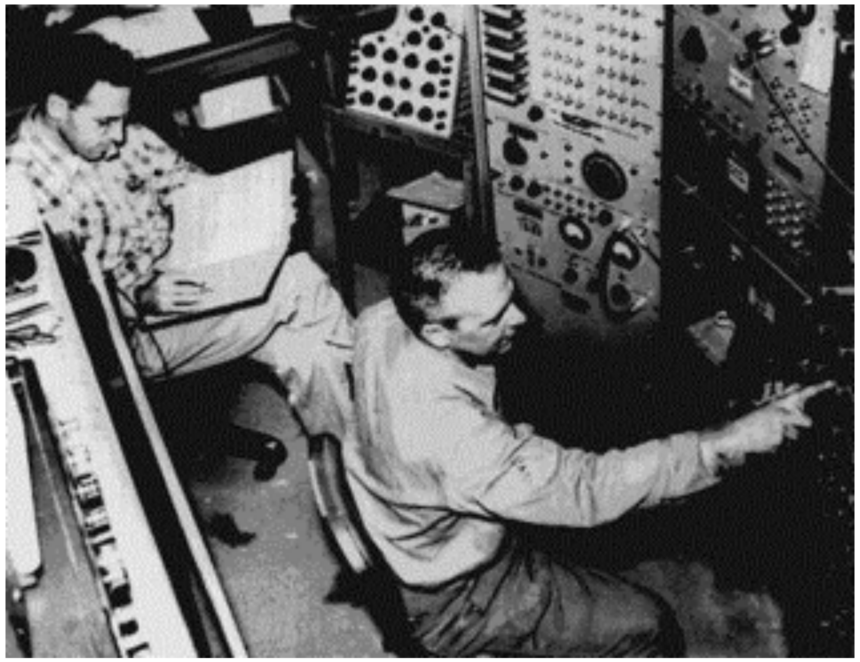
Experimental Neutrino Physics: Lecture 2

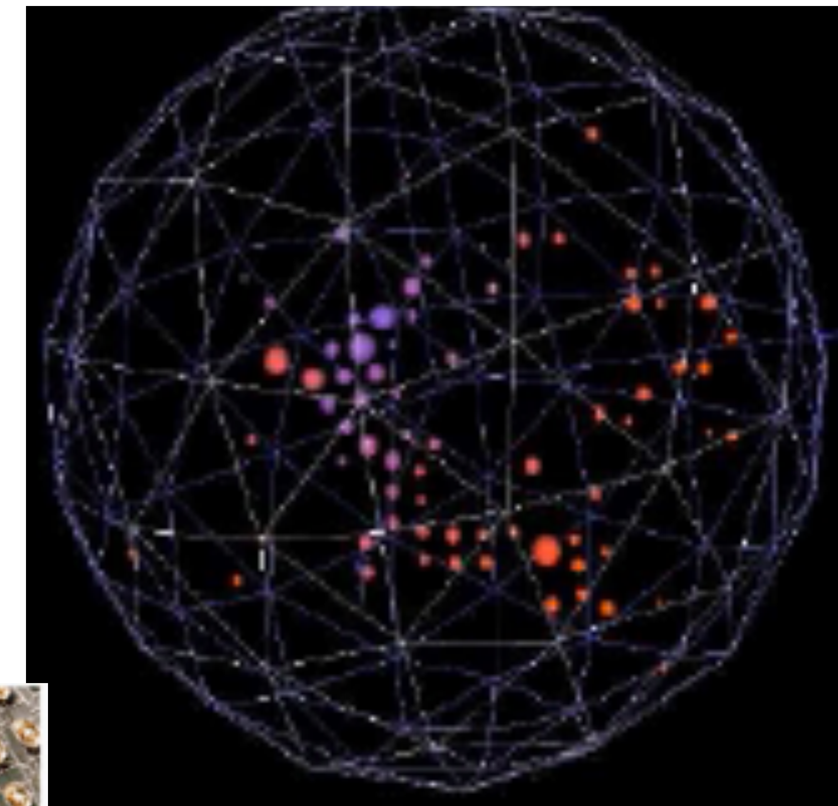


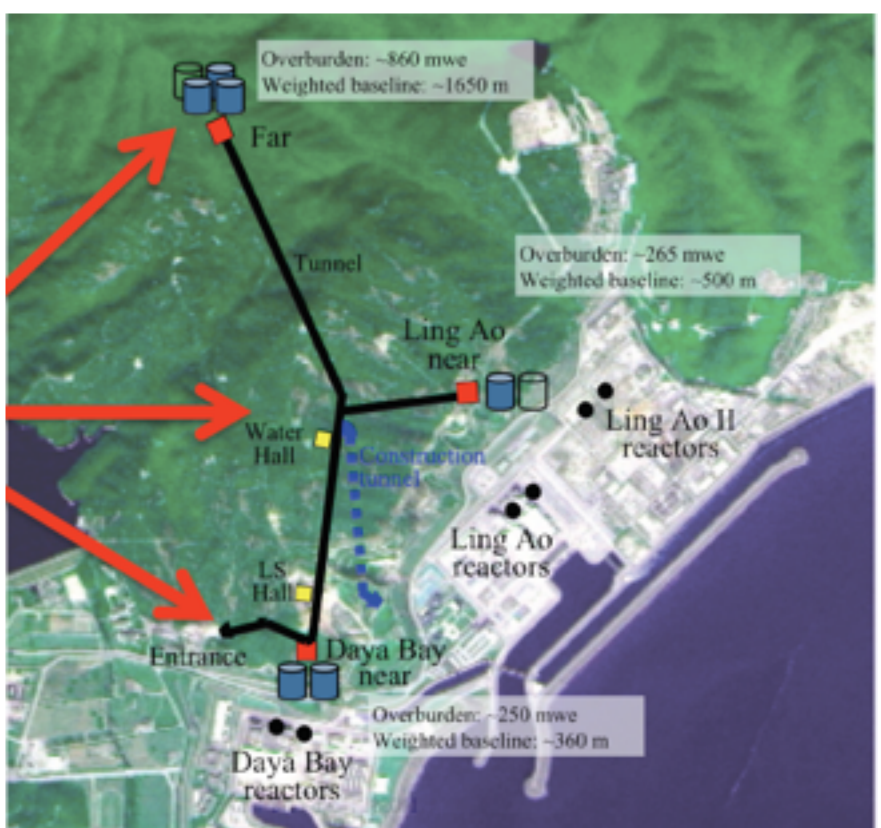
Jonathan M. Paley

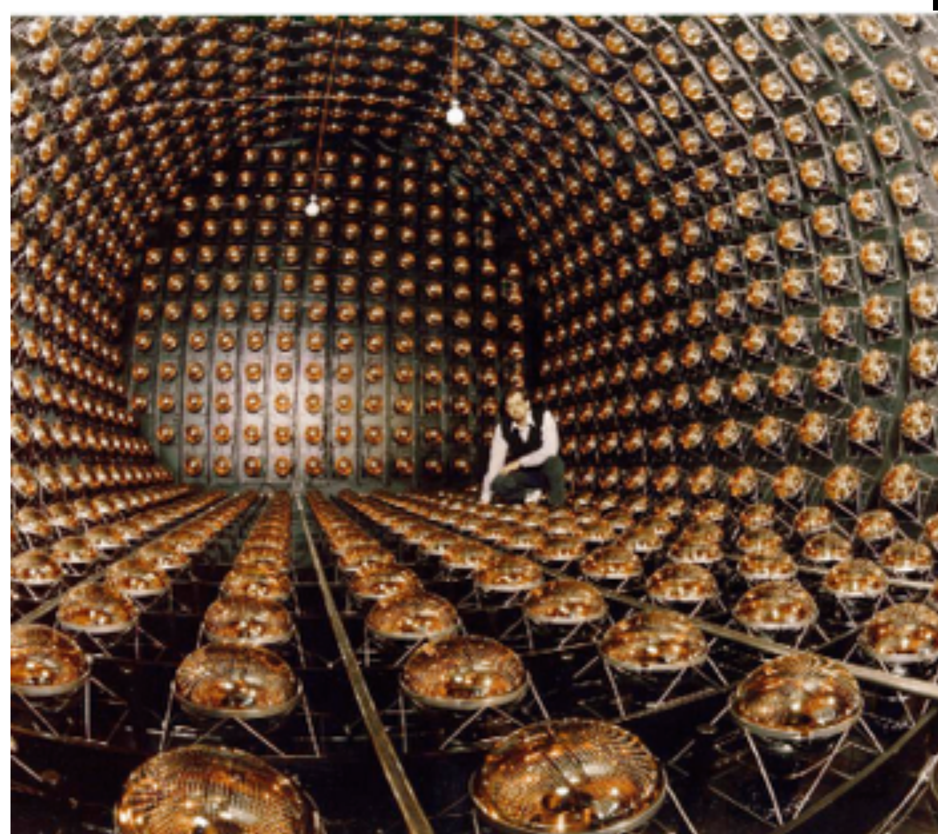
BCVSPIN - MSPF - Mitchell

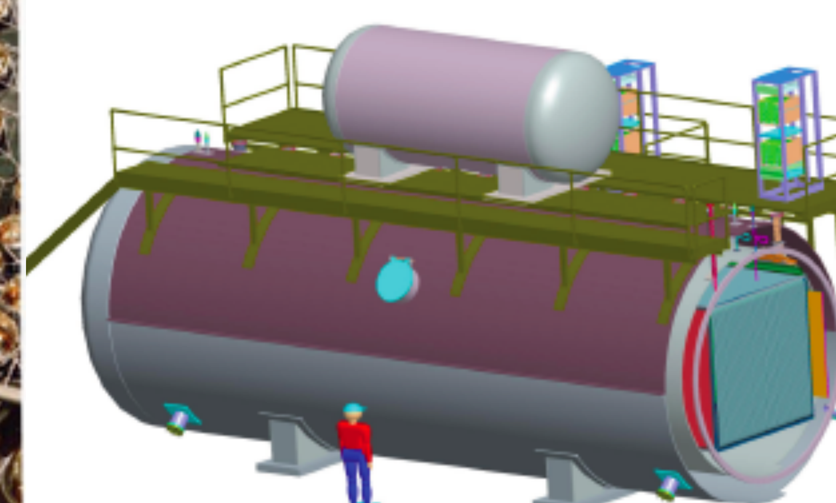
Manzanillo, Mexico

December 11, 2014



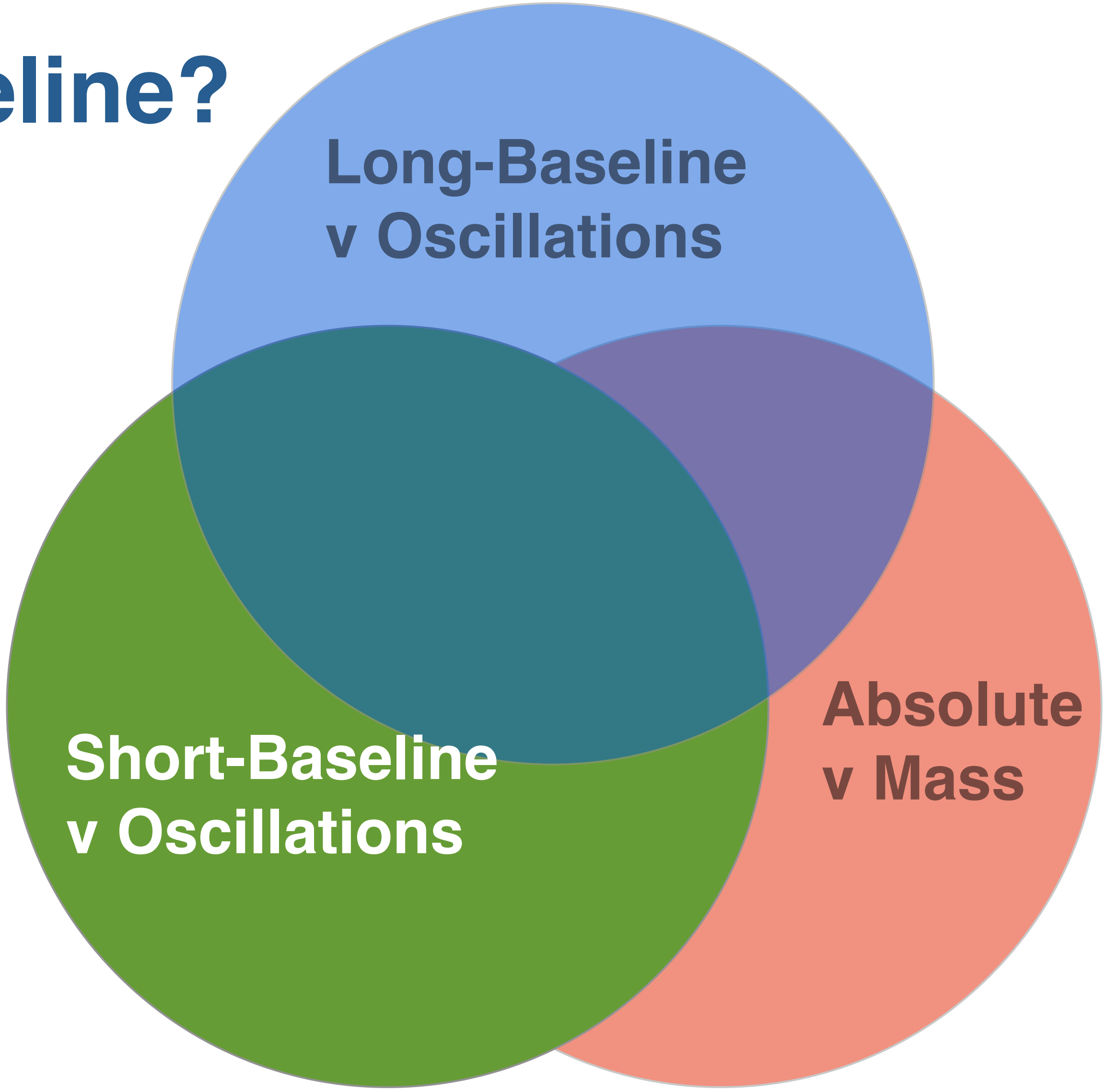


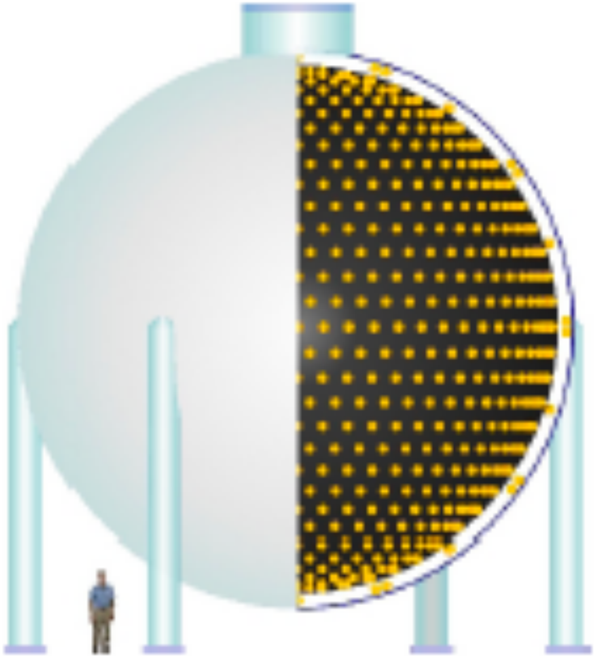


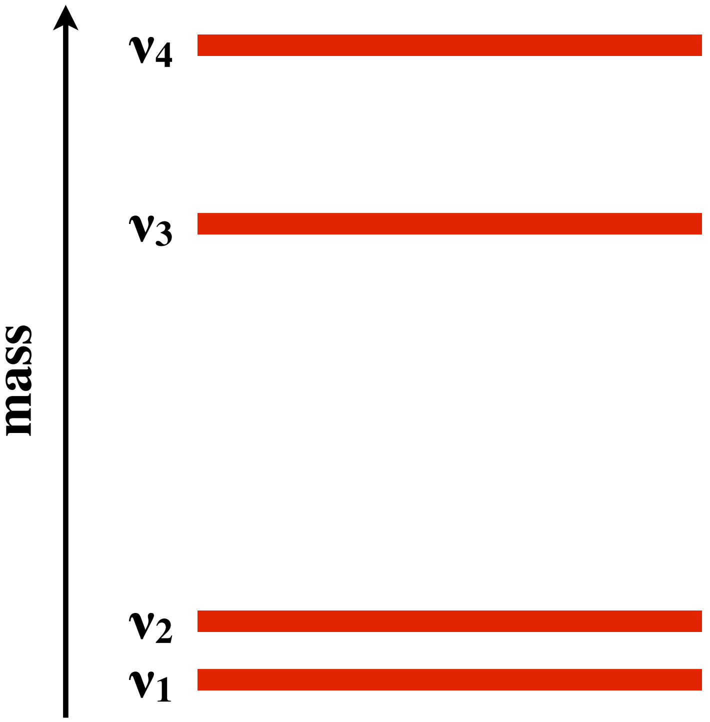


What Do I Mean By Short-Baseline?

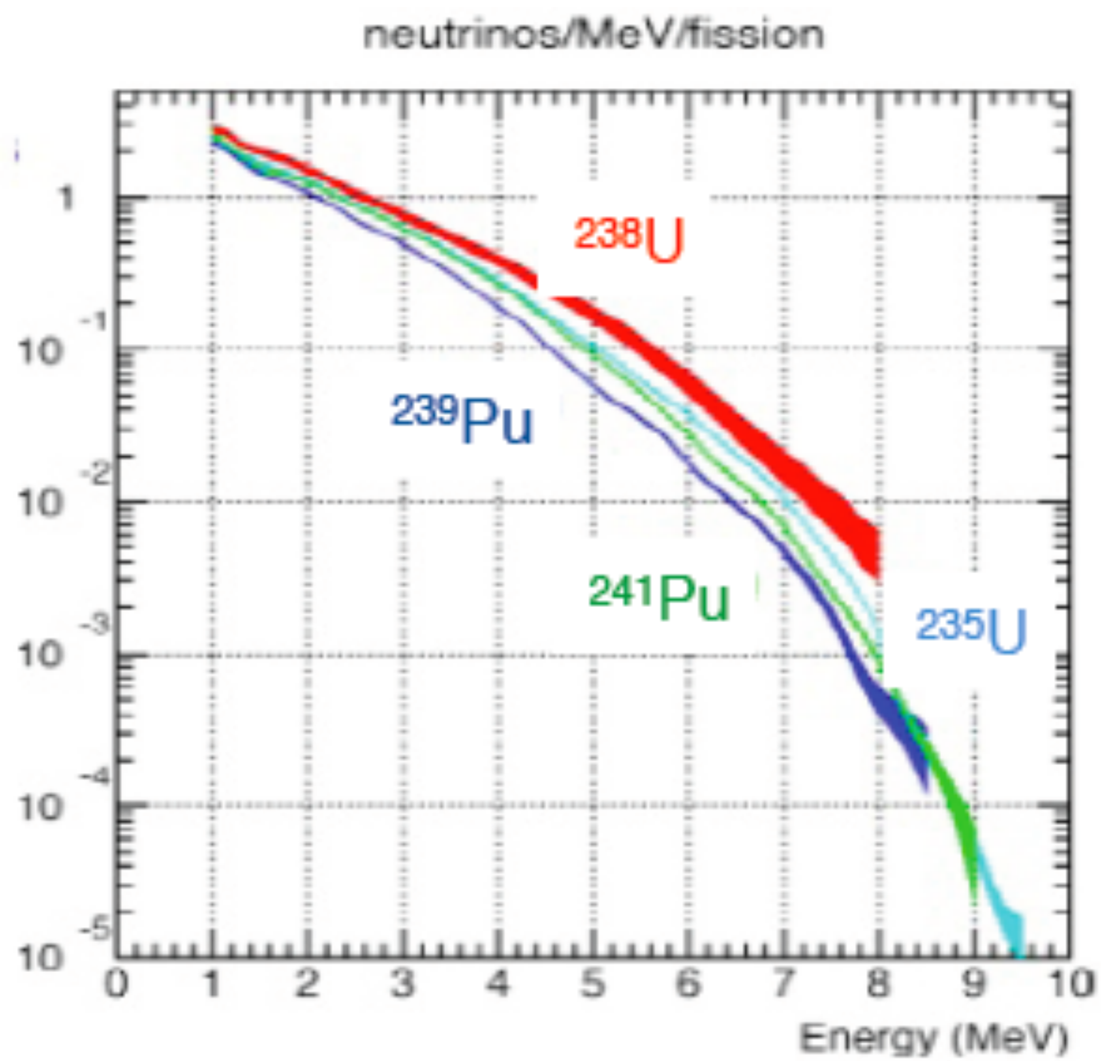
- Short-baseline neutrino oscillations:
  - reactor-based measurements of ν_e *disappearance* are sensitive to θ_{13}; Double Chooz, Daya Bay, RENO
  - measurements involving ν_e appearance with L/E ~ 1 km/GeV (1 m/MeV); LSND, MiniBooNE

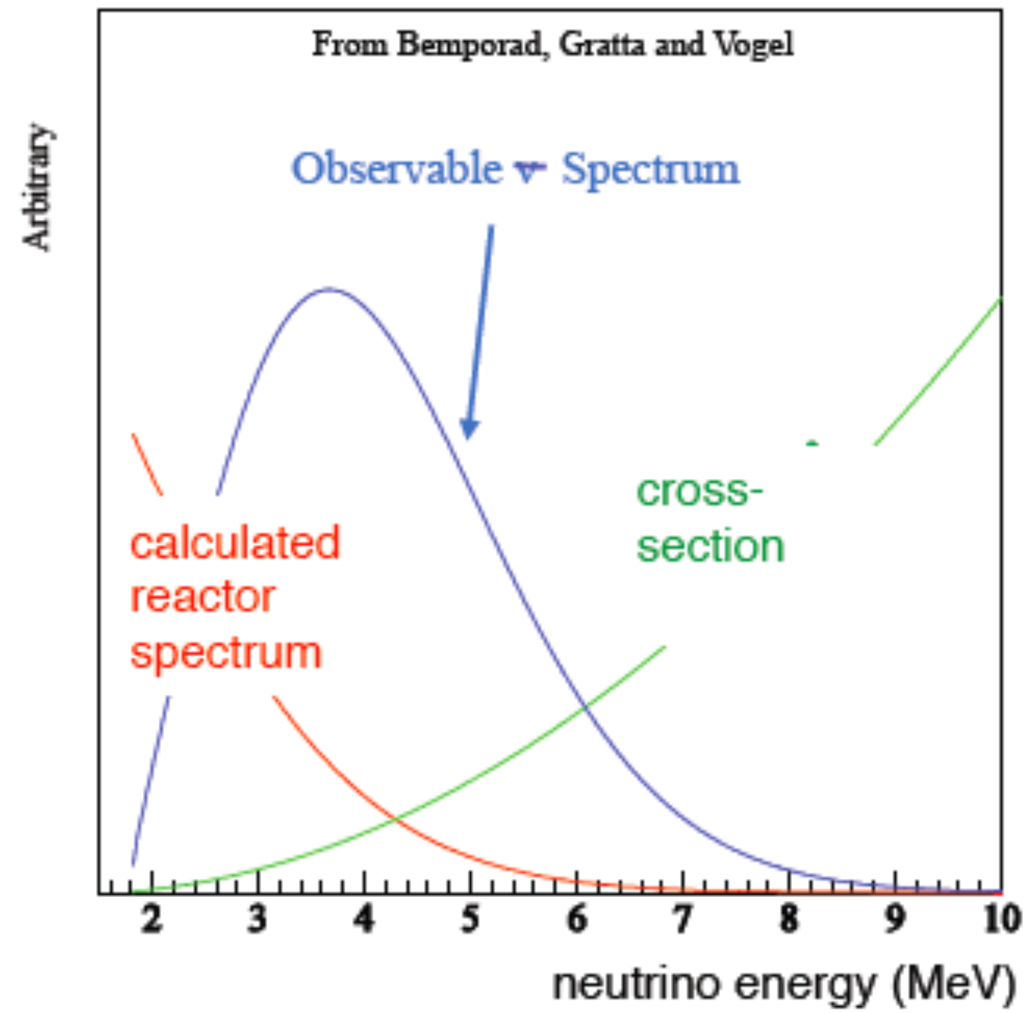






Reactor Experiments





$^{235}U:^{238}U:^{239}Pu:^{241}Pu = 0.570 : 0.078 : 0.0295 : 0.057$

detection method: inverse beta decay

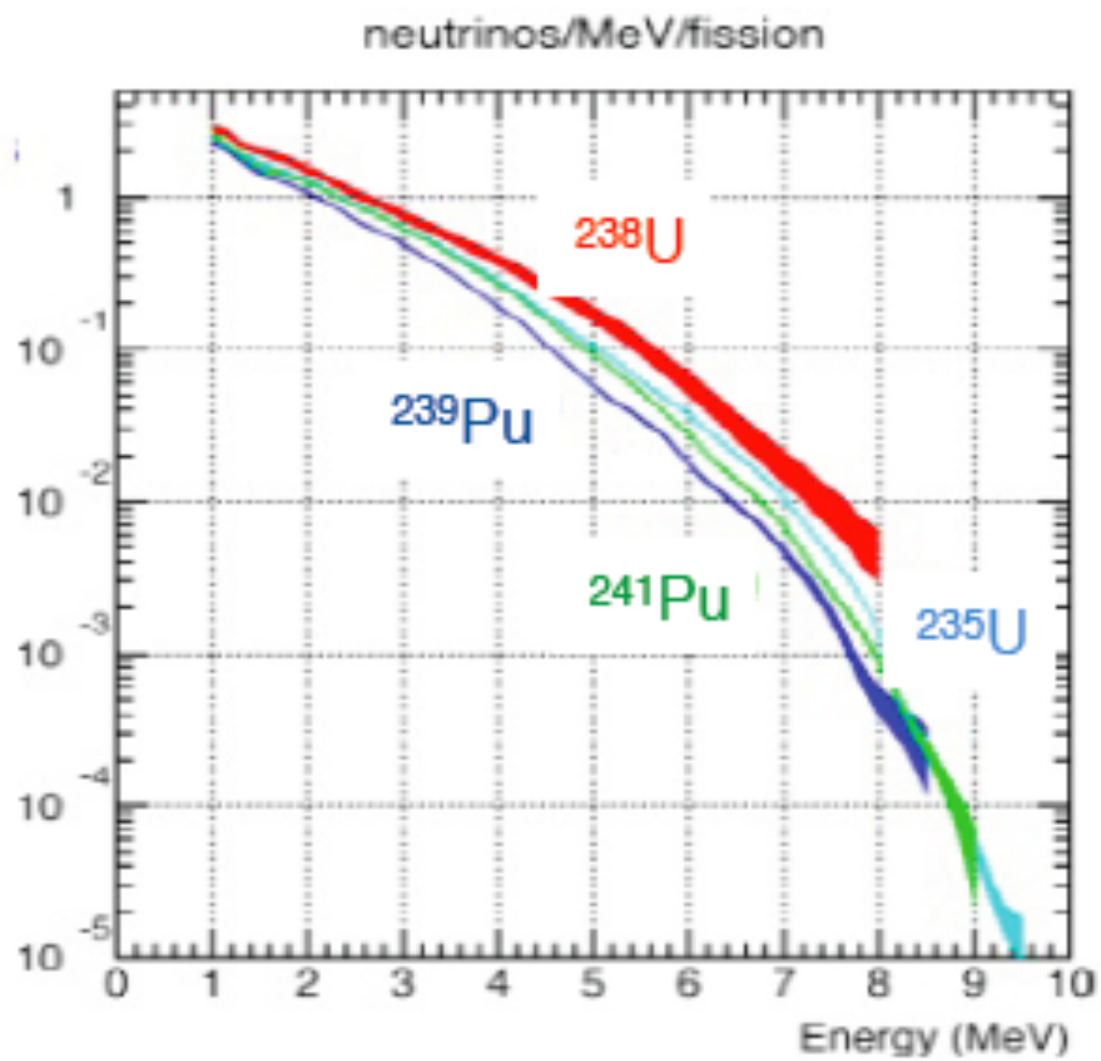
$\overline{\nu}_e + p \rightarrow e^+ + n$

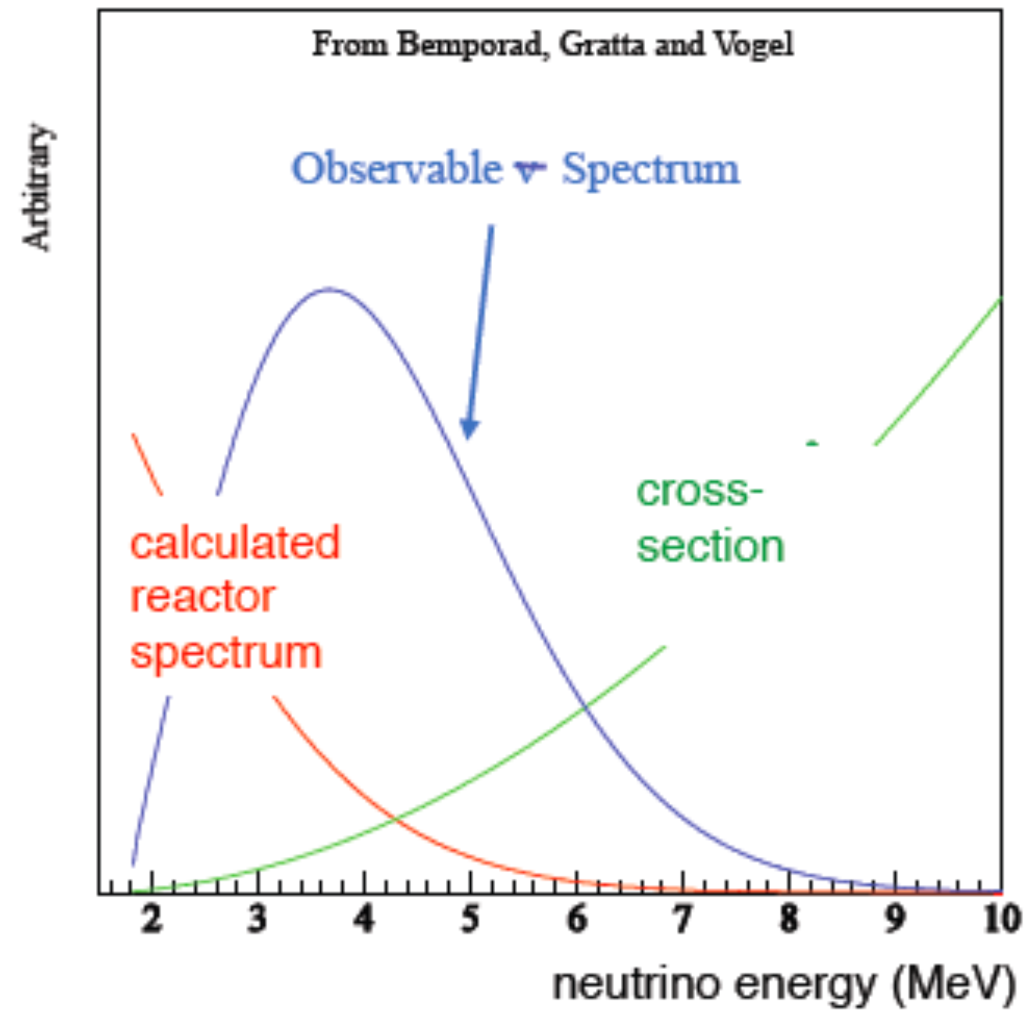
6 antineutrinos per fission, ~200 MeV per fission

~2 x 10^{20} $\overline{\nu}_e/GW_{th}/sec$

Reactor Experiments

- Measure $P(\overline{\nu}_e \to \overline{\nu}_e)$ using reactors as the anti-neutrino source





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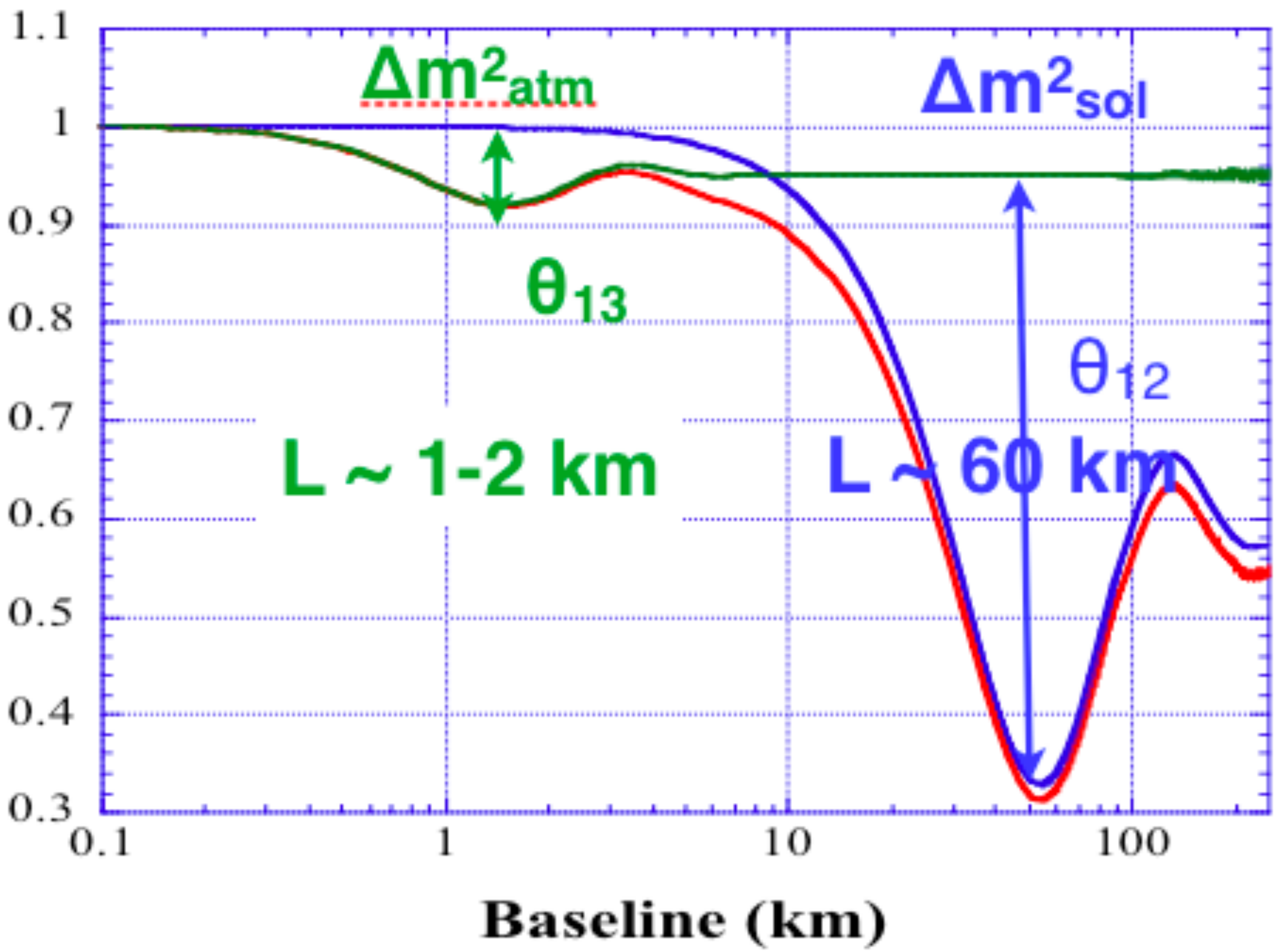
Reactor Experiments

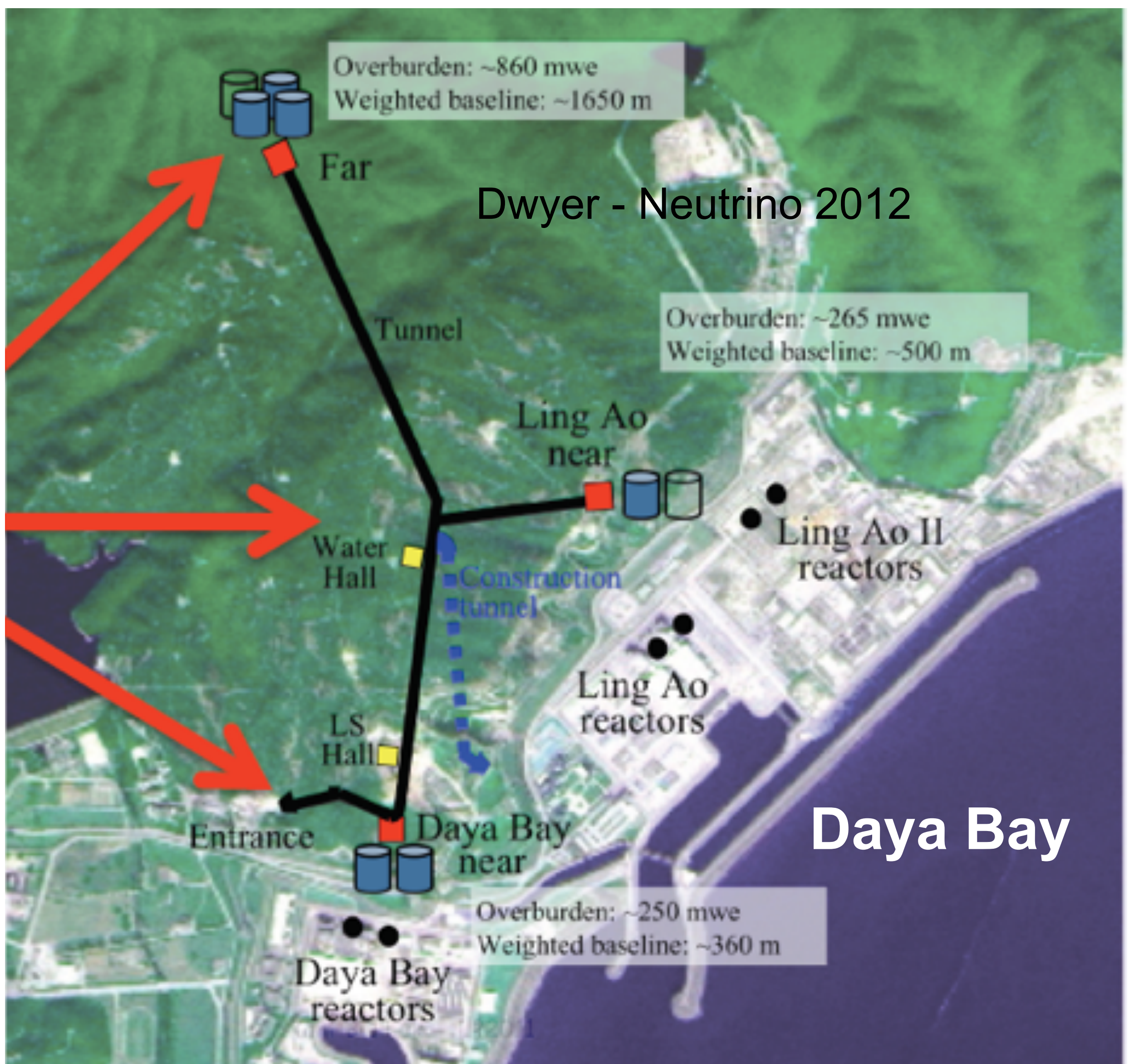
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

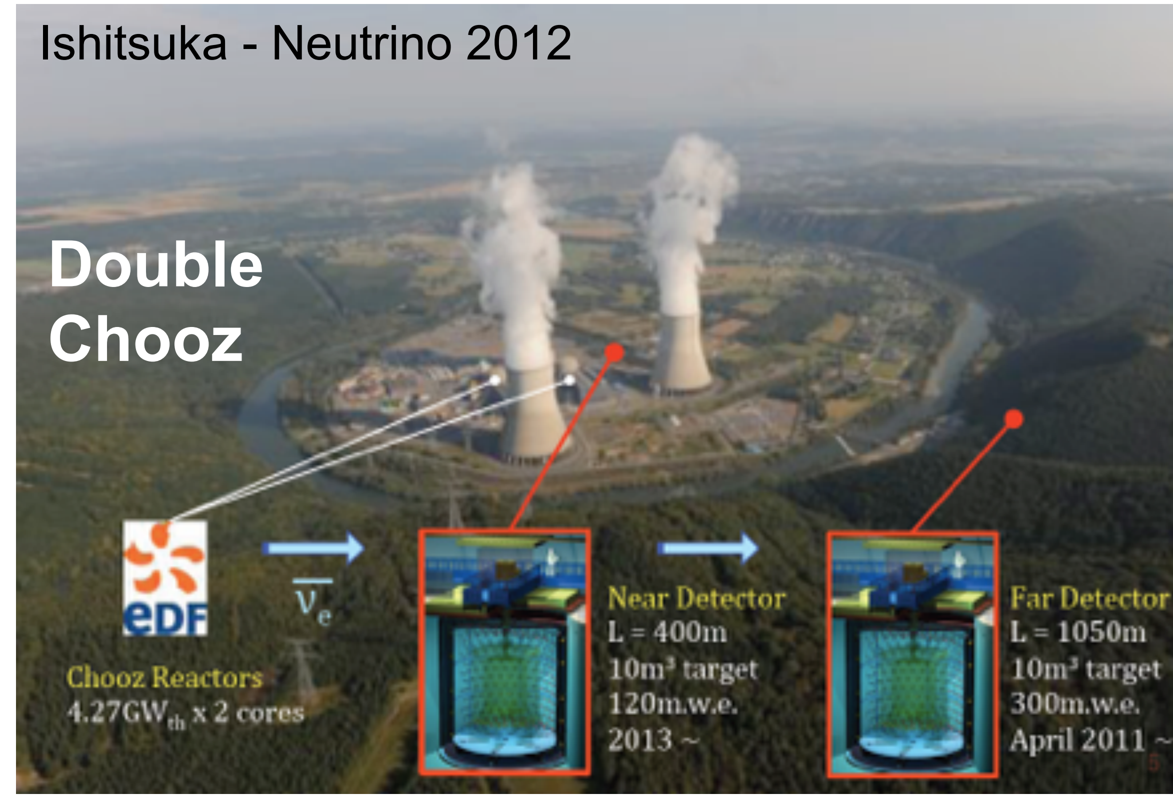


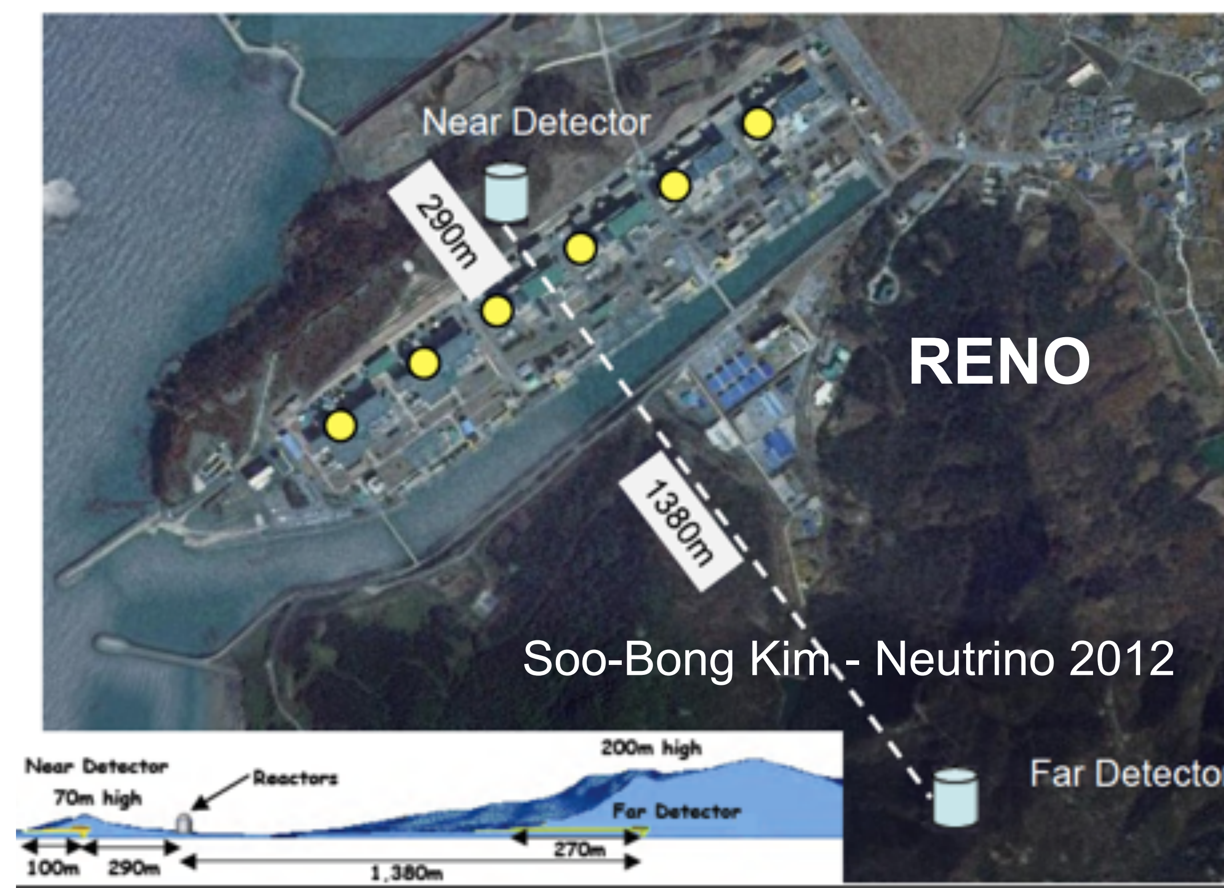
- "Long-baseline" reactor experiments (eg, KamLAND) are sensitive only to the solar mass splitting.
- "Short-baseline" reactor experiments (eg, Double Chooz, Daya Bay) are sensitive only to the atmospheric mass splitting and θ_{13}!

2012: The Year of the Reactor Experiments!

- In 2012, three reactor neutrino experiments reported measurements of θ_{13}.







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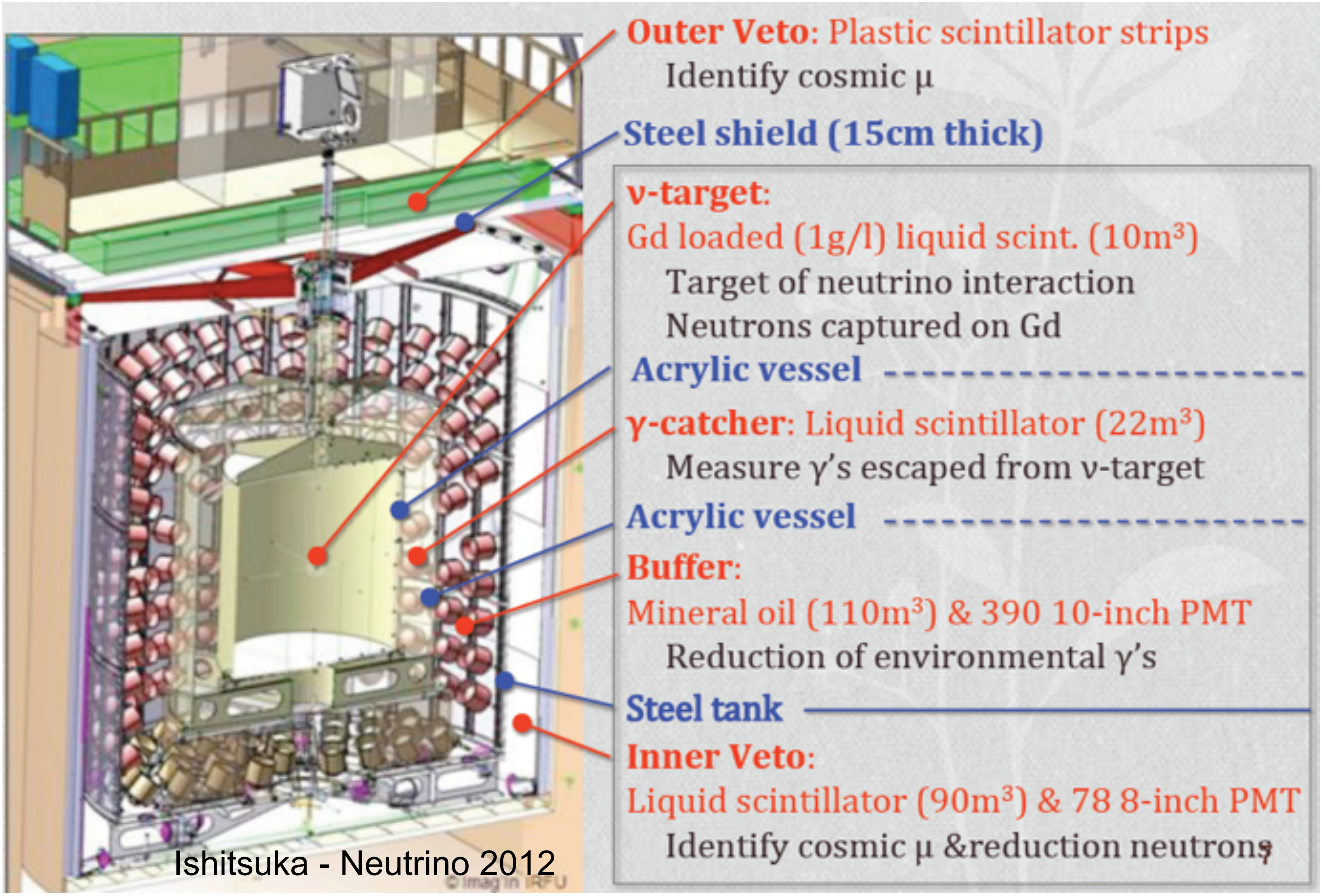

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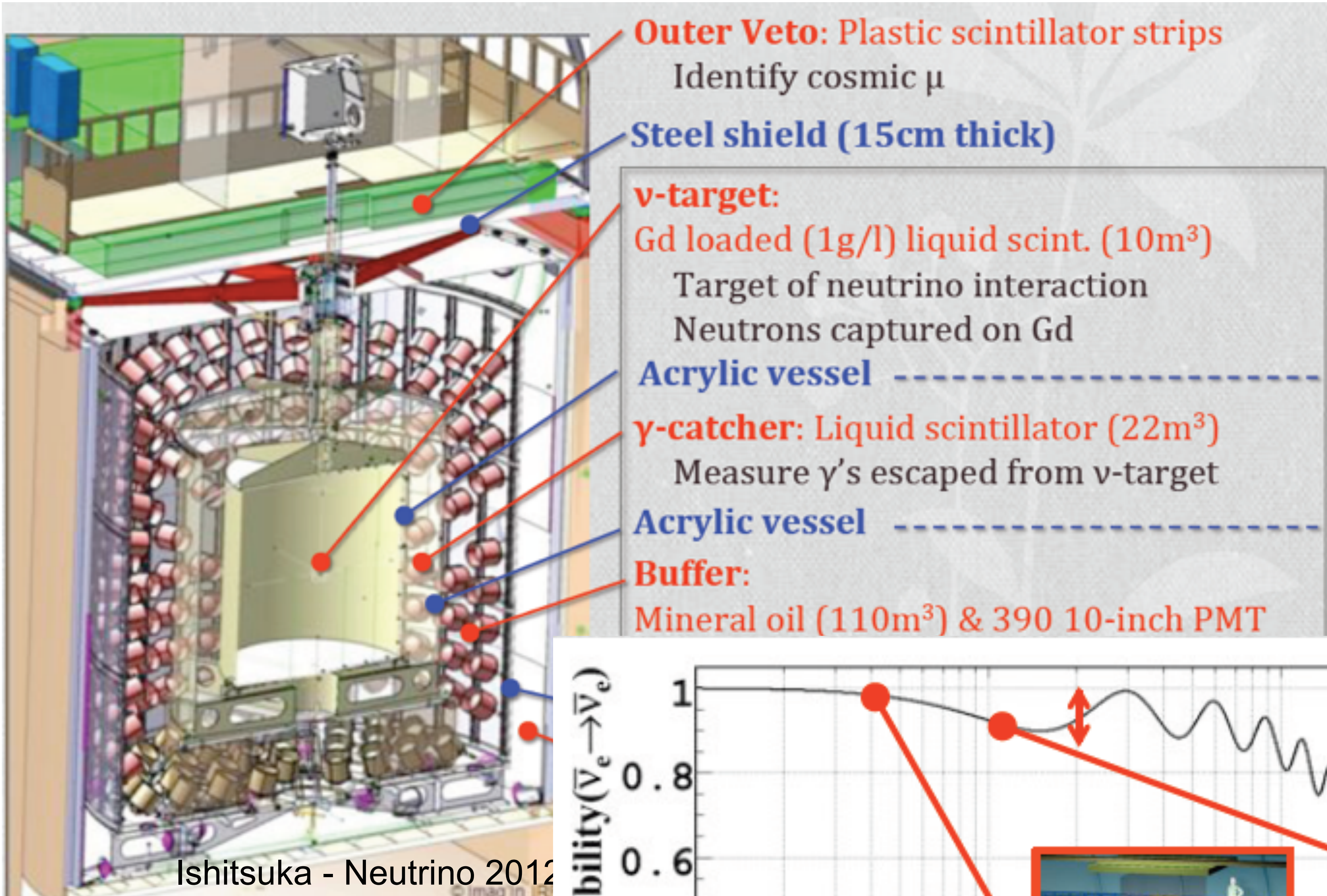
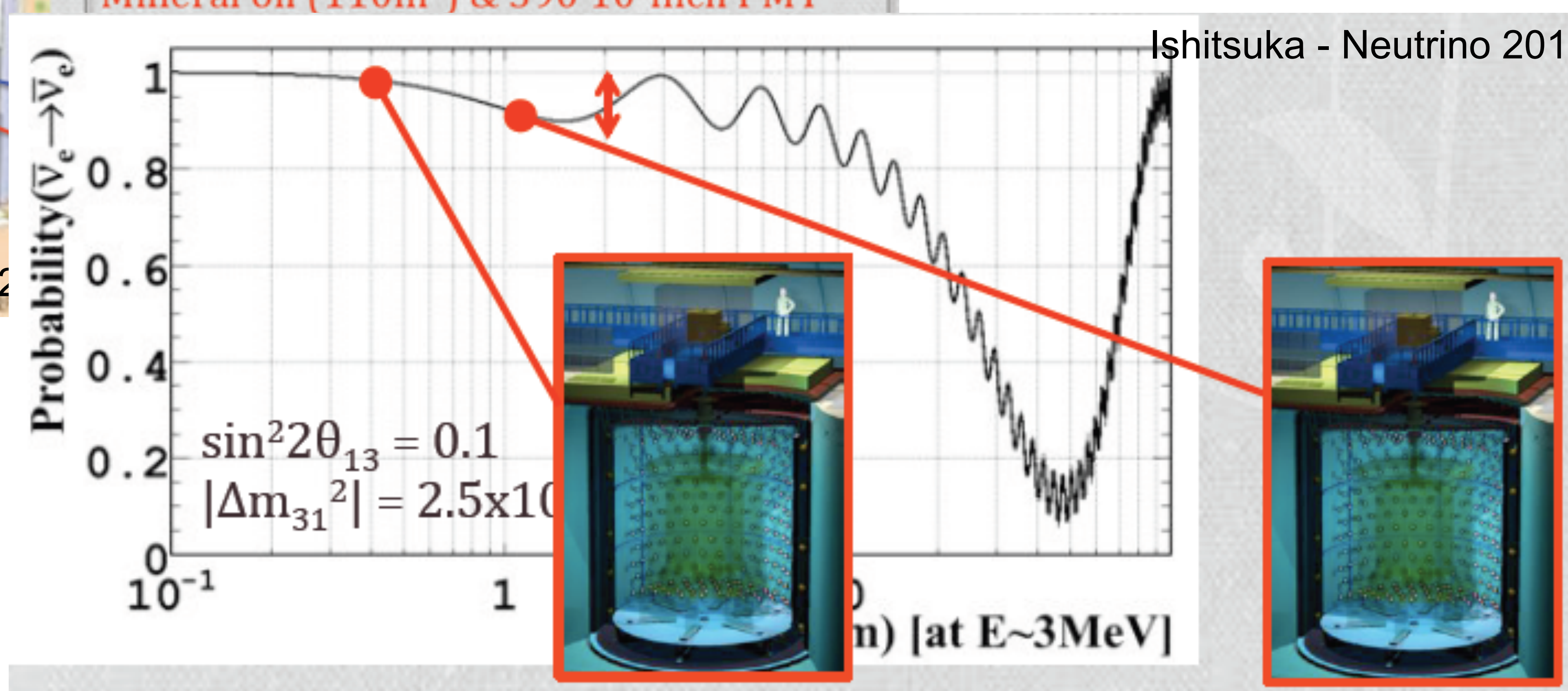
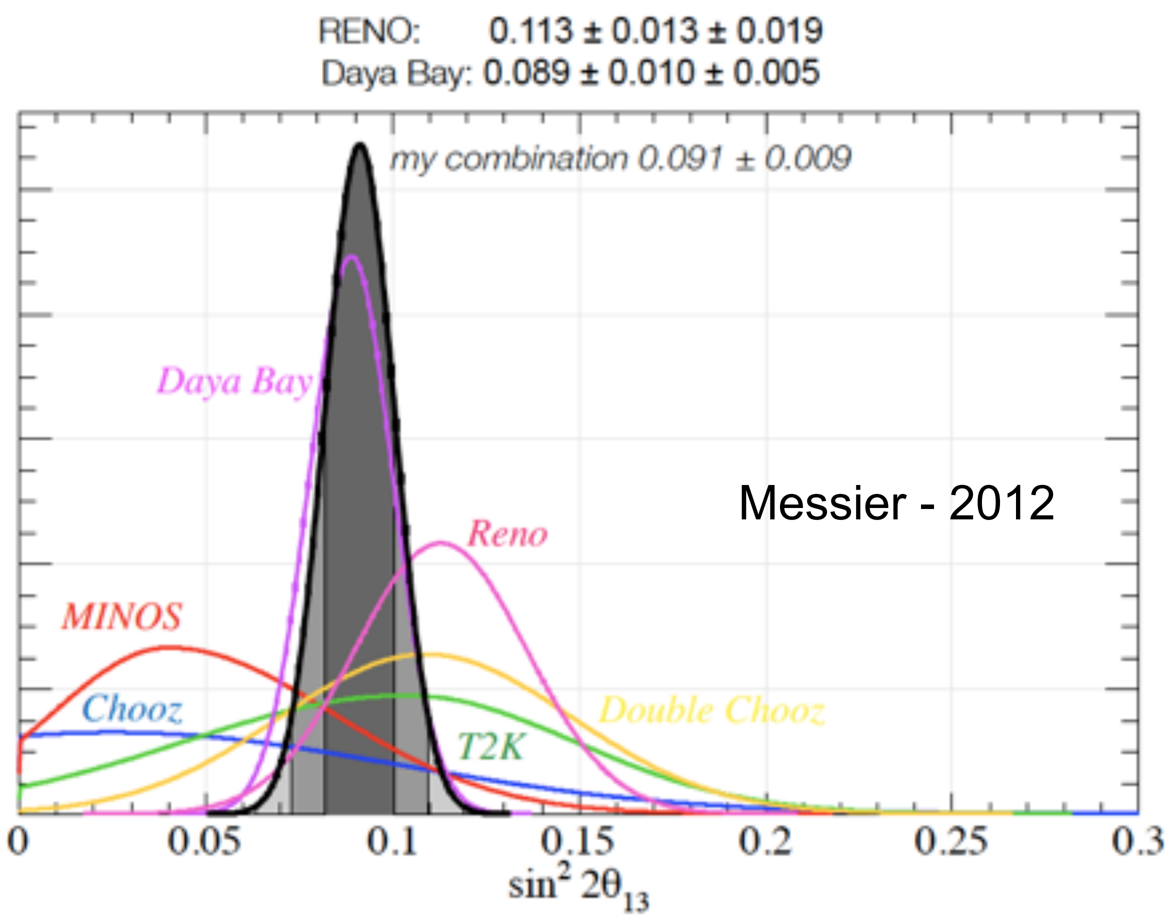
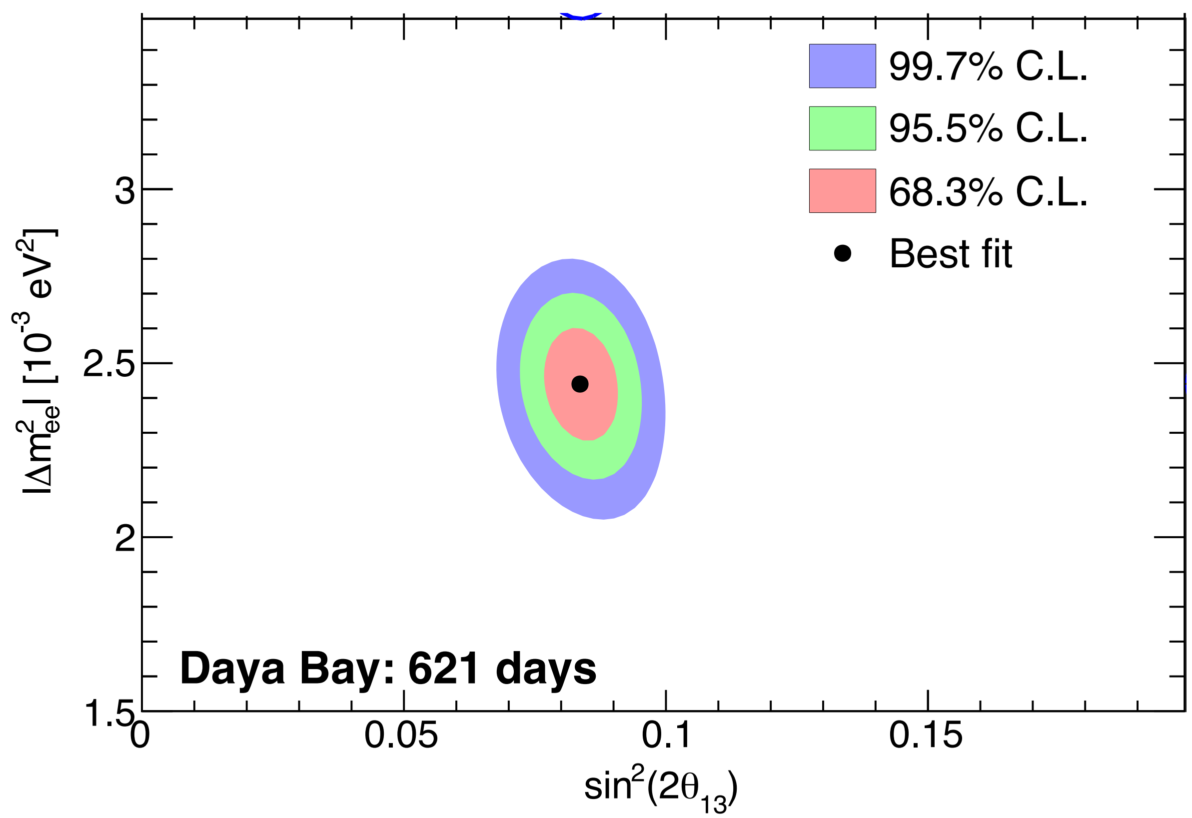




Two Years of Measurements of θ_{13}





- 11% → 6%
- spectral analysis also provides measurement of Δm^2_{31} (aka Δm^2_{ee}), consistent with MINOS results (and comparable precision)

Zhang - Neutrino 2014

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

What's Next for the Reactor Experiments

- All three experiments will continue to collect statistics and reduce their systematics.
- θ_{13} will be the most precisely measured mixing angle within a couple of years, at the level of ~3%.
- Proposed JUNO and RENO 50 experiments
  - could determine the mass hierarchy as well as measure $\sin^2\theta_{12}$ to ~2%.
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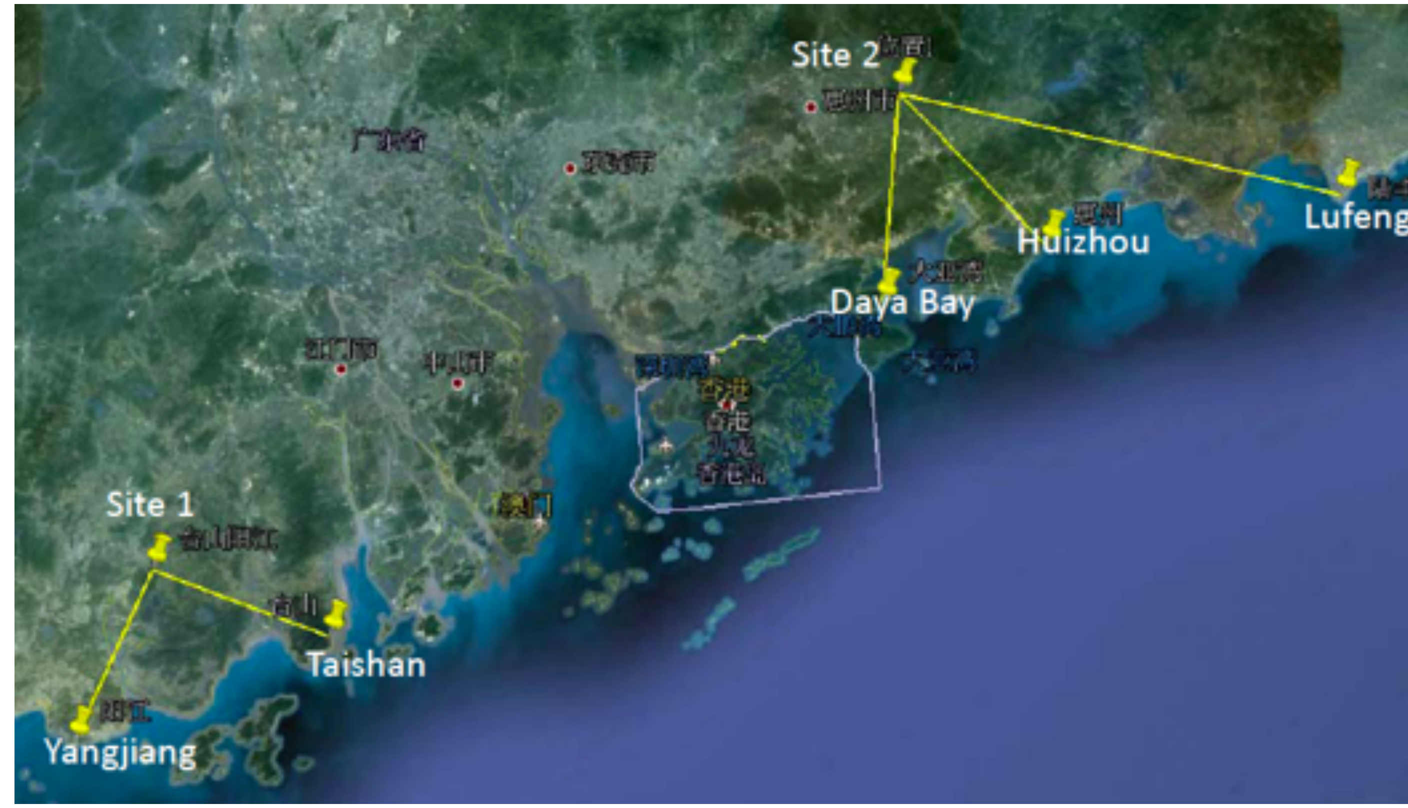
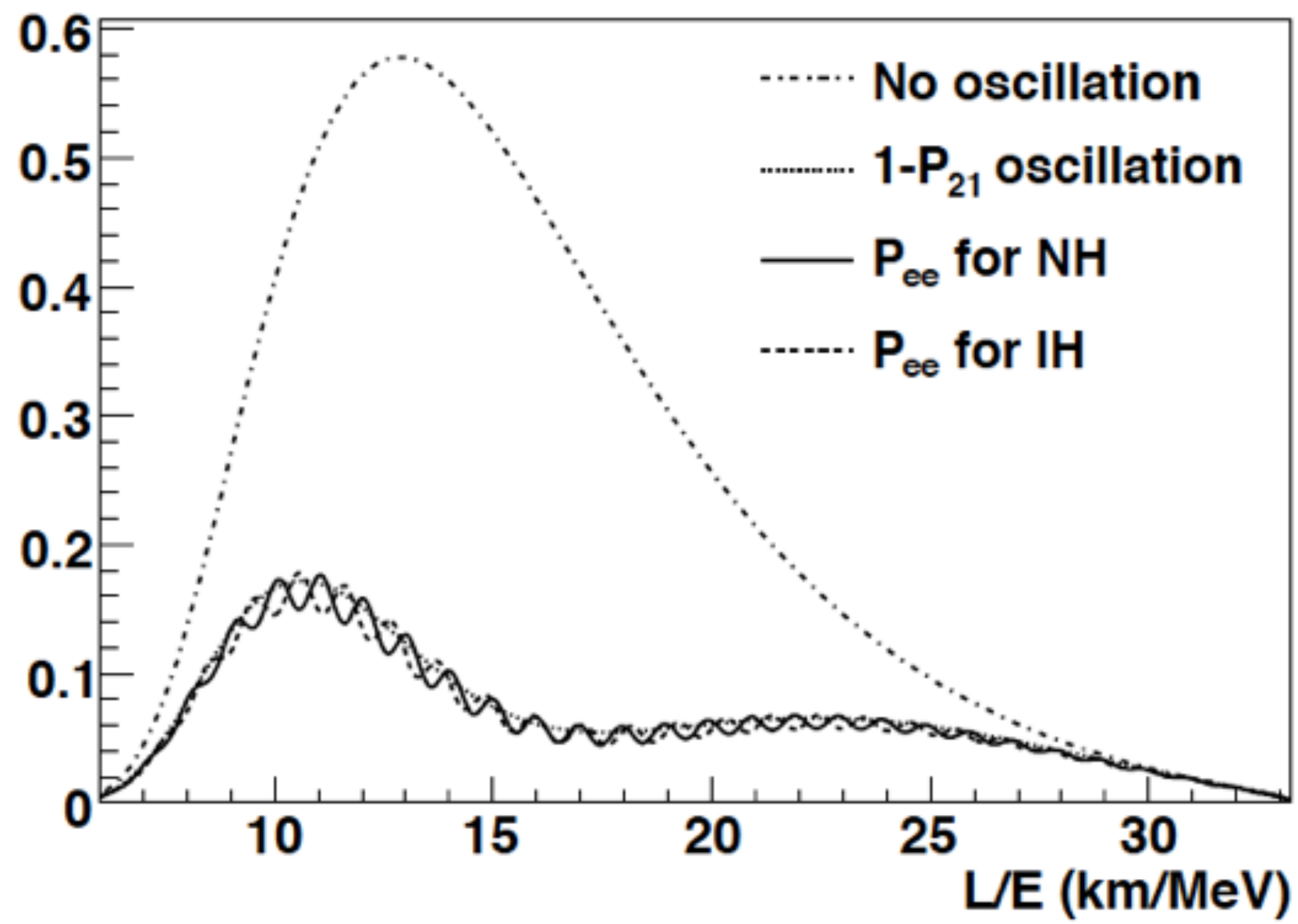
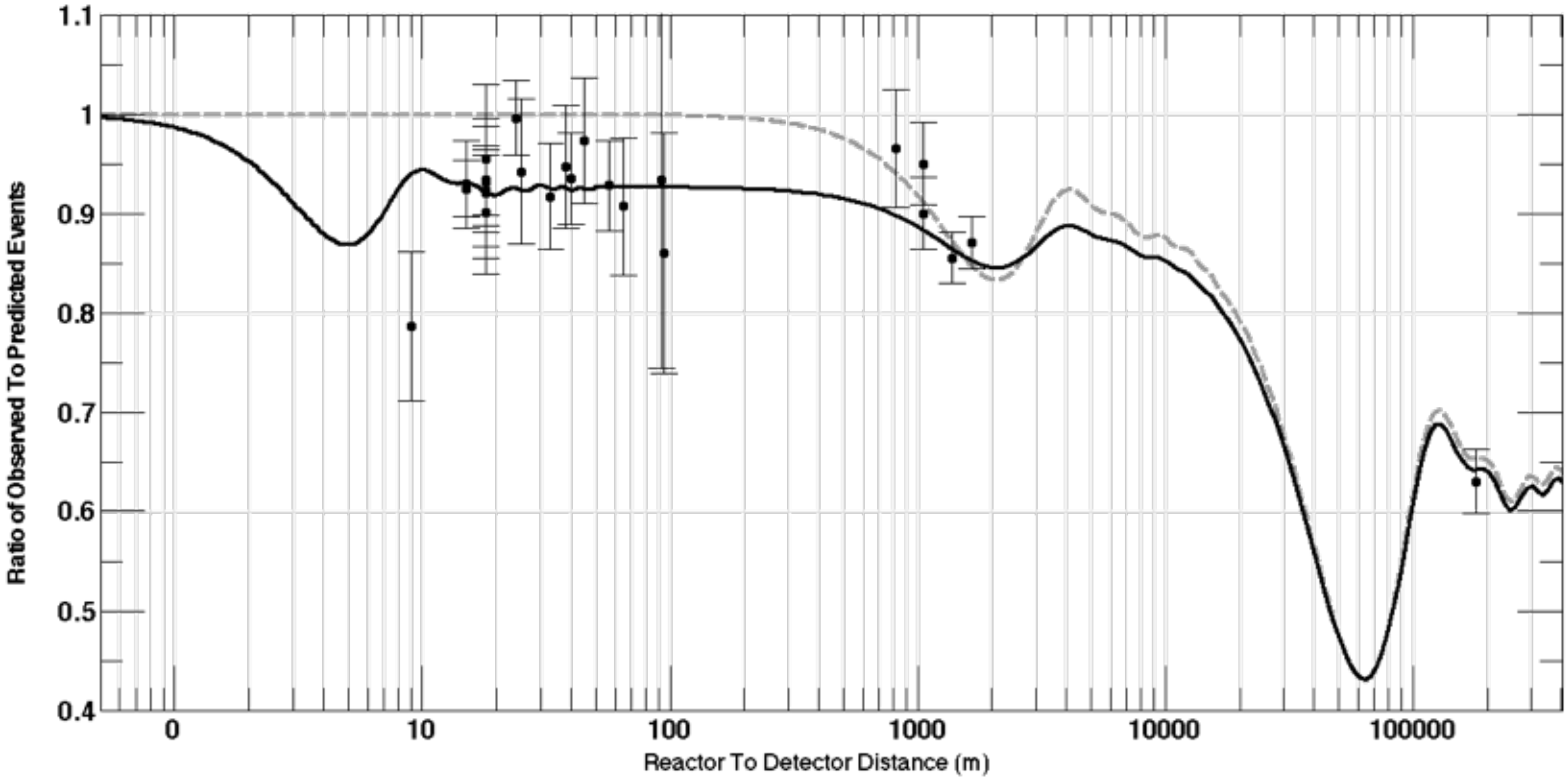


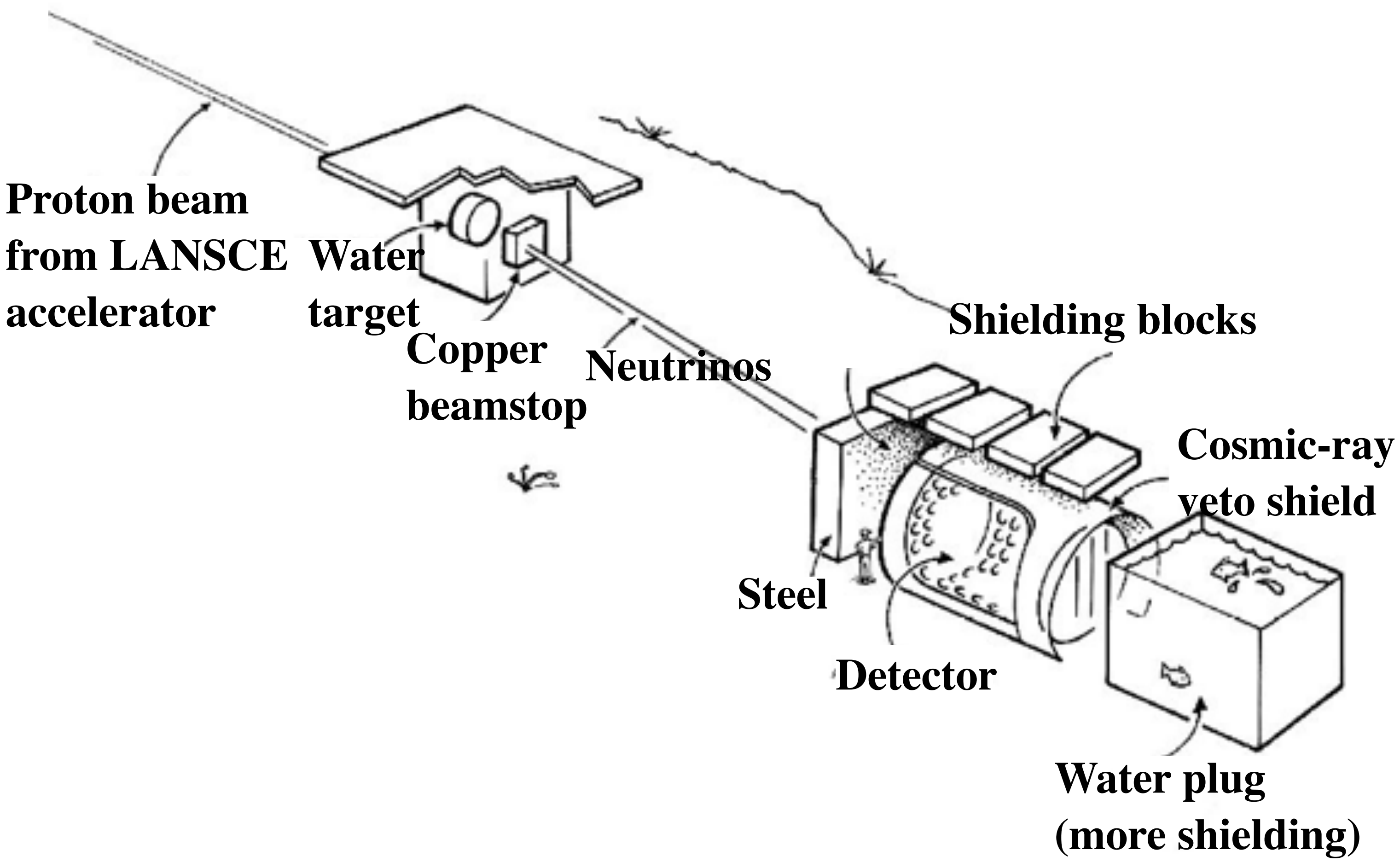


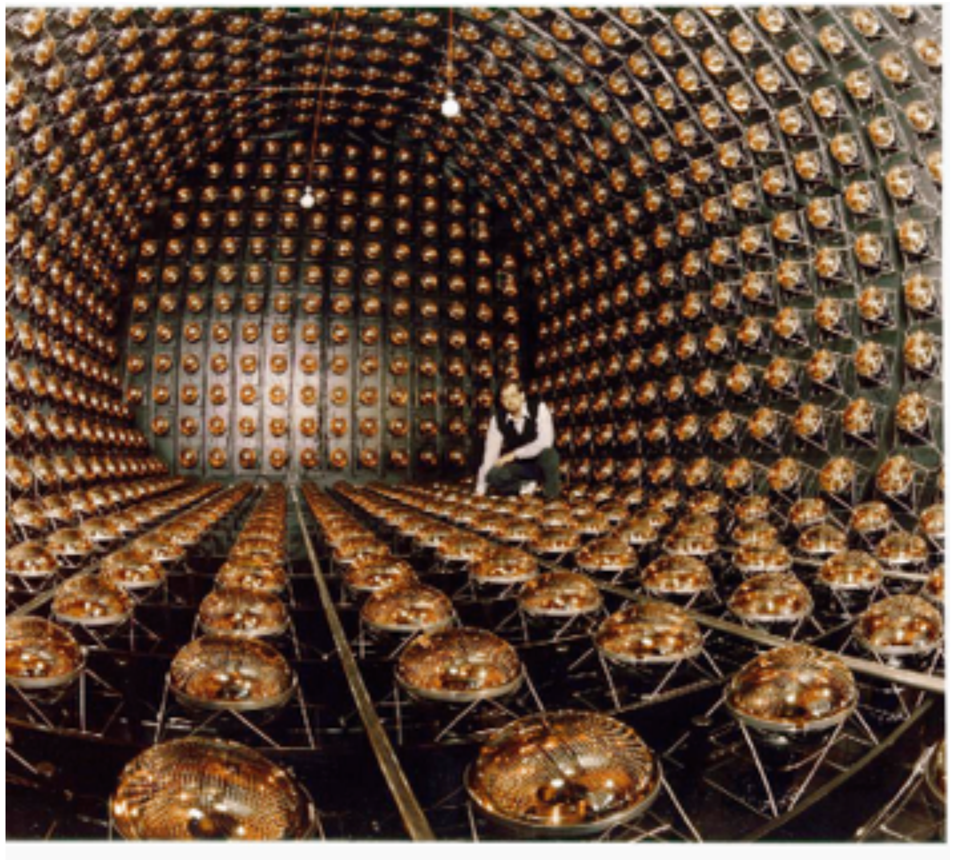
But Wait! Not All is Well in Reactor-land...



- New calculation of reactor flux (with ~2% uncertainty) predicts a higher rate than was observed in previous experiments!
- This implies that neutrinos actually DID oscillate in previous experiments.
- The only way this can happen is there is a different mass-splitting, with at least one more neutrino.

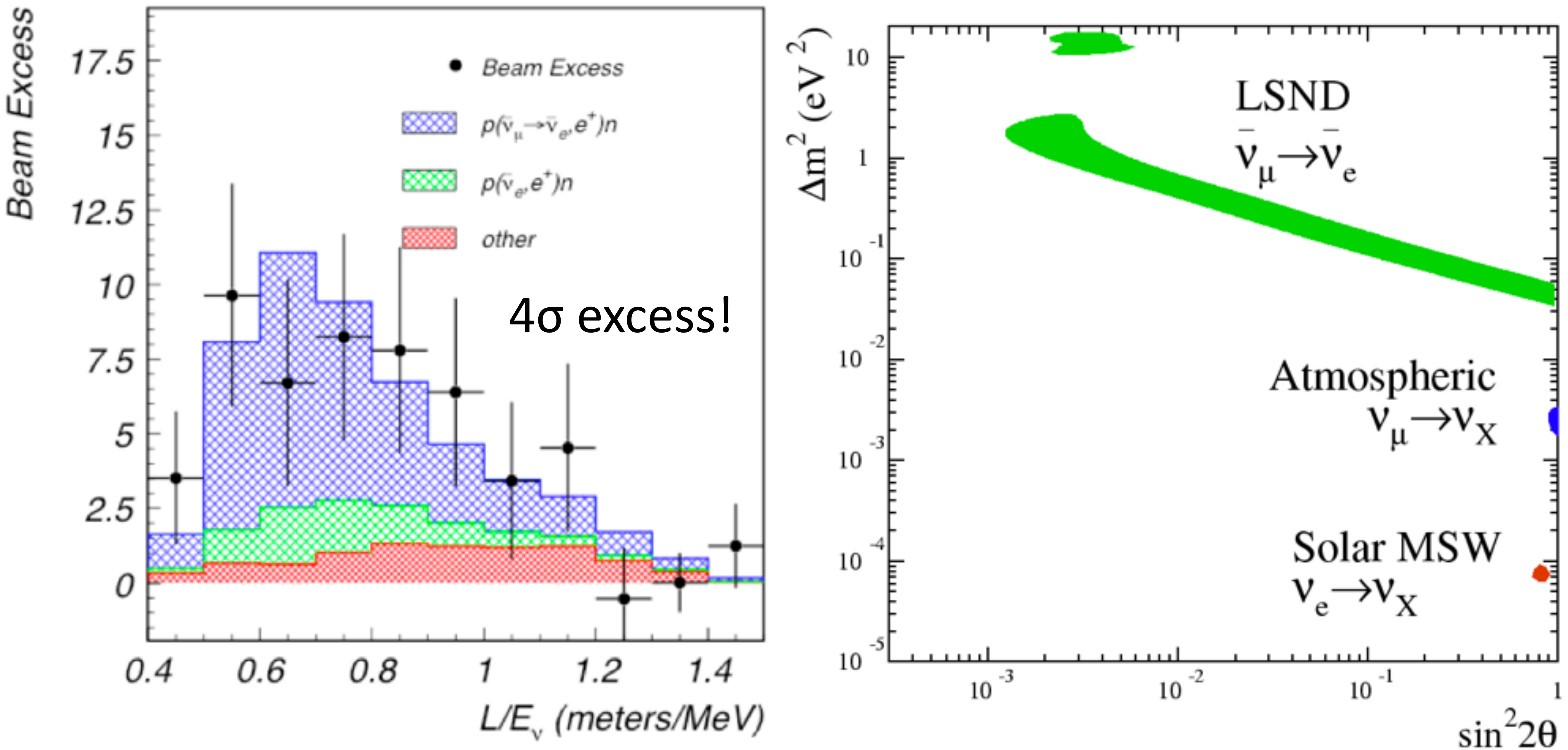
The LSND Anomaly





- Single 167 ton liquid scintillator detector (1000 PMTs)
- Used stopped pion beam, E_ν ~ 20-53 MeV, L ~ 30 m

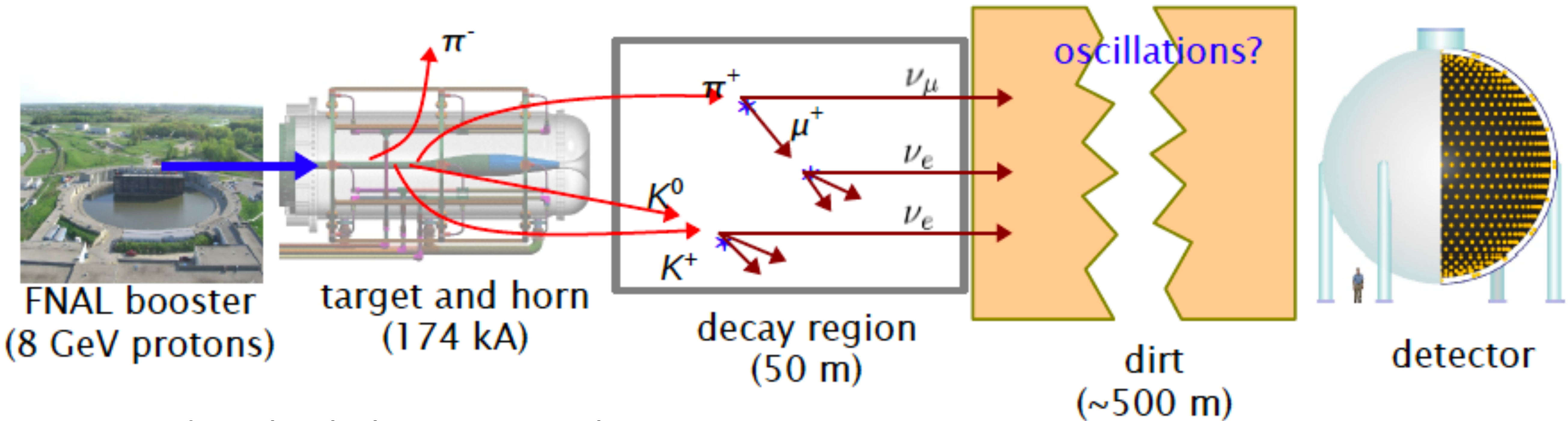
The LSND Anomaly



- Taking the LSND result at face value, the most straightforward explanation is the existence of another neutrino.

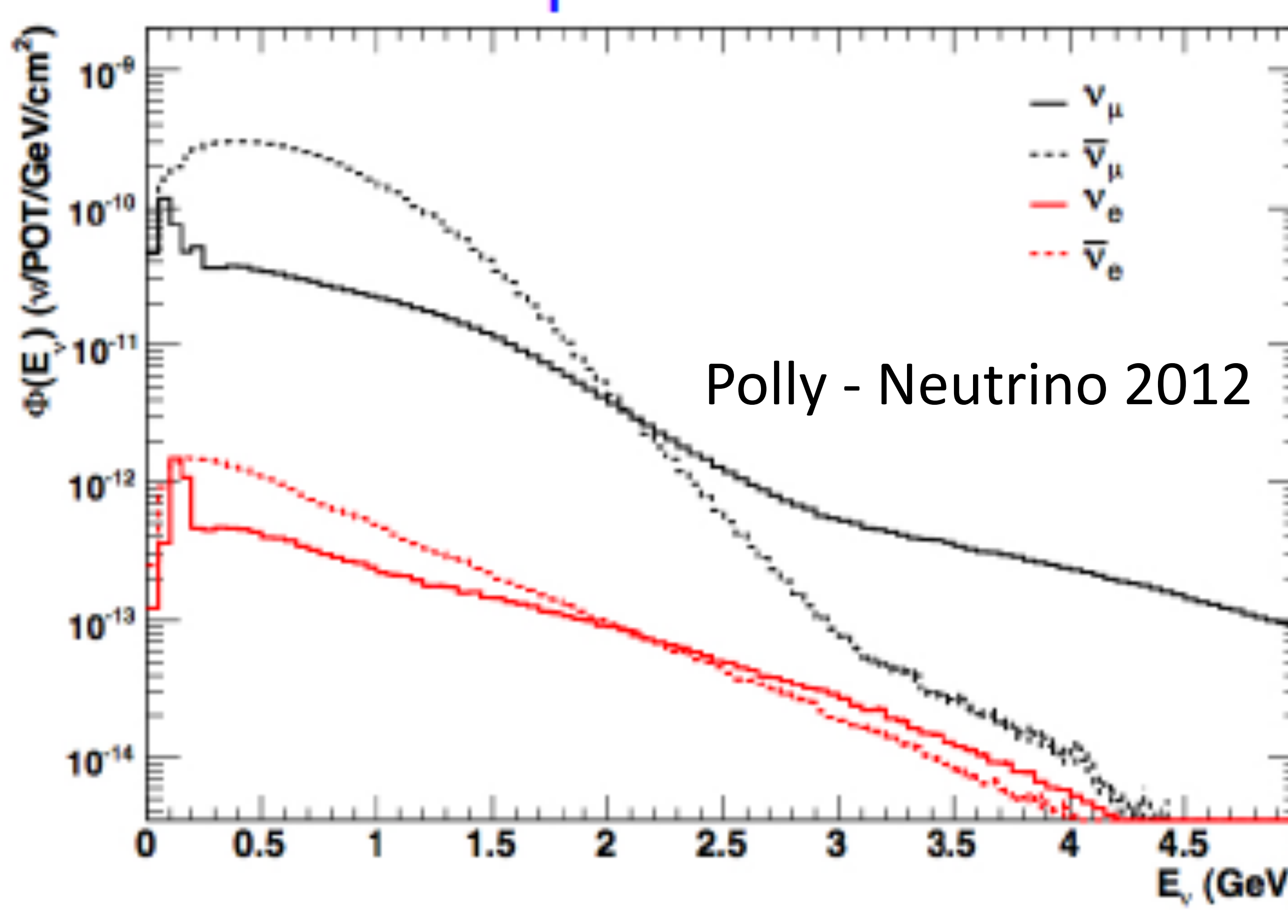
- Neutrino does not interact via the weak force: STERILE

And Along Comes MiniBooNE...



- Designed to check the LSND result
- Average energy of neutrinos ~10x larger than LSND, so x10 increase in cross-section (more neutrino interactions in detector)
- Use of horn increased neutrino flux, allows one to measure rates for either neutrinos or anti-neutrinos
- However, different backgrounds than LSND, eg:
  - wrong-sign neutrinos
  - intrinsic beam ve from K-decays

anti-ν_μ Mode Flux



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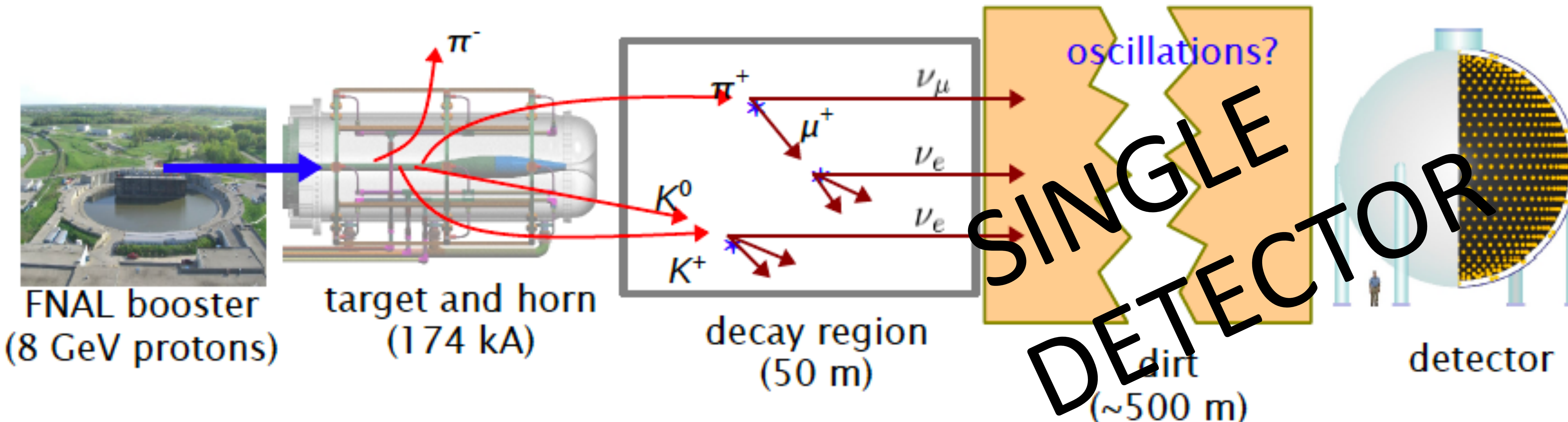

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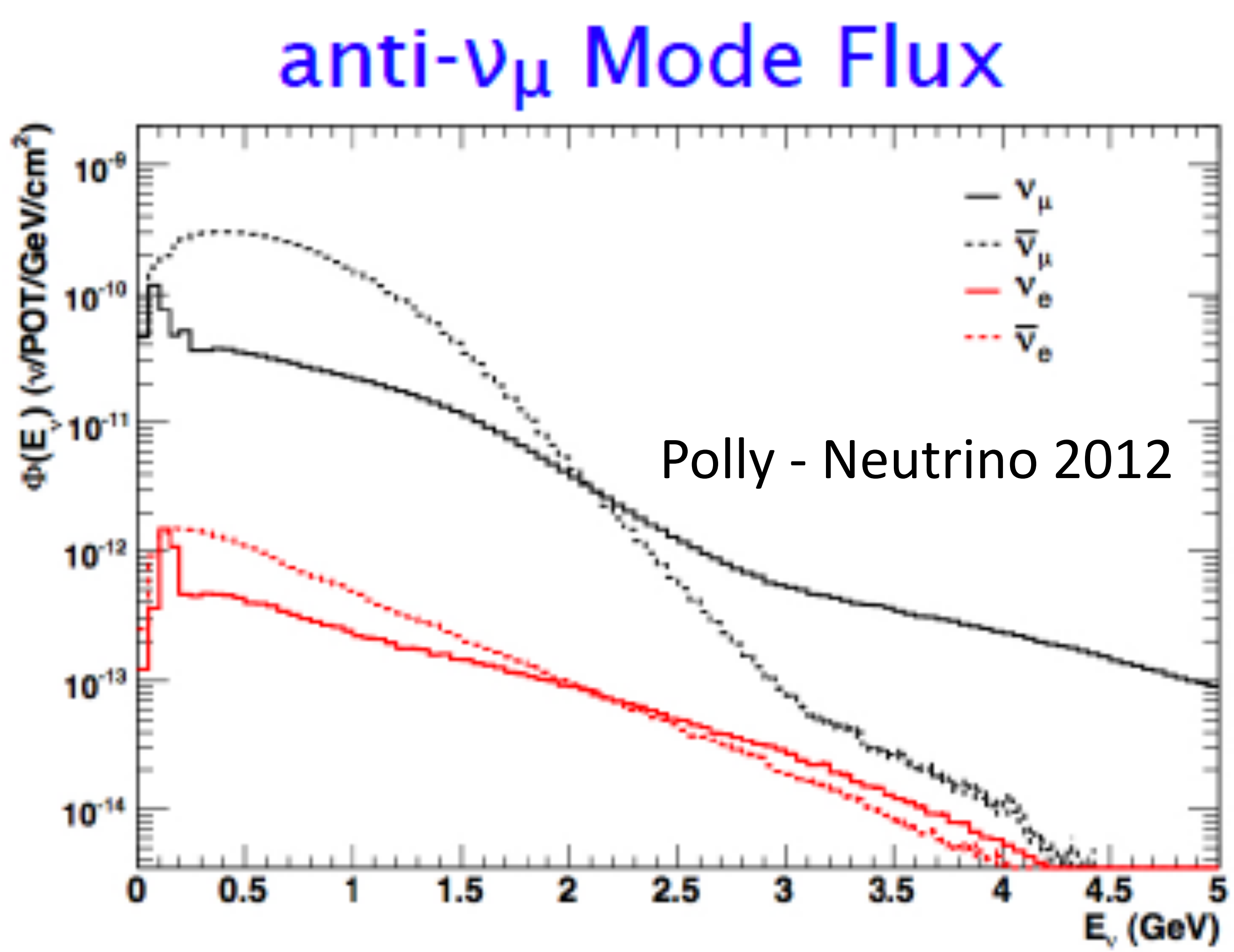
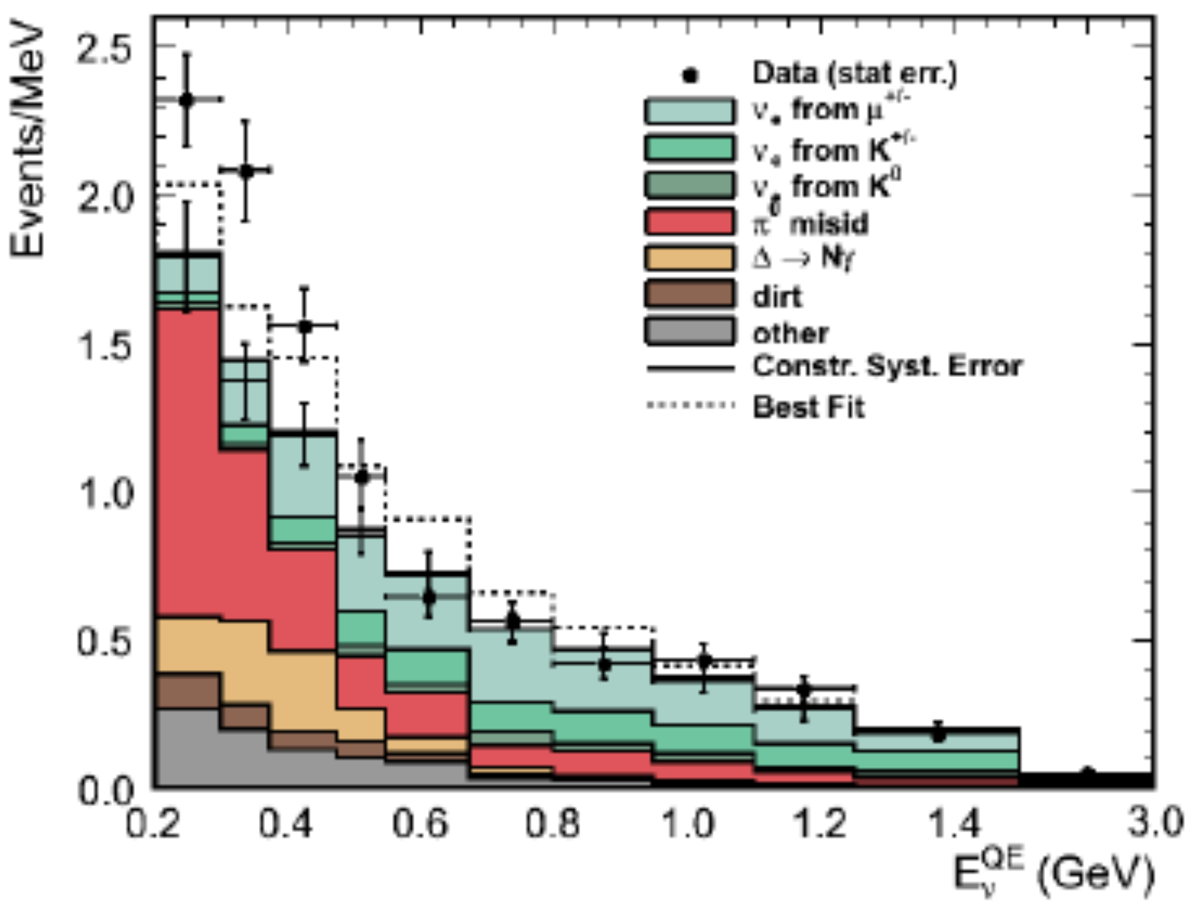
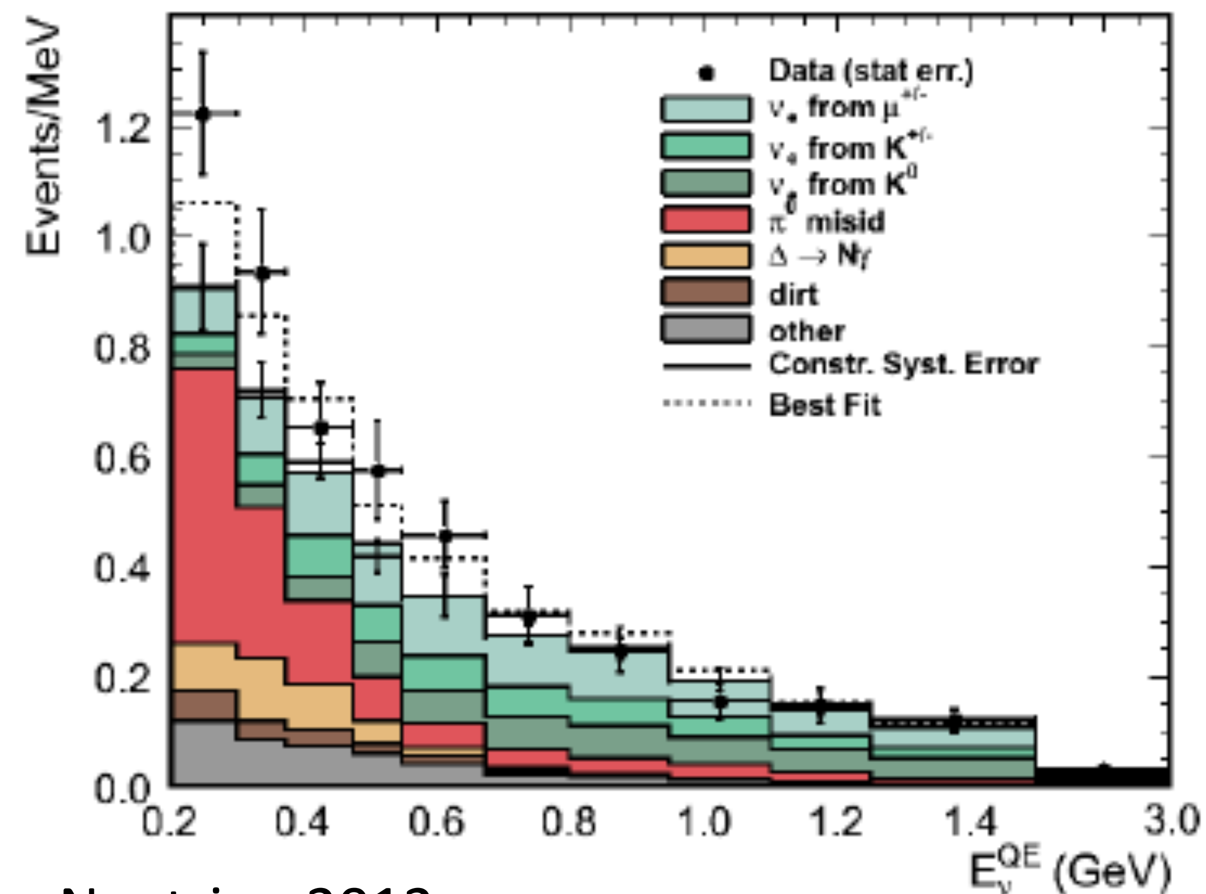


MiniBooNE Results

6.5e20 POT neutrino mode w/ 3+1 fit



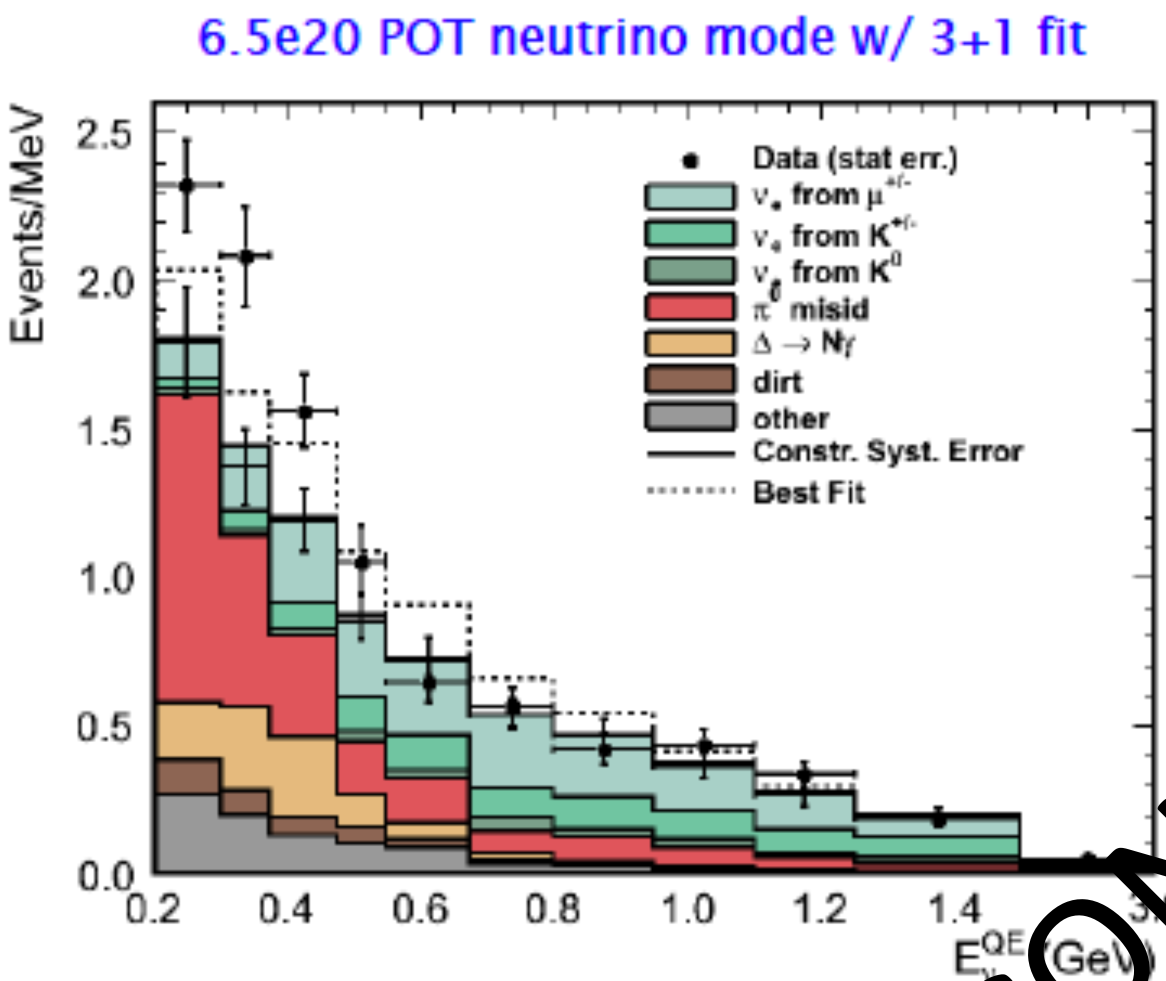
11.3e20 POT anti-neutrino mode w 3+1 fit

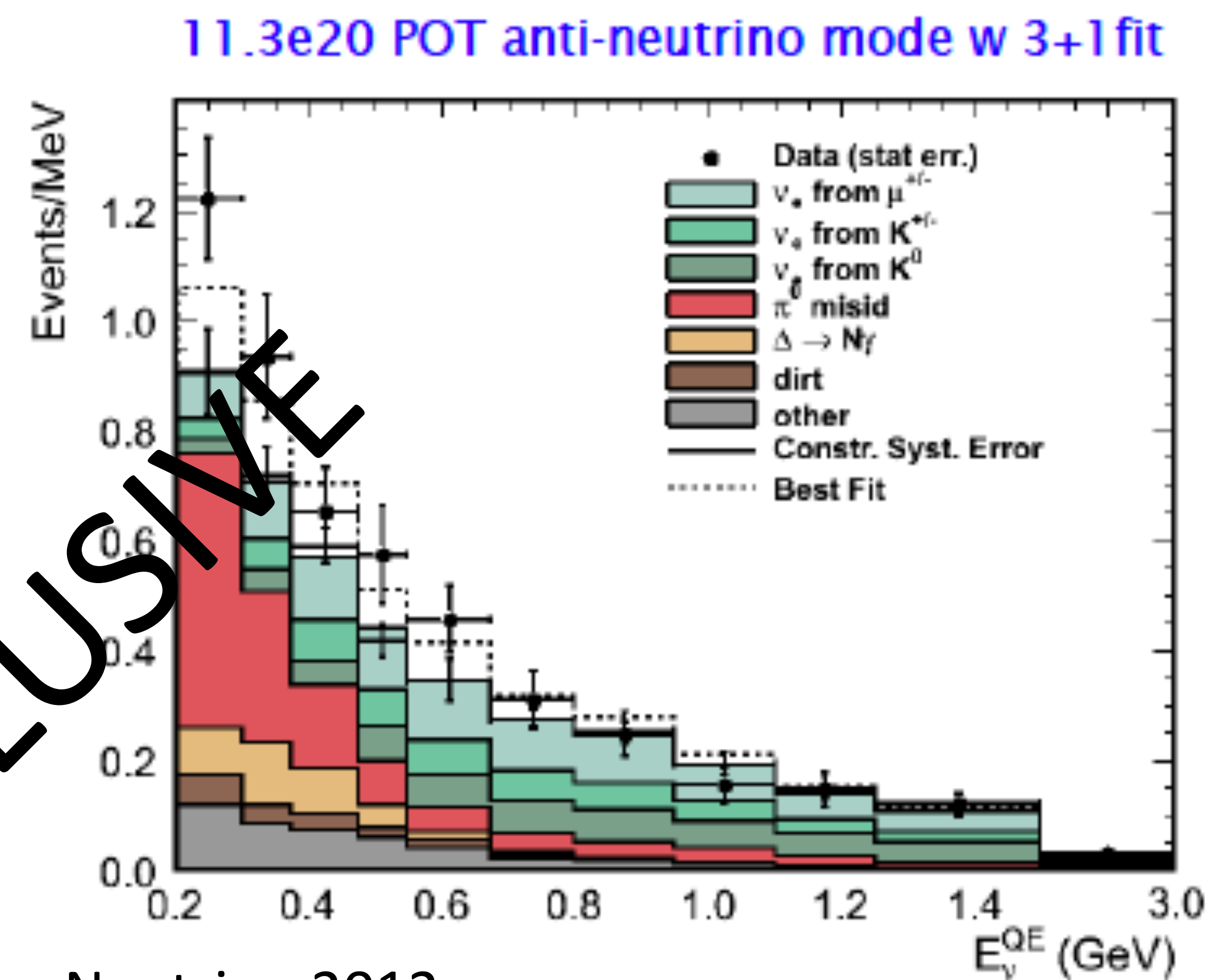


Polly - Neutrino 2012

- neutrino-mode:
  - excess of ν_e from 200-1250 MeV
  - however, excess is all at lower energies (< 475 MeV) where backgrounds are very large
  - LSND result predicts that excess should be in the range of 600-800 MeV
- Similar results in latest measurement of anti-neutrinos
- Not clear if the low-energy excesses are due to oscillations, some unrecognized background, or something else.

MiniBooNE Results





INCONCLUSIVE

Polly - Neutrino 2012

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So… Umm… [Scratch Head…]

- We have some hints for $\Delta m^2 \sim 1$ eV^2 oscillations:
  - LSND: 3.8σ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - MiniBooNE: 3.8σ (combined $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - Reactor: 3.0σ ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)
  - Gallium/Sage: 2.7σ (solar $\nu_e \rightarrow \nu_e$)
- On the other hand, many other experiments see no such indications:
  - MiniBooNE restrictions on ν_μ and $\bar{\nu}_\mu$ disappearance
  - MINOS restrictions on $\nu_\mu \rightarrow \nu_s$
  - Super-K restrictions on $\nu_\mu \rightarrow \nu_s$
  - and many more...
- Furthermore, 3+1 models are not very compatible with the positive data. 3+2 models are a bit better, but not great.

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- We have some hints for
  - LSND: 3.8
  - MiniBooNE: 3.8
  - Reactor: 3.0
  - Gallium/Sage: 2.7
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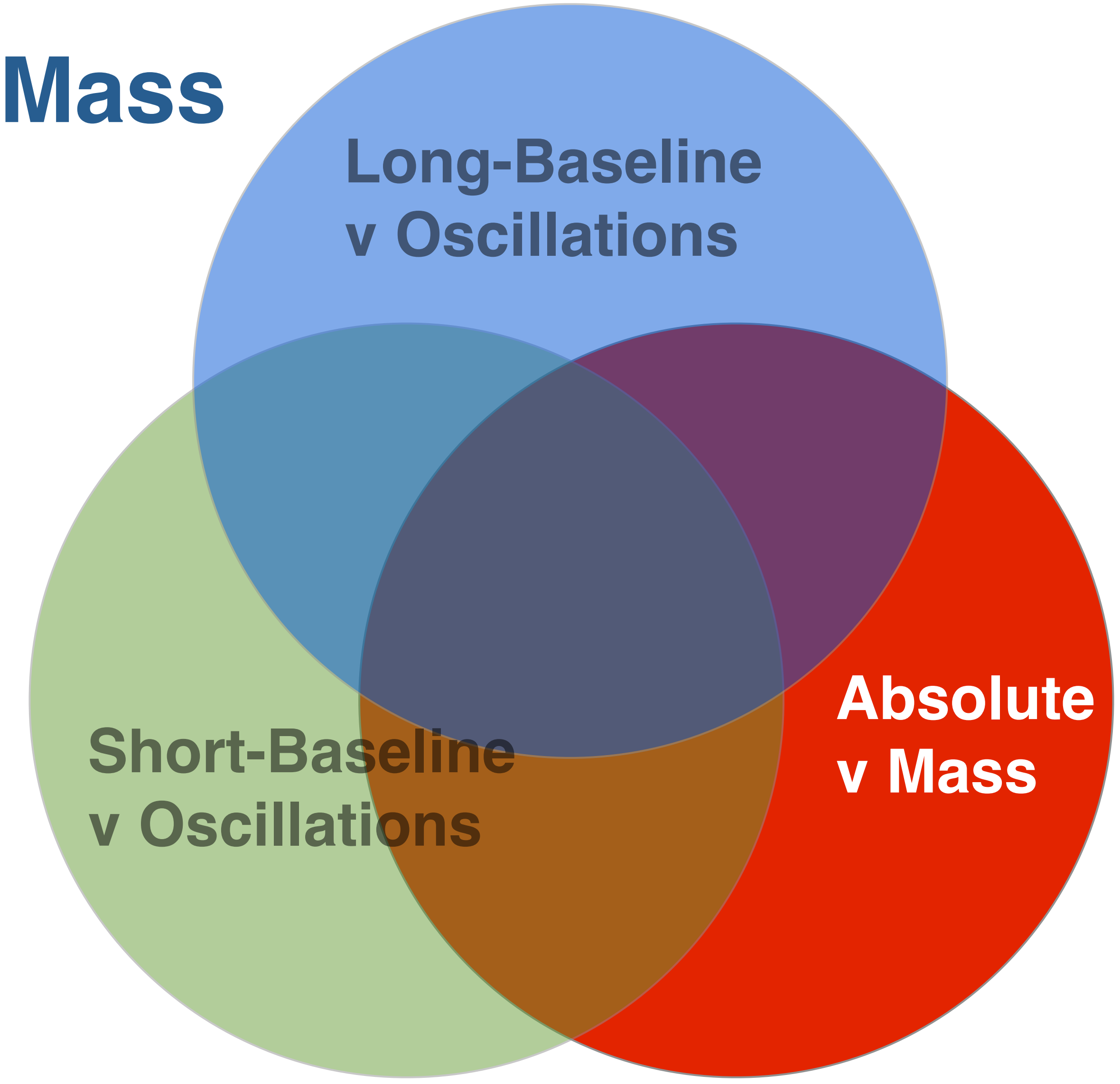
Need a definitive measurement!

Definitive Measurements?

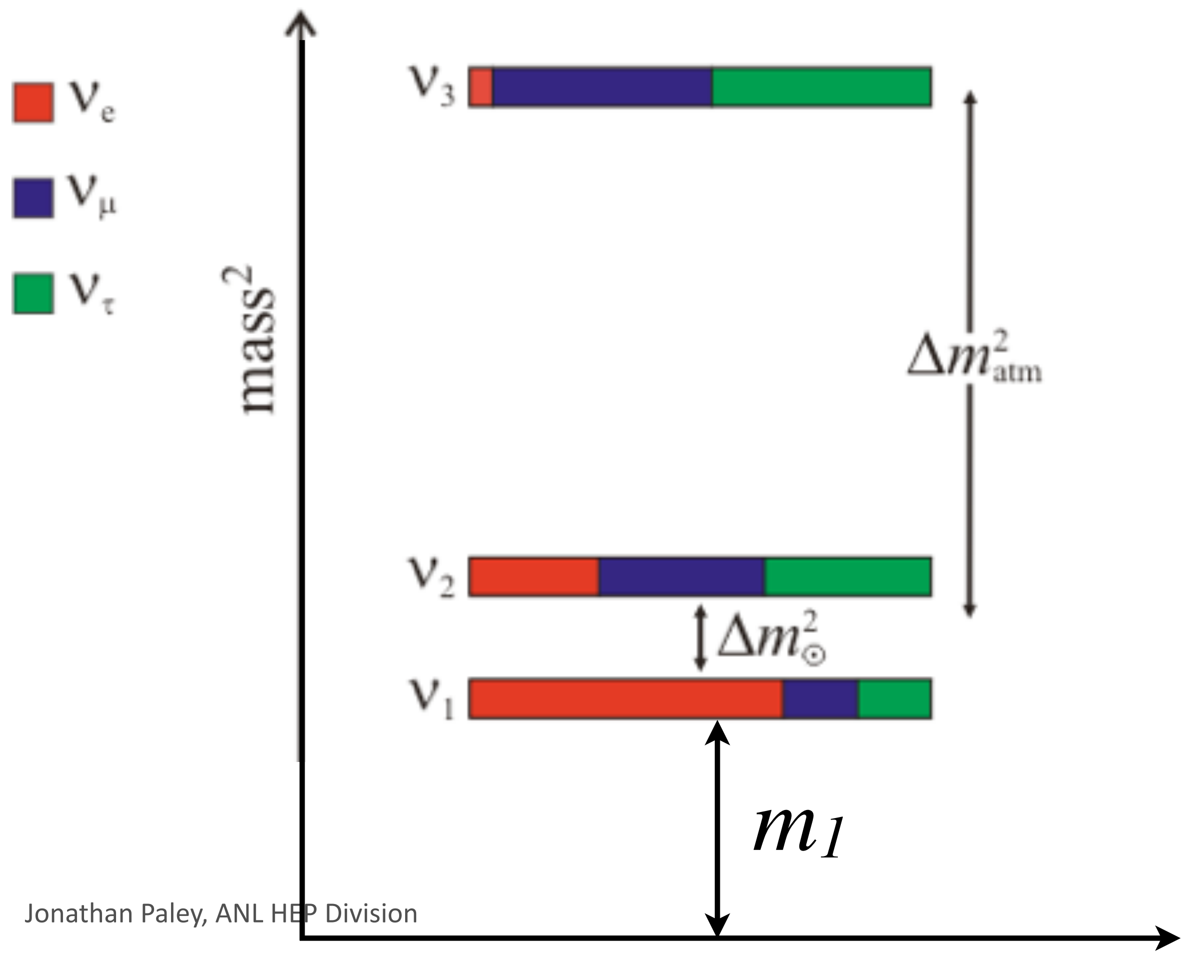
	Primary Channel	Other osc channels	Definitive sterile?	Other physics	Tech R&D?	Cost	Why worry?	Comment
MicroBooNE (π DIF)	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$		GeV-scale xsec	Yes	$20M	tech, cosmics	Exists!
LAr1-ND (π DIF)	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$		GeV-scale xsec	Yes	$13M	tech, cosmics	
ICARUS@FNAL (π DIF)	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$		GeV-scale xsec	Yes	Under study	tech, cosmics	
TripleLAr@FNAL (π DIF)	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$	Probably	GeV-scale xsec	Yes	Under study	tech, cosmics	Work in progress. Anti-nu?
OscSNS (π,μ DAR)	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_e \to \nu_e$	Yes	Supernova xsec	No	$20M	intrinsic $\bar{\nu}_e$	
JPARC MLF (π,μ,K DAR)	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_e \to \nu_e$ $\nu_\mu \to \nu_e$	Not in phase 1	Supernova and 235 MeV ν_μ xsec	No	$5M	intrinsic $\bar{\nu}_e$	Phase 1
IsoDAR-KamLAND (Isotope DAR)	$\bar{\nu}_e \to \bar{\nu}_e$	-	Yes	$\bar{\nu}_e e^-$ (electroweak)	Yes	$30M	timeline, tech	
nuSTORM (μ DIF)	$\nu_e \to \nu_\mu$	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ $\nu_e \to \nu_e$	Yes	GeV-scale xsec	Yes	$300M	timeline, tech, cost	P5 says no

Spitz - Neutrino 2014

Paths to Measuring Neutrino Mass



- Direct Measurements
  - Time-of-flight
  - Beta-decay
- Indirect Measurements
  - 0νββ
  - cosmology



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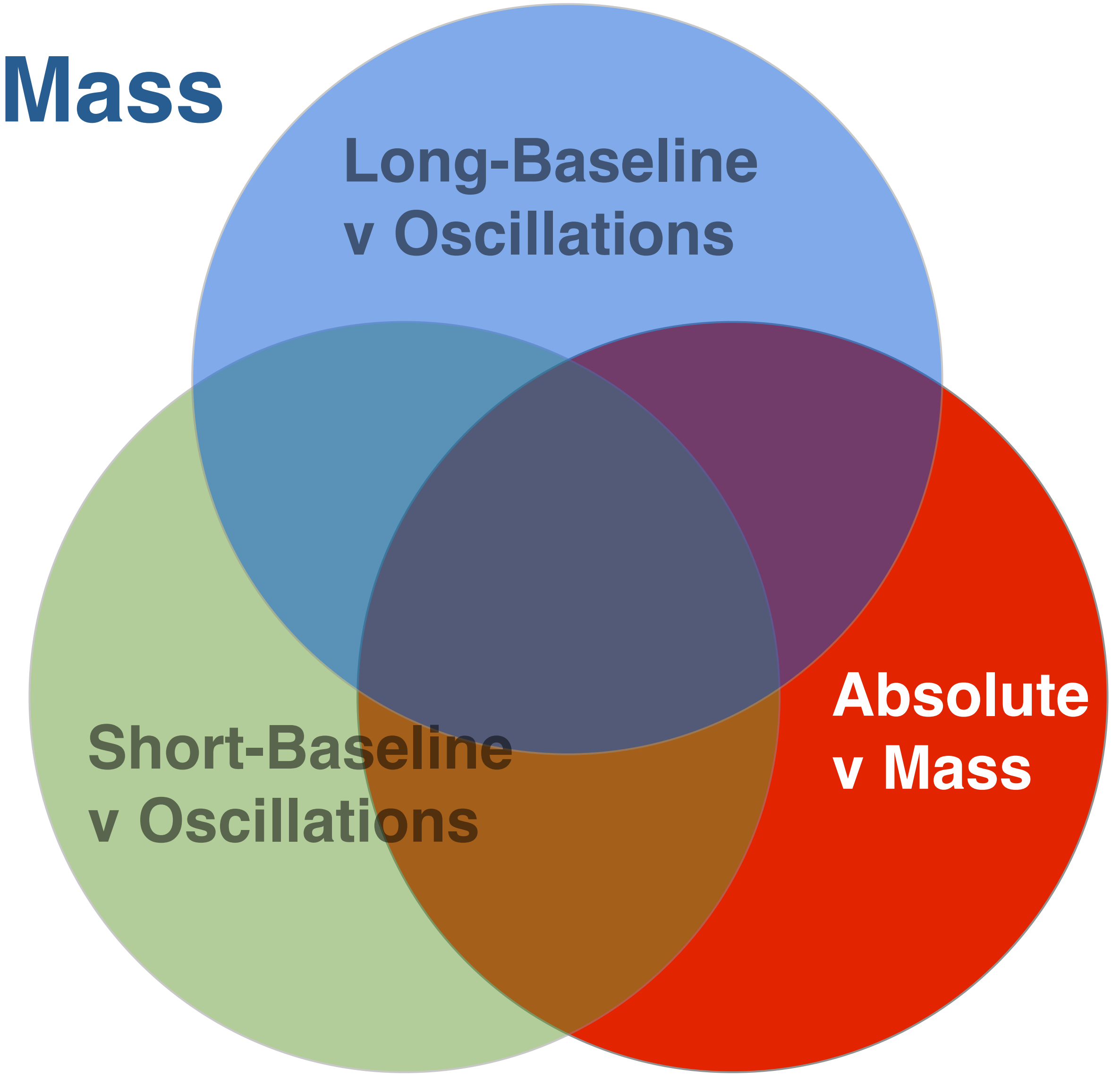
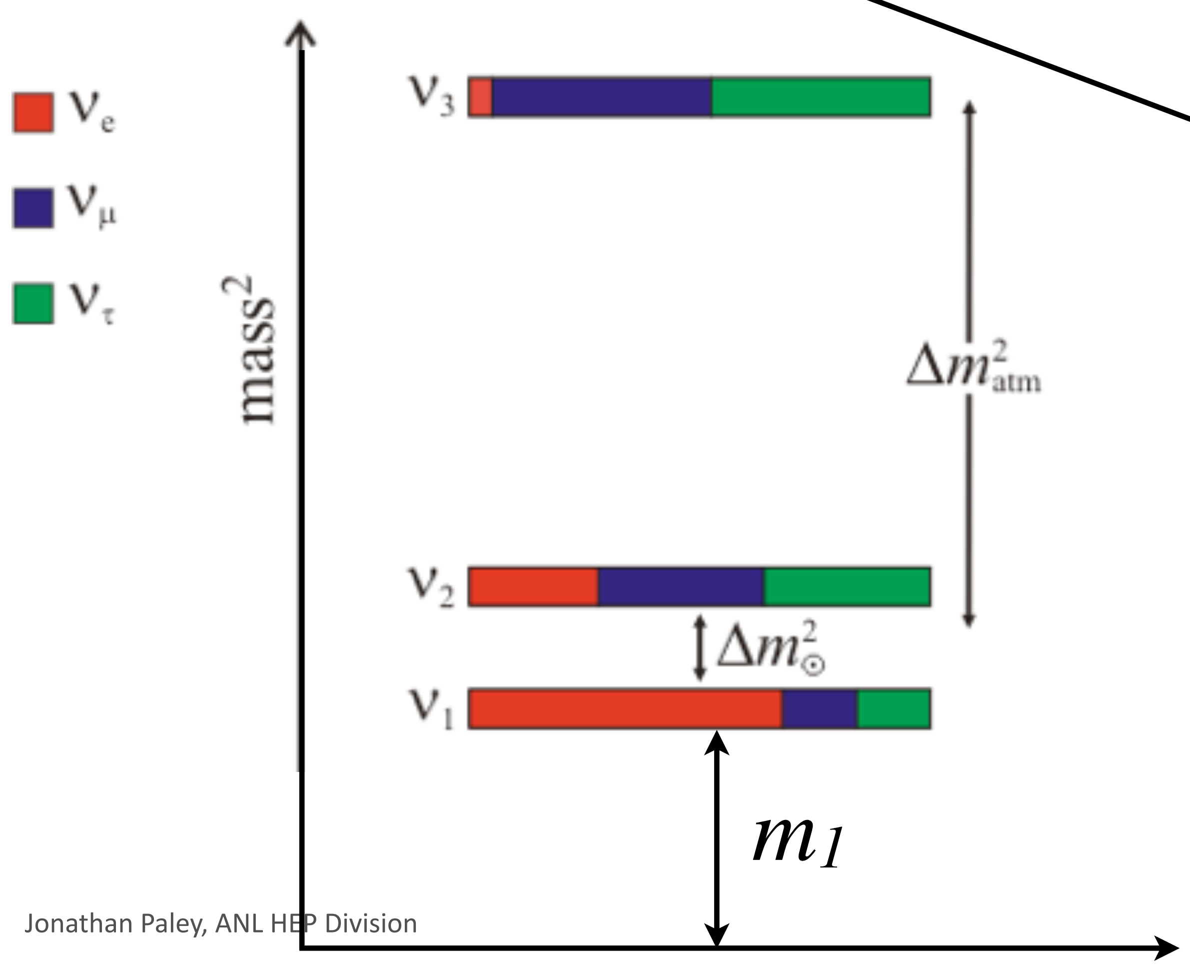
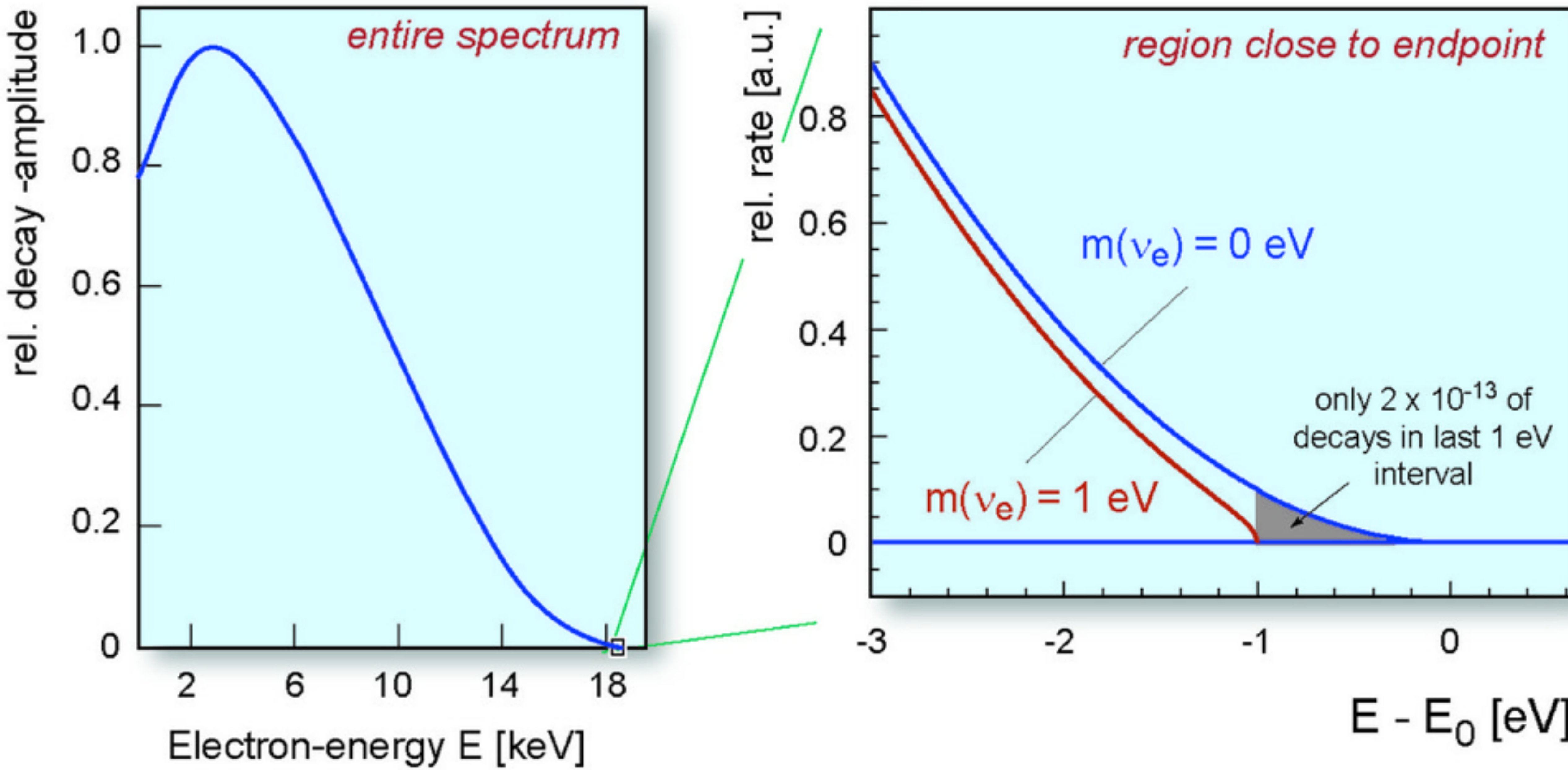




Majorana vs. Dirac!

Mass Measurement Using Beta Decay



$$\frac{dN}{dE} = |< l| < \nu_l|T|I >|^2 = \left|\sum_i U_{li}^* < l| < \nu_i|T|I >\right|^2 \propto p_e E(E-E_0)^2\left[1-\frac{m_\nu^2}{(E-E_0)^2}\right]^{1/2}$$

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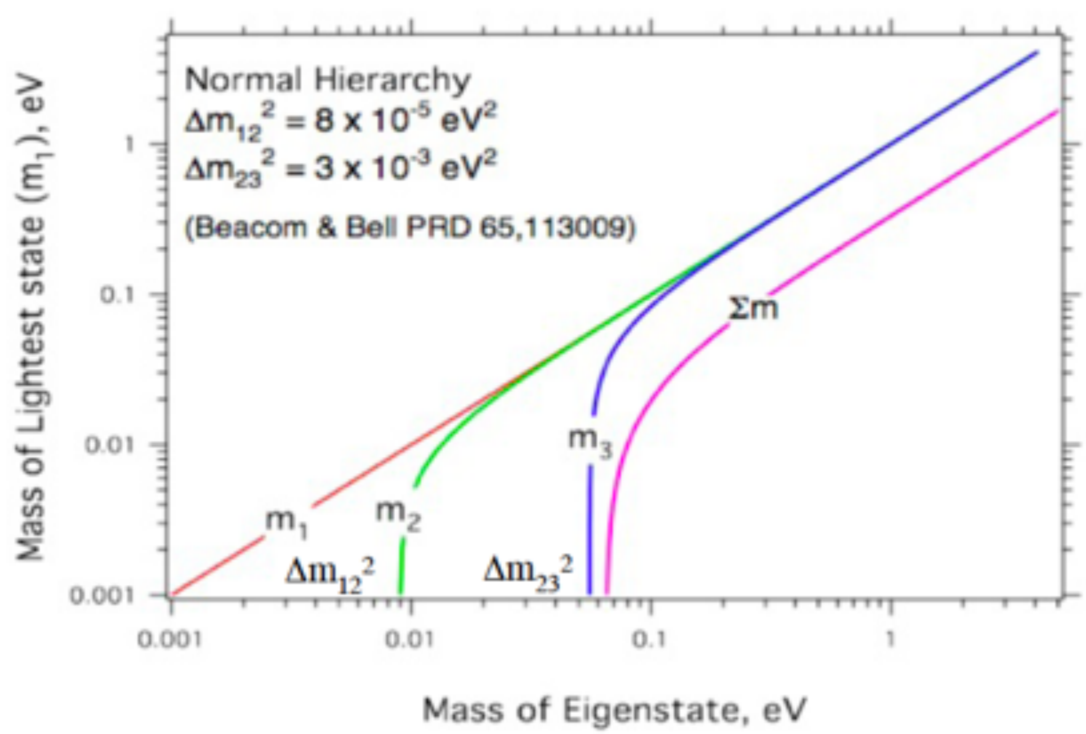
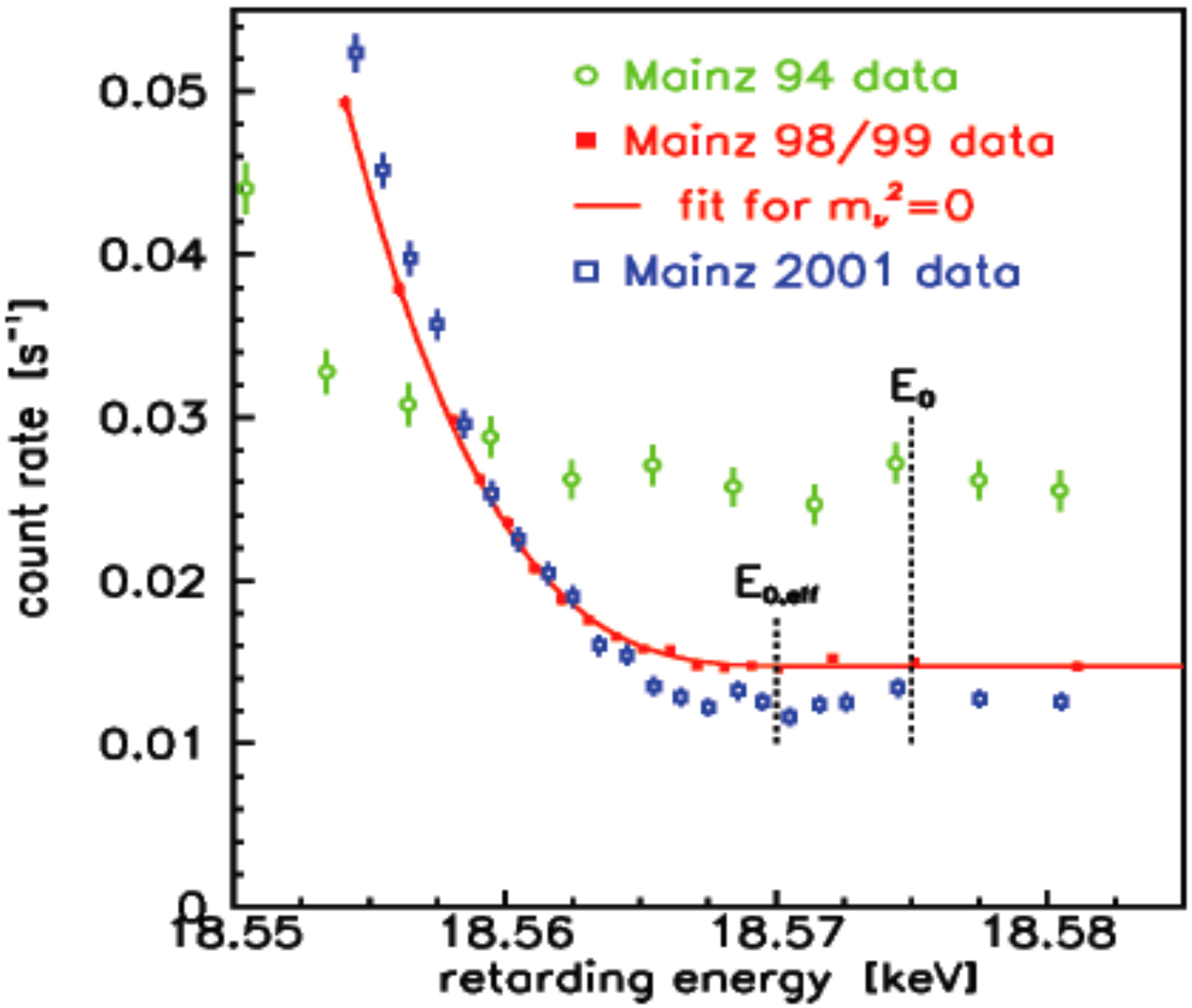


$$m_\beta = \left[\sum_i |U_{ei}|^2 m_i^2 \right]^{\frac{1}{2}}$$

Final Mainz Result -- Kraus et al. hep-ex/0412056



Improved S/N tenfold over 1994 data

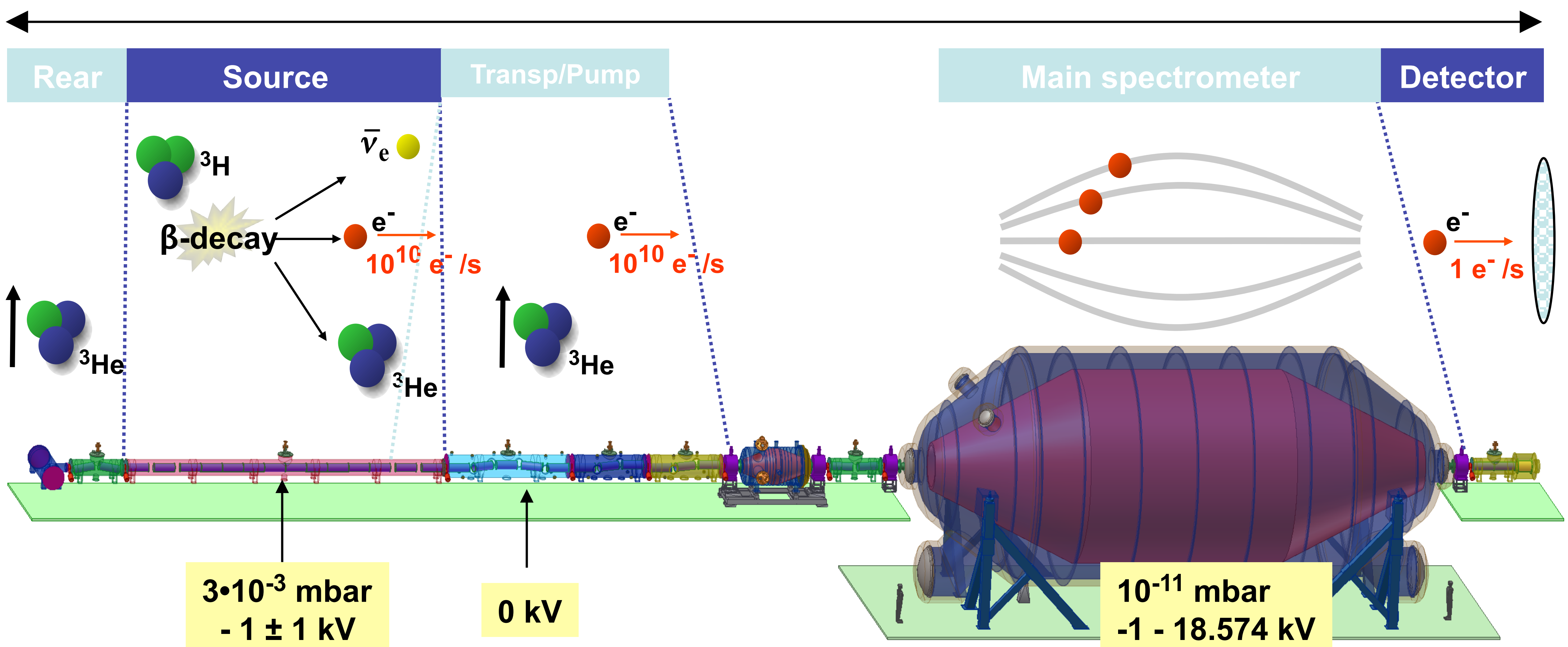
20 weeks of data in 1998, 1999, 2001

Stable background: pulsed RF clearing field applied at 20-s intervals

$$m^2(\nu_e) = (-0.6 \pm 2.2_{\rm stat} \pm 2.1_{\rm syst})\ {\rm eV}^2/{\rm c}^4$$
$$\chi^2/{\rm d.o.f.} = 208/194$$

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

The KArlsruhe TRItium Neutrino (KATRIN) Experiment



Rear System: Monitor source parameters

Source: Provide the required tritium column density

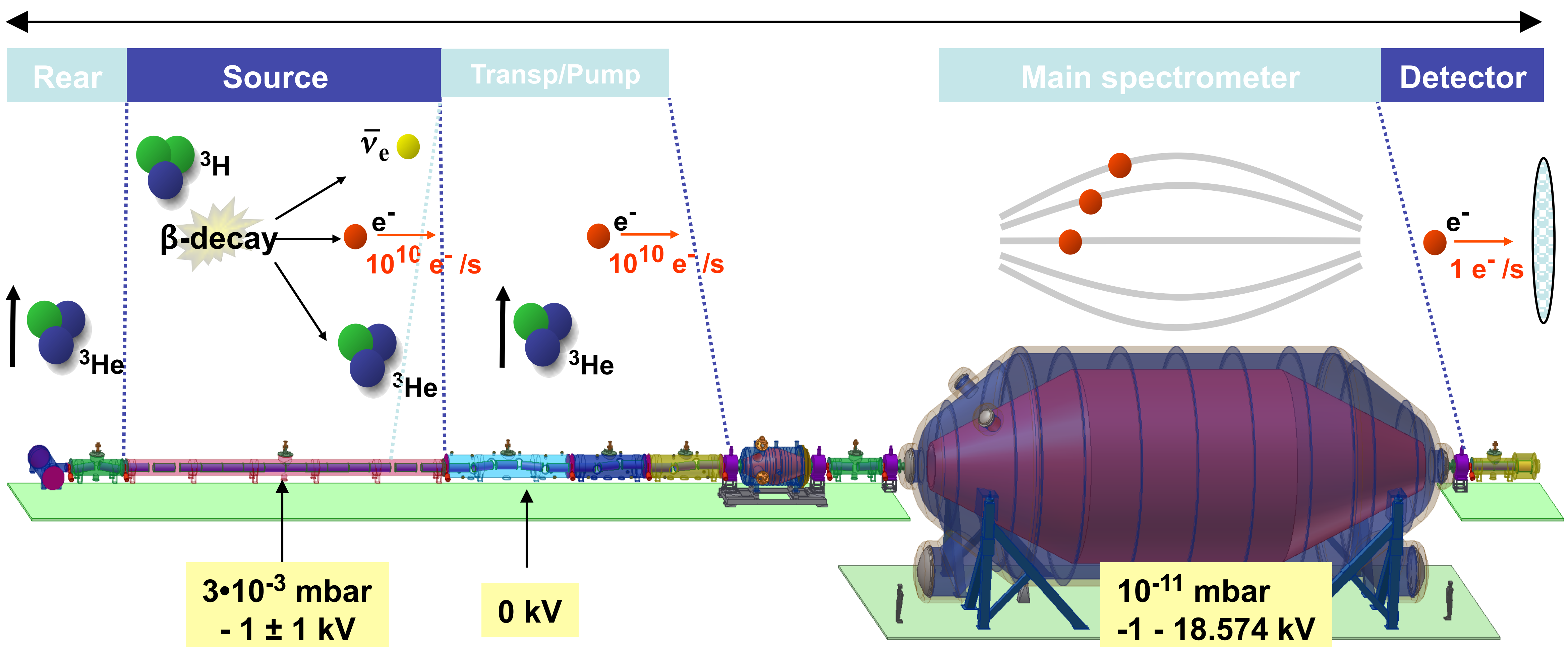
Transp. & Pump system: Transport the electrons, adiabatically and reduce the tritium density significantly

Main-spectrometer: Rejection of electrons below endpoint and adiabatic guiding of electrons

Detector: Count electrons and measure their energy

The KArlsruhe TRItium Neutrino (KATRIN) Experiment

- Next generation experiment, with goal of measurement down to 0.2 eV (100x improvement in energy resolution!)



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Voyage of the KATRIN Main Spectrometer

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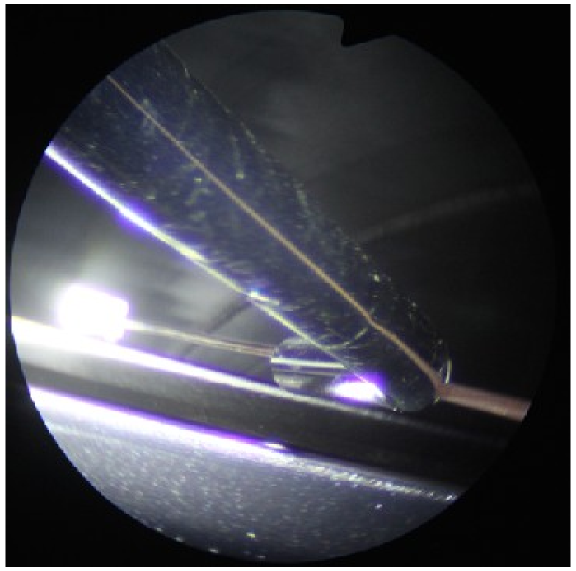
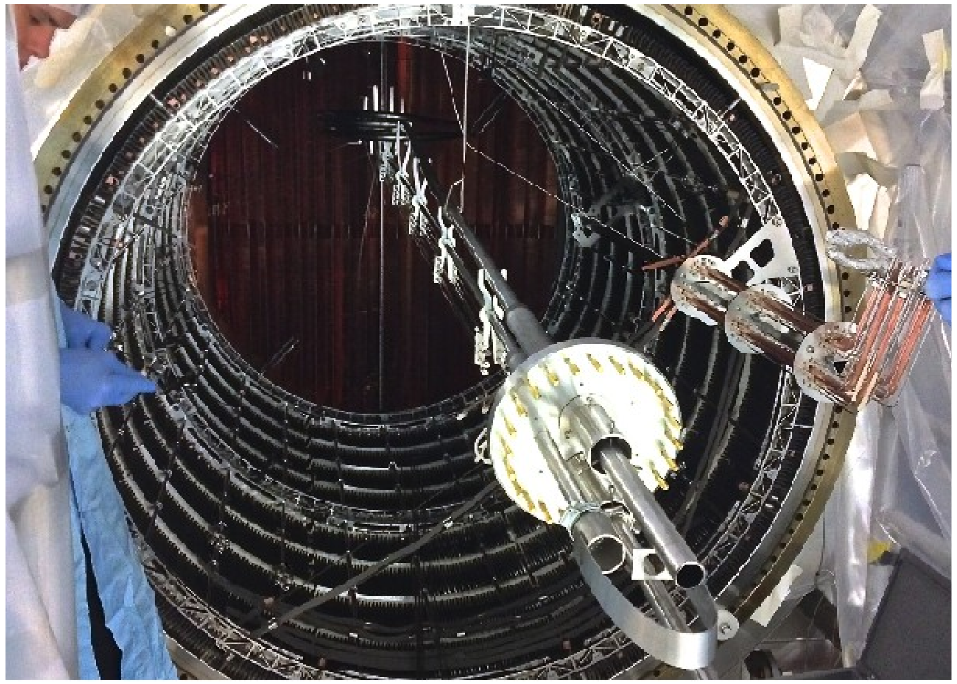
Status of KATRIN

- Commissioning spectrometer & detector phase 2 Q3+4/2014

* dual layer wire electrode (in central part at least)
* better egun
* better alignment
* better high voltage settings
* full magnetic zeroing
* full operational LN_2 baffles
* electrical heated NEG pumps





Weinheimer - Neutrino 2014

- Tritium retention units DPS and CPS functional Q2/2015

- Tritium source WGTS final mounting completed mid-2015

- Spectrometer upgrade completed Q3/2015

- All source elements & tritium loops integrated Q4/2015

- First tritium in source, ramp up to nominal ρd Q1-Q2/2016

- First tritium data with entire beam line mid-2016

Beyond KATRIN

Beyond KATRIN

- Two very interesting prospects (IMO):

Beyond KATRIN

$$^{163}_{67}\text{Ho} \rightarrow ^{163}_{66}\text{Dy}^{*} + \nu_e$$

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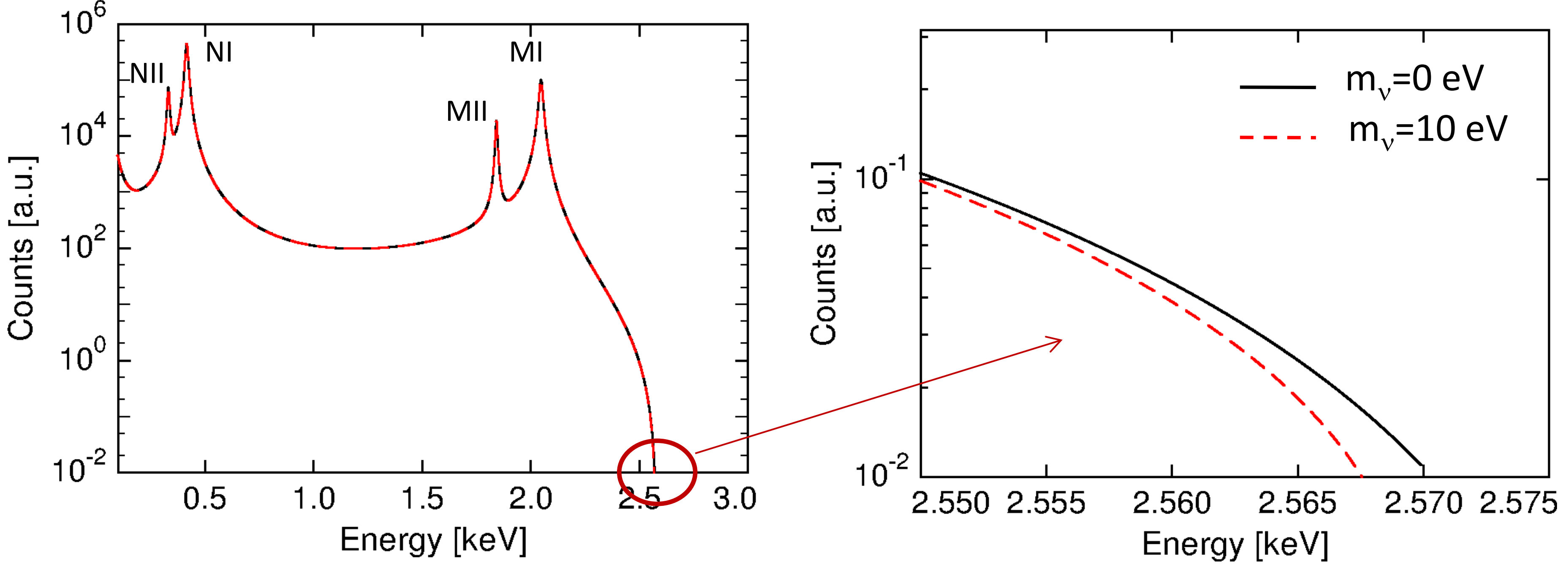
Gastaldo - Neutrin 2014



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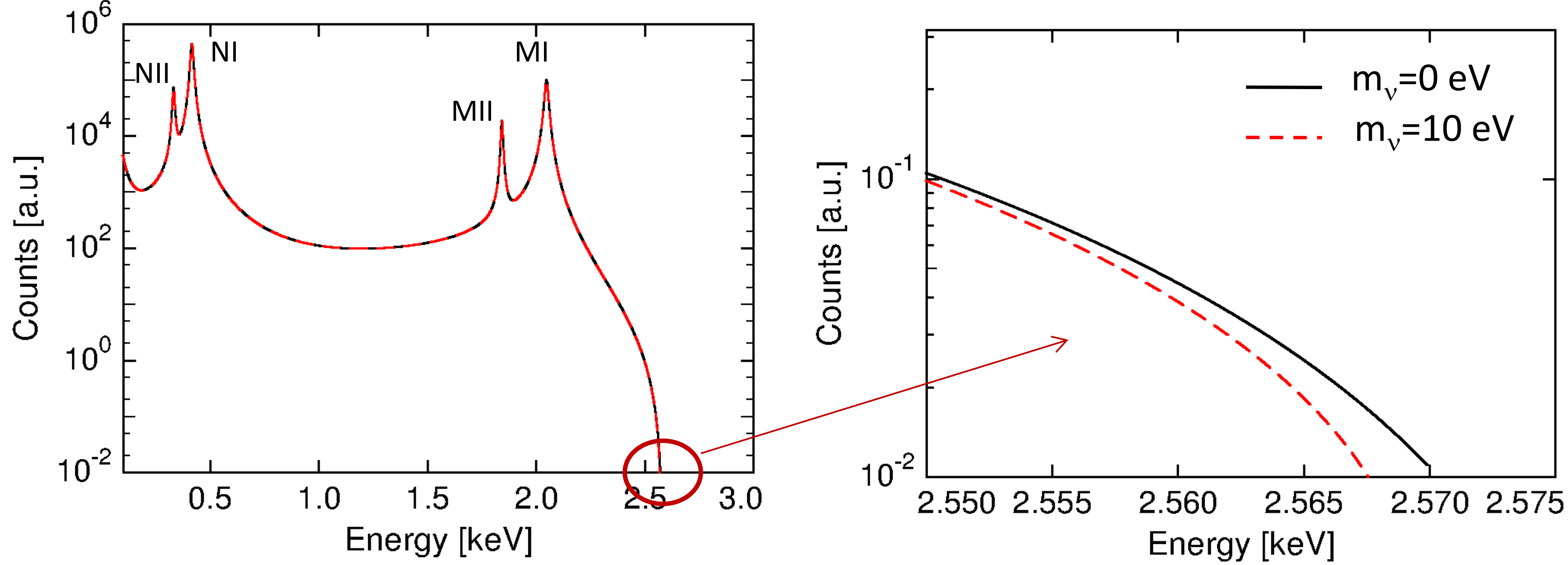

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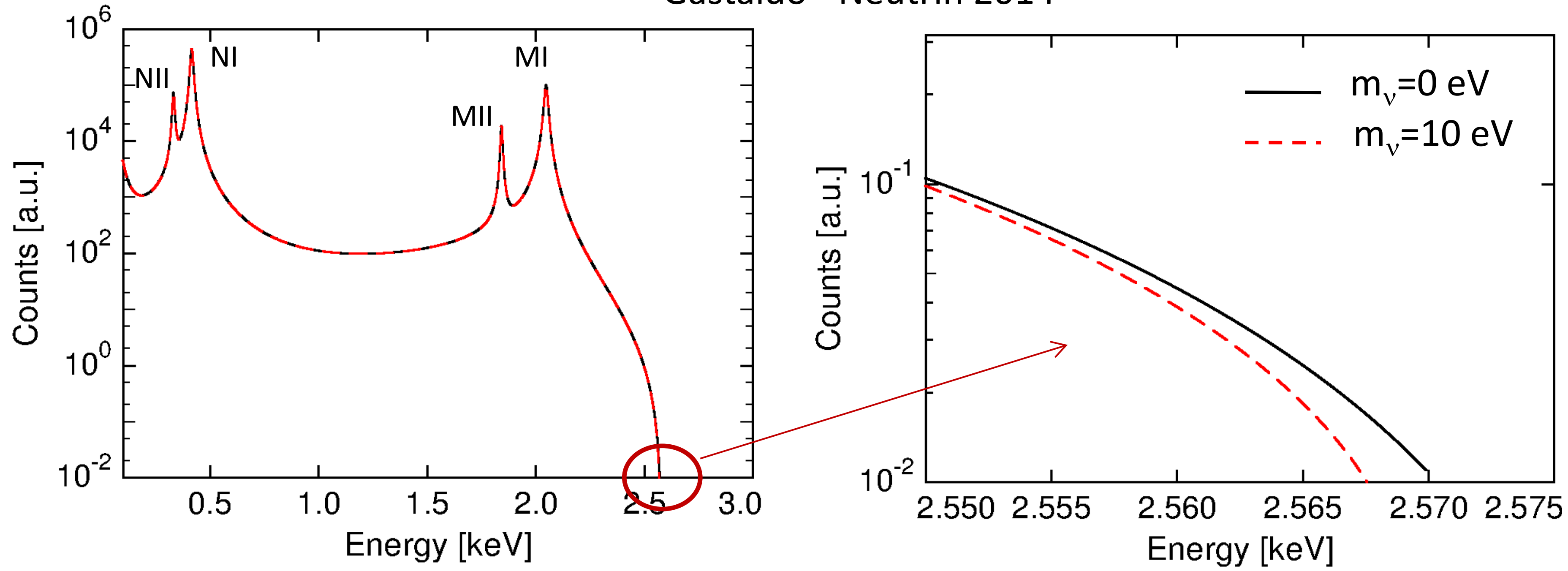

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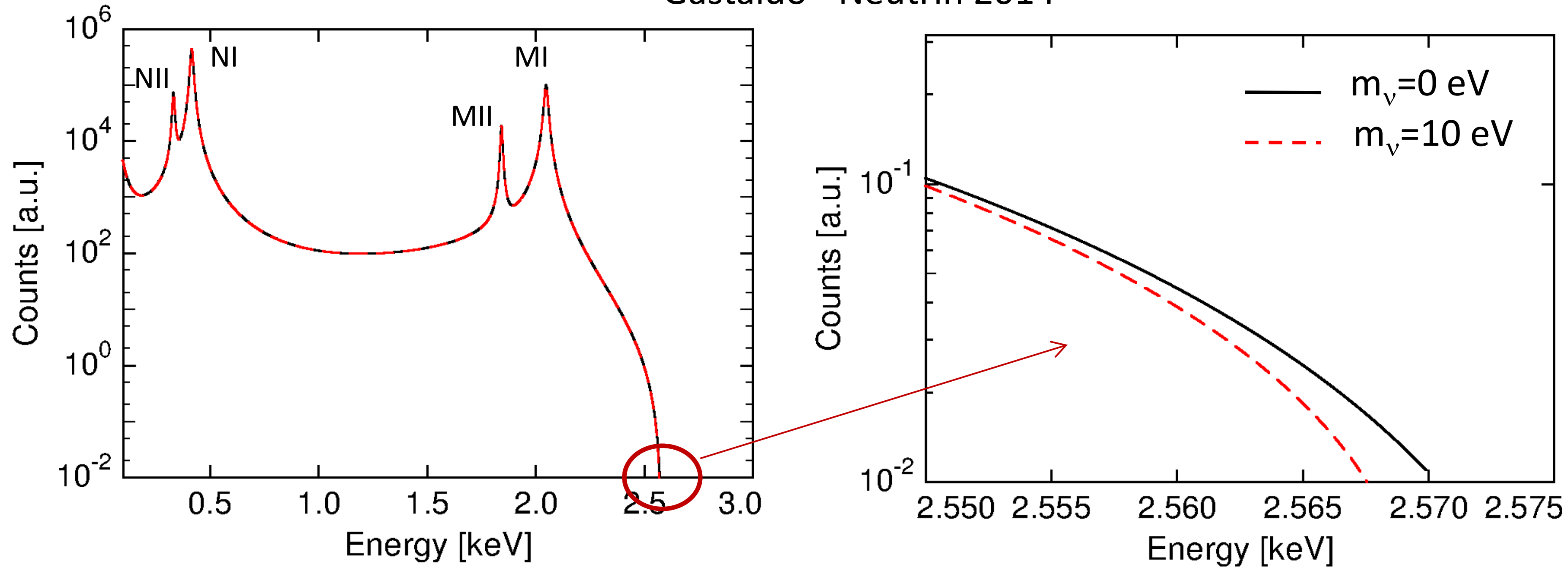

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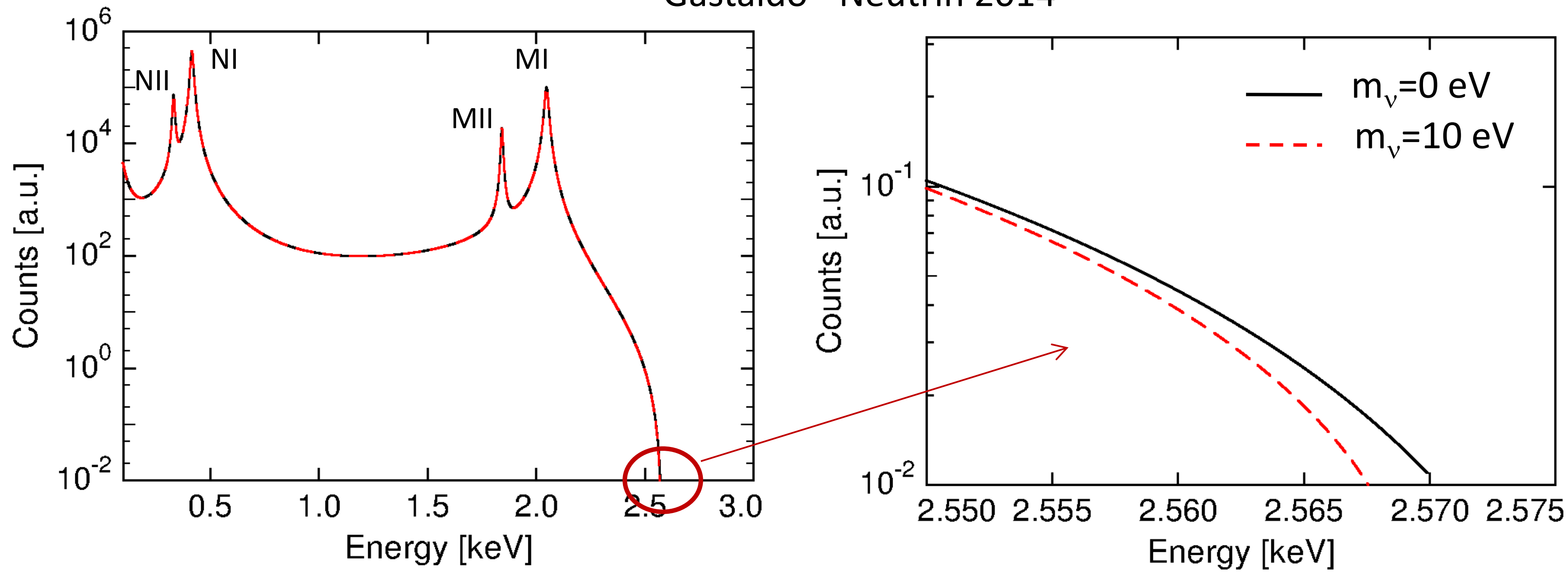

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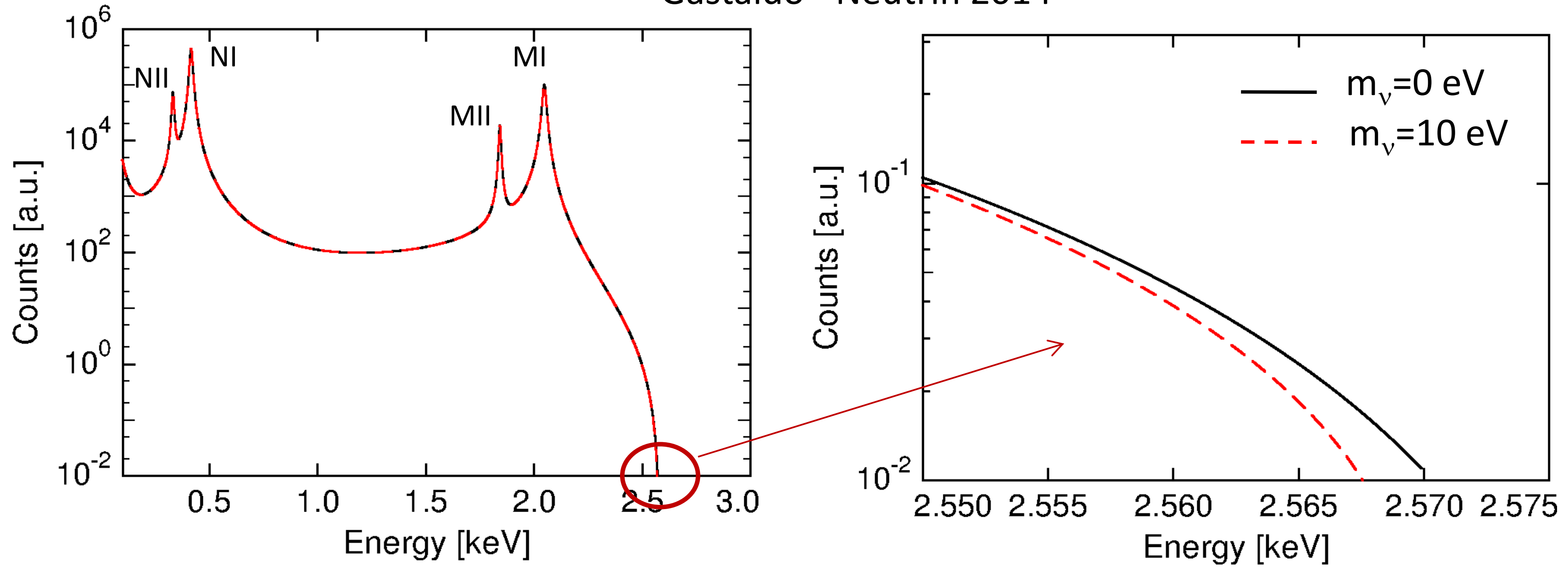

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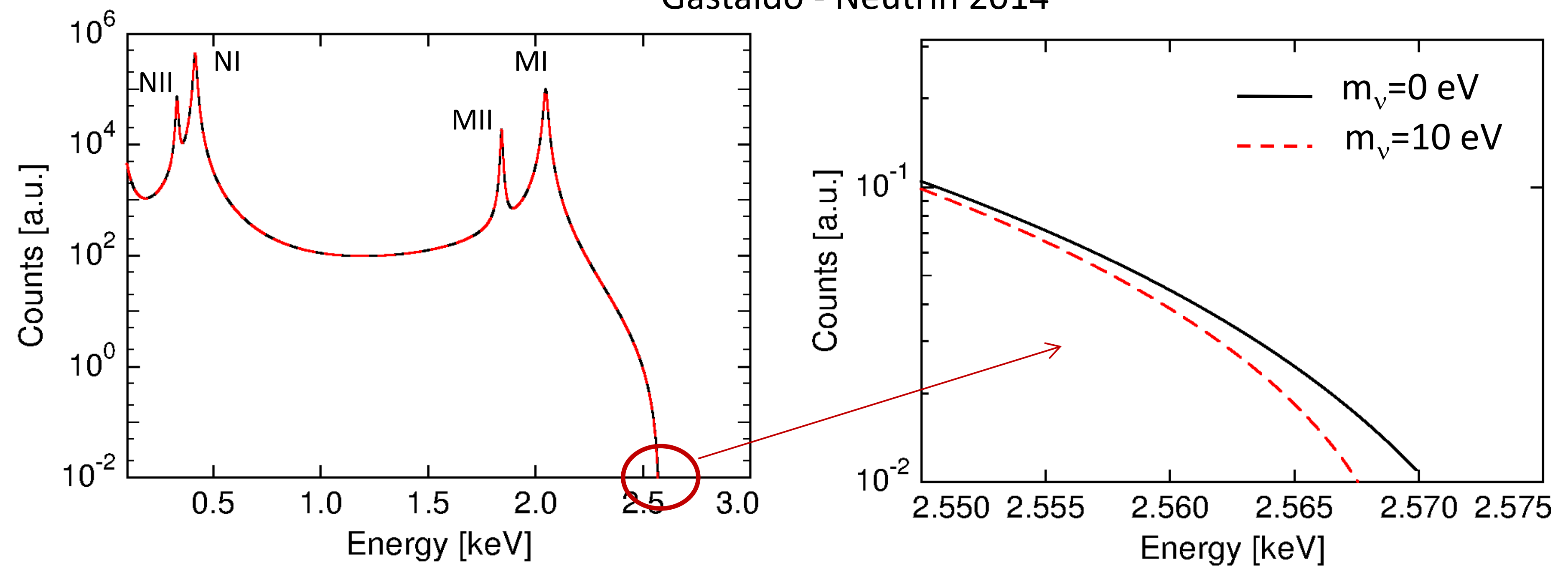

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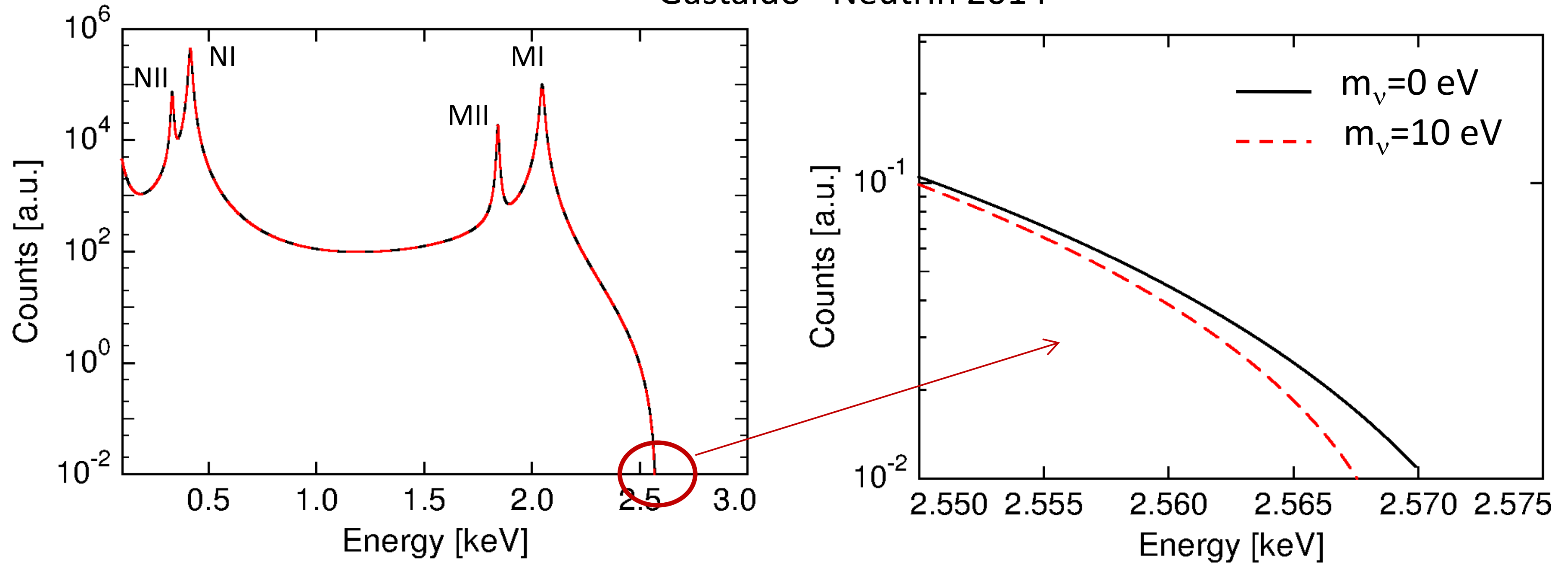

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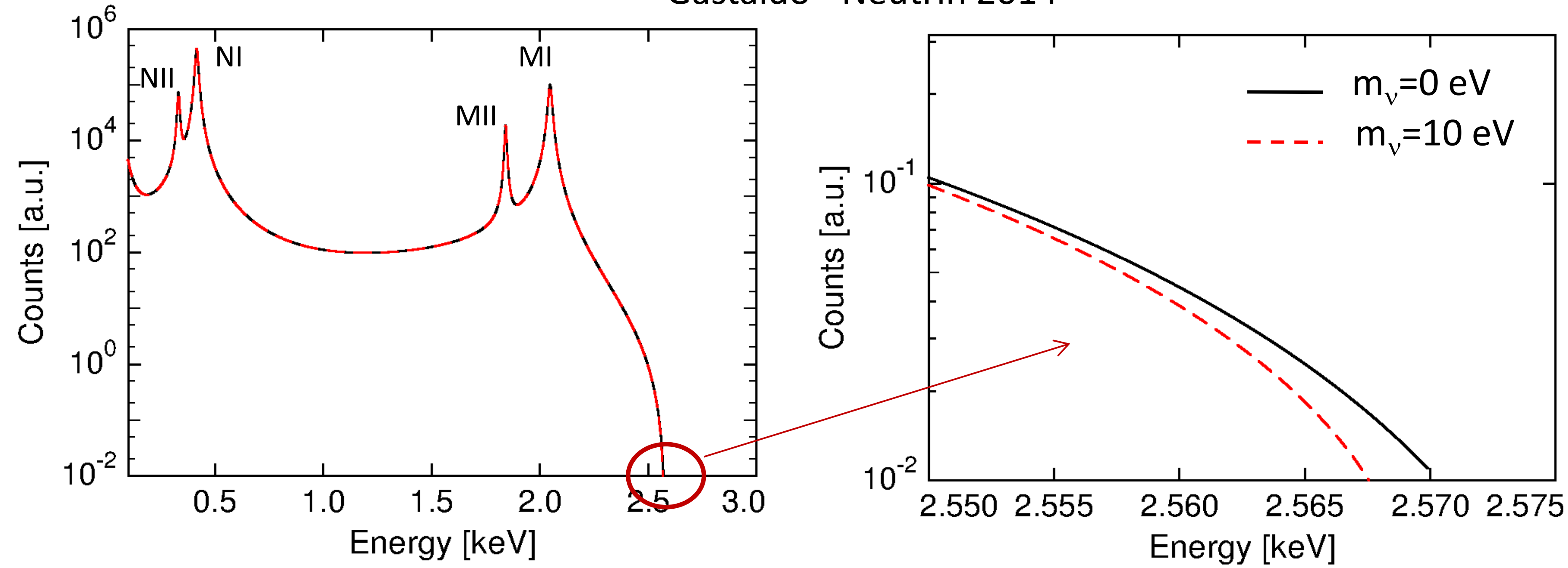

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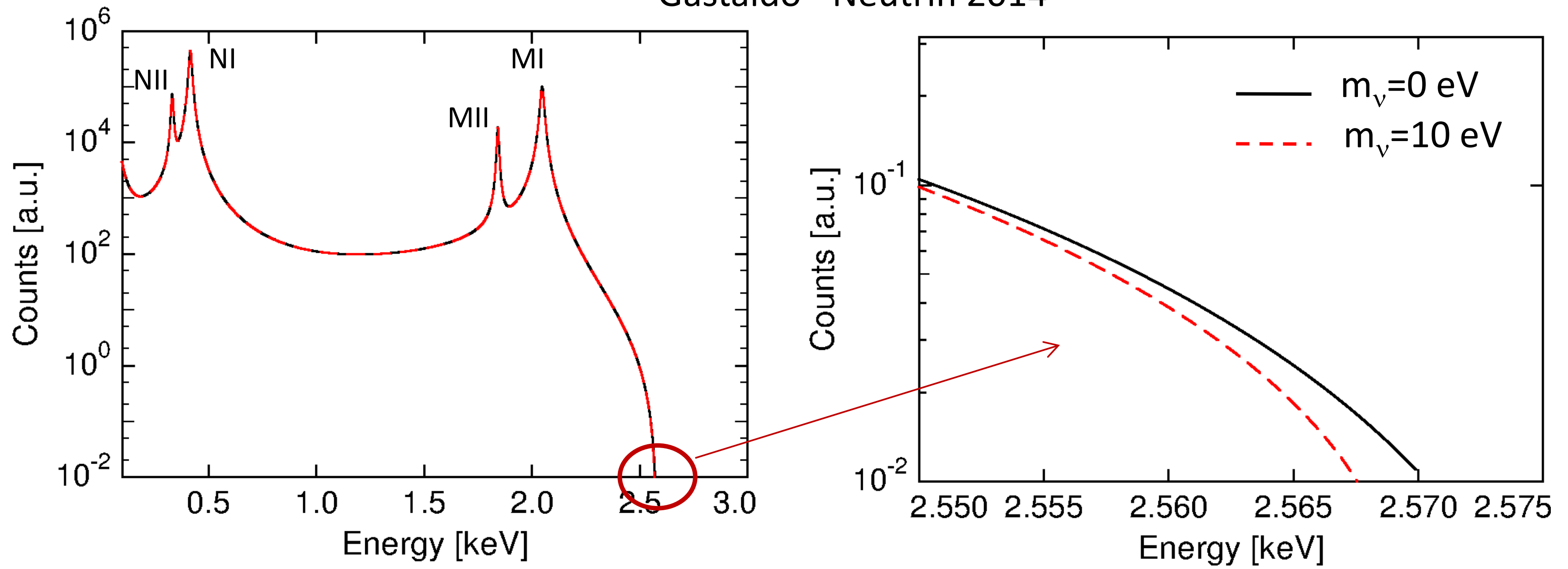

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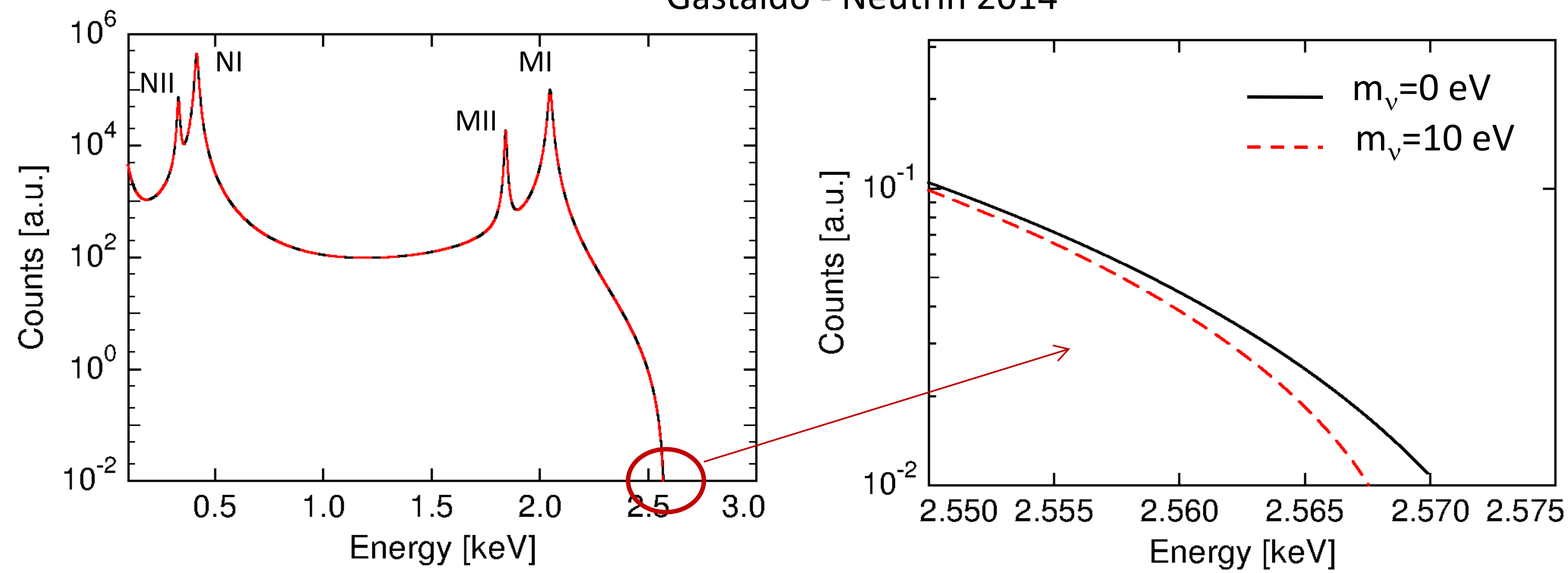

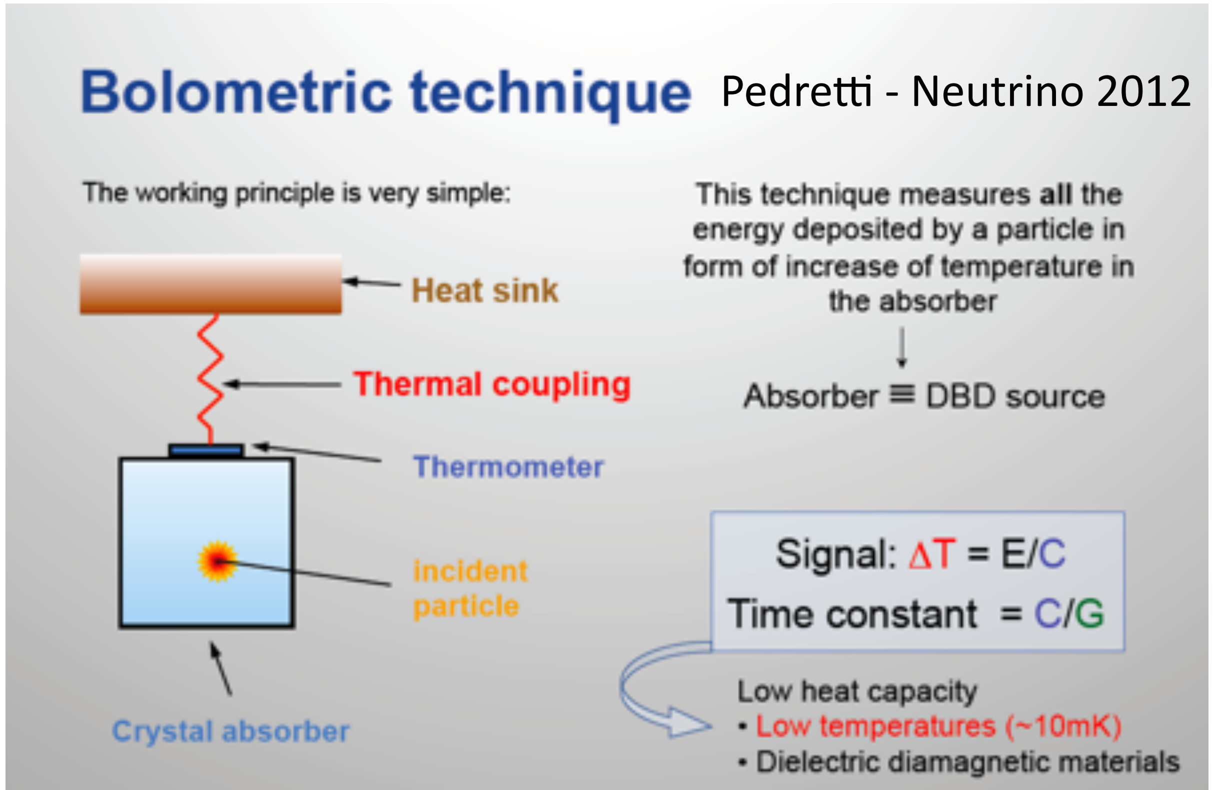

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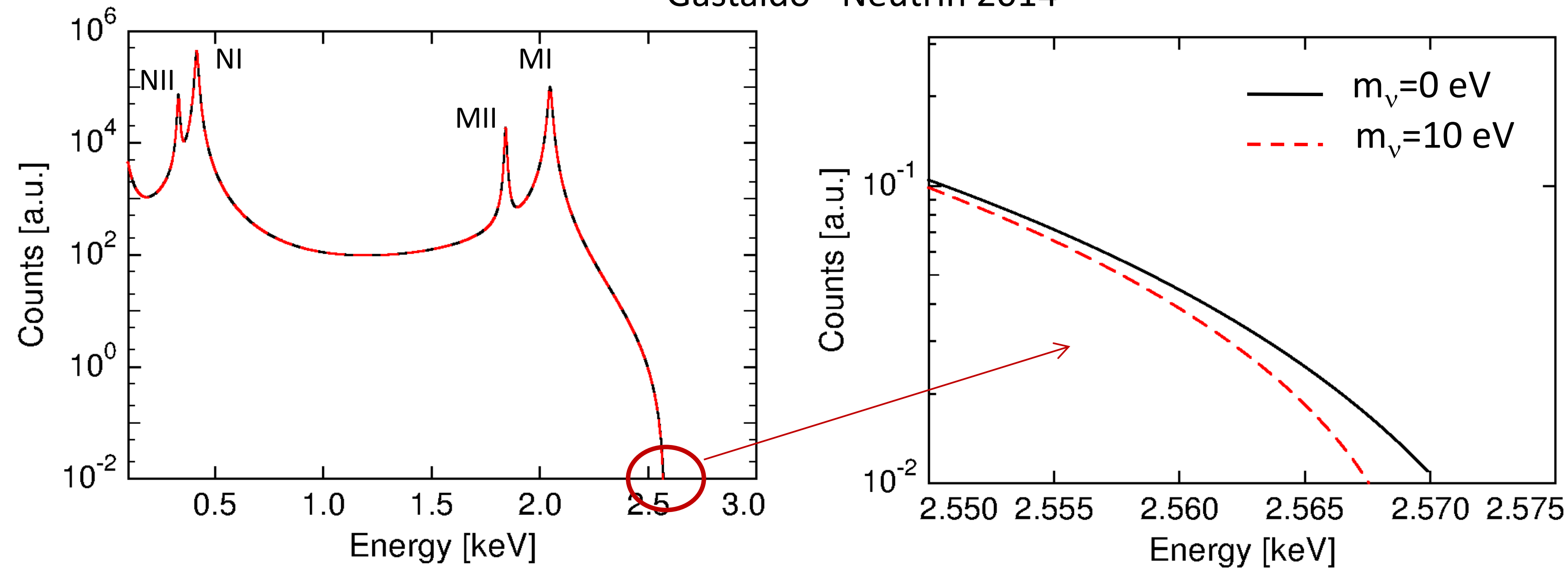

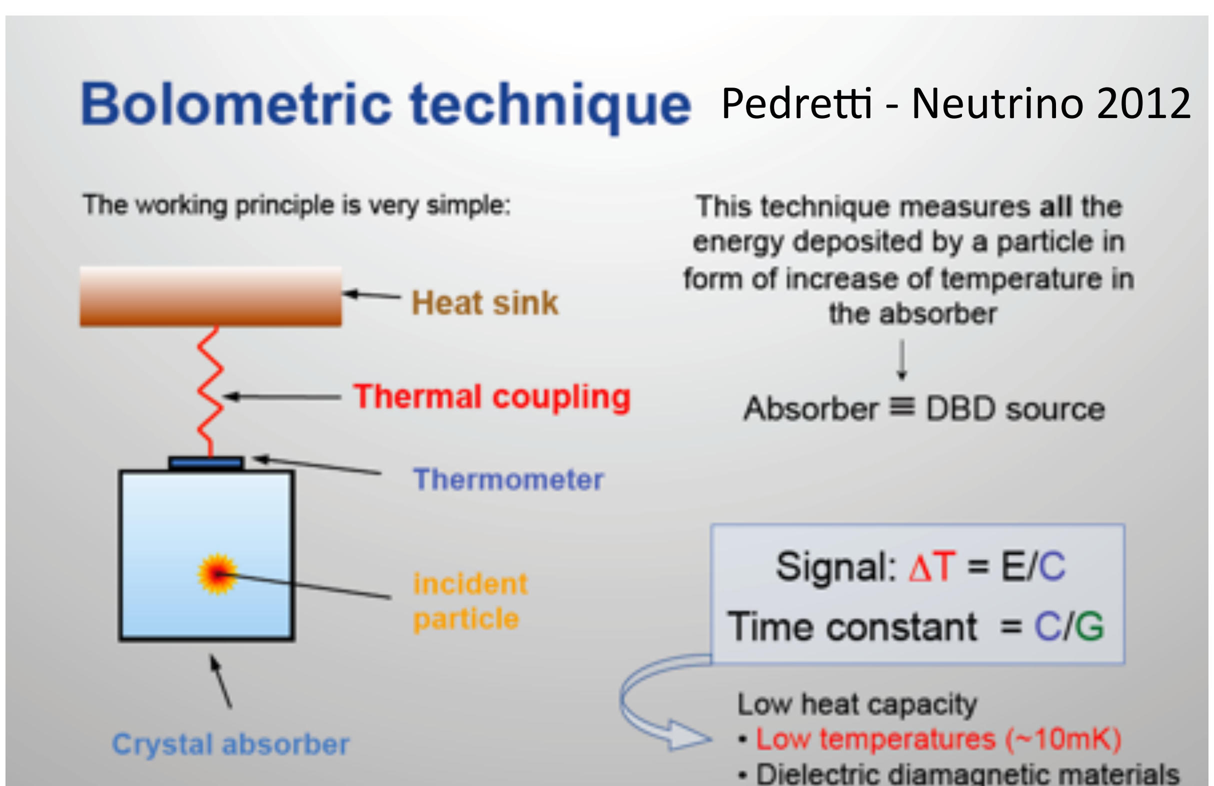

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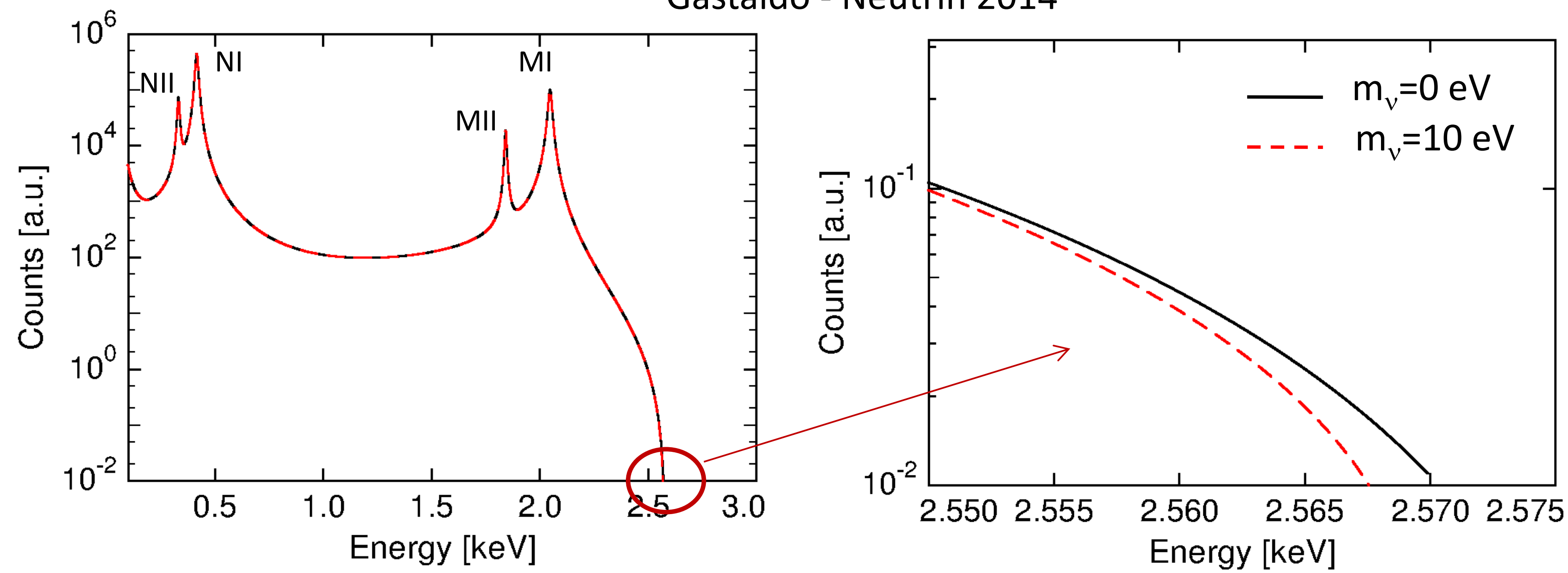

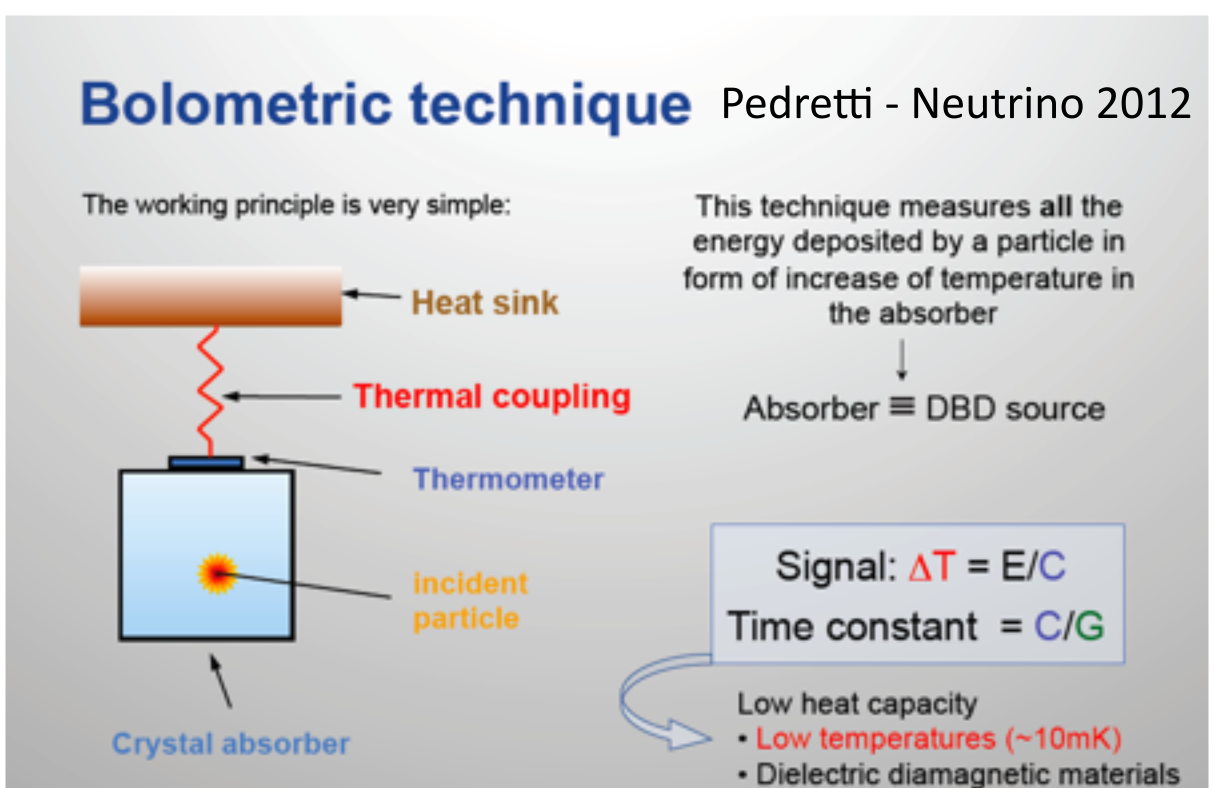

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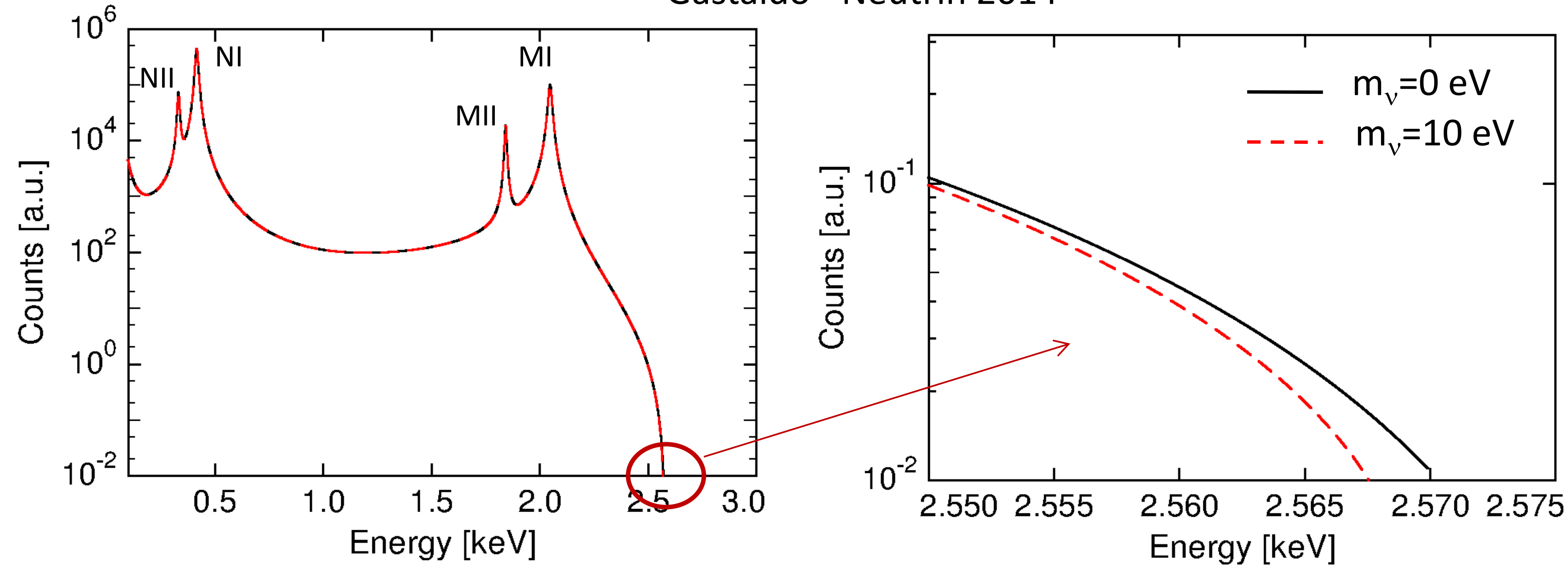

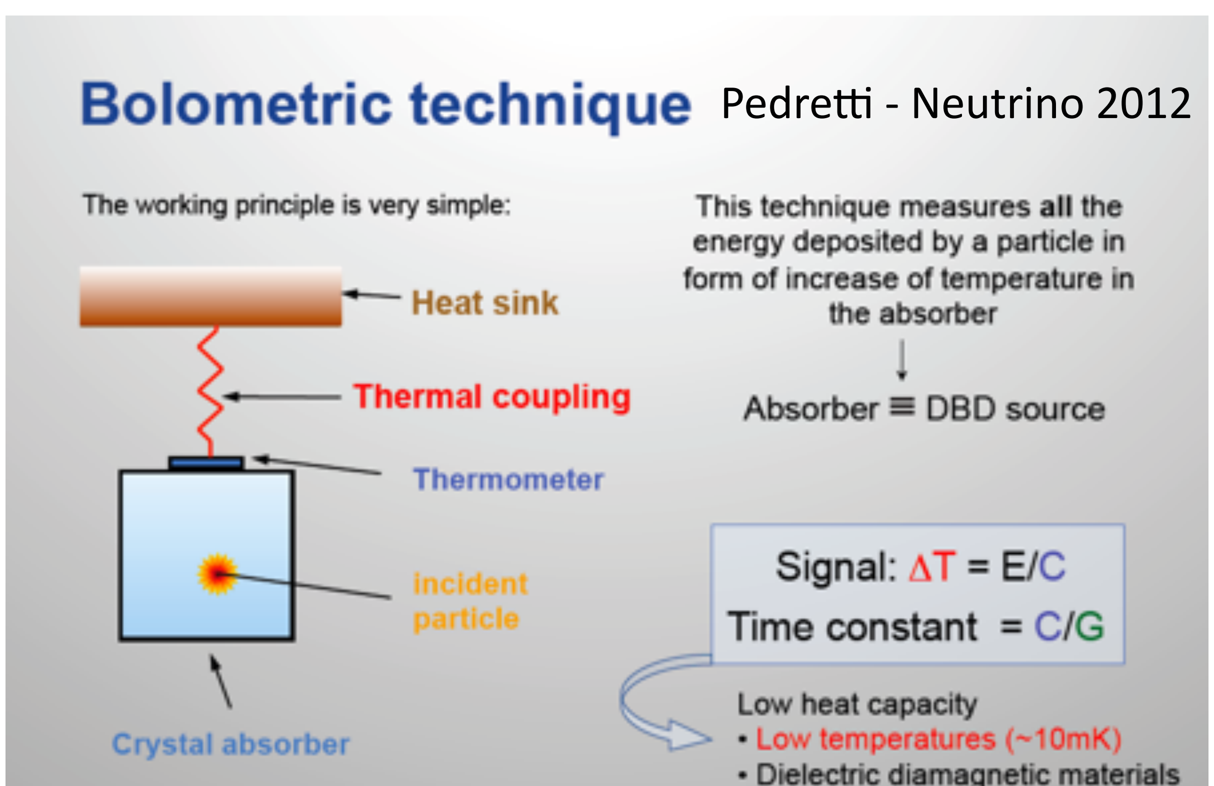

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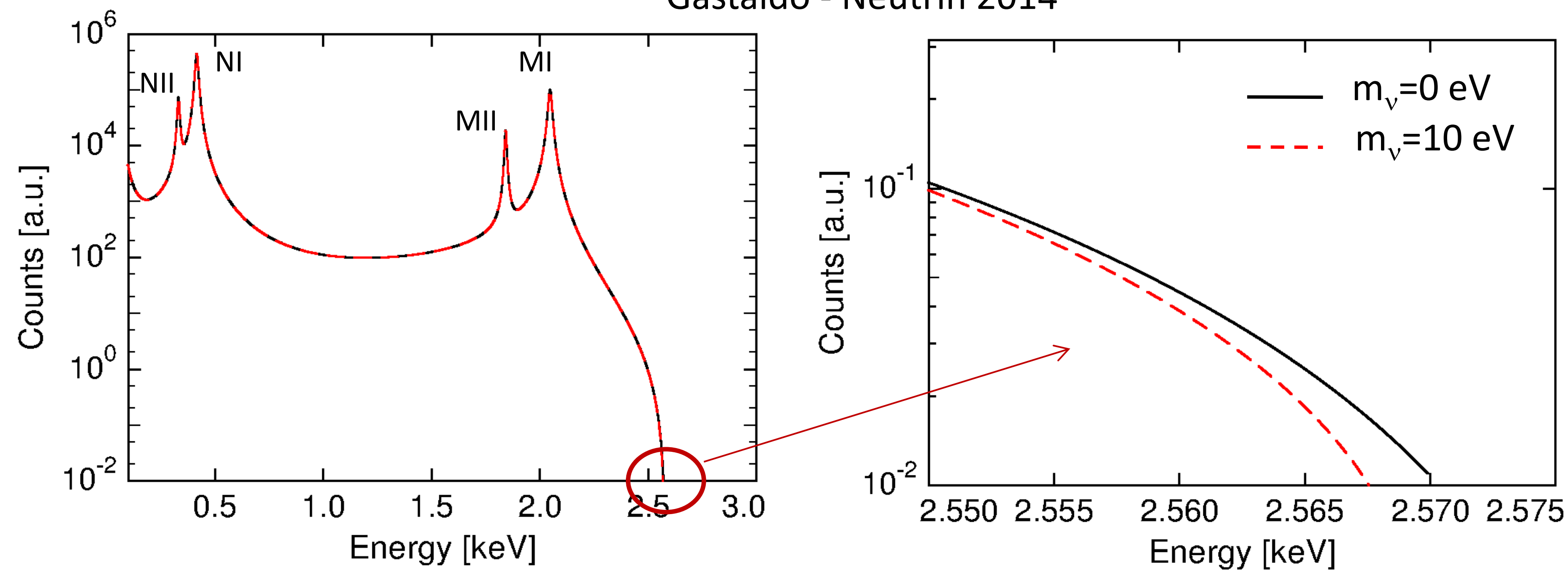

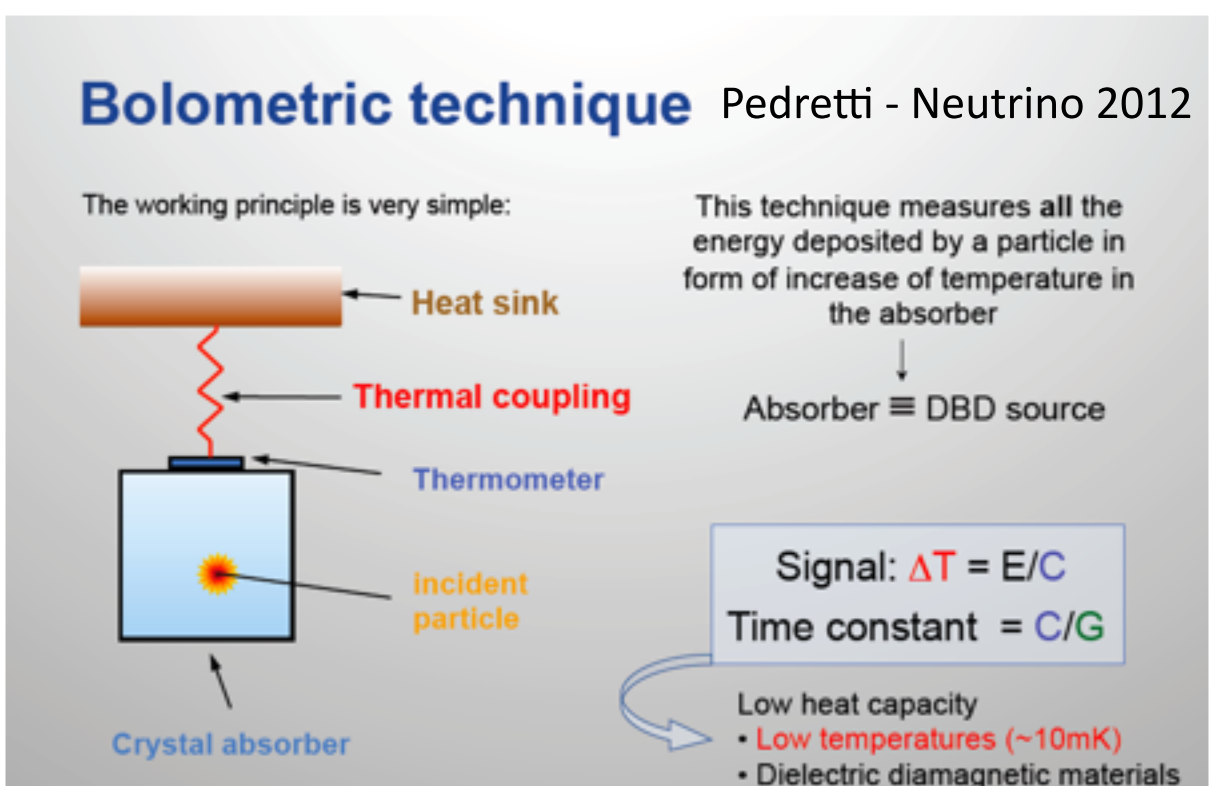

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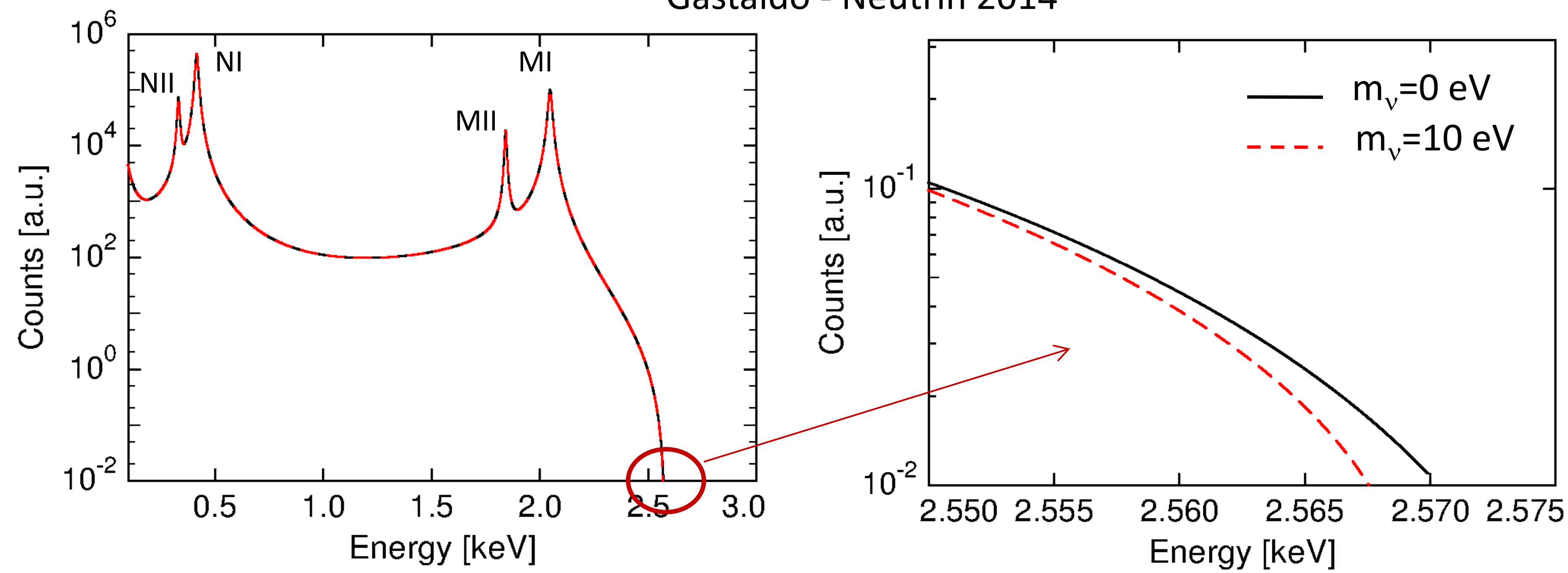

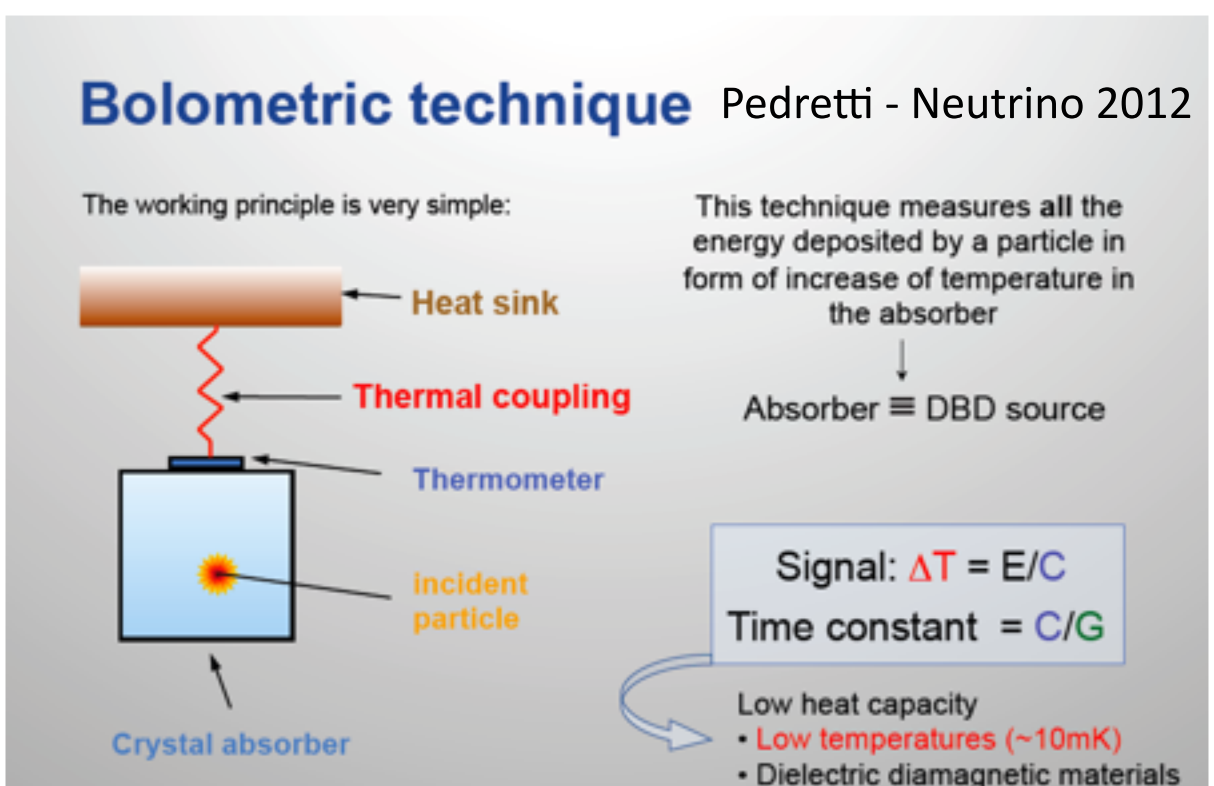

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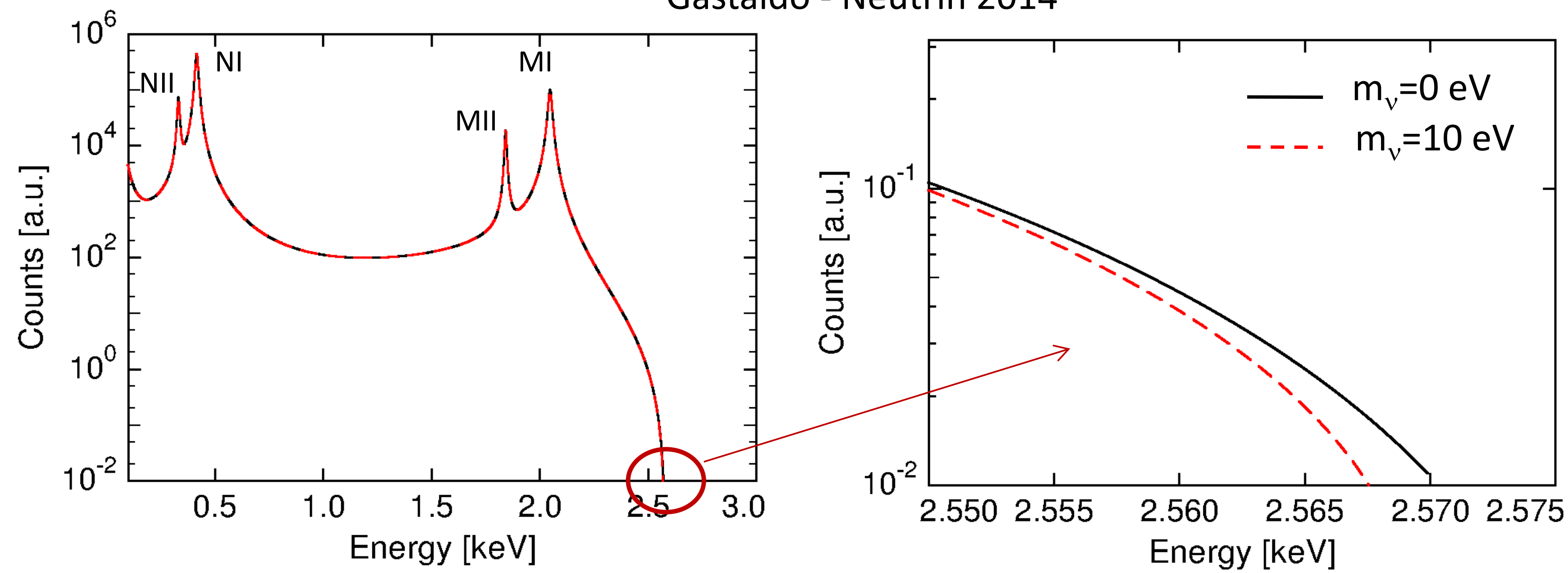

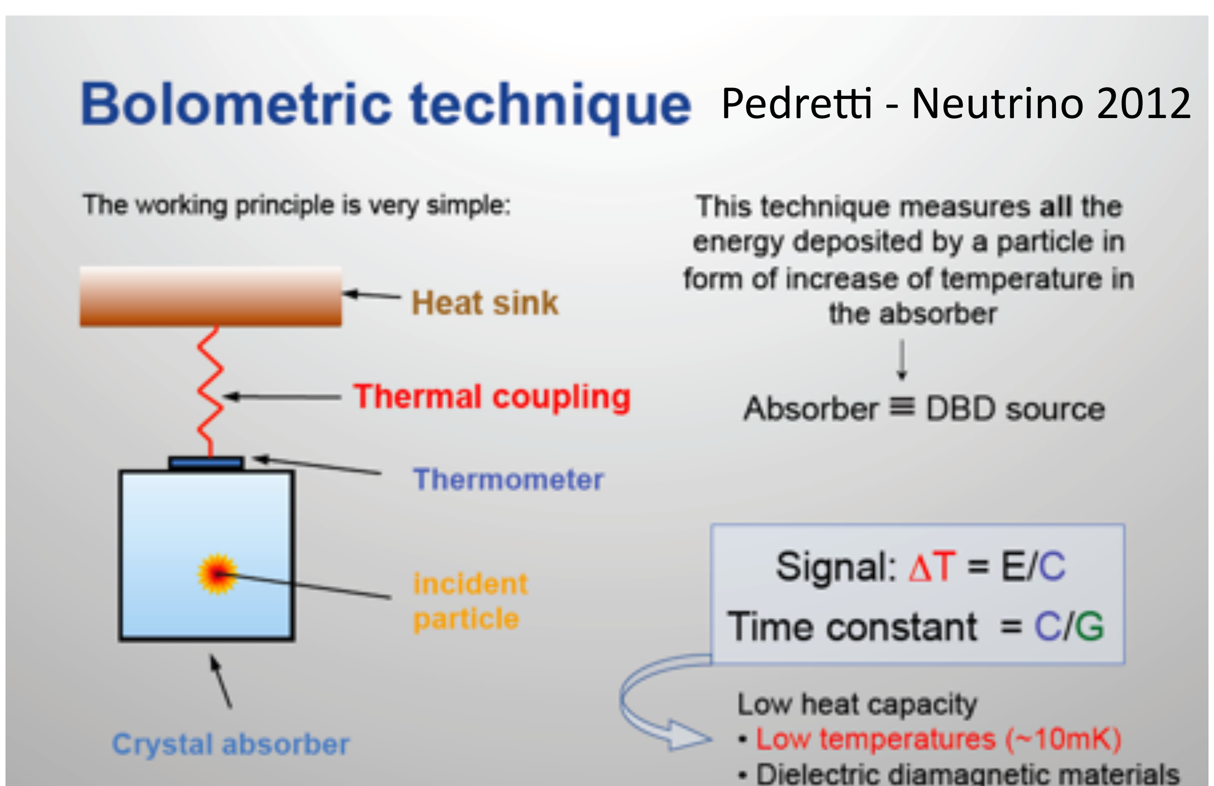

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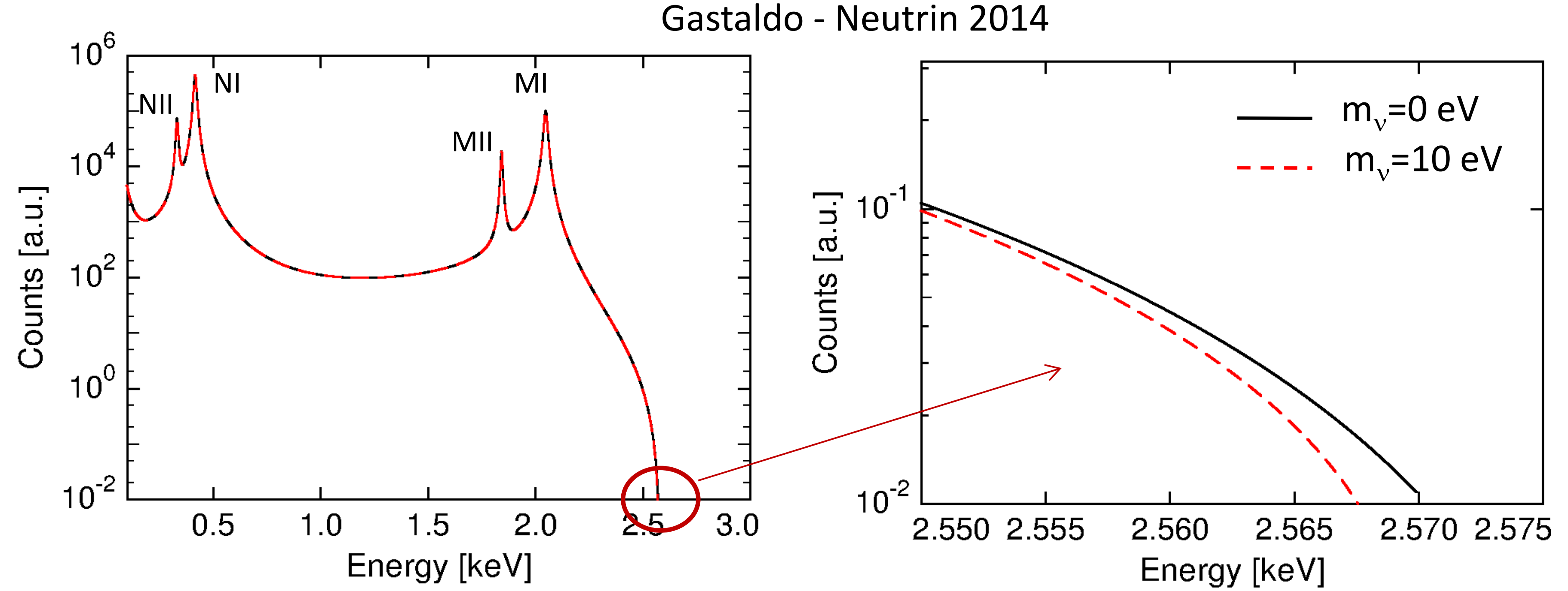

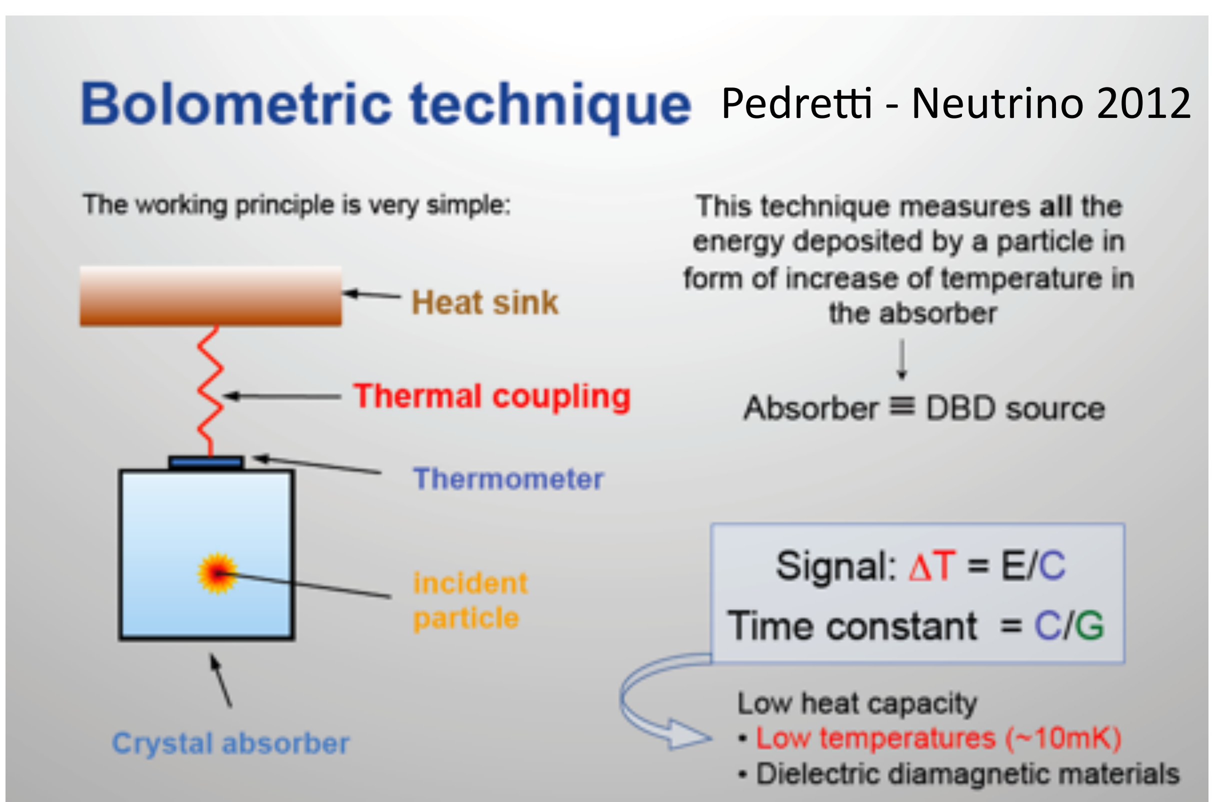

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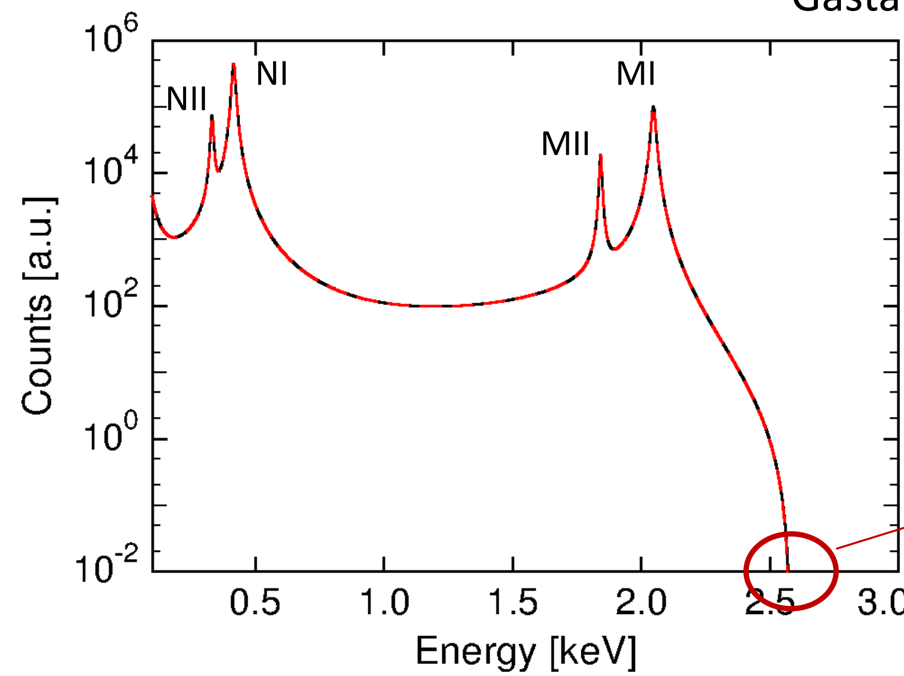

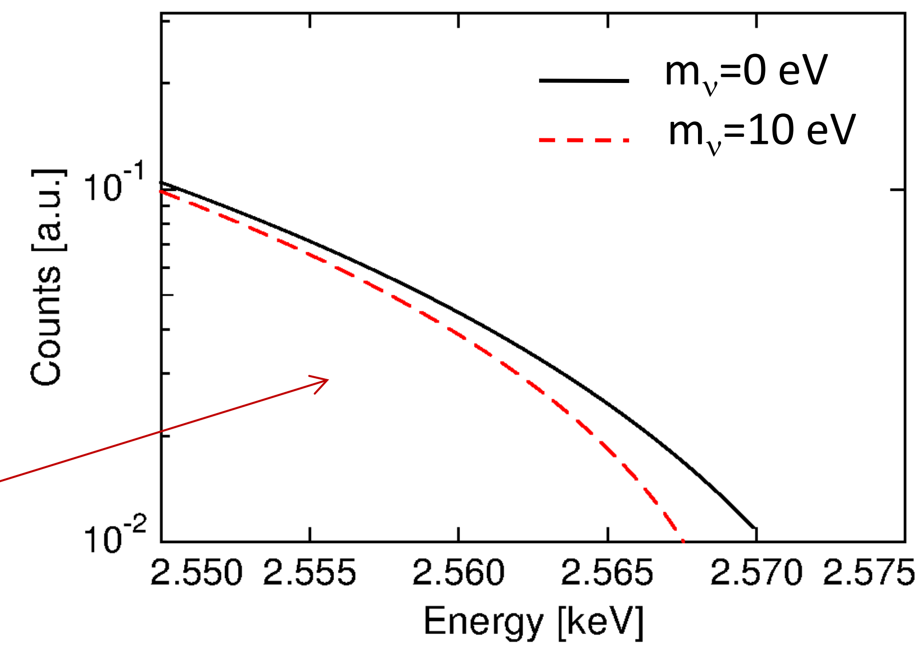

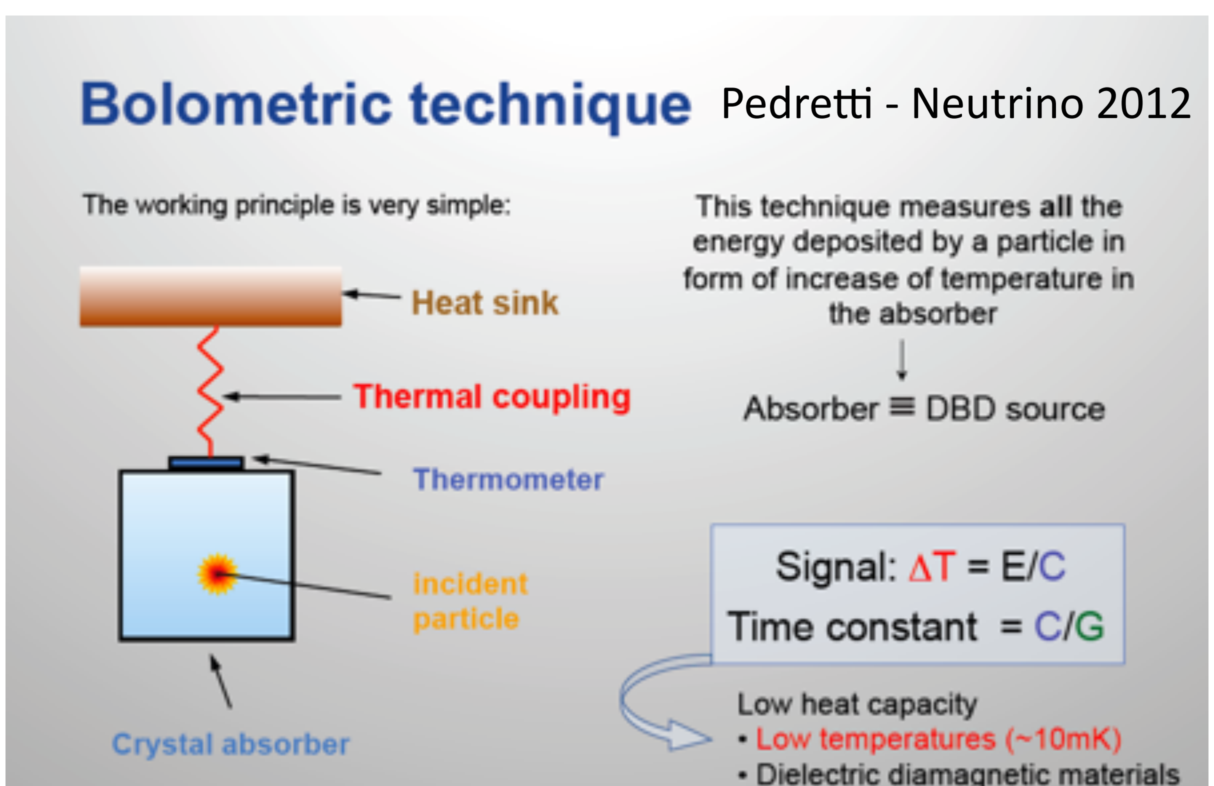

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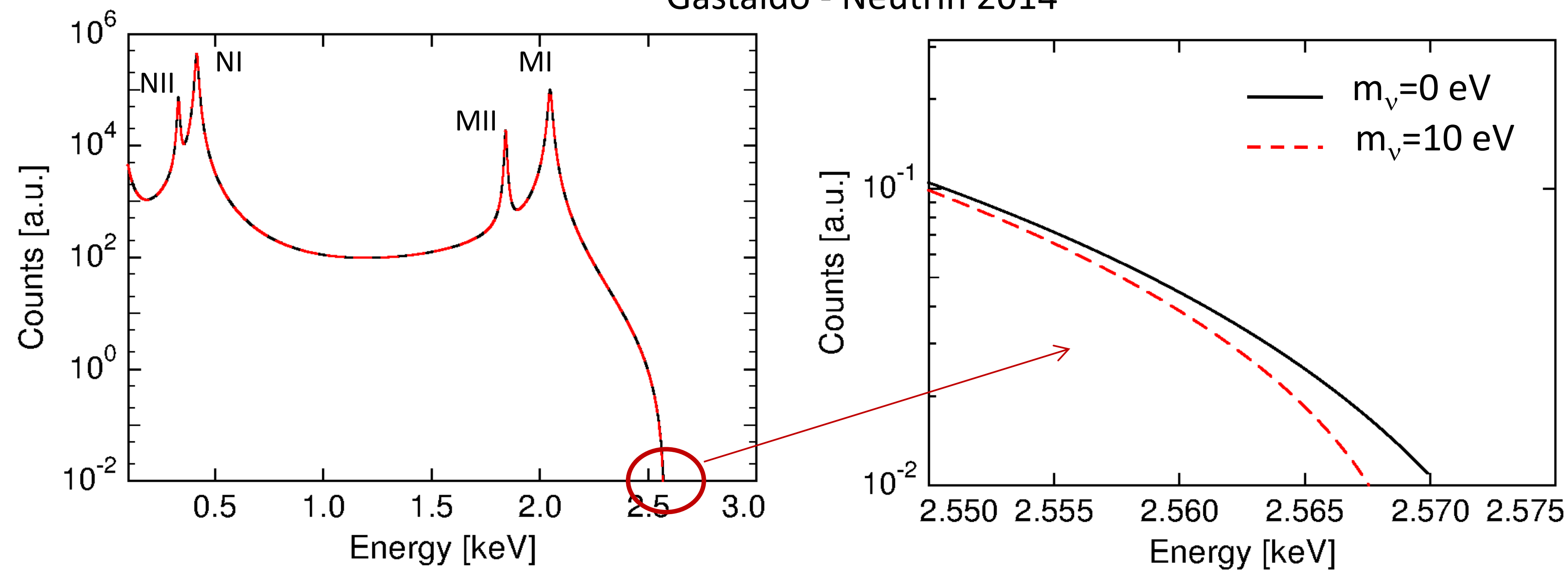

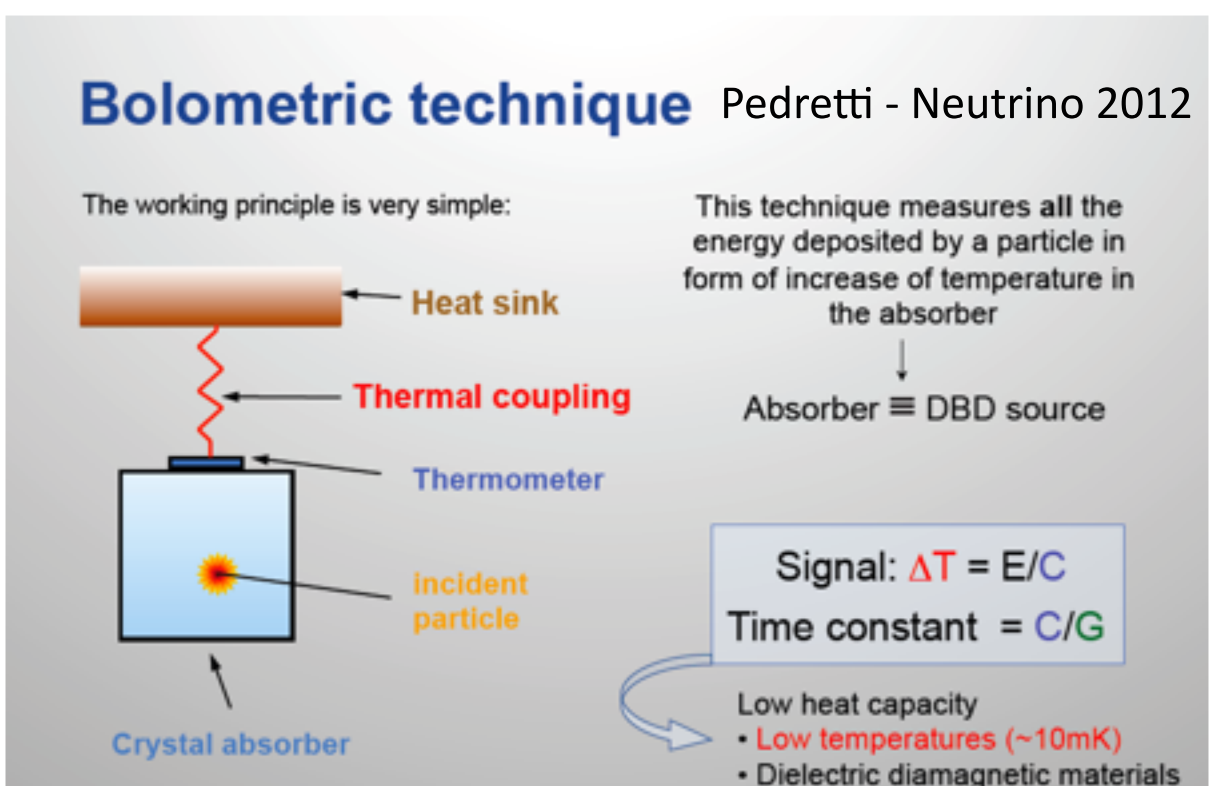

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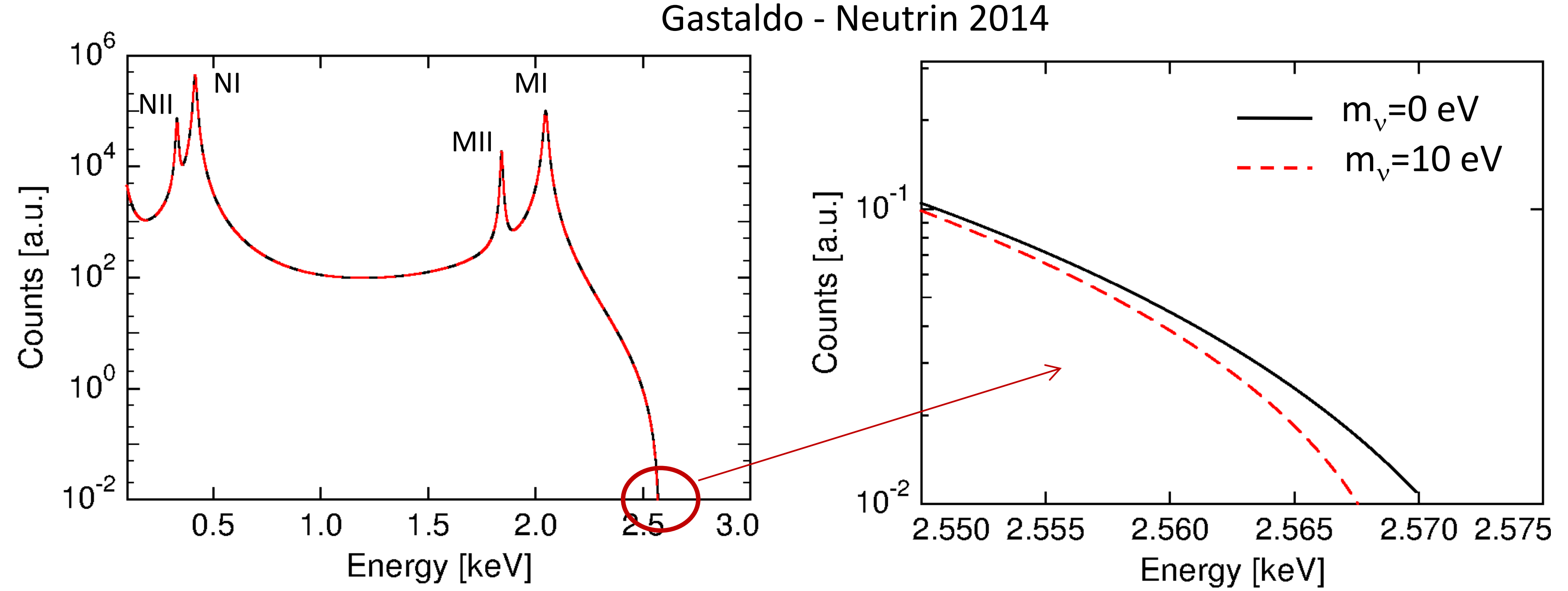

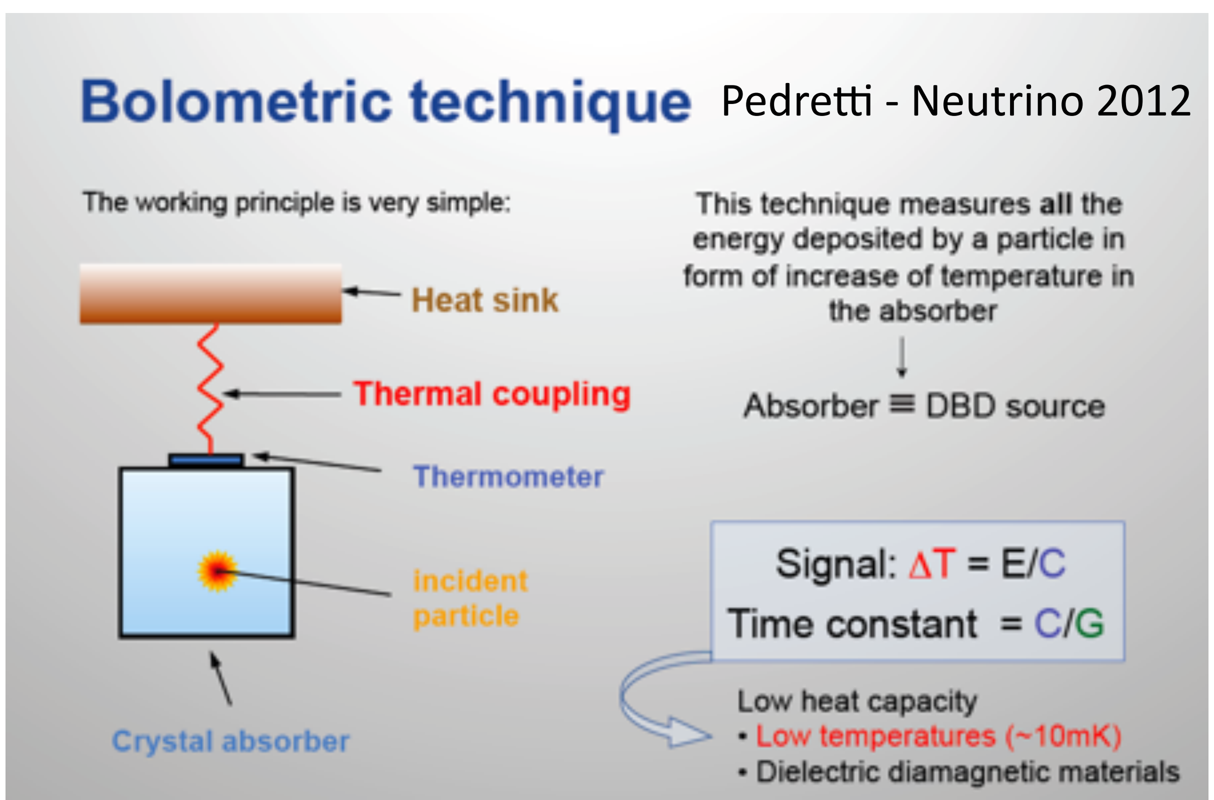

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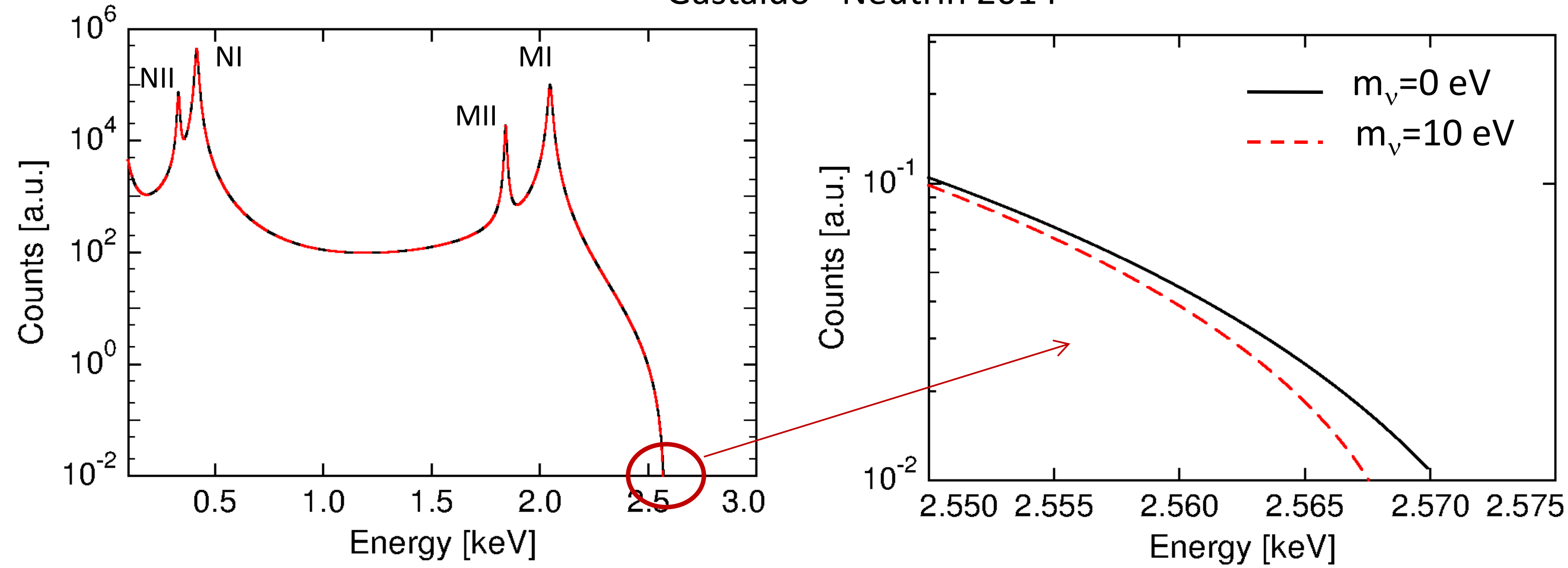

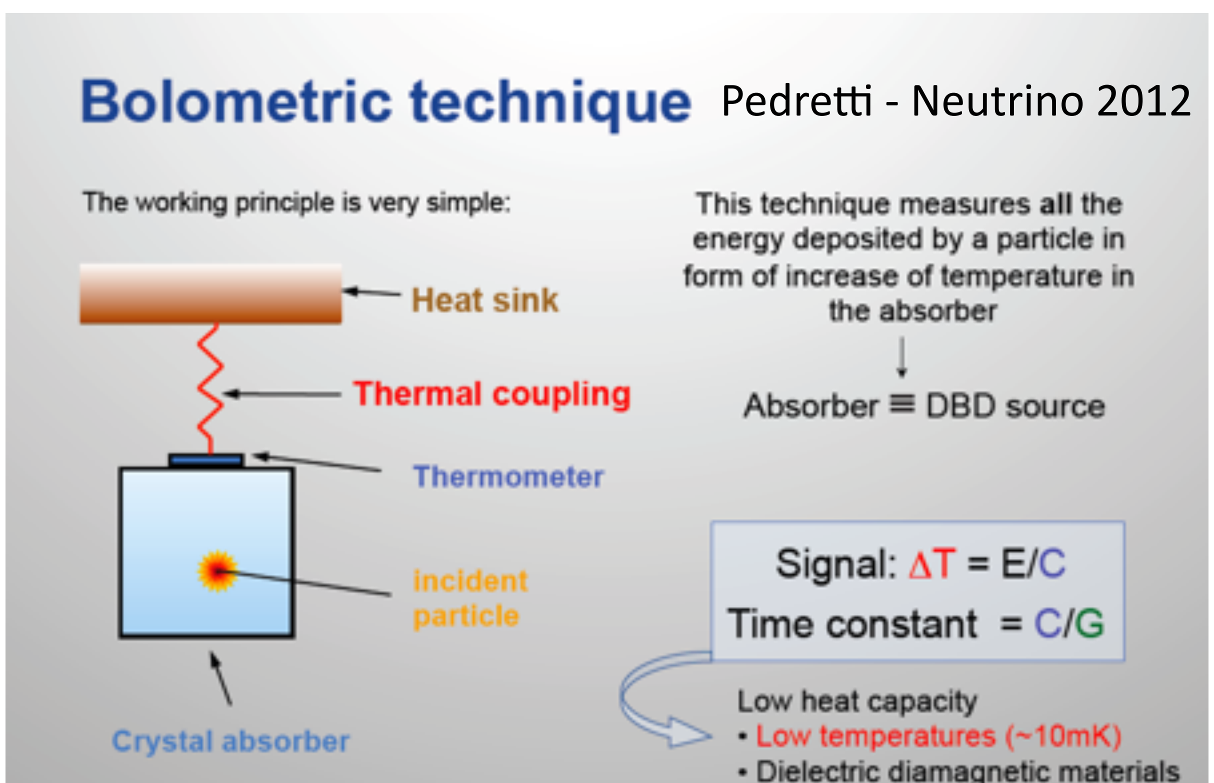

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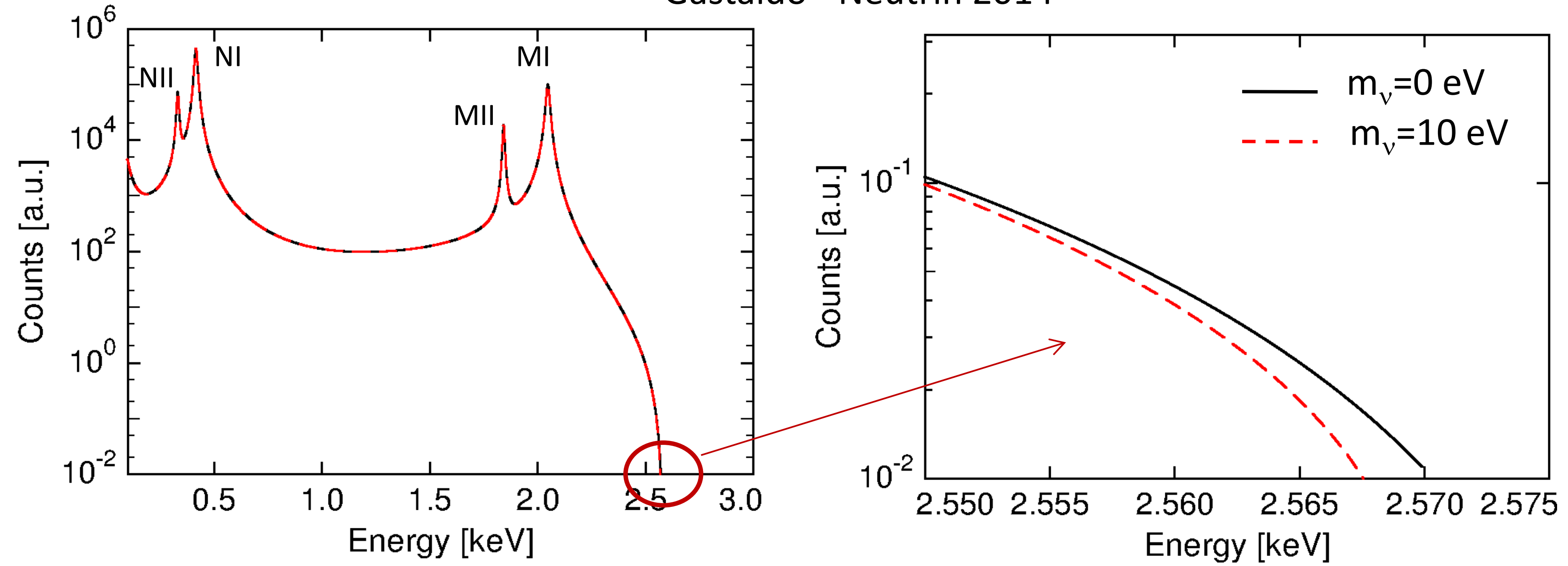

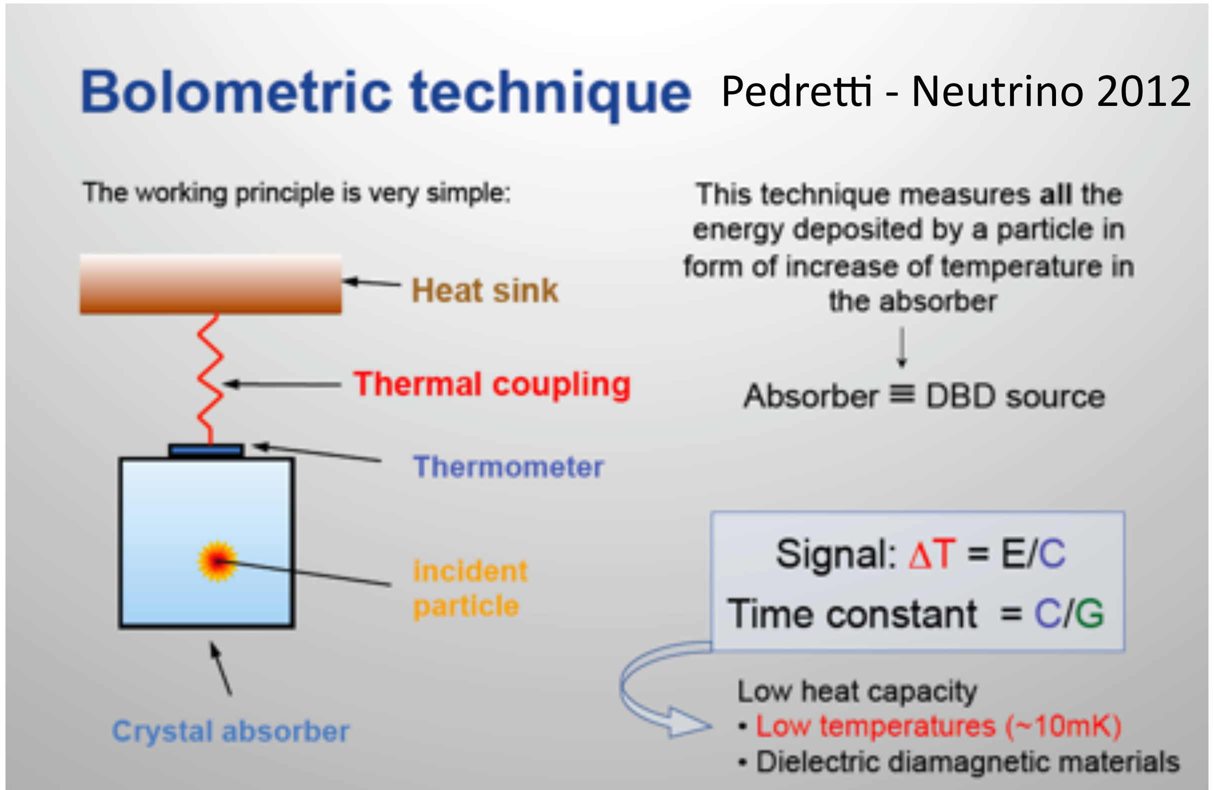

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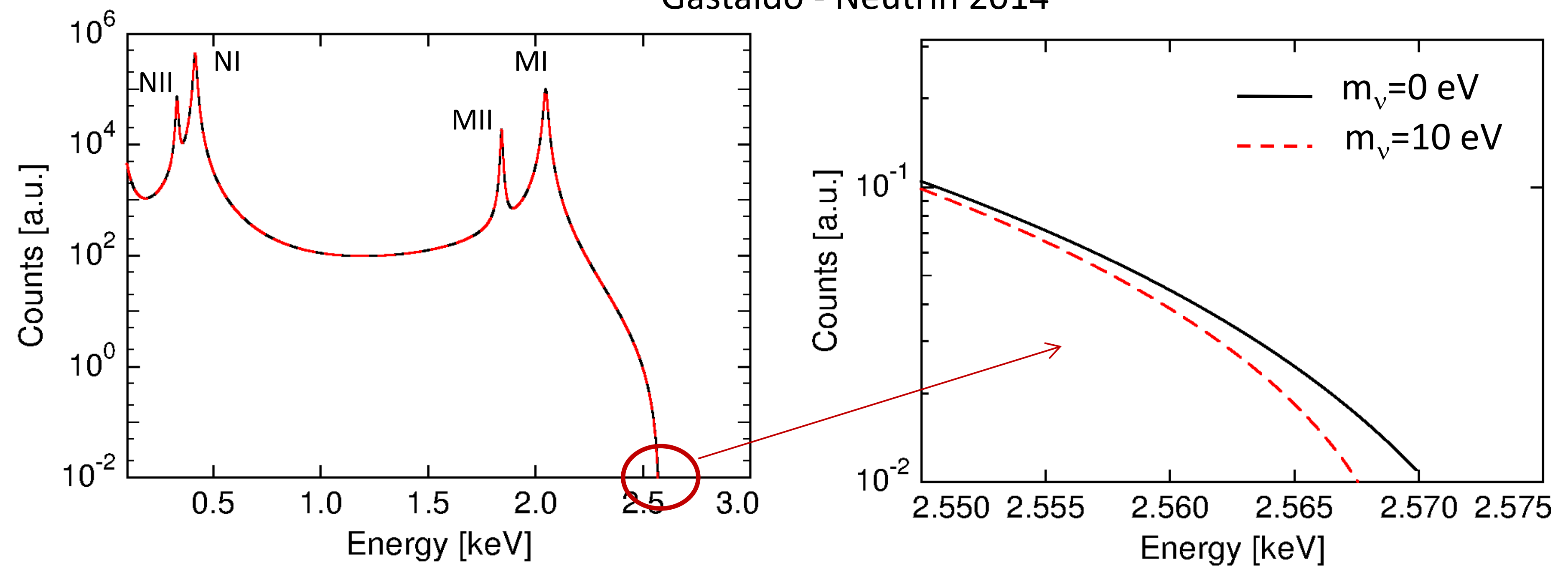

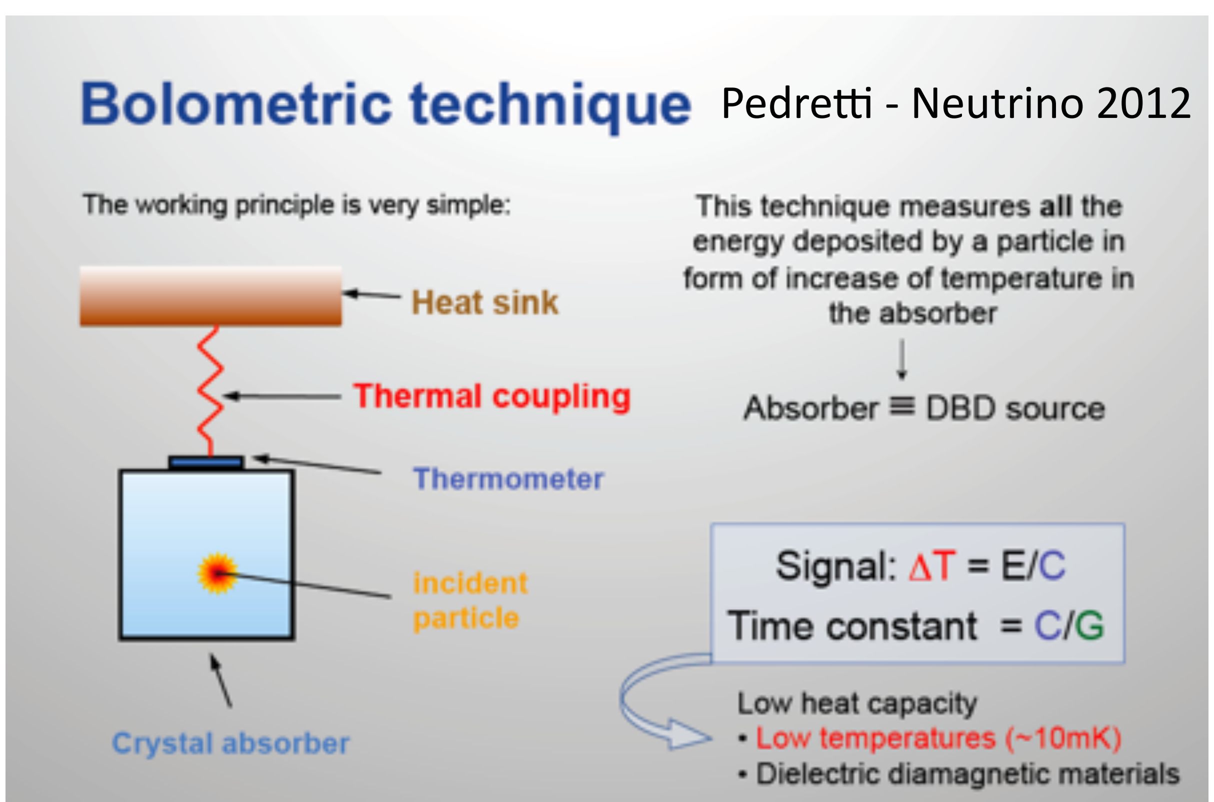

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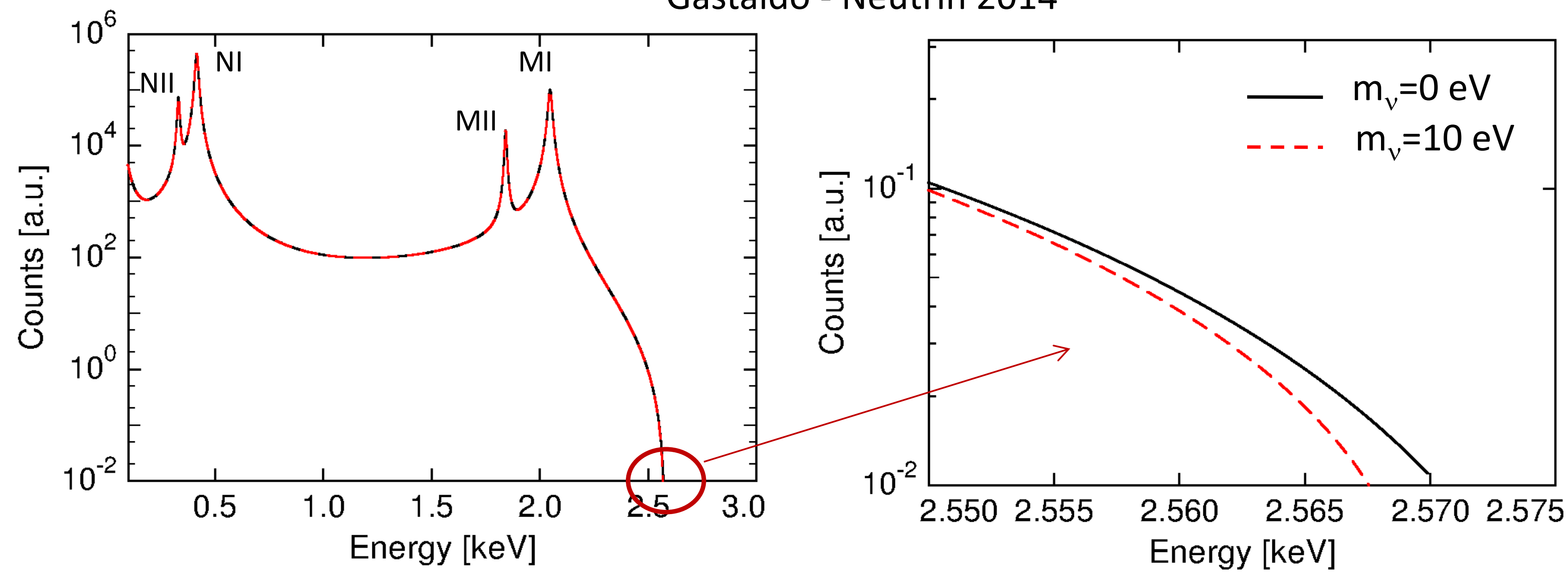

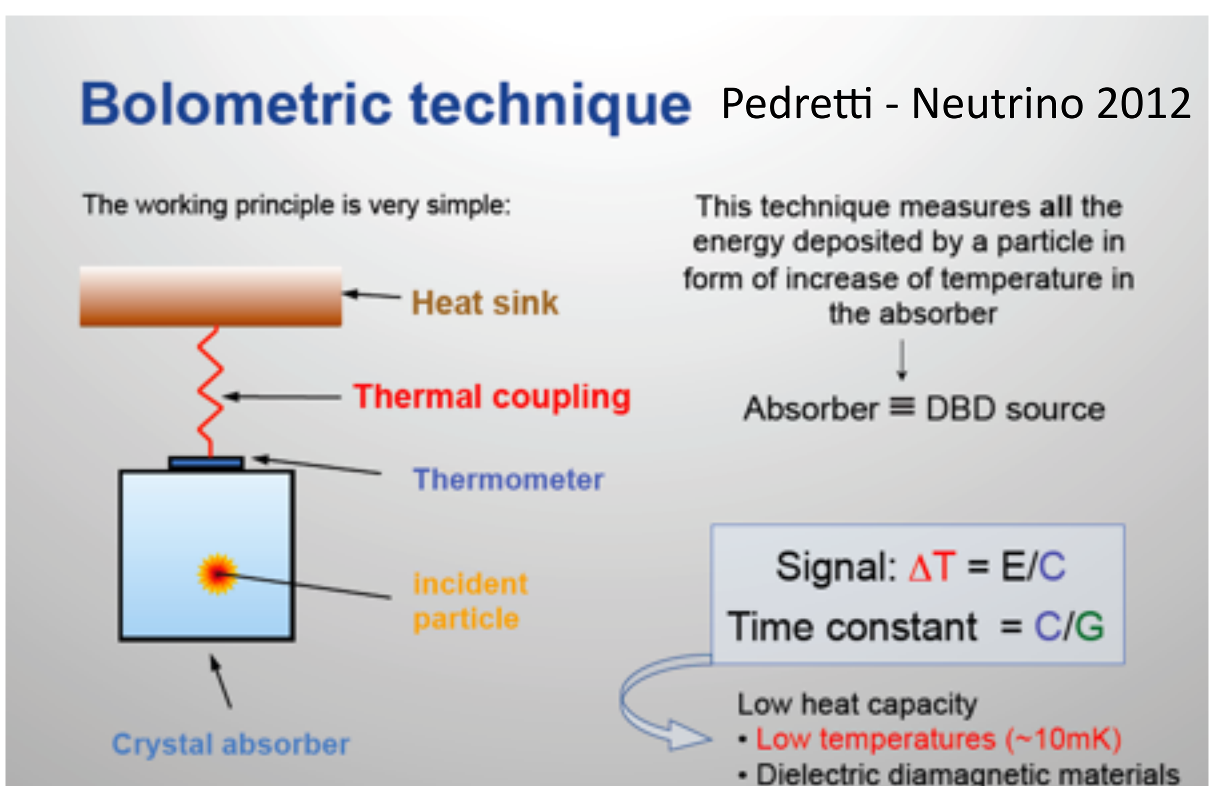

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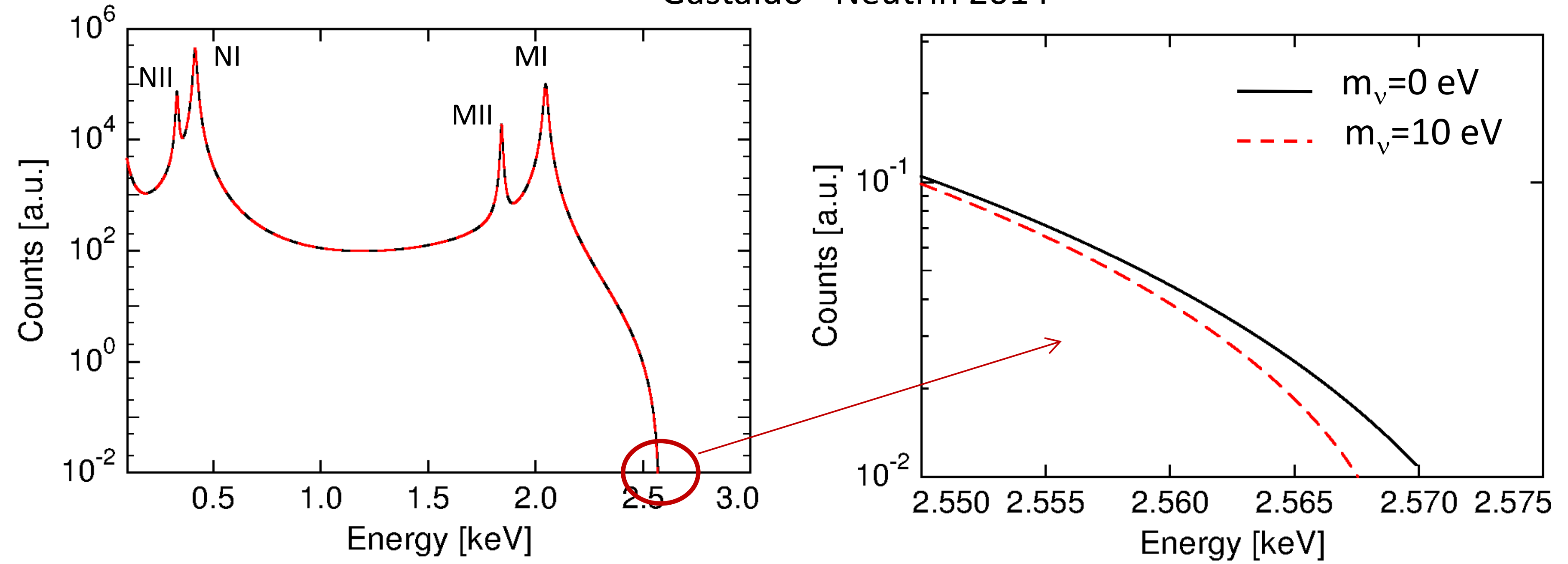

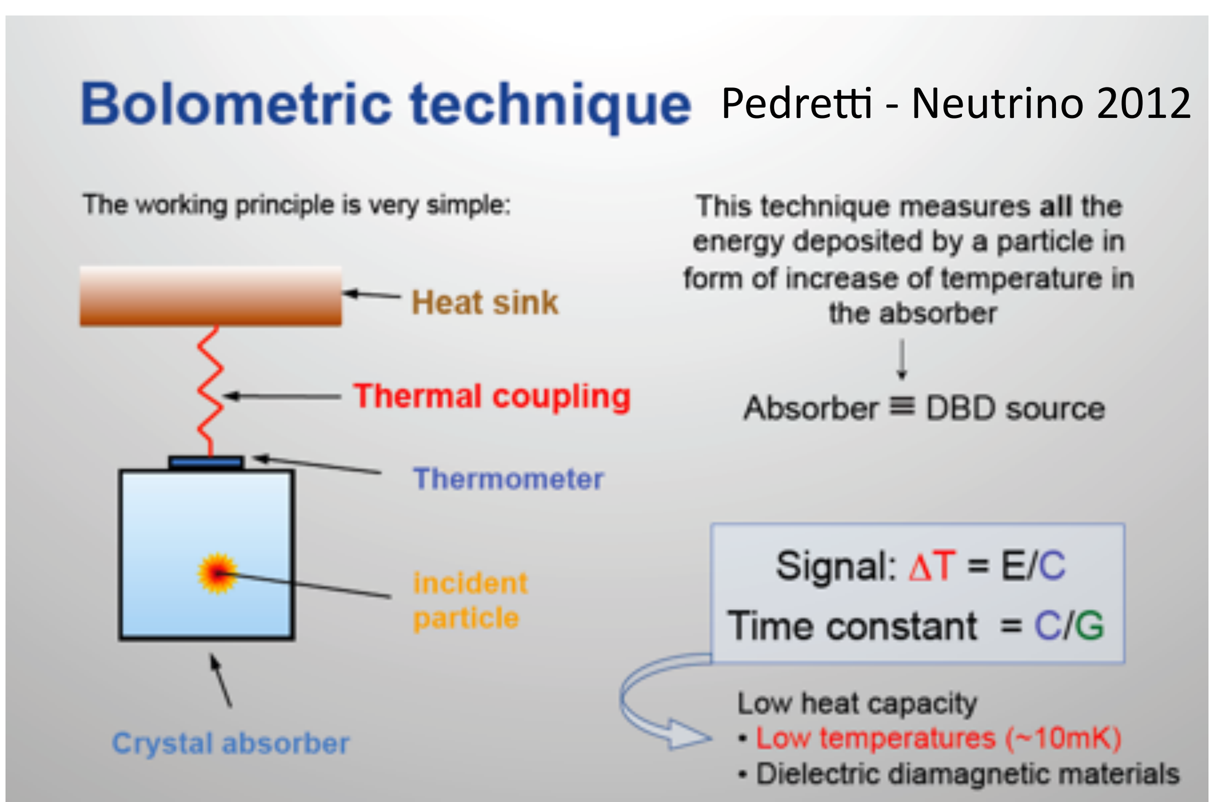

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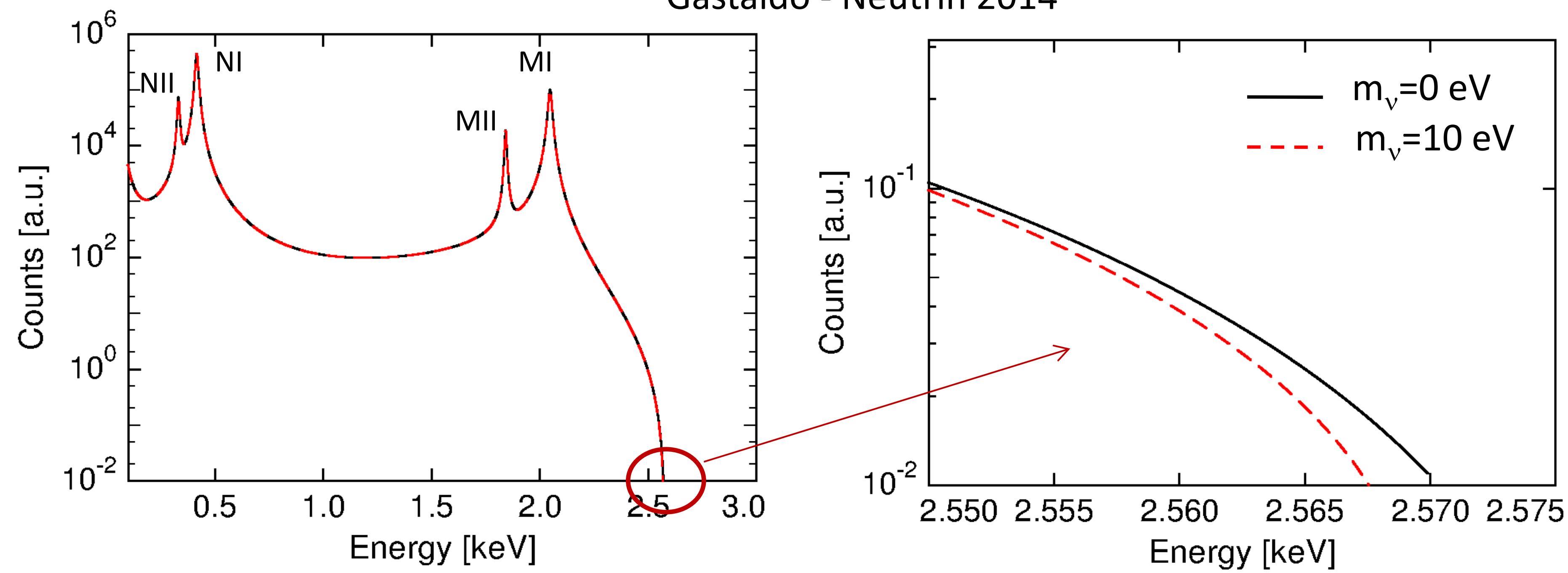
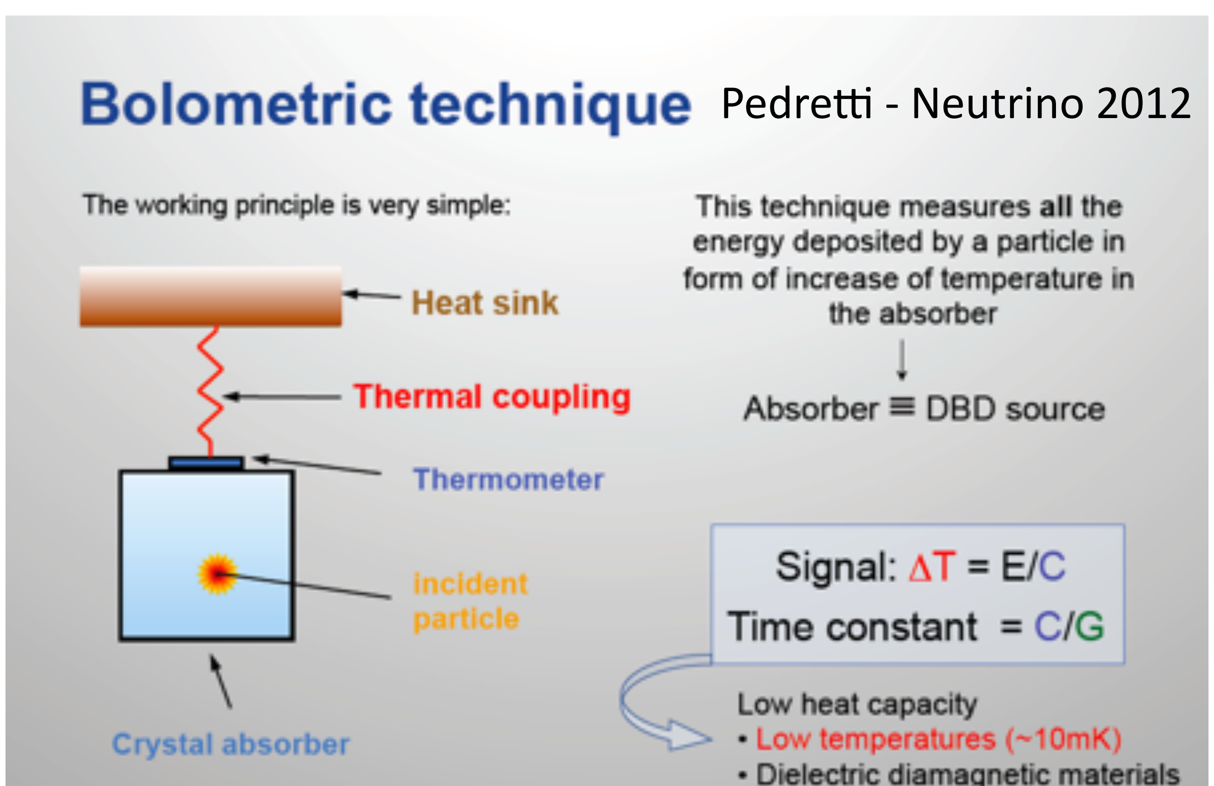


Pedretti - Neutrino 2012



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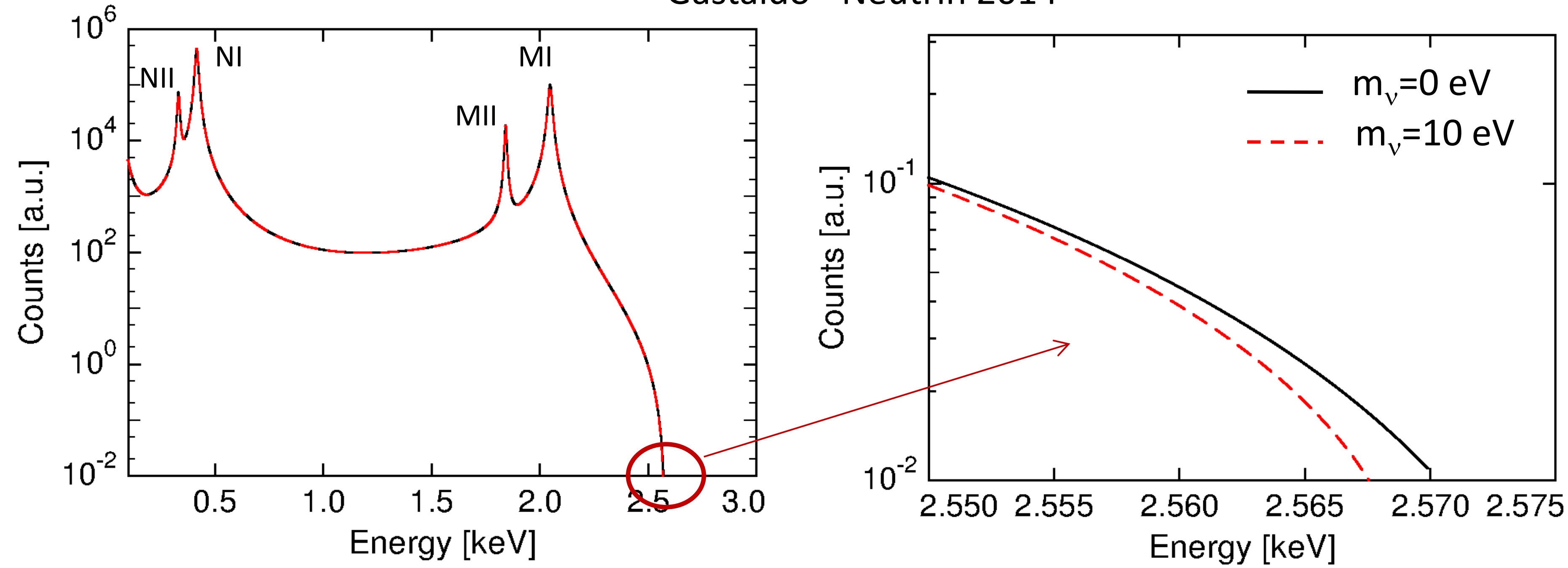

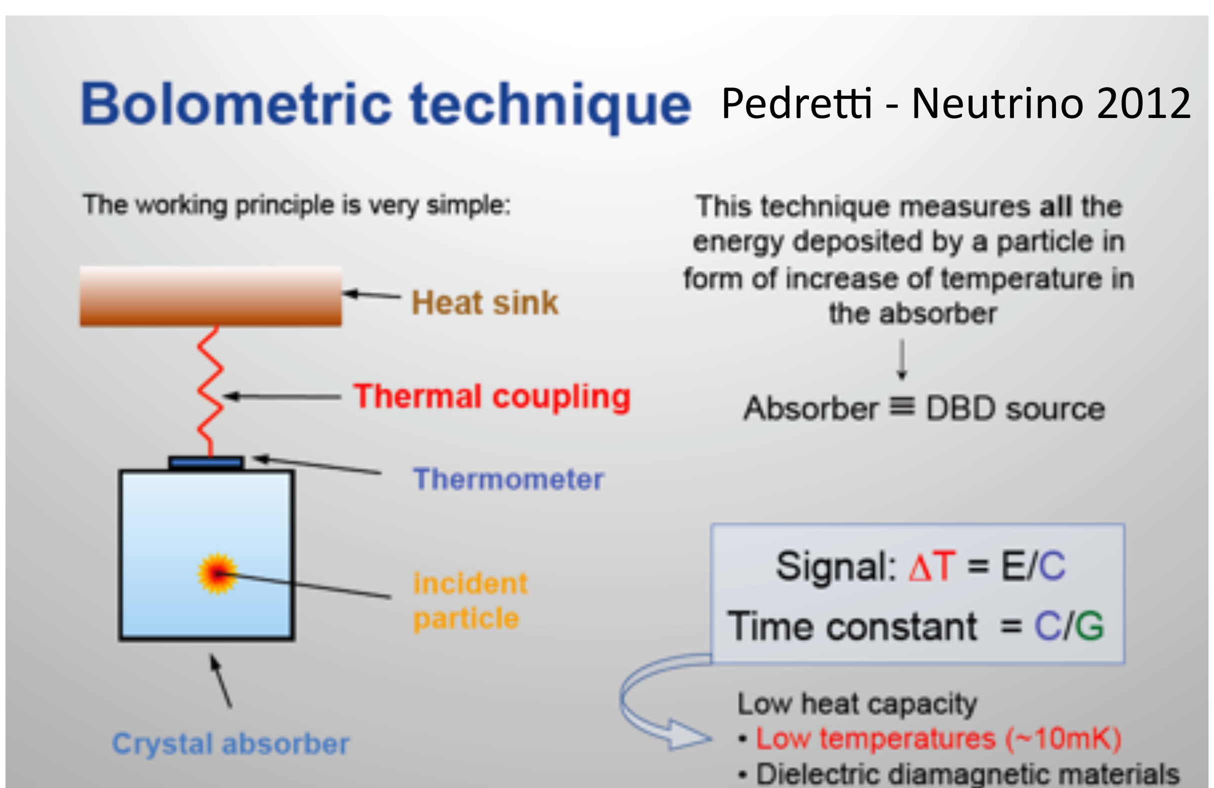

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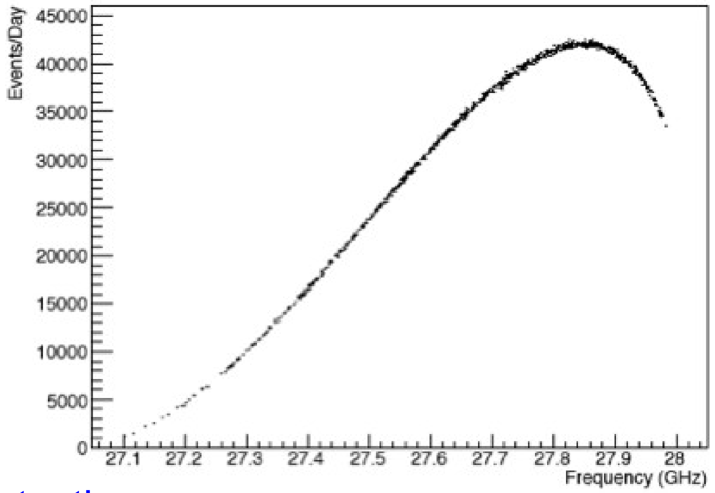

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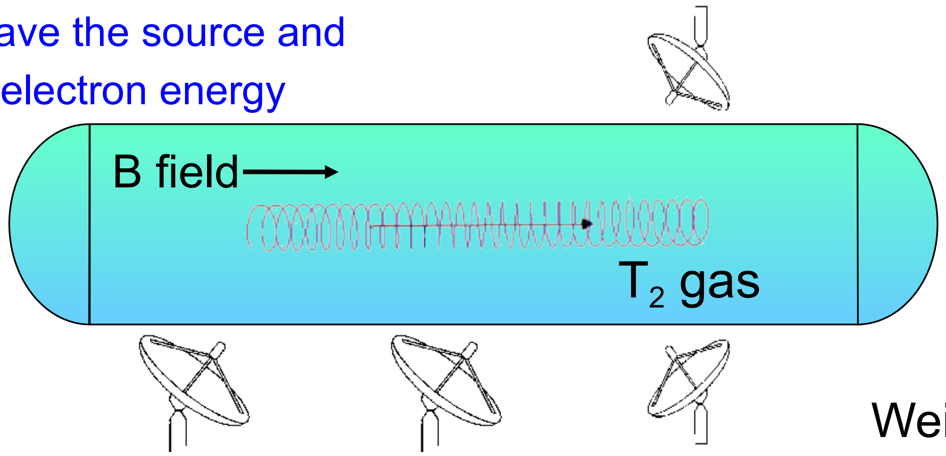

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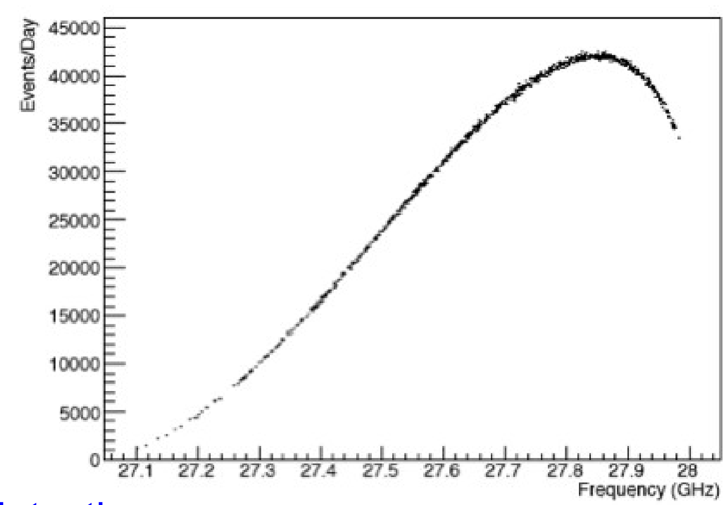

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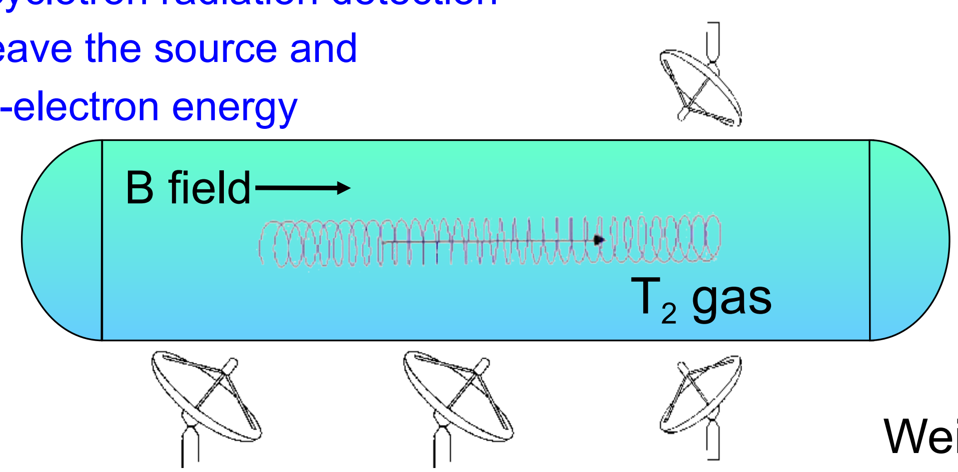

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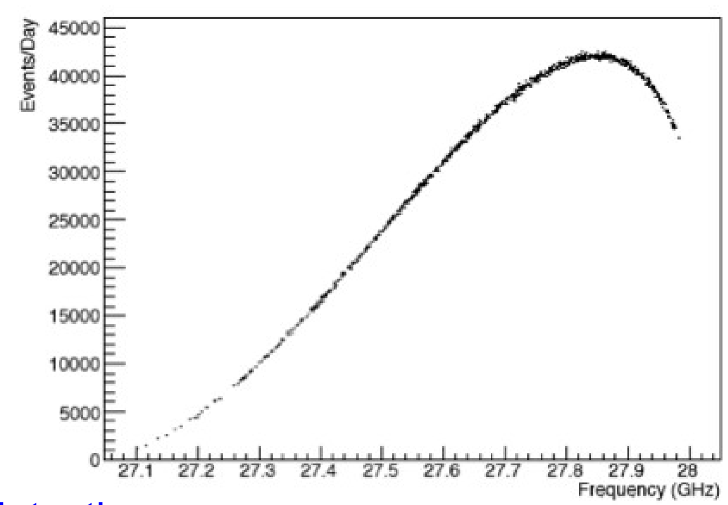

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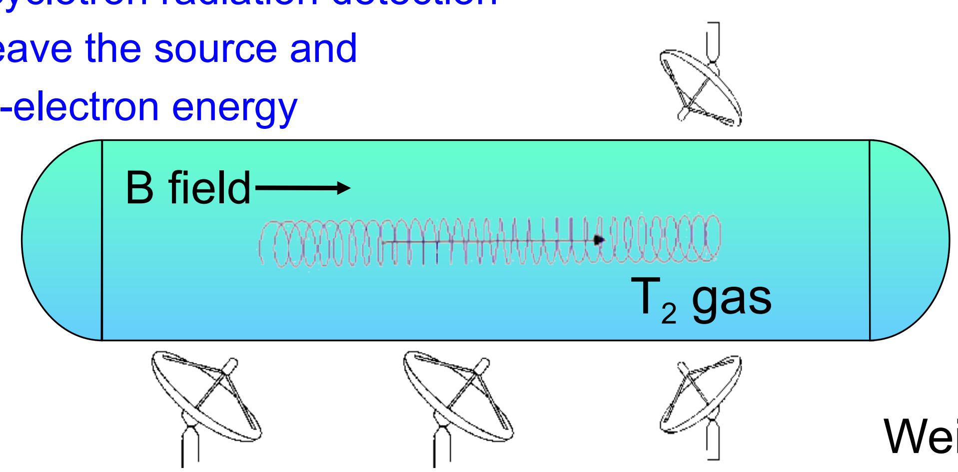

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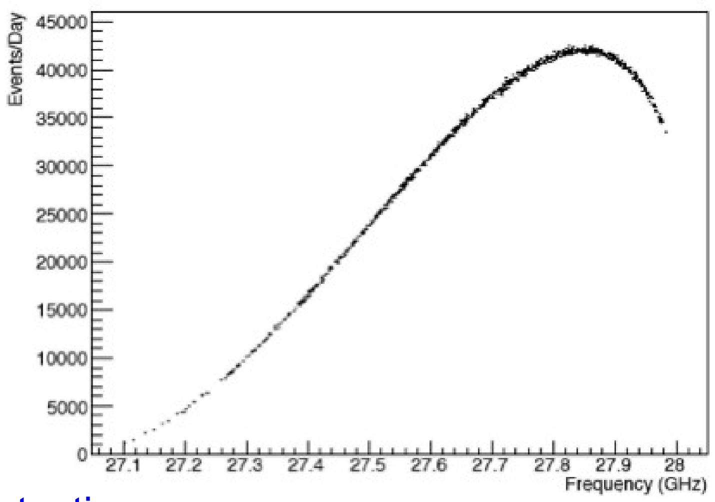

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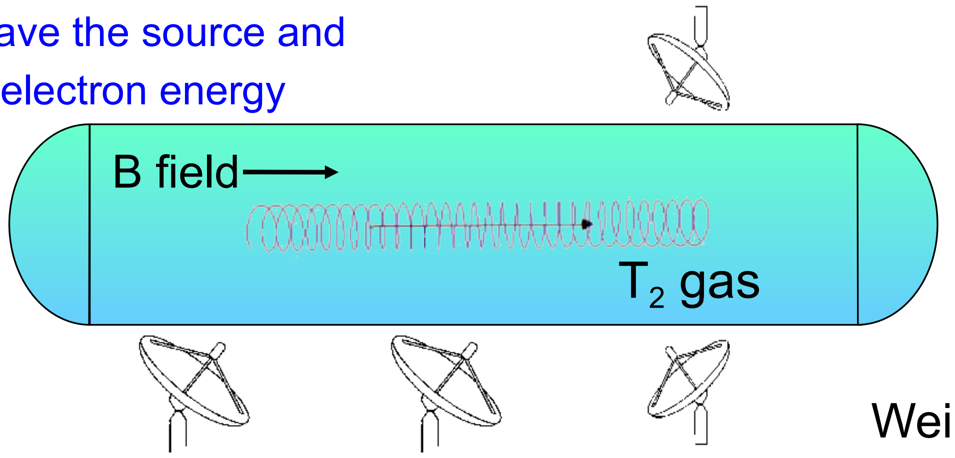

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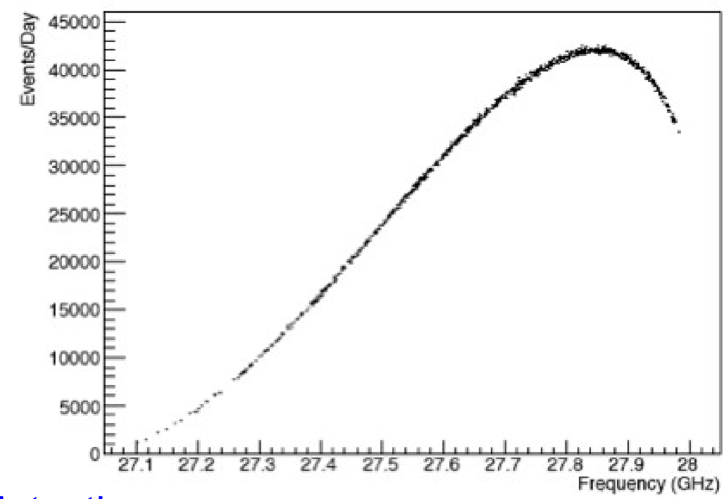

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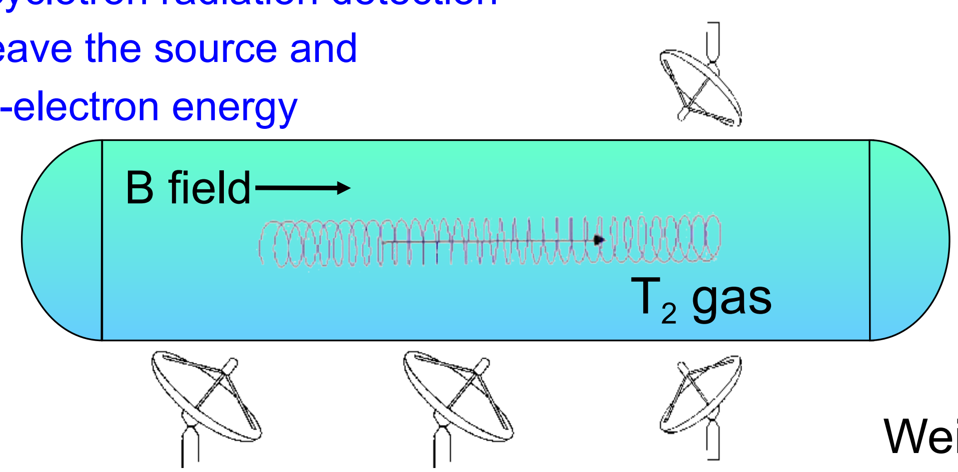

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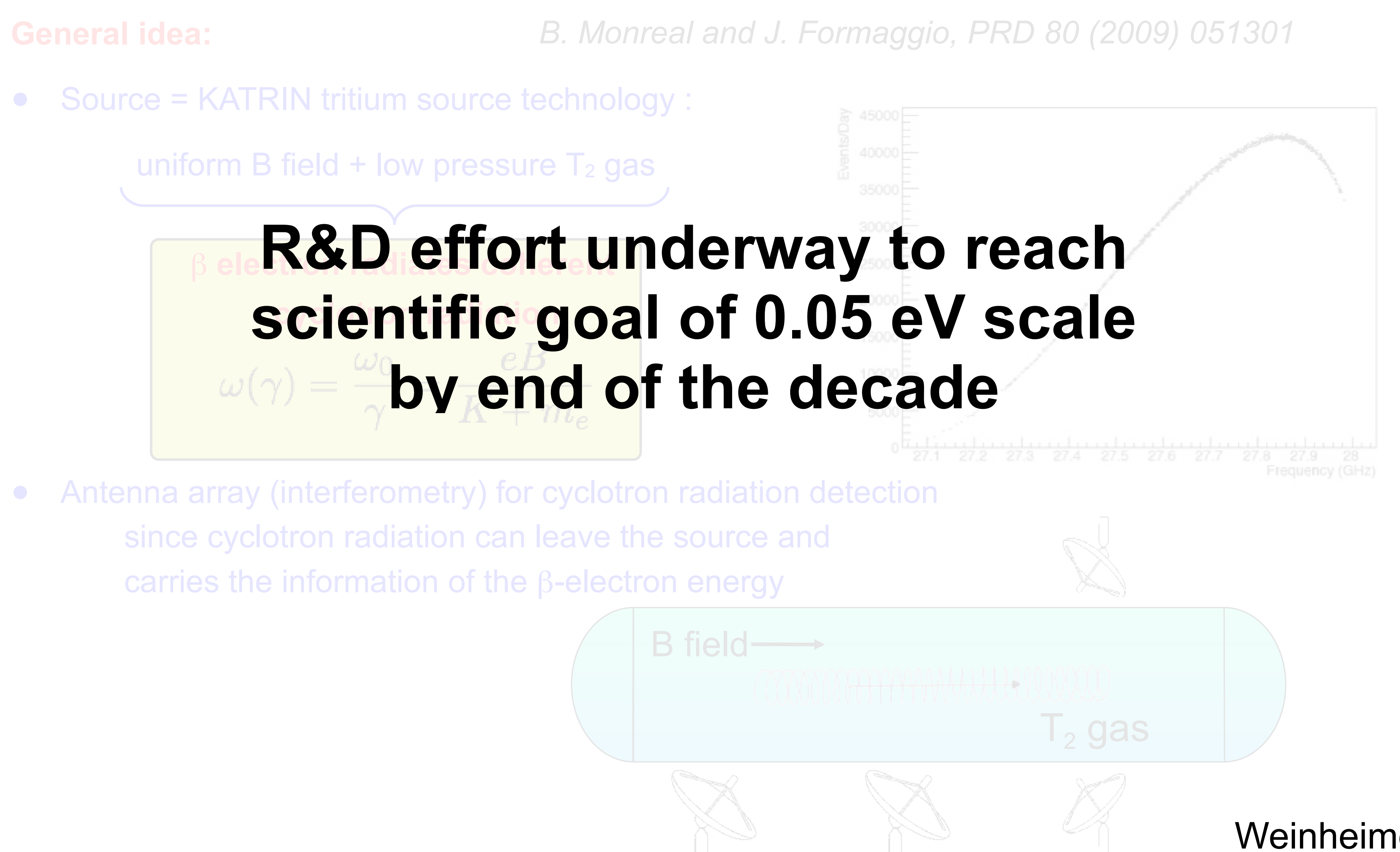

R&D effort underway to reach scientific goal of 0.05 eV scale by end of the decade

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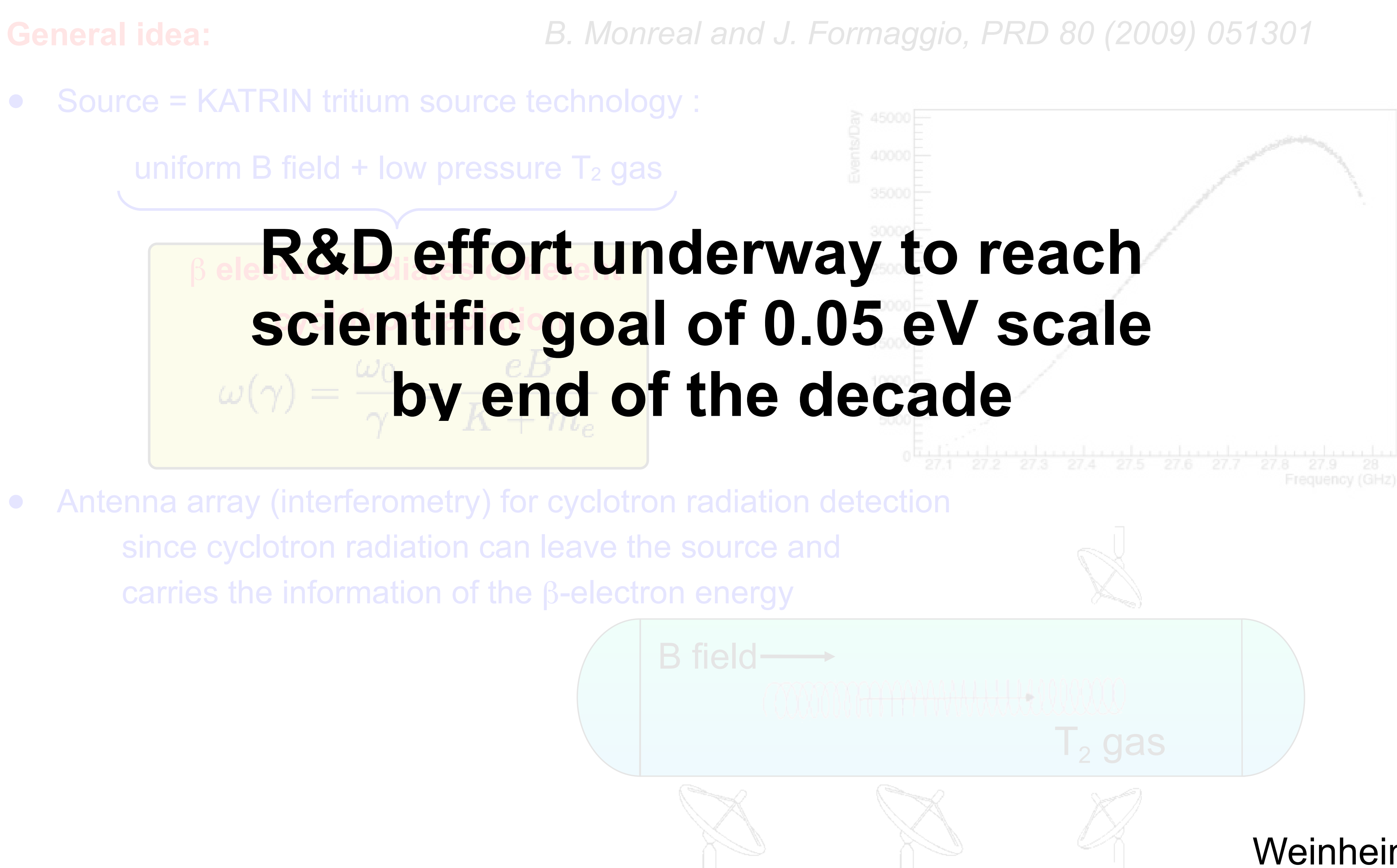

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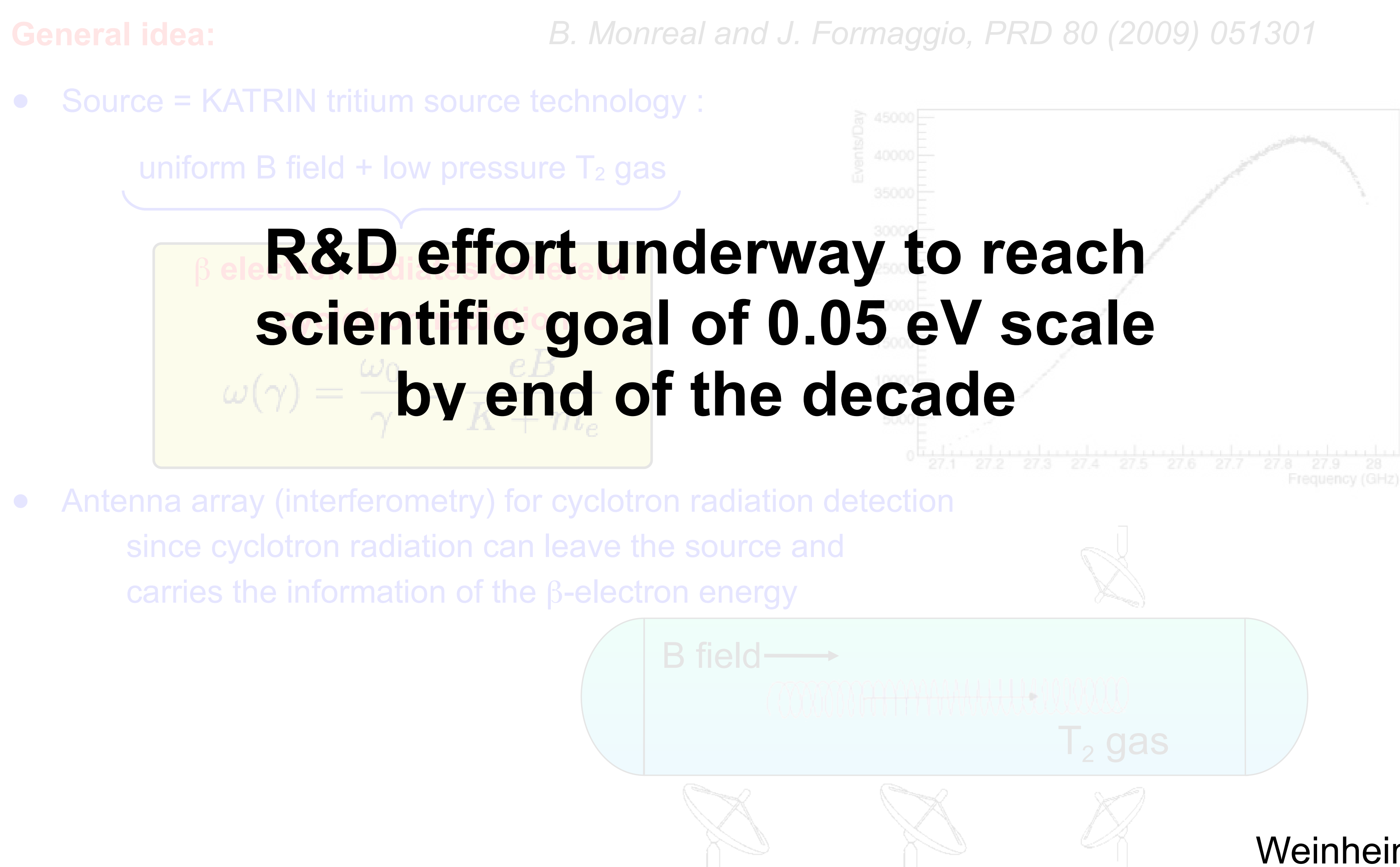

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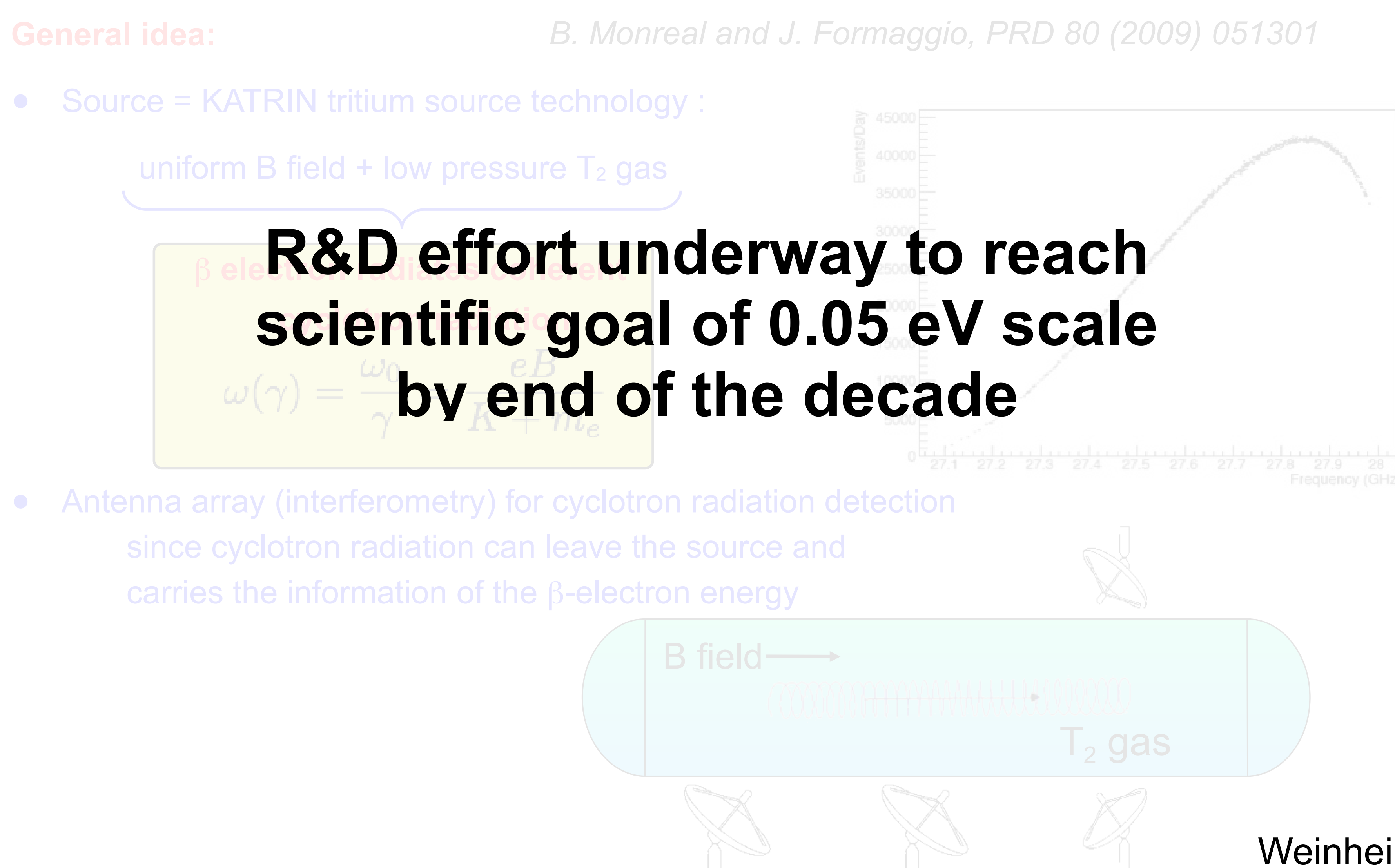

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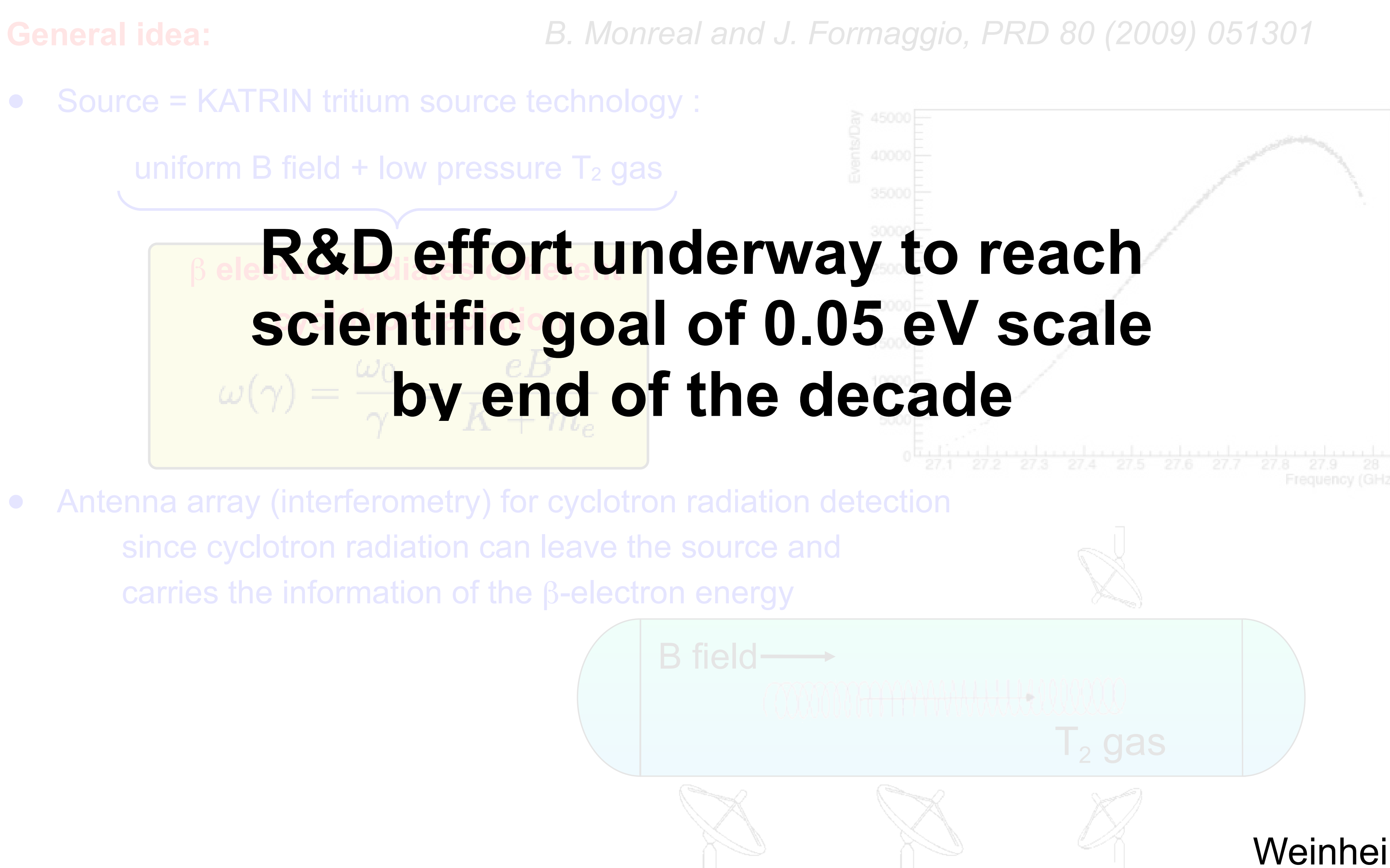

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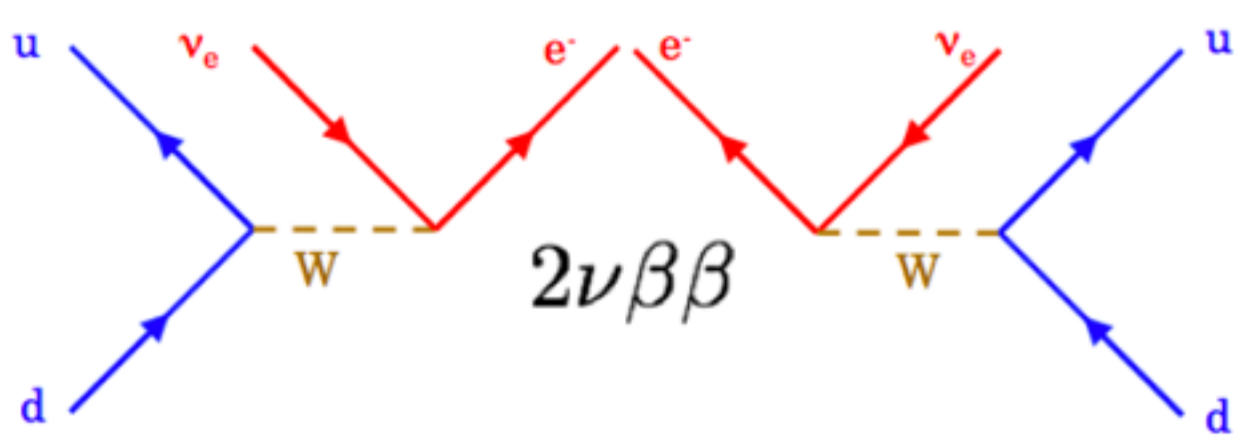

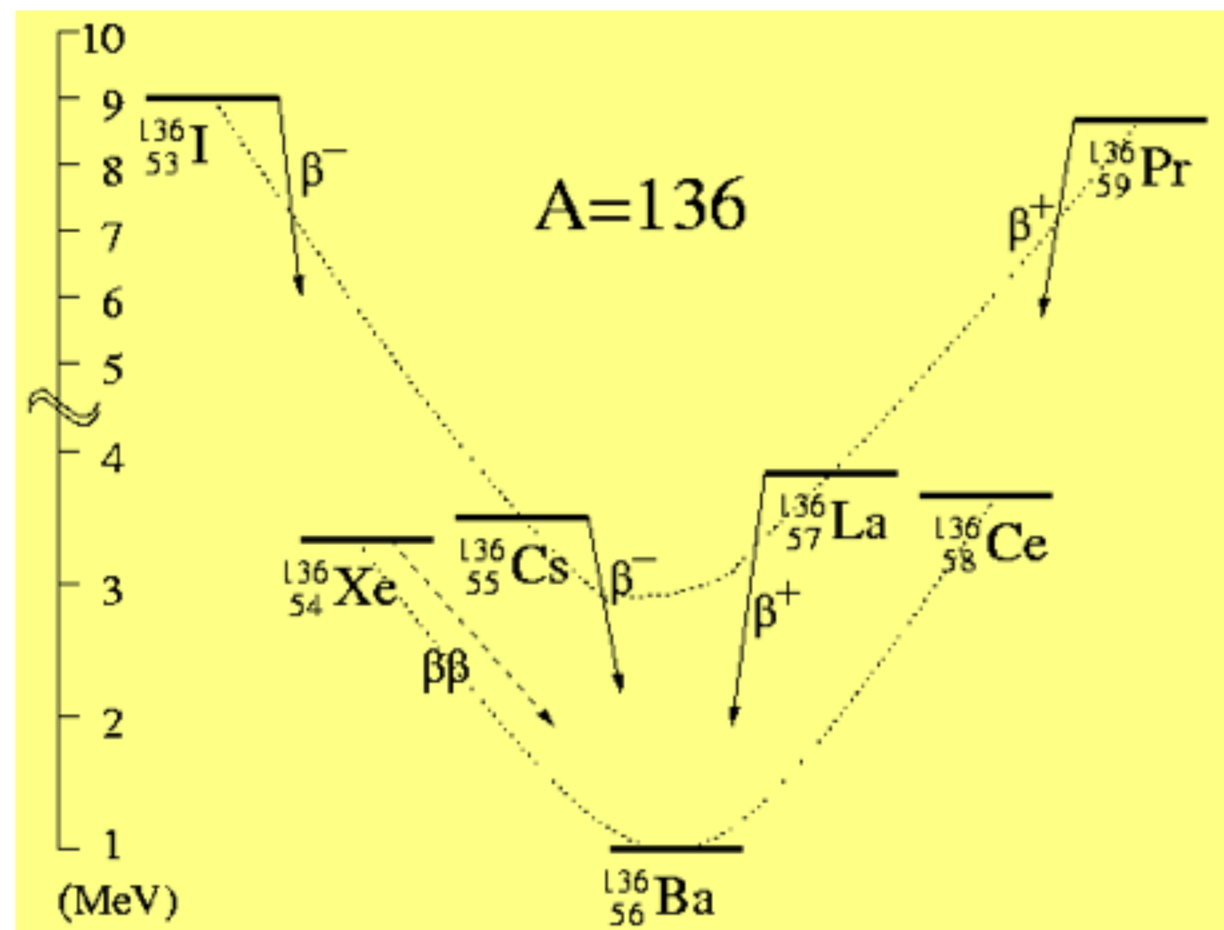

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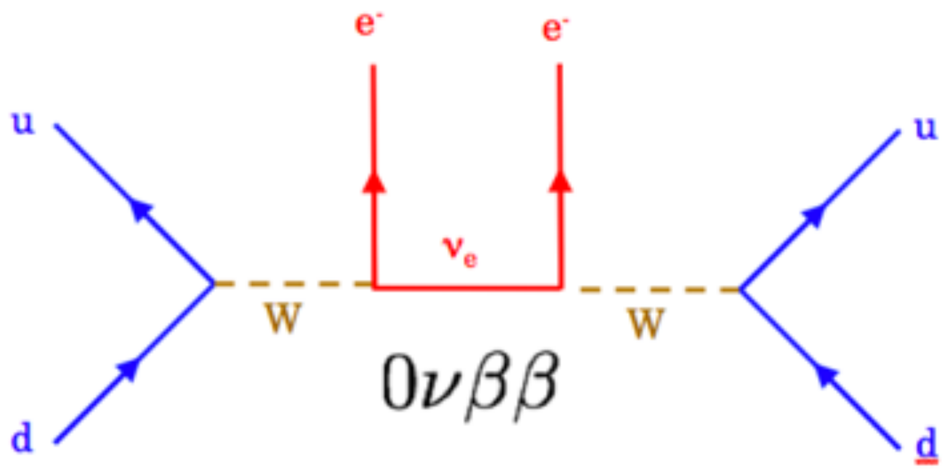
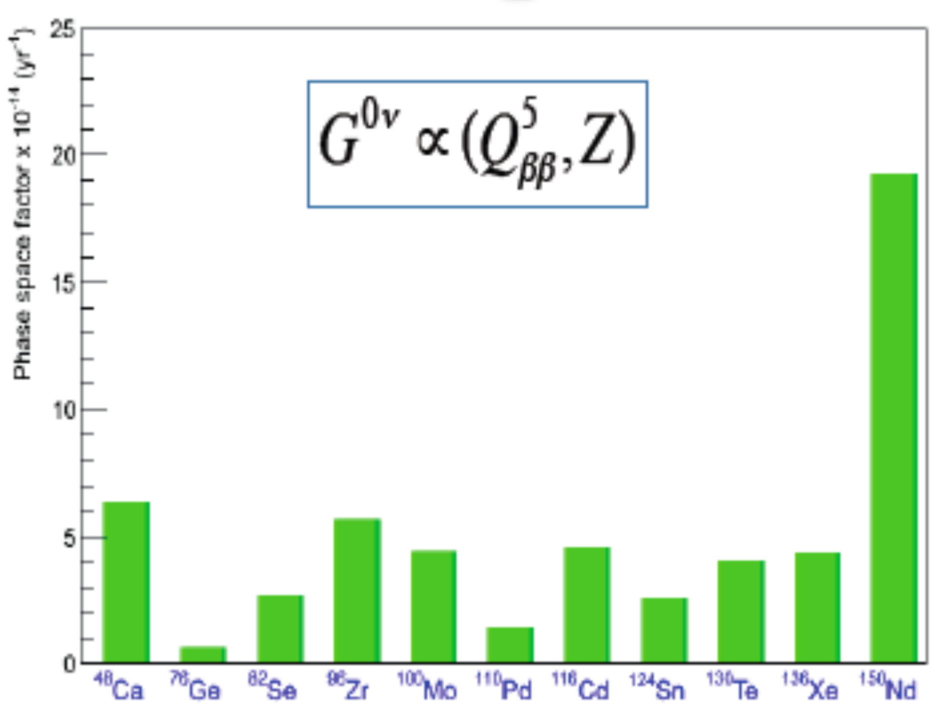
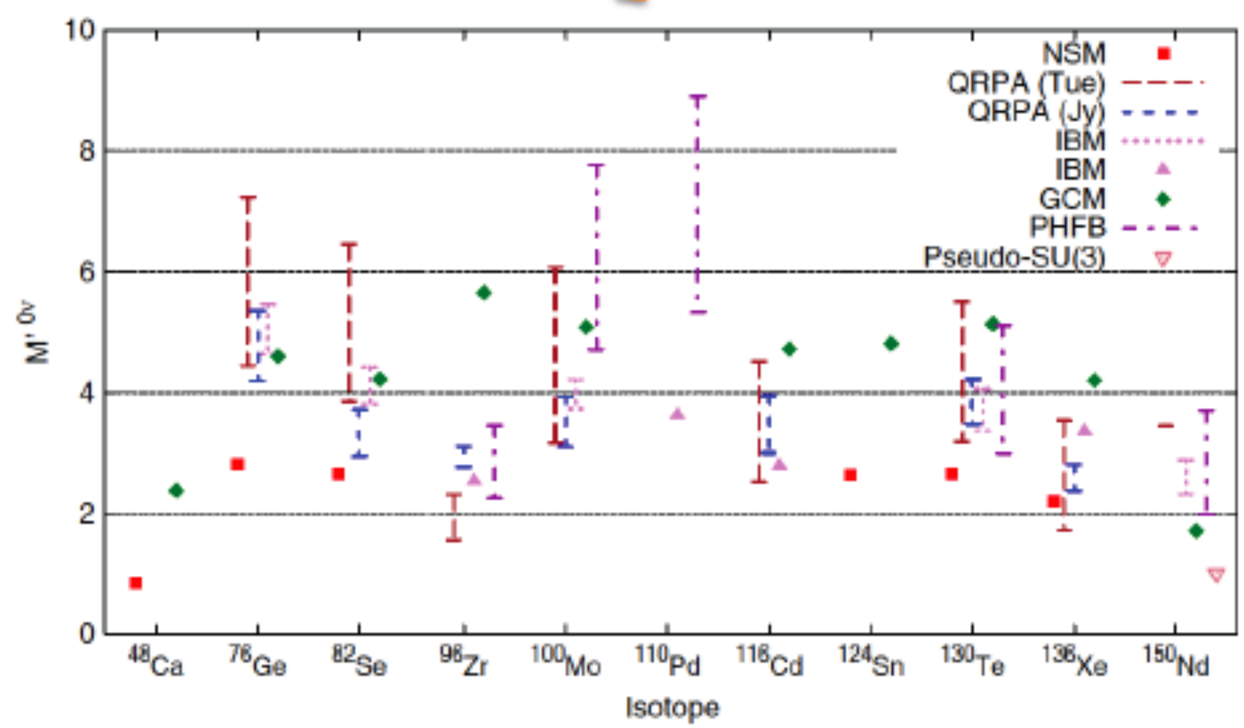


$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2$$

Piquemal - Neutrino 2012

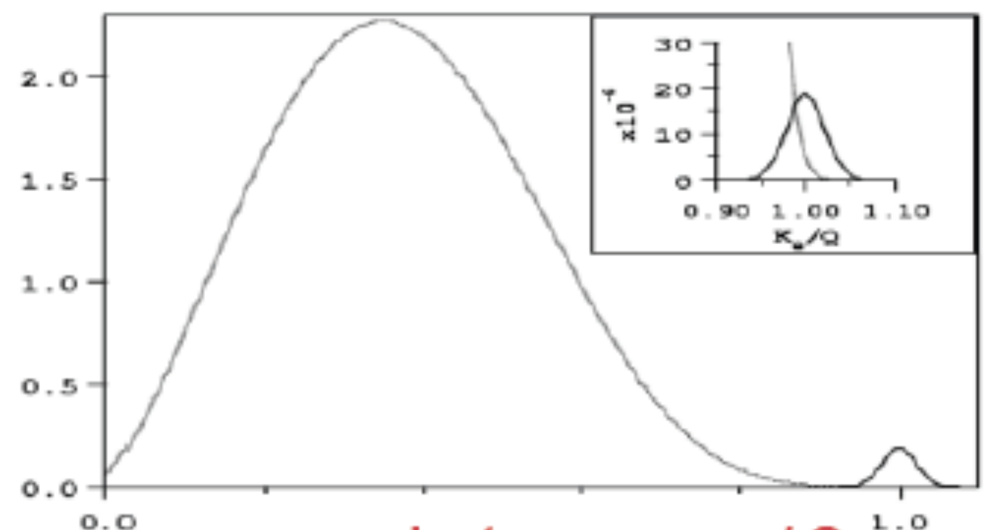




Dueck et al. Phys,. Rev. D 83 113010(2011)

Double beta decay observables

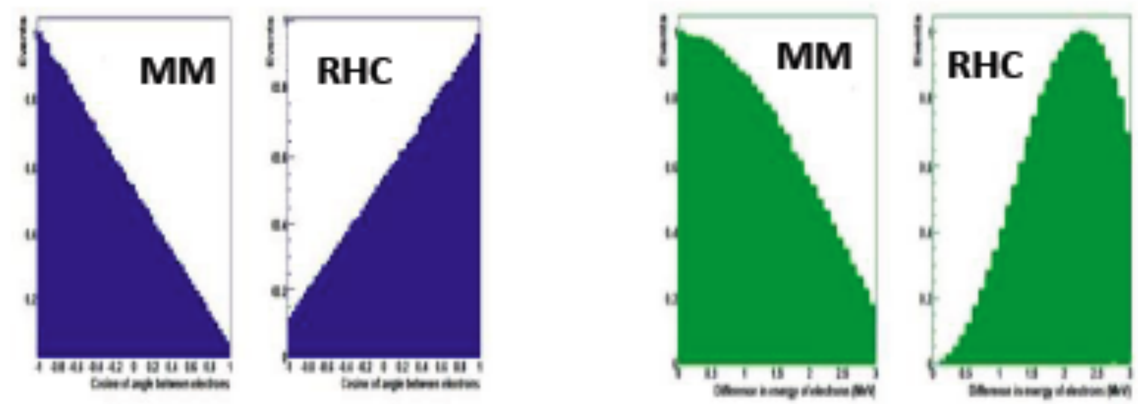
$(A,Z) \longrightarrow (A,Z+2) + 2\,e^-$



sum electron energy / Q

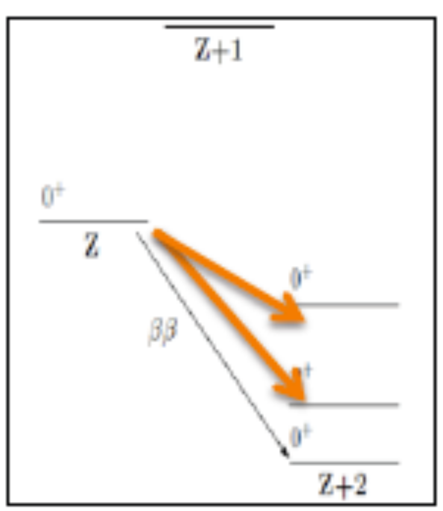
Angular distribution

$Ee_1 - Ee_2$ distribution



Mass vs Right-Handed Current mechanism

Piquemal - Neutrino 2012



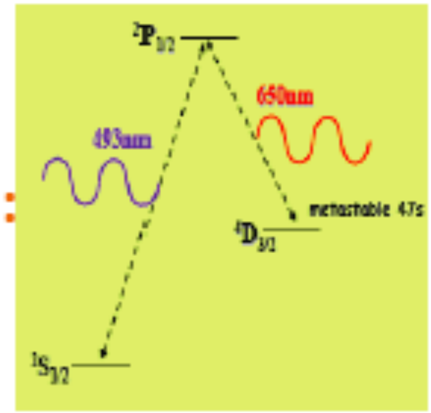
Decay to Excited States

$(A,Z) \rightarrow (A, Z+2) + 2\,e^- + 1,2\,\gamma$

1 or 2 additonnal γ-rays

Identification of daugther nucleus :

$Xe \rightarrow Ba^{++} + 2\,e^-$



Neutrinoless Double Beta Decay

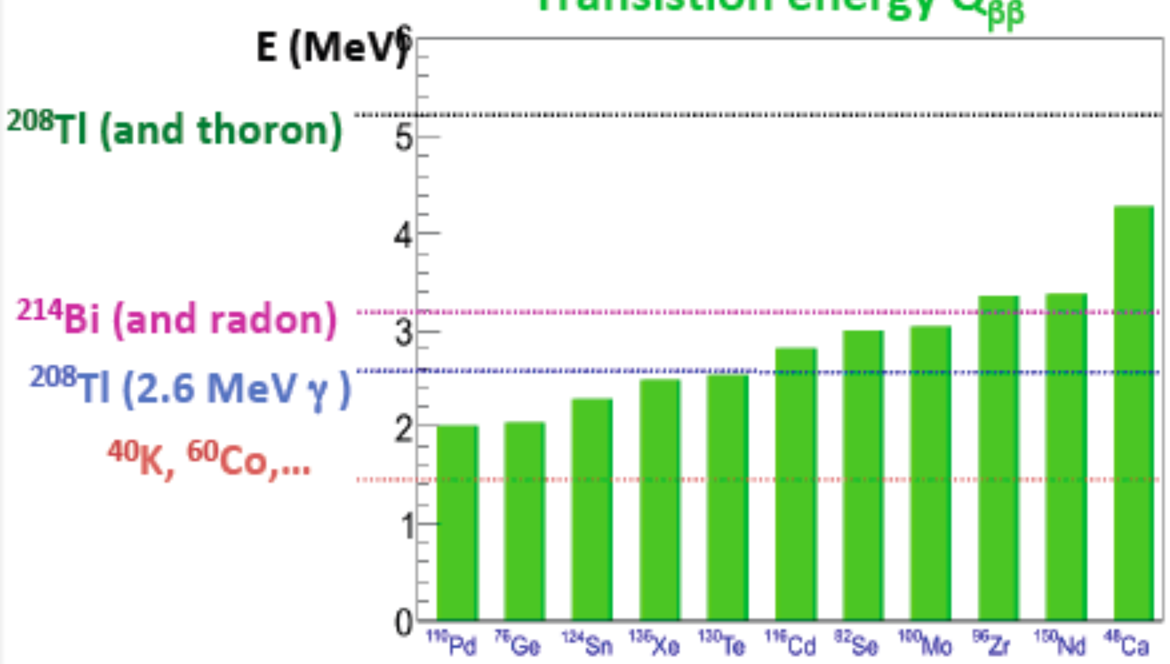
WITH Background

$$T_{1/2}^{0\nu}(y) \propto \frac{\varepsilon}{A}\sqrt{\frac{M\,.\,t}{N_{Bckg}\,.\,\Delta E}} \qquad \langle m_\nu \rangle \propto \sqrt[4]{M}$$

ε :efficiency, M: Mass, t: time, N_{bckg}: Background events, ΔE: energie resolution, A: isotope mass

Background origins

Natural radioactivity



Other sources of background:

- Muons (underground labs)
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- α emitters from bulk or surface contaminations for calorimeters
- ββ(2ν) if modest energy resolution

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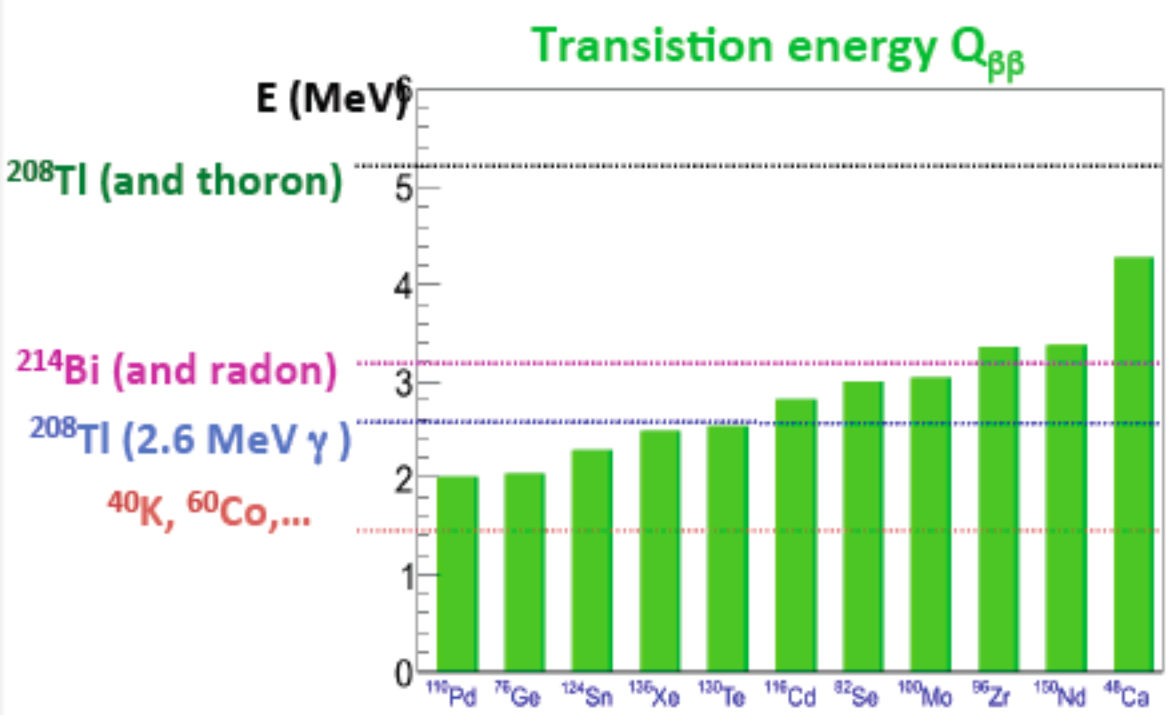

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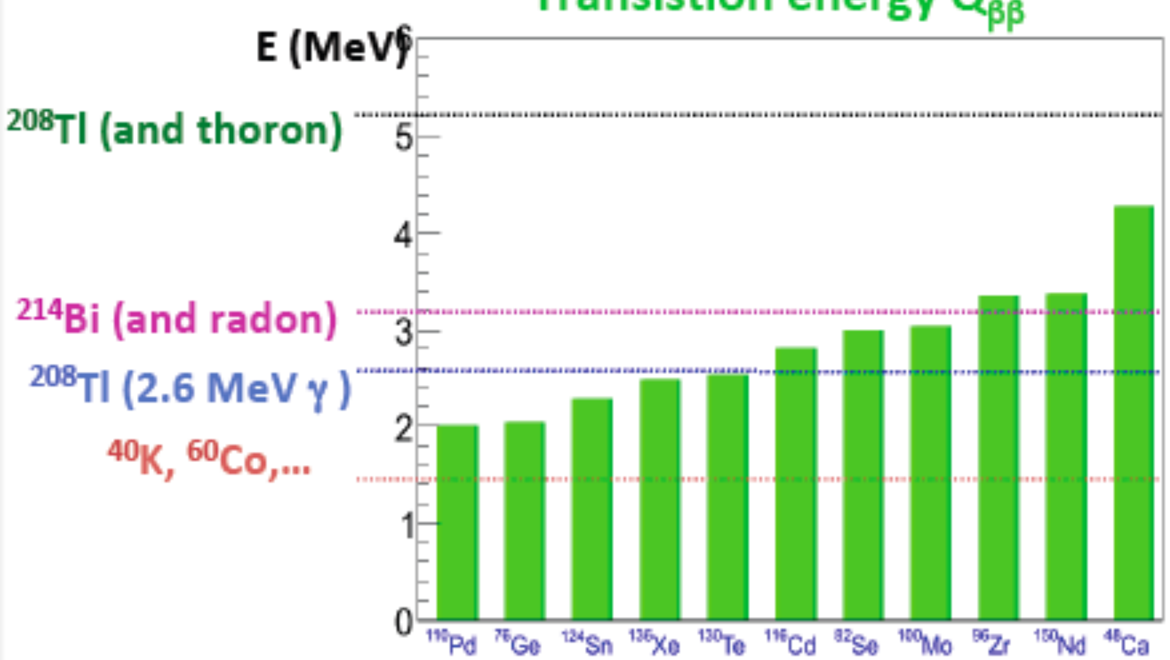
Transistion energy $Q_{\beta\beta}$



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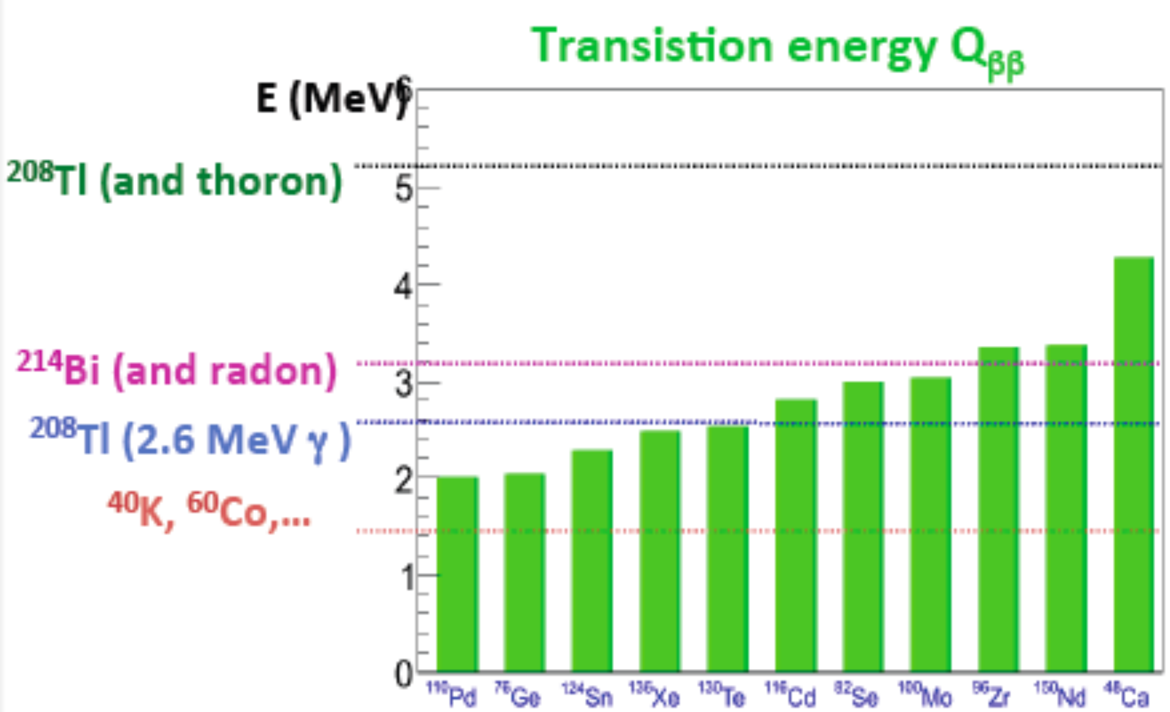

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- These experiments are INCREDIBLY difficult!

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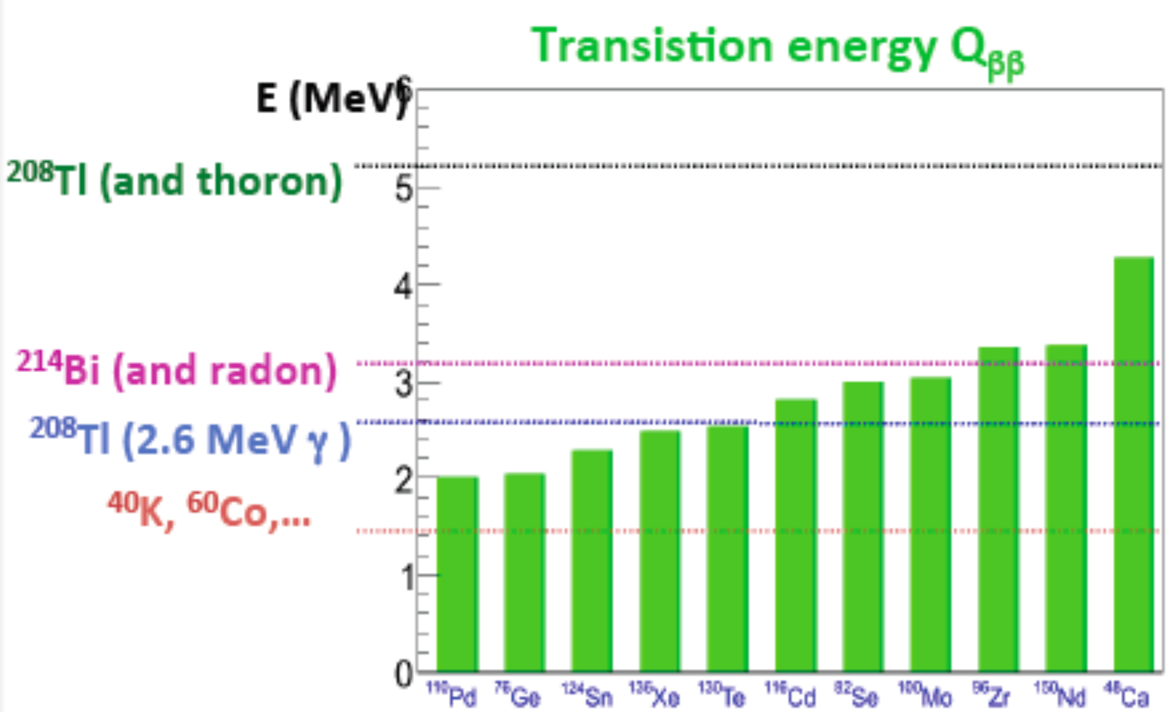

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A *Small* Sample of 0νββ Experiments

NEMO-3

NEMO 3

Tracking detector: drift chambers (6180 Geiger cells)
$\sigma_t = 5$ mm, $\sigma_z = 1$ cm (vertex)

Calorimeter (1940 plastic scintillators and PMTs)
Energy Resolution FWHM=8 % (3 MeV)

Identification e^-, e^+, γ, α
Very high efficiency for background rejection

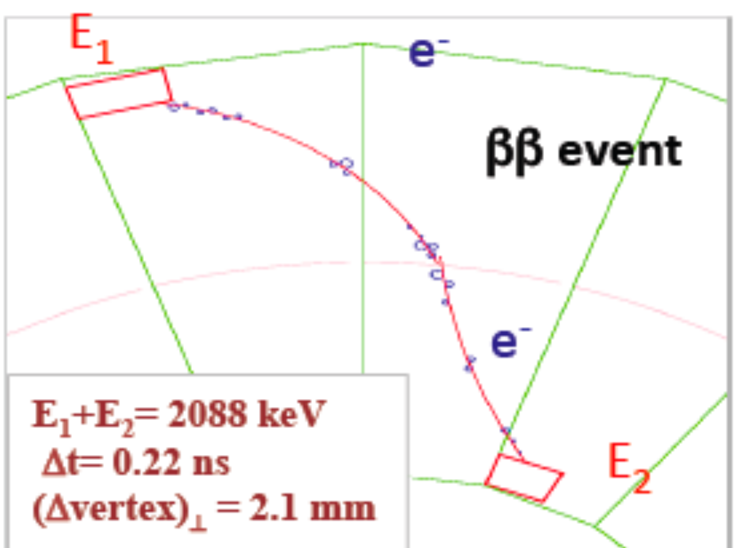
Background level @ $Q_{\beta\beta}$ [2.8 – 3.2 MeV] : 1.2 10^{-3} cts/keV/kg/y

Multi-isotope (7 measured at the same time)

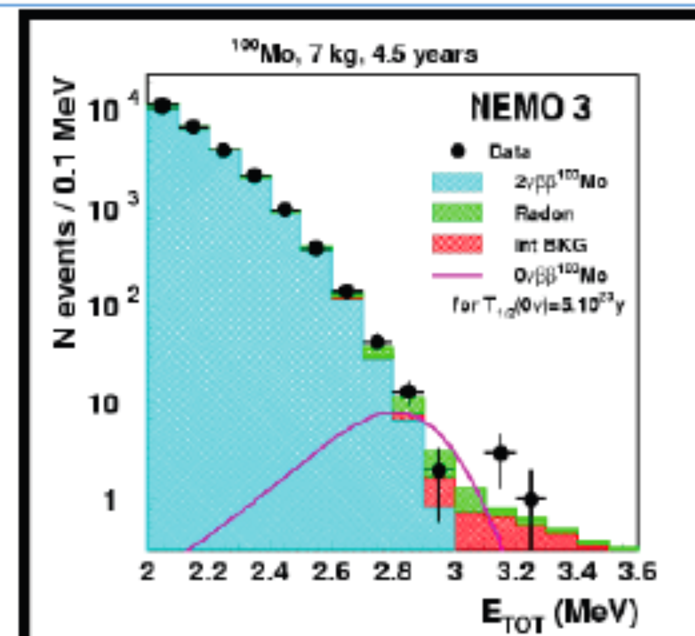
Running at Modane underground laboratory (2003 - 2011)

Unique feature

Measurement of all kinematic parameters: individual energies and angular distribution



Measurement of 7 isotopes $\beta\beta(2\nu)$ half-lifes
Excited states, Majoron limits for $\beta\beta(0\nu)$



[2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected

^{100}Mo $T_{1/2}$ ($\beta\beta0\nu$) > 1.0 10^{24} y (90% C.L.)

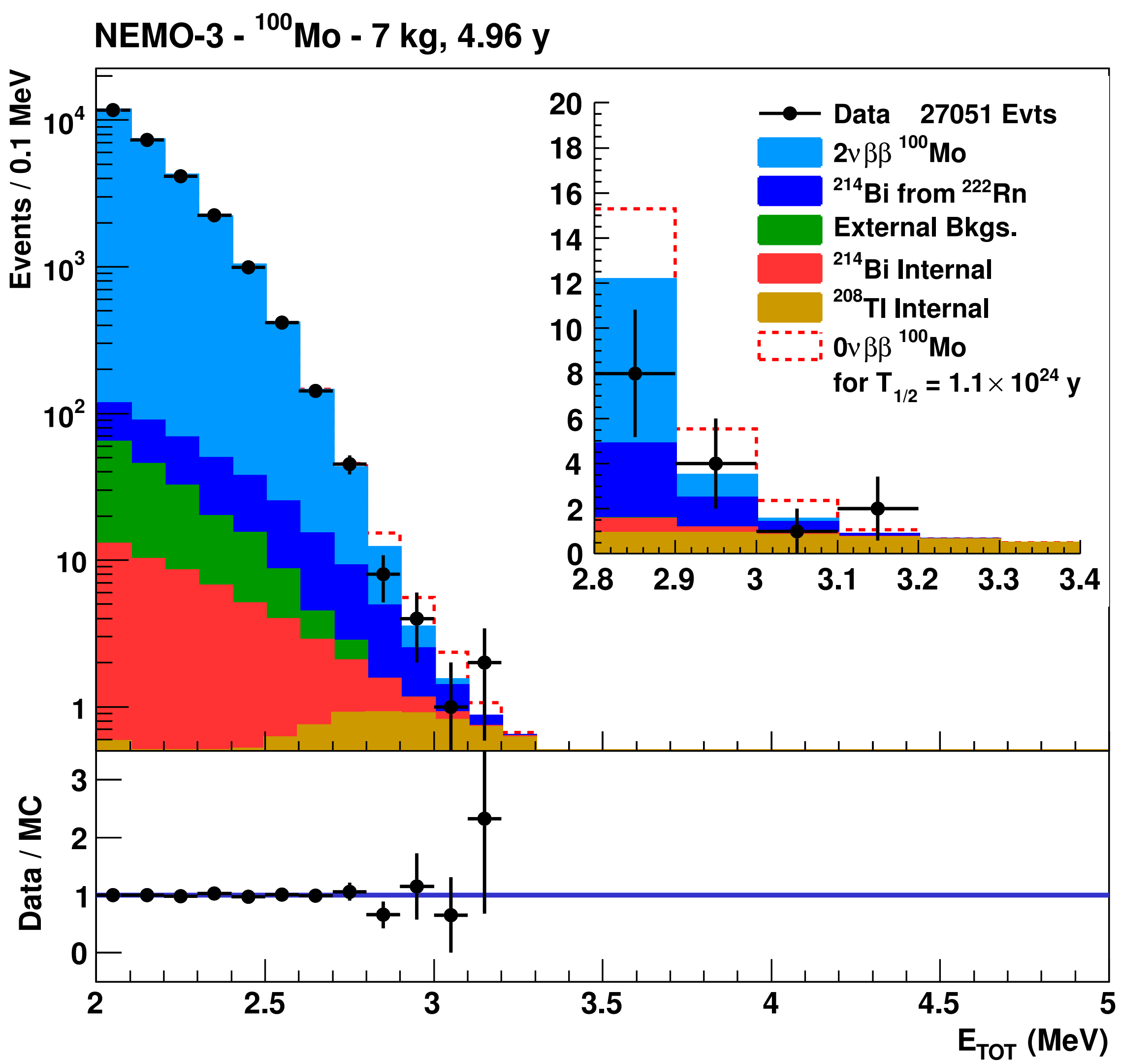
$\langle m_\nu \rangle$ < 0.31– 0.79 eV

NEMO-3

NEMO-3 $0\nu2\beta$ Search with ^{100}Mo

Bongrand - Neutrino 2014

- Detection efficiency $\mathcal{E}_{0\nu}$ = 4.7 % in the [2.8 – 3.2] MeV region
- No event excess observed in ^{100}Mo after 34.3 kg·y exposure: $\mathcal{T}^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y (90 % CL)



Expected background in [2.8 – 3.2] MeV	
$2\nu2\beta$	8.45 ± 0.05
^{214}Bi from radon	5.2 ± 0.5
External	< 0.2
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
Total	**18.0 ± 0.6**
Data	**15**

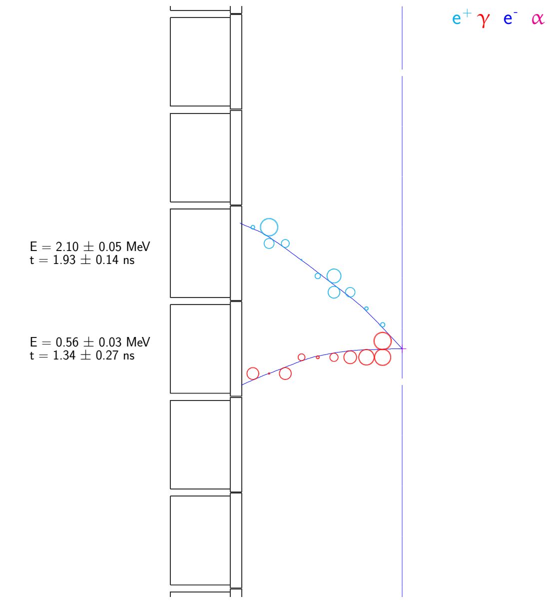
Total background
1.3×10^{-3} cts·keV^{-1}·kg^{-1}·y^{-1}

SuperNEMO

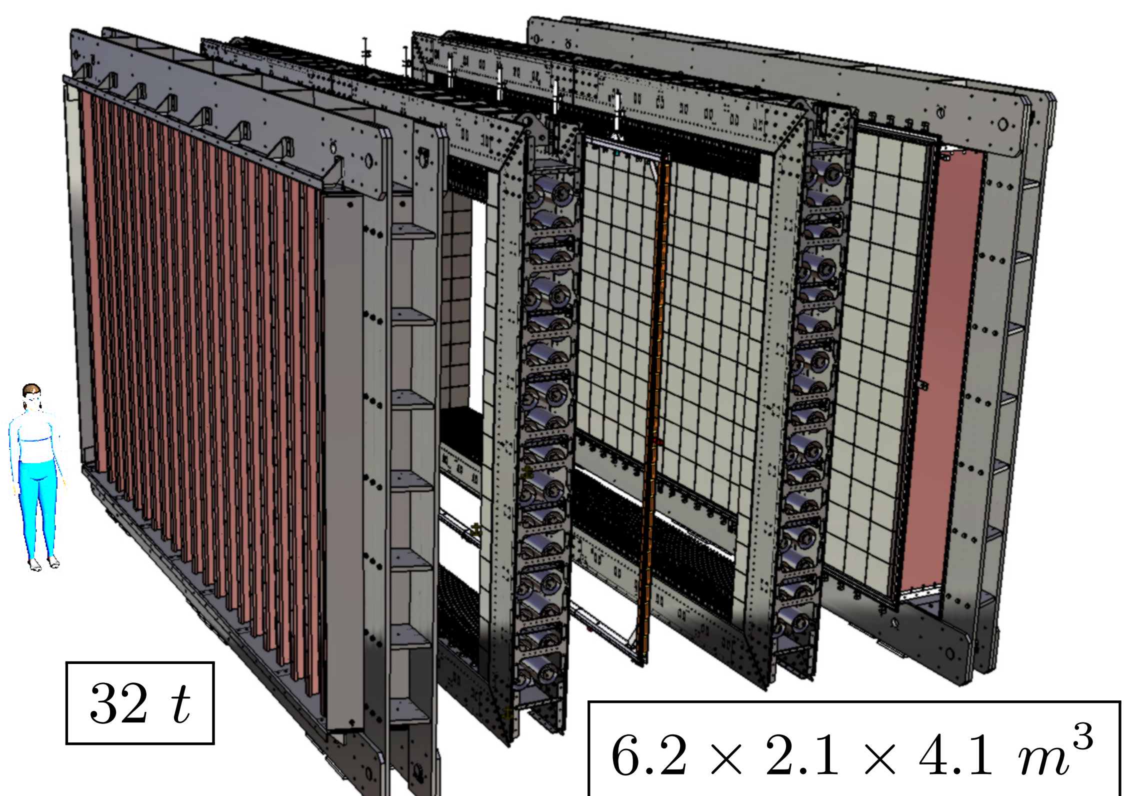
SuperNEMO Demonstrator Goals

Bongrand - Neutrino 2014

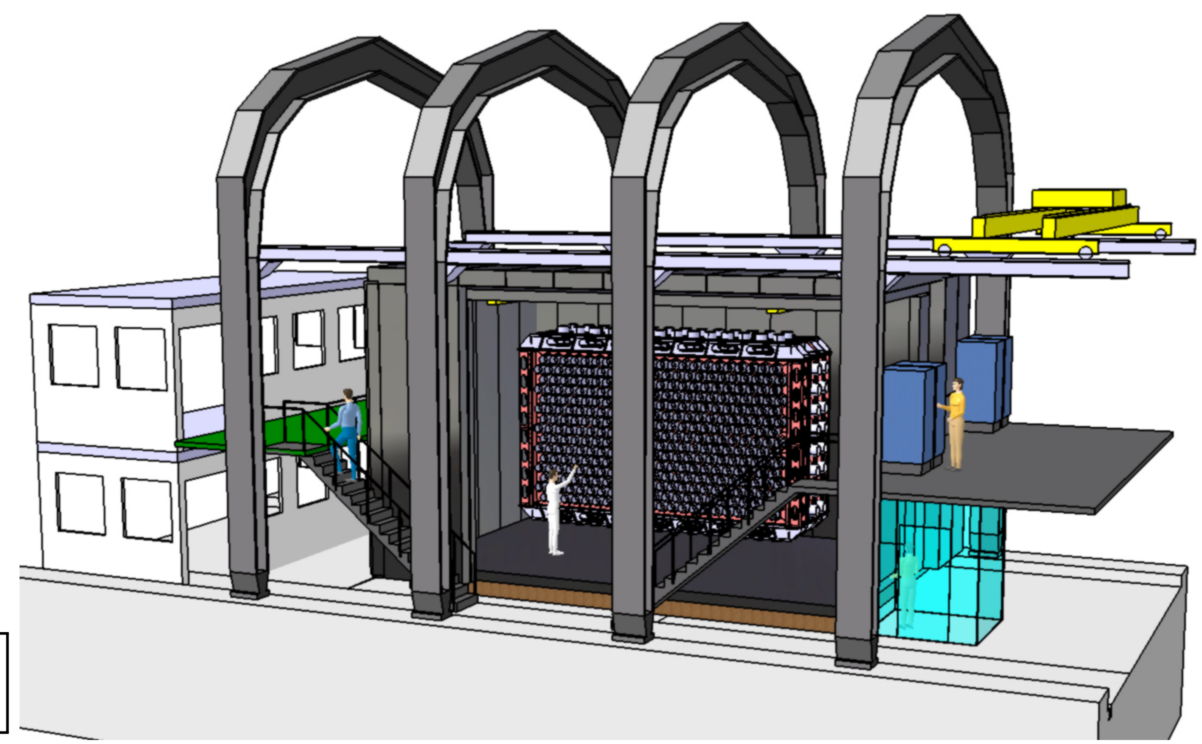
- SuperNEMO demonstrator module construction started in 2012
  - NEMO-3 sensitivity in only 5 months (90 % CL):
    $\mathcal{T}^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y $\rightarrow \langle m_\nu \rangle < 0.33 - 0.87$ eV
  - No background in the $0\nu 2\beta$ region in 2.5 years for 7 kg of ^{82}Se
  - Sensitivity after 17.5 kg·y exposure (90 % CL):
    $\mathcal{T}^{0\nu}_{1/2} > 6.5 \times 10^{24}$ y $\rightarrow \langle m_\nu \rangle < 0.20 - 0.40$ eV



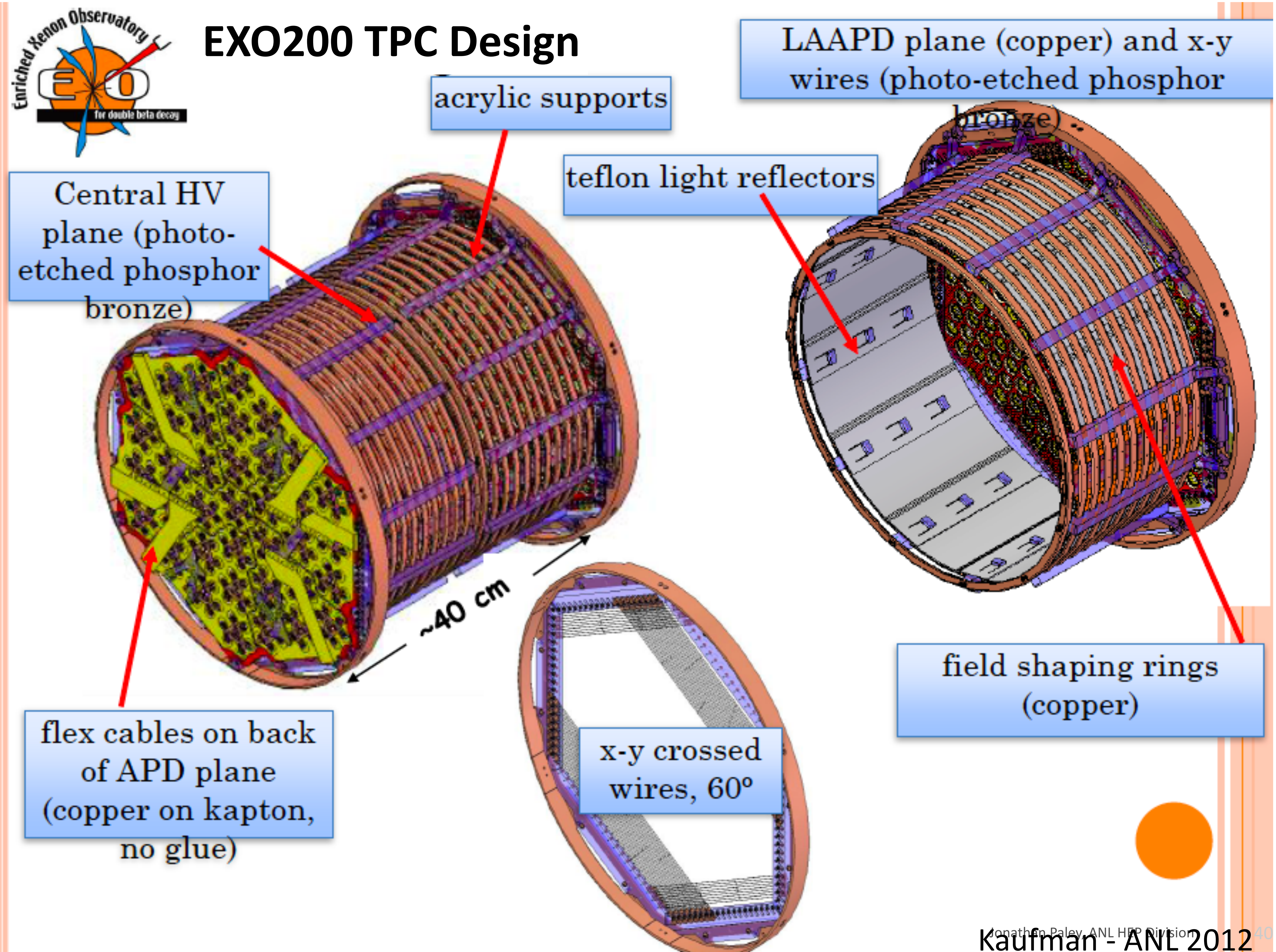
- Commissioning and physics data taking expected in Summer 2015



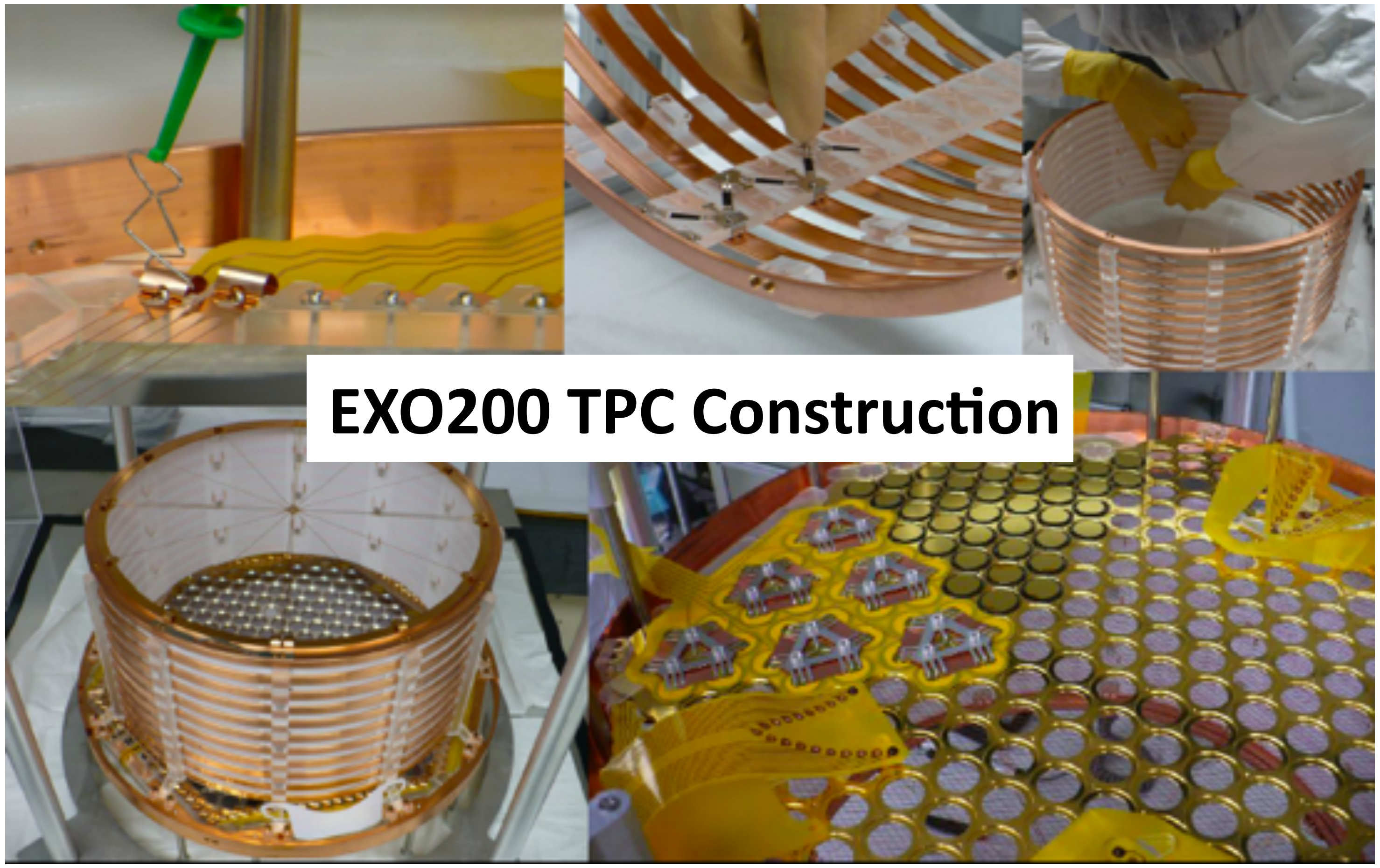
Replacing NEMO-3 in the actual LSM



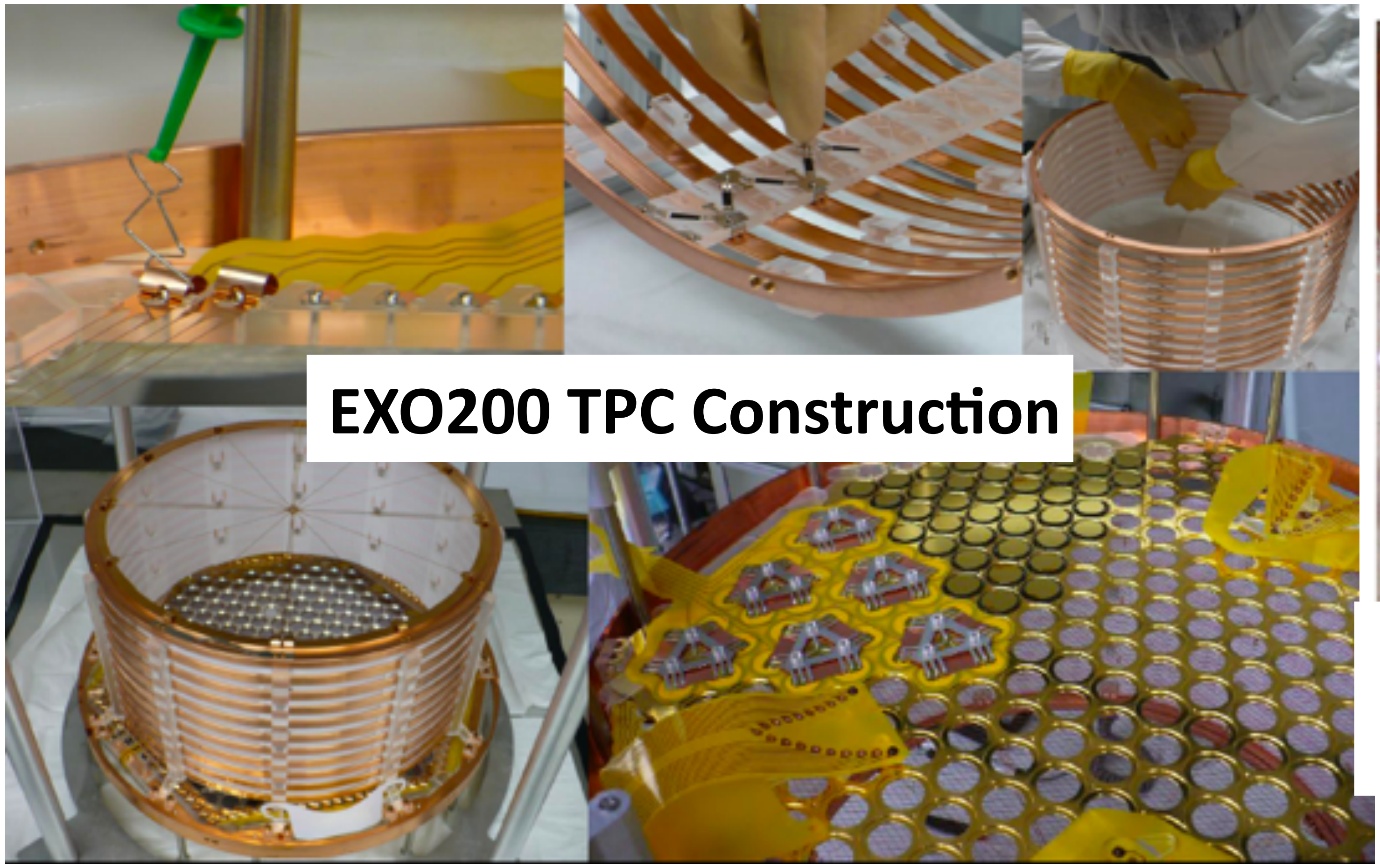
EXO-200


Enriched Xenon Observatory
for double beta decay
EXO200 TPC Design
acrylic supports
LAAPD plane (copper) and x-y wires (photo-etched phosphor bronze)
teflon light reflectors
Central HV plane (photo-etched phosphor bronze)
~40 cm
field shaping rings (copper)
flex cables on back of APD plane (copper on kapton, no glue)
x-y crossed wires, 60°
Jonathan Paley, ANL HEP Division

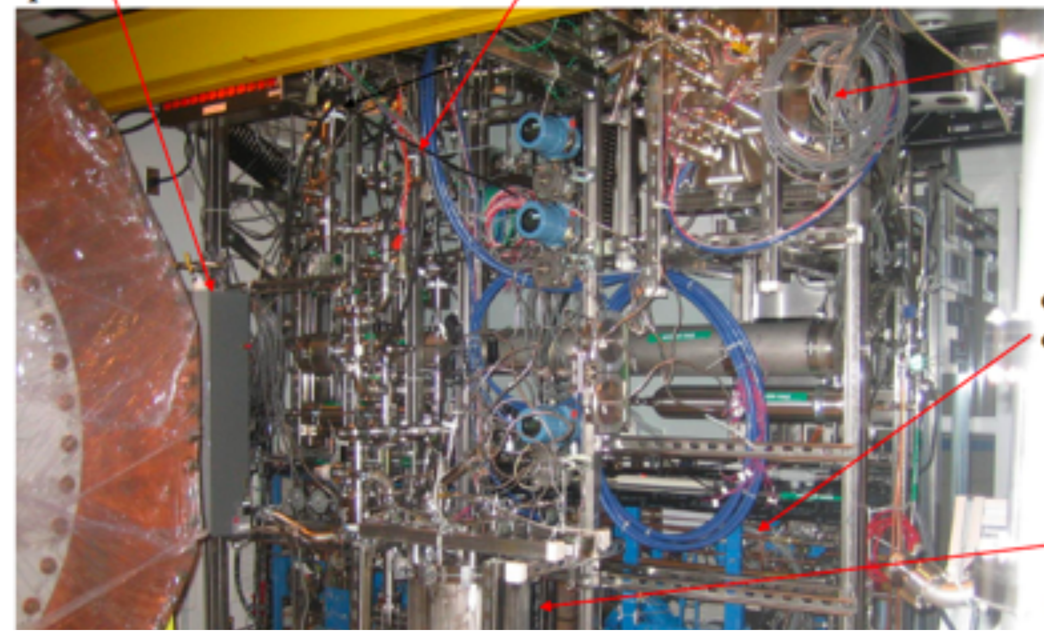
EXO-200



EXO-200

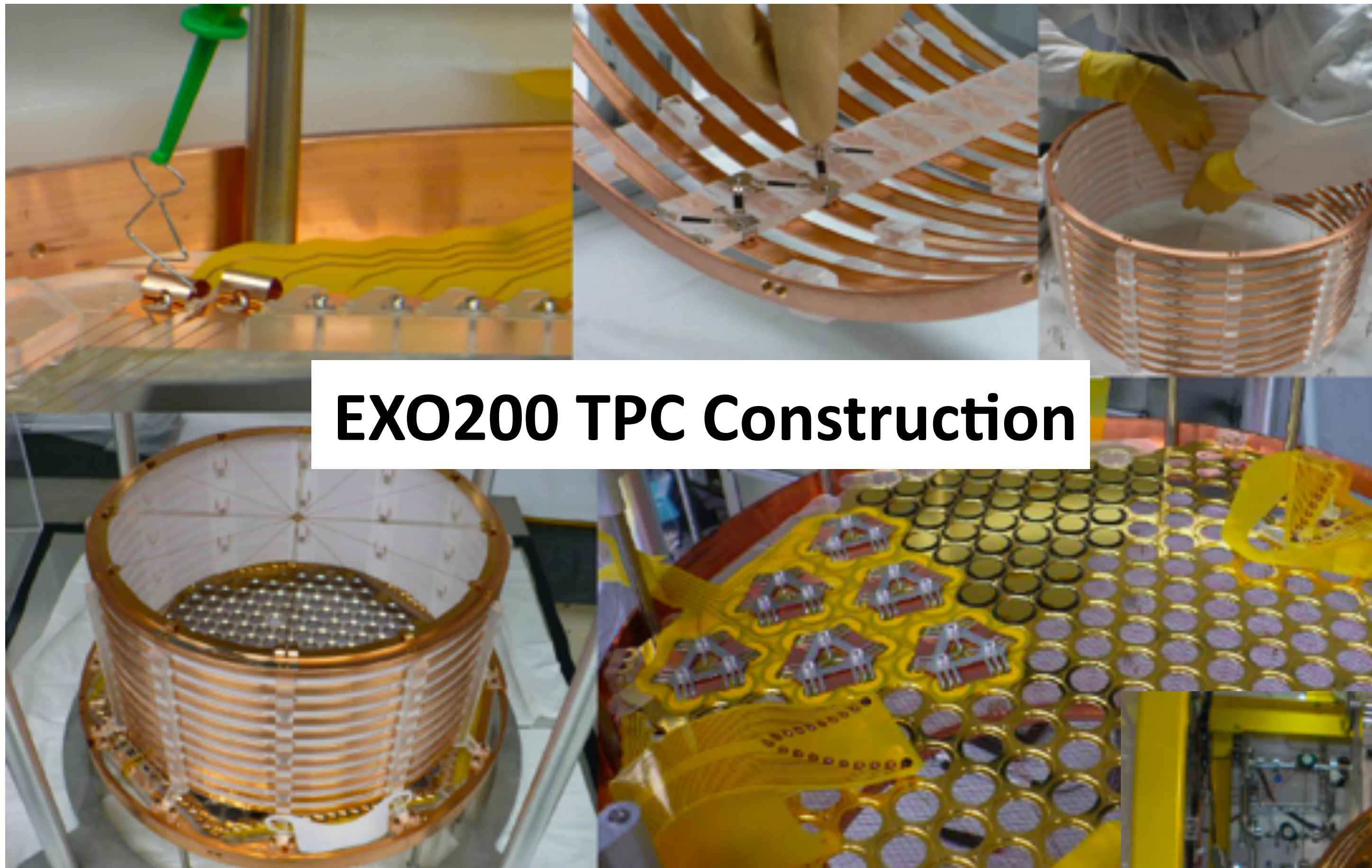


EXO200 TPC Construction

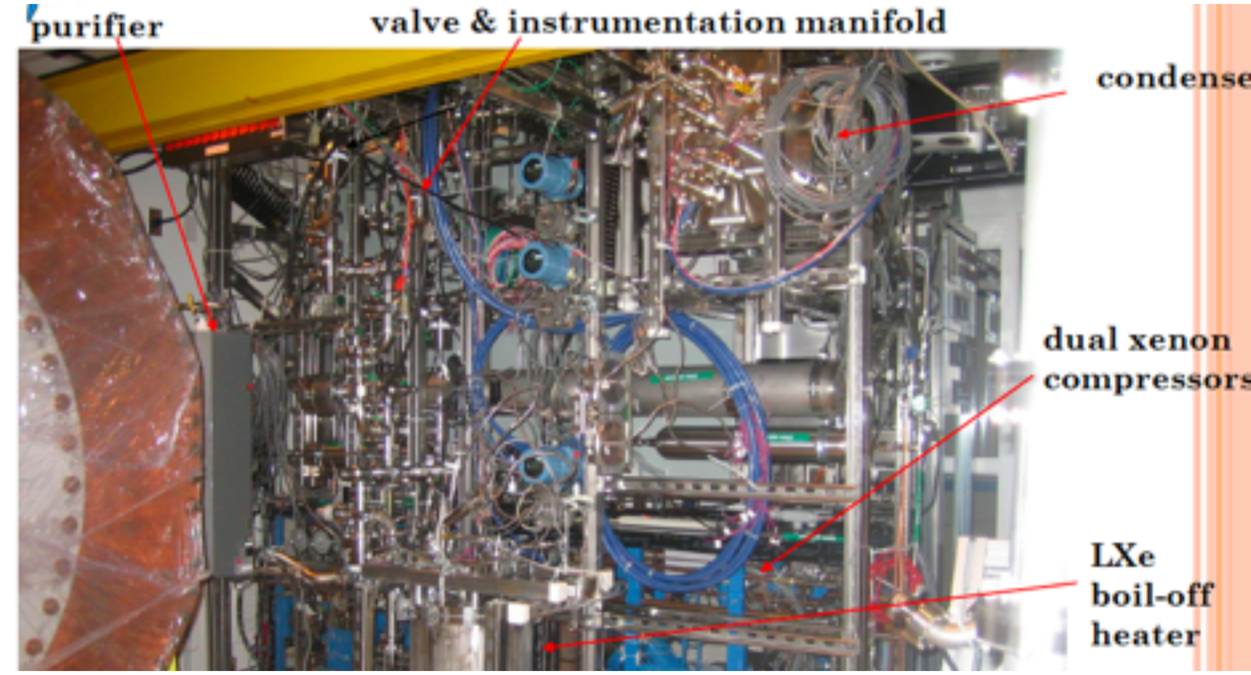


EXO200 Xenon Handling and Purificatin System

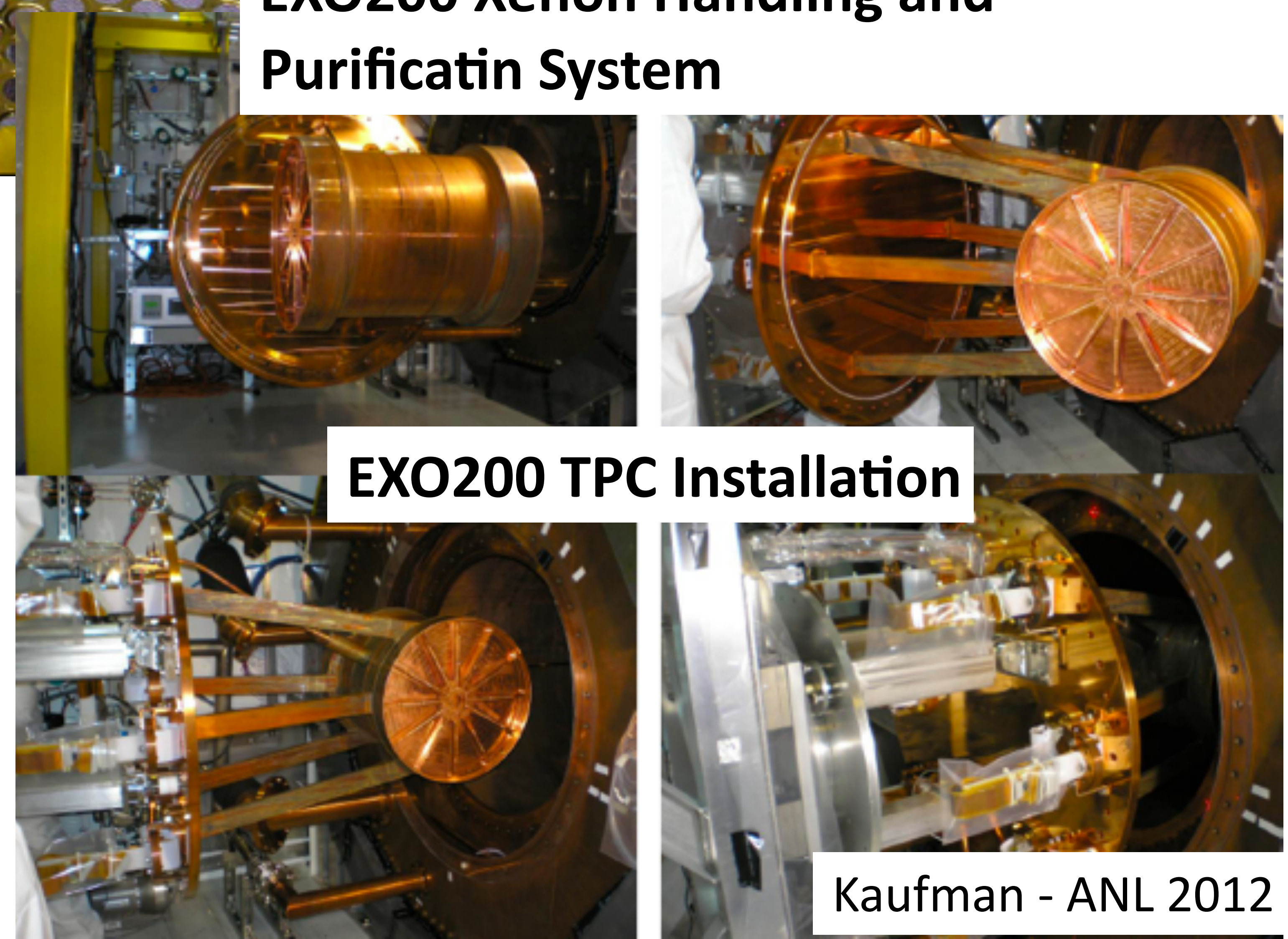
EXO-200



EXO200 TPC Construction

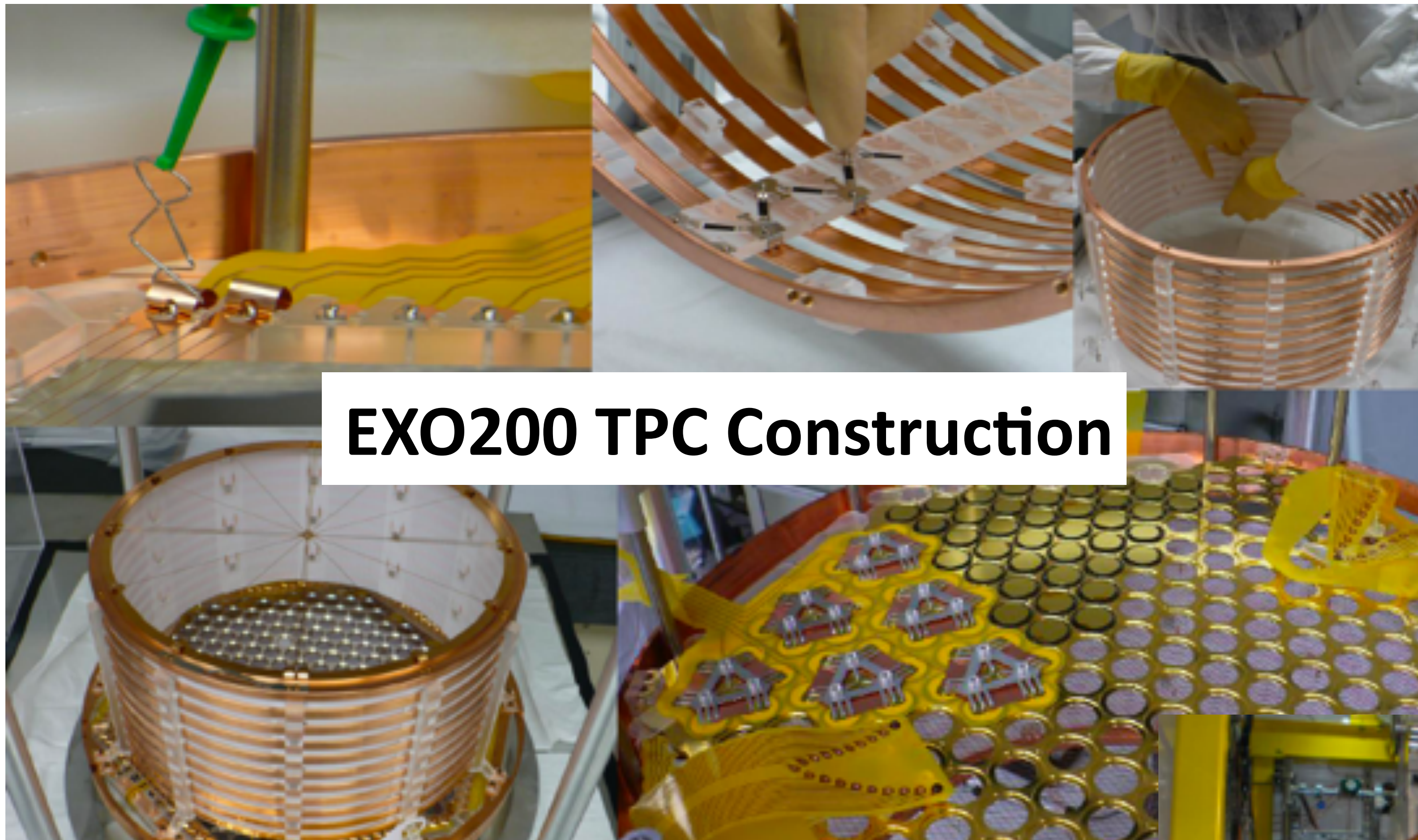


EXO200 Xenon Handling and Purificatin System

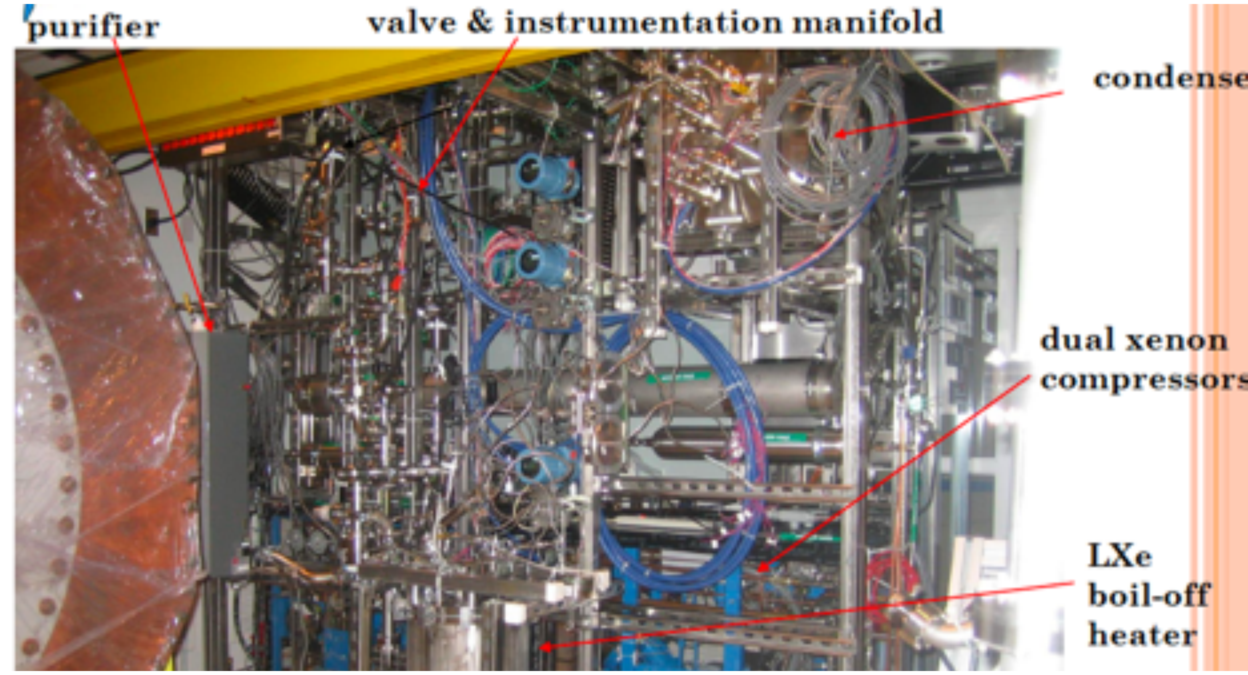


EXO200 TPC Installation

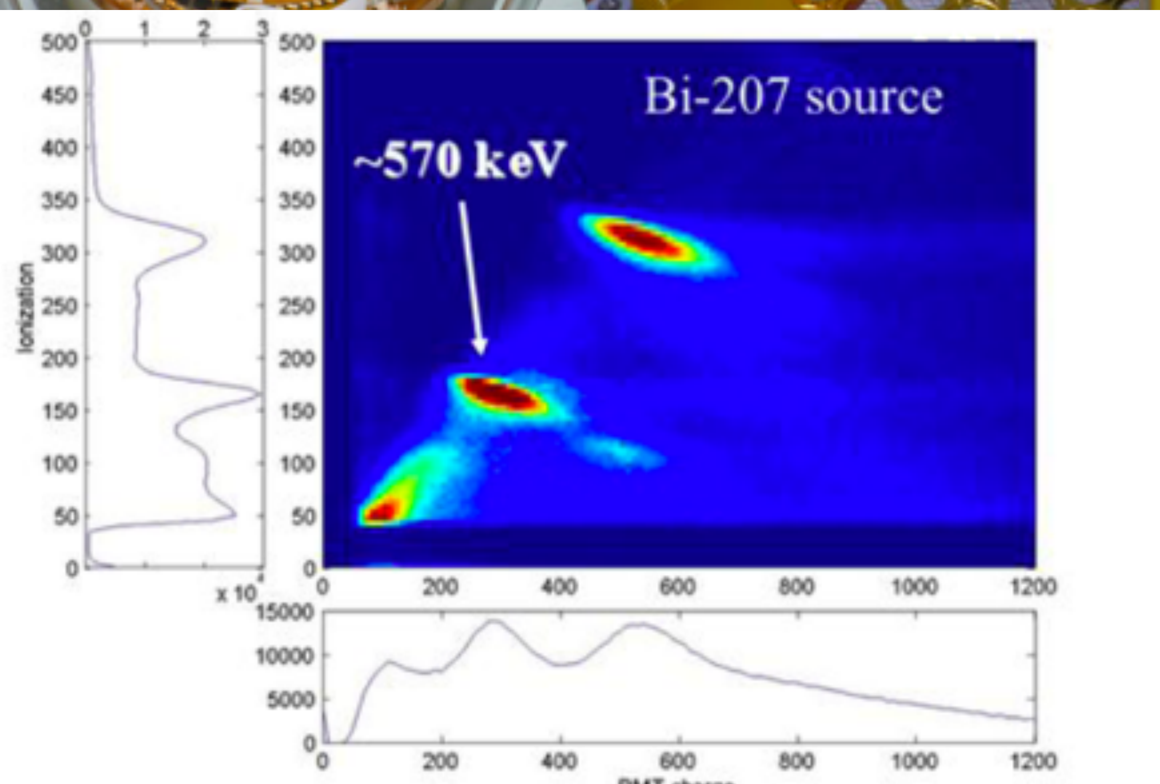
EXO-200



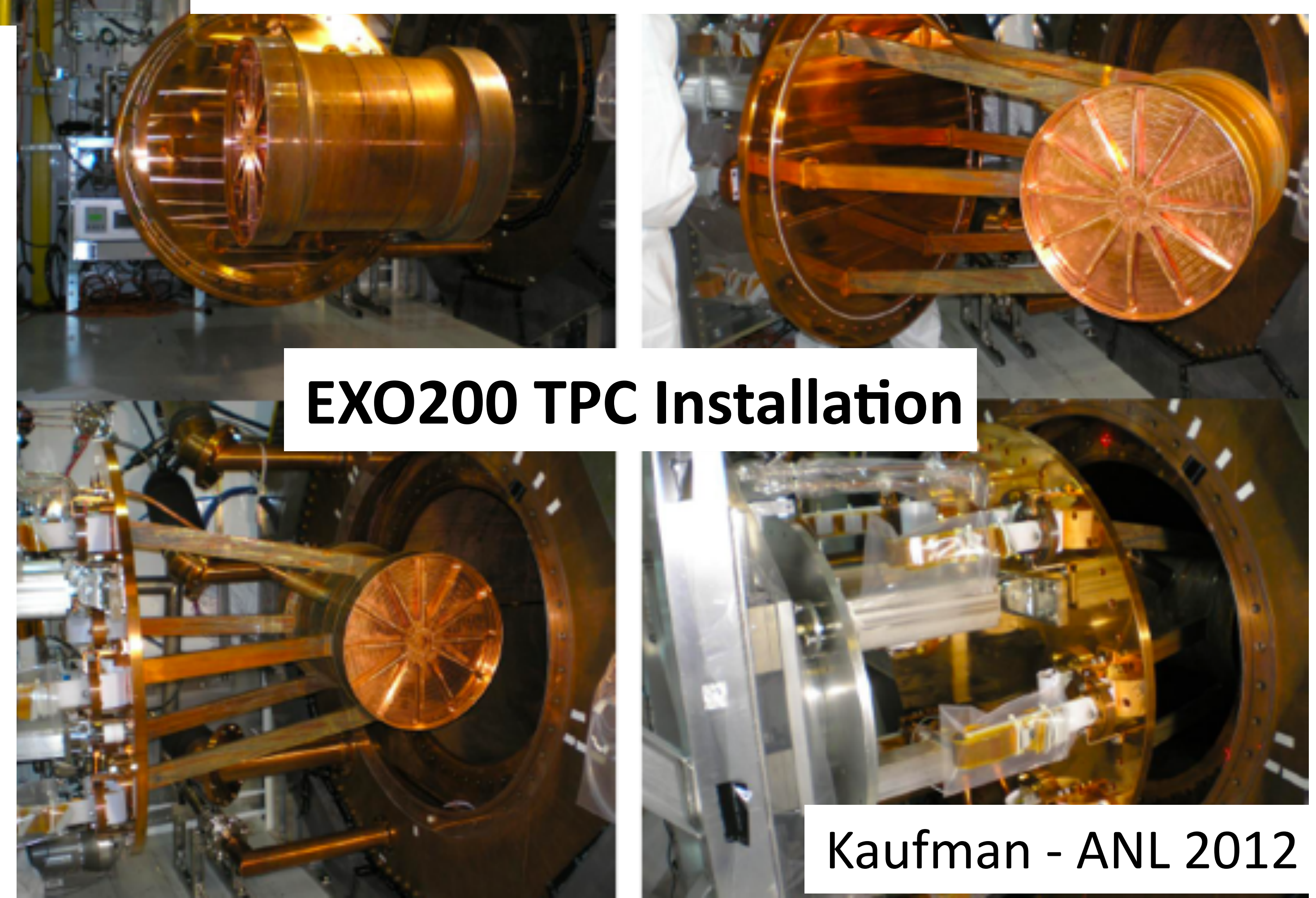
EXO200 TPC Construction



EXO200 Xenon Handling and Purificatin System



Ionization alone: 3.8% @ 570 keV or 1.8 % @ Q(ββ)
Ionization & Scintillation: 3.0% @ 570 keV or 1.4 % @ Q(ββ)
E.Conti et al., *Phys. Rev.* B **68** 054201 (2003)

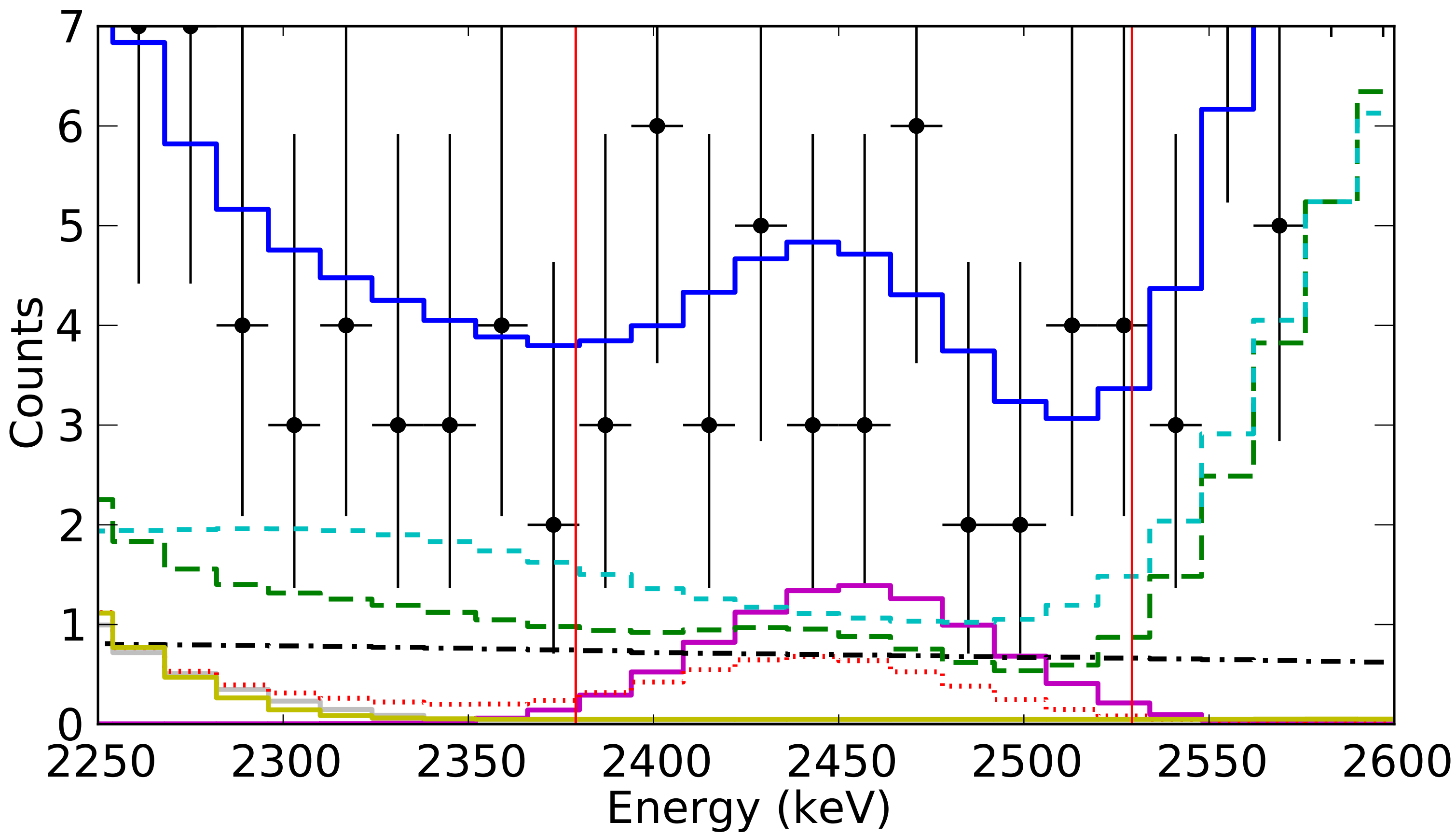


EXO200 TPC Installation

EXO-200

Marino - Neutrino 2014

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:

$T_{1/2}^{0\nu\beta\beta} > 1.1\cdot10^{25}$ yr

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

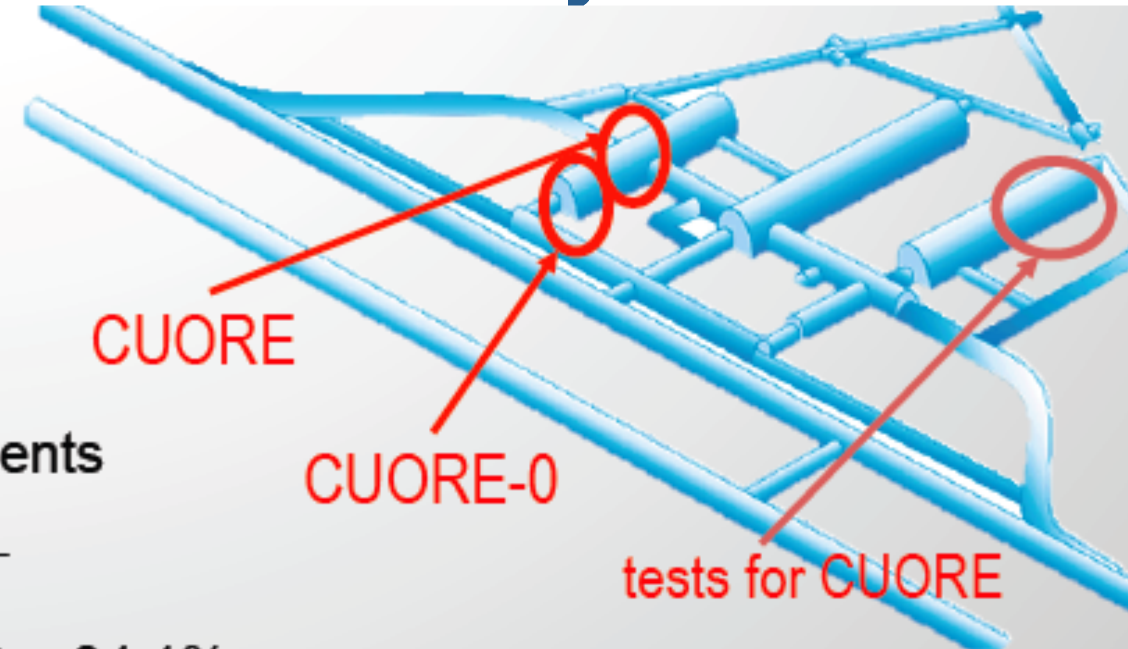
(90% C.L.)

Nature **(2014)**

doi:10.1038/nature13432

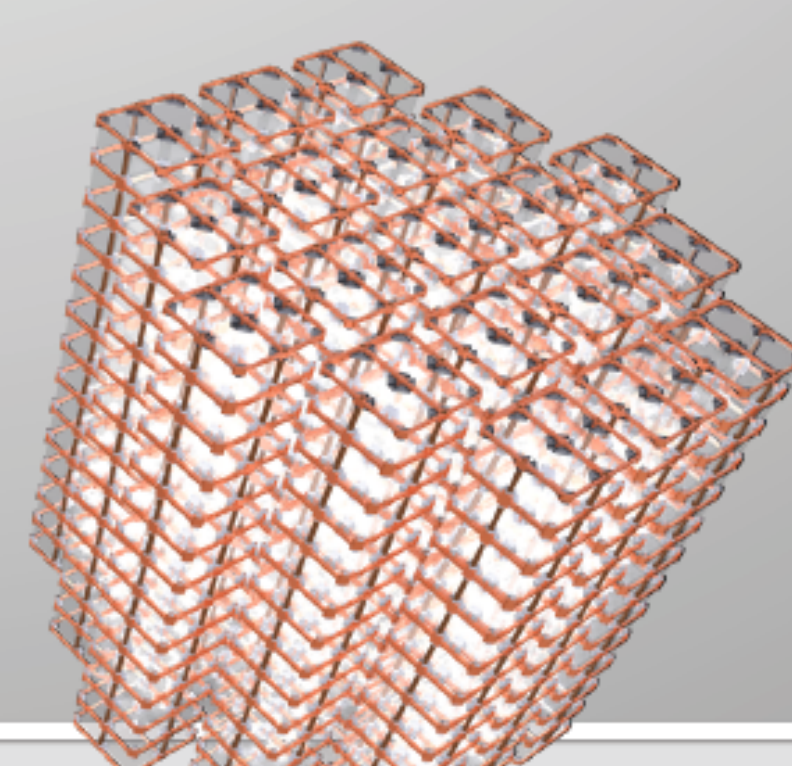
Neutrinoless Double Beta Decay

CUORE experiment



Cryogenic Underground Observatory for Rare Events

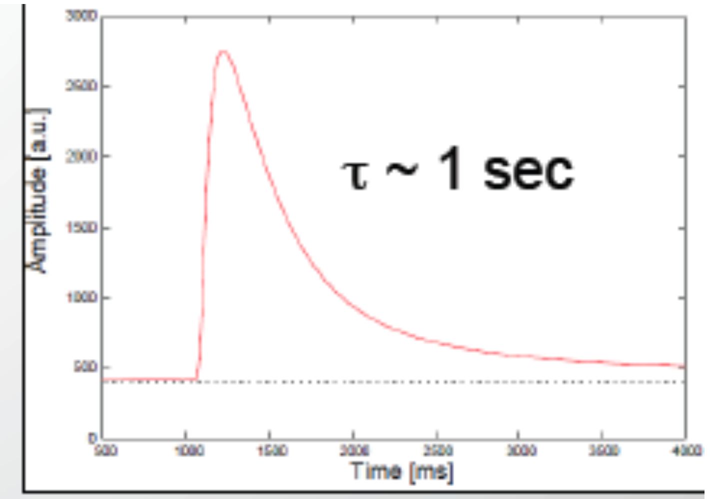
Source:	^{130}Te: $^{130}Te \rightarrow {}^{130}Xe + 2\,e^-$
	$Q_{\beta\beta}$ = 2527 keV a.i. (^{130}Te) = 34.1%
Location:	LNGS (Italy) a 3500 m.w.e. shield
Technique:	bolometric
Detector:	988 TeO_2 bolometers (~1 ton)
	19 towers, 13 floors
	9.6×10^{26} ^{130}Te nuclei

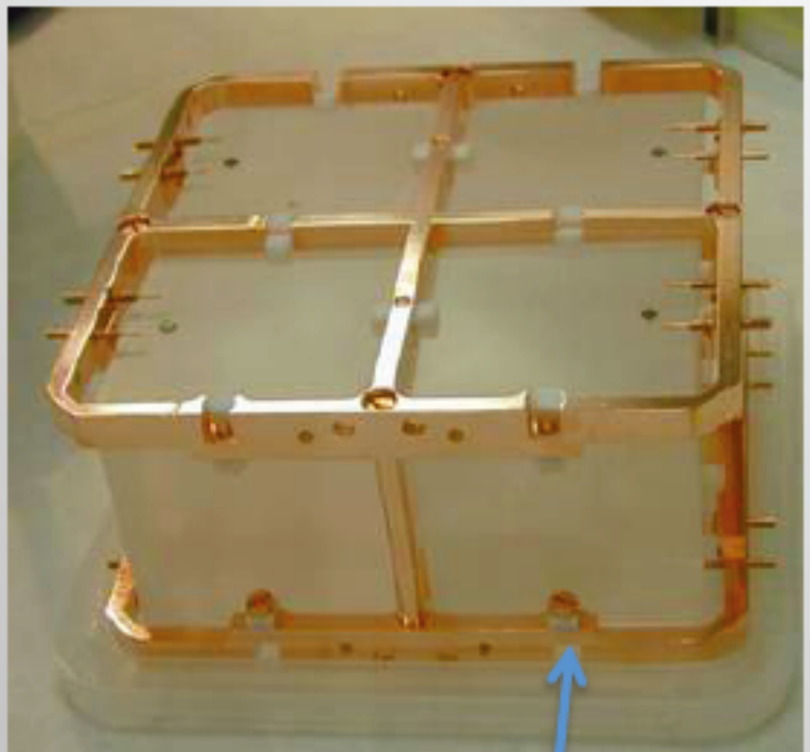


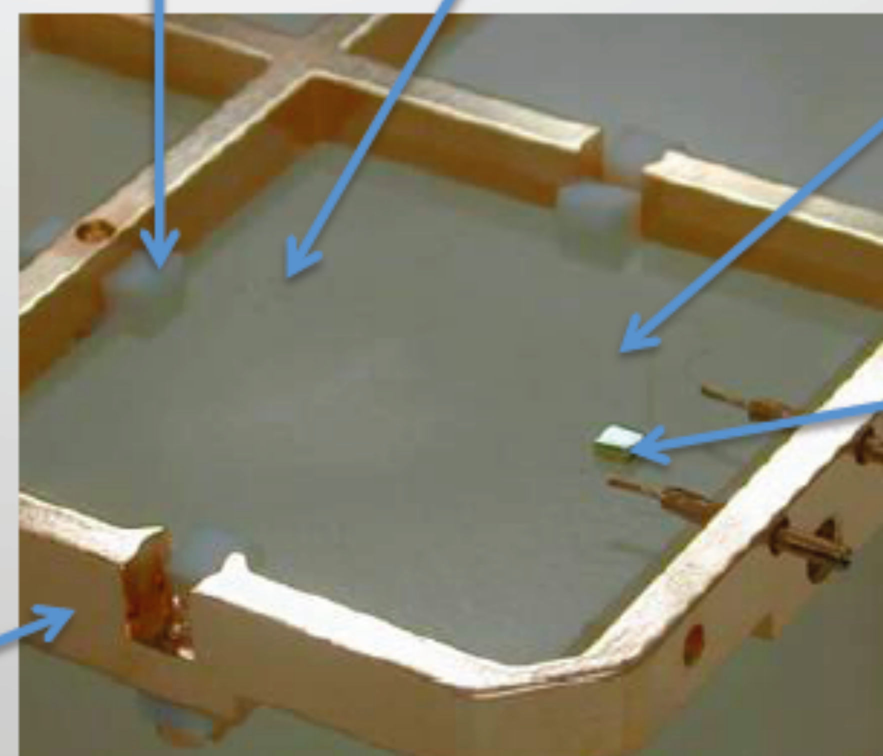
Pedretti - Neutrino 2012

Neutrinoless Double Beta Decay

TeO_2 Bolometers







PTFE pieces

TeO_2 crystal

25 μm gold wire connection

Neutron Transmutation Doped Ge sensor

Copper holder

Pros: - good energy resolution
- different sources could be investigated
- high efficiency (internal sources)

Cons: - no dead layer
- low temperature tech required
- slow pulses

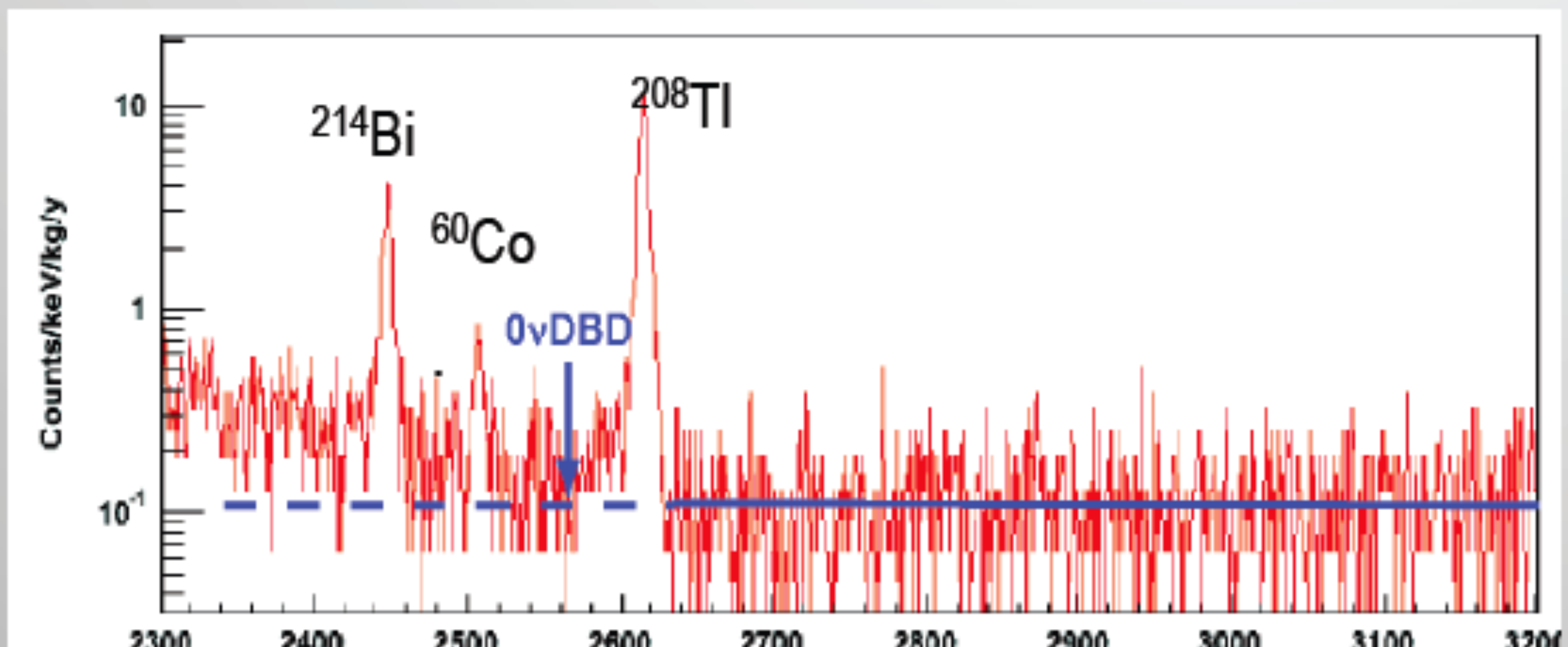
These advantages could be crucial in view of future experiments that aim to investigate all the inverted hierarchy region

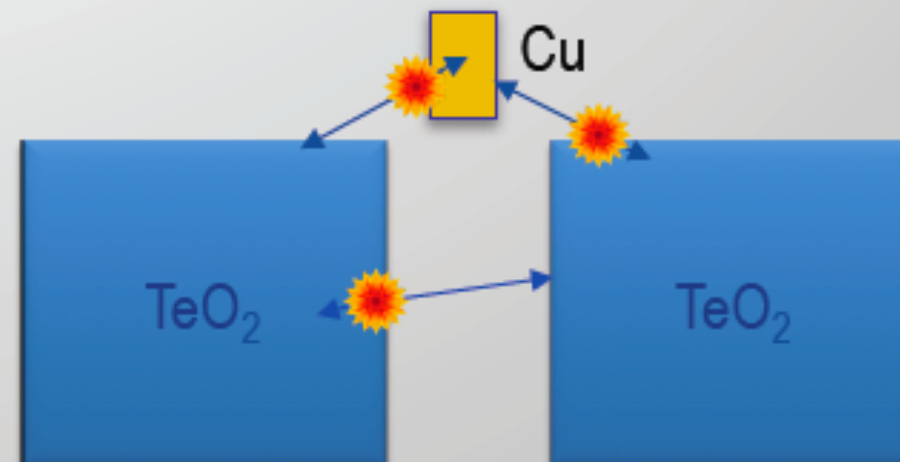
Pedretti - Neutrino 2012

CUORICINO lesson: background

Sensitivity of current generation bolometric DBD experiment is limited by bkg.

MC: the background in CUORICINO is due to degraded alpha particles which release only part of their energy in the detector (surface contamination)





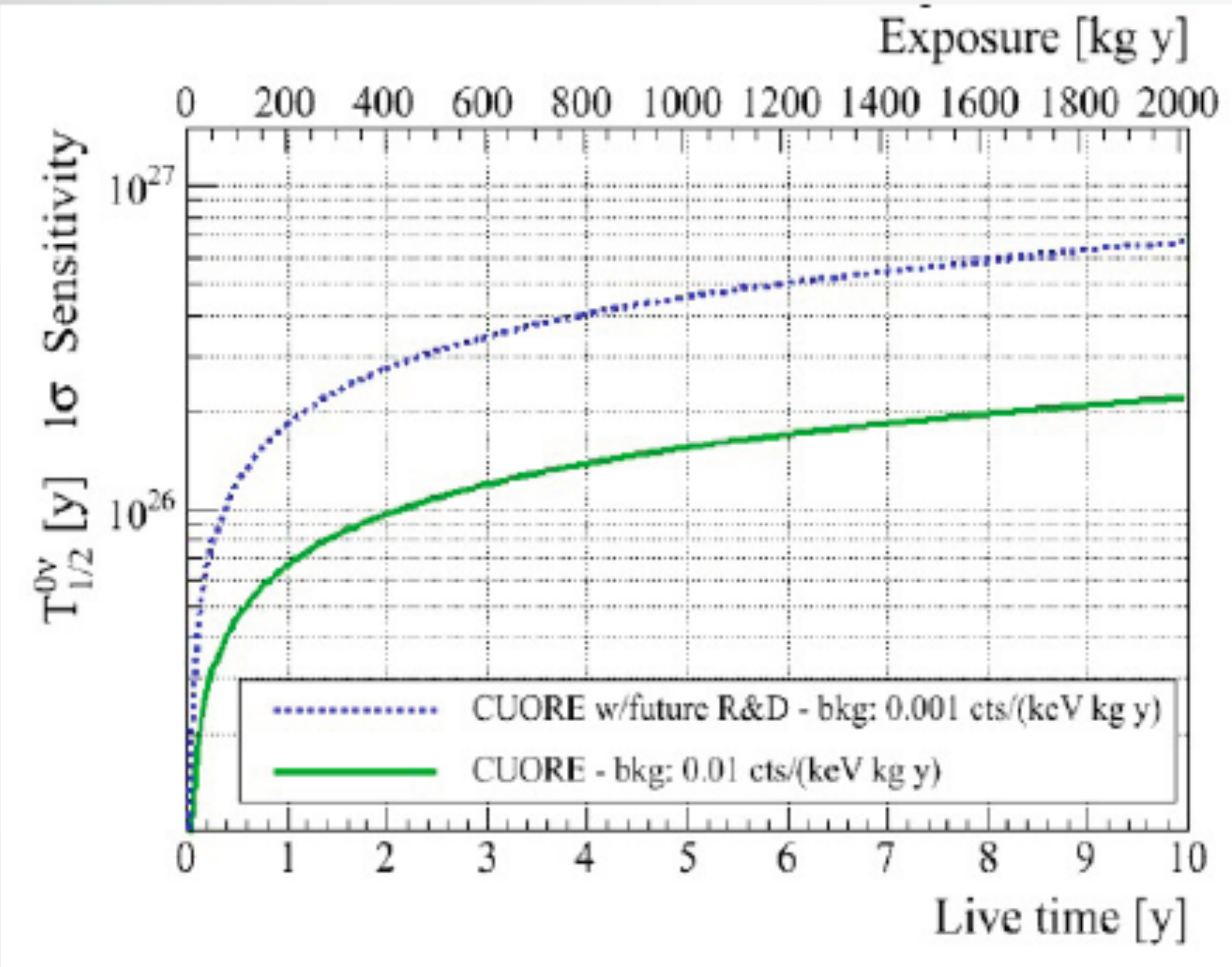
$b_{CUORICINO}$ = 0.169 c/keV/kg/y due to:

- ^{232}Th in cryostat (30 ± 10%) → γ
- TeO_2 surfaces (10 ± 5%)
- Surfaces facing detectors (50 ± 20%)

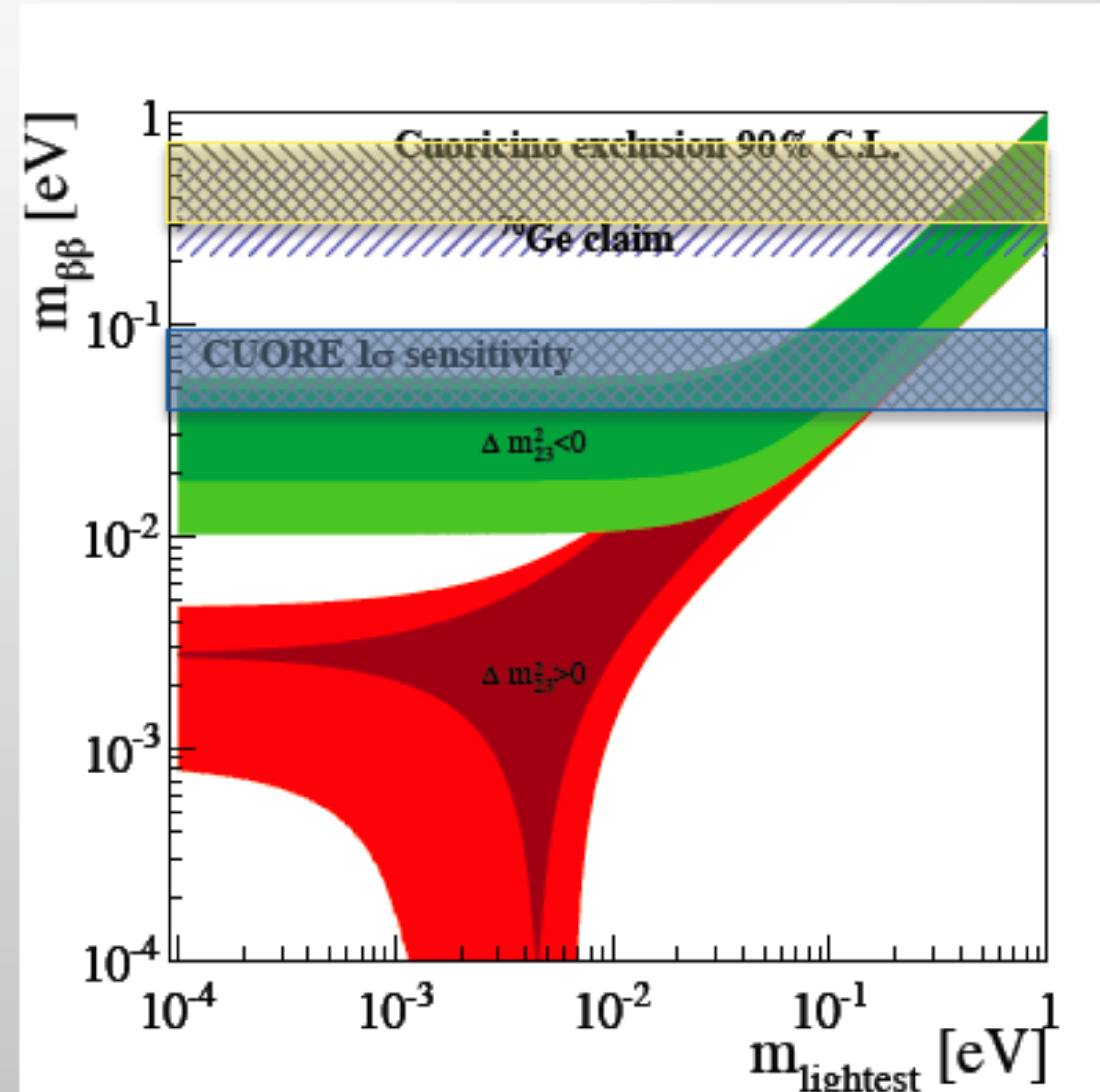
} degraded α particles

Pedretti - Neutrino 2012

CUORE sensitivity



F. Alessandria et al. [CUORE coll.]
http://arxiv.org/abs/1109.0494v1

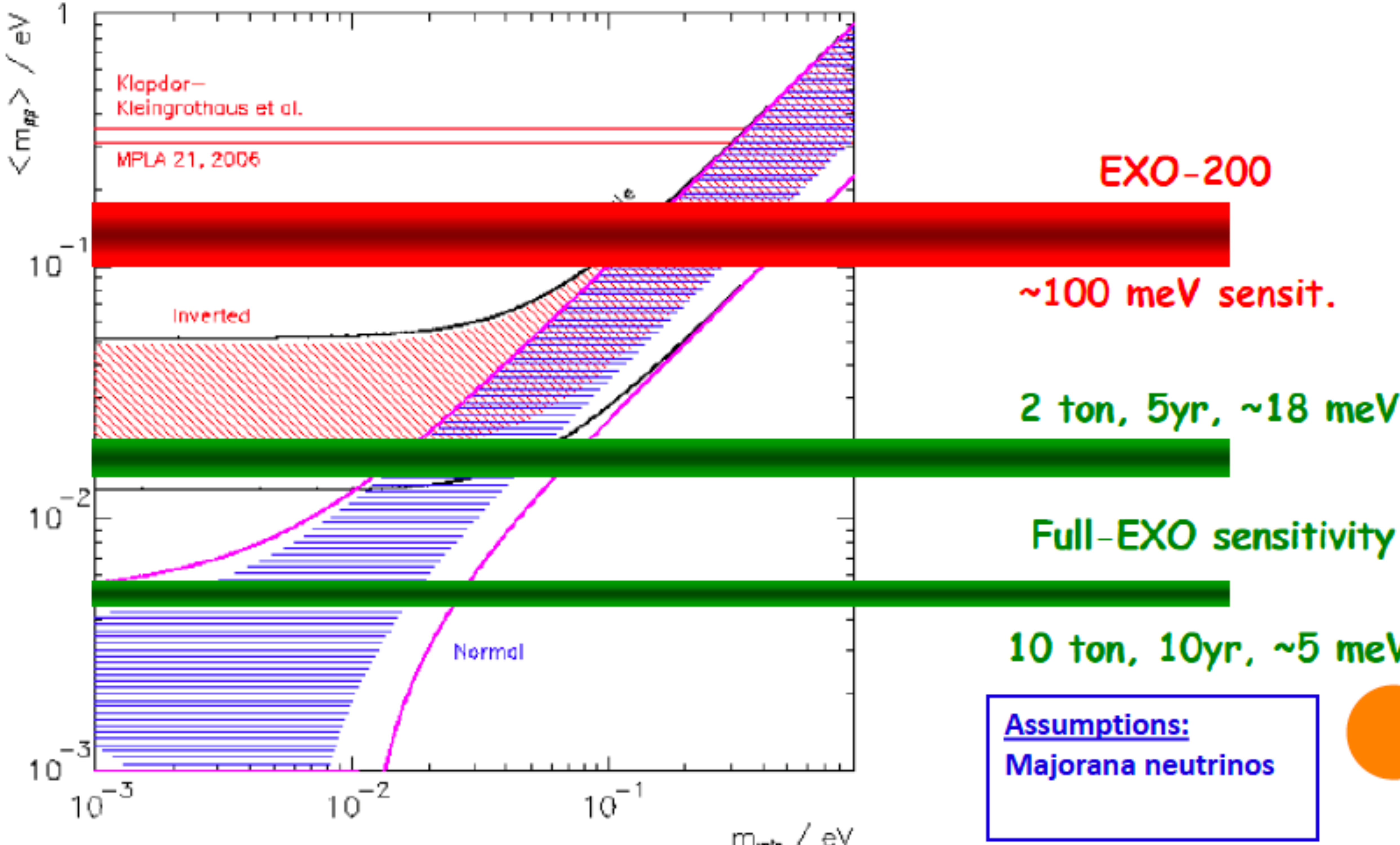


$T_{1/2}^{0\nu}$ (^{130}Te) > 1.6 x 10^{26} y (1σ)

$m_{\beta\beta}$ < 40 - 90 meV

Neutrinoless Double Beta Decay

EXO Sensitivities

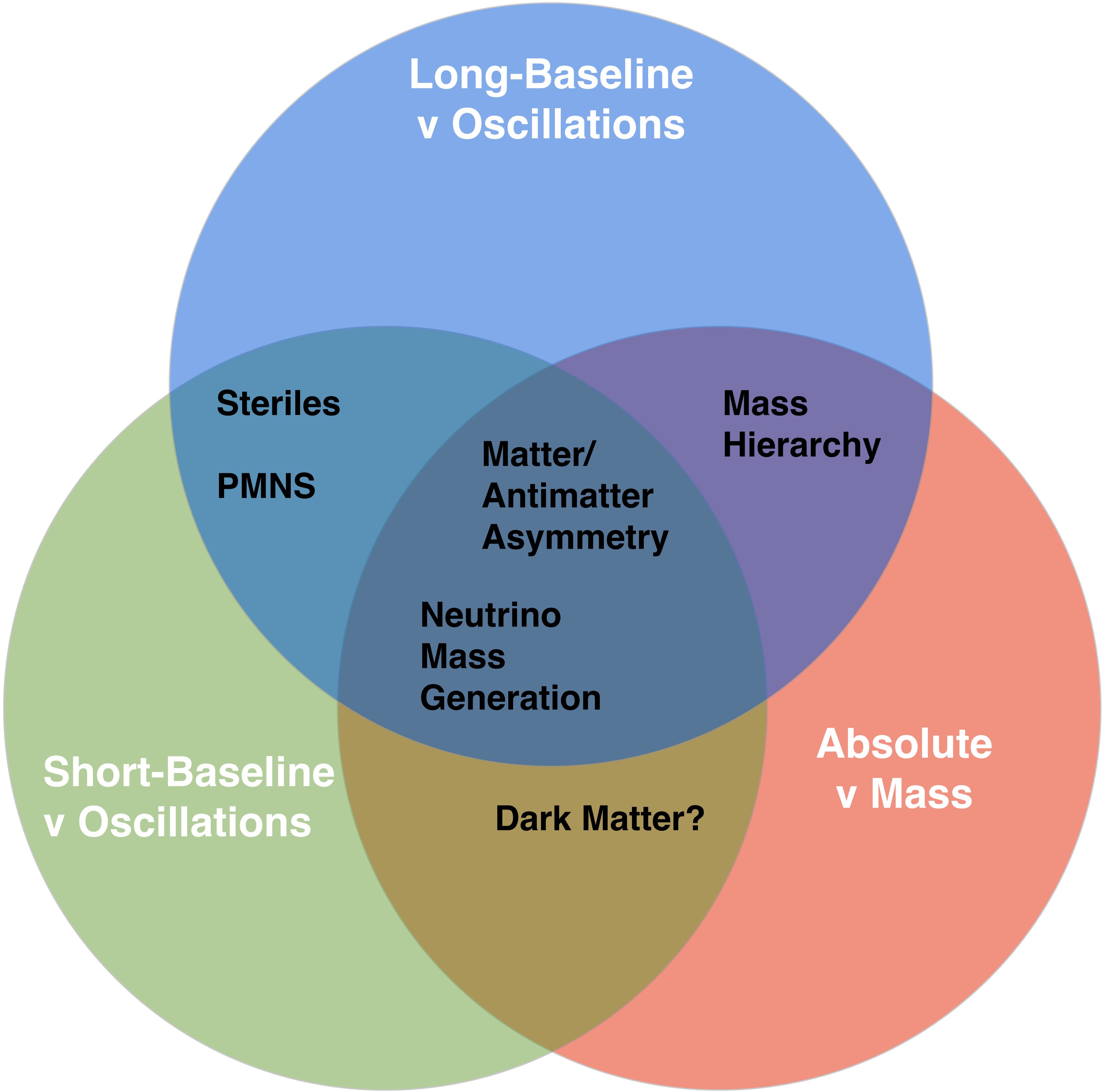


Assumptions:
Majorana neutrinos

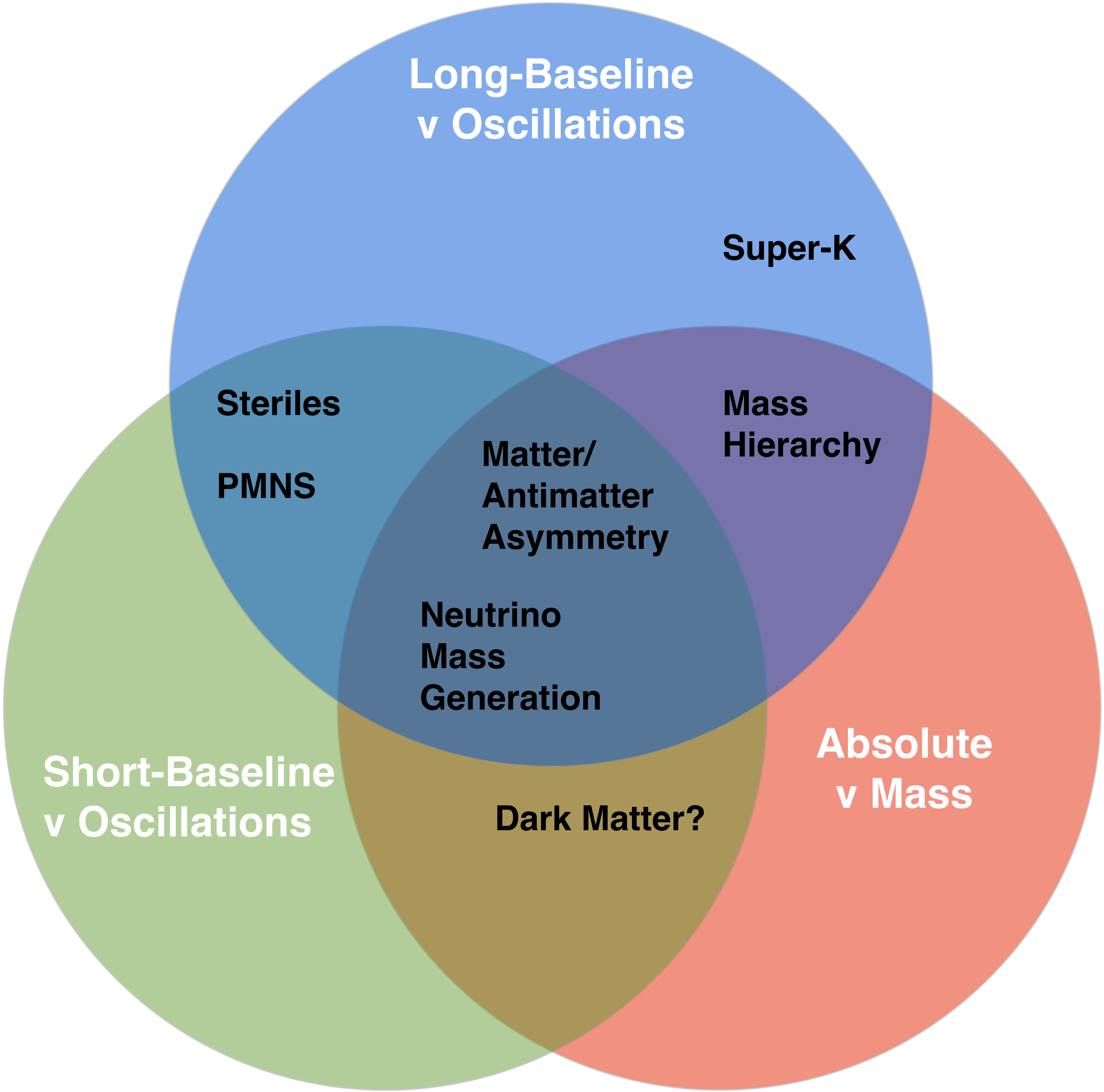
Summary

- Short-baseline reactor-based experiments have resulted in precise measurements of θ_{13}, but new calculations of reactor fluxes imply existence of sterile neutrinos.
- Short-baseline accelerator-based experiments also indicate ν_e appearance, but at the wrong Δm^2. Results imply existence of sterile neutrinos.
- Short-baseline anomalies are in stark contrast with results from long-baseline measurements. Future experiments will try to put this issue to rest.
- Neutrino mass measurements are extremely challenging!
- Direct measurements provide the best way to determine the neutrino mass.
- Indirect measurements provide several cross-checks, but rather large uncertainties.
- Neutrinoless double beta decay experiments provide an opportunity to determine not only the nature of the neutrino, but also an effective mass.

Summary


Long-Baseline
ν Oscillations
Steriles
PMNS
Matter/
Antimatter
Asymmetry
Mass
Hierarchy
Neutrino
Mass
Generation
Short-Baseline
ν Oscillations
Dark Matter?
Absolute
ν Mass

Summary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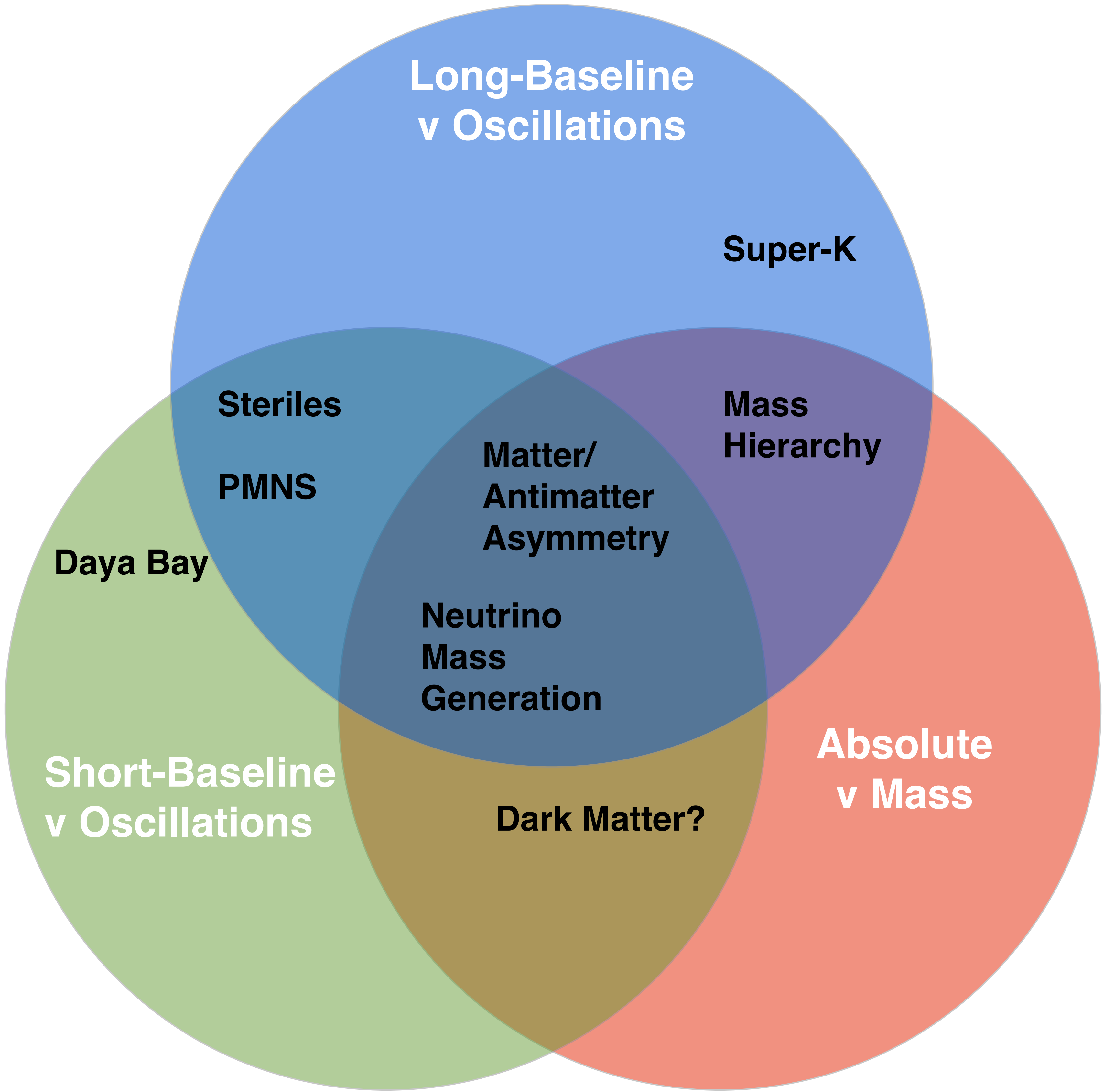
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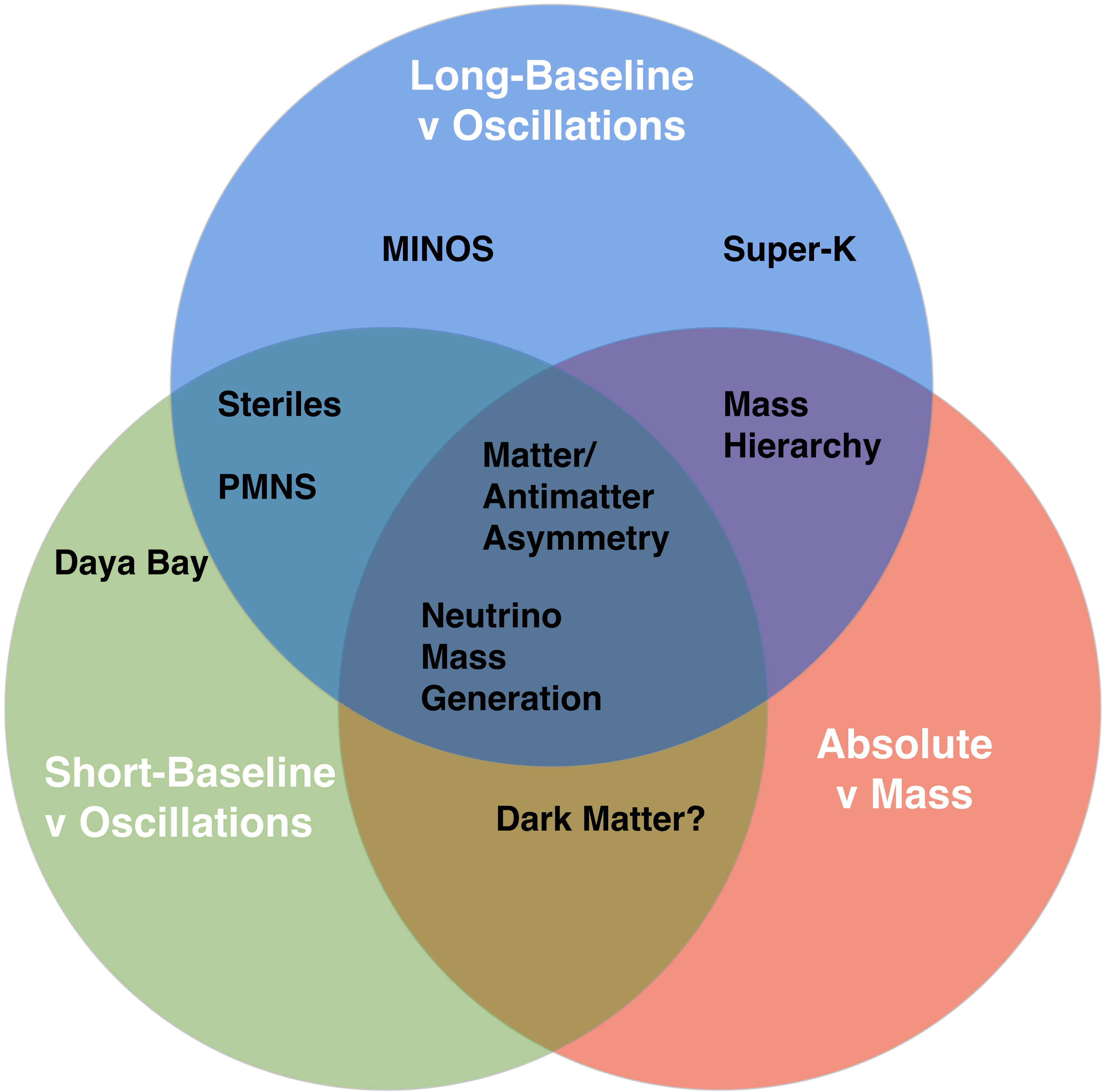
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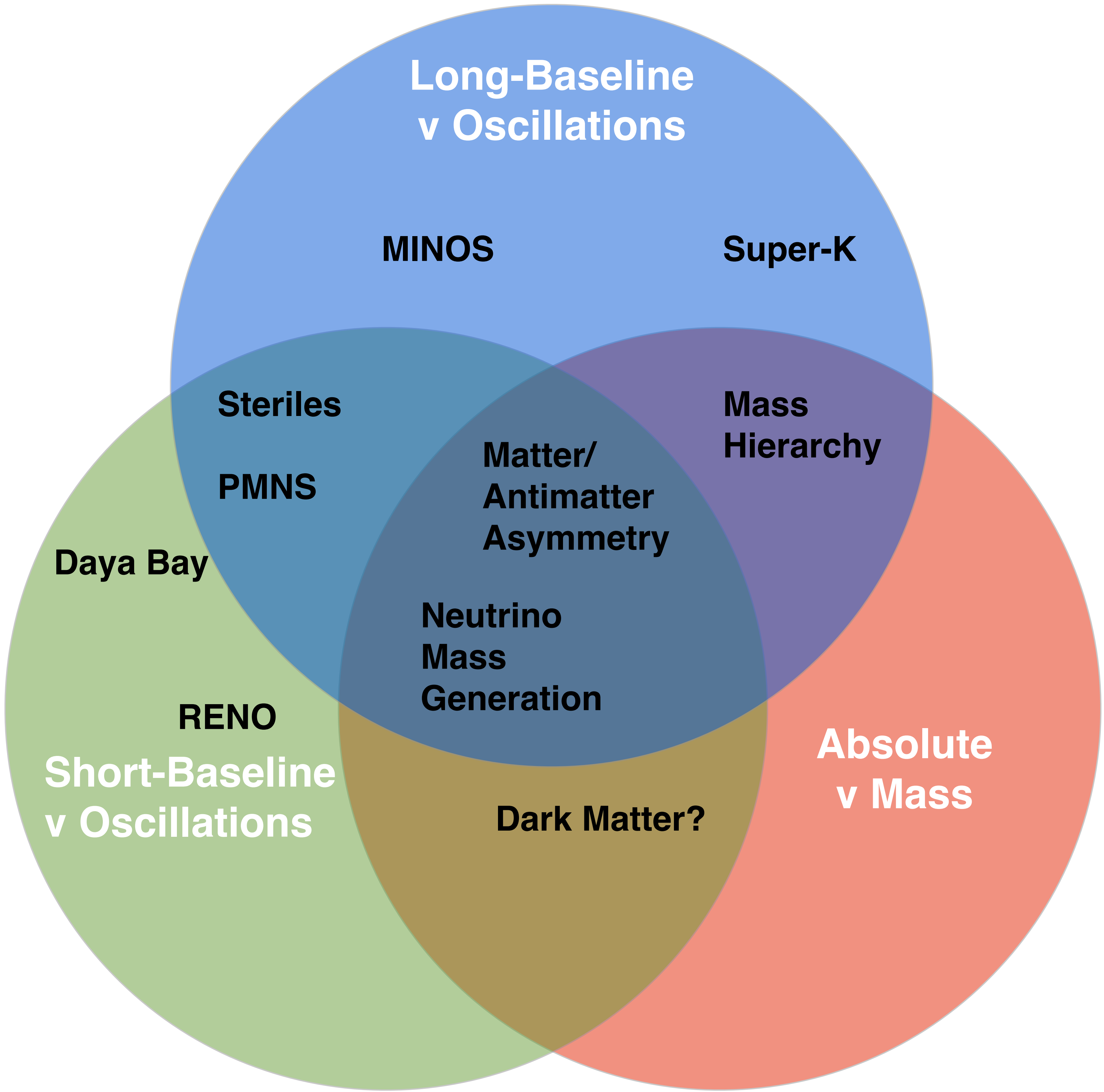

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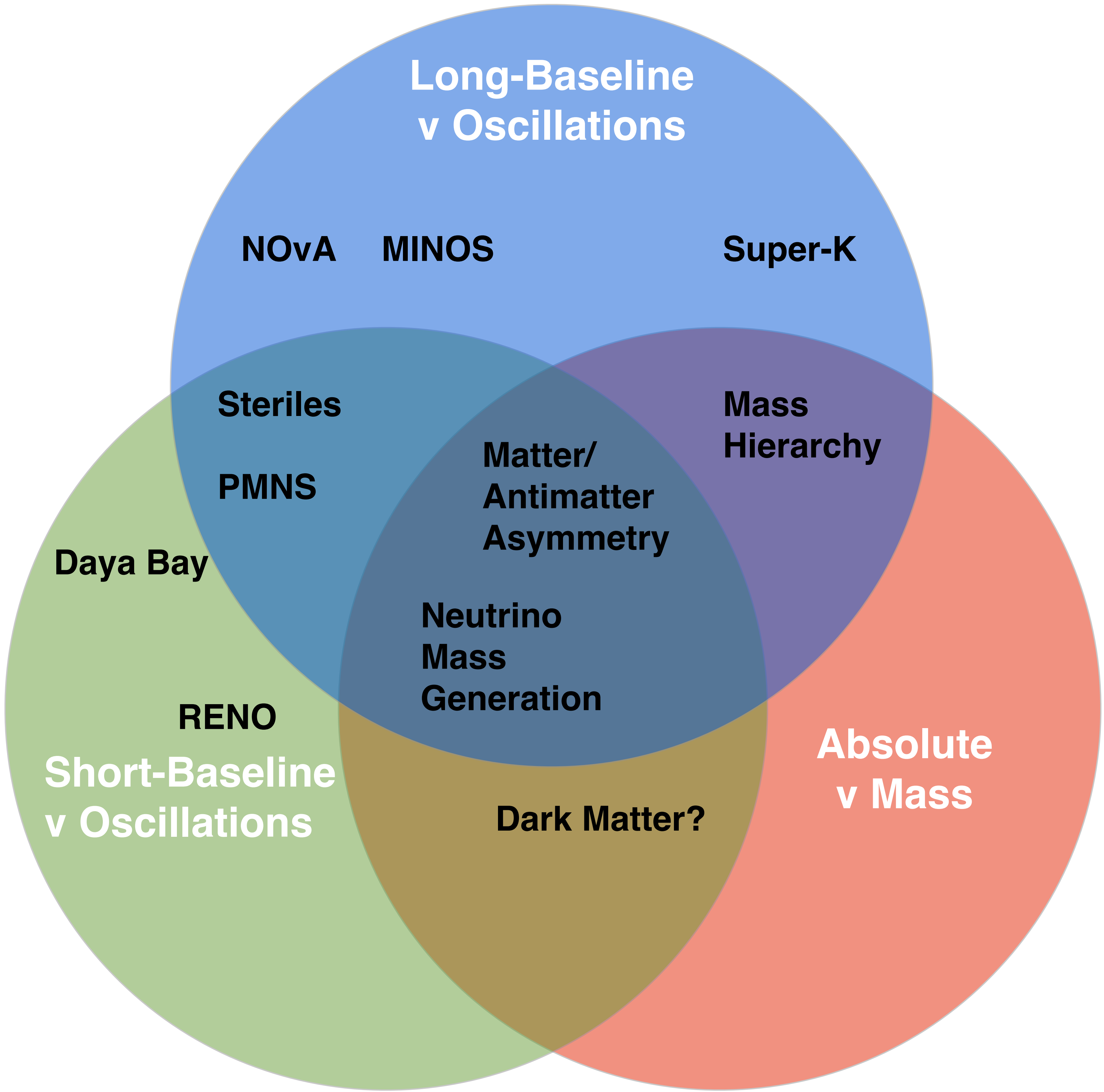

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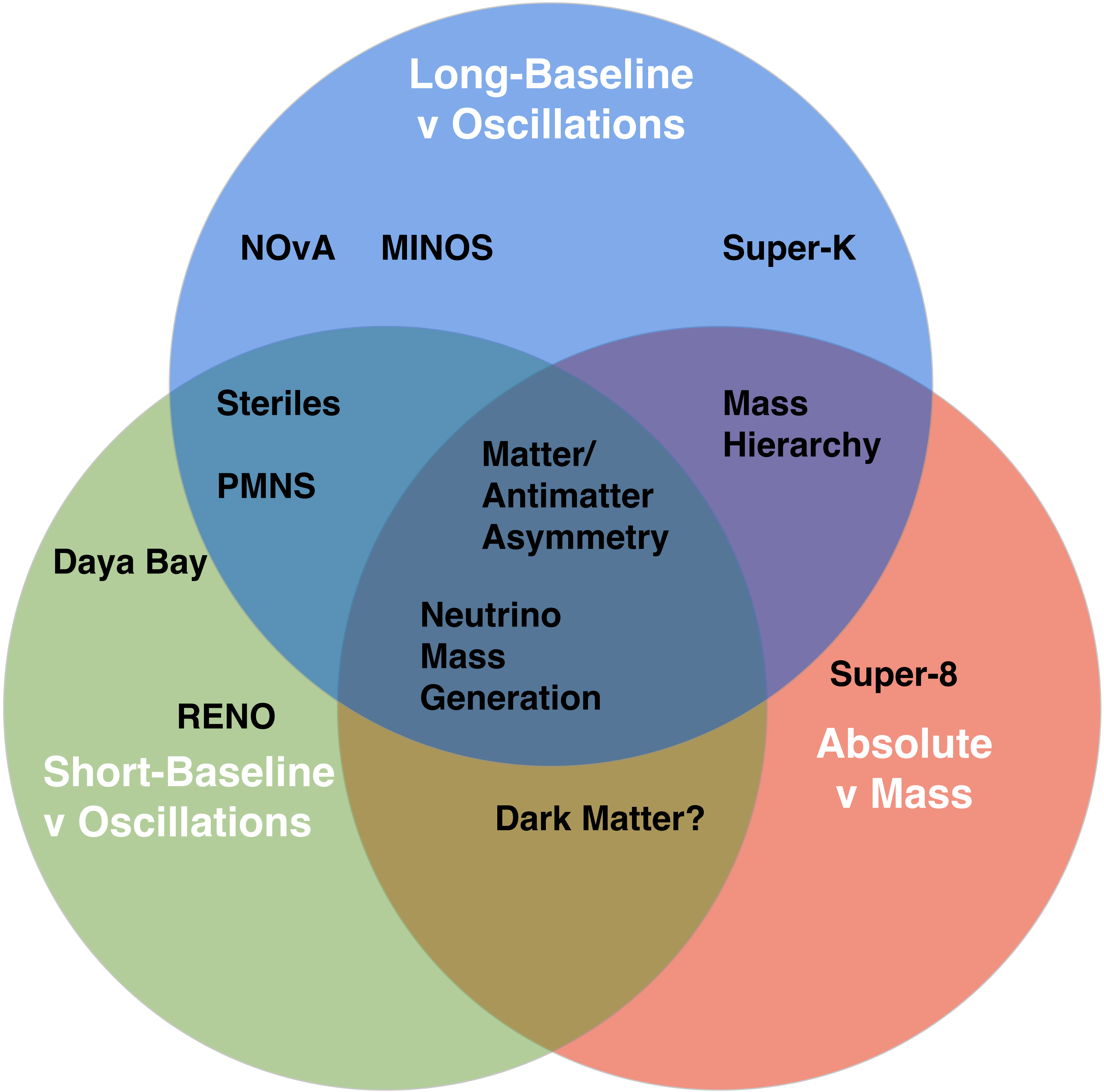

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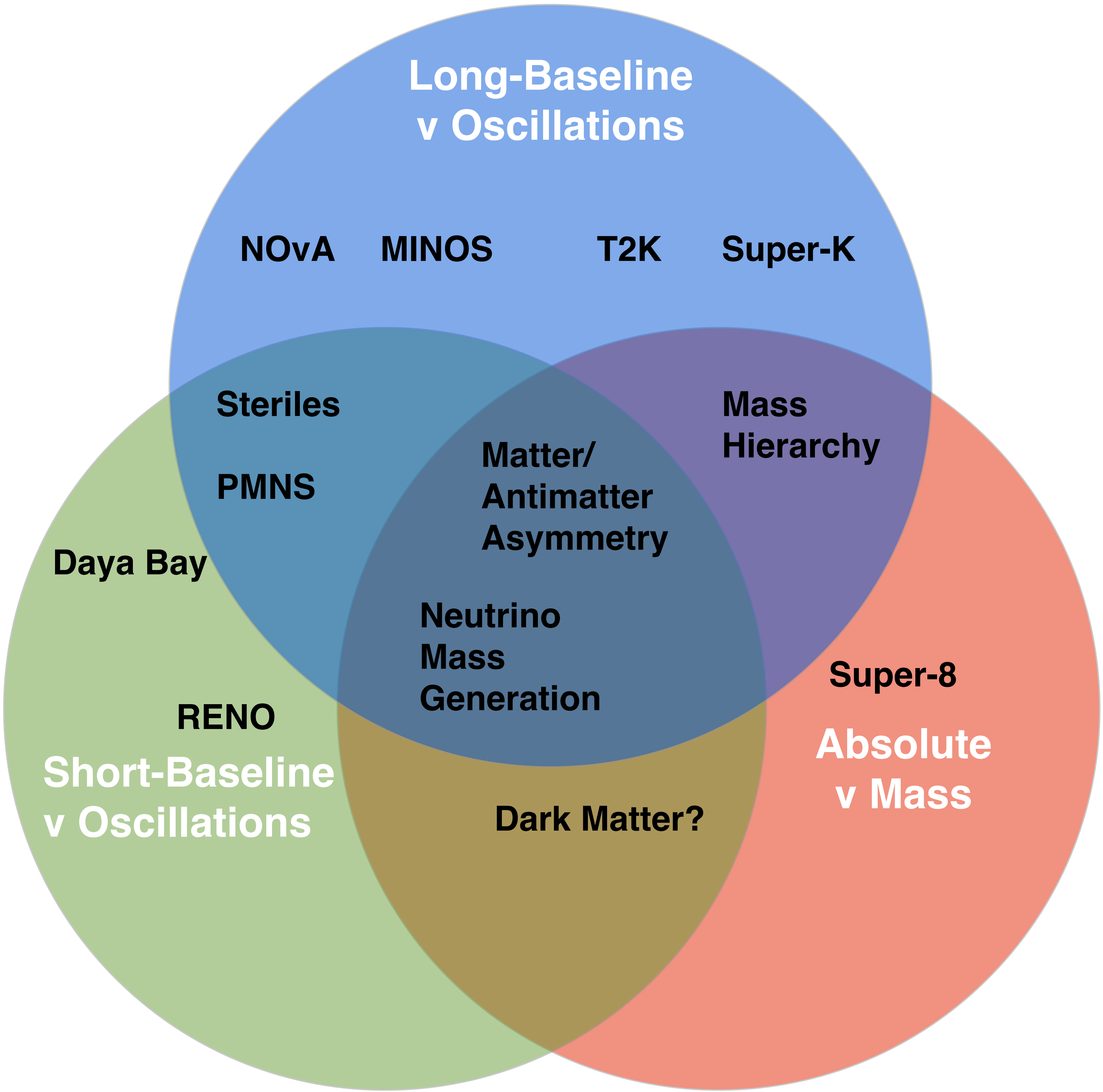
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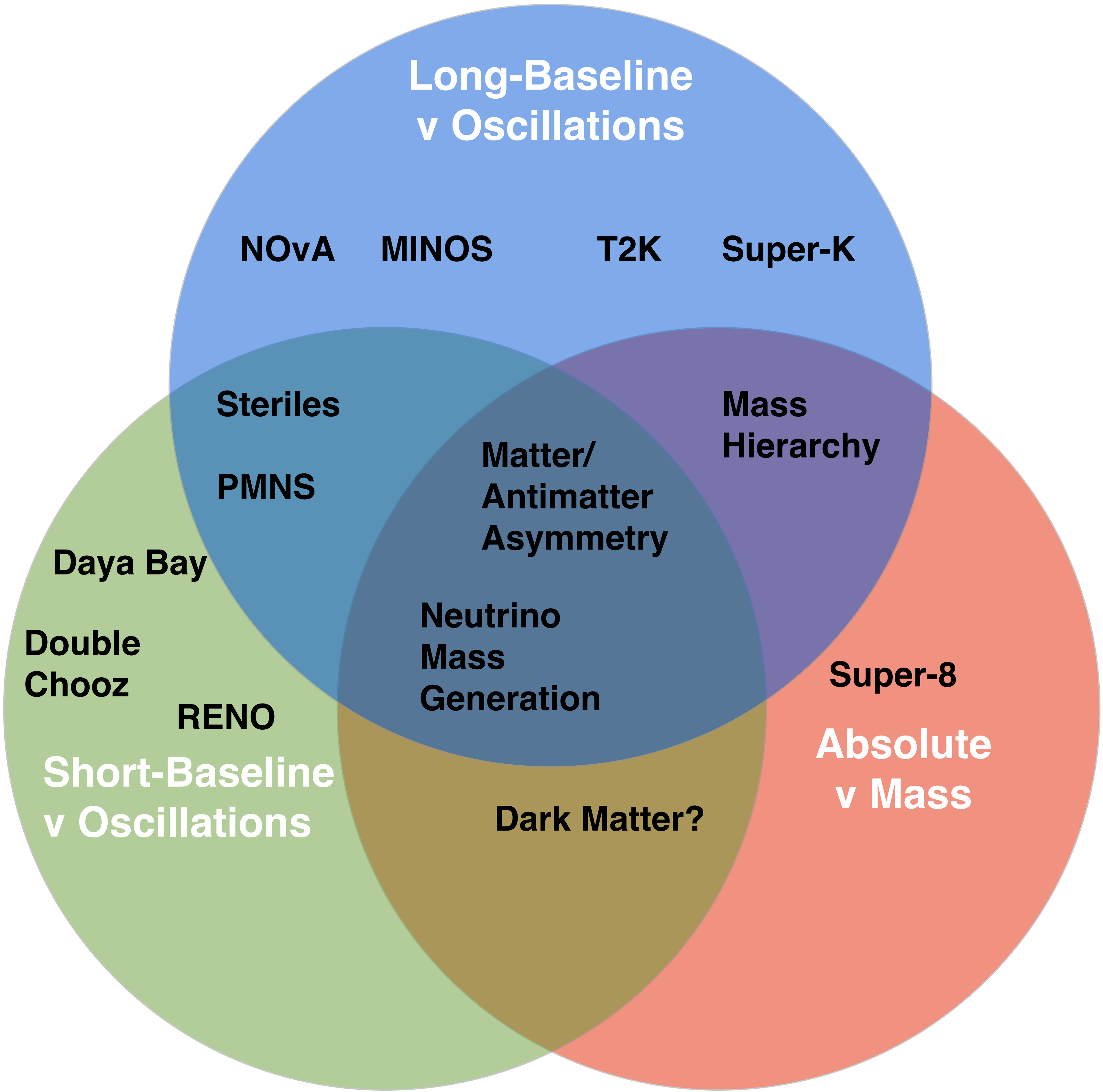

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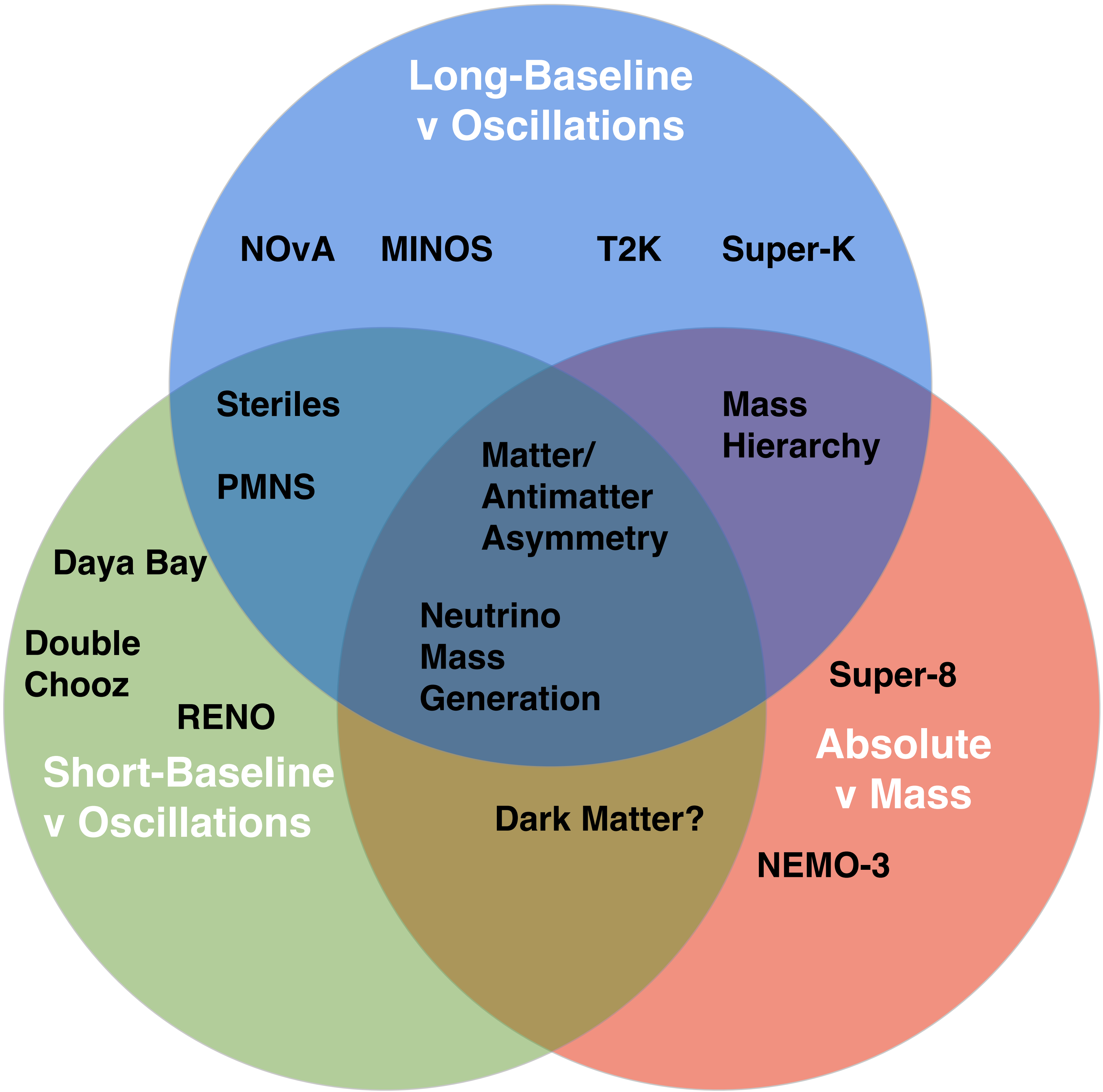

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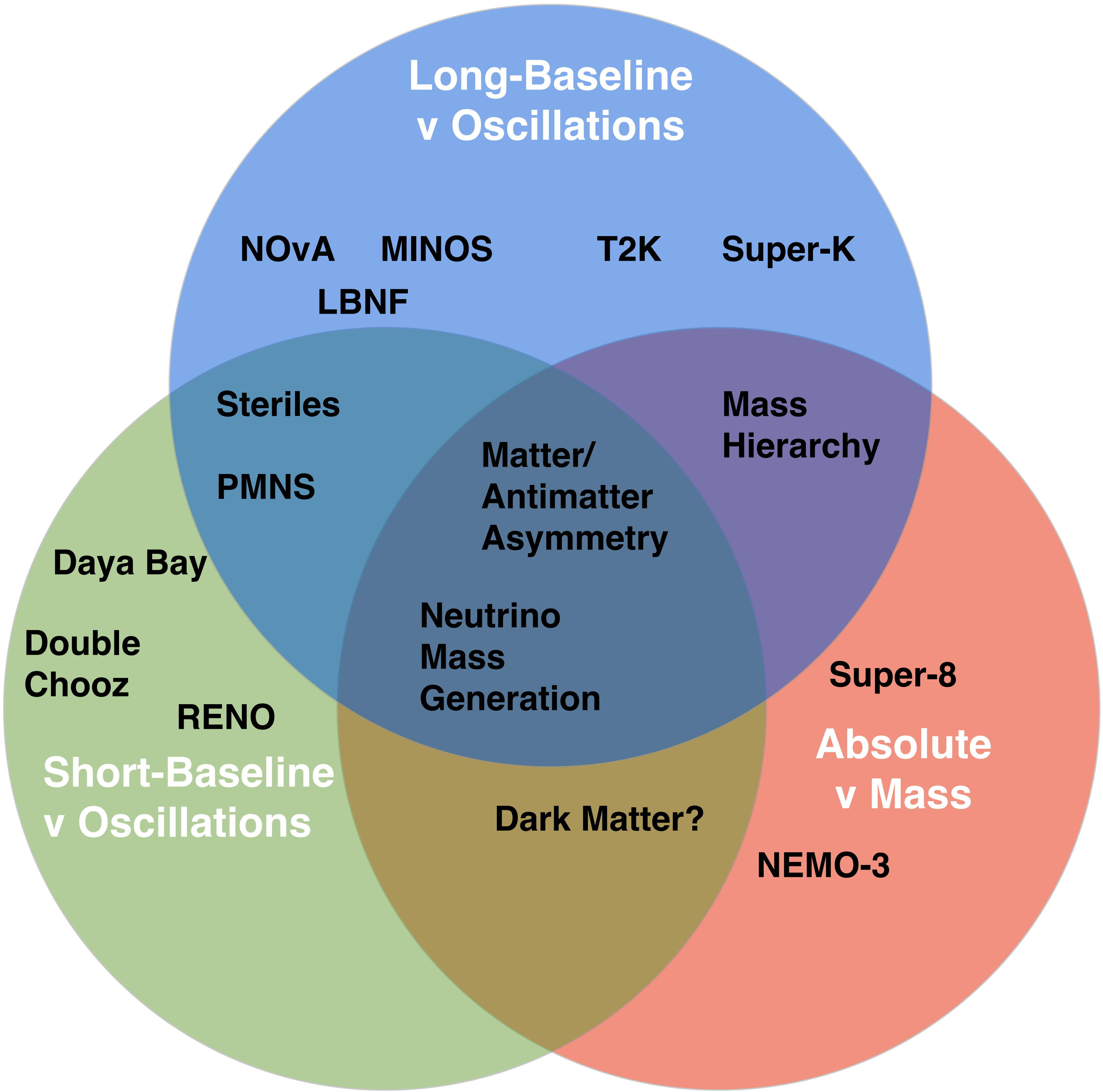
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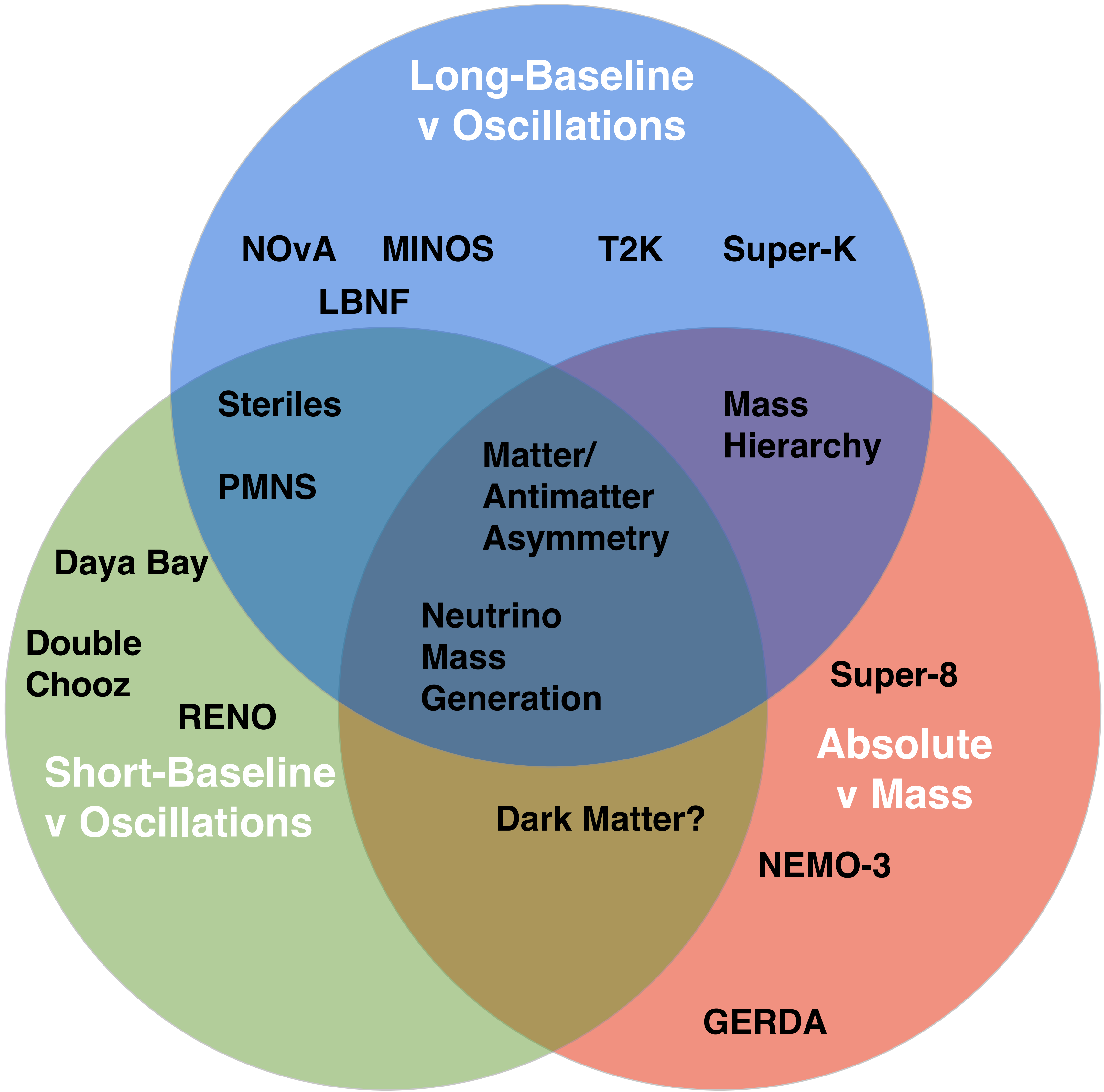

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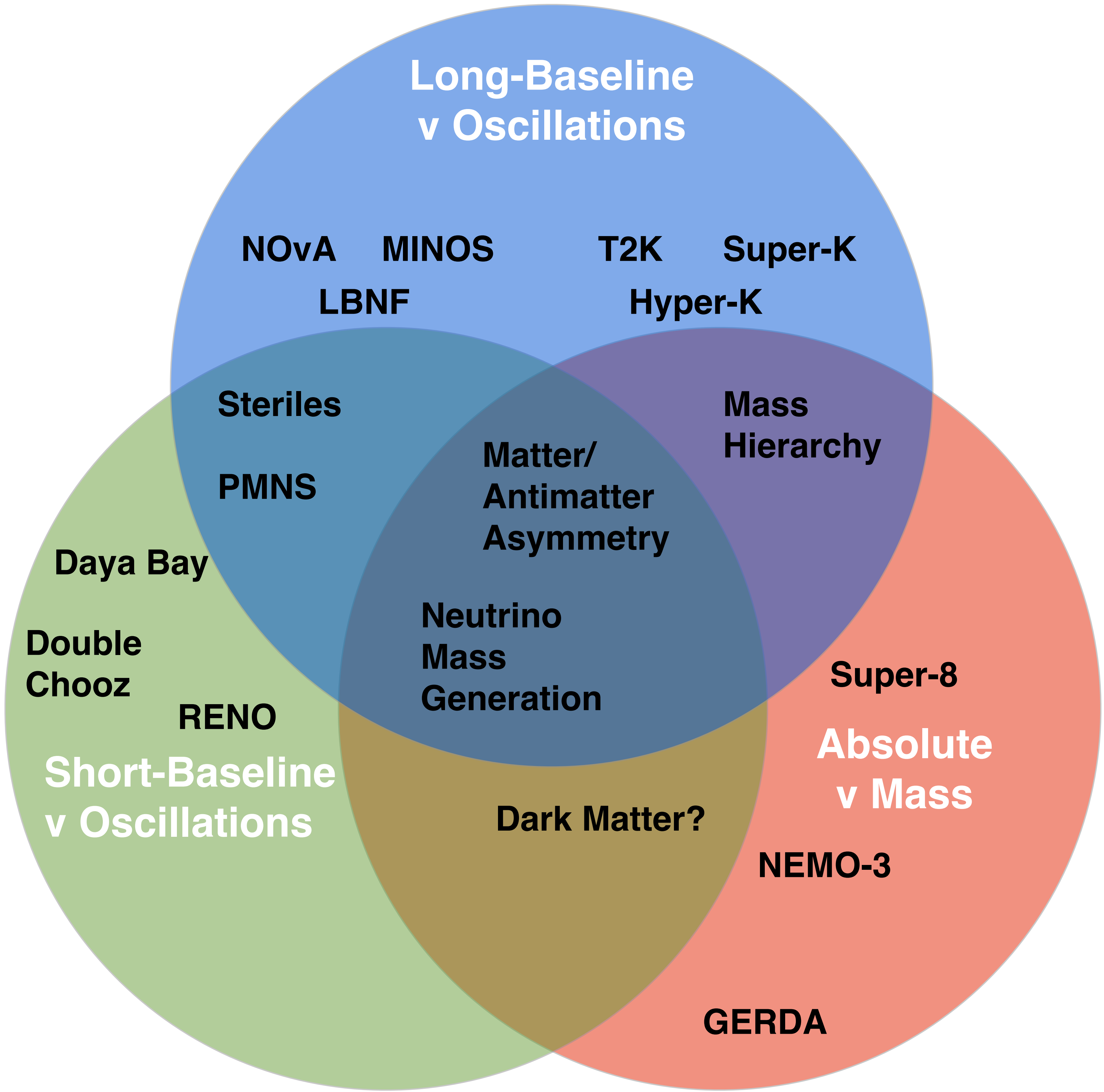

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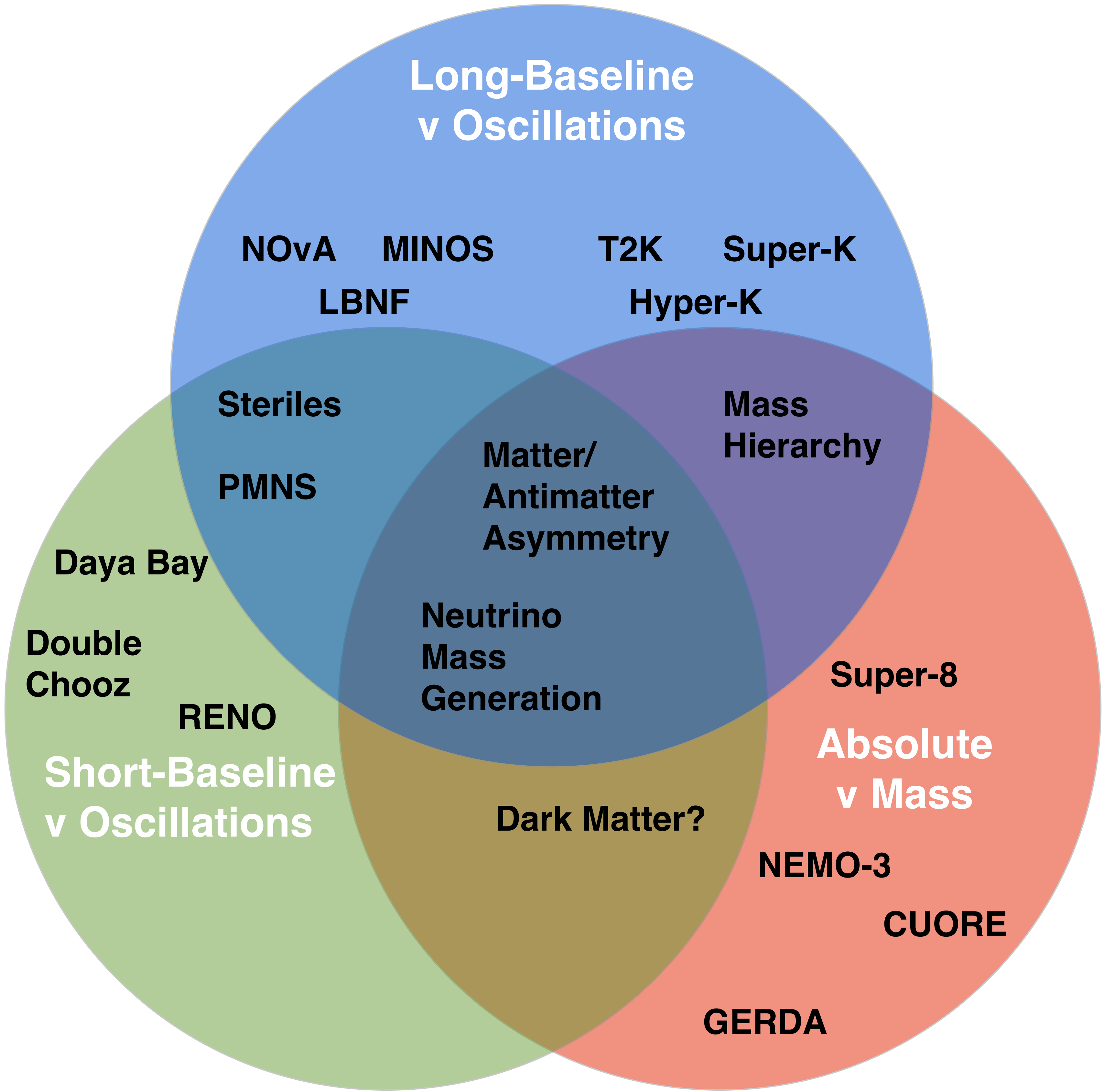
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CUORE
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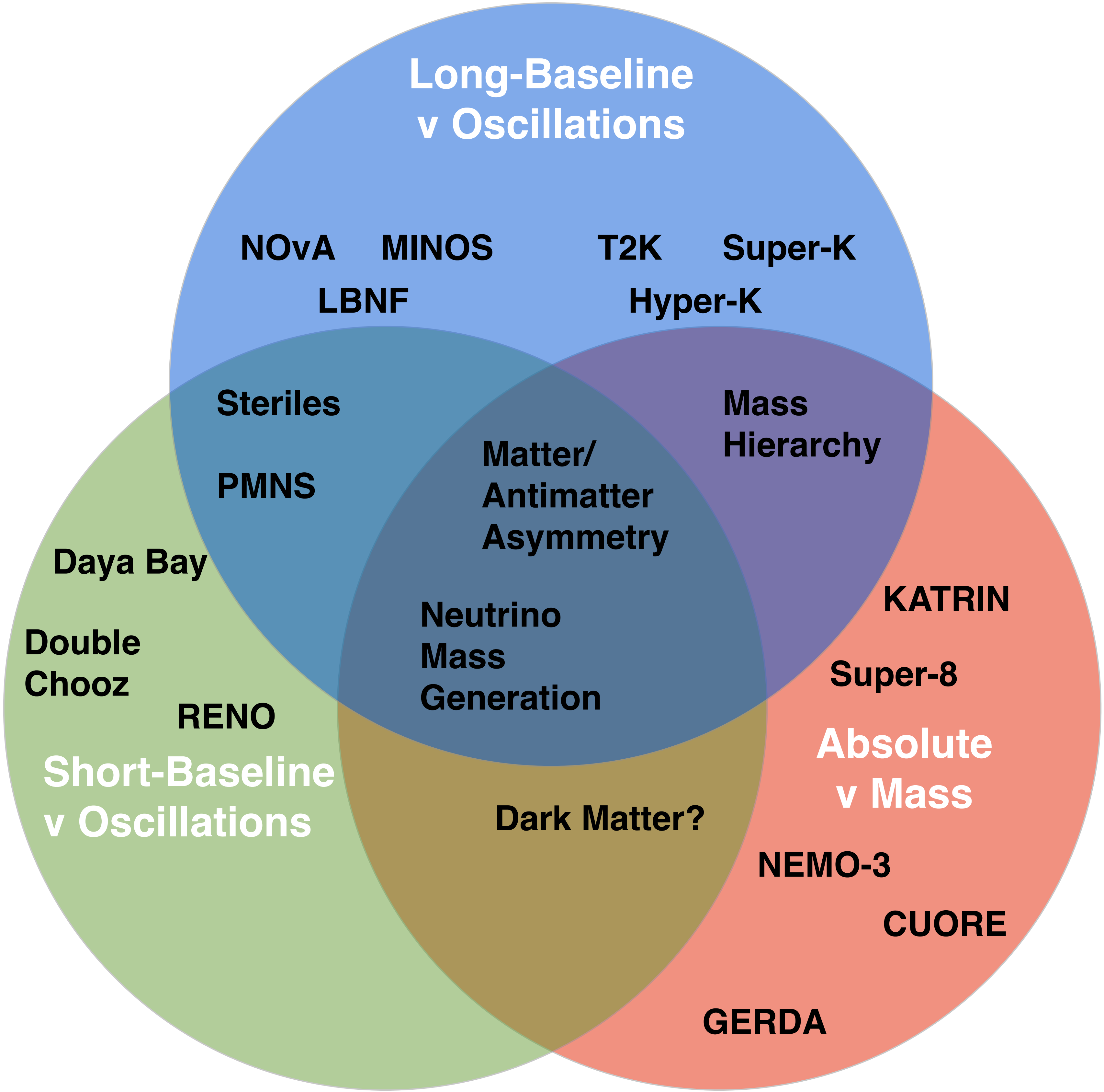
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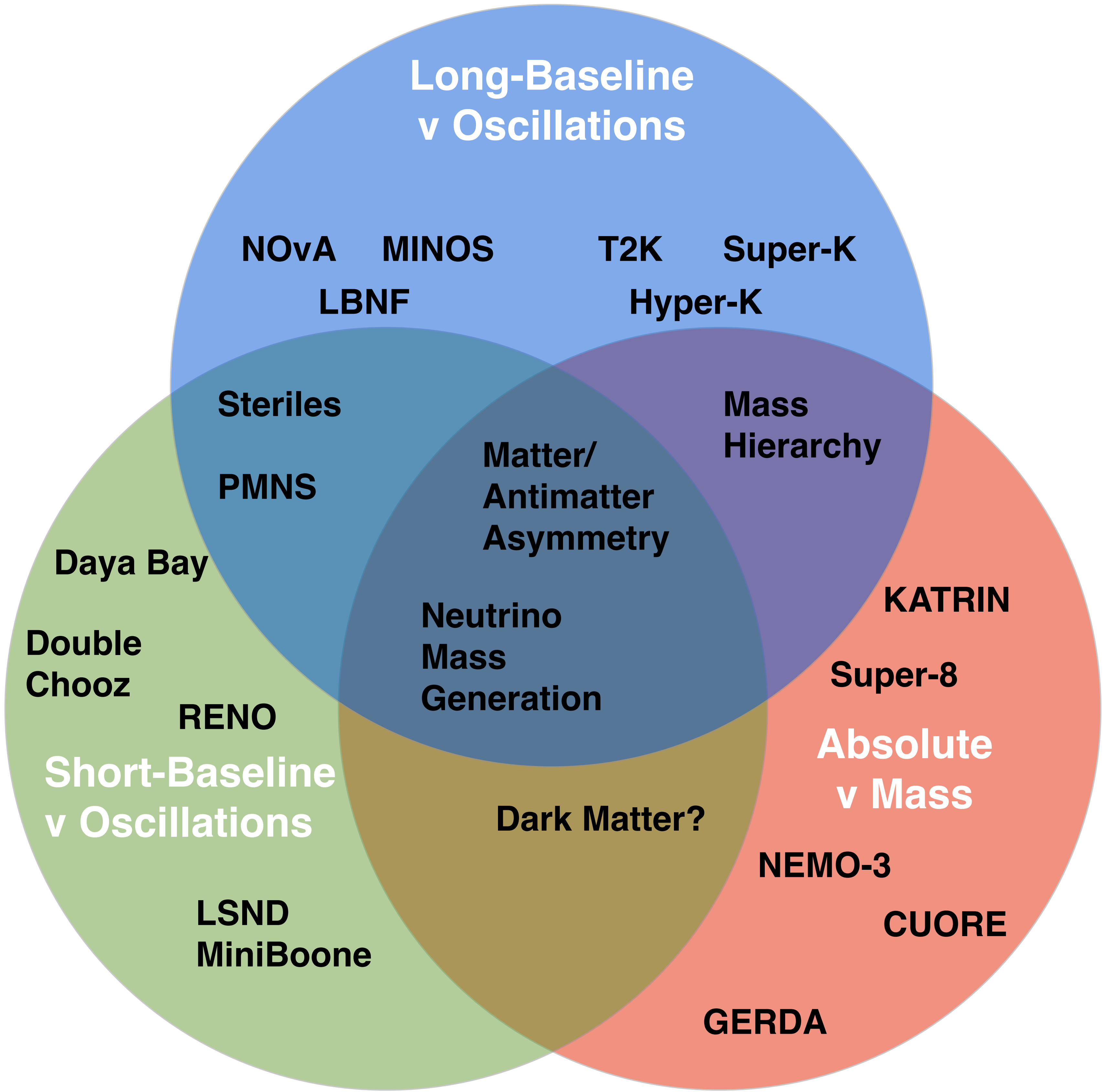

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MiniBoone
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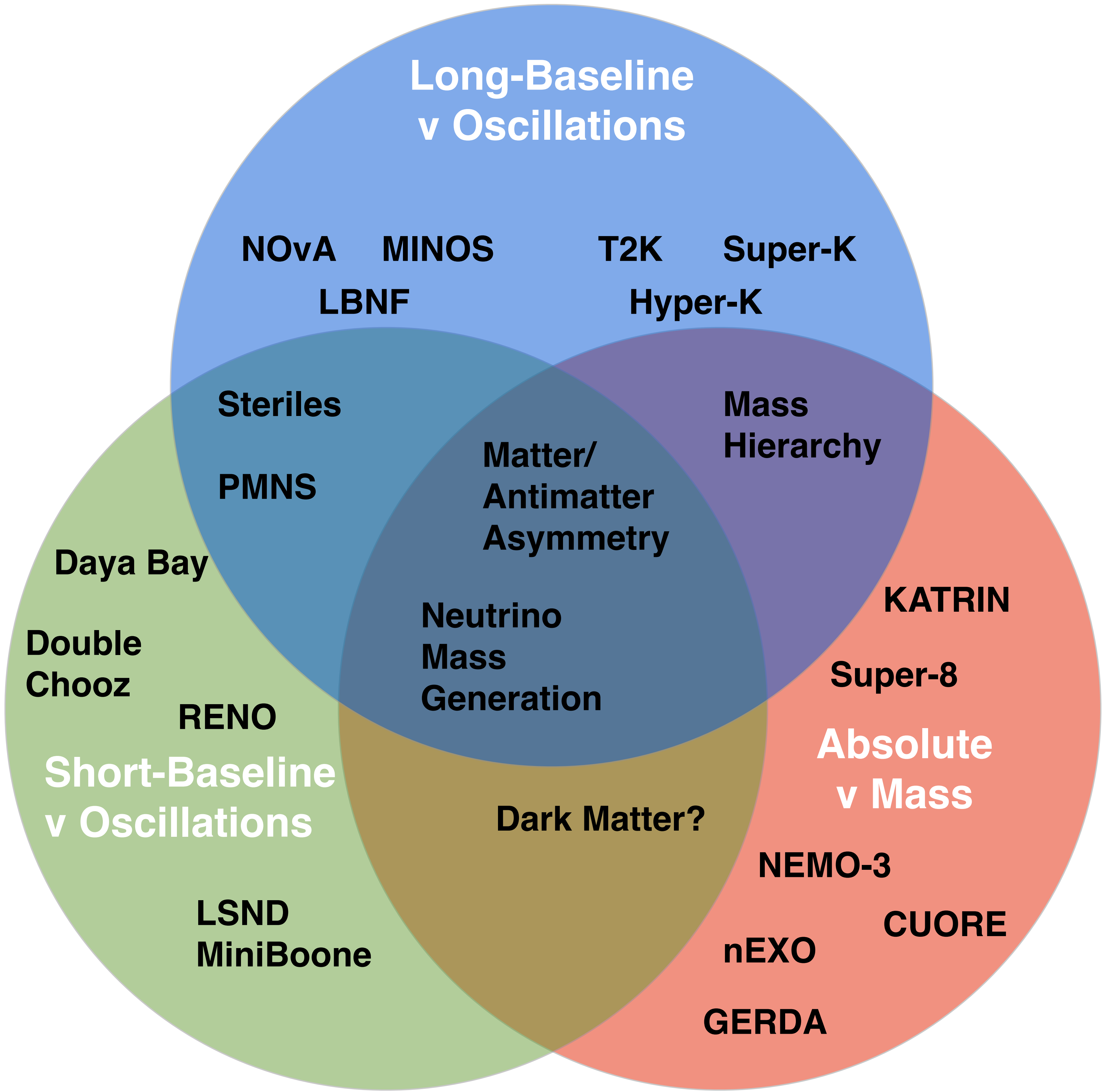
GERDA

Summary

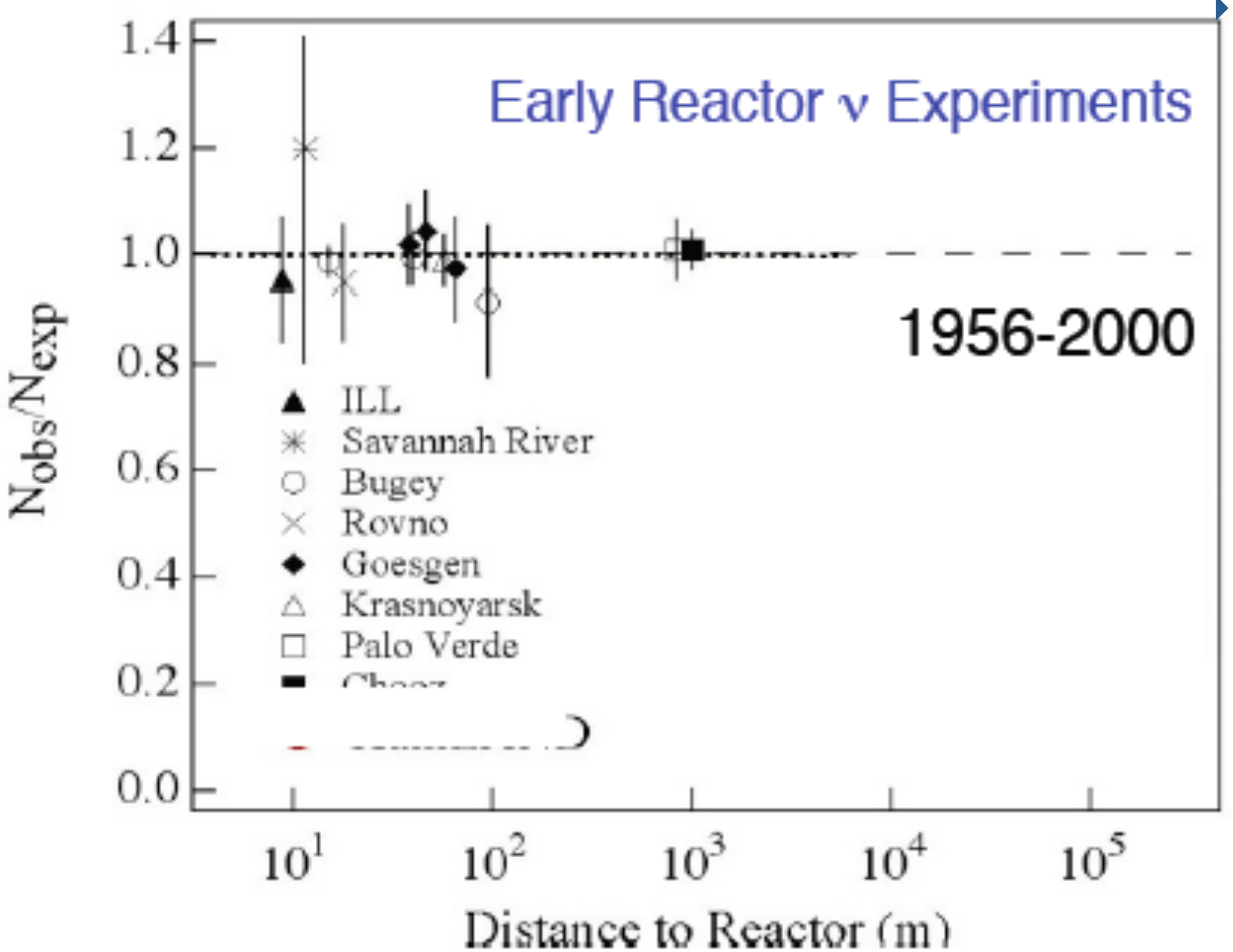

Long-Baseline
ν Oscillations
NOvA
MINOS
T2K
Super-K
LBNF
Hyper-K
Steriles
PMNS
Mass
Hierarchy
Matter/
Antimatter
Asymmetry
Daya Bay
Double
Chooz
RENO
Neutrino
Mass
Generation
KATRIN
Super-8
Absolute
ν Mass
Short-Baseline
ν Oscillations
Dark Matter?
NEMO-3
LSND
MiniBoone
CUORE
nEXO
GERDA

QUESTIONS?

BACKUP

Why Did It Take Us So Long to Find θ_{13}?

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^{\ 2} L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^{\ 2} L}{4E_\nu}\right)$$



- Reactor experiments didn't really know where to "look" (Δm^2 was unknown)
- θ_{13} is pretty small
- **Systematics**
  - Uncorrelated backgrounds:
    - ambient radioactivity
    - accidentals
    - cosmogenic neutrons
  - Correlated backgrounds:
    - cosmic ray-induced neutrons from surrounding rock & buffer region
    - cosmogenic radioactive nuclei that emit delayed neutrons in the detector (eg, ^{9}Li ($T_{1/2}$=178 ms))

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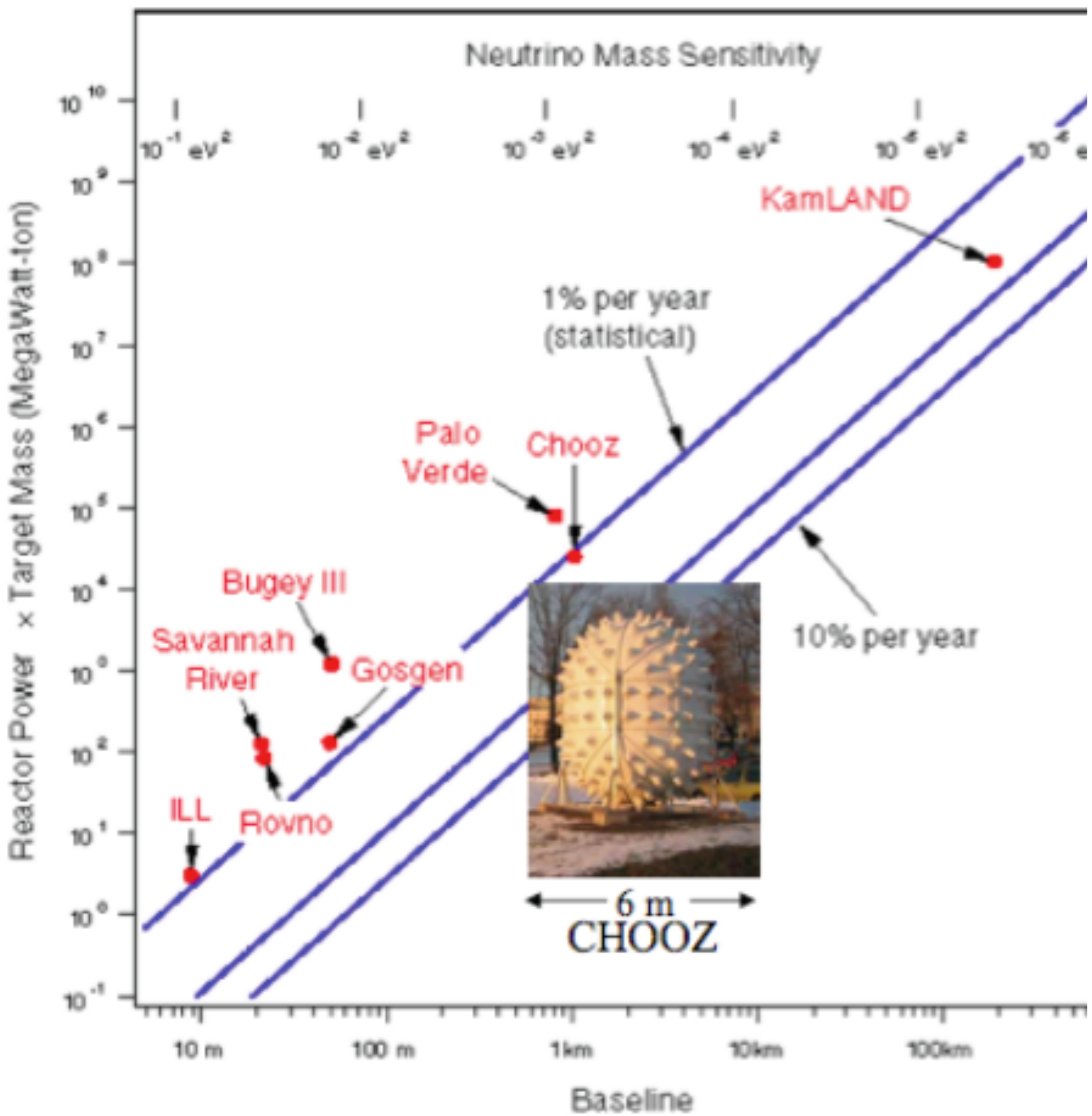

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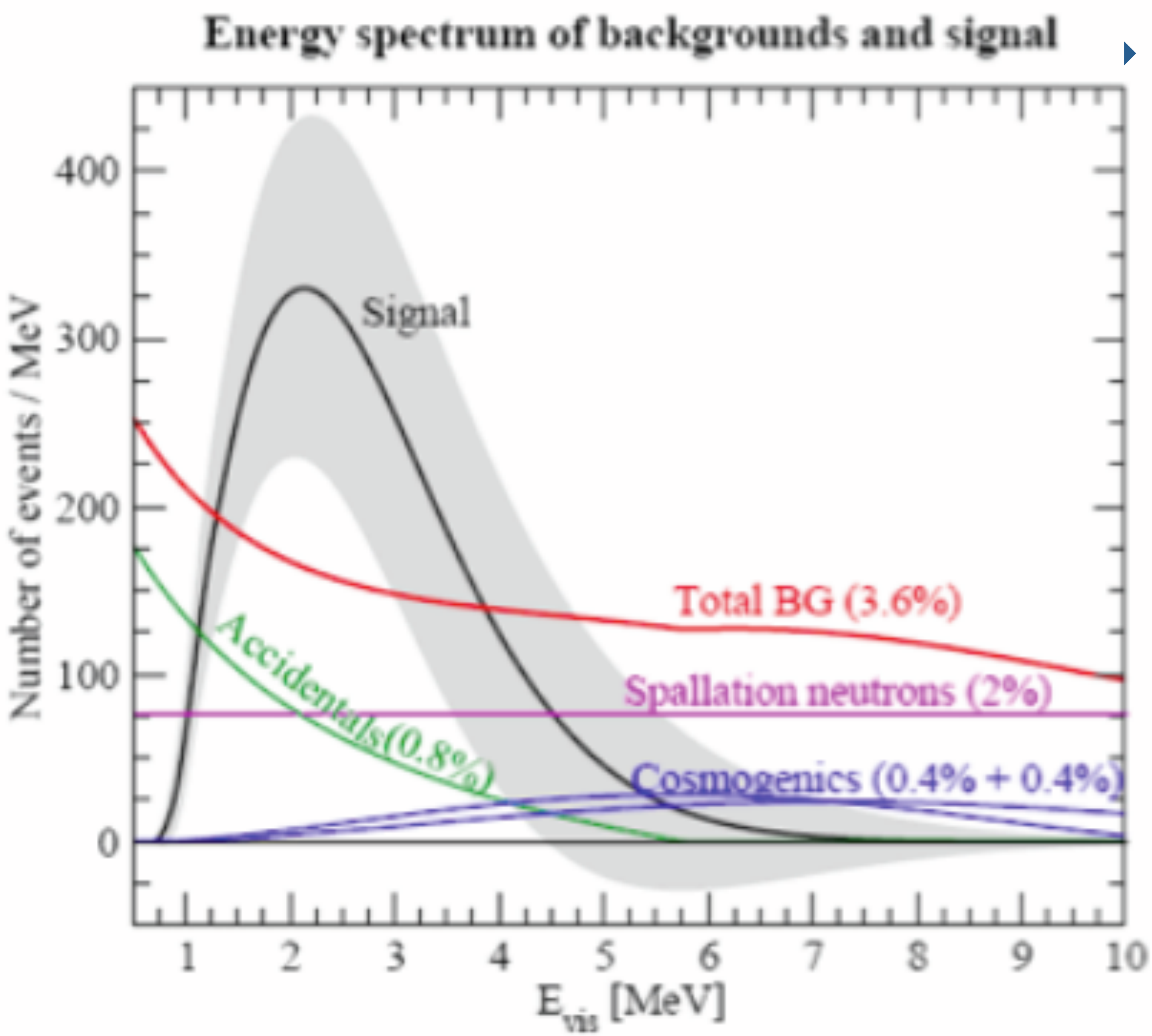

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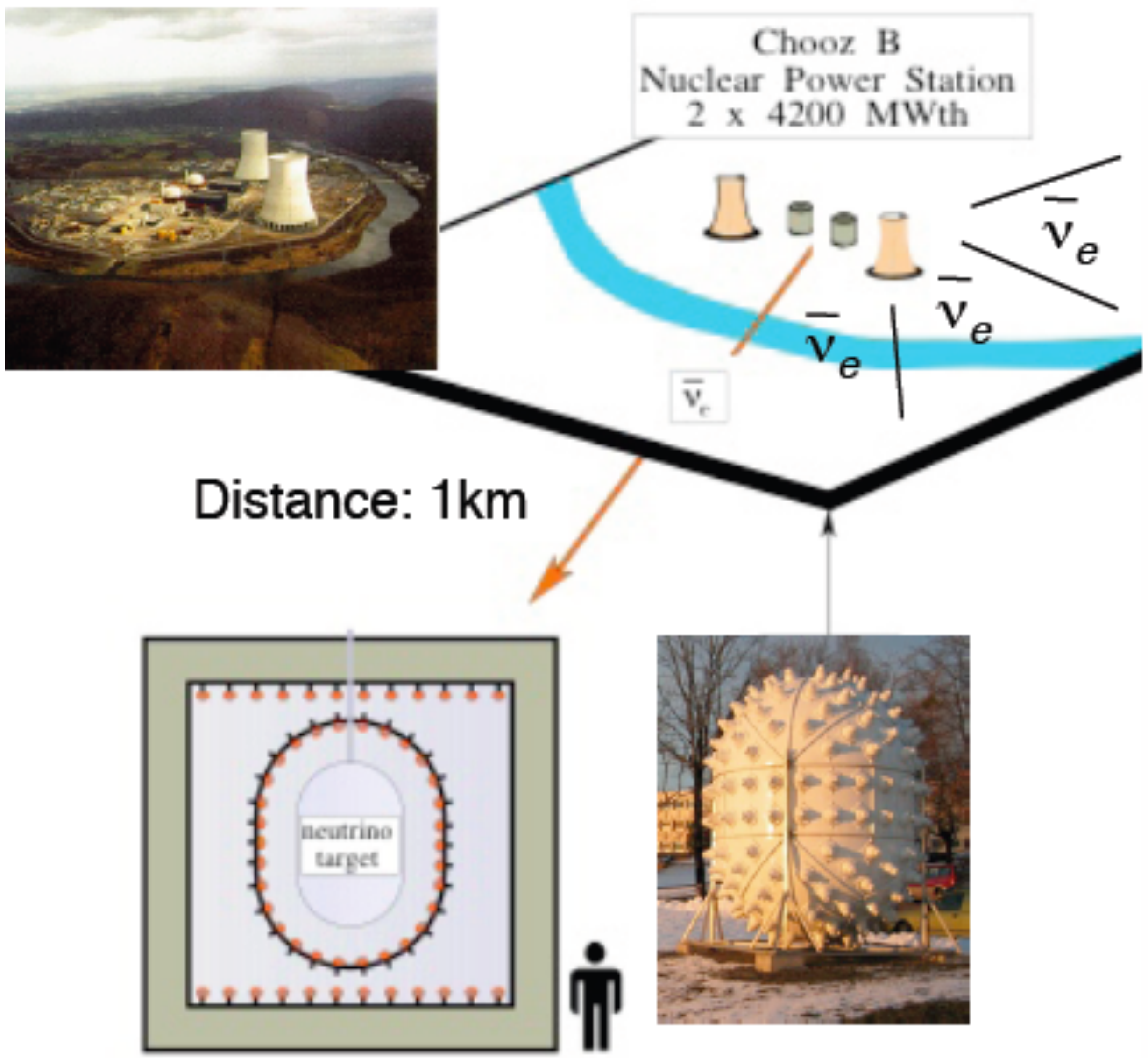
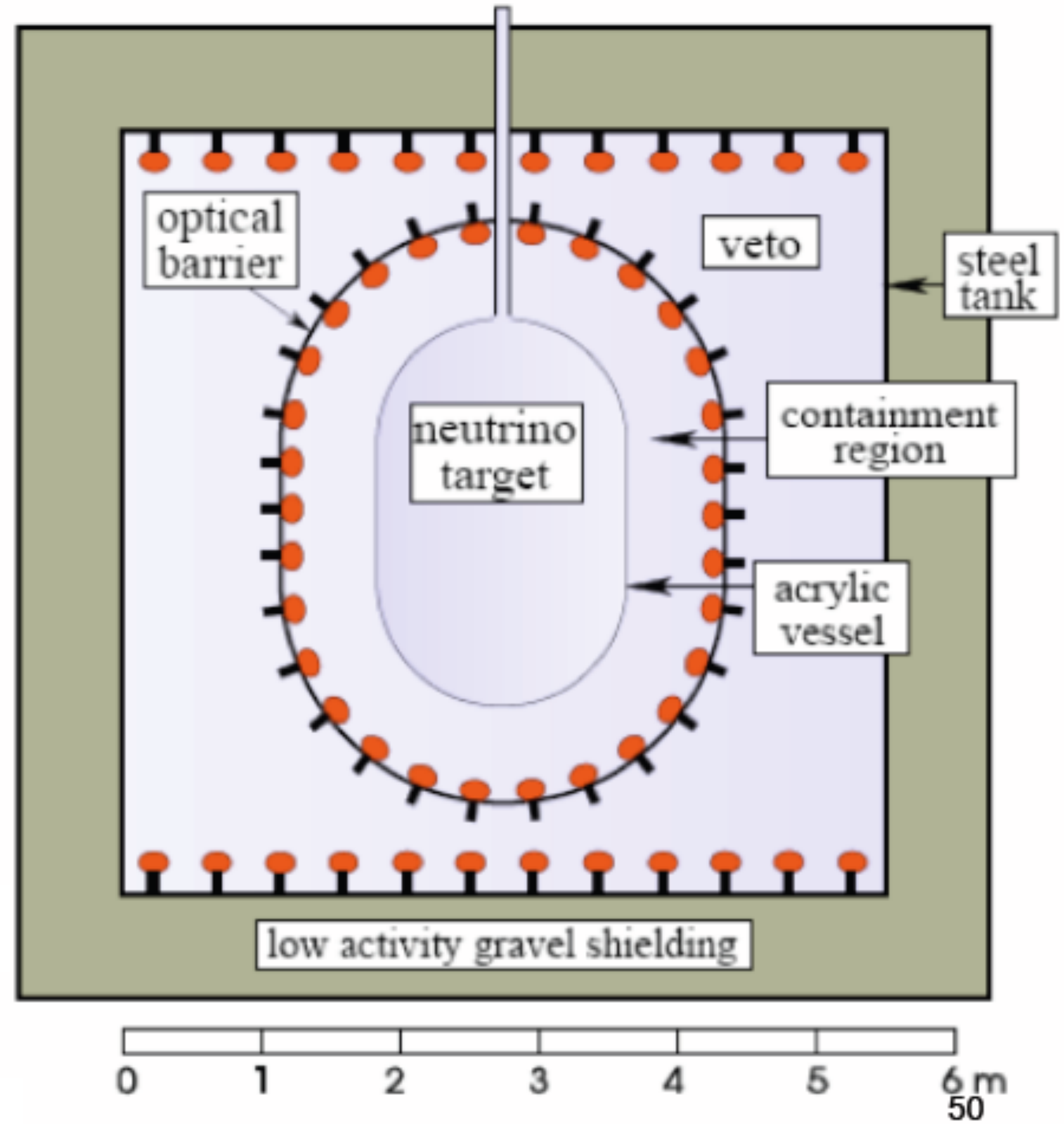
Previous Searches w/ Reactor Antineutrinos



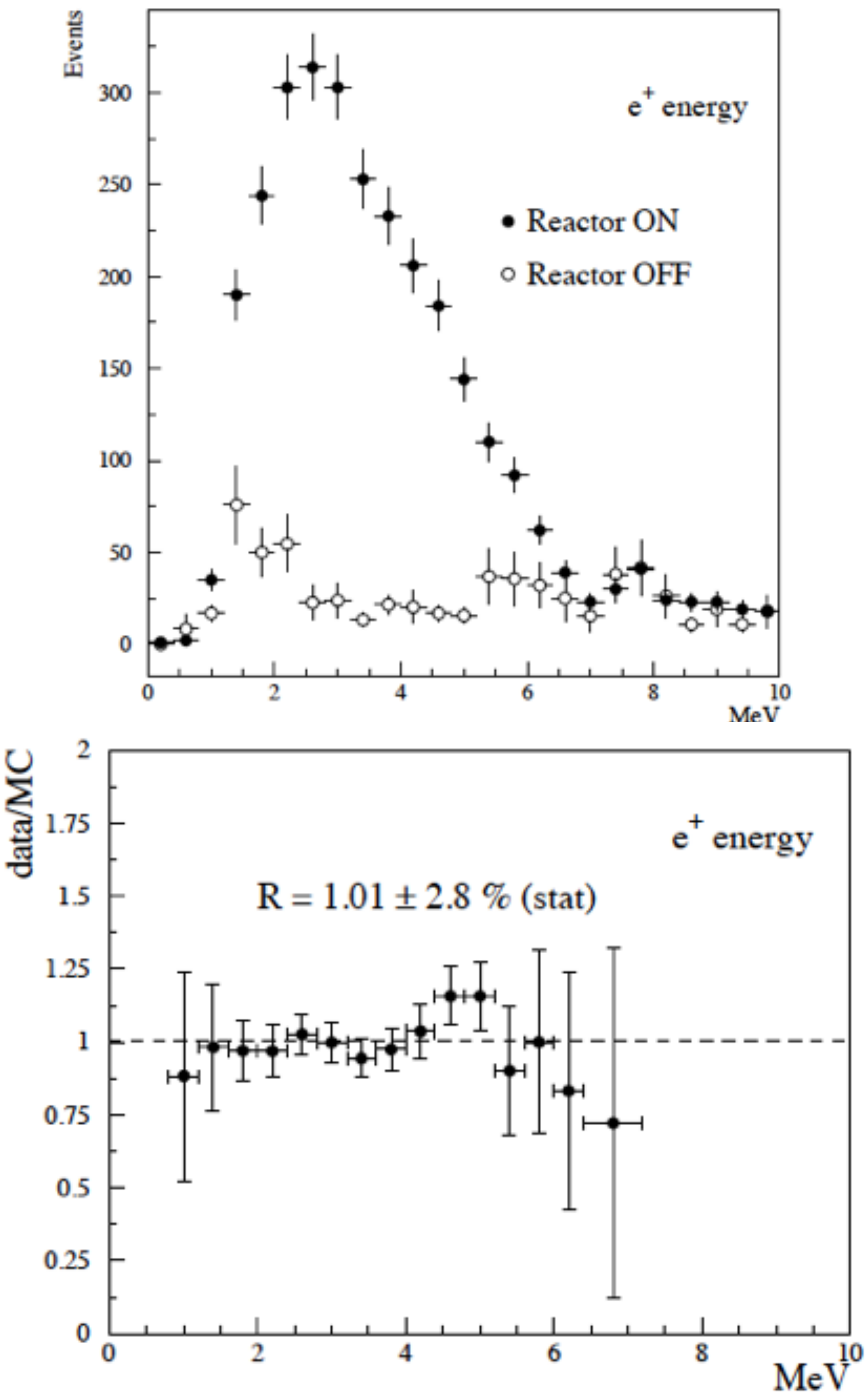
Absolute measurement with 1 detector

detector size: several tons

Karsten Heeger, Univ. of Wisconsin

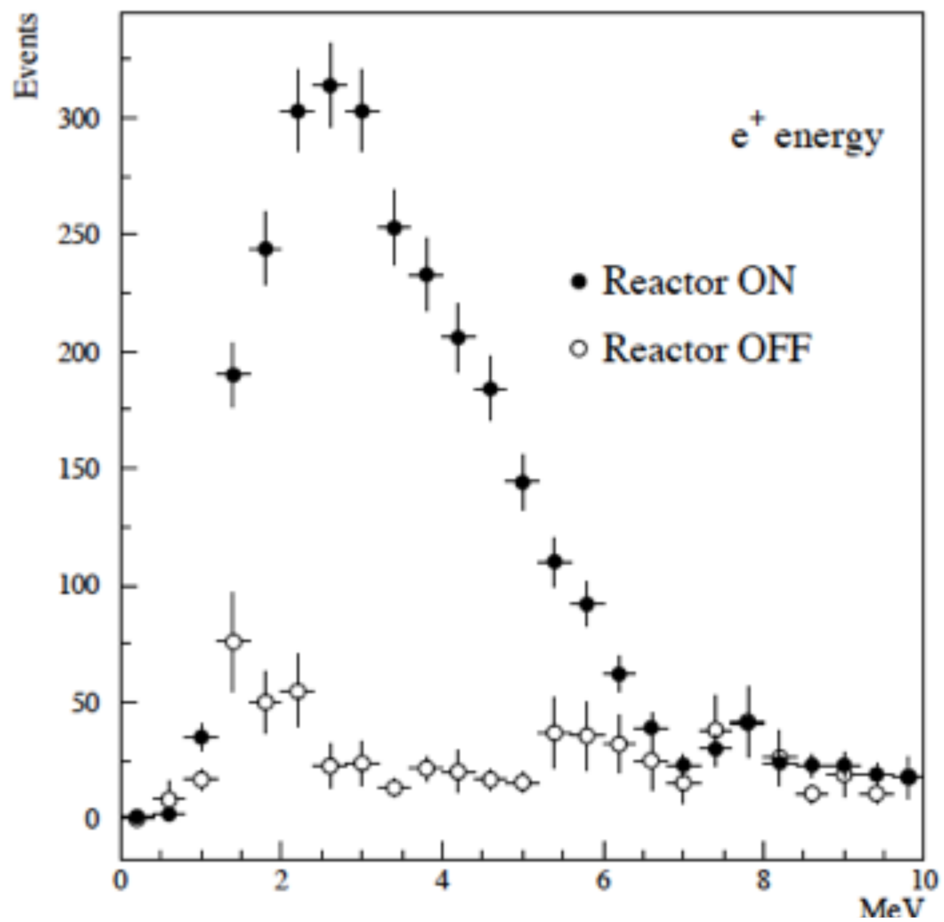


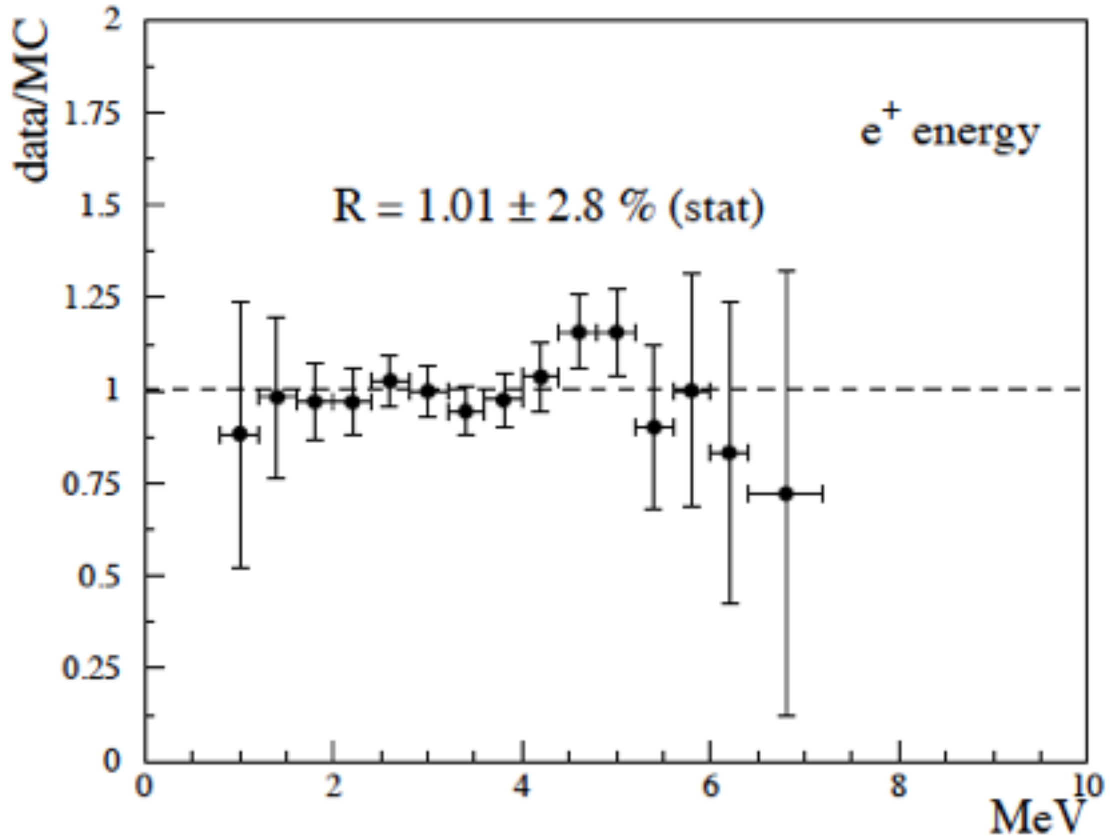
Chooz Results

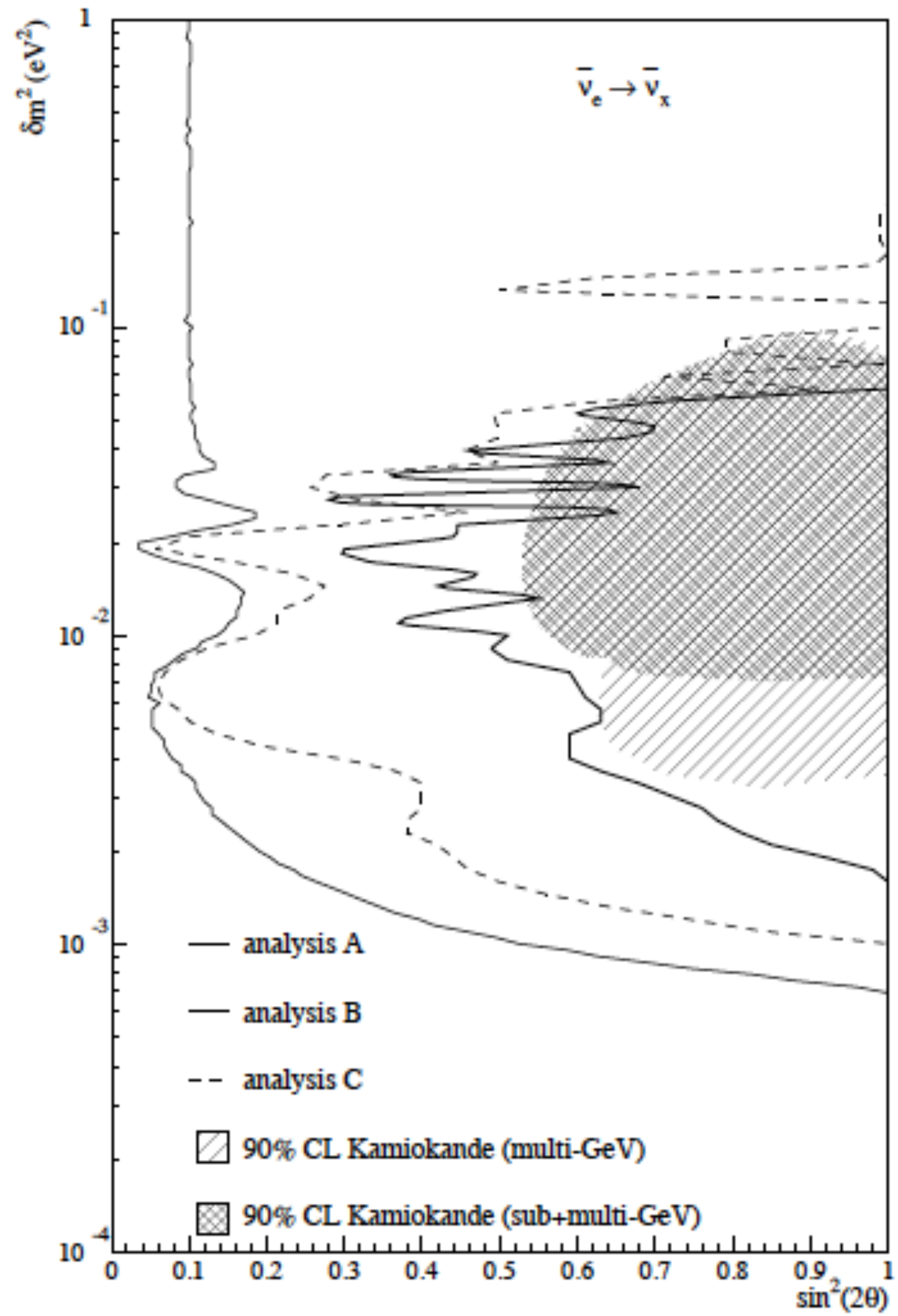


parameter	relative error (%)
reaction cross section	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%

Chooz Results







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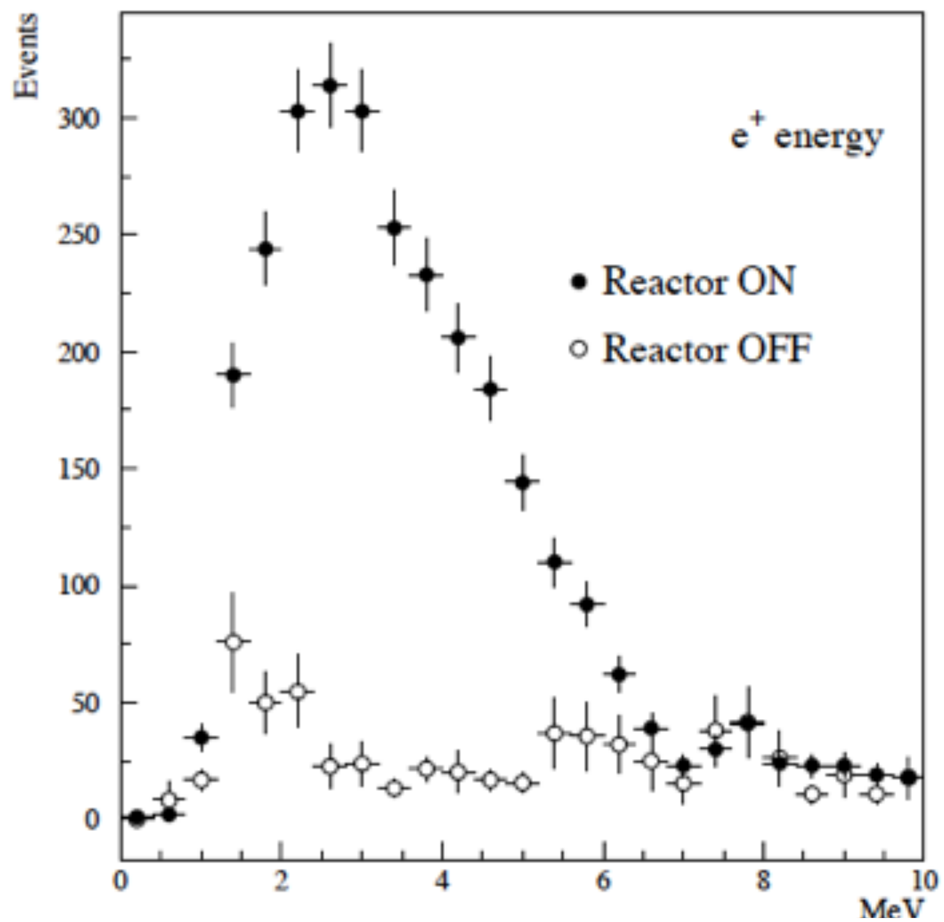

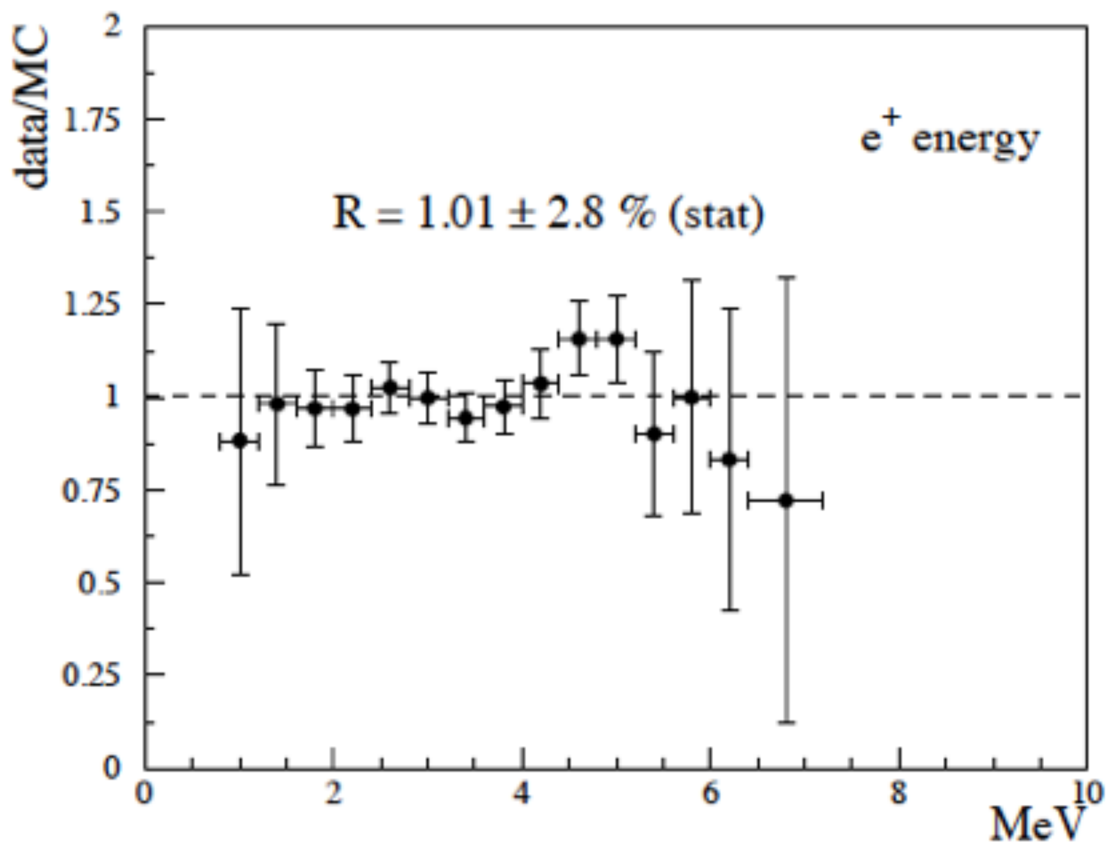

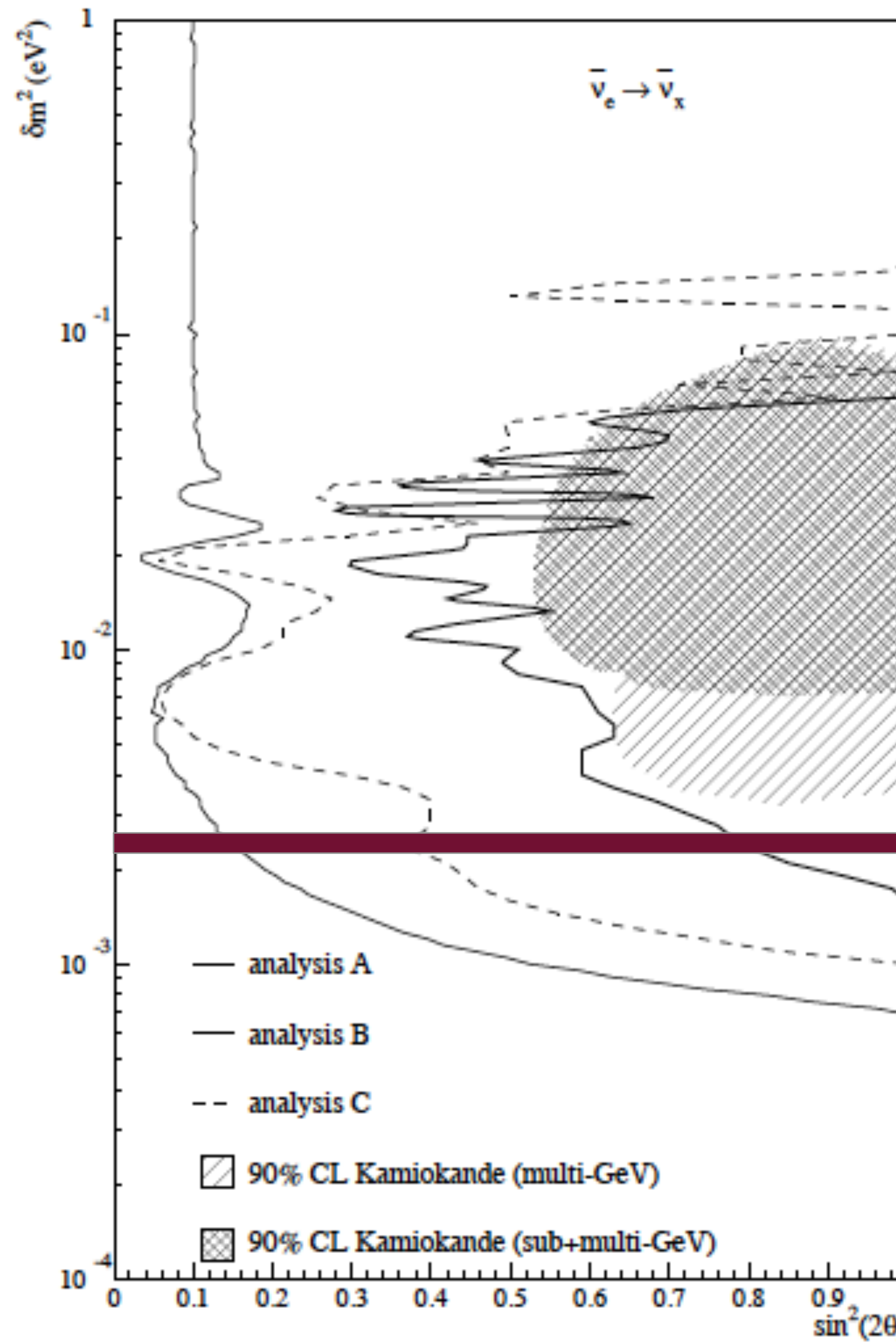

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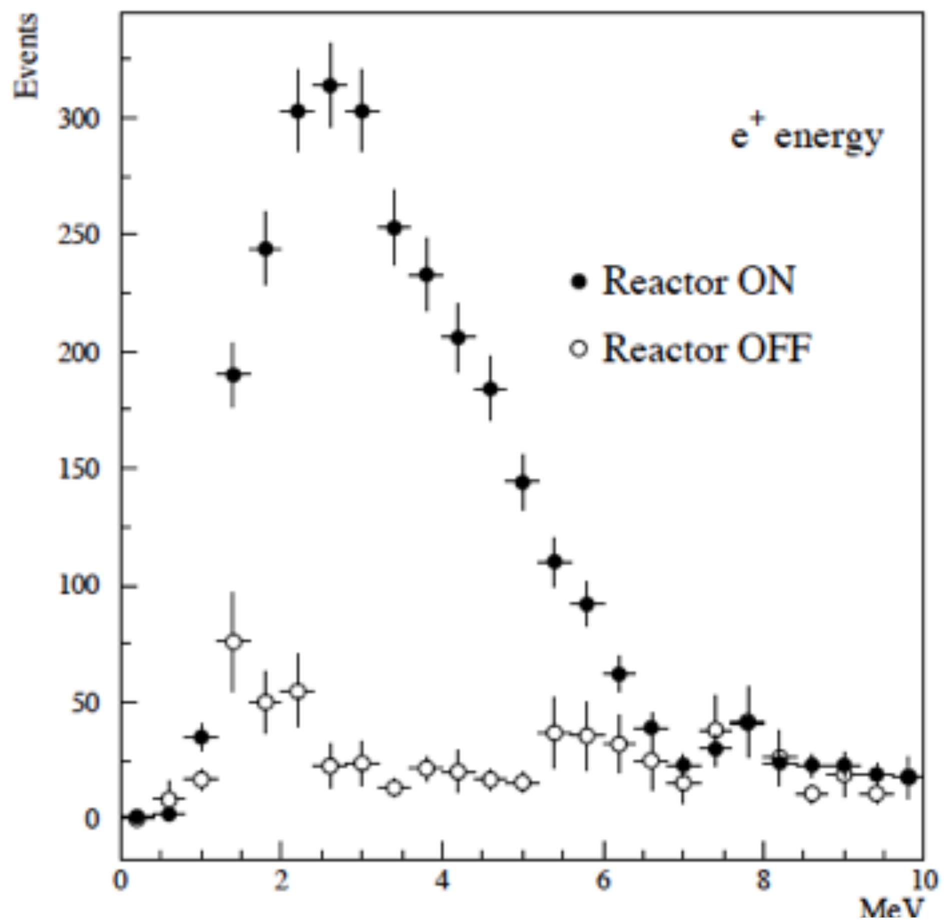

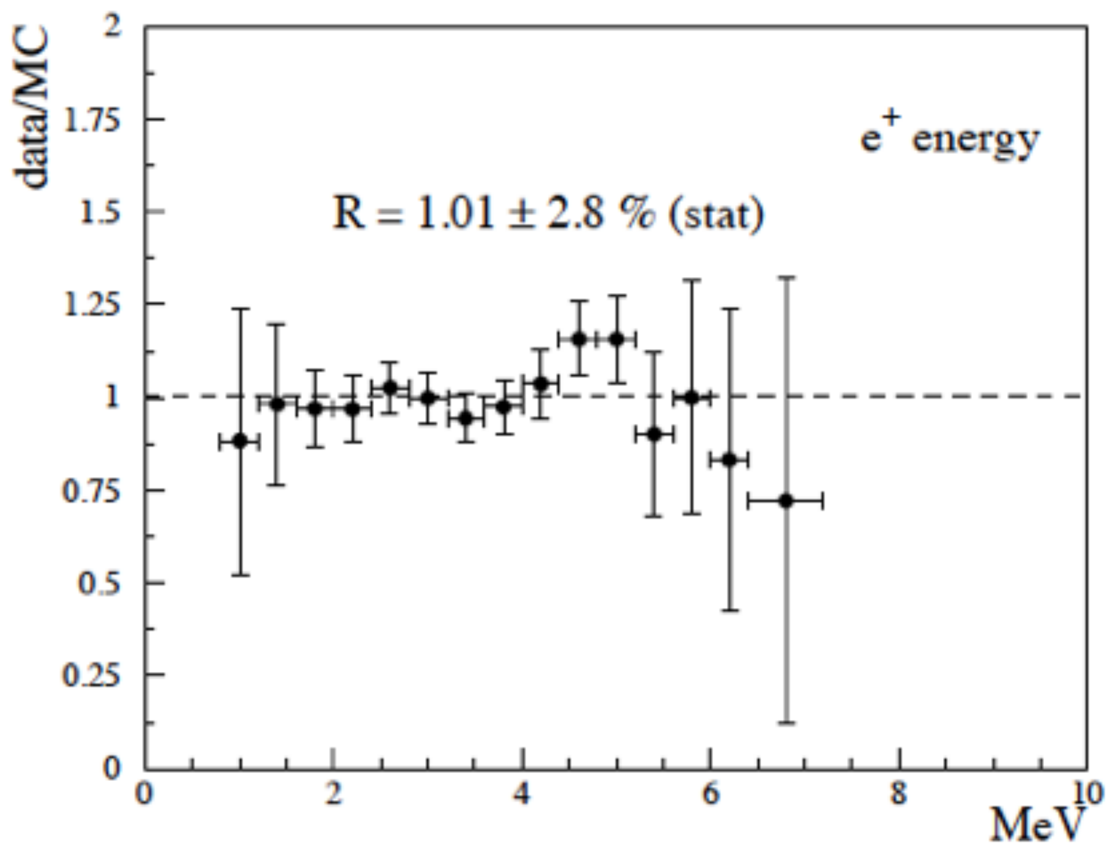

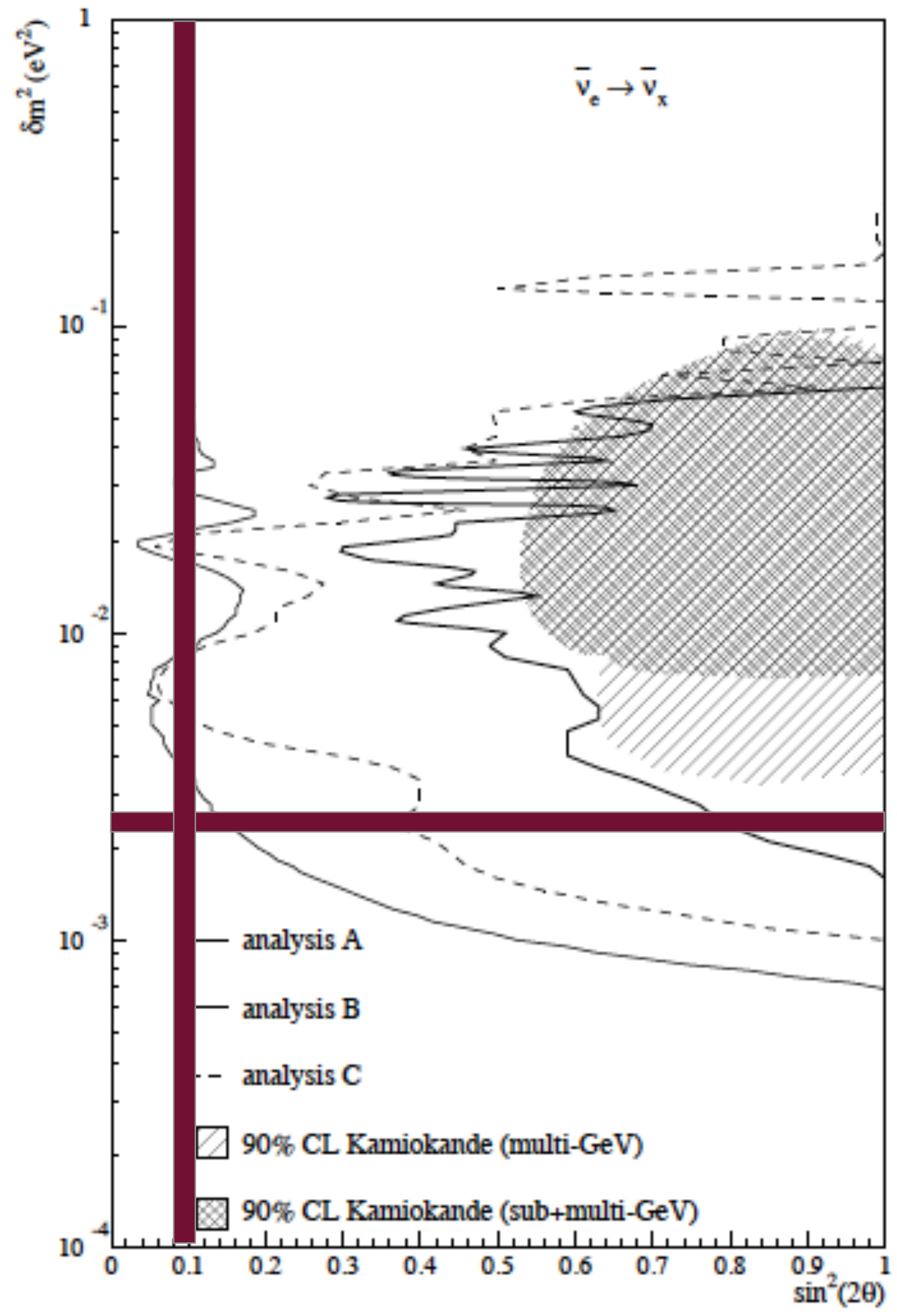

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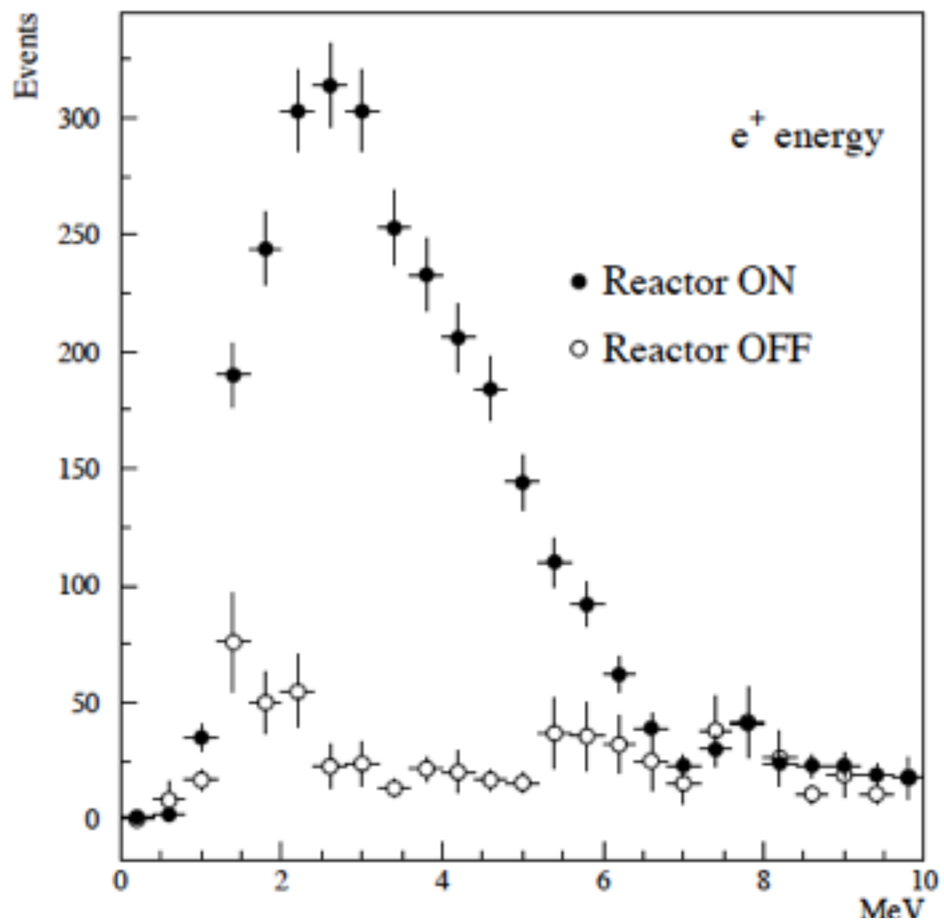
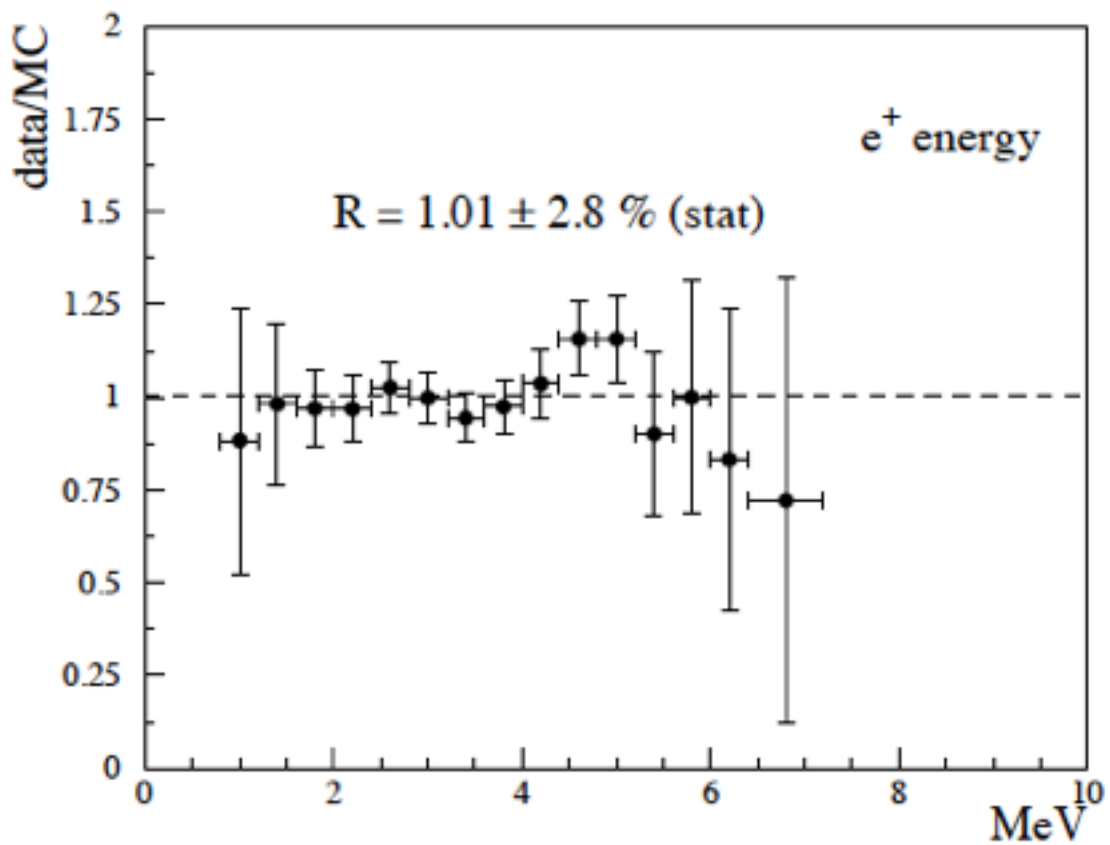
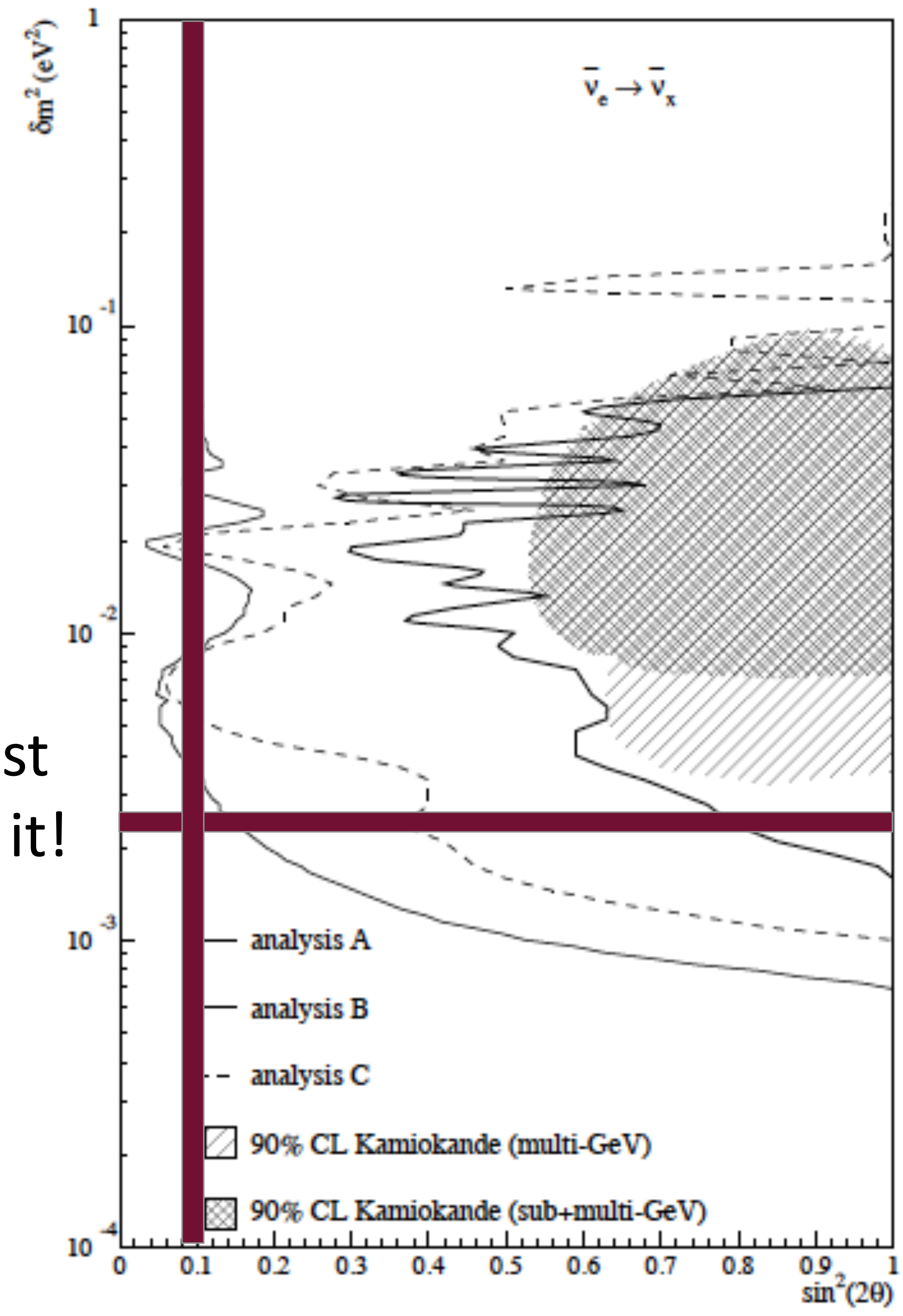


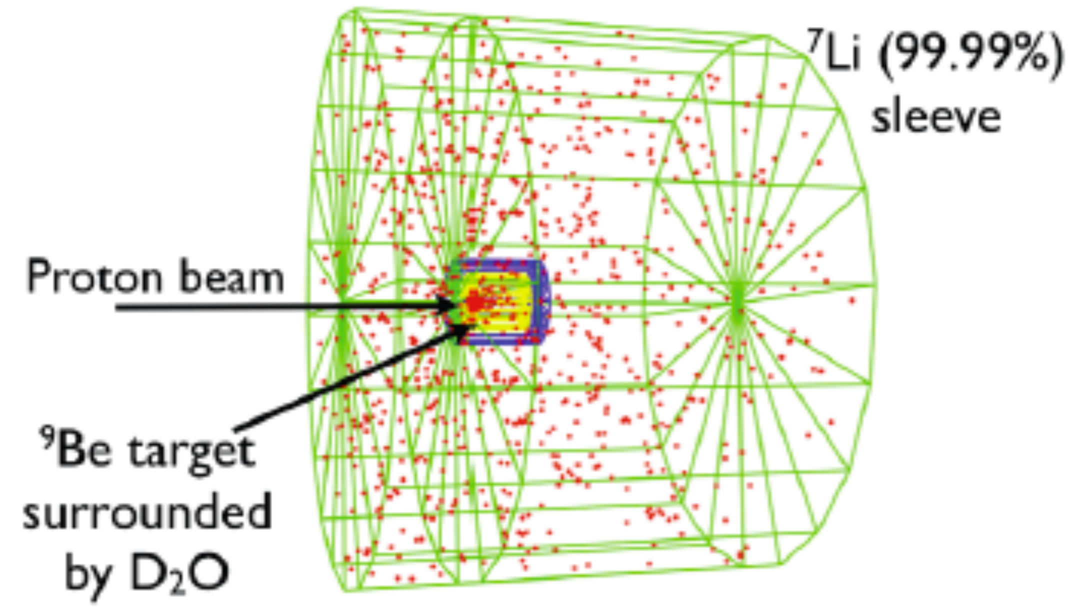


They just missed it!

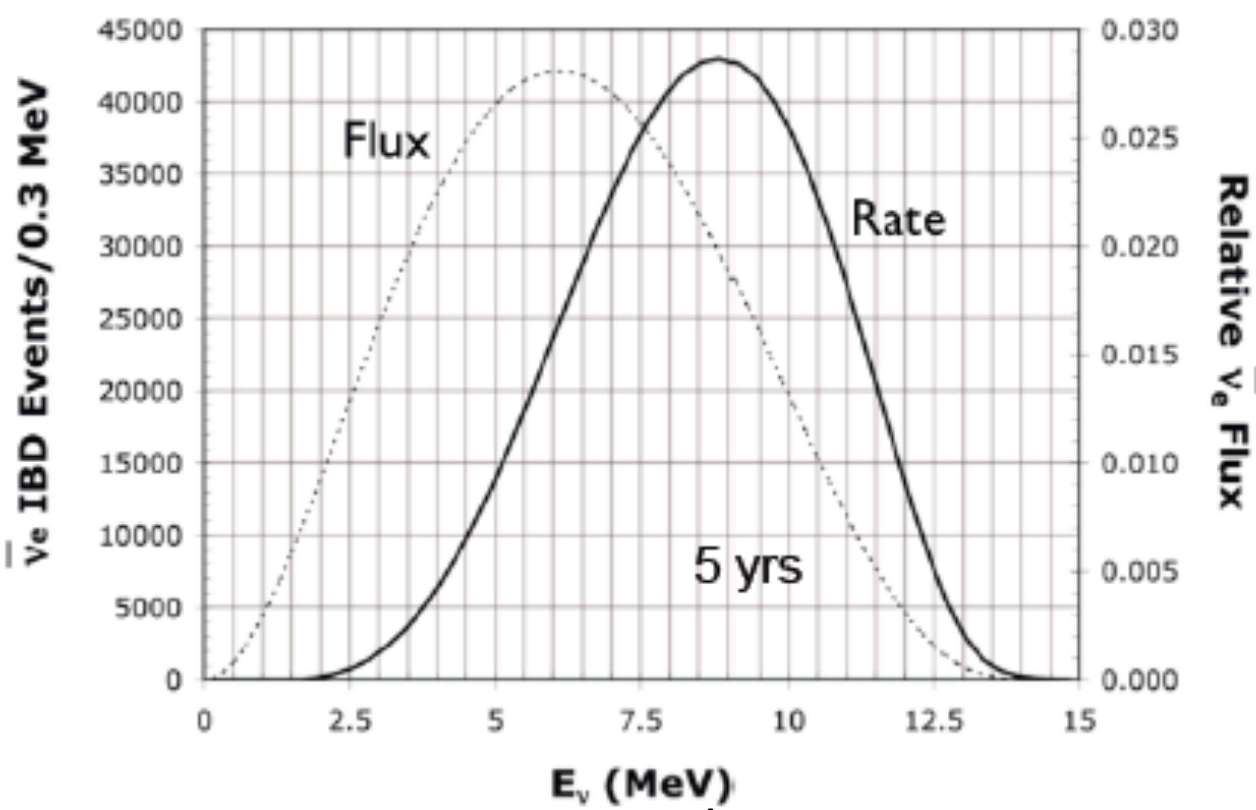


IsoDAR Neutrino Source and Events

- p (60 MeV) + $^{9}Be \rightarrow {}^{8}Li$ + 2p
  - plus many neutrons since low binding energy
- n + ^{7}Li (shielding) $\rightarrow {}^{8}Li$
- $^{8}Li \rightarrow {}^{8}Be + e^{-} + \bar{\nu}_e$
  - Mean $\bar{\nu}_e$ energy = 6.5 MeV
  - 2.6×10^{22} $\bar{\nu}_e$ / yr
- Example detector: Kamland (900 t)
  - Use IBD $\bar{\nu}_e + p \rightarrow e^{+} + n$ process
  - Detector center 16m from source
  - ~160,000 IBD events / yr
  - Observe changes in the IBD rate as a function of L/E



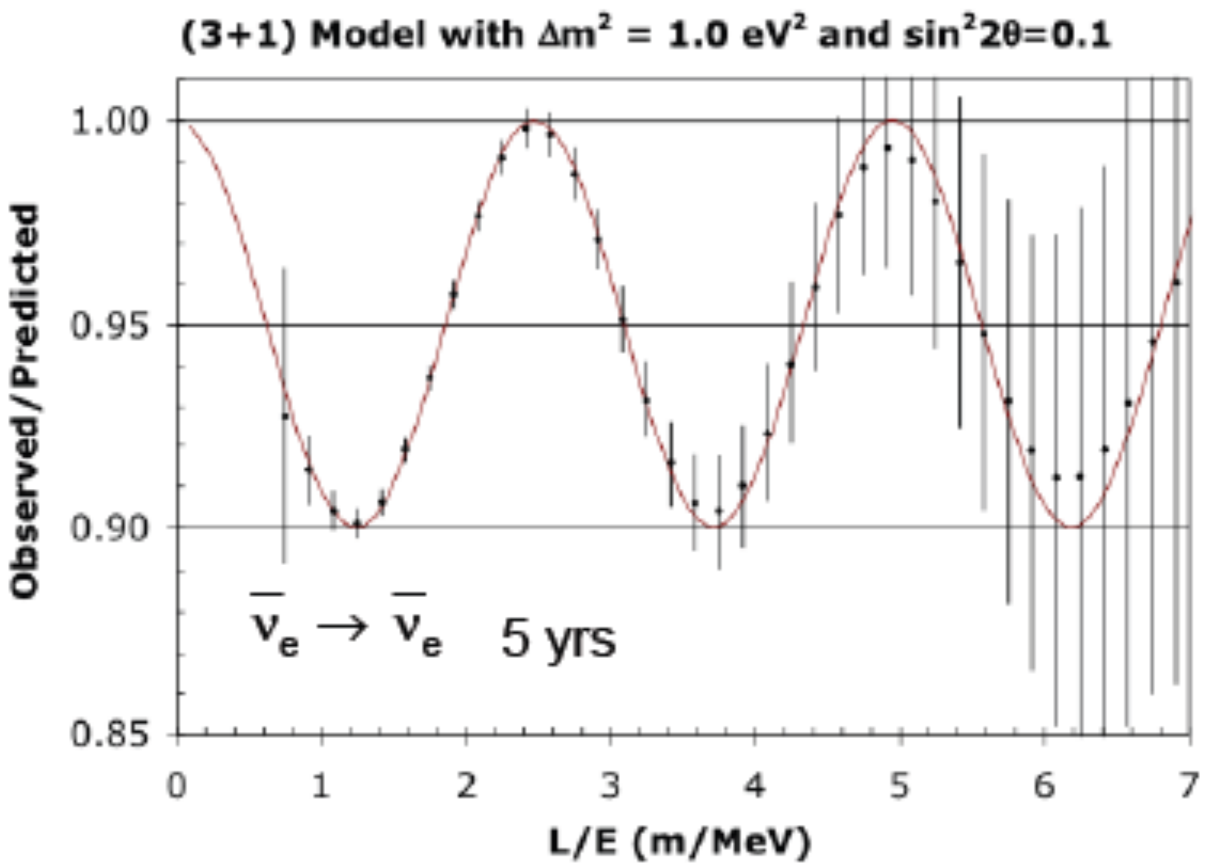
arXiv:1205.4419

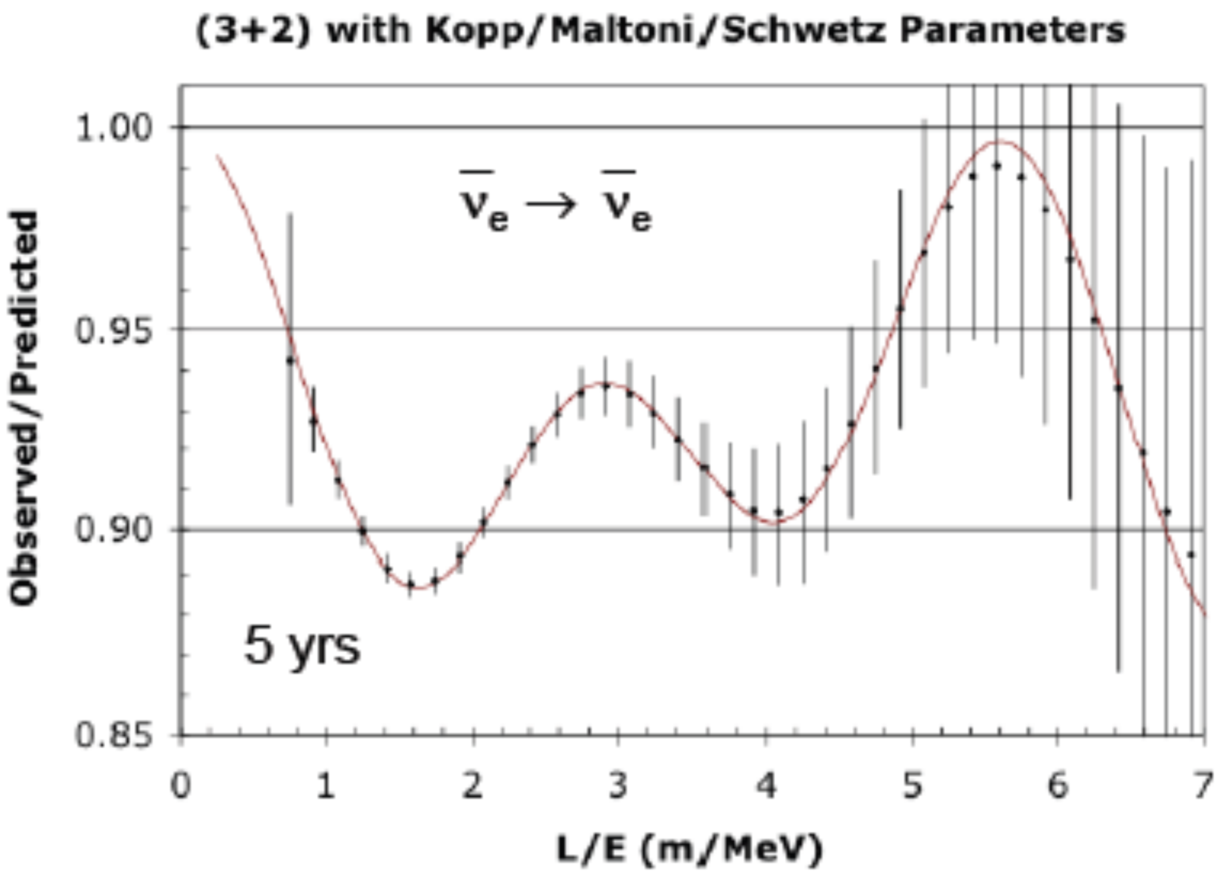


Shaevitz - Neutrino 2012

Oscillation L/E Waves in IsoDAR

Observed/Predicted event ratio vs L/E including energy and position smearing

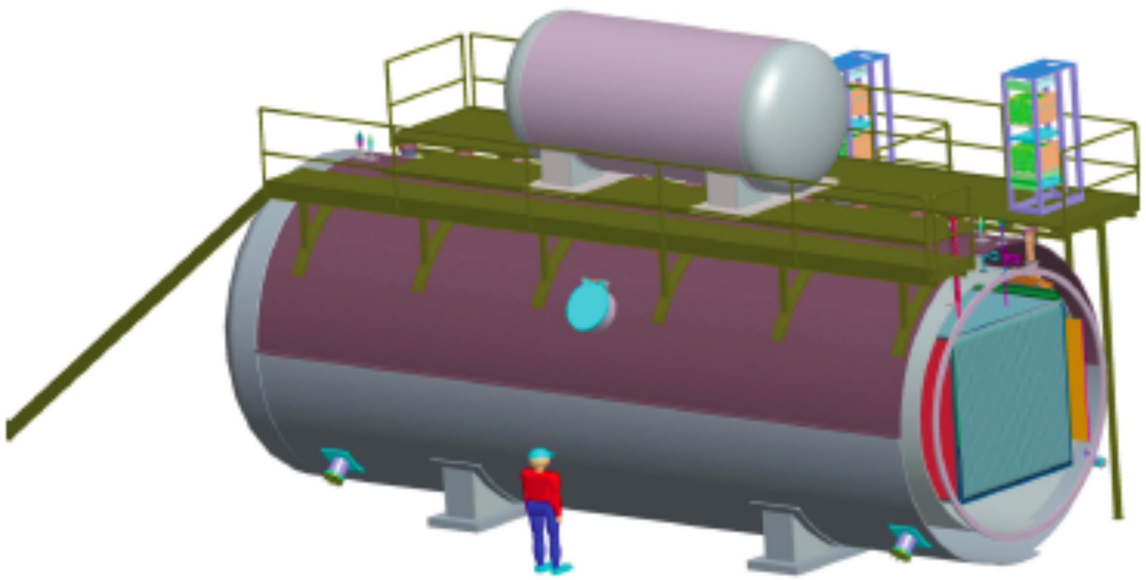


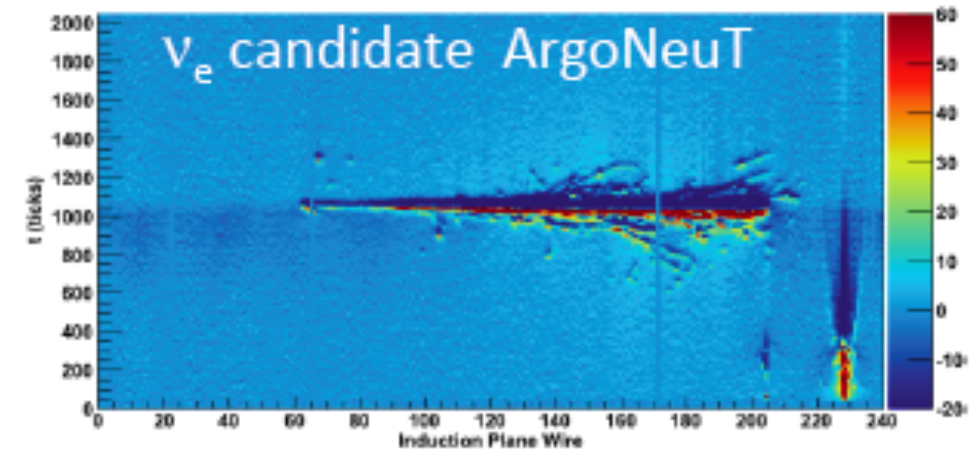


IsoDAR's high statistics and good L/E resolution gives good sensitivity to distinguish (3+1) and (3+2) oscillation models

Shaevitz - Neutrino 2012

MicroBooNE Experiment (Under Construction) using Fermilab Booster Neutrino Beamline (BNB)

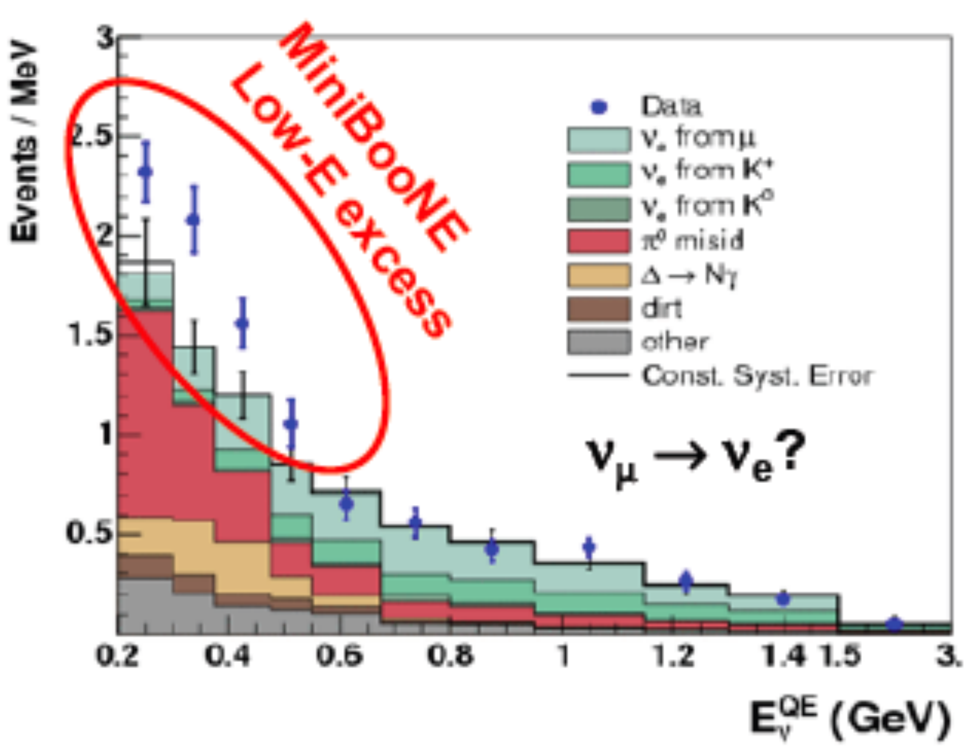




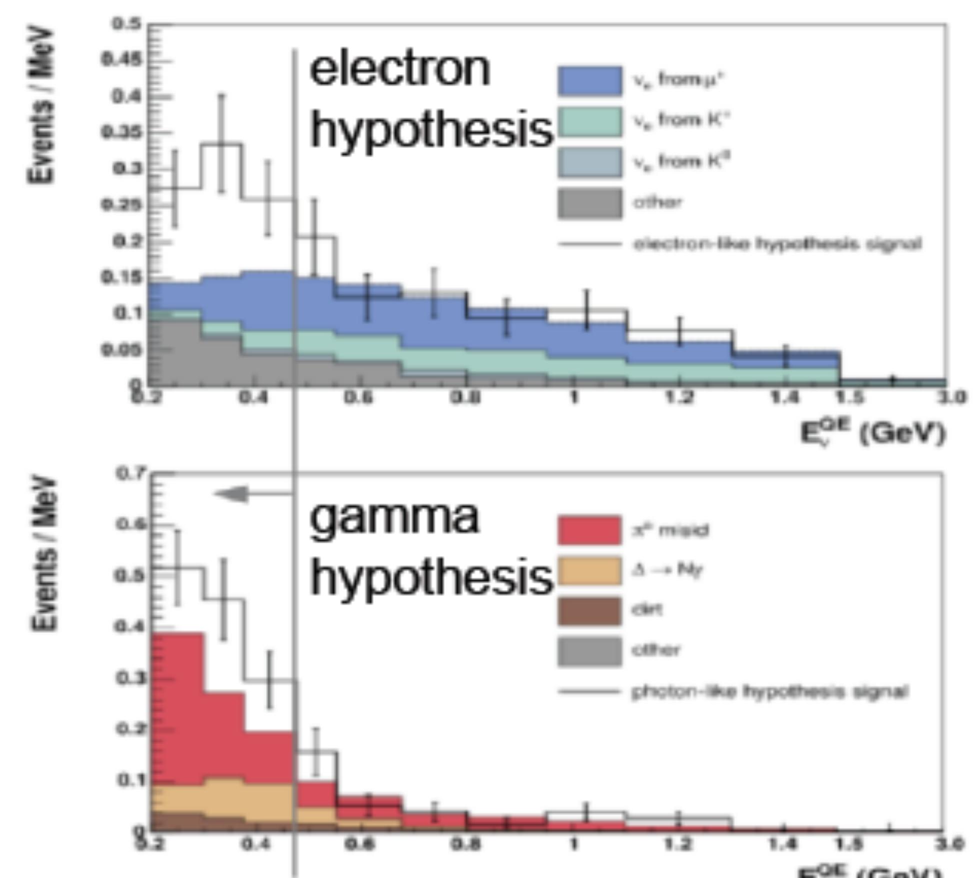
Use topology and dE/dx to differentiate electrons (signal) from gammas (background)

(Indistinguishable in Cerenkov imaging detectors)

See poster #167 G. Karagiorgi



Is it electrons or gammas?



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LAr1kton at Fermilab Booster ν Beamline (BNB)

- To directly address LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal, use multiple detectors in the Fermilab BNB
- Large (1 kton fiducial) LAr detector at 700m plus MicroBooNE at 200m (also maybe MiniBooNE with scintillator at 540 m)
- LAr capabilities significantly reduces gamma and other backgrounds

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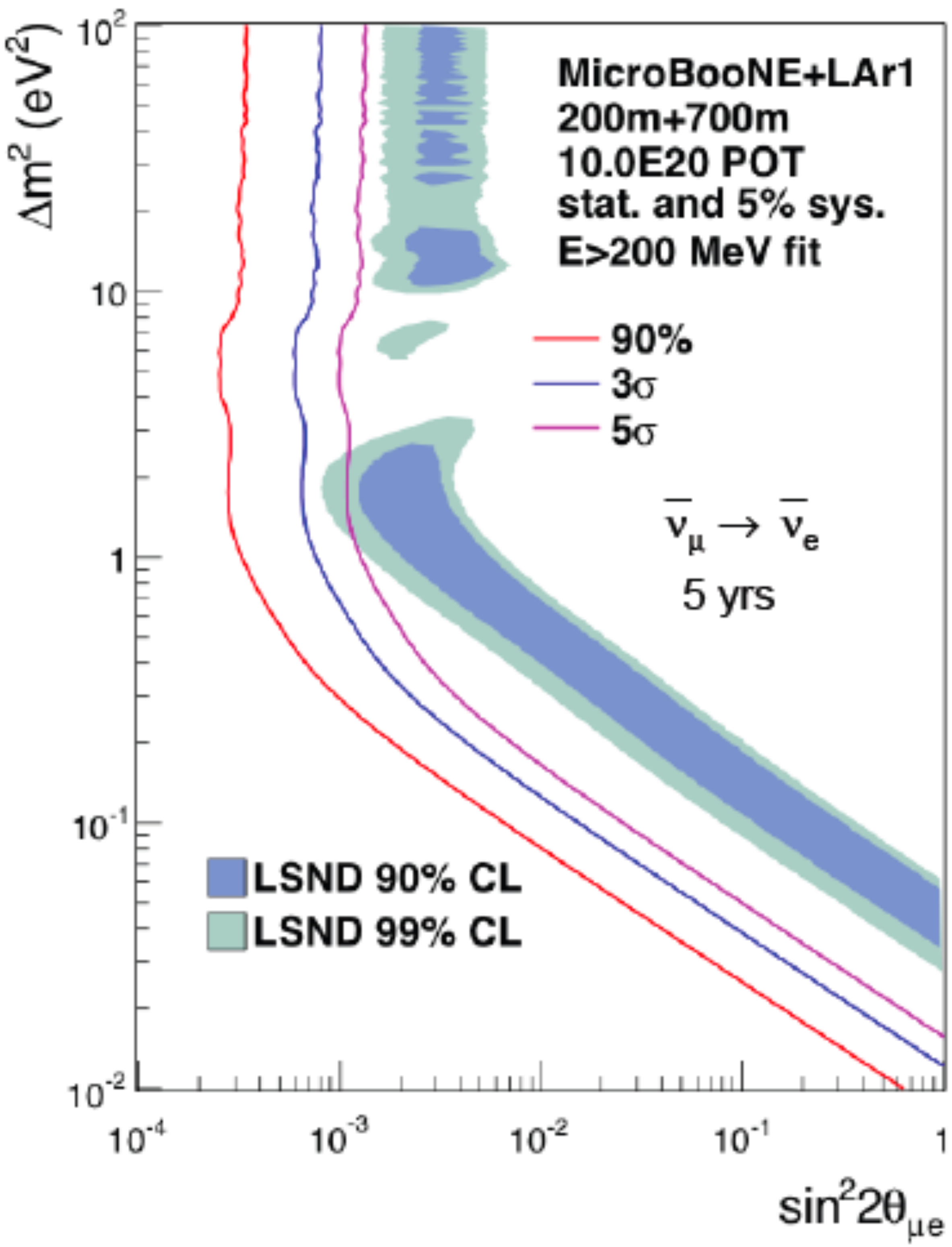
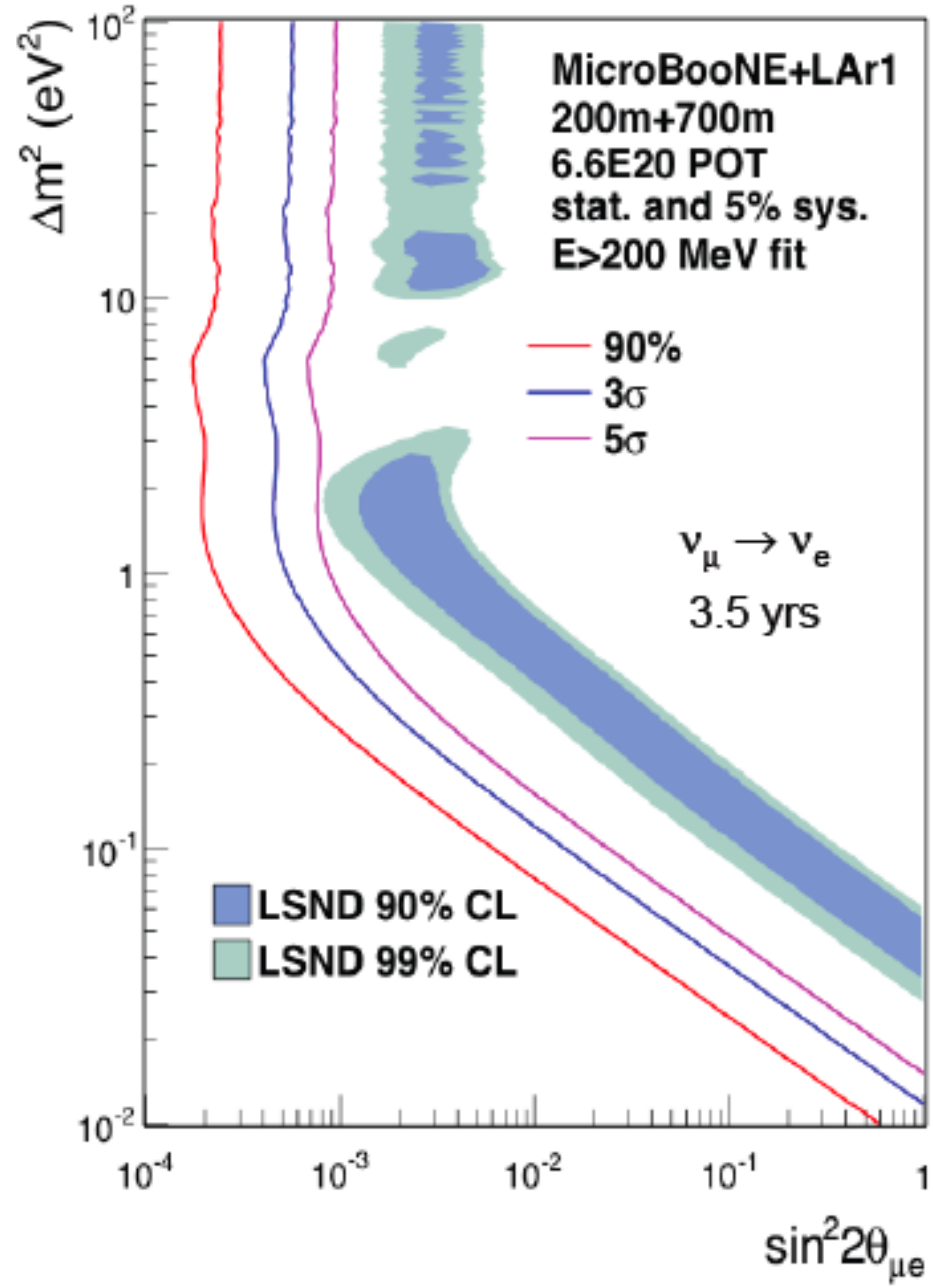
LAr1kton Sensitivity





Shaevitz - Neutrino 2012

Time-of-Flight

- Measurements of:
  - time neutrinos take to travel some distance (eg, between two detectors, or from supernovae to Earth)
  - muon momentum in pion decay
- Assuming neutrino mass is ~eV, then for E_ν ~ GeV and L~1000 km, need timing resolution of ~10^{-22} s. Good luck.
- Measurements of neutrinos from Supernova 1987A gave us an upper limit of ~20 eV for the neutrino mass. Would need tens of Gton of detector to make a good measurement of the mass.

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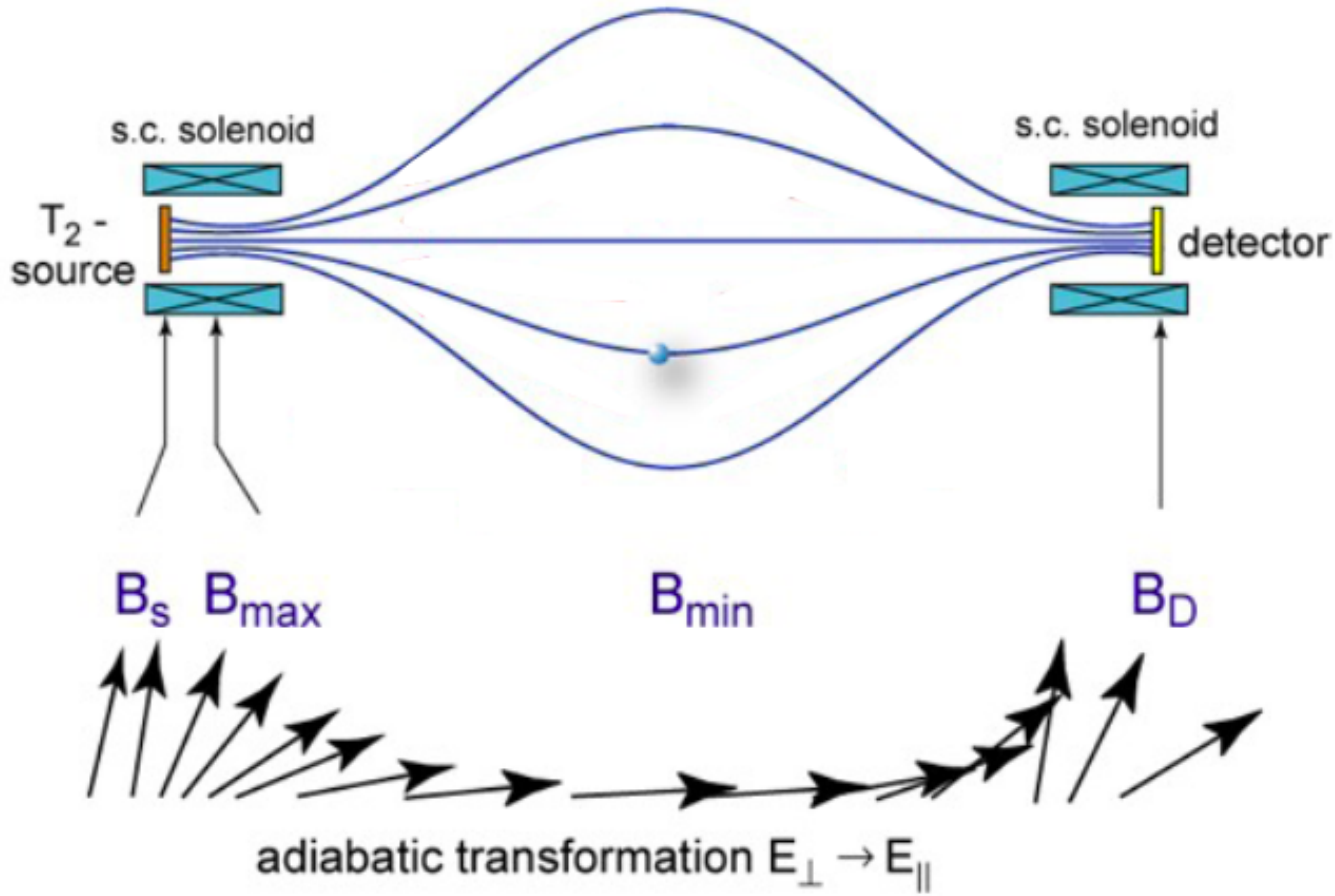
Solenoidal retarding electrostatic spectrometer

MAC-E - Magnetic Adiabatic Collimation followed by an Electrostatic filter

Developed independently by Mainz & Troitsk groups.

Adiabatic magnetic guiding
of β´s along field lines
in stray B-field of
s.c. solenoids:



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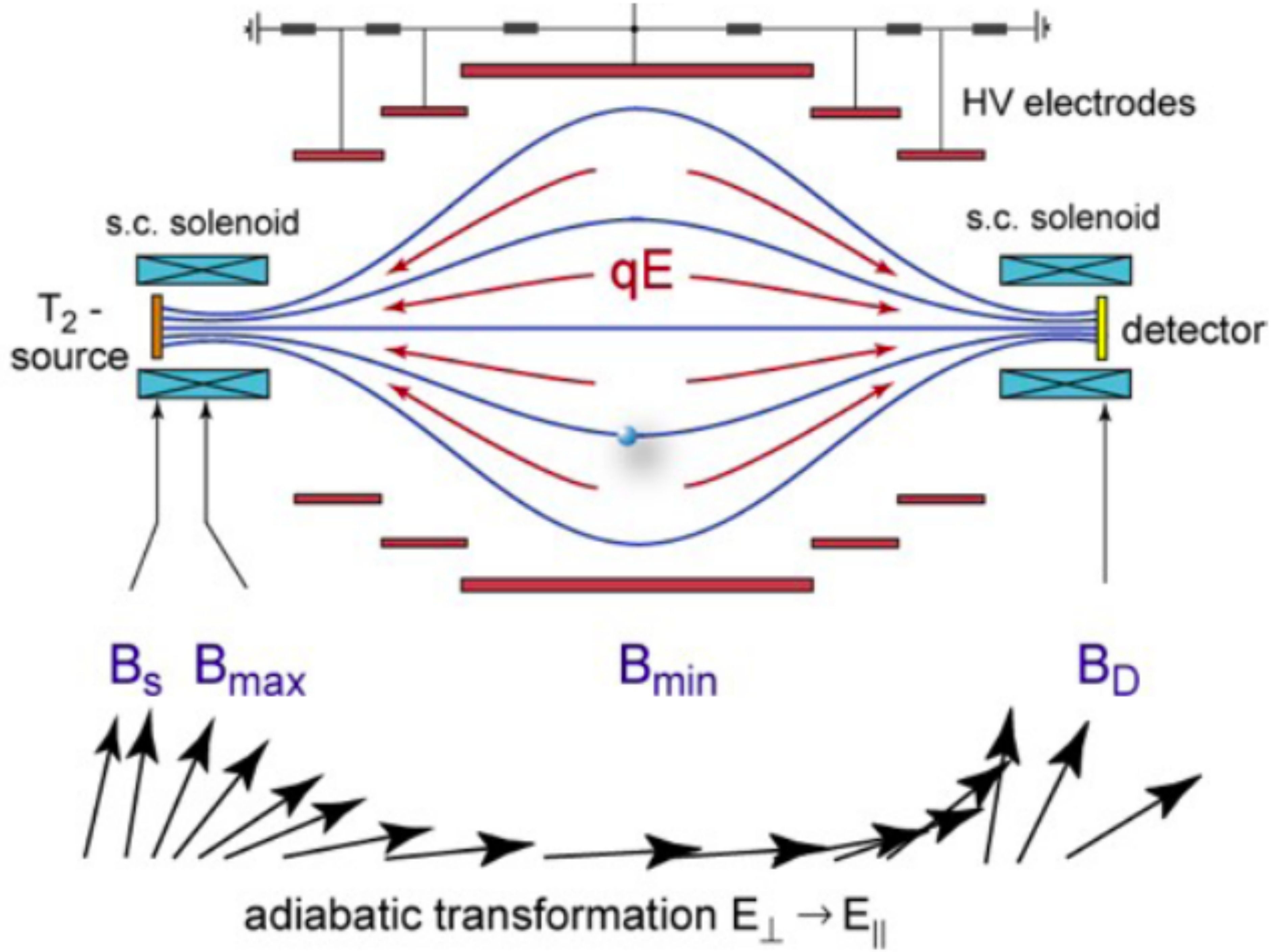
Developed independently by Mainz & Troitsk groups.

Adiabatic magnetic guiding of β´s along field lines in stray B-field of s.c. solenoids:

Energy analysis by static retarding E-field with varying strength:

High pass filter with integral β transmission for E>qU



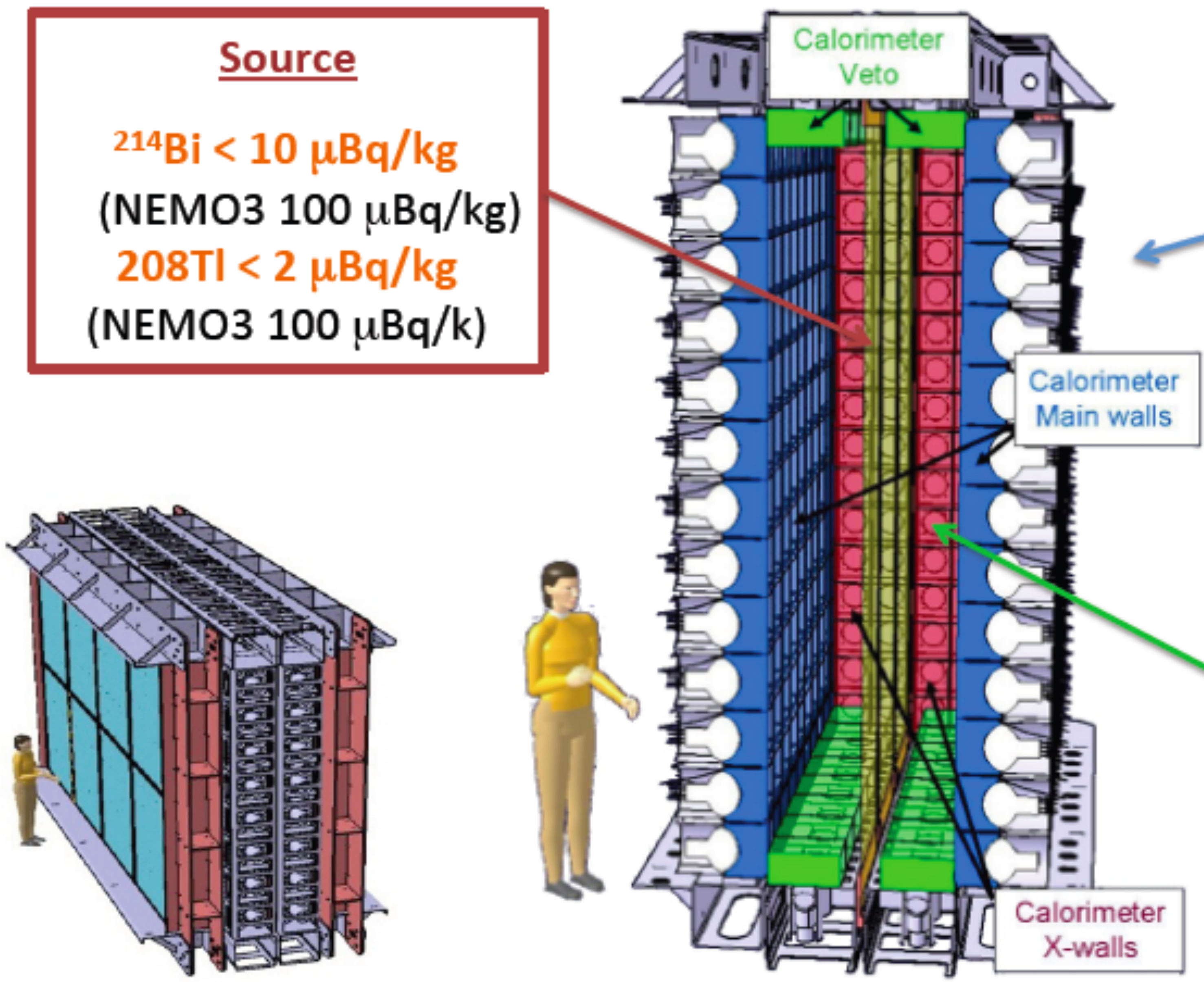
Neutrinoless Double Beta Decay

SuperNEMO Demonstrator

Objective: to reach the background level for 100 kg
to perform a no background experiment with 7 kg isotope of ^{82}Se in 2 yr

Source

$^{214}Bi < 10\ \mu Bq/kg$
(NEMO3 100 μBq/kg)
208Tl < 2 μBq/kg
(NEMO3 100 μBq/k)



Calorimeter

ΔE/E < 4% @ 3 MeV
(NEMO3 8.6% at 3MeV)

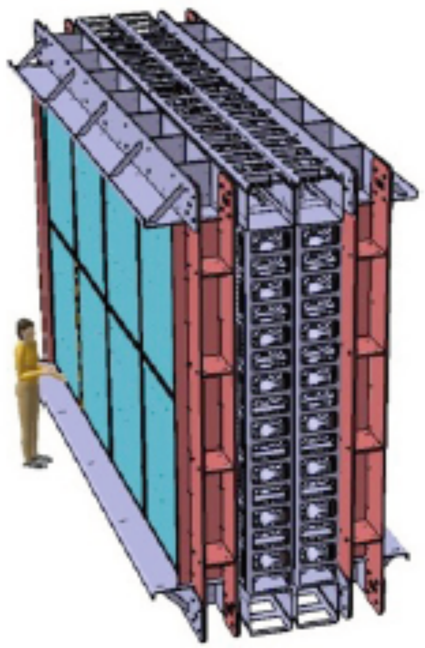
Tracker

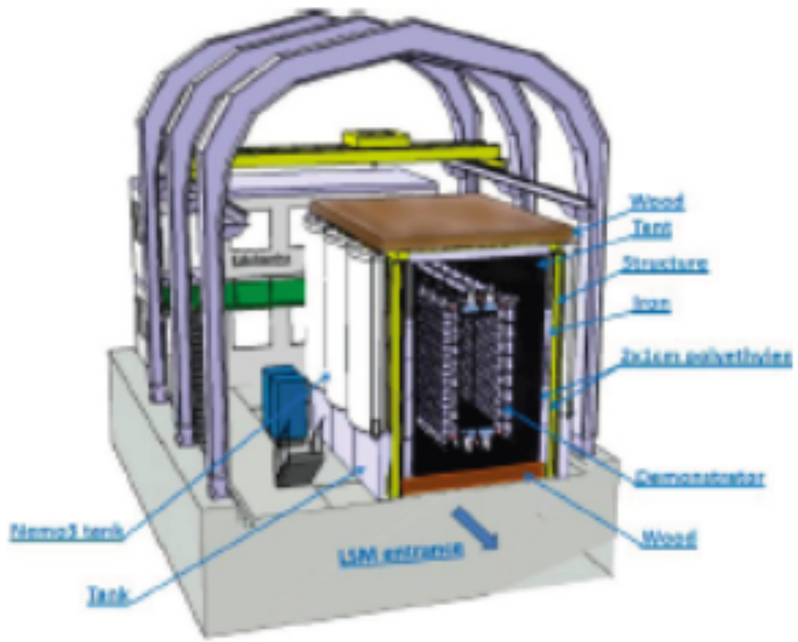
3.7 m long (NEMO3 2.7 m)
$\sigma_t = 5$ mm, $\sigma_z = 1$ cm
Radon < 0.15 mBq/m^3
(NEMO3 5 mBq/m^3)
Wiring robot

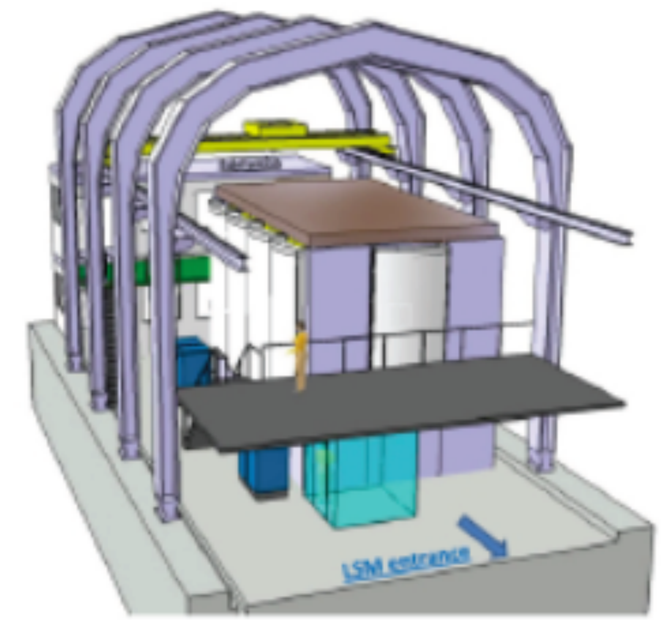
Global efficiency : 30 % (NEMO3 8%)

Neutrinoless Double Beta Decay

SuperNEMO demonstrator





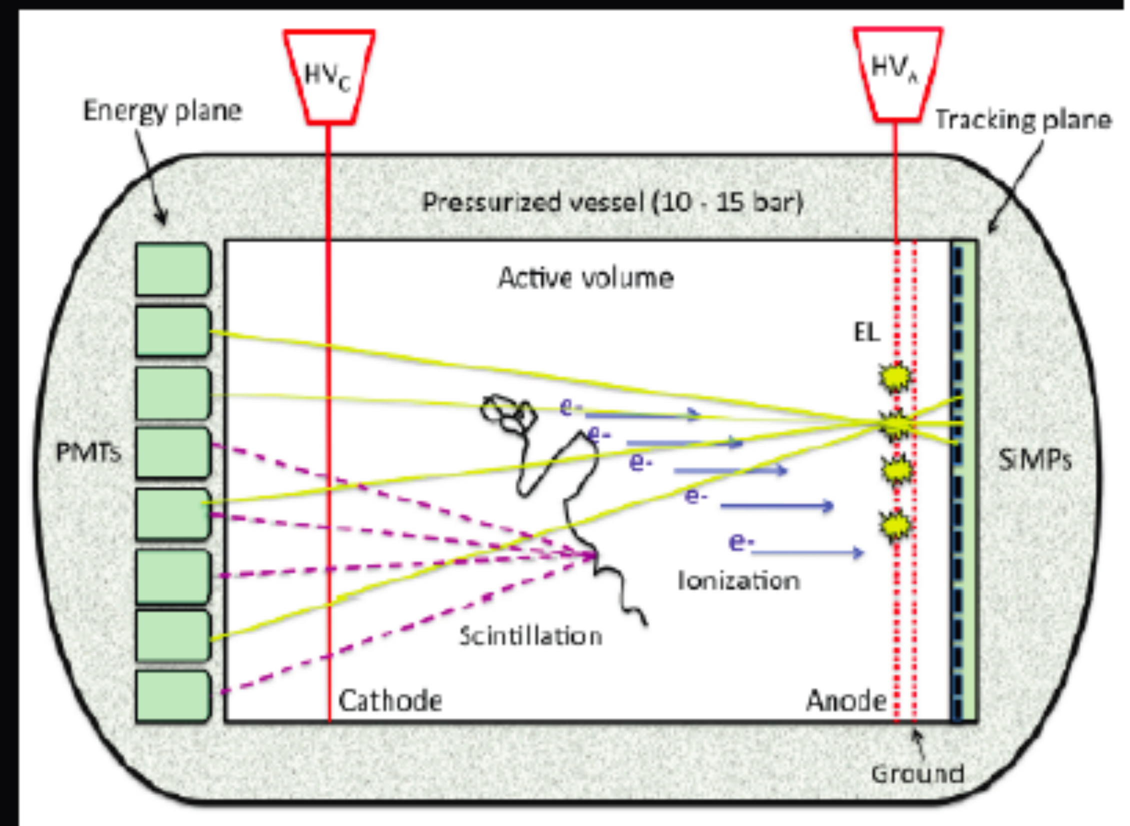


- ❑ Construction started in the laboratories
- ❑ Installation and commissioning (2013 – 2014) @ Modane Underground Laboratory
- ❑ Data taking in 2014
- ❑ No background expected
- ❑ Sensitivity after 2 years : $T_{1/2} > 6.6\ 10^{24}$ y and $<m_\nu> < 0.2$ -0.4 eV

NEXT

NEXT Detection Concept

- Cylindrical single drift volume
- Scintillation signal for t_0
- Ionization signal for separated energy and tracking measurements
    - Converted into EL light
- Instrumented endcaps
    - PMTs on energy plane
    - SiPMs on tracking plane
- TPB coating: 170 → 430 nm light



NEXT strengths:

- Scalability to ton-scale relatively easy
- 0.5-1% FWHM energy resolution
- Tracking and dE/dx information for event topology

Neutrinoless Double Beta Decay

NEXT

NEXT Progress since Neutrino 2010

- **Experience and results from prototypes**
  - Testing ground for all foreseeable technical hurdles in NEXT-100
  - 0.5-1% FWHM energy resolution at $Q_{\beta\beta}$ demonstrated
  - Tracking and event topology studies underway

Simulated $\beta\beta0\nu$ track in Xe at 10 bar

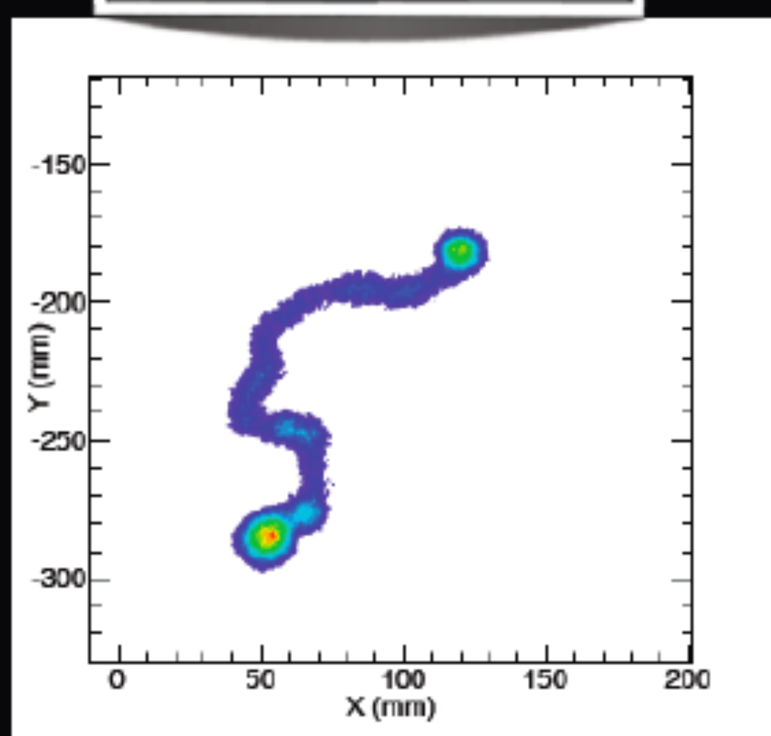
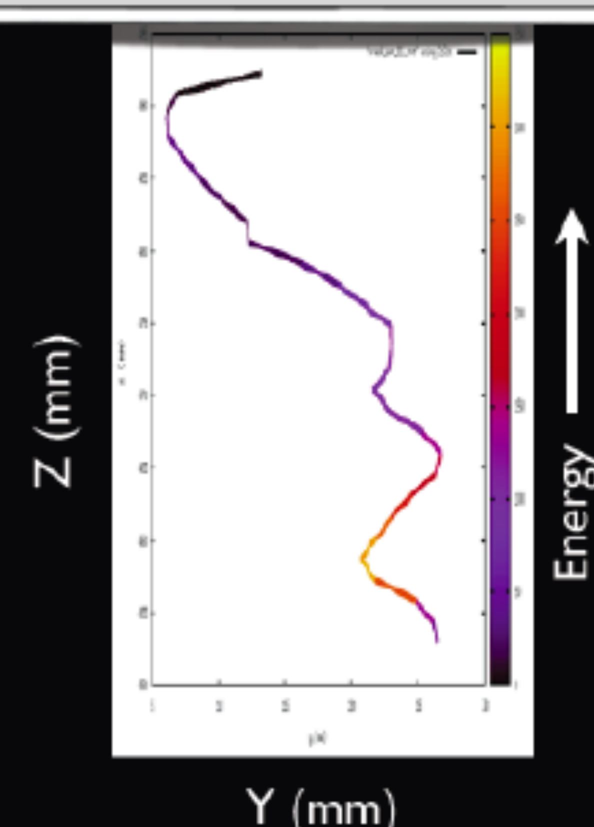


Photo-electron track from 662 keV gamma in NEXT-DEMO at 10 bar

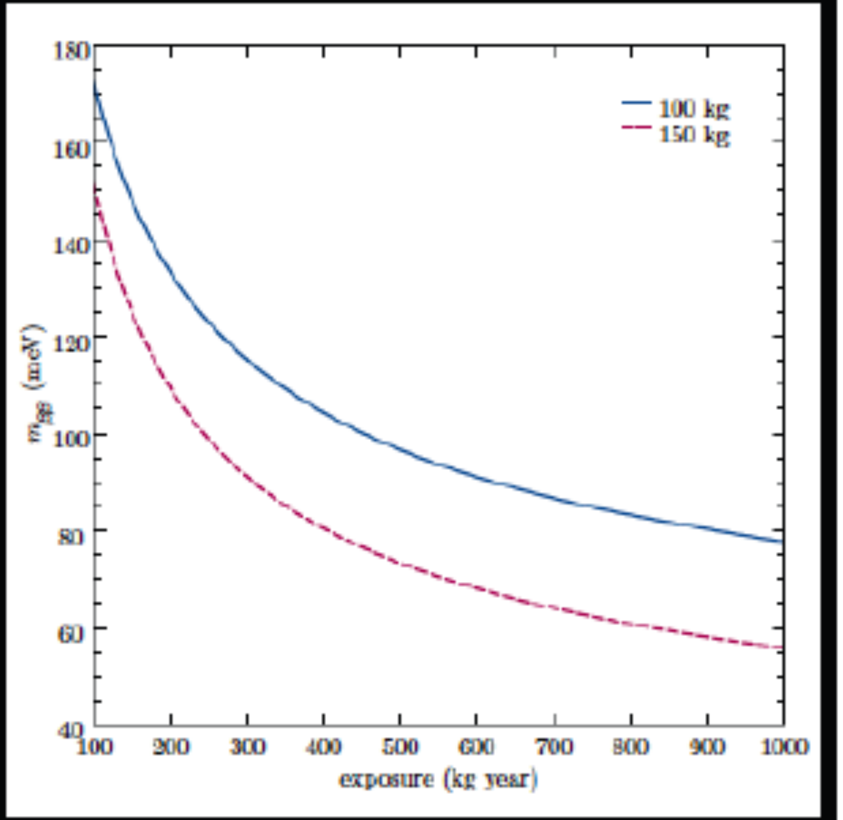


Neutrinoless Double Beta Decay

NEXT

NEXT Sensitivity and Schedule

- NEXT-100 should be sensitive to effective Majorana masses as small as 100 meV after 5 years of operation
  - 90% CL, assuming 100 kg of xenon
  - half-life sensitivity: 6×10^{25} years
- Main backgrounds expected to be gammas from ^{214}Bi and ^{208}Tl
  - 2×10^{-7} background rejection factor
  - 8×10^{-4} counts/(keV·kg·y) background rate
  - Based on detailed background model

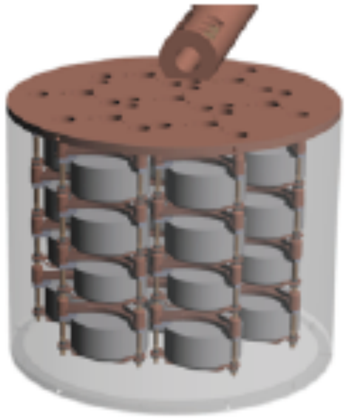


Schedule:
2012: complete R&D, NEXT-100 design, radiopurity campaign
2013: NEXT-100 construction
2014: NEXT-100 commissioning with non-enriched xenon
2015: start physics run with enriched xenon

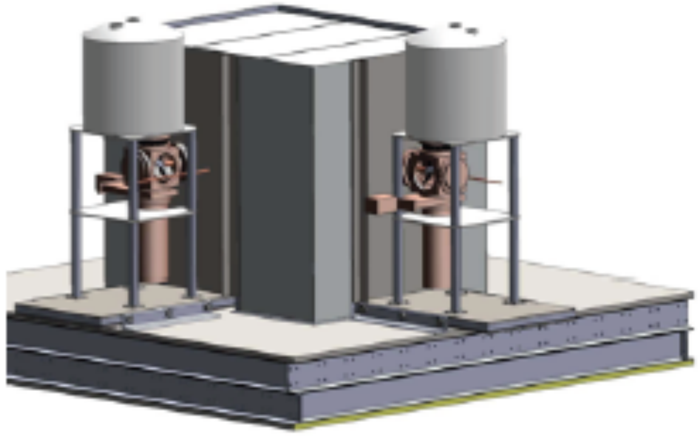
Neutrinoless Double Beta Decay

MAJORANA

^{76}Ge offers an excellent combination of capabilities & sensitivities.
(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)



- 40-kg of Ge detectors
  - Up to 30-kg of 86% enriched ^{76}Ge crystals required for science and background goals
  - Examine detector technology options focus on point-contact detectors for DEMONSTRATOR
- Low-background Cryostats & Shield
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto



- Agreement to locate at 4850' level at Sanford Lab
- Background Goal in the $0\nu\beta\beta$ peak ROI(4 keV at 2039 keV)

~ 3 count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)

Piquemal - Neutrino 2012

Neutrinoless Double Beta Decay

MAJORANA

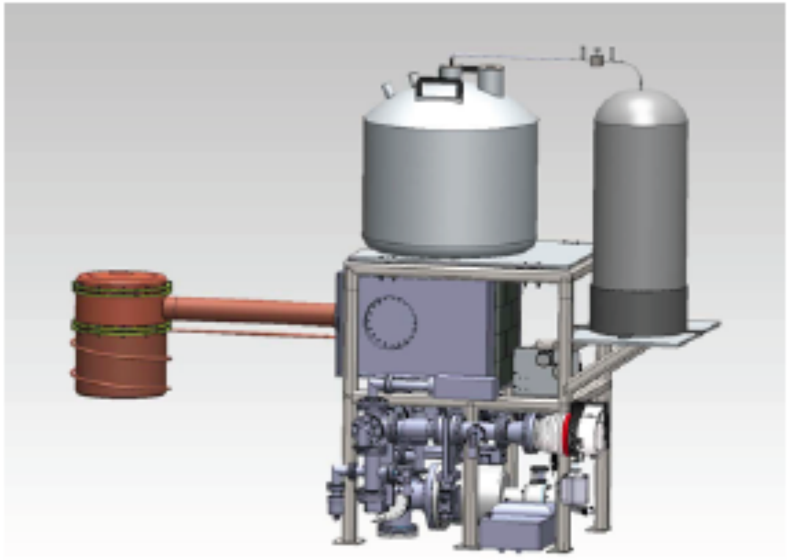
Three Phases

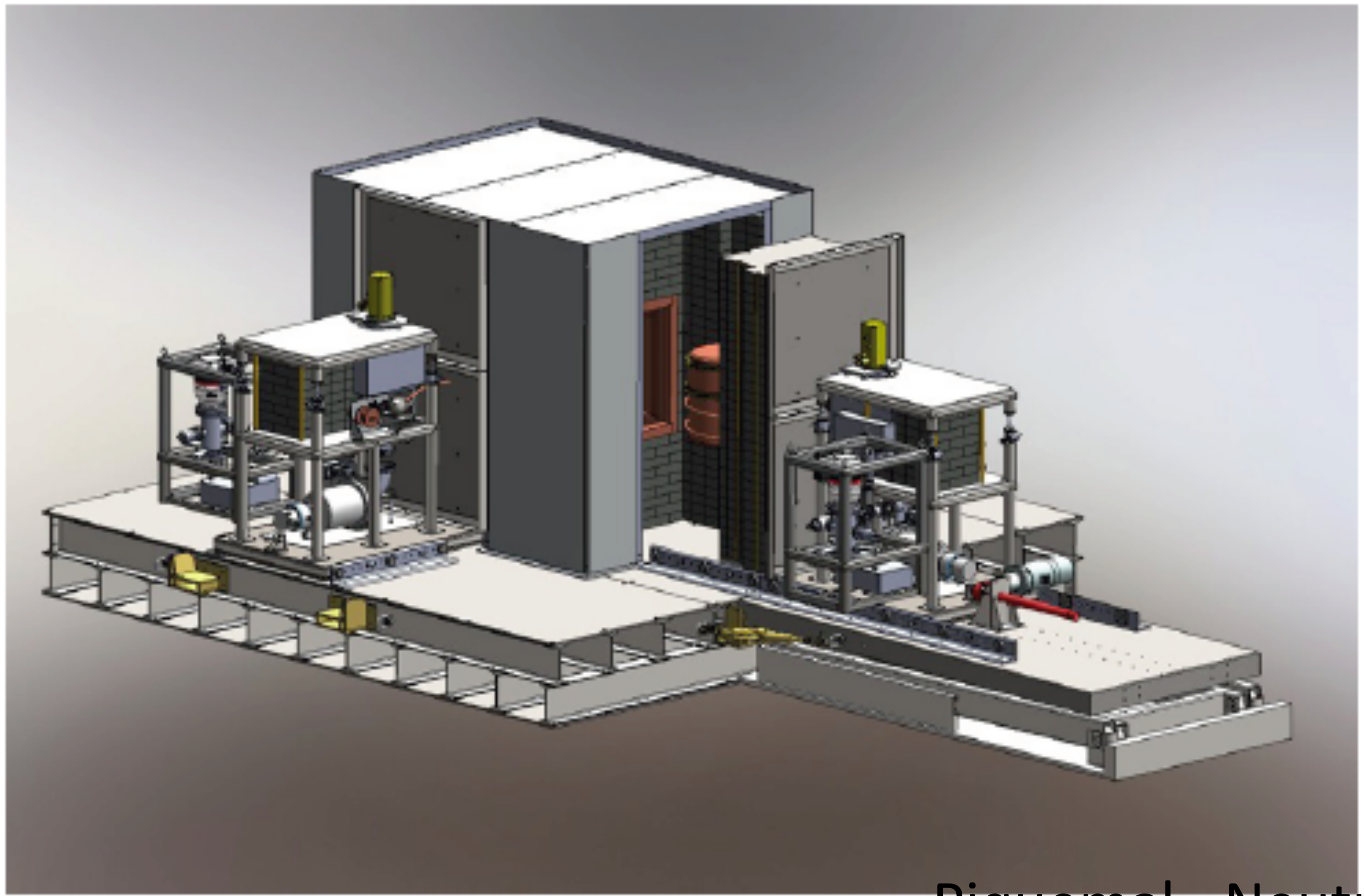
– Prototype cryostat (2 strings, ^{nat}Ge) **(End 2012)**

1st order of ^{enr}Ge (20 kg) on hand. 2nd order in process. Refinement/ processing facility in Oak Ridge (via NSF) has completed testing with ^{nat}Ge.

– Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge) **(Fall 2013)**

– Cryostat 2 (up to 7 strings ^{enr}Ge) **(Fall 2014)**





Piquemal - Neutrino 2012

Limits from Cosmology

- Data from WMAP, CMB and Large-scale structure measurements place limits on Σm_i

Robust neutrino constraints… on the total mass

Reid, et al 2010, WMAP+H0+MaxBCG, SDSS DR7 P(k)

$\sigma_8(\Omega_m/0.25)^{0.41} = 0.832 \pm 0.033.$

Bayesian upper 95% C.L. bound on $\sum m_\nu$

model	base dataset	–	+maxBCG	$+H_0$	+maxBCG+H_0
ΛCDM	WMAP5	1.3	1.1	0.59	[illegible]
ΛCDM	WMAP5+BAO+SN	0.67	0.35	0.59	[illegible]
ΛCDM $+\alpha$	WMAP5	1.34	1.25	[illegible]	[illegible]
ΛCDM $+r$	WMAP5	1.36	[illegible]	[illegible]	[illegible].40
wCDM	WMAP5+BAO+SN	0.80	[illegible]	[illegible]	0.47

Also: Thomas et al. (2010), [illegible] et al (2010), Giusarma et al (2011)
Riemer-Sørensen ([illegible]) [illegible]tc.

dePutte[illegible] (SDSS DR9 BOSS)

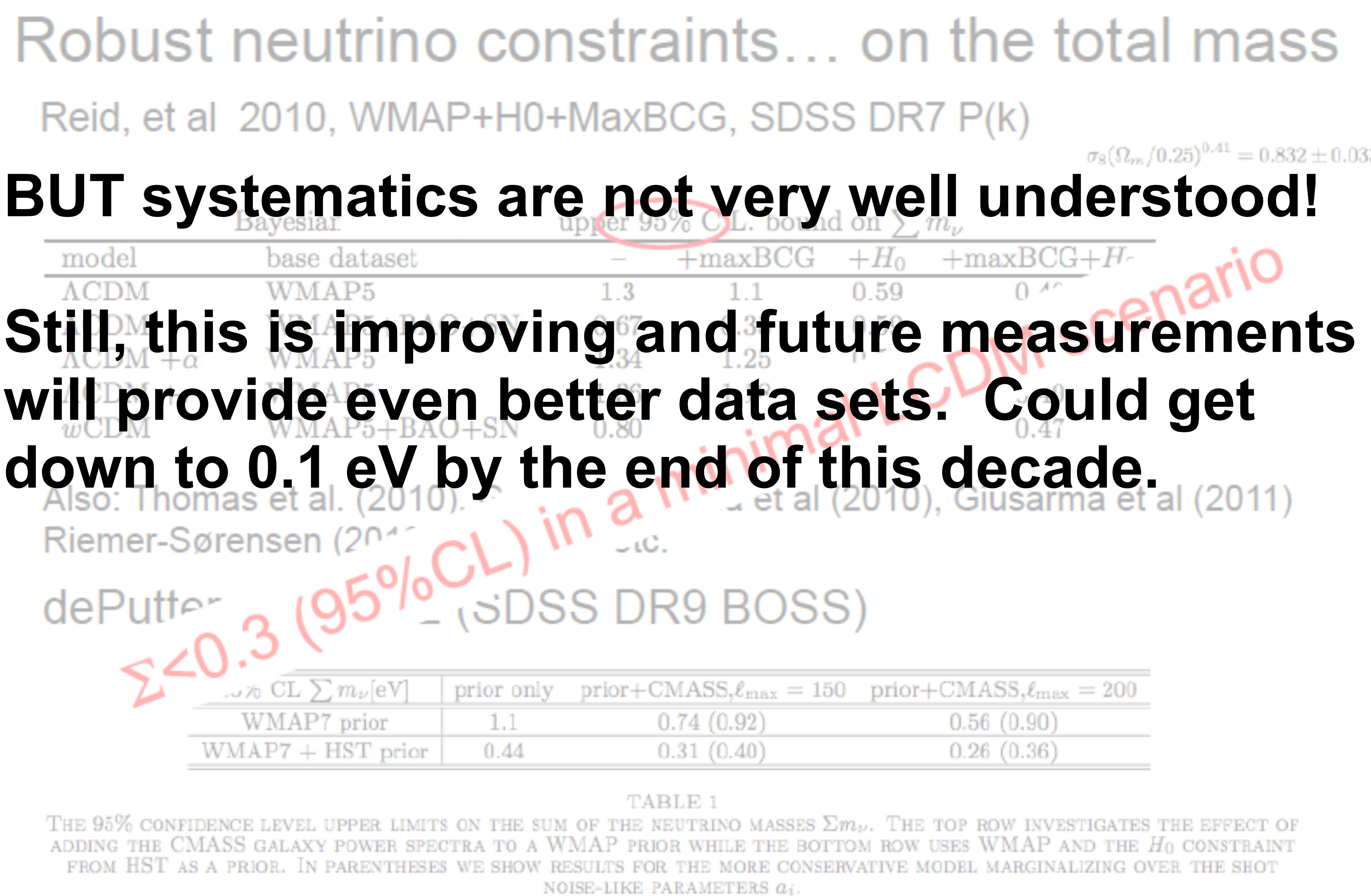
Σ<0.3 (95%CL) in a minimal LCDM scenario

[illegible]% CL $\sum m_\nu$[eV]	prior only	prior+CMASS,$\ell_{max} = 150$	prior+CMASS,$\ell_{max} = 200$
WMAP7 prior	1.1	0.74 (0.92)	0.56 (0.90)
WMAP7 + HST prior	0.44	0.31 (0.40)	0.26 (0.36)

TABLE 1
THE 95% CONFIDENCE LEVEL UPPER LIMITS ON THE SUM OF THE NEUTRINO MASSES Σm_ν. THE TOP ROW INVESTIGATES THE EFFECT OF ADDING THE CMASS GALAXY POWER SPECTRA TO A WMAP PRIOR WHILE THE BOTTOM ROW USES WMAP AND THE H_0 CONSTRAINT FROM HST AS A PRIOR. IN PARENTHESES WE SHOW RESULTS FOR THE MORE CONSERVATIVE MODEL MARGINALIZING OVER THE SHOT NOISE-LIKE PARAMETERS a_i.

Limits from Cosmology

- Data from WMAP, CMB and Large-scale structure measurements place limits on Σm_i



BUT systematics are not very well understood!

Still, this is improving and future measurements will provide even better data sets. Could get down to 0.1 eV by the end of this decade.