Neutrino Physics Status 2020: looking back to Neutrino 2020

João Pedro Athayde Marcondes de André

IPHC, Strasbourg

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Disclaimer: This comes from a personal selection, I can't possibly cover everything

Outlook

- Introduction
- Neutrino Mass
- Neutrino Interactions & Detectors
- Standard Neutrino Oscillations
- Light Sterile Neutrinos
- Using Neutrinos to look at the universe

The conferences

- As with all conferences this summer, they were virtual
- Large differences however on their organizations/interactions however

Neutrino 2020 (22/06 – 02/07)

- plenary + VR posters
- no replays
- 800 $\rightarrow$ 4k participants
- lots of interaction over slack
- moderators asked questions

image from CERN Courier website

ICHEP 2020 (28/07 – 06/08)

- plenary + parallel + ‘short talk’ posters
- scheduled replays
- 3k participants
- mattermost not very active
- questions ‘mode’ depended on track

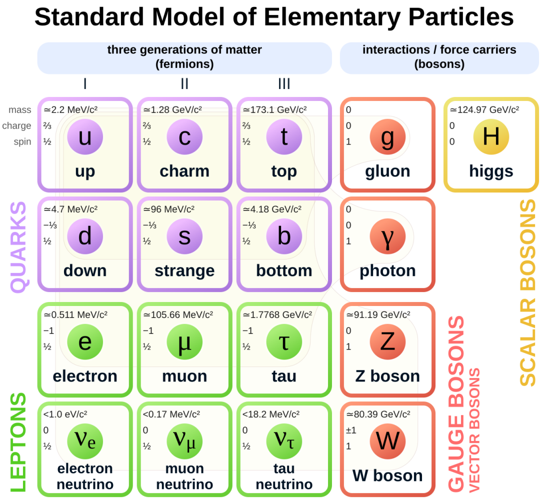
- ICHEP slides in red boxes,
  Neutrino slides in black boxes
  - Boxes have links to indico
  - For Neutrino talks: video or slides
  - For ICHEP talks: only slides

The Standard Model and Neutrinos

ν properties:

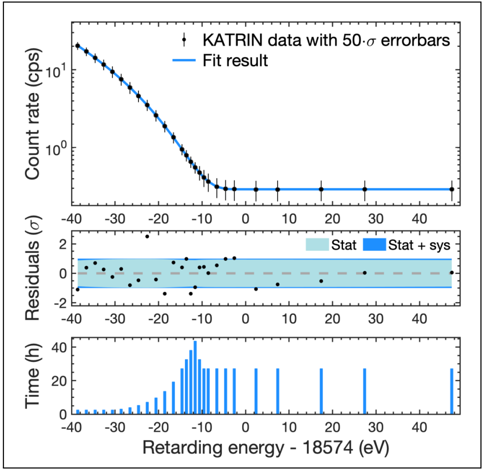
- charge = 0
- spin = 1/2
- only interact weakly
  - in SM: ν_L, but no ν_R
- mass = 0 in SM
  - From oscillations, $m_\nu > 0$
  - $m_\nu \ll m_{u,d,e}$
- 3 families:

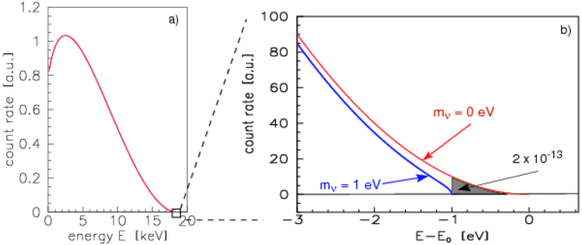
flavor: ν_e, ν_μ, ν_τ
mass: ν_1, ν_2, ν_3

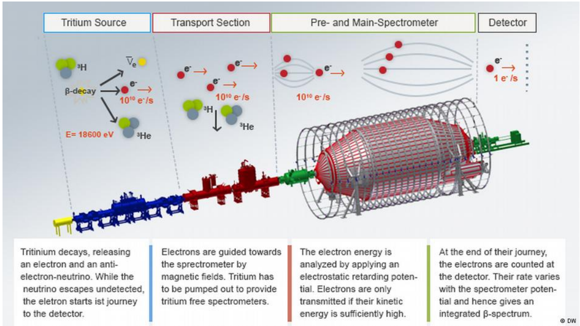


Absolute Neutrino Mass: Direct Measurement – KATRIN

- $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$
  - Measure e^- energy close to end-point

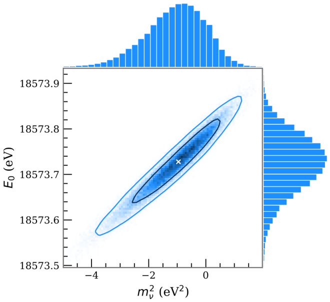






Absolute Neutrino Mass: Direct Measurement – KATRIN

Final fit result



Best fit results:

$m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ eV²

→ compatible with zero

→ probability of 16%, if true m_ν = 0 eV

$E_0 = 18573.7 \pm 0.1$ eV

→ Q-value : 18575.2 ± 0.5 eV

→ good agreement with literature (Q = 18575.72 ± 0.07 eV)

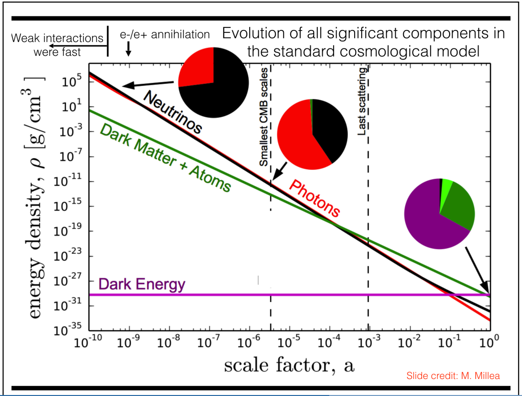
E. Myers et al. Phys. Rev. Lett. 114, 013003 (2015)

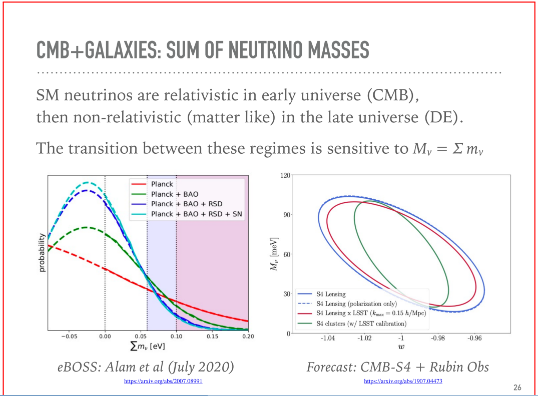
Susanne Mertens

- $m_{\nu_e} < 1.1$ eV (90% CL) – run 1 (stats limited)
- 2× more events to be unblinded soon; started run 3 with improved detector

Absolute Neutrino Mass: Cosmology limits

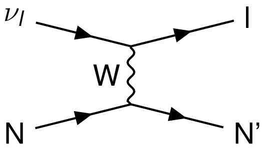
- ν play a role in structure formation in the universe
  - some model dependency in results
    - or we are really getting cosmology wrong. . . and getting good fits while at it
  - Measures $\sum m_\nu$ and N_ν^{eff}
- Current limits: $\sum m_\nu <$ 100 – 252 meV [arXiv:2007.08991]





Detecting neutrinos

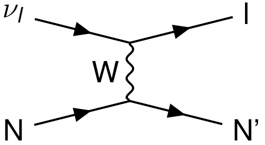
- We cannot detect the ν 'flow' $\rightarrow$ detect only neutrinos that interact



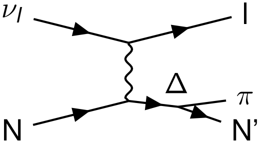
- What we can (potentially) measure:
  - charge of lepton $\rightarrow$ ν vs $\bar{\nu}$
  - flavor of lepton $\rightarrow$ distinguish between ν_e, ν_μ, ν_τ
  - direction of l or l+N' $\rightarrow$ neutrino direction
  - momentum of l or l+N' $\rightarrow$ energy of neutrino
  - position of interaction

Neutrino Charged Current Interaction with matter

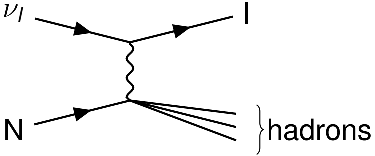
Quasi-Elastic (QE)

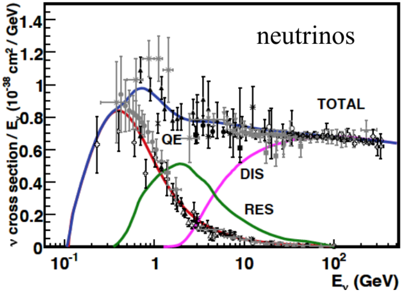


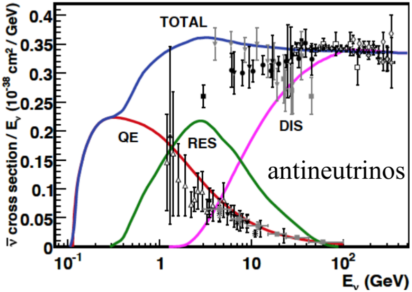
Resonant (RES)



Deep Inelastic (DIS)





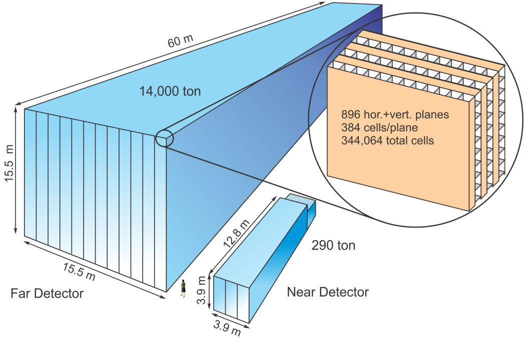


- data from ν_μ CC cross section (per nucleon)
- low interaction probability $\rightarrow$ large target mass and neutrino flux

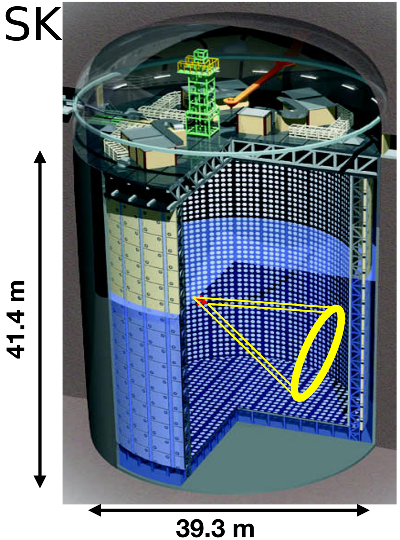
Neutrino Detectors – examples

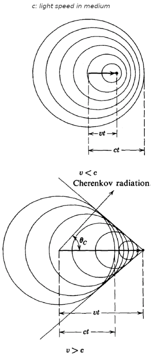
non exaustive list of types. . .

NOνA



SK

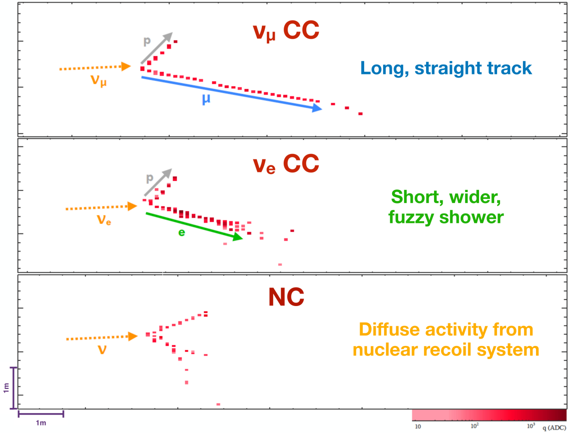


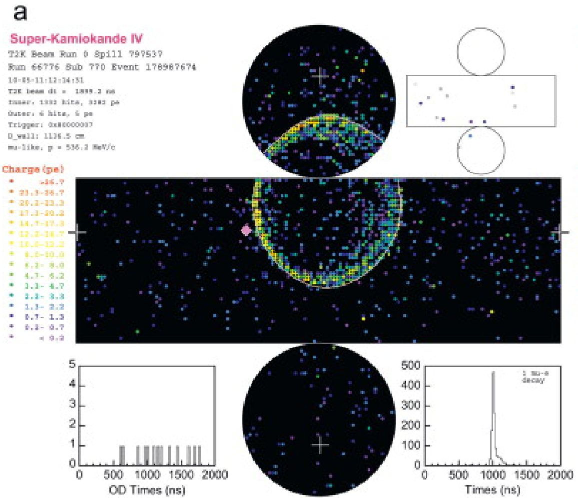


Neutrino Detectors – examples

non exaustive list of types. . .

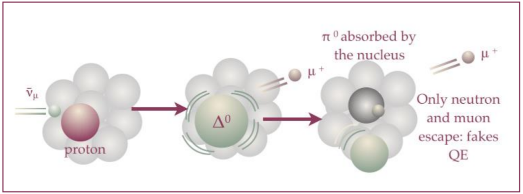
NOνA





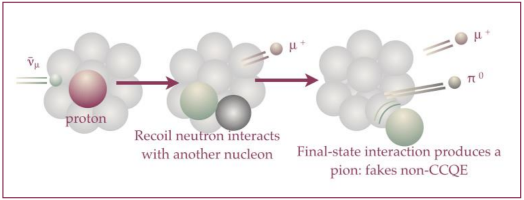
However interactions don't happen on free nuclei. . .

Oregon State



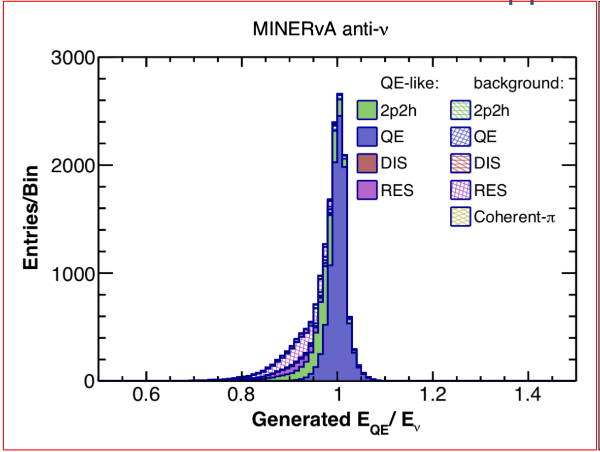
Initial interaction is not CCQE
But the observed event looks like it

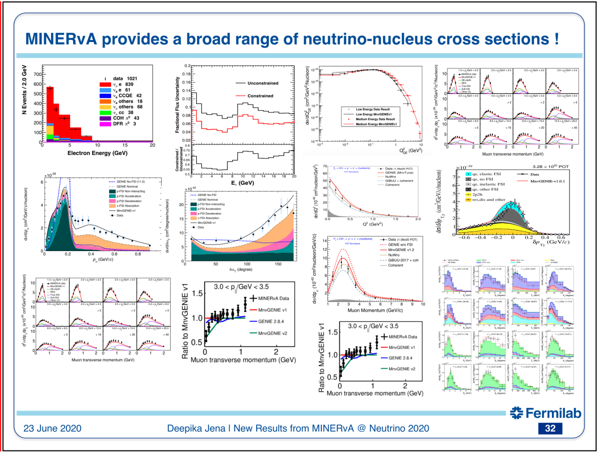
Misidentification



Initial interaction is CCQE but the observed event is not!

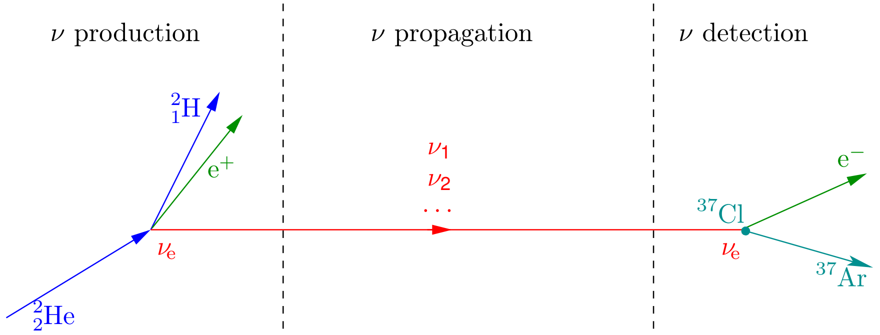
However interactions don't happen on free nuclei. . .





- Extensive work from many collaborations to measure cross-section & tune models
  - A few experiments *dedicated* to this purpose!
- Different atoms, energies, . . .
- Still remains an important systematic to be taken into account!

Neutrino Oscillation (in vacuum) – overview



$|\nu_e\rangle = \sum_j U^*_{ej}\,|\nu_j\rangle$ $\quad$ $|\nu_j\rangle \to e^{-iE_j t}\,|\nu_j\rangle$ $\quad$ $|\nu_j\rangle = \sum_\alpha U_{\alpha j}\,|\nu_\alpha\rangle$

$$P(\nu_e \to \nu_e, t) = ||\langle\nu_e|\nu_e, t\rangle||^2$$

- For oscillations to happen $\{|\nu_\alpha\rangle\}$ and $\{|\nu_j\rangle\}$ different

Neutrino Oscillations – simplest case

2 flavor case, vacuum

- 2 ν interaction flavours (ν_e and ν_μ)
- mass eigenstates $\{|\nu_j\rangle\} = \{|\nu_1\rangle, |\nu_2\rangle\} \neq \{|\nu_\alpha\rangle\}$ flavour eigenstates
- mixing matrix U: $|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$ with $UU^\dagger = \mathbb{1}$ (ie, U rotation matrix)

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- Propagate through space time as plane waves in mass state:

$$|\nu_e, t\rangle = \sum_j U^*_{ej} e^{-iE_j t} |\nu_j\rangle = \cos\theta e^{-iE_1 t} |\nu_1\rangle + \sin\theta e^{-iE_2 t} |\nu_2\rangle$$

- $P(\nu_e \to \nu_e, t) = ||\langle\nu_e|\nu_e, t\rangle||^2 = 1 - \sin^2(2\theta)\sin^2[(E_2 - E_1)t/2]$
- Given m_i small: $E_i = \sqrt{m_i^2 + p^2} \approx p + \frac{1}{2}\frac{m_i^2}{p}$ and $t \approx L$, therefore $(E_2 - E_1)t \approx \frac{1}{2}\frac{m_2^2 - m_1^2}{p} L \approx \frac{\Delta m^2 L}{2E}$

$\Rightarrow$ $P(\nu_e \to \nu_e, L) = 1 - \sin^2(2\theta)\sin^2\left(\Delta m^2 \frac{L}{4E}\right)$

Neutrino Oscillations

3 flavor case, vacuum

$$P(\nu_\alpha \to \nu_\beta) = \sum_{j,k} U_{\beta j} U^*_{\alpha j} U^*_{\beta k} U_{\alpha k} e^{-i\Delta m^2_{jk} \frac{L}{2p}}, \qquad \Delta m^2_{jk} = m^2_j - m^2_k$$

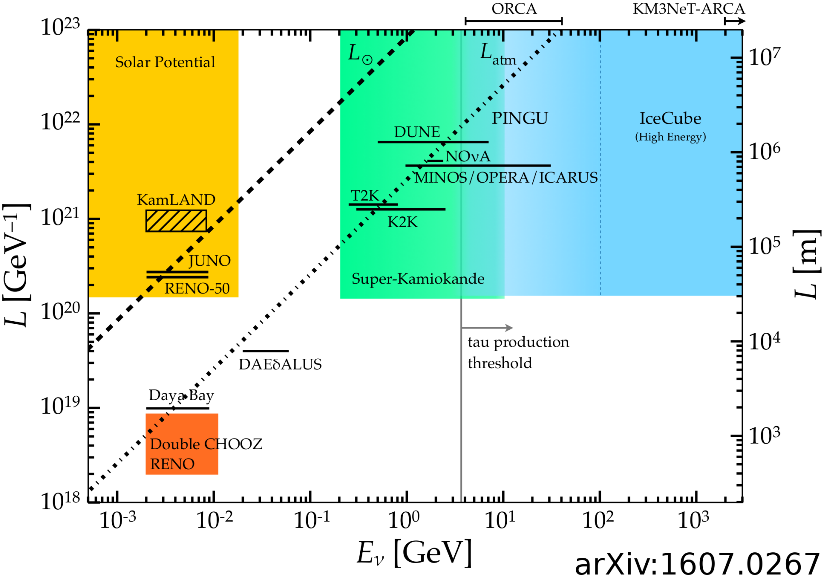
- 3 known ν interaction flavours : ν_e, ν_μ and ν_τ $\Rightarrow$ matrix U is 3×3

$$U = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{“atmospheric sector”}} \times \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}^{\text{“reactor sector”}} \times \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{“solar sector”}}$$

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

- θ_{23}, θ_{13}, θ_{12}: ν mixing angles
- Δm^2_{32}, Δm^2_{21}: ν mass splitting
  - Note: $\Delta m^2_{31} = m^2_3 - m^2_1 = \Delta m^2_{32} + \Delta m^2_{21}$
- δ_{CP}: leptonic CP violation phase $\to$ different oscillations for ν and $\bar{\nu}$

Neutrino Oscillations: Experimental Overview



arXiv:1607.02671

Neutrino Oscillations Matter Effects

- In vaccum Hamiltonian H_0 is

$$H_0 = \frac{1}{2E} U \,\text{diag}(m_1^2, m_2^2, m_3^2)\, U^\dagger$$

- In matter, Hamiltonian $H_m = H_0 + H_{int}$, with H_{int} describing interaction ν – matter
  - ν – u and ν – d not interesting as $H^u_{int} \propto \mathbb{1}$ and $H^d_{int} \propto \mathbb{1}$
  - ν – e interesting: $H^e_{int} = \text{diag}(V^W, 0, 0) + V^Z \mathbb{1}$, with $V^W = \pm\sqrt{2} G_F N_e$
    - ★ N_e: electron density in medium
    - ★ $+$ sign for ν and $-$ sign for $\bar{\nu}$

- For 2-flavor osc.: $\theta \to \theta_m$ related to matter mass-eigenstates $|\nu_i^m\rangle$

$$\tan 2\theta_m = \frac{\tan 2\theta}{1 \mp N_e/N_e^r}\,;\ \Delta m_m^2 = \Delta m^2 \cos 2\theta \sqrt{\left(1 \mp \frac{N_e}{N_e^r}\right)^2 + \tan^2 2\theta}\,;\ N_e^r = \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2} G_F}$$

- Resonance condition for specific densities if ν and $\Delta m^2 > 0$ (or $\bar{\nu}$ and $\Delta m^2 < 0$)
- Large matter effects in Solar (Δm^2_{21}) & Atmospheric (Δm^2_{32}) ν
- As δ_{CP}, produce $\nu - \bar{\nu}$ asymmetry (size of effect depends on L)

Experimental data (pre-Neutrino2020)

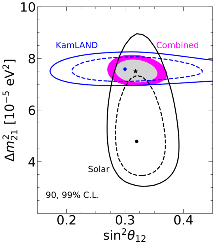
de Salas et al, arXiv:2006.11237

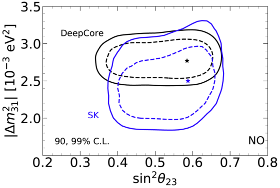
solar sector

Cl, Ga, SK

SNO, Borexino

KamLAND





atmospheric results

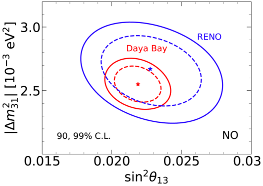
Super-K

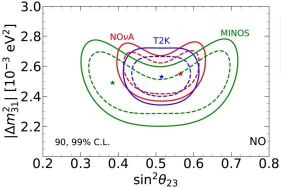
IC-DeepCore

SBL reactors

Daya Bay

RENO





LBL experiments

MINOS

T2K

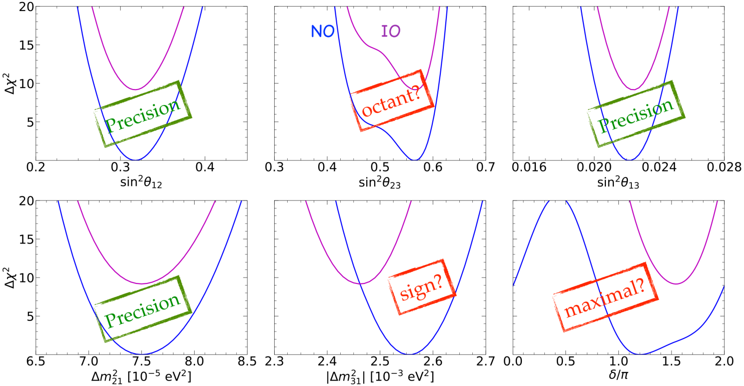
NOvA

de Salas et al, arXiv:2006.11237

parameter	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\text{eV}^2]$	2.7%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	1.2%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	
$\sin^2\theta_{12}$ $/10^{-1}$	5.2%
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	4.9%
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	4.8%
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	3.0%
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	
δ/π (NO)	17%
δ/π (IO)	8%

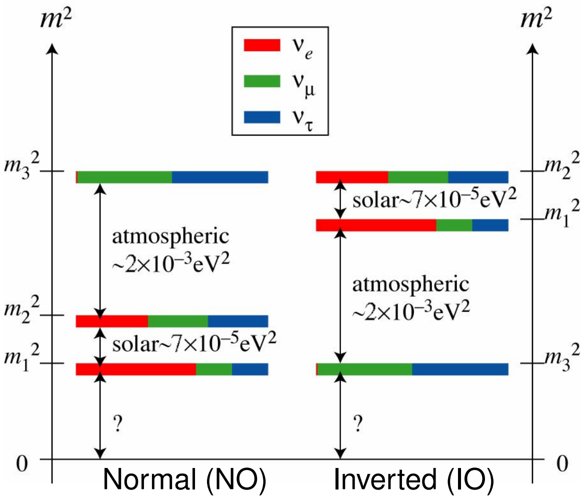
Global fit to ν oscillation parameters

de Salas et al, arXiv:2006.11237



Neutrino Mass Ordering

- Sign of Δm^2_{21} determined thanks to matter effects in sun
- Sign of Δm^2_{32} yet unknown
- This means ν_1 (mostly ν_e) might not be lightest ν!
  - 'Inverted' ordering $\rightarrow$ IO
- NB: You might see 'hierarchy' rather than 'ordering' (NO$\rightarrow$NH; IO$\rightarrow$IH)



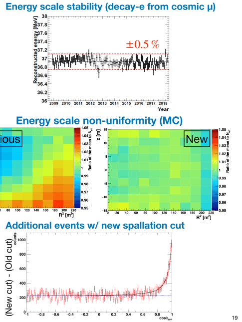
Updates to solar neutrinos from SK

Analysis Improvements

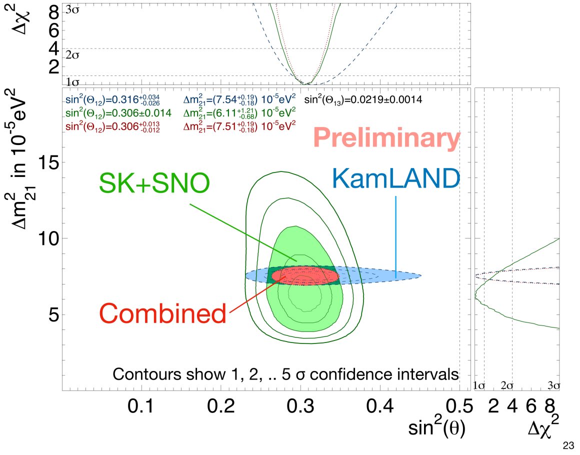
- Detector simulation improvements [Poster #350: Y. Nakano]
  - Improved PMT hit timing simulation
  - Improved modeling of water quality non-uniformity
- Analysis improvements [Poster #350: Y. Nakano]
  - Correction for PMT gain drift (introduced in 2017)
  - Improved correction for non-uniform energy response

    E-scale non-uniformity (MC) 1.7% → 0.5%
- Improved spallation cut [Poster #166: S. Locke]
  - 12% more signal efficiency while keeping spallation rejection efficiency at a similar level (~90%)

    Gained ~1 year worth statistics

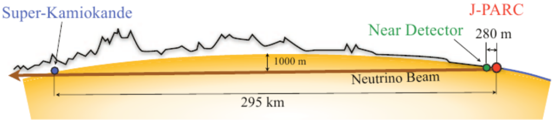


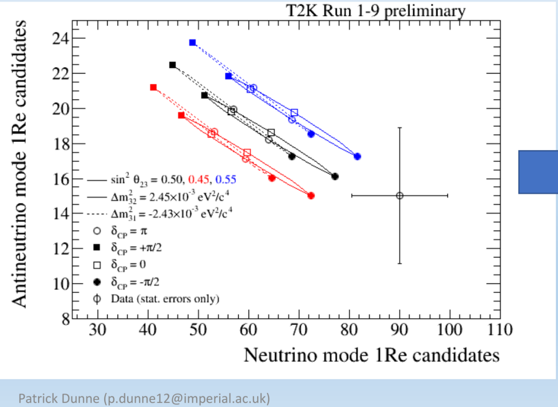
SK+SNO fit disfavors the KamLAND best fit value at ~1.4σ (was ~2σ)

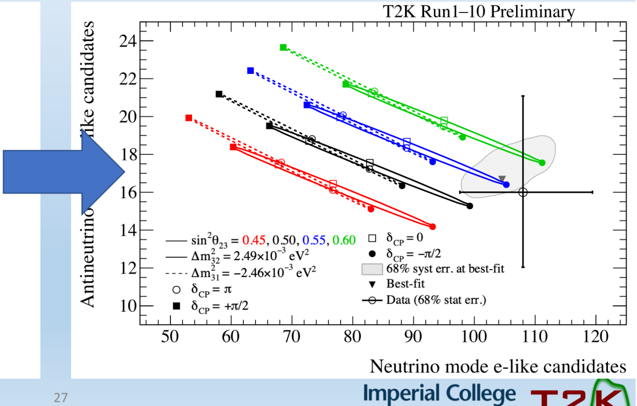


Updates to T2K results

T2K

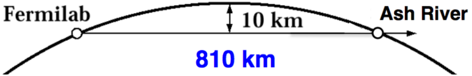






Updates to NOνA results

NOvA



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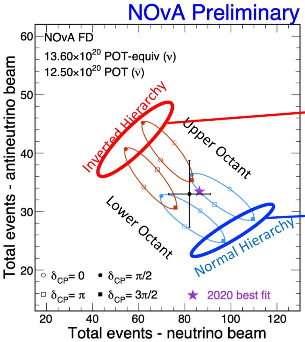
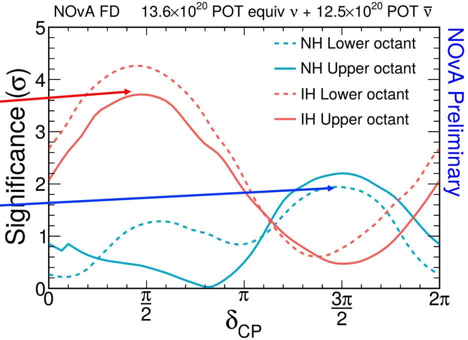
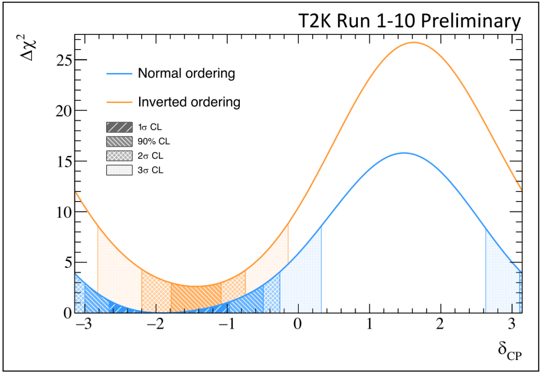
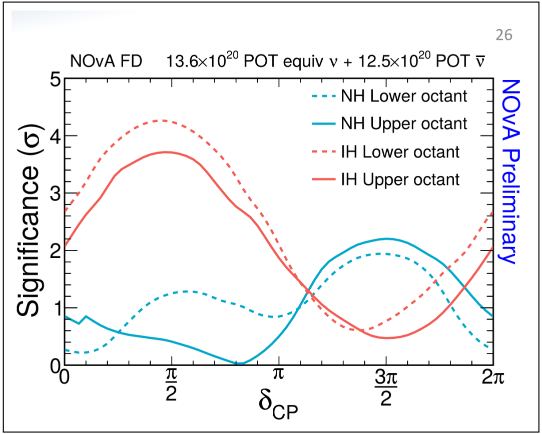




- We see no strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$
- Disfavor hierarchy-δ combinations which would produce that asymmetry

T2K vs NOνA



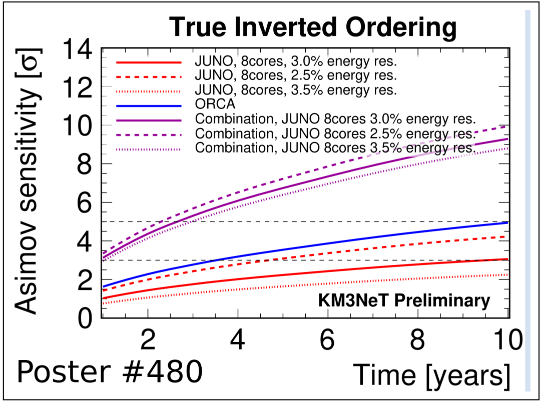


- T2K sees large $\nu_\mu \to \nu_e$ vs $\bar{\nu}_\mu \to \bar{\nu}_e$ asymmetry, NOνA doesn't
- However, to complicate things: different baselines $\Rightarrow$ different matter effects
- Better agreement between exps for IO, but both prefer NO themselves...
- T2K and NOνA working on joint analysis
- T2K and NOνA are still running... (with improvements to come)

Future Neutrino Oscillations Experiments

Determine the ordering

- JUNO: reactor neutrinos
- ORCA: atmospheric neutrinos



Determine δ_{CP}

- HK and DUNE: accelerator neutrinos

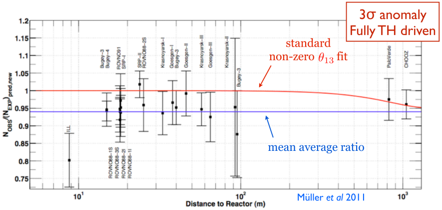
- Further on the future ESSνSB, THEIA, T2HK, . . .

Light Sterile Neutrinos

- LSND
- Reactor

A recalculation of fluxes lead to ~ 6% discrepancy with 2% error bars

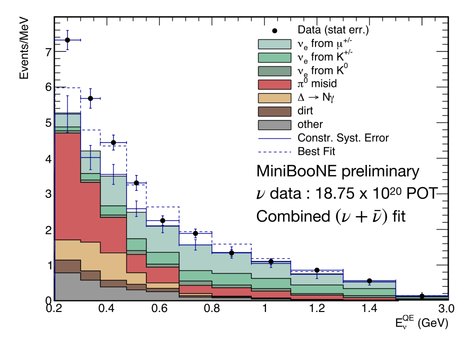
Müller *et al* 2011, Huber 2011



But others say that the error bar should be more like 5%

Hayes et al 2013

- MiniBooNE



- Gallium

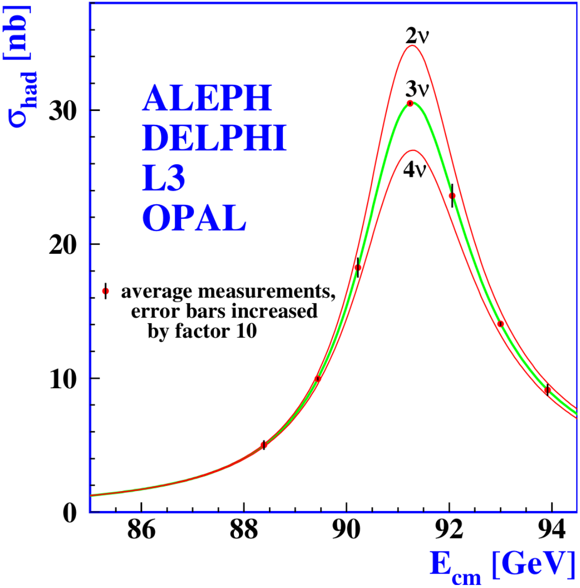
Reactor and Gallium anomalies may be theory problem
(though there may be wiggles…)

LSND and MiniBooNE anomalies: same L/E, no obvious culprits, difficult to imagine correlated background

All four anomalies come from **very** different experiments

Why 'sterile' neutrinos?

- LEP measured width of Z^0 boson
  - only 3 ν with $m_\nu < 45$ GeV
  - from SM symmetries, and small m_ν
    $\Rightarrow$ only 3 families of particles
- However, if ν_4 needed
  - it doesn't interact in the SM!
  - 'doesn't interact' $\rightarrow$ 'sterile'



Light Sterile Neutrinos – tensions

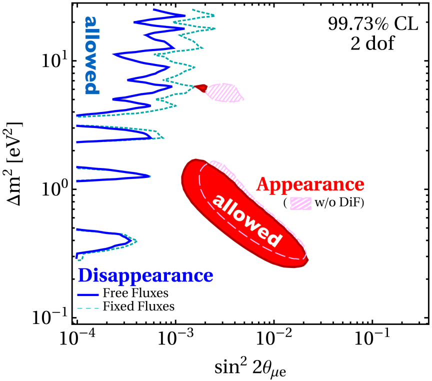
Global analysis

How well the model fits the data?

χ^2/dof ✗

goodness of fit ✓

see Maltoni Schwetz 2007



ν_μ to ν_e appearance

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}|^2|U_{\mu 4}|^2$$

ν_e disappearance ν_μ disappearance

Data sets:

ν_e and ν_μ disappearance

vs.

ν_e appearance

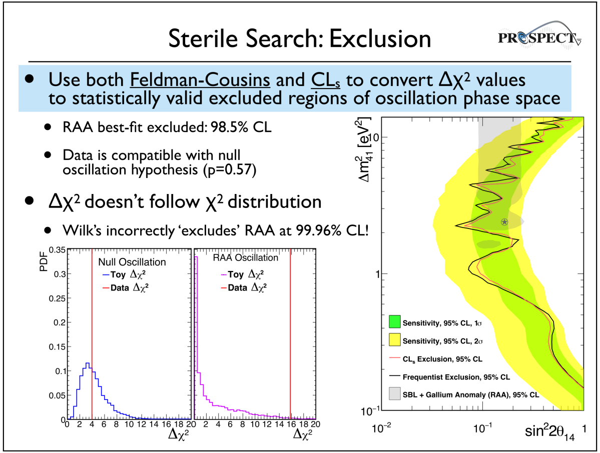
4.7 σ tension

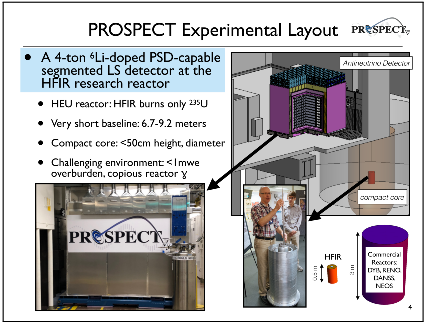
between DISAPP and APP data sets under eV sterile interpretation

Exercise: remove each experiment and see if agreement improves

Fermilab
pmachado@fnal.gov

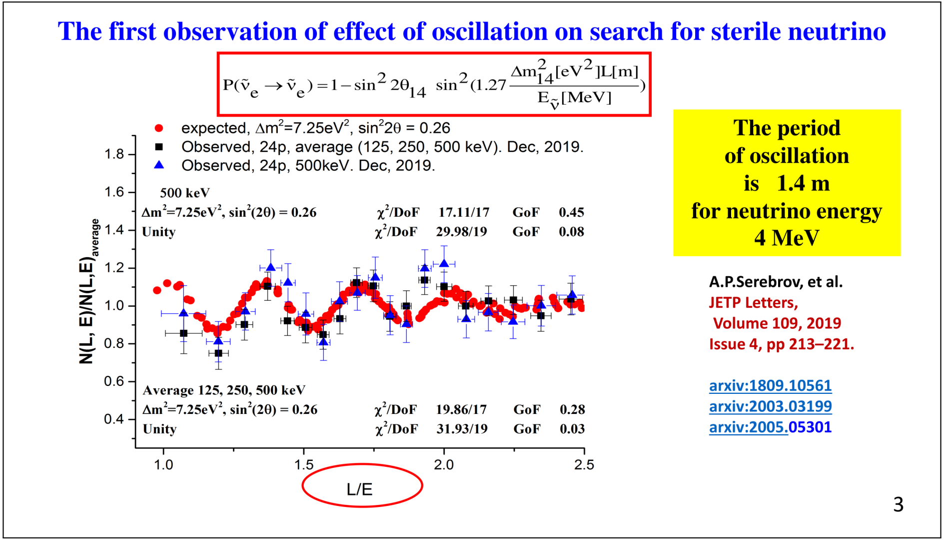
Light Sterile Neutrinos: Very Short Baseline Reactor





- PROSPECT, STEREO, DANSS exclude reactor anomaly best fit (RAA)
- Neutrino 4, rejects RAA, but claims discovery of $\Delta m^2 = 7\ \mathrm{eV}^2$ oscillation
  - assumes Wilks theorem valid. . .

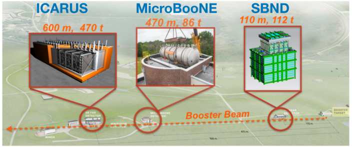
Light Sterile Neutrinos – Neutrino 4 claim



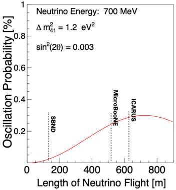
Light Sterile Neutrinos – on-going work for other anomalies

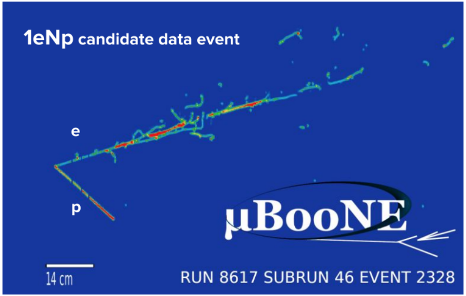
Short Baseline Program (SBN)

- LArTPC detectors at different baselines from Booster neutrino beam searching for sterile neutrino oscillations measuring both appearance and disappearance channels with three detectors



arXiv:1503.01520





- SBND: under construction
- μBooNE: taking data, unblinding soon
- ICARUS: starting commissioning

- JSNS[2] aims to test the LSND anomaly directly.
  - uses the same neutrino source (muon), target (H) and detection principle (IBD), but much smaller accidental background due to Gd-loaded LS and low duty factor J-PARC MLF beam.

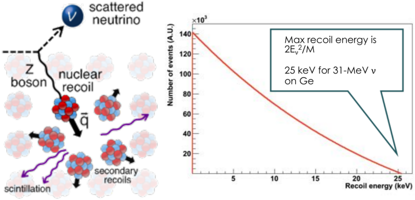
Summary

- **The BEST experiment - first direct search for neutrino oscillations into 4-th flavor with radioactive source has started 5 July 2019 in BNO INR RAS**
- **The first stage of BEST is finished and the second stage is nearing completion. Currently preparatory works have begun for the implementation of the third final one.**

Testing SM – coherent scattering

Coherent elastic neutrino-nucleus scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV



CEvNS cross section is well calculable in the Standard Model

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

CEvNS cross section is large! $\propto N^2$

- Predicted in 1974 by D. Freedman
- Interesting test of the standard model
  - Sensitive to **non-standard interactions**
  - Largest cross section in **supernovae** dynamics
  - Background for future **dark matter** experiments
  - Sensitive to nuclear physics, **neutron skin** (neutron star radius)
- "act of hubris" - D. Freedman
  - Need a low threshold detector
  - Need an intense neutrino source

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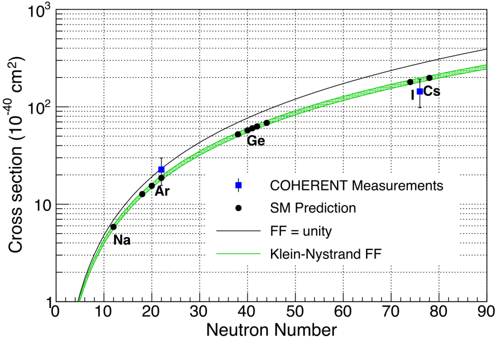
Testing SM – coherent scattering

First Confirmation of SM Prediction of N^2 Dependence



More to come …

CsI

- ✓ Twice the statistics
- ✓ Live-time correction
- ✓ New QF Measurement
- ✓ Verified Linearity of QF PMT *

LAr

- – Twice the statistics in hand and ~5σ by December 2020
- ✓ Improved Neutron Shielding
- ✓ Data release this week!

https://doi.org/10.5281/zenodo.3903810

* Alexey Konovalov 2019 M7s Presentation

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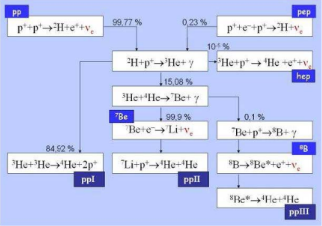
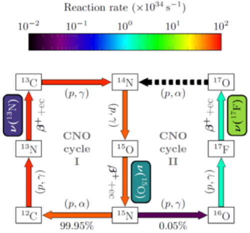
Solar Neutrinos – understanding the sun

Standard Solar Model : "engine" of the Sun, solar neutrinos production and spectrum predictions

Developed by **John Bahcall** for more than 40 years



pp chain

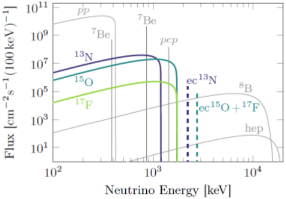


Dominant in massive stars

>99% of the energy in the Sun

the remaining <1% in the Sun ?

Latest SSM spectral prediction
A. Serenelli EPJA, volume 5, id 78 (2016)
N. Vinyoles et al. The Astrophysical Journal, 835:202 (16pp), 2017



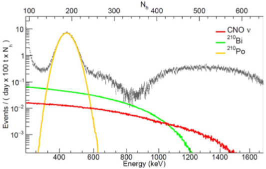
Controversy about the surface metallicity composition of the Sun: predictions differ up to 28% for the CNO ν flux using lower (LZ) or higher Z (HZ) models

2020 Jun 23

G. Ranucci - First detection of solar neutrinos from CNO cycle with Borexino

3

Quest for CNO neutrinos



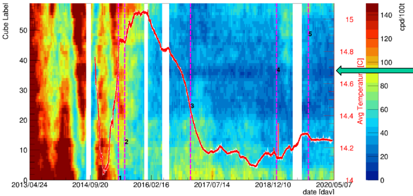
$$^{210}\mathrm{Bi} \xrightarrow[7.23\,\mathrm{d}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[199.1\,\mathrm{d}]{\alpha} {}^{206}\mathrm{Pb}$$

^{210}Po is "easier" to identify wrt ^{210}Bi:
- Monoenergetic decay → "gaussian" peak
- α decay → pulse shape discrimination

→ The quest for CNO is turned into the quest of ^{210}Bi through ^{210}Po !

Thermal insulation & Active Gradient Stabilization System

A 2D detailed view - Polonium data spatial mapping vs. time



Crucial observation: "Low Polonium Field" 20 tons size from which we can infer the intrinsic ^{210}Po and hence the ^{210}Bi - **agreement with simulations see next slide**

Convective condition before insulation

Quiet situation after insulation

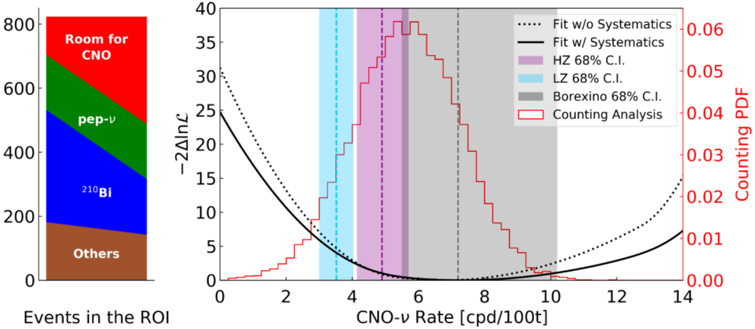
1. Beginning of the Insulation Program
2. Turning off the water recirculation system in the Water Tank
3. Start of the active temperature control system operations
4. Change of the active control set points
5. Installation and commissioning of the Hall C temperature control system.

Stabilization measures were very effective at reducing the ^{210}Po motion

2020 Jun 23 G. Ranucci - First detection of solar neutrinos from CNO cycle with Borexino 10

Solar Neutrinos – first measurement of CNO neutrinos!

Compendium of the results



The enduring Borexino quest of the CNO neutrinos has finally produced the first observation of the signal

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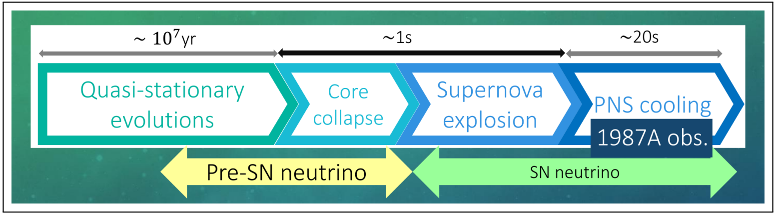
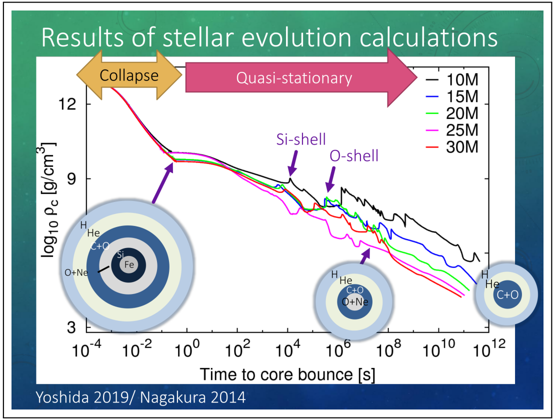
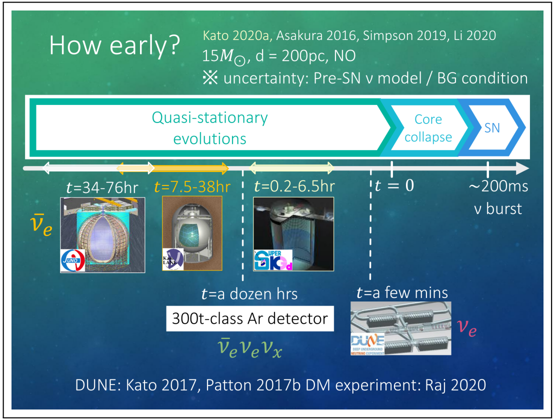
Pre-SN ν



~ 10^7yr
~1s
~20s
Quasi-stationary evolutions
Core collapse
Supernova explosion
PNS cooling
1987A obs.
Pre-SN neutrino
SN neutrino

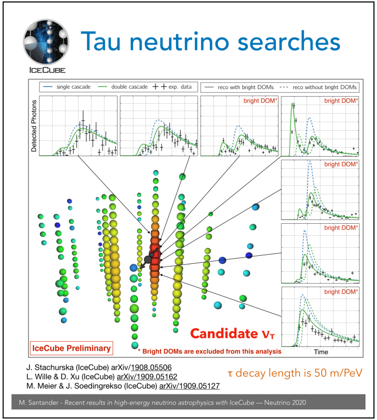


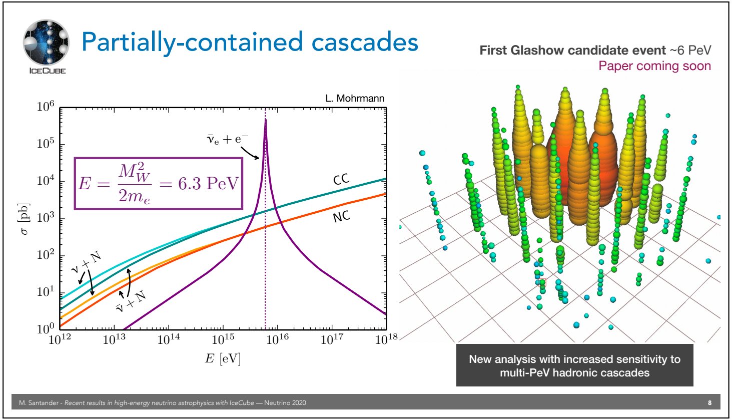
Results of stellar evolution calculations
Collapse
Quasi-stationary
10M
15M
20M
25M
30M
Si-shell
O-shell
$\log_{10} \rho_c$ [g/cm^3]
Time to core bounce [s]
H
He
C+O
Si
Fe
O+Ne
Yoshida 2019/ Nagakura 2014



How early?
Kato 2020a, Asakura 2016, Simpson 2019, Li 2020
$15M_\odot$, d = 200pc, NO
※ uncertainty: Pre-SN ν model / BG condition
Quasi-stationary evolutions
Core collapse
SN
t=34-76hr
t=7.5-38hr
t=0.2-6.5hr
$t = 0$
~200ms
ν burst
$\bar{\nu}_e$
t=a dozen hrs
300t-class Ar detector
$\bar{\nu}_e \nu_e \nu_x$
t=a few mins
ν_e
DUNE: Kato 2017, Patton 2017b DM experiment: Raj 2020

HE ν: ν_τ & glashow resonance candidate events





And much more...

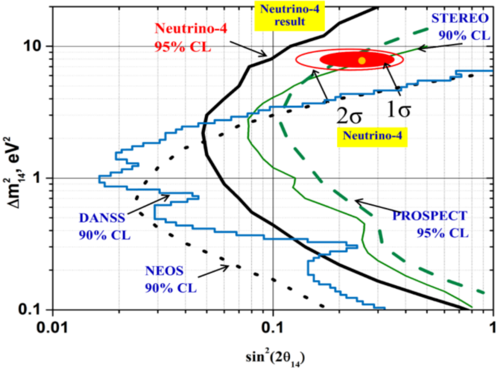
- Neutrinoless 2β decay – ν Majorana particles?
- Short Baseline Reactor neutrino oscillations
- Atmospheric neutrino oscillations
- keV sterile neutrino searches
- BSM theory
- Neutrinos for non-proliferation
- Diffuse SN ν background
- ν Dark Matter or searches for Dark Matter with ν
- Multi messenger astronomy
- ...

- Improvements in facilities
- For several areas I didn't show *all* people working on them...

Backup slides

Light Sterile Neutrinos – Neutrino 4 claim

COMPARISON WITH OTHER RESULTS OF EXPERIMENTS AT RESEARCH REACTORS AND NUCLEAR POWER PLANTS



In experiments on nuclear power plants sensitivity to identification of effect of oscillations with $\Delta m^2_{14} \approx 7.25\text{eV}^2$ is considerably suppressed because of the big sizes of an active zone. The period of oscillation for neutrino energy 4 MeV is 1.4 m.
But size of reactor core is about 4 m.

Experiment Neutrino-4 has some advantages in sensitivity to large values of Δm^2_{14} owing to a compact reactor core, close minimal detector distance from the reactor and wide range of detector movements.

30