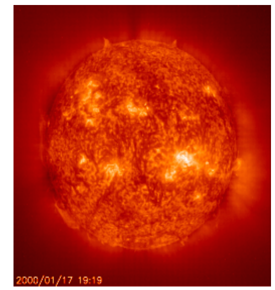
Miscellaneous topics...

Kate Scholberg
Duke University
NNPSS 2014

Lecture Plan

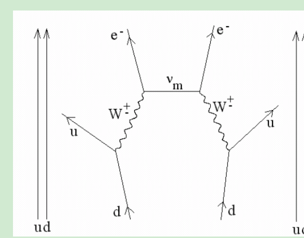
Lecture #1: **Neutrino Mass and Oscillations**

Lecture #2: **Solar Neutrinos**



Lecture #3: **Supernova Neutrinos**

Lecture #4: Miscellaneous topics



Part I: **Neutrino Physics at the SNS**

Part II: **Absolute neutrino Mass**

Part III: **Neutrinoless Double Beta Decay**

Part I Outline

Low-energy cross sections overview:
physics motivation

The SNS as a neutrino source

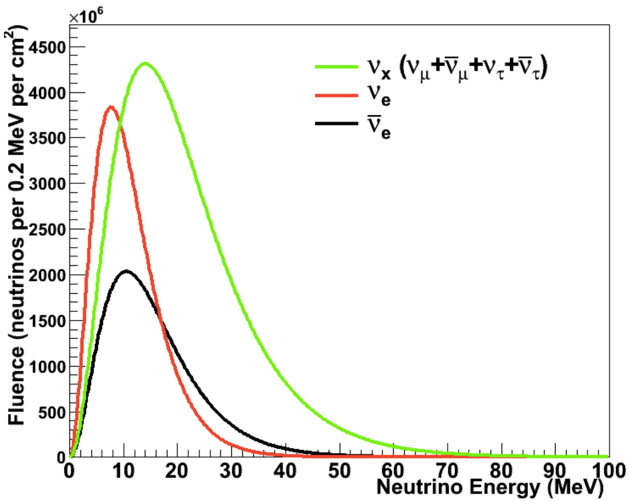
Cross-section experiments at the SNS

➔ Focus on the COHERENT experiment

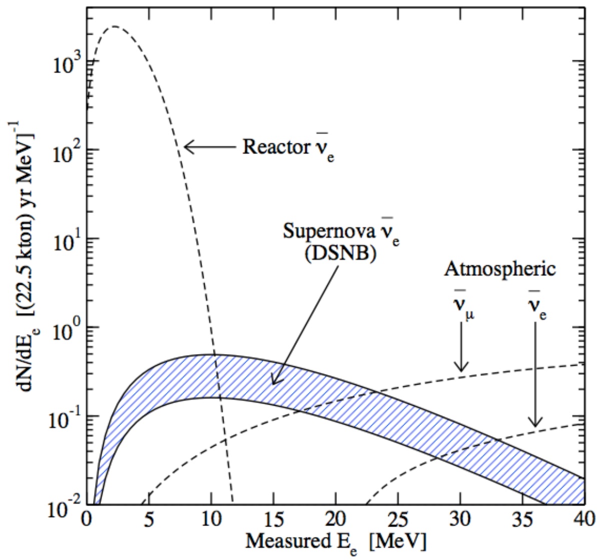
Work underway and prospects

Neutrino Cross-Section Experiments at the Spallation Neutron Source

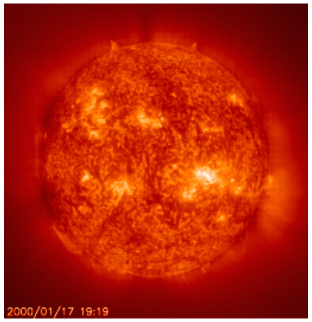
Neutrino interactions in the few-100 MeV range are relevant for:

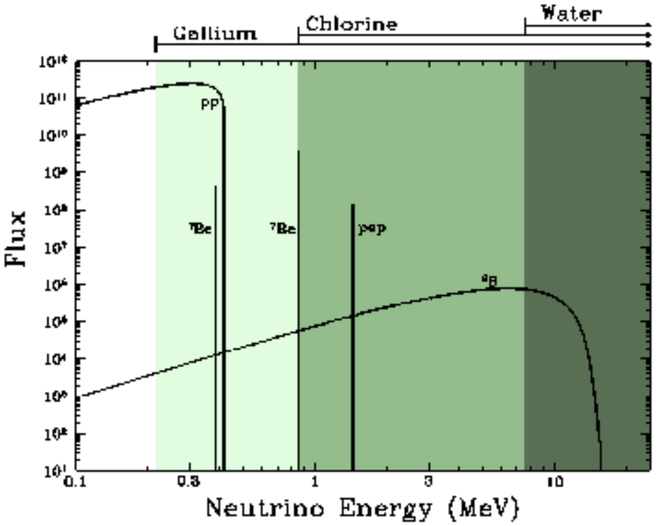


supernova neutrinos, burst & relic

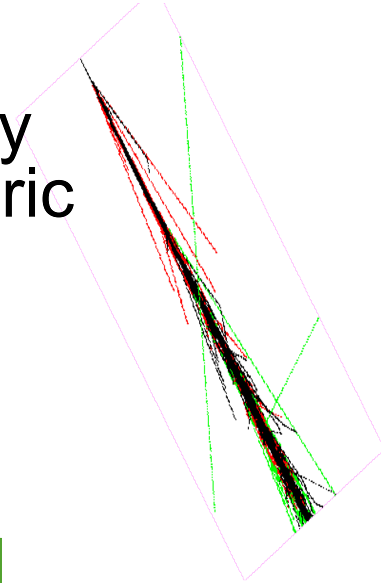


solar neutrinos



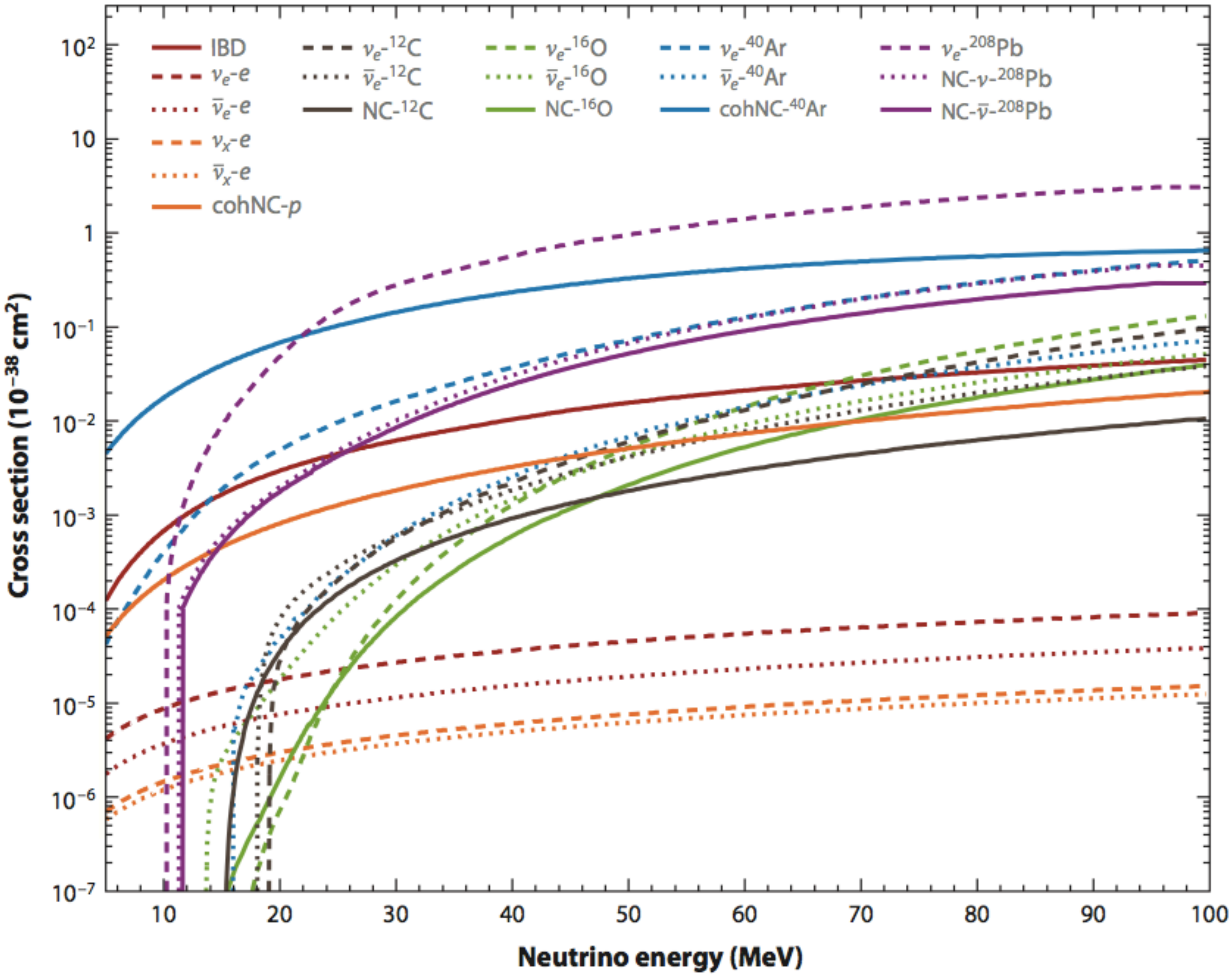


low energy atmospheric neutrinos



Physics: oscillation, SM tests, astrophysics

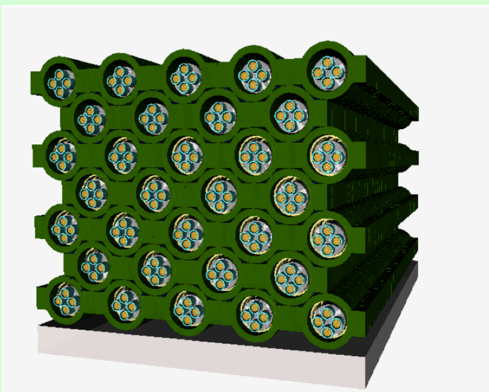
Cross-sections in this energy range



IBD and ES on electrons well understood... but
so far only ^{12}C is the *only* heavy nucleus with ν interaction
cross sections well (~10%) measured in the tens of MeV regime

Supernova-neutrino-relevant cross sections to understand in this energy range

Lead



HALO at SNOLAB

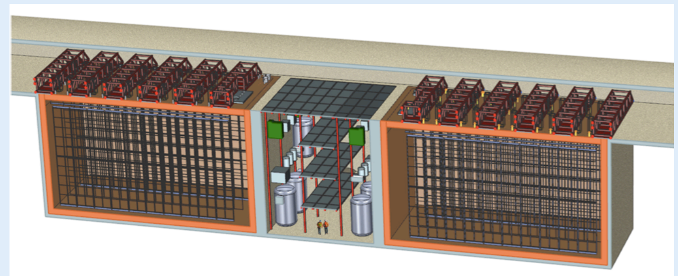
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$

↘ 1n, 2n emission

$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$

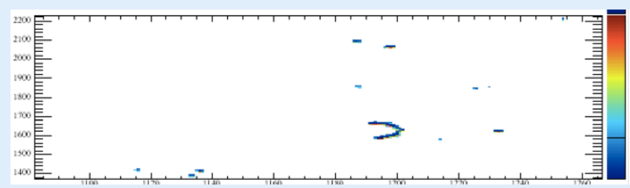
↘ 1n, 2n, γ emission

Argon



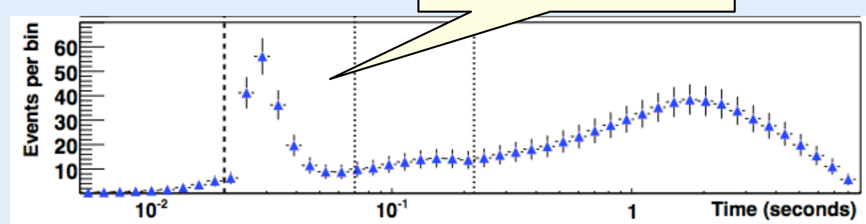
LBNE

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



electron + γ's

Neutronization burst visible

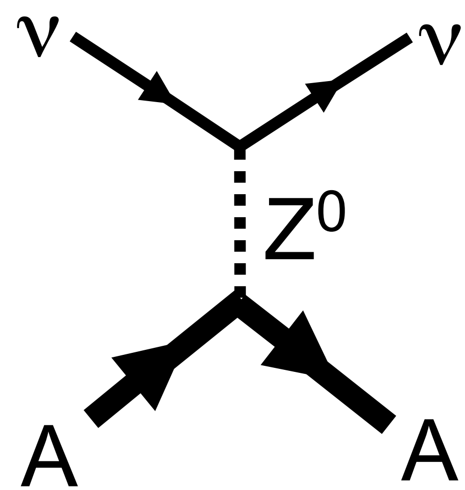


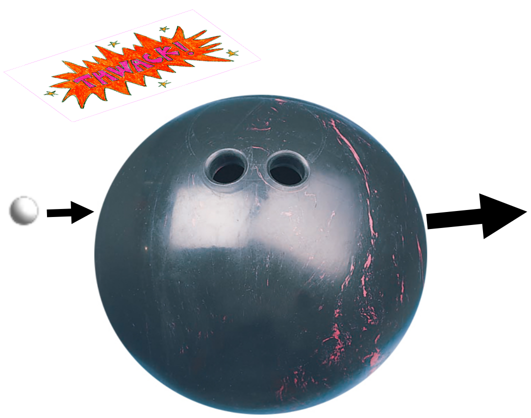
also: oxygen, iron, carbon,...

Coherent elastic neutral current neutrino-nucleus scattering (CENNS)

$$\nu + A \rightarrow \nu + A$$

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils;
coherent up to $E_\nu \sim 50$ MeV



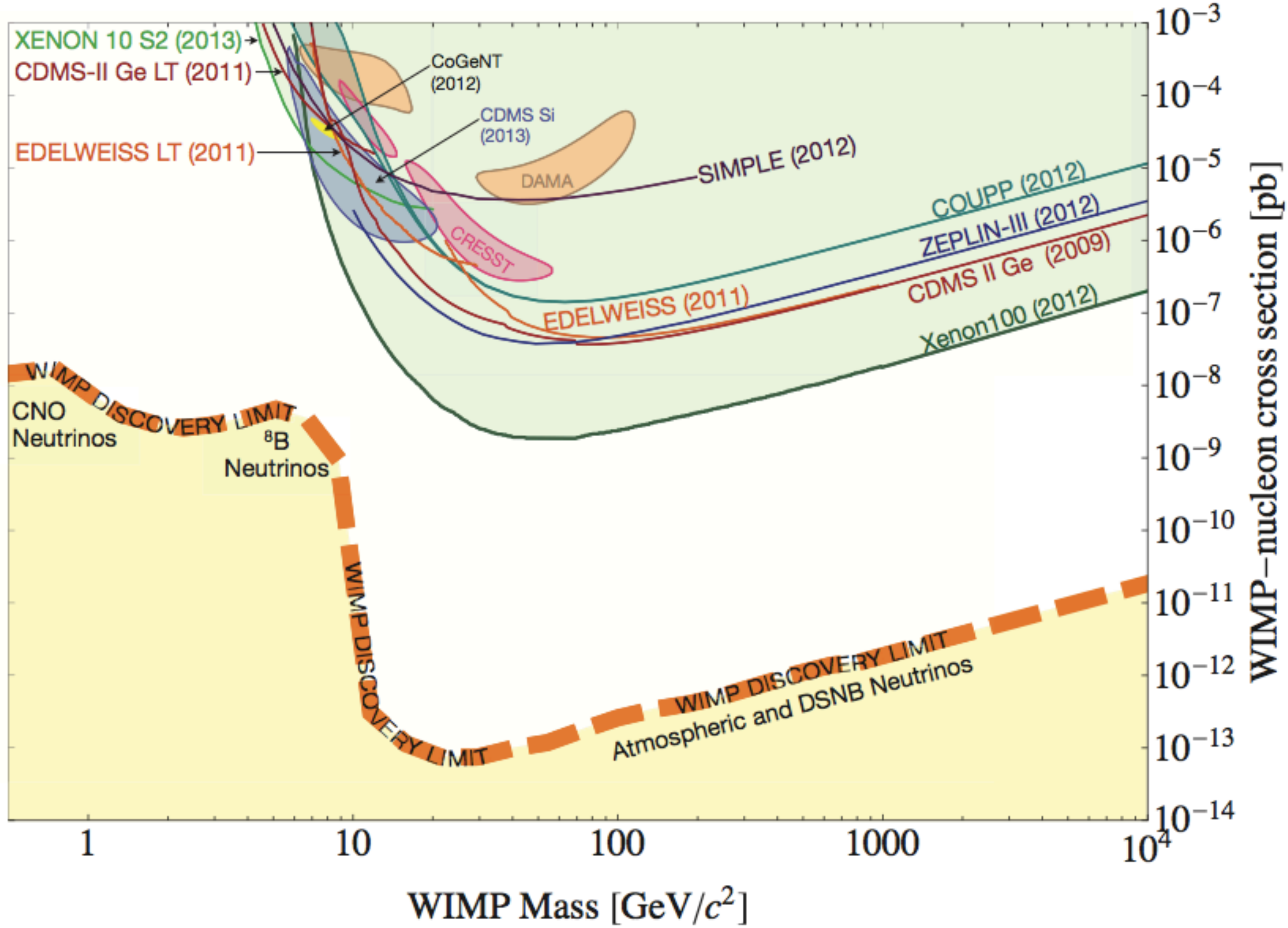


- Important in SN processes & detection
- Well-calculable cross-section in SM: SM test, probe of neutrino NSI
- Possible applications (reactor monitoring)

A. Drukier & L. Stodolsky, PRD 30:2295 (1984)
Horowitz et al. , PRD 68:023005 (2003) astro-ph/0302071

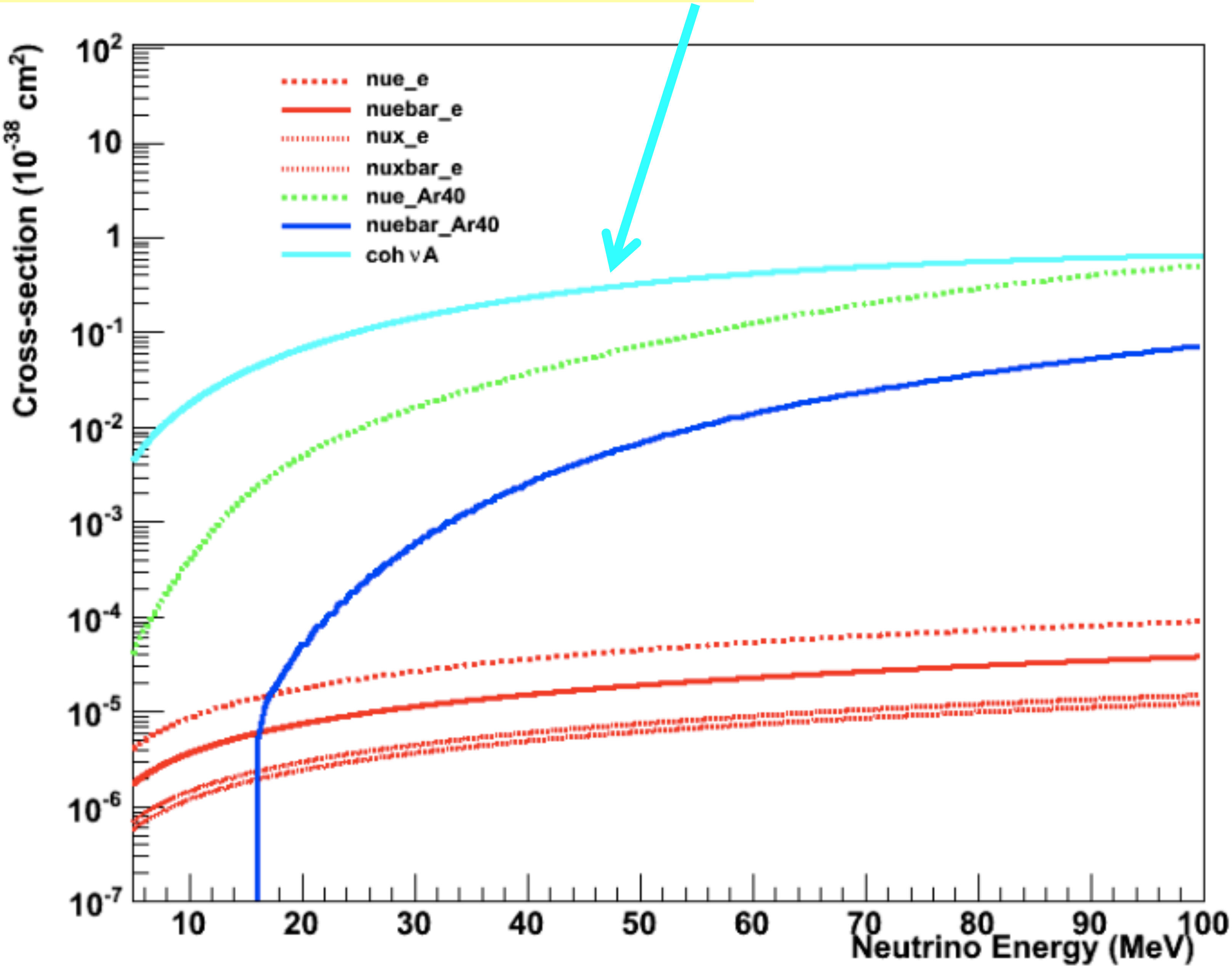
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

CENNS from natural neutrinos creates ultimate background for direct DM search experiments



J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

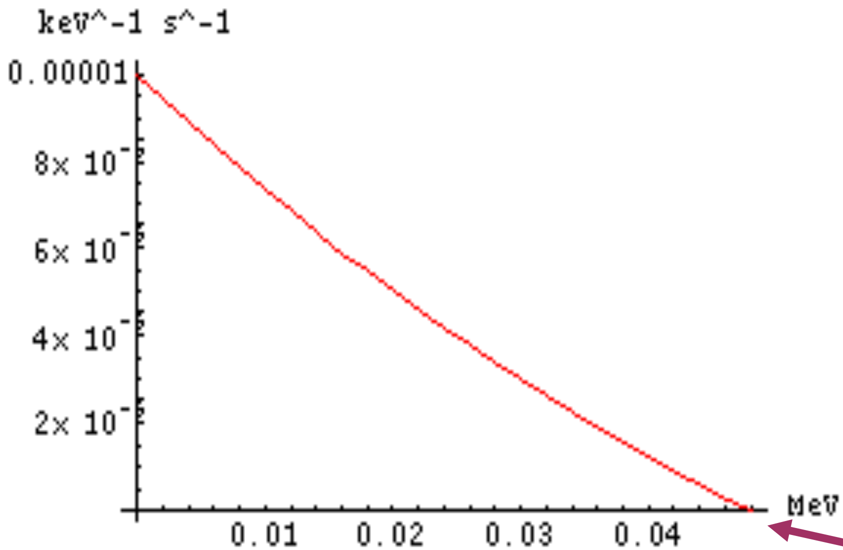
The cross-section is *large*



But CENNS has never been observed...

Why not?

Nuclear recoil energy spectrum for 30 MeV ν



Max recoil energy is $2E_\nu^2/M$ (48 keV for Ar)

Recoil energies are tiny!

Most neutrino detectors (water, gas, scintillator) have thresholds of at least ~MeV: so these interactions are hard to see...

➔ but WIMP detectors developed over the last ~decade are sensitive

Physics reach for CENNS experiments

Basically, any deviation from SM x-scn is interesting...

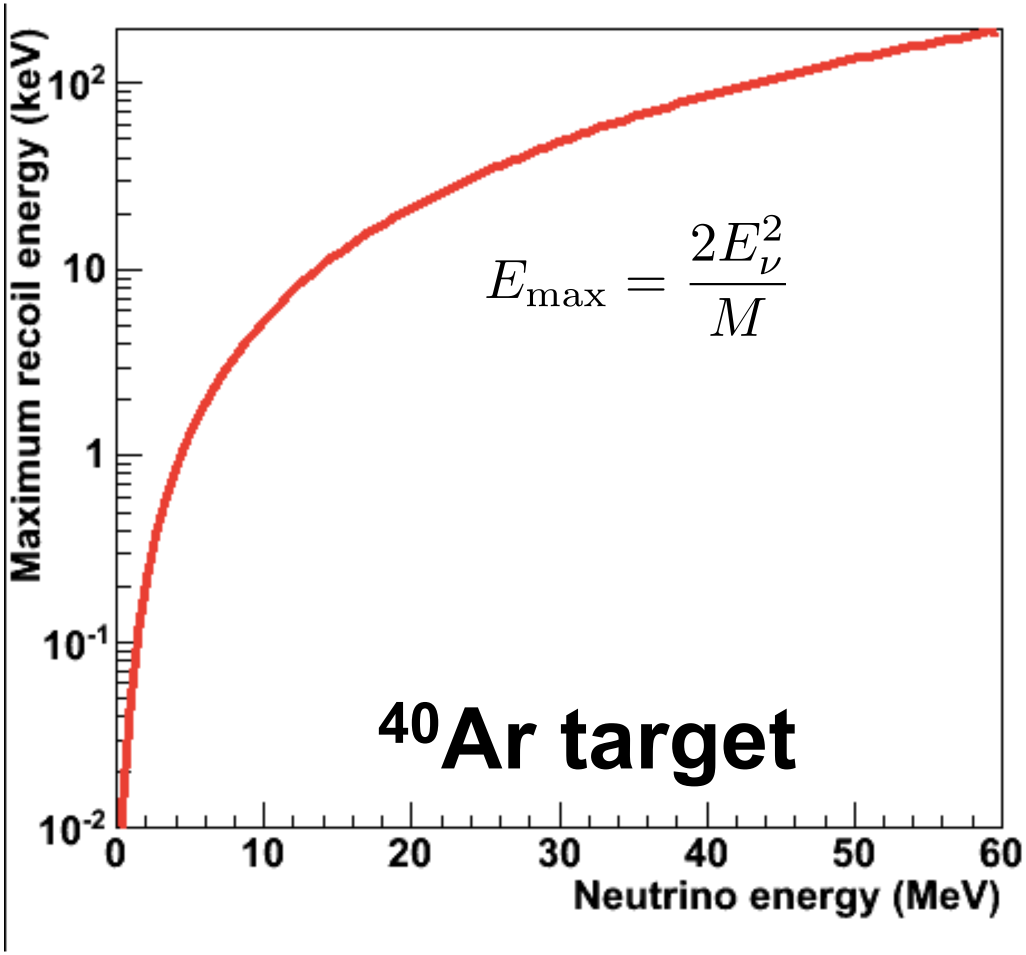
- **Standard Model weak mixing angle:**
  could measure to ~5% (new channel)
- **Non Standard Interactions (NSI) of neutrinos:**
  could significantly improve constraints
- **(Neutrino magnetic moment):**
  hard, but conceivable; need low energy sensitivity
- **(Sterile oscillations):**
  hard, but also conceivable

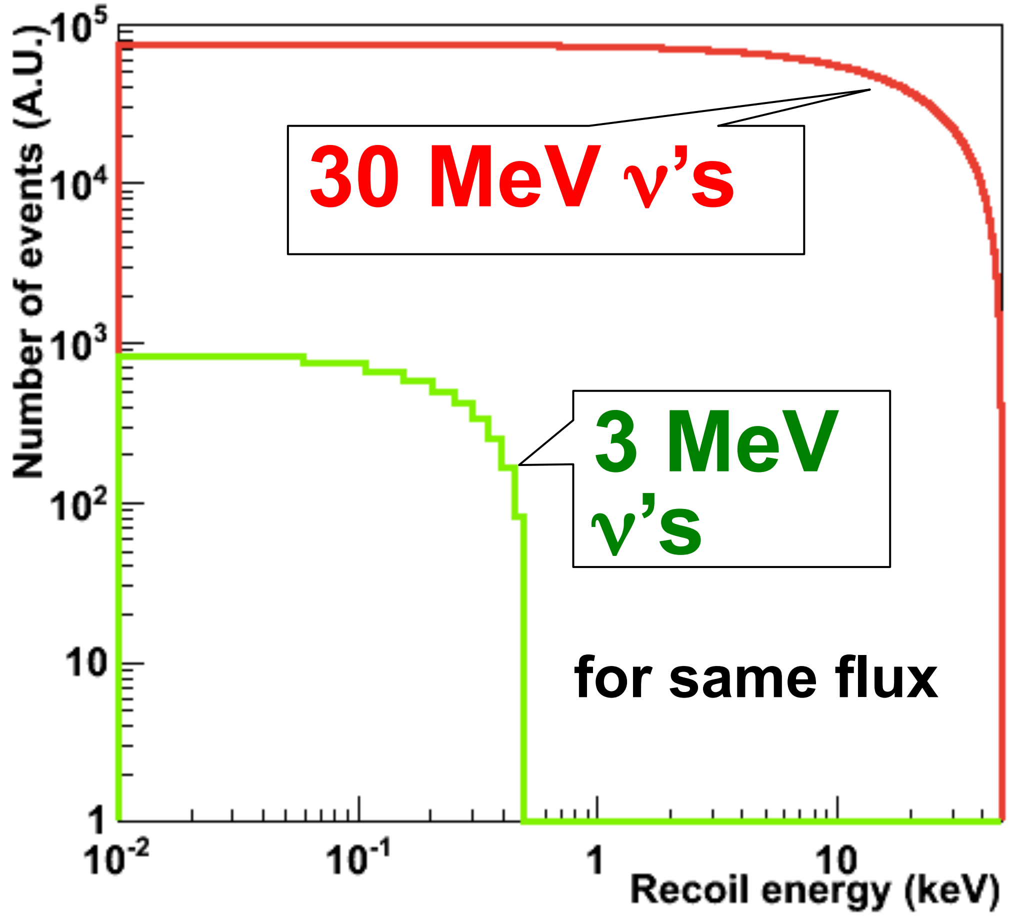
At a level of experimental precision better than that on the nuclear form factors:

- **Neutron form factor:**
  hard but conceivable; need good energy resolution, control of systematics

What do you want to detect CENNS?

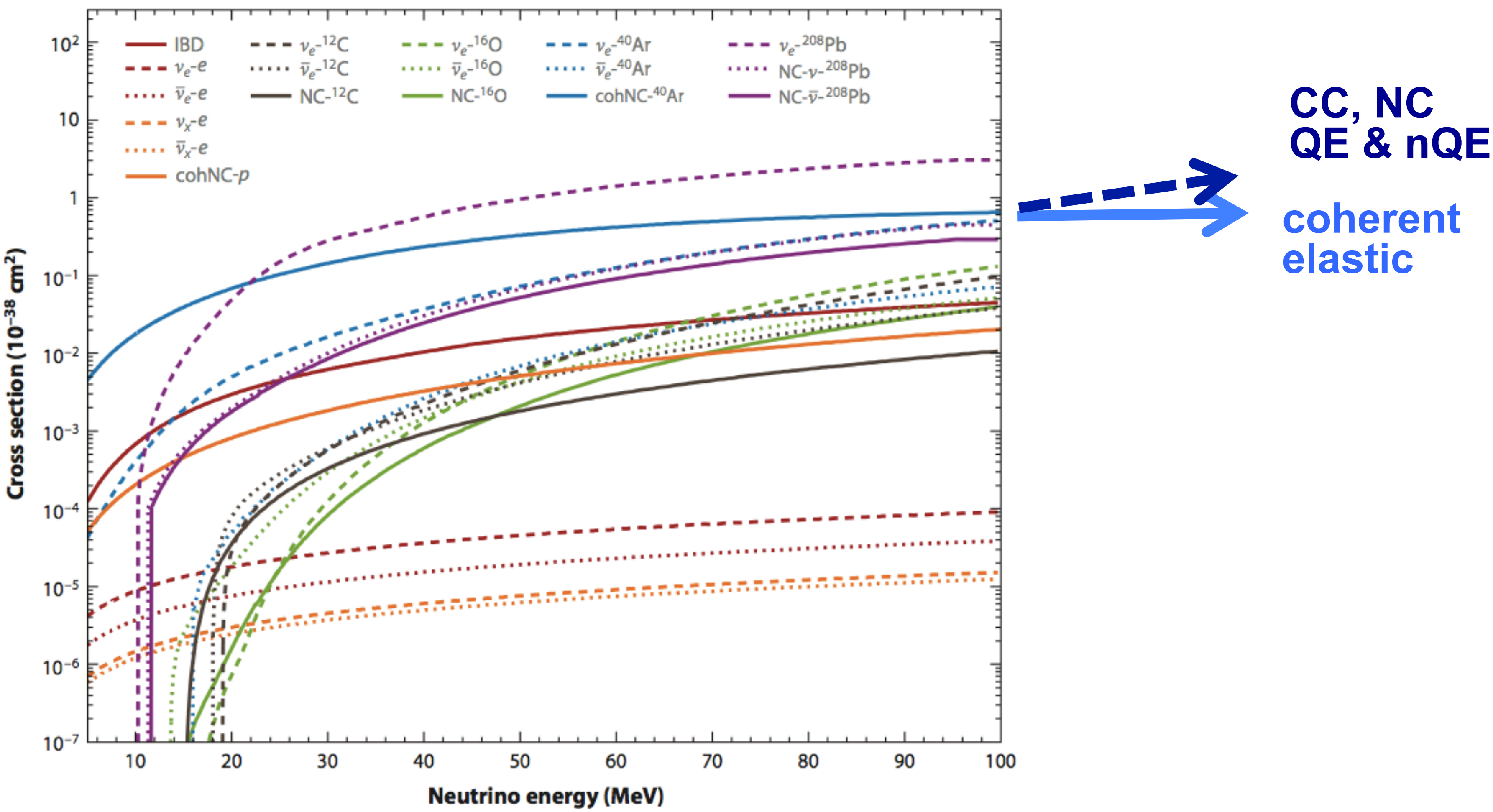
High-energy neutrinos, because both cross-section and maximum recoil energy increase with neutrino energy





... but...

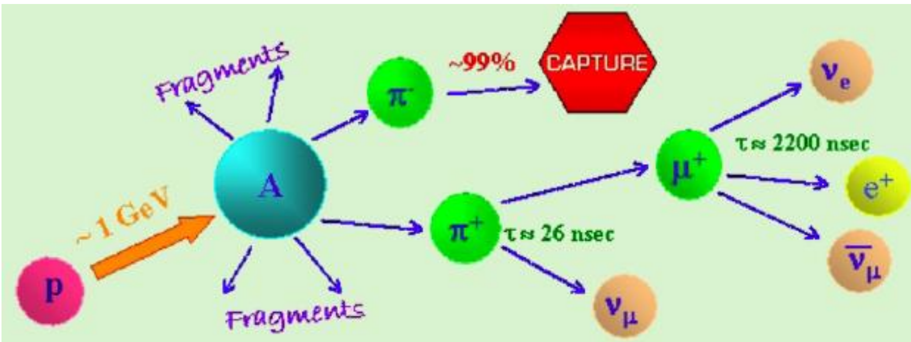
... neutrino energy should not be *too* high...

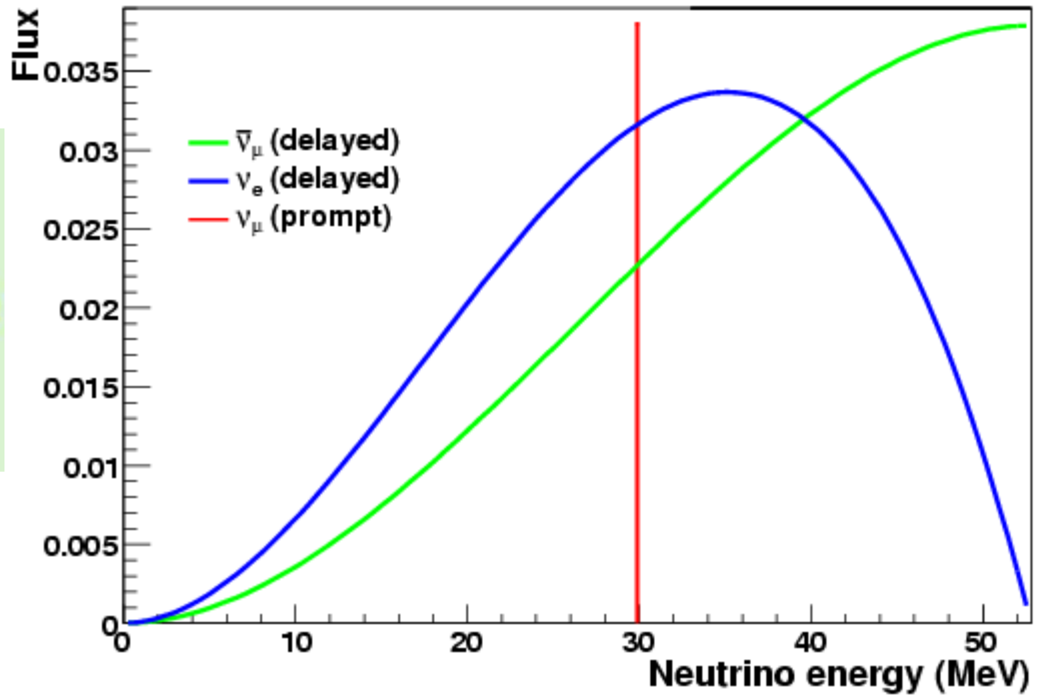


The coherent cross-section flattens, but inelastic cross-section increases (eventually start to scatter off *nucleons*)

➔ **want E_ν~ 50 MeV to satisfy** $Q \lesssim \frac{1}{R}$

Stopped-Pion (DAR) Neutrinos





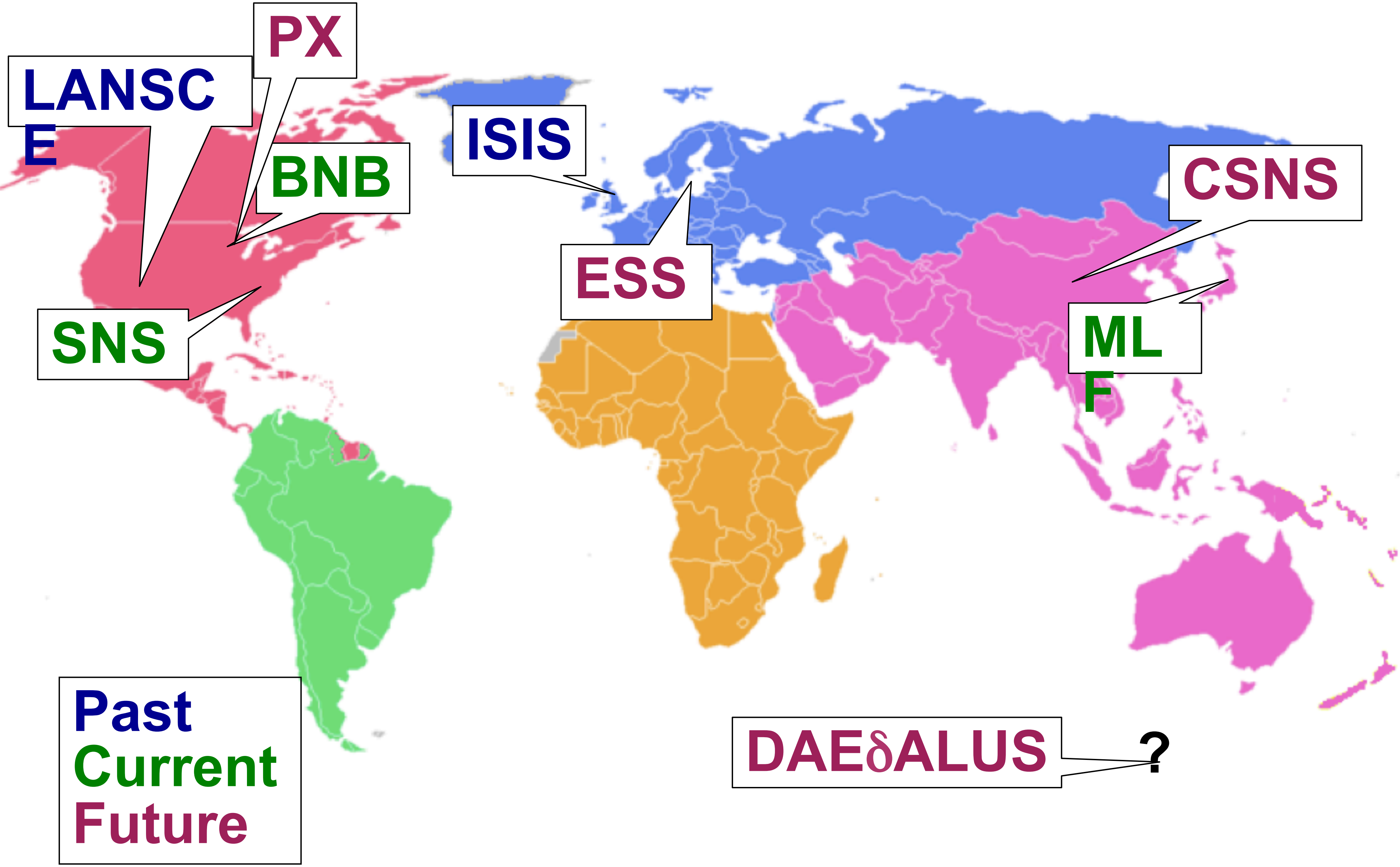
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

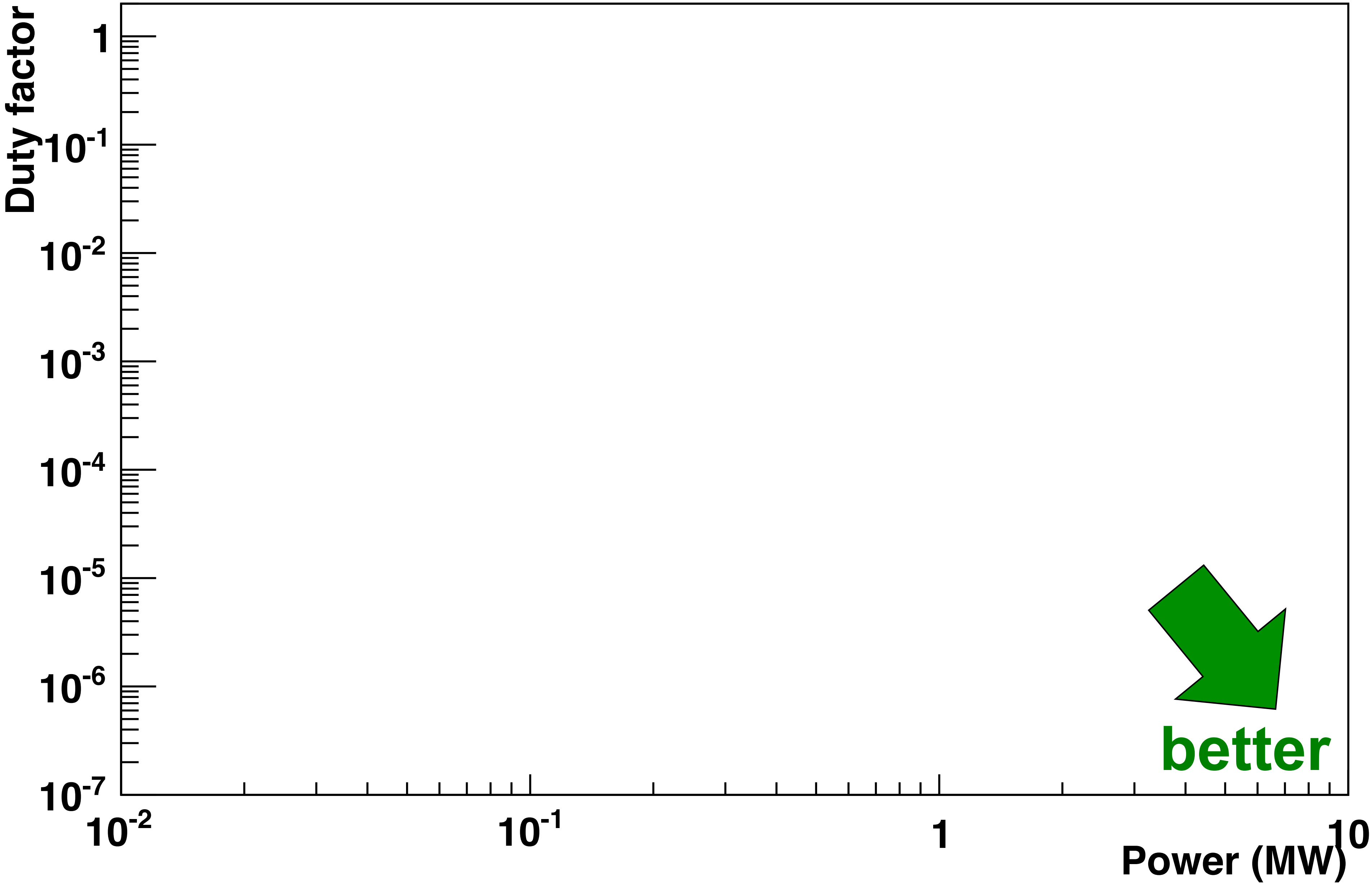
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

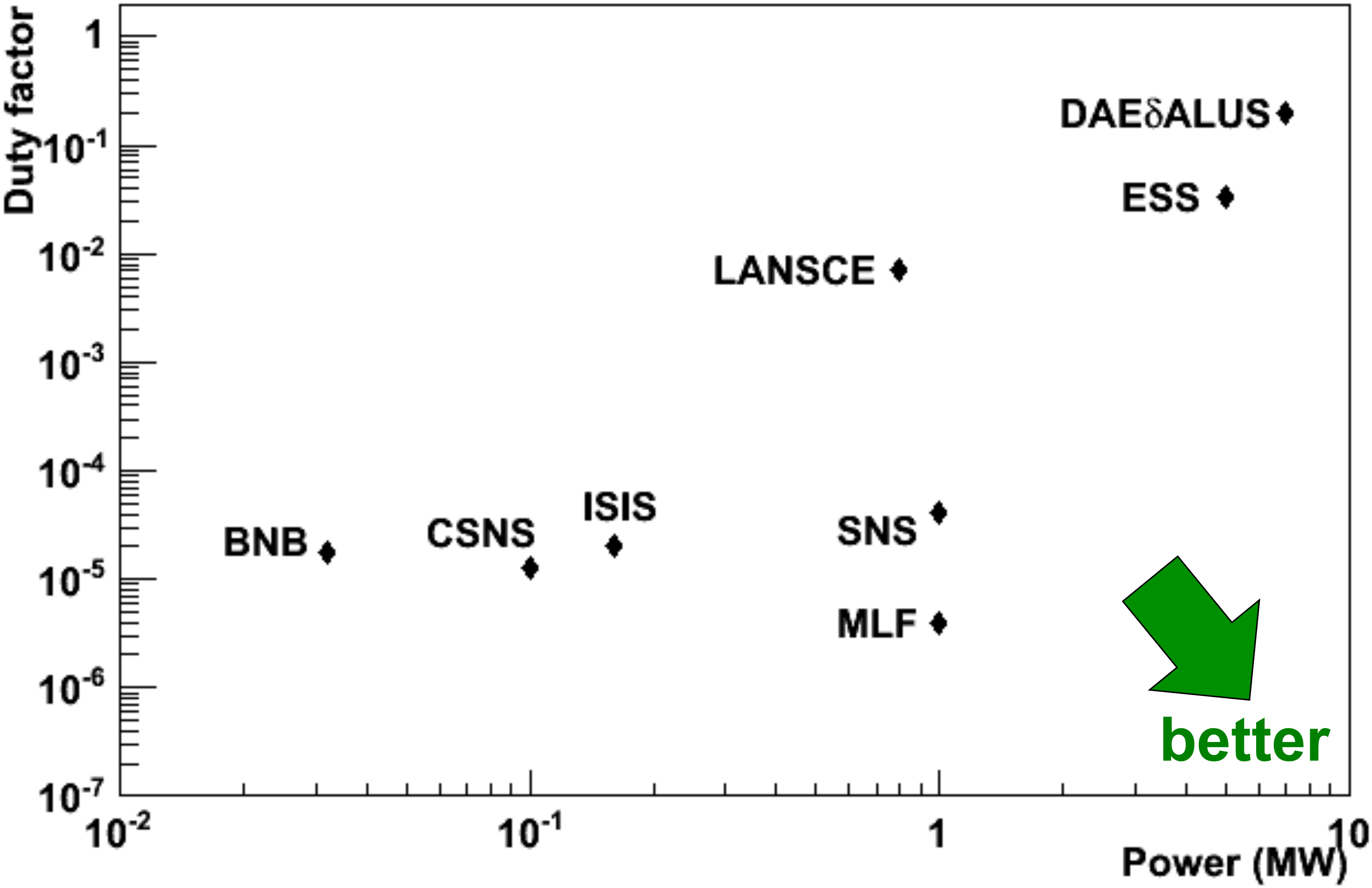
Stopped-Pion Sources Worldwide



Flux ∝ power: want bigger!
Duty factor: want smaller!

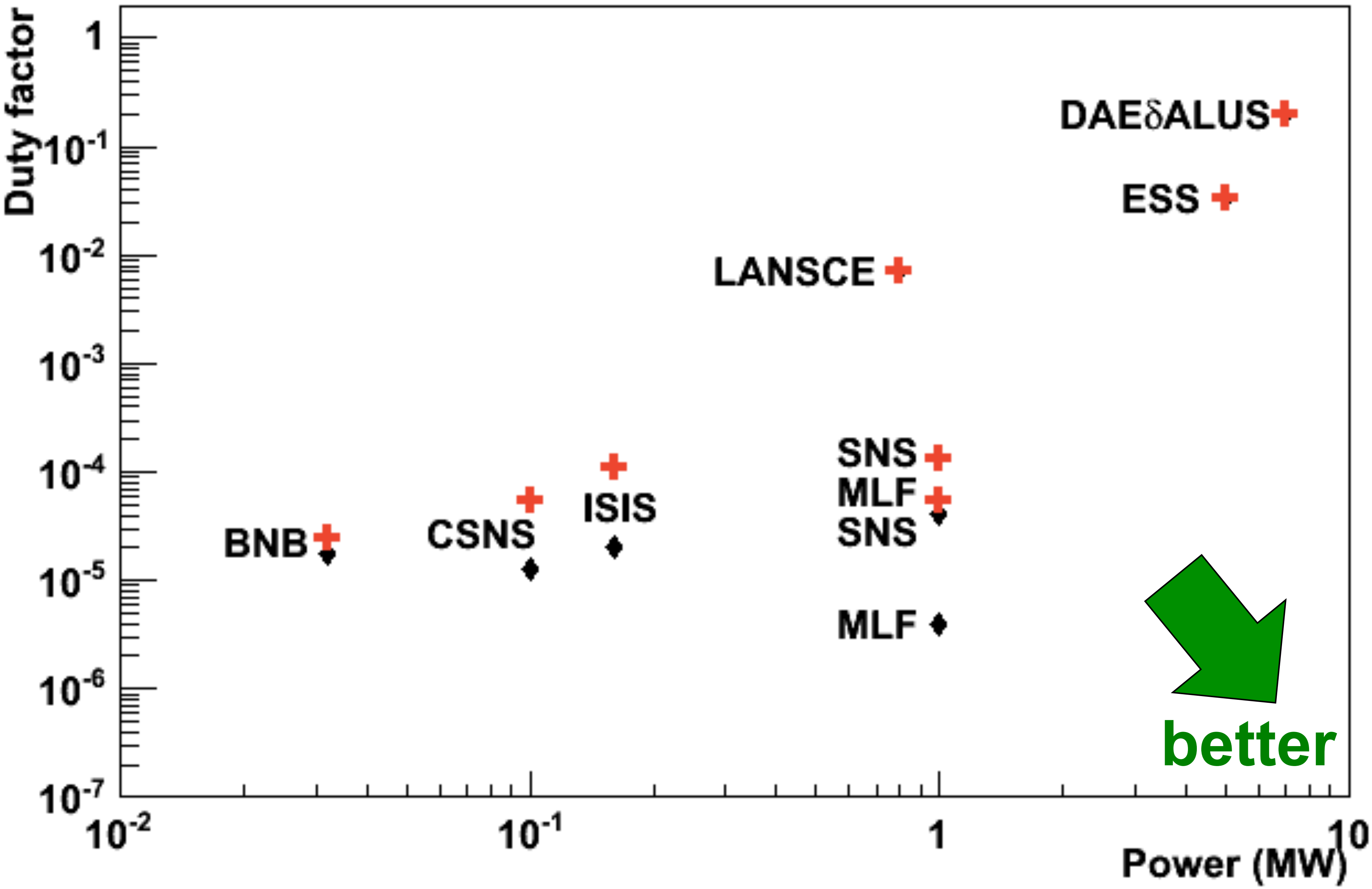


Flux ∝ power
Duty factor = T*rate (◆)

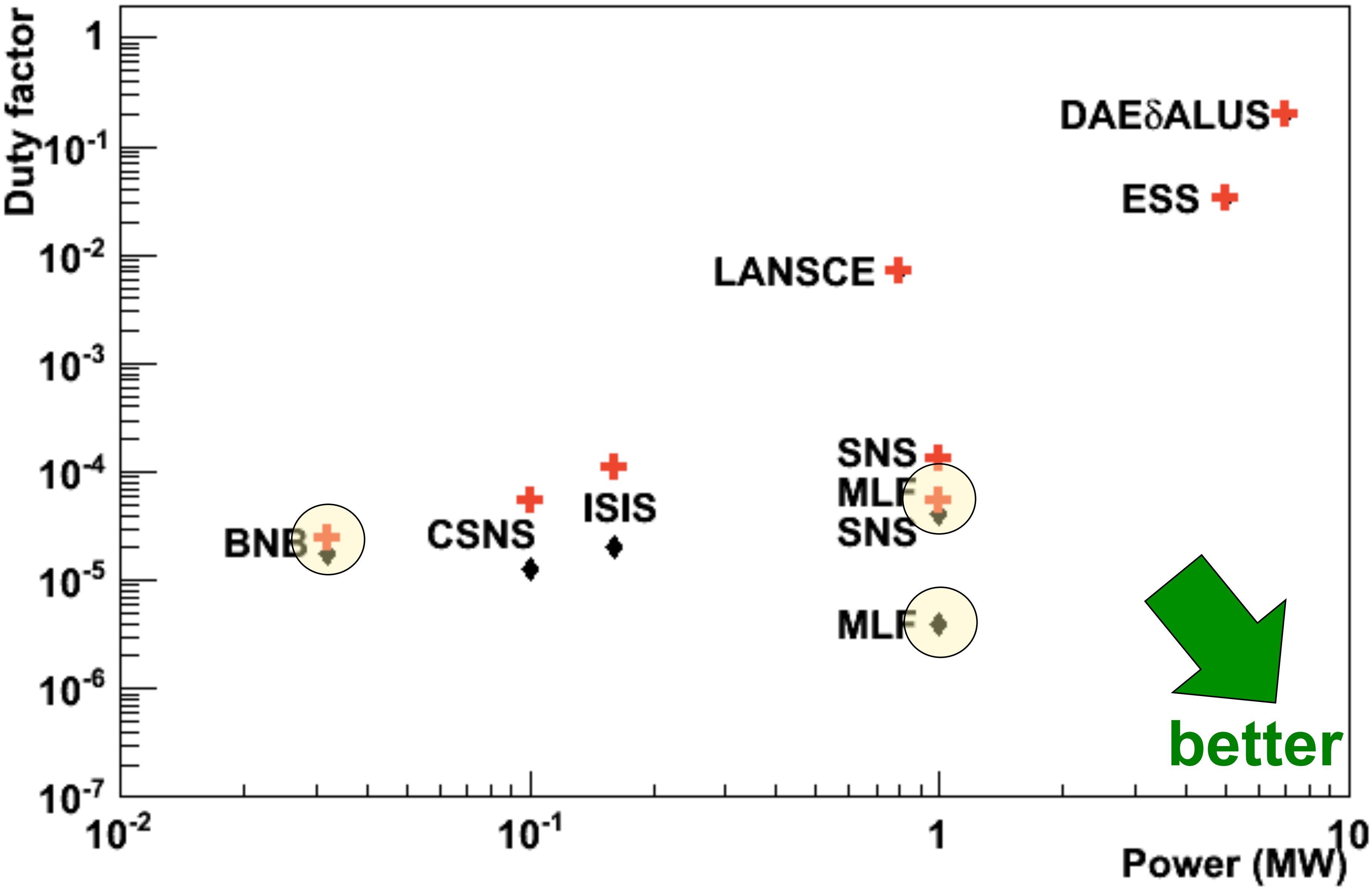


Flux ∝ power
Duty factor = T*rate (◆)
= max(T, 2.2 μs)*rate (+ for μdk ν's)

it doesn't help that much to be faster than μdk timescale



Flux $\propto$ power, ◯ high energy protons (non-DAR contamination)
Duty factor = T*rate (◆)
= max(T, 2.2 μs)*rate (+ for μdk ν's)



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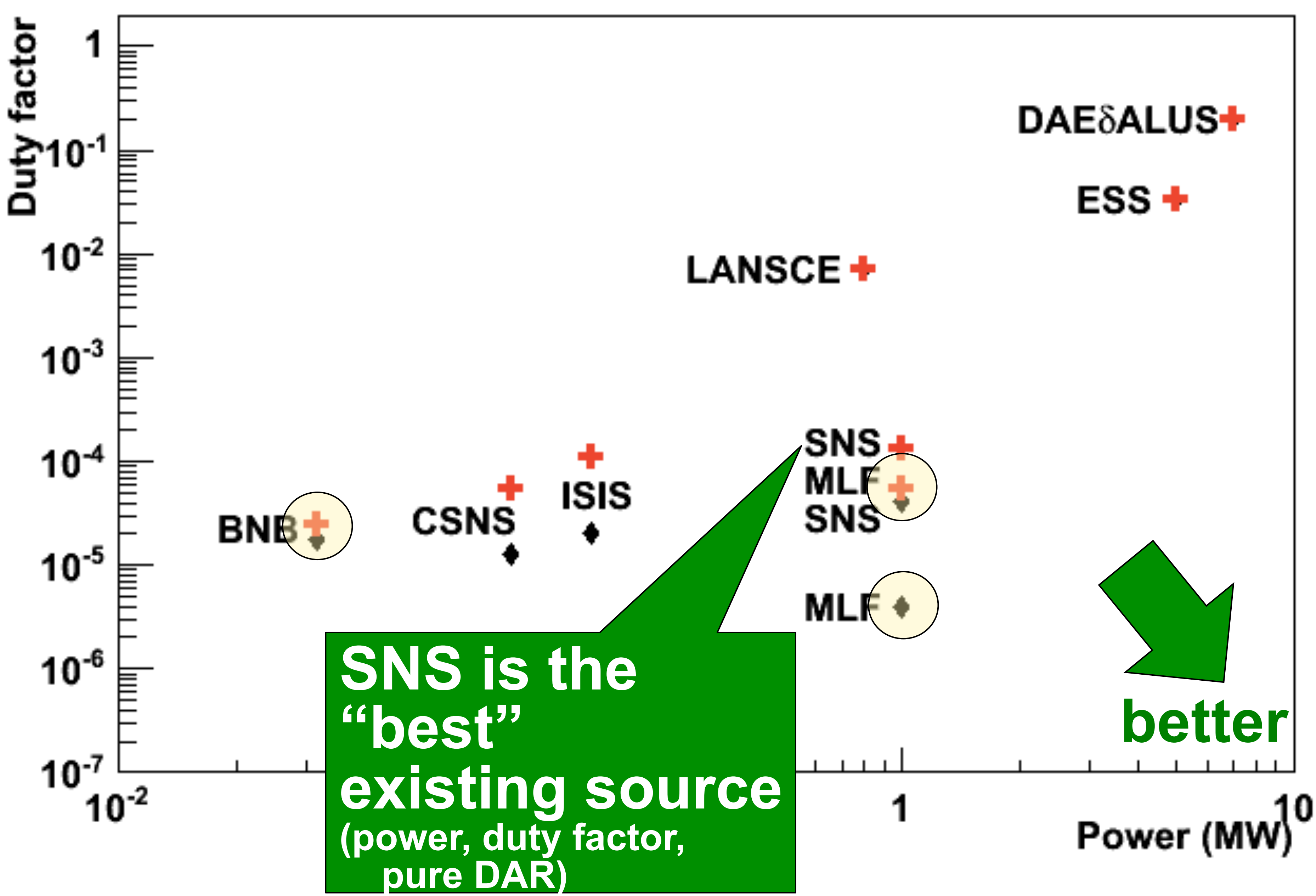


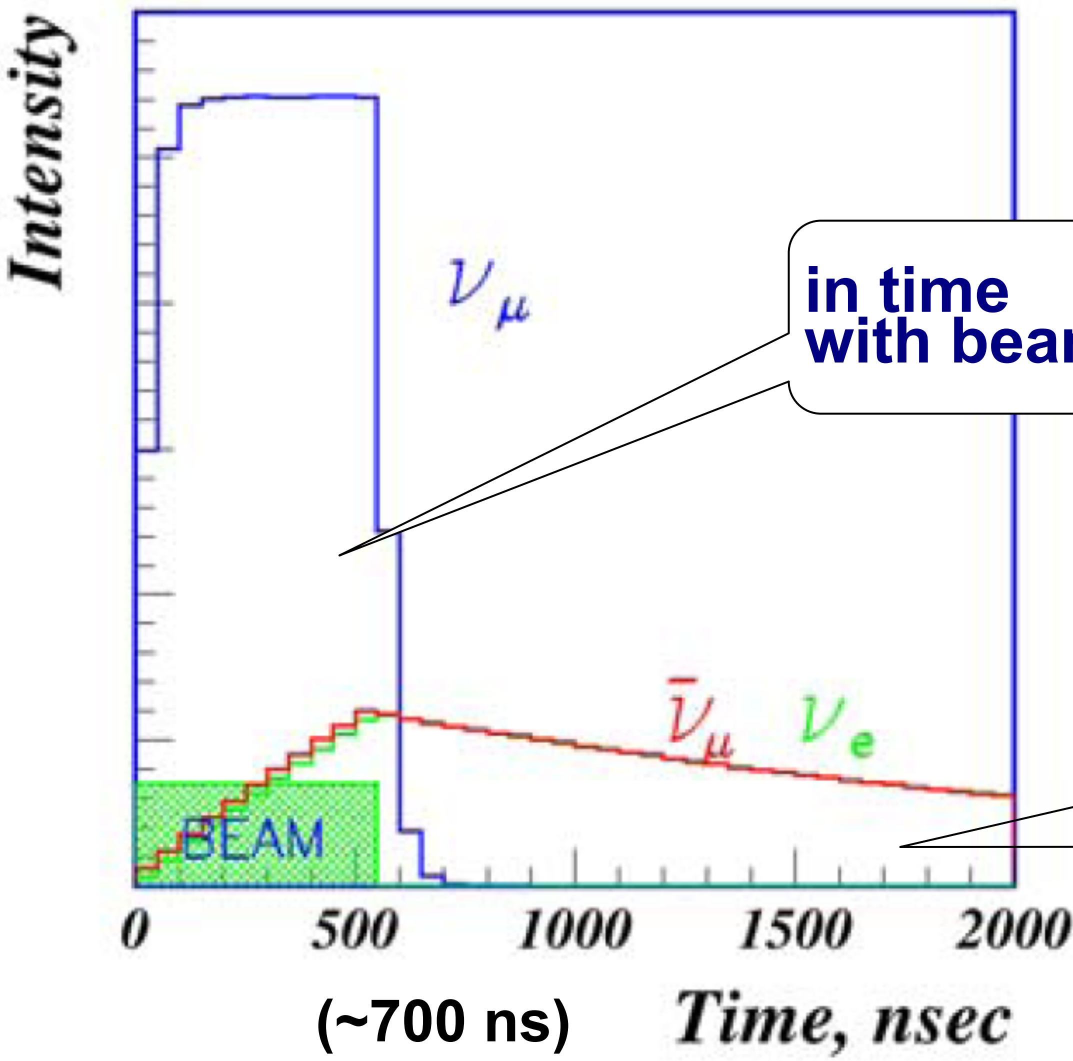
Prospects at the SNS: Free Neutrinos!

These are *not* crummy old cast-off neutrinos...

They are of the highest quality!

Time structure of the SNS source

F. Avignone and Y. Efremenko, J. Phys. G: 29 (2003) 2615-2628

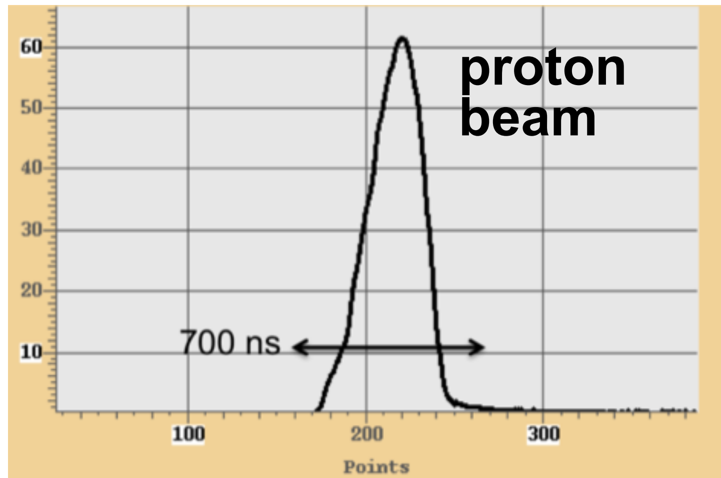


in time with beam

(~700 ns)

delayed on μ decay timescale (2.2 μs)

60 Hz *pulsed* source



proton beam

Background rejection factor ~few x 10^{-4}

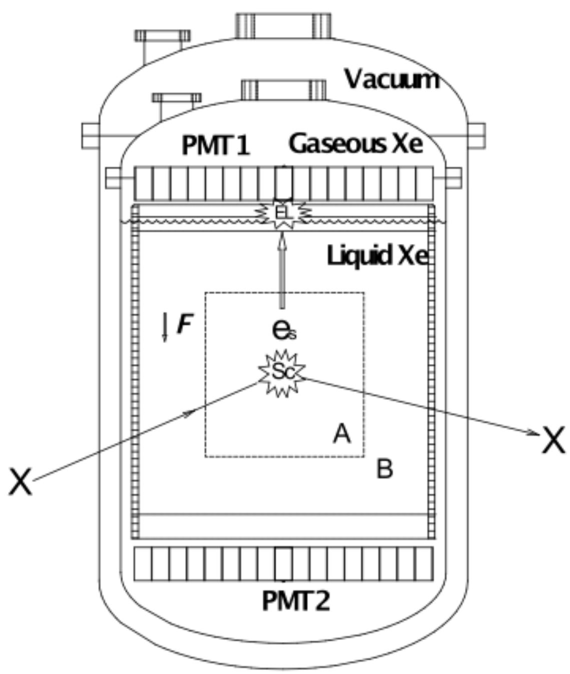
Neutrino flux: few times 10^7 /s/cm^2 at 20 m

~0.13 per flavor per proton

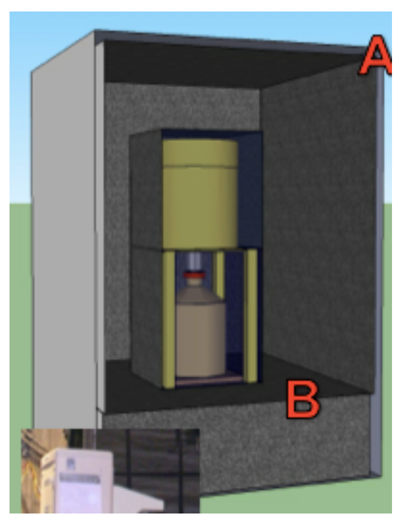
Newly-formed COHERENT collaboration

Three possible technologies under consideration for short-term deployment

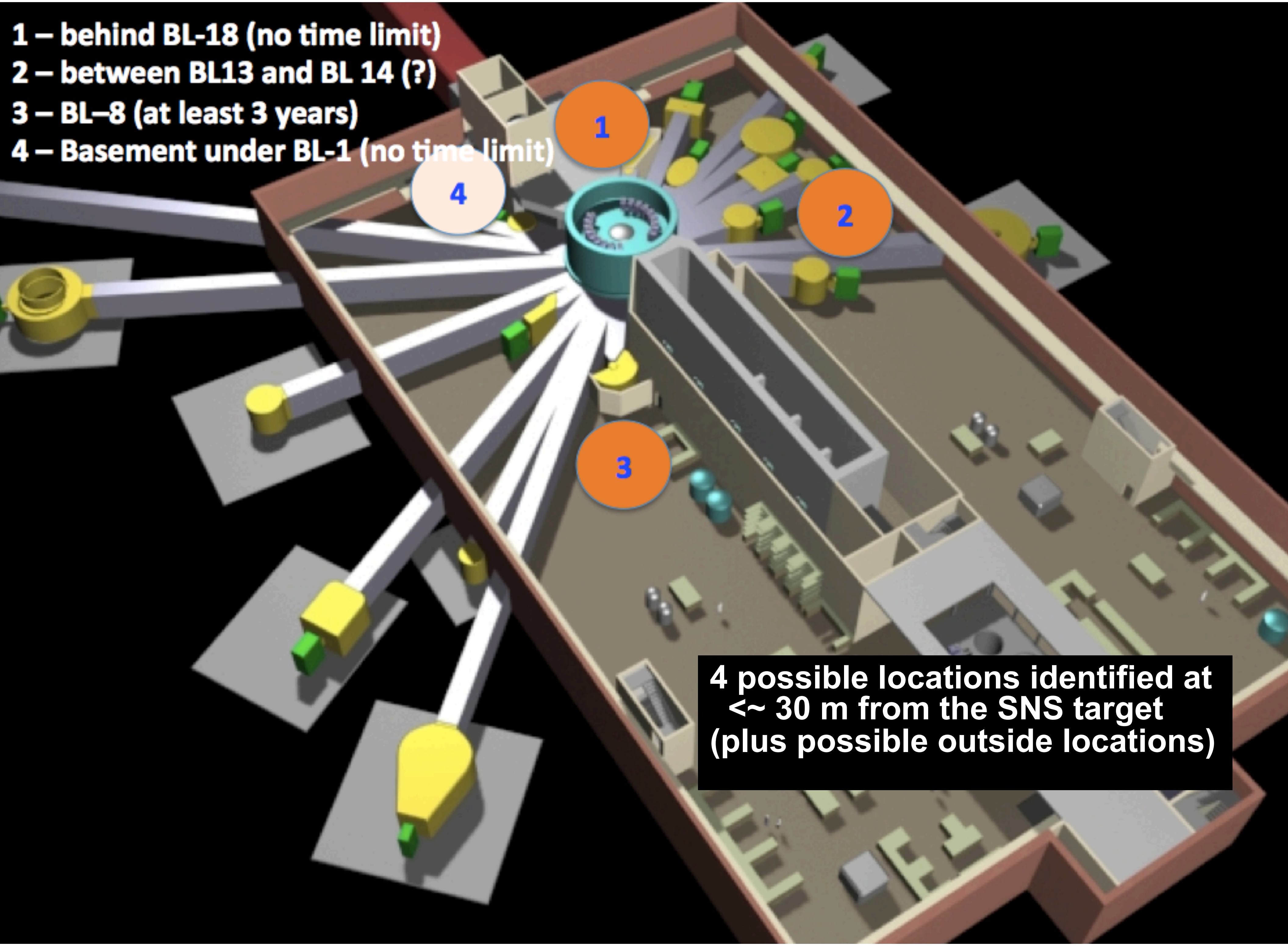
Two-phase LXe



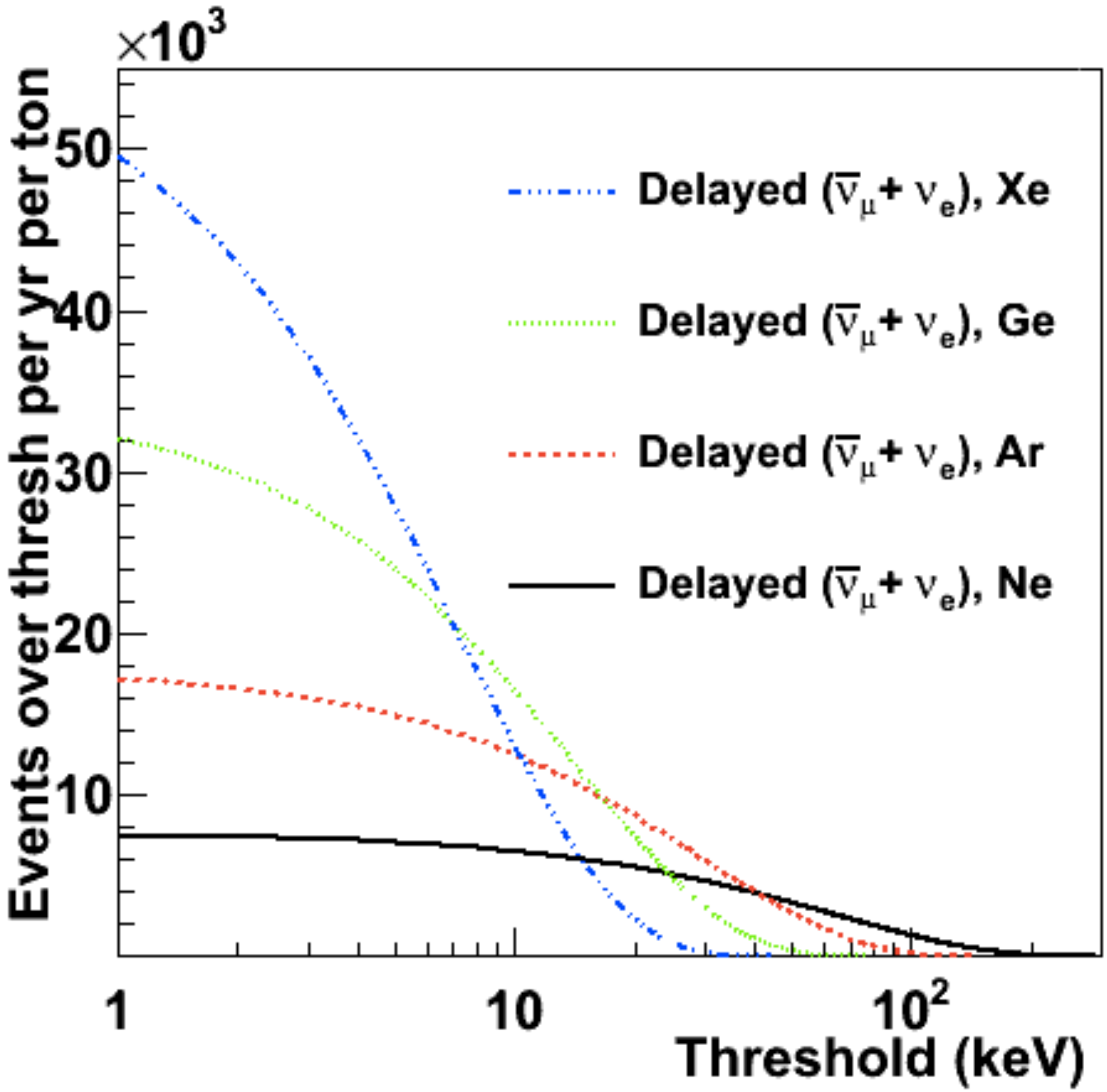
CsI



HPGe PPC


1 – behind BL-18 (no time limit)
2 – between BL13 and BL 14 (?)
3 – BL–8 (at least 3 years)
4 – Basement under BL-1 (no time limit)
1
2
3
4
4 possible locations identified at <~ 30 m from the SNS target (plus possible outside locations)

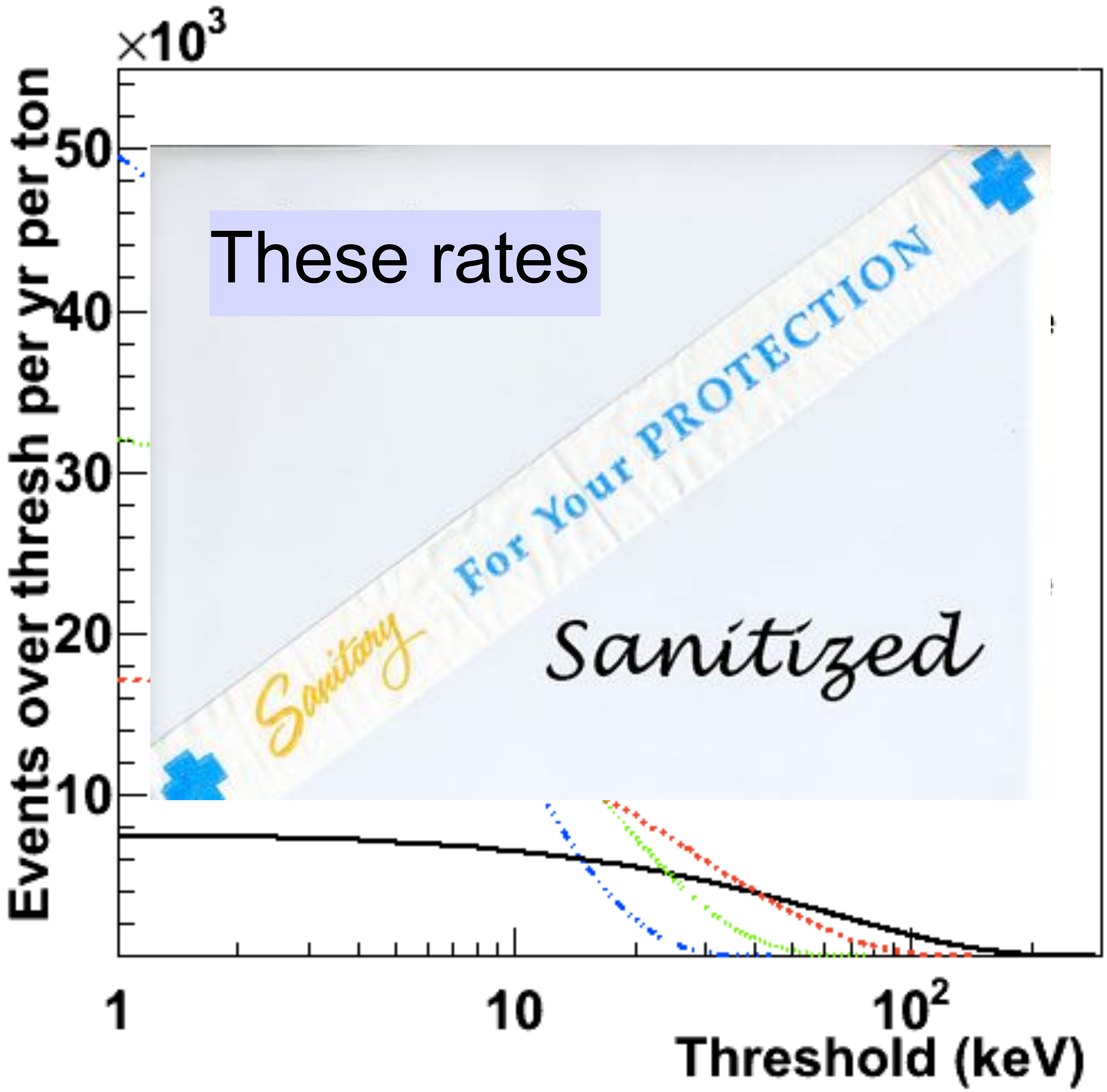
Integrated SNS CENNS yield for various targets



20 m

Lighter nucleus
⇒ expect fewer interactions, but more at higher energy

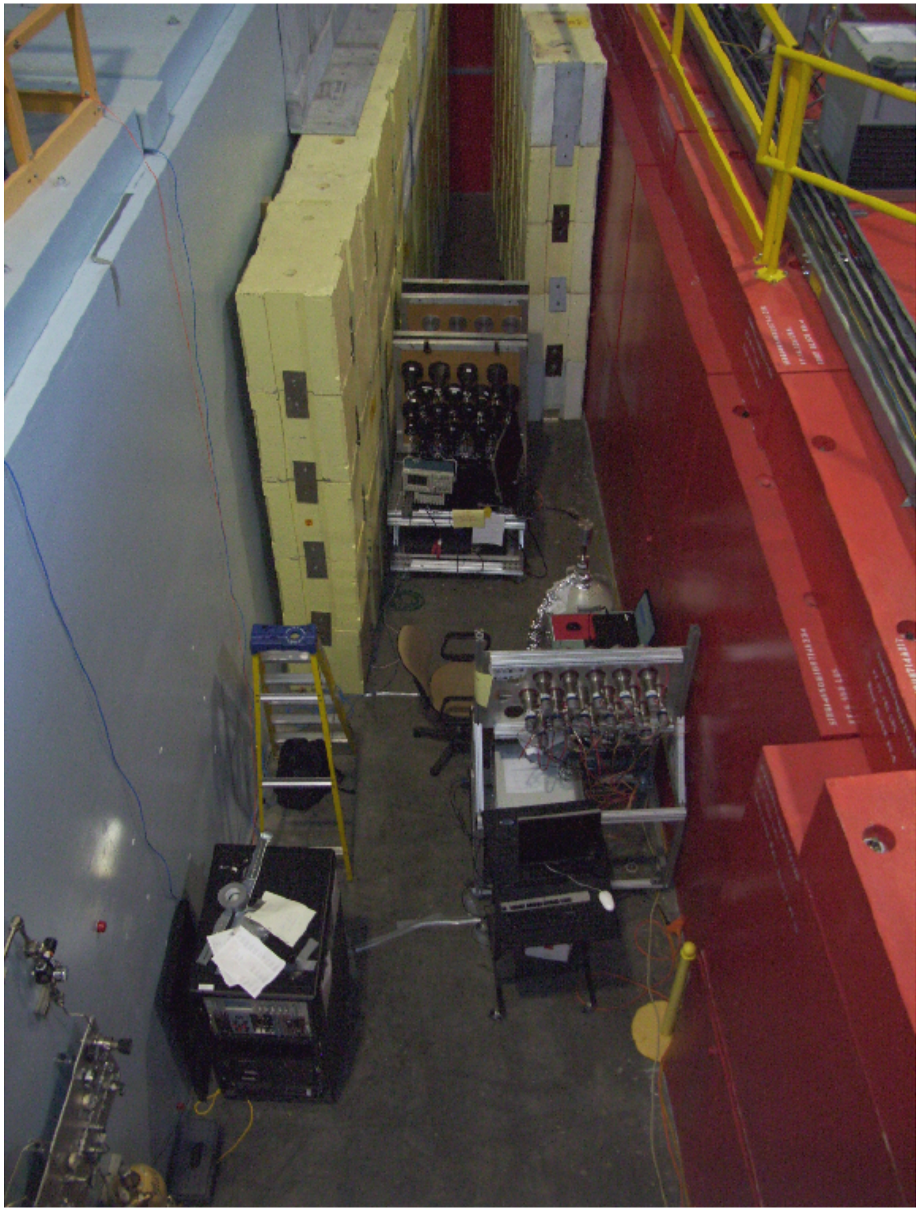
Integrated SNS CENNS yield for various targets



20 m

➔Neutron background is a serious concern...

Neutron background measurements underway inside the SNS target building: so far sites 2, 4



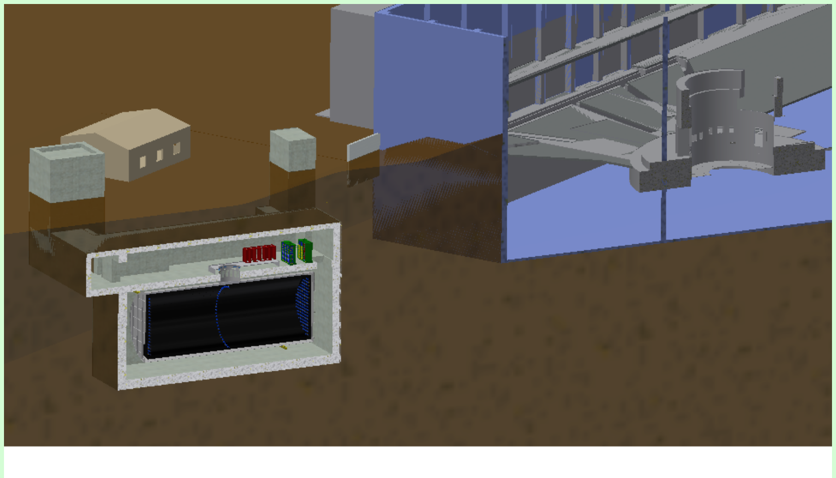
- Scintillator array (ORNL)
- Neutron scatter camera (Sandia)
- BEGe (LBNL)

Data under analysis... preliminary results show site 4 is promising

Proposal planned for fall

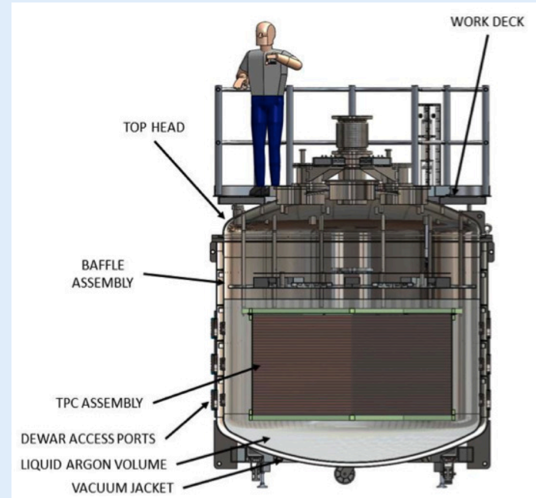
Other neutrino experiments proposed for the SNS

OscSNS



- 800-ton, 10-m long scintillator detector @ 60 m
- primary goal is direct test of LSND anomaly
- cross sections on ^{12}C also possible

CAPTAIN



- 5-ton LArTPC
- SN-relevant cross sections on argon
- current run plan is far off-axis @FNAL BNB before SNS

Common concerns with COHERENT (flux, background)

More information

Comprehensive white paper on neutrino physics opportunities at the SNS

arXiv.org > hep-ex > arXiv:1211.5199

Search or Articl

High Energy Physics – Experiment

Opportunities for Neutrino Physics at the Spallation Neutron Source: A White Paper

A. Bolozdynya, F. Cavanna, Y. Efremenko, G. T. Garvey, V. Gudkov, A. Hatzikoutelis, W. R. Hix, W. C. Louis, J. M. Link, D. M. Markoff, G. B. Mills, K. Patton, H. Ray, K. Scholberg, R. G. Van de Water, C. Virtue, D. H. White, S. Yen, J. Yoo

(Submitted on 22 Nov 2012)

Snowmass white paper on CENNS measurements

arXiv.org > hep-ex > arXiv:1310.0125

Search or Artic

High Energy Physics – Experiment

Coherent Scattering Investigations at the Spallation Neutron Source: a Snowmass White Paper

D. Akimov, A. Bernstein, P. Barbeau, P. Barton, A. Bolozdynya, B. Cabrera-Palmer, F. Cavanna, V. Cianciolo, J. Collar, R.J. Cooper, D. Dean, Y. Efremenko, A. Etenko, N. Fields, M. Foxe, E. Figueroa-Feliciano, N. Fomin, F. Gallmeier, I. Garishvili, M. Gerling, M. Green, G. Greene, A. Hatzikoutelis, R. Henning, R. Hix, D. Hogan, D. Hornback, I. Jovanovic, T. Hossbach, E. Iverson, S.R. Klein, A. Khromov, J. Link, W. Louis, W. Lu, C. Mauger, P. Marleau, D. Markoff, R.D. Martin, P. Mueller, J. Newby, J. Orrell, C. O'Shaughnessy, S. Pentilla, K. Patton, A.W. Poon, D. Radford, D. Reyna, H. Ray, K. Scholberg, V. Sosnovtsev, R. Tayloe, K. Vetter, C. Virtue, J. Wilkerson, J. Yoo, C.H. Yu

“CSI” is now “COHERENT”

Summary: Part I

Cross sections on nuclei in the few tens-of-MeV regime are very poorly understood
... measurements especially relevant for SN neutrinos

CENNS also never before measured, and now within reach with WIMP detector technology

Stopped-pion neutrinos offer opportunities for these measurements

The SNS is the current "best" facility

Background measurements for COHERENT underway; multiple detector technologies under consideration

Part II Outline

Determining absolute neutrino mass

(Cosmology)

Kinematic experiments

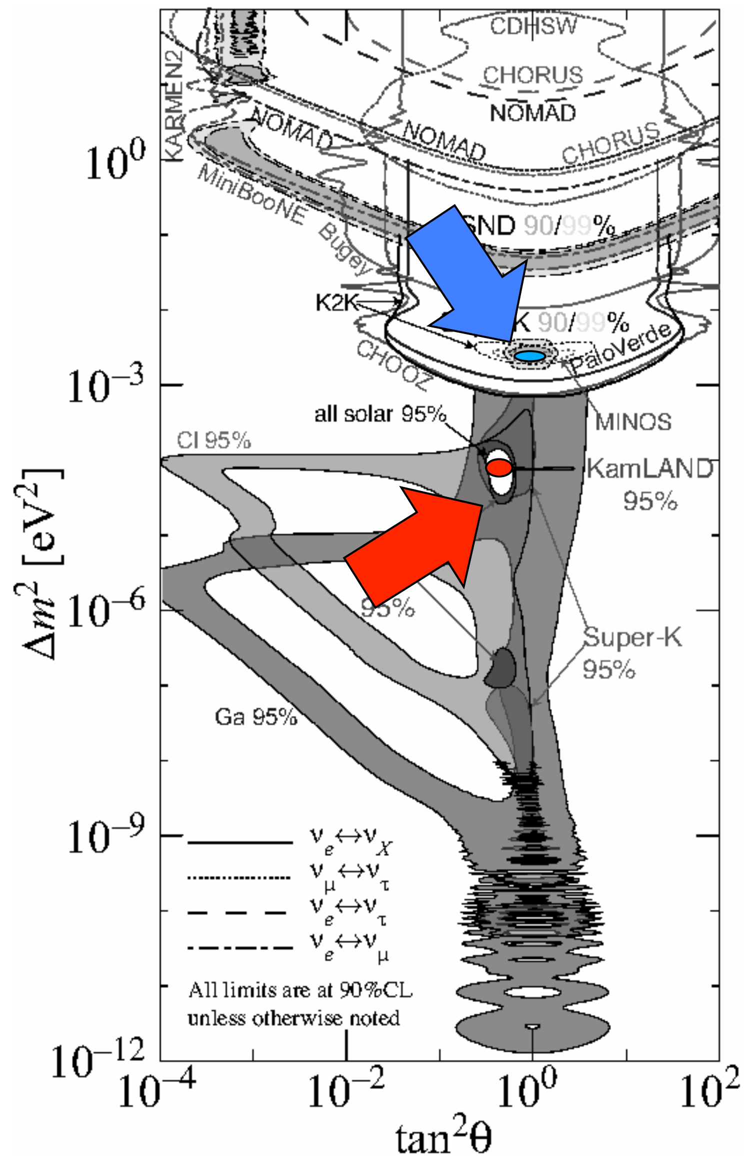
- MAC-E Filter Spectrometers
- Bolometers
- Project 8

Prospects

From oscillations (in the 3-flavor picture) we know there are at least two non-zero mass states

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

$$P(\nu_f \rightarrow \nu_g) = \delta_{fg} - 4 \sum_{i>j} \Re(U^*_{fi} U_{gi} U_{fj} U^*_{gj}) \sin^2(1.27 \Delta m^2_{ij} L/E)$$
$$\pm 2 \sum_{i>j} \Im(U^*_{fi} U_{gi} U_{fj} U^*_{gj}) \sin(2.54 \Delta m^2_{ij} L/E)$$

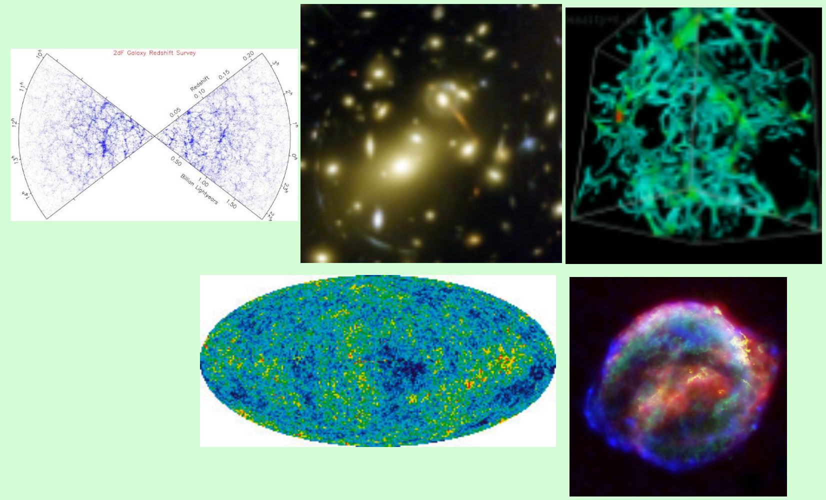


Recall: oscillations inform only about mass ***differences***... what about absolute mass scale?

Cosmology: information on absolute neutrino mass

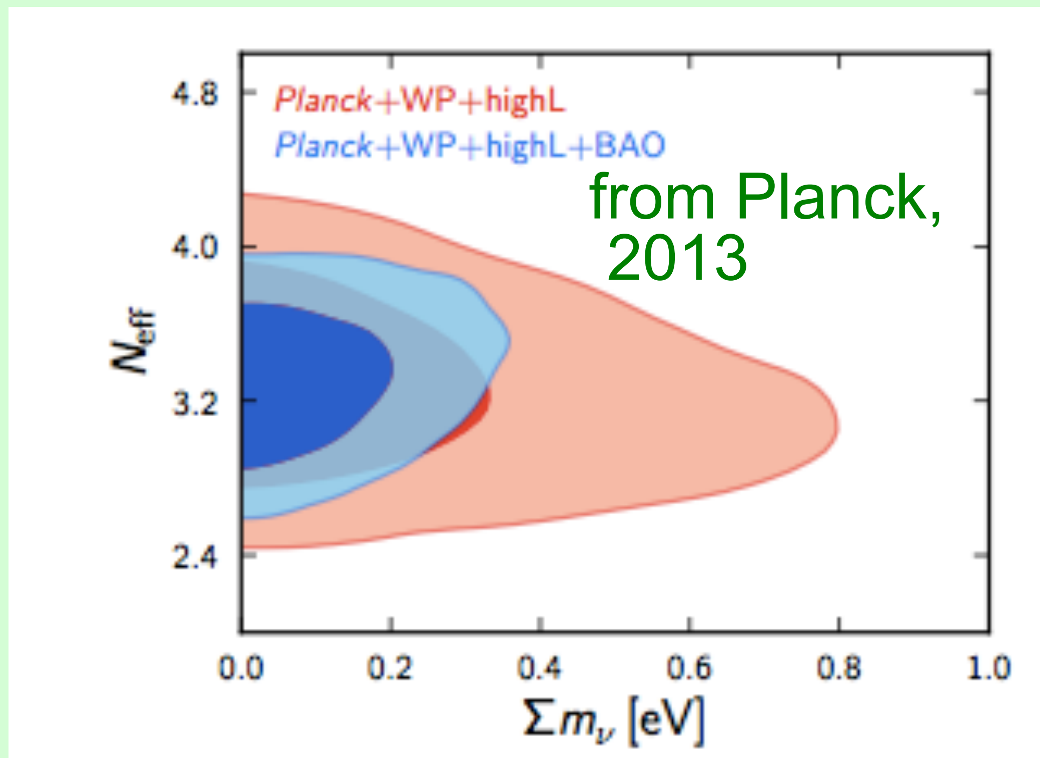
Fits to cosmological data:
CMB, large scale structure,
high Z supernovae,
weak lensing,...

(model-dependent)

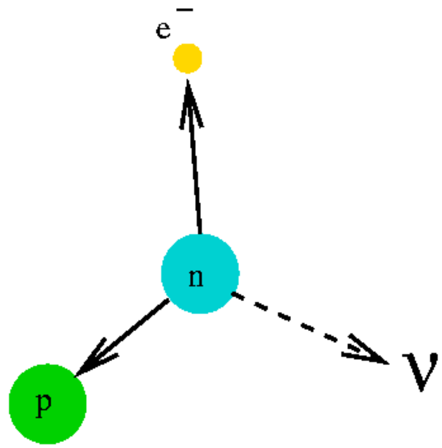


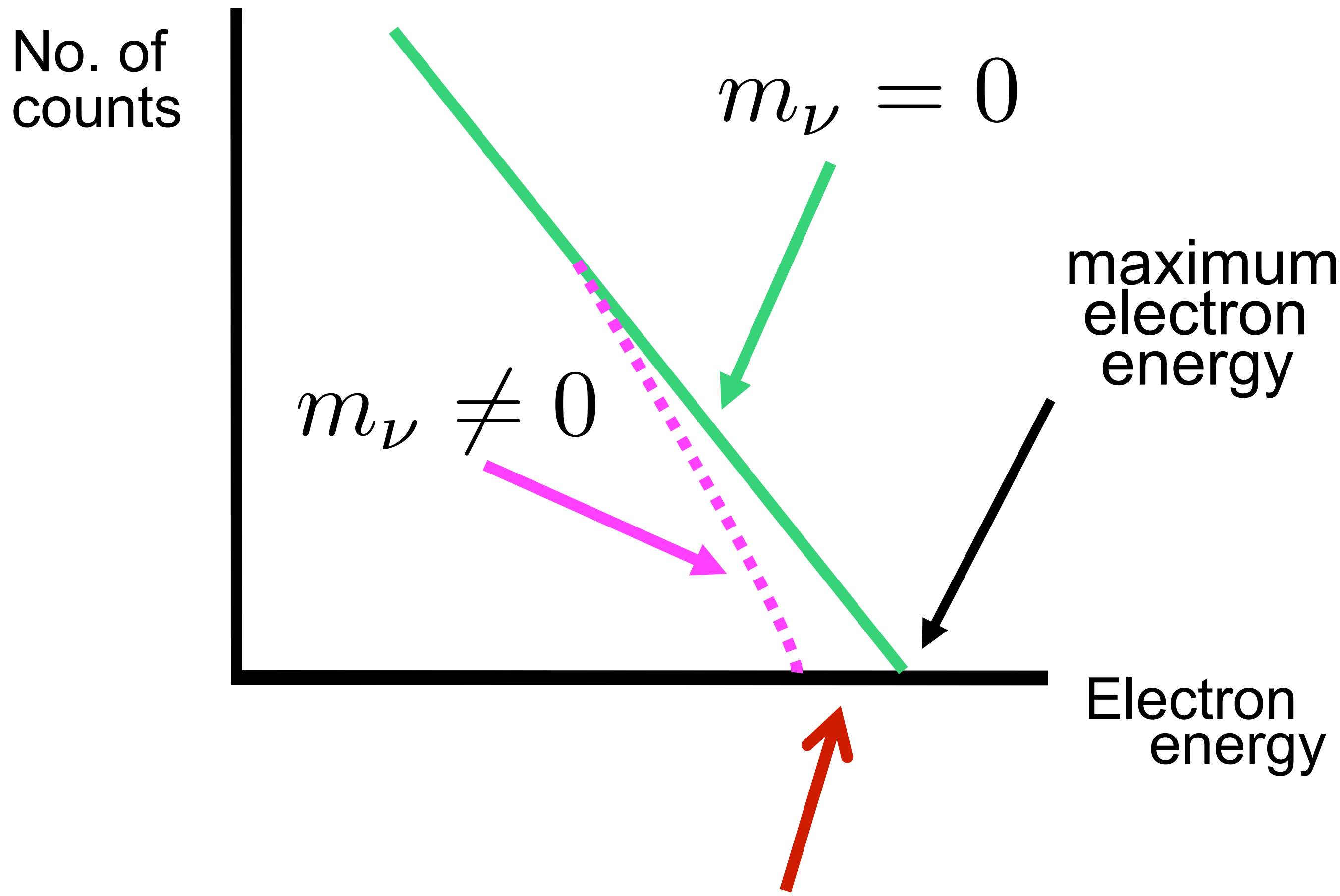
Information on **sum** of neutrino masses

$$\sum m_i <\sim 0.6 \text{ eV}$$



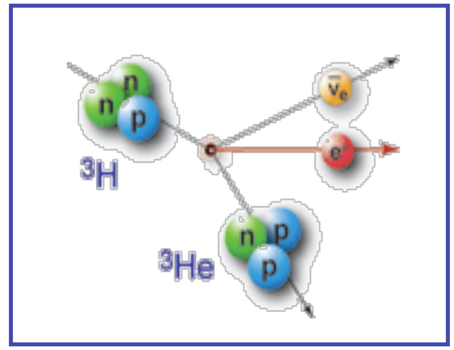
Kinematic experiments for absolute neutrino mass





Look for distortion of β-decay spectrum near endpoint

Tritium beta spectrum,
including flavor mixing



$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\rm nuc}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$

$$m_i^2 = \Delta m_{i0}^2 + m_0^2$$

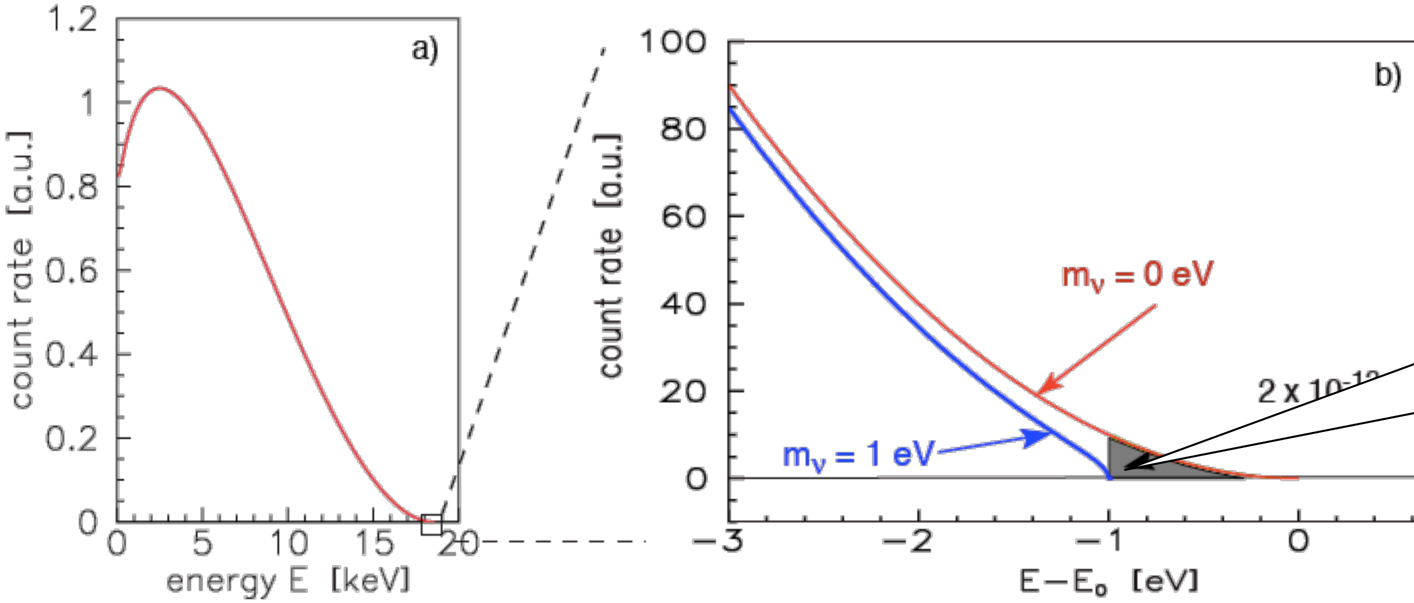
from oscillations

mass scale

flavor mixing

neutrino masses

T: electron kinetic energy



tiny fraction of the decays!

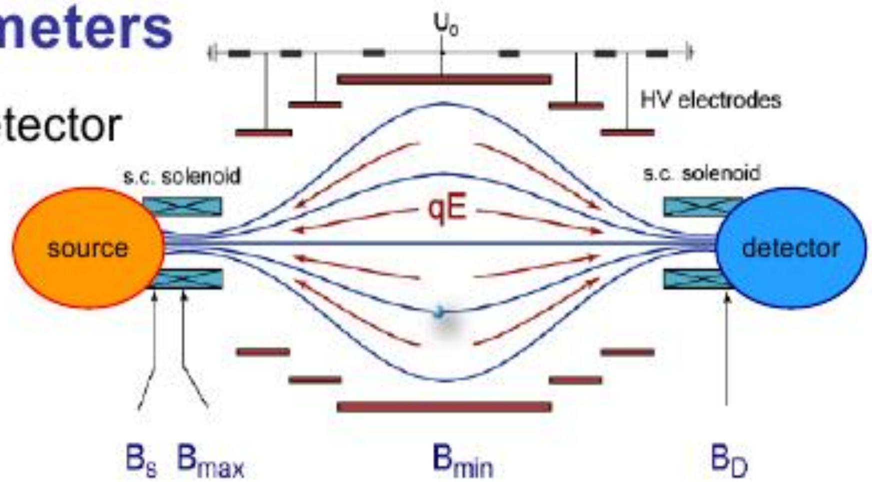
H. Robertson

Need: *statistics*, *energy resolution*

Experimental approaches: aiming for sub-eV sensitivity

Spectrometers

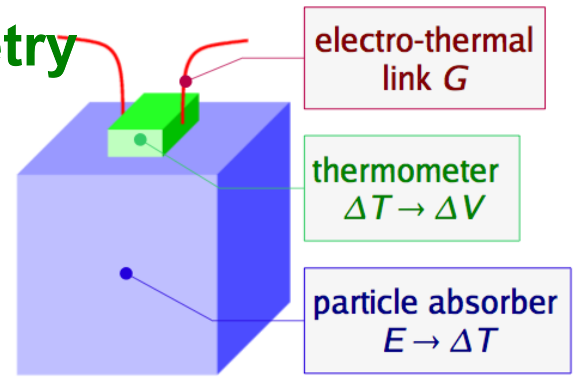
Source ≠ Detector



$$^3\mathrm{H} \rightarrow ^3\mathrm{He} + e^- + \bar{\nu}_e$$

18.6 keV endpoint

Thermal calorimetry

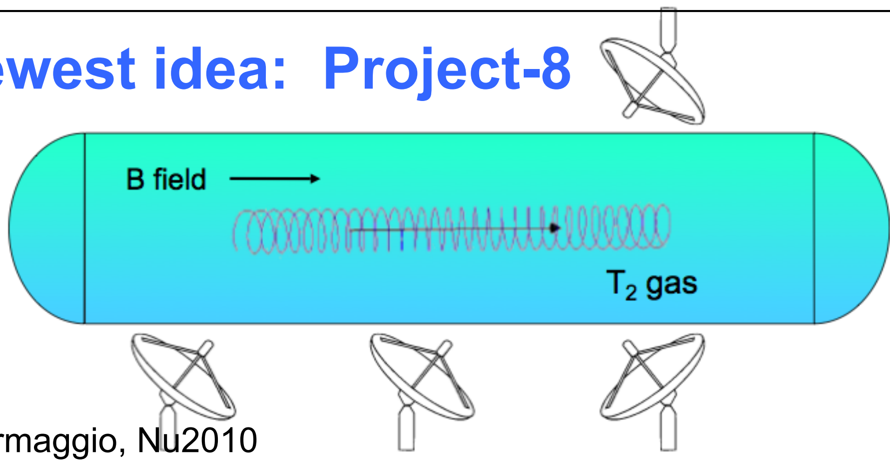


A. Nucciotti, Nu2010

$$^{187}\mathrm{Re} \rightarrow ^{187}\mathrm{Os} + e^- + \bar{\nu}_e$$

2.5 keV endpoint
MARE

Newest idea: Project-8

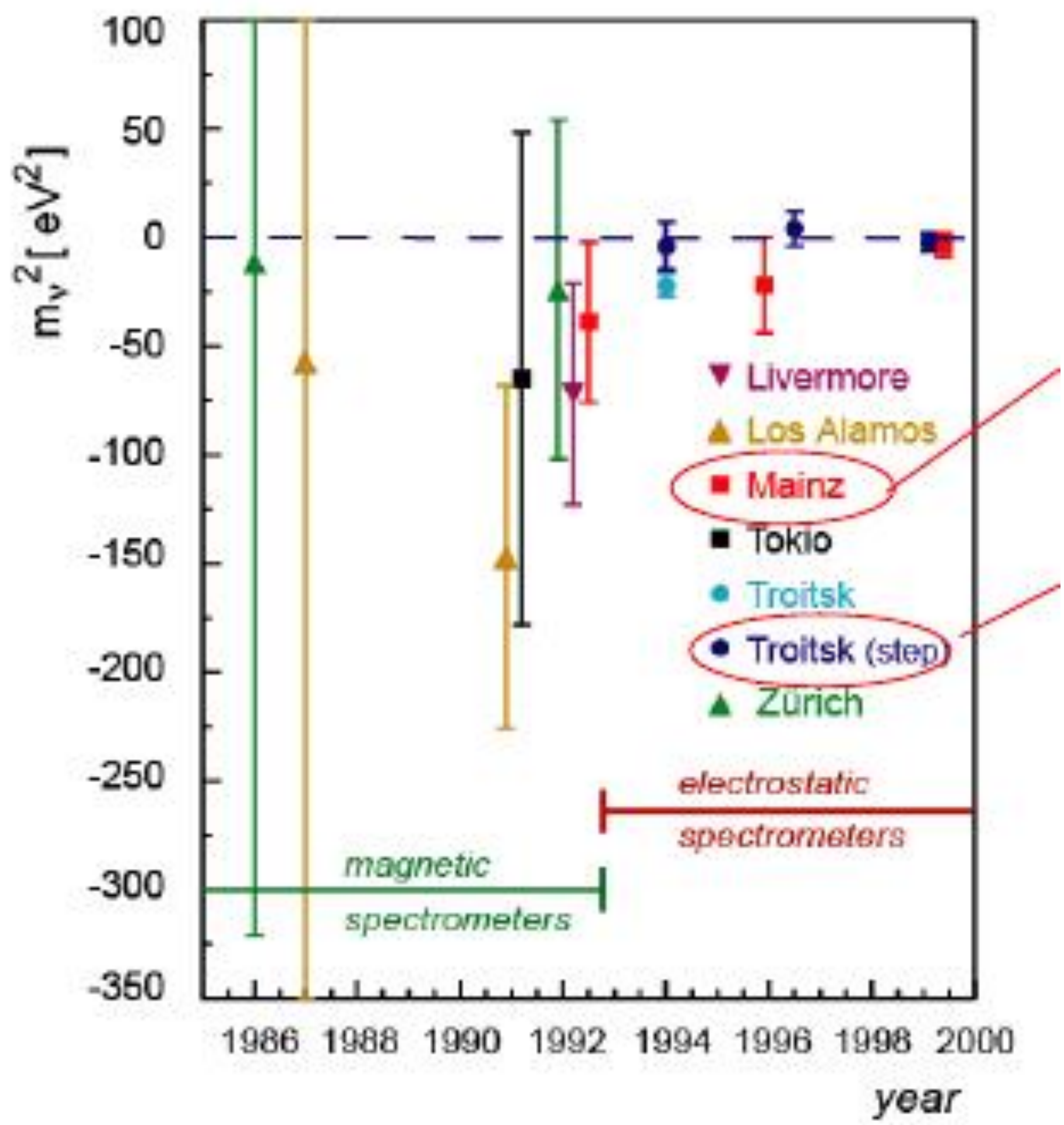


J. Formaggio, Nu2010

$$^3\mathrm{H} \rightarrow ^3\mathrm{He} + e^- + \bar{\nu}_e$$

Measure energy via cyclotron frequency

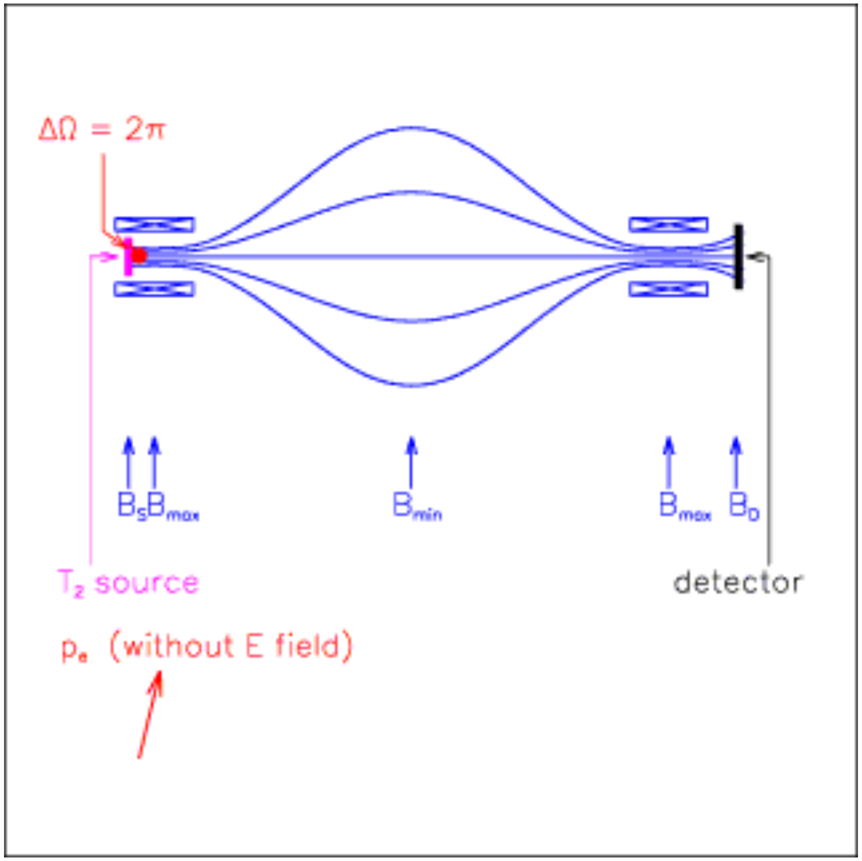
History of ^3H β-decay experiments

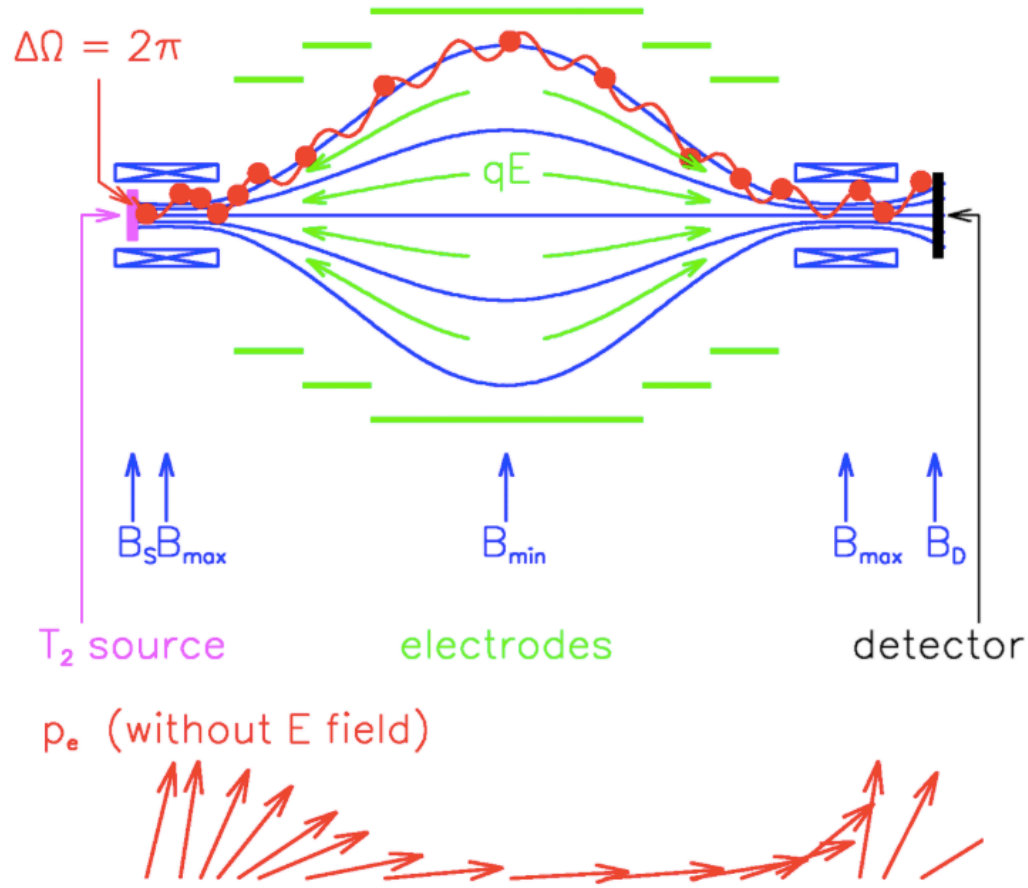


Best limits so far from Mainz and Troitsk spectrometers

MAC-E Filter

(Magnetic Adiabatic Collimation with Electrostatic Filter)





- electrons from T_2 gas guided to low-field region, where electrostatic field filters out low-energy electrons
- need thin source to avoid energy loss by scattering ➔ need large area

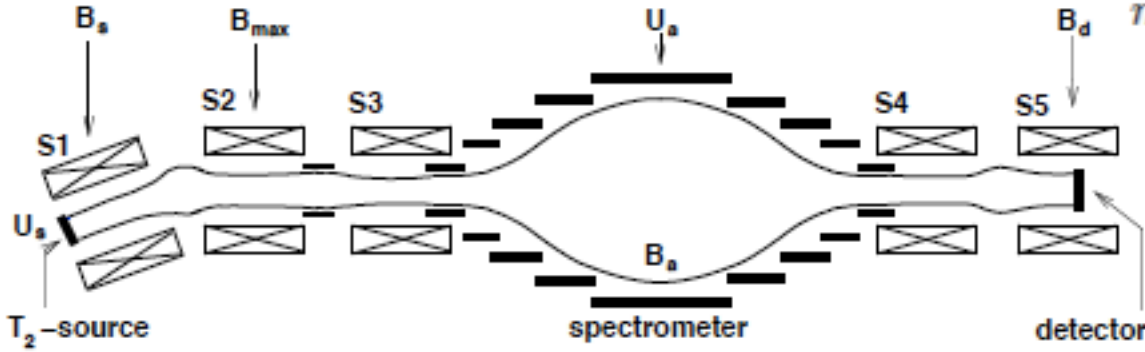
CURRENT STATUS OF DIRECT MASS MEASUREMENT

Mainz: solid T_2, MAC-E filter

C. Kraus et al., Eur. Phys. J. C40, 447 (2005)

$$m^2(\nu_e) = (-0.6 \pm 2.2_{\text{stat}} \pm 2.1_{\text{syst}})$$

$$m(\nu_e) < 2.3\ \text{eV}/\text{c}^2 \quad (95\%\ \text{C.L.})$$

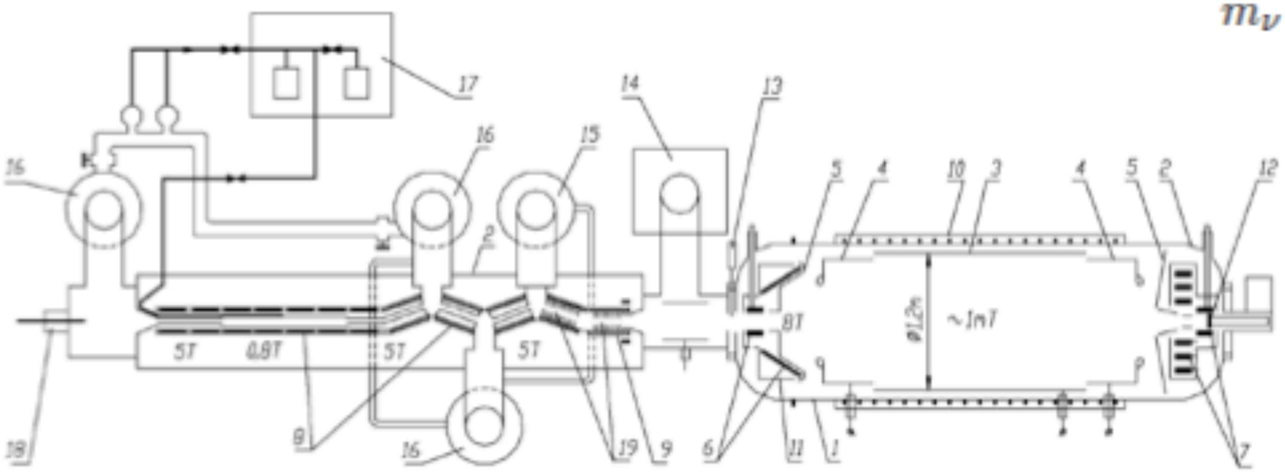


Troitsk: gaseousT_2, MAC-E filter

V. Aseev et al., PRD in press (2011)

$$m_\nu^2 = -0.67 \pm 1.89_{stat} \pm 1.68_{syst}$$

$$m_\nu < 2.05\ eV,\ 95\%\ C.L.$$



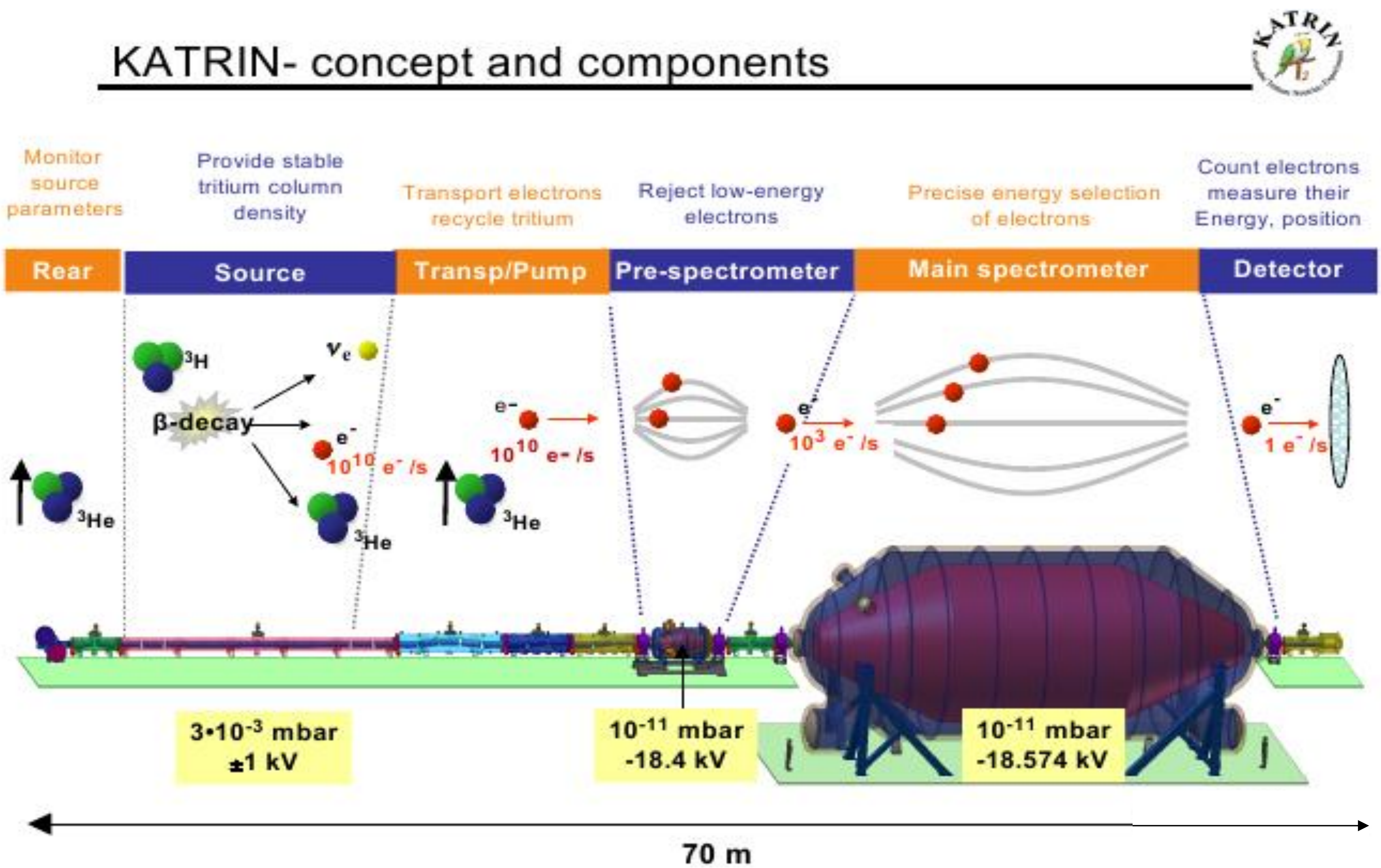
Together:…
$m_\nu < 1.8$ eV
(95% CL)

H. Robertson

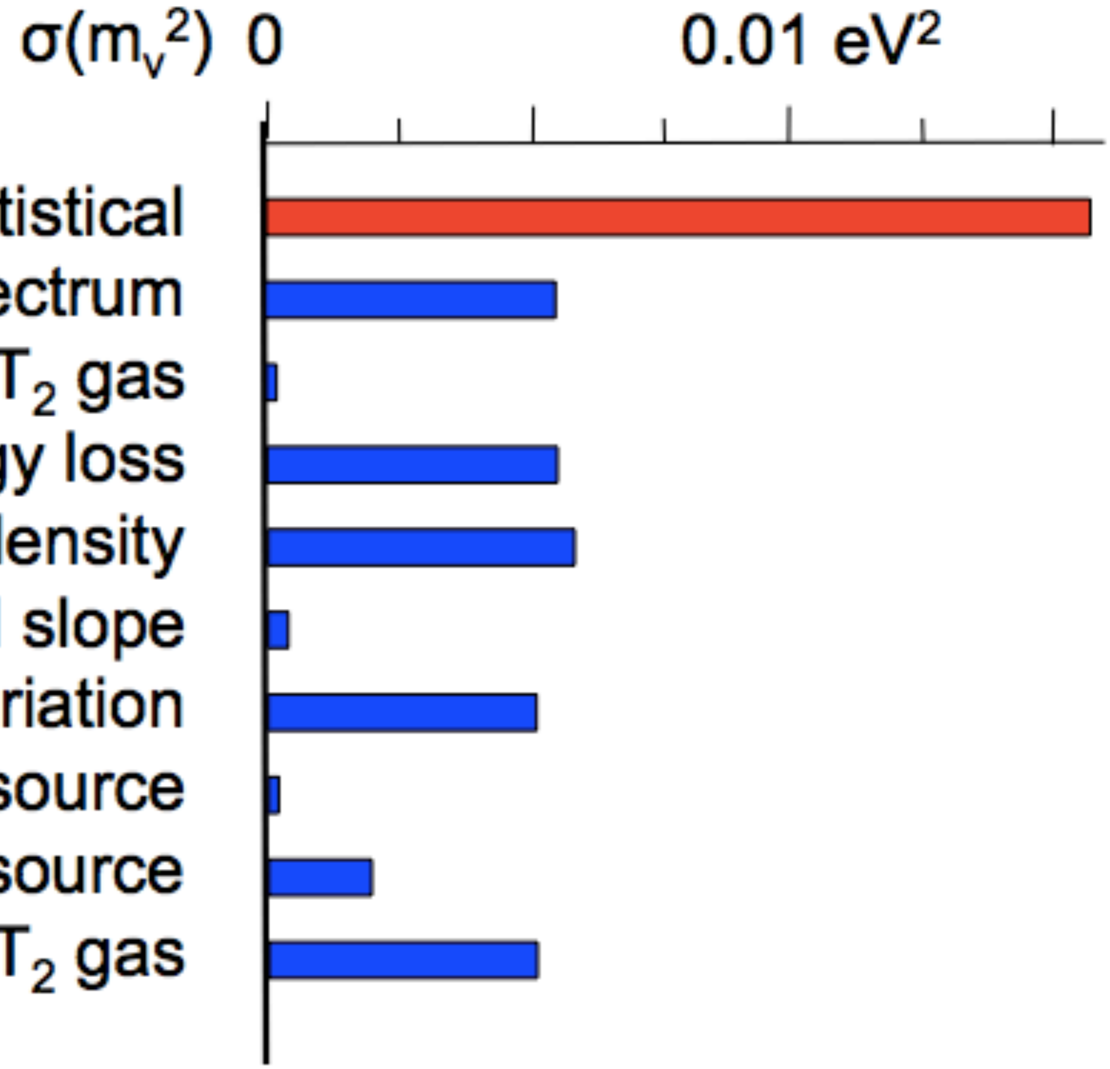
Next plans for *sub-eV* kinematic measurements:

KATRIN in Karslruhe, Germany

~ 75 m long with
40 superconducting solenoids



KATRIN' S UNCERTAINTY BUDGET



Sensitivity down to ~0.2 eV

$\sigma(m_\nu^2)_{total} = 0.025\ eV^2$

$m_\nu < 0.2$ eV (90 % CL)

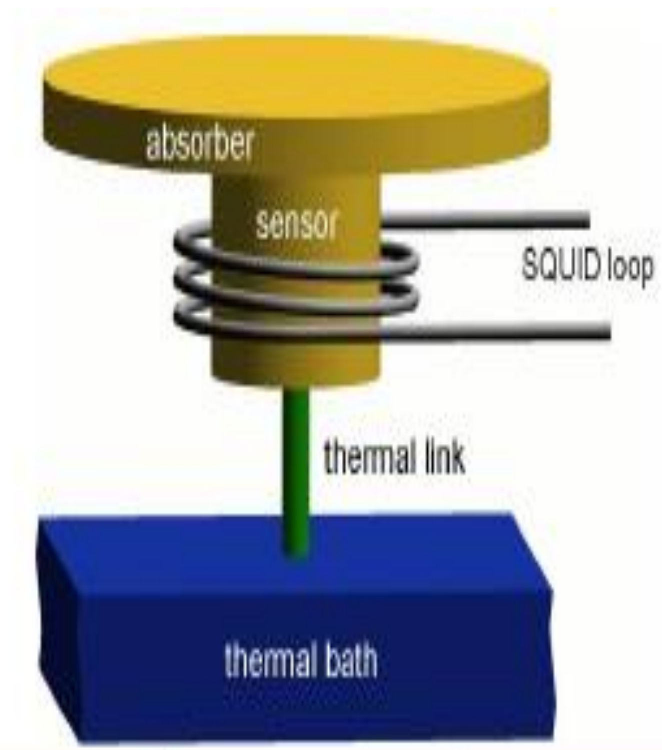
H. Robertson

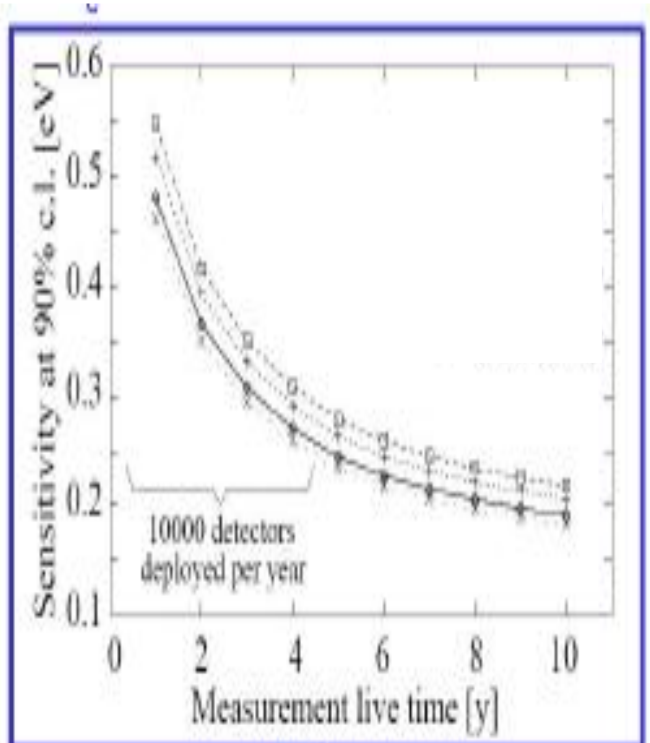
Another experimental approach: **bolometers**

MARE: Microcalorimeter Arrays for a Rhenium Experiment

$$^{187}\mathrm{Re} \rightarrow ^{187}\mathrm{Os} + e^{-} + \bar{\nu}_e$$

2.5 keV endpoint



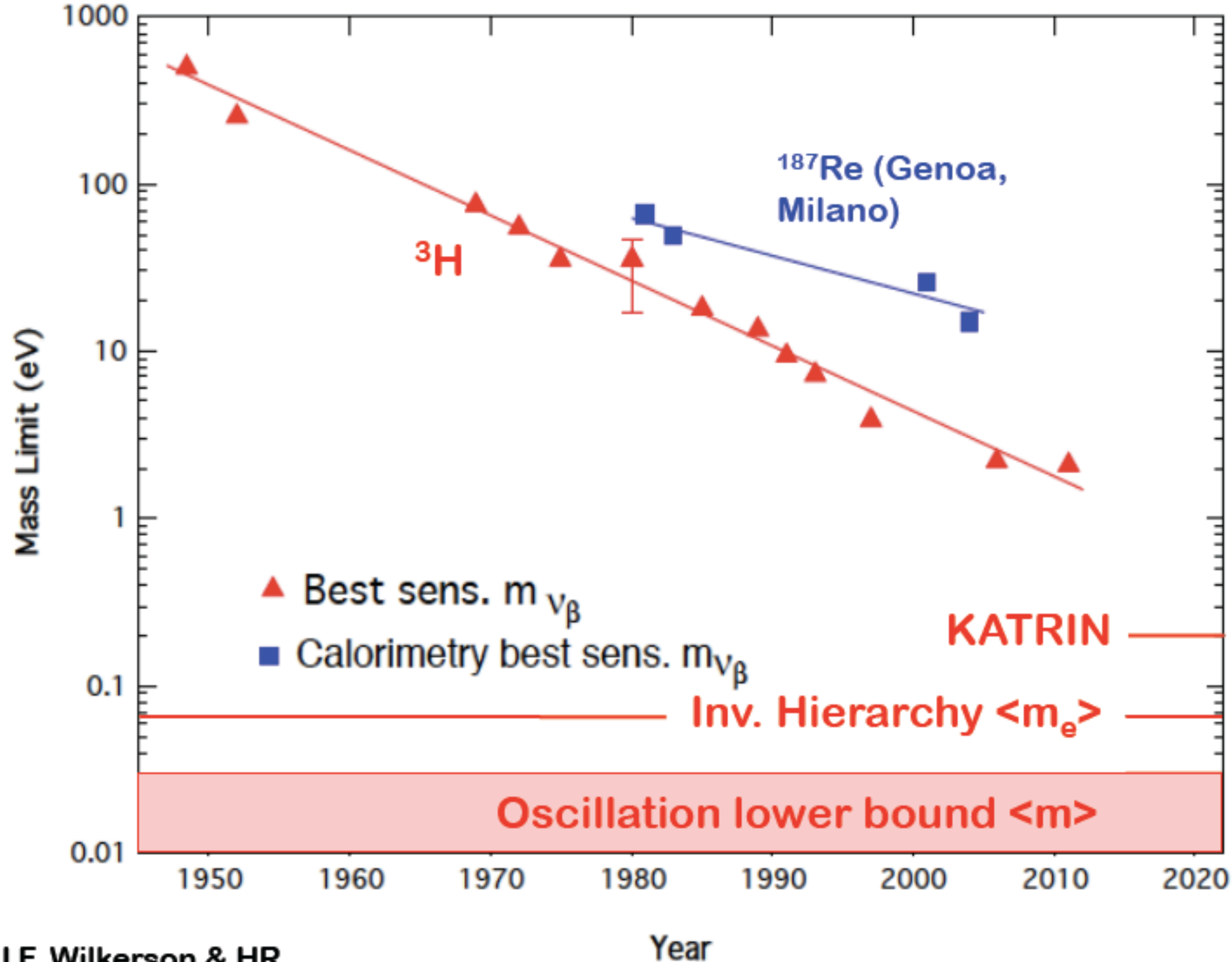


No thin-source requirement and lower energy sources possible...

fraction in endpoint region scales as $(m_\nu/E_0)^3$

... but ^{187}Re has long half-life, and these are hard to scale up

Neutrino mass limits from beta decay



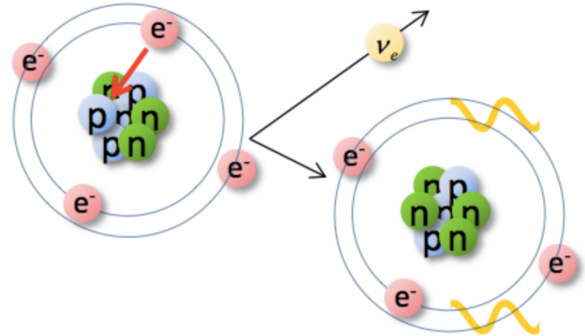
J.F. Wilkerson & HR

H. Robertson

A new fad: **holmium**

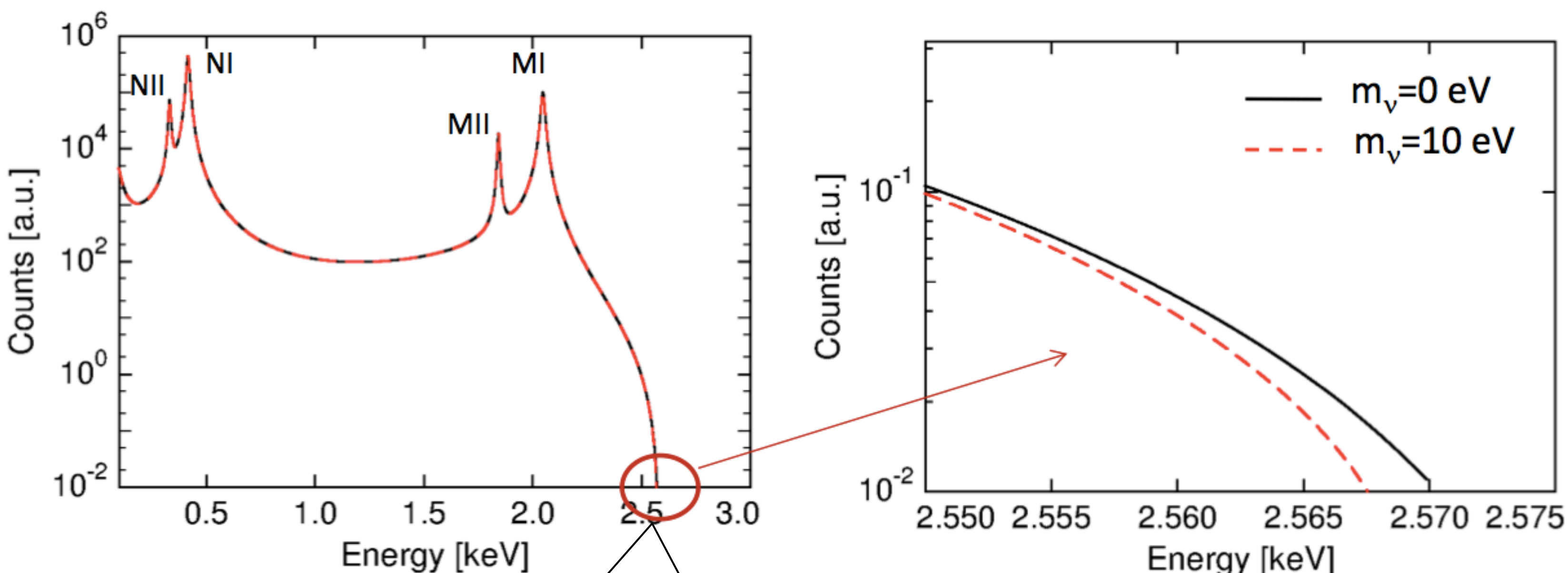
ECHo HOLMES

electron capture decay



$${}^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

$${}^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

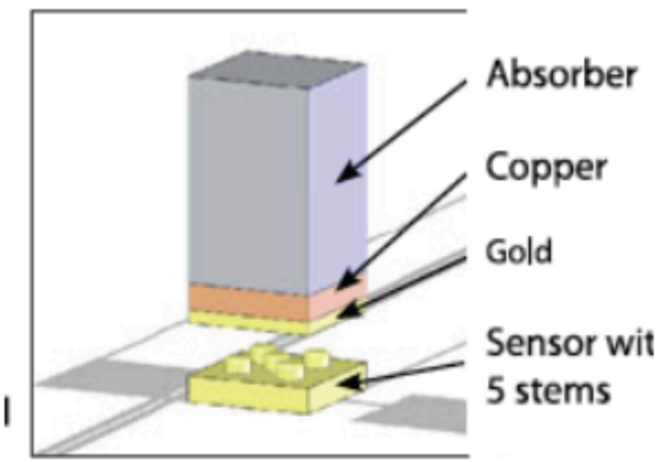


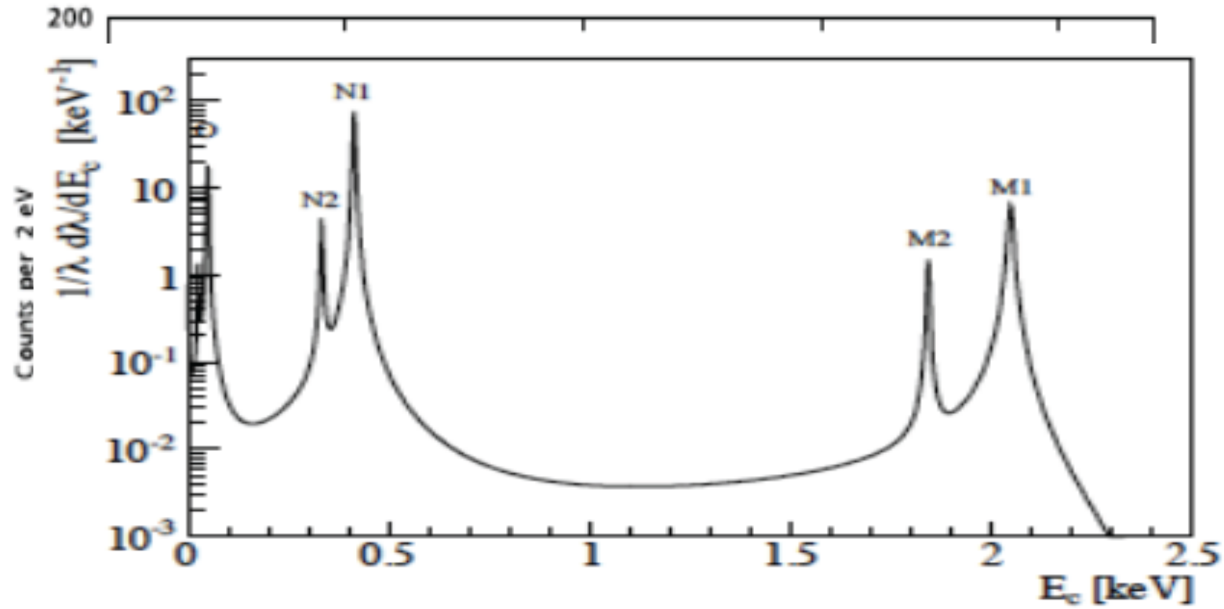
Deexcitation spectrum is affected by neutrino mass

L. Gastaldo

Holmium prospects

- Using low-temperature Metallic Magnetic Calorimeters to study both Re and ^{163}Ho.
  - should be able to achieve ultimate resolution ~ 2 eV and rise-times of 90 ns



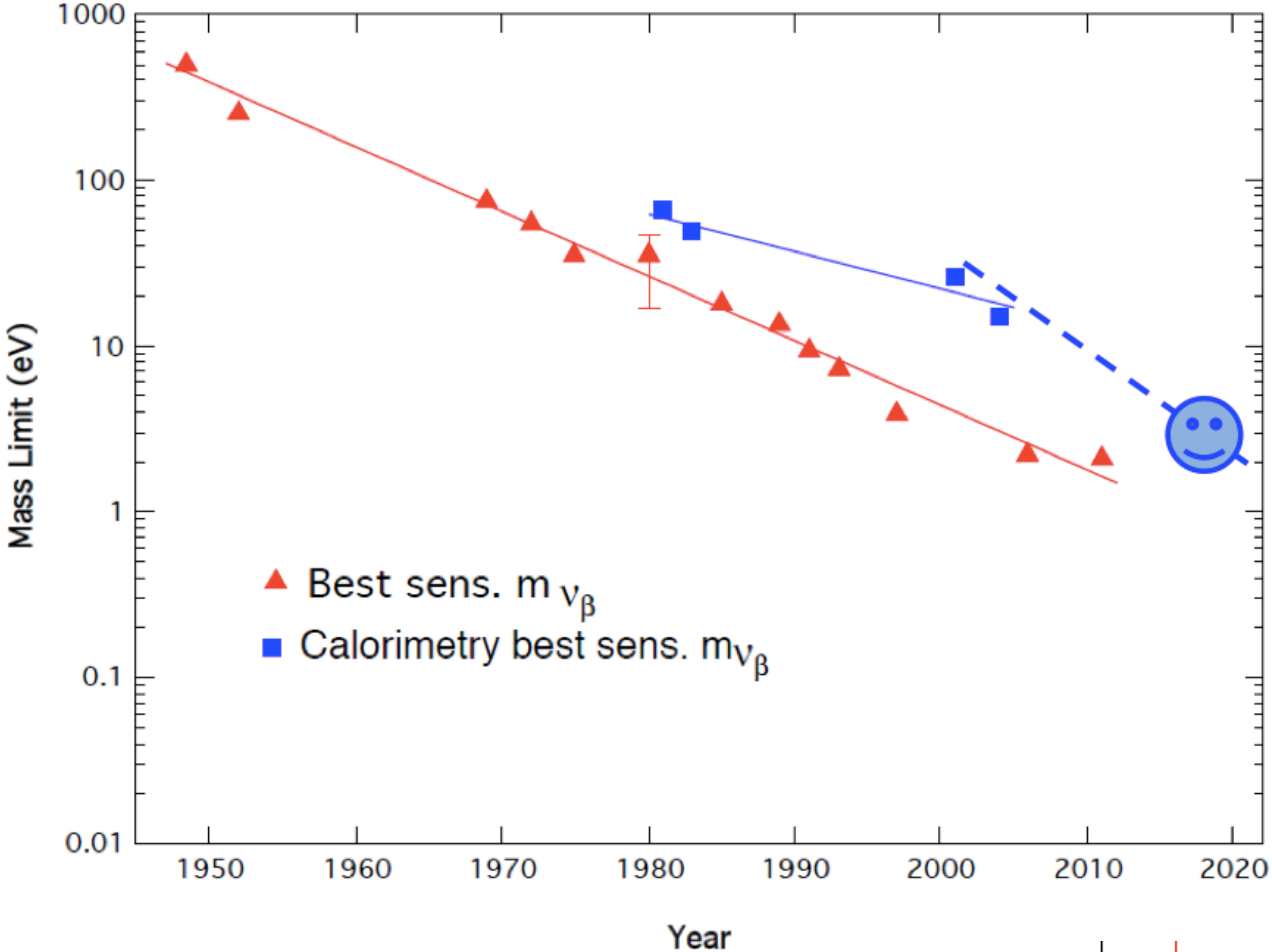


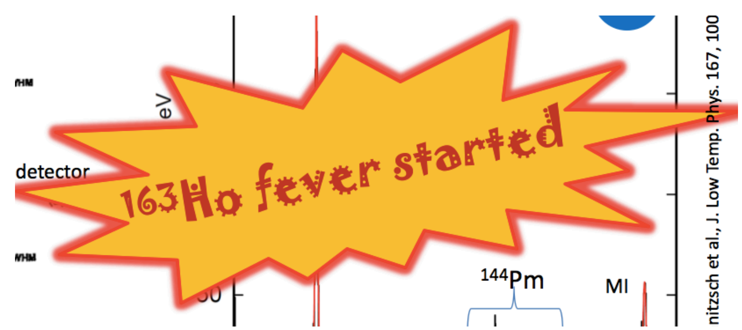
  - report Q_{EC} = 2.80 ± 0.16 keV
  - shapes of N and M lines not entirely understood

Challenges: detector performance, purity of sources, background, systematics...

H. Robertson

But proponents are optimistic...



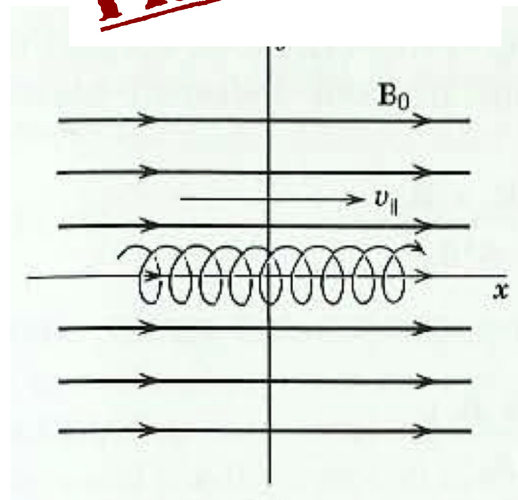


New idea:

use cyclotron radiation to measure spectrum

(B. Monreal and J. Formaggio, PRD 80:051301, 2009)

PROJECT 8



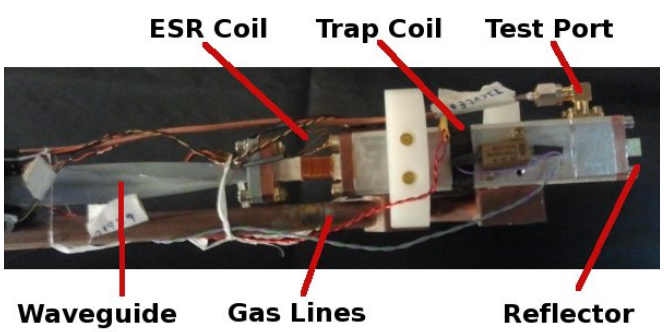
$$\omega = \frac{qB}{\gamma m} \equiv \frac{\omega_c}{\gamma}$$

measured frequency maps to electron energy

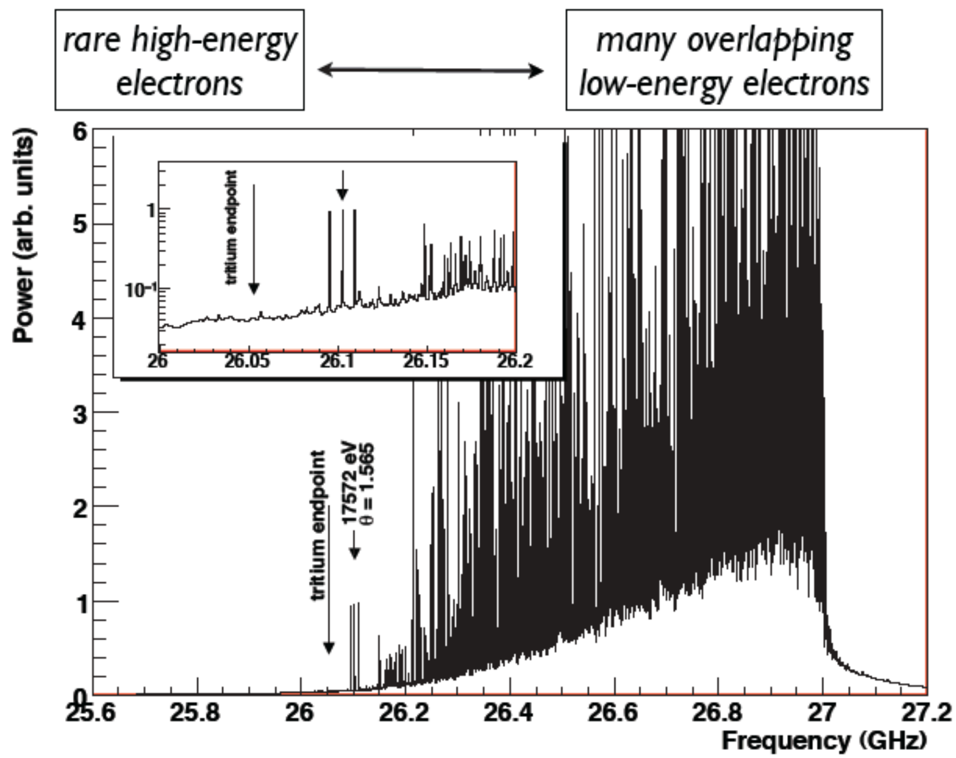
$$\omega_c = 1.758820150(44) \times 10^{11} \text{ rad/s/T}$$

Avoid the limiting systematics of the MAC-E filter technique for tritium decays

... R&D underway



25.5-GHz waveguide cell



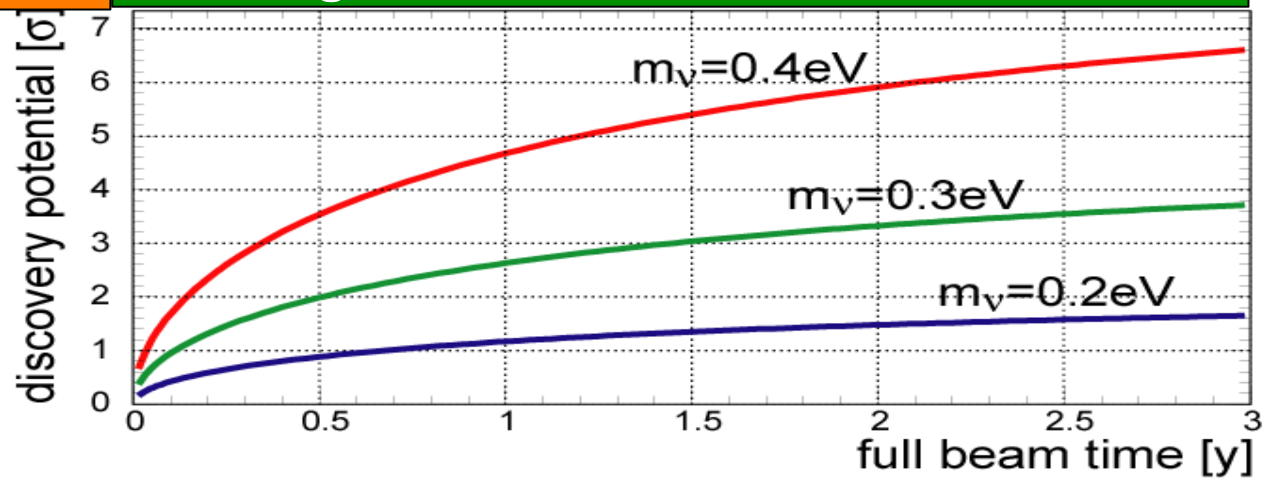
100,000 tritium decays in 30μs

H. Robertson

Neutrino mass: some milestones

Construction | Running

KATRIN:



Project 8:

Proof concept | Prototype | Phase I

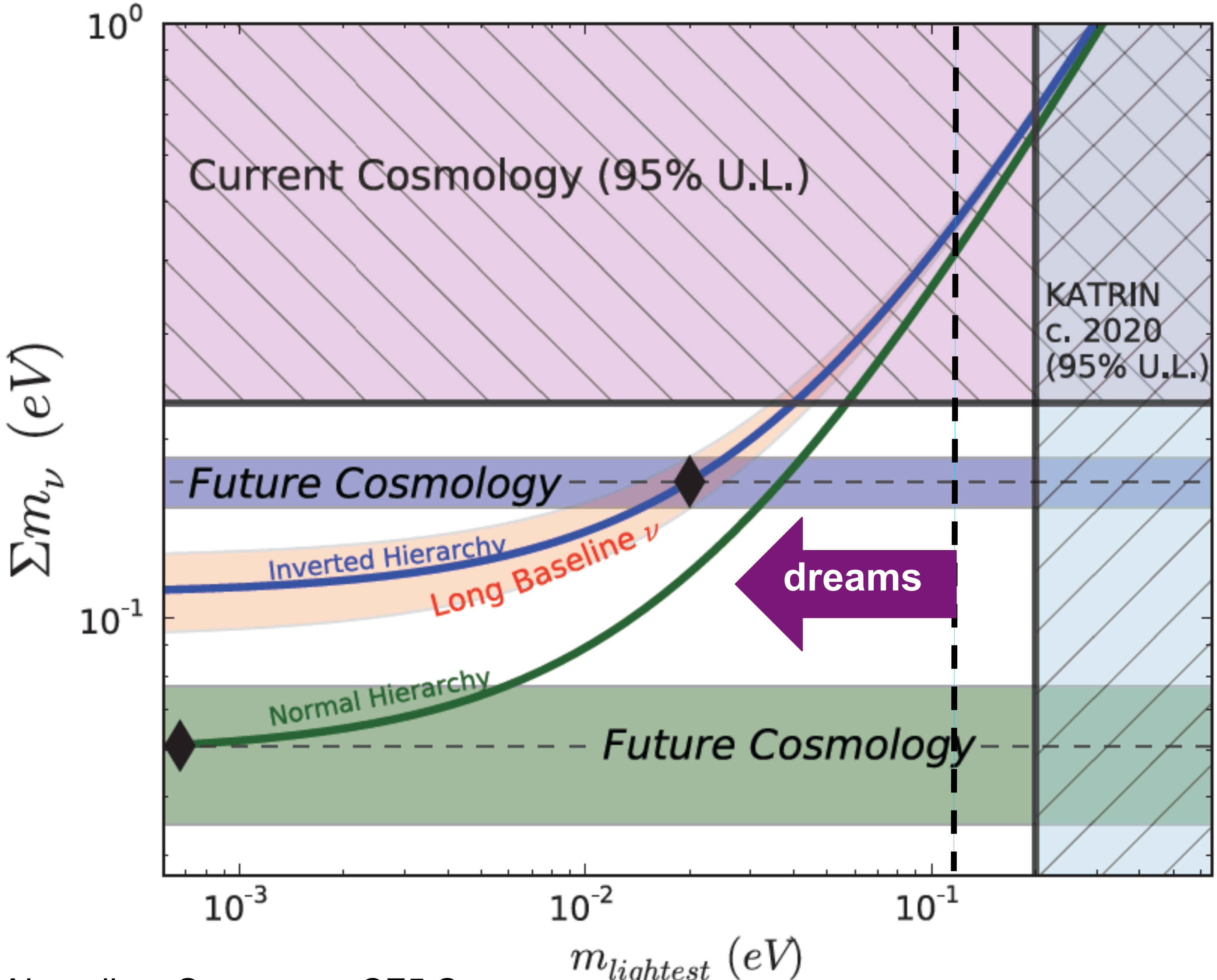
Planck:

Analysis 1 | Analysis 2

2012 2013 2014 2015 2016 2017 2018

H. Robertson

Where we can get to for direct neutrino mass measurements in the reasonably near future....



K. Abazajian, Snowmass CF5 Summary

Summary: Part II

Cosmology (sum of neutrino masses) will improve by ~1 order of magnitude

Reasonable prospects to get to ~0.2 eV from Katrin by the end of the decade

Several ideas to go beyond...

Part III Outline

Neutrinoless double beta decay

Experimental issues

Selected current results

Future experiments

Are neutrinos **Majorana** or **Dirac**?

$\nu = \bar{\nu}$

2 states

Lorentz, CP

$\nu_L \leftrightarrow \nu_R$

$\nu \neq \bar{\nu}$

4 states

Lorentz

$\nu_L \leftrightarrow \nu_R$

$\updownarrow$ CP $\updownarrow$

$\bar{\nu}_R \leftrightarrow \bar{\nu}_L$

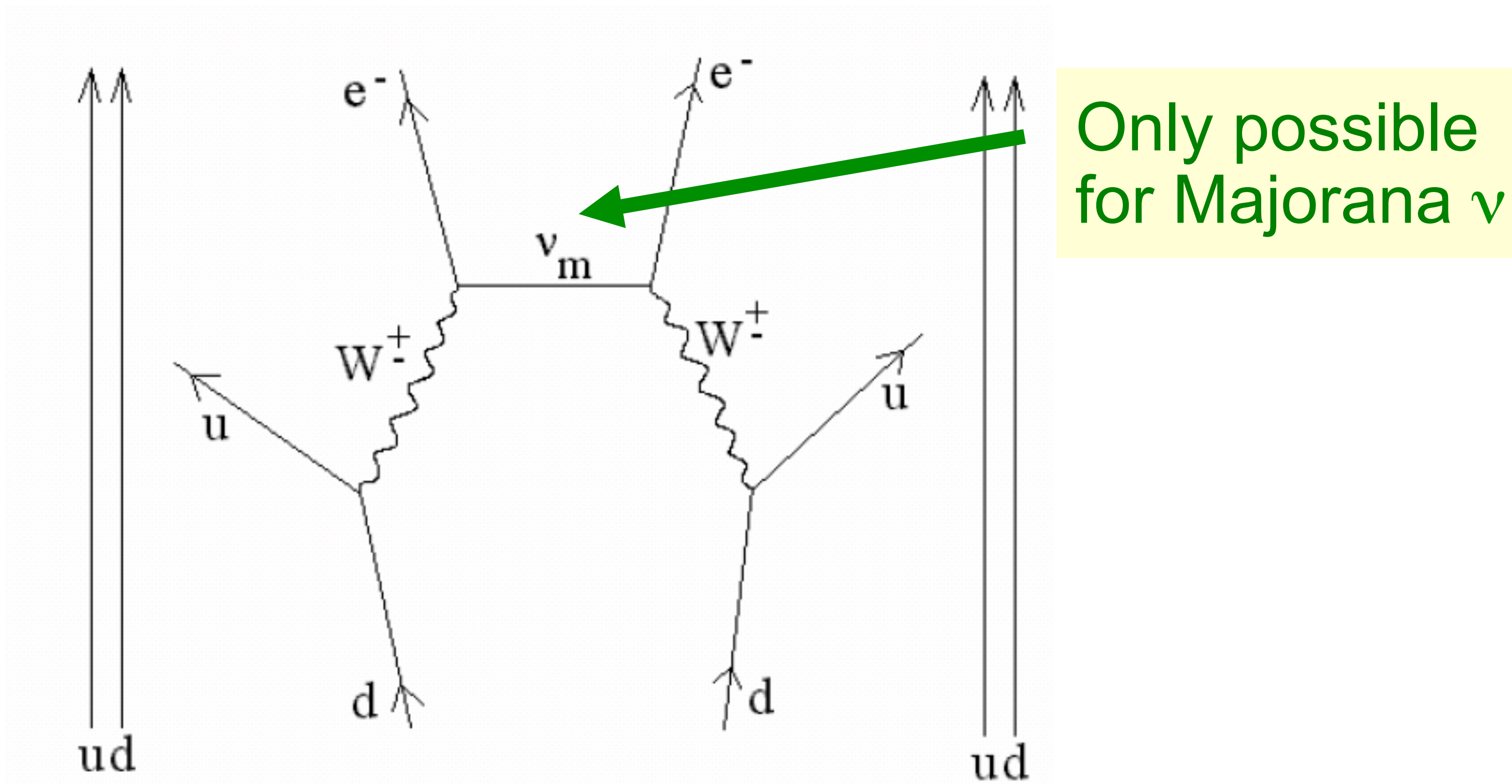
Essential for ν mass understanding....

$$\mathcal{L}_m \sim m_D\,[\,\bar{\psi}_L \psi_R + \ldots\,] + [m_L \bar{\psi}_L^c\, \psi_L + m_R \bar{\psi}_R^c\, \psi_R + h.c.\,]$$

e.g. "see-saw" mechanism $\Rightarrow$ Majorana ν

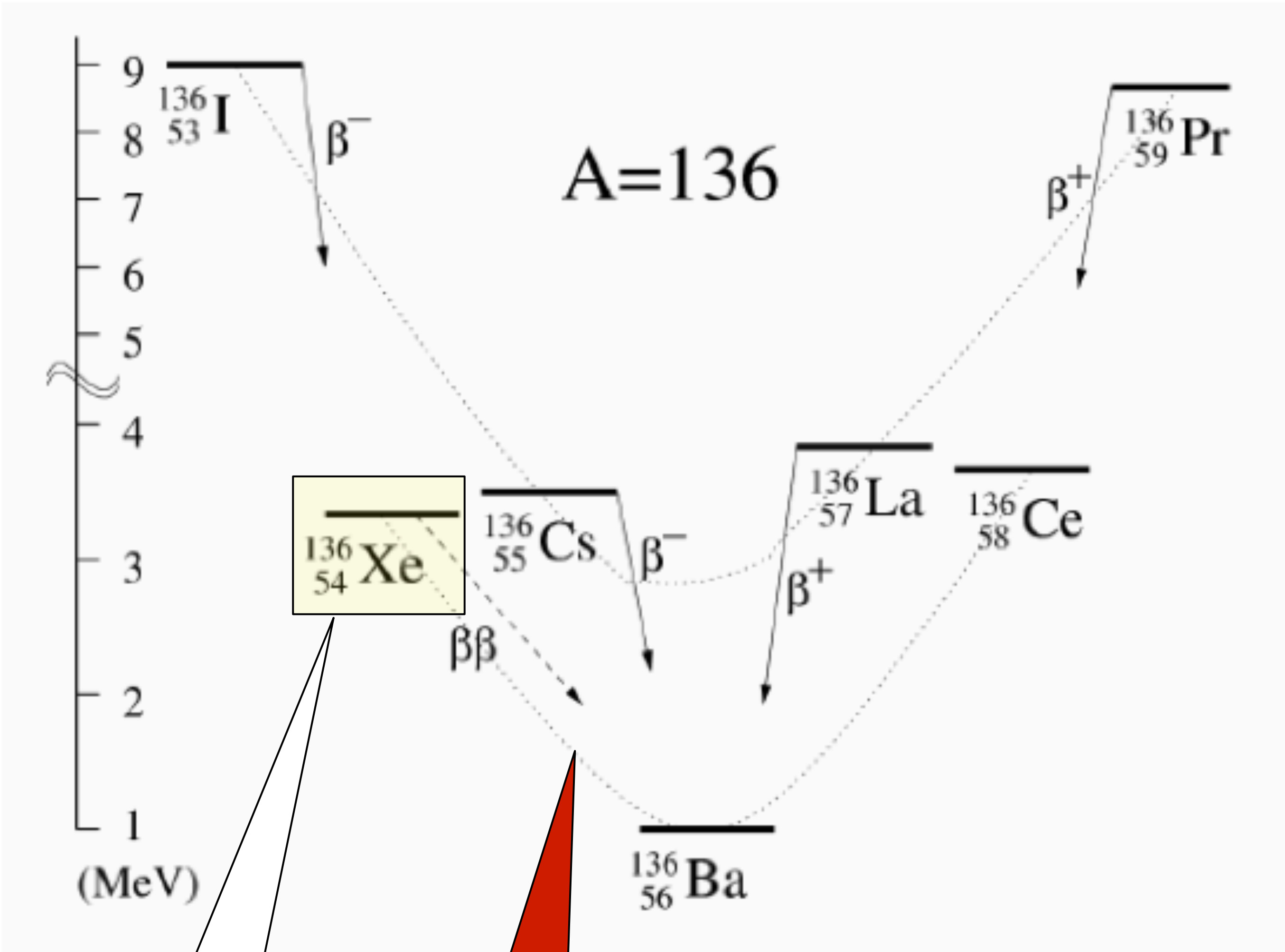
... may be helpful for leptogenesis...

Neutrinoless Double Beta Decay



Look at nuclides for which this is energetically possible and which cannot α, 1β decay

For example:



Stable against ordinary β^- decay

But can decay via β^- β^-

Candidate nuclei with Q>2 MeV

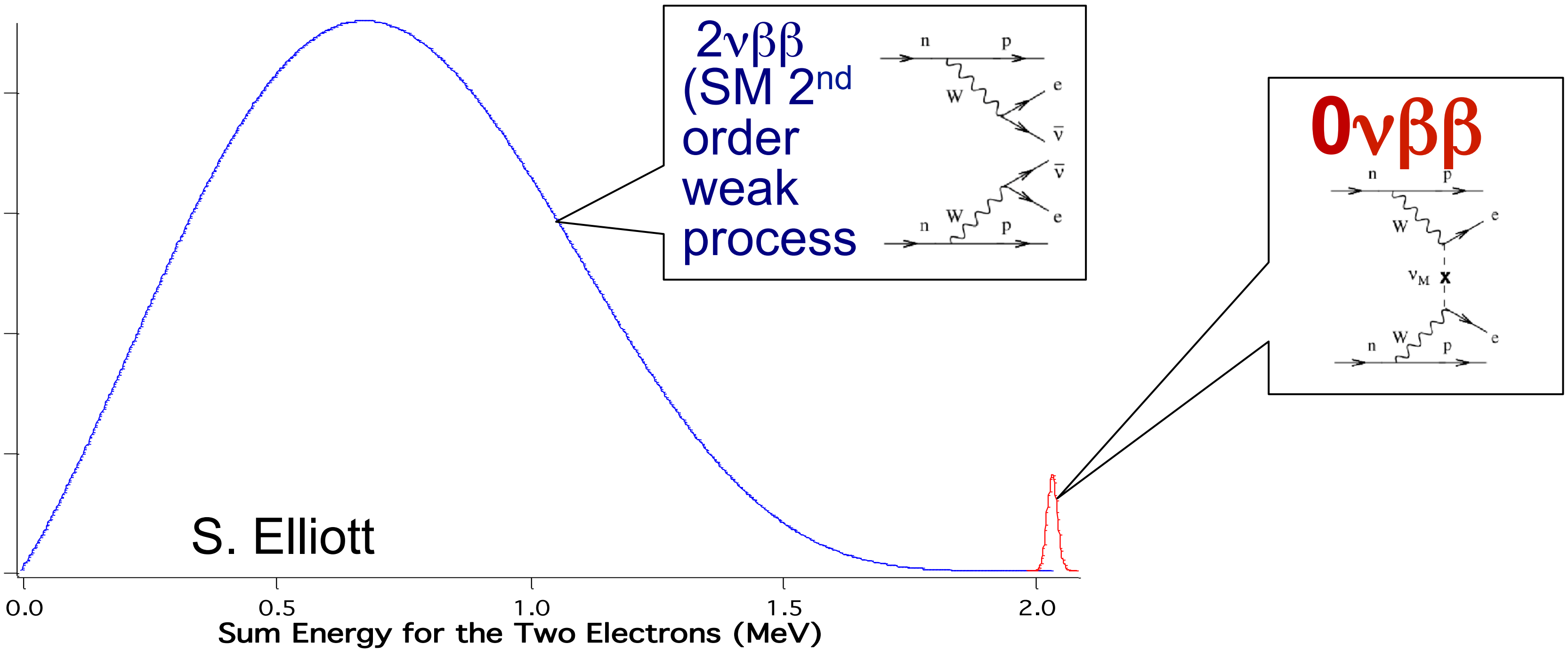
Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

G. Gratta

want large Q value!

want high natural abundance!

Experimental strategy: look for peak in the two-electron spectrum corresponding to neutrinoless final state



Require ultra-clean, high resolution detectors

Observed half-life:

$$(T_{1/2,0\nu\beta\beta})^{-1} = G_{0\nu}|M_{0\nu}|^2 \langle M_{eff}\rangle^2, \text{ where } \langle M_{eff}\rangle^2 = |\Sigma\, U_{ei}^2\, M_i\,|^2$$

phase space

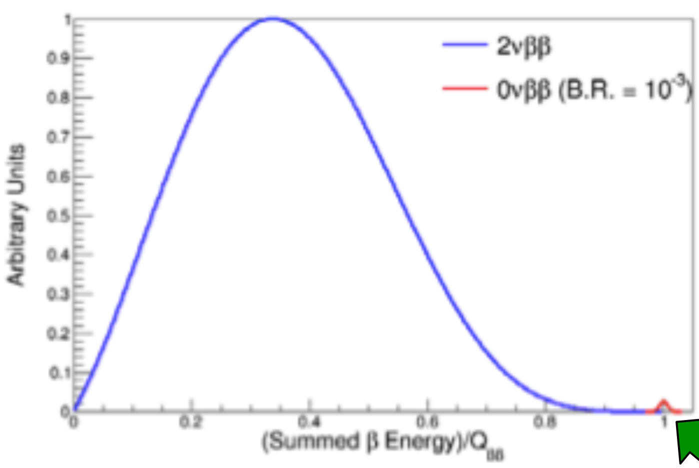
matrix element

effective mass

Experimental sensitivity

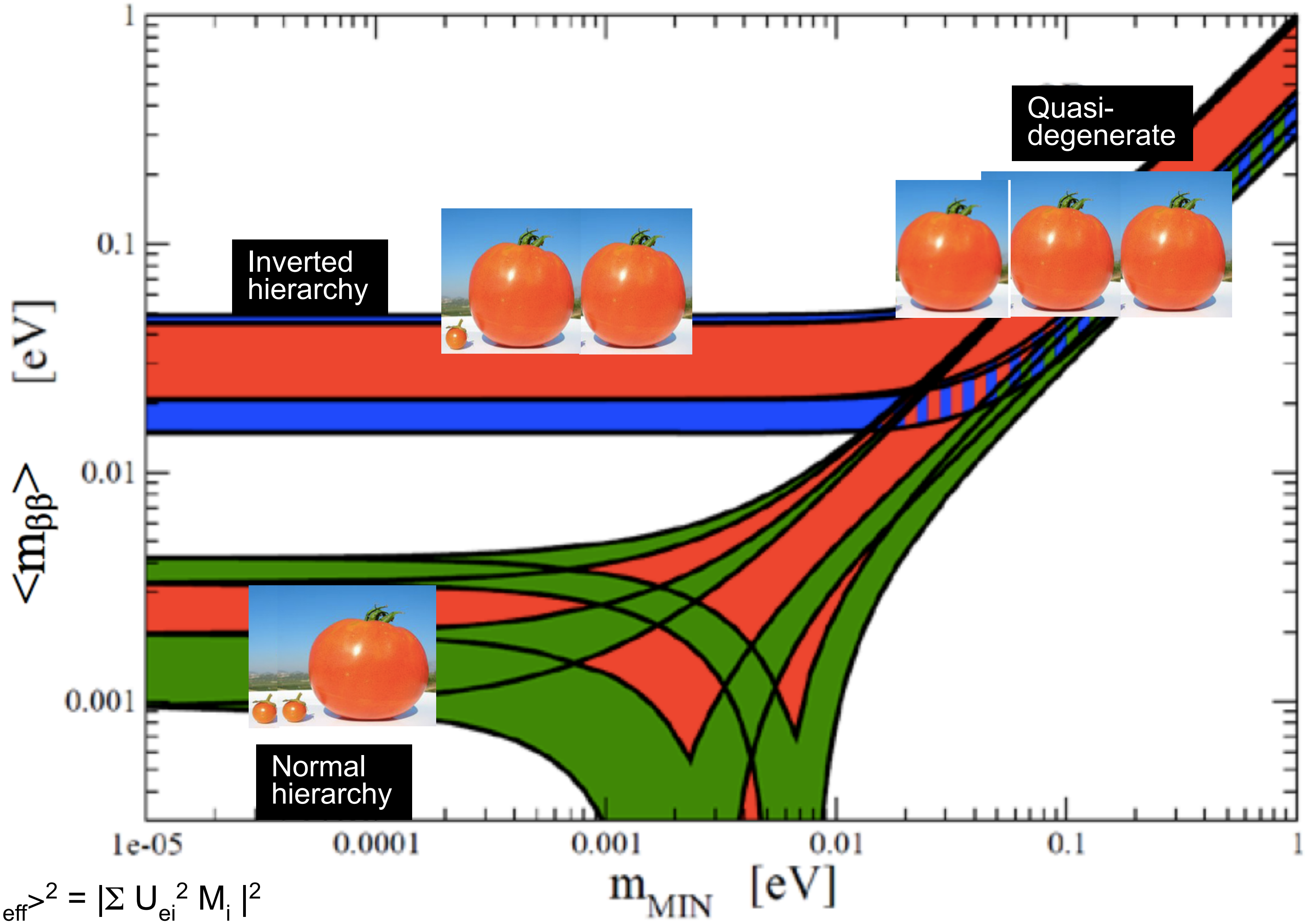
$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE



It's all about reducing background in the Region of Interest

The NLDBD T-Shirt Plot



$<M_{eff}>^2 = |\Sigma\, U_{ei}^2\, M_i\,|^2$

If **neutrinos are Majorana, experimental results must fall in the shaded regions**

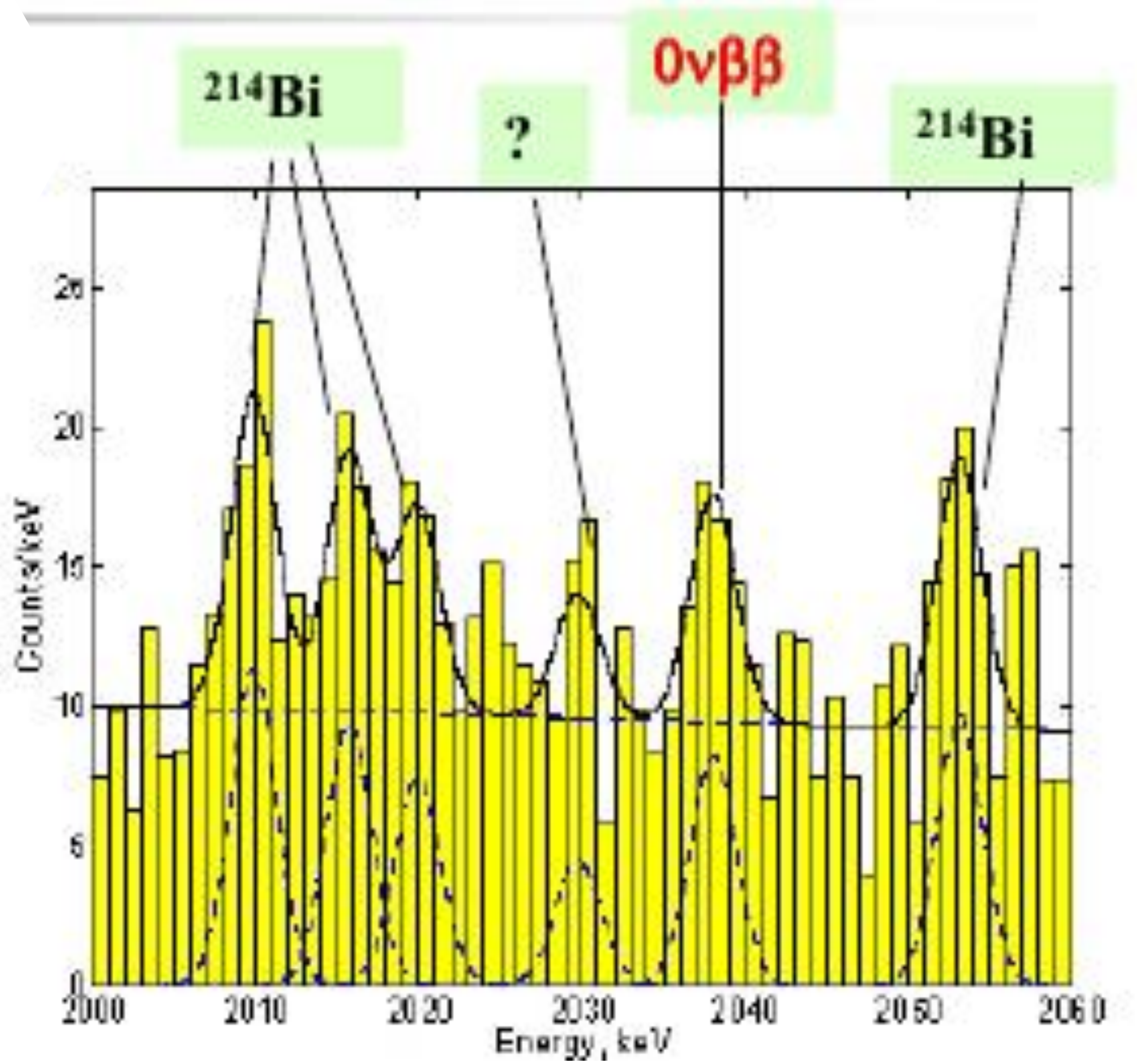
Extent of the regions determined by uncertainties on mixing matrix elements and Majorana phases

A controversial claim:

Heidelberg-Moscow experiment

Klapdor-Kleingrothaus et al.

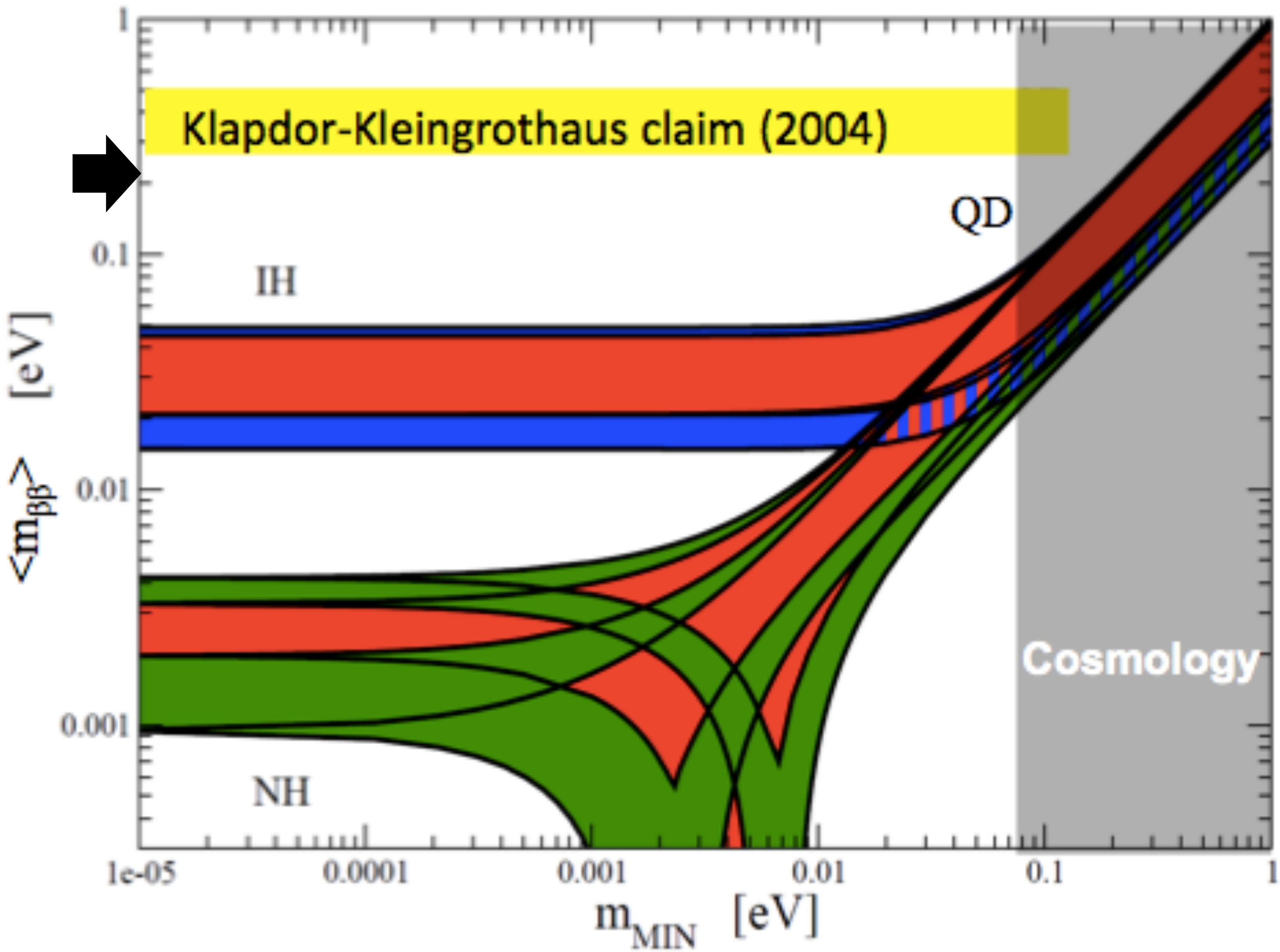
NIM A522, 371 (2004)



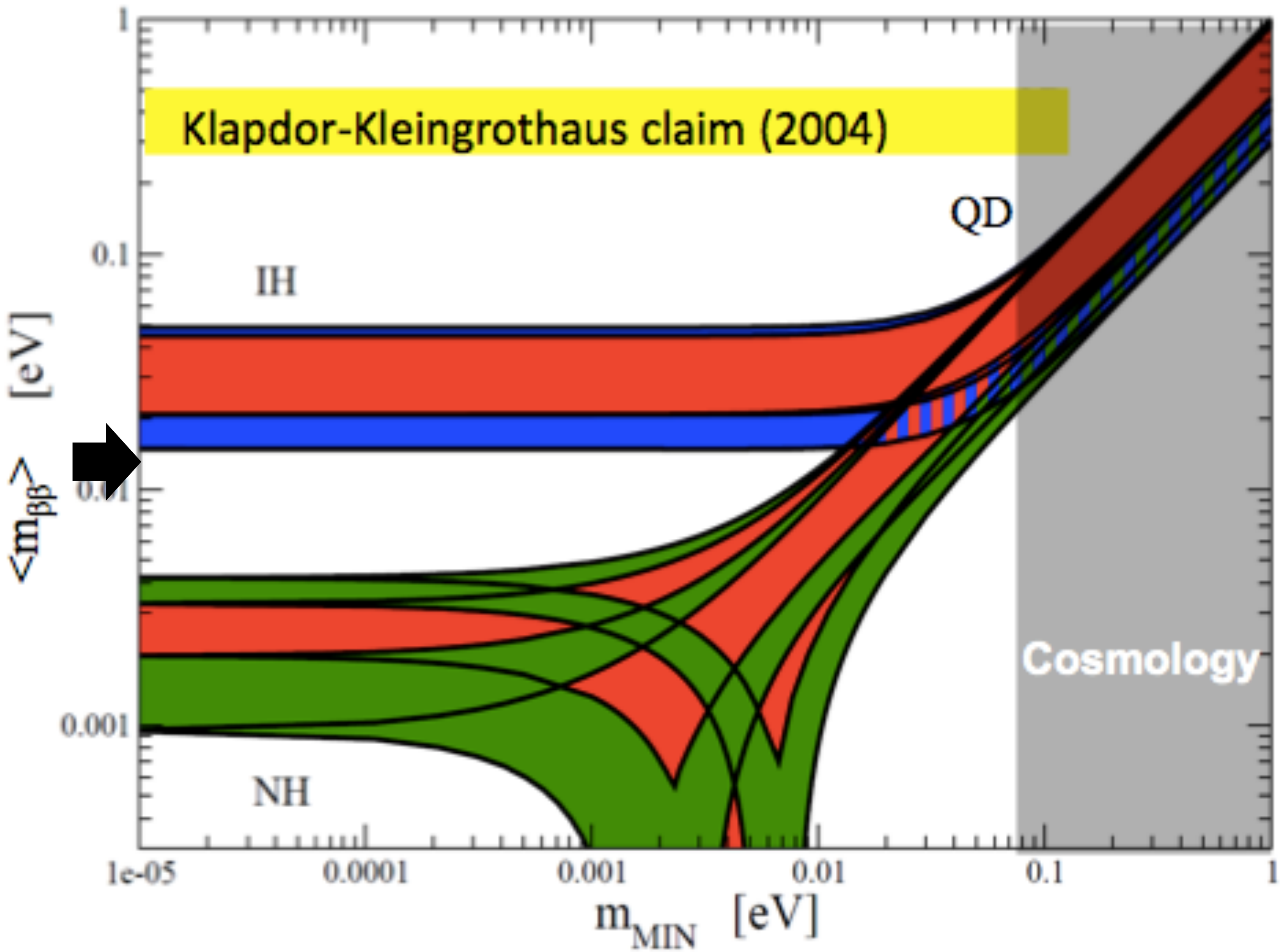
Ge crystal, 70 kg-years

Claim $<m_{eff}>$ = 440 meV

Over the last decade the NLDBD experimental goal has been to attain sensitivity better than this claim...

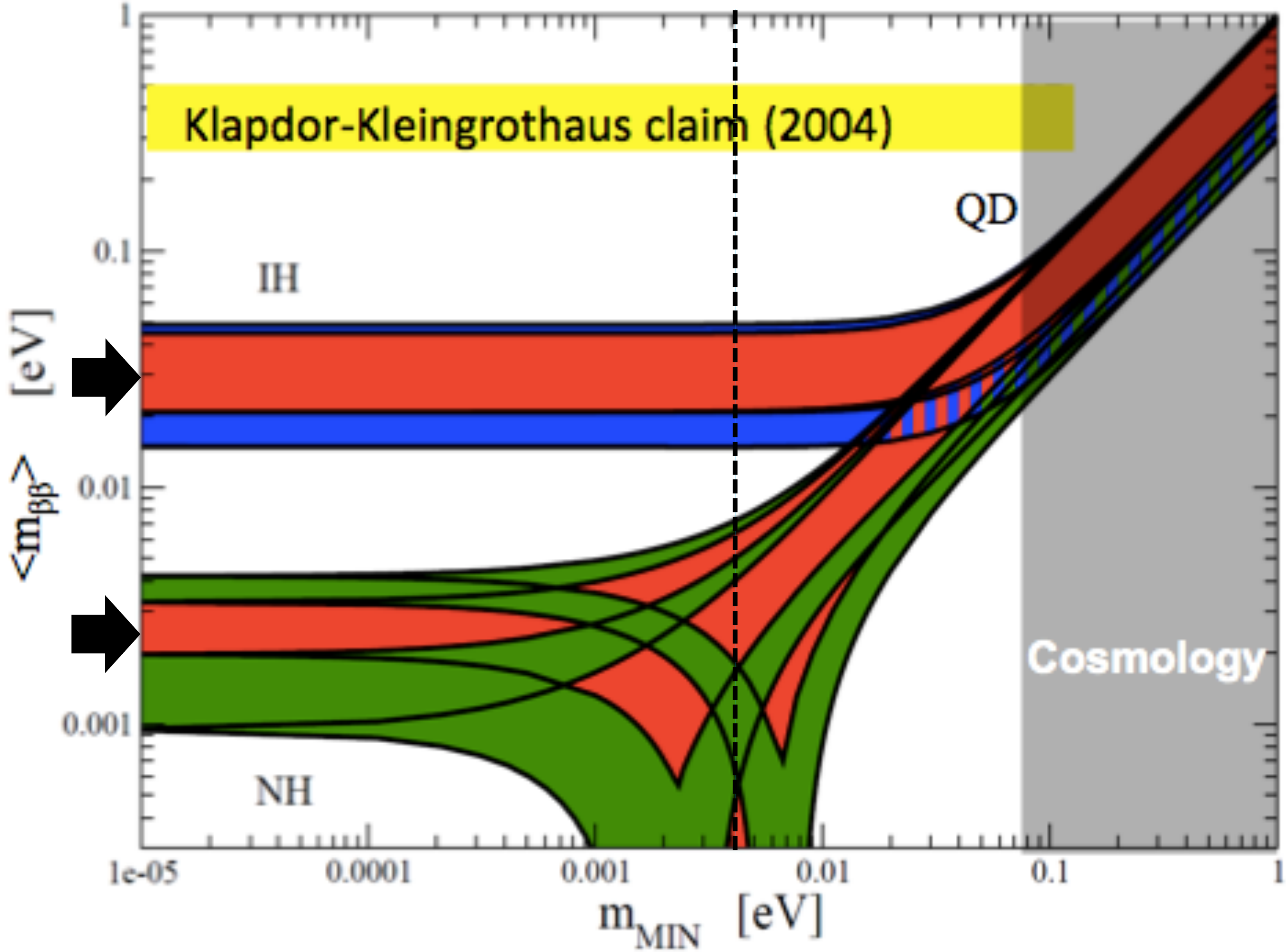


New goal, however, is to get below the inverted hierarchy region

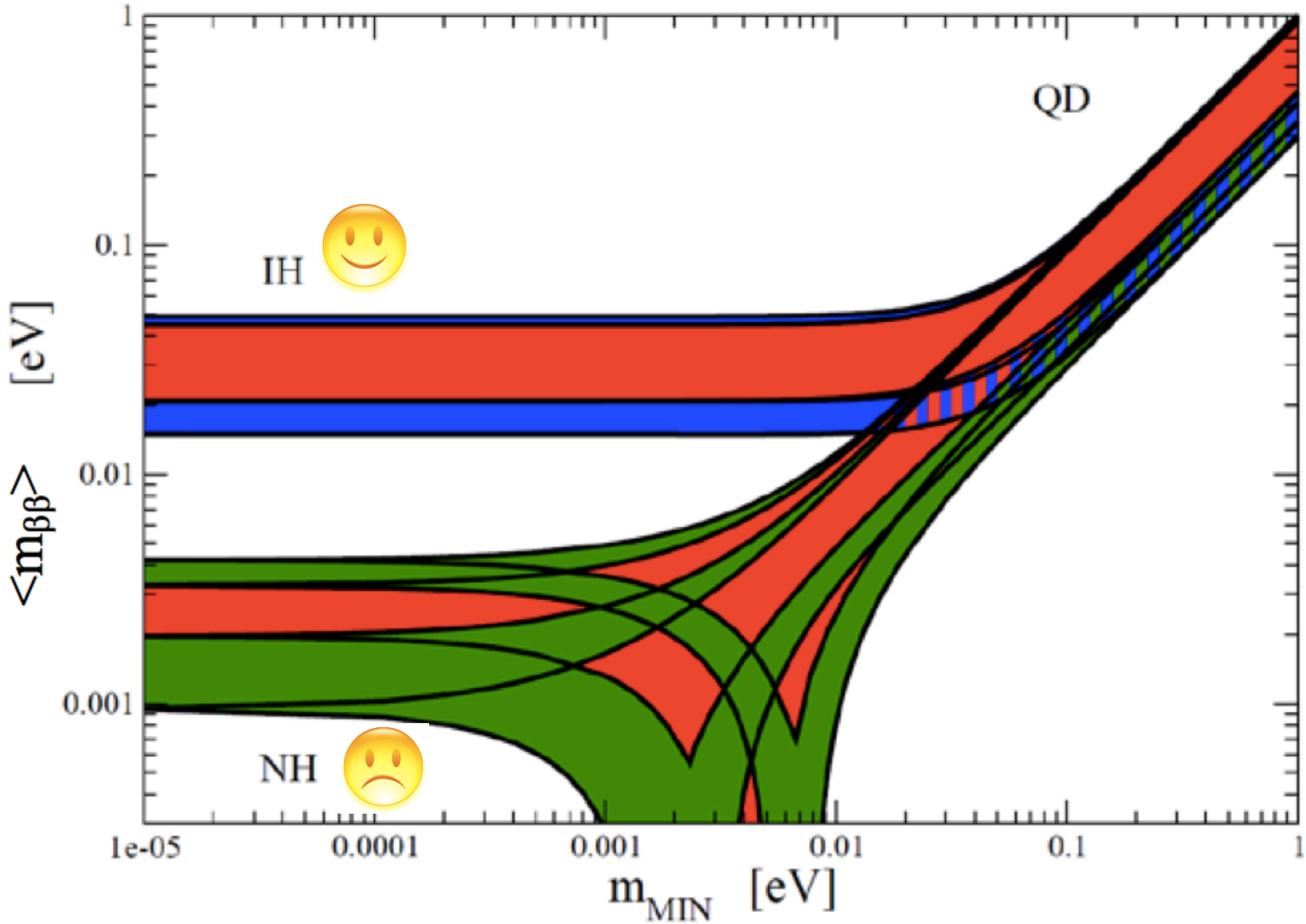


Comments:

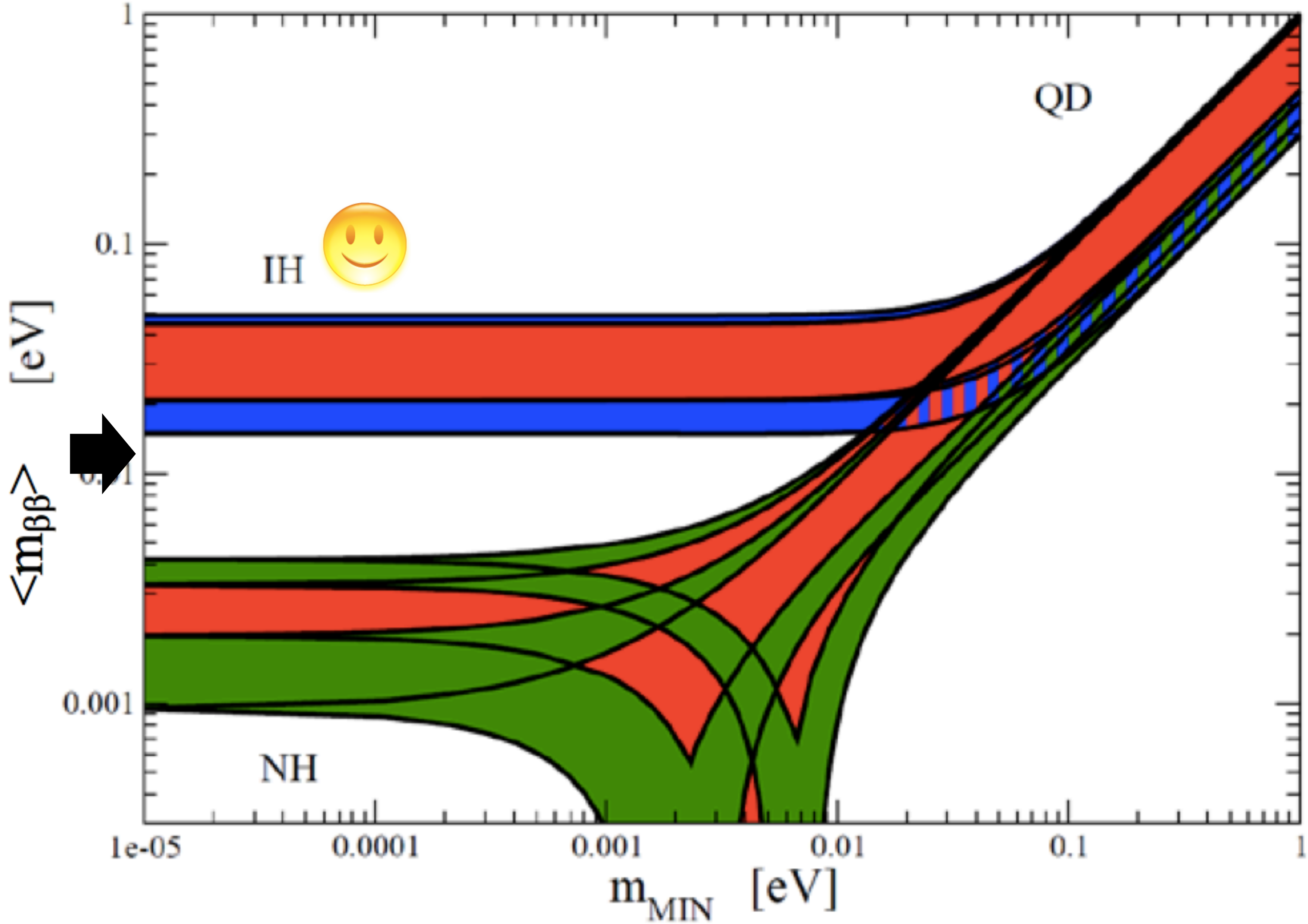
if you measure a NLDBD signal, in either
IH or NH region, and direct mass limit is sufficiently low
(not likely in near future) then
in principle you determine the hierarchy....



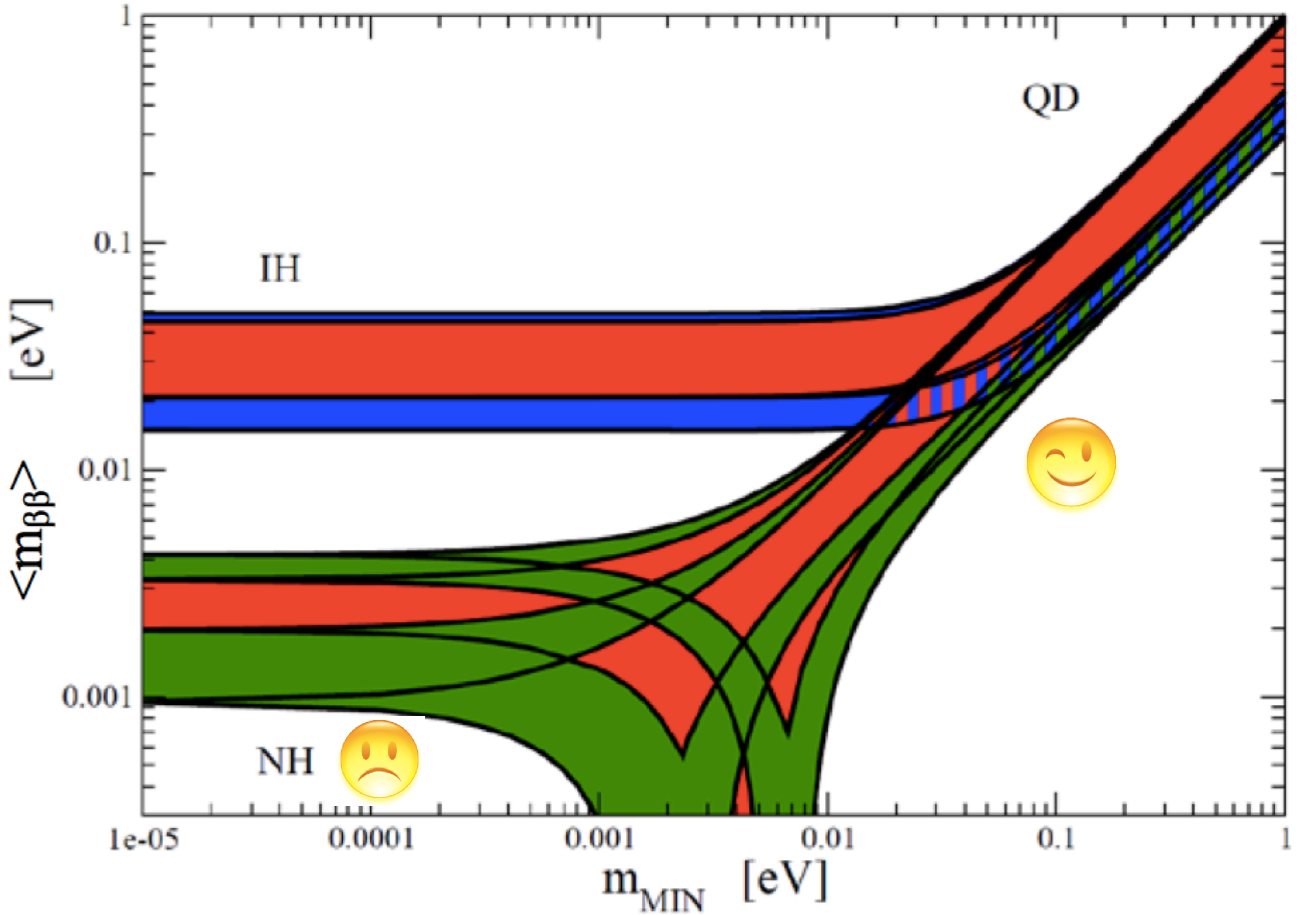
... but much more likely is that the the hierarchy is determined *first* by long-baseline experiments...



... and if you know independently the hierarchy to be inverted, *and* you measure a limit below IH region, then you know (assuming Nature is not diabolical) that neutrinos are not Majorana!



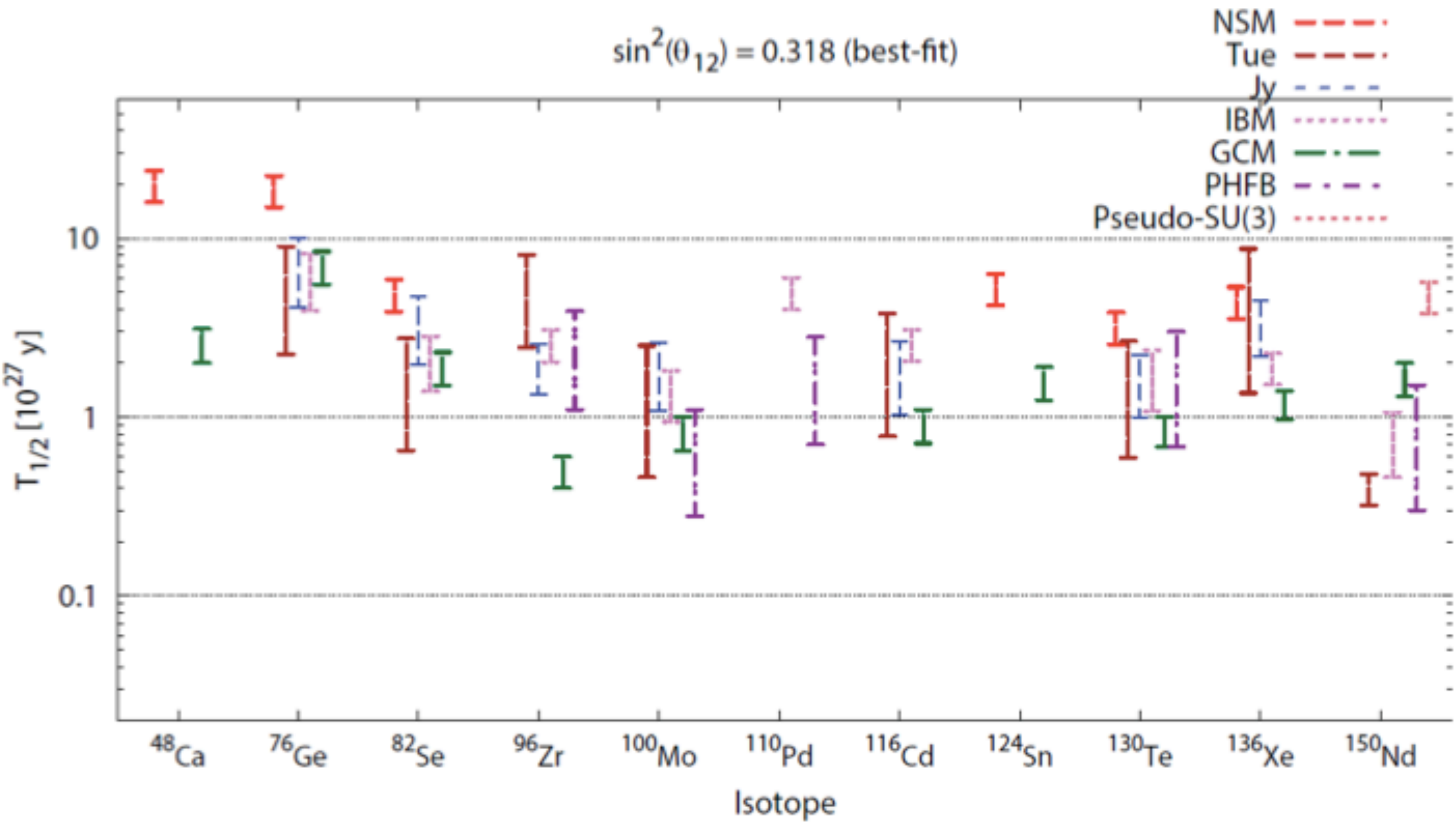
If the hierarchy is known independently to be normal, then life could be hard, unless absolute mass scale large



Effect of nuclear matrix elements

$(T_{1/2,0\nu\beta\beta})^{-1} = G_{0\nu}|M_{0\nu}|^2 \langle M_{eff}\rangle^2$

Neutrinoless double beta decay half-lives, assuming $\langle M_{eff}\rangle$ at bottom of IH region, for different matrix element calculations

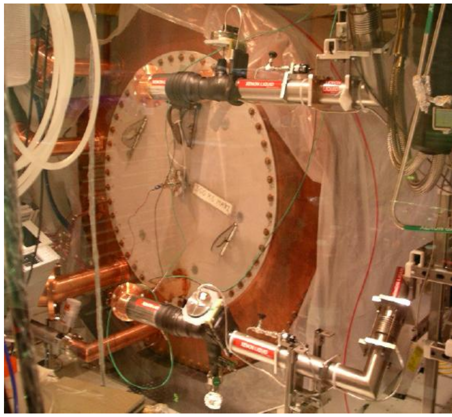


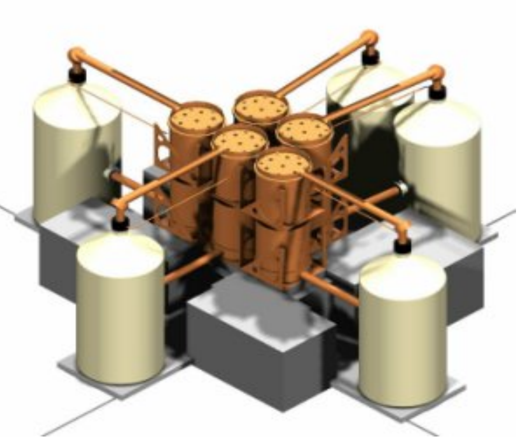
Calculations vary by ~order of magnitude ➔ need more theory!

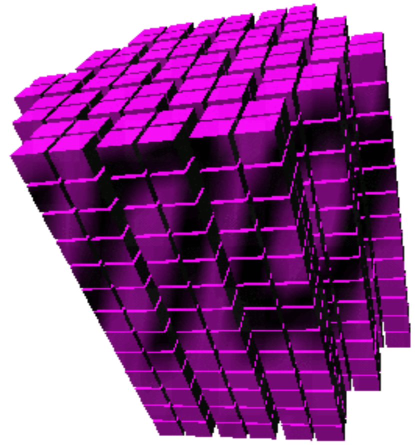
(and a measurement may need confirmation w/more than one isotope)

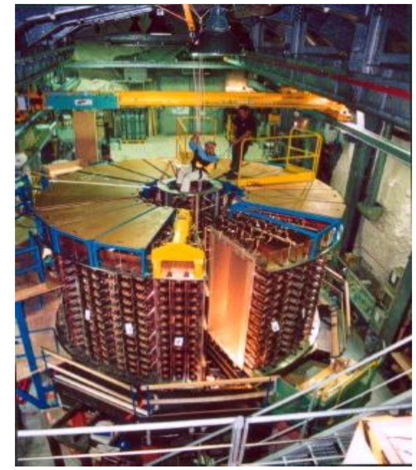
Neutrinoless Double Beta Decay Experiments:

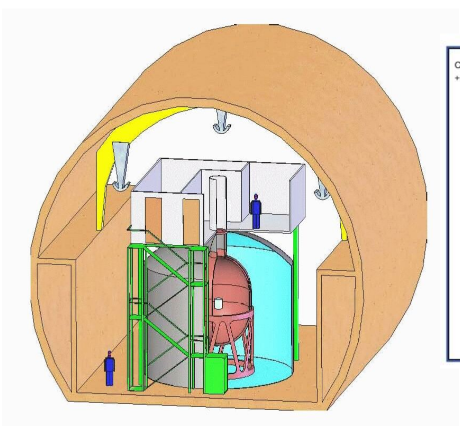
many isotopes and technologies

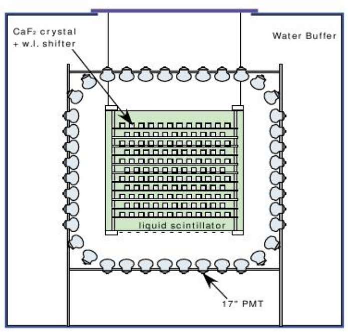


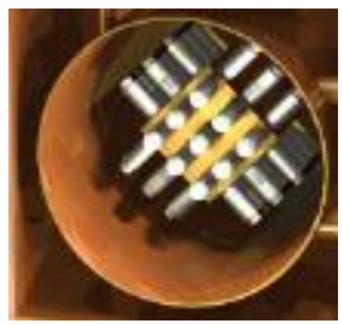


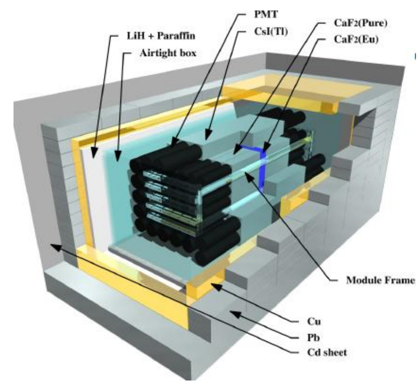












Scintillating, tracking, solid state, calorimetry,....

From arXiv: 1310.4340

Experiment	Isotope	Mass	Technique	Status	Location
AMoRE [164, 165]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES [166]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL [167]	^{48}Ca	1 ton	CaF_2 scint. crystals	Devel.	Solotvina
COBRA [168]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0 [151]	^{130}Te	11 kg	TeO_2 bolometers	Constr. (2013)	Gran Sasso
CUORE [151]	^{130}Te	206 kg	TeO_2 bolometers	Constr. (2014)	Gran Sasso
DCBA [169]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200 [152, 153, 154]	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
nEXO [155]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLAB
GERDA [150, 170]	^{76}Ge	∼35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO [171]	^{160}Gd	2 t	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen [156, 158]	^{136}Xe	400 kg	^{enr}Xe dissolved in liq. scint.	Op. (2011)	Kamioka
LZ [161]	^{136}Xe	600 kg	Two-phase ^{nat}Xe TPC/scint	Proposal	SURF
LUCIFER [172, 173]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [147, 148, 149]	^{76}Ge	30 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [174]	^{100}Mo	1 t	^{enr}Mo foils/scint.	Devel.	
SuperNEMO-Dem [162]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO [162]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [159, 160]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
SNO+ [39, 175, 176]	^{130}Te	800 kg	Te-loaded liq. scint.	Constr. (2013)	SNOLAB

Current Projects

Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved (10^{26} yr)
CUORE	^{130}Te	206	>0.028
MAJORANA	^{76}Ge	24.7	
GERDA	^{76}Ge	18-20	>0.21
EXO200	^{136}Xe	79	>0.11
NEXT-100	^{136}Xe	100	
SuperNEMO	^{82}Se+	7	>0.001
KamLAND-Zen	^{136}Xe	434	>0.19
SNO+	^{130}Te	160	
LUCIFER	^{82}Se	8.9	

R. McKeown

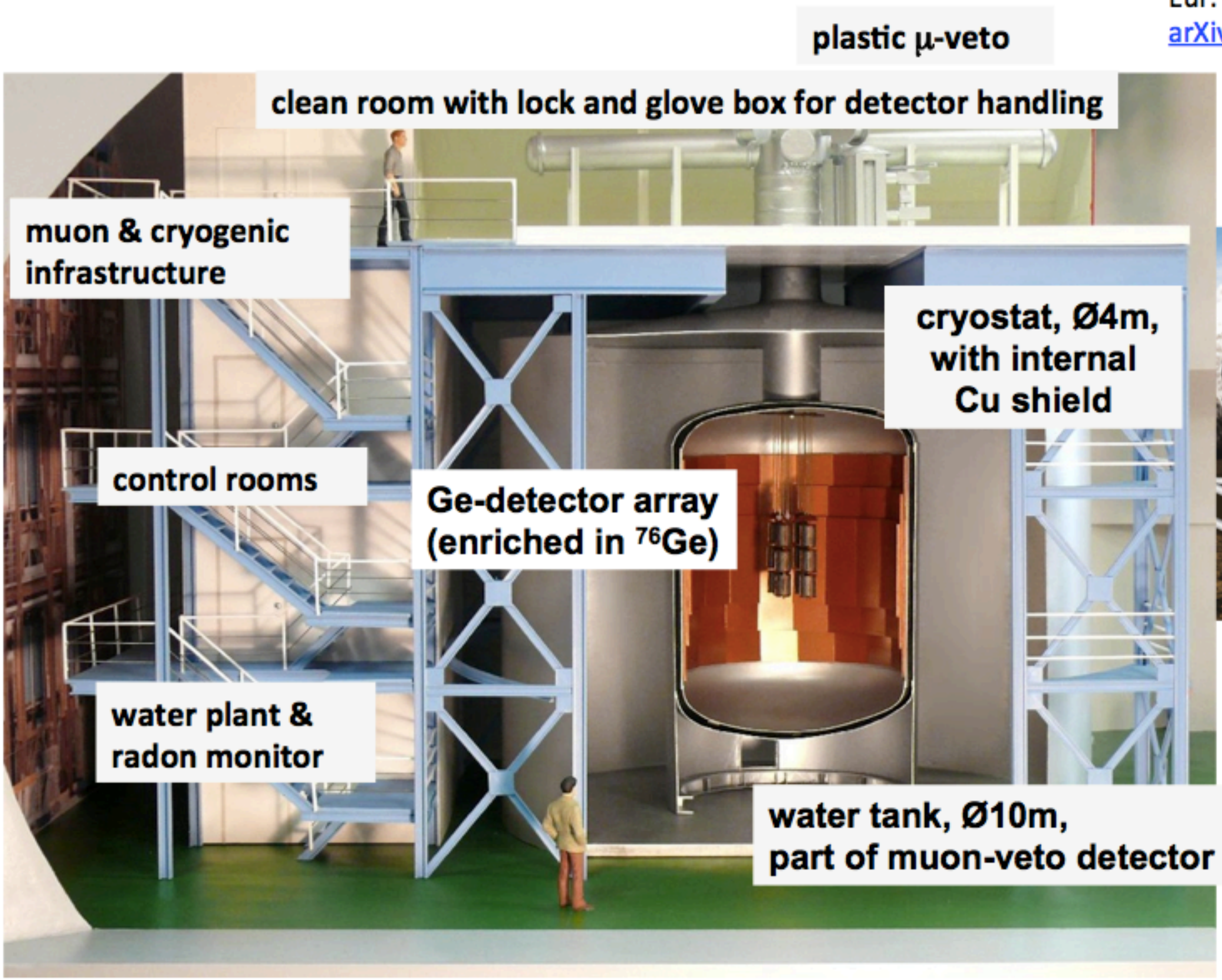
Focus on two recent results and one future project

Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved (10^{26} yr)
CUORE	^{130}Te	206	>0.028
MAJORANA	^{76}Ge	24.7	
GERDA	^{76}Ge	18-20	>0.21
EXO200	^{136}Xe	79	>0.11
NEXT-100	^{136}Xe	100	
SuperNEMO	^{82}Se+	7	>0.001
KamLAND-Zen	^{136}Xe	434	>0.19
SNO+	^{130}Te	160	
LUCIFER	^{82}Se	8.9	

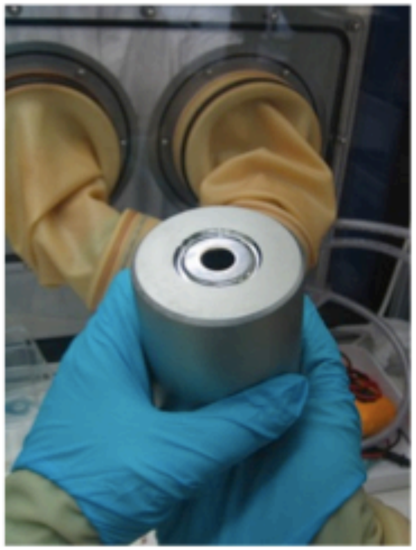
Slides from Neutrino 2014

The GERDA experiment @ LNGS

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



Nov 2011: deployment of 3-string & start of Phase I physics runs

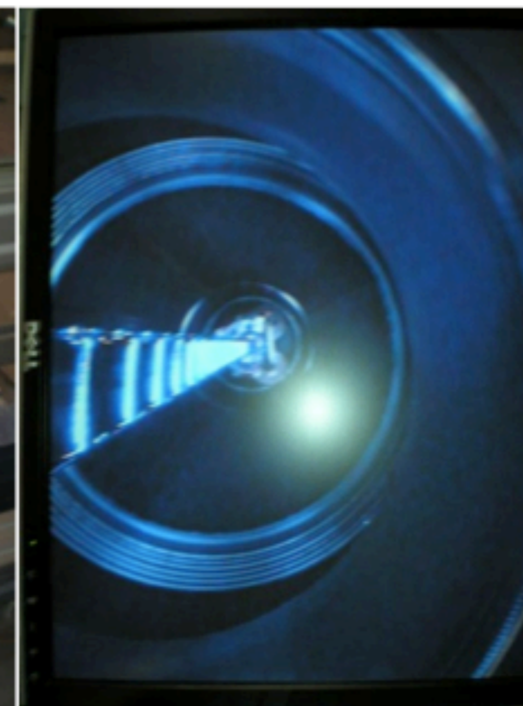


8 refurbished enriched diodes from HdM & IGEX

- 86% isotopically enriched in Ge-76
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

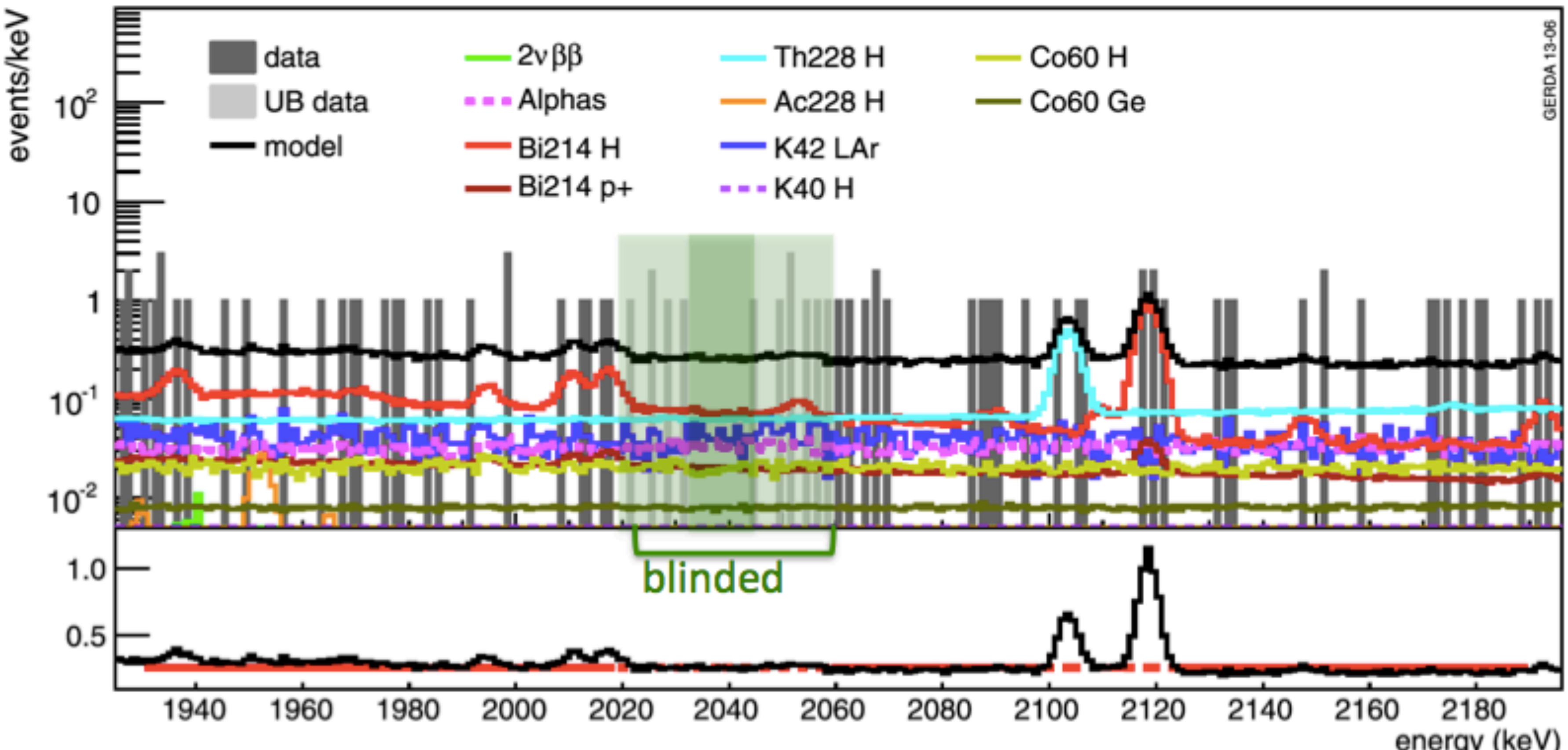
2 diodes shut off because leakage current high:

- total enriched enriched detector mass 14.6 kg



Physics run: background model and prediction of BI at $Q_{\beta\beta}$

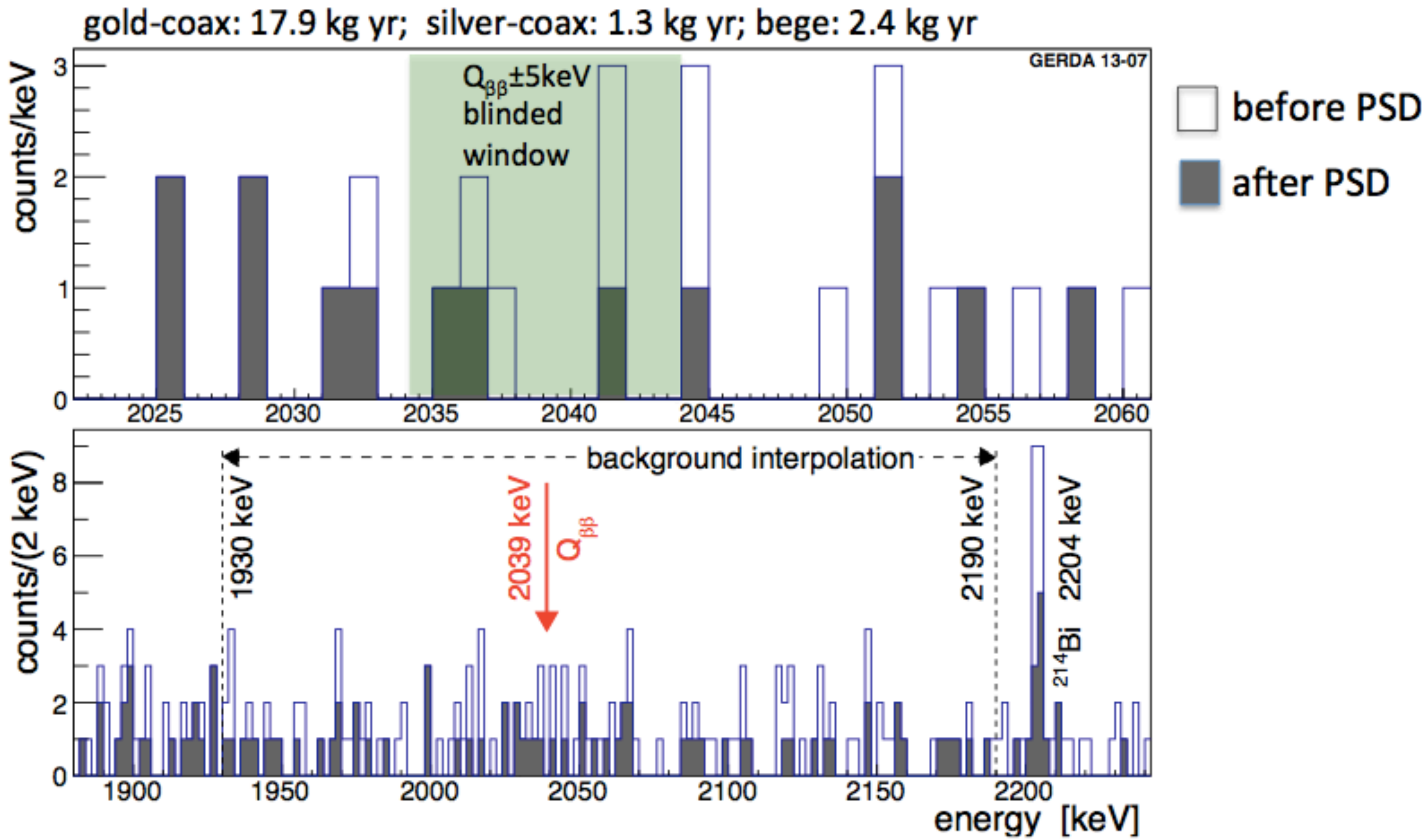
Eur. Phys. J. C (2014) 74:2764



- **No background peaks** expected around $Q_{\beta\beta}$ expected
- BI at $Q_{\beta\beta}$ **(17.6-23.8) x 10^{-3} cts/(keV kg yr)** depending on assumptions for location of sources
- Spectrum can be modeled with **flat background** (red line) in 1930-2190 keV excluding known peaks at 2104 and 2119 keV
- **Statistical uncertainty** of BI from interpolation **coincides** numerically **with systematic** uncertainty from model
- Prediction for 30 keV blinded side wings: Min./Max Mod: 8.2-9.1 / 9.7-11.1 observed.: 13

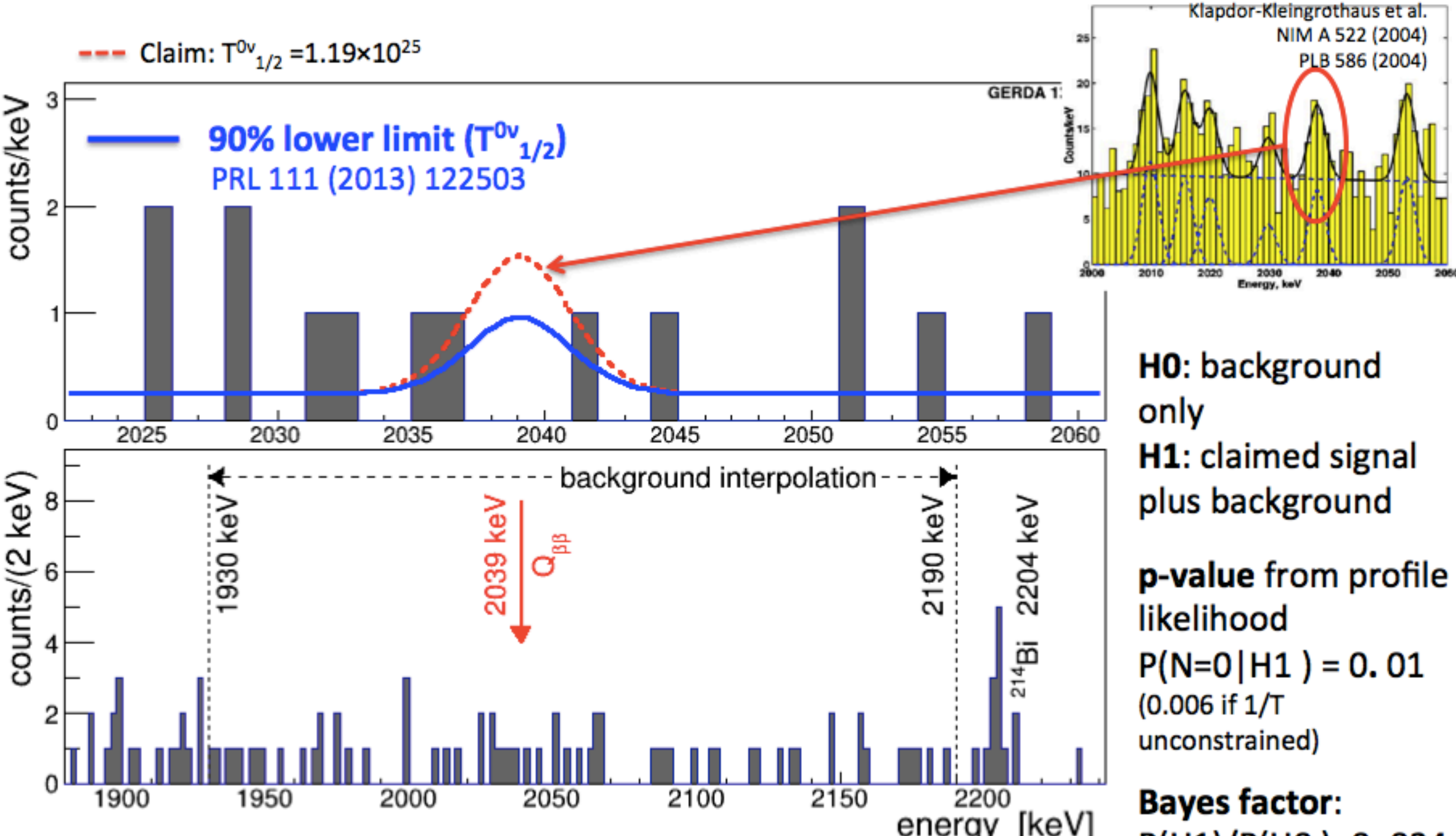
Unblinding: full data set (21.6 kg yr)

PRL 111 (2013) 122503



Full data set:	7 events obs. in blinded window	vs. 5.1 expected for bgd only
	3 events survive PSD cut	vs. 2.5 expected for bgd only

Comparison with Phys. Lett. B 586 198 (2004) 0νββ claim in ^{76}Ge



H0: background only
H1: claimed signal plus background

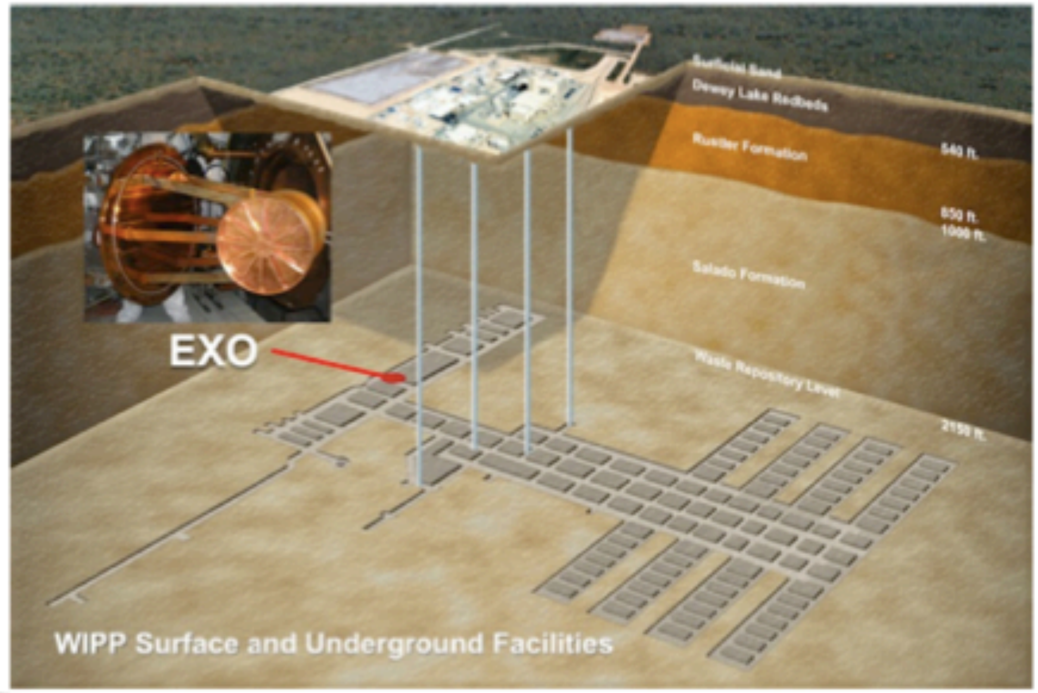
p-value from profile likelihood
P(N=0|H1) = 0. 01
(0.006 if 1/T unconstrained)

Bayes factor:
P(H1)/P(H0)=0. 024

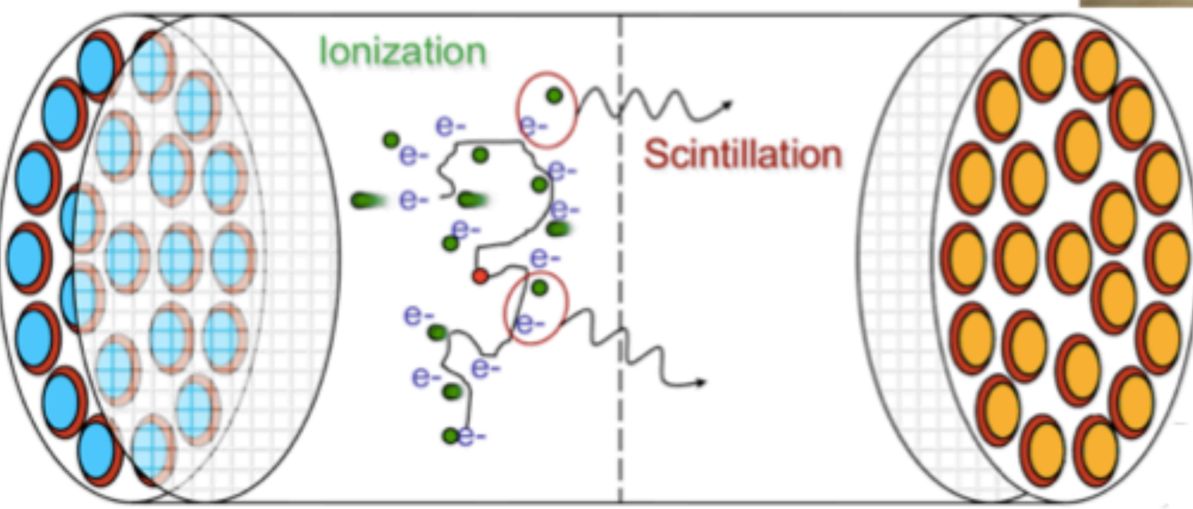
➔Claim refuted with high probability independent of NME and lepton number violating mechanism

EXO
Enriched Xenon Observatory

- Liquid Xe Time Projection Chamber (TPC)
- Enriched ^{136}Xe to 80.6%
- Q-value 2458 keV

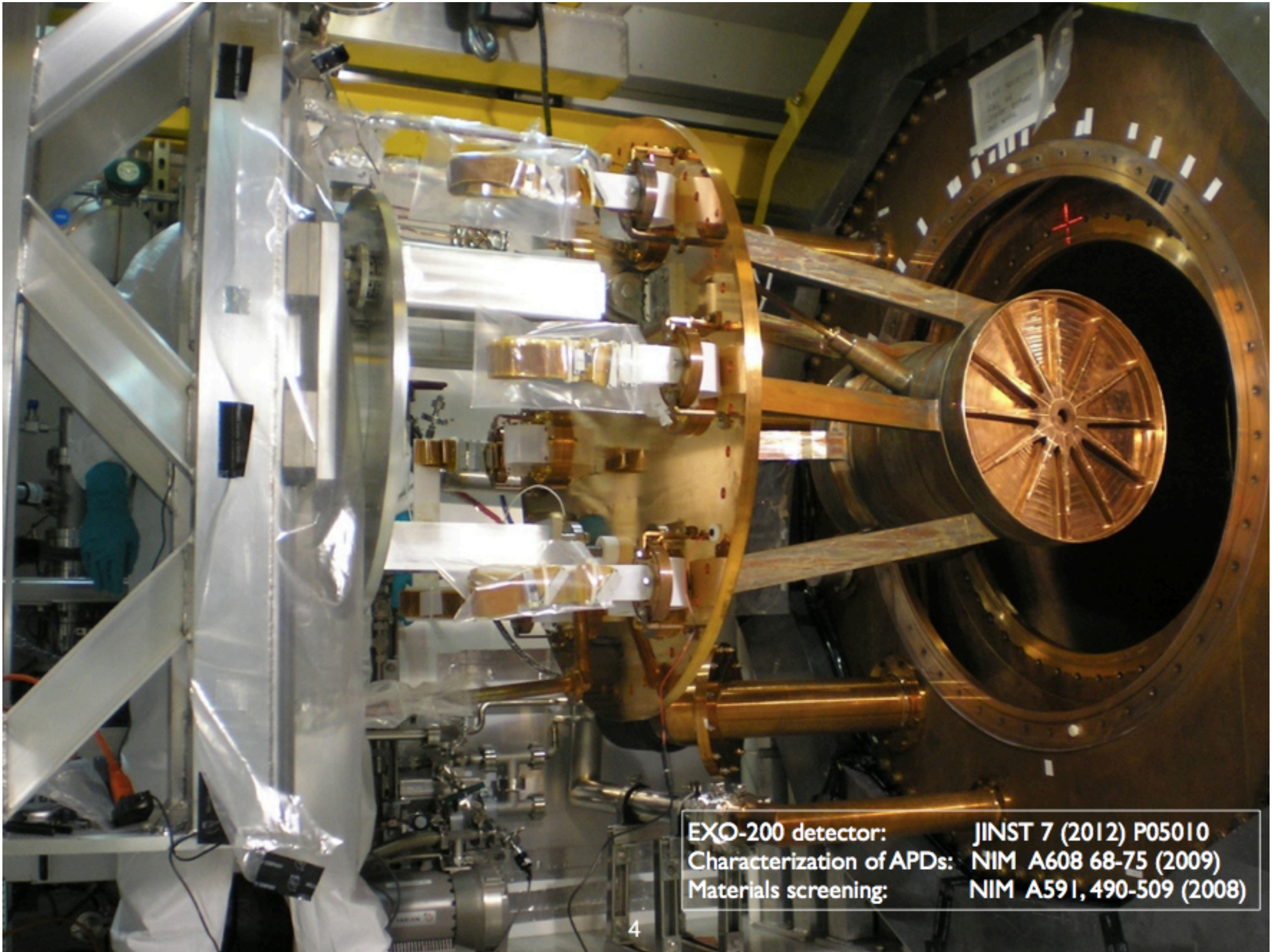


-8 kV



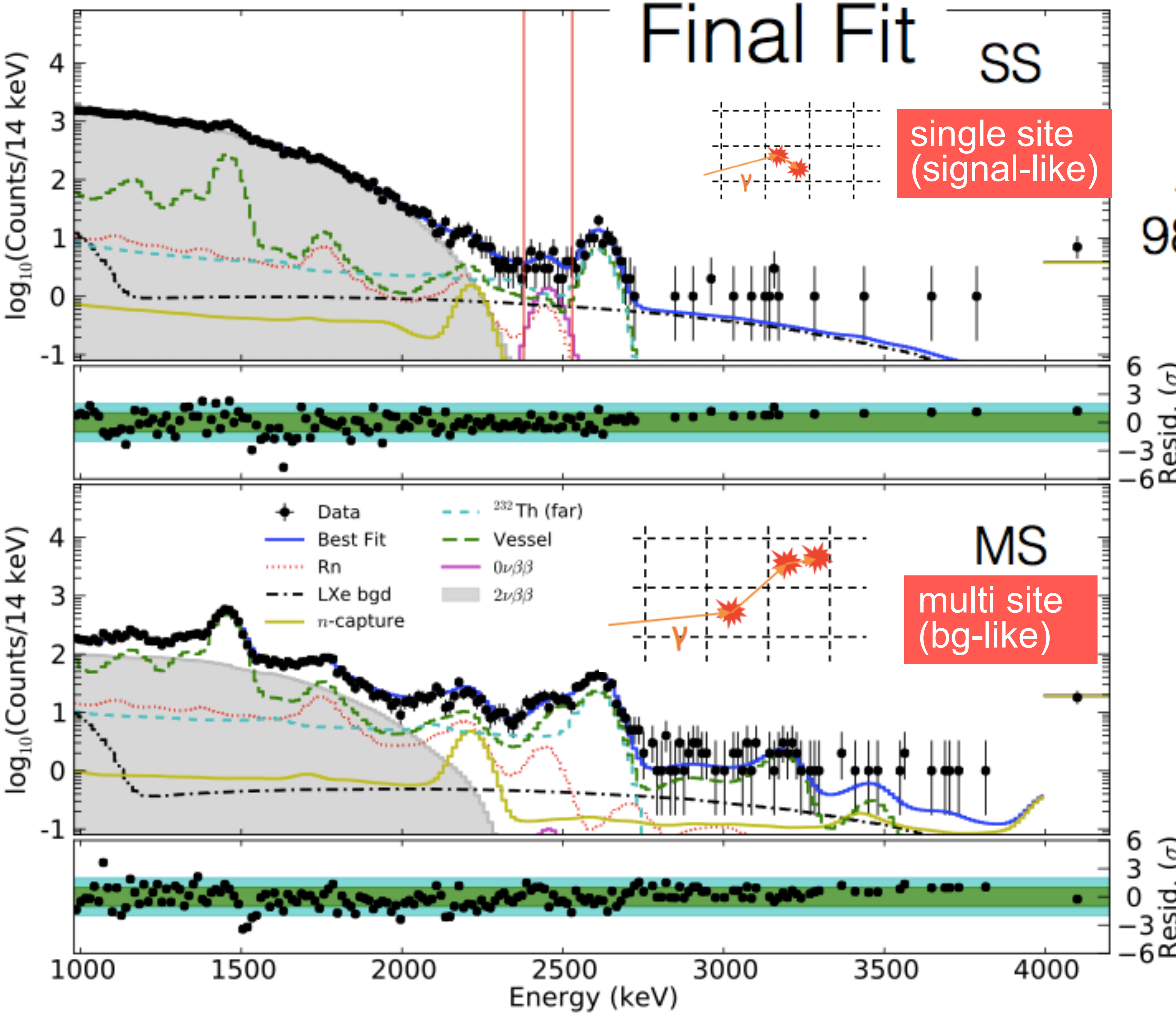
Avalanche Photo Diodes

- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- 1585 meters water equivalent



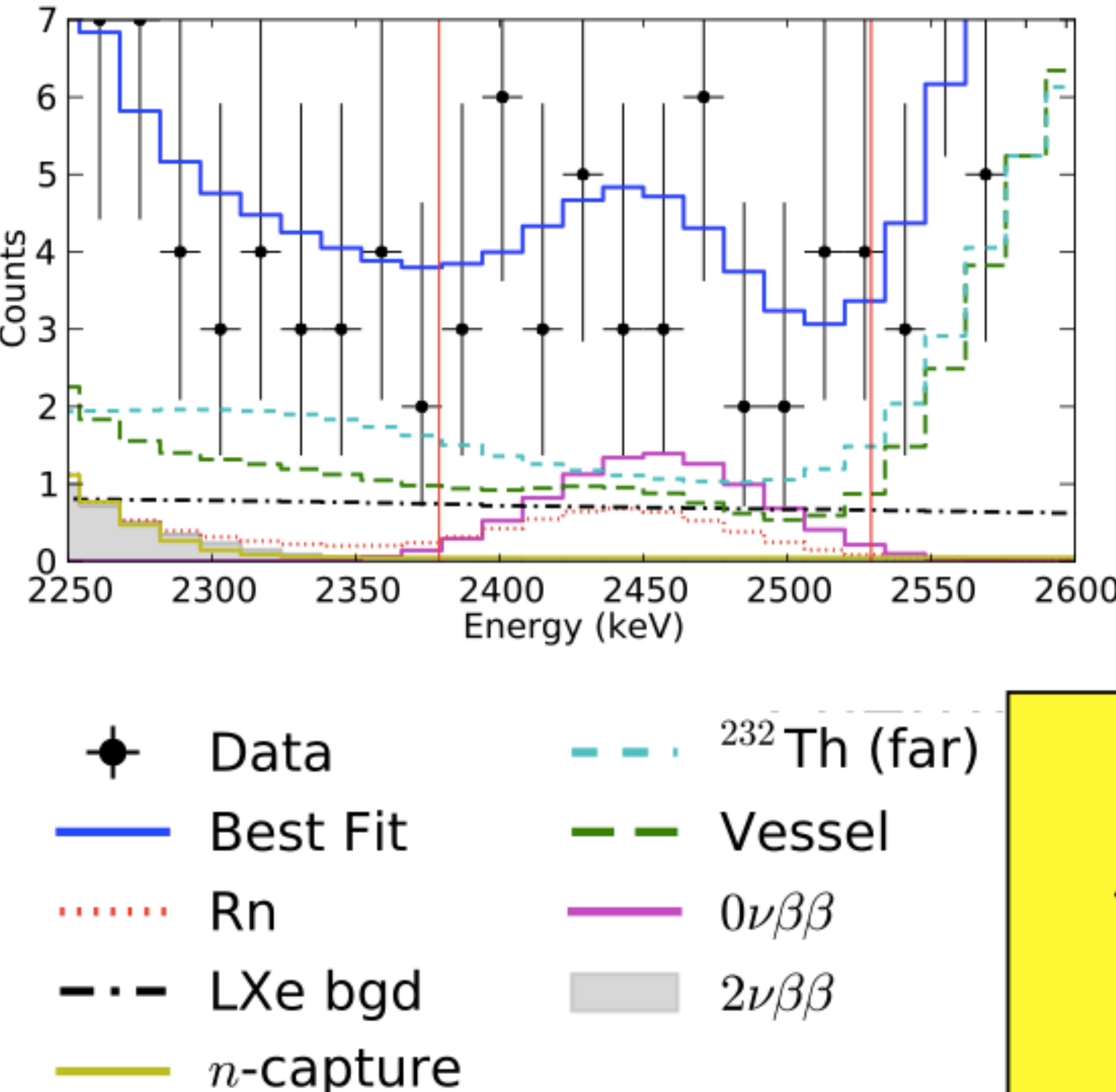
EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Materials screening: NIM A591, 490-509 (2008)

Final Fit



Analysis:
980 to 9800 keV

Looking for 0νββ



Backgrounds in ± 2σ ROI	
Th-228 chain	16.0
U-232 chain	8.1
Xe-137	7.0
Total	**31.1 ± 3.8**

From profile likelihood:

$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr

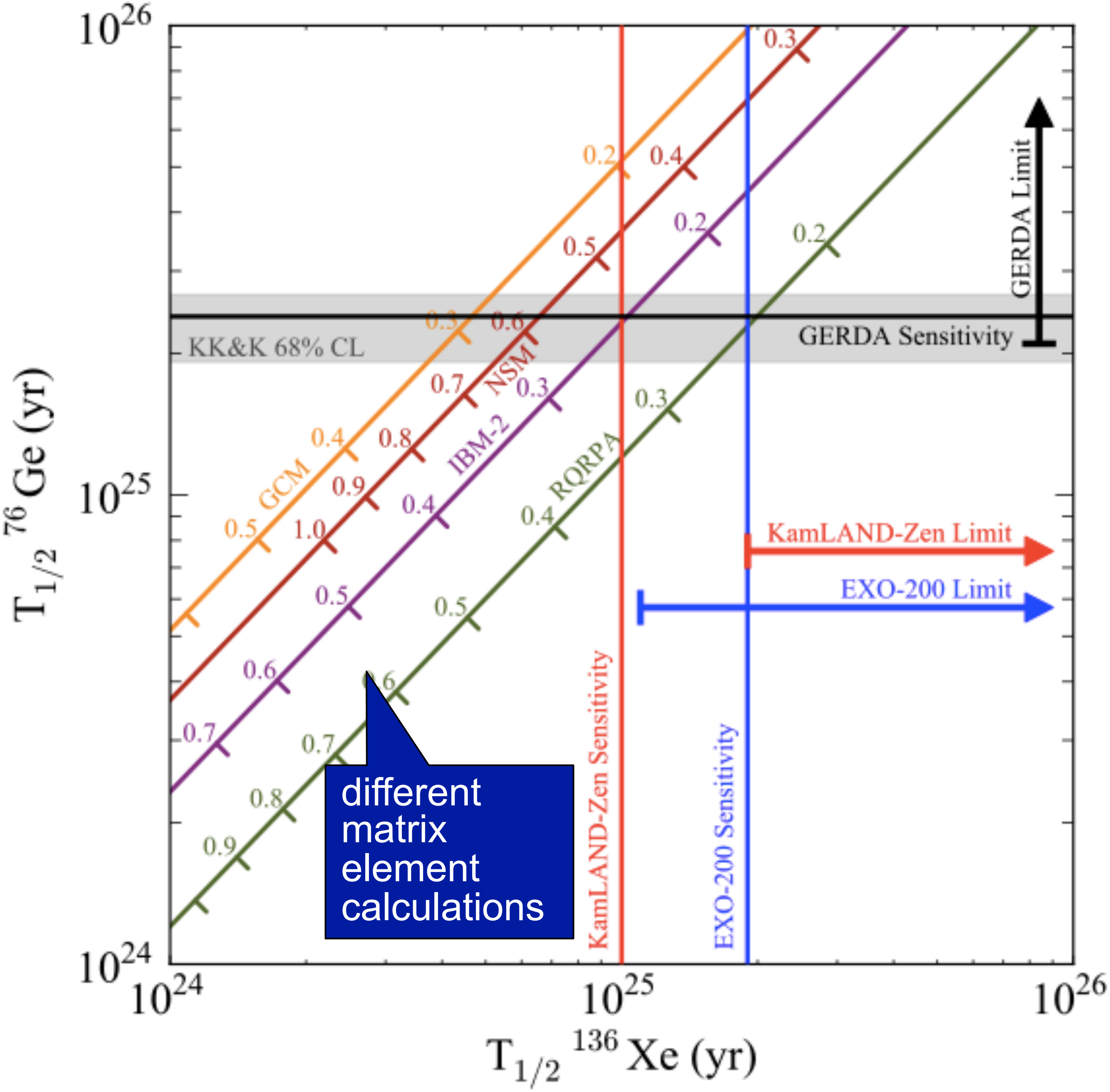
$\langle m_{\beta\beta} \rangle$ < 190 – 450 meV

(90% C.L.)

***Nature* (2014)**

doi:10.1038/nature13432

0νββ status comparison



EXO-200:
***Nature* (2014),**
doi:10.1038/nature13432

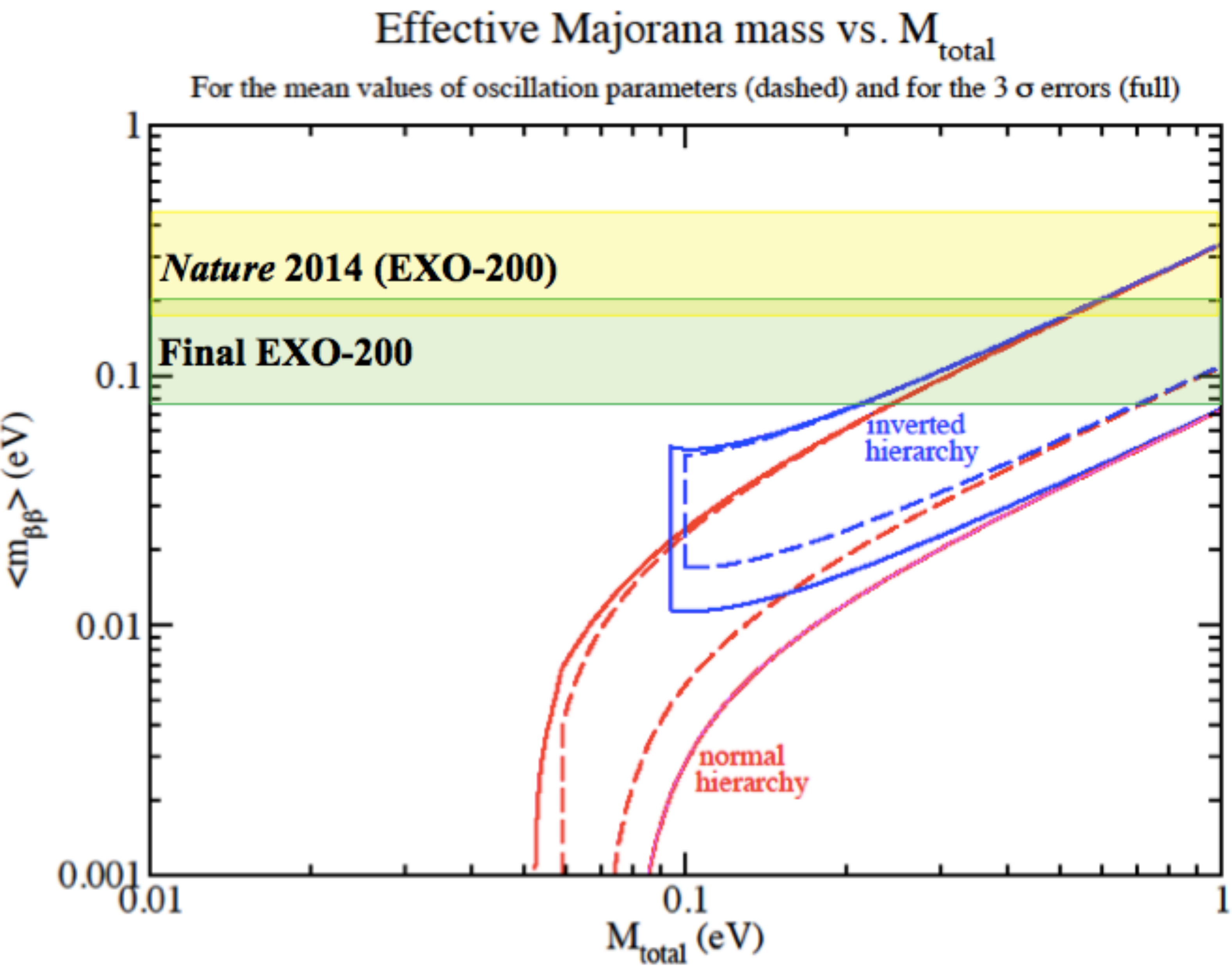
GERDA Phase 1:
PRL 111 (2013) 122503

KamLAND-Zen:
PRL 110 (2013) 062502

KK&K Claim:
Mod. Phys. Lett., A21 (2006) 1547

Klapdor claim under serious stress...

Sensitivity outlook

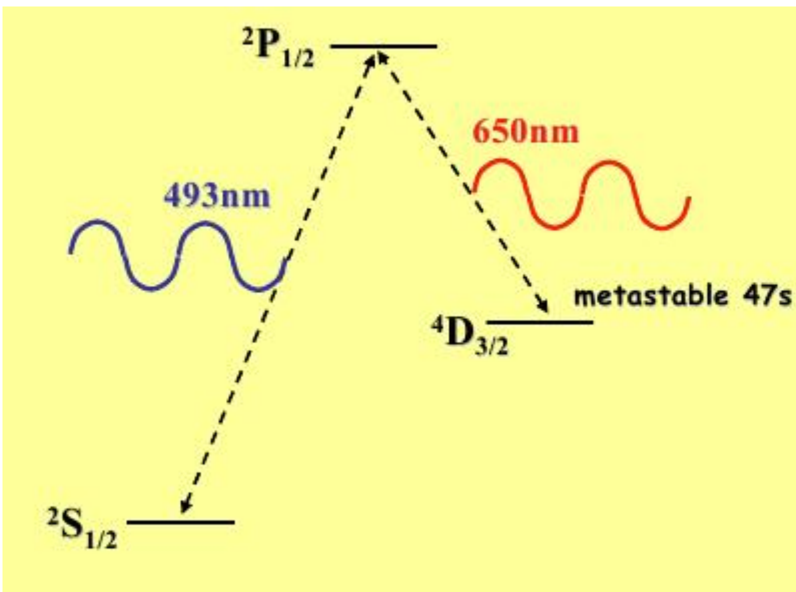


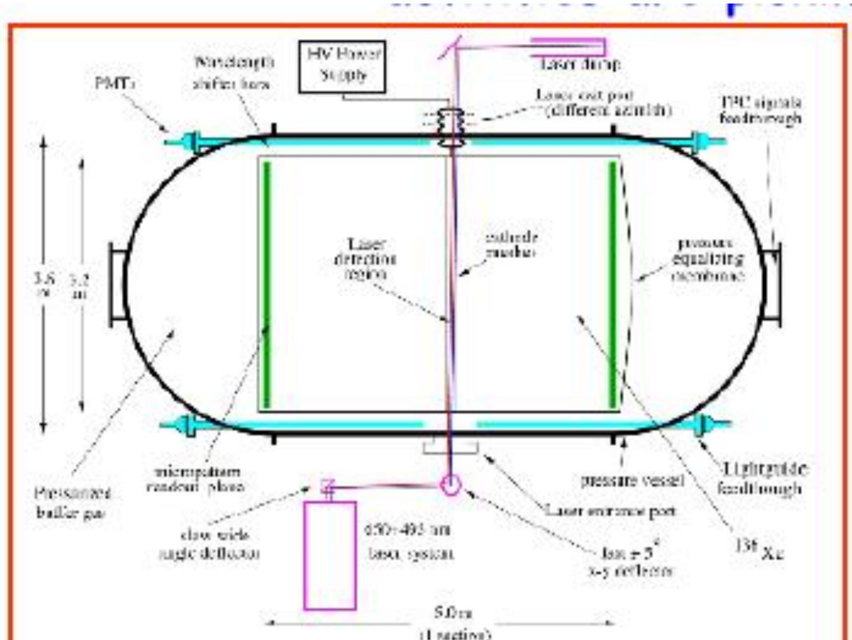
EXO-200 ultimate sensitivity (90%CL):
2 years additional livetime with Rn removal

A possibility under R&D for liquid or gaseous xenon upgrades to EXO:

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + e^- + e^-$$

Barium tagging: find the resulting barium ion by laser spectroscopy to reduce background

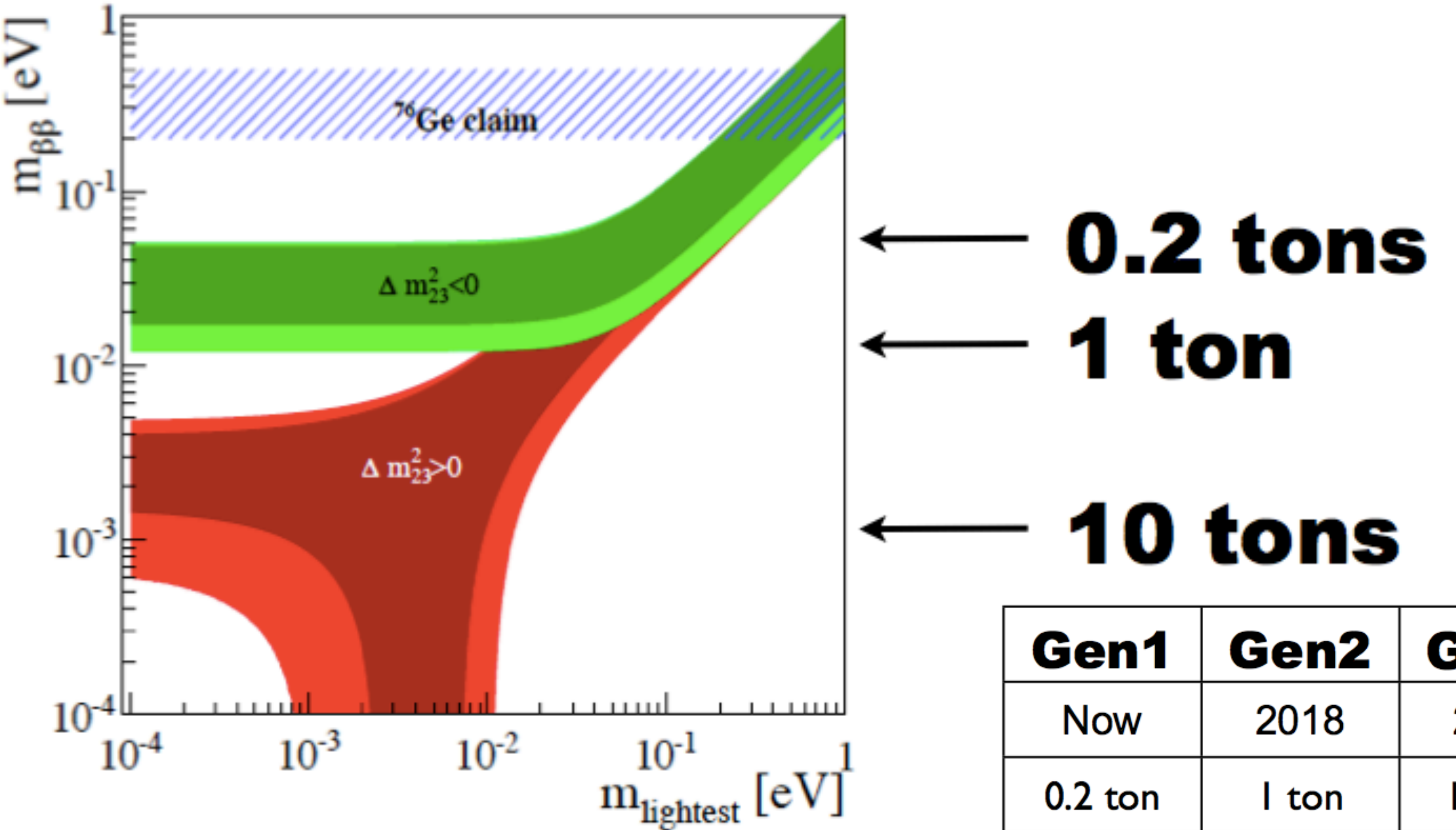




EXO GXe concept
M.Danilov et al, Phys Lett 480 (2000) 12

G. Gratta

The Next Generation: Scaling Up

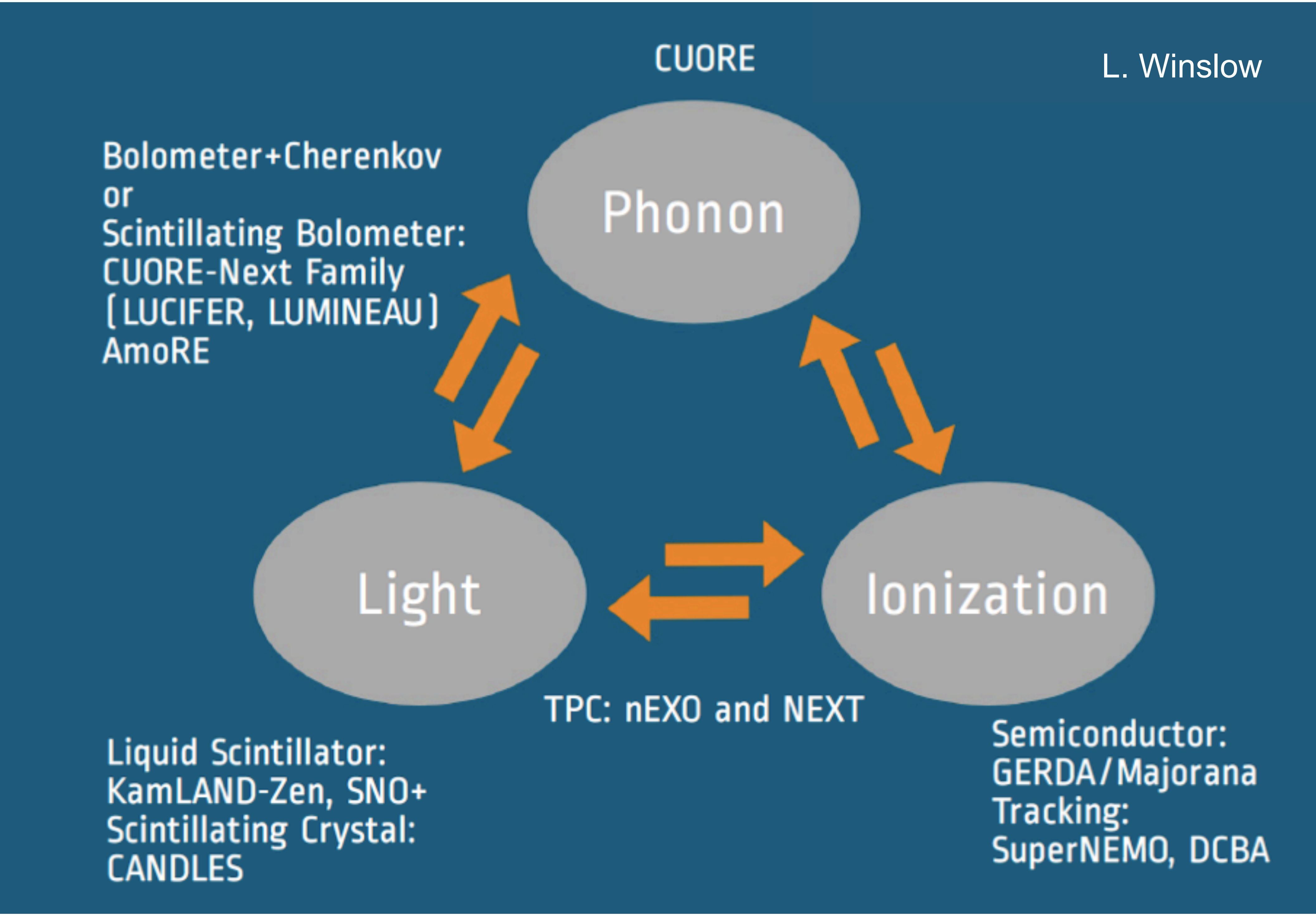


Gen1	Gen2	Gen3
Now	2018	2025
0.2 ton	1 ton	10 ton
150 meV	15 meV	1.5 meV

Warning: Factors of 5 hanging around.

L. Winslow

Next Generation Technologies



The massive statistics approach... dope a huge detector w/ NLDBD isotope

SNO+ detector

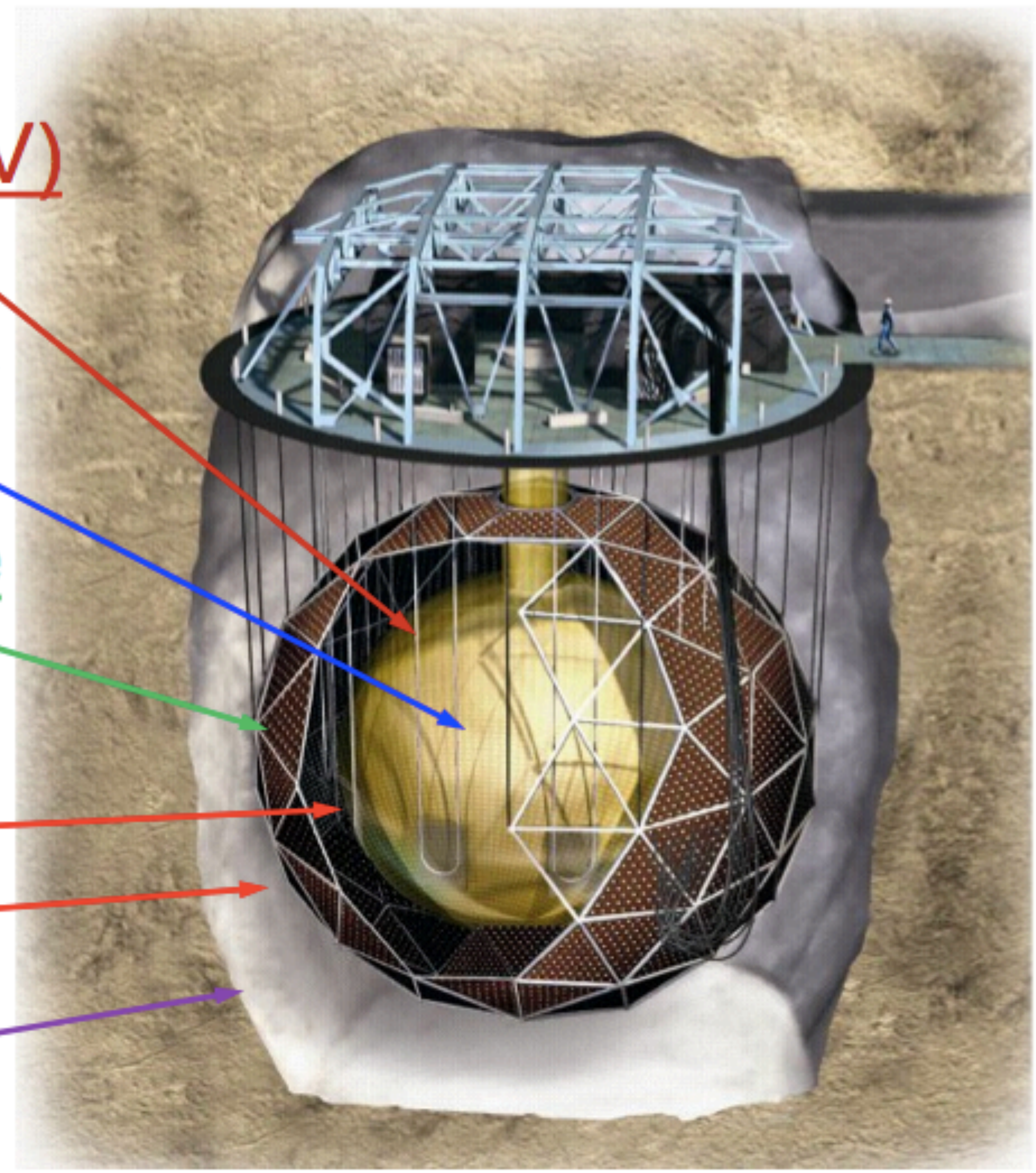
Acrylic Vessel (AV)
-12 m diameter

Liquid scintillator
- 780 t

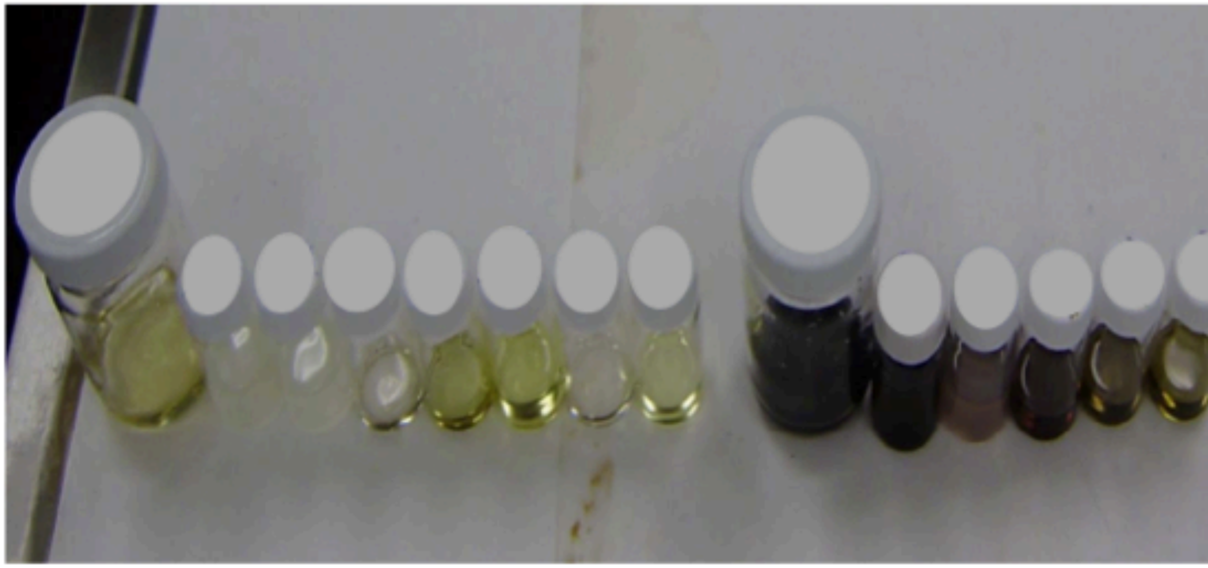
Phototube sphere
- 9500 PMTs

Water shielding
- 1700 t inner
- 5300 t outer

Urylon liner
- radon seal



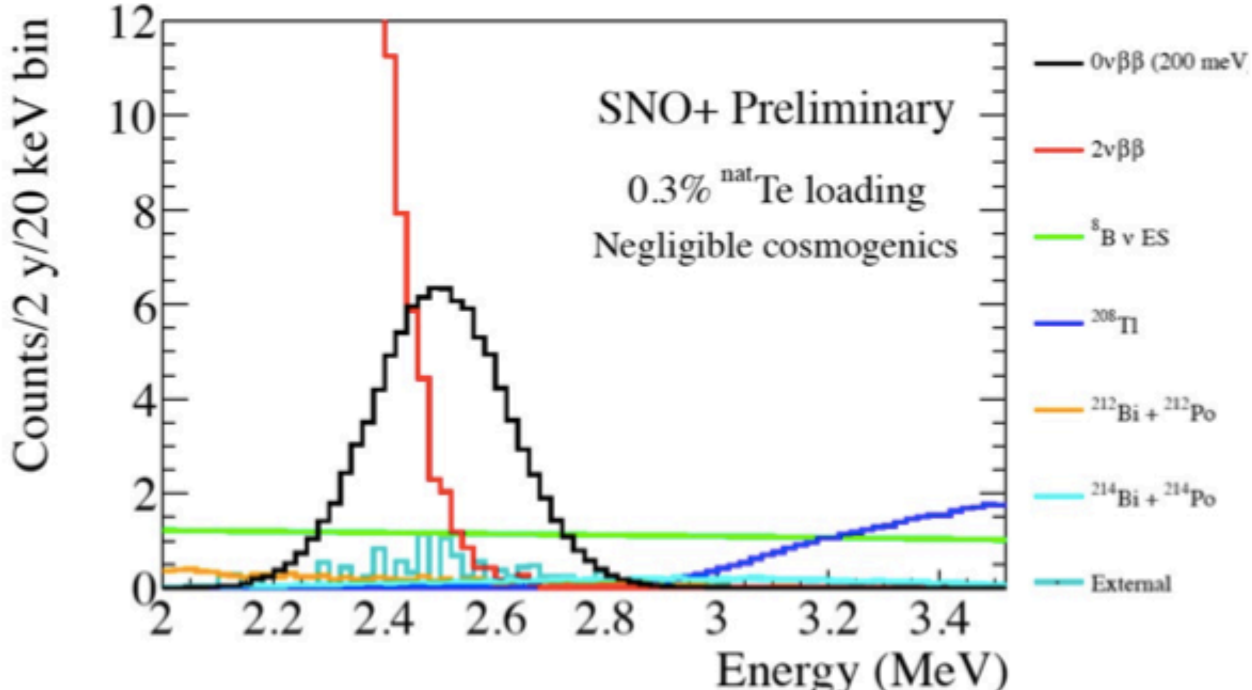
Loading Te



- New loading technique (BNL): Dissolve telluric acid in water and add few percent of this mixture with LAB using a surfactant
- Clear and stable > 1 year explicitly demonstrated
- Initial 0.3% Te loading

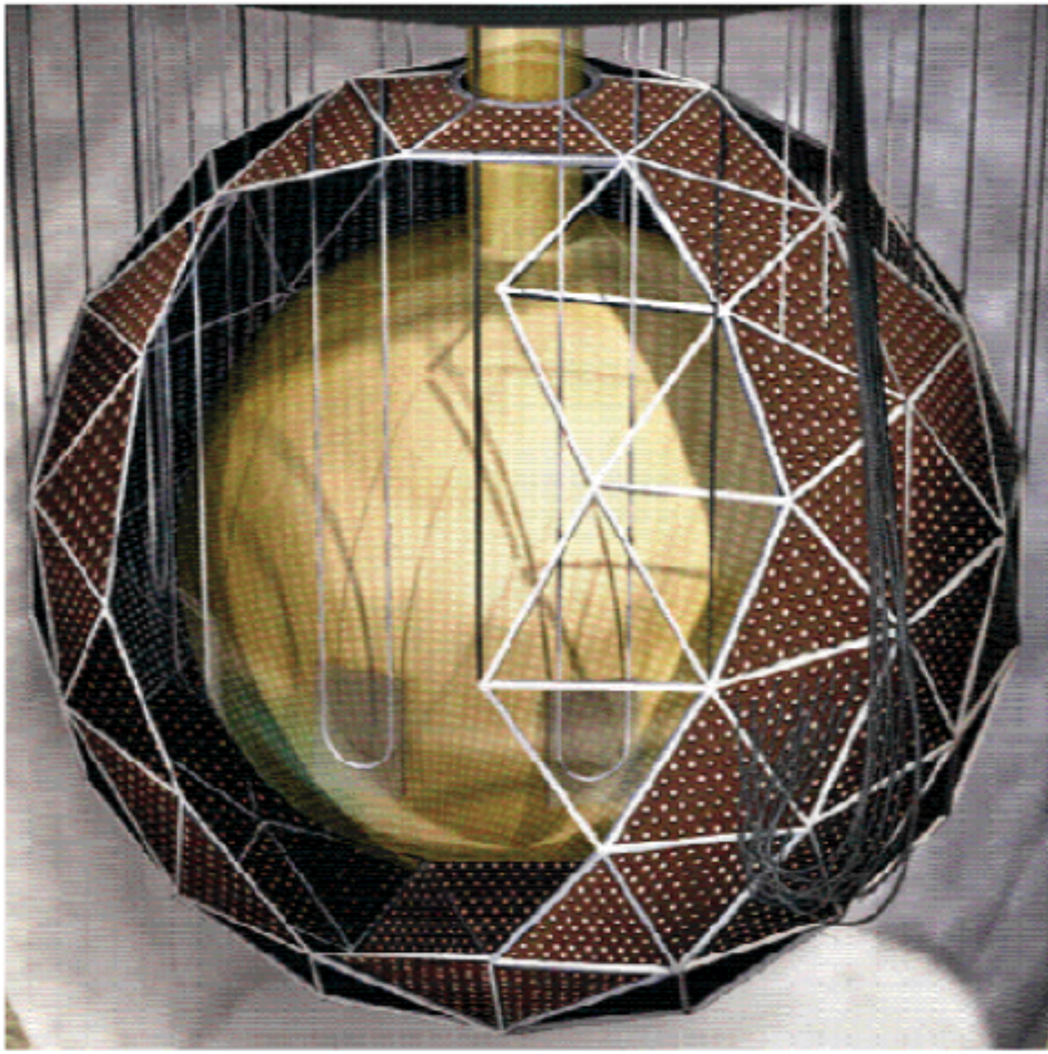
Expected energy spectrum

- 3.5 m (20%) fiducial volume cut
- 2 years
- >99.99% efficient ^{214}Bi tag
- 97% efficient internal ^{208}Tl tag
- Factor 50 reduction ^{212}BiPo
- Negligible cosmogenics
- $<m_\nu>=200$ meV

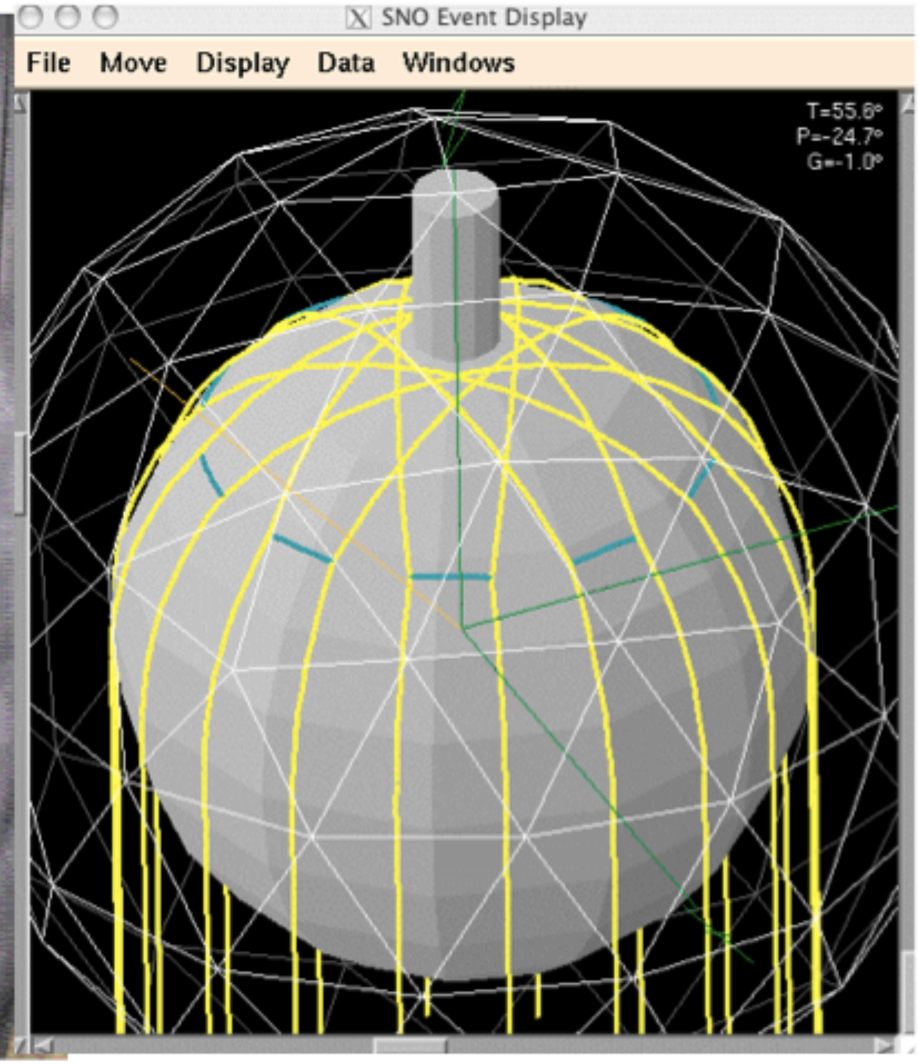


SNO+ status

SNO (hold up ropes)

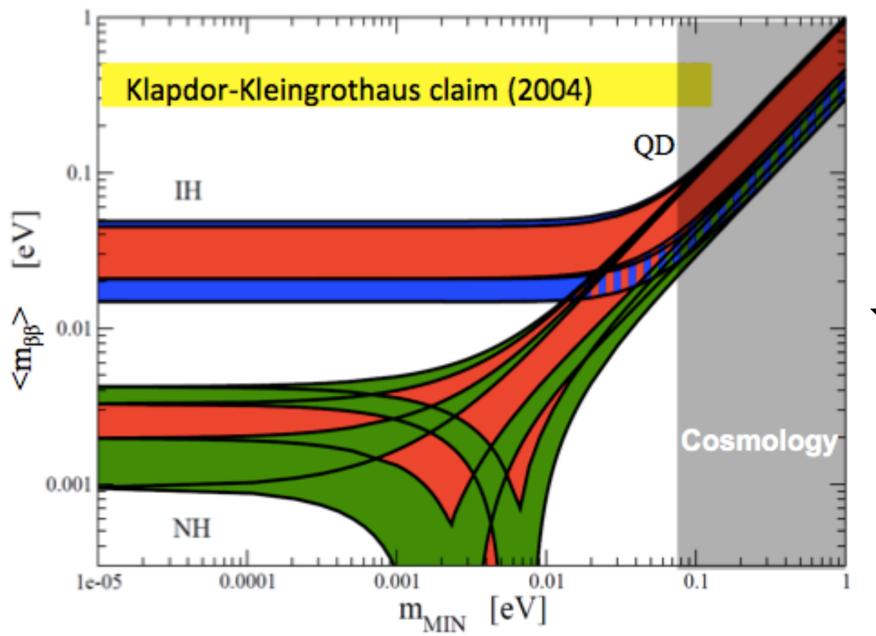


SNO+ (hold down ropes)



Summary: Part III

Neutrinoless double beta decay pretty much the only way of getting at the Majorana vs. Dirac question



KK claim now pretty much disfavored ... next generation trying to get below IH region

Multiple approaches and technologies... in the long term will need more than one isotope

Theory needed too!

Overall Summary

The last two decades of neutrino physics have been fantastic... but still many questions:

What are the remaining 3-flavor parameters?
Is there CP violation in the neutrino sector?
What is the absolute mass scale?
Are neutrinos Majorana or Dirac?
Is there new physics to be found?

There's more ahead