Enhancing our astrophysical reach:
On the capabilities of a hypothetical LIGO, VIRGO and IceCube network

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Overview

IceCube: Neutrino Detector in Operation and Upgraded Yearly

LIGO, VIRGO: Interferometric Gravitational Wave Detectors in Operation

Both: A few small signals buried in background noise

Completely Independent Detectors

→ Probability of accidental coincidence by background noise: Very Low

LIGO → Coincidence Analysis ← IceCube

High Confidence Detection

In this talk

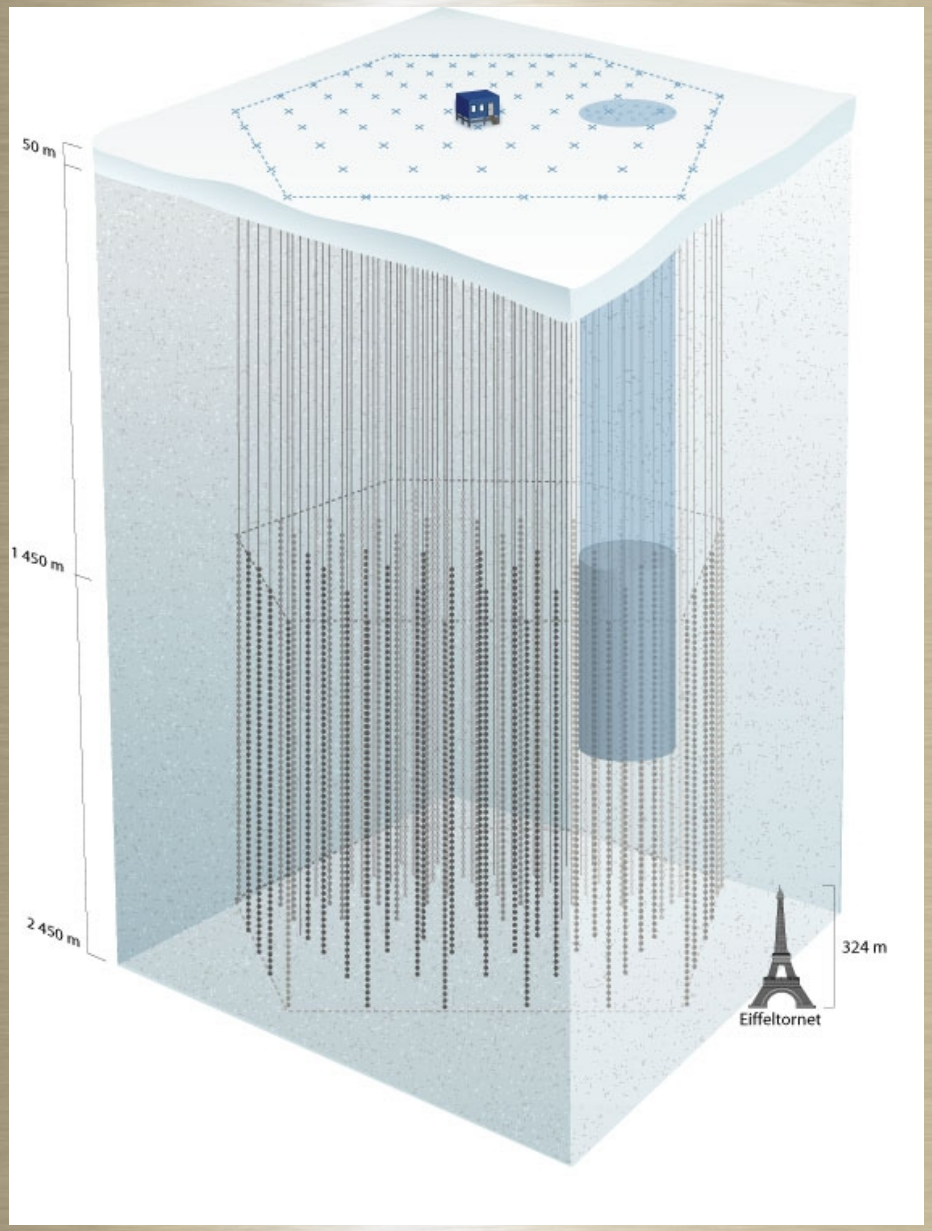
Outline of the Coincidence method

Estimate of False Alarm Rate with Simulated Data (LIGO-IceCube)

Contents

- IceCube neutrino detector
- Coincidence analysis method
  - Motivation
  - Analysis pipeline
  - Monte Carlo results
- Conclusion
- Future plans

IceCube



- Antarctic neutrino detector
- High energy neutrinos

$$\sim 10^{11} - 10^{21}\,\mathrm{eV}$$

- Good directional resolution
  (~2° for 9 strings configuration)
- Upgraded yearly
  - Currently 22 strings
  - Completion expected by 2011

Design Overview

- 1 km^3 -- 1 Gton instrumented volume
- 80 strings
  - 1.5 km – 2.5 km deep
  - 125 m spacing between strings
- 60 Optical Modules per string
  - 17 m vertical spacing between modules

IceCube

- Antarctic neutrino detector

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2011

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·17 m vertical spacing between modules

LIGO-VIRGO – IceCube Coincidence Analysis

Motivation

Traditionally

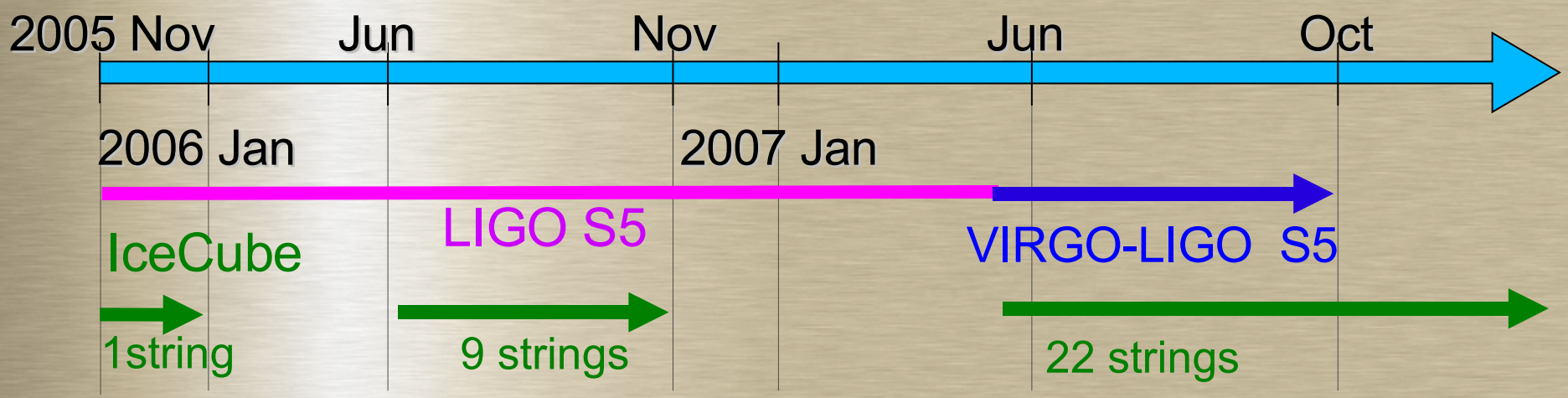
- Signals are buried in noise or background events
- Difficult to declare a detection with high confidence

Ultra low accidental coincidence rate between two detectors

If we see something → High confidence detection

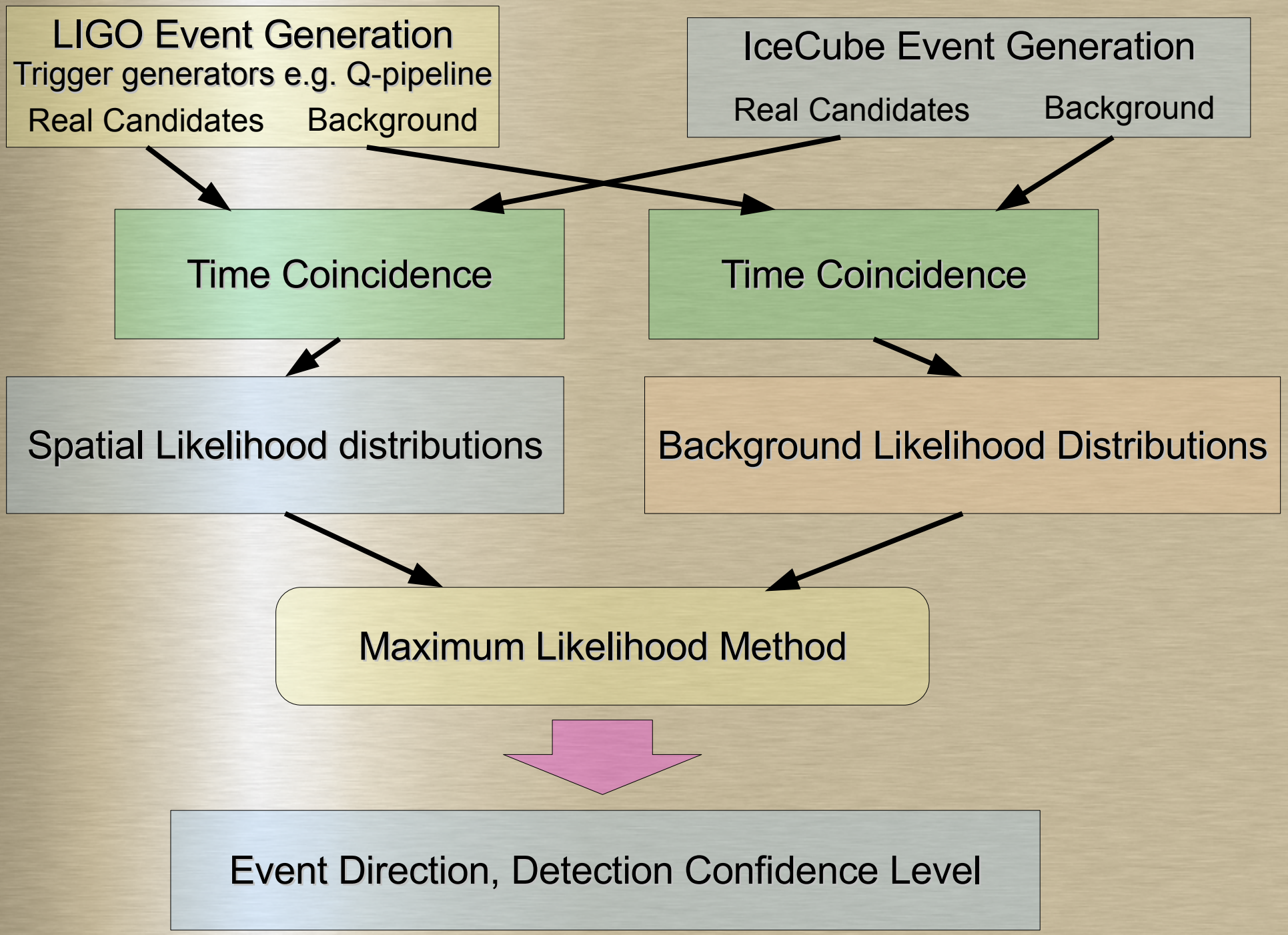
Possible Sources: GRBs, AGNs, but largely unknown

Expected overlap of observing time



note: there is no official data exchange agreement yet

Analysis Pipeline



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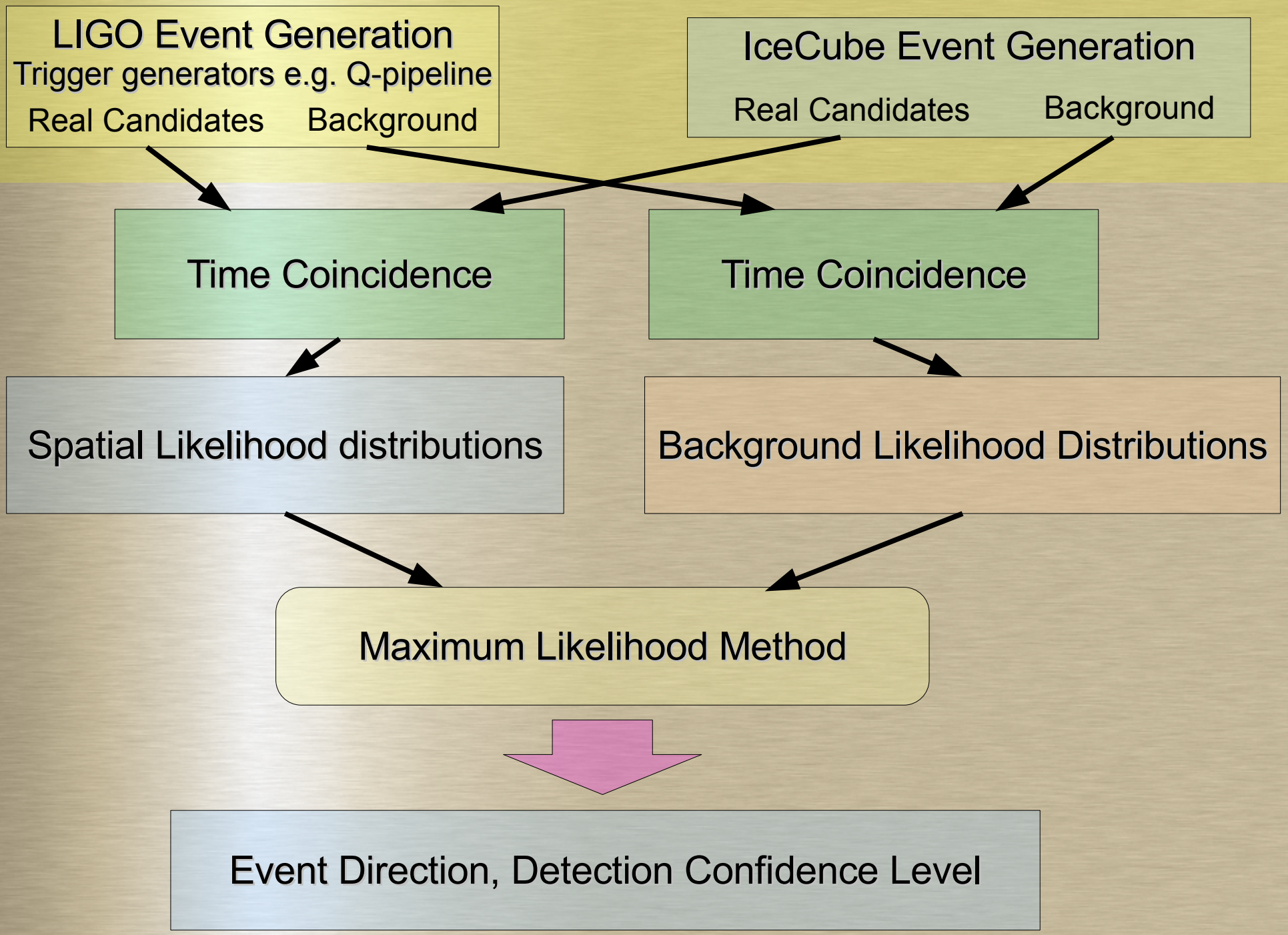

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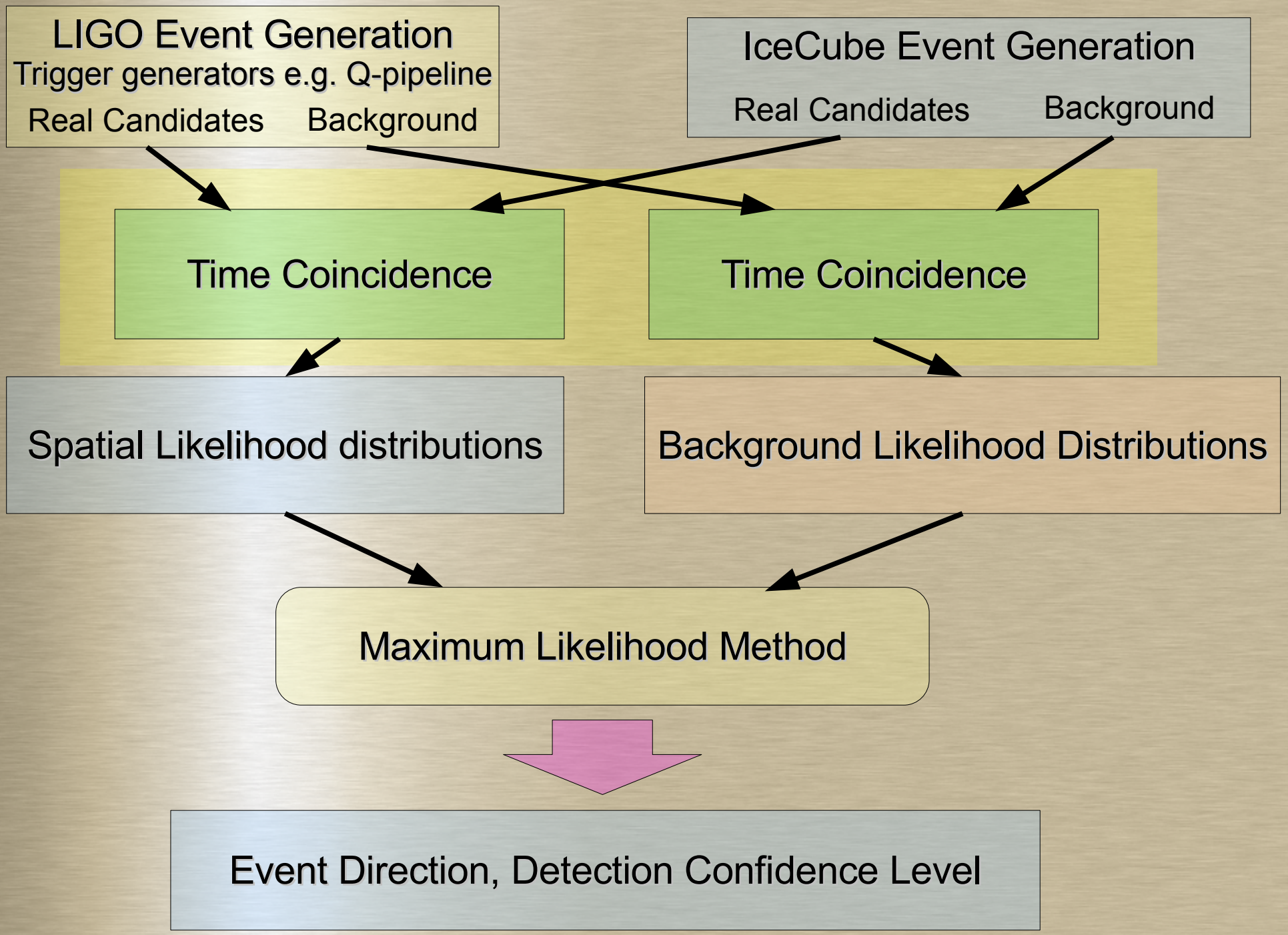

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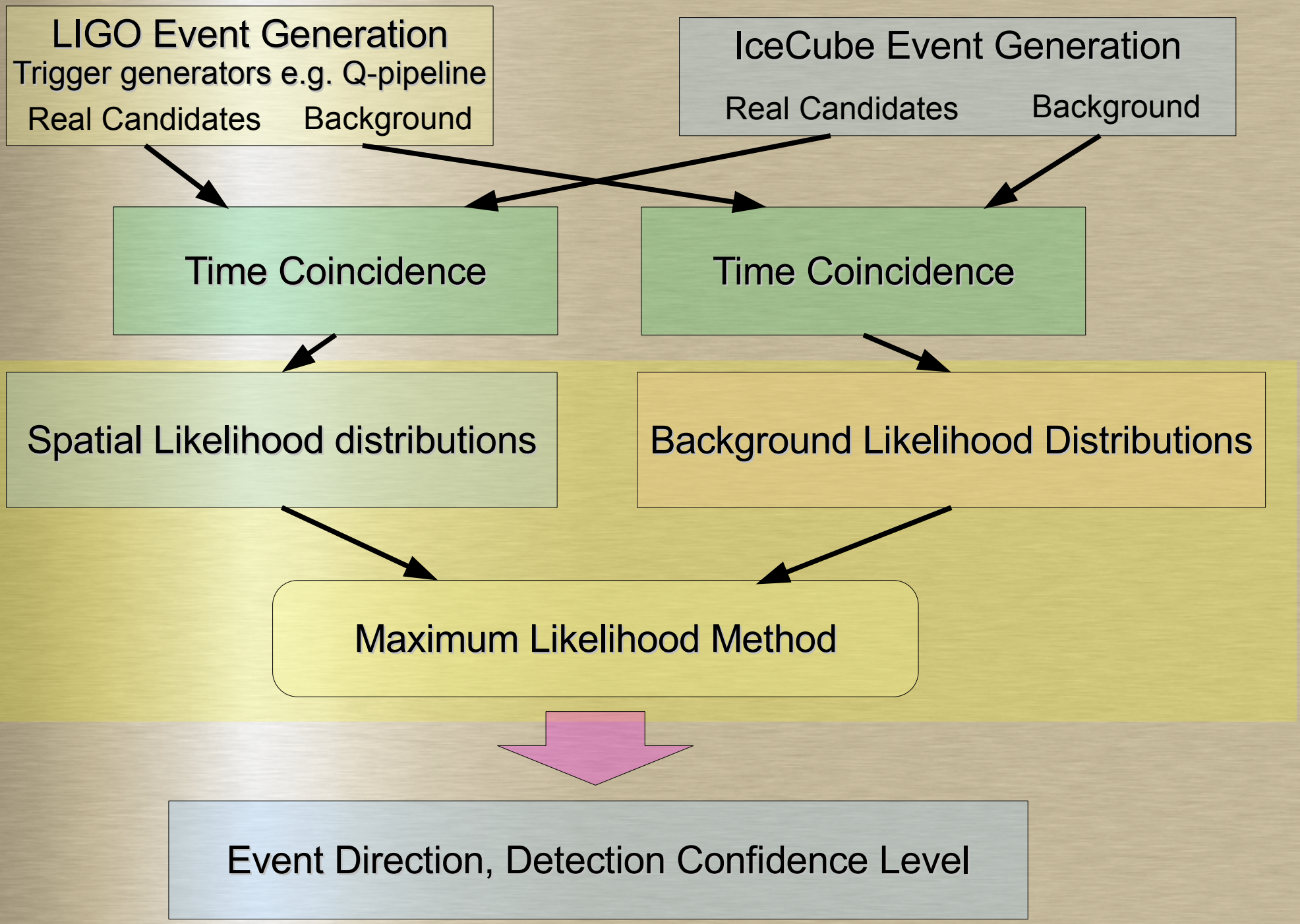

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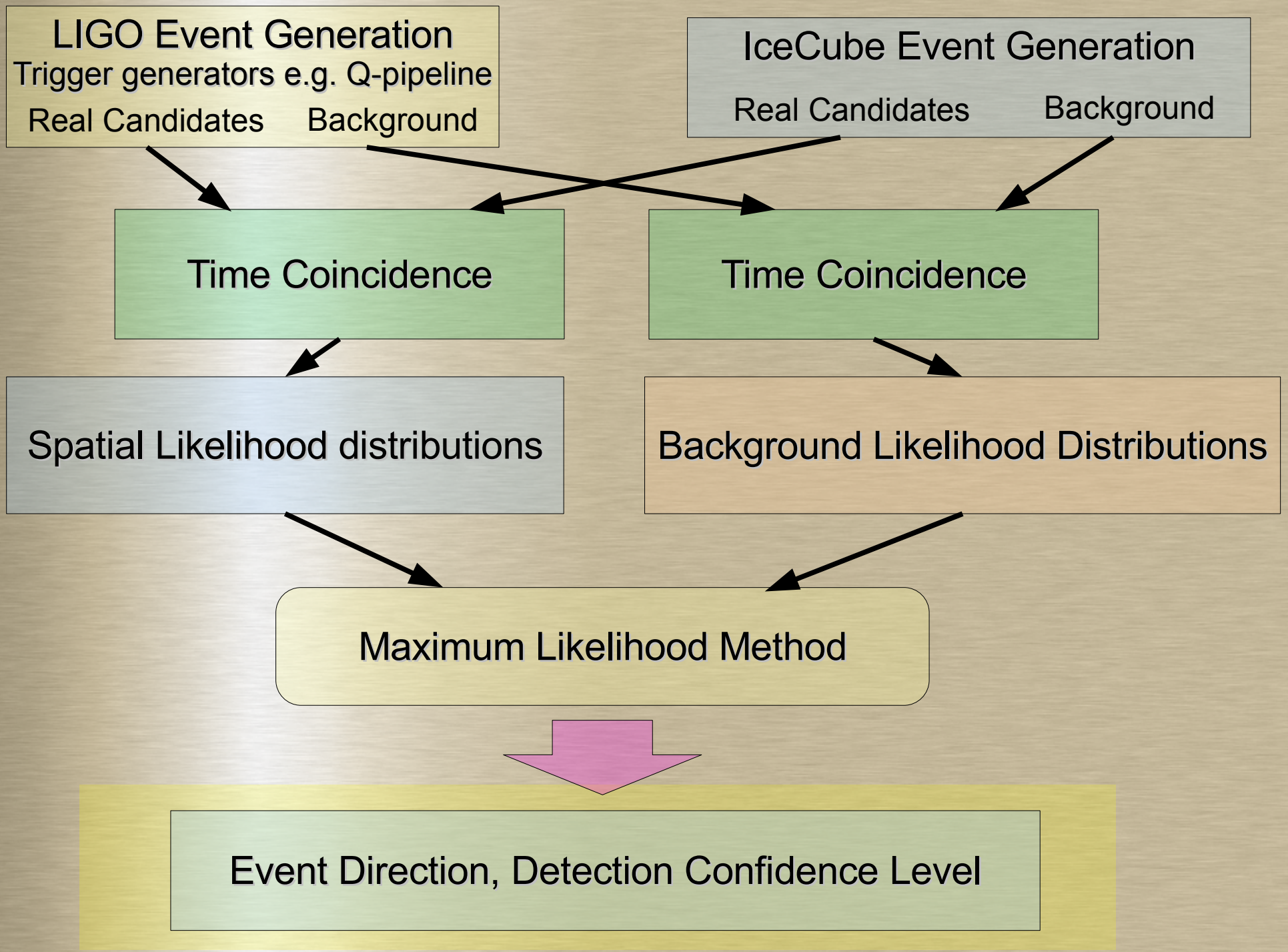
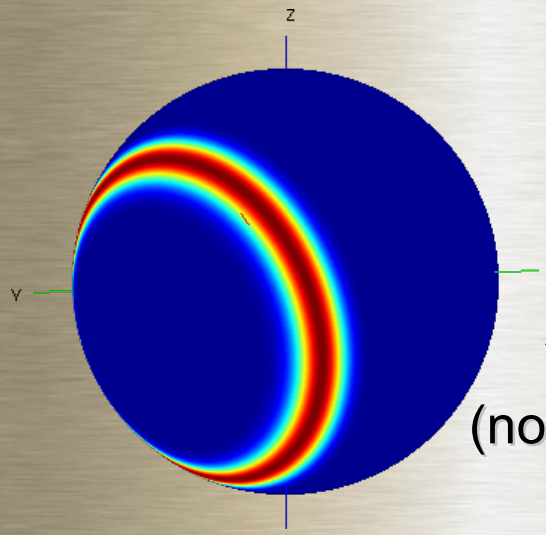


GW Events

LIGO only case:
H1-L1 time difference
→ A ring on the sky



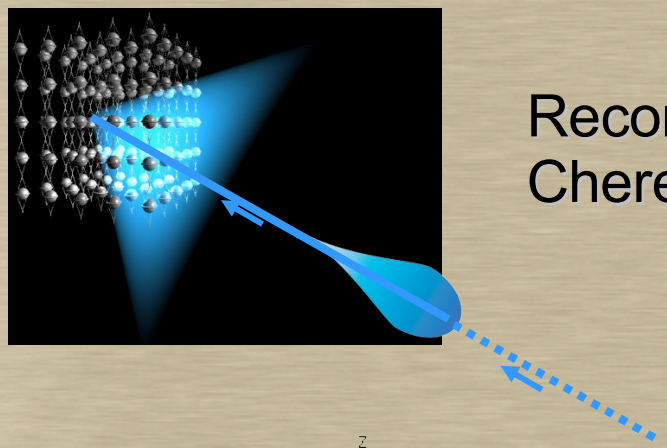
Likelihood Distribution

$$P_{\mathrm{GW}}(\theta,\phi)$$

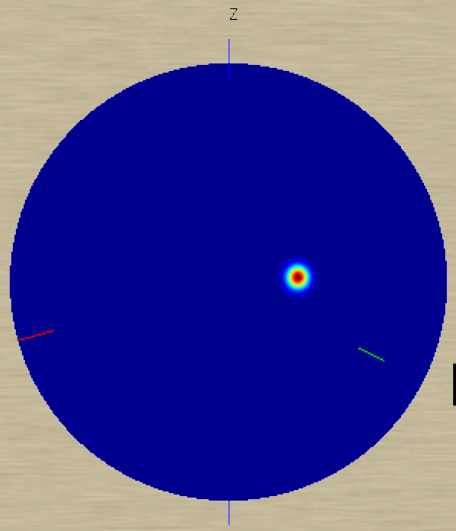
(normalized over the sky)

LIGO-VIRGO case:
Spot(s) on the sky
We will use a coherent method

IceCube Events



Reconstructed from Cherenkov photons



A spot on the sky

(The northern sky only)

Likelihood Distribution

$$P_{\nu}(\theta,\phi)$$

(normalized over the sky)

Background Generation

- GW detectors: Time shifts
- IceCube: Monte Carlo simulation

Time Coincidence

- GW-Nu time-delay: Unknown
  Probably very small
- Several time windows:
  e.g. 0.1, 1, 10 sec

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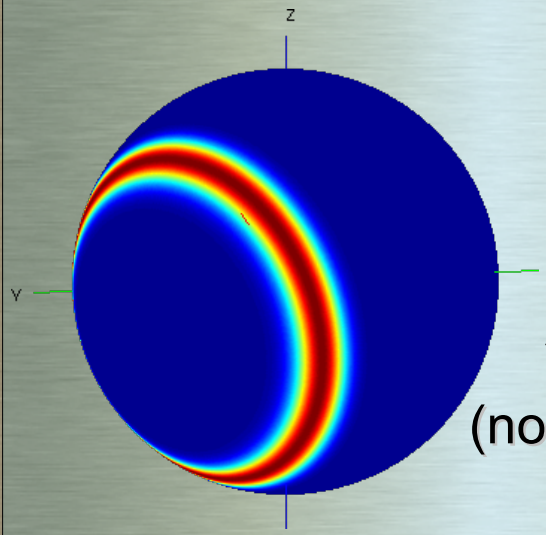

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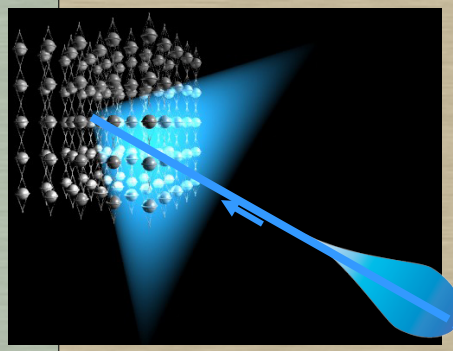

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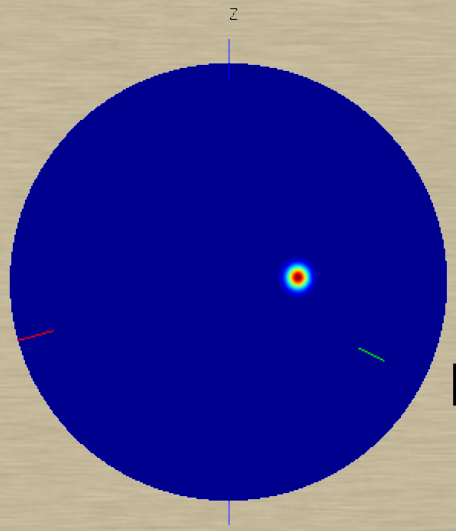

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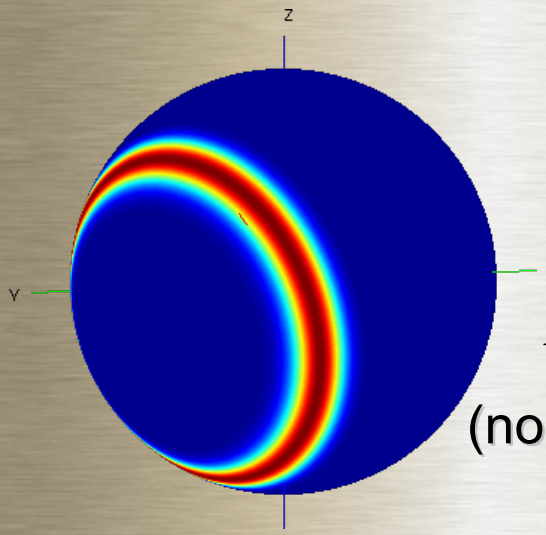

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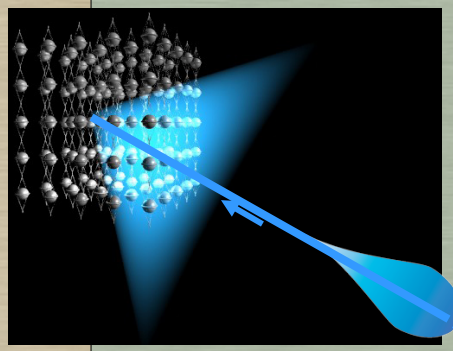

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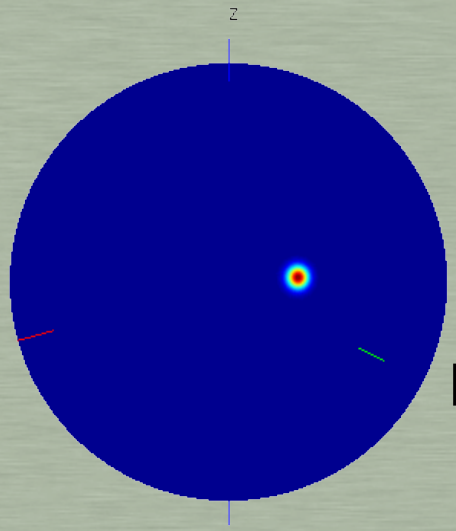

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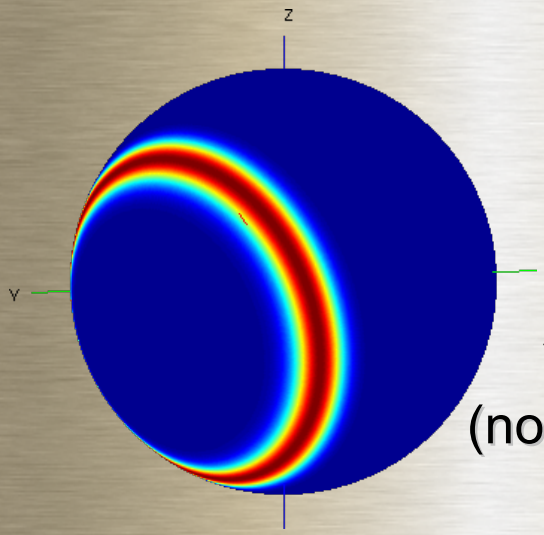

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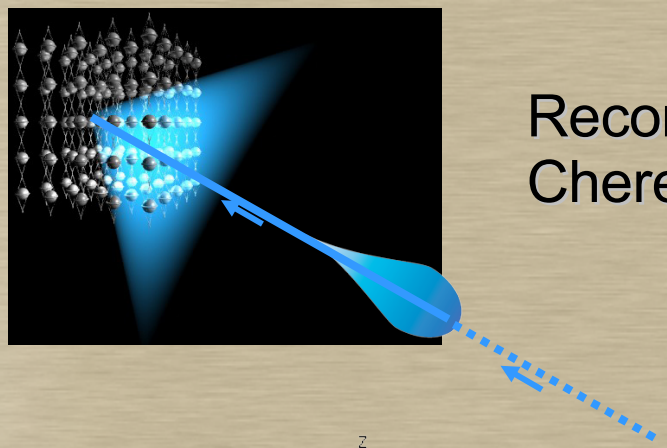

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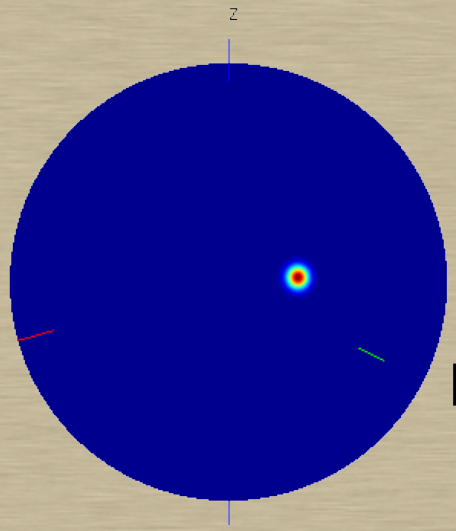

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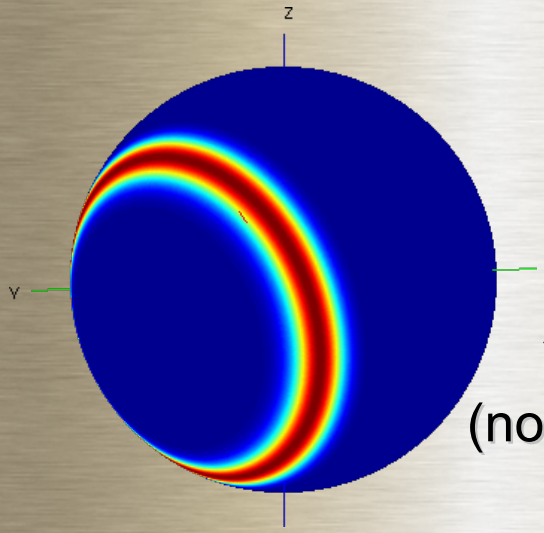

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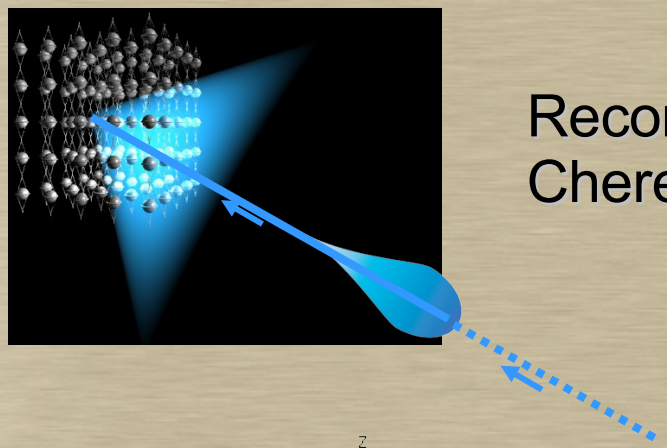

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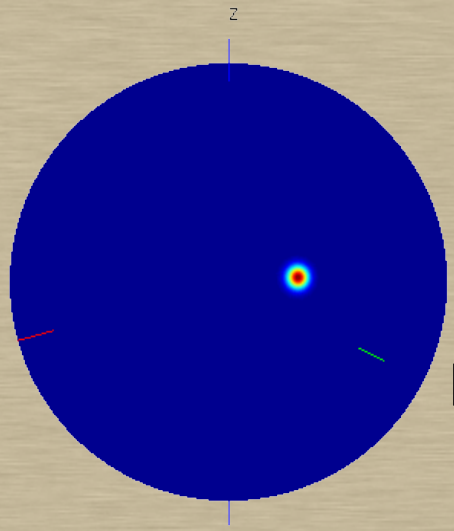

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Maximum Likelihood Method

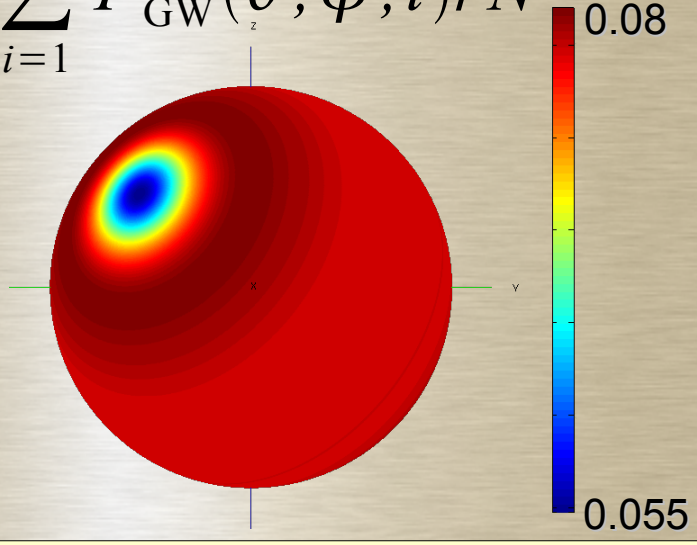
Find the most likely direction of the source

Averaging background events (We work in Earth based coordinates)

→ Background Likelihood Distribution

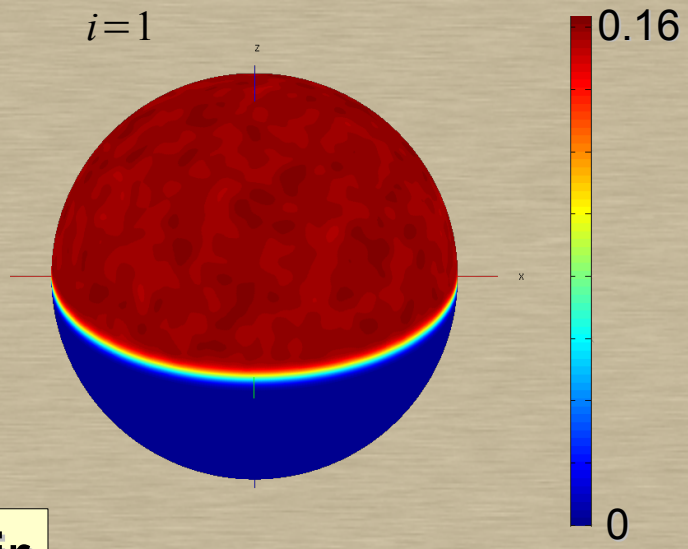
GW Background Distribution

$$P_{\mathrm{GW}}^{\mathrm{BG}}(\theta,\phi)=\sum_{i=1}^{N} P_{\mathrm{GW}}(\theta,\phi,i)/N$$



Neutrino Background Distribution

$$P_{\nu}^{\mathrm{BG}}(\theta,\phi)=\sum_{i=1}^{N} P_{\nu}(\theta,\phi,i)/N$$



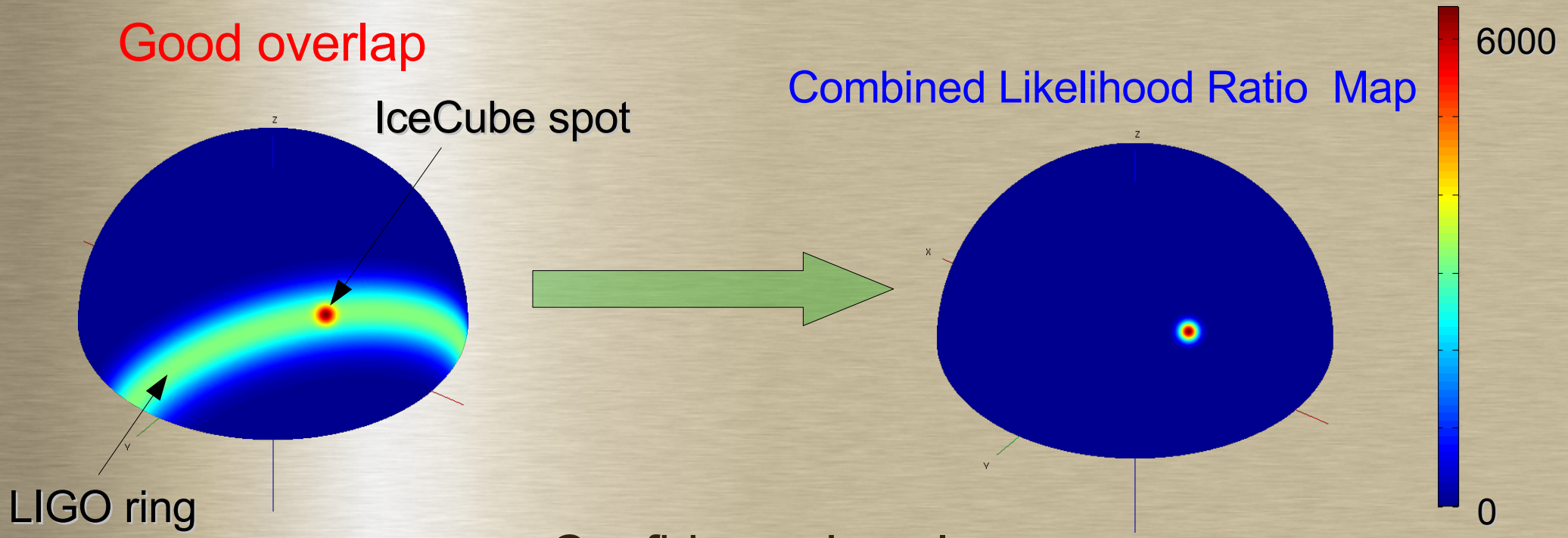
For each time coincident $\mathrm{GW}-\nu$ event pair

Combined Likelihood Ratio: $$L(\theta,\phi)=\frac{P_{\mathrm{GW}}(\theta,\phi)}{P_{\mathrm{GW}}^{\mathrm{BG}}(\theta,\phi)}\cdot\frac{P_{\nu}(\theta,\phi)}{P_{\nu}^{\mathrm{BG}}(\theta,\phi)}$$

Maximum Likelihood: $$L_{\max}=max\left(L(\theta,\phi)\right)=L(\theta_{\max},\phi_{\max})$$

Example: A large Lmax event

Good overlap



Confidence Level

From Background Events

→ Distribution of Lmax for background: $P_{\mathrm{BG}}(L_{\max})$

Each event: $L_{\max}^{\mathrm{event}}$ How significant is this from the background ?

p-value: $$p = \int_{L_{\max}^{\mathrm{event}}}^{\infty} P_{\mathrm{BG}}(L_{\max})\, dL_{\max}$$

(Chance of a background event having $L_{\max} \geq L_{\max}^{\mathrm{event}}$)

Monte Carlo Simulation

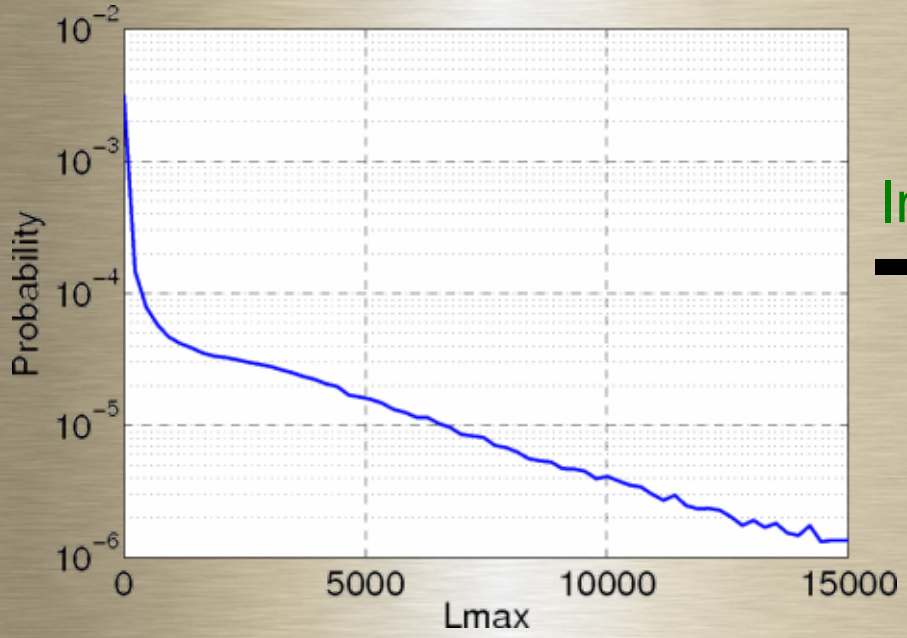
LIGO Events

- H1-L1 time difference τ
  Distributed uniformly in [-10ms, 10ms]
- $\delta\tau$ (error of τ): Follows a gamma distribution peaked at $\delta\tau \sim 0.5\,\mathrm{msec}$
- Event Rate:
  H1-L1 coincidence = 13 events/day

IceCube Events

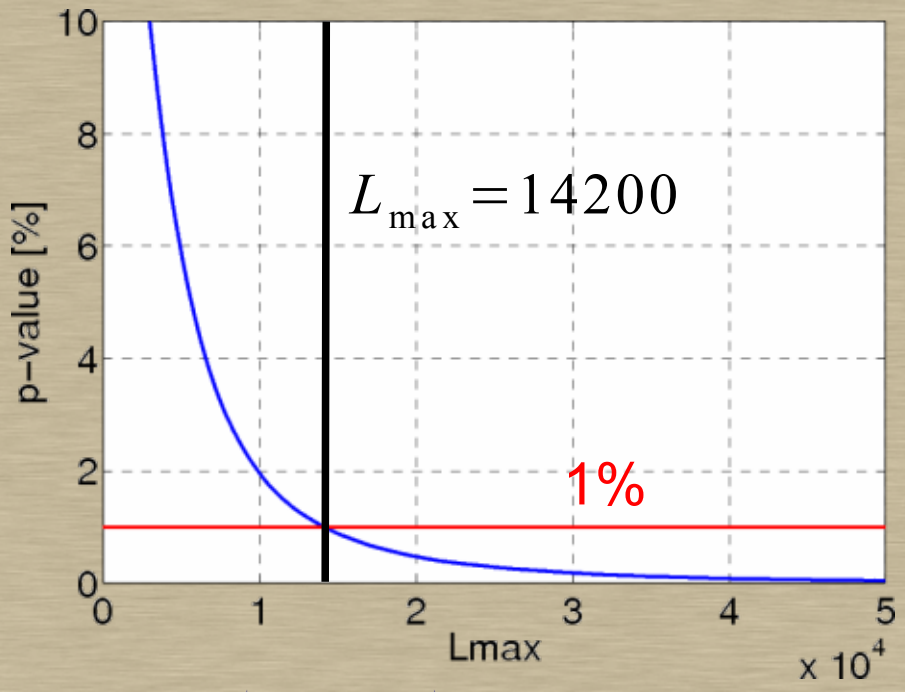
- Uniformly distributed over the northern sky
- Spot size = 2°
- Event Rate:
  2 events/day (9 strings)

Lmax Probability Distribution ($P_{\mathrm{BG}}(L_{\max})$)



Integrate

p-value of Lmax



(Rate of false events produced by the background)

$$\text{False Alarm Rate [events/year]} = \frac{1}{435}\left(\frac{p}{1\,\%}\right)\left(\frac{T_{\mathrm{w}}}{1\,\mathrm{sec}}\right)$$

T_{w} : Time Window

p : p-value

Conclusion

- Coincidence analysis method: LIGO-VIRGO-IceCube
- Time coincidence with various window sizes
- Spatial coincidence with the Maximum Likelihood Method
- Monte Carlo simulation (LIGO-IceCube):
  False Alarm Rate = 1/435 years for 1% p-value, 1 sec time window

Small FAR → Relaxed trigger threshold (e.g. SNEW standard = 1/100 years)
→ Dig deeper into the noise

Future Plan

- Include VIRGO
  Coherent method to determine the direction.
  Include the antenna factors.
- Sensitivity test using signal injection
  Estimate False Dismissal Rate
- Apply the method to real Data
- Other Neutrino Detectors ?