

on behalf of the **LiquidO** team...

# Liquid

a novel detection technology — originally for neutrino, but...

**“CALOR 2022” Conference @ Sussex University**

May 2022

**Anatael Cabrera**  
**CNRS/IN2P3**  
IJCLab (Orsay)

**IJCLab**  
**Irène Joliot-Curie**



université  
PARIS-SACLAY

FACULTÉ  
DES SCIENCES  
D'ORSAY

Université  
de Paris

# Transparency...

**organic scintillators** (typically)  $\approx 10^4$   $\gamma/\text{MeV}$  (10  $\gamma/\text{keV}$  or  $10^7$   $\gamma/\text{GeV}$ )



**BIG** ( $\leq 20\text{kton}$ )...

~10,000 PMTs (8" diameter)

...instead an **Opaque** solution?

but... **opaque photo-detection?**

# LiquidO Consortium\*

J. dos Anjos<sup>a</sup>, L. Asquith<sup>v</sup>, J.L. Beney<sup>u</sup>, T.J.C. Bezerra<sup>v</sup>, M. Bongrand<sup>u</sup>, C. Bourgeois<sup>g</sup>, D. Brasse<sup>b</sup>, D. Breton<sup>g</sup>, M. Briere<sup>g</sup>, J. Busto<sup>b</sup>, A. Cabrera<sup>†g</sup>, A. Cadiou<sup>u</sup>, E. Calvo<sup>c</sup>, H. Carduner<sup>u</sup>, V. Chaumat<sup>g</sup>, E. Chauveau<sup>i</sup>, M. Chen<sup>r</sup>, P. Chimentif<sup>f</sup>, F. Dal Corso<sup>a</sup>, A. Dahmane<sup>h</sup>, S. Dusini<sup>a</sup>, A.D. Earle<sup>v</sup>, C. Frigerio-Martins<sup>f</sup>, J. Galán<sup>w</sup>, J.A. García<sup>w</sup>, R. Gazzini<sup>g</sup>, A. Gibson<sup>v</sup>, D. Giovagnoli<sup>h</sup>, P. Govoni<sup>ik,l</sup>, M. Grassi<sup>o</sup>, W.C. Griffith<sup>v</sup>, F. Haddad<sup>u</sup>, J. Hartnell<sup>v</sup>, A. Hourlier<sup>h</sup>, G. Hull<sup>g</sup>, I.G. Irastorza<sup>w</sup>, L. Koch<sup>j</sup>, P. Lanièce<sup>g</sup>, P. Lasorak<sup>v</sup>, C. Lefevre<sup>r</sup>, F. Lefevre<sup>u</sup>, P. Loaiza<sup>g</sup>, G. Luzón<sup>w</sup>, J. Maalmi<sup>g</sup>, F. Mantovani<sup>d,e</sup>, C. Marquet<sup>i</sup>, M. Martínez<sup>w</sup>, J. Martino<sup>u</sup>, L. Ménard<sup>g</sup>, D. Navas-Nicolás<sup>g</sup>, H. Nunokawa<sup>q</sup>, M. Obolensky<sup>g</sup>, J.P. Ochoa-Ricoux<sup>s</sup>, C. Palomares<sup>c</sup>, P. Pillot<sup>u</sup>, J.C.C. Porter<sup>v</sup>, M. S. Pravikoff<sup>z</sup>, M. Roche<sup>i</sup>, B. Roskovec<sup>p</sup>, M.L. Sarsa<sup>w</sup>, S. Schoppmann<sup>j</sup>, A. Serafini<sup>n,o</sup>, L. Simard<sup>g</sup>, M. Sisti<sup>k</sup>, D. Stocco<sup>u</sup>, V. Strati<sup>d,e</sup>, J.-S. Stutzmann<sup>u</sup>, F. Suekane<sup>†t</sup>, M.A. Verdier<sup>g</sup>, A. Verdugo<sup>c</sup>, B. Viaud<sup>u</sup>, A. Weber<sup>j</sup>, and F. Yermia<sup>u</sup>

[LiquidO-Contact-L@in2p3.fr](mailto:LiquidO-Contact-L@in2p3.fr)

<sup>a</sup>Centro Brasileiro de Pesquisas Físicas (CBPF), Rua Xavier Sigaud 150, Rio de Janeiro, 22290-180, Brazil

<sup>b</sup>Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

<sup>c</sup>CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Av. Complutense 40, E-28040 Madrid, Spain

<sup>d</sup>INFN, Ferrara Section, Via Saragat 1, 44122 Ferrara, Italy

<sup>e</sup>Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy

<sup>f</sup>Departamento de Física, Universidade Estadual de Londrina, Rodovia Celso Garcia Cid, PR 445 Km 380, Campus Universitário Cx. Postal 10.011, CEP 86.057-970, Londrina – PR, Brazil

<sup>g</sup>IJCLab, CNRS/IN2P3, Université Paris-Saclay, Université de Paris Cité, 15 rue Georges Clémenceau, 91400 Orsay, France

<sup>h</sup>Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

<sup>i</sup>Université de Bordeaux, CNRS, LP2I Bordeaux, UMR 5797, F-33170 Gradignan, France

<sup>j</sup>Johannes Gutenberg Universität Mainz, Institut für Physik, Staudingerweg 7, 55128 Mainz, Germany

<sup>k</sup>INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy

<sup>l</sup>Dipartimento di Fisica, Università di Milano-Bicocca, I-20126 Milano, Italy

<sup>m</sup>INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy

<sup>n</sup>Dipartimento di Fisica e Astronomia, Università di Padova, via Marzolo 8, I-35131 Padova, Italy

<sup>o</sup>Institute of Particle and Nuclear Physics Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2 180 00 Prague 8, Czech Republic

<sup>q</sup>Department of Physics, Pontifícia Universidade Católica do Rio de Janeiro, C.P. 38097, 22451-900, Rio de Janeiro, Brazil

<sup>r</sup>Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario K7L3N6, Canada

<sup>s</sup>Department of Physics and Astronomy, University of California at Irvine, 4129 Frederick Reines Hall, Irvine, California 92697, USA

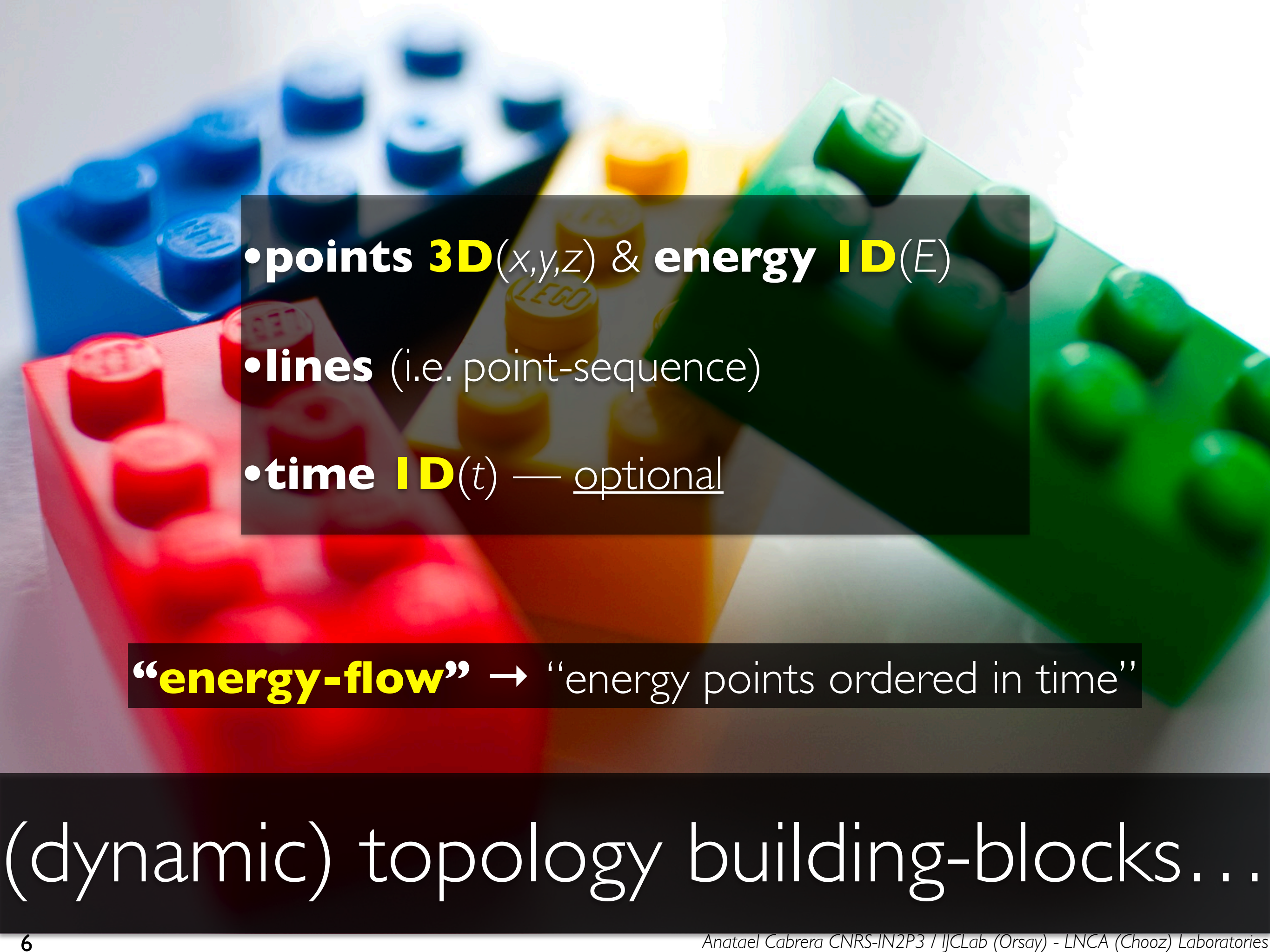
<sup>t</sup>RCNS, Tohoku University, 6-3 AzaAoba, Aramaki, Aoba-ku, 980-8578, Sendai, Japan

<sup>u</sup>Subatech, CNRS/IN2P3, Nantes Université, IMT-Atlantique, 44307 Nantes, France

<sup>v</sup>Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

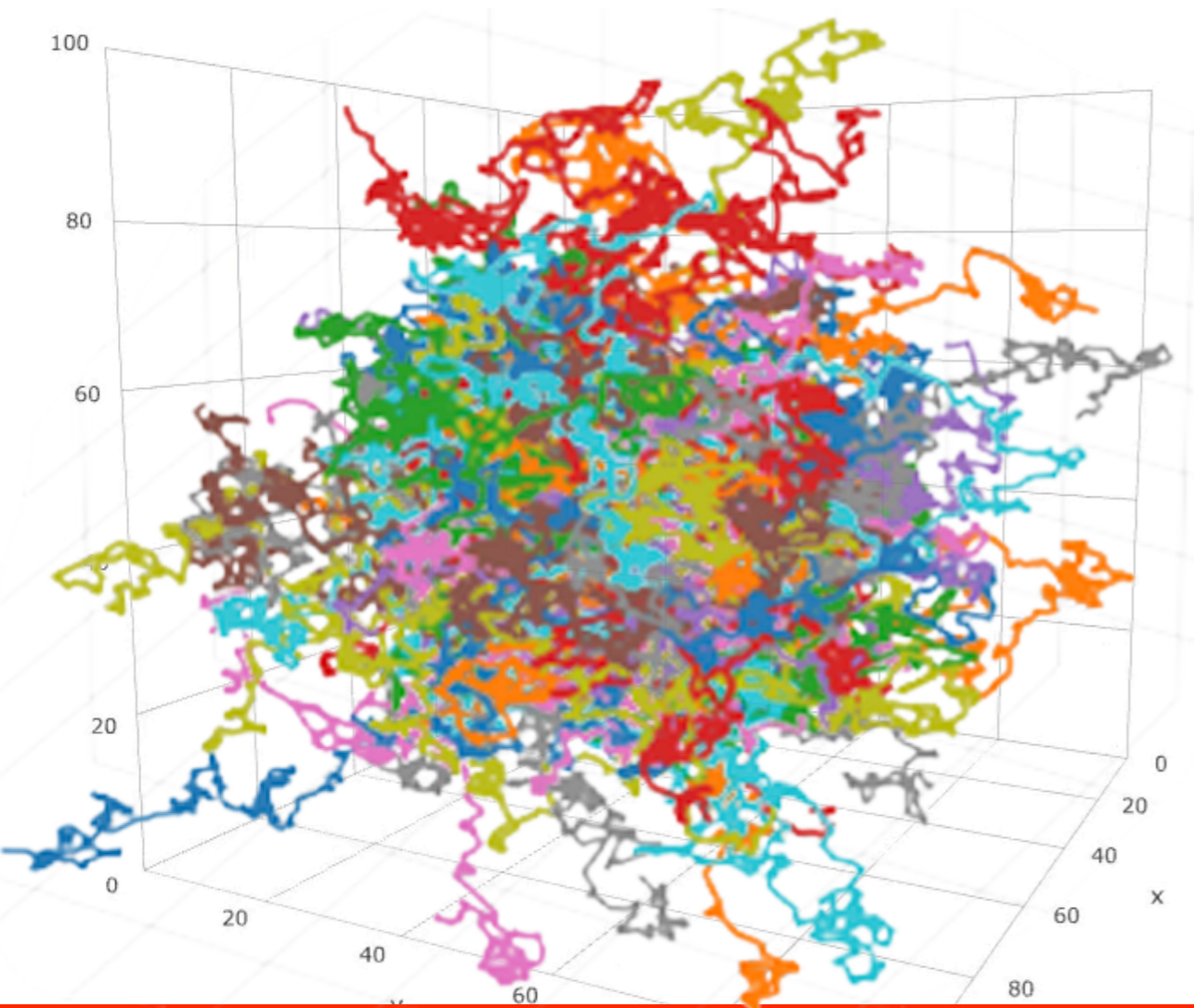
<sup>w</sup>Centro de Astropartículas y Física de Altas Energías (CAPA), Universidad de Zaragoza, Calle Pedro Cerbuna 12, 50009 Zaragoza, Spain

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

- 
- **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) topology building-blocks...



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

- **scattering** → **random walk** → **light ball** [order 1 cm]
  - scattering mean-free-path order 1mm:  $\times 10^{-4}$  smaller than usual

- **lossless scattering:**
  - **Mie scattering:** achromatic & tiny losses ["cloudy" touch]
  - **Rayleigh scattering:** chromatic & lossless
  - **Internal Reflection** (Snell's law lossless)
- warning:** avoid reflection (losses @ order  $\sim 1\%$ /reflection)

**LiquidO** ⇔ **unique stochastic light confinement**  
 ⇒ **must NOT be transparent!!**

**also Rayleigh Scattering**

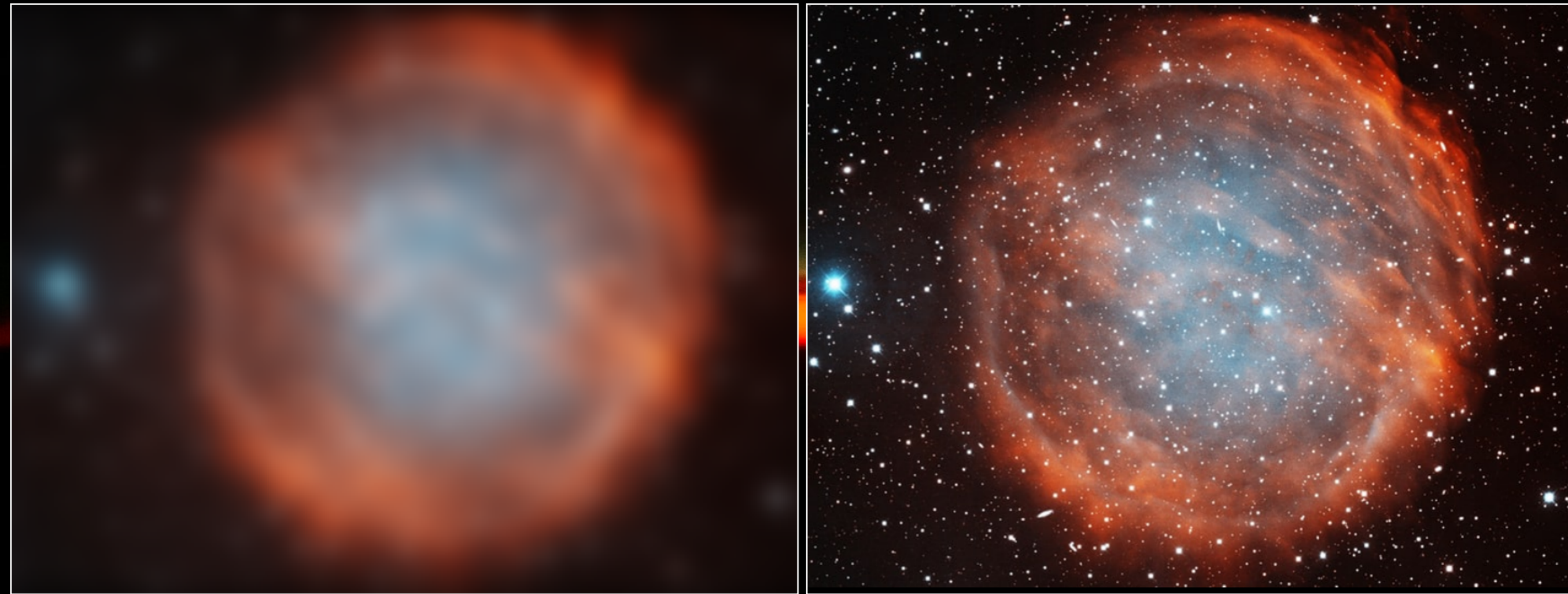
**Transparency**  
 $\lambda(\text{scattering}) \geq 10m$



**Mie Scattering**  
 $\lambda(\text{scattering}) \leq 1 cm$

stochastic light confinement...

# LiquidO little counter-intuitive...



**diffusion**  $\implies$  **shaper images!!**



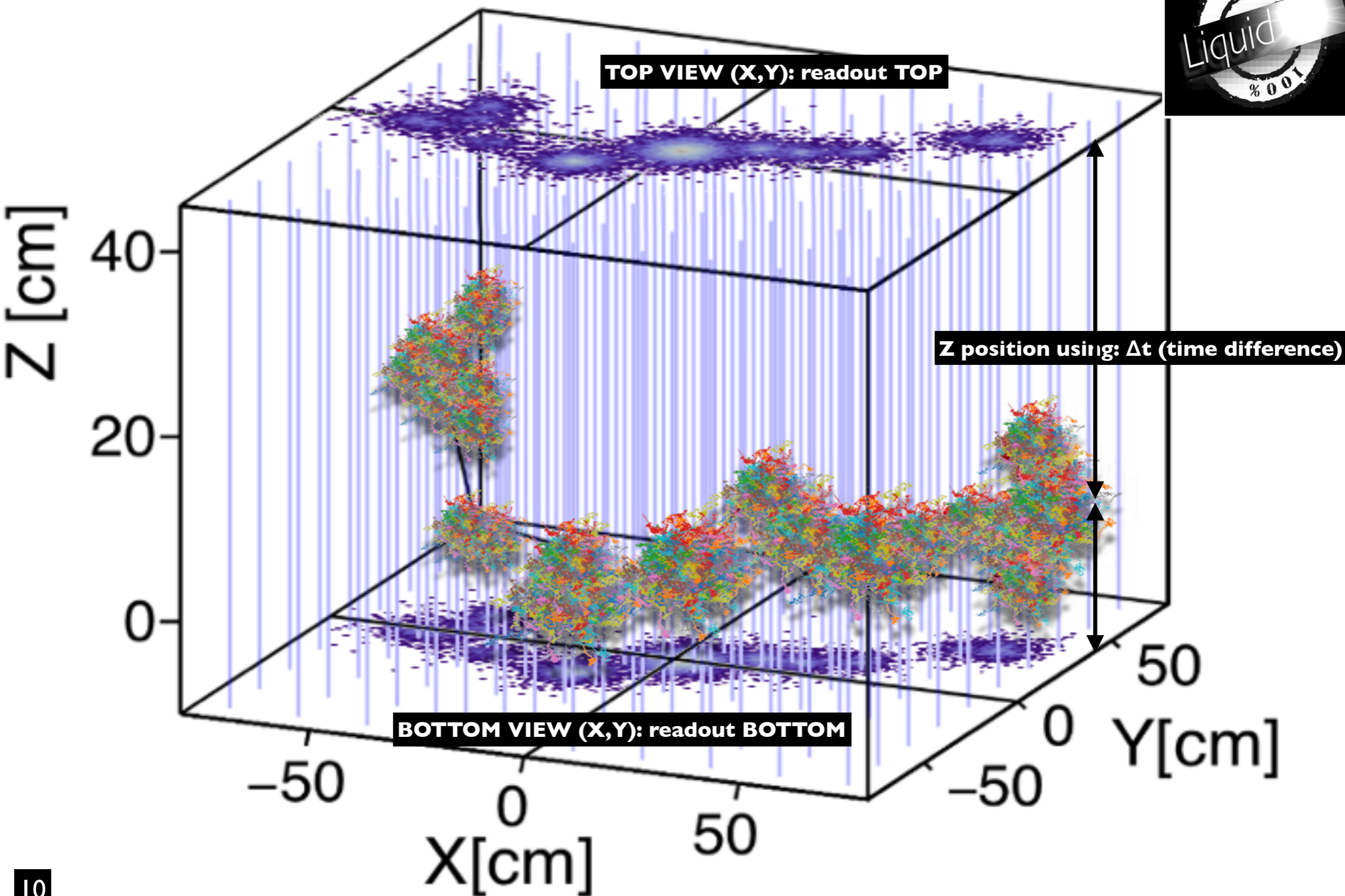
topology	physics	LiquidO Information	
point	unresolved ( $\lesssim$ few cm)	point-like	sub-mm possible (primitive)
track	points-like sequence	track-like	sub-mm possible (enhanced)
point's $\oplus$ track's	complex event	combination $\oplus$ timing	reconstruction (energy $\oplus$ x,y,z $\oplus$ t)

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

imaging & outcome (upon reco)...

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

**Simplest LiquidO: fibre Lattice along Z-axis (up to 3 possible)**



# dope it? non-native capability...

- adding **non-native physics via doped elements/isotopes**
- modify the **radiation behaviour** ( $\rho$ ,  $\langle Z \rangle$ , etc)
- **enhance detection**: neutron (production / capture), etc
- **new interactions** and/or **novel physics capabilities**
- etc... (long)

# LiquidO: **light “opaque”** medium

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



## LiquidO (**5D primitive info**)

light-based **“TPC”** (highest duty-cycle)

⊕

**Time-of-Flight** ( $4\pi$  acceptance)

⊕

**uniform calorimeter** (scintillation → precision)

⊕

**features** (PID, magnetisable, exchangeable, etc)

⊕

**[doping: variable composition/density]**

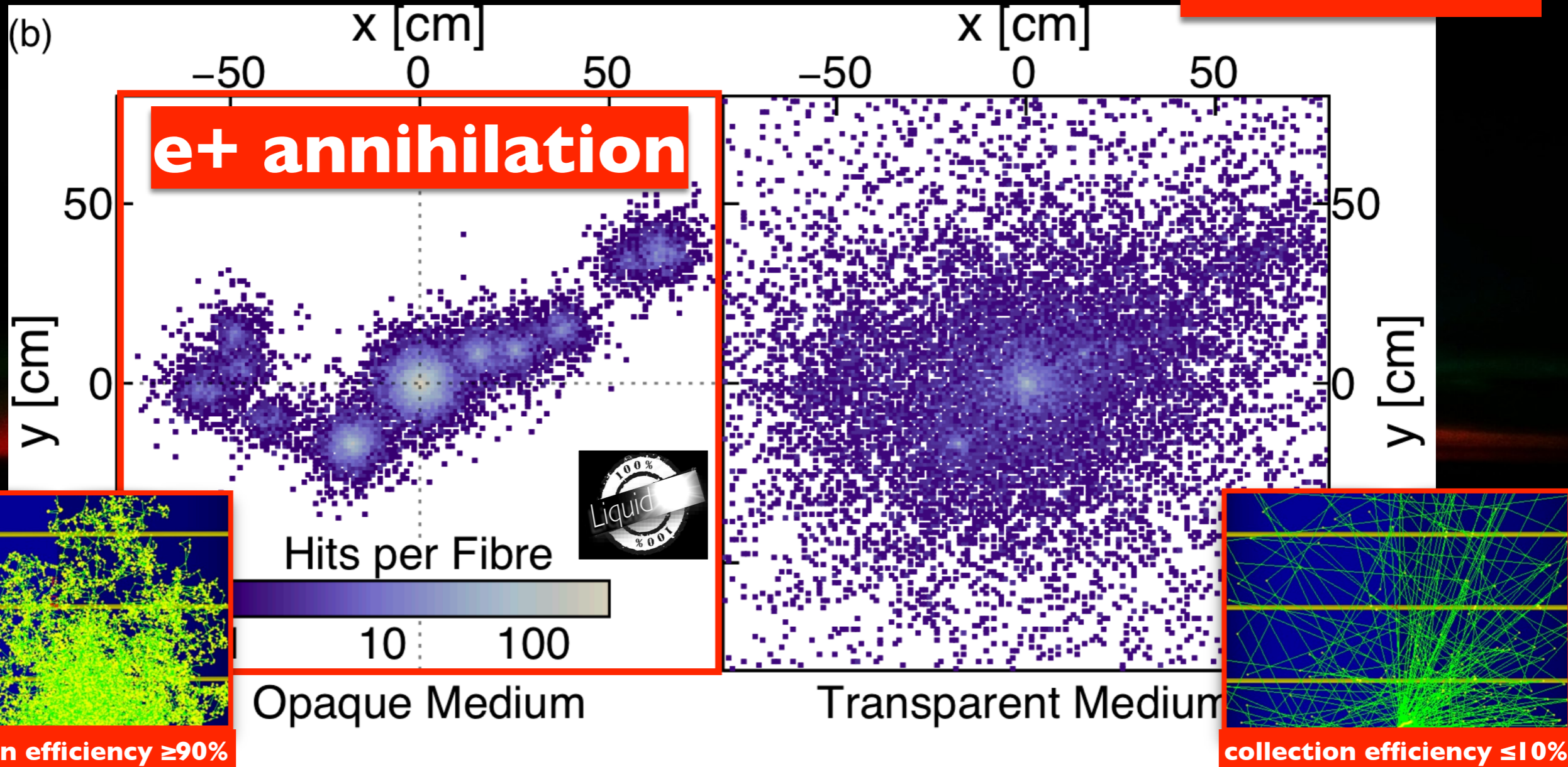


**physics...**

a **e+** (example)...

# LiquidO: sub-nuclear MeV imaging...<sup>14</sup>

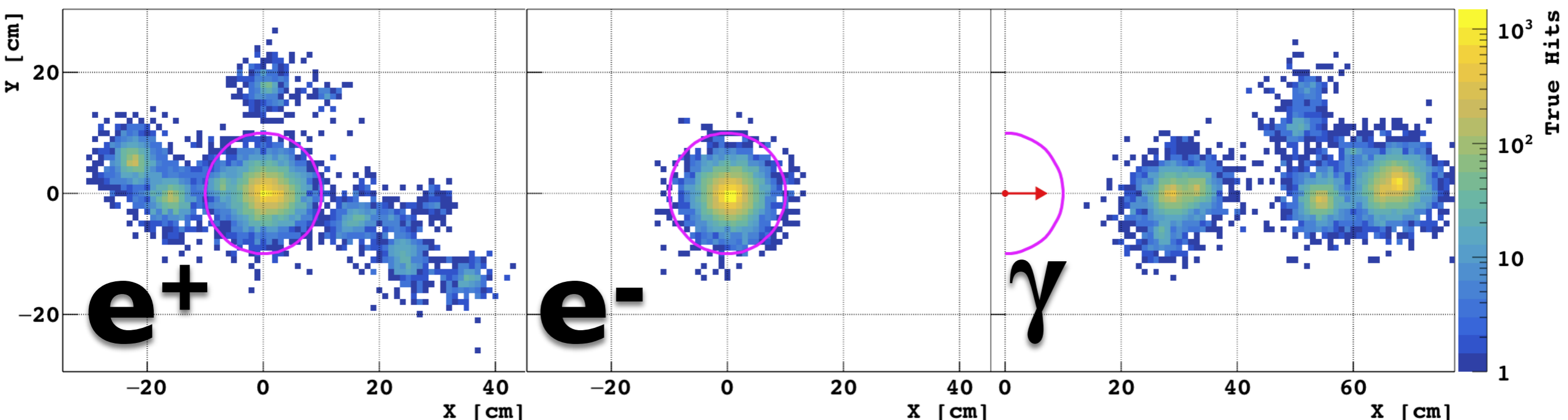
~ 1 MeV



opaque medium  $\rightarrow$  stochastic light confinement  
(**self-segmentation**)

# unprecedented **PID@MeV**...

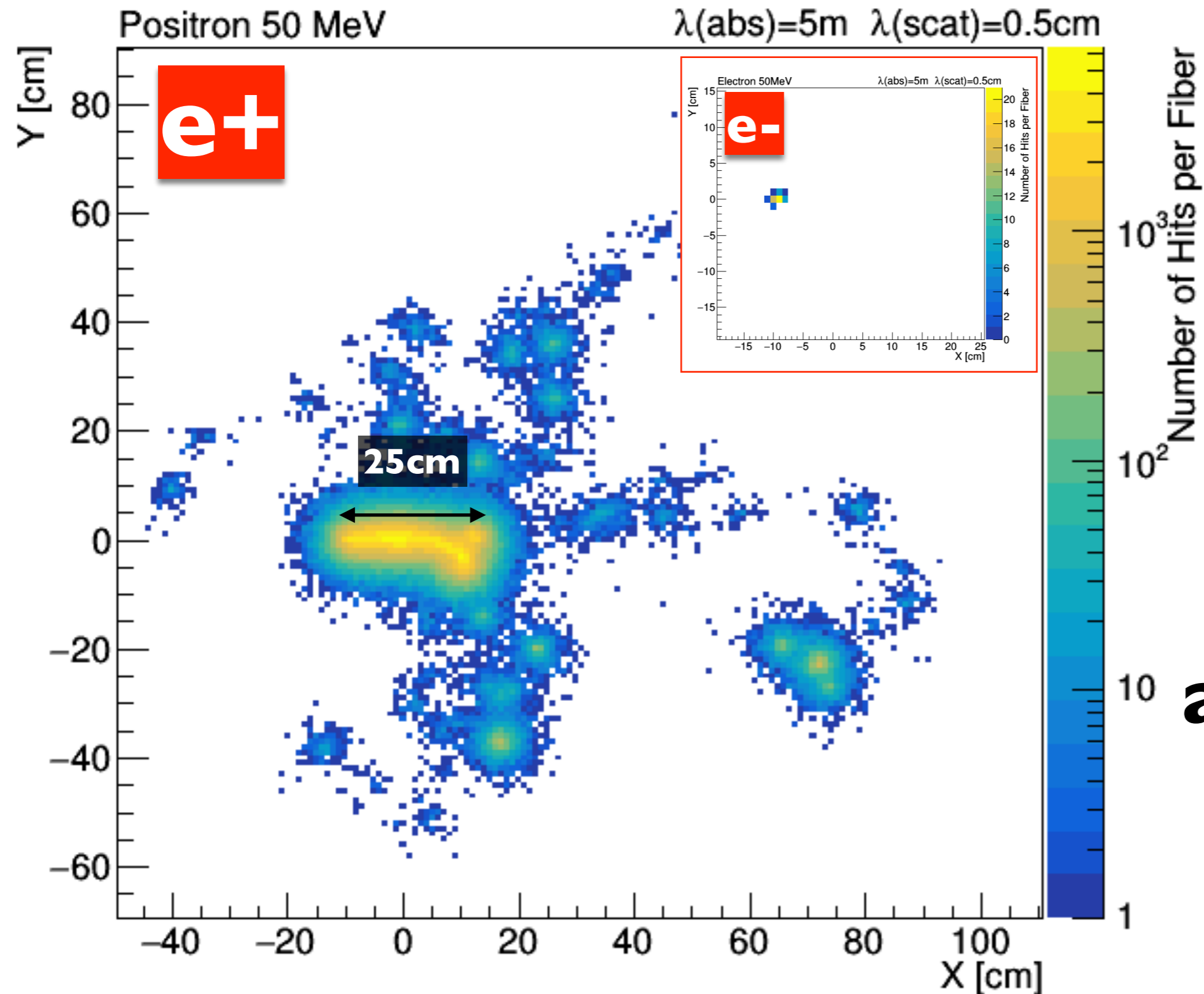
**potential: reduce overburden/shielding**



**opacity** → (native) self-segmentation

**needless segmentation** → **problematic@MeV!** (complex/pollution/cost/etc)

**~50MeV**



**PID**

**matter**

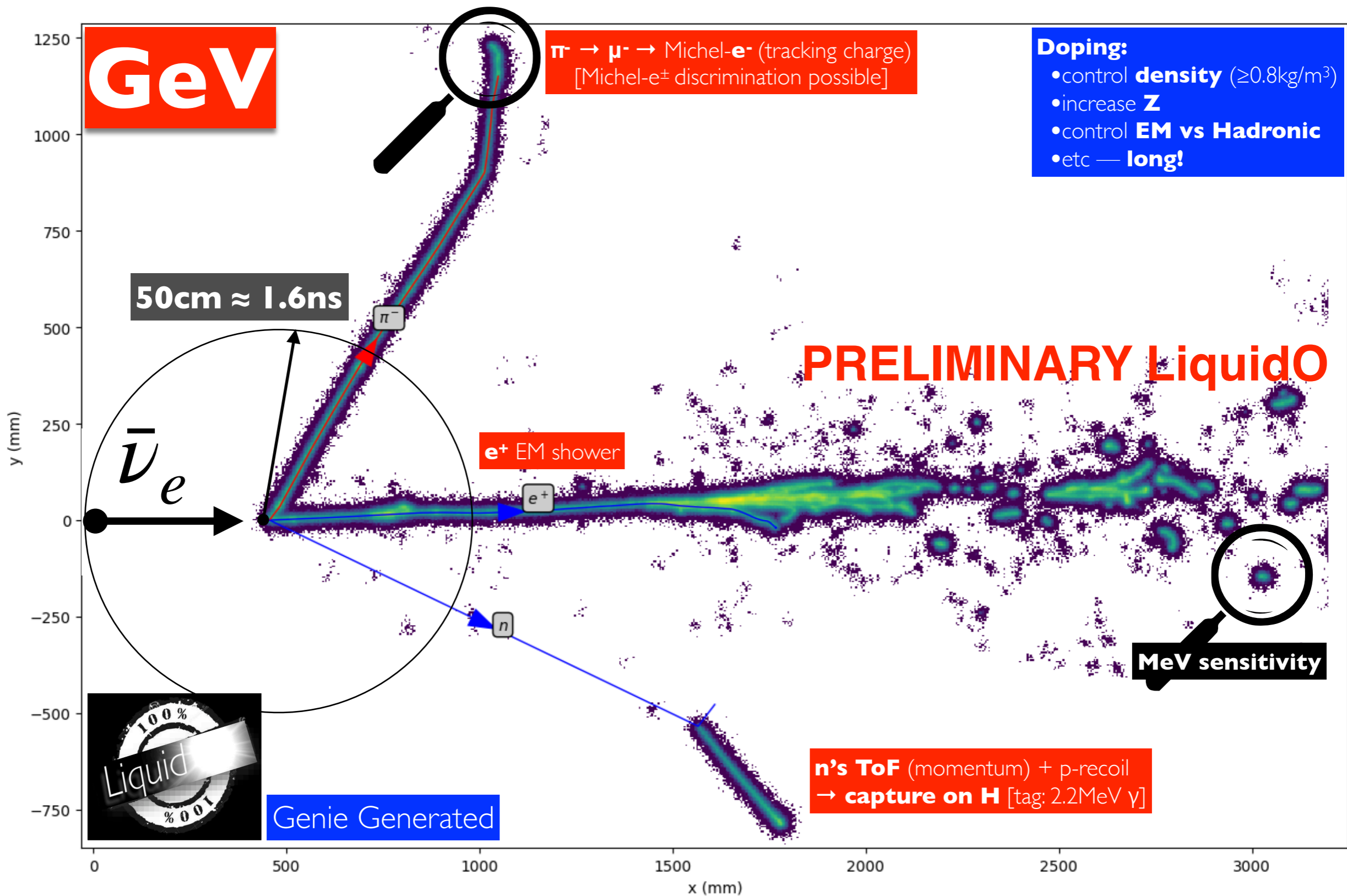
versus

**anti-matter**

**e<sup>-</sup>/e<sup>+</sup> discrimination with no B-field!**

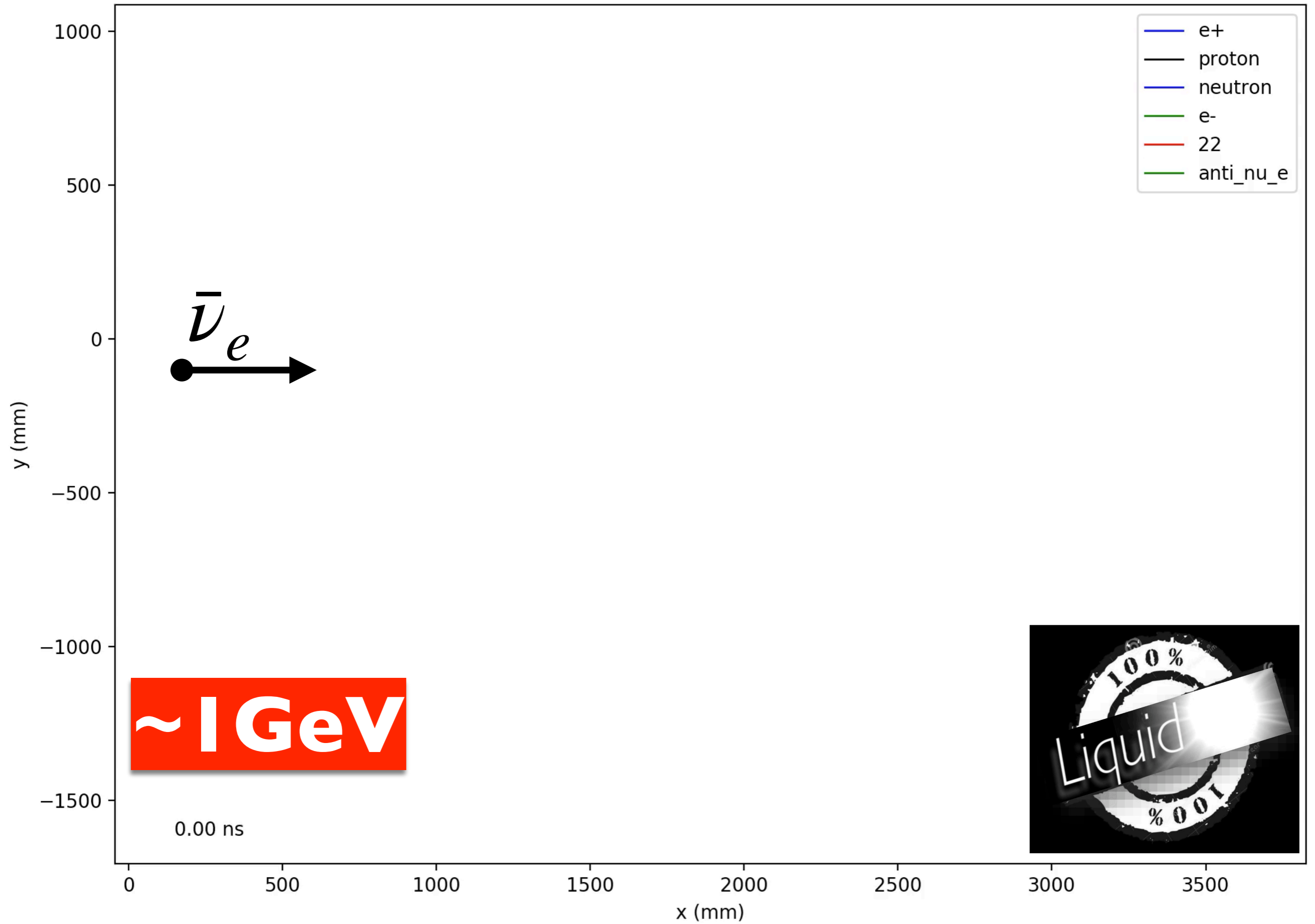


# complex events with LiquidO...



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

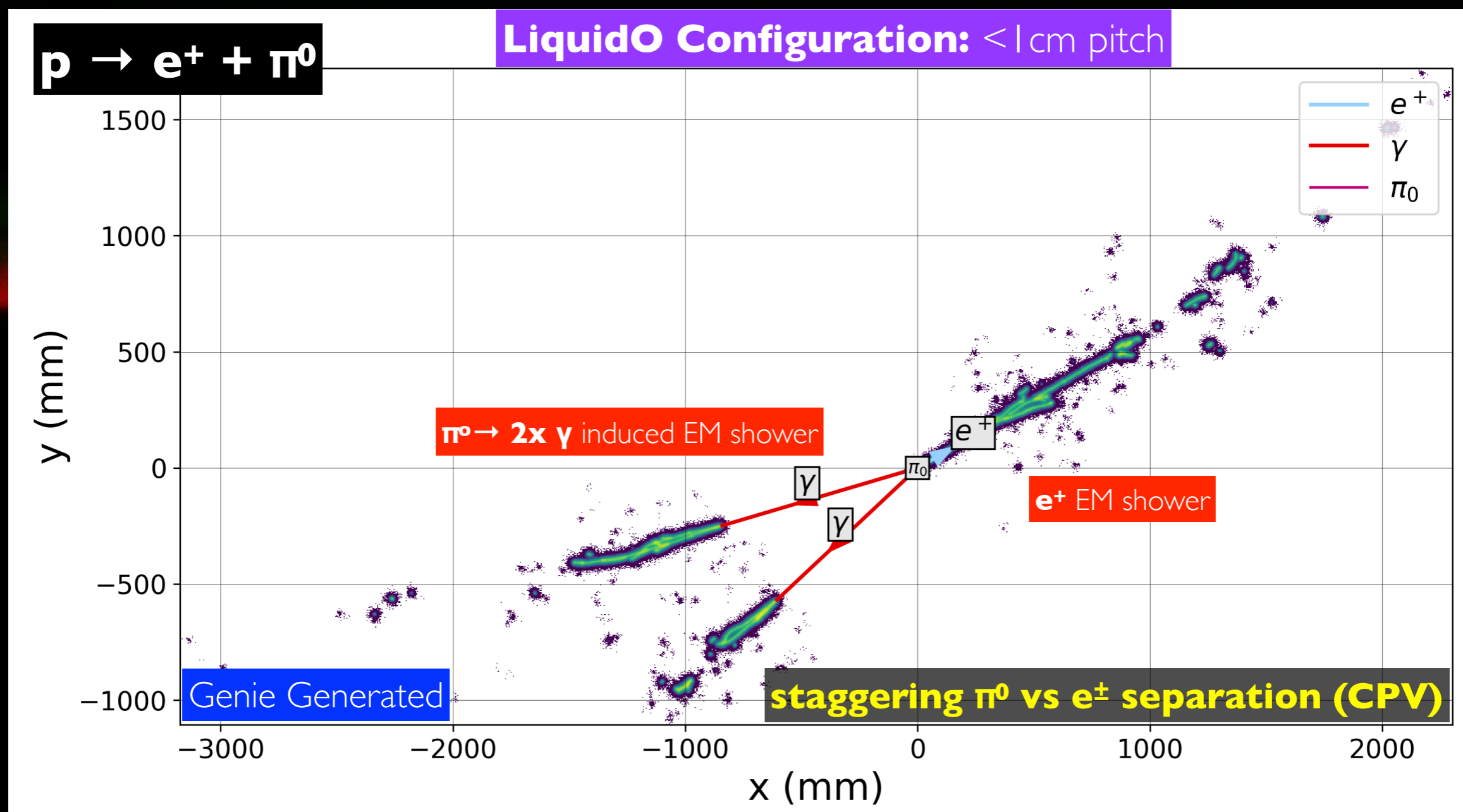
# energy flow: EM evolution of energy in time



# discovery channels too...

**$m(\text{proton}) \sim 1 \text{ GeV}$**

**free-H per unit of mass:**  
**water:**  $\sim 10\%$   
**scintillator:** up to  $20\%$



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](#)

**1438** Accesses | **10** Altmetric | [Metrics](#)

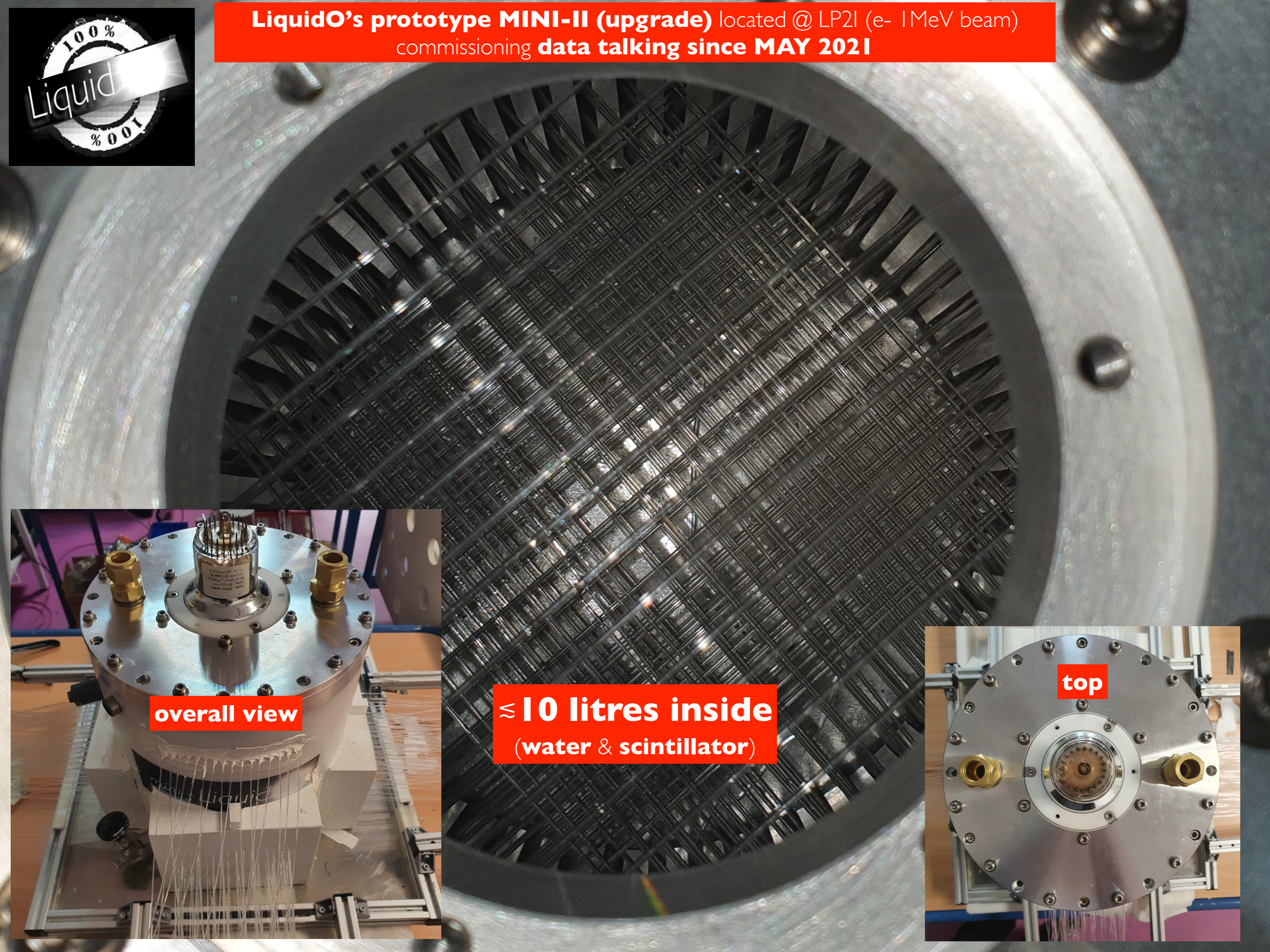
### Abstract

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.

[www.nature.com/articles/s42005-021-00763-5](https://www.nature.com/articles/s42005-021-00763-5)

our first publication...

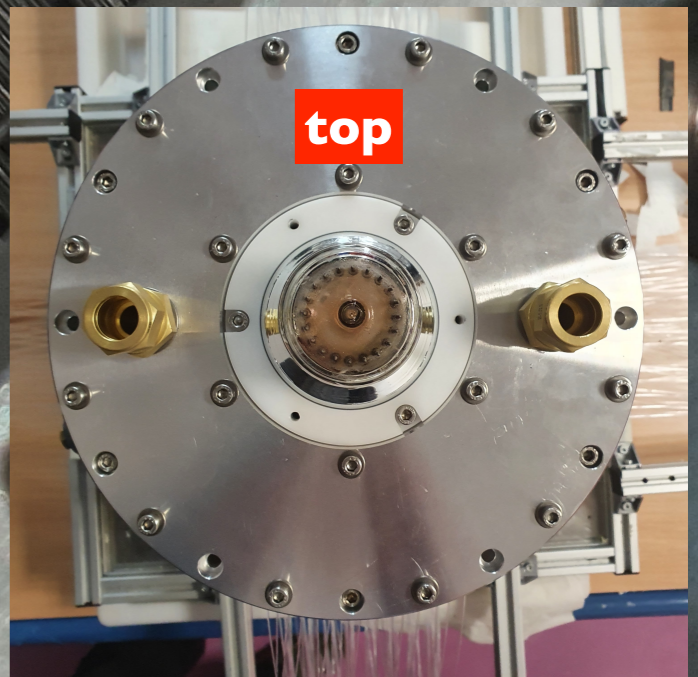
**LiquidO's prototype MINI-II (upgrade) located @ LP2I (e- 1MeV beam)**  
commissioning **data talking since MAY 2021**



**overall view**

**$\approx$  10 litres inside**  
**(water & scintillator)**

**top**



# new results 3rd June...

**NEUTRINO 2022**  
 XXX International Conference on Neutrino Physics and Astrophysics  
*Virtual Seoul* May 30 (Mon) - June 4 (Sat), 2022

The 50<sup>th</sup> Anniversary

**Topics**

- Neutrino Oscillation • Leptonic CP Violation • Neutrino Mass • Neutrinoless Double Beta Decay
- Neutrino Interactions • Reactor Neutrinos • Accelerator Neutrinos • Geo Neutrinos • Atmospheric Neutrinos
- Solar Neutrino • Diffuse Supernova Neutrino Background • Astrophysical Neutrinos • Neutrinos and Cosmology
- Sterile Neutrinos • BSM Searches in Neutrinos • New Neutrino Technologies • Other Interesting Neutrino Physics



# LiquidO: opacity-based light collection system

**any source** ✓ (Cherenkov / ✓ scintillation / others?)

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

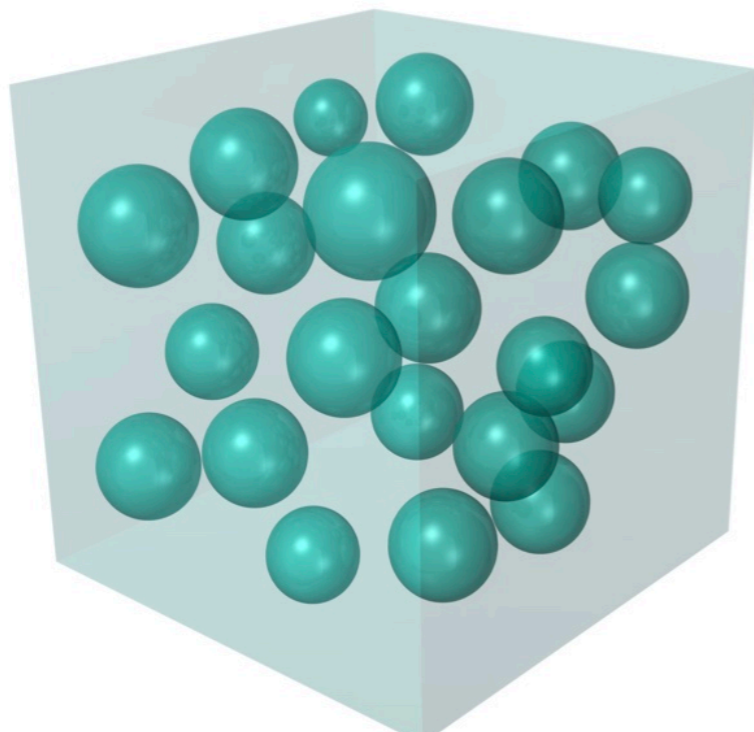
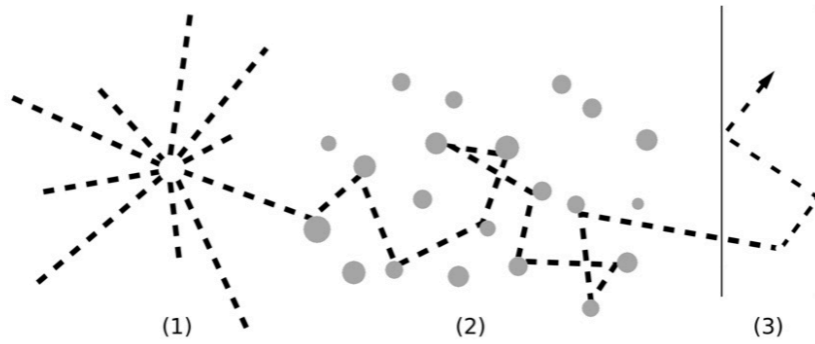
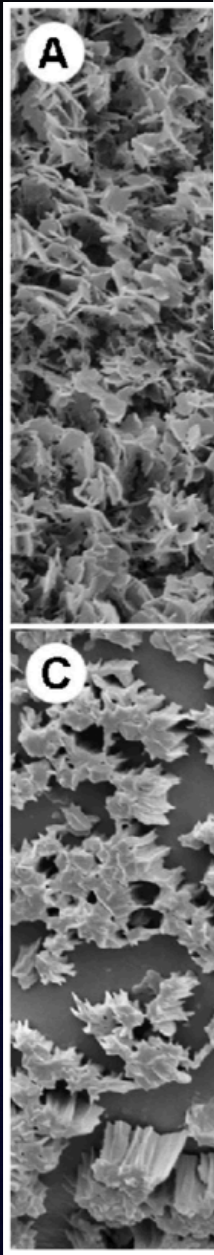
✓ **doping:** a powerful (optional) “byproduct”

new technology: **opaque scintillation?**

the quintessence of LiquidO...

## LiquidO's R&amp;D (new projects...)

## LiquidO R&amp;D (prototypes now)

**“Myco-Crystal Scintillator”**

S. Wagner, M. Grassi, A. Cabrera

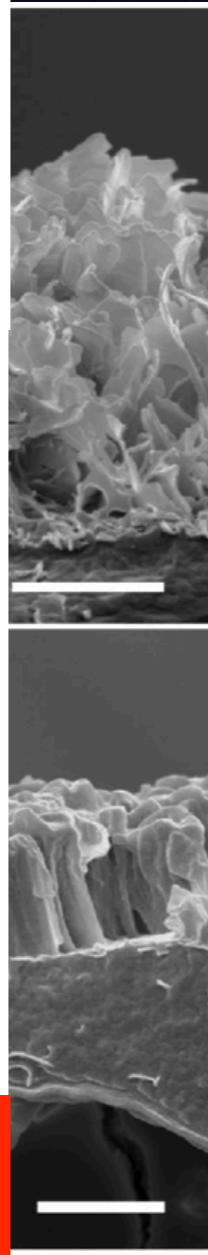
[arXiv:1807.00628](https://arxiv.org/abs/1807.00628)**liquid scintillator**

(optional)

⊕

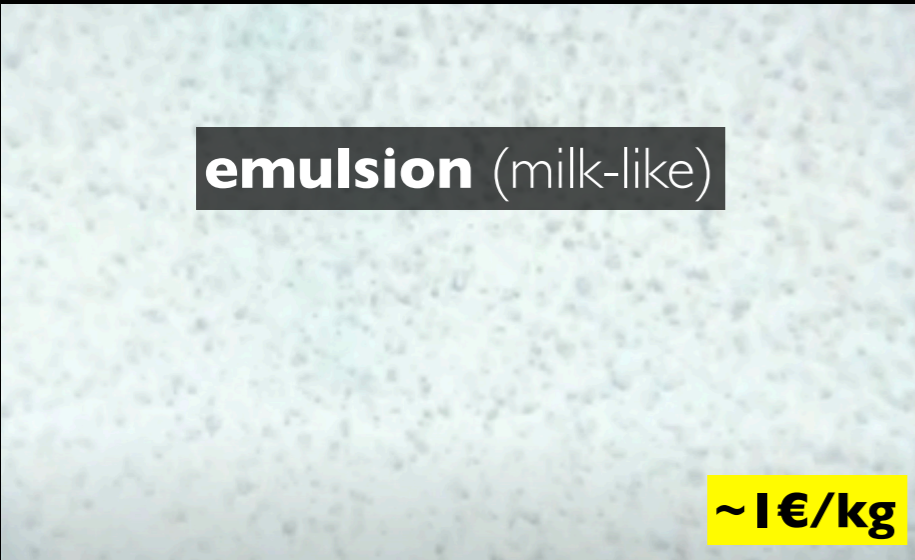
**micro-crystal scintillator**

(doped)

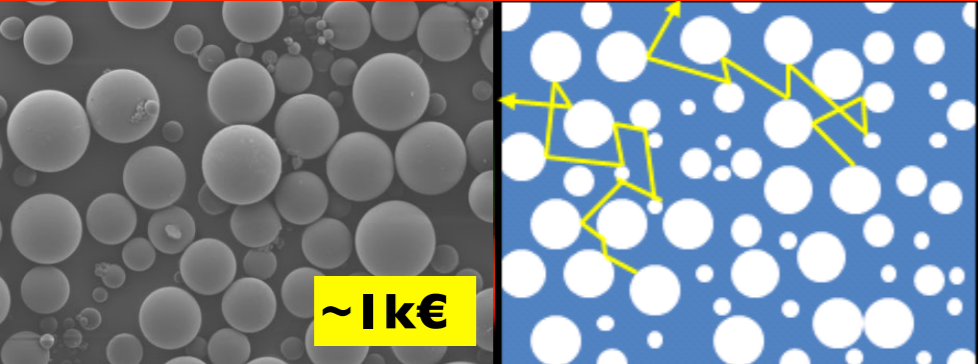
**First Opaque Scintillator @MPIK  
(breakthrough)**[arXiv:1908.03334](https://arxiv.org/abs/1908.03334)**“amorphous WAX-based”****[prototyping: tune scattering with T]**



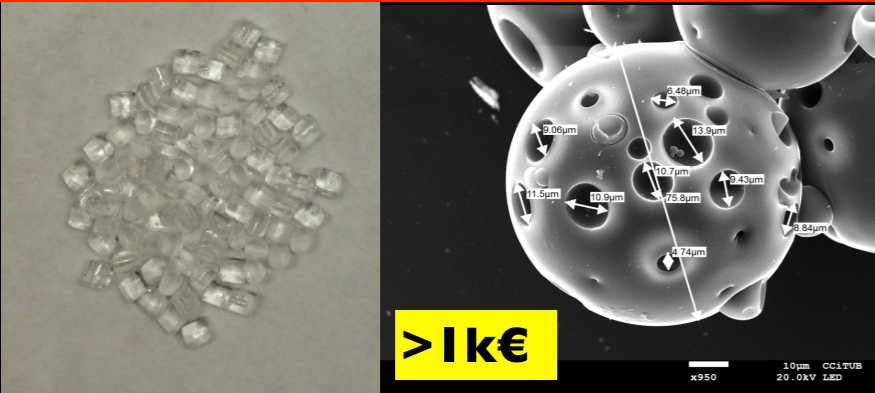
# μ-Crystal development...



liquid easy scattering — cheap & free



μCrystals possible too — expensive



nanoStructures possible too — very expensive

Conceptual strategy **IN2P3 (~2015)** — ideas: **arXiv in 2018** [**arXiv:1807.00628**]

≤**2020**: collaboration with **Tohoku University** & etc (CMS-ECAL; HEP calorimetry) and early discussion with industry **St Gobain** and **ISMA**.

**First μCrystal** detection prototype **BiPo@IN2P3** (2017-2020) [mainly **Barcelona-U**] — promising results!

**Working** → even Pulse-Shape Discrimination for BiPo tagging

**PRELIMINARY**

~100μm  
scintillating  
μSpheres



UNIVERSITAT DE BARCELONA



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

**new results** on the **3rd of June...**



# Tech

exploring anti-matter PID at the industrial level?

innovation & deep-tech...

**nuclear** (EU's **EIC-Pathfinder**: **IJCLab**⊕**CIEMAT**⊕**Mainz-U**⊕**Subatech**⊕**Sussex-U**⊕**EDF**)

**medical** (France's **ANR**: **CNRS**⊕**INSERM**)

European  
Innovation  
Council



AGENCE NATIONALE DE LA RECHERCHE  
**ANR**

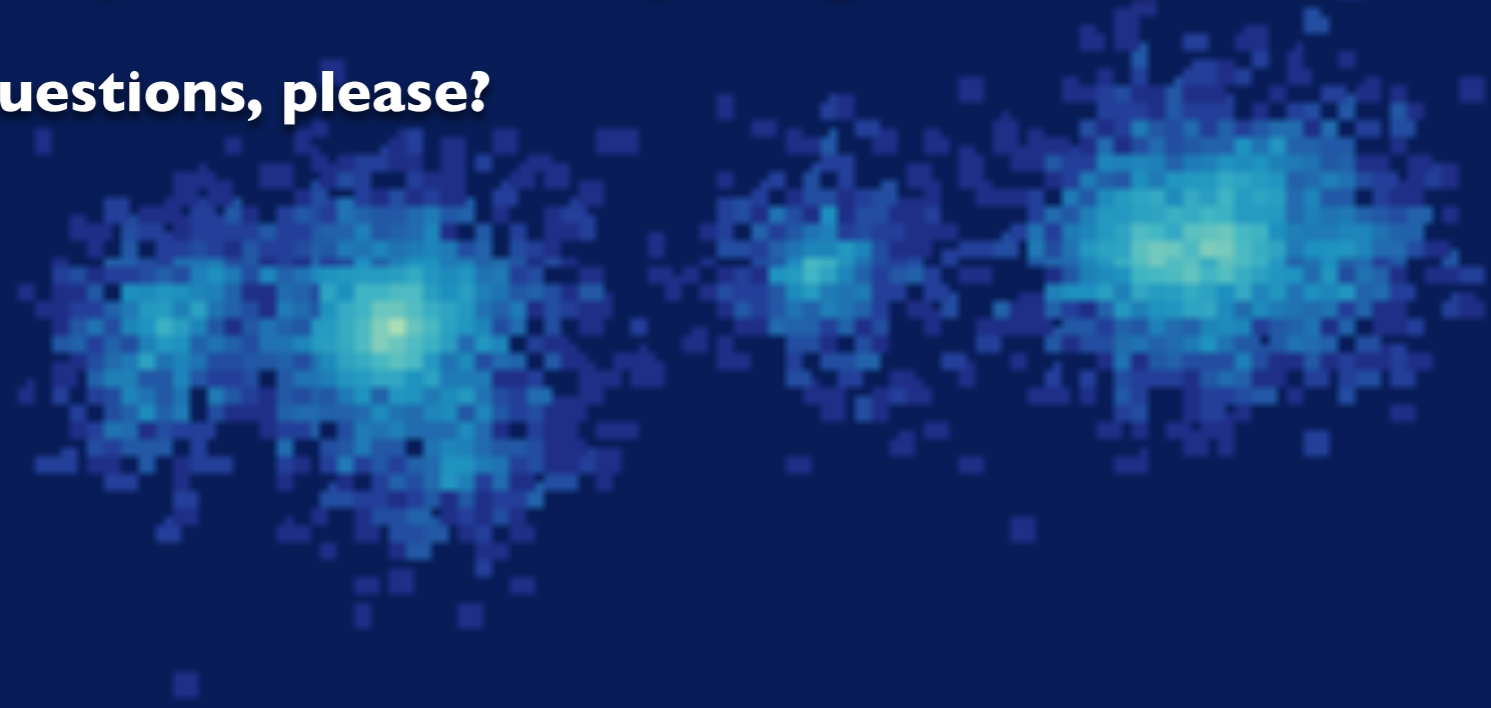
# LiquidO [*scintillation* based for now, but also beyond]

art of **clustering light** (**transparency**) with **excellent imaging/PID** & lots of **doping** (purity)  
*[light clustering for direct imaging]*

**enormous range of physics** — with limitations too

**first phase of R&D completing: results @ Neutrino 2022** (early June)

questions, please?



**for discussion: one of our core teams @ Sussex University (J. Hartnell et al)**

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