

Preparing for gravitational wave detection with LISA

J. Martijn Smit
**SRON Netherlands Institute for Space
Research**

- 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

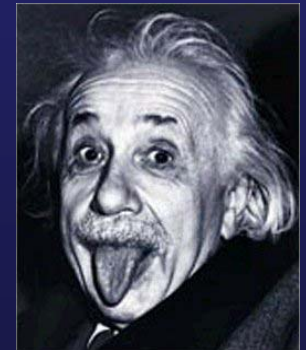
- Space-time is curved by mass (energy)
- Space-time is an elastic medium
- Space-time can sustain transverse waves: Gravitational Waves
- For the specialist:

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

Metric

Minkowski-
metric

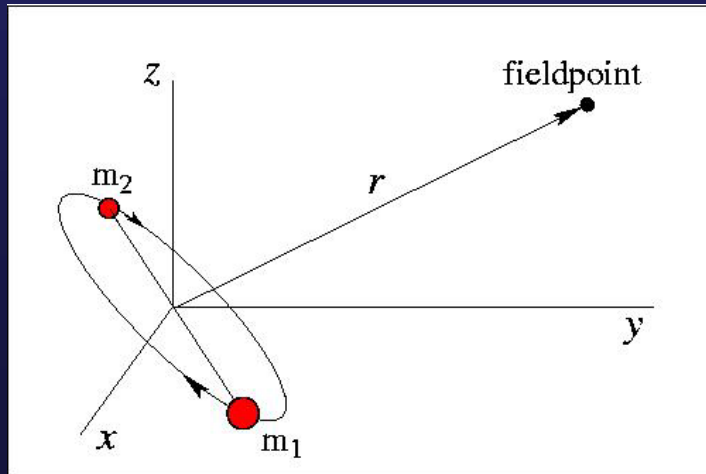
Strain



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 $2f$.
- 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 \rightarrow period drift (“chirping”) in frequency spectrum



Detection of Gravitational Waves on Earth

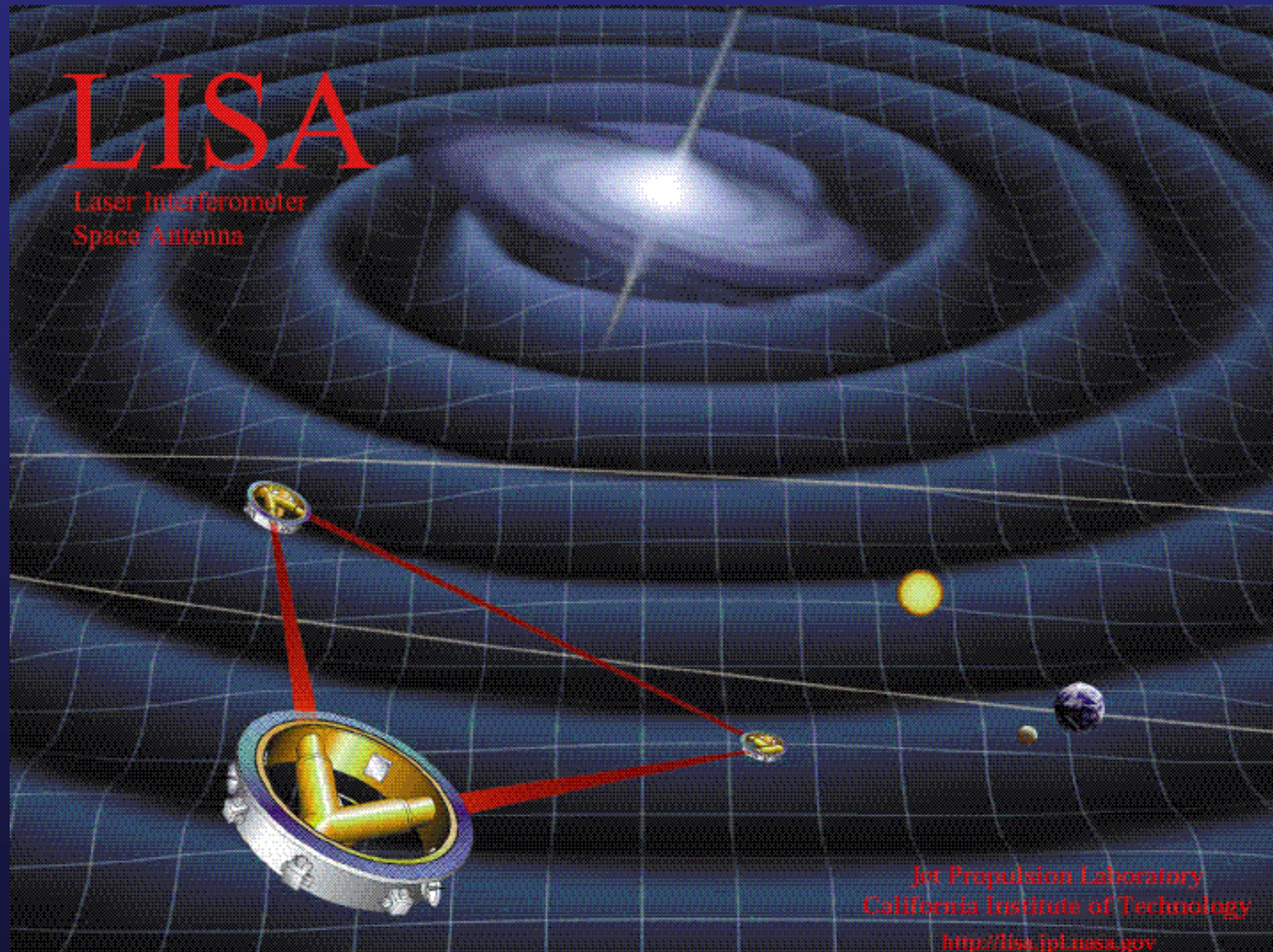
- Resonant mass detectors
 - miniGrail (NI), spherical mass (operational!)
 - Nautilus (It), bar
 - Explorer (Swz), bar
 - Allegro (USA), bar
 - ...
- Laser Interferometers
 - LIGO (USA)
 - VIRGO (Fr, It)
 - GEO 600 (Ger)
 - TAMA 300 (Jp)
 - AIGO (Au)



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: 5×10^6 km.

- Induced variations from $h=10^{-21}$ (galactic binary) are $\Delta L \sim 2.5 \times 10^{-10}$ cm $\sim 0.03 r_H$.

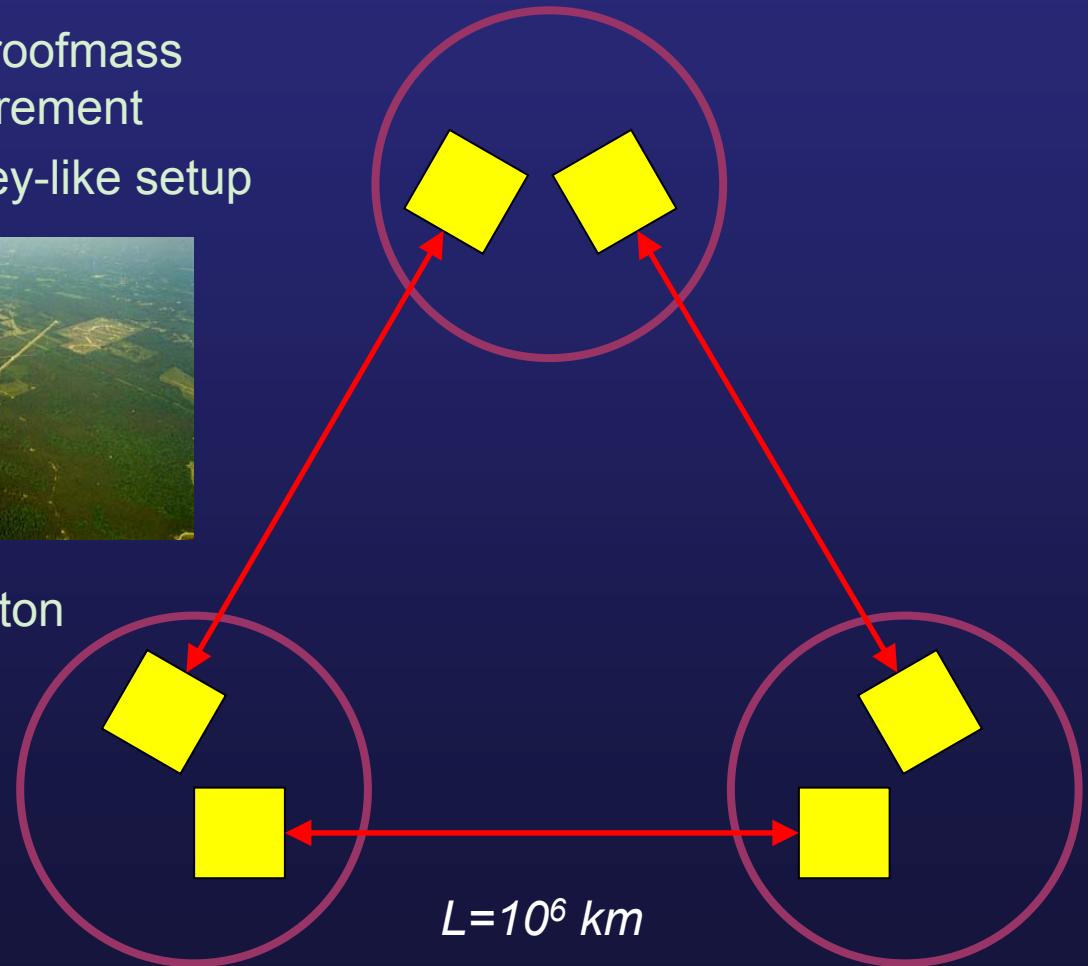


LISA system

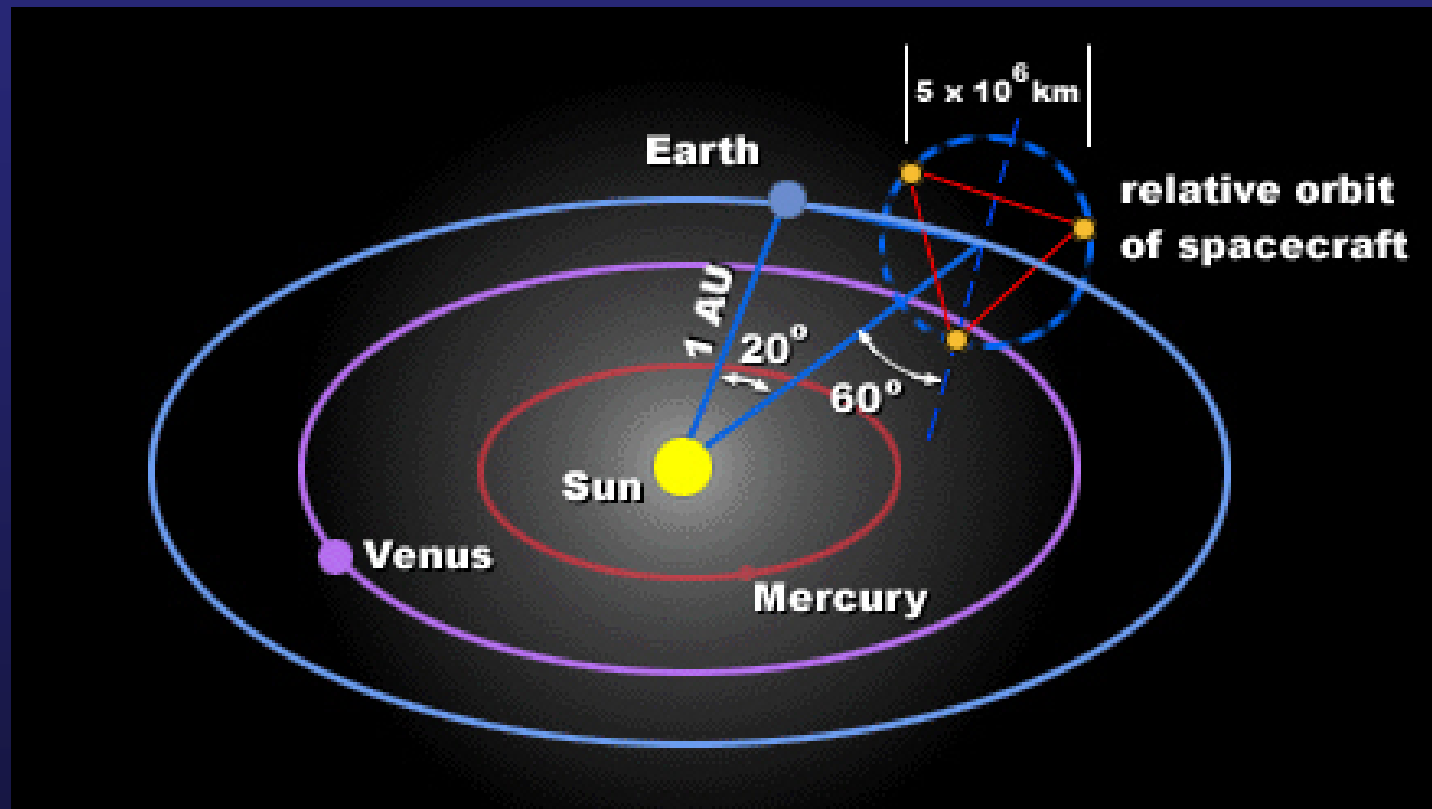
- Proofmass-to-proofmass distance measurement
- Michelson-Morley-like setup



LIGO-Livingston
 $L=4\text{ km}$



LISA orbit



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*

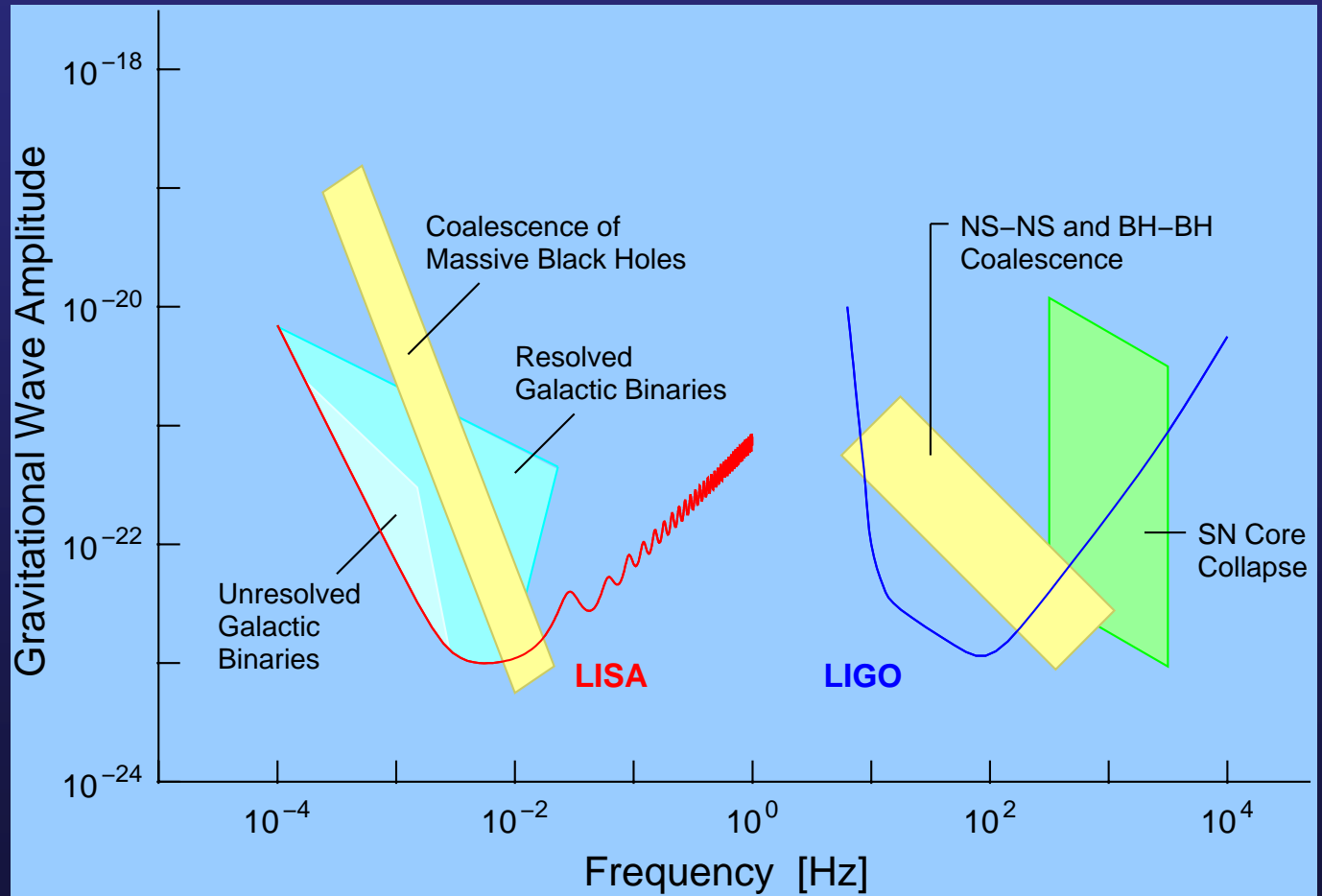


LISA Scientific objectives (2)

- 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)



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...



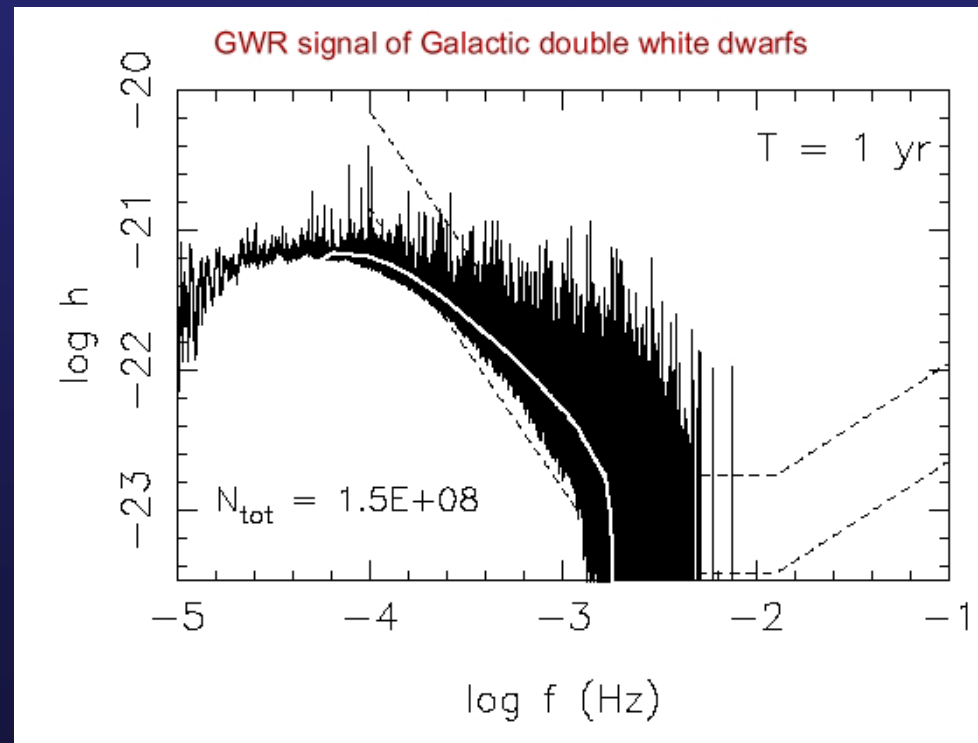
Galactic binaries: WD-WD systems

- 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.

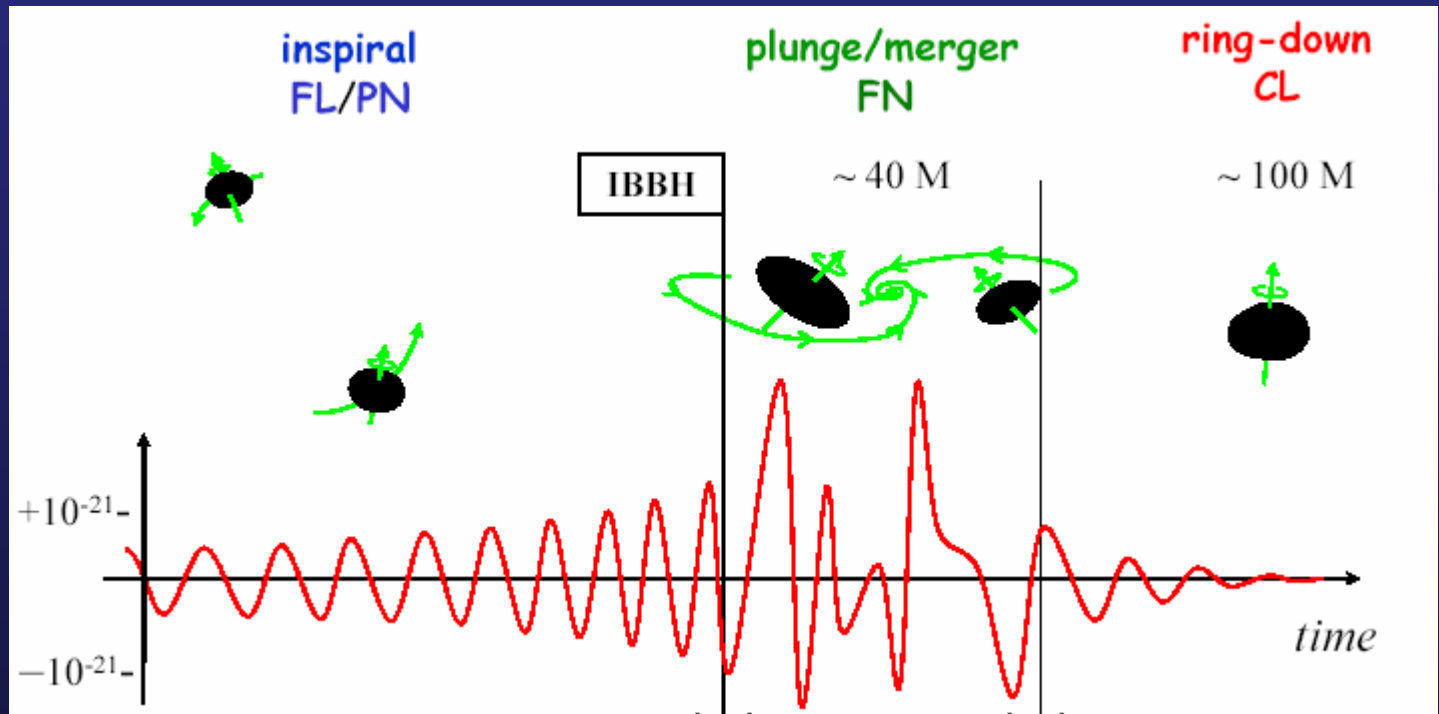


Massive Black holes

- 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

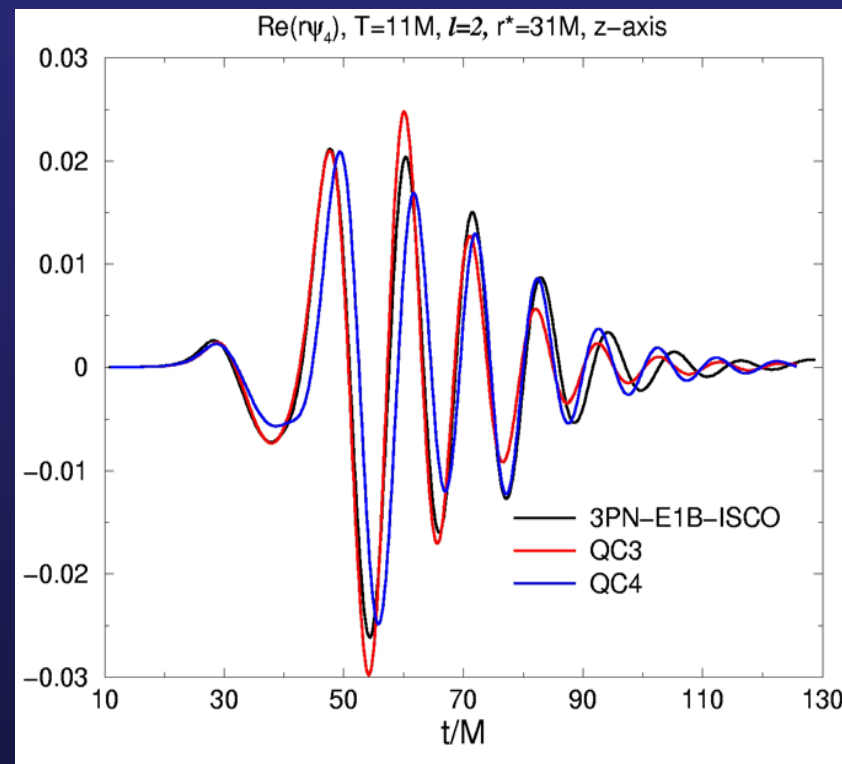


MBH Merger signal



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, chirp rate and polarization give distance!
 - Formation and evolution
 - Cosmological info: deceleration 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

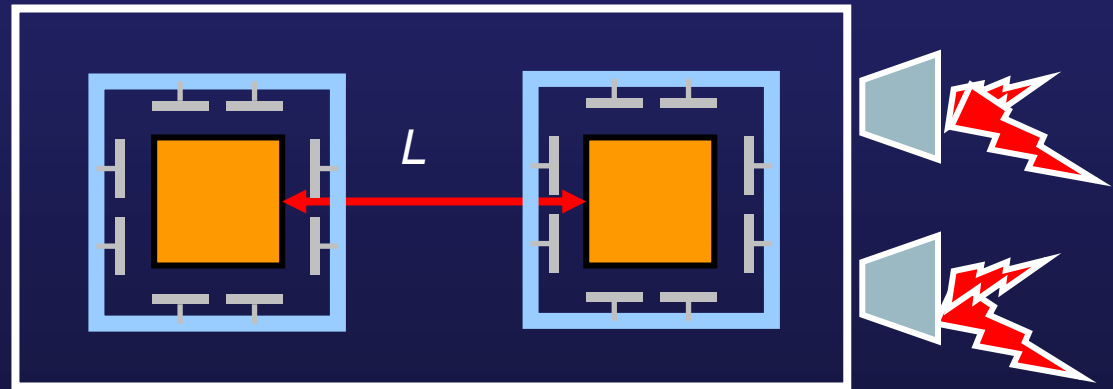
$$h(t) = \sum_k A_k \cos(2\pi f_k t + \varphi_k) + \dots$$

- Retrieve $A_k, \omega_k, \varphi_k, \dots$ from $h(t)$.
- Cocktail party problem: record the party and then reconstruct each conversation.
- Needed: A-priori knowledge of signals waveforms



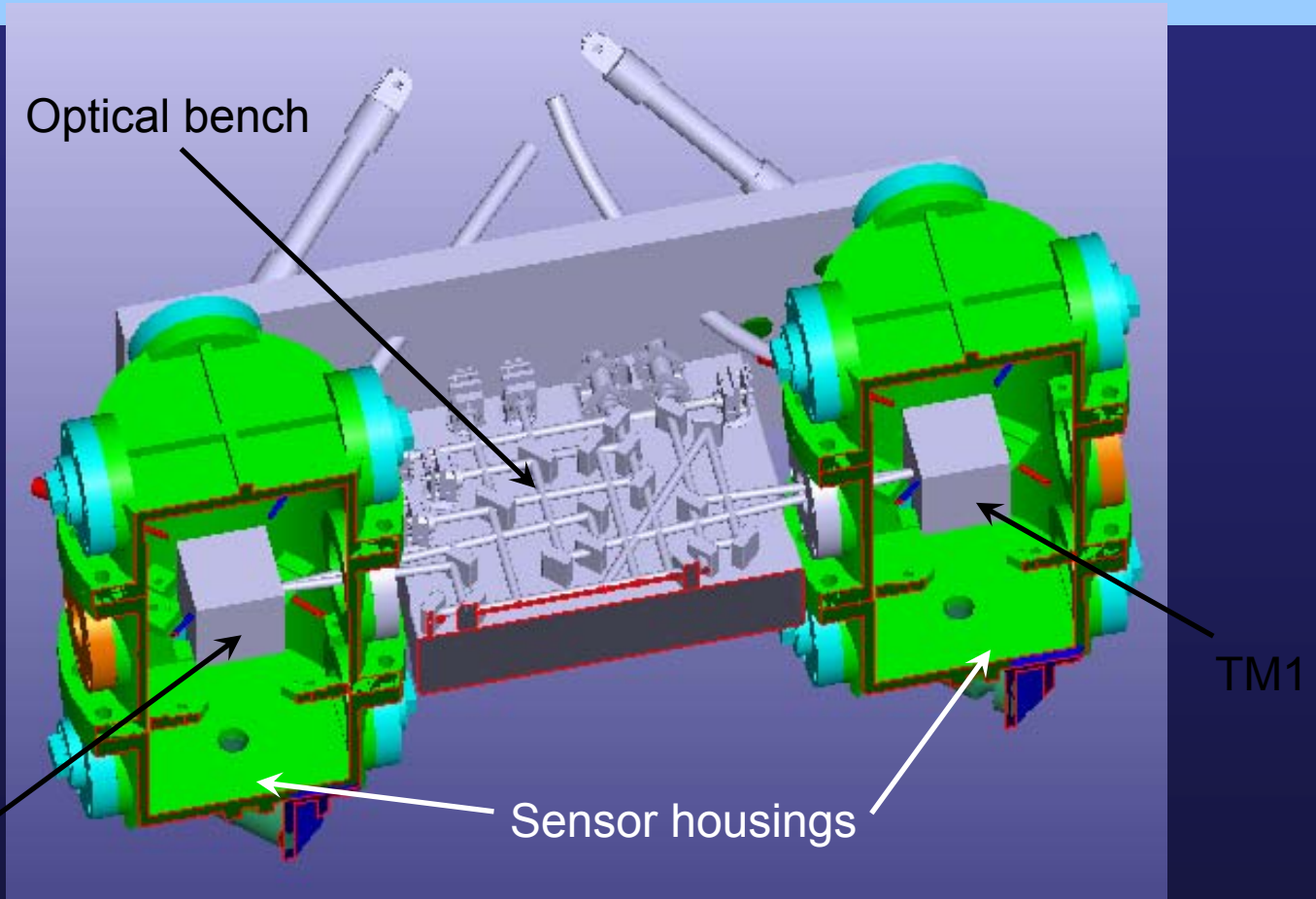
LISA Pathfinder

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



- Spacecraft = shield

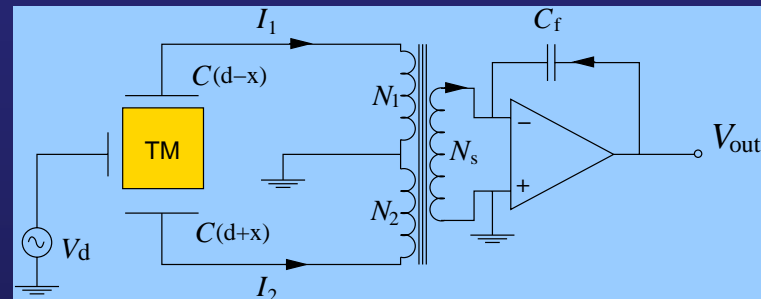
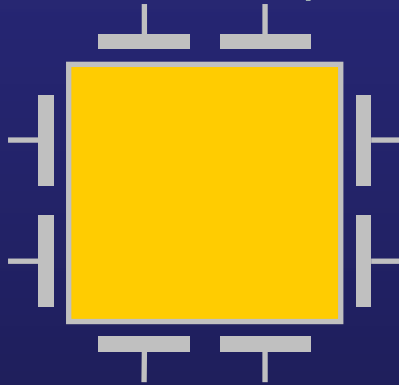
LISA Pathfinder



Dimensions: 640 mm x 375 mm x 375 mm

LISA Pathfinder key technologies

- Test-mass position sensing: Capacitive sensing.



- Drag-Free control.
- FEED 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...

