SPAATIND 2020– 26TH NORDIC PARTICLE PHYSICS MEETING

SKEIKAMPEN 2–7 JANUARY 2020

Neutrinos - Part II

Francesca Di Lodovico
King's College London

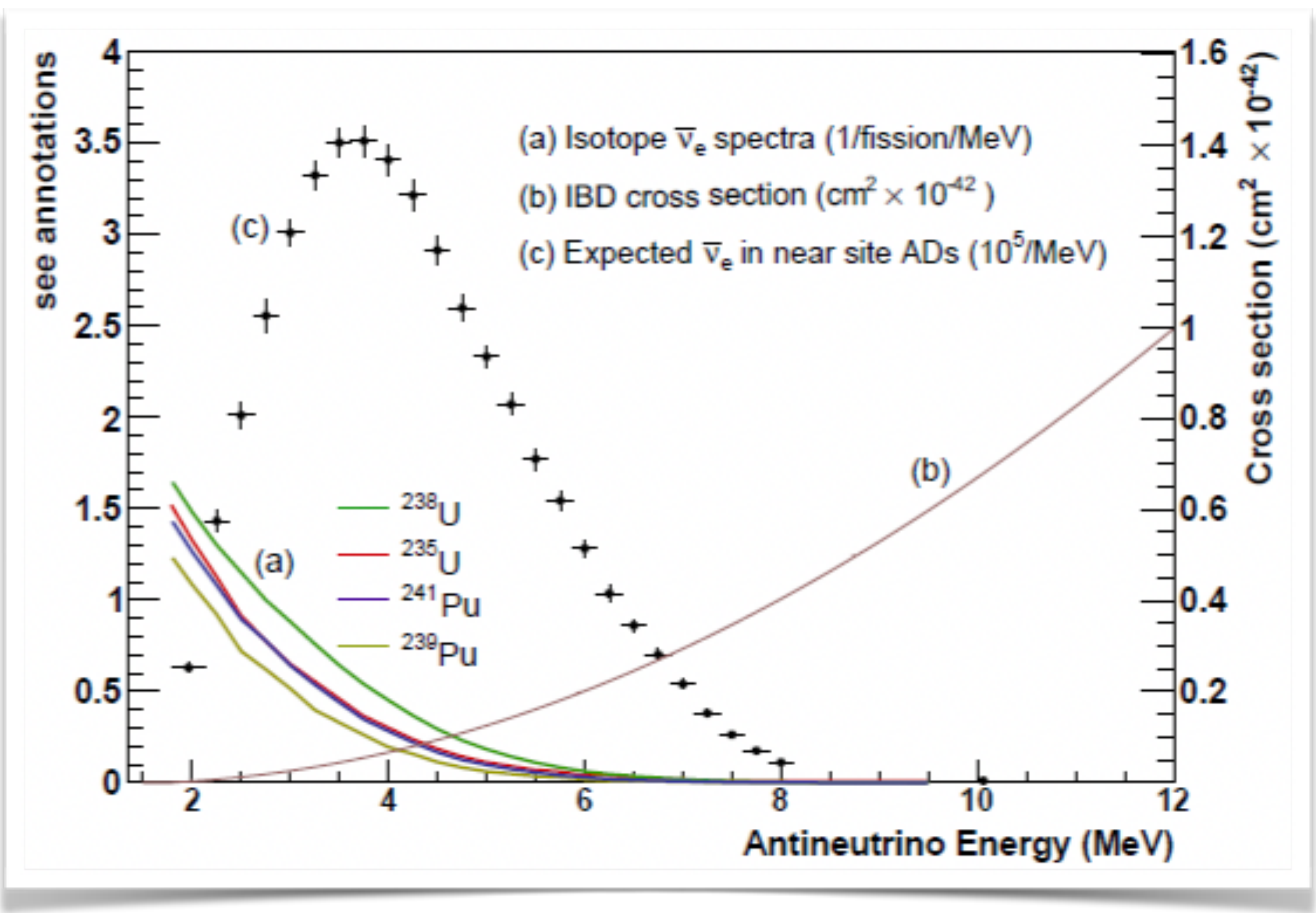
OUTLINE

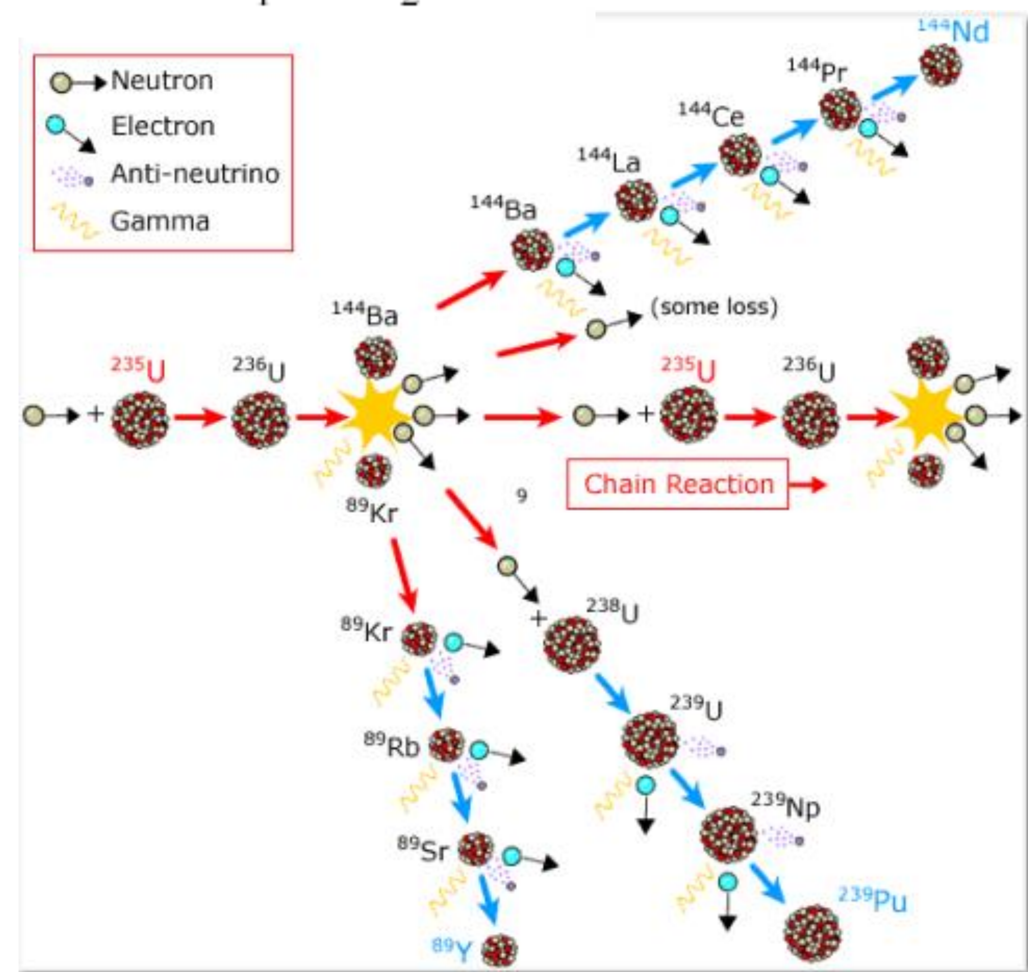
- Part I
  - What we know about neutrinos
  - Matter Antimatter Asymmetry & the role of Neutrinos
  - Study of Neutrinos using Long Baseline Neutrino Experiments
- Part II
  - Study of Neutrinos using Reactor Experiments
  - How we can measure the neutrino mass?
  - What is the nature of neutrinos? Dirac or Majorana?
  - Astrophysical neutrinos
  - Sterile neutrinos

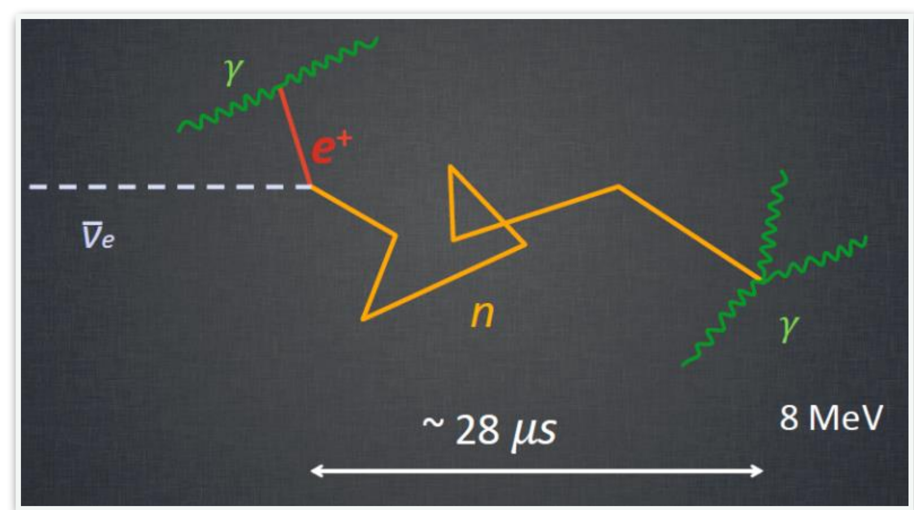
REACTOR NEUTRINO FLUX

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

- Pure electron antineutrinos $\overline{\nu}_e$
- $2 \times 10^{20}\, \overline{\nu}_e$/second/GW$_{\mathrm{th}}$
- Produced by fission products from four major isotopes: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu
- $\sim 6\, \overline{\nu}_e$ per fission
- Detect neutrino via an inverse beta decay





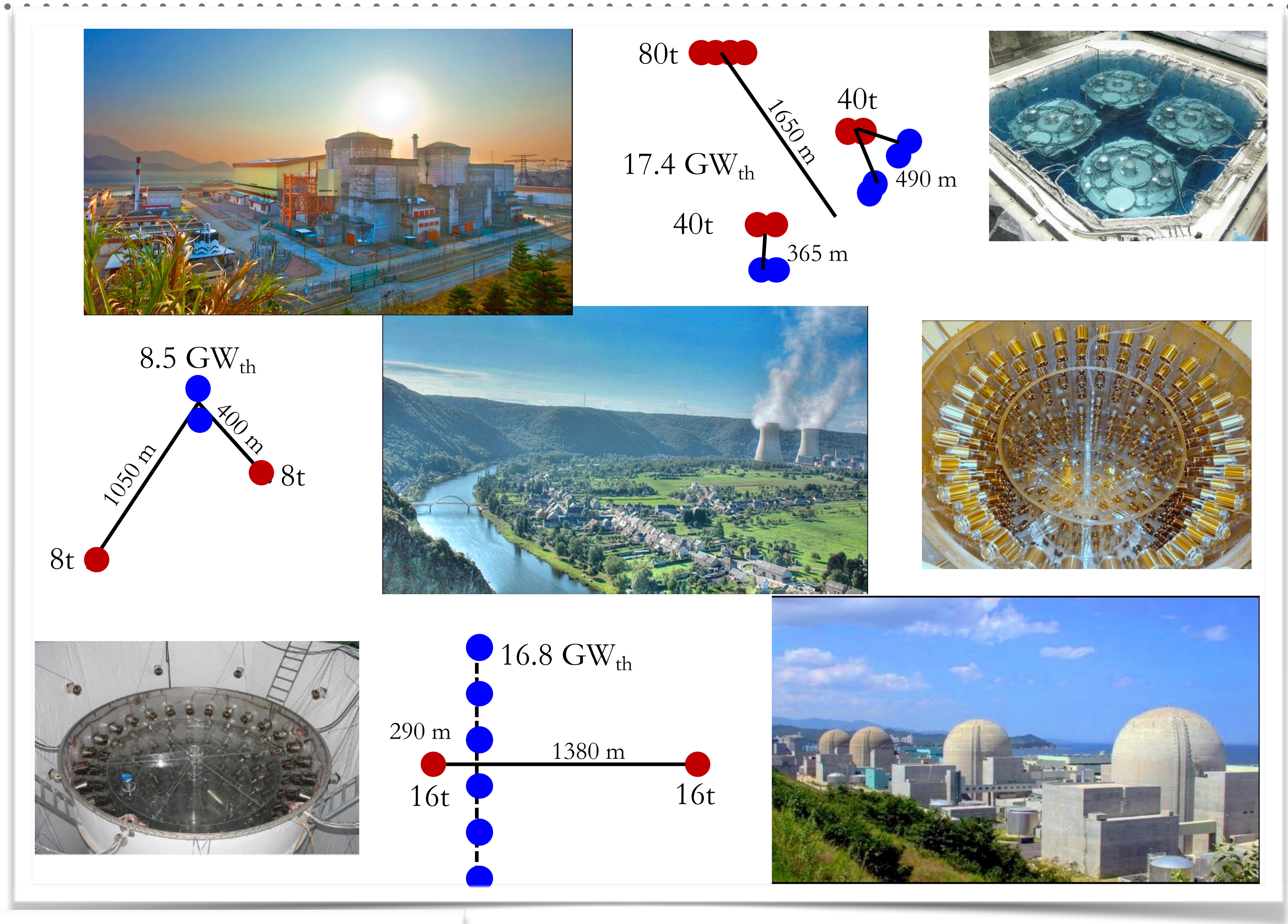


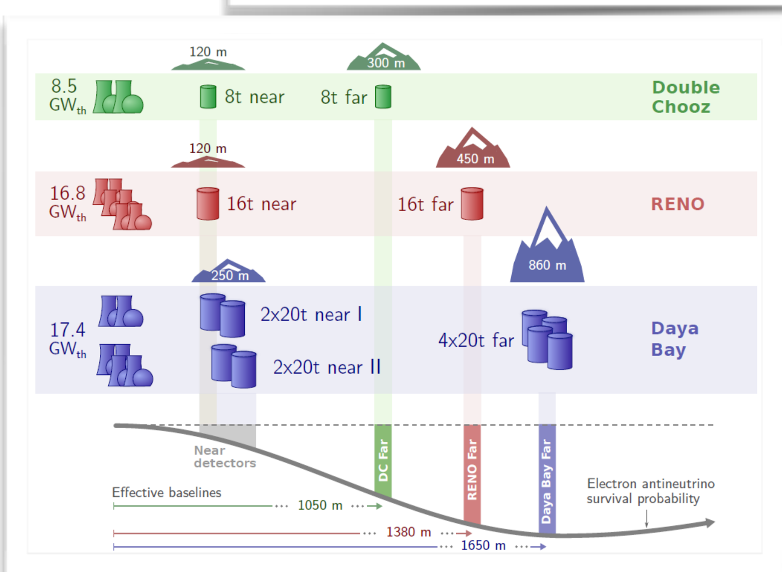
DAYA BAY, RENO AND DOUBLE CHOOZ FOR θ_{13}

Daya Bay (China)

Double Chooz (France)

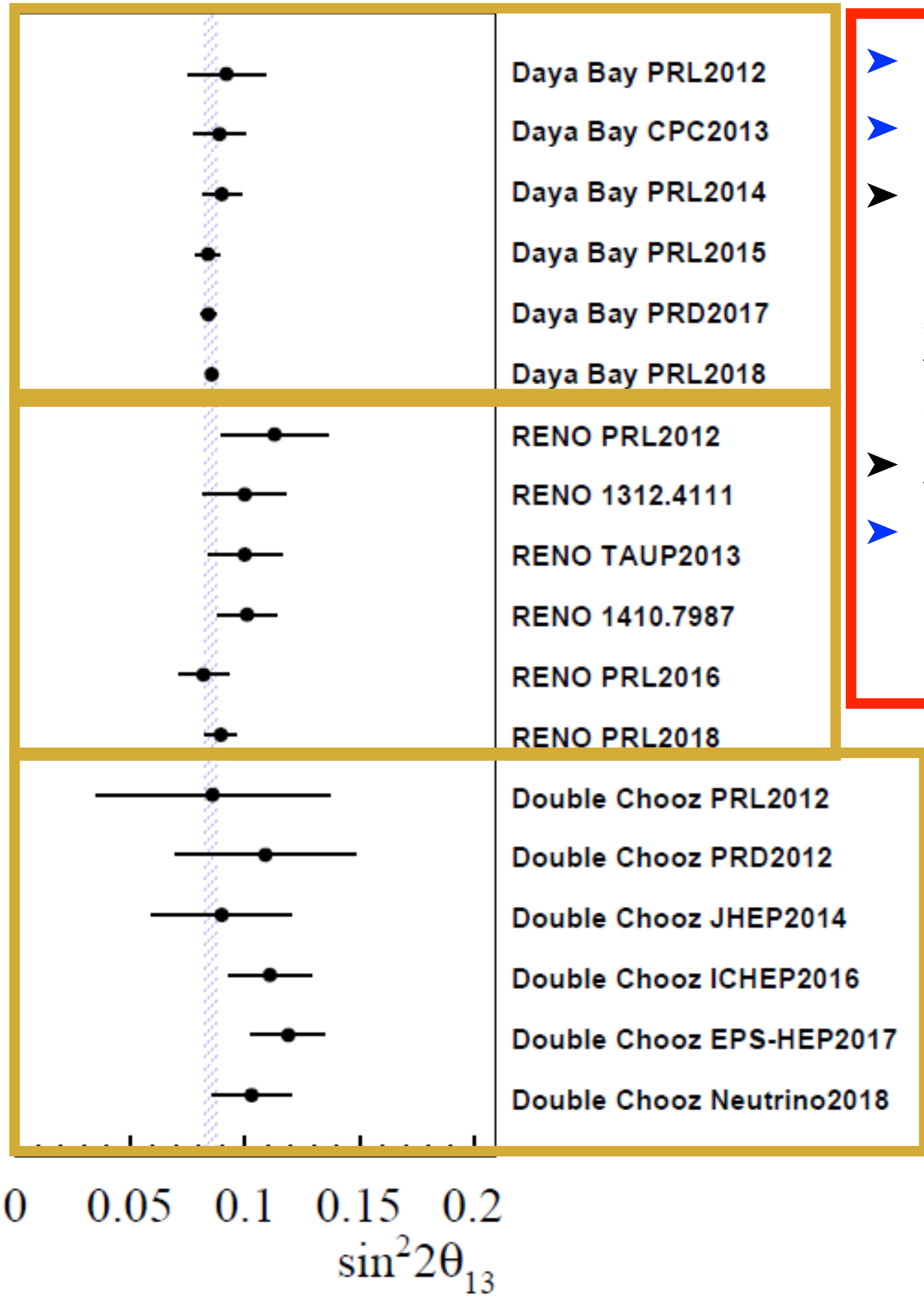
RENO (Korea)



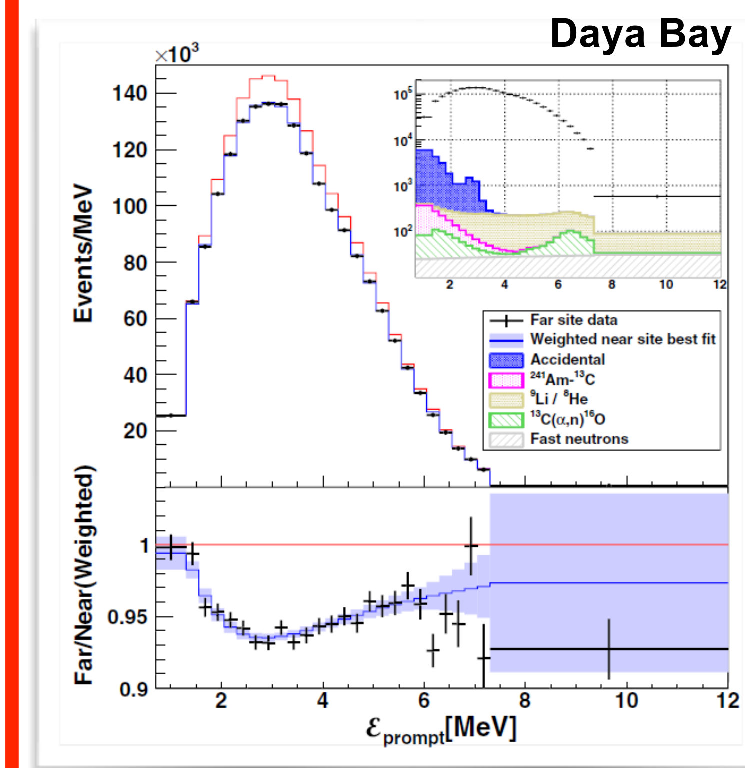


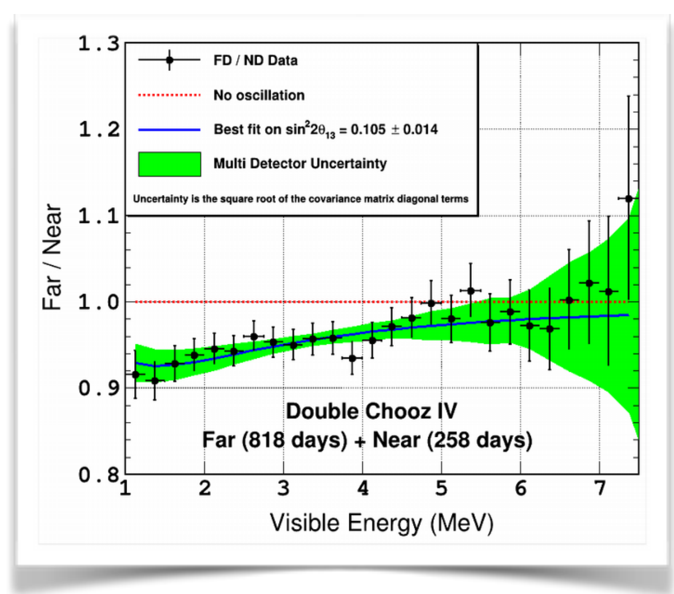
- Measure $\bar{\nu}_e \to \bar{\nu}_e$ disappearance
- No dependence on CP phase and θ_{23}

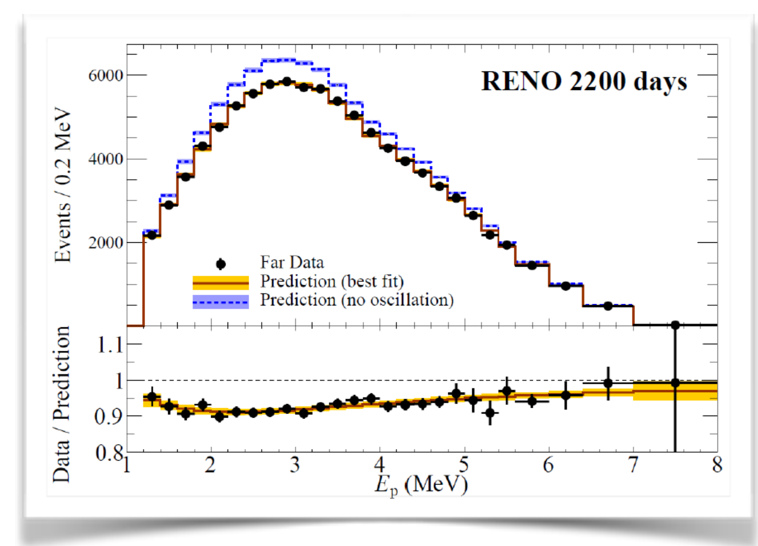
REACTOR EXPERIMENTS – CURRENT RESULTS



- Best precision at Daya Bay
- Still dominated by statistics
- Great success and rapid improvement on the precision: 20%➔3.4% from 2012 to 2019
- More data taking
- Ultimate precision: 3% from Daya Bay



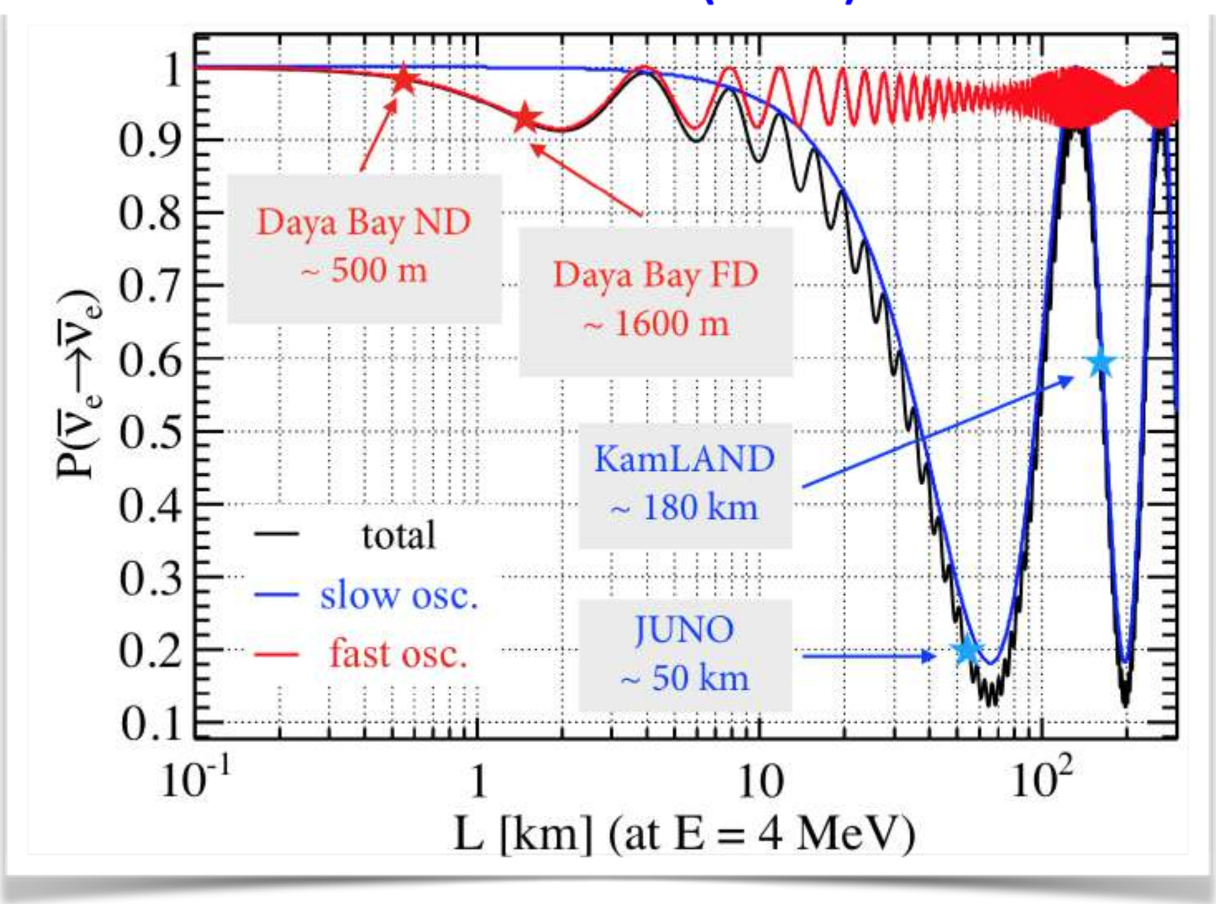




REACTOR NEUTRINO OSCILLATIONS FOR MASS ORDERING

- Interference effects between Δm^2_{12} and Δm^2_{32} driven oscillations can be used by reactor experiments to infer the neutrino mass hierarchy $\Rightarrow$ made possible by “large value” of θ_{13}

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \underbrace{\cos^4 \vartheta_{13} \sin^2 2\vartheta_{12} \sin^2 \frac{\boxed{\Delta m^2_{21}} L}{4E}}_{\text{(slow)}} - \underbrace{\sin^2 2\vartheta_{13} \left(\cos^2 \vartheta_{12} \sin^2 \frac{\boxed{\Delta m^2_{31}} L}{4E} + \sin^2 \vartheta_{12} \sin^2 \frac{\boxed{\Delta m^2_{32}} L}{4E} \right)}_{\text{(fast)}}$$



Solar (slow)

Atmospheric (fast)

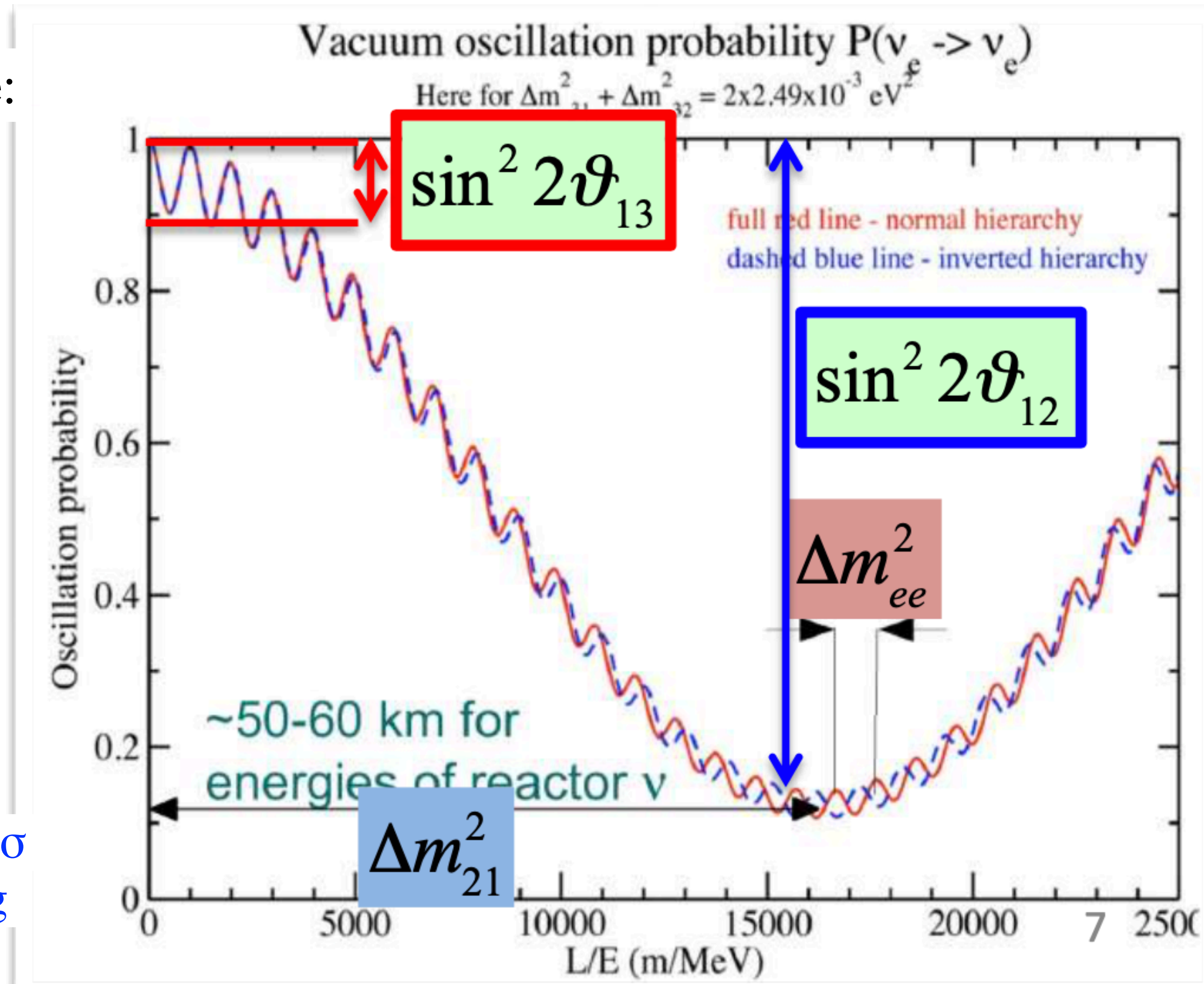
- JUNO will be the first experiment able to measure **simultaneously** the fast (Δm^2_{31}) and slow (Δm^2_{21}) oscillations
- 2-3-km oscillation: θ_{13} and Δm^2_{ee}
- 50-km oscillation: θ_{12} and Δm^2_{12}

MASS ORDERING WITH JUNO

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \underbrace{\cos^4\vartheta_{13}\sin^2 2\vartheta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}}_{\text{(slow)}} - \underbrace{\sin^2 2\vartheta_{13}\left(\cos^2\vartheta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}+\sin^2\vartheta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right)}_{\text{(fast)}}$$

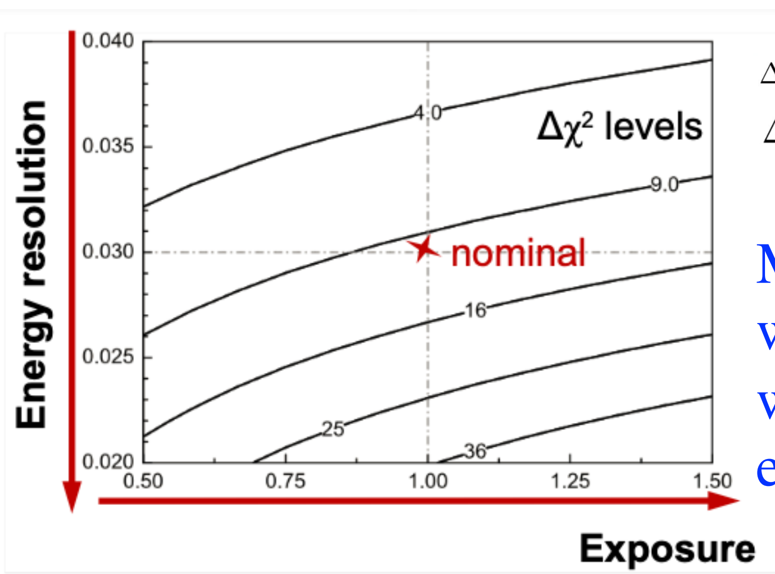
Effective neutrino mass-squared difference:

$$\Delta m^2_{ee} = (cos^2\vartheta_{12}\Delta m^2_{31} + sin^2\vartheta_{12}\Delta m^2_{32})$$



Difference between:

- Normal Ordering
- Inverted Ordering



$\Delta\chi^2_{MH} = |\chi^2_{min}(N) - \chi^2_{min}(I)|$

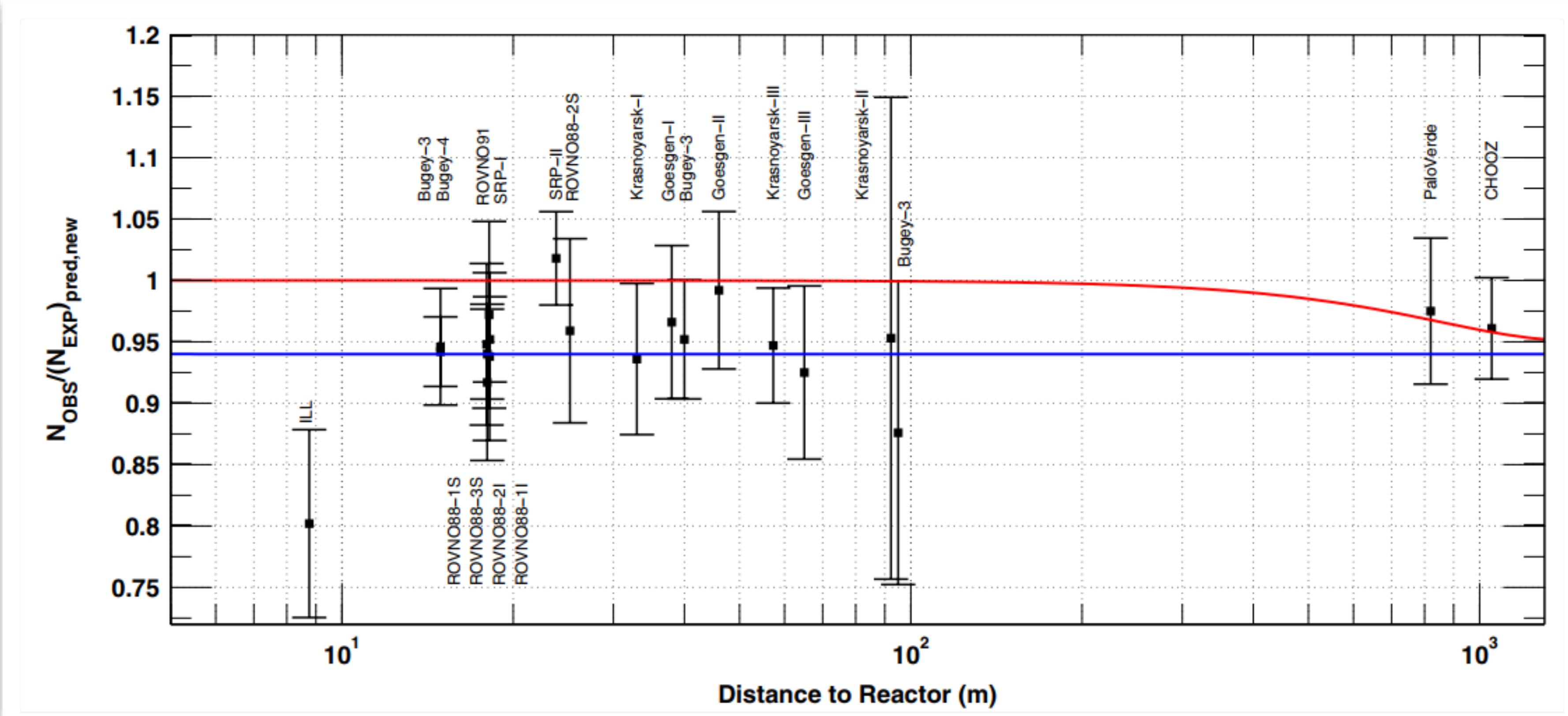
$\Delta\chi^2_{MH}$ contour plot

Mass hierarchy 3~4 σ with 6 years running with 80% signal efficiency

J. Phys. G **43** (2016) 030401

REACTOR NEUTRINO ANOMALIES

➤ Reactor Antineutrino Anomaly (RAA) ⇨ Institut Laue–Langevin (ILL) spectra agree w/ data; 2011, Huber-Mueller spectra higher than data by 6%; Sterile neutrino? Inaccurate prediction?



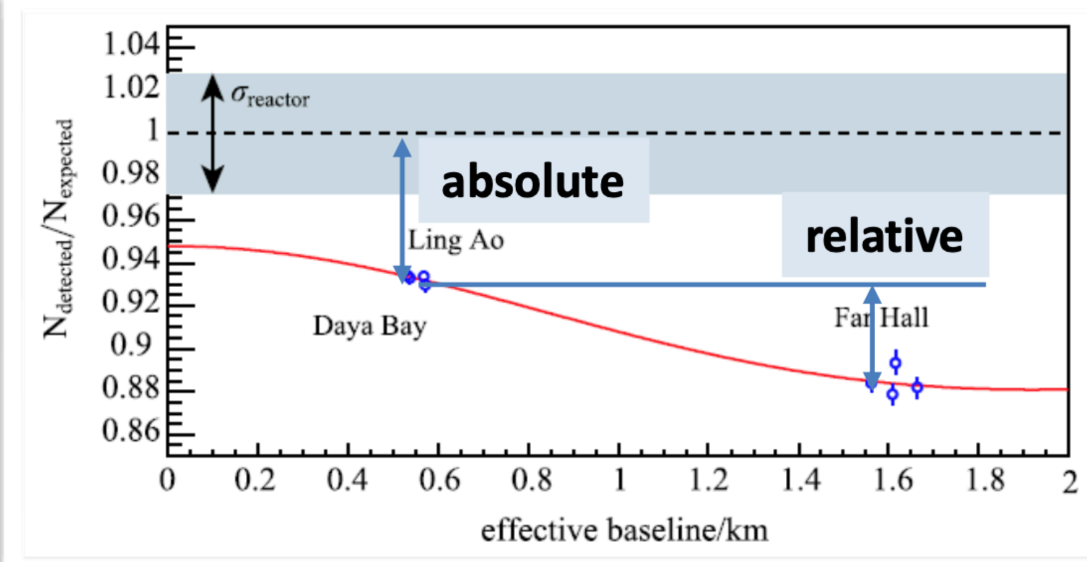
G. Mention et al.
PRD83 (2011) 073006

➤ Summation (Ab initio): Nuclear database, Σ fragments, Σ chains, Σ branches à 10% uncertainty (e.g. Vogel et al., PRC24, 1543 (1981)).

➤ Conversion: ILL measured the β-spectra and convert to neutrino spectra
- **ILL spectra: Use spectra of 30 virtual (allowed) decays, fit amplitude and endpoints (ILL-Vogel spectra)**
- **Mueller: 90% ab initio + 10% fit à rate anomaly**
- **Huber: fit w/ improved nuclear effects (Huber-Mueller spectra, 2-3%)**

FUEL EVOLUTION

- Near/far relative measurements in oscillation cancel the flux uncertainty.
- The observed number of IBD events in near detectors yields absolute measurement of neutrino flux.
- Uncertainty dominated by detection efficiency.
- Both Daya Bay and RENO confirmed the deficit in RAA

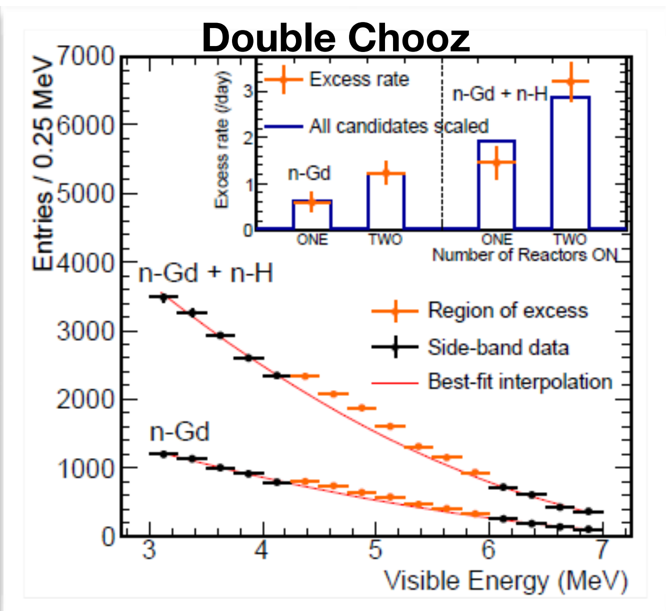


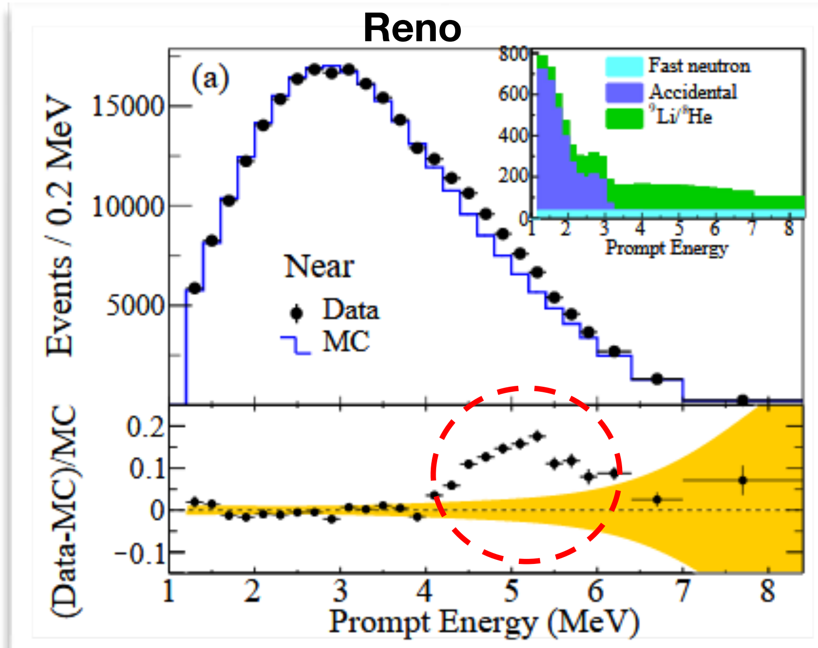
Daya Bay: Data/Huber-Mueller = 0.952 ±0.014(exp.)±0.023 (model)

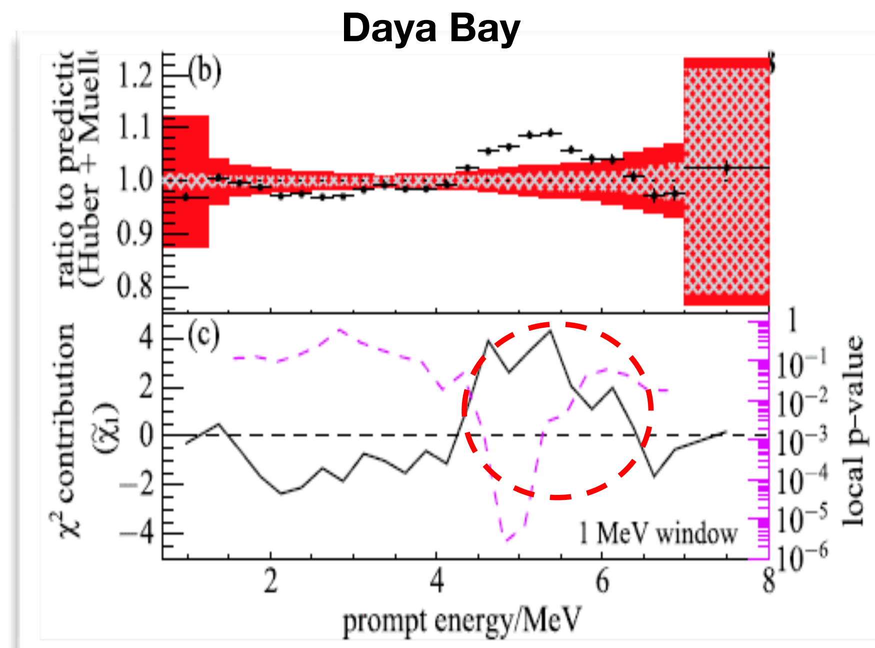
- Rate measurement is hard to improve. However, we could study the **relative rate** of different **isotopes**
- Daya Bay new measurement (arXiv:1904.07812):
  - ^{235}U: 0.920 ± 0.023(exp) ± 0.021(mod)
  - ^{239}Pu: 0.990 ± 0.057(exp) ± 0.025(mod)
- Further work ongoing both experimentally and theoretically to explain the RAA.

REACTOR NEUTRINO ANOMALIES

- Spectrum excess (4-6 MeV bump)

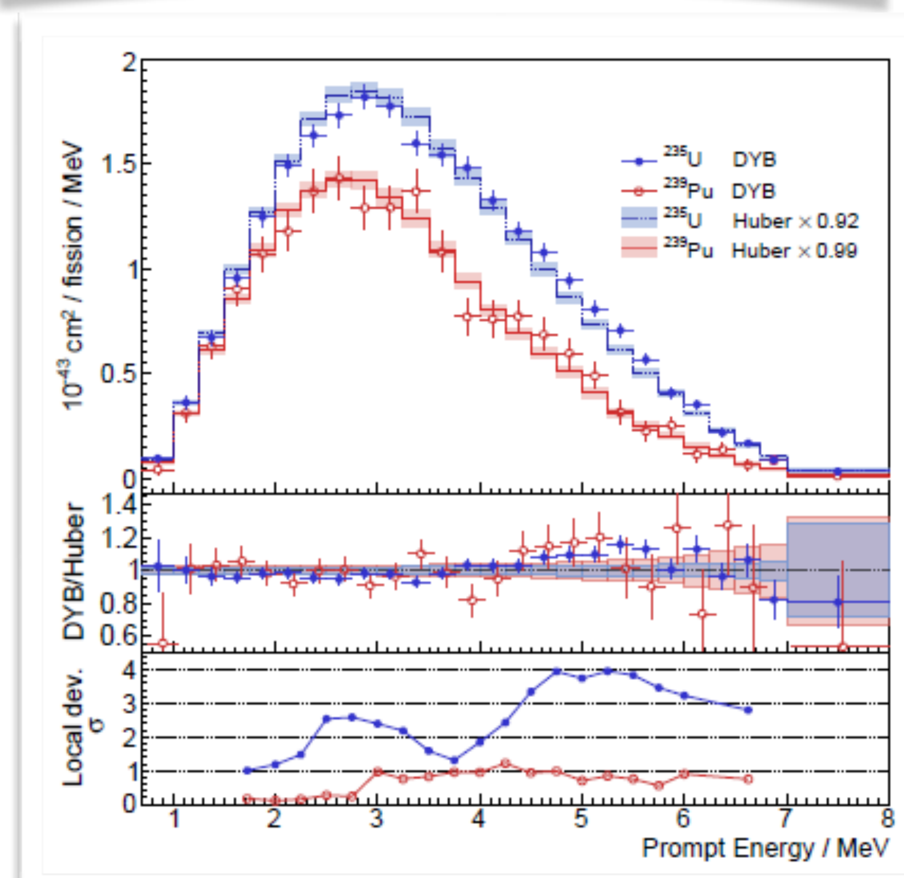






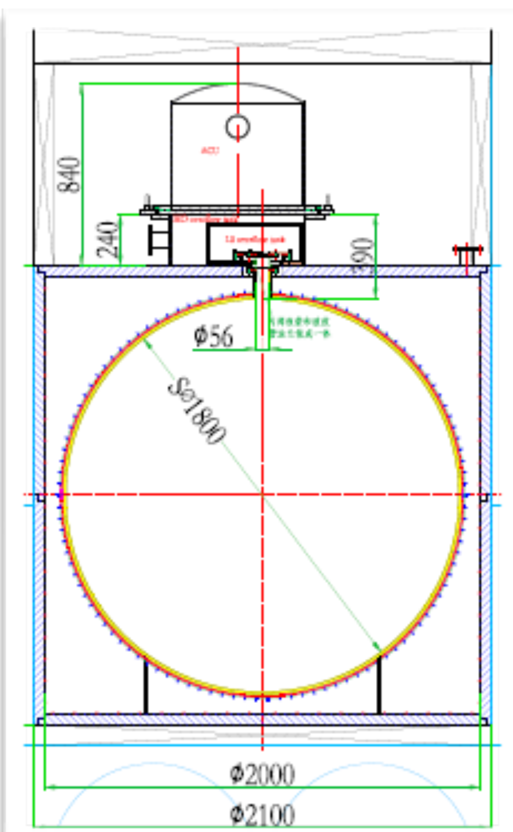
Latest results from Daya Bay

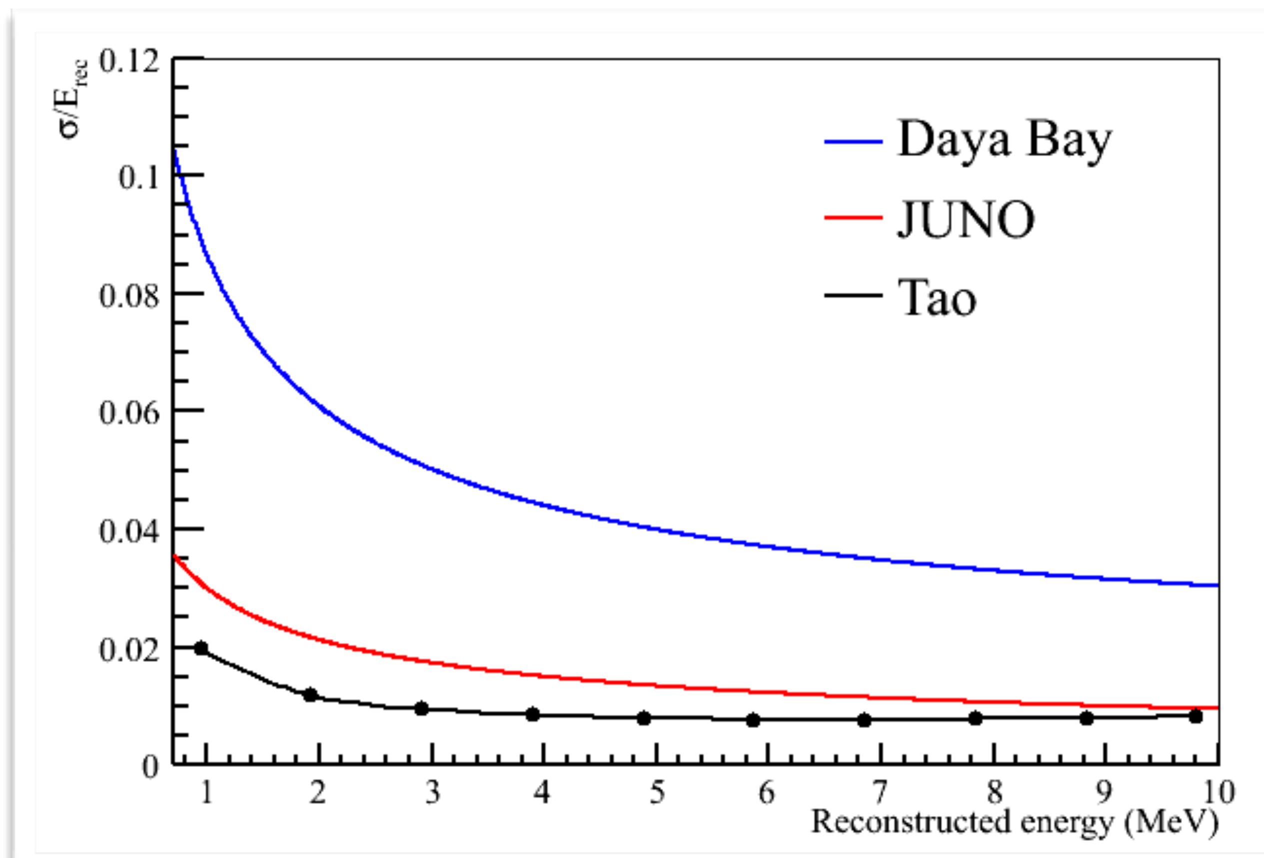
- 6.3σ in 4-6 MeV range disagree w/ H-M model, 5.3σ for whole spectrum
- First decomposition spectra for U235 and Pu239 (or Pu239+Pu241). 7% (9%) excess for the U235 (Pu239 First measurement of ^{235}U spectrum in commercial reactors
- **Excess of events in the bump is proportional to reactor flux (fuel evolution irrelevant)**
- Summation spectrum also has similar structure (ongoing)



JUNO-TAO

- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution Liquid Scintillator detector at 30 m from the core, a satellite exp. of JUNO.
- Measure reactor neutrino spectrum w/ sub-percent E resolution.
  - model-independent reference spectrum for JUNO
  - a benchmark for investigation of the nuclear database
- Provide reference spectrum for JUNO, to remove model dependence by measuring fine structures
- Provide a benchmark to examine nuclear database, measuring fine structures





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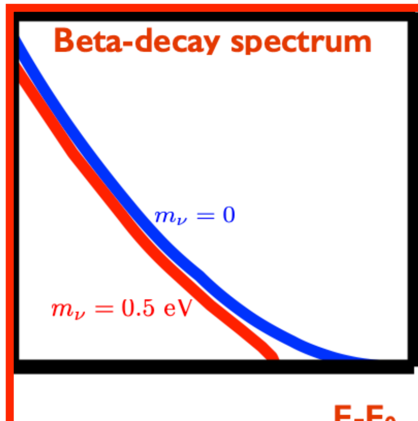
MEASURING NEUTRINO MASSES

- Mass ordering via neutrino oscillation in matter in long baseline neutrino experiments (NOvA, DUNE), atmospheric neutrinos (Hyper-K) or in vacuum (JUNO). Measurement expected this decade.
- Absolute mass scale.

Kinematics of ß-decay

potential: m_β = 50 - 200 meV

$m_\beta^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$



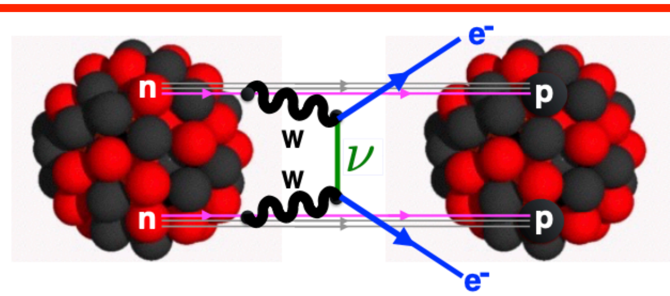
Beta decay

$$m_\beta \equiv \sqrt{\sum_i U_{ei}^2 m_i^2}$$

Search for 0νßß

potential: $m_{ßß}$ = 7 - 17 meV

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



Neutrinoless dbeta decay

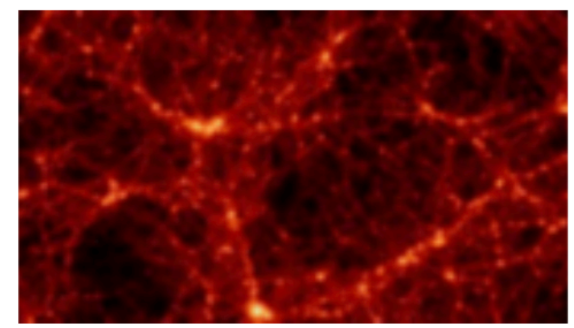
$$m_{\beta\beta} = f(m_i, \alpha_{21}, \alpha_{31}, \delta)$$

Cosmology

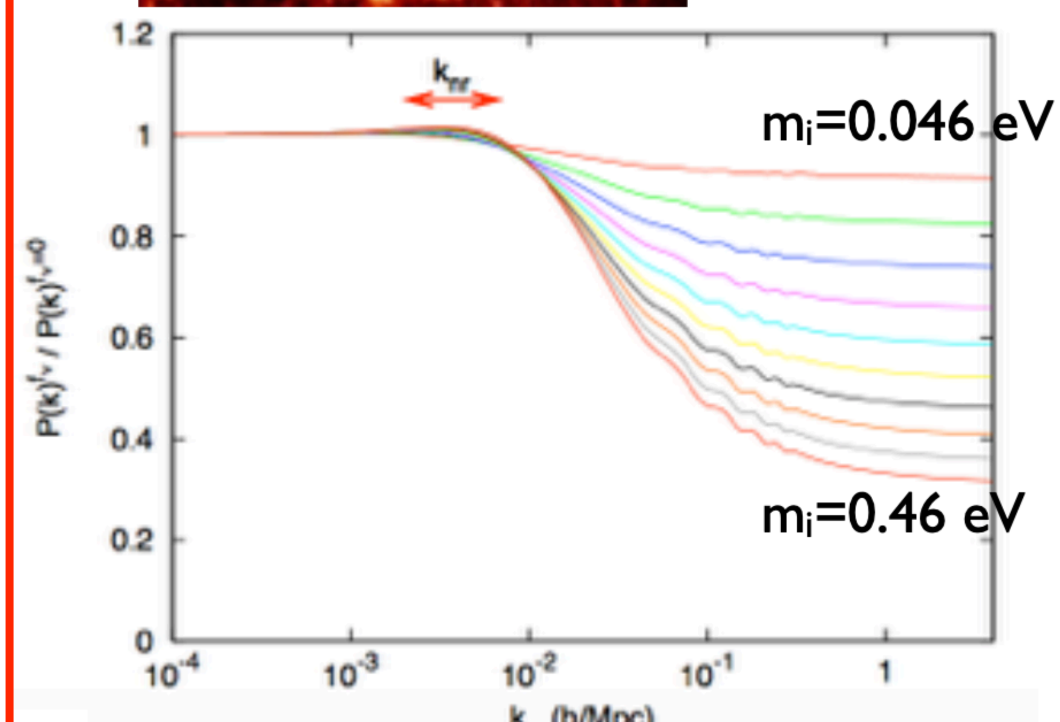
potential: m_ν = 10 - 50 meV

$m_\nu = \sum_i m_i$

Cosmology



$$\sum_i m_i$$



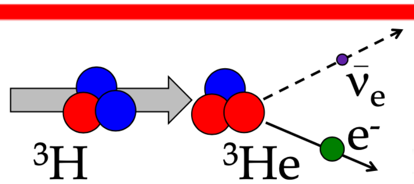
J. Lesgourgues and S. Pastor, Phys. Rep. 429

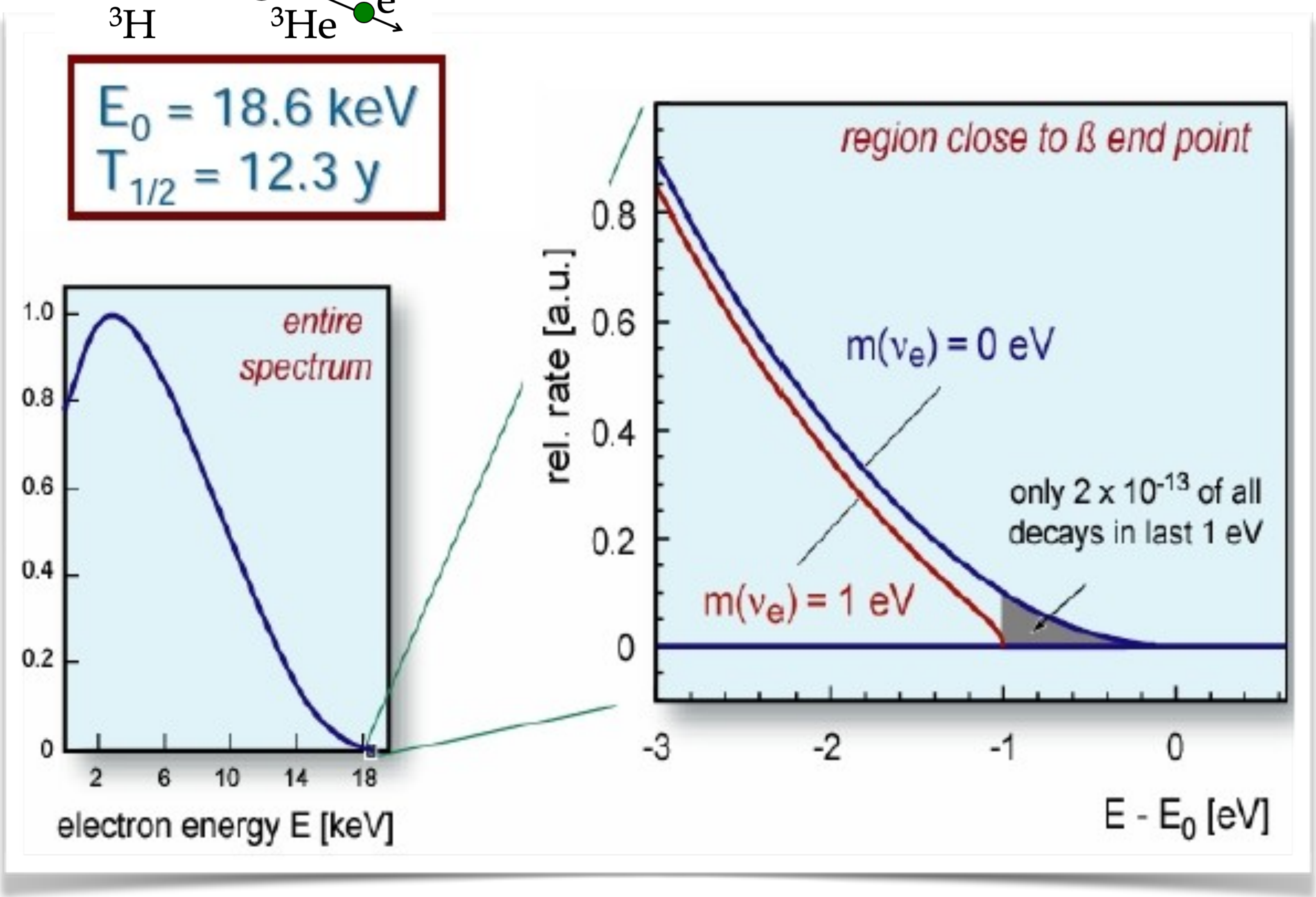
DIRECT MEASUREMENT OF THE ELECTRON NEUTRINO MASS

- **Measurement of ν_e mass from kinematics of β decay.**

$$\frac{d\Gamma_i}{dE} = C\, p(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_\nu^2}\,F(E)\,\theta(E_0-E-m_\nu$$

Observable is m_ν^2

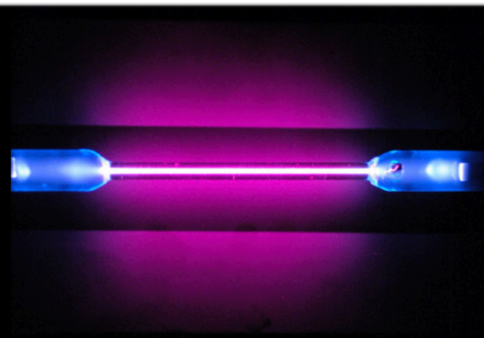
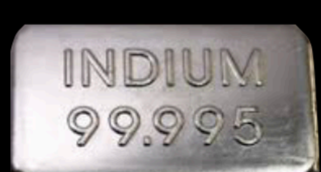




Requirements:

- # electrons close to the endpoint should be large
- Good (and well-understood) electron energy resolution.
- No (or minimal) electron energy loss within the source
- Minimal atomic and nuclear final state effects, of excited transitions

TECHNIQUES

	^{3}H 18.5 keV $\tau_{1/2}$ 12.3 yrs	Electromagnetic/ Frequency KATRIN - Project 8
	^{163}Ho 2.83 keV $\tau_{1/2}$ 4570 yrs	Calorimetric ECHO - HOLMES
	^{187}Re 2.5 keV $\tau_{1/2}$ 4.5 Gyrs	MARE (ended)
	^{115}In 155 eV $\tau_{1/2}$ 4.1×10^{20} yrs	No experiment yet

- Use photon emission from magnetic field interaction to infer beta energy
- **Frequency-Based (Cyclotron Resonance Emission Spectroscopy)**

- Electromagnetic filtering of electron of selected energy
- **Electromagnetic collimation (MAC-E Filter)**

- Electron transfers all of its energy to the absorbing medium.
- **Calorimetric (Cryogenic Bolomers)**

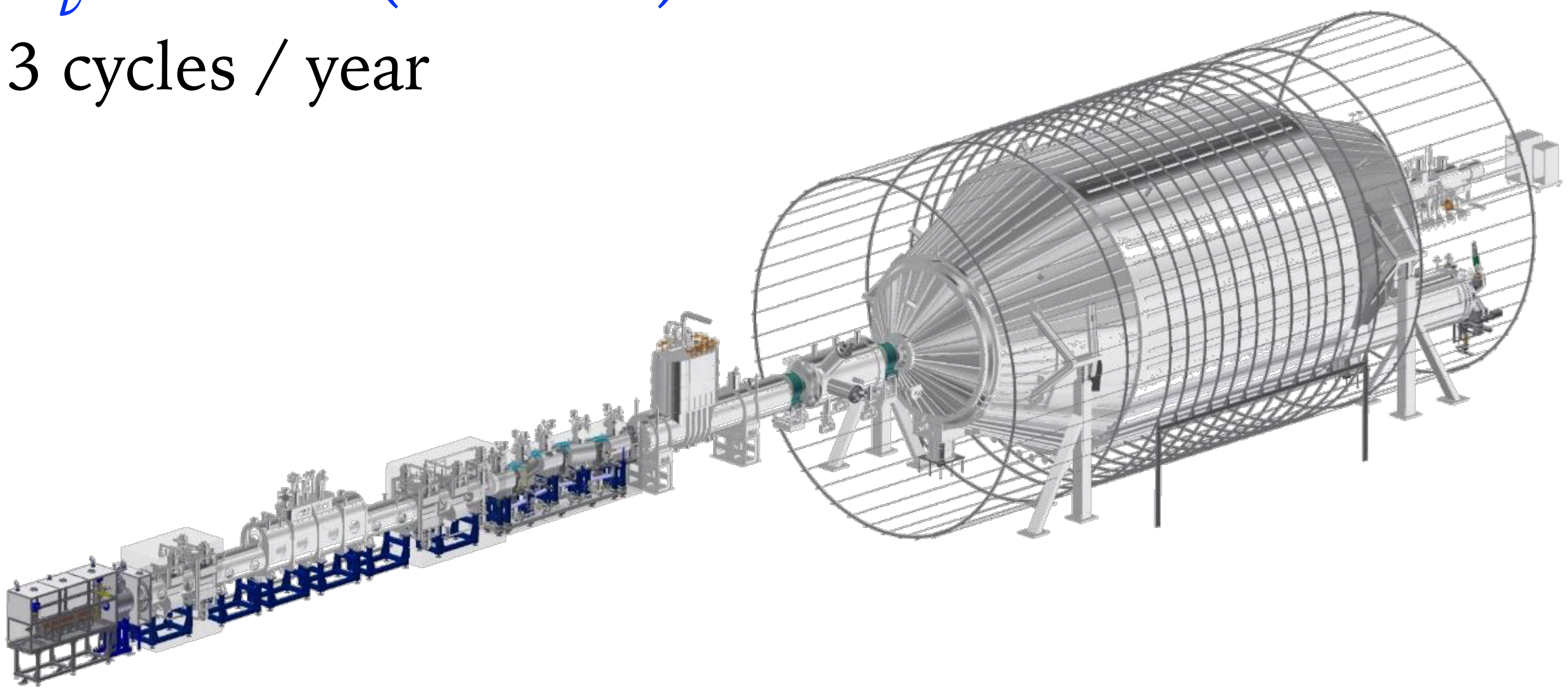
J. Formaggio

CURRENT EXPERIMENTS

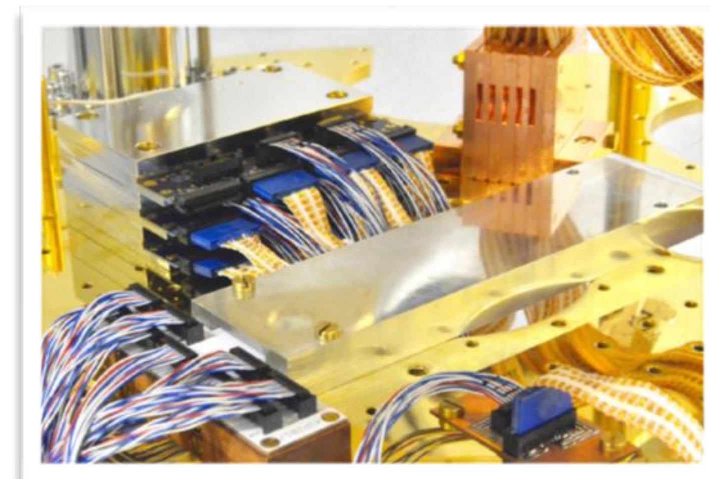
KATRIN: first neutrino mass result

m_ν< 1.1 eV (90 % CL)

3 cycles / year



ECHo: goal m_ν <20 eV in 2020



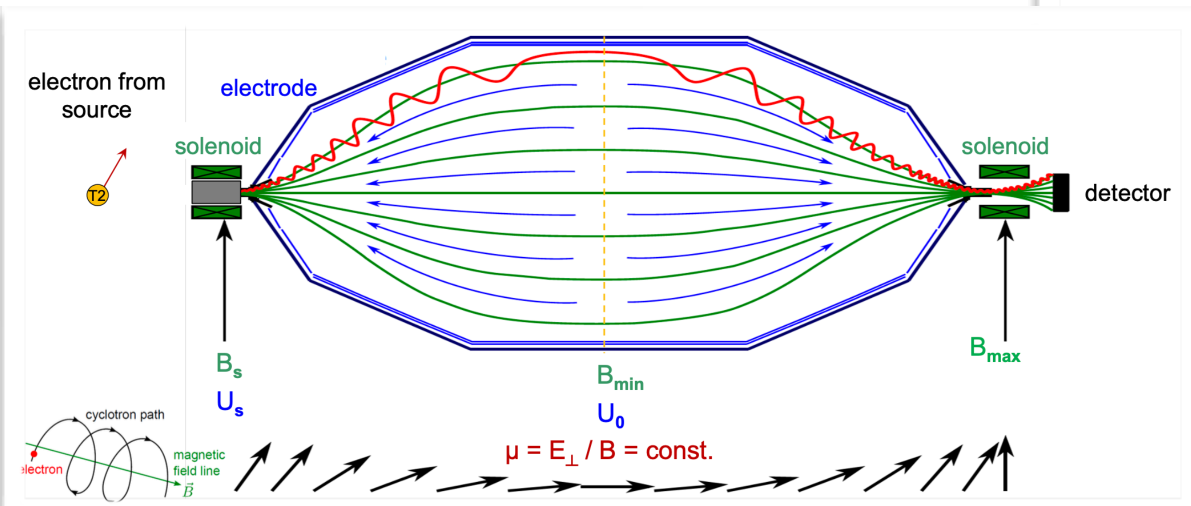
HOLMES: significant R&D progress

Project8: first tritium CRESS spectrum

KATRIN

The MAC-E filter

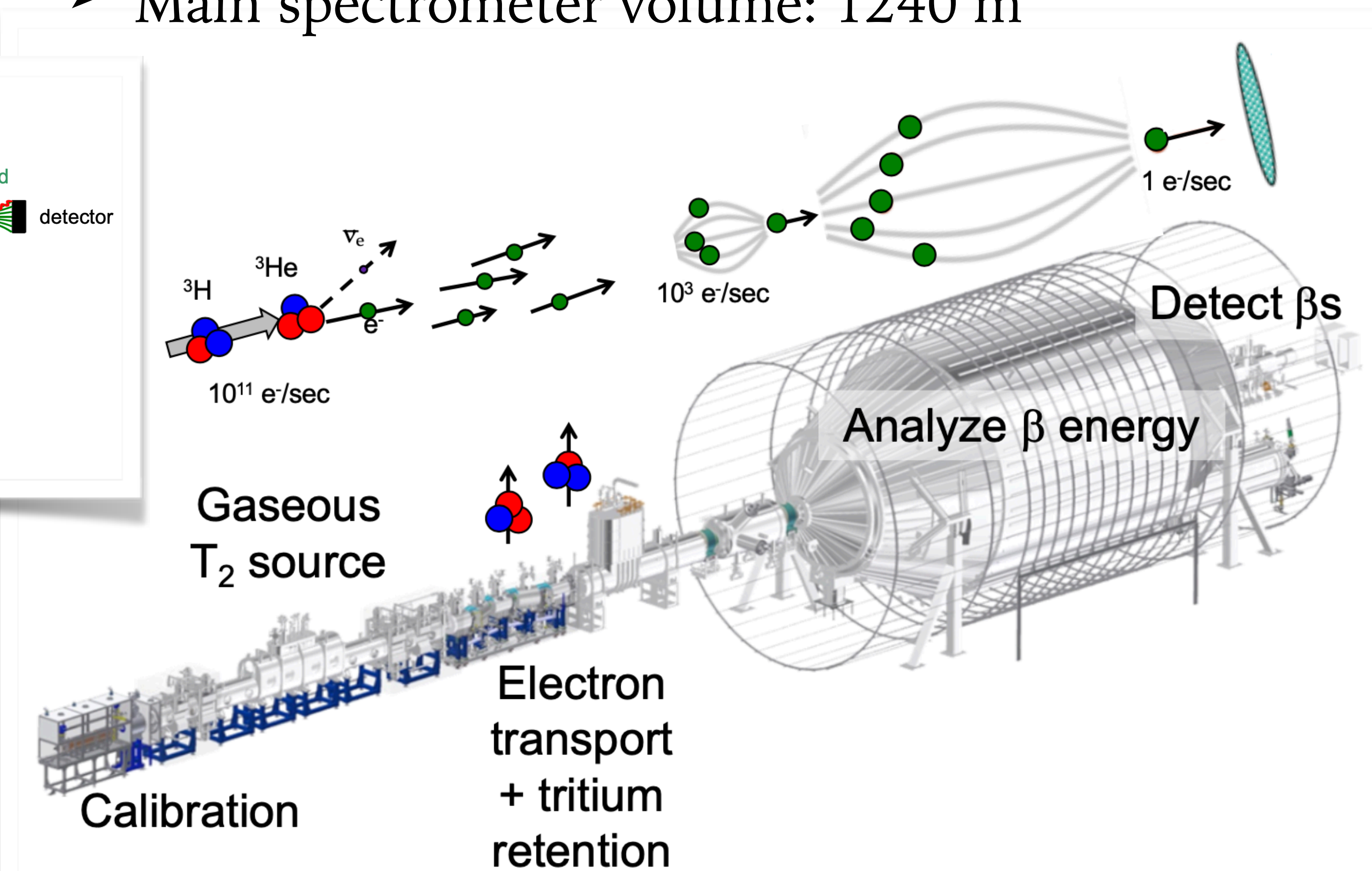
- Measure integral spectrum with moving threshold
- **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter



$$\mu = \frac{E_\perp}{B} = \text{const} \qquad \frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}$$

Kleesiek et al.
EPJC ***79*** *204 (2019)*

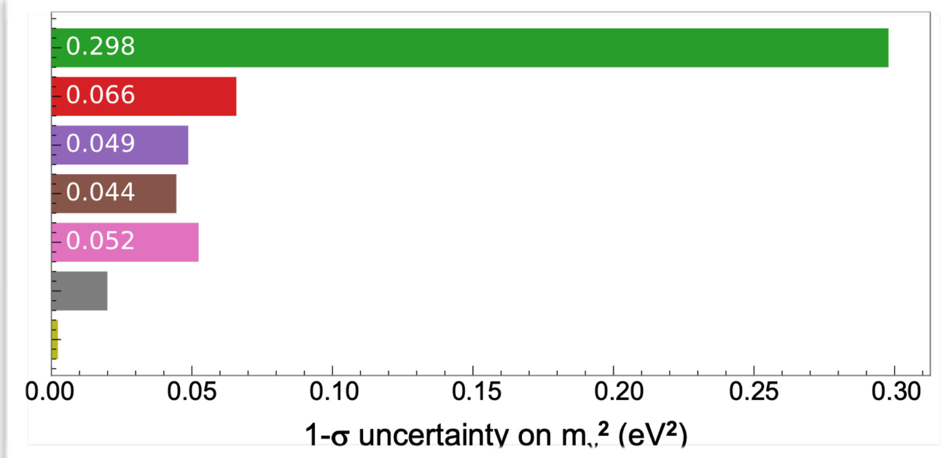
- Expected m_ν sensitivity in 5 calendar years:
  0.2 eV at 90% confidence
- Magnetic field range 3 G – 60,000 G
- Source activity: 10^{11} decays every second
- 95% tritium purity
- Main spectrometer volume: 1240 m^3



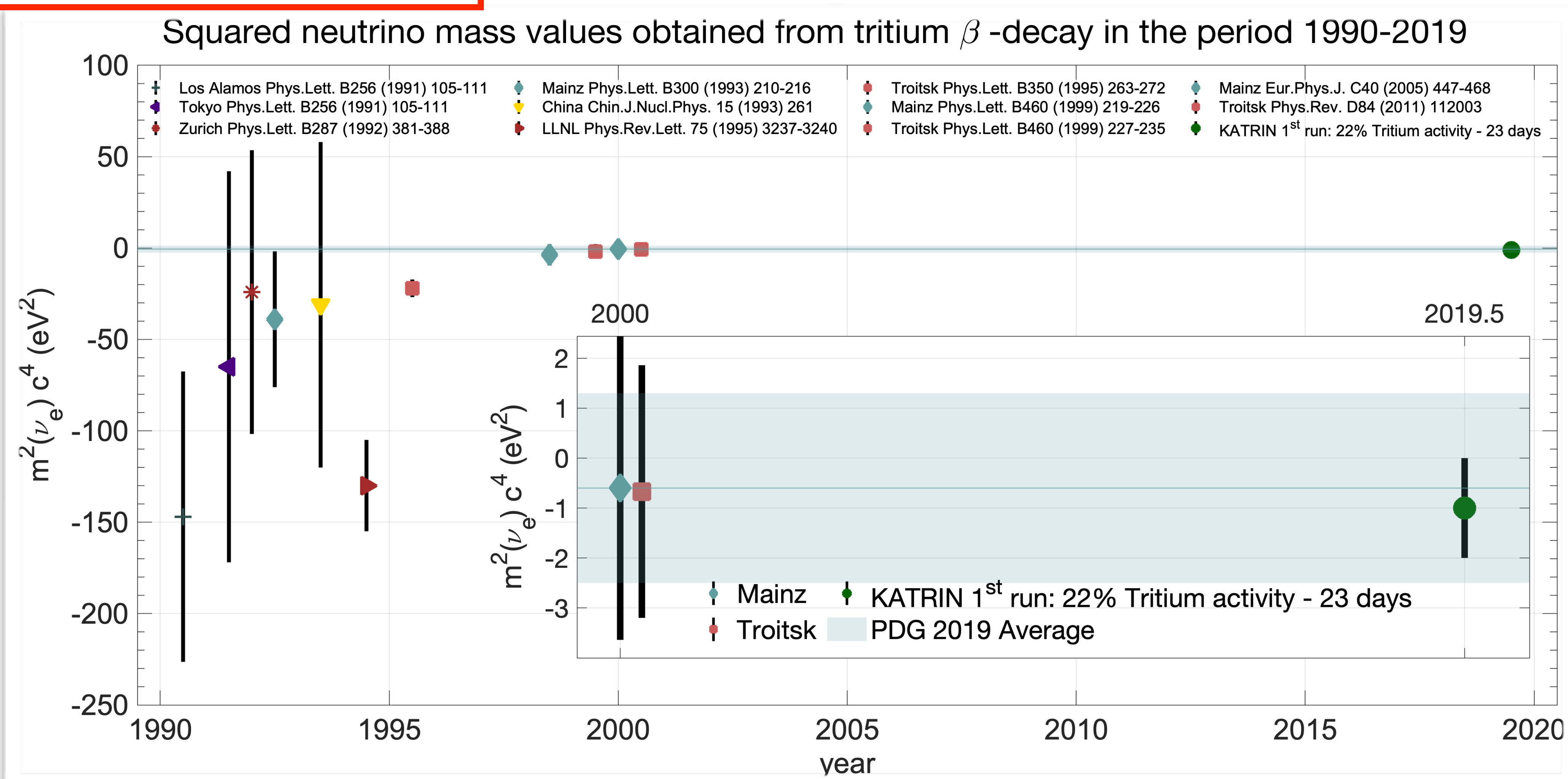
KATRIN RESULTS

Well-understood systematics budget σ_{syst} (with $\sigma_{syst} < \sigma_{stat}$)

- total statistical uncertainty budget $\sigma_{stat} = 0.97\ \mathrm{eV}^2$
- total systematic uncertainty budget $\sigma_{syst} = 0.32\ \mathrm{eV}^2$

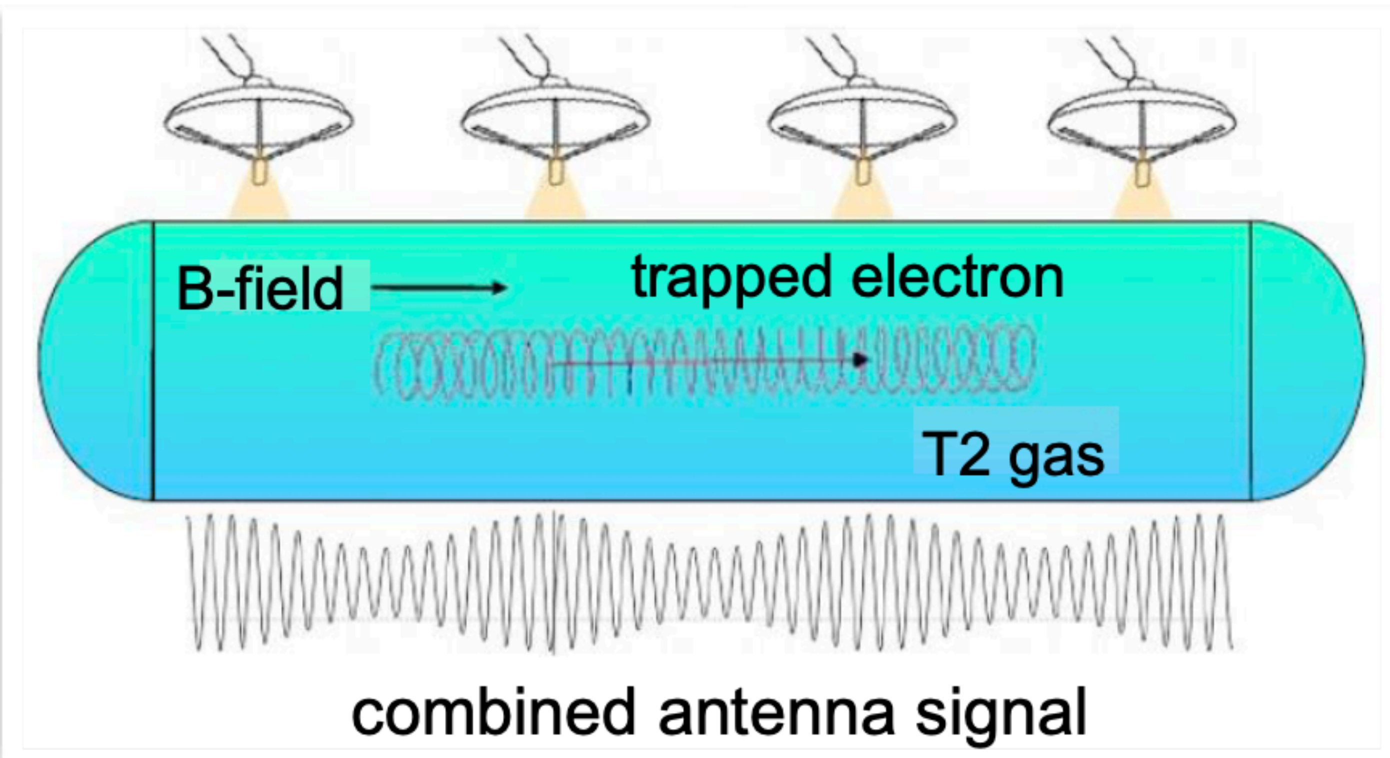


$$\boxed{m_\nu^2 = (-1.0^{+0.9}_{-1.1})\ \mathrm{eV}^2 \qquad m_\nu < 1.1\ \mathrm{eV}\ (90\%\ \mathrm{C.L})}$$



PROJECT8

- A novel spectroscopic approach
- **Cyclotron Radiation Emission Spectroscopy (CRES)**
  - CRES of *trapped* electrons from tritium β-decay in homogeneous strong magnetic field B



B.Monreal, J. Formaggio

$$\boxed{\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{e \cdot B}{m_e + E_{e,kin}}}$$

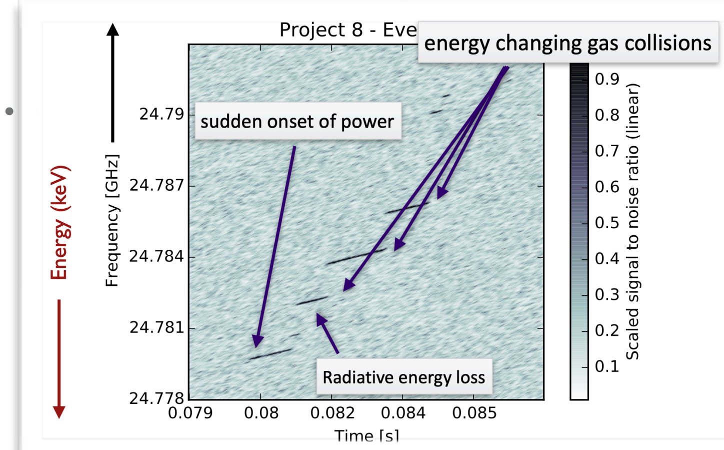
Precise measurement of ω yields electron kinetic energy $E_{e,kin}$

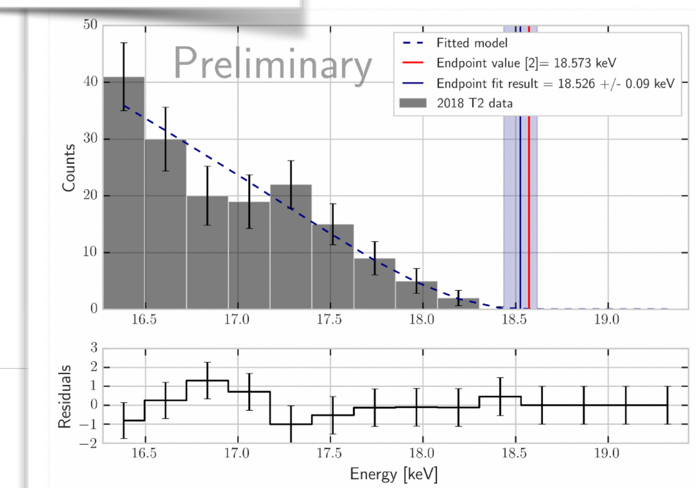
B=1T, $E_{e,kin} = 18.57$ keV, $f_0 = \omega_0/2\pi \sim 27GHz$

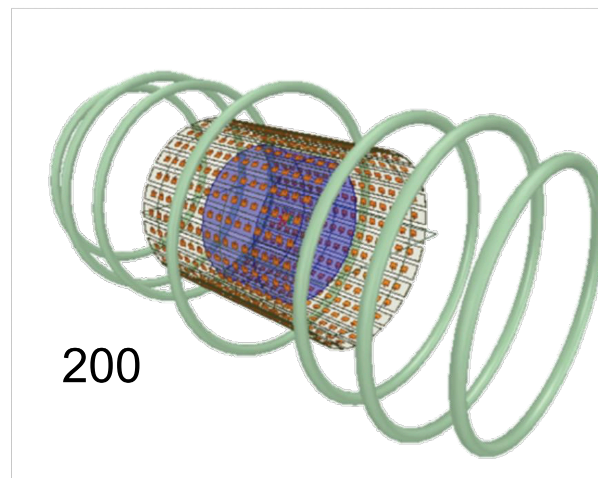
$\Delta\omega \sim 1/t_s \Rightarrow$ sampling time $t_s \sim$ several μs (magnetic bottle)

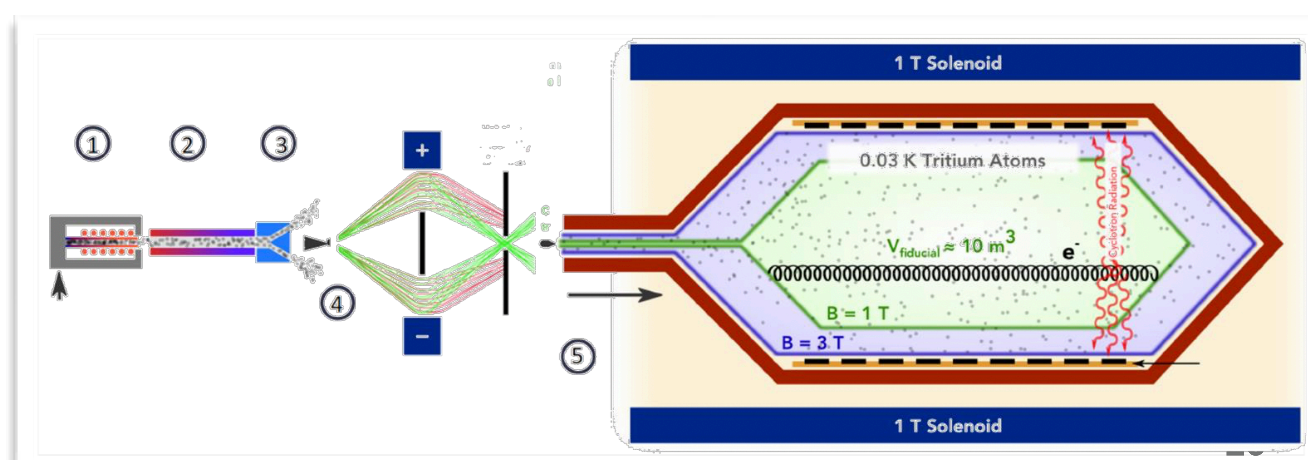
PROJECT8 – A STAGED APPROACH

- Phase – I: 2010-2016 – demonstrate CRES technique on ^{83m}Kr monoenergetic electrons. Status: Complete! Technique demonstrated.
- Phase - II: 2015 - 2020 - First T2 spectrum. Extract endpoint. Study systematics and backgrounds. Status: Ongoing until beginning of 2020.
- Phase - III: Provide a first demonstration of CRES technique using tritium. Use a large volume demonstrator based on multi-antenna array in MRI tritium spectrum for $m(\nu_e) \sim 2$ eV
- Phase - IW: Towards an atomic triutium source. Goal: inverted mass hierarchy for $m(\nu_e)$

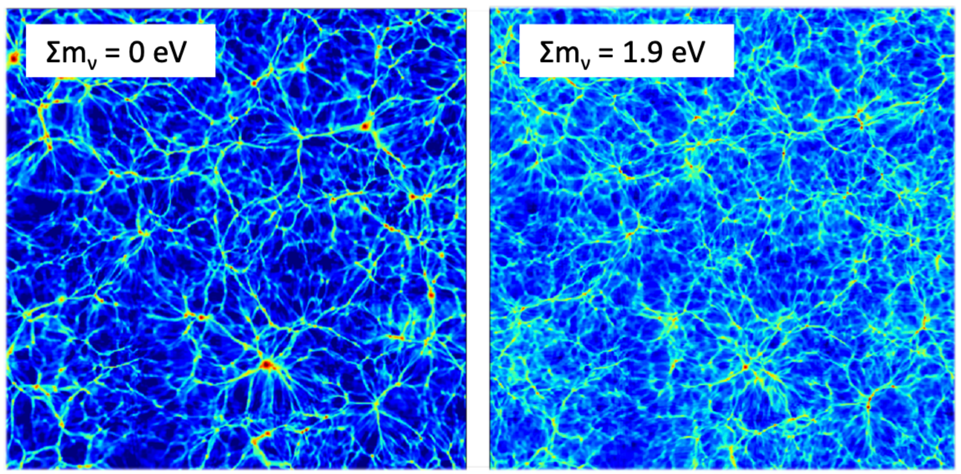






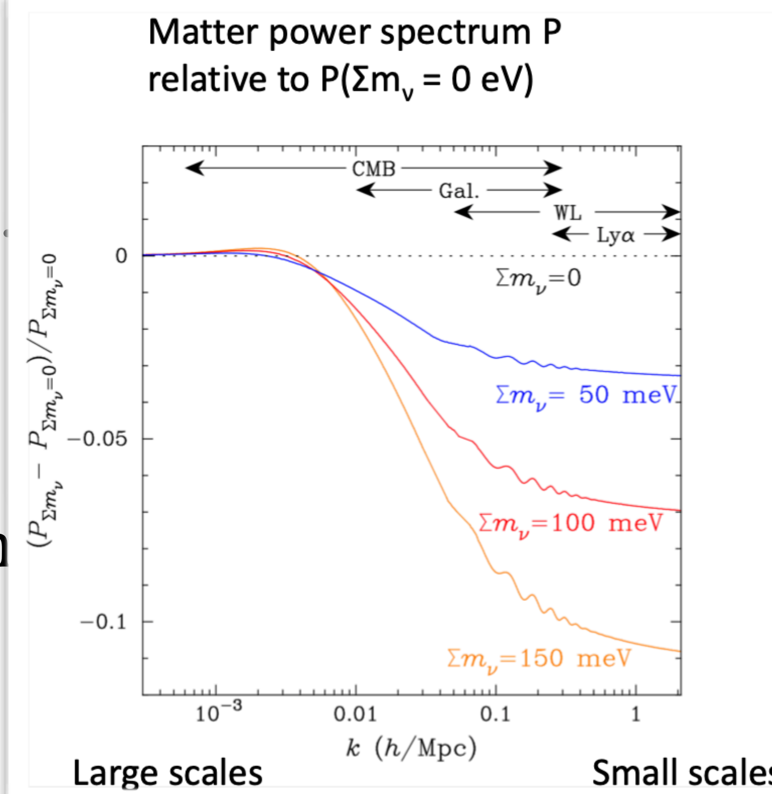


COSMOLOGICAL BOUNDARIES

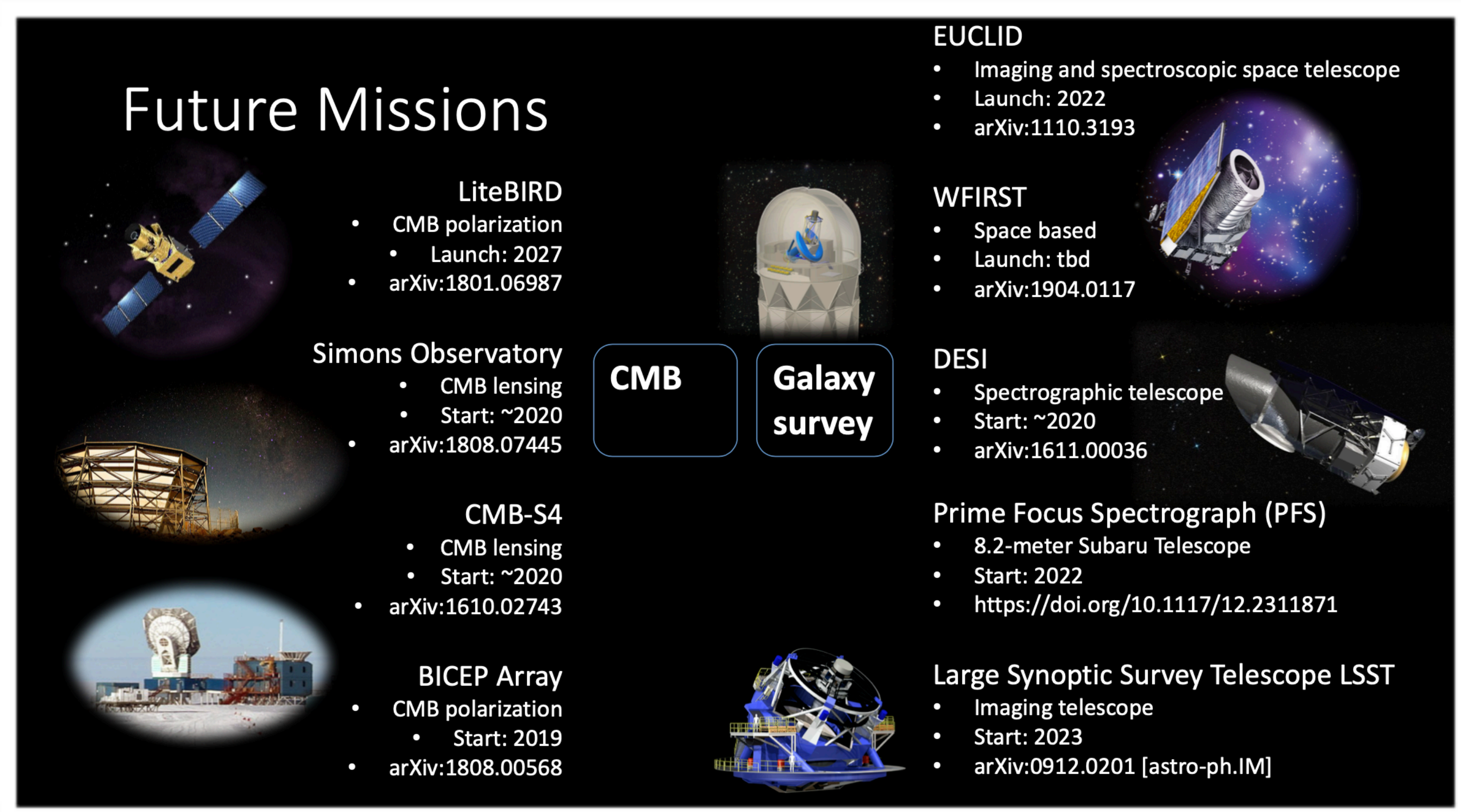


General Idea:

- ➤ Influence on structure growth
- ➤ Influence on the expansion rate of the universe



- ➤ Current probes:
  - Cosmic Microwave Background (CMB)
    - ➡ CMB temperature anisotropy
    - ➡ CMS lensing
    - ➡ ….
  - Galaxy Surveys:
    - ➡ galaxy clustering
    - ➡ weak lensing at different redshifts
    - ➡ …
- ➤ Current limit:
  - $\sum m_{\nu} < 230 - 540$ meV (Planck)
- ➤ Future missions:
  - $\sigma \sum m_{\nu} \sim 50$meV(CMB)
  - $\sigma \sum m_{\nu} \sim 20$ meV (CMB + BAO)
  - $\sigma \sum m_{\nu} \sim 10$meV(CMB+BAO+LSS)



S. Mertens

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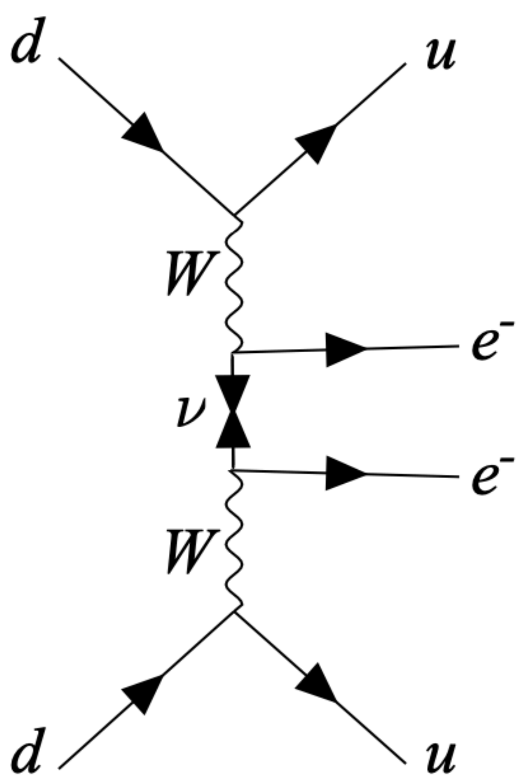
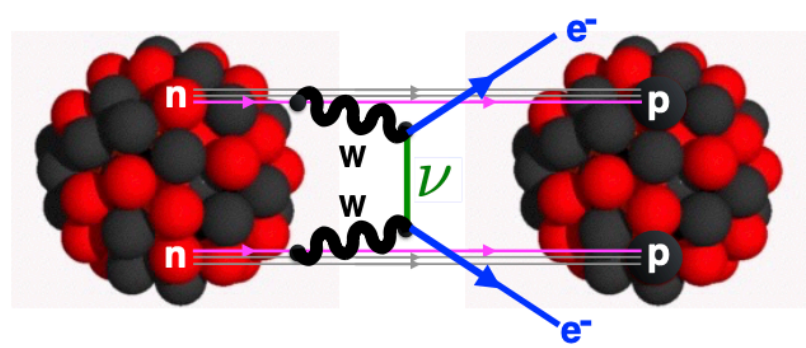
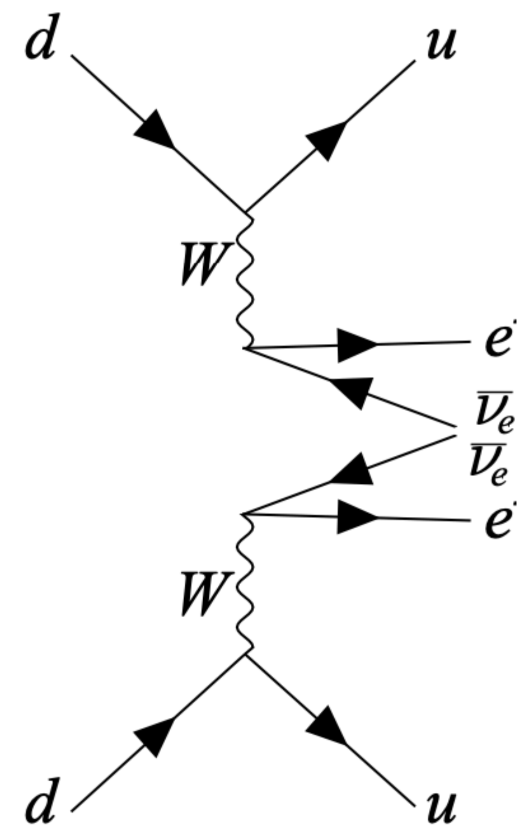
NEUTRINOLESS DOUBLE BETA DECAY

- Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2 e, will test the nature of neutrinos



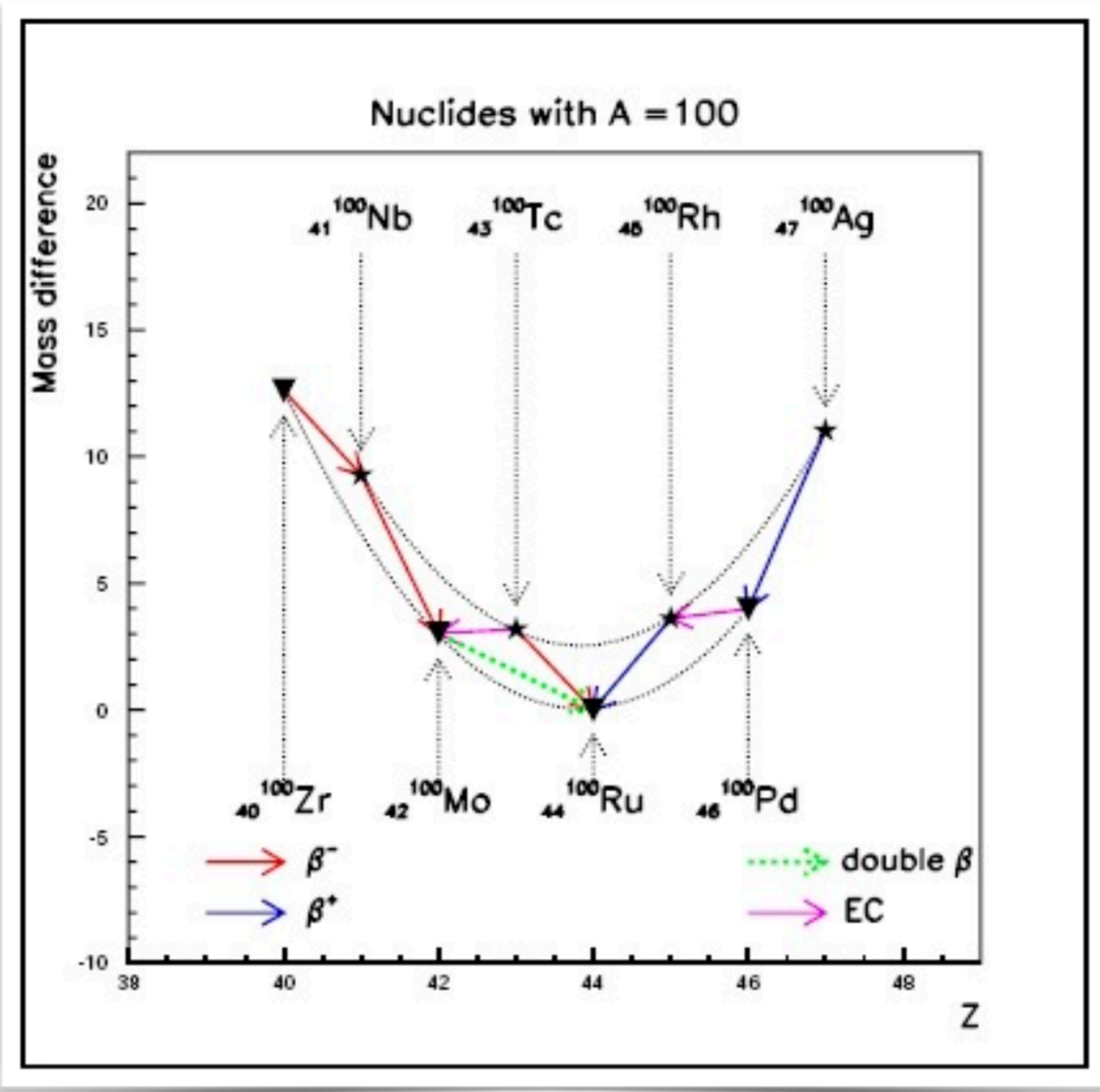




- Massive Majorana neutrinos mediate this process.

- It has a special role in the study of neutrino properties as it probes lepton number violation and the nature of neutrinos and can provide information on neutrino masses.

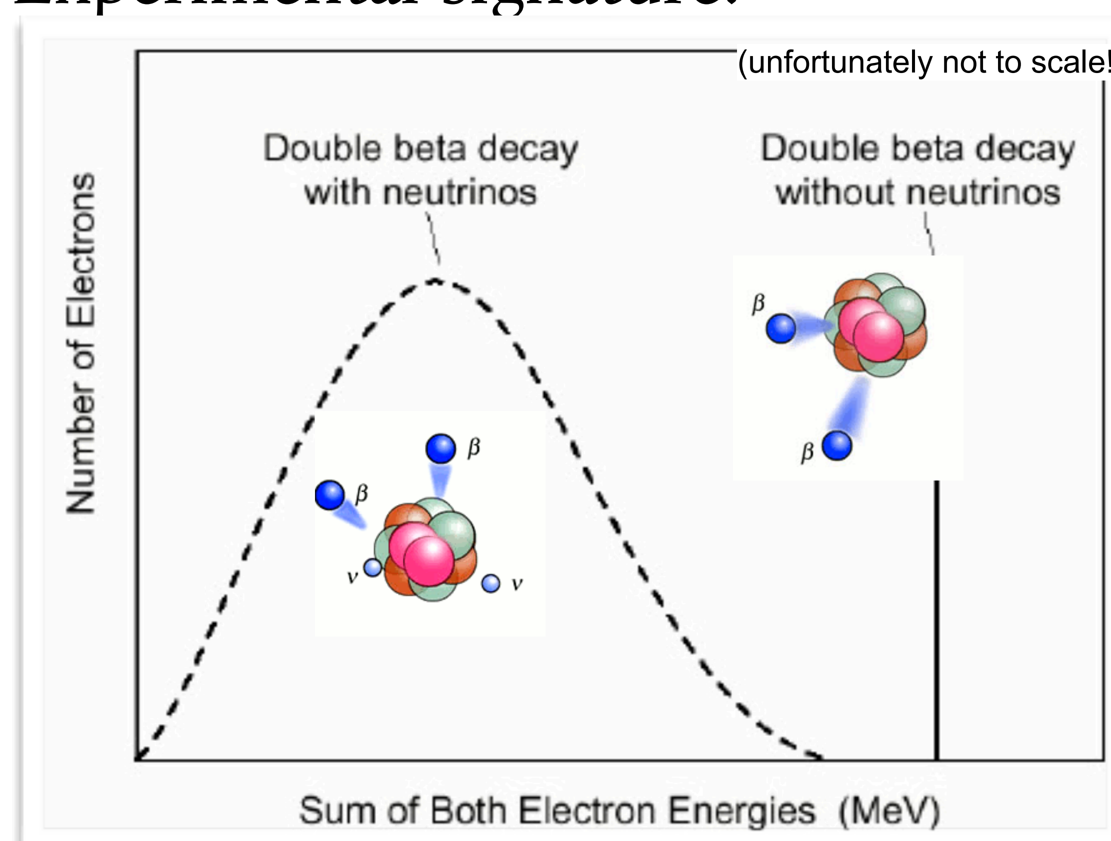
NEUTRINOLESS DOUBLE BETA DECAY



- In some nuclei β decay is forbidden but double beta decay is not

$$(Z,A) \rightarrow (Z+2,A) + 2e^{-} + 2\bar{\nu}_e$$

- Over **40 nuclei** can undergo **ββ**-decay (including $\beta^+\beta^+$ and 2K-capture)
- Only ~**9** experimentally **feasible**
- Rarest natural radioactive decay extremely long half-lives
- Experimental signature:



- The peak in the plot exceeds current limits by ~1 order of magnitude
- Must measure summed electron kinetic energy to distinguish from SM 2ν process

NEUTRINOLESS DOUBLE BETA DECAY

Isotope	Nat. Abundance (%)	$Q_{\beta\beta}$ (MeV)
Ca48	0.187	4.274
Ge76	7.8	2.039
Se82	9.2	2.996
Zr96	2.8	3.348
Mo100	9.6	3.035
Cd116	7.6	2.809
Te130	34.5	2.530
Xe136	8.9	2.462
Nd150	5.6	3.367

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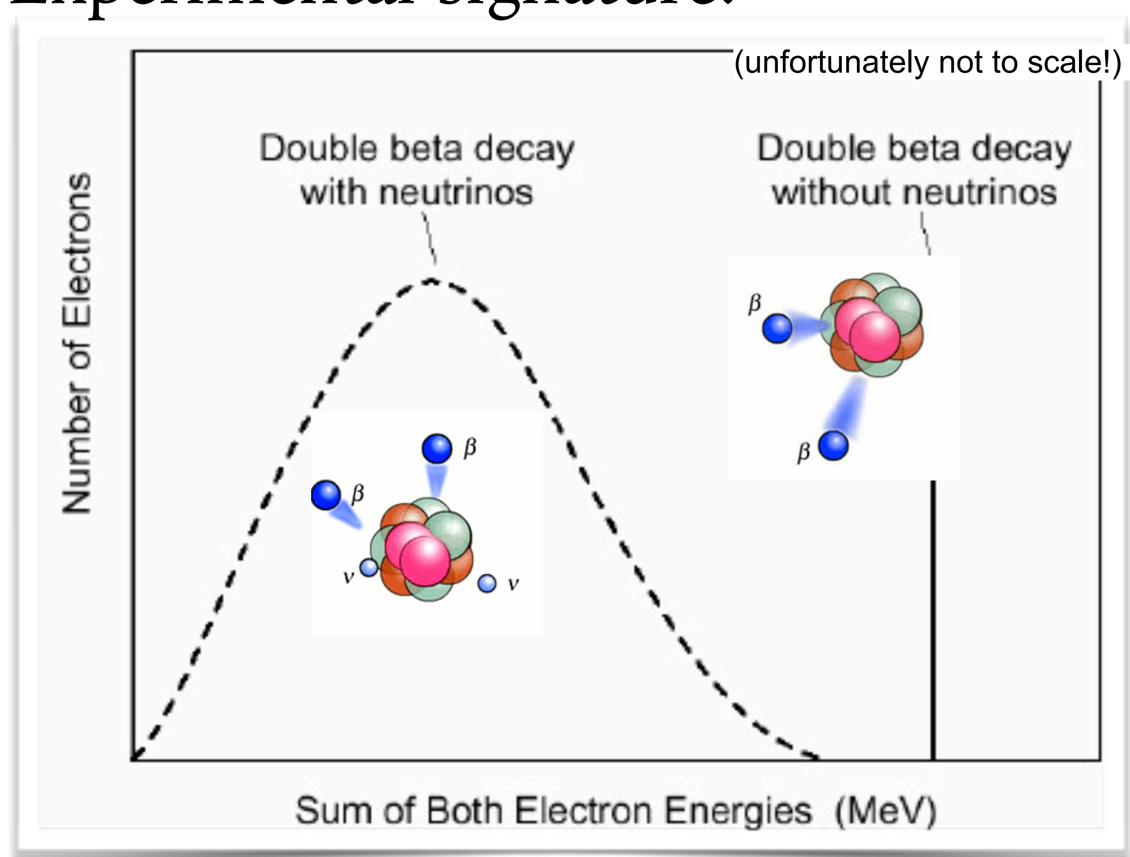


- The peak in the plot exceeds current limits by ~1 order of magnitude
- Must measure summed electron kinetic energy to distinguish from SM 2ν process

NEUTRINOLESS DOUBLE BETA DECAY

- Second order process in perturbation theory
- Severe test for nuclear matrix element calculation
- Nuclear structure effects cause variations in the nuclear matrix elements of factors of 10

$$\begin{pmatrix}\overline{\nu}_L & \overline{N}_R\end{pmatrix}\begin{pmatrix}0 & m_D\\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L\\ N_R\end{pmatrix}$$

$$\begin{pmatrix}\overline{\nu} & \overline{N}\end{pmatrix}\begin{pmatrix}m_D^2/M_R & 0\\ 0 & M_R\end{pmatrix}\begin{pmatrix}\nu\\ N\end{pmatrix}$$

$$\nu = \nu_L + \frac{m_D}{M_R}N_R$$

$$N = N_R + \frac{m_D}{M_R}\nu_L$$

- The rate dependence on $\boxed{T_{1/2}^{-1} \simeq \frac{G_{0\nu}}{m_e}|m_{\beta\beta}|^2 M_{\mathrm{NUCL}}^2}$ via the effective Majorana mass parameter

CPV phases (unknown)

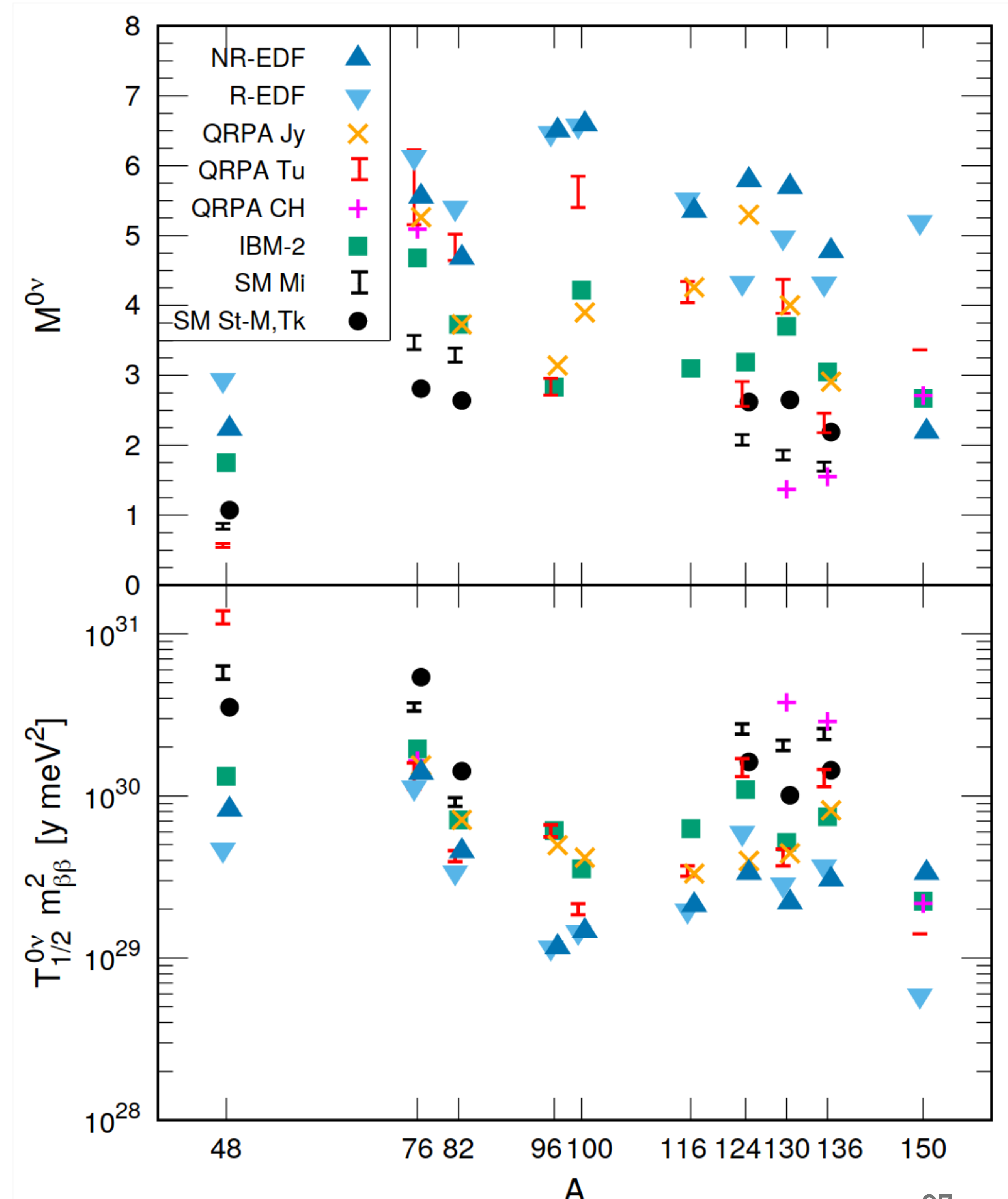
Mixing Angles (known)

$$\boxed{|m_{\beta\beta}| \equiv \left|m_1|U_{\mathrm{e}1}|^2 + m_2|U_{\mathrm{e}2}|^2\, e^{i\alpha_{21}} + m_3|U_{\mathrm{e}3}|^2\, e^{i(\alpha_{31}-2\delta)}\right|}$$

NUCLEAR MASS MATRIX ELEMENTS UNCERTAINTIES

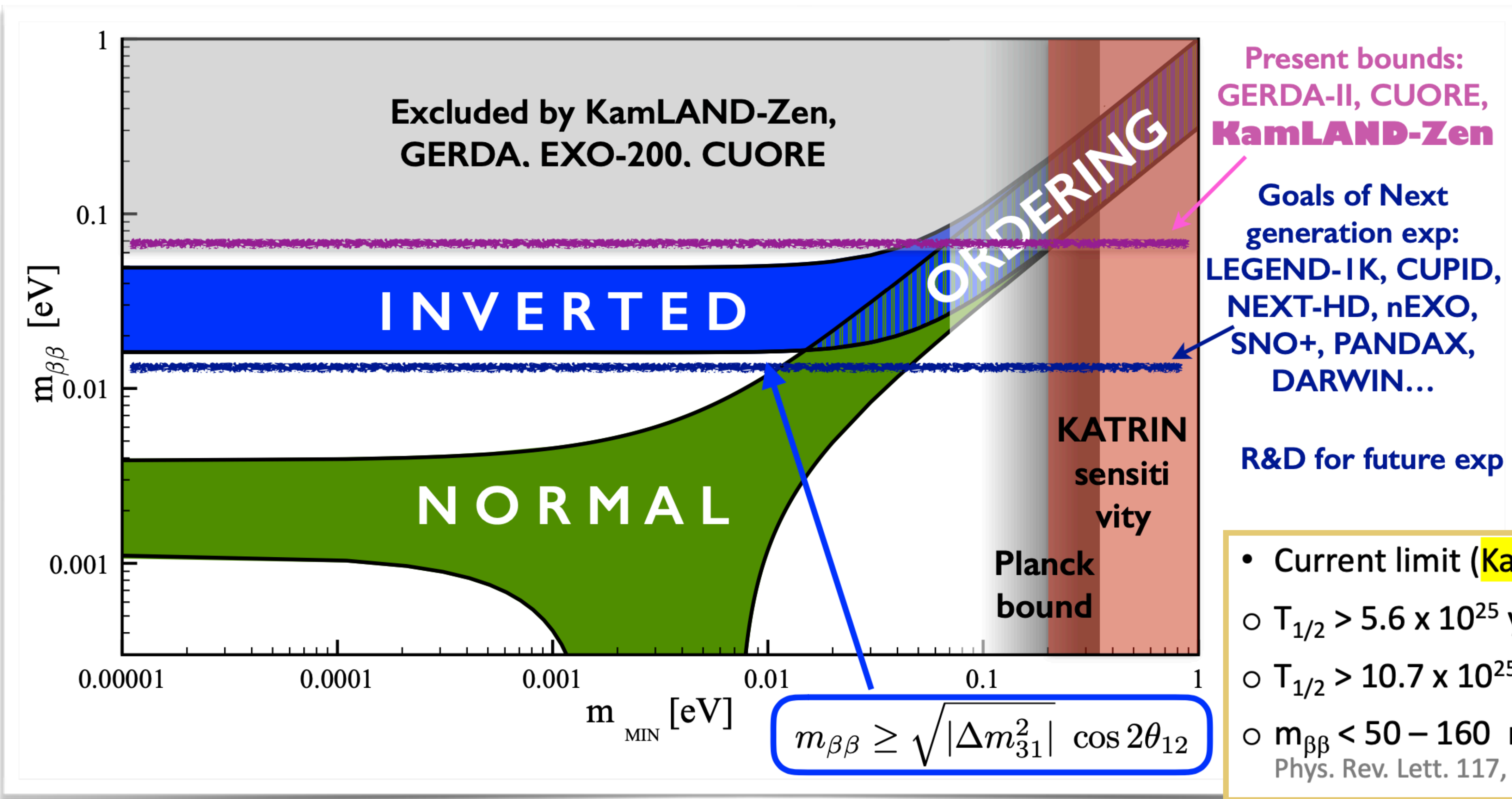
- The computation of Nuclear Mass Elements (NME) relies on nuclear theory
  - **Dependence** on isotope and specific operator
  - Differences between different nuclear models
  - **“the g_A problem”** quenching of the axial-vector coupling?
- Typically an uncertainty of 2-3 is attributed to NME and affects the extraction of $m_{\beta\beta}$ from $T_{1/2}$
- Recent developments in terms of ab-initio computations are promising.

Engel, Menendez,ARRPP 2017



NEUTRINOLESS DOUBLE BETA DECAY

- The predictions for $m_{\beta\beta}$ depend on the neutrino masses



- Current limit (KamLand Zen):
  - $T_{1/2} > 5.6 \times 10^{25}$ y (90% CL - sensitivity)
  - $T_{1/2} > 10.7 \times 10^{25}$ y (90% CL - data)
  - $m_{\beta\beta} < 50 - 160$ meV*

  Phys. Rev. Lett. 117, 082503 (2016)

- IO reach is the minimum simple goal post for future experiments
- Wide experimental program which is ongoing.The next generation is well into planning and R&D for future. A positive signal would indicate L violation!

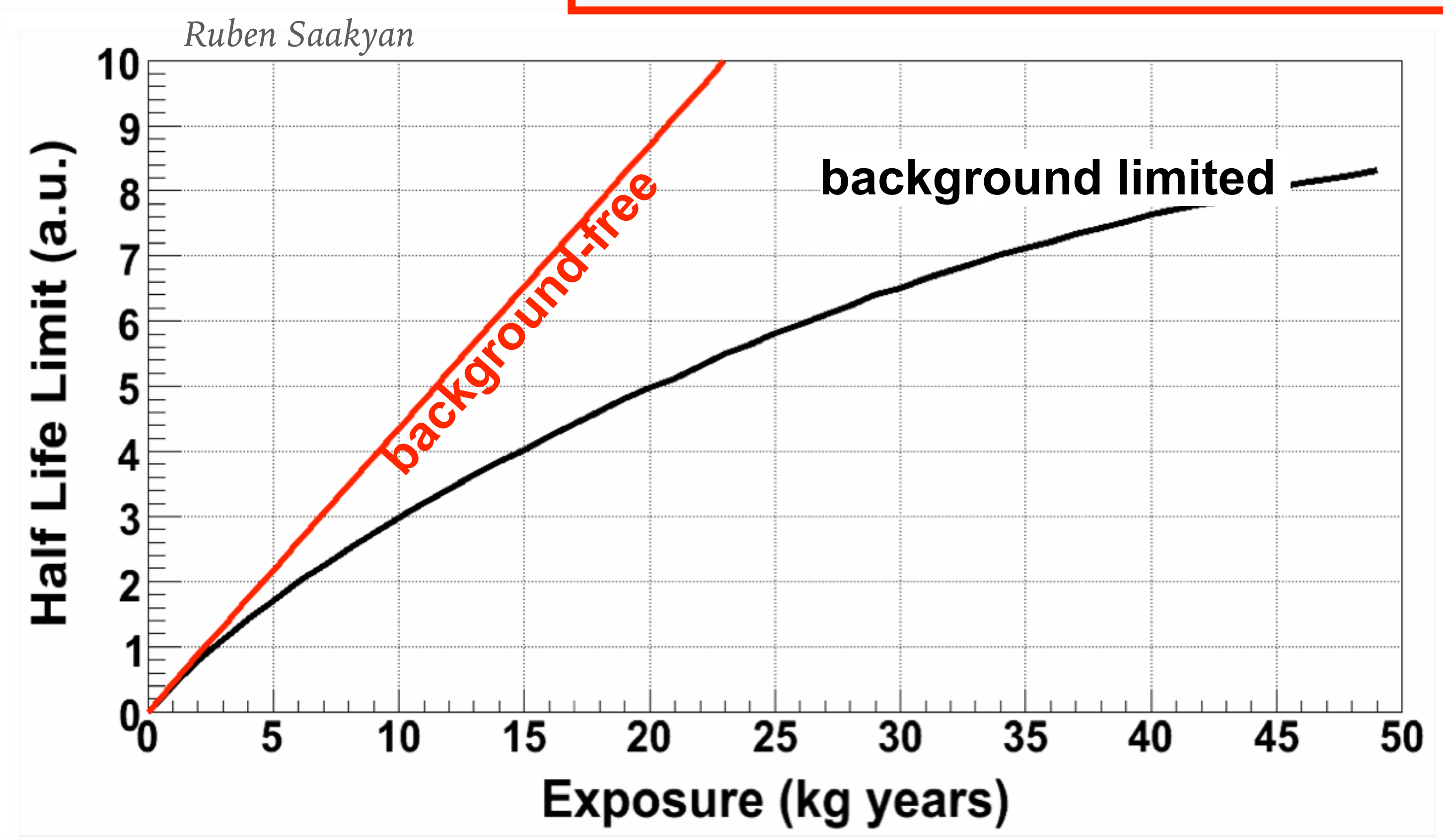
EXPERIMENTAL SENSITIVITY

maximise efficiency & isotope abundance

maximise exposure = mass (isotope) × time

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

minimise background & energy resolution



Extremely slow decay rates ($0\nu\beta\beta$ $T_{1/2}$ ~10^{26}-10^{27} years). Experimental requirements:

- Large isotope mass
  - Detector as source
- Superior background suppression
  - Ultra-clean radiopure material
  - The ability to discriminate signal from background
- Good energy resolution
  - Minimise $0\nu\beta\beta$ peak ROI to maximise S/B
  - Separate from $0\nu\beta\beta$ from irreducible $2\nu\beta\beta$ (~$T_{1/2}$ ~10^{19}-10^{21} years)

Backgrounds:

- Cosmic ray muons (underground lab is a must)
- Natural radioactivity ^{238}U, ^{232}Th, neutrons,…
- $2\nu\beta\beta$

EXPERIMENTAL TECHNIQUES

- **Scintillators (KamLAND-Zen, SNO+, CANDLES)**
  - Measure energy ($\sigma \sim$ 3-10%) + position from scintillation light; some PID
- **TPCs (EXO, NEXT, PandaX, AXEL)**
  - Collect scintillation + ionization: measure energy ($\sigma \sim$1-3%) + tracks / position + PID
- **Bolometers (CUORE, CUPID, AMORE)**
  - Measure energy ($\sigma \sim$ 0.2%) from phonons; granularity gives position info
  - R&D underway for instrumenting with photon detectors for background rejection
- **Semiconductors (GERDA. MAJORANA, COBRA, SELENA)**
  - Measure energy (~0.1-0.3%) from ionization; some tracking / position sensitivity
- **External Trackers (NEMO, SuperNEMO, DCBA)**
  - Trackers + calorimeters, measure energy ($\sigma \sim$ 3-10%) + tracks / positions + PID

APPROACHES AND EXPERIMENTS

A.Giuliani
NEUTRINO2018

source = detector			NOW	MID-TERM	LONG-TERM
Scalability	Fluid embedded source	Xe-based TPC	EXO-200		nEXO
			NEXT-10	NEXT-100 PandaX-III	NEXT-2.0 PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800		KamLAND2-Zen
			SNO+ phase I		SNO+ phase II
High ΔE and ε	Crystal embedded source	Germanium diodes	GERDA-II MJD	LEGEND 200	LEGEND 1000
		Bolometers	AMoRE pilot, I	AMoRE II	
			CUORE CUPID-0, CUPID-Mo		CUPID

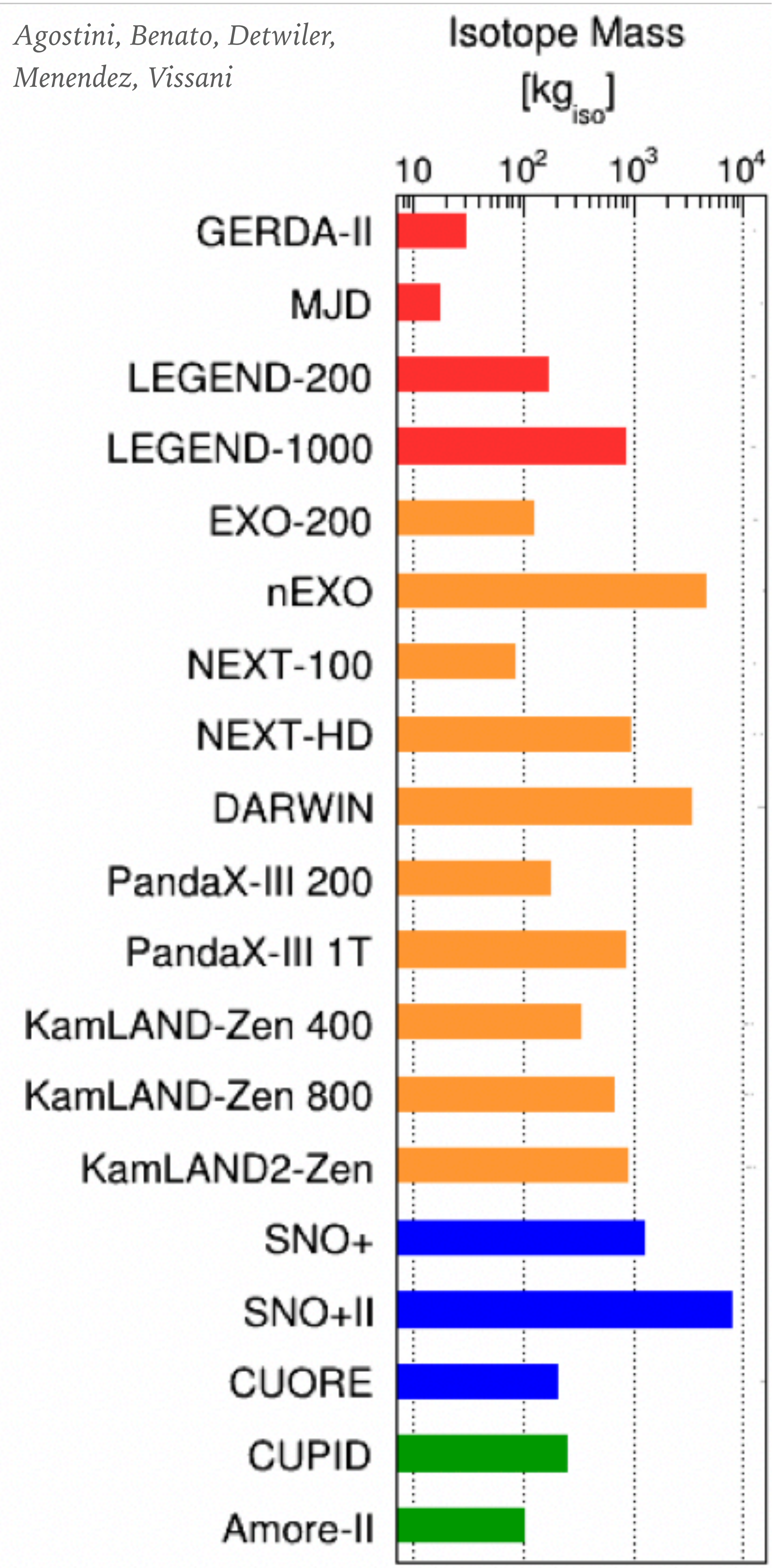
The ultimate goal of the next generation of experiments is $m_{\beta\beta}$~15-20meV

EXPERIMENTS

J. Wilkinson

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	^{48}Ca	305 kg CaF_2 crystals - liq. scint	0.3 kg	Operating
CARVEL	^{48}Ca	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	^{76}Ge	Ge diodes in LAr	15 kg	Complete
GERDA II	^{76}Ge	Point contact Ge in active LAr	44 kg	Operating
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
NEMO3	^{100}Mo/^{82}Se	Foils with tracking	6.9 kg/0.9 kg	Complete
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF6 high pressure gas TPC	50 kg	R&D
AMoRE	^{100}Mo	CaMoO4 bolometers (+ scint.)	5 kg	Construction
CUPID	^{100}Mo	Scintillating Bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE-0	^{130}Te	TeO_2 Bolometer	11 kg	Complete
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
SNO+ Phase II	^{130}Te	3% ^{nat}Te in liquid scint.	8 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scint.	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scint.	750 kg	Operating
KamLAND2-ZEN	^{136}Xe	2.7% in liquid scint.	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	Xe liquid TPC	3.5 tonnes	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DCBA	^{150}Nd	Nd foils & tracking chambers	30 kg	R&D

R&D   Construction   Operating   Complete



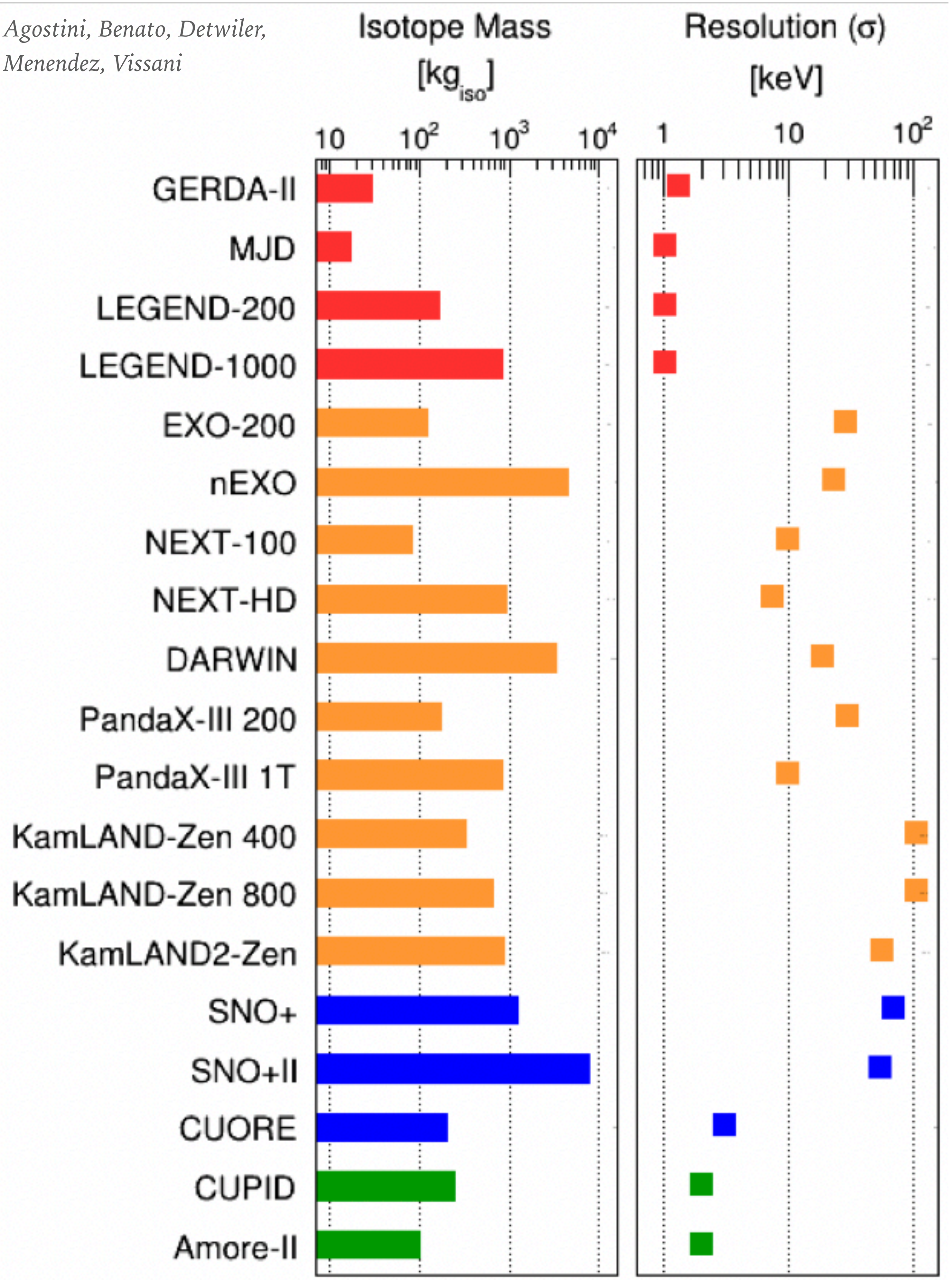
Germanium (^{76}Ge) experiments

Xenon (^{136}Xe) experiments

Tellurium (^{130}Te) experiments

Molybdenum (^{100}Mo) Experiments

Agostini, Benato, Detwiler, Menendez, Vissani



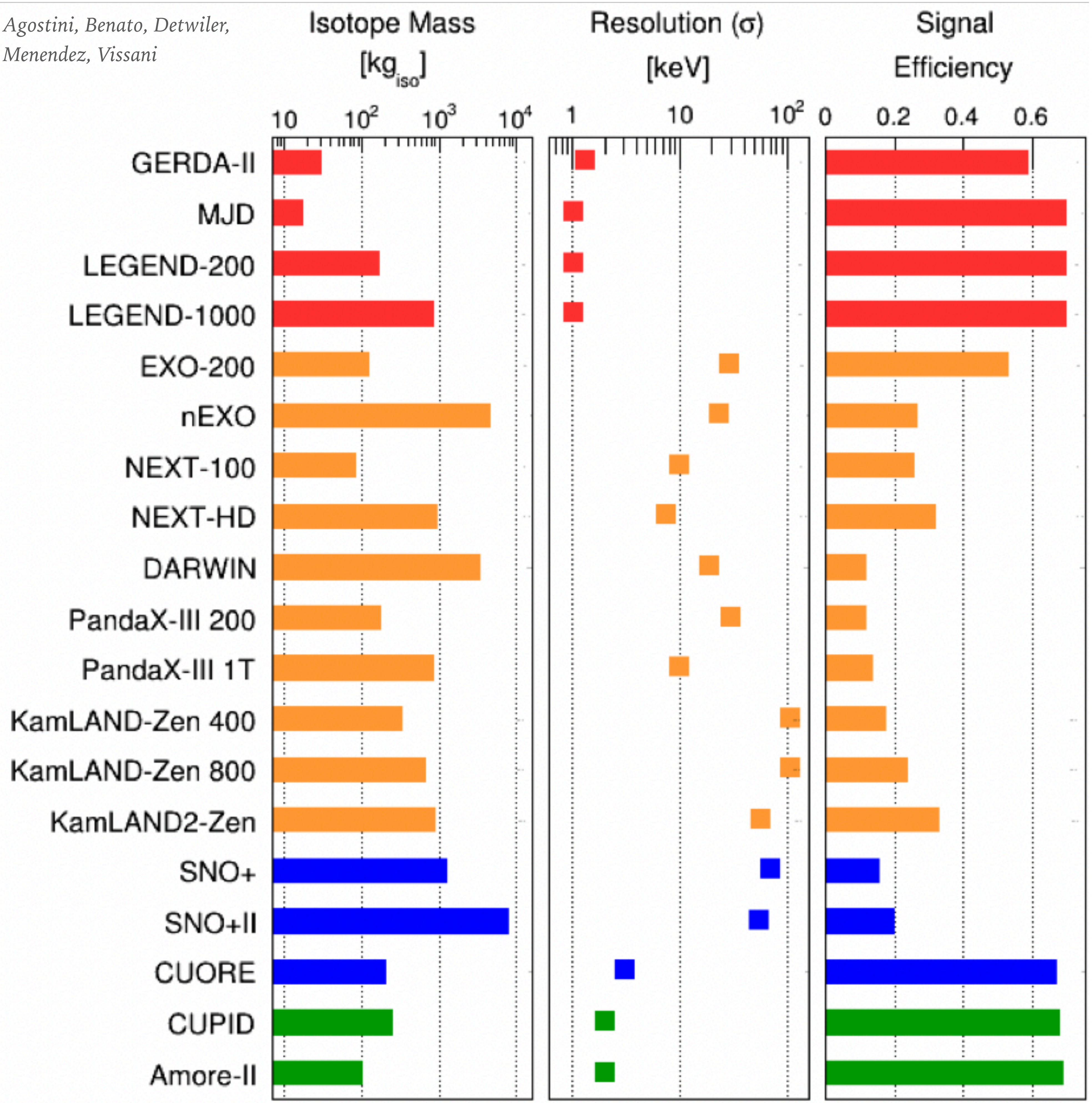
Semiconductor

Liquid/gas TPC

Liquid Scintillator

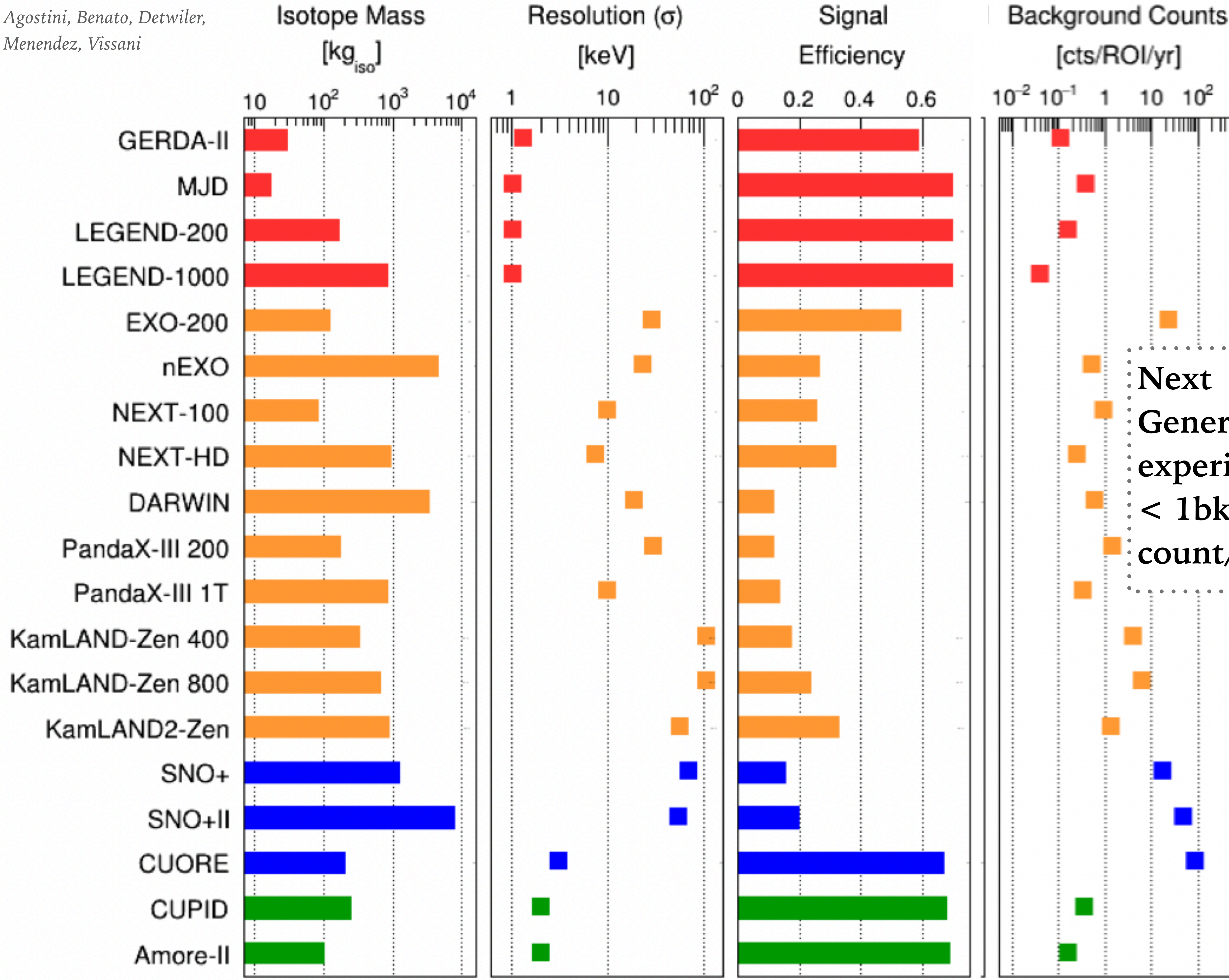
Bolometer

Agostini, Benato, Detwiler, Menendez, Vissani



Low efficiency due to fiducialisation

Agostini, Benato, Detwiler, Menendez, Vissani

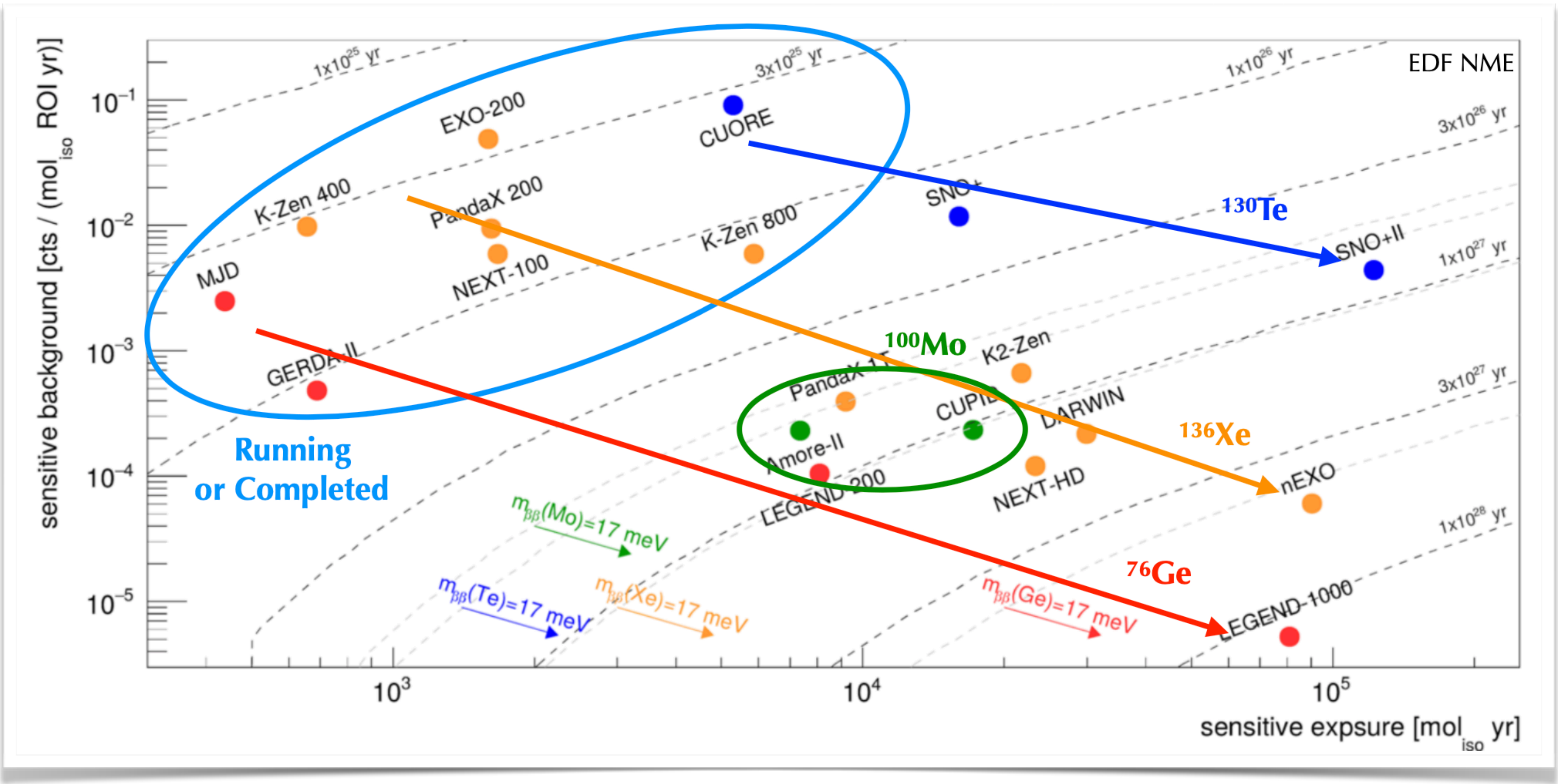


Next Generation experiments: < 1bkgd count/year

Agostini, Benato, Detwiler, Menendez, Vissani

DISCOVERY SENSITIVITY COMPARISONS

Agostini, Benato, Detwiler, Menendez, Vissani



OUTLINE

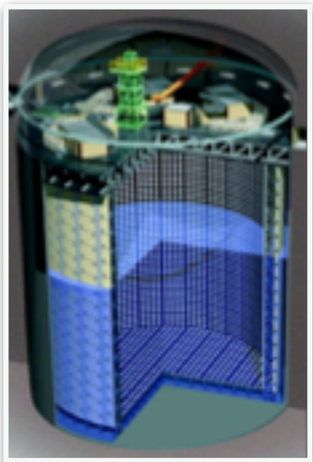
- Part I
  - What we know about neutrinos
  - Matter Antimatter Asymmetry & the role of Neutrinos
  - Study of Neutrinos using Long Baseline Neutrino Experiments
- Part II
  - Study of Neutrinos using Reactor Experiments
  - How we can measure the neutrino mass?
  - What is the nature of neutrinos? Dirac or Majorana?
  - Astrophysical neutrinos
  - Sterile neutrinos

CURRENT AND FUTURE LARGE SCALE DETECTORS

Water Cherenkov | **Liquid Scintillator** | **Liquid Ar**

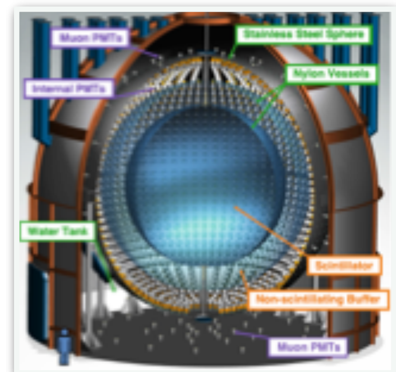
Current

Super-Kamiokande

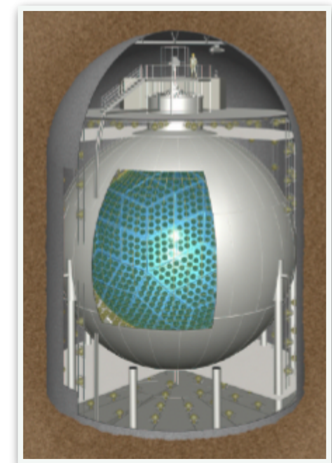


SK-Gd

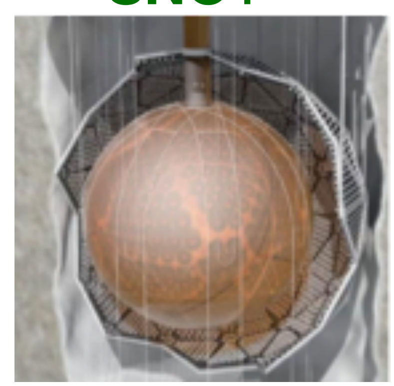
Borexino



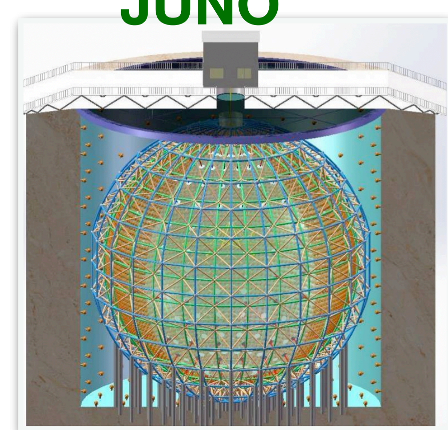
KamLAND



SNO+

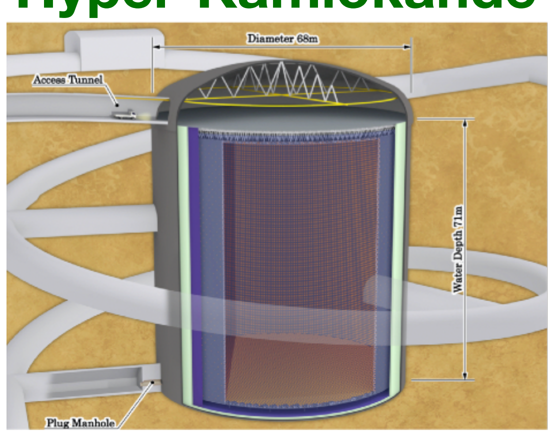


JUNO

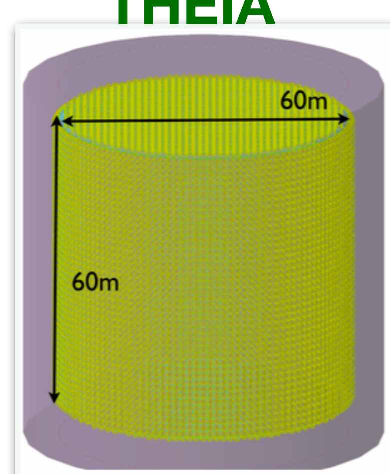


Future

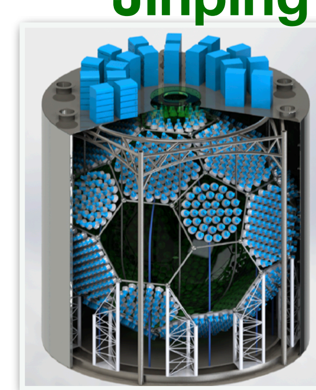
Hyper-Kamiokande



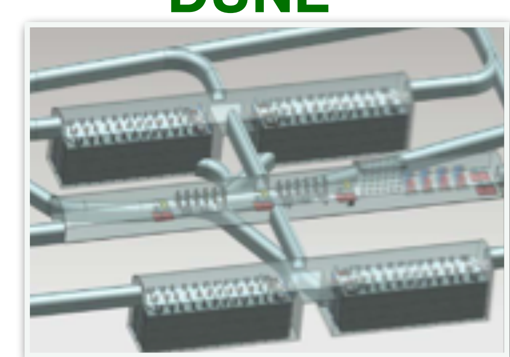
THEIA



Jinping

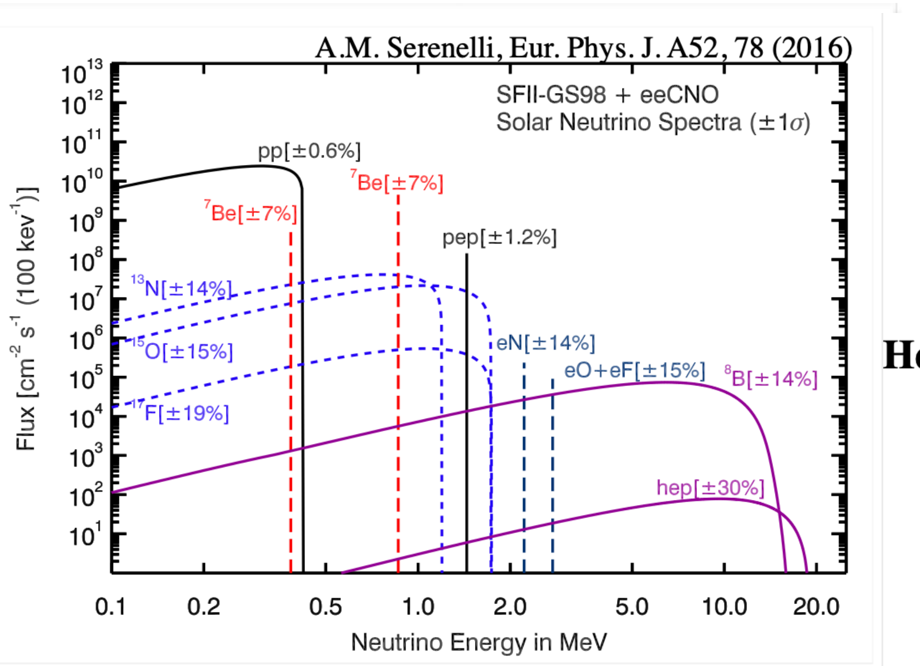


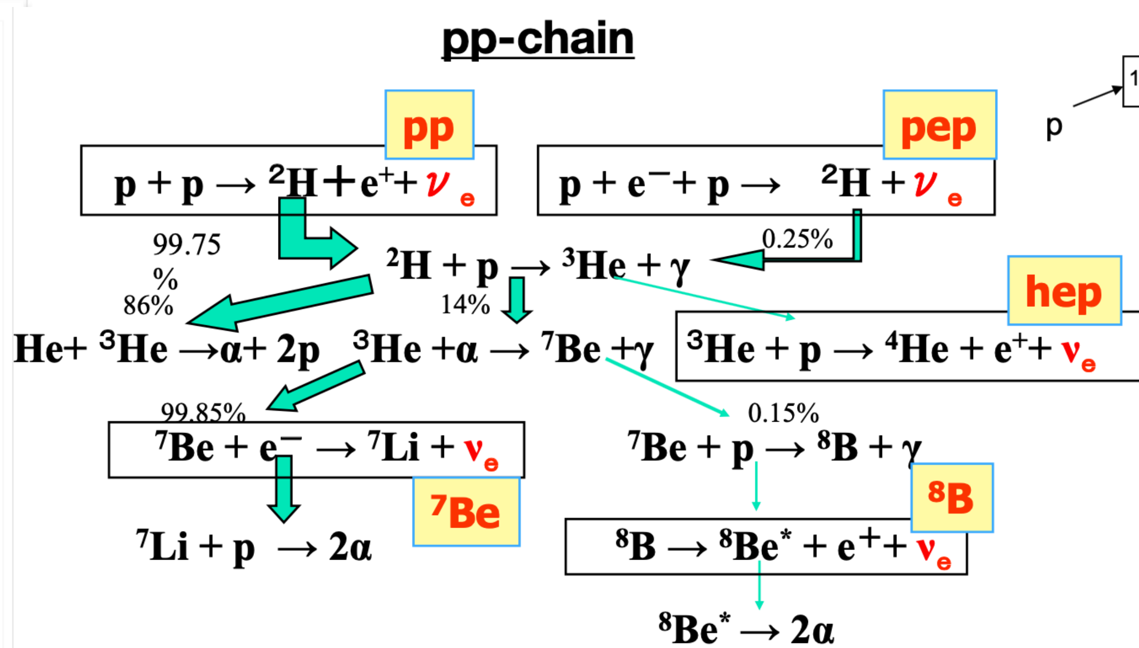
DUNE

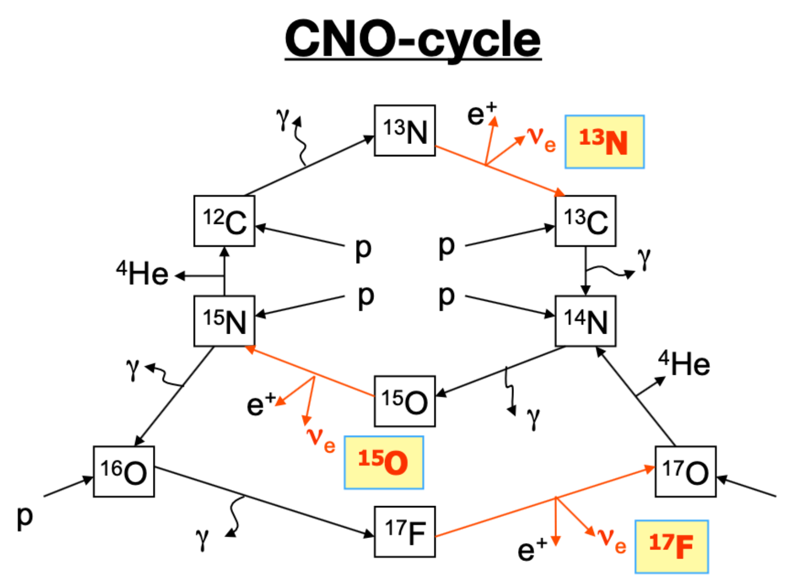


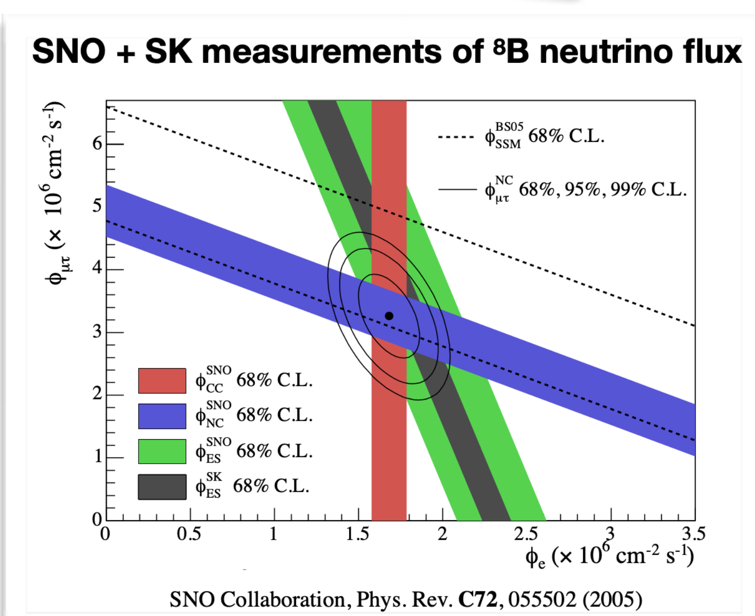
SOLAR NEUTRINOS

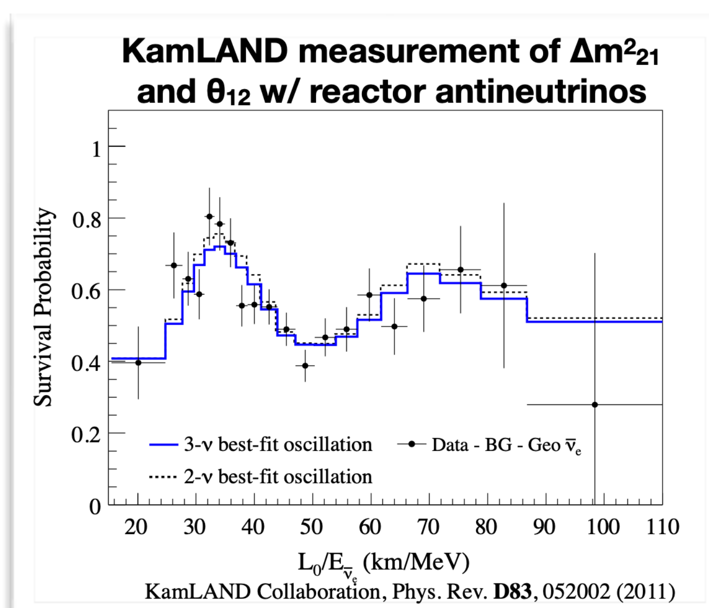
- Intense neutrinos from nuclear fusion in the Sun's core.
- Majority (99%) of flux from the pp-chain.
- Subdominant contribution (<1%) from the CNO-cycle









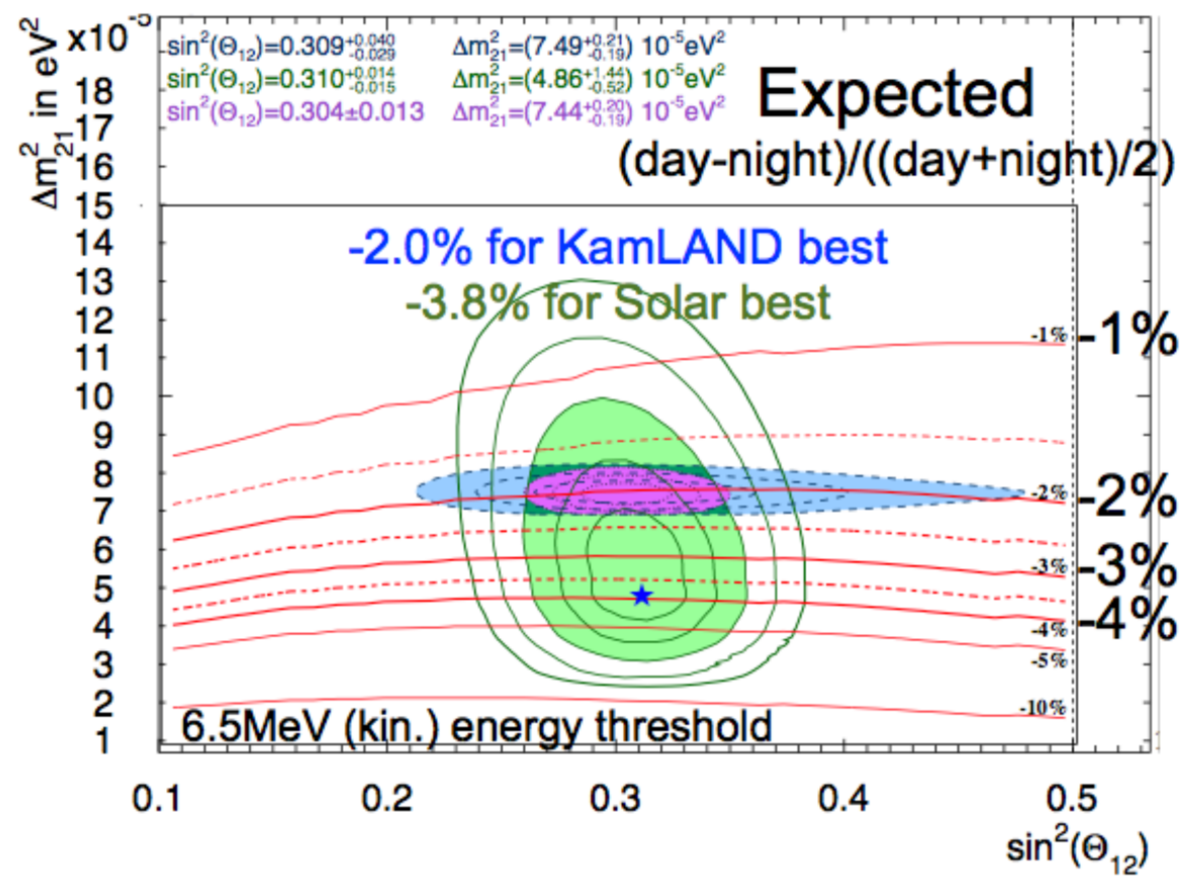


- Interplay solar and reactor experiments

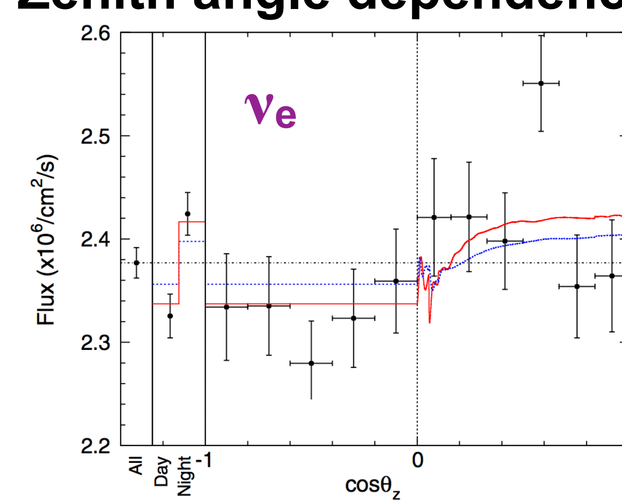
THE Δm^2_{12} TENSION

- Super-K data best constrains Δm^2_{21}
- SNO data best constrains $\sin^2\theta_{12}$
- SNO and Super-K together define global *solar* neutrino fit
- Agreement with anti-ν_e data (KamLAND) for $\sin^2\theta_{12}$
- 2σ tension in for Δm^2_{21}
- Tension driven by:
  - Relatively large Day/Night asymmetry
    - ➡ MSW in Earth would regenerate ν_e in Night time solar flux, expected asymmetry $\approx 1\%$
  - Flatteness of the survival probability of the observed ^{8}B spectrum

Oscillation parameters: Solar and KamLAND



Zenith angle dependence



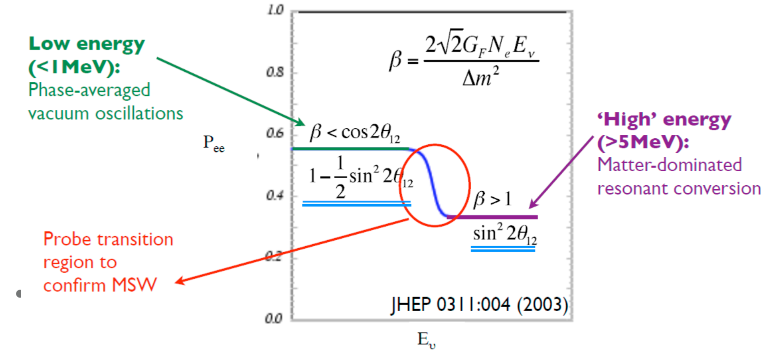
$$A_{\rm DN}^{\rm fit} = [-3.2 \pm 1.1({\rm stat}) \pm 0.5({\rm syst})]\%$$

non-zero significance

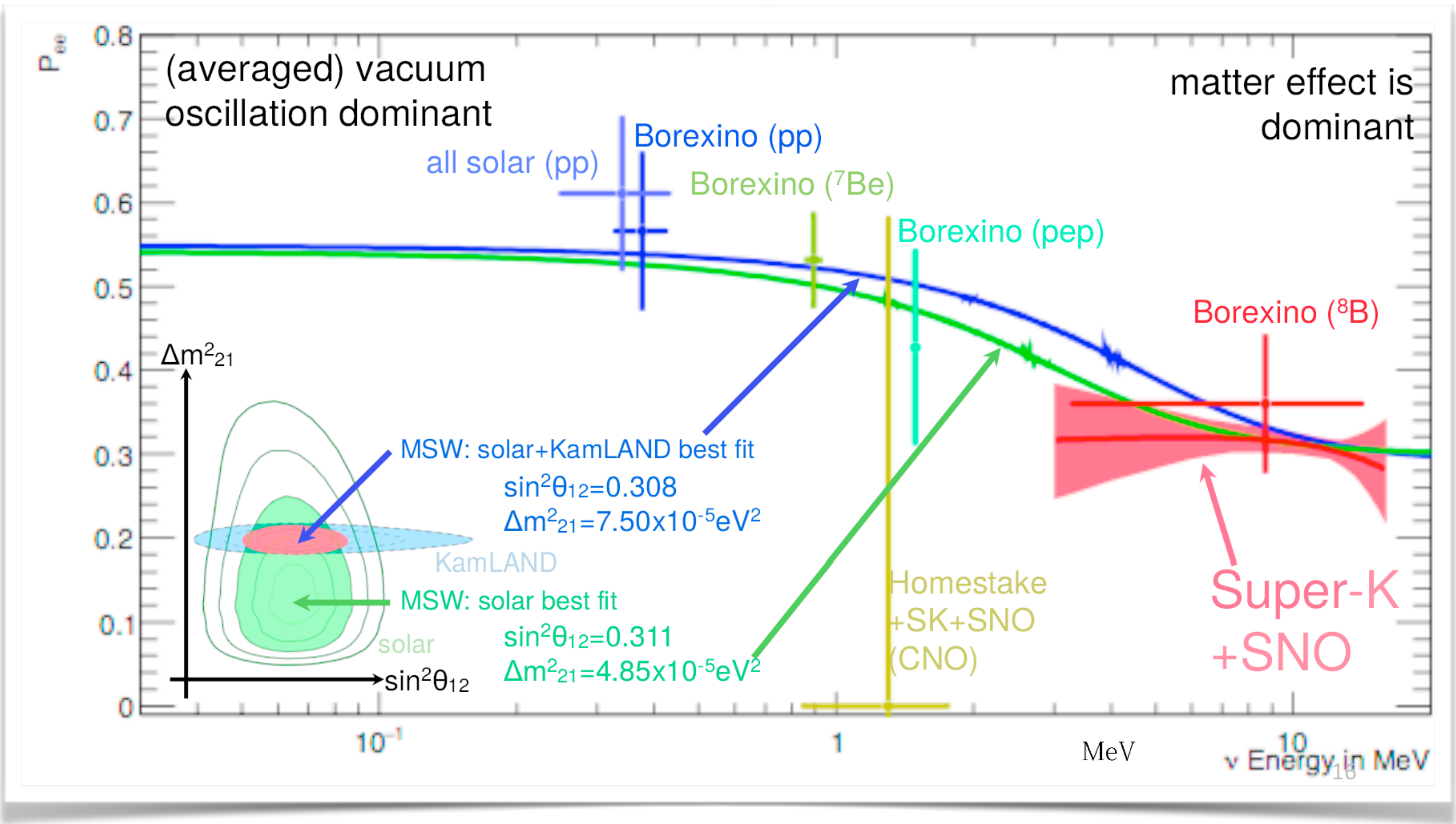
dominant error

mainly from BG

LATEST RESULTS

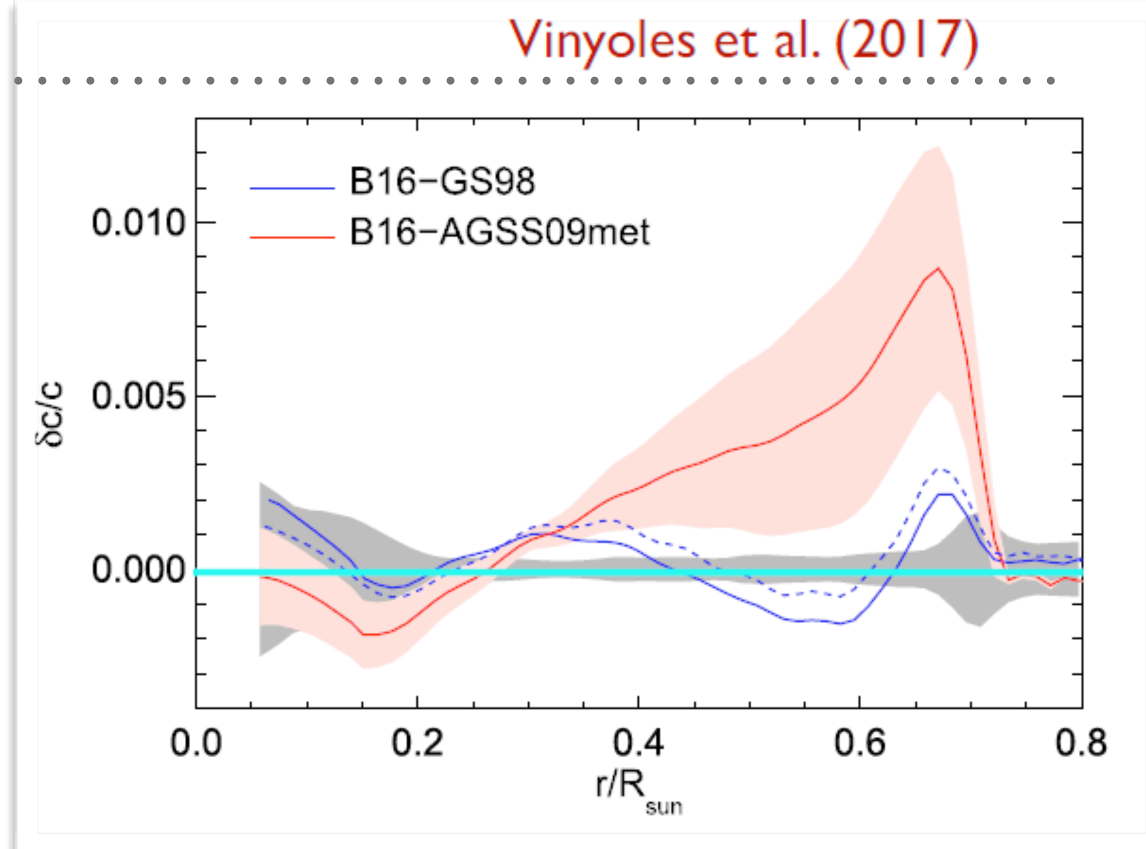


Latest results from Borexino and Super-Kamiokande

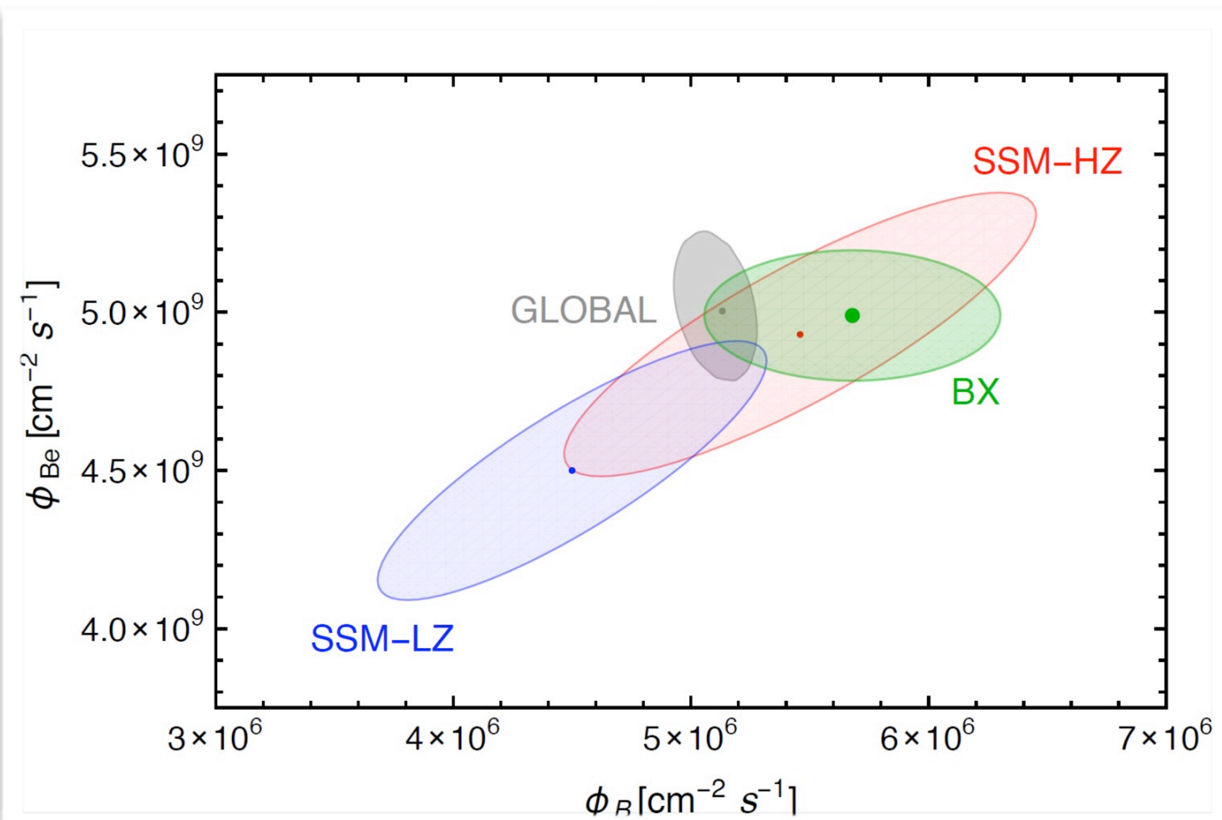


- **A 2σ tension with the MSW upturn for the solar and solar+KamLAND best fit parameters.**
- The Super-K recoil electron spectrum is consistent within ∼1σ with the MSW upturn for the solar global best fit parameters
- Many beyond-standard models proposed to explain the flatness of the ^{8}B neutrino survival probability

METALLICITY PUZZLE

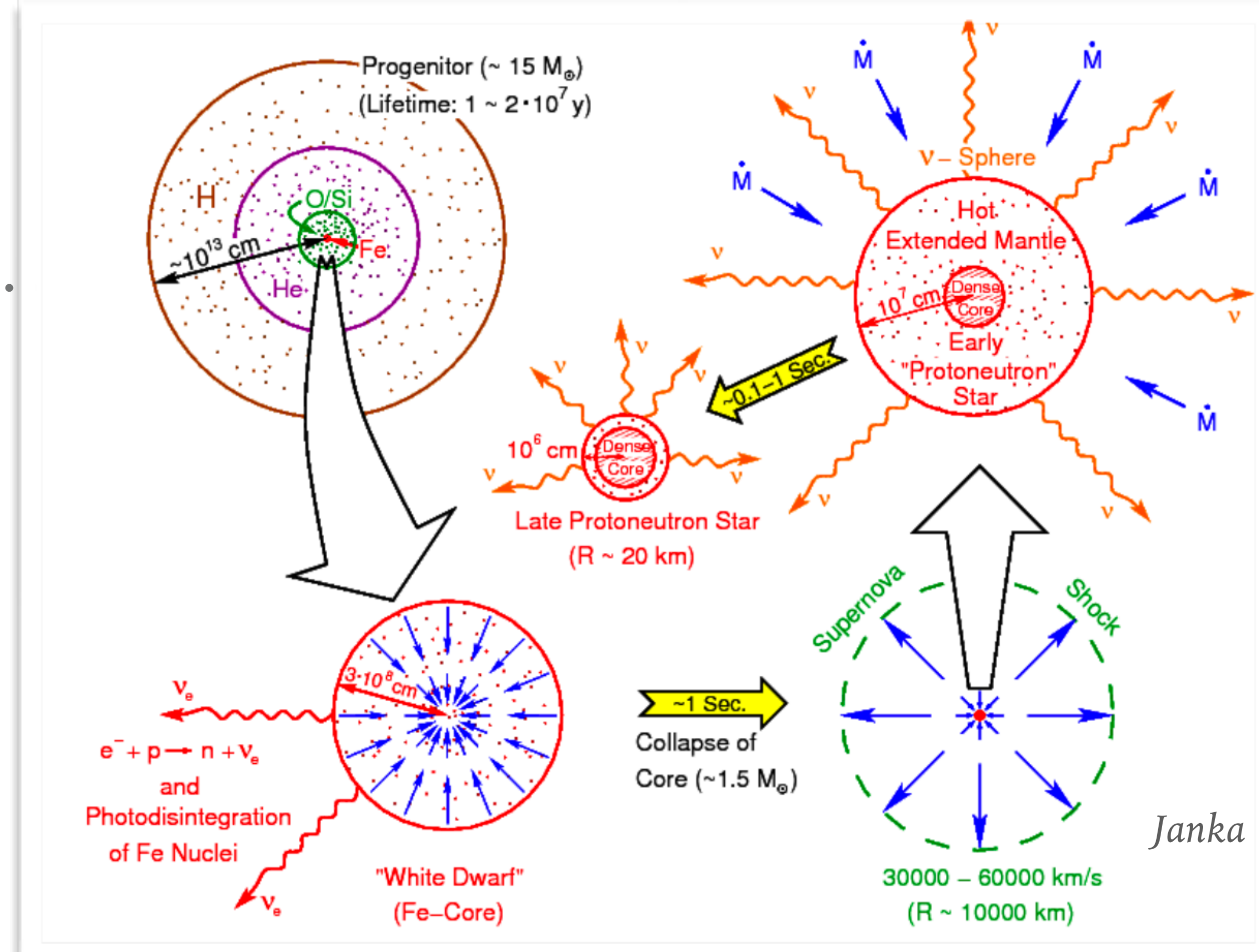


- Metallicity=abundance of volatile heavy elements like N,O,Ne,Ar….Fe
- SSM takes initial metallicity as input
- Metallicity issue:
  - Old models (98) indicated high metallicity
  - In 2004, observation of the photosphere indicated lower CNO abundance (i.e. lower metallicity)

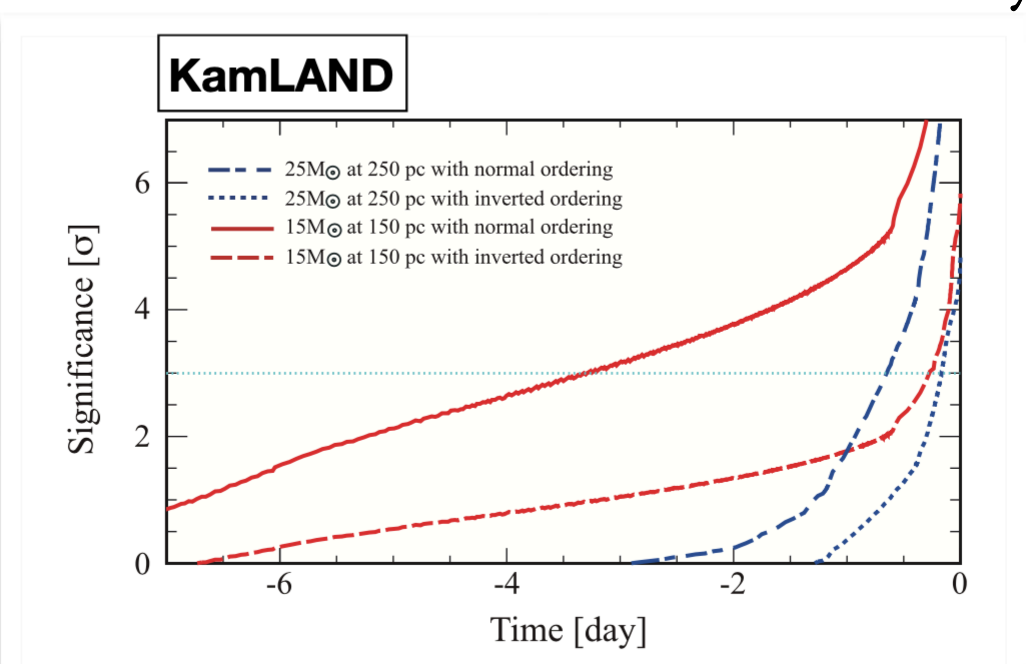


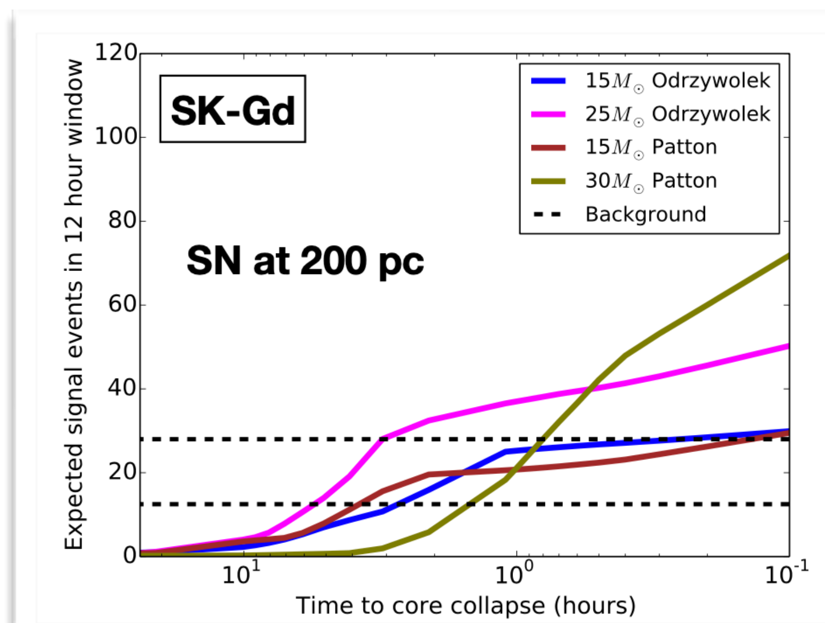
- CNO flux directly proportional to metallicity in the core
- Also heavily temperature dependentI
- Experimentally limited sensibility to CNO due to ^{210}Bi background
- Borexino measurement of 7B/8B ratio ratio favours high-metallicity model though sensitivity limited by theoretical uncertainties.
- **Key observation so resolve the situation: CNO neutrinos**

SUPERNOVA NEUTRINOS



- Rich science outcomes from observing neutrinos from core-collapse supernovae
  - SN burst model
  - Neutrino property (mass ordering etc)
- SN alert (SNEWS etc)
- Observation so far: still only ~20 events from SN1987A
- Precursor signal from Si-burning can also be detectable for nearby SN bursts
- KamLAND warning system have been implemented and running
- SK-Gd will also have sensitivity.



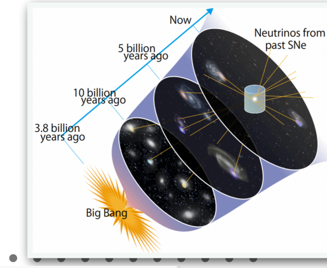


SUPERNOVA NEUTRINO DETECTORS

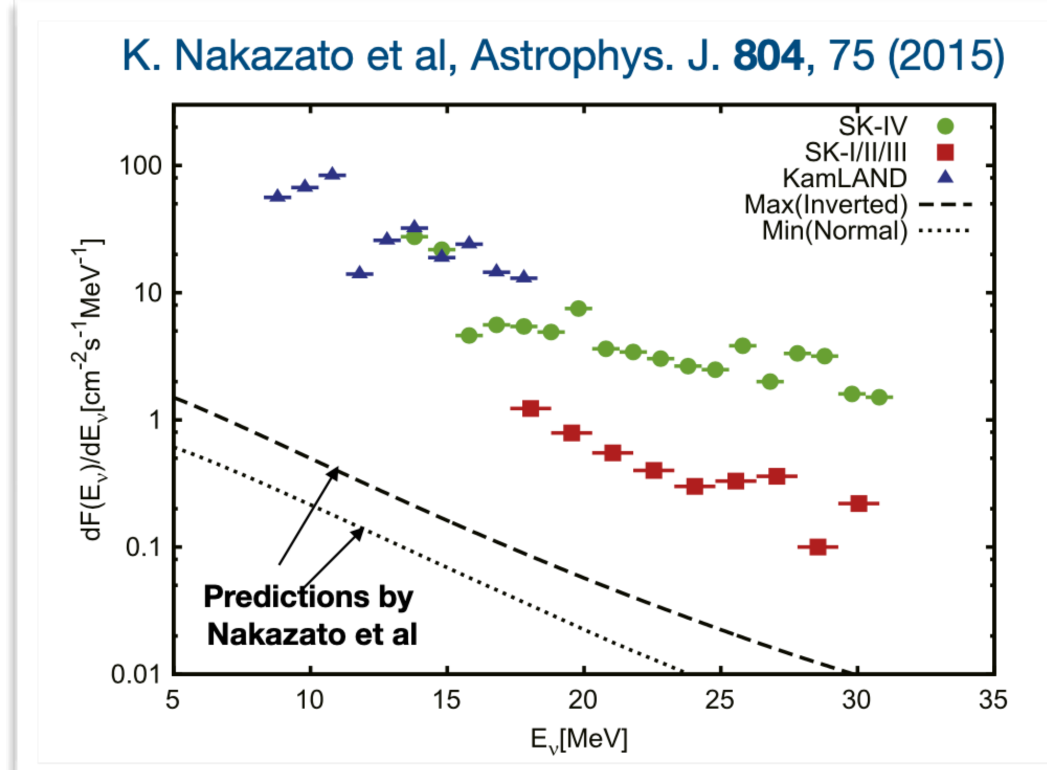
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(106)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BooNE	Scintillator	USA	0.7	200	(Running)
HALO	Lead	Canada	0.079	20	Running
DayaBay	Scintillator	China	0.33	100	Running
NOvA	Scintillator	USA	15	3000	Running
SNO+	Scintillator	Canada	1	300	Running
MicroBooNE	Liquid argon	USA	0.17	17	Running
DUNE	Liquid argon	USA	34	3000	Planned
Hyper-K	Water	Japan	187	50,000	Planned
JUNO	Scintillator	China	20	6000	Under construction
PINGU	Long string	South pole	(600)	(106)	Proposed

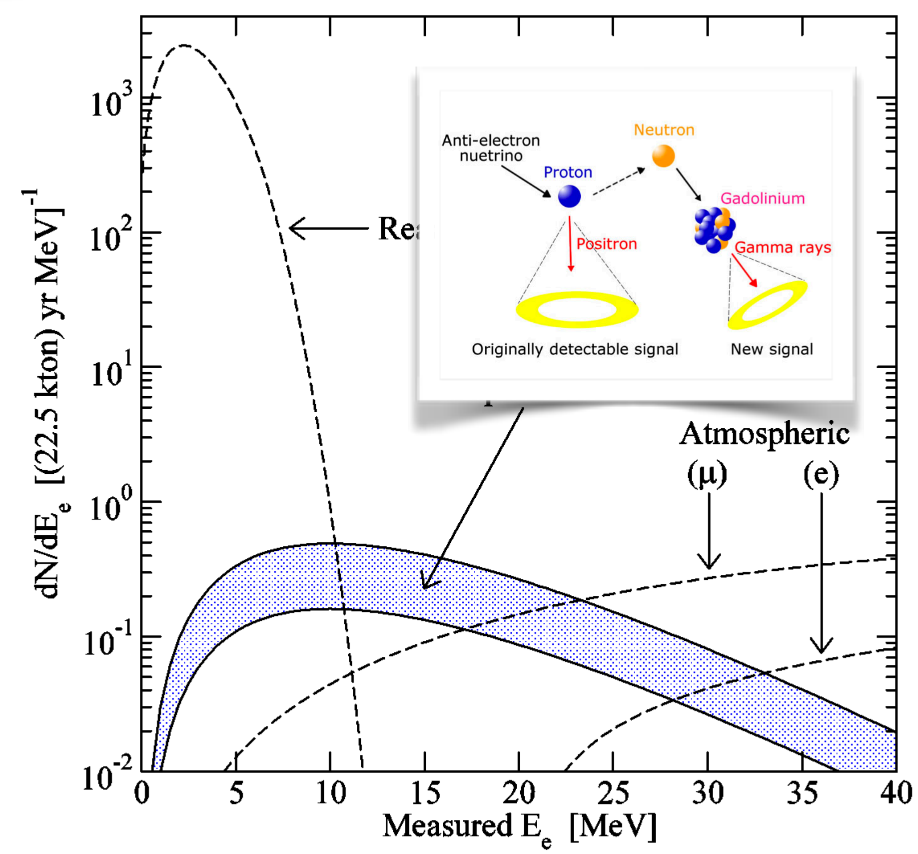
Based on arXiv: 1707.06384 with updates

DIFFUSE SUPERNOVA NEUTRINO BACKGROUNDS



- Diffused Supernova Neutrino Backgrounds: Neutrinos produced from the past SN bursts and diffused in the current universe.
  - $\sim$ a few SN explosions every second $O(10^{18})$ SNe so far in this universe
- Can study history of SN bursts with neutrinos
- **SN rate problem**: Observed SN burst rate lower than prediction from cosmic star formation rate
- DSNB signal will help resolving the puzzle
- Reducing backgrounds is the key for the first observation of DSNB
- First observation within reach of SK-Gd and JUNO





OUTLINE

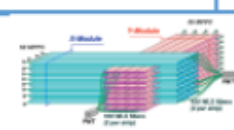
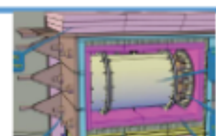
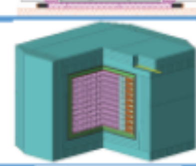
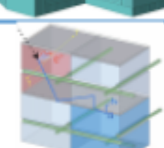
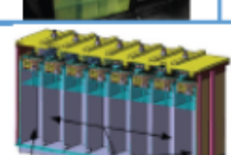
- Part I
  - What we know about neutrinos
  - Matter Antimatter Asymmetry & the role of Neutrinos
  - Study of Neutrinos using Long Baseline Neutrino Experiments
- Part II
  - Study of Neutrinos using Reactor Experiments
  - How we can measure the neutrino mass?
  - What is the nature of neutrinos? Dirac or Majorana?
  - Astrophysical neutrinos
  - Sterile neutrinos

VERY SHORT BASELINE REACTOR EXPERIMENTS

- Different technologies: (Gd, Li, B) (seg.) (movable) (2 det.)
- Most have sensitivity 0.02~0.03 @Δm^2 ~1eV^2 @90%CL

Disagreements with expectations:

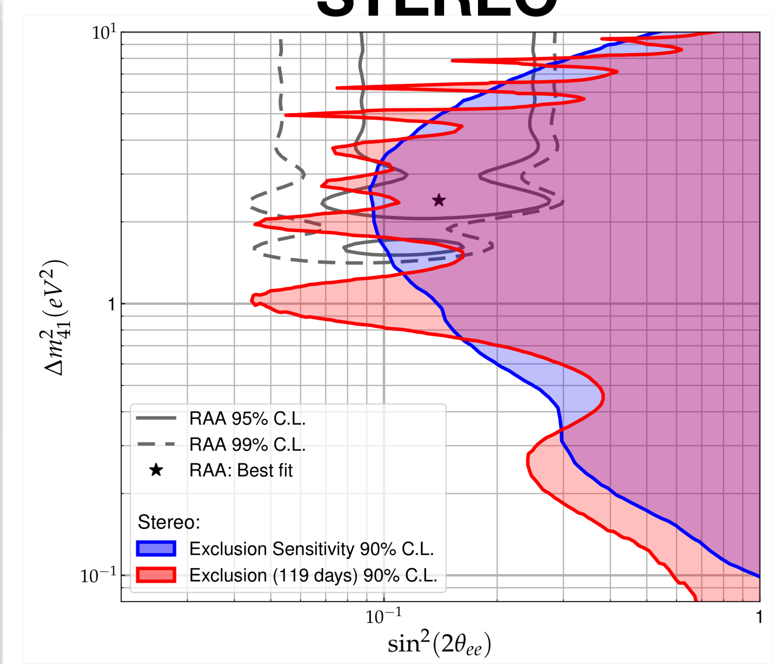
- Reactor Antineutrino Anomaly
- LSND anomaly: excess of events in neutrino beam, similar results in MiniBooNE.
- Sterile neutrinos?

Experiment		Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)		3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)		2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA)		40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)		100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)		85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France)		57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

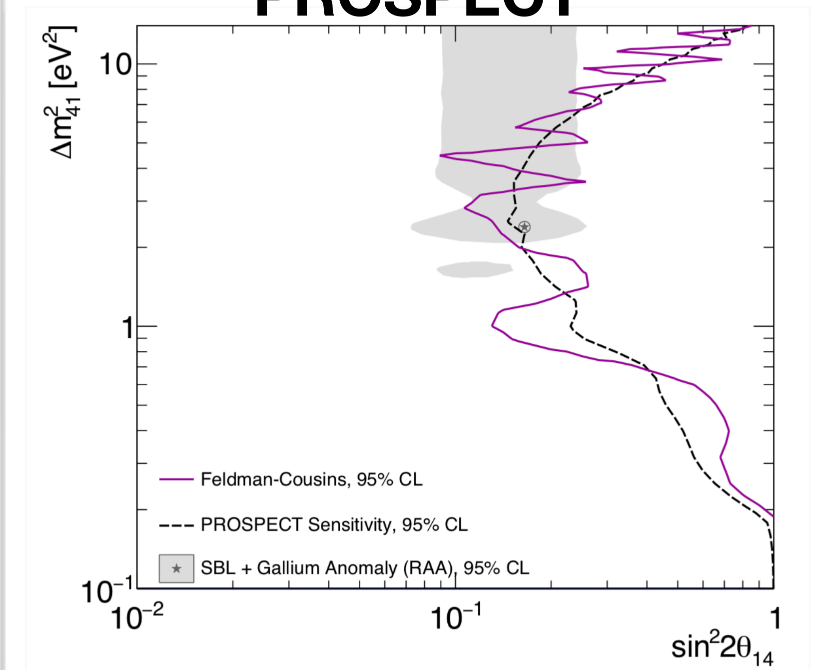
Nathaniel Bowden

LIMITS ON STERILE NEUTRINOS

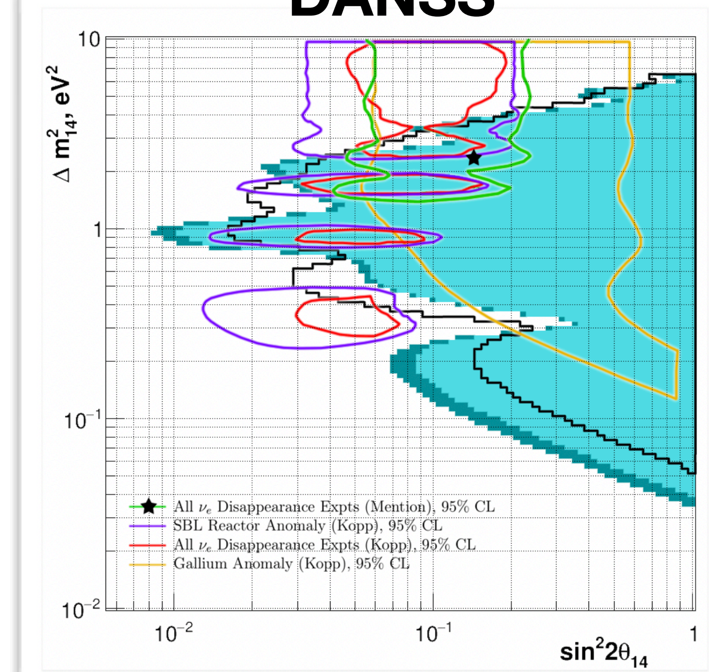
STEREO



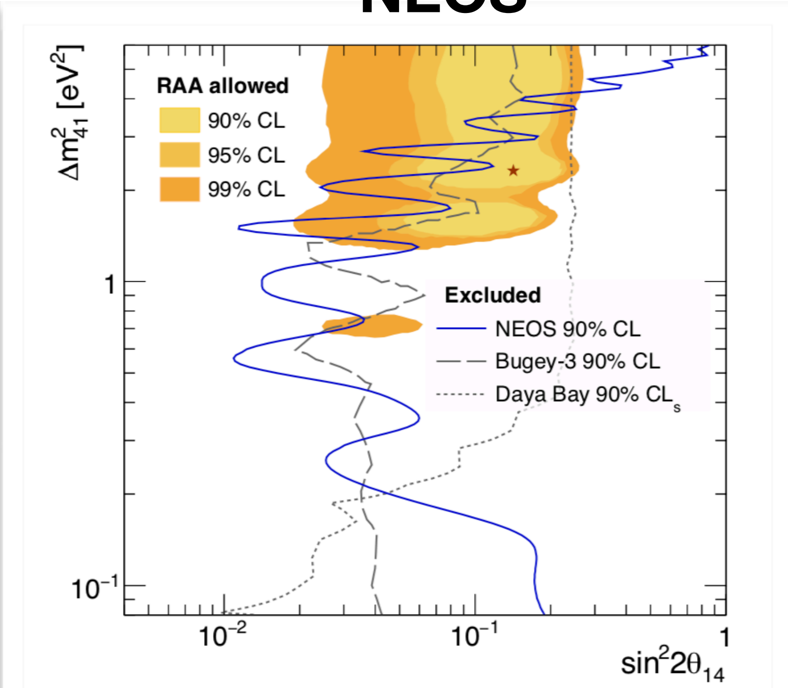
PROSPECT



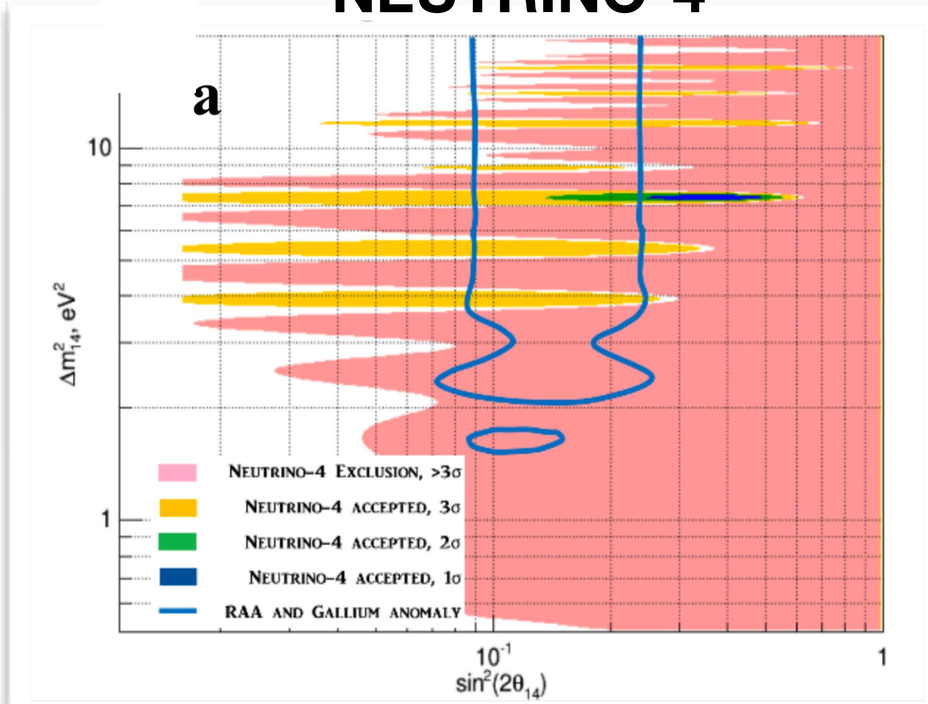
DANSS



NEOS

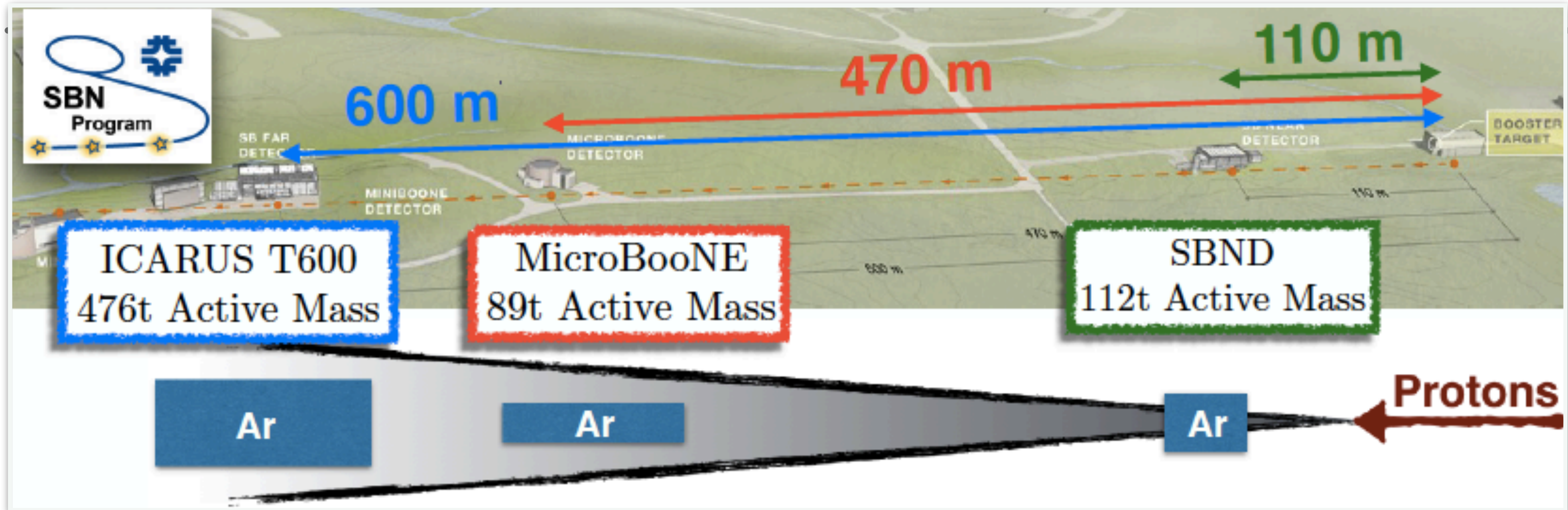


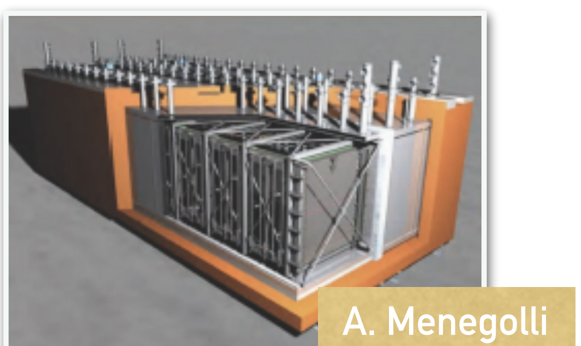
NEUTRINO-4



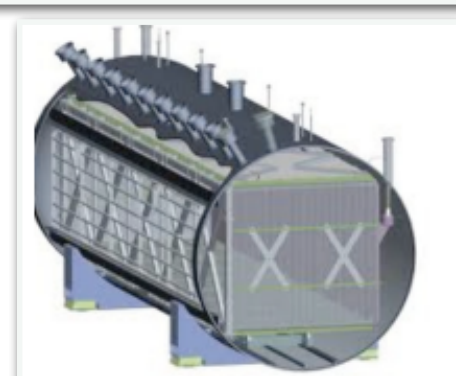
- ➤Limits keep improving
- ➤Region favoured by anomalies already largely excluded
- ➤Neutrino-4 sees oscillation at $\Delta m^2_{14} \sim 7 eV^2$ $\sin^2 2\theta_{14} \sim 0.4$
- ➤Parameters incompatible with Data Bay & RENO results
- ➤Data taking continues…

SHORT BASELINE NEUTRINO (SBN) PROGRAMME

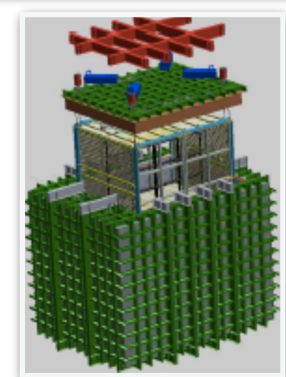




ICARUS- Being installed. Data taking by the end of the year.

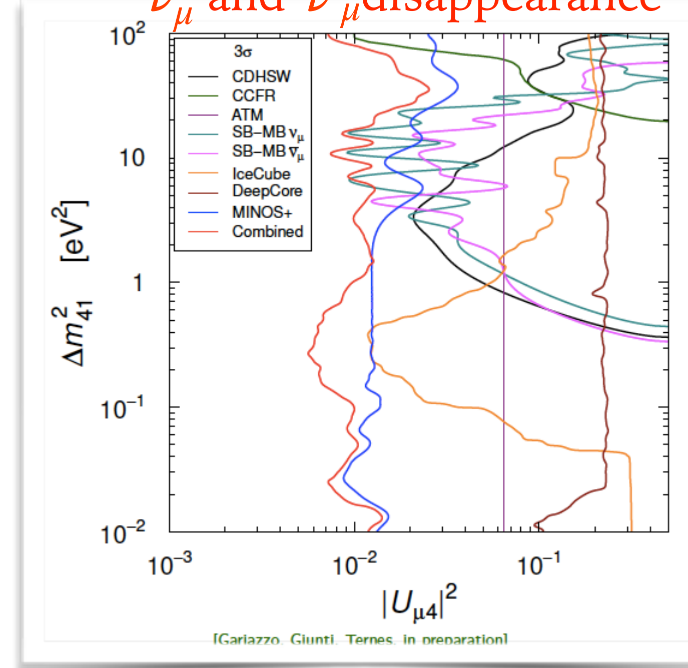


MicroBooNE
Running



SBND
Construction ongoing
Commissioning in 2020
Data taking in 2021

ν_μ and $\bar{\nu}_\mu$disappearance

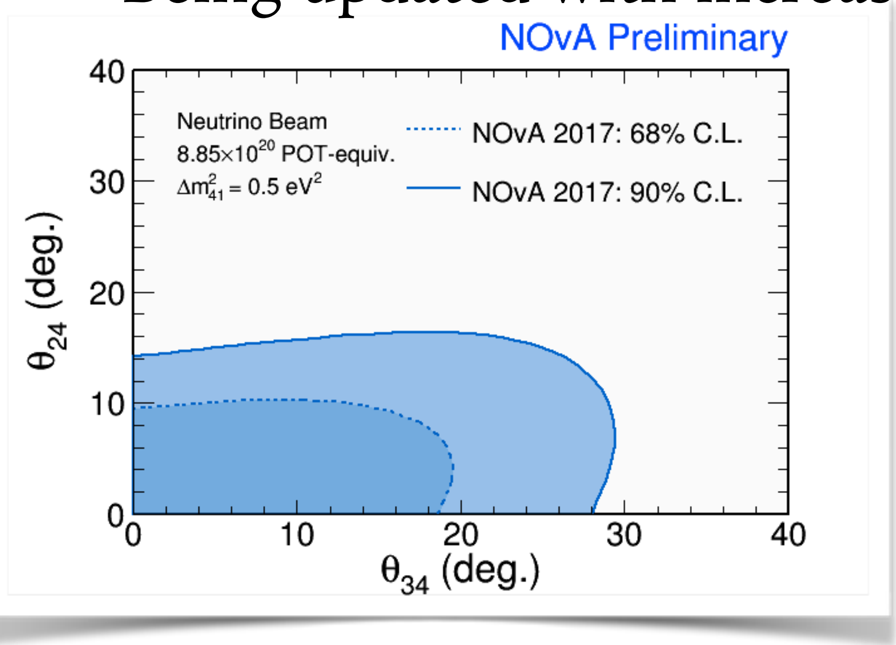


SBN aims to:

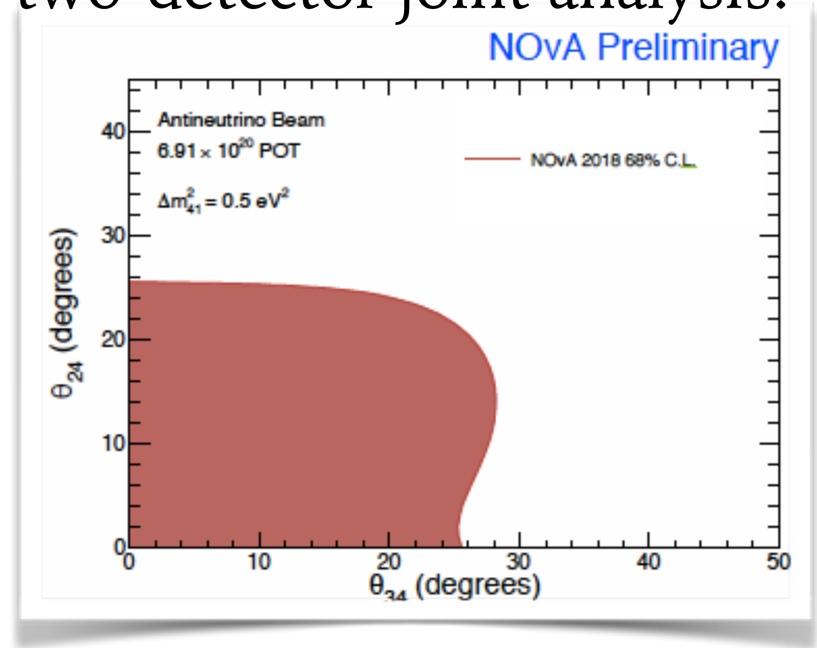
- study the baseline dependence of the appearance and disappearance channels.
- make a high precision measurement on ν-Ar cross sections
- develop LArTPC technology for future large neutrino experiments like DUNE

NOVA AND OPERA STERILE NEUTRINO SEARCHES

- NOvA: No evidence of neutral current disappearance and limits sets.
- Being updated with increased $\bar{\nu}$ dataset and two-detector joint analysis.



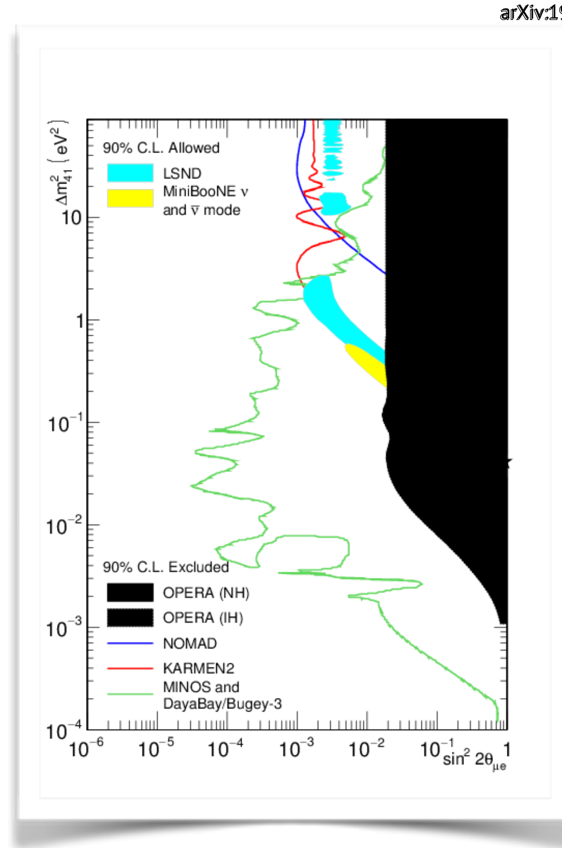
$\theta_{24} < 16.2°$
$\theta_{34} < 29.8°$
(90% C.L.)

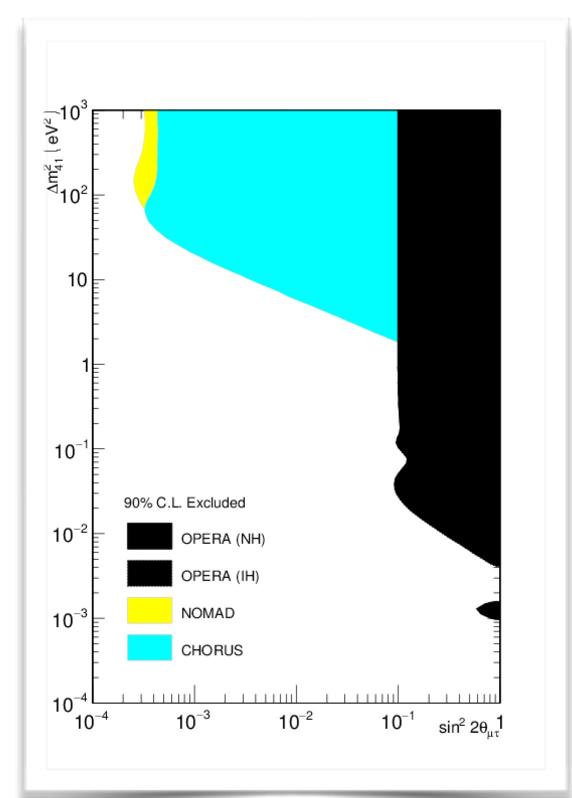


$\theta_{24} < 25.5°$
$\theta_{34} < 31.5°$
(68% C.L.)

- OPERA: Final results
- ν_τ and ν_e appearance channels were combined for the first time to constrain parameters of the 3 + 1 sterile mixing model.
- For $\Delta m^2_{41} > 0.1 eV^2$, upper limits on $\sin^2 2\theta_{\mu\tau}$ and $\sin^2 2\theta_{\mu e}$ are set to 0.10 and 0.019 for NH and IH. The MiniBooNE best-fit values are excluded with 3.3σ significance.

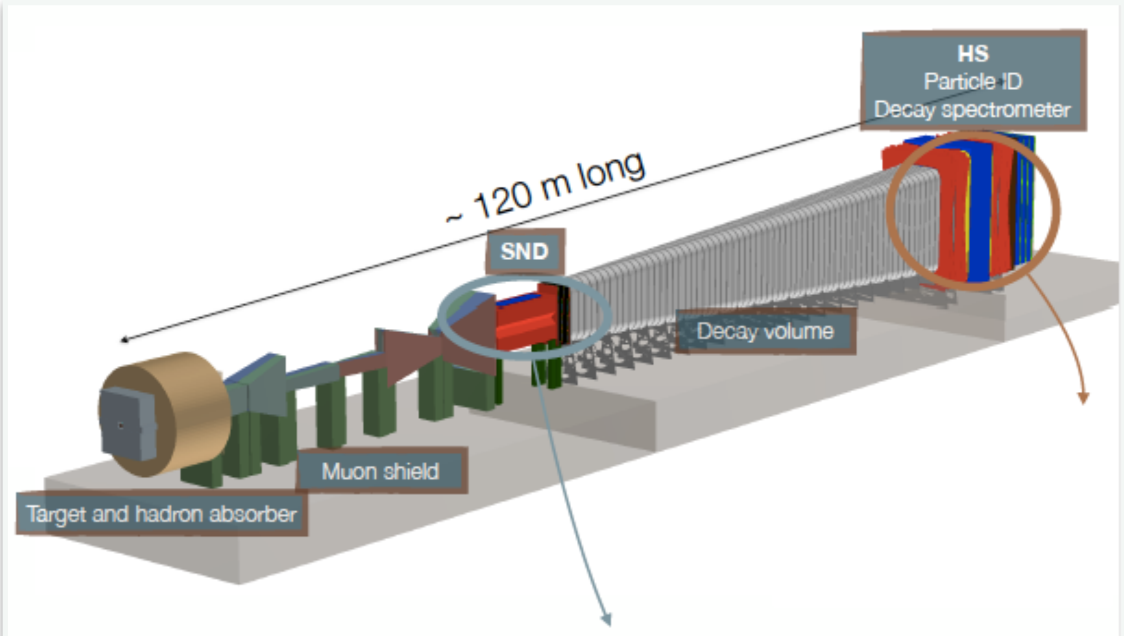
arXiv:1904.05686

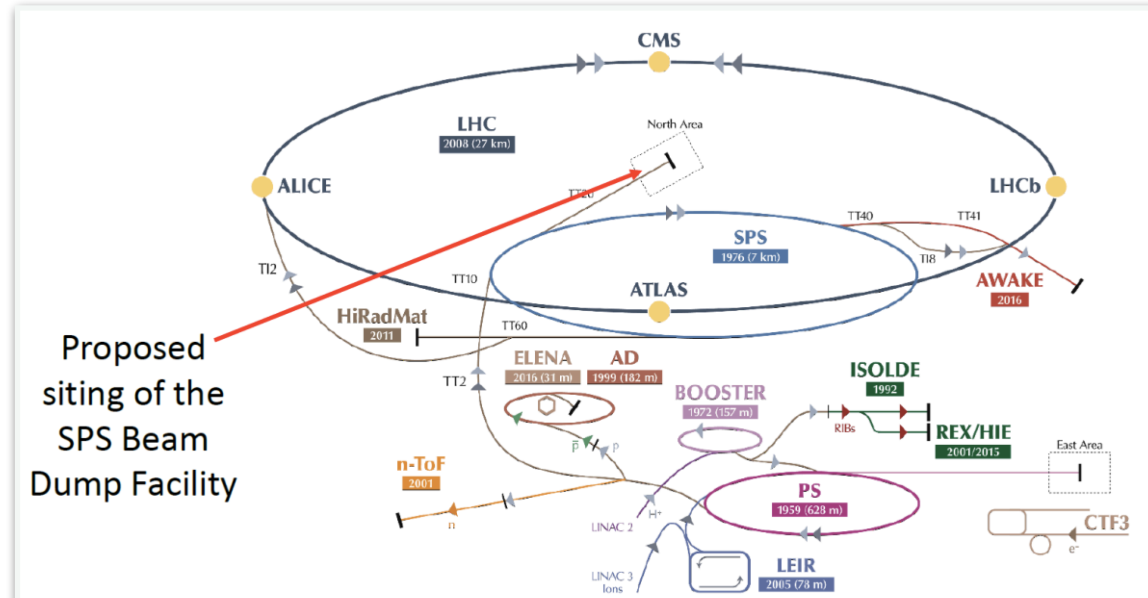




SHIP

arXiv:1504.04956, JINST 14(2019)03 P03025, CERN-SPSC-2019-010



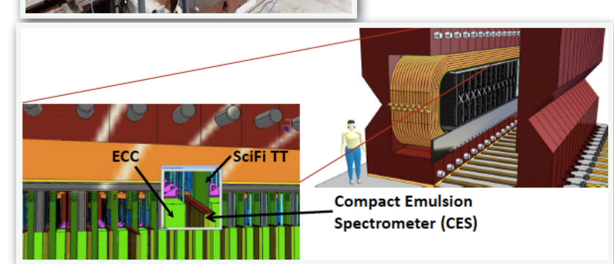


Planned SHIP CDS by 2019

Dual detector system:

- Hidden Sector detector (HS) ⇒ search for new, weakly coupled, long lived particles from the Hidden Sector
- Scattering and Neutrino Detector (SND) ⇒ neutrino physics and Light Dark Matter searches
- SND based on re-development of Opera concepts
- Magnet allows distinguishing between neutrino and anti-neutrino interactions

RPC prototypes built and successfully operated for muon flux and charm production measurement at SPS in 2018



Testbeam at DESY in 2019

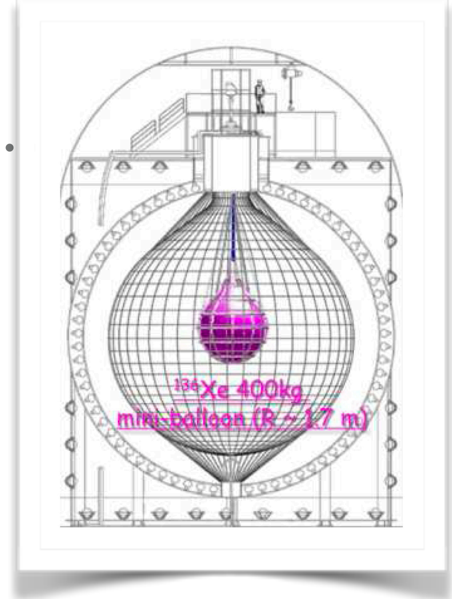
CONCLUSIONS PART II

- Reactor neutrinos can helpd in further understanding neutrinos oscillations and complement the long-baseline neutrino results.
- Direct mass searches are the predominant tool to address the measurement of the neutrino mass.
- The nature of neutrinos is a major open question being addressed by neutrinoless double beta decays.
- The current and future experiments will allow to further address the astrophysical neutrinos and investigate sterile neutrinos.

ADDITIONAL SLIDES

KAMLAND-ZEN 400,800⟶KAMLAND2-ZEN

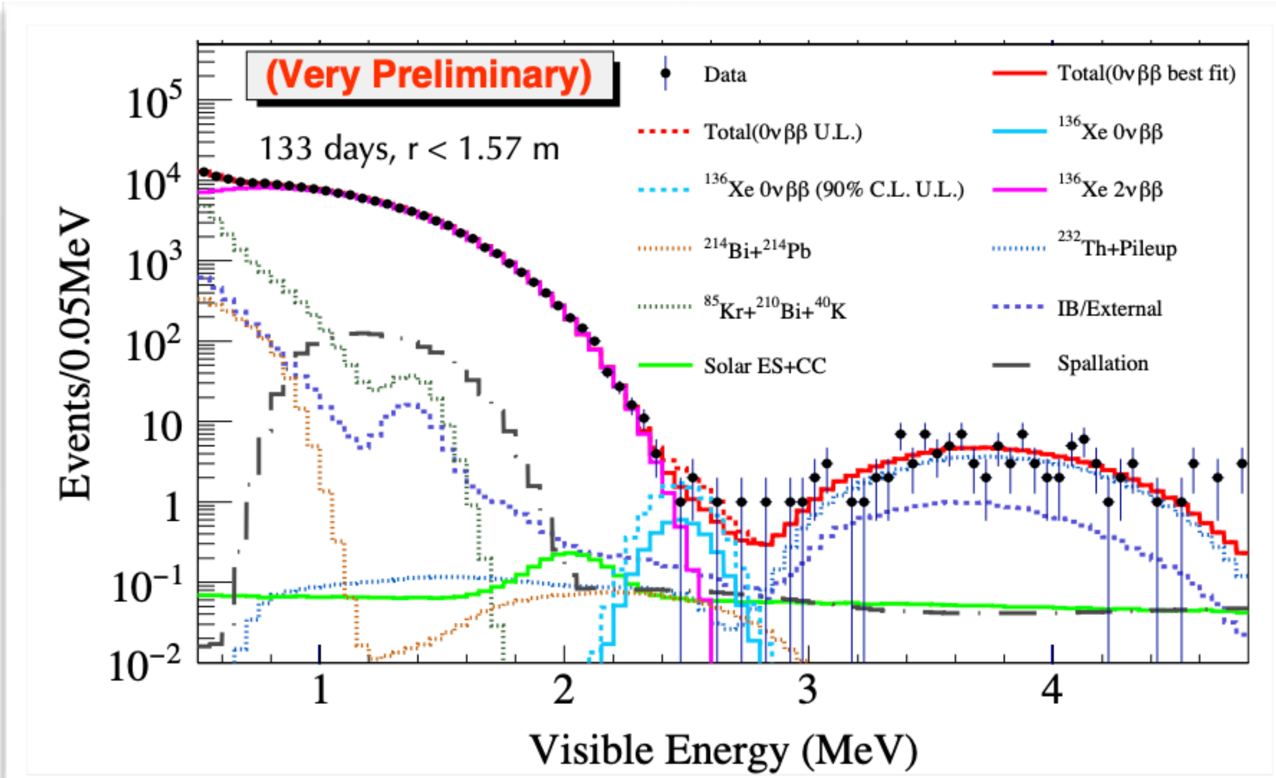
- KamLAND-Zen 400 (Kamioka- Japan): data taking completed
- Results: $T_{1/2} > 1.07 \times 10^{26}$y $m_{\beta\beta} < 45 - 160$ meV



- KamLAND-Zen 800: Similar to KamLAND-400
- Major new points:
  - More isotope - 750 Kg ^{136}Xe
  - New balloon
- Data taking commenced Jan 22. Initial BG dominated by 2νββ. No sign of ^{110m}Ag.
- TAUP 19 results (133 days):

  $T_{1/2}(^{136}Xe) > 4 \times 10^{25}$ yr

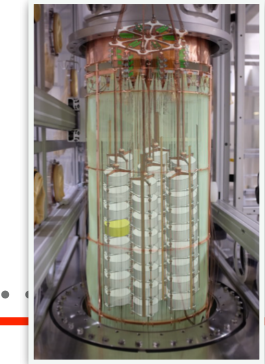
  Limit sensitivity ~8×10^{25} yr



- Projected 5-year limit sensitivity >3×10^{26} yr. Expect to reach ~5×10^{26} yr with improved BG rejection

- Future upgrade: KamLAND2-Zen with refurbished detector

GERDA PHASE II



Phase I (Nov 2011- May 2013):

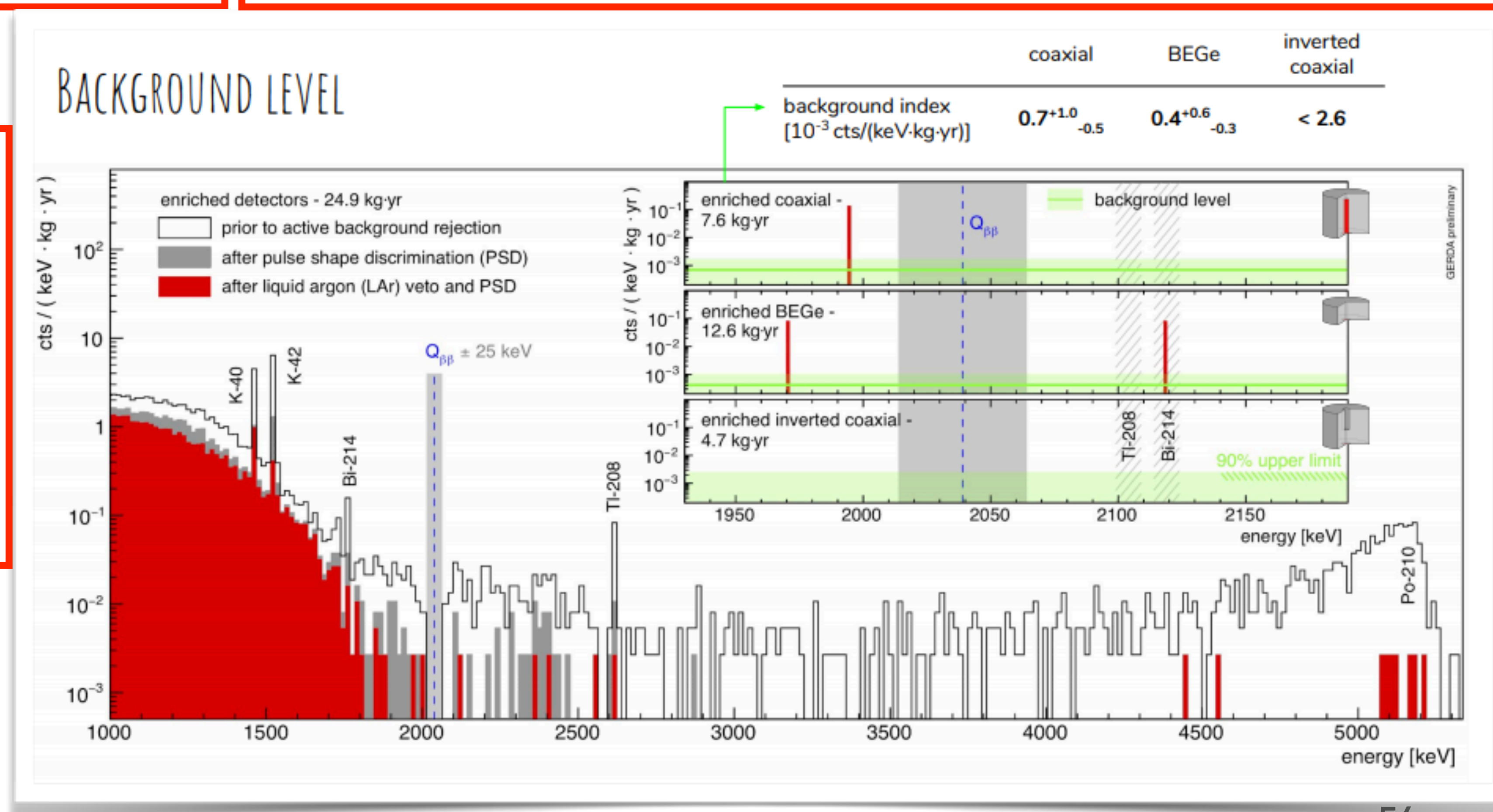
- 18 kg refurbished HdM and IGEX + new BEGes
- BG ≈ 30 cts/(FWHM t yr)
- No LAr readout (passive shield)

Phase II (Dec 2015 - ongoing):

- Add new 87% ^{enr}BEGe detectors (20 kg)
- LAr active shield: BG ~3 cts/(FWHM t yr)
- Upgrade: new ICPC's + improved LAr readout

Latest Combined Result:

- Exposure: 82.4 kg yr
- $T_{1/2}(^{76}Ge) > 0.9 \times 10^{26}$ yr
- Limit sensitivity: 1.1 x 10^{26} yr



LEGEND

GERDA

Exposure: 59 kg × y
Background index: $0.6^{+0.4}_{-0.3}$ c/(keV ton y)
$T_{1/2} > 0.9 \times 10^{26}$ y
$m_{\beta\beta} < 110 - 260$ meV

MAJORANA demonstrator

Exposure:26 kg × y
Background: 11.9±2 c/(FWHM ton y)
$T_{1/2} > 2.7 \times 10^{25}$ y
$m_{\beta\beta} < 210 - 440$ meV

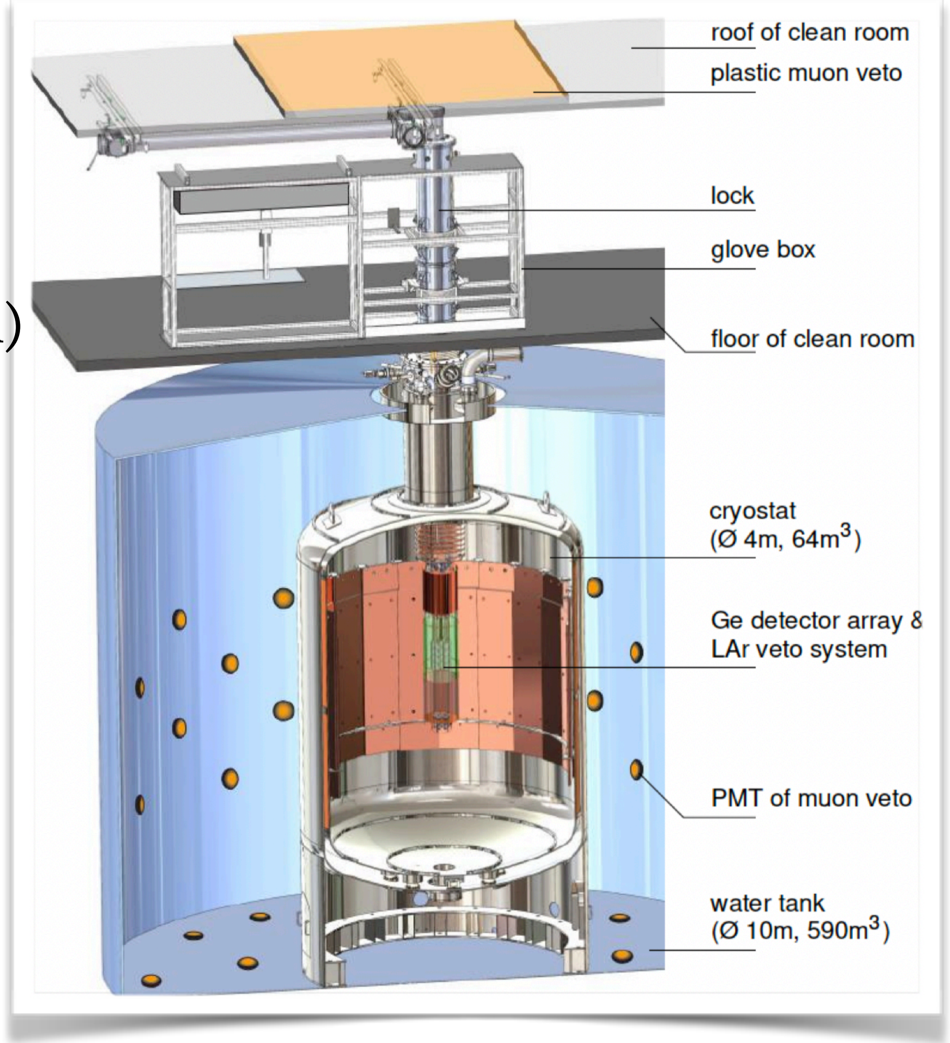
Combining the best of GERDA and MAJORANA

LEGEND-200 (LNGS)

- Initial phase
- ~ 200 kg in upgraded existing GERDA infrastructure
- Background goal: 0.6 counts/FWHM t yr (3x lower than GERDA)
- Data-taking could start as early as 2021
- Sensitivity: > 10^{27} y for 1 tonne × y $m_{\beta\beta} < 35 - 75$ meV

LEGEND-1000

- Ultimate goal
- 1000 kg (phased) required to cover neutrino-mass IO
- Timeline connected to US DOE down-select process
- Background goal: 0.1 counts/FWHM-t-yr
- Location TBD



^{130}Te, ^{100}Mo

CUORE → CUPID

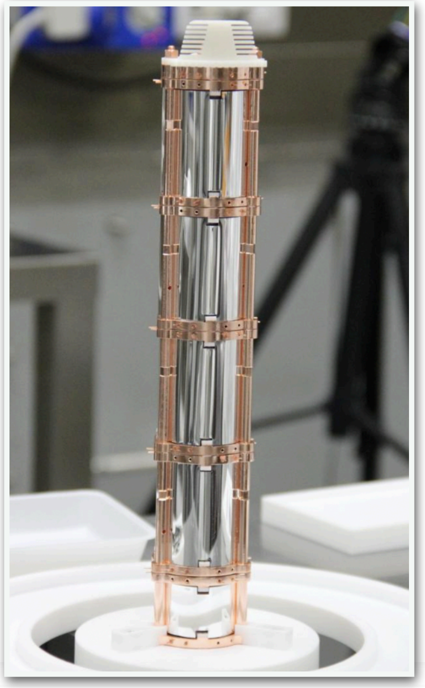
CUORE (LNGS) is collecting data successfully

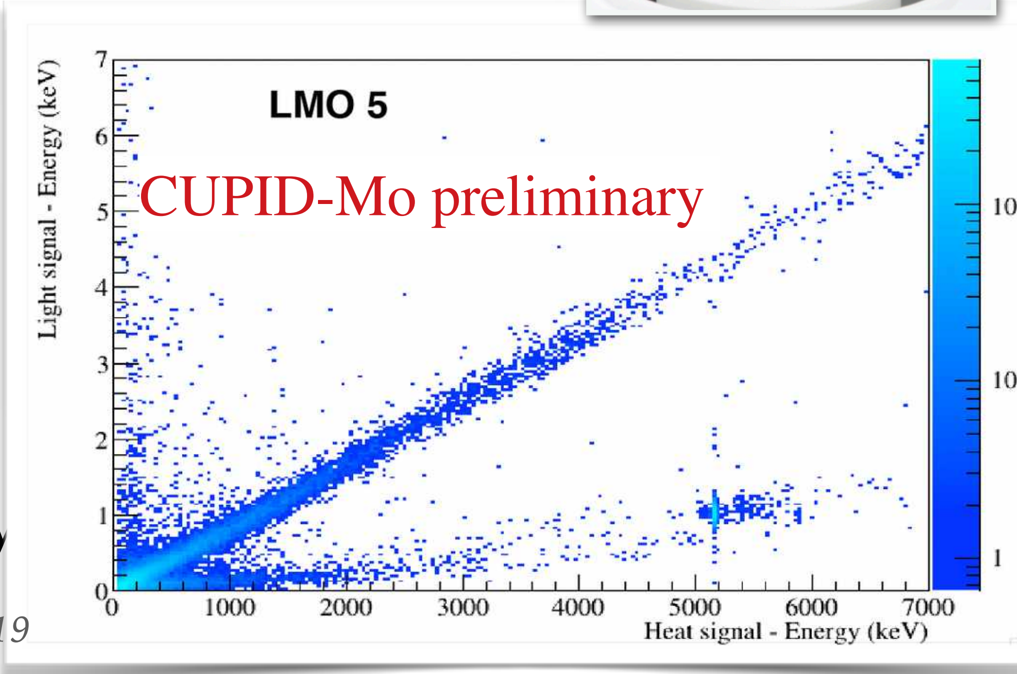
- 5 y projected half-life sensitivity: ~10^{26} y $m_{\beta\beta} < 50 – 190$ meV
  - Background according to expectations: $1.4 \pm 0.2 \times 10^{-2}$ c/(keV·kg·yr)
  - Energy resolution close to expectations
- Analysis of ~1000 individual bolometers is feasible

CUPID

- New detector technology: luminescent bolometers → R&D and demonstrators
- Full CUORE background model + information from demonstrators
- CUPID-0 ZnSn crystals and CUPID-Mo Li_2MoO_4 crystals operated
- Excellent α rejection achieved (>99.9%)
- Discovery sensitivity for 10 years livetime: $T_{1/2} \sim 10^{27}$ y

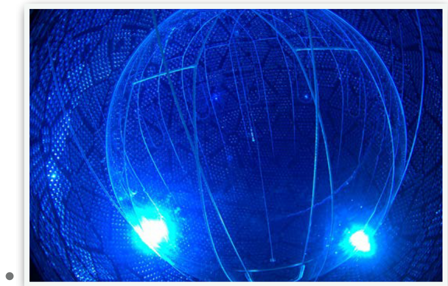
CUPID-0





Pavan, schmidt, Casali, TAUP19

SNO+



Reuse existing infrastructure of SNO – Canada

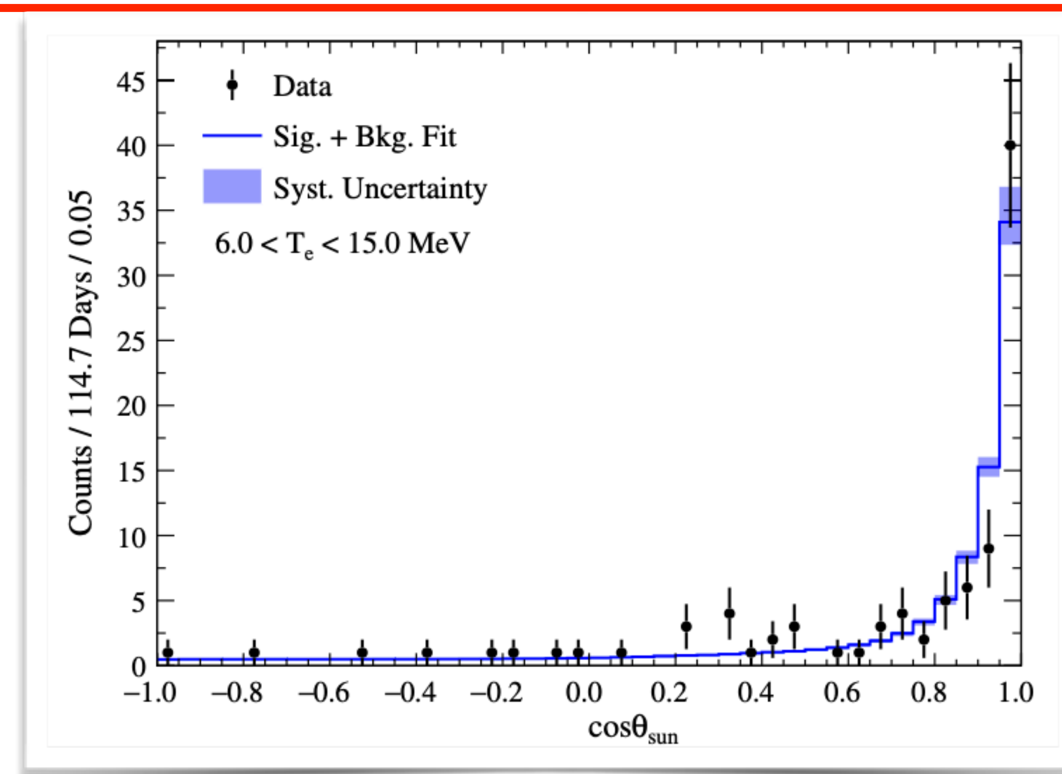
SNO+ phase I

- SNO acrylic vessel filled with LAB loaded with 800 kg ^{130}Te
- 5 y sensitivity: $T_{1/2} > 1.9\times10^{26}$ y $m_{bb} < 35 – 140$ meV
- Ran with water May 2017 - Fall 2018
  - BG ~free ^{8}B solar ν: PRD **99**, 012012 (2019)
  - Nucleon decay search: PRD **99**, 032008 (2019)
- Now filling LS
  - Internal BG measurement, CNO ν, antineutrinos
- ^{130}Te loading in 2020

Possible SNO+ phase II (ongoing R&D)

- Increase Te concentration (it does not affect background)
- Increase light yield
- Improve transparency
- Improve light detectors

Further evolution of this technology with new concepts: THEIA project



SOLAR NEUTRINOS

- Over the last few decades of the pioneering experiments, the solar neutrino deficit has been determined to be due to oscillations
- The last decade was dominated by the long-time running Super-K experiment and Borexino.
- Special highlights are the real time measurement of the dominant ppcylce and the whole pp-chain neutrinos by Borexino
- Super-K has seen the day night effect by almost 3 sigma
- Future very large scale detectors in a parasitic way could add more solar measurements in the future.
- The ultimate measurement will be the detection of CNO neutrinos and Borexino is in favourite position

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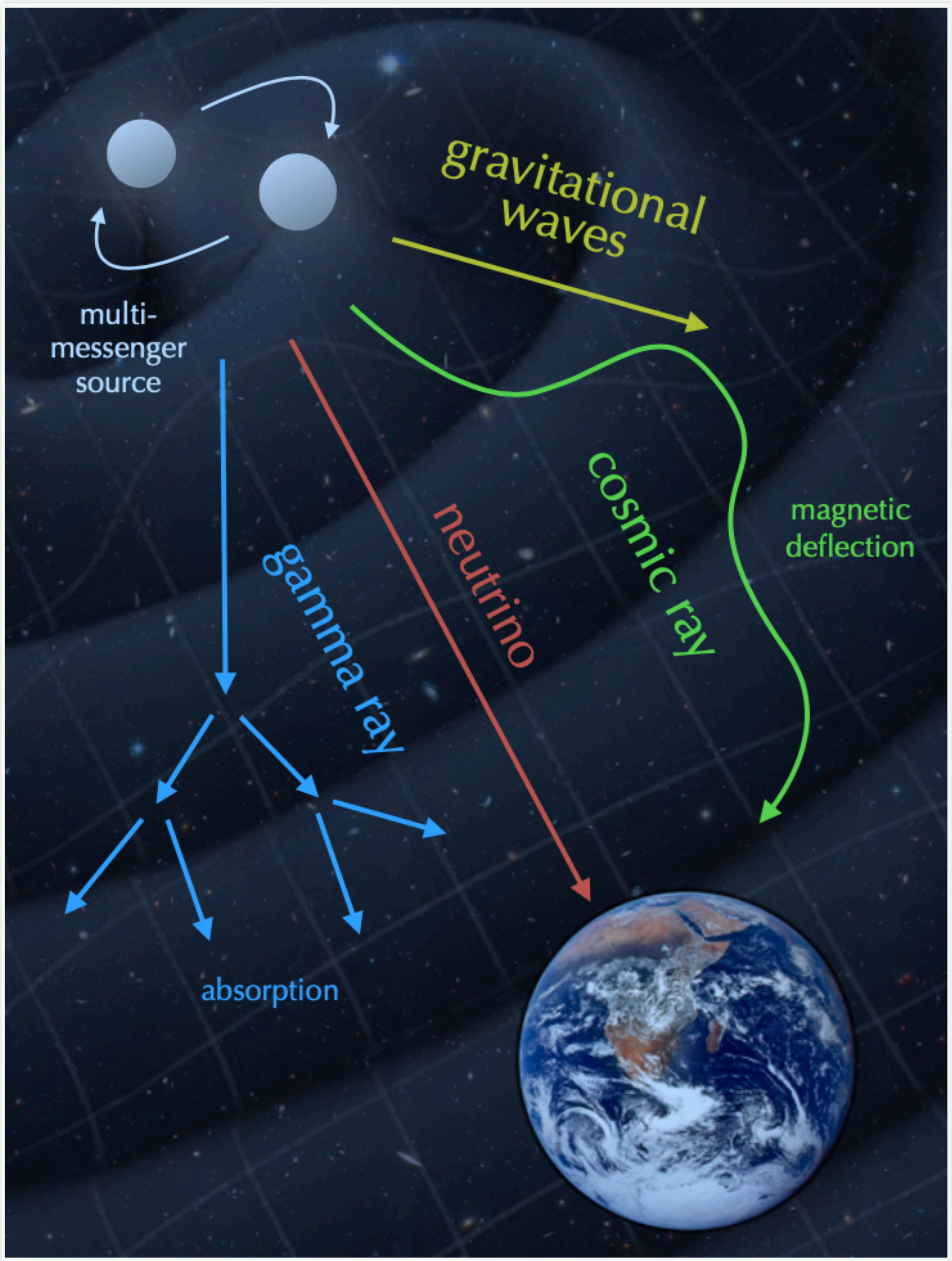
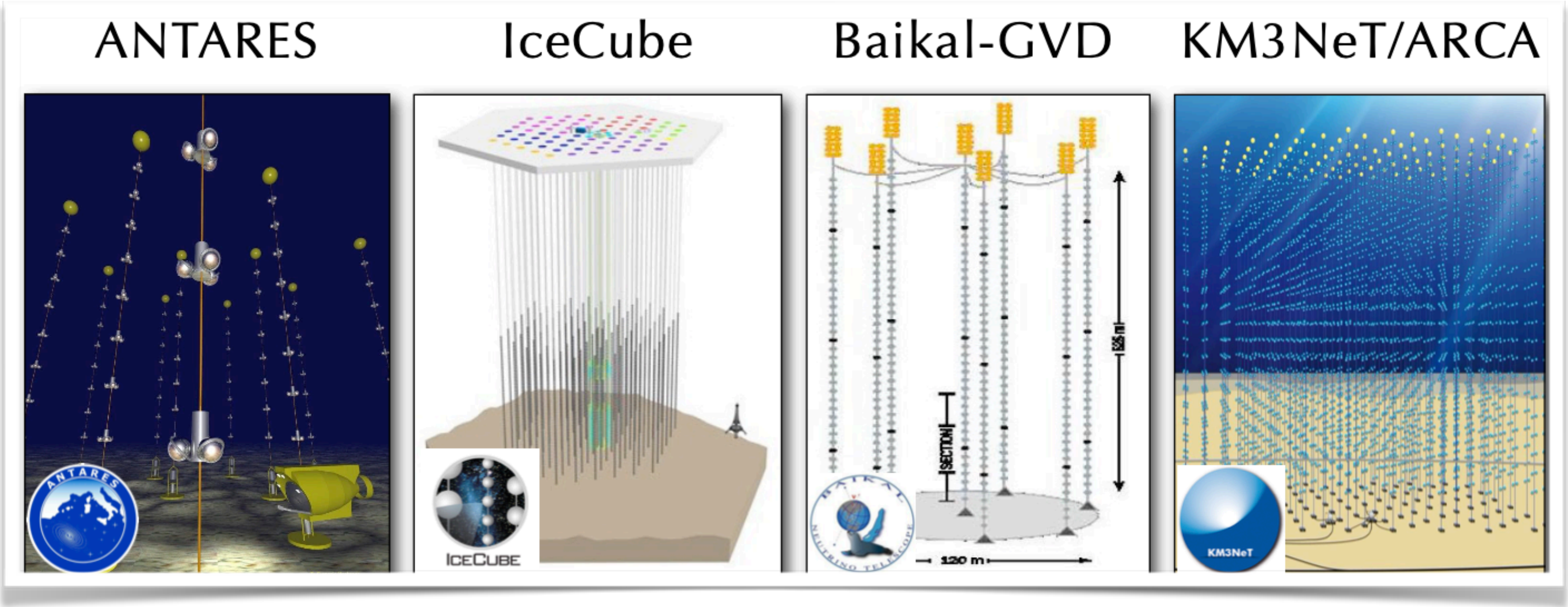
MULTIMESSANGER ASTRONOMY



- Unique abilities of **cosmic neutrinos**: **no deflection** in magnetic fields (unlike cosmic rays)
- **no absorption** in cosmic backgrounds (unlike gamma-rays)
- **smoking-gun** of unknown sources of cosmic rays
- **coincident** with photons and gravitational waves

...but difficult to detect...

CHERENKOV OBSERVATORIES



Mediterranean	South Pole	Lake Baikal	Mediterranean
2008–2020	fully instrumented since 2011	under construction (5 out of 8 clusters)	under construction (3 out of 230 DUs)
~0.01 km^3	~1 km^3	~0.4 km^3 (Phase 1) ~1 km^3	~0.1 km^3 (Phase 1) ~1 km^3
885 OMs (10″)	5160 OMs (10″)	2304 OMs (10″)	4140 OMs (31x3″)

- Real time multi-messenger campaigns involving photons, gravitational waves and neutrinos are becoming routine.
- With next-generation telescopes we will go from discovery to astronomy.