

# *Liquid*

physics potential...

**NOW Conference @ Ostuni (Italia)**

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CNRS / IN2P3 @ APC (Paris)

# what's is LiquidO?





**LiquidO** = **new detection framework**  
(liquid scintillator based)

**LiquidO** = **international proto-collaboration**  
(**physics** ↔ **demonstration ⊕ R&D**)

**~40 scientists ⊕ 16 institutions ⊕ 9 countries**  
**[Brasil, Canada, Chile, France, Germany, Italy, Japan, Spain, USA]**

# R&D

an appetiser ahead...

# first LiquidO presentation...





# our novel detection strategy...



**neutrino detection → art of transparency...**  
[Reines&Cowan since 50's]



## “perfection” since Reines&Cowan...

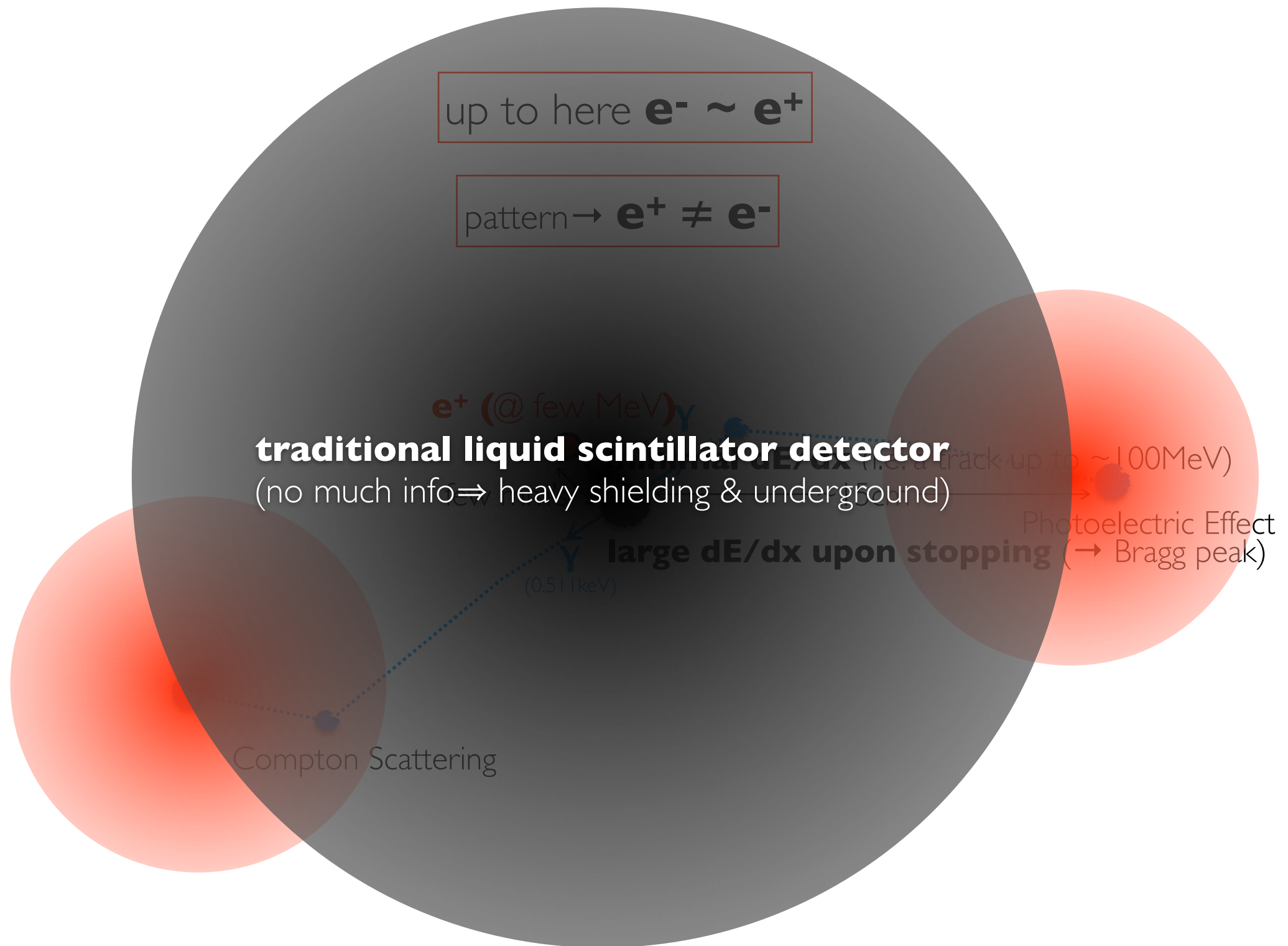
- exquisite **radio-purity**
  - **scintillation PSD** (“some” **PID**)
- at the expense...**
- **buffer volume** (PMT’s poor radio-purity)
  - **PID loss?** **[this talk]**

**PMT**( $\sim 1\text{ns}$ )  $\Leftrightarrow$  **Transparency**  $\Rightarrow$  **~~PID~~?**



an **Opaque** solution to PID....?

# $e^+$ PID limitation (illustration)...



**powerful event pattern washed out  $\Rightarrow$  hardly any ID!**

# *Liquid*

(first?)  $\nu$  opaque detector



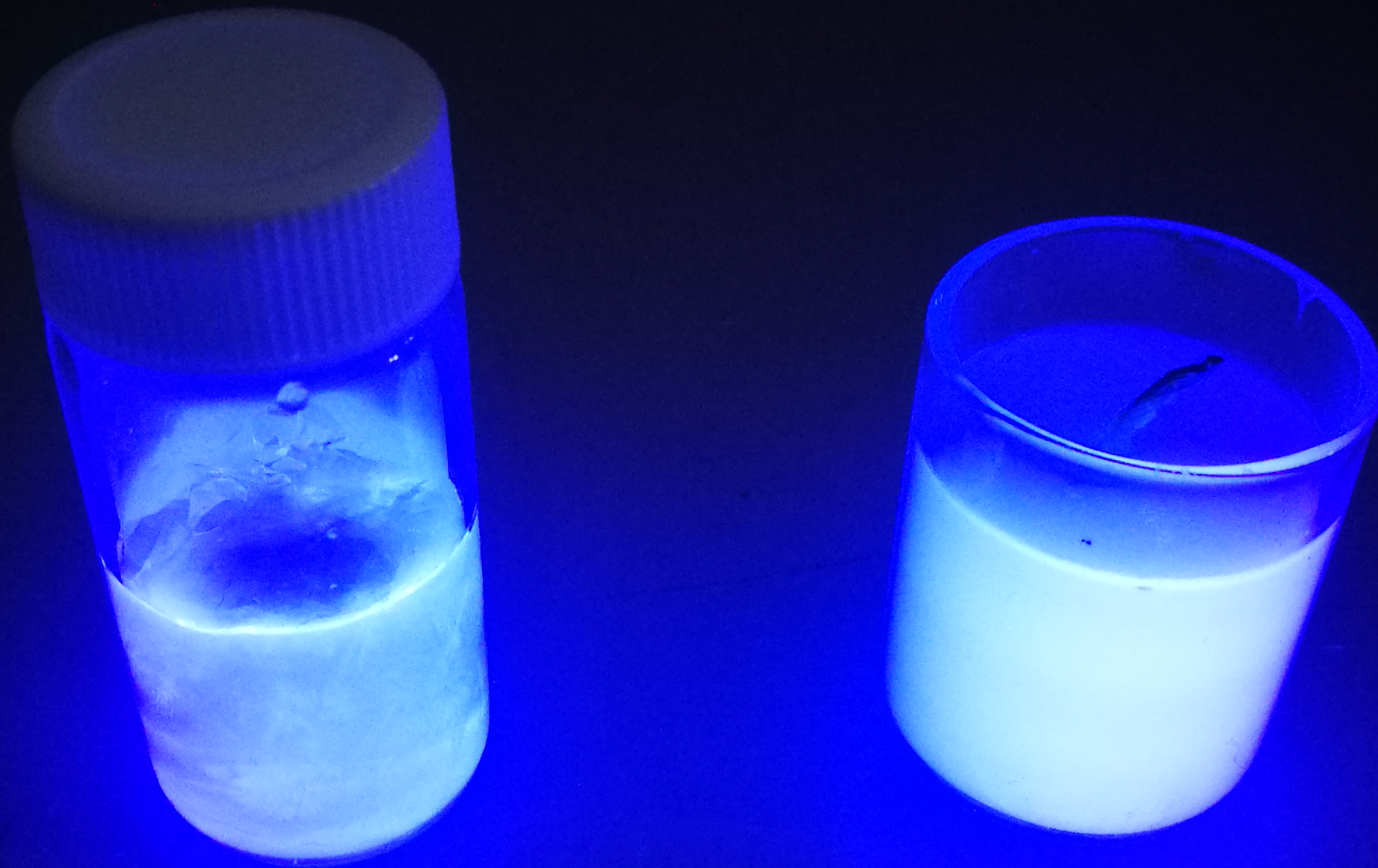


does



**LiquidO** = Liquid ⊕ Opaque





**liquid~wax behaviour**

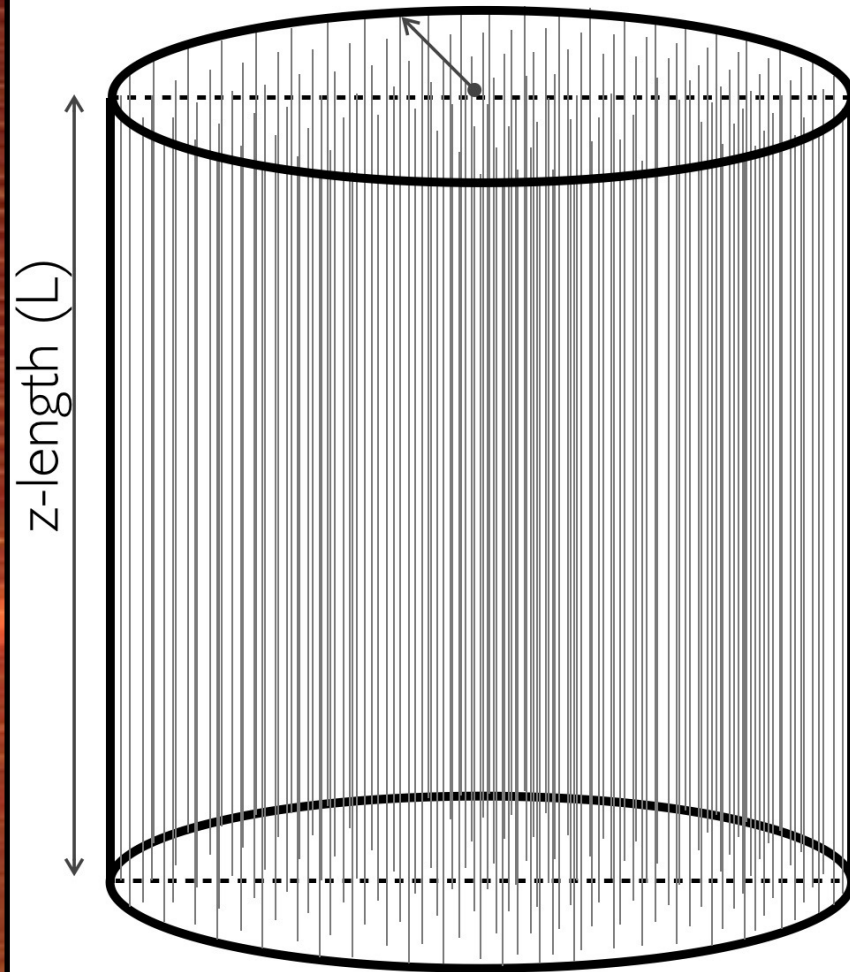
in reality, more like this...



# simplest LiquidO design: $2D \oplus \text{time}$ ...

very simple: **fibres** (a lot) + **LS**

radius (R) (plane x-y)



lattice distance:  $\xi$   
(a few cm)

**(x,y) info** [lattice  $\xi$ ]  $\rightarrow$  **image pixelation** (up to  $\sim 1$  cm)  
**(z) info** [along fibre]  $\rightarrow$  **time difference** (up to cm's)  
(also z-pixelation possible  $\rightarrow$  envisaged for R&D)

**image: multi-wire chamber**  
(by G. Charpak @ CERN)



**LiquidO  $\approx$  TPC (“drifting” light)**  
[highest possible duty-cycle]



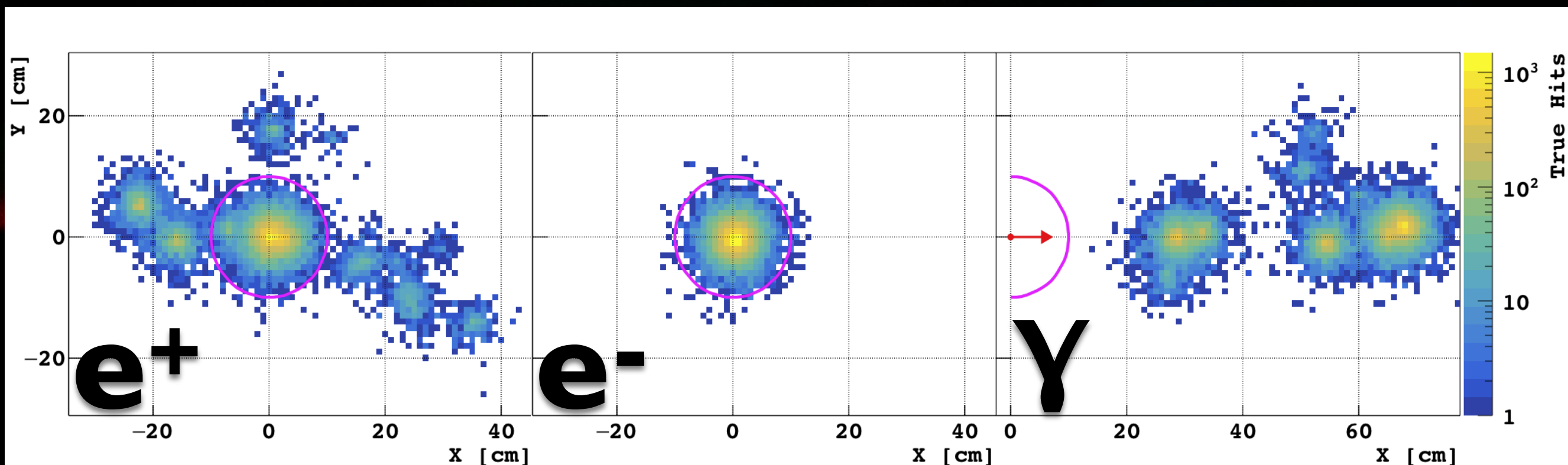


stunning event-pattern...



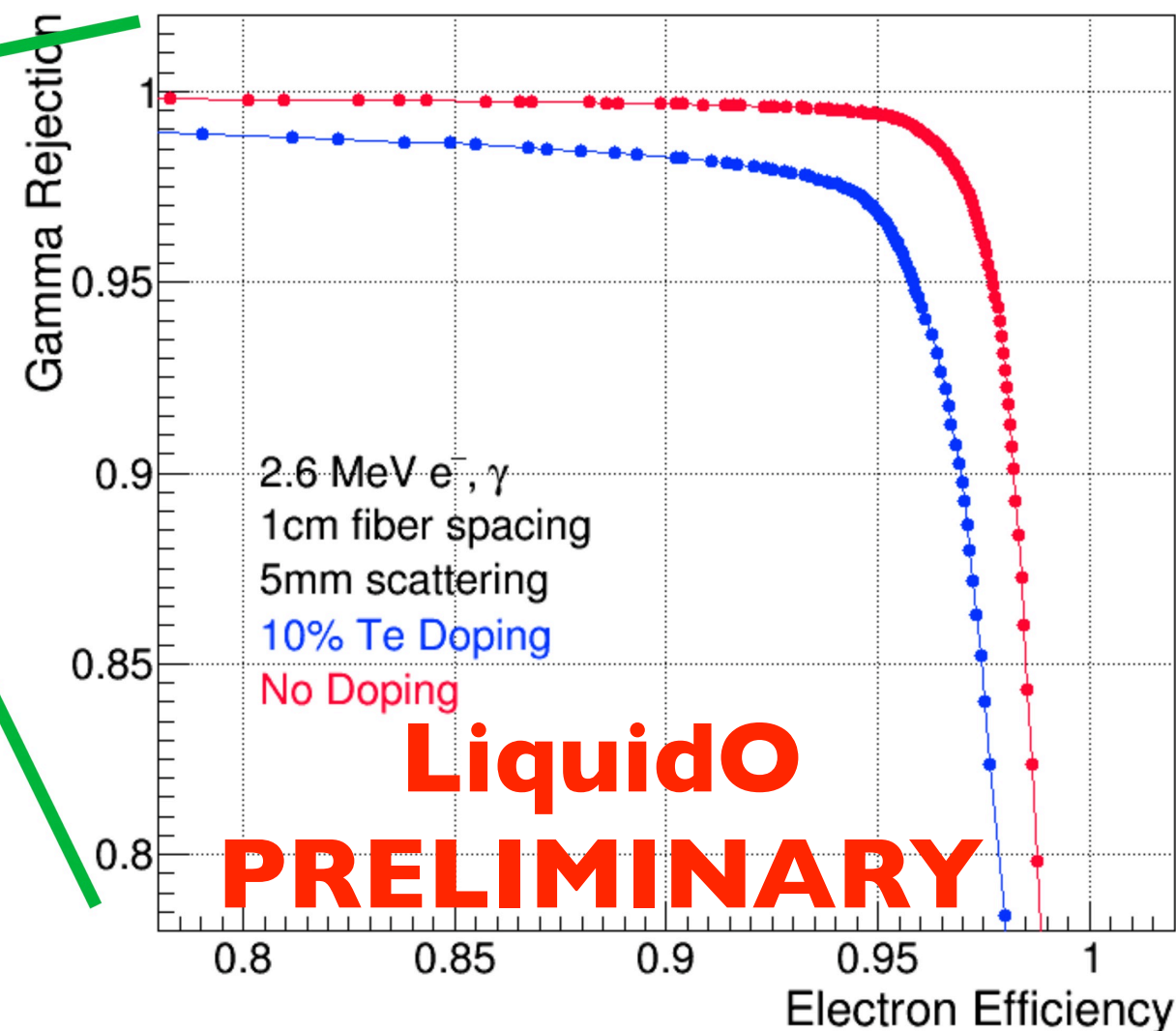
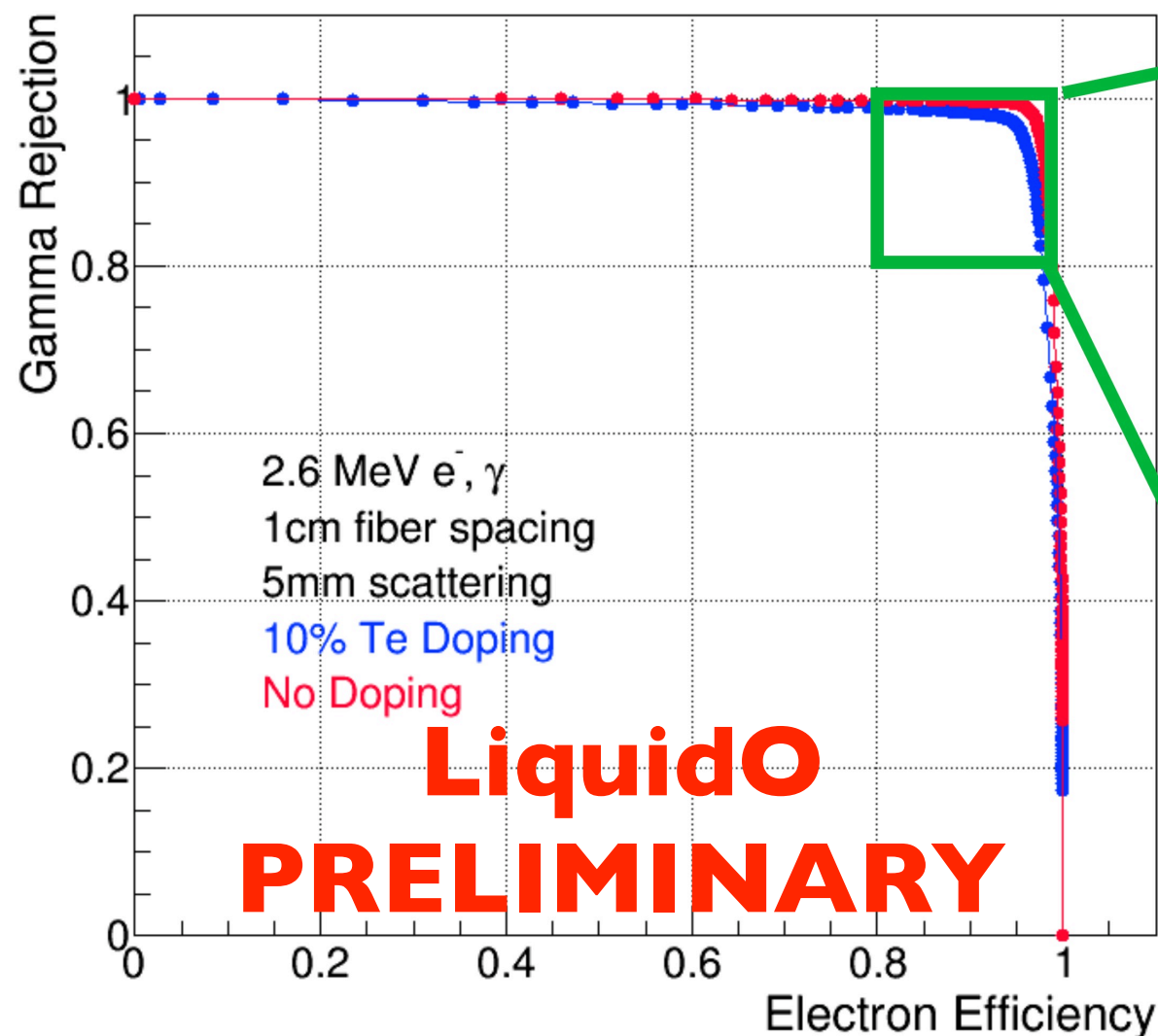
powerful PID expected...

**2MeV**



(rather evident)

# PID( $e^-:\gamma$ ) $\Rightarrow$ $\gamma$ rejection...



## PID $\gamma:e^-$ separation

- $I:\approx 10^3$  (native)
  - $I:\approx 10^2$  (10% heavy loading)
- [@ 80% detection efficiency]**

**unprecedented (major)  $\gamma$ -rejection! ( $\approx 100$ )**

indeed, an **Opaque** solution...!  
(so it appears)

(no need for segmentation)



**dope it?** non-native capability...





# physics under study...

- geo-neutrino?
- reactor neutrino (background-less)?
- solar neutrino (including pp)?
- supernova's CC ( $\nu_e$  &  $\bar{\nu}_e$ ) & NC?
- proton-decay?

[**sorry, no time!**]

# what physics?

(example)  $\beta\beta$ -decay...

Liquidon



Liquid  $\text{Ov}$ 

✓? maybe?

!!! R&amp;D

← ?

Toward NO

(K. Inoue, ICFA Seminar, 2017)

approx.

half lives

required mass

 $10^{25}$  y

10 kg ✓

 $10^{26}$  y

100 kg ✓

 $10^{27}$  y

1 ton

 $10^{28}$  y

10 ton X

 $10^{29}$  y

100 ton X

best results today!

today's aim!

&gt; I ton not know...

• how to do it!

nor

• how pay for it?

[enrichment: ~50M€/ton]

Because of the importance of

Ov  
gl  
sh  
the best way to

25

heavy

 $10^{-1}$  $10^{-2}$  $10^{-3}$  $10^{-4}$  $10^{-5}$  $10^{-6}$  $10^{-7}$  $10^{-8}$  $10^{-9}$  $10^{-10}$  $10^{-11}$  $10^{-12}$  $10^{-13}$  $10^{-14}$  $10^{-15}$  $10^{-16}$  $10^{-17}$  $10^{-18}$  $10^{-19}$  $10^{-20}$  $10^{-21}$  $10^{-22}$  $10^{-23}$  $10^{-24}$  $10^{-25}$  $10^{-26}$  $10^{-27}$  $10^{-28}$  $10^{-29}$  $10^{-30}$  $10^{-31}$  $10^{-32}$  $10^{-33}$  $10^{-34}$  $10^{-35}$  $10^{-36}$  $10^{-37}$  $10^{-38}$  $10^{-39}$  $10^{-40}$  $10^{-41}$  $10^{-42}$  $10^{-43}$  $10^{-44}$  $10^{-45}$  $10^{-46}$  $10^{-47}$  $10^{-48}$  $10^{-49}$  $10^{-50}$  $10^{-51}$  $10^{-52}$  $10^{-53}$  $10^{-54}$  $10^{-55}$  $10^{-56}$  $10^{-57}$  $10^{-58}$  $10^{-59}$  $10^{-60}$  $10^{-61}$  $10^{-62}$  $10^{-63}$  $10^{-64}$  $10^{-65}$  $10^{-66}$  $10^{-67}$  $10^{-68}$  $10^{-69}$  $10^{-70}$  $10^{-71}$  $10^{-72}$  $10^{-73}$  $10^{-74}$  $10^{-75}$  $10^{-76}$  $10^{-77}$  $10^{-78}$  $10^{-79}$  $10^{-80}$  $10^{-81}$  $10^{-82}$  $10^{-83}$  $10^{-84}$  $10^{-85}$  $10^{-86}$  $10^{-87}$  $10^{-88}$  $10^{-89}$  $10^{-90}$  $10^{-91}$  $10^{-92}$  $10^{-93}$  $10^{-94}$  $10^{-95}$  $10^{-96}$  $10^{-97}$  $10^{-98}$  $10^{-99}$  $10^{-100}$  $10^{-101}$  $10^{-102}$  $10^{-103}$  $10^{-104}$  $10^{-105}$  $10^{-106}$  $10^{-107}$  $10^{-108}$  $10^{-109}$  $10^{-110}$  $10^{-111}$  $10^{-112}$  $10^{-113}$  $10^{-114}$  $10^{-115}$  $10^{-116}$  $10^{-117}$  $10^{-118}$  $10^{-119}$  $10^{-120}$  $10^{-121}$  $10^{-122}$  $10^{-123}$  $10^{-124}$  $10^{-125}$  $10^{-126}$  $10^{-127}$  $10^{-128}$  $10^{-129}$  $10^{-130}$  $10^{-131}$  $10^{-132}$  $10^{-133}$  $10^{-134}$  $10^{-135}$  $10^{-136}$  $10^{-137}$  $10^{-138}$  $10^{-139}$  $10^{-140}$  $10^{-141}$  $10^{-142}$  $10^{-143}$  $10^{-144}$  $10^{-145}$  $10^{-146}$  $10^{-147}$  $10^{-148}$  $10^{-149}$  $10^{-150}$  $10^{-151}$  $10^{-152}$  $10^{-153}$  $10^{-154}$  $10^{-155}$  $10^{-156}$  $10^{-157}$  $10^{-158}$  $10^{-159}$  $10^{-160}$  $10^{-161}$  $10^{-162}$  $10^{-163}$  $10^{-164}$  $10^{-165}$  $10^{-166}$  $10^{-167}$  $10^{-168}$  $10^{-169}$  $10^{-170}$  $10^{-171}$  $10^{-172}$  $10^{-173}$  $10^{-174}$  $10^{-175}$  $10^{-176}$  $10^{-177}$  $10^{-178}$  $10^{-179}$  $10^{-180}$  $10^{-181}$  $10^{-182}$  $10^{-183}$  $10^{-184}$  $10^{-185}$  $10^{-186}$  $10^{-187}$  $10^{-188}$  $10^{-189}$  $10^{-190}$  $10^{-191}$  $10^{-192}$  $10^{-193}$  $10^{-194}$  $10^{-195}$  $10^{-196}$  $10^{-197}$  $10^{-198}$  $10^{-199}$  $10^{-200}$  $10^{-201}$  $10^{-202}$  $10^{-203}$  $10^{-204}$  $10^{-205}$  $10^{-206}$  $10^{-207}$  $10^{-208}$  $10^{-209}$  $10^{-210}$  $10^{-211}$  $10^{-212}$  $10^{-213}$  $10^{-214}$  $10^{-215}$  $10^{-216}$  $10^{-217}$  $10^{-218}$  $10^{-219}$  $10^{-220}$  $10^{-221}$  $10^{-222}$  $10^{-223}$  $10^{-224}$  $10^{-225}$  $10^{-226}$  $10^{-227}$  $10^{-228}$  $10^{-229}$  $10^{-230}$  $10^{-231}$  $10^{-232}$  $10^{-233}$  $10^{-234}$  $10^{-235}$  $10^{-236}$  $10^{-237}$  $10^{-238}$  $10^{-239}$  $10^{-240}$  $10^{-241}$  $10^{-242}$  $10^{-243}$  $10^{-244}$  $10^{-245}$  $10^{-246}$  $10^{-247}$  $10^{-248}$  $10^{-249}$  $10^{-250}$  $10^{-251}$  $10^{-252}$  $10^{-253}$  $10^{-254}$  $10^{-255}$  $10^{-256}$  $10^{-257}$  $10^{-258}$  $10^{-259}$  $10^{-260}$  $10^{-261}$  $10^{-262}$  $10^{-263}$  $10^{-264}$  $10^{-265}$  $10^{-$

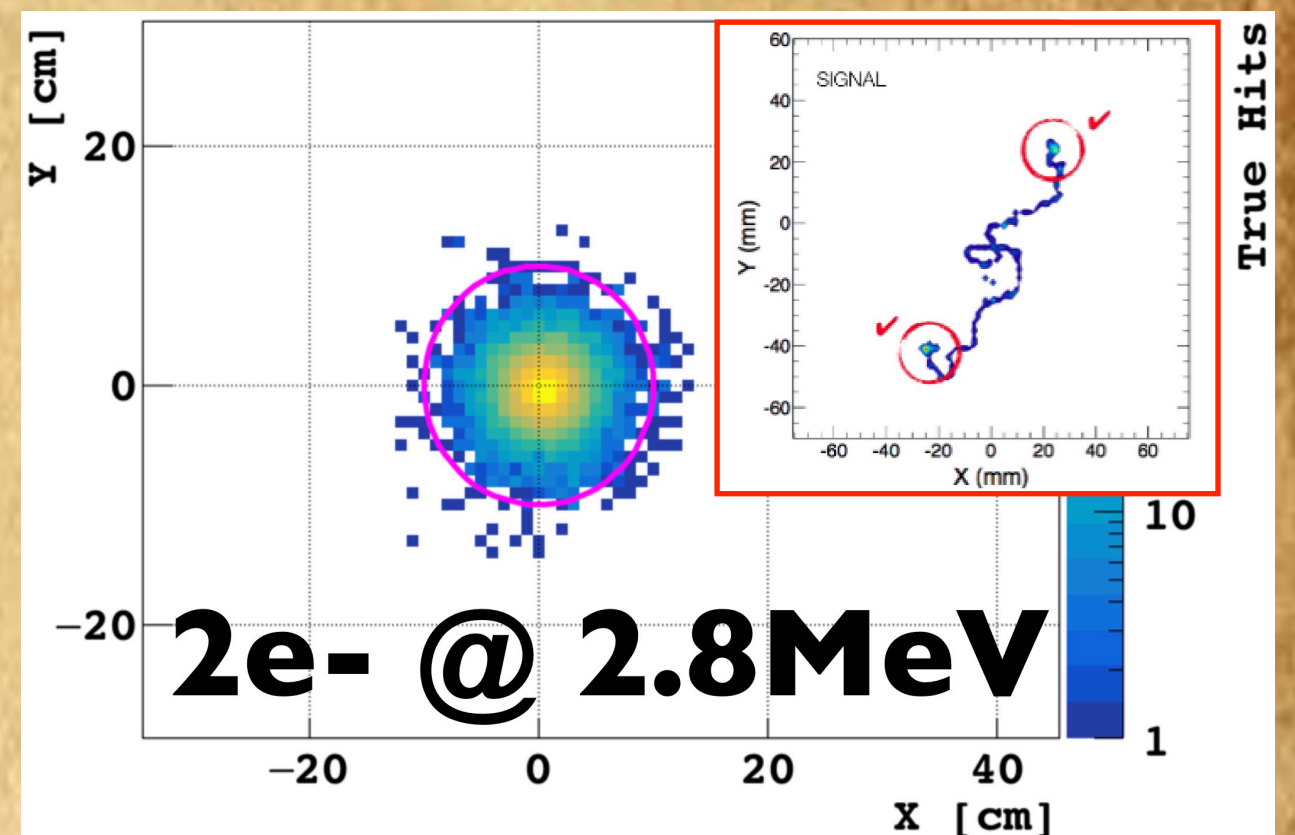
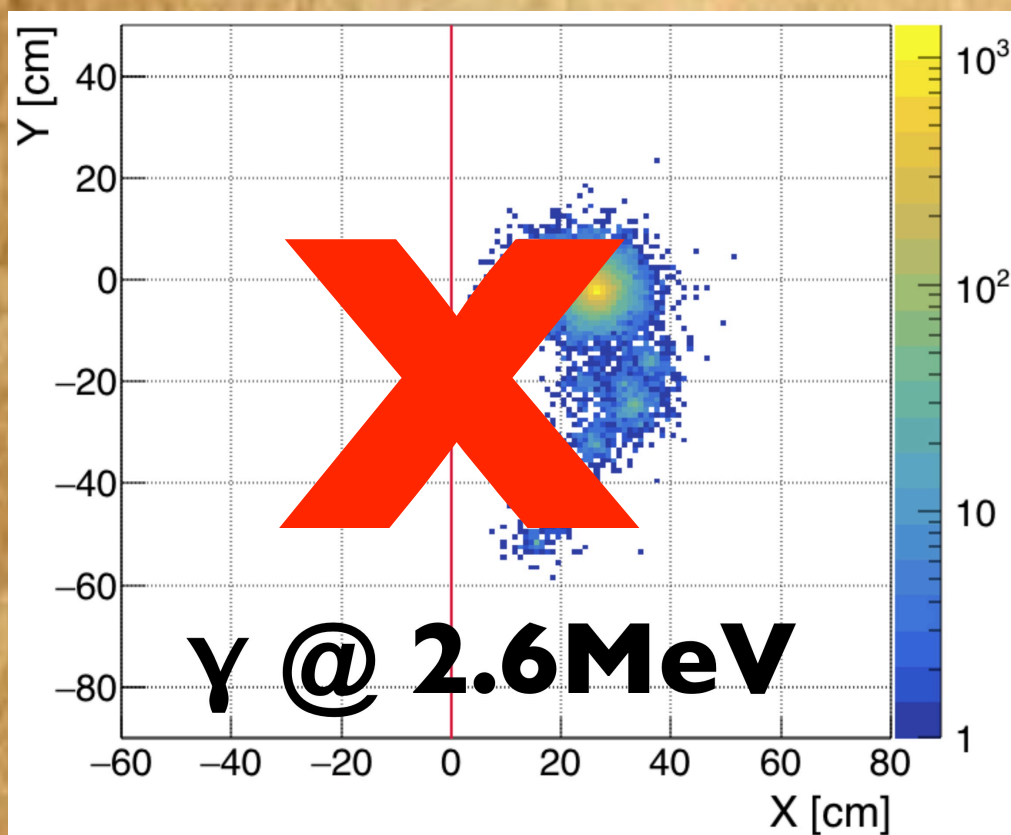
the Normal Ordering challenge...

Liquidov



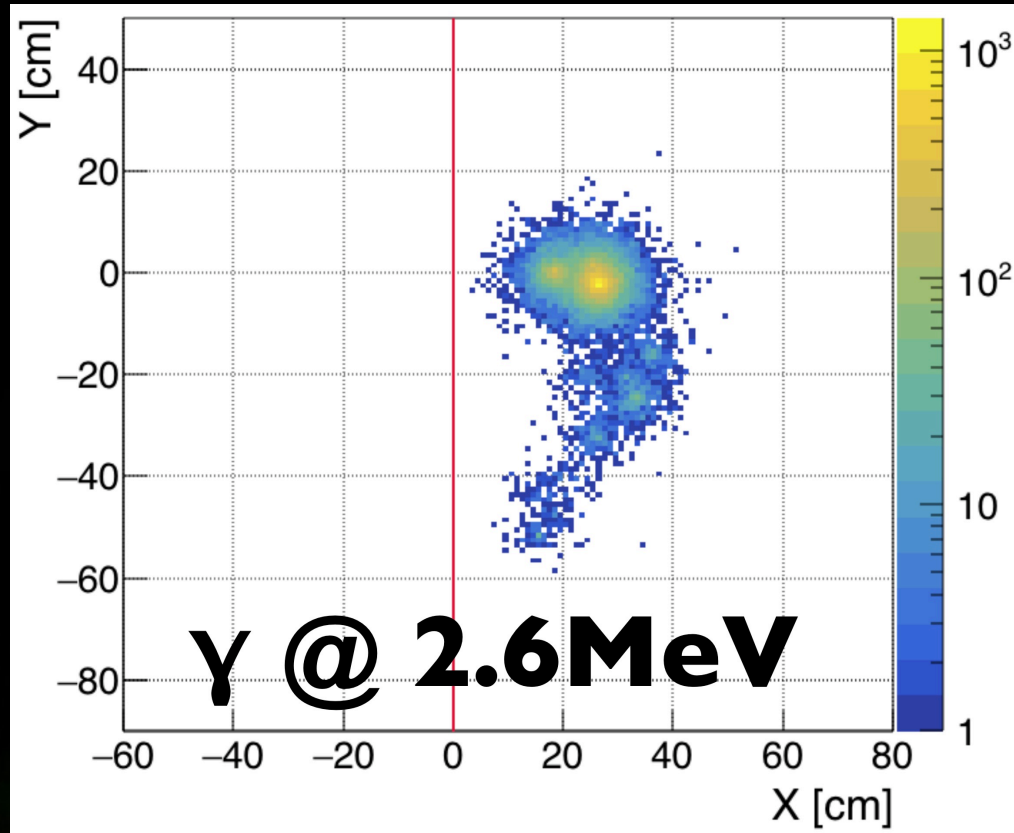
# WANTED

## DEAD OR ALIVE



**REWARD** unprecedented neutrino physics!!





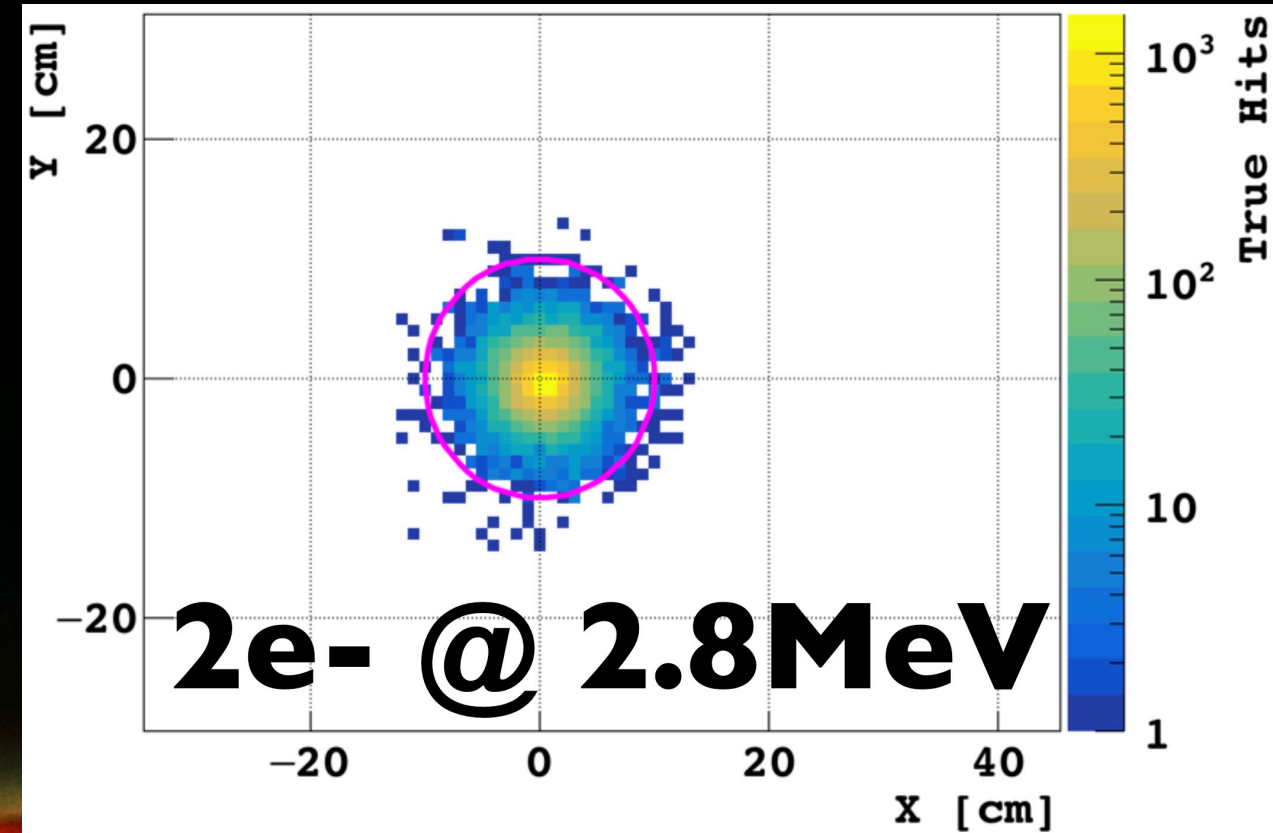
## non point-like

### natural radio-activity ( $\gamma$ )

- internal & external  $^{208}\text{Tl}$  and  $^{214}\text{Bi}$

→ **PID reduced & acceptance [next]**

- **no(?) exotic  $\gamma$  decays (no enrichment)**



## point-like

### natural radio-activity ( $e^-$ ) or $2\beta 2\nu$

internal & irreducible

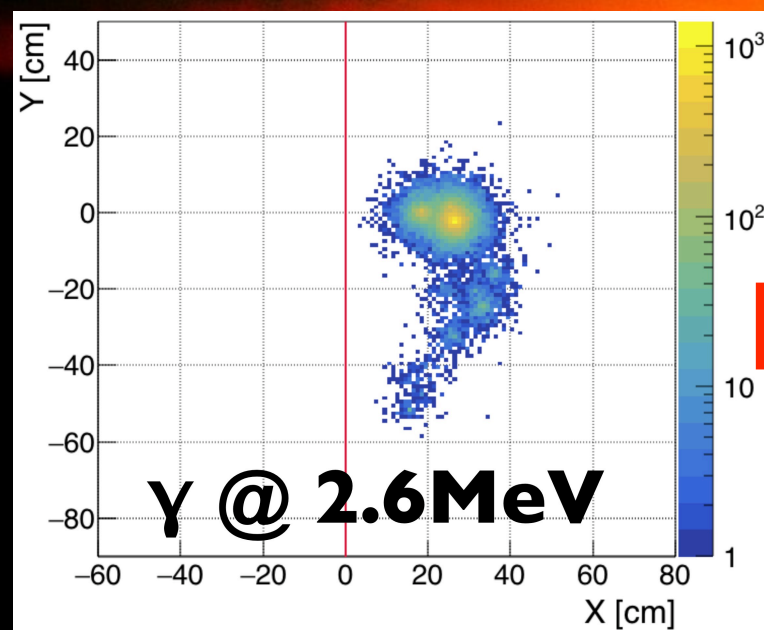
### no(?) $\alpha$ -BG

$\alpha$ -response quenched  $\leq 1\text{ MeV}$   
[cross-check Ge or Bolometers]

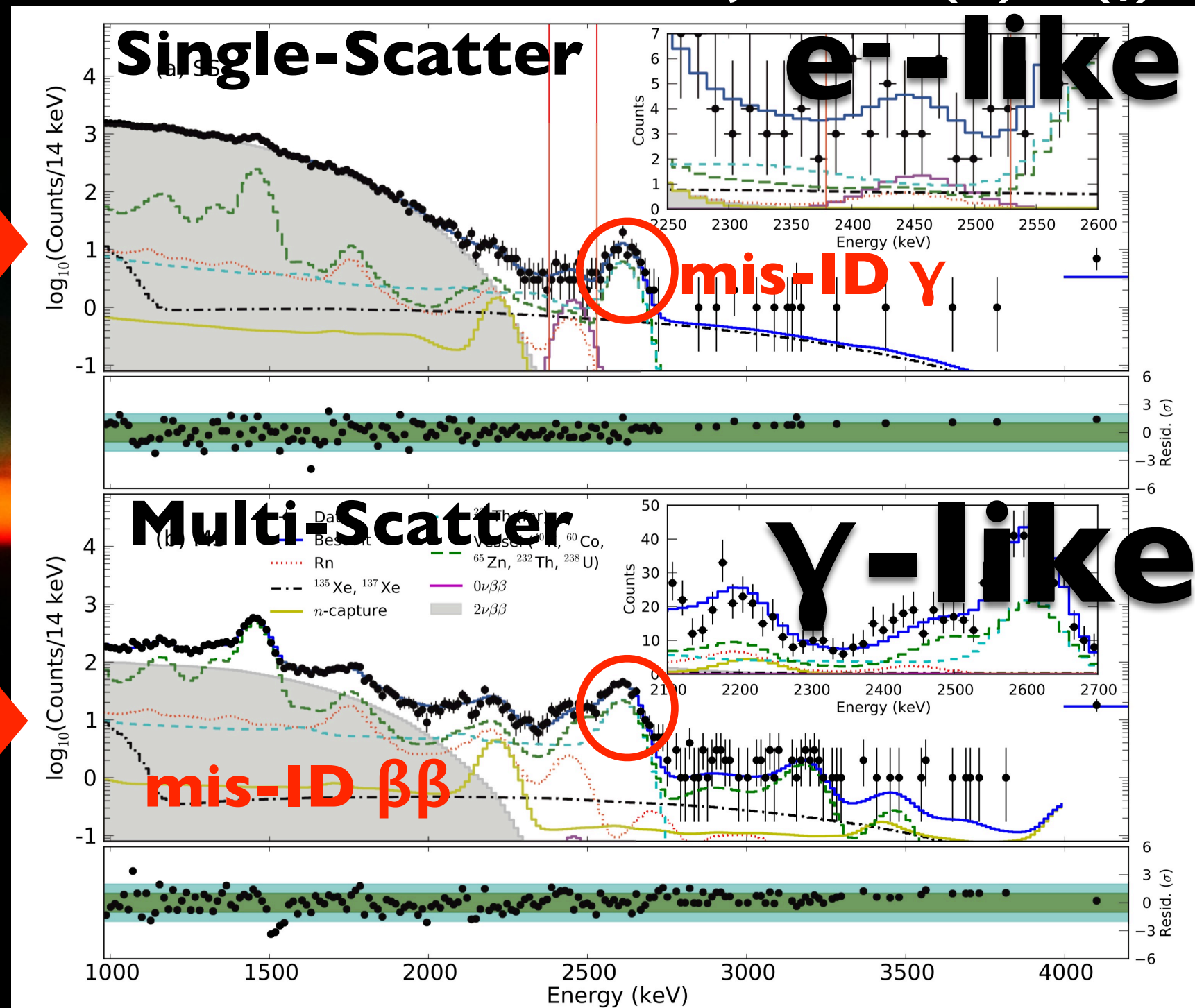
### no(?) Rn

hermetic solidified scintillator  
(no liquid convection)

## EXO's rejection $I(e^-):I_0(\gamma)??$

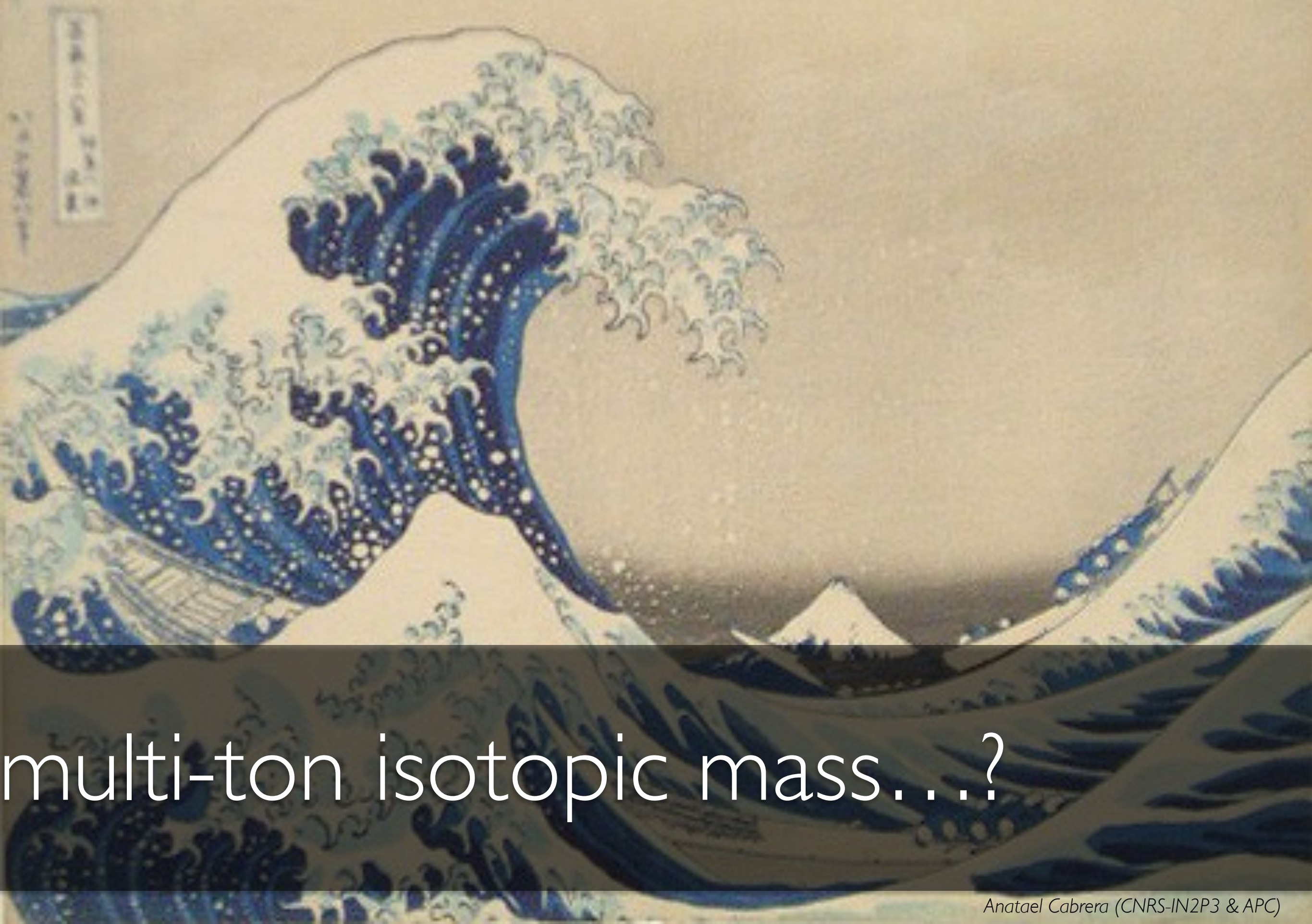


**rejected  $\gamma$  [ $1:\geq 10^2$ ]**



**no PID  $\Rightarrow$  only one spectra with ALL BG in [SNO+/KLZ]**





multi-ton isotopic mass...?



# LiquidO's multi-tone $\beta\beta$ loading strategy...

detector size		100m <sup>3</sup>				3000m <sup>3</sup>	
isotopic ton		0.1	1.0	10.0	100.0	100.0	1000.0
enriched	mass	0.1ton	~1ton	10ton	100ton	100ton	
	loading	<b>0.1%</b>	<b>1.0%</b>	<b>10.0%</b>	<b>100.0%?</b>	<b>3.3%</b>	
	cost	[1,5]M€	[10,50]M€	[100,500]M€	[1,5]G€	[1,5]G€	
natTe NA( <sup>130</sup> Te):33.8%	mass	0.3ton	2.9ton	29ton	290ton	290ton	2900ton
	loading	<b>0.3%</b>	<b>2.9%</b>	<b>29.0%</b>	<b>290%</b>	<b>10%</b>	<b>100%?</b>
	cost	[2.9,29]k€	[29,290]k€	[0.3,2.9]M€	[2.9,29]M€	[2.9,29]M€	[29,290]M€
natNd NA( <sup>150</sup> Nd):5.6%	mass	1.8ton	17.9ton	179ton		1790ton	
	loading	<b>1.8%</b>	<b>17.9%</b>	<b>179%</b>		<b>60%</b>	
	cost	[20,200]k€	[0.2,2.0]M€	[2,20]M€		[20,200]M€	
natCd NA( <sup>106</sup> Cd):1.2%	mass	8.3ton	83.3ton				
	loading	<b>8.3%</b>	<b>83.3%?</b>				
	cost	[83,833]k€	[0.8,8.3]M€				
sensitivity		ruled out	~10 bound	Normal Ordering exploration			

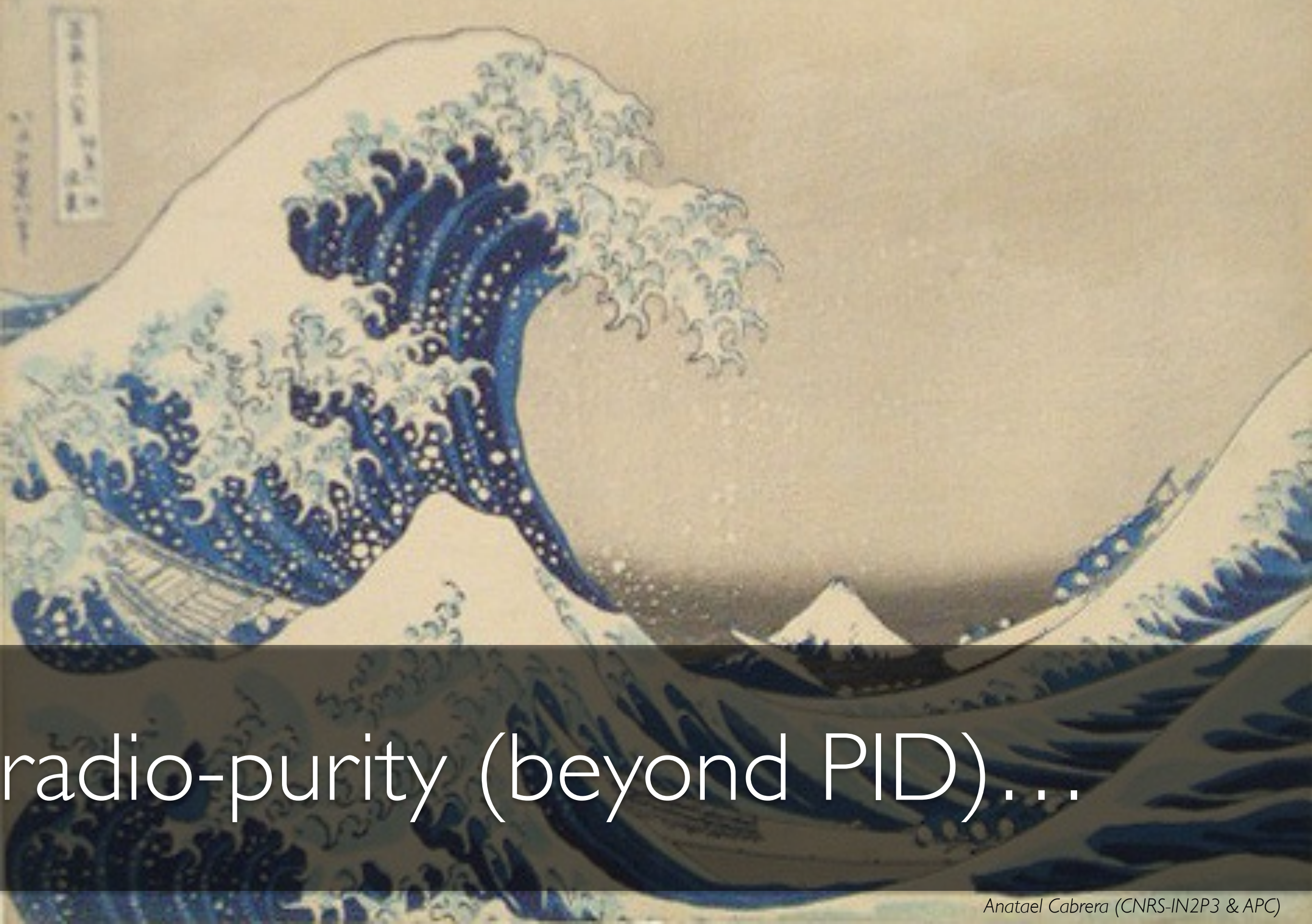
R&D Te & Nd by SNO+

**Te & Se?/Mo? → 10ton** (DC-like detector)

**Te & Nd → several 100ton** (KLZ/SNO-like detector)

preliminary costing is promising thanks to the **large enriched costing**





radio-purity (beyond PID)...

**scintillator** → R&D Borexino ✓  
⊕

**fibres** → R&D GERDA ✓?  
**(under study)**  
⊕

~~**photo-detector**~~ → **outside!** ✓  
⊕

**Te** → R&D SNO+/CUORE ✓?  
or

**Nd** → R&D SNO+ ✓?

**only natural radioactivity**

[no enrichment → less contamination risk?]





fibres are rather ok!! **good enough?**  
**(under estimation)**



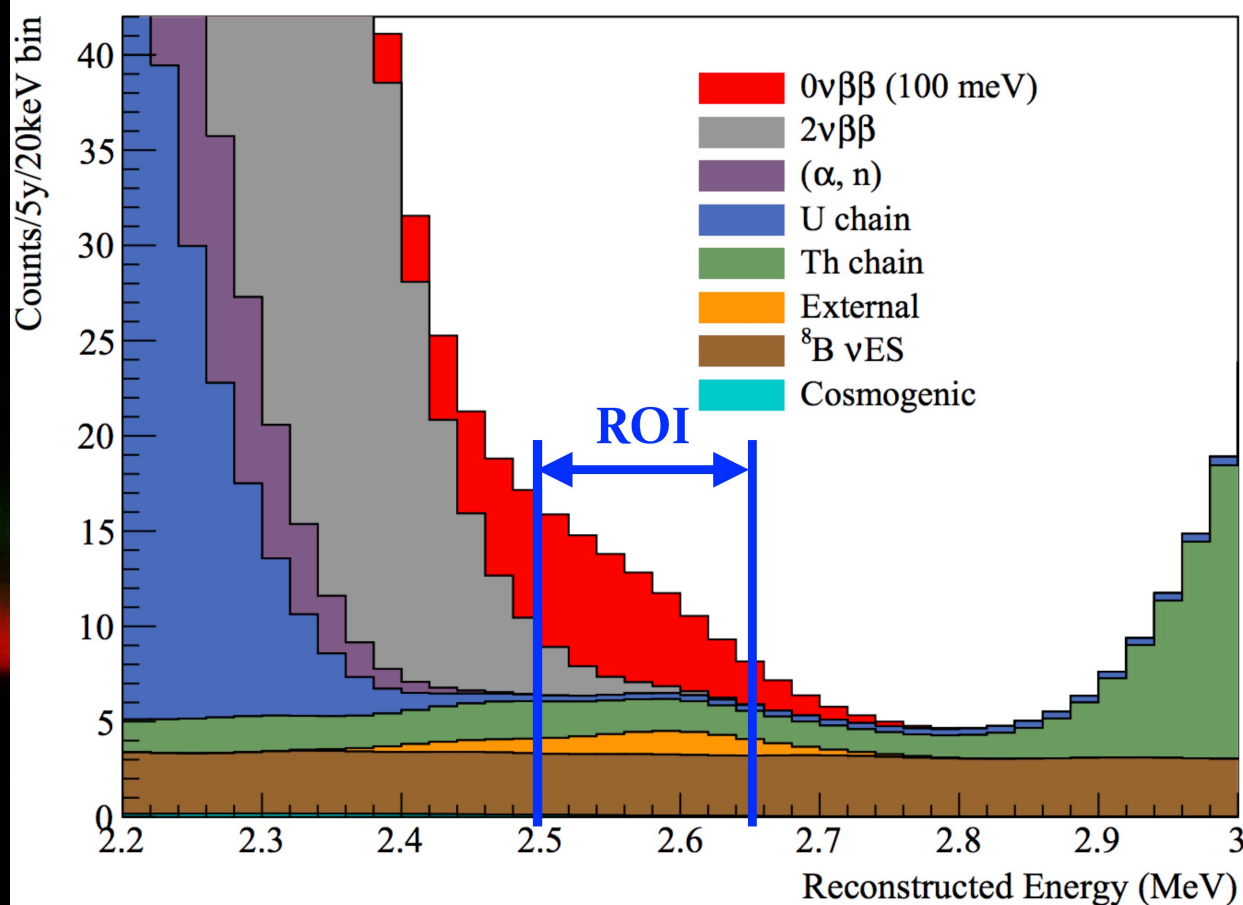
**energy resolution?**  
(like KLZ or SNO+)

**7%@1MeV → 4%@3MeV**  
[LiquidO expected  $\leq 400\text{PE/MeV(max)}$ ]

**2 $\beta$ 2 $\nu$  not a show-stopper**  
[sensitivity demonstrated]



# SNO+ Spectrum



ROI:  $-0.5 - 1.5 \sigma$  (2.49-2.65 MeV)

Predict 12.4 counts/yr in yr 1

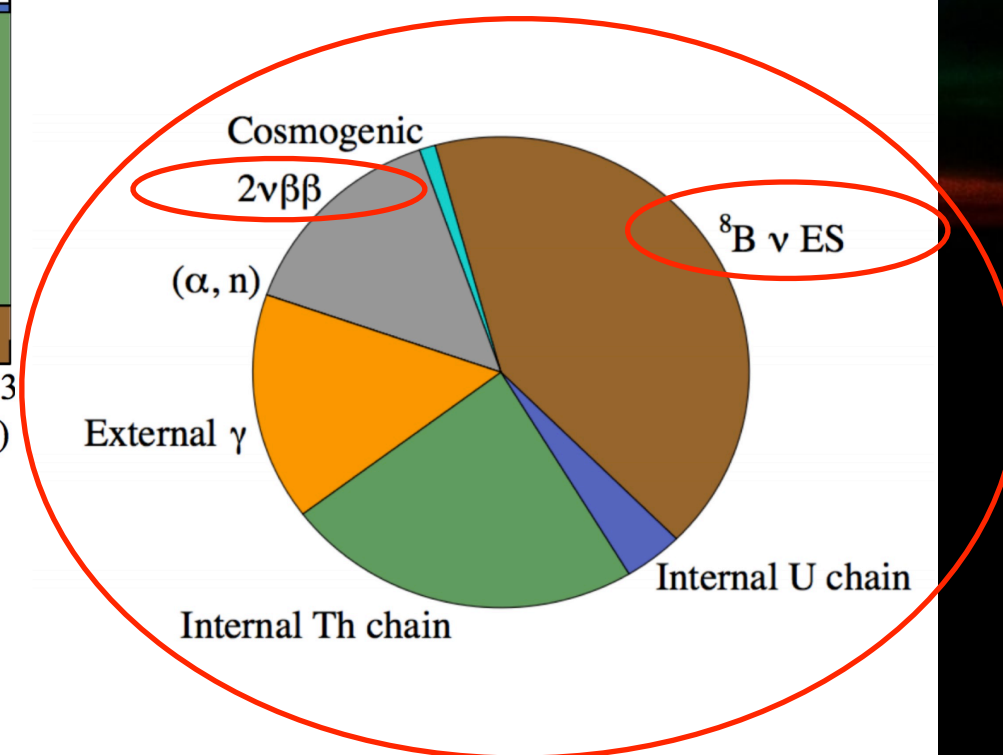
$\sim 10^{-6}/\text{keV.kg.yr}$

## Detector configuration:

0.5% natural Te

5 years live time

3.3m fiducial volume (17%)



LiquidO- $\beta\beta$ (Nd) = SNO+(R&D-Nd)  $\oplus$  fibres  $\oplus$  PID  
**[potentially more BG robust via Q-value]**





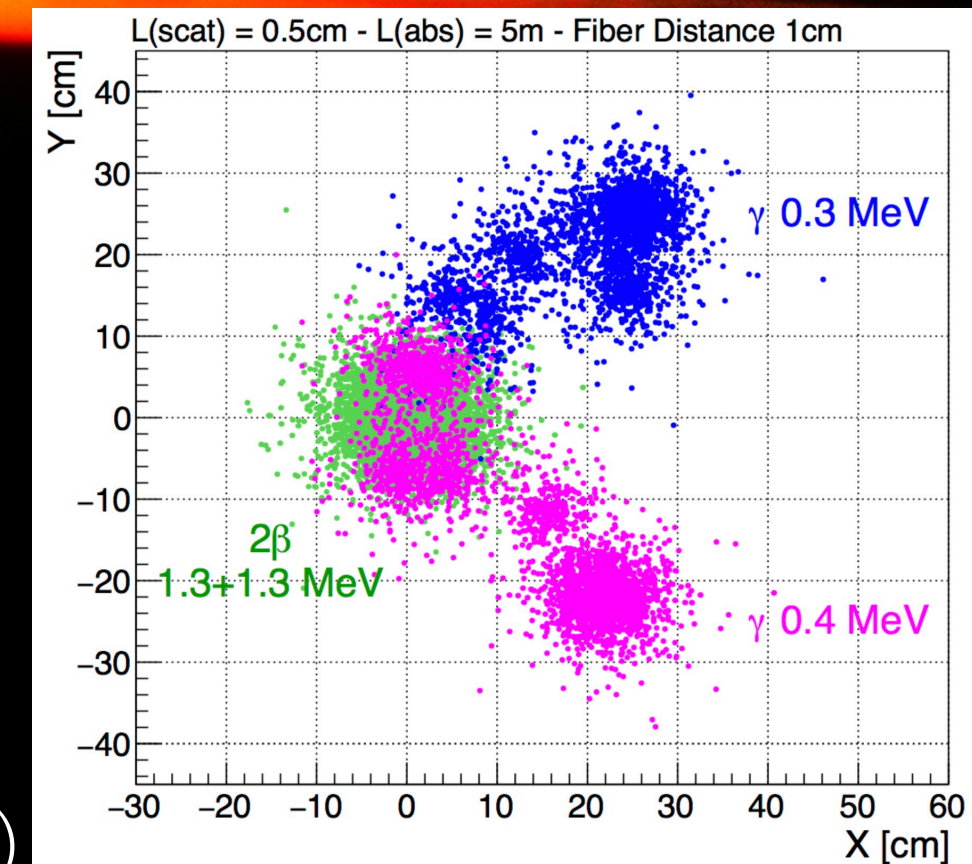
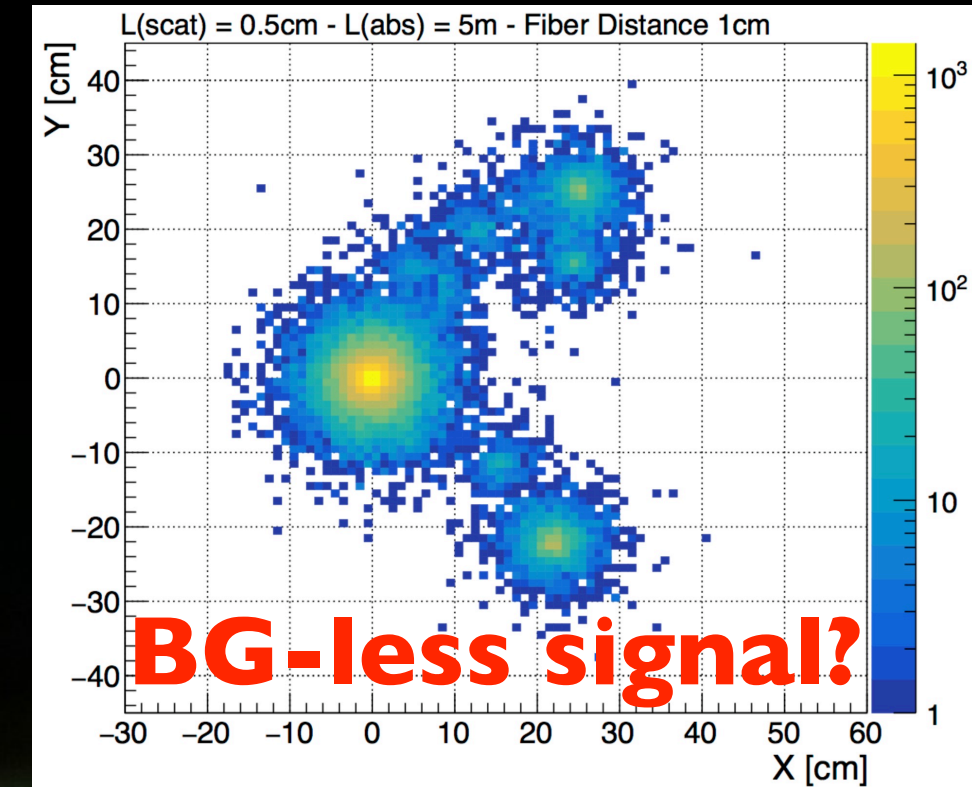
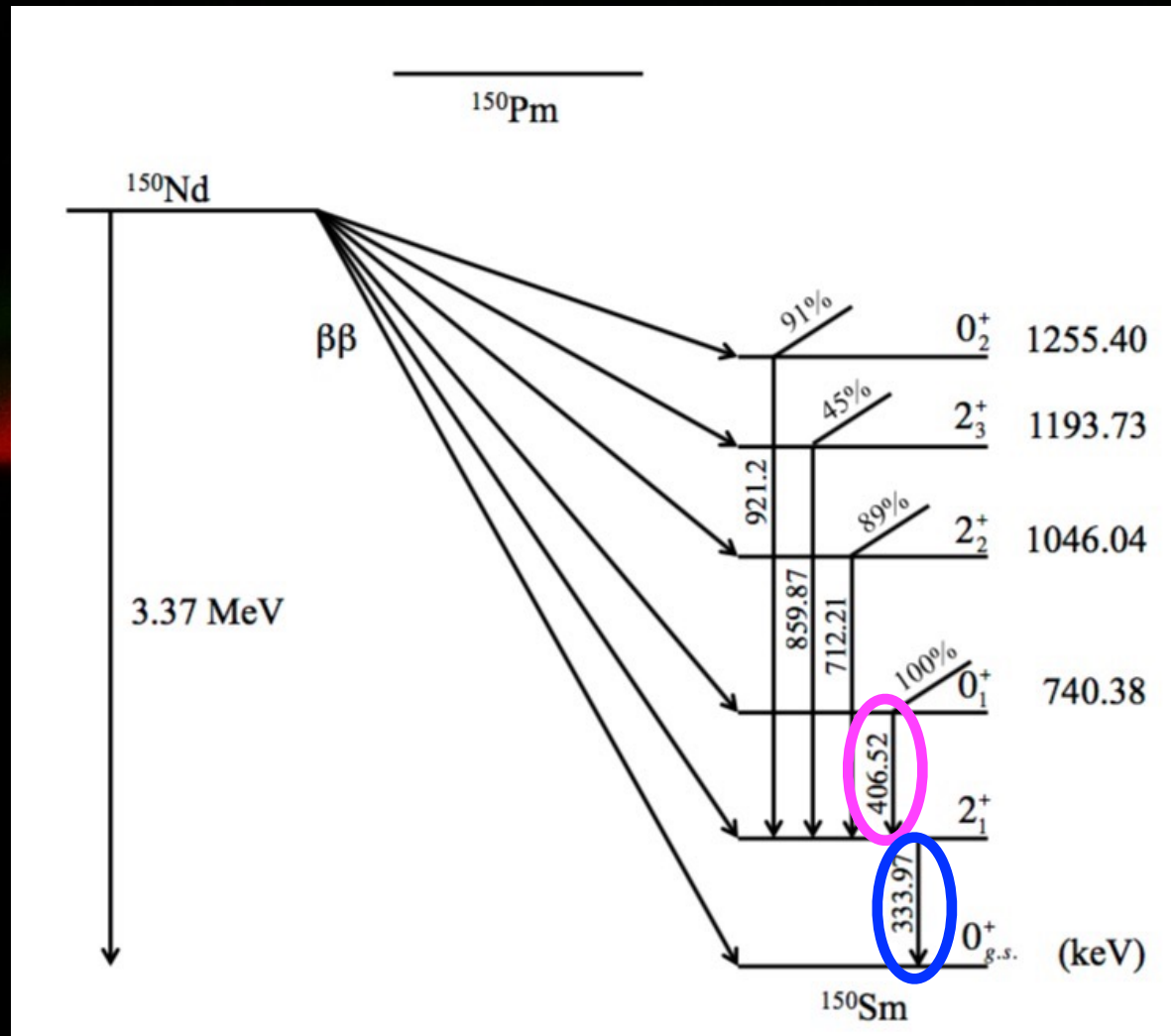
(unique?) signal redundancy...



$$\beta\beta [E = Q(3370\text{keV}) - E(\gamma 1) - E(\gamma 2)]$$

$\gamma 1$  (~406 / ~712 / ~859 / ~921) keV

$\gamma 2$  (~334 keV)



**if discovery → internal validation!**

(same detector ⊕ same Q-value ⊕ **different BG**)

full sensitivity (not yet)...

**$O(100\text{ton})$  potential needed  
for Normal Ordering**

(BG will tell if possible)

(BG evaluation)

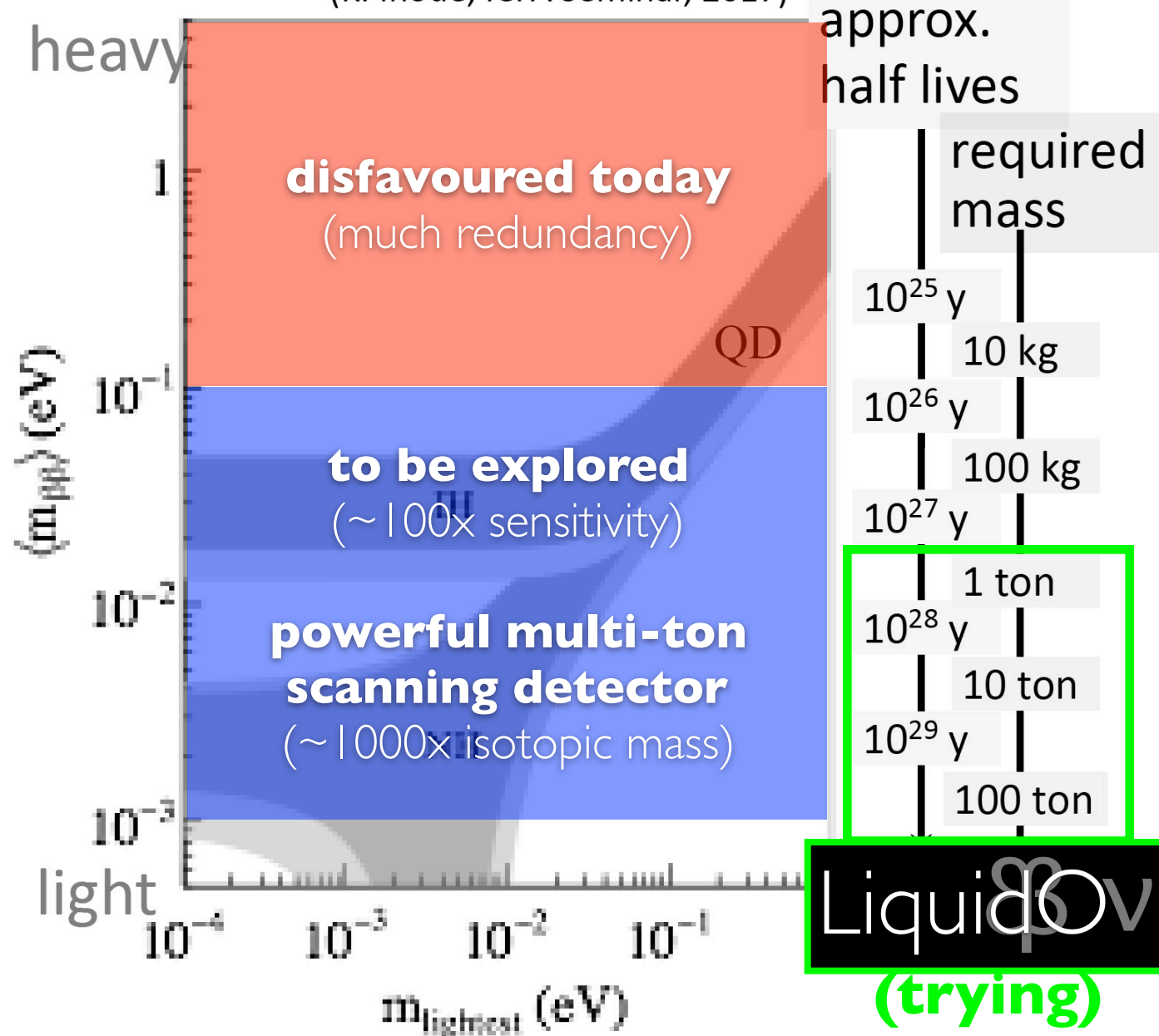


# exploring potential R&D...

- ✓• **huge mass capability** (→ enrichment cost impractical)
- ✓• **powerful PID** [full reconstruction → better?]
- ??• exquisite radio-purity potential → **good enough?**
- ✓• **BG redundancy** → accurate BG model prediction & control
- ✓• modest energy resolution (→  $2\beta 2v$  seems acceptable)
- ✓• **unique signal redundancy** → discovery ambiguity

# Toward NO

(K. Inoue, ICFA Seminar, 2017)



If we want to cover most of NO, we need;

- ✓ ~100 ton class detector,
- ✓ with reduced background (BG rate must be reduced by 1/mass · time or better),
- ✓ ....

Because of the importance of  $0\nu\beta\beta$ , I really think that the global neutrino community should work together, and find the best way to observe them.

**phase-I: vast exploring machine** (LHC-like; i.e. not a “Ferrari”) → **LiquidO pragmatic enough?**

**phase-II: upon discovery** → high precision on signal (LEP-like) → **the ultimate “Ferrari”?**



# physics under study...

- geo-neutrino?
  - reactor neutrino (background-less)? [**backup**]
  - solar neutrino (including pp)?
  - supernova's CC ( $\nu_e$  &  $\bar{\nu}_e$ ) & NC?
  - proton-decay?
- [**sorry, no time!**]

## what physics?



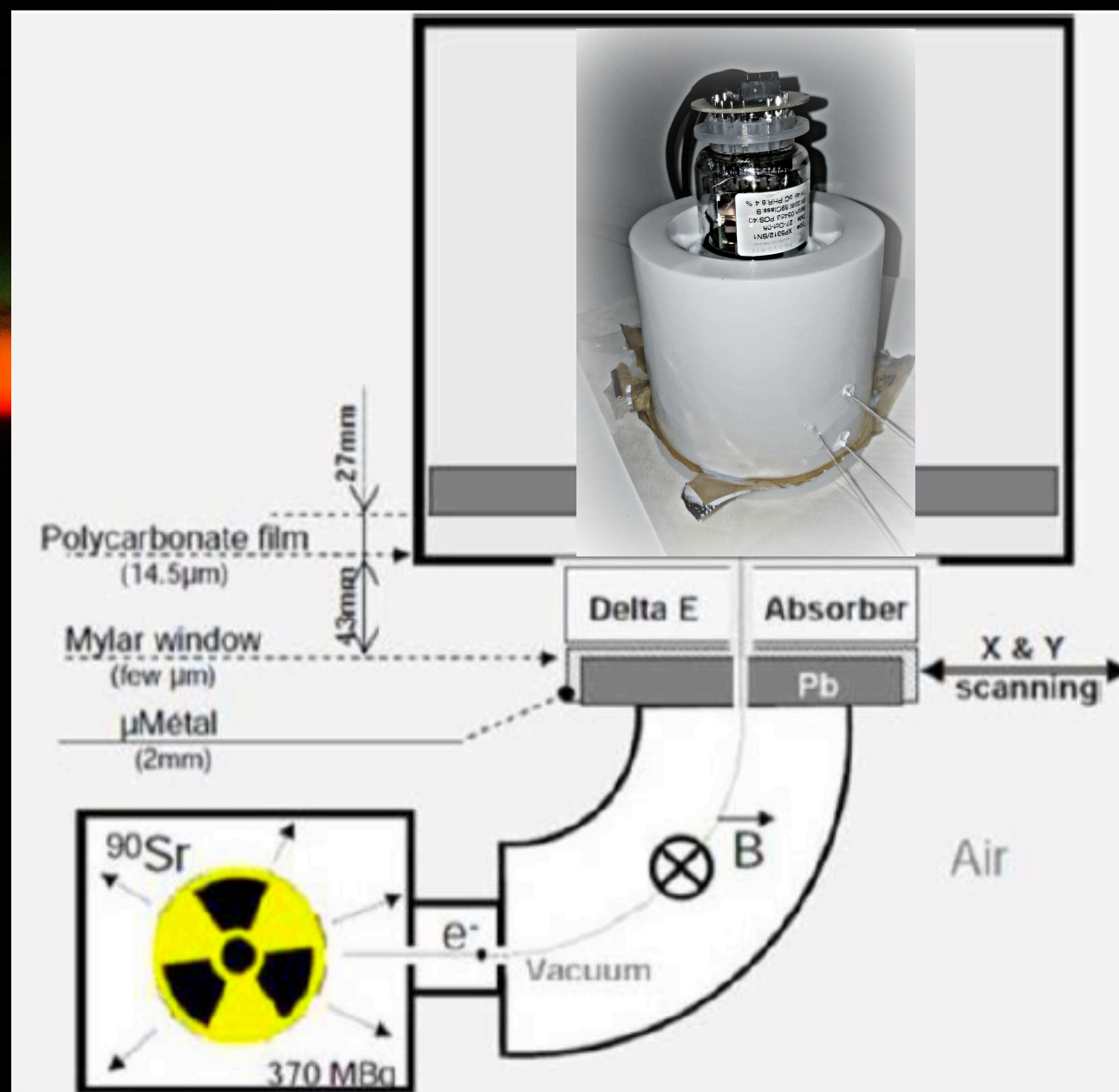
news!!!



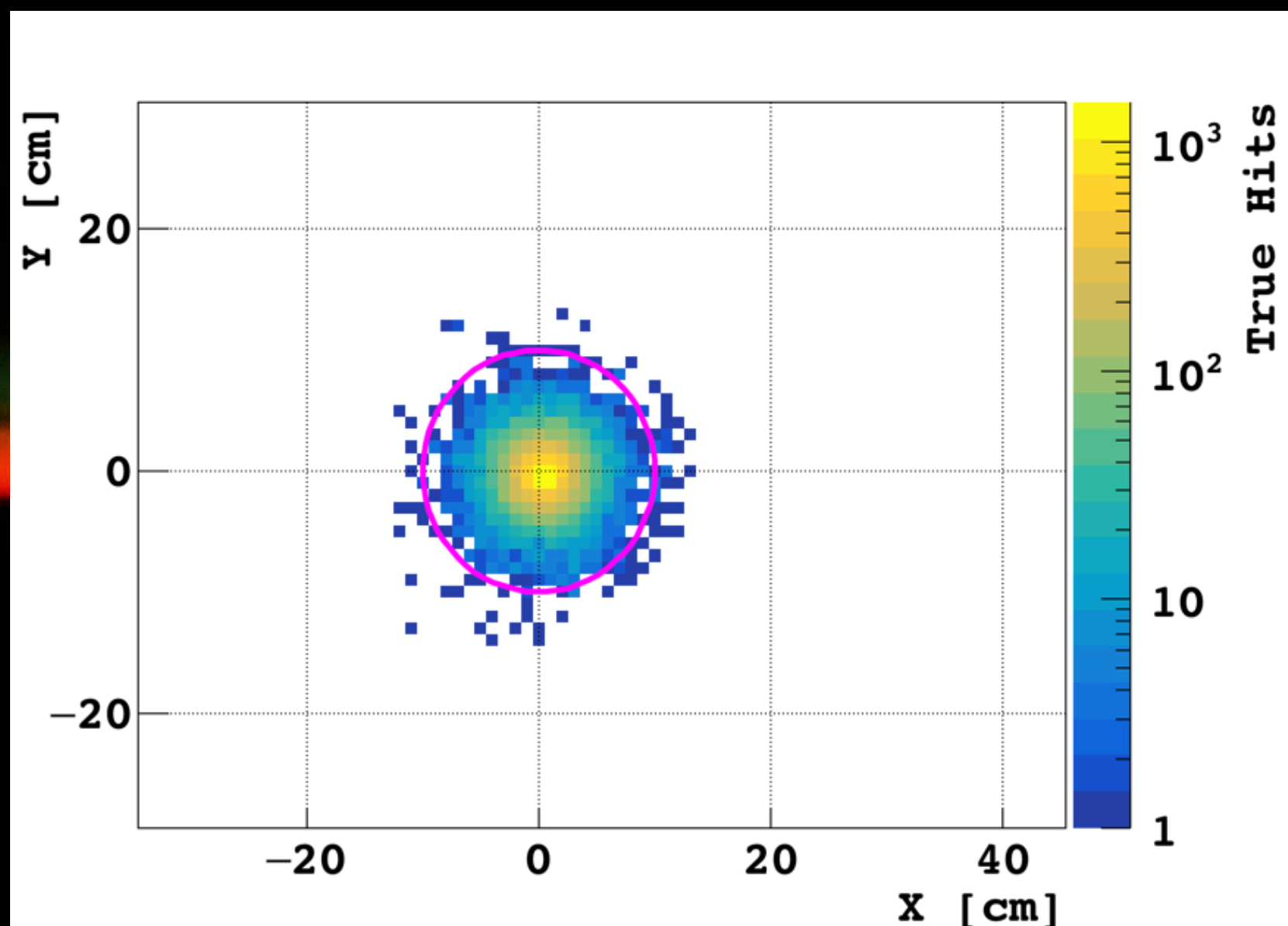
first experimental validation



# $\mu$ -LiquidO prototype...



the goal: 1 MeV  $e^-$  injection....



**LiquidO unique signature!**



**3x fibres:**

- fibre-0: 1.0cm
- fibre-1: 2.5cm
- fibre-2: 4.0cm

**~5cm tall**  
(PMT face)

**e<sup>-</sup>⊙**

**Mylar**

**2 scintillators**

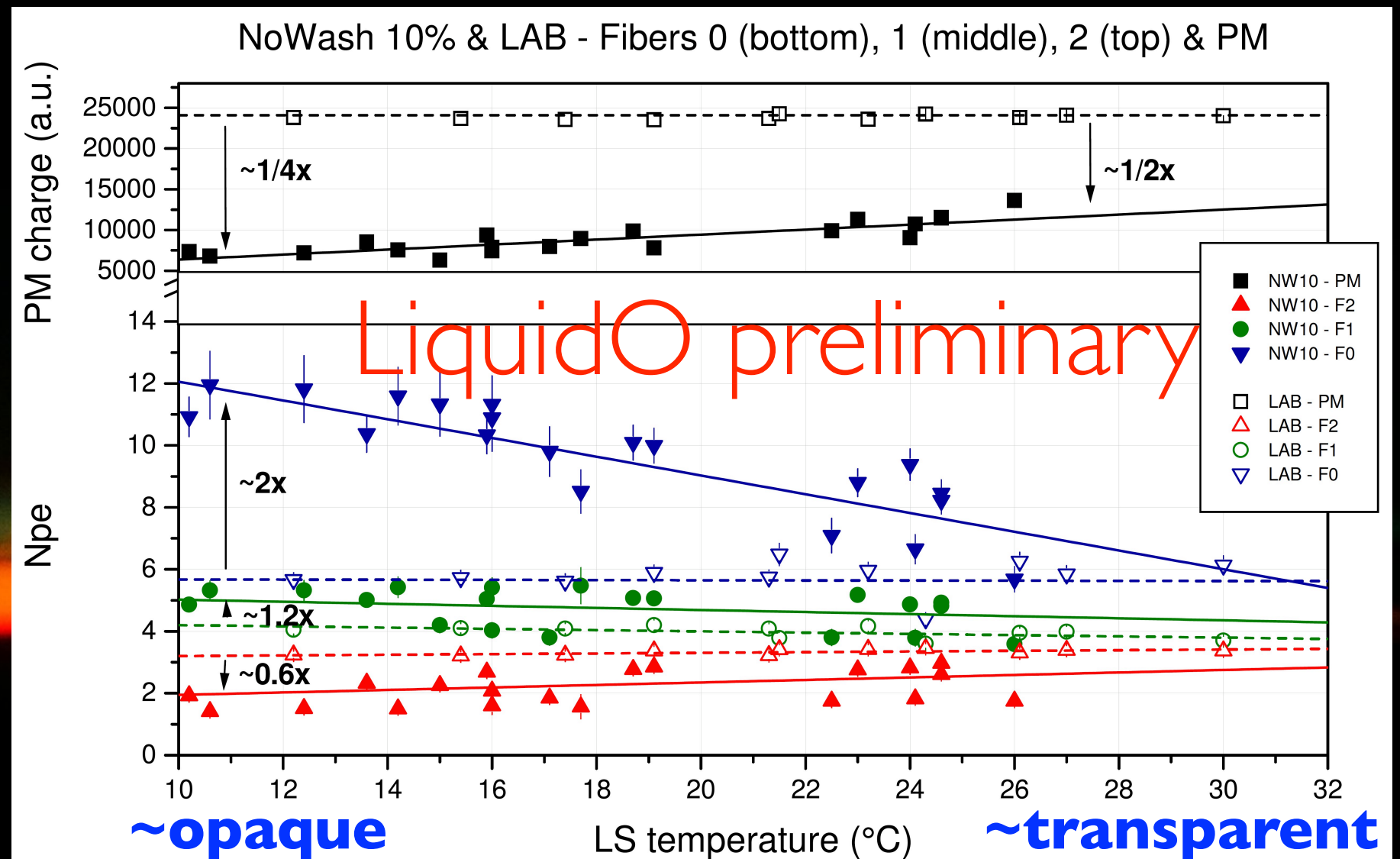
- LAB (transparent)
- new (LAB-based⊕opaque)

**1 fibre only**  
(example)





# LiquidO detection 1<sup>st</sup> evidence? 45



**High T(transparent)→Low T(opaque):**

• **PMT:** major light loss ( $\geq 4x$  in 5cm)

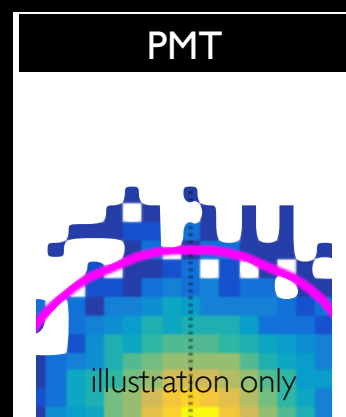
• **F0:** light not lost but increased ( $\sim 2x$ )

• **F1:** light stable ( $\leq 20\%$ ) [by accident?]

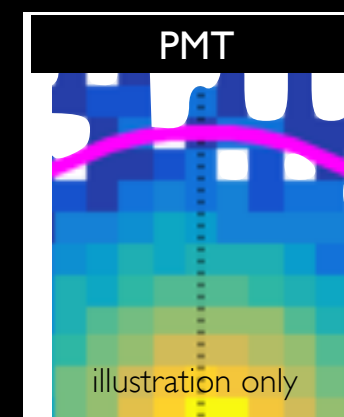
• **F2:** light is lost ( $\sim 60\%$  or  $\sim 1/2x$ )

→ **trivial light absorption ruled out**

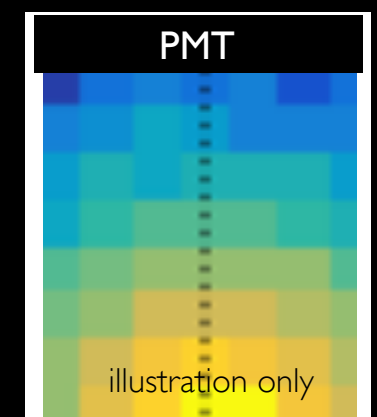
→ **3 fibres:  $\Sigma \approx 20PE/MeV \Rightarrow$  light boost?**



$e^-$



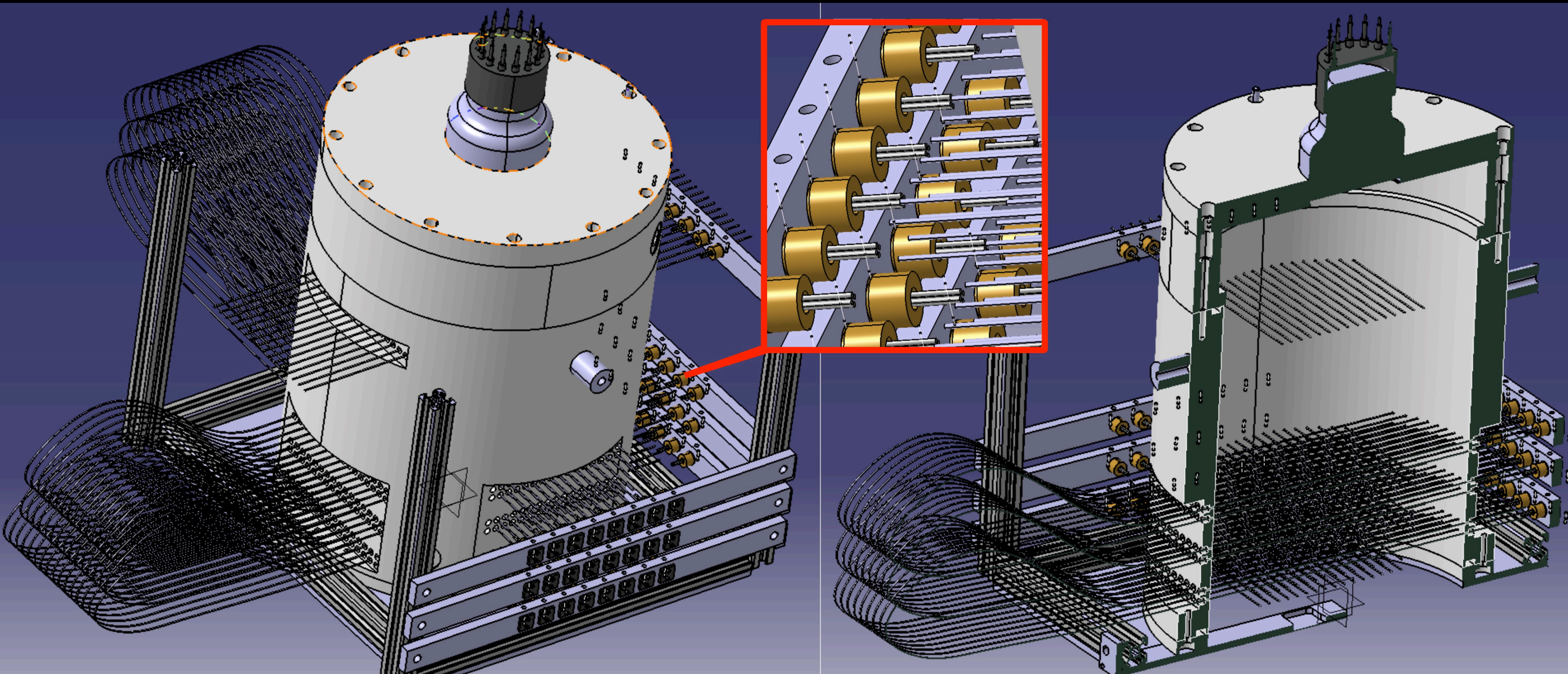
$e^-$



$e^-$



# mini-LiquidO soon...



## built & demonstration soon

# what to remember?





# R&D

more soon...

the first  $\geq 10$ ton detector R&D....

# Liquid

(no competition  $\rightarrow$  1ton must happen)



on behalf of LiquidO team...

the  
**bright age**  
of  
**darkness**  
**(i.e. opaqueness)**  
is ahead... **LiquidO?**

thank you...  
grazie...