DRD2@CERN WORKSHOP

OPAQUE SCINTILLATION

Anatael Cabrera (CNRS / Université Paris-Saclay - IJCLab@Orsay / LNCA@Chooz)

NEW PARADIGM IN SCINTILLATION…

L I Q U I D O

the **advent of LiquidO** (~2012) forced us to "pioneer" ***Opaque Scintillators***

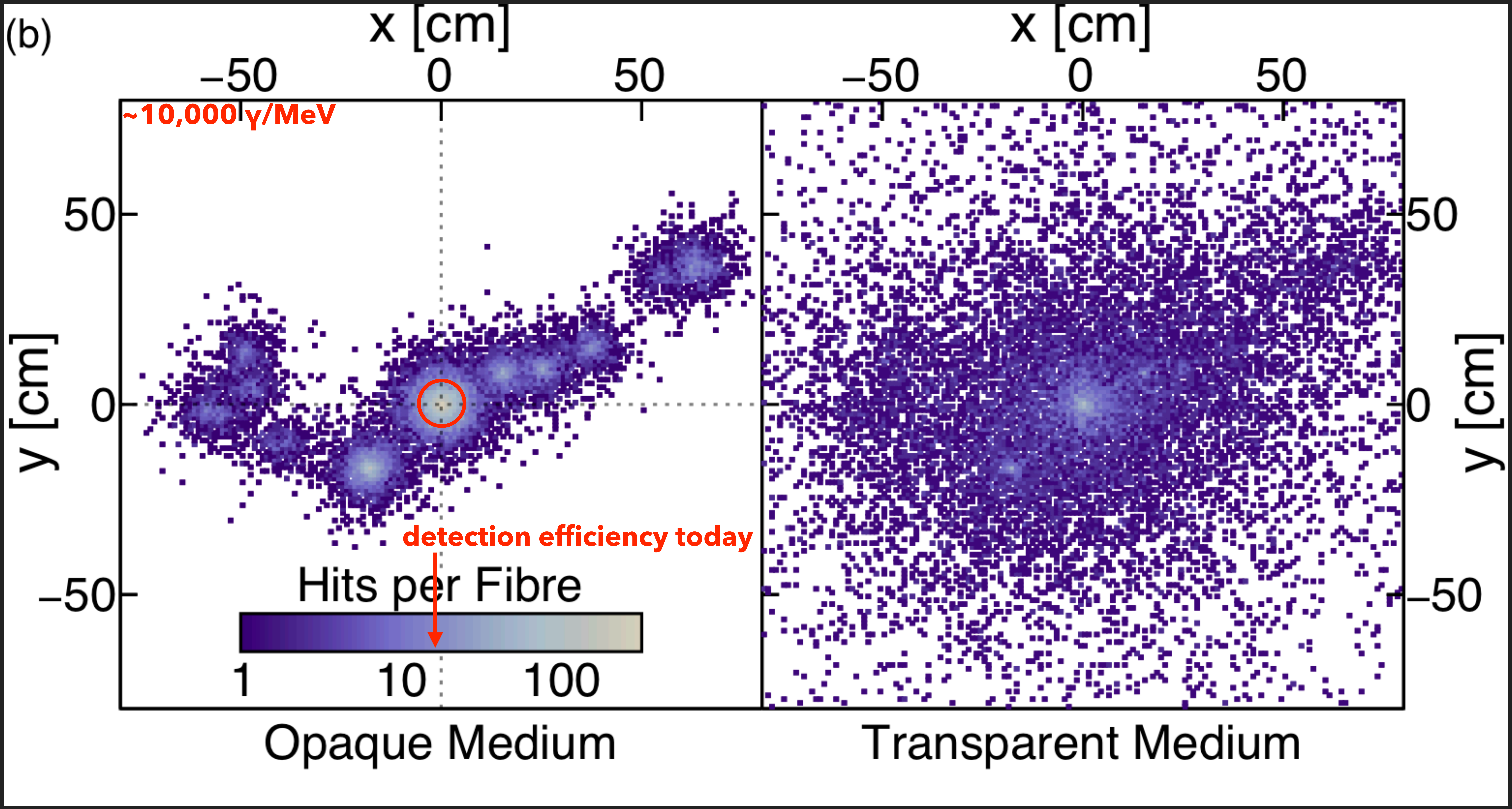
note: some of that always there however what's new is this may (beautifully!) work – against our initial intuition

LiquidO ⇔ **opacity** (even without scintillation)

…NEW OPPORTUNITIES!

LIQUIDO: THE ART OF STOCHASTIC LIGHT CONFINEMENT — FIRST TIME!

→LiquidO's talk this morning [J. Hartnell et al.]



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

LiquidO Consortium$^{(a-z)*}$

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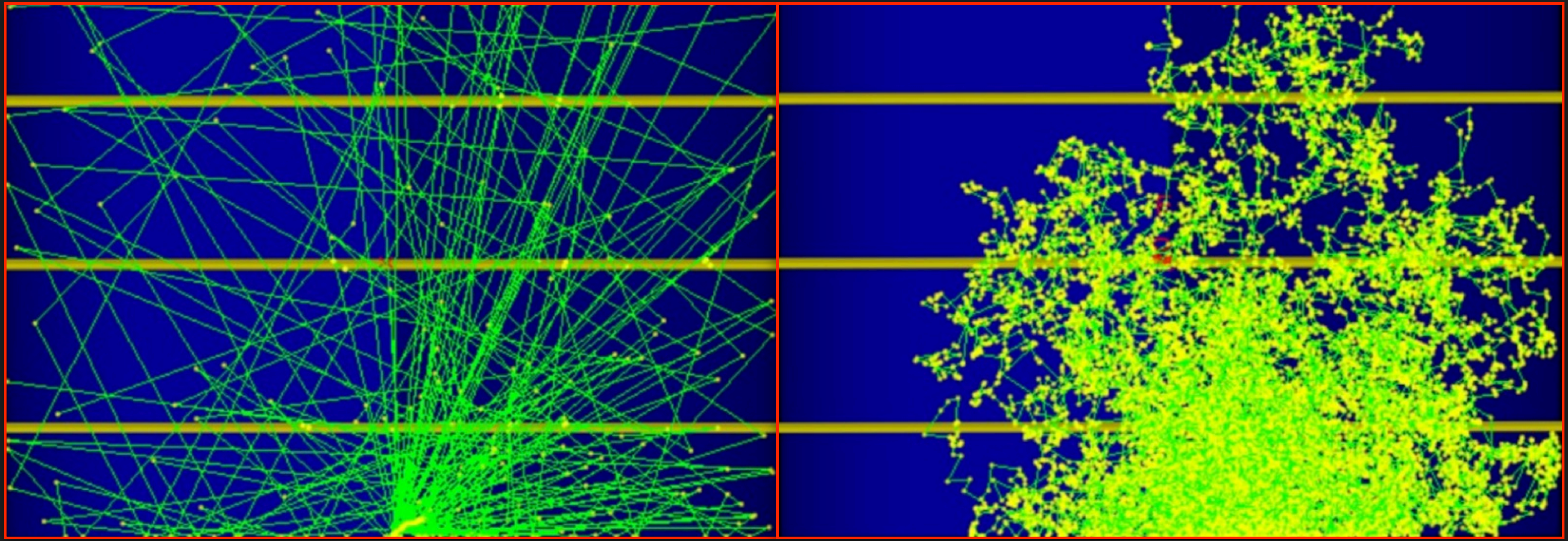
WHAT'S AN OPAQUE SCINTILLATOR?

- (our neutrino bias) since *Reines et al.*: any "scintillating solution" is transparent
    - long attenuation length → many meters [e.g. JUNO ≥20m]
    - short attenuation length → bad?, or small detector (neutrino compliant?)
- attenuation = absorption (i.e. loss photons) ⊕ scattering (i.e. longer paths)
    - absorption: killing photons always bad (prevents detection) – new ideas?
    - new paradigm: opacity ↔ huge scattering (short attenuation length)
        - low absorption (still meters) & extreme scattering (now millimetres)
        - pioneered by LiquidO – a necessity, even if not scintillating!
        - powerful topological ID event-wise from MeV [Jeff's talk]

IMAGE WORTH MORE THAN WORDS…

Mie & Rayleigh scattering (elastic = lossless)



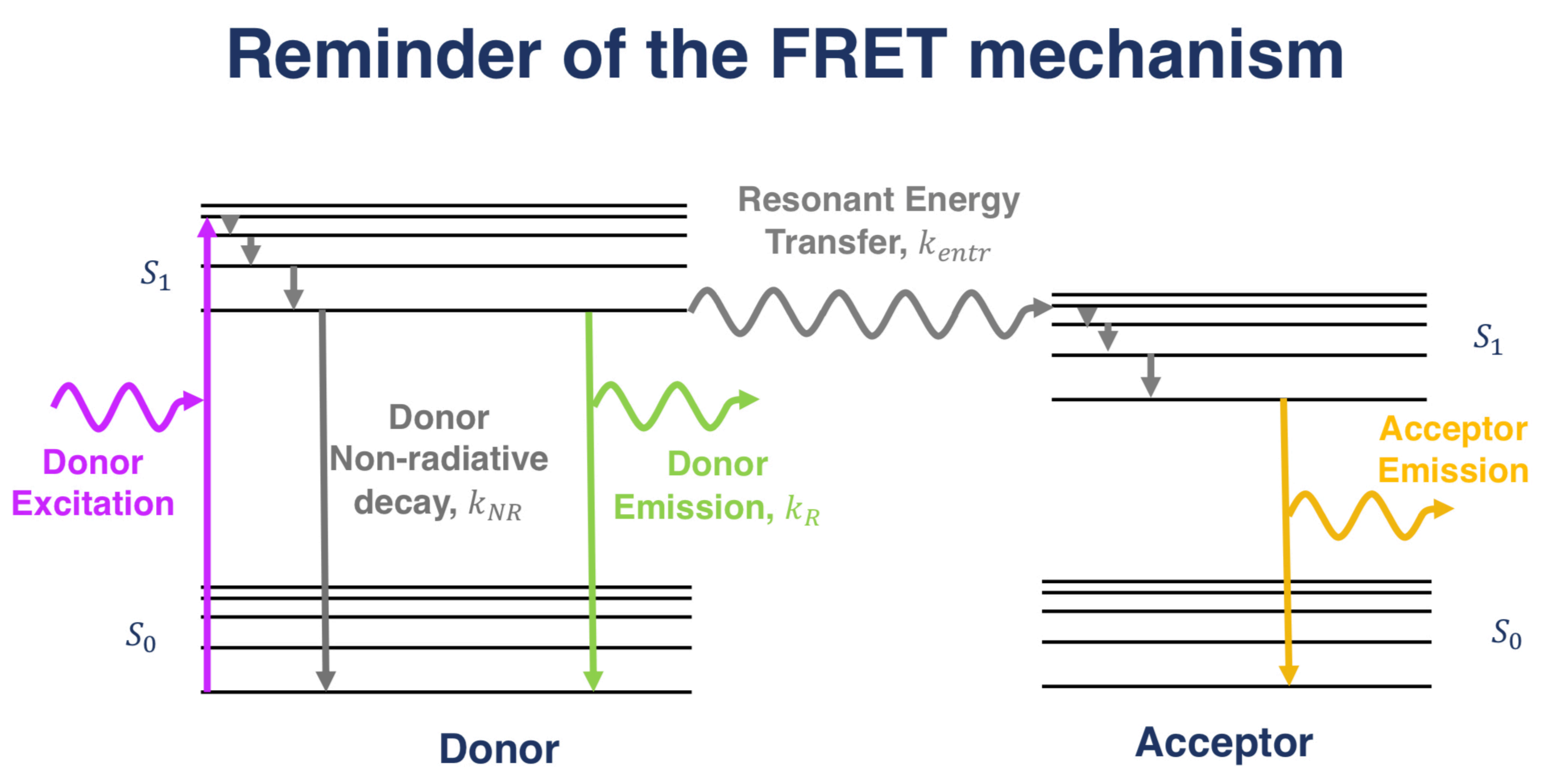
NO Scattering in Medium: each photon ≈ "ray"
(scatter only off surfaces, etc)

Scattering in Medium: each photon ≈ "whirlpool"
(scatter also on surfaces, etc)

SEGMENTATION: use reflectivity to confine light

(a good (98%) reflector loses ~90% of the light after ~100 reflections)

REMINDER ABOUT "TRADITIONAL" LIQUID SCINTILLATORS…



Upon excitation (dE/dx ⊕ complex chain), mainly **radiative de-excitation via SINGLETs** & much less **radiative de-excitation via TRIPLETs**

[TRIPLETS de-excitation is slower⟹ suffers from "competition" with <u>other non-radiative mechanisms</u>]

dE/dx (particle dependently) can change the <u>relative SINGLET to TRIPLET ratio</u> and <u>overall light yield</u> (Birk's constant) ⟹ **Pulse Shape Discrimination**

	Solvent		Scintillator I	Scintillator II	Photosensor
transparent	•quantum energy "collector" •transparent medium		•main scintillation emission	•scintillation emission (colour shift to "reder")	•single-photon detection
example	LAB	Non-Radiative (FRET)	PPO	Bis-MSB (optional)	PMT (QE≤30%) (ultimate spectral sensitivity)
fraction	≥99% (transparent medium)		≤1%	≤1%	≥10% photo-coverage
opaque	•quantum energy "collector" •opaque medium		•main scintillation emission	•fibre light collection •scintillation emission (colour shift to "reder")	•single-photon detection
example	LAB⊕X (opacity: X doping)	Non-Radiative (FRET)	PPO	Kuraray-B3 (a must)	SiPM (QE≤60%) (ultimate spectral sensitivity)
fraction	~99% (opaque medium)		≤1% (the same)	~1% (LiquidO)	(not easy metric)

Naive light yield estimation for comparison in the **"small detector" limit** (i.e. neglect attenuation effects)

- **Transparent:** easy hundreds of PE/MeV [JUNO: up to order 1000] – ultimately limited by **PMT-QE**.
  - Ex. LAB⊕PPO [10,000 γ/MeV] ⊕ PMT [photocathode-coverage@30% ⊕ QE@30%]⟹ ≈900 PE/MeV [increase via photocathode coverage]
- **Opaque:** potential for hundreds of PE/MeV – ultimately limited by **Fibre's Trapping** [under demonstration]
  - Ex. LAB⊕X⊕PPO [10,000 γ/MeV] ⊕ LiquidO [CollectionX@80%] ⊕ Fibre [Trapping@20%] ⊕ SiPM[QE@60% ⊕ Coupling@85%]⟹ ≈800 PE/MeV

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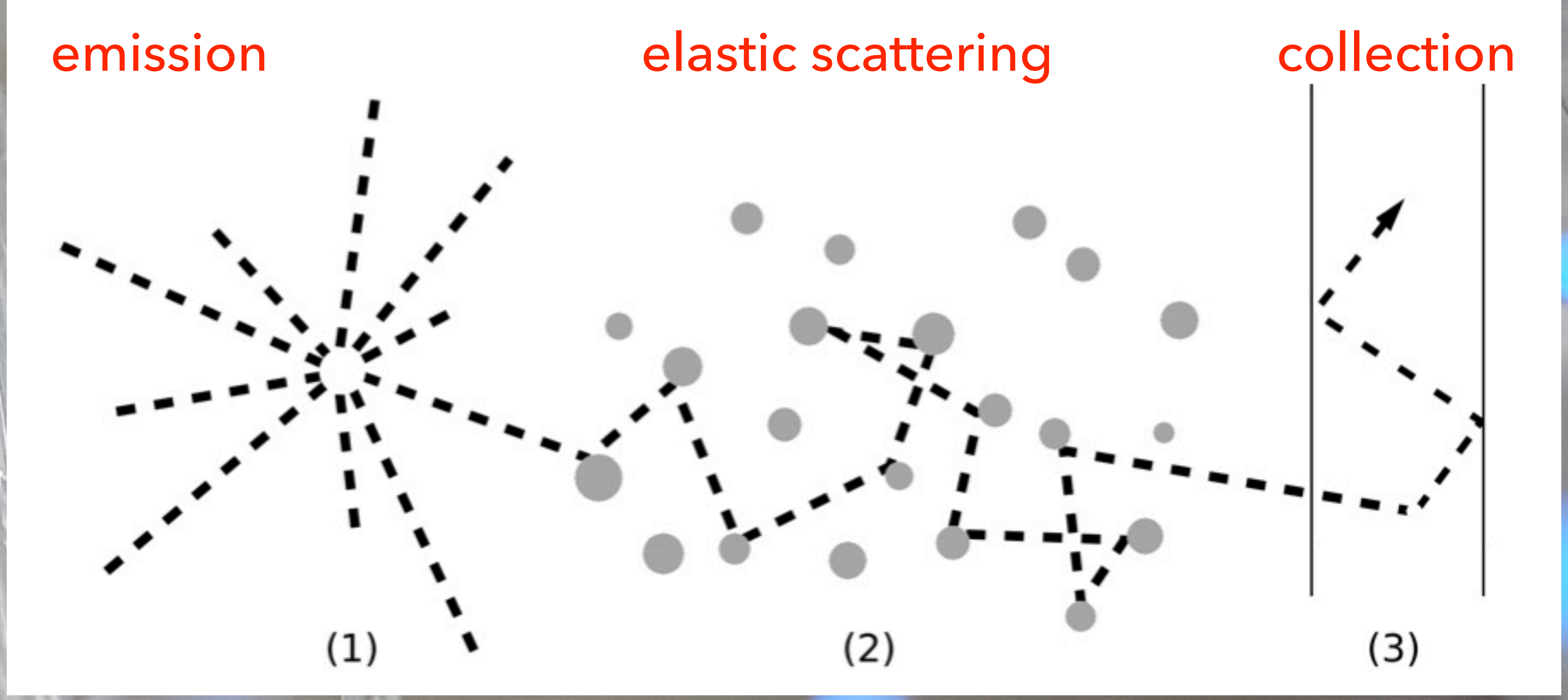
FIBRES: A MUST (SO FAR)



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TODAY: OPACIFYING TRANSPARENT SCINTILLATORS — DEVELOPMENTS

	Basis	Opacity Dopant	Intuitive	Where? (likely incomplete)
"NOWaSH" (arXiv:1908.03334)	LAB/DIN/etc PPO	wax (pioneered for LiquidO)	candle/yoghurt like (→solidification)	Germany
"Emulsion" (WbLS like: 2014)	LAB/DIN/etc PPO	water (a la WbLS)	mayonnaise like	US/Canada
"μ-Crystal" (arXiv:1807.00628)	LAB/DIN/etc PPO?	crystal-scintillators (more light?)	powdery gel	France/Germany
"nano-Crystal" (not sure, sorry)	???	quantum-dots, nano stuff (?)	never seen	US/UK/Germany
new ideas!! (cagy efforts)	various options (confidential)		confidential	**several** (France, Canada, Portugal, UK, Germany, US, etc)

please email me, if you are missing – sorry!

LIQUIDO: FRAMEWORK FOR COOPERATION SO FAR

GROWING FIELD — EXCITING RESULTS SOON!

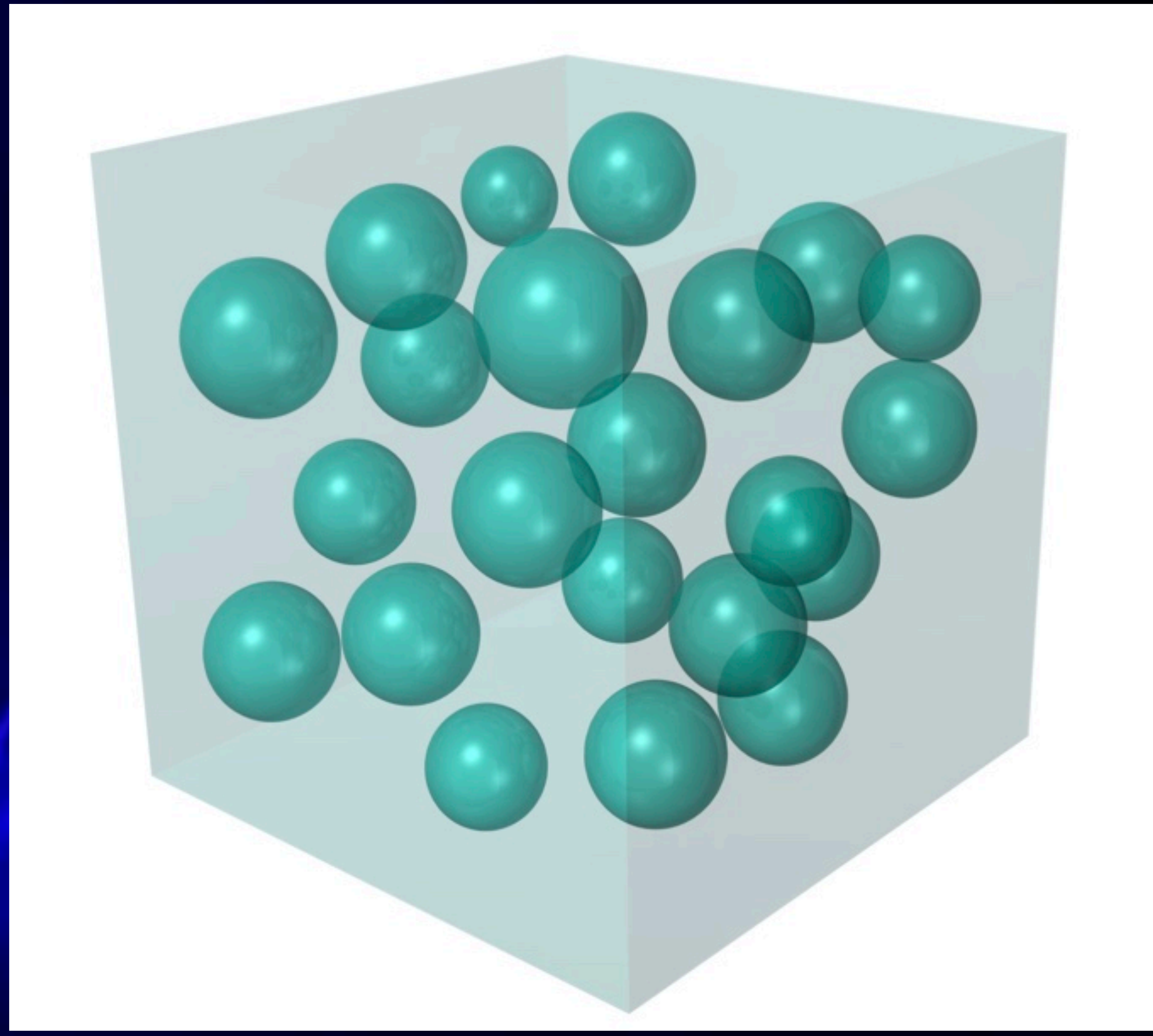

FIRST "NOWASH" SYSTEM (PROTOTYPING) — GERMANY CIRCA 2018
arXiv:1908.03334
Anatael Cabrera (CNRS / Université Paris-Saclay)

FIRST "MICRO-CRYSTAL" PROOF-OF-PRINCIPLE — FRANCE CIRCA 2018

arXiv:1807.00628

pulverised inorganic μ-Crystals in a liquid system (scintillating or not) to maximise light output

note: possible quantum energy transfer under active R&D



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EMULSIONS: A NATURAL SOLUTION

- MILK*-like: water-based solution with unmixed μ-droplets of oil (i.e. scintillator⊕scattering) – used in "traditional **WbLS**"

- MAYONNAISE-like: oil-based solution (i.e. scintillator**) with unmixed μ-droplets of water (i.e. scattering): **NEW formulation!**

both schemes benefit (very similar) exploit **micelles** for μ-level scattering: Mie & Raleigh scattering → **LiquidO**

***milk**'s extreme "whiteness" (due to Mie scattering), only needs a few % of fat content.

**the more scintillator, the higher the light yield – water does not scintillate.

OPAQUE SCINTILLATION POTENTIAL

HEAVY DOPING…

FACT: MOST OPACIFICATION STRATEGIES (SO FAR) ARE ACHIEVED VIA DOPING — NO METALS YET (SOON)

COMPARING POTENTIALS OPAQUE VS TRANSPARENT SCINTILLATORS — APPROXIMATIVE

Feature	Transparent	Opaque	Comment
Light Yield	≤12,000 γ/MeV (so far, same technology)		**Same a priori.** Opaque technology inherits directly Transparent – decades of expertise. Still Transparent (highly optimised) has an edge over today's Opaque (not optimised; still R&D demonstration) thanks to simplicity. Opaque may deviate in the future via new formulations, different chemistry/materials, etc., thus benefiting from its a priori robust immunity to transparency (always delicate). **SYNERGY with all existing (WbLS, etc.) and new technologies (R&D).**
Event Imaging Topology	very limited (very energy dependent)	✓ (from fraction of MeV)	Large difference, by construction. Opaque systems, born with LiquidO (i.e. exploitation of "stochastic light confinement"), were created to boost this feature at the potential expense of other features, which may be optimised later on to minimise performance losses. Transparent may exploit segmentation (a well-known technique), but this has severe limitations, especially at low energies (radiopurity, dead materials, etc.). **Rather UNIQUE.**
Photosensors	QE limiting Timing ~1ns	QE ~OK Timing ~0.1ns	Here, differences are significant and exciting abilities to customise either system, with cost being often the leading limitation. Transparent use predominantly "traditional" PMT (QE≤30% and timing ~1ns), while Opaque benefits from the latest SiPM (higher QE and timing ≤0.1ns) – still improving (much R&D). There are exceptions, and solutions depend heavily on application optimisation and cost. **SYNERGY with all existing and new technologies (R&D).**
Pulse Shape Discrimination	✓	✓	**Same a priori.** PSD remains a feature that needs to be optimised in the scintillator formulation: not all formulations or solutions have the same potential. PSD allows ID via dE/dx mechanism (separation among e±/γ, proton and alphas), including quenching effects (i.e. Birk's constants). **SYNERGY with all existing and new technologies (R&D)**
Cherenkov / Scintillator	✓	✓	**Assuming timing drives (slow scintillator, etc.), both systems are broadly similar.** Opaque medium is expected to diffuse the Cherenkov single-ring topology; thus, Transparent holds an edge here. Nonetheless, Cherenkov light topology is highly diffused for e± due to their Molière Radius at ~1MeV along with low yield due to threshold. Opaque's topology overcomes much of this limitation: direct directionality, high-multiplicity, etc. **SYNERGY with all existing and new technologies (R&D).**
Vertex Spacial Resolution	≥5cm	sub-cm? (proving)	Significant difference, by construction. Opaque, again, benefits from the powerful self-segmentation of LiquidO, so light is concentrated in a "light-ball" native and tuneable topology with a radius as small as order 1 cm. The vertex of the light-back can be measured to sub-cm precision, depending on the fibre configuration setup (highly optimisable). **Rather UNIQUE.**
Doping Capability	up to ~1.0% (proven)	up to ~10.0%? (to be proven)	Major difference. Again, Opaque may be more robust regarding immunity to transparency. This relaxes dramatically the optical constraints. However, doping typically affects the light yield, caused by non-radiative energy losses. Opaque may have means to recover (ex. "μ-Crystal" rationale), but this remains to be proven – much R&D ahead. Major potential for much physics in neutrino but also ββ decay explorations, etc. **SYNERGY with all existing and new technologies (R&D).**
Density / State	liquid only (water-like)	very tuneable (above water-like)	This is a specialised tuneable consequence of doping if desired – not too typical for neutrino detection at MeV. This is, however, useful for HEP calorimetry purposes. Here again, the μ-Crystal approach pushes the boundaries by using very dense crystal scintillators (Pb, W, etc), while the liquid scintillation function may be reconsidered. Opaque systems have been experimentally demonstrated to work in liquid, gel-like and even solid configurations. **Rather UNIQUE.**

TOMORROW? NOVEL NATIVE OPAQUE SCINTILLATOR — MORE LIGHT?

European Innovation Council

UK Research and Innovation

AntiMatter Tech

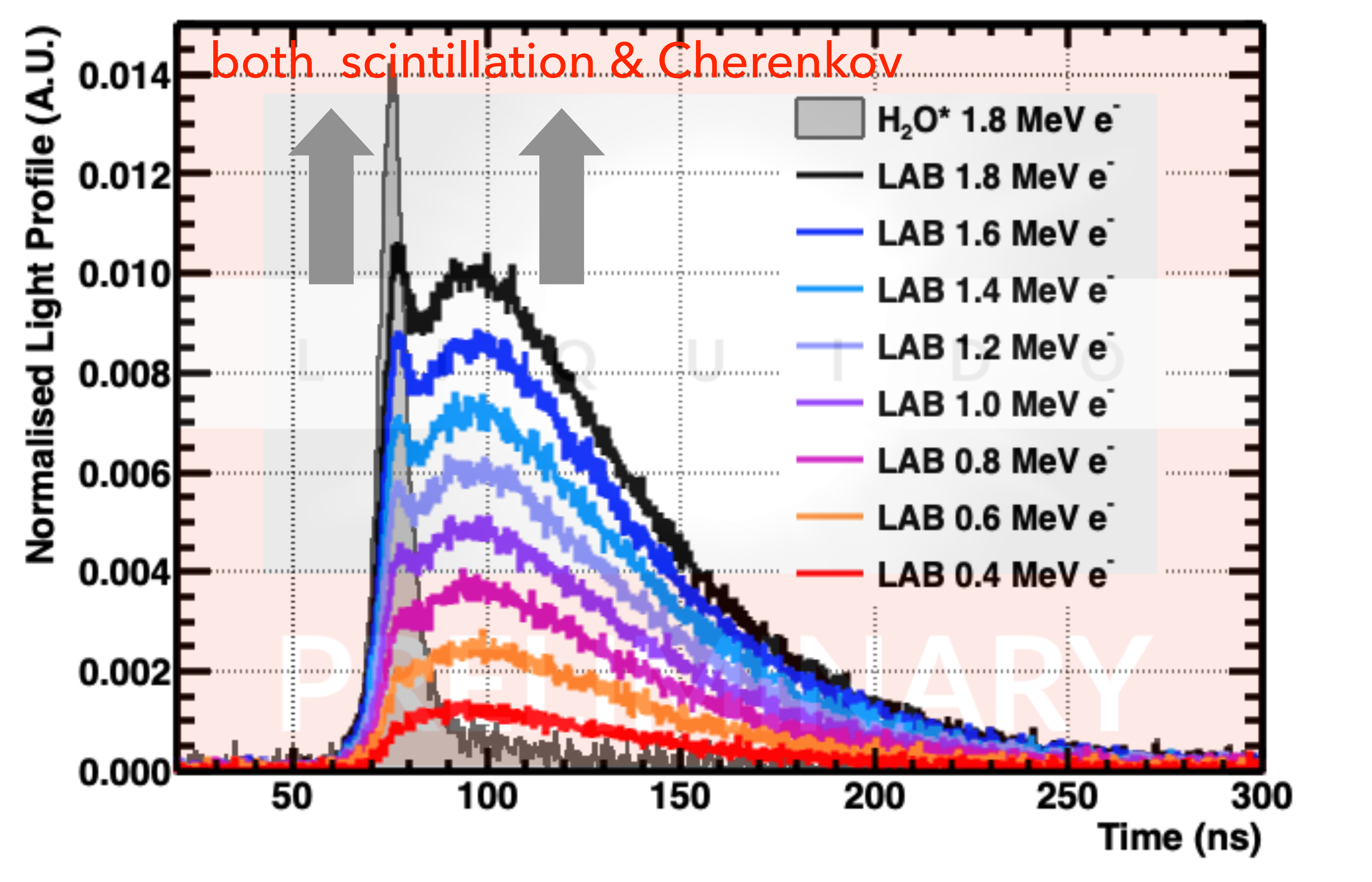
France, Germany, Portugal, Spain, UK with tight links to Canada
(tight work with the **CLOUD collaboration:** 20 institutions, 11 countries)

EIC just approved **extra ~1M€** [LiquidO specialised technology]

- new (opaque) scintillator formulation [→photo-chemistry]
- new (transparent) wave-shifting/scintillating fibres [→industry]
- technological solutions beyond LiquidO only scope

https://antimatter-otech.ijclab.in2p3.fr/

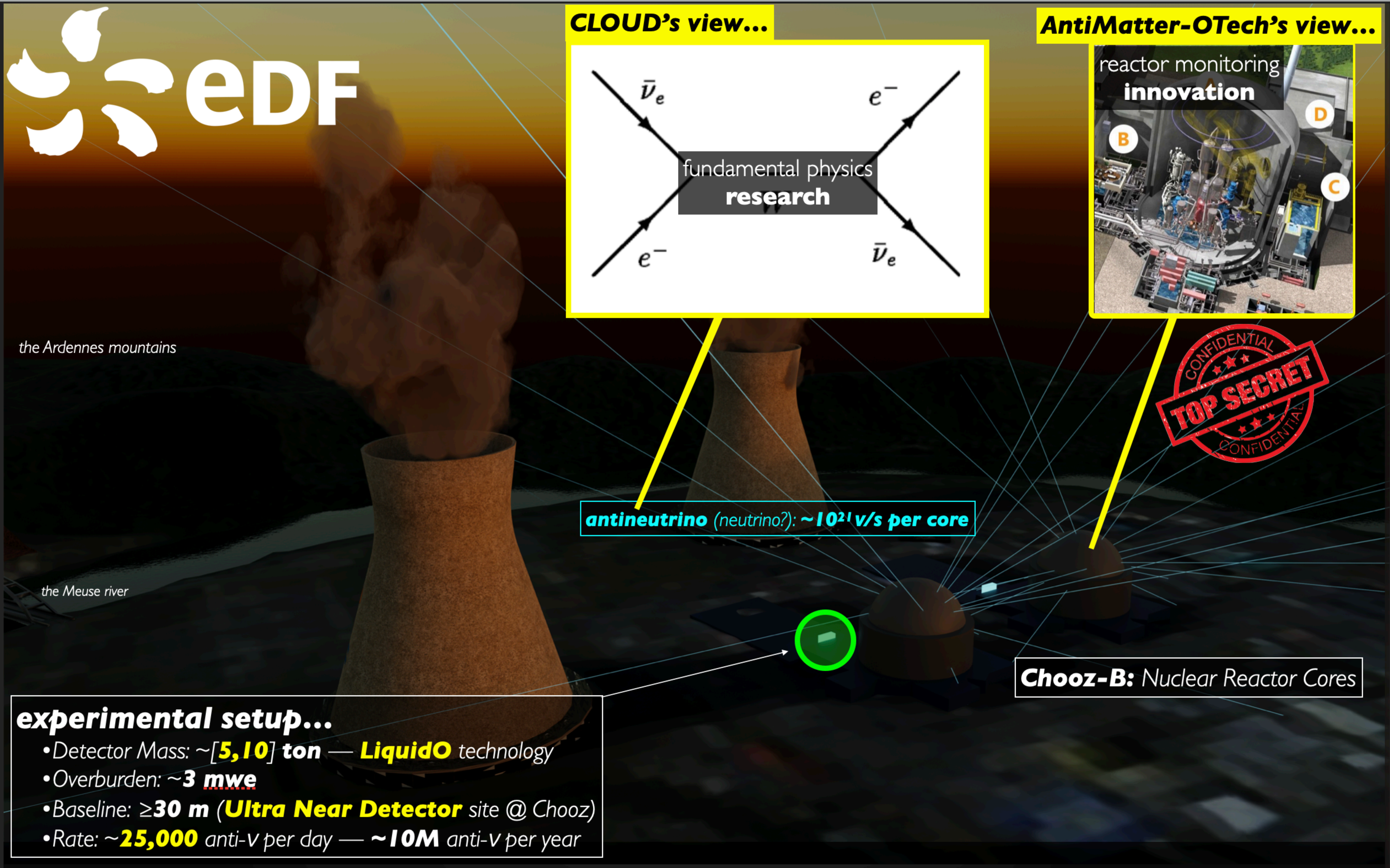
kuraray



NEW FIBRE(S) & SCINTILLATION TECHNOLOGY

MORE LIGHT…

ANTIMATTER-OTECH/CLOUD EXPERIMENT: FIRST MULTI-TON EXPERIMENT



CLOUD vs AntiMatter-OTech…

https://antimatter-otech.ijclab.in2p3.fr/

OPACITY: A SCINTILLATOR REVOLUTION?

QUESTIONS…

Stefano Dusini @ CERN – even more questions!

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