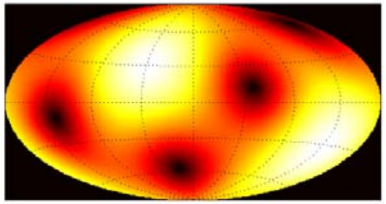
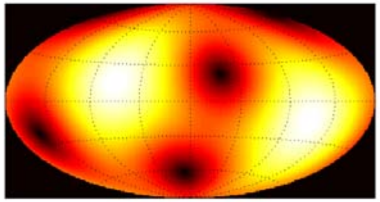
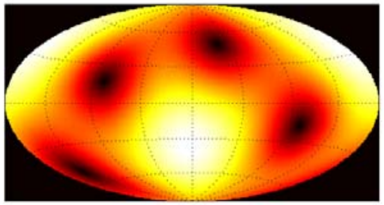
Gravitational wave search in the LIGO-Virgo network



Hanford



Livingston



Virgo

Gravitational Wave Data Analysis Workshop

General Relativity Semester

Institut Henri Poincaré

M.-A. Bizouard LAL-Orsay 11/16/2006

Overview

- Sources concerned by a network search
  - Coalescing binaries
  - Burst
  - Stochastic background
- Virgo-LIGO network
- Network data analysis techniques
- What is the gain?
  - Detection potential
  - Source parameters estimation
  - Source location estimation
- Examples

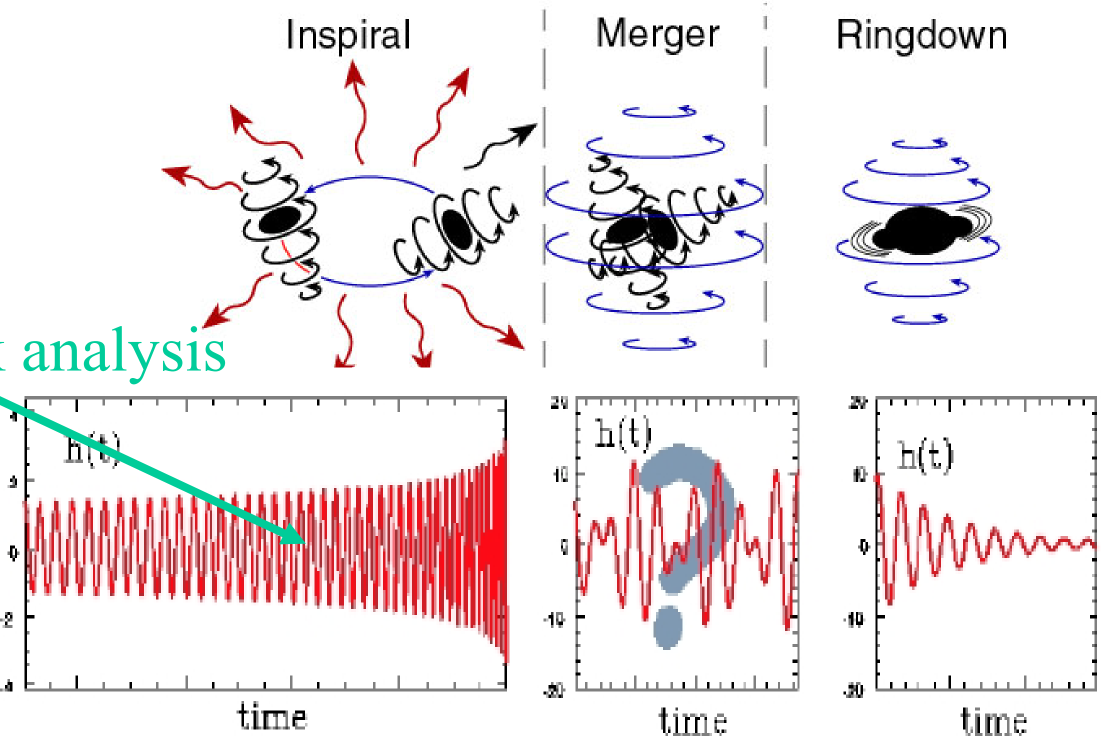
LSC-Virgo working group Activities

(MOU between the LSC and Virgo to be signed soon hopefully)

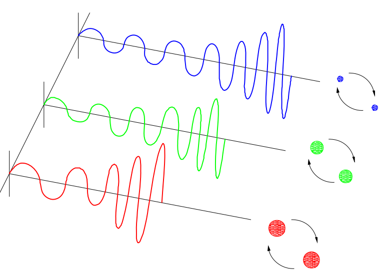
Sources for ground based detectors ...

Coalescence of 2 compact objects binaries: NS-NS, BH-BH and BH-NS

Network analysis



BH ringdown
well modelled

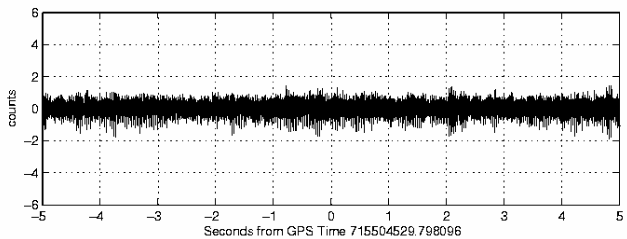


Well known
Long phase
L. Blanchet
(Living Rev. Relativity 9)

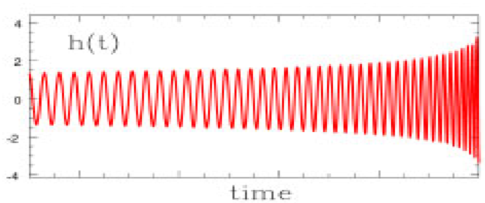
Recent breakthrough
done in Numerical Relativity
for BHBH merger:
Praetorius (2005)
Campanelli (2006)
Baker(2005)

Matched filtering technique

GW Channel
+ simulated inspiral

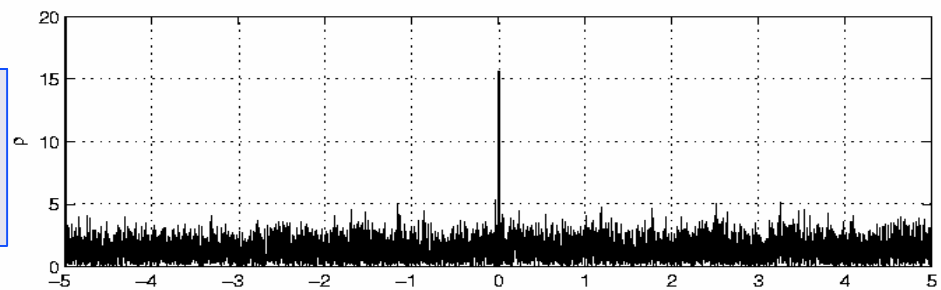


Filter to suppress high/low freq



SNR

$$\rho = 4\int_0^{+\infty} \frac{\tilde{h}(f) \times \tilde{t}(f)^*}{S_h(f)}\, df$$



Coalescence Time

Coalescence binary sources parameters

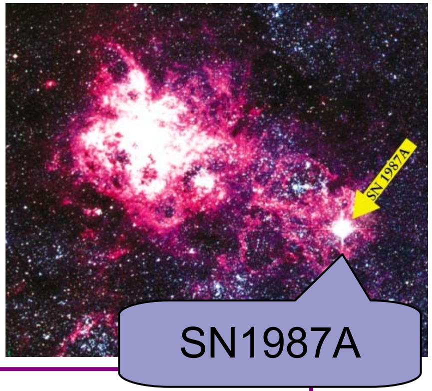
- Distance from the earth
- Masses of the 2 bodies
- Time at coalescence
- Phase at coalescence
- Eccentricity of the orbit
- Spins of the 2 bodies

- Inclination angle of the orbit plane
- Polarization angle
- Source location

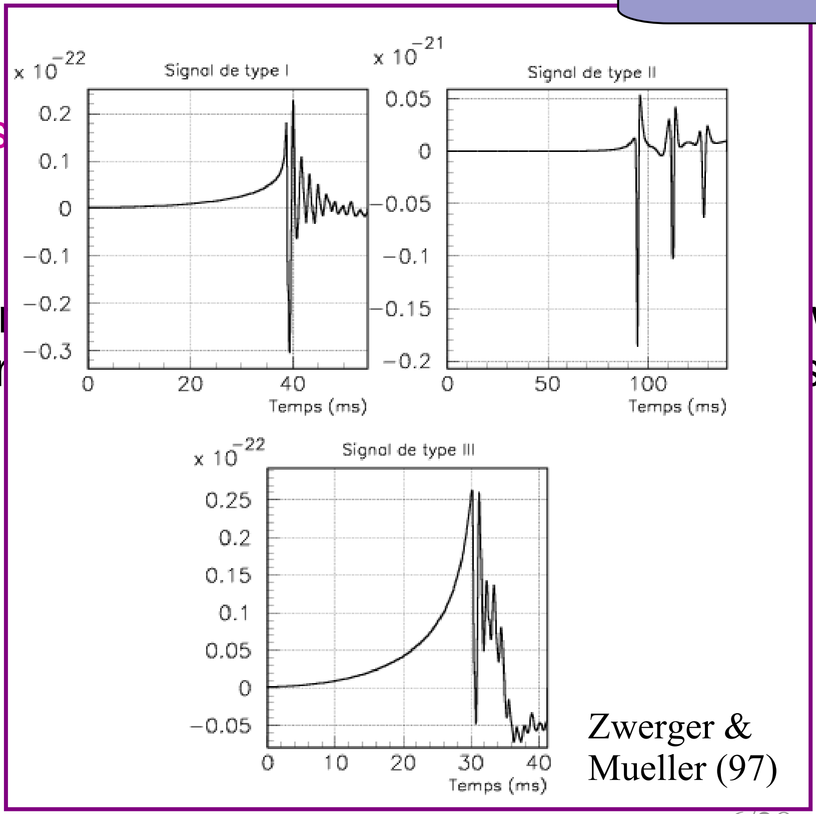
Need a network of at least 3 ITFs

Burst sources for ground based detectors …

- Massive star collapses
  - Type II supernova
  - Black hole formation
- Instabilities in newborn rapidly spinning neutrons stars
- Mergers of couples of compact stars
- Black hole ring down
- Cosmic string cusps and kinks
- Others ….



Not well r … wn)
Main char … s



Zwerger & Mueller (97)

Burst sources searches

- SN: catastrophic astrophysical events associated with neutrinos and electromagnetic emission
- Astrophysical engines that generate Gamma Ray Burst can emit GW

⇒ "Triggered" searches tailored by external "signals" (multi-detector search)
⇒ "Untriggered" searches : all-sky, all-times blind search

In both cases:

using minimal assumption on the waveform shape

many burst search algorithms have been developed so far:

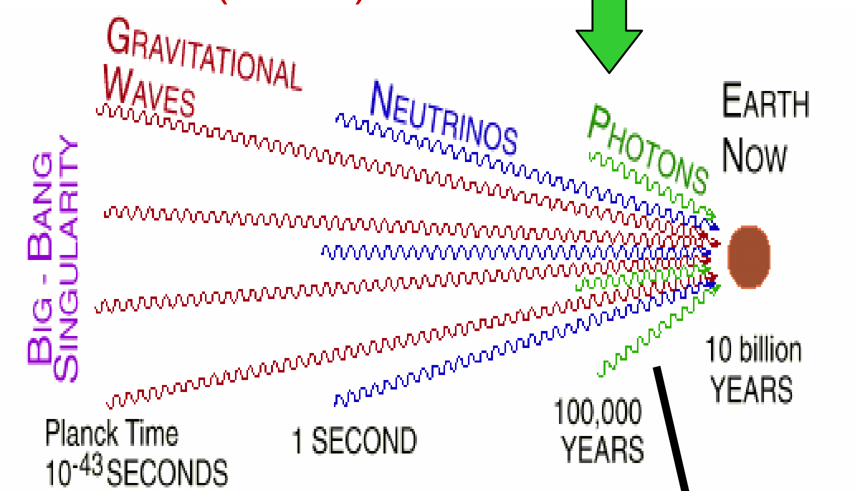
Example: search of excess power in time-frequency plane (see S. Klimenko's talk)

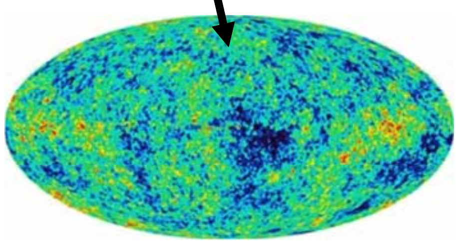
Stochastic background source …

- Cosmological GW from BigBang (inflation model for instance)

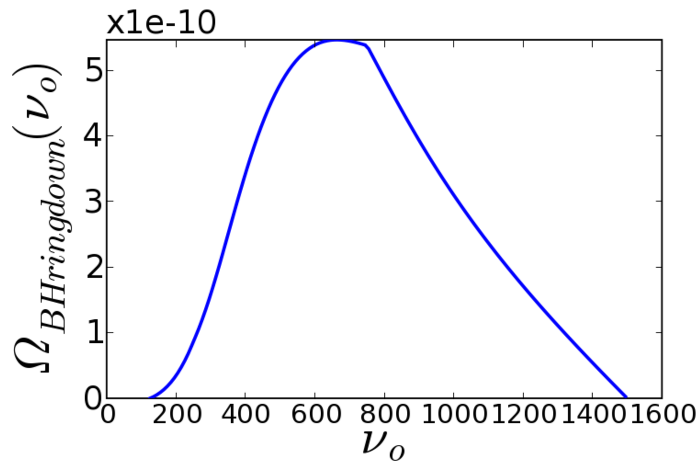
cosmic GW background (10^{-22}s)

CMB (10^{+12}s)





- Astrophysical background of unresolved GW emitted so far



GW spectrum due to cosmological BH ringdowns (Regimbau & Fotopoulos)

Stochastic background search technique

- Given an energy density spectrum $\Omega_{gw}(f)$, there is a GW strain power spectrum

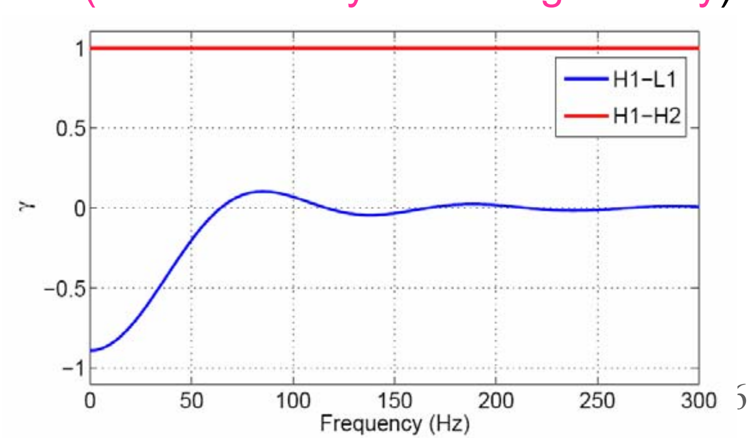
$$\Omega_{GW}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{GW}}{d(\ln f)} \quad \Rightarrow \quad S_{gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3} \Omega_{gw}(f)$$

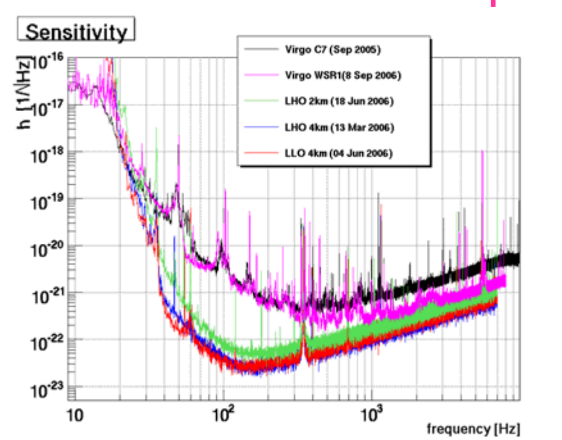
- Optimal filtering: cross correlation of 2 independent data streams x_1, x_2:

$$Y = \int_{-\infty}^{\infty} df \, \tilde{x}_1^*(f) \frac{\gamma(f)\, \Omega_{GW}(f)}{N f^3 \, P_1(f)\, P_2(f)} \tilde{x}_2(f)$$

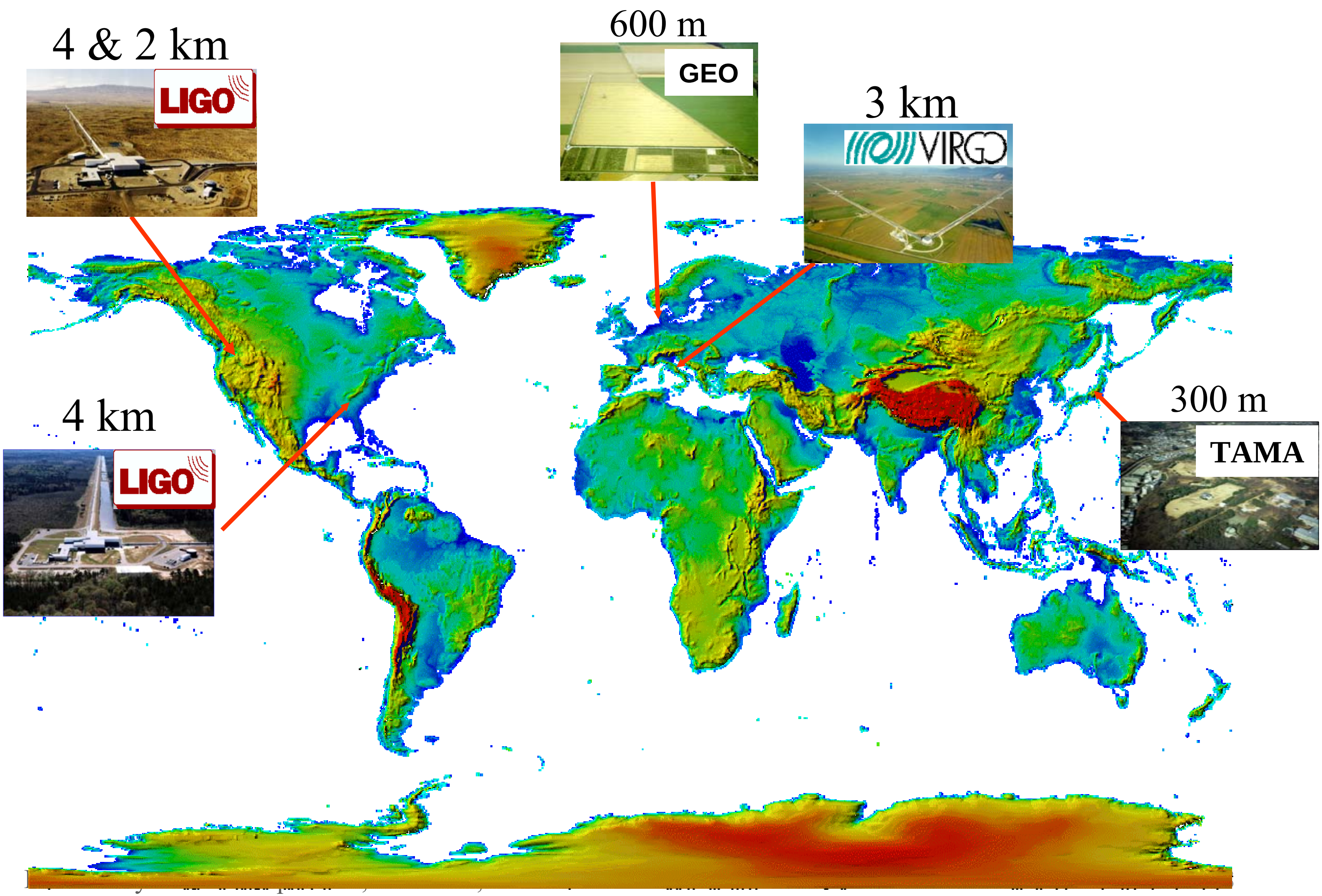
"Overlap Reduction Function"
(determined by network geometry)

Detector noise spectra





Growing ground based interferometers network



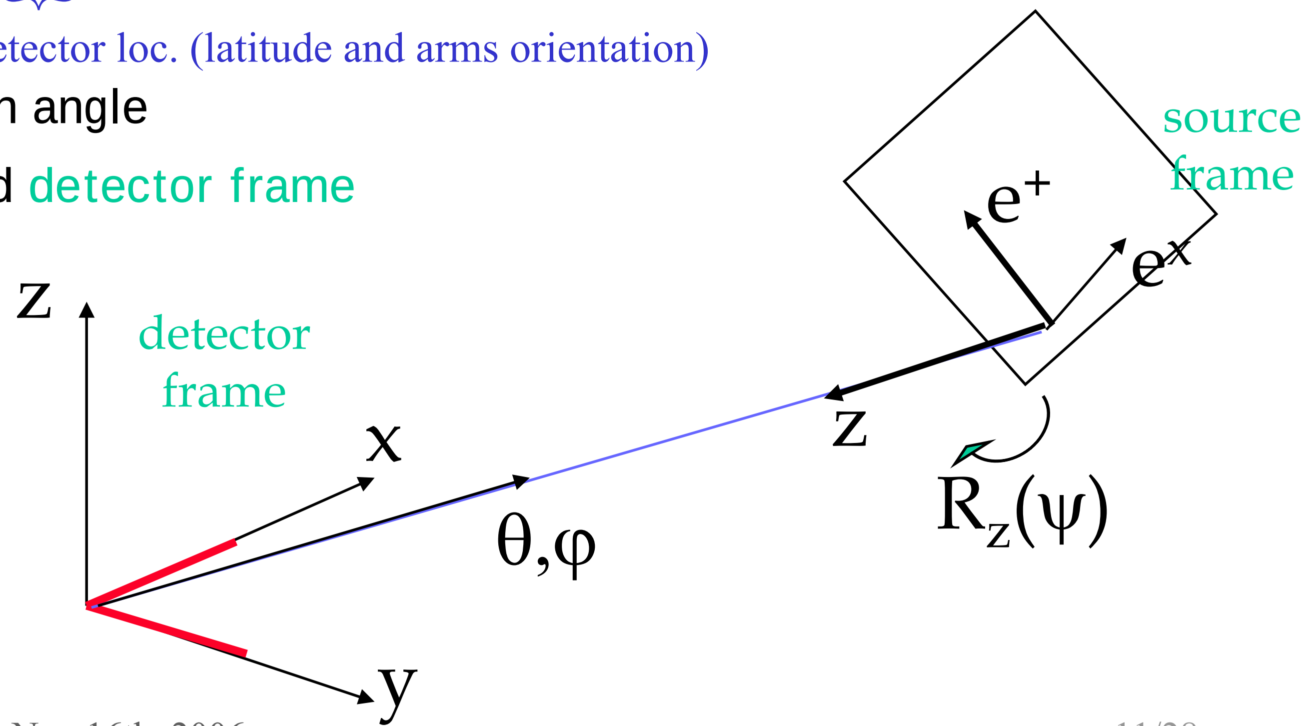
Sources … wave seen in an ITF

- A GW has 2 polarizations: h_+ and h_x in the TT jauge frame of the source
- Coordinates of a source on the sky sphere:
  - α: right ascension
  - δ: declination
- The detector answer is the projection: $h(t) = F_+ h_+(t) + F_x h_x(t)$
- $F_{x,+} = F_{x,+}(\alpha, \delta, l, \gamma, \psi)$

source loc. detector loc. (latitude and arms orientation)

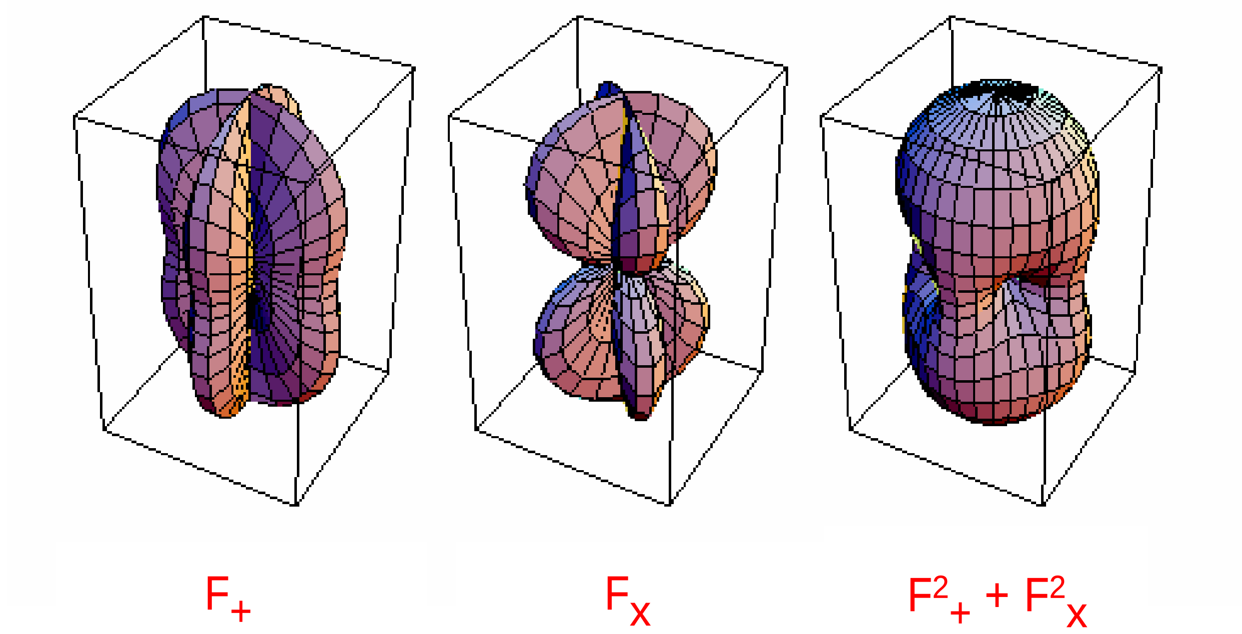
Ψ: source polarization angle

bet. source frame and detector frame

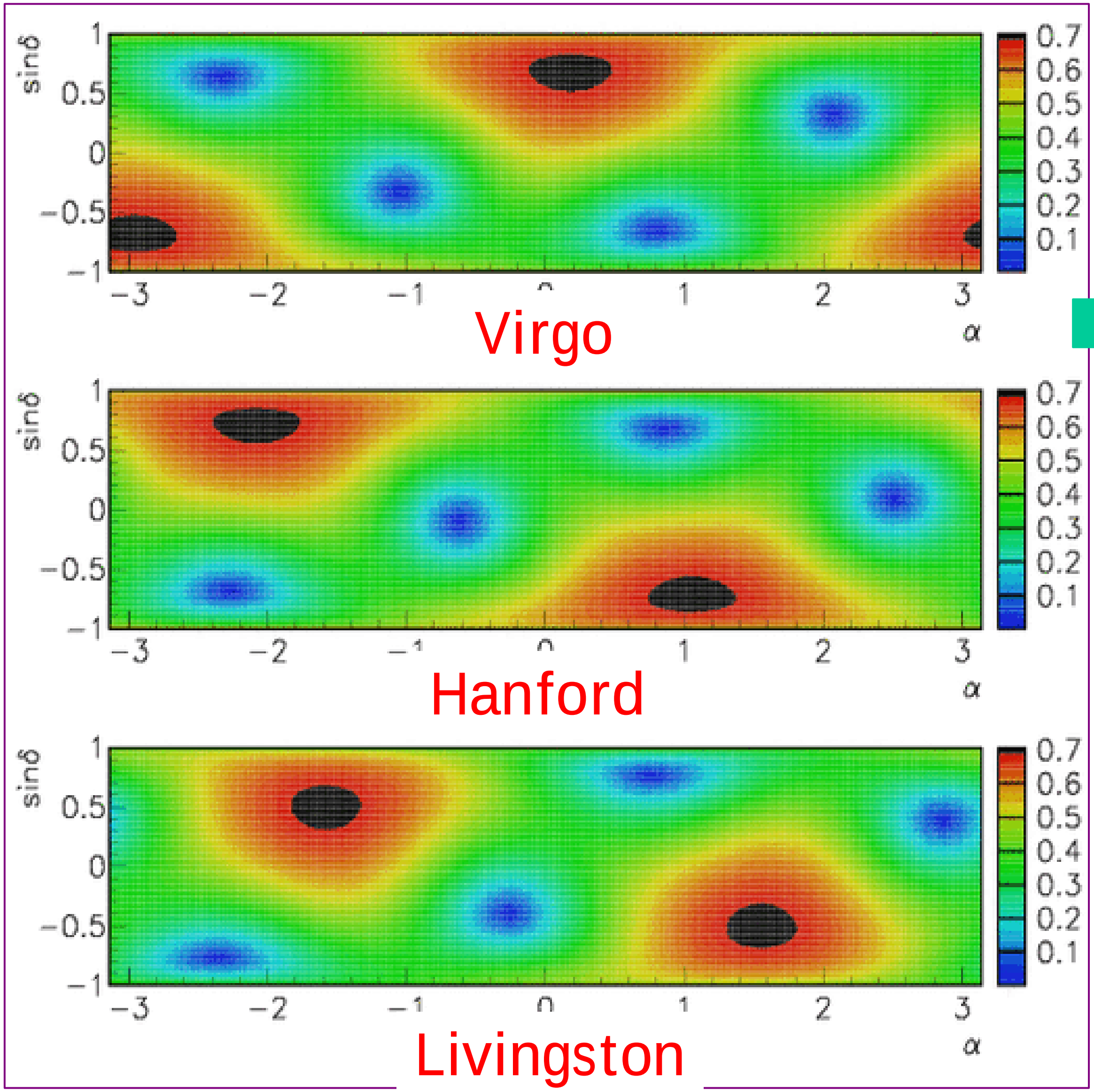


Antenna patterns

- Directional and differential answer of an ITF
- Maximal answer when the source incidence is normal to the detector plane
- There are blind regions …



Sky coverage of the LIGO-Virgo detectors



"orthogonal" to LIGO detectors

Virgo and LIGO Don't see the Same region of sky What is the gain?

relatively well aligned

Why performing a network search?

- Confirm the discovery of a GW event (or reject a false event)
- Determination of the source position in the sky
- Detection potential increase / reject more false alarm
- Better estimation of the parameters of the source

→ require a network of comparable sensitivity

LIGO + Virgo

- Mandatory for the stochastic background (cross-correlation between 2 detector data streams)

Network data analysis techniques (CB & burst)

- **Un-coherent:**
  - Generate event trigger lists for each detector
  - Perform coincidence using:
    - timing information
    - frequency information
    - template parameters
    - …

Main advantage: very simple and fast

- **Coherent:**
  - The output of the different detector are combined in a unique variable (a likelihood function e.g.) which depends on the source sky position
  - Allows to use "maximally" all information recorded in all detectors
  - Check the compatibility of the SNR seen in each ITF weighted by beam patterns

Coincidence analysis: using only time information

Definition of a time window depending on time delay between detectors

$$\Delta t^{ij} = t^j - t^i = \frac{\vec{n}.\overrightarrow{D^i D^j}}{c}$$

- The source location is not known: loose coincidence

$$\Delta t^{ij} < \Delta t^{ij}{}_{\max} + \eta.\Delta t^{ij}_{RMS} \qquad (\Delta t^{ij}_{\max} \sim 10ms....28ms)$$

Hanford-Livingston Hanford-Virgo

Δt^{ij}_{RMS} has been determined on simulation (SNR dependence): (<0.3 ms for SNR>5)

$$\Delta t^{ij}_{RMS} \sim 0.15ms \left(\frac{\omega}{1ms}\right)\left(\frac{10}{SNR}\right)$$

for SNR>6

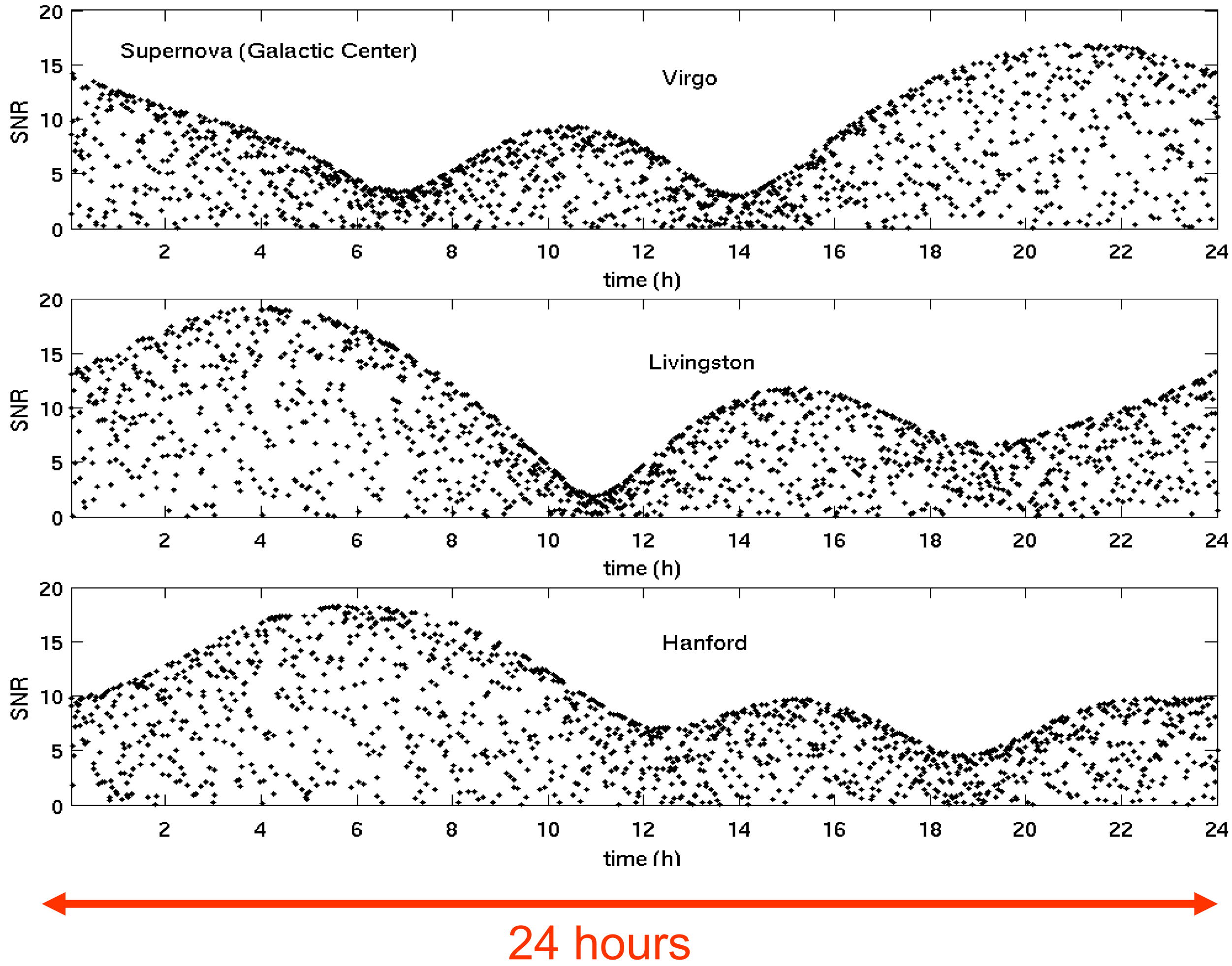
Burst LIGO-Virgo network sky coverage

Example: source in the direction of the Galactic center

Burst SNR seen in each ITF as function of time

Virgo and LIGO ITFs do not see the Galaxy center at the same time …

→ is there an interest of coincidence analysis?



Coincident burst search in LIGO-Virgo network

- Several possible coincidence analysis:
  - Three-fold: HLV
  - Two-fold: HL or LV or HV

The false alarm rate will decrease by a factor assuming that false events rate follow a Poisson distribution:

$$fa_1 \,.\, fa_2 \,.\, 2\,\Delta_{12} \;\; \text{(Hz)}$$

- But the efficiency will drop as well due to bad alignment of the net.

- So what is the real gain??

  - Tests with simulated data
  - Source in the direction of the galactic center
  - Average the polarization angle over 24 hours

⇒ Average performance over 24 hours

Burst coincidence search: performance of the HLV network

- Example: A2B4G1 (SN) waveform
- Single interferometer results:
  - Best efficiency among 5 filters
  - False alarm rate 0.1 Hz (~10 000 FA per day)

efficiency

H	L	V
63%	60%	55%

- Coincidence:
  - Require time (and frequency) coincidence
  - Double coincidence:
    - False alarm: 10^{-6} Hz

efficiency

HL	HV	LV	HL∪HV∪LV
41%	22%	22%	60%

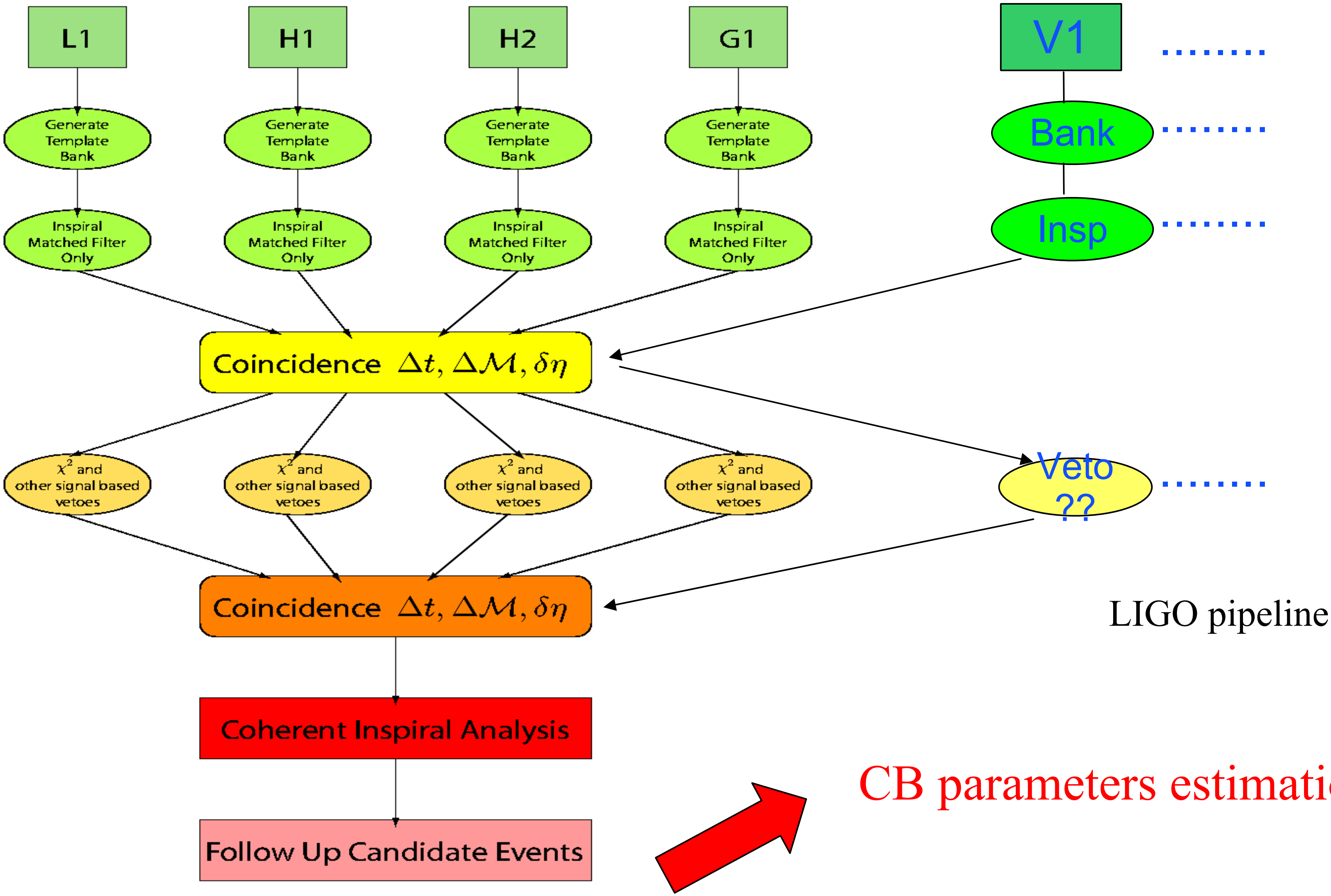
  - Triple coincidence:
    - False alarm: 10^{-6} Hz

efficiency

HLV
19%

Adding Virgo to LIGO increases the network efficiency by ~50%

CB search: un-coherent pipeline



CB parameters estimation

Example: source in 2 clusters of Galaxy

- Single interferometer results:
  - SNR threshold at 6
  - False alarm rate 0.1 Hz

efficiencies

H	L	V	H∪L∪V
61%	62%	56%	75%

- Coincidence:
  - Require time and mass coincidence
  - Triple coincidence
    - False alarm in 24 hours: 0

	M87 (16 Mpc)	NGC 6744 (10 Mpc)
HLV	24%	**48%**

quite high → source location often possible!

  - Double coincidence:
    - False alarm in 24 hours: 1
    - **Adding Virgo gives ~25% increase in efficiency for M87**

M87

HL	HV	LV	HL∪HV∪LV
42%	32%	30%	56%

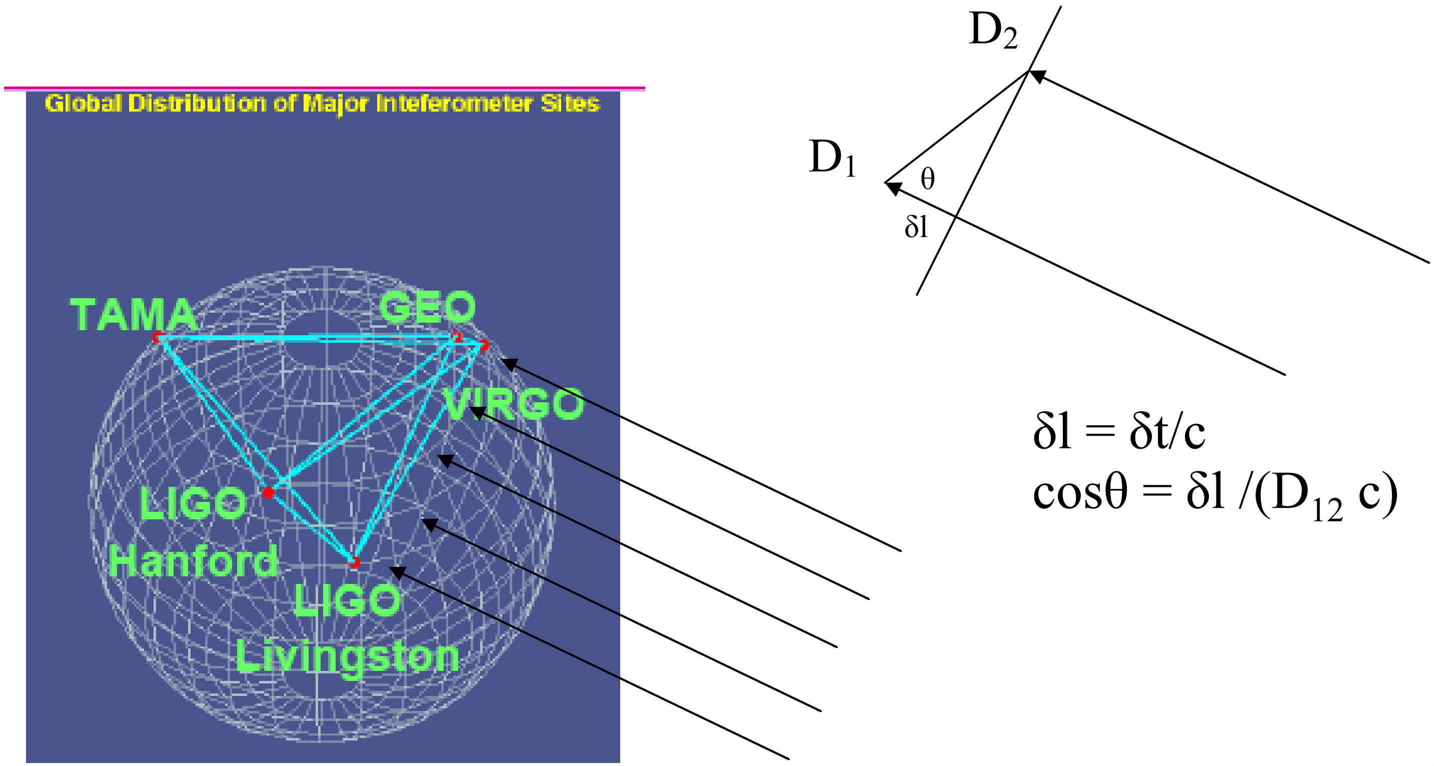
Source parameters estimation

- Burst: waveform not well modeled
  - Sky source location
  - Waveform?

- Coalescing binaries
  - Sky source location
  - All parameters of the CB

  Use of techniques such as Markov Chain Monte Carlo to estimate all parameters all together making Bayesian hypothesis.

Network GW search : source location

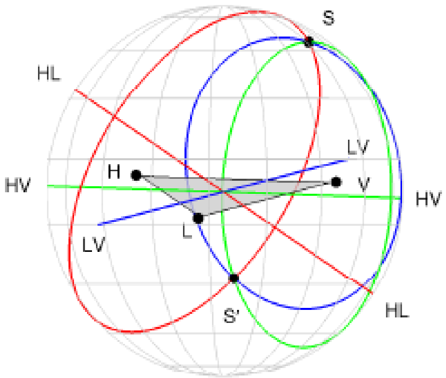


$\delta l = \delta t / c$

$\cos\theta = \delta l / (D_{12}\, c)$

If arrival times are measured
the angular source parameters can be estimated

Actually needs at least 3 detectors !



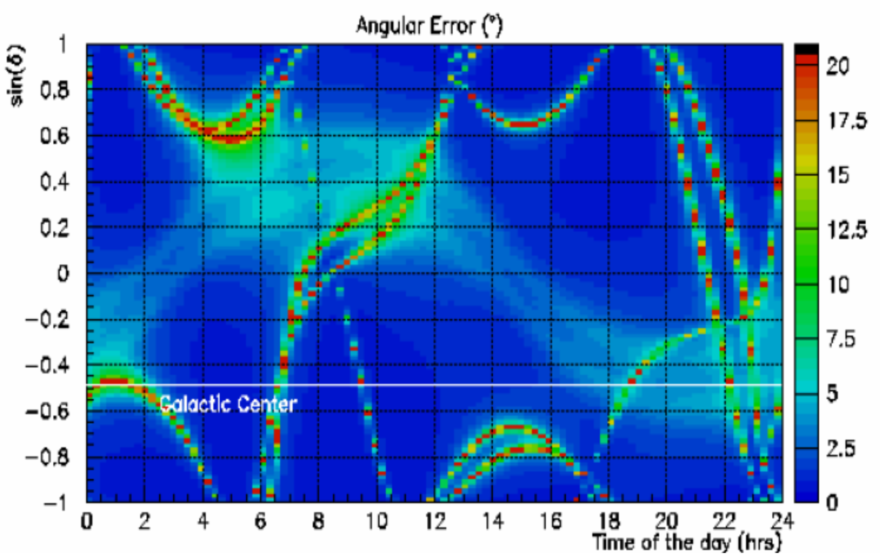
gr-qc/0605002

Burst source location estimation in a network

- Coincidence analysis:
  - list of coincident events arrival time (t_i, σ_i)
  - Fit of the source sky position α, δ by minimization of a χ^2

$$\chi^2 = \sum_{i=1}^{n} \frac{\left(t_i - (t_0 + \Delta_i^{Earth}(\alpha,\delta))\right)^2}{\sigma_i^2} \longrightarrow \sigma_i = \frac{\sigma_0}{(SNR_i)^{\gamma}}$$

where t_0 is the arrival time of the signal at the center of the Earth and $\Delta t_i^{Earth}(\alpha,\delta)$ is the delay between the i^th ITF and the center of the Earth.



Cavalier (2006)

Angular error obtained as function of the sidereal time

On average: error < 1.7deg

Bad resolution regions: regions corresponding to “blind” detector

CB parameter estimations in the HLV network

- Use of Markov Chain Monte-Carlo technique (MCMC)
- Single Detector: 5 parameters:
  - m_1, m_2, effective distance d_L, phase ϕ_c and time t_c at coalescence

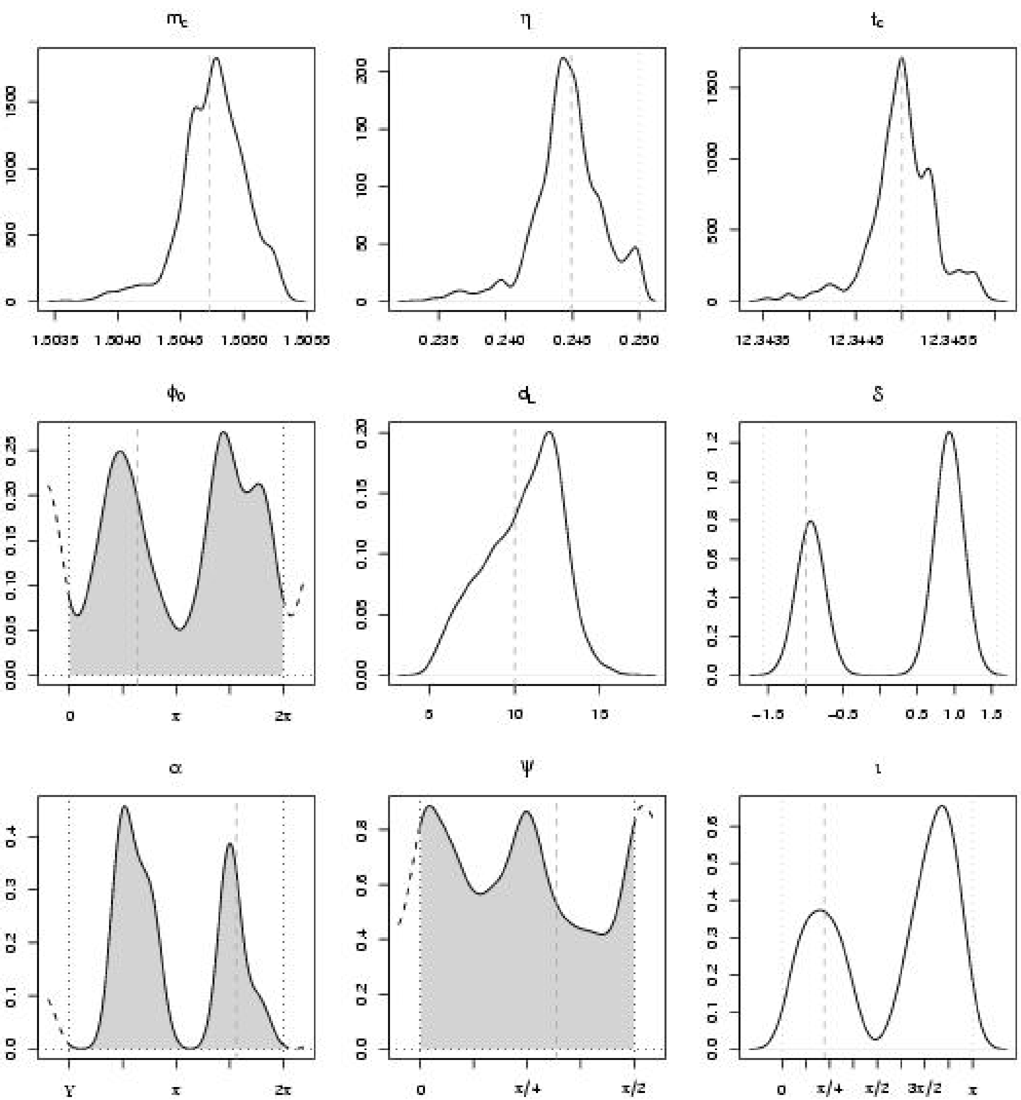
- For multi-detectors- coherent addition of signals
  - m_1, m_2, actual distance d, phase ϕ_c and time t_c at coalescence
  - sky position: α,δ
  - polarization angle ψ
  - angle of inclination of orbital plane ι

2.5 PN (amplitude),
3.5 PN (phase)

$$\mathcal{L}^{(I)}\left(\theta^{(I)}\right) \propto \exp\left(\frac{-2}{\delta_t}\sum_{i=i_L}^{i_U}\frac{|\overbrace{\tilde{z}(i\times\Delta_f)}^{\text{data}} - \overbrace{\tilde{s}(i\times\Delta_f,\theta^{(I)})}^{\text{template}}|^2}{\underbrace{S_n(i\times\Delta_f)}_{\text{noise PSD}}}\right)$$

Multi-detector likelihood $\mathcal{L}(\theta^{\oplus}) = \prod_I \mathcal{L}^{(I)}(\theta^{(I)})$

Marginal posterior distributions of the parameters



true parameters:

m_c = 1.505

η = 0.2449

t_c = 700009012

d_L = 10.0

δ = −0.995

α = 4.896

ψ = 1.000

ι = 0.700

ϕ_0 = 2.000

Every 25th out of

iterations 20000 to 67925

from 1 parallel chain(s)

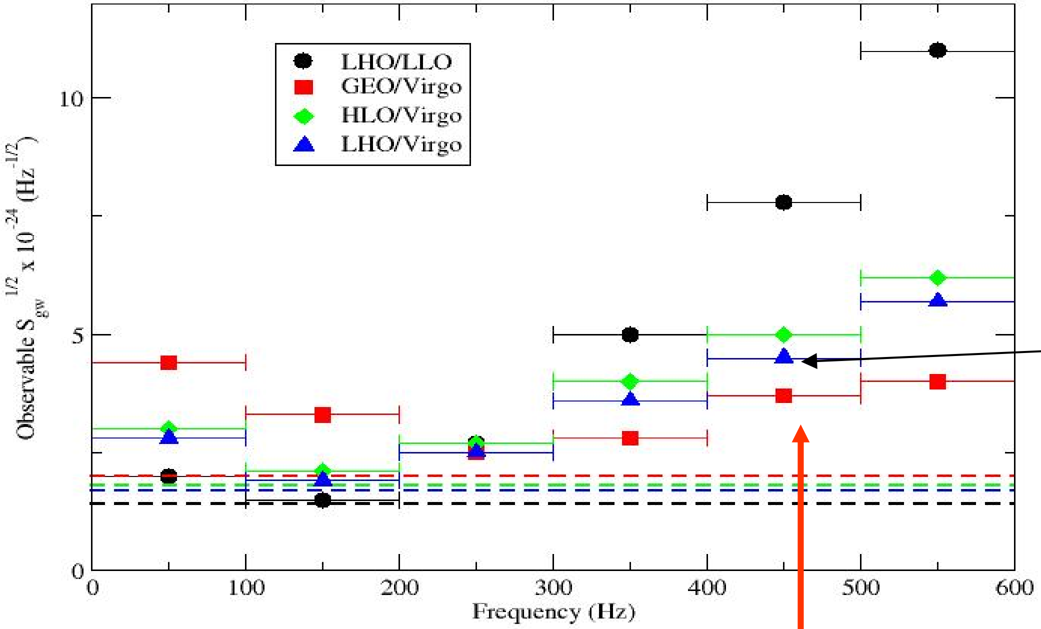
(1918 samples).

Acceptance rate: 43.4%

Including a "blind" detector (low SNR) Improves the source sky location estimation

Stochastic background search in LIGO-Virgo

- Cross-correlation between streams of 2 detectors
- Overlap reduction function: 2 important parameters:
  - Distance between detectors
  - Orientation of the detectors



f> 300 Hz: Virgo-GEO performs well!

Stochastic bck LSC-Virgo working group just started …

Virgo-LIGO search focused on f>200Hz

First detectors generation sensitivity: Ω_{GW}~4 x 10^{-6} → advanced detectors needed!

LIGO-Virgo network searches status

- Virgo adds a discovery potential to Hanford-Livingston network

- LIGO is taking data since one year (S5 data taking) ... until mid 2007
- Virgo is still under commissioning (still a factor 10 missing in the horizon)
- Virgo hopes to join S5 mid 2007 (which sensitivity?)

- Joint data taking LSC-Virgo to be planned (provided the MOU is signed)