NuToPs

Neutrino Tagging with ortho-Positronium

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AAP - Paris - 16th December 2014

NuToPs

- NuToPs is an ANR JCJC project involving APC Paris and IPHC Strasbourg (P.I. D.Franco from APC) aiming at the **electron antineutrino tagging** based on the **ortho-Positronium (o-Ps) observation**.

- Antineutrinos are typically detected observing the **twofold coincidence** between the **prompt positron** signal and the **delayed neutron** signal in the Inverse Beta Decay process:

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

Delayed signal

Prompt signal

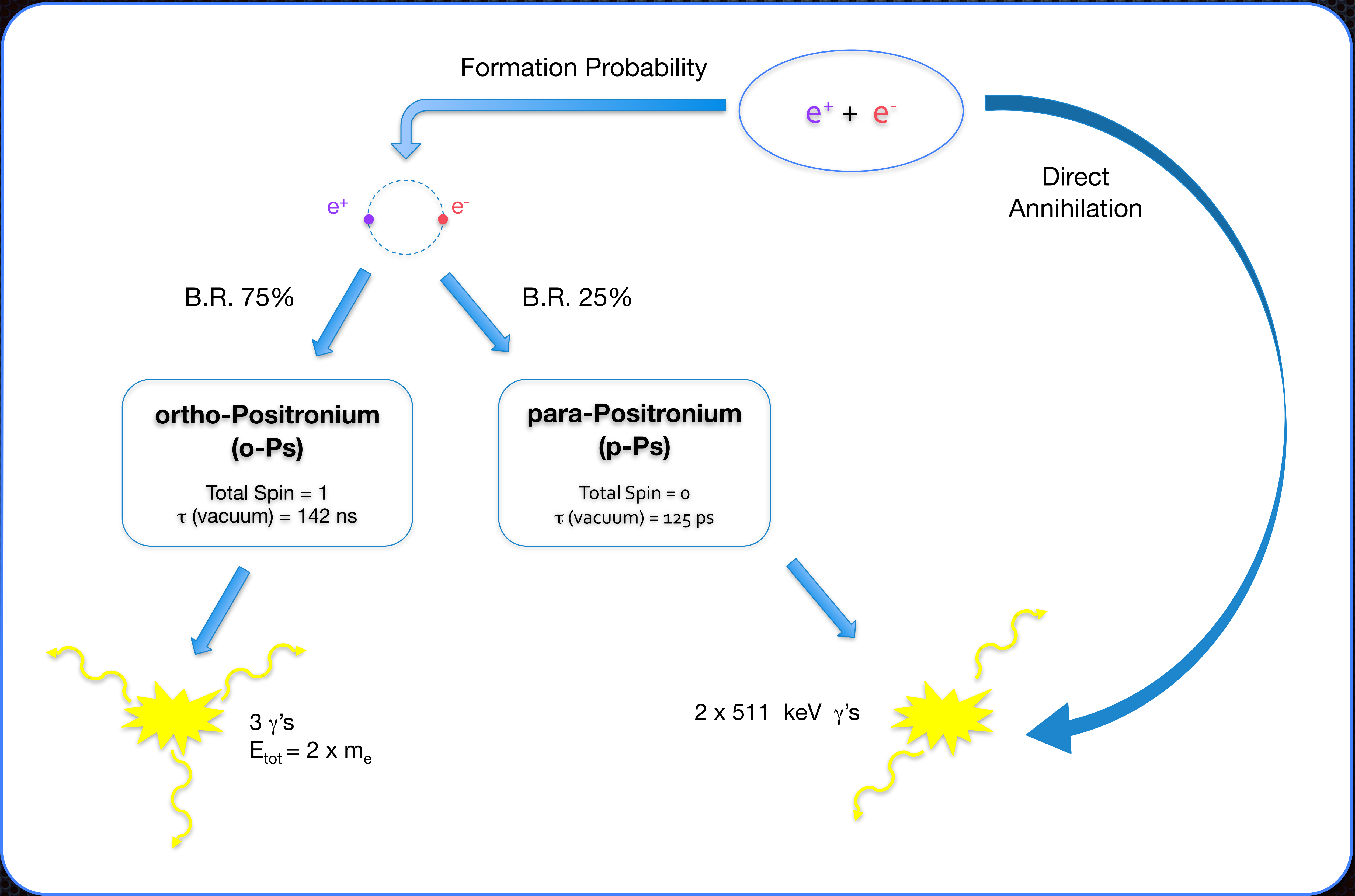
Time correlation depending on the absorption target nucleus

- To reduce accidental (typically radioactivity γ's + cosmic μ induced neutron) and correlated (cosmic μ induced neutron giving proton recoil + absorption or cosmogenic isotopes such as ^{9}Li) **backgrounds**, the detectors typically need **underground** locations and/or large active and passive **shielding**.

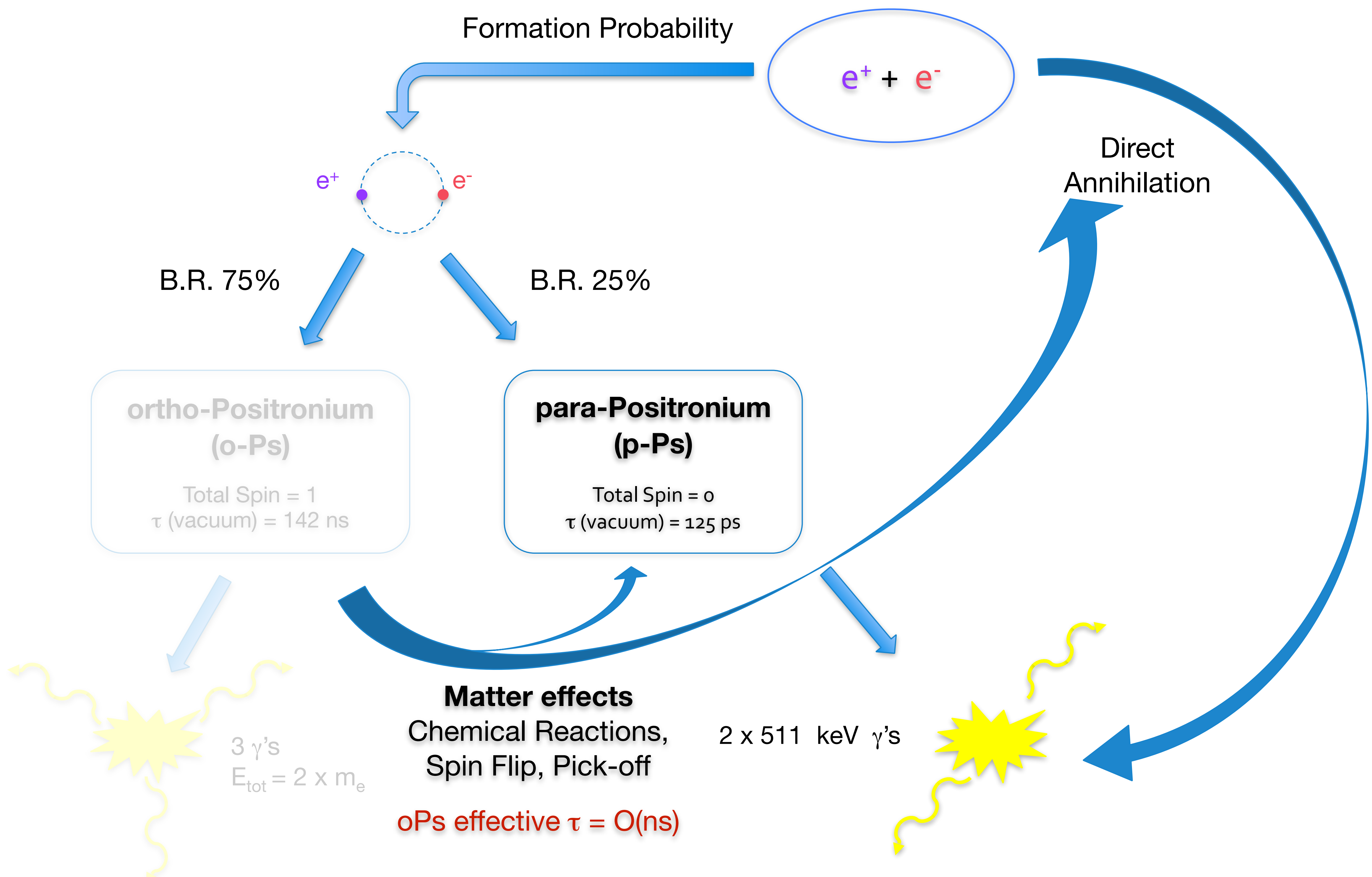
Can we reduce the background enhancing the signal over noise ratio using a **threefold coincidence** relying on **o-Ps** tagging?

Main NuToPs goal

Positronium Formation



Positronium Formation



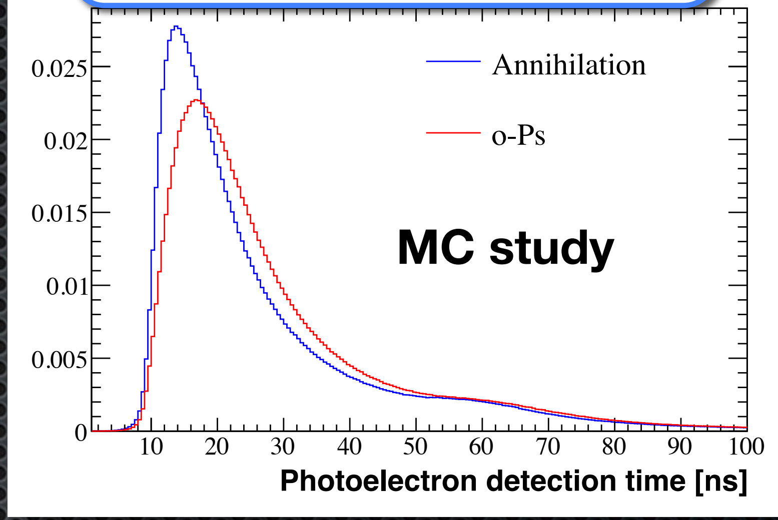
o-Ps observation

- Despite the typical short lifetime of o-Ps in matter, the possibility to detect it in **liquid scintillators** (o-Ps lifiteme of the order of 3 ns) observing a **pulse shape distortion** was investigated (Phys.Rev. C83 (2011) 015504).

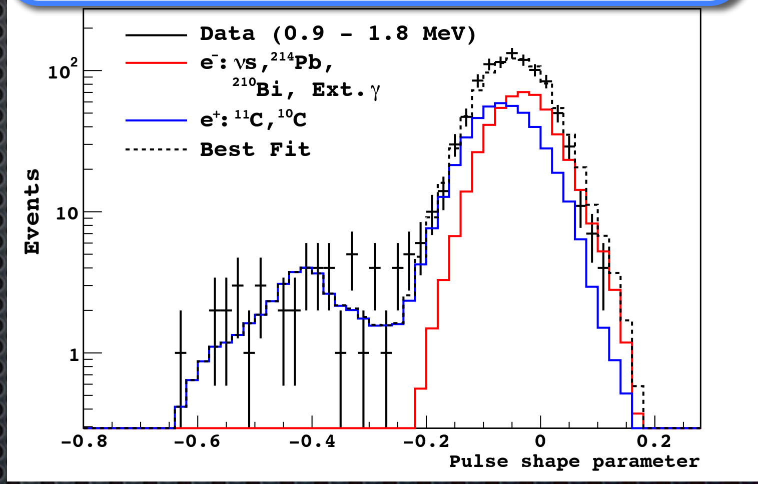
- The BOREXINO collaboration used this distortion to perform a statistical separation of e+/e- to reduce the cosmogenic ^{11}C β^+ background (Phys.Rev.Lett. 108 (2012) 051302).

- The Double Chooz experiment detected for the first time o-Ps on event by event basis in electron antineutrino events observing multiple pulses in the pulse time profile (JHEP 1410 (2014) 32) on a selected sample.

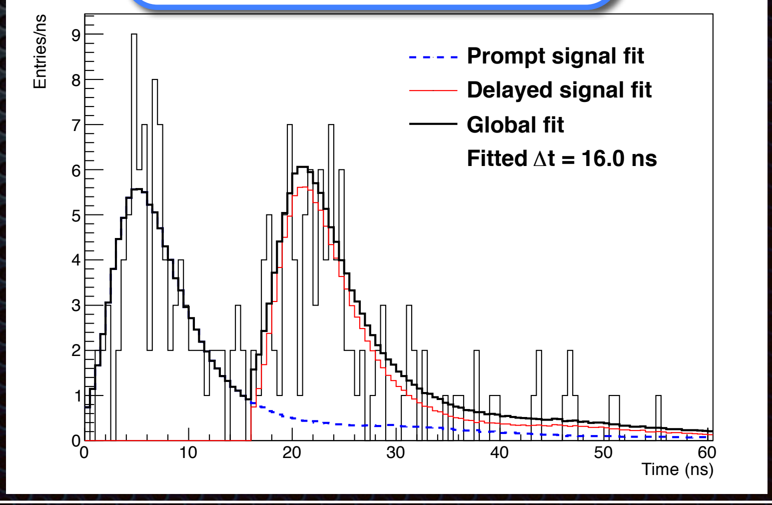
Phys.Rev. C83 (2011) 015504



Phys.Rev.Lett. 108 (2012) 051302



JHEP 1410 (2014) 32



o-Ps improvements needed

- The **short lifetime** of o-Ps in actual liquid/plastic scintillators makes it **difficult** to use it as a **background rejection** tool on event by event basis.
- Our **final goal** is the **enhancement of o-Ps lifetime and formation** to make it a possible signature in a **threefold coincidence for antineutrino detection** (e.g. reactor monitoring or sterile neutrino search).
- To reach our goal we worked on:

Liquid Scintillators →	Study of o-Ps properties as a function of the solvents and of the dopers concentrations
Plastic scintillators →	Study of o-Ps properties in plastic scintillators and the possibility to enhance them doping the scintillator with nano cavities
Non-scintillating porous materials →	Study of o-Ps properties enhancement in non scintillating porous materials for a sandwich-like detector

Liquid scintillators

Solvents

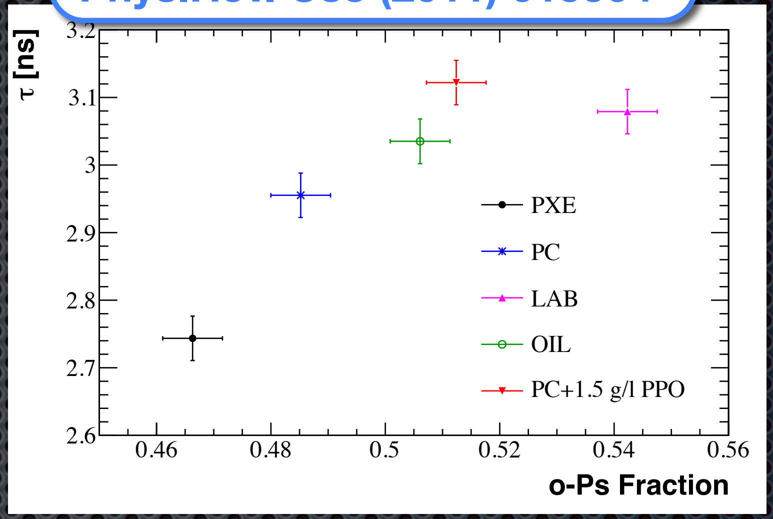
- Different solvents were studied: **PXE**, **PC**, **oil** and **LAB**.
- A maximum difference of 0.4 ns on the o-Ps lifetime and 8% on the formation fraction were found changing solvent (Phys.Rev. C83 (2011) 015504).

Dopants

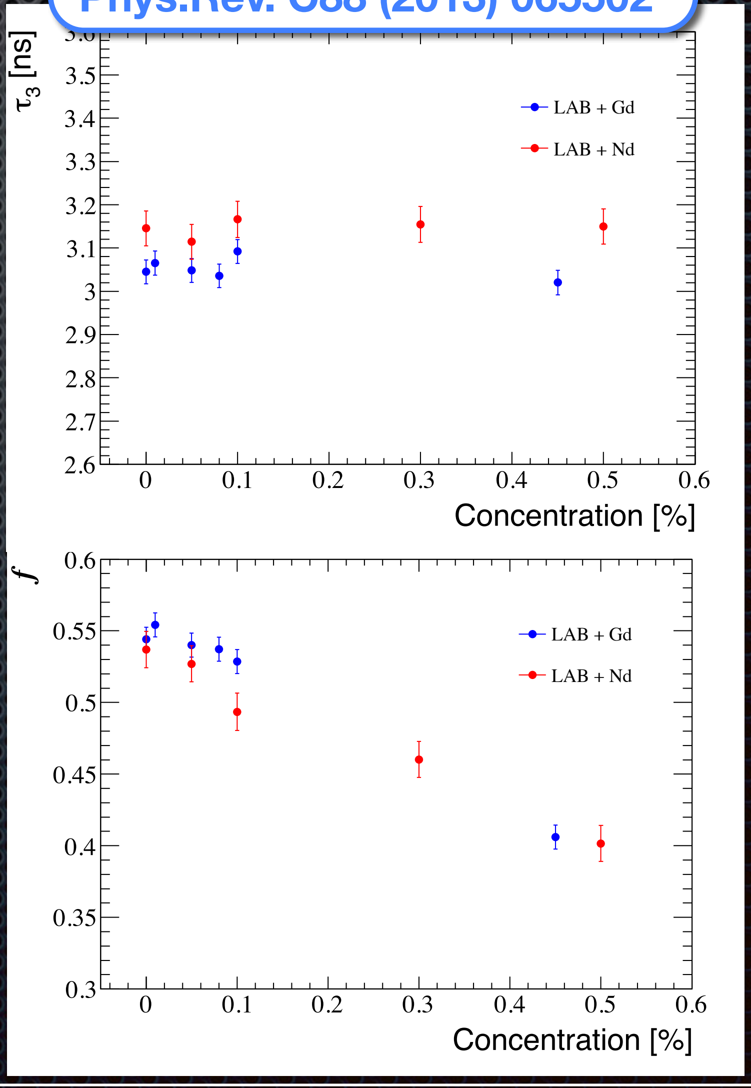
- We studied the effect of different concentrations of **Gd**, **Nd**, **Te** and **Li** in **LAB** based scintillators (Phys.Rev. C88 (2013) 065502).
- Changing Gd and Nd concentration we observed a relative stable o-Ps lifetime and a formation fraction decrease as the concentration increases.
- Similar results were found for Li and Te.

No liquid scintillator showed enhanced o-Ps lifetime larger than 3.2 ns

Phys.Rev. C83 (2011) 015504



Phys.Rev. C88 (2013) 065502

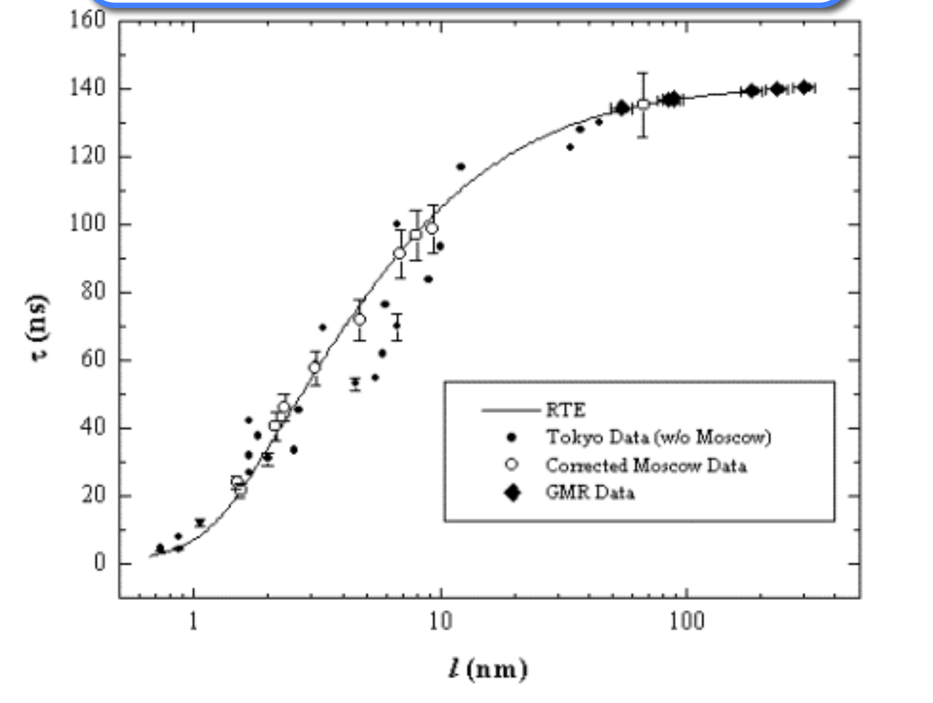


Plastic scintillators

- Standard plastic scintillators were measured, in particular **EJ200** from Eljen (equivalent of BC-408 from St.Gobain) yielded an o-Ps lifetime of **2.2 ns** and a formation fraction of about **40%**.

- The lifetime is definitely too short to be exploited for o-Ps tagging. However it is known that the o-Ps lifetime is strongly dependent on the cavity dimensions in the material (Tao-Eldrup model).

o-Ps lifetime Vs pore diameter



- We investigated the possibility to **dope polystyrene** with different **mesoporous silica nanoparticles** with pore sizes between 2 and 10 nm (nanoparticles produced by Sudan University Shanghai, and incorporated into polystyrene by University of Bradford UK).

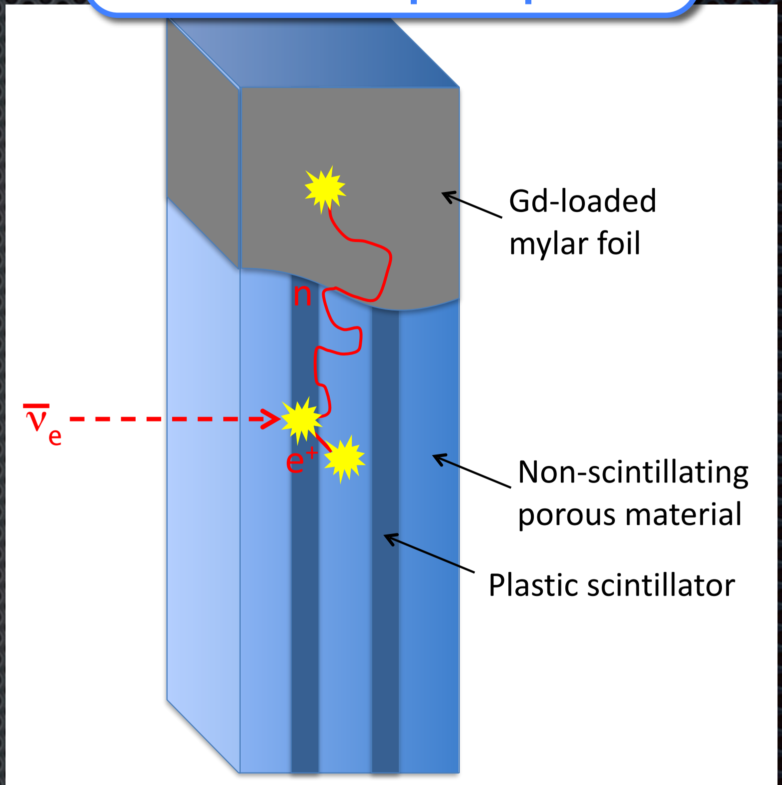
- Unfortunately all the samples tested showed **no significant enhancement of the o-Ps lifetime** (density of pores too low to have a high fraction of o-Ps trapped inside) whereas the **optical transparency** of the scintillator was **strongly degraded**.

Non-scintillating porous materials

- Given the deceiving results obtained on the studied material we investigated the possibility of using a **segmented detector** based on layer of standard plastic scintillator interleaved by a **non-scintillating porous material** with a high o-Ps formation fraction and lifetime.

- We studied several non-scintillating porous material looking for the **best compromise between o-Ps lifetime**, **o-Ps formation fraction**, and **density** (the highest the density the largest the probability for the positron to stop in the passive material.

Detection principle



Materials	Maximal o-Ps formation	Respective o-Ps lifetime	Notes
Silica aerogel based	29.6 ± 1.9 %	58.8 ± 0.7 ns	Commercial Cabot
Nanoporous silica based	20.8 ± 1.5 %	46.3 ± 0.5 ns	Produced by IS2M
Syndiotactic polystyrene	6.9 ± 0.6 %	44.3 ± 1.3 ns	Produced by ICS
Porous glasses	6.2 ± 0.5 %	56.6 ± 1.8 ns	Commercial Schott

Aerogel seems the best material but it is very **fragile** and **expensive** (about 200$ for 5 x 7.5 x 0.7cm^3 tile) therefore not suitable for a large detector.

However, Lumira aerogel particles are cheap (about $450 for 20 liters) and have similar properties:
o-Ps lifetime = 60.2 ± 2.6 ns
o-Ps formation fraction = 25.7 ± 2.6 %

Segmented detector

- We studied the possibility to use a **segmented** sandwich **detector** made of **layers** of **plastic scintillator** bars and layers of **aerogel** powder for antineutrino detection (paper in preparation).

Thick EJ200 bars	**Advantages** →	Large mass, i.e. more neutrino interactions. Higher gamma detection efficiency.
Thick aerogel layer	**Advantages** →	Higher fraction of positrons stopping in aerogel i.e. higher o-Ps formation.

- In particular we considered about **1 m^3 detector** with EJ200 plastic scintillator bars of 100 x 0.5 x 2.5 cm^3 and aerogel layers with a thickness of 3 cm where the thicknesses were "optimized" via MC simulation to yield the largest fraction of antineutrino detected.

- **NOTE** that the following results are **preliminary** and a full MC with a complete parameter scan for a better detector optimization is ongoing.

- To prove the feasibility two critical points were addressed:

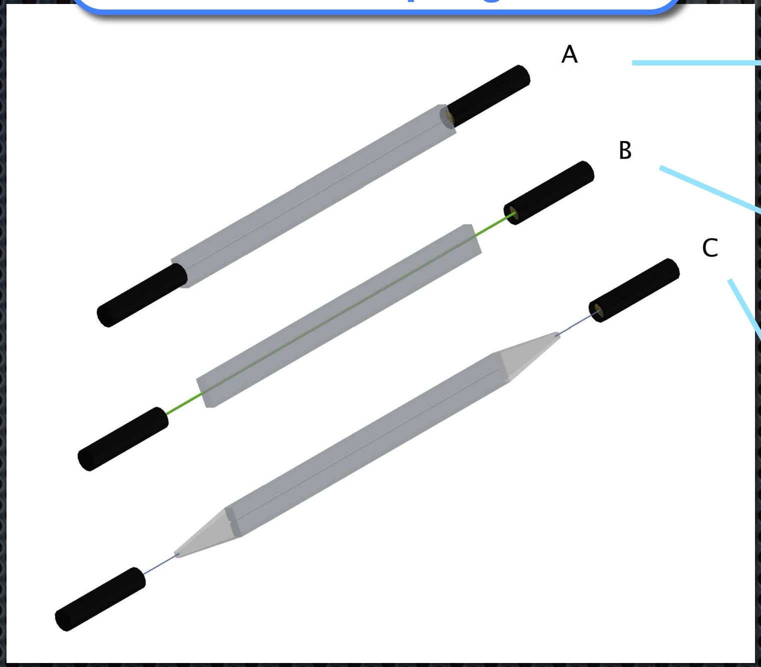
  1. The optics i.e. which is the **light yield** achievable.

  2. The number of channels is large using 1 PMT at each bar extremity (about 2200). Can it be reduced grouping the bars in **modules**? If so do we have the **time resolution** to observe o-Ps in one module?

EJ200 light yield

- The light yield measurements were carried out using a smaller bar (30 x 1 x 2.5 cm^3) wrapped into a reflecting mylar foil.
- The bar was coupled to two fast Hamamatsu 19 mm PMTs (R3478).
- Three **different PMT couplings** were tested.

PMT couplings



Direct coupling :
~ 300 p.e. per MeV

Wavelength shifting fiber coupling coupling :
~ 40 p.e. per MeV

Light guide with quartz fiber coupling :
< 3 p.e. per MeV

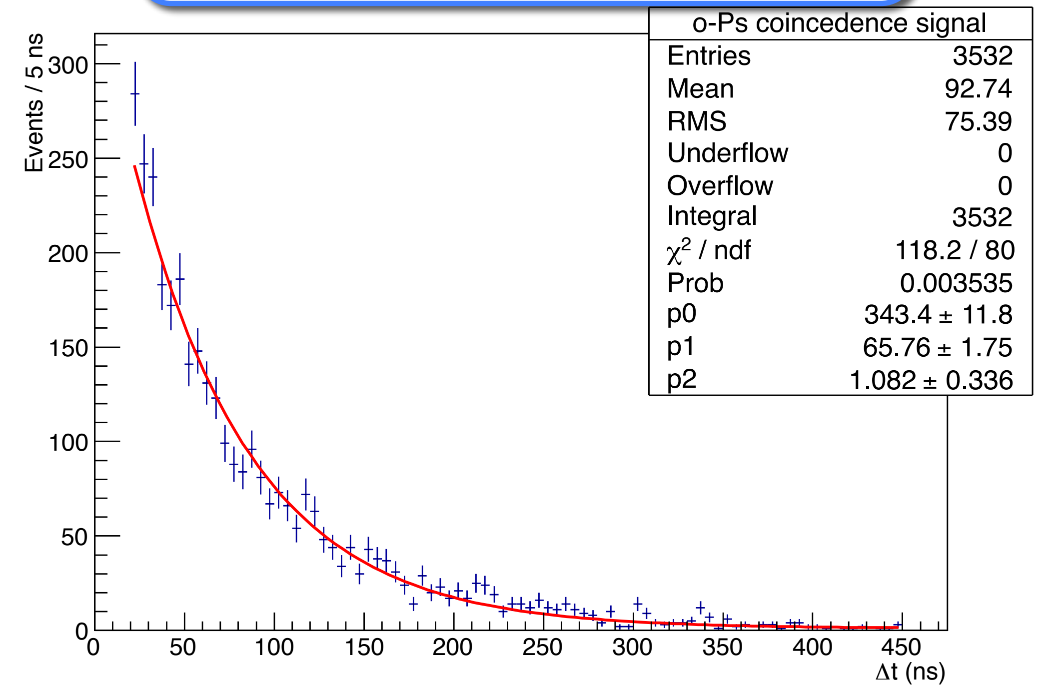
To reduce the number of PMTs fibers + multi channel PMT can not be used

The only solution is the optical clusterization of bars

Time resolution

- To have a bar optical clusterization we need to make sure that we have the needed time resolution to **observe o-Ps signal in a cluster**.
- Using a 500 Bq ^{22}Na source in aerogel, we observed on a single bar the time difference between the positron emission (1.27 MeV gamma emitted in the Na decay) and the o-Ps decay (one of the 511 keV gamma).
- To select the signal we used appropriate energy thresholds and the coincidence was looked for in a time window between 20 and 450 ns.
- The distribution of the time difference between the two signals was fitted with a double exponential (signal + accidental).
- A τ of **65.8 ± 1.8 ns** was found in reasonable **agreement** with the measured o-Ps lifetime of 60.2 ± 2.6 ns.
- The fraction of accidental (2.7 ± 1.9%) is also in agreement with the expected 0.7% computed from singles rates.

o-Ps decay time in a single bar

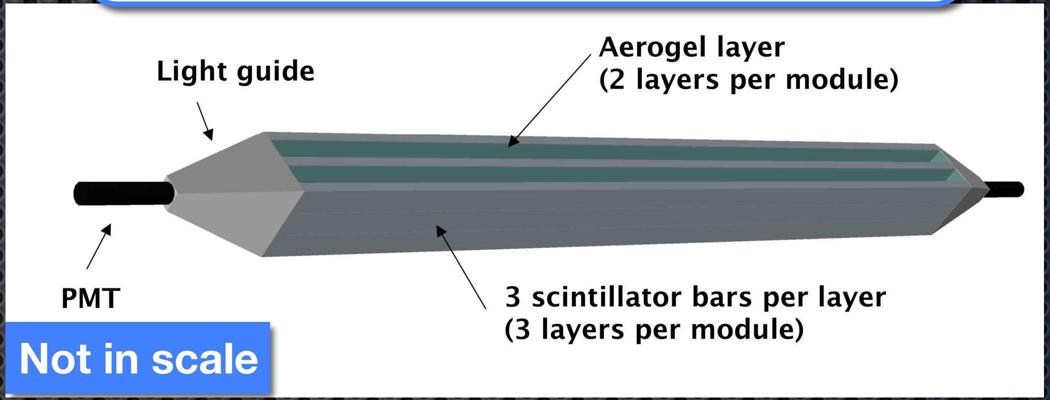


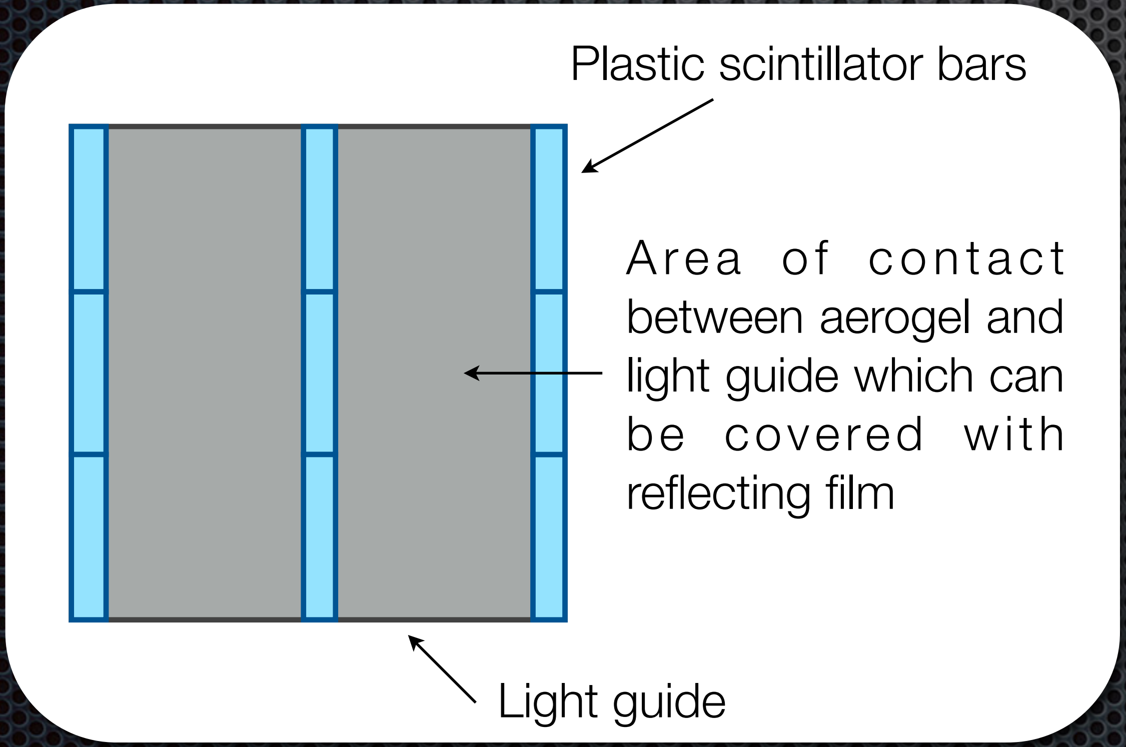
This shows that we can see o-Ps in a single cluster

Module light yield

- We grouped 9 bars in one module.
- A light guide is used to go from the 7.5 x 7.5 cm^2 section of the module to a surface of 5.3 x 5.3 cm^2 which is directly coupled to a 3 inch PMT (9821B Electron Tube).
- The light yield for each bar position was measured with and without reflecting film between aerogel and light guide.

Bar clusterization into modules





Scintillator bar position	Reflecting film	p.e. per MeV	Reduction w.r.t. maximum
Center	yes	272	-
Center	no	246	10%
Top/Bottom	yes	252	7%
Corner	yes	232	15%
Side	yes	228	16%

The obtained light yield shows that a modular readout can be used

Detector layout

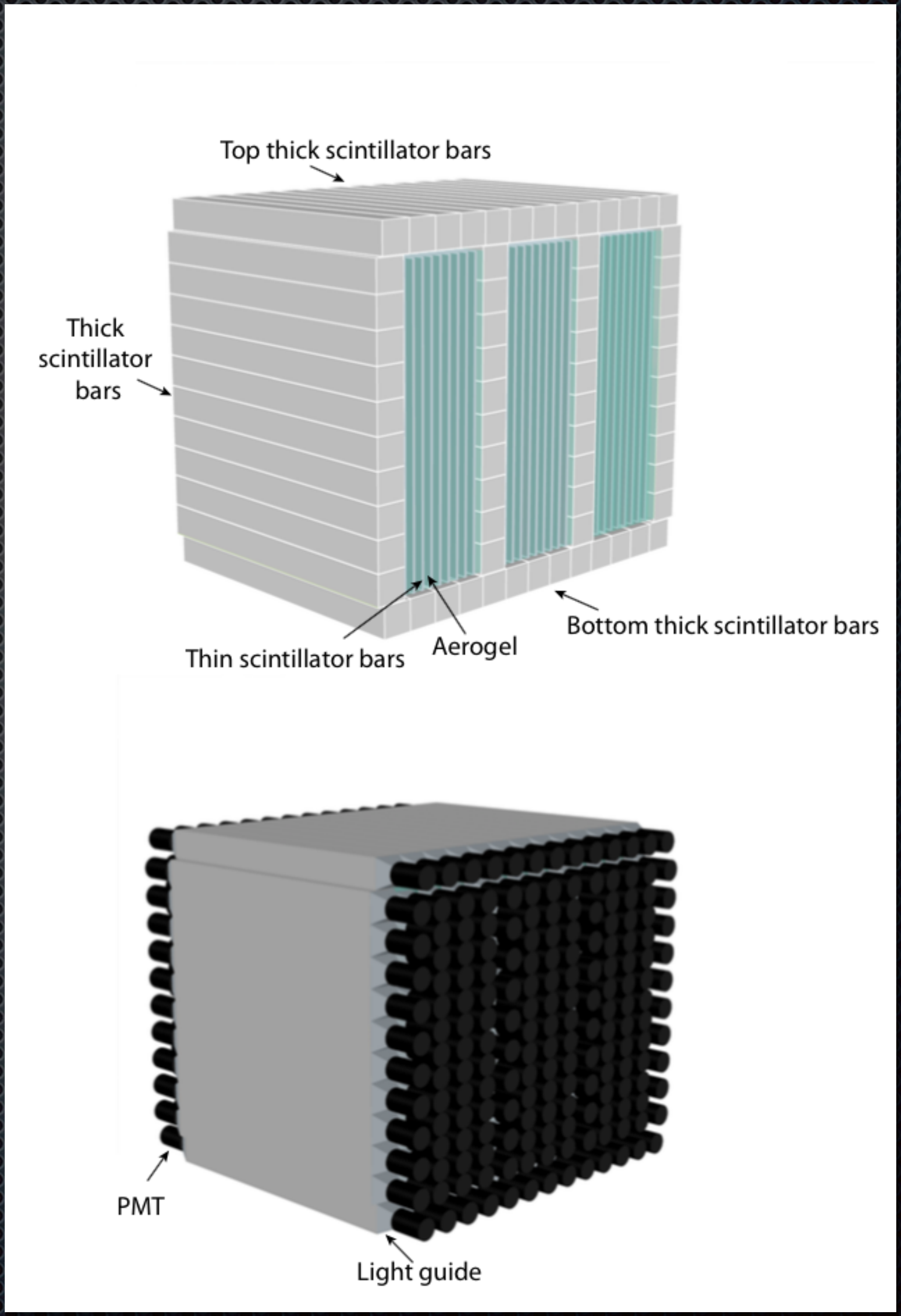
- Further MC optimization were performed to maximize the gamma's detection (both from o-Ps and neutron capture).
- We considered a Gd doped mylar reflecting foil wrapping the scintillator bars to enhance neutron capture signal.
- Blocks of thick plastic scintillators of 10 x 10 x 100 cm^3 were added around the detector, and interleaved to the optical modules each 3 optical modules.

The detector in a few numbers

Total volume = ~ 1.6 m^3 (135 x 100 x 120 cm^3)
Effective volume (modules) = ~ 0.9 m^3 (94.5 x 100 x 97.5 cm^3)
Effective mass (plastic bars) = 135 kg

Number of modules = 117
Number of bars = 1053
Number of modules PMT = 234

Number of thick bars = 66
Total number of PMTs= 366



Selection cuts

- To study signal and background efficiencies we simulated antineutrino IBD interactions inside the plastic bars, and mono energetic neutrons (1 MeV - 10 GeV range) and gammas (1 MeV - 10 MeV range) assuming the angular dependence at the Earth surface.
- We optimized the cuts for a maximal IBD signal acceptance and background rejection.

Cut	Threefold Coincidence
General	Only modules with at least 4 p.e. are considered.
Positron	Signal between 50 and 1200 p.e. in less than 10 ns. No more than two adjacent modules.
o-Ps	Signal between 50 and 200 p.e. between 10 and 300 ns. At least two modules. All modules triggered in a window of 10 ns. At least two modules in opposite hemispheres.
n+Gd	Signal between 50 and 2000 p.e. in between 1 and 150 μs. At least two modules. All modules triggered in a window of 10 ns.

Twofold comparison

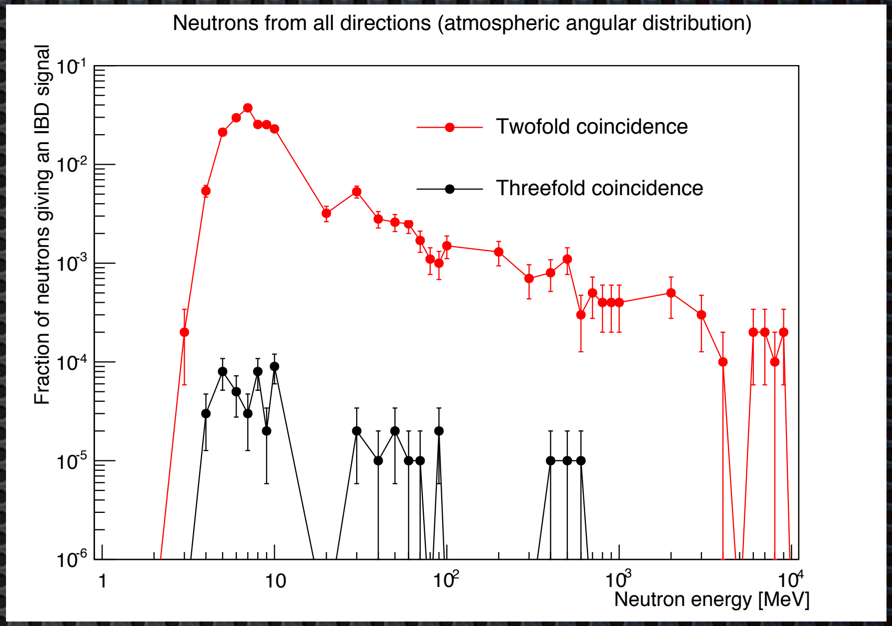
- To compare the performance of the threefold to the twofold coincidence in a fair way we considered a detector optimized to observe antineutrinos tagging the twofold coincidence of IBD in plastic scintillator i.e. a PANDA-like detector (Nucl.Instrum.Meth. A757 (2014) 33-39).
- We assumed 1 m^3 detector made of 100 scintillator bars 10 x 10 x 100 cm^3 each, coupled to the PMTs through light guides.
- Such a geometry was coded in the same MC we used for our proposed detector and the cuts were optimized for a maximal IBD signal acceptance and background rejection based on the PANDA analysis.

Cut	Twofold Coincidence
Prompt	All signals in 1 μs. Total energy between 1.2 and 10 MeV. Highest bar energy smaller than 6 MeV. Second highest bar energy between 0.2 and 0.5 MeV.
n+Gd	All signals between 6 and 200 μs. Total energy between 3 and 8 MeV. Highest bar energy smaller than 5 MeV. Second highest bar energy larger than 0.5 MeV.

Background rejection

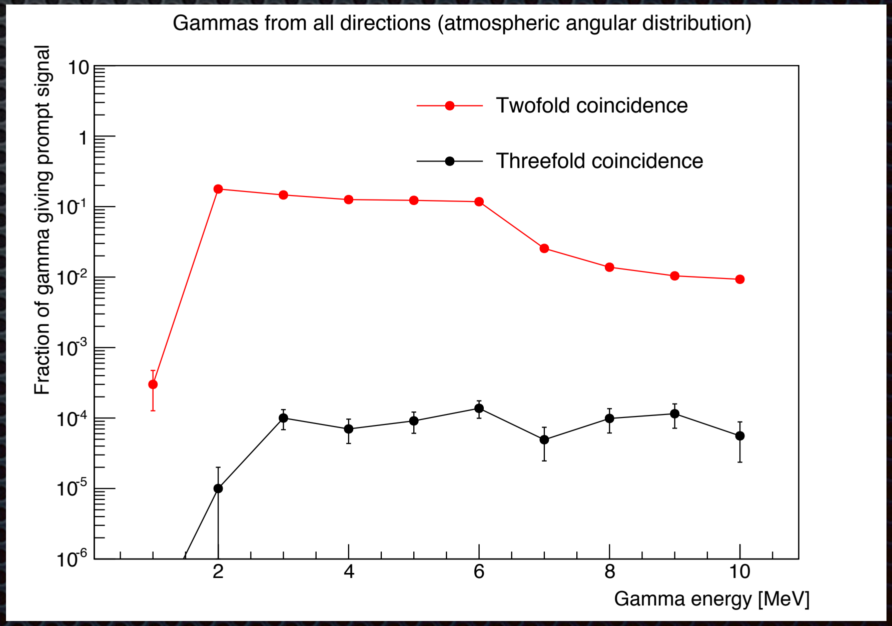
Neutrons

- The fraction of neutrons selected as IBD was computed as a function of their energy.
- For the threefold coincidence, we have a **rejection power larger** by a factor of **500 to 1000** depending on the energy with respect to the twofold coincidence.



Gammas

- For the gammas we computed the fraction of events giving a “prompt-like” signal, since this is important in accidental background whereas the neutron absorption on Gd in coincidence is identical for the twofold and threefold coincidence.
- For the threefold coincidence, we have a **rejection power larger** by more than **1200** below 5 MeV with respect to the twofold coincidence.



Signal efficiency

- The signal **efficiency** is unfortunately quite **low**: about **1.2 %** with the **threefold** coincidence.
- For a comparison the efficiency of the **twofold** coincidence is about **15%**.
- The major reduction comes from the positrons stopping in aerogel and the o-Ps formation, and not from the selection algorithms.

	Efficiency	Total efficiency
Positrons stopping in aerogel	23.4%	23.4%
Positrons forming o-Ps	26%	6.1%
o-Ps decaying after 10 ns	85%	5.2%
Fraction of n captured on Gd	92.9%	4.8%
o-Ps detection (algorithm selection)	50%	2.4%
n+Gd detection (algorithm selection)	49.2%	1.2%

Intrinsic efficiency (first four rows)

Selection efficiency (last two rows)

The efficiency x mass per unit volume must be increase to be competitive to "standard" detectors

Conclusions

- The possibility to use **o-Ps formation** signature in IBD events to **detect antineutrinos** was investigated.
- Studies on o-Ps formation fraction and lifetime were carried out on liquid and plastic scintillator as well as on passive porous materials.
- Given the results and the actual materials available the optimal solution so far is a **sandwich detector** made of active layers of **plastic scintillator** and passive layers of **aerogel**.
- Dedicated **measurements** on the **optics** and **time resolution** achievable were carried out to prove the feasibility of such a detector.
- Full MC simulations were developed to **compare** the physics potential of the **threefold** coincidence with respect to the **twofold** one.
- The proposed detector could **reduce** the background by about **three orders of magnitudes** with respect to detectors using the standard twofold coincidence (comparison carried out at equal volume and no shielding).
- The **weakness** of the proposed technique is the low antineutrino **detection efficiency** at the level of **1.2%**.
- To competitively build a detector based on the proposed technique **improvements** would be needed on the **material** side to **enhance** the fraction of formed **o-Ps**.