Liquid

novel neutrino detection

CERN

June 2019

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CNRS/IN2P3
LAL@Orsay
LNCA@Chooz

what is LiquidO?

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…

today's technology…

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

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

Reines & Cowan (*et al*) around 1950

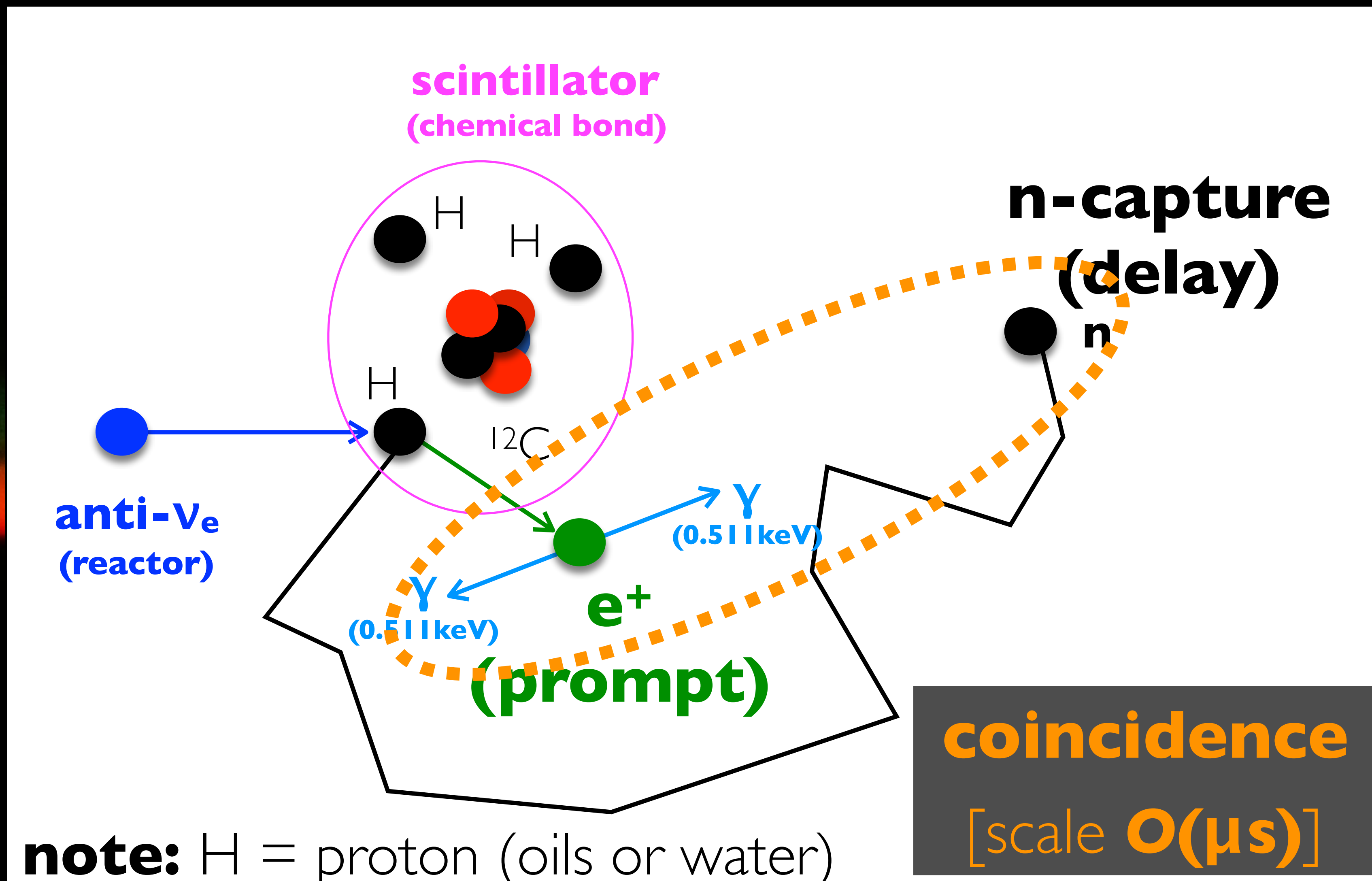
discover the neutrino (upon 1930's Pauli's hypothesis)
[Nobel prize 1995]

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

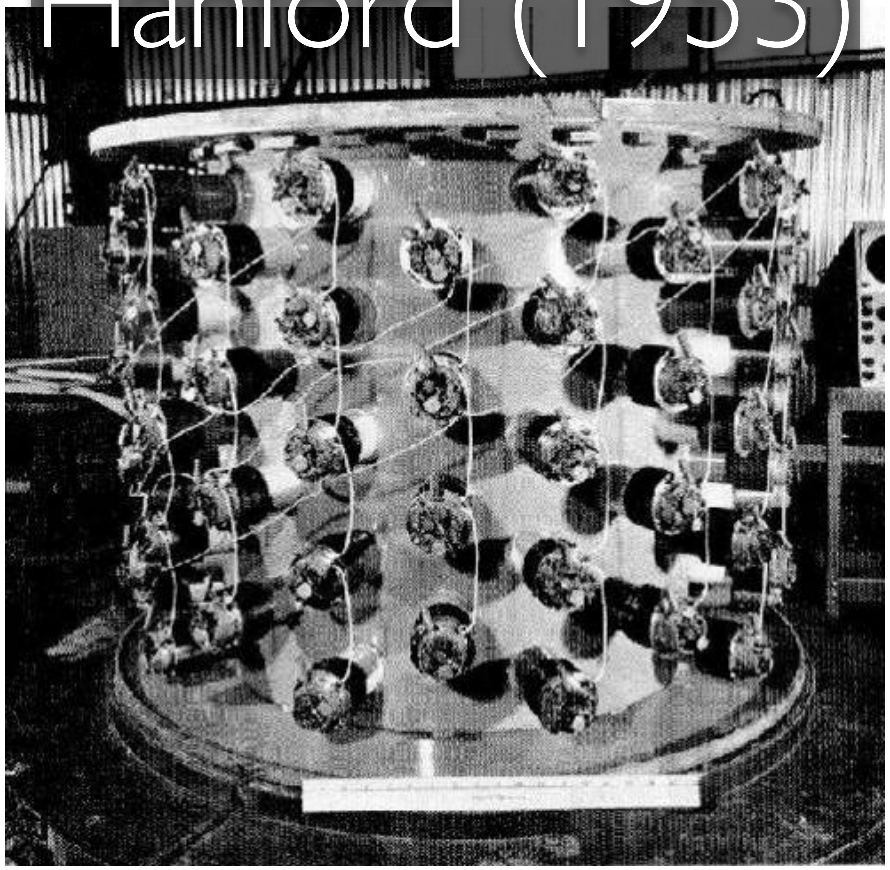


no e+ PID implies

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

Reines&Cowan pioneering detection…

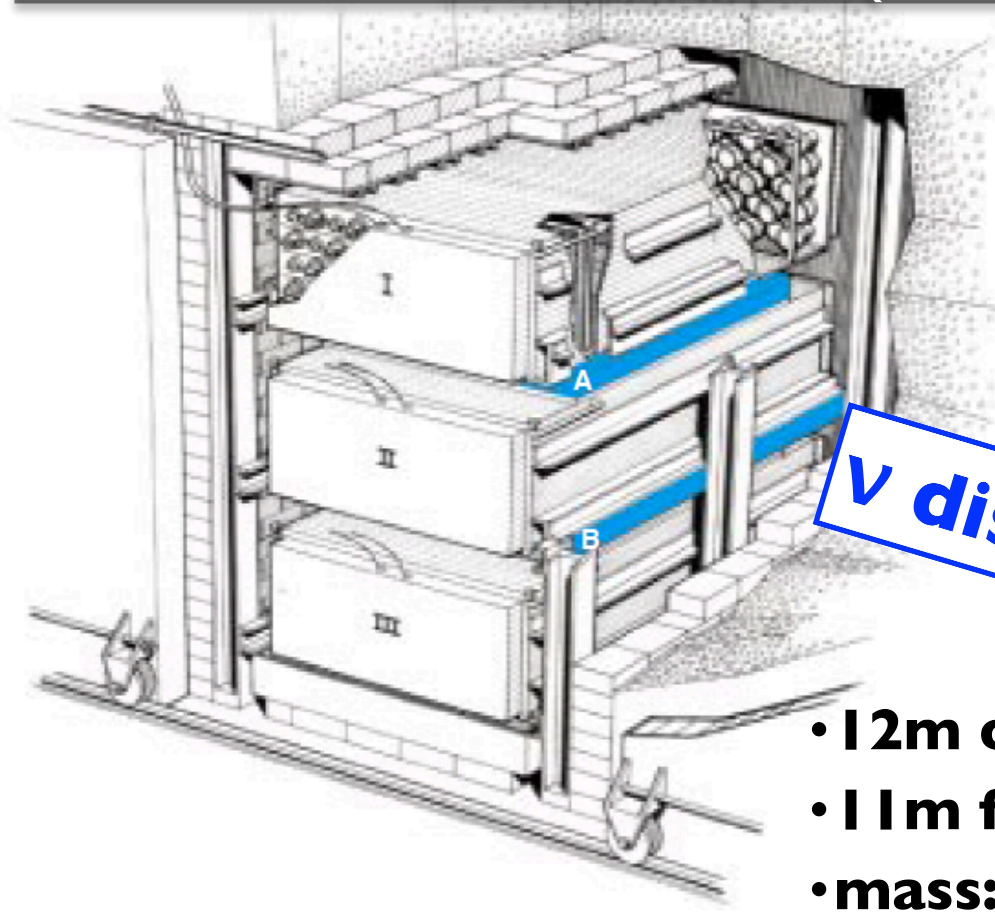
Hanford (1953)



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

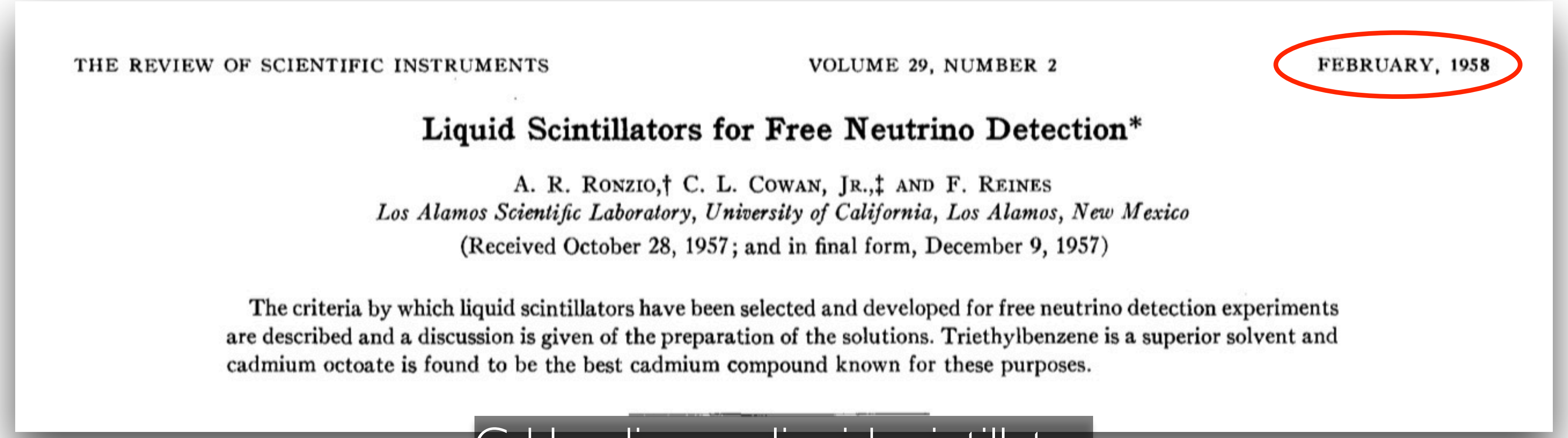
ν hint?

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)

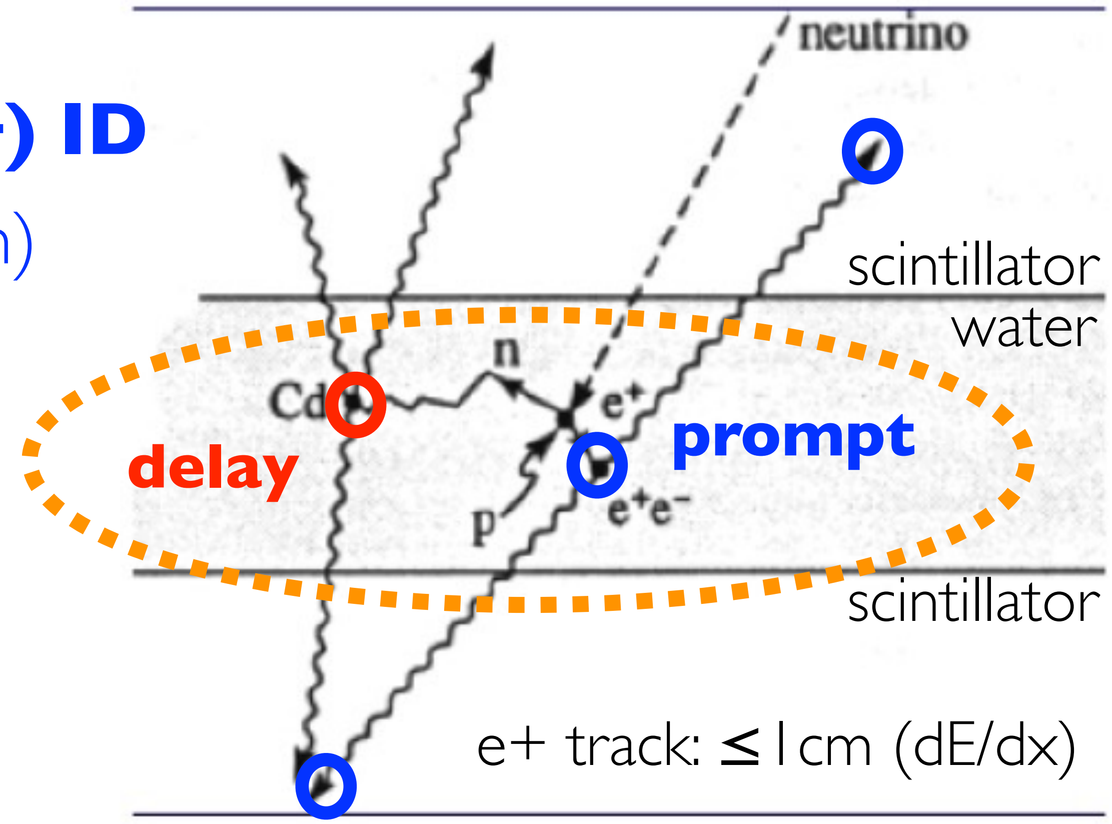
The criteria by which liquid scintillators have been selected and developed for free neutrino detection experiments are described and a discussion is given of the preparation of the solutions. Triethylbenzene is a superior solvent and cadmium octoate is found to be the best cadmium compound known for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

Cd loading on liquid scintillator

Reines& Cowan powerful coincidence (IBD)…

annihilation (e+) ID

(→segmentation)



coincidence

[scale **O(μs)**]

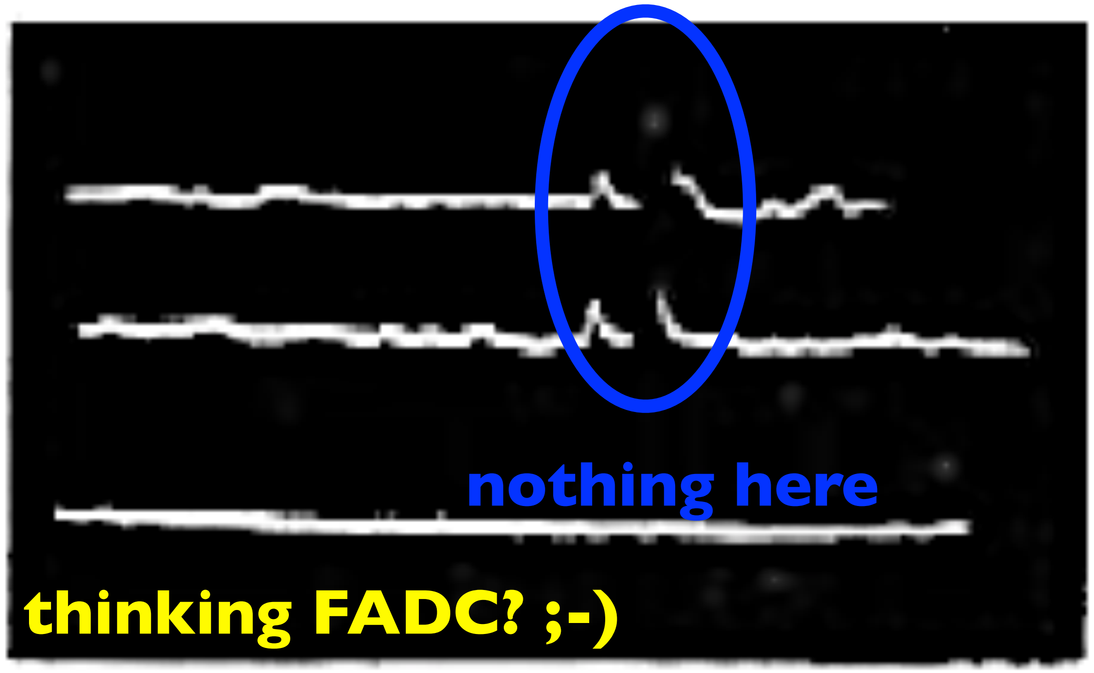
e+ annihilation (2x 0.511MeV)

n-Cd capture (~9MeV)

I

II

III



(a) Positron scope

Neutron scope

Reines&Cowan **detection strategy**…

PMT ⇔ transparent medium

overburden (μ-cosmic shielding)

external shielding (radioactivity shielding)

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

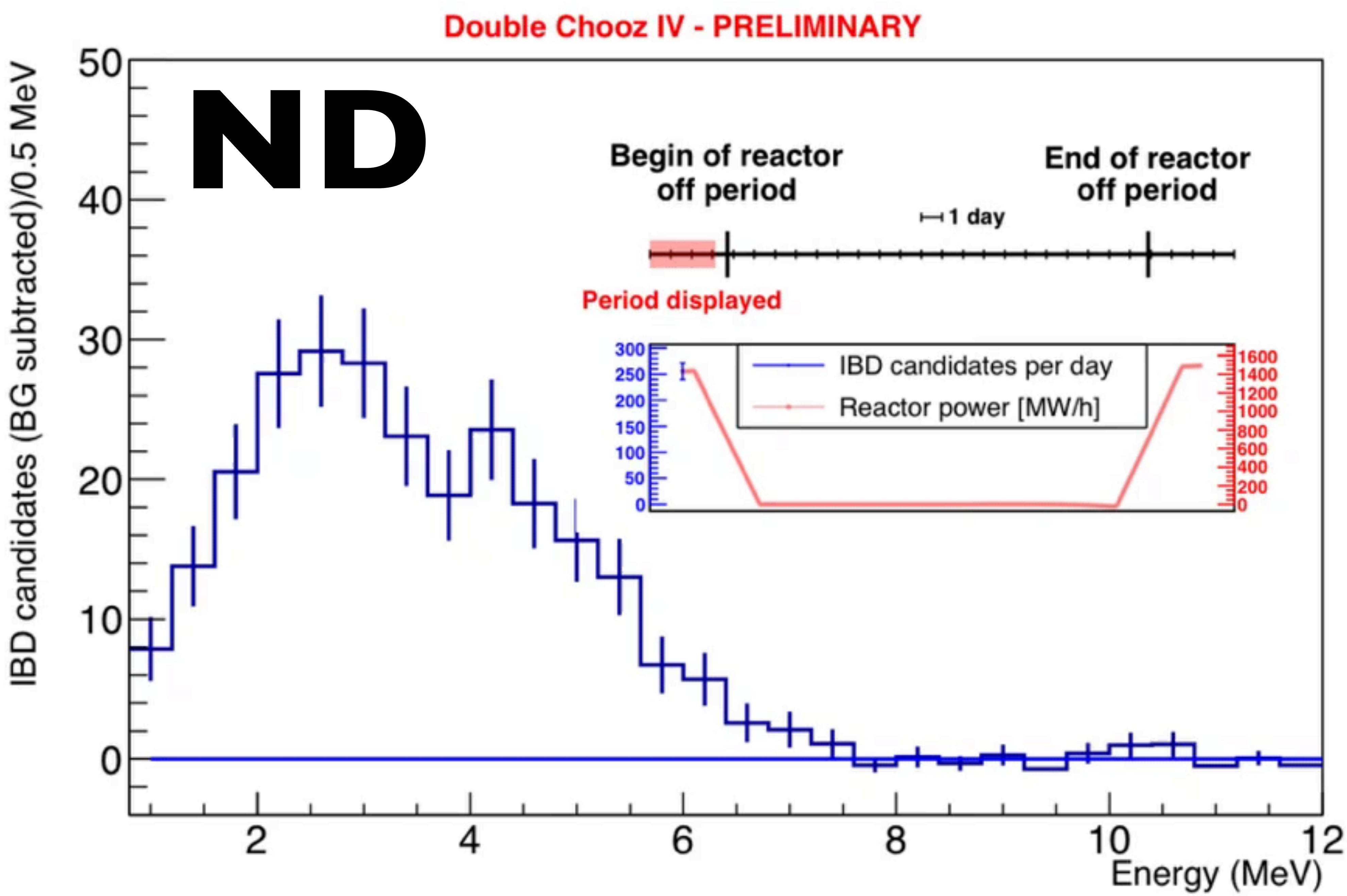
(reactor source) **modulation ON vs OFF**

~70years ago similar to today!


reactor-OFF…

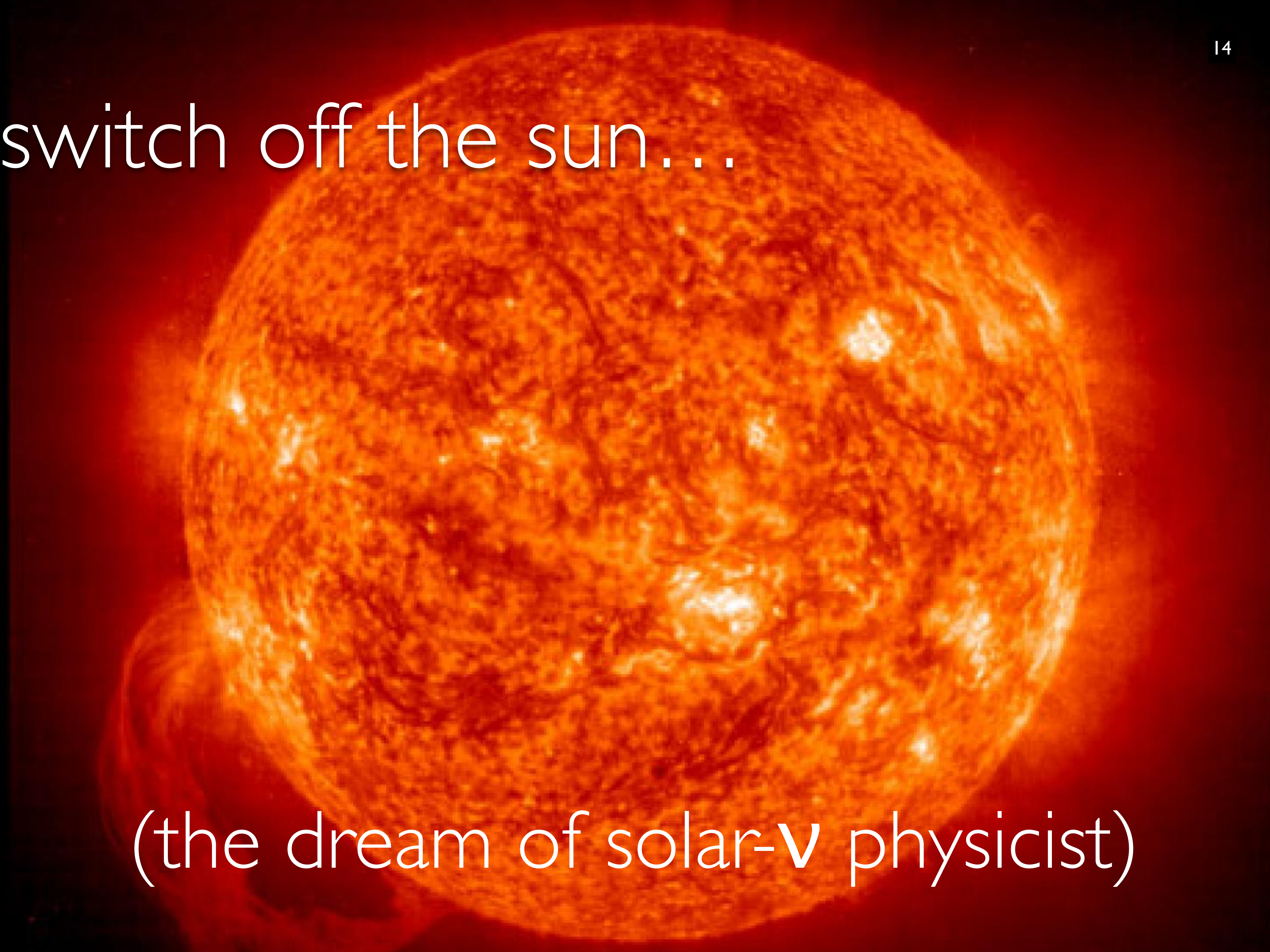
Double Chooz reactor-OFF: signal analysis…

rate(1 reactor) ≈ 3 IBDs/min



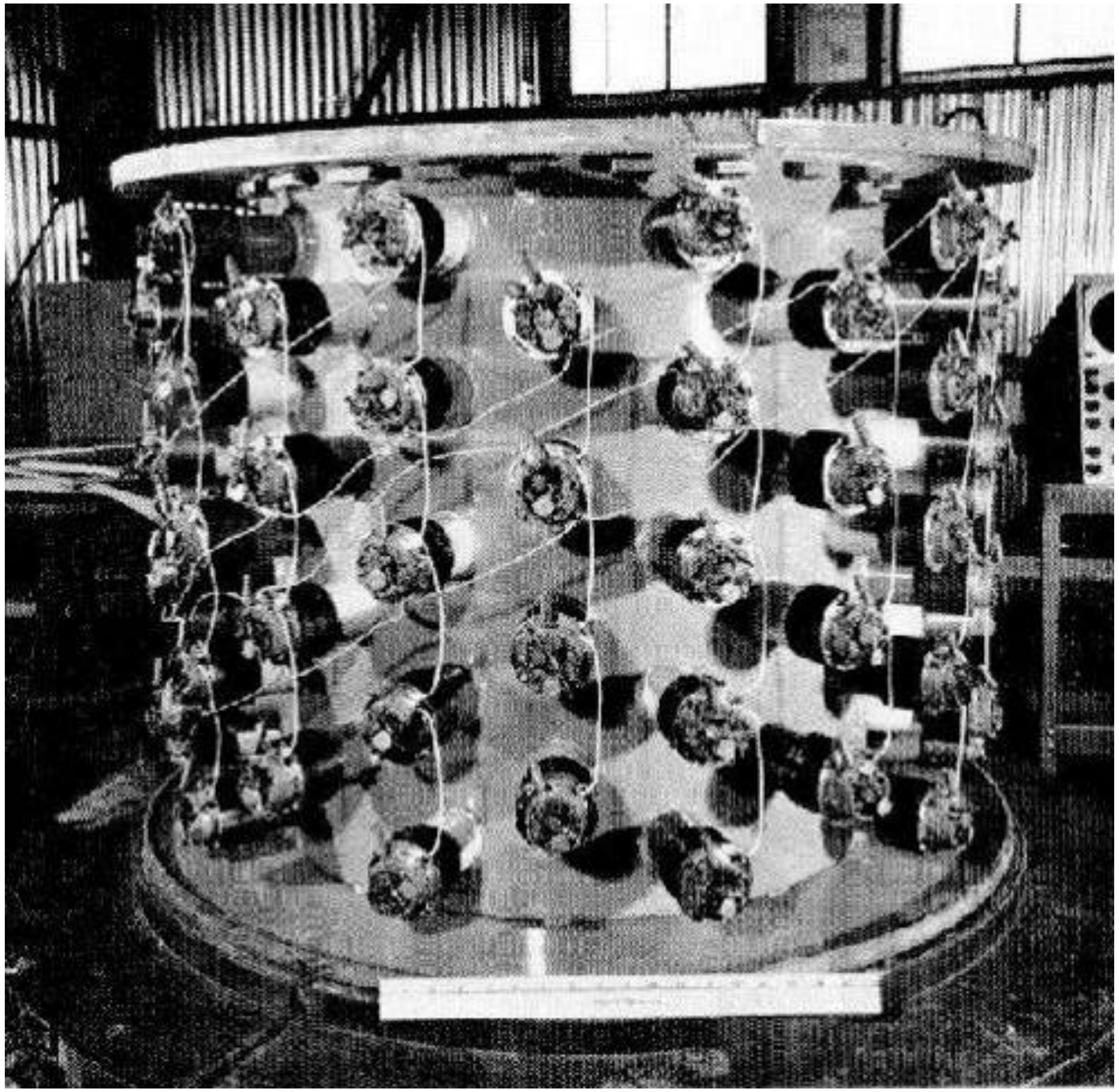
BG subtracted

switch off the sun…



(the dream of solar-ν physicist)

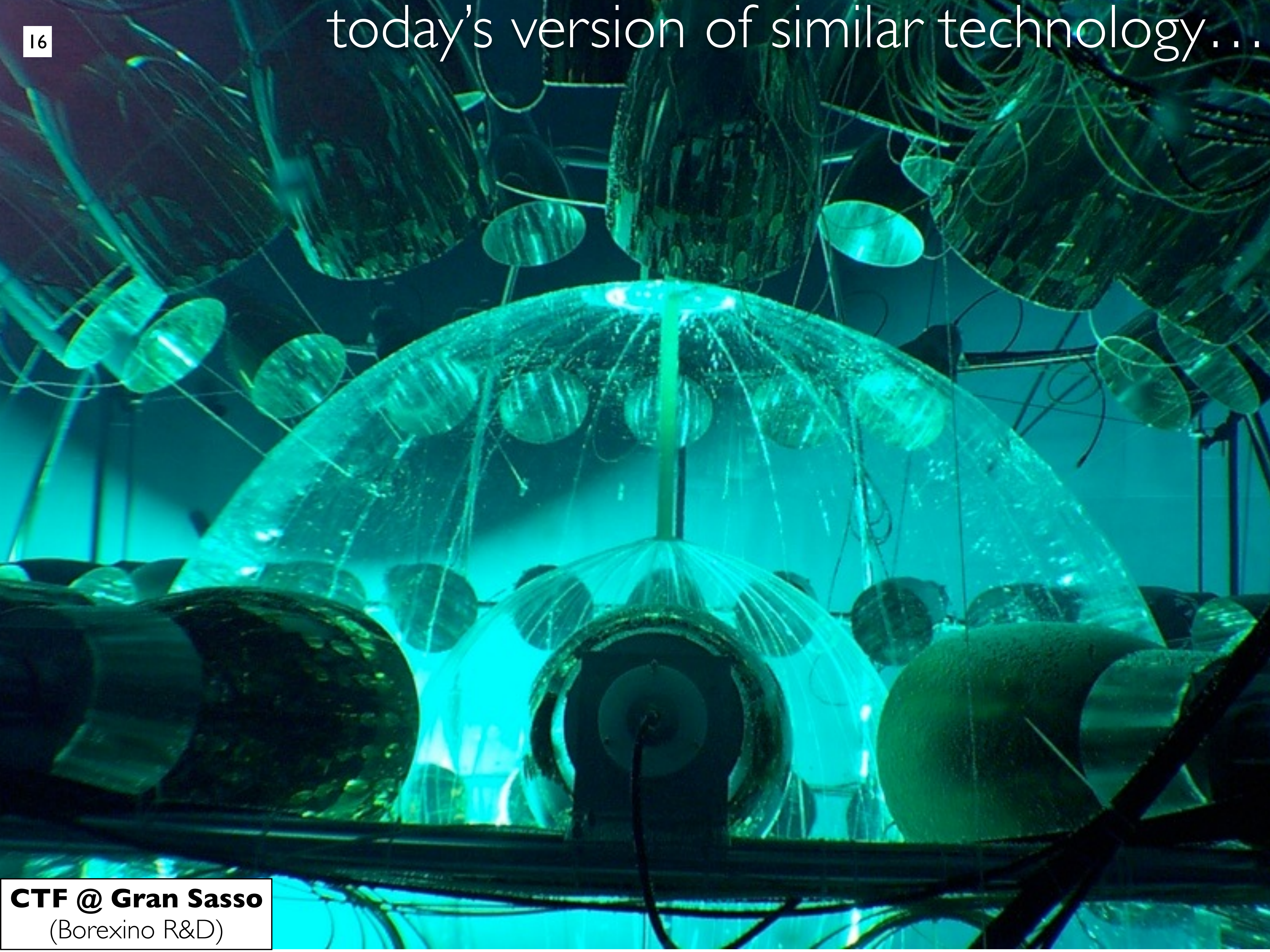
Reines & Cowan detector (300kg)…



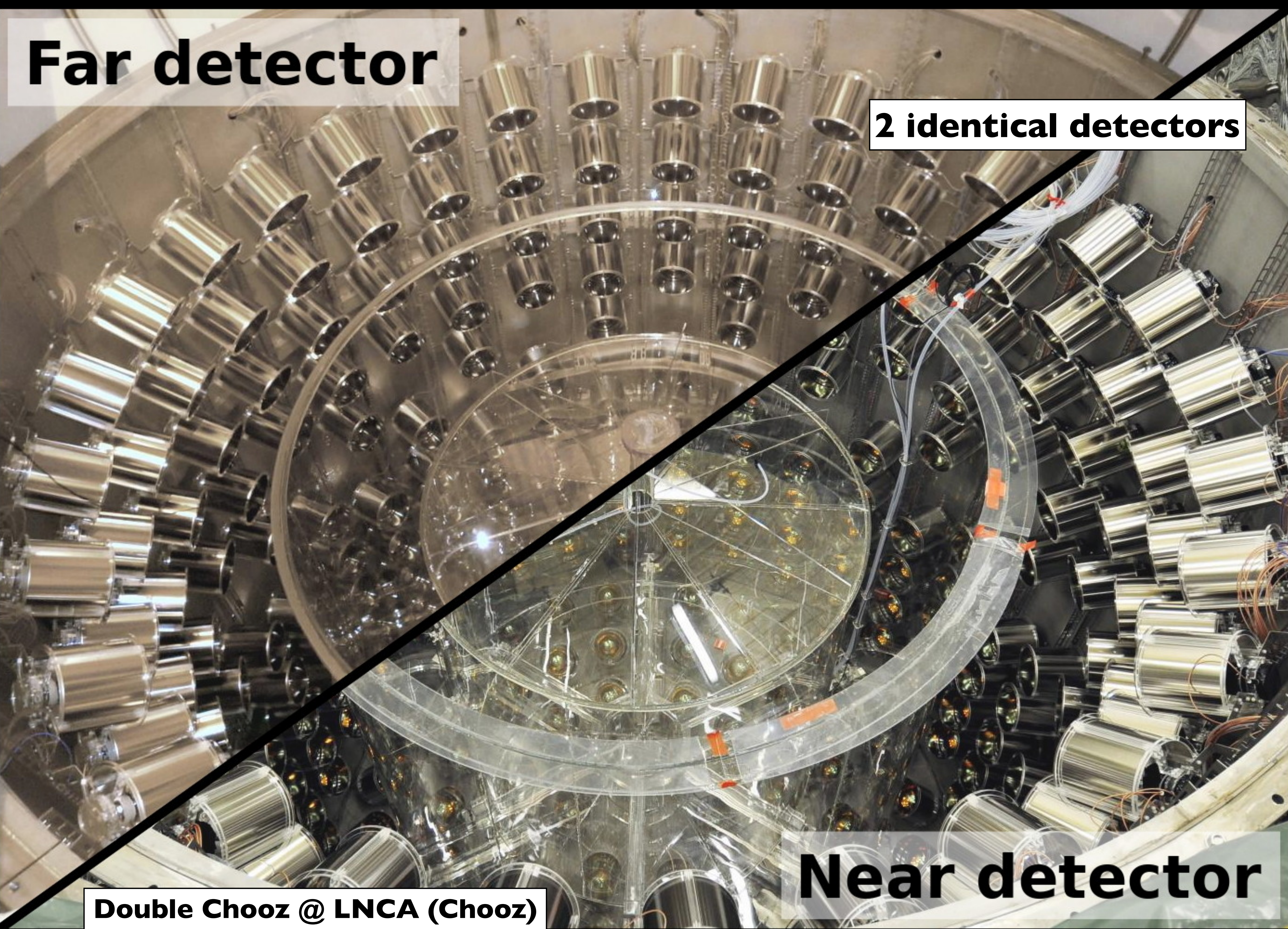
today's inspiration!

Handford (1953)

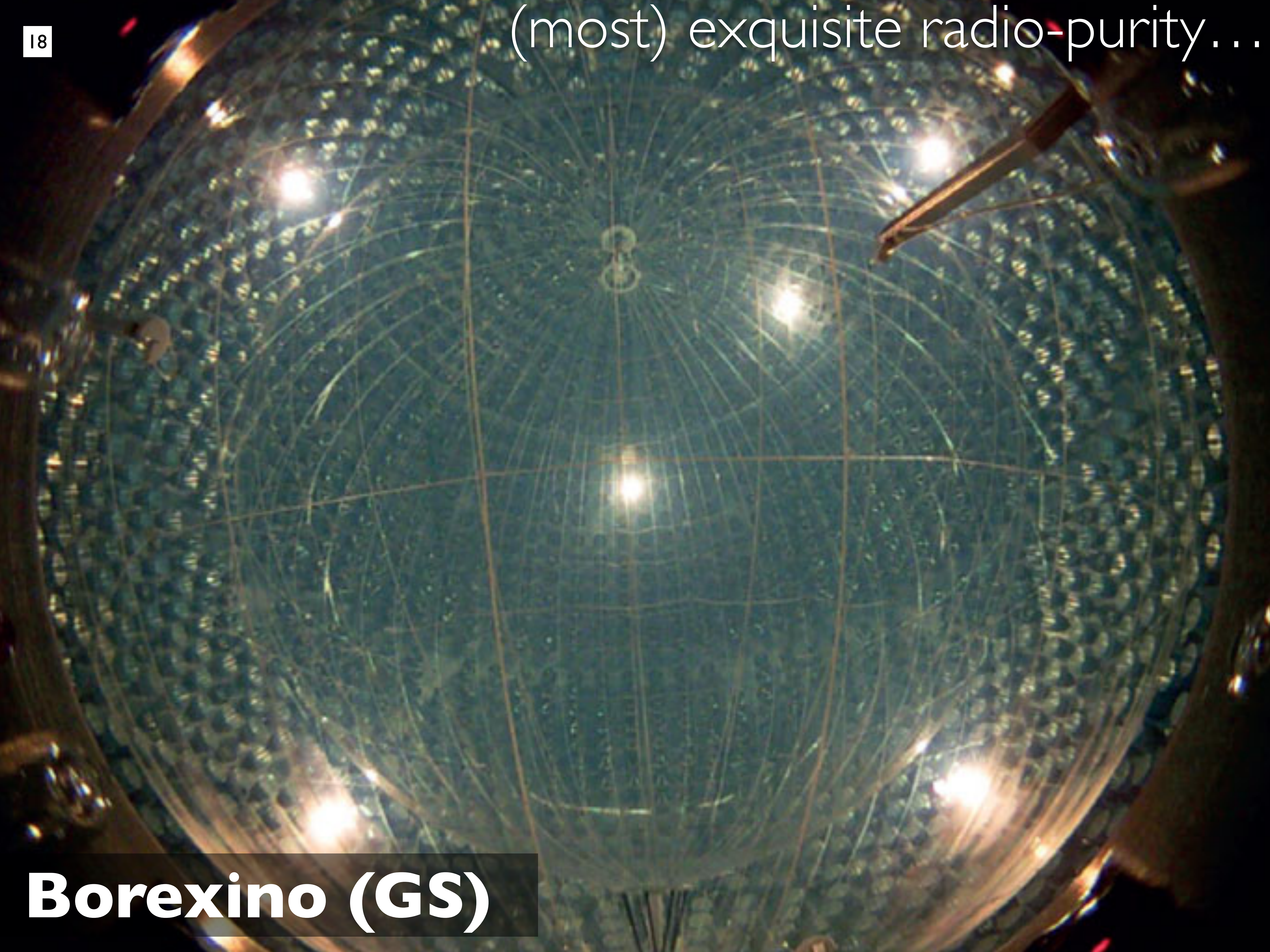
today's version of similar technology…



CTF @ Gran Sasso
(Borexino R&D)


Far detector
2 identical detectors
Near detector
Double Chooz @ LNCA (Chooz)
(Buffer: ~100 ton)

(most) exquisite radio-purity…



Borexino (GS)

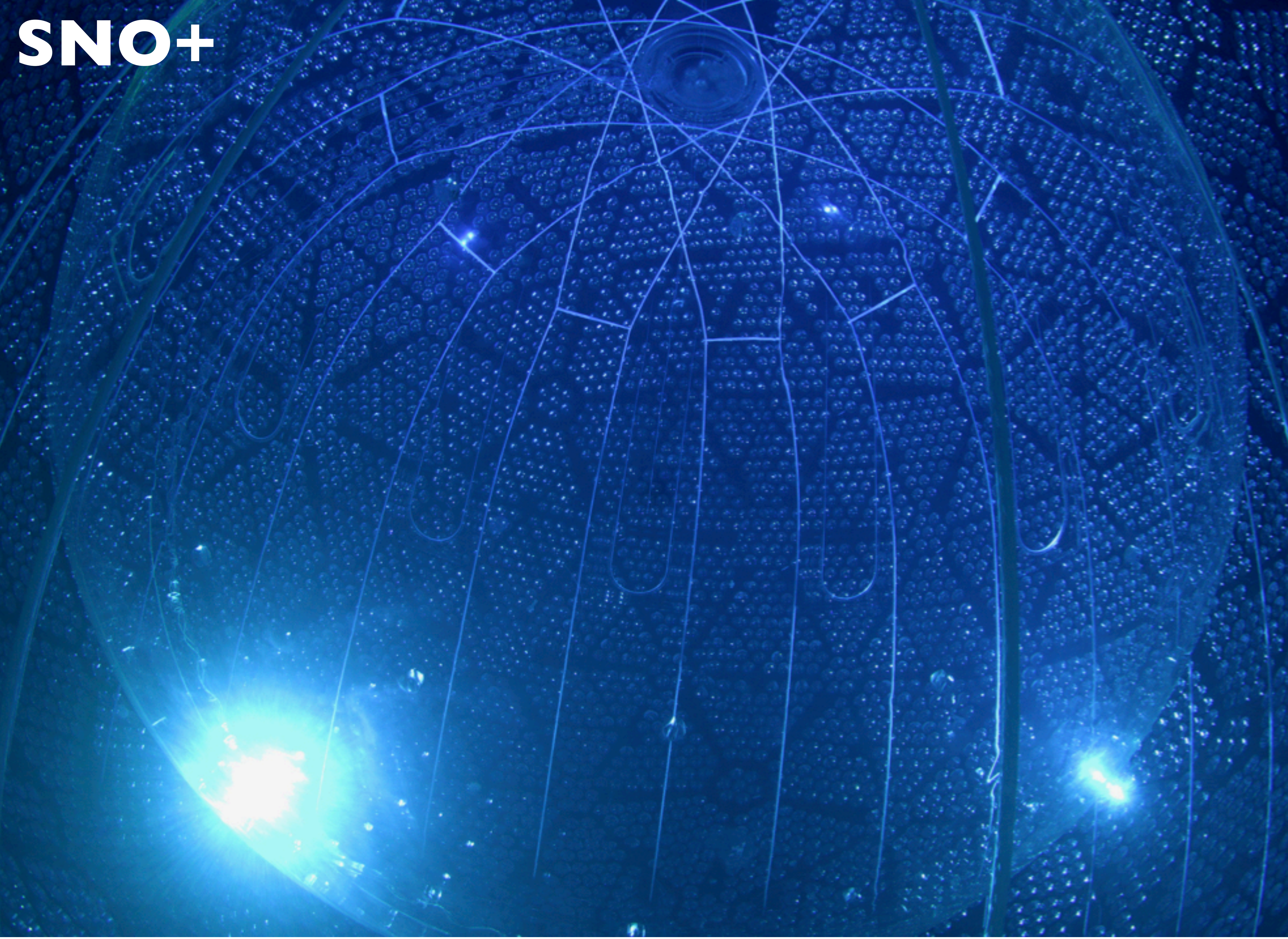
SNO

large (1k ton)...

SNO @ Canada
(Nobel prize 2015)

NOTE: KamLAND similar size but balloon

SNO+



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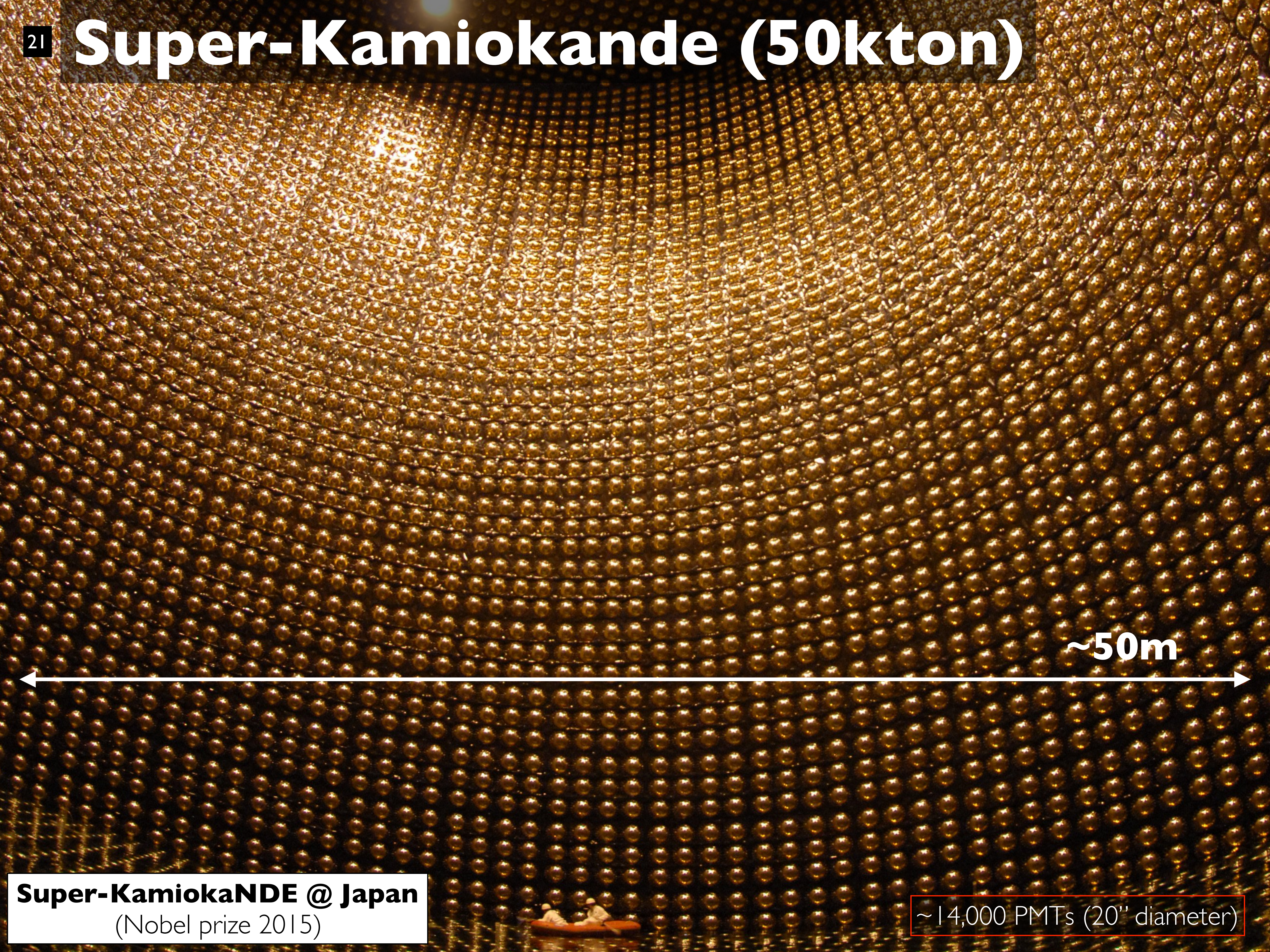
Super-Kamiokande (50kton)



neutrino detection ↔ art of transparency

[Reines&Cowan since 50’s]

LiquidO's motivation…

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

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]

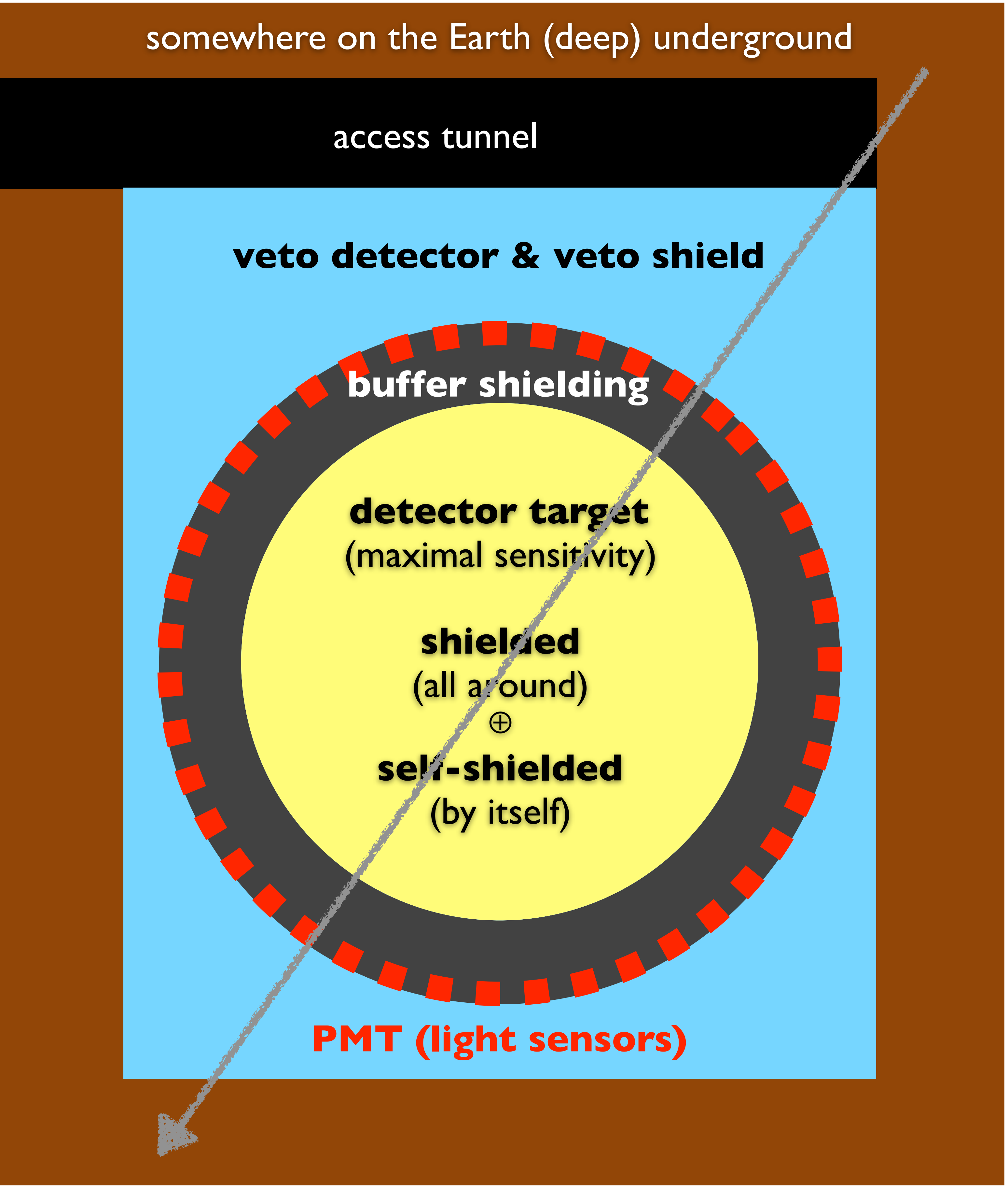
PMT(~1ns) ⇔ **Transparency** ⟹ ~~**PID**~~**?**

CTF @ Gran Sasso
(Borexino R&D)

an **Opaque** solution to PID…?

a **shielding** story…

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:

$\Longrightarrow$ **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:

$\Longrightarrow$ **no native track topology!!**

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

today's technology is much about **lot of shielding**
(several layers: **active** & **passive**)

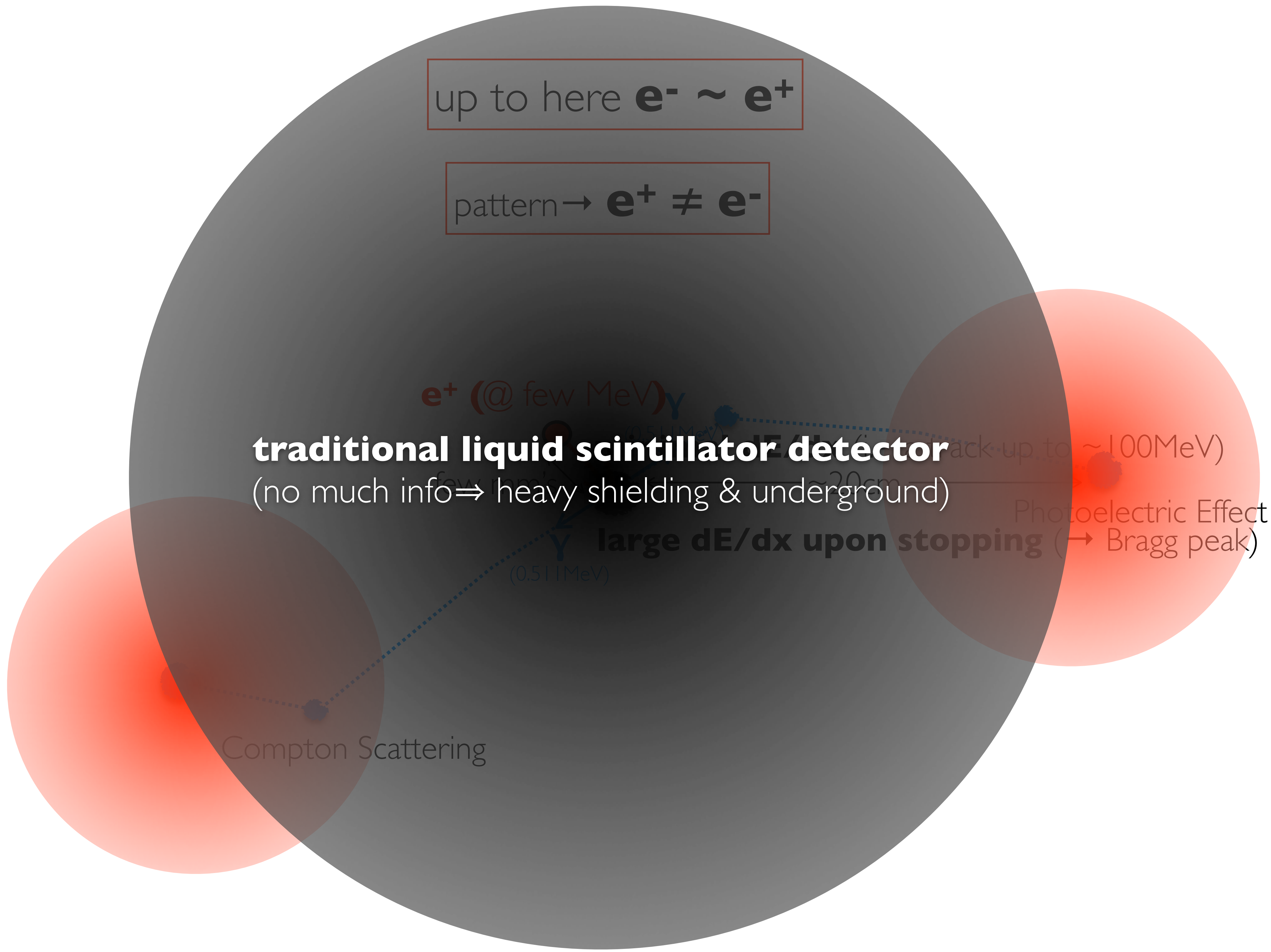
up to several kilometres of overburden needed
(if new underground facility was needed: large cost for construction & running)

(typically)
$\geq$half of the excavated volume "wasted" into shielding
(buffer very precious/expensive volume since fully instrumented)

if more shielding than detector, I wonder…
is this the right detector for that purpose?

why limited self-shielding?

e+ PID limitation (illustration)…

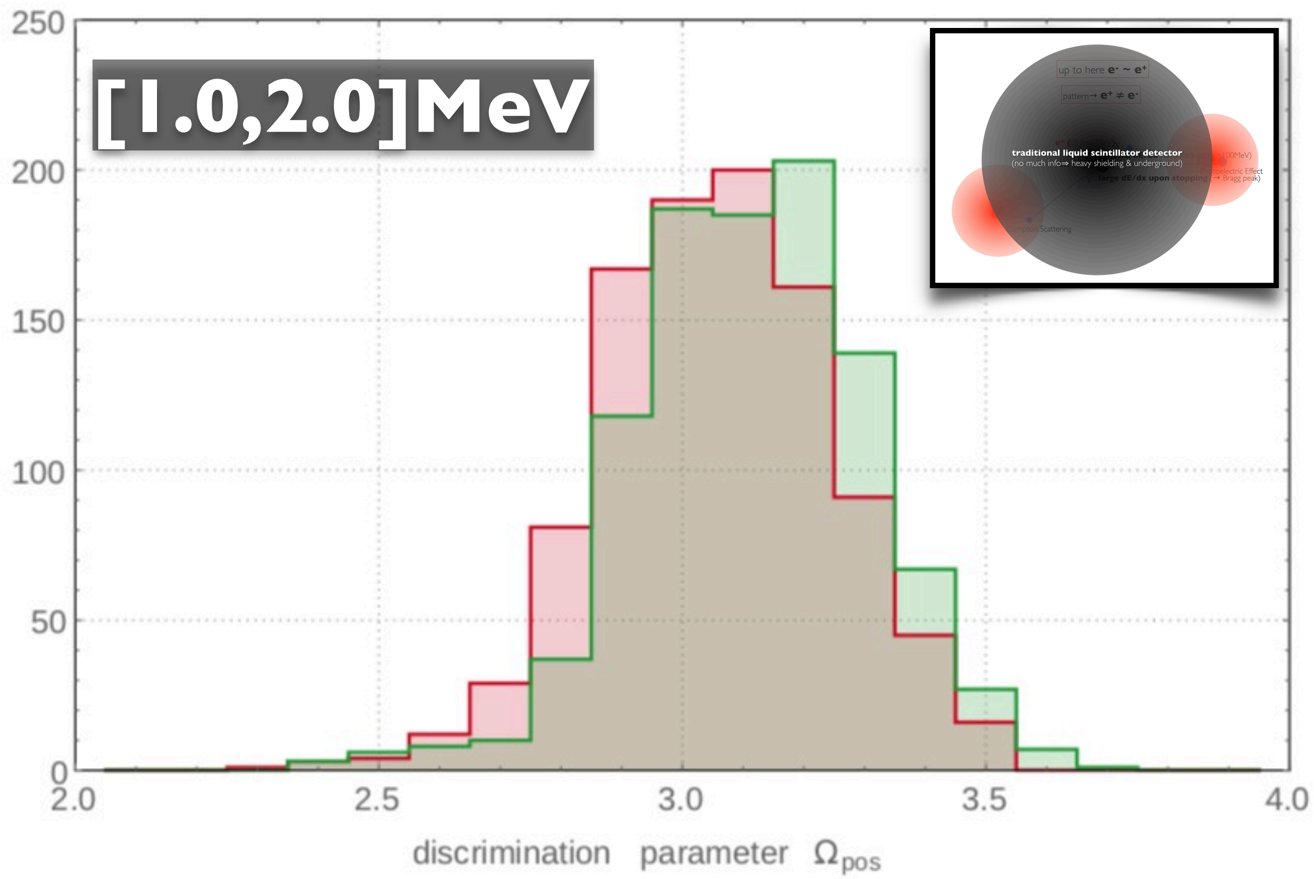


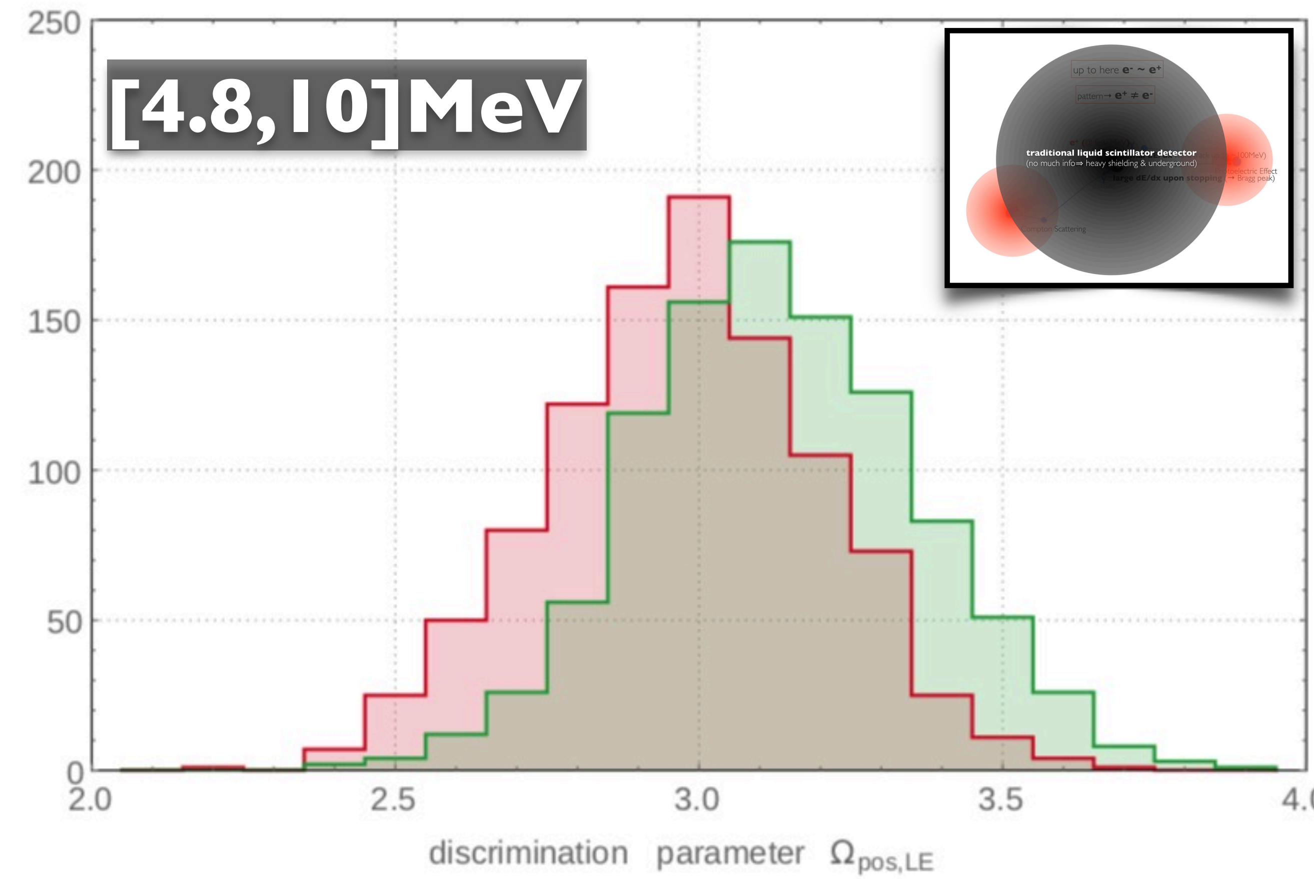
powerful event pattern washed out⇒ hardly any ID!

powerful Pulse-Shape ID @ Double Chooz …

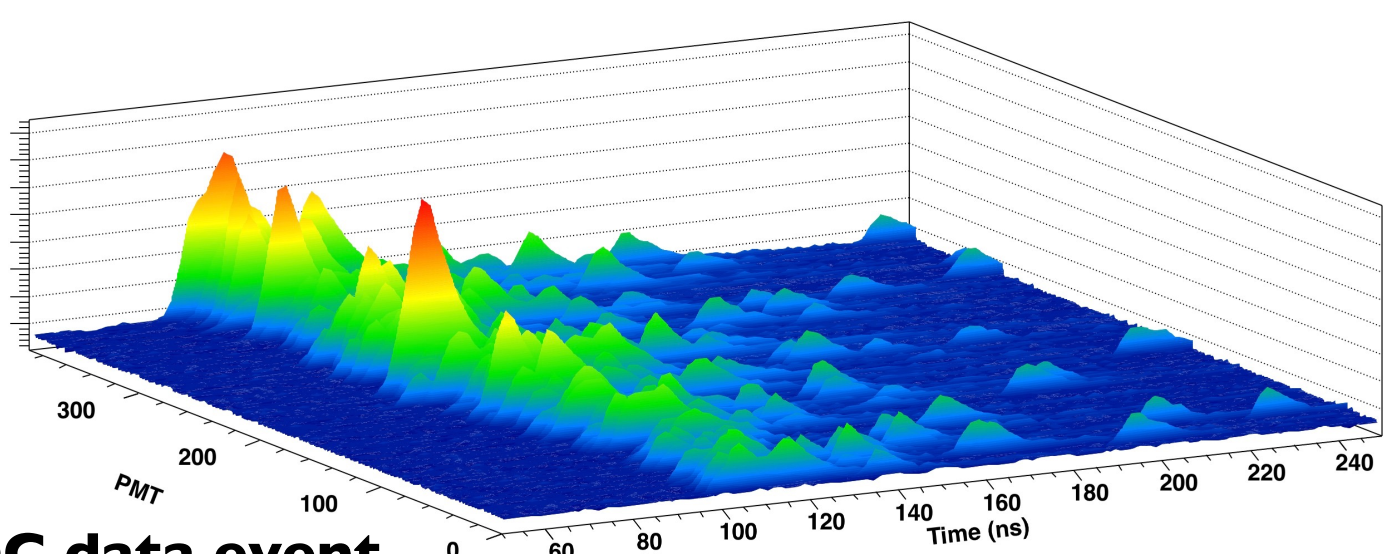
arXiv: 1710.04315

e+ (exclude OPS)
e-





Ω(PID) = scintillator $\oplus$ FADC $\oplus$ Fourier



example of FADC data event

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 [individual vertex]

liquid→(easy) loading BUT risks transparency!!

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

true still today?

PMT (precious technology from 30's)…

but

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

- **low-ish QE** (≤30%)
  [SiPM: ≤60%]

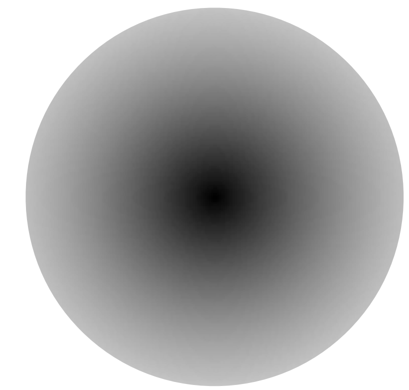
- **PMT photocathode radioactive!!**
  [**buffer**→≥50% volume lost]

let's dream **what we want**…

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

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

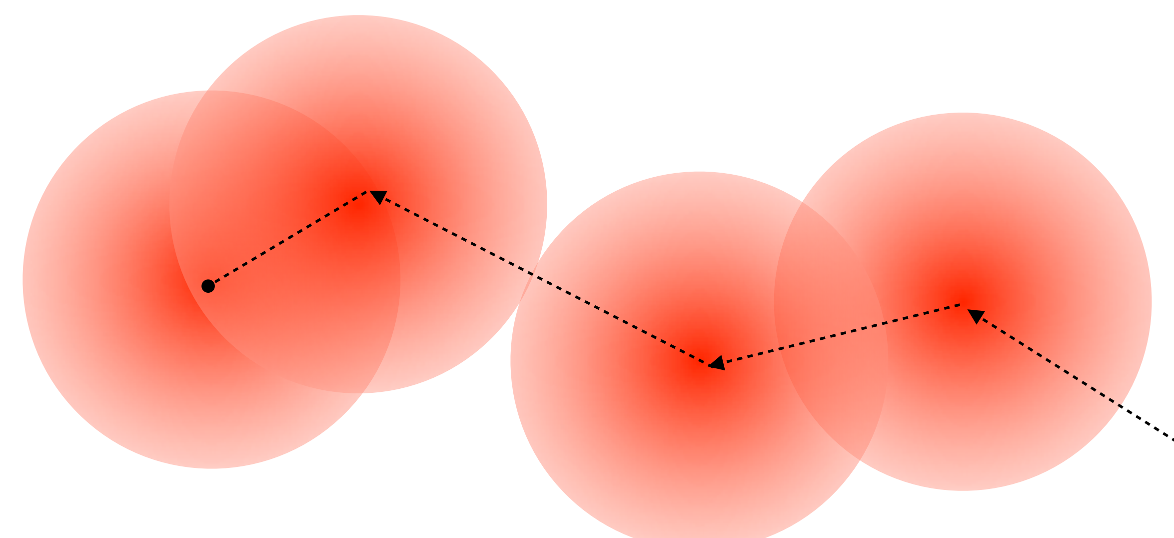
e⁻ ≈ α ≈ p-recoil (fast-n)



dE/dx→ Bragg peak
(e- starts as MIP)

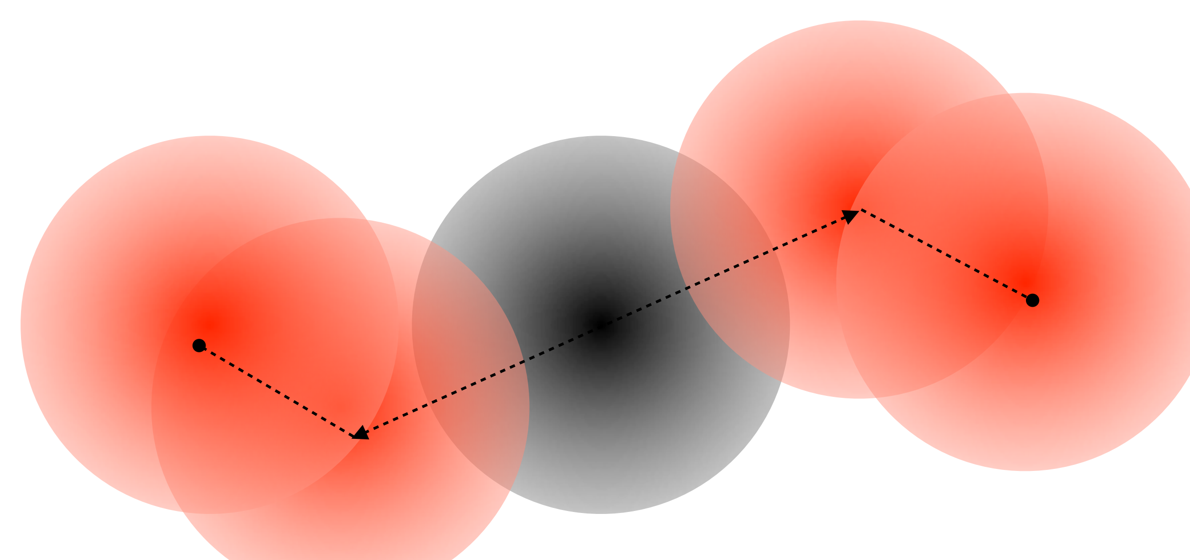
e⁻, **α** and **p** are **scintillation quenched→ PSD is possible!**

γ (gamma ray)



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

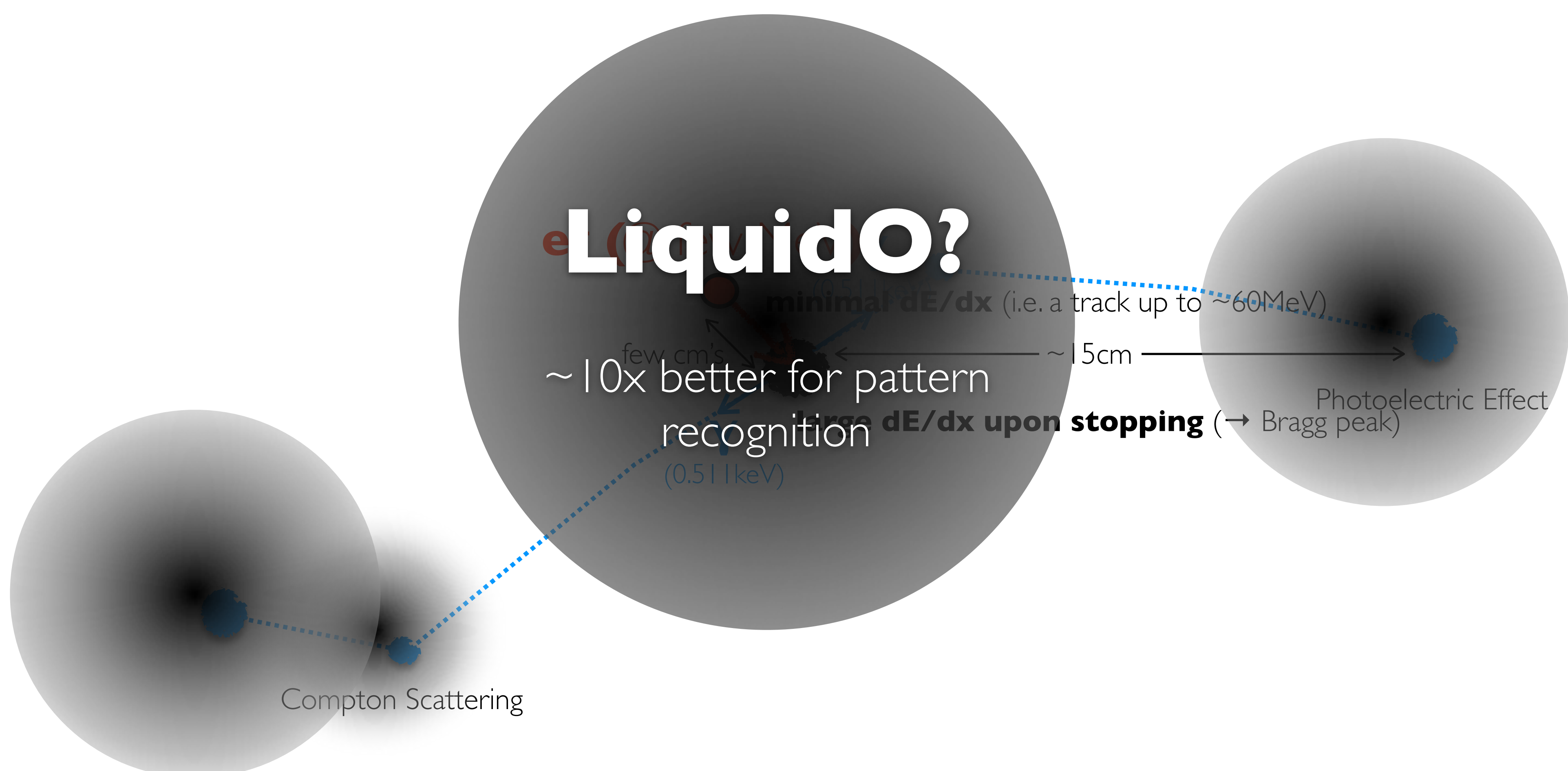
e⁺ ≈ e⁻ + 2x **γ**(511keV)



hybrid-like event

PID beyond today's LS technology…

pattern→ **$e^{+} \neq e^{-}$**



powerful event pattern⇒ differentiate particles (i.e. ID)

…and (maybe) much more!

LiquidO…

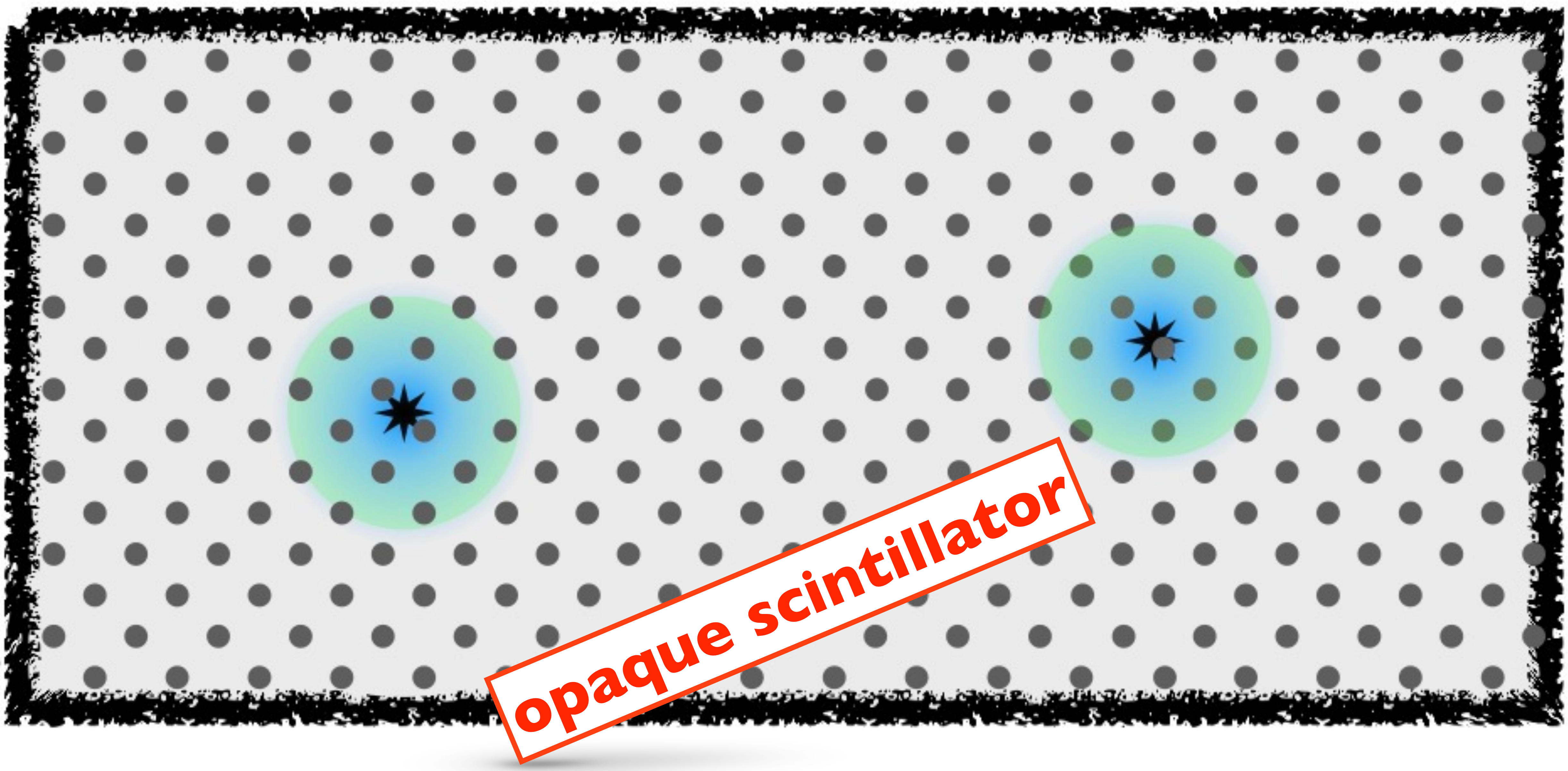
Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

Liquid

(first?) ν opaque detector

LiquidO: the detection principle…

confine energy deposition locally → freeze information

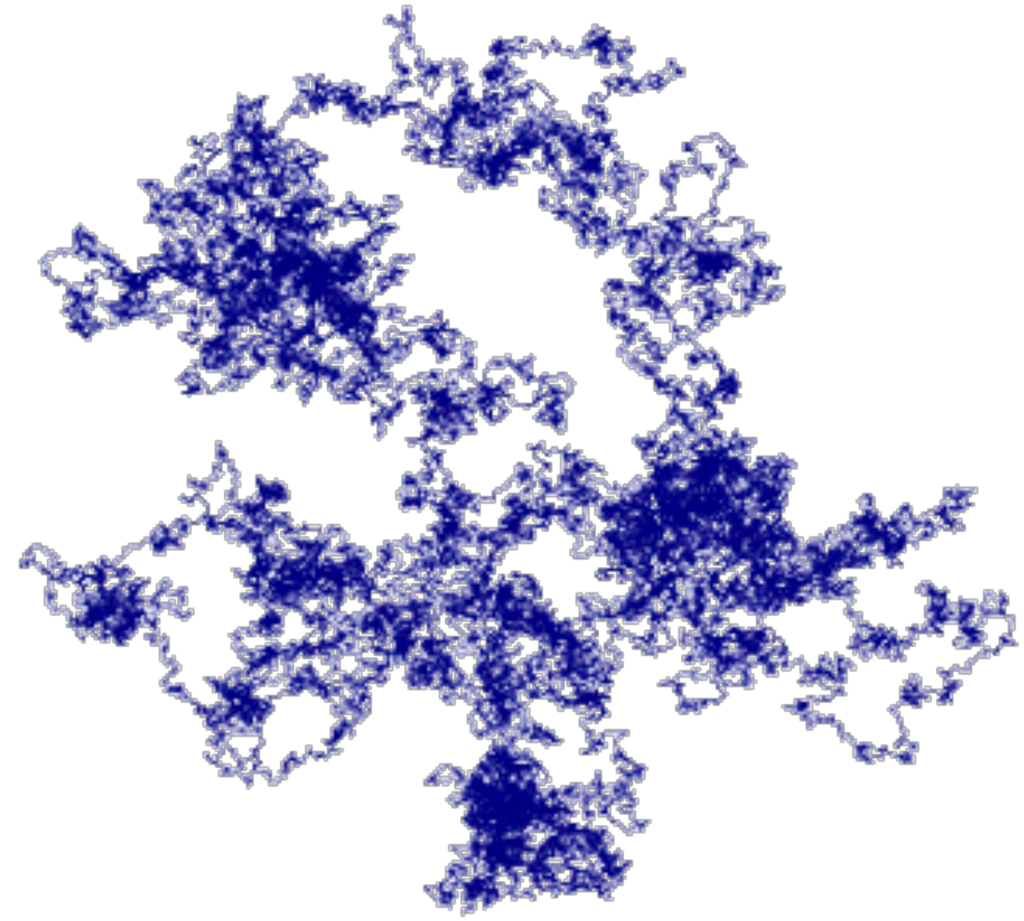


readout: wave-shifting-fibres⊕SiPM's

PMTs → become useless (unreachable light)

so, must confine light locally…

known light confinement strategies…

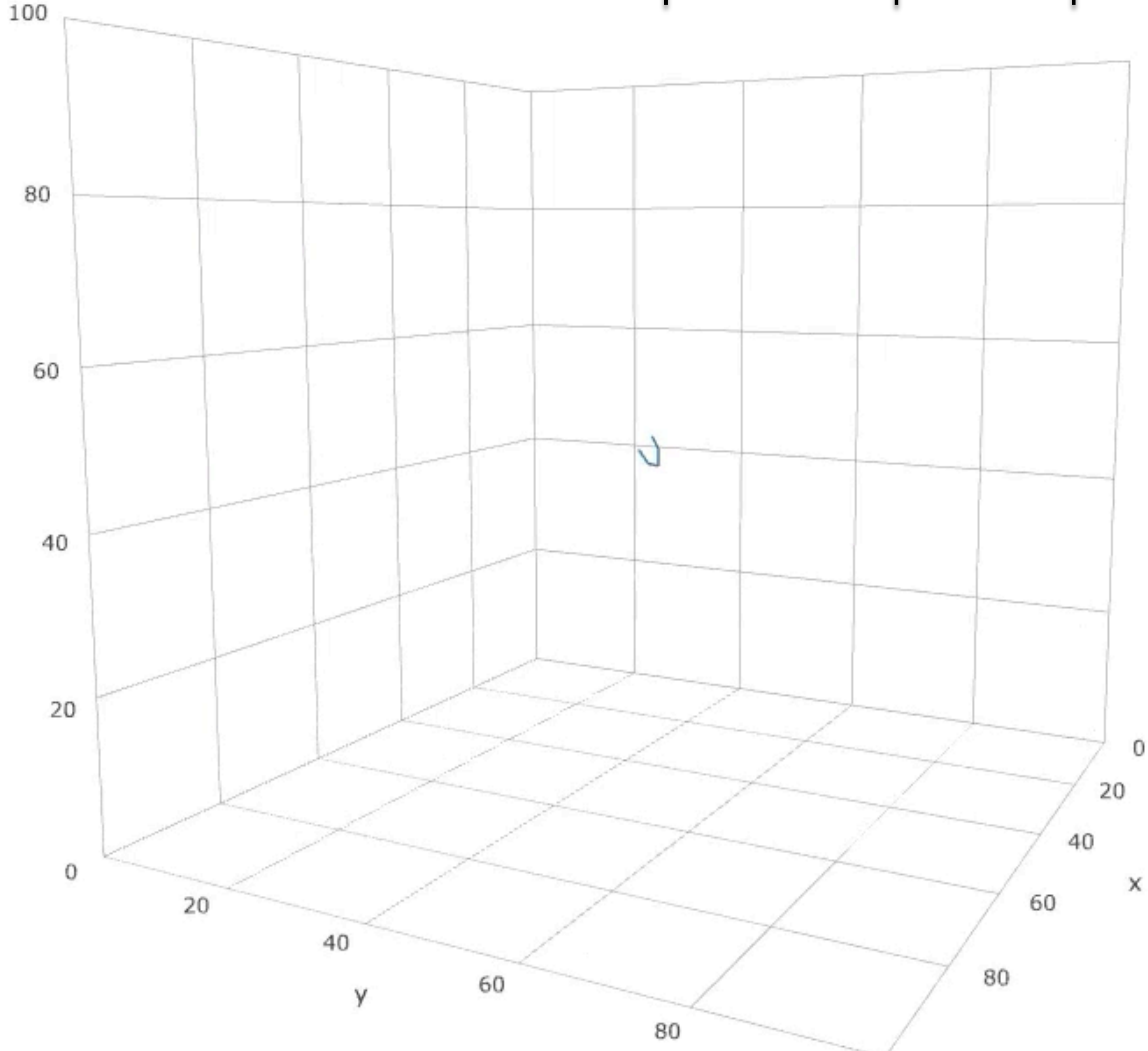


gravitational confinement
(ex. a black hole)

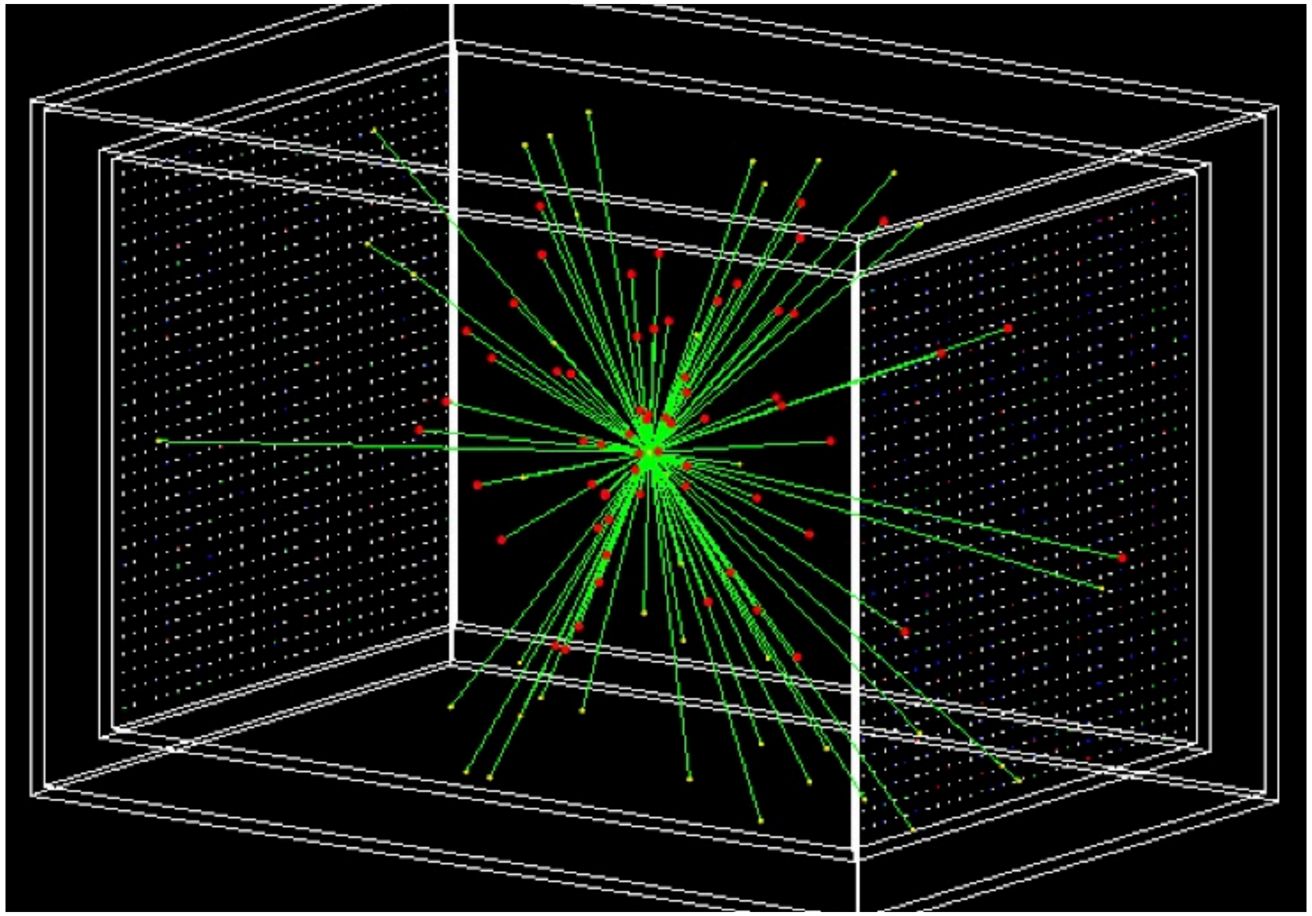
stochastic confinement
(ex. random walk)

light position restricted (both cases)

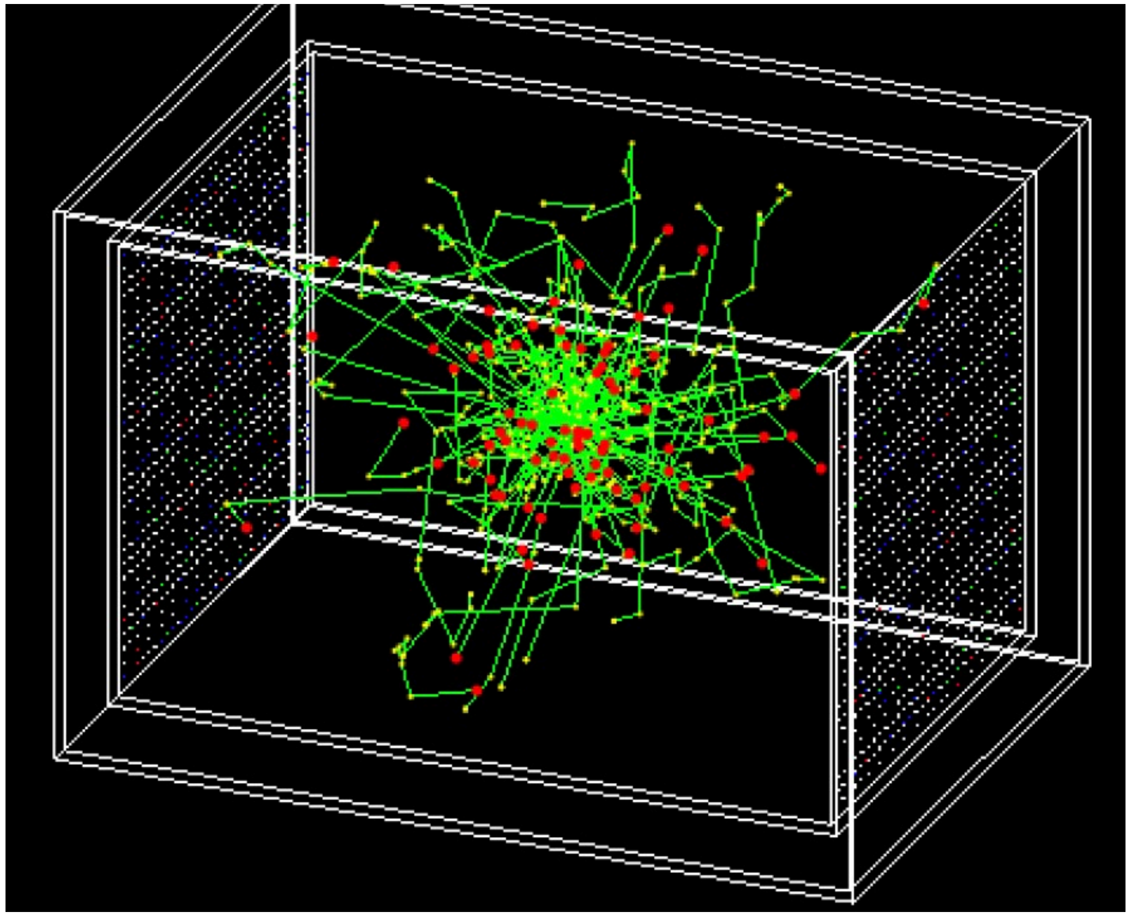
the life of LiquidO optical photon…



LiquidO recipe: just "bread & butter" physics…



today's technology



LiquidO technology

light ball size: scattering⊕fibres

(sampling optimisation)

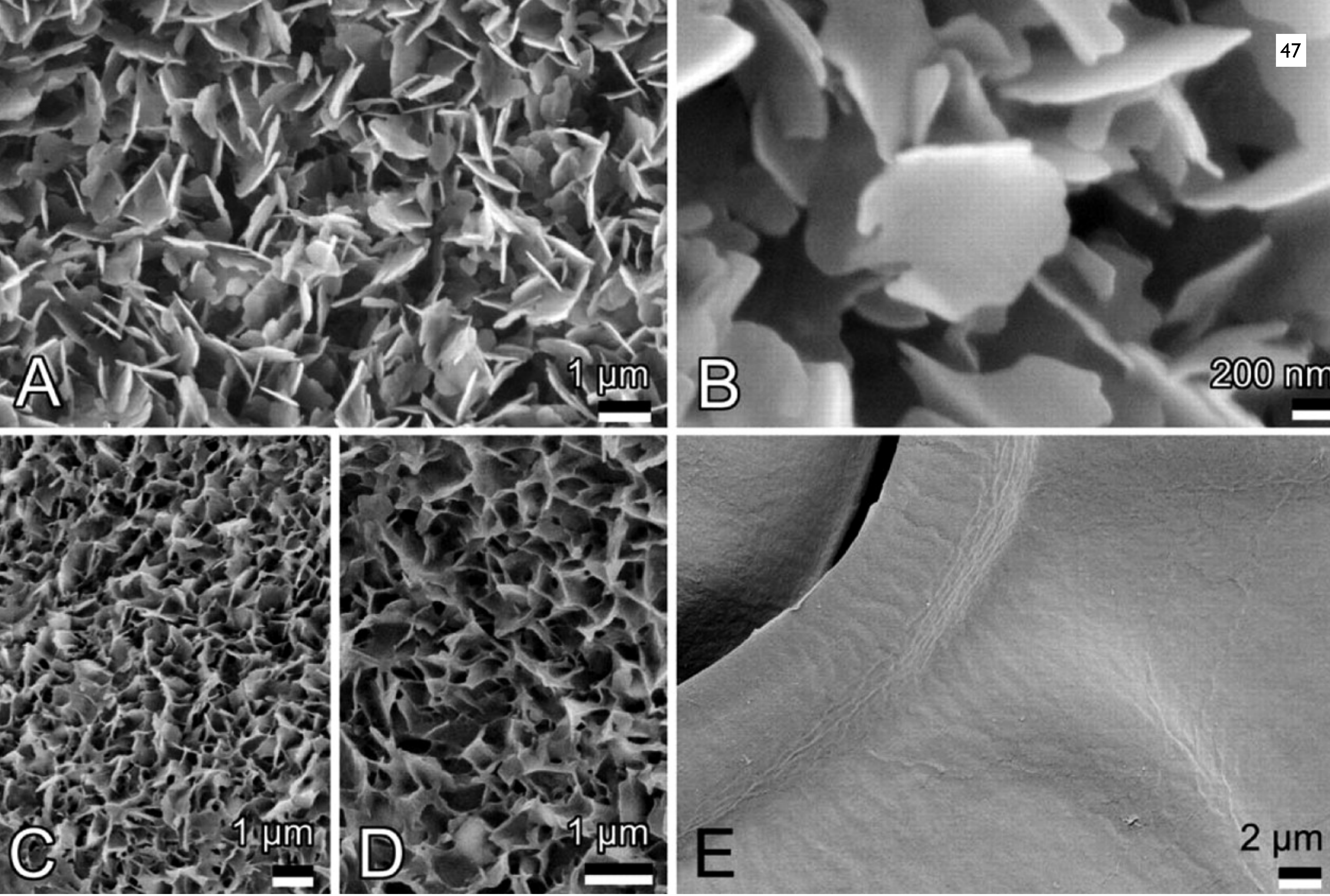
like this? (Ireland)

doe

like this? (France)

LiquidO = Liquid ⊕ Opaque

in reality, more like this…



wax random (amorphous) structure…

LiquidO implies (“theorem”)…

“milky” / “cloudy” / “waxy”

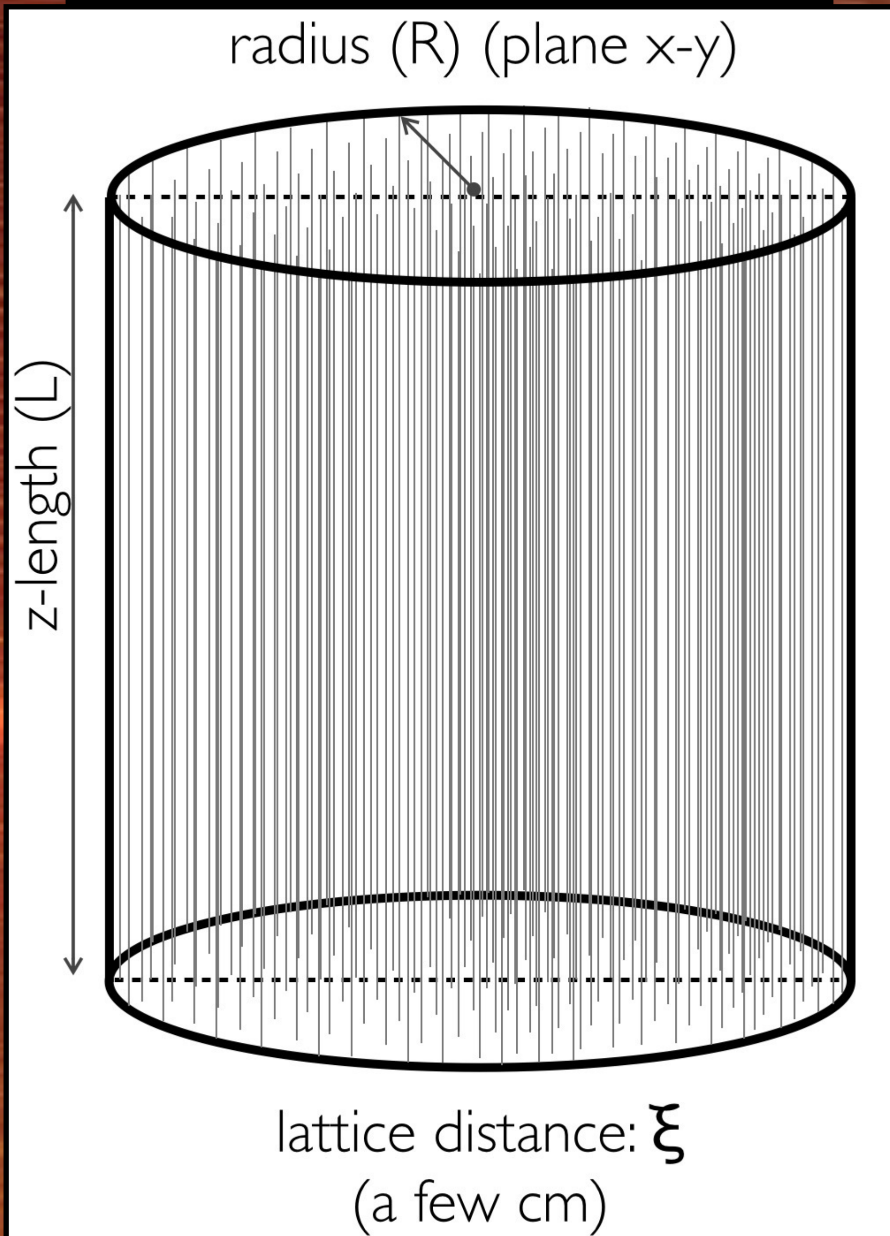
scintillator

(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 ~1cm)

(z) info [along fibre]→ **time difference** (up to cm's)

(also z-pixelation possible→ envisaged for R&D)

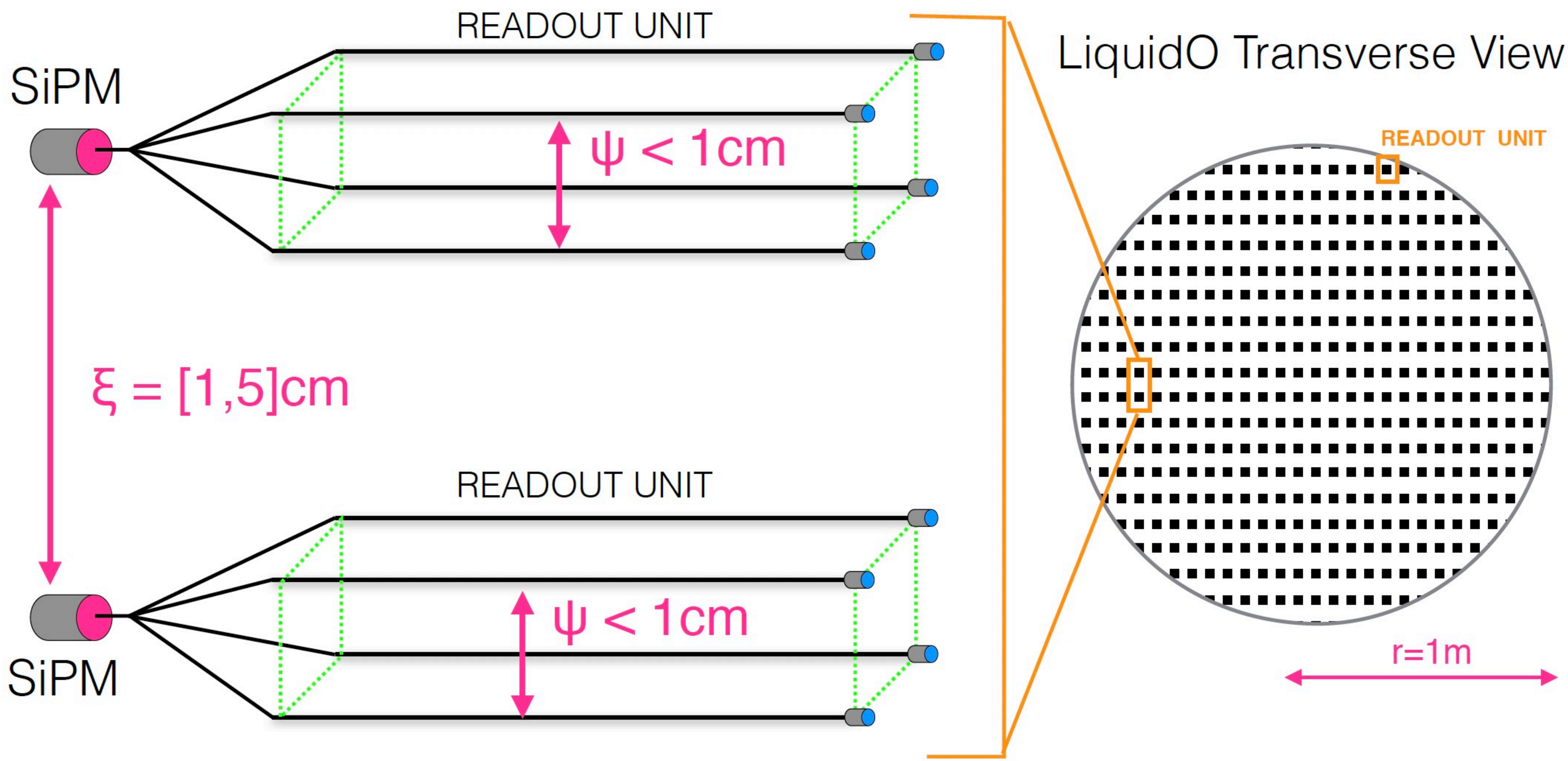
image: multi-wire chamber

(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…

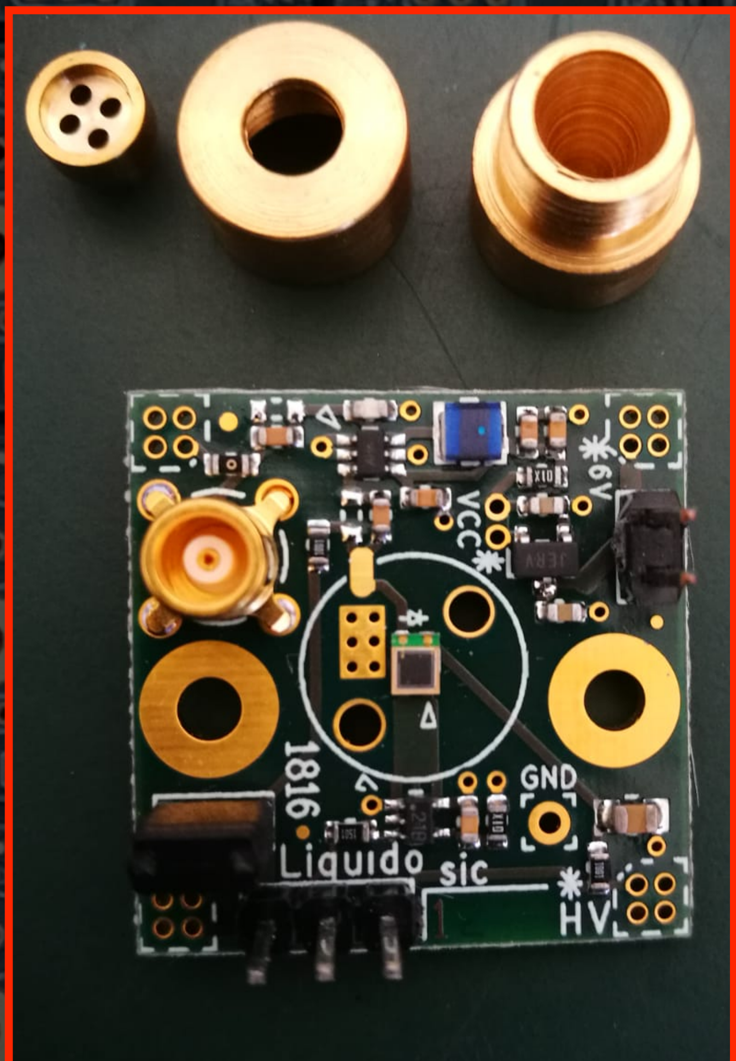


“infinitesimal” fibres→ MeV calorimetry

(reduce non-stochastic terms)

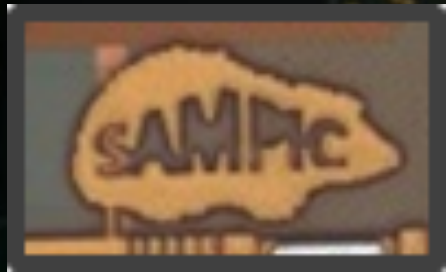
light readout via "collectors"…

(fastest) SiPM electronics readout…

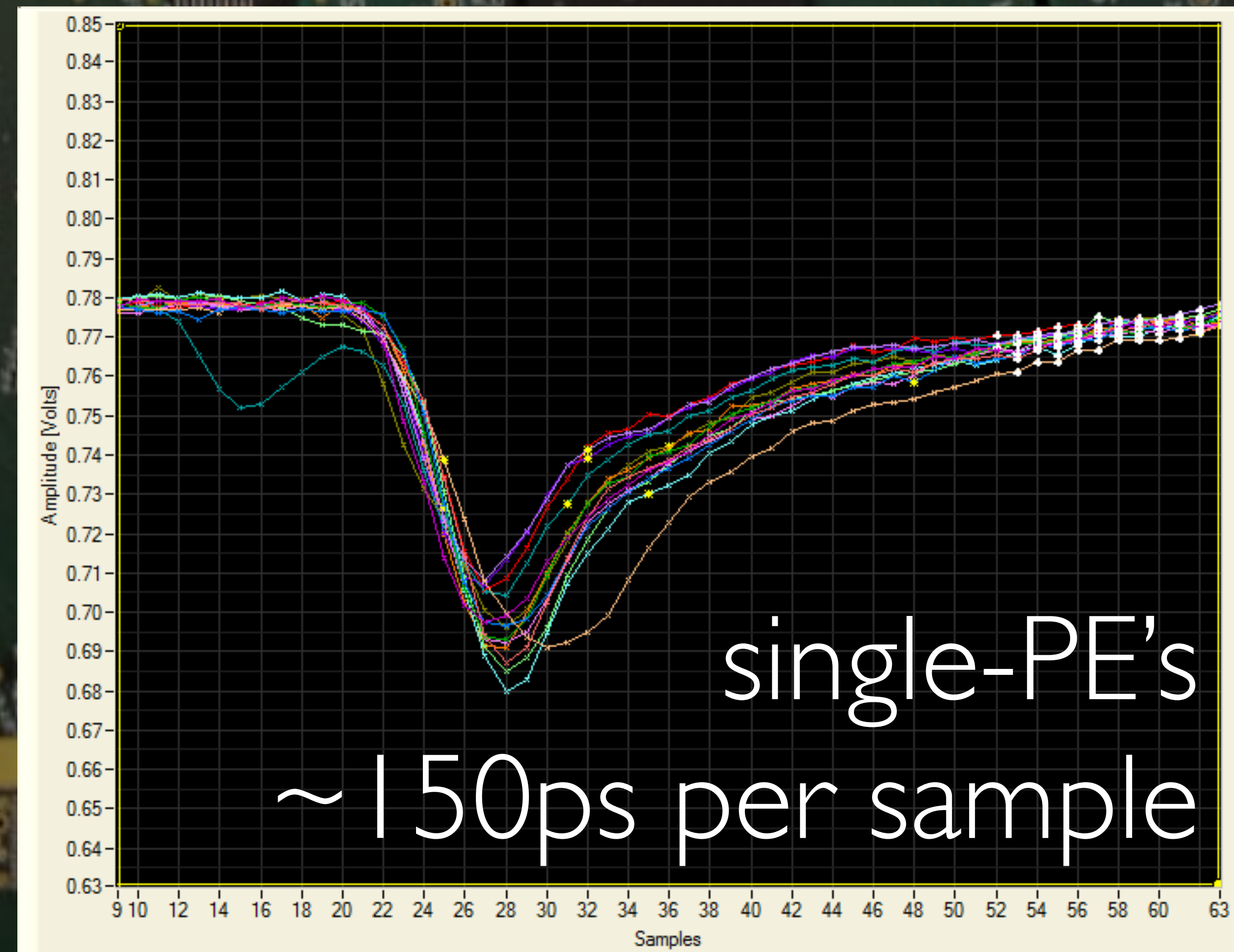


(expected) **time resolution: ≤100ps/PE**

(i.e. ≤3cm/PE @ speed of light)



our digitisation electronics…



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

(i.e. ≤3cm/PE @ speed of light)

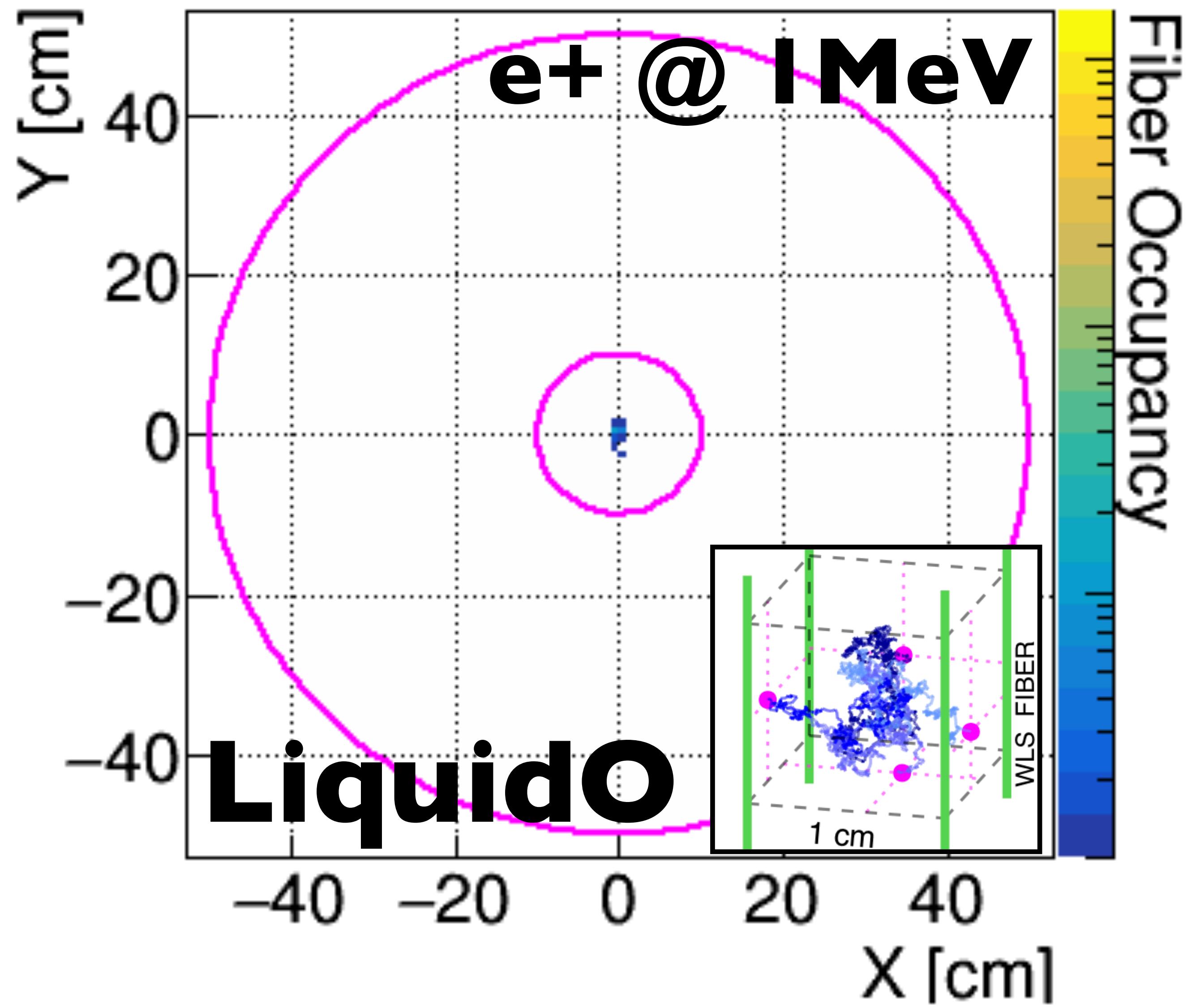
IEEE NSS (2014): The SAMPIC Waveform and Time to Digital Converter
NIM paper (2016): Measurements of timing resolution of ultra-fast silicon detectors with the SAMPIC Waveform Digitizer

(instrumentation-wise)

$\boxed{\textbf{LiquidO} \approx \textbf{“light” TPC} \oplus \textbf{4}\pi\textbf{-ToF}}$

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**]

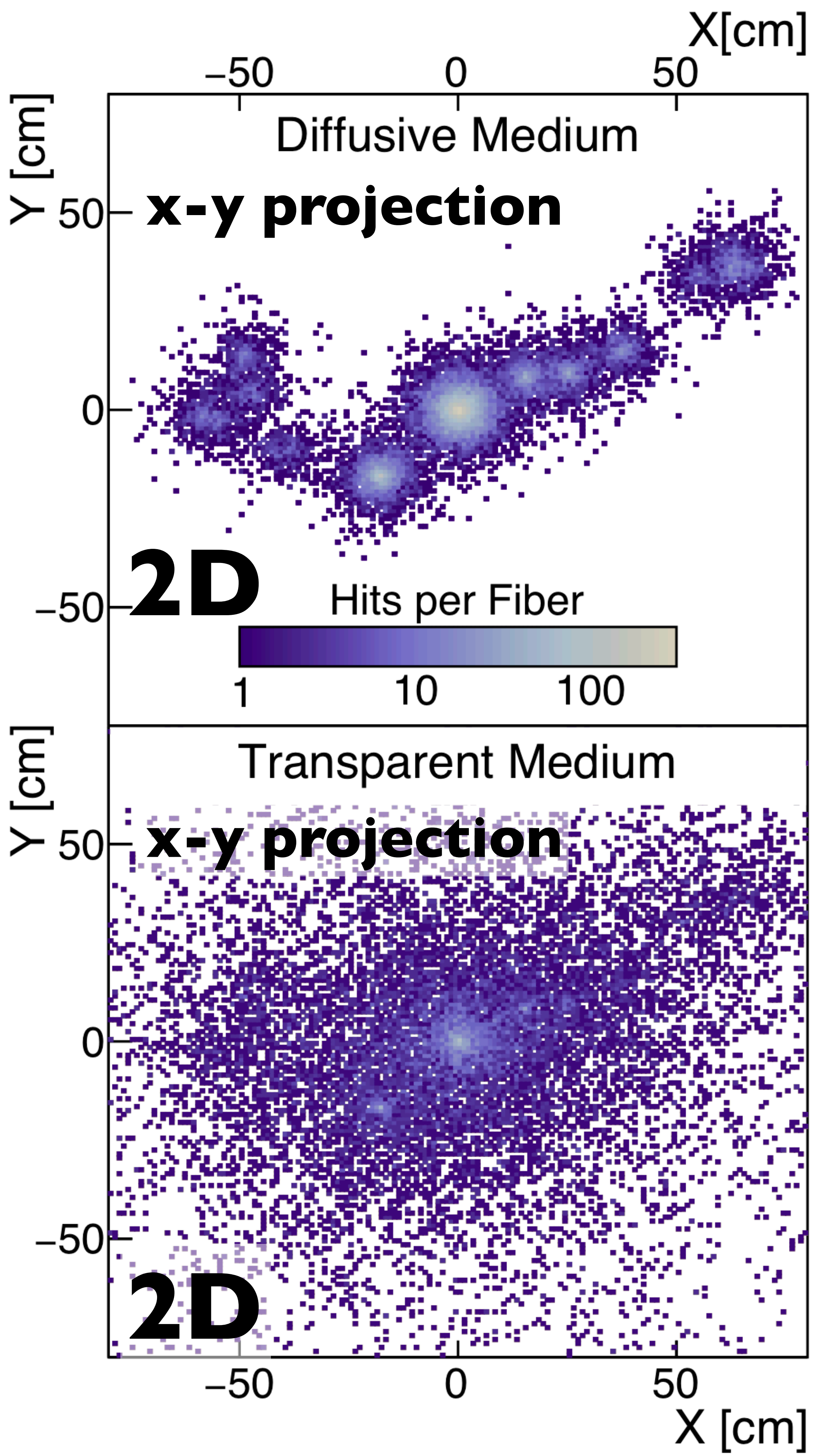
MC says LiquidO works!!

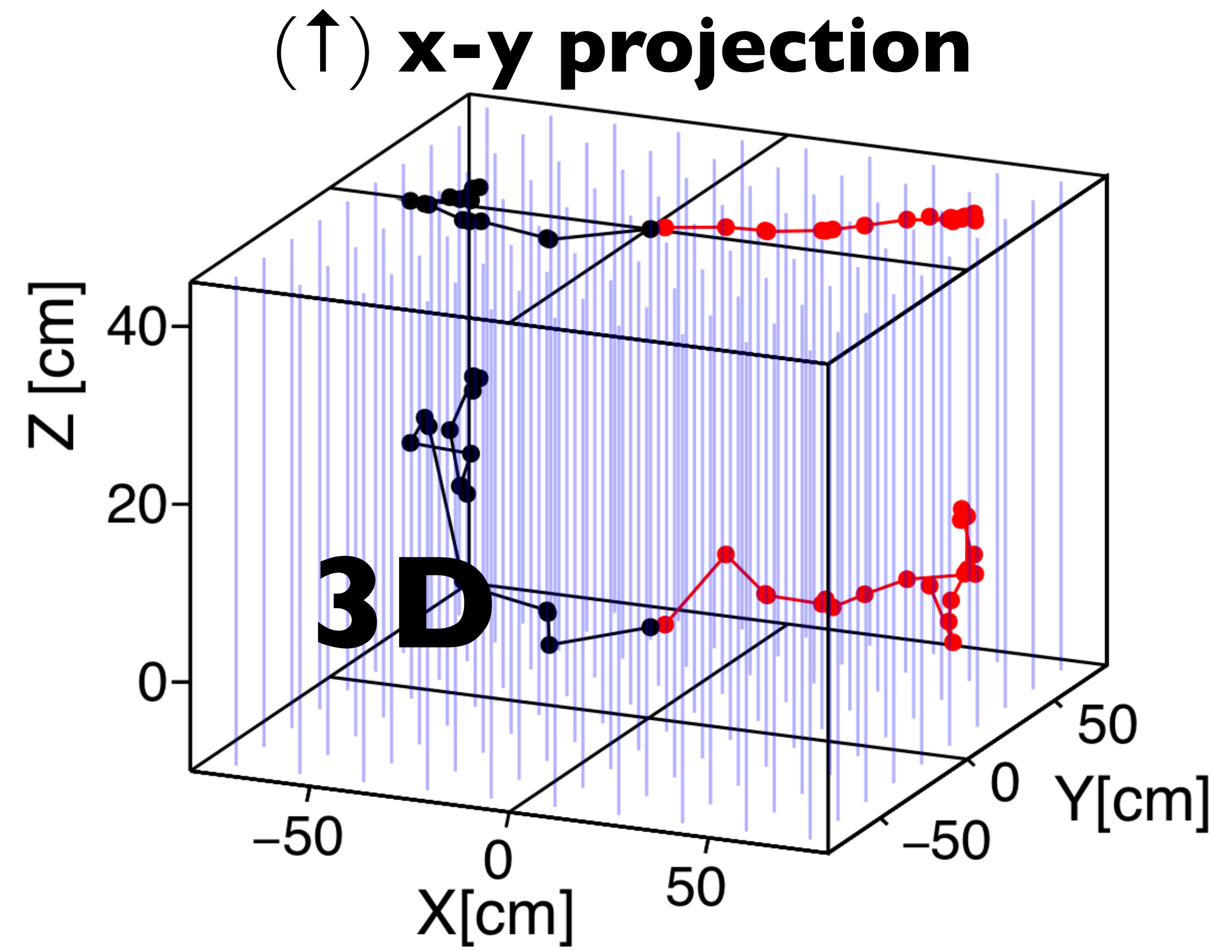
[bread-&-butter physics]

LiquidO's multi-axes…

LiquidO

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





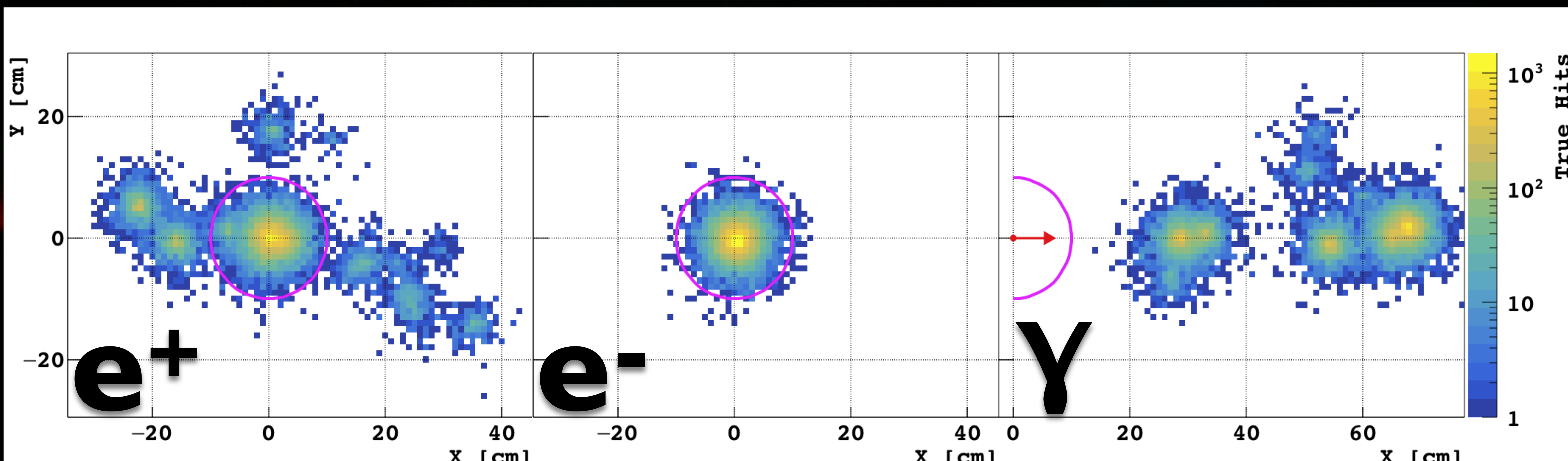
z projection (not yet fully exploited)

Transparent Scintillator⊕Fibres

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

powerful PID expected…

2MeV

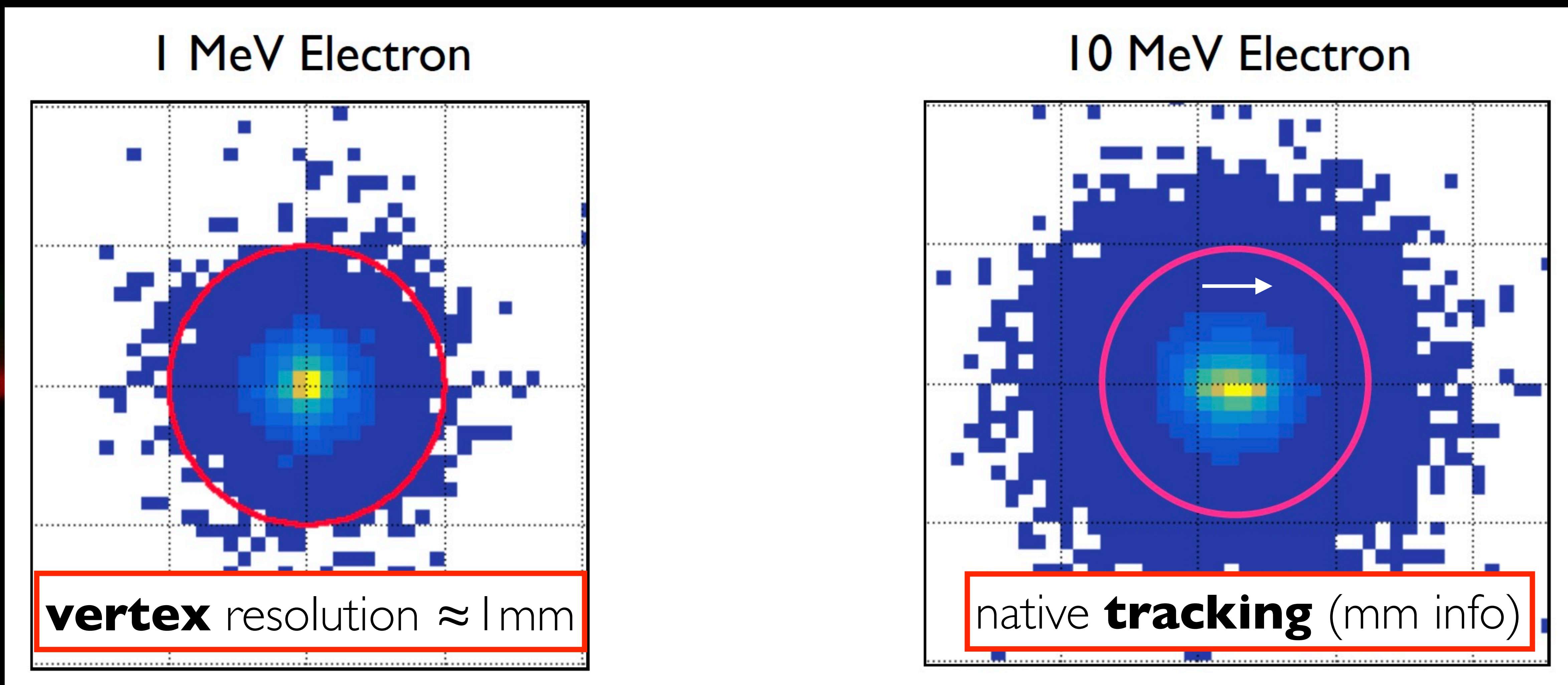


no need for segmentation→problematic! (cost/complex)

(**opacity→self-segmented**)

event topology…

LiquidO resolution (translucide medium) ⊕ **dE/dx per particle** (≤100MeV)

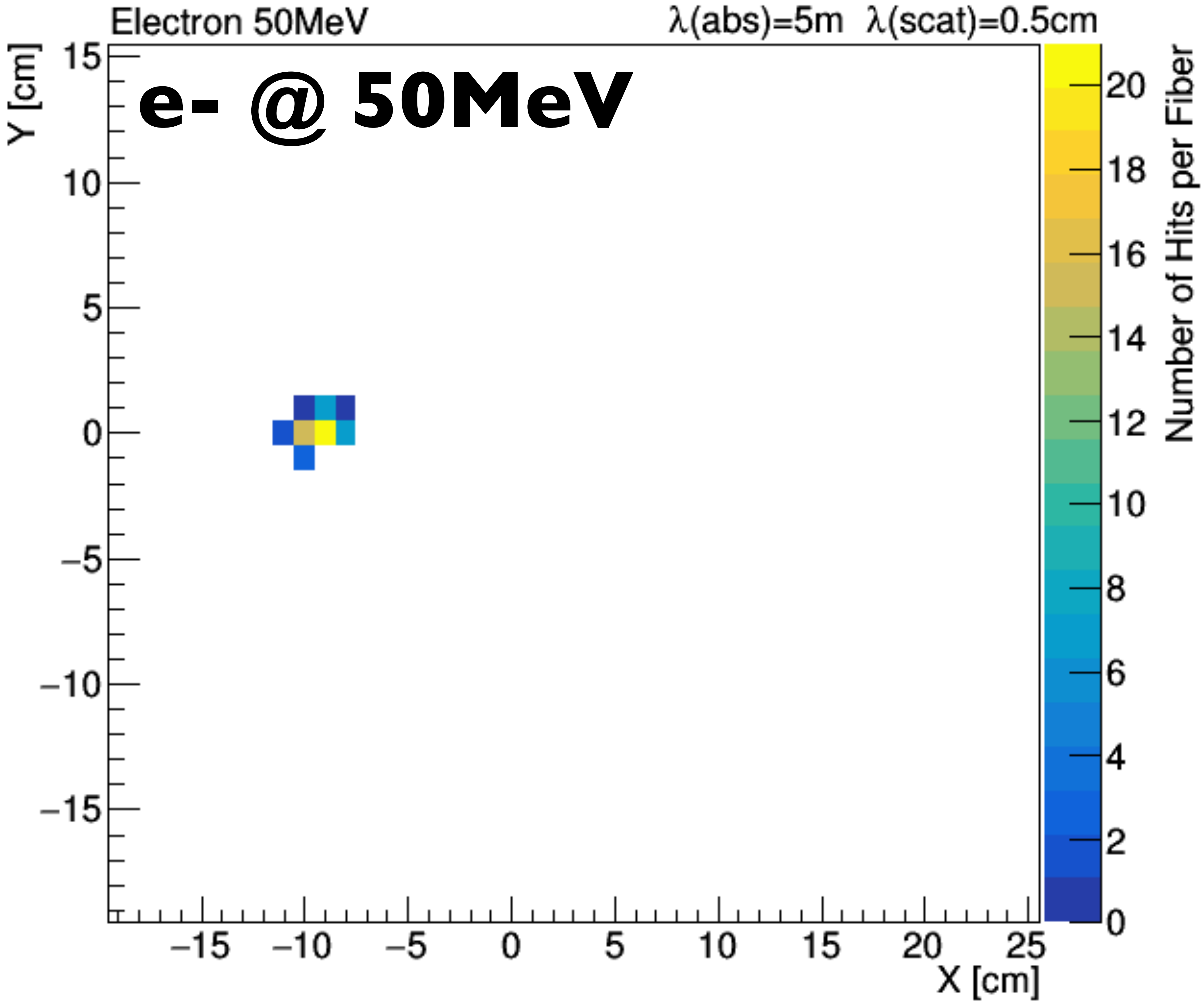


effective point
(Bragg peak dominated)

effective track
(MIP dominated)

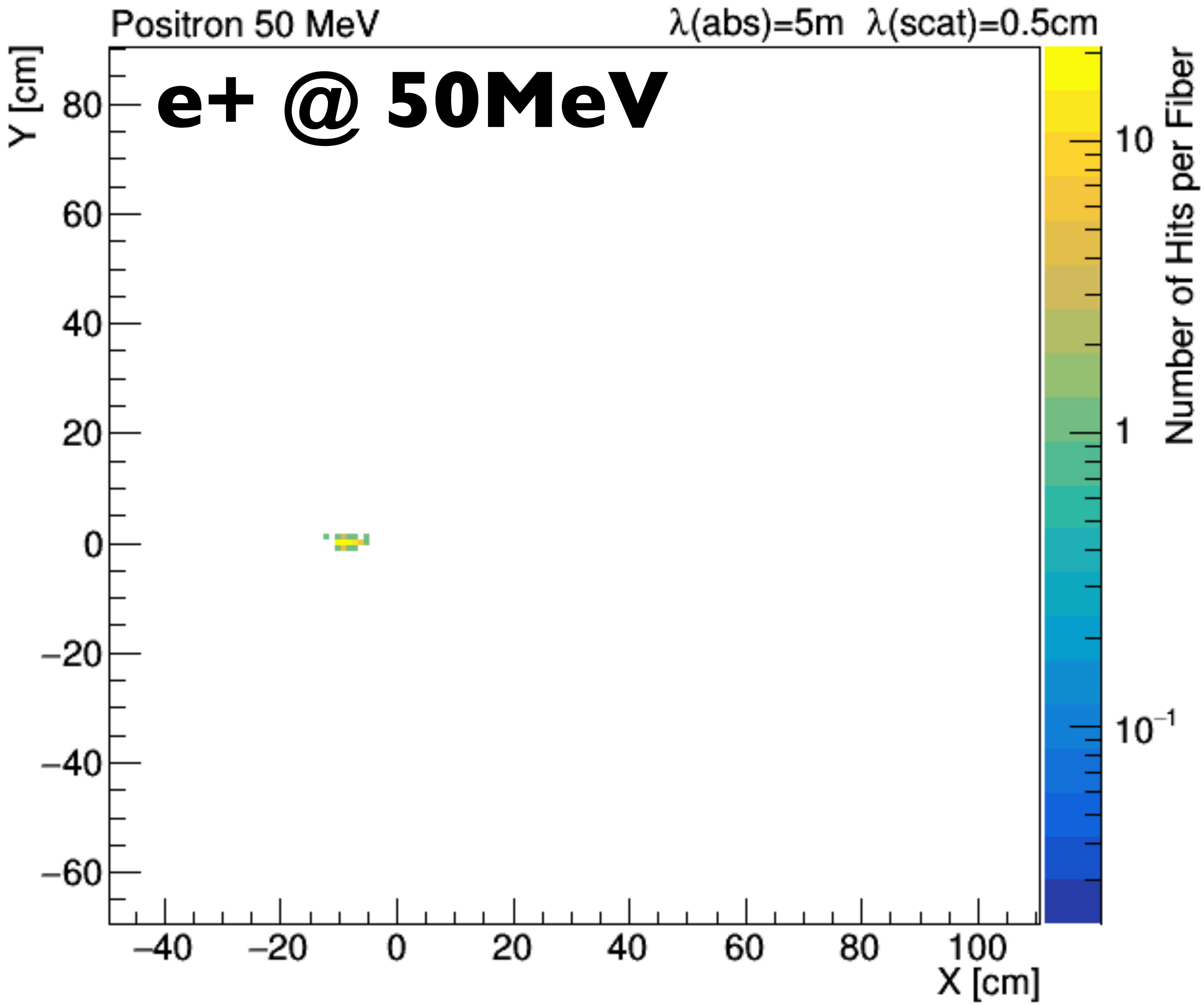
NOTE: traditional liquid scintillator: poor vertex resolution (~10cm @ 1MeV) & no tracking!!

LiquidO native tracking: even e-…



e- tracking (μ even easier)

e-/e+ discrimnation…



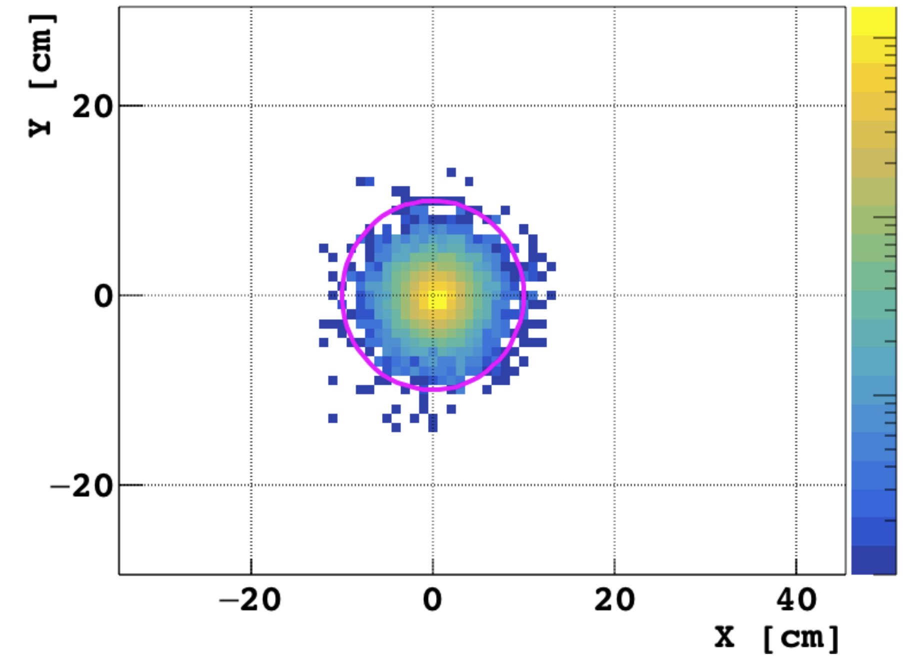
e-/e+ discrimnation with no B-field!

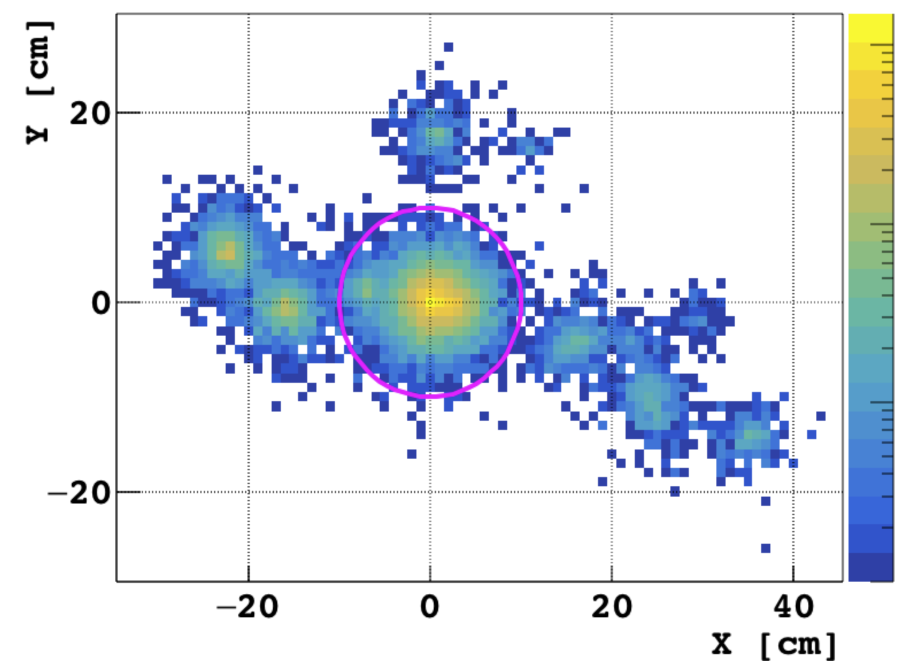
[but we can magnetise]

CC ν interaction observables…

$\nu_e \rightarrow e^-$

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

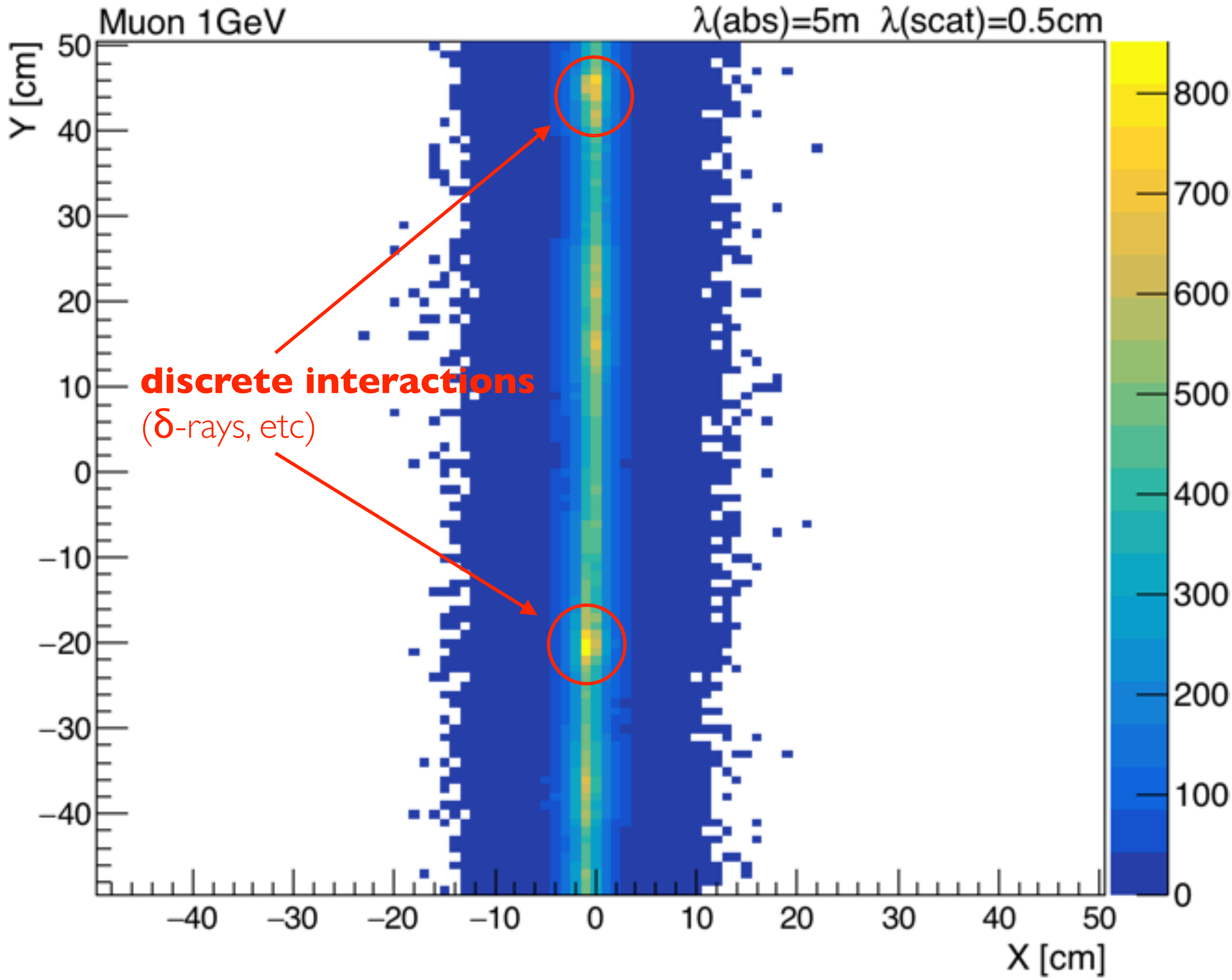




a breakthrough capability ≤100MeV

(→only possible with ν_μ's so far)

a through-going μ…



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

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

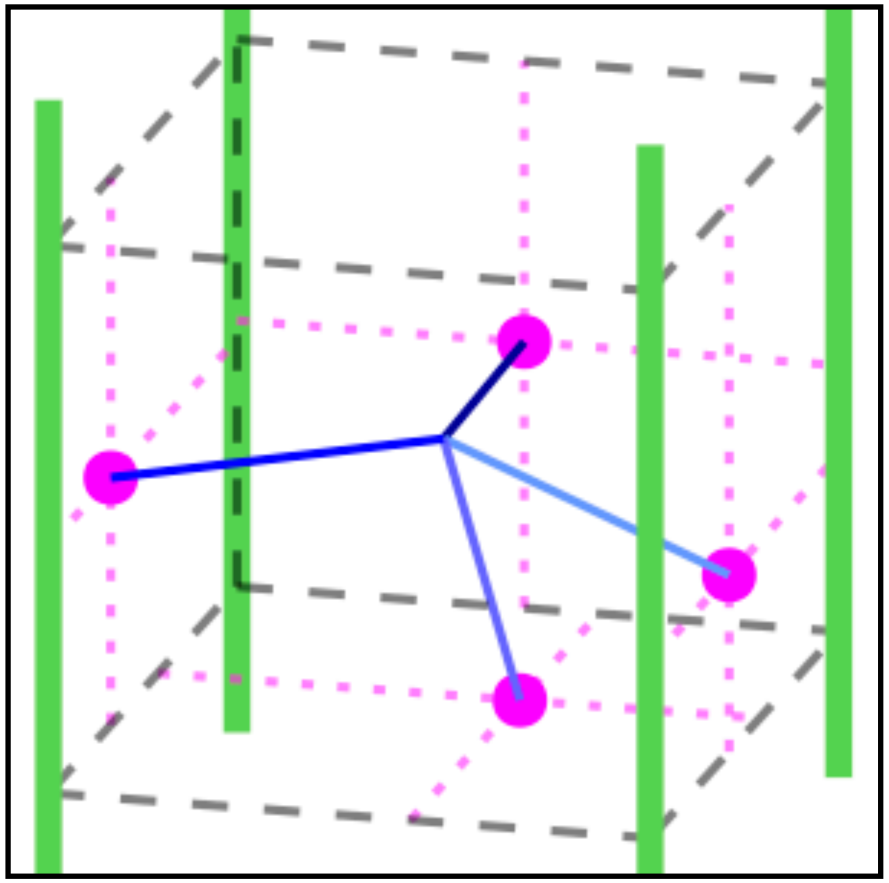
beyond "just pattern"...

pattern = energy deposition as t→∞

[static information: photo]

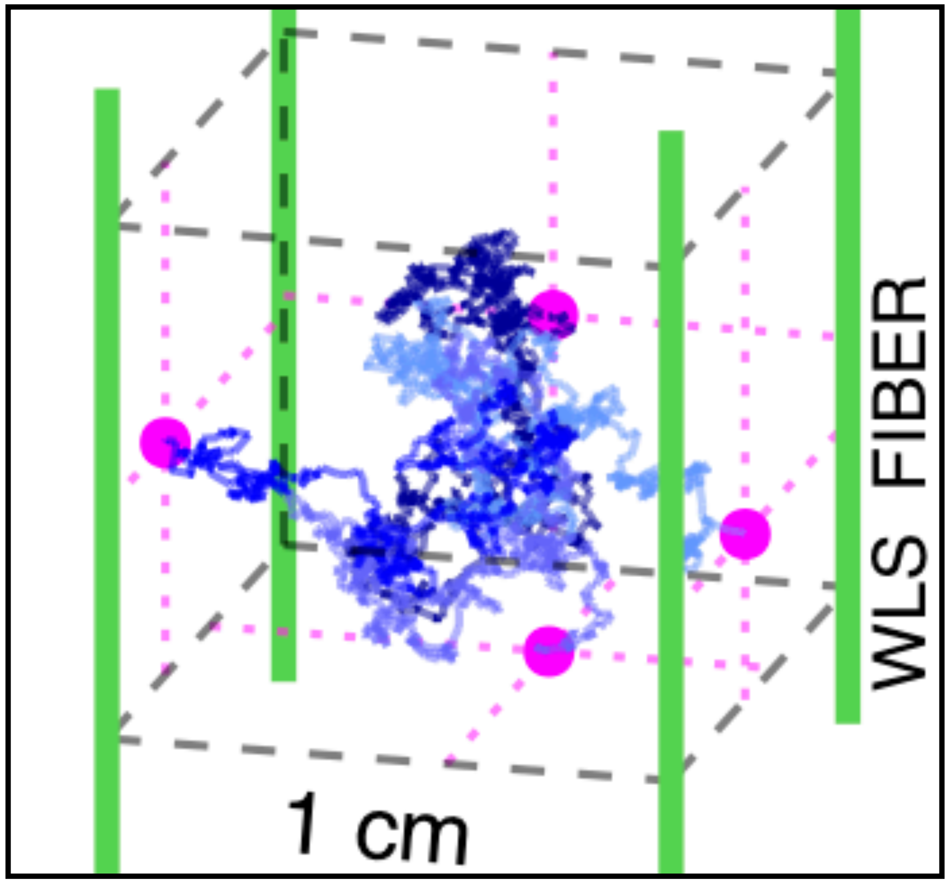
dynamic energy flow within few ns?

[**a film**]



transparent

versus

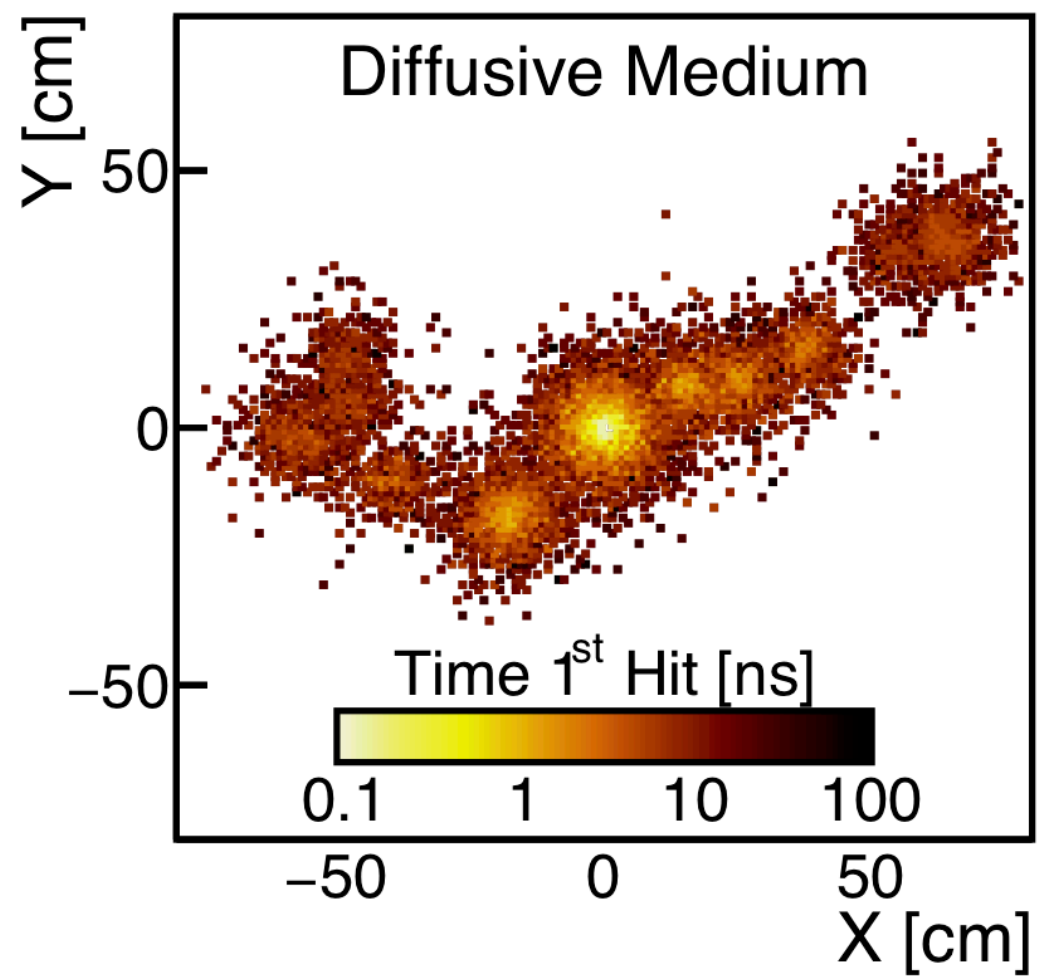


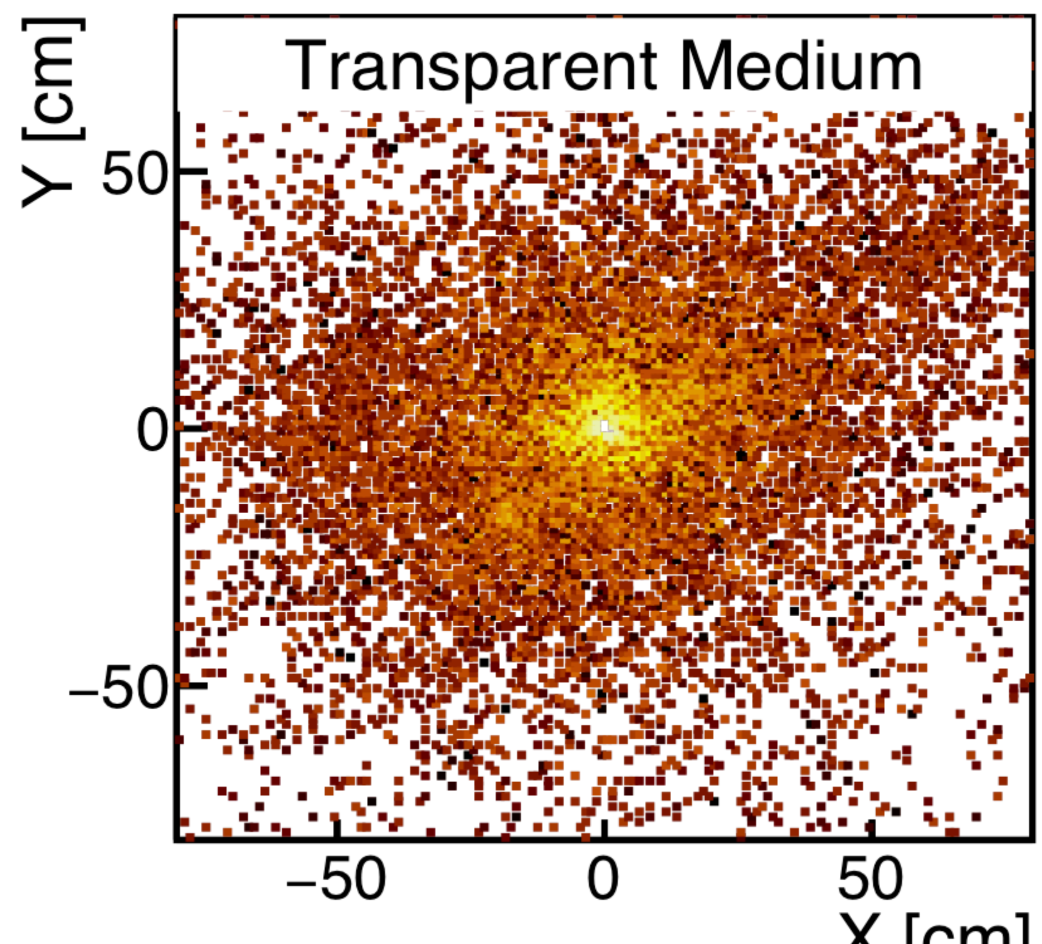
scattering

"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

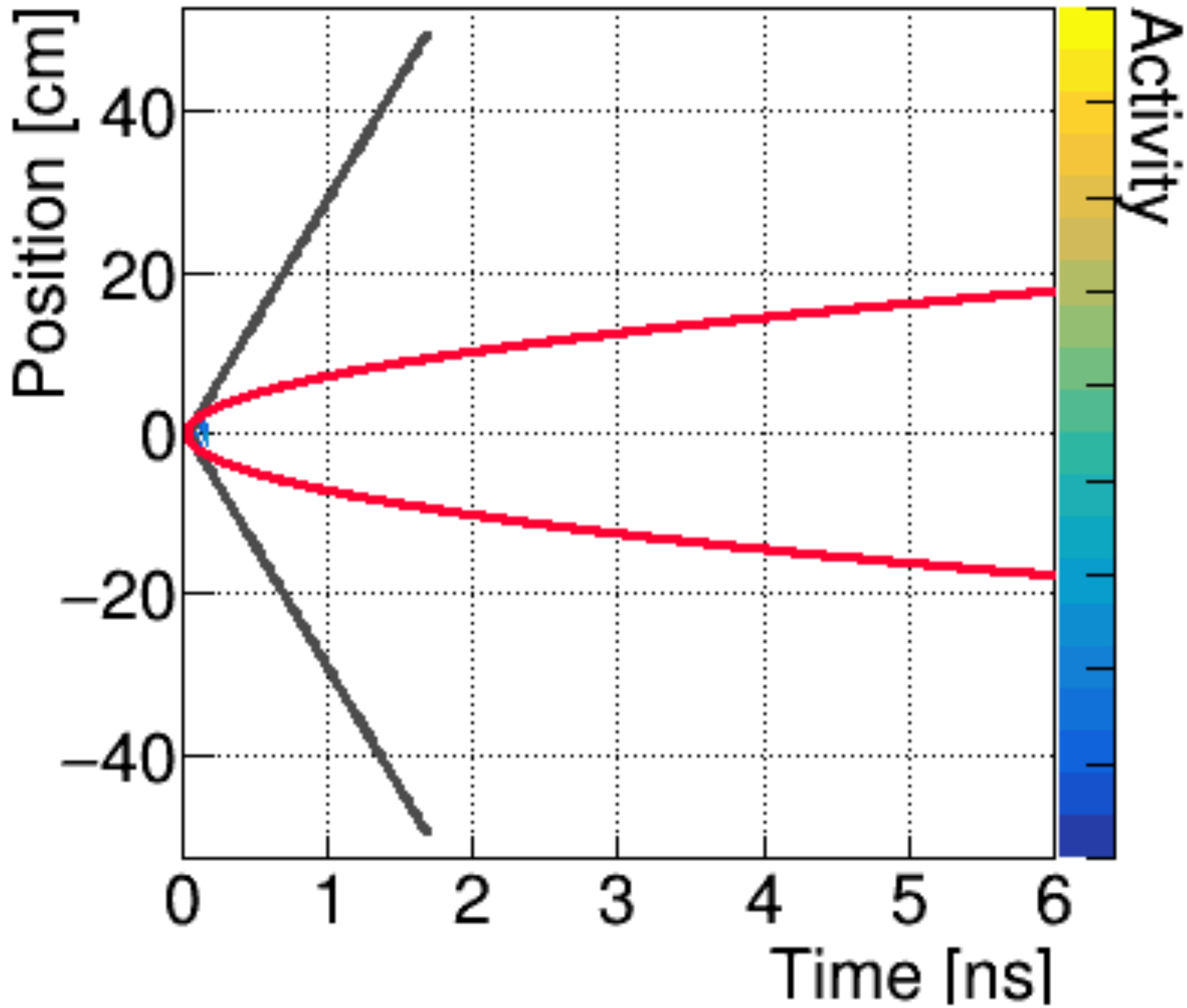
v(particle) ≈ v(light in scintillator) = v(light in fibre)
[no decoupling]

Transparent

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

LiquidO implies imaging ⊕ energy flow…

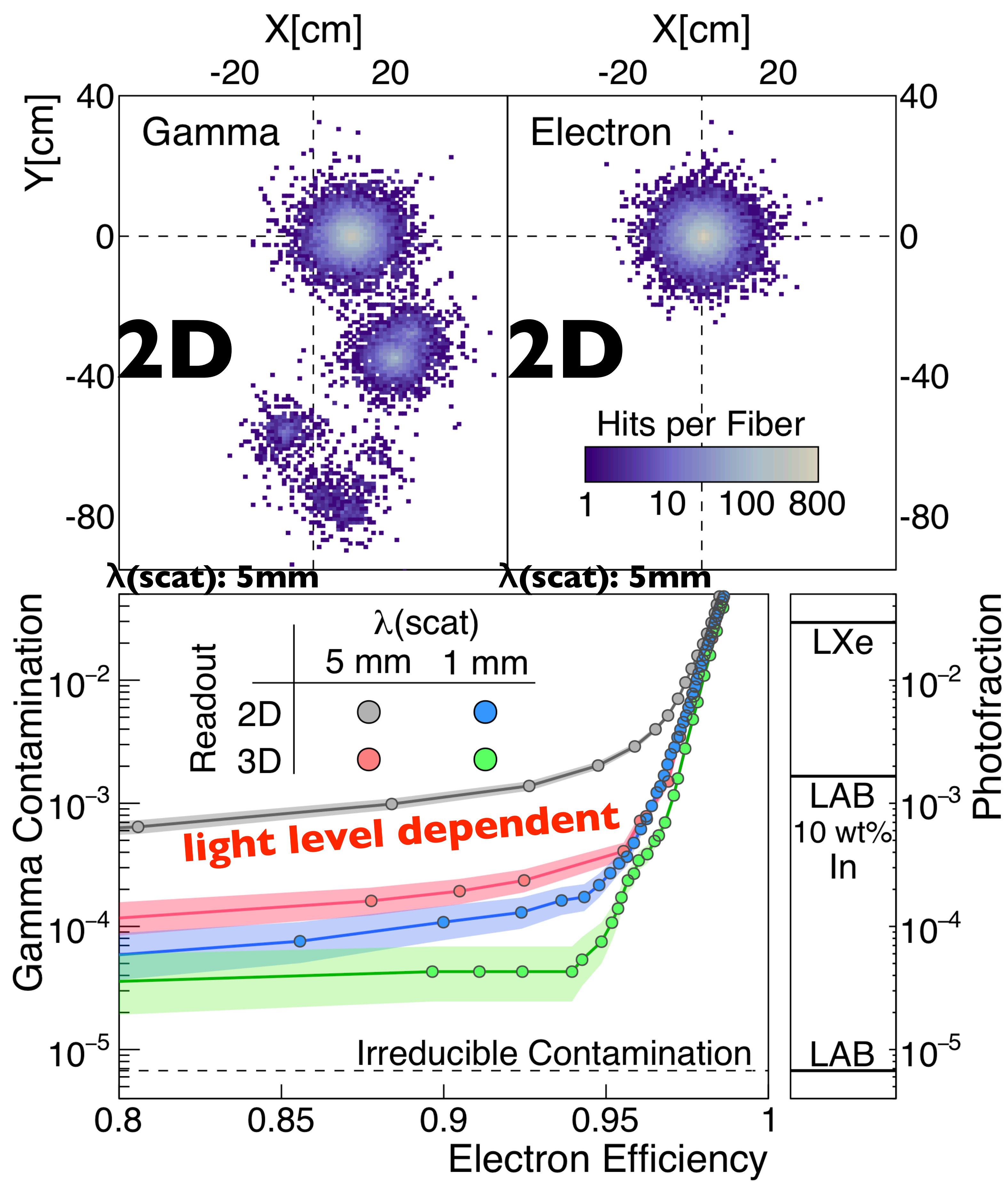
c defines "line of interaction causality"

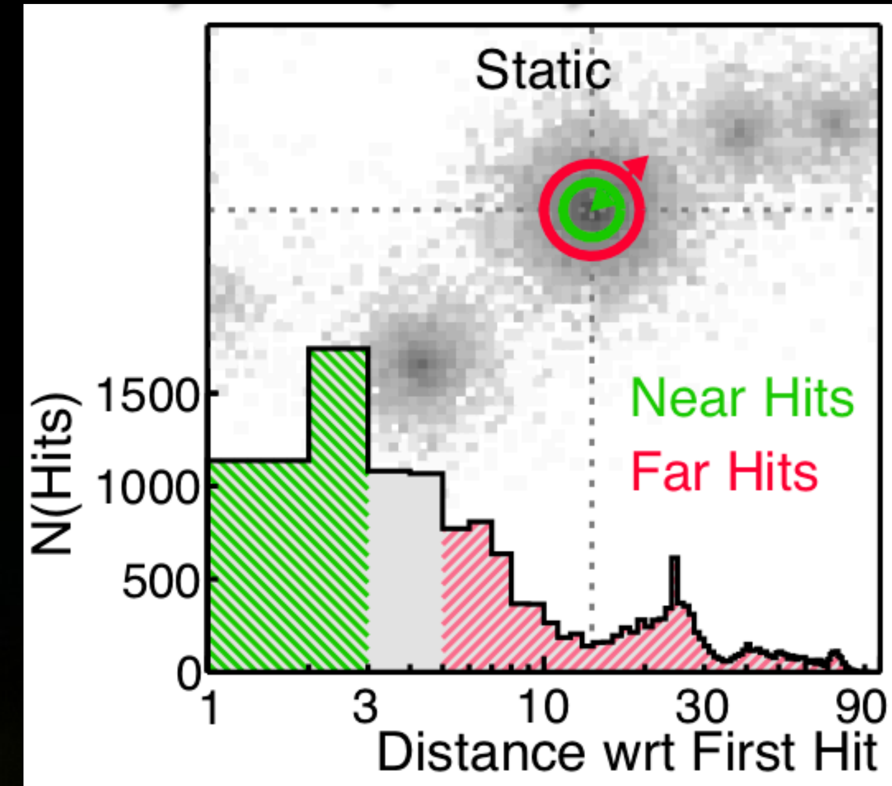


critical control of all time-dispersion mechanism

(example) γ to e^- separation...

PID(e^-:γ) @ 2.5MeV → major γ rejection…





(reco) "event size" only

[calls for neural network, etc]

≥90% detection efficiency

PID[γ:e^-] separation

1:≲10^4 (scintillator native)

1:≲10^2 (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**)

how about radio-purity control?

scintillator→R&D ✓ (Borexino)

⊕

photo-detector (**outside!**) ✓

[finally no PMT→ no buffer!!]

⊕

fibres→R&D ✓**?** (example: 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**…!
(<u>the</u> solution?)

LiquidO is still more!

dope it? non-native capability…

CA)

why going beyond native composition?

organic scintillator = H + ^{12}C + ^{x}C($\leq$1%) [+ impurities]

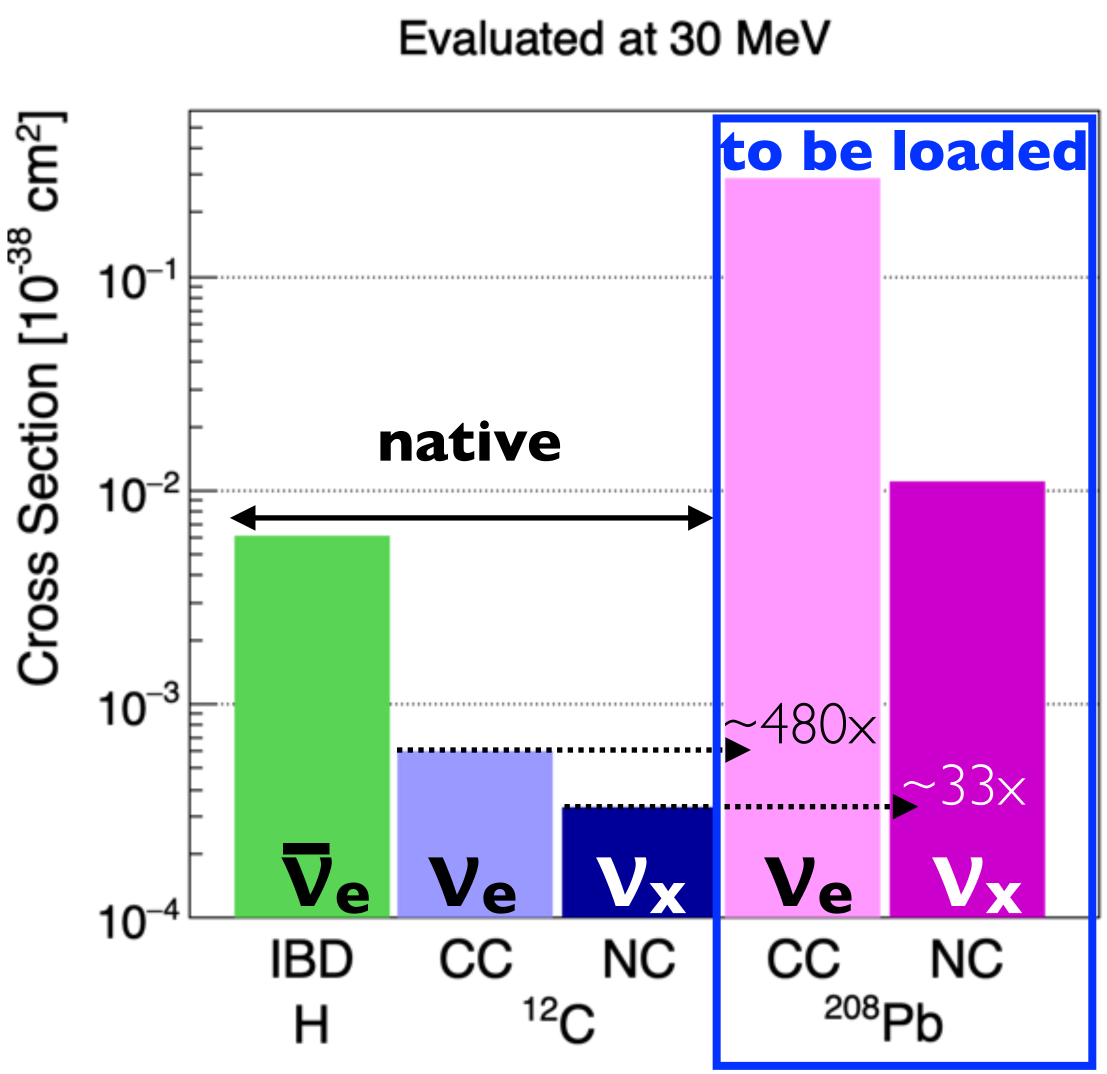
detection efficiency enhancement

neutrino interaction(s) enhancement

rare decay source enhancement

Cd loading
[Reines et al]

Gd/Li loading
[typical in reactors]



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!**

enrichement costing is [10,100]M€/ton

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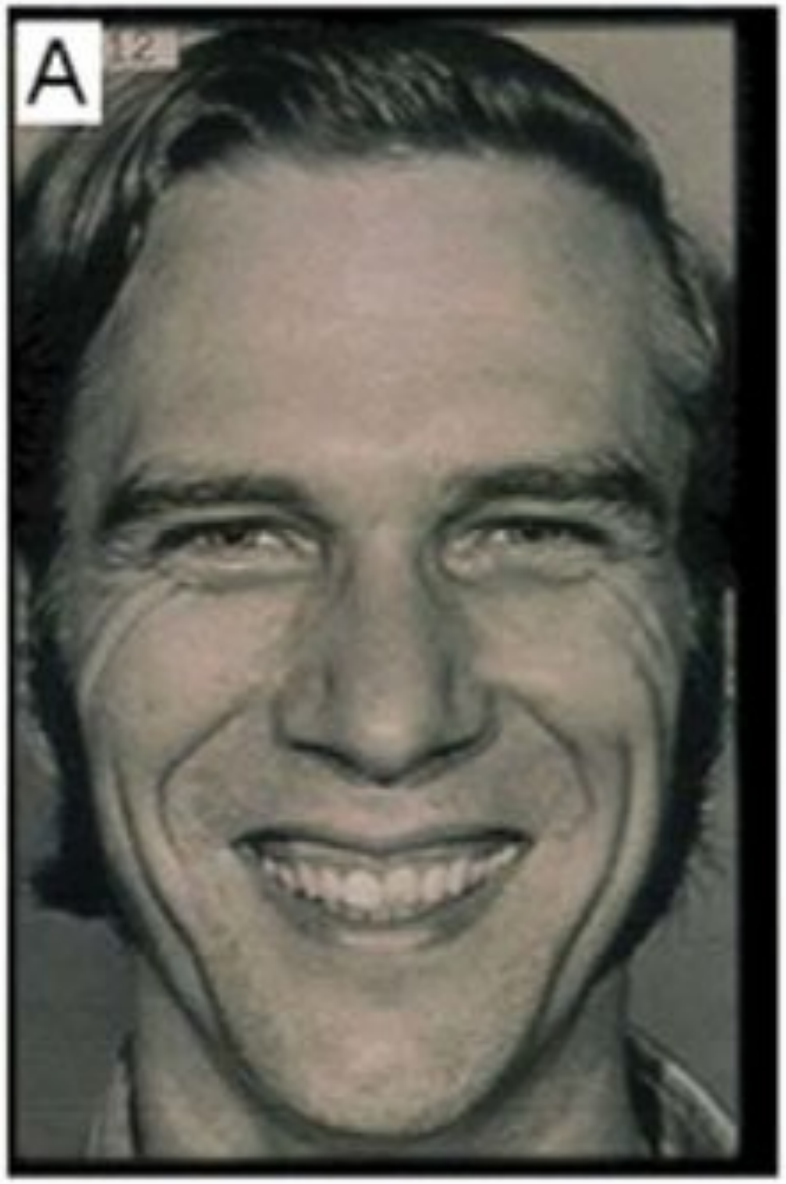
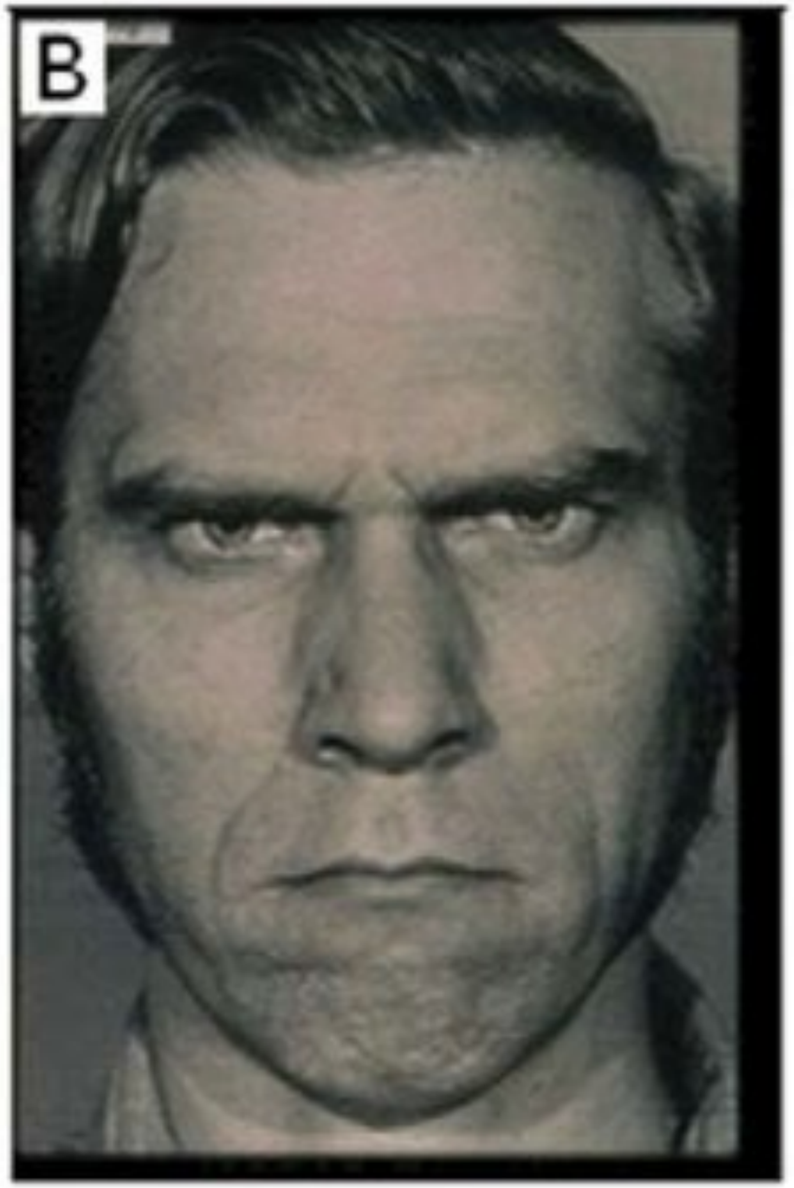
doping stability via solidification…
(beyond chemical stability)



cool!



really?

[we did too for long!]

upon novelties, always duality…

does LiquidO work?

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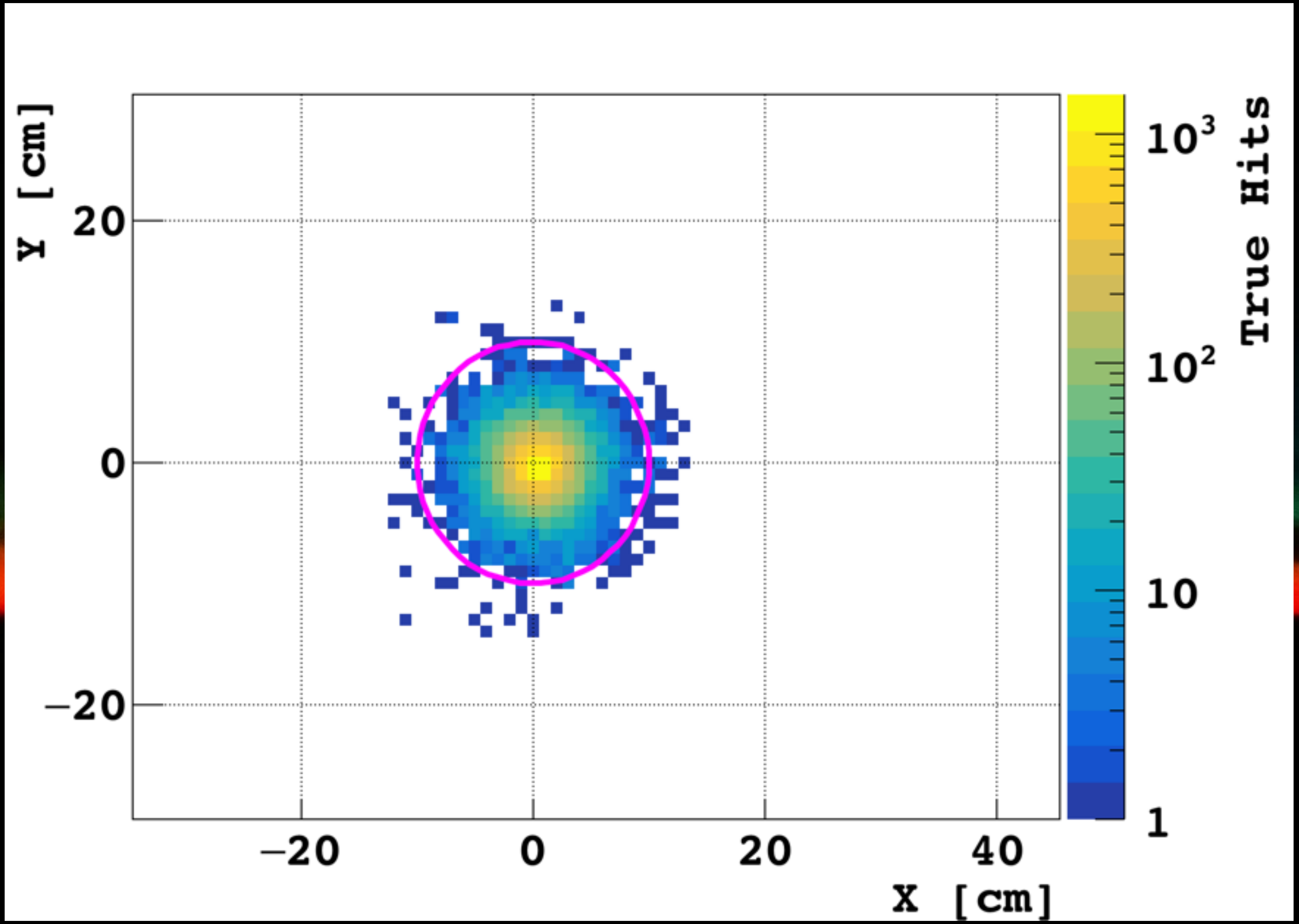
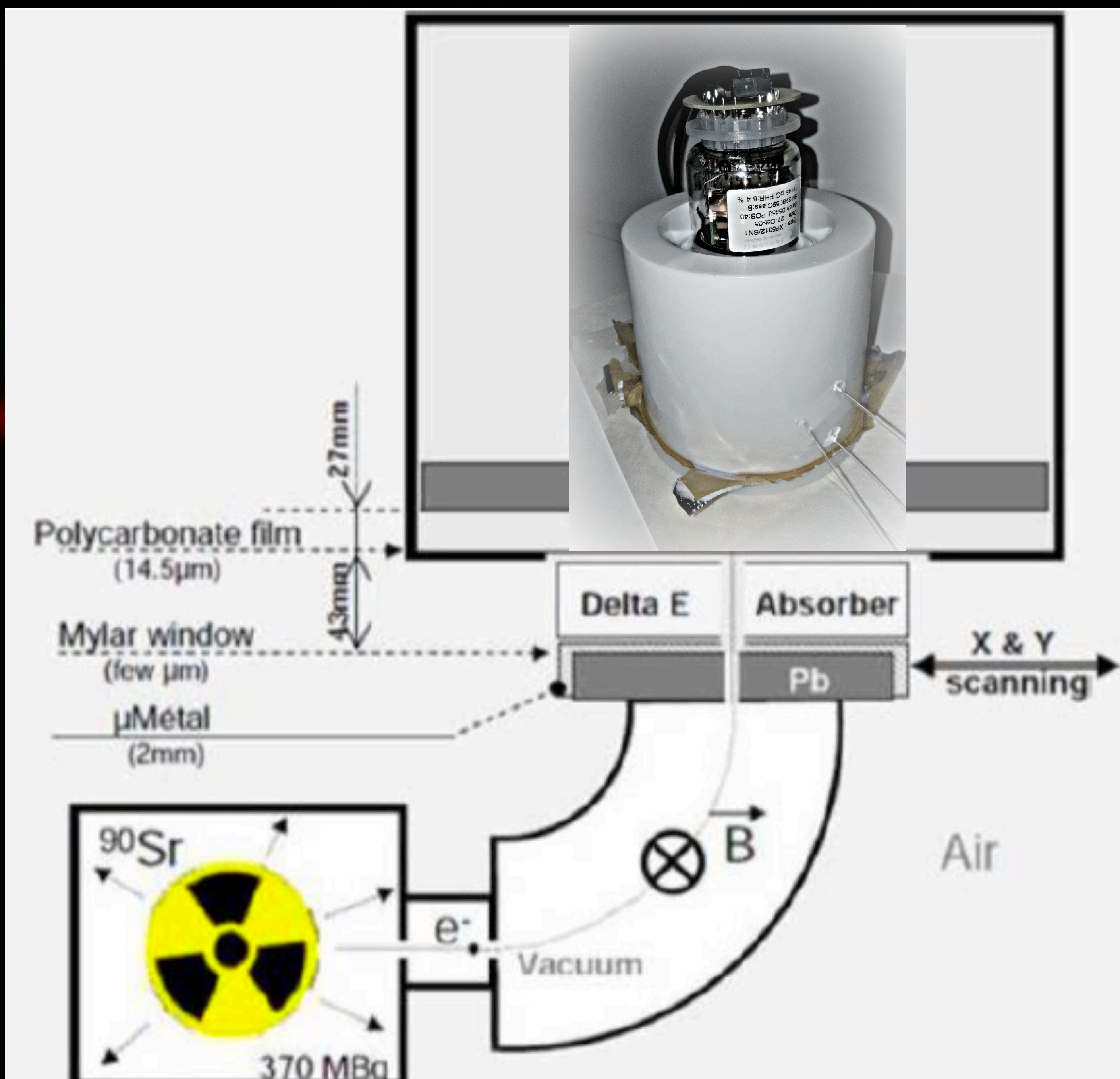
low energy e- ≈ "light ball"...

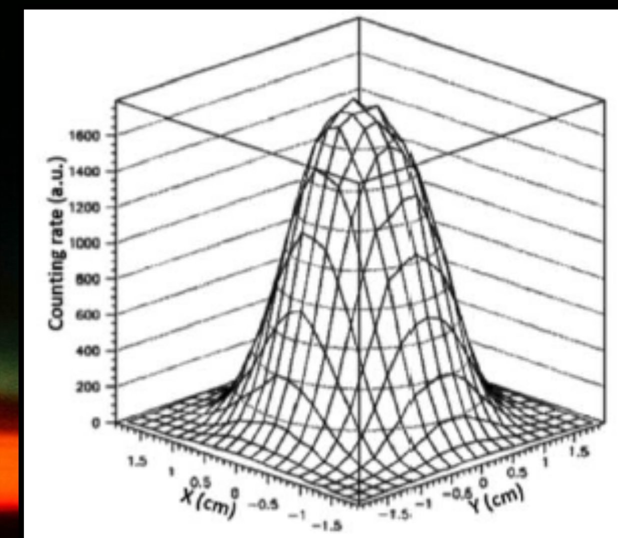


LiquidO means light confinement!

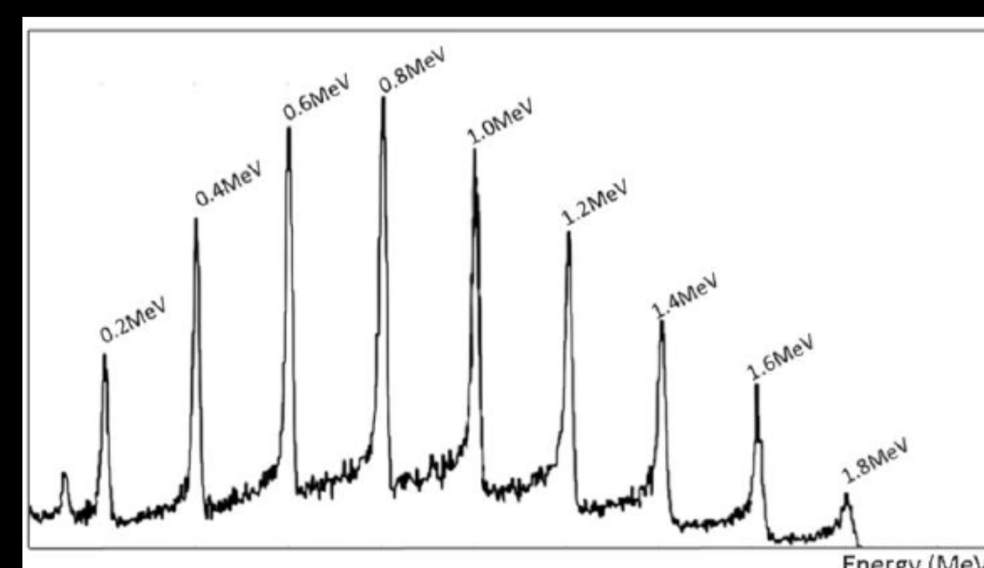
(everything else → corollaries)

μ-LiquidO @ our e⁻ beam…





e- position ≤1mm



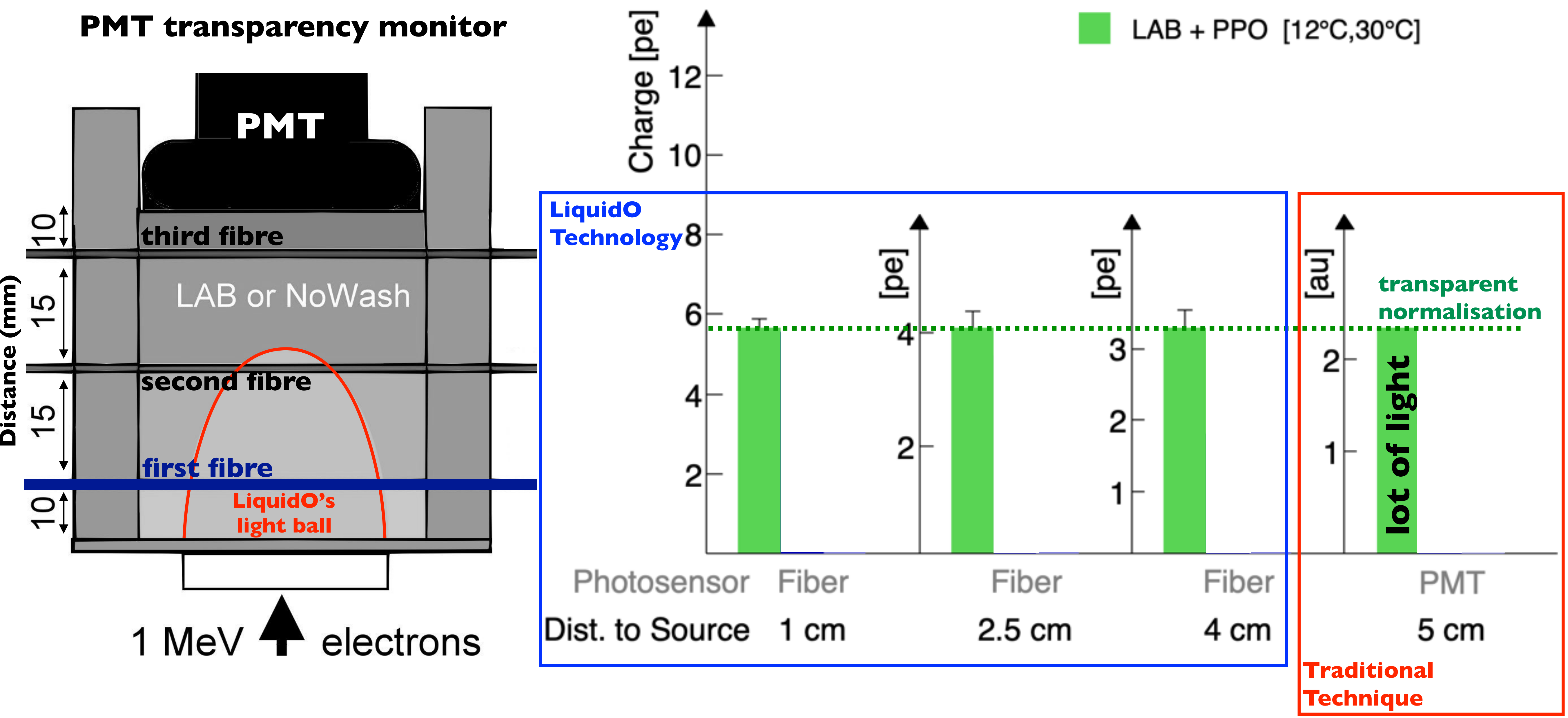
e- energy ≤1% up to 1.8MeV

μ-LiquidO inside…

3x fibres:
- fibre-0: 1.0cm
- fibre-1: 2.5cm
- fibre-2: 4.0cm

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

first experimental proof of principle…



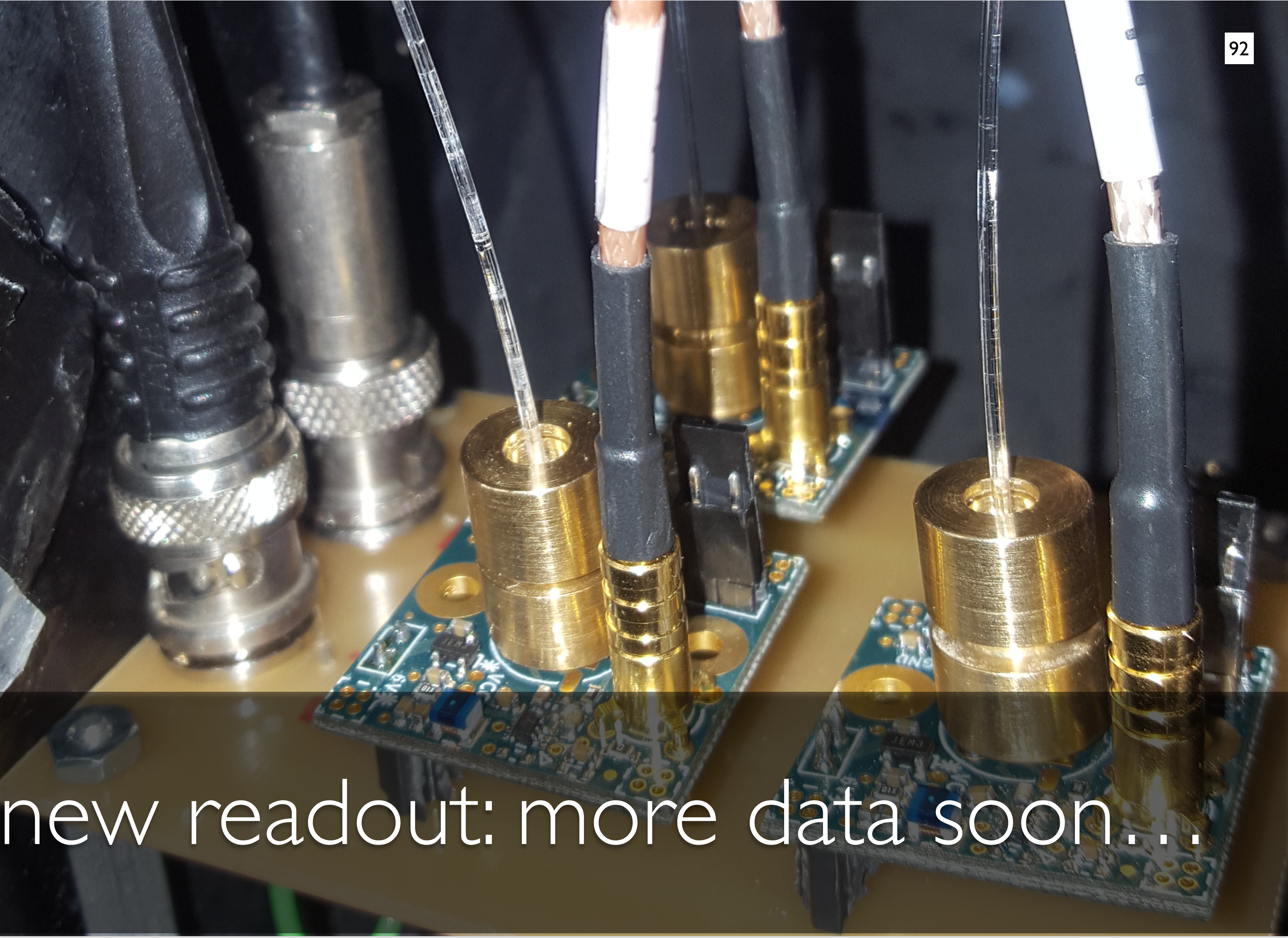
light bending→light confinement!

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

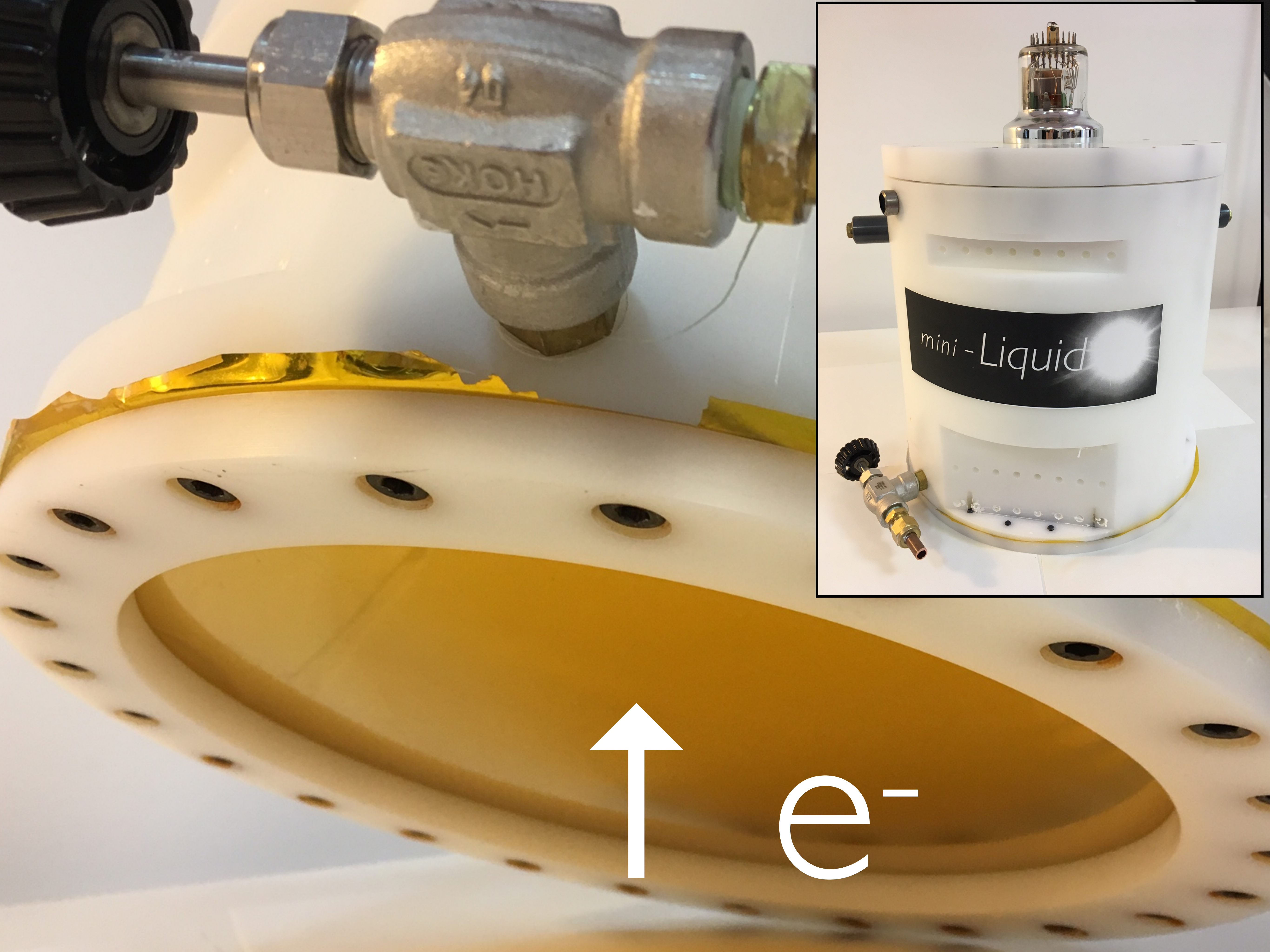
λ(scat) driven [consistent with negligible light loss @ 10% loading]

R&D

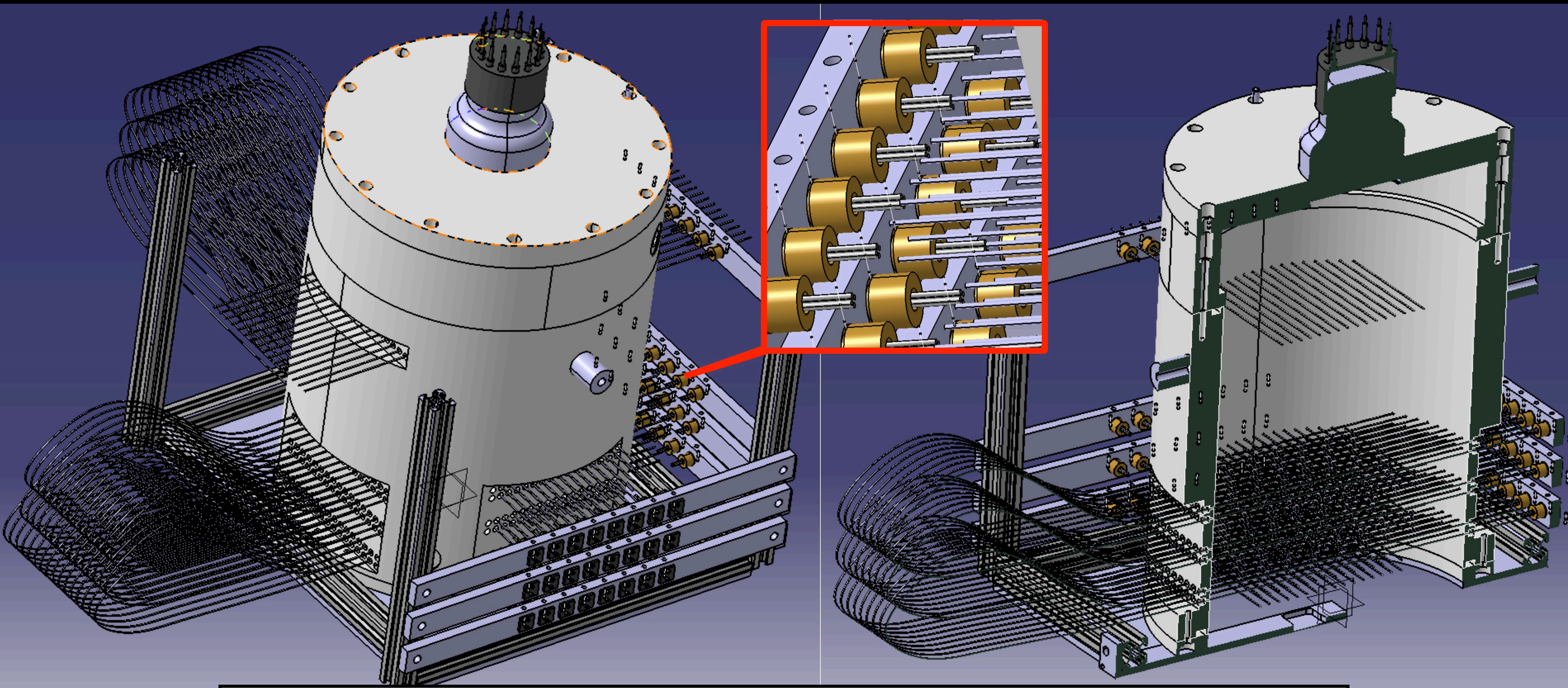
✓proof-of-principle experimental



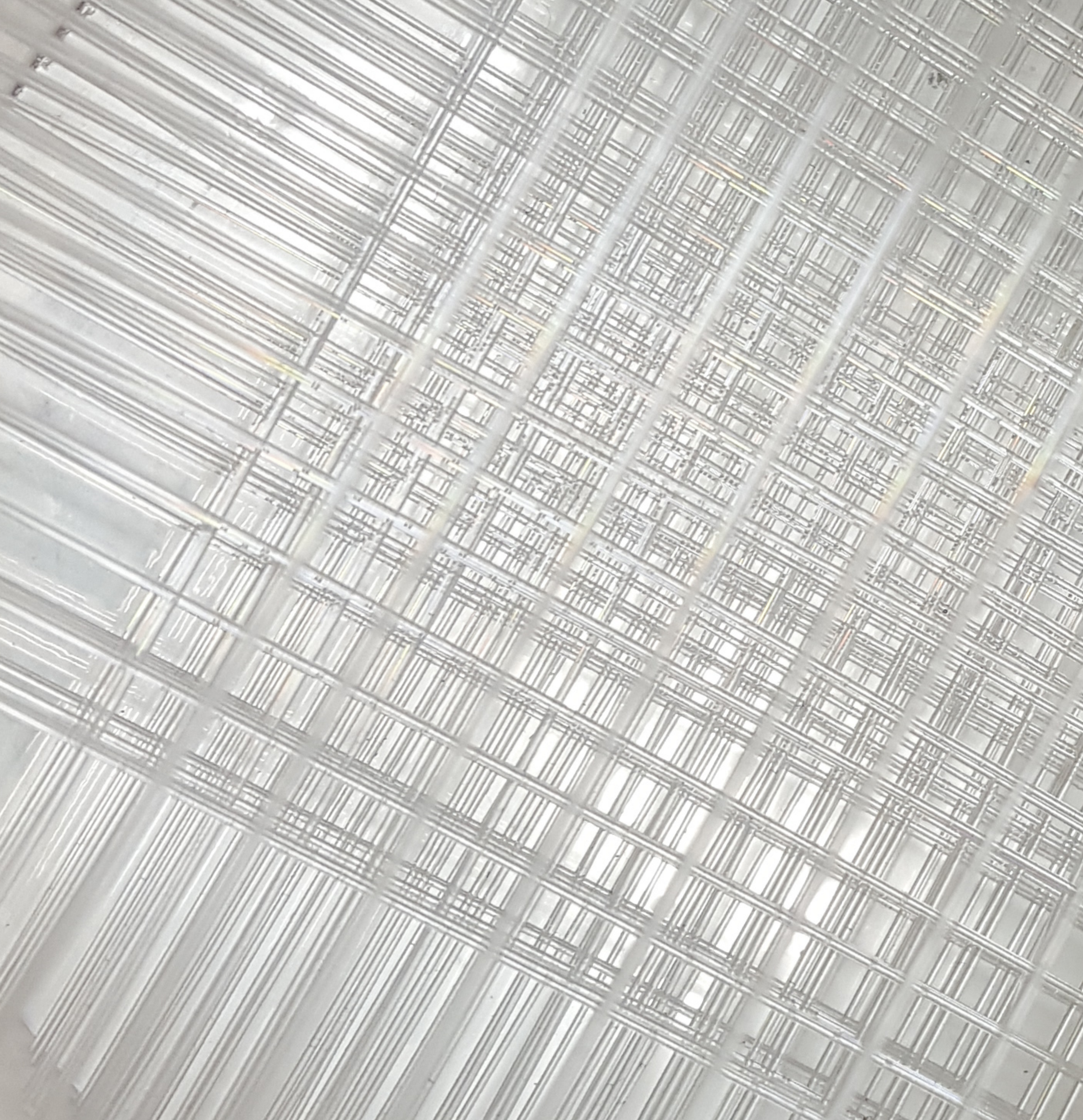
new readout: more data soon…

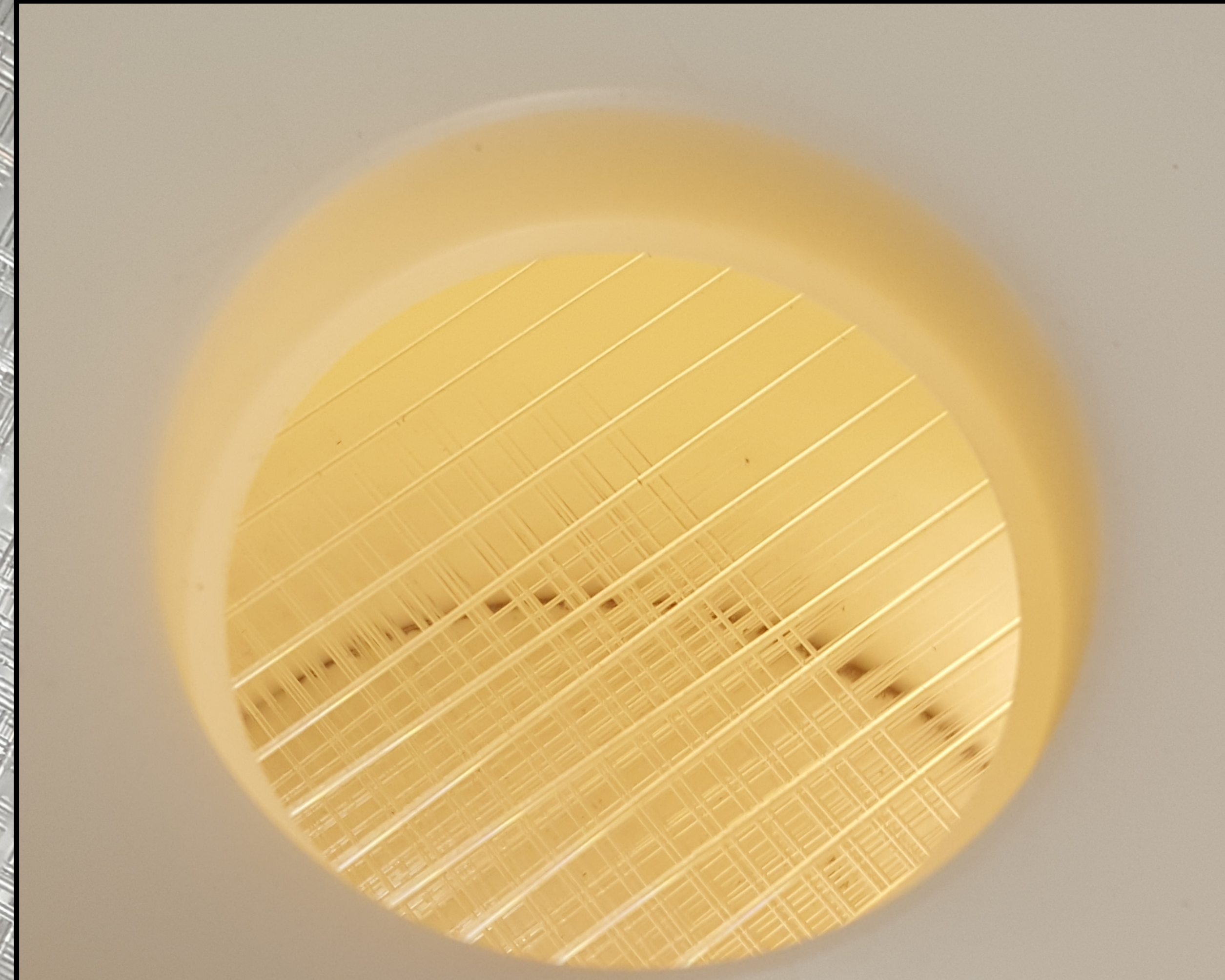

e⁻
mini -Liquid

mini-LiquidO soon…

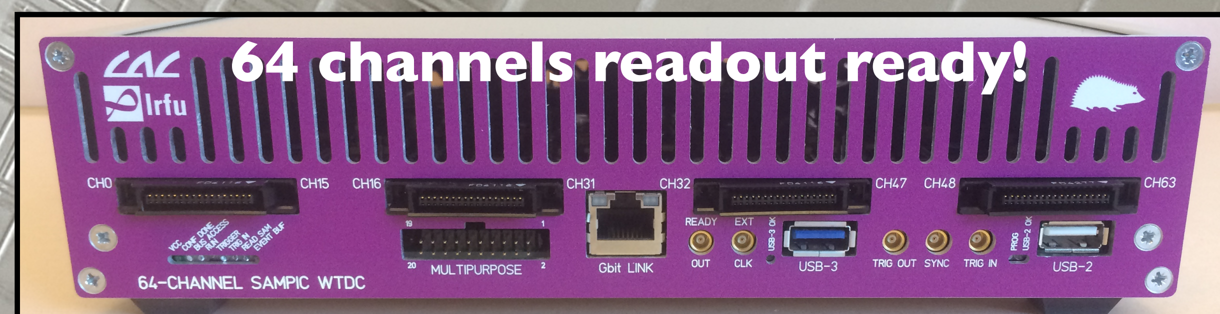


all piece built→assembly





closed detector now (PMT window)



packed lattice → data soon…

R&D

further prototyping effort…

a physics appetiser…

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

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 & little systematics
  - **@GeV:** conventional beam &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?
- also technology: medical, non-proliferation, Radom detection

[sorry, no time!]

physics potential...

R&D

(performance optimisation, detector scaling, etc)

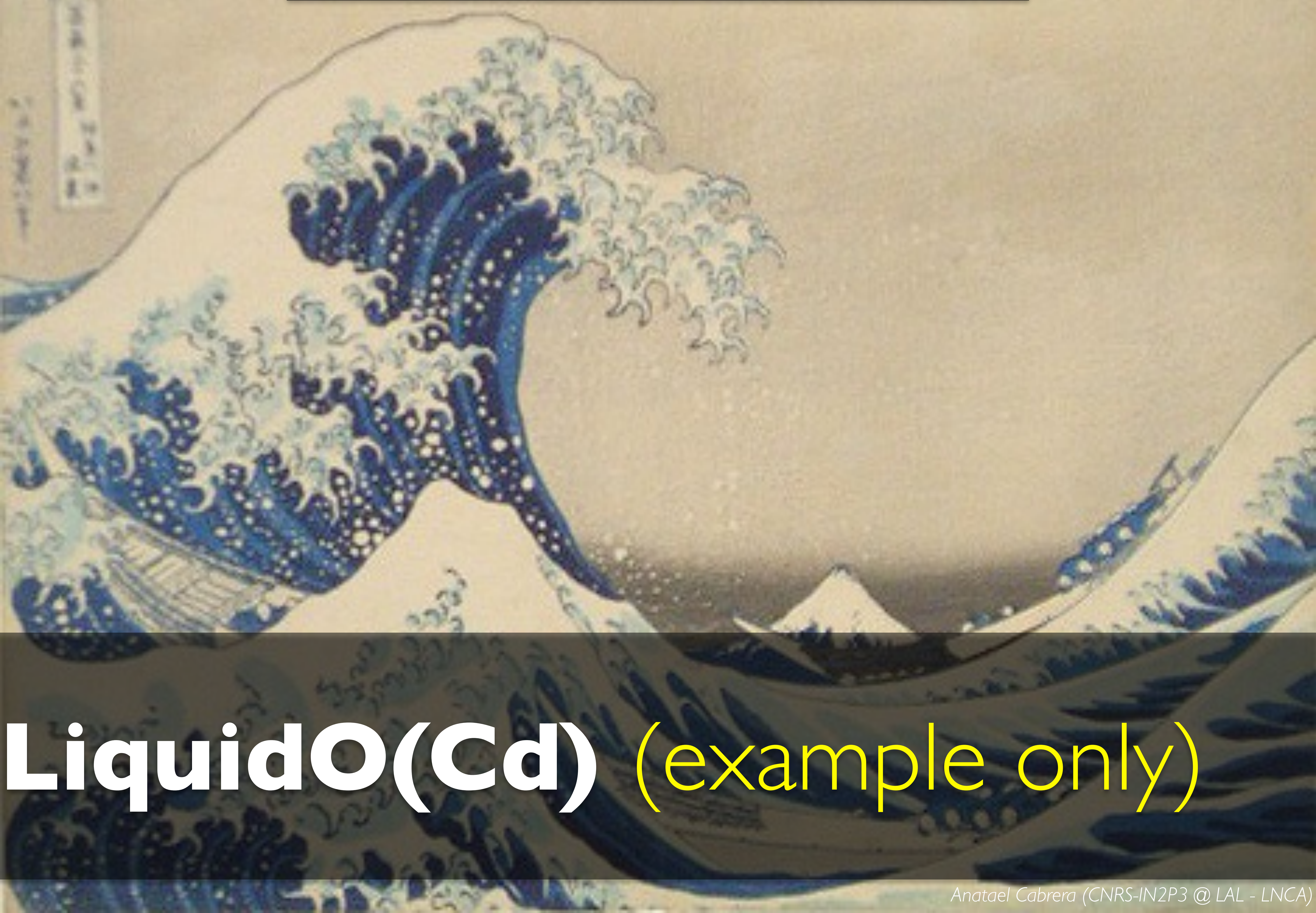
NO "experiment" proposal (yet)

EUROPEAN PHYSICAL SOCIETY HEP2019

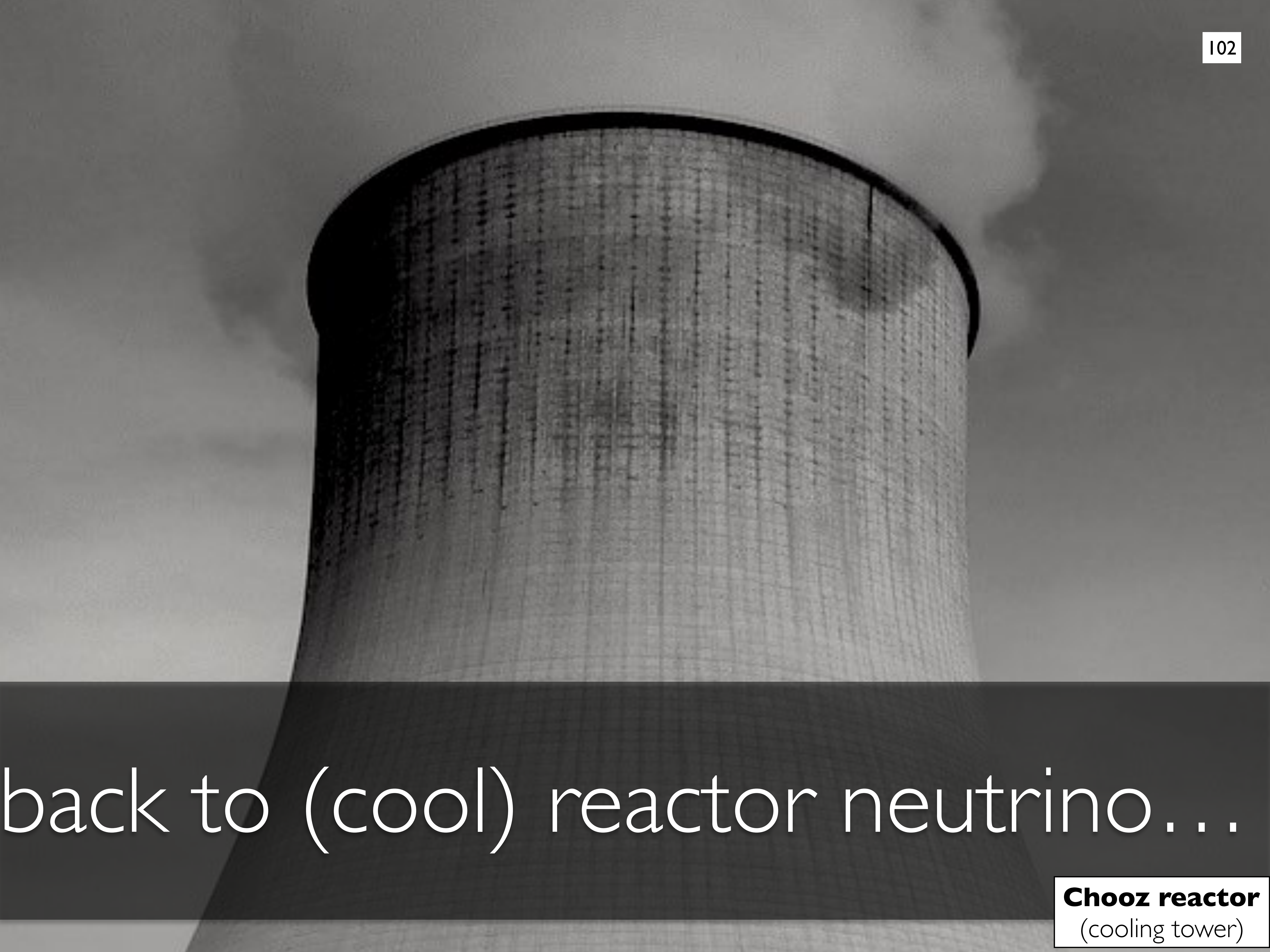
early July 2019

first physics proposal @ EPS…

tribute to Reines&Cowan

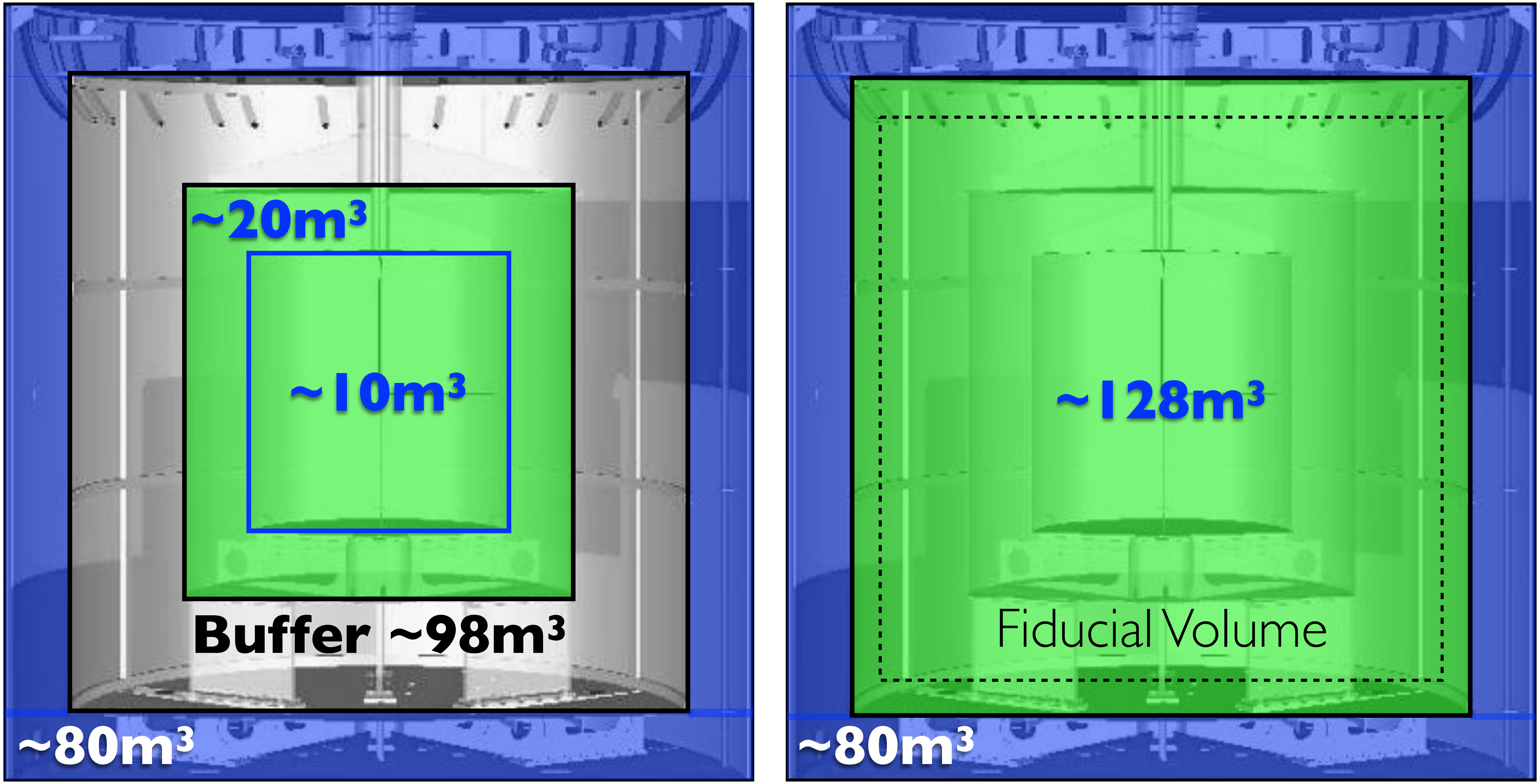


LiquidO(Cd) (example only)


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%)

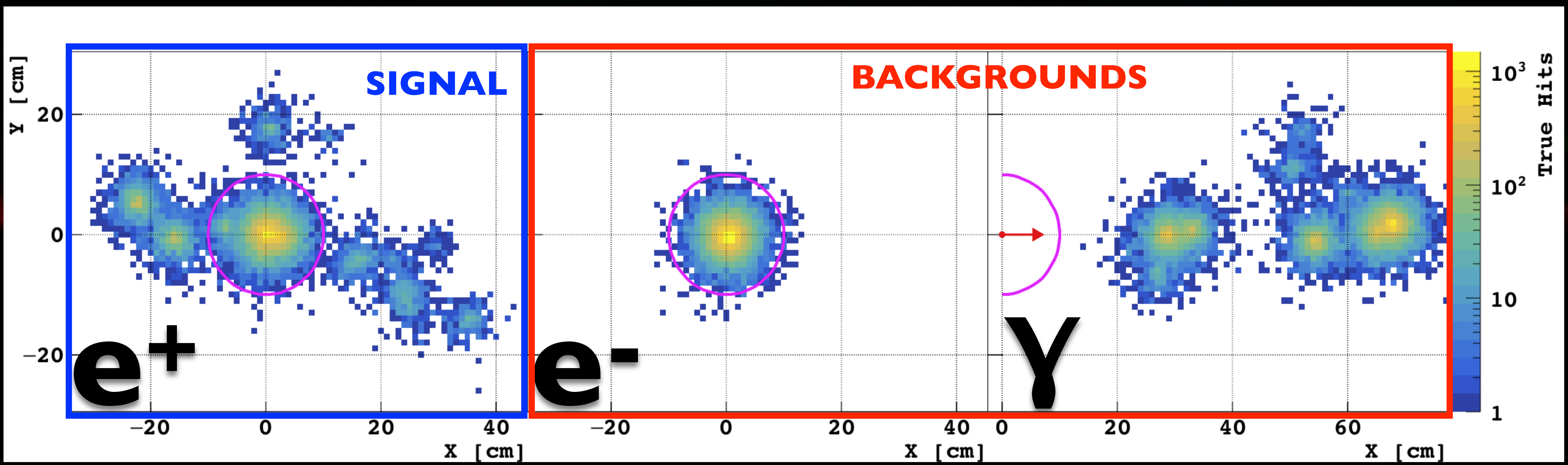
wasted >2/3 equipped volume

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

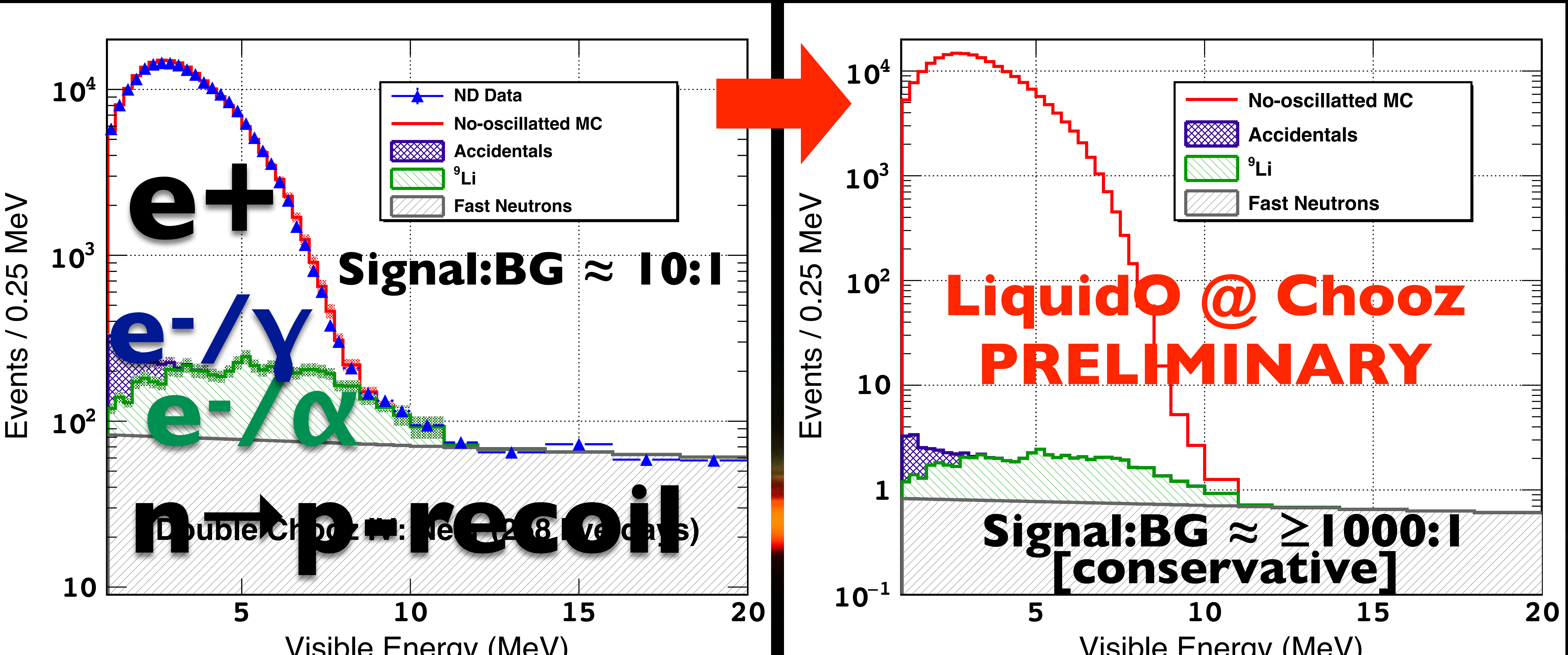
all other detectors (KamLAND, Borexino, etc) **are just alike**…

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…

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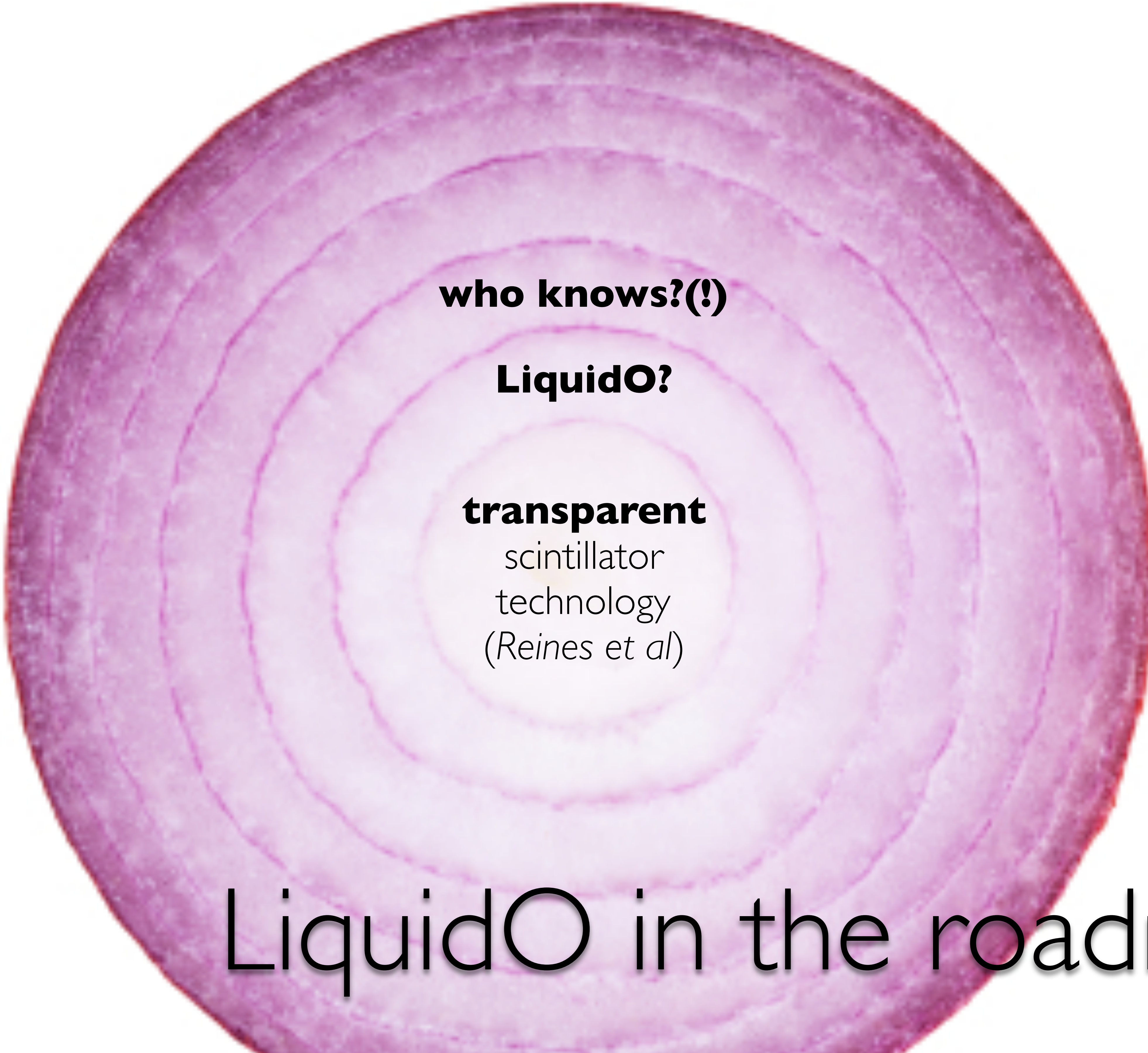


LiquidO in the roadmap?

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

R&D

“ν demonstrator” detector NEXT STEP

specialisation towards physics purposes

✓proof-of-principle (data & MC)

LiquidO physics potential appears LARGE!!

several studies quantifying→**publications soon!**

first publication aiming within JUNE 2019

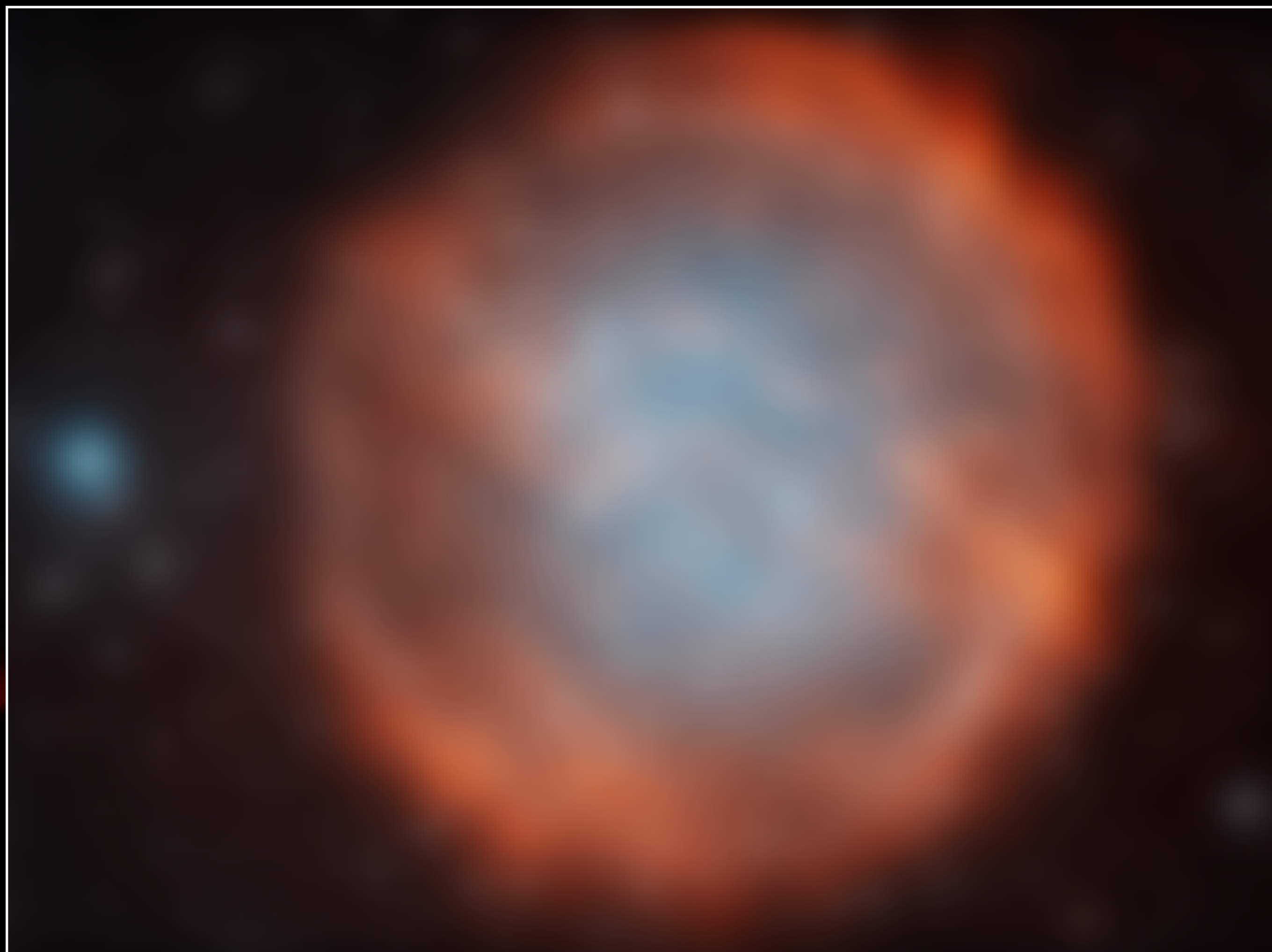
LiquidO detection technique→proof-of-principle

(further prototyping ongoing)

detector performance optimisation→what physics?

(**experimental proposal(s) soon**)

(always question) why people did not see before?



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

more questions, please?

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

anatael@in2p3.fr