# Physics with upgraded Osiris

Particle physics day
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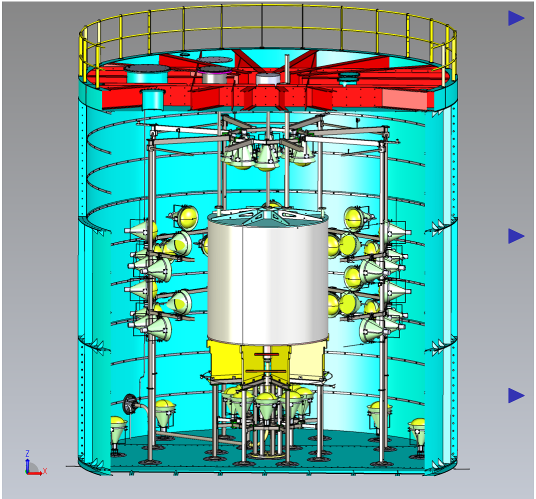
# Physics with upgraded Osiris

Introduction – Osiris




- Pre-detector for JUNO
  - monitors the purity of the liquid during the filling phase
  - EPJC 81 (2021) 973 : The design and sensitivity of JUNO's scintillator radiopurity pre-detector Osiris
- Liquid scintillator detector (LAB)
  - mass 20 tons
  - cylinder shape; length and diameter 3 m
  - light yield $\sim 10^4$ photons/MeV
- Water buffer
  - cylinder shape; length and diameter 9 m
  - 66 20-inch PMTs (QE $\simeq$ 30%)

# Physics with upgraded Osiris

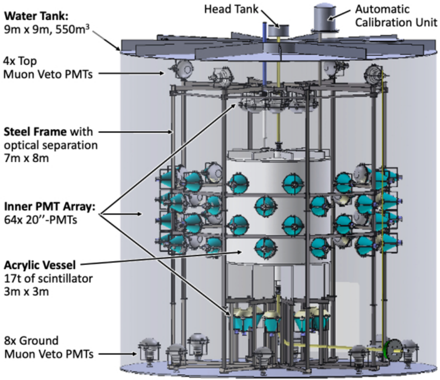
## Physics topics

- What could be done with Osiris after JUNO filling has been completed?
- Detector upgrade needed (for any physics studies)
  - utilizing the JUNO liquid handling and purification facility possible
- Two ideas so far
  - a precision measurement of solar pp-neutrinos
    - neutrino oscillation $\theta_{12}$ (comparing $\nu$ and $\bar{\nu}$ mixing angles)
    - solar luminosity constraint (precise comparison with the Standard Solar Model)
    - first design study performed: EPJC 82 (2022) 779
  - double-$\beta$ decay
    - two-neutrino double-$\beta$ decay, for example: $^{78}\mathrm{Kr}$, $^{106}\mathrm{Cd}$, or $^{124}\mathrm{Xe}$ (i.e., $\beta^+$ modes)
    - $\beta^+$ mode not well known
    - to improve nuclear structure information
    - work in progress ...

# Physics with upgraded Osiris

## Introduction – Osiris upgrade

| Detector property | OSIRIS | Serappis | Unit |
| --- | --- | --- | --- |
| Effective photo coverage | 9% | ≤75% | |
| Photo electron yield $Y_{pe}$ | 275 | ≤2,000 | p.e./MeV |
| Energy resolution ($\sigma$) | 6% | ∼2.2% | at 1 MeV |
| Position resolution ($\sigma$) | 13 cm | ∼5 cm | at 1 MeV |
| External background rate | 6 Bq | ≤2.3 mBq | |




} increasing number of PMTs, or adding reflective cones to the existing PMTs

additional shielding of 25 cm of steel

For solar neutrinos:
concentration of $^{14}$C in the liquid scintillator:
$\sim 10^{-18} \implies \sim 10^{-20}$

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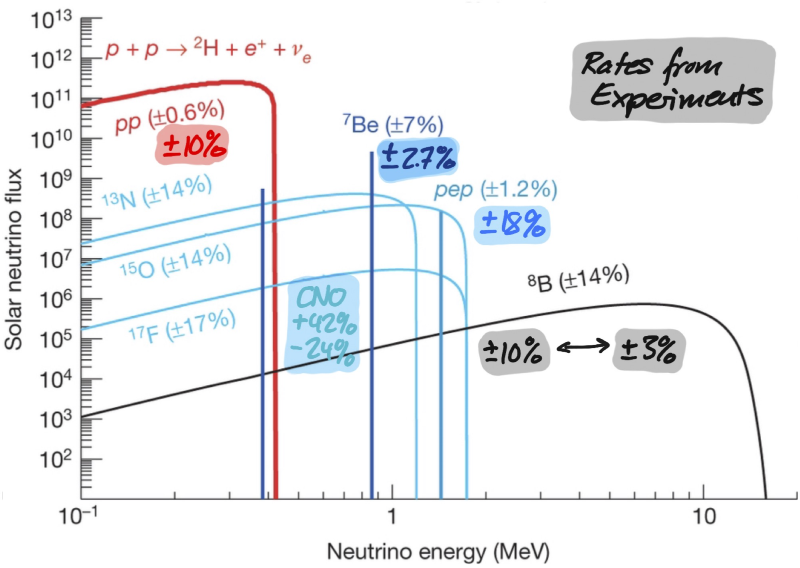
## Physics topics – solar neutrinos in Stardard Solar Model



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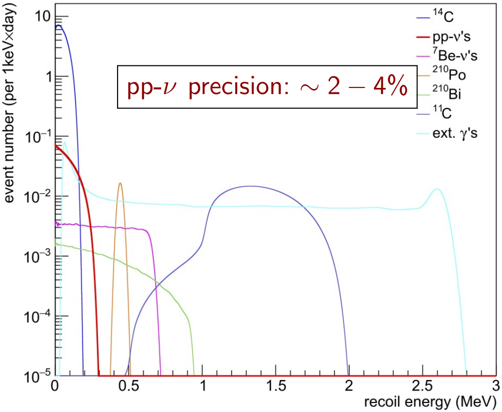
Results of simulations for solar neutrinos – EPJC 82 (2022) 779




| Contribution | Rate ($d^{-1}$) |
|---|---|
| *pp* neutrinos | 12.5 |
| $^{7}$Be neutrinos | 4.5 |
| $^{14}$C | 1360 |
| $^{210}$Po | 1.6 |
| $^{210}$Bi | 1.6 |
| $^{11}$C | 13.3 |
| external $\gamma$'s | 35 |

- pp- and $^{7}\mathrm{Be}$-neutrinos and $^{210}\mathrm{Bi}$: Borexino rate assumed
- $^{14}\mathrm{C}$: concentration $^{14}\mathrm{C}/^{12}\mathrm{C} = 10^{-20}$ assumed (Borexino: $2 \times 10^{-18}$)
- external background: with additional 25 cm steel shielding assumed

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Physics topics – double-$\beta$ decay

- $0\nu2\beta$ decay has not yet been observed

- For $\beta^-$ mode, $2\nu2\beta$ decay is known for ∼12 isotopes
- For $\beta^+$ mode (ECEC, EC$\beta^+$, $\beta^+\beta^+$), $2\nu2\beta$ decay reported only for one isotope, $^{124}\mathrm{Xe}$ (ECEC mode)
- Observation of $2\nu2\beta$ decays provide a way to improve the nuclear structure information (nuclear matrix elements) for $0\nu2\beta$ decays

$$\frac{1}{T^{2\nu}_{1/2}} = G_{2\nu}(Q_{\beta\beta}, Z) \cdot |M_{2\nu}|^2$$

- A more detailed study ongoing for isotopes $^{78}\mathrm{Kr}$, $^{106}\mathrm{Cd}$, and $^{126}\mathrm{Xe}$ ($2\nu$EC$\beta^+$) with upgraded Osiris
  - separation of Cherenkov and scintillation light, background conditions
  - test isotope loading (∼3% of LS weight)

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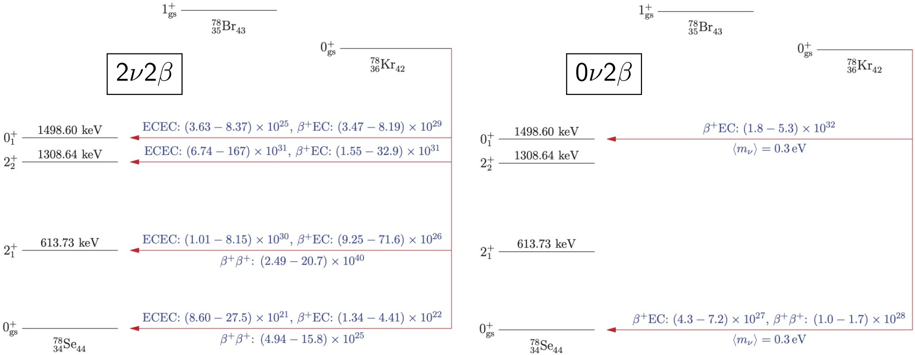
## Double-$\beta$ decay – isotope $^{78}$Kr




- J. Suhonen, PRC 87 (2013) 034318

$$\beta^+\mathrm{EC}:\ 1.34 - 4.41 \times 10^{22}\ \text{years}$$

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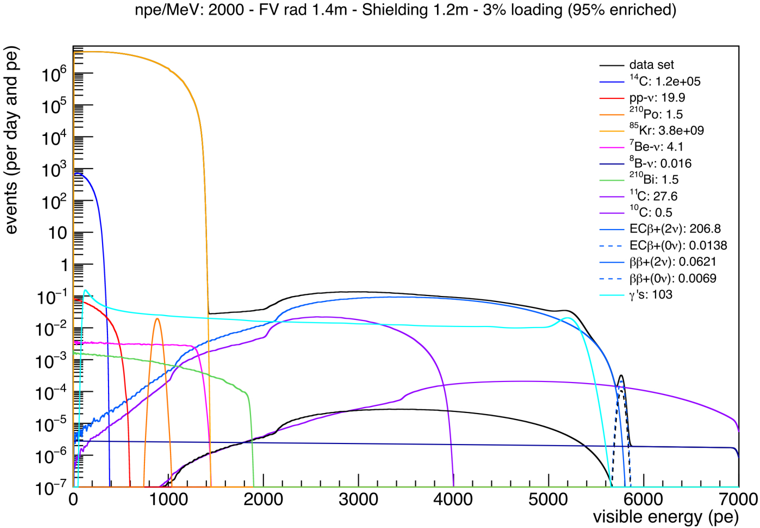
Double-$\beta$ decay – isotope $^{78}\mathrm{Kr}$, energy spectrum



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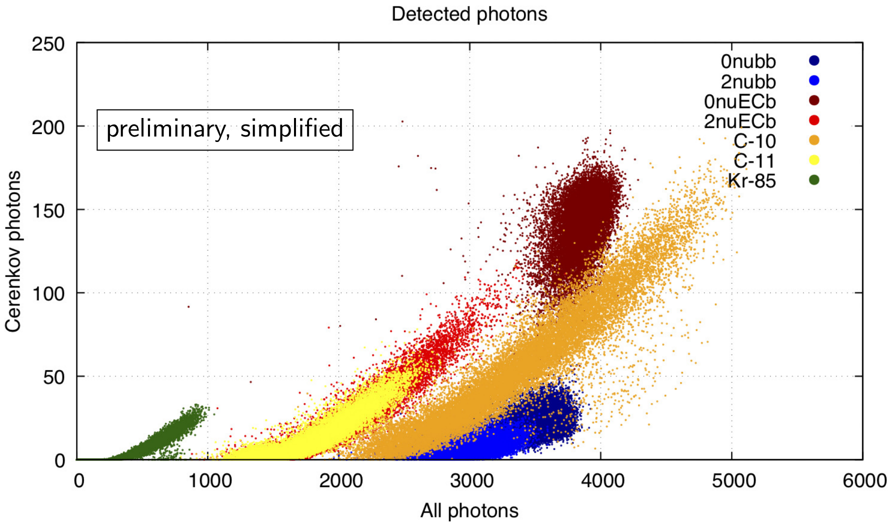
Double-$\beta$ decay – isotope $^{78}\mathrm{Kr}$, Cherenkov and scintillation separation



# Physics with upgraded Osiris

## Conclusions

- Osiris
  - JUNO pre-detector for monitoring liquid scintillator purity, available for other uses after JUNO filling is completed
  - possible to upgrade with relatively low costs (better photon coverage and thicker shielding, possible low-$^{14}\mathrm{C}$ scintillator)
  - utilization of JUNO purification facility possible
- Possible physics topics of the upgrade
  - precise solar pp-$\nu$ measurement
    $\Longrightarrow$ luminocity constraint test
    $\Longrightarrow$ mixing angle $\theta_{12}$ (for $\nu$ and $\bar{\nu}$)
  - double-$\beta$ decay measurement of $^{78}\mathrm{Kr}$ for 2$\nu$EC$\beta$ (isotopes $^{106}\mathrm{Cd}$ and $^{124}\mathrm{Xe}$ also possible)
    $\Longrightarrow$ $\beta^+$ mode not well known
    $\Longrightarrow$ better nuclear structure information
    $\Longrightarrow$ developing methods for Cherenkov and scintillation light separation

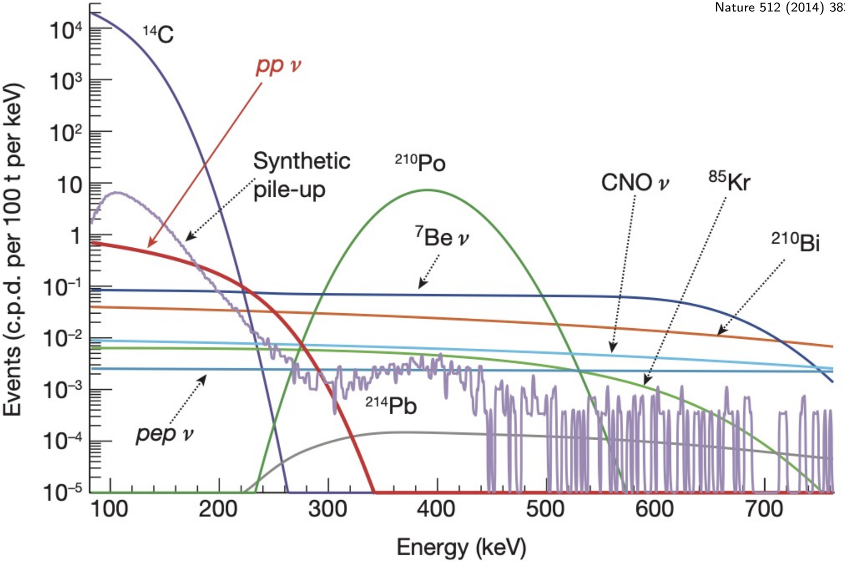
# Physics with upgraded Osiris

## Backup slides

# Physics with upgraded Osiris

Borexino – solar pp-$\nu$ measurement

Nature 512 (2014) 383



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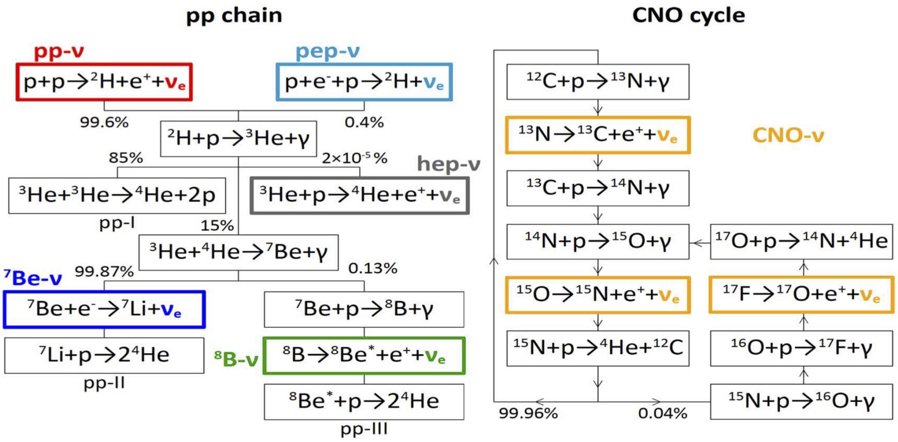
## Solar proton-proton chain and CNO cycle



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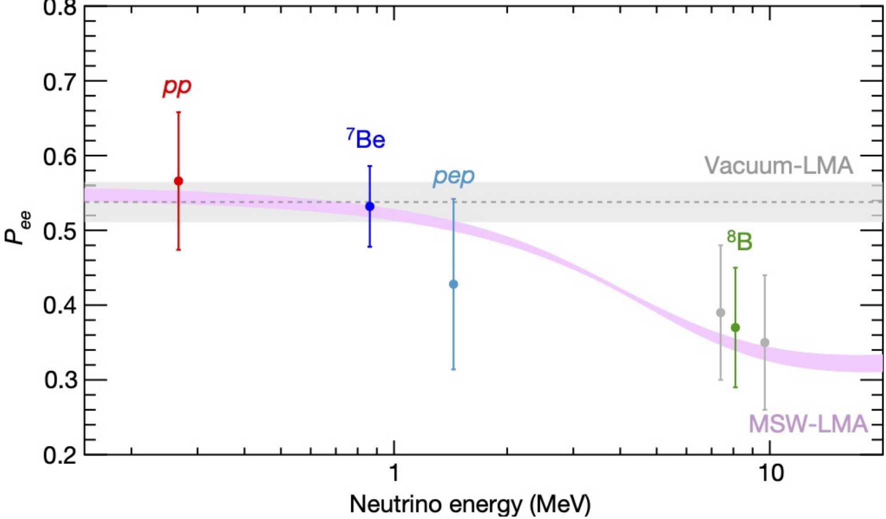
## Electron neutrino survival probability

Nature 562 (2018) 505



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## pp neutrino results



**Table 4** Dependence of the relative *pp* flux uncertainty measured by Serappis, $\delta_{pp}$, on (a) the $^{14}$C content of the scintillator, (b) the photo electron yield, (c) the measuring time $T$, and (d) the level of internal $^{210}$Bi background. All other parameters are kept according to the default scenario. For row (e), $R = 10^{-22}$, $Y_{pe} = 2000$ pe/MeV and $T = 3000$ d is assumed while studying the impact of external constraints on the $^{14}$C and $\gamma$ rates. Row (f) studies the dependence of the result on an external constraint on the Weinberg angle $\theta_W$. All values quoted are median sensitivities

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (a) | $R(^{14}\mathrm{C})$ | Borex | $10^{-18}$ | $10^{-19}$ | **$10^{-20}$** | $10^{-21}$ | $10^{-22}$ |
| | $\delta_{pp}$ | 5.6% | 5.0% | 4.2% | **3.4%** | 2.8% | 2.5% |
| (b) | $Y_{pe}$ [pe/MeV] | 250 | 500 | 750 | 1,000 | **1,500** | 2,000 |
| | $\delta_{pp}$ | 4.3% | 4.1% | 3.7% | 3.6% | **3.4%** | 3.3% |
| (c) | $T$ [d] | 500 | 1000 | **1500** | 2000 | 2500 | 3000 |
| | $\delta_{pp}$ | 6.1% | 4.2% | **3.4%** | 3.0% | 2.7% | 2.5% |
| (d) | $^{210}$Bi [/(dt)] | $10^{-2}$ | **0.16** | 0.5 | 1 | 5 | 10 |
| | $\delta_{pp}$ | 3.4% | **3.4%** | 3.6% | 3.8% | 4.9% | 5.8% |
| (e) | $\sigma(^{14}\mathrm{C}, \gamma)$ | **1** | 0.1 | 0.05 | 0.02 | 0.01 | $10^{-3}$ |
| | $\delta_{pp}$ | 1.9% | 1.8% | 1.7% | 1.5% | 1.3% | 1.2% |
| (f) | $\sigma(\theta_W)$ | **0.07%** | 0.1% | 1% | 5% | 10% | 100% |
| | $\delta_{pp}$ | **3.4%** | 3.4% | 3.5% | 3.6% | 3.8% | 13% |

Bolded values indicate the default scenario described in Sect. 5.1