GRAVITATIONAL WAVE EXPERIMENTS: CURRENT STATUS

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IUCAA

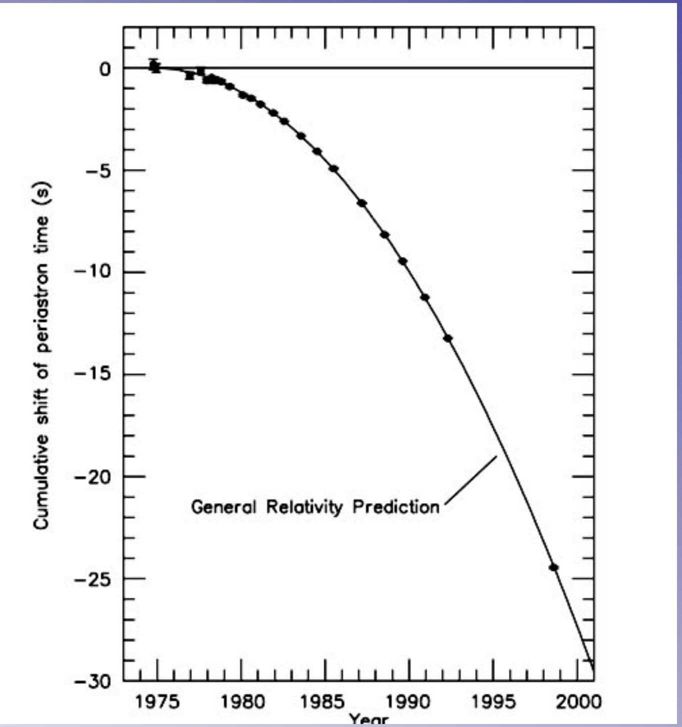
PUNE

GRAVITATIONAL WAVES

General Relativity predicts the existence of gravitational waves

Observation:

Decay in the orbit of the binary pulsar PSR 1913+16



Nobel Prize to

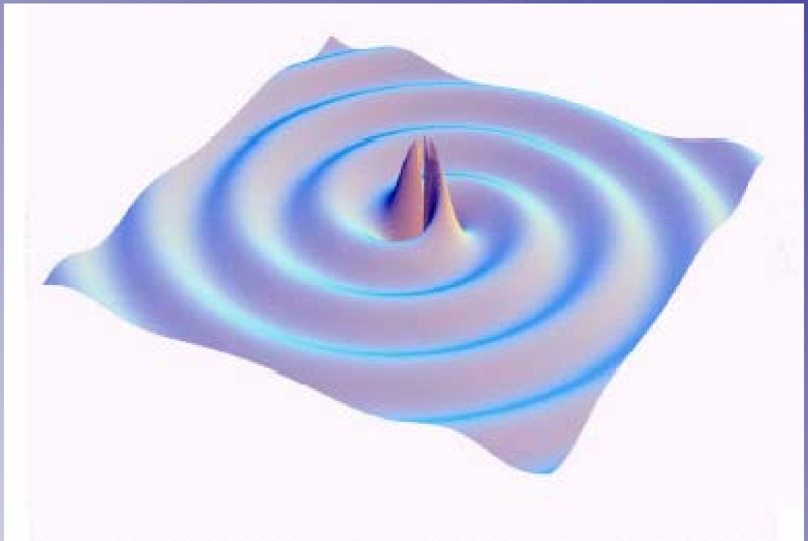
Hulse & Taylor 1993

Gravitational Waves EXIST !

GRAVITATIONAL WAVE ASTRONOMY

- Enormous differences between GW and EM

- Produced by bulk motions of matter
- Compact objects: Blackholes, neutron stars



Binary Inspiral of NS, BH

PROBES OF THE UNIVERSE

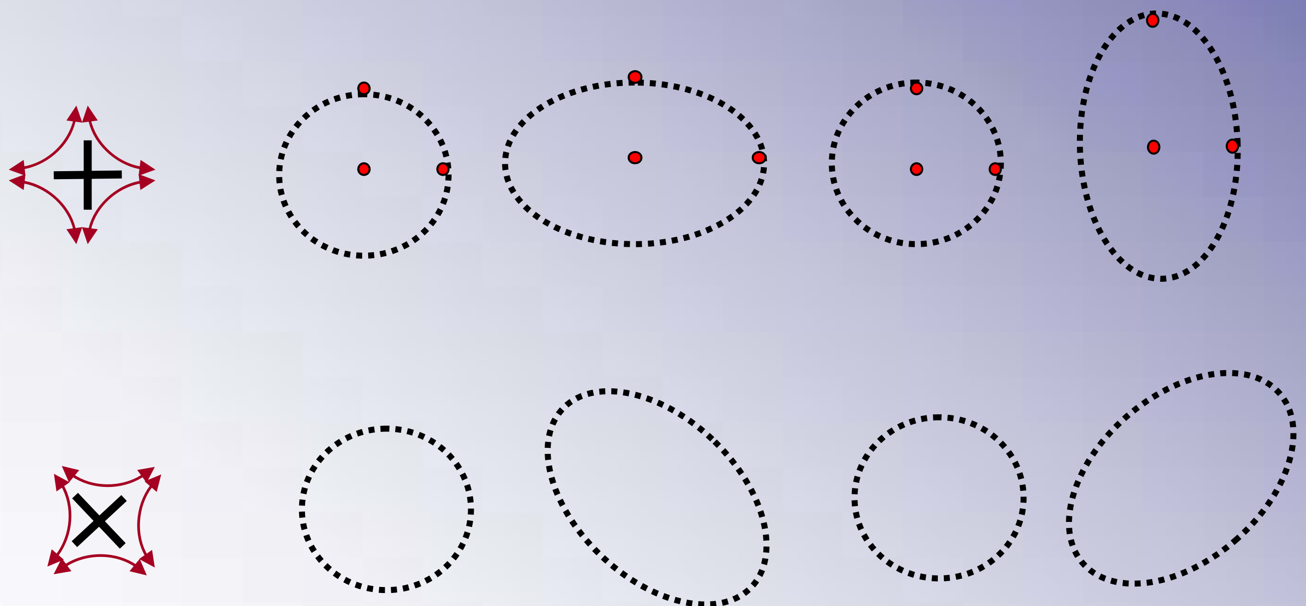
GW ASTRONOMY !!

Effect on a ring of test particles

Metric:

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial}{\partial t^2}\right) h_{ik} = 0$$

General Wave: $h_{ik} = h_+ (t - z/c)\, e_{ik}^{+} + h_\times (t - z/c)\, e_{ik}^{\times}$



But h is awfully small !

Quadrupole formula :

$$h \sim \frac{G}{c^4} \left(\frac{E^{kin-ns}}{0.1\, M_\odot c^2} \right) \left(\frac{R}{100\ Mpc} \right)^{-1} 10^{-21}$$

Geodesic deviation – change in armlength:

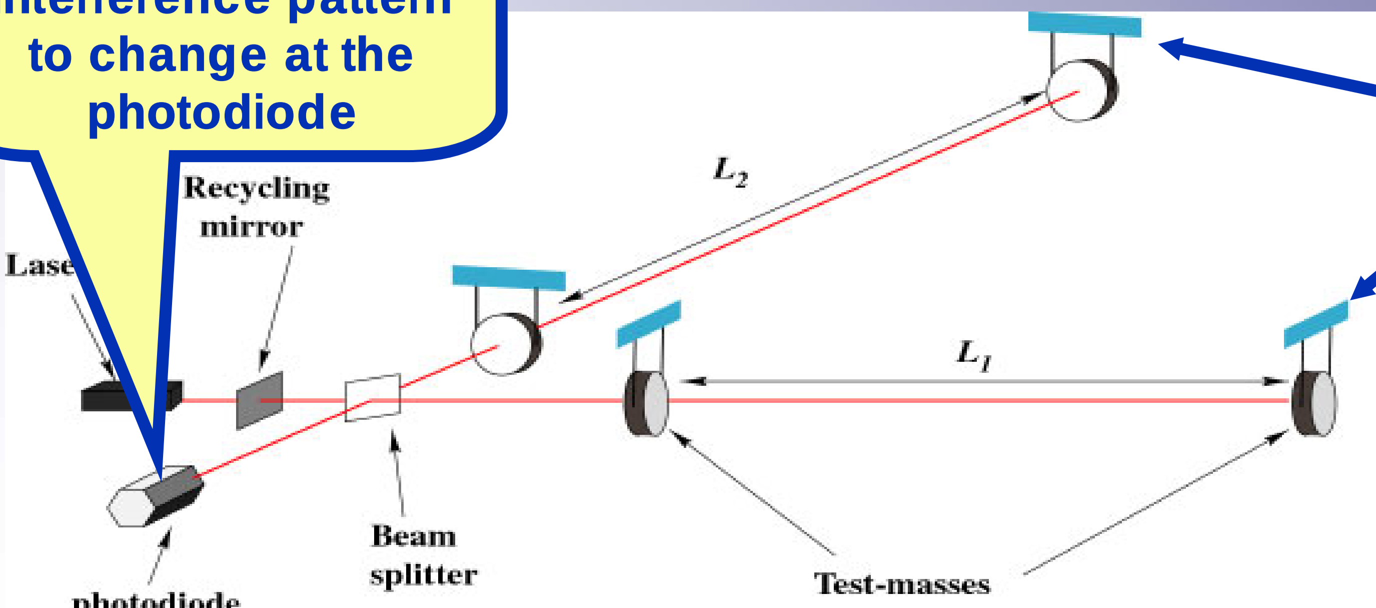
$$\delta L \sim h\ L$$

Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms

- **Arms in LIGO are 4km**
- **Measure *difference in length to one part in 10^{21} or 10^{-18} meters***

...causing the interference pattern to change at the photodiode



Suspended Masses

LIGO Louisiana 4 km armlength (US)

CURRENT DETECTOR STATUS

- Several large scale laser interferometric detectors constructed: armlength of 300 m to 4 km

- LIGO, VIRGO, GEO, TAMA, AIGO

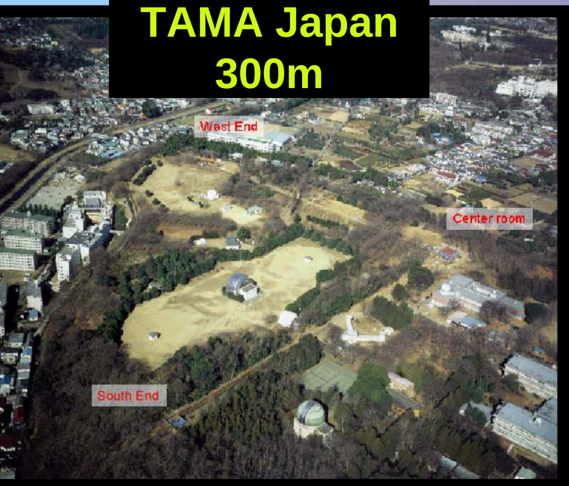
- S5 run of LIGO in progress from November 2005

- VIRGO: Science run

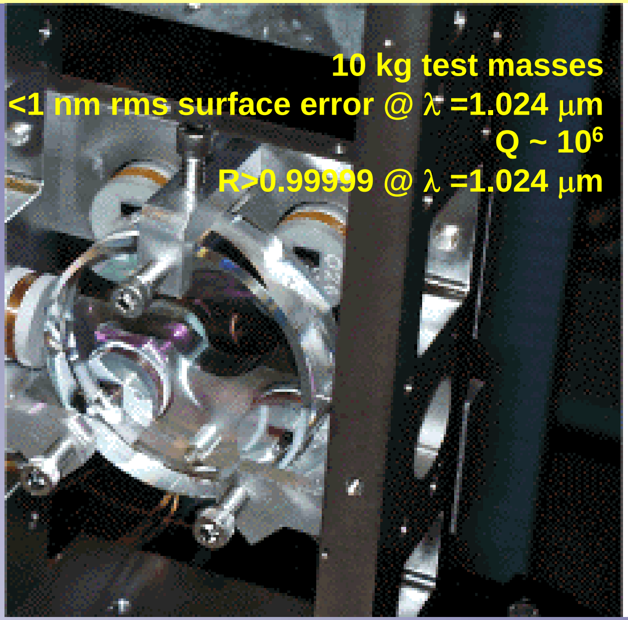
  - Space based detector LISA – 5 million km

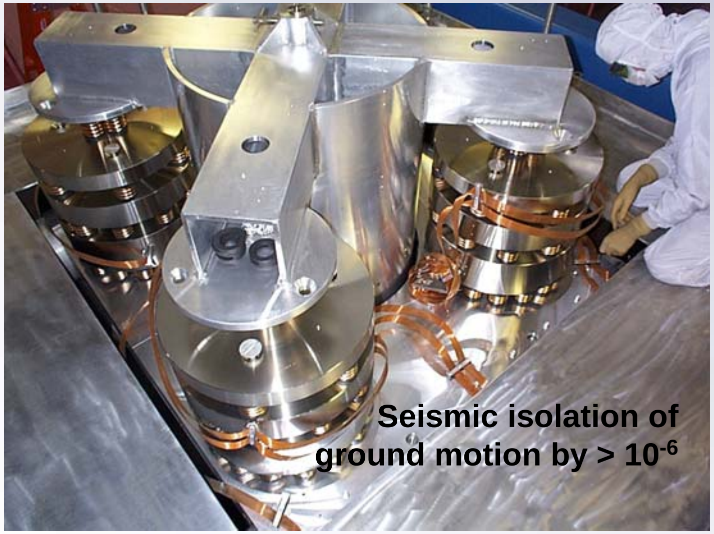
  - Launch in 2015

Interferometric Detectors

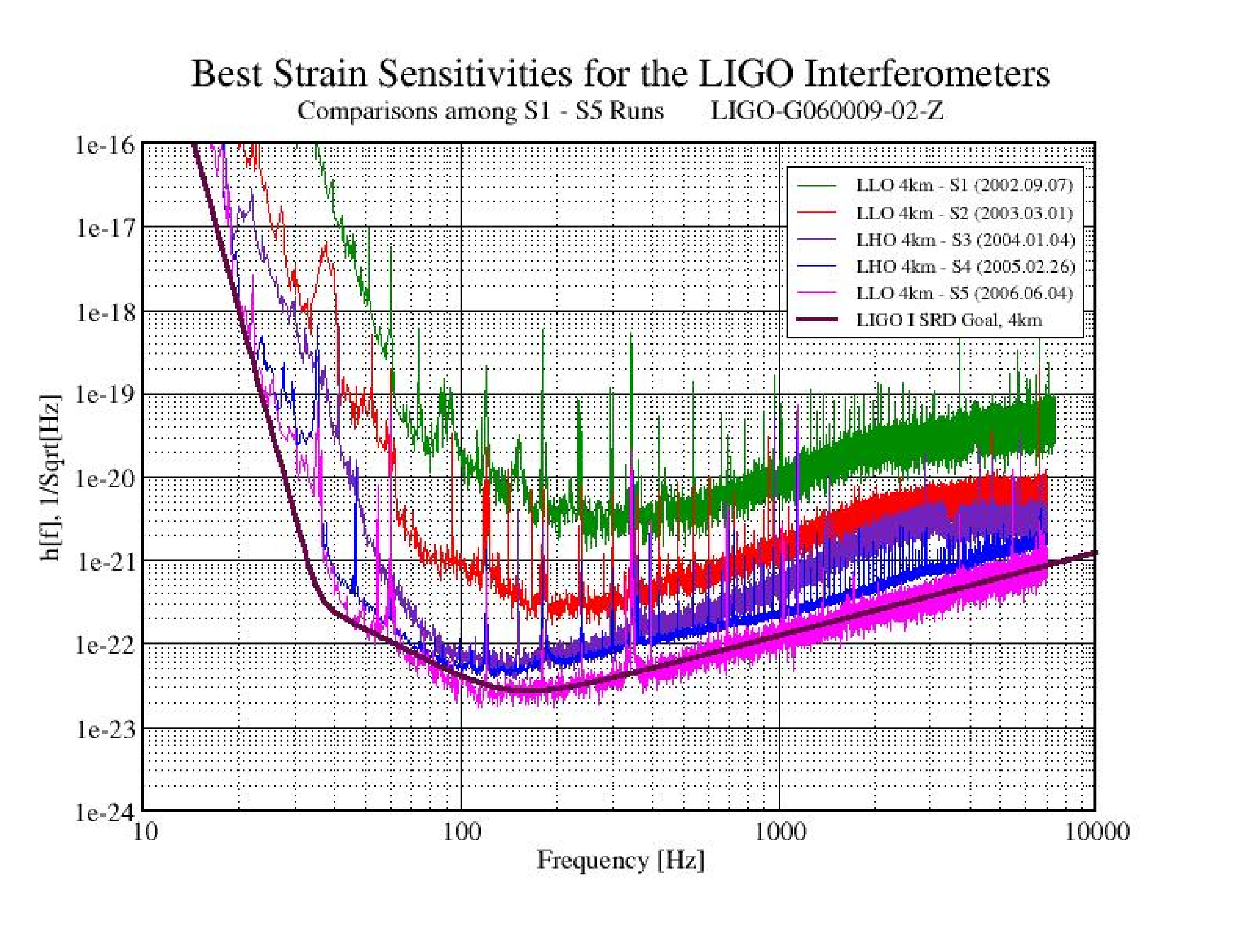


Technology pushed to the limits





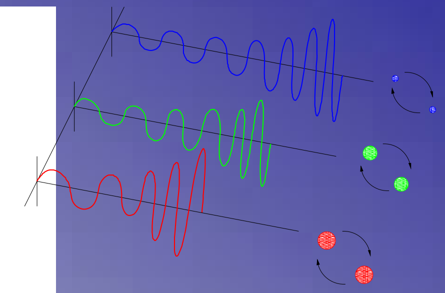
Experimental noise curves: Initial LIGO S1 – S5



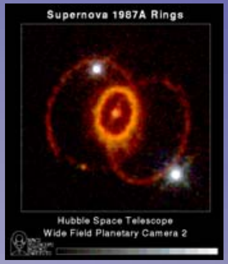
*http://www.ligocaltech.edu/~lazz/distribution/LSC_Data

Astrophysical Sources

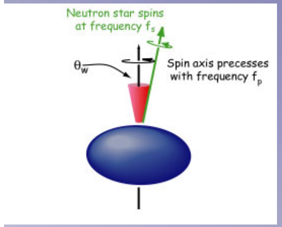
- Compact binary inspiral: *"chirps"*
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



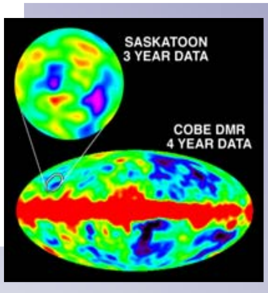
- Supernovae / GRBs: *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors



- Pulsars in our galaxy: *"periodic"*
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)



- Cosmological Signals *"stochastic background"*



Source Strengths

Binary inspiral:

$$h \sim 2.5 \times 10^{-23} \left[\frac{M}{M_{sun}} \right]^{5/3} \left[\frac{r}{100\ Mpc} \right]^{-1} \left[\frac{f_a}{100\ Hz} \right]^{2/3}$$

Periodic:

$$h \sim 1.9 \times 10^{-25} \left[\frac{I}{10^{45}\ gm.cm^2} \right] \left[\frac{f}{500\,Hz} \right]^2 \left[\frac{r}{10\ kpc} \right]^{-1} \left[\frac{\varepsilon}{10^{-5}} \right]$$

Stochastic background:

$$\tilde{h}(f) \sim 10^{-26} \left[\frac{f}{10\ Hz} \right]^{-3/2} \left[\frac{\Omega_{GW}(f)}{10^{-12}} \right]^{1/2}$$

Data Analysis !

Setting upper limits

• Although at this early stage no detection can be announced we can place upper limits for example on the inspiral event rate

$$P(\rho > \rho^*) = 1 - e^{-N_G(\rho^*)\,R\,T}$$

For example for S2 data:

$$R_{90\%} < 35\, y^{-1}\, MWEG^{-1}$$

A rate > than above means there is more than 90% probability that one inspiral event will be observed with SNR > highest SNR observed in the data.

Much better event rate from S3, S4, S5 data!

Astrophysical Results

- Chirps:
  - S2: 385 hours of coincident (2X, 3X) interferometer operation
  - Sensitive to D ~ 2 Mpc
  - R 90% < 35 events/year/MWEG (Component masses: 3 Msun - 20 Msun)

- Bursts:
  - S2: For $h \sim 10^{-19} - 10^{-20}$, R 90% < 0.26/day (limited by observation time)
  - Minimum $h \sim 10^{-20}$ - ~ **8 times better** over previous S1 result
  - S2: 50% detection efficiency $h \sim 10^{-20}$

- Periodic:
  - S2: LIGO & GEO interferometers -- Targeted 28 known pulsars
  - $h < 1.7 \times 10^{-24}$ (J1910-5959D)
  - $e < 4.5 \times 10^{-6}$ (J2124-3358) - Bayesian methods employed
  - Crab limit on h within 30X of spindown rate, if spindown were due to GW emission
  - **Order of magnitude better than S1 results**
  - All sky search upper limit: $h \sim 4.43 \times 10^{-23}$

- Stochastic background:
  - S4: cross-correlation statistics – **13 times** improvement over previous S3
  - Sensitivity estimated to be $\Omega_{GW} < 6.5 \times 10^{-5}$ 50 Hz < f < 150 Hz

The LIGO Scientific Collaboration

500 scientists at 42 institutions
27 US & 15 international

Towards the Detection of Gravitational Waves

- From Initial LIGO → Advanced LIGO
  → Next Generation LIGO (QND)
- From 14 Mpc (NN inspiral) → 200 Mpc and beyond
- From Upper Limits → Searches → Detections
- From Generic Waveforms → Specified Waveforms
- From Single Detectors → Global Networks

Stochastic GW background: Directed search

S.Mitra, SVD, T. Souradeep, A. Lazzarini, V. Mandic, S. Bose (2007)

• Produced by unresolved gravitational wave sources – Blackhole mergers, r-modes, LMXBs, …

Waveforms not well modelled

• **Statistic**: Cross-correlation between two detectors

with a directed optimal filter Q

$$S\left(\hat{\Omega}\right) = \int dt \iint dt'\, dt''\; s_1(t')\, s_2(t'')\; Q(\hat{\Omega}; t, t' - t'')$$

The Directed Optimal Filter

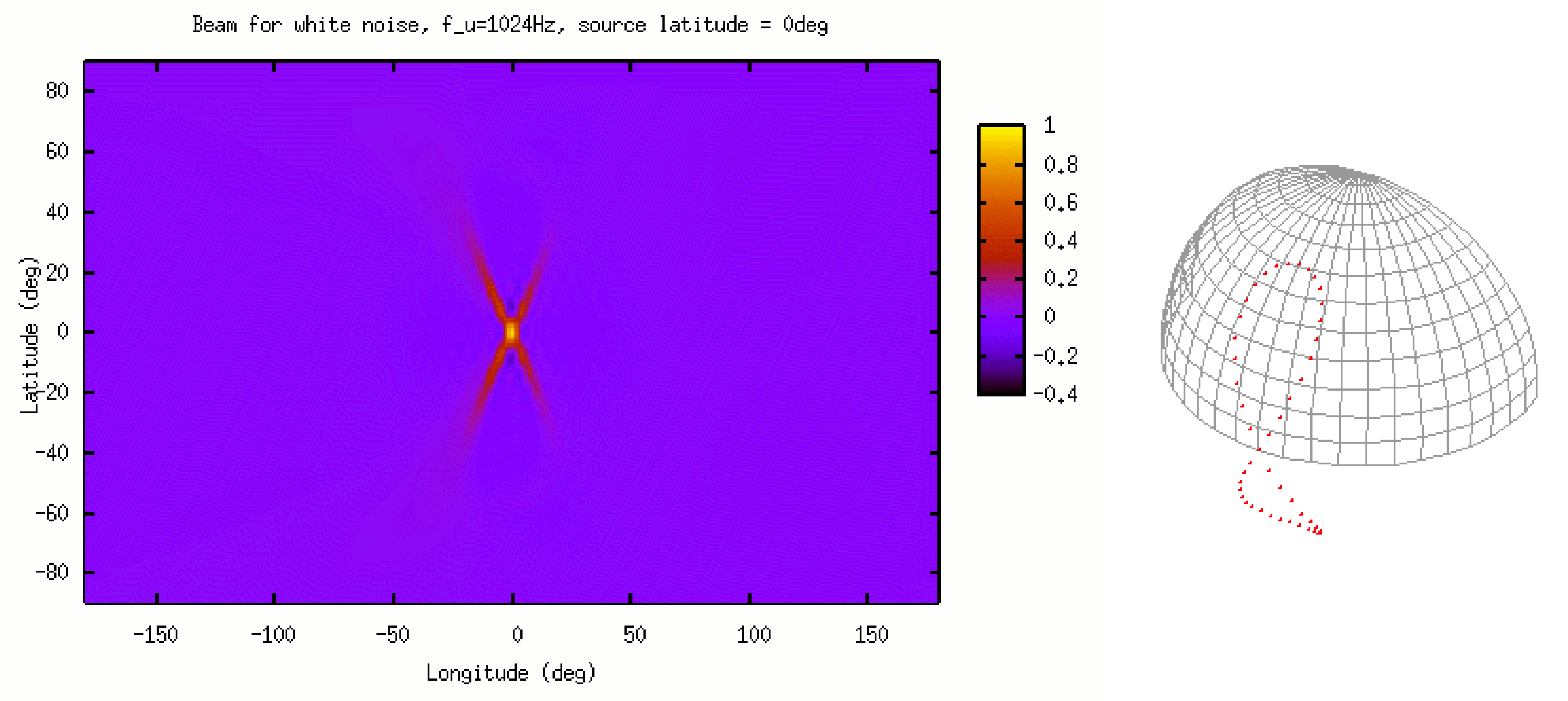
The Fourier transform of Q:

$$\tilde{Q}\left(\hat{\Omega}, t; f\right) = \frac{H(f)}{P_1(f)\,P_2(f)}\,\gamma^*(\hat{\Omega}, t; f)$$

For a point source with equal power in both polarisations:

$$\gamma(\hat{\Omega}, t; f) = \left[F_{1+}(t;\hat{\Omega})\,F_{2+}(t;\hat{\Omega}) + F_{1\times}(t;\hat{\Omega})\,F_{2\times}(t;\hat{\Omega})\right] e^{2\pi i f \hat{\Omega}\bullet\Delta\vec{x}(t)/c}$$

The Kernel or Point Spread Function



LIGO detectors

Point Source on the equator – **Image not a point !**

De-convolving the GW sky-map

The integral equation must be inverted !

$$\mathbf{D} = \mathbf{B}\,.\,\mathbf{P} + \mathbf{n}, \qquad D_i = D(\Omega_i)$$

D : data

B : known beam matrix

P : GW power distribution over sky pixels

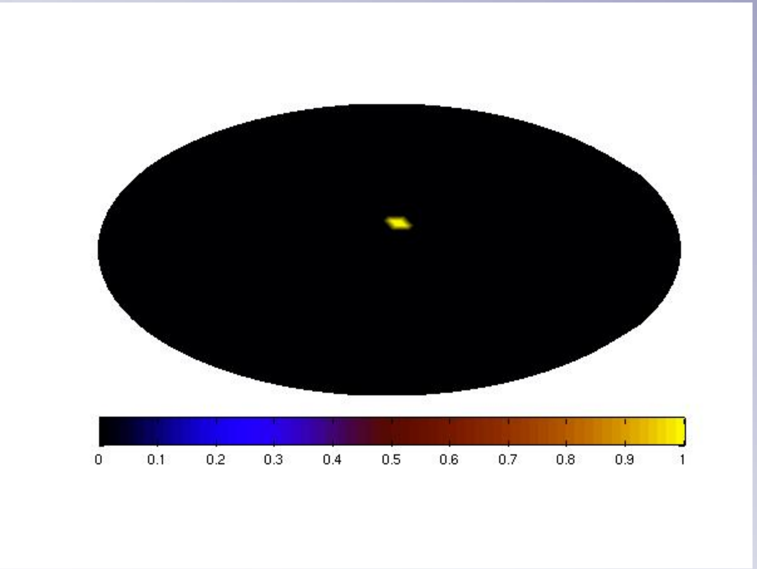
n : noise Gaussian distributed

Solution:

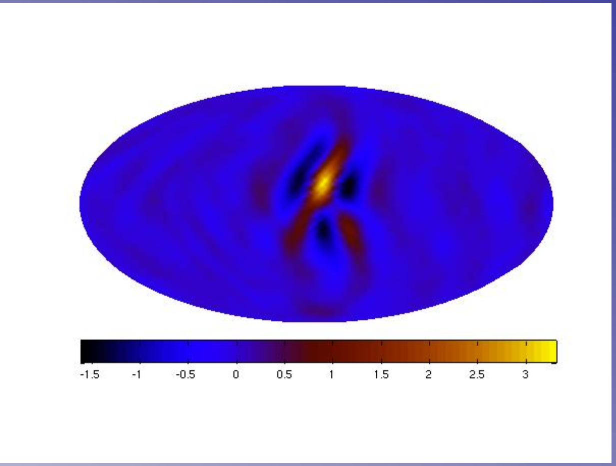
ML estimator: $$\hat{\mathbf{P}} = (\mathbf{B}^{T}\mathbf{N}^{-1}\mathbf{B})^{-1}\mathbf{B}^{T}\mathbf{N}^{-1}.\mathbf{D}$$

Solution for a broadened point source

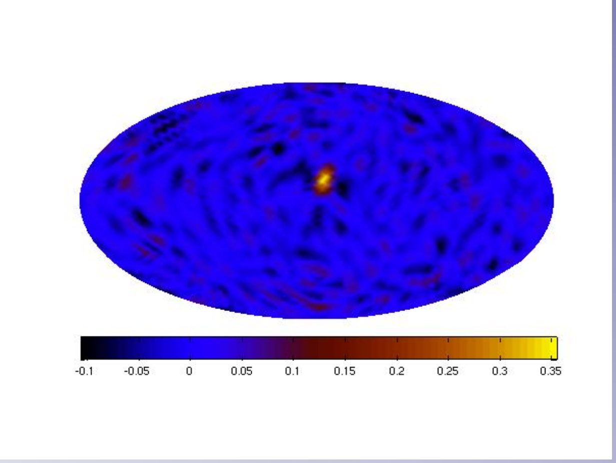
Source 4 pixels:



Dirty:

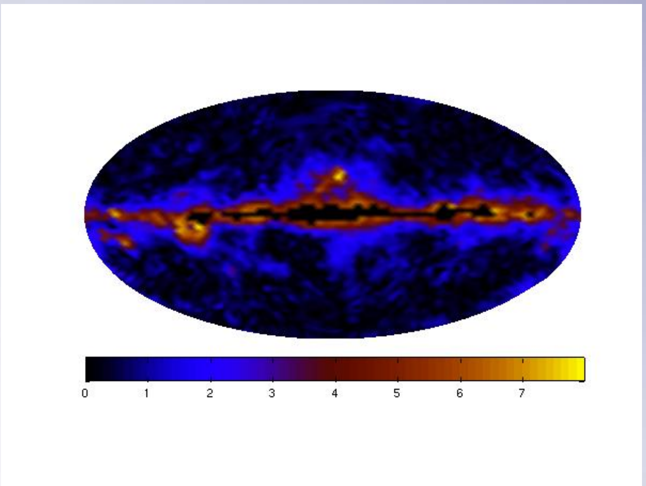


Cleaned:



Solution for a `galactic distribution’

Source:



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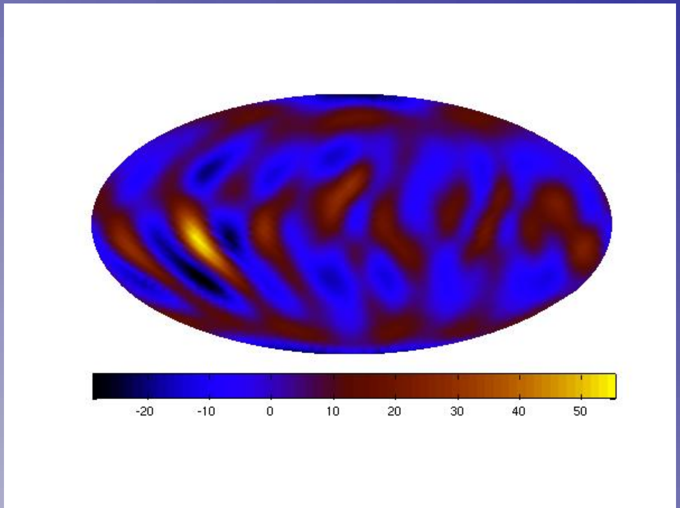

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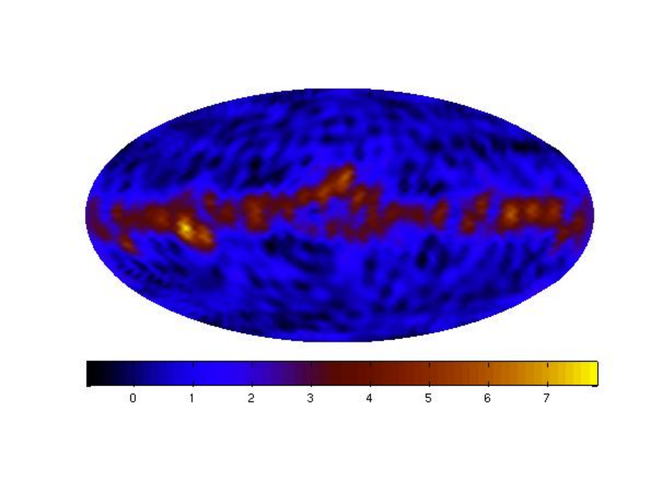
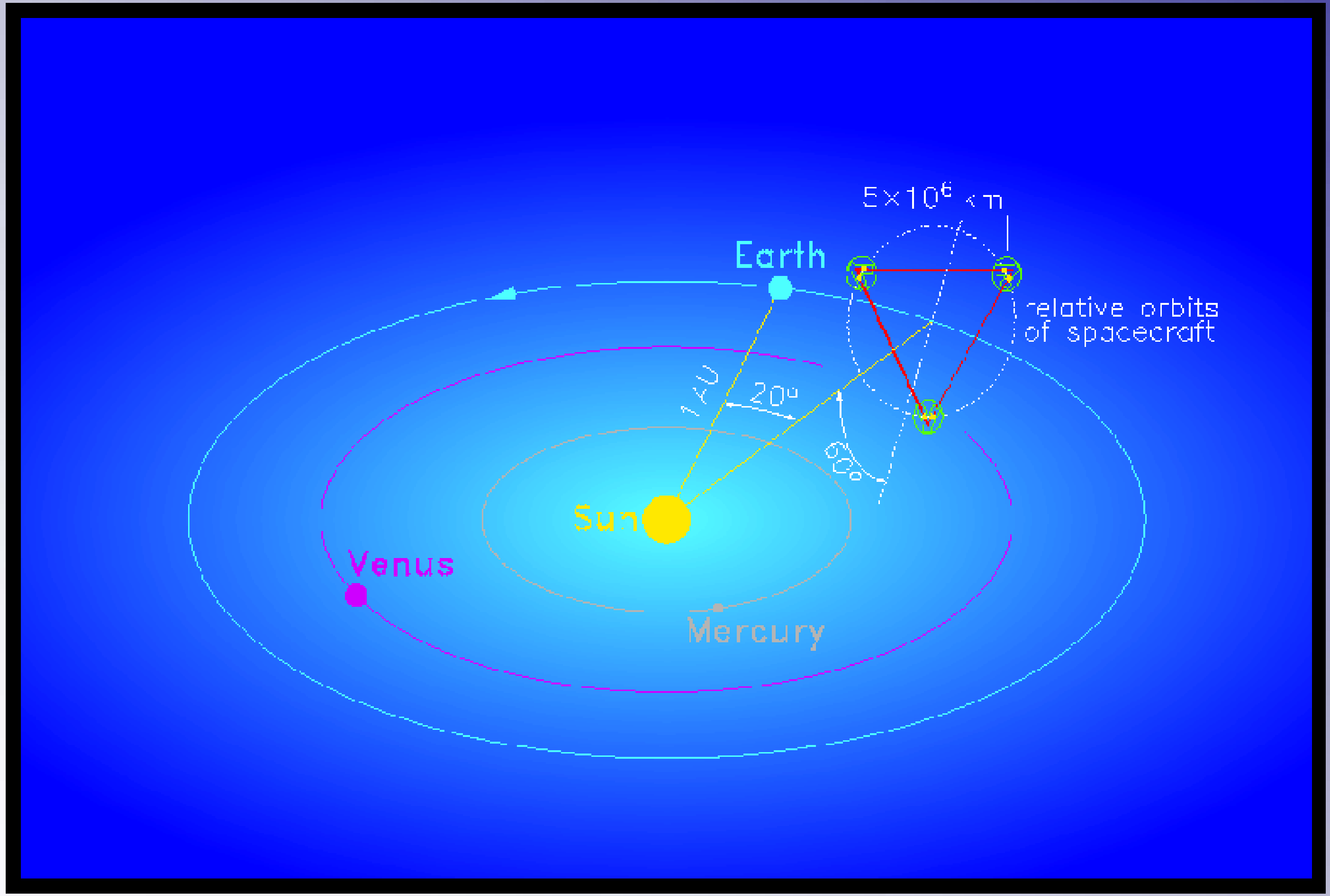


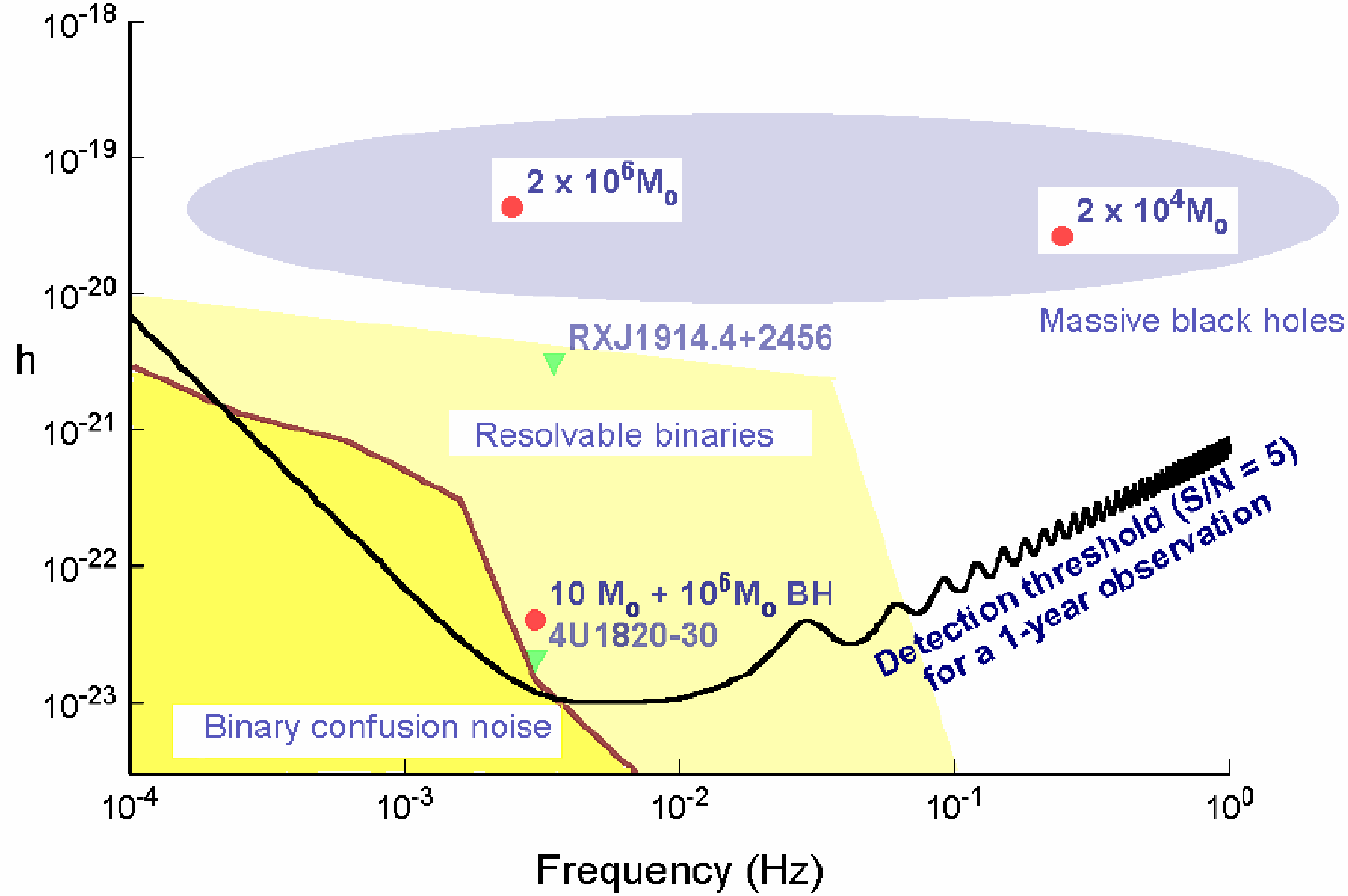
LISA

- A Collaborative ESA / NASA Mission to observe low-frequency gravitational waves
- Cluster of 3 S/C in heliocentric orbit at 1 AU
- Equilateral triangle with 5 Million km arm-length
- Trailing the earth by 20°
- S/C contain lasers and free-flying test masses
- Equivalent to a Michelson interferometer

LISA: Space based detector for detecting low frequency GW



LISA sensitivity curve



- Confusion noise – problem not faced by ground-based detectors
- Low frequency long duration sources

LISA SCIENCE

Fundamental Physics:

- Tests of strong field GR by mergers of comparable mass BHs:

  - Area theorem – before(inspiral)/after(ringdown) measurements of M and J
  - Cosmic Censorship – is a/M > 1 after merger?

  - EMRIs – typically $\mu/M \sim 10^{-5}$ – 10 $M_\odot$ BH falling into 10^6 $M_\odot$ BH – event rate ~ 100 /yr out to z ~ 1

  High SNR: 30 - 300 - Test no-hair theorem ~ detailed waveforms with 10^5 cycles in the last year – M, S to fractional accuracy ~ 10^{-4}

  Kerr quadrupole moment = $- S^2 / M = Q$

  $\Delta Q \sim 10^{-2} - 10^{-4}$ at SNR = 100 (Barack & Cutler 2006)

- Observe GW bursts from cosmic strings or other exotic sources

LISA SCIENCE contd

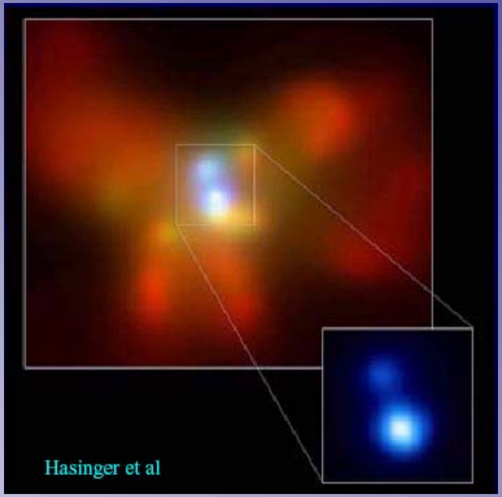
Astrophysics:

- Detect MBH $\geq 10^5 M_\odot$ mergers

  Event rate: 10 – 35 yr $^{-1}$

  SNR ~ 10^3 at z = 1 for M ~ 10^5 $M_\odot$

  E. Berti (2006), Sesana, Volonteri (2006)



- Study compact WD binaries

  - obtain mass spectrum …

- Detect hundreds of EMRIs

  - obtain spectrum of masses, spins

- Discover unexpected sources, dark matter components

LISA data analysis at IUCAA

Time-delay Interferometry (TDI)

- Cancellation of laser frequency noise and other systematic noises – optical bench motion, clock jitter, etc,

IUCAA-Nice group – SVD, J-Y Vinet, R. Nayak, A. Pai, S. Koshti, B. Chauvineau

$$\frac{\Delta \nu}{\nu_0} \sim 10^{-14} \qquad h \sim 10^{-21}$$

Noise cancellation required to 1 part in $\sim 10^7$

Combine time-delayed data streams: Algebraic operation

Module of syzygies: Space of TDI combinations

SVD, R. Nayak, J-Y Vinet, Phys. Rev. D 65, 102002 (2002)

Real World Model of LISA

- Previous analysis for stationary LISA – Analysis needs to be generalised to include moving LISA, changing arm-lengths - second generation TDI: Tinto & SVD Liv. Rev. Rel. 8, 4 (2005) combinatorial approach M. Vallisineri, Phys.Rev. D 72, 042003 (2005).

- Non-stationarity – Sagnac effect: $\Delta (L_1 + L_2 + L_3) \sim$ 28 km

- Changing armlengths – $\dot{\Delta L} \sim 10\, m / \sec$

General relativistic **dynamical** model of LISA required: Sagnac effect, changing arm-lengths, gravitational redshift, Shapiro delay
LISA simulator: SVD, J-Y Vinet, B. Chauvineau (2007)

Basic questions: What is operationally a time-delay?
GPS, Fermi-Walker transport of the LISA frame

FUTURE DIRECTIONS

- Global Network of detectors LIGO, VIRGO, TAMA, GEO, AIGO

- Advanced detectors: Improvement in amplitude, bandwidth sensitivity

  Event rate improvement: ~ 10^4

- LISA will open the low frequency window: 10^{-4} Hz – 1 Hz

Hopefully detections should begin soon with ground- based detectors!