

Liquid

a novel neutrino detection



Anatael Cabrera

CNRS/IN2P3
LAL/FLUO @ Orsay
LNCA @ Chooz

LiquidO is both...

LiquidO = new detection framework
(liquid scintillator based)



LiquidO = collaboration[⊕]cooperation team
(physics ↔ demonstration[⊕]R&D)

~40 scientists \oplus ~20 institutions \oplus ~10 countries

[Brasil, Canada, Chile, France, Germany, Italy, Japan, Spain, USA, UK]



LiquidO: ensuring correctness...

today's technology...





the V discovery (1950's)...

PMT \Leftrightarrow transparent medium

interaction coincidence and/or tagging

overburden (μ -cosmic shielding)

external shielding (radioactivity shielding)

loaded medium (^{113}Cd) \rightarrow non-native detection!

(reactor source) **modulation ON vs OFF**

~70years ago similar to today!

neutrino detection \leftrightarrow art of transparency

[Reines&Cowan since 50's]

today's technology is much about **shielding**
(active and/or **passive**)

overburden (up to km's)
(if new facility: large construction cost)

(typically)
≥ half excavated volume in shields
(buffer precious/expensive)

large (1k ton)...



~10,000 PMTs (8" diameter)

NOTE: KamLAND similar size but balloon

SNO @ Canada
(Nobel prize 2015)

LiquidO ...



Neutrino Physics with an Opaque Detector

A. Cabrera^{*1,9,10}, A. Abusleme¹⁵, J. dos Anjos^{†3}, T. J. C. Bezerra¹⁸, M. Bongrand⁹, C. Bourgeois⁹, D. Breton⁹, C. Buck¹², J. Busto⁶, E. Calvo⁵, E. Chauveau⁴, M. Chen¹⁶, P. Chimenti¹¹, F. Dal Corso¹³, G. De Conto¹¹, S. Dusini¹³, G. Fiorentini^{7a,7b}, C. Frigerio Martins¹¹, A. Givaudan¹, P. Govoni^{2a,2b}, B. Gramlich¹², M. Grassi^{1,9}, Y. Han^{1,9}, J. Hartnell¹⁹, C. Hugon⁶, S. Jiménez⁵, H. de Kerret^{‡1}, A. Le Neve⁹, P. Loaiza⁹, J. Maalmi⁹, F. Mantovani^{7a,7b}, L. Manzanillas⁹, C. Marquet⁴, J. Martino¹⁸, D. Navas⁵, H. Nunokawa¹⁴, M. Obolensky¹, J. P. Ochoa-Ricoux^{8,15}, G. Ortona²⁰, C. Palomares⁵, F. Pessina¹⁴, A. Pin⁴, M. S. Pravikoff⁴, M. Roche⁴, B. Roskovec⁸, N. Roy⁹, C. Santos¹, A. Serafini^{7a,7b}, L. Simard⁹, M. Sisti^{2a,2b}, L. Stanco¹³, V. Strati^{7a,7b}, J.-S. Stutzmann¹⁸, F. Suekane^{*§1,17}, A. Verdugo⁵, B. Viaud¹⁸, C. Volpe¹, C. Vrignon¹, S. Wagner¹, and F. Yermia¹⁸

¹APC, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité University, 75205 Paris Cedex 13, France

^{2a}Università di Milano-Bicocca, I-20126 Milano, Italy

^{2b}INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy

³Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, RJ, 22290-180, Brazil

⁴CENBG, UMR5797, Université de Bordeaux, CNRS/IN2P3, F-33170, Gradignan, France

⁵CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), E-28040 Madrid, Spain

⁶Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

^{7a}Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy

^{7b}INFN, Ferrara Section, Via Saragat 1, 44122 Ferrara, Italy

⁸Department of Physics and Astronomy, University of California at Irvine, Irvine, California 92697, USA

⁹LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France

¹⁰LNCA Underground Laboratory, CNRS/IN2P3 - CEA, Chooz, France

¹¹Departamento de Física, Universidade Estadual de Londrina, 86051-990, Londrina – PR, Brazil

¹²Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

¹³INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy

¹⁴Department of Physics, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, RJ, 22451-900, Brazil

¹⁵Pontificia Universidad Católica de Chile, Santiago, Chile

¹⁶Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario K7L3N6, Canada

¹⁷RCNS, Tohoku University, 6-3 AzaAoba, Aramaki, Aoba-ku, 980-8578, Sendai, Japan

¹⁸SUBATECH, CNRS/IN2P3, Université de Nantes, IMT-Atlantique, 44307 Nantes, France

¹⁹Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

²⁰INFN, Sezione di Torino, I-10125 Torino, Italy

August 9, 2019

arXiv:1908.02859v1 [physics.ins-det] 7 Aug 2019

The discovery of the neutrino by Reines & Cowan in 1956 revolutionised our understanding of the universe at its most fundamental level and provided a new probe with which to explore the cosmos. Furthermore, it laid the groundwork for one of the most successful and widely used neutrino detection technologies to date: the liquid scintillator detector. In these detectors, the light produced by particle interactions propagates across transparent scintillator volumes to surrounding photo-sensors. This article introduces a new approach, called LiquidO, 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 fibres. The principles behind LiquidO's detection technique and the results of the first experimental validation are presented. The LiquidO technique provides high-resolution imaging that enables highly efficient identification of individual particles event-by-event. Additionally, the exploitation of an opaque medium gives LiquidO natural affinity for using dopants at unprecedented levels. With these and other capabilities, LiquidO has the potential to unlock new opportunities in neutrino physics, some of which are discussed here.

^{*}Contact: anatael@in2p3.fr and suekane@awa.tohoku.ac.jp.

[†]Also at Observatório Nacional, Rio de Janeiro, Brasil

[‡]Deceased.

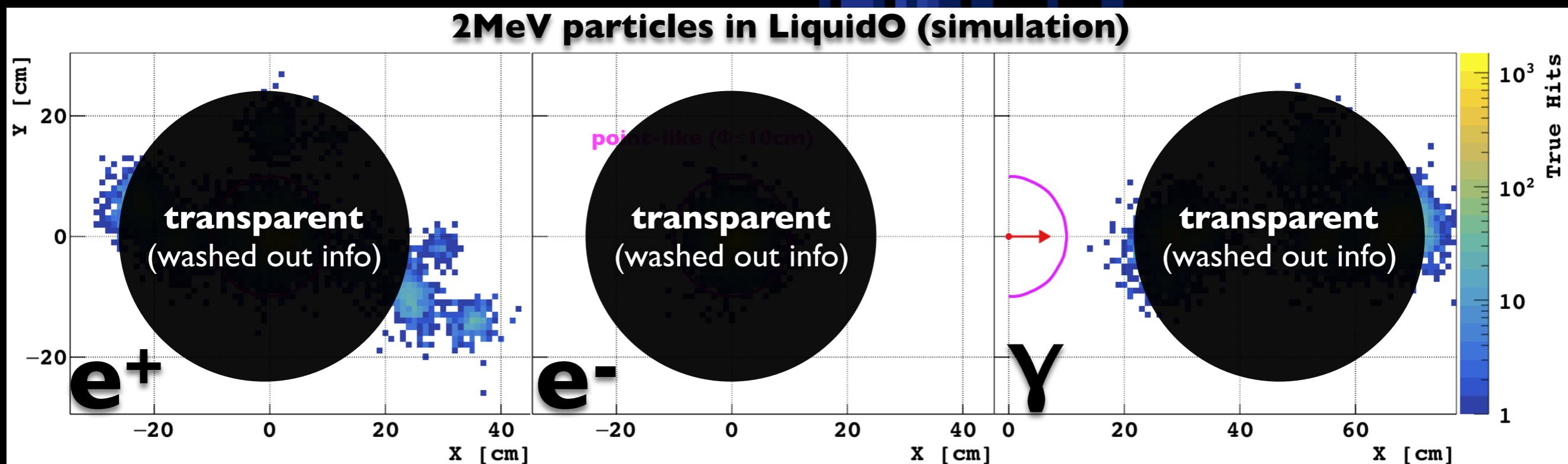
[§]Blaise Paschal Chaire Fellow.

arXiv:1908.02859

out first paper...

LiquidO in a nut-shell...

Imaging → powerful Particle-IDentification (PID)

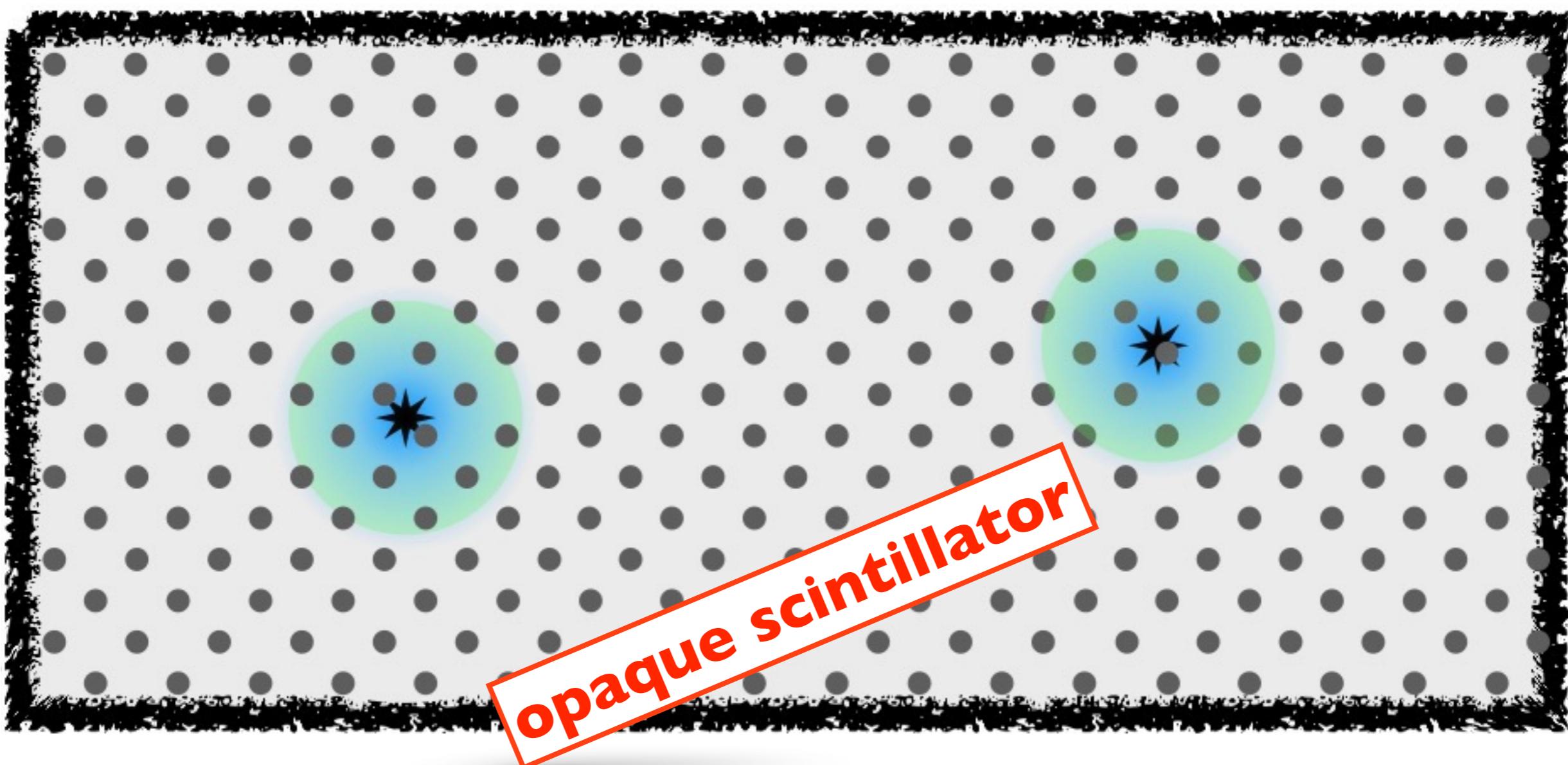


LiquidO \approx PID \oplus (high) Doping

physics beyond detector “native composition” (H,C)

LiquidO: the detection principle...

confine energy deposition locally → freeze information



readout: wave-shifting-fibres \oplus SiPM's

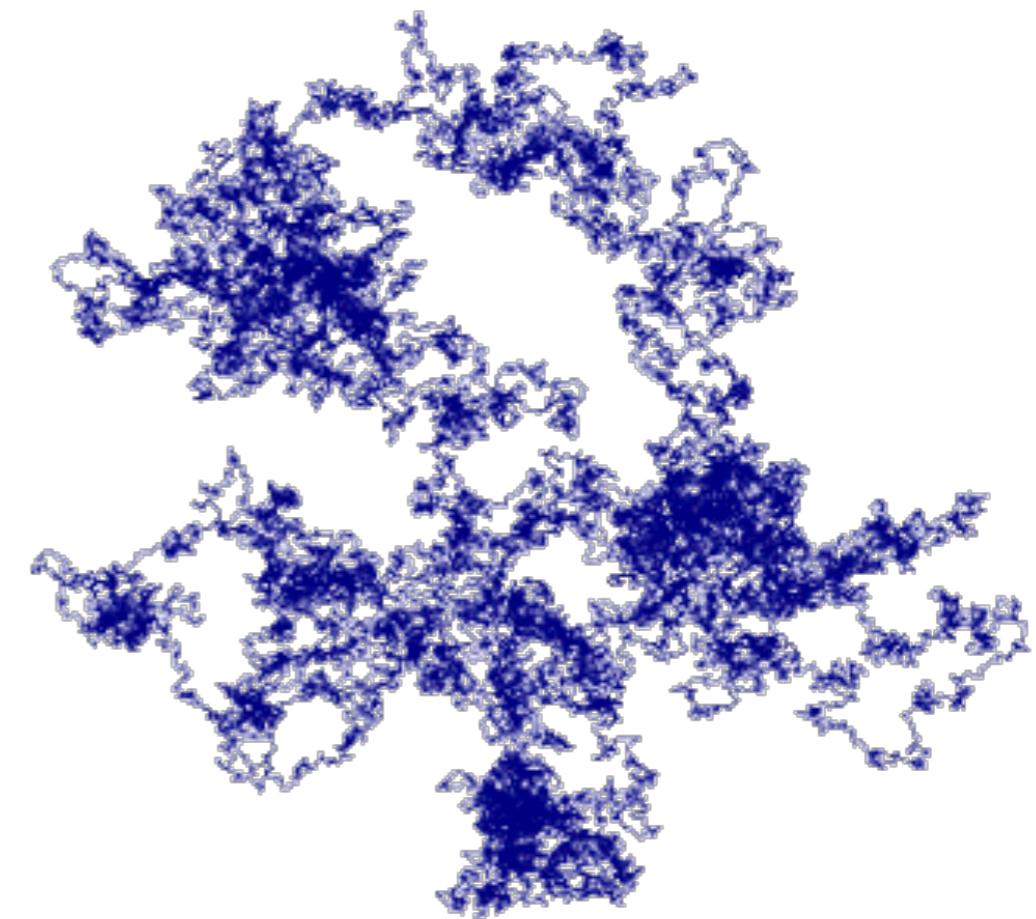
PMTs → become useless (unreachable light)

known light confinement strategies...

Event Horizon Telescope: Black Hole's Mapping



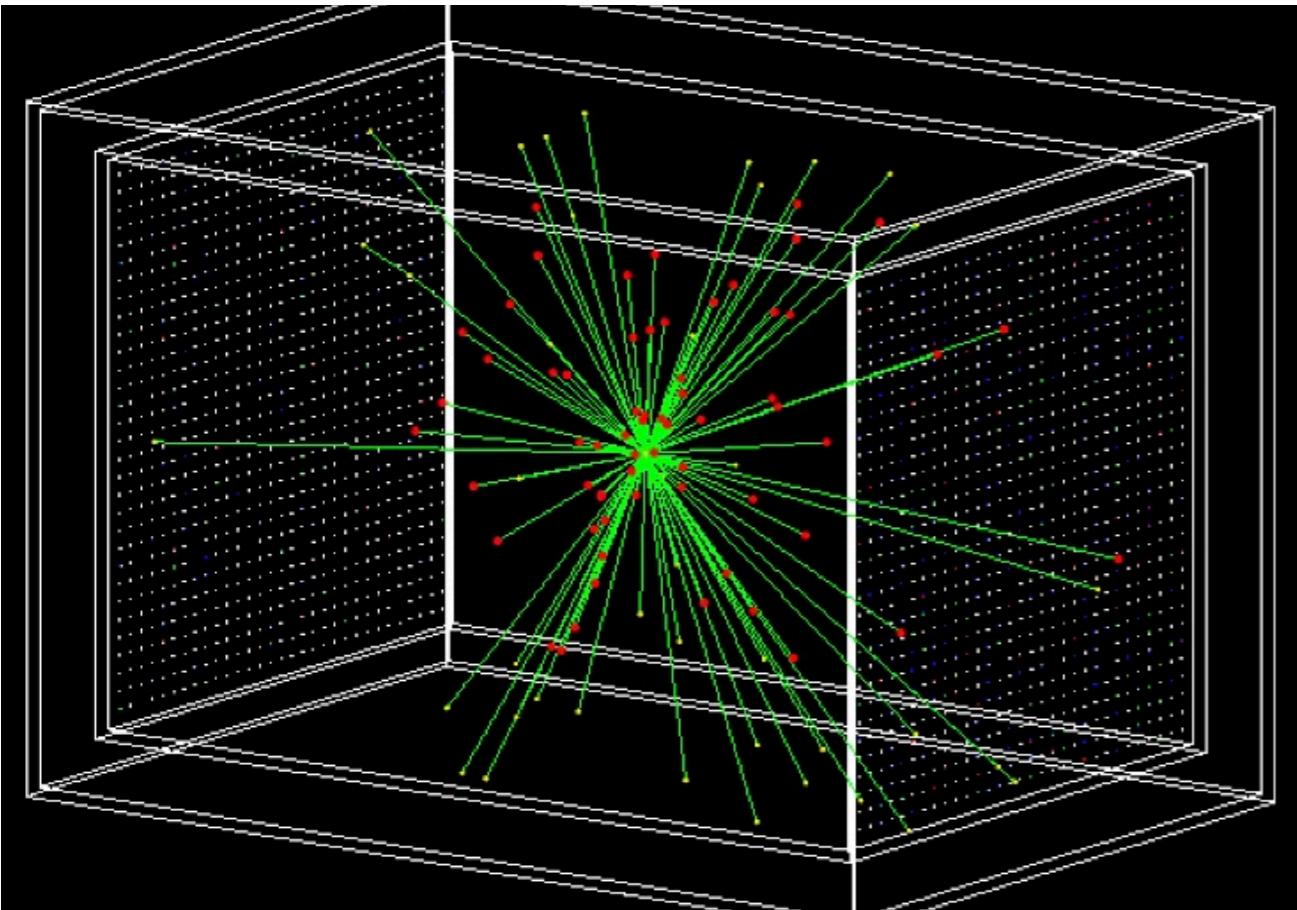
gravitational confinement
(ex. a black hole)



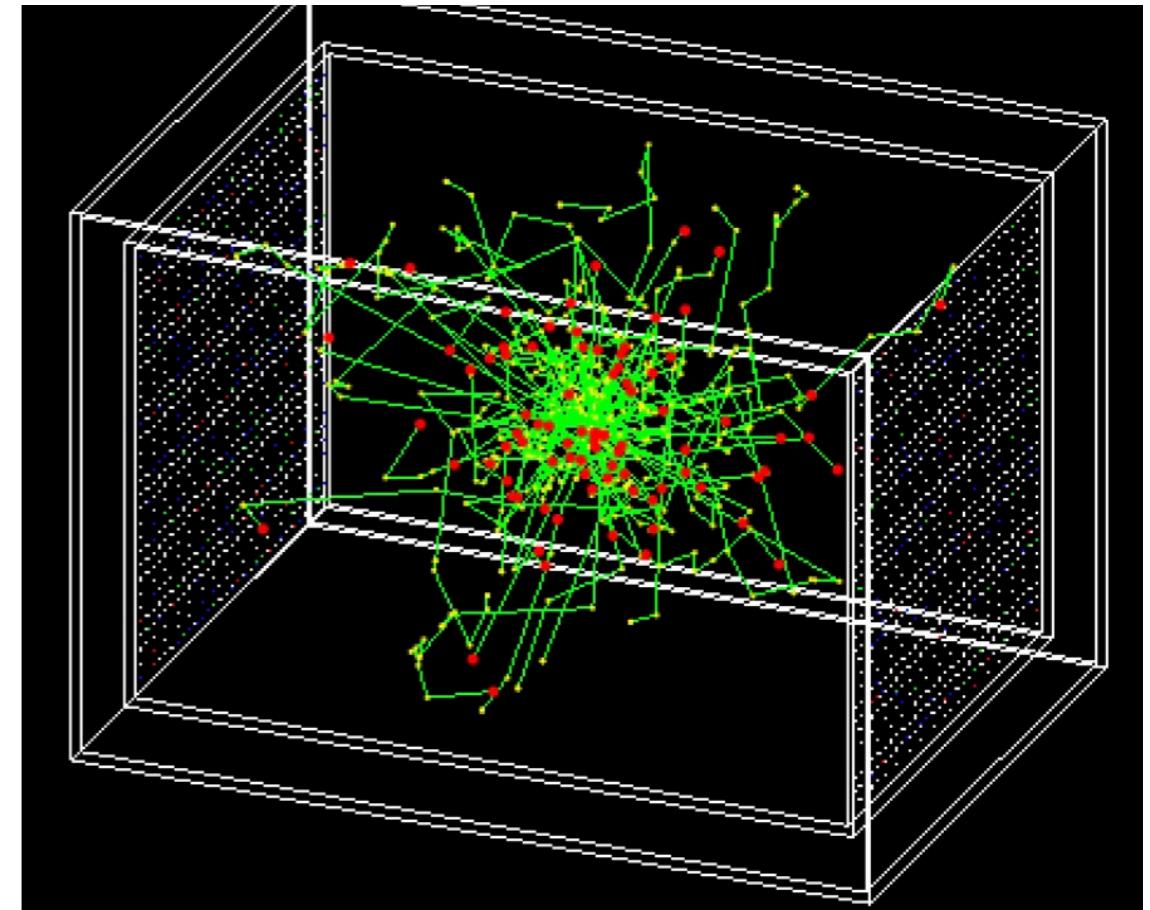
stochastic confinement
(ex. random walk)

**light position restricted
(both cases)**

LiquidO recipe: just “bread & butter” physics...



today's technology



LiquidO technology

light ball size: scattering \oplus fibres
(sampling optimisation)



like this?
(Ireland)

does



like this? (France)

LiquidO = Liquid + Opaque

First Opaque Scintillator: arXiv:1908.03334



liquid~wax behaviour

reality is more like this...

LiquidO implies (“theorem”) . . .



“milky” / “cloudy” / “waxy”
scintillator
(gas↔liquid↔solid)

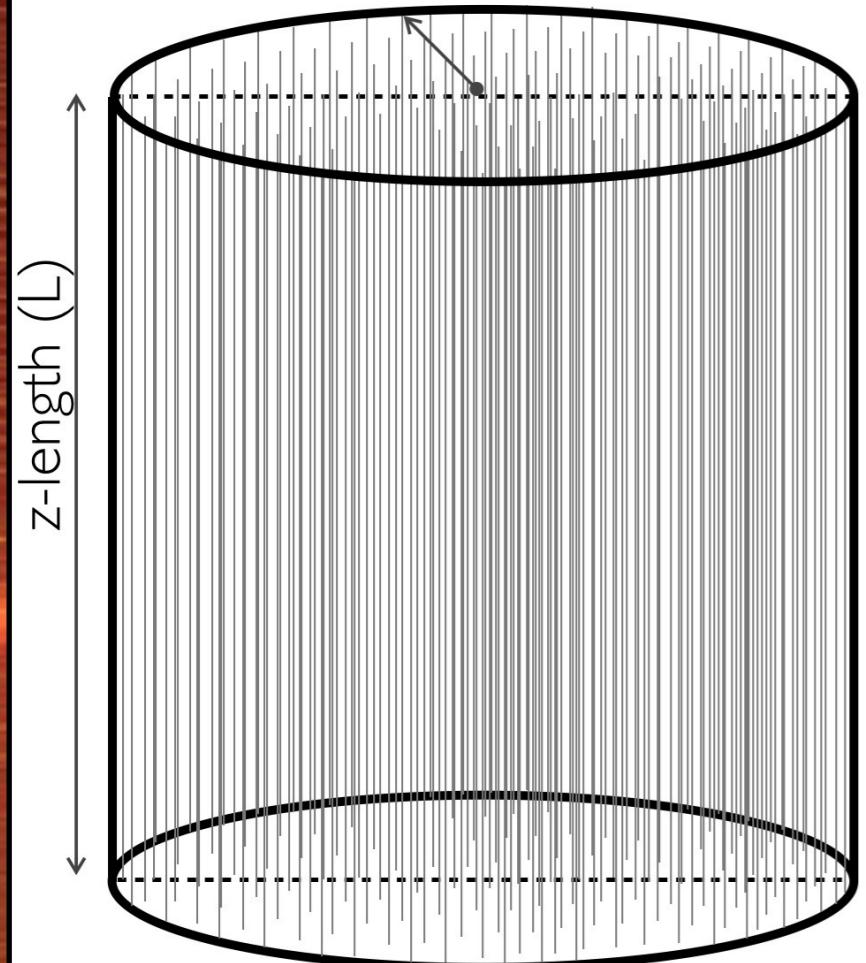


LiquidO detector articulation...

simplest LiquidO design: 2D+time...

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

radius (R) (plane x-y)



lattice distance: ξ
(a few cm)

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

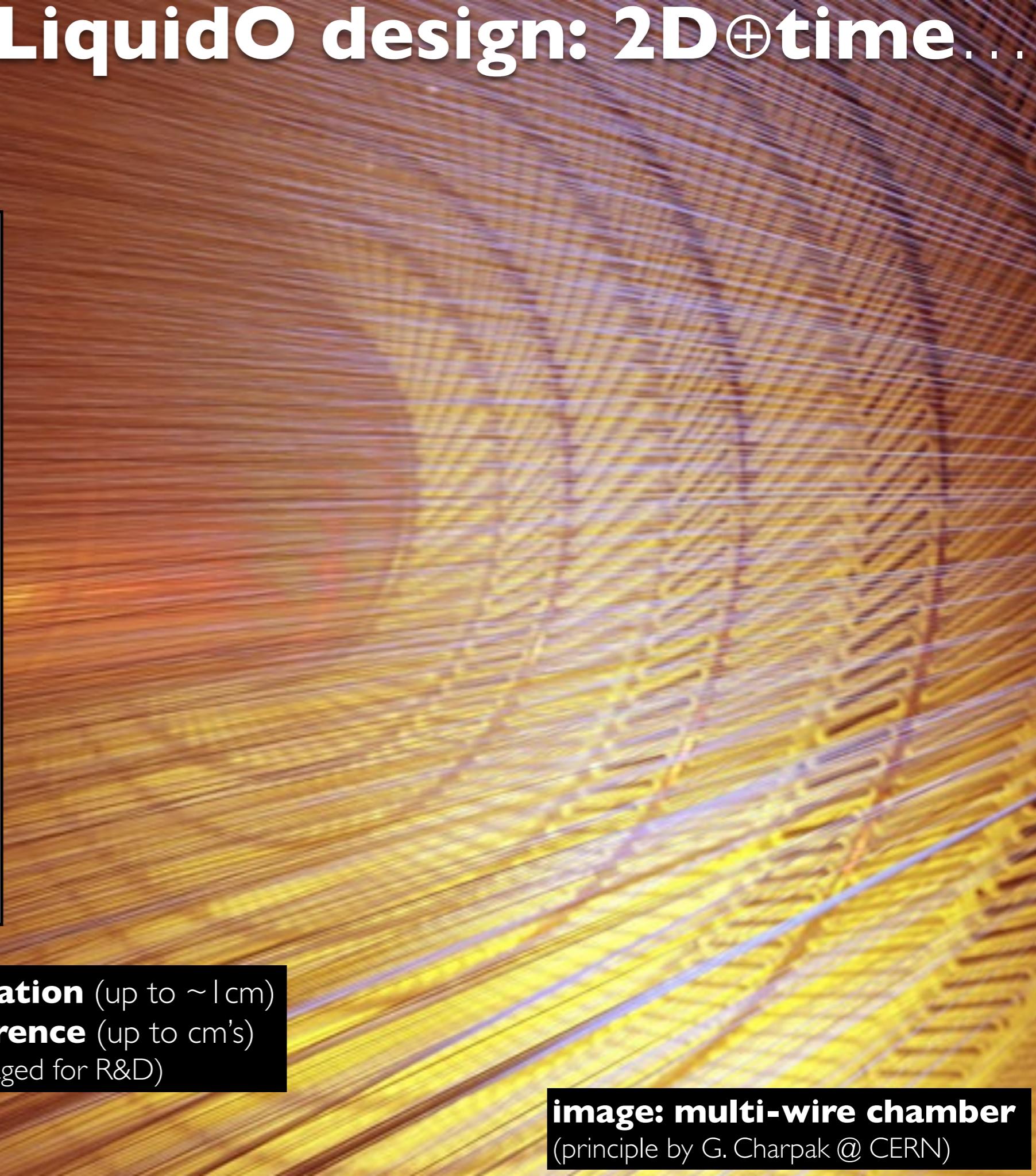
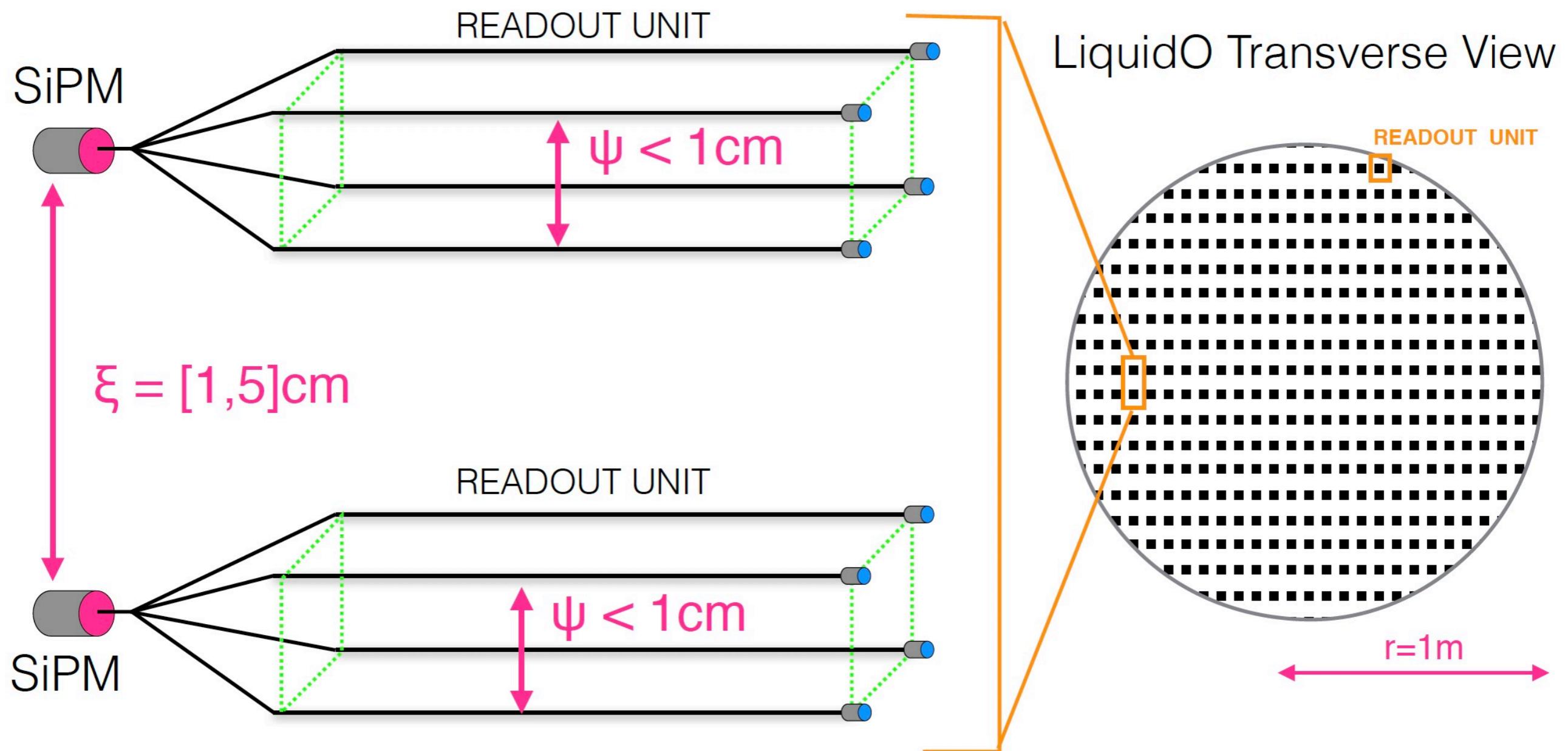


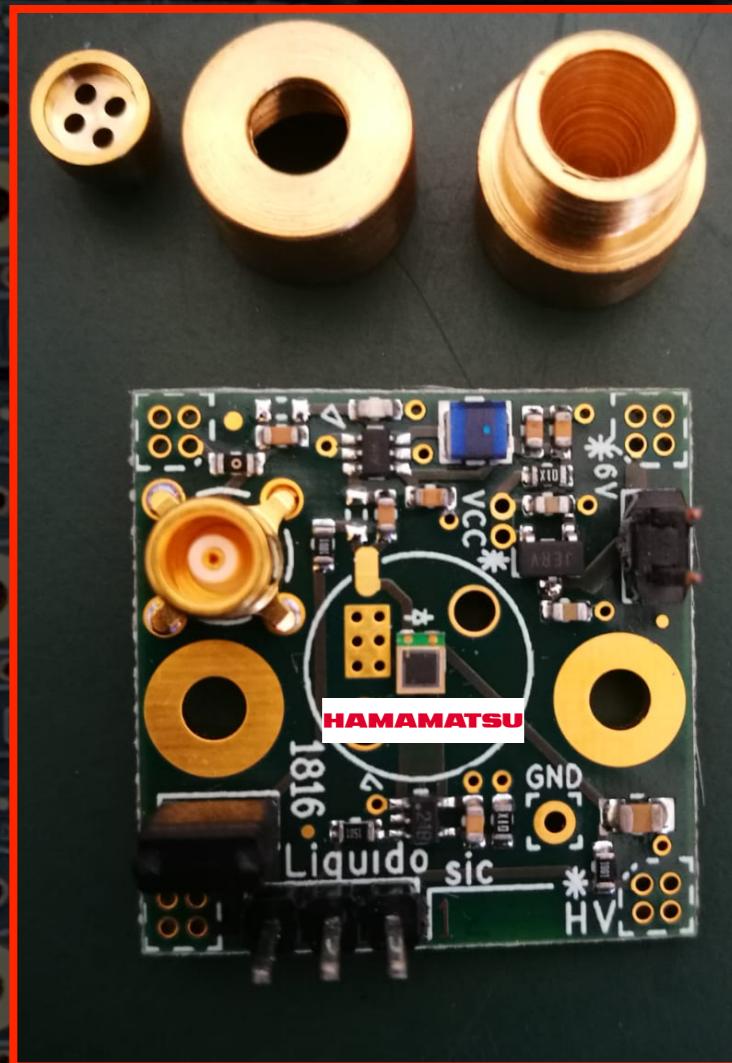
image: multi-wire chamber
(principle by G. Charpak @ CERN)

detector articulation & readout...



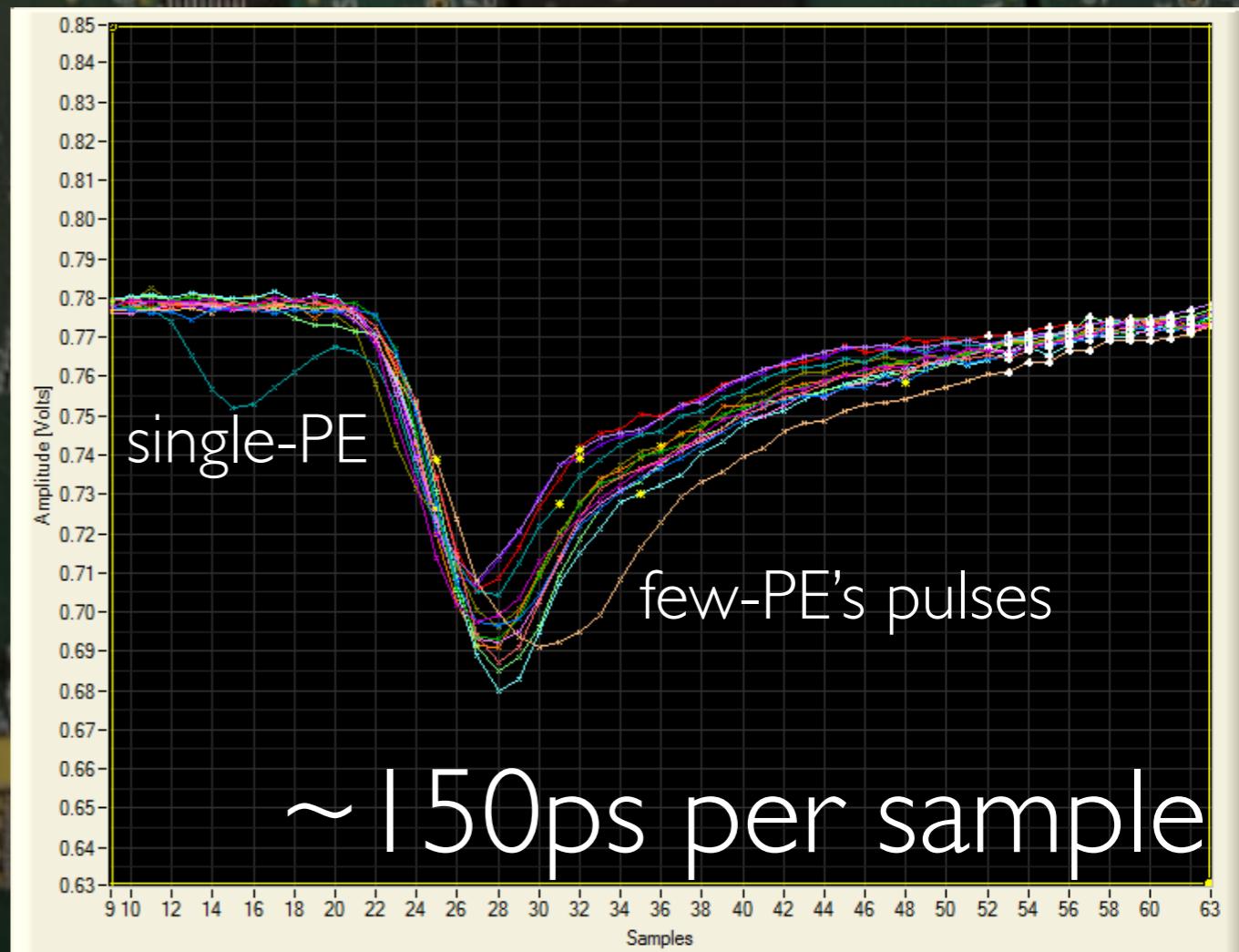
“infinitesimal” fibres → MeV calorimetry
 (reduce non-stochastic terms)

(fastest) SiPM electronics readout...



(expected) **time resolution: $\leq 100\text{ps/PE}$**
(i.e. $\leq 3\text{cm/PE}$ @ speed of light)

our digitisation electronics...



(expected) **time resolution: $\leq 100\text{ps/PE}$**
(i.e. $\leq 3\text{cm/PE}$ @ speed of light)

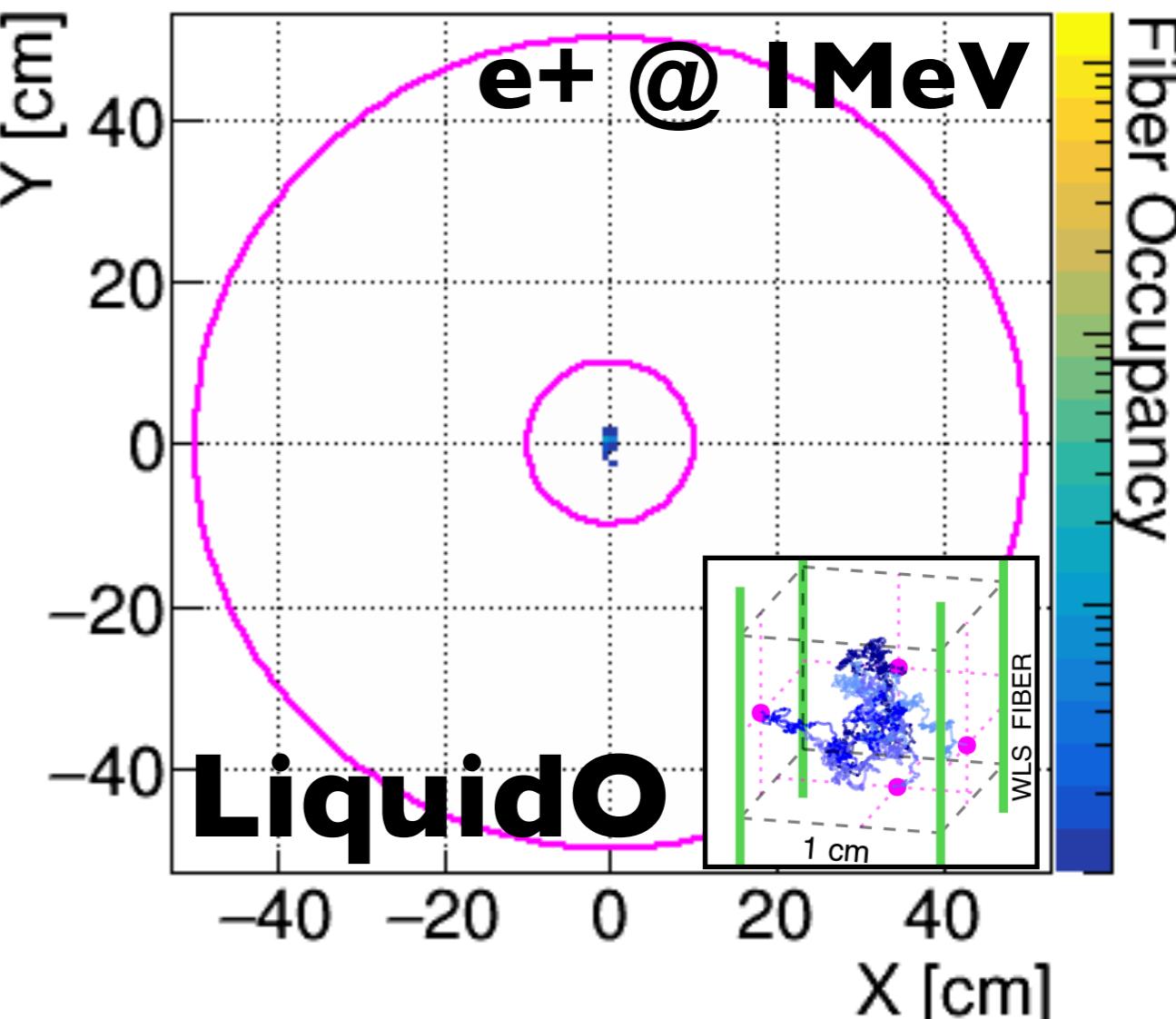
(instrumentation-wise)

LiquidO \approx “light” TPC \oplus 4 π -ToF



stunning event pattern...

LiquidO vs “traditional LS” (example: e+)



why opacity? [up to now the death of LS]

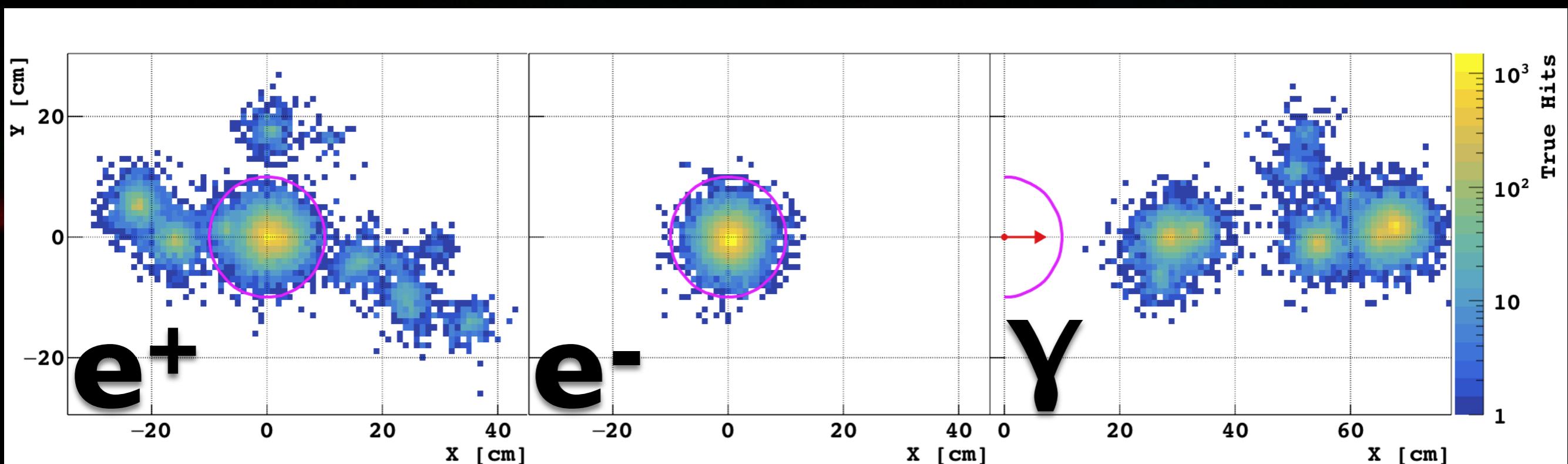
- **stochastic light confinement** (few cm's) → powerful energy pattern (**PID**)
- **slow down speed of light** ($\sim 1/10x$) → **energy flow & causality [next]**
- **maximal light collection** ($\geq 90\%$) → light level up to **$\leq 400 \text{PE/MeV? [R&D]}$**

MC says LiquidO works!!

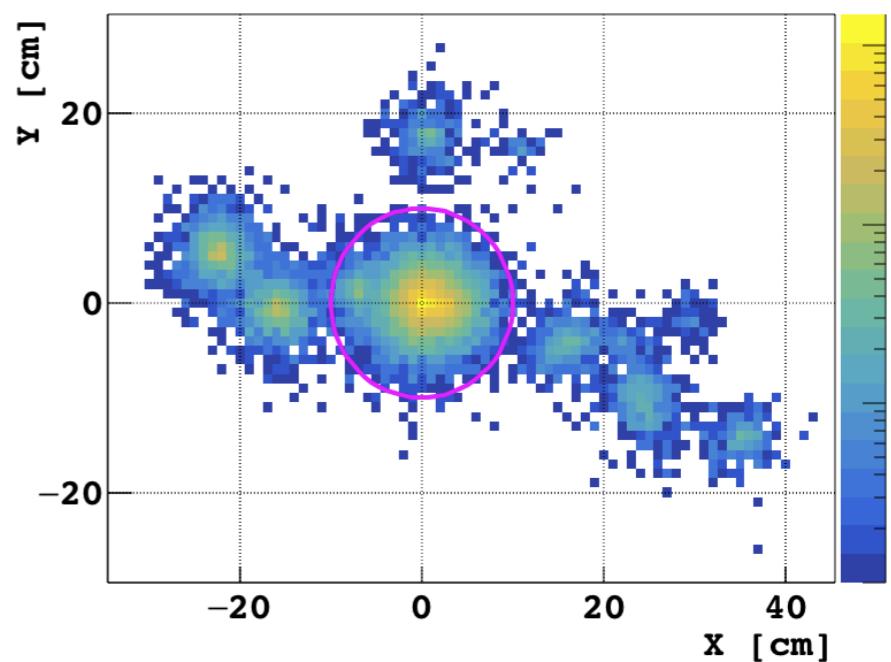
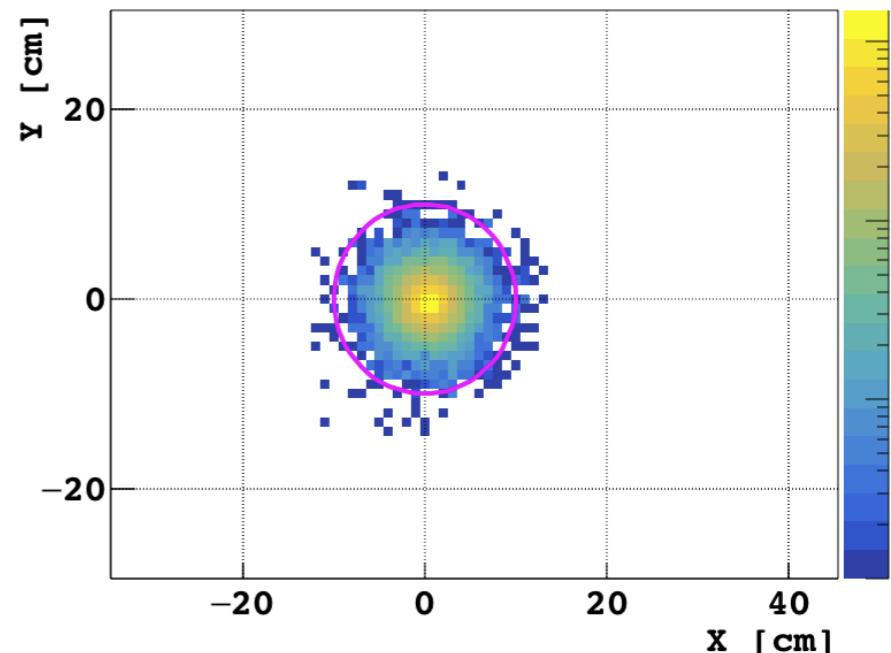
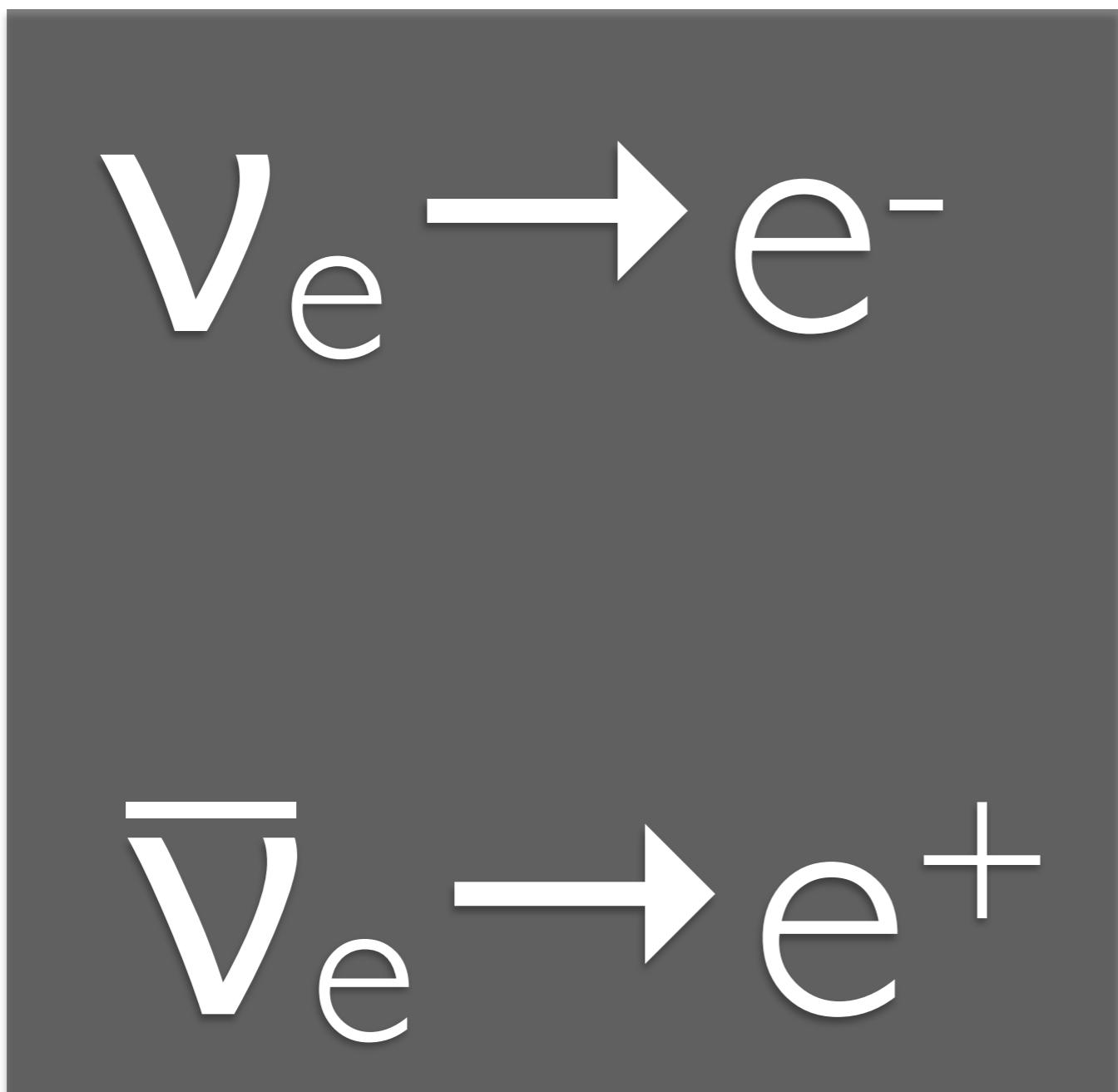
[bread-&-butter physics]

powerful PID expected...

2MeV



no need for segmentation → problematic! (cost/complex)
(opacity → self-segmented)

CC ν interaction observables...

a breakthrough capability $\leq 100\text{MeV}$
 (\rightarrow only possible with ν_μ 's so far)

LiquidO resolution

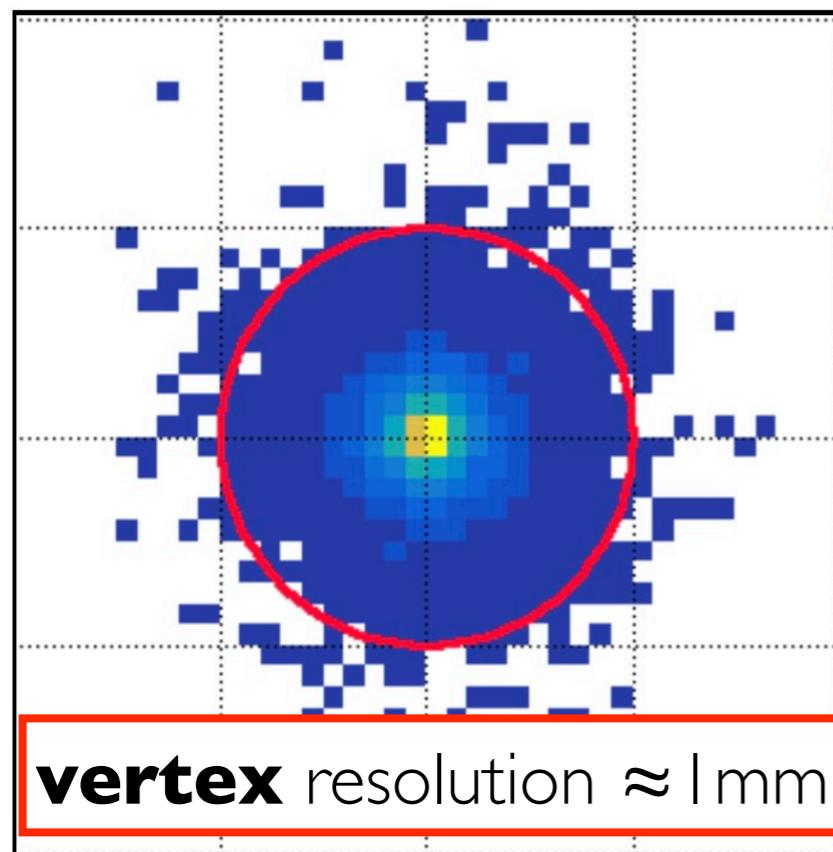
(translucide medium)



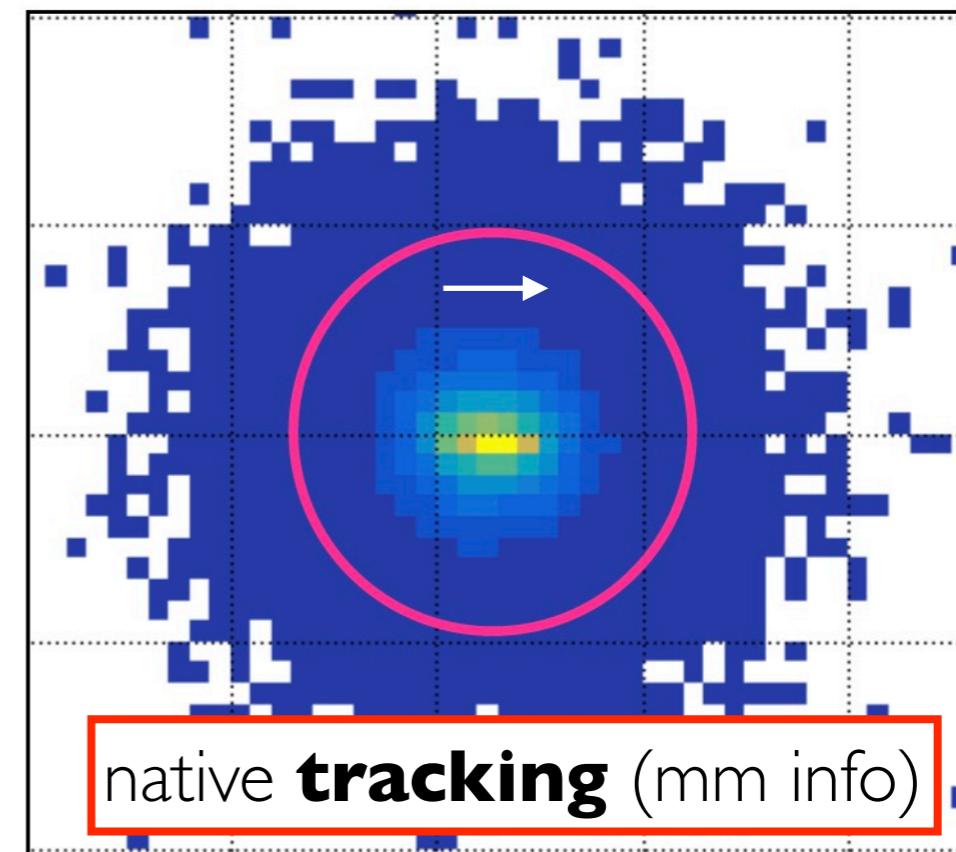
dE/dx per particle

($\leq 100\text{MeV}$)

1 MeV Electron



10 MeV Electron

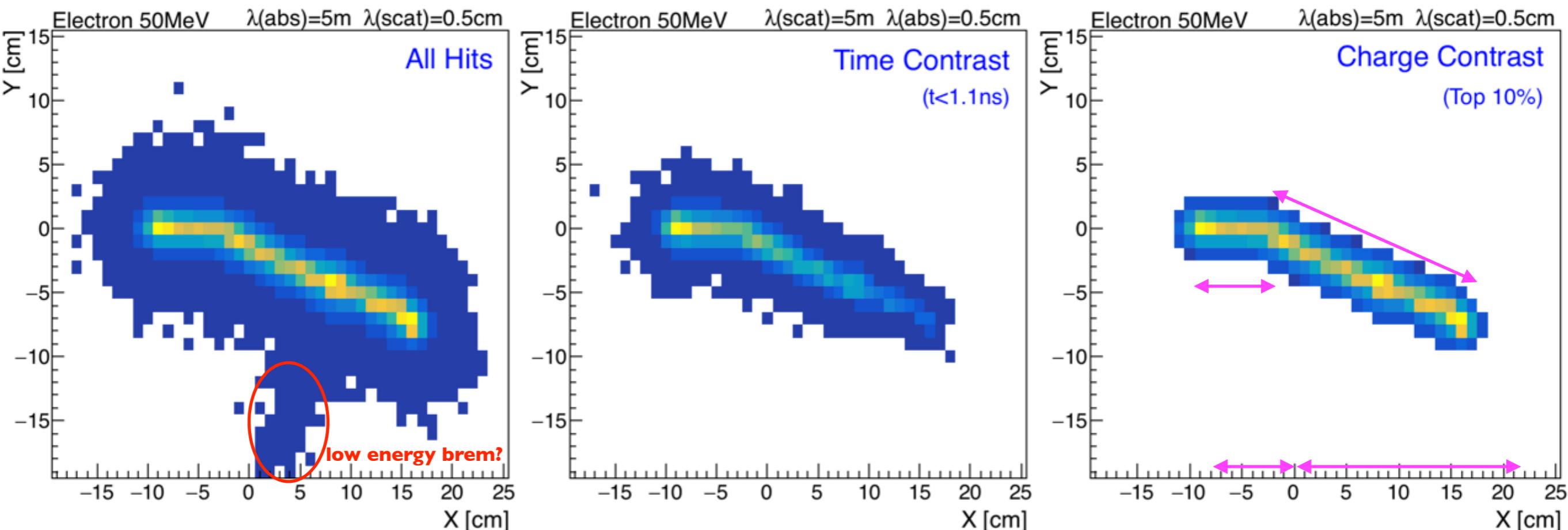


effective point
(Bragg peak dominated)

effective track
(MIP dominated)

30 consider an **e⁻ @ 50MeV (ν_e CC or Michel)...**

dE/dx: ionisation till $\sim 100\text{MeV}$ (E_c for scintillator)



simple calculation (by eye!)

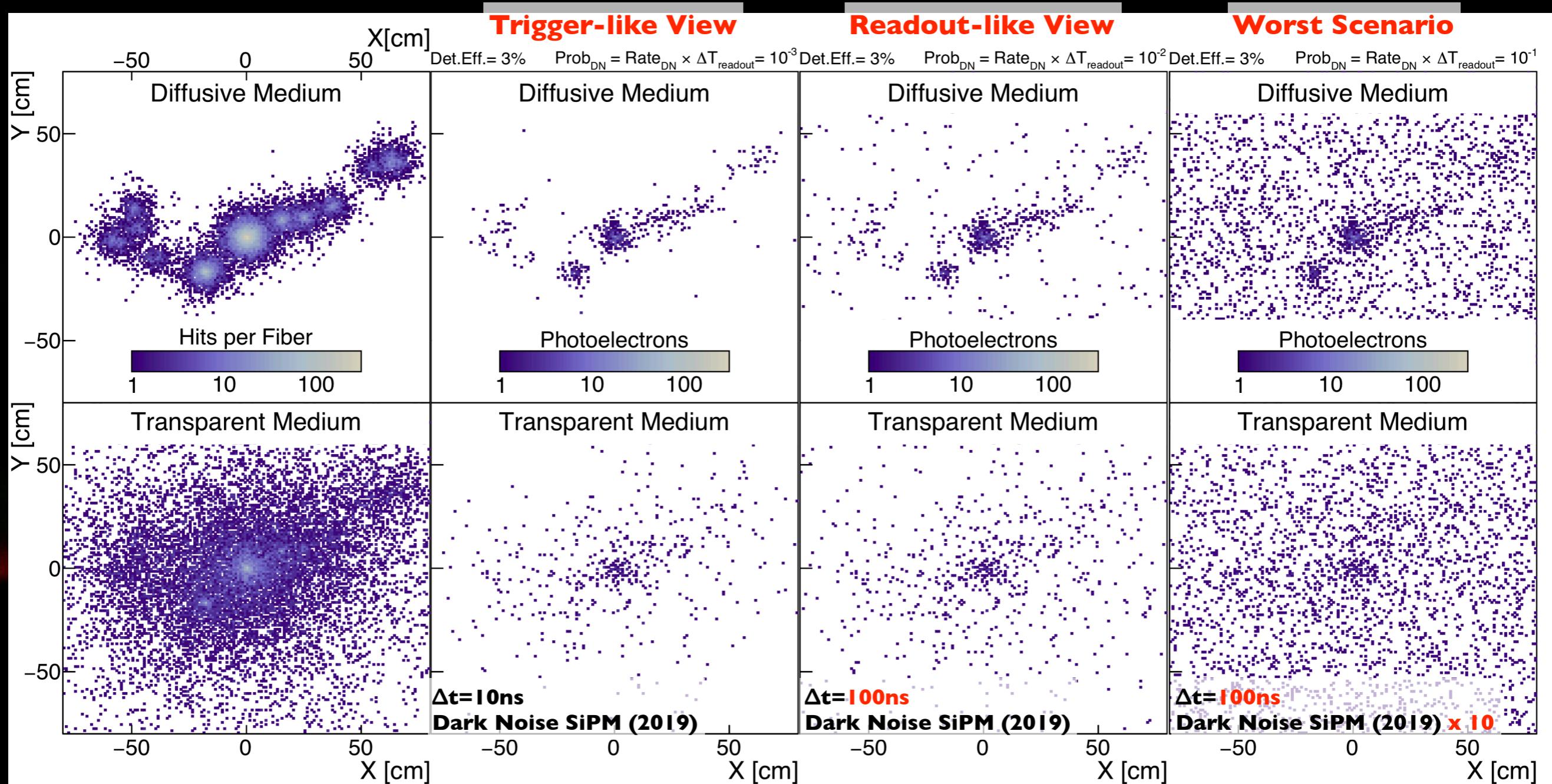
$\sim(30 \pm 2)\text{cm}$ (length) [50MeV] \Rightarrow **$(1.7 \pm 0.1)\text{MeV/cm}$** [expected: **$\sim 1.8\text{MeV/cm}$**]

(systematic: dE/dx is not uniform along track due to Bragg-peak)

energy measurement: both calorimetry (typical) & range (only LiquidO)

LiquidO stunning information level (with pros and cons)

LiquidO \oplus readout (today's technology) effect....



NOTE: SiPM cooling under consideration: $\Delta T=-10^\circ \rightarrow 1/2x$ less dark-noise

detection photons \rightarrow reduce information

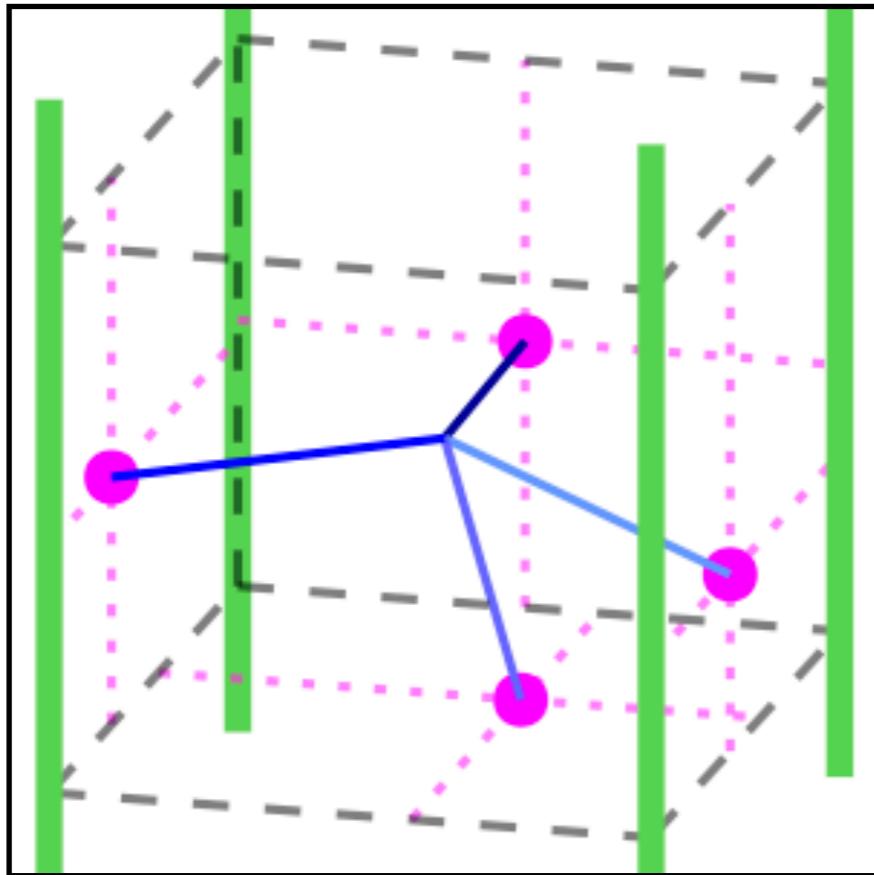
[technology dependent: conservative assumption]

readout dark-noise (LiquidO light confinement critical)

Opaque scintillator → **new technology!**
(so far only transparent considered)

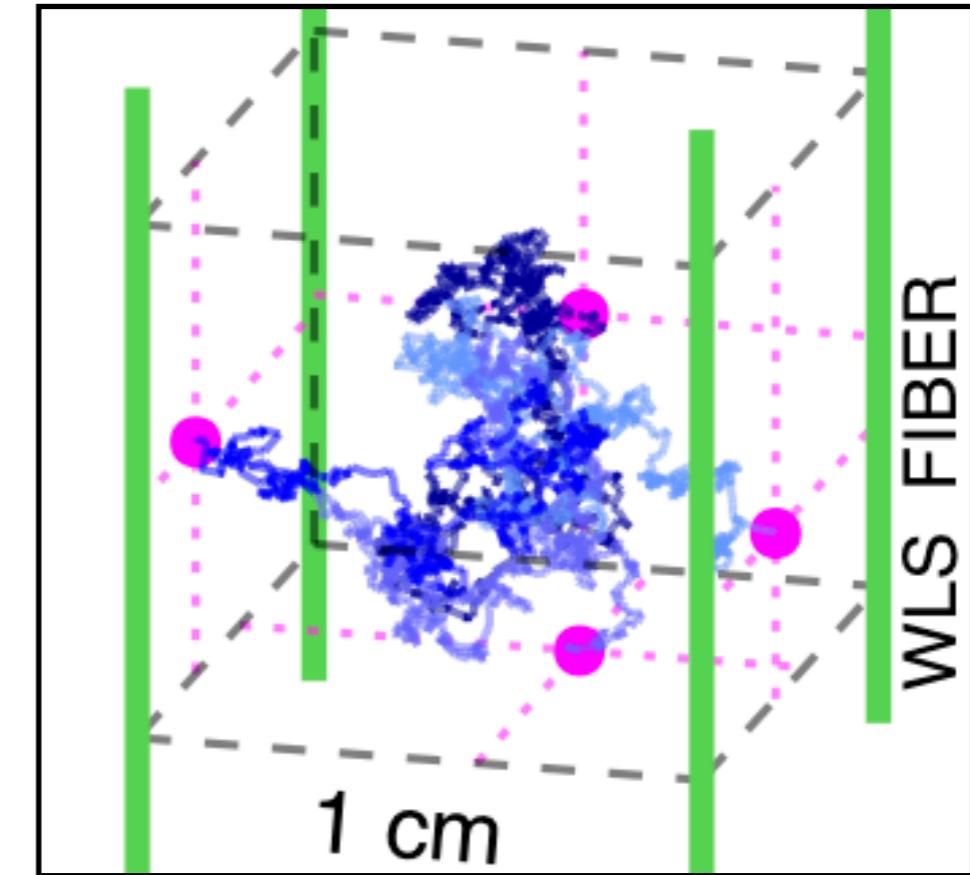


beyond ‘‘just pattern’’...



transparent

versus



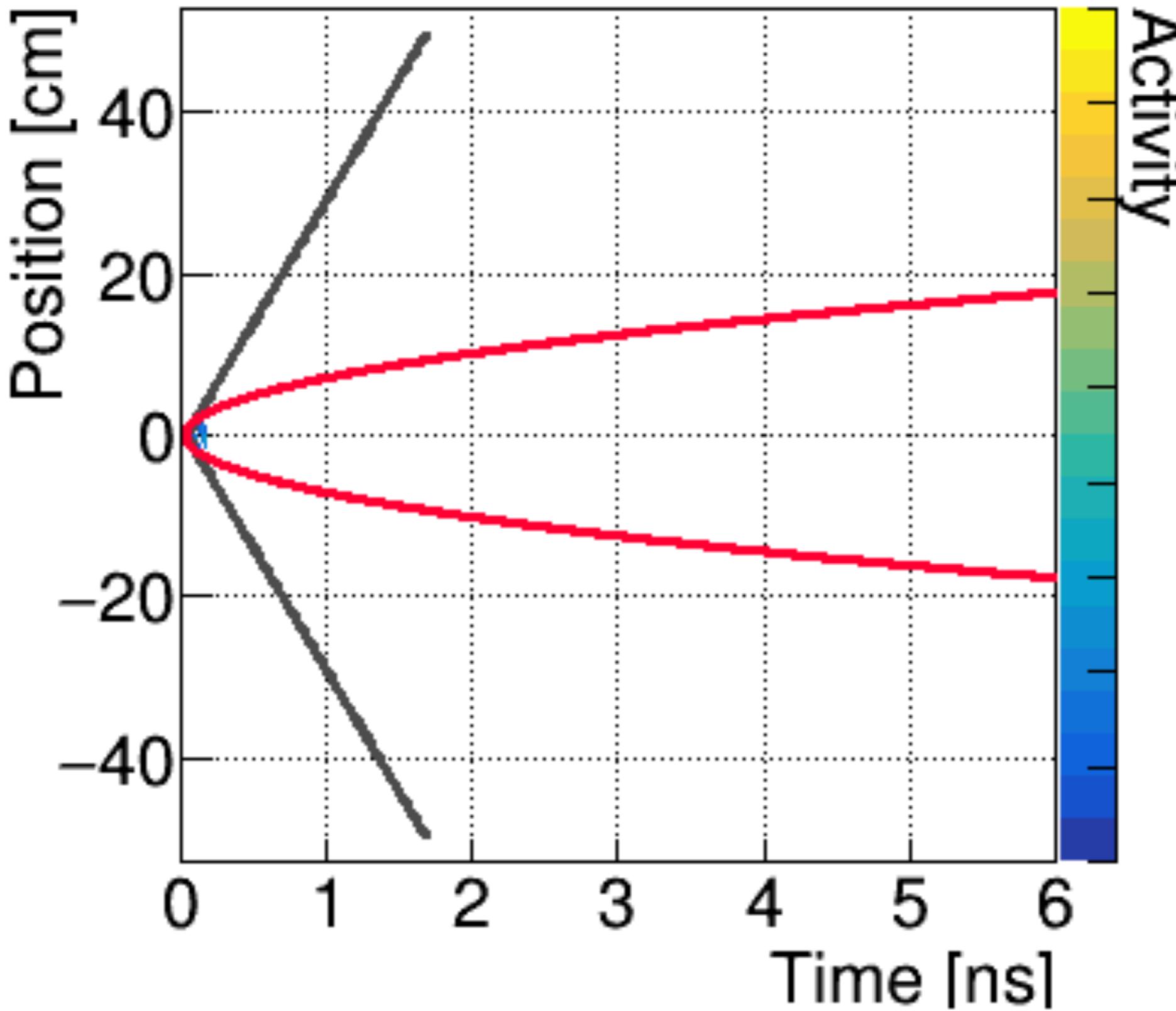
scattering

“straight” light covers Δx in a shorter Δt

v(light) effective slow down...
($v = \Delta x / \Delta t$)

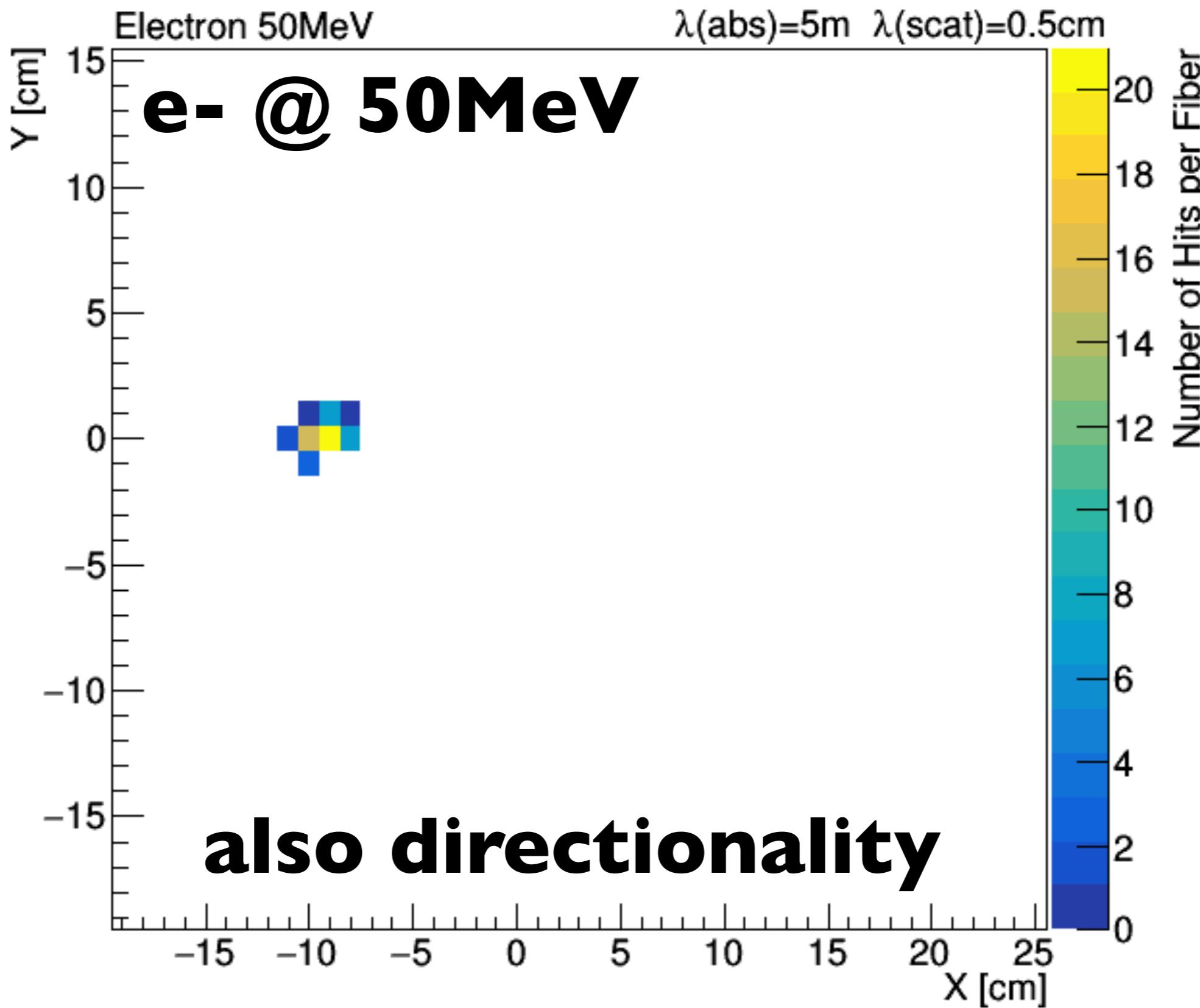
LiquidO implies imaging \oplus energy flow...

c defines “line of interaction causality”

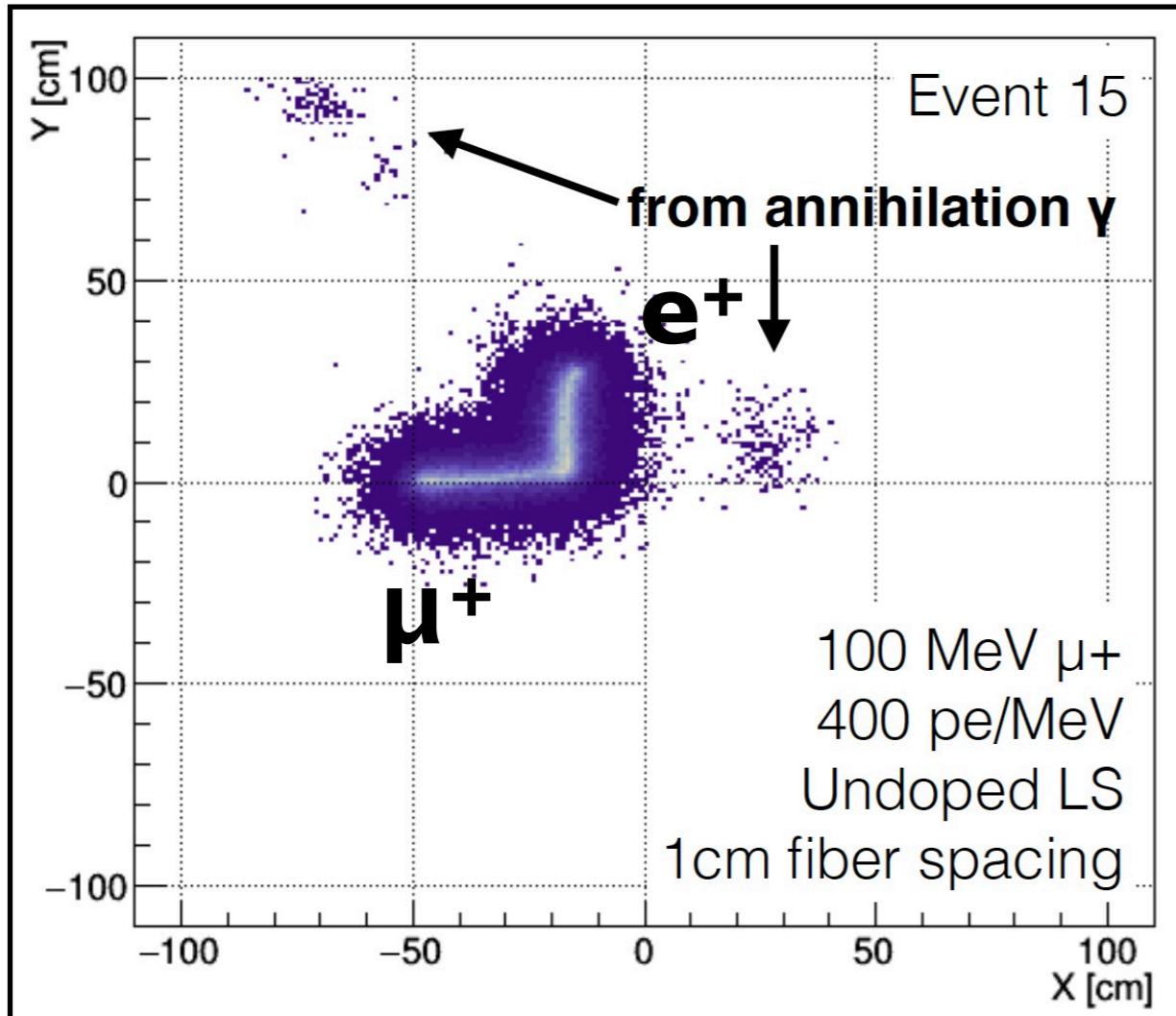


R&D: implies critical control of ALL time-dispersion mechanism

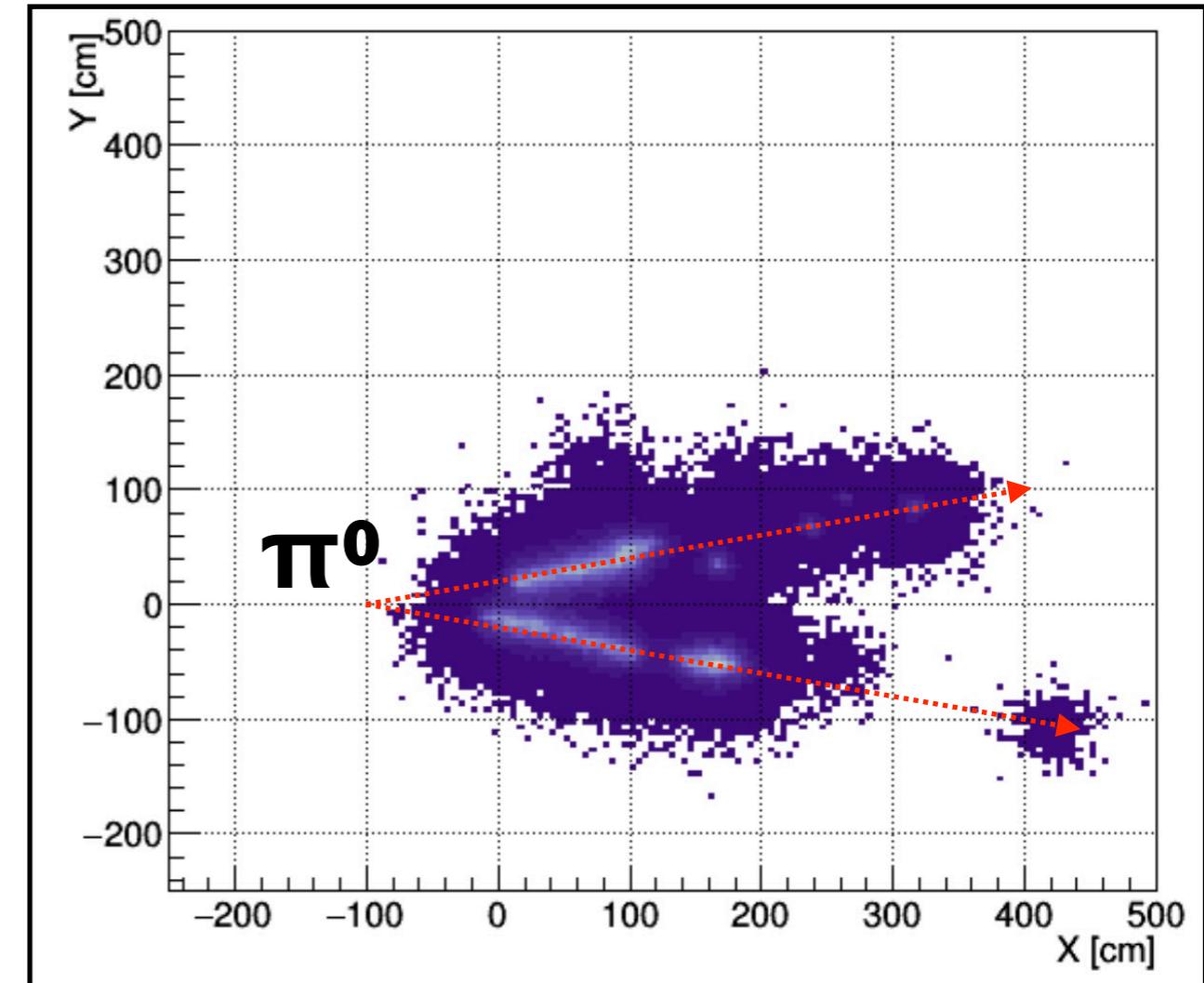
LiquidO native tracking: even e-...



e- tracking (μ even easier)



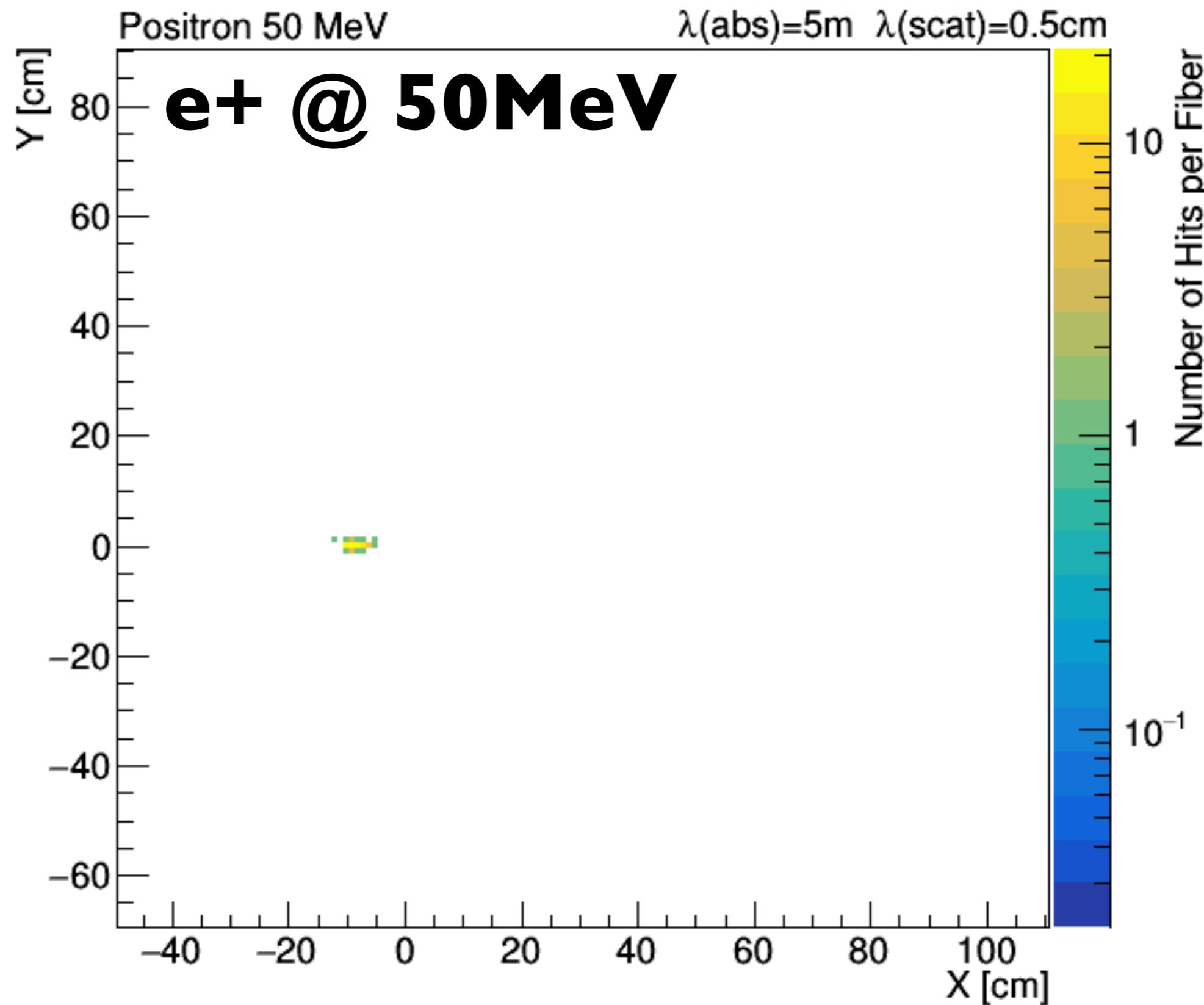
stopping μ^\pm (decay into Michel- e^\pm)



700MeV π^0 ($\gamma\gamma$ decay) [MC]

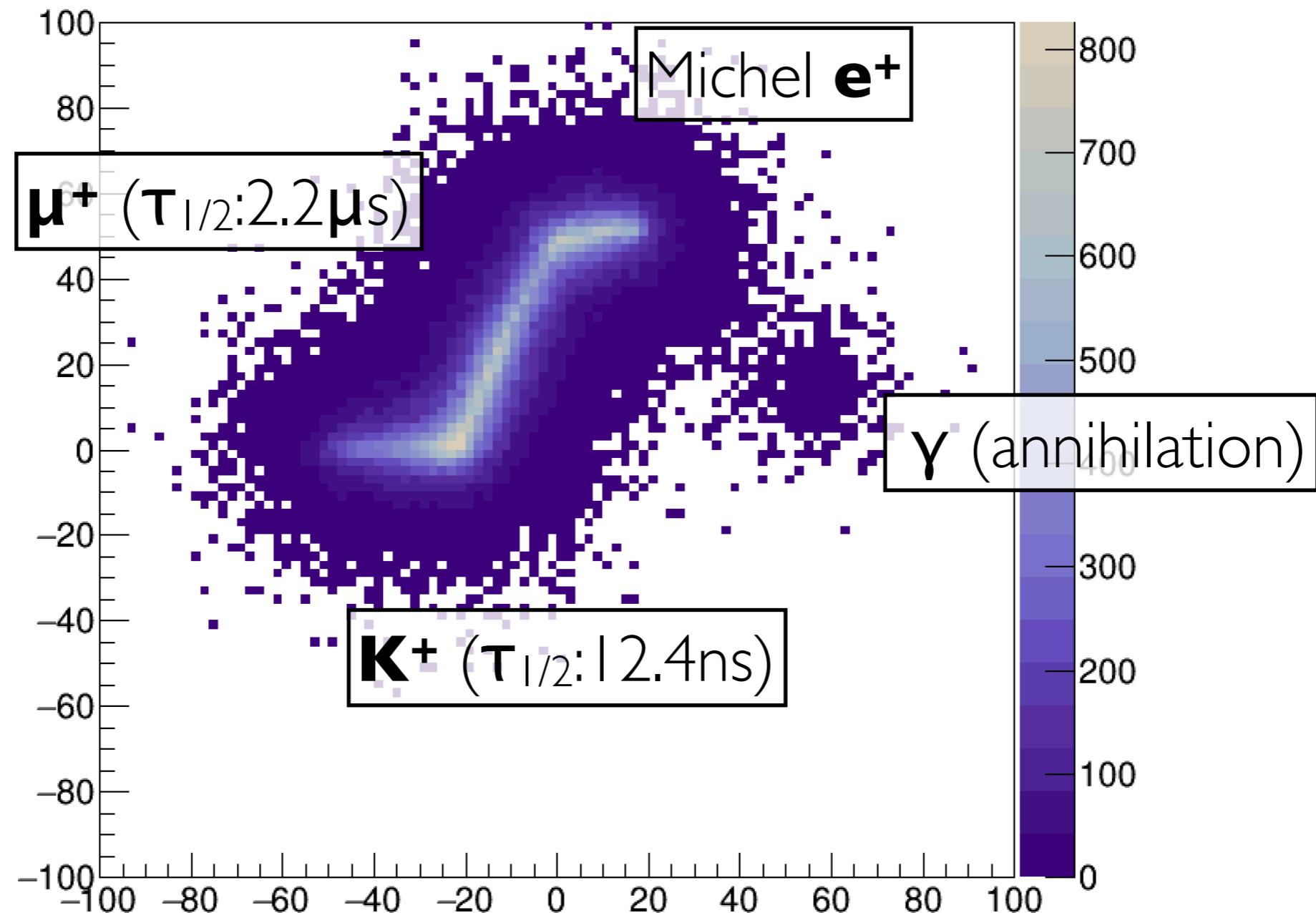
more complex events is better...

e-/e+ discrimination...



e+ discrimination with no B-field!

[but we can magnetise]



K^+ decay (64%): $\mu^+ \rightarrow e^+ \dots$
(sign tracking through decay)

R&D

✓ proof-of-principle simulation



make it large and/or clean?

NOvA~10k ton (scintillator+fibres+photo-detector)

42



**GeV might be OK!! BUT ~1 MeV physics @ 10kton?
(R&D)**

✓ **scintillator** (ex. ✓ Borexino)



✓ **photo-detector outside!**

[no PMT → **no buffer**]



? **fibres** → **R&D!**

(under further study)



NO SEGMENTATION

only natural radio-activity

GERDA's fibre curtain...



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

indeed, **Opaque** seems **a solution...**!
(the solution?)

LiquidO is still more!

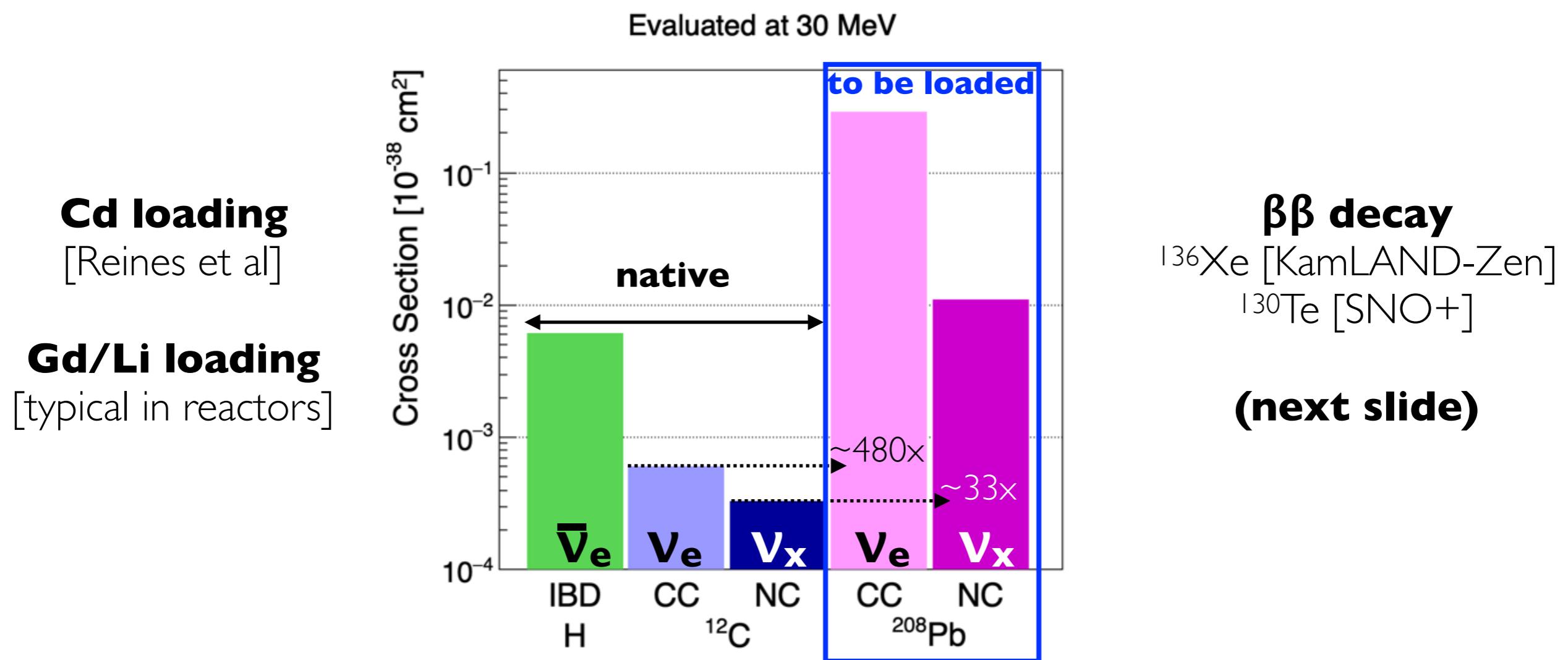
dope it? non-native capability...



why going beyond native composition?

organic scintillator = H + ^{12}C + ^{12}C (~1%) [+ impurities]

detection efficiency enhancement **neutrino interaction(s) enhancement** **rare decay source enhancement**





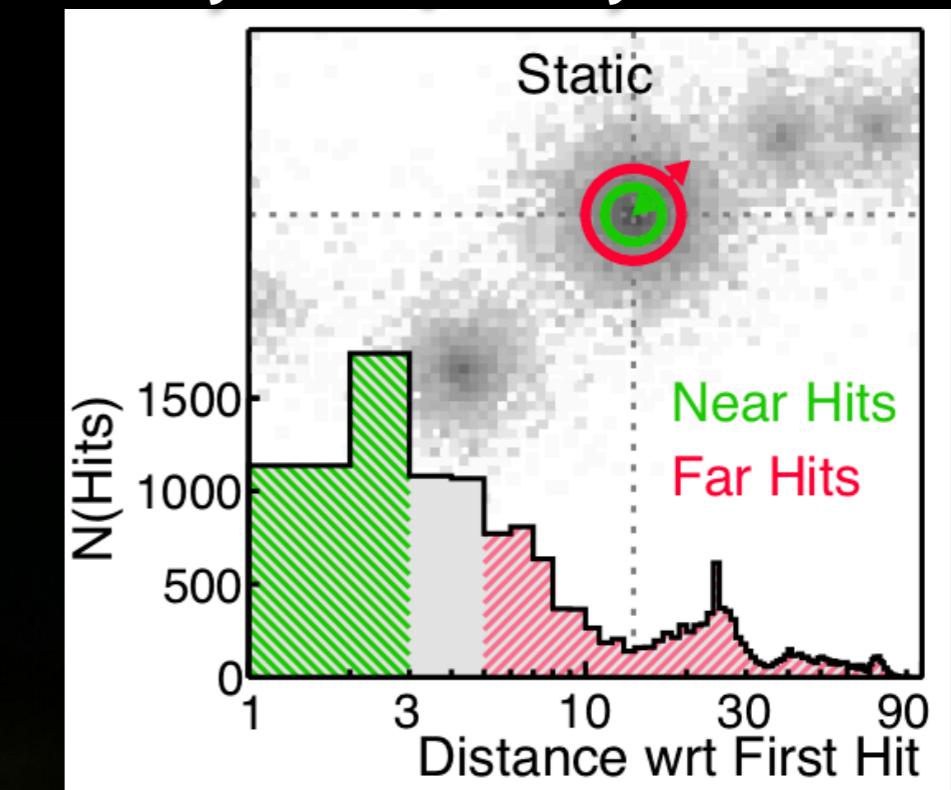
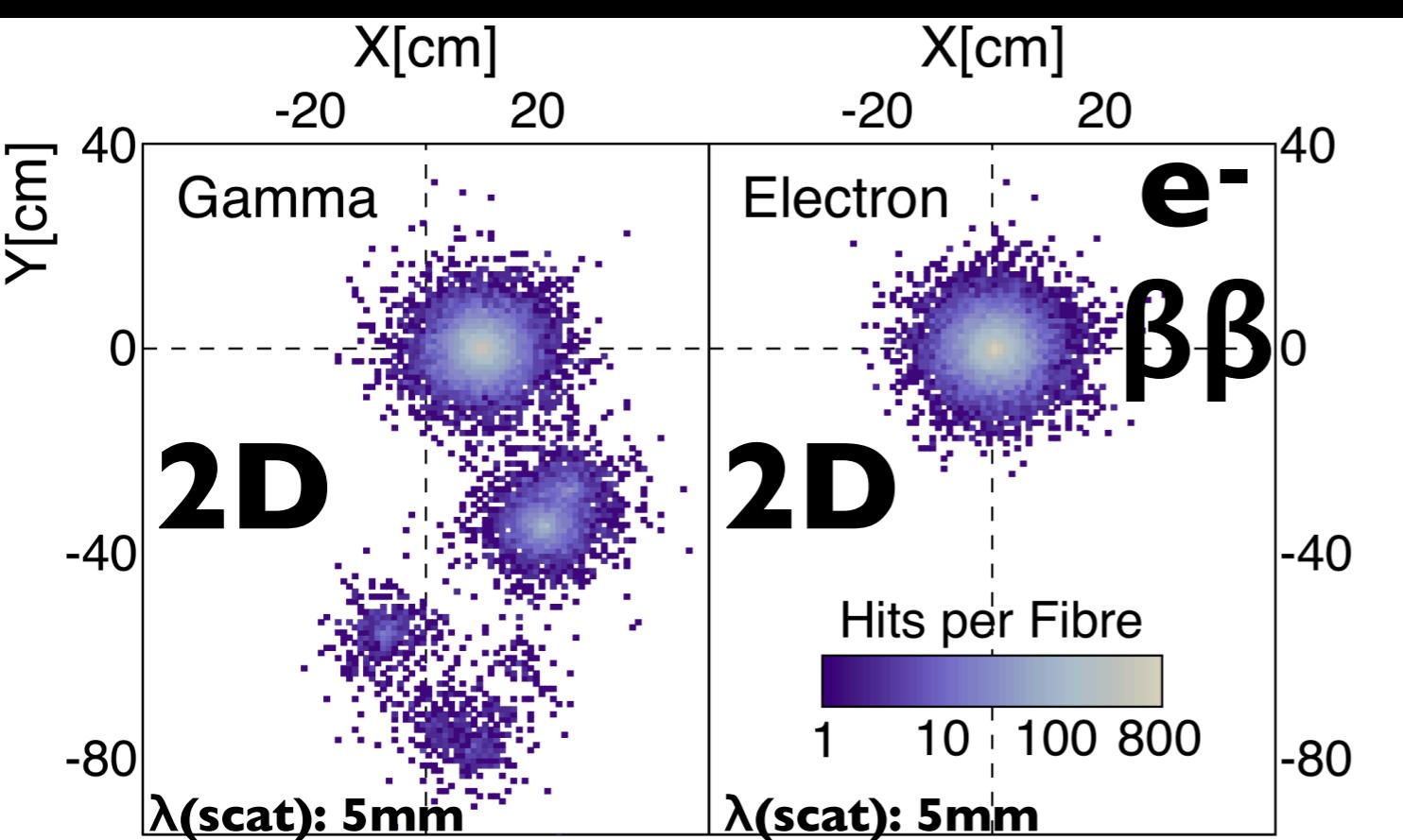
doping stability via solidification...

(beyond chemical stability)

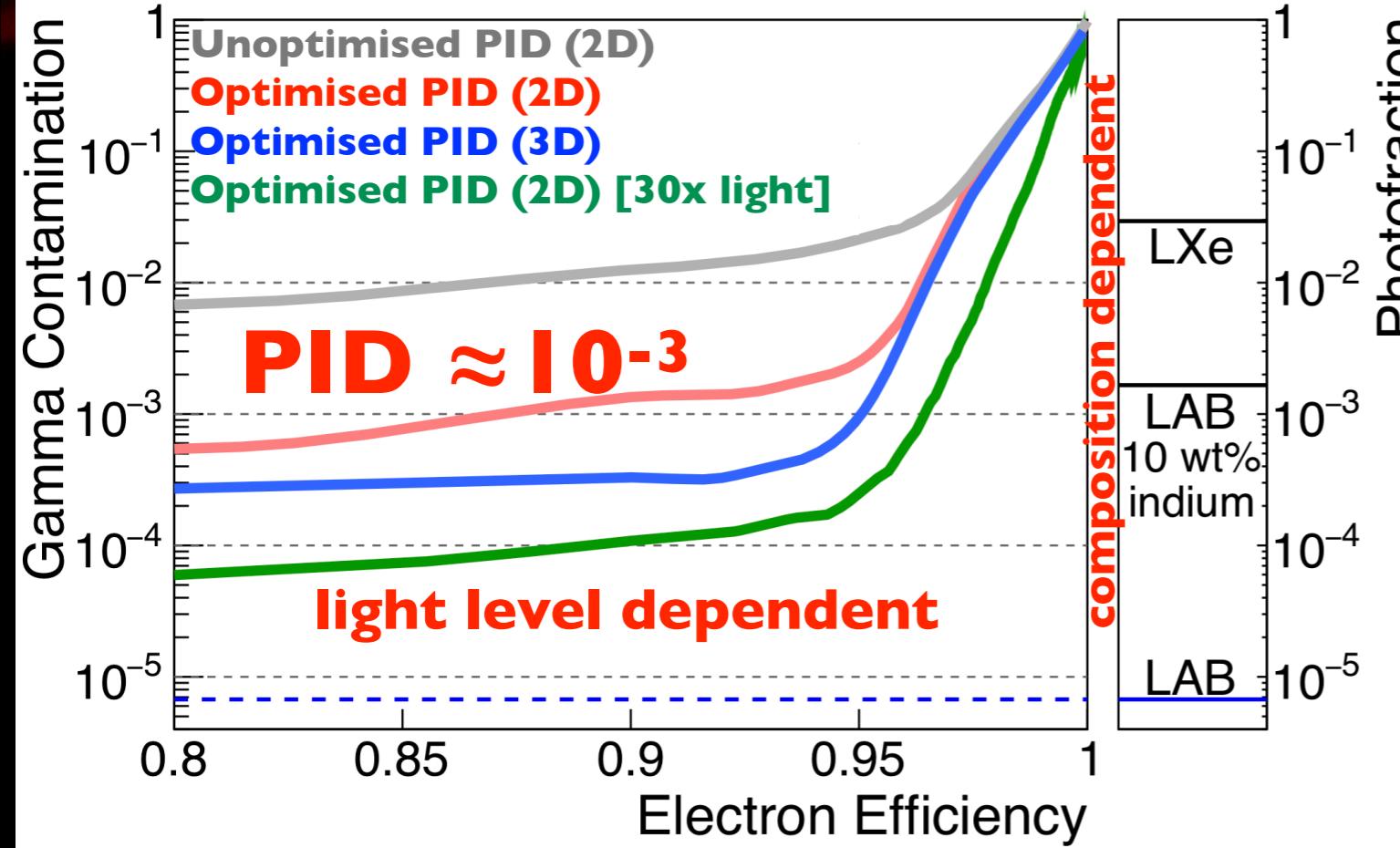


(example) γ to e^- separation...

PID($e^-:\gamma$) @ 2MeV → major γ rejection...



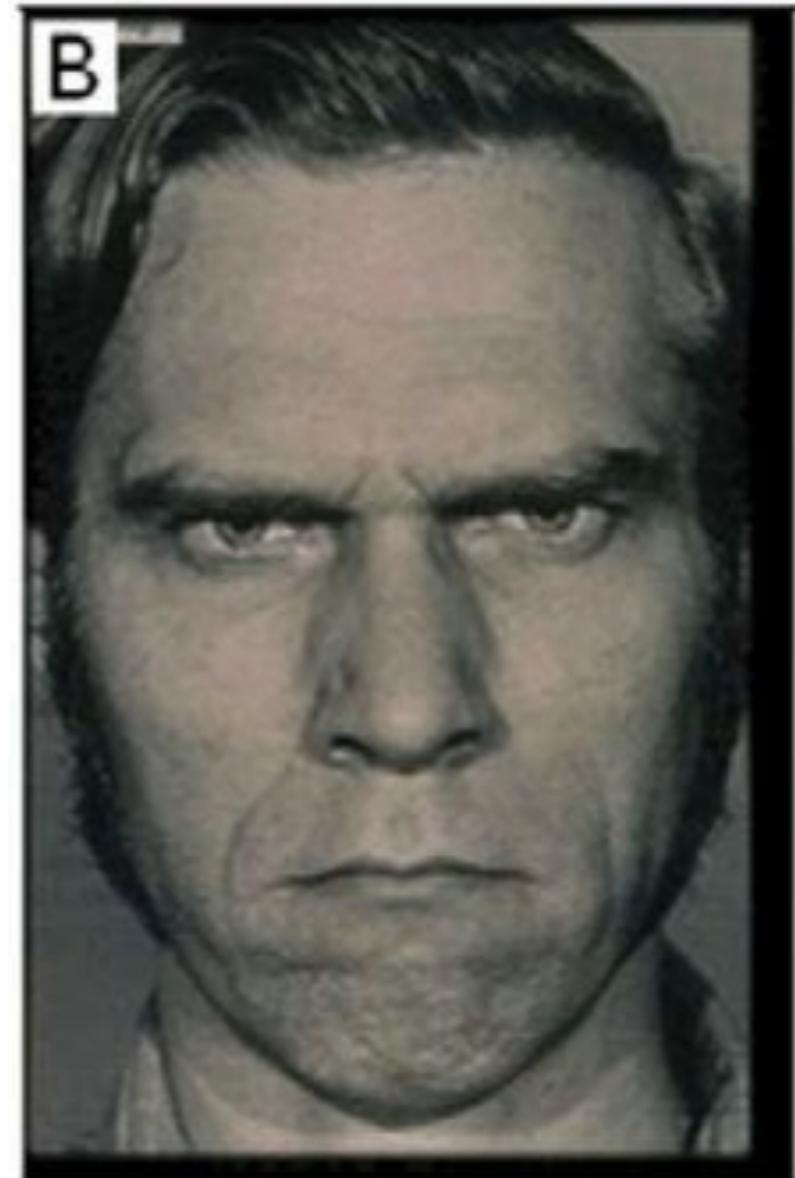
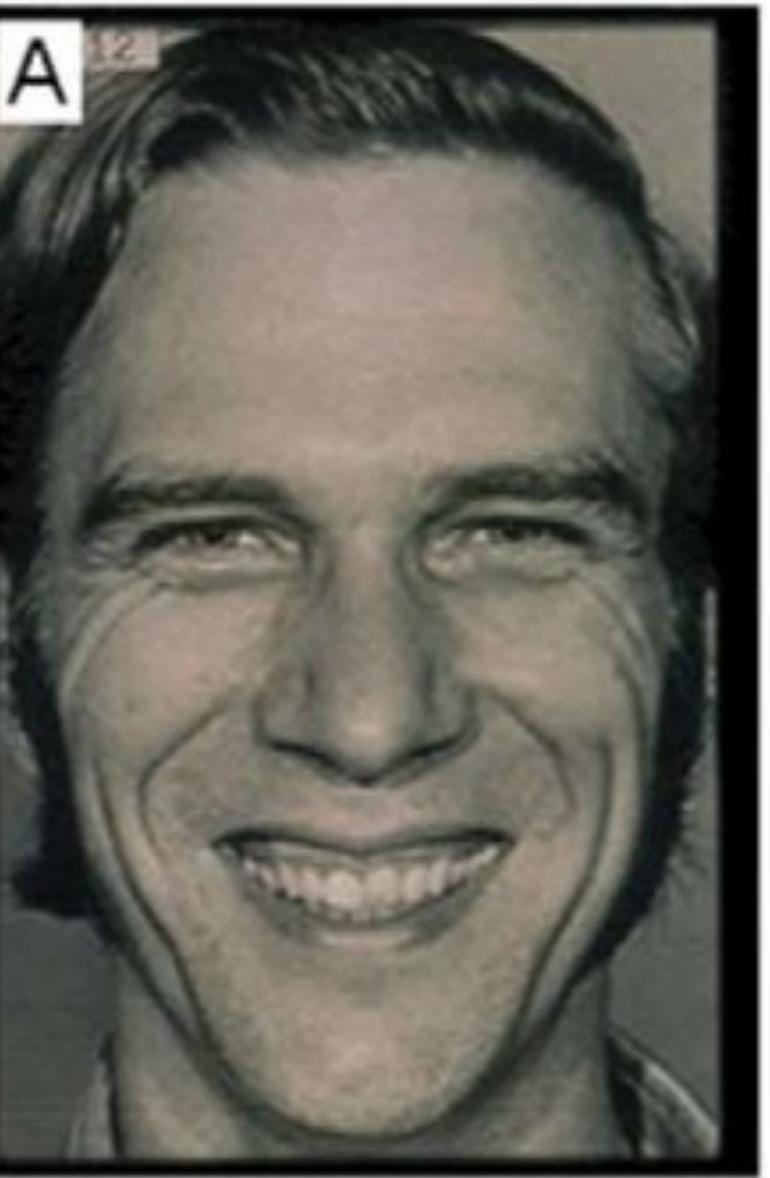
(reco) “event size” only
[calls for neural network, etc]



≥90% detection efficiency

PID[$\gamma:e^-$] separation
 $I \leq 10^4$ (scintillator native)
 $I \leq 10^2$ (heavy loaded)

not practical so far!!!



cool!

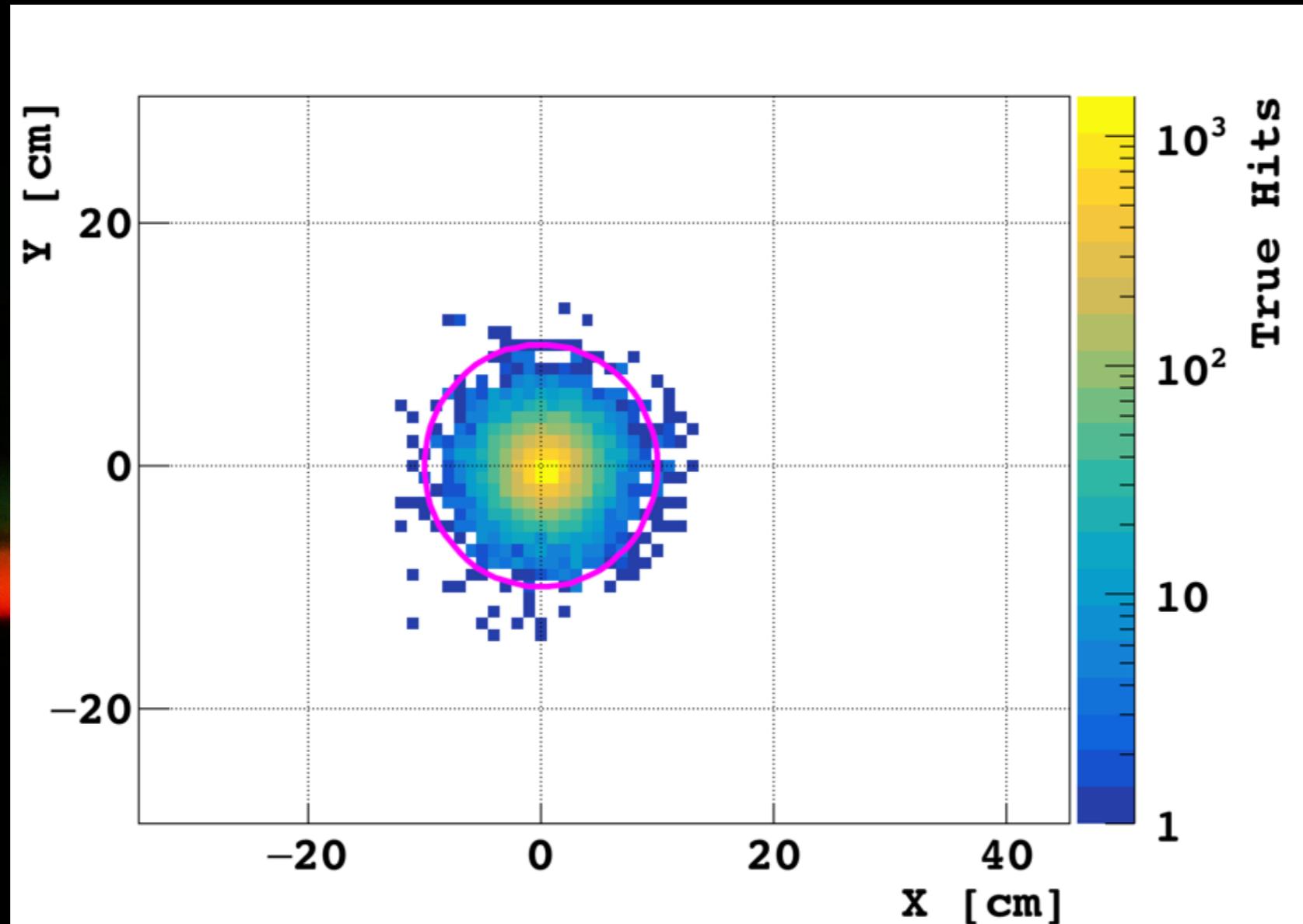
really?

upon novelties, duality...

first proof-of-principle...

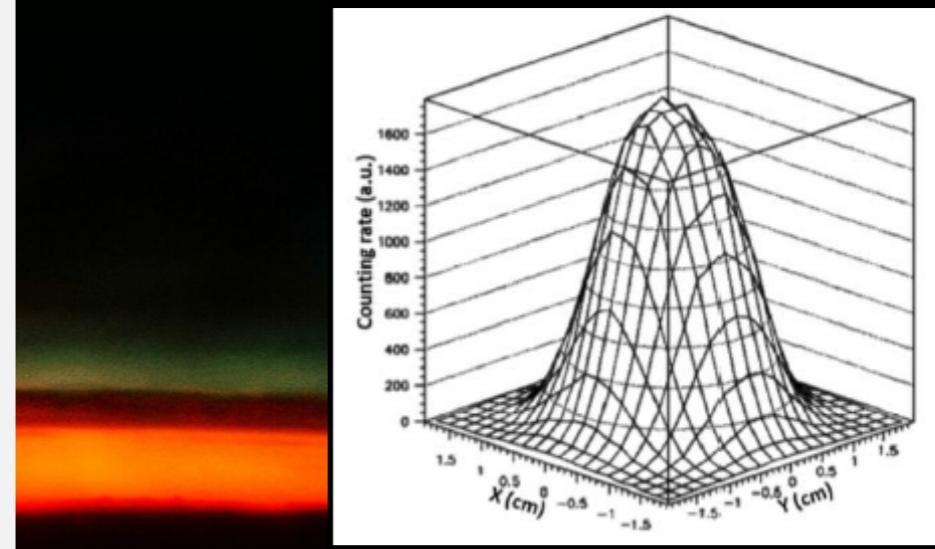
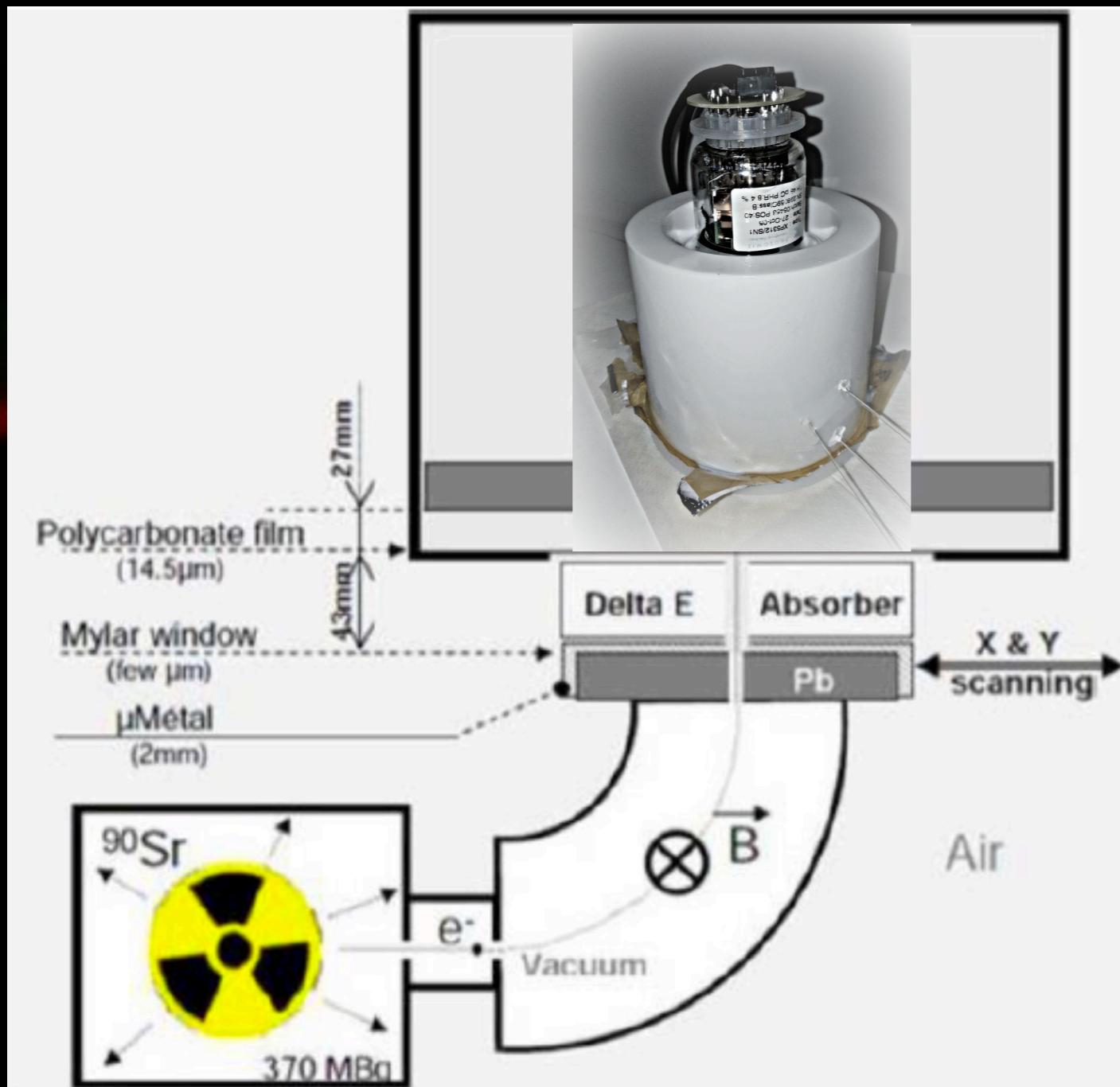


low energy e⁻ \approx “light ball”...

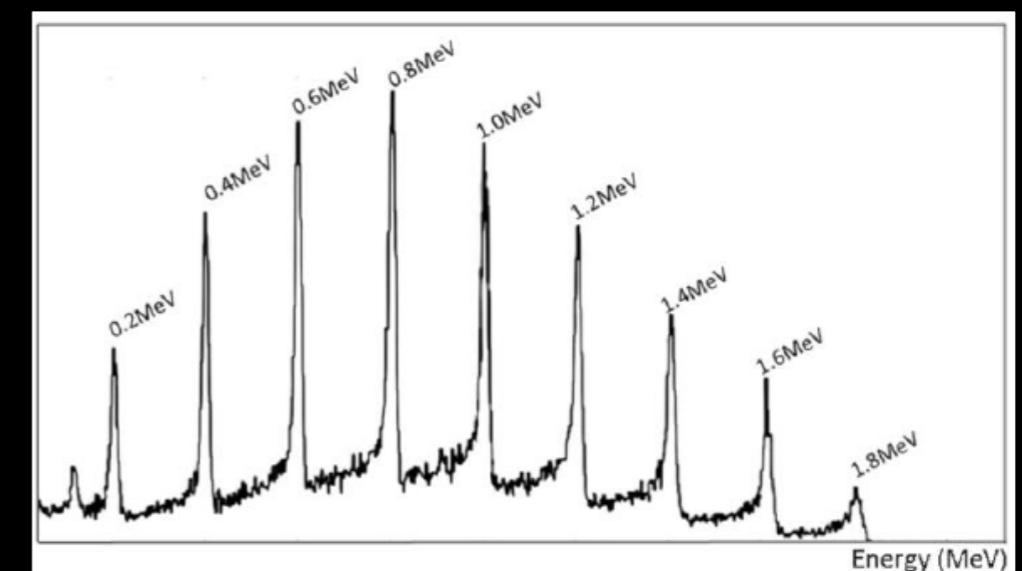


LiquidO means light confinement!
(everything else \rightarrow corollaries)

μ -Liquido @ our e⁻ beam...



e^- position $\leq 1\text{ mm}$



e^- energy $\leq 1\%$ up to 1.8MeV

μ -LiquidO inside...

3x fibres:

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

~5cm tall
(PMT face)

scintillator
filled

e⁻○

2 scintillators

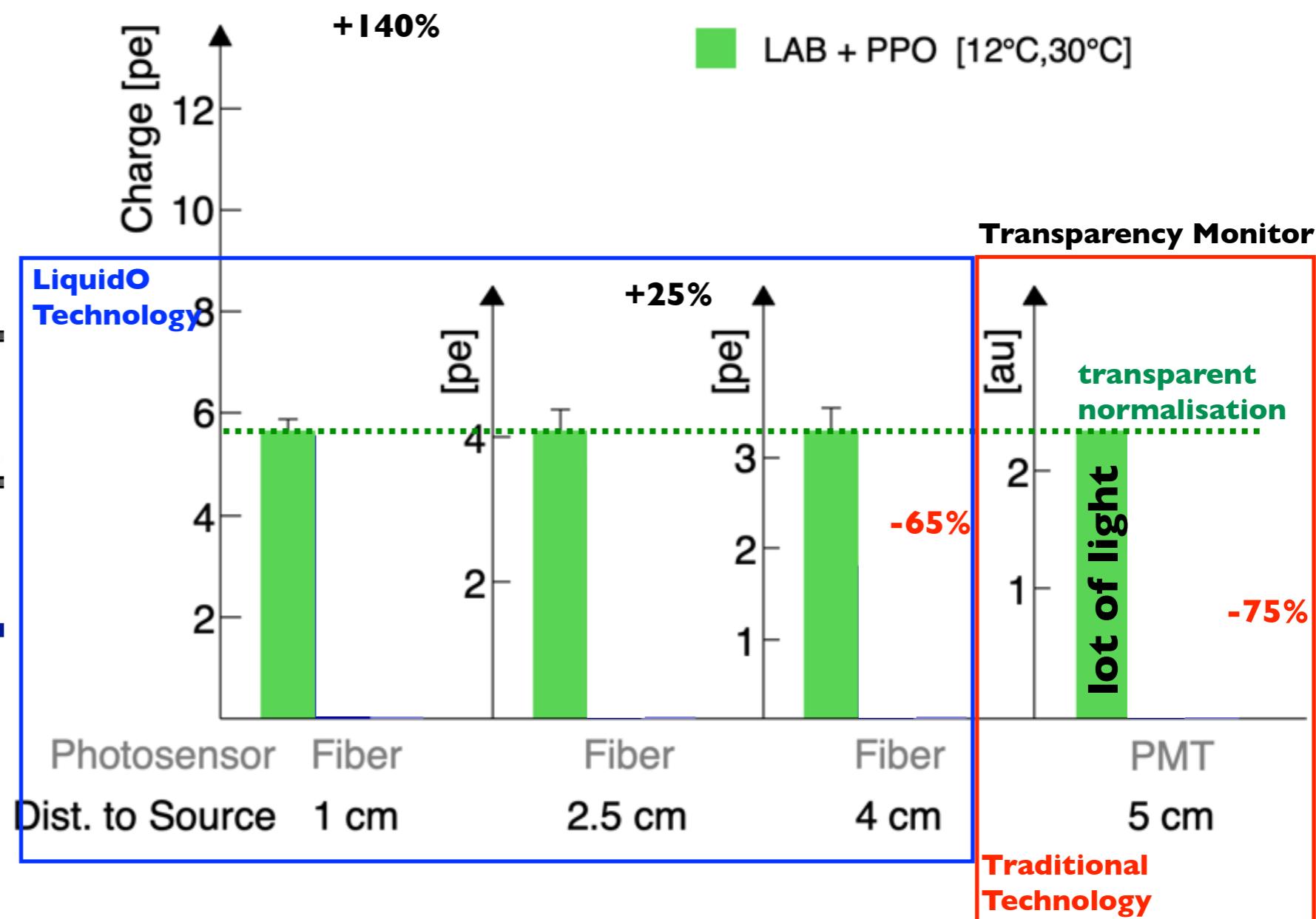
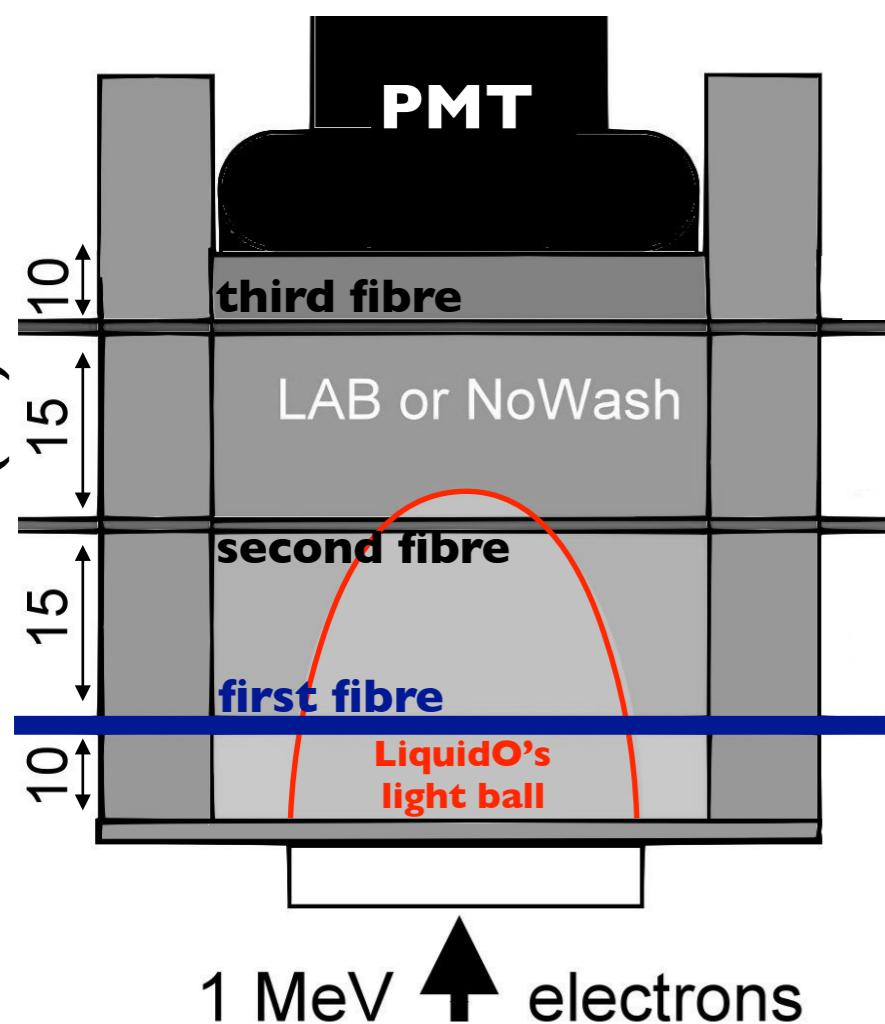
- LAB (transparent)+3g/l PPO
 - new (LAB-based+opaque)
- polymer [10,20] % loading

Mylar (few μm 's)

1 fibre only
(example)

first experimental proof of principle...

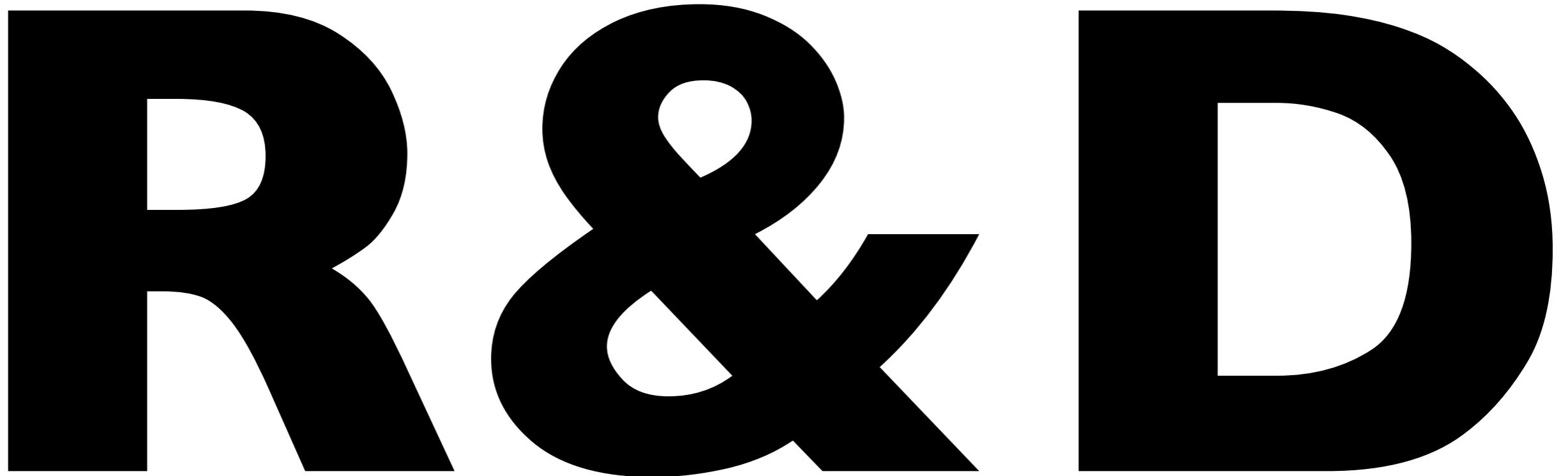
PMT transparency monitor



light bending → light confinement!
(data-driven reference — no need MC)

R&D

✓ proof-of-principle experimental



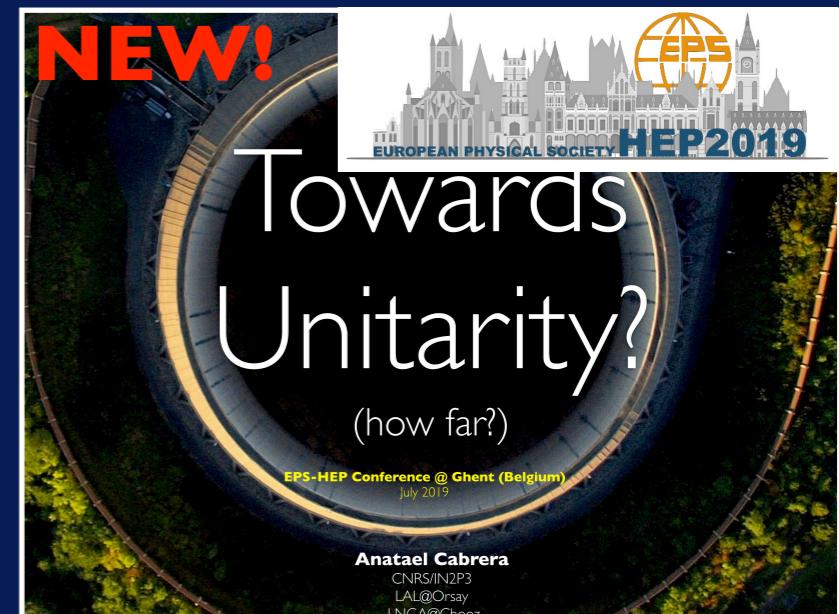
further prototyping effort...

applications?



- **MeV physics @ “Super Chooz”?**

- **PMNS Unitarity?** → θ_{13} & $|\Delta m^2(ee)|$
- supernova [$\nu(e)$, anti- $\nu(e)$, $\nu(x)$]
- proton-decay ([several channels])
- solar neutrino on Indium [**R&D**]



Conference @ HEP-European Physics Society
(July 2019 @ Ghent, Belgium)

Web: <https://indico.cern.ch/event/577856/contributions/3421609/>

- **^{40}K geo-neutrinos? YESTERDAY!**

- **$\beta\beta$ multi-ton ($\geq 10\text{ton}$ non-enriched & doping) [**R&D: Te/Nd/Mo**]**

- **ν -beam physics (NOvA update) under study** (ND and/or FD)

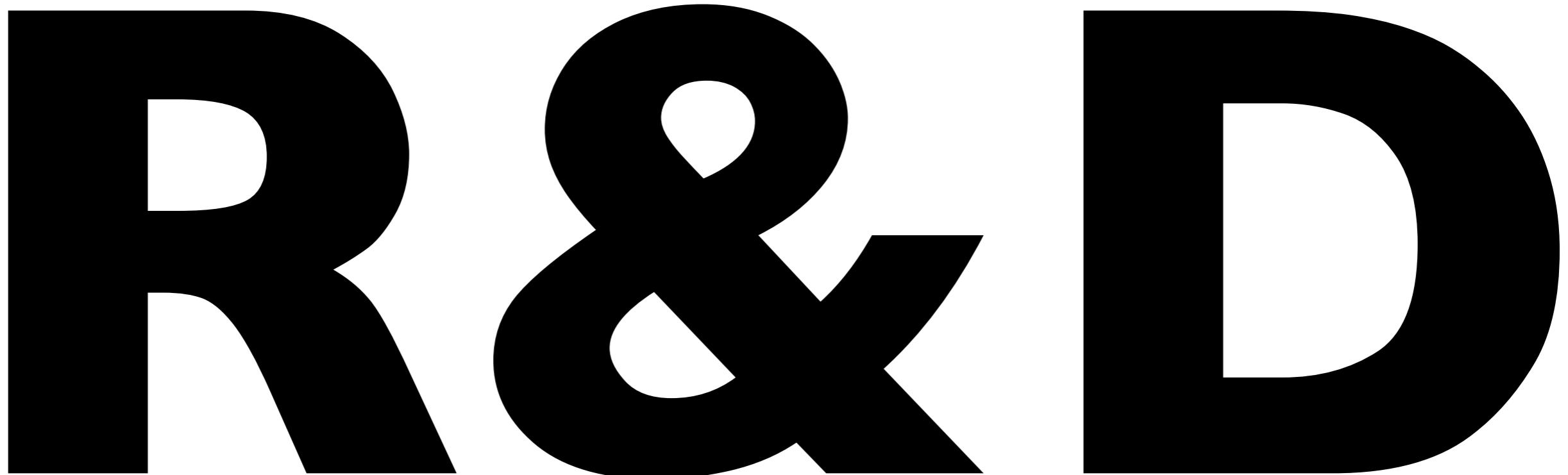
- H and ^{12}C target + loading (nuclear physics)

- **HEP:** high energy calorimetry (under study) — colliders, γ -astronomy, etc

- **society/industry:** medical physics, reactor monitoring, radioprotection...

what to remember...



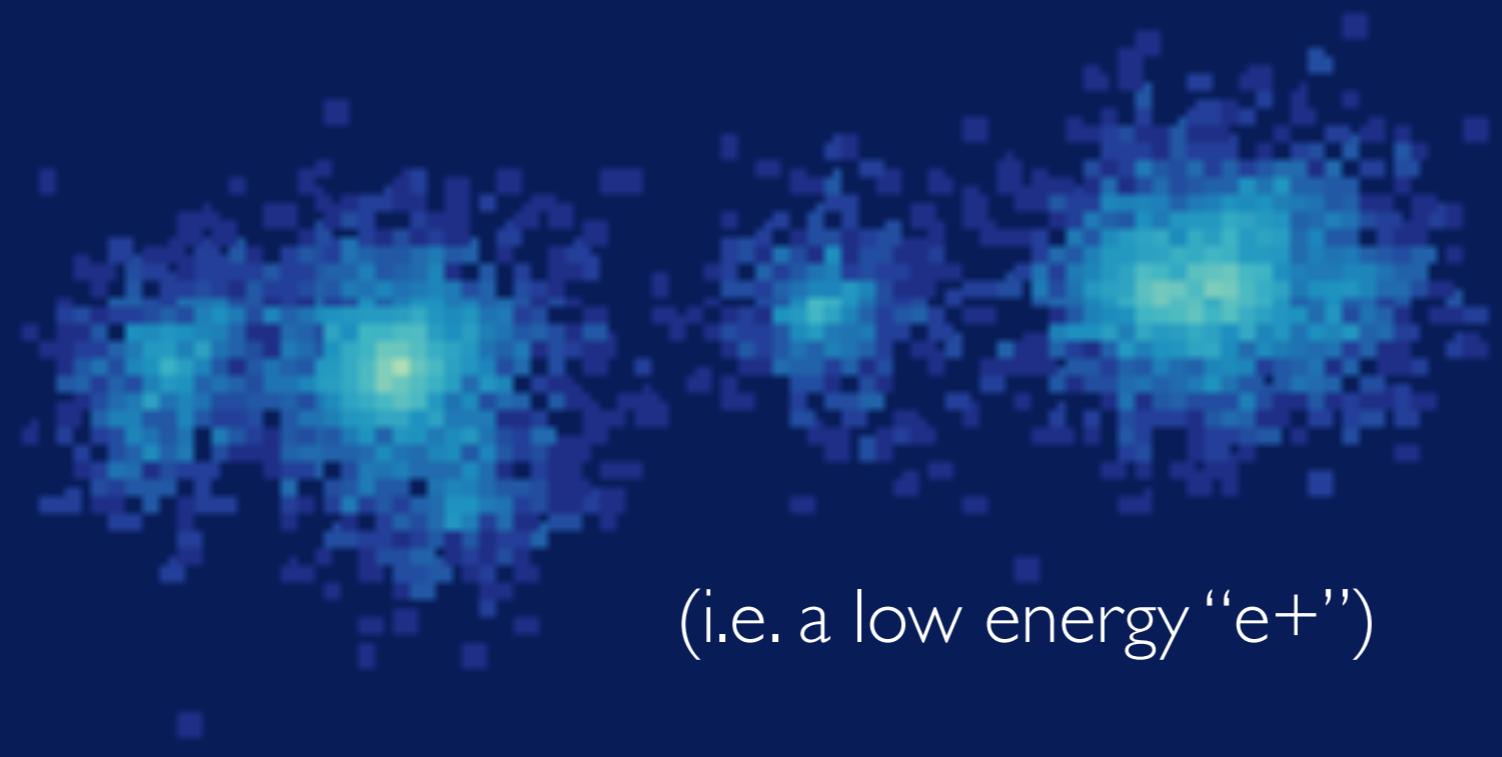


“ ν demonstrator” detector NEXT STEP

data needed → towards physics experiments

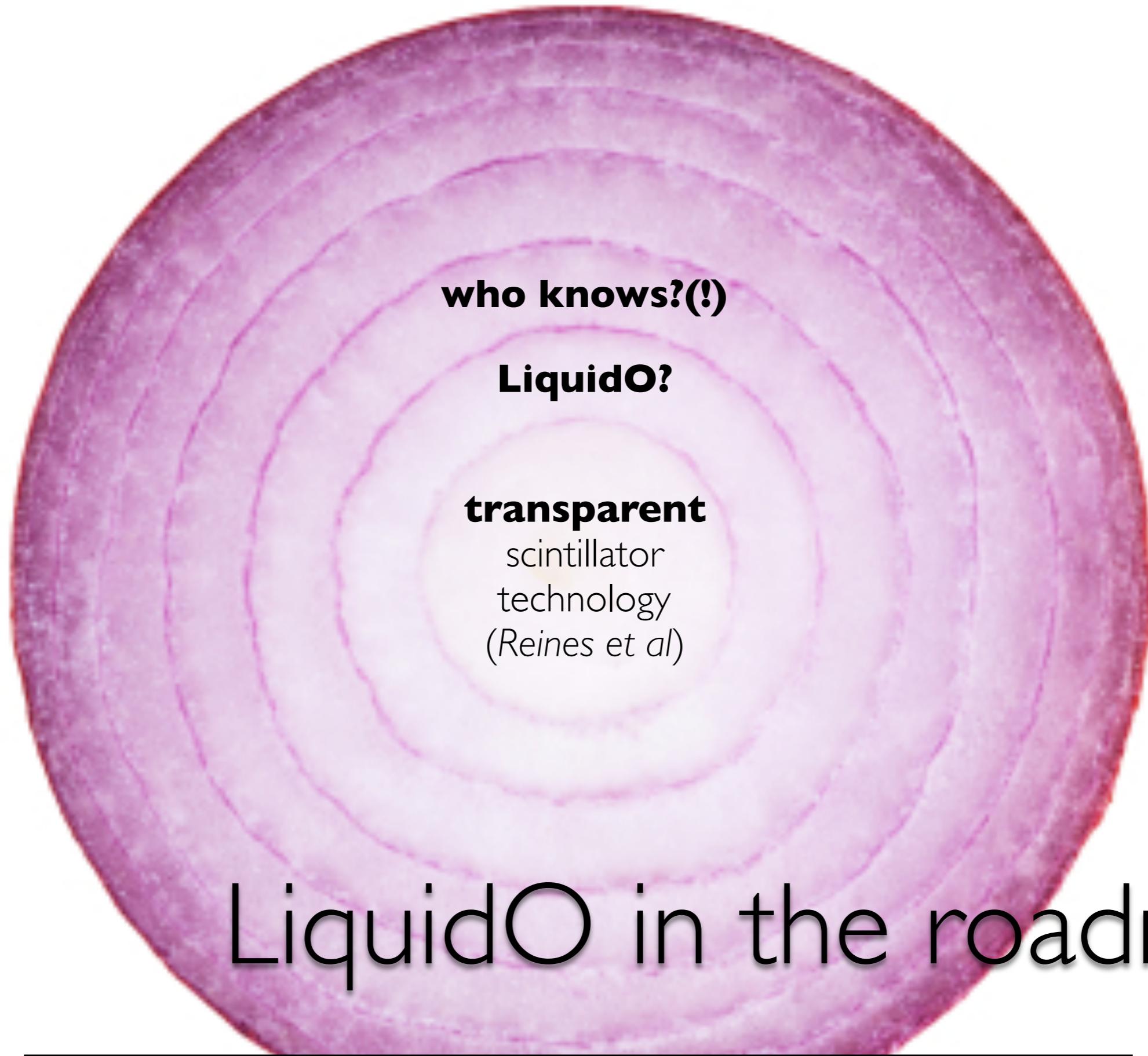
✓ proof-of-principle (data & MC)

questions, please?



(i.e. a low energy “e⁺”)

merci...
ありがとう...
danke...
고맙습니다...
obrigado...
Спасибо...
grazie...
謝謝...
hvala...
gracias...
شكرا...
thanks...



LiquidO inherits ~80 years of technology/expertise
(simplifies dramatically LiquidO R&D)