on behalf of the **LiquidO consortium**…

L I Q U I D O

Journée R&T IN2P3
Oct 2022 — Lyon, France

Anatael Cabrera
CNRS/IN2P3
IJCLab/Université Paris-Saclay
(Orsay)

European Innovation Council

LiquidO Consortium*

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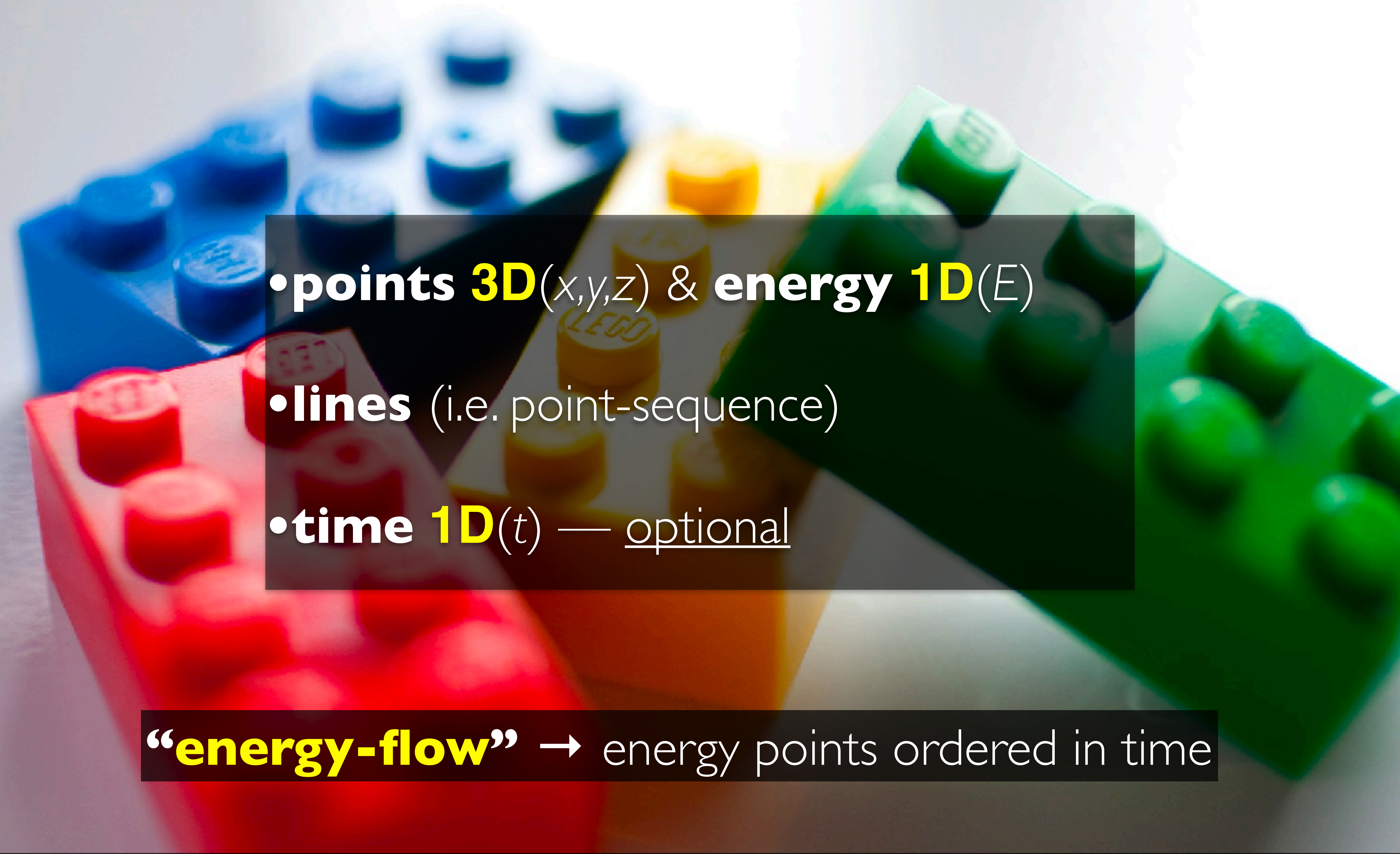
invention/conception 2012-2013 — since 2016 consortium (~20 institutes & 10 countries)

L I Q U I D O

LiquidO: light detector with **opaque** medium

⟹ event-wise **imaging⊕topology** & **PID** (high doping scenario)

what's LiquidO?



- **points** **3D**(*x*,*y*,*z*) & **energy** **1D**(*E*)
- **lines** (i.e. point-sequence)
- **time** **1D**(*t*) — optional

“energy-flow” → energy points ordered in time

(dynamic) **imaging** building-blocks…

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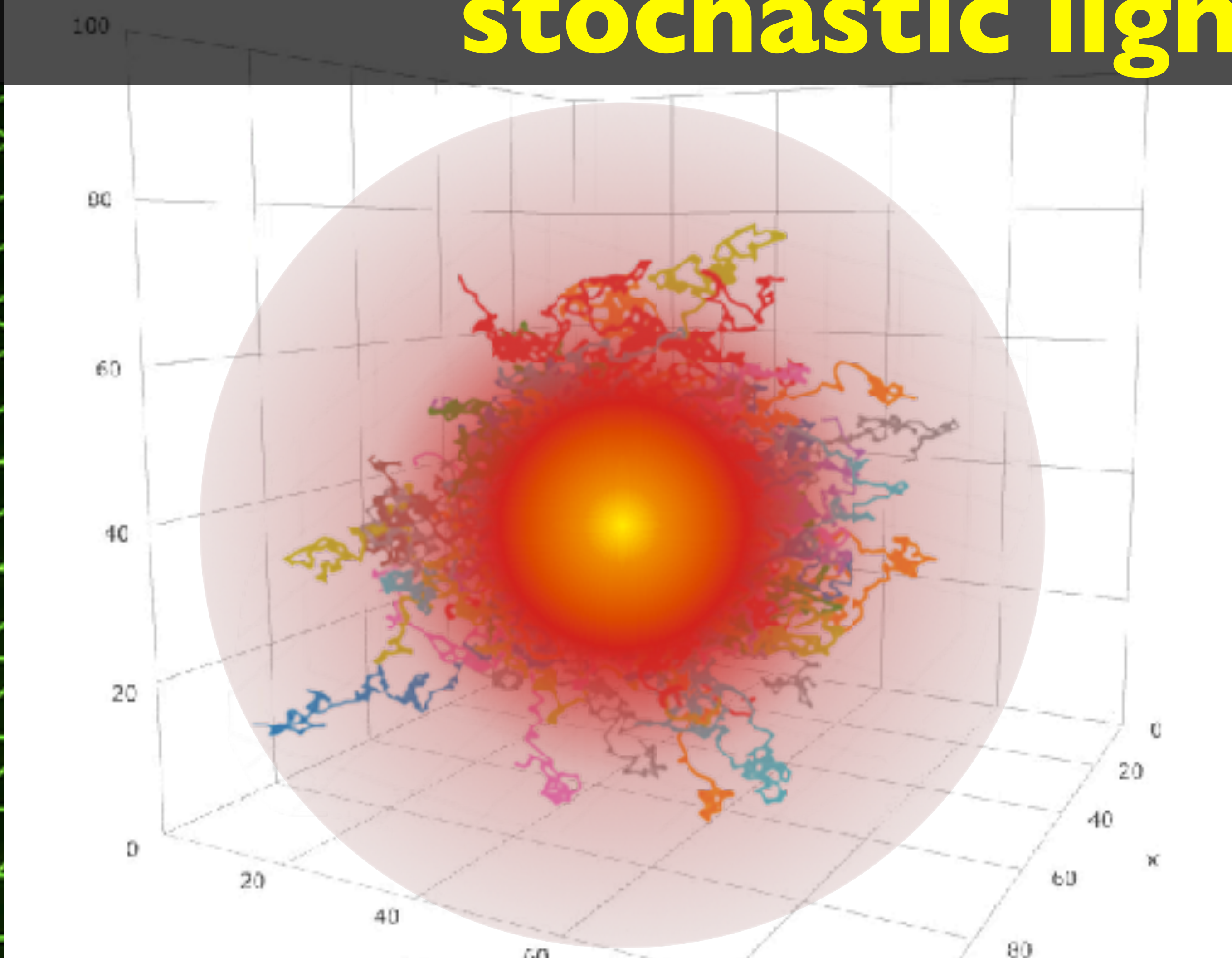
stochastic light confinement



LiqudiO→ photon's "random walk" (self-confinement)

- **scattering→random walk→light ball** [order 1cm]
  - scattering <u>mean-free-path order 1mm</u>: x10^{-4} smaller than usual
- **lossless scattering:**
  - **Mie scattering:** achromatic & tiny losses ["cloudy" touch]
  - **Rayleigh scattering:** chromatic & lossless
  - **Internal Reflection** (Snell's law lossless)

  warning: <u>avoid reflection</u> (losses @ order ~1%/reflection)

LiquidO ⇔ unique stochastic light confinement

⟹ **must NOT be transparent!!**

Transparency
λ(scattering)**≥10m**

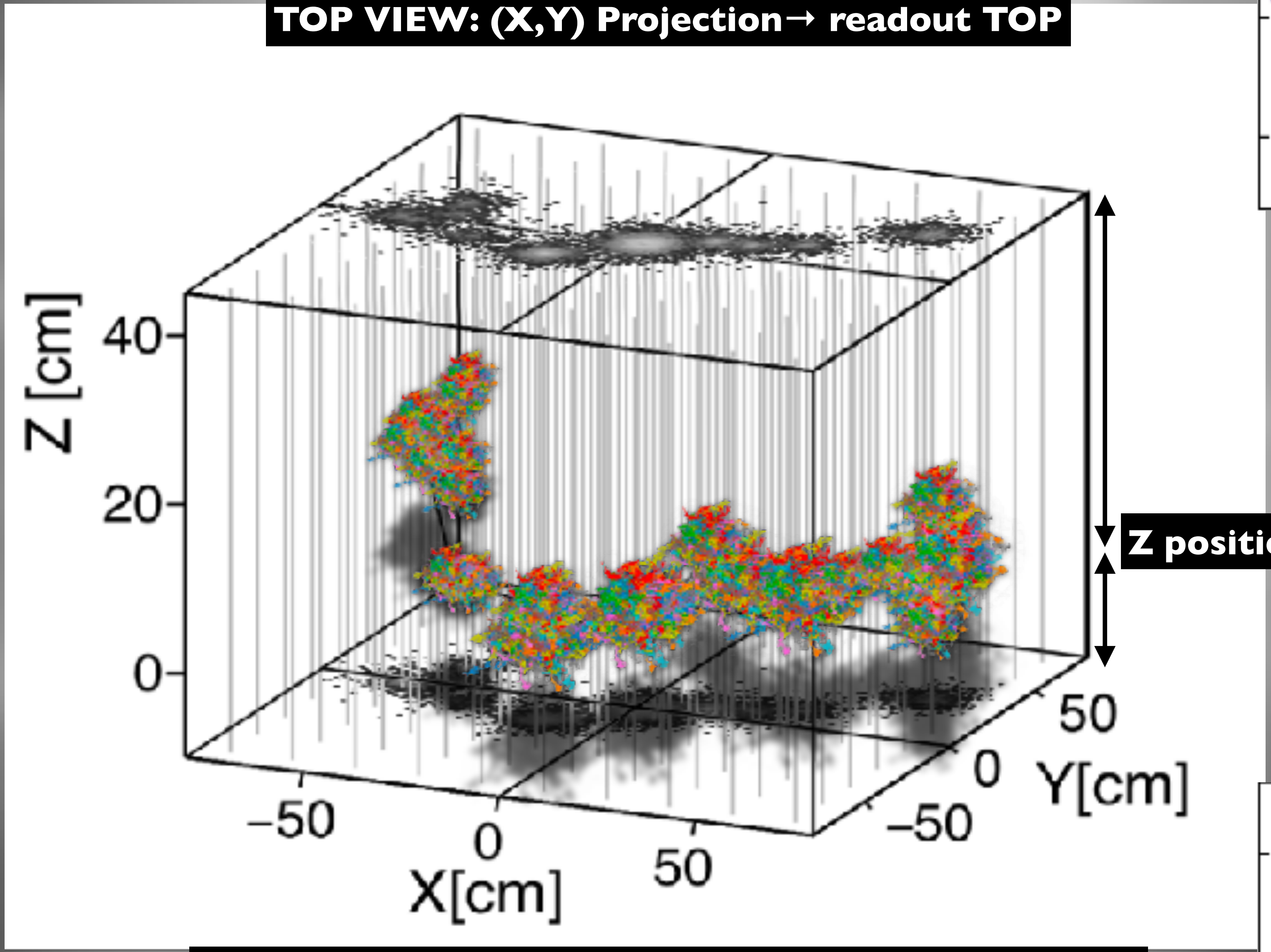
Rayleigh & Mie Scattering
λ(scattering)**≤1cm**

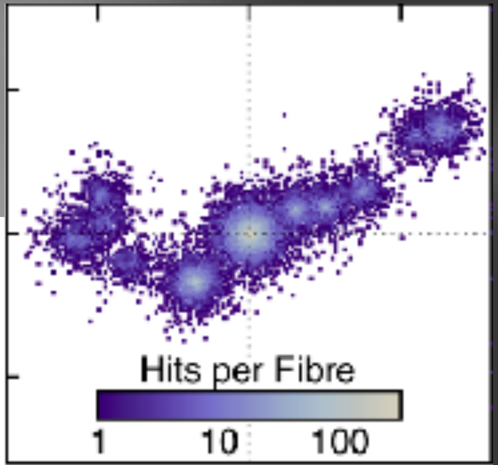
inducing light (lossless) to a point…

Topology (X,Y) direct & native (PID)→ possible **sub-mm vertex precision**

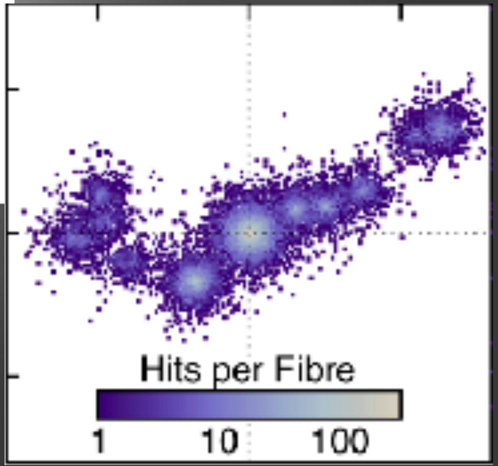
Vanilla LiquidO: 1D lattice (fibres along Z-axis only)

TOP VIEW: (X,Y) Projection→ readout TOP





Z position using: Δt (time difference)



BTTOM VIEW: (X,Y) Projection→ readout BOTTOM

LiquidO can have up 3 orthogonal fibre lattice orientations (3D)

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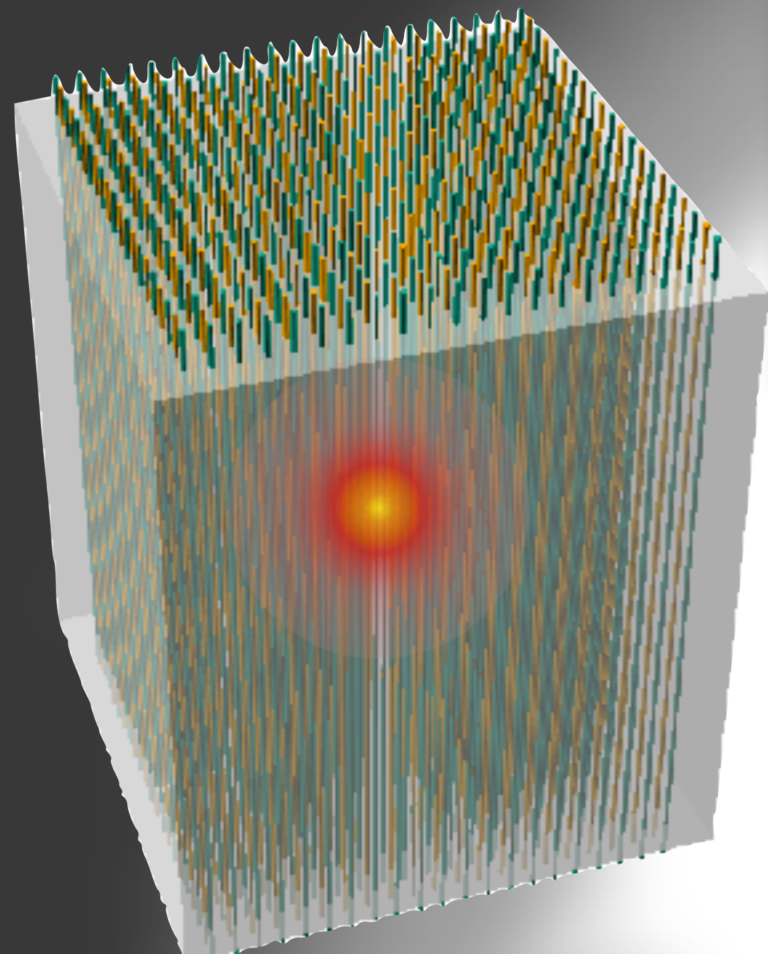
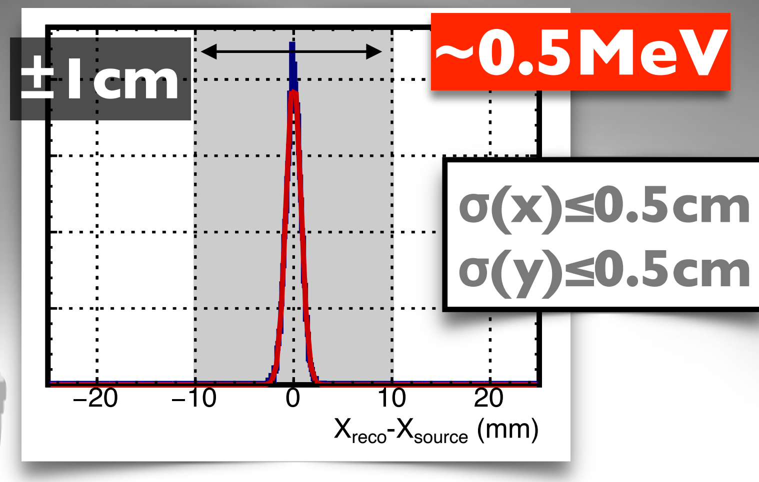
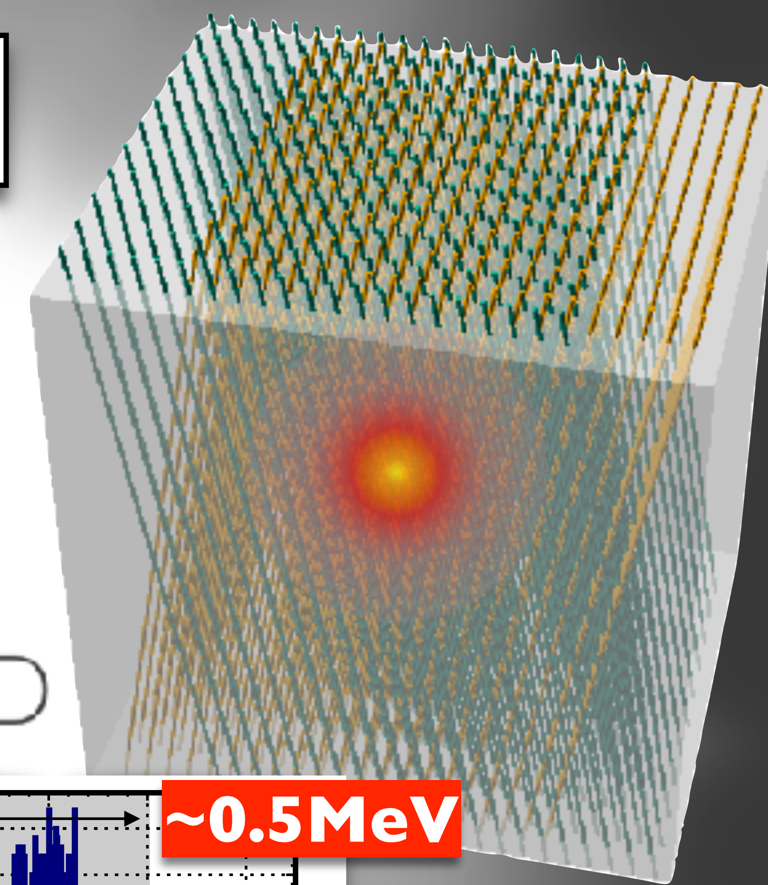
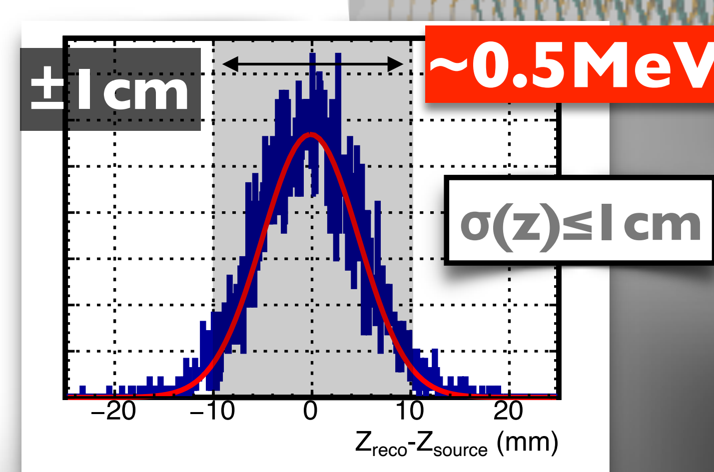
LiquidO novel engineering solutions…





I Q U I D





1x Axis(Z) — low cost & simplicity
- (X,Y): topology→ **mm resolution** (robust)
- Z: timing→ **few cm resolution** **→some fragility:** light yield, rise-time, etc

2x Axes — complexity & cost…
- (X,Y,Z): topology→ **mm resolution** (robust)
- (X,Y,Z): timing→ cheap-readout / over-constrained

3x Axes — useless?

"1x" Axis(twisted-Z @ ≤10º**) — development**
- (X,Y): topology→ **mm resolution** (robust)
- Z: topology→ **≤1cm resolution** (robust)
- (X,Y,Z): timing→ over-constrain & **energy-flow**

more Axes: necessary?

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≳0.1MeV

topology	physics	LiquidO Information	
point	unresolved (≲few cm)	**point-like**	sub-mm possible (primitive)
track	points-like sequence	**track-like**	sub-mm possible (enhanced)
point's ⊕ **track's**	complex event	combination ⊕ **timing**	reconstruction (energy⊕x,y,z⊕t)

input 5D→ energy-flow, kinematics$(\bar{p})$, **PID**, etc (derived)

imaging & outcome (upon reco)...

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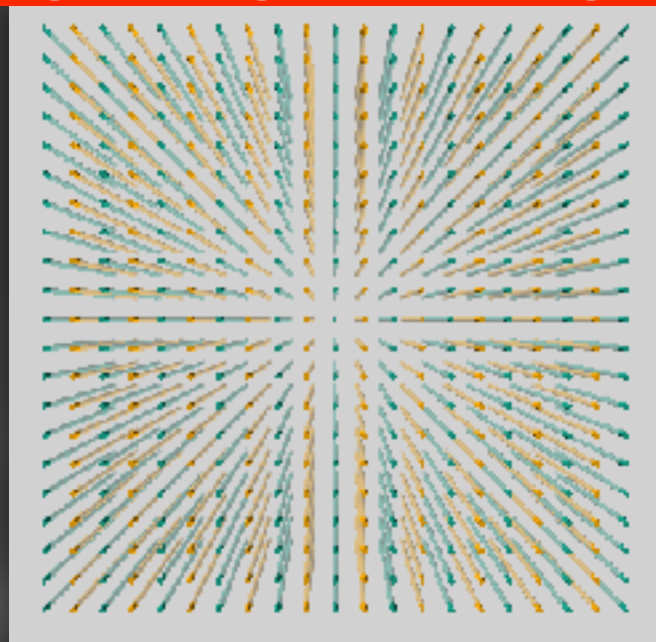
main technological ingredients…

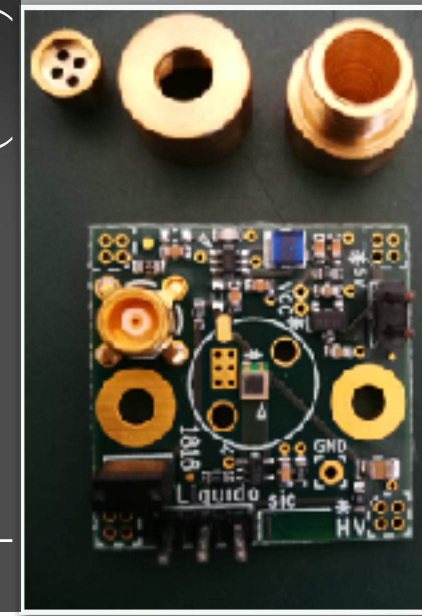
full engineering for "floating fibres"



⊕

sub-100ps custom front-end & digitisation

LiquidO Front-End (SiPM)

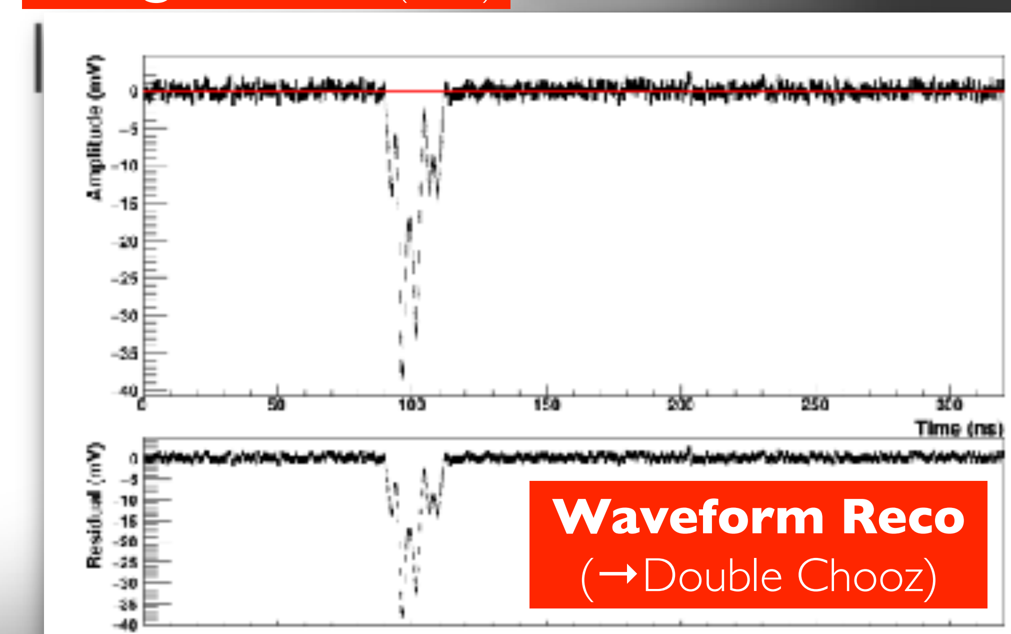


⊕

WaveCatcher & SAMPIC

SiPM @Hamamatsu (so far)

new scintillation & fibres technologies
(Cherenkov / scintillation / etc)



fast readout ⊕ reconstruction
(potential resolution ≤100ps)

new framework for light detection→ several new ideas…

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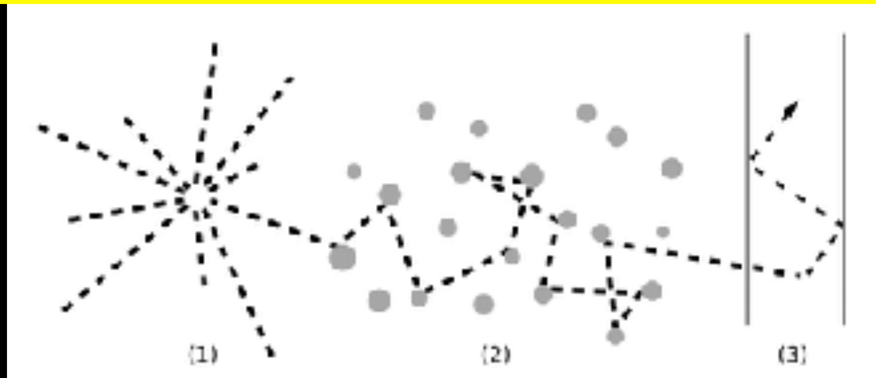
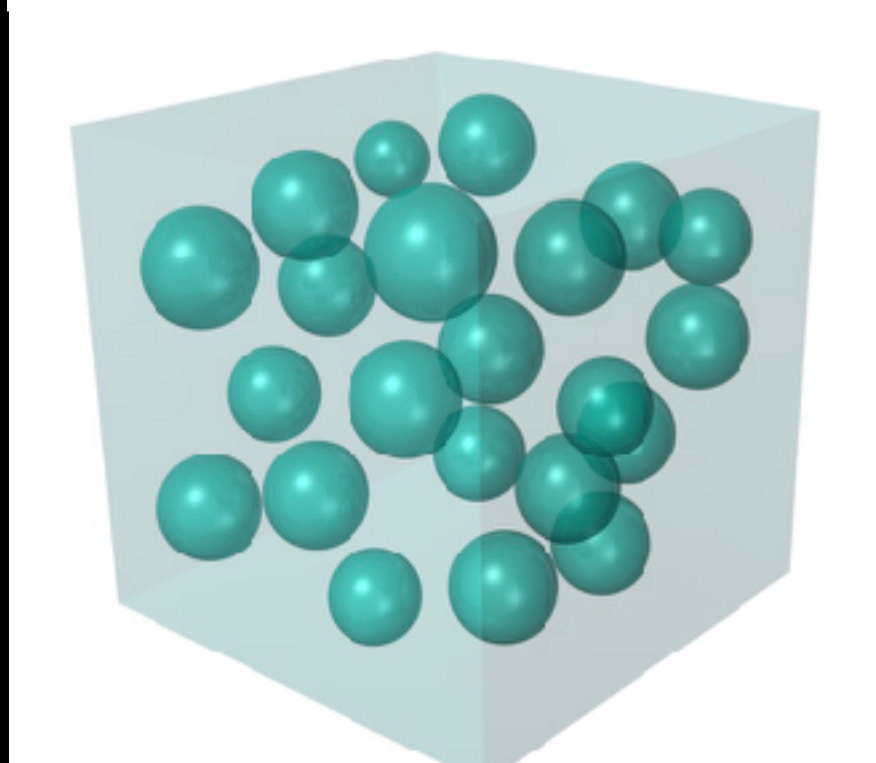
new μCrystal scintillators…

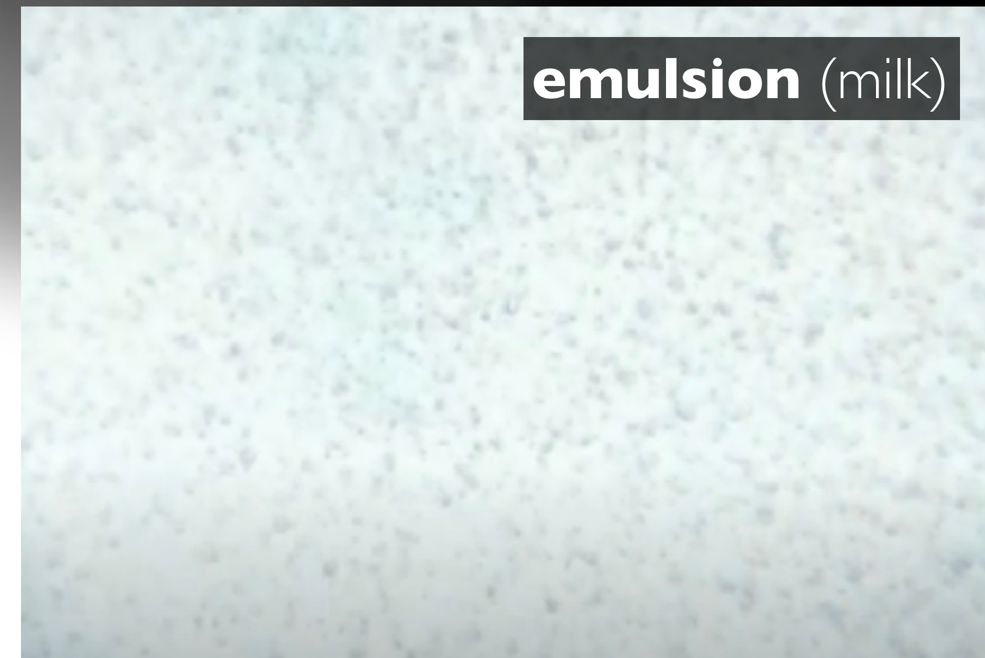
LiquidO's R&D (new projects…)



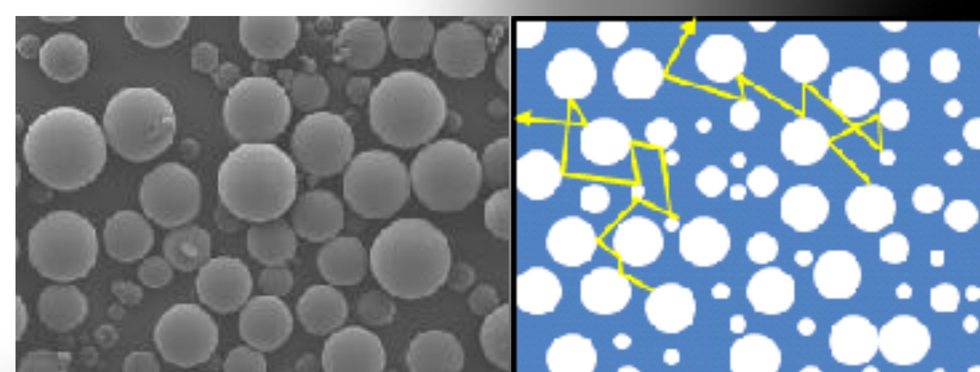


"Mycro-Crystal Scintillator"
S. Wagner, M. Grassi, A. Cabrera
arXiv:1807.00628

liquid scintillator(s)
(optional)
⊕
μCrystal inorganic scintillator(s)
(doping)



liquid easy scattering — cheap & free



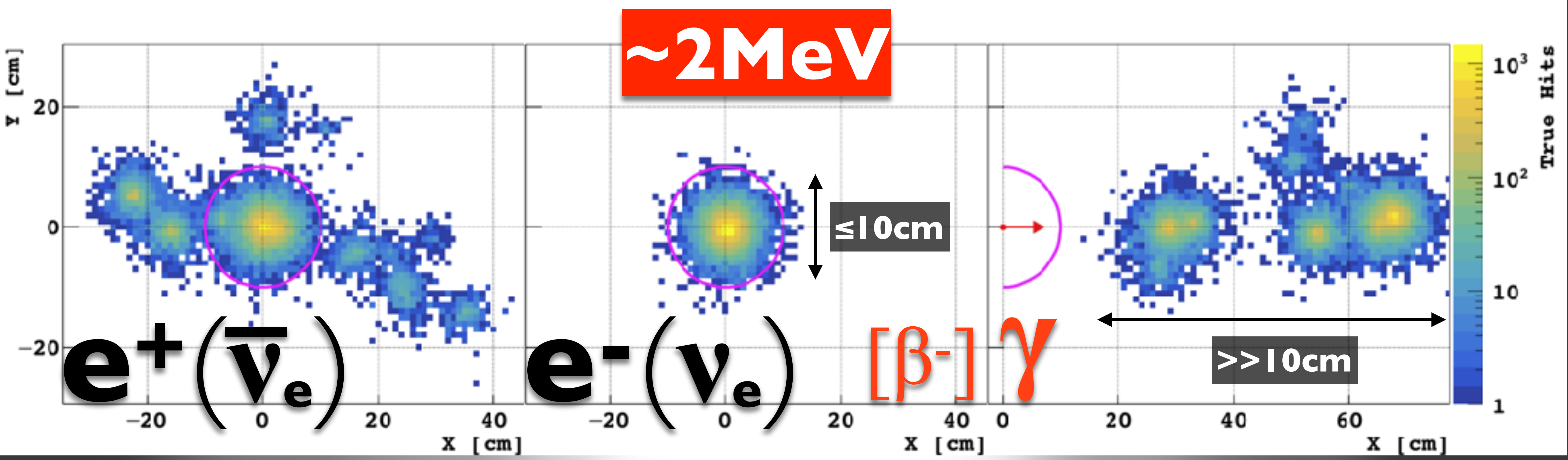
μCrystals possible too — exploring…

nano stuff possible — extremely expensive: practical?

physics appetiser… (simulation)

unprecedented PID@MeV…

potential: reduce overburden/shielding

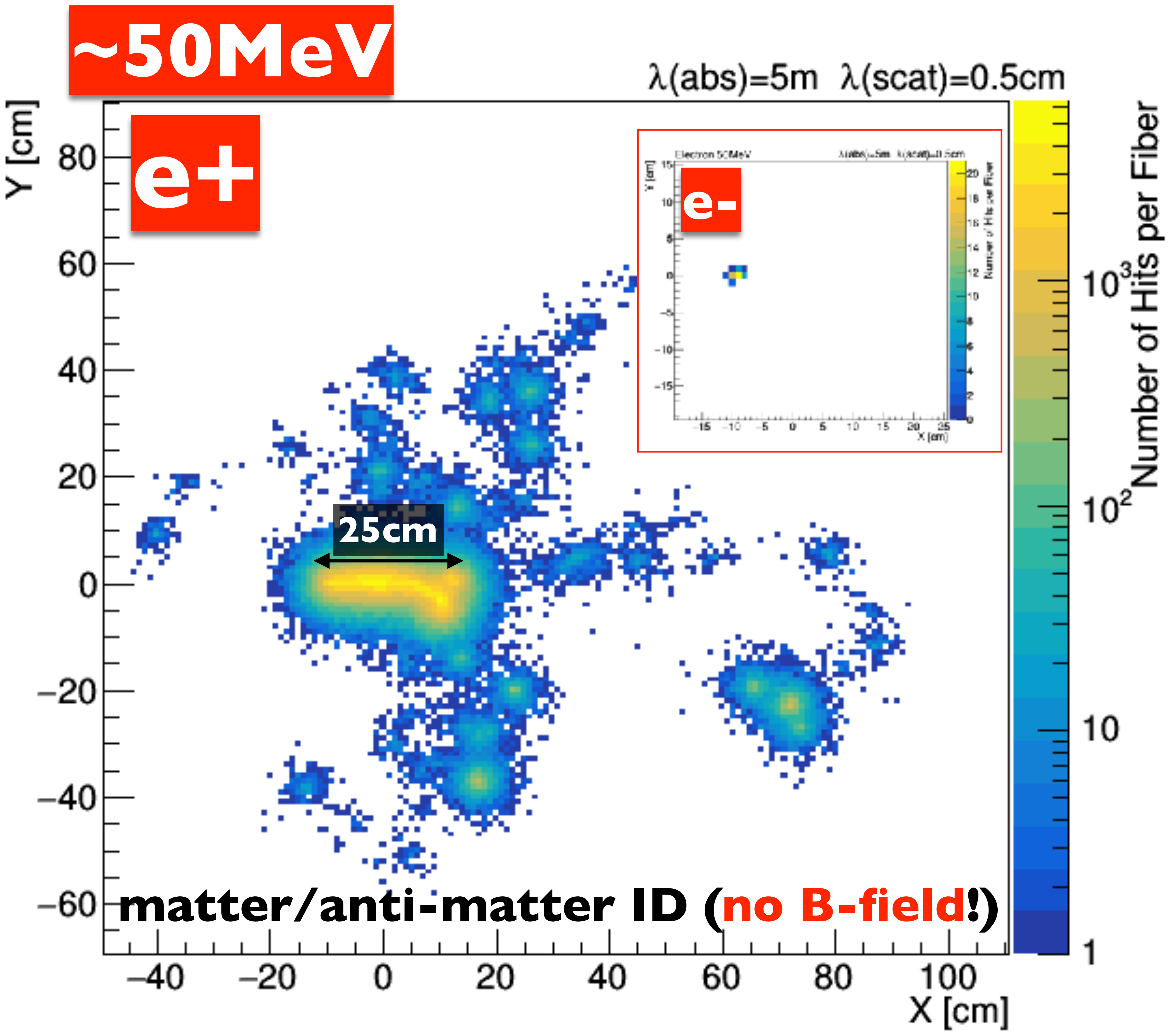


opacity→ (native) self-segmentation

needless segmentation: problematic @ 1MeV (pollution, cost⊕complex, etc)

~1MeV: reactor, geoneutrino, solar, ββ-decay, etc

multi-MeV improves (more light too)…



- **powerful PID**
- **energy flow**
- **tracking** (mm)
  →cosmogenic BG tagging
- **directionality**
- **dE/dx** (range)

~10MeV: D@R (μ,π,K)**, supernovae** (remnant, core-collapse)**, atmospherics, Michel-e±** (μ-decay)**, etc**

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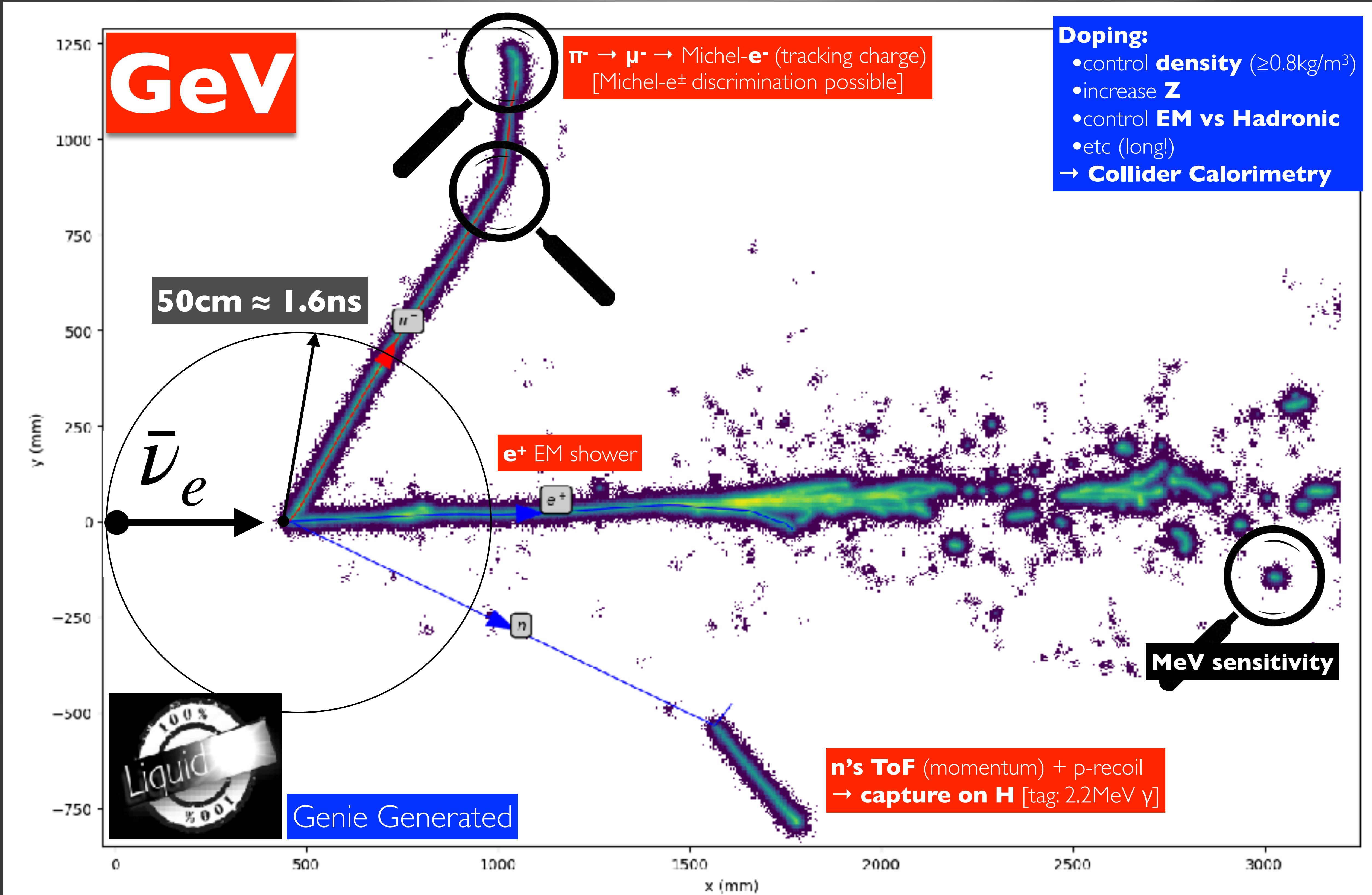
complex GeV with LiquidO…



Stochastic calorimetry order 0.1% [~10^5 PE/GeV] — excellent control of non-stochastic

≥100MeV: accelerator, atmospheric, p-decay, etc

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L I Q U I D O

experimental demonstration (data)

our first publication…

nature
communications physics

Article | Open Access | Published: 21 December 2021

Neutrino physics with an opaque detector

LiquidO Consortium

Communications Physics 4, Article number: 273 (2021) | Cite this article

1867 Accesses | 1 Citations | 10 Altmetric | Metrics

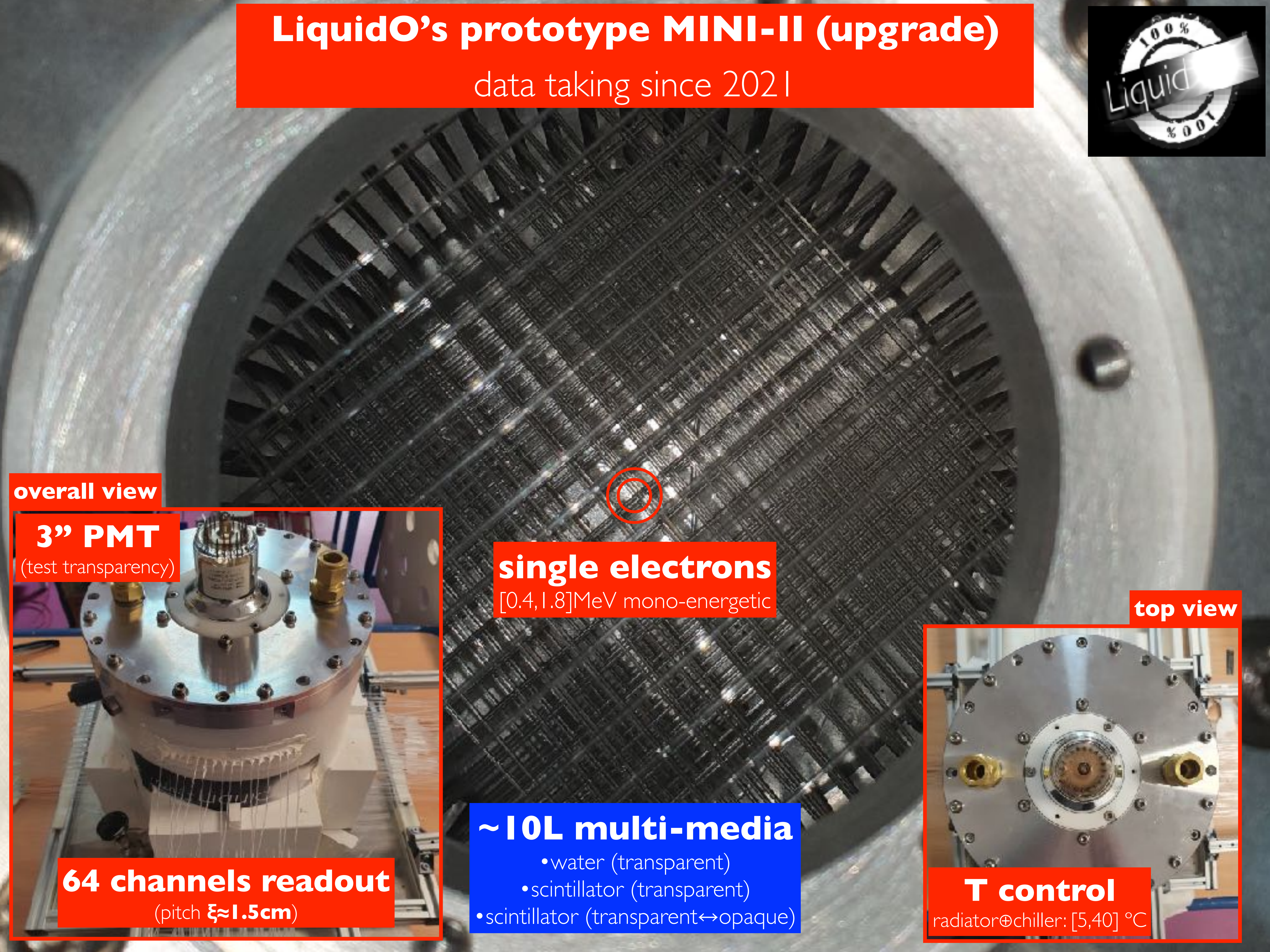
Abstract

In 1956 Reines & Cowan discovered the neutrino using a liquid scintillator detector. The neutrinos interacted with the scintillator, producing light that propagated across transparent volumes to surrounding photo-sensors. This approach has remained one of the most widespread and successful neutrino detection technologies used since. This article introduces a concept that breaks with the conventional paradigm of transparency by confining and collecting light near its creation point with an opaque scintillator and a dense array of optical fibres. This technique, called LiquidO, can provide high-resolution imaging to enable efficient identification of individual particles event-by-event. A natural affinity for adding dopants at high concentrations is provided by the use of an opaque medium. With these and other capabilities, the potential of our detector concept to unlock opportunities in neutrino physics is presented here, alongside the results of the first experimental validation.

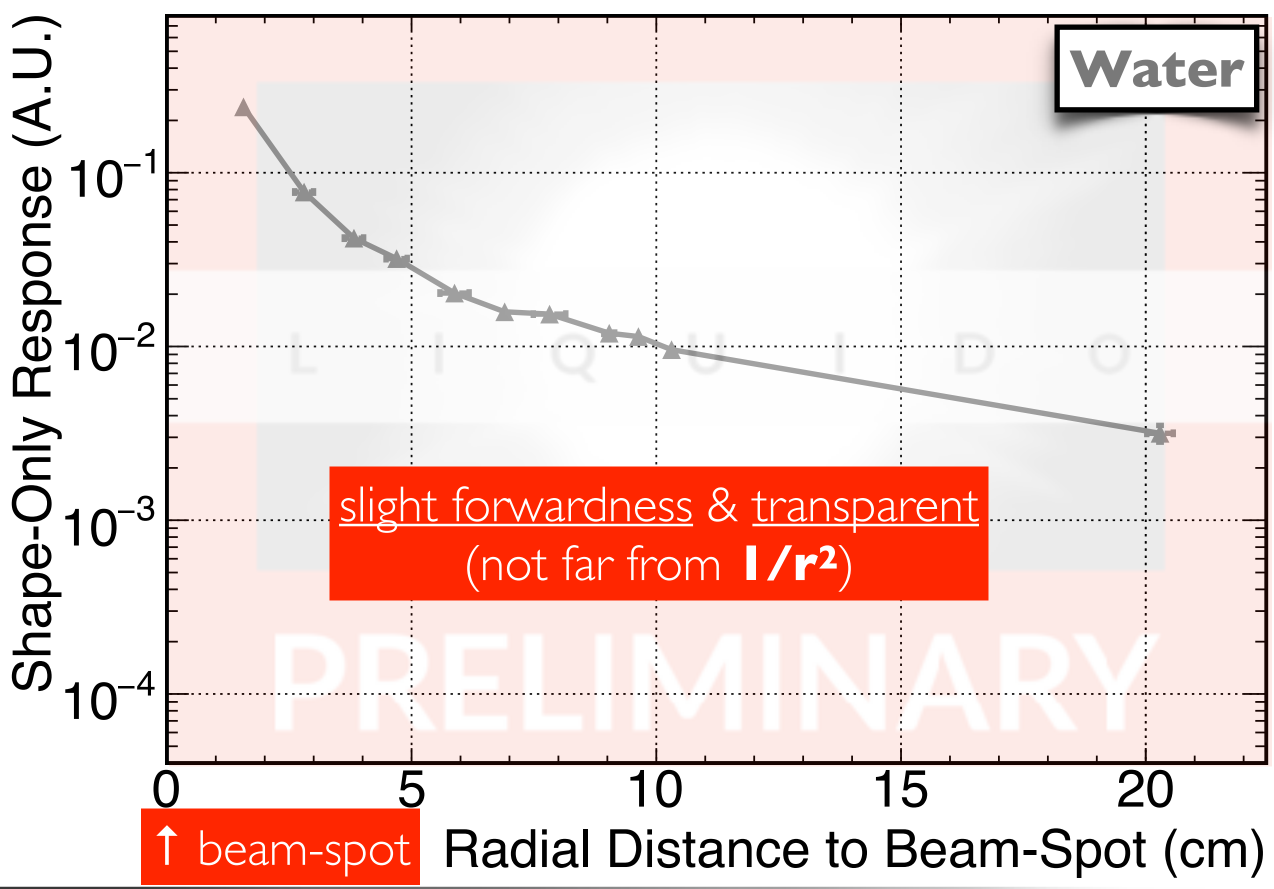
proof-of-concept: *simulation* & data [**μ-LiquidO**]

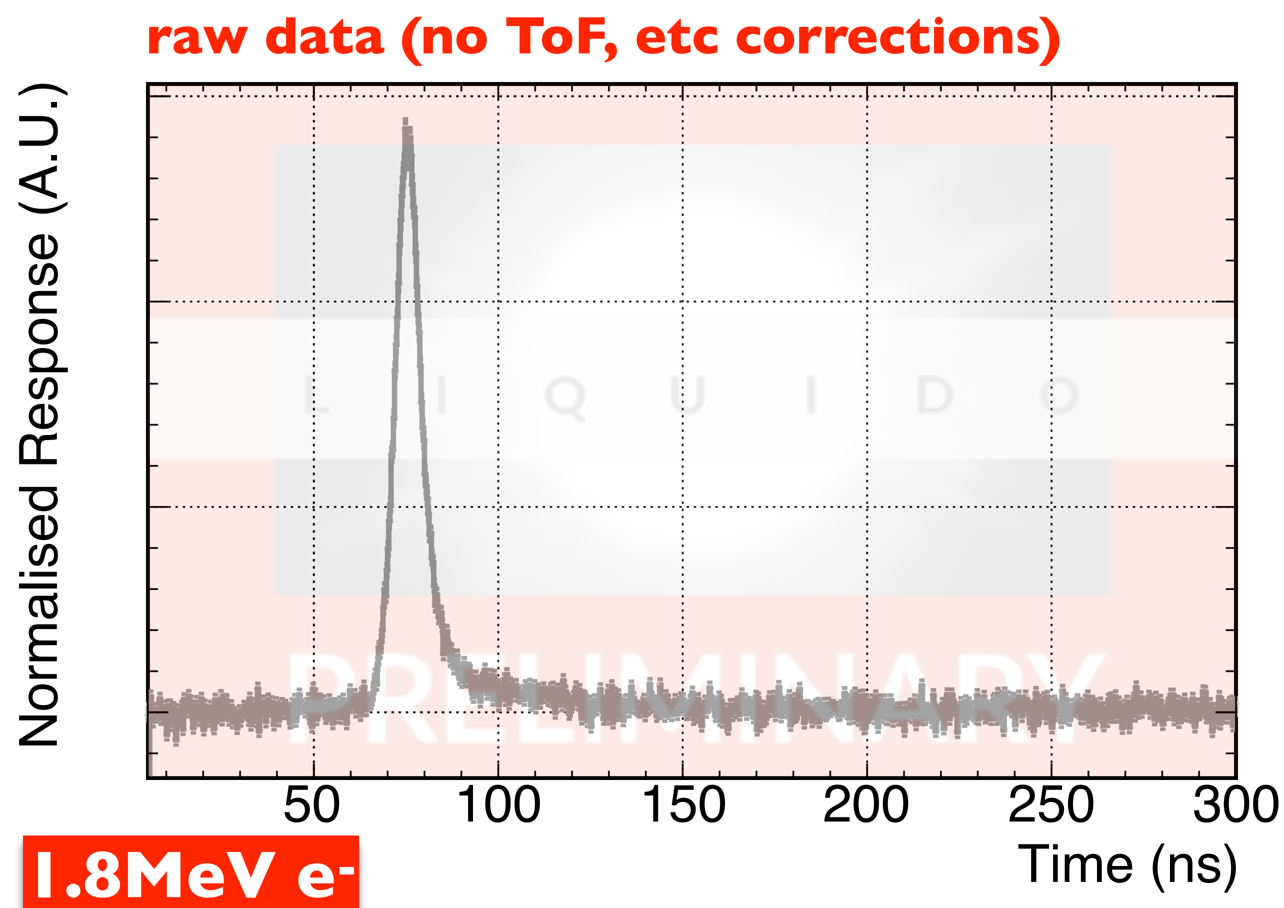
physics potential — appetiser

www.nature.com/articles/s42005-021-00763-5


LiquidO's prototype MINI-II (upgrade)
data taking since 2021
overall view
3" PMT
(test transparency)
64 channels readout
(pitch ξ≈1.5cm)
single electrons
[0.4,1.8]MeV mono-energetic
~10L multi-media
•water (transparent)
•scintillator (transparent)
•scintillator (transparent↔opaque)
top view
T control
radiator⊕chiller: [5,40] °C

Water: single e- Cherenkov only





little light: Cherenkov only & transparent (LiquidO's lowest acceptance)

→validate detector's integral timing readout — dominated by fibre's excitation?

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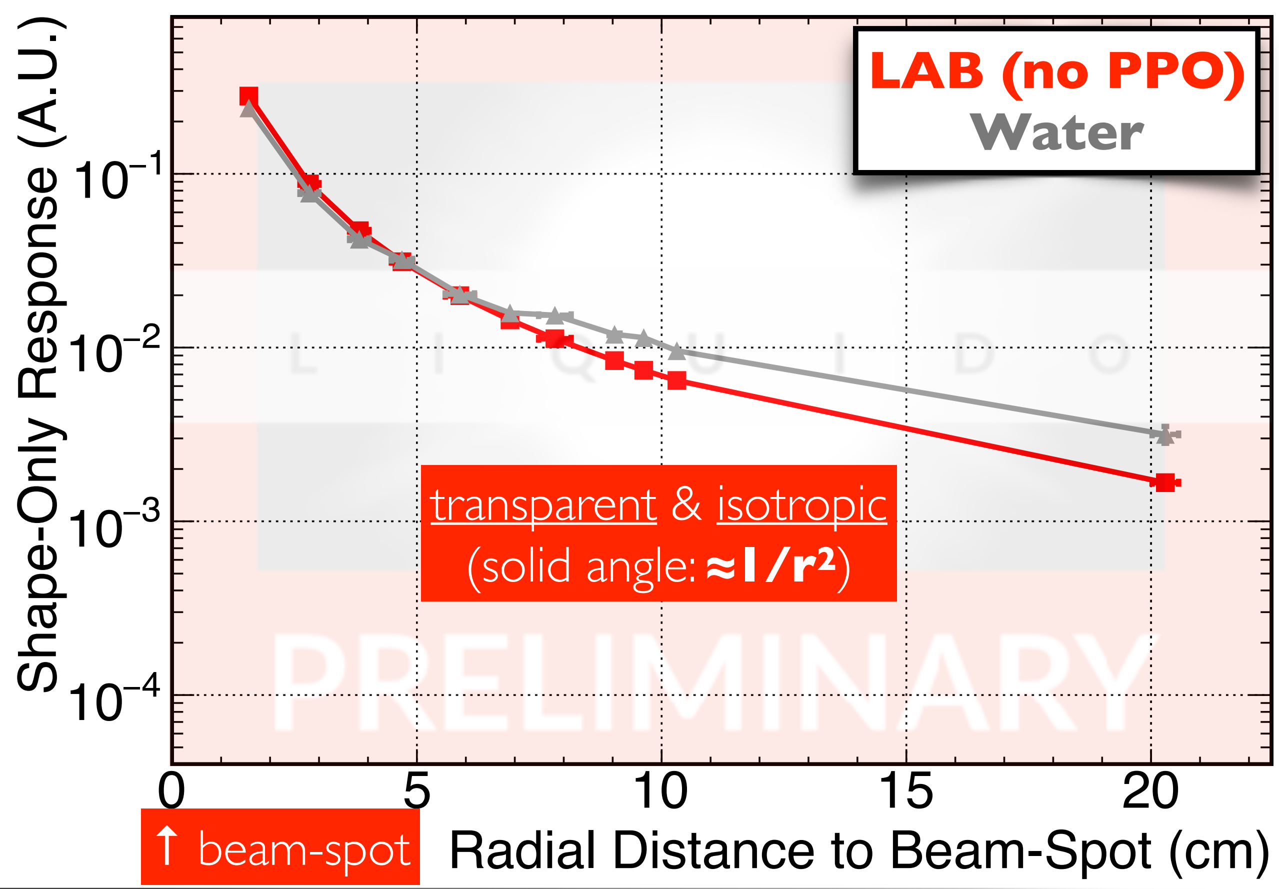
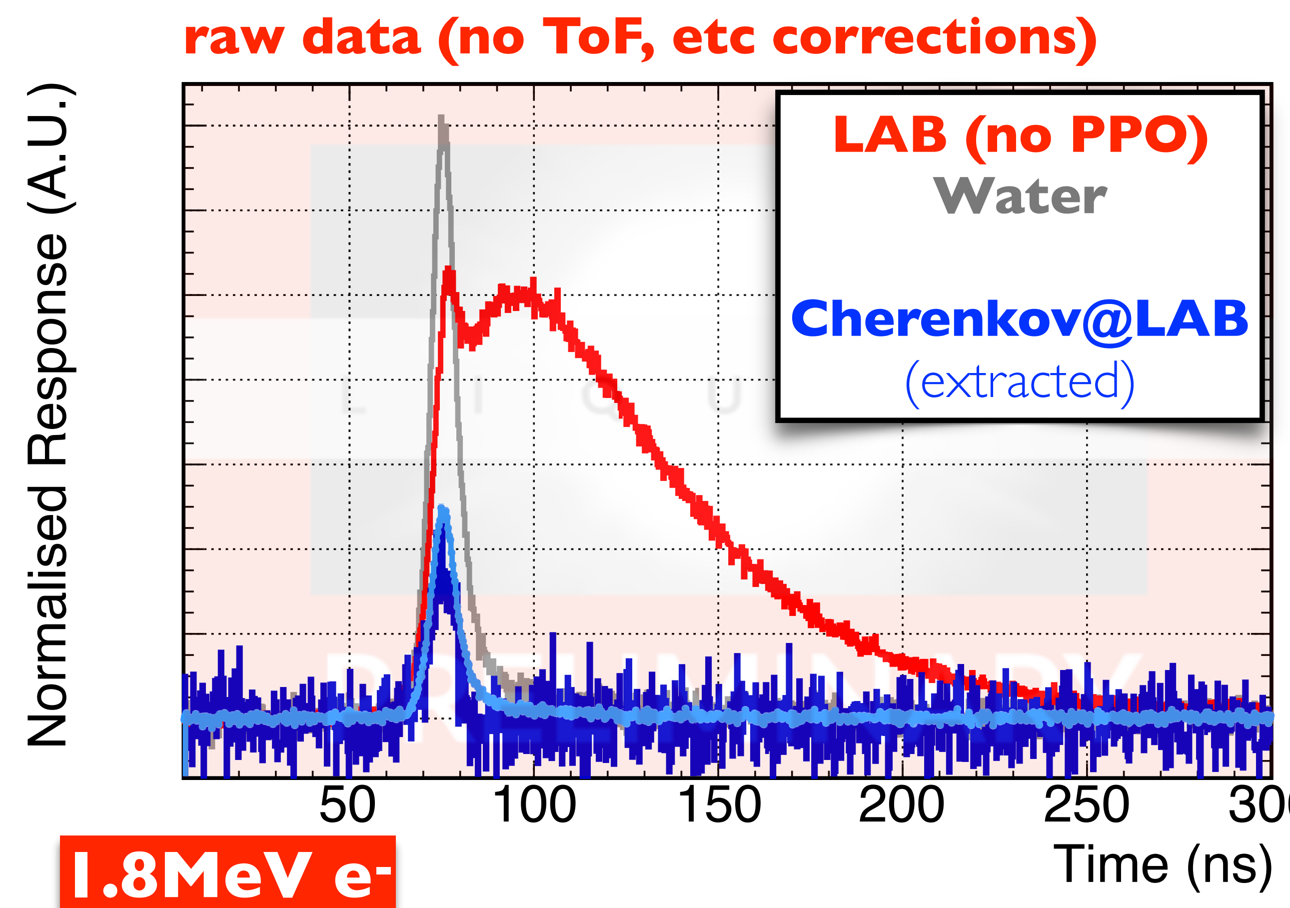
LAB: Scintillation⊕Cherenkov





~8.7x more light due to LAB's scintillation
[with PPO(≤3g/L) up to ~4x more]

Cherenkov excites the scintillator — loss ≥50% (optimisation)

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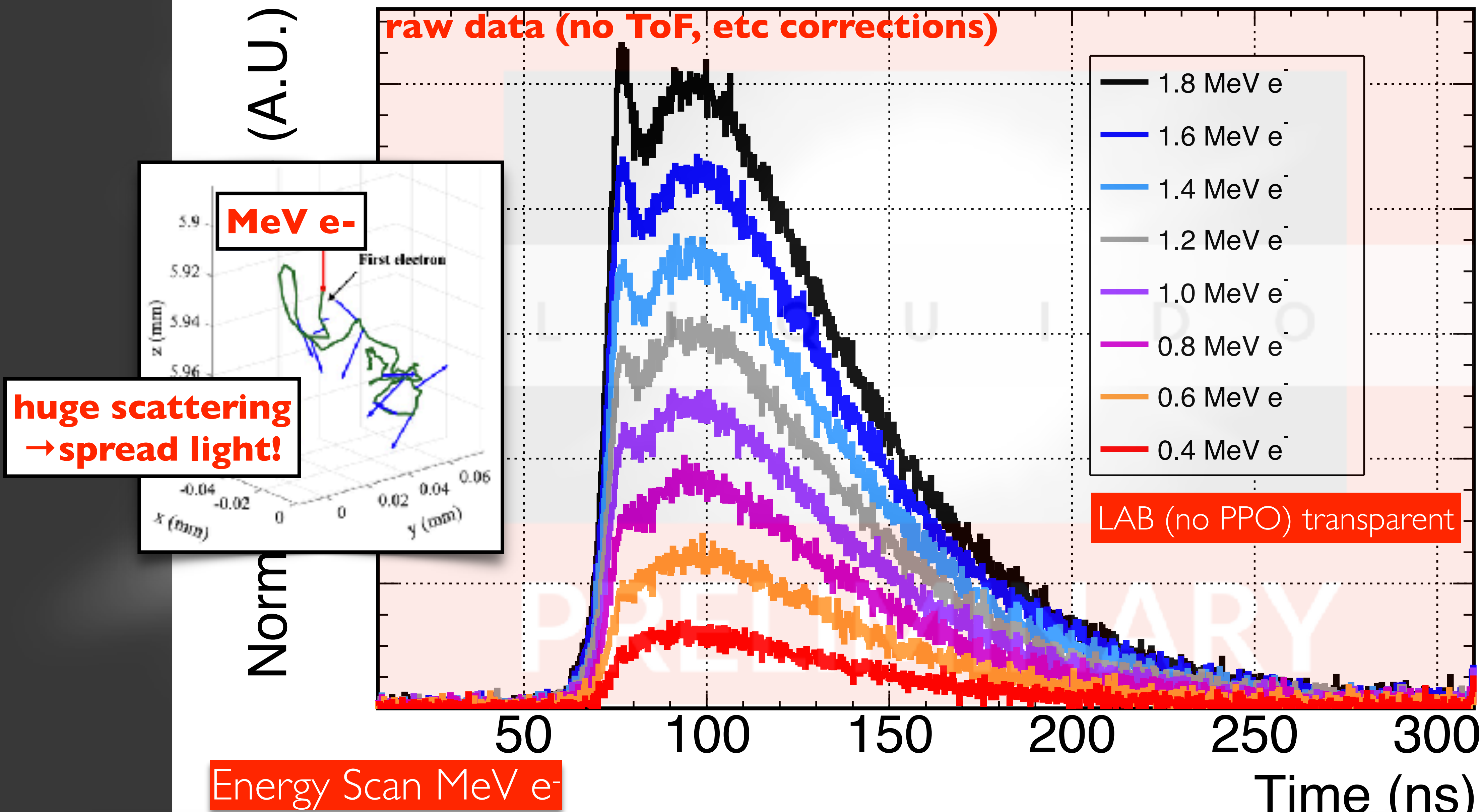
Cherenkov / Scintillation ID…

Cherenkov time-only ID — threshold

(no topology exploited — unlike μ's)



LiquidO's timing potential — under quantification & optimisation

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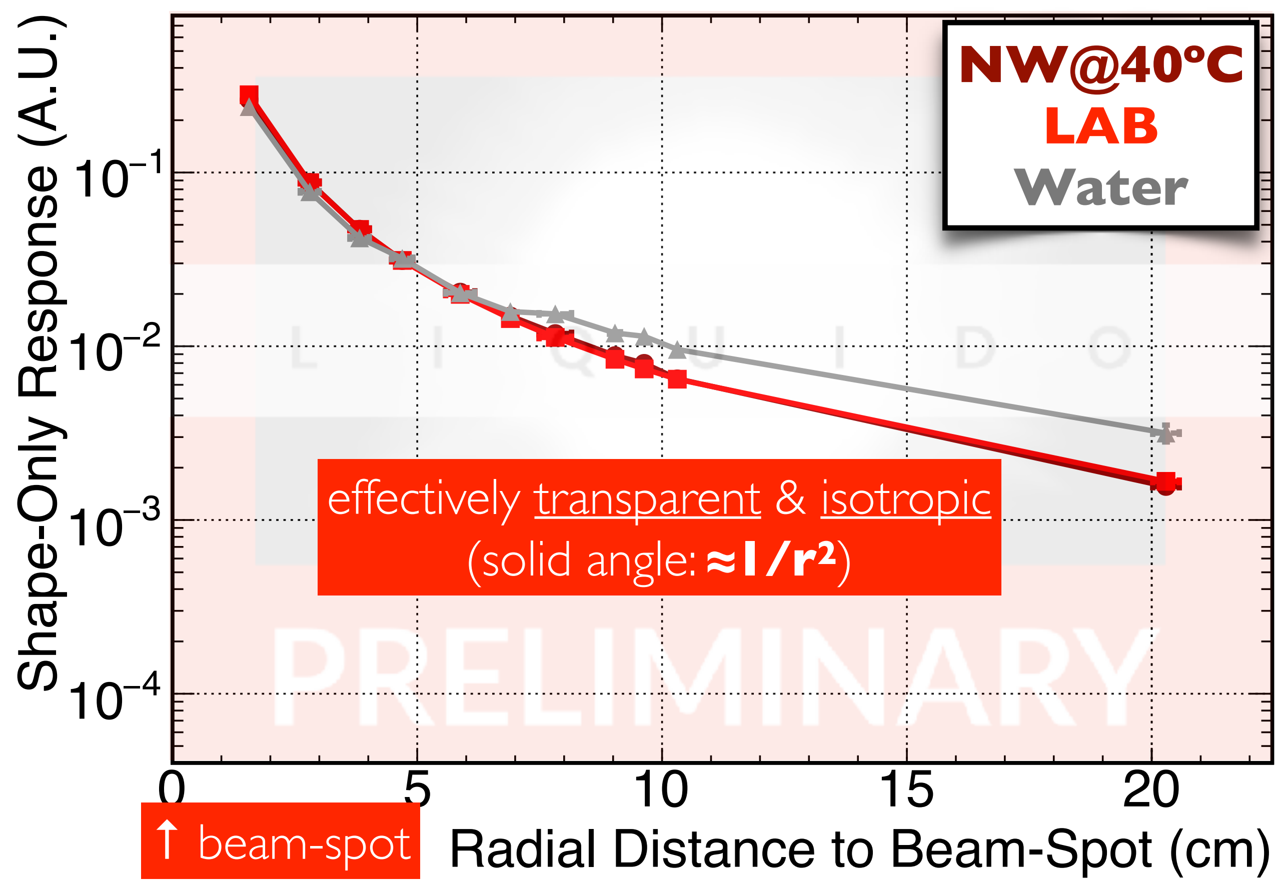
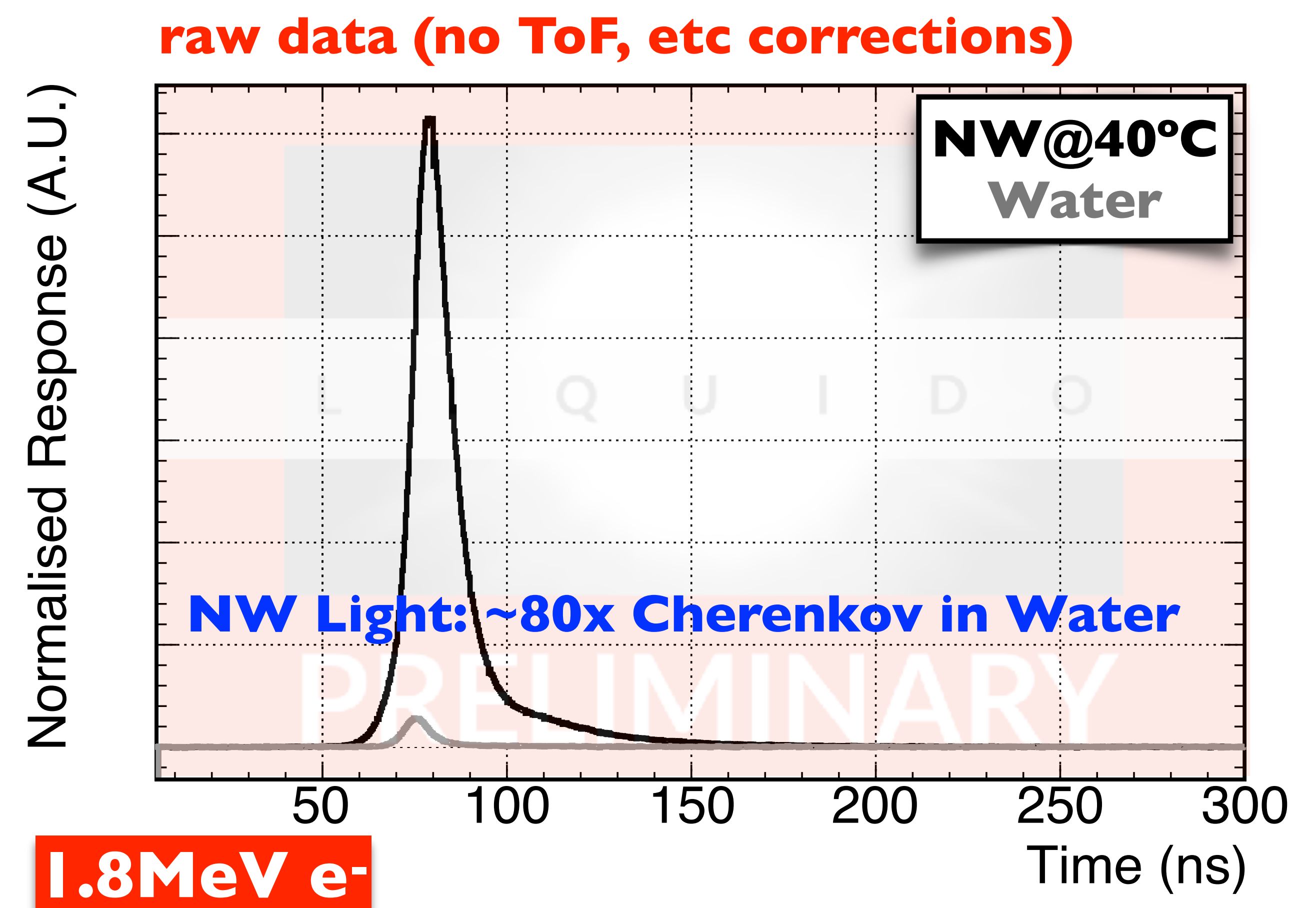
NW@40°: Scintillation ⊕ ~~Cherenkov~~

"NW" = NoWaSH scintillator [see C. Buck's talk]





"transparent" — effectively like LAB or Water

more light? scattering enhances fibre's collection → **translucent** regime

Cherenkov reduced by paraffine? — under investigation

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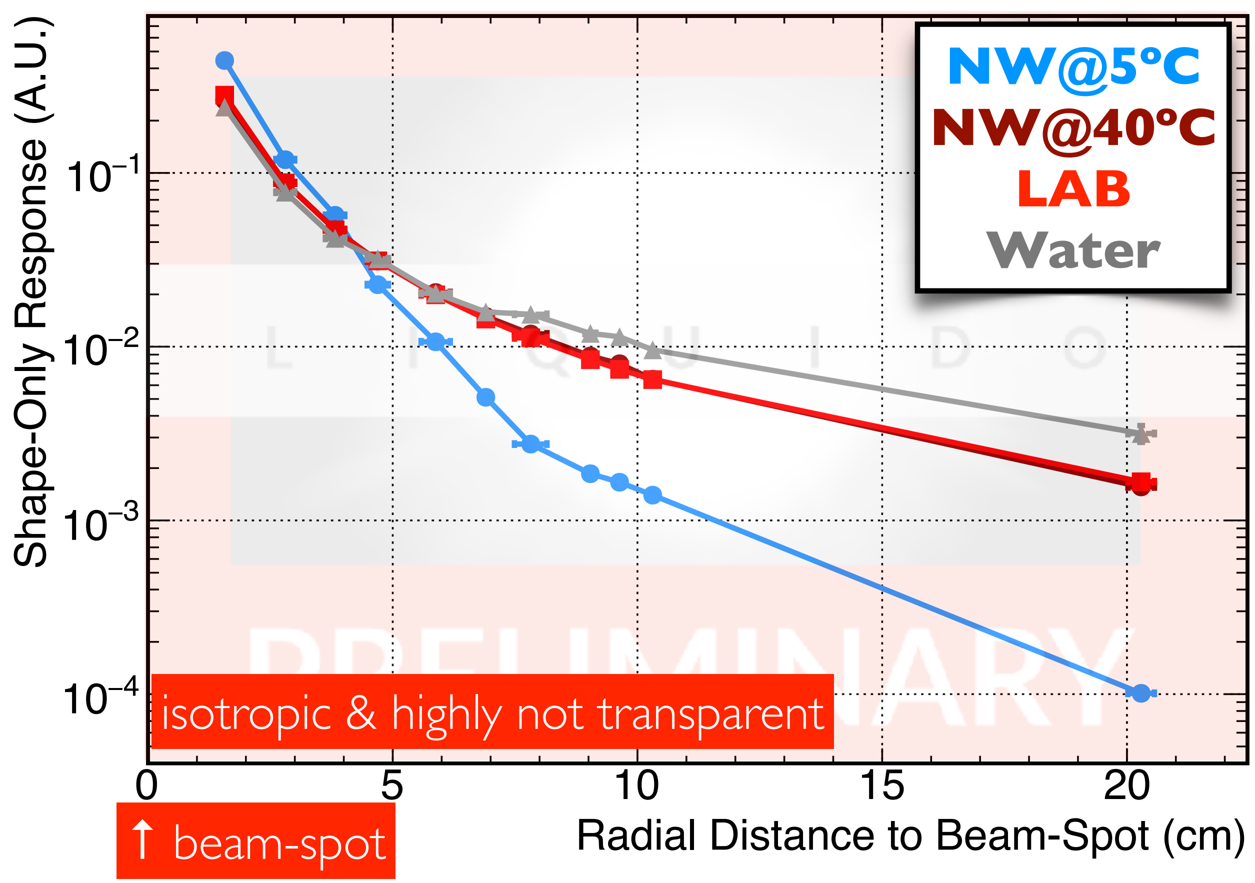
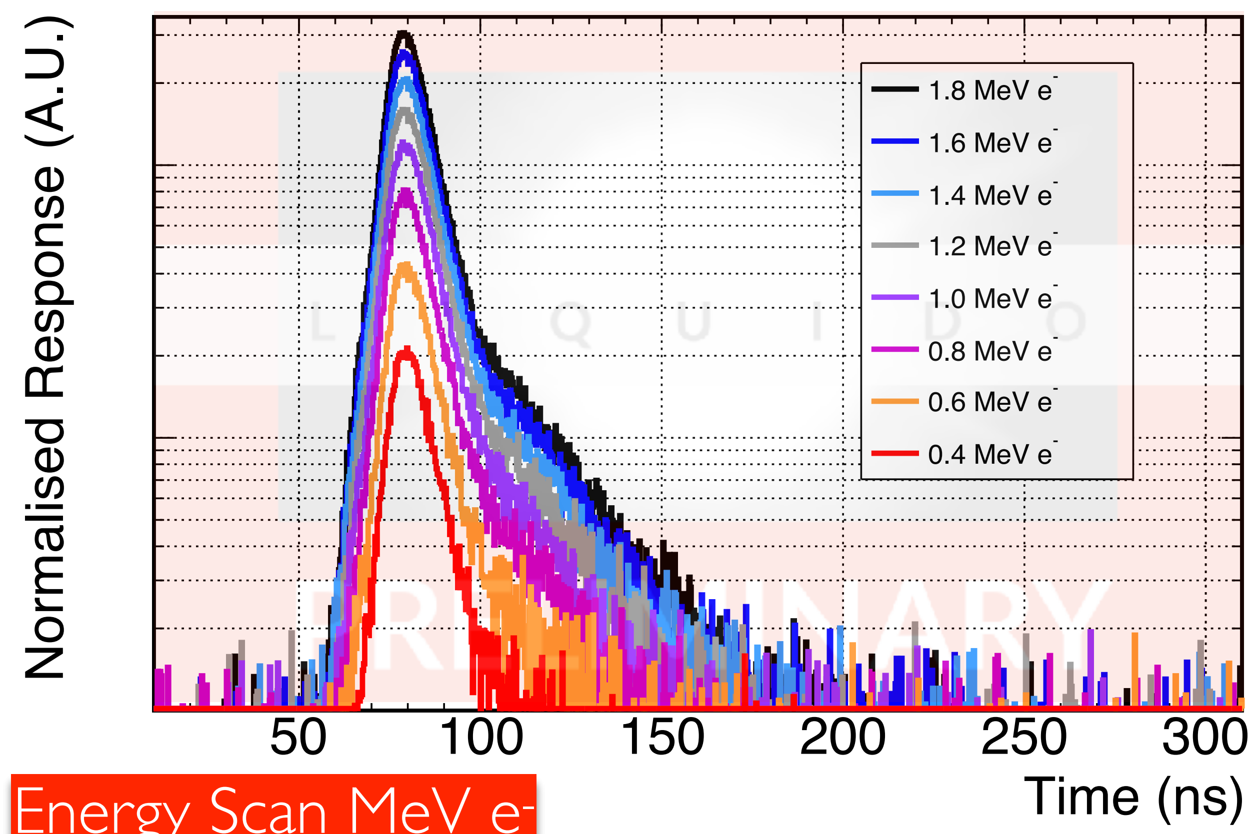
NW@5°: LiquidO (Scintillation)

light falls by almost 4 orders of magnitude in 20cm — very opaque indeed



raw data (no ToF, etc corrections)



~2x more light due to LiquidO's aggressive scattering…

- faster collection & better light containment
- formation **topology** → **stochastic light confinement** →LiquidO

self-segmentation → <u>lossless light scattering</u> [data → **negligible losses**]

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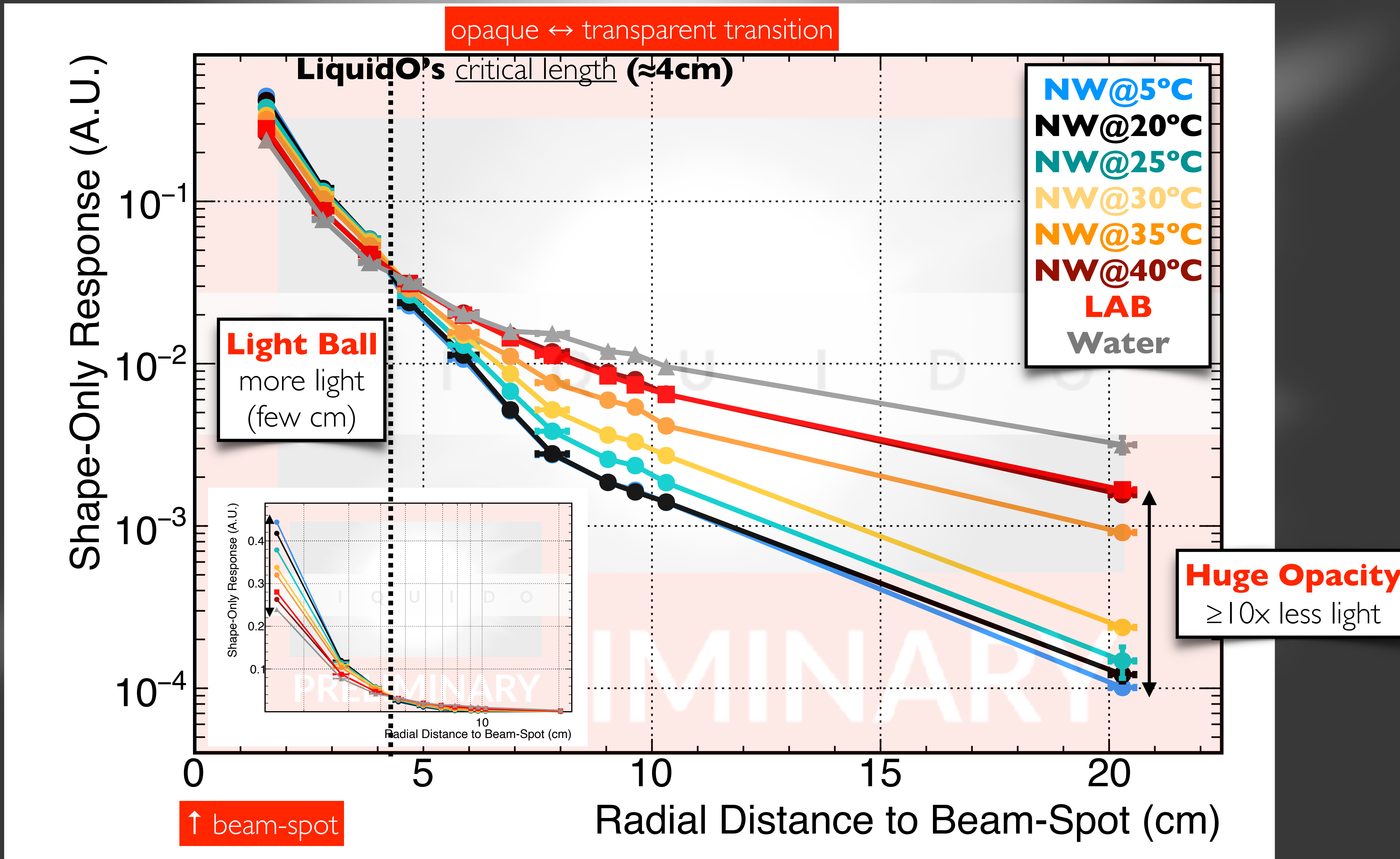
opacity metamorphosis…



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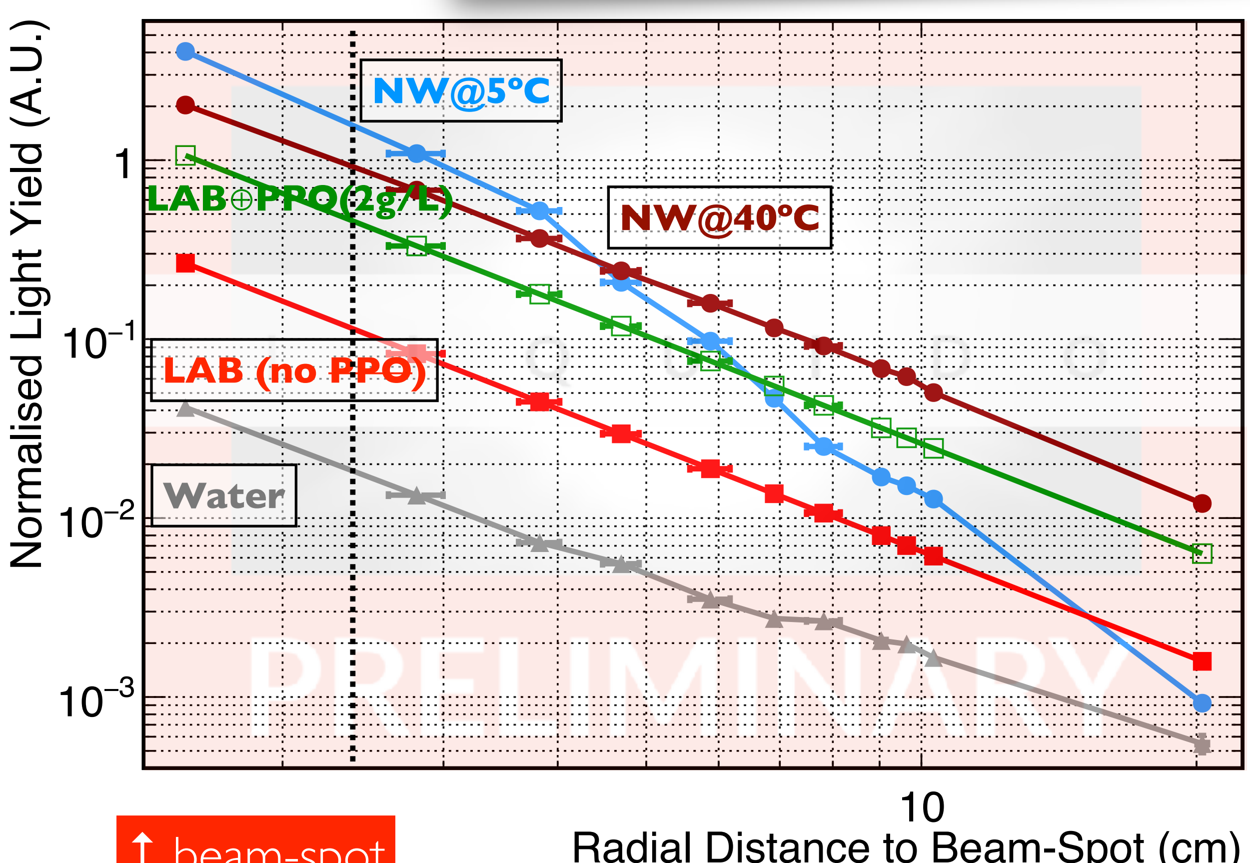
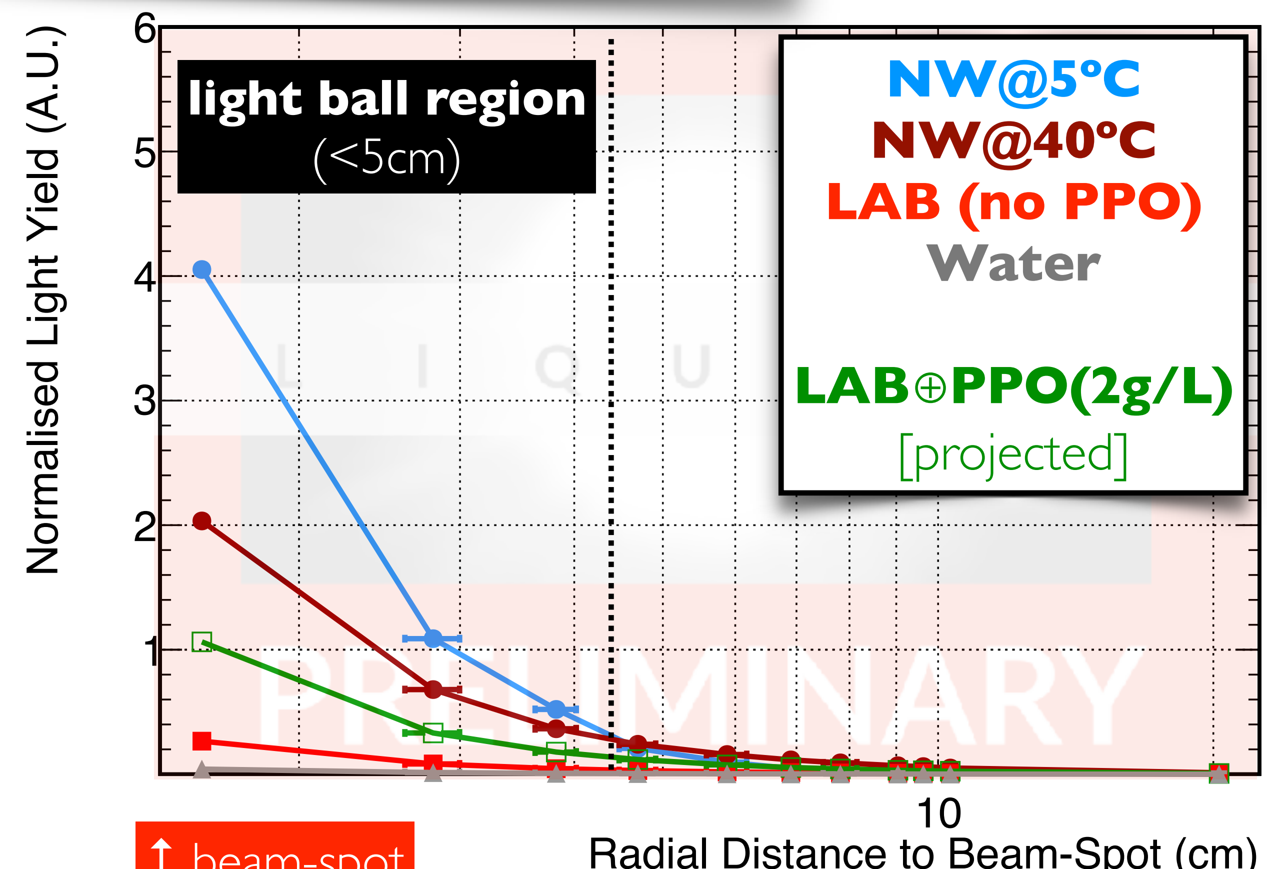
light yield exploration…

LiquidO: ~80% light collected within 5 cm's





↑ beam-spot

↑ beam-spot

brightest while light falls by almost 4 orders of magnitude in 20cm

effective detected light yield >120PE/MeV [@ SiPM]

≥250PE/MeV — **optimisation** (ongoing engineering)

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light-opacity duality…

LiquidO's Duality: lightness & darkness coexist

"one is cause/consequence of the other"

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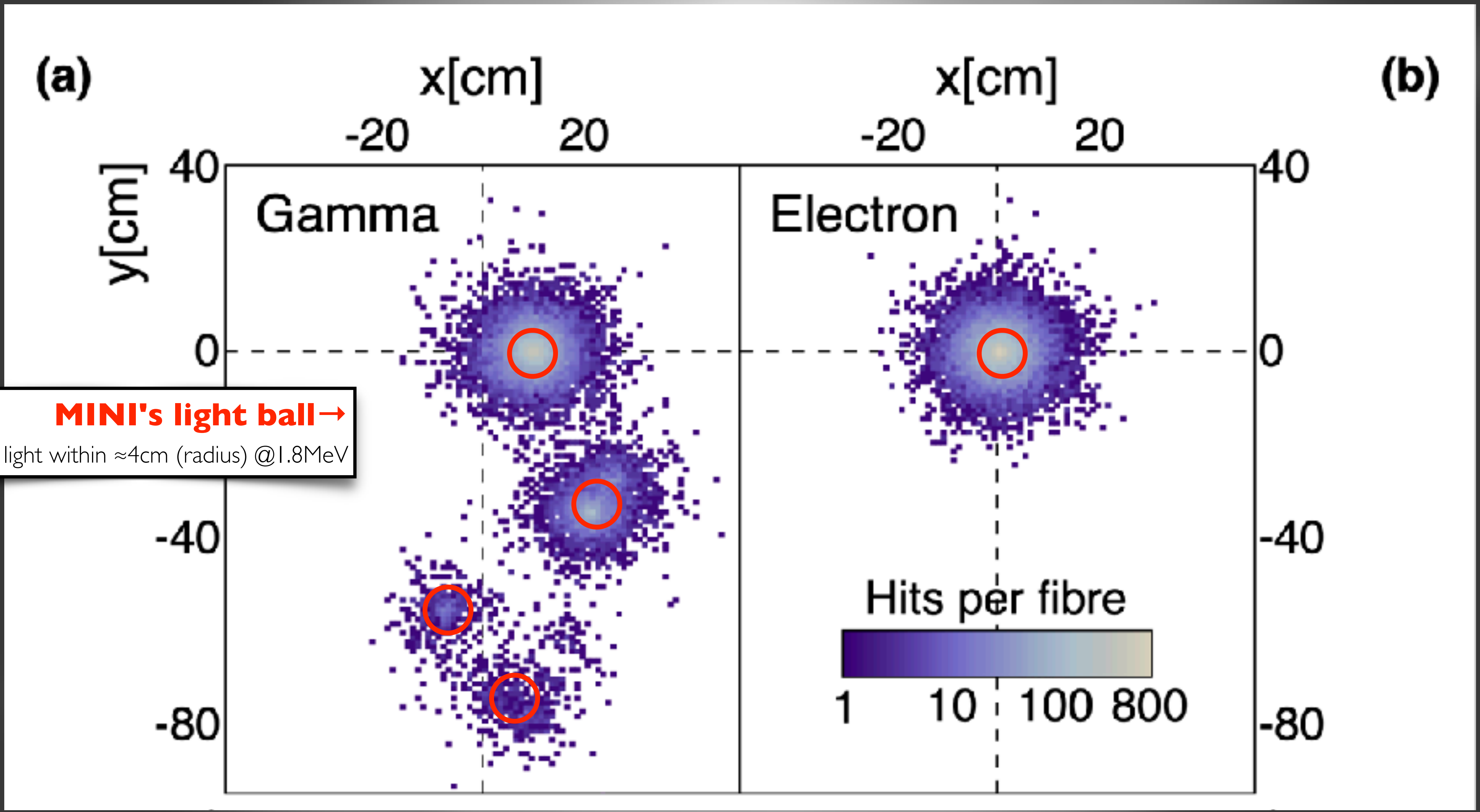
topology's PID (no timing)…

PID e/γ should be ≥100:1 rejection @ ≥90%



MINI's light ball→

~80% light within ≈4cm (radius) @1.8MeV

Neutrino physics with an opaque detector

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topology's PID (no timing)…

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MINI's light ball→

~80% light within ≈4cm (radius) @1.8MeV

←normally (r≳30cm ⇔ ≳1.5ns for σ^{PMT})

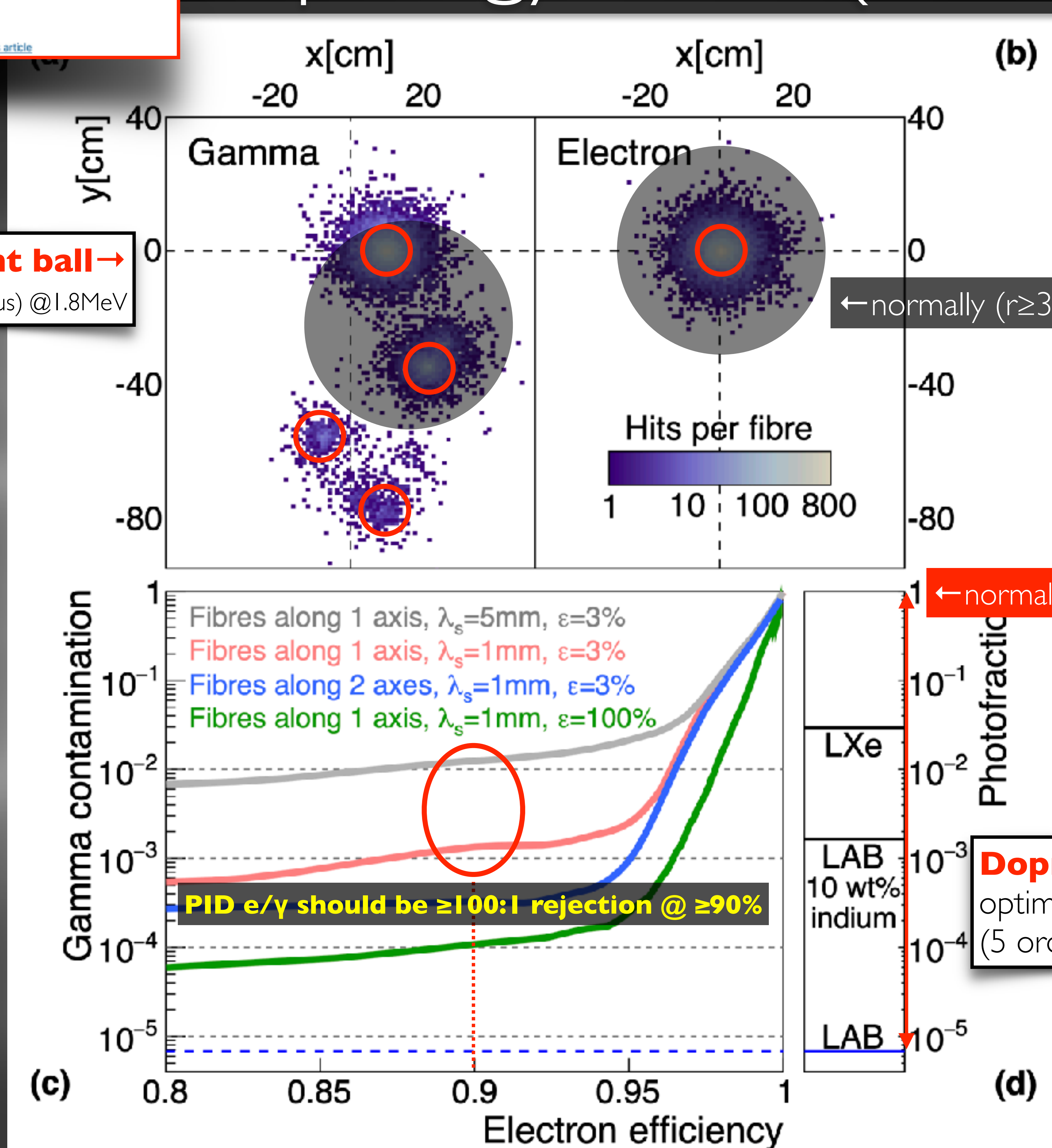
←normally here: **NO e/γ PID**

PID e/γ should be ≥100:1 rejection @ ≥90%

Doping Impact

optimisation **PID vs doping**

(5 orders of magnitude)



Anatael Cabrera (CNRS-IN2P3) — IJCLab / Université Paris-Saclay (Orsay)

LiquidO: light/opacity→stochastic light confinement

any source (Cherenkov / scintillation / **any light**)

any media (liquid / solid / (impractical?) gas?)

doping: a powerful (optional) "byproduct"

new technology: **opaque scintillation…**

↑ see Michi's & Christian's previous talks

Anatael Cabrera (CNRS-IN2P3) — IJCLab / Université Paris-Saclay (Orsay)

LiquidO: light detector with **opaque** medium

[*stochastic light confinement*→**imaging**⊕topology & **PID**]

⇓

LiquidO (5D primitive imaging info)

L I Q U I D O

light-based **"TPC"** (highest duty-cycle)

⊕

uniform calorimeter (scintillation)

⊕

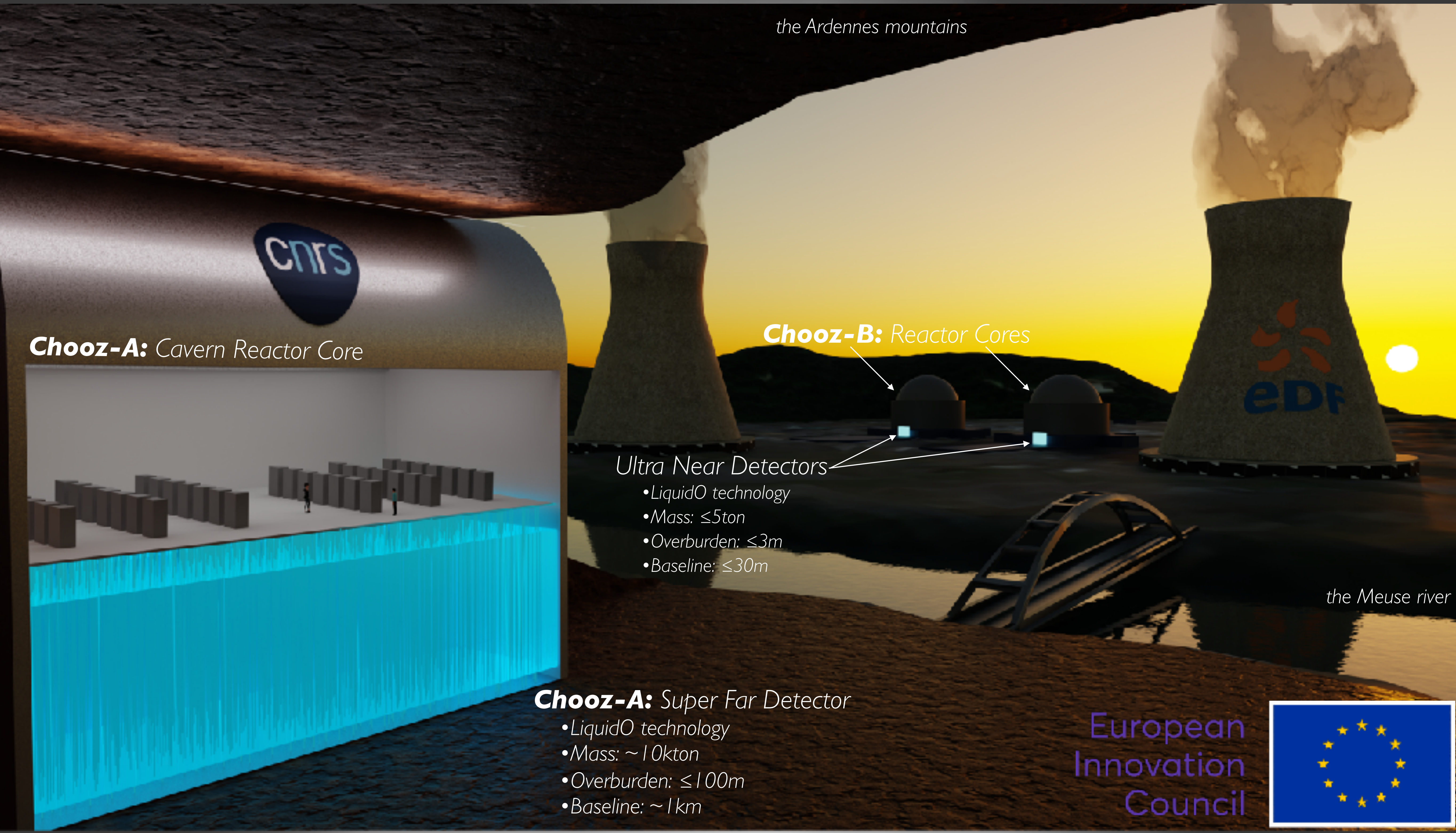
Time-of-Flight (4π acceptance)

⊕

imaging (PID, energy-flow, magnetisable, etc)

⊕

doping (variable composition/density & more physics)



https://liquido.ijclab.in2p3.fr/superchooz

SuperChooz Pathfinder…

first experiment…

European Innovation Council

UK Research and Innovation

C L O U D

Innovation Programme (confidential for now) — "Antimatter-OTech"
Fundamental Science Programme (soon)

- **EDF** (France) — **first time in neutrinos!**
- **CIEMAT** (Spain)
- **IJCLab**/Université Paris-Saclay (France)
- **J-G Universität Mainz** (Germany)
- **Subatech**/Nantes Université (France)
- **Sussex University** (UK)

—

- **Charles University** (Czech Republic)
- **INFN-Padova** (Italy)
- **UC-Irvine** (US)
- **Universidade Estadual de Londrina** (Brasil)
- **PUC-Rio** de Janeiro (Brasil)
- **Queen's University** (Canada)
- **University of Zaragoza** (Spain)
- **Tohoku University** / **RCNS** (Japan)

CLOUD collaboration (EDF⊕13 institutions over 10 countries)

Дякую…
merci…
고맙습니다…
ありがとう…
danke…
obrigado…
спасибі…
grazie…
谢谢…
hvala…
gracias…
شكرا…
thanks…

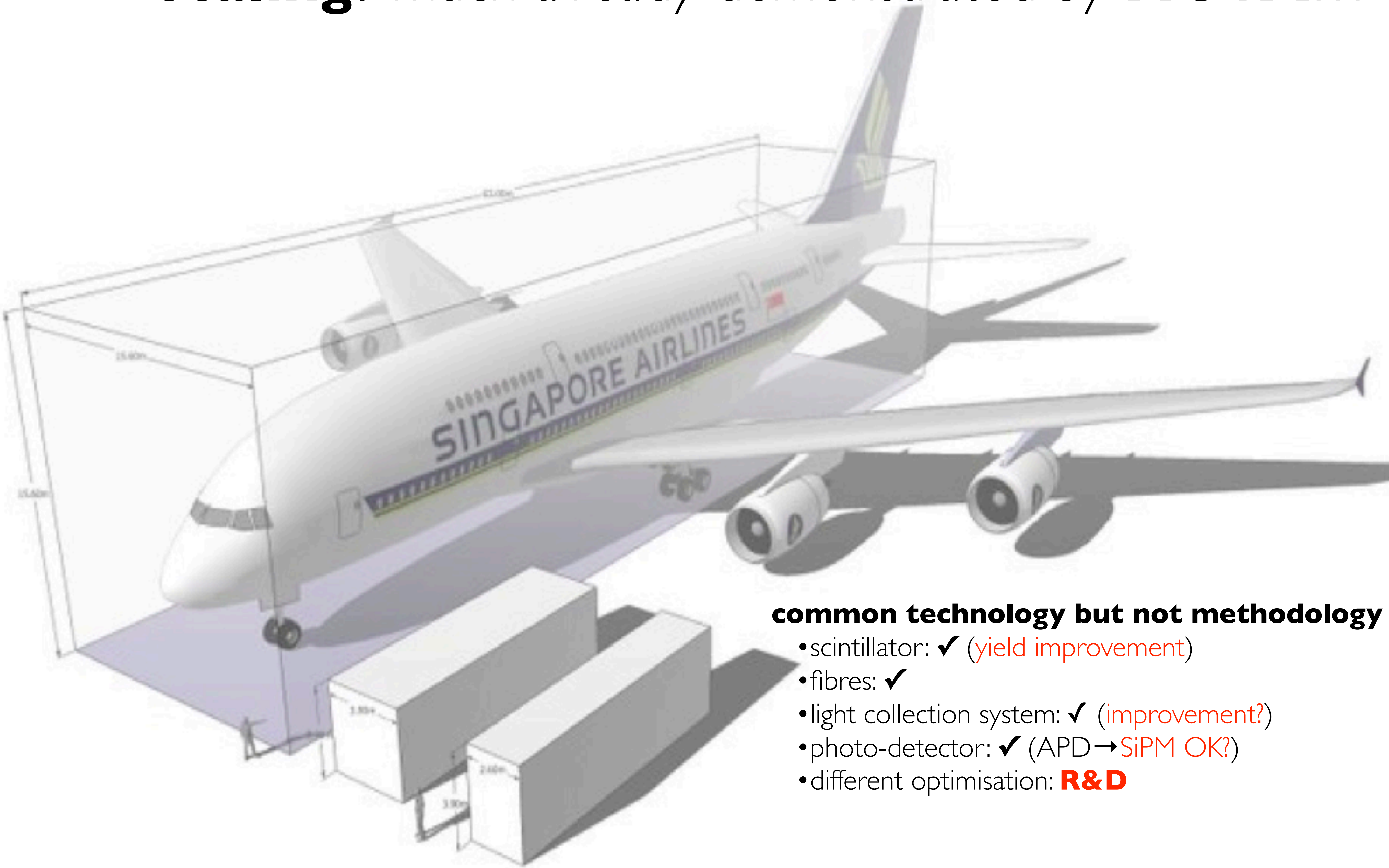
L I Q U I D O

https://liquido.ijclab.in2p3.fr/

LiquidO — foreseen performance appears largely **proved** **(→experiments)**

- how far? **data suggest still some more**… [**publication soon**]
- **robust & rich detection framework** — sub-atomic imaging/topology, sub-mm vertex, PID, heavy, doping, etc
- **R&D: enhance & specialise performance** — ex. new opaque scintillators [e.g. previous talks]
- **CLOUD/AM-OTech** (innovation): fundamental science physics programme [**publication soon**]

scaling? much already demonstrated by **NOvA**…



common technology but not methodology

- scintillator: ✓ (yield improvement)
- fibres: ✓
- light collection system: ✓ (improvement?)
- photo-detector: ✓ (APD→SiPM OK?)
- different optimisation: **R&D**

GeV OK!! But **~1MeV physics @ 10kton?**

(**R&D**)