Far-field Monitoring of Rogue Nuclear Activity

Applied Antineutrino Physics Workshop

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Motivation for Far-field Monitoring

- **The best type of monitoring is intrusive**
  - Requires cooperation from operators
- **Recent events (North Korea, Iran):**
  - Some operators refuse to cooperate
- **Is it possible to monitor without operator cooperation?**

Nuclear Monitoring with Neutrinos?

- Neutrinos are by-products of nuclear fission

- A typical nuclear reactor produces ≈ 1 GWt of thermal power
- This corresponds to about 2×10^{20} neutrinos per second

- The yield of the first atom bombs were 10-20 kilo-ton TNT equivalent
- 1 kilo-ton TNT produces ≈ 4200 Giga-Joule
- About ≈ 8×10^{23} neutrinos are released within ≈ 10 seconds

Detecting Neutrinos

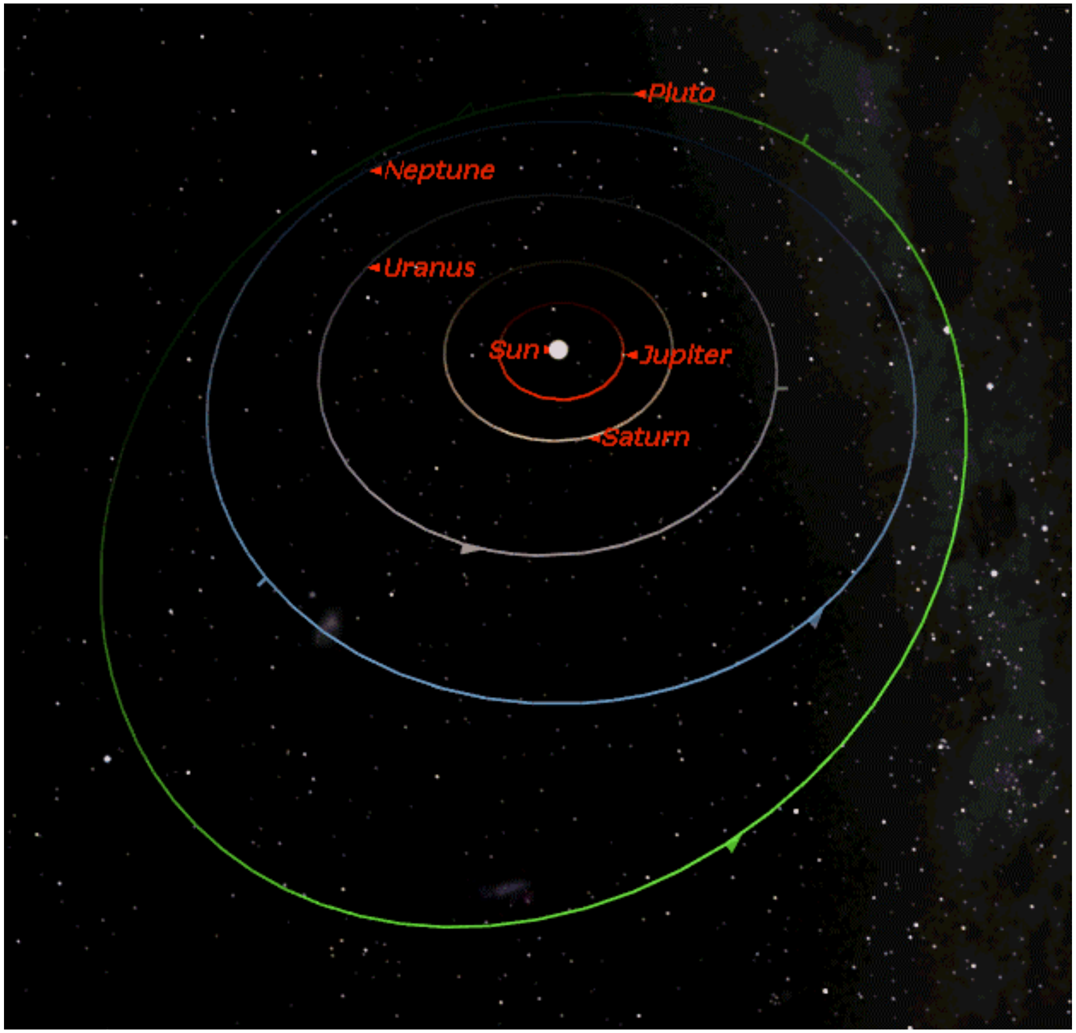
- Neutrinos produced by nuclear reactors must come within $\approx 10^{-21}$ cm of a target particle in order to interact
  - The density of "stuff" on Earth is several grams per cm^3
  - This corresponds to about $\approx 10^{-8}$ cm between particles

A 13 order-of-magnitude gap in length scale!

IN MOJAVE DESERT, MAYBE THERE IS ONE PERSON EVERY $\approx$ 100 KM^2

A PERSON HAS AN ASPECT AREA OF ABOUT 1 M^2

THE ODDS THAT A RANDOMLY DROPPED PENNY WOULD HIT A PERSON IS $\approx 1:10^8$



THE ODDS THAT A NEUTRINO WOULD HIT AN ATOM IT PASSES BY IS ABOUT THE SAME AS THAT OF A RANDOMLY THROWN PENNY HITTING SOMEBODY SOMEWHERE IN THE SOLAR SYSTEM!

Necessary Conditions for Neutrino Detection

To beat the odds, one needs to:

(1) Produce as many neutrinos as possible ← **Can't control**

(2) Get as close as possible

(3) Provide as many target particles as possible ← **Can control** (to some extent)

(4) Observe as long as possible

Beating the odds: (the best that can be reasonably expected)

(2) Place detectors within ≈ 100 km of suspected sites

(3) One module can probably be made to be ≈ 1 mega-ton

(4) Observation time of ≈ 1 year

Neutrino Detection Rate

$$0.45 \text{ Events} \times \left(\frac{100\text{ km}}{D}\right)^2 \times \left(\frac{P}{10\text{ MW}_{\text{th}}}\right) \times \left(\frac{N_{\text{target}}}{10^{32}\text{ free protons}}\right) \times \left(\frac{T}{1\text{ year}}\right)$$

≈ 1 kilo-ton of target material

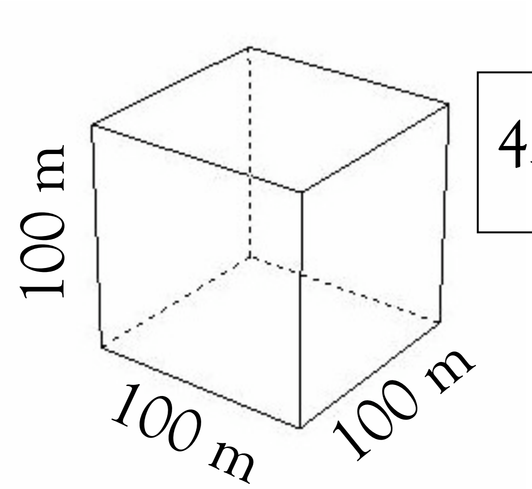
- **This is an unacceptably low rate**

$$450 \text{ Events} \times \left(\frac{100\text{ km}}{D}\right)^2 \times \left(\frac{P}{10\text{ MW}_{\text{th}}}\right) \times \left(\frac{N_{\text{target}}}{10^{35}\text{ free protons}}\right) \times \left(\frac{T}{1\text{ year}}\right)$$

≈ 1 **mega-ton** of target material

A Megaton Detector

- To have any hope of detecting antineutrinos in a realistic scenario, the detector needs to have a mass of at least 1 megaton



$$450 \text{ Events } \times \left(\frac{100 \text{ km}}{D}\right)^2 \times \left(\frac{P}{10 \text{ MW}_{th}}\right) \times \left(\frac{N_{target}}{10^{35} \text{ free protons}}\right) \times \left(\frac{T}{1 \text{ year}}\right)$$

$\approx$ 1 Megaton

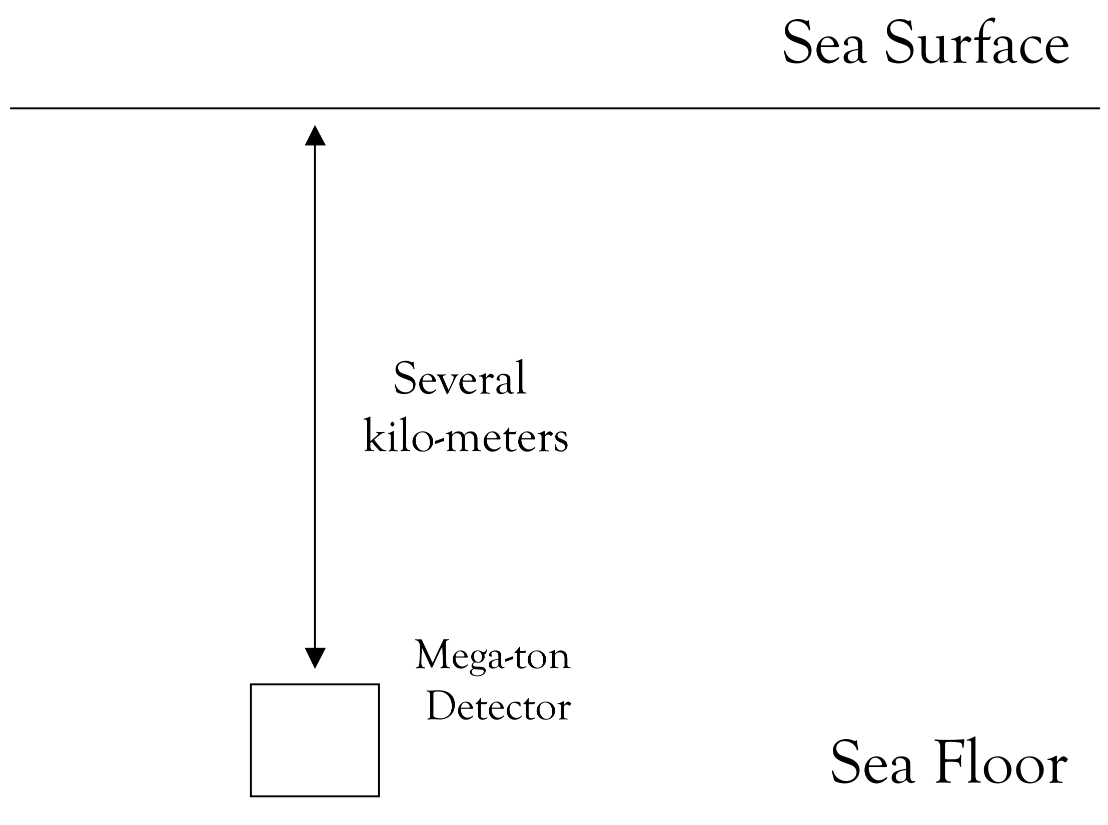
- Economics $\Rightarrow$ water as target material
- Dope with $GdCl_3$ to allow antineutrino detection

Background Noise

1. **Internal & environmental radioactivity**
2. **Cosmic ray**
3. **Neutrinos from legitimate (and natural?) nuclear reactors**

- Thanks to extensive R & D over the past decade, (1) is under control
- Need thick (**kilometers** of rock or water) shielding for (2)
- Can't do anything about (3)

The Basic Setup



Test Scenario: North Korea

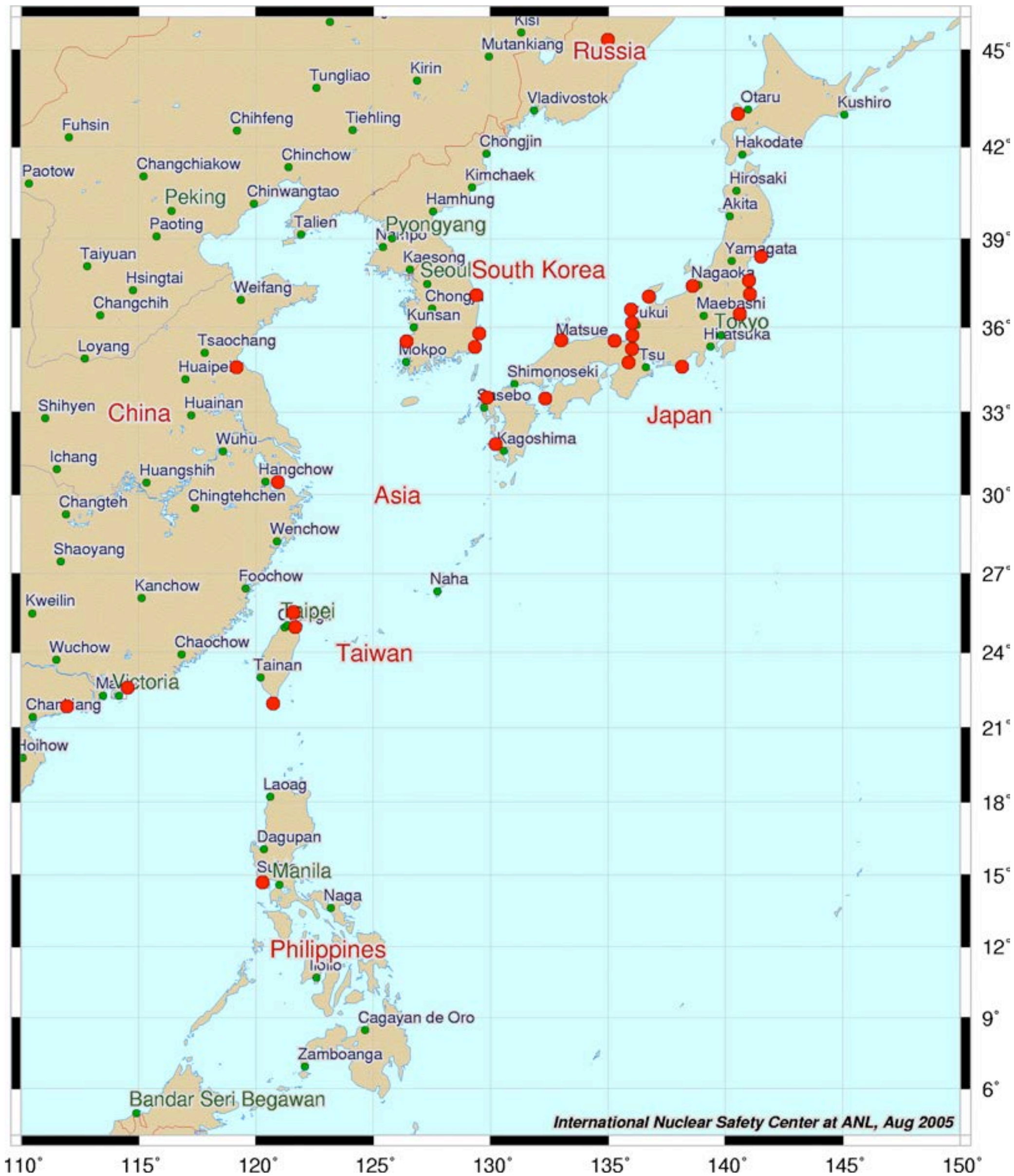
No pre-existing large-scale nuclear reactors

Assume that a rogue reactor exists deep in North Korean terrirtory

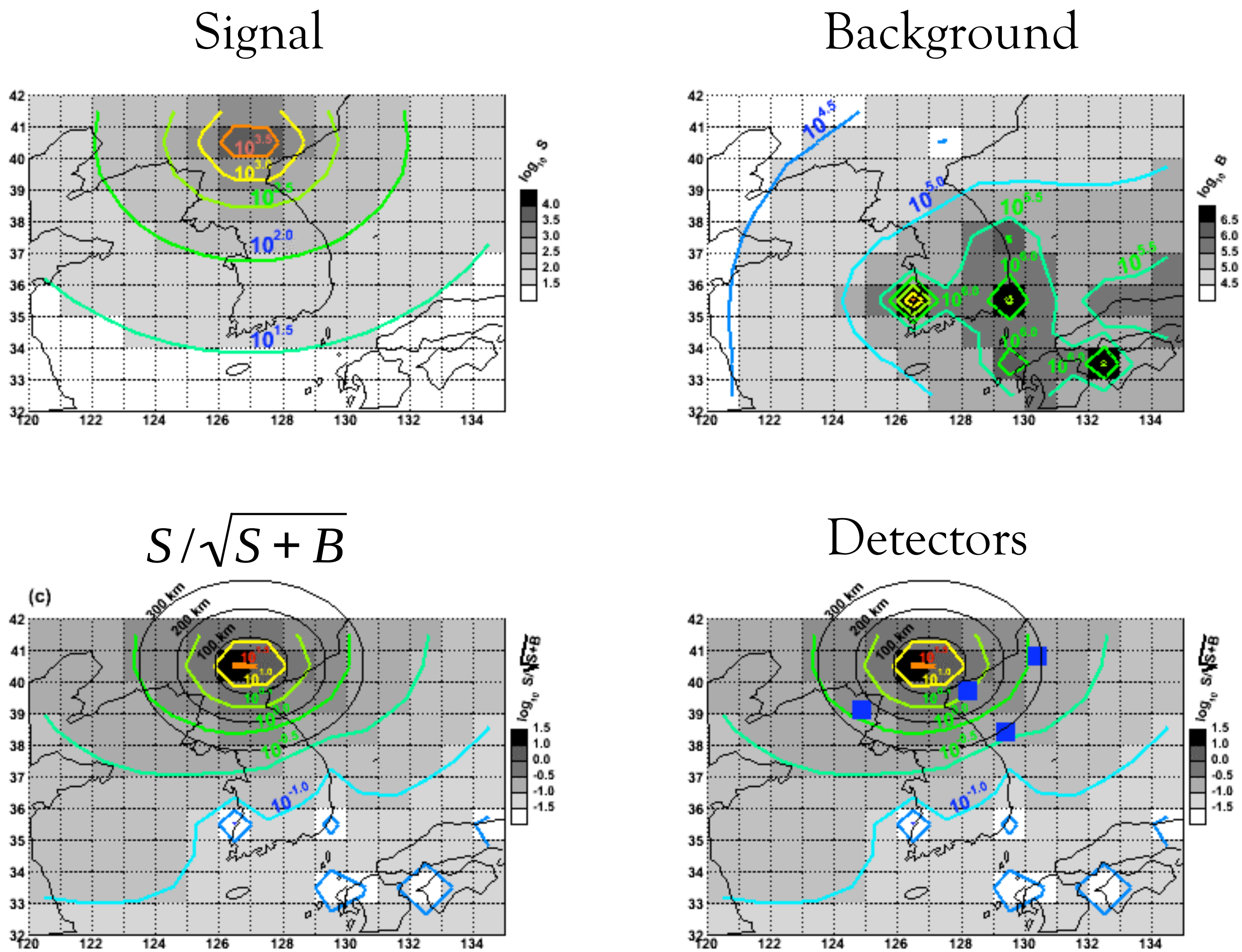
127° East, 40.5° North

Power ≈100 MWt

Nuclear Reactors Surrounding North Korea

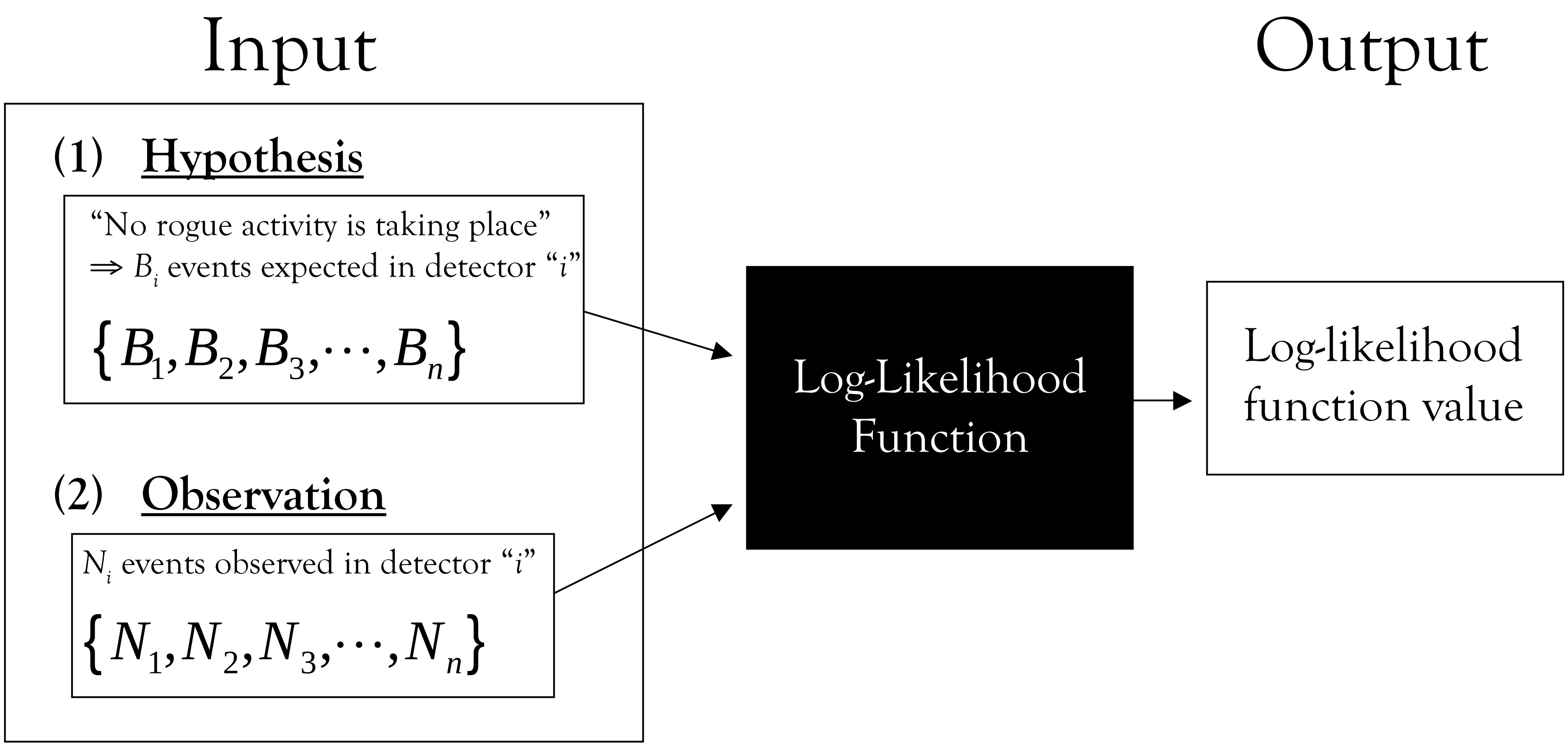


These reactors produce intense background to nuclear monitoring

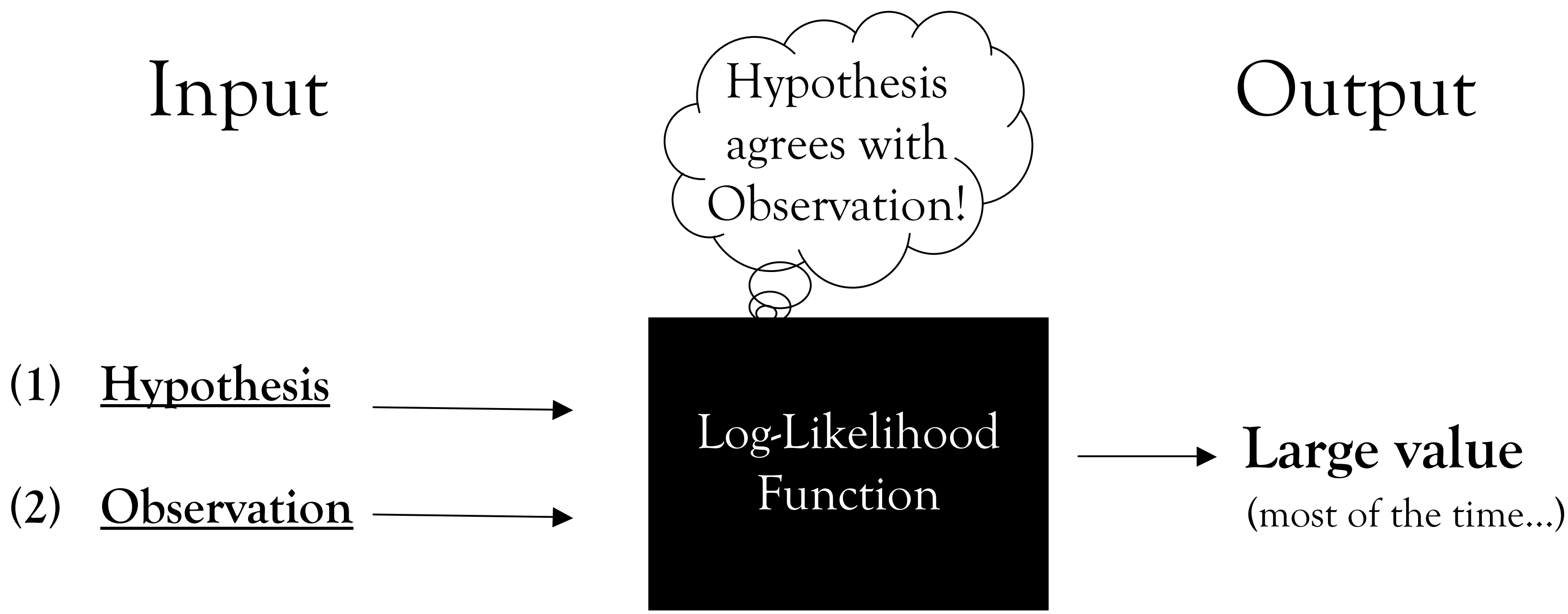


Signal
Background
$S/\sqrt{S+B}$
Detectors
(c)
300 km
200 km
100 km
log10 S
log10 B
log10 S/√S+B

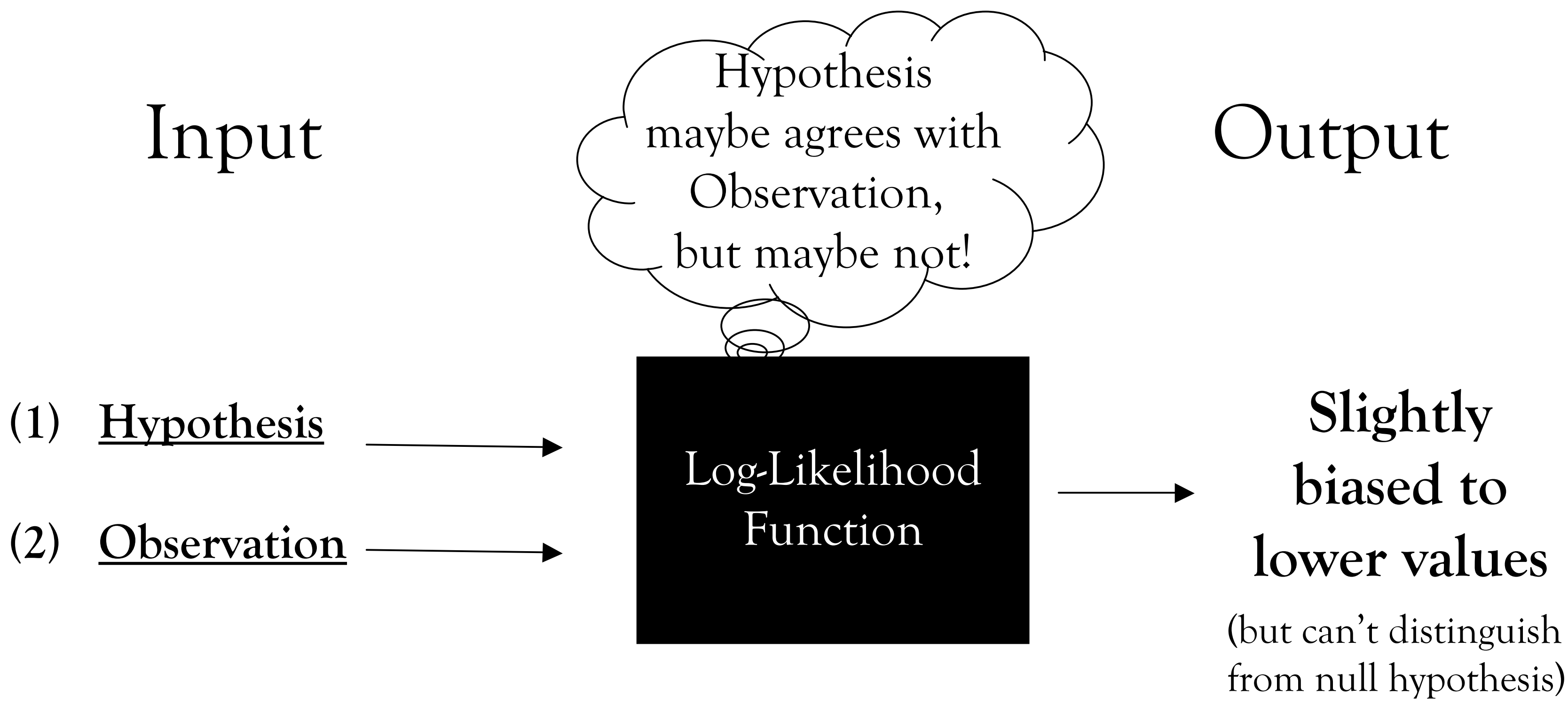
Rogue Activity Detection Strategy



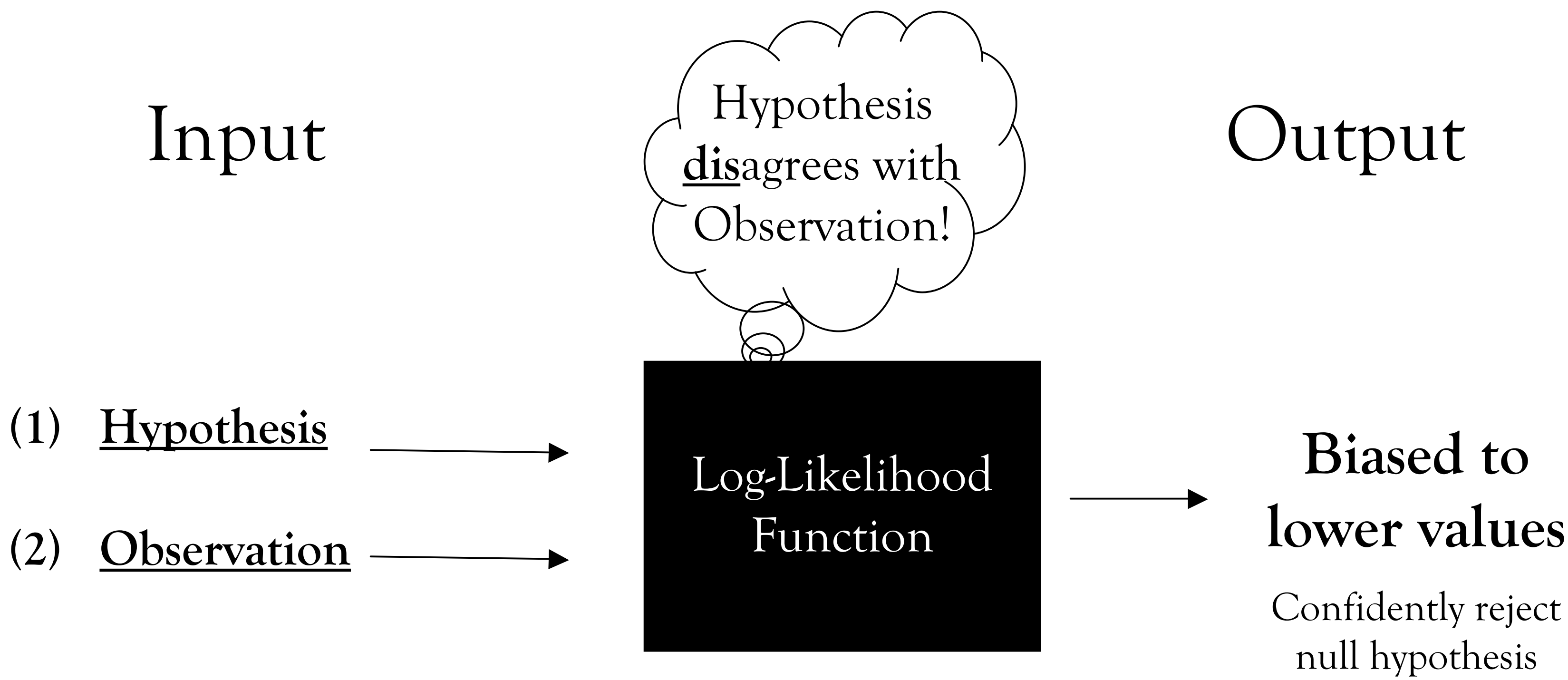
Scenario 1: No Rogue Activity



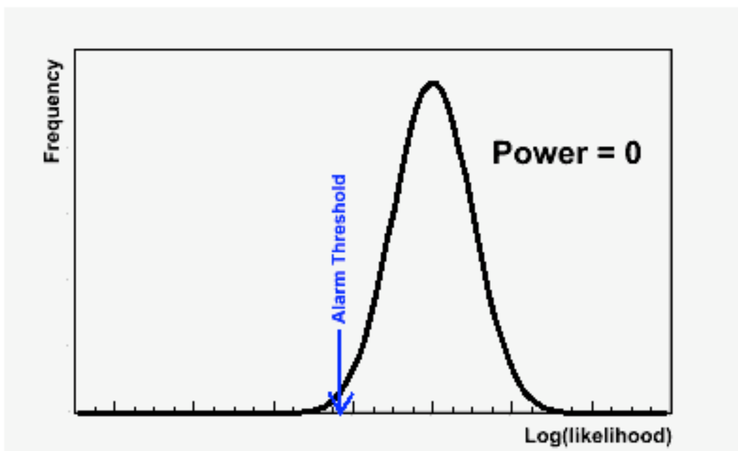
Scenario 2: Small Rogue Activity



Scenario 3: Large Rogue Activity



Likelihood Distribution for Scenario 1

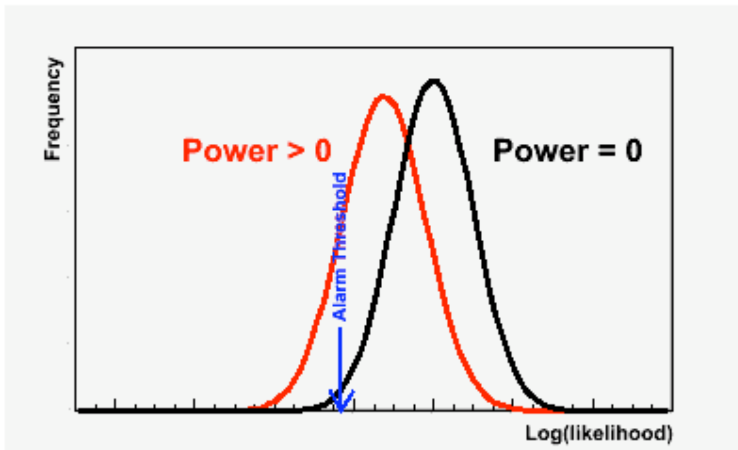


If value < threshold, ALARM!

1% False Positive

- The value varies from measurement to measurement because of statistical variation
- The distribution is known *a priori*

Likelihood Distribution for Scenario 2



If the rogue power is small, the bias is too small

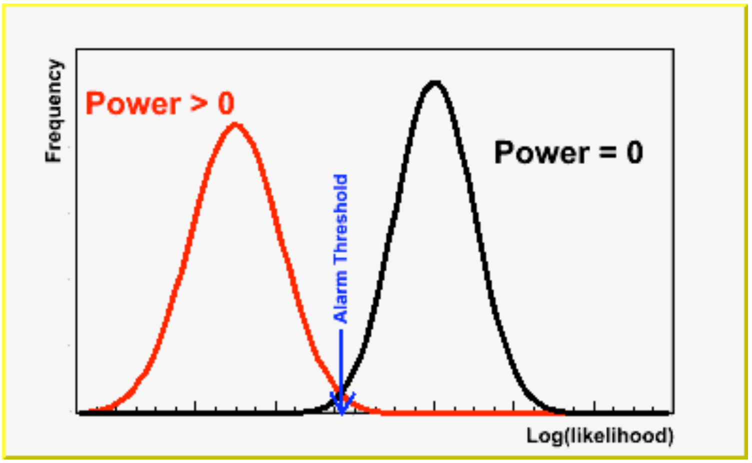
⇩

Large overlap with null distribution

⇩

False negative happens too often

Likelihood Distribution for Scenario 3



Define a quantity called "**P_{99}**"

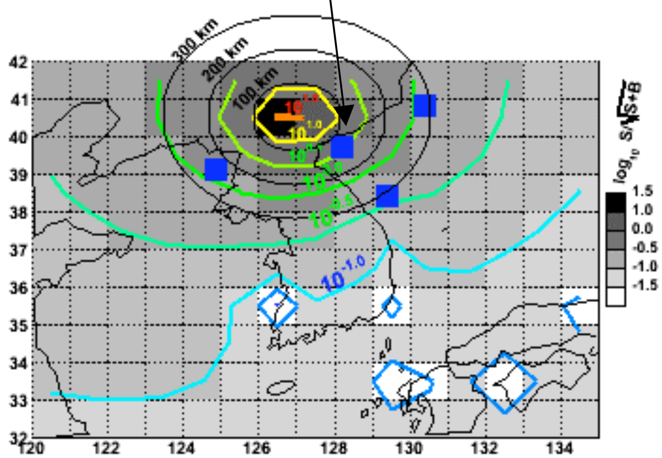
⇩

P_{99} = the power above which the chance of false negative AND false positive is < 1%

Typical Outcome

What Happens Almost Invariably?

The distance to the closest detector primarily determines P_{99}



The other detectors help remove the ambiguity between the power and the distance

At least three detectors are needed to remove the ambiguity

Having many detectors does not improve the sensitivity to a given location

However, it does increase the chance of being close to a reactor whose location is not known

P_{99} for the Test Scenario

Assuming 100% efficiency $\qquad P_{99}$ = 128 MWt

More realistically:

Neutrino energy > 3.8 MeV ⇨ 58% acceptance

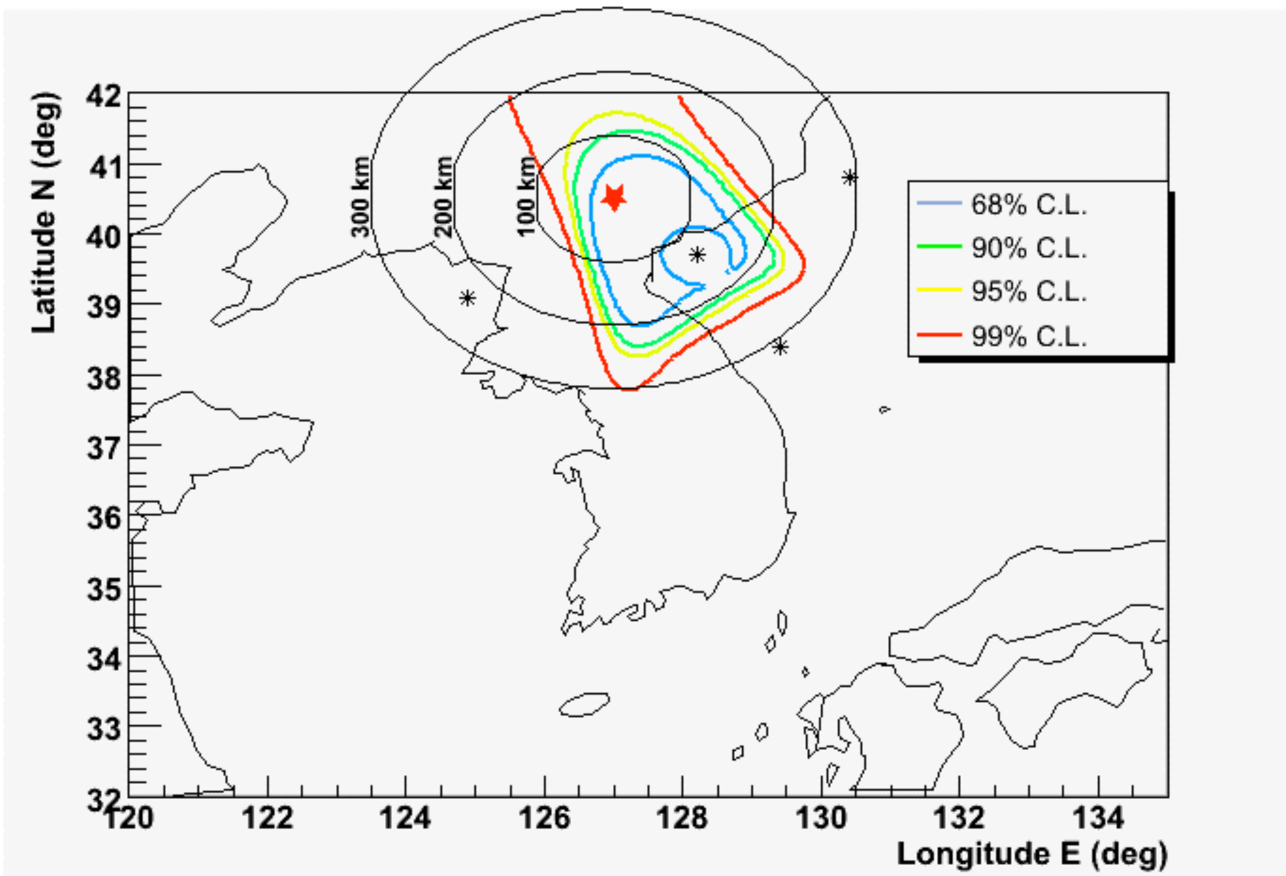
Event selection cuts ⇨ 86% acceptance

Combined efficiency = 0.58*0.86 = 50%

⇩

P_{99} = 169 MWt

How Well Can We Locate the Rogue Reactor?



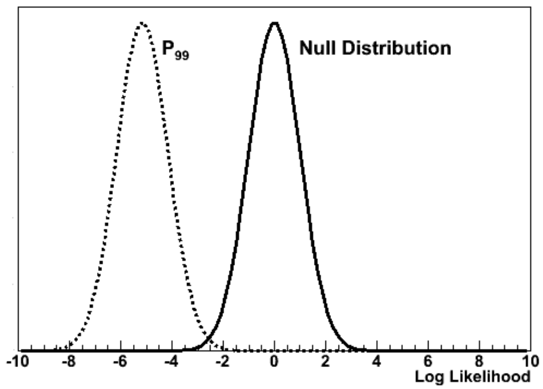
The shape of this contour depends on the **Confidence Level**.

For P_{99}, this is the best that can be done, regardless of where the detectors are.

E.g. if the nearest detector moves closer, P_{99} decreases.

What if We Relax the False Positive/Negative Probability?

99%



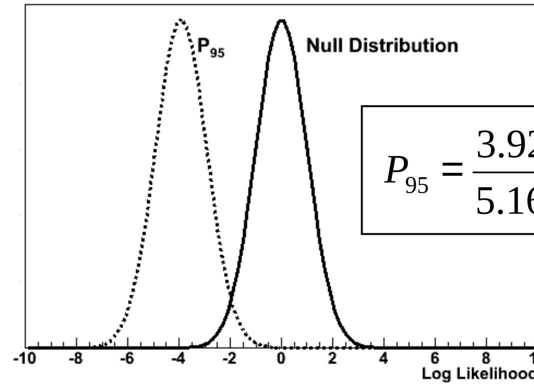
5.16 σ separation

To first order, P_{XX} (XX = confidence level) is proportional to the separation

$$S \ll B \quad \longrightarrow \quad \frac{S}{\sqrt{S+B}} \approx \frac{S}{\sqrt{B}}$$

Since S << B, the sensitivity grows linearly with signal strength

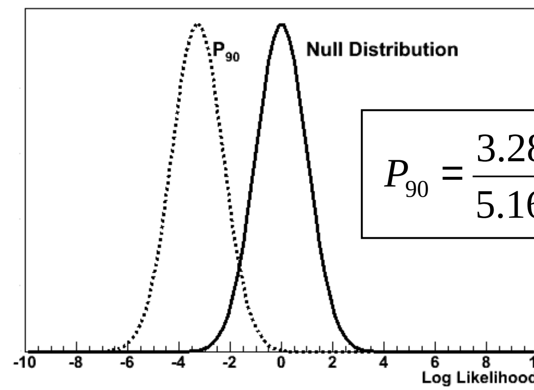
95%



$$P_{95} = \frac{3.92}{5.16} \times P_{99}$$

3.92 σ separation

90%



$$P_{90} = \frac{3.28}{5.16} \times P_{99}$$

3.28 σ separation

- Note: this is a simplified illustration

  The actual behavior is more complicated, but similar

What if We Relax the False Positive/Negative Probability?

P_{99}	Distance = 5.16 σ	⟶	169 MWt
P_{95}	Distance = 3.92 σ	$P_{95} \approx \frac{3.92}{5.16} \cdot P_{99}$ ⟶	128 MWt
P_{90}	Distance = 3.28 σ	$P_{90} \approx \frac{3.28}{5.16} \cdot P_{99}$ ⟶	107 MWt

Benefit of Relaxing the Threshold

- Greater probability of detecting surreptitious activity

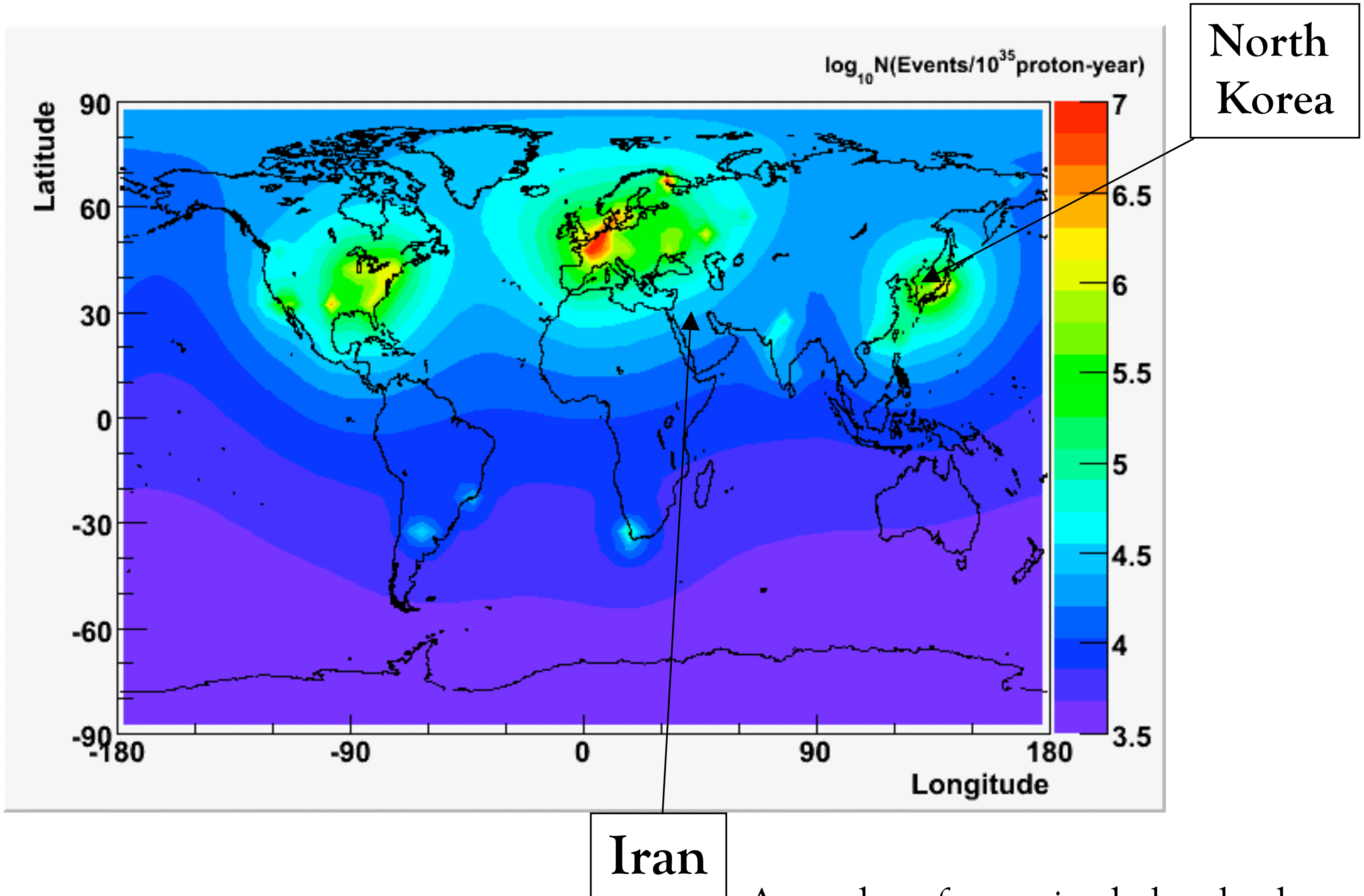
Liabilities

- Greater probability of false-positive
- Worse ability to reconstruct location

What if the Background Were Not So Intense

- North Korea represents (more or less) a worst-case scenario
  - Intense background from South Korea and Japan
- Most of the rest of the world has much lower background

Nuclear Reactor Background



An order of magnitude less background

Sensitivity for Different Background Levels

For example, use the same scenario as North Korea, but decrease the background by 50% & 90%

	Alarm Level Power (MWt)		
Background Level	**P_{99}**	**P_{95}**	**P_{90}**
100%	169	127	107
50%	84	64	53
10%	38	29	24

Range vs. Background Level

Distance of the nearest detector for sensitivity to a 100 MWt reactor

N.B. The nearest detector distance for the North Korea scenario was 135 km

	Distance of the Nearest Detector (km)		
Background Level	**Alarm Level = 99%**	**Alarm Level = 95%**	**Alarm Level = 90%**
100%	104	120	131
50%	147	169	185
10%	219	251	276

Fission Bomb

Anti-neutrino Rate from a Fission Bomb

$$2.25\ \text{Events} \cdot \left(\frac{M}{1\ \text{Mega-ton}\ H_2O}\right) \cdot \left(\frac{100\ \text{km}}{D}\right)^2 \cdot \left(\frac{Y}{1\ \text{kilo-ton TNT}}\right)$$

This is integrated over ≈ 10 sec.

Background

$10^4 \sim 10^6$ events / year ⟶ 0.01 ~ 1 event / 10 sec.

Background is not an issue.

The signal, however, is very weak.

After 50% efficiency → **1 event per explosion @ 1 kilo-ton TNT**

Positive ID of a Fission Bomb Event

To positively identify a fission bomb event:

- Need to detect ≈ 2.5 events to detect > 0 events 90% of the time
- Need to detect ≈ 4.5 events to detect > 0 events 99% of the time

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Only 1 event is detected @ 100 km with a 1 mega-ton detector

- This corresponds to a detection efficiency of 63%

To achieve > 90% detection efficiency:

- Decrease distance to ≈ 50 km
- Increase detector mass by ≈ ×3 ~ ×5

N.B. It is unlikely to help to increase the number of 1 mega-ton modules because, typically, the closest one completely determines the sensitivity

Cost

- Photomultiplier Tubes
  - (120,000 PMTs/module) × ($1000/PMT)
- Detector structure
- Detector transport & placement
- Water purification
- Manpower
- Insurance?

All told, one module could easily cost ≈ $1 billion

The cost of an array is probably like ≈ $10 billion

Pre-requisites for Realizing a Mega-ton Antineutrino Detector Array

- Show that a gadolinium-doped water-based detector can be used to detect antineutrinos from nuclear fission
  - ✣ Gadzooks! ~3-year time-scale

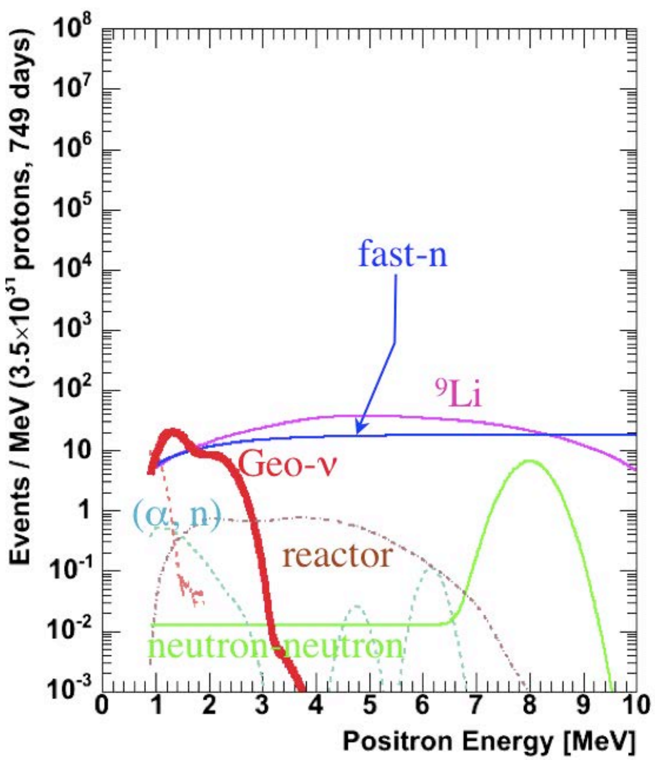
- Show that an anti-neutrino detector can be successfully deployed in a deep-sea environment
  - ✣ Hanohano ~5-year time-scale

- Show that a mega-ton (anti-)neutrino detector can be successfully operated on land
  - ✣ Hyper-K? UNO? ~10-year time-scale?

Shallow Surface Detectors?

- At last year's Neutrino Science 2005 conference (Univ. Hawaii, Manoa), T. Mitsui gave a presentation on placing a large number of relatively cheap anti-neutrino detectors with modest shielding (300 m.w.e.) from cosmic rays
- This array is envisioned for detecting geo-neutrinos

Background Spectra for a Shallow Antineutrino Detector



Adopted from T. Mitsui, "Neutron background and possibility for shallow experiments"

- This level of background is achievable only after much effort (see T. Mitsui's presentation for details)
- Scaling to 10^{32} proton-year (about 1 kilo-ton-year), the two main background rates are:
  - ^{9}Li ⇒ 200 / 10^{32} proton-yr
  - Fast-n ⇒ 110 / 10^{32} proton-yr

Signal Rate

$$4.5 \text{ Events} \left(\frac{100\text{ km}}{D}\right)^2 \left(\frac{P}{100\text{ MW}_{th}}\right) \left(\frac{N_{target}}{10^{32}\text{ free protons}}\right) \left(\frac{T}{1\text{ year}}\right)$$

A shallow detector needs to be much closer!

Conclusion

Basic conditions:

- ✼ Rogue reactor power ≈ 10 to 100 MWt
- ✼ Target material: 1 mega-ton H_2O
- ✼ Closest detector at ≈ 100 km from reactor

⇨ Sensitive to 20 to 200 MWt, depending on the location (i.e. reactor background level) & tolerance for false positive/negative

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Fission bomb monitoring:

- ✼ Background is not a problem
- ✼ The problem is low counting rate
- ✼ For the above conditions, only 63% efficient
- ✼ Realistically, need to be at about 50 km or less

Go cheap with many small, shallow detectors?

- ✼ Needs to be much closer (less than 10 km)

Cost

- ✼ ~$10 billion

Technical Hurdles

Gadzooks! →	Hanohano →	Hyper-K / UNO
3 yrs	5 yrs	10 yrs

The Bottom Line

- In principle, under suitable (and not unrealistic) conditions, far-field monitoring of 20-200 MWt reactors can be done with an array of several 1 mega-ton detectors
- The cost is probably in the ball park of $10 billion
- Several proof-of-principle experiments must first be carried out successfully
- If this should be realized, construction may (at the very earliest) begin 10 years from now

Other Slides

The Challenge of Far-field Monitoring

Small event rate:

$$0.45 \text{ Events} \times \left(\frac{100 \text{ km}}{D}\right)^2 \times \left(\frac{P}{10 \text{ MW}_{th}}\right) \times \left(\frac{N_{target}}{10^{32} \text{ free protons}}\right) \times \left(\frac{T}{1 \text{ year}}\right)$$

Roughly 1000 tons of detector material

The situation is actually worse:

- Neutrino oscillations ⇒ × 0.57
- Energy threshold ⇒ × 0.58
- Detection Efficiency ⇒ × 0.86 (for deep detectors)

→ Only 28% of the above are observed

Nuclear Monitoring with Neutrinos?

- **Neutrinos are by-products of nuclear fission**
  - About 6 neutrinos are produced per fission
  - A typical (GWt) commercial nuclear power plant produces $\mathbf{2 \times 10^{20}}$ neutrinos per second
- **Neutrinos are elusive**
  - From the point of view of neutrinos, "stuff" looks tiny!
  - To us, an atom has an area of about a Bohr radius squared **(≈10^{-16} cm^2)**
  - To a neutrino, the same atom has a radius of **≈10^{-42} cm^2**

A **26-order of magnitude gap** that needs to be made up somehow