Liquid

novel neutrino detection

University Liverpool (UK)

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Anatael Cabrera

CNRS/IN2P3
LAL@Orsay
LNCA@Chooz

what is LiquidO?

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

LiquidO is both…

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

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

~45 scientists ⊕ ~20 institutions ⊕ ~10 countries
[Brasil, Canada, Chile, China, France, Germany, Italy, Japan, Spain, USA, UK]

LiquidO: ensuring correctness…

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

today's technology…

"**A long time ago in a galaxy far, far away**…"

Reines & Cowan (*et al*) around 1950

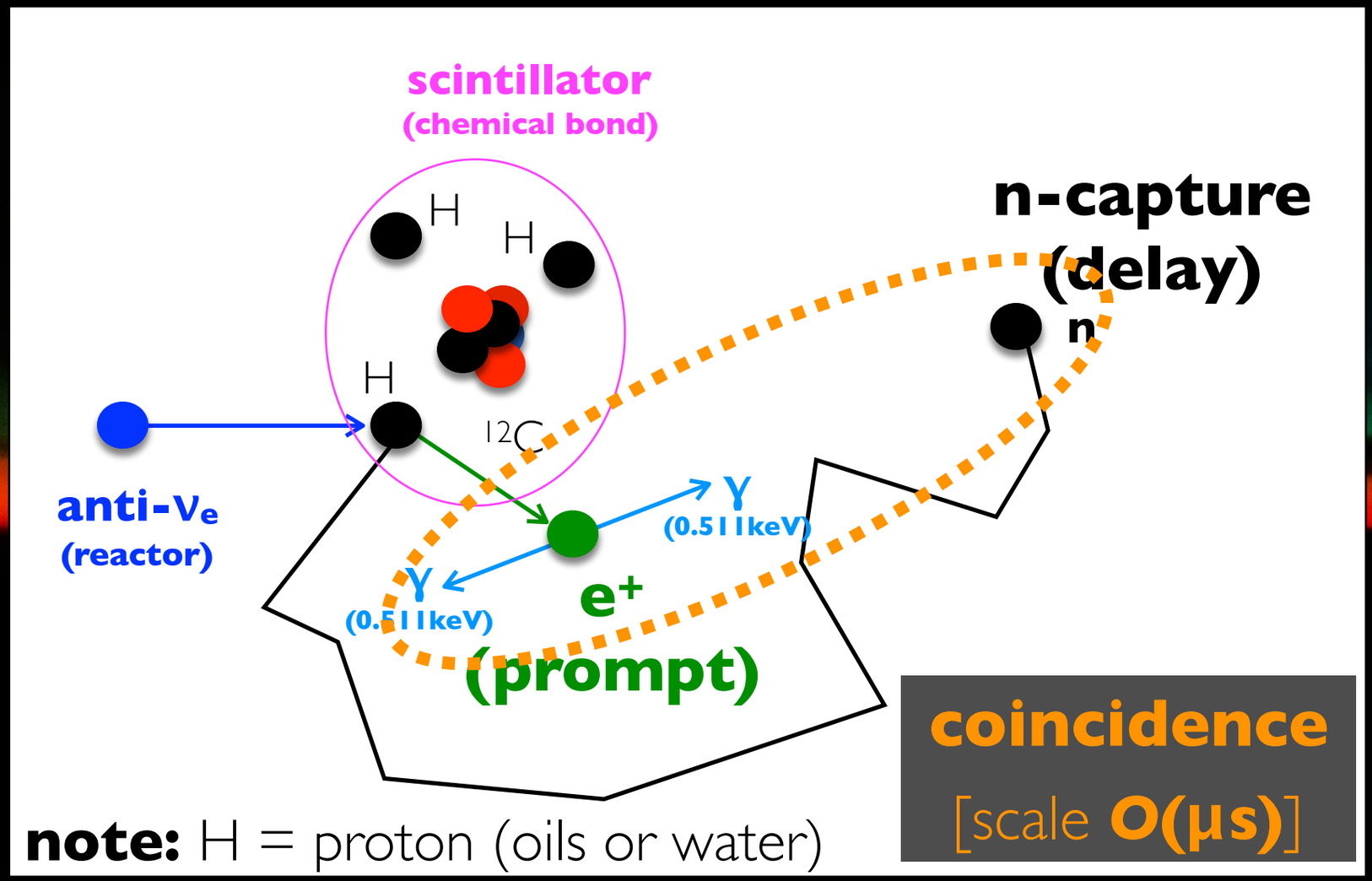
discover the neutrino (upon 1930's Pauli's hypothesis)
[Nobel prize 1995]

pave much of today's technological ground
[even ~70 years later, **dominant today**]

the ν discovery (1950's)...

inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n

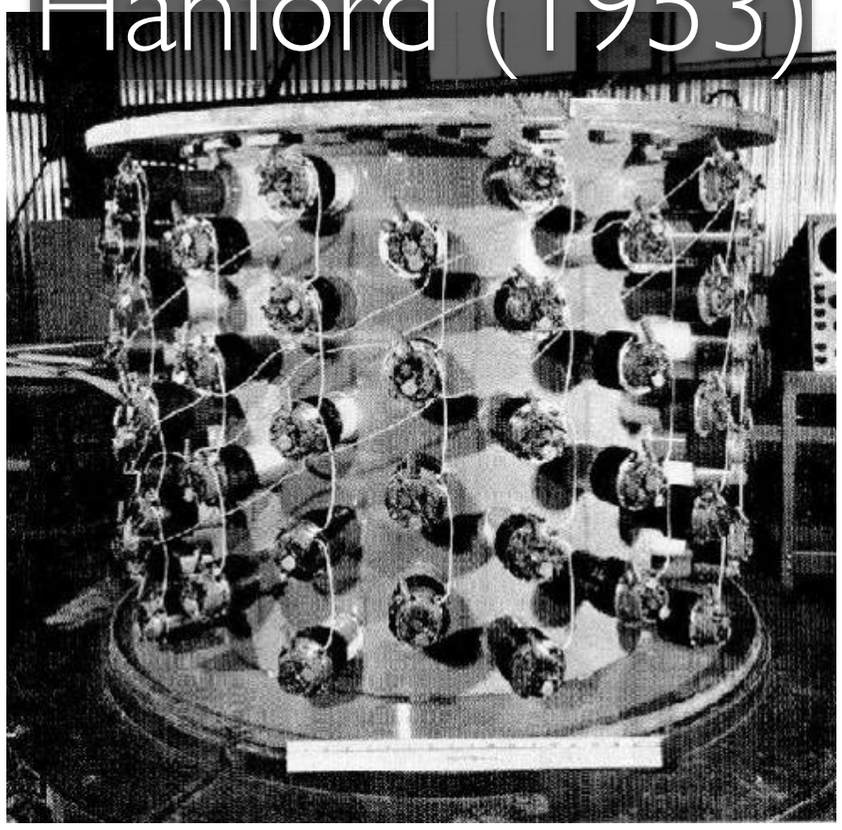


no e+ PID implies

γ ≈ e^- ≈ e^+ ≈ α ≈ p-recoil (fast-n)

Reines&Cowan pioneering detection…

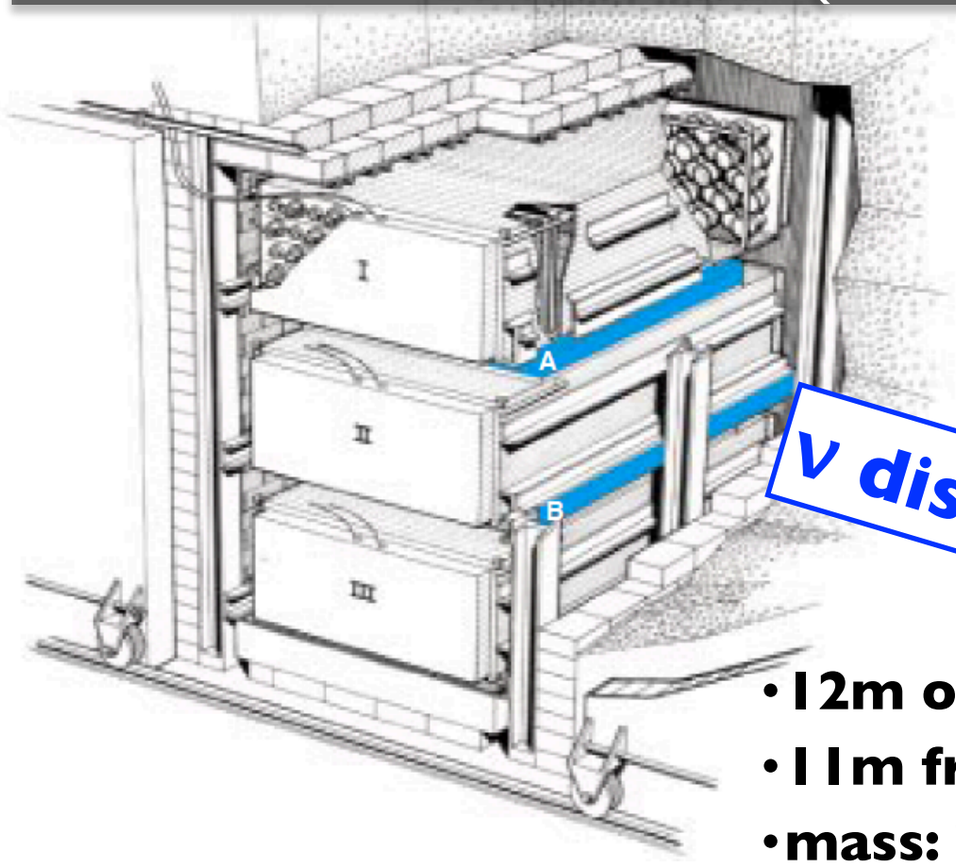
Hanford (1953)



- **surface** (inside a truck)
- >15??m from reactor
- **mass:** ~300kg
- **target:** scintillator + Cd (loading?)

ν hint?

Savannah River (1956)



ν discovery!!

- **12m overburden**
- **11m from reactor**
- **mass:** 2x 200kg
- **target:** water + Cd
- **I+II+II:** scintillator
- **rough segmentation**

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 29, NUMBER 2 FEBRUARY, 1958

Liquid Scintillators for Free Neutrino Detection*

A. R. RONZIO,† C. L. COWAN, JR.,‡ AND F. REINES
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received October 28, 1957; and in final form, December 9, 1957)

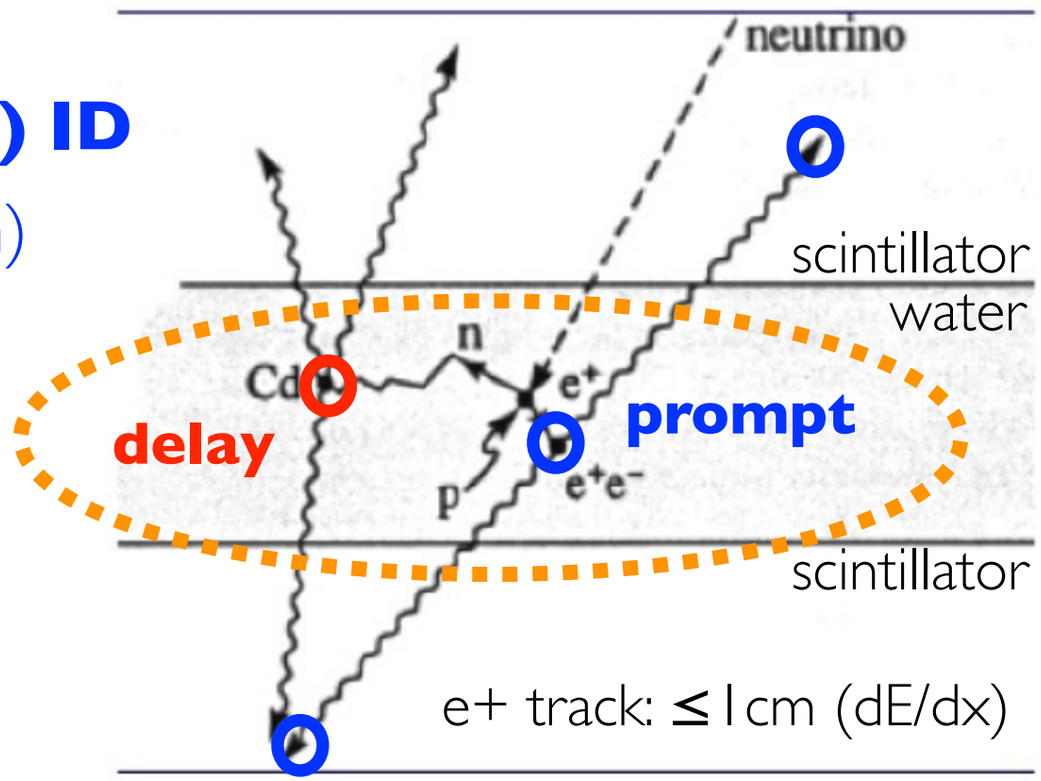
The criteria by which liquid scintillators have been selected and developed for free neutrino detection experiments are described and a discussion is given of the preparation of the solutions. Triethylbenzene is a superior solvent and cadmium octoate is found to be the best cadmium compound known for these purposes.

Cd loading on liquid scintillator

Reines& Cowan powerful coincidence (IBD)…

annihilation (e+) ID

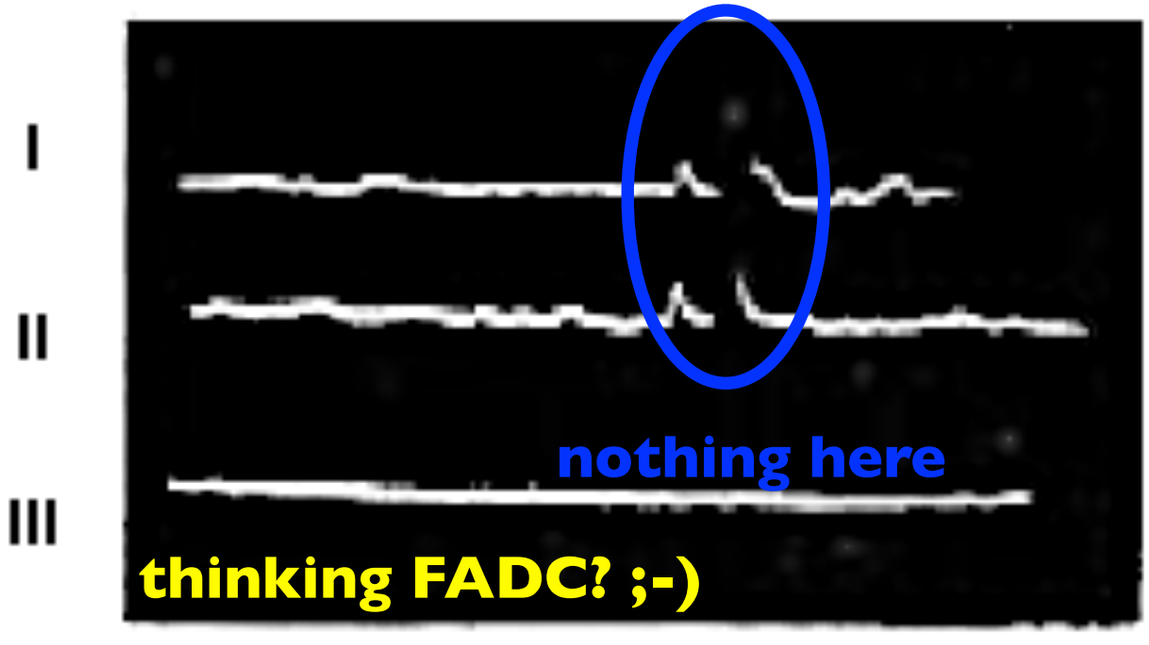
(→segmentation)



coincidence

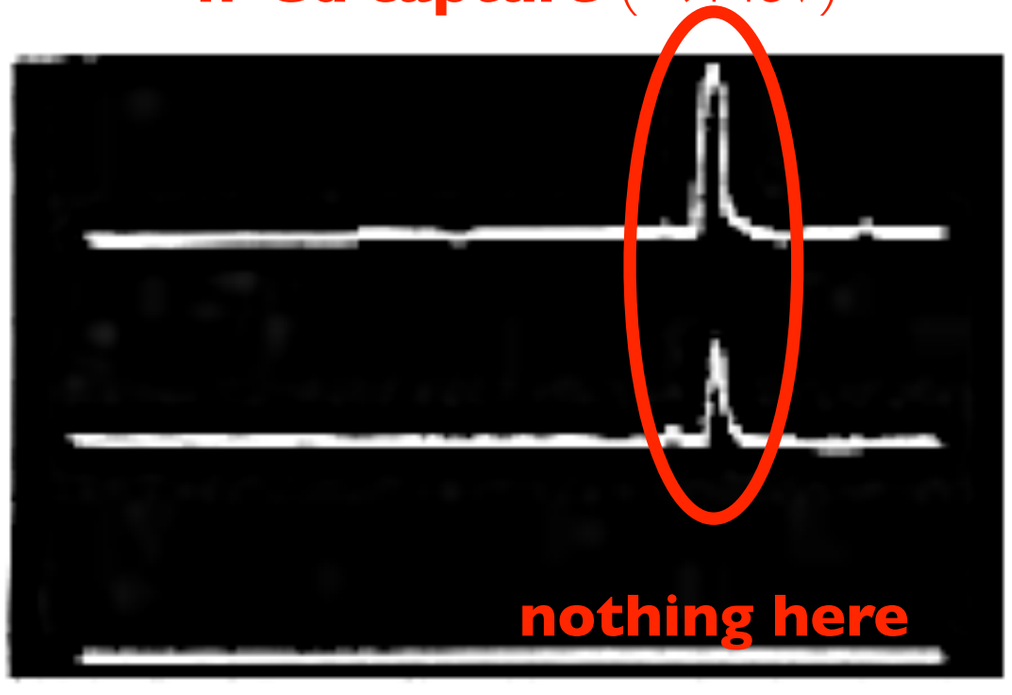
[scale **O(μs)**]

e+ annihilation (2x 0.511MeV)



(a) Positron scope

n-Cd capture (~9MeV)



Neutron scope

Reines&Cowan **detection strategy**…

PMT ⇔ transparent medium

interaction coincidence and/or tagging

overburden (μ-cosmic shielding)

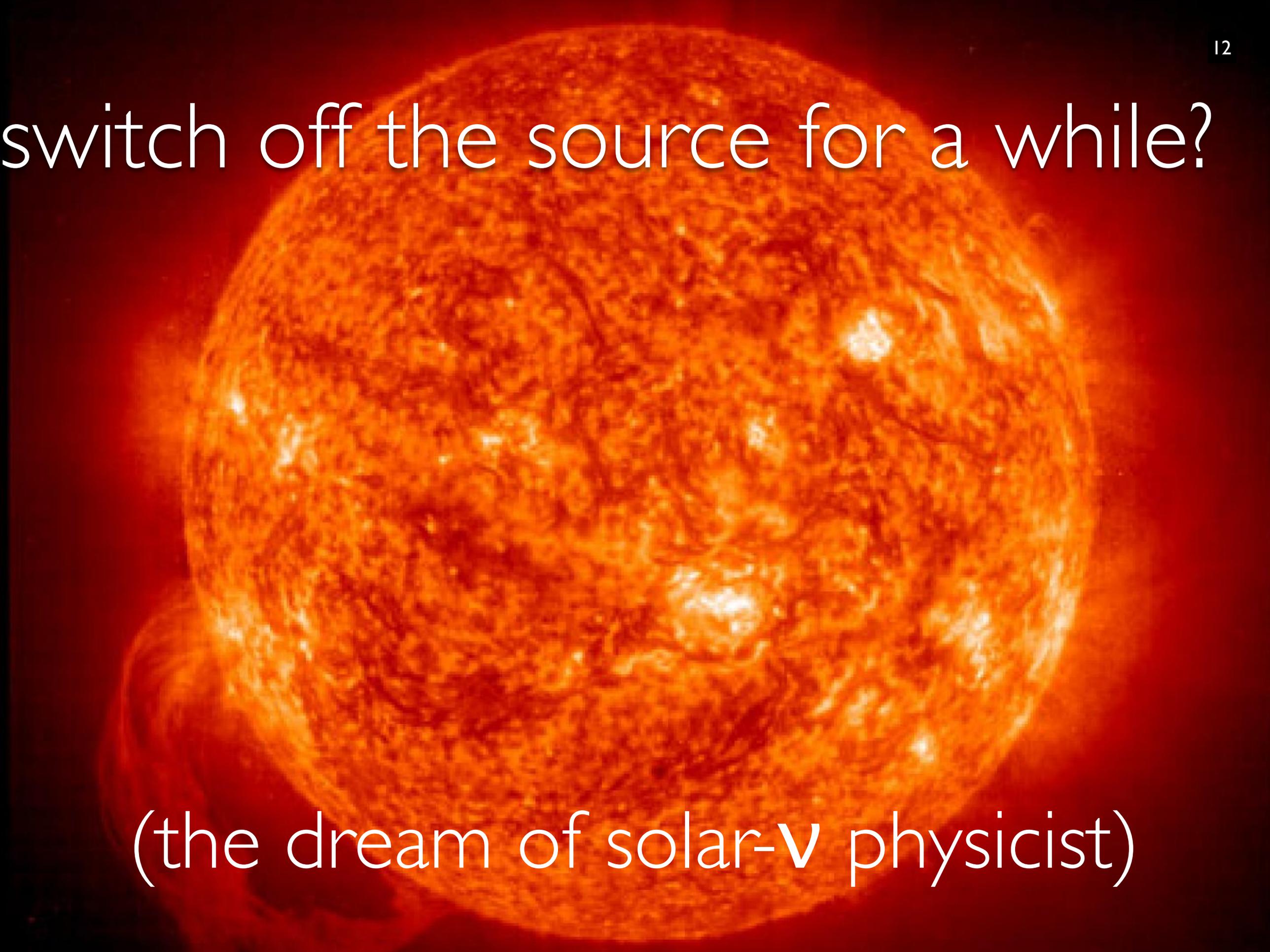
external shielding (radioactivity shielding)

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

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

~70years ago similar to today!

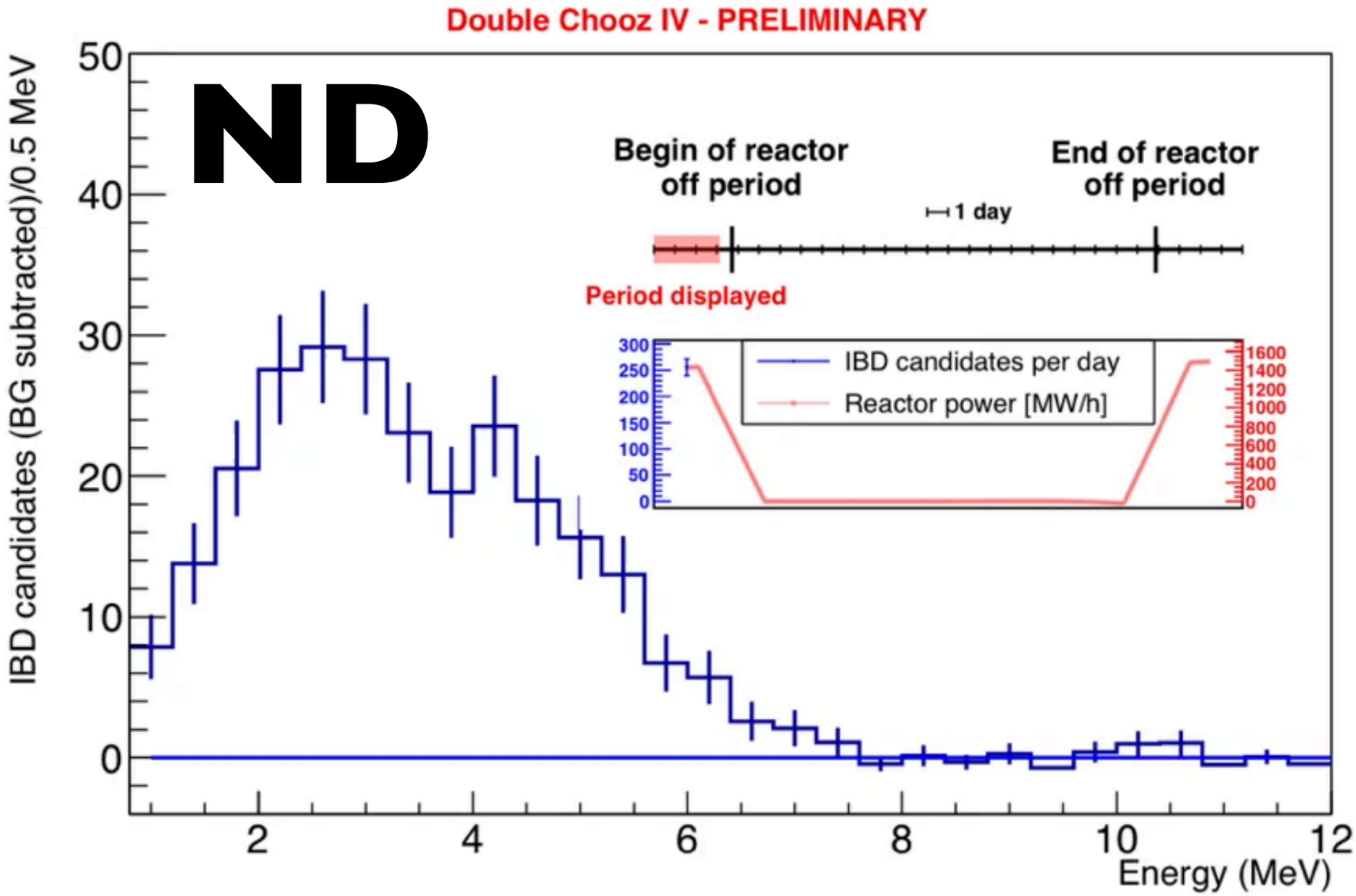
switch off the source for a while?



(the dream of solar-ν physicist)

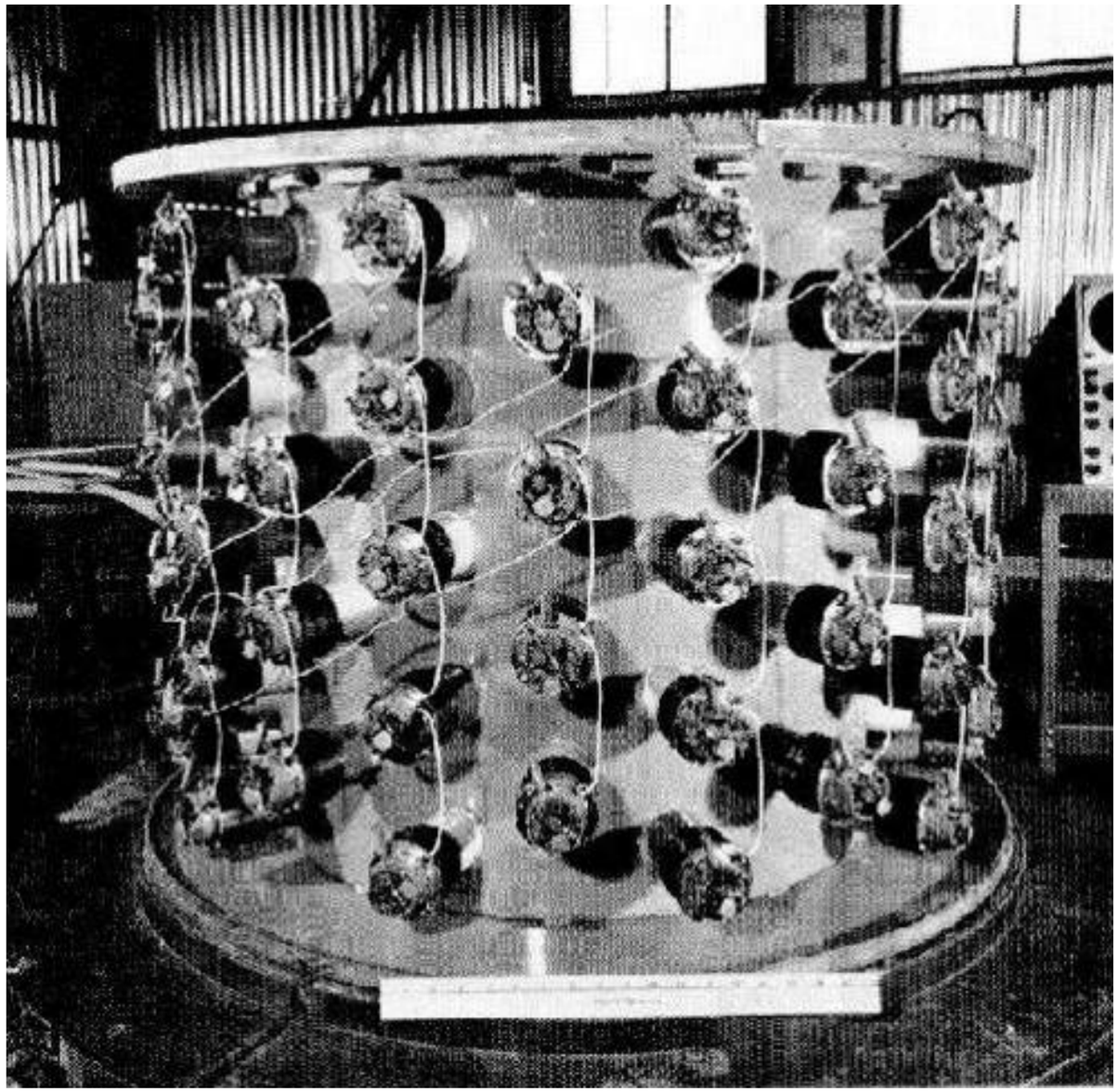
Double Chooz reactor-OFF: signal analysis…

rate(1 reactor) ≈ 3 IBDs/min



BG subtracted

Reines & Cowan detector (300kg)…



today's inspiration!

Hanford (1953)

today's version of similar technology…

CTF @ Gran Sasso
(Borexino R&D)

Far detector

2 identical detectors

Near detector

Double Chooz @ LNCA (Chooz)
(Buffer: ~100 ton)

Anatael Cabrera (CNRS-IN2P3 & APC)

(most) exquisite radio-purity…

Borexino (GS)

SNO

large (1k ton)…

~10,000 PMTs (8" diameter)

SNO @ Canada
(Nobel prize 2015)

NOTE: KamLAND similar size but balloon

SNO+

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

Super-Kamiokande (50kton)

~50m

Super-KamiokaNDE @ Japan
(Nobel prize 2015)

~14,000 PMTs (20" diameter)

neutrino detection ↔ art of transparency

[Reines&Cowan since 50's]

why LiquidO is needed…

liquid scintillator state of the art…

“perfection” since Reines&Cowan…

- exquisite **radio-purity**
- **scintillation PSD→** “some” **PID**

at the expense…

- **buffer volume** (PMT radioactivity)
- **topological event-wise PID?**

  [this talk]

PMT(~1ns) ⇔ **Transparency** ⟹ ~~**PID**~~**?**

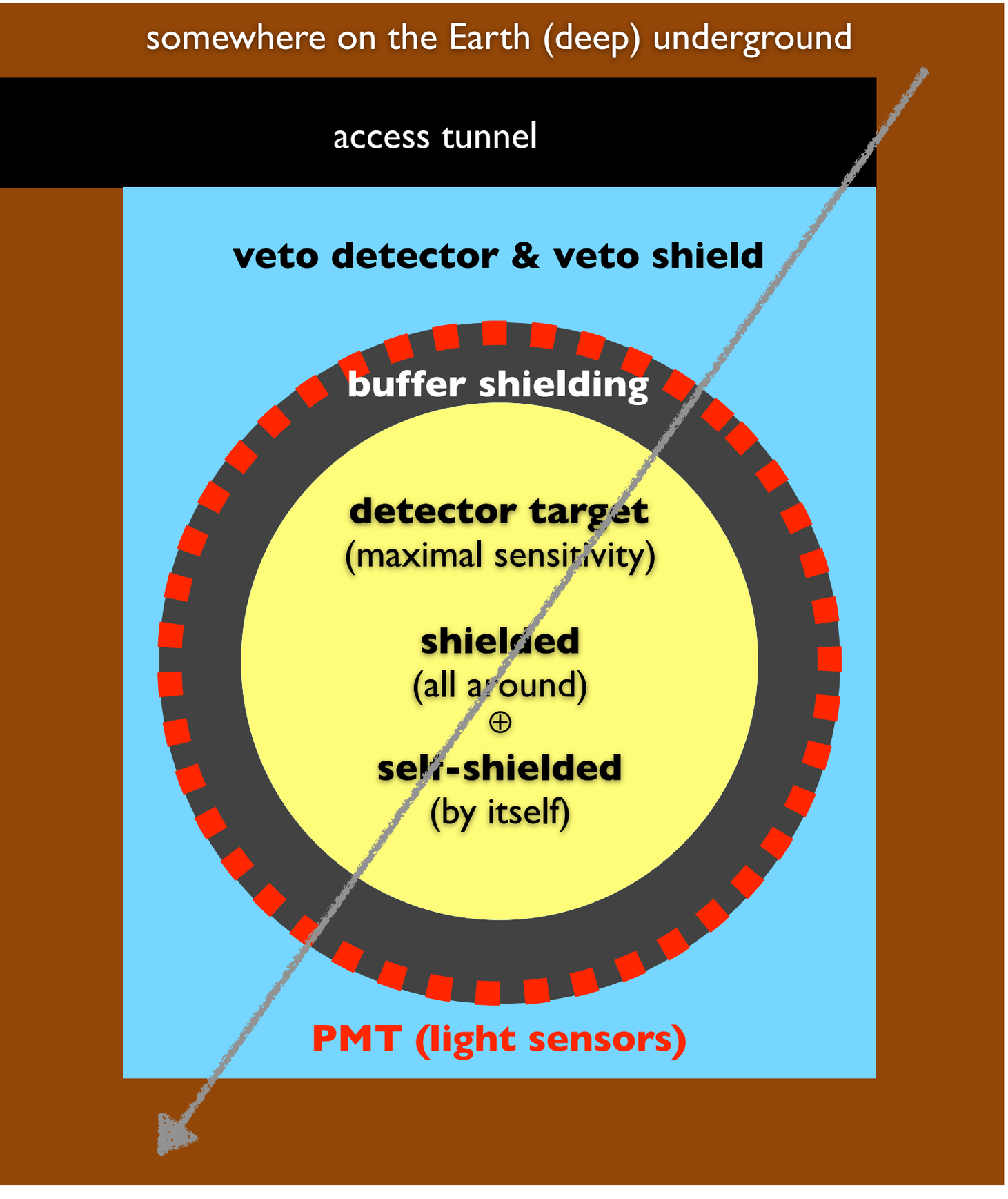
CTF @ Gran Sasso
(Borexino R&D)

an **Opaque** solution to PID…?

a **shielding** story…

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

today's detector strategy in a nut-shell…



shield breakdown…

- **rock** (many meters→kilometres)
  [cosmogenic]
- **veto detector (active)**
  [cosmogenic & radiogenic]
- **buffer shield (passive)**
  [radiogenic mainly]
- **neutrino detector (active)**
  [radiogenic mainly→**self-shielding**]

transparent limitation:

⟹ **little self-shielding→little PID!!**

[ex: **e+≈e-≈γ: no event-wise ID** so far]

tracking capability…

μ-track→cosmogenic tracing
[reduce and/or understand cosmogenic]

transparent limitation:

⟹ **no native track topology!!**

"μ" ≈ light "blast" ⊕ entry/exit points

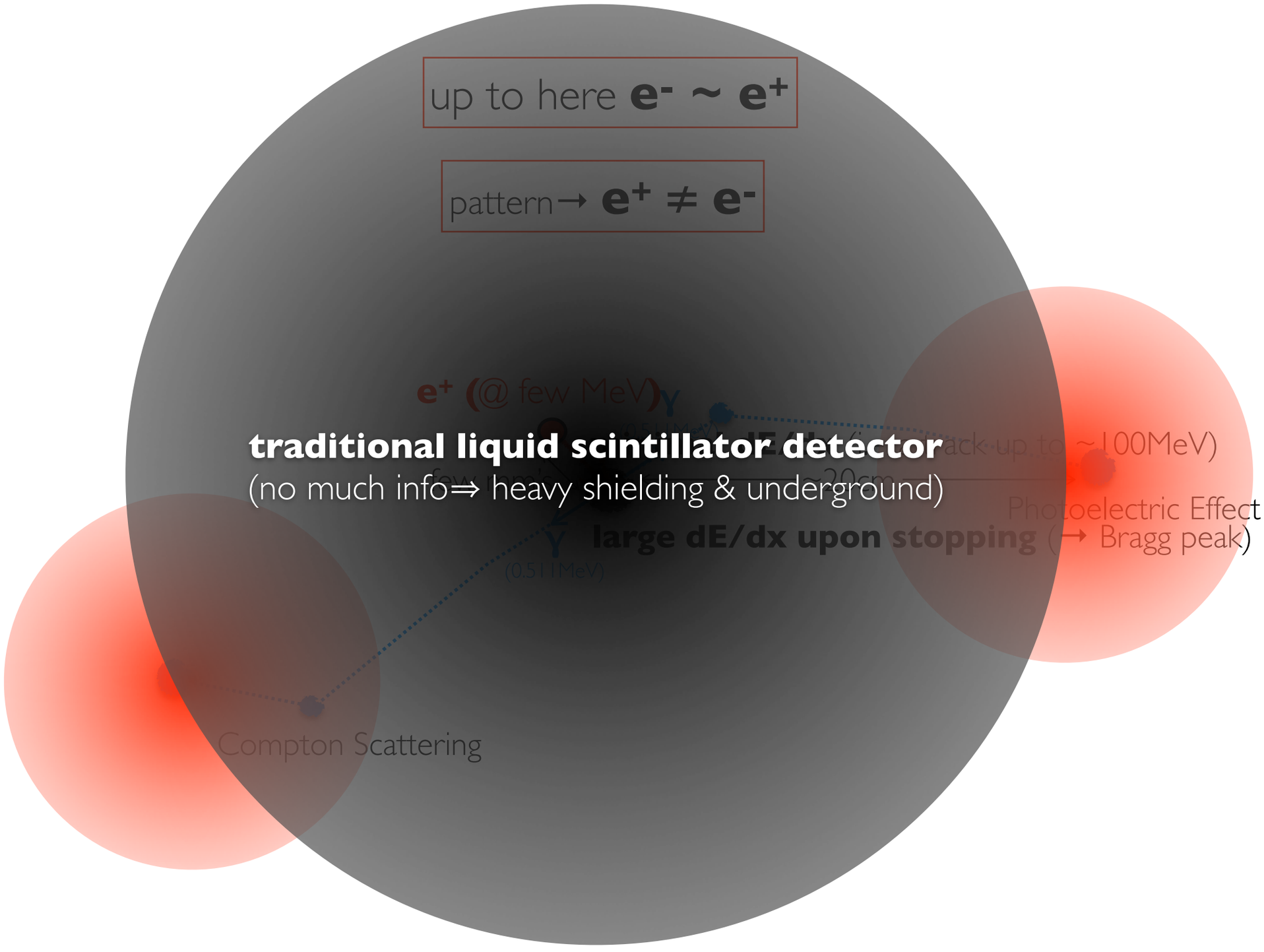
today's technology is much about **shielding**
(**active** and/or **passive**)

overburden: up to several kilometres
(if new facility: large construction cost)

(typically)
≥half excavated volume "wasted" (→shields)
(buffer very precious/expensive volume since fully instrumented)

why limited self-shielding?

e+ PID limitation (illustration)…



traditional liquid scintillator detector
(no much info⇒ heavy shielding & underground)

powerful event pattern washed out⇒ hardly any ID!

why "poor" event-wise PID?

no event-wise PID (beyond PSD)

$\gamma \approx e^- \approx e^+ \approx \alpha \approx$ p-recoil (fast-n)

PMT ↔ medium **transparency** → **little PID**

↓

σ(time)≳1ns ⇔ σ(space)≳20cm [unresolvable]

↓

σ(vertex)≈10cm ["center of mass vertex" regardless of particle]

liquid → (easy) loading BUT risks transparency!!

PMT (precious technology from 30's)…

but

- **slow** (TTS ≥ 1 ns/PE)
[SiPM: 0.1 ns/PE]

- **low-ish QE** (≤30%)
[SiPM: ≤60%]

- **PMT photocathode radioactive!!**
[**buffer** → ≥50% volume lost]

Reines & Cowan used their 50's state of the art: **scintillation⊕PMT's**

true still today?

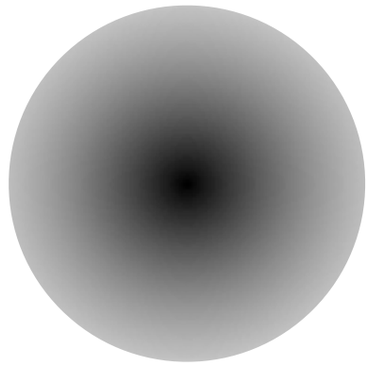
(beyond vintage)

let's dream **what we want**...

hypothesise a **O(1cm) resolution** detector…

scintillator/water very low-Z material with lots of "stable" H

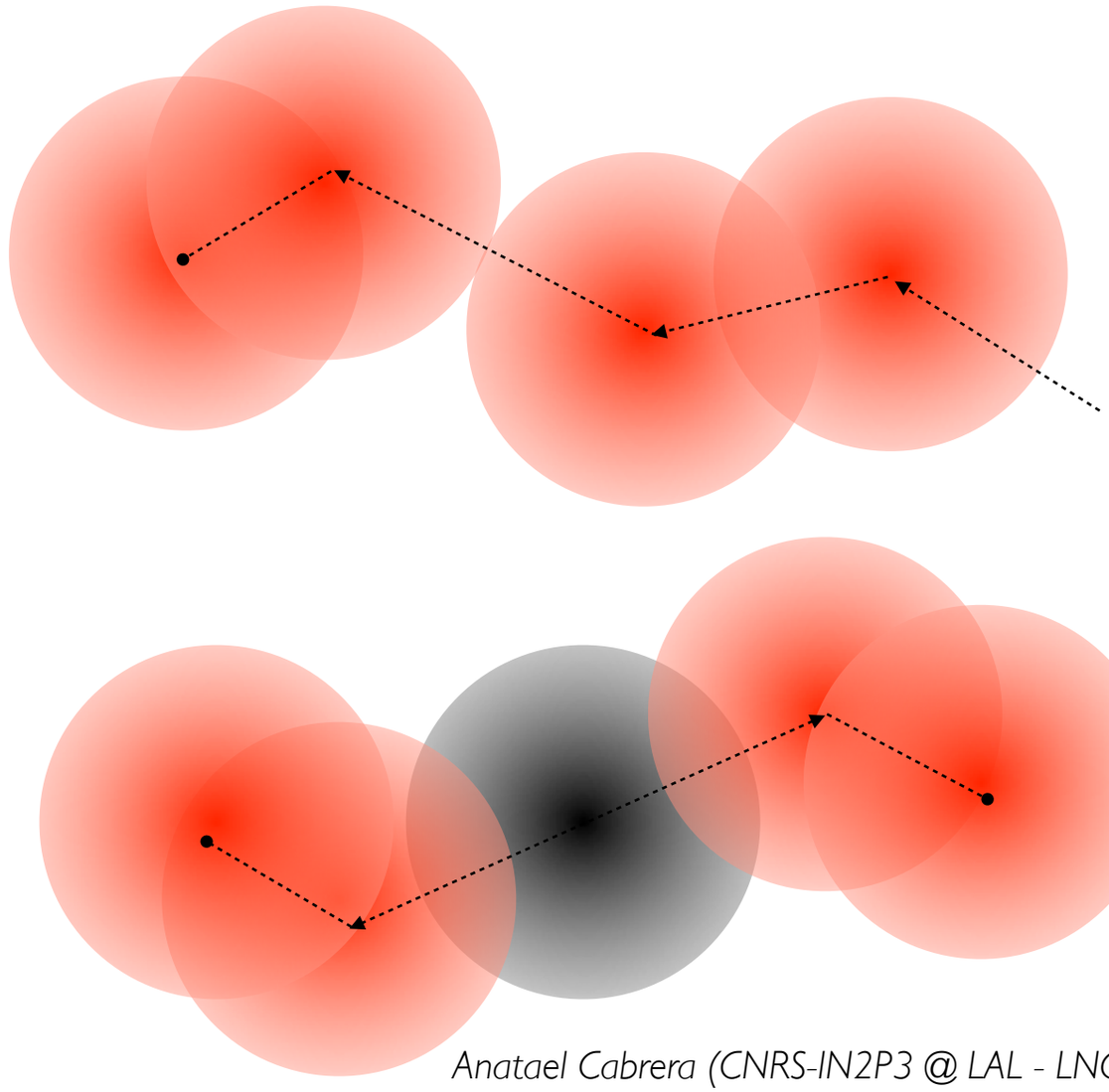
e^- ≈ α ≈ **p-recoil** (fast-n)



dE/dx→ Bragg peak
(e- starts as MIP)

e^-, **α** and **p** are **scintillation quenched→ PSD is possible!**

γ (gamma ray)



@ few MeV→ Compton scattering
(ended by photon-electric effect)

e^+ ≈ e^- + 2x γ(511keV)

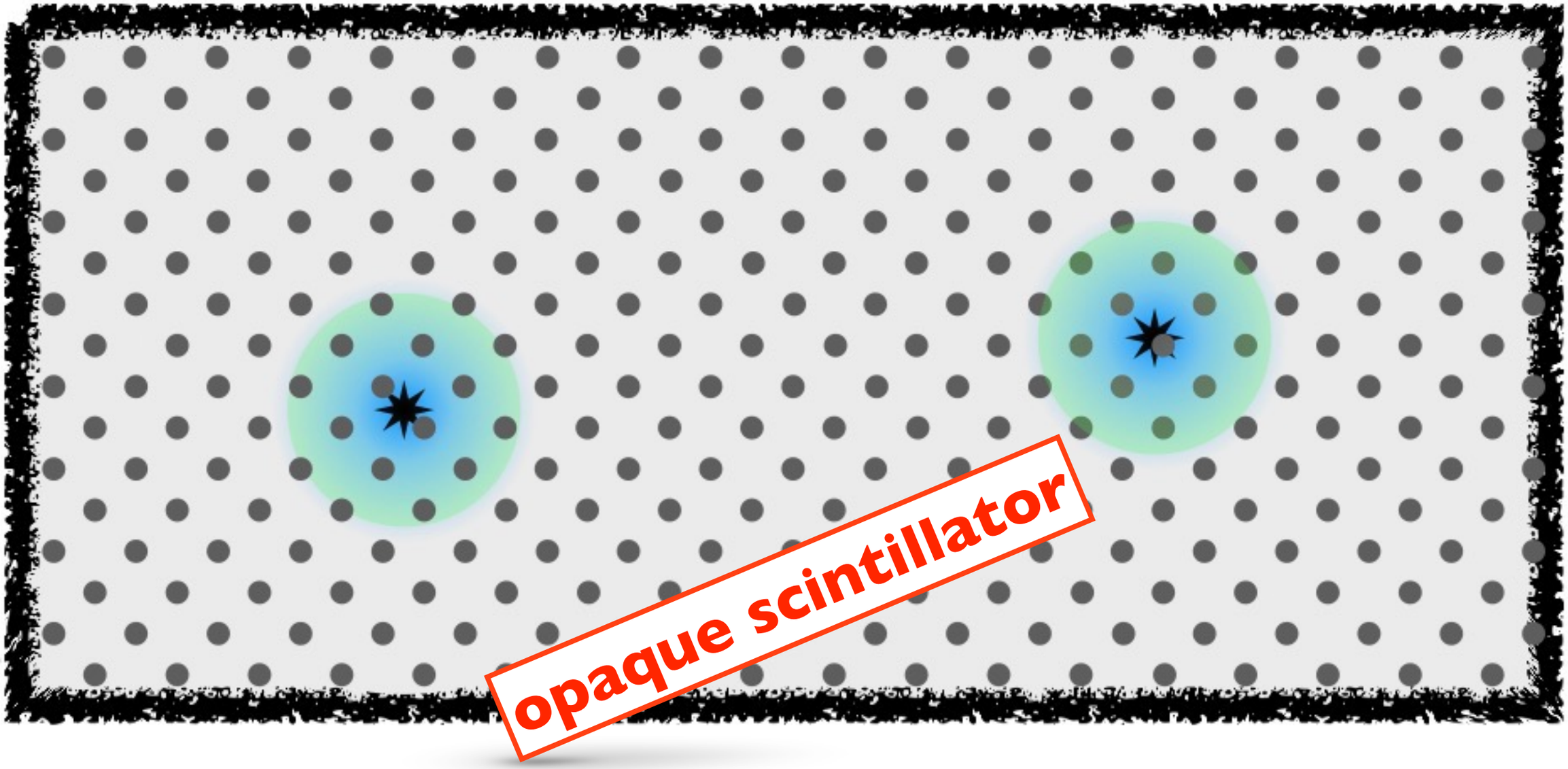
hybrid-like event

LiquidO…

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

LiquidO: the detection principle…

confine energy deposition locally → freeze information



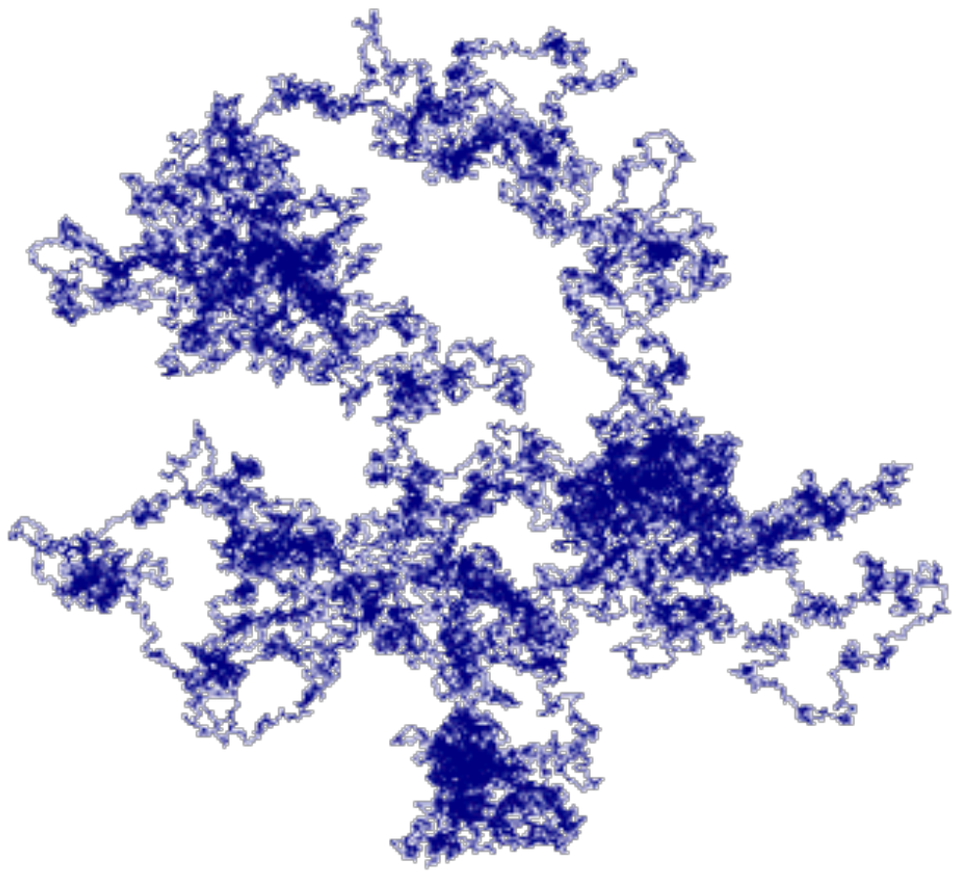
readout: wave-shifting-fibres⊕SiPM's

PMTs → become useless (unreachable light)

must confine light locally… **how?**

known light confinement strategies…

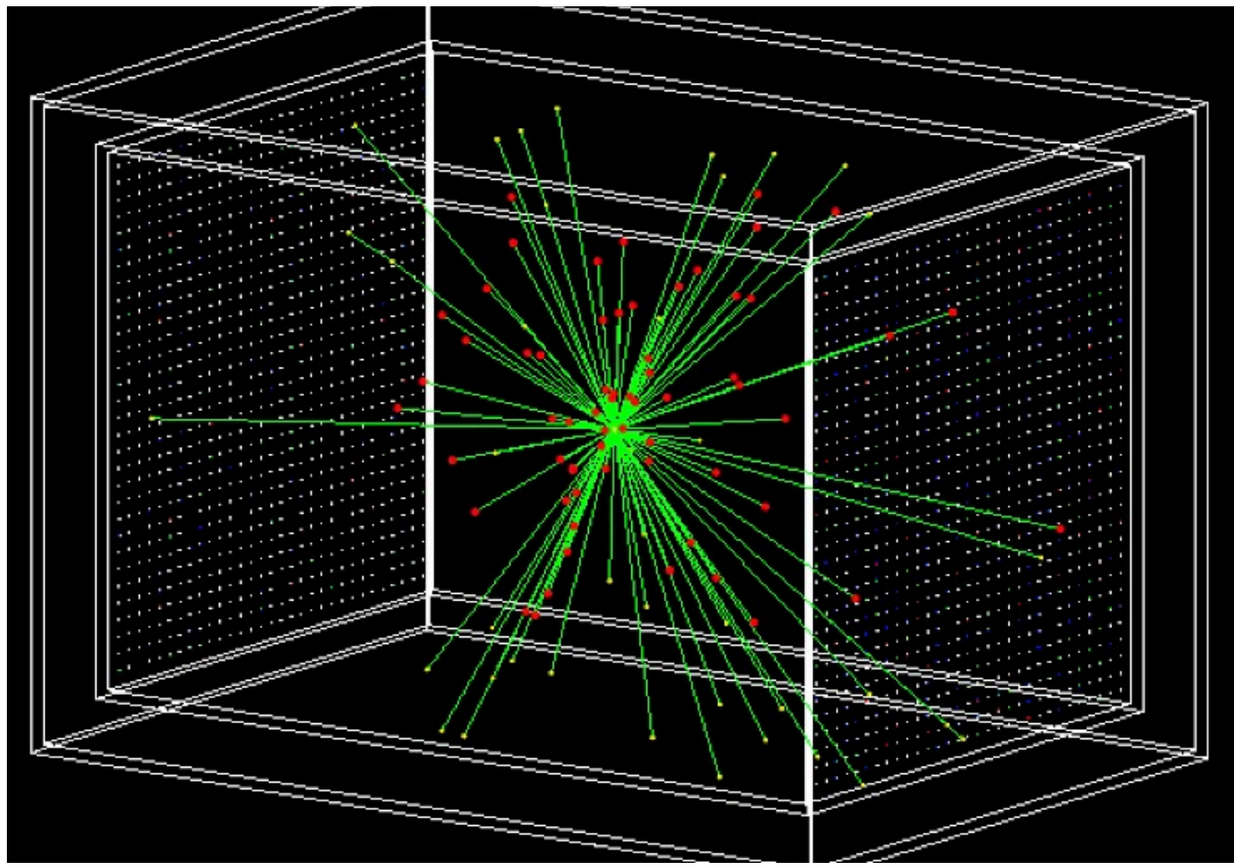
gravitational confinement
(ex. a black hole)



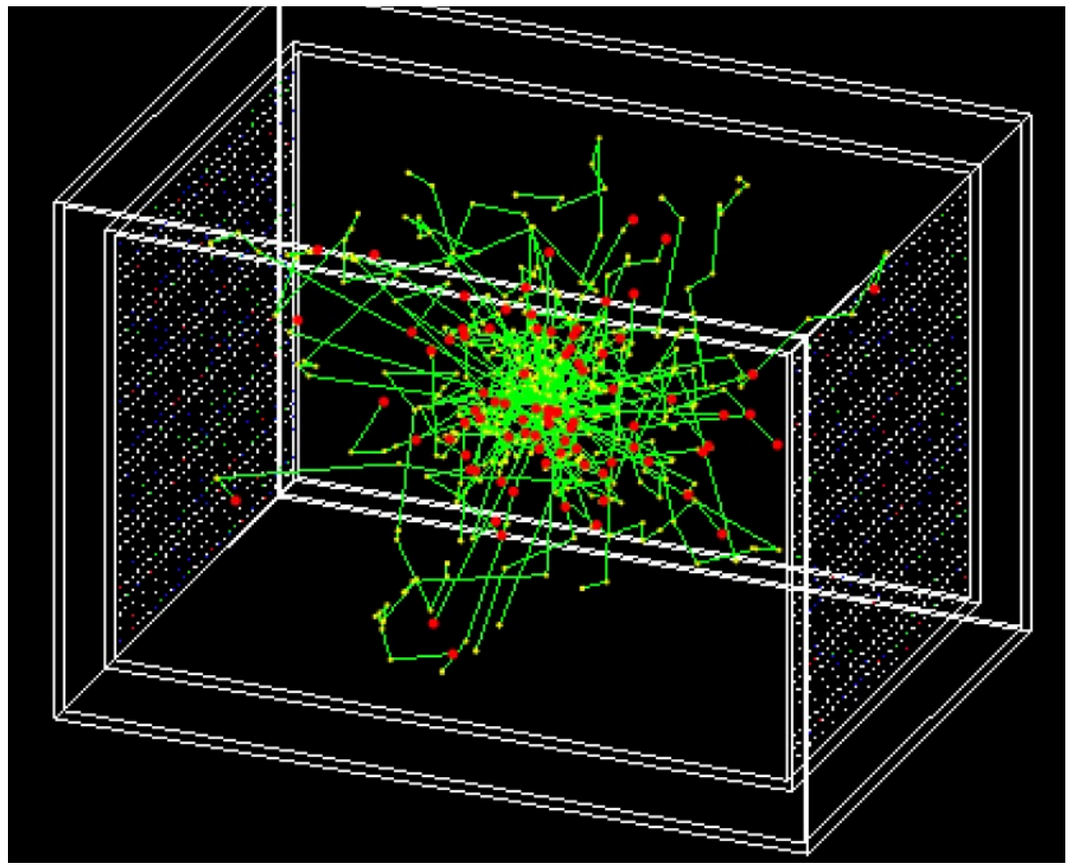
stochastic confinement
(ex. random walk)

light position restricted
(both cases)

LiquidO recipe: just "bread & butter" physics…



today's technology



LiquidO technology

light ball size: scattering⊕fibres

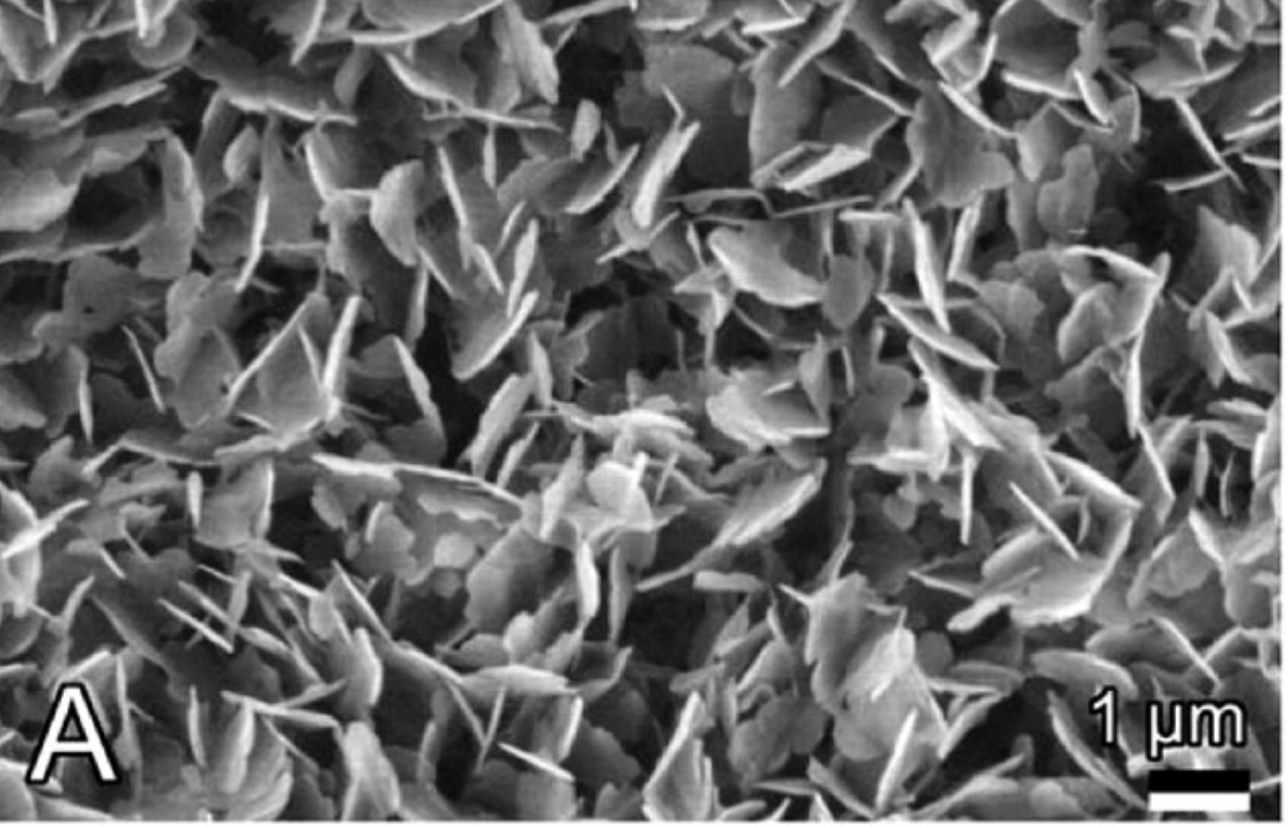
(sampling optimisation)

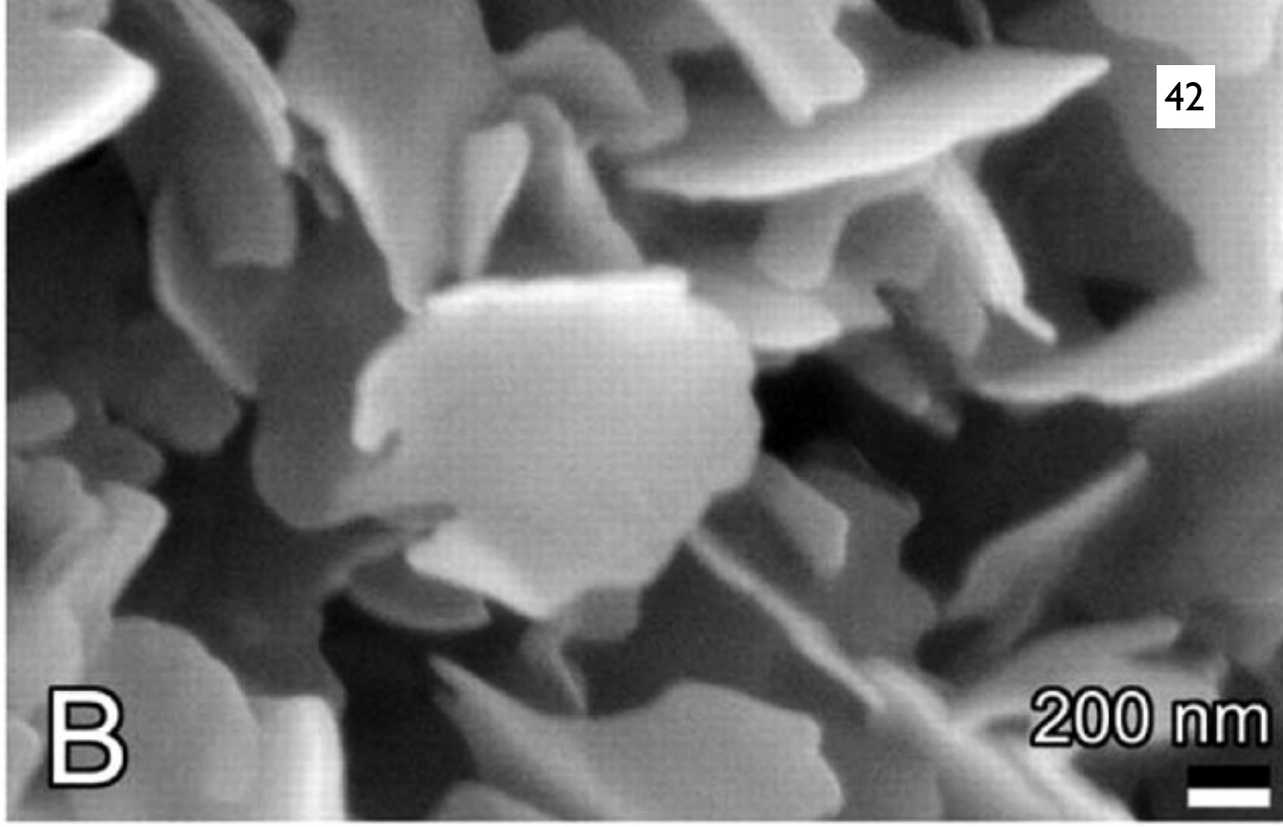
doe

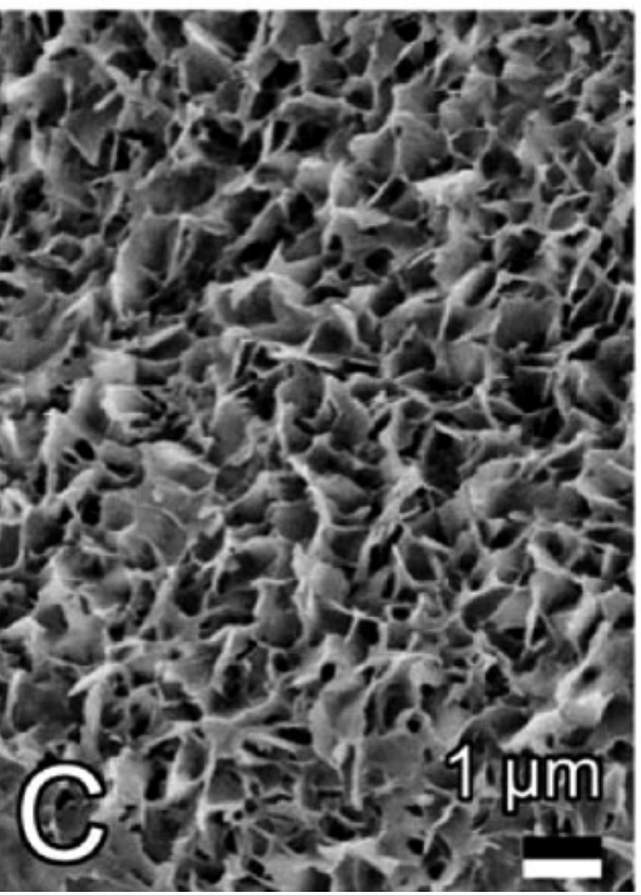
LiquidO = Liquid ⊕ Opaque

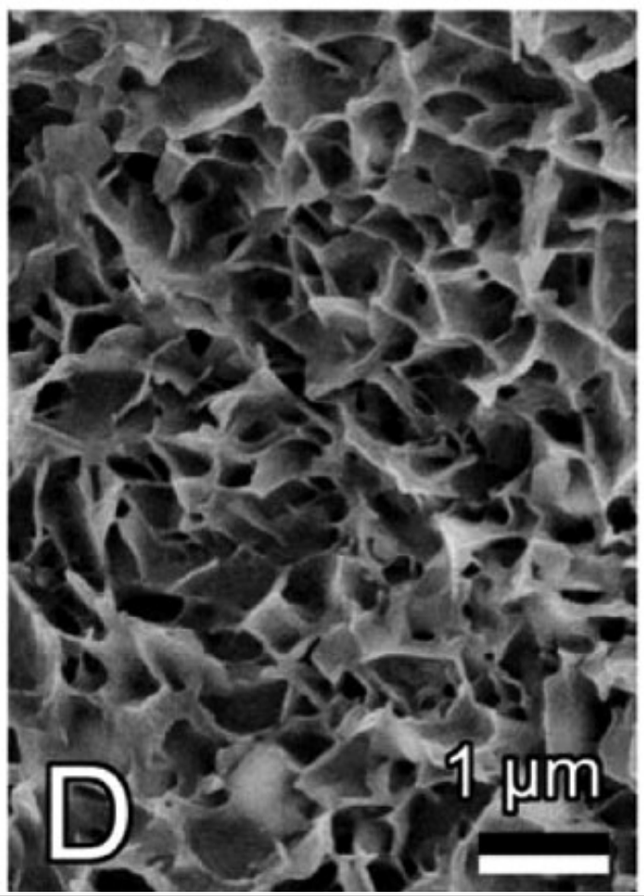
liquid~wax behaviour

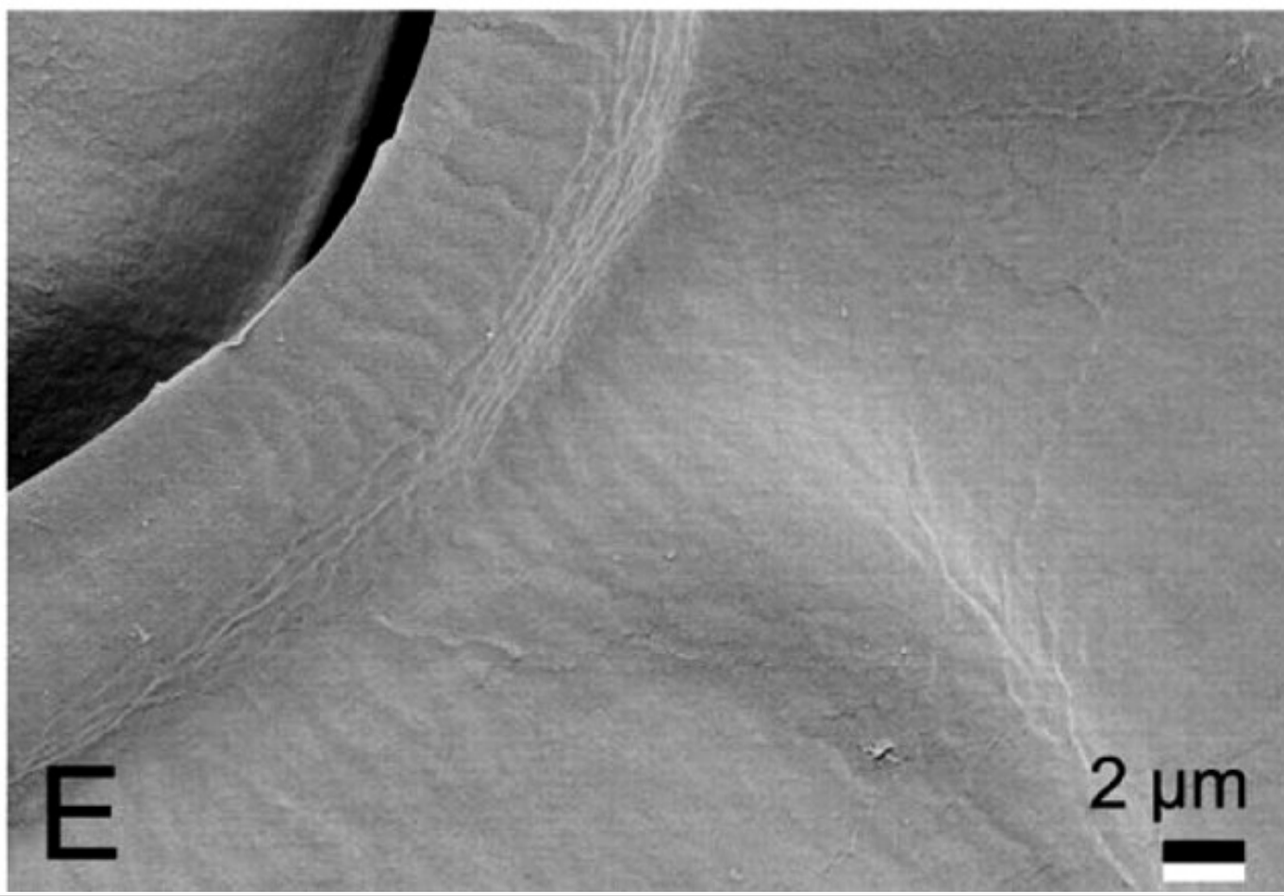
in reality, more like this…











wax random (amorphous) structure…

LiquidO implies (“theorem”)…

“milky” / “cloudy” / “waxy”

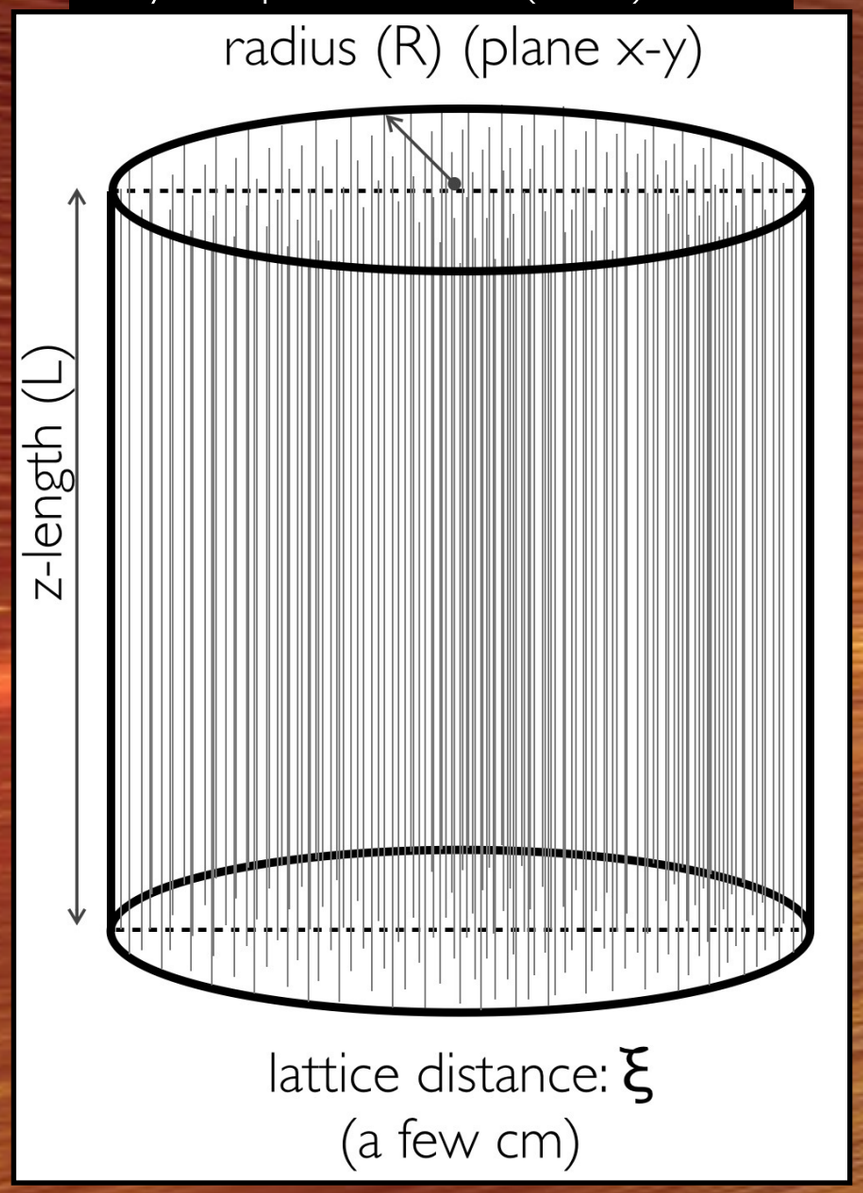
scintillator

(gas↔liquid↔solid)

a LiquidO detector…

simplest LiquidO design: 2D⊕time...

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



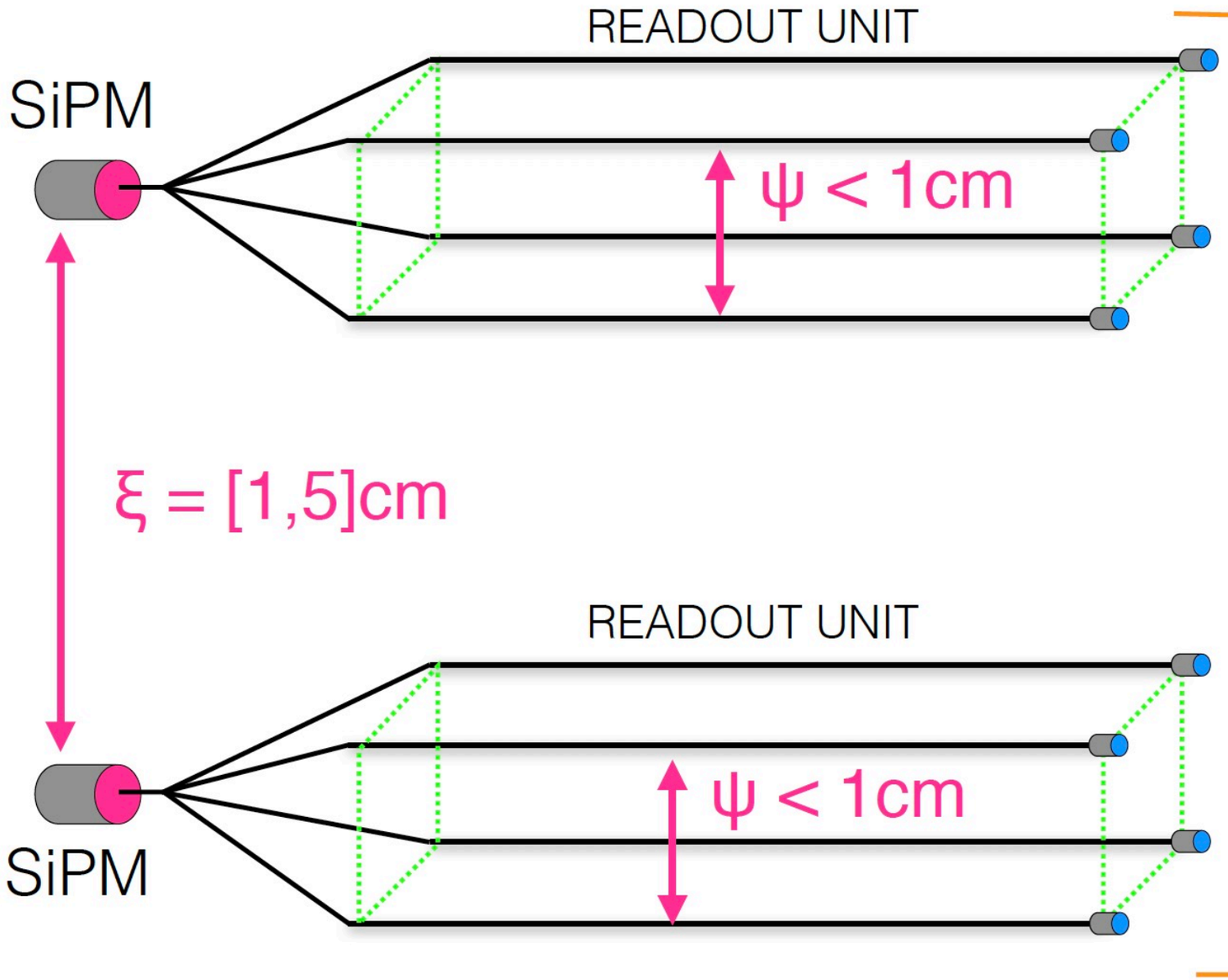
(x,y) info [lattice ξ]→ **image pixelation** (up to ~1 cm)
(z) info [along fibre]→ **time difference** (up to cm's)
(also z-pixelation possible→ envisaged for R&D)

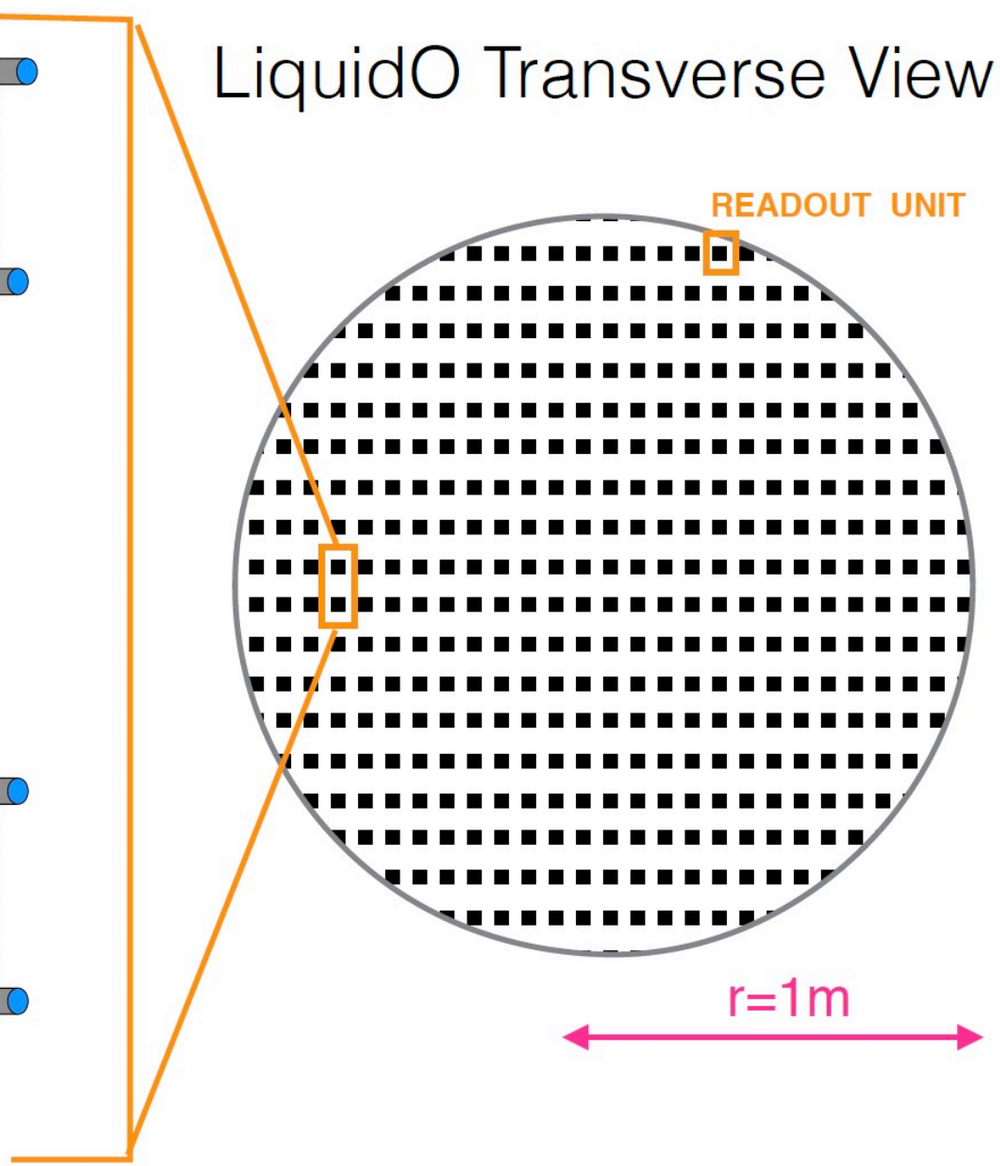
image: multi-wire chamber
(principle by G. Charpak @ CERN)

LiquidO ≈ "TPC-like" drifting light
[highest possible duty-cycle]

drifting (the fastest) photons instead of (slow) electrons
[traditional TPC]

detector articulation & readout…



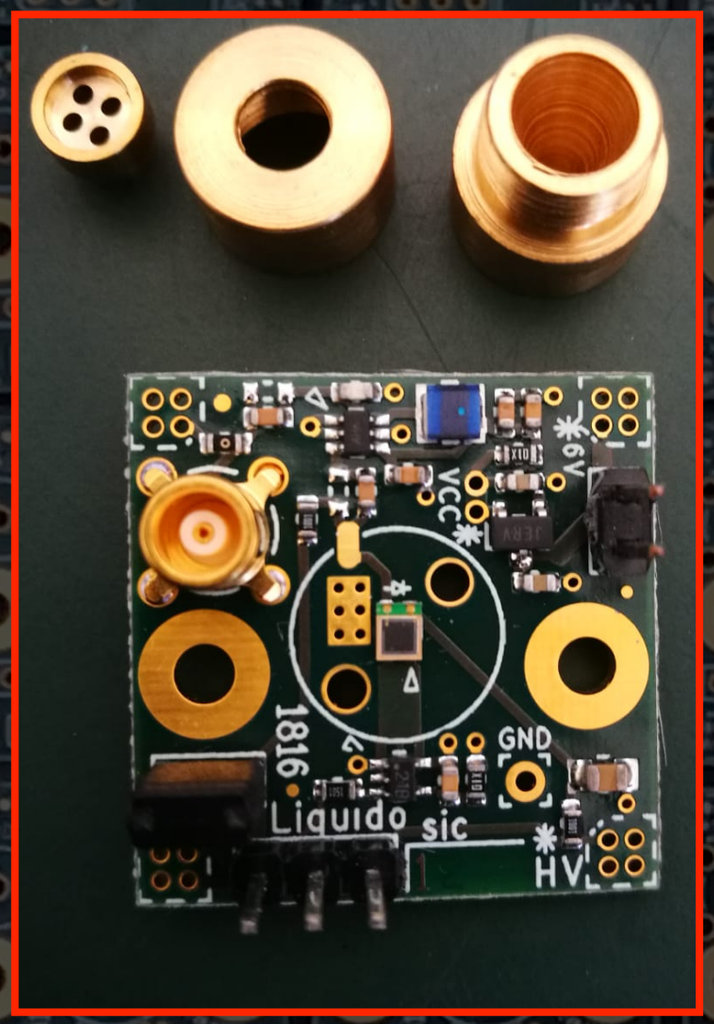


“infinitesimal” fibres→ MeV calorimetry

(reduce non-stochastic terms)

light readout via “collectors”…

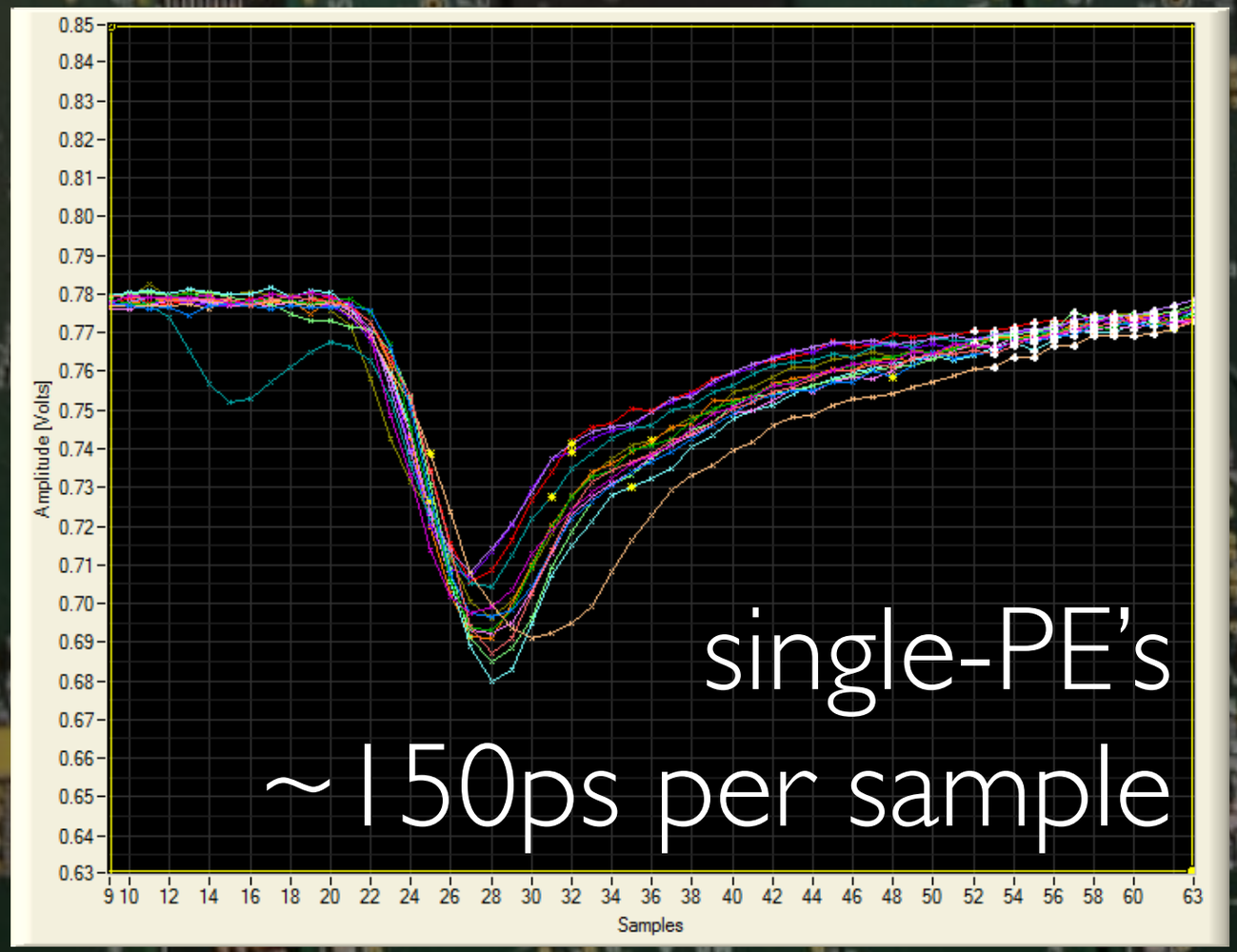
(fastest) SiPM electronics readout…



(expected) **time resolution: ≤100ps/PE**

(i.e. ≤3cm/PE @ speed of light)

our digitisation electronics…



single-PE's

~150ps per sample

(expected) **time resolution: ≤100ps/PE**

(i.e. ≤3cm/PE @ speed of light)

IEEE NSS (2014): The SAMPIC Waveform and Time to Digital Converter

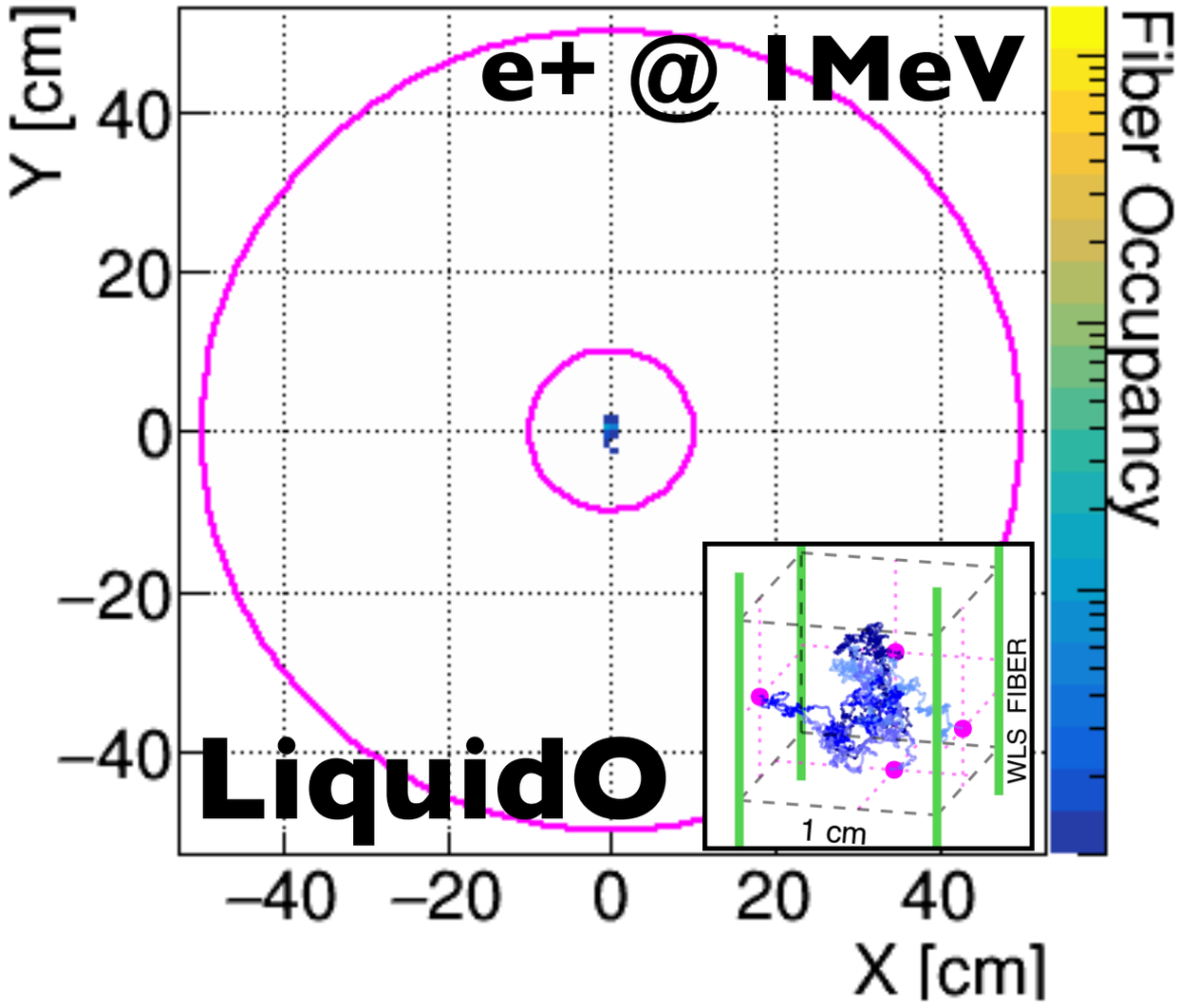
NIM paper (2016): Measurements of timing resolution of ultra-fast silicon detectors with the SAMPIC Waveform Digitizer

(instrumentation-wise)

LiquidO ≈ “light” TPC ⊕ 4π-ToF

stunning event pattern...

LiquidO vs "traditional LS" (example: e+)



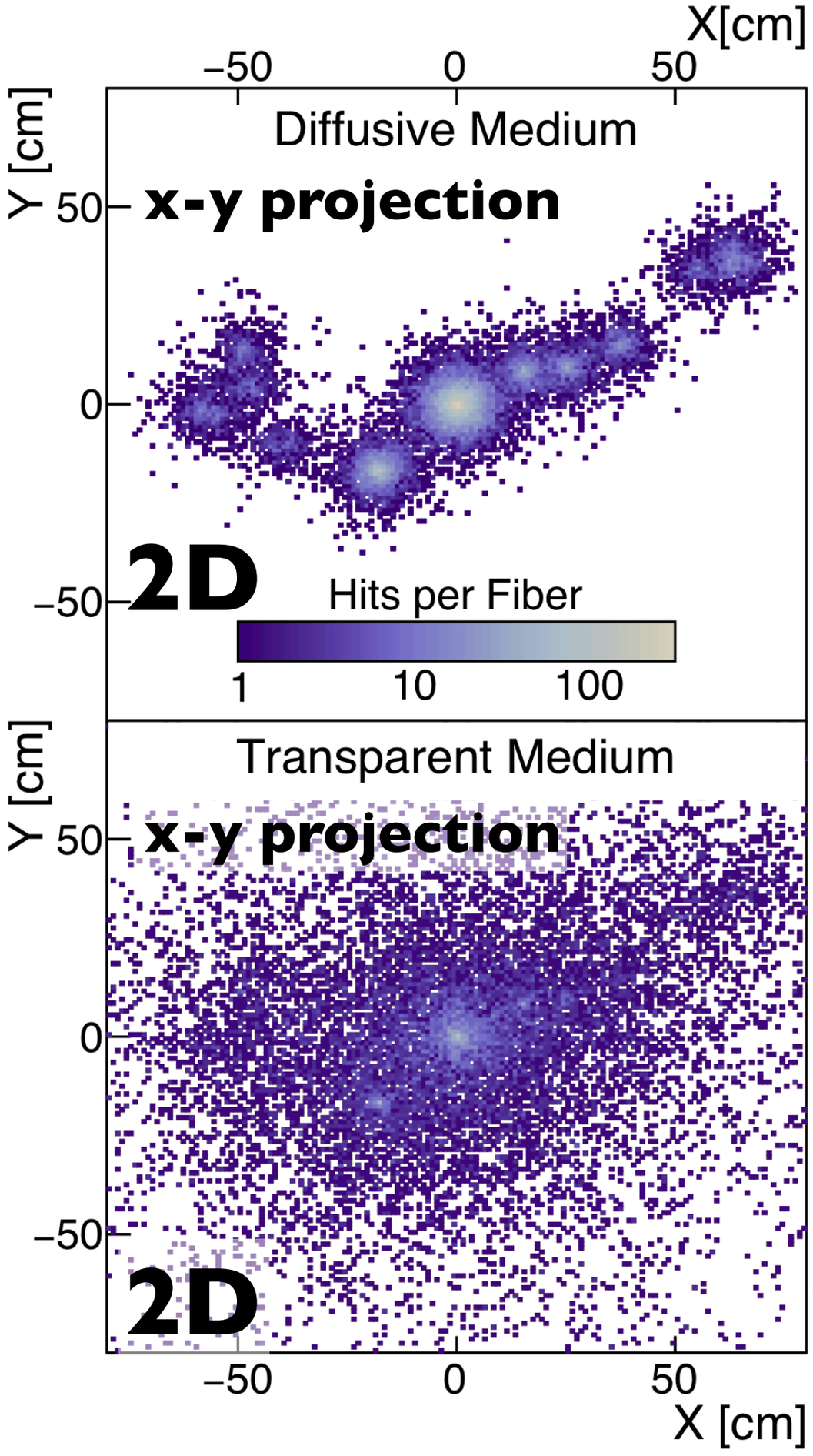
why opacity? [up to now the death of LS]

- **stochastic light confinement** (few cm's)→ powerful energy pattern (**PID**)
- **slow down speed of light** (~1/10x)→ **energy flow** & **causality** [**next**]
- **maximal light collection** (≥90%)→ light level up to **≤400PE/MeV?** [**R&D**]

MC says LiquidO works!!

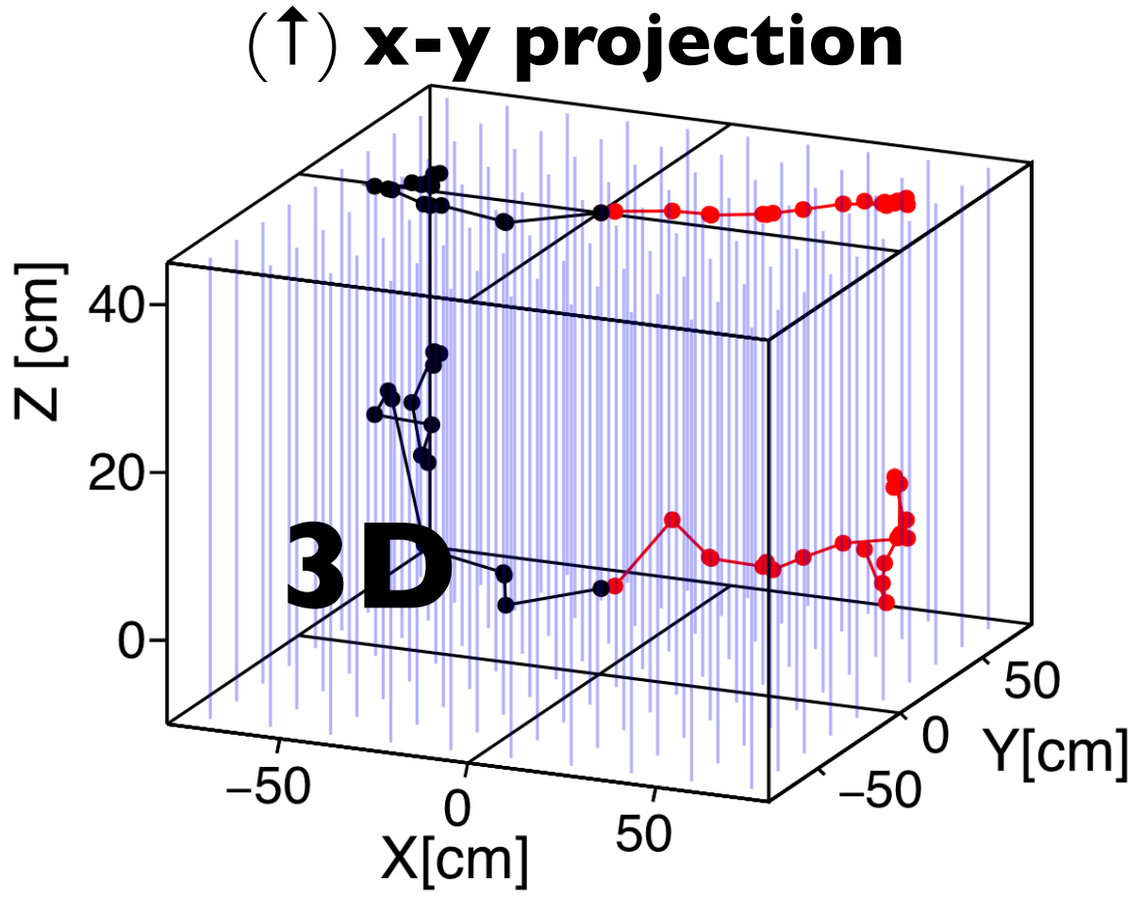
[bread-&-butter physics]

LiquidO's multi-axes…



LiquidO

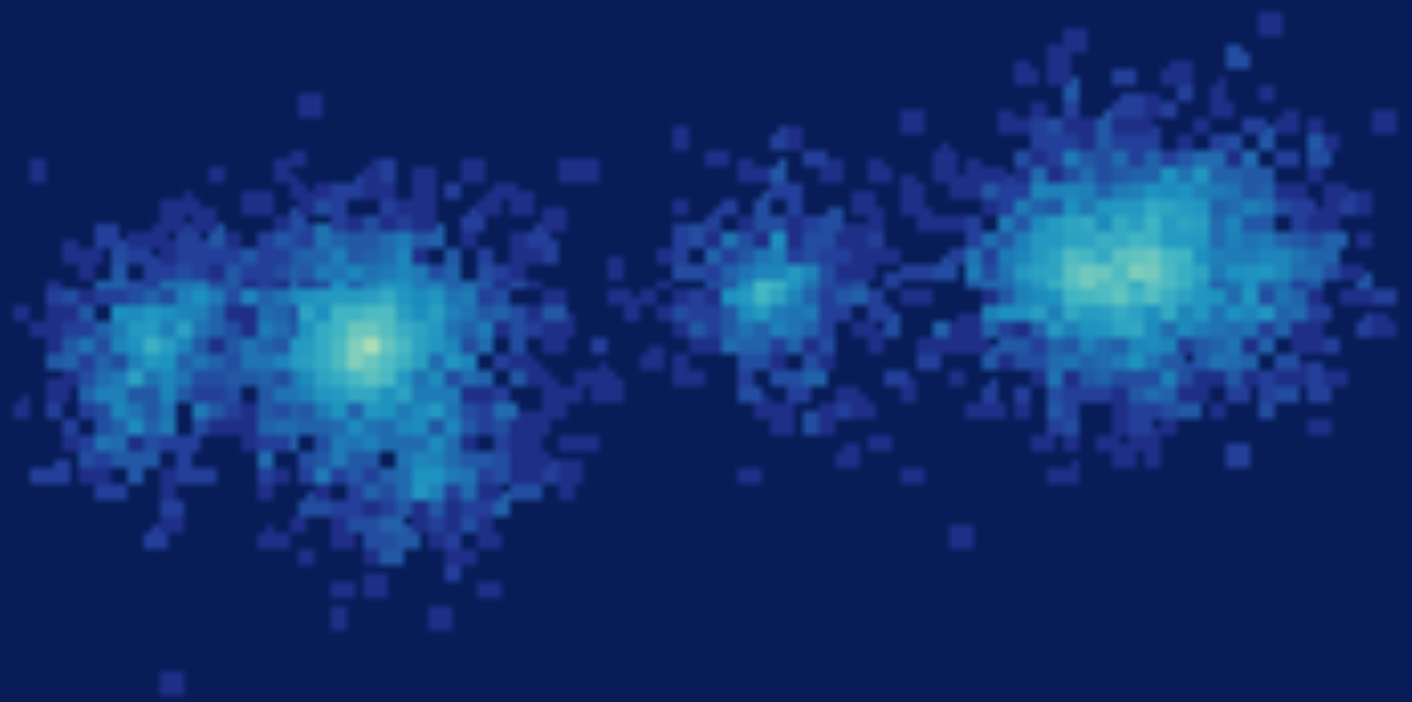
up to 3 axes (unlike drift-TPC) → **needed?**



z projection (not yet fully exploited)

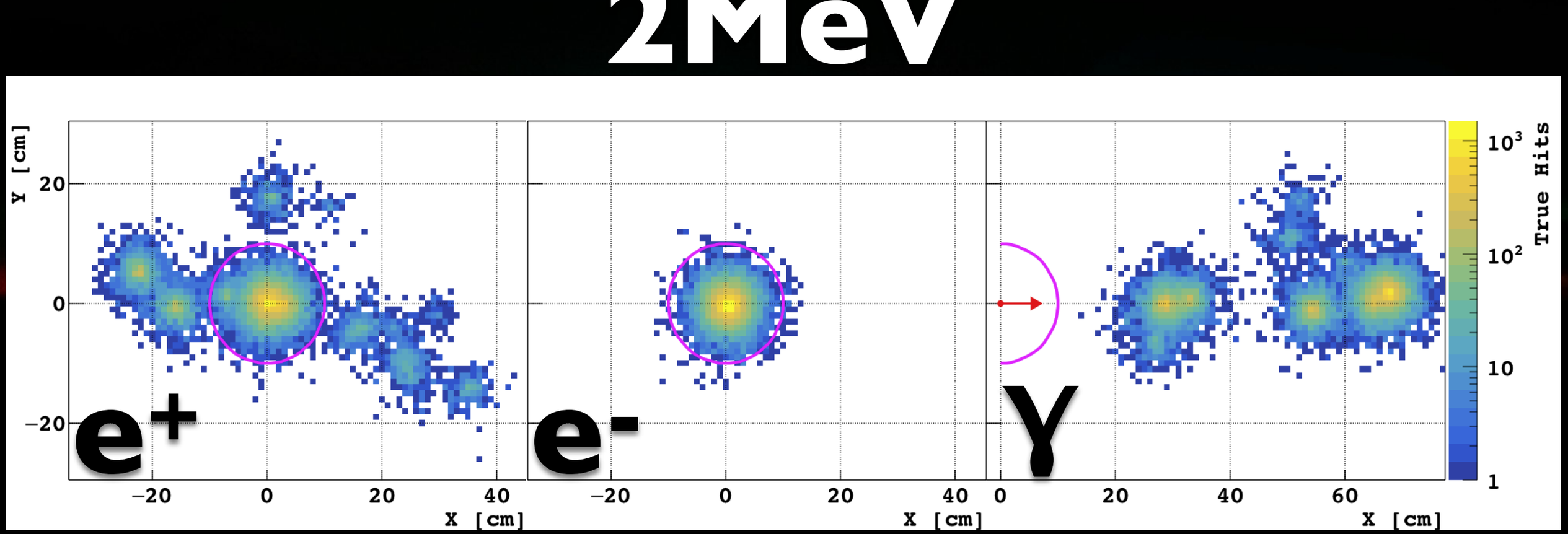
Transparent Scintillator⊕Fibres

a few 100KeV e+ now looks like this…



powerful PID expected…

2MeV

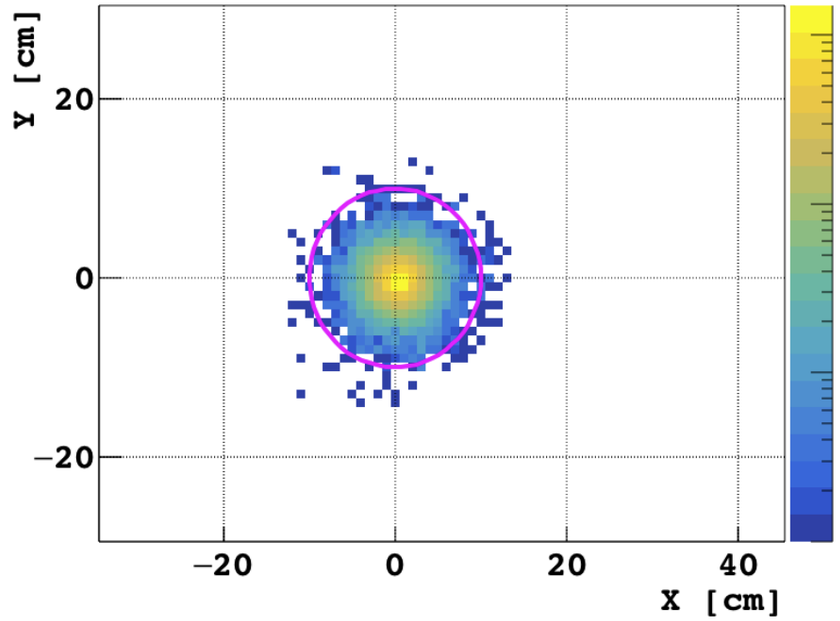


no need for segmentation→problematic! (cost/complex)

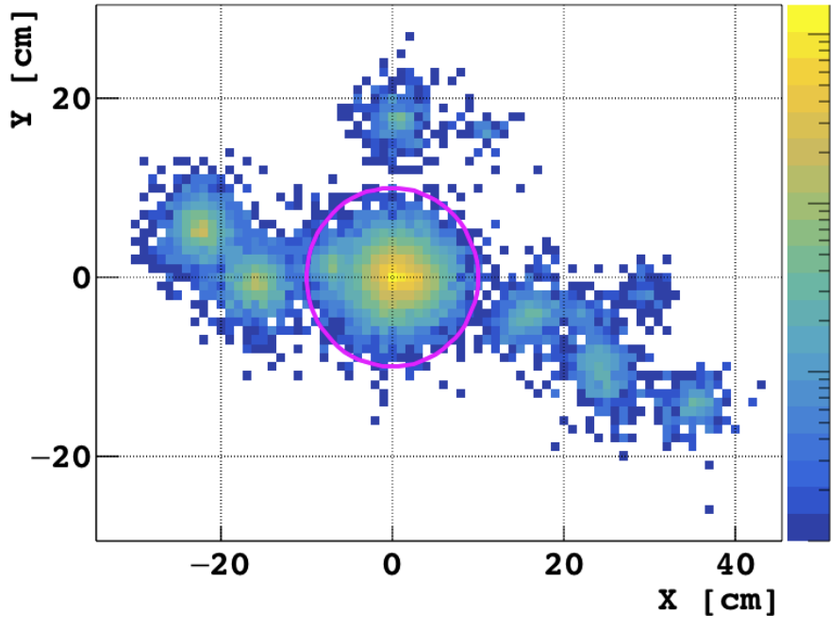
(**opacity→self-segmented**)

CC **ν** interaction observables…

$\nu_e \rightarrow e^-$



$\bar{\nu}_e \rightarrow e^+$



a breakthrough capability ≤100MeV

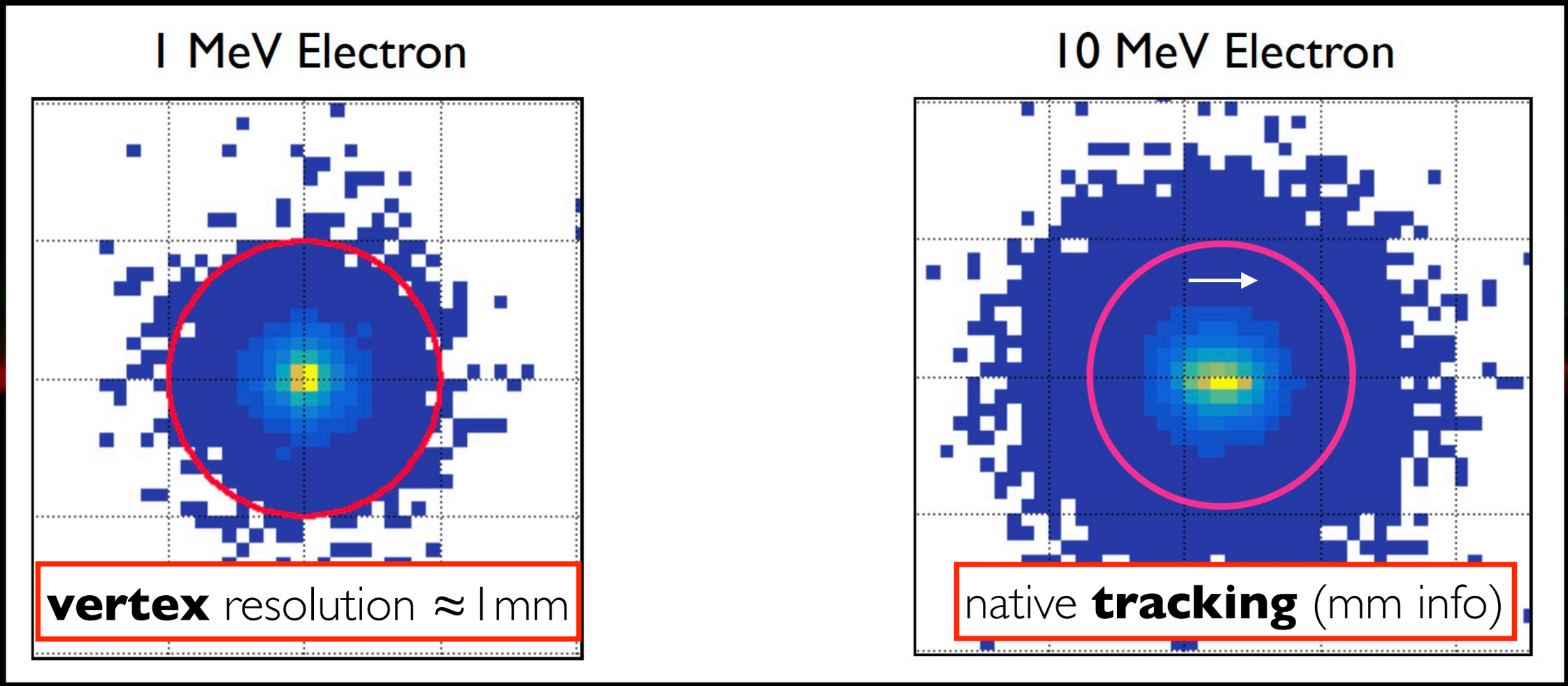
(→only possible with ν_μ's so far)

event topology…

LiquidO resolution
(translucide medium)

⊕

dE/dx per particle
(≤100MeV)

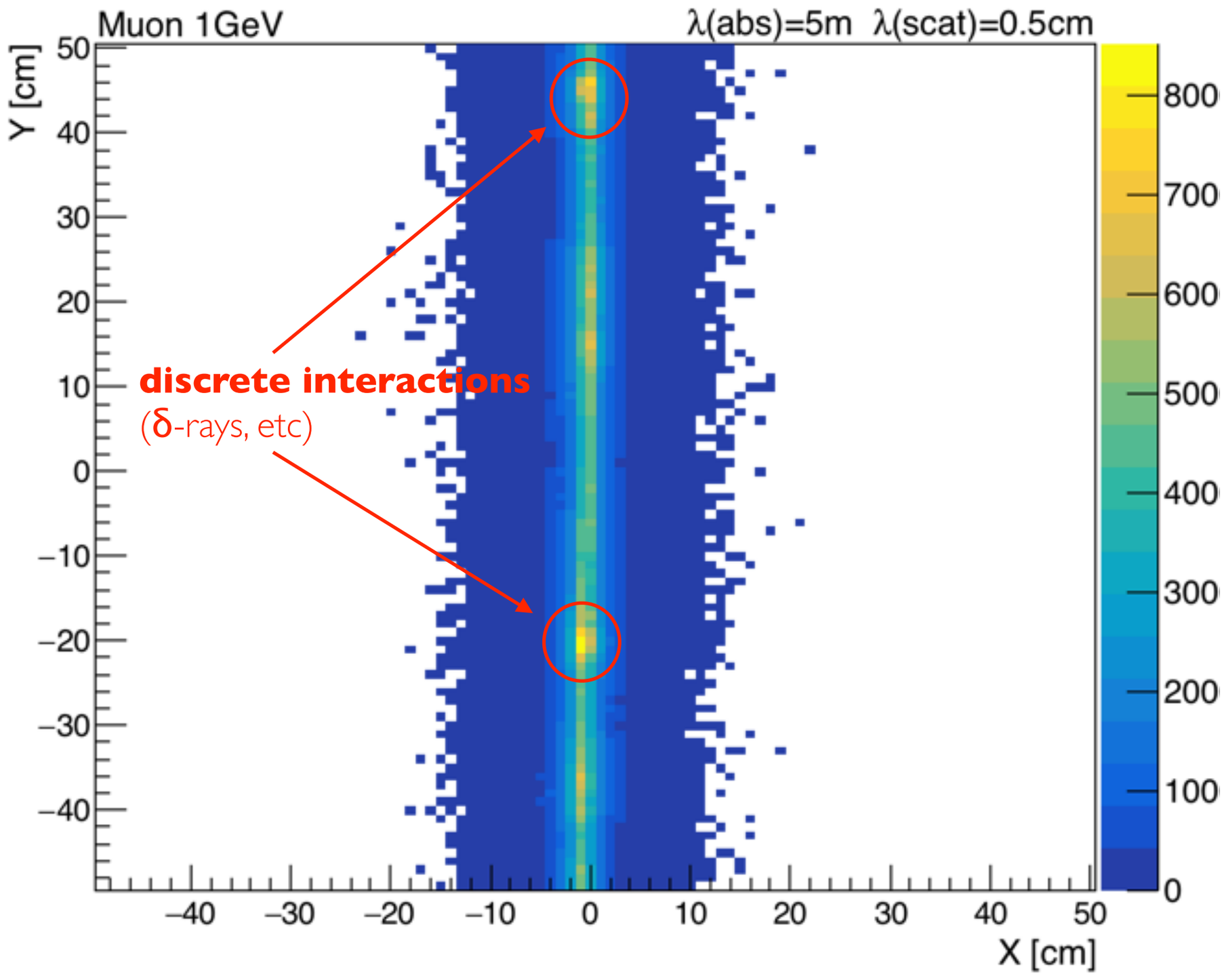


effective point
(Bragg peak dominated)

effective track
(MIP dominated)

NOTE: traditional liquid scintillator: poor vertex resolution (~10cm @ 1MeV) & no tracking!!

a through-going **μ**…

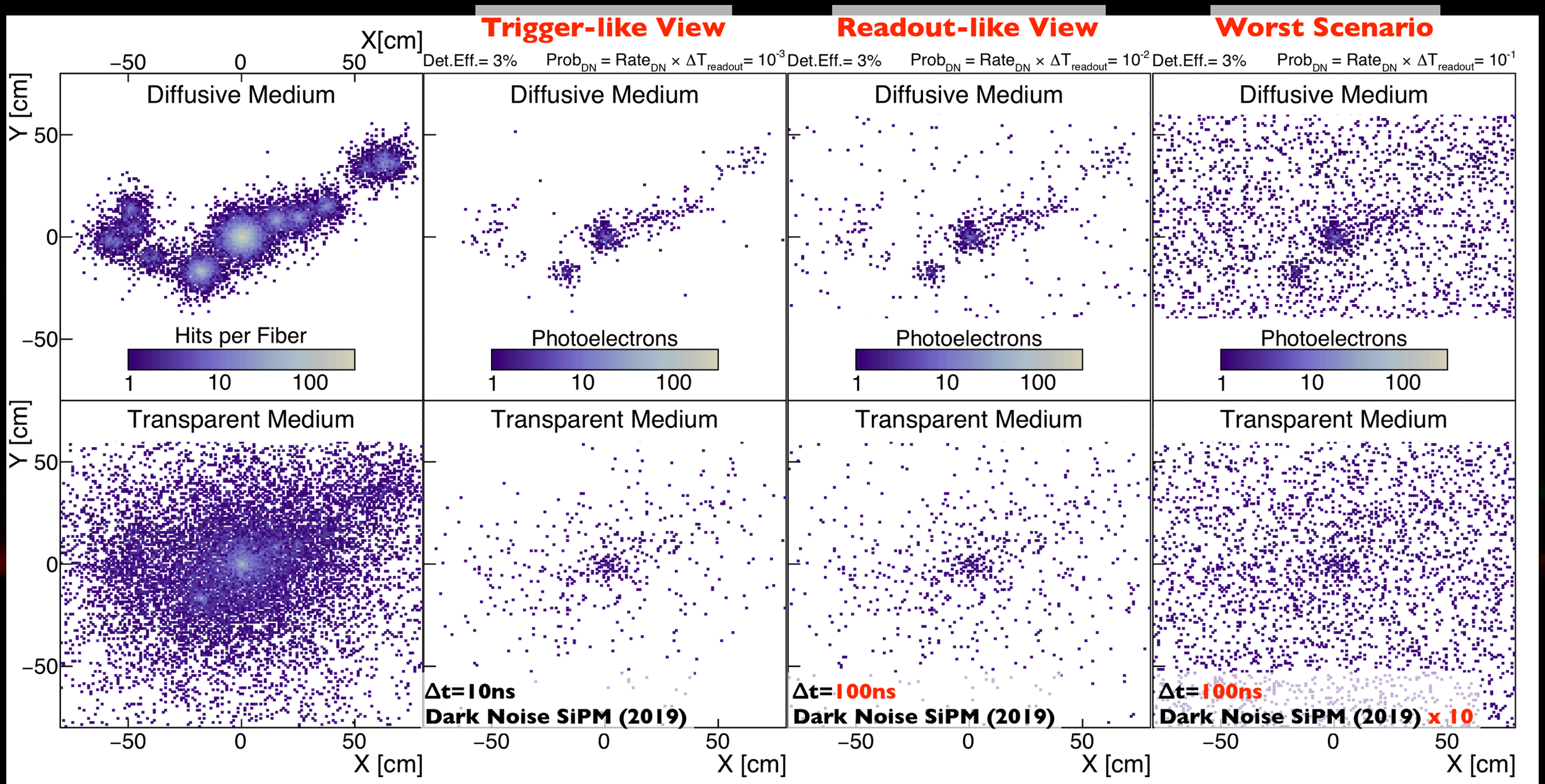


track ≈ "infinite" sequence of point (MIP: average @ ~2MeV/cm)

(no **μ** saturation→ light confined locally→ no deadtime upon each **μ**!!)

how about after readout...

LiquidO ⊕ readout (today's technology) effect....



NOTE: SiPM cooling under consideration→better than here shown

detection photons→reduce information

[technology dependent: conservative assumption]

readout dark-noise (LiquidO light confinement critical)

Opaque scintillator→ **new technology!**

(so far only transparent considered)

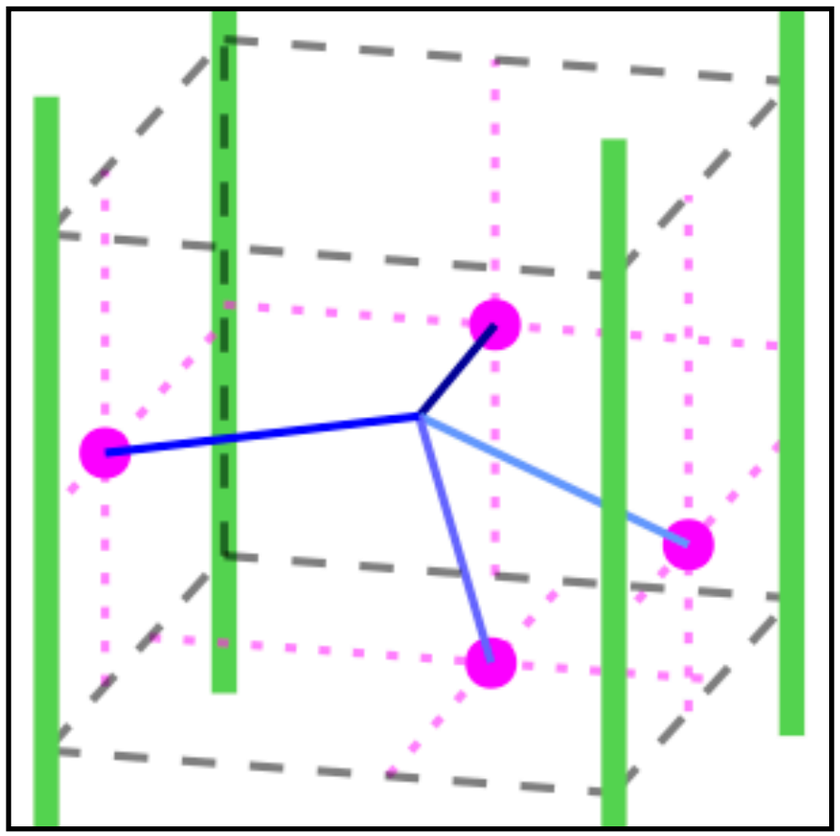
beyond “just pattern”...

pattern ≡ energy deposition as $t \rightarrow \infty$

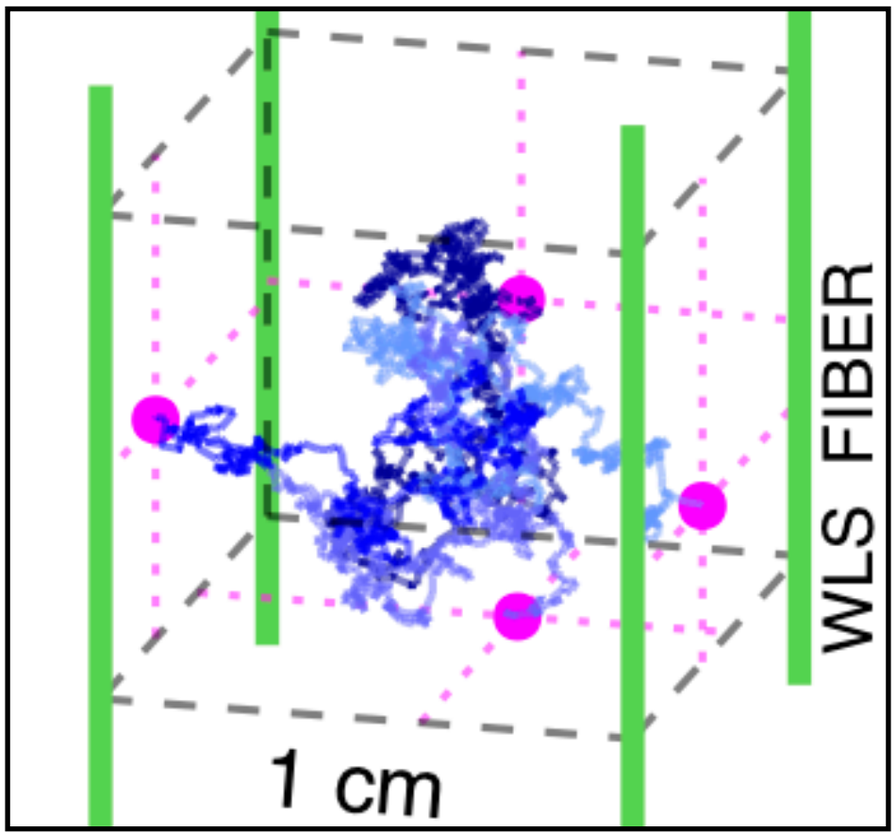
[static information: photo]

dynamic energy flow within few ns?

[a film]



versus



transparent **scattering**

“straight” light covers Δx in a shorter Δt

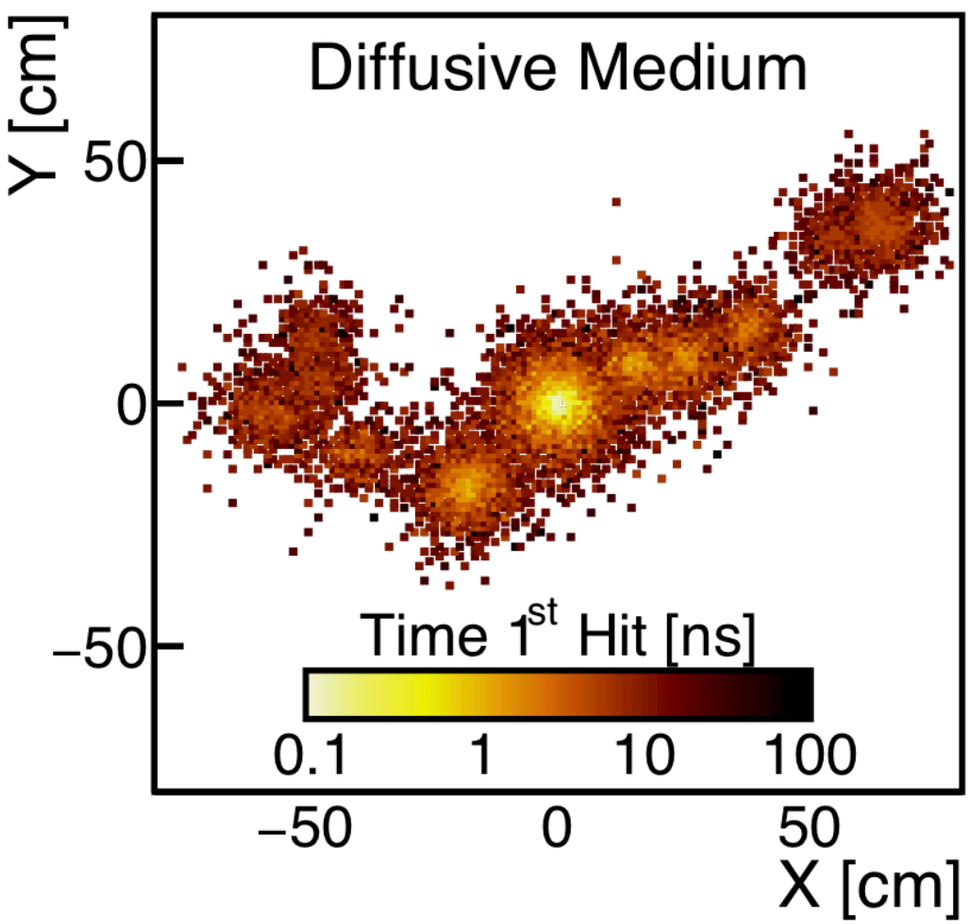
v(light) effective slow down…

(v = Δx/Δt)

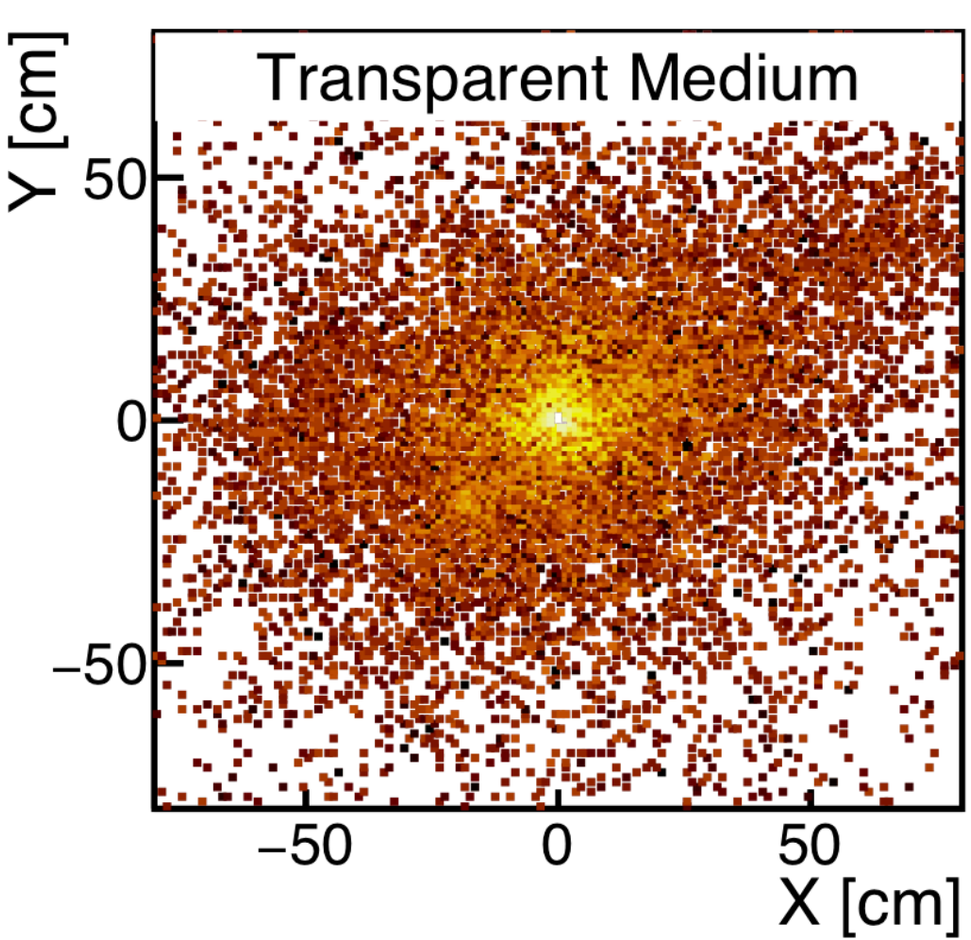
dynamics: not just photos…

scattering→ relented effective speed of light ~10x
[i.e. effective photon "viscosity"]

v(particle) ≠ v(light in scintillator) ≠ v(light in fibre)
["speed decoupling"]



LiquidO

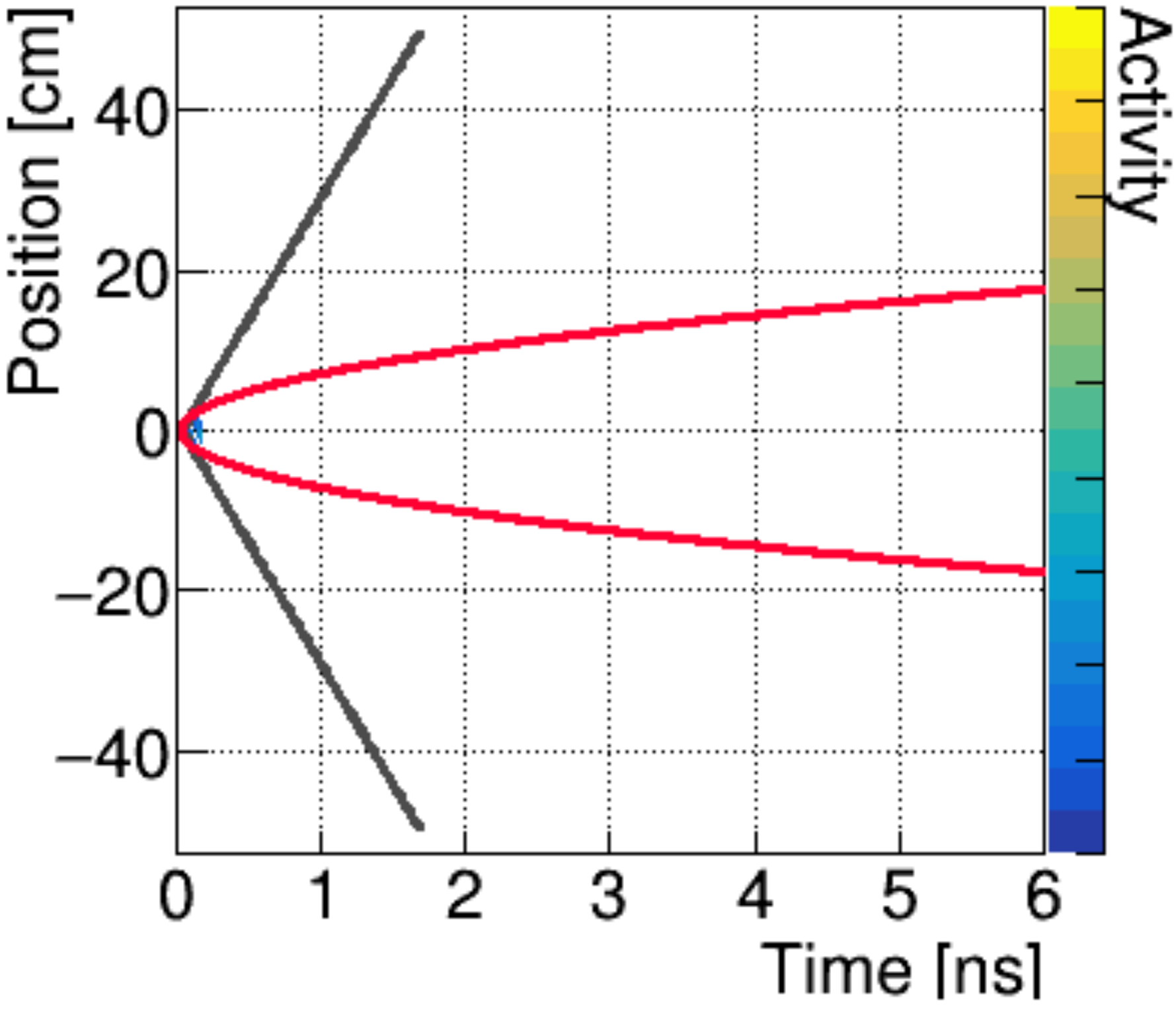


v(particle) ≈ v(light in scintillator) = v(light in fibre)
[no decoupling]

Transparent

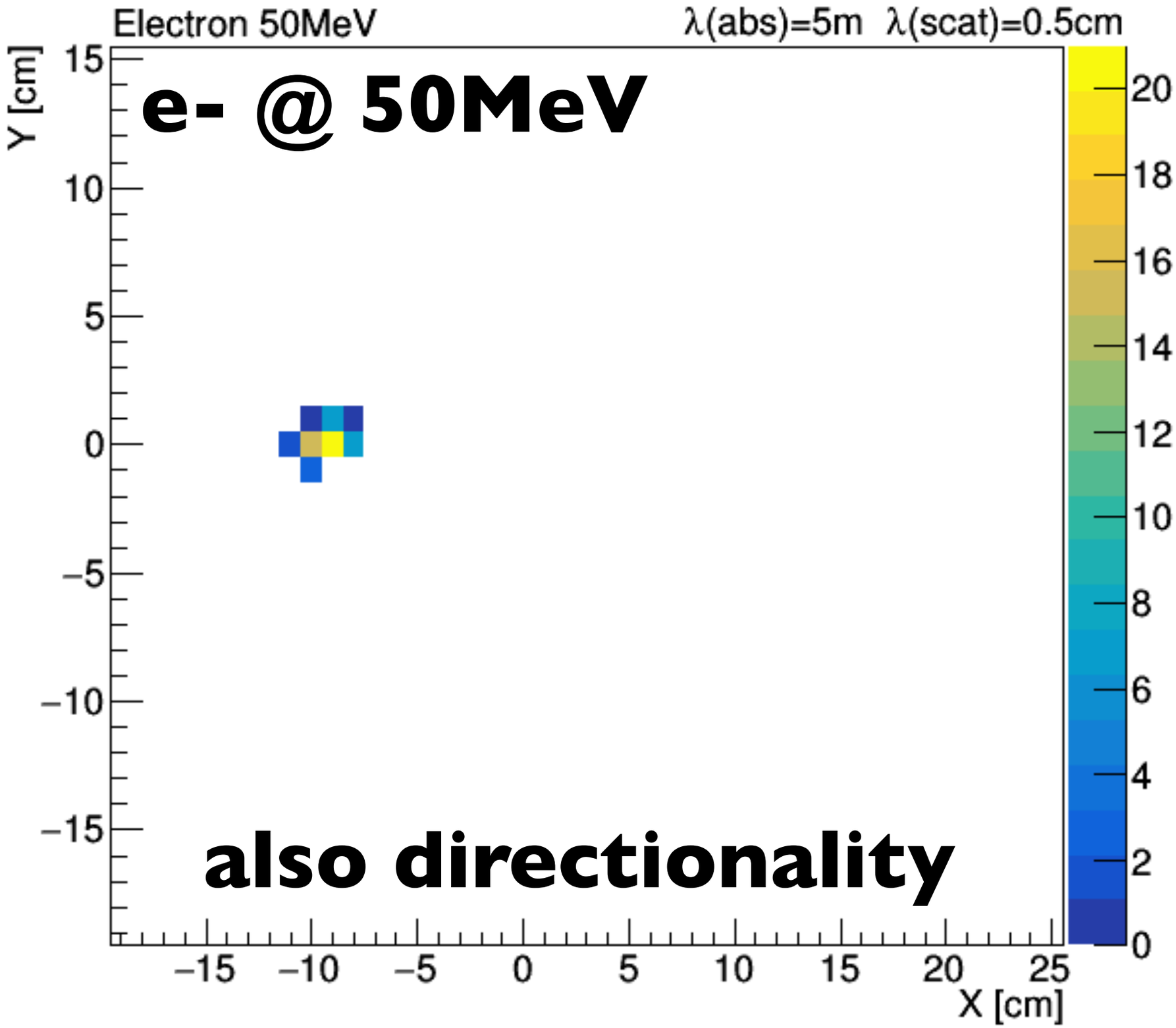
LiquidO implies imaging ⊕ energy flow…

c defines "line of interaction causality"



critical control of all time-dispersion mechanism

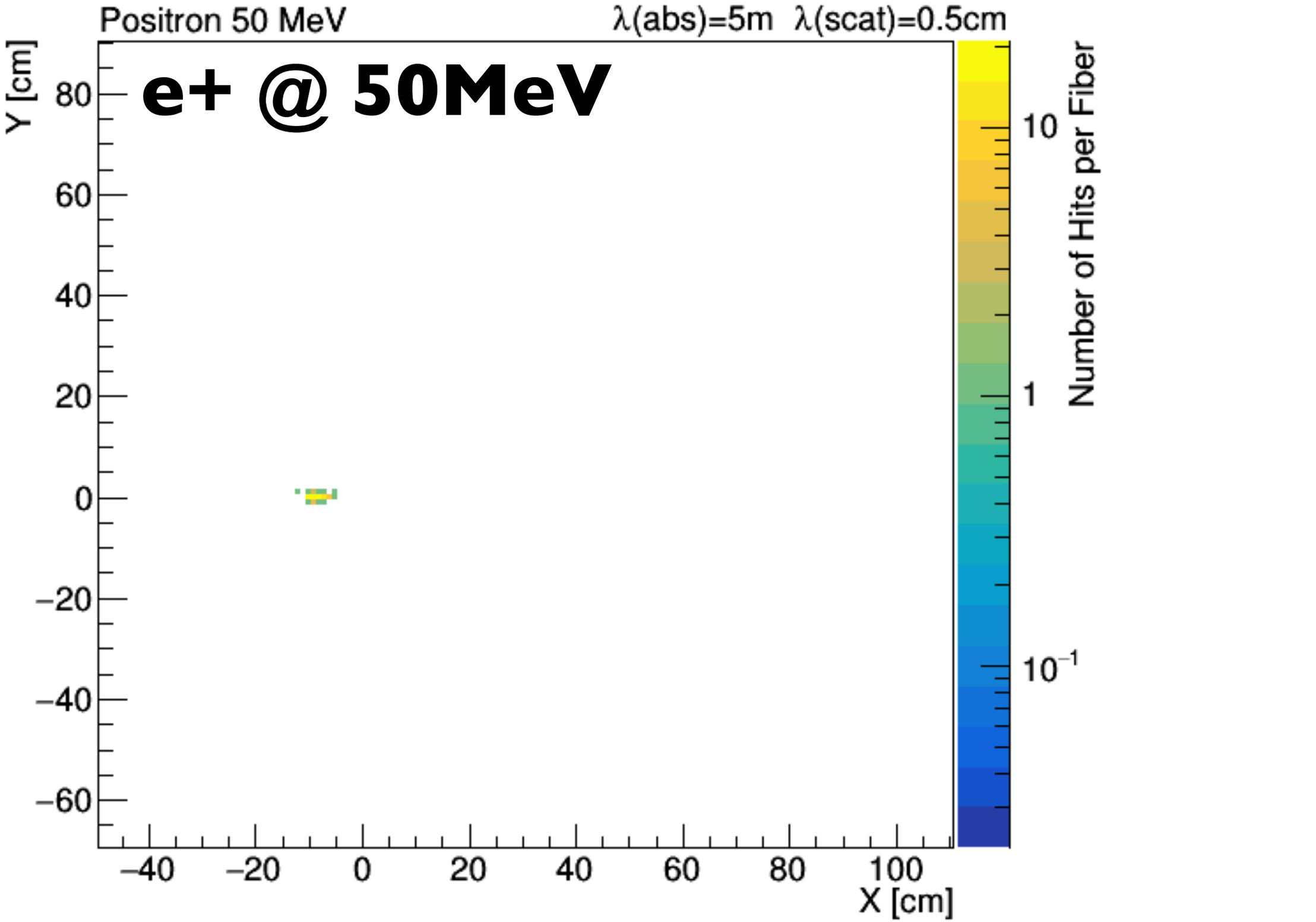
LiquidO native tracking: even e-…



also directionality

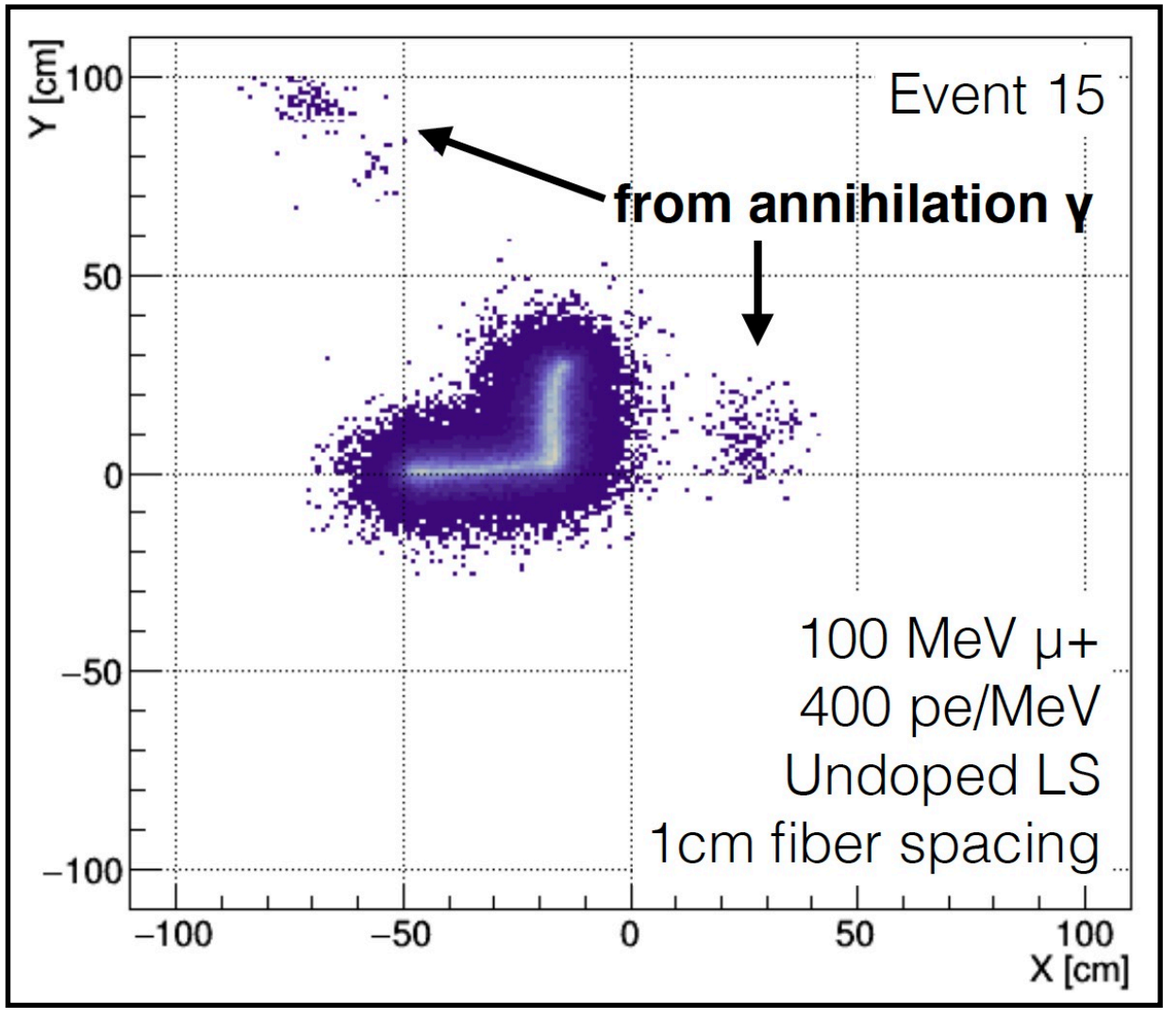
e- tracking (μ even easier)

e-/e+ discrimnation…

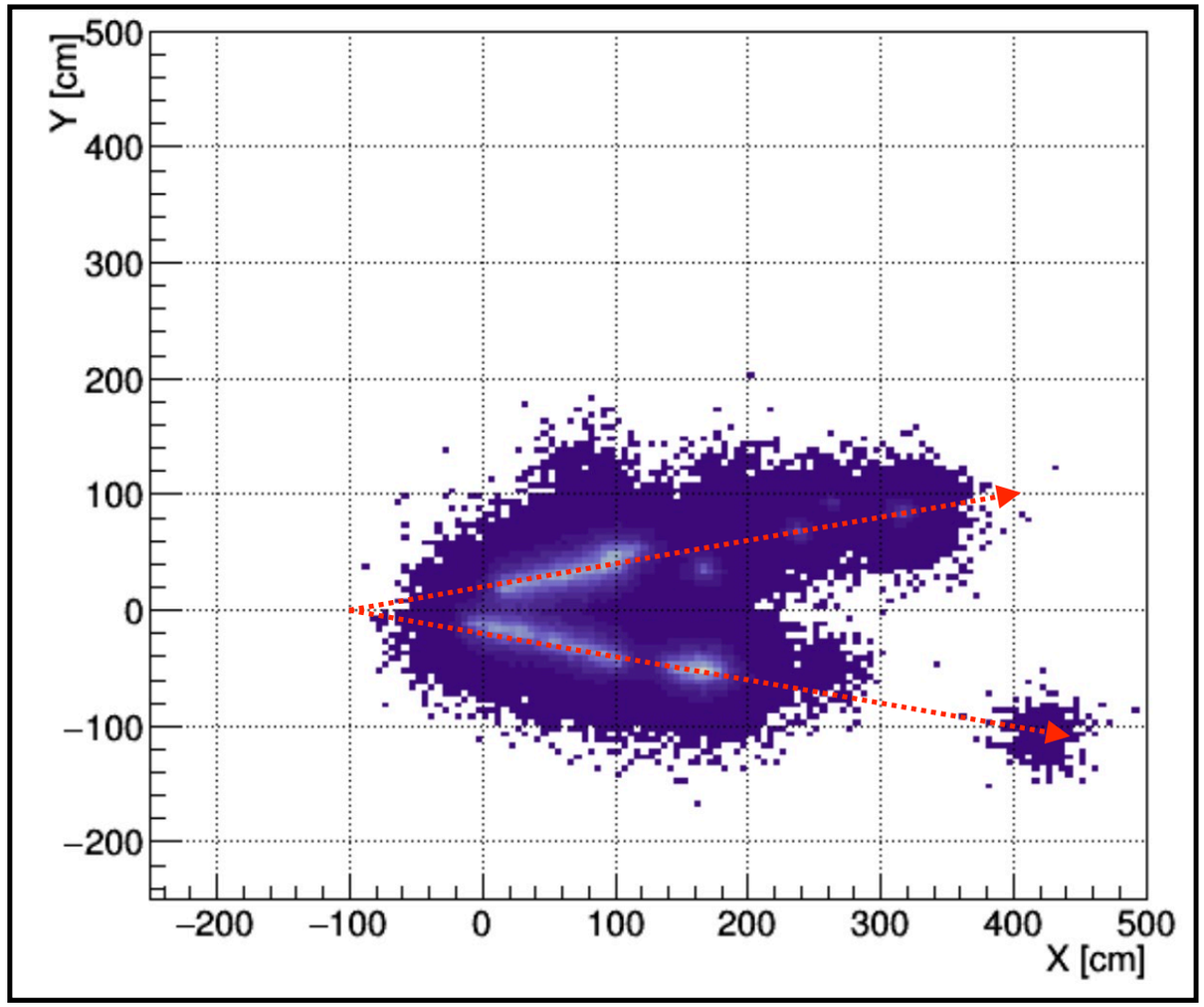


e-/e+ discrimnation with no B-field!

[but we can magnetise]



stopping μ± (decay into Michel-e±)

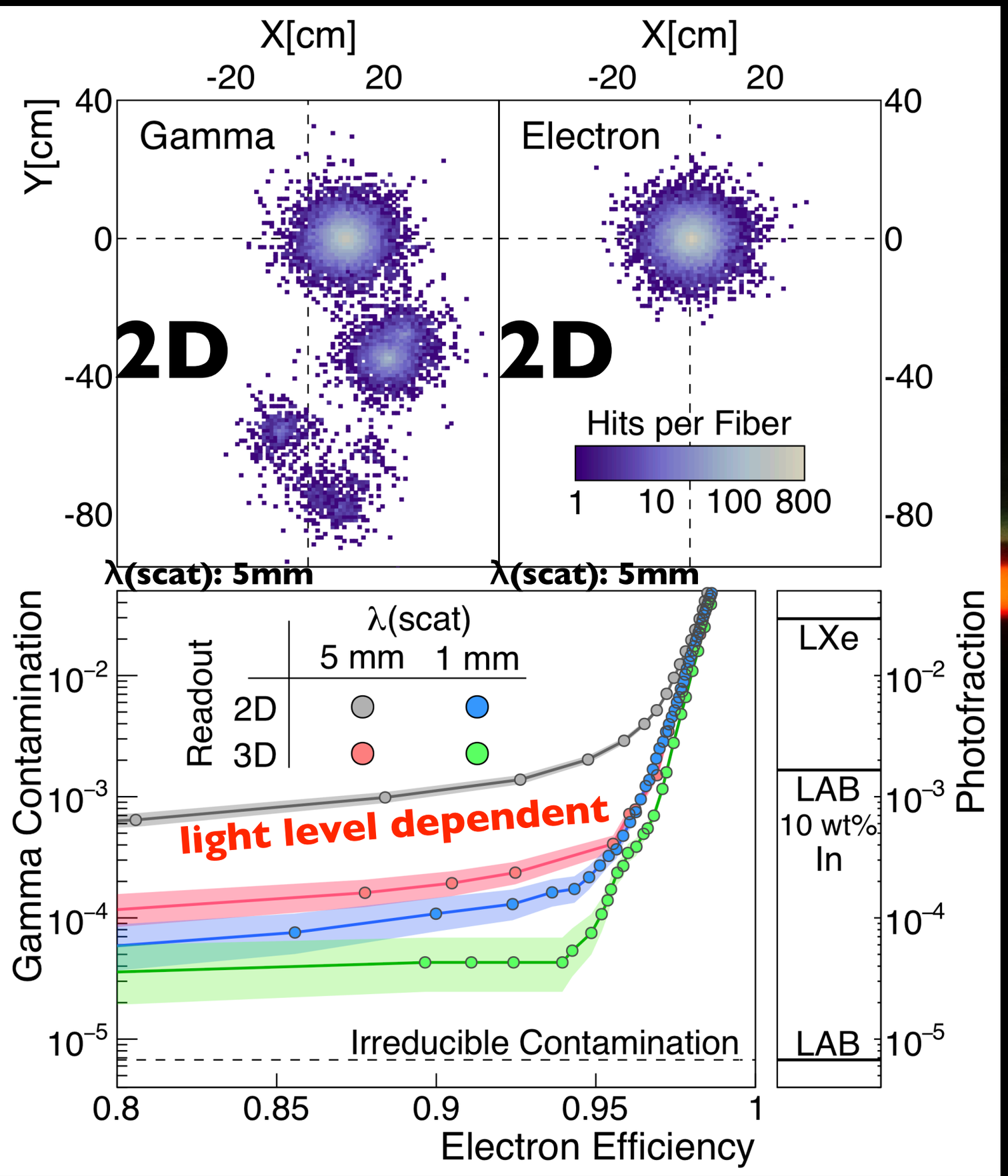


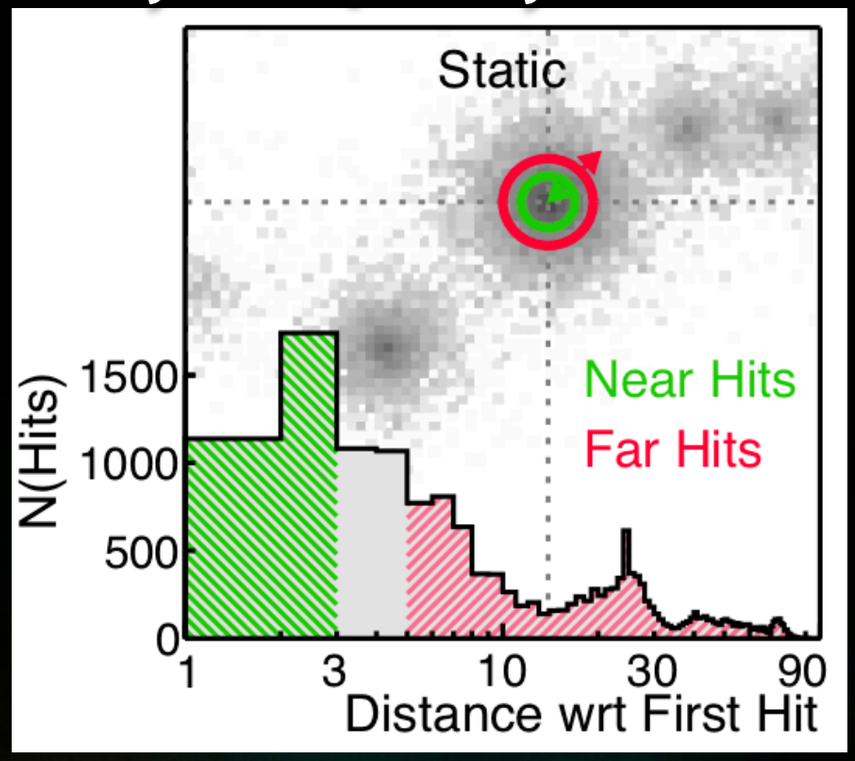
700MeV π⁰ (γγ decay) [MC]

more complex events is better…

(example) γ to e⁻ separation…

PID(e⁻:γ) @ 2MeV→ major γ rejection…





(reco) "event size" only

[calls for neural network, etc]

≥90% detection efficiency

PID[γ:e⁻] separation

1:≤10⁴ (scintillator native)

1:≤10² (heavy loaded)

not practical so far!!!

cannot boost ν's cross-section!

how about making it large?

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

GeV might be OK!! BUT **~1MeV physics @ 10kton?**

(**R&D**)

radio-purity control?

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

✓ **scintillator** (ex. ✓ Borexino)

⊕

✓ **photo-detector outside!**

[no PMT → **no buffer**]

⊕

? fibres → R&D (ex. ✓GERDA)

(under further study)

only natural radio-activity

GERDA's fibre curtain…

fibres are rather ok!! **good enough?**

(under estimation)

R&D

✓proof-of-principle simulation

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

LiquidO is still more!

dope it? non-native capability…

CA)

why going beyond native composition?

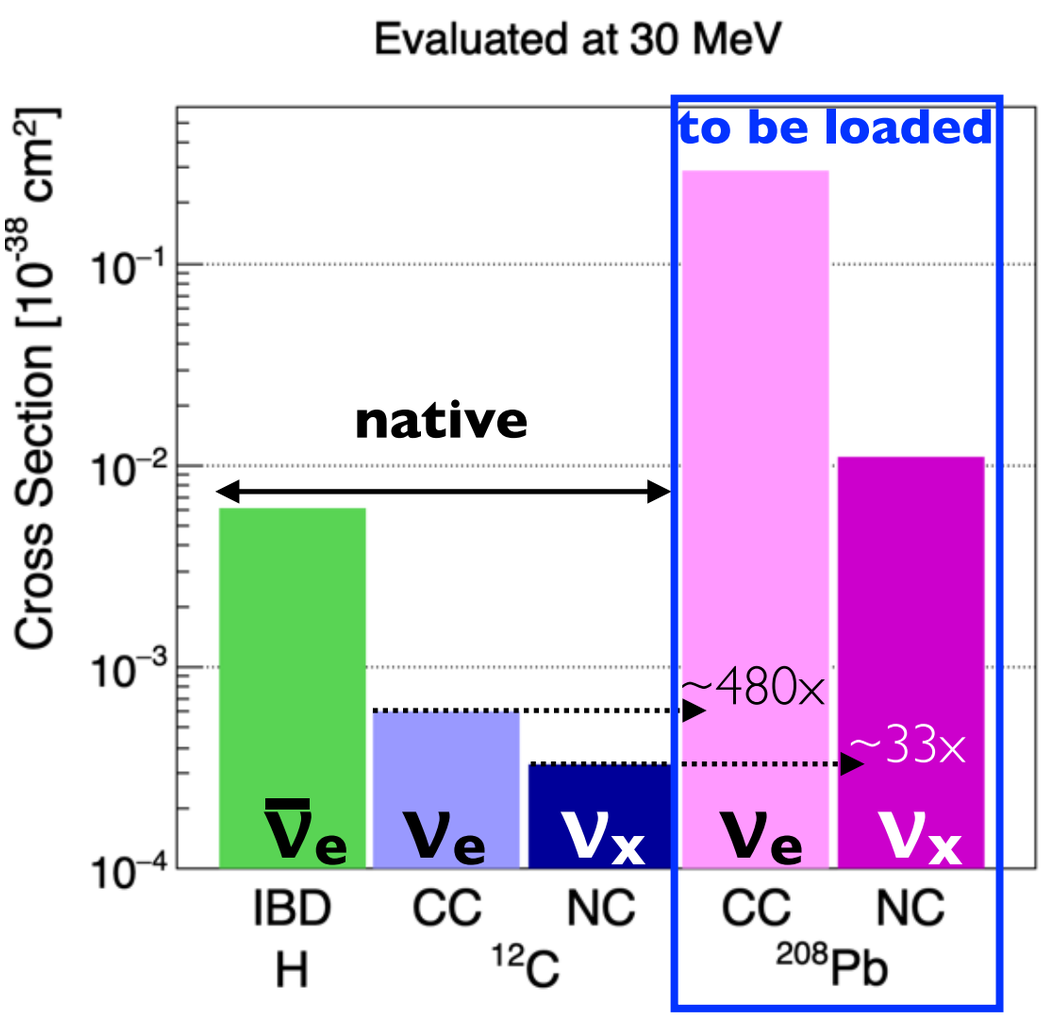
organic scintillator = H + ^{12}C + ^{12}C(~1%) [+ impurities]

detection efficiency enhancement

Cd loading
[Reines et al]

Gd/Li loading
[typical in reactors]

neutrino interaction(s) enhancement



rare decay source enhancement

ββ decay
^{136}Xe [KamLAND-Zen]
^{130}Te [SNO+]

(next slide)

isotopic mass: loading vs enrichment…

isotopic loading (% or kg/kg^{LS})

≲**1.0ton**
≳**1.0ton**

isotopic fraction (abundance) \ **m^{iso}(ton)** [V=1000m^3]	**0.1** 1g/l	**0.5** 5g/l	**1.0** 10g/l	**5.0** 50g/l	**10.0** 100g/l	**50.0** 250g/l	**100.0** 1000g/l
1.0							
5.0							
10.0							
33.0							
90.0 **enriched**							

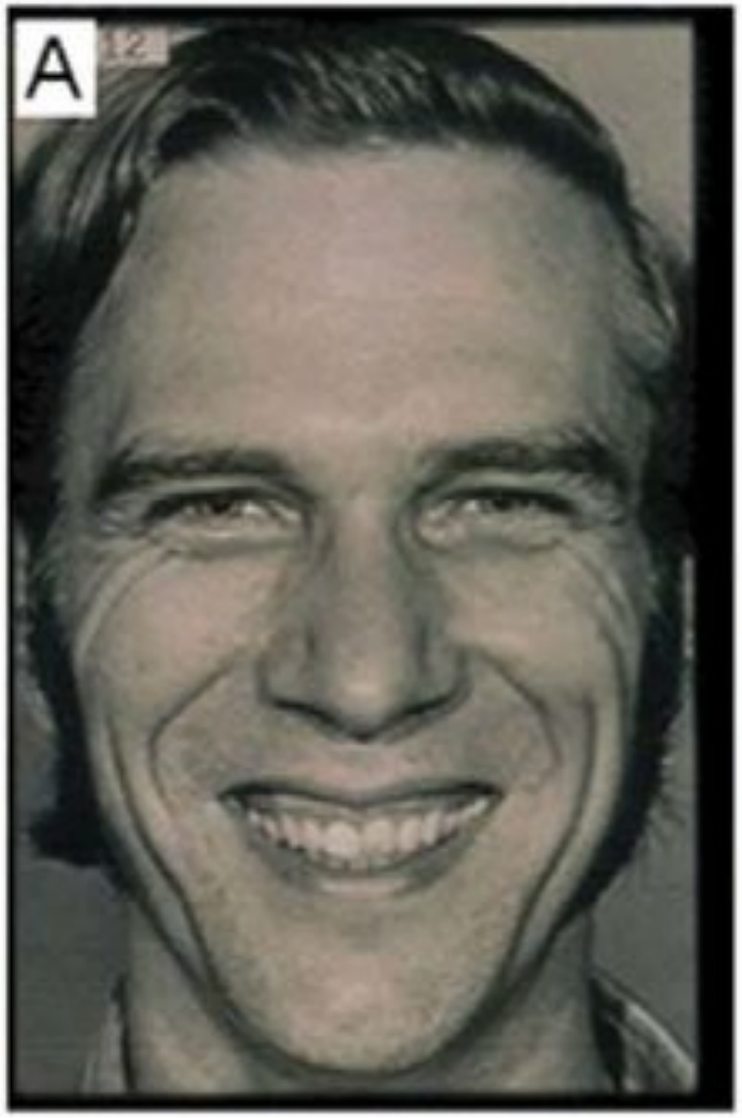
today reactor — SNO+ — LENS & SNO+ R&D (done) → **new R&D?**

massive loading capability (**R&D**)⇒ **no enrichment!**

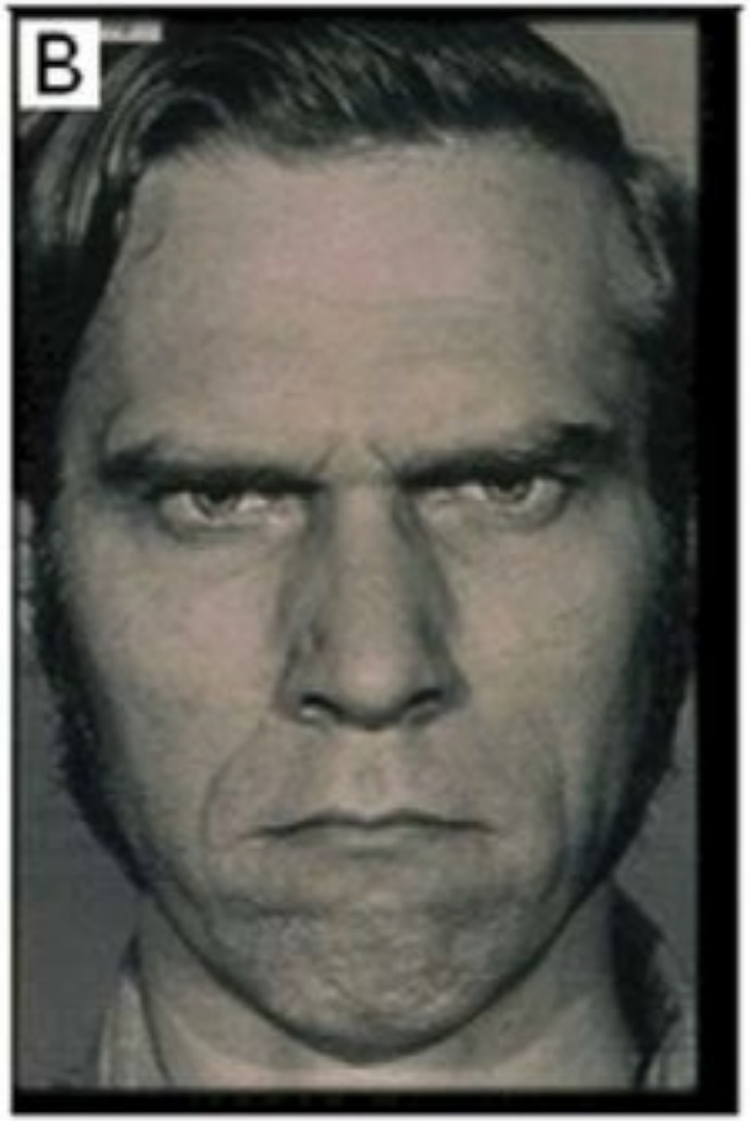
enrichment costing: [10,100]M€/ton

doping stability via solidification…

(beyond chemical stability)



cool!



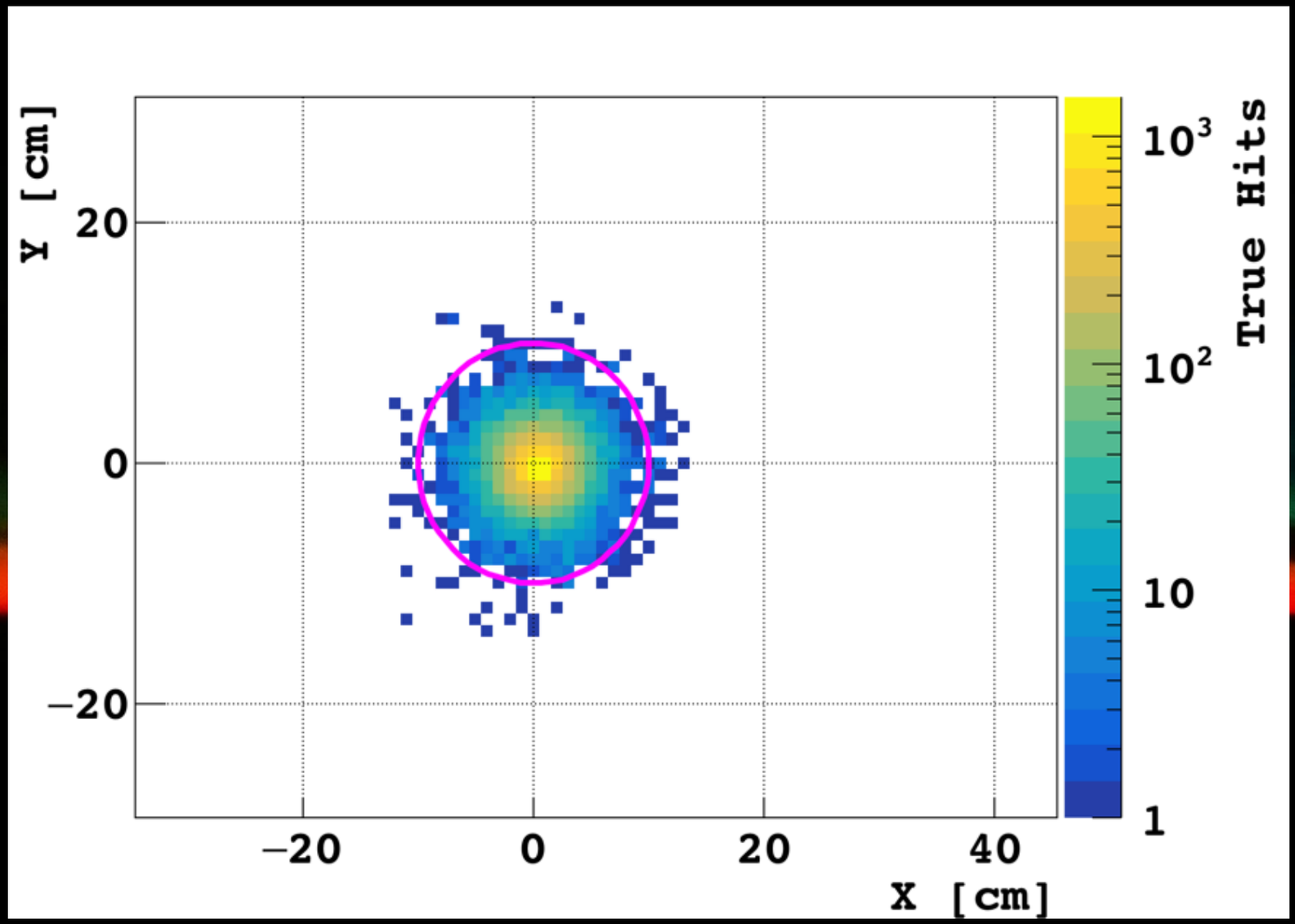
really?

[we did too for long!]

upon novelties, always duality…

first proof-of-principle…

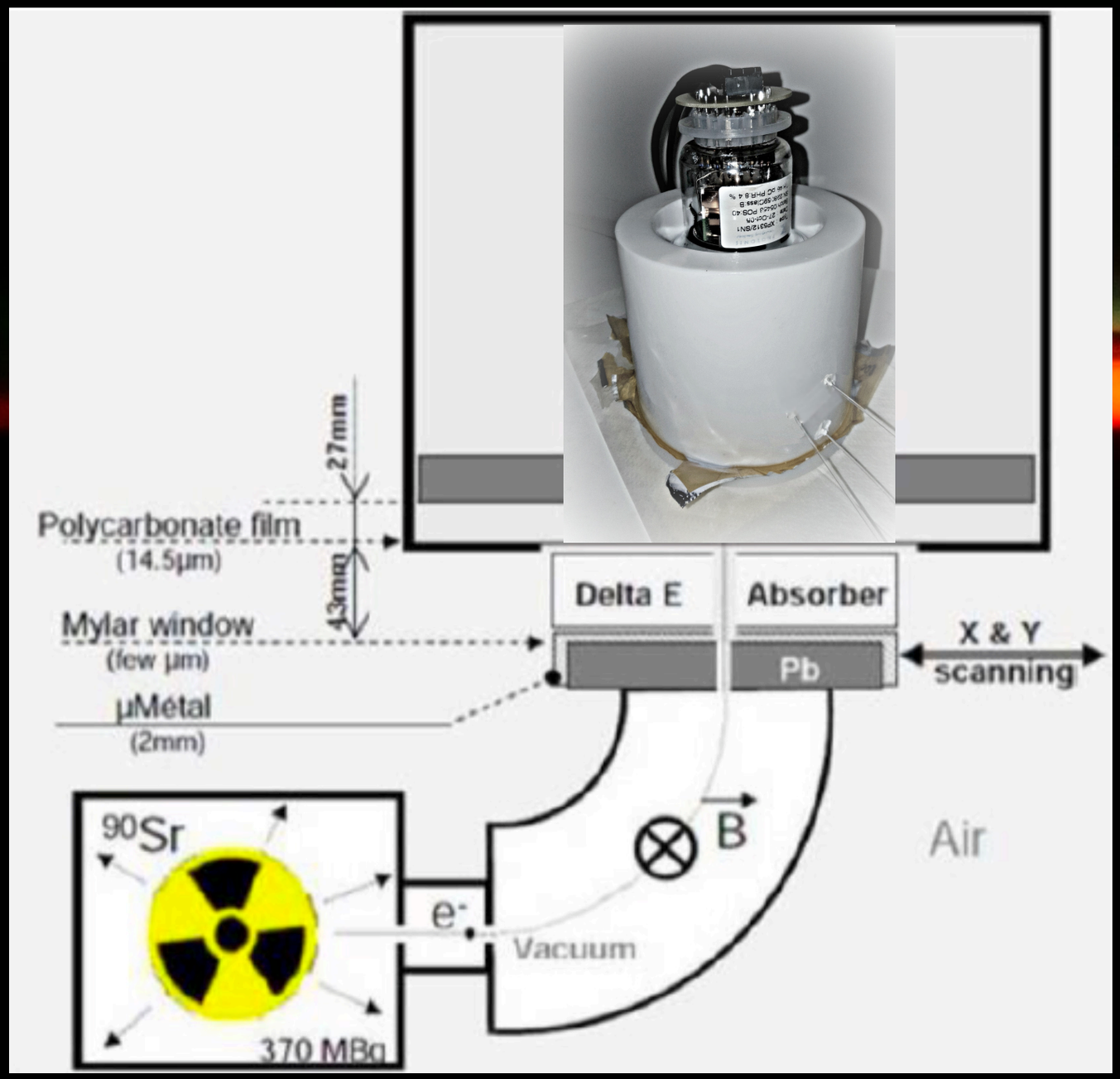
low energy e- ≈ "light ball"...

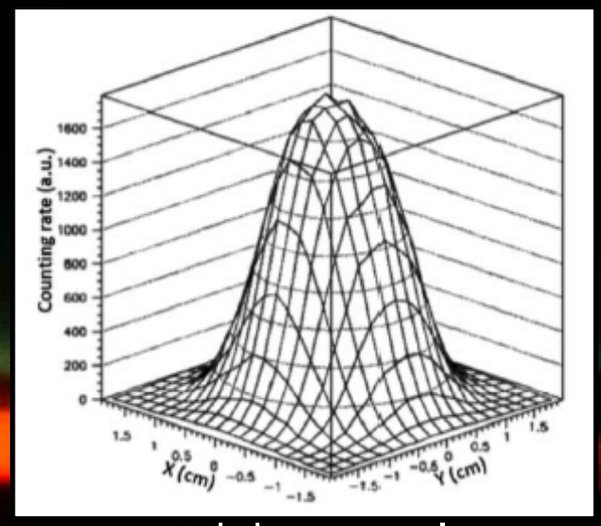


LiquidO means light confinement!

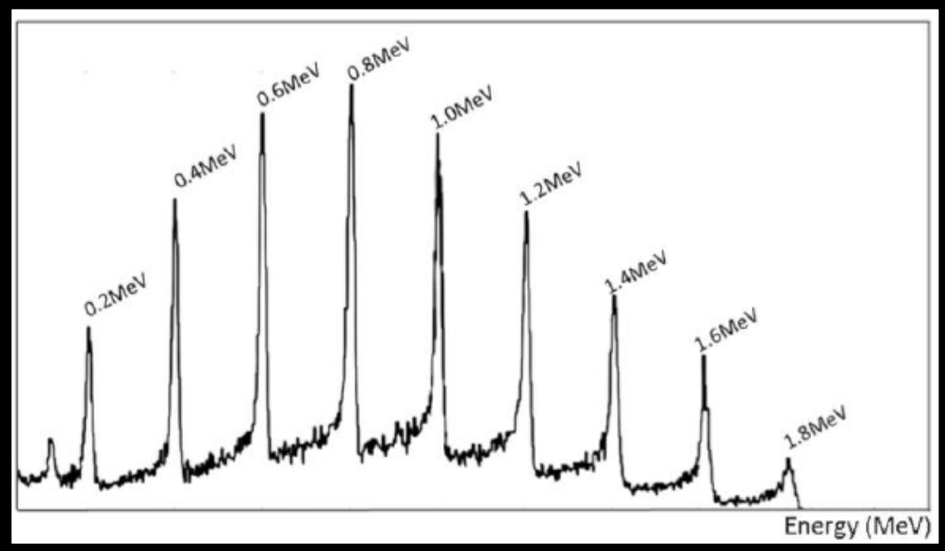
(everything else→corollaries)

μ-LiquidO @ our e⁻ beam…





e- position ≤1mm



e- energy ≤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

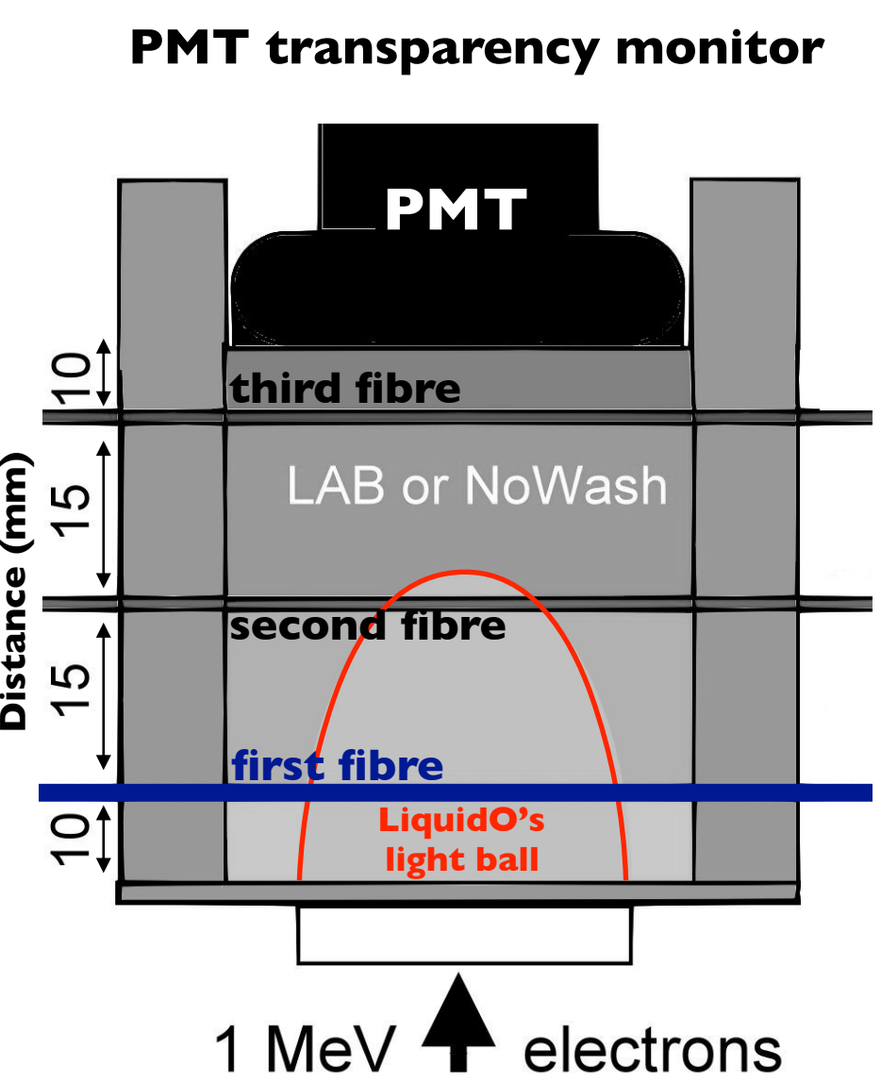
2 scintillators
- LAB (transparent)+3g/l PPO
- new (LAB-based⊕opaque)

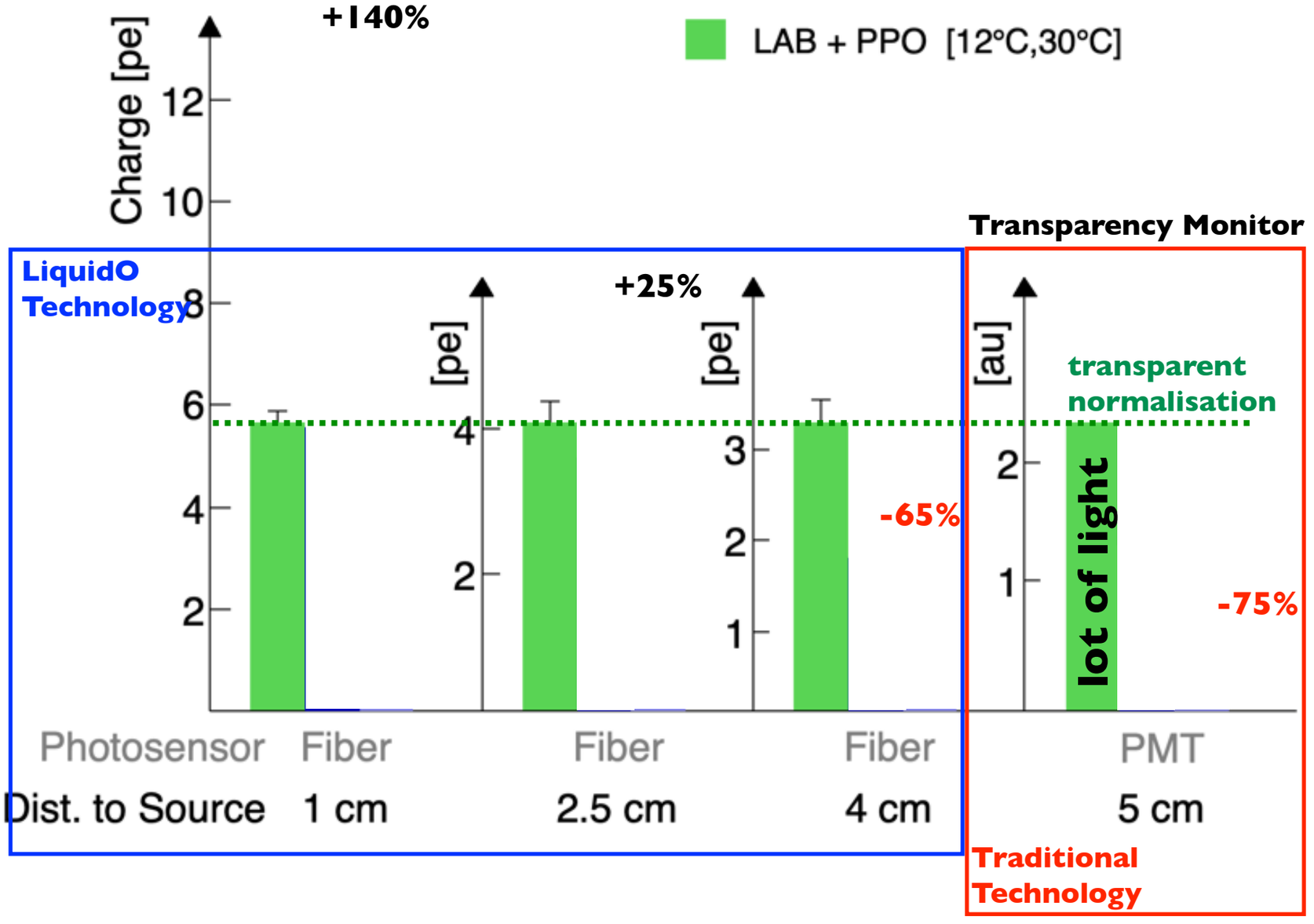
→**polymer [10,20]% loading**

Mylar (few μm's)

1 fibre only
(example)

first experimental proof of principle…





light bending→light confinement!

(**data-driven reference** — no need MC)

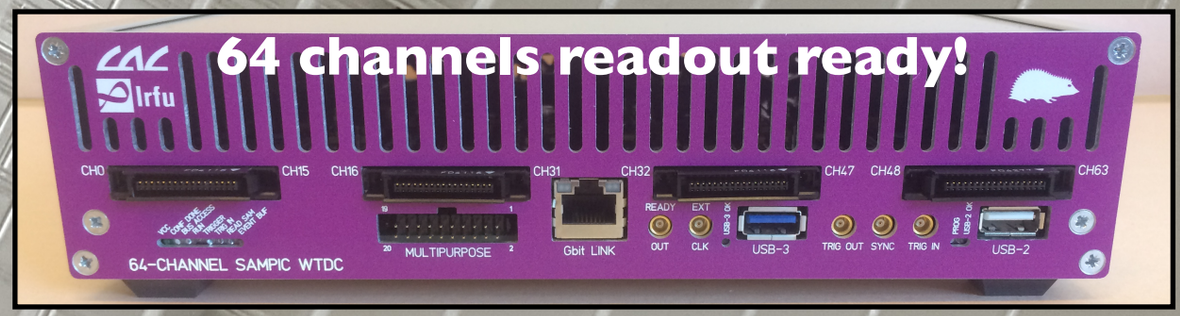
λ(scat) driven [consistent with negligible light loss @ 10% loading]

R&D

✓proof-of-principle experimental

e^-

closed detector now (PMT window)



packed lattice → data soon…

R&D

further prototyping effort…

a physics appetiser…

vast physics under study...

- **geo-neutrino→ first ^{40}K detection?**
- **reactor neutrino→ background-less detection?**
- **CP-Violation via ν_e & anti-ν_e**
  - **@MeV:** vacuum oscillation & low systematics?
  - **@GeV:** conventional beam & larger matter effects
- **solar neutrino→ high precision & maybe pp?**
- **supernova neutrino→ CC (ν_e & anti-ν_e) & NC detection?**
- **≥10ton ββ detection? [much R&D still]**
- **multi-channel proton-decay detection?**
- **TeV collider calorimetry articulation?**
- **applications: medical, non-proliferation, Radom detection**

[sorry, no time!]

physics potential...

R&D

(performance characterisation & scaling, etc)

[demonstration with ν's]

NO "experiment" proposal (yet)

early July 2019

towards first experiment @ EPS…

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

tribute to Reines&Cowan

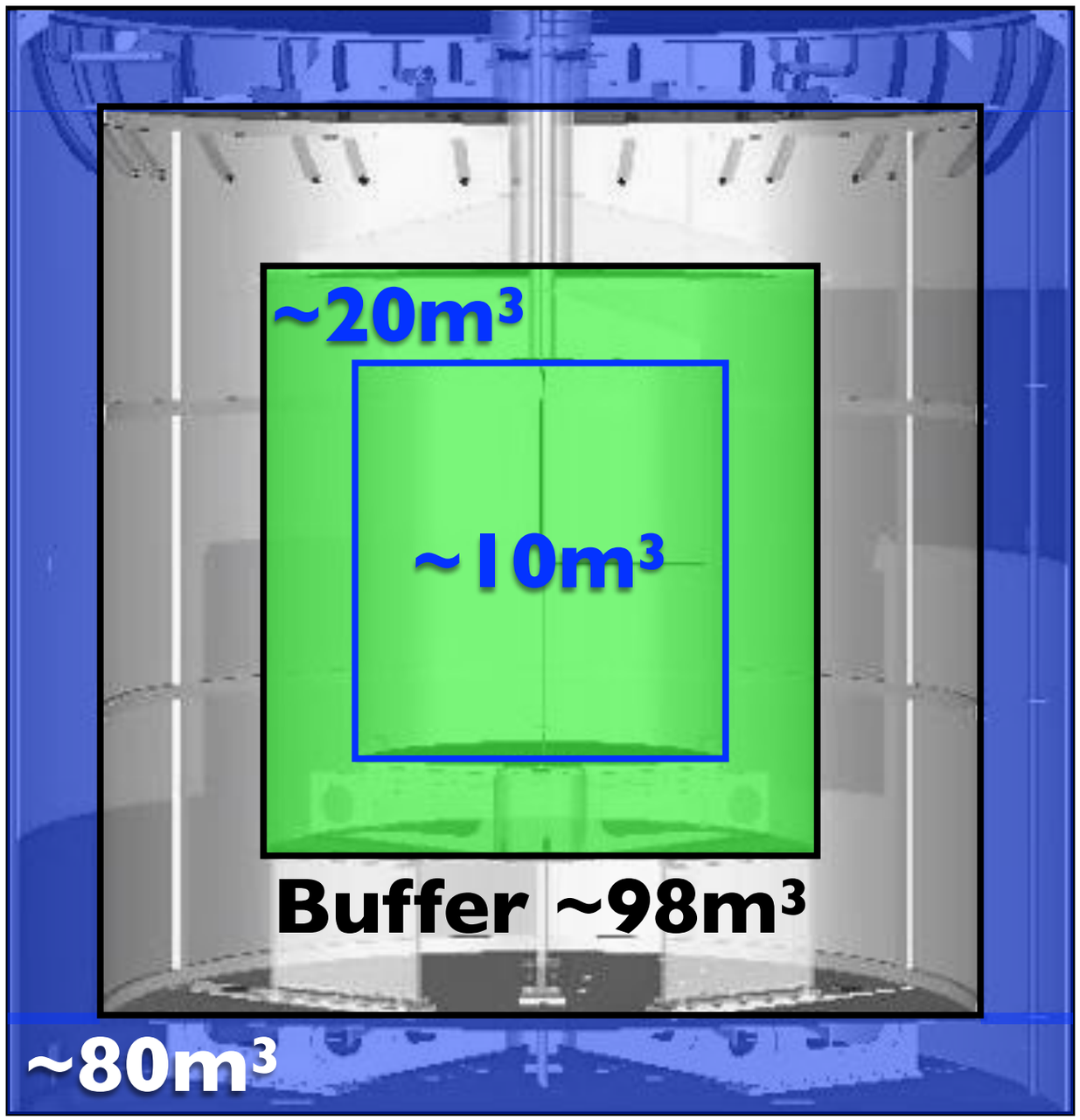
LiquidO(Cd) (example only)

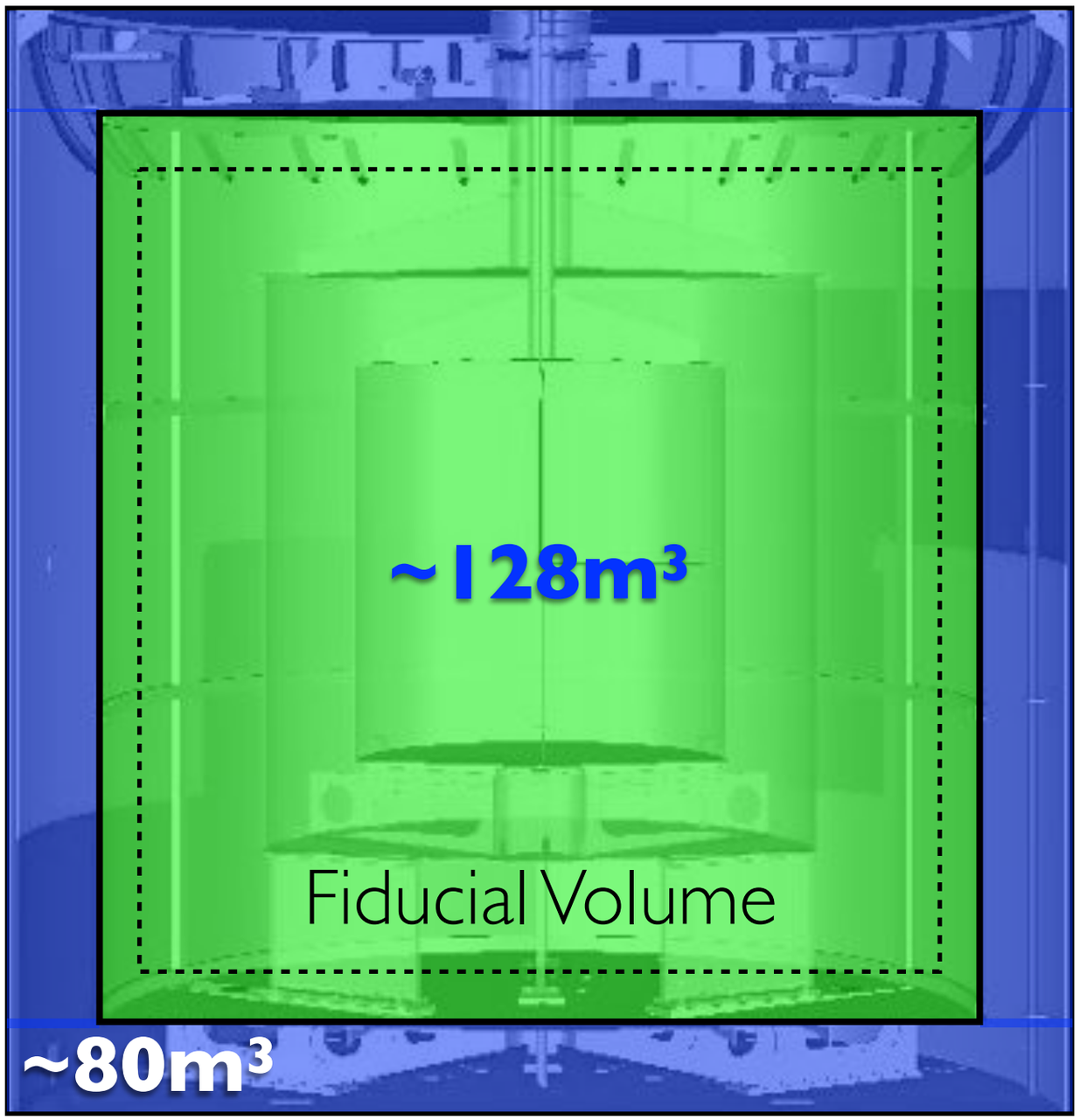
back to (cool) reactor neutrino…

Chooz reactor
(cooling tower)

larger detectors in same cavity?

more detection volume (same cost)…





Double Chooz: buffer (77%):detector(23%)

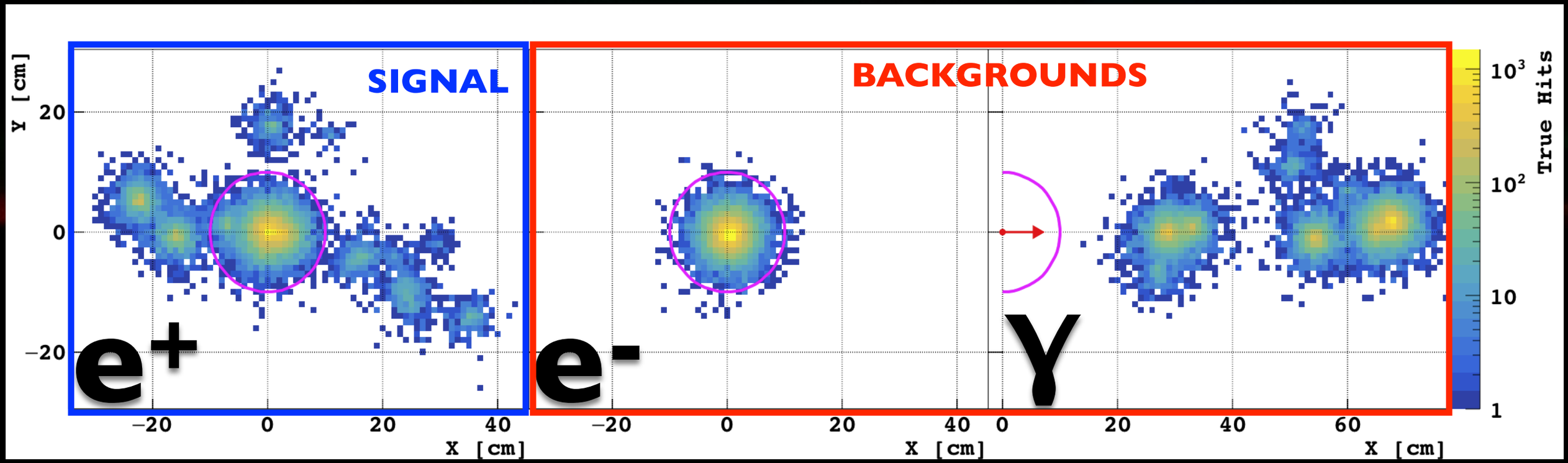
wasted >2/3 equipped volume

(**buffer** is a desperate option, not a solution)

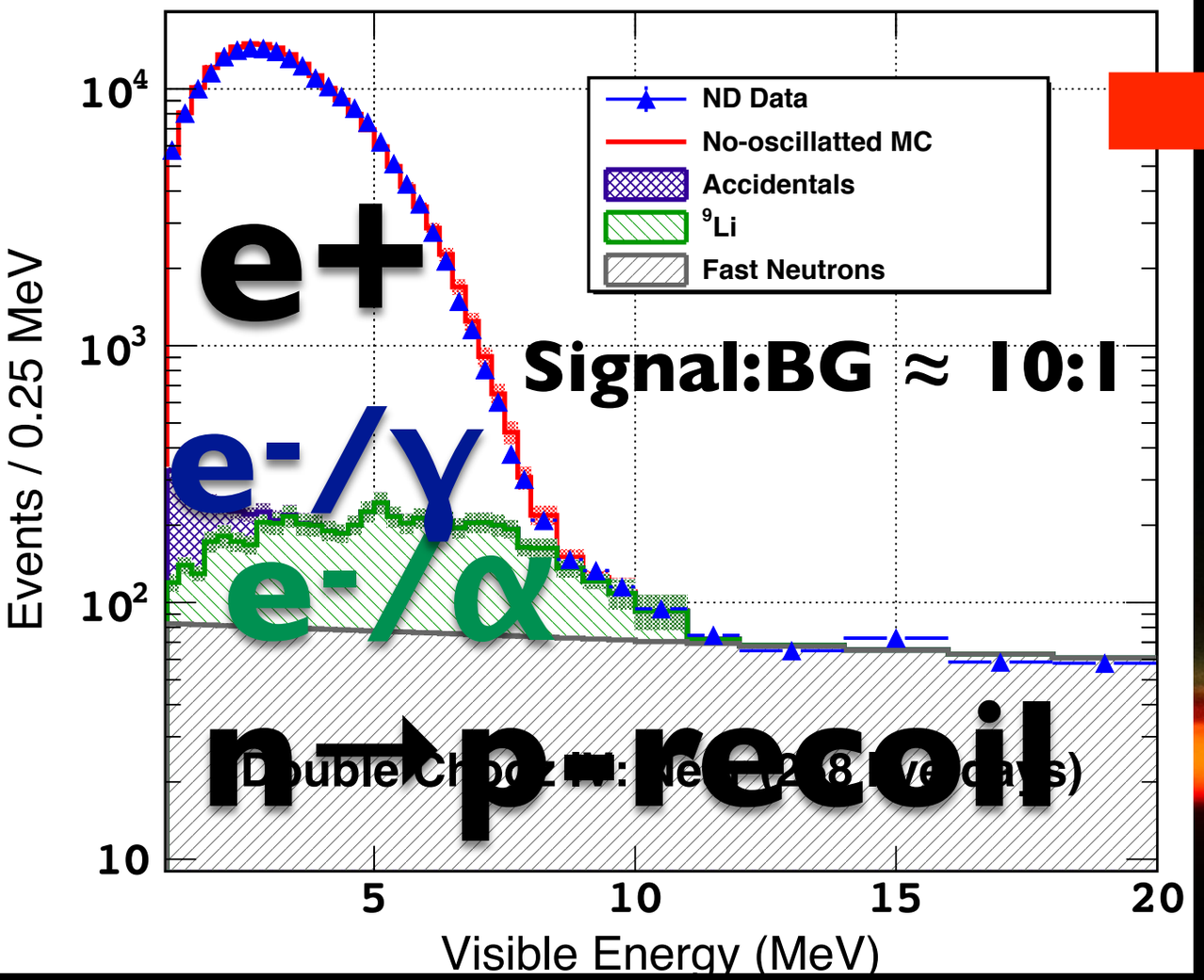
all other detectors (KamLAND, Borexino, etc) **are just alike**…

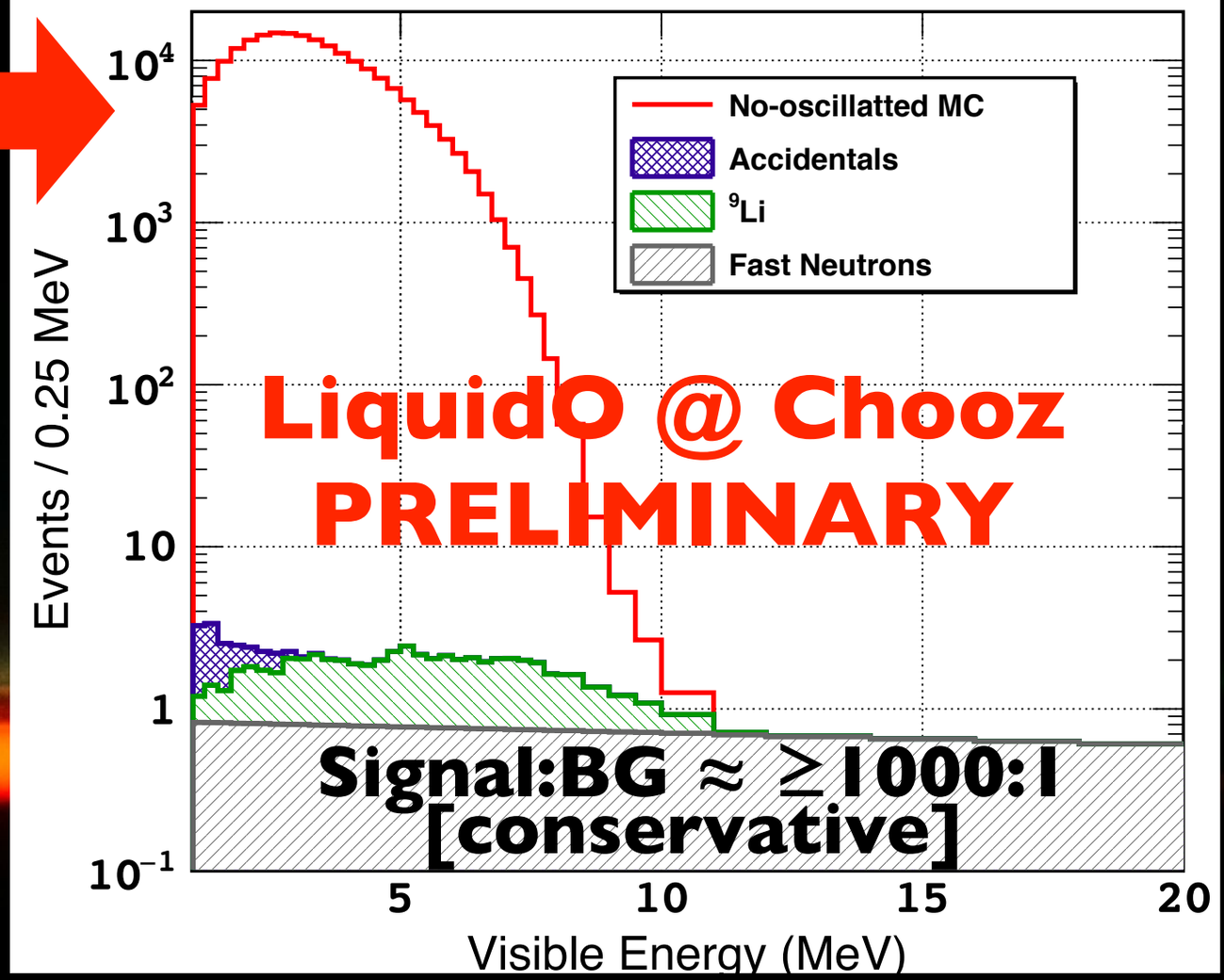
IBD: e+ (else background)…

2MeV



from Double Chooz to LiquidO…





cosmogenic rejection→ **PID(e+:e-) ≥100x** (conservatives)

accidentals rejection→ **≥100x** [time⊕space coincidence & PID(e+)]

“background-less” IBD detection?

physics beyond "IBD"?

less overburden?

either way: major impact!

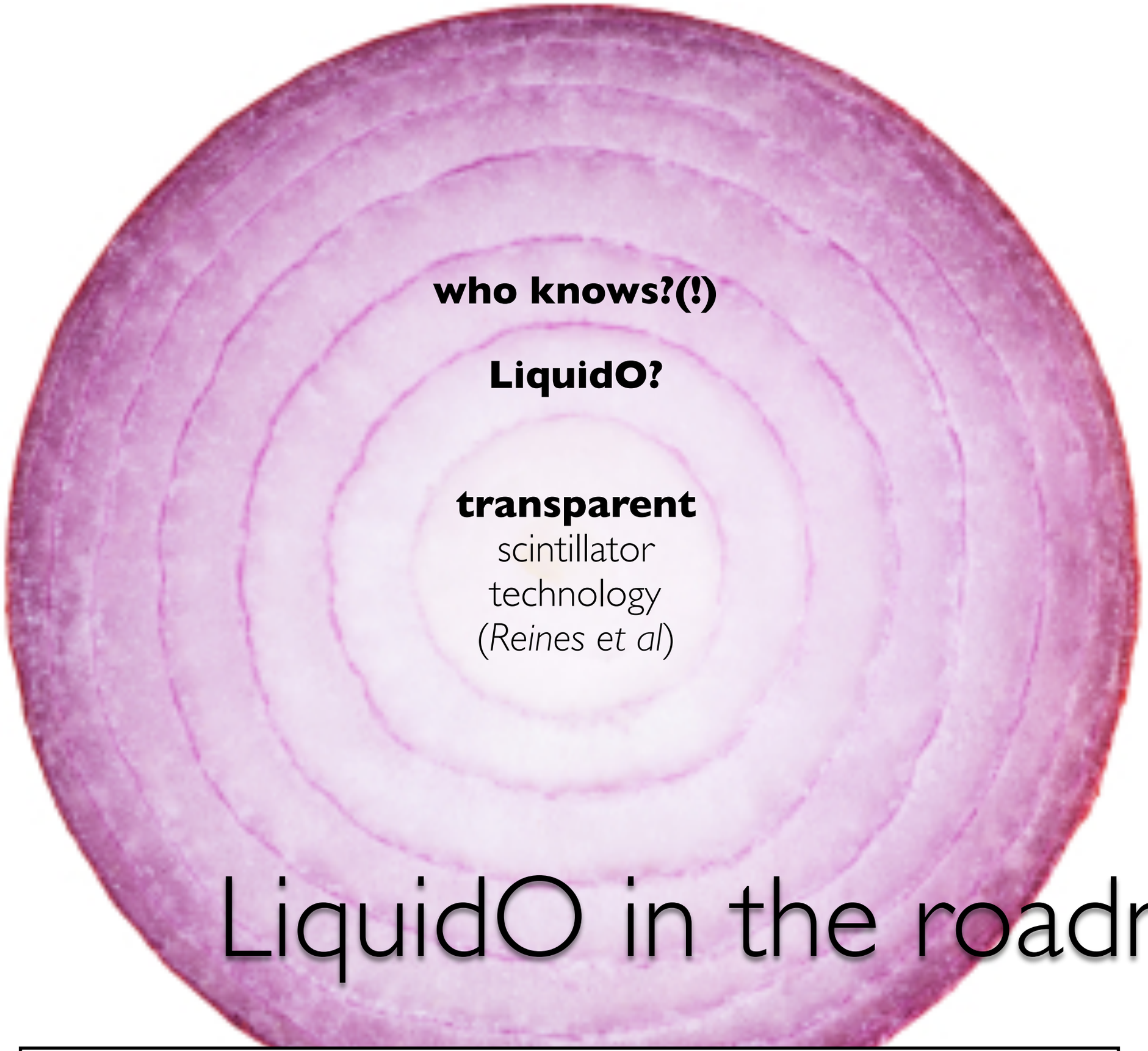
what to remember…

R&D

“ν demonstrator” detector NEXT STEP

data needed→towards physics experiments

✓proof-of-principle (data & MC)



LiquidO in the roadmap?

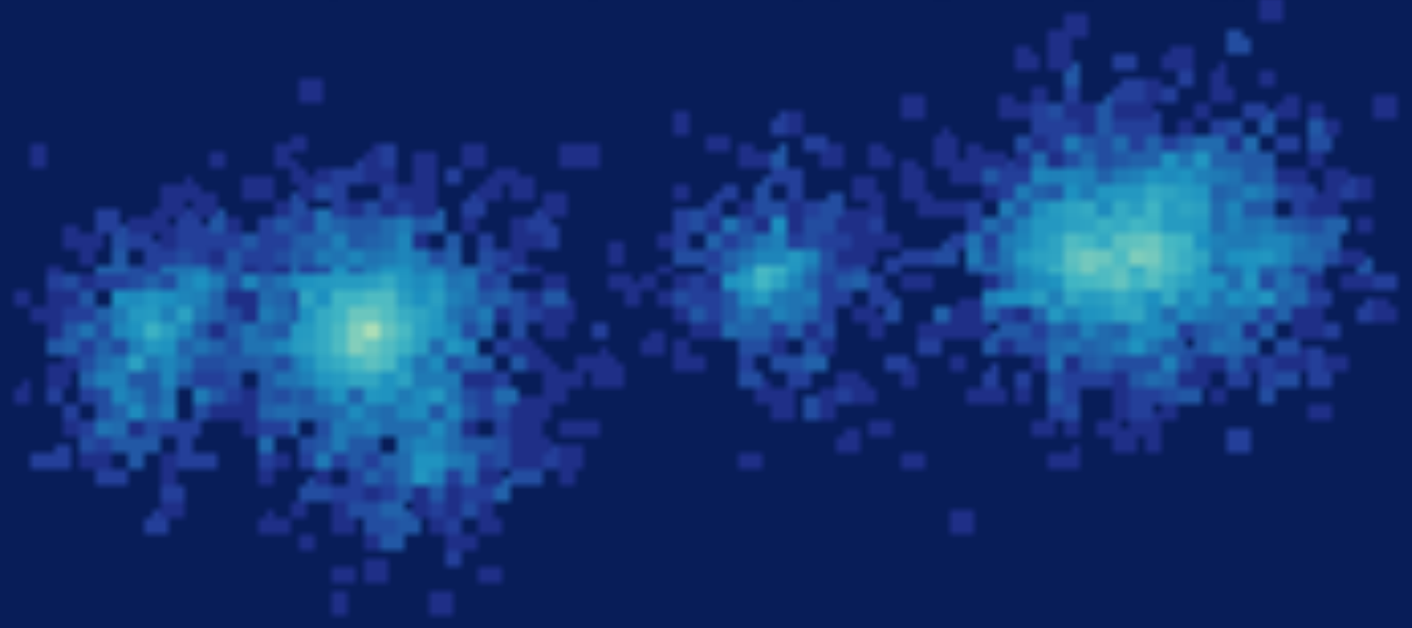
LiquidO inherits ~80 years of technology/expertise
(**simplifies dramatically LiquidO R&D**)

LAL - LNCA)

LiquidO physics potential appears large!!
several studies quantifying→**publications soon!**

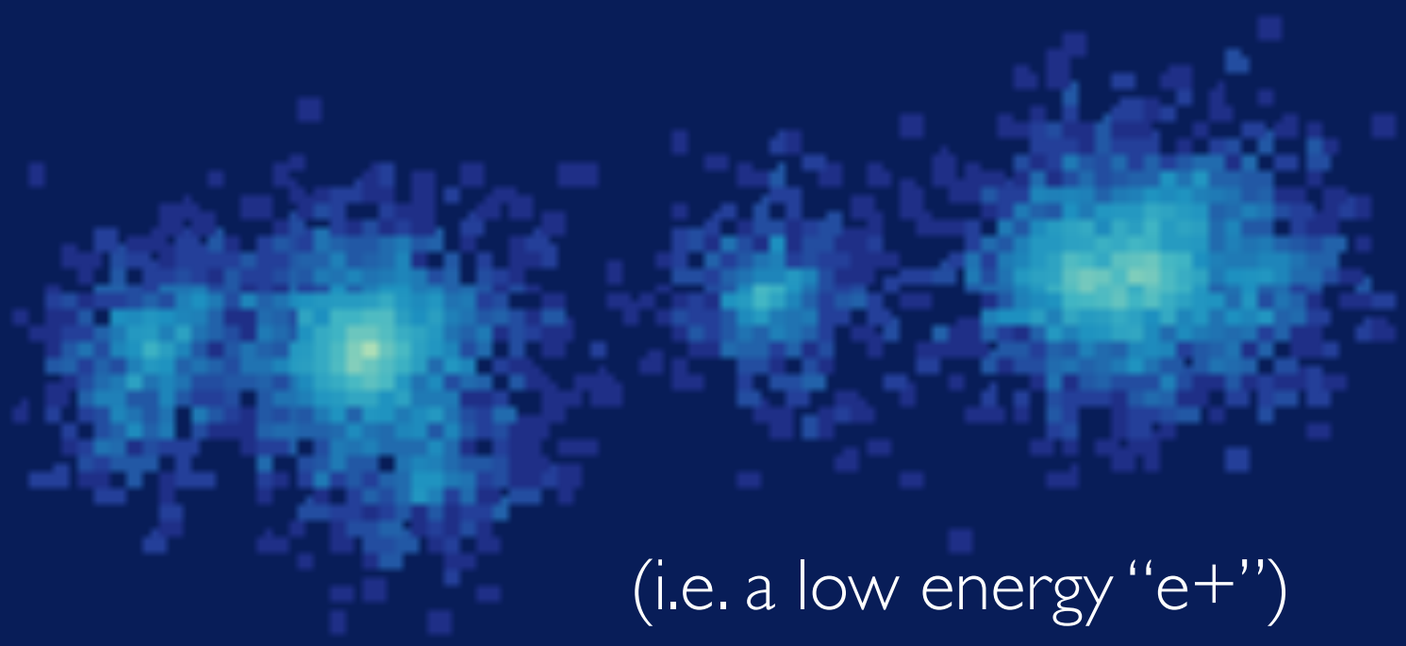
first publication aiming within JUNE 2019

LiquidO detection technique→proof-of-principle
(further prototyping ongoing)



detector performance optimisation→what physics?
(**experimental proposal(s) soon**)

questions, please?

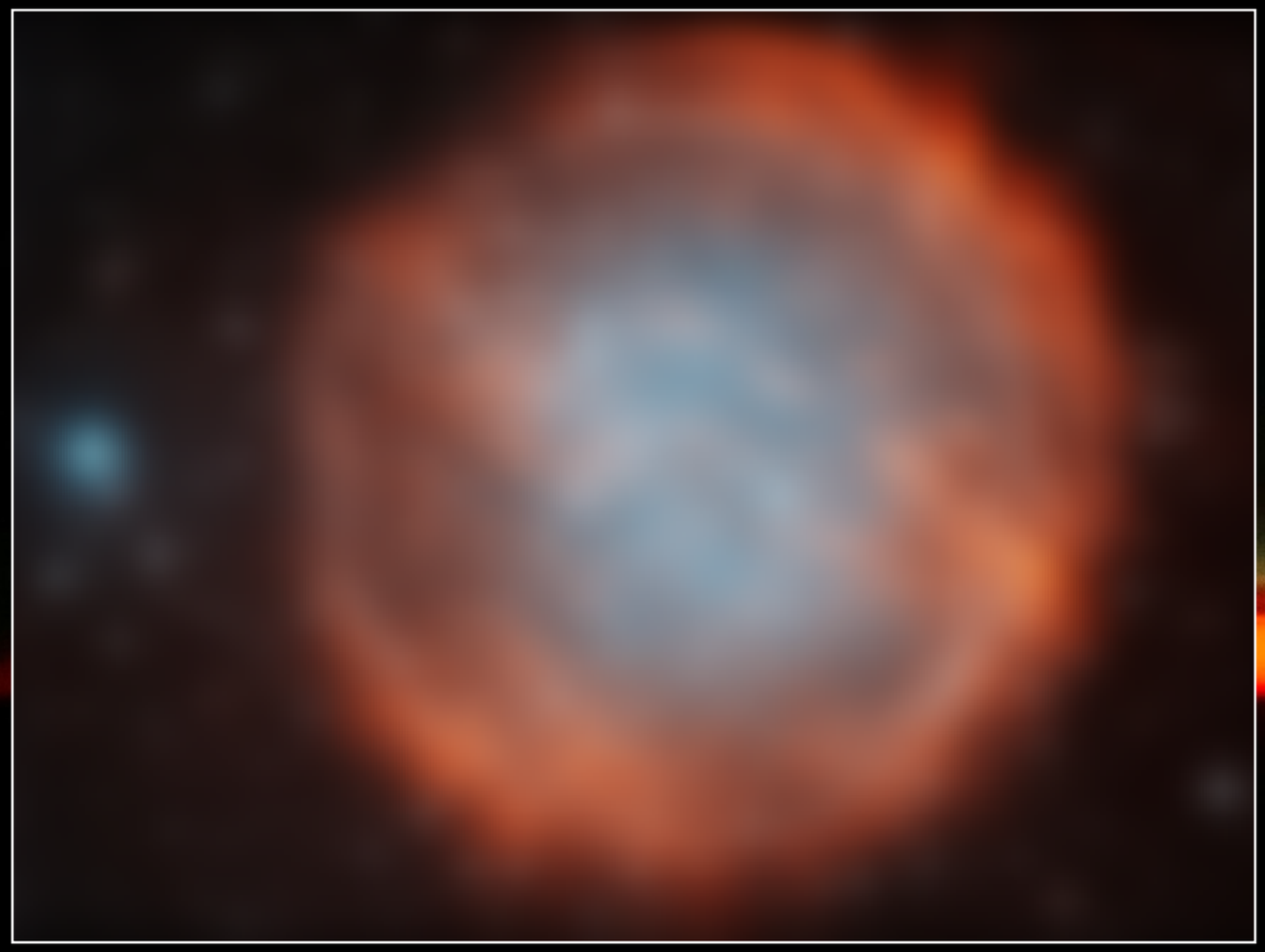


(i.e. a low energy "e+")

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

anatael@in2p3.fr

(always question) why people did not see before?



“blurring” (i.e. scattering) mechanism
to yield
“shaper” imagines
(rather counter intuitive)