Preparing for gravitational wave detection with LISA

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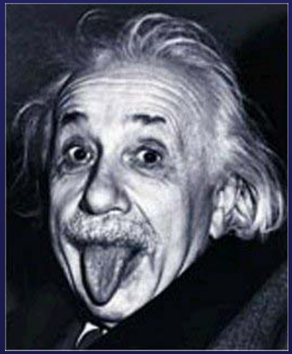
- Gravitational Waves
- Laser Interferometer Space Antenna in a nutshell
- LISA Target Sources
- LISA Pathfinder: a precursor mission
- Dutch contribution to LISA Pathfinder

General Theory of Relativity

- Space-time is curved by mass (energy)
- Space-time is an elastic medium
- Space-time can sustain transverse waves: Gravitational Waves
- For the specialist:

$$g_{\mu\nu} - \eta_{\mu\nu} \equiv h_{\mu\nu} = A_{\mu\nu} \cos(2\pi f t - \vec{k} \cdot \vec{x})$$

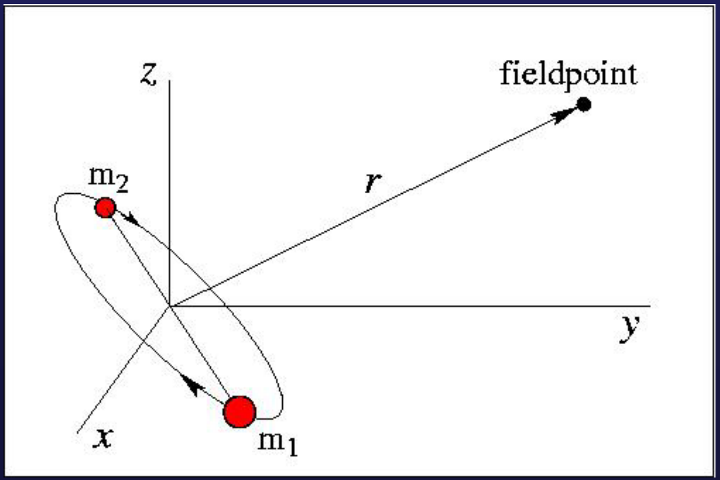
Metric — Minkowski-metric — Strain



Sources of Gravitational Waves

- Source = accelerating masses
- EM waves: predominantly dipole
- GR waves: predominantly quadrupole:

$$\mathbf{h}(t) = \frac{2G}{c^4}\frac{1}{r}\frac{d^2}{dt^2}\int \rho(\mathbf{x},t)\mathbf{x}\mathbf{x}dV$$



- Note: *1/r* dependence of strain *h*

Typical Sources of GW's: binary sources

- Binary with period of 1 hour induces strain variation of 1/2 hour: Binary orbital frequency *f* is observed at 2*f*.
- Signal strength decreases with source distance ($h \sim 1/r$)
- Stable periods give a "delta"-peak in frequency spectrum
- Close binaries have observable slowdown of period due to GW radiation losses -> period drift ("chirping") in frequency spectrum

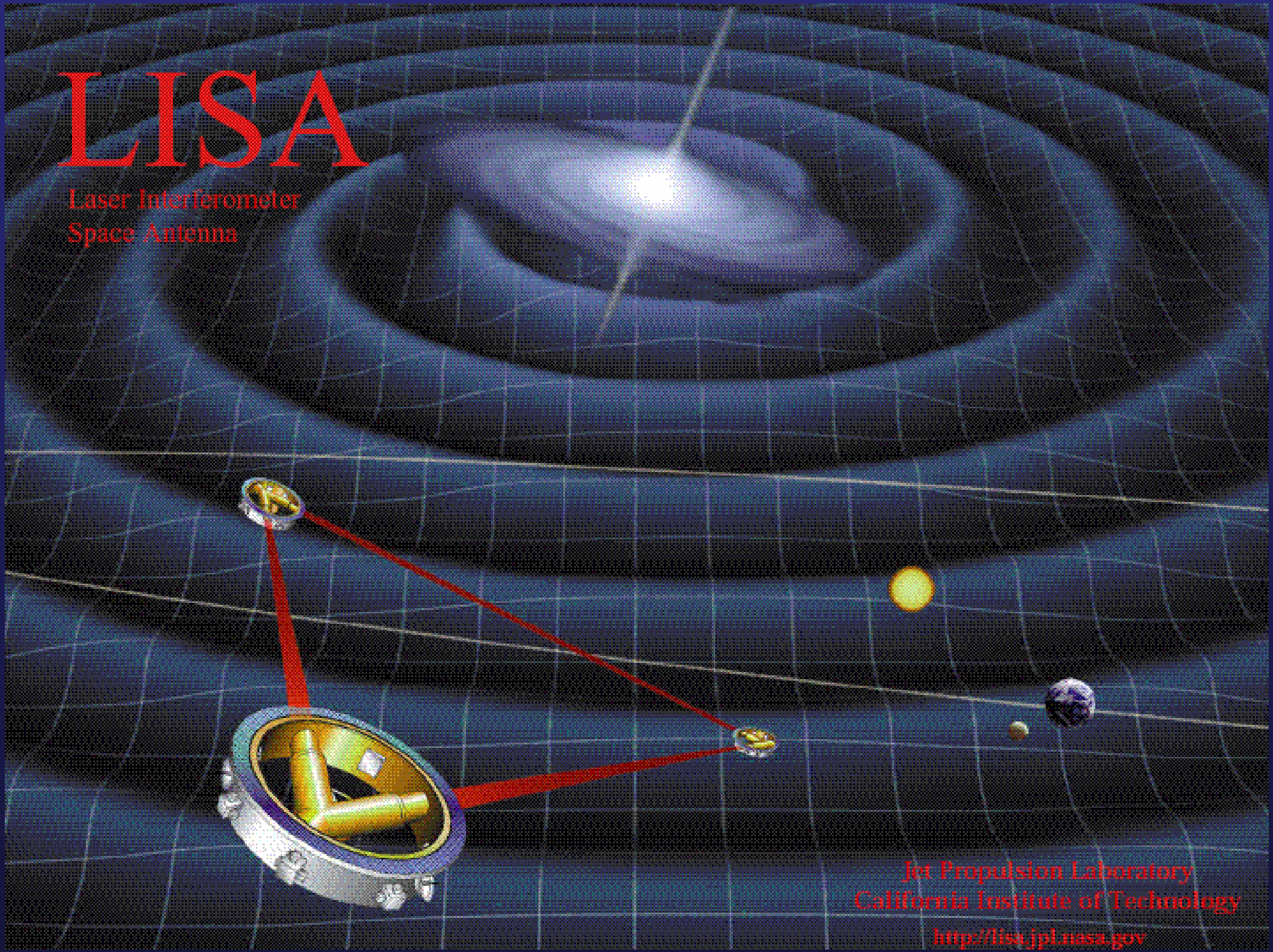
Detection of Gravitational Waves on Earth

- Resonant mass detectors
  - miniGrail (Nl), spherical mass (operational!)
  - Nautilus (It), bar
  - Explorer (Swz), bar
  - Allegro (USA), bar
  - ...
- Laser Interferometers
  - LIGO (USA)
  - VIRGO (Fr, It)
  - GEO 600 (Ger)
  - TAMA 300 (Jp)
  - AIGO (Au)

G-Waves have never been detected directly so far….but more & more ground based observatories are operational!

LISA (Laser Interferometer Space Antenna)

Launch: ~2012



LISA summary

- Laser Interferometer Space Antenna
- **Goal** : Detection and observation of low-frequency Gravitational Waves

  ($10^{-4} < f < 10^{-1}$ Hz)
- Method: Laser Interferometry
- ESA + NASA mission
- Target launch date: 2012

LISA measurement principle

- Strain variations induce length variations:

$$\frac{\Delta L}{L} = \frac{1}{2} h$$

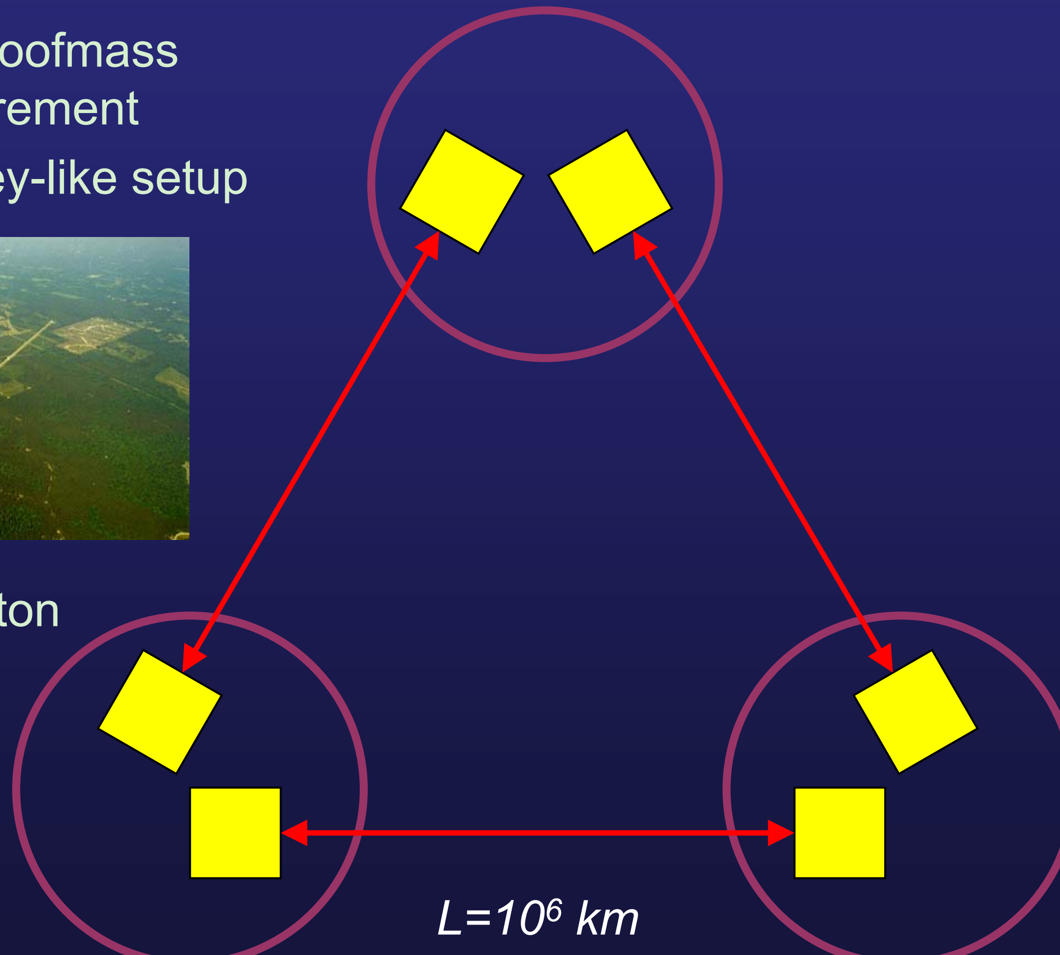
- Gravitational wave detection principle: Set up an arm of length L and detect changes ΔL in arm-length.
- Method: Laser Interferometry.

- LISA arm-length: $5\text{x}10^6$ km.
- Induced variations from $h=10^{-21}$ (galactic binary) are ΔL ~ $2.5\text{x}10^{-10}$ cm ~ 0.03 r_H.

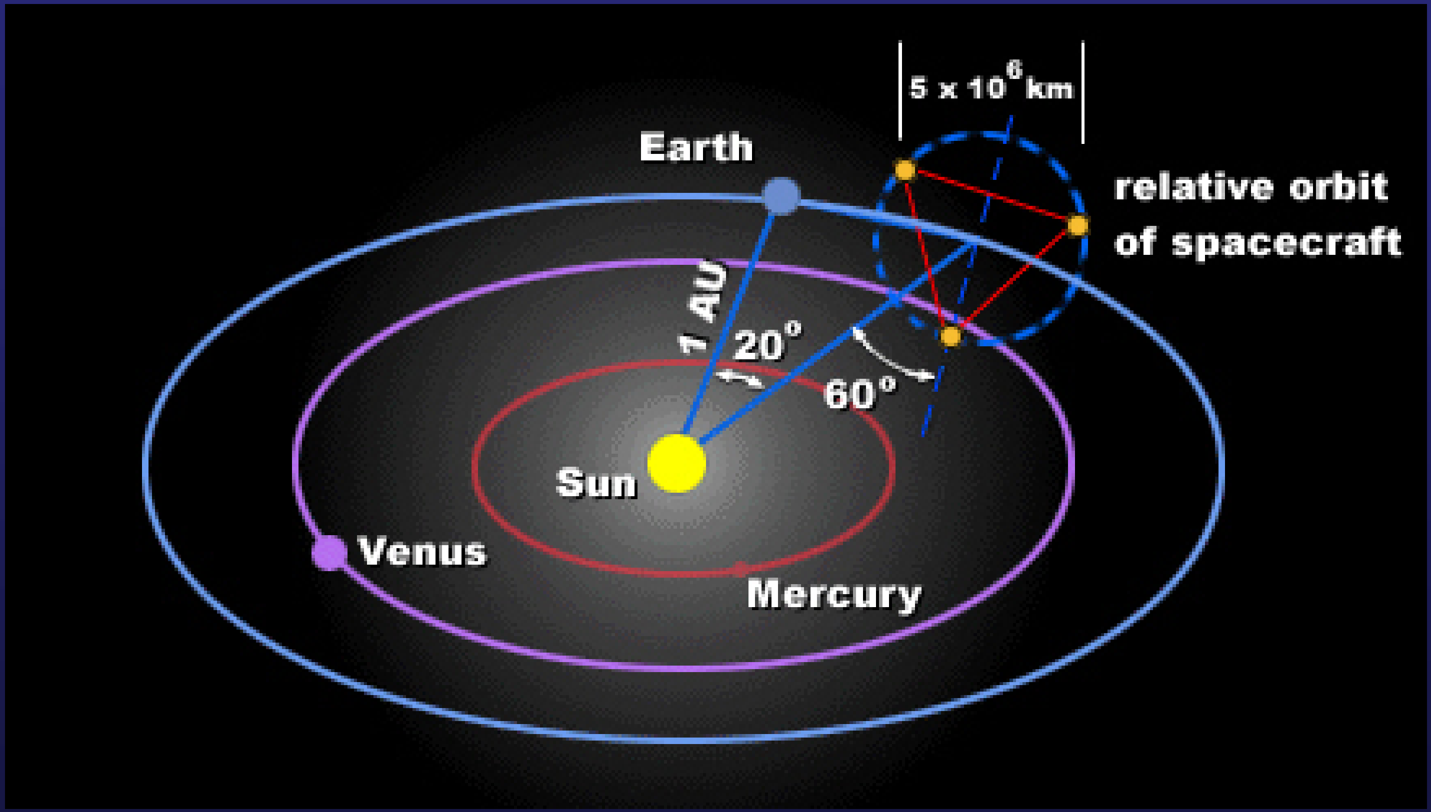
LISA system

- Proofmass-to-proofmass distance measurement
- Michelson-Morley-like setup

LIGO-Livingston
L=4 km



LISA orbit



5 x 10^6 km
Earth
relative orbit
of spacecraft
1 AU
20°
60°
Sun
Venus
Mercury

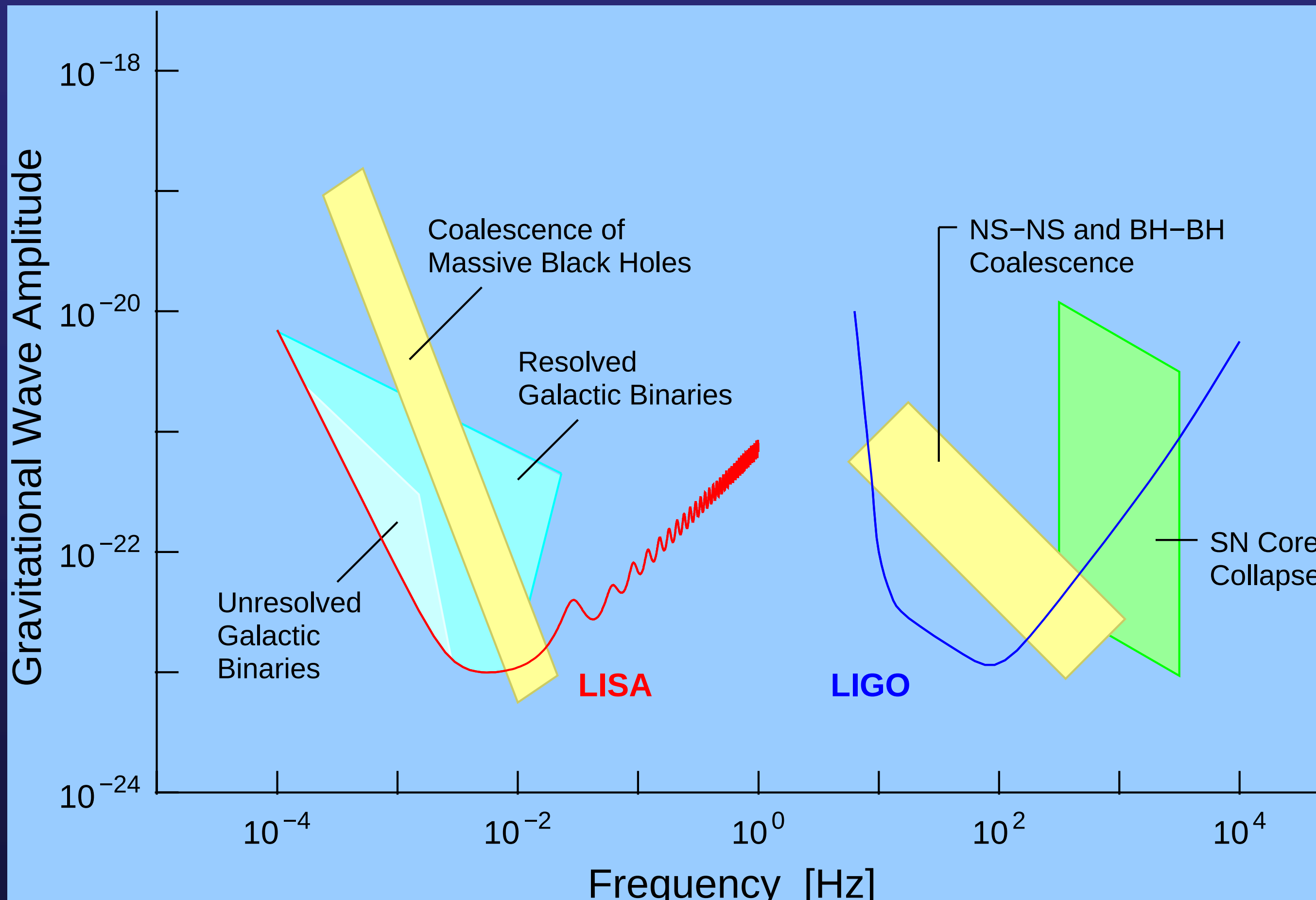
LISA Scientific objectives (1)

- Merging supermassive black holes (SMBH) in galactic centers
  - *Formation, evolution, relation to galaxy formation and mergers, cosmological information, numerical modelling*
- Signals from gravitational capture of small BHs by SMBHs
  - *Event rates, modelling of very complex waveform (radiation-reaction), accuracy of tests of BH uniqueness theorems of general relativity*

LISA Scientific objectives (2)

- Survey of all galactic binaries with sufficiently short periods
  - *Population statistics, confusion by large population at lower frequencies, confusion limit on signal extraction, information extraction from observations*
- Backgrounds, astrophysically generated and from the Big Bang
  - *Strength and spectrum of astrophysical backgrounds, production of early-universe radiation, relation to fundamental physics (string theory…)*
- Bursts, unexpected sources

LISA Sensitivity (& LIGO)



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LISA Target sources

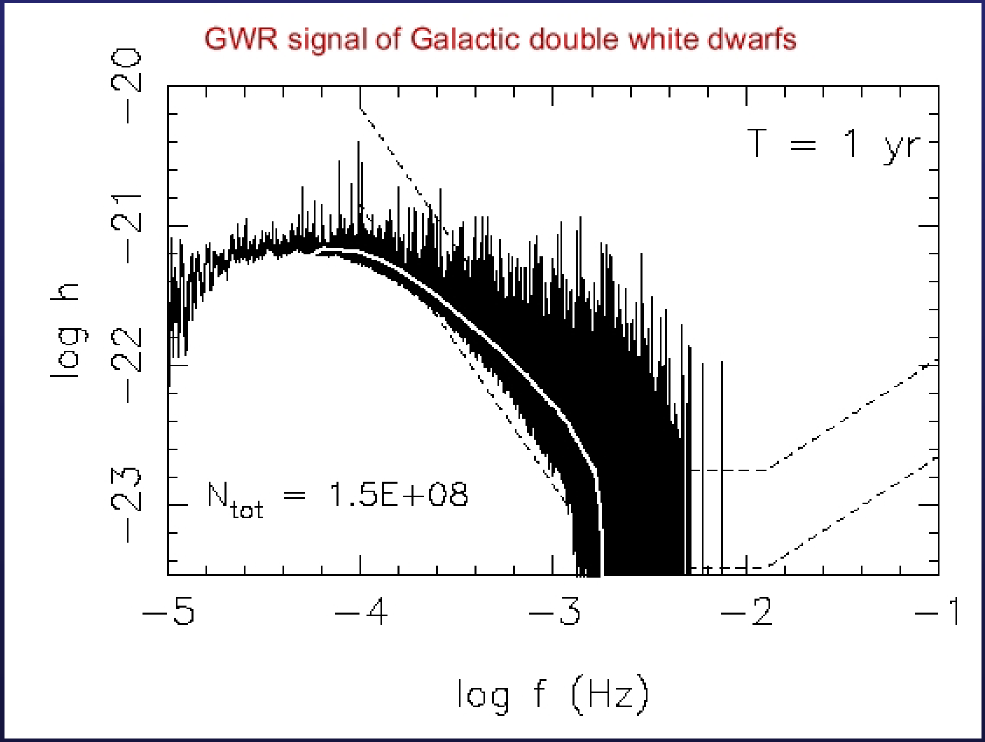
- Galactic Binaries
  - Hulse-Taylor NS-NS like systems
  - NS+BH, MS+BH, …
  - WD-WD systems
- Massive Black holes
  - Merging MBH’s in colliding galaxies
  - Capture of small BH by MBH
- Others…

Galactic binaries: WD-WD systems

- WD-WD Binaries are numerous (billions), but:
- In one LISA frequency bin more than one source

Galactic Binaries: WD-WD systems

- Population synthesis models predict GW signal from WD-binaries



Gijs Nelemans et al (2002).

Galactic binaries & LISA

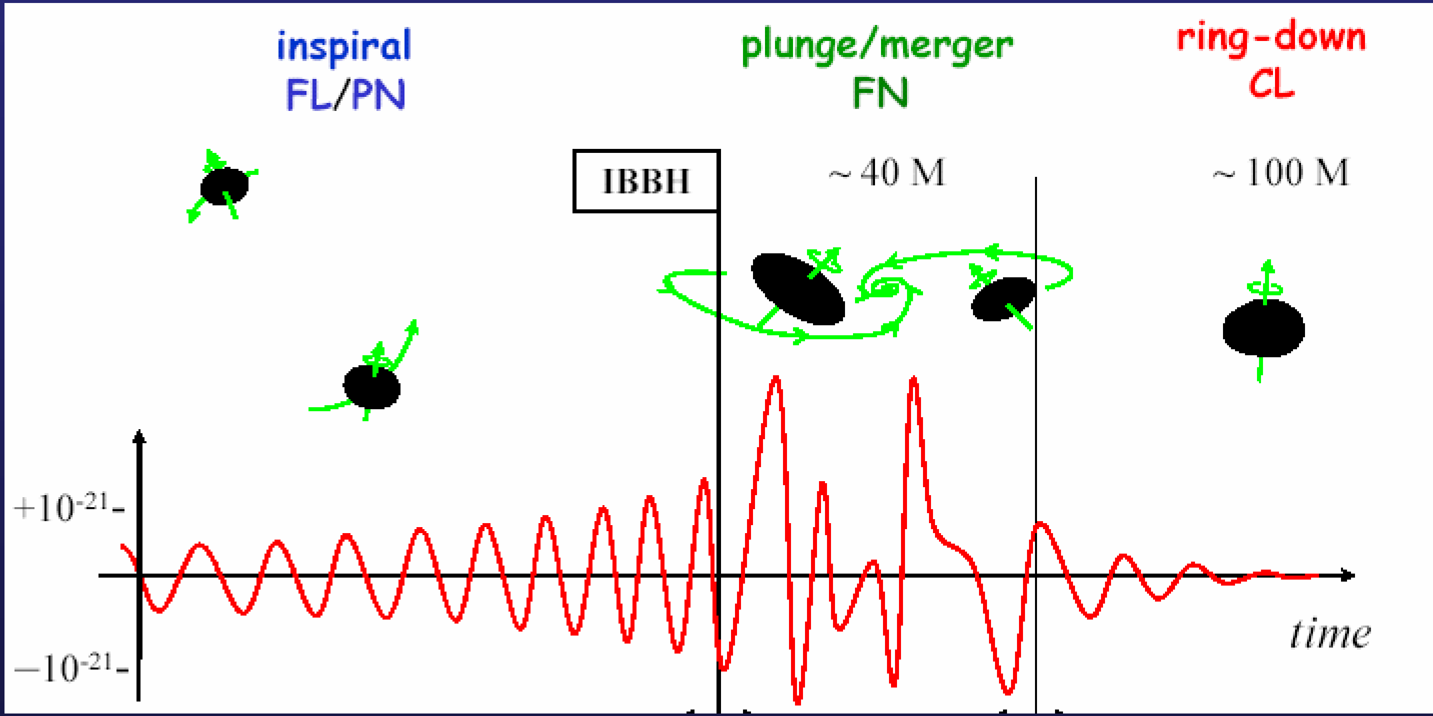
What can be learned from LISA observations?

- For identified binary LISA gives orbital inclination and orientation.
- From isolated and identified sources confusion limited background shape can be inferred.
- Constraints on NS-NS, WD-WD birthrates and galactic spatial structure.

Massive Black holes

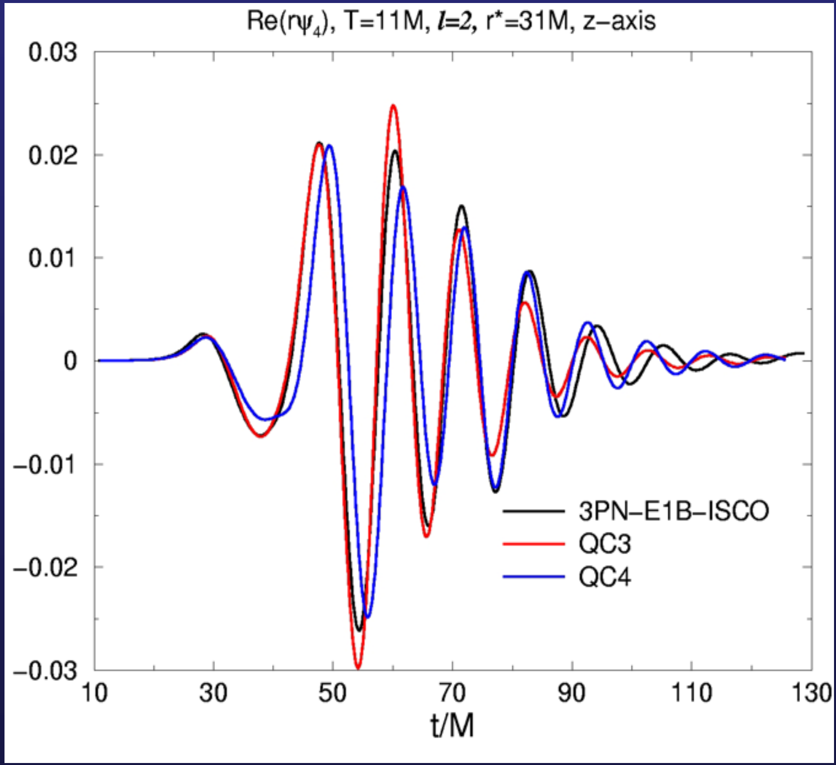
- Black holes in galactic cores: BH Mass ranges 10^4 -10^9 M
- Formation scenario of (V)MBHs: merger of MBHs.
  - Most energetic phenomena in universe
  - Dark in EM, all energy in G-waves.
  - Power: LISA will see it from anywhere in the universe
  - MBHs originate from colliding galaxies.
- Formation scenario 2: MBH eats small BHs

MBH Merger signal



Modeling MBH Merger

- Modeling of merging MBHs= Number crunching numerical solution of Einstein (non-lin.) eq'ns.
- Outcome: detected waveform
- Solution depends on approach/assumptions
- LISA will be able to discern between solutions



Massive Black Holes & LISA

What can be learned from LISA observations?

- Merging massive black holes:
  - Amplitude, chirprate and polarization give distance!
  - Formation and evolution
  - Cosmological info: decceleration rate
- Merging of BH with MBH:
  - Event rates
  - Understanding of complex waveform (radiation-reaction)
  - Mapping Spacetime near Kerr Black Hole
  - Accuracy of tests of BH uniqueness theorems of general relativity (BH=probe of MBH)

Today's challenge: LISA data reduction

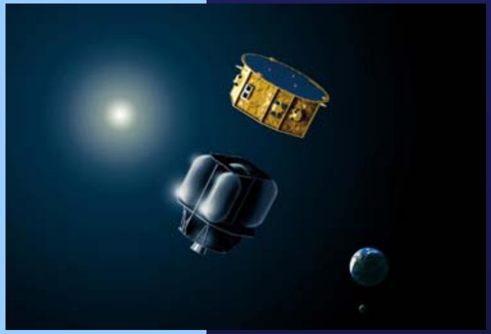
- Detected signal *h(t)* is sum of signals from all sources from everywhere

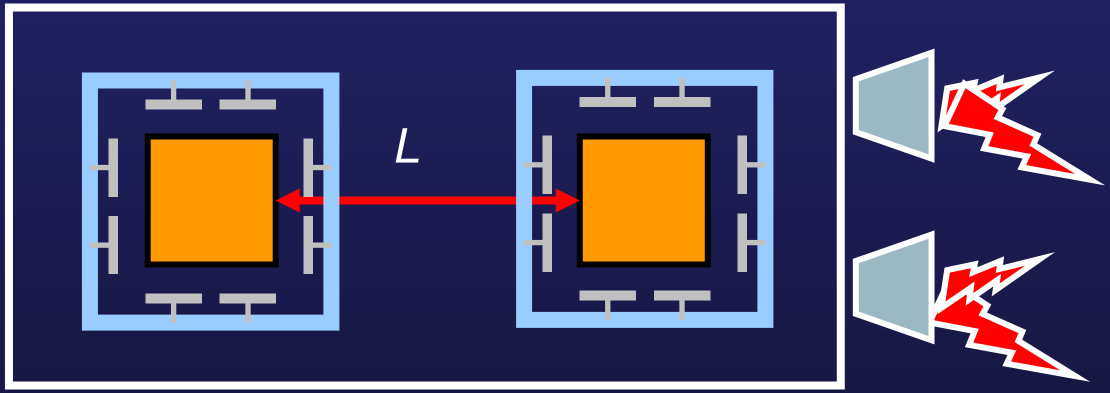
$$h(t) = \sum_k A_k \cos(2\pi f_k t + \varphi_k) + \ldots$$

- Retrieve A_k, ω_k , $\varphi_{k,}$,… from *h(t).*
- Cocktail party problem: record the party and then reconstruct each conversation.
- Needed: A-priori knowledge of signals waveforms

LISA Pathfinder

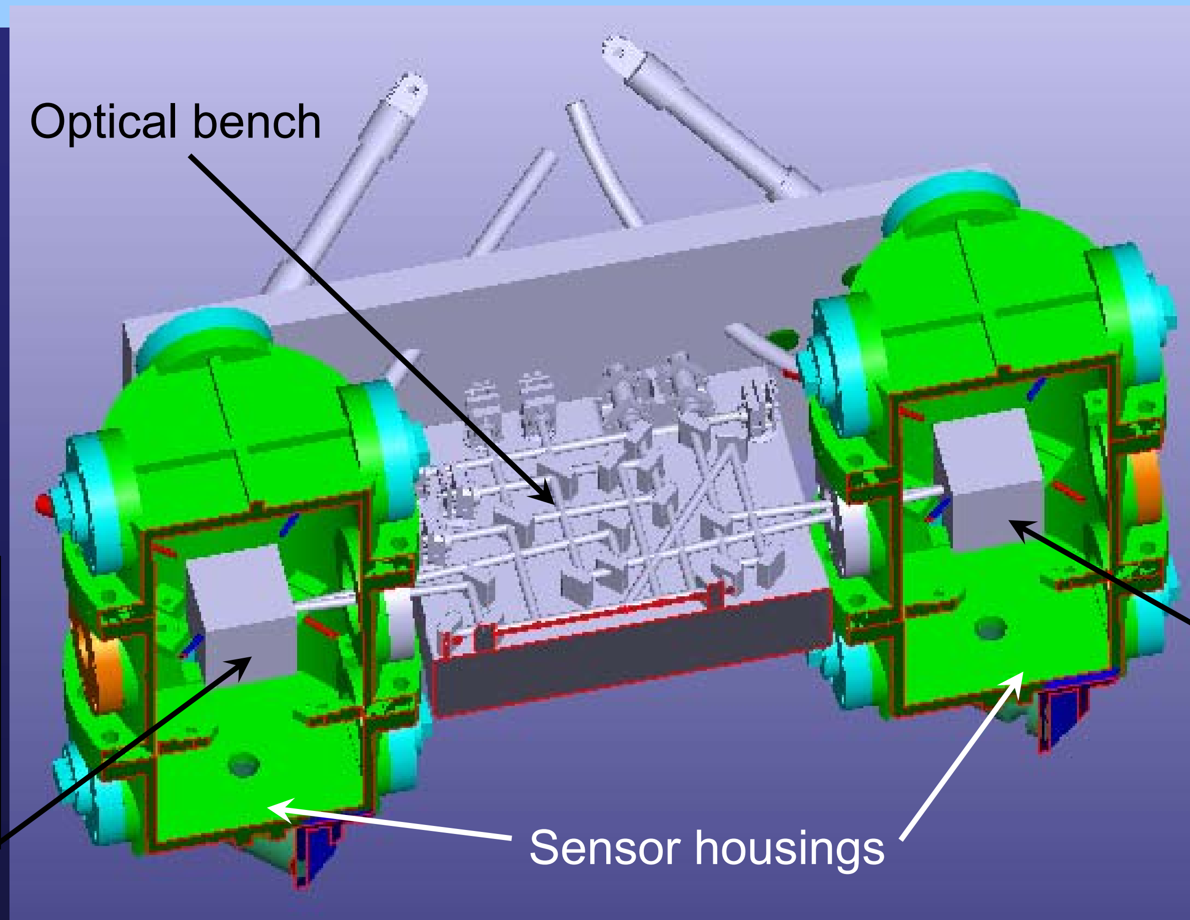
- **Goal** : demonstrate free-fall of a proofmass, i.e., isolation from non-gravitational disturbances.
- Method: Laser Interferometry between two proofmasses (PMs)





- Spacecraft = shield

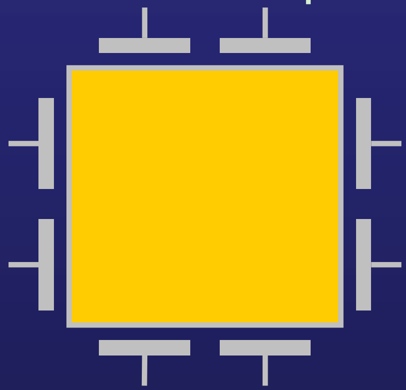
LISA Pathfinder

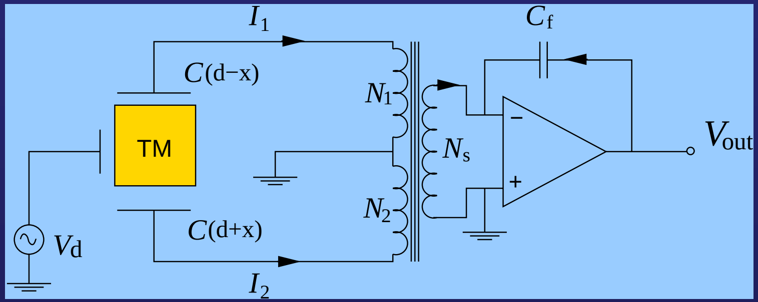


Dimensions: 640 mm x 375 mm x 375 mm

LISA Pathfinder key technologies

- Test-mass position sensing: Capacitive sensing.





- Drag-Free control.
- FEEP micro-Newton thrusters.

NL in LISA Pathfinder

SRON:

- Test equipment for position sensor read-out electronics in on-ground tests of the satellite system
- Simulation software modules of the position sensors, used in system simulations

TNO-TPD:

- Test equipment of the Laser Optical Bench
- Decaging Mechanism (TBC)

Bradford Engineering

- Cold Gas propulsion (TBC)

Preparing for LISA

Dutch participation in LISA…?

- Ambition: Hardware contribution
  - SRON: Read-out electronics
  - TNO: De-caging of test-mass
  - …..
- Science challenges:
  - A-priory knowledge of signal sources
  - Galactic overpopulation of GW sources
  - Understanding MBH merging phenomena and
  - associated waveforms
  - MBH merger rates
  - LISA data reduction process
  - Etc…