Exploring the Cosmic Frontier

Gravitational wave astronomy facilities

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LIGO Livingston

LIGO Hanford

Gravitational Wave Astronomy has begun!

- **First results of LIGO Science Collaboration LSC (LIGO Hanford, LIGO Livingston, GEO600 Hannover) from S1 run August-September 2002 (all on gr-qc)**

⇒ Stochastic GW background

$\Omega_0 h_{100}^2 \leq 18$ for 40 Hz < f < 314 Hz

⇒ Binary neutron star coalescence rate

$R_{90\%}$ (Milky Way) < 170 /a

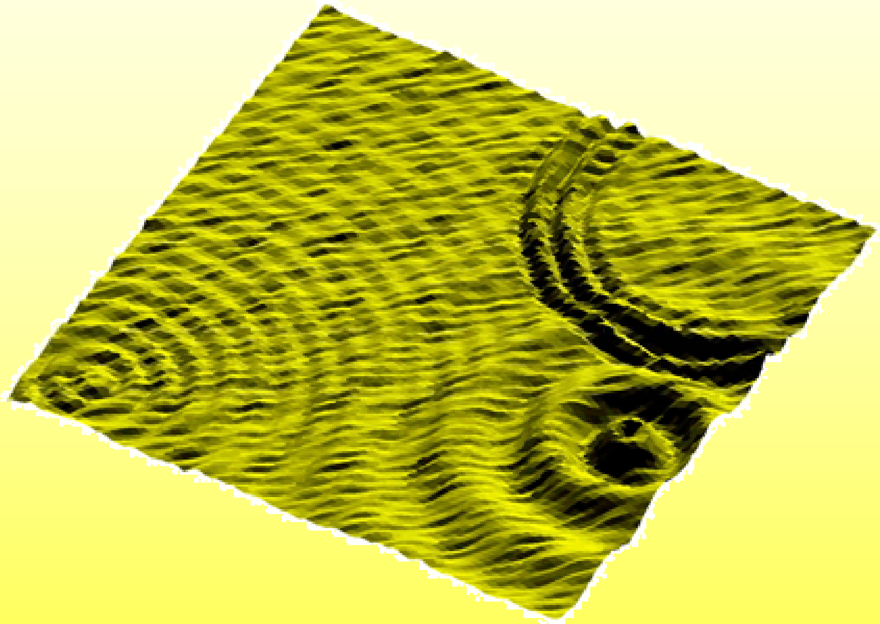
⇒ GW radiation and ellipticity of PSR J1939+2134

$h_{max} < 1 \times 10^{-22}$ ($e < 3 \times 10^{-5}$ @ 3.6 kpc)

GEO600 Hannover

Gravitational Waves

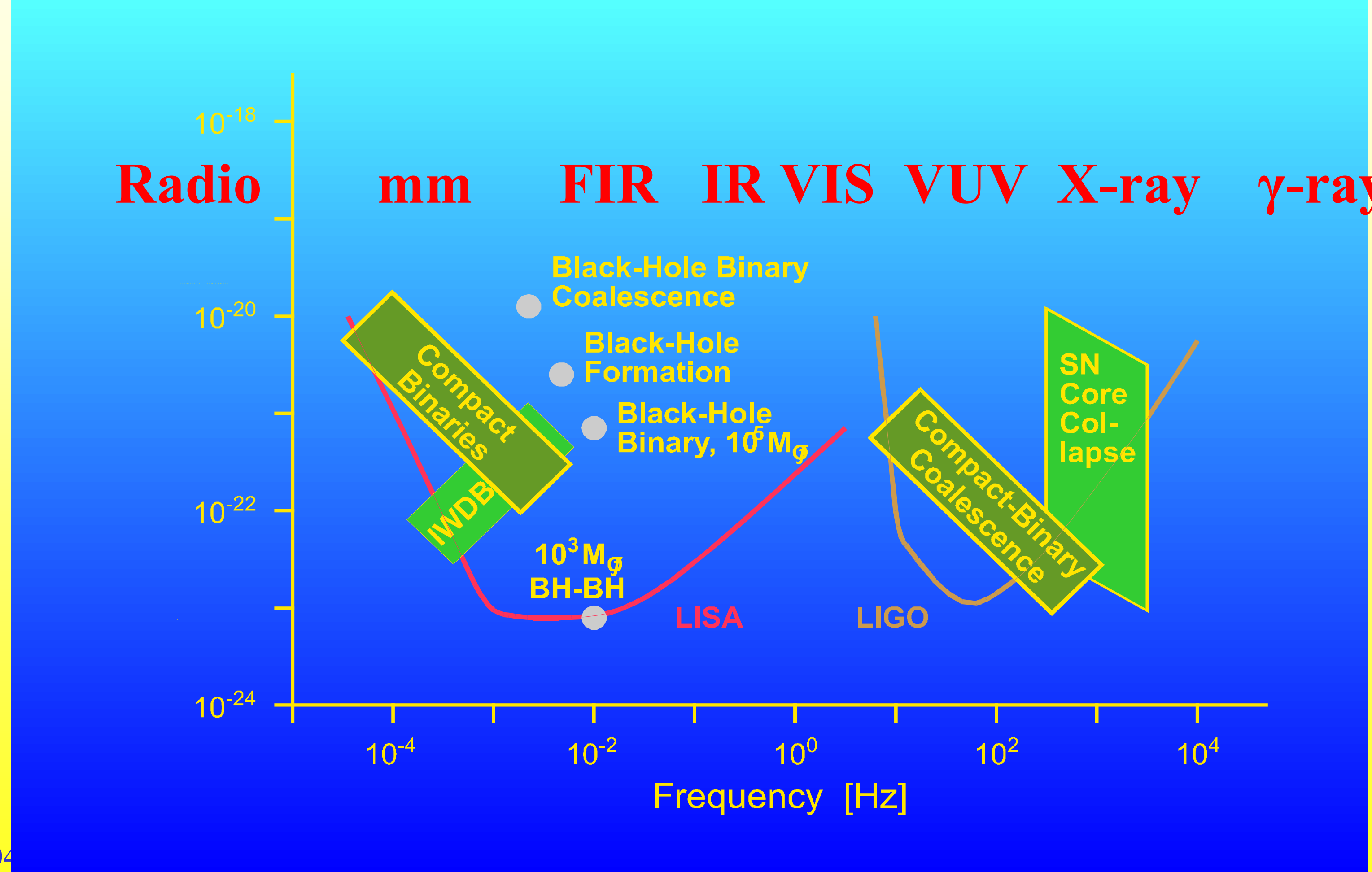
- Dynamical part of gravitation, all space is filled



- Very large energy,
  almost no interaction
- Ideal information carrier,
  almost no scattering
  or attenuation
- **The whole Universe has been transparent for GWs, all the way back to the Big Bang!**

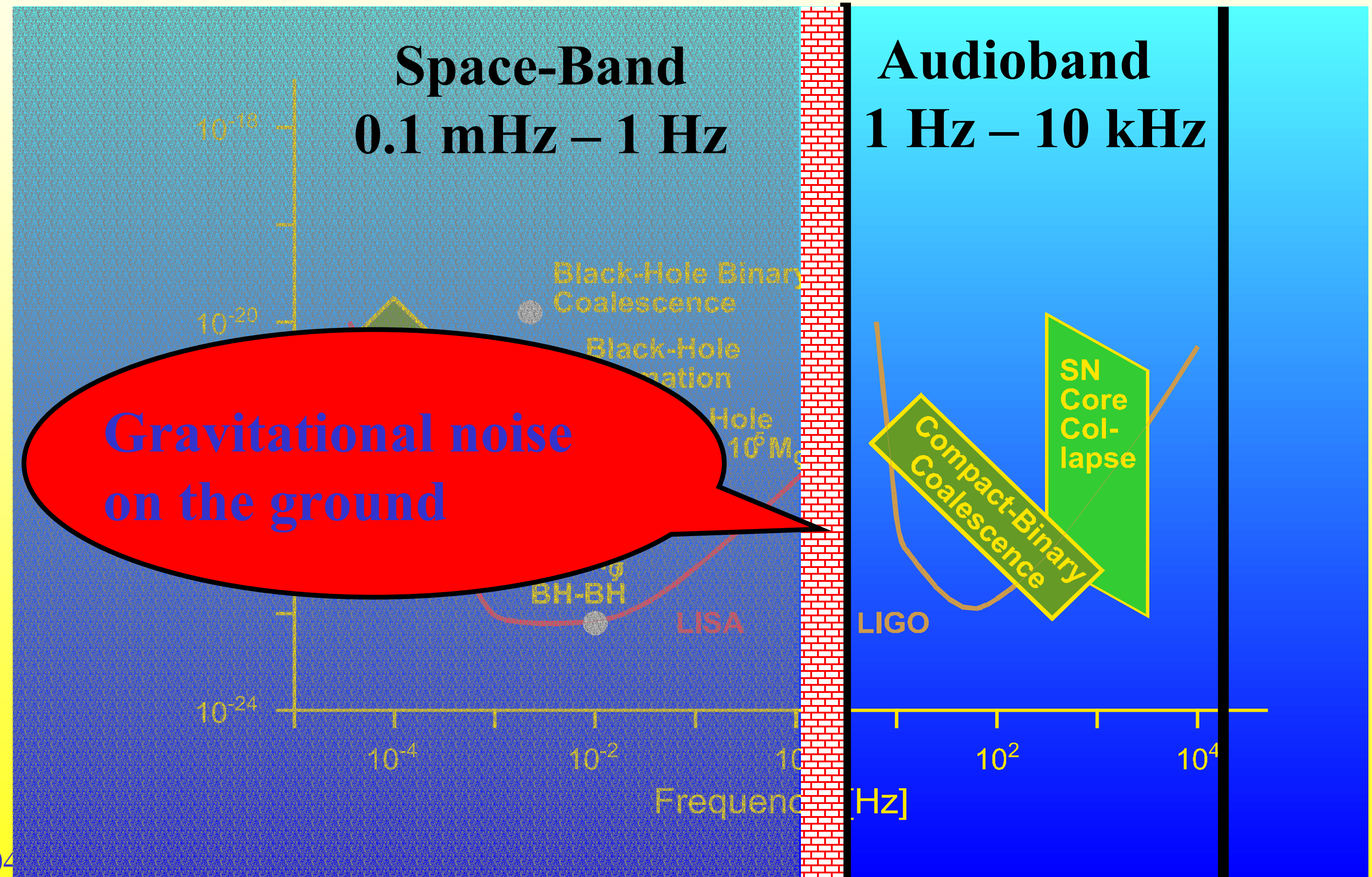
The Gravitational Wave Spectrum (1)

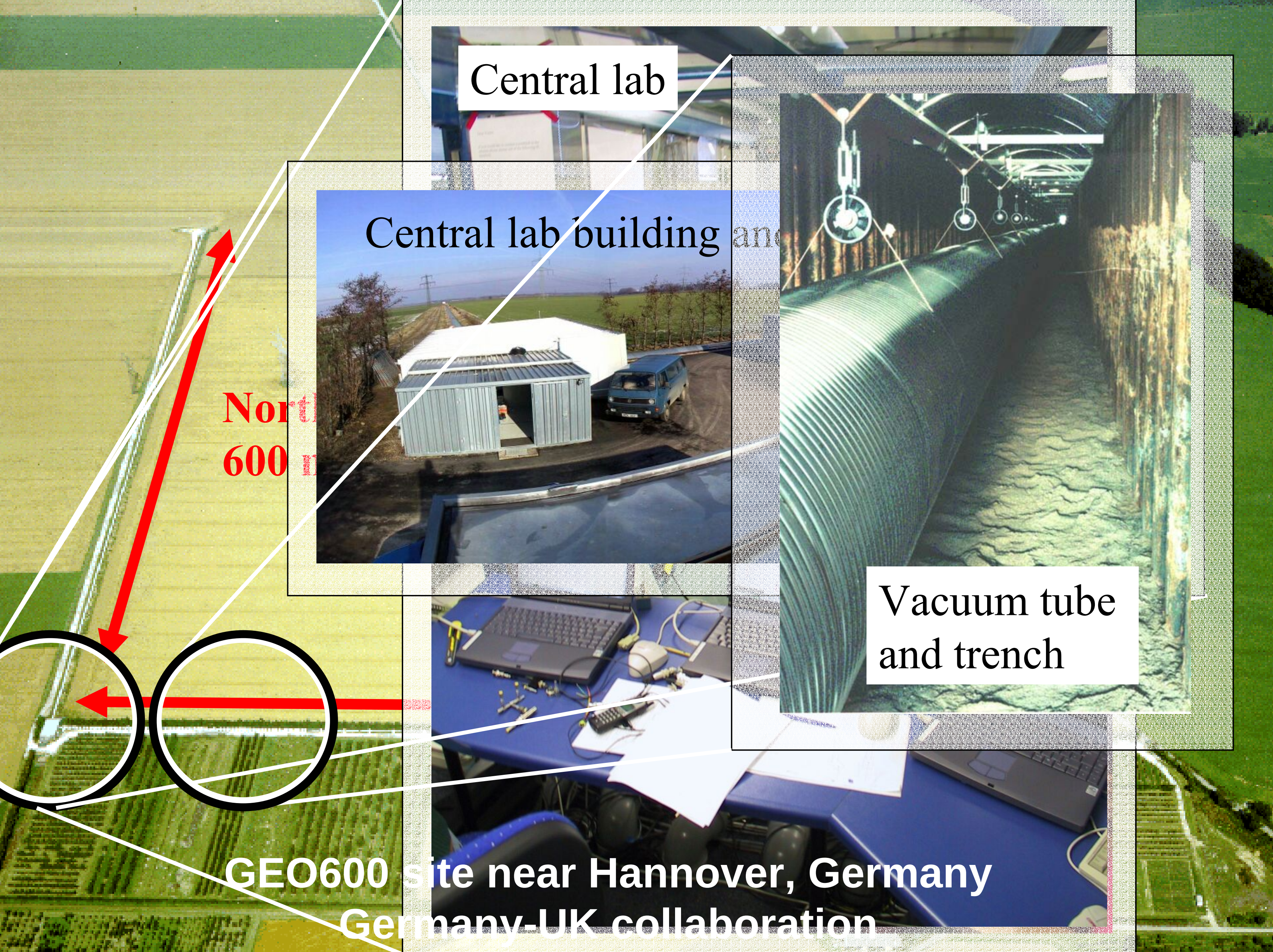
- More than 10 decades in frequency



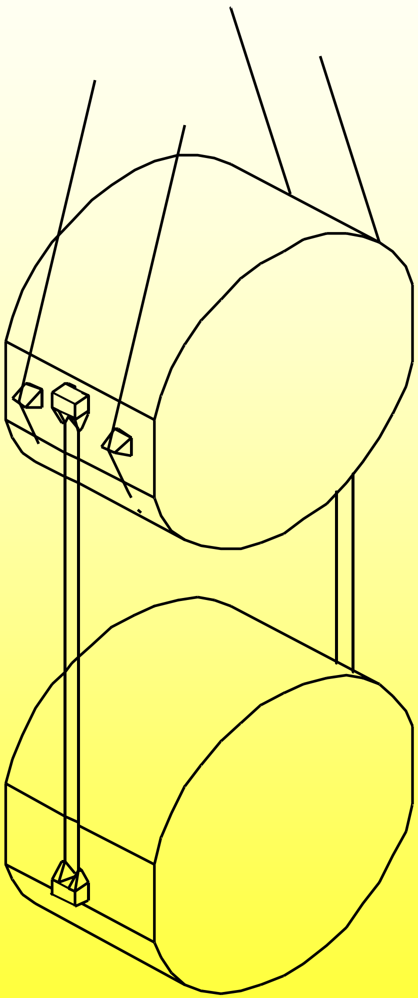
The Gravitational Wave Spectrum (2)

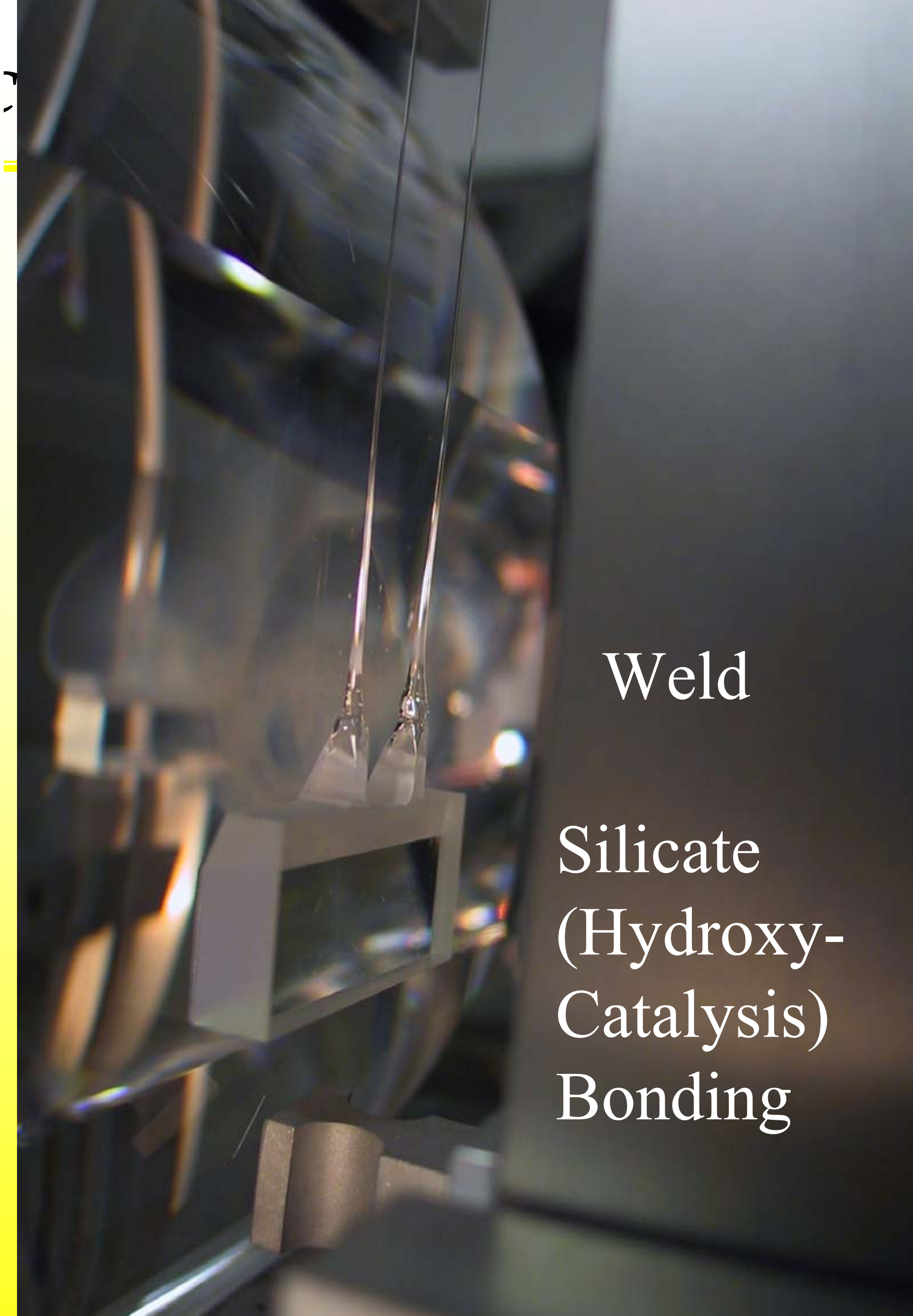
- Detectors on the ground listen to the audioband
- In space we listen to the low-frequency band




Central lab
Central lab building
Vacuum tube and trench
GEO600 site near Hannover, Germany
Germany-UK collaboration

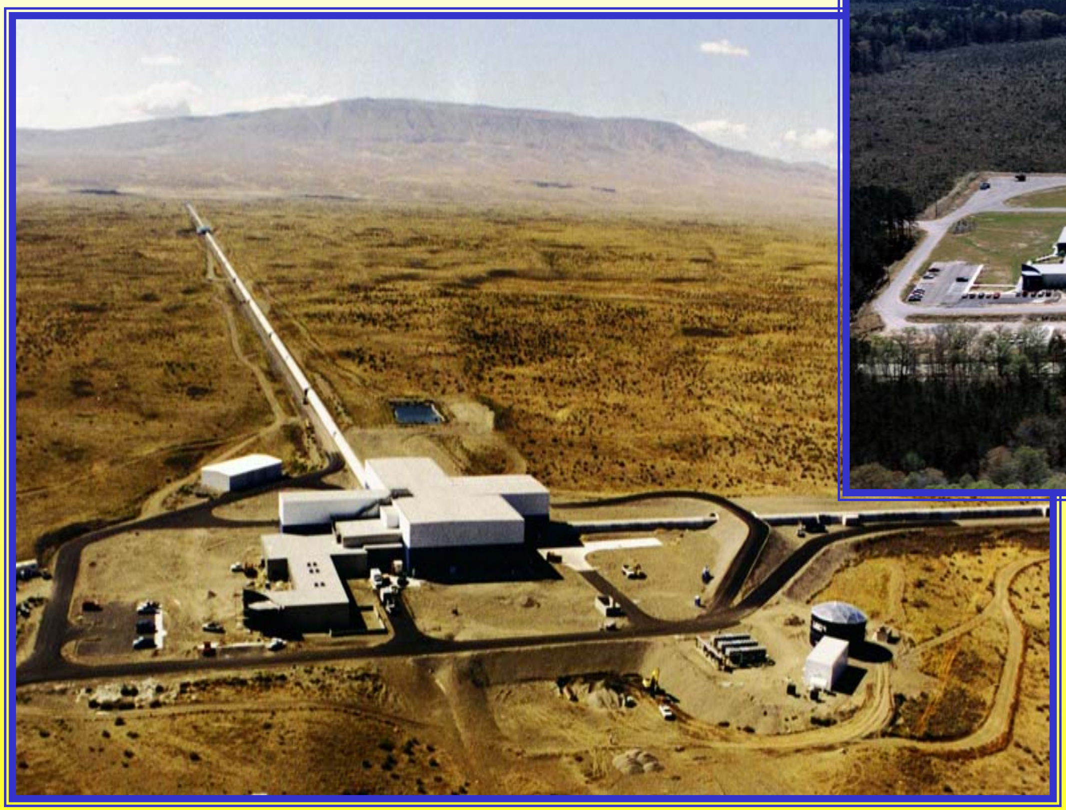
Monolithic Suspension





LIGO : Two sites 3000 km apart

Hanford, Washington



Livingston, Louisiana

VIRGO: The French-Italian Project
3 km armlength near Pisa

Beginning of Data Taking

23.8.2002 - 9.9.2002: S1 Run with LIGO, GEO600, and partly TAMA (Japan).

14.02.2003-14.04.2003: S2 Run, only LIGO

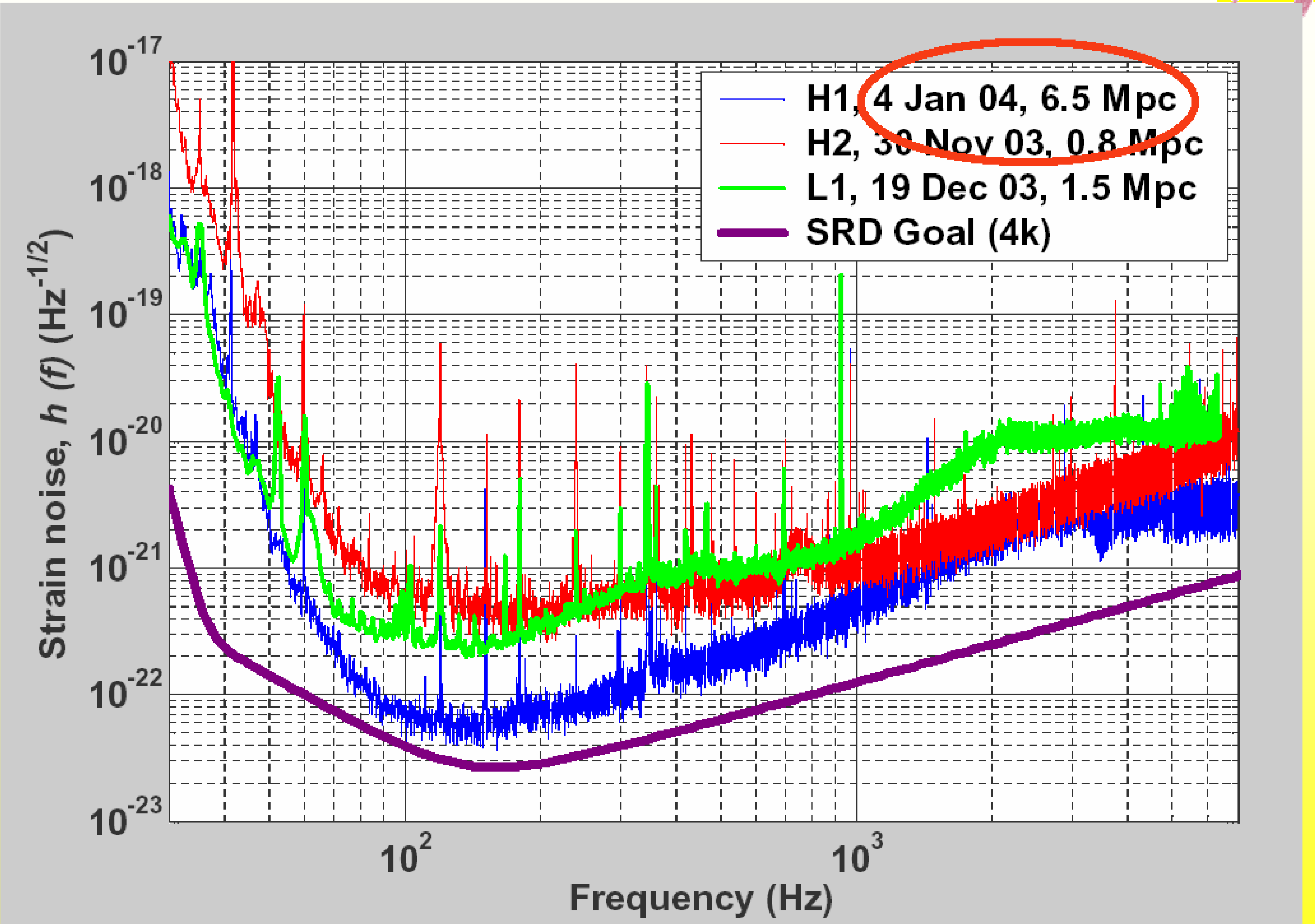
1.11.2003-12.1.2004: S3 Run with LIGO and GEO600

Further runs planned:
S4: 1.11-20.12.2004
S5: 1.04.2005+6 months
VIRGO may join by then.

Recording GW signal and detector status (all error and feedback signals, environment, time base, ...)

GEO600 data rate:
50 GB/day

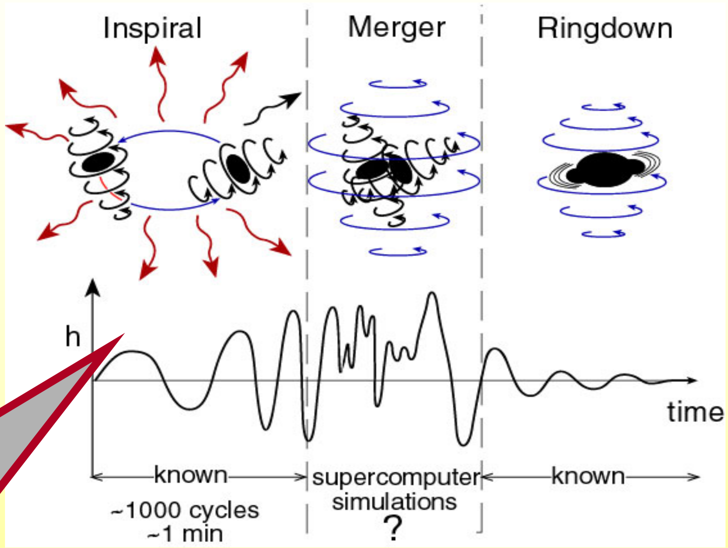
S3 Peak Sensitivities in LIGO

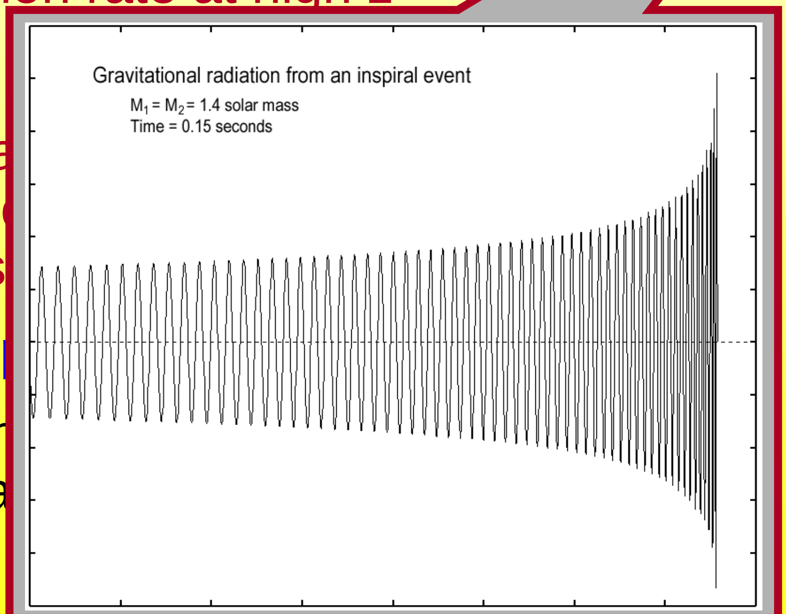


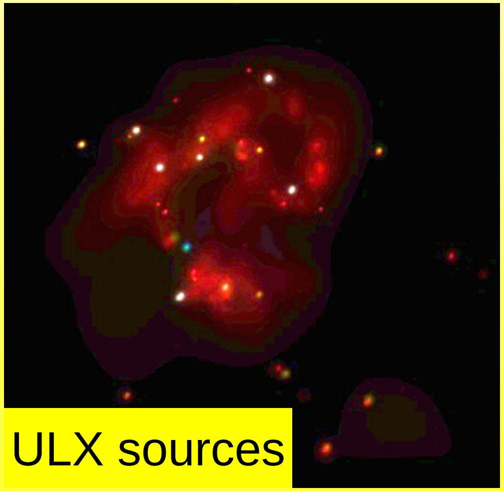
Ground-based sources:
1. Coalescing Binary Neutron Stars & Black Holes

Near-term/long-term goals

- **Astronomy**
  - ⇒ Perhaps first source to be detected (?)
  - ⇒ Survey of NS's and BH's to z ~ 0.1/1.5
  - ⇒ NS and BH demographics: wide mass range (from sub-solar mass to several x10^3 $M_\odot$)
  - ⇒ Star formation rate at high z
- **Cosmology**
  - ⇒ New standa
    determinati
    parameters
- **Fundamental**
  - ⇒ Exploring th
    gravitationa



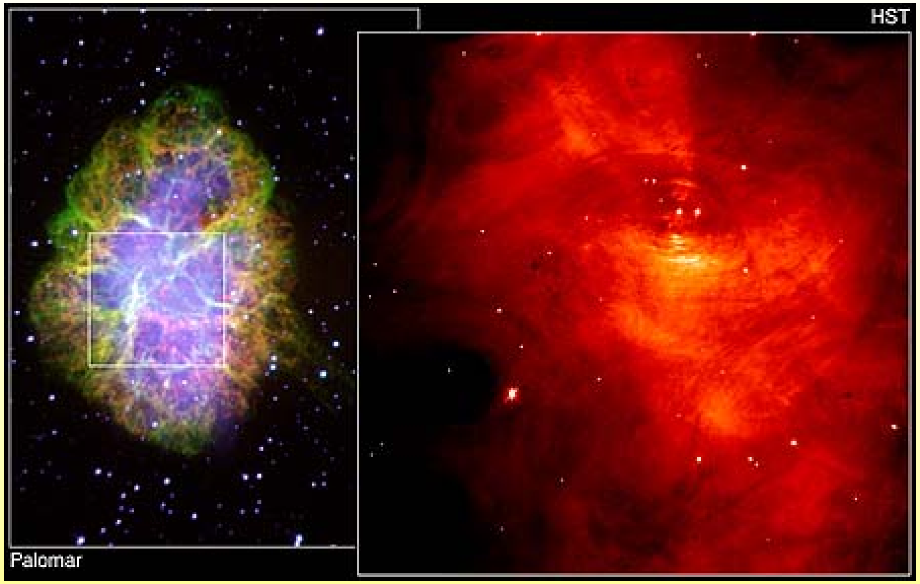




Ground-based sources:
2. Pulsar physics and formation

Near-term/long-term goals

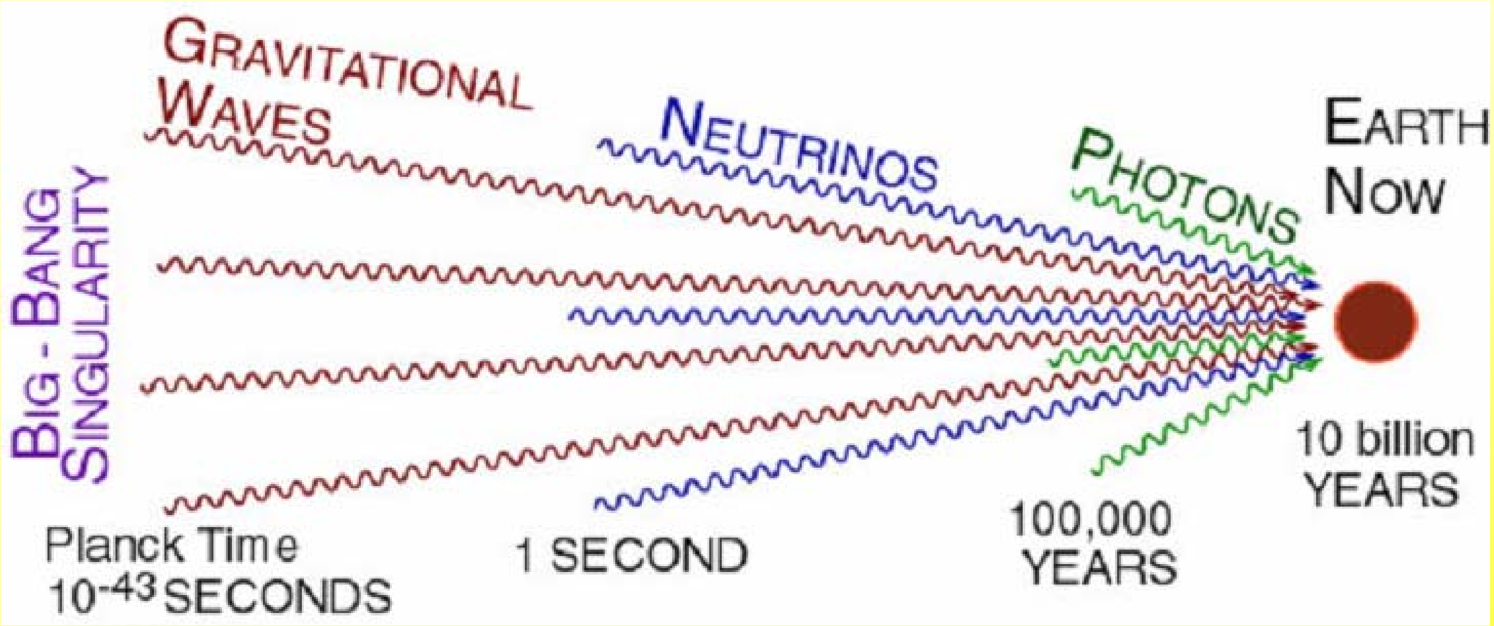
- **Neutron star oscillations: Asteroseismology and fundamental physics**
  - ⇒ NS equation of state
  - ⇒ Super-conductivity/super-fluidity
  - ⇒ Ultra-high density nuclear (and exotic) matter
- **Rapidly rotating neutron stars: "GW pulsars"**
  - ⇒ Probing the galactic neutron star population (only ~1300 known radio pulsars)
  - ⇒ LMXB's and the puzzle of the missing sub-msec pulsars



- **Supernovae: NS and BH birth**
  - Direct view of the SN core
  - Large sample: about one SN per minute
  - Neutron star instabilities?

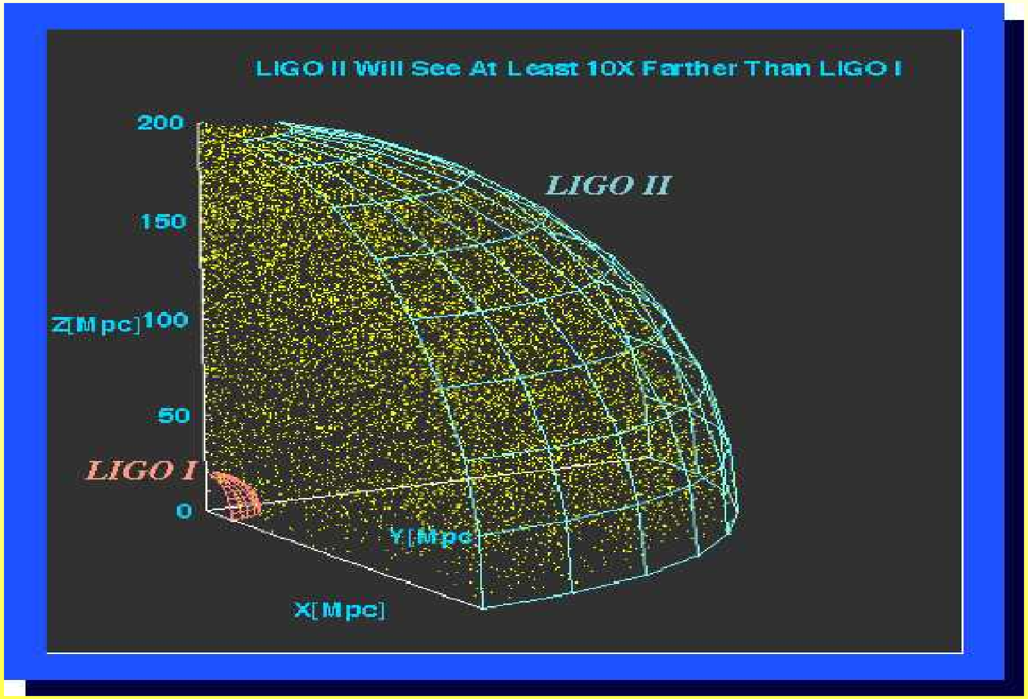
Ground-based sources:
4. Cosmological Background

- GWs are the ideal tool for probing the very early universe
- Spectrum unaltered (except for redshift) since GWs generated
- Probe phase transitions, non-standard inflation models



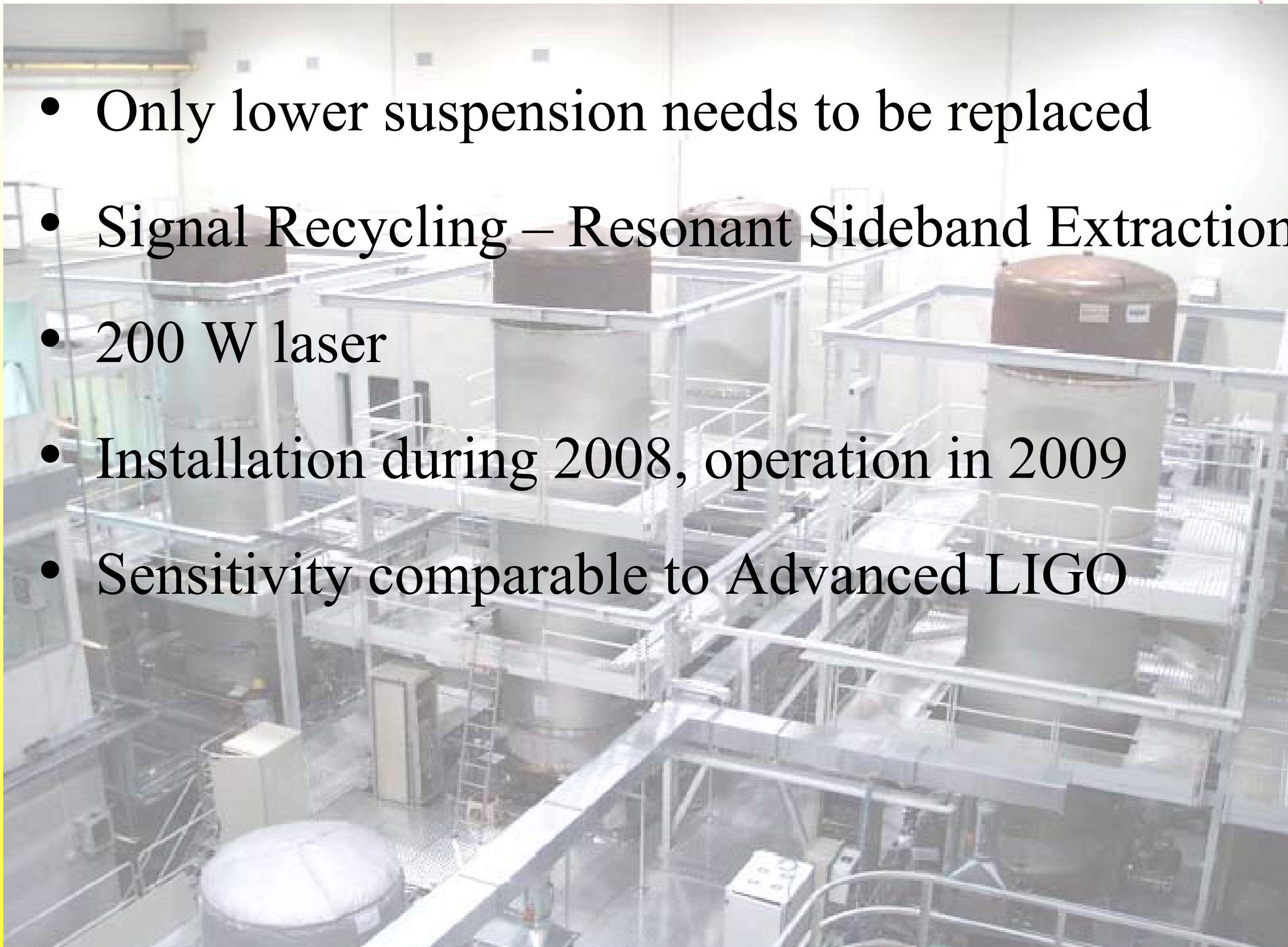
Future Plans: Advanced LIGO

- Sensitivity > ten times LIGO
- Uses GEO600 concepts in LIGO vacuum system
- Installation 2007
- Data taking 2009
- Replace suspensions
- Sapphire optics
- 200 W lasers



- Signal Recycling – Resonant Sideband Extraction

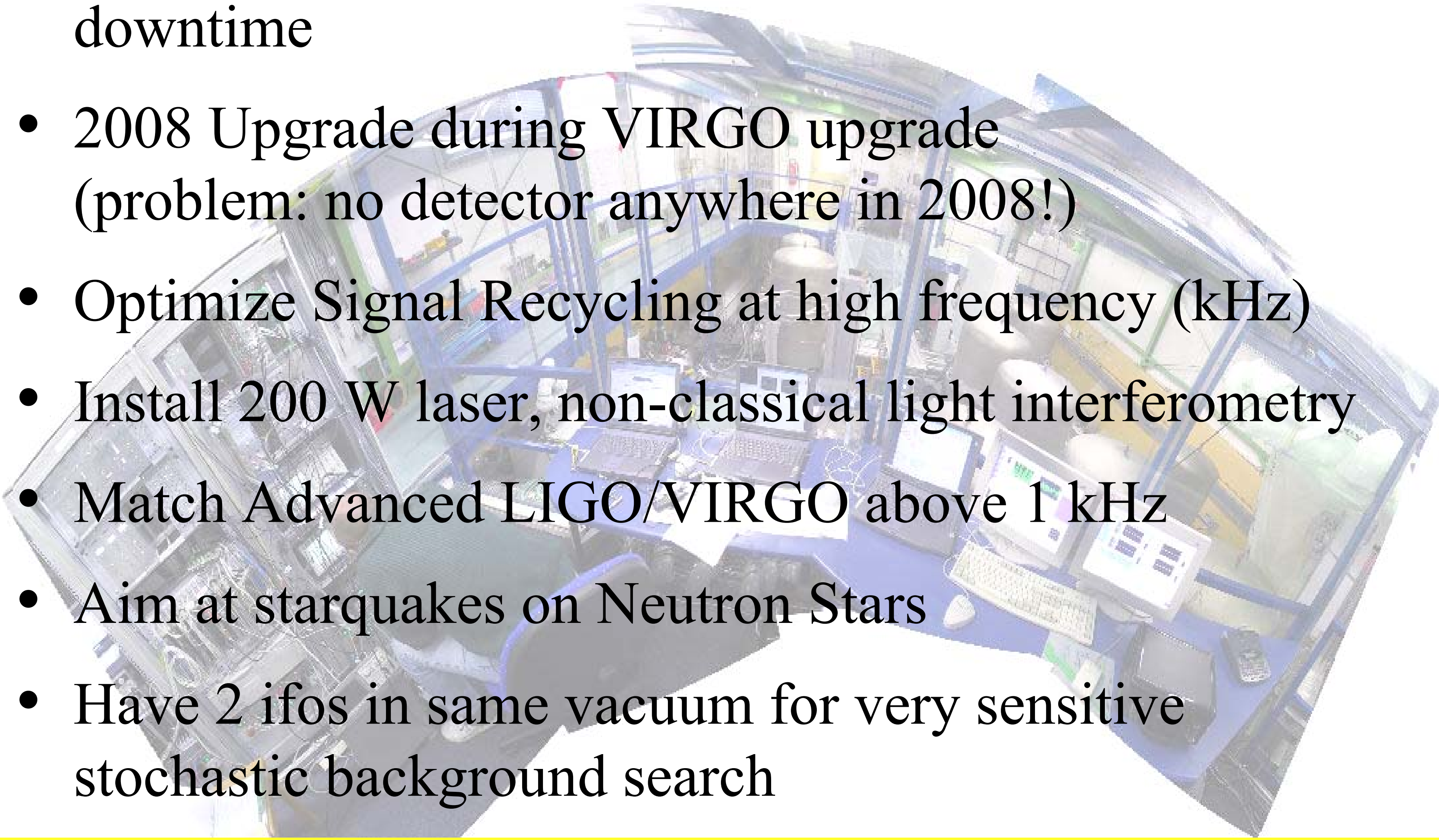
Future Plans: Advanced VIRGO



- Only lower suspension needs to be replaced
- Signal Recycling – Resonant Sideband Extraction
- 200 W laser
- Installation during 2008, operation in 2009
- Sensitivity comparable to Advanced LIGO

Future Plans: GEOupgrade

- 2007 Take data with VIRGO during 1st year of LIGO downtime
- 2008 Upgrade during VIRGO upgrade (problem: no detector anywhere in 2008!)
- Optimize Signal Recycling at high frequency (kHz)
- Install 200 W laser, non-classical light interferometry
- Match Advanced LIGO/VIRGO above 1 kHz
- Aim at starquakes on Neutron Stars
- Have 2 ifos in same vacuum for very sensitive stochastic background search



The Quantum Limit and Beyond…

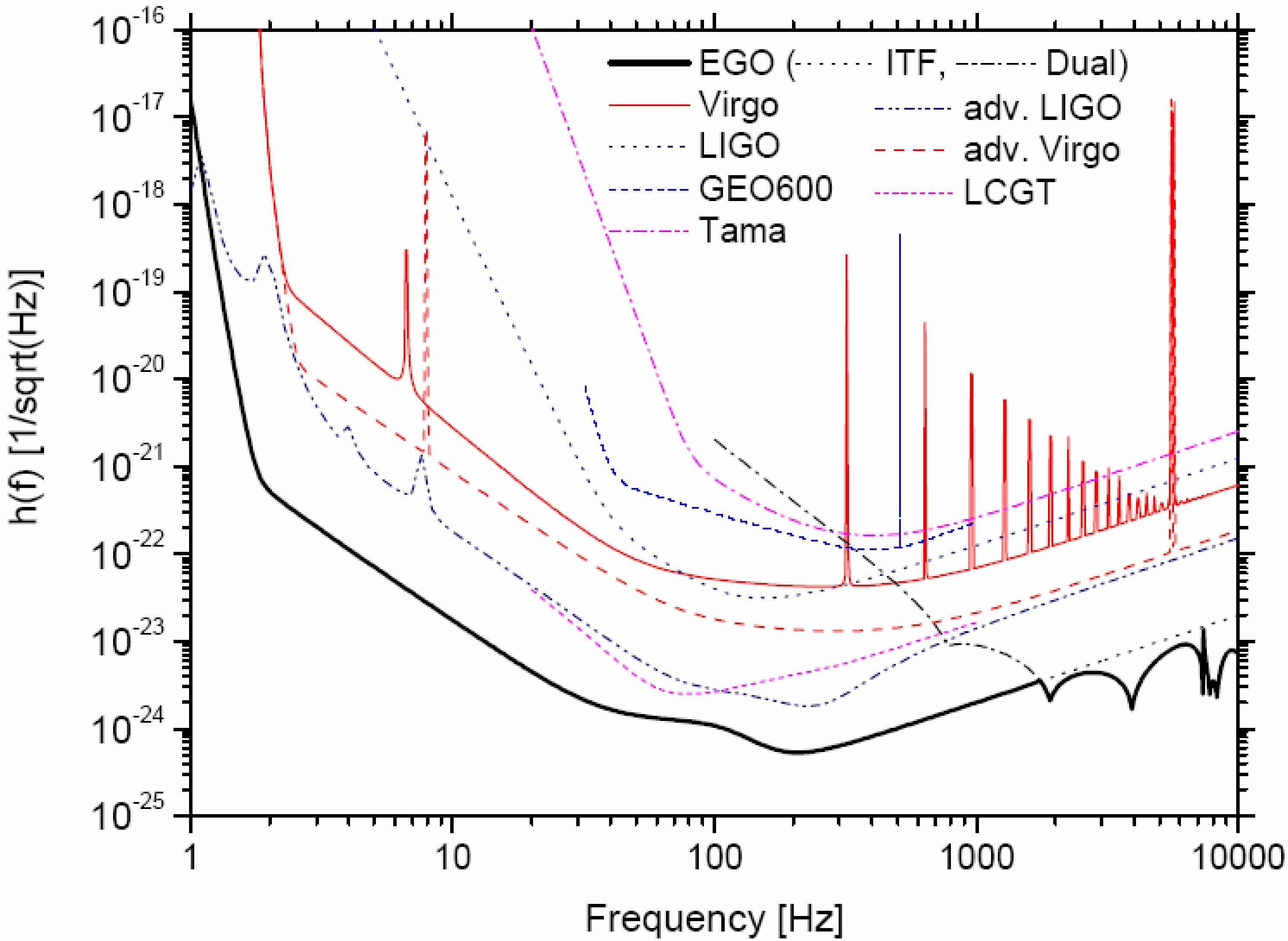
- Signal Recycling creates correlations and parametric effects
- Any interferometer with Detuned Signal Recycling (like GEO600) may beat the Standard Quantum Limit (Buonanno et al., 2001)
- In fact, even the existing GEO600 does (Harms et al., AEI Hannover, 2002)

EGO: The European Advanced Gravitational Wave Observatory

- A design study by the whole GW community in Europe including VIRGO, GEO and resonant mass detector communities
- Goal: a broadband observatory in Europe with sensitivity from 1 Hz to 10 kHz
- Sensitivity ten times in amplitude (100 times in intensity) beyond Advanced LIGO

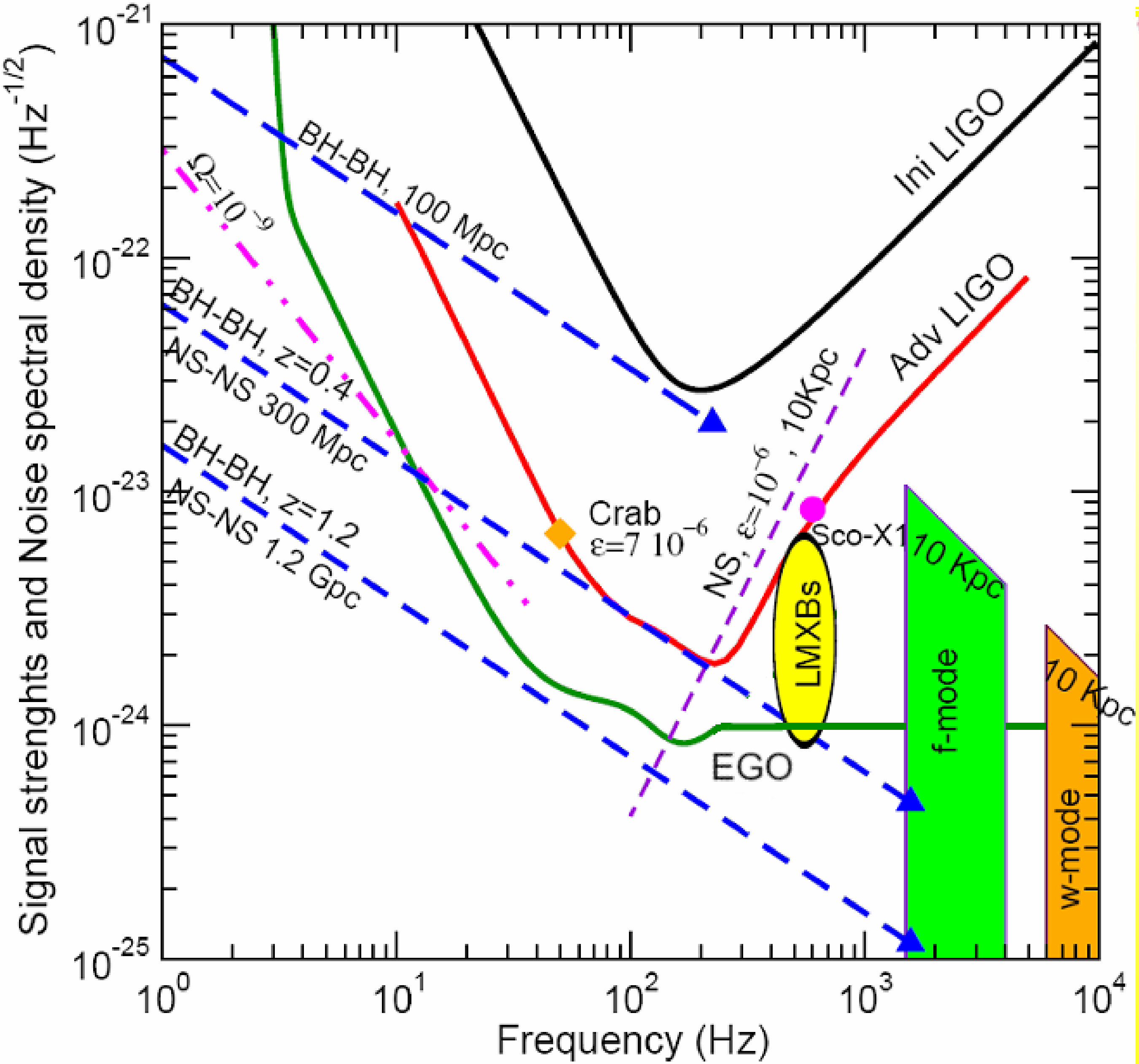
EGO Baseline Sensitivity

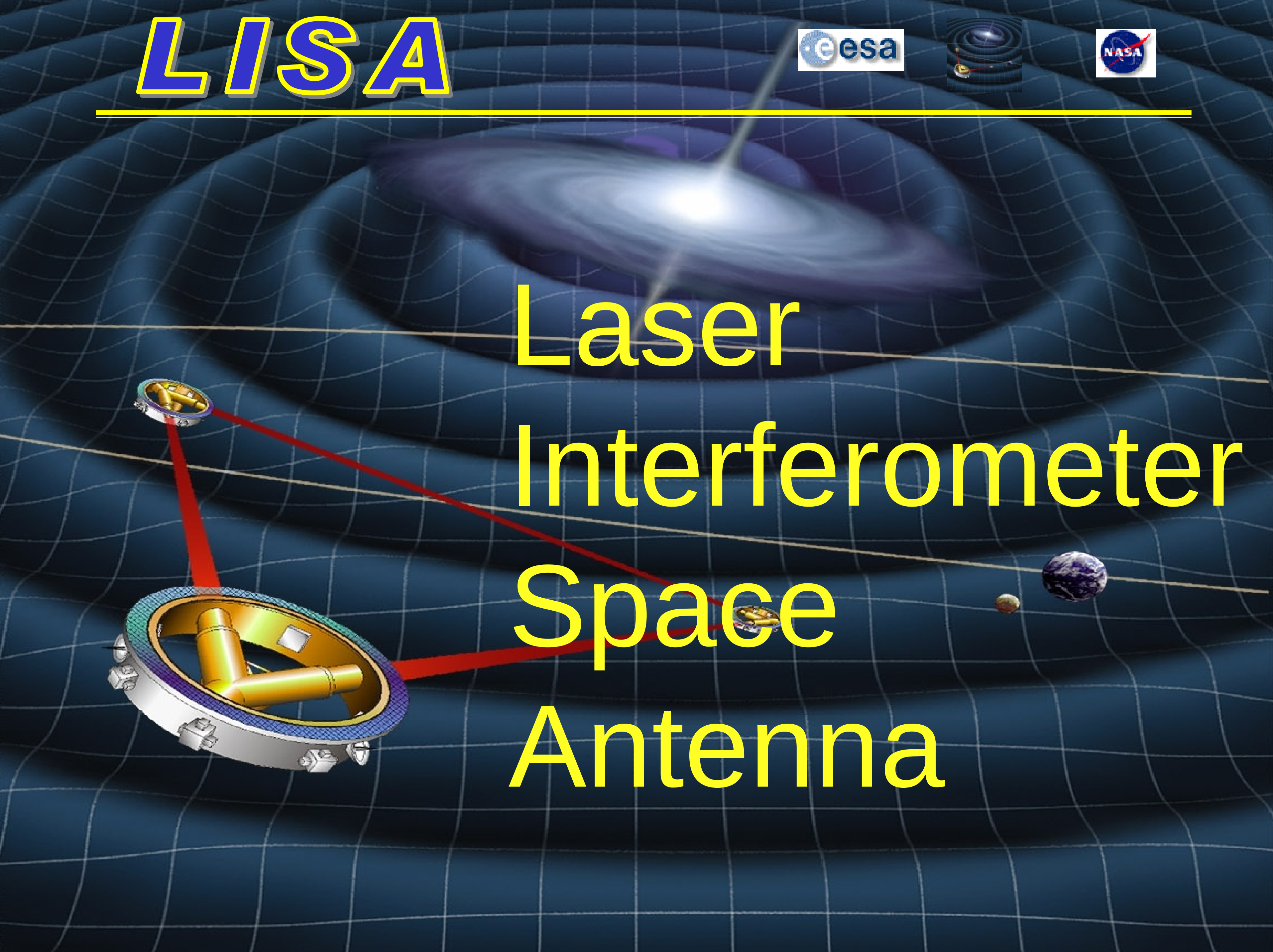
- BH-BH (< 1000M$_\odot$) at z<1.2,   NS-NS at <1 Gpc, $\Omega > 10^{-10}$



Sensitivity of Ground-based Detectors

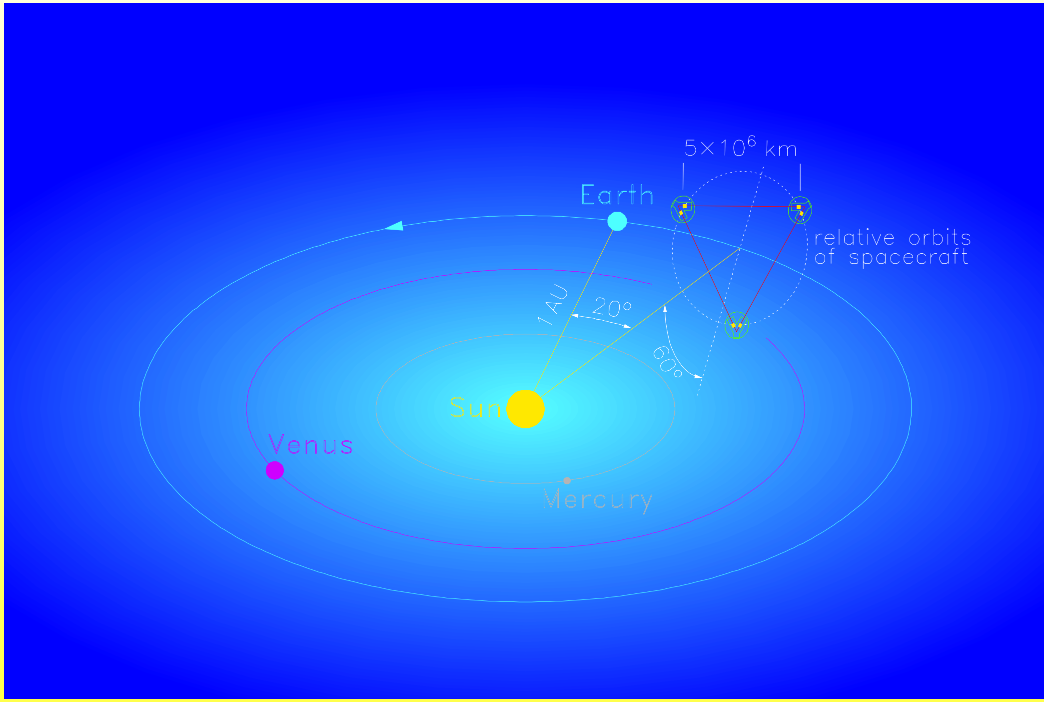
In 15 years:
- 100 x range,
- 10^6 x volume surveyed




LISA
Laser
Interferometer
Space
Antenna

A Collaborative ESA/NASA Mission

- **Cluster of 3 S/C in heliocentric orbit**
- **Free flying test masses shielded inside the S/C**
- **Trailing the earth by 20 ° (50 Mio km)**
- **Equilateral triangle with 5 Mio km arms**

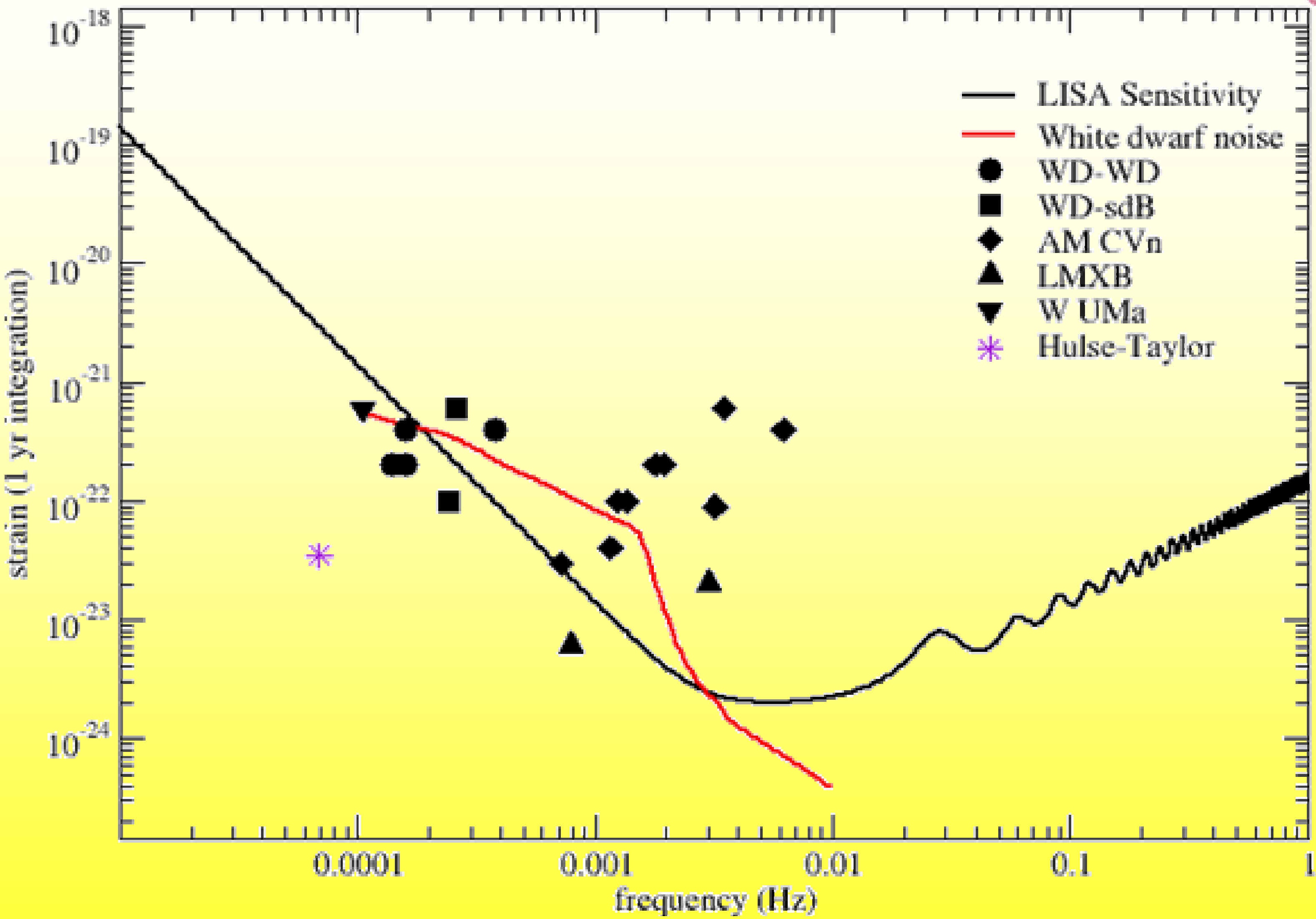


- **Inclined against ecliptic by 60 °**

Status of LISA today

- Proposed to ESA 1993, approved as a Cornerstone Mission 1996
- Collaborative ESA/NASA mission with a 50/50 sharing ratio
  - ⇒Europe: Spacecraft, 50% share of the payload (nationally funded).
  - ⇒US: Launcher (Delta IV), Operations, System Engineering, Software, 50% share of the payload
- Joint LISA International Science Team (LIST)
- "Beyond Einstein Initiative" in the US budget for 2004.
  - ⇒2 "Einstein Great Observatories", Constellation X and LISA
  - ⇒3 "Einstein Probes"
  - ⇒Technology Development and Research
- LISA PF in 2007
  - ⇒Europe: LISA Technology Package (LTP)
  - ⇒US: Disturbance Reduction System (DRS)

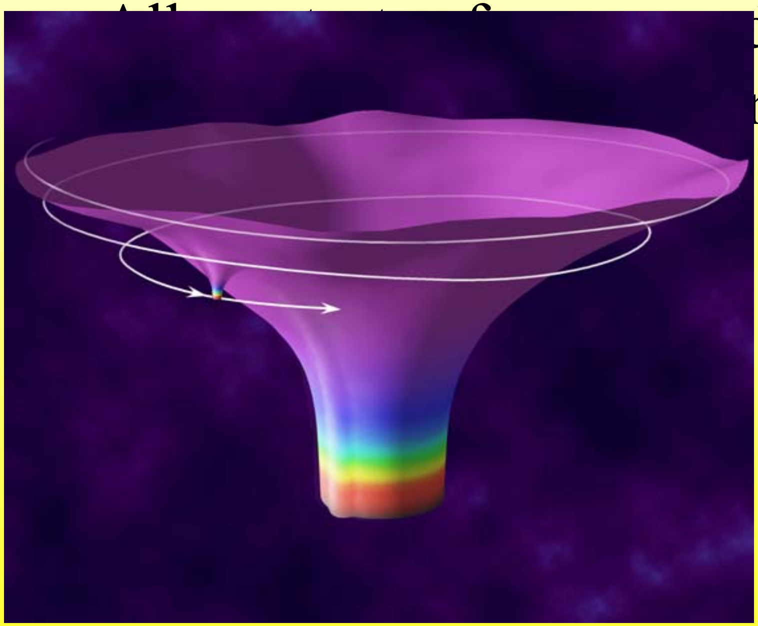
LISA Verification Binaries

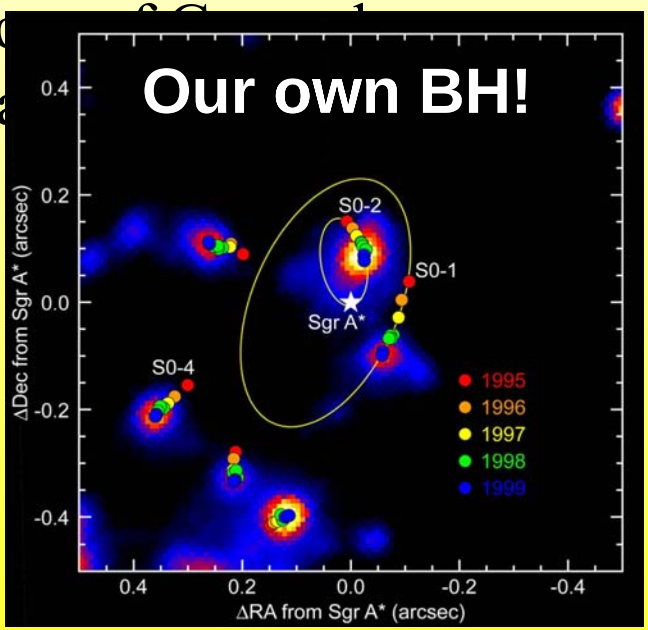


At the Edge of a Black Hole

- Capture by Massive Black Holes

⇒By observing 10,000 or more orbits of a compact object as it inspirals into a massive black hole (MBH), LISA can map with superb precision the space-time geometry near the black hole

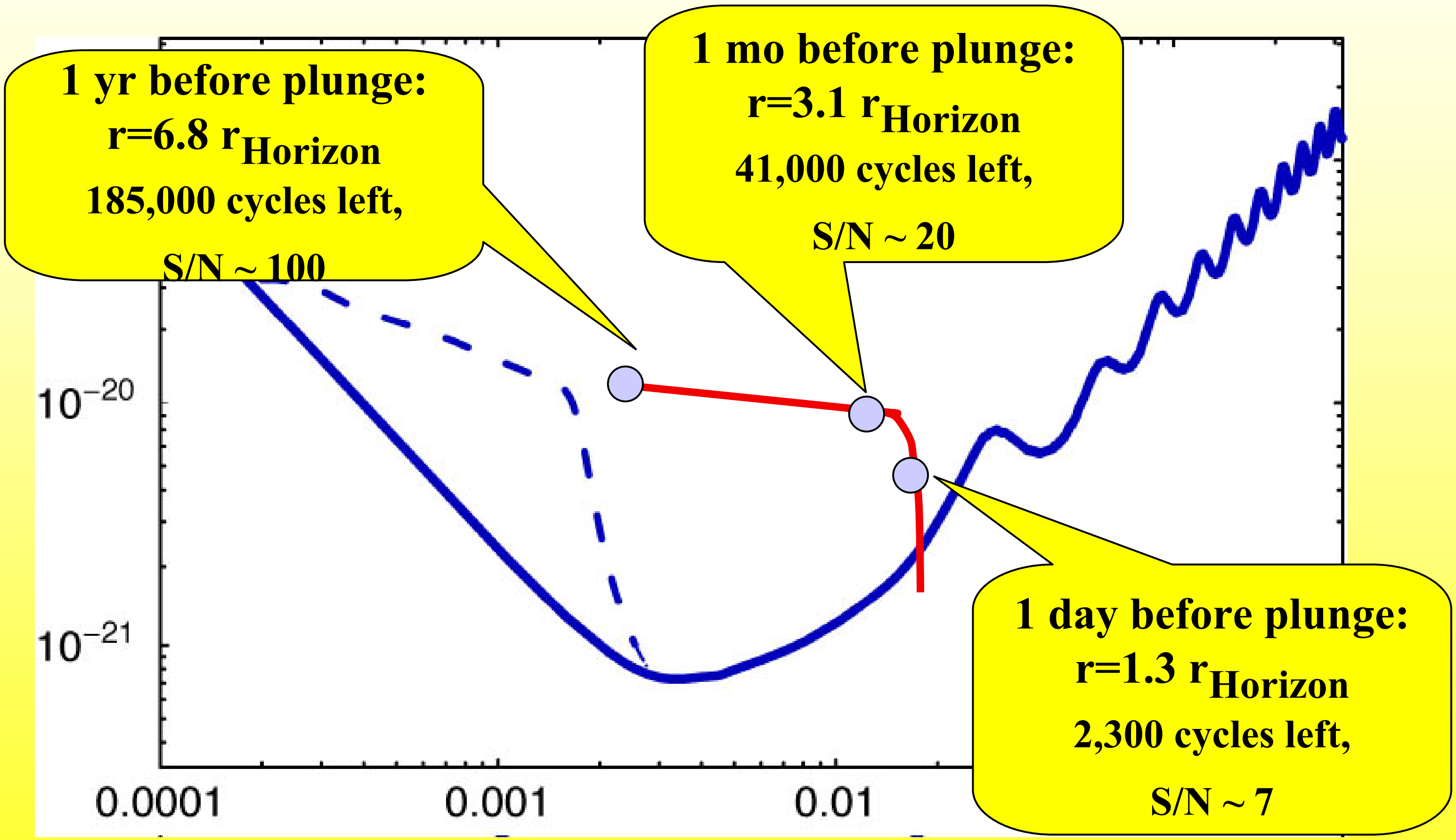




Ghez et al. 1998 ApJ 509, 678, Eckart et al. 2002 MNRAS 331, 917

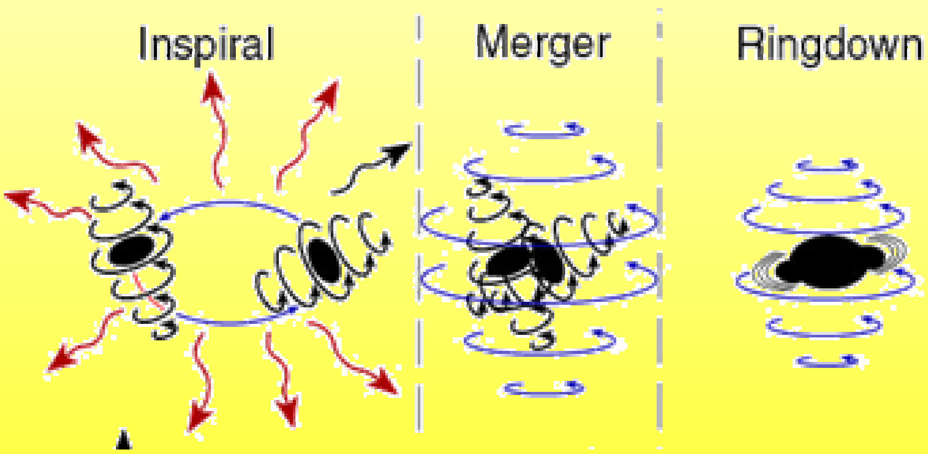
LISA does precision Bothrodesy (BH Science)

Here: 10 $M_\odot$ BH into 10^6 $M_\odot$ BH; large spin [Finn&Thorne]



Mergers of Massive Black Holes

- Coalescing Supermassive Binary Black Holes at z=1 give amplitude signal-to-noise of 1000 or more
- Standard Candles at cosmological distances
- Provide precision distance scale independent of electromagnetic observations



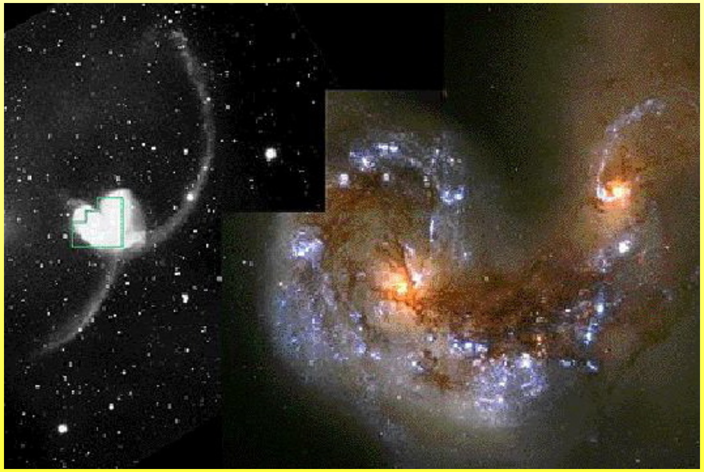
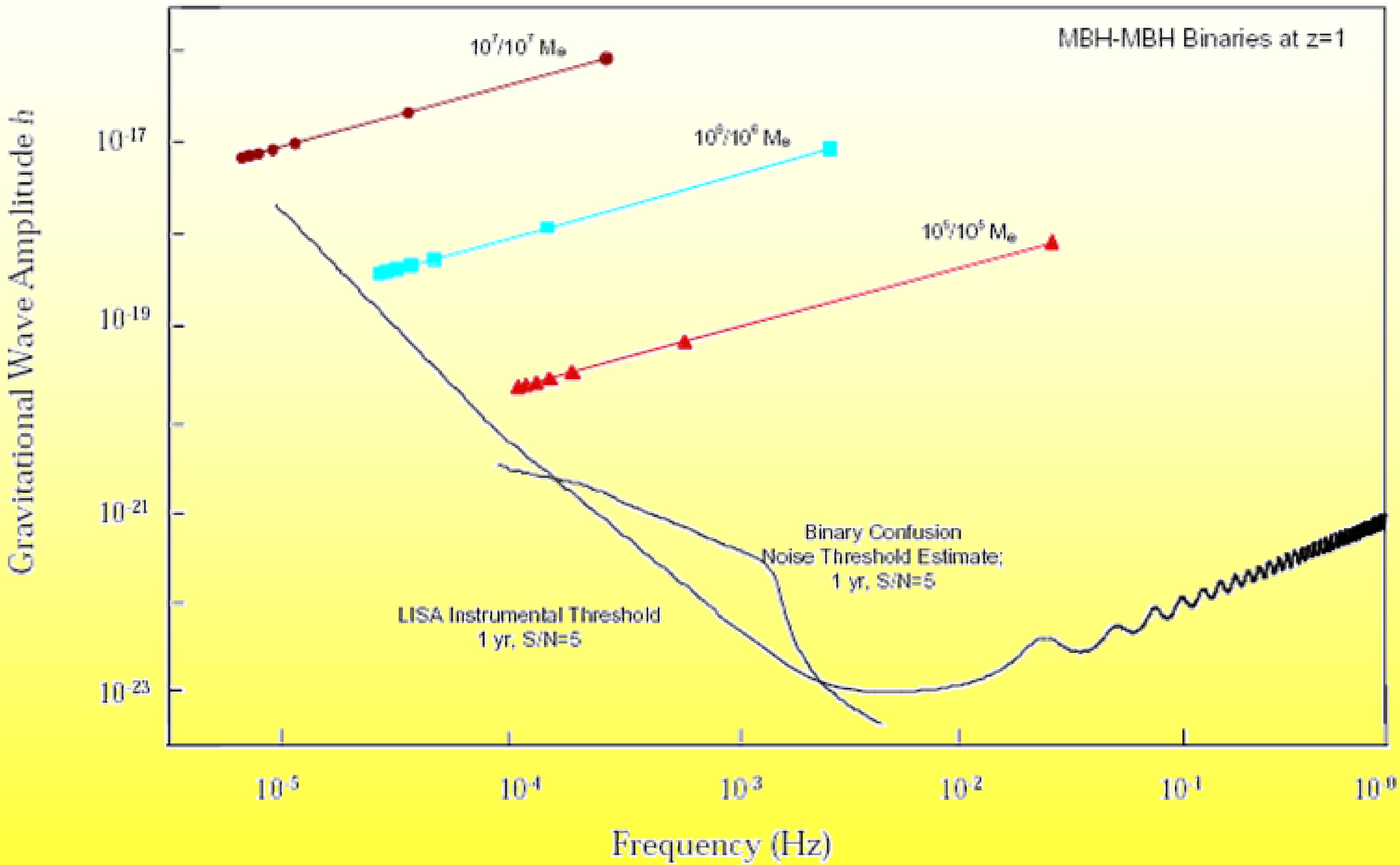


Image by B. Whitmore (STSci), F. Schweizer (DTM), NASA

Evolution of SMBH binaries

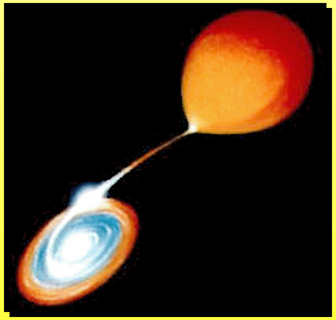


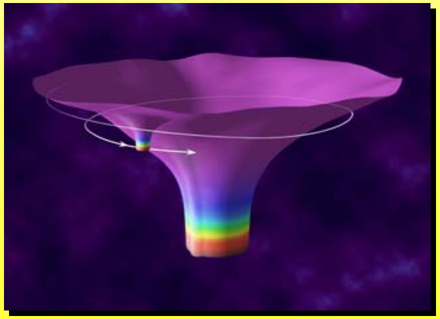
B Schutz (AEI)

LISA Science Goals

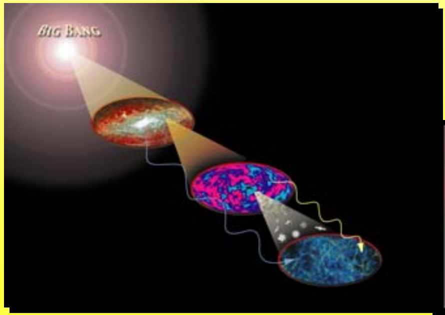
- Role of massive black holes in galaxy evolution
- Precision tests of General Relativity
- Population census of ultra-compact binaries
- Physics of the early universe

- Merging supermassive black holes
- Merging intermediate-mass/seed black holes
- Gravitational captures
- Galactic and verification binaries
- Cosmological backgrounds and bursts

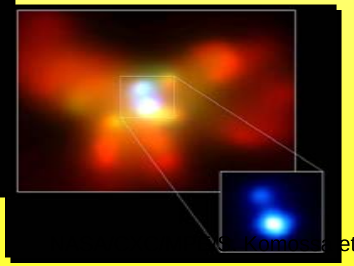




K. Thorne (Caltech)



NASA, Beyond Einstein



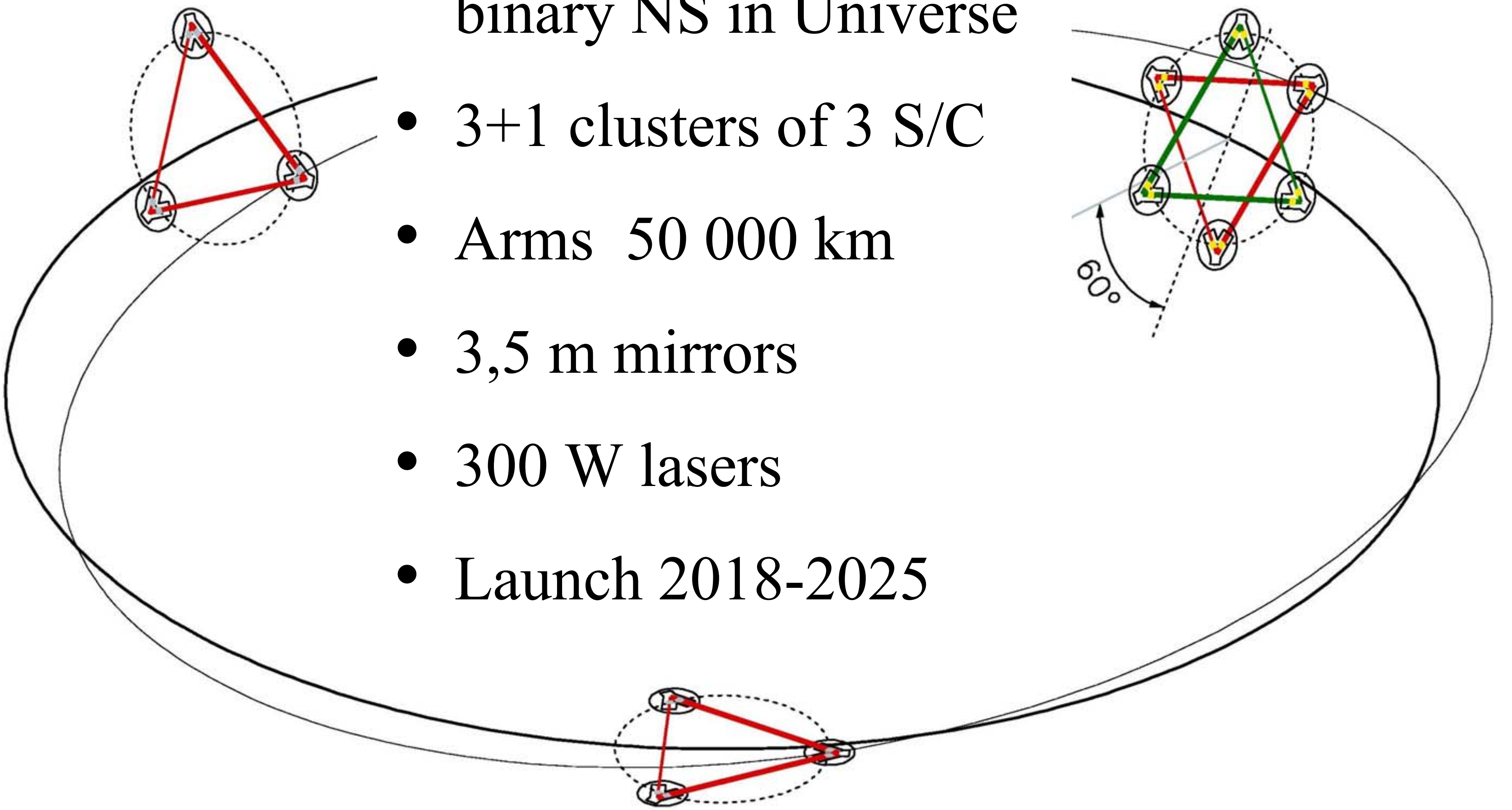
S. Komossa et al.

LISA Pathfinder:

Big Bang Observer (BBO)

NASA Concept Study for 2020+

- Resolve and remove all binary NS in Universe
- 3+1 clusters of 3 S/C
- Arms 50 000 km
- 3,5 m mirrors
- 300 W lasers
- Launch 2018-2025



The Future of Observatories (1)

- 1st Generation going into operation this year *(GEO600, LIGO, TAMA, VIRGO)*
- 2nd Generation follows 2007, design is ready *(Advanced LIGO Proposal, recent positive review; Advanced VIRGO, from operating funds)*
- 3rd Generation 2010+, concepts are being developed *(GEO upgrade in 2007, EGO, LIGO III)*
- *Sensitivity improves more than tenfold at each step, observed volume thousandfold!*

The Future of Observatories (2)

- LISA Pathfinder (SMART-2) as technology demo
  30 cm armlength
  Launch 2007
- LISA detector in space for low frequencies
  5 Million km armlength,
  Launch 2012
- Big Bang Observer (BBO) to look for
  Gravitational Waves from the early universe
  Proposal VM03-0021-0021 to NASA on 11 Sept 2003
  50 000 km armlength,
  Launch 2018/25