# SUPERNOVA NEUTRINO SENSITIVITY AND PHYSICS REACH OF THE PICO-500 EXPERIMENT

PICO

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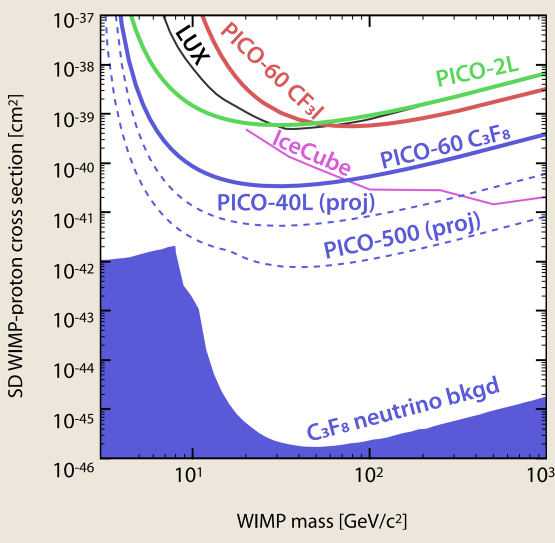
## PICO-500

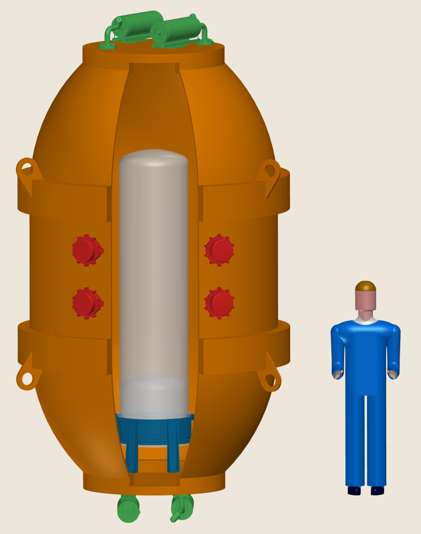
### Idea

- In 2018 the Canadian government announced funding for the PICO-500 detector at SNOLAB;
- Planned setup: an active mass of about 1t of $C_3F_8$ in a "right-side-up" bubble chamber;
- Main purpose: the search for spin-dependent dark matter capitalizing on the excellent spin enhancement of the cross section between fluorine and spin carrying dark matter particles;
- The low mass number of $^{19}F$ allows PICO to explore parameter space inaccessible to heavy liquid noble detectors due to the $A^2$ enhancement of the coherent neutrino-nucleus scattering.




*Sensitivity limit of the PICO-500 detector for spin-dependent WIMP-proton interactions.*

### Design



*Setup geometry: PICO-500 chamber inside its pressure vessel. Credits: Mathieu Laurin, Université de Montréal.*

- Baseline geometry: two concentric cylinders made from synthetic quartz with the smaller one serving both as active liquid containment and as piston for the compression of the bubble chamber after a nucleation;
- Quartz vessels: following the design of the PICO-40L detector, but scaled up by a factor of two in both the radial and axial dimensions;
- Pressure vessel: likewise scaled up so that neutron backgrounds from the steel pressure vessel will not limit the sensitivity of the detector; will have to be brought into SNOLAB in three pieces and assembled underground.
- All remaining components of the detector hardware (the image entropy-based optical trigger algorithm, the camera and optical system, the compression system, the pressure control and thermal control systems) will be simple copies of the technology developed for PICO-40L and previous PICO chambers.
- The detector inside its pressure vessel will be mounted inside a water shield (diameter 5.6, height 7.9m), which will be instrumented with PMTs to detect Cherenkov light from passing high-energy muon events.

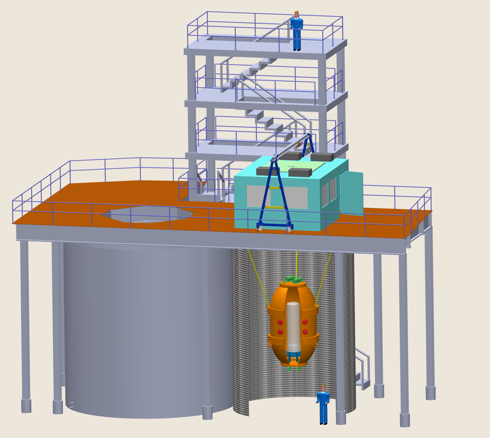


*Image of the setup of the PICO-500 experiment at SNOLAB in the experimental area of the Cube Hall. The pressure vessel for PICO-500 is suspended below the existing deck area. Credits: Mathieu Laurin.*

### Timeline

- 2018 — funding for PICO-500 announced
- 2019 — construction begins
- 2020 — data collection begins
- 2022 — expected end of the first run; preparation for the next runs begins

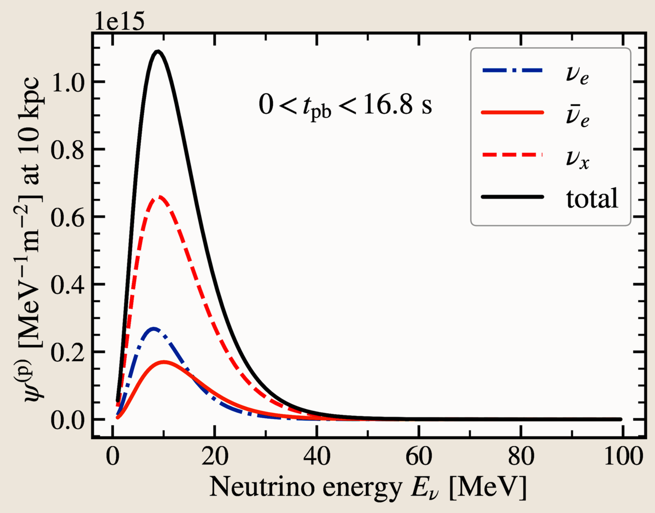
## Supernova neutrinos

### Emission

- Most probable distance to the next supernova within the Milky Way: 12-15 kpc;
- For the PICO-500 sensitivity study, we assume a $20M_\odot$ progenitor located at 10 kpc distance from the Earth;
- Simulated 1D (direction-averaged) neutrino signal from the Garching Core-Collapse Supernova Archive† allows us to extract time dependence of the neutrino flux density:

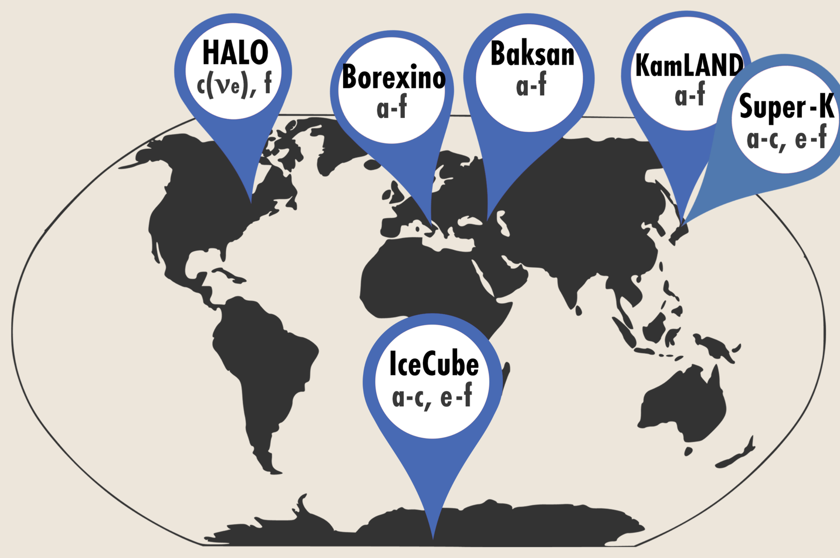
$$\psi^{(\mathrm{p})}(E_\nu,t) = C(t)\left(\frac{E_\nu}{\langle E_\nu\rangle(t)}\right)^{\alpha(t)} \exp\left[-(\alpha(t)+1)\frac{E_\nu}{\langle E_\nu\rangle(t)}\right]$$

- $\langle E_\nu \rangle$ — mean ν energy, $1.5 \lesssim \alpha \lesssim 7$ — pinching parameter, $C$ — normalization constant.




*Pinched neutrino spectrum integrated over 16.8s post-bounce for a $20M_\odot$ progenitor leaving $1.96M_\odot$ baryonic mass neutron star after explosion. Total radiated energy: $4.3 \times 10^{53}$ ergs.* †

### Current detection methods




The worldwide scientific community is prepared for detecting supernova neutrino interactions with matter via the following channels:

| | |
|---|---|
| a $\bar{\nu}_e + p \to n + e^+$ | d $\nu_x + p \to \nu_x + p$ |
| b $\nu_e/\bar{\nu}_e + e^- \to \nu_e/\bar{\nu}_e + e^-$ | e $\nu_x + e^- \to \nu_x + e^-$ |
| c $\nu_e/\bar{\nu}_e + A \to e^{-/+} + B^*$ | f $\nu_x + A \to \nu_x + A^*$ |

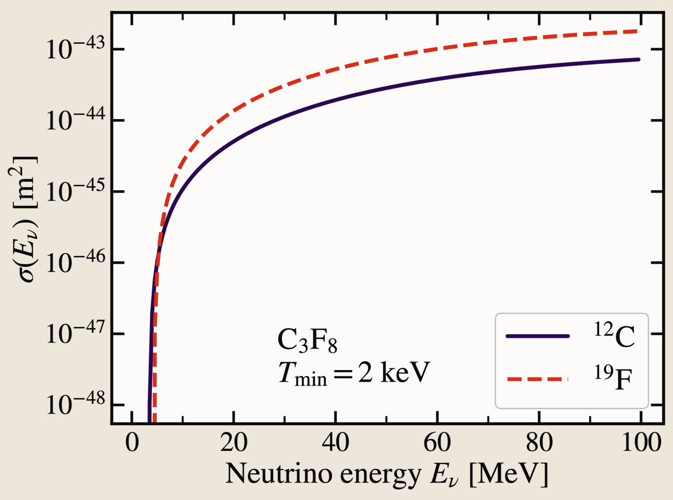
For classic neutrino detectors, coherent elastic neutrino-nucleus scattering (**CEvNS**) is not among them due to small (keV-scale) recoil energies and high (MeV-scale) detection thresholds.

### CEvNS channel

- Predicted in 1973, experimentally observed in 2017 by COHERENT collaboration;
- Projections for direct dark matter search detectors (LZ, XMASS, XENON1T) have shown that they are all sensitive to CEvNS of SN neutrinos;
- Differential cross section of CEvNS is given by:

$$\underbrace{\frac{\mathrm{d}\sigma}{\mathrm{d}T}}_{\text{recoil energy}} = \frac{G_F^2}{4\pi}\overbrace{M}^{\text{target nucleus mass}} \cdot \left[\underbrace{(Q_W^V)^2}_{\text{vector weak charge}}\left(1-\frac{MT}{2E_\nu^2}\right) + \overbrace{(Q_W^A)^2}^{\text{axial-vector weak charge}}\left(1+\frac{MT}{2\underbrace{E_\nu^2}_{\text{true ν energy}}}\right)\right] \cdot \underbrace{F(Q^2)^2}_{\text{form factor at momentum transfer Q}}$$

- For PICO-500 with its "step function" response, these cross sections are to be integrated from detection threshold $T_{\mathrm{min}}$ to $T_{\mathrm{max}}(E_\nu)$.




*Recoil energy integrated cross sections of coherent elastic scattering of supernova neutrinos off C and F nuclei in $C_3F_8$ (PICO-500 target fluid).*

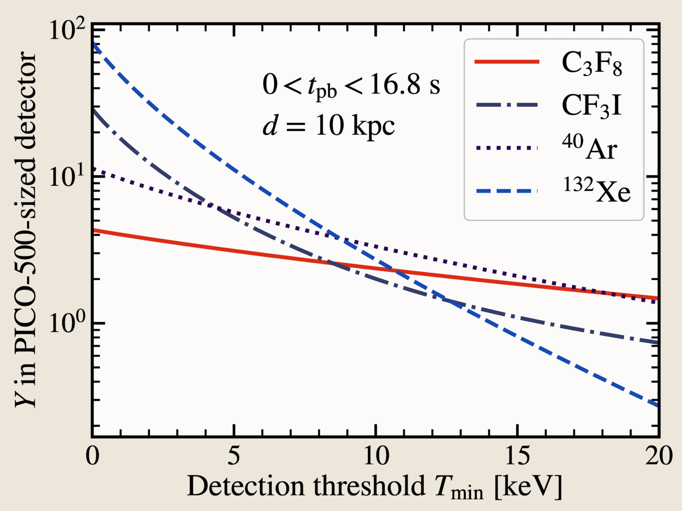
## Projections for PICO-500

### Expected rates

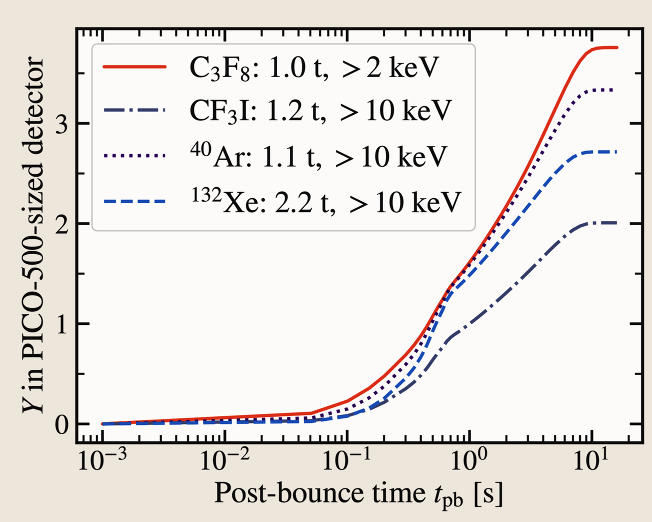
- The total expected bubble yield: $Y = N \times \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \sigma(E_\nu)\psi^{(\mathrm{p})}(E_\nu)\mathrm{d}E_\nu$

  ($N$ — number of target nuclei in the nominal 725L volume)

- Time-integrated yields:




- Time-resolved yields:




- Bubble yields above selected thresholds:

| Target | > 0.5 keV | > 2 keV | > 5 keV | > 10 keV |
|---|---|---|---|---|
| $C_3F_8$ (1t) | 4.2 | 3.8 | 3.1 | 2.4 |
| $CF_3I$ (1.1t) | 22.5 | 12.5 | 5.2 | 2.0 |
| LAr (1.2t) | 10.5 | 8.4 | 5.7 | 3.3 |
| LXe (2.2t) | 62.1 | 31.9 | 11.1 | 2.7 |

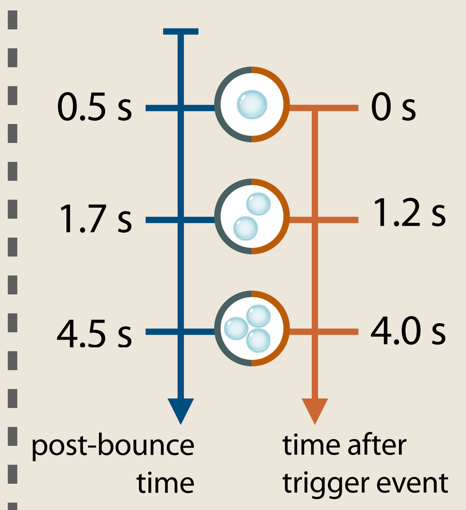
- Post-bounce time [s] after which we can expect $k$ bubbles:

| $k$ | $C_3F_8$ | $CF_3I$ | LAr | LXe |
|---|---|---|---|---|
| 1 | 0.5 | 1.0 | 0.5 | 0.6 |
| 2 | 1.7 | 12.0 | 1.8 | 2.4 |
| 3 | 4.5 | N/A | 6.0 | N/A |

- For $C_3F_8$, same results apply to the case of a 25t chamber and a supernova at 50 kpc.

### Impact

- On detector design (for 1t of $C_3F_8$):




The amount of time that the detector is kept in the superheated state after the trigger event (first CEvNS-caused bubble) should be minimized but can be adjusted to observe the desired number of scatters.

- On supernova neutrino studies:
  - Even with small numbers of scatters detected, such a measurement could serve as another confirmation of the SN event, complementary to that by ;
  - Such an observation would also unlock a completely new channel for SN neutrino detection, currently inaccessible to .

### Acknowledgements


- Natural Sciences and Engineering Research Council of Canada (NSERC)
- Canada Foundation for Innovation (CFI)
- University of Alberta Undergraduate Research Initiative (URI)

†
- R. Bollig
- H.-T. Janka
- T. Melson
- K. Scholberg
- B. Broerman
- L. Strigari
- I. Tamborra
- S. Riechard