Sky localization of burst sources with networks of GW detectors

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for LSC and Virgo collaboration

Science benefits
Reconstruction method
Reconstruction challenges
Preliminary results

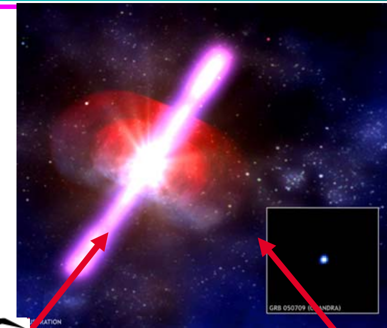
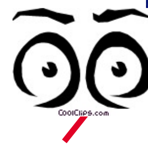
GW Astronomy

- **Position reconstruction of sources is a “must” tool for future GW astronomy**
  - identification of host galaxies
  - population studies of GW events
- **Position reconstruction is part of the source parameter estimation**
  - coupled to the waveform reconstruction
  - for template searches, where waveforms are known, coordinates are included into set of source parameters
  - a challenging task for un-modeled burst searches,

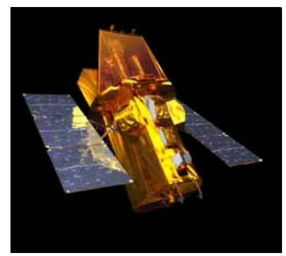
    such as supernova, SRGs, GRBs, binary mergers,...
    where waveforms are not well known

Multimessenger Astronomy

- observation and measurement of the same astrophysical event
  - better confidence of GW event
  - extract physics of source engine

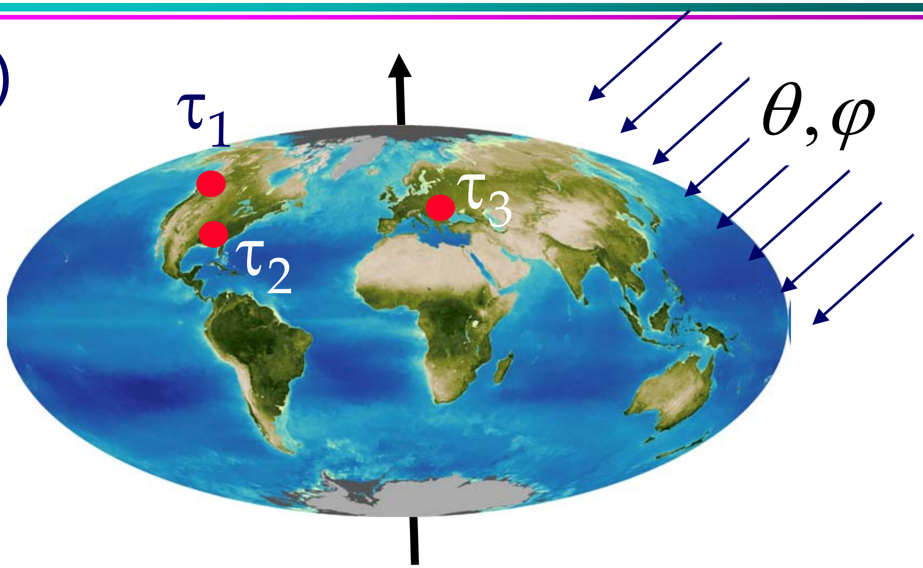

- Externally triggered strategy
  - fold in measured time of arrival and source location into GW searches



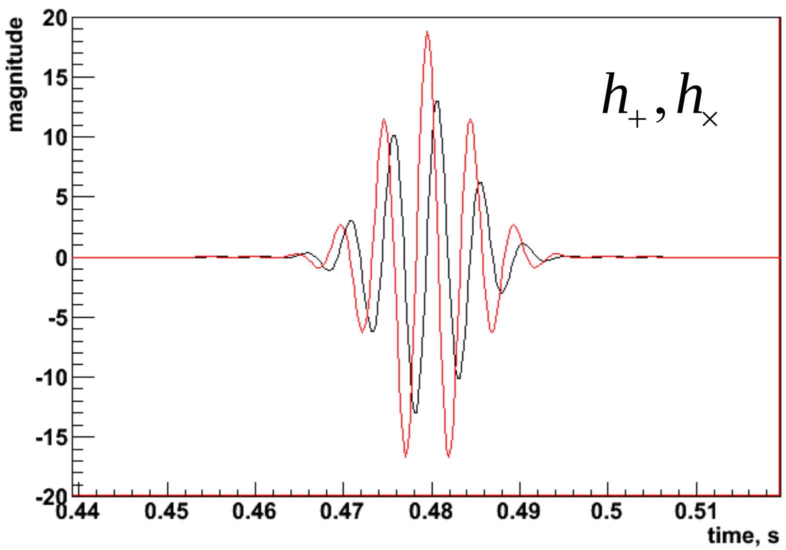

- Look-Up strategy
  - search for EM counterpart with optical and radio telescopes
  - need development of prompt pointing capabilities for GW detectors

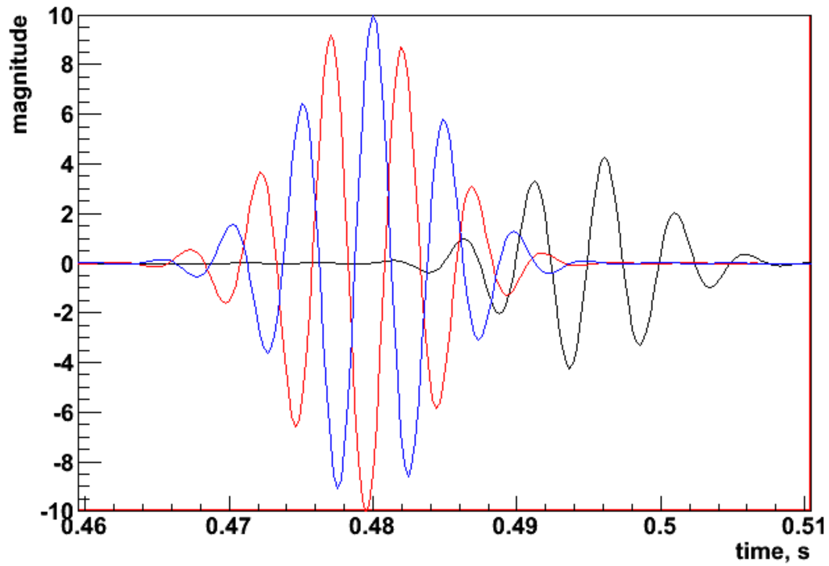

Reconstruction method

- Based on triangulation $(\tau_1,\tau_2,\tau_3,..)$
  - 3 or more sites
- Coupled to reconstruction of waveforms
  - simple triangulation assumes identical detector responses
  - in general reconstruction of burst signals requires coherent network approach



$$h_{det} = F_+ h_+ + F_\times h_\times$$



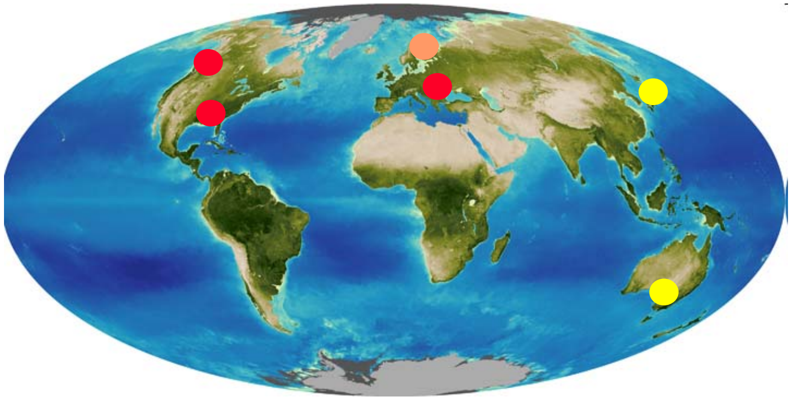


Challenges

- dependence on antenna patterns & detector noise
- dependence on GW waveforms and polarization state
- reconstruction bias due to algorithmic assumptions
- effect of calibration errors
- high computational cost *(loop over o(100,000) sky locations)*

- ….there are many ways to get it wrong
  - need "smart" algorithms
  - eventually need more detectors

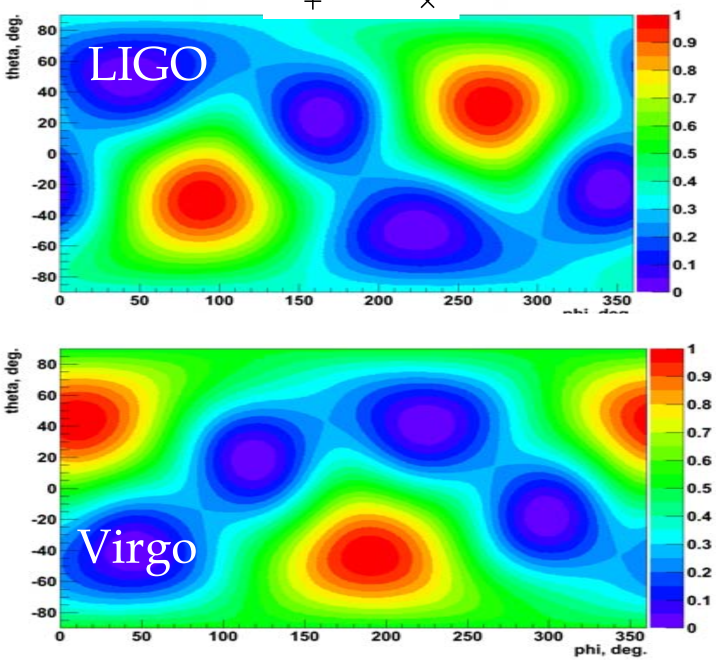
- LIGO, VIRGO (operational)
- GEO600 (limited sensitivity, HF?)
- LCGT, AIGO (future detectors)

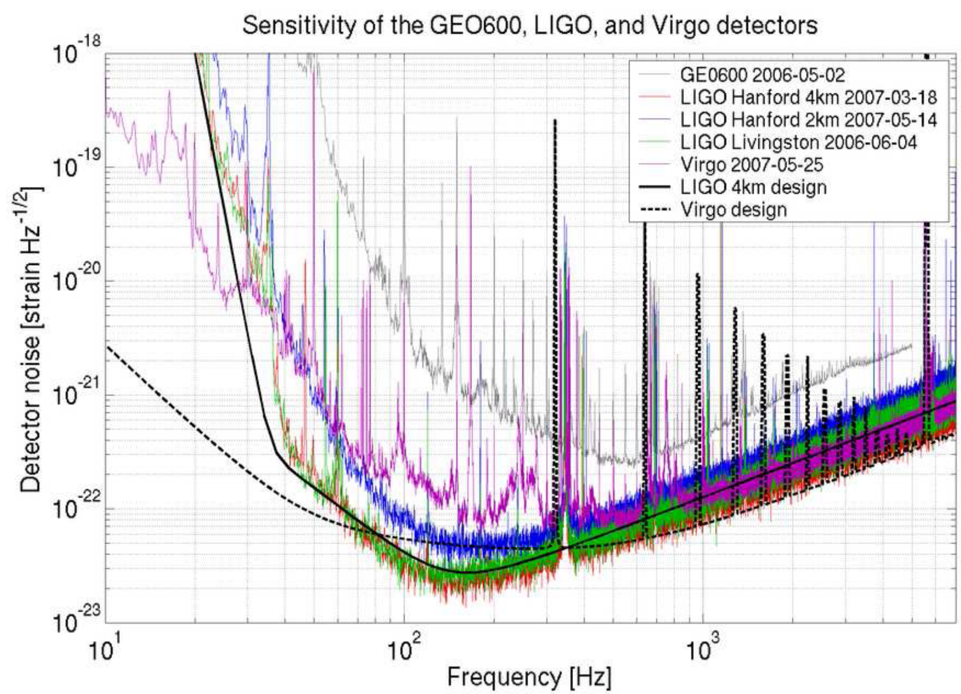


Antenna patterns & noise

- network sensitivity: $$\vec{f}_+ = \left\{\frac{F_{+1}}{\sigma_{+1}}, \ldots, \frac{F_{+K}}{\sigma_{+K}}\right\},\ \vec{f}_\times = \left\{\frac{F_{\times 1}}{\sigma_{\times 1}}, \ldots, \frac{F_{\times K}}{\sigma_{\times K}}\right\}$$
- network SNR $$SNR \approx \sqrt{|f_+|^2\langle h_+^2\rangle + |f_\times|^2\langle h_\times^2\rangle},\ \langle h_{+,\times}^2\rangle = \int h_{+,\times}^2(t)dt$$
- detectors with small ***F/σ*** do not contribute to reconstruction
  - effectively deal with 2 detector network → lose triangulation
  - desirable to have more than 3 sites for robust reconstruction

$$F_+^2 + F_\times^2$$





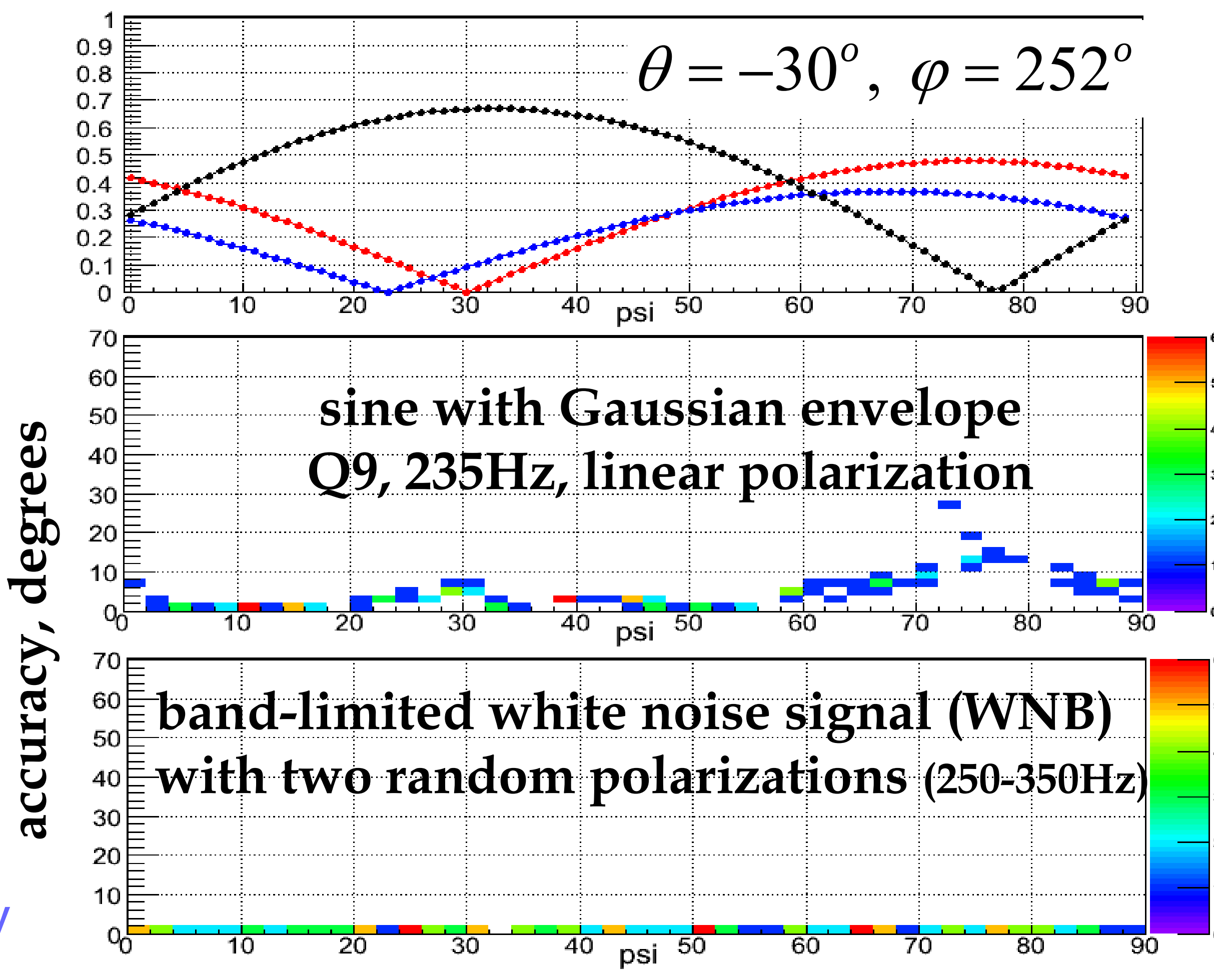
Waveforms & polarization

$|F_+|$, V1-black, L1-red, H1-blue

when $F_+ \sim 0$

- For SGQ9 effectively lose a detector
- For WNB recover reconstruction due to the 2nd polarization
- This effect strongly depends on the sky location

4th site would be handy



Position Reconstruction Task

- **Goal:** study coordinate reconstruction with GW detectors
- **Network:** V1 L1 H1 (expected for S6/VSR2 run)
- **Data Set:** one week of simulated and real data

  (only results for simulated data are reported)
- **Simulated signals:**
  - several types of adhoc waveforms with different frequencies and polarization states evenly spaced on the sky
- **Reconstruction Algorithms**
  - **Triangulation: reconstruction from measured time delays**

    J. Markowitz et all, Phys. Rev. D 78, 122003 (2008)
  - **Omega: marginalize over signal waveforms by using different Bayesian priors (see talk by A.Searle)**

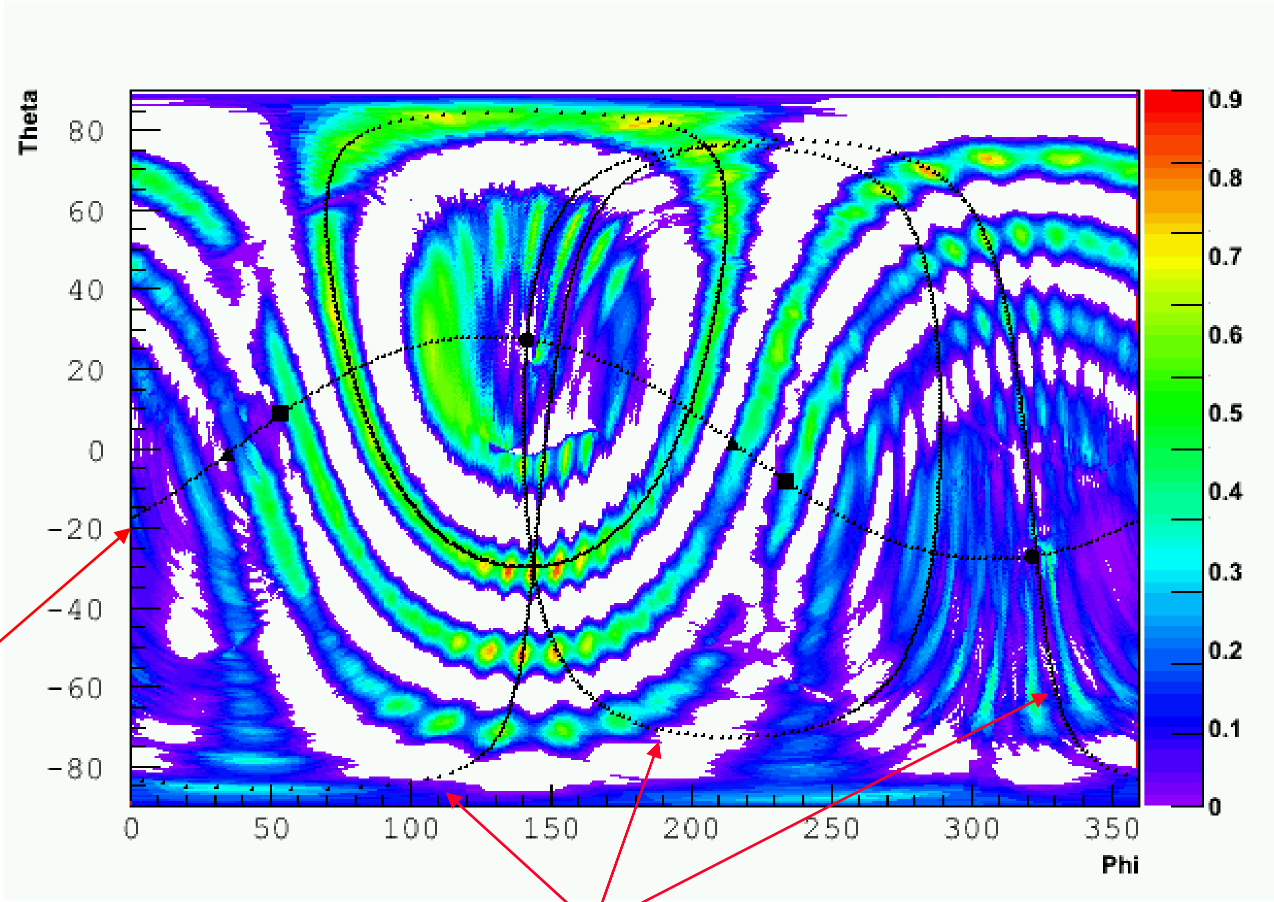
    A.Searle et al Class. Quantum Grav. 25, (2008) 114038
  - **Coherent WaveBurst (cWB): explicit waveform reconstruction and localization by using constrained likelihood method (see talk by M.Drago)**

    S.Klimenko et al., Class. Quantum Grav. 25, (2008) 114029

Probability Sky Map

PSM shows how consistent are reconstructed waveforms and time delays as function of θ,ϕ. Source location is at PSM max.

probability map: coherent network analysis

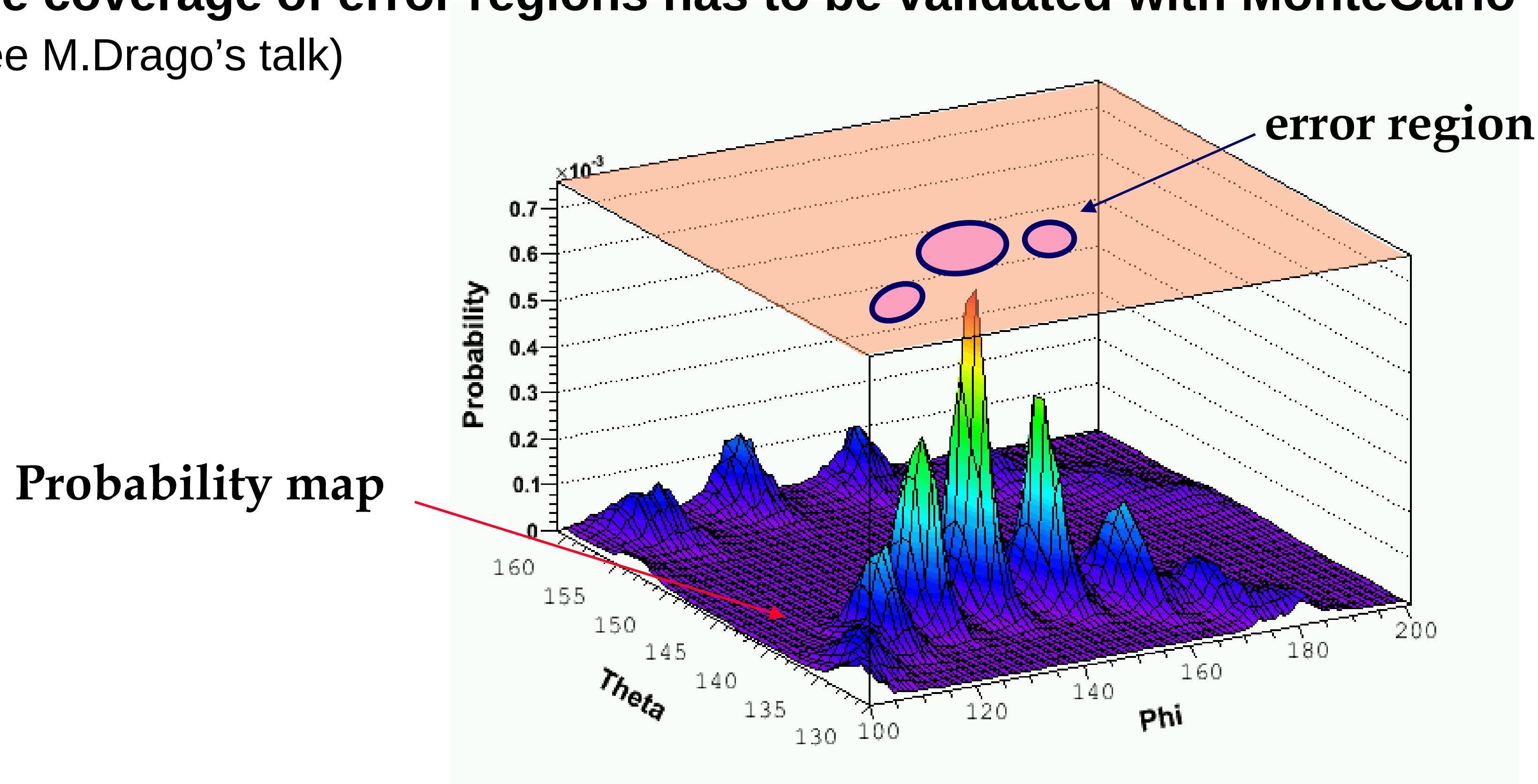


detector plane

constant delay rings for detector pairs

Error Regions

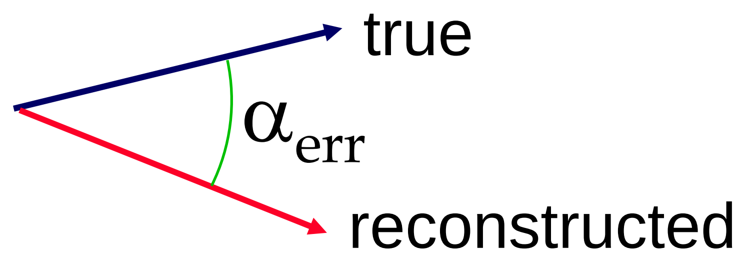
- **Source location is characterized by a spot in the sky (error region) rather than by a (θ,ϕ) direction**
  - x% error region - a sky area with cumulative probability of x%
- **The coverage of error regions has to be validated with MonteCarlo** (see M.Drago's talk)



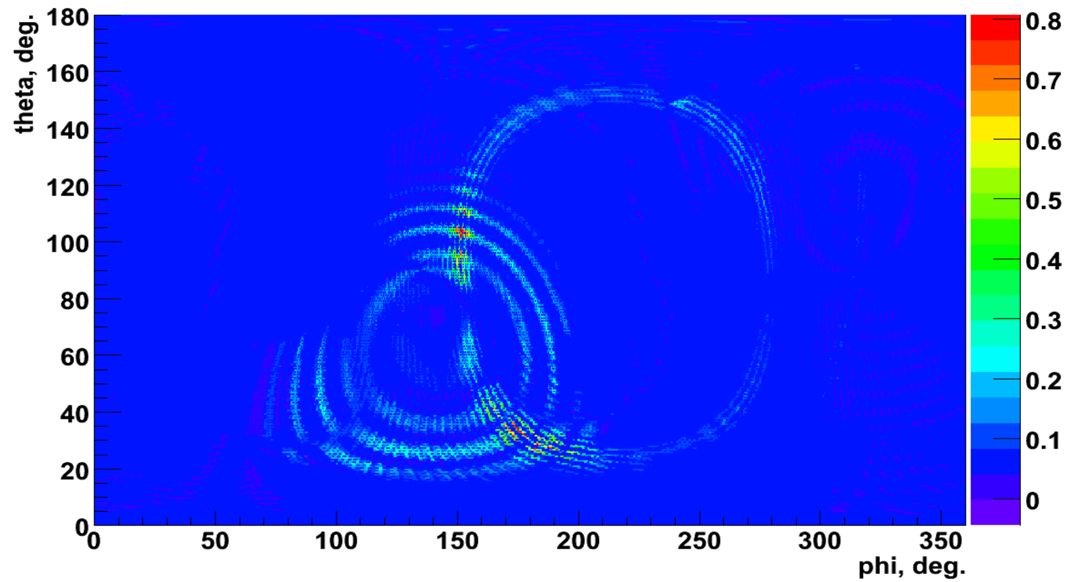
- **Error regions should be reported for optical/radio followup**
  - may consist of disjoint sky areas

Error Angle

- **Describes how well sources can be localized in the sky**
- **deviation from true source location**
  - Not a robust measure when there is an ambiguity in the sky

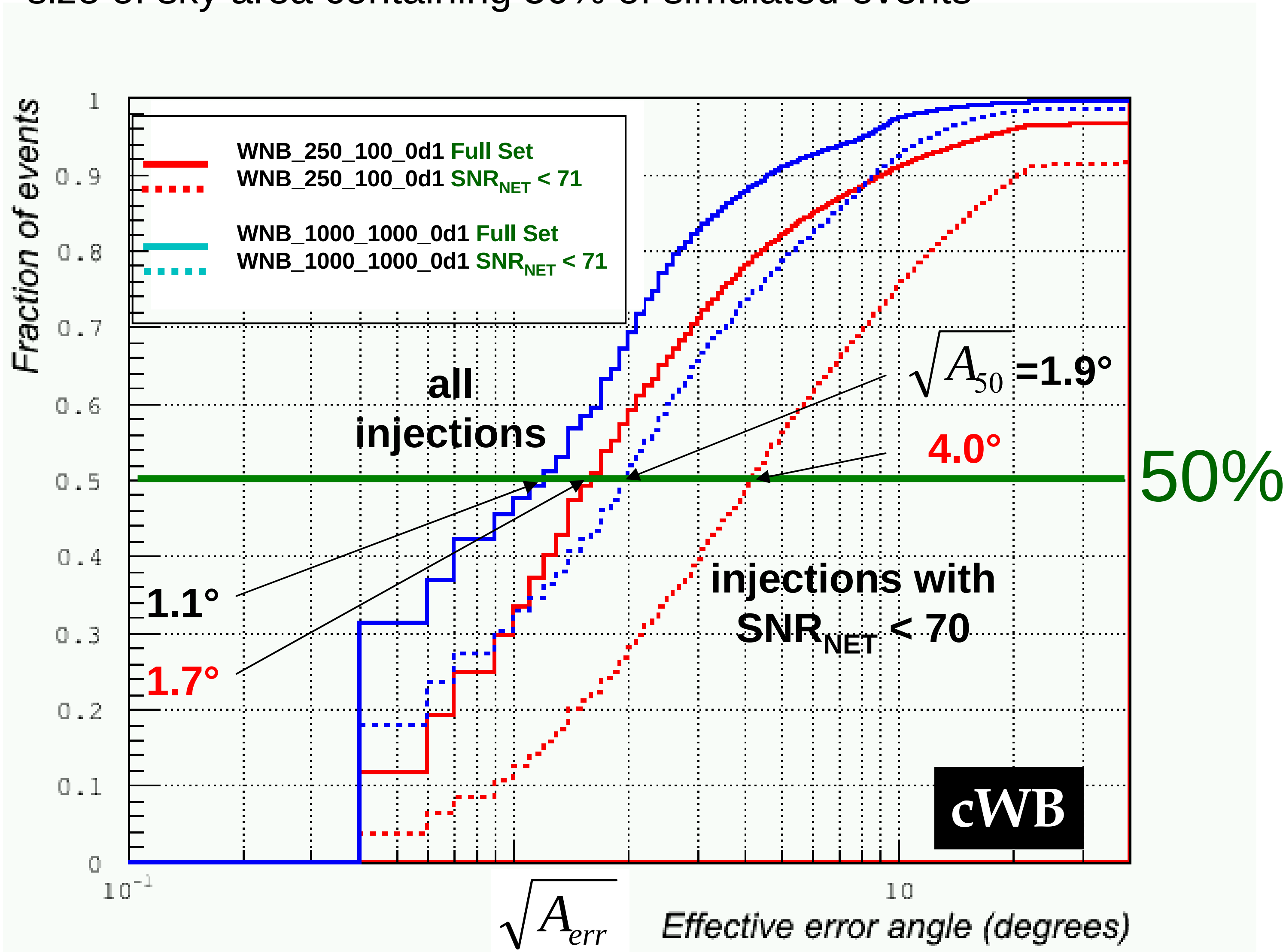


- $\sqrt{A_{err}}$ **:** ***A_{err}* – sky area with P(θ,ϕ)>P(source)**
  - Handles mirror image and multiple patches of high probability in the sky.

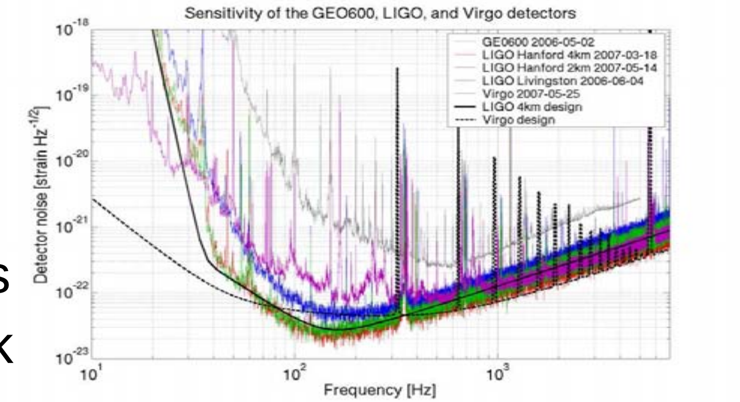


Median Error angle

- **characterizes overall reconstruction performance:**
  - A_{50} – size of sky area containing 50% of simulated events



Preliminary Results



- simulation sets: 1 – S5-like sensitivity, 2 – equally sensitive detectors
- sine-gausian (SGQ9) – linear polarization
- white noise bursts (WNB) – two polarizations
- snr – total signal-to-noise ratio in the network

$\sqrt{A_{50}}$ **cWB**	WNB(0.1) 250-350 Hz	SGQ9 235 Hz	WNB(0.1) 1-2 kHz	SGQ9 1035 Hz
high snr, simulation 1	1.7°	2.6°	1.1°	2.5°
snr<70, simulation 1	4.0°	7.0°	1.9°	3.5°
snr<70, simulation 2	3.3°	4.9°	1.9°	3.5°
ellipt, snr<70, simulation 2	-	3.7°	-	2.1°

- resolution is better
  - If detectors have about the same sensitivity
  - If reconstruction is constrained by signal model
  - For GW signals with two polarization

Summary

- **GW detectors are capable to find source location with a few degrees resolution**
  - at least three detectors are required
  - several reconstruction algorithms are employed by LV burst group
- **Resolution can be significantly improved when**
  - source models are used during reconstruction
  - more than three sites are available
- **Use L1H1V1 source localization capabilities during S6/VSR2**
  - perform reconstruction with low latency (few minutes)
  - report sky coordinates and error regions for EM follow up
- **Still a lot to do**
  - comparison of different reconstruction algorithms
  - better understanding of biases due to segmentation and algorithms
  - improve sky discretization/resolution for high frequency searches
  - obtain more uniform error region coverage
  - ....