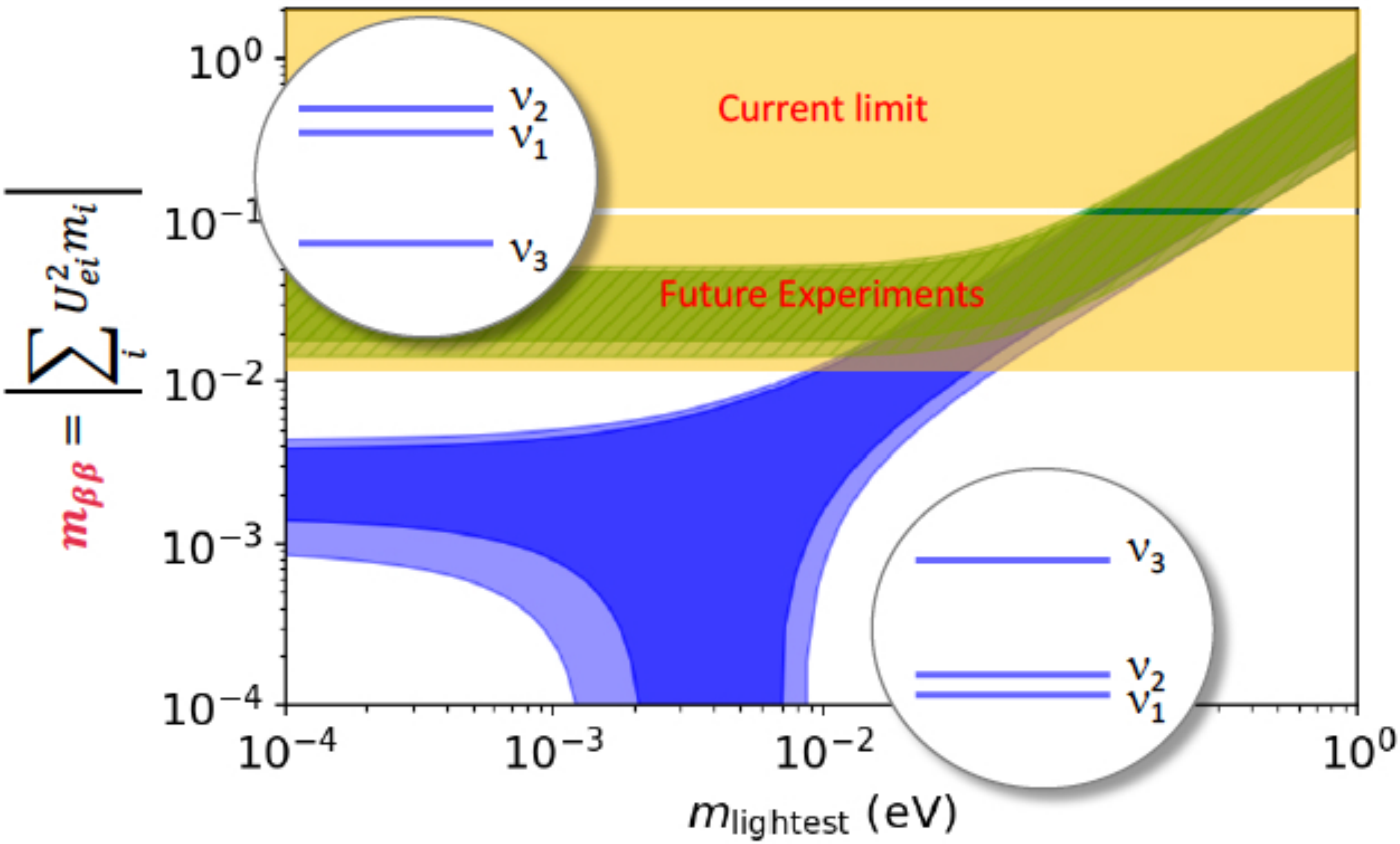
credit: M. Dolinski, INSS2017
credit: Andreas Piepke

State of 0vββ results

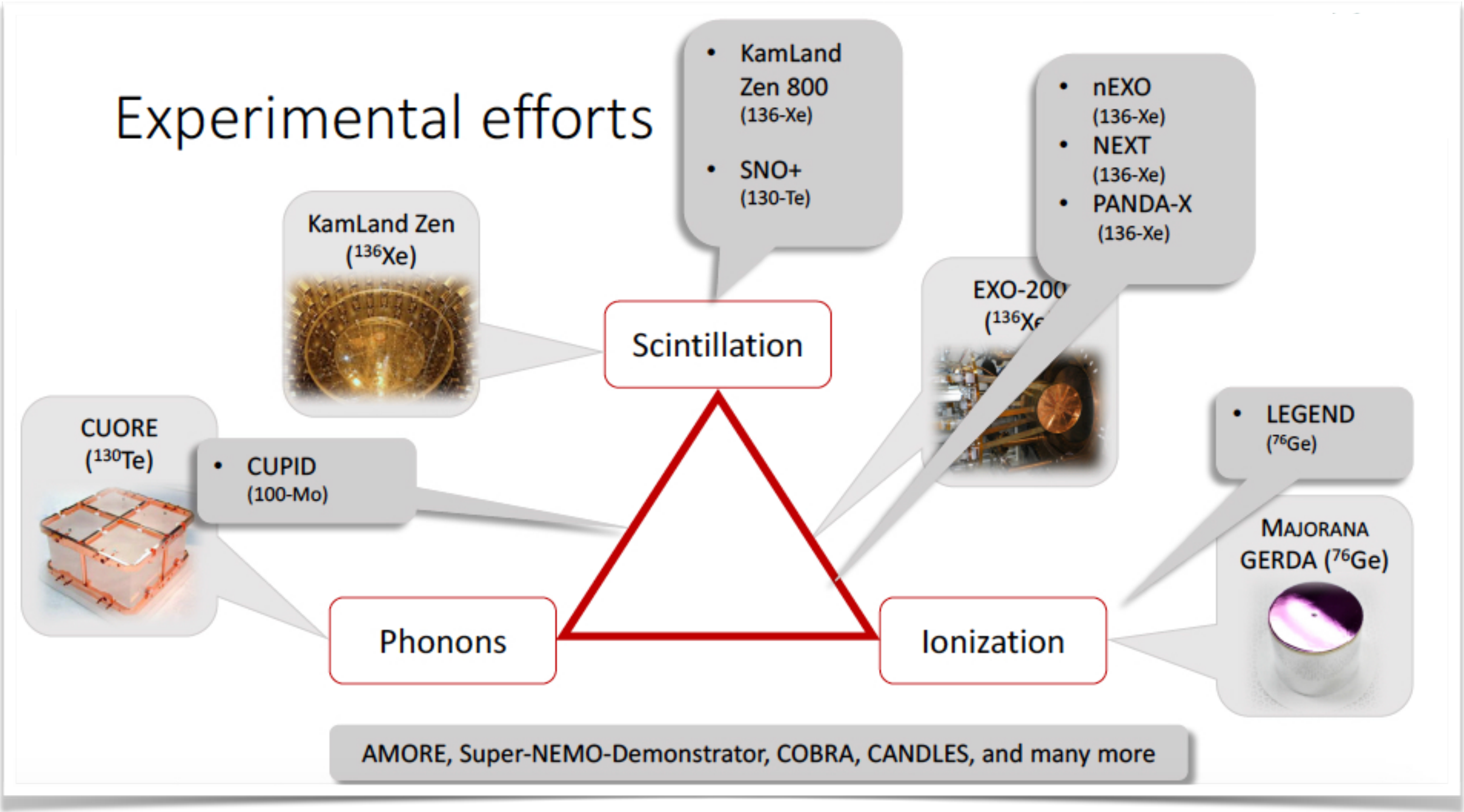


credit: S. Mertens, APS2019

And future searches for 0v$\beta\beta$



credit: S. Mertens, APS2019

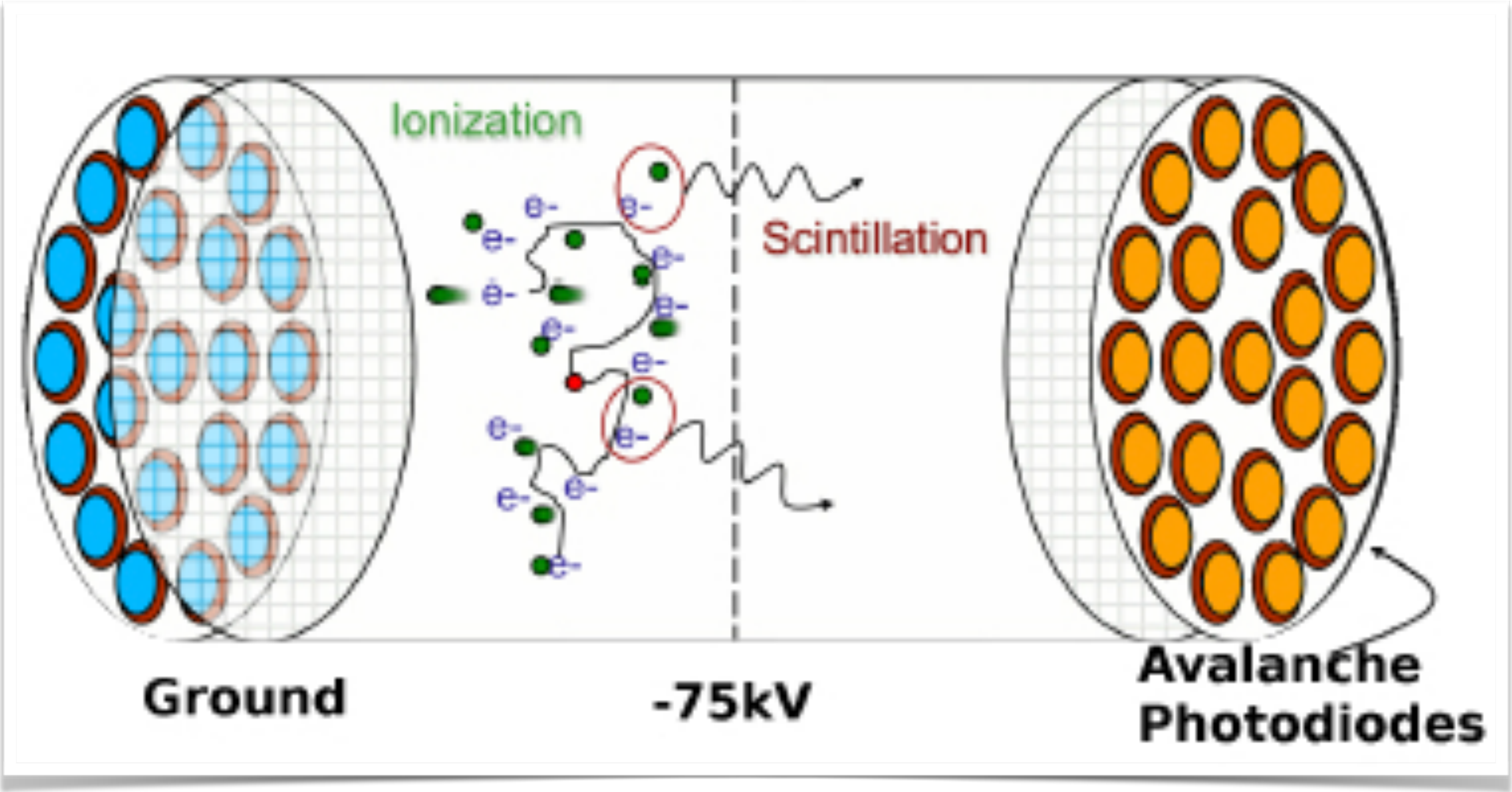


credit: S. Mertens, APS2019

Extremely challenging experiments

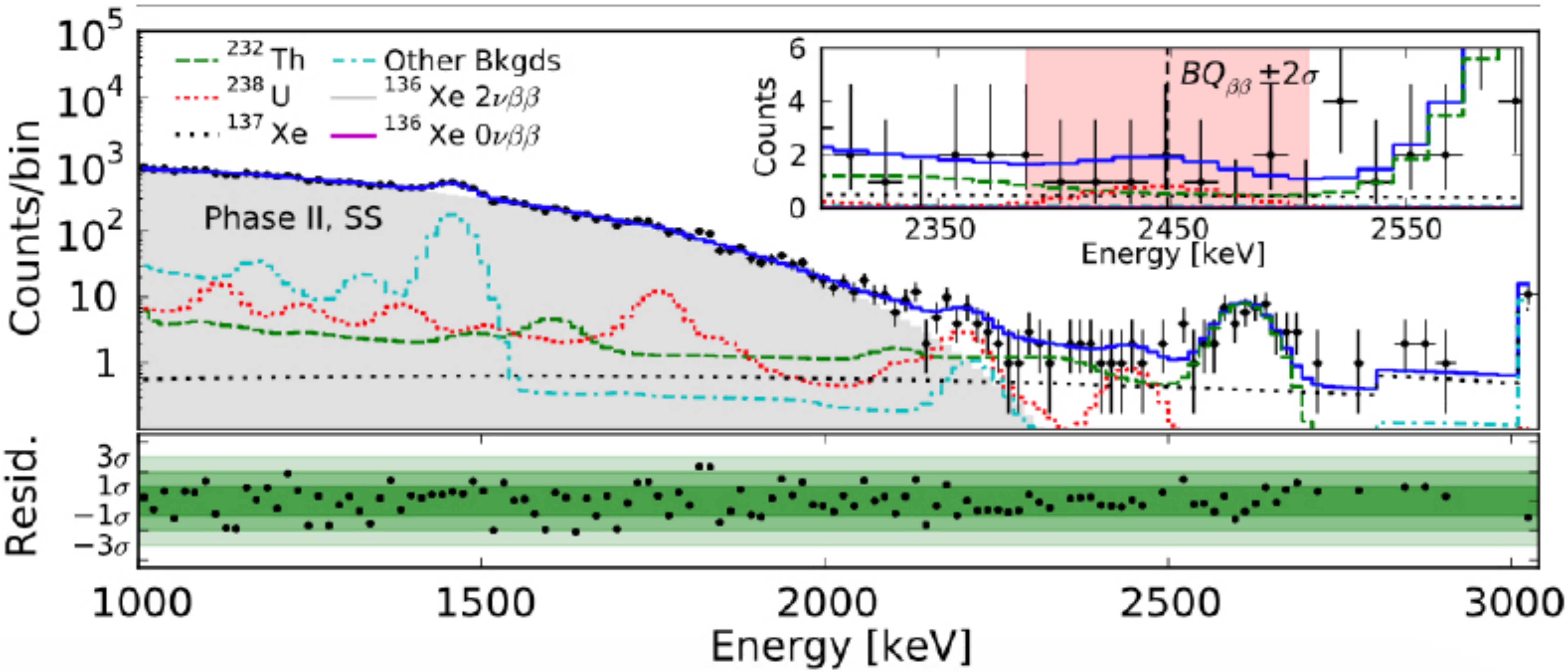
Radiopurity Noise Backgrounds

EXO experiment - principle



credit: S. Mertens, APS2019

EXO experiment - results



$T_{1/2} > 3.7 \times 10^{25}$ y (90% CL - sensitivity)

$T_{1/2} > 1.8 \times 10^{25}$ y (90% CL - data)

$m_{\beta\beta} < 147 – 398$ meV*

Phys. Rev. Lett. 120 (2018) 072701

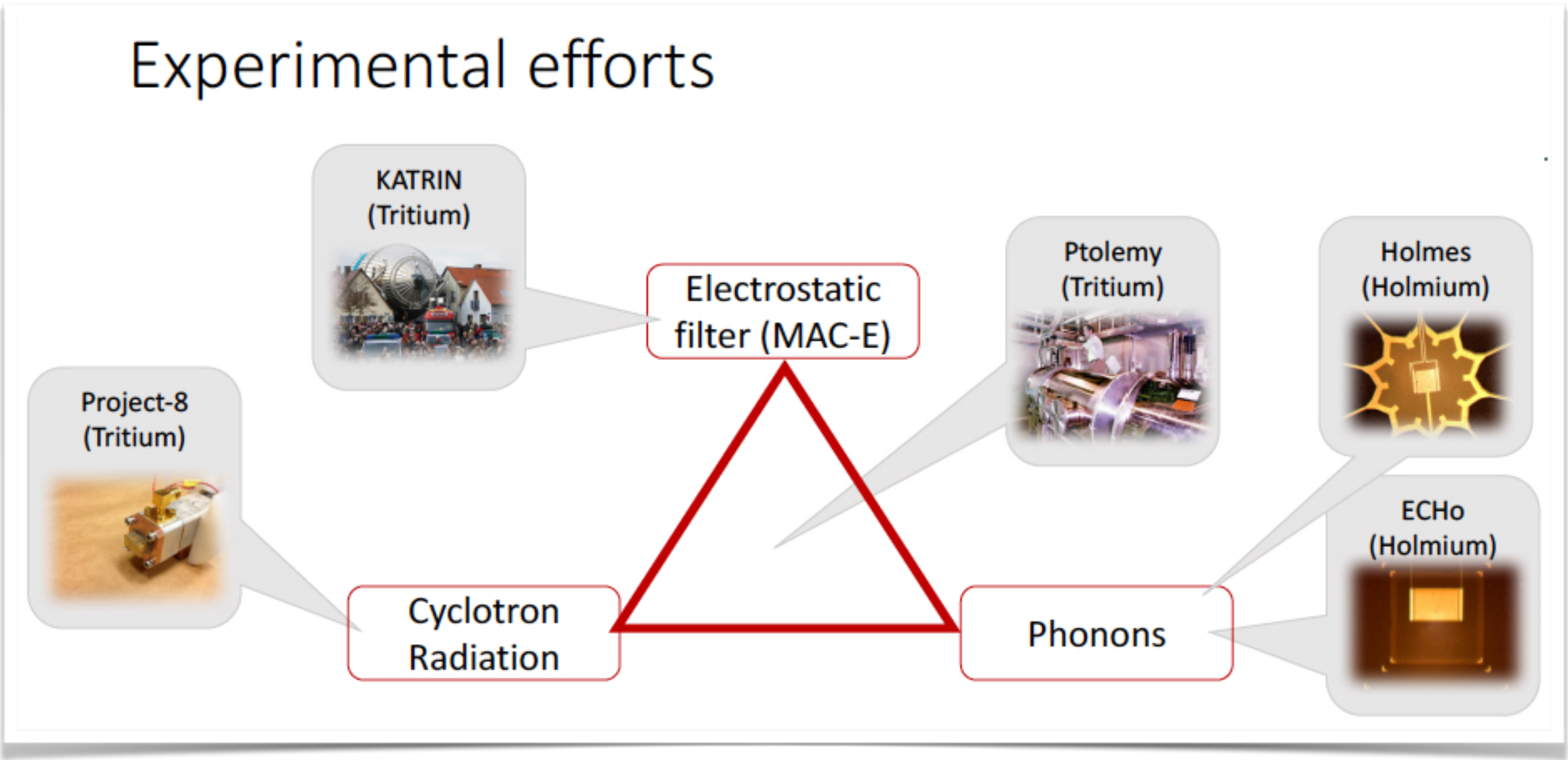
Limits also set by many other experiments on different target materials - no observation yet

How do we measure neutrino mass?

www.istockphoto.com

Constraints from:

- Cosmology
- Searches for neutrino-less double beta decay (rare process)
- Kinematics of beta decay "direct mass"



credit: S. Mertens, APS2019

All ongoing experiments

KATRIN experiment

Karlsruhe Tritium Neutrino Experiment

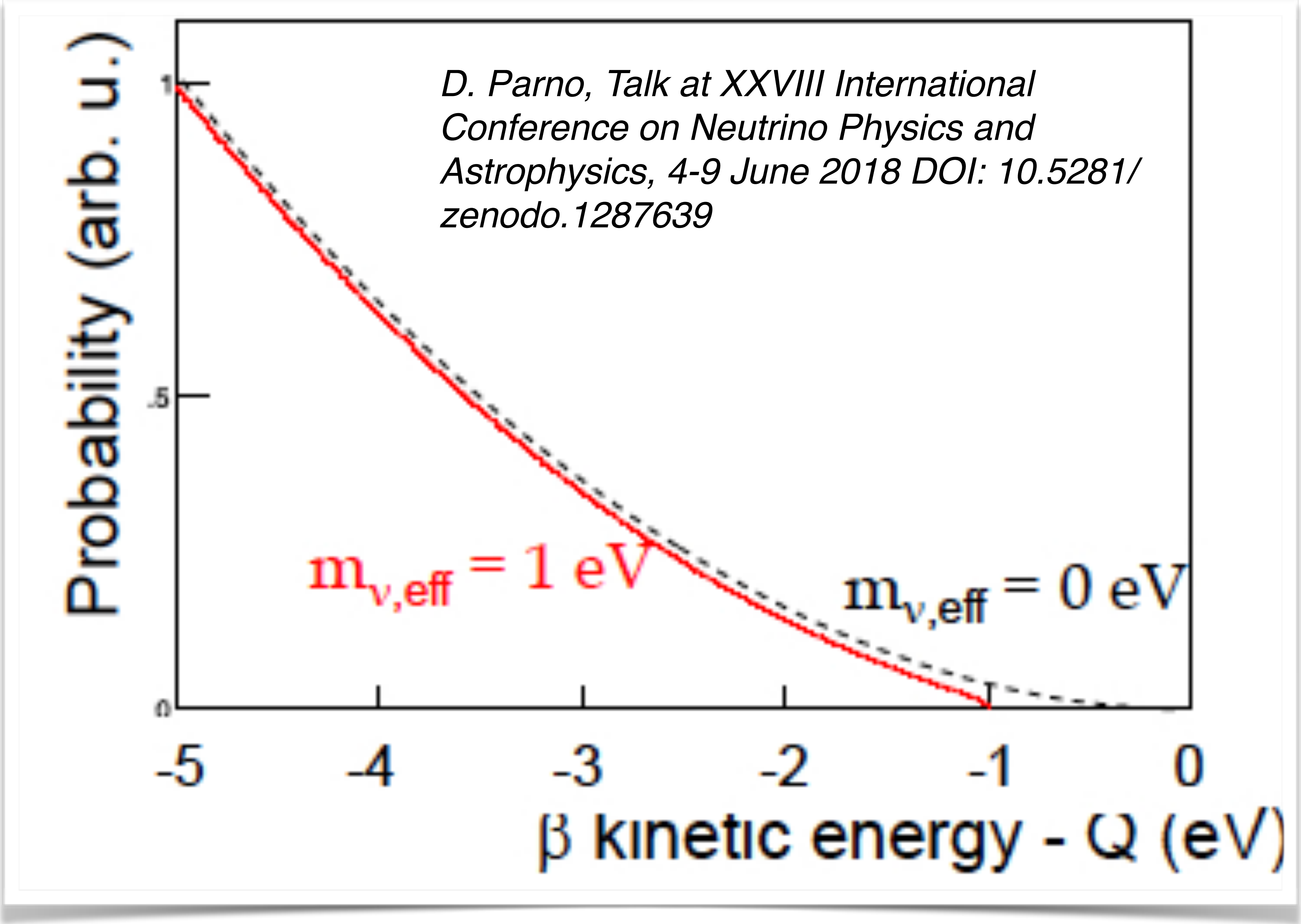
www.katrin.kit.edu

phys.org

Tritum source decays…

electrons are channeled to a **high resolution spectrometer**

KATRIN experiment

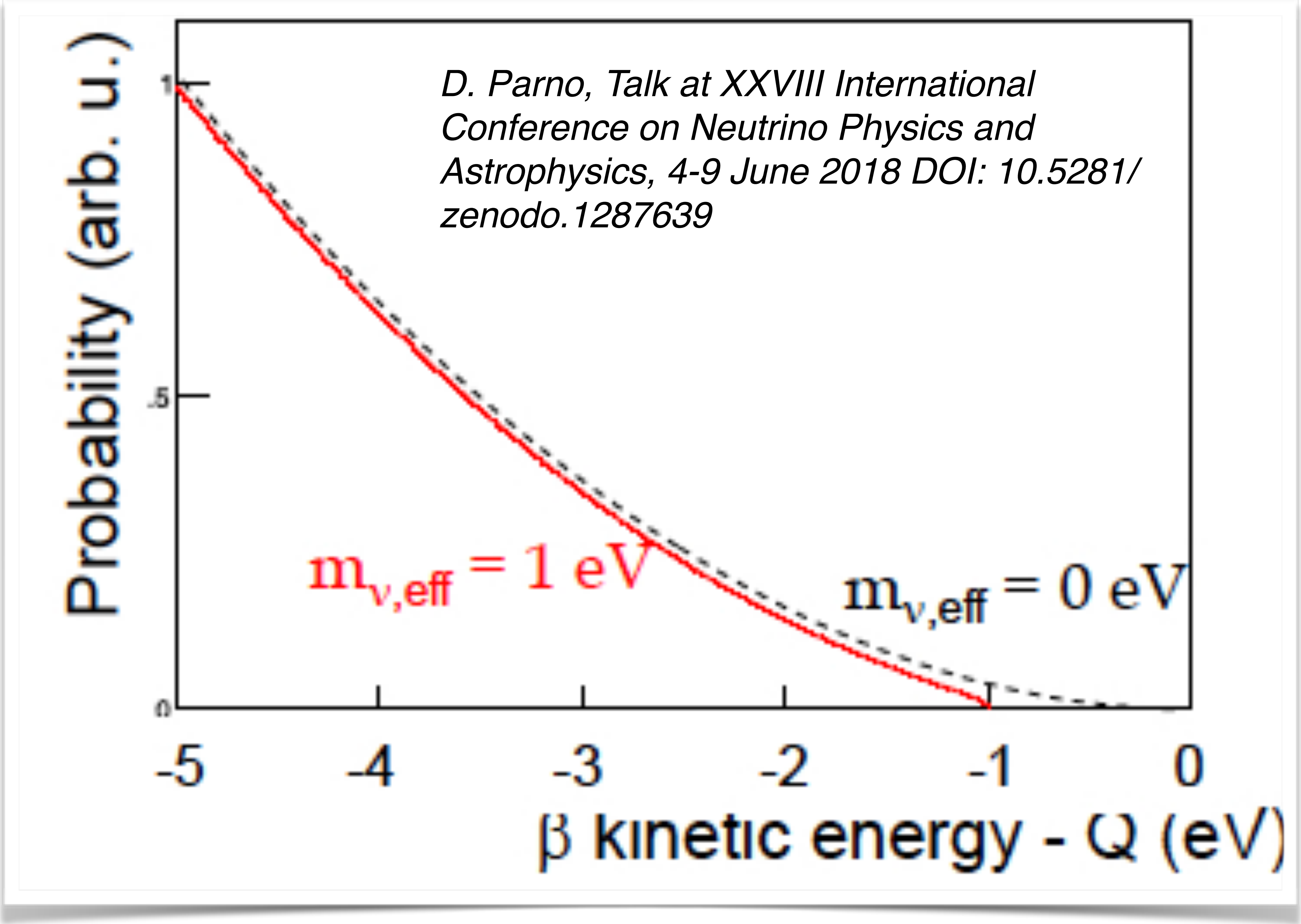


Tritum source decays…

electrons are channeled to a **high resolution spectrometer**

… endpoint energy is measured

KATRIN experiment



Tritum source decays…

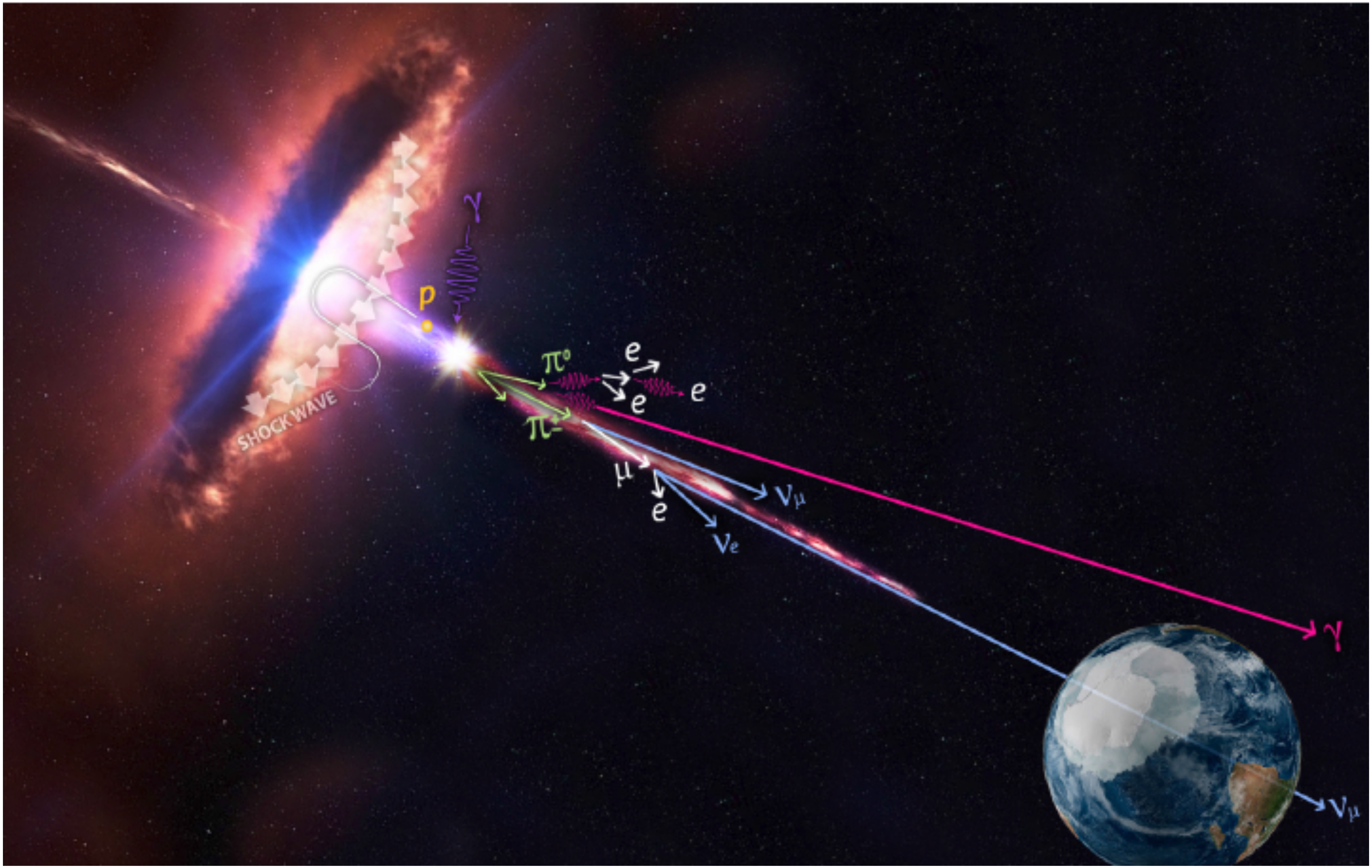
electrons are channeled to a **high resolution spectrometer**

… endpoint energy is measured

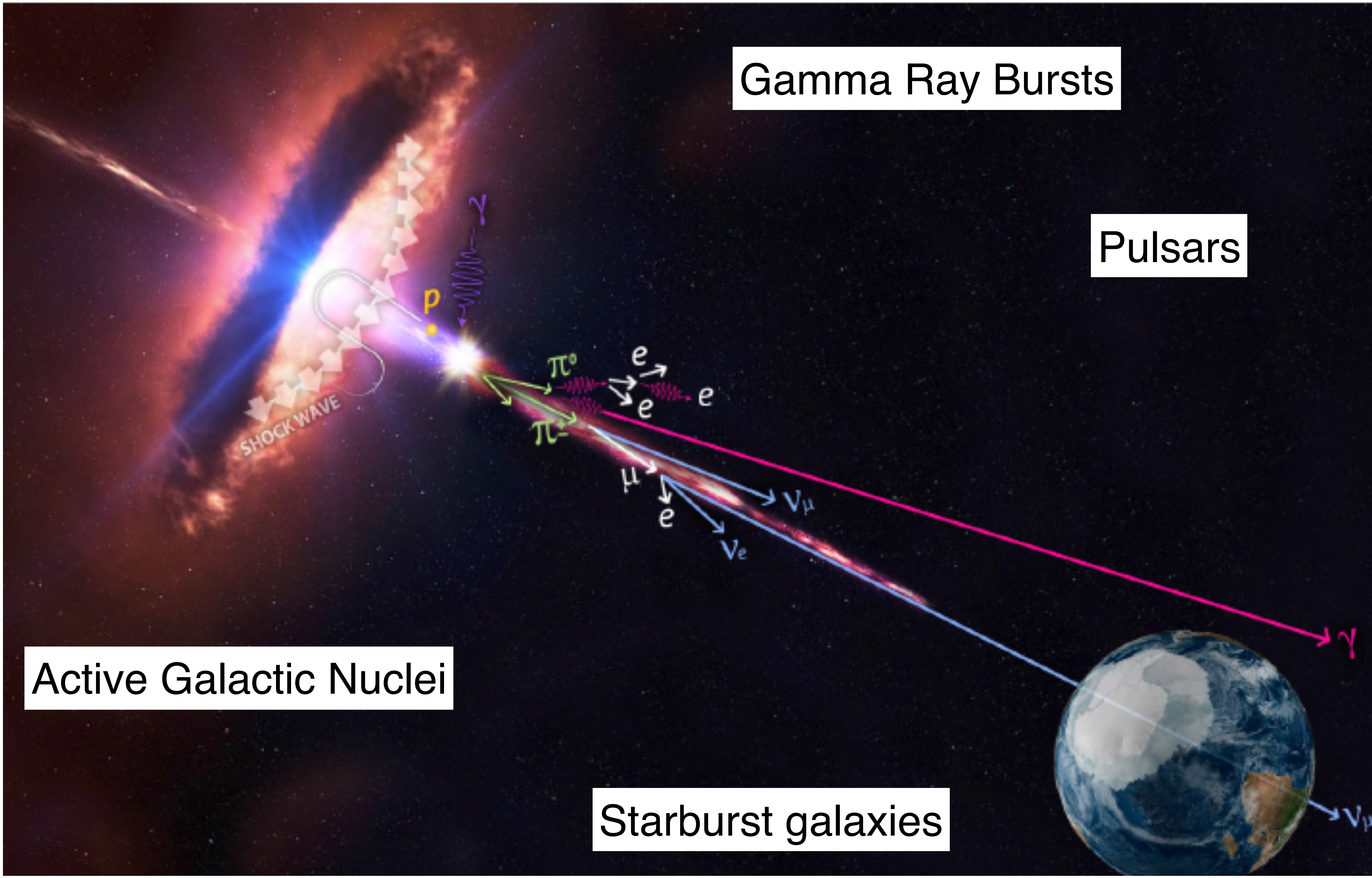
Experiments can also search for keV scale steriles

Outline

Neutrinos as probes: **neutrino astrophysics**, coherent neutrino scattering



D. Grant, TeVPA 2018



Gamma Ray Bursts
Pulsars
Active Galactic Nuclei
Starburst galaxies
SHOCK WAVE
γ
p
π⁰
π±
e
e
e
μ
e
ν_μ
ν_e
γ
ν_μ

Astrophysics with neutrinos

Neutrinos are:

- ☑ Undeflected by magnetic fields
- ☑ Not absorbed or rescattered by dust

Astrophysics with neutrinos

Neutrinos are:

- ☑ Undeflected by magnetic fields
- ☑ Not absorbed or rescattered by dust

Big questions

- Where do the highest energy cosmic rays come from?
- Do we understand various astrophysical sources and signals?

Principles of high-energy ν detection

- Water Cherenkov
  - ν-induced charged particles emit a detectable pattern of Cherenkov radiation
  - backgrounds from cosmic ray μ and atmospheric ν reduced via event timing, direction, energy and vetoing techniques
- Radio (Askaryan)
  - radio λ's are comparable to size of ν-induced shower of charged particles; resulting coherent radiation can be very powerful
- Penetrating or upward-going air shower
  - air Cherenkov (e.g. Auger)
- Acoustic
  - localized ν-induced heating: sharp sonic pulse
  - tests in polar icecap yielded too small λ_{att}
    - water could be better (the Dead Sea?)

D. Grant, TeVPA 2018

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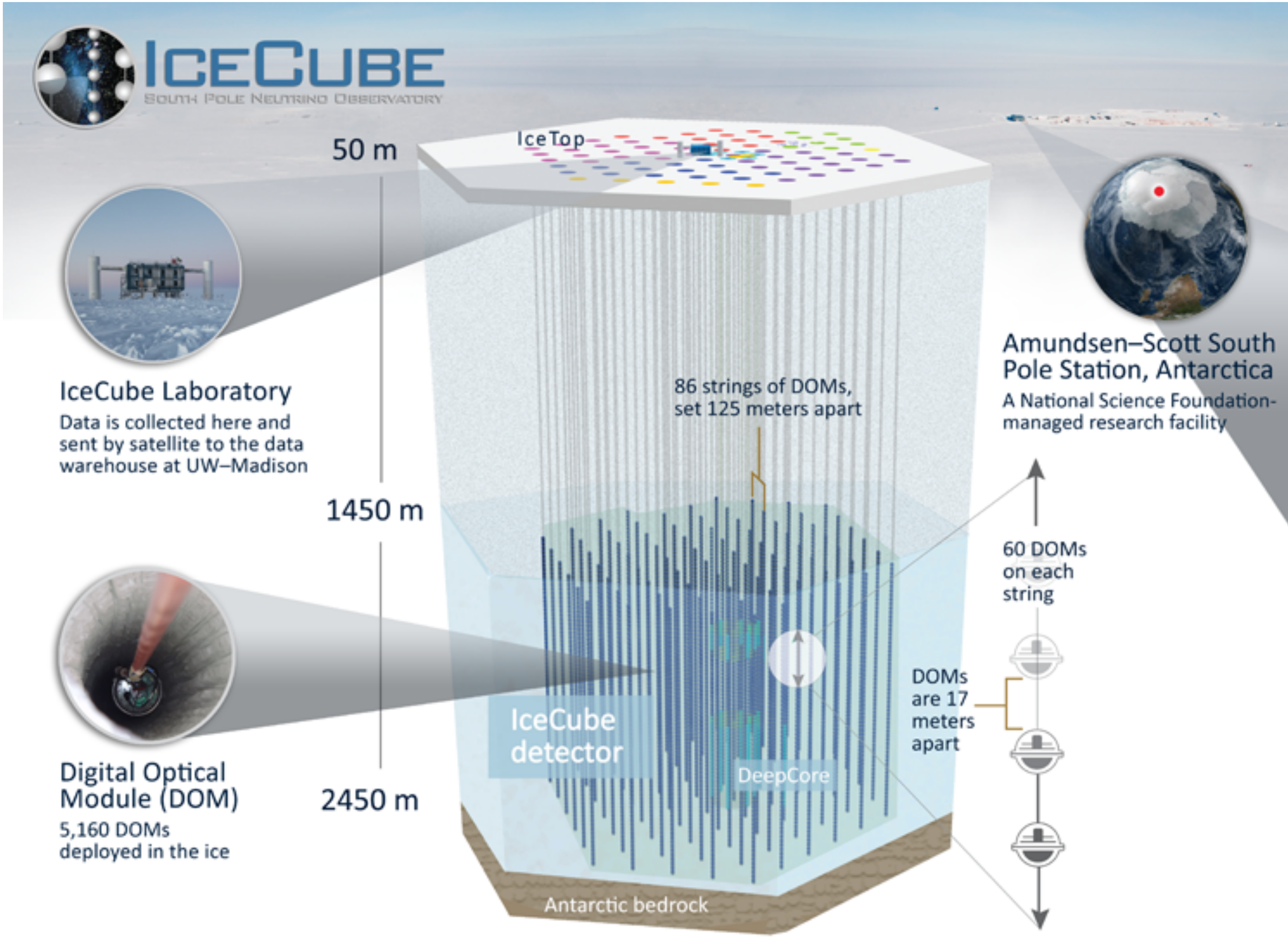
ANTARES

antares.in2p3.fr

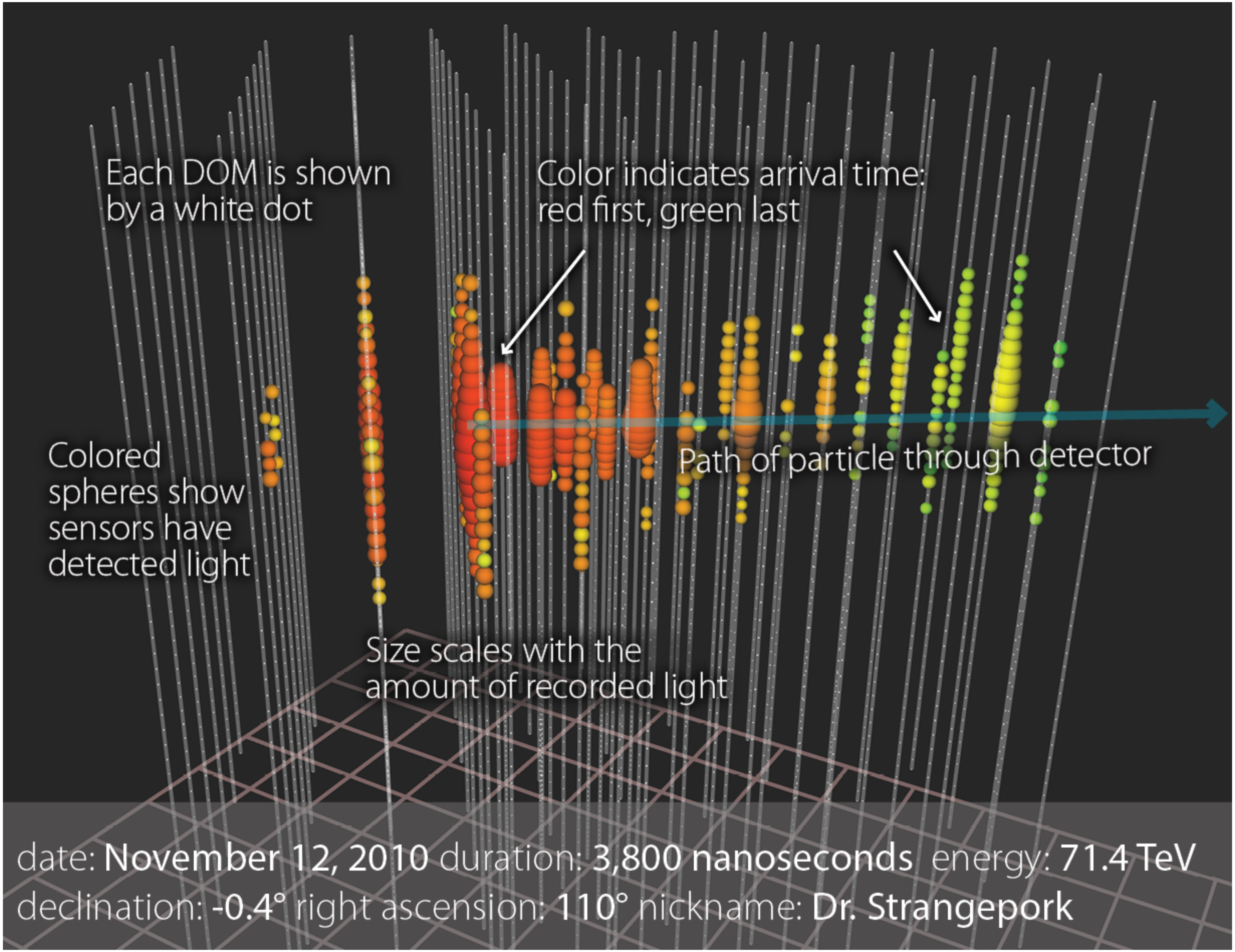
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

https://icecube.wisc.edu/

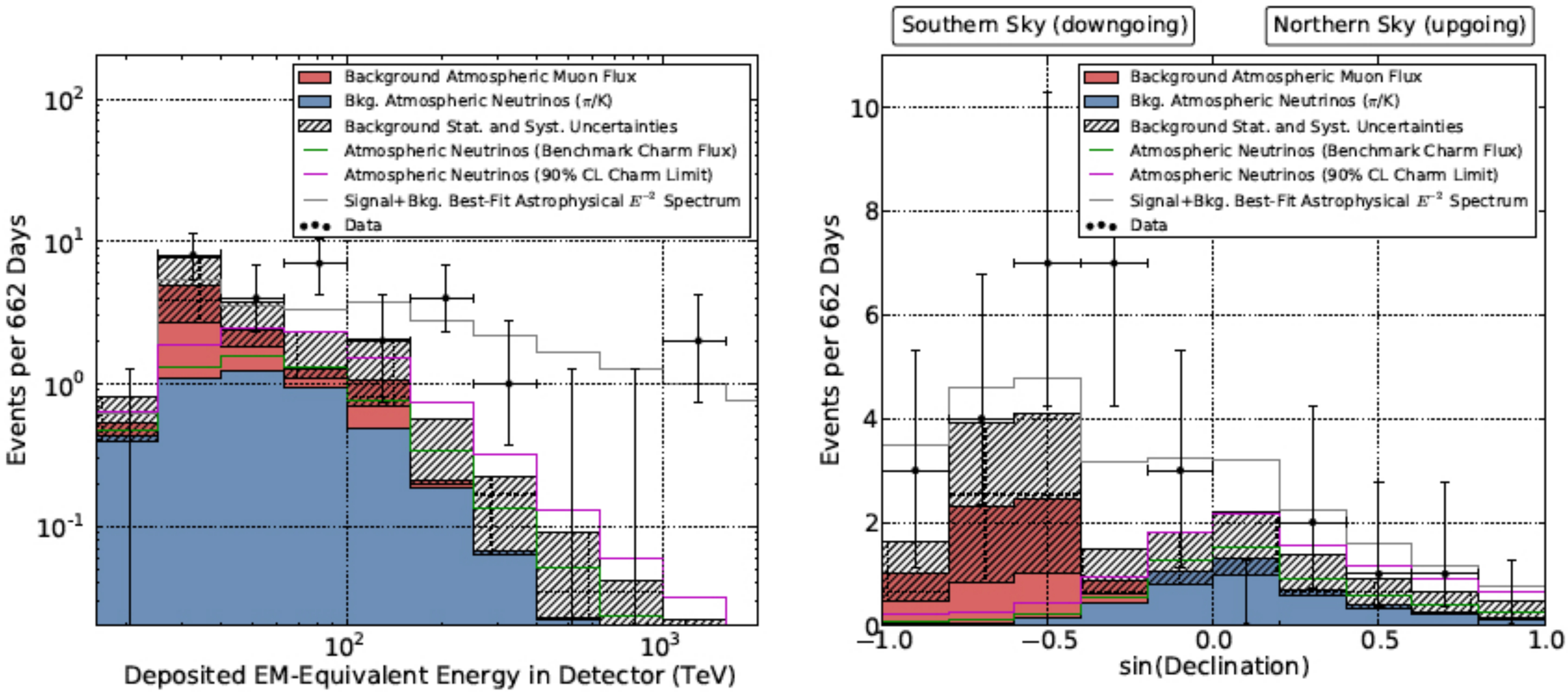
Example: IceCube



Example: IceCube



IceCube diffuse astrophysical neutrinos



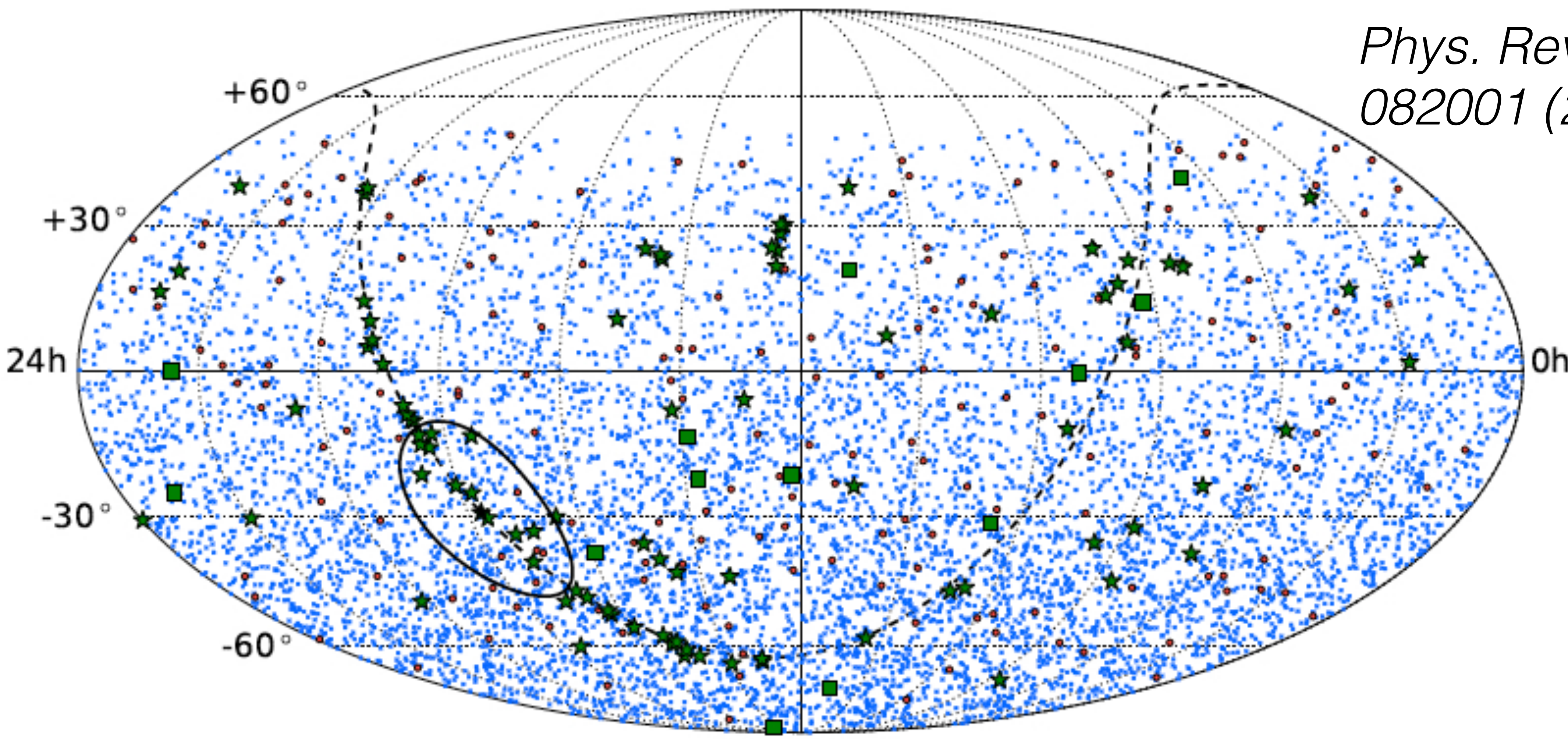
Science 342 (2013) 1242856

Phys.Rev.Lett. 113 (2014) 101101

Excess of highest energy events above background

- Era of neutrino astronomy

ANTARES point source search



Phys. Rev. D 96, 082001 (2017)

- Searched for 106 source candidates and 13 IceCube very high energy candidates; no significant excess found
- Complementary to IceCube search (northern sky vs. southern sky sensitivity)

CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Astrophys.J. 848 (2017) no.2, L12

New multimessenger era:

- Do signals correlate across time?
- Between gravitational waves/x-rays/gamma-rays/radio/neutrino/etc?

CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
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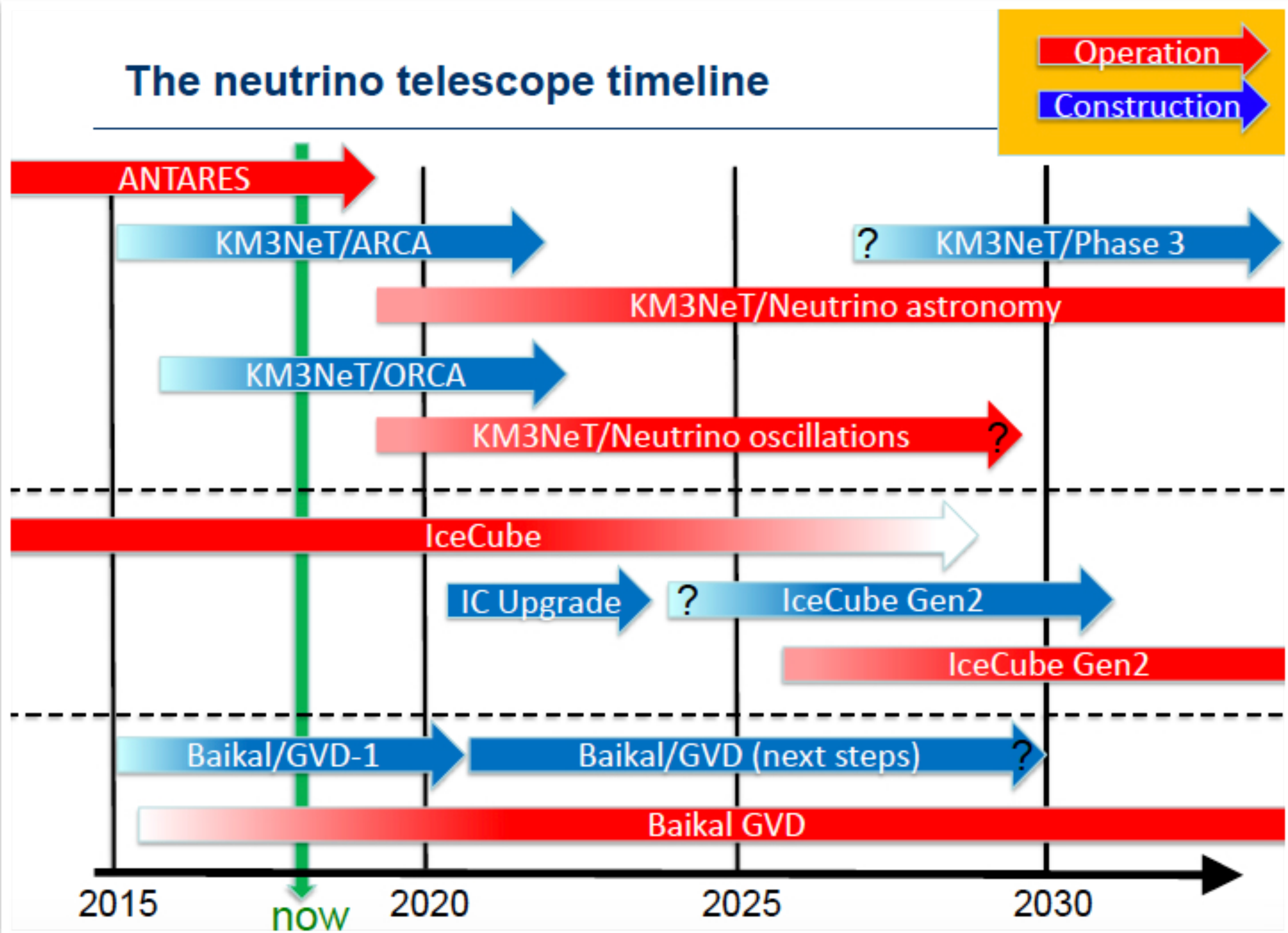
Astrophys.J. 848 (2017) no.2, L12

"No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches"

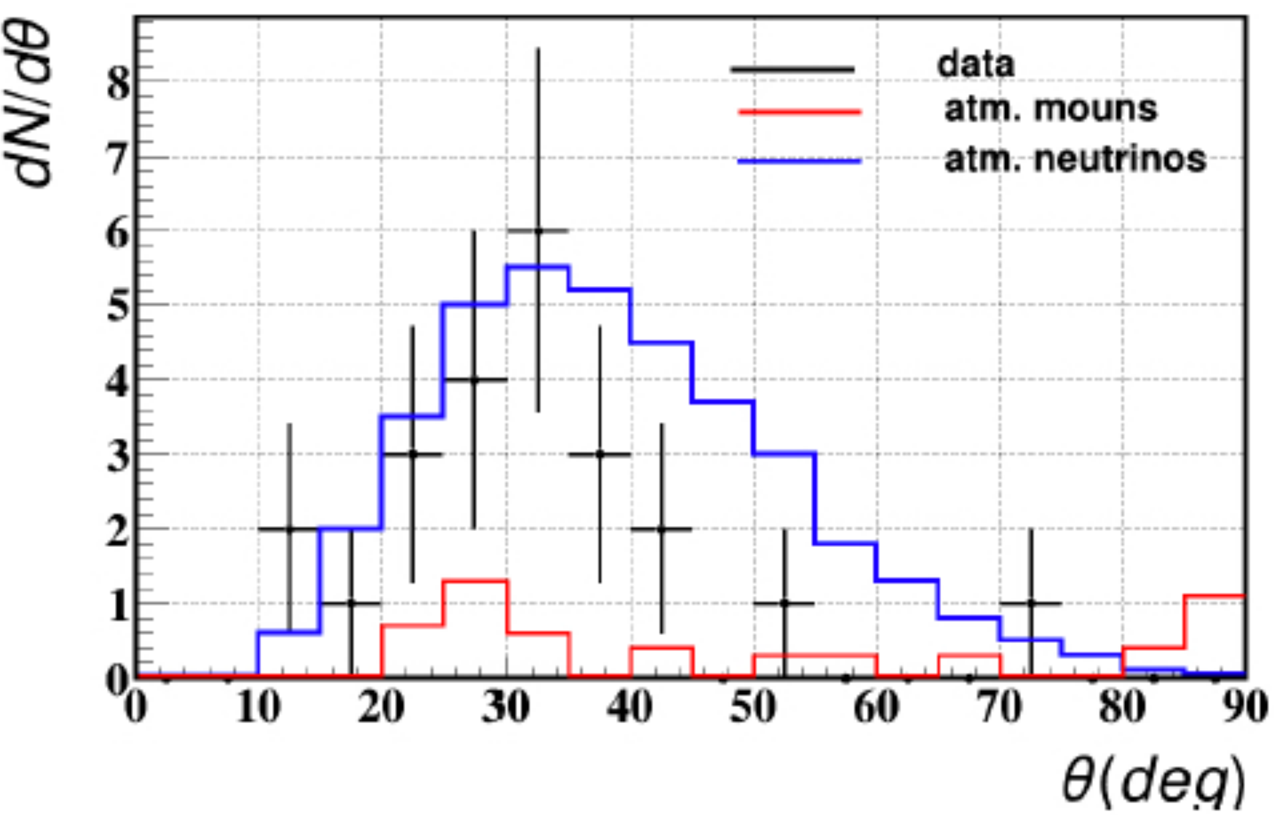
But now these searches are possible!

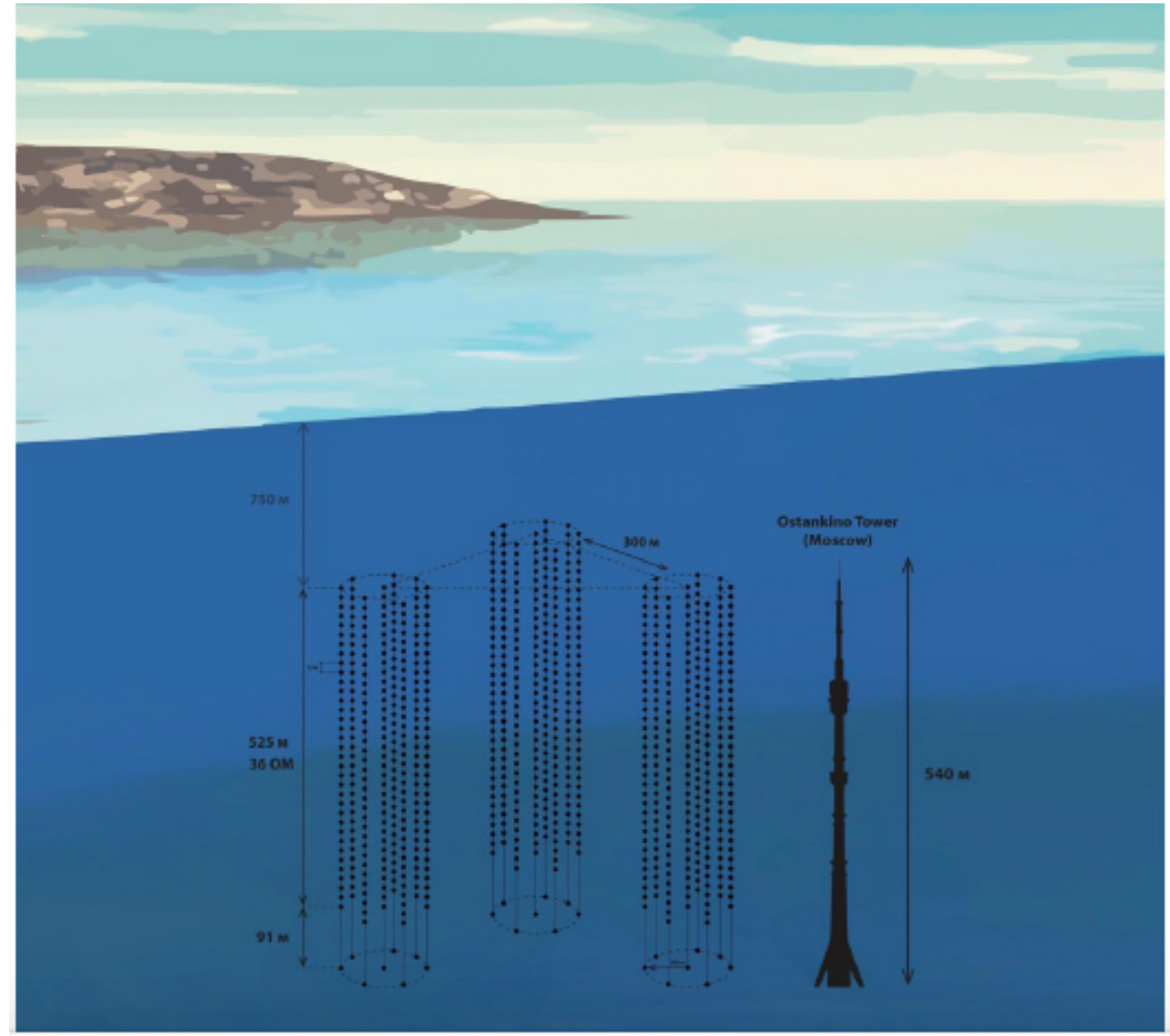


U. Katz, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: 10.5281/zenodo.1287685

Baikal GVD

https://arxiv.org/abs/1808.10353





Commissioning: 3 clusters operational; eventual goal is 27 clusters
First neutrinos observed

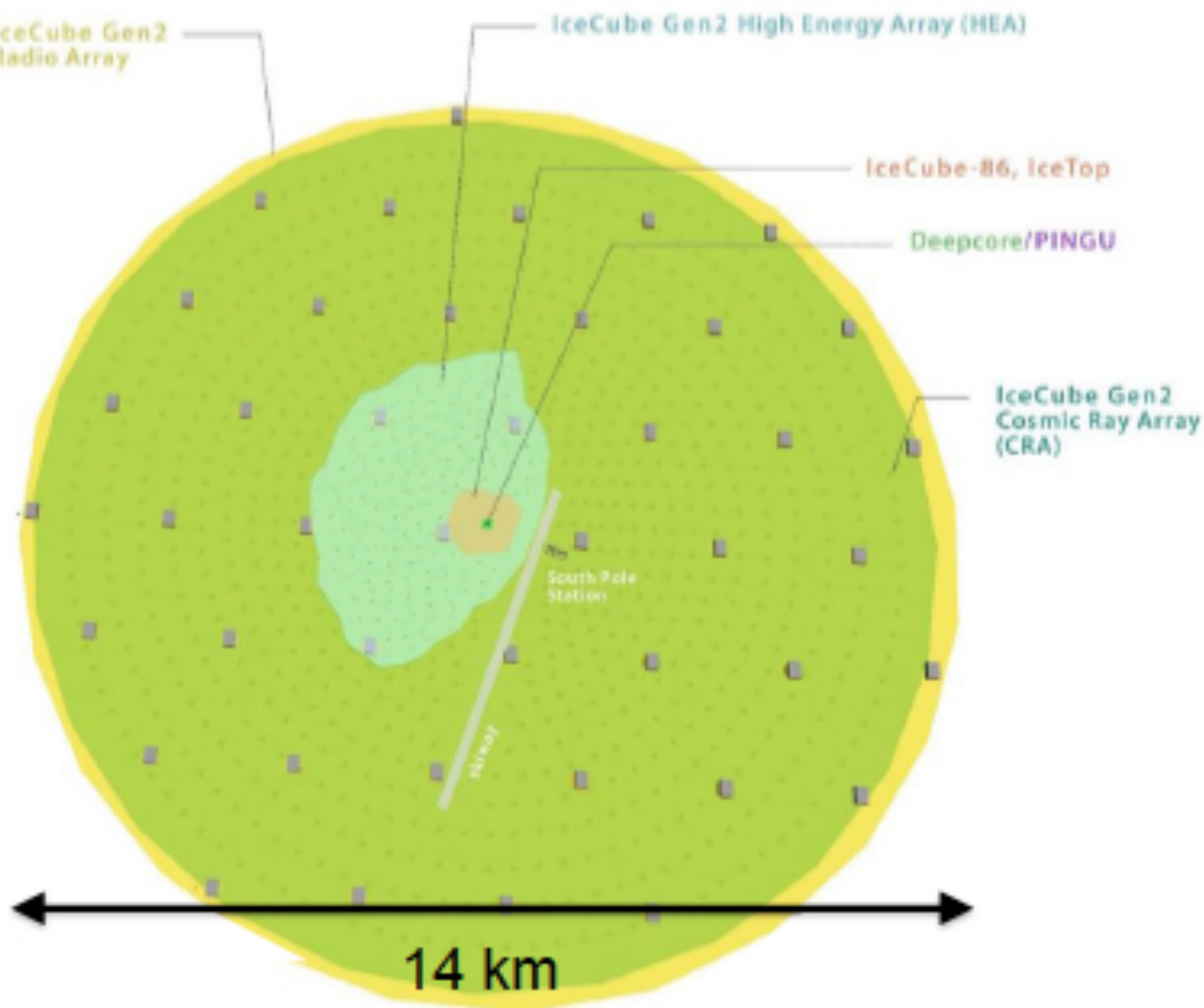
https://arxiv.org/abs/1412.5106

The IceCube Gen2 Facility

- Next-generation neutrino observatory at South Pole, with
  - High-energy deep-ice detector (High-energy array, HEA)
  - Cosmic-ray and veto surface array (CRA)
  - Radio array (RA)
  - High-density core for low-energy neutrinos (PINGU)
- Funding application expected in NSF MREFC scheme (~2020)

Deployment 2025-31

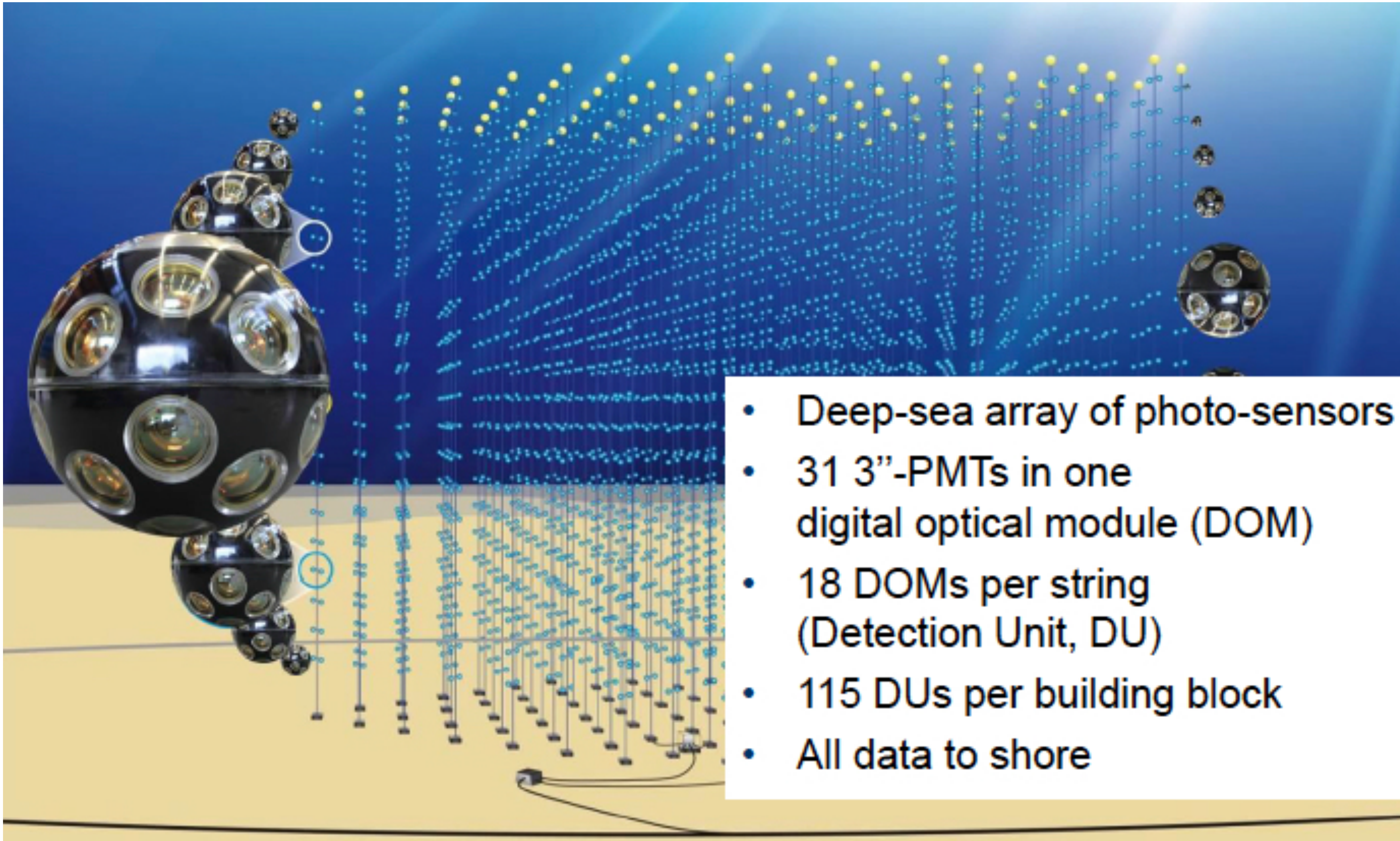
time



Near term: IceCube Upgrade; increased density in clear ice region

U. Katz, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: 10.5281/zenodo.1287685

KM3NeT 2.0



- Deep-sea array of photo-sensors
- 31 3”-PMTs in one digital optical module (DOM)
- 18 DOMs per string (Detection Unit, DU)
- 115 DUs per building block
- All data to shore

JPhyG Nuclear and Particle Physics, 43 (8), 084001 - letter of intent

Supernova neutrinos

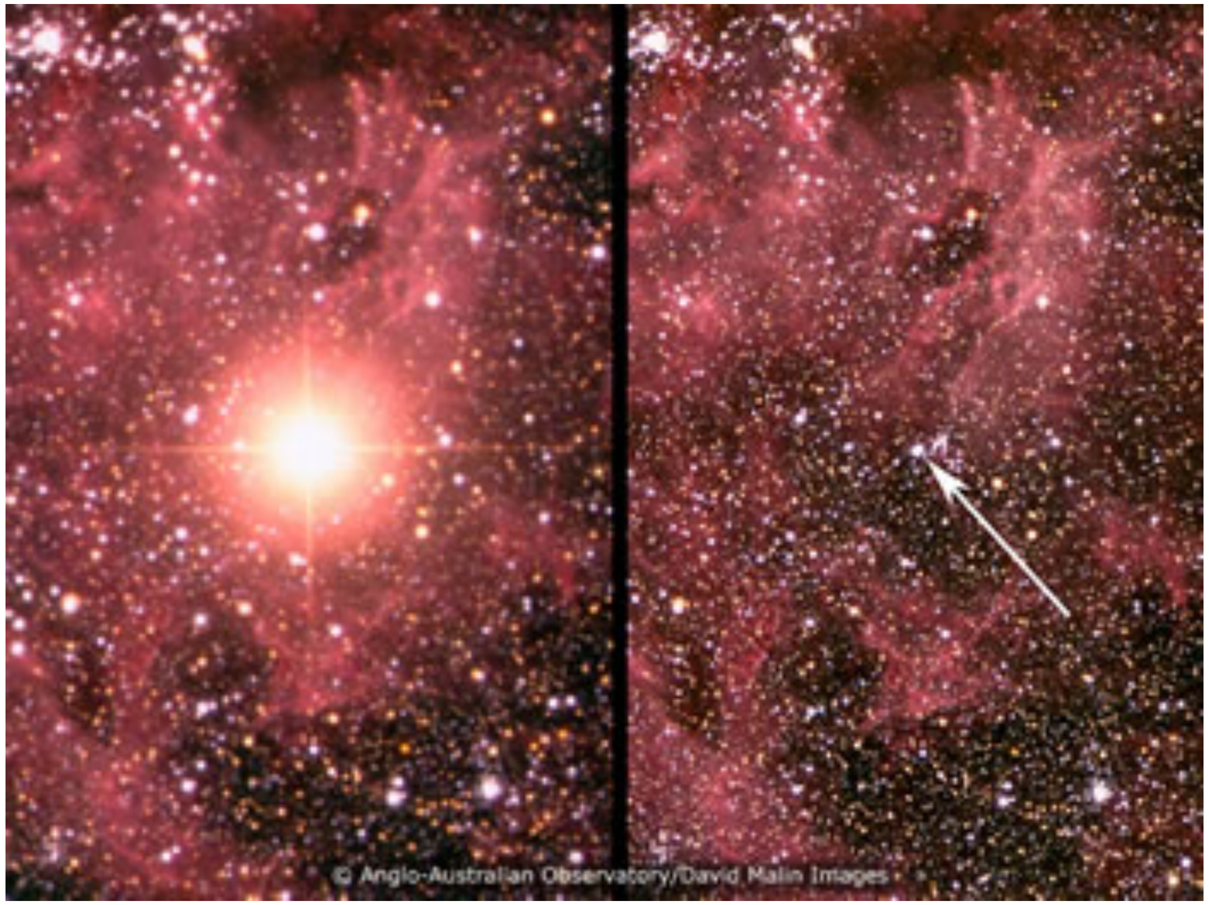
- 10^{58} neutrinos are emitted
- 99% of the energy is carried by neutrinos
- Neutrinos arrive early!
- **Neutrinos are a key probe of how core collapse supernovas occur**

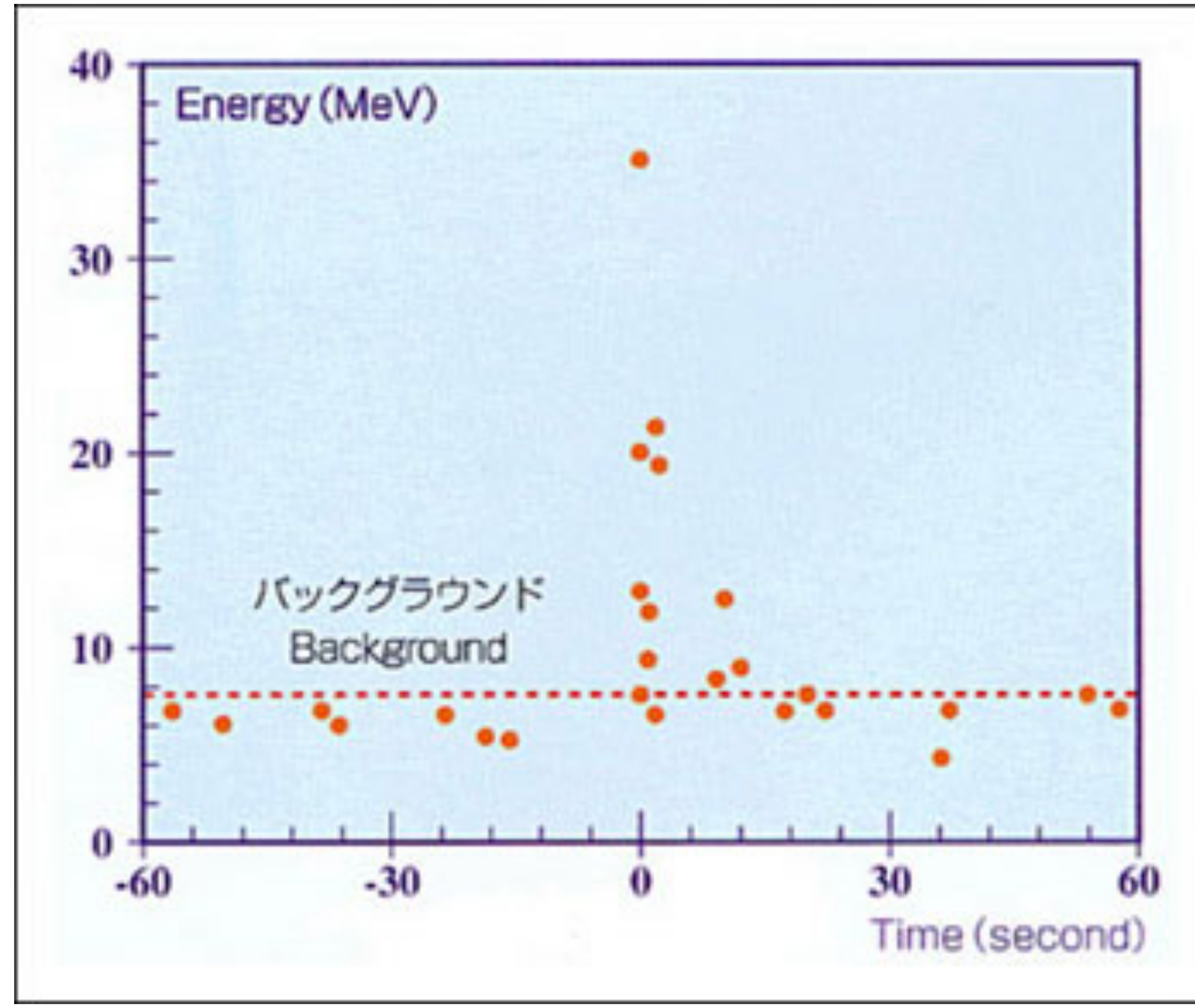
flavor time energy

Kepler's Supernova
wikipedia

Ann.Rev.Nucl.Part.Sci. 62 (2012) 81-103
Astropart.Phys. 31 (2009) 163-176

Supernova 1987A



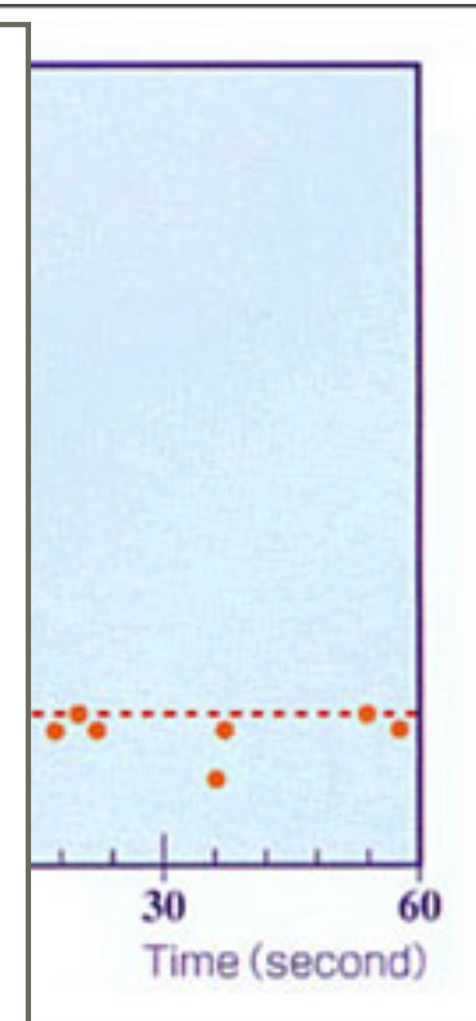


Kamiokande detected 11 events; IMB and Bakusan detectors also observed events

Timing relative to light signature and burst structure were very useful

http://www-sk.icrr.u-tokyo.ac.jp/sk/sk/supernova-e.html

Supernova 1987A



Development of SNEWS (Supernova Early Warning System)

Notify astronomers, coordinate/unify information collection

https://snews.bnl.gov/

Kamiokande de
IMB and Bakus
observe

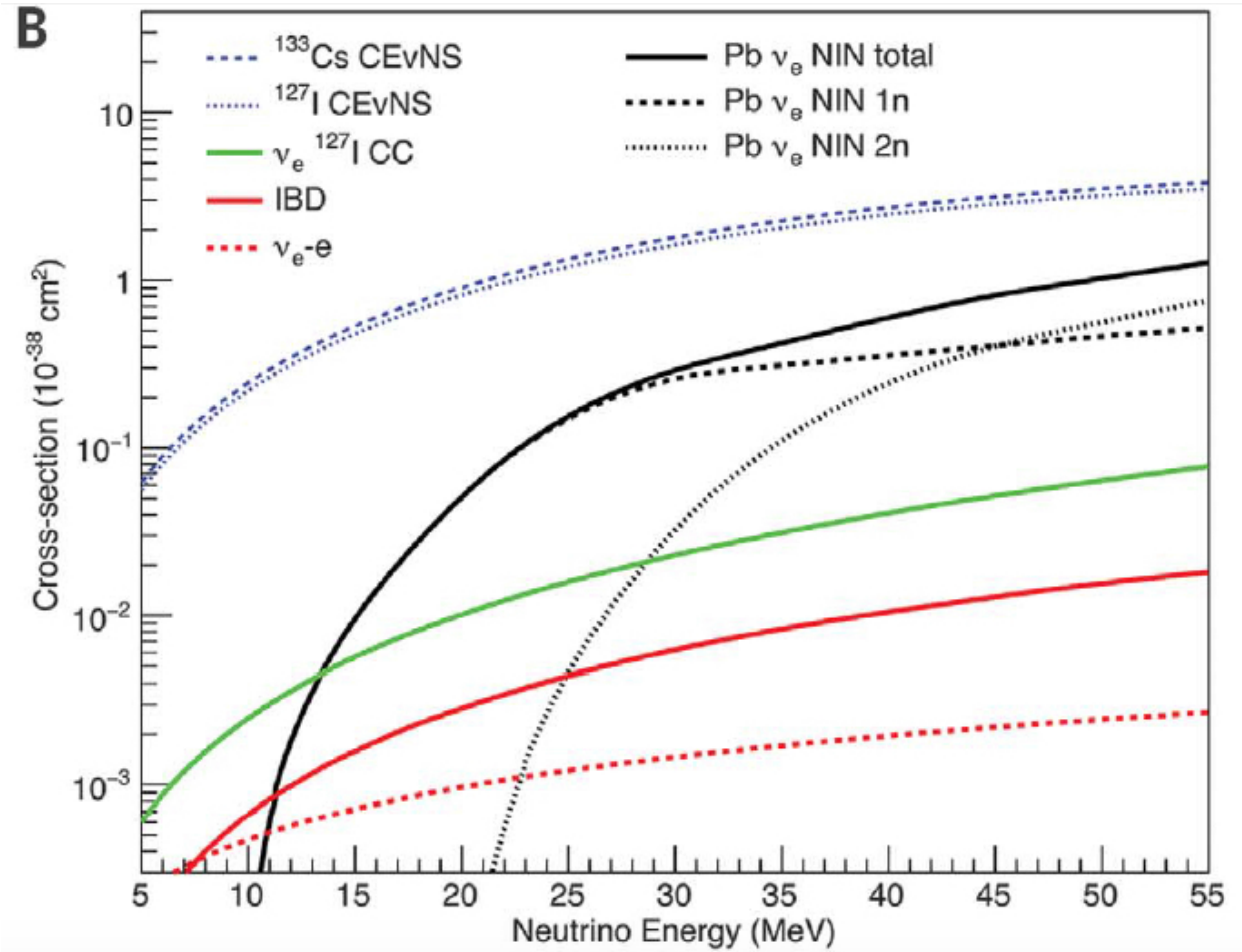
nt signature
were very

http://

Outline

Neutrinos as probes: neutrino astrophysics, **coherent neutrino scattering**

What is CEvNS?



Science 357 (2017) no.6356, 1123-1126

Coherent elastic scattering of a neutrino on a nucleus

- But, small nuclear recoil (~keV is difficult to detect)

Definitions of CEvNS

\begin{aside}

Literature has CNS, CNNS, CENNS, ...

- I prefer including "E" for "elastic"... otherwise it gets frequently confused with coherent pion production at ~GeV neutrino energies
- I'm told "NN" means "nucleon-nucleon" to nuclear types
- CEvNS is a possibility but those internal Greek letters are annoying

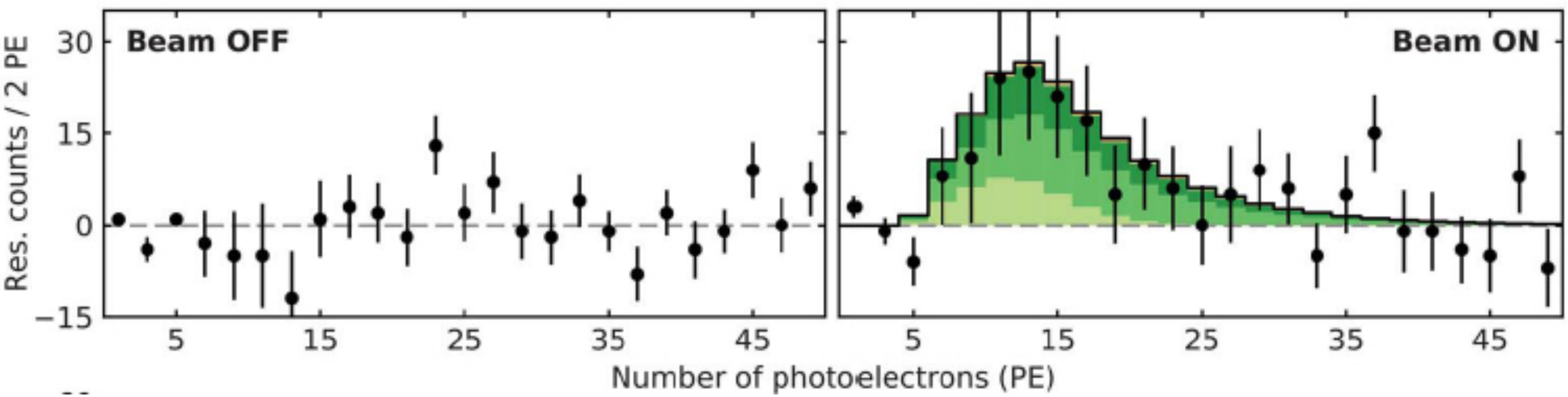
➔**CEvNS**, pronounced "sevens"...

spread the meme!

K. Scholberg **\end{aside}**

Observation of CEvNS by COHERENT

Science 357 (2017) no.6356, 1123-1126

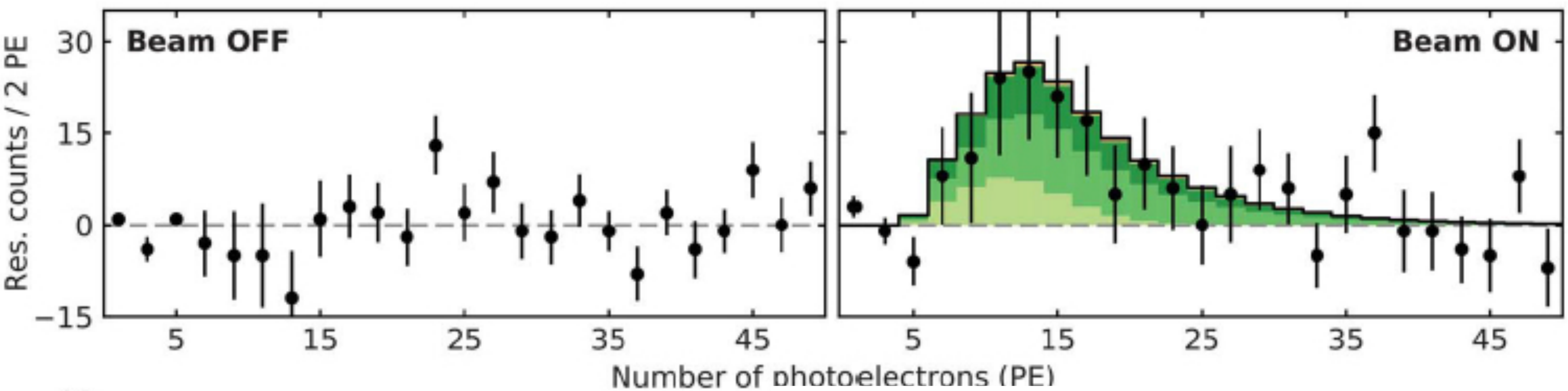


Pion decay at rest beam produced from intense Spallation Neutron Source

- Low threshold (6.5keV) CsI crystal

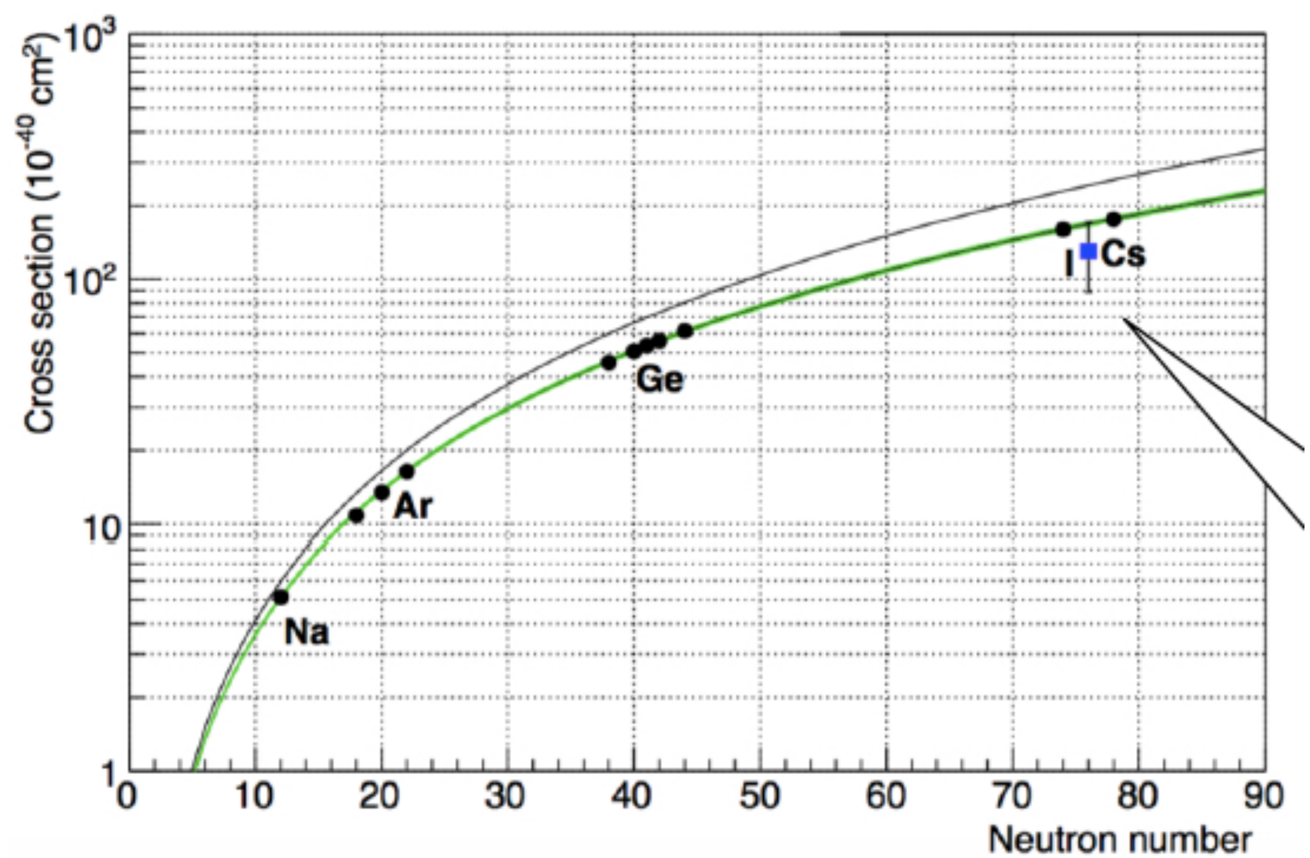
Observation of CEvNS by COHERENT

Science 357 (2017) no.6356, 1123-1126



Pion decay at rest beam produced from intense Spallation Neutron Source

- Low threshold (6.5keV) CsI crystal
- Additional detectors located along "neutrino alley" to measure N dependance



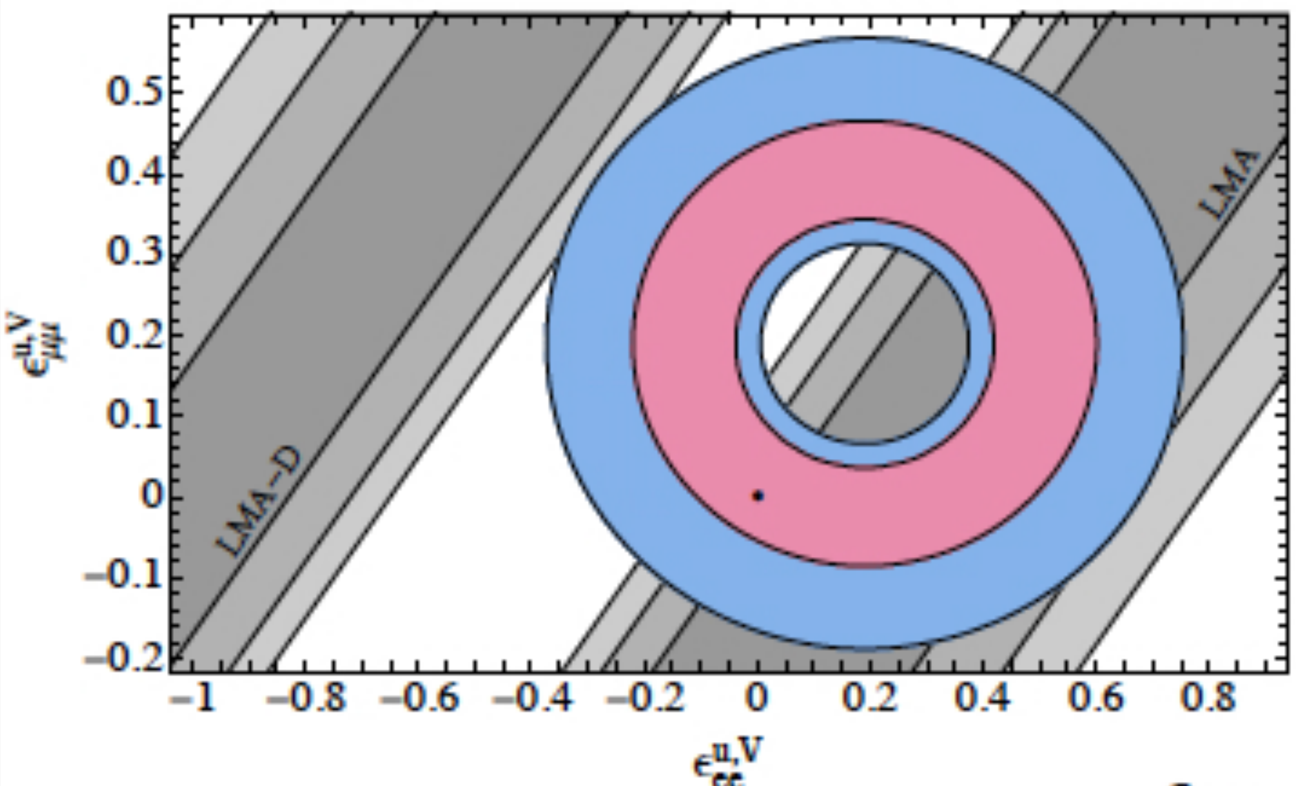
Worldwide program of CEvNS

Experiment	Technology	Location
CONNIE	Si CCDs	Brazil
CONUS	HPGe	Germany
MINER	Ge/Si cryogenic	USA
Nu-Cleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe
νGEN	Ge PPC	Russia
RED-100	LXe dual phase	Russia
RIcochet	Ge, Zn bolometers	France
TEXONO	p-PCGe	Taiwan

New physics probe: CEvNS

Supernova physics - Could play a role in dynamics of core-collapse SNe [1] and offers potential way to *observe* SNe neutrinos [2]

Weak mixing angle - Unique probe of Q_W^2 at a unique Q in a region sensitive to dark Z boson models [3]



Non-standard neutrino interactions - explicit dependence on non-universal and flavor-changing neutral currents [4]

Nuclear form factor - Provides a way to measure neutron distributions using neutrino scattering [5], possibly refining nuclear structure models and informing understanding of neutron star EoS [6]

Fundamental properties of neutrinos - sensitivity to effective neutrino charge radius and magnetic moment [7] *and* lift degeneracy of "dark side" solution to θ_{12} that would complicate mass-order determination from oscillation experiments [8]

Neutral-current sterile neutrino search - all-flavor disappearance experiment [9]

*See poster by Sinev & **Scholberg** on NSI with COHERENT*

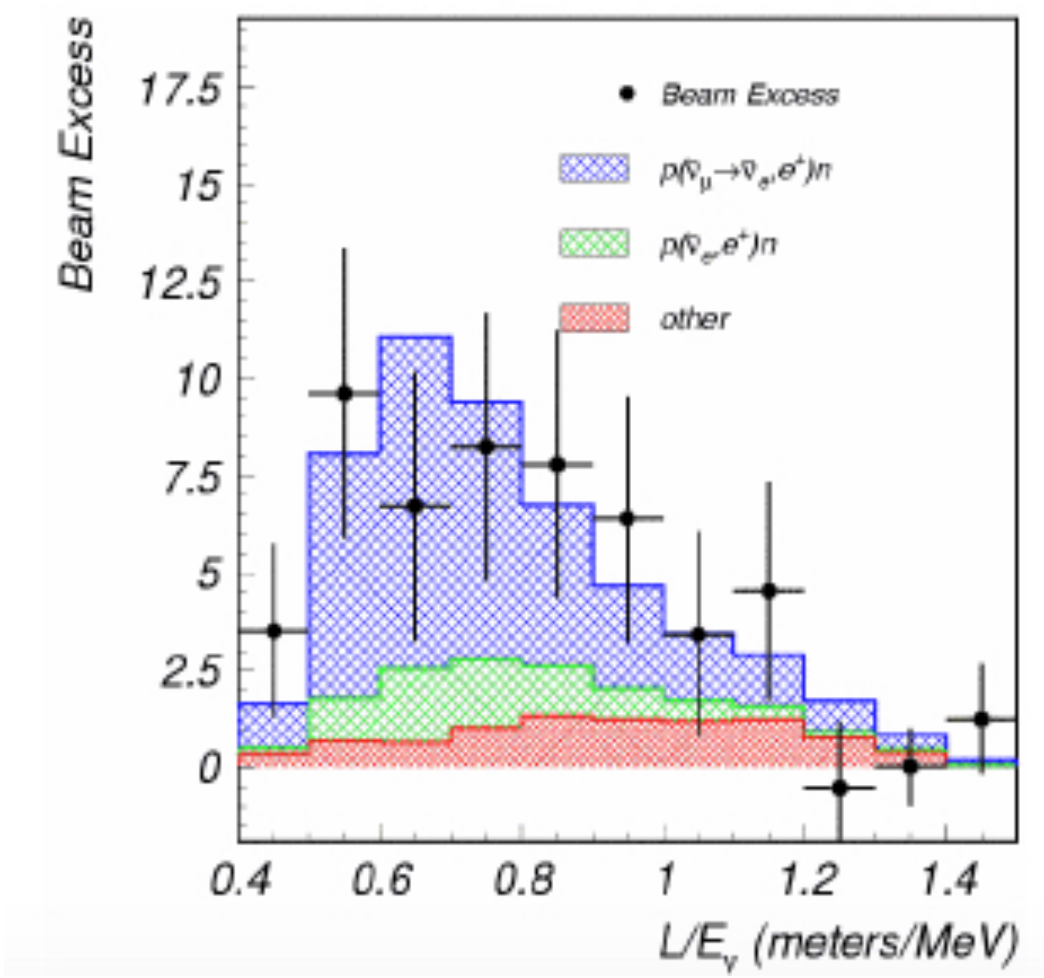
[1] D.Z. Freedman, Phys. Rev. D 9 (1974)
[2] C. Horowitz *et al.*, Phys. Rev. D 68 (2003)
[3] H. Davoudiasl *et al.*, Phys. Rev. D 89 (2014)
[4] J. Barranco *et al.*, Phys. Rev. D 76 (2007)
[5] K. Patton *et al.*, Phys. Rev. C 86 (2012)
[6] C. Horowitz & J. Piekarewicz, Phys. Rev. Lett. 86 (2000)
[7] K. Scholberg, Phys. Rev. D 73 (2006)
[8] P. Coloma *et al.*, Phys. Rev. D 96 (2017)
[9] A.J. Anderson *et al.*, Phys. Rev. D 86 (2012)

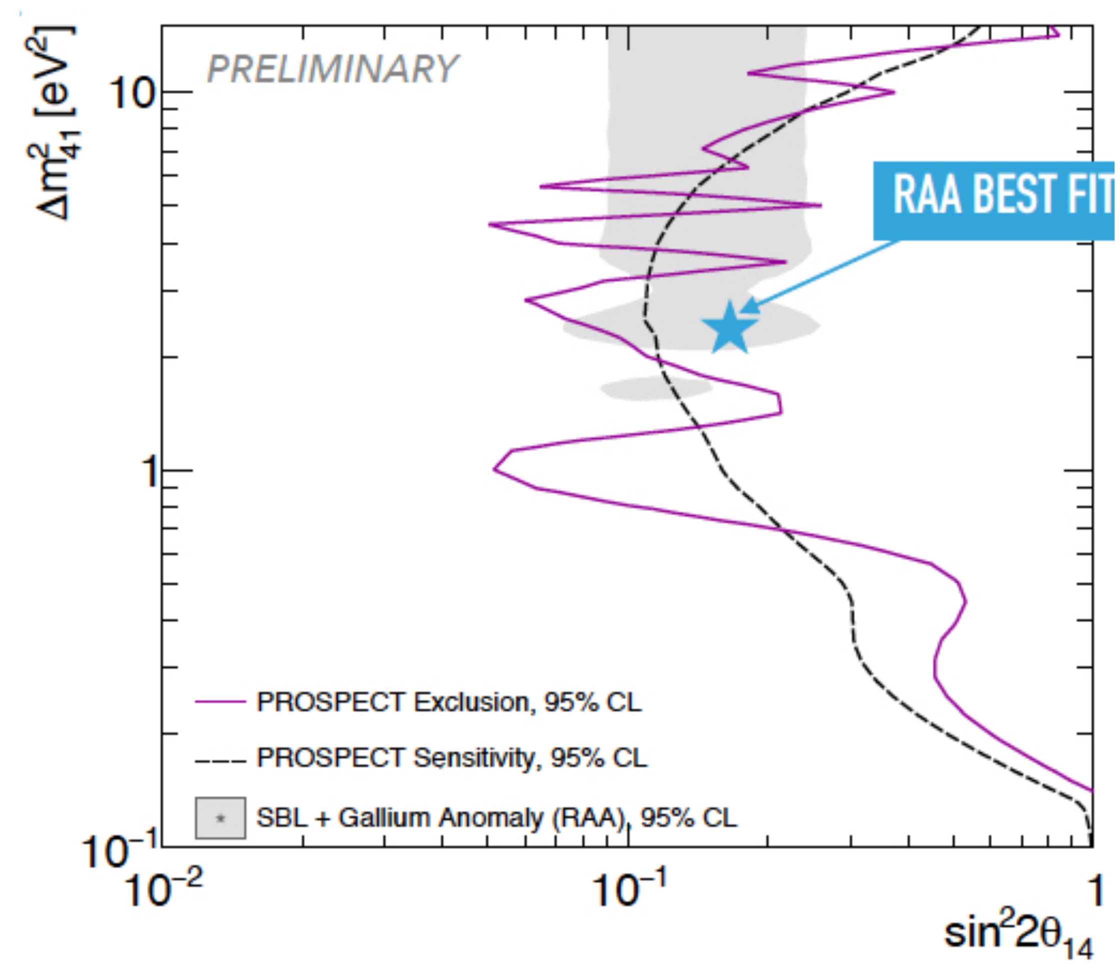
Figure from [8]

G. Rich, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: 10.5281/zenodo.1286967

Summary for lecture 2

Hints that our understanding is not complete - *sterile neutrinos*





Summary for lecture 2

Tests of sterile neutrinos are possible with a wide variety of dedicated and multipurpose experiments

COHERENT SNS

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

SBN Program

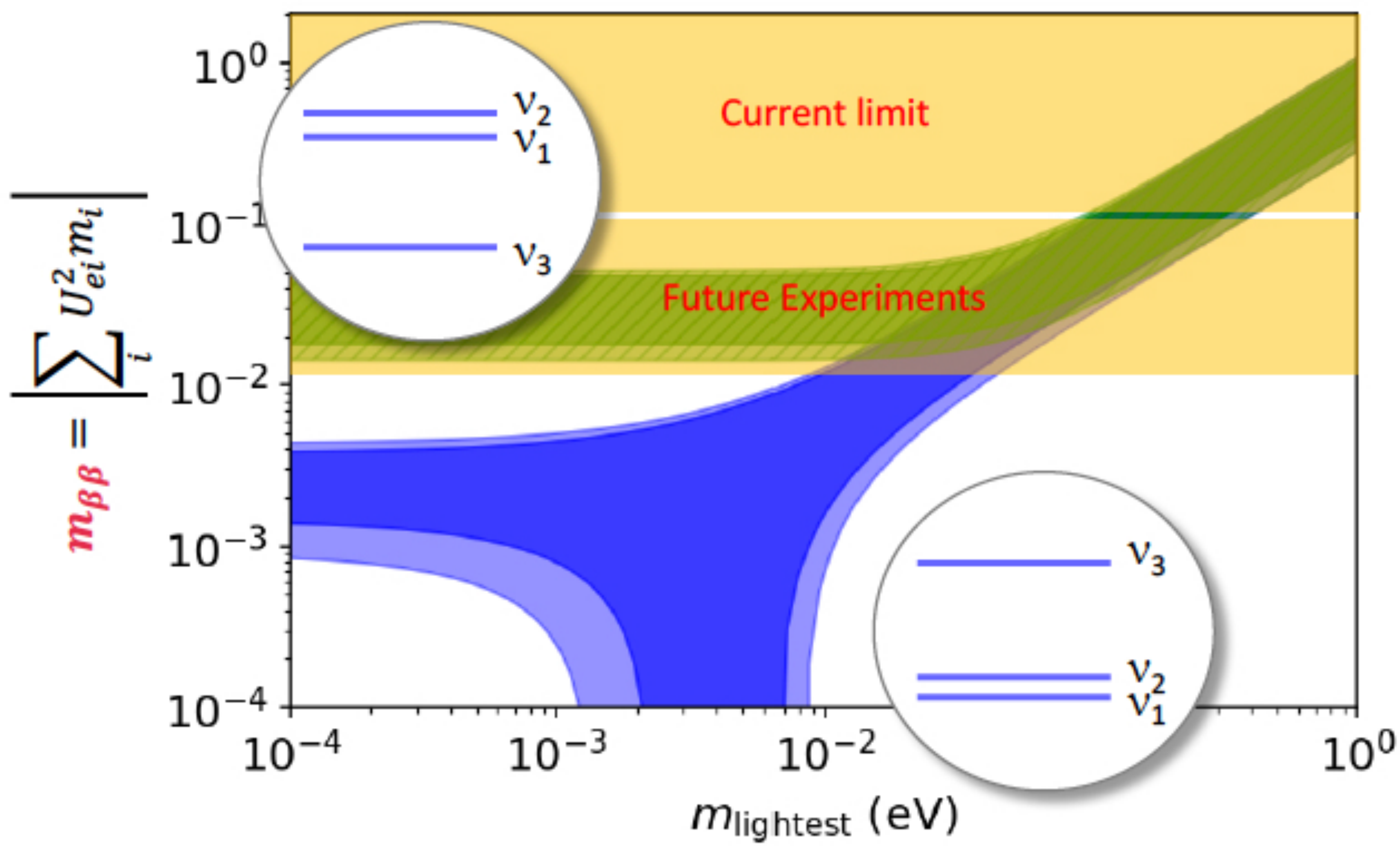
KATRIN
Karlsruhe Tritium Neutrino Experiment

PROSPECT
Precision Oscillation and Spectrum Experiment

Not even remotely a complete list

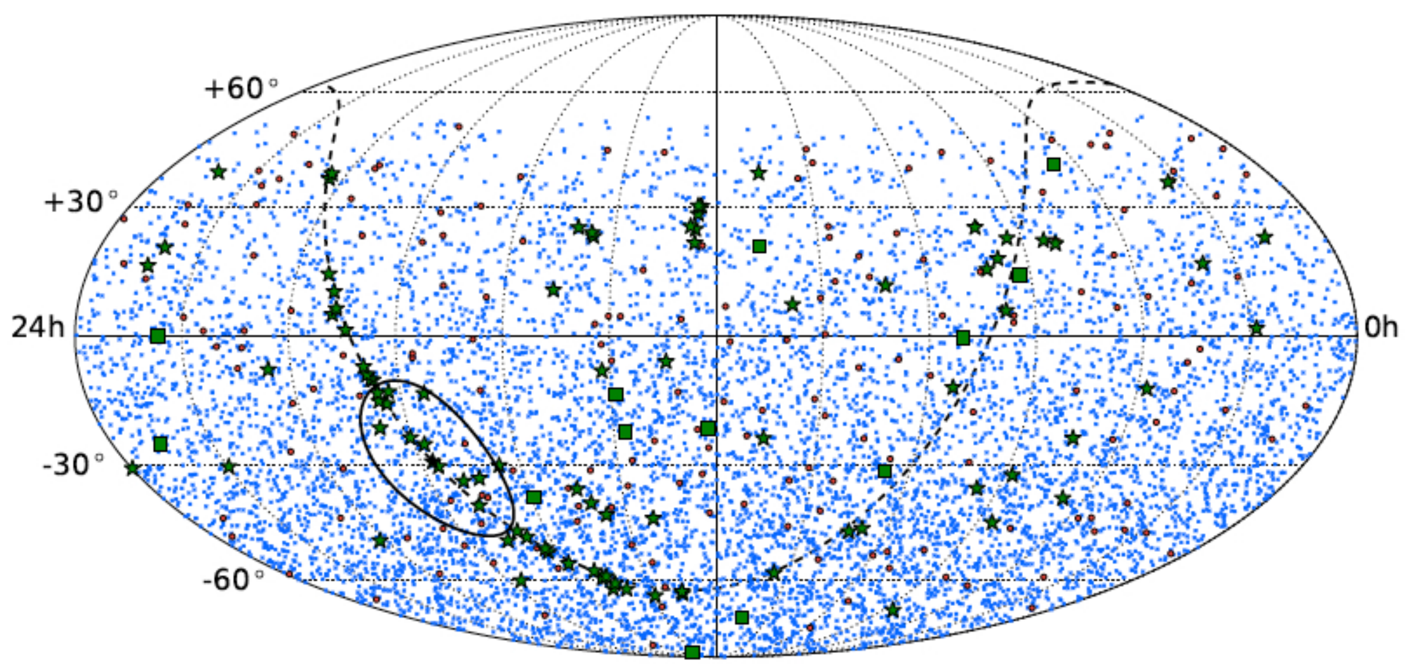
Summary for lecture 2

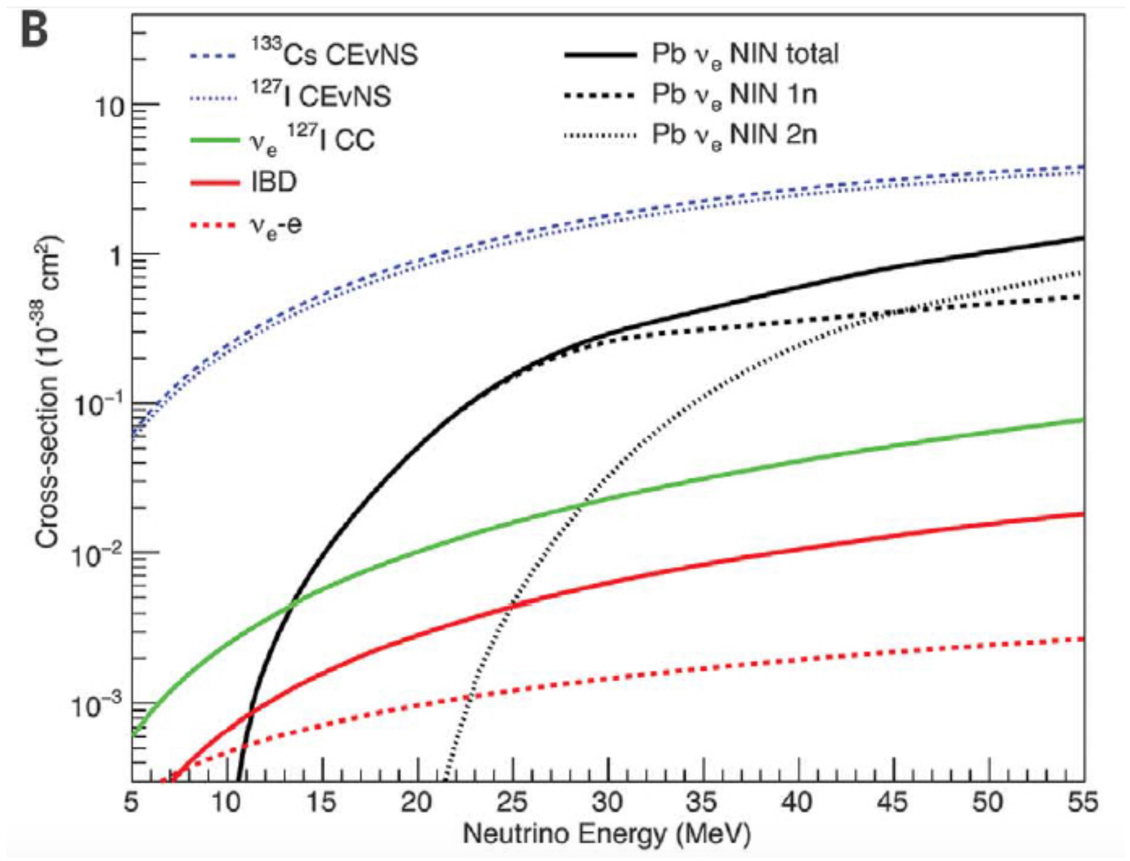
Direct mass and neutrino-less double decay experiments are being realized



Summary for lecture 2

And, what do we learn in the era of neutrino astronomy? And new probes like coherent elastic neutrino scattering?





Thank you for your time, attention

Thank you to the organizers for the invitation and support

Bonus material

Encore from lecture 1

OPERA:

CERN to Gran Sasso, Italy (730km)

On-axis beam ($E_\nu \approx 17$ GeV)

OPERA physics run:

Operated from 2008-2012

Neutrinos: 1.8×10^{20} POT

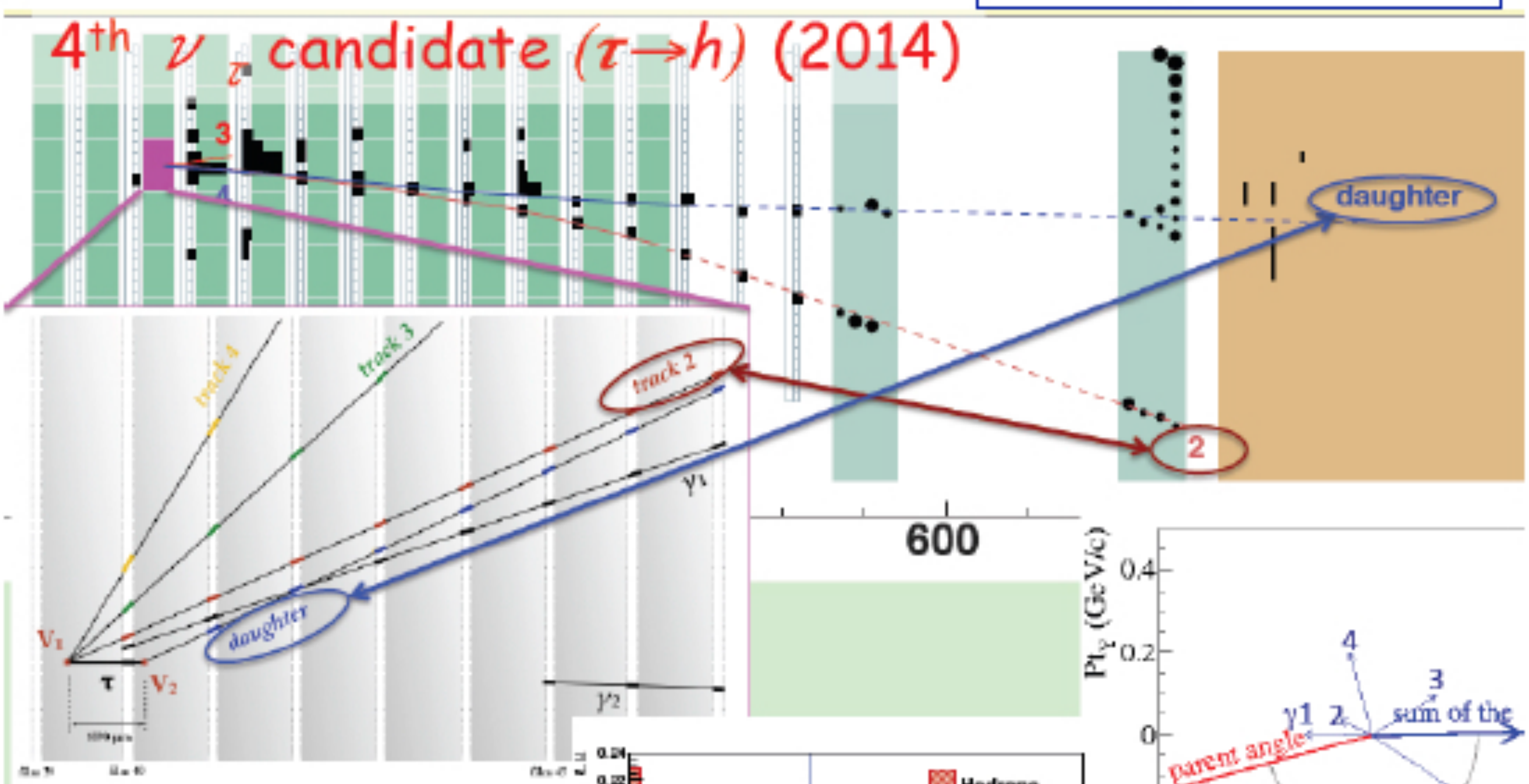
Measurements of:

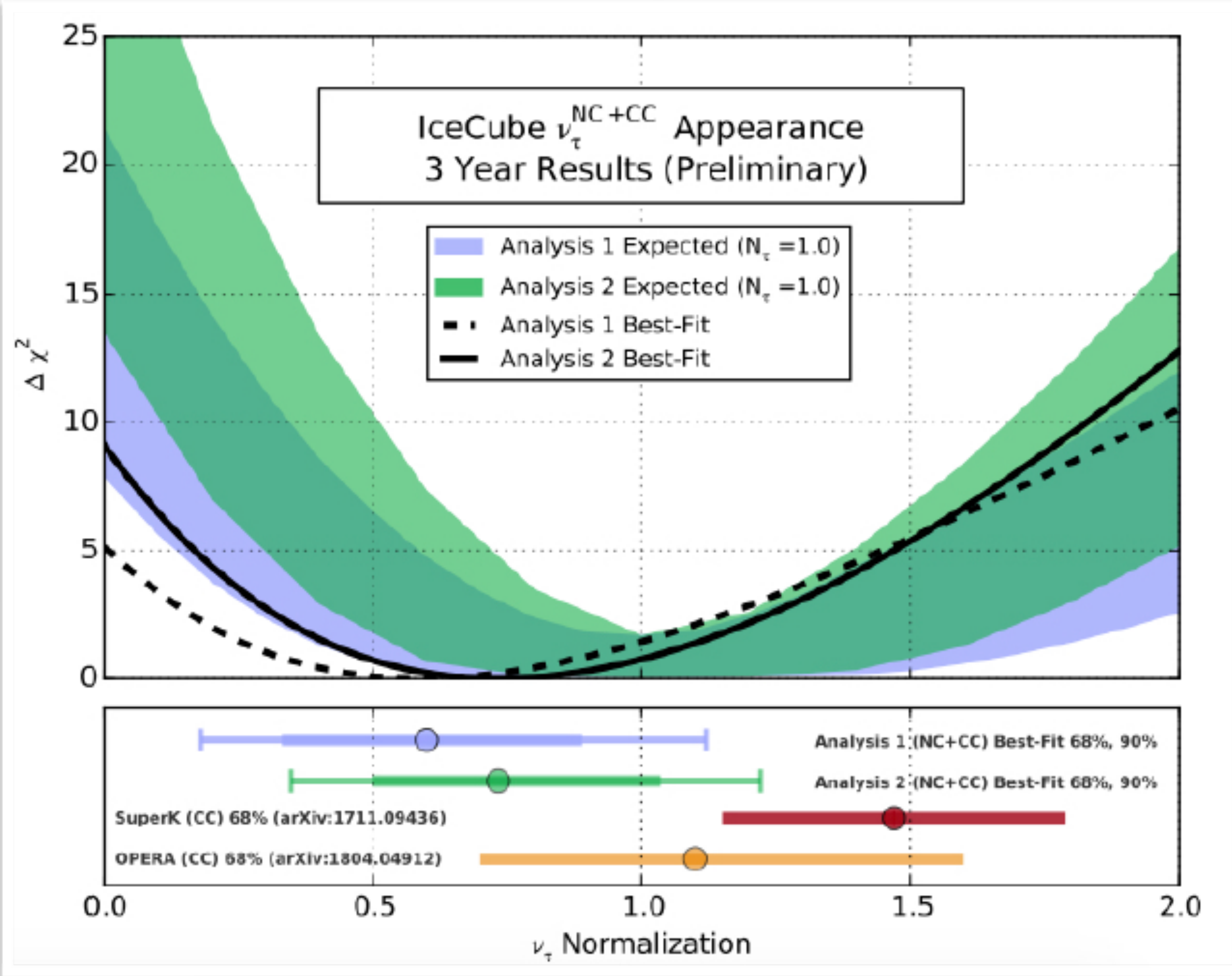
ν_τ **appearance**, expected signal 2.10±0.4, with background 0.23±0.04

Observed 4 candidate events

(no oscillation excluded at 4.2σ)

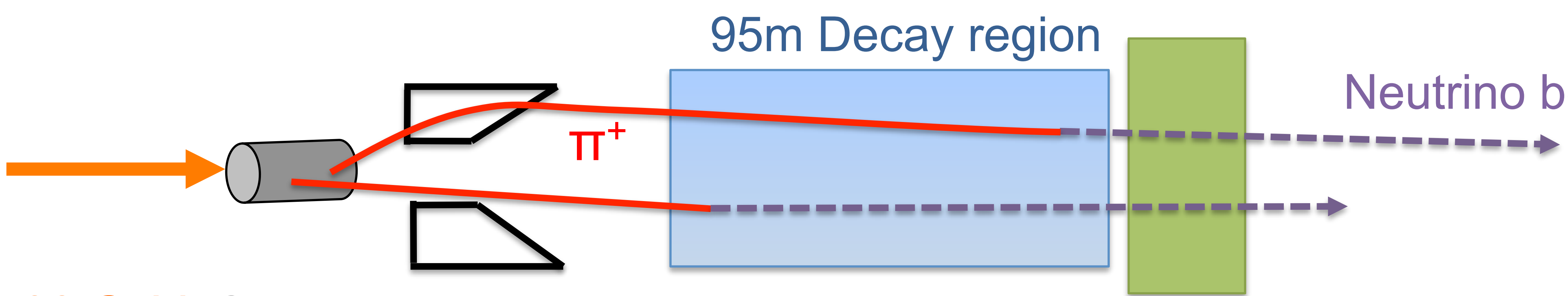
S. Dusini, Neutrino2014



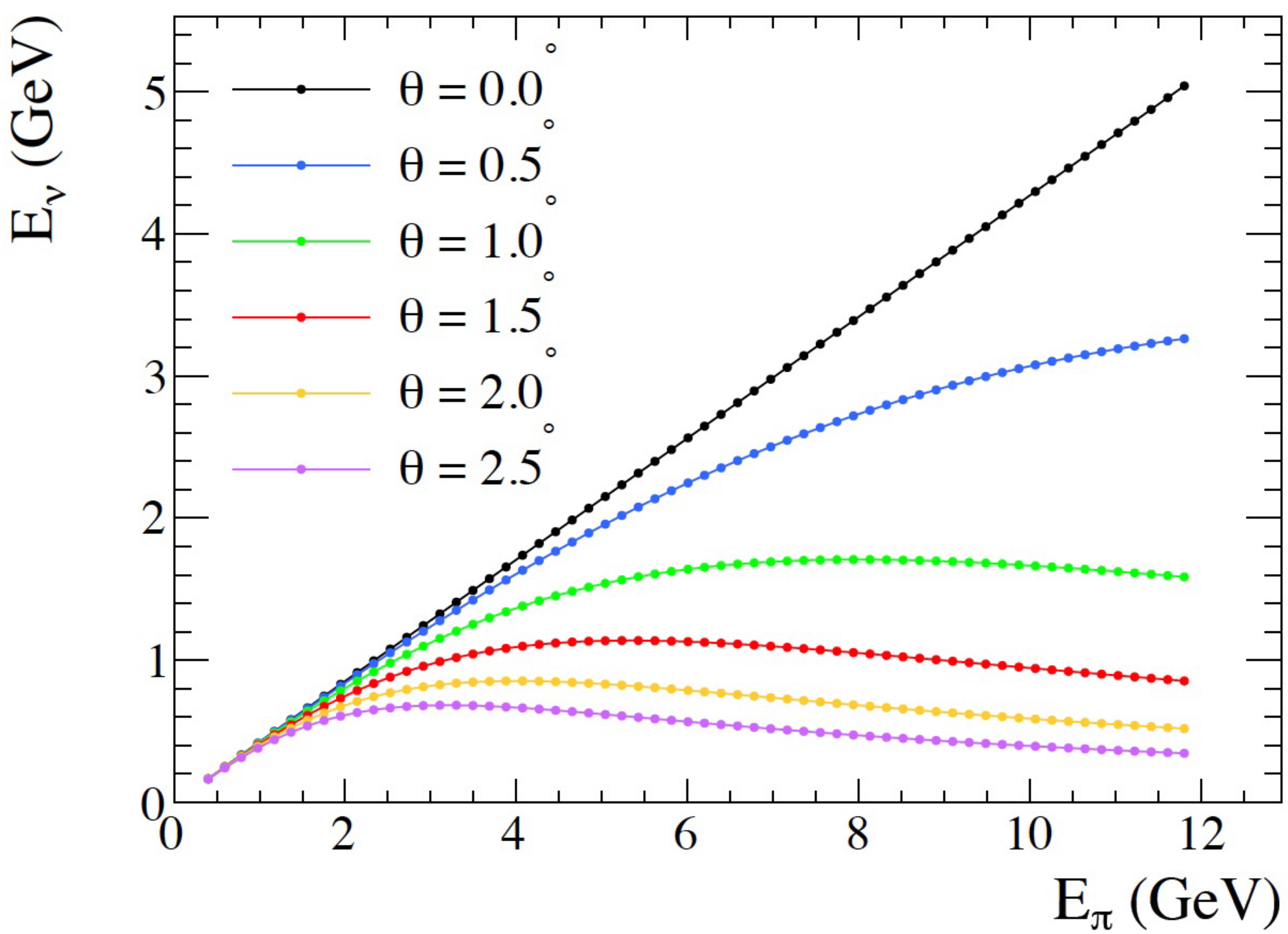


T. DeYoung, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: 10.5281/zenodo.1286851

Accelerator-produced neutrino beams

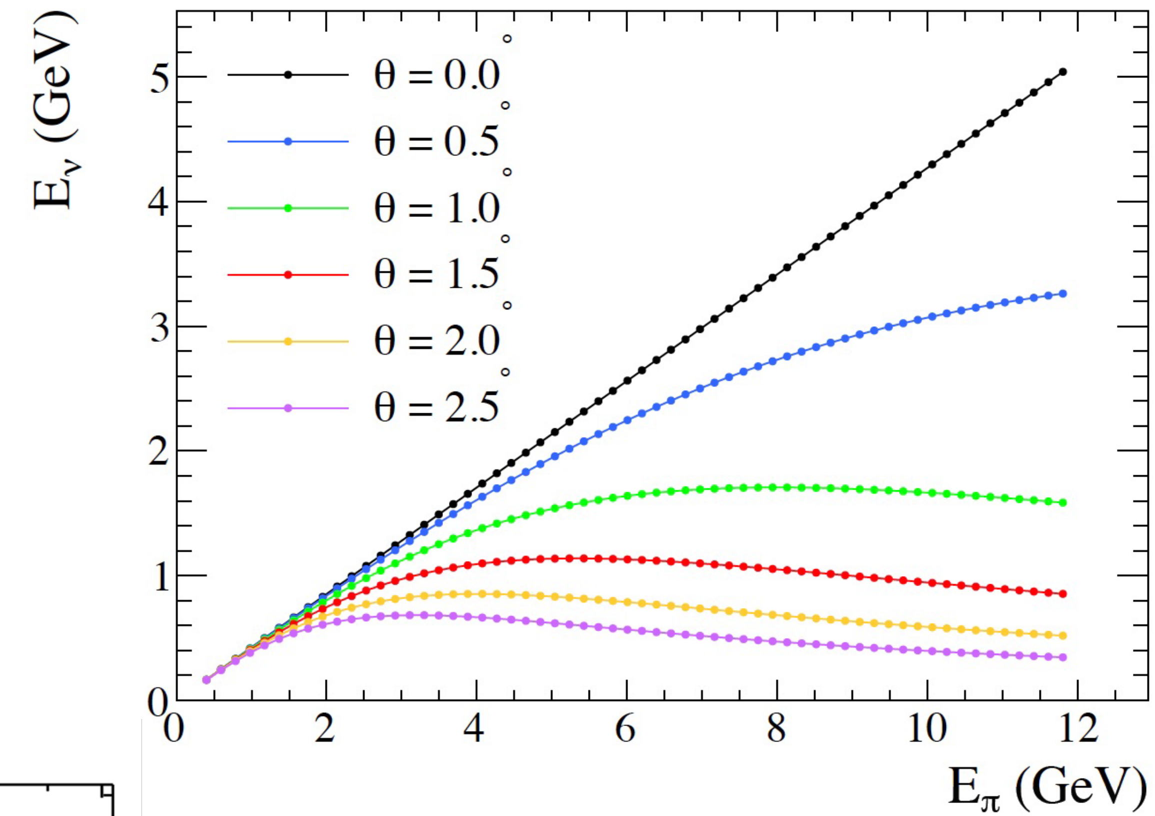


Tunable energy!

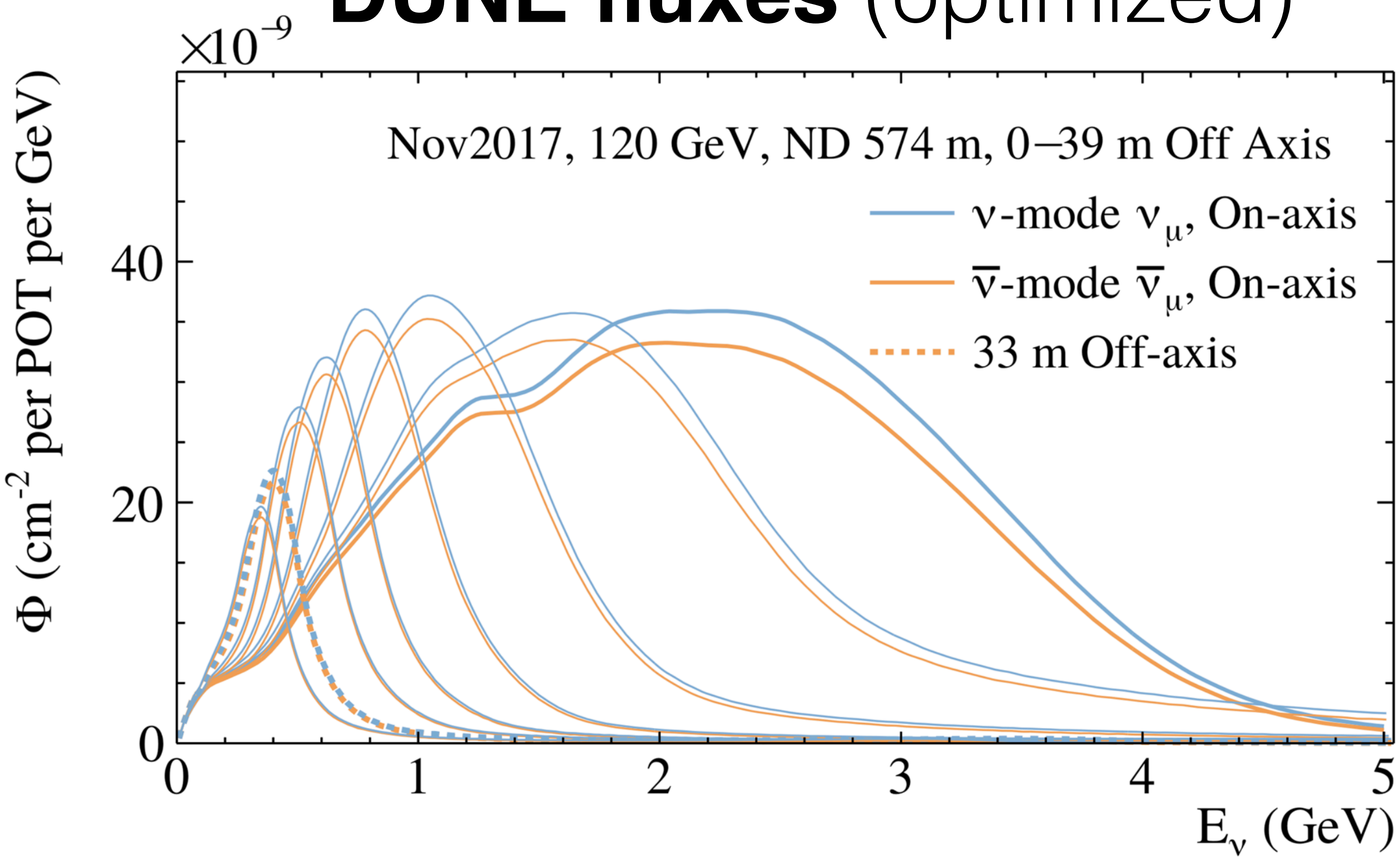


Credit: K. Duffy thesis

Accelerator-produced neutrino beams



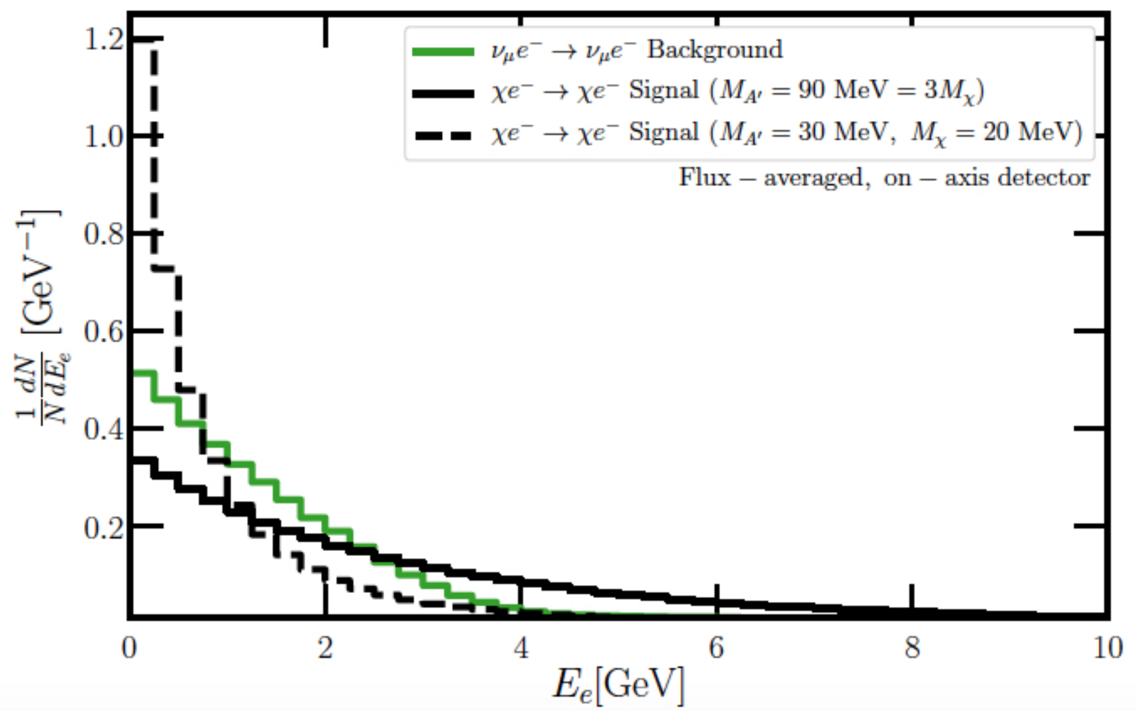
DUNE fluxes (optimized)

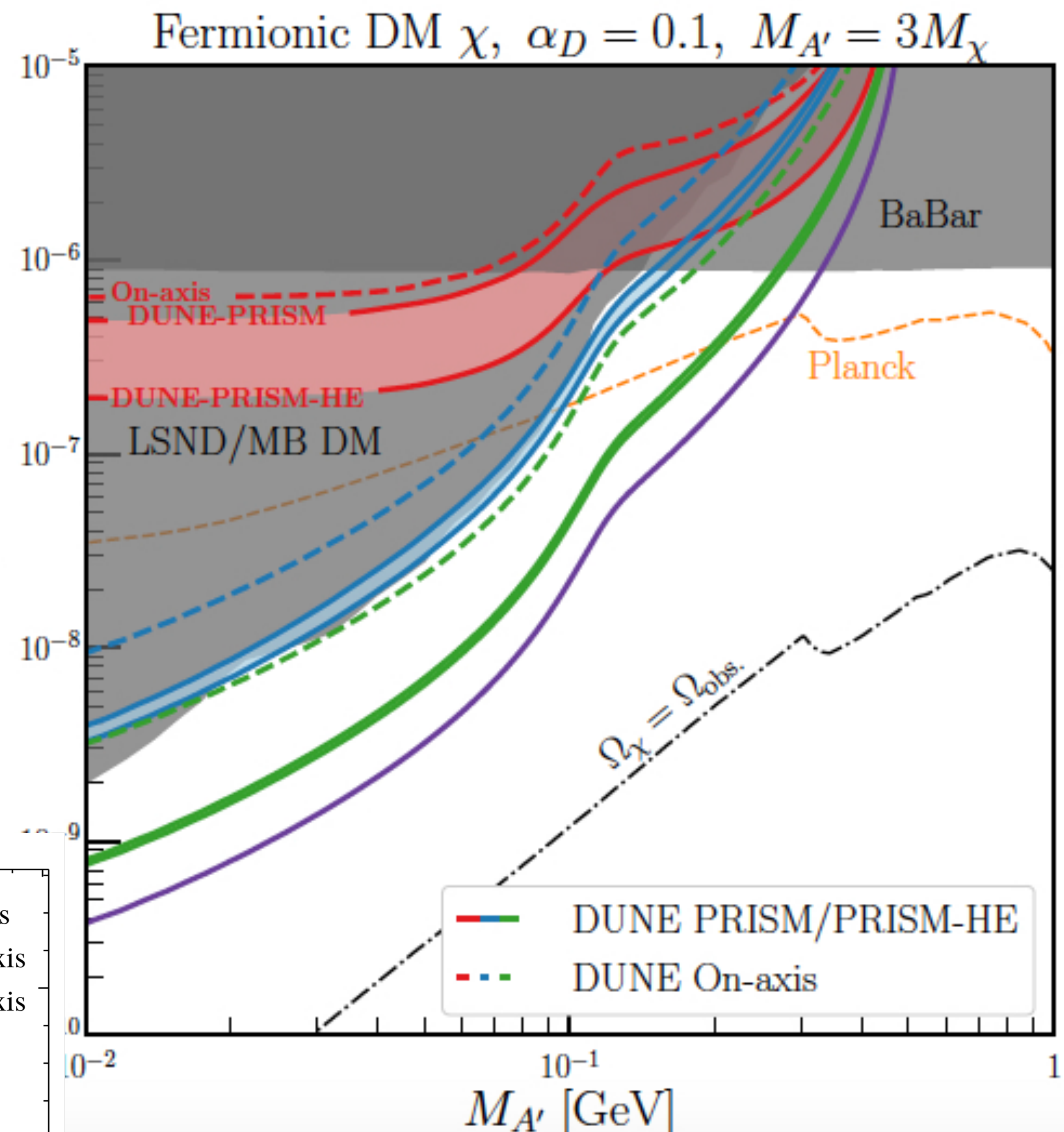


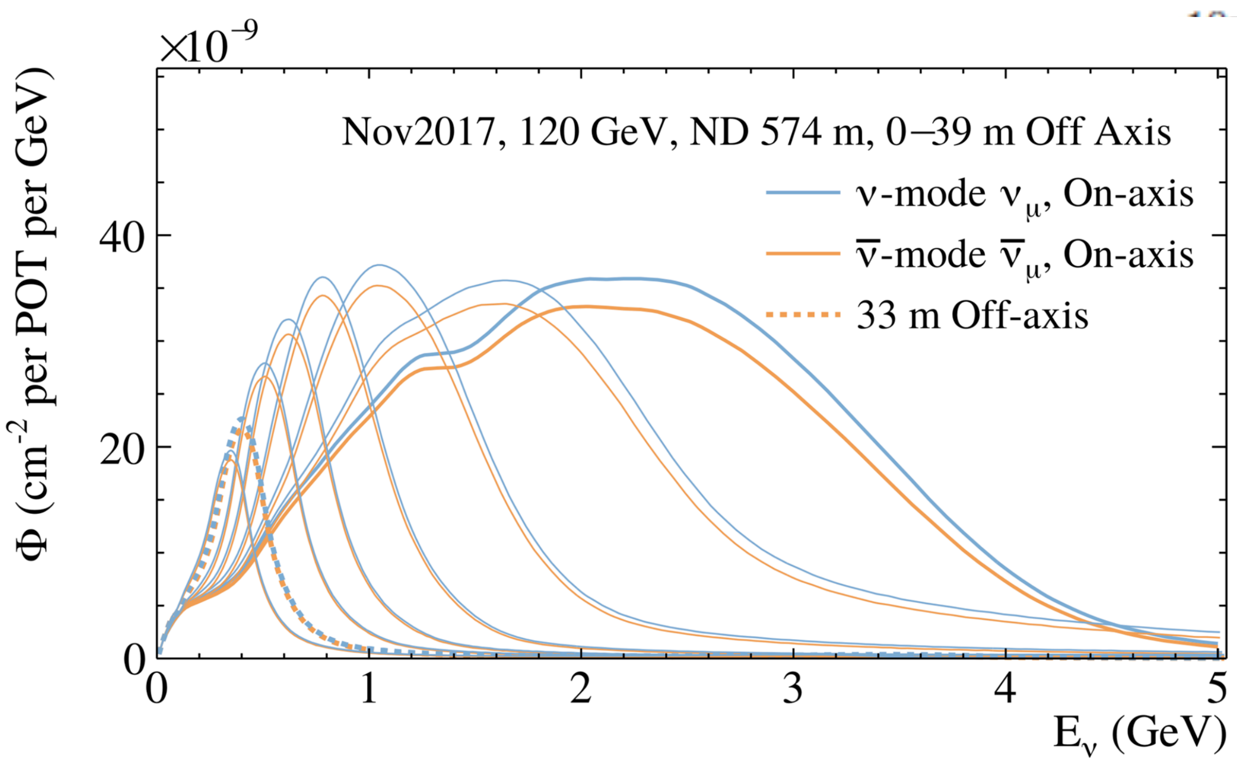
DUNE PRISM

Precision Reaction Independent Spectrum Measurement

Dark matter searches at neutrino beams







https://arxiv.org/abs/1903.10505

Backup