Gravitational wave detectors network data analysis

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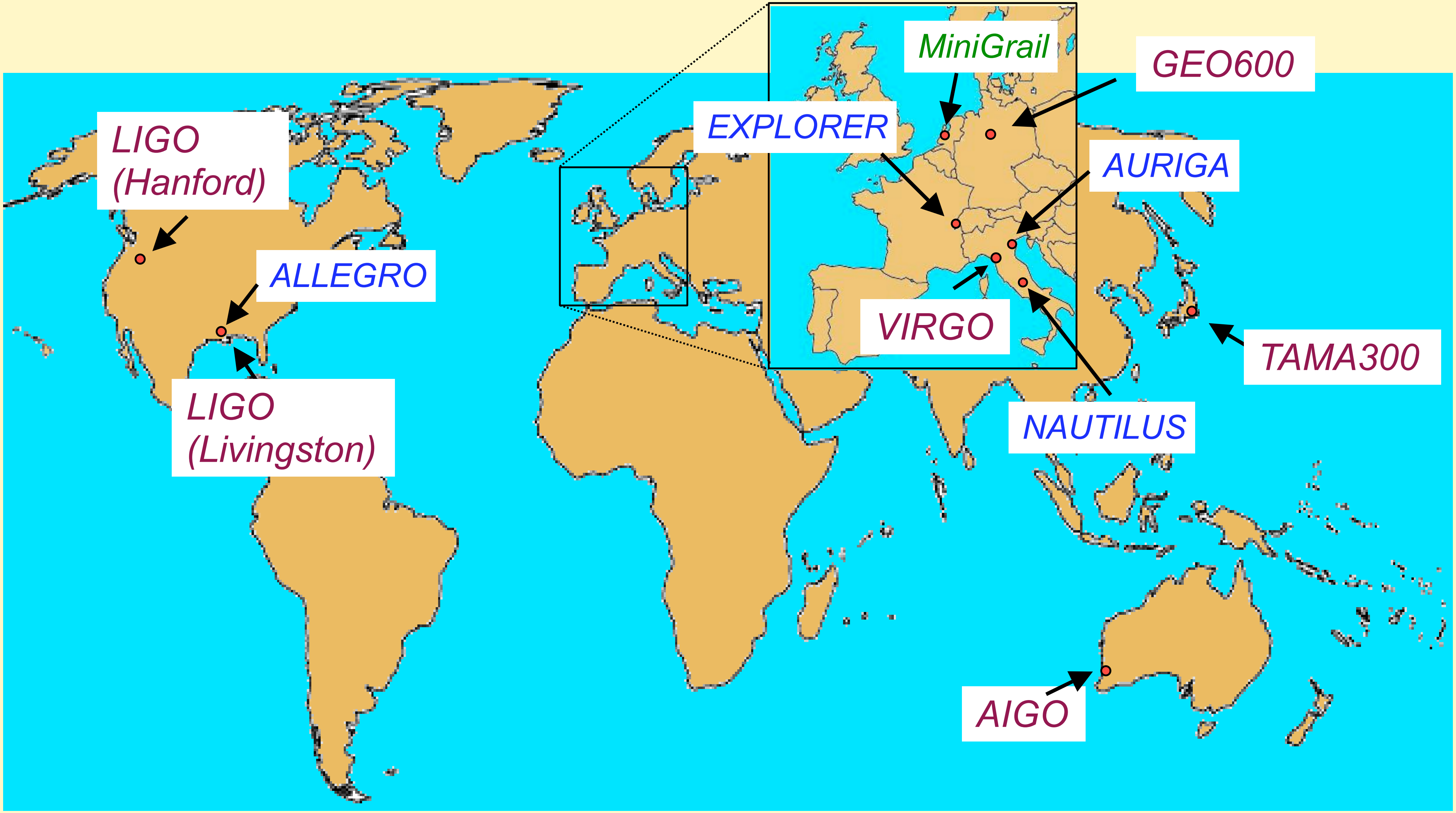
Outline

- Introduction
- Coherent burst gravitational wave searches
  - all-sky searches
  - triggered searches
- Coherent analysis for Inspiral signals

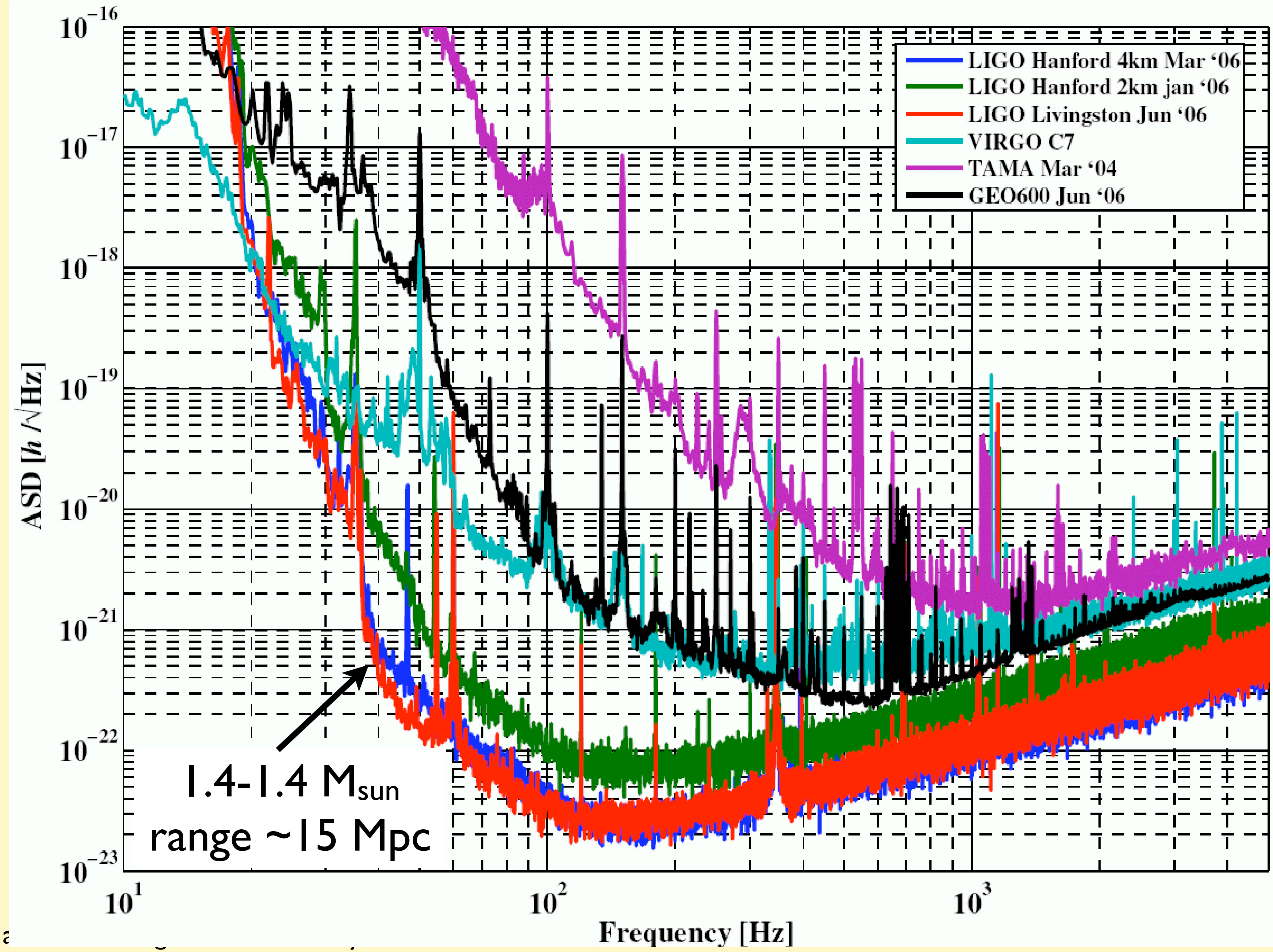
ILIAS N5 WG2

- joint analysis of data from network of detectors
  - co-chairs: G. Guidi & I.S. Heng
- brings together many gravitational wave data analysts from across Europe
  - also have joint meetings with theoretical astronomers
- discuss common issues in development of techniques
- address issues in joint analysis of European network of detectors
  - analysis of data jointly acquired by Virgo interferometer and European resonant-bar detectors
  - IGEC2: global network of resonant-bar detectors
  - implement search for stochastic gravitational radiation background with GEO-Virgo network
- gaining stronger focus on searches associated with triggers in the EM spectrum, addressing data analysis issues for future generations of gravitational wave detectors
  - eg. spin in binary black hole systems, parameter estimation of detected signals

Gravitational wave detectors worldwide

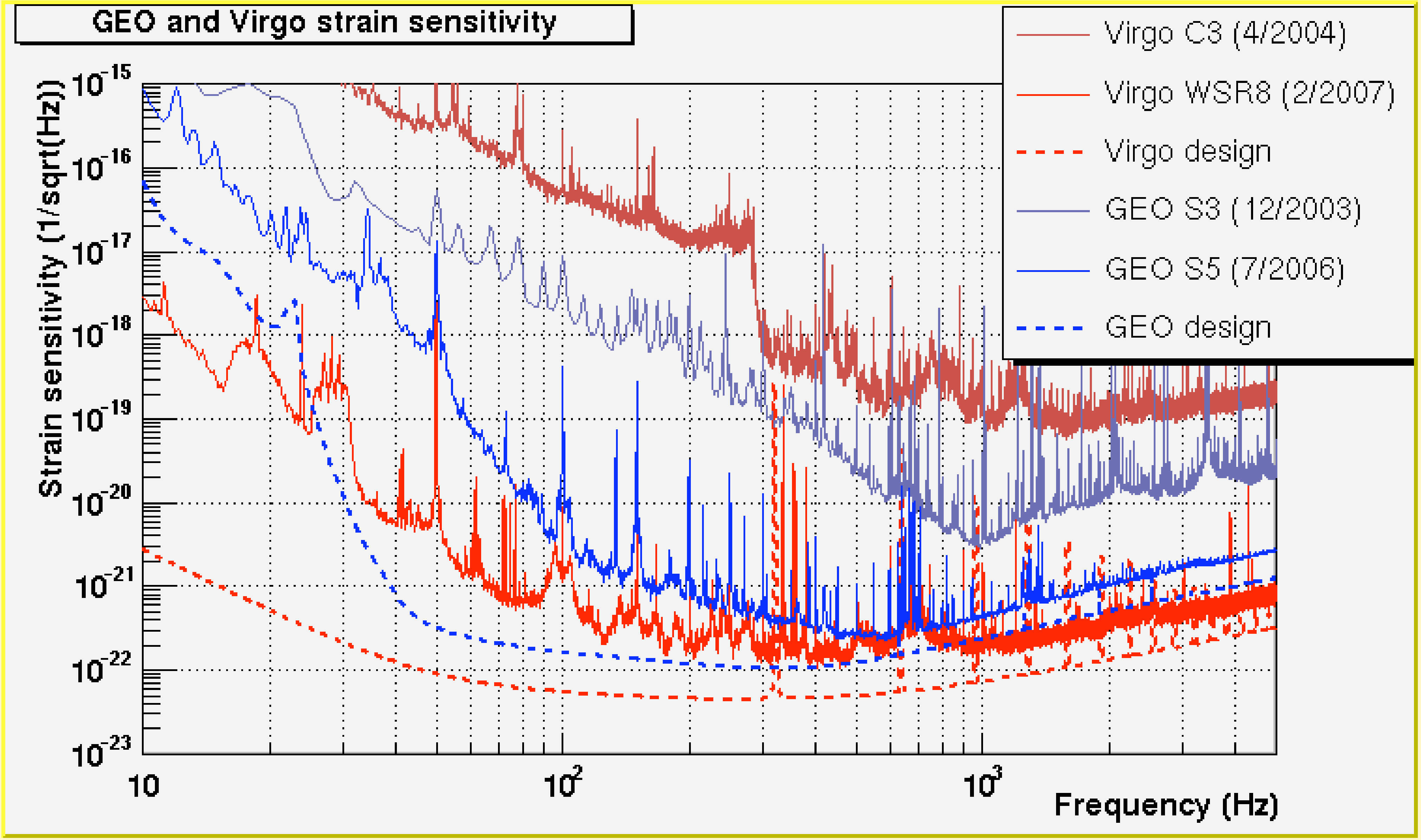


Interferometer sensitivities

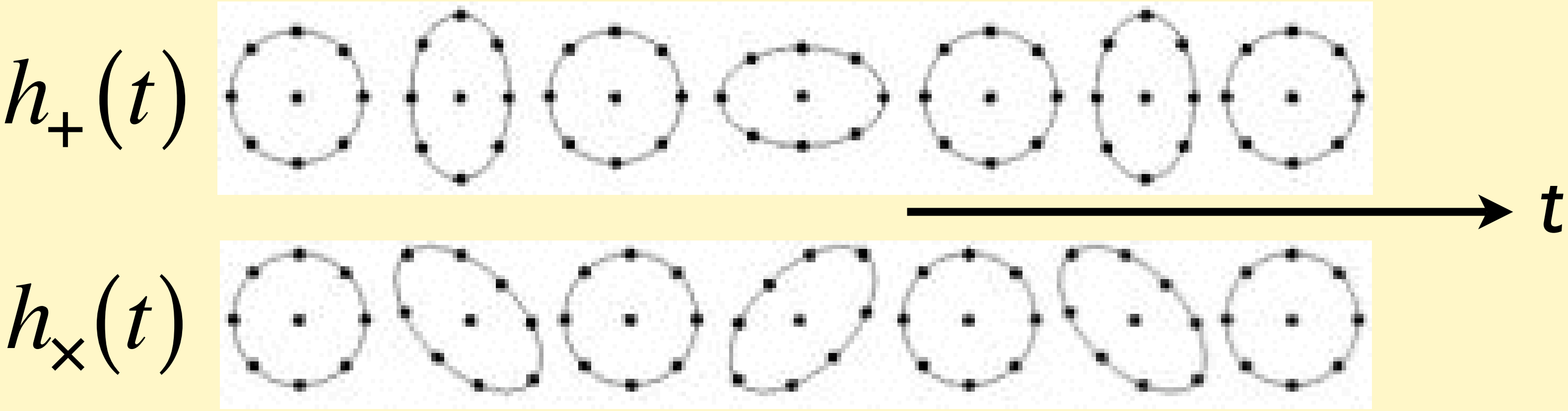


1.4-1.4 M_{sun}
range ~15 Mpc

Virgo and GEO600



Detectors & polarisations

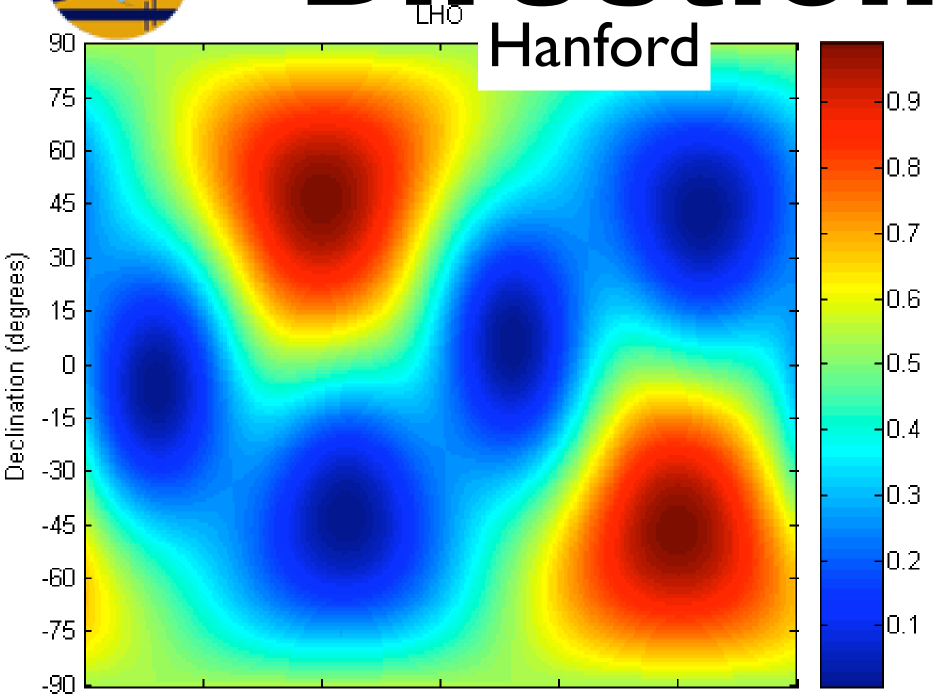


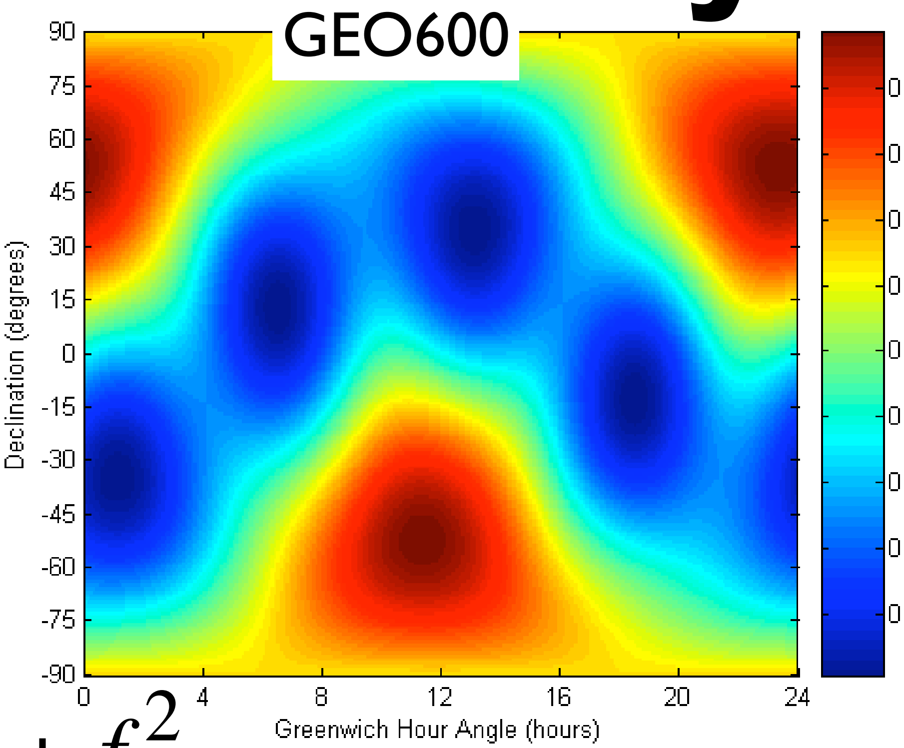
- gravitational wave signal as seen by the detector

$$h_i(t) = f_{i,+}h_+(t) + f_{i,\times}h_\times(t)$$

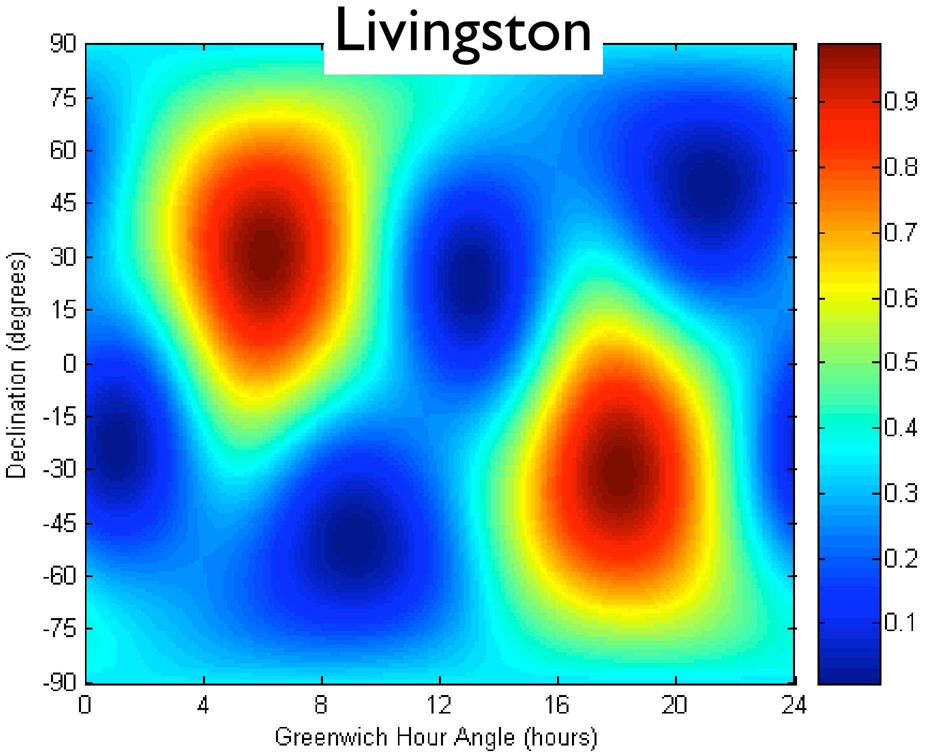
- $f_{i,+}$ and $f_{i,x}$ are a function of the sky location of source
- for detectors that are aligned, $f_{i,+}$ and $f_{i,x}$ are very similar
  - applicable for LIGO network
- for worldwide network, detectors are not aligned to each other

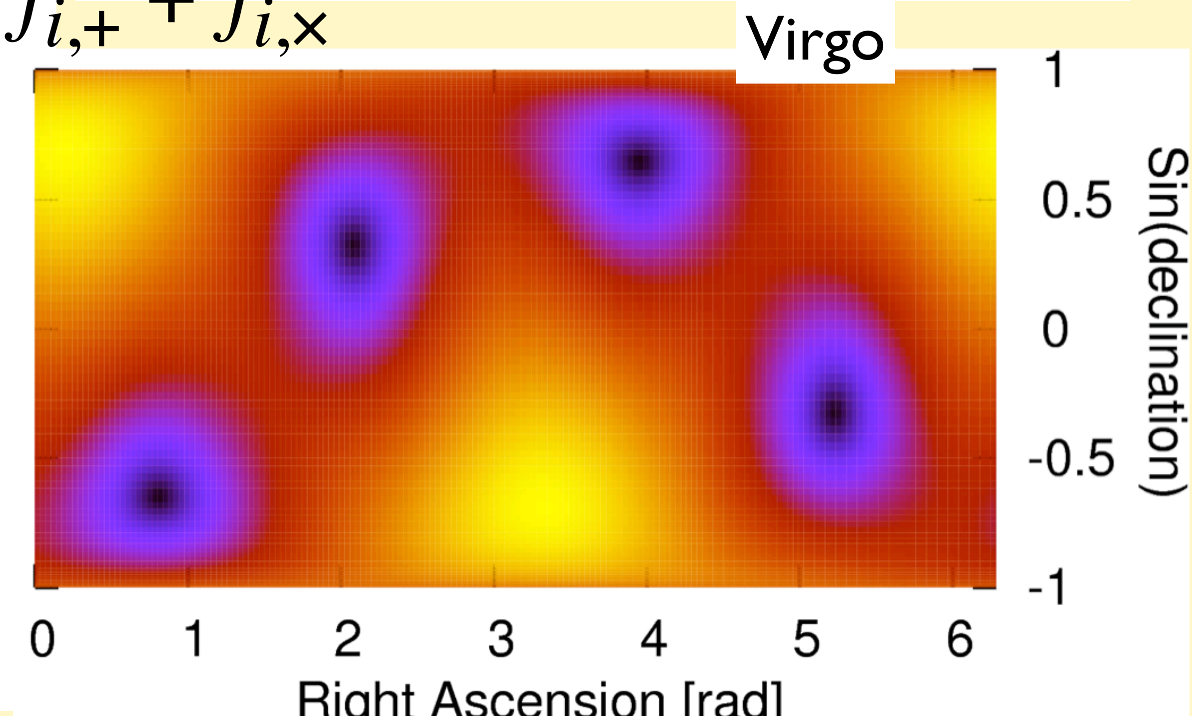
Directional sensitivity


Hanford


GEO600

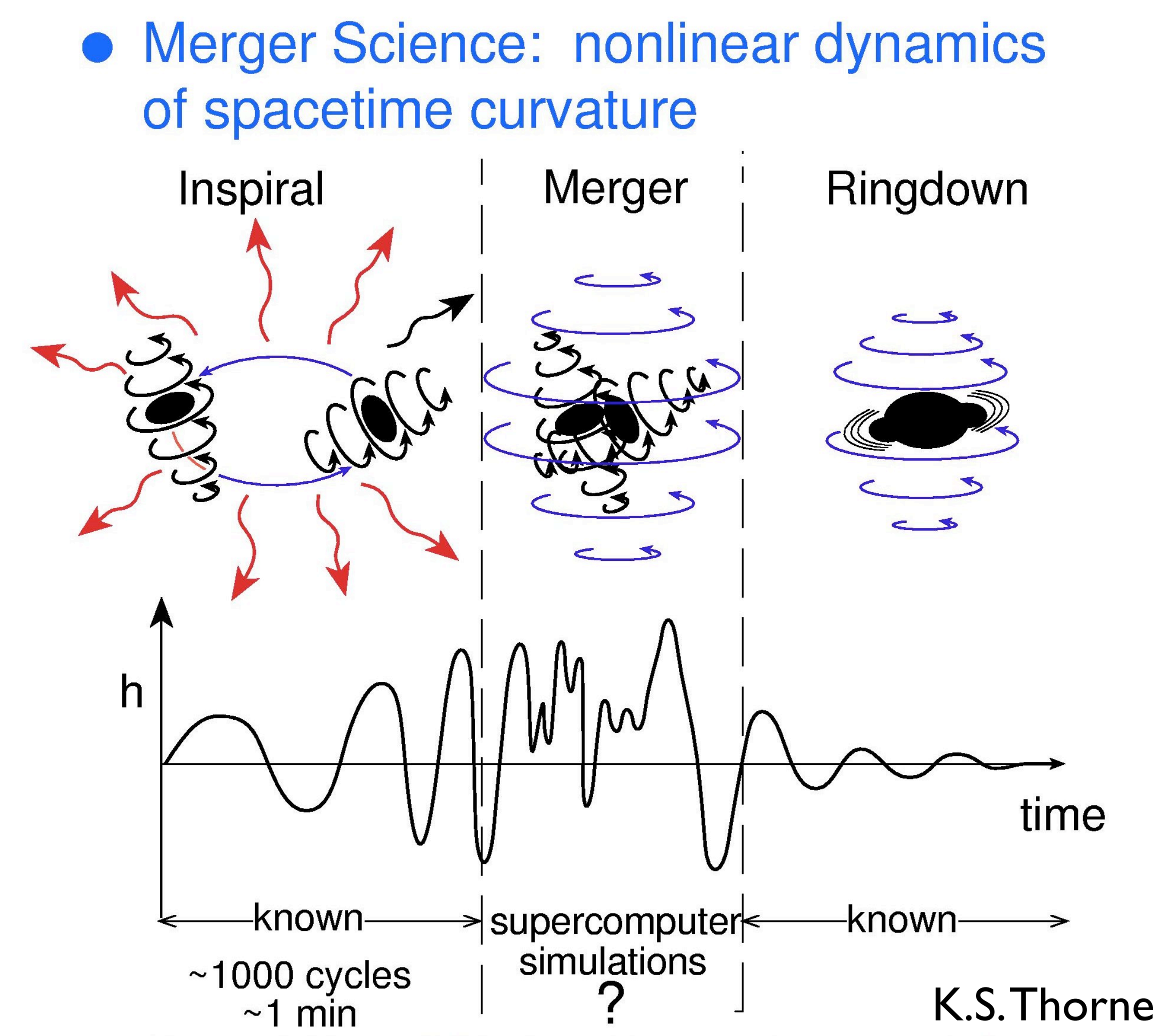
$$f_{i,+}^2 + f_{i,\times}^2$$


Livingston


Virgo

Inspiral and Bursts

- Bursts
  - unmodelled pulses of GW
- Inspirals
  - coalescing binary compact objects
- Periodic
  - non-axisymmetric rotating neutron stars
- Stochastic
  - background of GW from, for example, superposition of relic GW signals



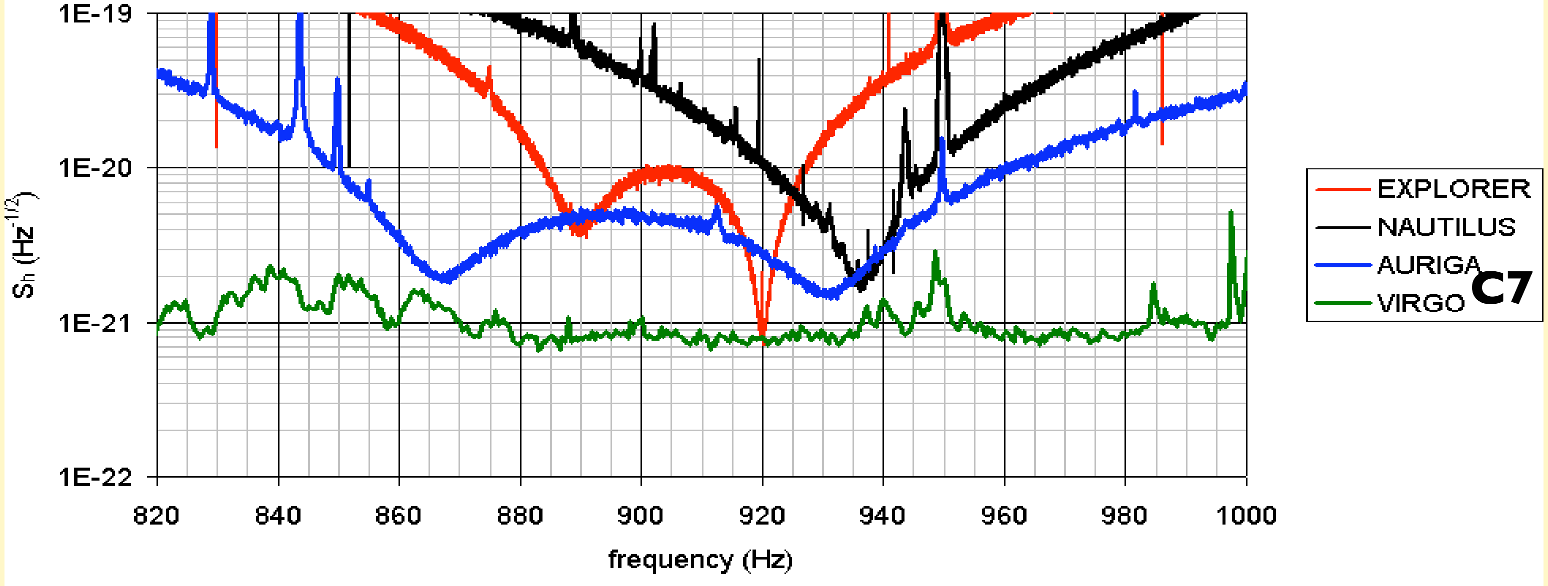
- Merger Science: nonlinear dynamics of spacetime curvature

K.S.Thorne

Burst gravitational wave searches

- short (~1ms) pulses of gravitational waves
- sources include supernovae core collapse and merger phase of binary neutron stars
- two broad categories of burst searches:
  - all-sky: unknown source parameters, maximise detection efficiency over entire sky
  - triggered: search is triggered by observation in EM spectrum (eg. GRB, pulsar glitch)
- most common approach is to search for coincident excess power in network of detectors
  - LIGO detectors are aligned to each other use a cross-correlation follow up

Virgo-bars & IGEC2



- Virgo-bars
  - exchange 24 hours of data
  - L. Baggio (funded by ILIAS Fellowship) part of analysis team
  - null hypothesis confirmed: finalising results and setting upper limit
- IGEC2 (resonant-bar network)
  - exchange 6 months of data: 130 days triple coincidence
  - no Science data available from other detectors during this period
  - null hypothesis confirmed

Coherent burst analysis

- coherent analysis merge data from multiple detectors while taking into account the different noise level and directional sensitivities of each detector
  - improve efficiency of the network
  - reduce false alarms
- one can take two approaches for coherent burst analysis
  - “data combination”
  - “likelihood methods” based on work by Gruesel and Tinto PRD 40, 3884 (1989)
- note that use of coherent methods allow for parameter estimation of detected signal
  - sky location of signal source
  - waveform reconstruction
- other coherent methods:
  - M. Rakhmanov, CQG 23, S673 (2006)
  - L. Wen, gr-qc 0702096

Coherent burst analysis

- “data combination” approach first proposed by J. Sylvestre, PRD 68, 102005 (2003)
- combination outputs of detectors into a single data stream

$$h_{rec} = \sum_{i} f_{i,+} h_i\left(t + \delta t_i\right) / \sigma_i$$

Estimated SNR for source from Galactic Centre for one instance in time

increasing signal amplitude ↓

Coherent	Virgo	Livingston	Hanford
4.5	3.5	3.0	1.2
5.3	4.2	3.5	1.4
7.9	6.3	5.3	2.1
13.2	10.5	8.9	3.4

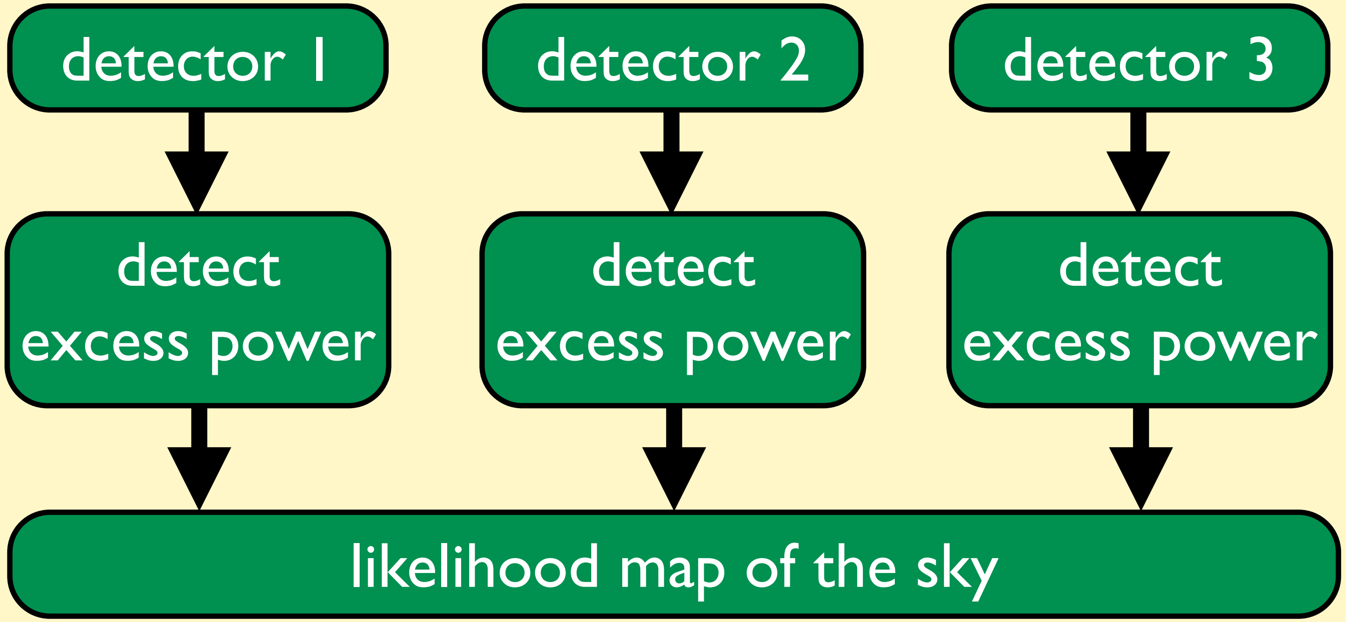
work done by N. Leroy

Coherent burst analysis

- calculate likelihood of signal originating from all sky locations

$$L = \sum_t \sum_i \frac{1}{2\sigma_i^2}\left[\underbrace{x_i^2(t)}_{\text{detected power}} - \underbrace{\left(x(t) - \xi(t)\right)^2}_{\text{noise energy}}\right]$$

ξ - reconstructed GW signal



Klimenko et al.
PRD 72 122002
(2005)

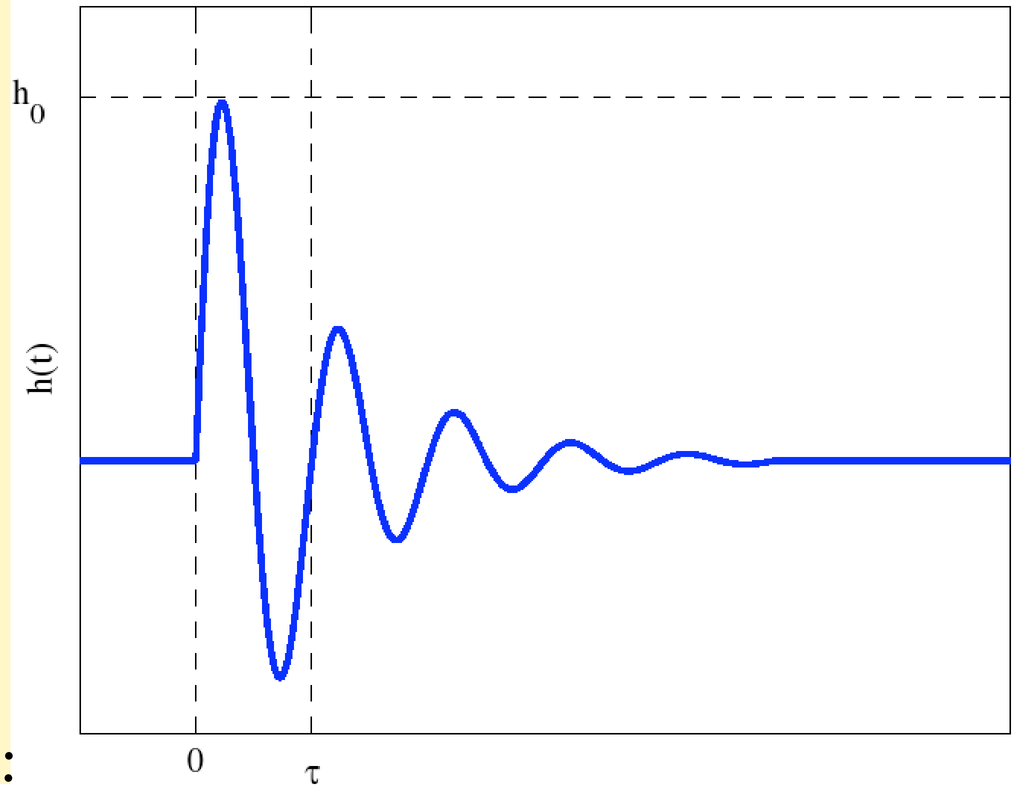
Chatterji et al.
PRD 74 082005
(2006)

- one implementation using Wavelet transforms (coherent Waveburst) has been used on data acquired by LIGO and GEO600
- preliminary results show improved sensitivity with respect to non-coherent methods

Triggered burst searches

- burst searches triggered by observation in electromagnetic spectrum
- gamma-ray bursts associated with merger of two neutron stars
- glitches in pulsar timing associated with "star quake" leading to normal mode oscillations of neutron star
- fewer free parameters to search over compared to all-sky search
    - know time, sometimes direction and distance
- previous searches have used cross-correlation in data from LIGO detectors
- planning to use coherent analyses to incorporate more detectors
- also developing Bayesian approach for ringdown analysis

Bayesian ringdown search



- excitation induces “ringing” neutron star or black hole
- search for ringdowns in black holes using LSC detectors performed by L. Goggin (Caltech)
  - matched filtering approach
- Bayesian approach begin developed by J. Clark (Glasgow)
- Detection statistic is the odds ratio:

$$O_{12} = \boxed{\frac{p(\,\mathcal{M}_1 \mid I)}{p(\,\mathcal{M}_2 \mid I)}} \times \boxed{\frac{p(\,\{\mathcal{D}\} \mid M_1,\; I)}{p(\,\{\mathcal{D}\} \mid M_2,\; I)}}$$

prior odds

Bayes factor

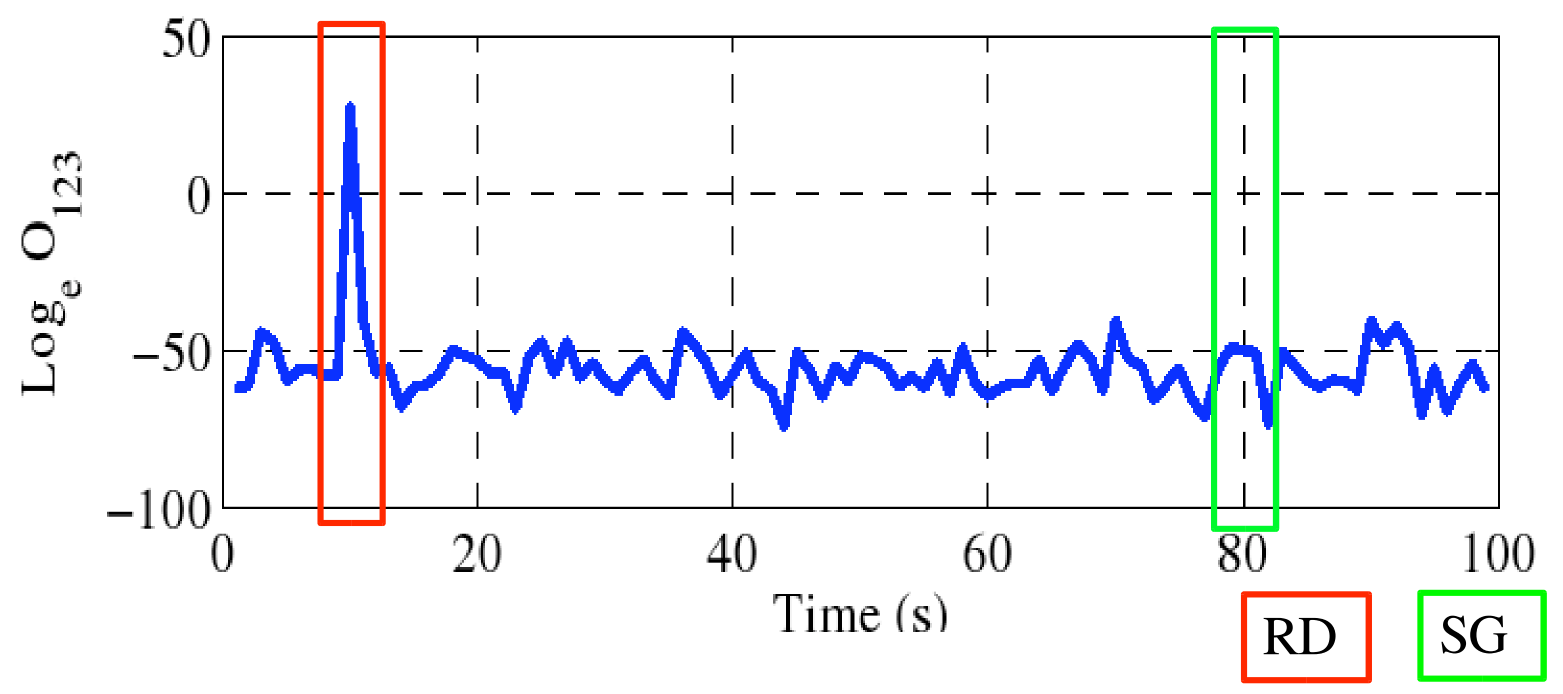
- p({D} | Mi, I) is the evidence for model i given the data, D
  - marginalise over unknown parameters
- model 1: data contains ringdown, model 2: white noise

Bayesian ringdown search

- can be extended to take into account non-gaussian “glitches”

$$O_{123} = \frac{p(\mathcal{M}_1 \mid \mathcal{D},\ I)}{p(\mathcal{M}_2 \mid \mathcal{D},\ I) + p(\mathcal{M}_3 \mid \mathcal{D},\ I)}$$

glitch evidence



- begun collaboration with A. Corsi (INAF-IASF) on ringdowns associated with GRBs
- coherent version of this analysis:

$$p(M_{GW} \mid \{D\}, I) = p(M_{GW} \mid I) \prod_i \frac{p(D_i \mid M_{GW}, I)}{p(D_i \mid I)}$$

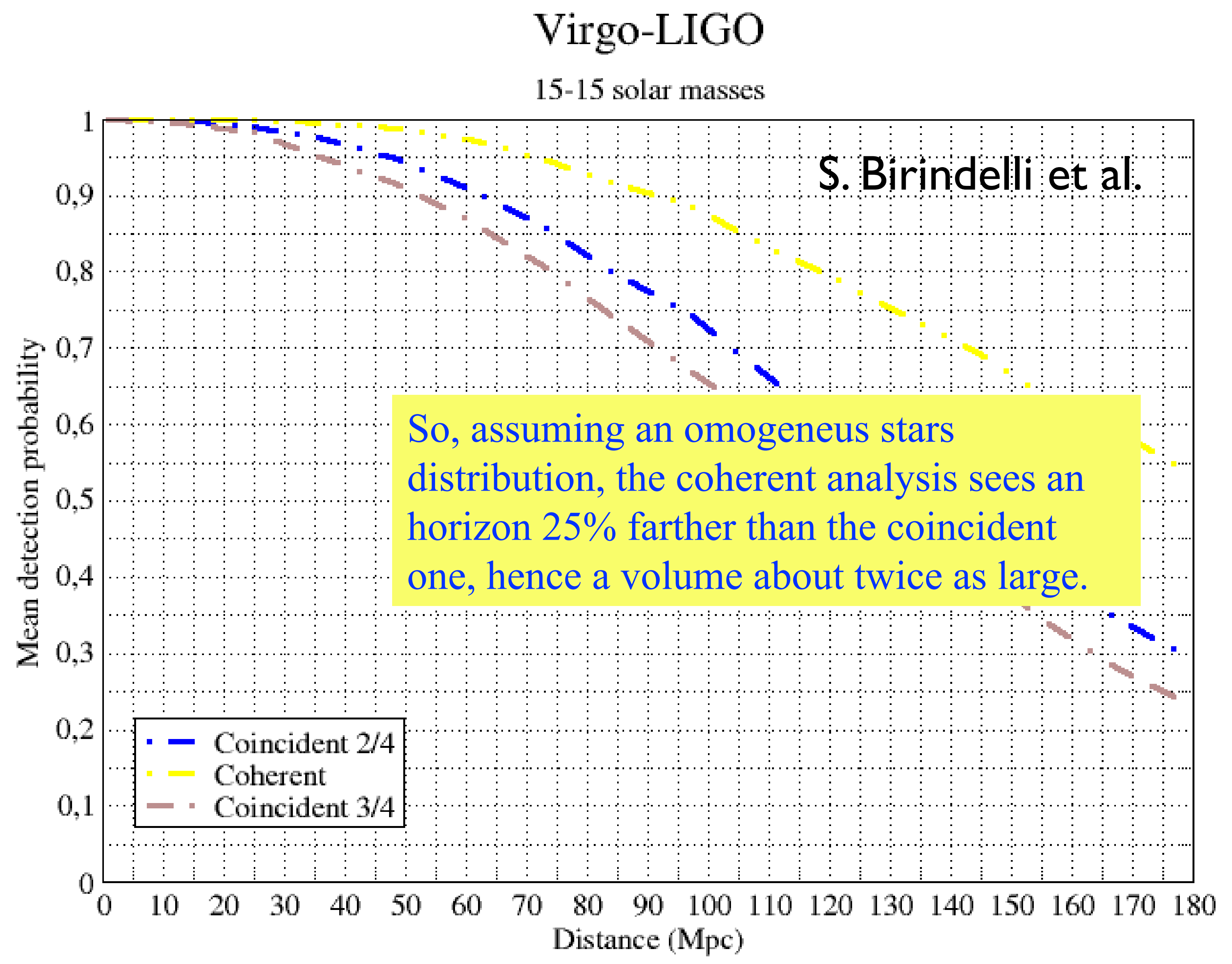
Coherent inspiral analysis

- Inspiral gravitational wave signals arise from inspiral compact objects in binary system
- for coherent inspiral analysis, the log likelihood ratio is derived by A. Pai, S. Dhurandar and S. Bose PRD 64 042004 (2001)

$$LLR = \sum_i \left(\langle s_i, x_i \rangle_i - \frac{1}{2} \langle s_i, s_i \rangle_i \right)$$

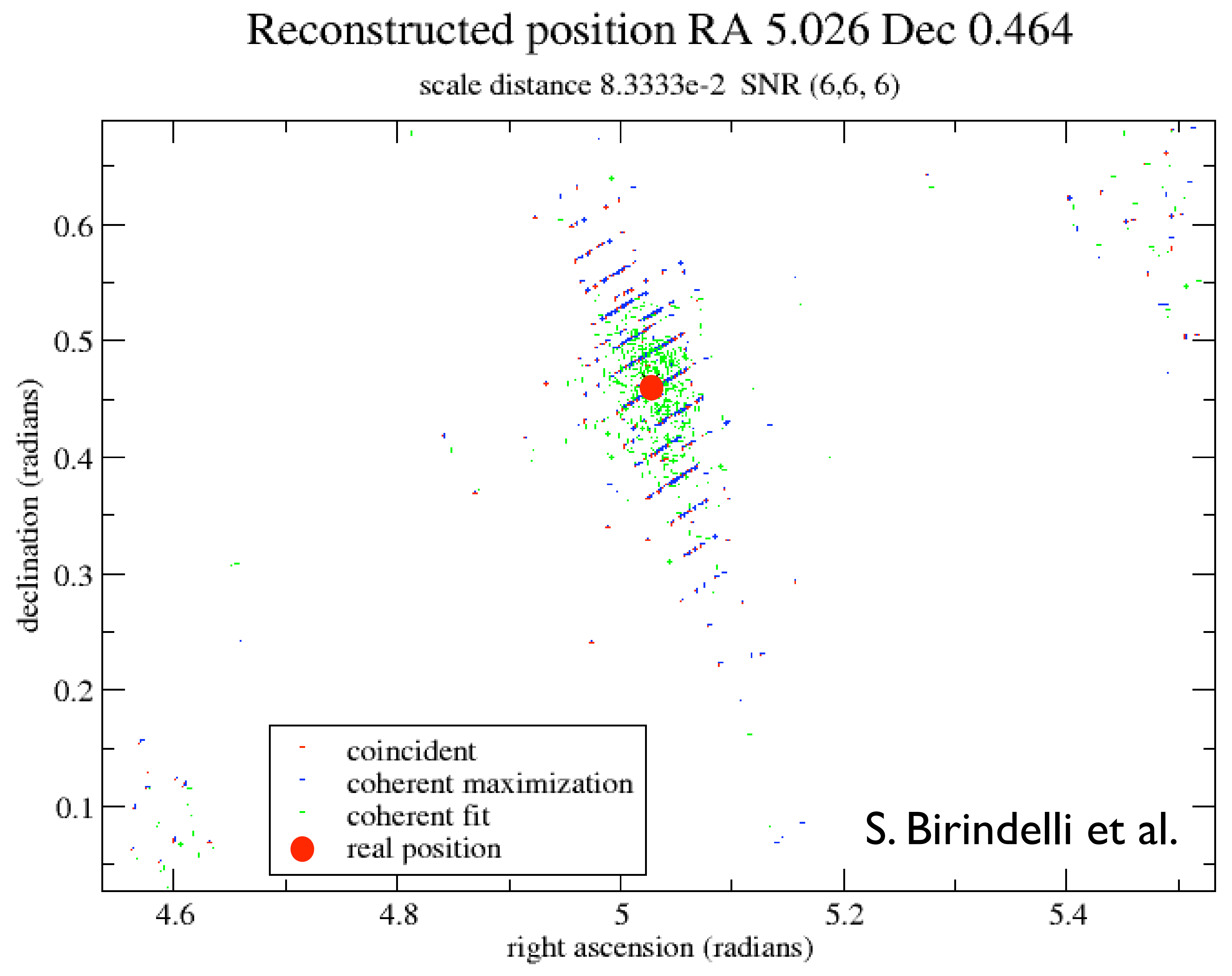
- investigation into use of coherent inspiral analysis performed by two groups
  - S. Bose et al.
  - S. Birindelli, L. Bosi, F. Marion and A. Vicere

Inspiral range



So, assuming an omogeneus stars distribution, the coherent analysis sees an horizon 25% farther than the coincident one, hence a volume about twice as large.

Sky location estimation



S. Birindelli et al.