Directional Detection of Antineutrinos

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for the AIT / WATCHMAN Collaboration
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Antineutrino Directionality

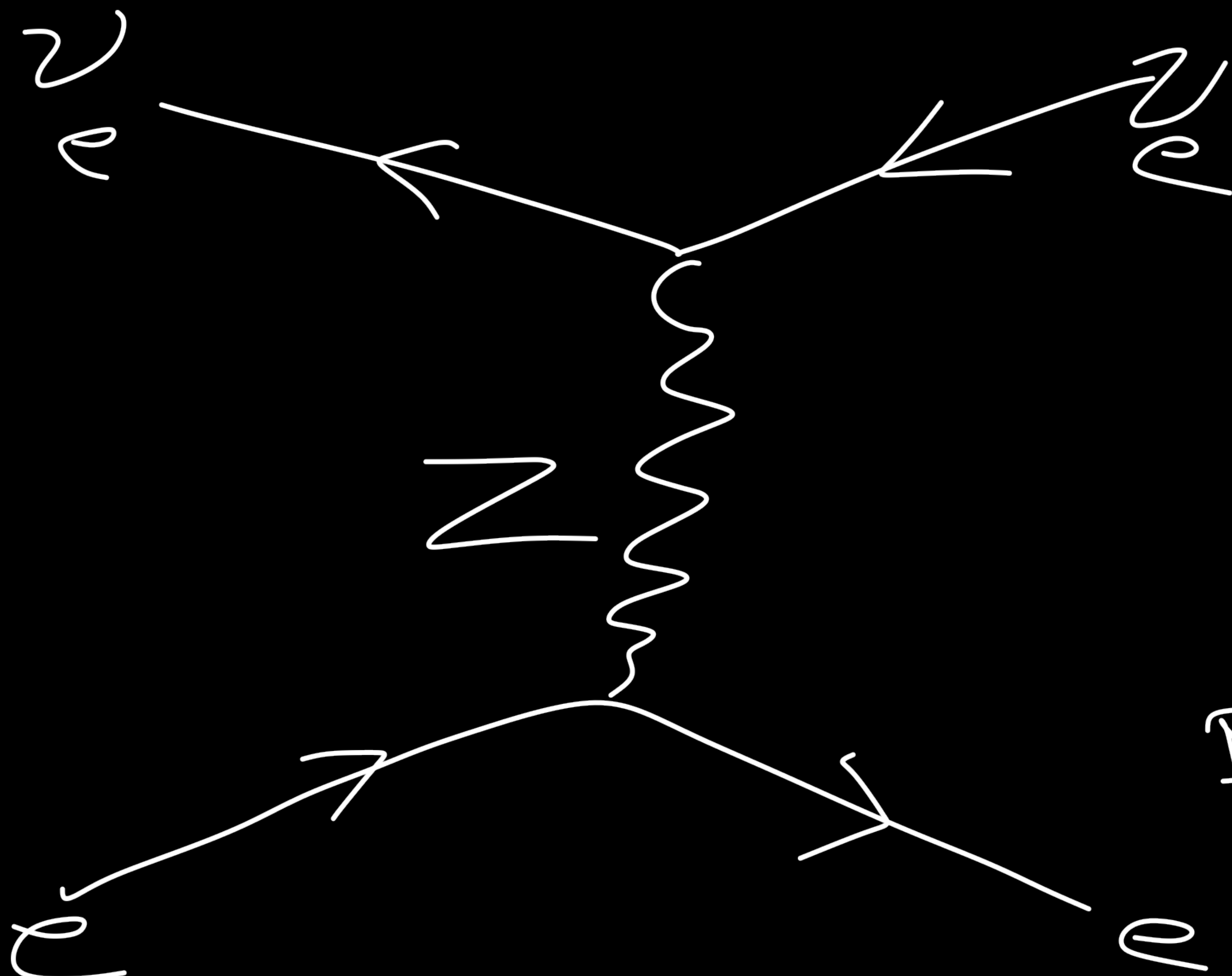
elastic scattering
neutral current
$\bar{\nu}_e + e^- \rightarrow \nu_e + e^-$

e- Cherenkov light carries direction

inverse beta decay
charged current
$\bar{\nu}_e + p \rightarrow e^+ + n$

n carries direction

- **this work also uses e+ scintillation weak directionality**
- **advanced detectors can also separate e+ Cherenkov light**



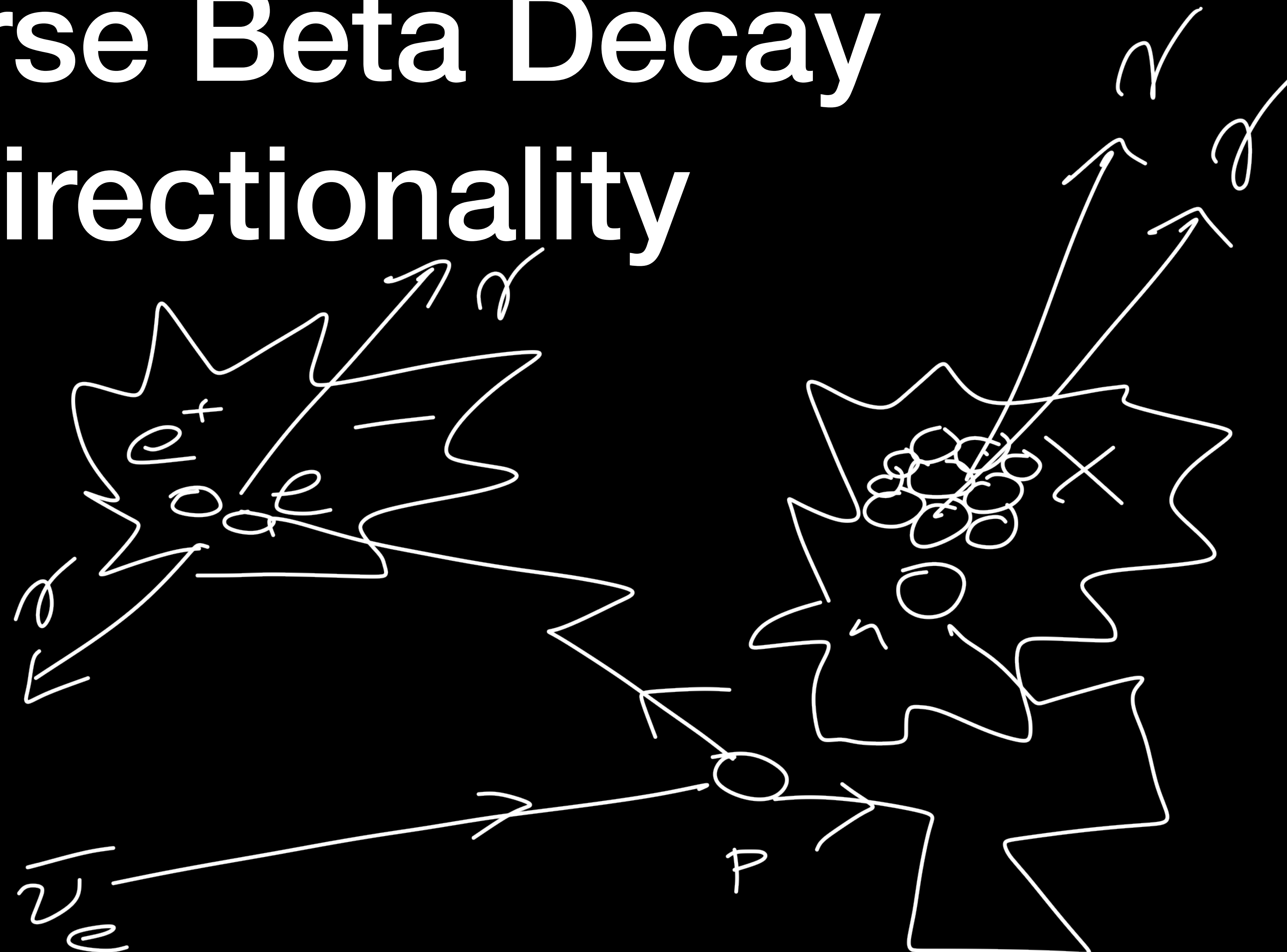
Directionality Applications

- Elastic Scattering
  - Supernova early pointing
  - Nuclear nonproliferation? (Steven Dazeley)
- Inverse Beta Decay
  - Geoneutrinos from Earth’s mantle and crust
  - Nuclear Nonproliferation Monitoring

“GLSMAN”

- Hypothetical GdLS detector
- Whereas WATCHMAN will be Water-based, “GLSMAN” would be Gd-LS based
- WATCHMAN-like geometry

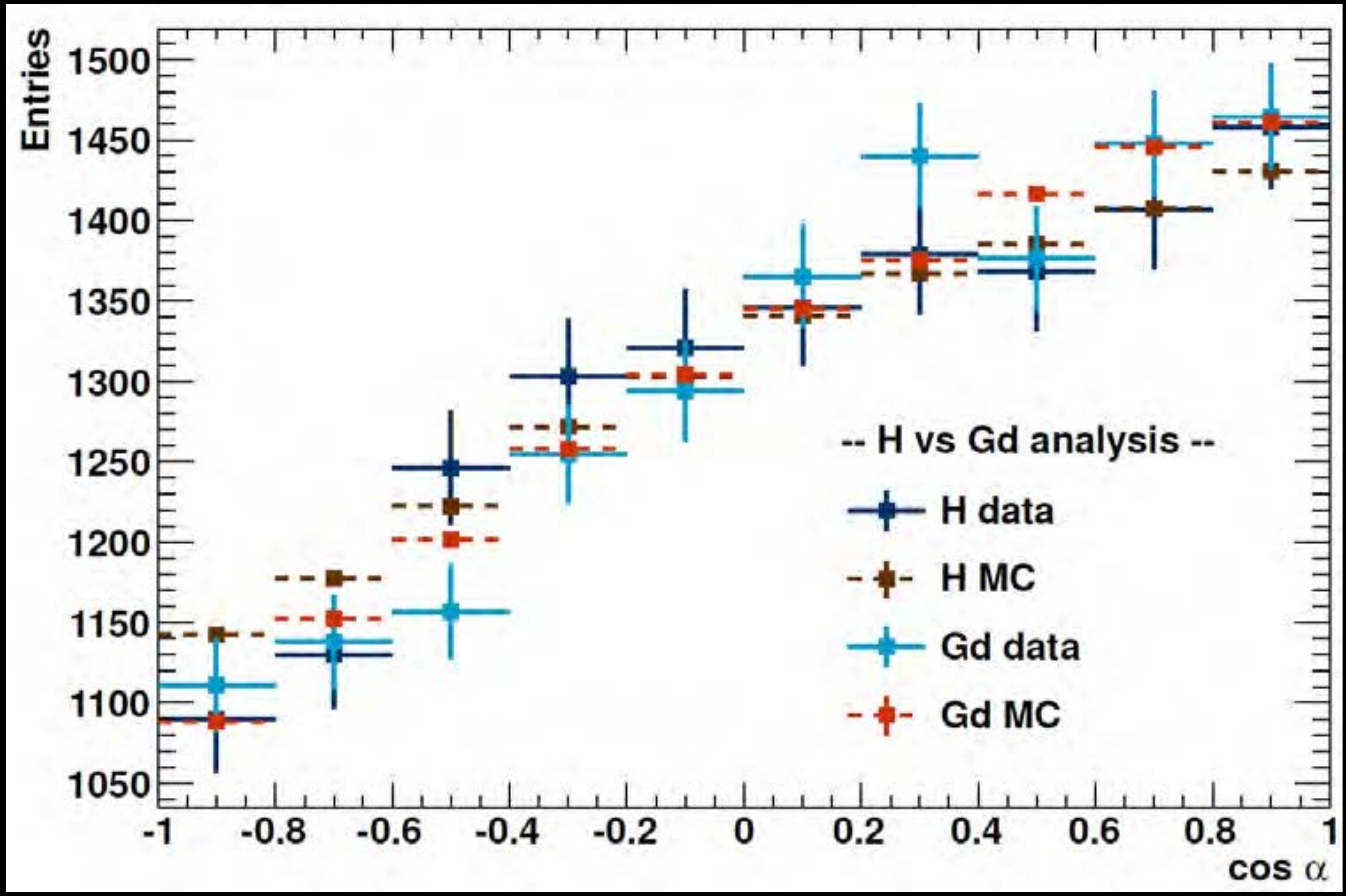
Inverse Beta Decay Directionality



- Prompt positron scintillation and annihilation
- Delayed neutron capture
  - Common neutron targets: H, Gd, ^{6}Li

Directionality in Monolithic Detectors

- Double Chooz far detector
- 10.3 m^3 liquid scintillator doped with 1 g/l of Gd
- Statistical directionality—requires many events

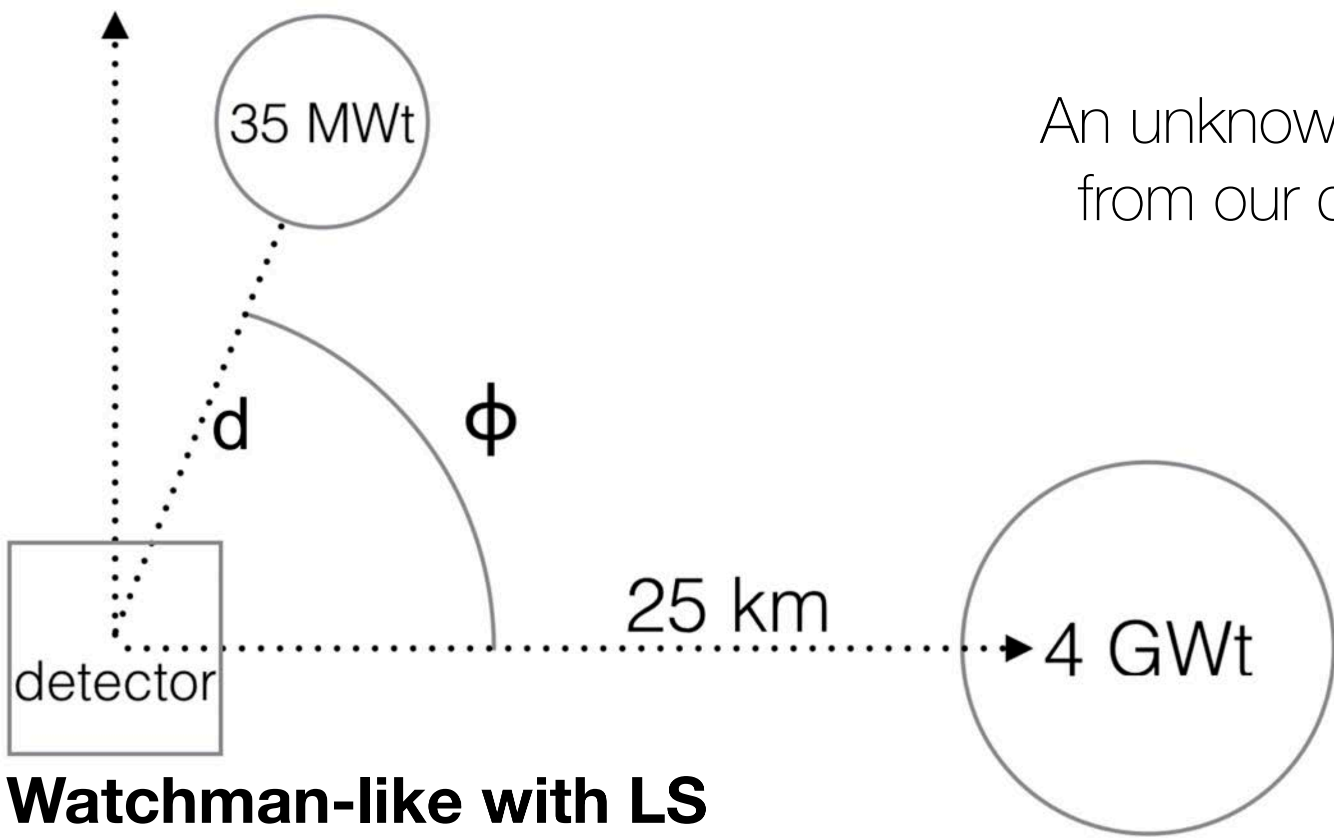


13048 H captures
17358 Gd captures
http://www.ipgp.fr/sites/default/files/ngs2015_gomez.pdf

Recent Work

- Can the Double Chooz directionality technique be applied in a nonproliferation monitoring scenario?

A 1 kT Gadolinium-doped liquid scintillator detector is stationed 25 km from a 4±2% GWt reactor, whose existence is known.



Watchman-like with LS "GLSMAN"

An unknown 35 MWt reactor powers up at a distance d from our detector site, with an azimuthal separation ϕ relative to the 4 GWt reactor.

For how long, in reactor-on time, must we monitor to detect the unknown reactor? Neglecting backgrounds to set a baseline result for the method.

Inverse Beta Decay Rate

$$\langle N_i \rangle (t) \approx \varepsilon n_{\mathrm{p}} \frac{t}{4\pi L_i^2} \frac{p_i}{\epsilon} \int_0^\infty \sigma(E) P_{\mathrm{ee}}(L_i/E) \varphi(E) dE$$

where ε is the total IBD detection efficiency, n_{p} is the number of free fiducial protons, L_i is the propagation baseline, p_i is the reactor's thermal power, $\epsilon = 200$ MeV is the fission energy, E is antineutrino energy, σ models the IBD cross section, P_{ee} is the electron antineutrino survival probability, and φ models the fractional reactor flux density

80% efficiency

Reactor flux: C. Bemporad, G. Gratta, and P. Vogel, Rev. Mod. Phys. 74, 297 (2002).

Highlight: a better simple IBD cross-section model from A. Strumia and F. Vissani.

4% to 10% more accurate in the reactor energy domain than $\sigma \approx 9.52 \times 10^{-44} \frac{p_e E_e}{\mathrm{MeV}^2}\ \mathrm{cm}^2$

A. Strumia and F. Vissani. Precise quasielastic neutrino/nucleon cross-section. Physics Letters B, 564(1):42 – 54, 2003.

$$\sigma(\bar{\nu}_e p) \approx 10^{-43} \mathrm{cm}^2 p_e E_e E_\nu^{-0.07056 + 0.02018 \ln E_\nu - 0.001953 \ln^3 E_\nu}, \quad E_e = E_\nu - (m_n - m_p)$$

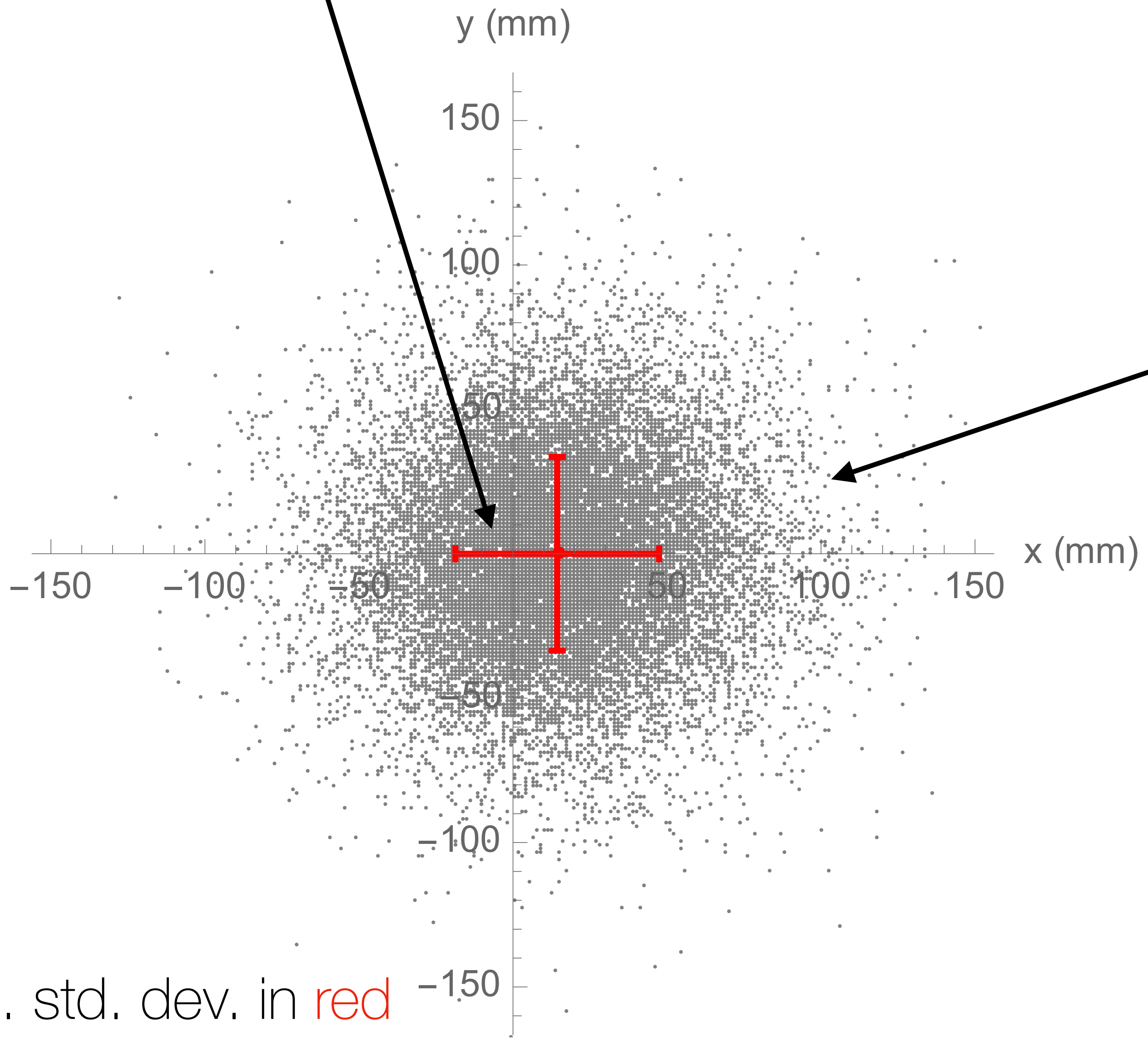
where all variables are expressed as numbers of MeV

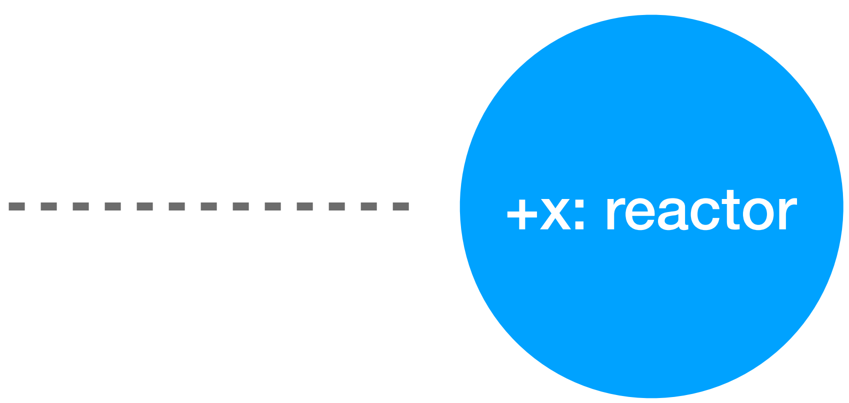
Interaction Vertices
for a **Single Reactor**

n capture defines origin

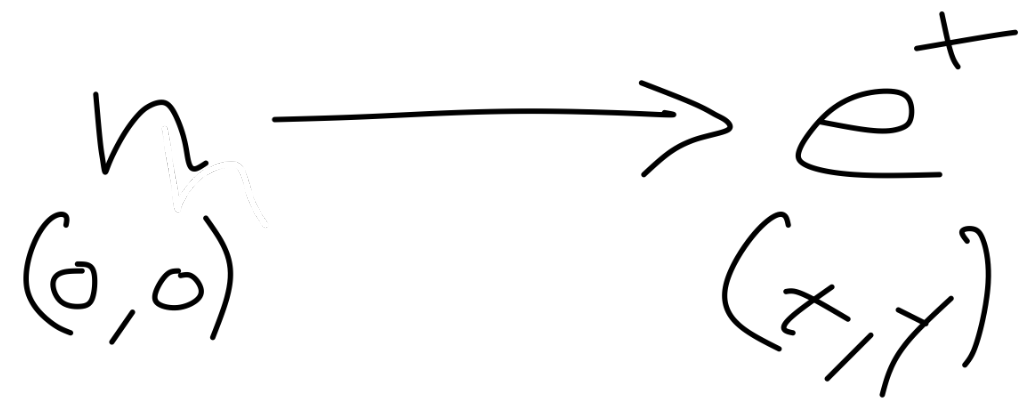
Geant4
20k IBD events in 0.1% Gd-LS

e^+ centroids plotted





pop. std. dev. in red



q	μ_q (mm)	σ_q (mm)
x	14.4 ± 0.2	33.1 ± 0.2
y	0.1 ± 0.2	33.5 ± 0.2
z	-0.3 ± 0.2	33.1 ± 0.2

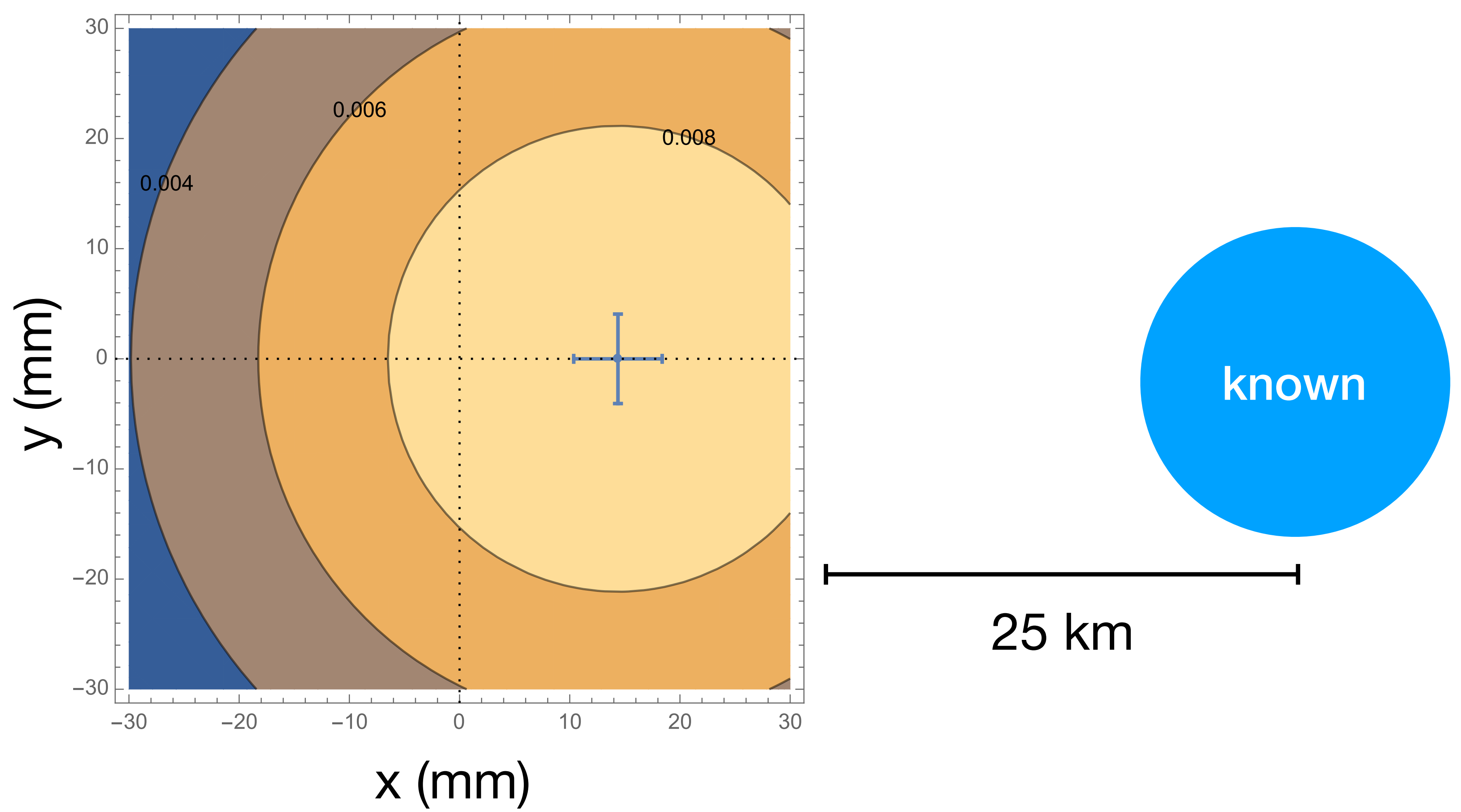
IBD Vertex Distribution

$$\frac{dN}{d^3r}(\vec{r}|\,n) = \sum_{i=1}^{n} \frac{N_i}{2\sqrt{2}\pi^{3/2}\sqrt{\sigma_i^3}} e^{\frac{-(\vec{r}-\vec{\mu_i})^2}{2\sigma_i}}$$

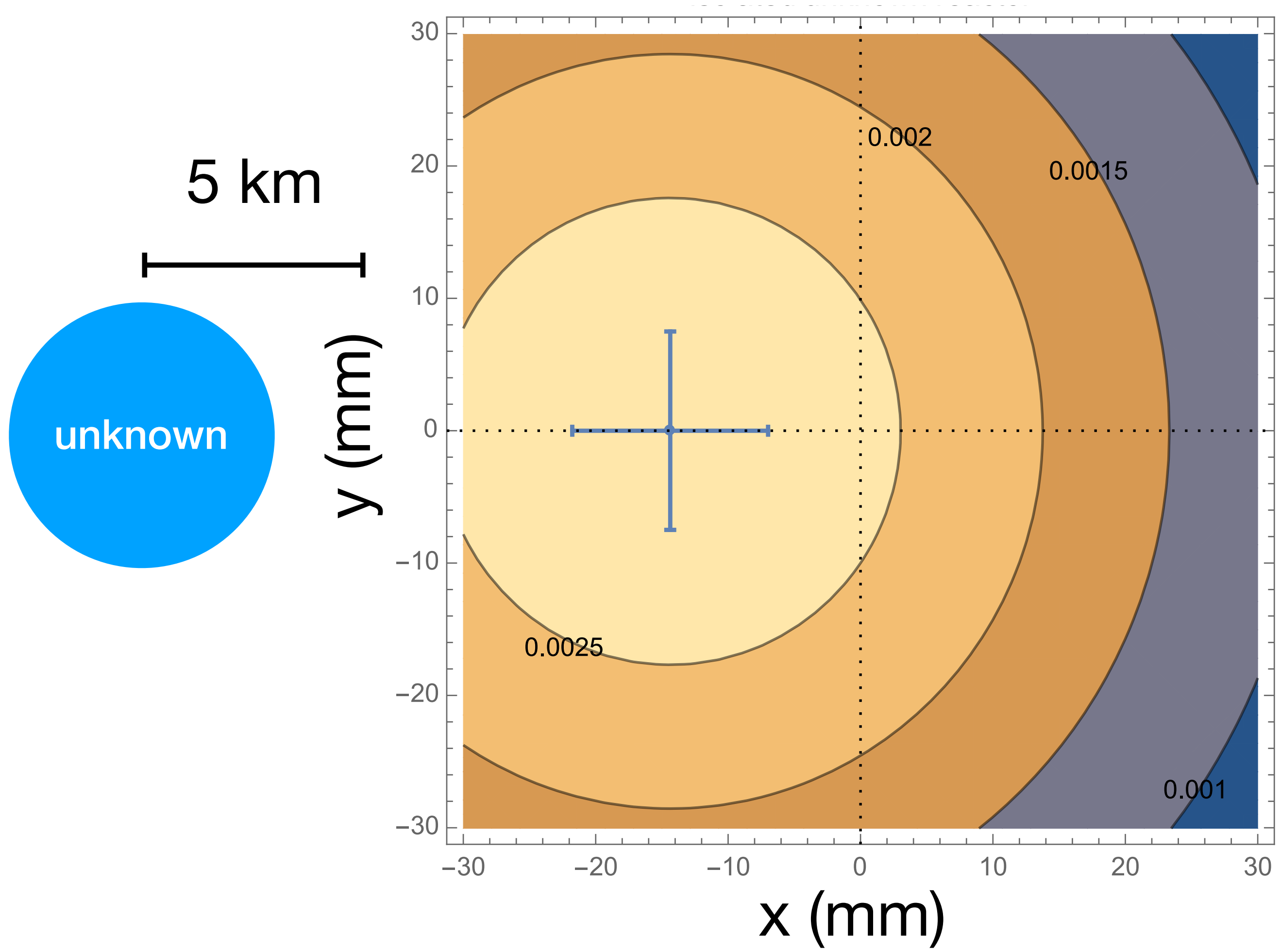
In this coordinate system, the relative positron vertex distribution can be modeled as a 3D gaussian. To model *n* reactors, combine *n* distributions, each weighted by its event count N_i after a period of monitoring.

known 4 GWt reactor

contours show level sets of the number density function
error bars show standard deviation on the mean after one month

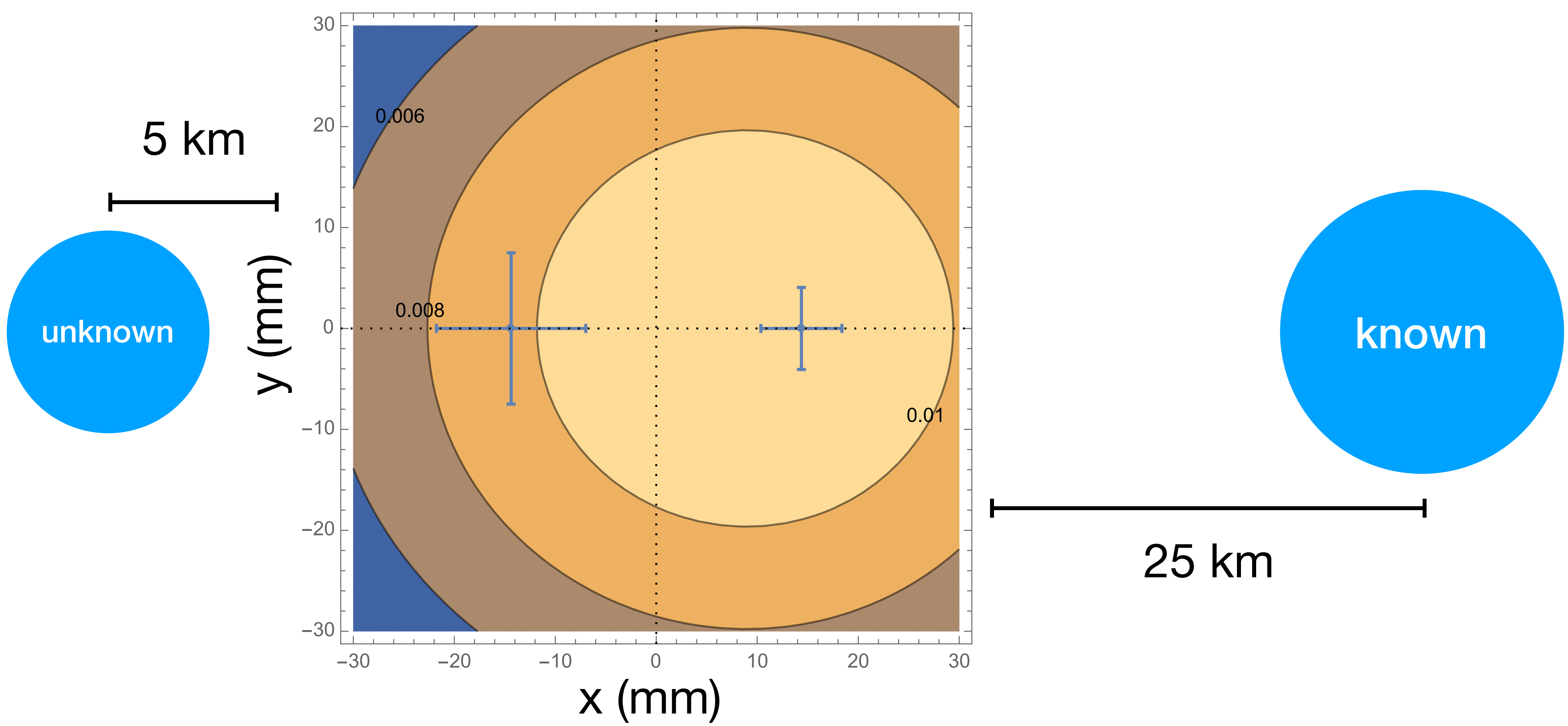


unkown 35 MWt reactor

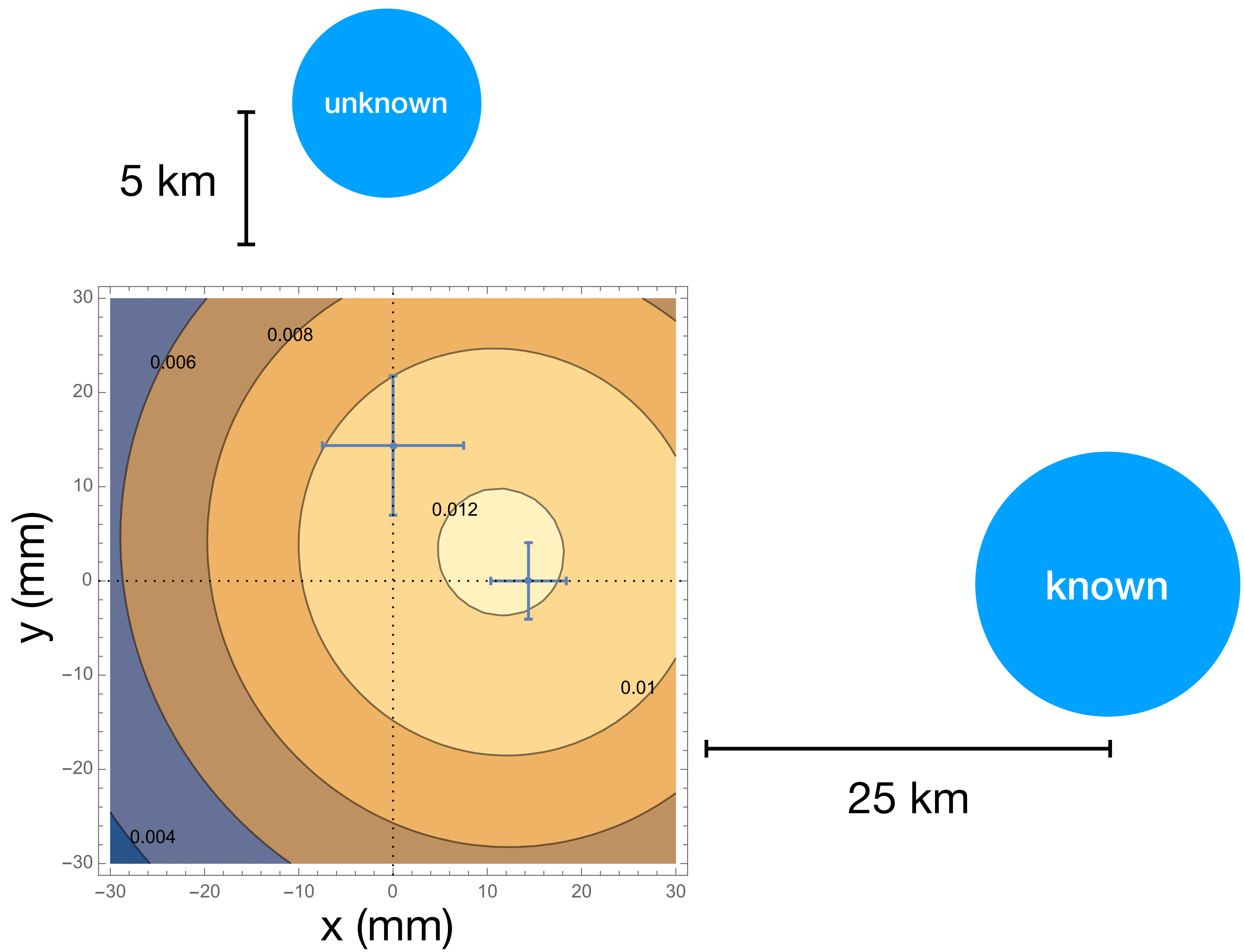


both reactors

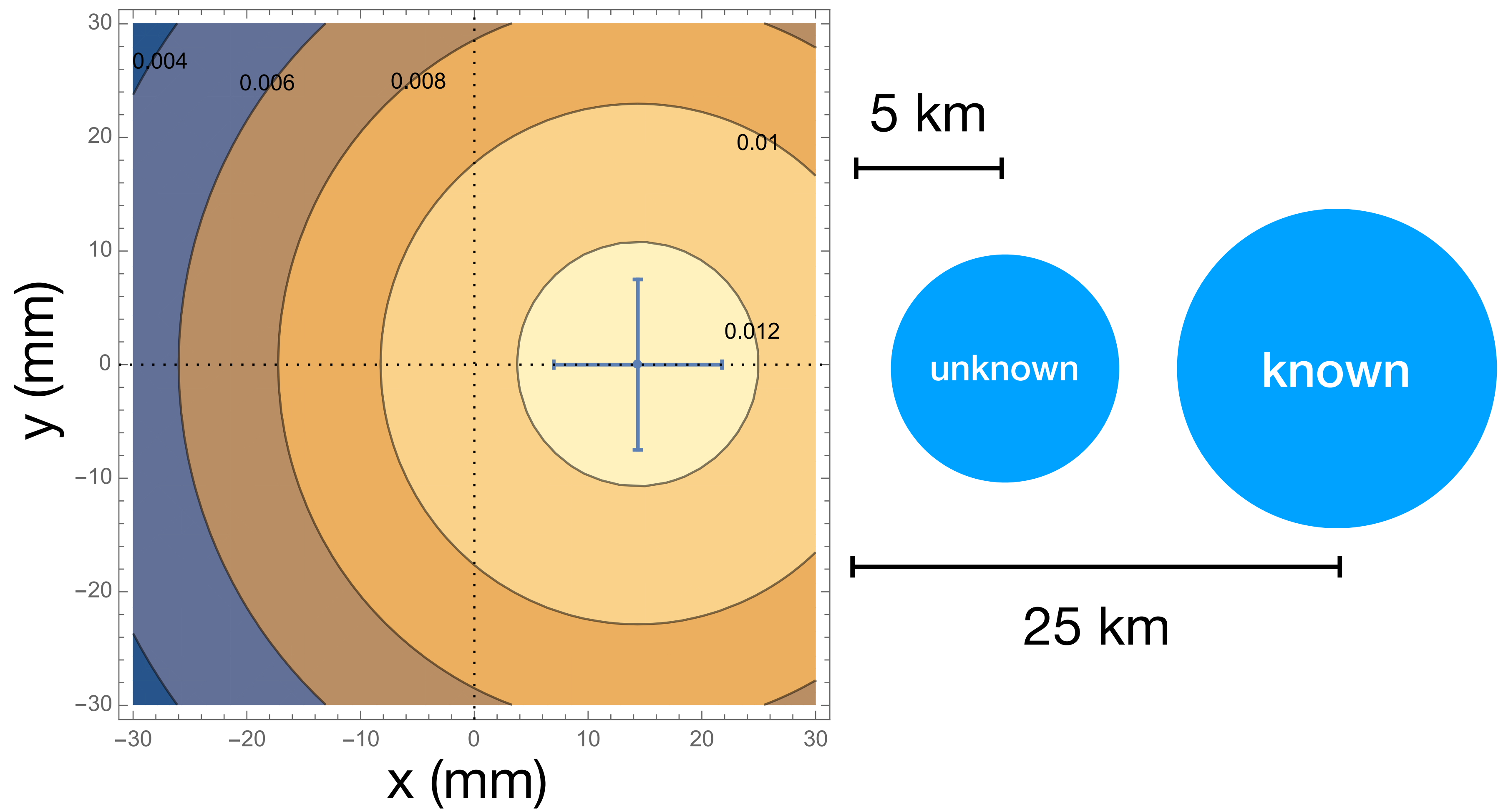
$\phi = \pi$



both reactors
$\phi = \pi/2$



both reactors
ϕ = 0



Reconstructed Vertex Distribution

$$\frac{dN}{d^3\tilde{r}}(\tilde{r}|n) = \frac{1}{2\sqrt{2}\pi^{3/2}\sqrt{\left(\delta r\sqrt{2/3}\right)^3}} \int_V e^{\frac{-(\tilde{r}-\vec{r})^2}{2(\delta r\sqrt{2/3})}} \frac{dN}{d^3 r}(\vec{r}|\, n) d^3 r$$

Vertex reconstruction error smears the vertex distribution with a reconstruction resolution of $\delta r\sqrt{2}$.

$\sqrt{2}$ because each point combines both reconstructed IBD vertices.

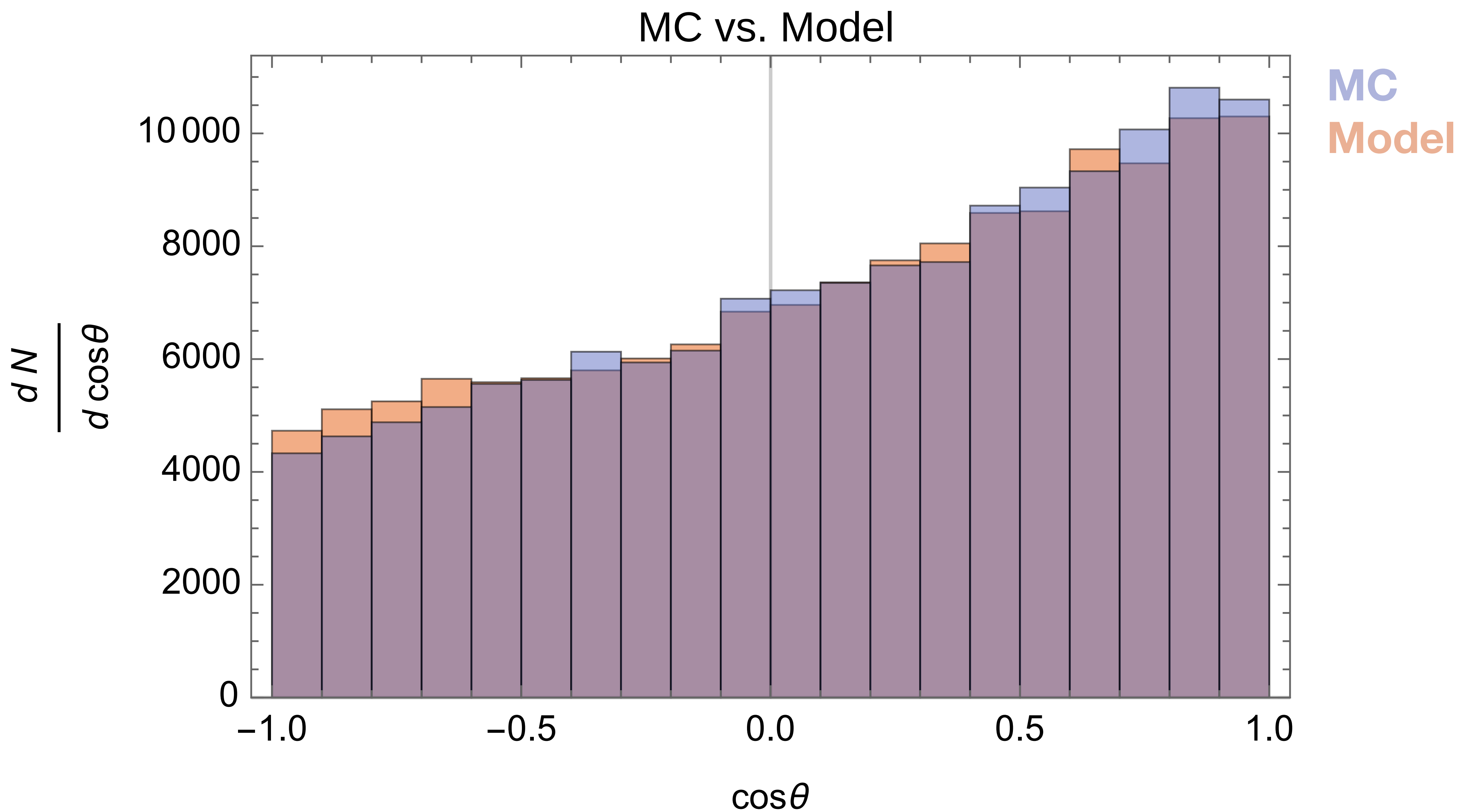
Let δr=15 cm, similar to Daya Bay and Double Chooz.

Reconstructed Cosine Distribution

$$\frac{dN}{d\cos\tilde{\theta}}\left(\cos\tilde{\theta}|n\right) = \int_0^{\infty}\int_0^{2\pi} \frac{dN}{d^3\tilde{r}}\,(\tilde{r}|\,n)|\tilde{r}|^2 d\varphi' d|\tilde{r}|$$

Finally, to focus on the angular and event rate information, marginalize to a cosine distribution.

Given perfect detector resolution, integrating the model into histogram bins shows good agreement with Monte Carlo.



This validates the analytical approach,
which is *much* faster to evaluate than Monte Carlo.

Systematic Uncertainties

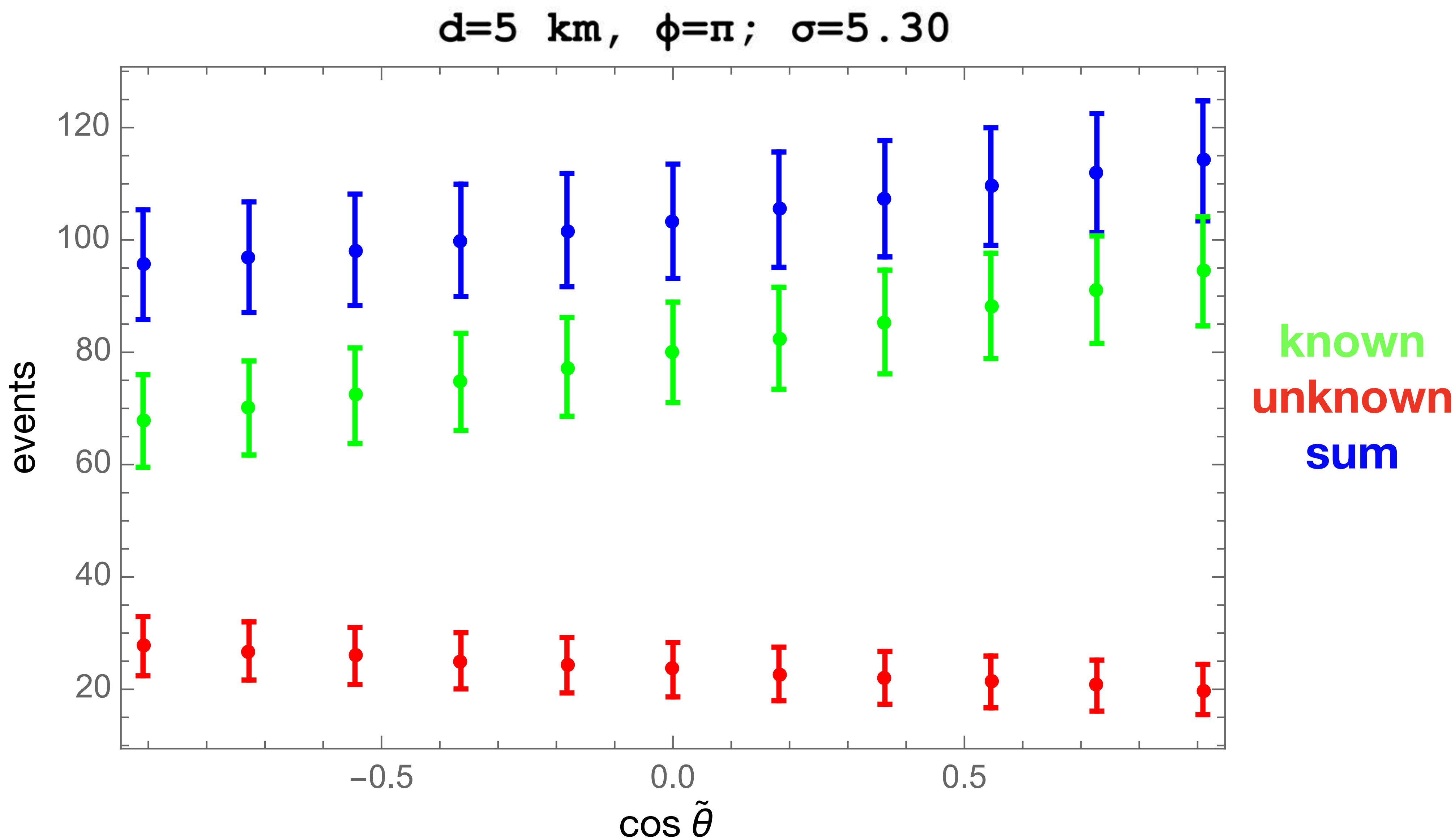
Systematic uncertainties enter through the χ^2 covariance matrix (or equivalently, pull terms) when testing the hypothesis that there is only one reactor present.

source	systematic uncertainty $(\sigma_s)_i / \langle N \rangle$
thermal power	2%
IBD cross section	0.5%
reactor neutrino anomaly	2%
oscillation parameters	See reference

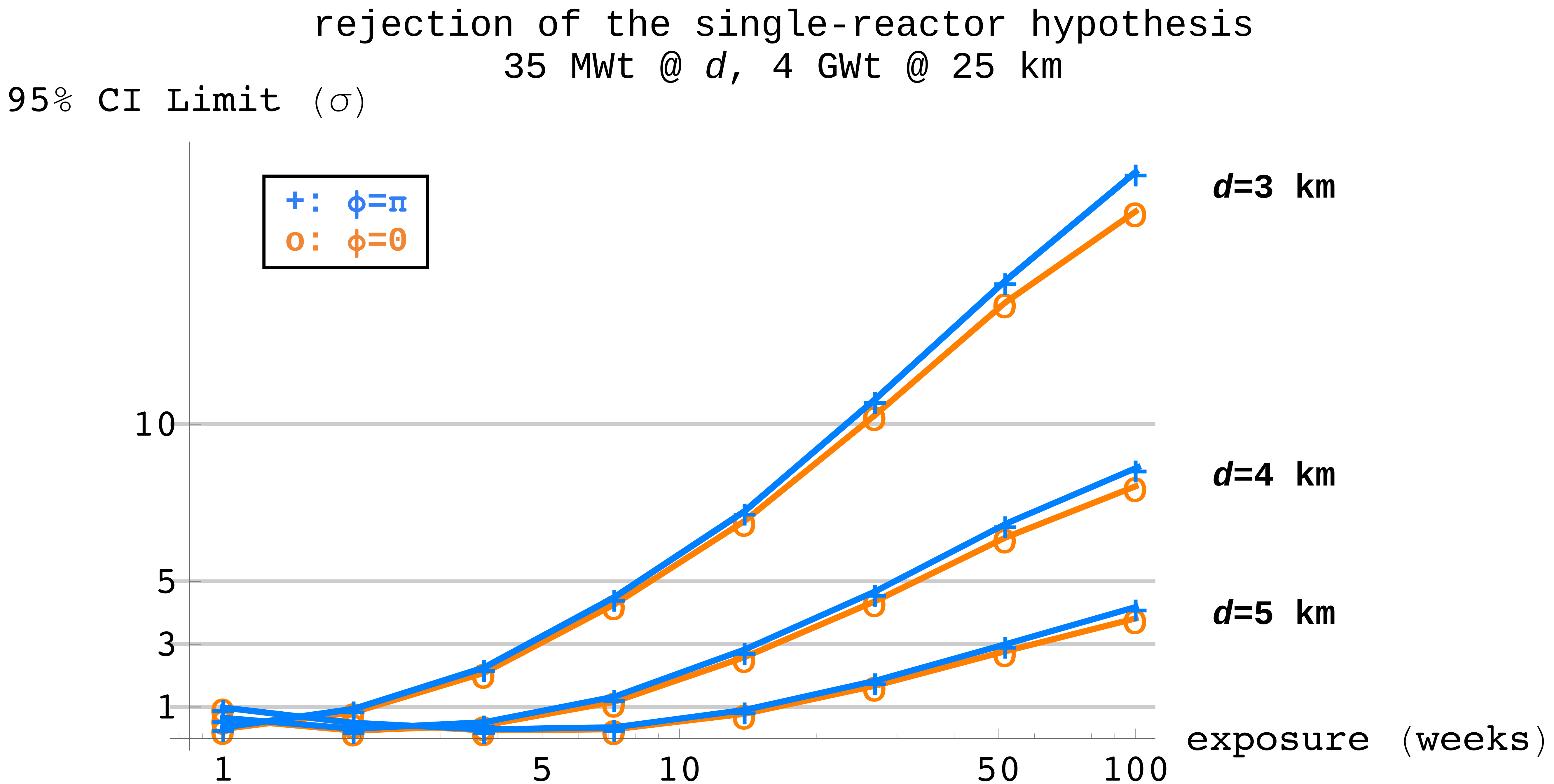
Oscillation Parameters obtained from the recent global fit:
F. Capozzi, E. Lisi, A. Marrone, D. Montanino, and A. Palazzo. Neutrino masses and mixings: Status of known and unknown 3ν parameters. Nuclear Physics B, 908:218 – 234, 2016. Neutrino Oscillations: Celebrating the Nobel Prize in Physics 2015.

Hypothesis Testing

A χ^2 test of a two-reactor signal against the known-reactor expectation gives a confidence σ to reject the null hypothesis that only one reactor exists.



reconstructed cosine histograms after one year exposure
statistical errors shown



The lower 95% CI limit on σ predicts:

3σ detection of the unknown reactor is likely within
5 weeks @ 3 km, 15-16 weeks @ 4 km, and 52-60 weeks @ 5 km

Azimuthal separation has a smaller effect, though is more significant at larger standoffs, providing an 8 week speedup at 5 km for reactors in opposite directions.

Publication

- New AIT / WATCHMAN paper forthcoming
- "Detecting a Second, Unknown Reactor with a 1 kT Cylinder of GdLS for Mid-Field Nonproliferation Monitoring," D. L. Danielson *et al.*
- In-depth presentation of this technique
- Stay tuned

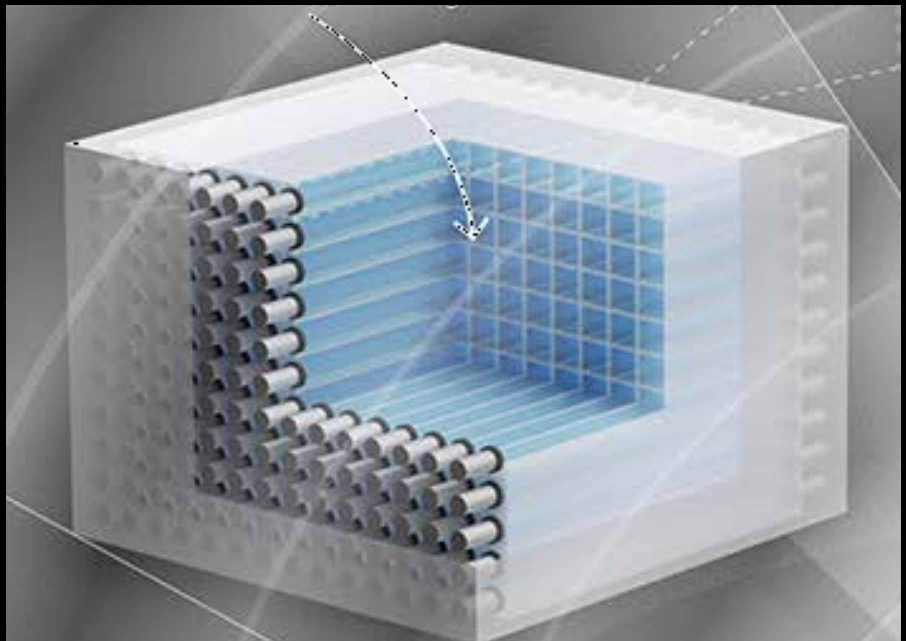
Improvements

Detector Composition

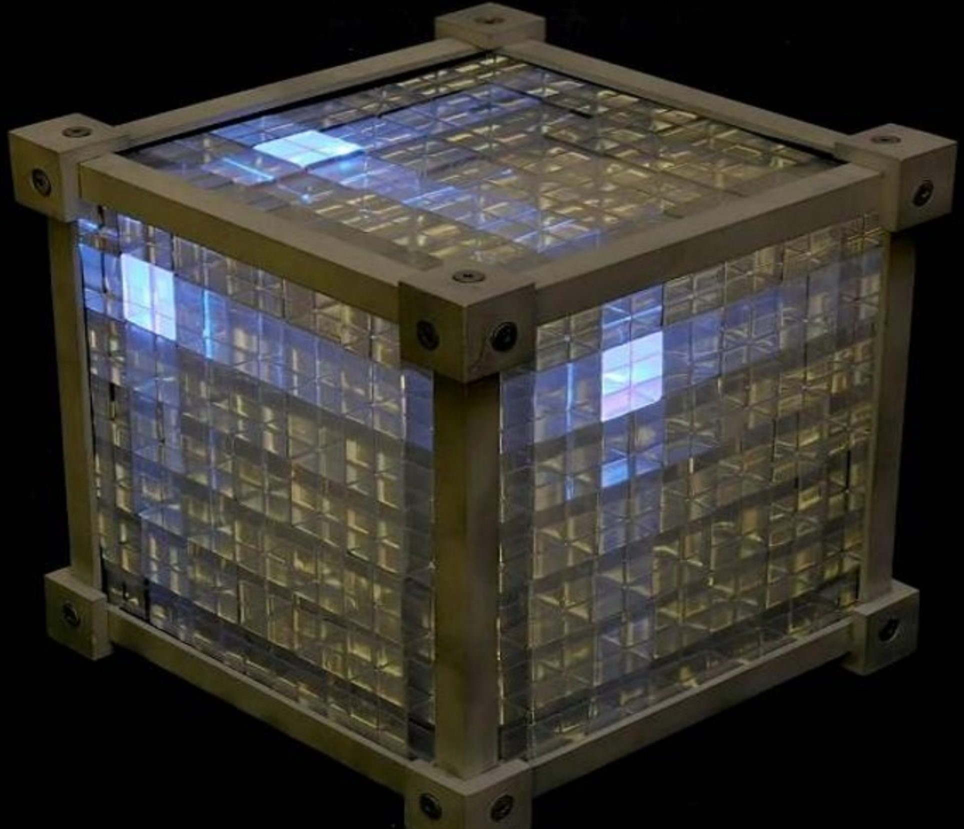
- Improved medium (e.g. WbLS, paired with LAPPDs)
- Improved dopants (e.g. ^{6}Li)

Segmented Detectors

- Bundle
  - PROSPECT
  - PANDA
  - Palo Verde
  - …
- Lattice
  - NuLat
  - LENS
  - CHANDLER
  - …



https://www.nist.gov/news-events/news/2016/12/search-sterile-neutrinos



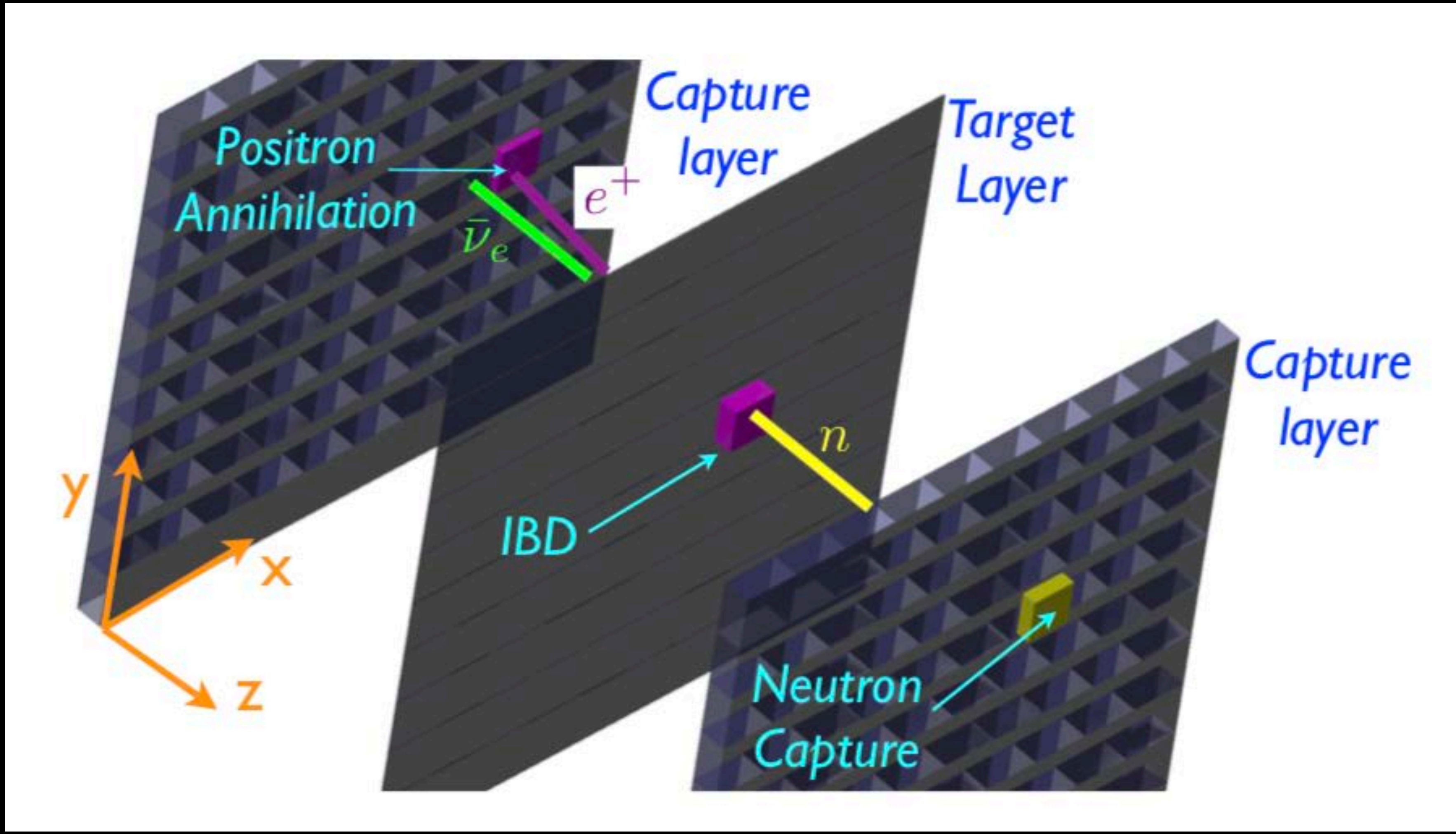
https://arxiv.org/abs/1501.06935

Potential
Future Directions

Event-By-Event Directionality?

SANTA

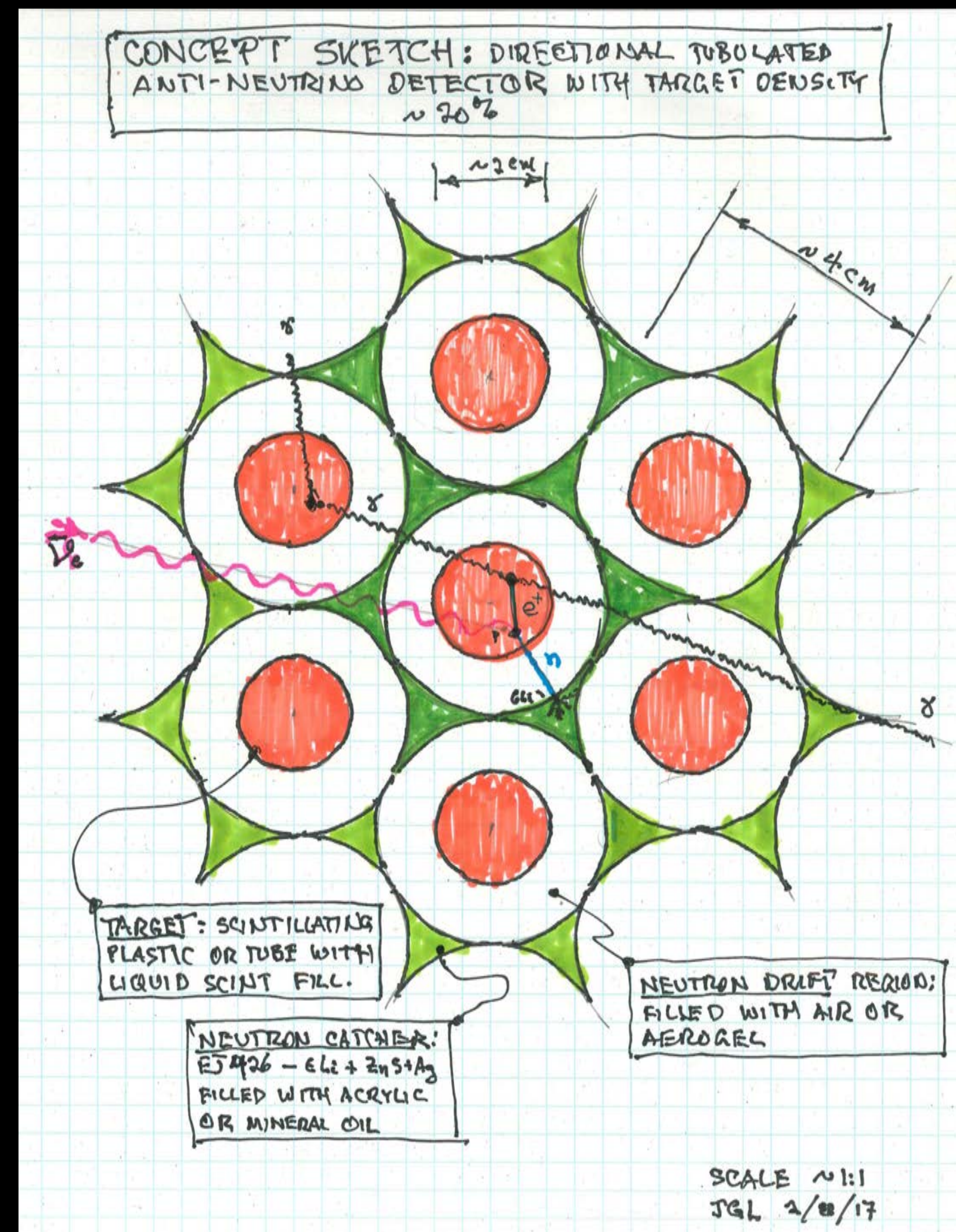
- Unprecedented directional sensitivity
- Small angular acceptance
- Small target, low event rate



Benjamin R. Safdi and Burkhant Suerfu
Phys. Rev. Lett. 114, 071802 – Published 20 February 2015

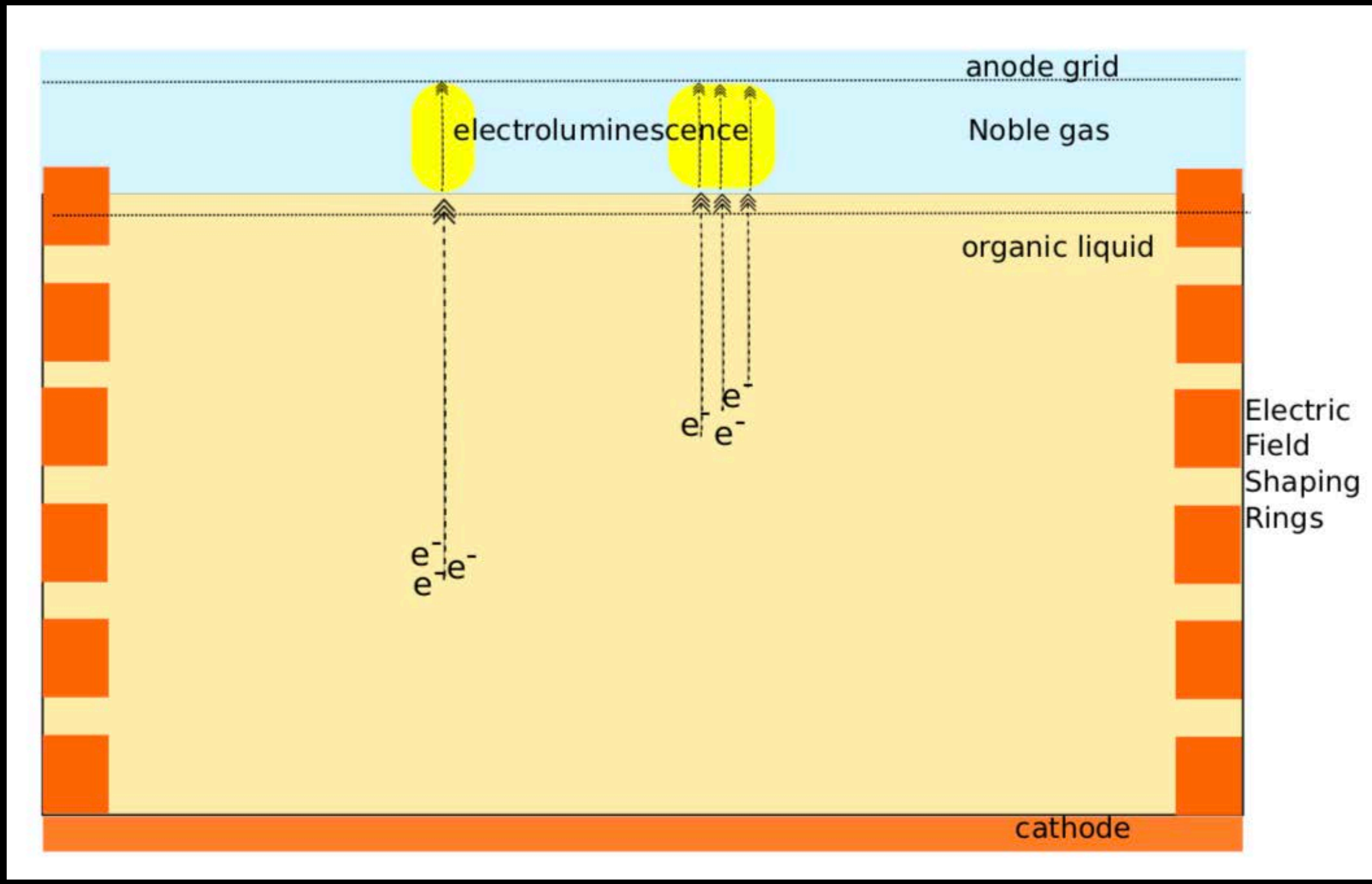
Hybrid

- New concept by John Learned
- Aims to combine strengths of SANTA with those of segmented detectors
- Potential for a large target volume
- 180° angular acceptance
- **Needs further study!**



Hydrogenous TPC

- sub-cm spatial resolution?
- **Very challenging**
- **More study required**



J V Dawson and D Kryn 2014 JINST 9 P07002
Laboratoire Astroparticule et Cosmologie
https://arxiv.org/pdf/1405.1308.pdf

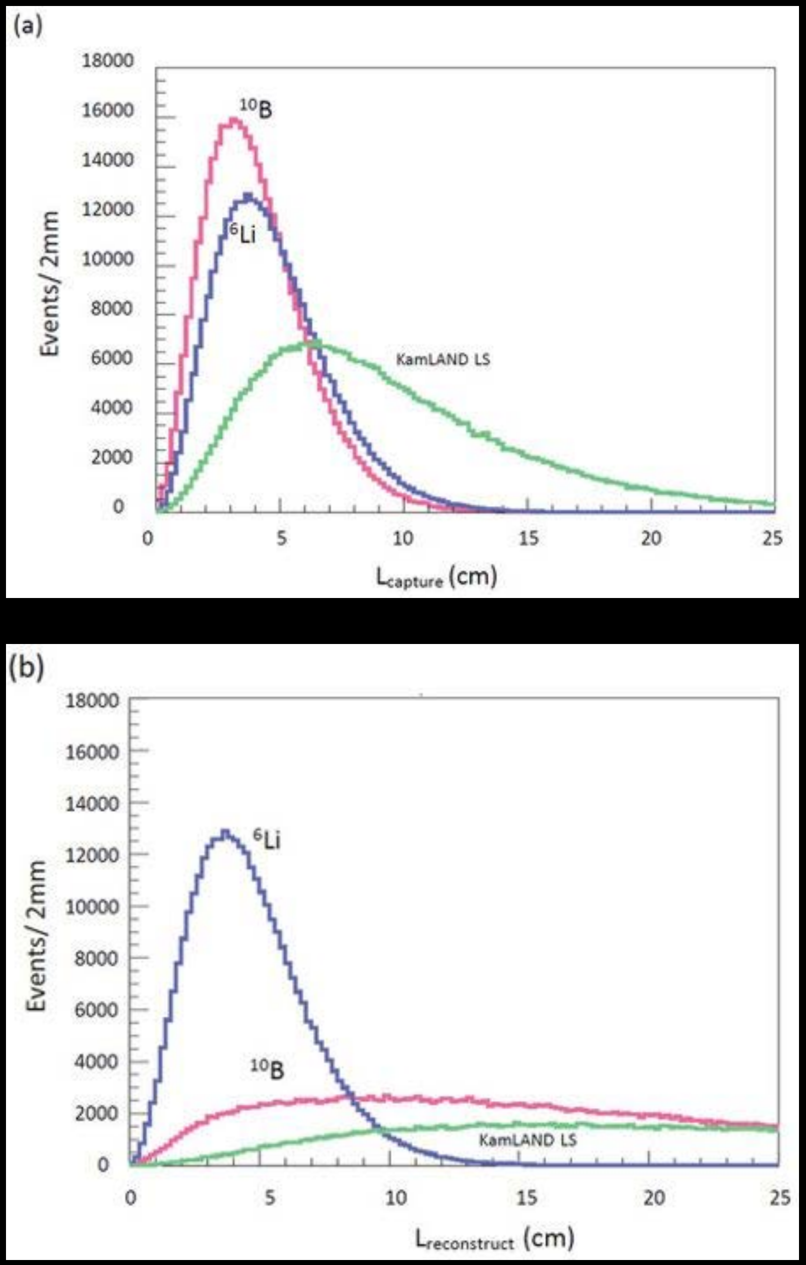
Questions?

Backup

Neutron Capture Dopants

- Gadolinium
  - 8 MeV mean gamma cascade
  - Diffuse into medium, smearing capture point
  - More visible energy
- Lithium-6
  - $^{6}Li + n \rightarrow t\ (2.73\ MeV) + \alpha\ (2.05\ MeV)$
  - Localized interactions preserve neutron capture vertex
  - Less visible energy

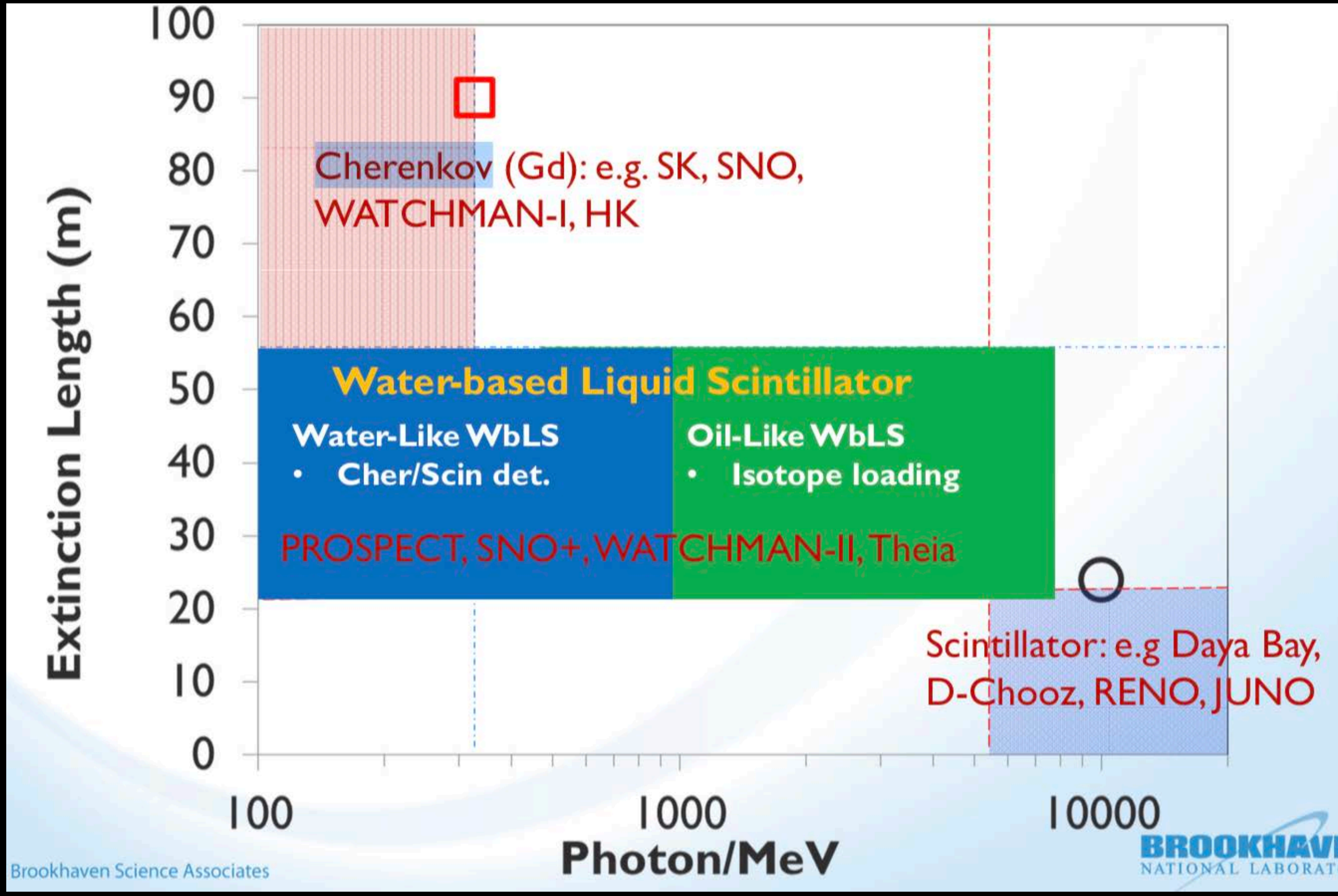
MC Comparison



https://www.nature.com/articles/srep04708/figures/2

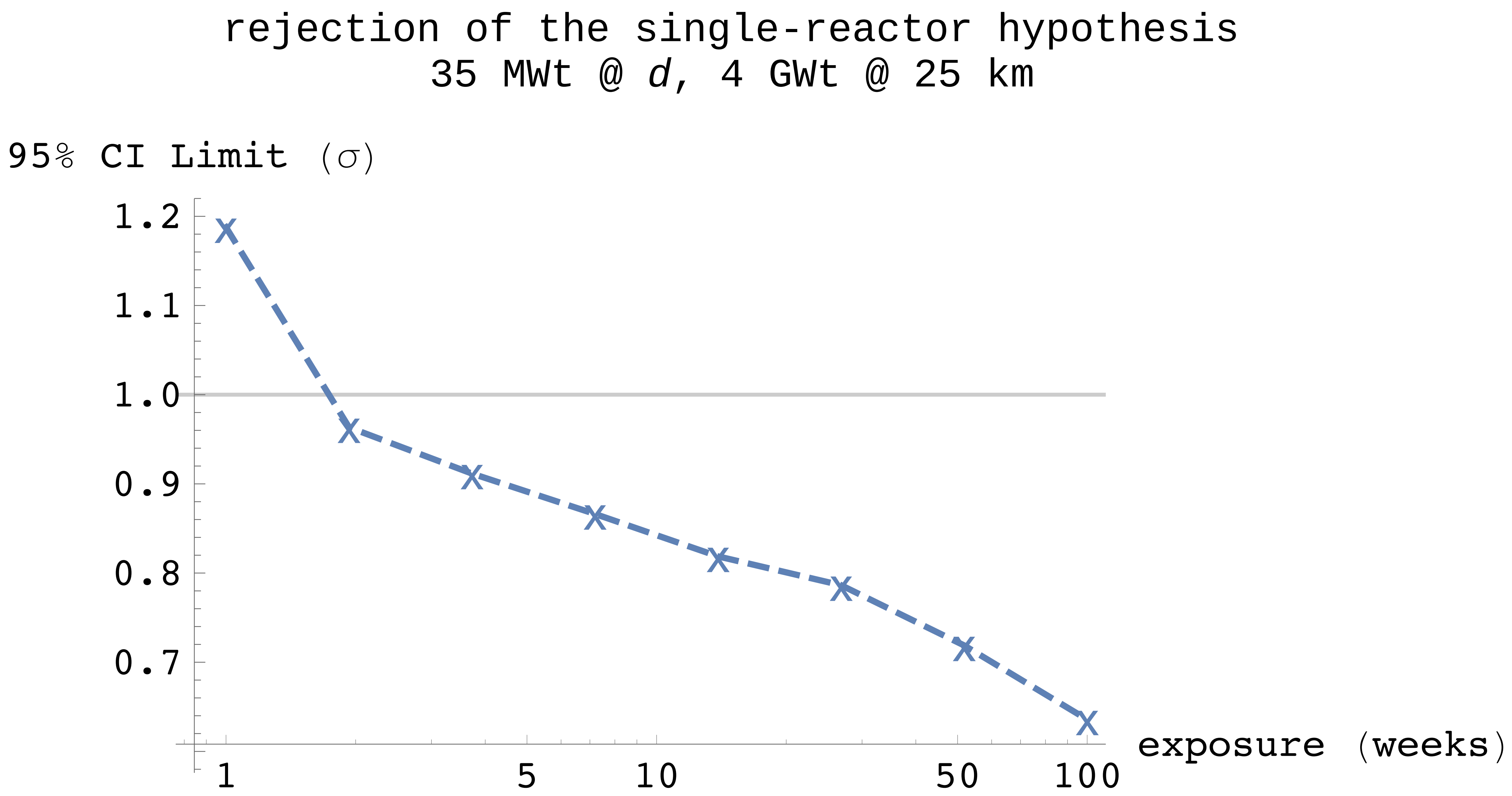
Detector Medium

- Mineral oil-based liquid scintillator
    - Higher initial light yield
- Water-based liquid scintillator
    - Reduced light attenuation
    - Faster Cerenkov light propagation



https://indico.bnl.gov/event/1383/contributions/2034/attachments/1648/1874/WbLS_status.pdf

In the **single known-reactor** case,
the upper 95% CI limit on σ shows that the method carries no bias towards detection.



We (rightly) fail to reject the single-reactor hypothesis
in the case where there is, indeed, just one reactor.