From the detection to measurement of transient gravitational waves

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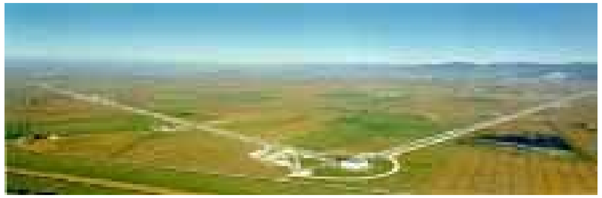
Scientific Motivations

- **Source parameters estimation is a "must" tool for future GW astronomy**

- **Position reconstruction**
  - identification of host galaxies
  - population studies of GW events
  - prompt localization of GW events for followup with optical/radio instruments
  - search for EM counterpart with optical and radio telescopes
    - better confidence of GW event
    - extract physics of source engine



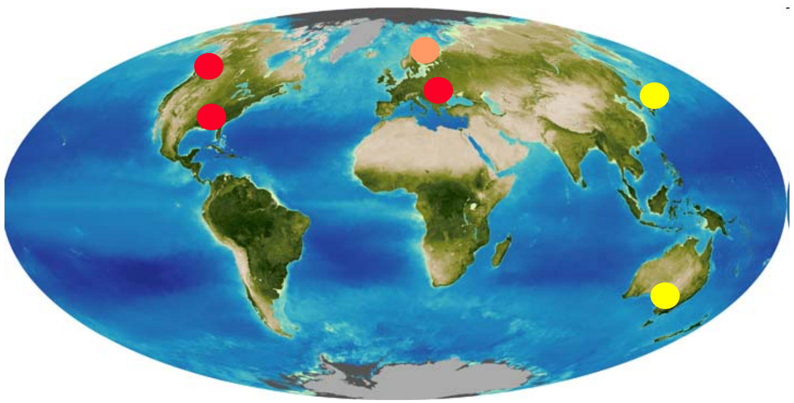
- **Waveform reconstruction**
  - Extraction of source parameters from the comparison of measured waveforms with source models

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**

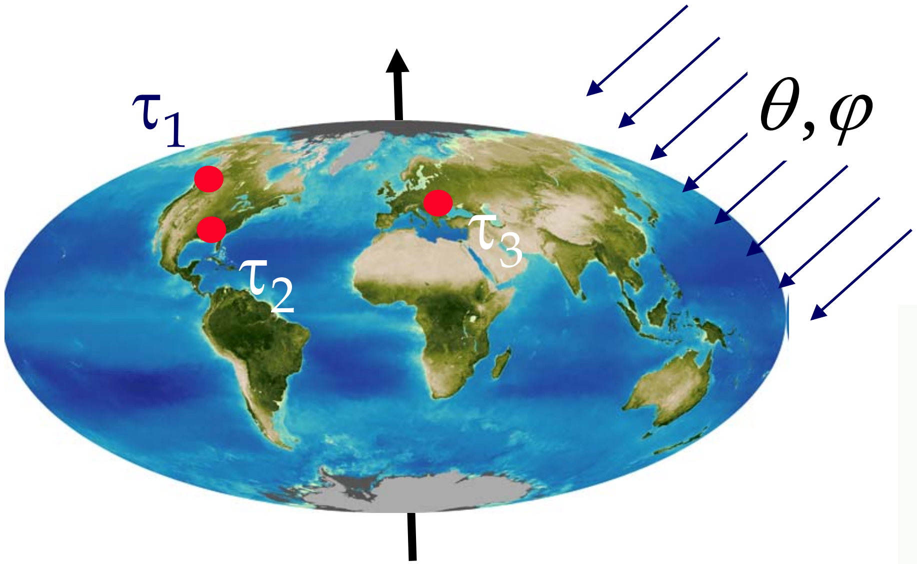
- LIGO, VIRGO (operational)
- GEO600 (limited sensitivity, HF?)
- LCGT, AIGO (future detectors)



- **Reconstruction Algorithm:**
  - **Coherent WaveBurst (cWB): explicit waveform reconstruction and localization by using constrained likelihood method**
    S.Klimenko et al., Class. Quantum Grav. 25, (2008) 114029
- **Network:** 3 detectors : V1-L1-H1, 4 detectors V1-L1-H1-T1
- **Data Set:** four days of simulated gaussian noise

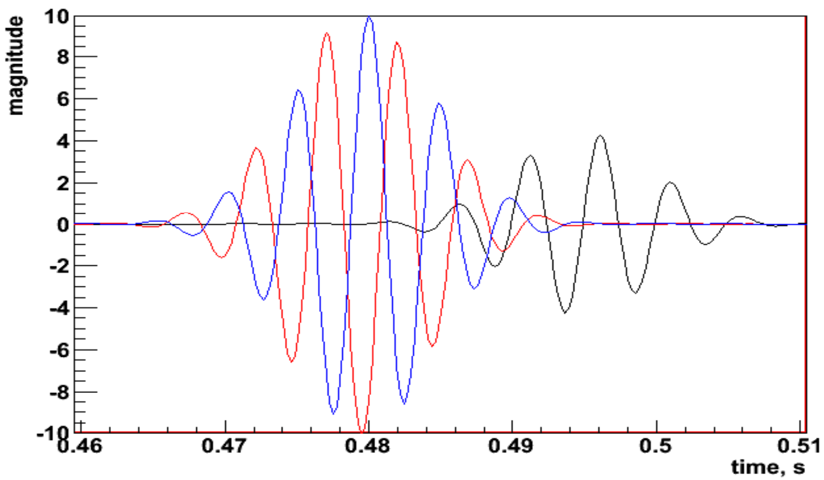
  (assuming H1/S5 sensitivity for all detectors)
- **Simulated signals:**
  - several types of waveforms with different frequencies, amplitudes and polarization states
    - *Sine Gaussian (SG) linear and circular polarized*
    - *Band limited White Noise Burst (WNB) random polarized*
  - source directions
    - *evenly spaced on the sky and from galaxies distribution*
- **Signal Model : Reconstruction is performed with no assumptions about source (un-modeled search) or for a certain GW polarization. Plan to add other source constraints in the future.**

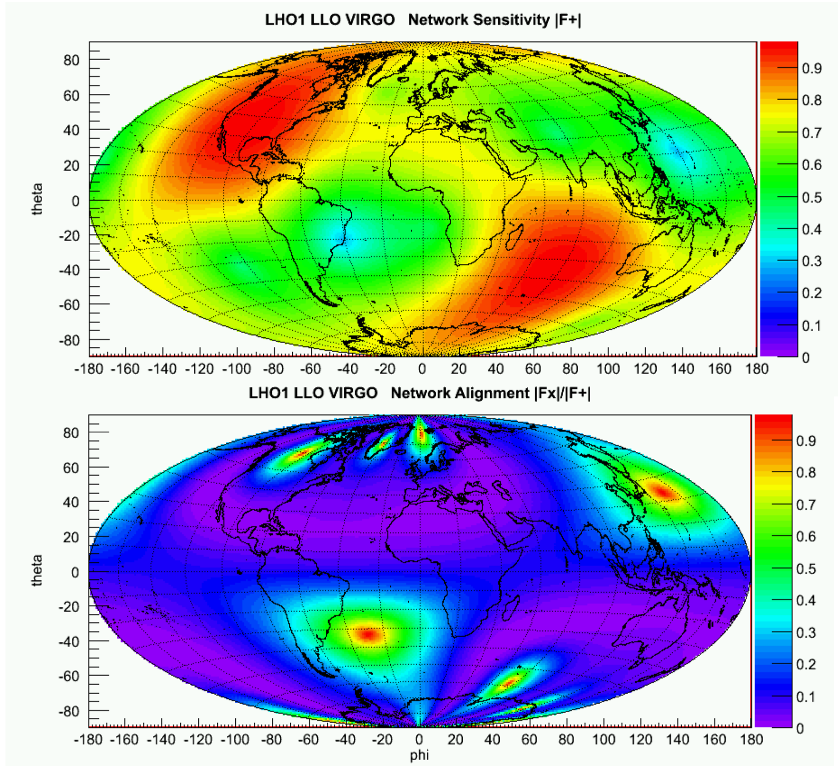
Coherent network analysis



- Fully exploit the GW signal and network properties
  - different arrival times
  - network sensitivity

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





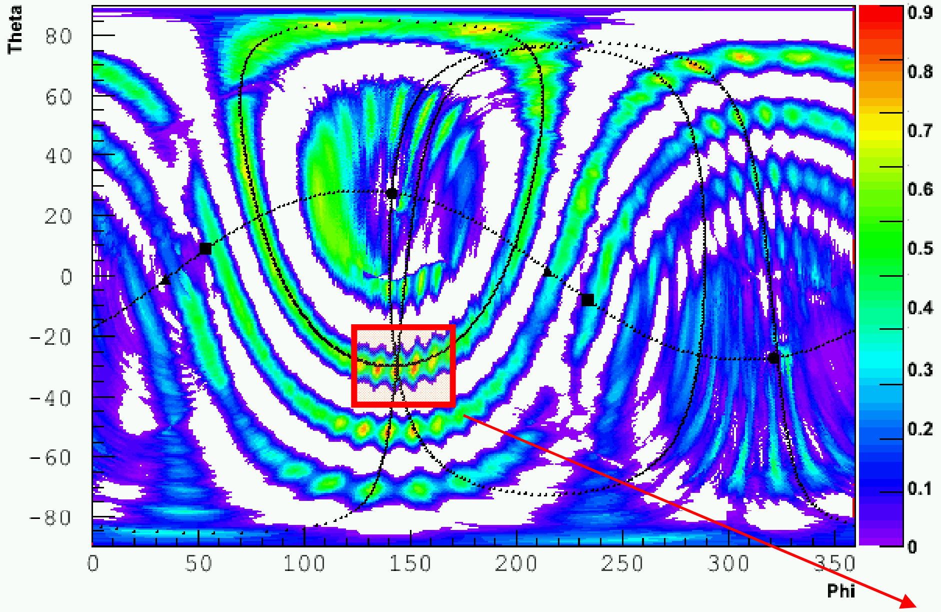
$|F_+|$

$\dfrac{|F_x|}{|F_+|}$

V1 L1 H1 network polarization sensitivities components in Dominant Polarization Frame

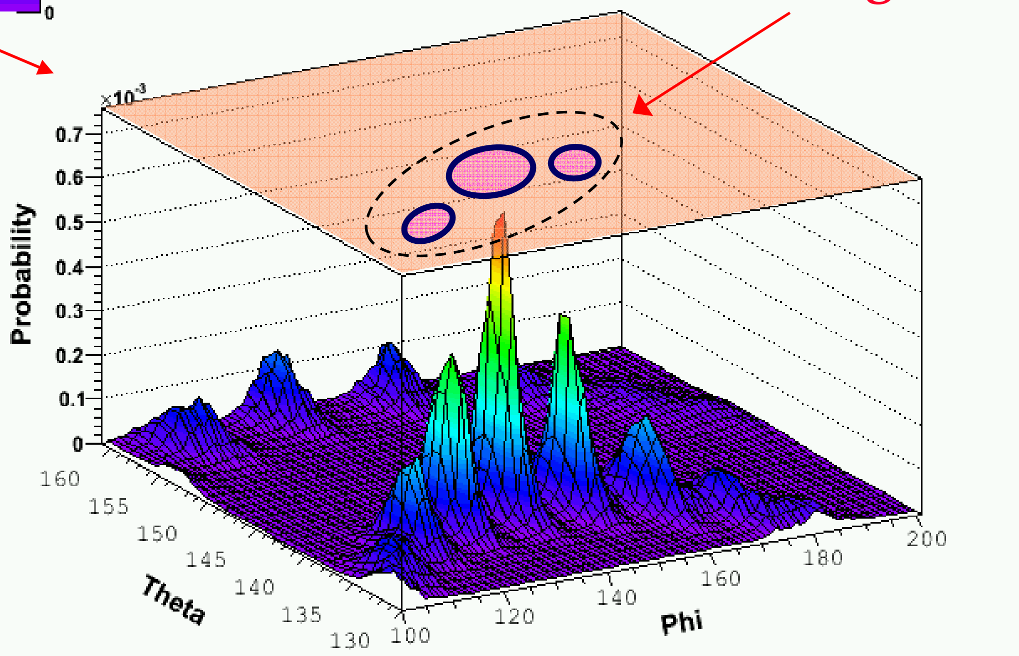
Klimenko et al, PRD 72, 122002 (2005)

Error Regions



cWB use likelihood to rank the most likely sky positions

Likelihood Sky Map shows how consistent are reconstructed waveforms and time delays as function of θ,ϕ.

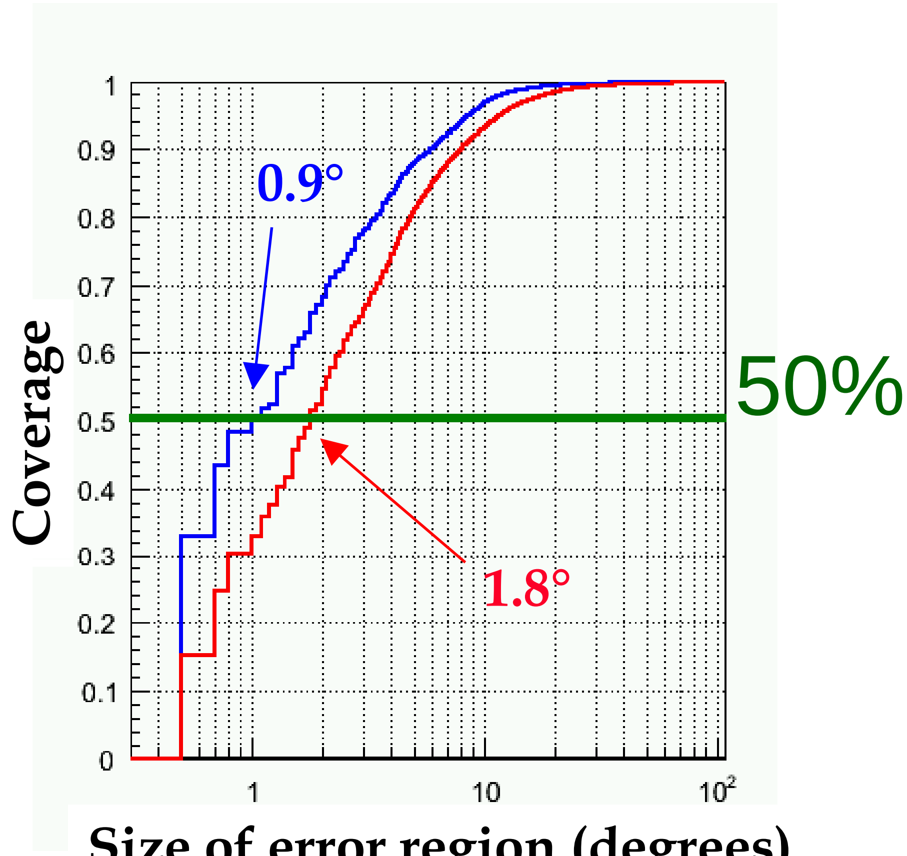


- **Source location is characterized by spots in the sky (Error Region) rather than by a (θ,ϕ) direction**
  - **may consist of disjoint sky areas**
  - **Error Regions are calibrated by Montecarlo to ensure a selected coverage.**
    - **different source directions**
    - **suitable models of waveforms**

Median error angle

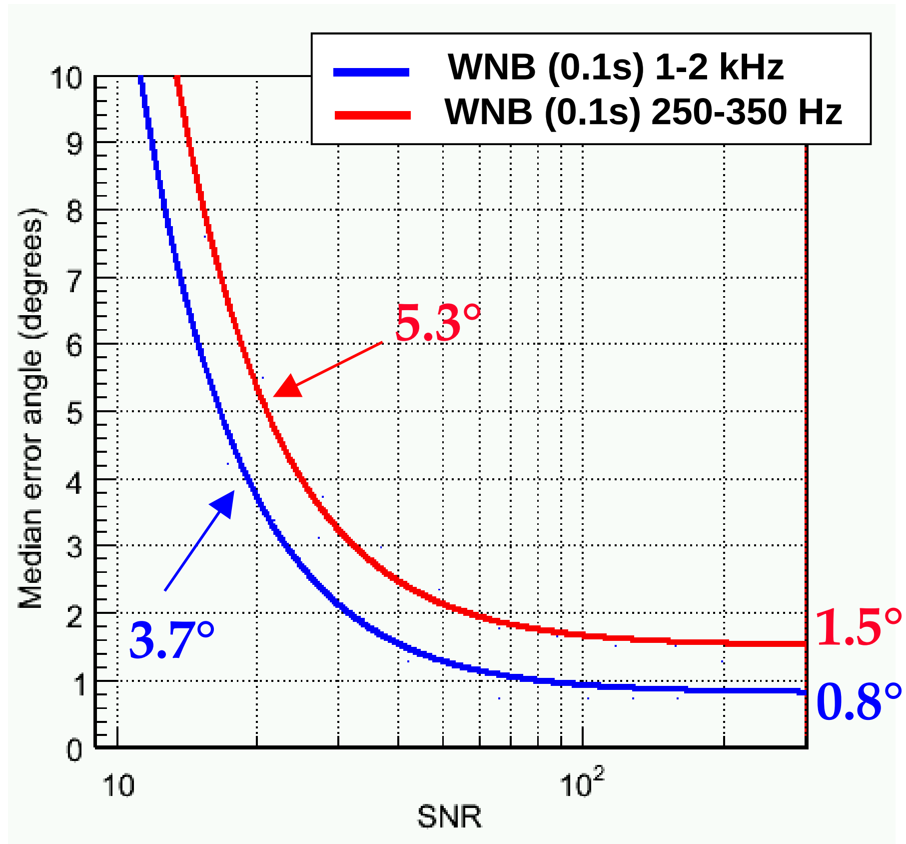
- **Median error angle** is the square root of error region with 50% coverage

Calibration of error region



Cumulative distribution
measured by Montecarlo

Median error angle vs SNR



$$SNR = \sqrt{\sum_{detector} SNR^2_{detector}}$$

Preliminary results (L1-H1-V1)

- Simulated data set : spectral noise similar to operating interferometers
- Injected waveforms evenly spaced on the sky
  - white noise bursts (WNB) – two polarizations
  - sine-gaussian (SGQ9) – linear polarization

$\sqrt{A_{50}}$	WNB(0.1) 250-350 Hz	SGQ9 235 Hz	WNB(0.1) 1-2 kHz	SGQ9 1035 Hz
Un-modelled Search	5.3° / 1.5°	6.3° / 1.6°	3.7° / 0.8°	3.8° / 1.4°
Elliptically Polarized Search	-	5.2° / 1.4°	-	3.1° / 0.9°
Linearly Polarized Search	-	3.3° / 0.7°	-	2.8° / 0.7°

- Table shows the median angle error at (SNR=20 / high SNR)
- Resolution is better
  - If reconstruction is constrained by signal model
  - for GW signals with two polarizations
    - reduce cases where only 1 or 2 detectors partecipate effectively to the network
  - for high frequency signals (norrowed fringes)

Robustness vs Calibration systematic errors

- L1-H1-V1 Network
- Coherence analysis could be affect by calibrations errors
- Analysis use an un-modeled short transients constrain
- Amplitude mis-calibration : V1=10%, H1=0%, L1=-10%
- Phase mis-calibration :
  - V1= -2.5°, H1=0°, L1= 2.5° @ 235 Hz
  - V1= -11.5°, H1=0°, L1=11.5° @ 1053 Hz

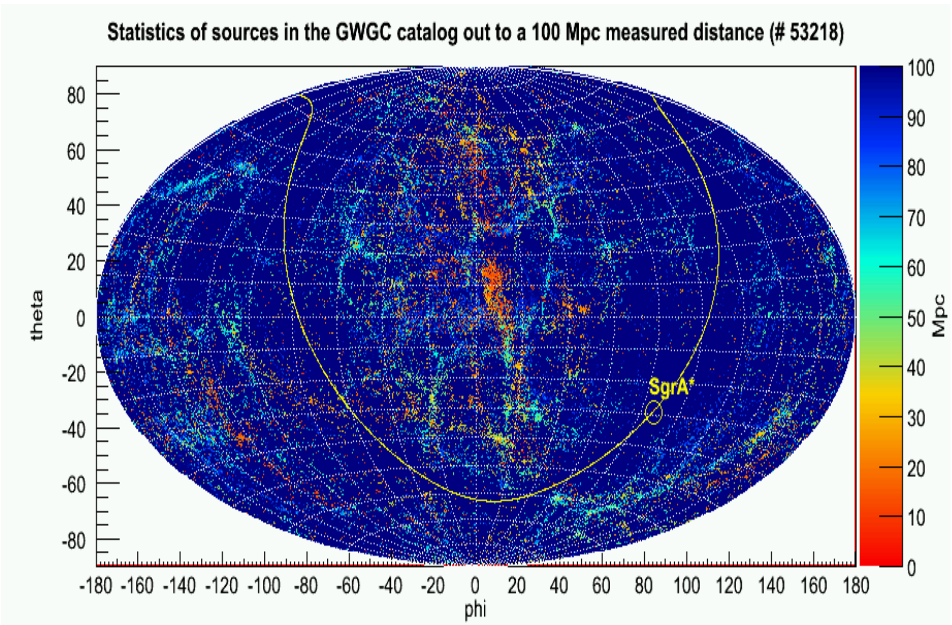
$\sqrt{A_{50}}$	WNB(0.1) 250-350 Hz	SGQ9 235 Hz	WNB(0.1) 1-2 kHz	SGQ9 1035 Hz
Calibrated data	5.3° / 1.5°	6.3° / 1.6°	3.7° / 0.8°	3.8° / 1.4°
Amplitude mis-calibration	5.8° / 1.8°	7.5° / 2.8°	3.7° / 0.9°	4.0° / 1.9°
Phase mis-calibration	5.3° / 1.6°	6.4° / 1.8°	4.2° / 1.2°	4.5° / 2.1°

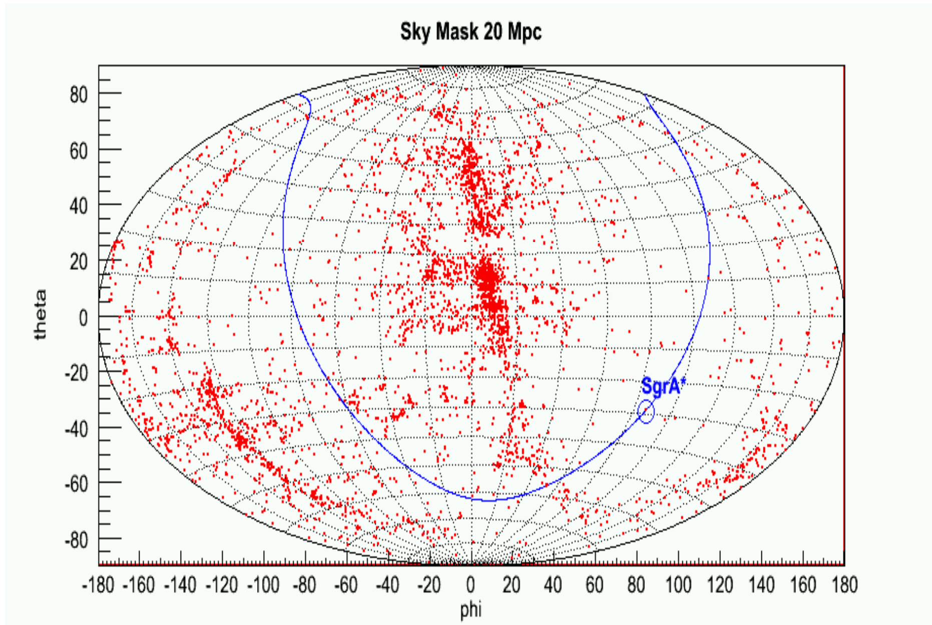
preliminary

- Table shows the median angle error at (SNR=20 / high SNR)
- Minor mis-calibrations do not affect performances
  - Calibration erros are still small respect to noise and algorithm approximations

Source Population Constrain

- In the all sky analysis all sky positions are tested
- Source population constrains allow to reduce the surveyed sky area
- Reducing the sky area improves the reconstruction performances
- The population of galaxies up to 20Mpc (left plot) can be analyzed searching within an area of 2% of the total sky area (right plot)
- There is no loss in efficiency performances



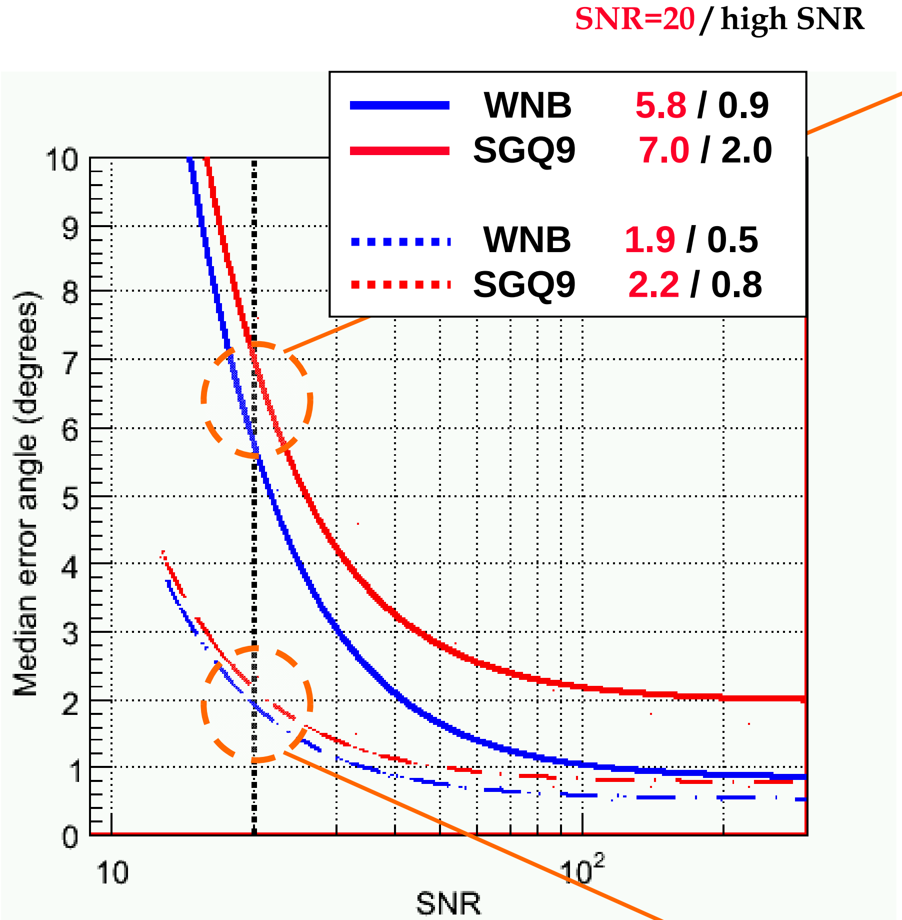


(see talk by F.Salemi)

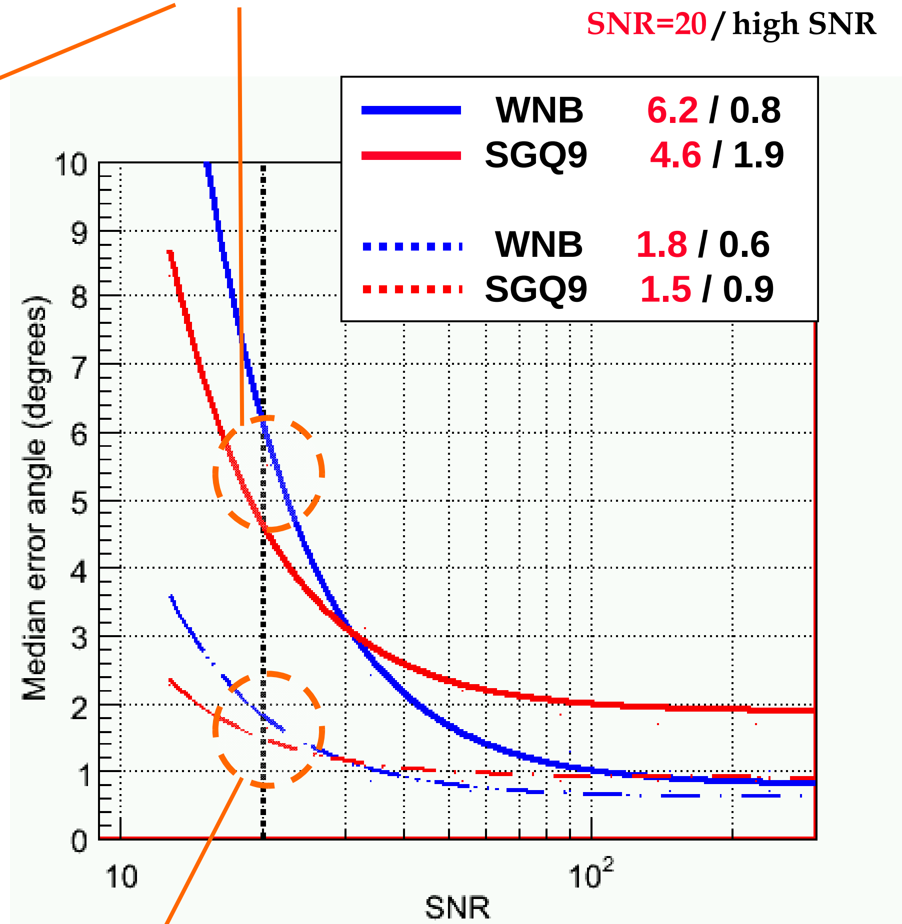
Galaxy Source Population Results

un-modeled search is used – L1-H1_V1 network

All sky search



Low Frequencies

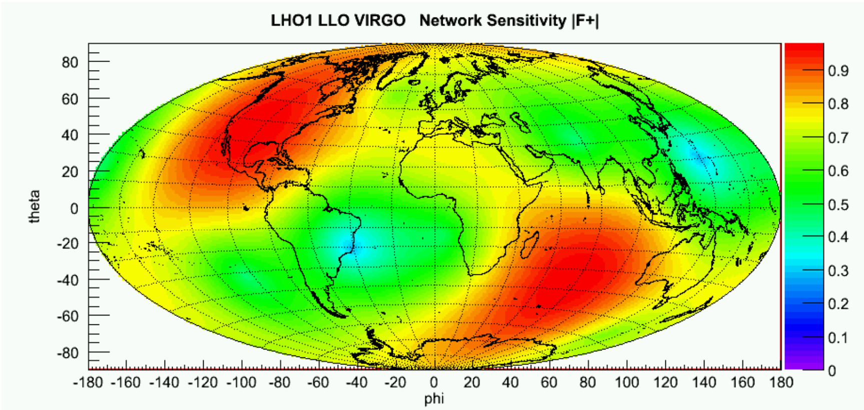


High Frequencies

reduced sky area search

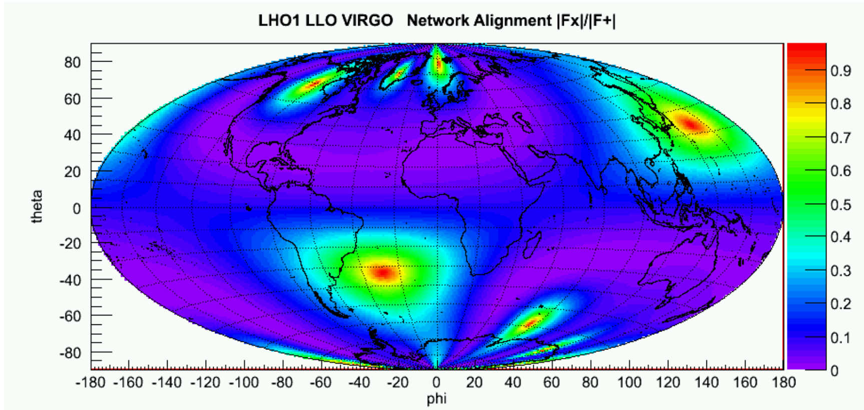
Network configuration

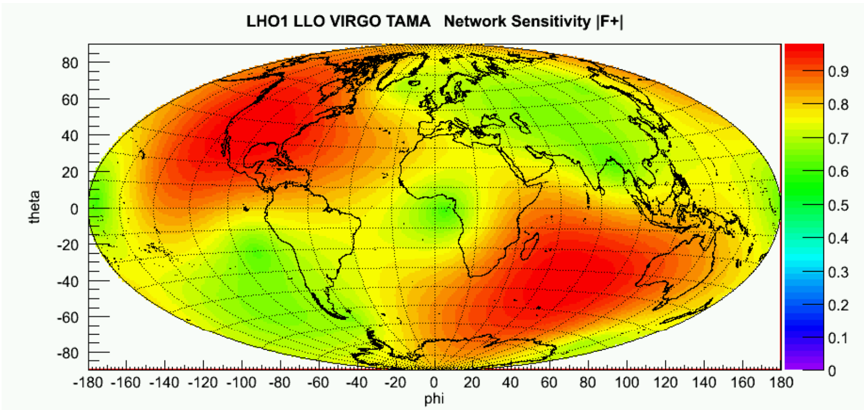
- The position reconstruction performances improves with more detectors
- A 4 detector network has better Fx coverage and one more arrival time



3 Det

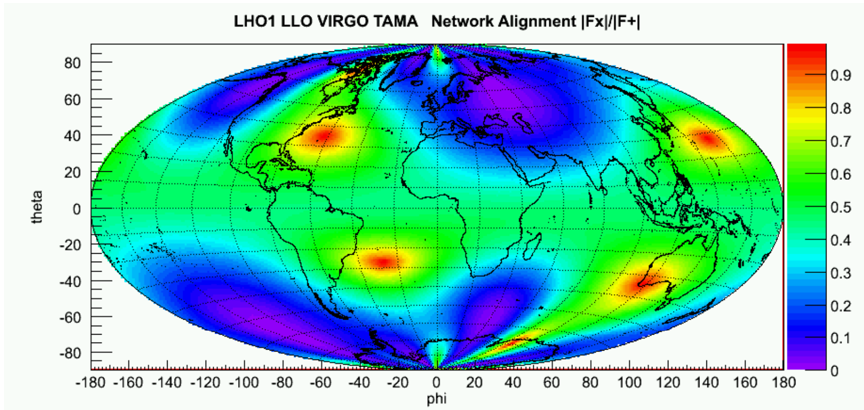
L1
H1
V1





4 Det

L1
H1
V1
T1



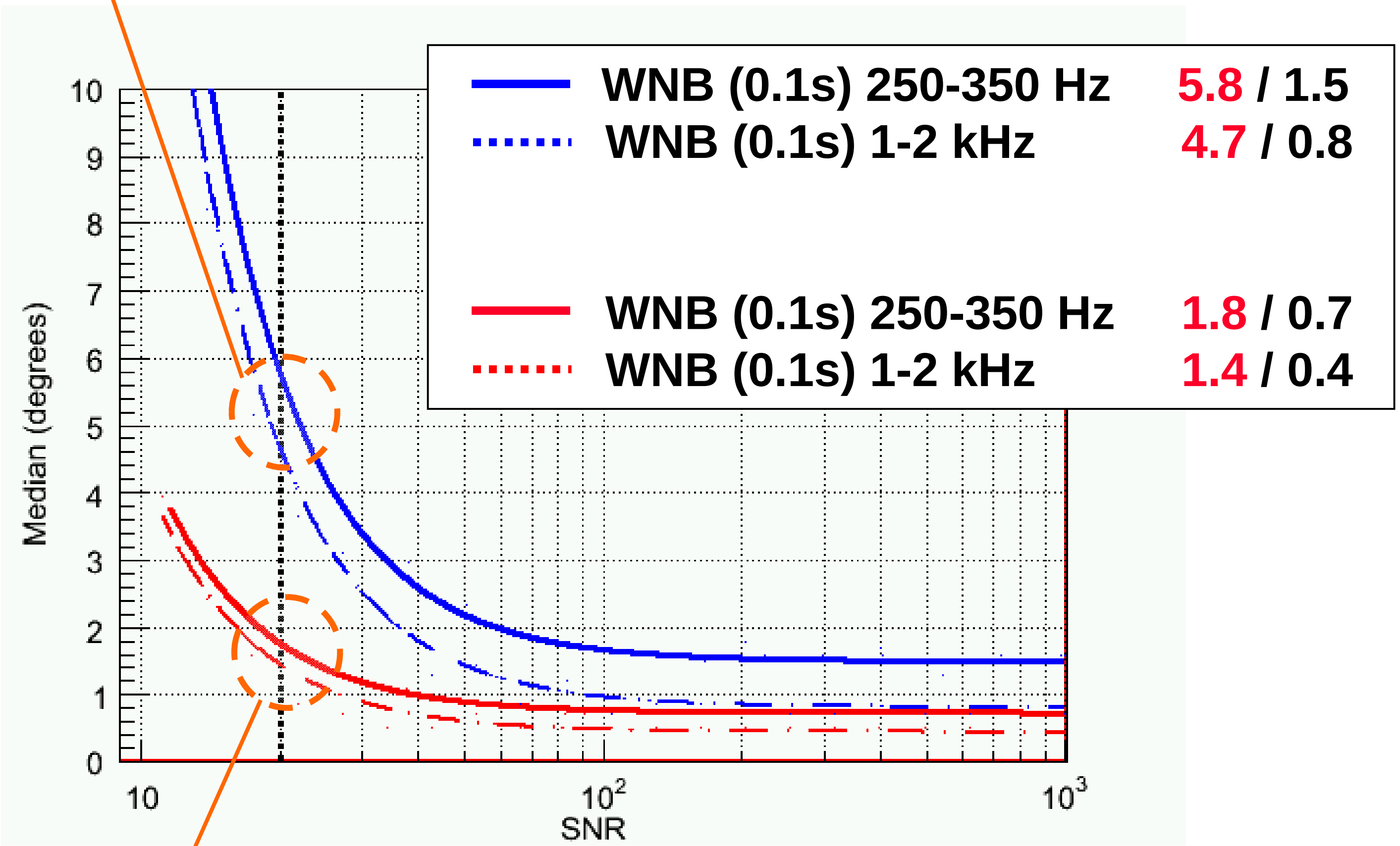
$|F_+|$ $|F_x|/|F_+|$

The figures show the network sensitivity $|F_+|$, $|F_x|$ calculated in the Dominant Polarization Frame

3 detectors vs 4 detectors

3 detectors : L1-H1-V1

SNR=20 / high SNR



4 detectors : L1-H1-V1-T1

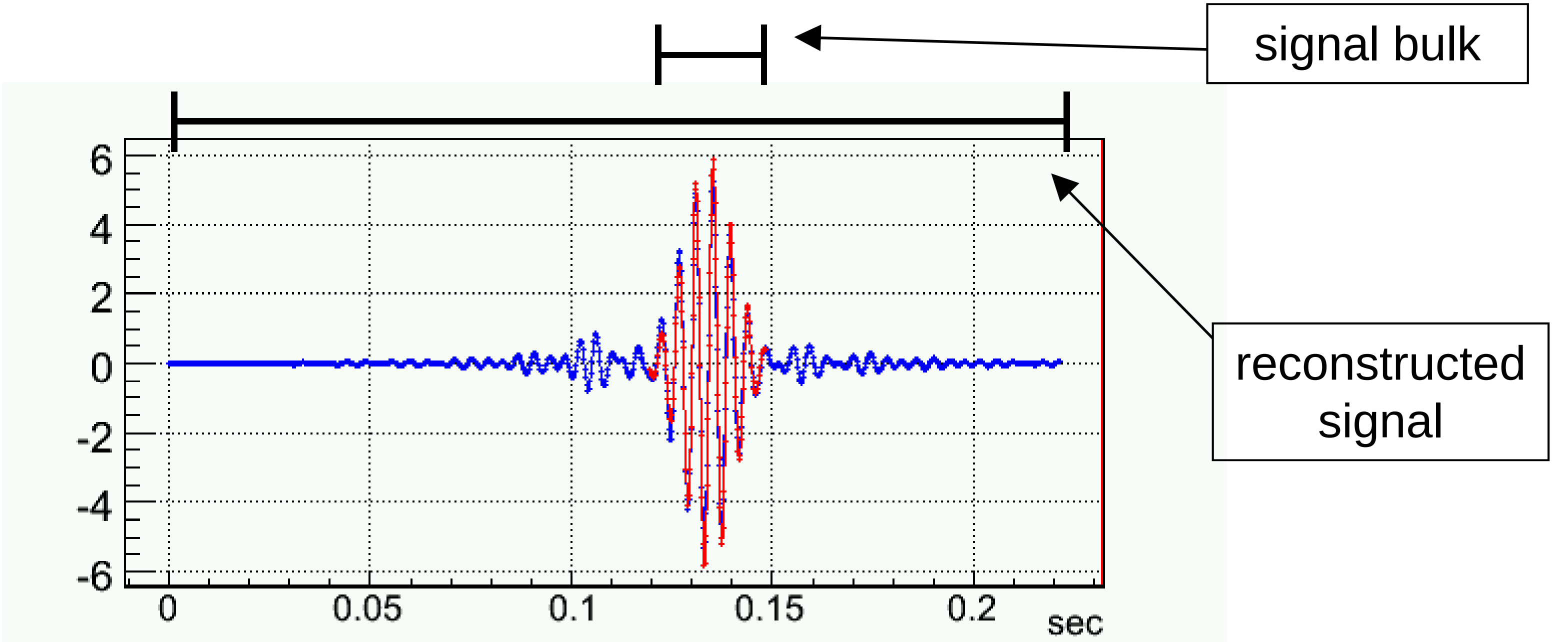
The 4 detectors network has 3 times better resolution at SNR=20

Waveform Reconstruction

If GW signal is detected, two polarizations and detector responses can be reconstructed and compared with source models for extraction of the source parameters

Whitened Data

Injected SNR=28

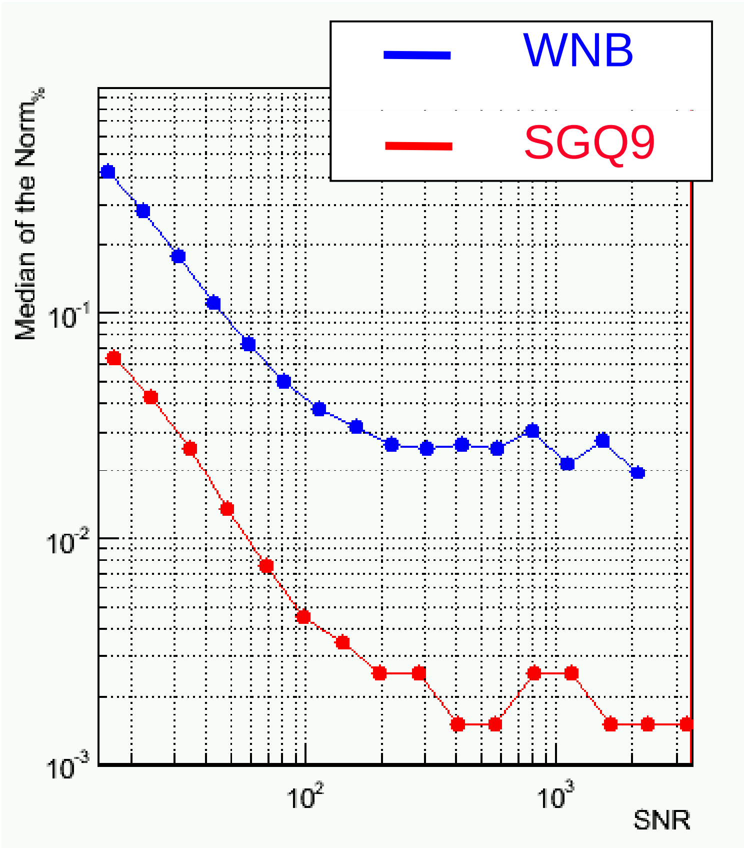


SG235Q8d9 – Injected / Reconstructed waveform

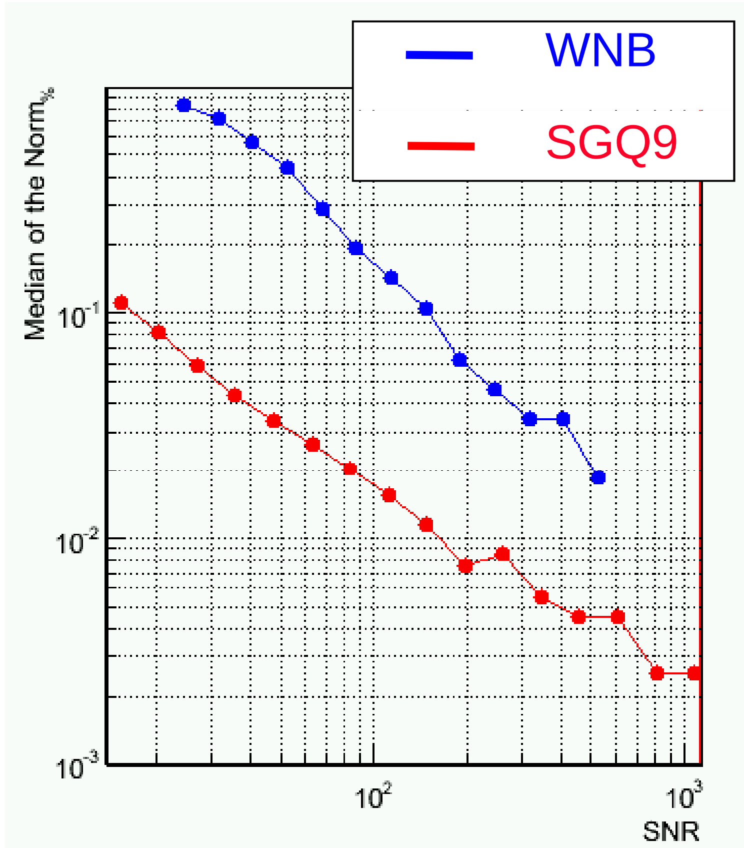
Figure of merit: median of the $$Norm_{\%} = \frac{\sum_n (rec_n - inj_n)^2}{\sum_n (inj_n)^2}$$

Waveform Reconstruction Performances

- Plots shows the $\text{Norm}_{\%}$ versus SNR for V1 detector
  - L1,H1 have similar performances
- WNB use an un-modeled search, SGQ9 use a linearly polarized search
- The $\text{Norm}_{\%}$ is computed taking into account only the injected signal bulk



Low Frequencies



High Frequencies

Summay

- **GW detectors are capable to find source location with a few degrees resolution**

- **Resolution can be significantly improved when**
  - source models are used during reconstruction
  - more than three sites are available
  - search is restricted within a limited sky area

- **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 (>2kHz)
  - obtain more uniform error region coverage over the sky
  - ....