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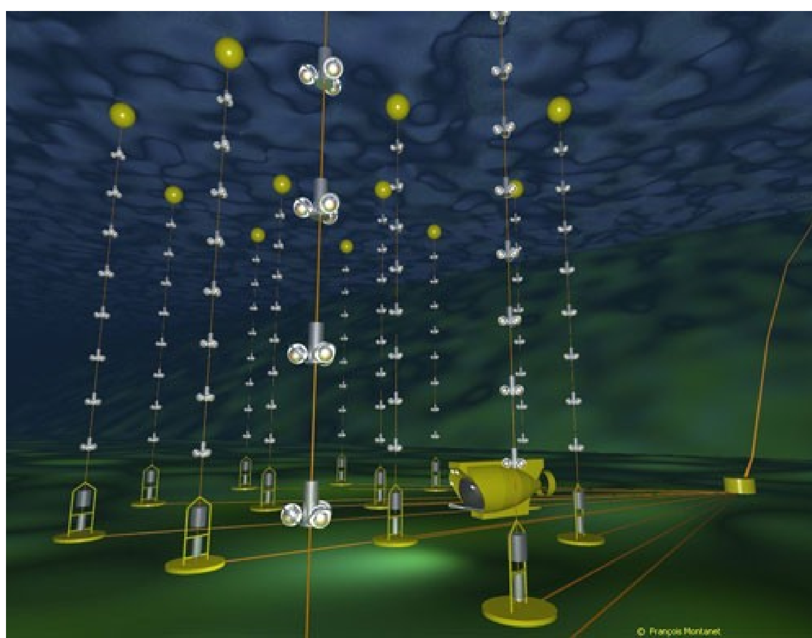
Joint Search between Gravitational-wave and High-Energy Neutrino Detectors



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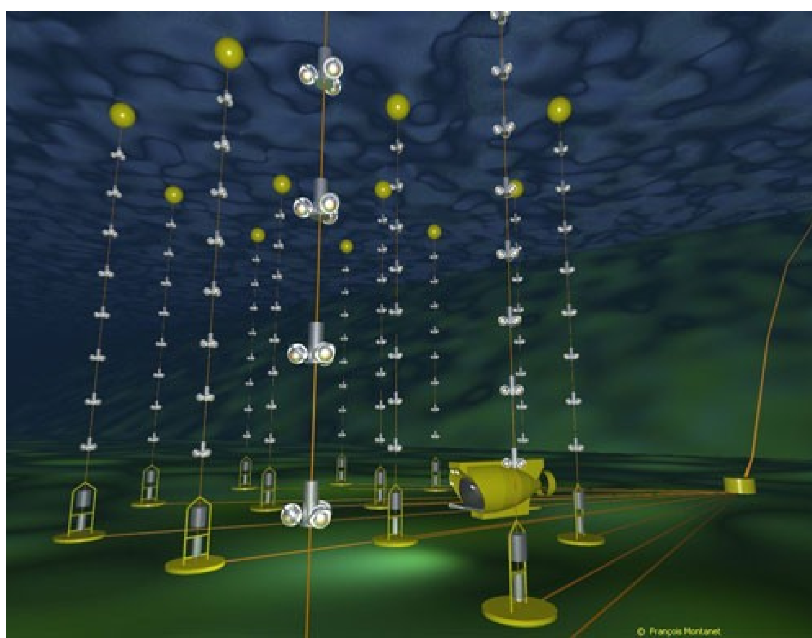

1. Motivation
2. Detectors
3. GW and HEN search methods
4. GWHEN search method
5. Conclusion/future plans

Motivation

a) Proof of common astrophysical source.
b) Unique insight on how central engines work.
c) Probing Quantum Gravity: differential propagation velocities.
e) So far we are opportunistic with GW detectors.
Independent background for GW and HEN:
→ high confidence detection
f) ?
g) ?

GW-HEN common sources

1. **Gamma Ray Bursts**
   - Failed (baryon-rich jets, thicker stellar envelope)
   - Low luminosity (hypernovae)
2. **Flares from Soft Gamma Repeaters (magnetars)**
3. **Microquasars**

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$\longrightarrow$ high confidence detection
f) ? - models, model parameters
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Independent background for GW and HEN:
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f) ? - models and model parameters
g) ? - unknown effects or sources

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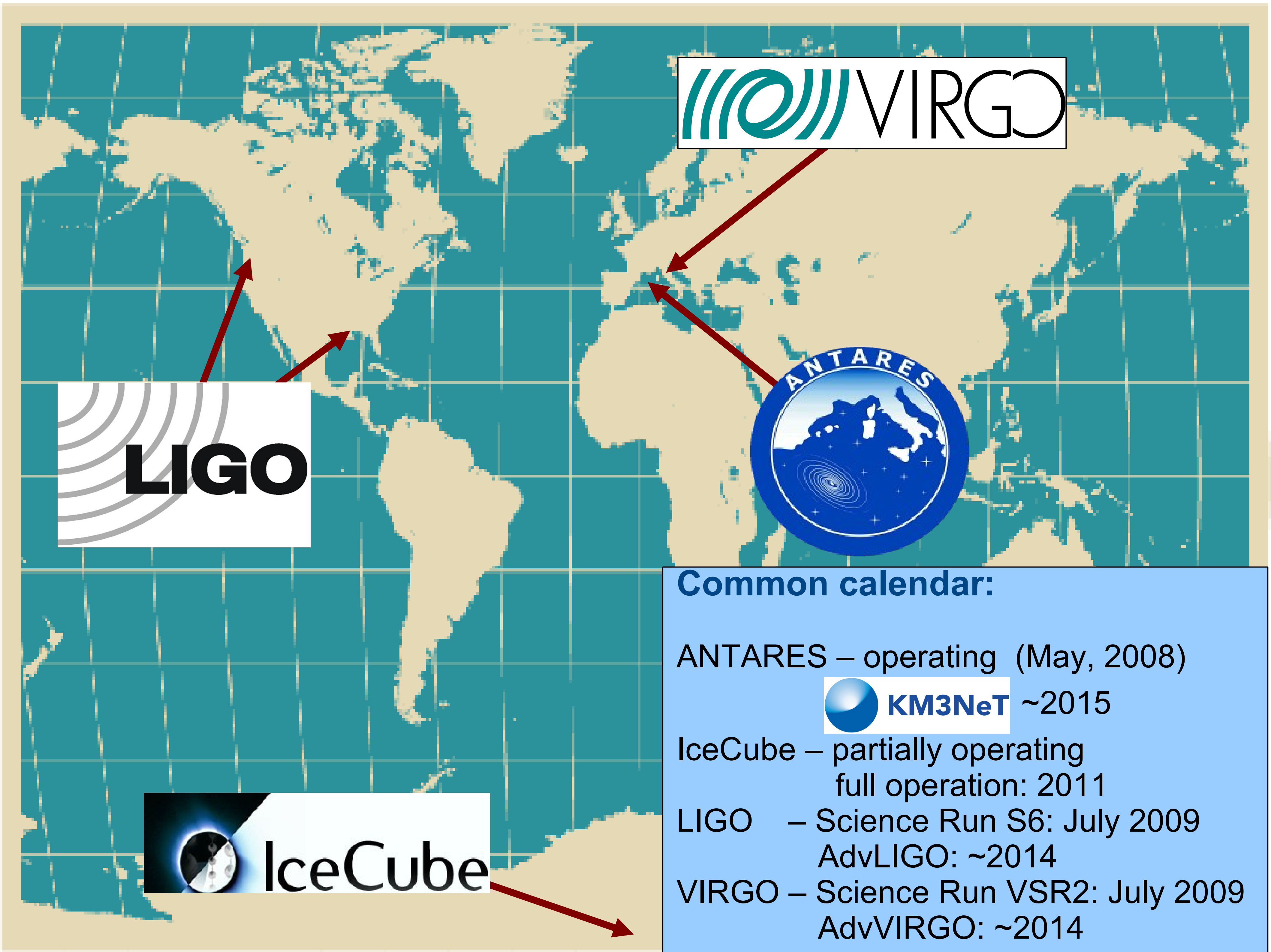


Common calendar:

ANTARES – operating (May, 2008)

KM3NeT ~2015

IceCube – partially operating
full operation: 2011

LIGO – Science Run S6: July 2009
AdvLIGO: ~2014

VIRGO – Science Run VSR2: July 2009
AdvVIRGO: ~2014

HEN pipeline

neutrino:

Direction
Energy
Arrival time

Source direction & probability

Background generation: **Monte Carlo**

Methods

- Likelihood-ratio method*
- EM algorithm**
  = likelihood-ratio
  + Bayesian neutrino origin determination

*   Braun *et al.*, 2008.
** Aguilar & Hernandez-Rey, 2008.

GW pipeline

gravitational wave:

Strain X 3

Source direction & probability

Background generation: **Time shifts**

Methods

Coherent search for unmodeled GW bursts.

- Ω pipeline*
  - Bayesian algorithm using sine-Gaussian templates
- coherent WaveBurst (cWB)**
  - coherent time-frequency analysis using wavelets

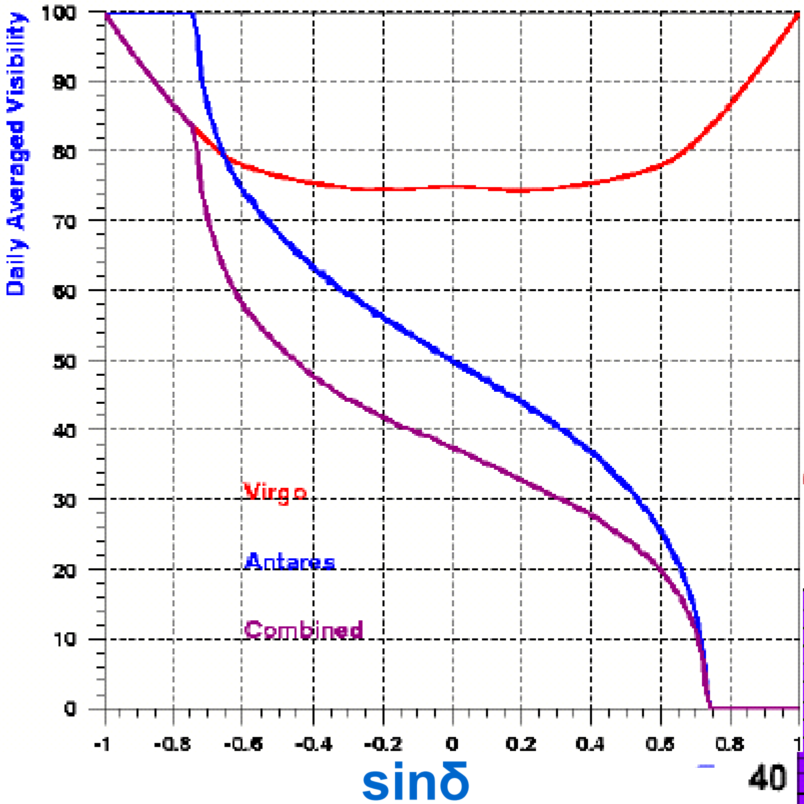
*   Searle et al, 2008.
** Klimenko et al, 2008.

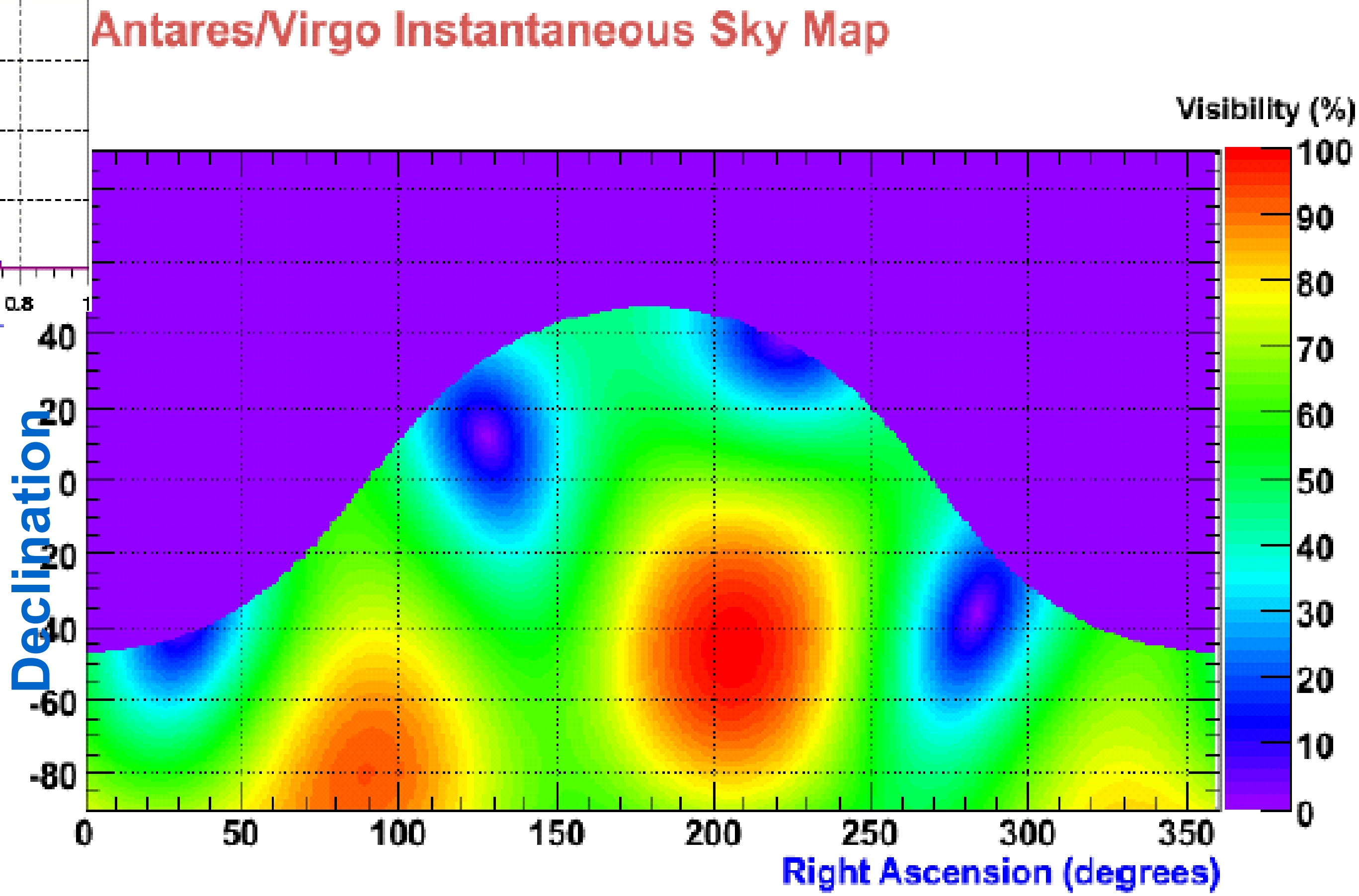
- Outputs: Skymaps (SPDF) for signal and background

Antares + VIRGO

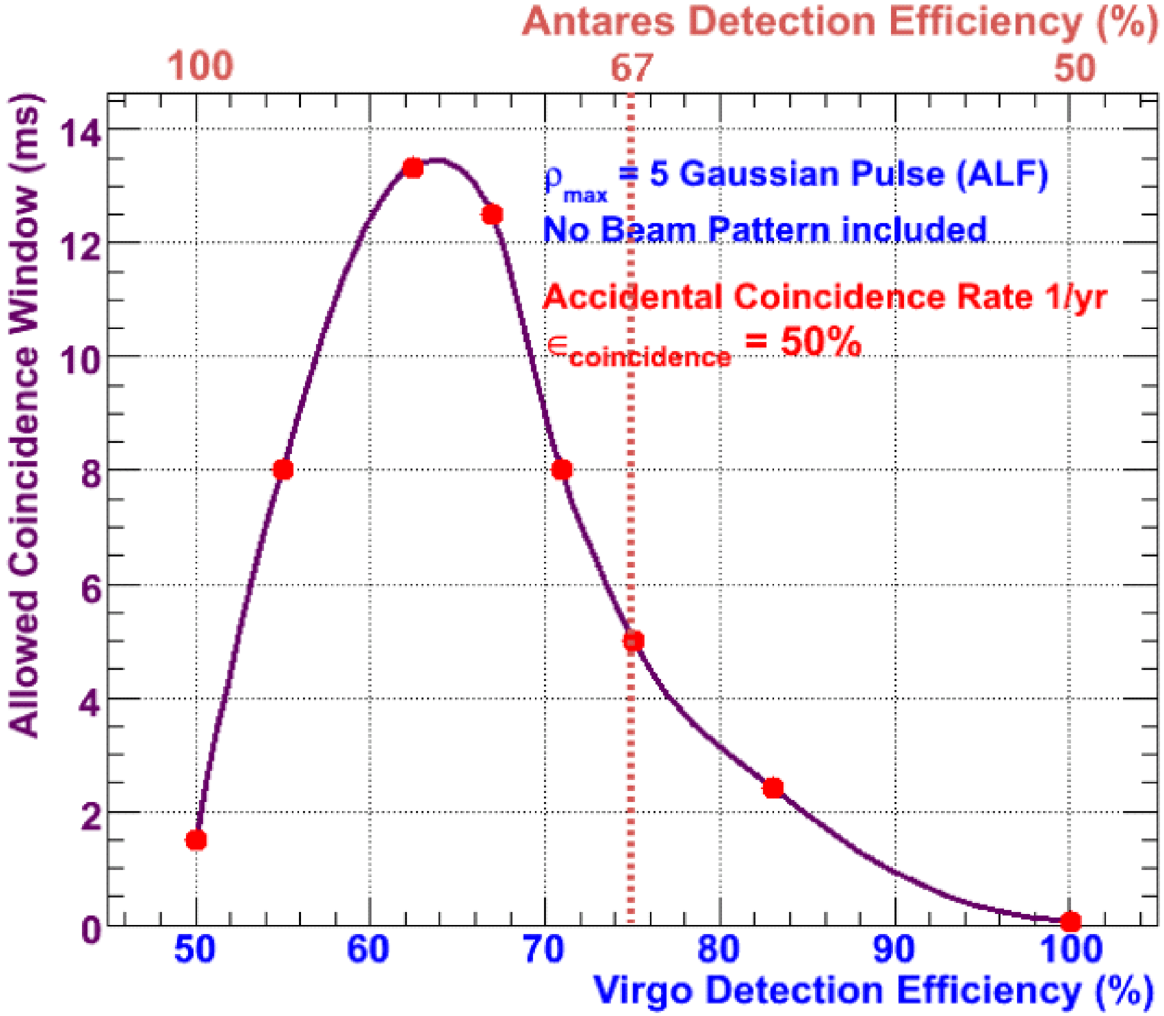
- Common sources
- Coincident signals
- Observability
- Detectability

T. Pradier, 2008





Antares + VIRGO



- Common sources
- Coincident signals
- Observability
- Detectability

T. Pradier, 2008

Allowed coincidence window

Allowing 50% accidental coincidence rate, one can maximize the allowed time window by tuning the efficiencies of the detectors.

Antares + VIRGO

- Common sources
- Coincident signals
- Observability
- Detectability

Quantum gravity:

dispersion relation:

$$c^2p^2 = E^2\left[1 + \xi\left(\frac{E}{E_{\mathrm{QG}}}\right) + \mathcal{O}\left(\frac{E^2}{E_{\mathrm{QG}}^2}\right) + \dots\right]$$

energy dependent propagation velocity

$$E_{\mathrm{graviton}} \sim hf \ll 1$$

$$E_{\nu} \sim \mathrm{TeV}$$

$$\boxed{\Delta t_{\mathrm{QG}}^{\mathrm{ms}} \propto 1/d \simeq 0.15\left(\frac{E_\nu}{1\ \mathrm{TeV}}\right)\left(\frac{10^{19}\ \mathrm{GeV}}{E_{\mathrm{QG}}}\right)}$$

Microquazars

Galactic sources: QG delay is independent of cosmological models

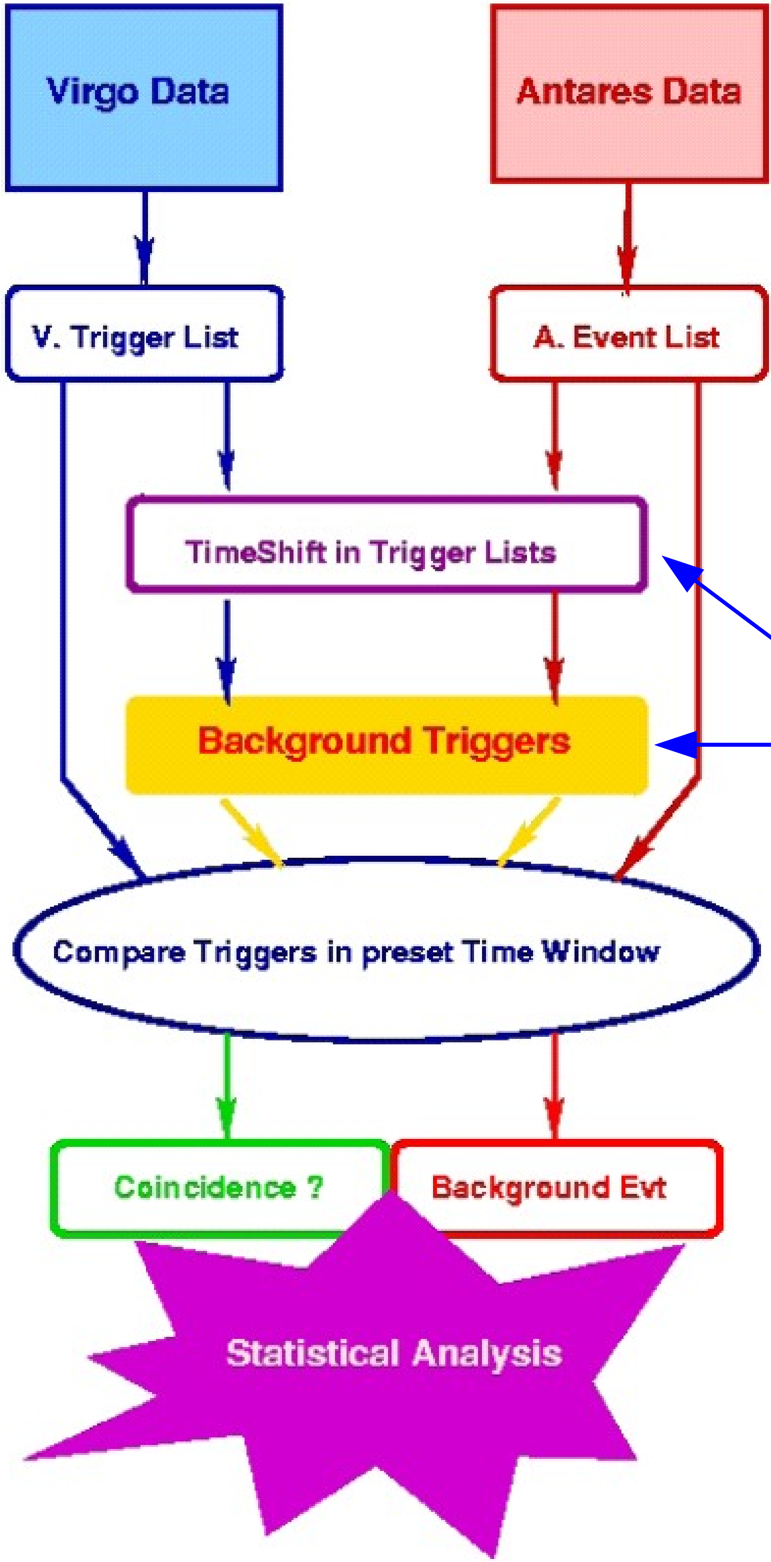
d = 10 kpc

$$E_{\mathrm{QG}} = E_{\mathrm{Planck}} = 10^{19}\ \mathrm{GeV}$$

Antares + VIRGO

- Common sources
- Coincident signals
- Observability
- Detectability

T. Pradier, 2008



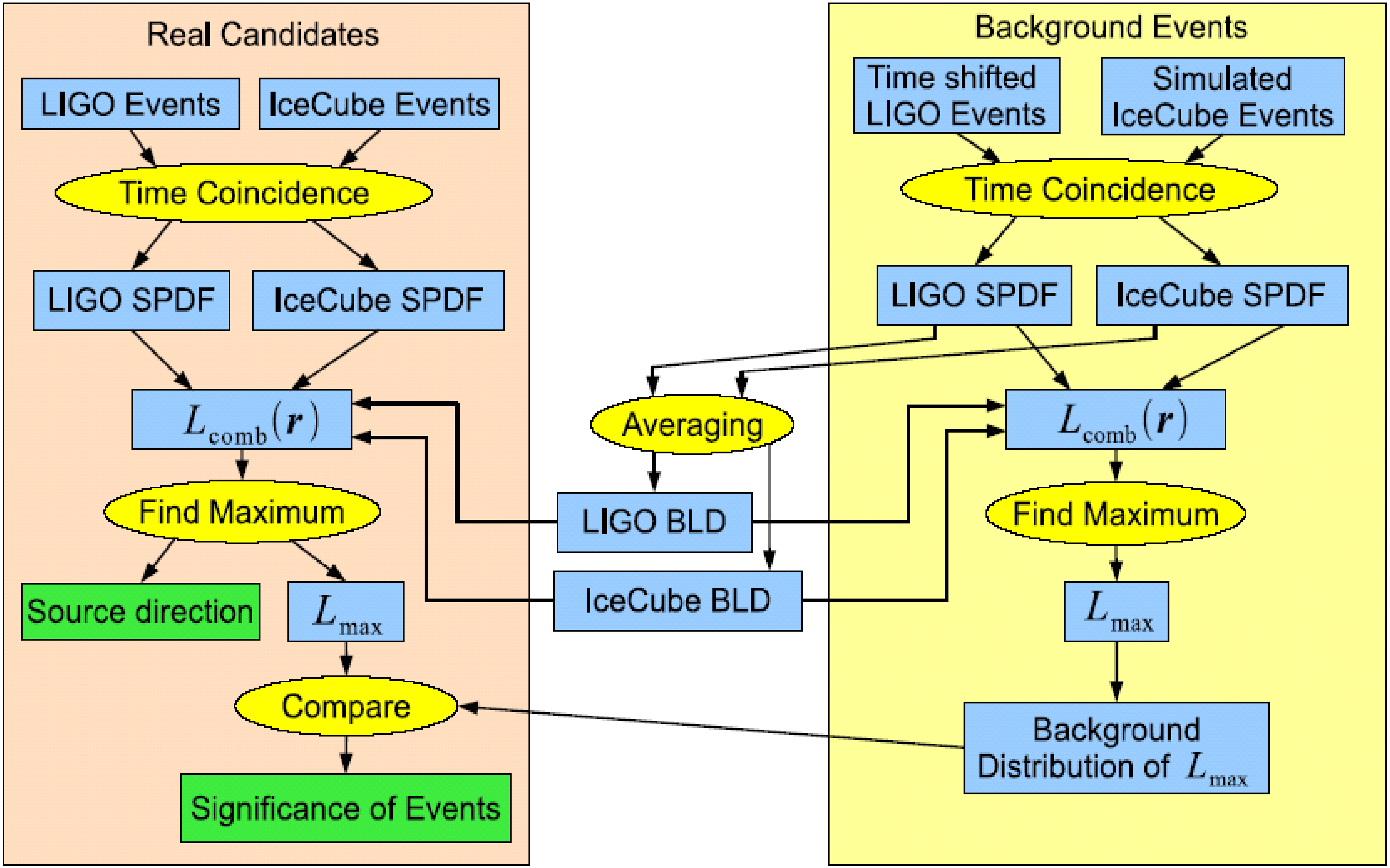
Trigger $\xleftrightarrow{\text{timeshift}}$ Background

No direction reconstruction with VIRGO

time coincidence

LIGO + IceCube

Y. Aso et al., 2008

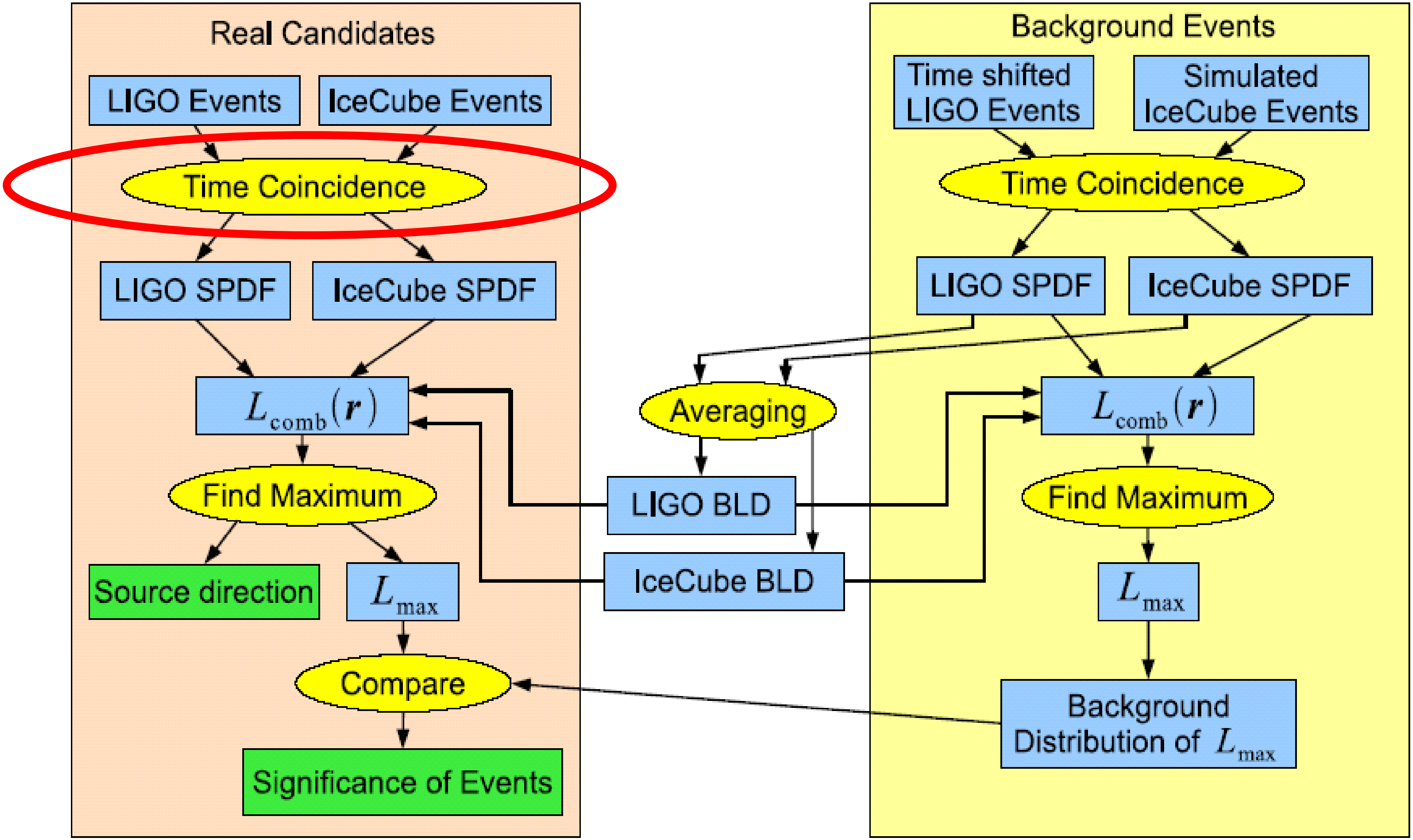


SPDF – spatial probability distribution function

BLD – background likelihood distribution

LIGO + IceCube

Y. Aso et al., 2008



Time coincidence

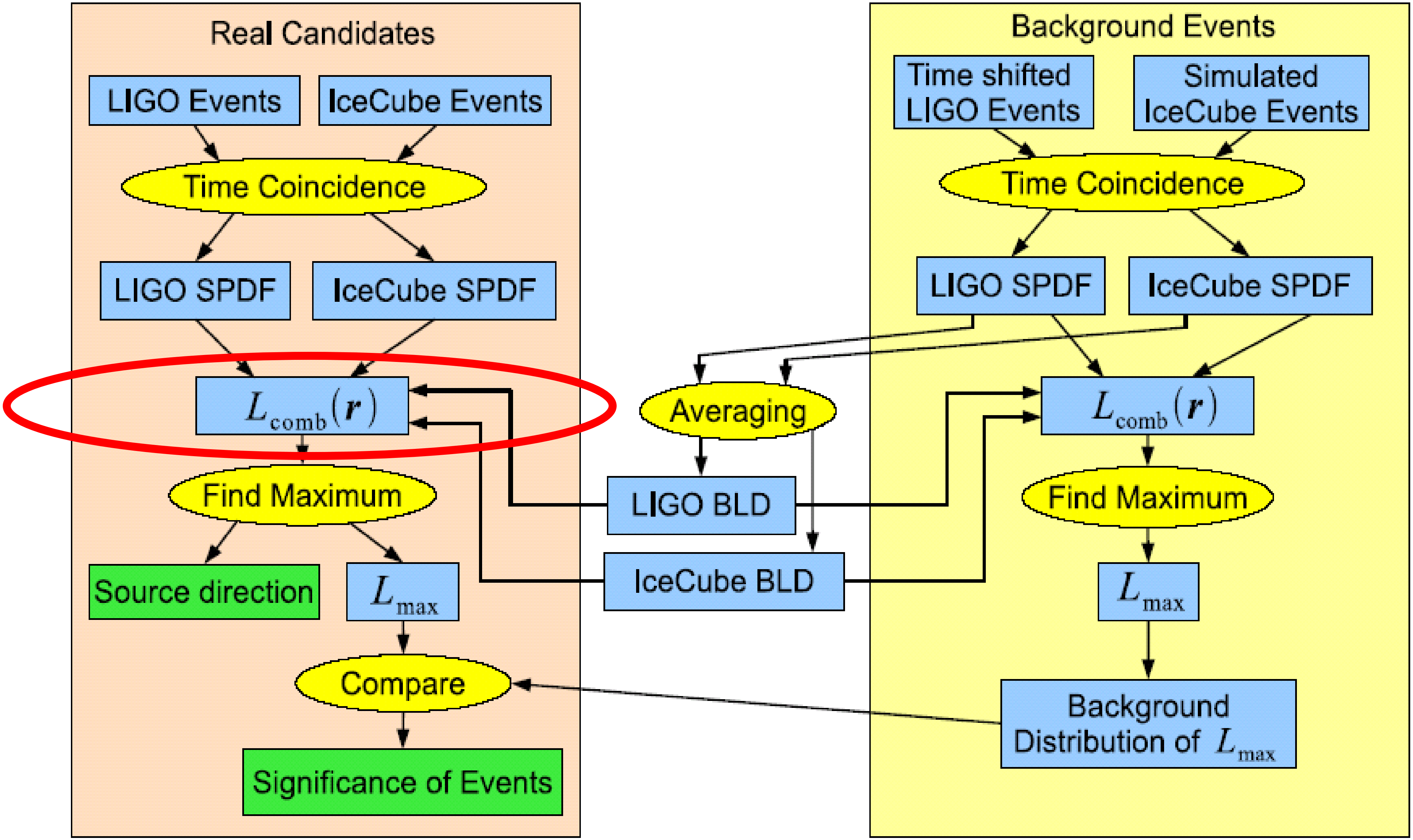
- Look for events which appear within a certain time window
  Time difference can be due to:
    - direction of signal
    - emission mechanism
    - QG effects

No assumption of the source → used time windows from 0.1s – 1 day

LIGO – IceCube time difference = 40ms.

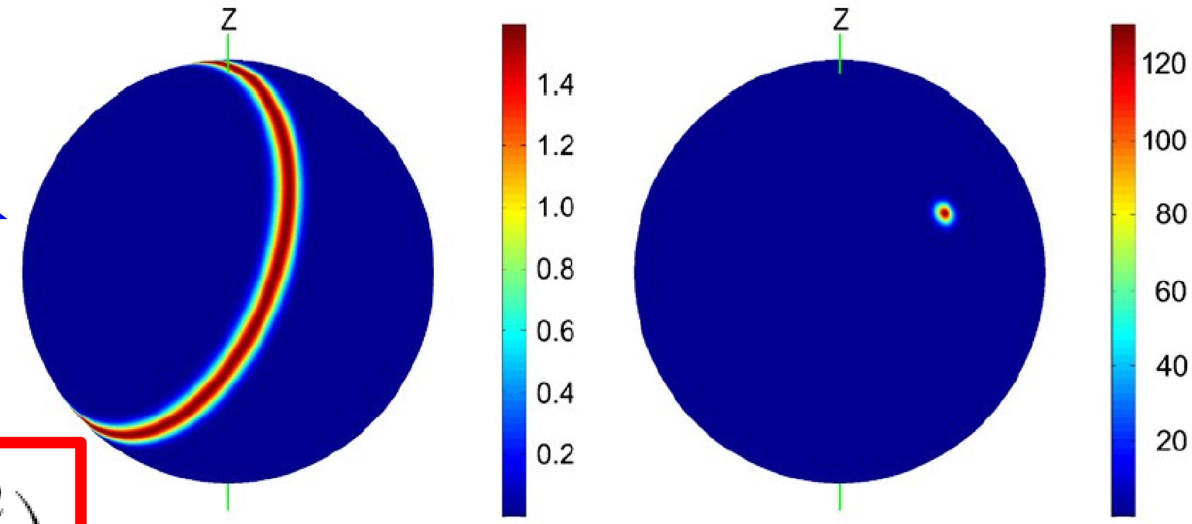
LIGO + IceCube

Y. Aso et al., 2008



Spatial Coincidence

- Take SPDFs (spatial PDFs) from LIGO and IceCube.



(a) (b)

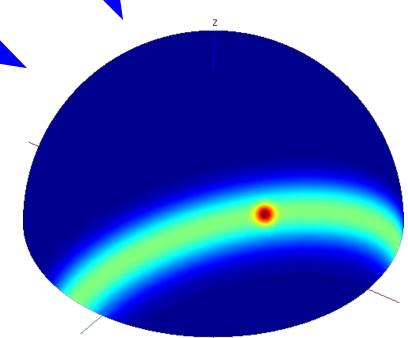
Example SPDFs.

IceCube – signal SPDF

$$S_\nu(\boldsymbol{r};\boldsymbol{r}_{\text{ev}},\sigma_\nu) = A_\nu \cdot \exp\left(\frac{-\psi^2}{2\sigma_\nu^2}\right)$$

2 LIGO detectors - signal SPDF

$$S_{\text{GW}}(\boldsymbol{r};\theta_{\text{ev}},\delta\tau) = A_{\text{GW}} \cdot \exp\left[-\frac{D^2(\cos\theta - \cos\theta_{\text{ev}})^2}{2\delta\tau^2 c^2}\right]$$



Overlap event

Background distributions:

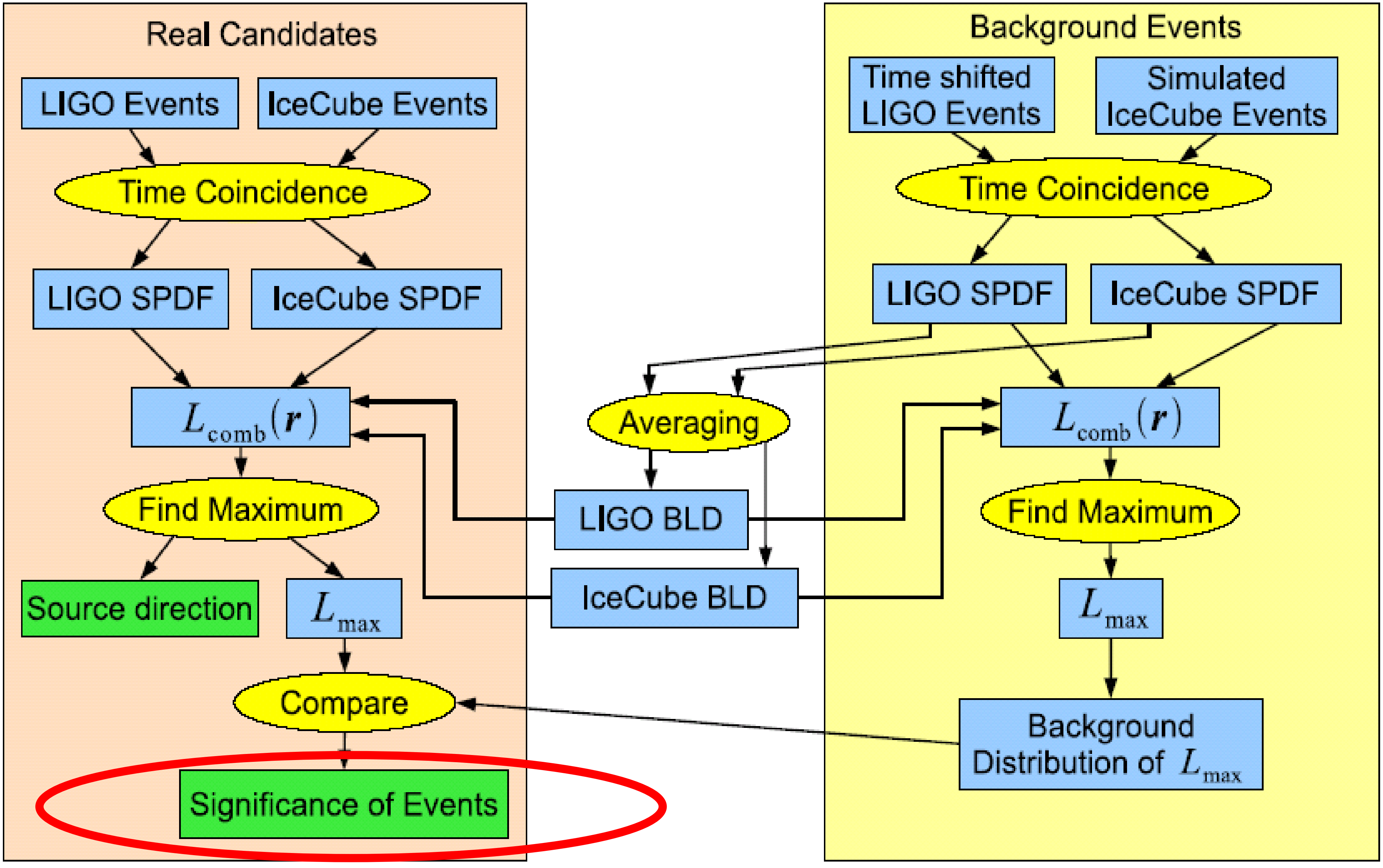
$$B_\nu(\boldsymbol{r}_{\text{ev}})$$

$$B_{\text{GW}}(\theta_{\text{ev}})$$

Based on statistics using off-source data

LIGO + IceCube

Y. Aso et al., 2008



Significance

Signal and background SPDFs:

Combined Likelihood function:

$$L_{\mathrm{comb}}(r) = \frac{S_{\mathrm{GW}}(r;\theta_{\mathrm{ev}},\delta\tau)\cdot S_{\nu}(r;r_{\mathrm{ev}},\sigma_{\nu})}{B_{\mathrm{GW}}(\theta_{\mathrm{ev}})\cdot B_{\nu}(r_{\mathrm{ev}})}$$

Most likely source direction: r_{max}

$$L_{\mathrm{max}} = L_{\mathrm{comb}}(r_{\mathrm{max}}) = \mathrm{Max}[L_{\mathrm{comb}}(r)]$$

Significance:

$$p = \int_{L_{\mathrm{ev}}}^{\infty} P^{\mathrm{BG}}_{L_{\mathrm{max}}}(L_{\mathrm{max}})\,\mathrm{d}L_{\mathrm{max}}$$

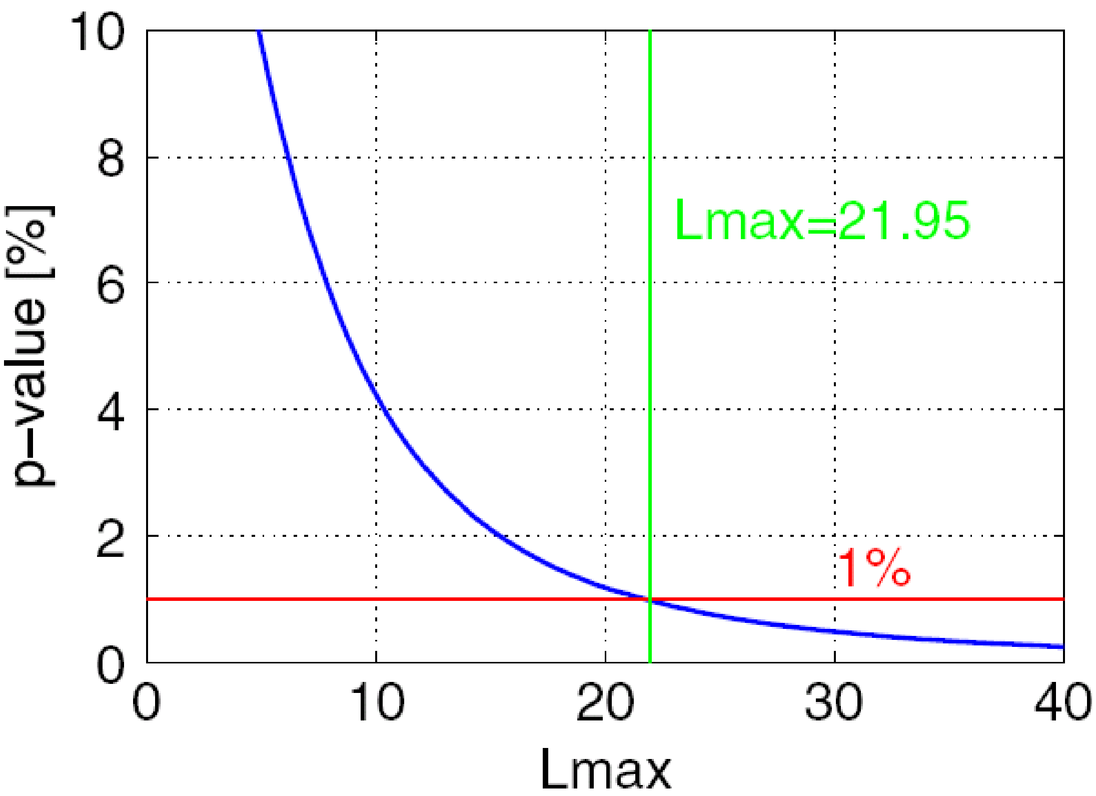
Probability that the event came from the background.

Background distribution of L_{max}

Significance - 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)

$$\mathrm{FAR} = \frac{1}{435}\left(\frac{p_0}{1\%}\right)\left(\frac{T_\mathrm{W}}{1\mathrm{s}}\right)\ (\mathrm{events/year})$$

T_W – time window

Conclusion

- Search for GW-HEN coincident event:
    - increases detection probability
    - scientifically interesting
- GW and HEN detectors
    - have common visibility directions
    - will be operating simultaneously
- GW and HEN methods are ready to be used in a coincidence search.

Future plans

- Include all detectors in one search method
- Apply method to real data
- Characterize effect of detection / non-detection on astrophysical models