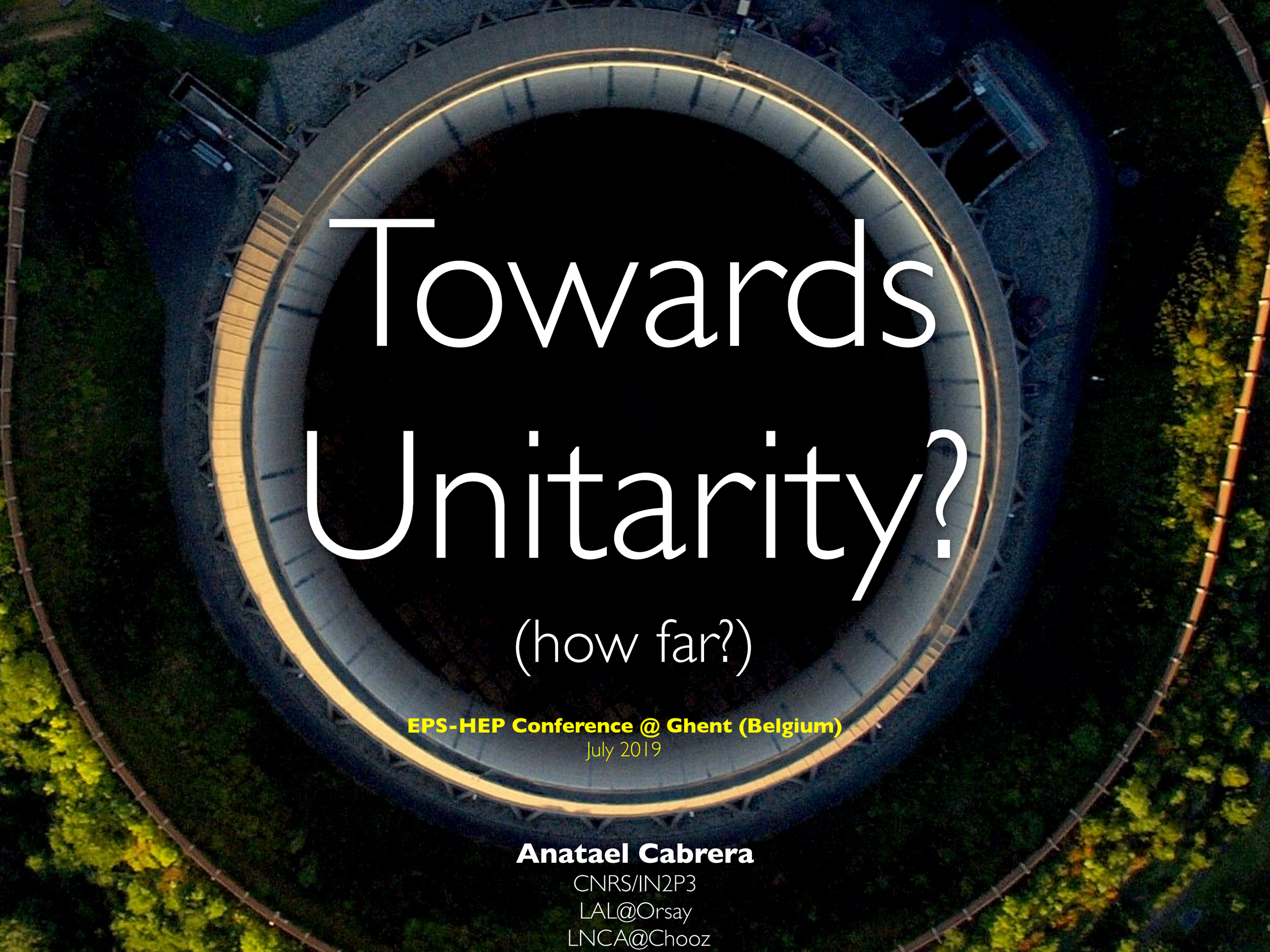


Towards Unitarity?

(how far?)

EPS-HEP Conference @ Ghent (Belgium)
July 2019

Anatael Cabrera
CNRS/IN2P3
LAL@Orsay
LNCA@Chooz

~50 years of neutrino oscillations…

huge experimental effort → well established
[discovery ⇔ Nobel 2015]

what is/are the next goal?

status on neutrino oscillation knowledge…

Standard Model(3 families)
&
PMNS$_{3\times3}(\theta_{12},\theta_{23},\theta_{13})$
&
$\pm\Delta m^2$ & $\pm\delta m^2$

no conclusive sign of any extension so far!!

(inconsistencies vs uncertainties)

must measure all parameters→characterise & test (i.e. over-constrain) ***Standard Model***

	today			**≥2030**		
	best knowledge		NuFIT4.0	foreseen	dominant	technique
θ_{12}	3.0 %	SNO	2.3 %	≲1.0%	JUNO	reactor
θ_{23}	5.0 %	NOvA	2.0 %	≲1.0%	DUNE⊕HK	beam (octant)
θ_{13}	1.8 %	DYB	**1.5 %**	**1.5 %**	DC⊕DYB⊕RENO	reactor
$+\delta m^2$	2.5 %	KamLAND	2.3 %	≲1.0%	JUNO	reactor
$\pm\Delta m^2$	3.0 %	T2K & DYB	1.3 %	≲1.0%	JUNO⊕DUNE⊕HK	reactor⊕beam
sign(Δm^2)	unknown	(SK *et al*)	NO @ ~3σ	@5σ	JUNO⊕DUNE⊕HK	reactor⊕beam
CPV	unknown	(T2K *et al*)	3/2π @ ~2σ	**@5σ?**	DUNE⊕HK⊕ALL	beam driven
			(Nov 2018)			(reactor-beam)

essentially JUNO⊕DUNE⊕HK will lead most of the field (**goal CPV**)→ **except θ_{13}!**

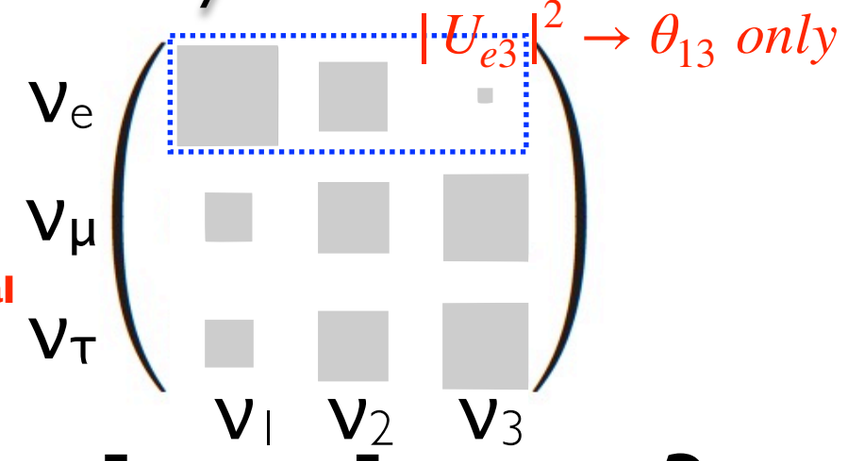
NOTE: ORCA⊕PINGU⊕IceCube complementary (Mass Ordering & Δm^2 measurements)

do we have all needed?

the “super” experiments era…

address PMNS unitarity & structure?

U_{PMNS} matrix $\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$ $\Longrightarrow$ **anything but diagonal (i.e. max-mixing)**



is U_{3x3} unitary?

[ex. test CKM]

$$UU^\dagger = U^\dagger U = I$$

why shape?

[≠CKM]

J(PMNS)≈3.3x10^{-2}⇒ large CPV?

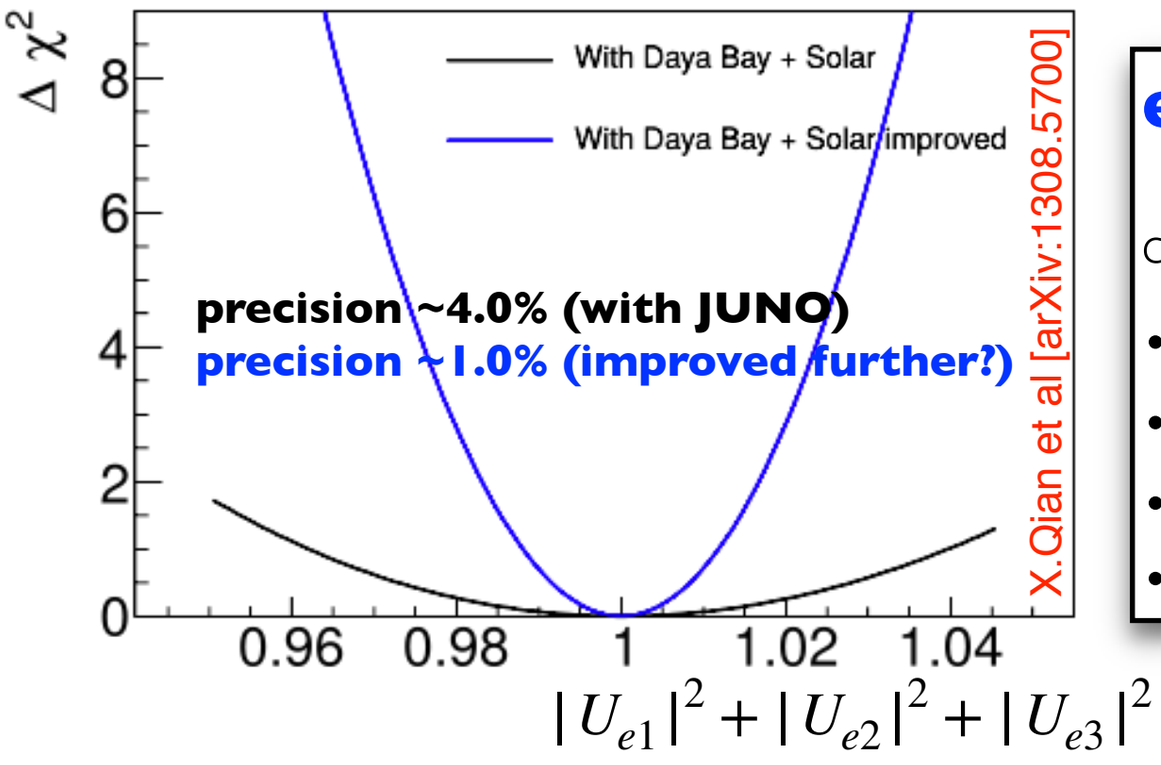
[larger J(CKM)]

$$|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1 \quad l = e, \mu, \tau$$

(other equations too)

⇒ **explore "electron top-row": knowledge? [θ12,θ13]**

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$$



envisage ≲1% precision?

challenging ingredients…

- **JUNO constraint ✓** — non improvable!
- **reactor-θ13 constraint→improvable? [this talk]**
- **solar constraint→improvable?**
- **other possible constraints?**

PRELIMINARY: ongoing calculation→**appetiser**

θ_{13} again?

summary on today's θ13 knowledge/experiments…

reactor-θ13 experiments
[DC⊕DYB⊕RENO]

•statistics: ~10^5 (far) [<10^6]
•systematics: ~0.1% (each)
•energy control: <1% precision

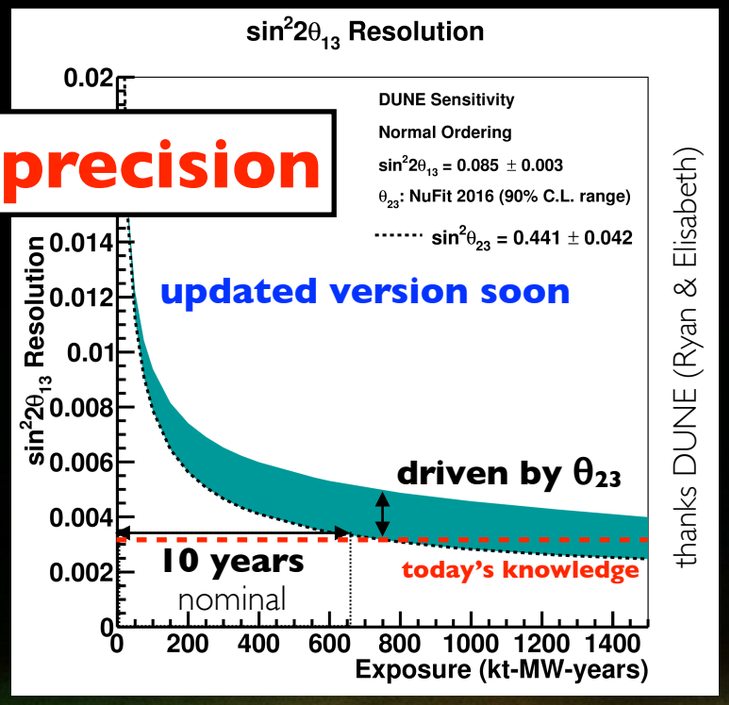
	<2010	today [2010-2020]			cancellation methodology
	total	total	rate-only	shape-only	
statistics	few %	~0.1%	—	—	~100/day @ 1.5km
flux	~2.2%	~0.1%	~0.1%	<0.1%	near-to-far monitor (ideal: iso-flux)
BG	few %	~0.1%	~0.1%	<0.1%	overburden→few/day
detection	2.0 %	~0.1%	~0.1%	—	identical detectors
energy	few %	~0.5%	—	~0.5%	identical detectors

"naively extrapolating" from reactor-θ13 experiments…
•statistics: ~$10^{x?}$ (far) [>10^6]
•systematics: ~0.01%??!! (each)
possible at all?

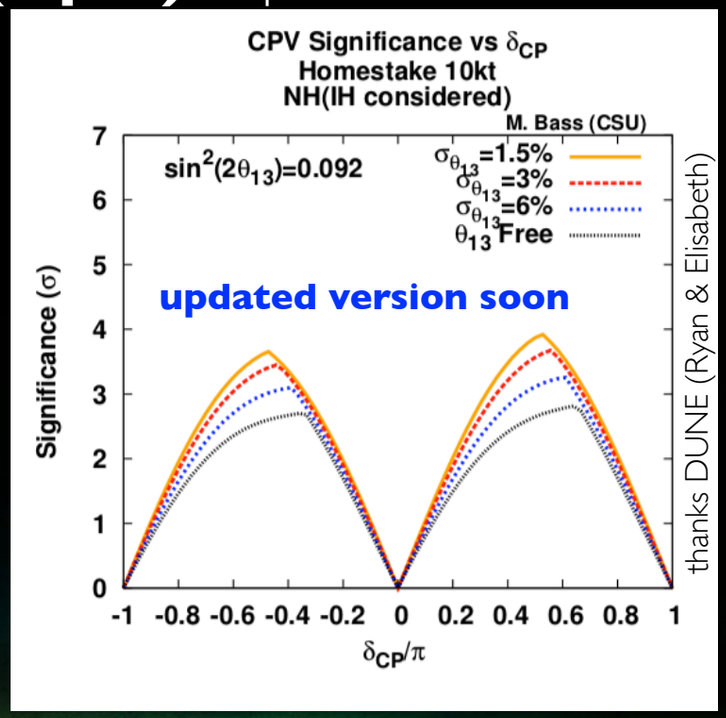
θ13 knowledge elsewhere?

DUNE

(output) nears precision by reactor-θ_{13}

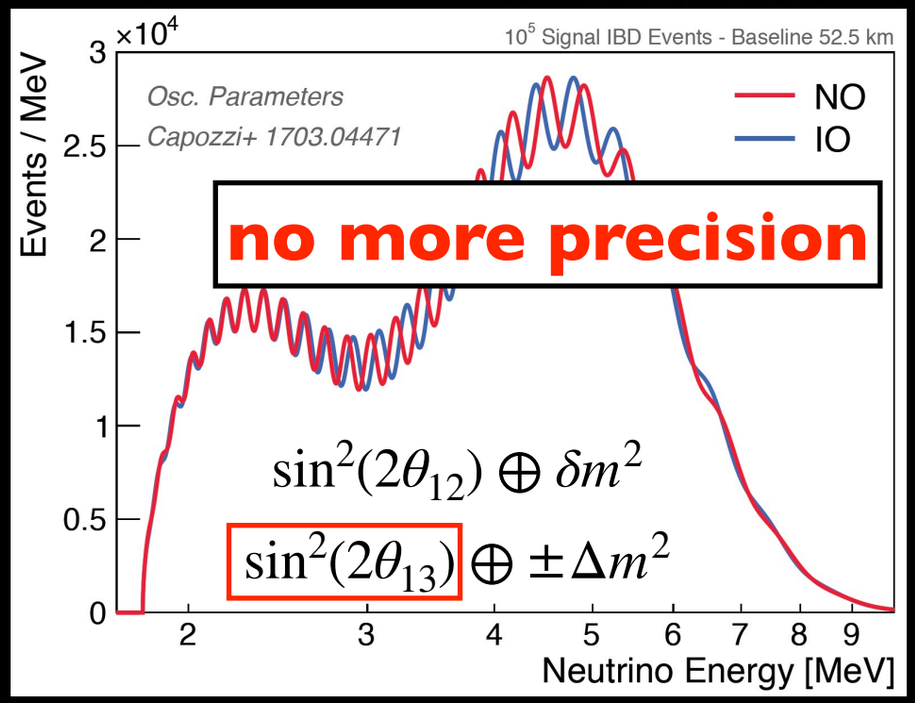


(input) improve CPV with θ_{13}?



a sub-percent θ_{13}⇒ help DUNE⊕HK⊕JUNO?

JUNO



- θ13 measurement: **shape-only**
- **complementary**: reactor-θ_{13} is <u>rate-driven</u>
- JUNO much less precise (5x larger)
- **JUNO benefit from a more precise θ13?**
  [robustness against "fast spectral distorsion"]

improve ~1‰ errors→possible?

reactor ⇒ “super” systematics…

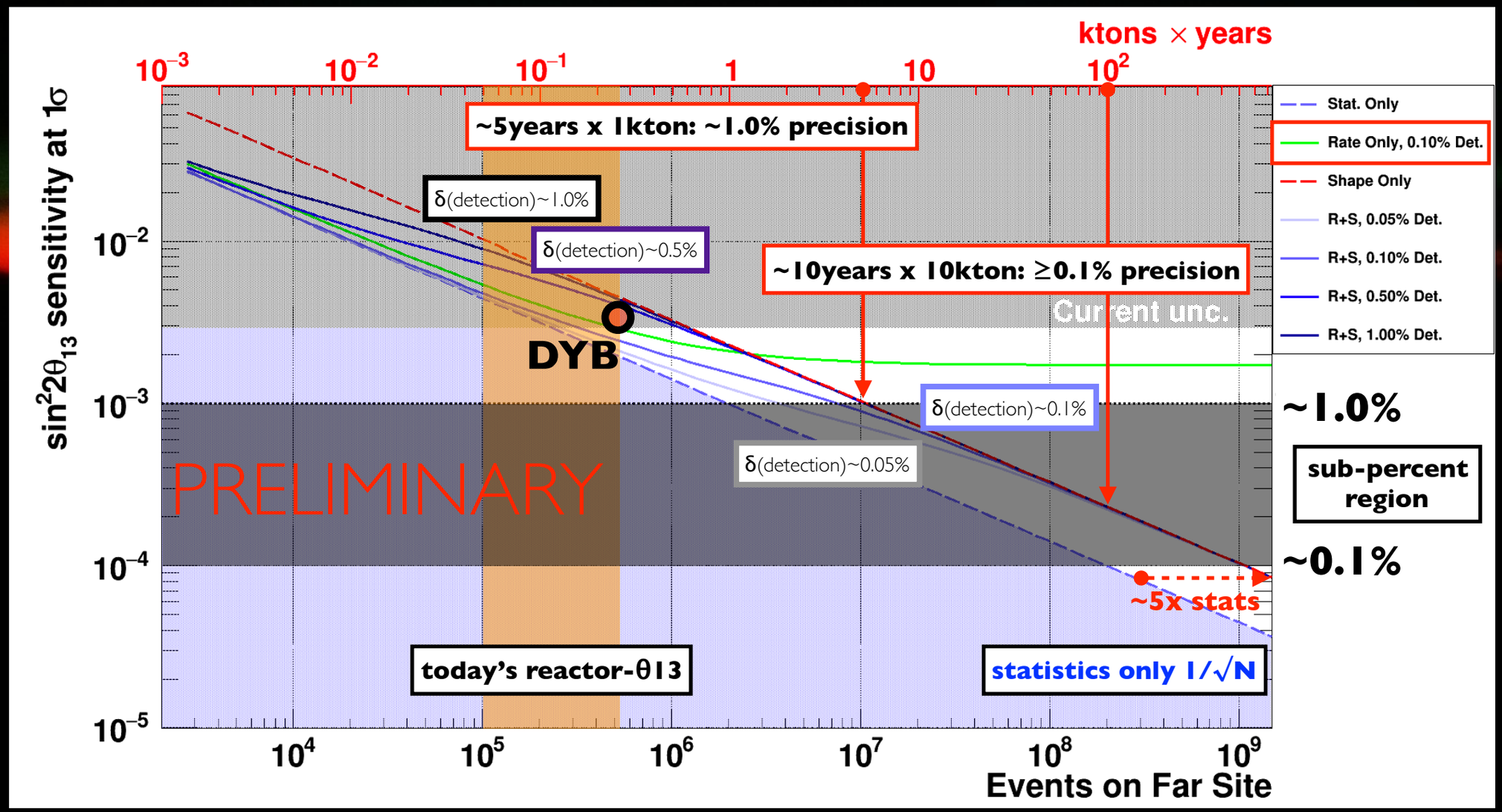
review reactor θ13 sensitivity evolution…

reactor sensitive has potential to go well beyond today [DC⊕DYB⊕RENO]

- **statistics: ≥ 10^7 (far) [≳20x today]**
- **detection systematics (~today: ~0.1%)**
- **energy control (<1% precision)**

⇒ flux & BG systematics→ new techniques!!

Today's reactor state of art knowledge
Power: 2x 4.2GW(thermal)
Baseline: ~1.1km
Detection efficiency: ~85%
Reactor duty-cycle: ~85% [**refuel**]



translator: 1 kton implies ~2x10^6 IBD/year→ **~4 IBD/min** [~50x today]

improving possible…

rate+shape→rate+shape

(today) **(new)**

subtle by powerful difference!

(rate systematics→negligible)

From Double Chooz to Triple Chooz — Neutrino Physics at the Chooz Reactor Complex

P. Huber[a], J. Kopp[b], M. Lindner[c], M. Rolinec[d], W. Winter[e]

arXiv:hep-ph/0601266v1 31 Jan 2006

θ13 systematics: need for new techniques…

larger statistics→ shape-driven info (systematics) matters
is this good enough? no!!

- **detection:** believed impossible to improve [**irreducible**]
- **flux:** BIG trouble→**must fully cancel**
- **BG:** must supress >10x→**more overburden?**

	<2010	today	>2025		cancellation methodology
	total	total	rate-only	shape-only	
statistics	few %	~0.1%	<0.01% (large)		**[25,250]k** IBD/day
detection	2.0 %	~0.1%	**~0.1%** just about possible	✓DC & ✓DYB	today's knowledge
energy	few %	~0.5%		**~0.5%**	today's knowledge
flux	~2.2%	**~0.1%**	**<0.01% (new)**		**full cancellation**
BG	few %	**~0.1%**	**<0.01% (new)**		**BG suppress >10x**

new techniques needed to yield δ(flux)→0 & δ(BG)→0!!

flux cancellation(!) & BG elimination (!!!)

"super" requirements… possible?

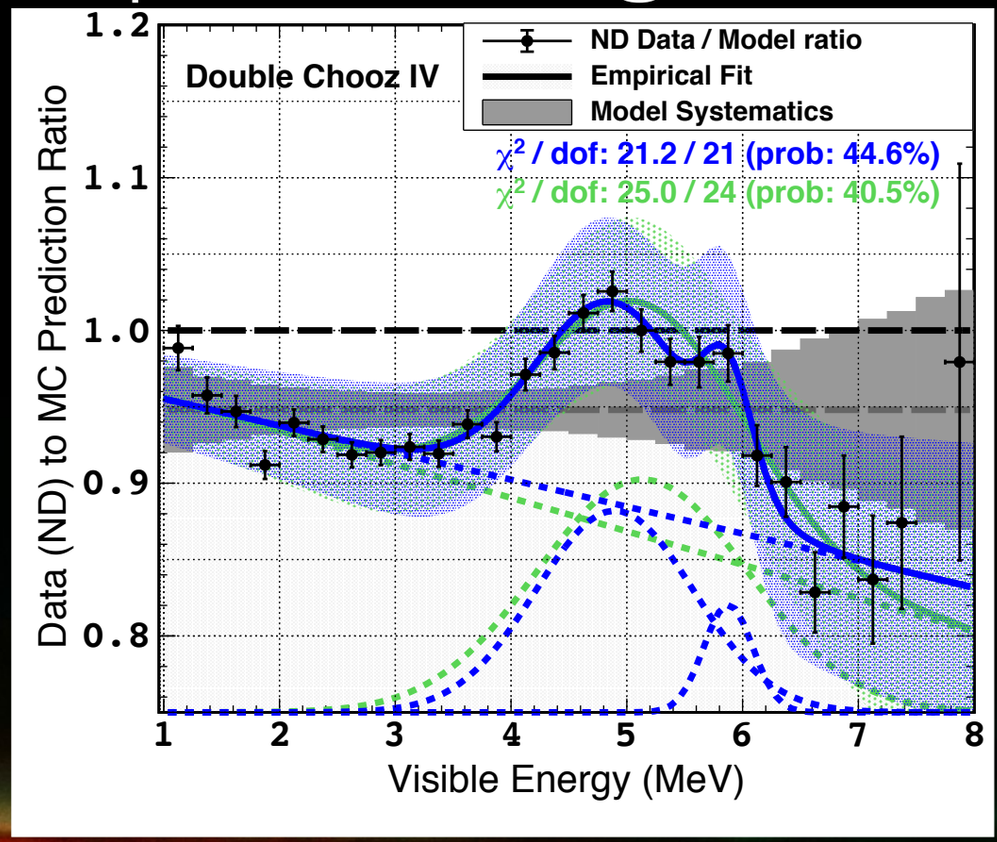
flux handled by the power of geometry…

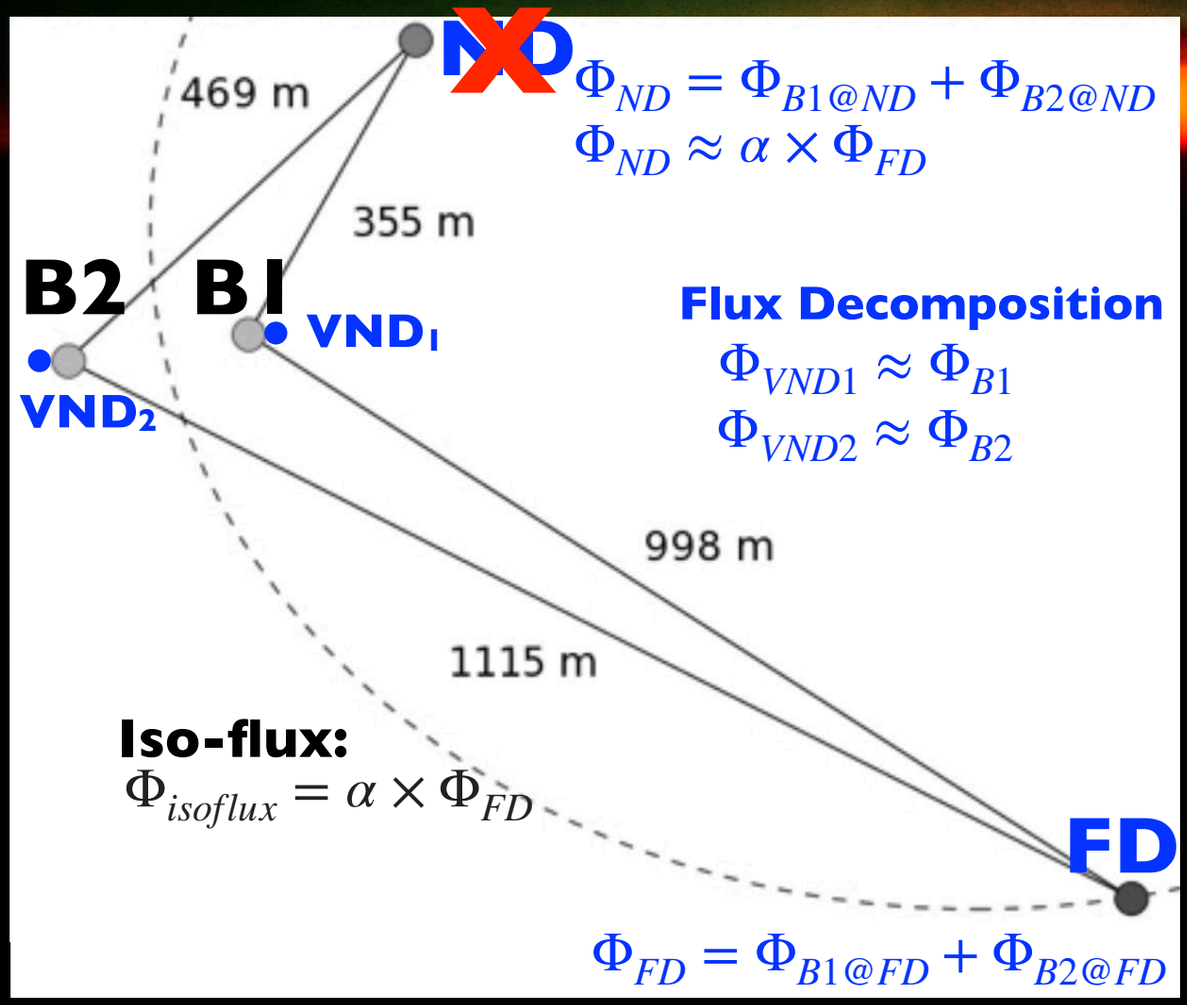
today's knowledge converges: BIG ISSUE!

reactor prediction is <u>inaccurate</u> (few %)
[unsurprisingly more complex than we thought]

- **rate off by ~6% [deficit]**
- **shape off by up to ≤15% [structure]**

⇒our knowledge ≳6%(?) [≲3% is very unlikely]





monitor rate+shape cancels (perfect?)

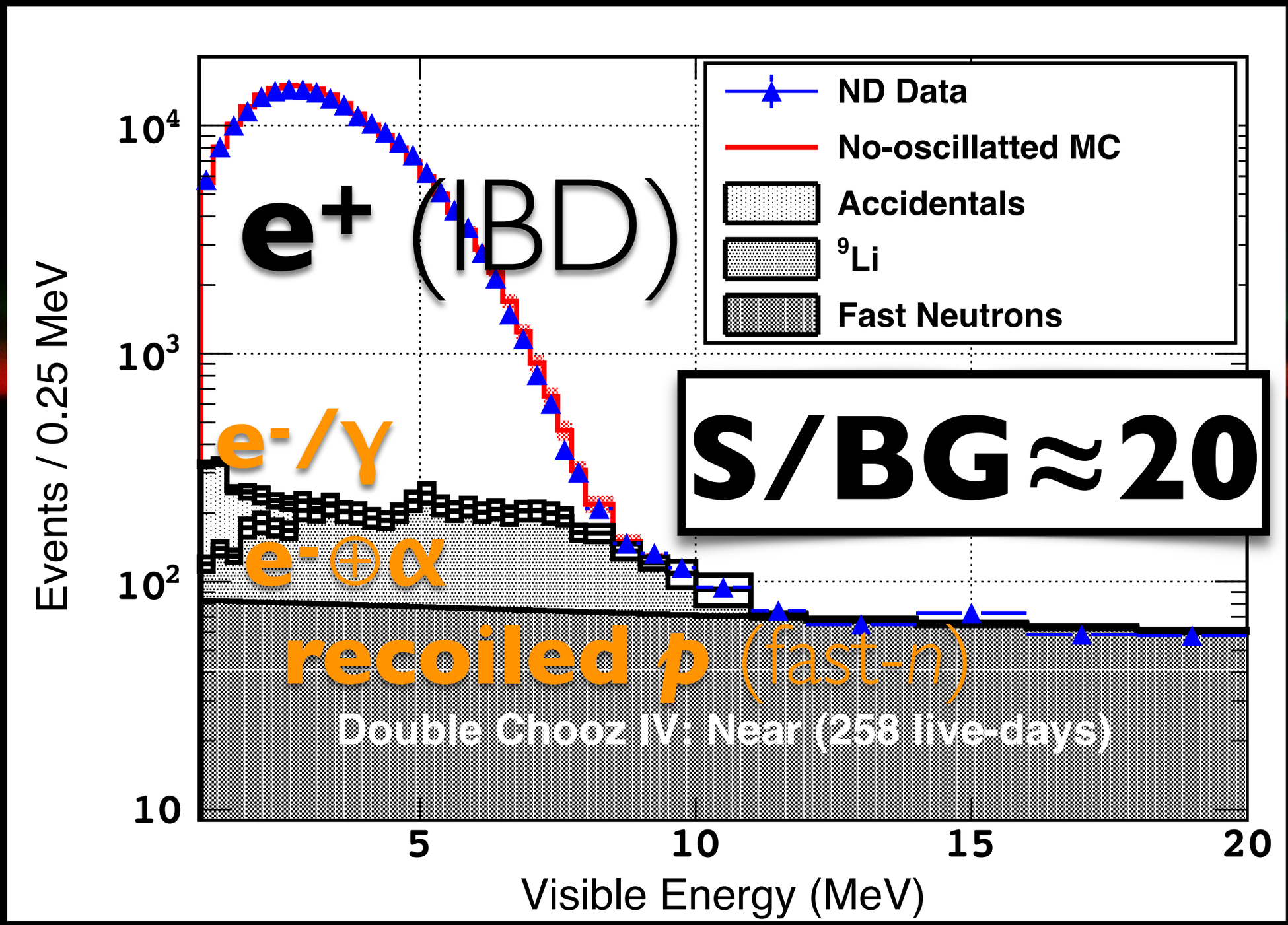
- **conventional ND: not good enough!**
  - →<u>degeneracy flux & θ13</u> (also far & small)
  - →slight offset to iso-flux⇒ unacceptable
- **flux decomposition (L≲40m): perfect!**
  - →very near detector (**VND**) per reactor
  - →<u>huge statistics</u>:
    1ton @ 20m: 8.2k IBD/day [FD: ≲2.2k IBD/day]
  - →<u>no civil construction</u> [→reactor space?]

how to reduce BG with no more overburden?

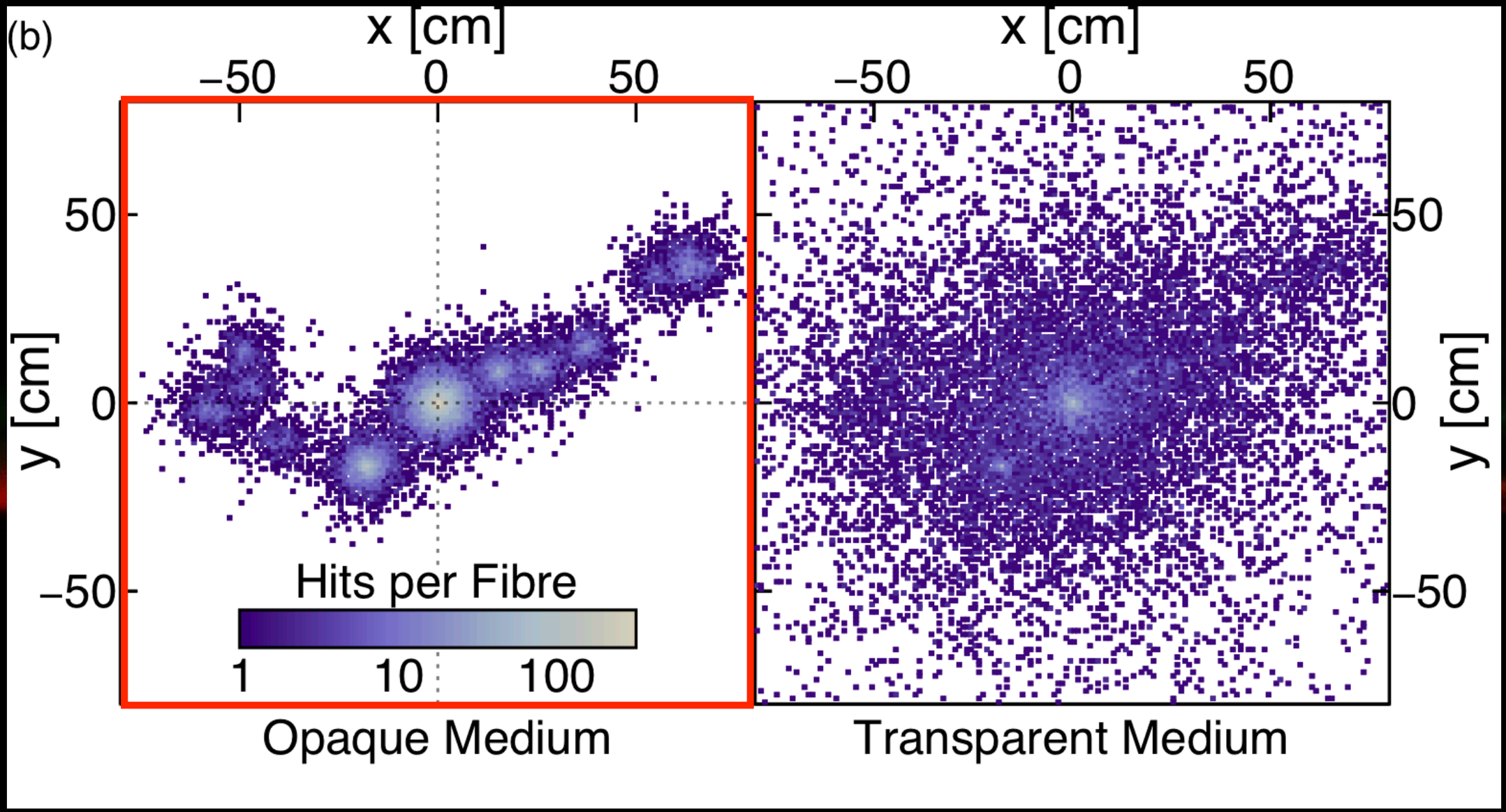
another lesson: avoid civil construction…

LiquidO: novel detection technology

(born in reactor)



LiquidO event-wise imaging…

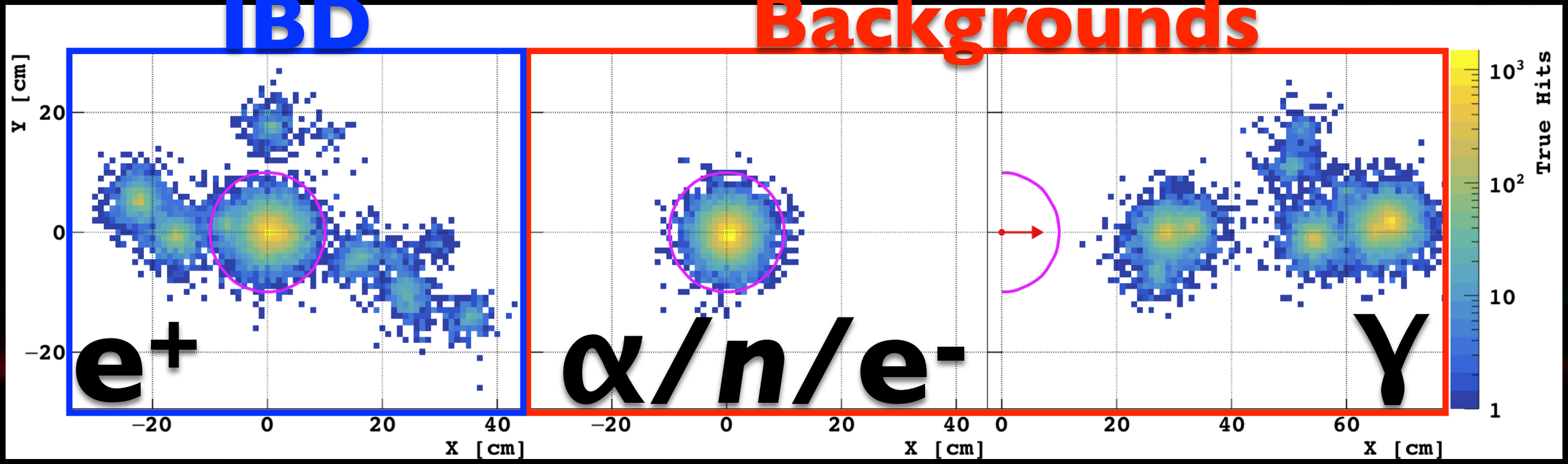


opaque scintillator→stochastic light confinement

(**self-segmentation**) **backup slide**

powerful PID…

2MeV



vertex resolution ≈ order mm

cosmogenic (^{9}Li & fast-neutrons)
accidentals (β^-, γ and α)

rejection ≳ 100x

[time⊕space coincidence & PID(e+)]

backup slide

LiquidO mean many things…

“background-less” IBD detection?

Detector Seminar

LiquidO: Novel Opaque Neutrino Detection Technology

by Anatael Cabrera Serra (IN2P3/CNRS)

Friday 7 Jun 2019, 11:00 → 12:00 Europe/Zurich

40/S2-A01 - Salle Anderson (CERN)

https://indico.cern.ch/event/823865/

first publication days away…

new sensitivity with LiquidO…

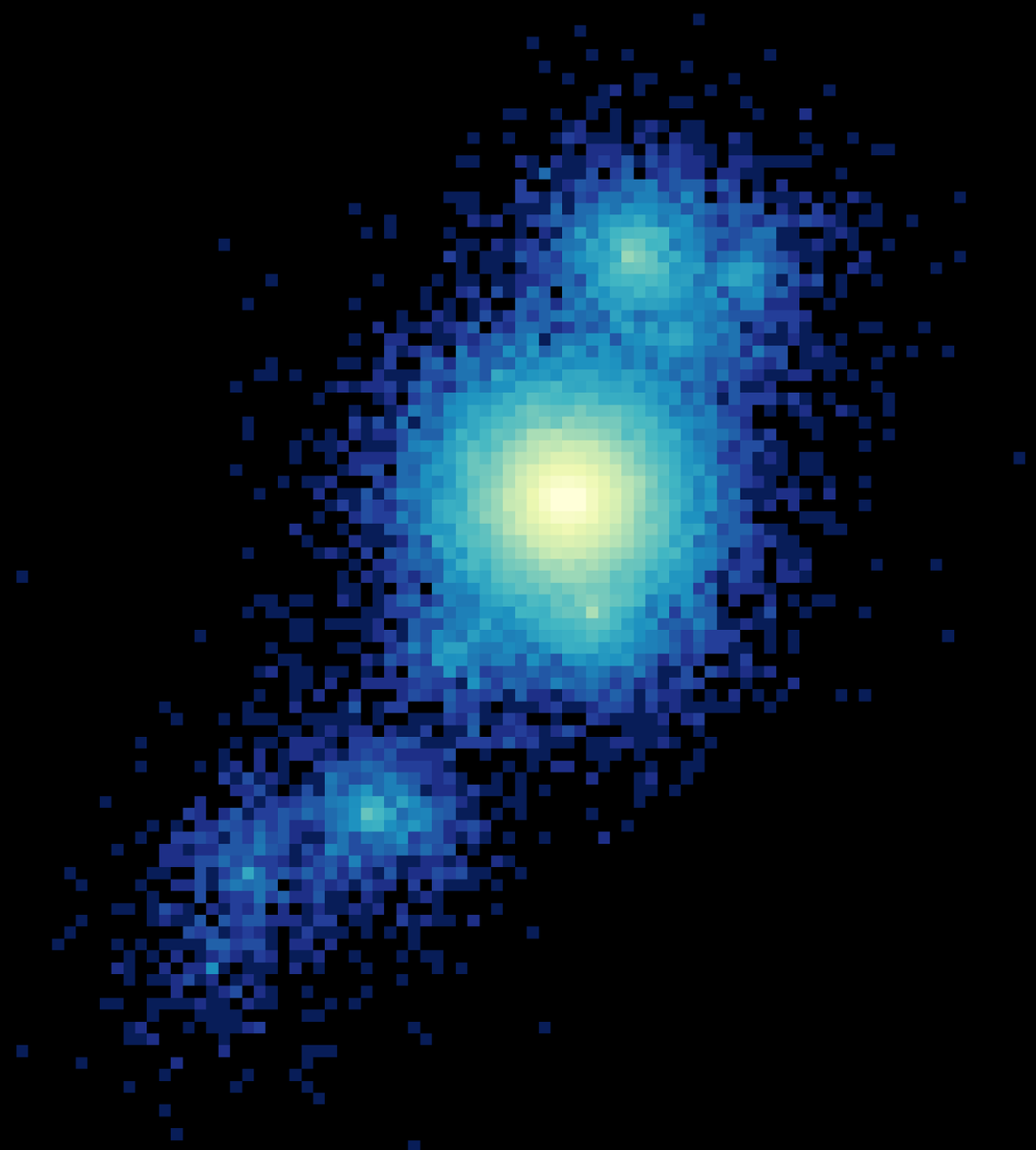


Image: a LiquidO 5MeV e^+ (full photon information)

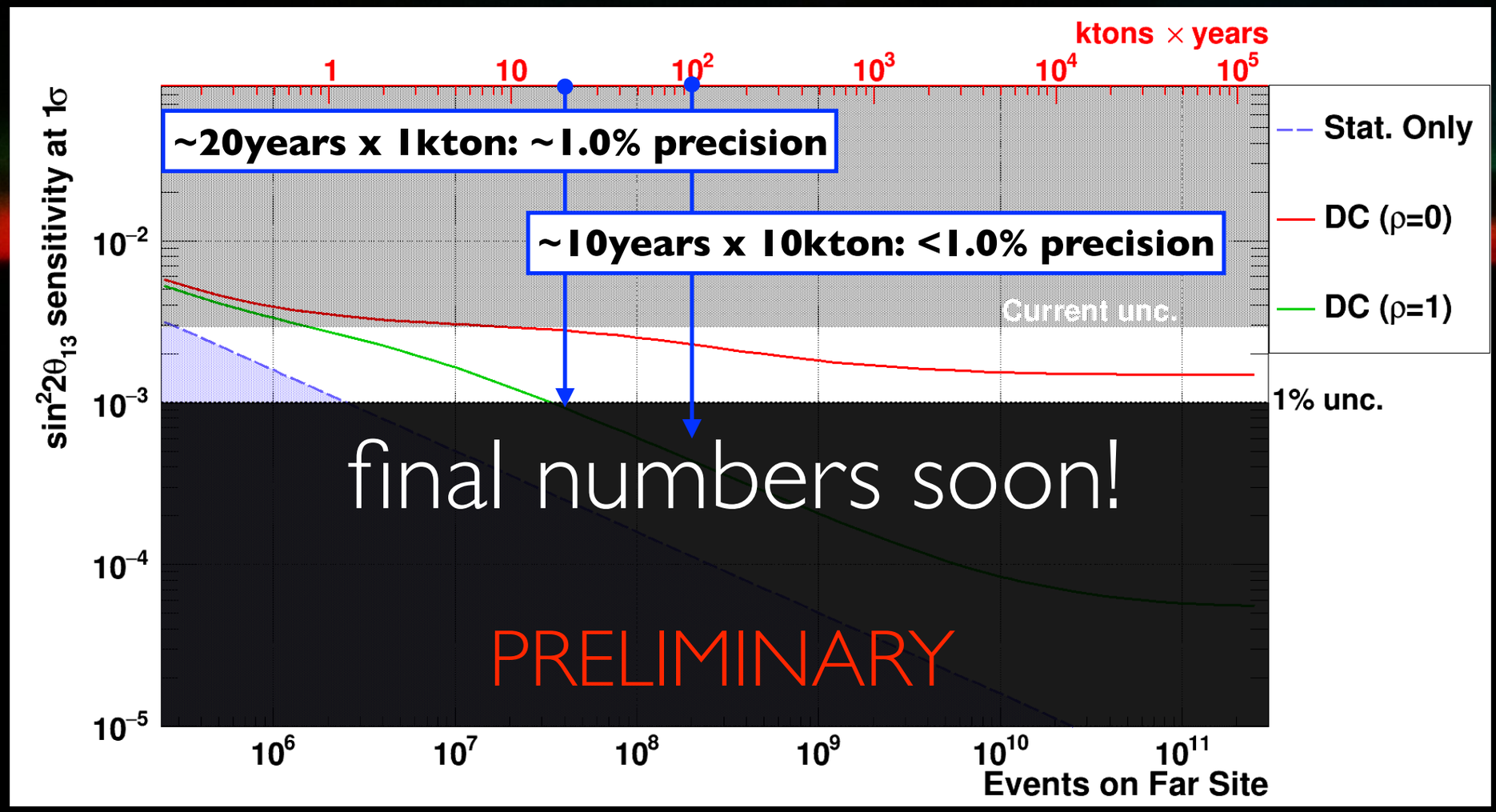
sub-percent θ13 seems possible (while not easy)…

•statistics: >4x10⁷ (far) & similar/better (VND's)

flux cancellation [new] & BG-less [new]
[LiquidO→ many advantages]
&
systematics detection & energy control
[today's technology demonstrated]

⇒ LiquidO 10kton possible? [NOvA⊕R&D backup]

Today's reactor state of art knowledge
Power: 2x 4.2GW(thermal)
Baseline: ~1.1km
Detection efficiency: ~85%
Reactor duty-cycle: ~85% [refuel]



inter-detector energy correlation (today: ρ=1.0)

LiquidO sensitivity: flux constraint via VND's ⊕ energy control (model DC or DYB) ⊕ negligible BG

NOTE: calculations on DYB site (equivalent performance)

sub-percent θ13 precision possible…

full range implications under study

(very soon)

European "super" site ready?

LNCA laboratory…

Chooz-B Lab
<L>≈410m
~30m overburden

Chooz-A Lab
<L>≈1050m
~100m overburden

Chooz Reactors
Power: ~8.4GW^{thermal}⇒ ~10^{21}ν/s
(2x N4 reactors)

new site here (built)

the Chooz-A underground system (former reactor)…

Cavern A: 20,000m³
[past: reactor Chooz-A]

Cavern B: 30,000m³
[past: fuel pool]

⇒ ≤10kton detector ⊕ water veto pool (which?)

Overburden: ~100m (**known BGs!**)

Civil Construction?
- refurbishment (remove structure)
- heavy cranes ready

Available? If so, around ≳2024

EDF @Chooz

"super" synergy with our colleagues in EDF

a **Super Chooz** project?

(too early to say but promising)

Choo

?

leading neutrino physics in Europe is important!

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

much physics beyond θ_{13}...

full menu (under construction)

- **sub-percent precision on θ13** [sin2(2θ13)] **& Δm²(reactor)** [not shown yet]
  [aid DUNE⊕HK to improve **CP-Violation** & JUNO to measure **±Δm²**(vacuum)]

- **burst & remnants supernovae ν_e, anti-ν_e and ν_x measurement** [**backup appetiser**]
  [10 kton & high efficiency]

- **multi-channel proton decay** [**backup appetiser**]
  [10 kton & high efficiency]

- **high precision reactor rate+shape spectra (B1 and B2) with VND's**
  [statistics & complementary to JUNO's TAO]
  ⇒demonstration of reactor monitor technology (high S/BG ~1ton detectors) [**industry?**]
  ⇒reactor spectral composition analysis upon switching ON/OFF (better reactor predictions?)

even more challenging thoughts...

- **measure solar neutrinos?** [**backup appetiser**]
  [unprecedented 10 kton precision with CC interactions]

- **measure θ_w via elastic scattering?** (interference CC & NC)
  [β^- BG is extreme challenge even with LiquidO but huge signal rate and ON/OFF helps]

- [bad news] **geo-neutrinos unlikely** ⇒ huge reactor-IBD BG…

note: PMNS Unitarity test ("top-electron-row")→ solar & other constraints: **a full programme?**

what to remember...

ready to address PMNS structure (head-on) to ≤1%?
[along with CPV, our next goal? do we have the global knowledge?]

feedback / work with phenomenologists

all needed to make the most of our "super-project" era?
[redundancy & complementarity→each step cost up to billions and/or decades]

a hypothetical "Super Chooz" add/complete to the overall picture?
[aid all other projects & address new physics→feasible with LiquidO?]

can LiquidO deliver the expected detector performance?
[breakthrough potential→must demonstrate immediately]

full programme envisaged

[EPS] Europe OK for much (or most) neutrino physics elsewhere?
[much of our physics "brewed/conceived" in Europe but then goes elsewhere]

the best "super" is timely/right decisions...

questions, please?

work led by (alphabetically)…
- Thiago Bezerra (SUBATECH, France)
- Pedro Ochoa (UCI, USA)
- Beda Roskovec (UCI, USA)
- AC (LAL, France)

and
- the LiquidO proto-collaboration

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

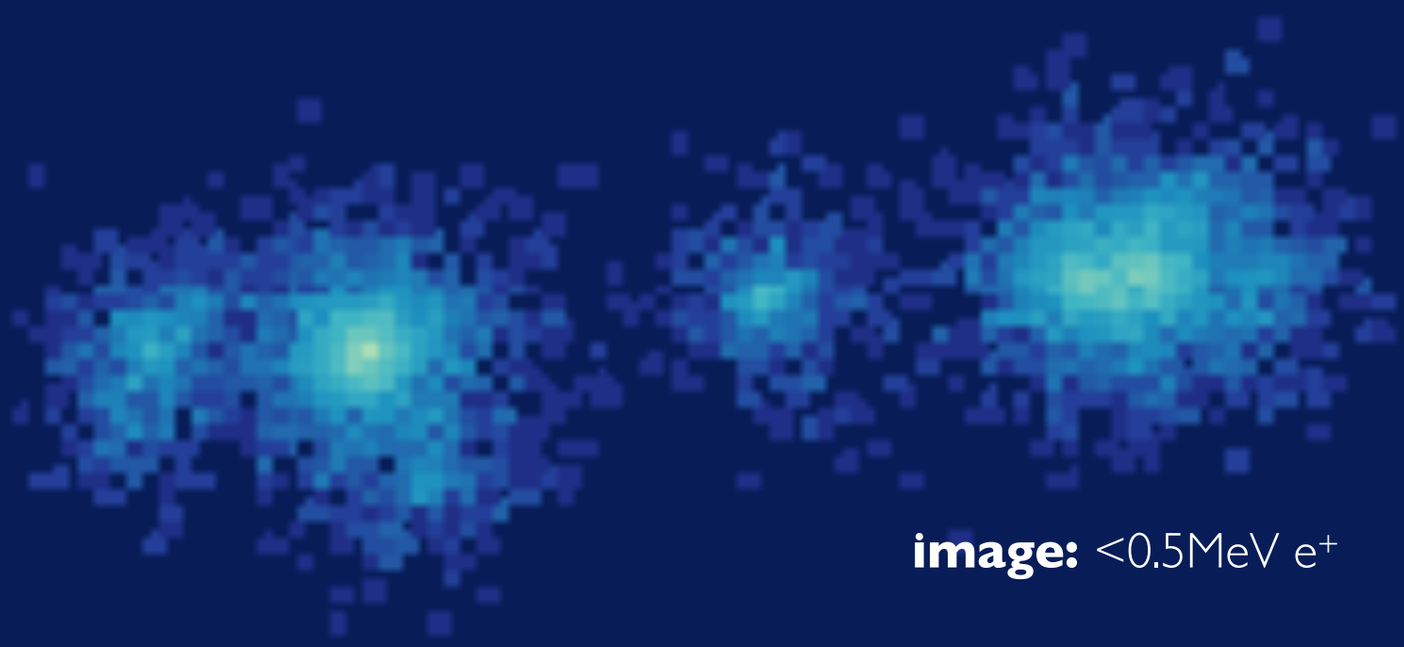


image: <0.5MeV e^+

full results soon!

[paper in preparation]

anatael@in2p3.fr