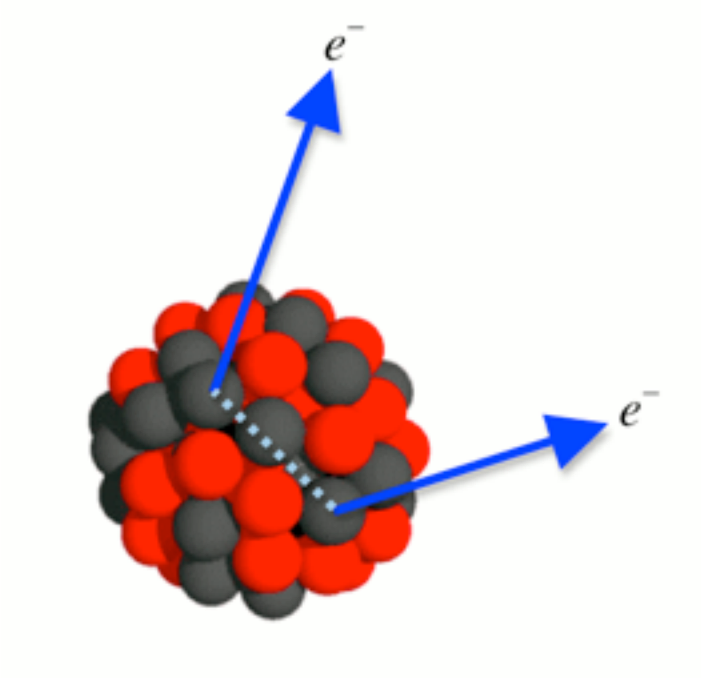
Neutrinoless Double Beta Decay Experiments

Outline

- Physics
- Experiments (Emphasis on UK programme)
- Roadmap



Ruben Saakyan

PPAP Community Meeting

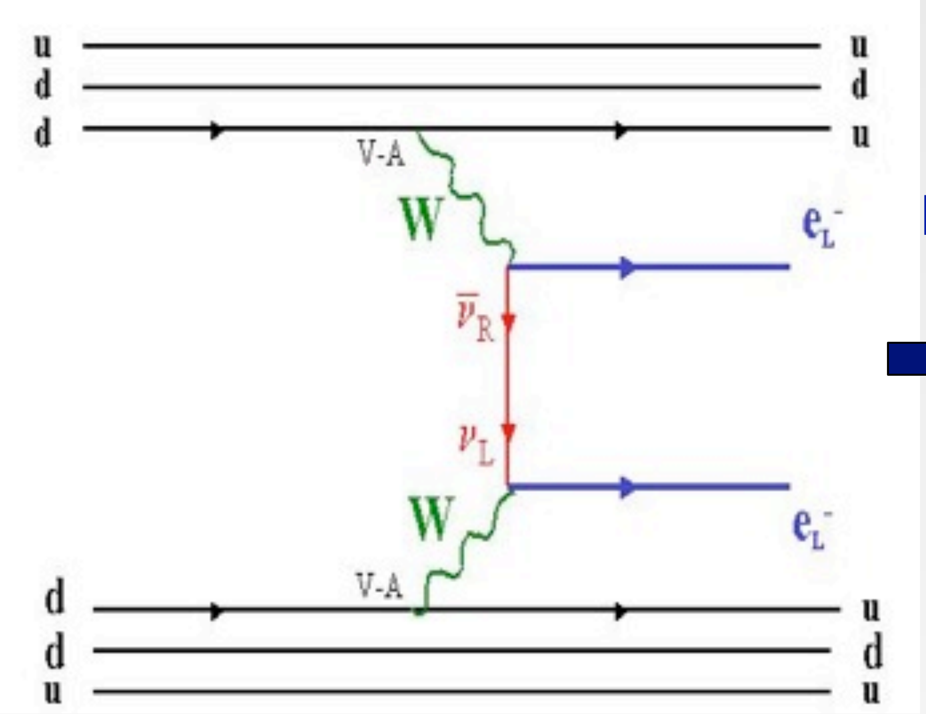
Birmingham

11 July 2011

0νββ decay - the only practical way to answer fundamental BSM physics questions:

Lepton Number violation
Is ν its own anti-particle?

$(A,Z) \rightarrow (A, Z+2) + 2e^-$



Light neutrino exchange

Majorana neutrino (ν=anti-ν)

Access to absolute neutrino mass

$$[T_{1/2}(0\nu)]^{-1} = G^{0\nu}(Q_{\beta\beta},Z)\ |M^{0\nu}|^2\ \langle m_\nu\rangle^2$$

$$\langle m_\nu\rangle = m_1|U_{e1}|^2 + m_2|U_{e2}|^2 . e^{i\alpha} + m_3|U_{e3}|^2 . e^{i\beta}$$

|Uei|: mixing matrix elements; α and β: Majorana phases

Other possible processes:

V+A current : $\langle\lambda\rangle$, $\langle\eta\rangle$

Majoron emission : $\langle g_M\rangle$

Supersymmetry : λ'_{111}, λ'_{113}

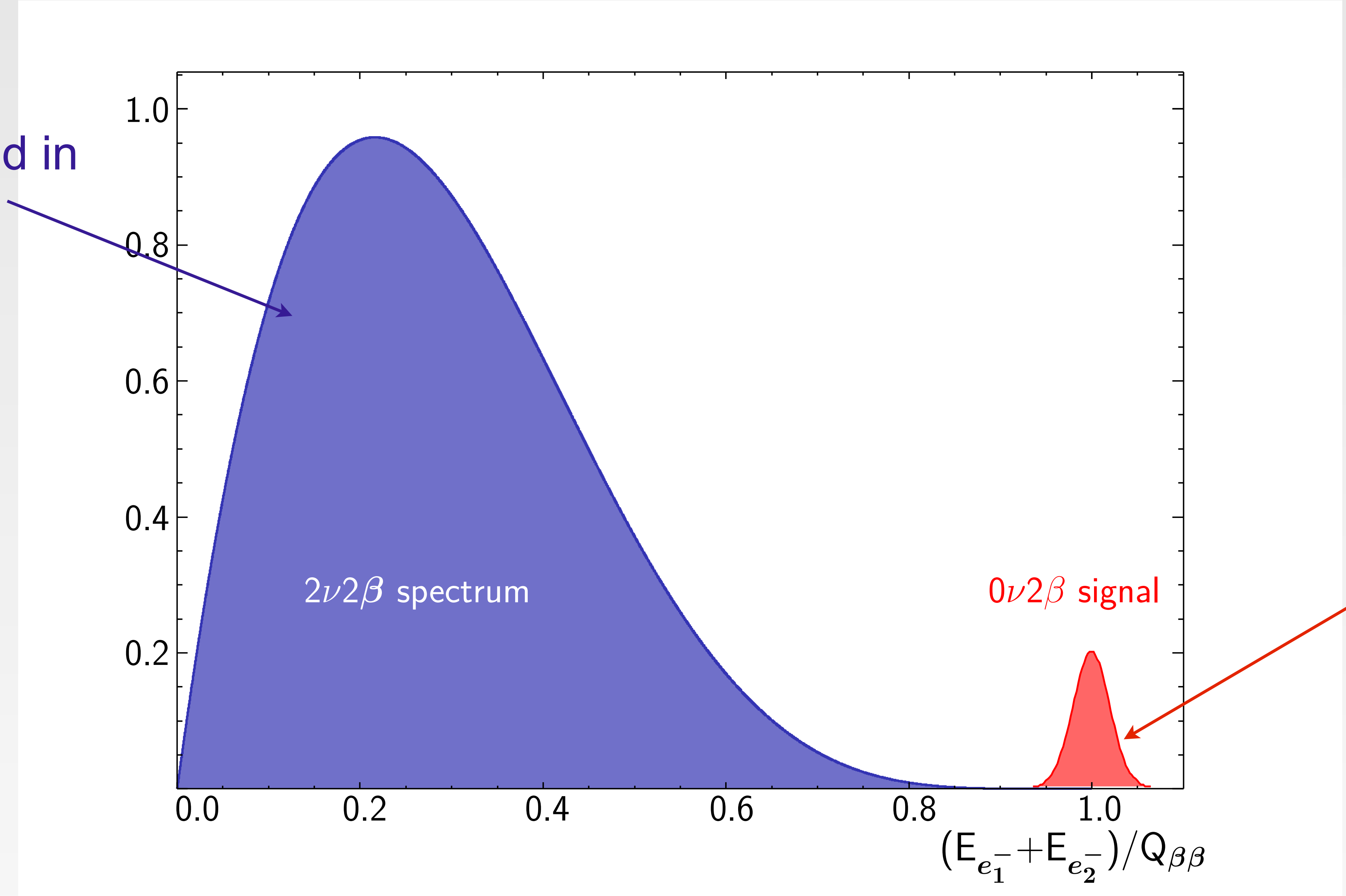
Physics implications:

1) Majorana neutrinos ⇒ See-Saw ⇒ CPV in M_R ⇒ Higgs + leptons ⇒ Leptogenesis ⇒ B-assymetry

2) Absolute ν mass scale and mass hierarchy

<u>Main observable:</u> Energy sum of two electrons emitted in the decay

Allowed in SM $\Delta L = 0$

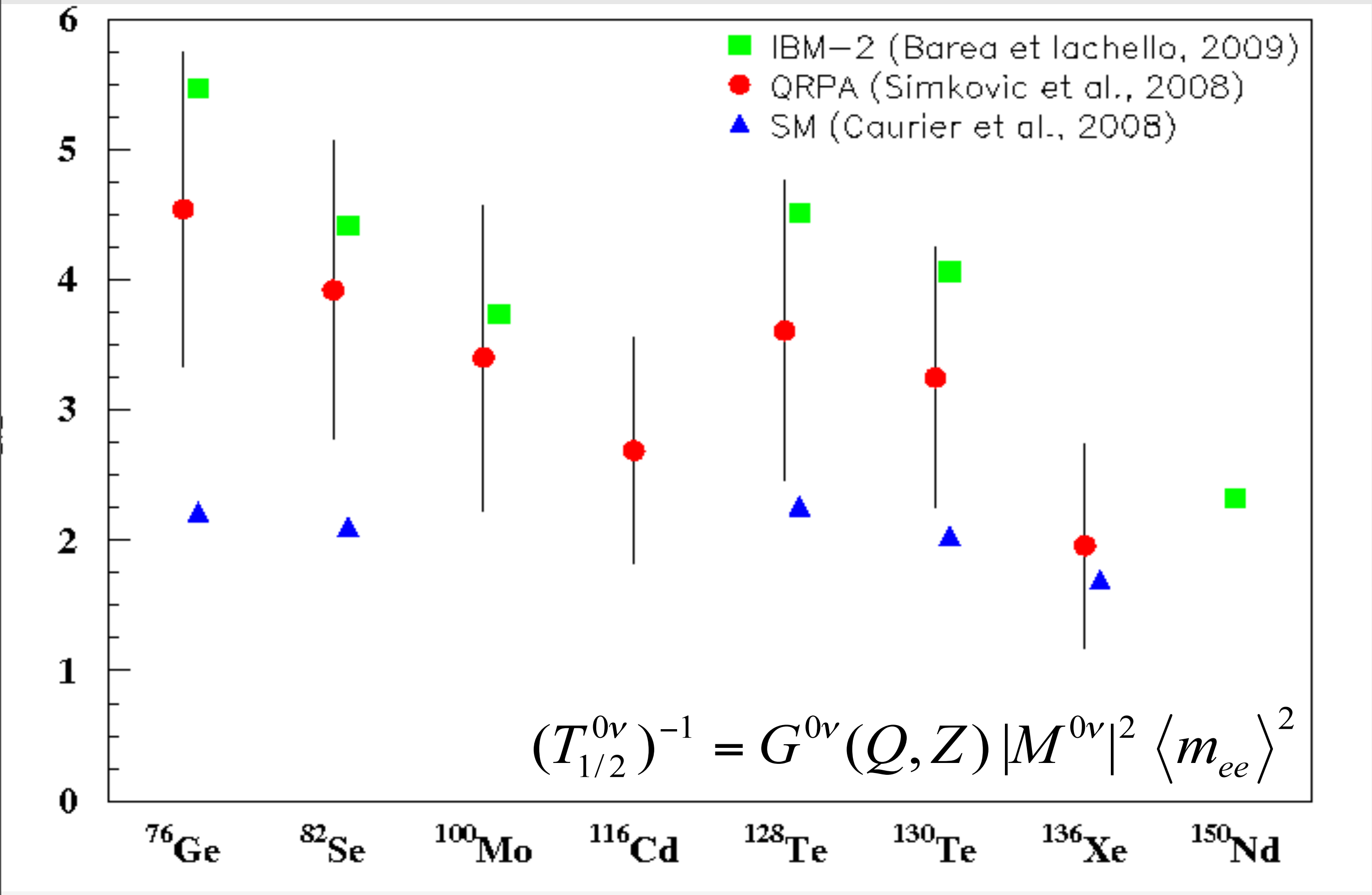


Forbidden in SM $\Delta L = 0$

<u>The challenge</u>: $T_{1/2}(2\nu) \sim 10^{19} - 10^{21}$ yr, $T^{1/2}(0\nu) > 10^{25}$ yr
c.f. $T_{1/2}$ (U/Th) $\sim 10^{10}$yr

<u>Double Beta Decay is about background suppression!</u>

Different Isotopes have to be studied



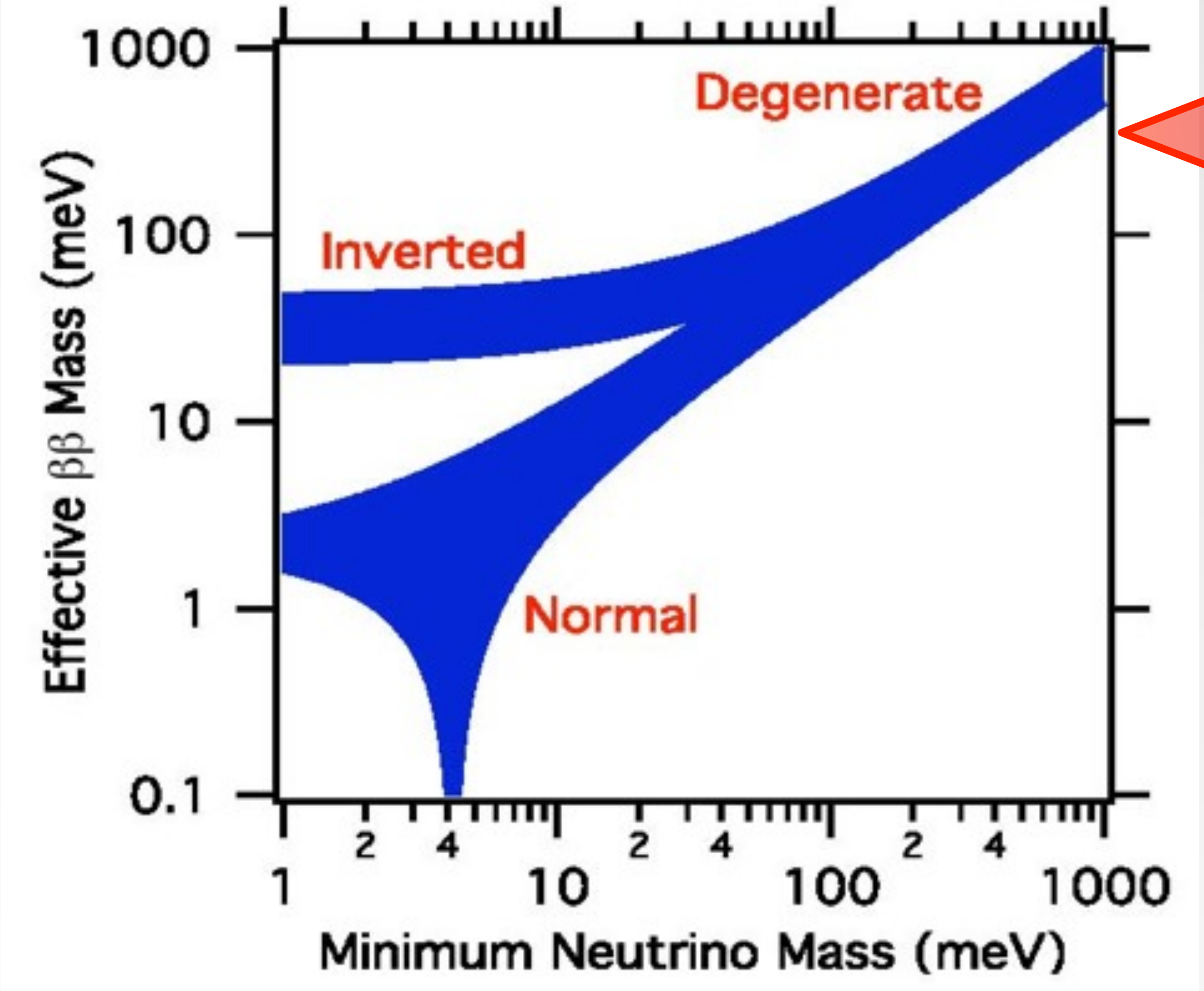
Isotope choice

- $Q_{\beta\beta}$
- Phase space
- Isotope abundance
- Enrichment opportunities
- NME (Nuclear Matrix Elements)
- $T_{1/2}(2\nu)$

Phase space factor

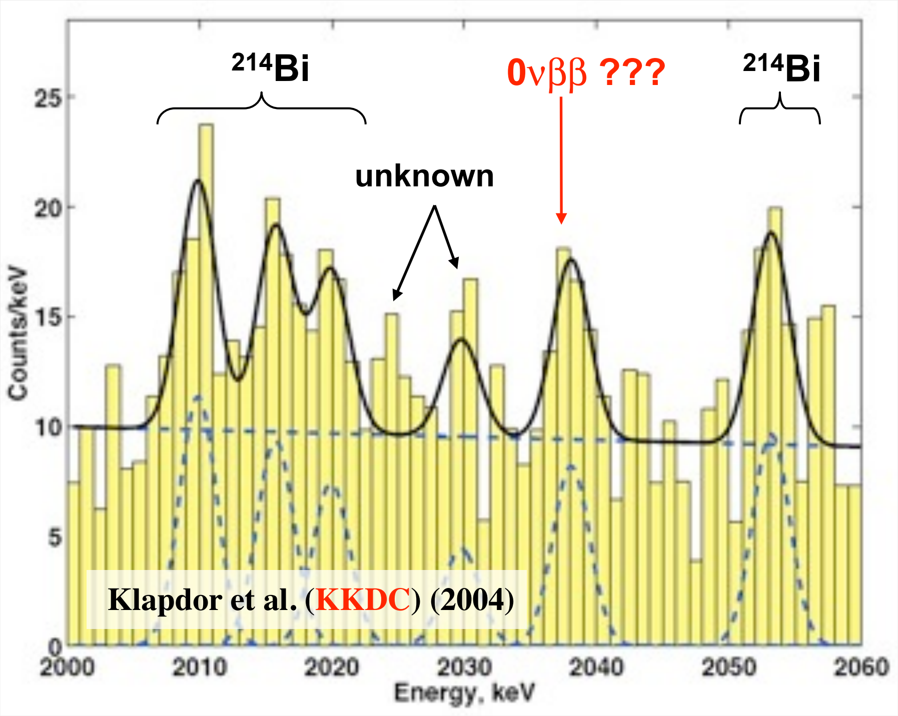
Isotope $Q_{\beta\beta}$, MeV	^{48}Ca 4.27	^{76}Ge 2.04	^{82}Se 3.0	^{96}Zr 3.35	^{100}Mo 3.03	^{116}Cd 2.8	^{130}Te 2.53	^{136}Xe 2.48	^{150}Nd 3.37
$G^{0\nu}$ $\times 10^{-15}$ yr^{-1}	75.8	7.6	33.5	69.7	54.5	58.9	52.8	56.3	249

0νββ results so far



Controversial KK claim

$$\langle m_\nu \rangle \sim 0.4 \text{ eV}$$



Experiment	Isotope	$\langle m_\nu \rangle$*, eV 90%CL
IGEX	^{76}Ge	<0.35-0.9
CUORICINO	^{130}Te	<0.3-0.7
NEMO3**	^{100}Mo	<0.3-0.9

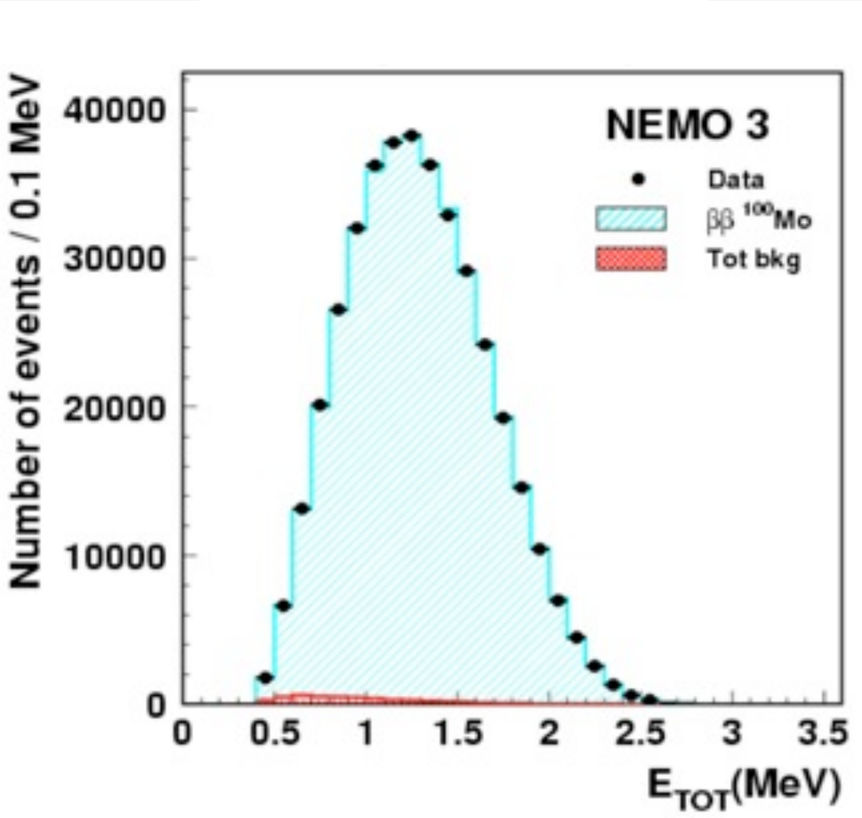
*Range due to NME uncertainties

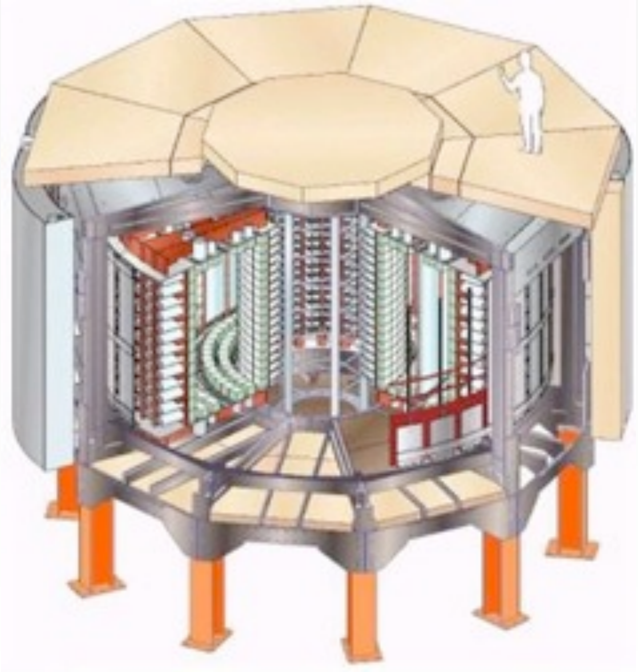
** Major UK involvement

SM allowed 2νββ results

Important: Experimental input for NME
Ultimate background in future experiments

Isotope	Best $T_{1/2}(2\nu)$, 10^{19} yrs	Experiment
^{48}Ca	4.4 ± 0.6	NEMO3
^{76}Ge	150 ± 10	Heidelberg-Moscow
^{82}Se	9.6 ± 1.0	NEMO3
^{96}Zr	2.35 ± 0.21	NEMO3
^{100}Mo	0.71 ± 0.05	NEMO3
^{116}Cd	2.8 ± 0.3	NEMO3
^{130}Te	70 ± 14	NEMO3
^{150}Nd	0.90 ± 0.07	NEMO3





NEMO3 stopped in January 2011 after 8 yrs of data taking to make way for SuperNEMO

Major UK involvement: UCL, Manchester, Imperial

A highly competitive field with large number of proposed experiments

Ge-diodes
Gerda/
Majorana

Bolometers
CUORE

Tracking
+Calorimeter
SuperNEMO

Liquid scintillator
SNO+/
KamLAND-Zen

Scintillating
bolometers
Lucifer/
BoLUX

LXe, EXO

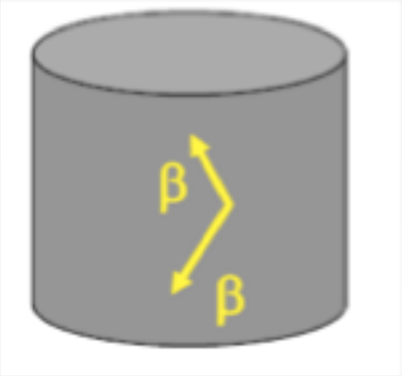
Scintillating
Crystals
CANDLES

CZT
COBRA

HPXe TPC
EXO-gas/
NEXT

Experimental Approaches

Calorimeter-only. Source = Detector



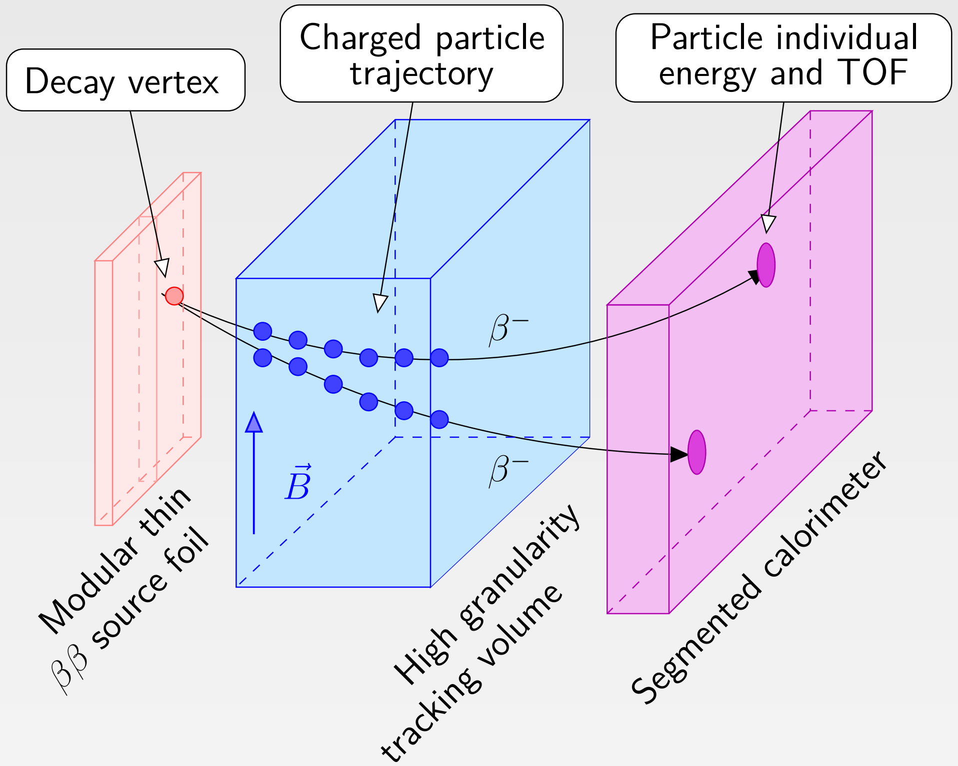
Main observable:
Deposited energy

Excellent ΔE/E
High efficiency
Relatively compact
Some particle ID capability

Main limiting factor: background

HPGe, Bolometers, (Liquid)-Scintillators, LXe.

Tracking + Calorimetry. Source ≠ Detector
(NEMO3 and SuperNEMO)



Full Topology Reconstruction

Strong background suppression and control
"Smoking gun" 0νββ signature
Sensitivity to different physics mechanisms of 0νββ

Main limiting factor: efficiency

R&D on technologies that include elements of both
CdZnTe, HPXe TPC

Figure of Merit

$$T_{1/2}^{0\nu}(90\%CL) = 2.54\times10^{26}\,\mathrm{y}\left(\frac{\varepsilon}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

ε – efficiency, W-mass number

$M\times t$ – exposure [kg × yr]

b – background [cnts kg^{-1}kev^{-1} yr^{-1}]

$\Delta E = 2\times FWHM$ around $Q_{\beta\beta}$

$$FOM = T_{1/2}^{0\nu}(90\%CL)\times\frac{G^{0\nu}}{G^{0\nu}_{^{76}Ge}}$$

← Phase-space factor normalised to ^{76}Ge

Normalised to exposure **500 kg yr** and assuming the **same NMEs**

Project	Isotope	ε in $Q_{\beta\beta}$ window	b [cnts kg^{-1}keV^{-1} yr^{-1}]	FWHM keV	Total B, counts	$T_{1/2}$ (90%CL) yr	$\frac{G^{0\nu}}{G^{0\nu}_{^{76}Ge}}$	F.O.M yr
GERDA	^{76}Ge	80%	0.01	4	40	2.1×10^{26}	1	2.1×10^{26}
SNEMO	^{82}Se	17%	6×10^{-5}	120	7	1×10^{26}	4.4	4.4×10^{26}
CUORE	^{130}Te	80%	0.01	5	185	5.7×10^{25}	6.9	4×10^{26}
EXO200	^{136}Xe	70%	6.3×10^{-4}	94	73	7.6×10^{25}	7.4	5.6×10^{26}
SNO+	^{150}Nd	70%	7.5×10^{-4}	300	3996	9.4×10^{24}	32.8	3.1×10^{26}

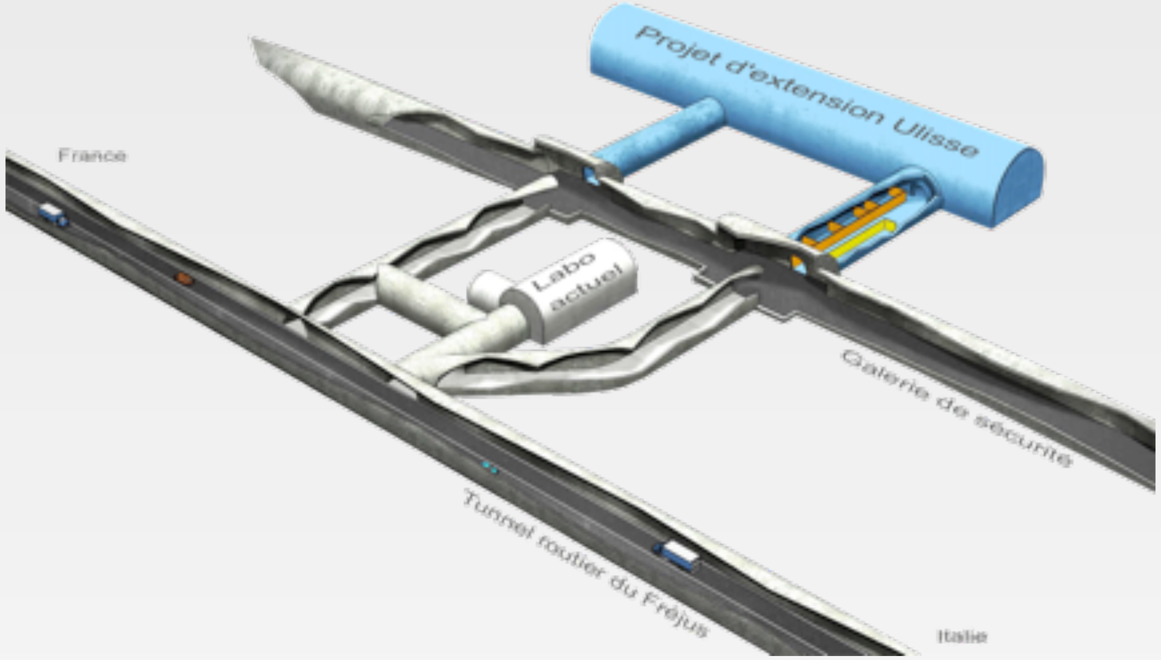
Reliability of expected performance numbers is **not** taken into account

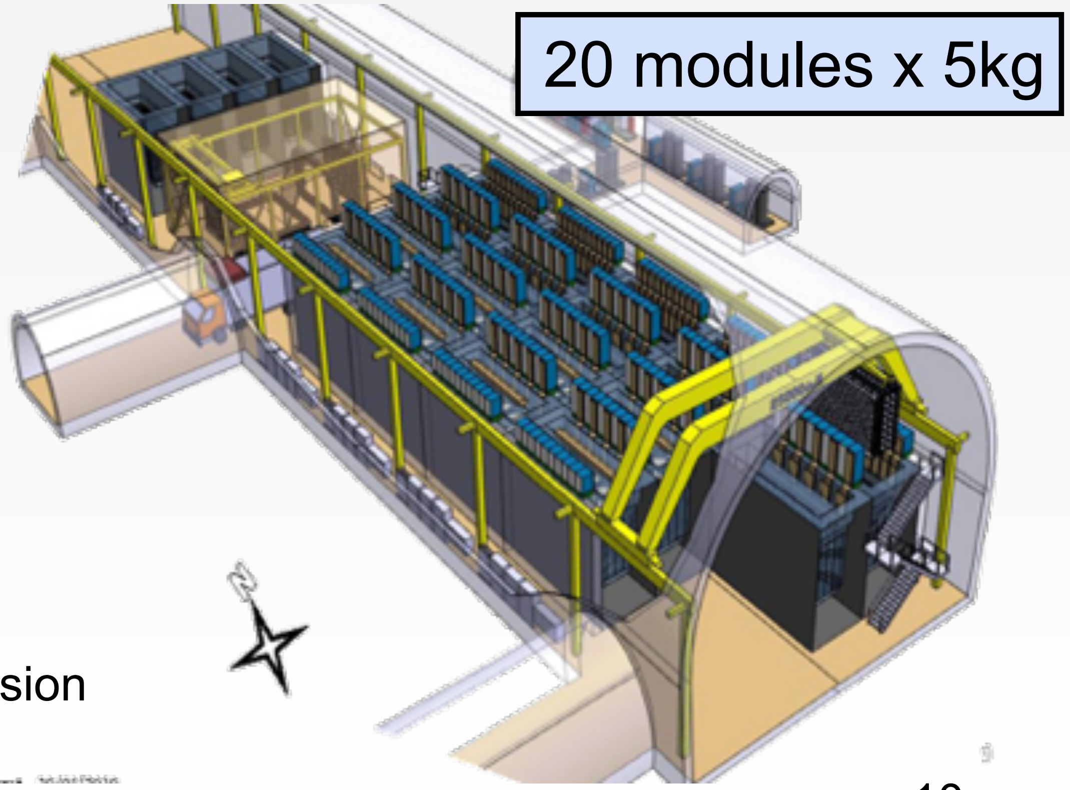
SuperNEMO at new LSM (Modane Underground Lab)

(~100 people)

UCL-HEP, UCL-MSSL,
Manchester, Imperial, Warwick

Exposure	500 kg x yr
Isotope	^{82}Se in first instance ^{150}Nd, ^{48}Ca under study
Background (2xFWHM around $Q_{\beta\beta}$)	7 events (Bgrd model based on NEMO3 experience)
$T_{1/2}^{0\nu}$ (90%CL)	10^{26} yr
$\langle m_\nu \rangle$	40-80 eV





20 modules x 5kg

Pros	Cons
Background suppression	Efficiency
Topology ("smoking gun")	Large footprint
Physics mechanism ID*	

*Superior sensitivity to alternative 0νββ mechanisms, e.g. with Majoron emission

SuperNEMO Module design

Planar and **modular** design:

~ 100 kg of enriched isotopes (20 modules x 5 kg)

1 module:

Source (~40 mg/cm²) 4 x 2.7 m²

^{82}Se first but almost any isotope possible

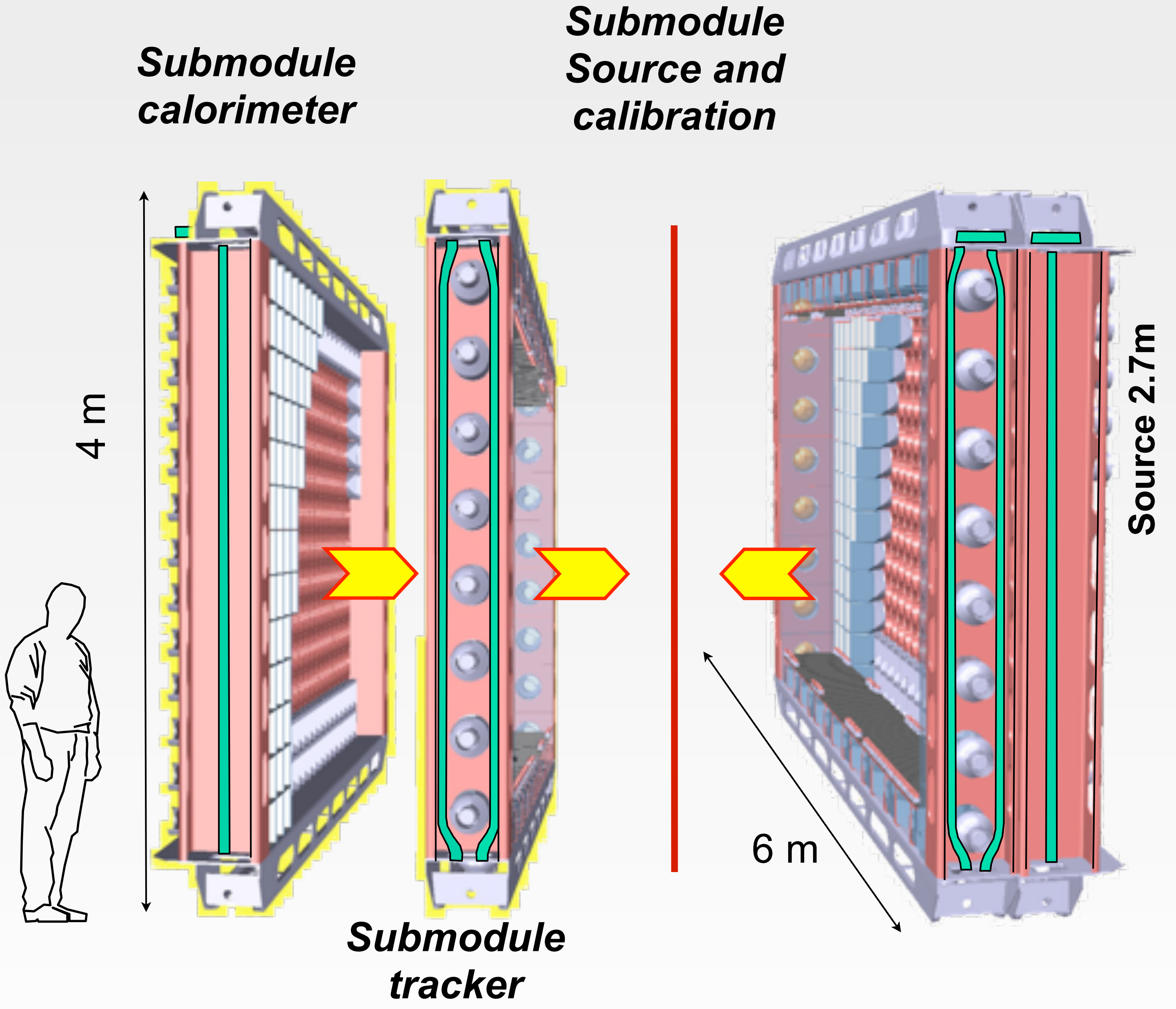
^{150}Nd, ^{48}Ca being looked at

Tracking : drift chamber ~2000 cells in Geiger mode

Calorimeter: scintillators + PMTs

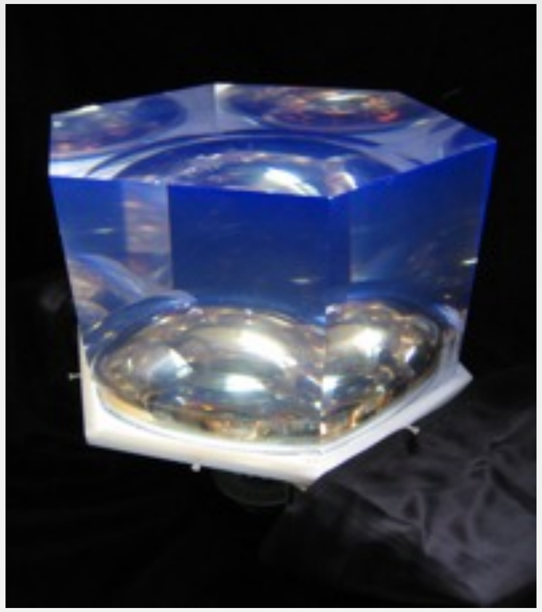
600 PMTs + scint. blocks

Modules surrounded by water passive shielding

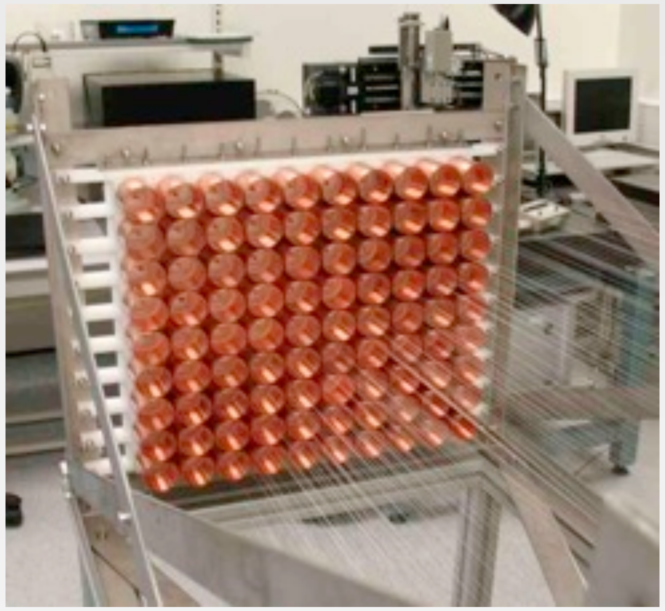


2 m (assembled, ~0.44m between source and calorimeter)

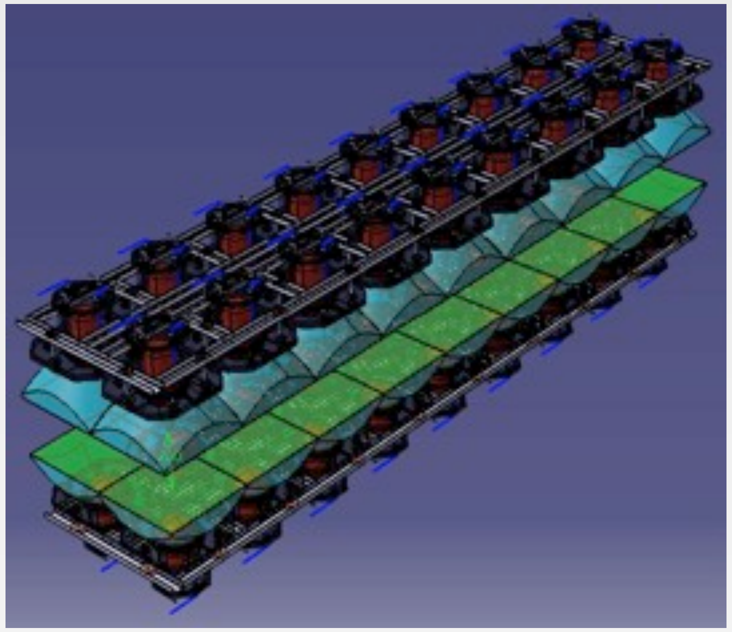
SuperNEMO R&D (2006-2010)



Calorimeter
FWHM = 4% at 3 MeV



Low Background
Tracker mass production



Ultra-LB detection technology

<u>UK groups:</u> UCL-HEP, UCL-MSSL, Manchester, Imperial

Decisive UK involvement (50% of effort and budget)

R&D Responsibilities: Tracker (sole responsibility), Calorimeter, Software.

SuperNEMO Demonstrator Construction (2010-2013)

Technology

Ultimate prove of BG levels

Physics

Sensitive to K-K claim

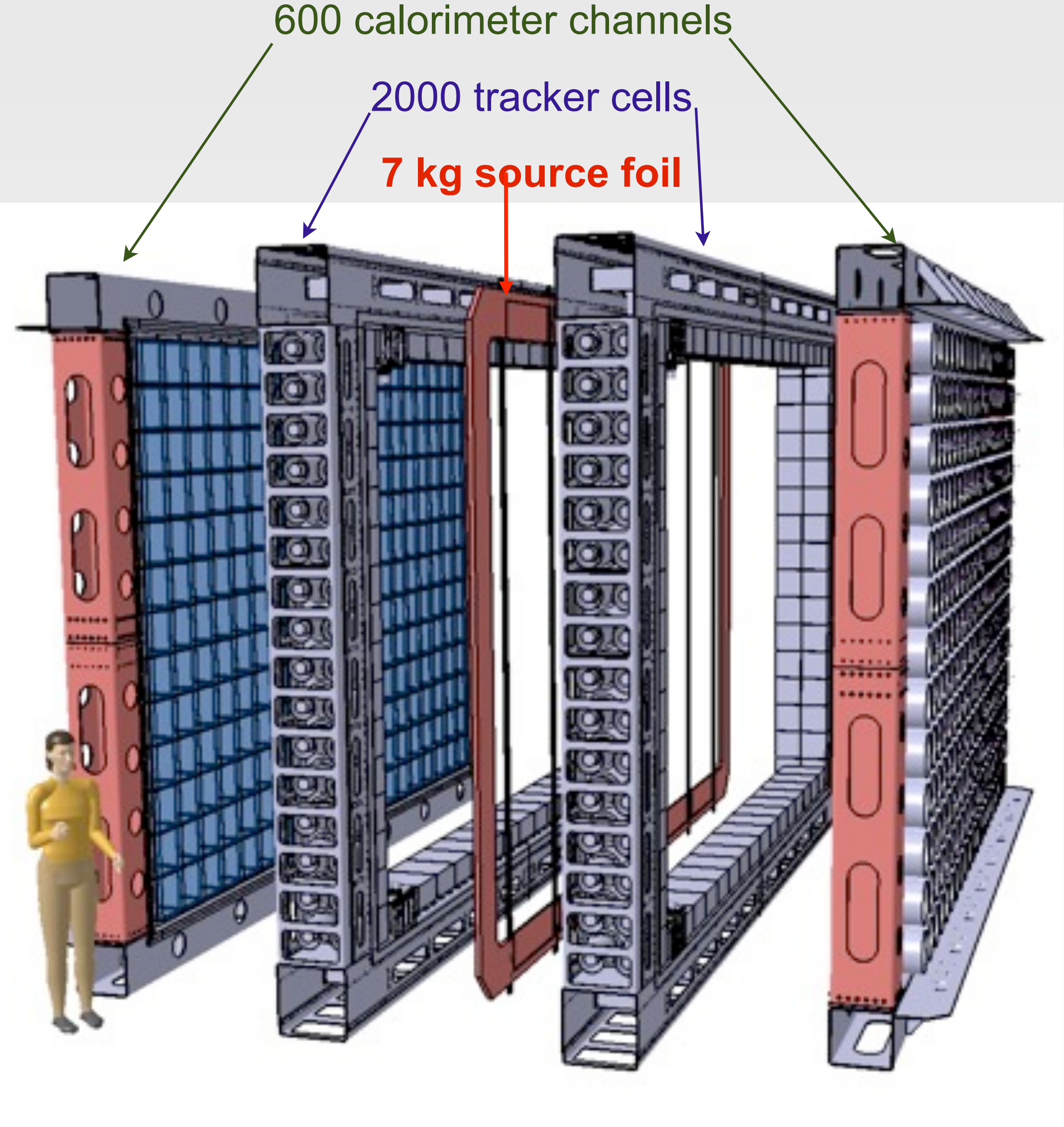
7kg of ^{82}Se

Bgrd ≤ 0.06 events/yr

The first 0 bgrd experiment

$$T_{1/2}^{0\nu}(90\%CL) = 2.56 \times 10^{24} \times t \ \text{yrs}$$

Gerda-I sensitivity in 2.5 years - 6.5×10^{24} yr (equivalent to 3×10^{25}yr with ^{76}Ge)



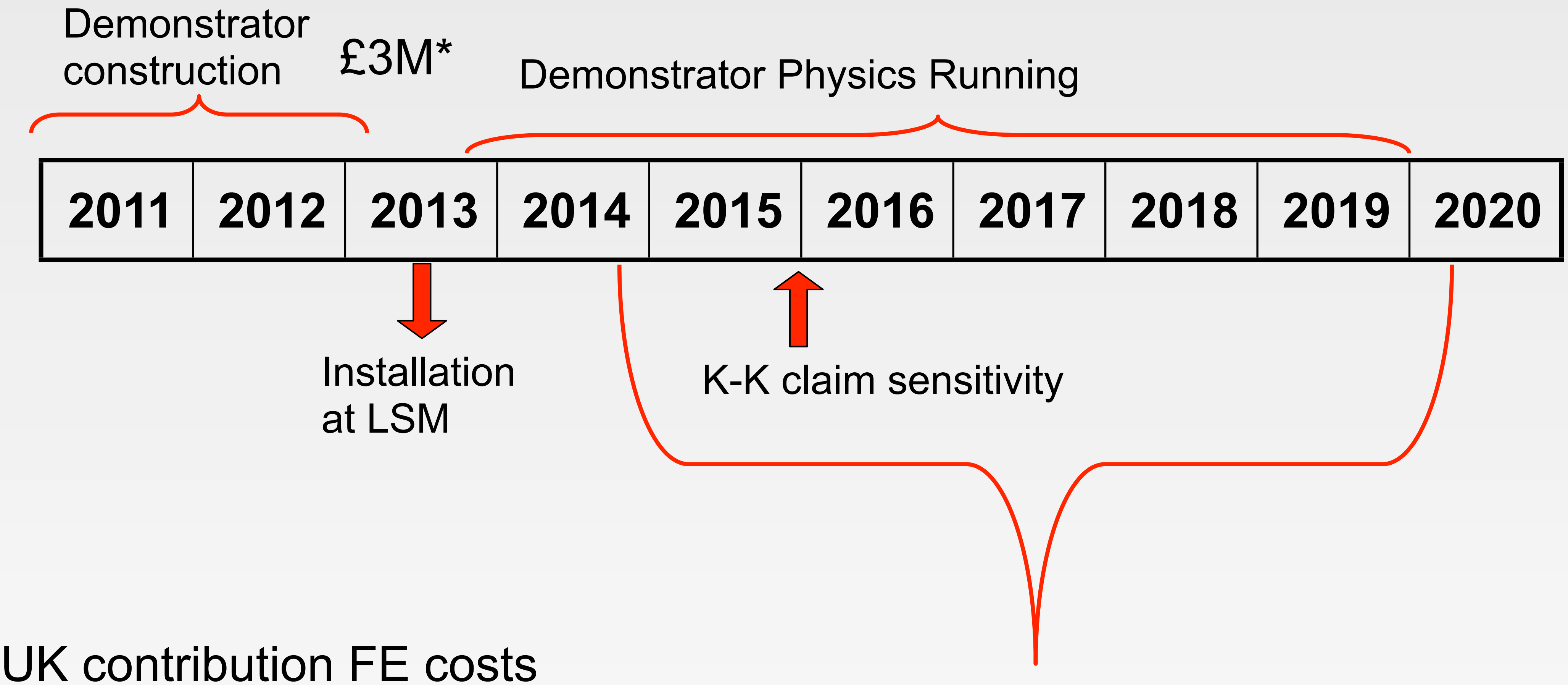
UK groups: UCL-HEP, UCL-MSSL, Manchester, Imperial, Warwick

Decisive UK involvement (40% of Demonstrator effort and budget)

Responsibilities: Entire Tracker, large software effort.

UK members lead a number of key WPs and provide international co-spokesperson (R. Saakyan)

SuperNEMO timeline and budget (UK)



Demonstrator construction £3M*

Demonstrator Physics Running

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020

Installation at LSM

K-K claim sensitivity

*UK contribution FE costs
** UK estimated contribution FE costs
(Total costs RG + Project Grant)

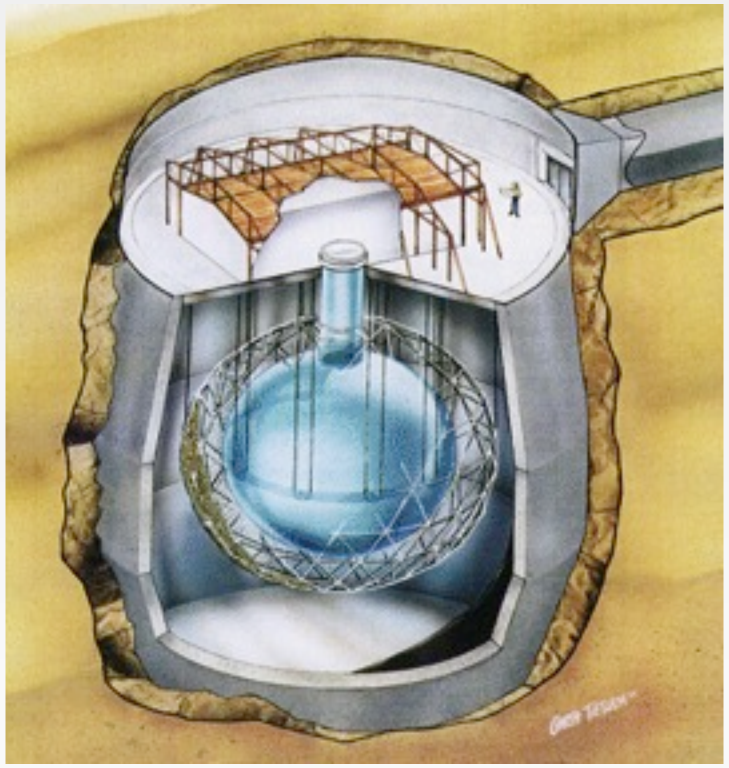
Construction and exploitation of full SuperNEMO detector

£10-15M*

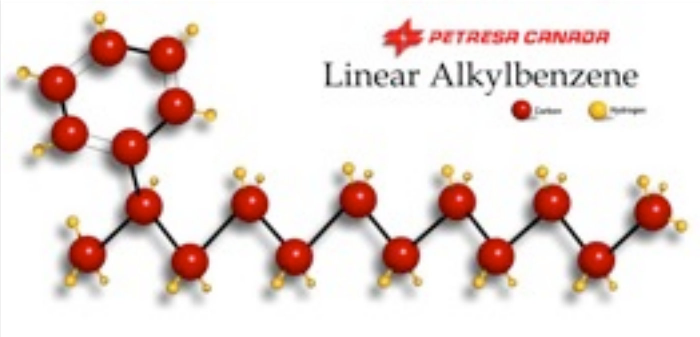
Modular Design
Continuous physics running in parallel with construction

Oxford, Sussex, Leeds,
Liverpool, Sheffield, QMUL

SNOLAB
Sudbury, Ontario
Canada



SNO+ Liquid Scintillator

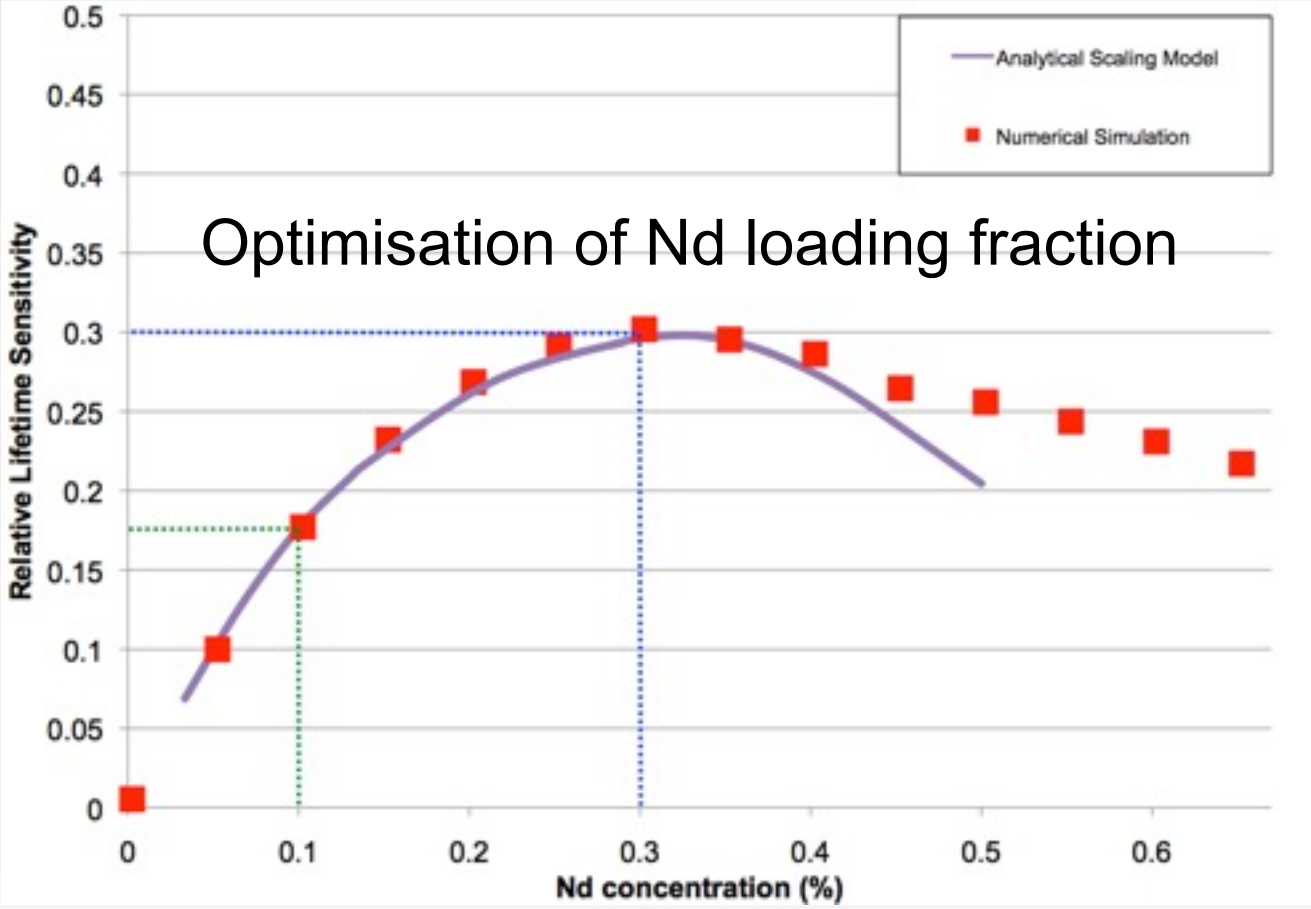


- compatible with acrylic, undiluted
- high light yield
- pure (light attenuation length in excess of 20 m at 420 nm)
- low cost
- high flash point 130°C safe
- low toxicity safe
- smallest scattering of all scintillating solvents investigated
- density r = 0.86 g/cm^3
- metal-loading compatible

Thanks to S. Biller for providing SNO+ slides

SNO+ Double Beta Decay

- A liquid scintillator detector has poor energy resolution... but HUGE quantities of isotope (high statistics) and low backgrounds help compensate
- Large, homogeneous liquid detector leads to well-defined background model
  - fewer types of material near fiducial volume
  - meters of self-shielding
- “Source in”/“Source out” capability to test backgrounds, improve purification, etc.
- Interesting new technique with a rapid timescale that could perhaps be pushed even further



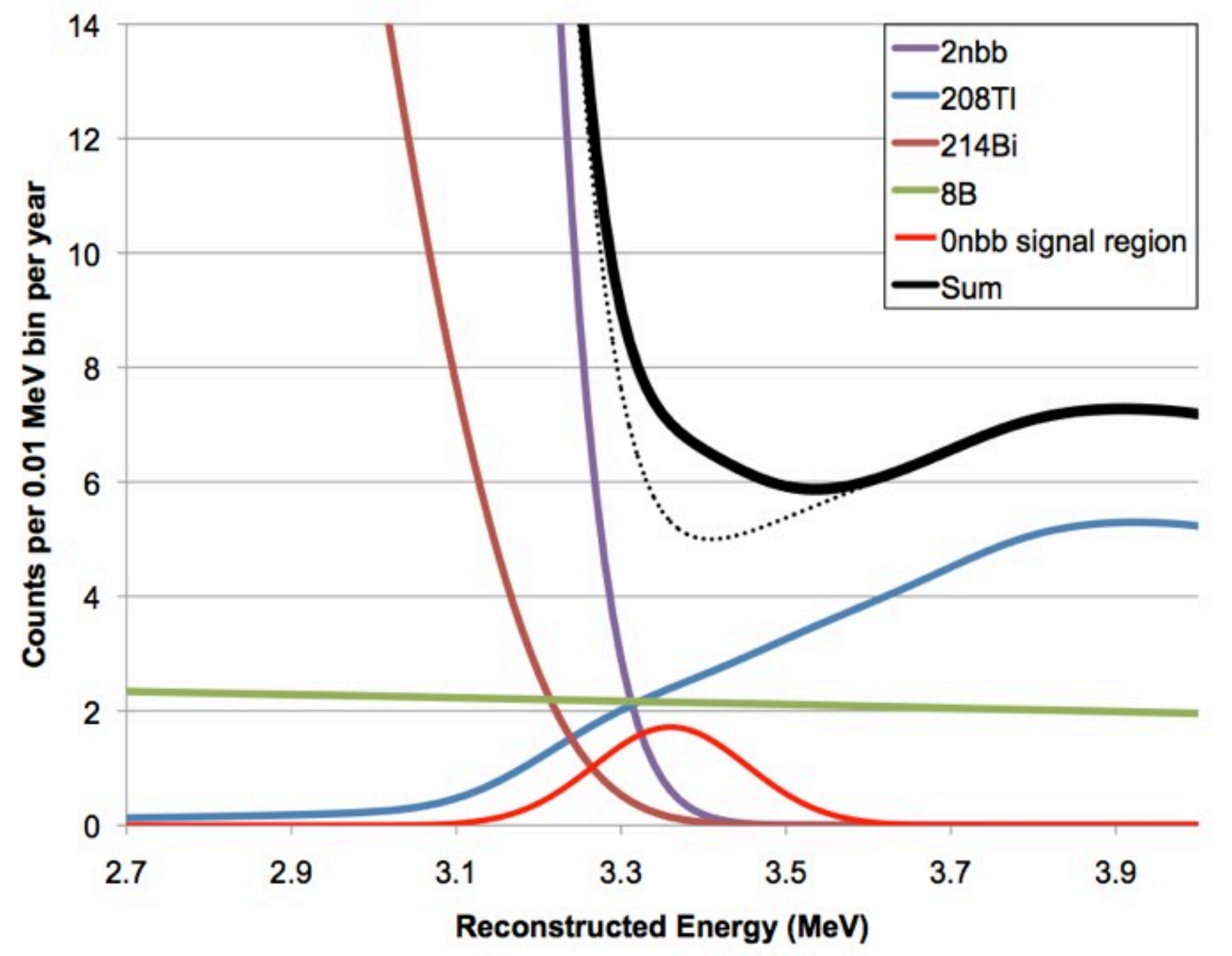
Optimisation of Nd loading fraction

- Isotope of choice ^{150}Nd ($Q_{\beta\beta}$ = 3.4 MeV)
- 0.1-0.3% load of ^{nat}Nd in ~800 ton of LS
  - ^{150}Nd abundance = 5.6%. 0.3%⇒ 135 kg of ^{150}Nd

Challenges

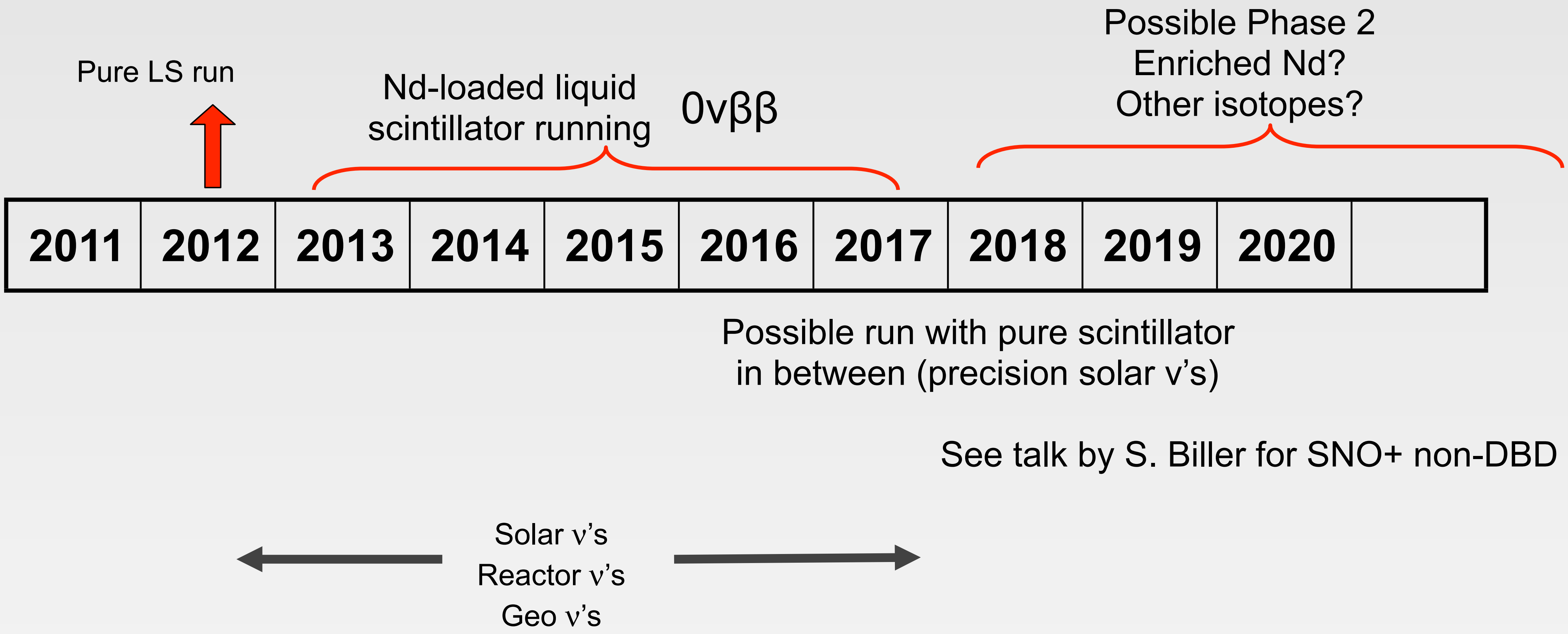
- Very stringent radiopurity requirements
  - < 10^{-17} g of U/Th per g of LS - demonstrated by Borexino
  - < 10^{-14} g of U/Th per g of Nd - very tough and to be demonstrated

SNO+ Double Beta Decay



Background Model and 0νββ signal. Likelihood fit to observe signal distortion

SNO+ Timeline and budget (UK)



See talk by S. Biller for SNO+ non-DBD physics

Old News:

Alpha-4 rated in last Prioritisation Exercise

Bridging funds provided by STFC until end of 2012

New News:

Modest PRD submitted for calibration system upgrade (~£58K).

Continued project support is entirely exploitation (travel, postdocs & academic time), so no further major requests are needed from PPRP.

Following positive SoI feedback exploitation support will be requested via the consolidated grants.

GERDA - ^{76}Ge

Enriched “naked” Ge diodes in LAr

High Efficiency
FWHM = 4 keV

Phase I :18 kg of 86% enriched detectors
Phase 2 : 40 kg of enriched detectors

Phase-I running starts this year!

Background goal: b = 0.01 cnts/(kg keV yr)
Recent result: b = 0.06 cnts/(kg keV yr)

Future ambitious goal: b = 0.001 cnts/(kg keV yr)

Eventually 1t joined GERDA and Majorana

CUORE - ^{130}Te

TeO_2 bolometers. ^{130}Te abundance 34%
High Efficiency
FWHM = 5 keV
741 kg of TeO_2 crystals ⇒ 200 kg ^{130}Te

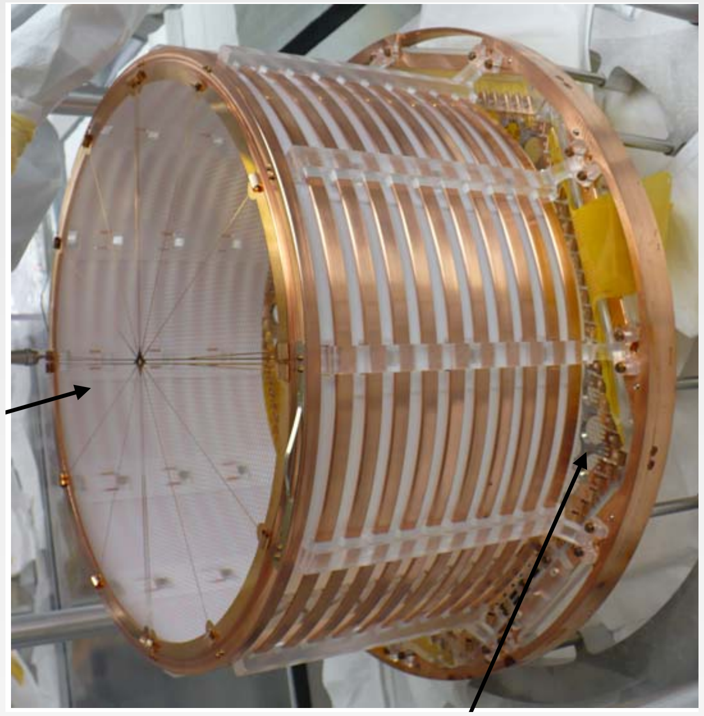
Background goal: b = 0.01 cnts/(kg keV yr)
Background with some crystals: b ~ 0.06 cnts/(kg keV yr)

Future ambitious goal: b = 0.001 cnts/(kg keV yr)

CUORE0 (1 out of 19 towers) starts 2012
Start-up of the rest ~2013-2014

EXO200 - ^{136}Xe

Technique: LXe - ionisation + scintillation
200 kg of LXe enriched to 80% of ^{136}Xe
Expected FWHM at $Q_{\beta\beta}$ = 3.8%



Expected b = 6.25×10^{-4} cnts/(kg keV yr) ⇒ 20 events/yr around $Q_{\beta\beta}$

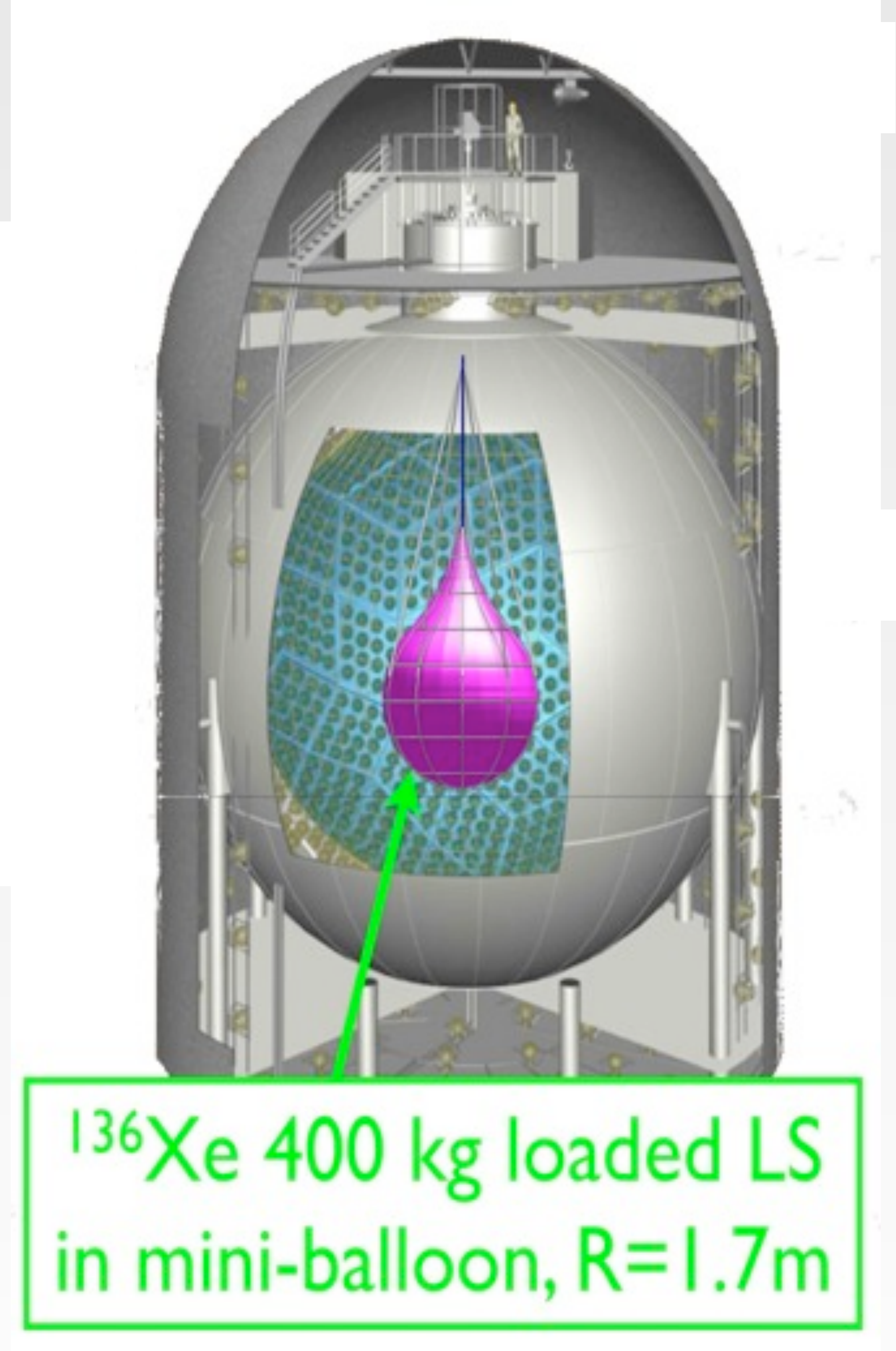
Engineering run at WIPP - December 2010

Started running with enriched Xe - spring 2011. Performance numbers to be released soon.

Ba+ tagging R&D under way.

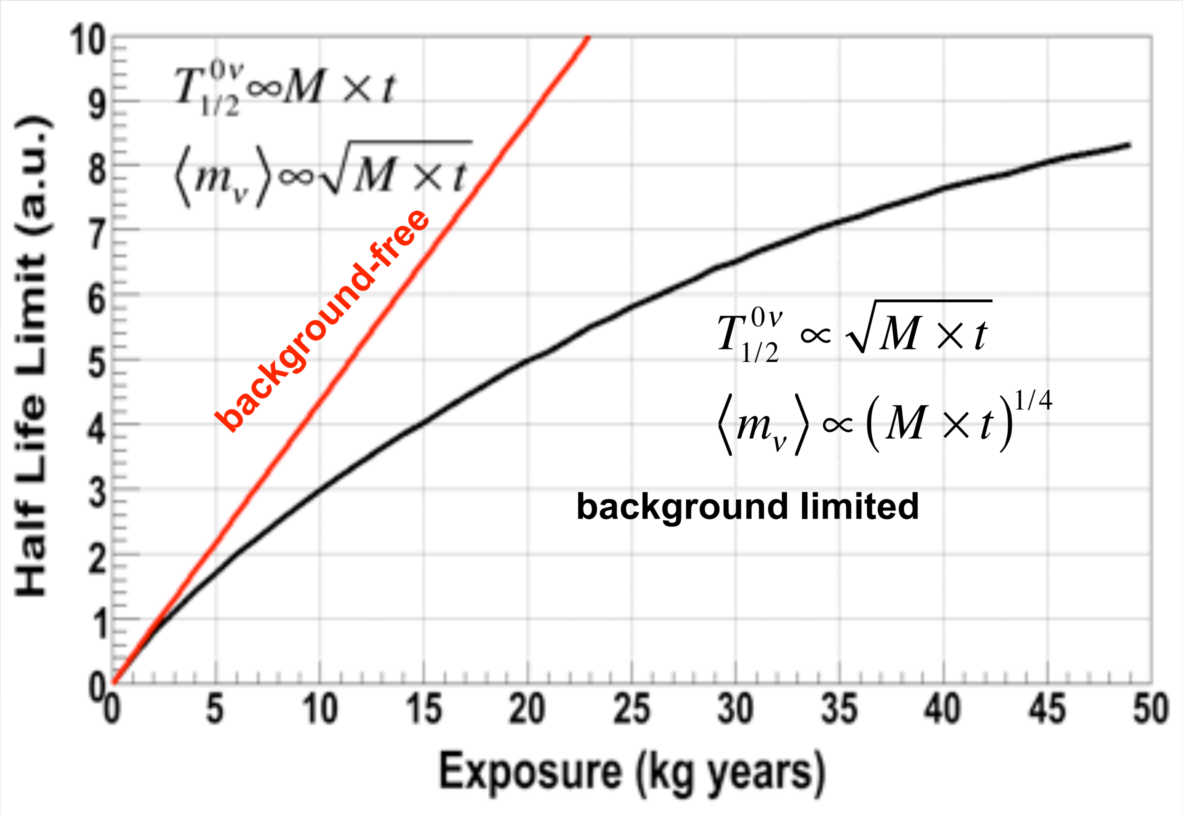
Study of ≥ 1t option underway

KamLAND-Zen
^{136}Xe



Ton-experiment, 10 meV and other speculations

- *O*(100kg) generation will reach FOM ~ **4×10^{26} yr** by **2018-2020**. <m$_\nu$> = **50-100 meV**
- To **exclude IH**, i.e. to get **10-20 meV**, we need FOM = **~10^{28} yr**.
- Example: ^{76}Ge (GERDA-Majorana) even with ambitious b = 0.001 cnts/(kg keV yr) one needs **30 tons** (!) of enriched (!!) **^{76}Ge** measured over 5yr! Similar for other projects.
- Thus for **≥ 1ton** stage we have to find a **“background-free” solution**



- Example:**150kg** x 5 yrs of **^{48}Ca**, if **no background** and ε~40% , gives required FOM =**10^{28} yr**.
  - NEMO3 had no background in this region after 8 years of running!
  - But we need to learn how to enrich ^{48}Ca (0.19% nat. abundance)

May not need 1t to reach 10-20 meV if background free

Future “Ton” experiments

^{222}Rn poses serious challenge (How to control **~1atom/N×m^3** contamination?)
Future may belong to **“Big Three”**

^{48}Ca	**^{96}Zr**	**^{150}Nd**
4.27 MeV	3.4 MeV	3.4 MeV

to break away from ^{222}Rn progeny

^{214}Bi
3.27 MeV

The Roadmap

Scenario 1

$$\langle m_\nu \rangle \sim 0.1\ \mathrm{eV}$$

2011 ——— 2015 ——— 2020

Measurements with several isotopes. Possibility to disentangle LNV physics mechanism (almost background free with S-NEMO). Possibility to access Majorana CP phases.

Scenario 2

$$\langle m_\nu \rangle \ll 0.1\ \mathrm{eV}$$

2011 ——— 2015 ——— 2020

Understanding backgrounds and limiting factors (Radon?)
with *O*(100kg) experiments
Isotope enrichment technology.

→

"Background-free"
detector technology
and isotope(s) choice.

→

"Ton" detector
construction

"Ton" Experiment must have the sensitivity to establish or exclude the IH

Message to take home

- **0νββ** is a **high risk high return** endeavour but (£/science) is among the best
  - **Only way** to answer questions on Full **Lepton Number violation** and nature and **mechanism** behind **neutrino mass**
- UK has a **healthy 0νββ programme**
  - Leadership role in **SuperNEMO**
  - Crucial player in **SNO+** through previous UK investment
- Both experiments are **competitive**
  - KK-claim by 2015, ~50 meV by 2020
- And **unique**
  - Clear **background model** ⇒ main input for future **"Ton" background free experiment**
  - Unlike most competitors can measure **many** (almost any?) **isotopes**, including the **"Big Three"** ⇒ a likely choice for **future 10 meV project.**

NON-DBD Physics with SNO+

Steve Biller (Oxford)

Physics with Liquid Scintillator

- ○**Neutrinoless double beta decay**
  - ® various isotopes possible
- ○**Low energy solar neutrinos**
  - ® pep, CNO, ^{8}B and potentially ^{7}Be & pp
- ○**Geo-neutrinos** ® unmatched
- ○**240 km baseline reactor neutrino oscillation**
  - ® Δm^2 resolution potentially better than KamLAND
- ○**Supernova neutrinos** ® major player
- ○**“Invisible” modes of nucleon decay**
  - ® unique sensitivity with initial water data

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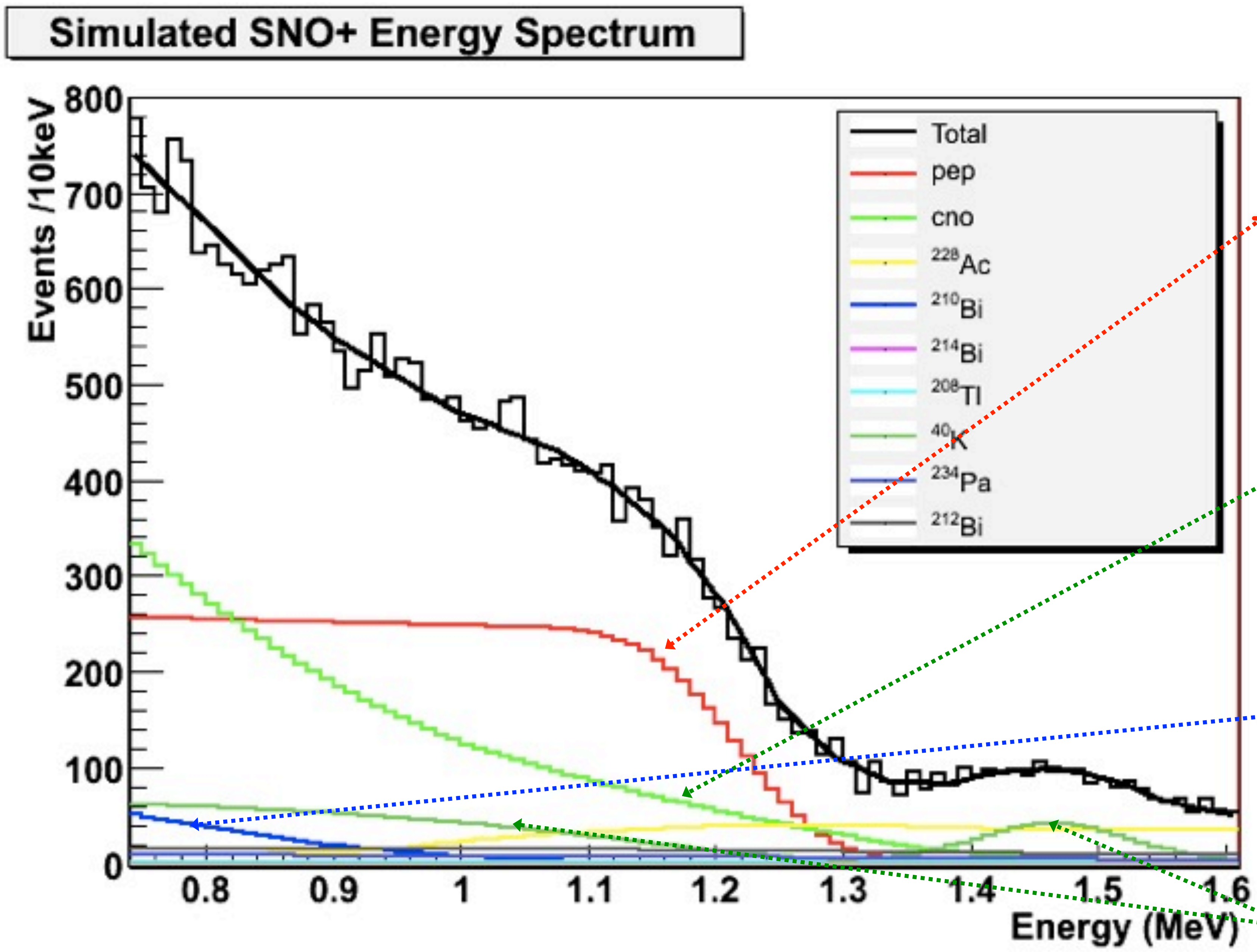


pep signal
(4000 events/yr)

After 3 years: ~5% uncertainty

CNO Signal

After 3 years: ~8% uncertainty

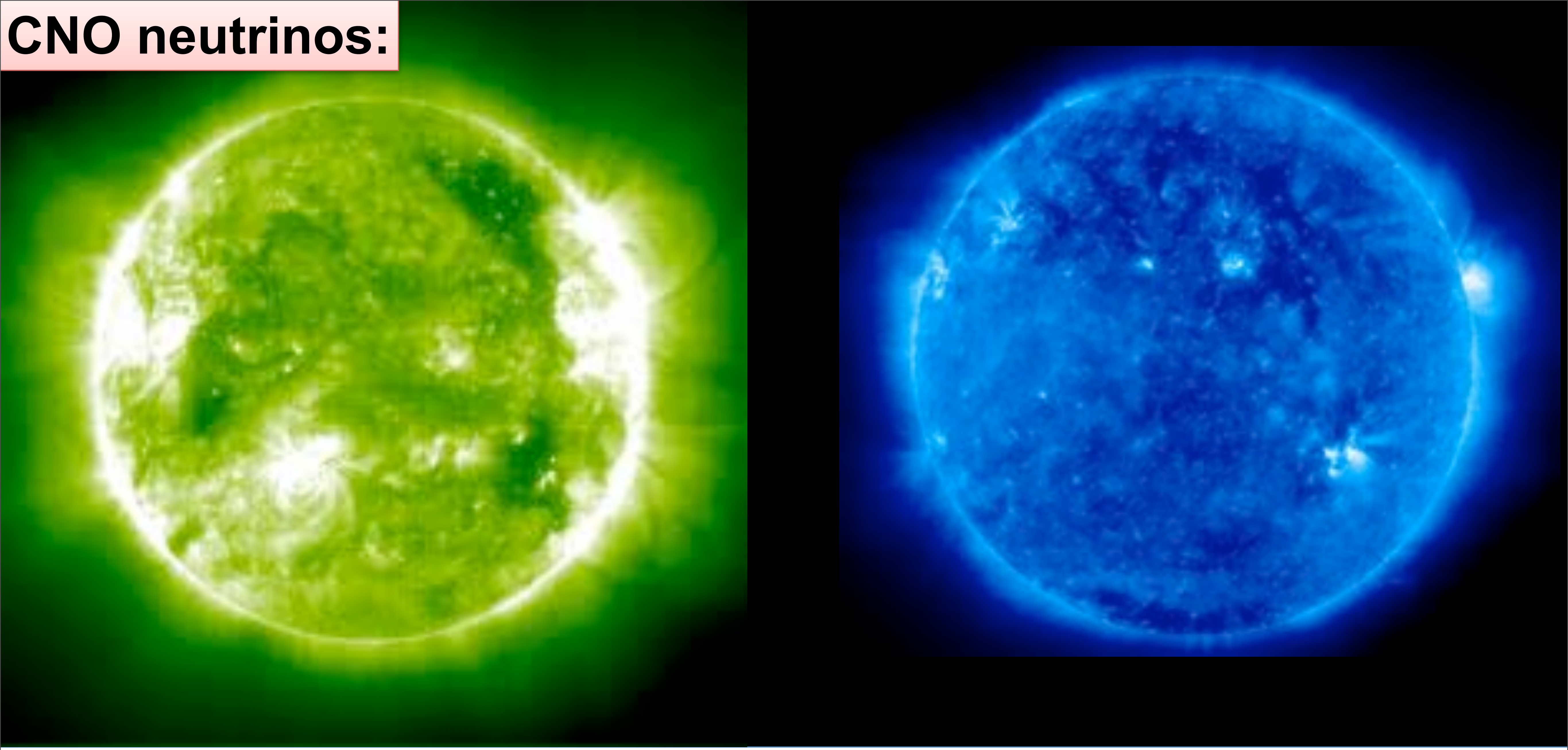
^{210}Bi background
Can be inferred from ^{210}Po peak

^{40}K background
Can be constrained by peak

3600 pep events/(kton·year), for electron recoils >0.8 MeV

SNOLAB depth of 6000 mwe gives a muon flux 800 times less than KamLAND and virtually eliminates background from ^{11}C, making SNO+ uniquely sensitive for a precision measurement.

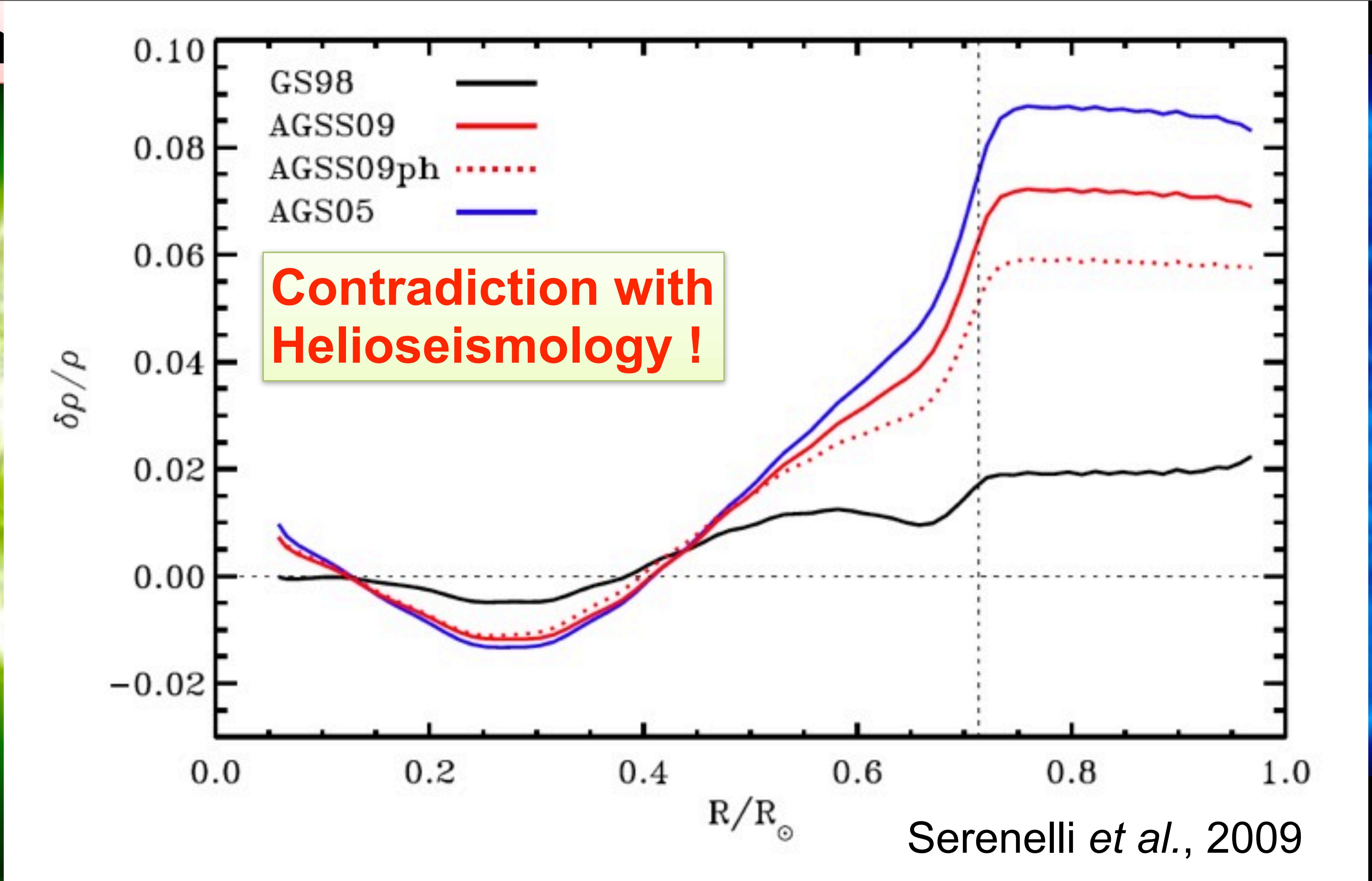
CNO neutrinos:



Improved solar spectral measurements and more detailed modeling yields an improved determination of solar photospheric composition that is ~25% lower in metallicity than values inferred over a decade ago

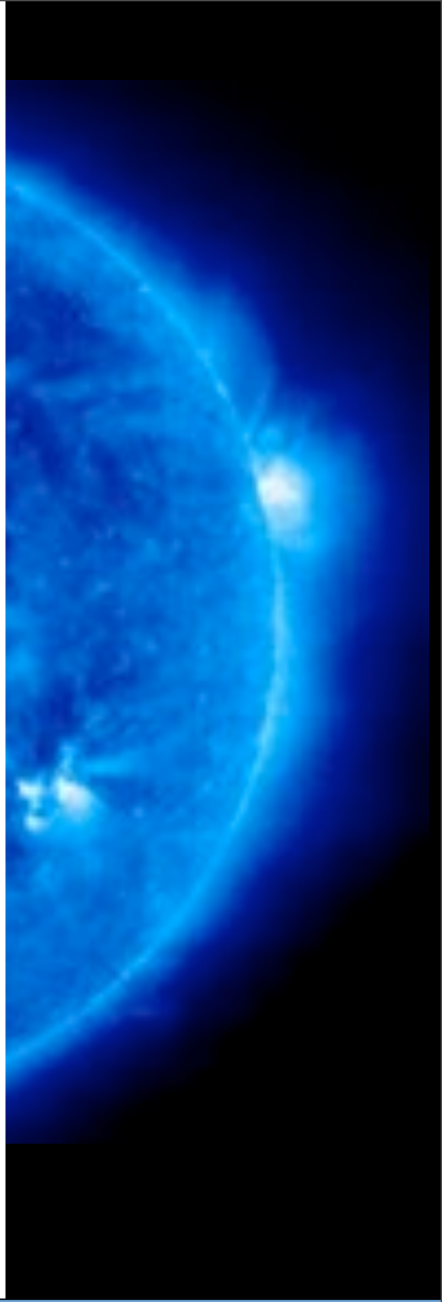
(Asplund *et al.*, 2005 & 2009)

CNO n



Contradiction with Helioseismology !

Serenelli *et al.*, 2009



Improved solar spectral measurements and more detailed modeling yields an improved determination of solar photospheric composition that is ~25% lower in metallicity than values inferred over a decade ago

(Asplund *et al.*, 2005 & 2009)

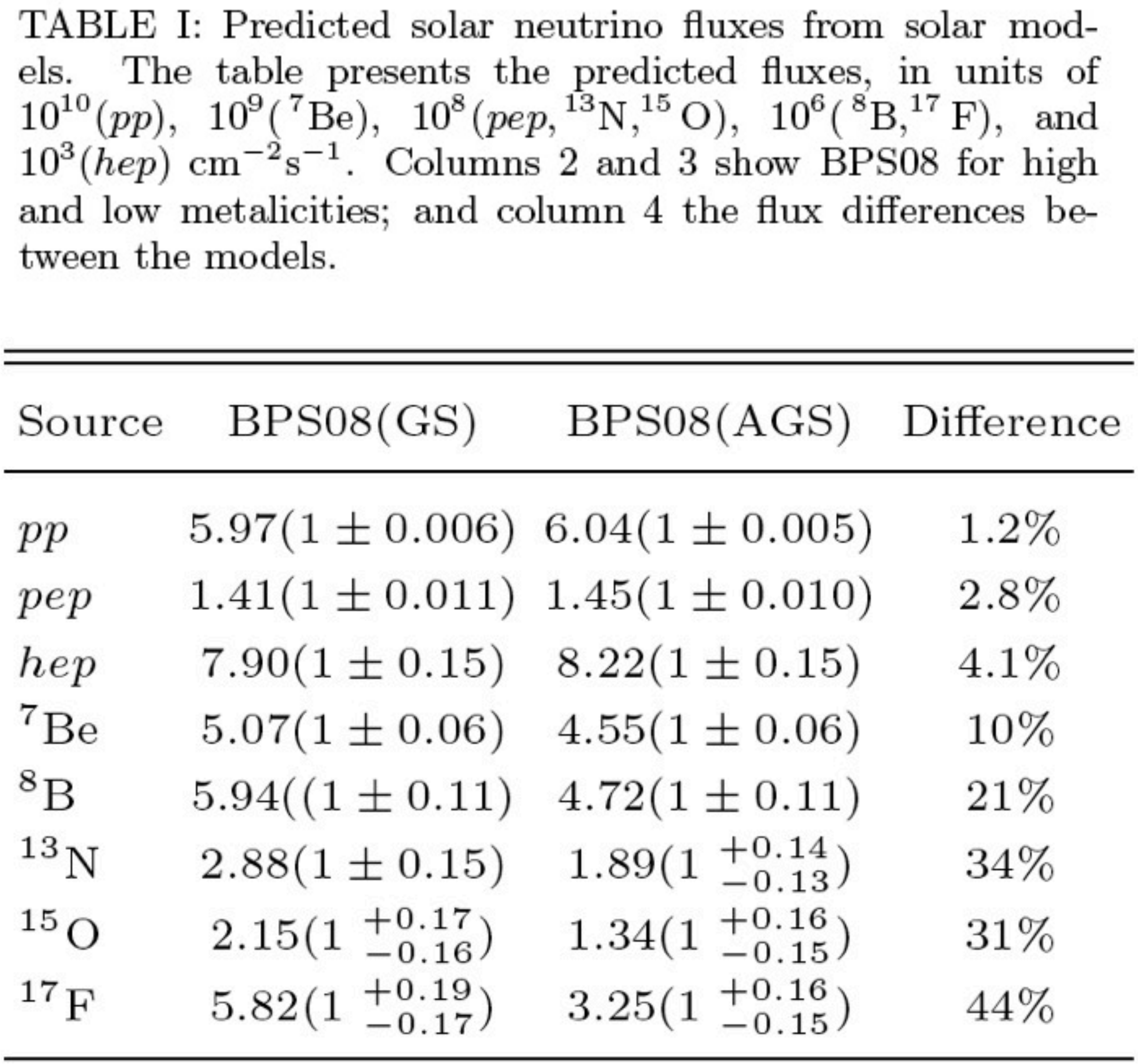


TABLE I: Predicted solar neutrino fluxes from solar models. The table presents the predicted fluxes, in units of $10^{10}(pp)$, $10^9(^7\mathrm{Be})$, $10^8(pep, ^{13}\mathrm{N}, ^{15}\mathrm{O})$, $10^6(^8\mathrm{B}, ^{17}\mathrm{F})$, and $10^3(hep)$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Columns 2 and 3 show BPS08 for high and low metalicities; and column 4 the flux differences between the models.

Source	BPS08(GS)	BPS08(AGS)	Difference
pp	$5.97(1 \pm 0.006)$	$6.04(1 \pm 0.005)$	1.2%
pep	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.010)$	2.8%
hep	$7.90(1 \pm 0.15)$	$8.22(1 \pm 0.15)$	4.1%
$^7\mathrm{Be}$	$5.07(1 \pm 0.06)$	$4.55(1 \pm 0.06)$	10%
$^8\mathrm{B}$	$5.94((1 \pm 0.11)$	$4.72(1 \pm 0.11)$	21%
$^{13}\mathrm{N}$	$2.88(1 \pm 0.15)$	$1.89(1\ ^{+0.14}_{-0.13})$	34%
$^{15}\mathrm{O}$	$2.15(1\ ^{+0.17}_{-0.16})$	$1.34(1\ ^{+0.16}_{-0.15})$	31%
$^{17}\mathrm{F}$	$5.82(1\ ^{+0.19}_{-0.17})$	$3.25(1\ ^{+0.16}_{-0.15})$	44%

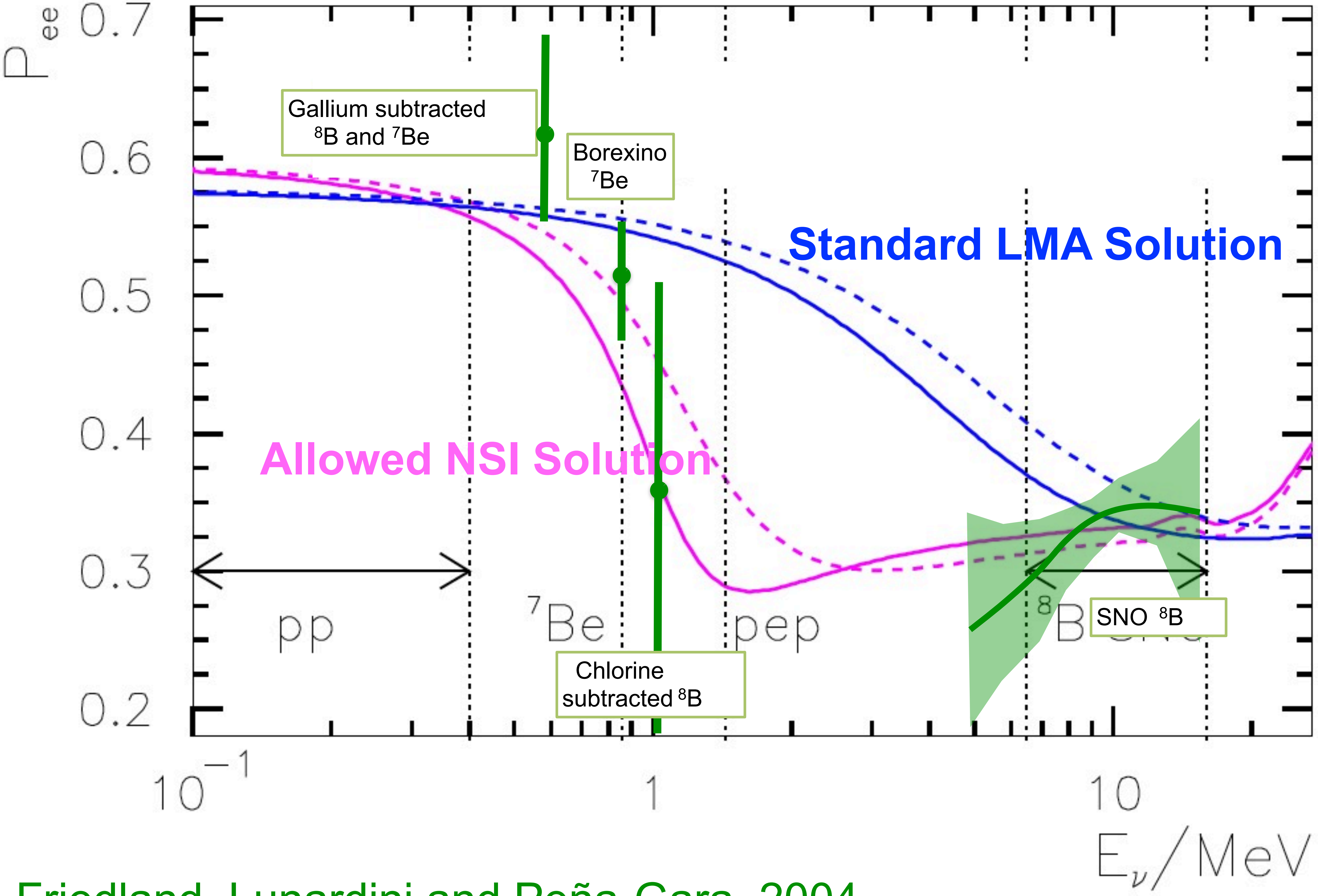
Pena-Garay and Serenelli, arXiv:0811.2424v1 (2008)

pep neutrinos:

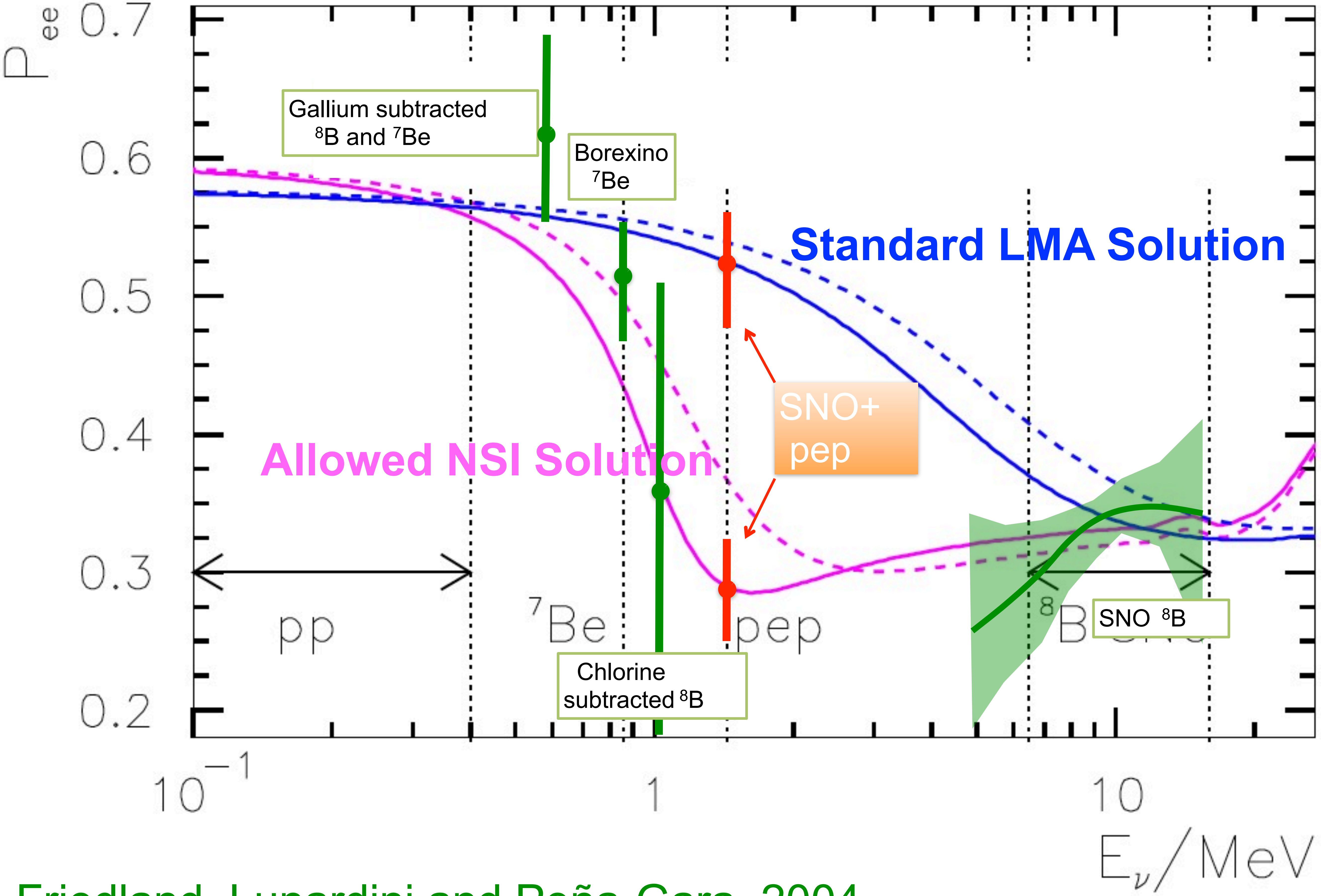
Observing change in ν_e survival probability over the MSW transition region probes the nature of the neutrino-matter interaction

Possible New Physics Includes:

- Sterile neutrino admixtures
- Neutrino Decay
- Mass Varying Neutrinos
- Non-Standard Interactions



Friedland, Lunardini and Peña-Gara, 2004



Friedland, Lunardini and Peña-Gara, 2004

An Odd Mixture of 3 !!

$$\begin{bmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu 1}|^2 & |U_{\mu 2}|^2 & |U_{\mu 3}|^2 \\ |U_{\tau 1}|^2 & |U_{\tau 2}|^2 & |U_{\tau 3}|^2 \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{bmatrix}.$$

$$\theta_{12} = \sin^{-1}\left(\frac{1}{\sqrt{3}}\right) \simeq 35.3^\circ \quad \theta_{23} = 45^\circ$$

$$\theta_{13} = 0 \qquad \delta = 0.$$

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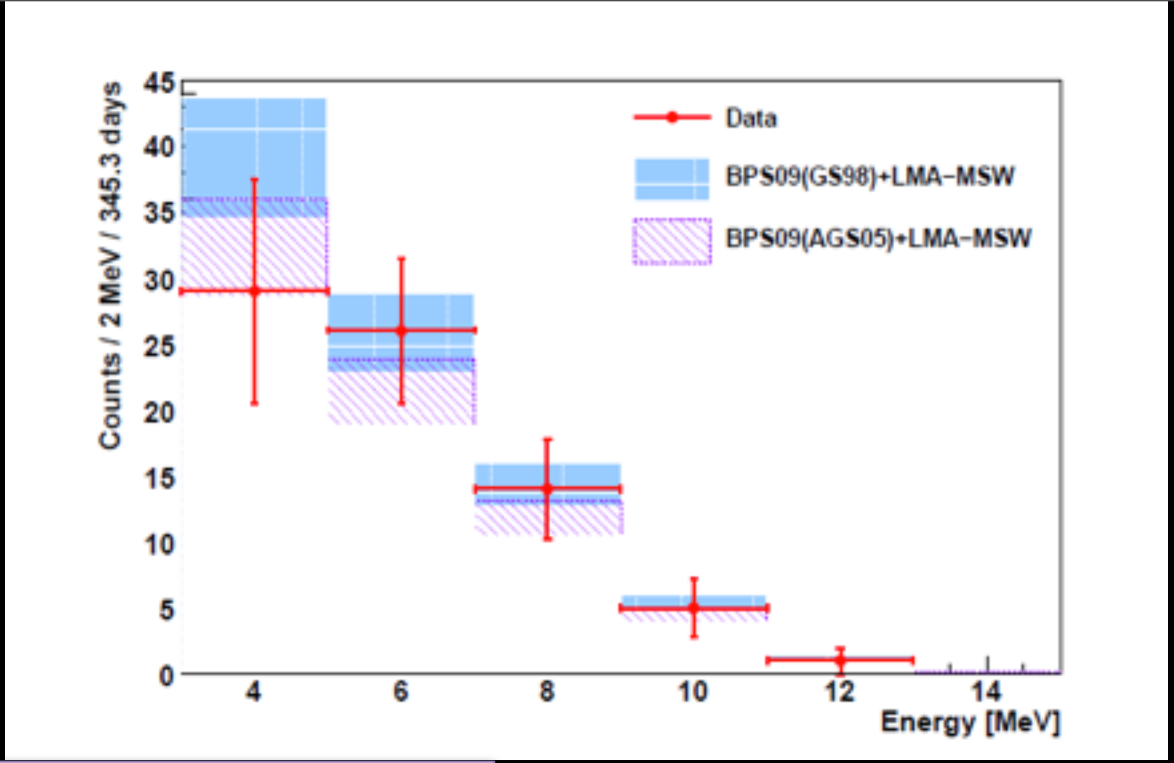
Need precision measurements of all mixing angles.

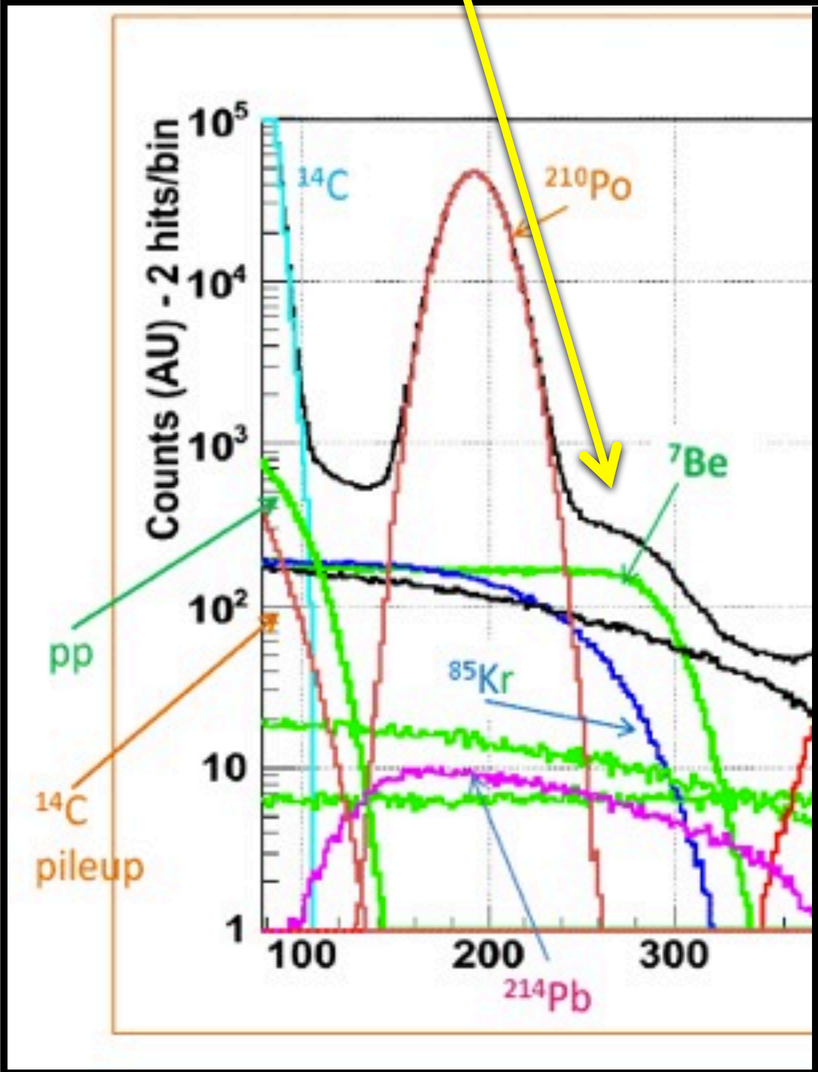
Solar ν's currently the **ONLY** practical way of improving θ_{12}

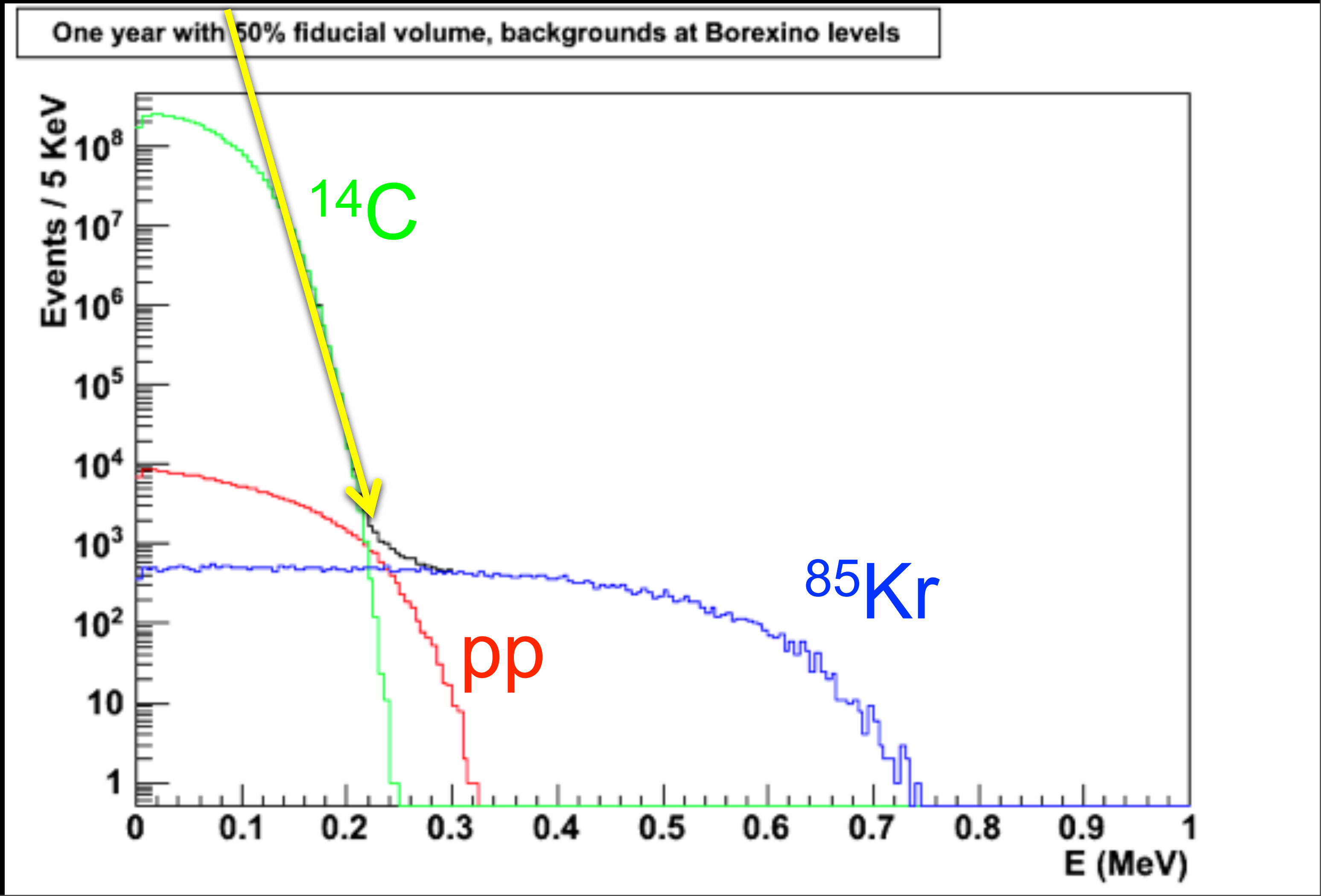
SNO+ will do better for low energy ^{8}B



Better measurement of ^{7}Be

Possibly 1st real-time measurement of pp



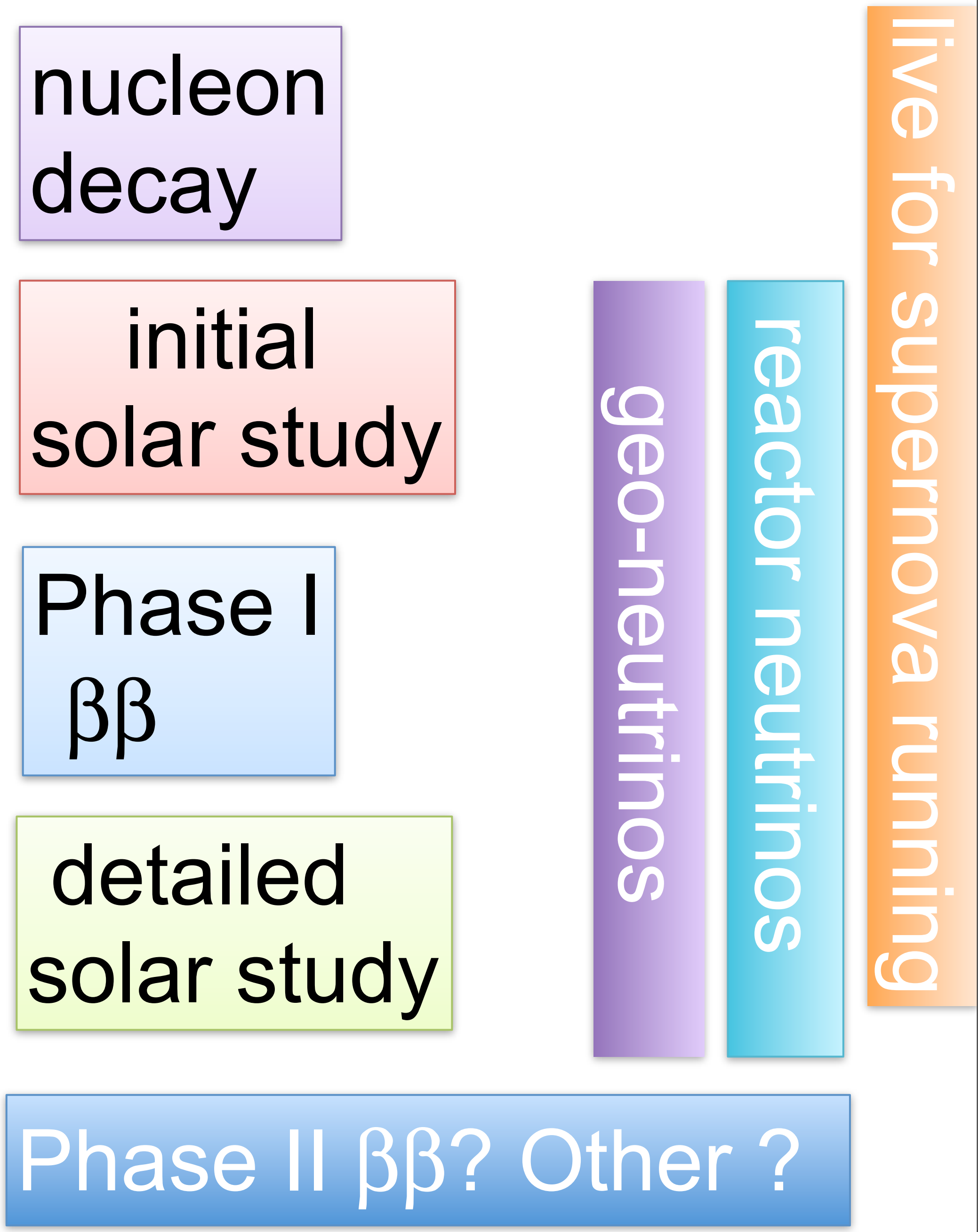


Lingering Issues

1. **Solar Composition Problem**
   - genuine mystery in need of resolution !
   - also want better understanding of CNO cycle
2. **Nature of MSW Transition**
   - critical probe of neutrino/matter interactions
   - numerous alternative models tested
   - current data looks intriguing
3. **Improve Precision on θ_{12}**
   - test Tri-Bi-Maximal scenarios
4. **Check Fundamental Processes**
   - testing basic understanding is what we do!

SNO+: First Data in 2012

Rough Order or Running:



H_2O ~ couple months

Pure Scintillator ~ several months

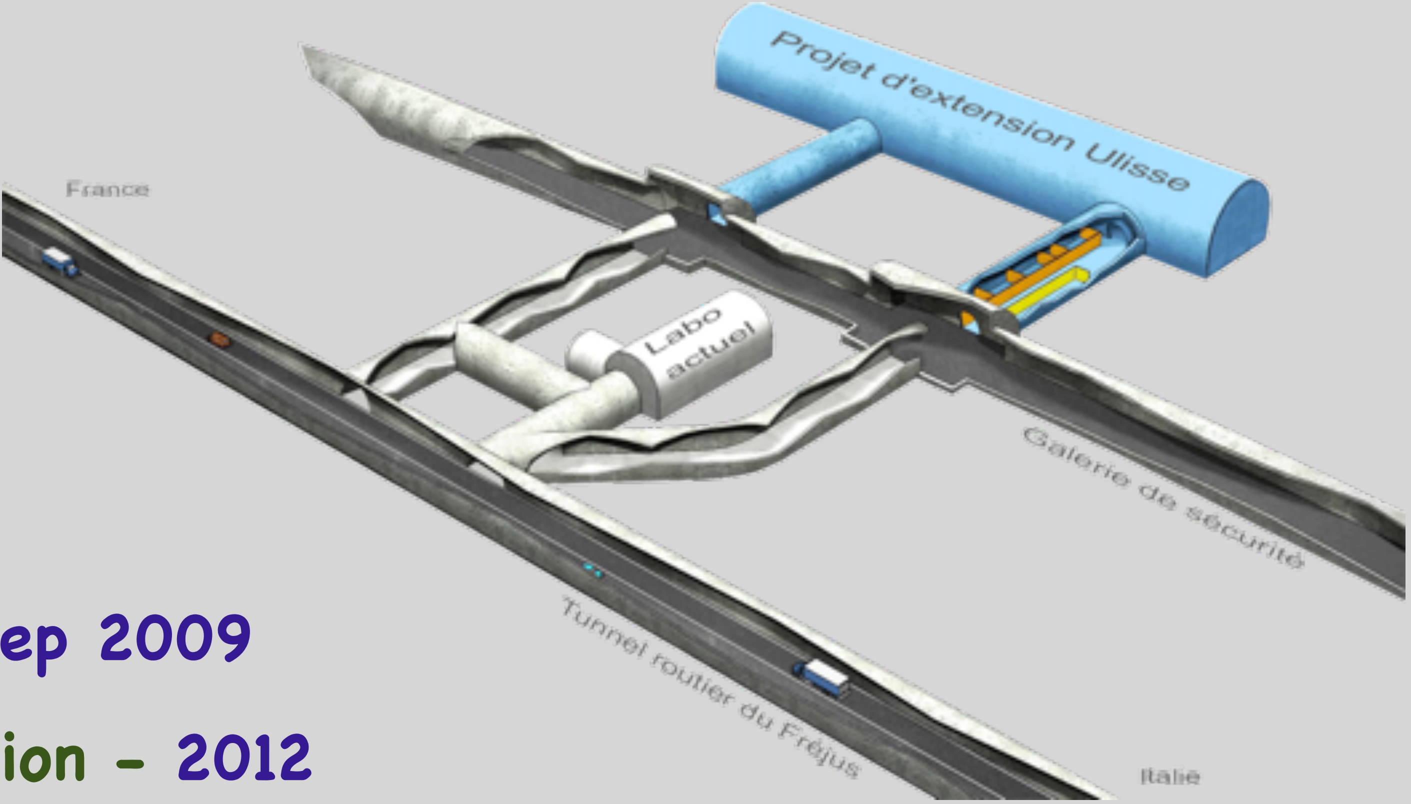
Nd-loaded Scintillator ~ few years

Pure Scintillator ~ few years

Follow-on Phase ~ ?

BACKUP

LSM Extension



Schedule

- Safety tunnel construction start - Sep 2009
- Safety tunnel, end of civil construction - 2012
- Detailed study of LSM extension (ULISSE) - 2010
- Deadline for final decision/money commitment - 2012
- Excavation of new Lab completed - 2013
- Outfitting completed, Lab ready to host experiments - 2014

Minimal scenario: 45,000m^3 (100m long), 12M€ excavation + 3M€ outfitting

2^d ULISSE workshop in October'09. 11 LOIs received.