Astrofizyka cząstek

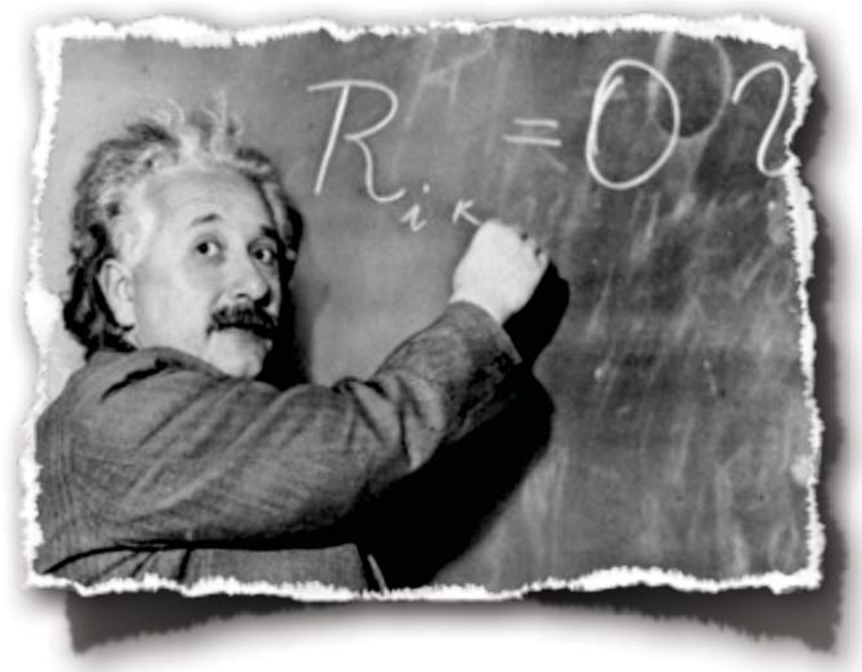
prof. dr hab. A.F.Żarnecki
Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład XII

- fale grawitacyjne
- detekcja fal grawitacyjnych
- przyszłe eksperymenty
- pomiar polaryzacji CMB

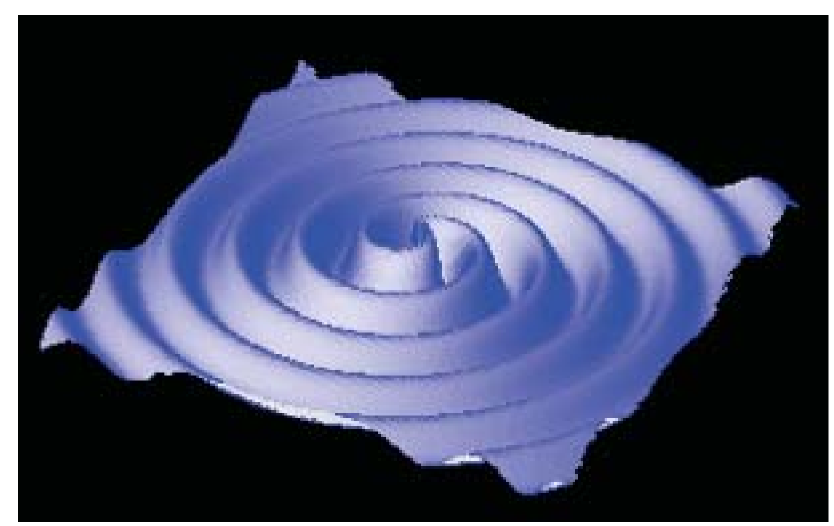
Gravitational waves

- The existence of gravitational waves (GWs) is one of the most intriguing predictions of General Relativity.
- GWs are freely propagating oscillations in the geometry of spacetime — ripples in the fabric of spacetime.



accelerating charges (time-varying dipole moment) → electromagnetic waves

accelerating masses (time-varying quadrupole moment) → gravitational waves



Gravitational waves in linearized GR

[More in GR lectures by Tiglio]

- Linearized gravity is an adequate approximation to GR when

small perturbation

$$g_{ab} = \eta_{ab} + h_{ab}, \qquad \|h_{ab}\| \ll 1$$

spacetime metric (analogous to potential ϕ in Newtonian theory)

"flat" metric diag(-1, 1, 1, 1)

On the surface of the Earth, where we aim to detect GWs, linearized gravity is an adequate approximation to GR.

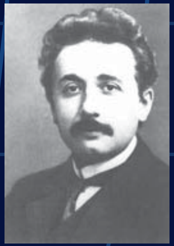
What are Gravitational Waves ?

Gravitational Waves (GW) are ripples of space-time

Theory of GW :

1. Einstein equations: $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$
2. Far from sources: $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0$$
3. Linearization: $$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$
4. Gauge TT: $$\nabla^2 h^{TT}_{\mu\nu} = 0$$

Propagation of some tensor field – *h* - on flat space-time



Prediction in 1916 !

Transverse-Traceless Gauge and Number of Degrees of Freedom

Plane-wave solutions:

$$\bar{h}^{\alpha\beta} = A^{\alpha\beta} \exp(2\pi\imath k_\mu x^\mu), \quad k_\alpha k^\alpha = 0$$

Gravitational waves travel at the speed of light.

Gauge conditions imply that $A^{\alpha\beta} k_\beta = 0$. Further gauge conditions

1. $A^{0\beta} = 0 \quad \Rightarrow \quad A^{ij} k_j = 0$: *Transverse* wave; and
2. $A^j{}_j = 0$: *Traceless* wave amplitude.

For a wave traveling in the z-direction then $k_z = k, \ k_x = k_y = 0$.

Gauge conditions, transversality and traceless conditions imply

$$A^{0\alpha} = A^{z\alpha} = 0, \ A^{xy} = A^{yx}, \ A^{yy} = -A^{xx}.$$

Only two independent amplitudes. Two independent degrees of freedom for polarization: plus-polarization and cross-polarization.

Gravitational Wave general properties

- GW propagate at speed of light
- GW have two polarizations "+" and "x"
- GW emission is quadrupolar at lowest order

Example: plane wave propagating along z axis with 2 polarization amplitudes h_+ and h_x:

$$h_{\mu\nu}^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Corresponding *Graviton* properties:

- Graviton has null mass
- Graviton has spin 2

Tidal Effect of Gravitational Waves

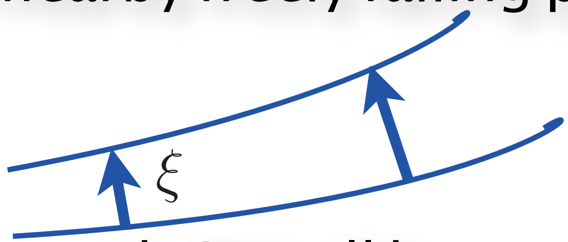
In the TT gauge, the effect of a wave on a particle at rest

$$\frac{d^2}{d\tau^2}x^i = -\Gamma^i{}_{00} = -\frac{1}{2}\left(2h_{i0,0} - h_{00,i}\right) = 0.$$

So a particle at rest remains at rest. TT gauge is a coordinate system that is comoving with freely falling particles.

The waves have a tidal effect which can be seen by looking at the change in distance between two nearby freely falling particles:

$$\frac{d^2}{d\tau^2}\xi^i = R^i{}_{0j0}\xi^j = \frac{1}{2}h_{ij,00}\xi^j.$$

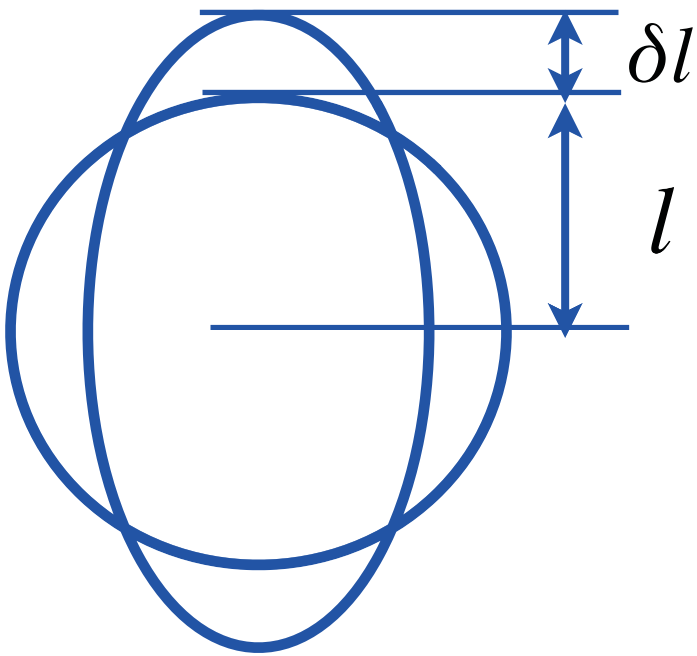


Isaacson showed that a spacetime with GW will have curvature with the corresponding Einstein tensor given by

$$G_{\alpha\beta} = 8\pi T^{(GW)}_{\alpha\beta} \qquad T^{(GW)}_{\alpha\beta} = \frac{1}{32\pi} h^{TT}_{\mu\nu}{}_{,\alpha} h^{TT\mu\nu}{}_{,\beta}.$$

GW Amplitude – Measure of Strain

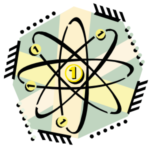
- Gravitational waves cause a strain in space as they pass
- Measurement of the strain gives the amplitude of gravitational waves



$$\delta l = \frac{h}{2} l$$

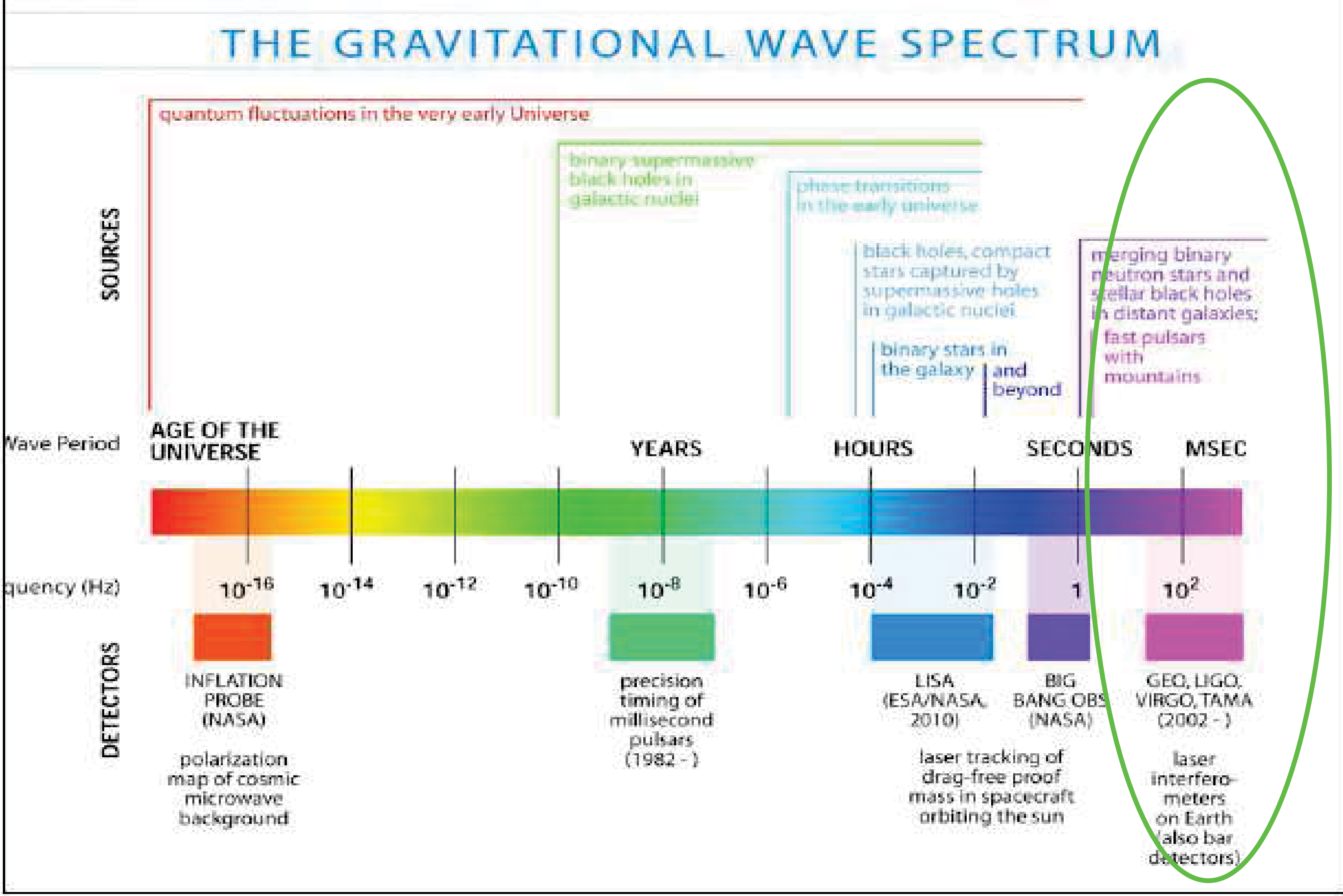
Expect strain (dl / l) of e.g. 10^{-21} ...

← 150 Mio. km →



Distance earth – sun changes by the diameter of a hydrogen-atom !

or: A 1 km long measurement distance changes by 1/1000 of an ATOMIC CORE diameter !!!



THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^-16
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
1
10^2
DETECTORS
INFLATION PROBE (NASA)
polarization map of cosmic microwave background
precision timing of millisecond pulsars (1982 -)
LISA (ESA/NASA, 2010)
BIG BANG OBS (NASA)
laser tracking of drag-free proof mass in spacecraft orbiting the sun
GEO, LIGO, VIRGO, TAMA (2002 -)
laser interferometers on Earth (also bar detectors)

Gravitational waves in linearized GR

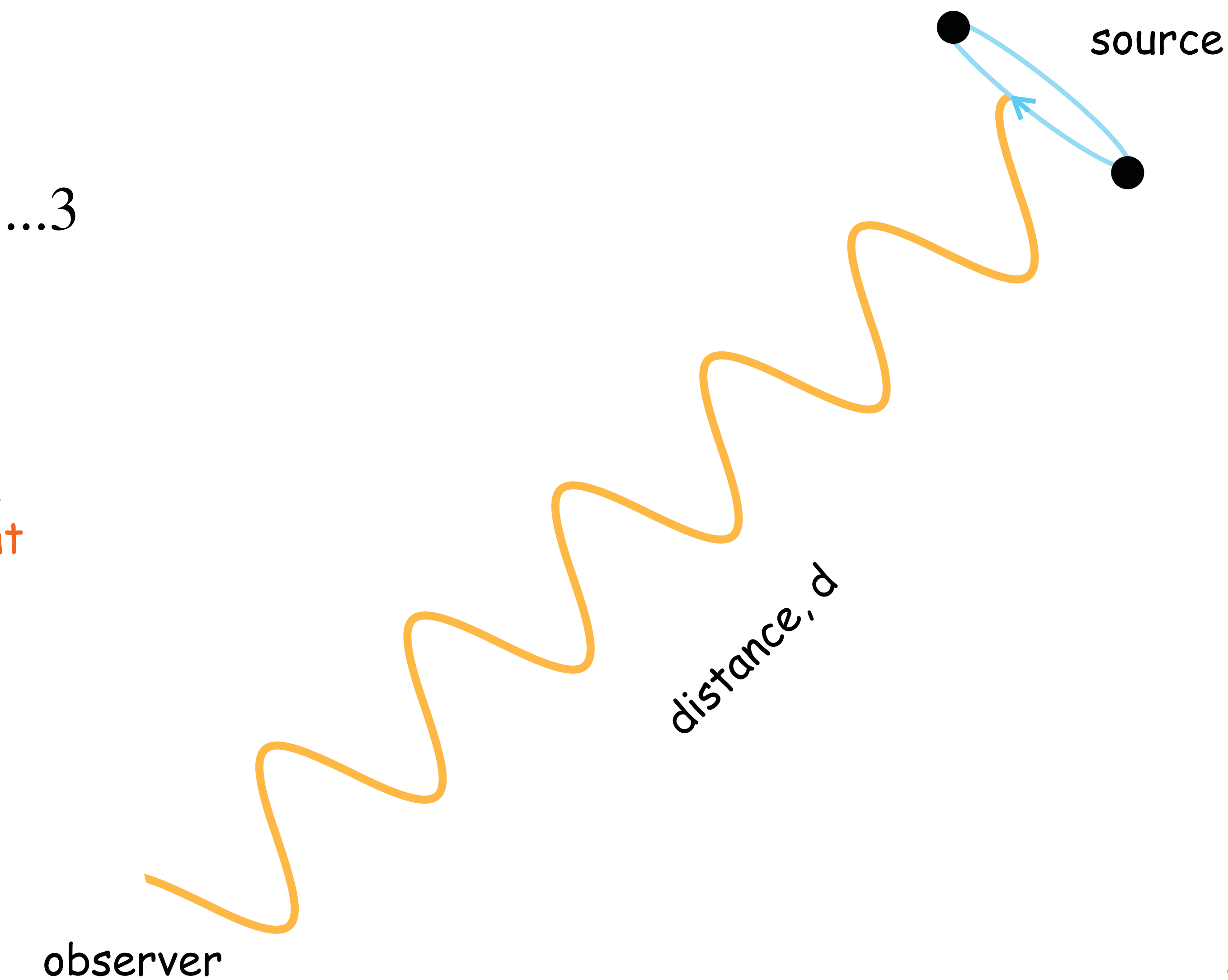
- In transverse-traceless gauge, the metric perturbation can be related to the quadrupole-moment of the source.

GW amplitude

$$h_{jk}(t) \sim \frac{2}{d}\,\ddot{Q}_{jk} \qquad j,k = 1 \ldots 3$$

distance to the source

second time-derivative of the quadrupole moment



Gravitational Wave emission

(*quadrupole formalism*)

Emission equation in the TT Gauge: $\nabla^2 h_{\mu\nu}^{TT} = -\frac{16\pi G}{c^4} T_{\mu\nu}$

Retarded solution: $h_{\mu\nu}^{TT}(\vec{x}, t) = \frac{2G}{Rc^4} \ddot{Q}_{\mu\nu}^{TT}(t - R/c)$

Hence: $h_{+}^{TT}(\vec{x}, t) = \frac{G}{Rc^4}\left[\ddot{Q}_{11}^{TT} - \ddot{Q}_{22}^{TT}\right](t - R/c)$ $h_{\times}^{TT}(\vec{x}, t) = \frac{2G}{Rc^4}\left[\ddot{Q}_{12}^{TT}\right](t - R/c)$

Where the ***reduced quadrupole*** moment:

$$Q_{\mu\nu}^{TT} = \iiint d^3x\, \rho\, (x_\mu\, x_\nu - \tfrac{1}{3}\delta_{\mu\nu} r^2)$$

Regular quadrupole (inertia) moment: $q_{\mu\nu} = \iiint d^3x\, \rho\, x_\mu x_\nu$

$\rho \sim T_{00}/c^2$: density of the source

Gravitational waves in linearized GR

- In transverse-traceless gauge, the metric perturbation can be related to the quadrupole-moment of the source.

reduced-mass of the source

"compactness" of the source

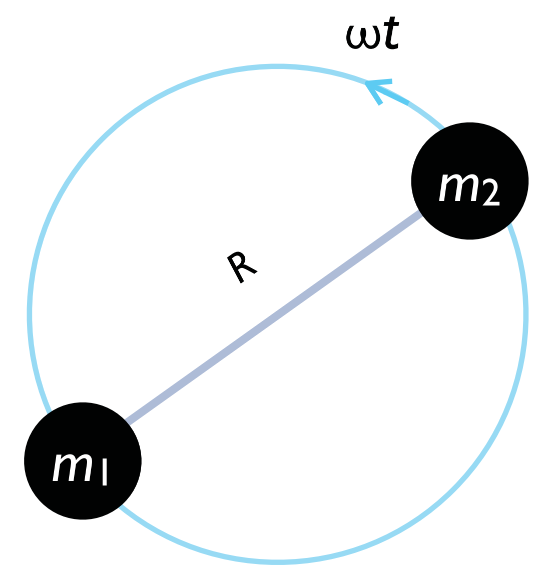
frequency of the source

$$h_{jk}(t) \sim \frac{2}{d}\ddot{Q}_{jk} \sim \left(\frac{G}{c^4}\right)\frac{4\mu}{d}\left(\frac{GM}{R}\right)\cos 2\,\omega t$$

10^{-45}!

Keplerian v^2

Most promising sources are **relativistic** phenomena involving **massive** and **compact** objects



$M = m_1 + m_2$

Gravitational Wave emission:
Orders of magnitude

Luminosity (Einstein quadrupole formula):

$$P = \frac{G}{5c^5}\left\langle \dddot{Q}_{\mu\nu}\,\dddot{Q}^{\mu\nu}\right\rangle$$

$G/5c^5 \sim 10^{-53}\ \mathrm{W}^{-1}$

Factor ridiculously « small » !

source	distance	*h*	*P* (W)
Steel bar, 500 T, ∅ = 2 m L = 20 m, 5 cycles/s	1 m	2×10^{-34}	10^{-29}
H bomb, 1 megatonne Asymmetry 10%	10 km	2×10^{-39}	10^{-11}
Supernova 10 $M_\odot$ asymmetry 3%	10 Mpc	10^{-21}	10^{44}
Coalescence 2 black holes 10 $M_\odot$	10 Mpc	10^{-20}	10^{50}

Hertz experiment is impossible for GWs ...

Gravitational Wave emission and compact stars

© J. Weber (1974)

Pb : G/c^5 is very « small ».

c^5/G would be much better !!!

Source : mass M, size R, period T, asymmetry a $\Rightarrow$ $\dddot{Q} \approx a\, M\, R^2 / T^3$

Quadrupole formula becomes :

$$P \approx \frac{G}{c^5} a^2 \frac{M^2 R^4}{T^6}$$

New parameters

- caracteristic speed v
- Schwarzchild Radius $R_s = 2GM/c^2$

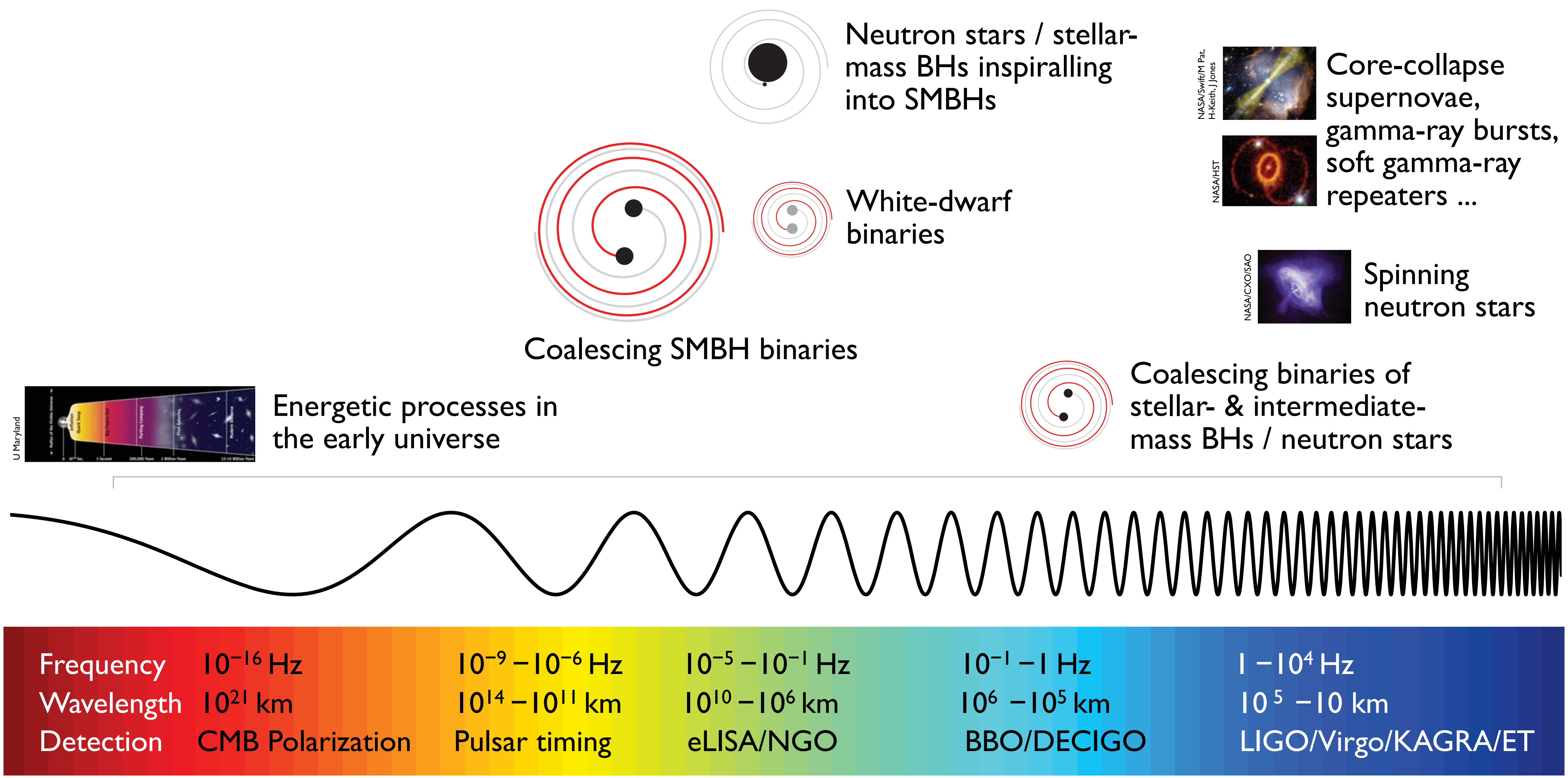
$$P \approx \frac{c^5}{G} a^2 \left(\frac{R_S}{R}\right)^2 \left(\frac{v}{c}\right)^6$$

Huge luminosity if

- $R \rightarrow R_s$
- $v \rightarrow c$
- $a \rightarrow 1$

compact stars

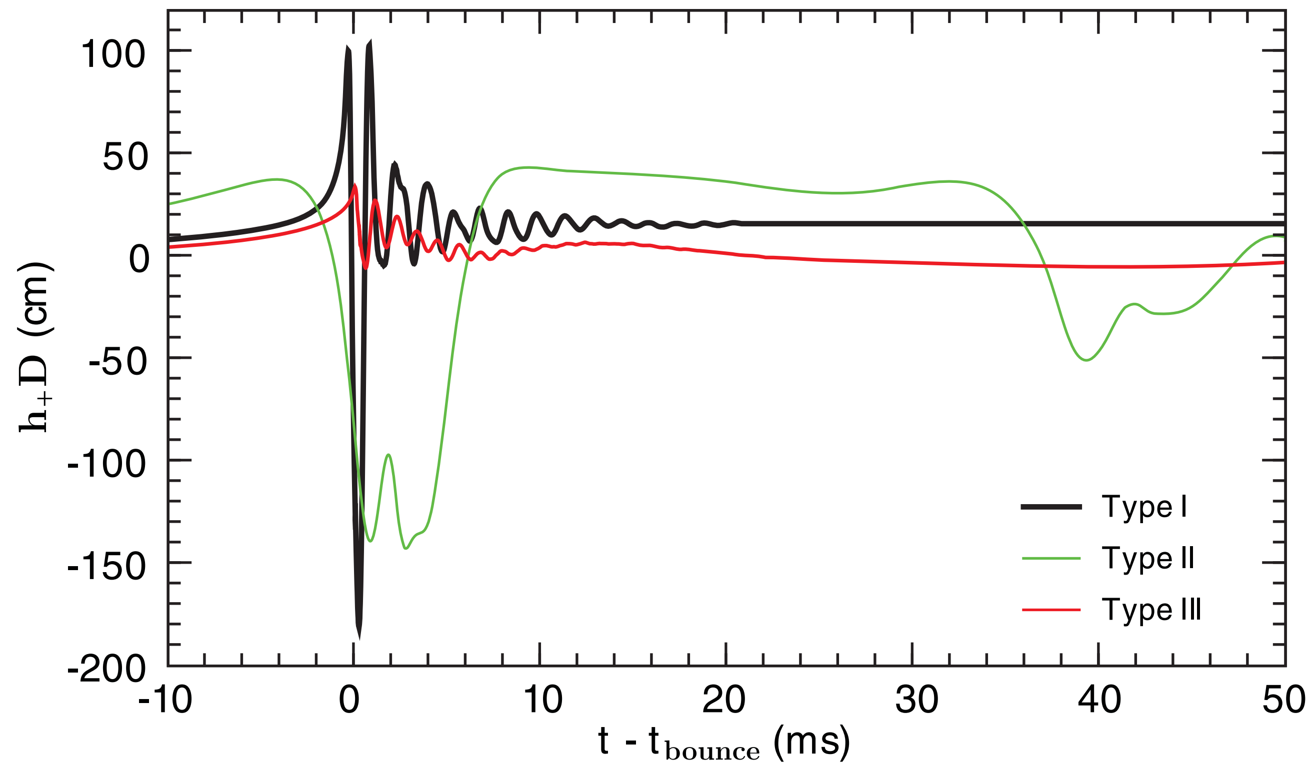
Expected sources of gravitational waves



Expected sources of gravitational waves

- **Burst sources** Collapse of massive stellar cores can produce a burst of GWs.

[Dimmelmeier et al (2002)]



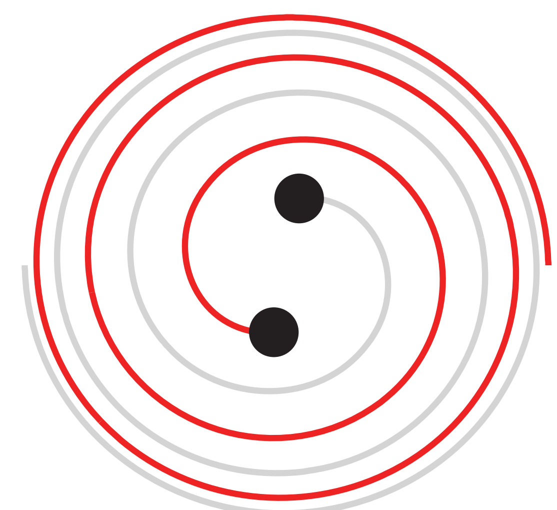
leaves behind
a compact object
(black hole or neutron star)

may also produce a
supernova/long GRB

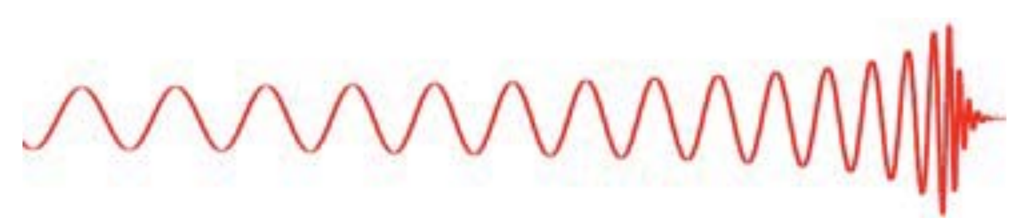
$$E_{GW} = 10^{-12} - 10^{-4}\ M_{\odot}\, c^2$$

Expected sources of gravitational waves

- **Burst sources** Collapse of massive stellar cores can produce a burst of GWs
- **Continuous sources** Spinning neutron stars with non-axisymmetric deformations.
- **Compact binary coalescences** driven by GW emission.



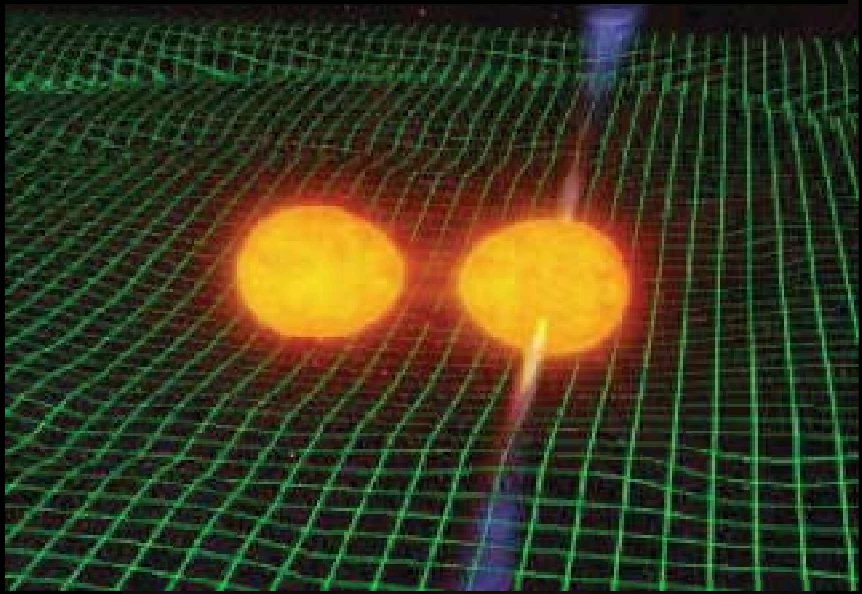
$$E_{\rm GW} \simeq 0.01 - 0.15\ Mc^2$$

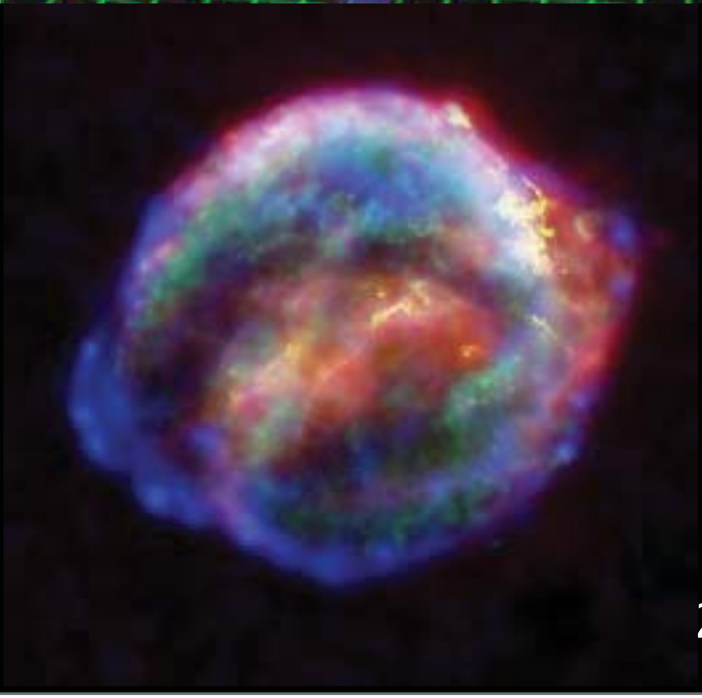


merger (involving NS) might also produce a short GRB

Gravitational wave searches

- Compact binary coalescences
  - Binary neutron stars – low–mass searches
  - Binary black holes – high–mass searches
- Unmodelled bursts of radiation
  - Un–triggered searches
  - Searches triggered by gamma–ray bursts, pulsar glitches, supernovae, etc.
- Continuous waves from rapidly rotating neutron stars
  - Radiation from known pulsars
  - All sky, blind searches
  - Pulsars in binary systems
- Stochastic radiation
  - Isotropic searches
  - Directed searches





Universitat de les Illes Balears

What can we expect to learn from GW observations?

Their detection would give us insight into fundamental physics and astronomy!

Astrophysics

- History of star formation, populations of black holes and neutron stars
- Physics at nuclear densities (neutron star equation of state and structure)
- Dark matter in Halos-MACHO objects
- Astrophysical stochastic backgrounds
- Discovery of new astronomical objects and phenomena

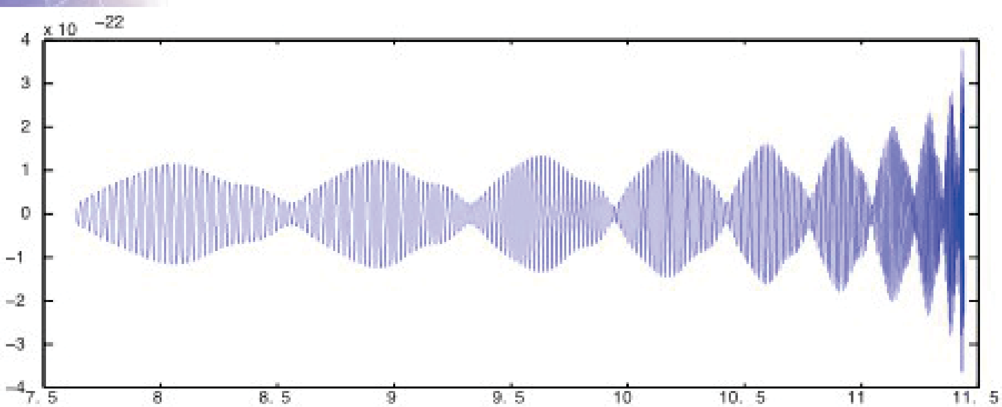
Tests of Relativity

- Confirm speed of gravitational waves, constrain graviton mass
- Measure polarization and test general relativity
- Two body dynamics (spin-orbit, spin-spin couplings)
- Non-linear gravity
- Uniqueness theorems on BH space-times
- Relativistic instabilities

Cosmology

- Cosmological parameters and their variation with red-shift
- Dark energy – equation of state and nature
- Origin of the Universe and connection between quantum theory and general relativity.

Testing the strong-field dynamics of gravity



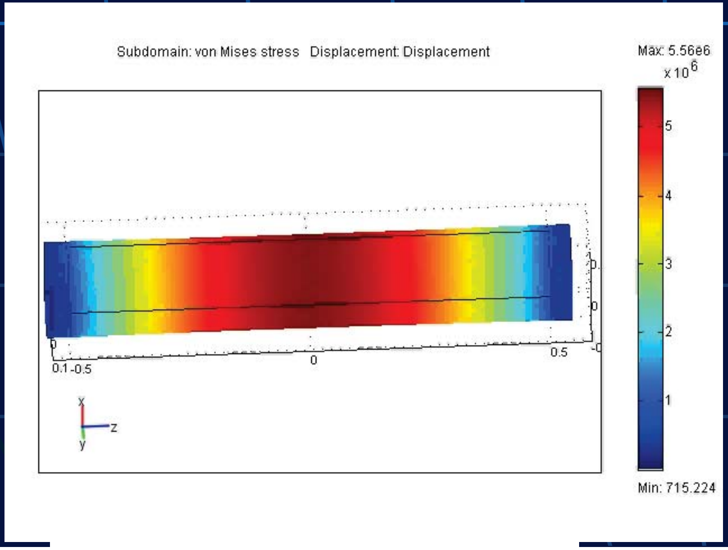
- Hulse-Taylor and similar binary pulsars only constrain dissipation at quadrupole level
- Most interesting dynamical effects occur starting at $(v/c)^3$ beyond leading order!
  - "Tail effects"
  - Spin-orbit interaction
  - ...
- Exploit rich dynamics at late stages of inspiral, and merger/ringdown
- Can only be done with direct detection of gravitational waves

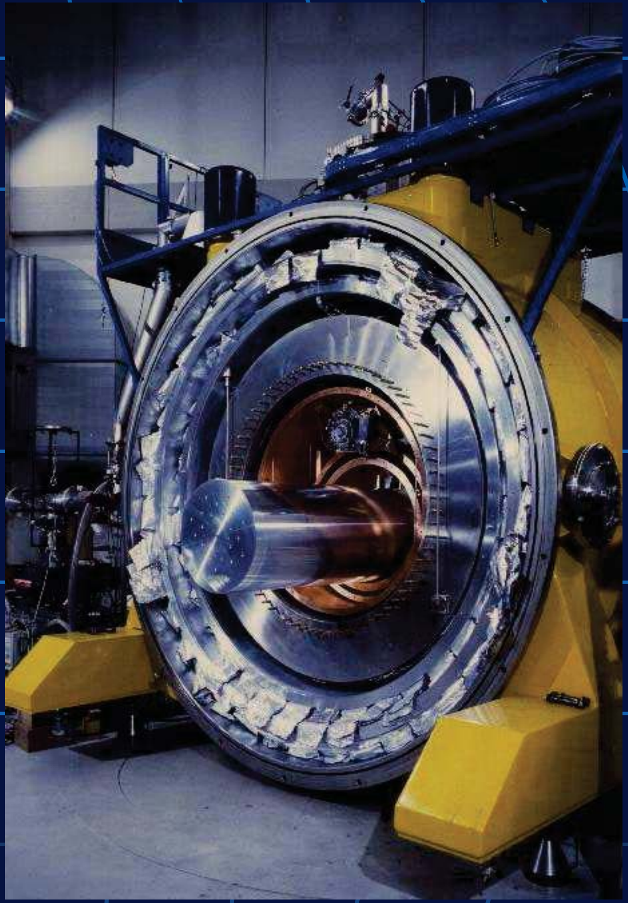
History

1960 1st detector (Weber)
1963 1st idea interferometric detection (Gersenshtein&Pustovoit, Weber)
1969 Wrong claim (Weber)
197X Weber detectors all over the world
1972 Itf feasibility study (Weiss) and 1st prototype (Forward)
1974 PSR1913+16 (Hulse&Taylor)
End 70s cryogenic bars, itf prototypes (Glasgow, Garching, Caltech)
1986 birth of collaboration VIRGO (France+Italy, *Nikhef joined in 2006*)
1989 **VIRGO proposal**, **LIGO proposal** (USA)
1992 LIGO funded
1993 VIRGO funded
1996 start construction VIRGO et LIGO
2005 LIGO in operation
2007 VIRGO in operation
2007-2011 LIGO-VIRGO joint data takings
2011-12 Start upgrades -> Advanced LIGO and Advanced VIRGO
2015 First science runs for aLIGO and AdVIrgo…

Resonant detectors
(Weber's bars)

From Weber (60's) …

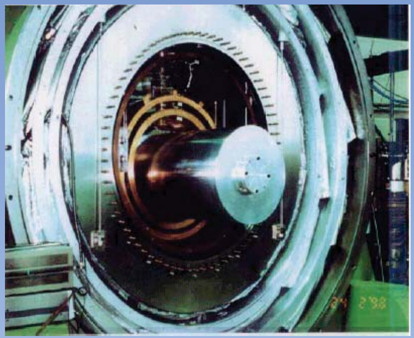




… to Auriga (2000s)

Resonant Bar Detectors

AURIGA
Legnaro, INFN (Italy)



NAUTILUS
Frascati, INFN (Italy)

EXPLORER
Geneva, CERN, INFN (Switzerland)

M ~ a few tons
L ~ 3 m
f ~ 900 Hz

ALLEGRO
Baton Rouge, LSU (USA)

NIOBE
Perth, UWA (Australia)

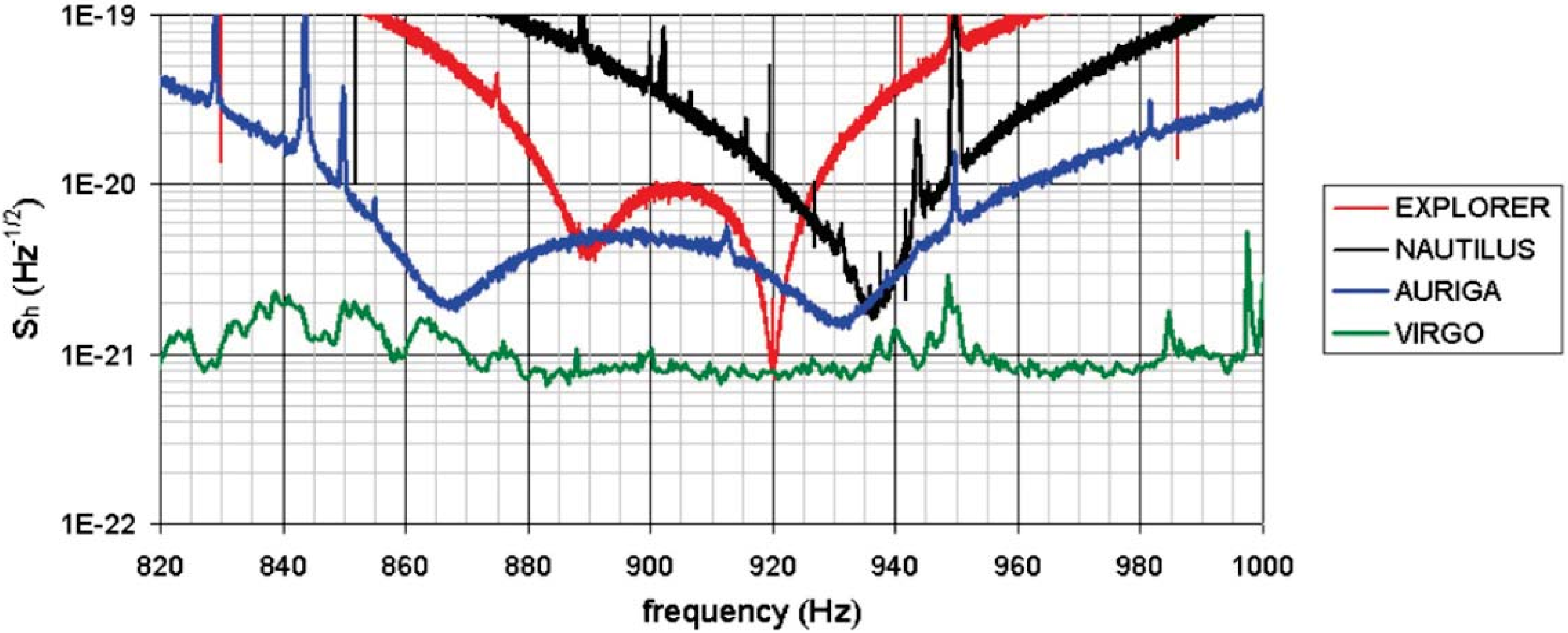
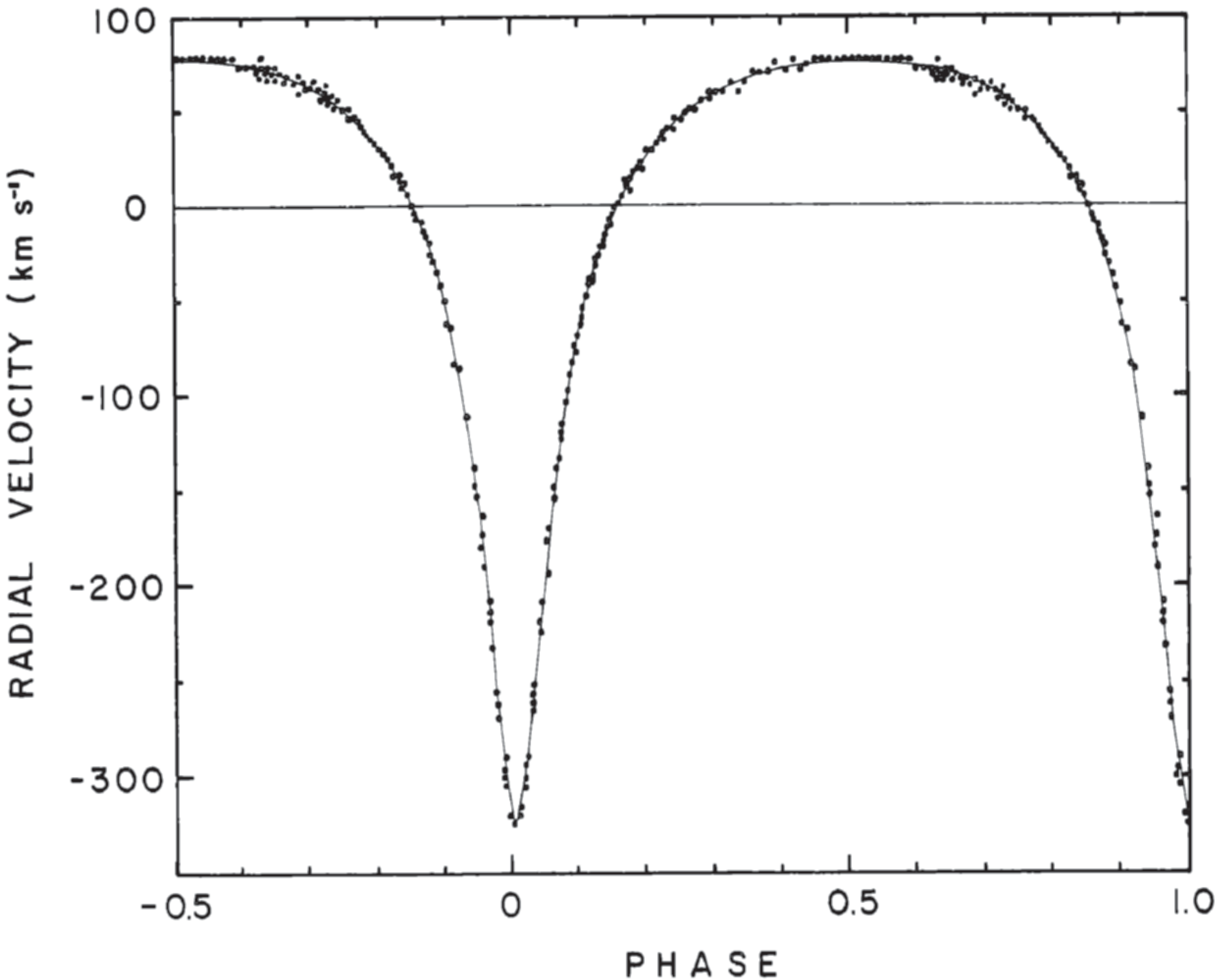


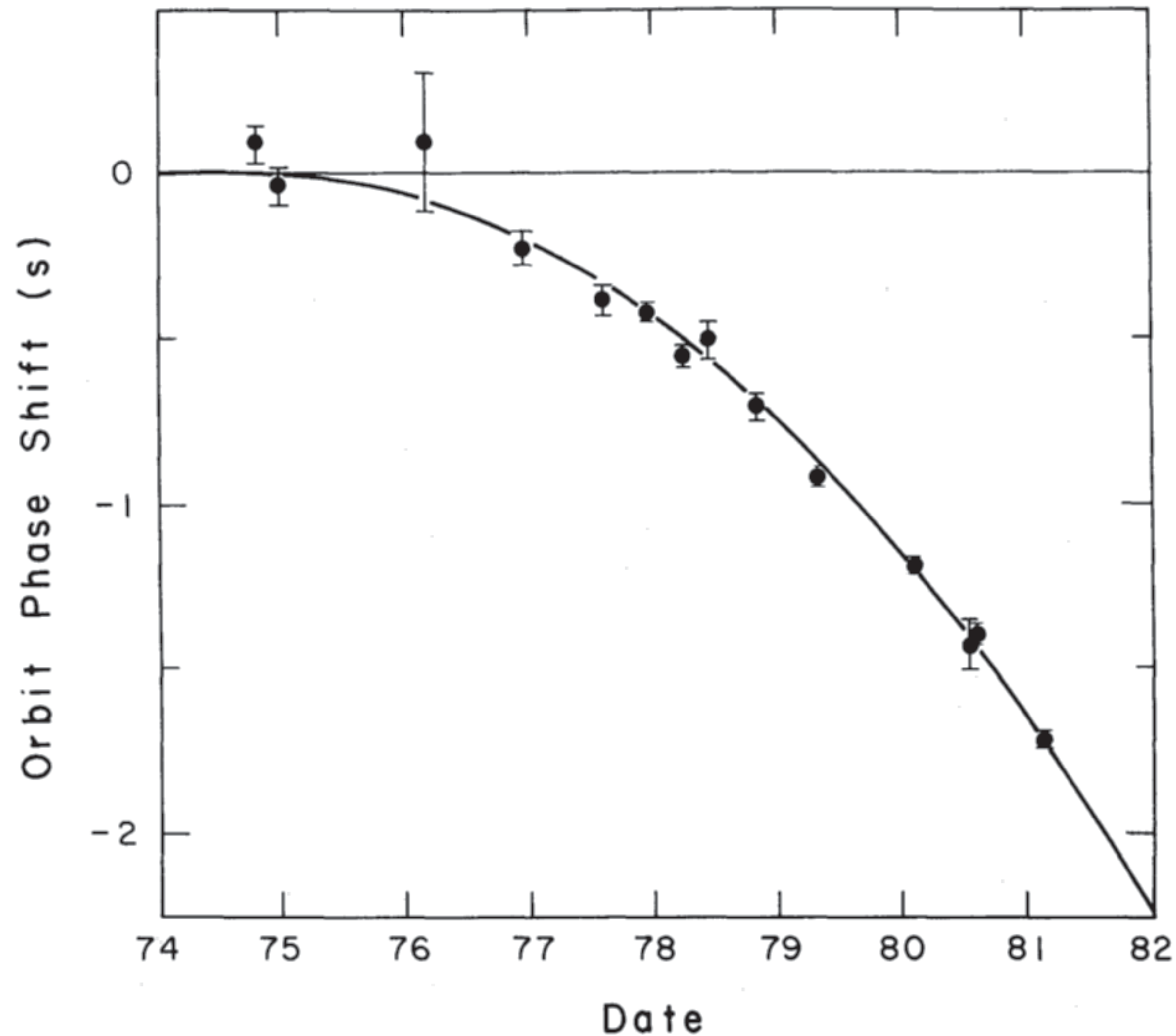
Figure 1. Typical spectral density of calibrated noise for the three resonant bar detectors during 2005 and for the Virgo interferometer in September 2005.

PSR 1913+16: orbit from pulsar timing



[*Hulse & Taylor (1975)*]

PSR 1913+16: orbital phase shift



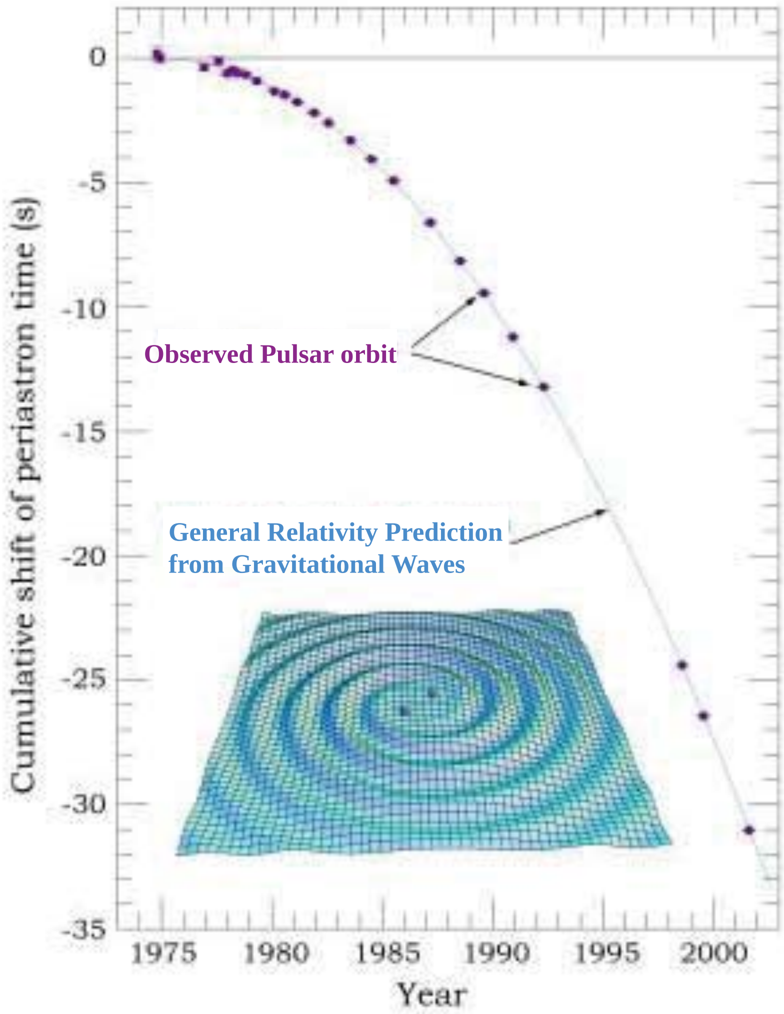
[*Taylor & Weisberg (1982)*]

Indirect evidence of gravitational radiation: PSR 1913+16

J. Taylor R. Hulse

- The emission of gravitational waves by a pair of neutron stars orbiting each other has been observed by measuring a tiny systematic shrinkage of the orbit.
- For this seminal discovery Hulse and Taylor were awarded the Nobel Prize in 1993.
- However, this dramatic observation is referred to as an indirect confirmation of the existence of gravitational waves, since what we have observed is the effect of the waves on the binary orbit rather than the waves themselves.

PSR 1913+16 orbit will continue to decay over the next ~300 million years, until coalescence. Gravitational wave emission will be strongest near the end.

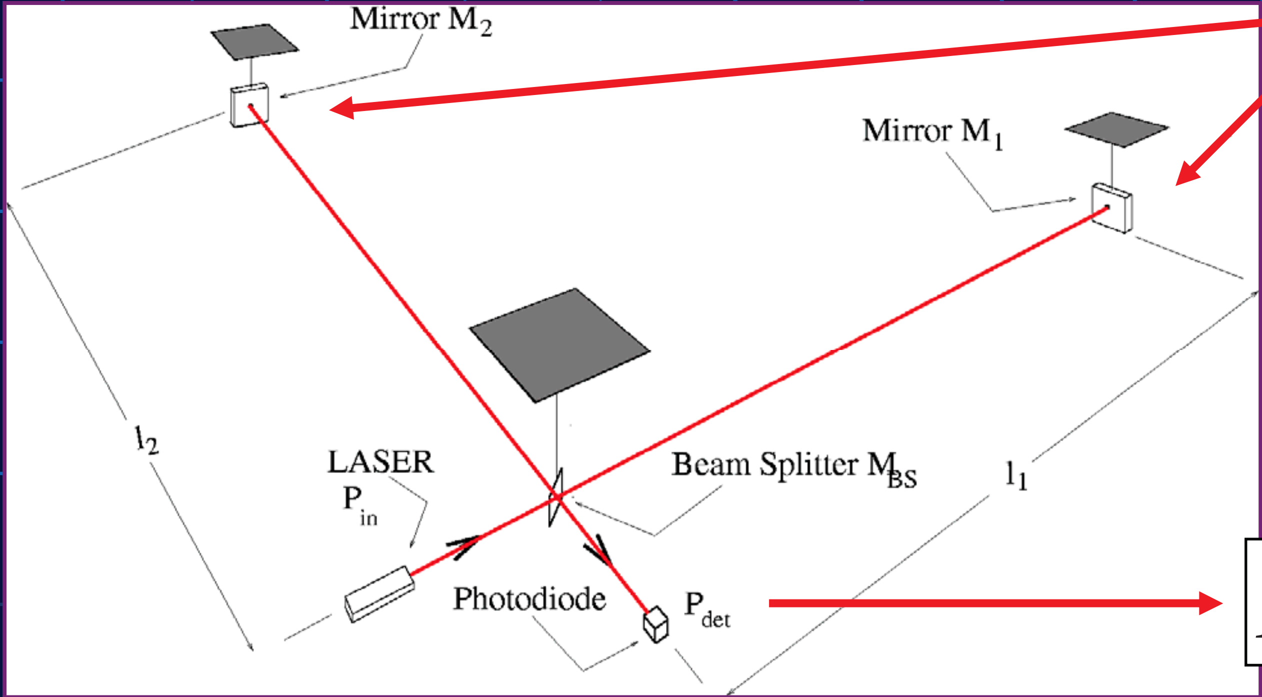


Virgo

Features of the Virgo Collaboration

- Established 1992
- Origin: two initially independent efforts
- Development of high quality optics (sources and mirrors): stringent requirements for gw interferometry
  - Work on light source stabilization A.Brillet
  - Large investment in coating facility : Laboratoire des Matériaux Avancés, Lyon, J.M. Mackowski
- Quest for low frequency detection: pulsar population, signal increase at low frequency
  - Development of passive seismic attenuation A. Giazotto

Itf detection principle

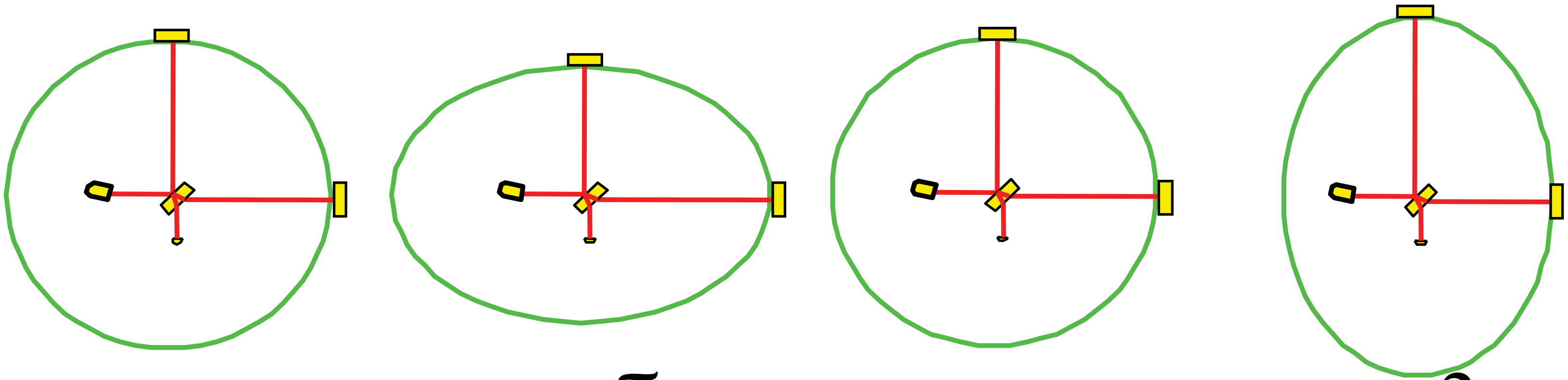


Suspended mirrors
⇔ Test masses

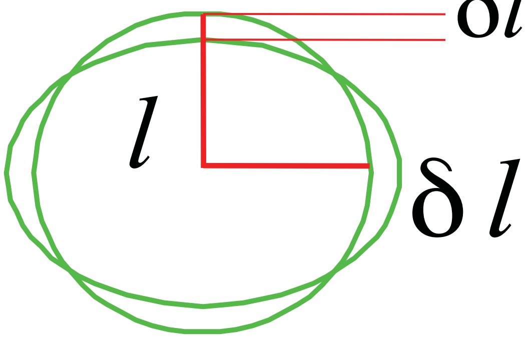
$$P_{det} = \frac{P_0}{2}\left[1 + C\cos(\Delta\phi)\right]$$

GW → optical paths are modified → detected power is modified

Interferometric gravitational wave detectors



$t = 0$ $\quad t = \frac{\tau}{4}$ $\quad t = \frac{\tau}{2}$ $\quad t = \frac{3\tau}{4}$



$$\delta l = \frac{h}{2} l$$

For Typical Astronomical sources

$$h = \frac{2\delta l}{l} \leq 10^{-22}$$

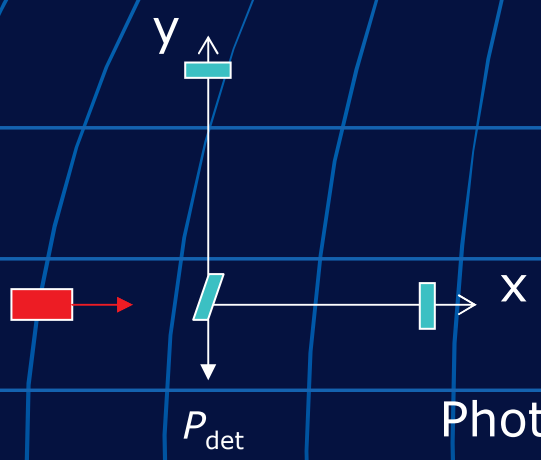
Noises in interferometric detectors

- optical readout noise (photon counting noise + radiation pressure noise)
- seismic noise (and filtering)
- thermal noise
- laser noises
- others

$\Rightarrow$ General design of itf detectors

Optical readout noise

2 aspects: photon counting noise (or shot noise) and radiation pressure noise

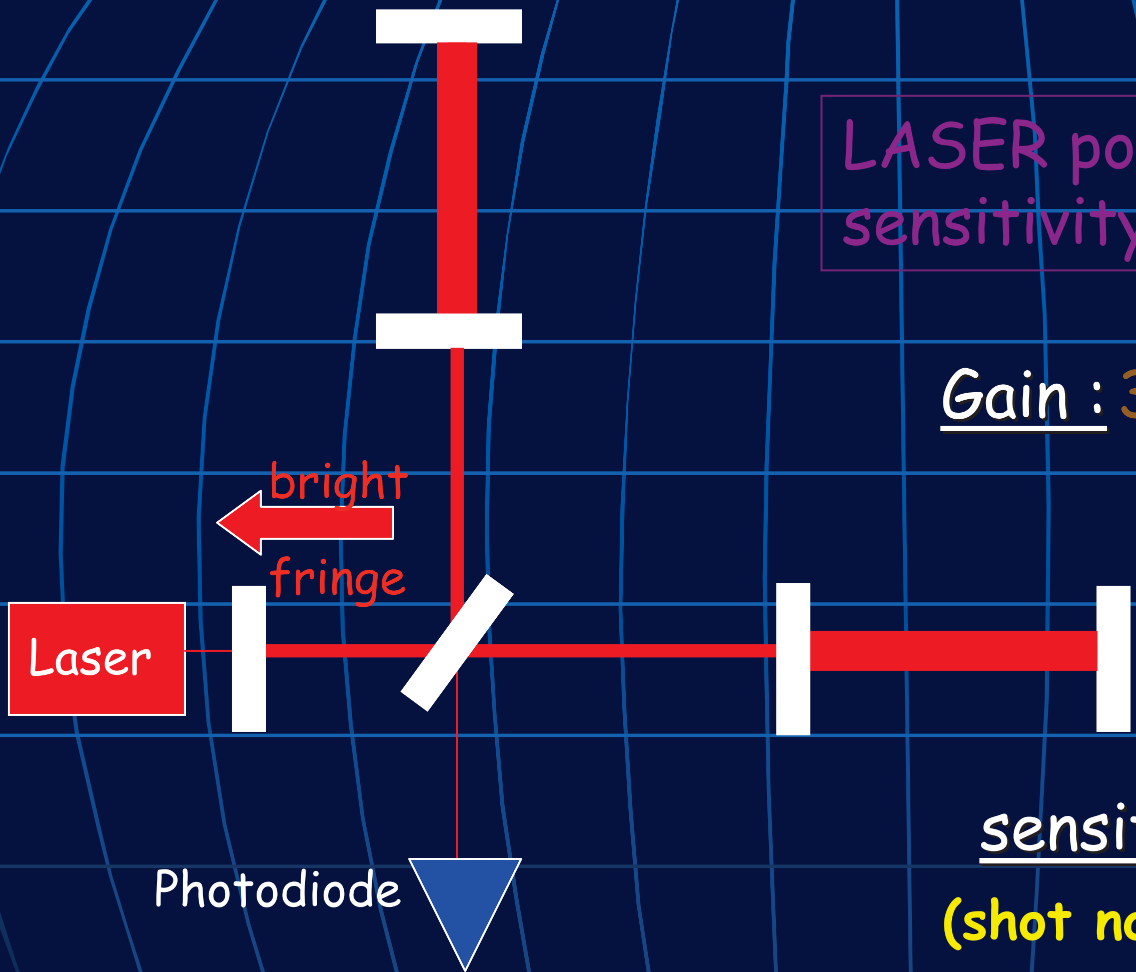


Photons detected by photodiode (PD) at the output

Counting statistics (Poisson):

- Let's note *n* = rate of arrival on PD (Hz)
- Average number of photons incident on the PD during time τ is then $N = n\tau$
- Standard deviation $\sigma_N = \sqrt{N}$
- Detected power $P_{\text{det}} = n\hbar\omega = N\hbar\omega / \tau$ in average
- Detected power fluctuation (RMS) : $\delta P_{\text{det}} = \sqrt{N}\hbar\omega / \tau$

Optical design is completed



LASER power : P_{in} = 20 W

sensitivity $h \propto 1 / \sqrt{P_{in}}$

Gain : 3000 × 30 × $\sqrt{50}$ ~ 10^6

sensitivity : $h \sim 3\ 10^{-22} / \sqrt{Hz}$

(shot noise)

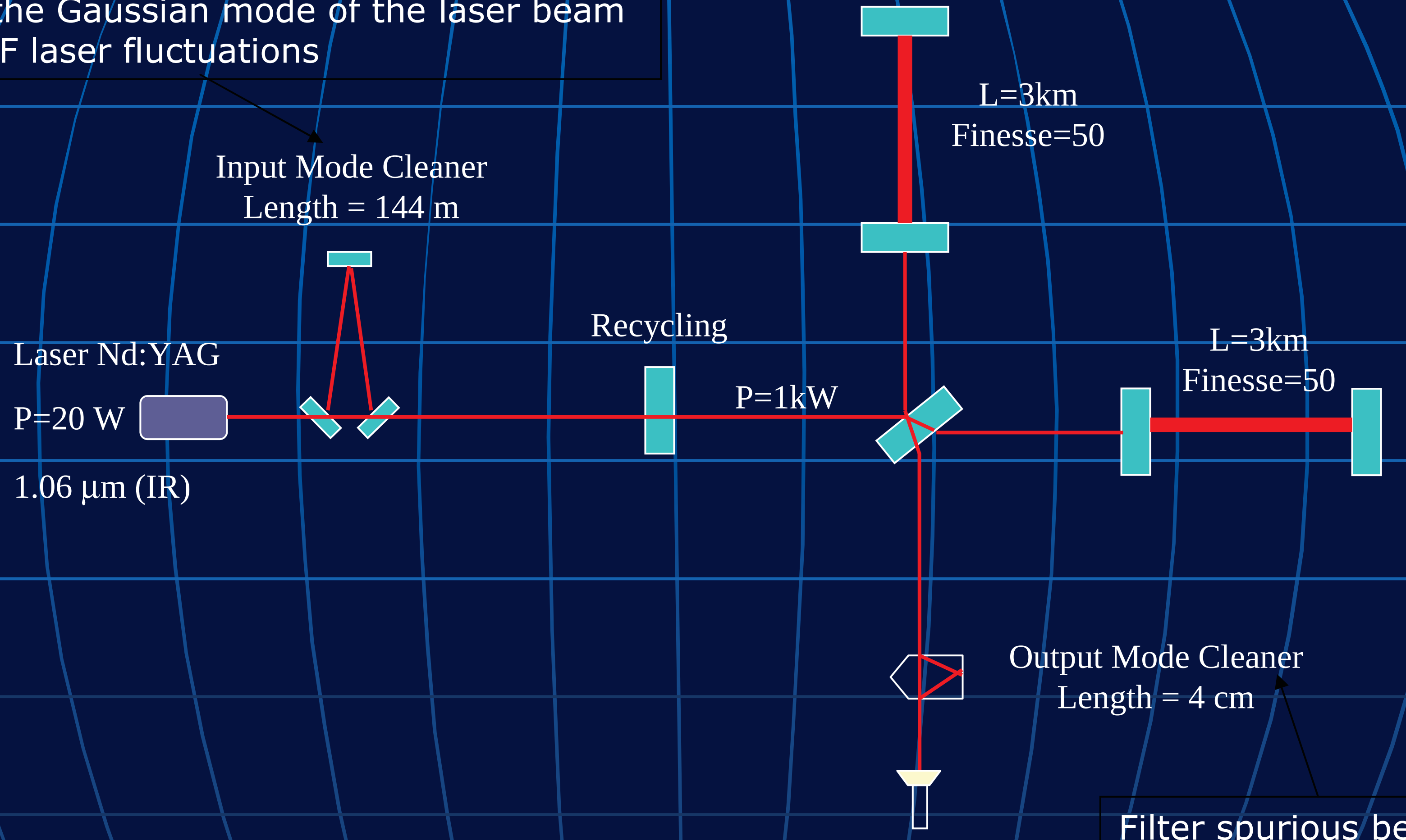
→ kilometric arm length : 1 m → 3 km

→ add Fabry-Perot cavities (Finesse = 50 ⇒ Gain ~ 30)

→ add « recycling » mirror (P = 1 kW on the beamsplitter)

Virgo optical design

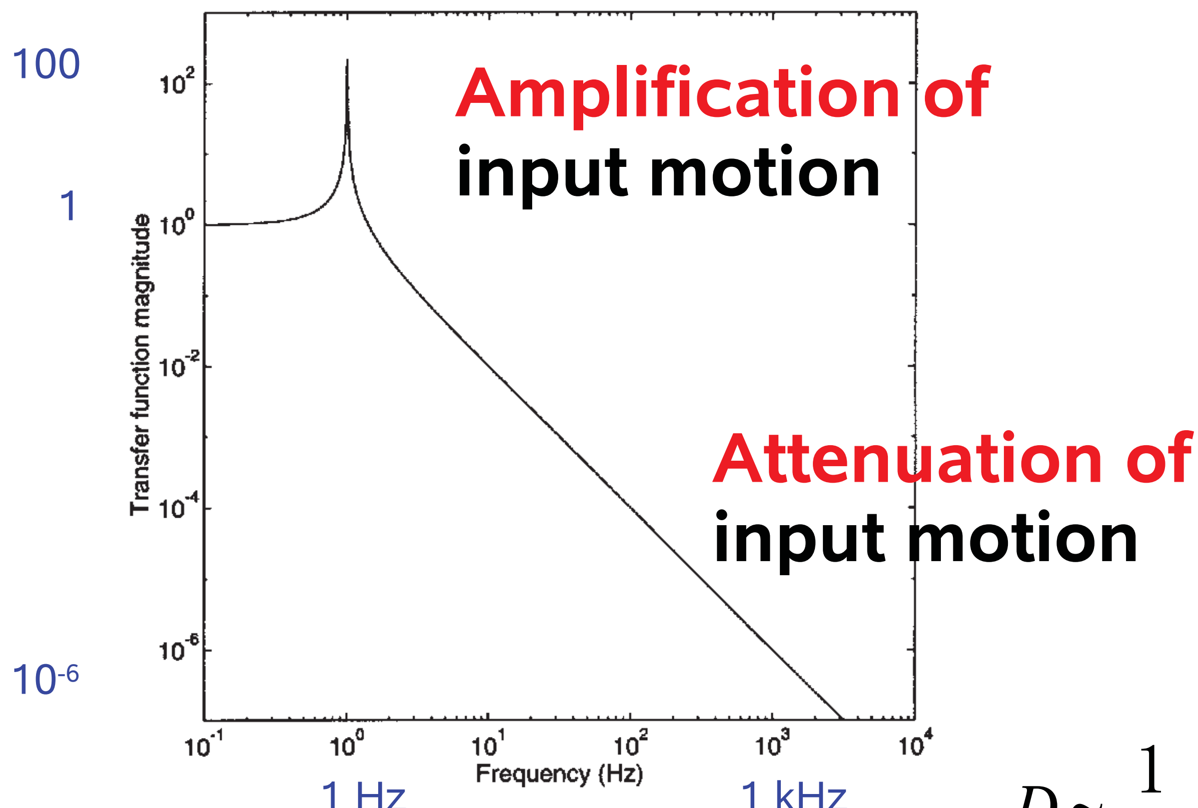
+ Clean the Gaussian mode of the laser beam
+ filter HF laser fluctuations



Filter spurious beams
(increase the contrast)

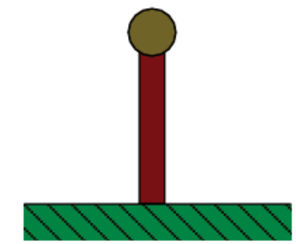
Let's swing!

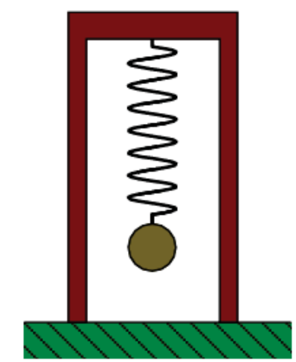
Transfer function of pendulum with f_0 = 1 Hz



$$D \sim \frac{1}{f^2}$$

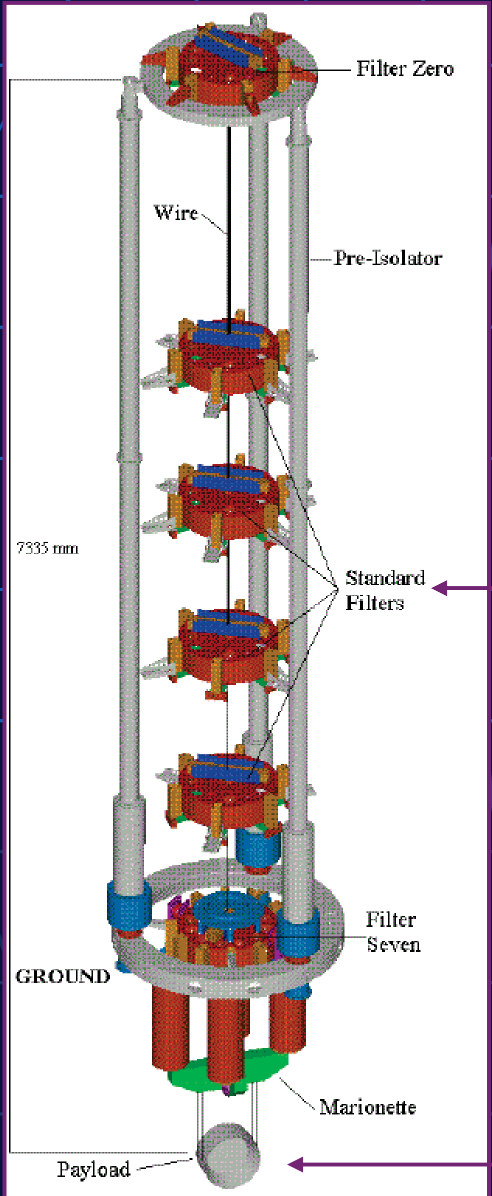
Mass is fixed

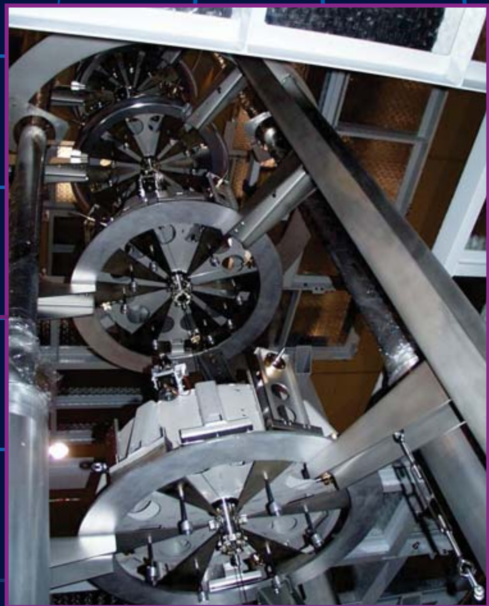




Mass is suspended as pendulum

Virgo « superattenuator »





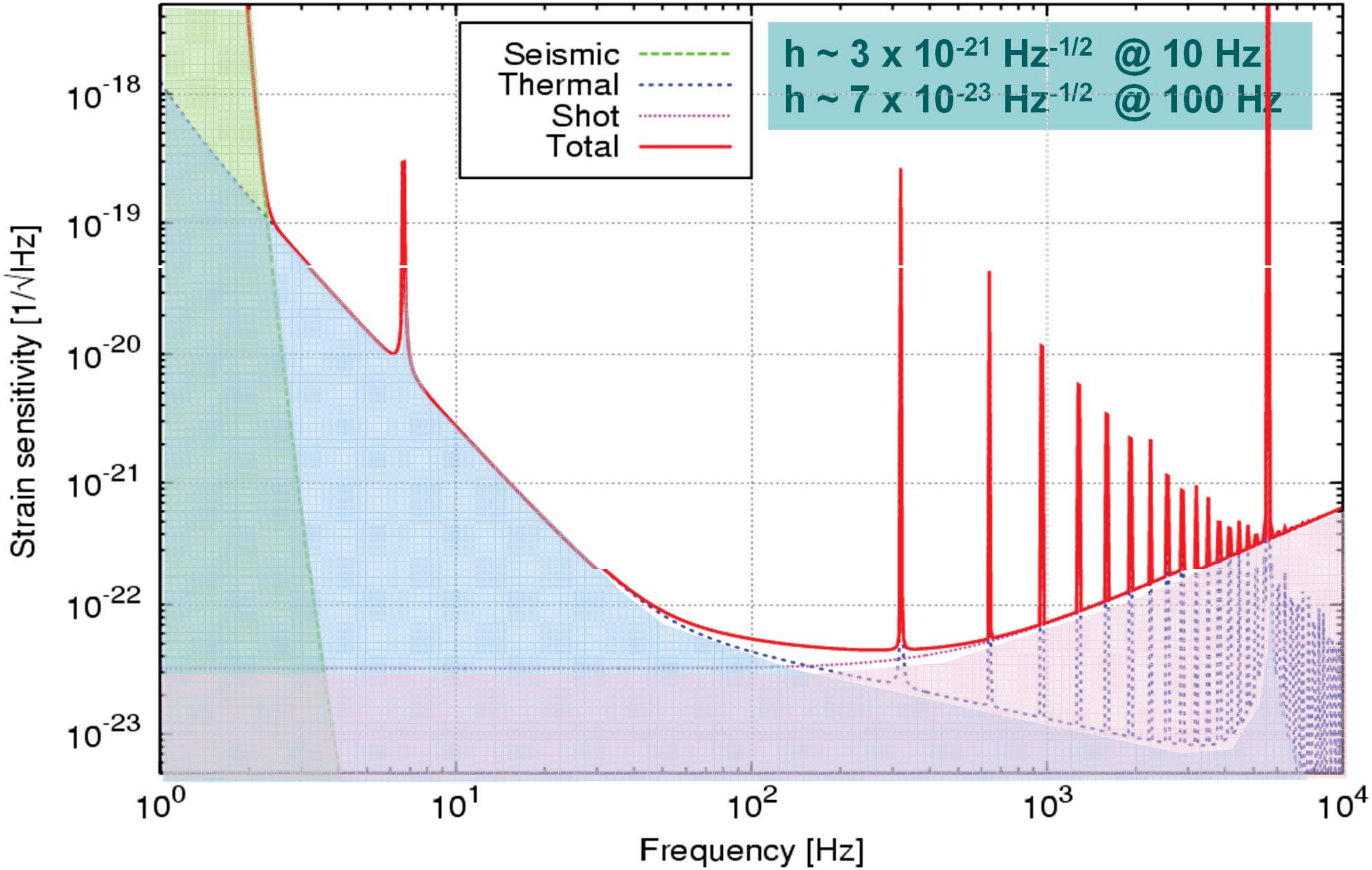
L ~ 7 m; M ~ 1 ton
+ inverted pendulum

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k}{m} - \frac{g}{l}}$$

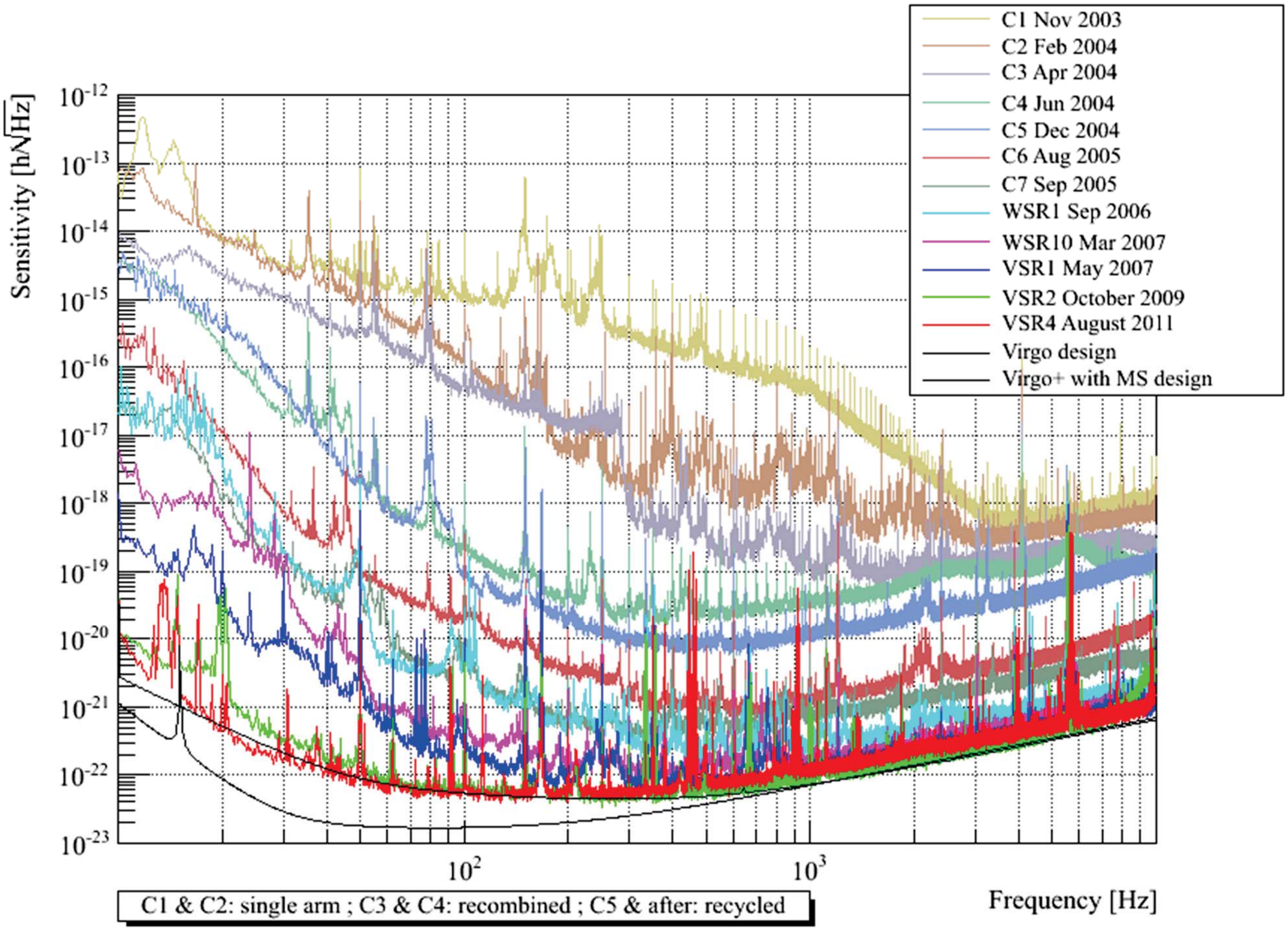
$\Rightarrow f_{res} \sim 30$ mHz

Seismic attenuation:
~ 10^{14} @ 10 Hz
(measured)

Issues in sensitivity (Virgo example)



Virgo sensitivity progress

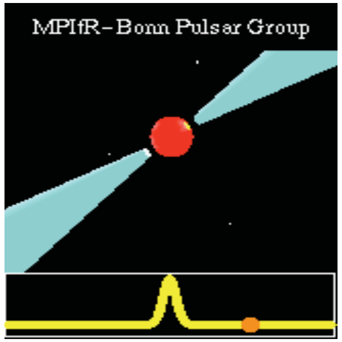


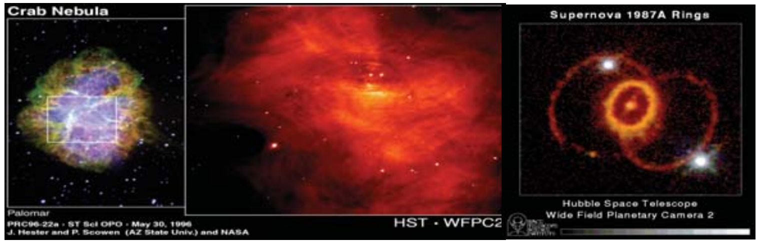

LIGO Hanford Observatory (WA)
H1 – in the desert


LIGO Livingston Observatory (LA)
L1 – in the jungle

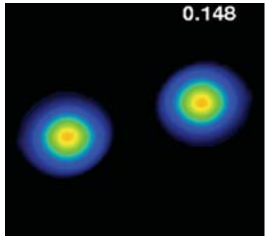

A
B
✓36 hours drive
✓10 ms if traveling at the speed of light

GW sources and methods

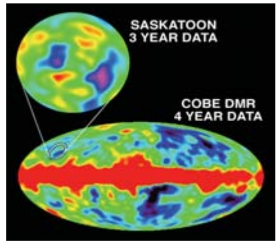




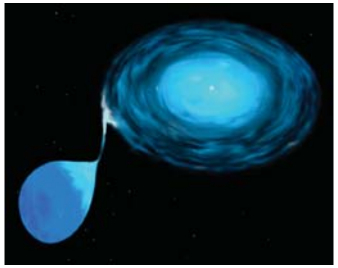
Supernovae, BH / NS formation



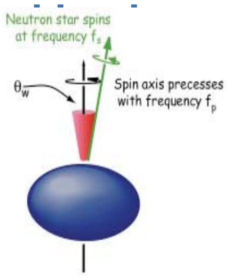
BH and NS Binaries



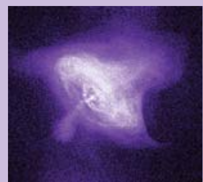
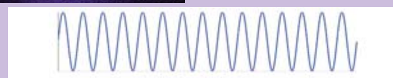
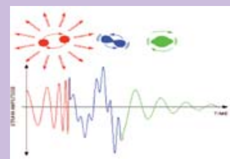
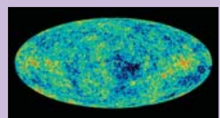
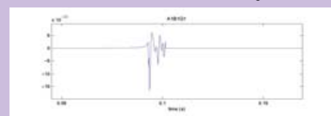
Stochastic background



Spinning NS in X-ray



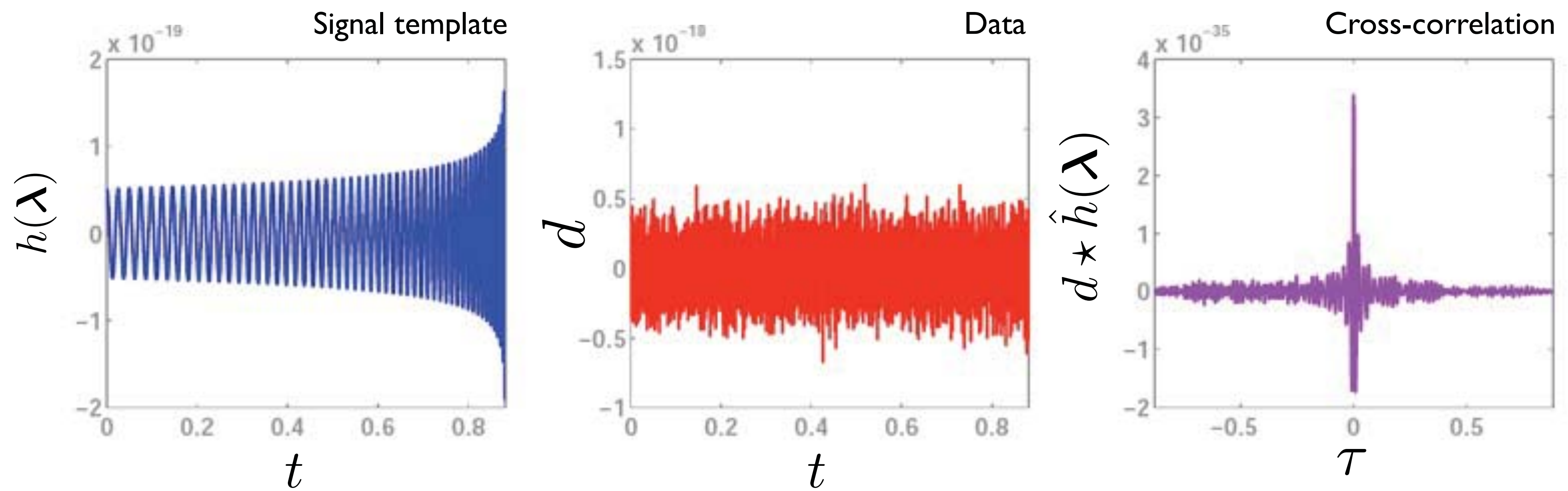
Wobbling NS

	Long duration	Short duration
Matched filter	  **CW**	  **CBC**
Template-less methods	 	  **?**

Search for GWs from CBCs: Matched filtering

Detection requires accurate models of the expected GW signals, as computed in GR.

Also, understanding the physics & astrophysics of sources requires accurate theoretical models of the source.



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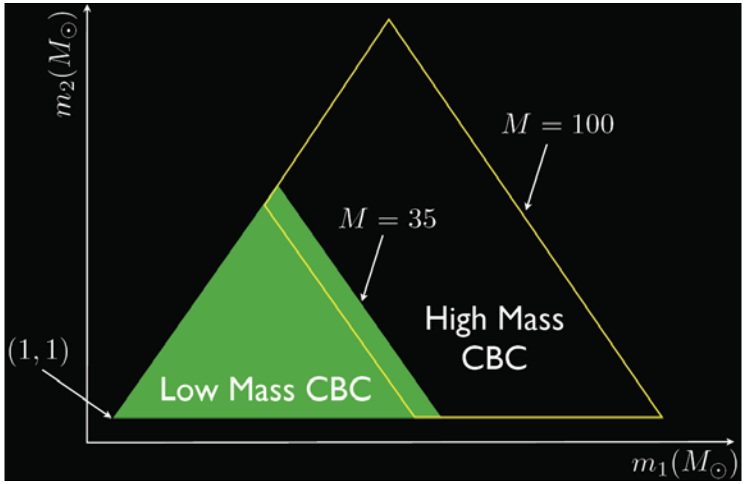
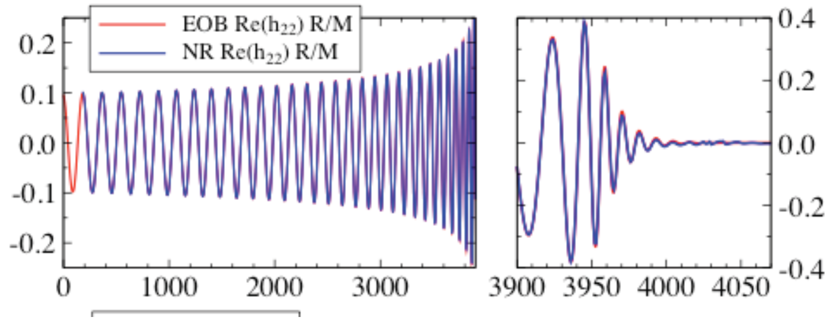
CBC searches



We have several analytic families of waveform covering inspiral, merger, ringdown



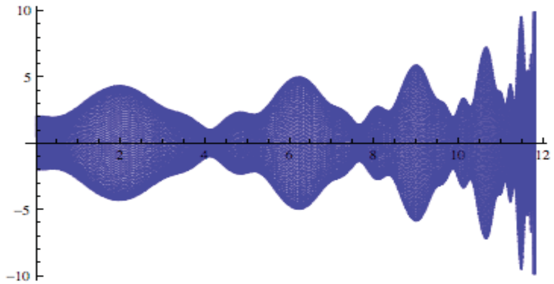
- Low mass search
  - Using non-spining and spining waveforms

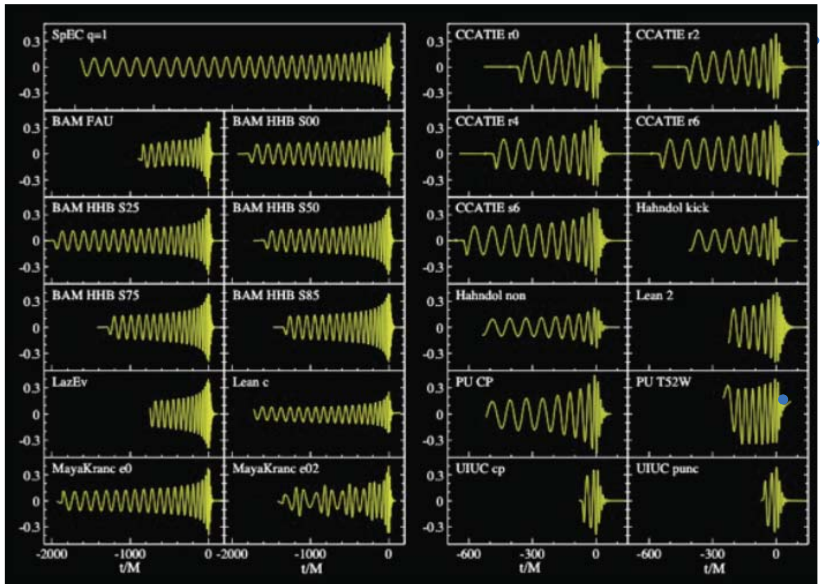
Spin adds 6 extra dimensions to the parameter space, and precession of the orbital plane

First efforts focused on non-precessing waveforms

– Spins aligned with orbital angular momentum

– Analytic models of these waveforms are available





Aylott et. al. 2009 Class. Quantum Grav. 26 165008

High mass search

– Major progress in numerical and analytical relativity has allowed us to use “complete” inspiral merger ringdown templates and extend search reach

– Search underway using these templates

Binary Inspiral Searches

Latest published results from LIGO+Virgo

[Abadie et al., PRD 85, 082002 (2012)]

Search using matched filtering

No inspiral signals detected

90% confidence limits on coalescence rates:

For binary neutron stars:

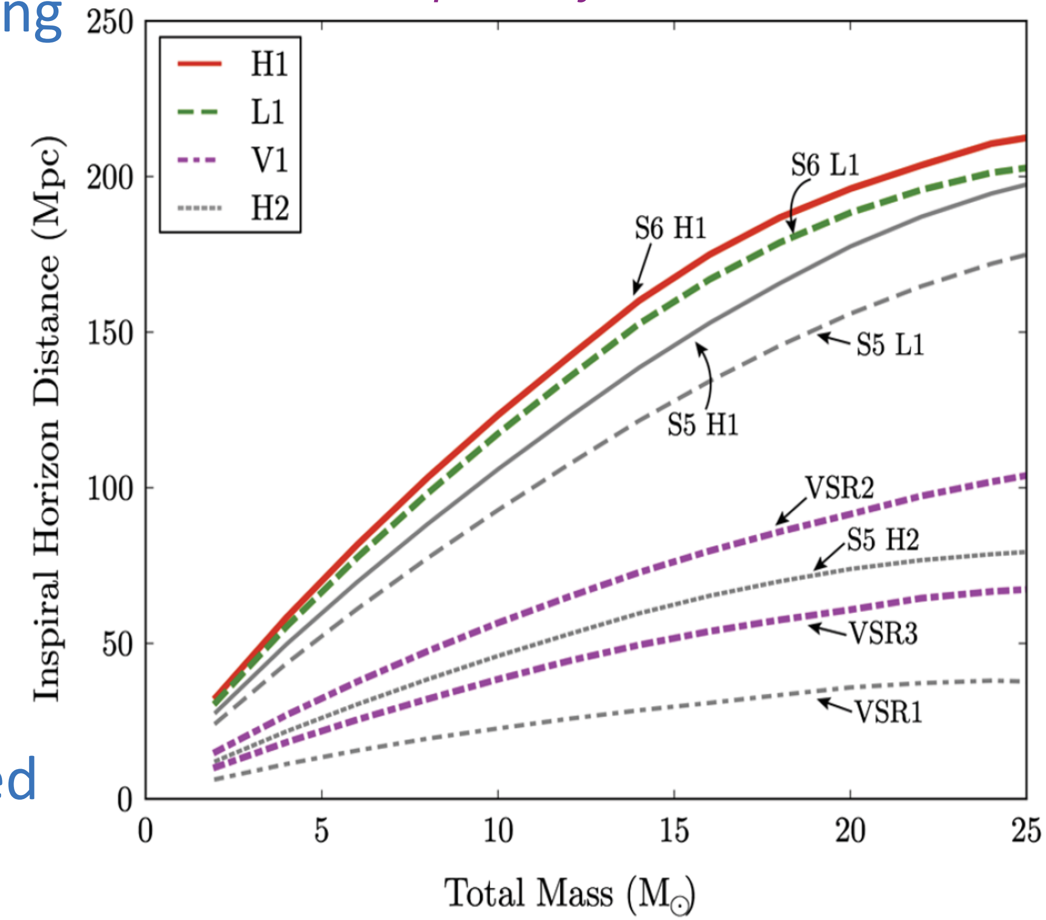
$< 1.3 \times 10^{-4}$

per Mpc³ per year

For binary black holes with $5+5\ M_{\odot}$: $< 6.4 \times 10^{-6}$

Not yet confronting expected range of merger rates

How far away could we hear?

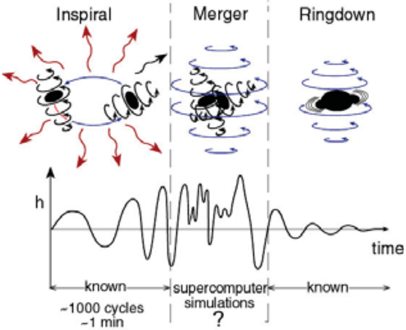


Crab-Pulsar

- Crab-Pulsar rotates with ~30Hz
- Gravitational waves (if mass-asymmetry) expected at ~60Hz
- Derivative of rotation frequency:
  dv/dt ~ -0.37 nHz / s
  yieds spin-down limit
- Plausible might be up to ~15% in GW
- GW-search result: Less than 2% of the energy loss are due to the emission of gravitational waves
- Best Ellipticity limit: 7e-8 for J2124− 3358., Vela spin down limit also beaten

Associated gravitational waves

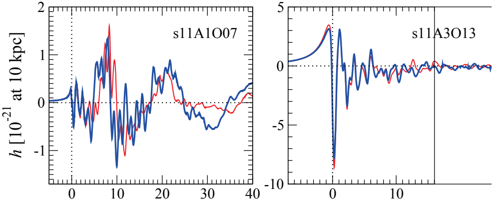
Binary coalescence



- Waveform mostly known

⇒ Template matched filtering

Hypernova



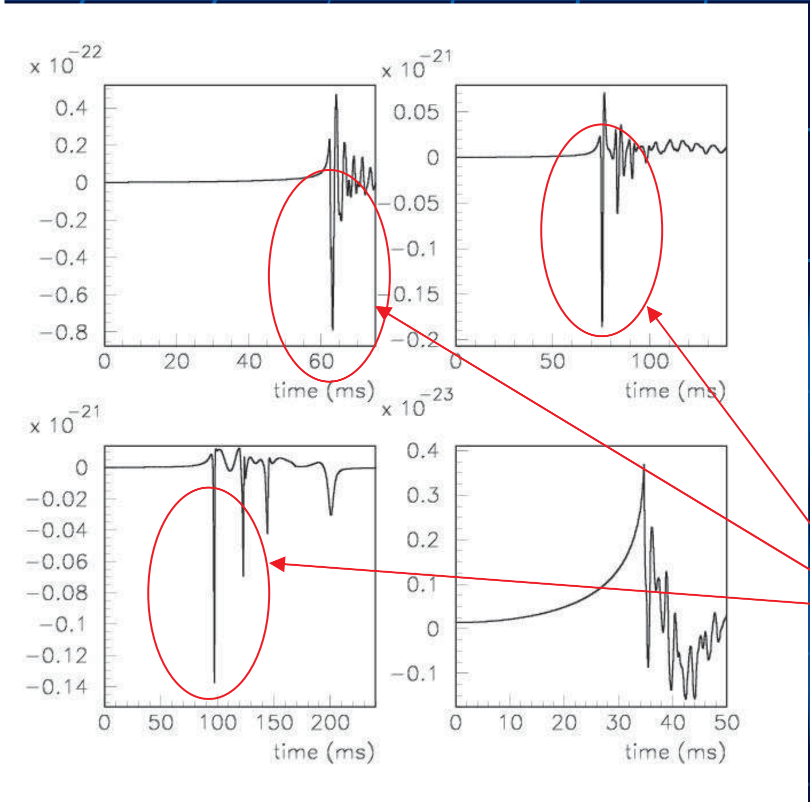
[Dimmelmeier et al., 2008]

- Waveform, amplitude uncertain
- Main emission mechanism unknown

⇒ "Unmodeled" search

The problem of burst data analysis

Supernova waveforms prediction



Not robust predictions => matched filtering can not be robust !

⇒Robust detections methods needed
(but necessarily suboptimal)

However matched filter can be used for catching some part of the signal

For example **Gaussian peak templates** can be used for detecting main peak appearing in some burst waveforms
(of course part of the signal SNR is lost)

Some other burst signals are also well known, e.g. black hole oscillations
<-> ringdown signals with 2 parameters (frequency and damping time) related to BH mass and angular momentum => matched filtering must be used. *(but marginal signals in term of detectability)*

Network data analysis

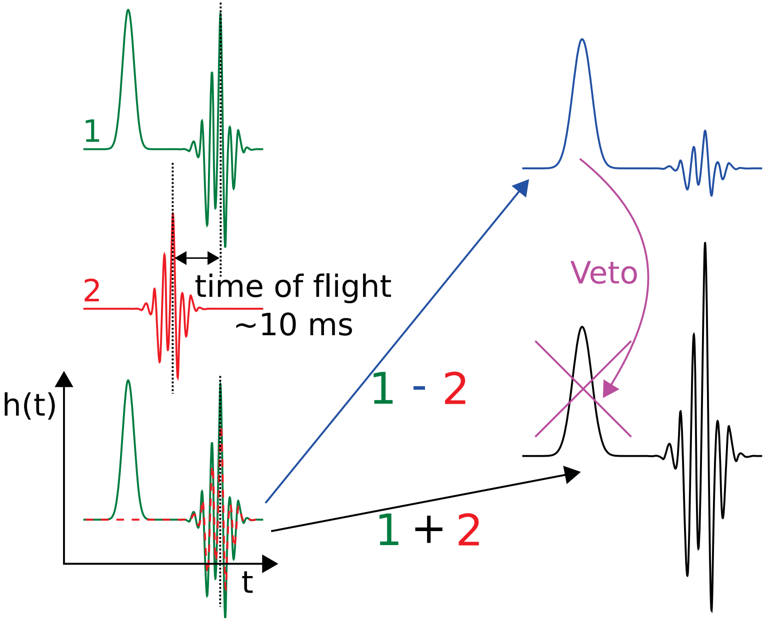
Light time of flight : HL ~ 10 msec., VL ~ 26 msec. and VH ~ 27 msec.

Times delays set the Source Reconstruction Accuracy:

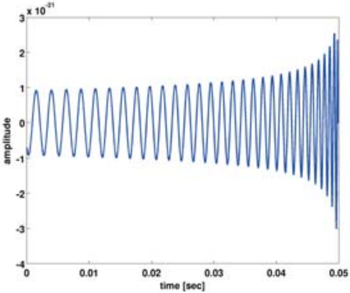
Minimal angular resolution ~ 1°

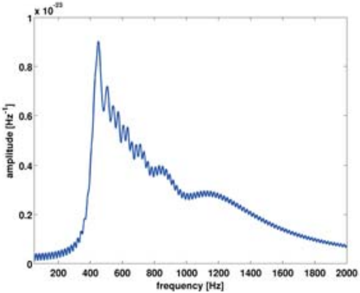
(could be much worse)

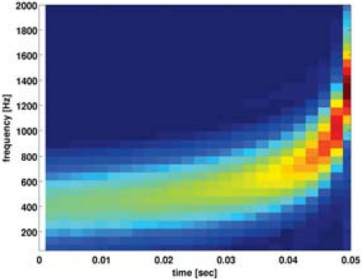
Coherent analysis



Time frequency maps



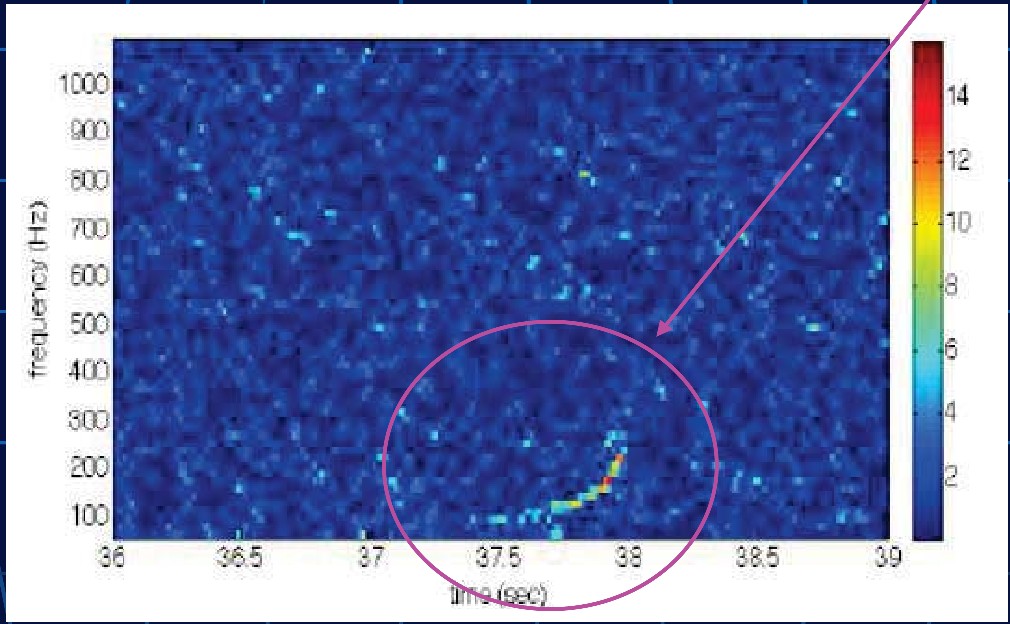




⇒ Concentrate signal energy in a small number of pixels

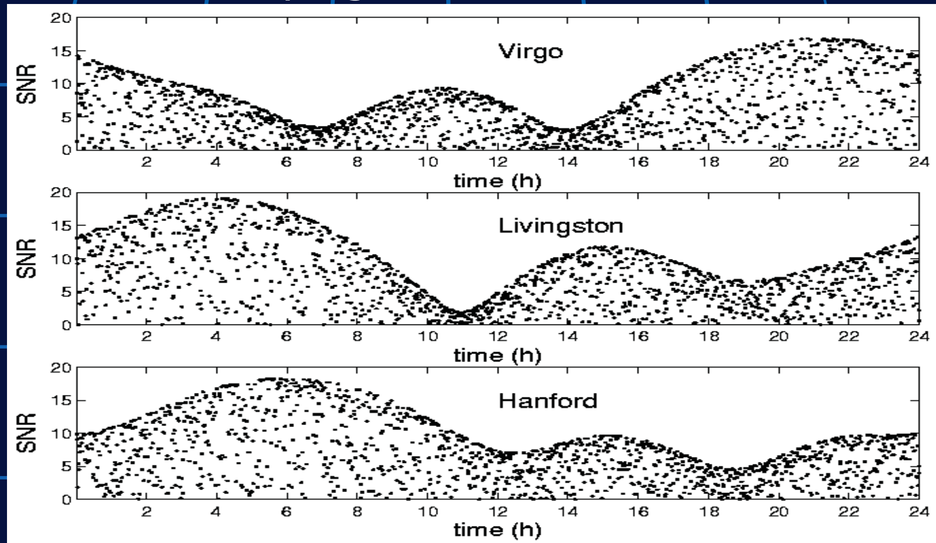
Burst data analysis
Time-frequency methods

Whatever the details of the method : search some ***excess power*** in a time-frequency map



Network data analysis
Coincident approach

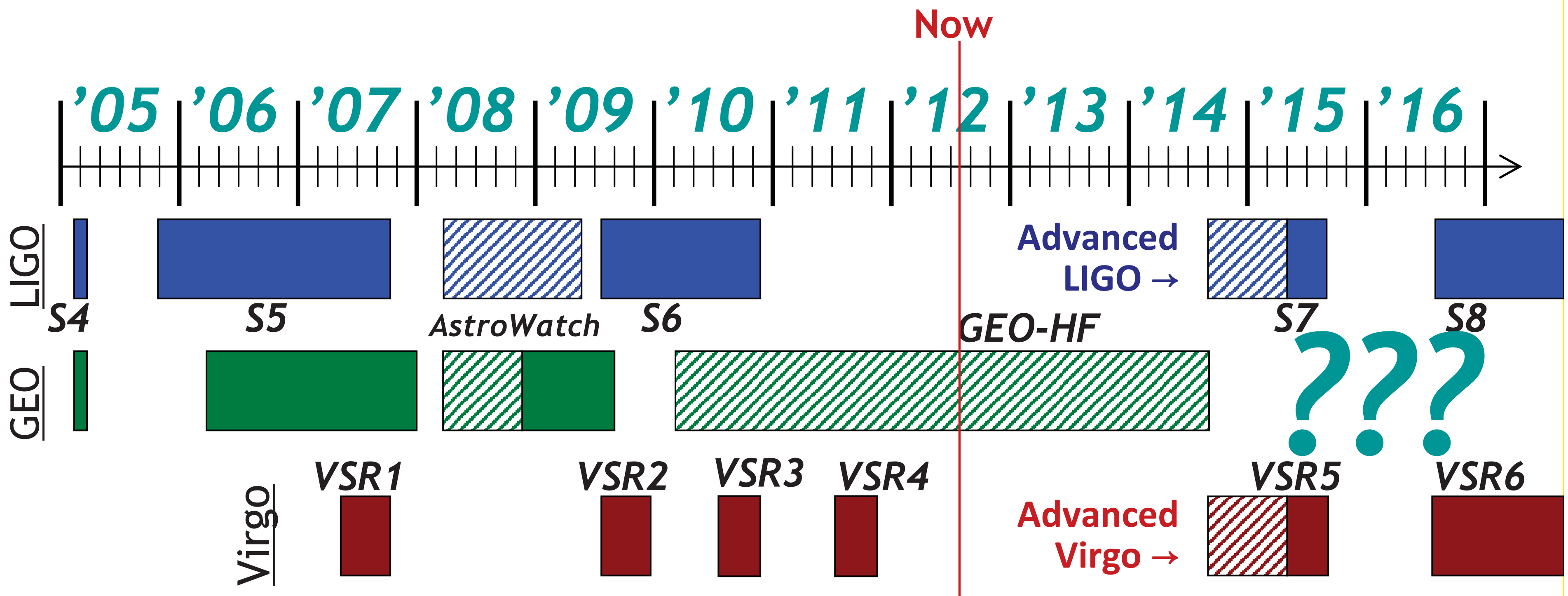
Trigger lists in one day of simulated data.
Simulated burst events with varying *h* from constant direction (Galactic center).



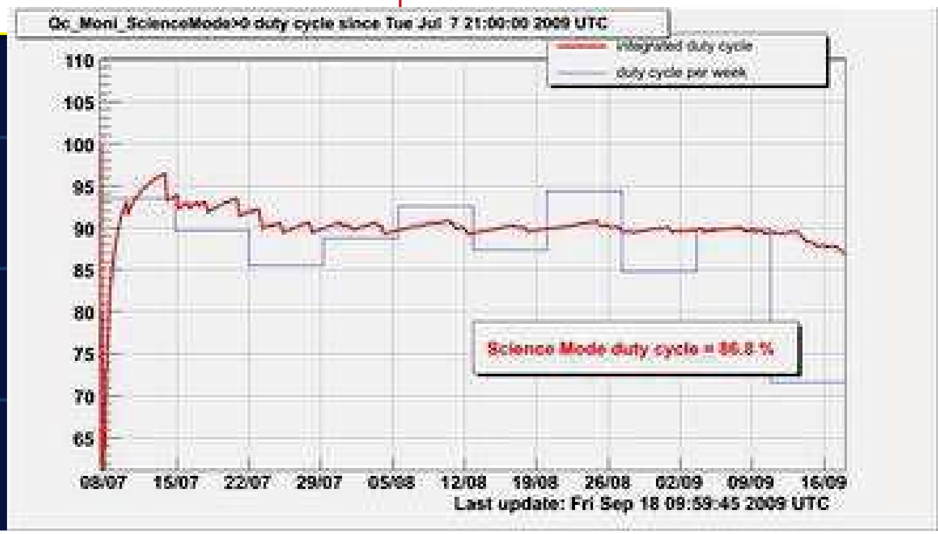
Coincidences efficiencies :

Bursts	H	L	V	HLV	HL	HV	LV	HL ∪ HV ∪ LV
False alarm rate (*Hz*)		0.1		10^{-6}		10^{-6}		~ 3.10^{-6}
Efficiency (%)	63	60	55	19	**41**	22	22	**60**

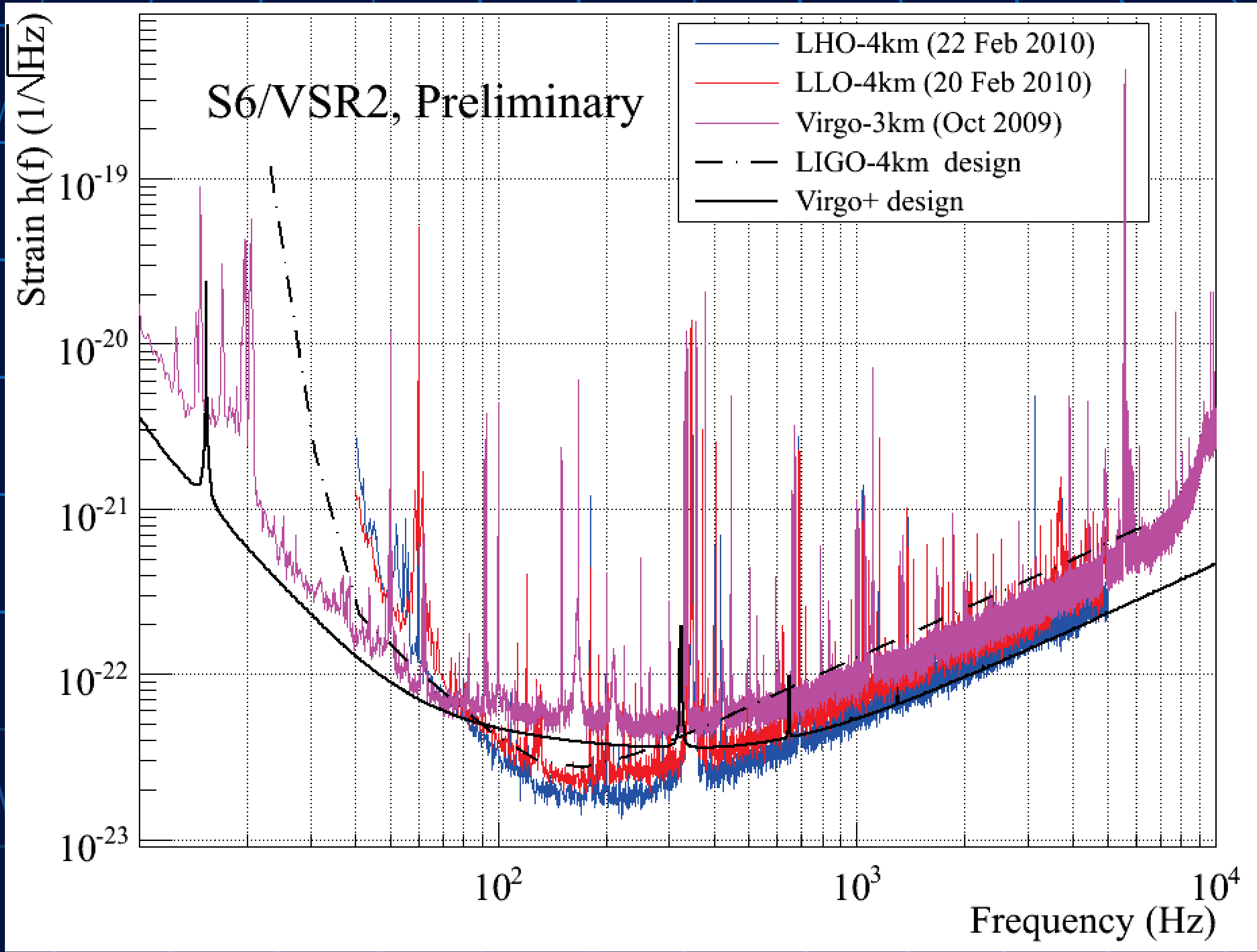
LIGO-Virgo joint data takings



Virgo duty cycle ~90%



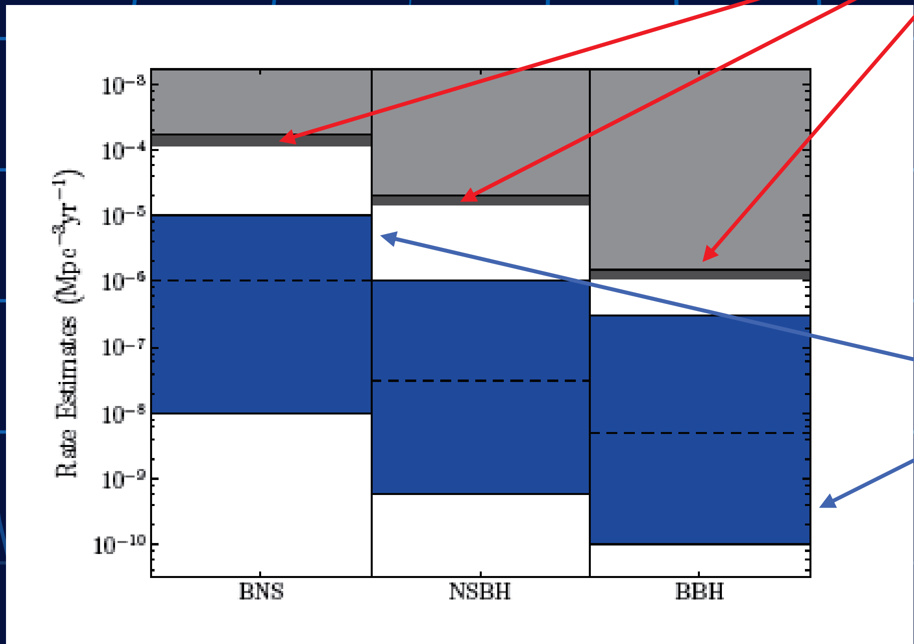
The LIGO-Virgo network
Compared sensitivities



The LIGO-Virgo network
A selection of scientific results

Search for compact binary coalescences:
No detection (yet)
–> ***upper limits*** on event rates

Best UL's



Range of astrophysical predictions

LIGO&Virgo coll., Phys.Rev.D **85**:082002 (2012)

The gap is less than 1 order of magnitude!
(important for advanced detectors)

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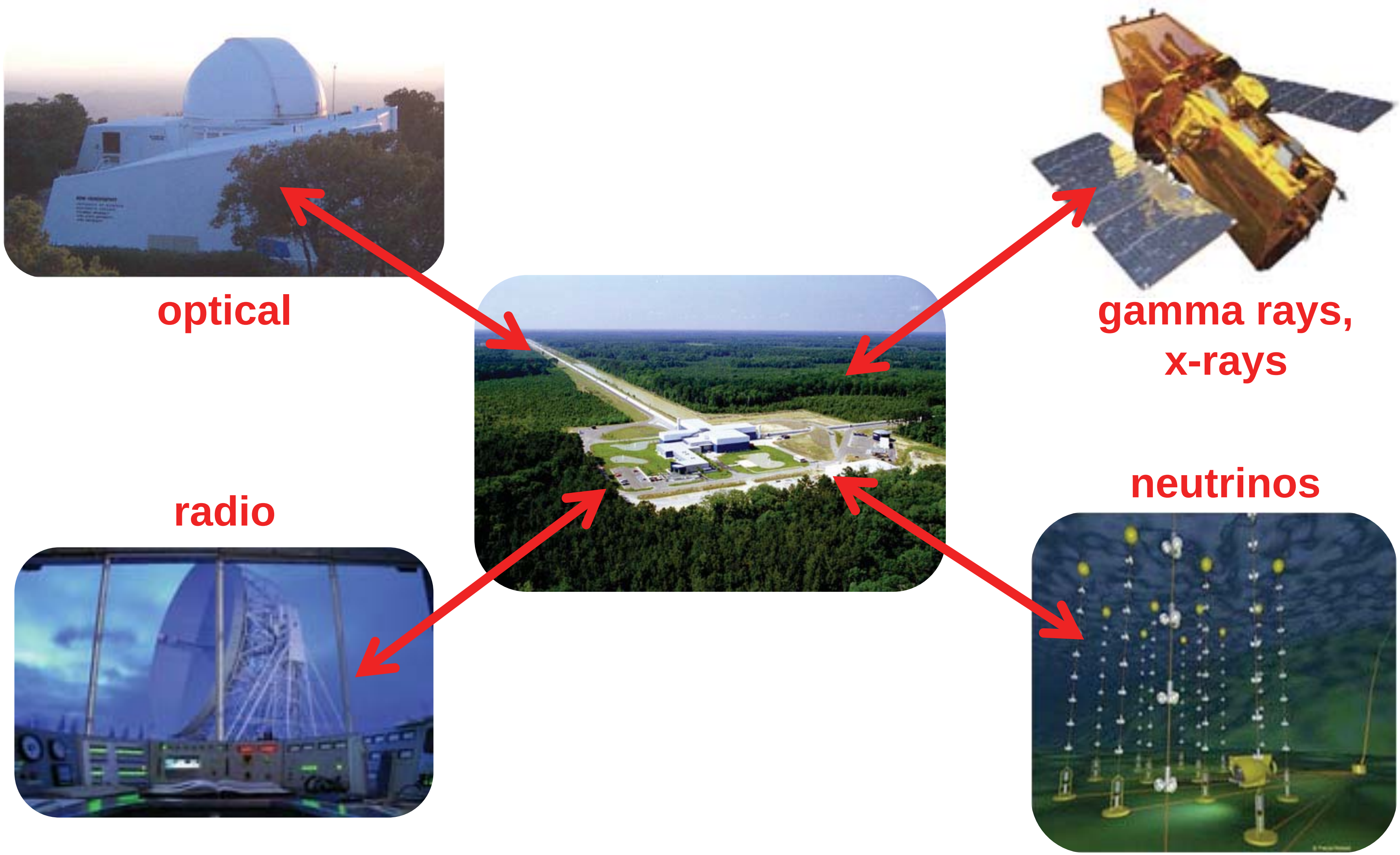
LIGO-Virgo is fully engaged in multi-messenger astrophysics



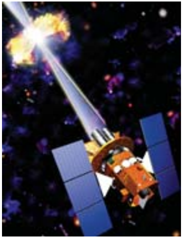
Searching GW in association with GRBs

- Gamma-ray burst observed by satellites (Swift, Fermi, ...)
  $\Rightarrow$ GCN: Gamma-ray bursts Coordinates Network

Known position and time

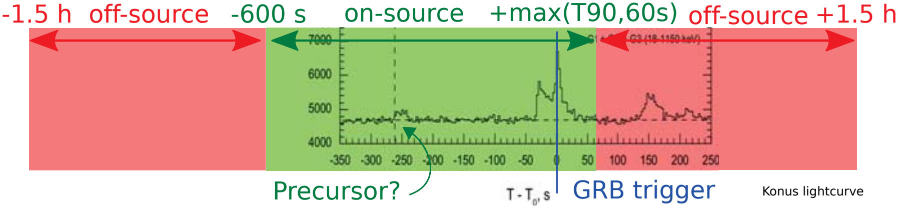
- Position $\rightarrow$ simplify coherent analysis (time delays between detectors known)
- Reduced time $\rightarrow$ reduced background

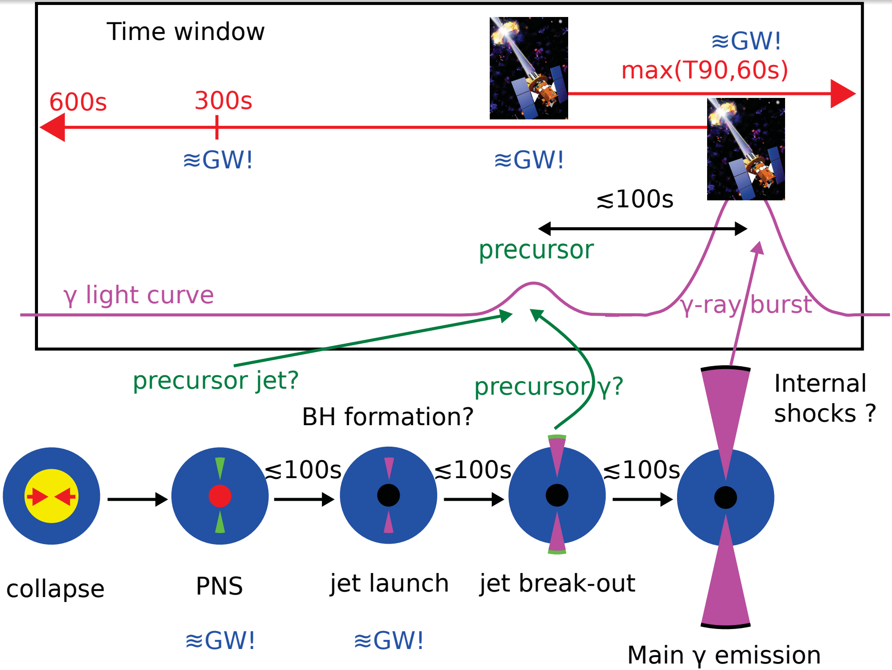
$\Rightarrow$ Better sensitivity by a factor ~ 2



- Time coincidence between GRB and GW: window $[-10, +1]$ min

$\rightarrow$ dictated by long GRB astrophysics (several sec for short GRBs)

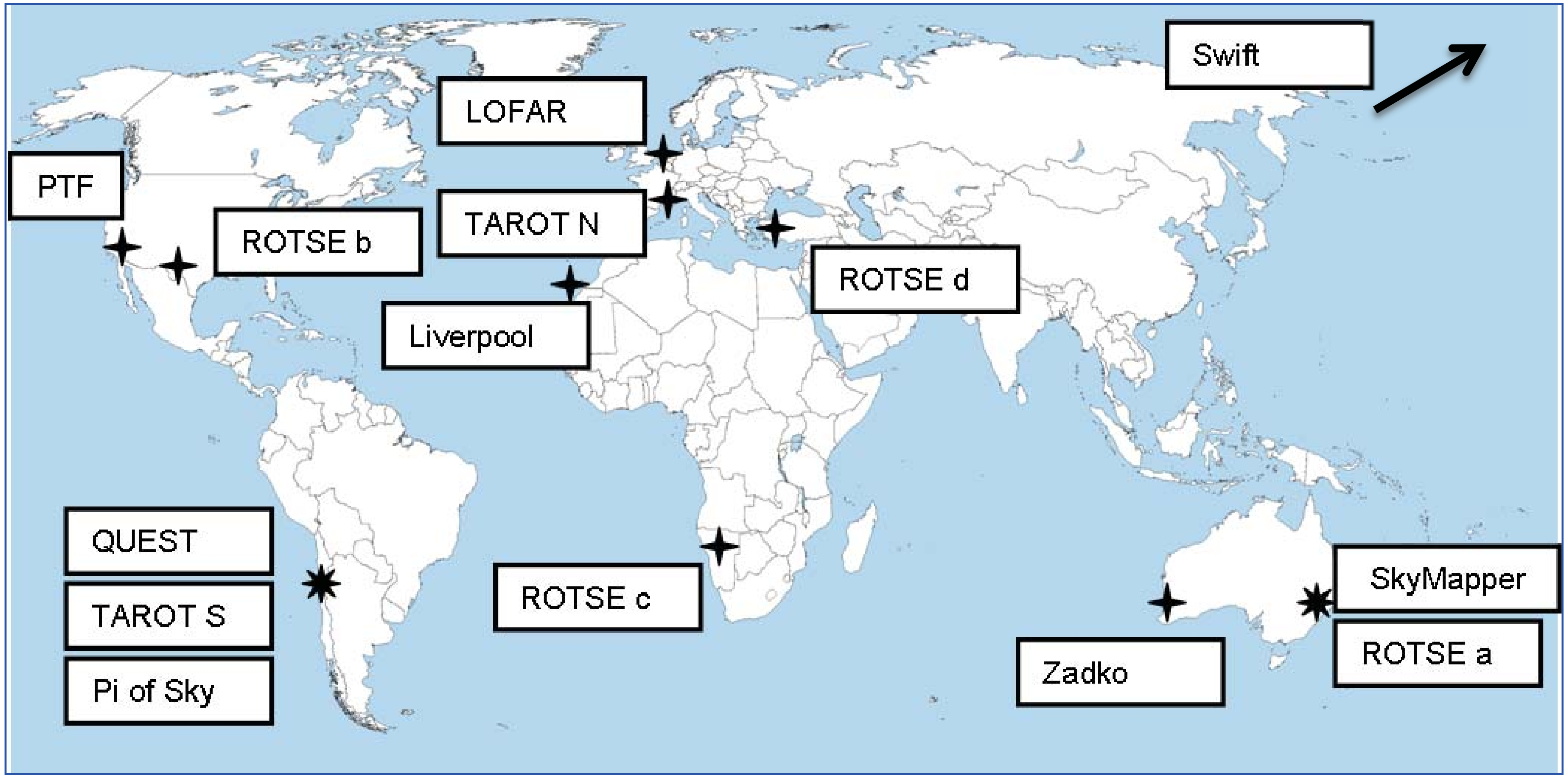




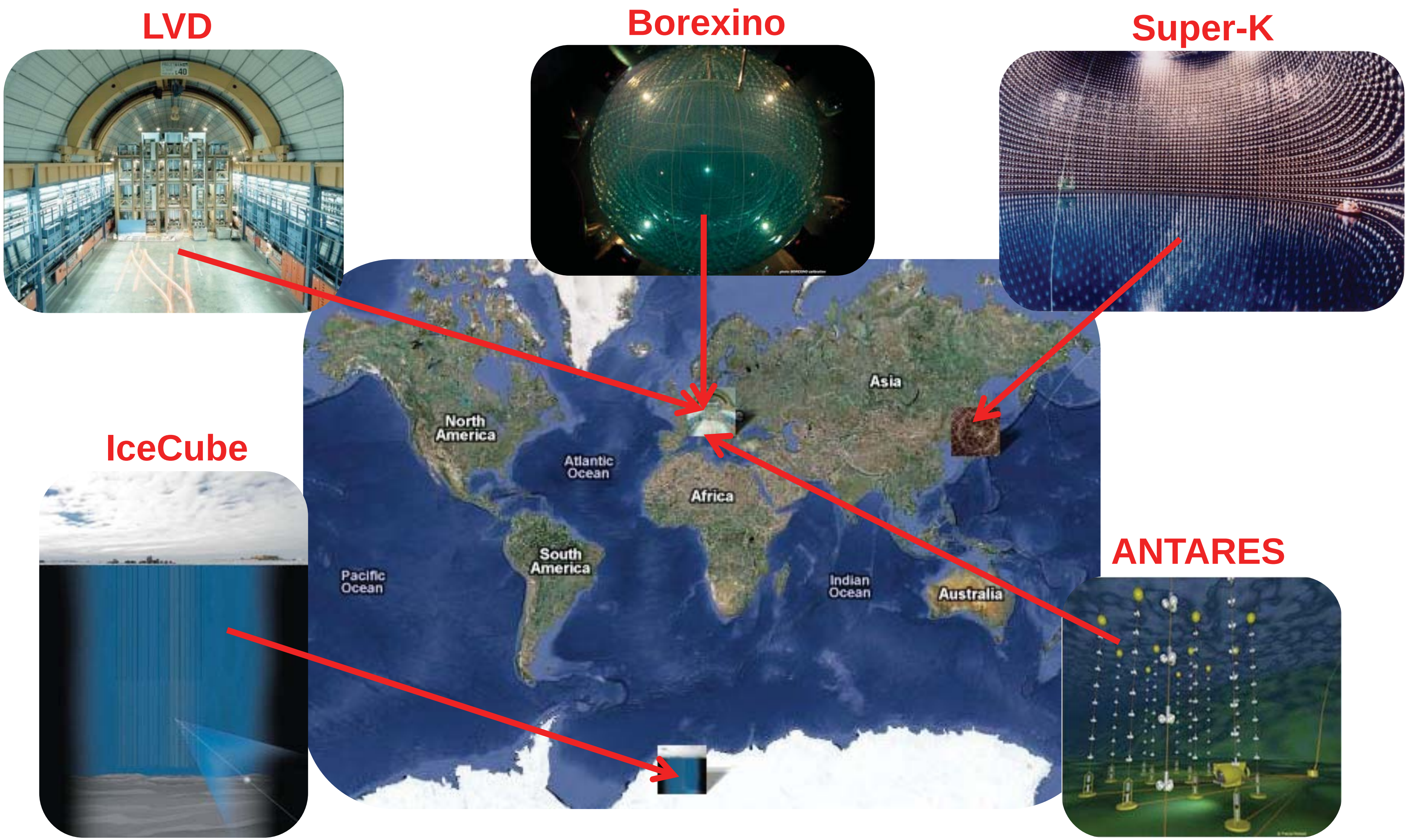
Time window
≋GW!
max(T90,60s)
600s
300s
≋GW!
≋GW!
≲100s
precursor
γ light curve
γ-ray burst
precursor jet?
precursor γ?
BH formation?
Internal
shocks ?
≲100s
≲100s
≲100s
collapse
PNS
jet launch
jet break-out
≋GW!
≋GW!
Main γ emission

Telescope Network

- LIGO and Virgo partnered with rapid-pointing telescopes for observation run in summer and fall of 2010.
- Total of 14 triggers sent out (FAR < ¼ d), 8 followed up.
- Image analysis in progress, participation by LIGO and Virgo scientists.
- Also Swift (one event) and LOFAR radio array (commissioning during run).



Gravitational waves and neutrinos
(nascent collaborations)



The flow of information

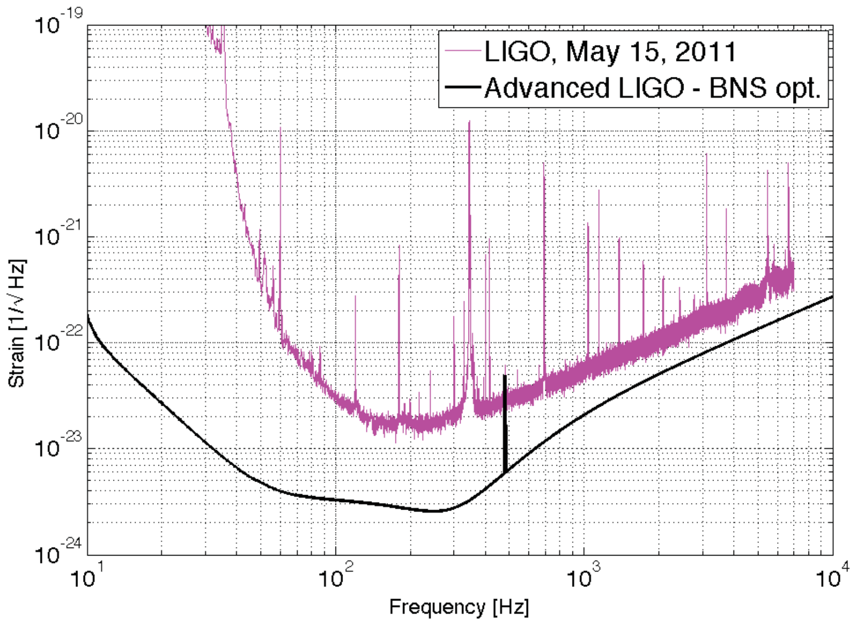
- EM triggers ⇒ GW detector analysis
  - From, eg, space-based X-ray and gamma ray telescopes
  - Knowing precise time and sky location of event reduces noise contamination in GW detector network; searches can go deeper
- GW detections ⇒ Pointing EM telescopes
  - To catch prompt emission, must point quickly
  - requires development of low-latency GW detection and sky localization pipelines, protocols to pass info, telescope scanning strategies and coordination

- GW detections + all-sky telescopes
  - Eg, neutrino detectors, optical transient surveys, wide-field radio transient surveys
  - Can be done offline, using data "in the can" – "data mining"
- Prototypes for all of these paths have been developed; they need to be flawless and ready in 2015!

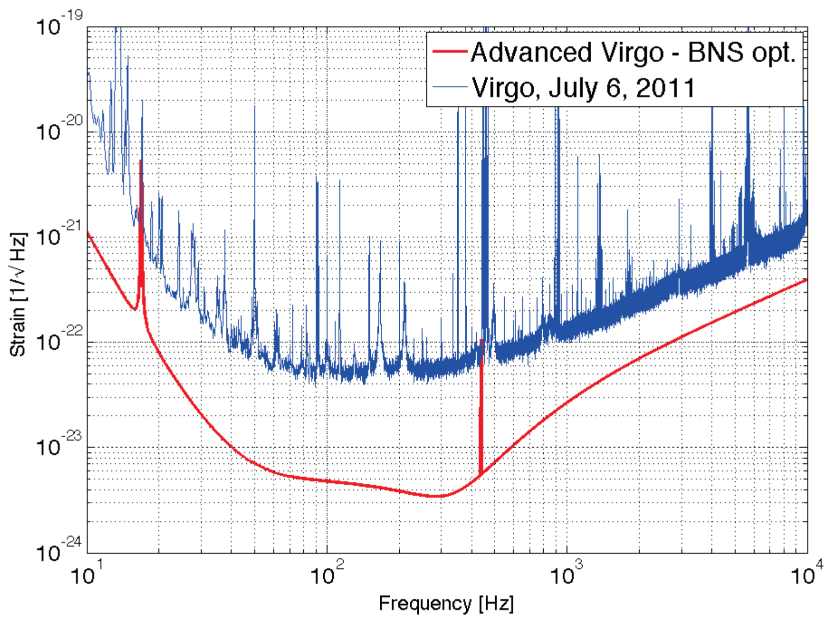
Advanced detectors

- 2nd generation detectors
  - BNS inspiral range >10x better than Virgo
  - Detection rate: ~1000x better
  - 1 day of Adv data ≈ 3 yrs of data

Measured spectrum from
http://www.ligo.caltech.edu/~jzweizig/distribution/LSC_Data/



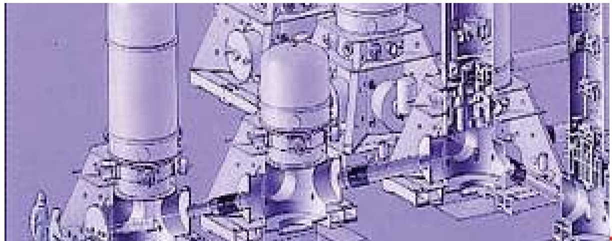
Measured spectrum courtesy of the Virgo Coll.



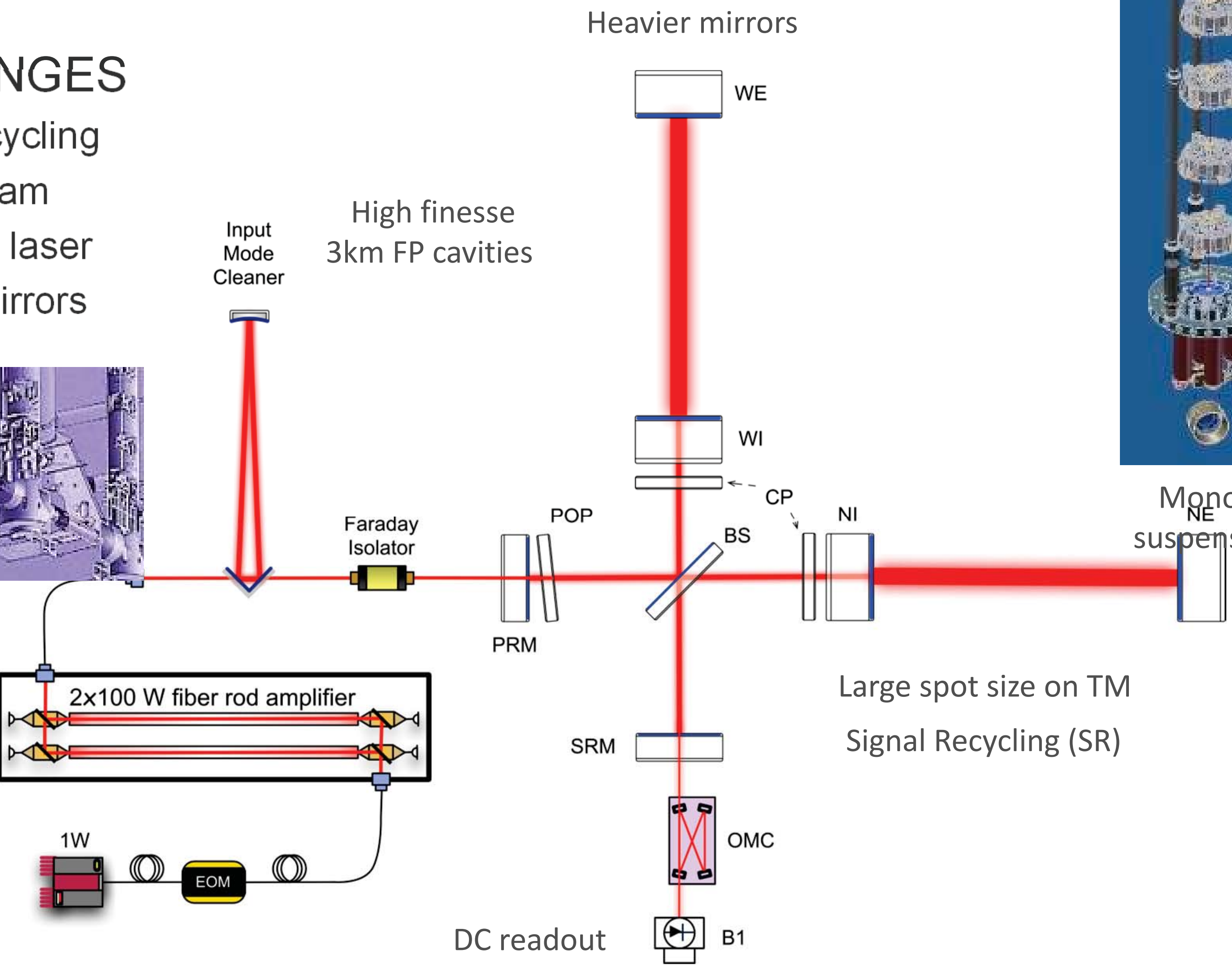
21

BASELINE DESIGN

- MAIN CHANGES
  - Signal recycling
  - Larger beam
  - 200W rod laser
  - heavier mirrors



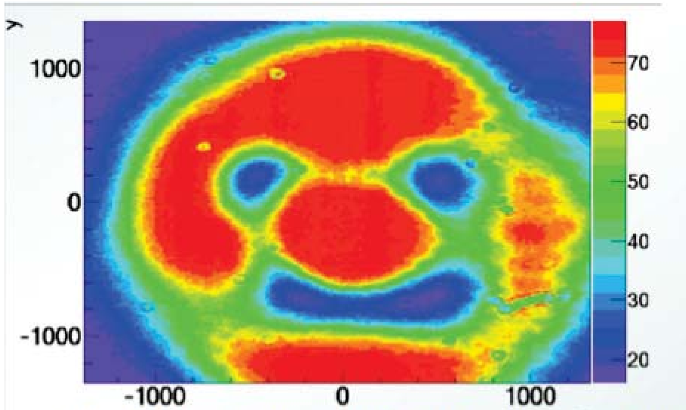
Larger central links
Cryotraps



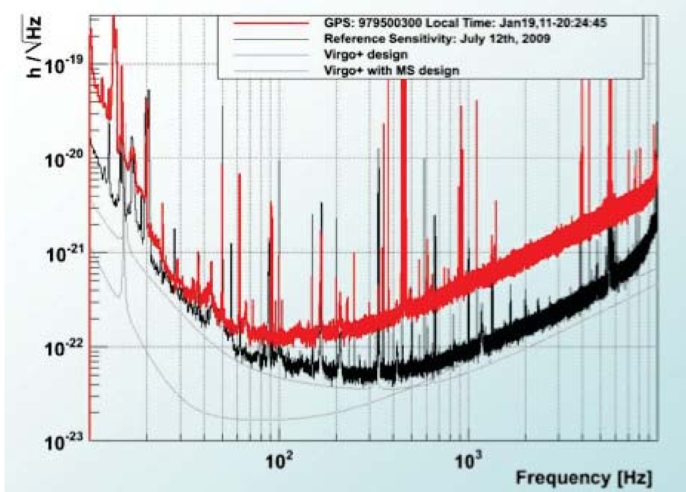
Monolithic suspensions

THERMAL COMPENSATION

- Aberrations (intrinsic mirror defects or thermal deformations of the mirrors) spoil the beam quality
- A set of sensors and thermal actuators has been conceived to get an "aberration free" interferometer

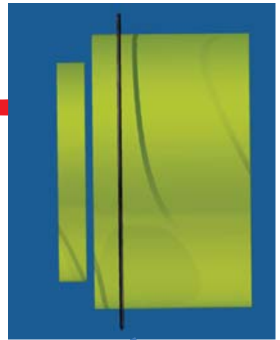


Dark fringe beam with high order modes



Effect of RoC asymmetry in Virgo+

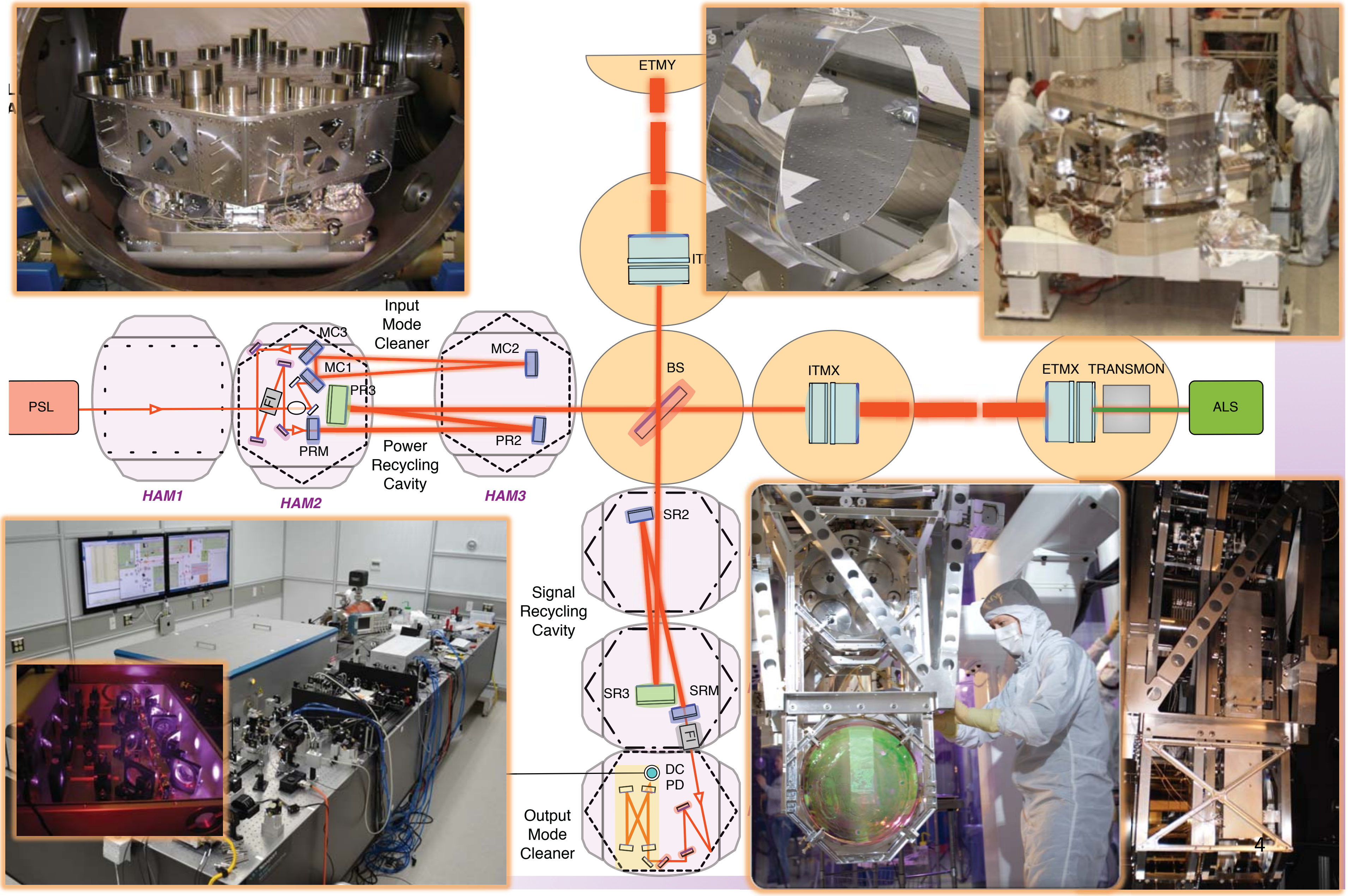
CO2 laser



CO2 laser shined on the mirror: heat deposition where needed to compensate for aberrations

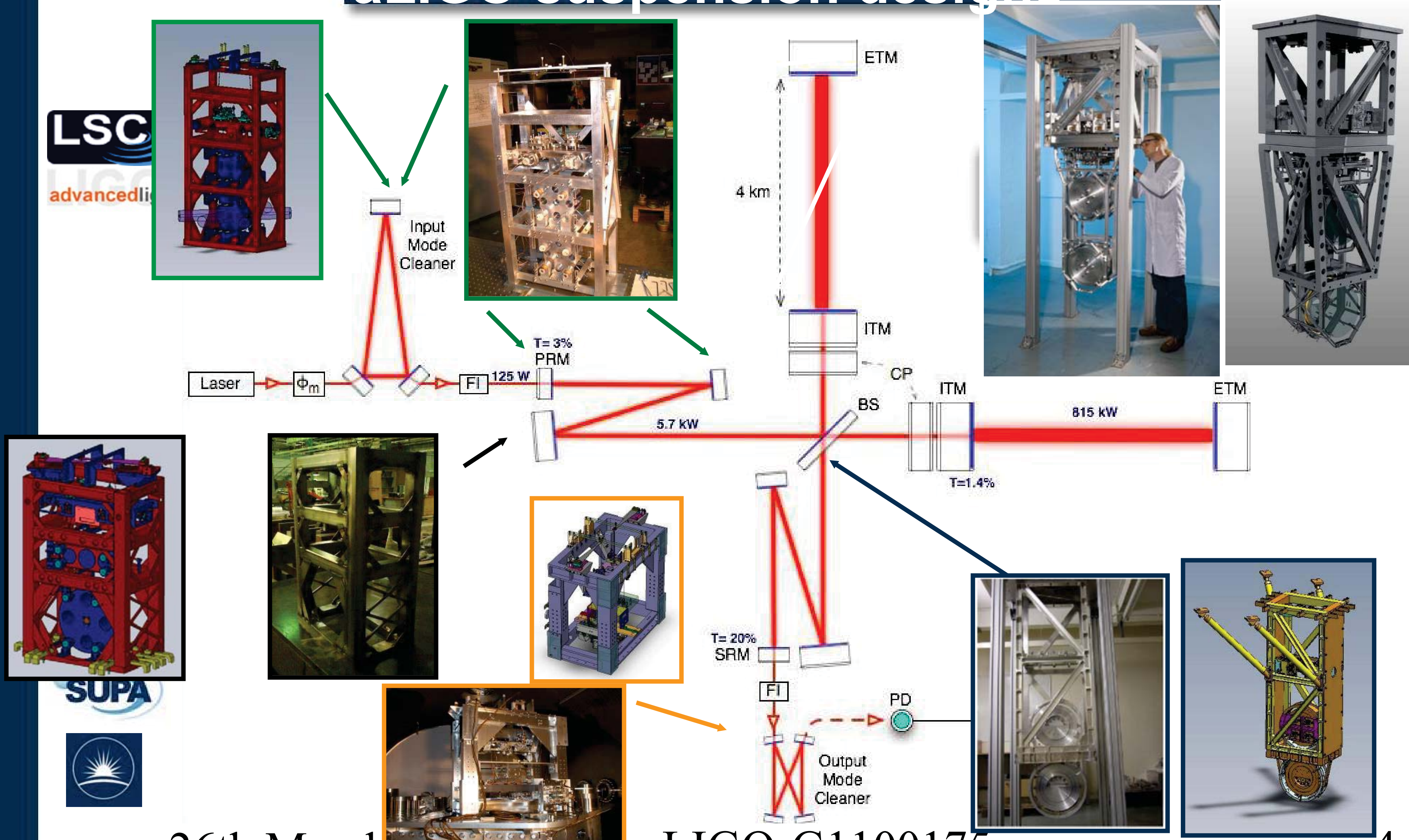
Heating rings around mirrors to tune RoC (accuracy: ~1m over 1500m)

Advanced LIGO: L1 & H1



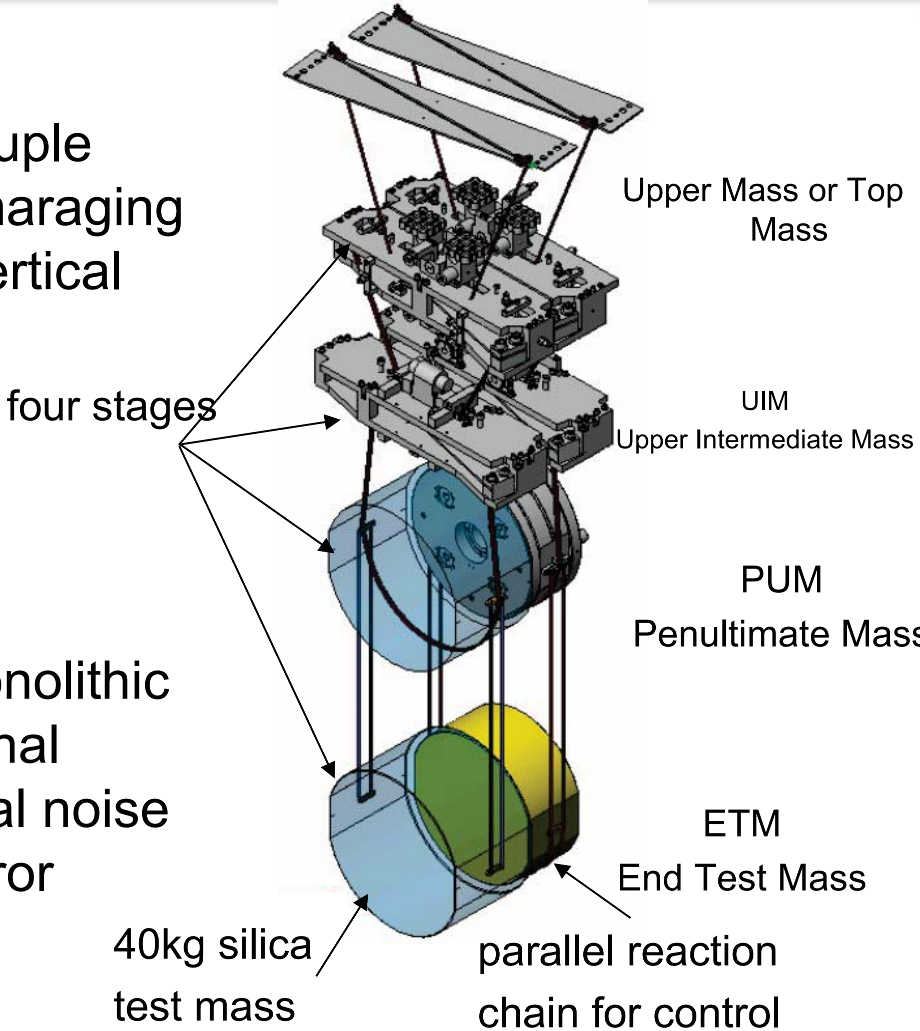
Slide from Norna Robertson, aLIGO suspensions lead

aLIGO suspension designs

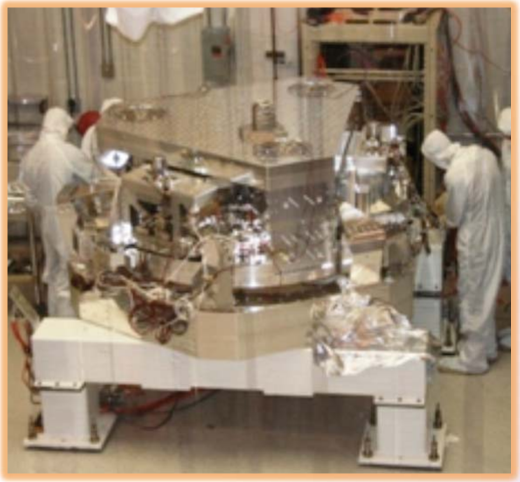


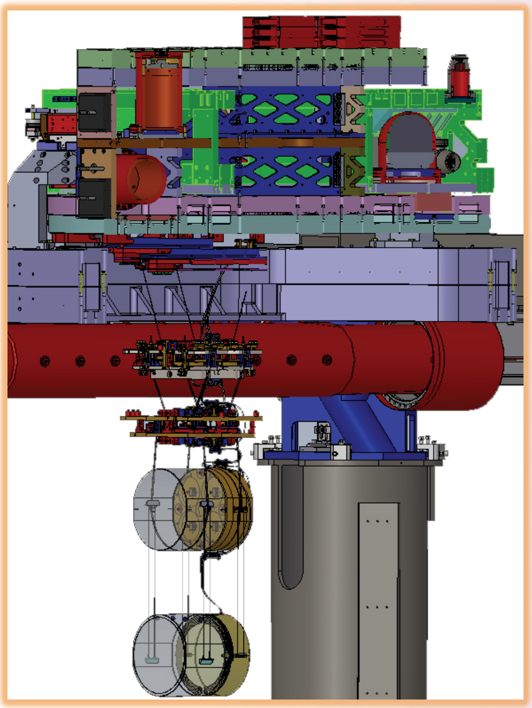
Quadruple suspension

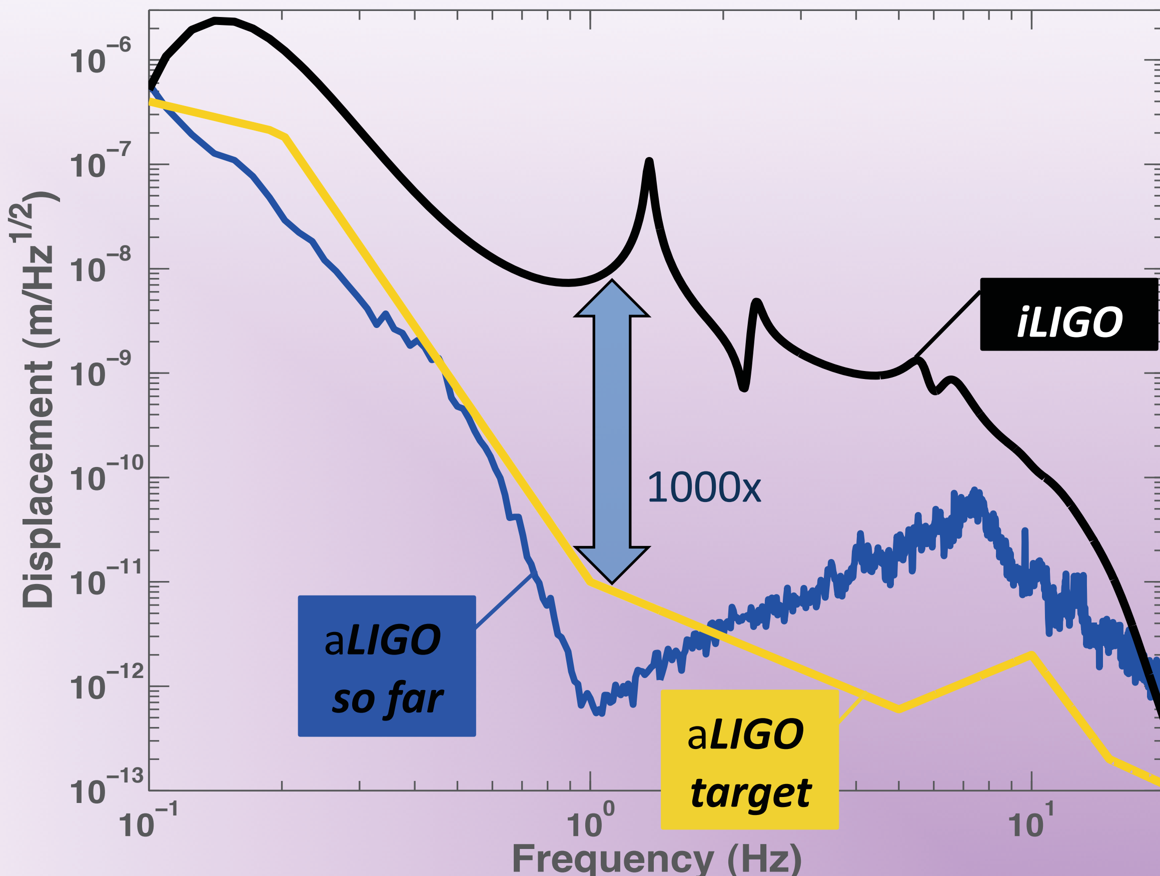
- Seismic isolation: use quadruple pendulum with 3 stages of maraging steel blades for enhanced vertical isolation
- Thermal noise reduction: monolithic fused silica suspension as final stage - low pendulum thermal noise and preservation of high mirror quality factor



Seismic isolation performance



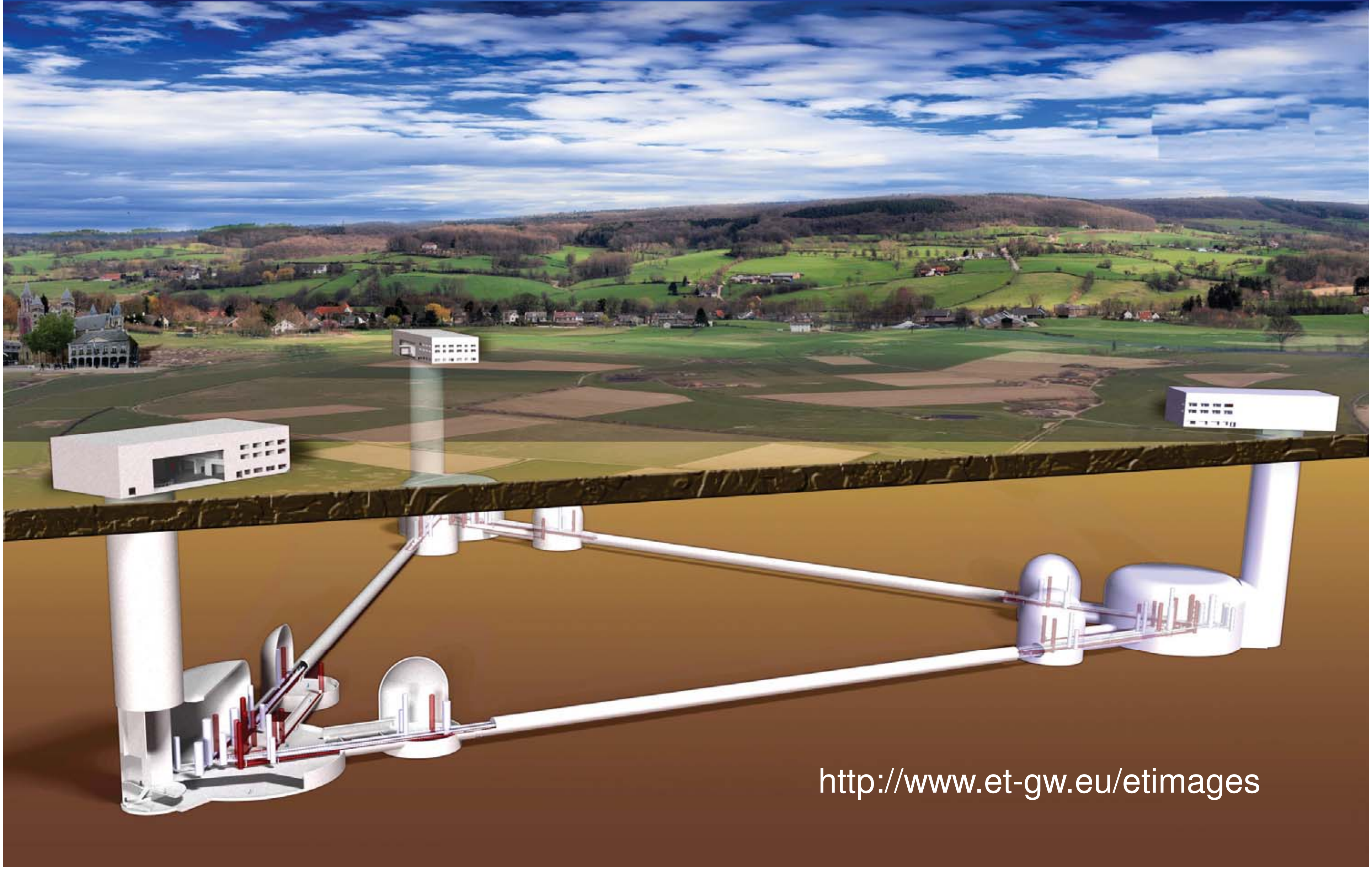




Upcoming Network in the Advanced Detector Era

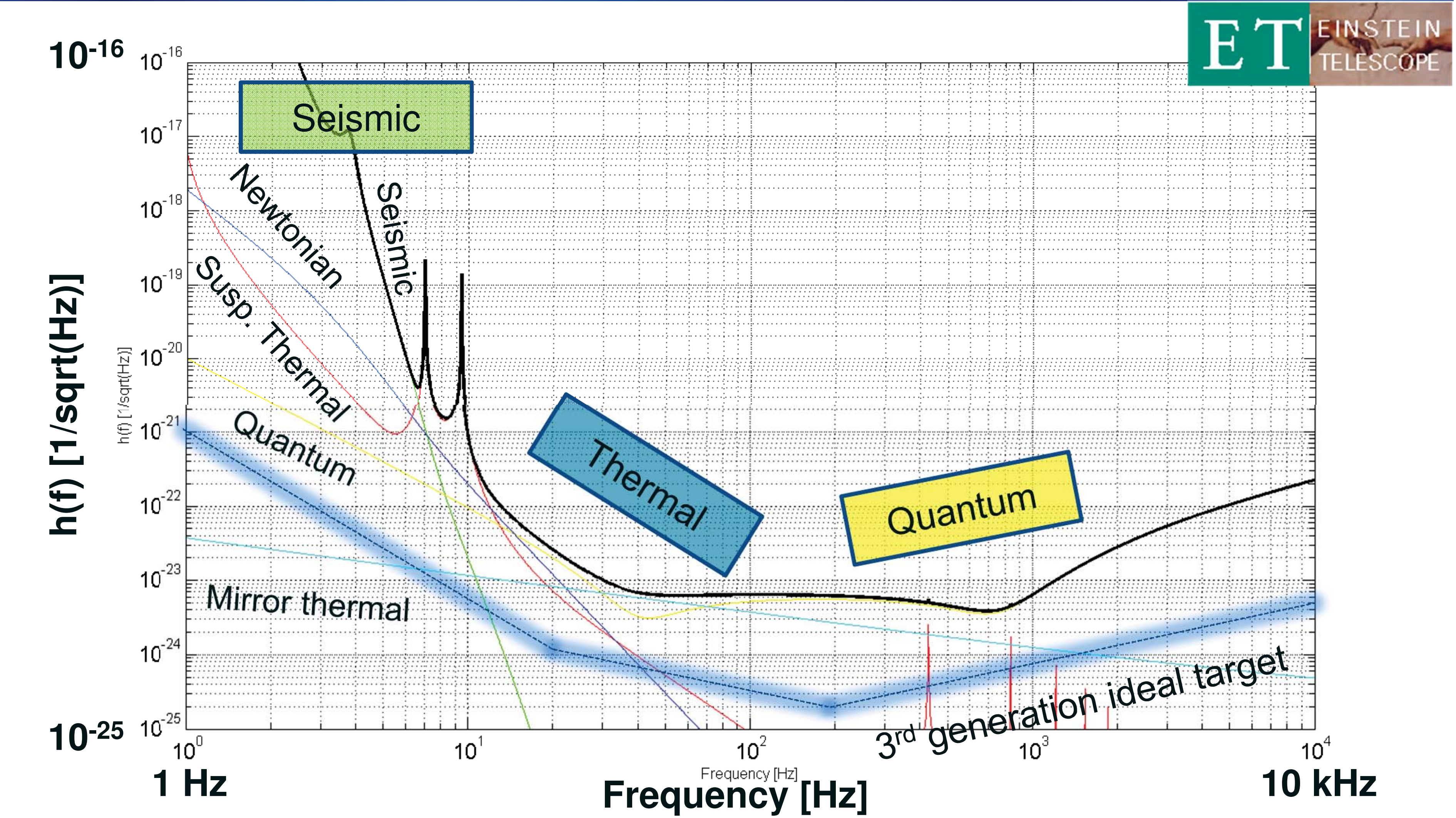
Credit: C. Mayhew & R. Simmon (NASA/GSFC), NOAA/ NGDC, DMSP Digital Archive

Einstein GW Telescope



http://www.et-gw.eu/etimages

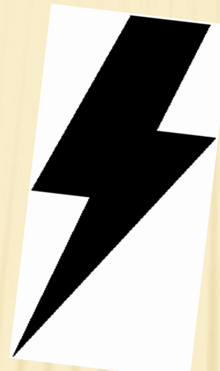
How a new infrastructure (and new technologies) pushes ET beyond the 2nd generation?



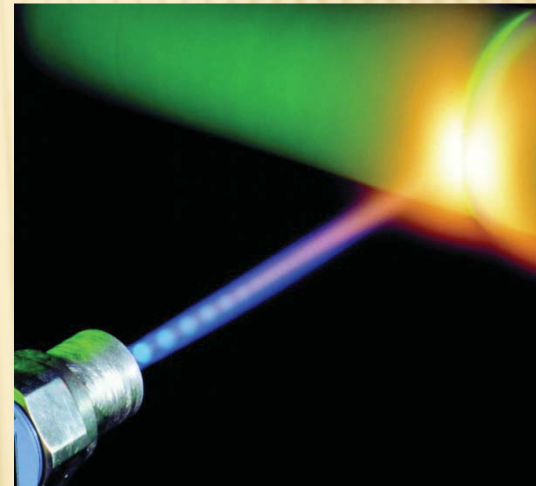
CONFLICT OF INTERESTS

Need Cryogenics for lowThermal Noise: 10K

www.miami.com



High Power for low Shot Noise: 3MW



jgindo.wordpress.com

http://s658.photobucket.com

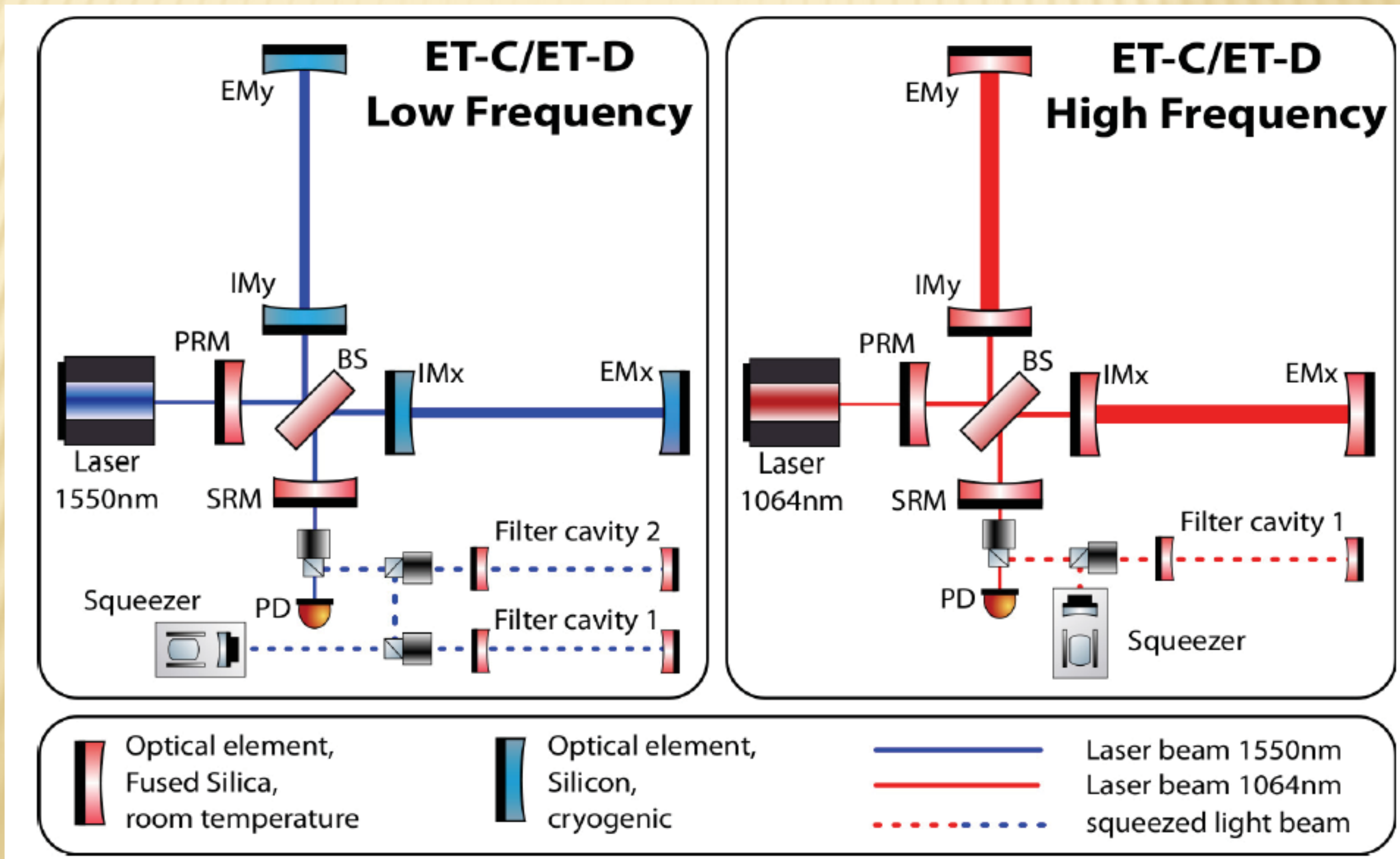
ET XYLOPHONE STRATEGY

Split detector into two interferometers optimised for

Low Frequencies and High Frequencies

10K, 18kW, 1550nm

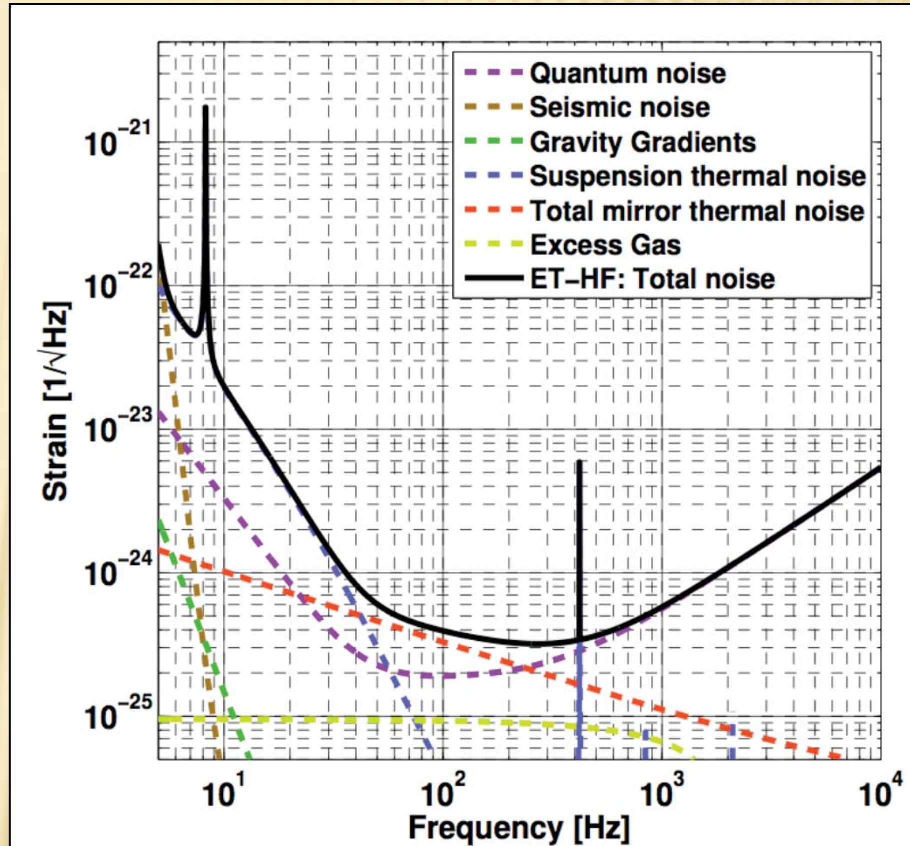
300K, 3MW, 1064nm

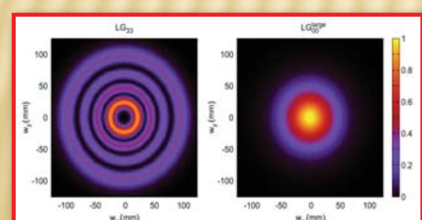


ET-D HIGH FREQUENCY DETECTOR

Slide: Christian Gräf, ET Symp., 2013, modified

- **Quantum noise:** 3MW, tuned Signal-Recyling, 10dB Squeezing, 200kg fused silica mirrors.
- **Suspension Thermal and Seismic:** Superattenuator (standard Virgo)
- **Gravity gradient:** No Subtraction needed
- **Thermal noise:** 290K, 12cm beam radius, fused Silica, LG33 (reduction factor of 1.6 compared to TEM00).

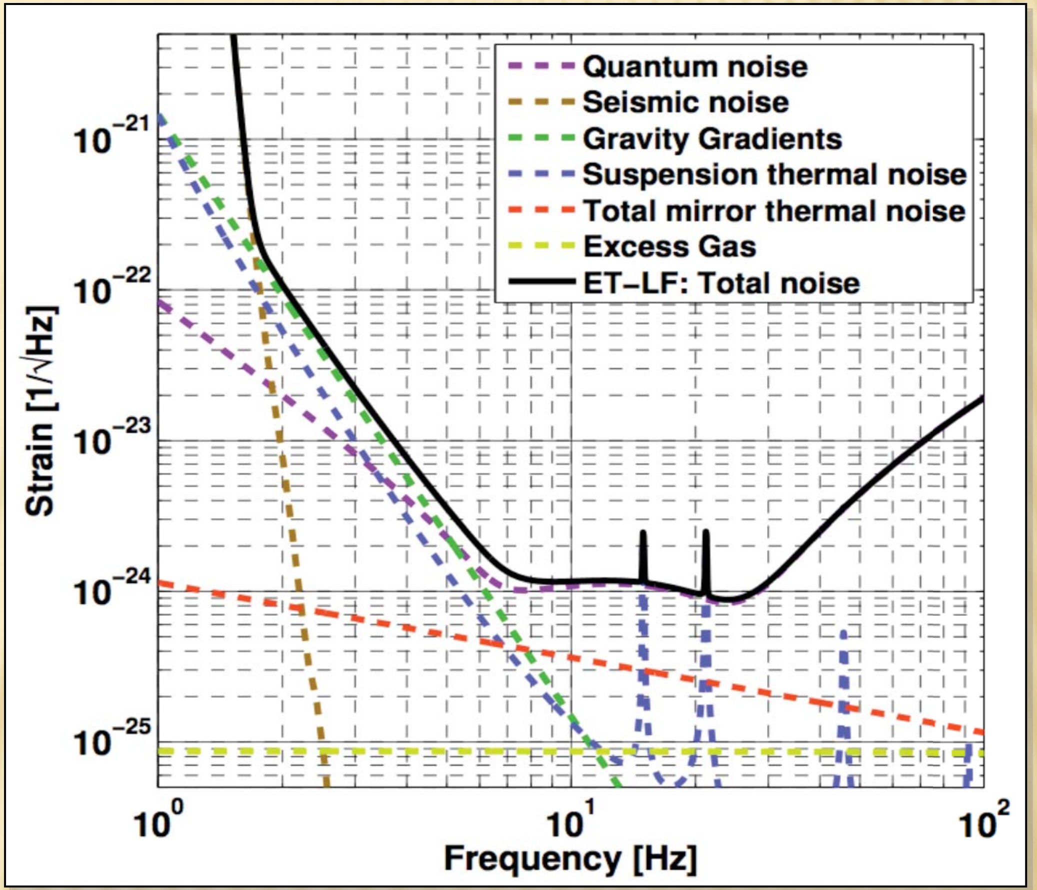




Coating Brownian reduction factors (compared to 2G):
3.3 (arm length), 2 (beam size) and 1.6 (LG33) = **10.5**
Shot Noise reduction factors (compared to 2G):
1.6 (arm length), 1.9 (power), 3.2 (squeezing (10dB)) = **9.7**

ET-D LOW FREQUENCY DETECTOR

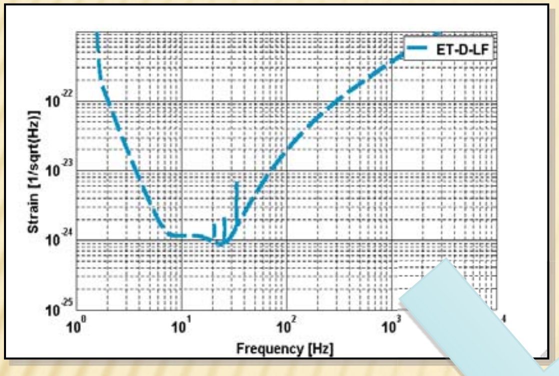
- **Quantum noise:** 18kW, detuned Signal-Recyling, 10 dB frequency dependent Squeezing, 211kg mirrors.
- **Seismic:** extended Superattenuator, 17m tall
- **Gravity gradient:** no subtraction assumed in noise curve
- **Mirror thermal :** 10K, Silicon, 12cm beam radius, TEM00.
- **Suspension Thermal:** penultimate mass@2K, 3mm diameter silicon fibres, 2m long; limiting noise contribution from 1Hz-10Hz



As mirror TN is no longer limiting, one could relax the assumptions on the material parameters and the beam size…

ET-D XYLOPHONE SENSITIVITY

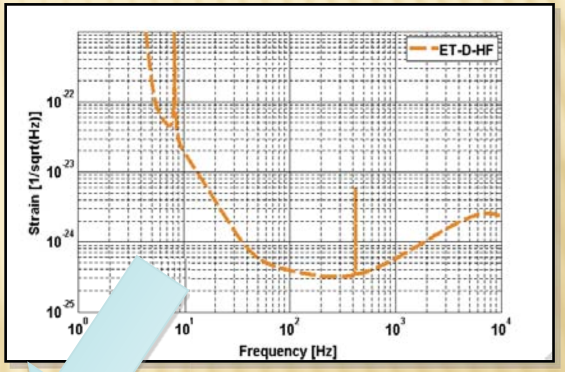
Slide: Christian Gräf, 2013, modified

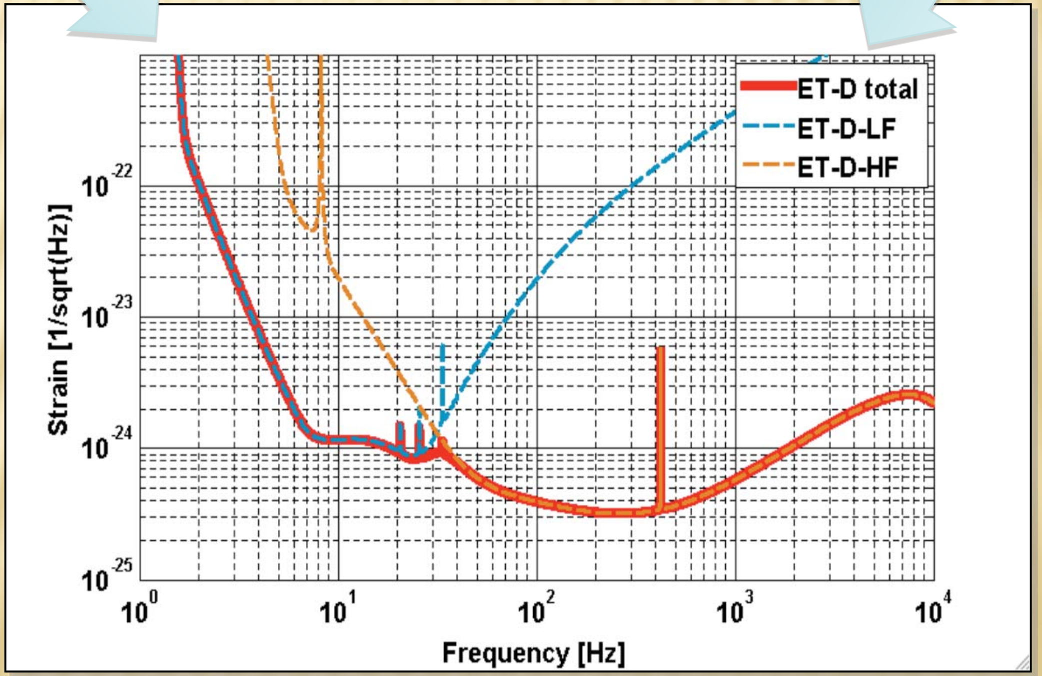


Combining the two interferometers

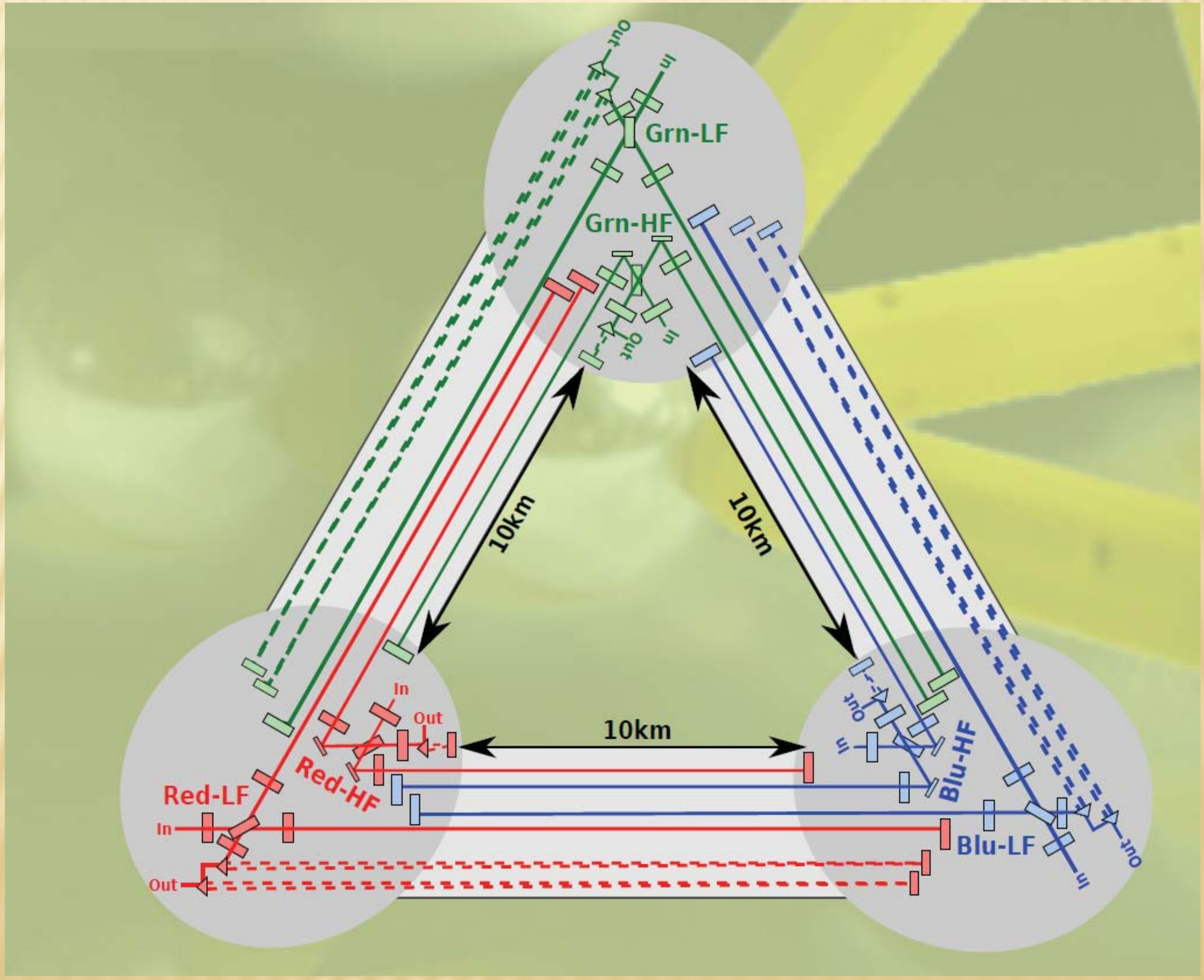
ET-D-LF

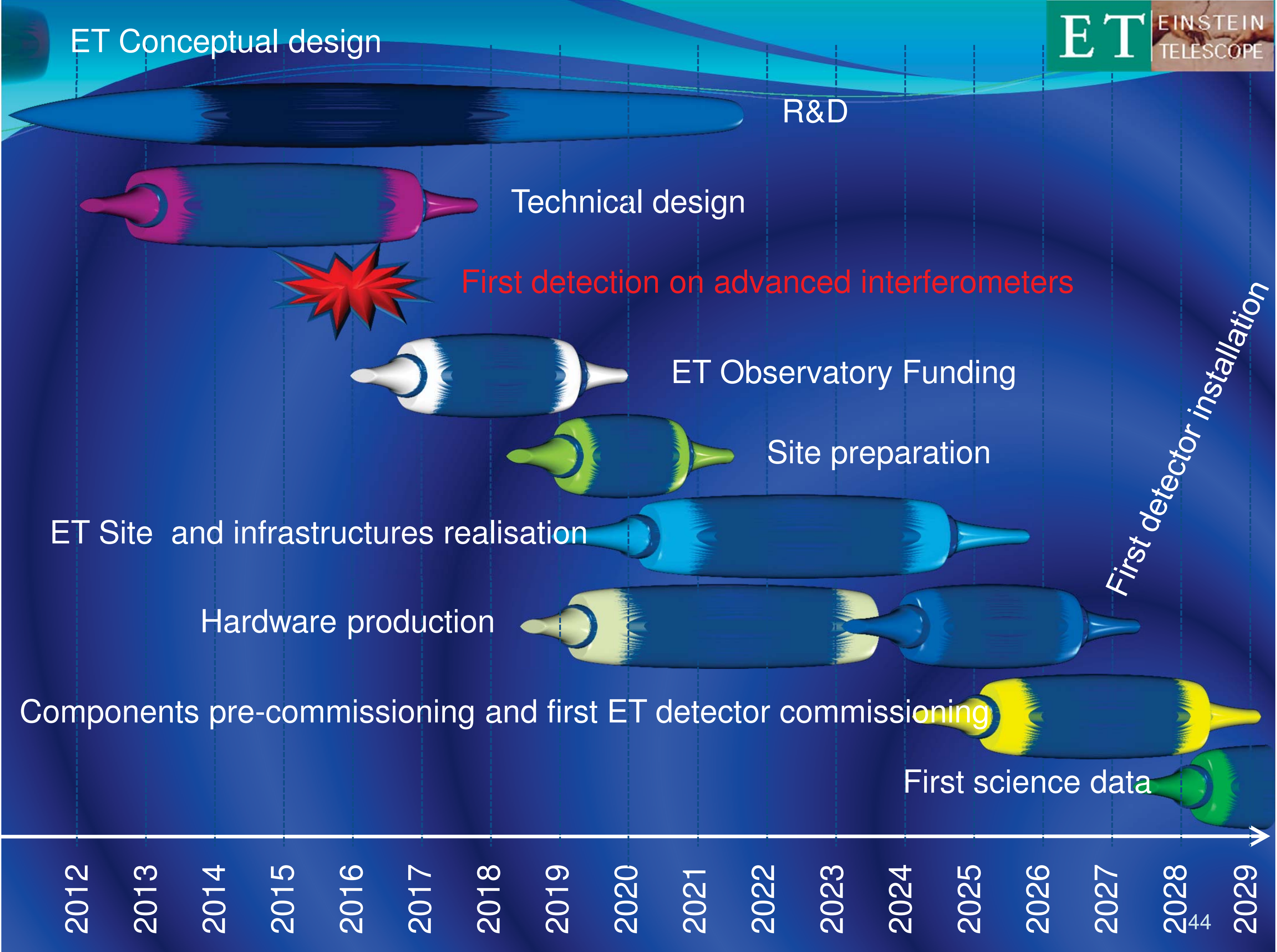
ET-D-HF



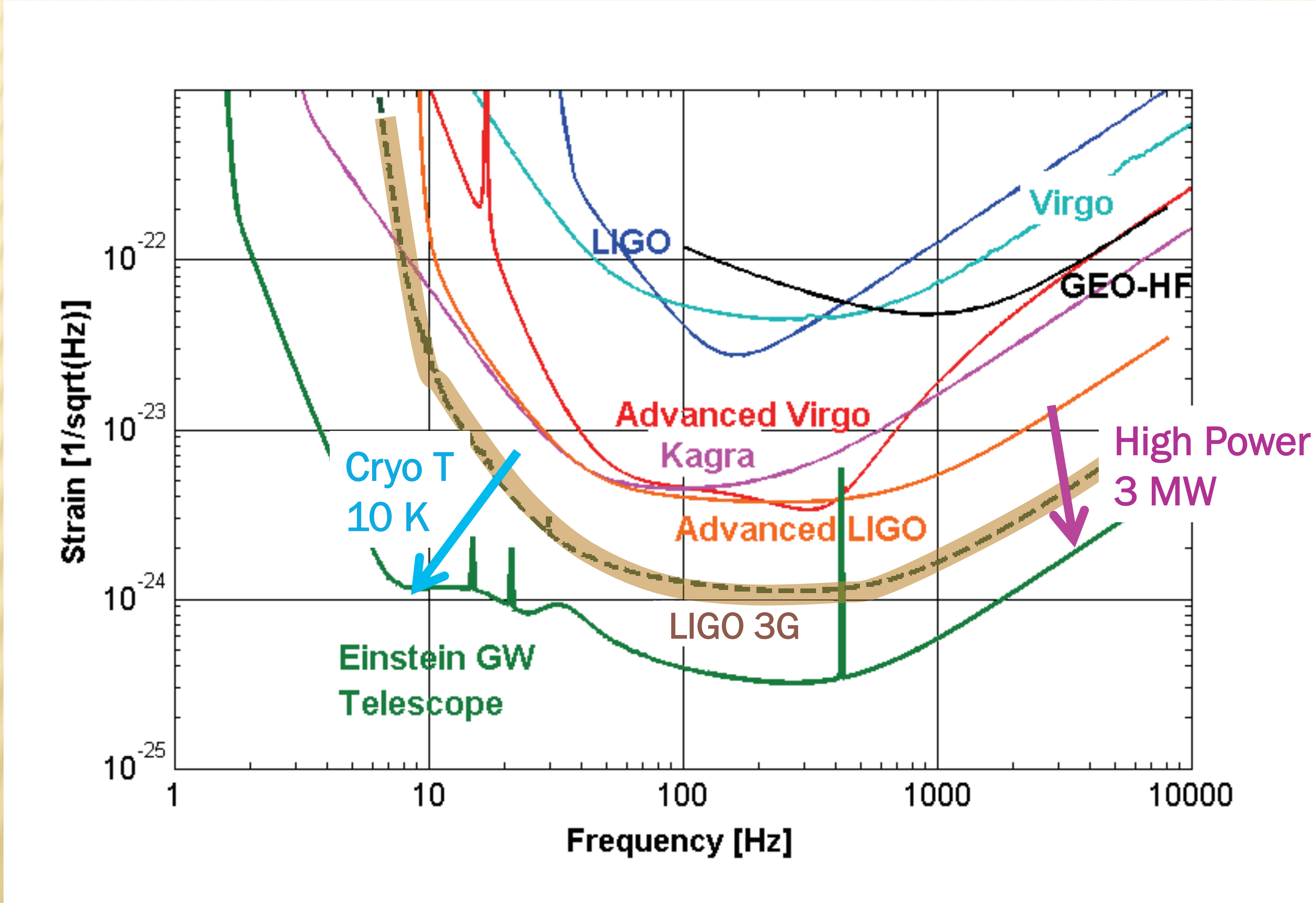


TRIANGULAR CONFIGURATION SIX INTERFEROMETERS IN TOTAL




ET Conceptual design
EINSTEIN TELESCOPE
R&D
Technical design
First detection on advanced interferometers
ET Observatory Funding
Site preparation
ET Site and infrastructures realisation
First detector installation
Hardware production
Components pre-commissioning and first ET detector commissioning
First science data
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029

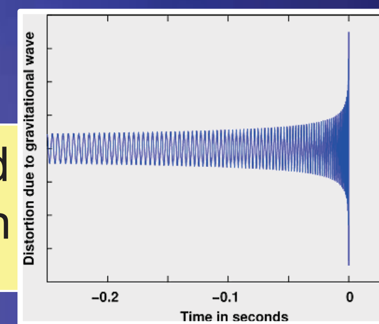
1ST, 2ND 2+, AND 3RD GENERATION



CB Signal detection method:
Matched Filtering & Templates bank

Matched filtering:

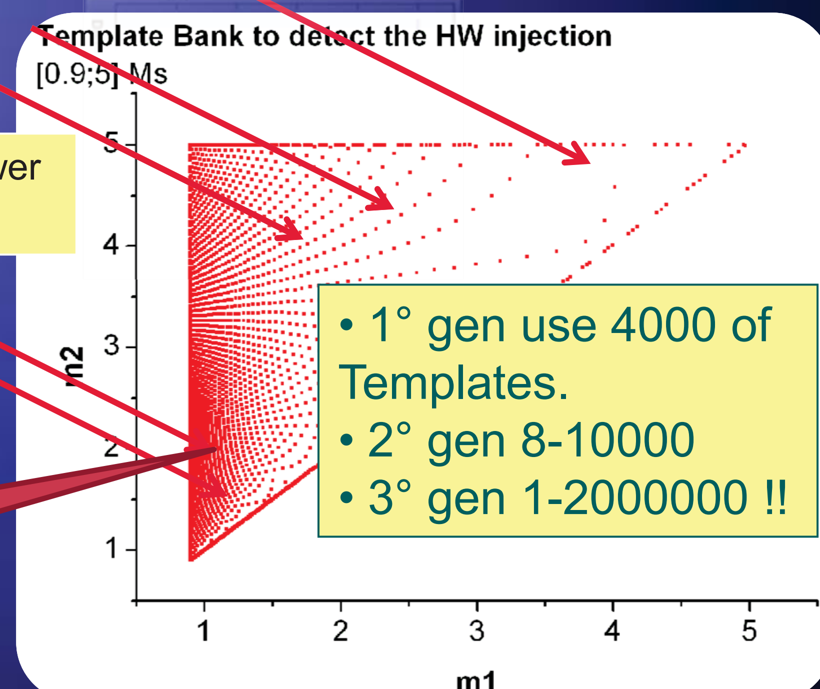
Reference signal, called ***template*** in freq. domain



$$z(t) = 4\int_0^\infty \frac{\tilde{s}(f)\,\tilde{h}^*(f)}{S_n(f)}\, e^{2\pi i f t}\, df$$

FFT (Detector Data)

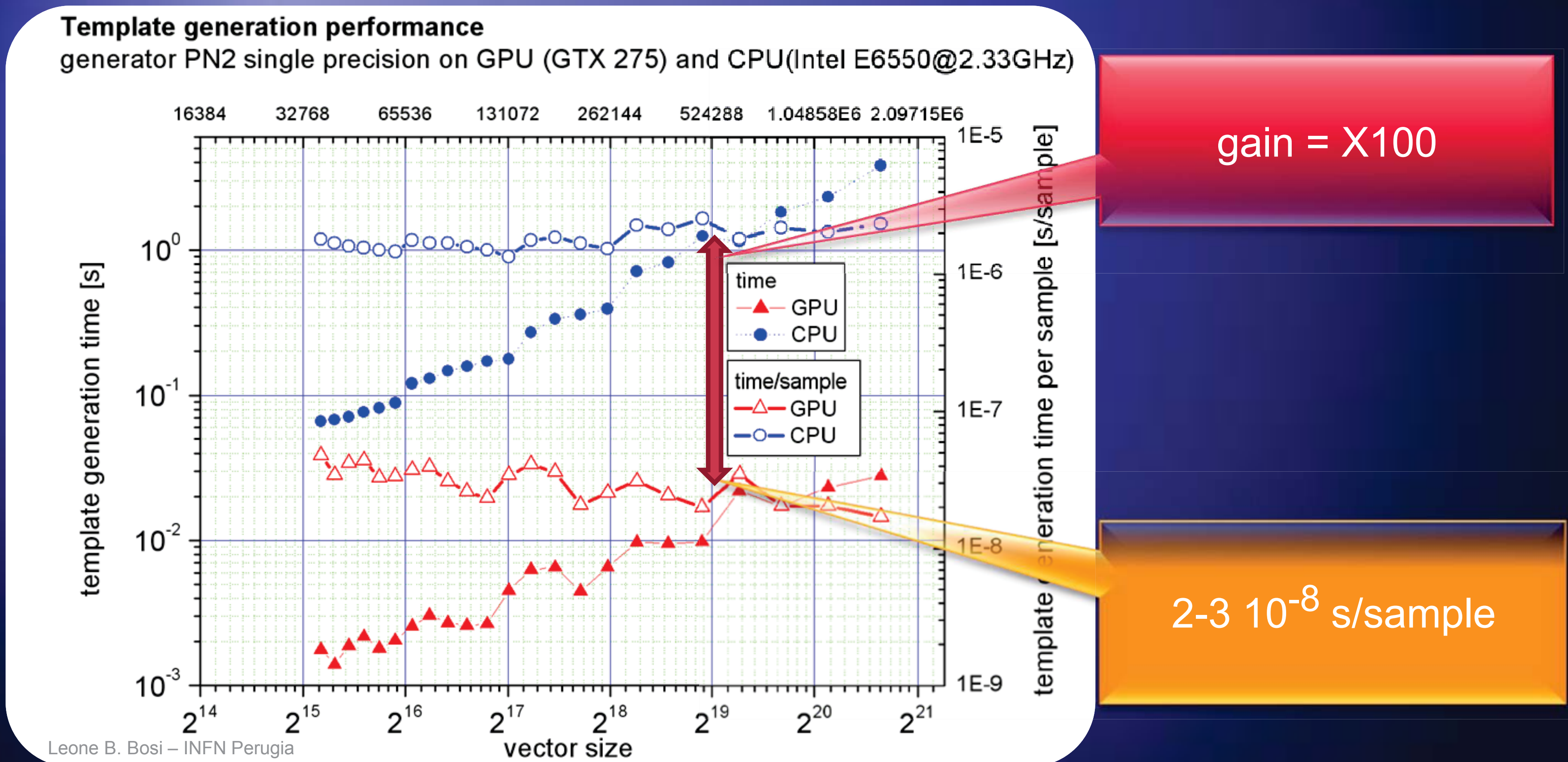
One-sided noise power spectral density

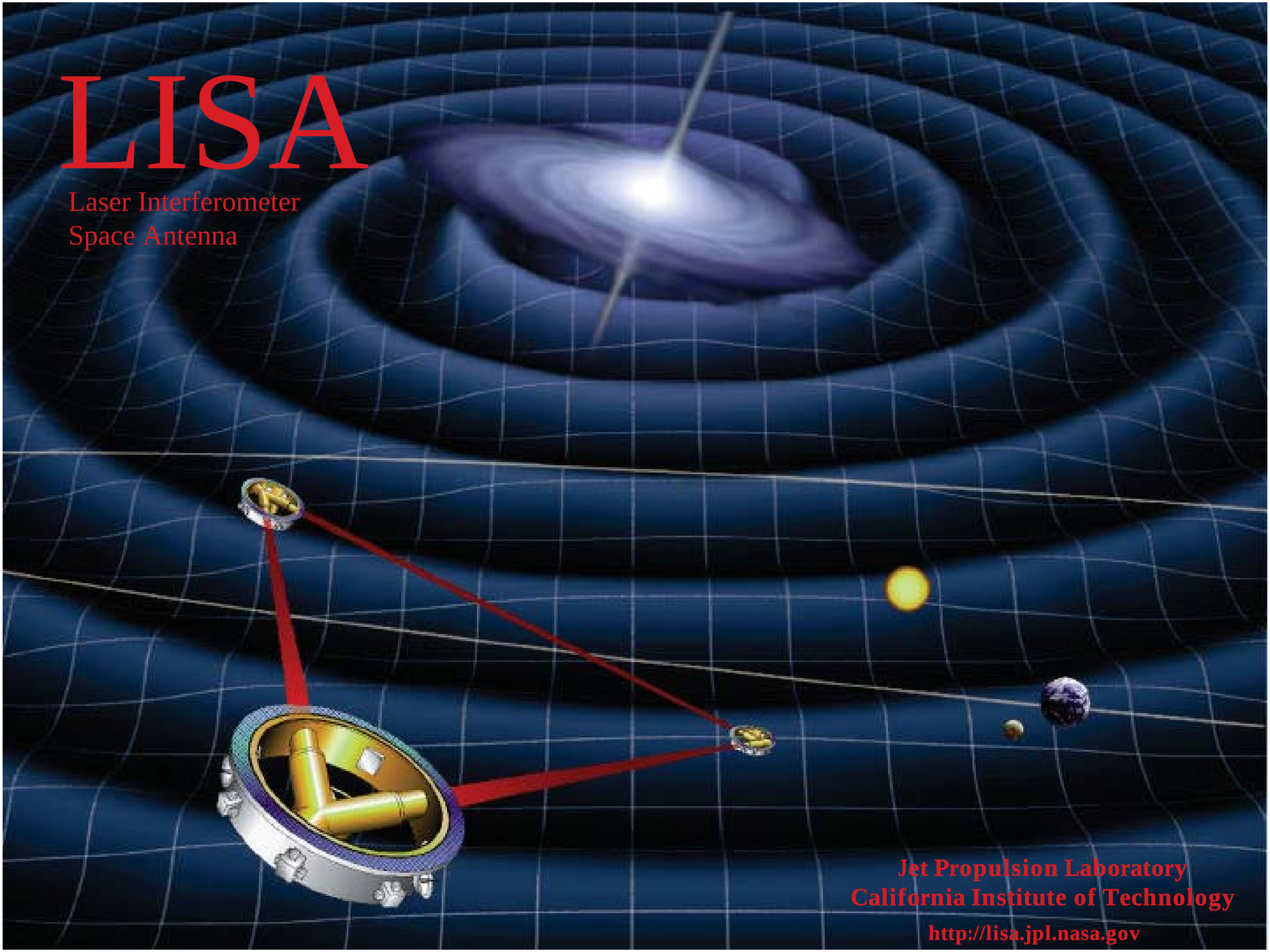


- 1° gen use 4000 of Templates.
- 2° gen 8-10000
- 3° gen 1-2000000 !!

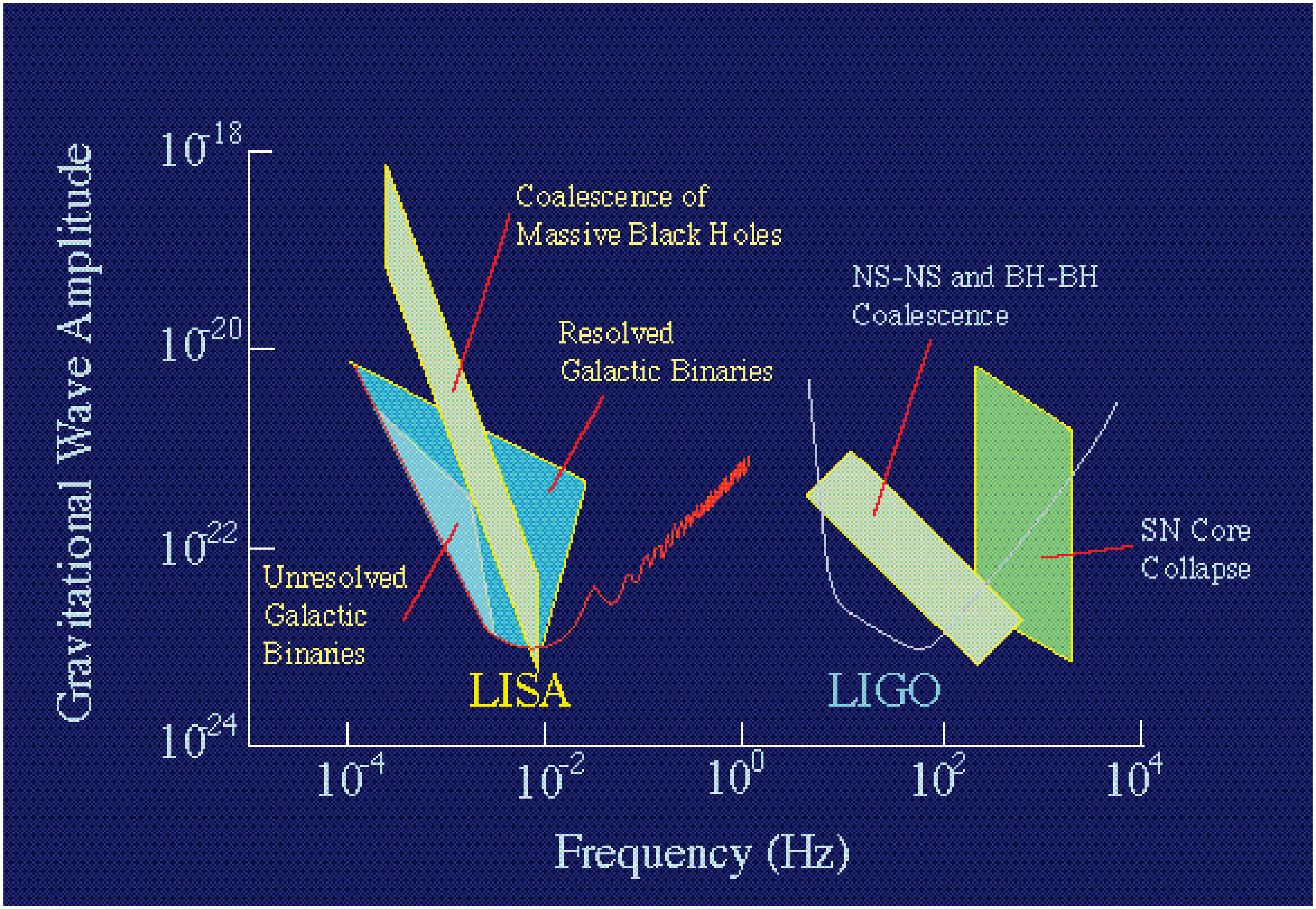
Looping over ALL templates for each timeslice of data.

Template Signal Generation: GPU vs CPU




LISA
Laser Interferometer
Space Antenna
Jet Propulsion Laboratory
California Institute of Technology
http://lisa.jpl.nasa.gov

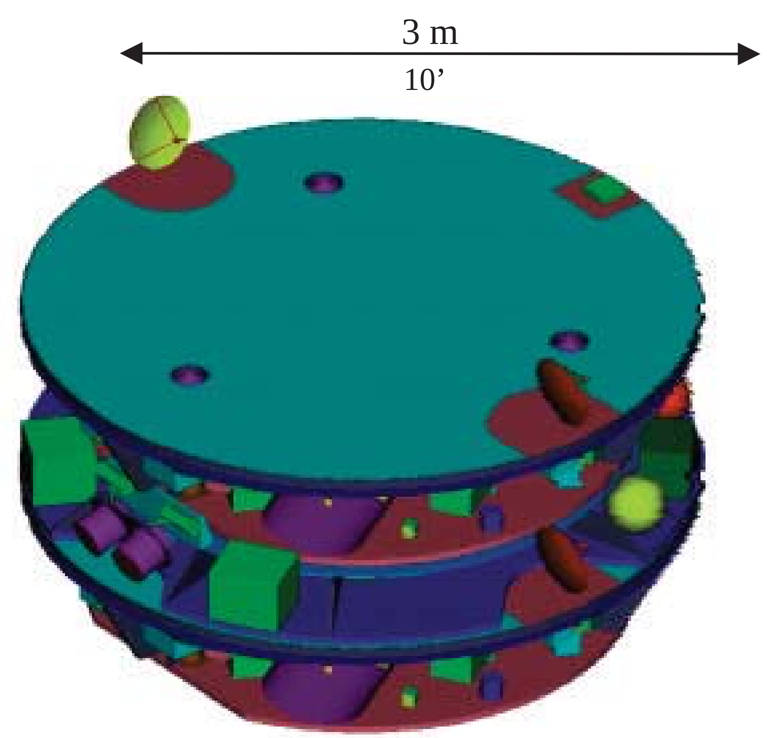
The Gravitational-Wave Spectrum

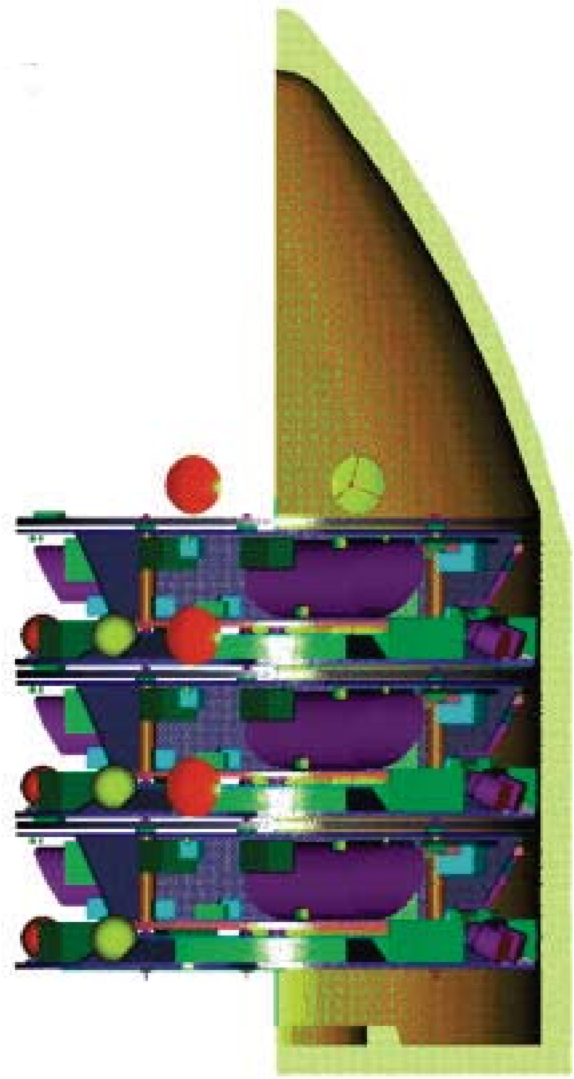


Launch Configuration

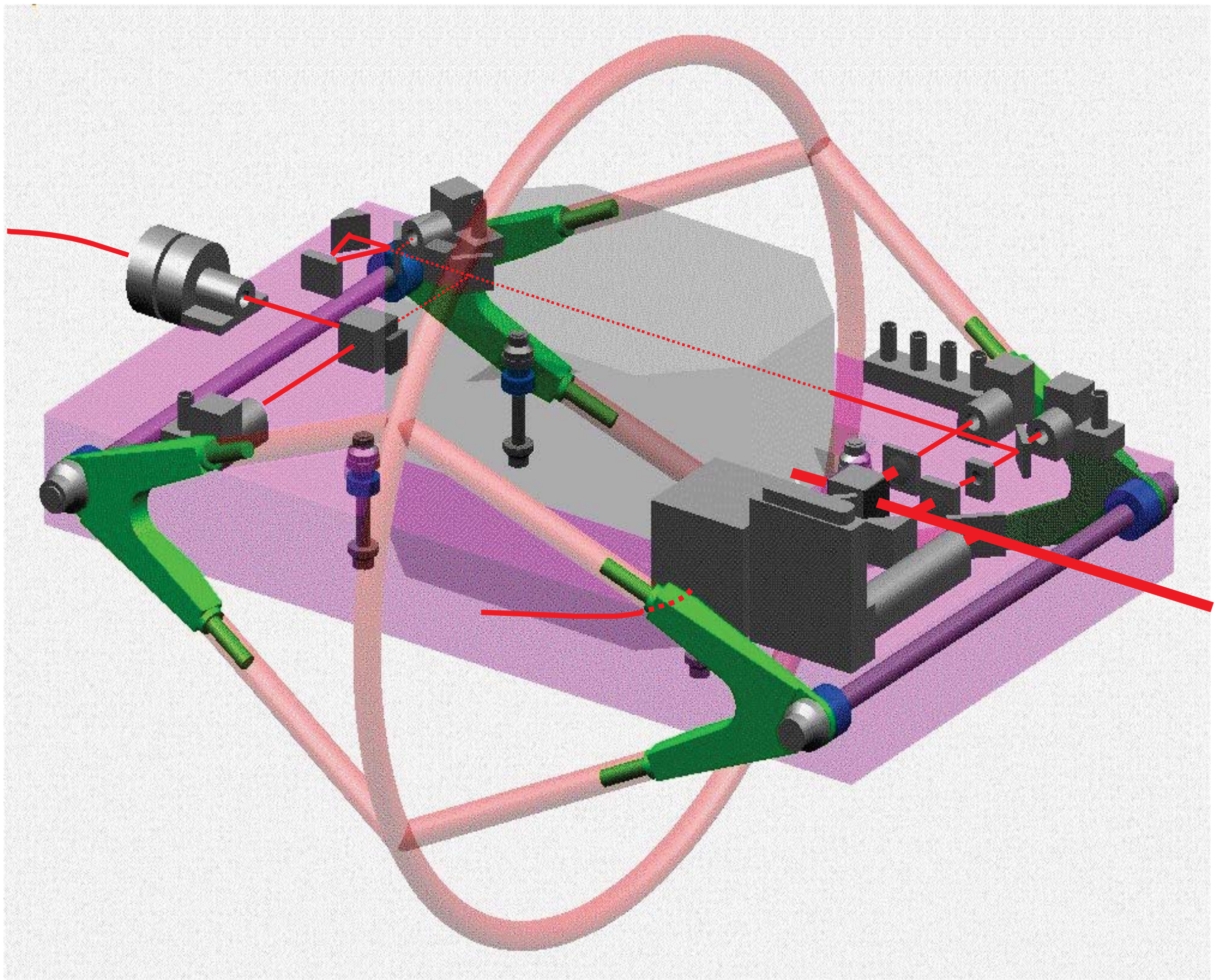
Spacecraft design constrained by volume of Launch vehicle shroud

Delta-II preferred because of lower cost

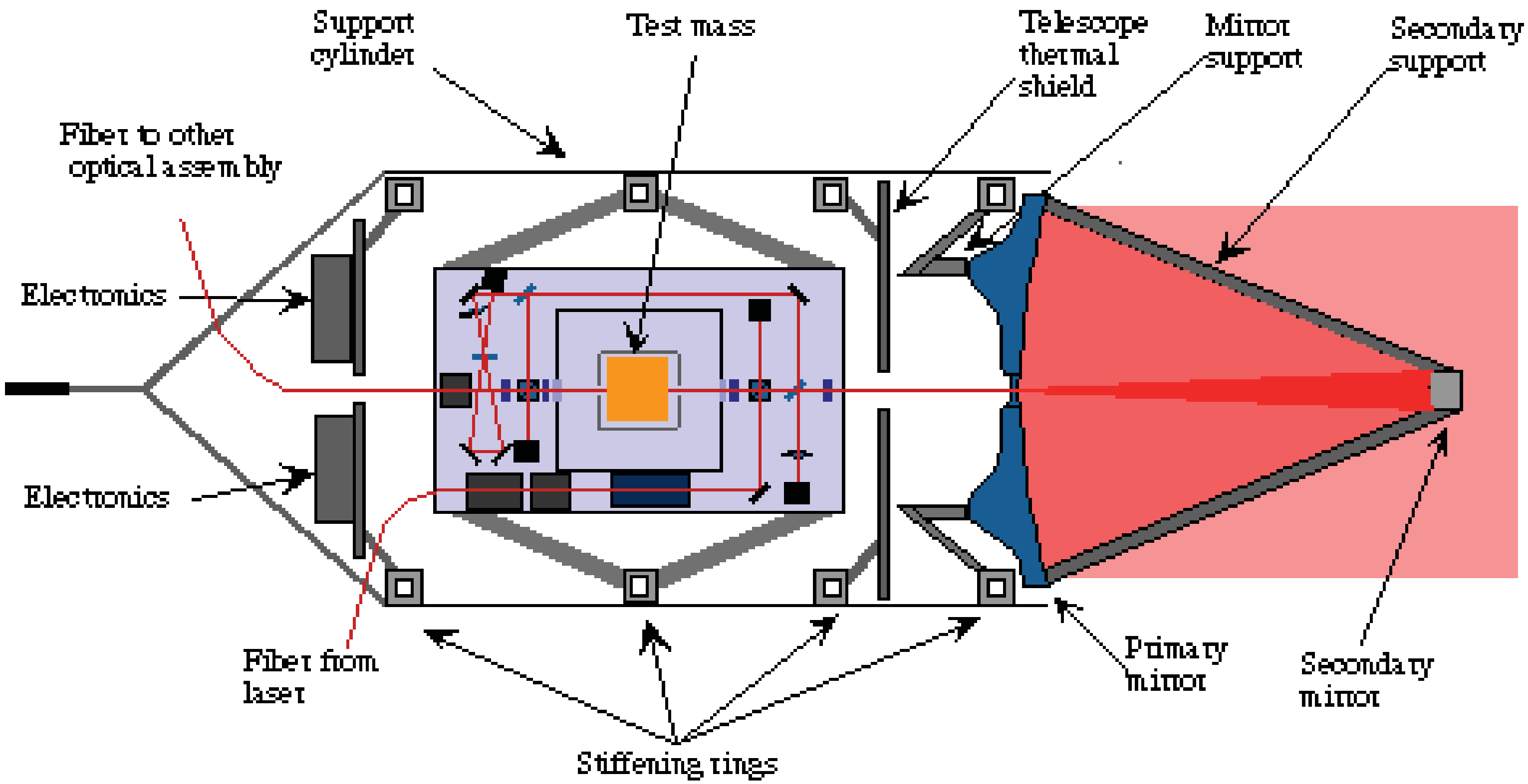




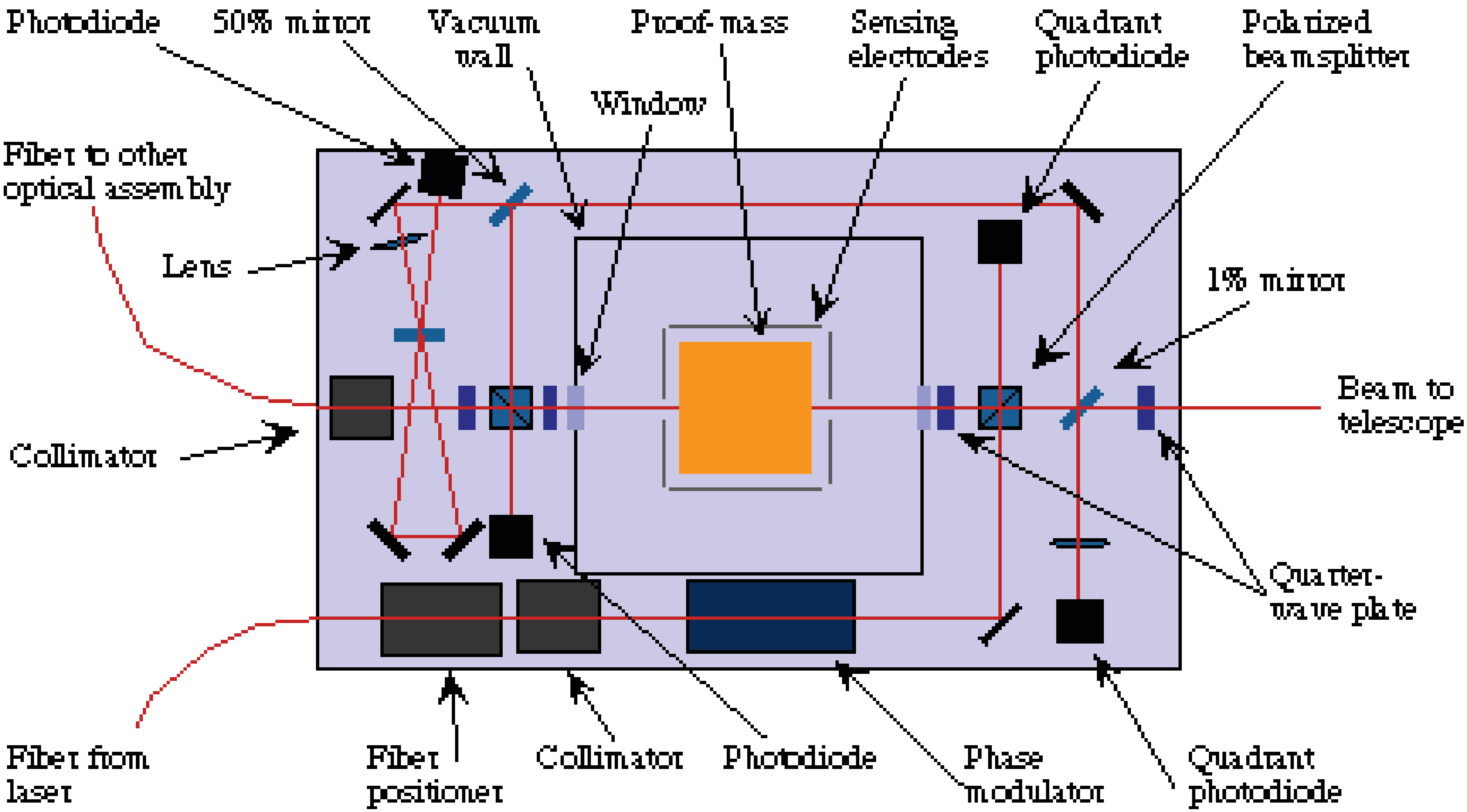
Payload Mounting Structure



Optical System

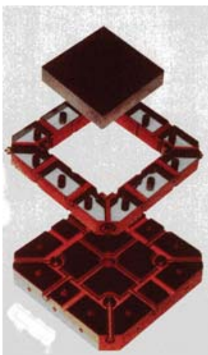


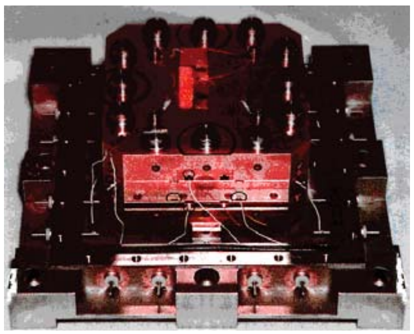
Optical Bench Schematic



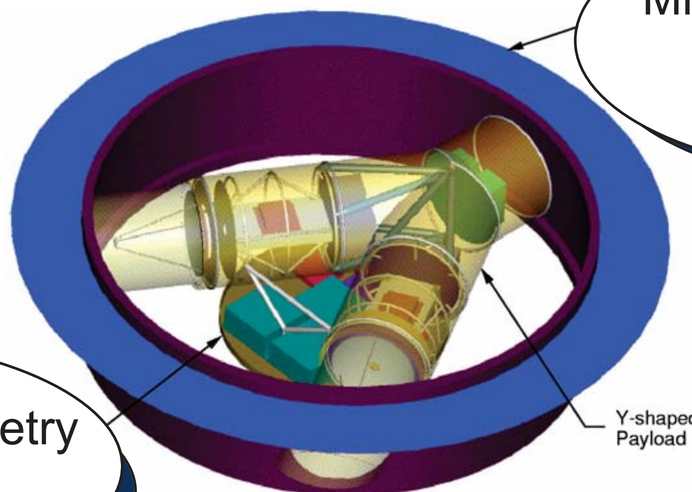
Technology Drivers

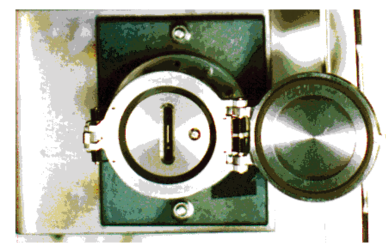
Gravitational sensors
Noise < 10^{-16} g
rms for 1000 s average





Micronewton thrusters
Range 1-100 μN
Noise <1 μN

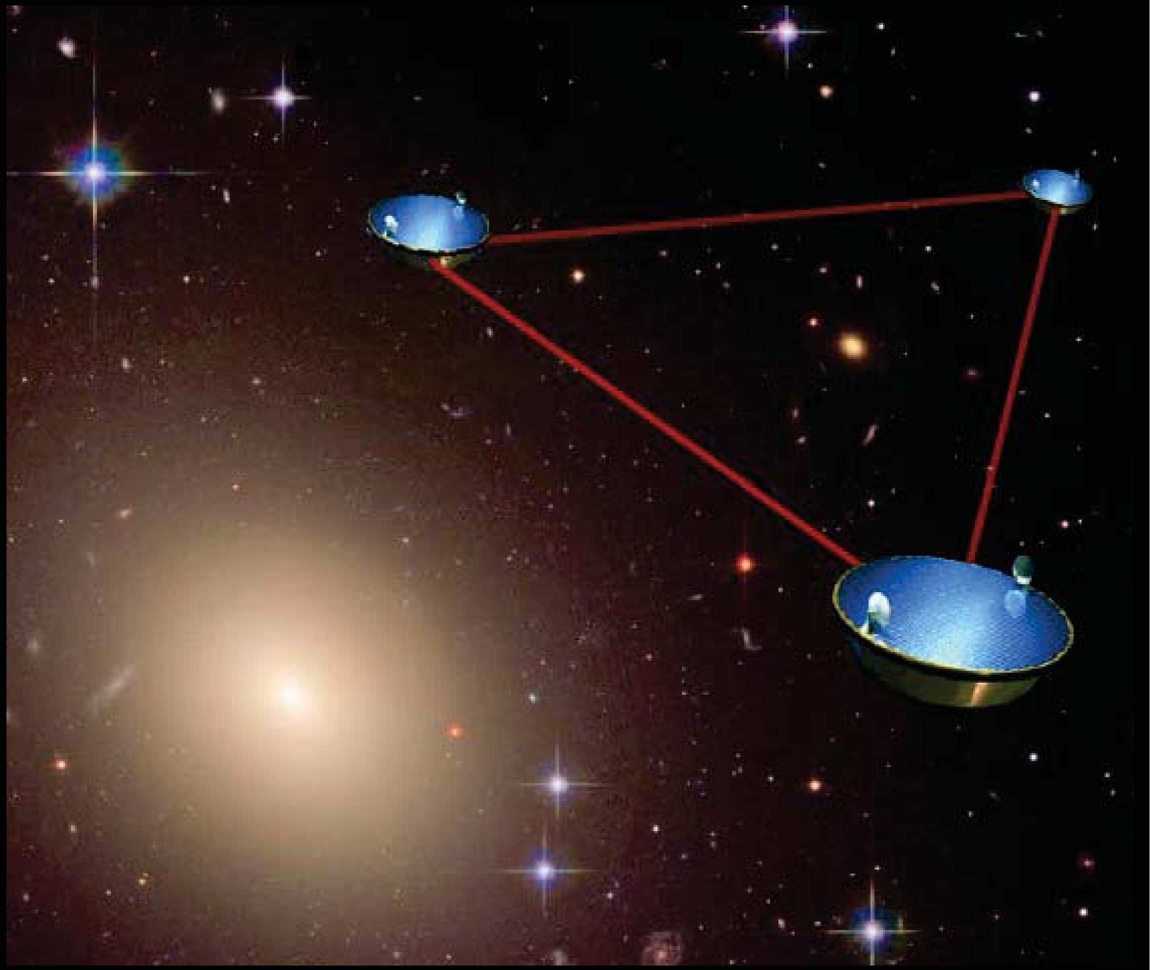




Picometer interferometry
Accuracy < 1 pm
rms for 1000 s average
1 W laser

Some history on GW detector in space

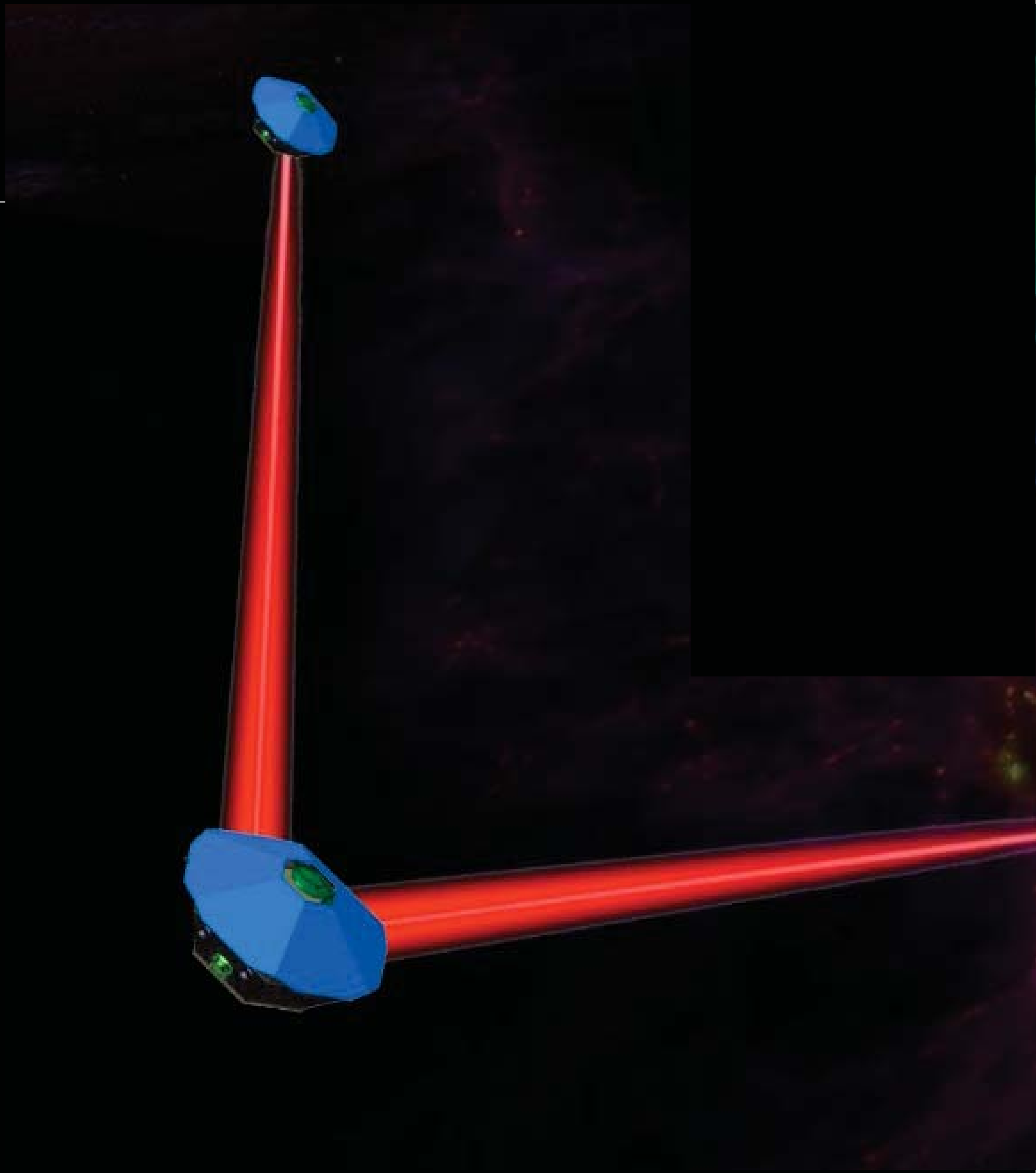
- Low-frequency gravitational wave mission first proposed in '80s (LAGOS)
- '90s: LISA as joint NASA/ESA mission
- In the end LISA became (1 of 3) L1 candidate for ESA Cosmic Vision program (decision foreseen in 2011)
- Early 2011, NASA: no money to contribute to any ESA L1 mission......
- Rapid definition teams for all L1 candidates to ESA-led mission. New mission (eLISA/NGO) developed, significant cost reduction, science still strong
- Now: April 2012, ESA will select 1 of 3 L1 candidates for launch ~2020

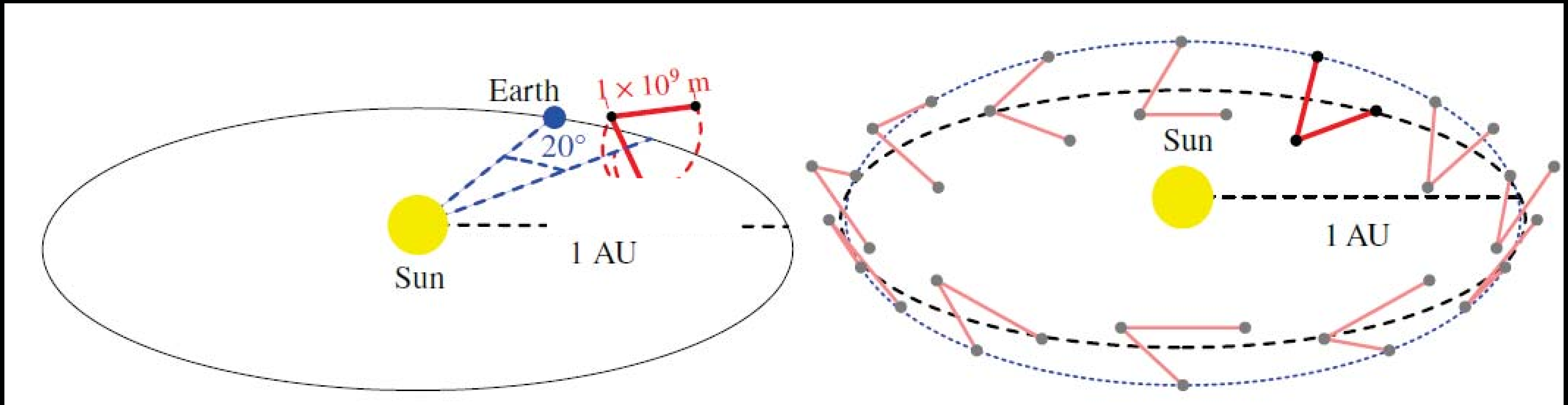


LISA

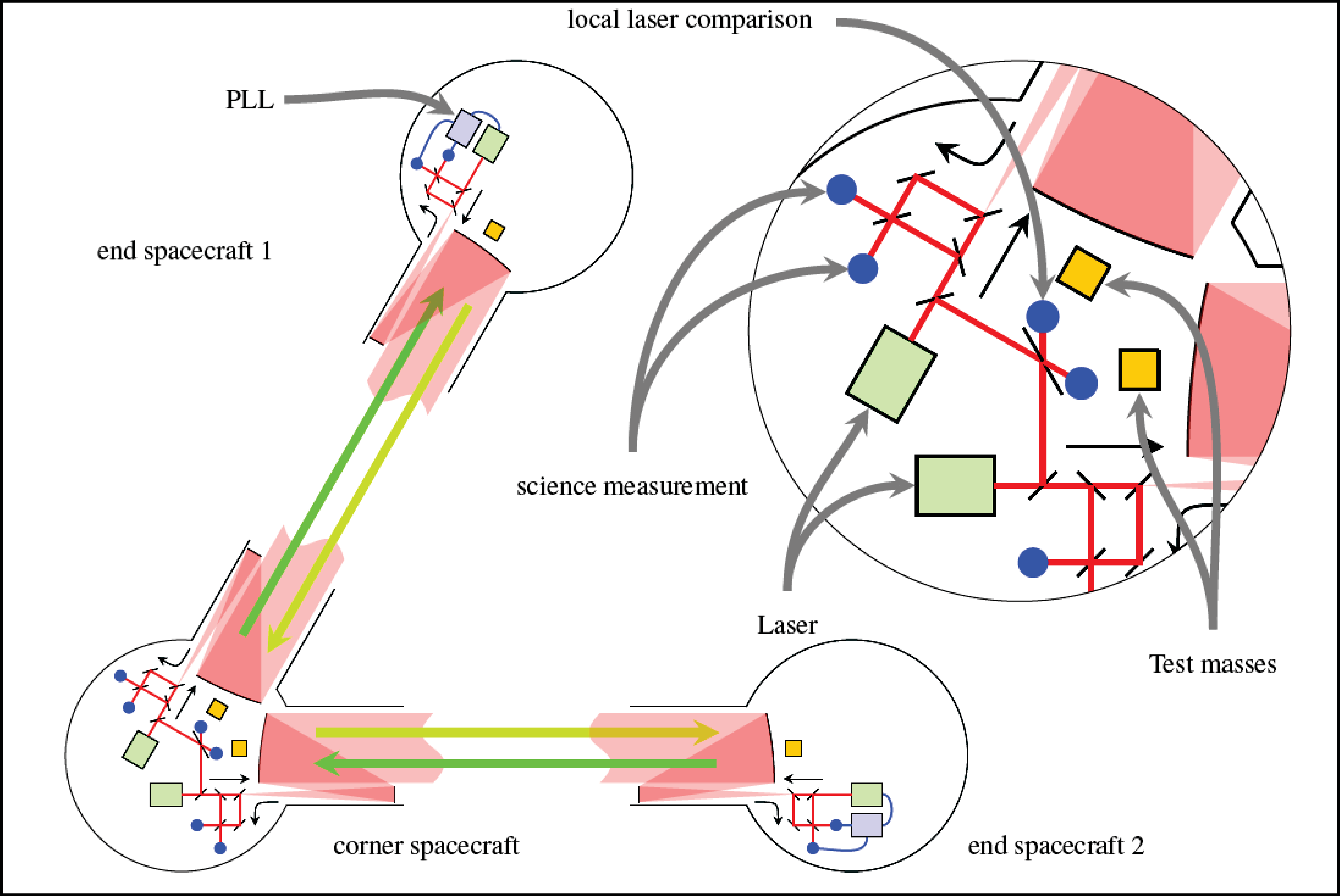
eLISA

- Affordable mission: smaller arms, closer to Earth (save on launcher)
- Mother-daughter system (i.e. 4 links only)
- Reuse much of LISA Pathfinder components
- Pay-load simpler and cheaper, telescopes smaller
- Member state contribution: pay load (as in all candidate L1 missions)
- Consortium to be formed





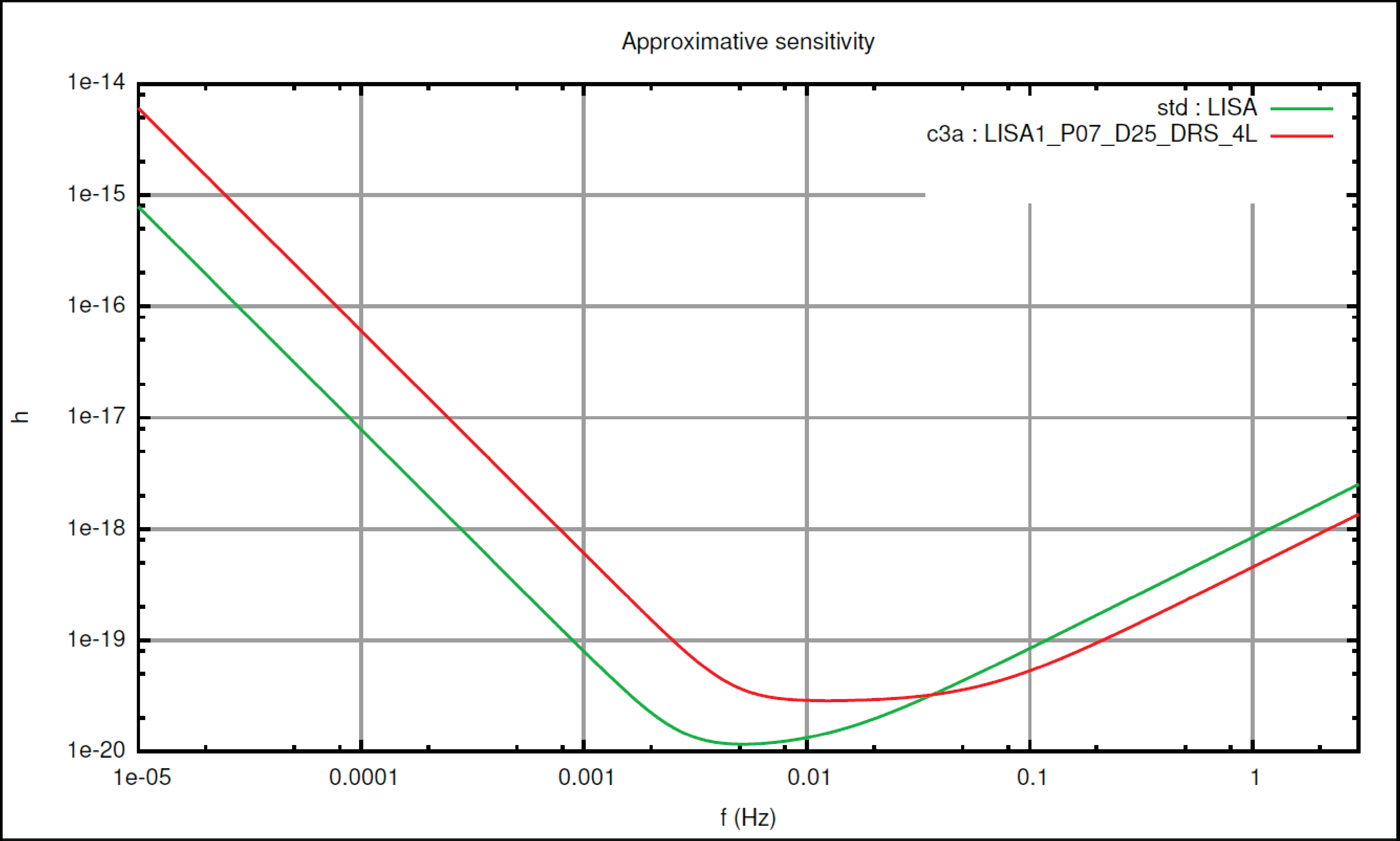
eLISA


local laser comparison
PLL
end spacecraft 1
science measurement
Laser
Test masses
corner spacecraft
end spacecraft 2

What is different from LISA?

eLISA	LISA
1 million km arms	5 million km arms
4 laser links	6 laser links
Smaller distance to Earth	Larger distance to Earth
2 Soyuz launch	Ariane 5 launch
Member state contributions	No member state contribution

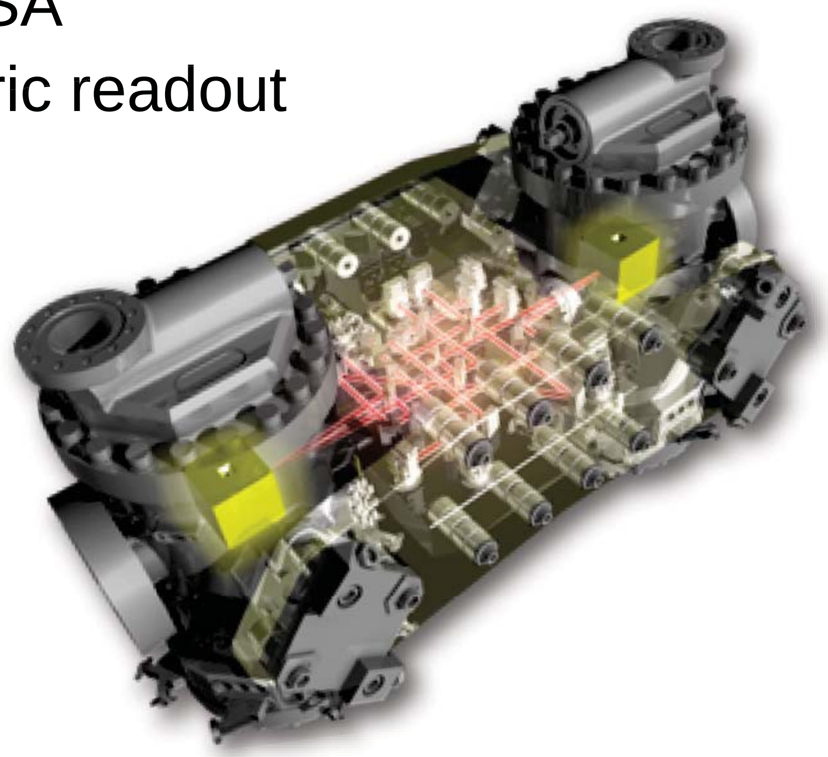
What is different from LISA?



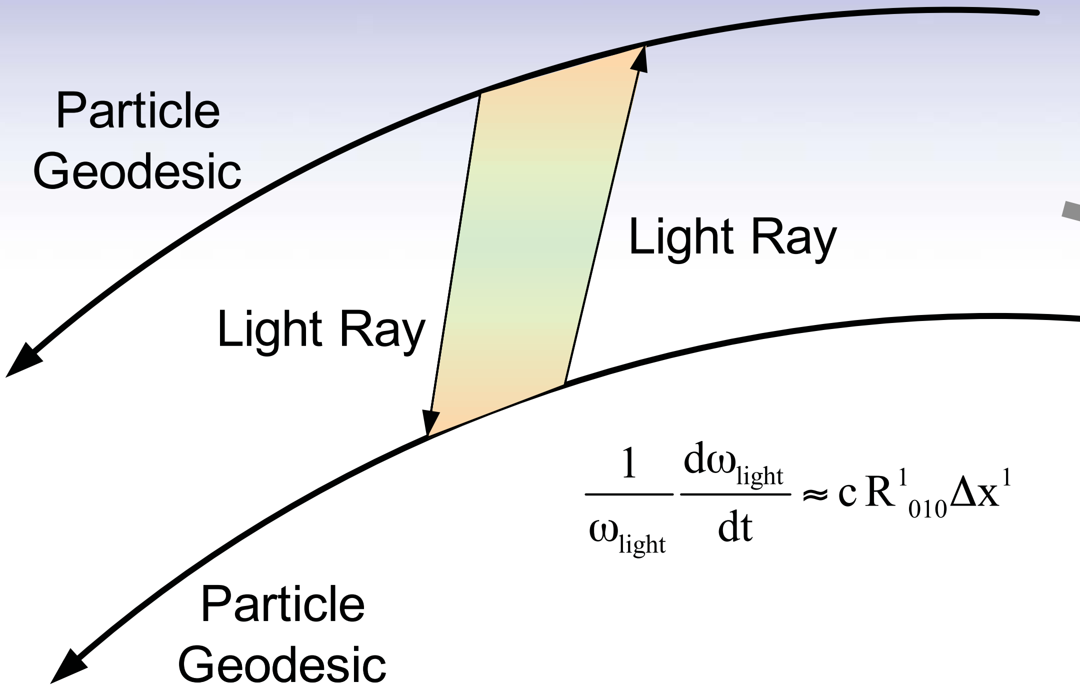
LISA Pathfinder Mission

- LISA Pathfinder can be functionally split into the spacecraft and payloads:
  - **Spacecraft**
    - Provided by ESA
      - Industrial Prime Contractor: Astrium UK
    - s/c includes the drag free control software and micro-Newton thrusters

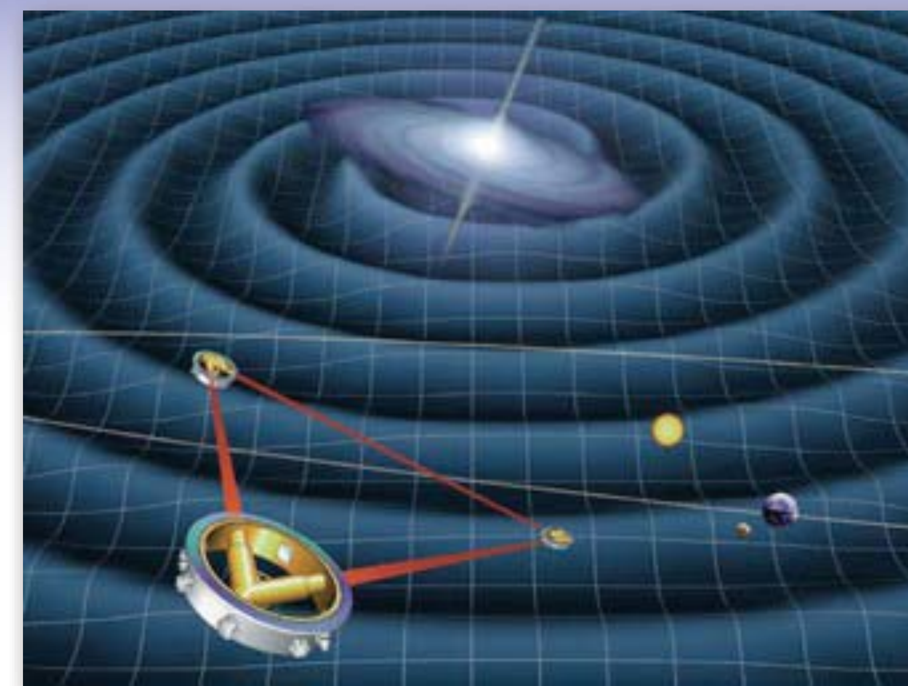
  - **Payloads**
    - **The LISA Technology Package (LTP)**
      - Provided by European member states and ESA
      - Consists of inertial sensors, and interferometric readout
    - **The Disturbance Reduction System (DRS)**
      - Provided by NASA-JPL
      - Consists of processor running drag-free control software and micro-Newton thrusters

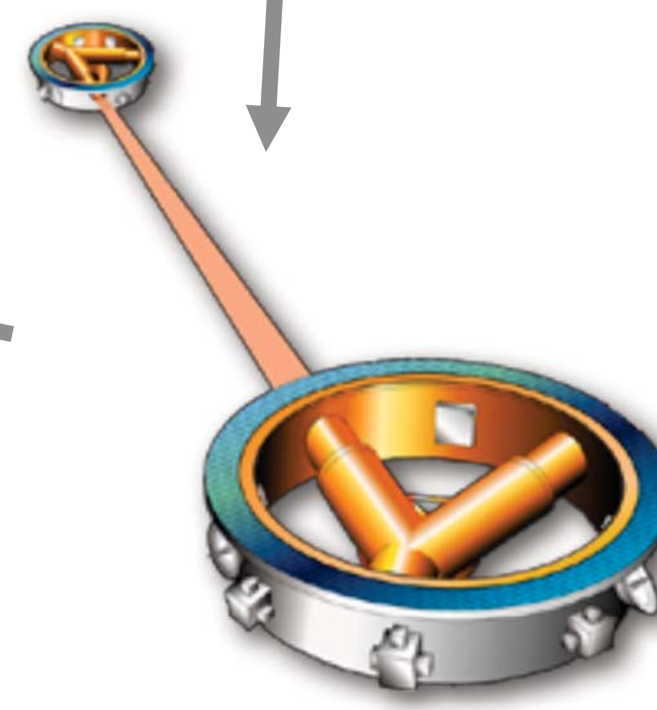


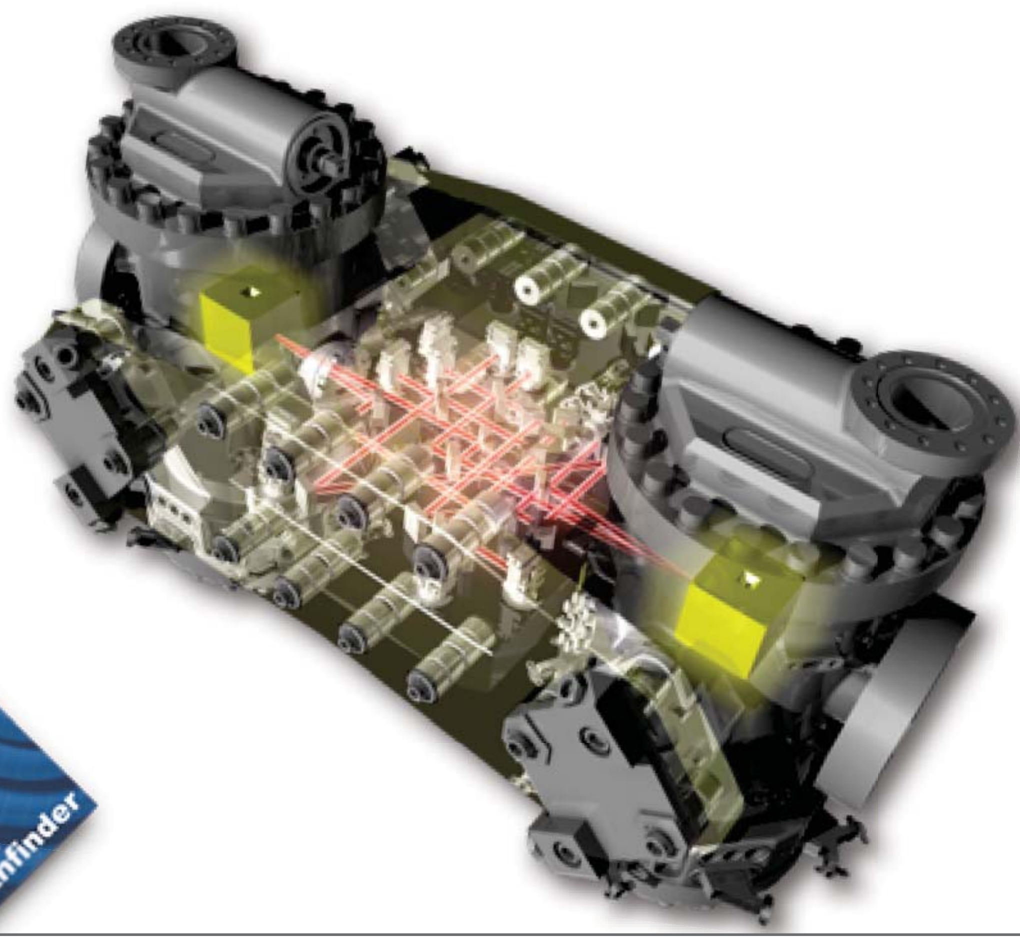
Mission Concept



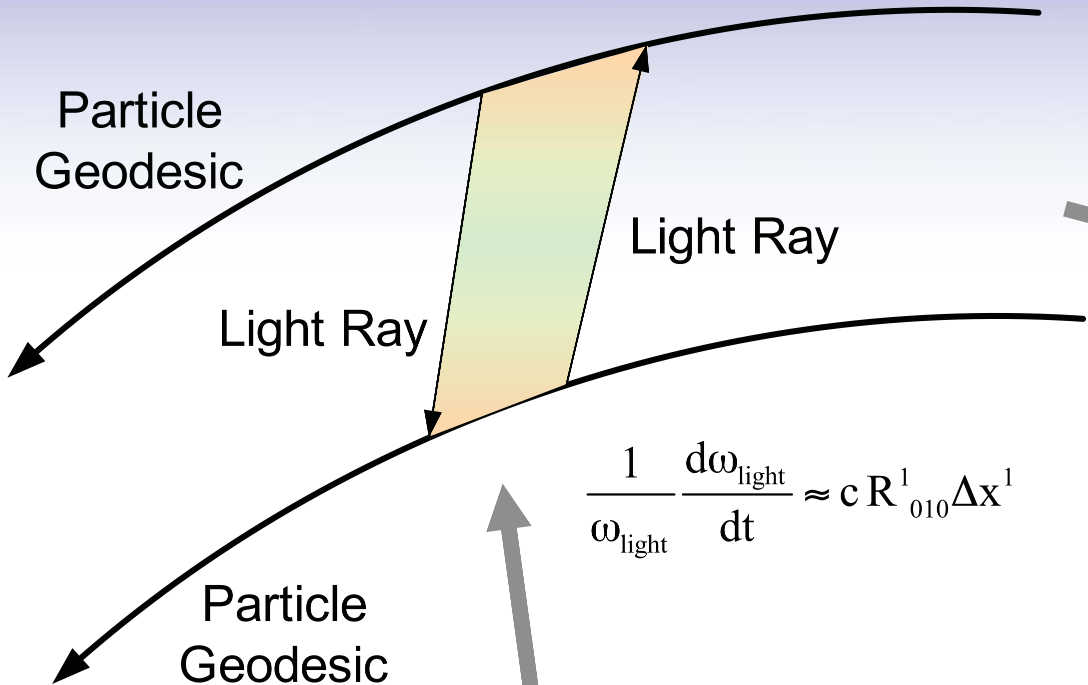
$$\frac{1}{\omega_{light}}\frac{d\omega_{light}}{dt} \approx c\, R^{1}{}_{010}\Delta x^{1}$$



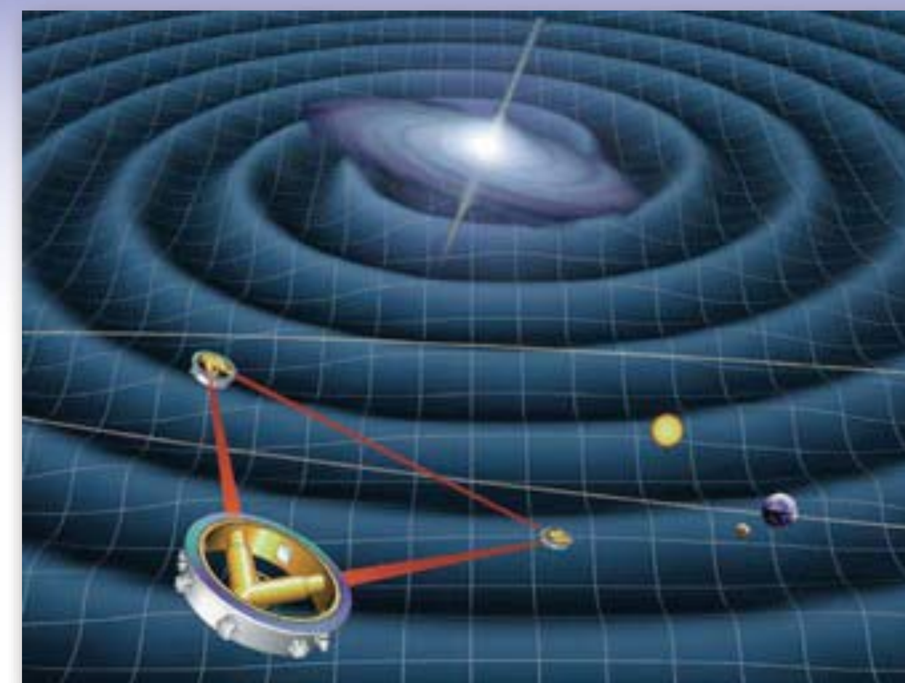


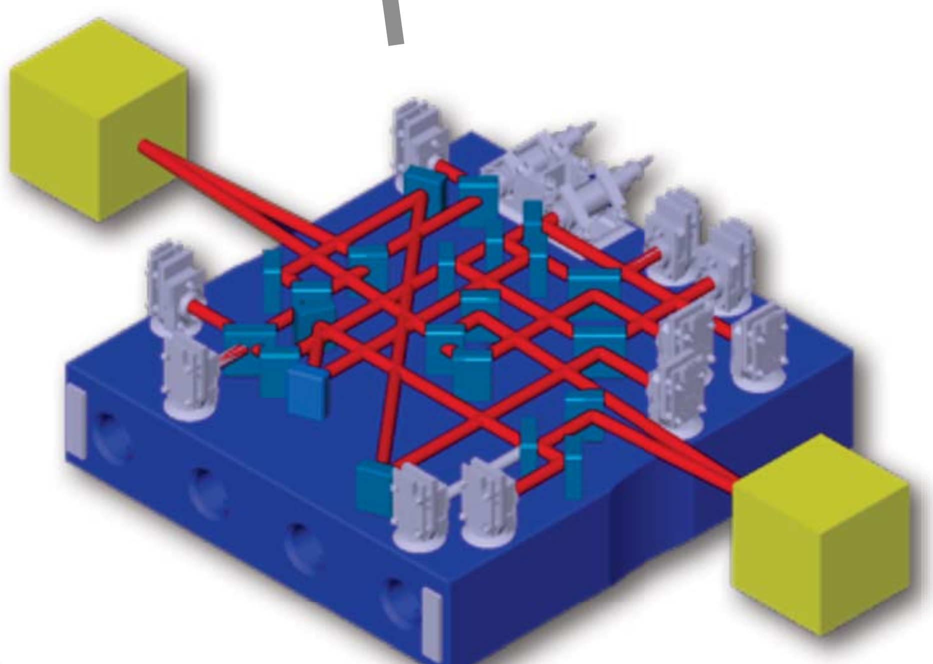


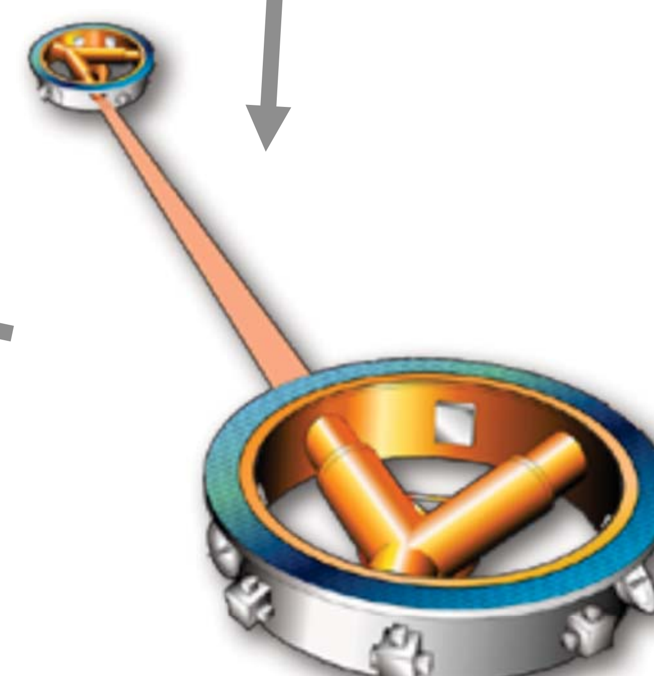
Mission Concept



$$\frac{1}{\omega_{light}}\frac{d\omega_{light}}{dt} \approx c\, R^{1}{}_{010}\Delta x^{1}$$







LPF Spacecraft

- The main role of the LPF spacecraft is to protect the test masses from external disturbances
  – The spacecraft follows the test mass

- Spacecraft integration is almost fully complete
  – All s/c bus electronic units are integrated, and most of the LTP electronic units are integrated
  – Only the LTP and micro-Newton thrusters are missing

- Spacecraft and Prop module are now at the testing centre (IABG) for the start of the environmental test campaign

Integrated Spacecraft

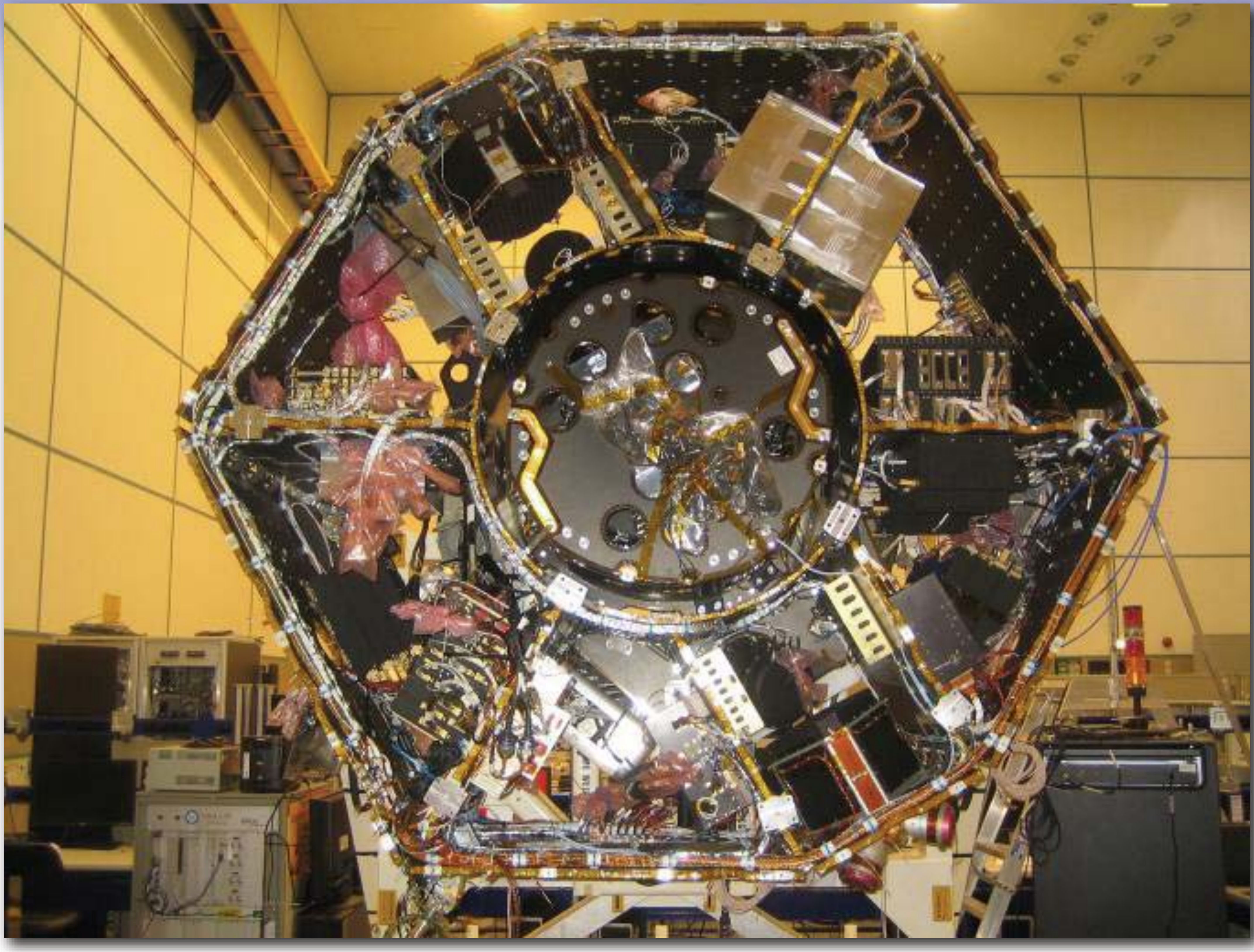
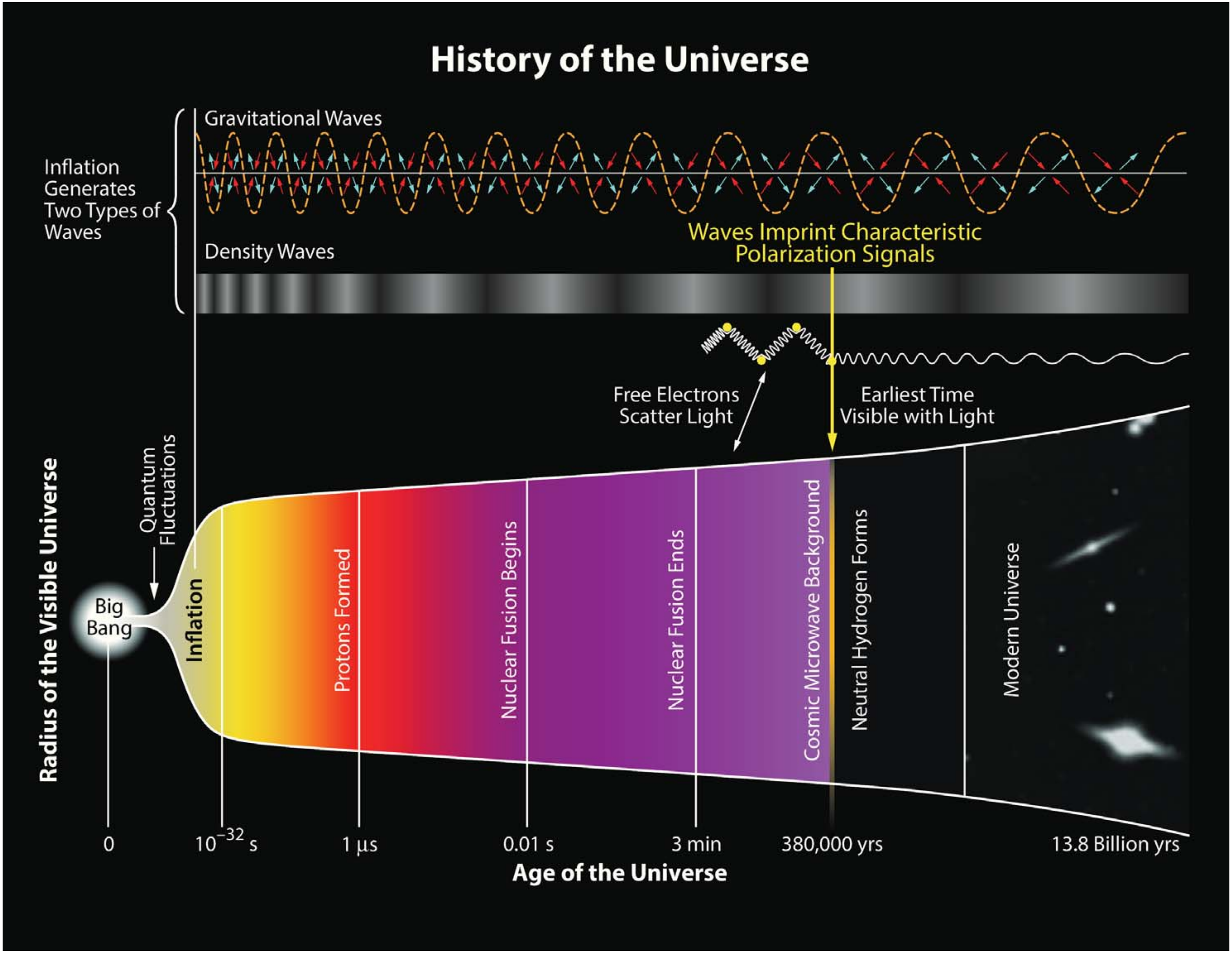


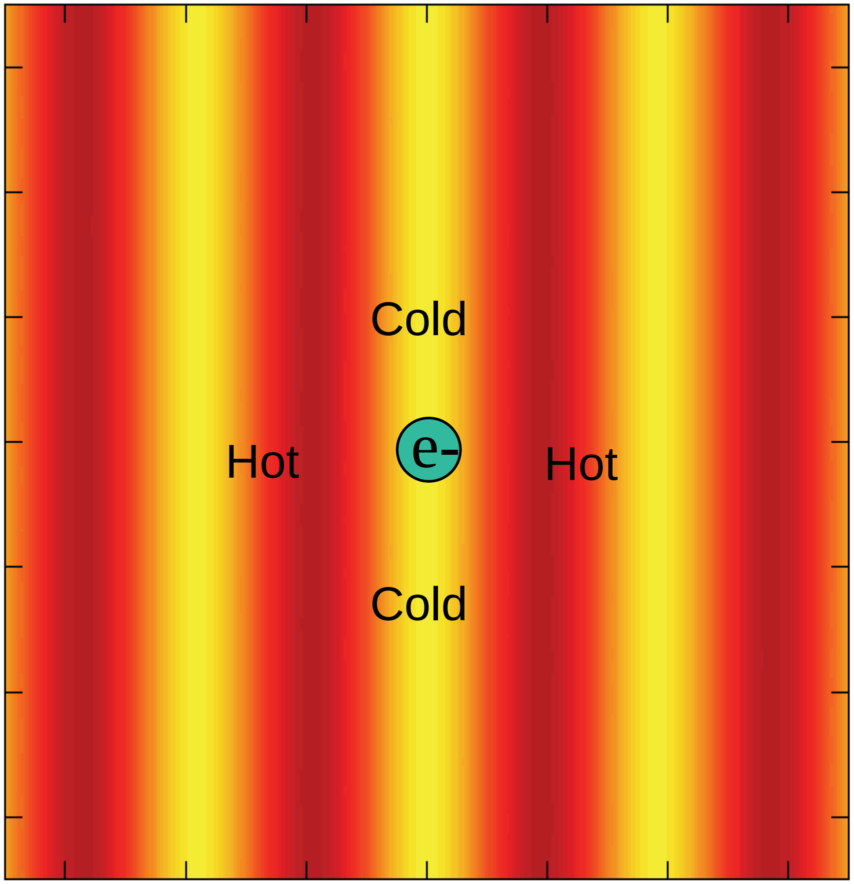

photo: Keith Vanderlinde



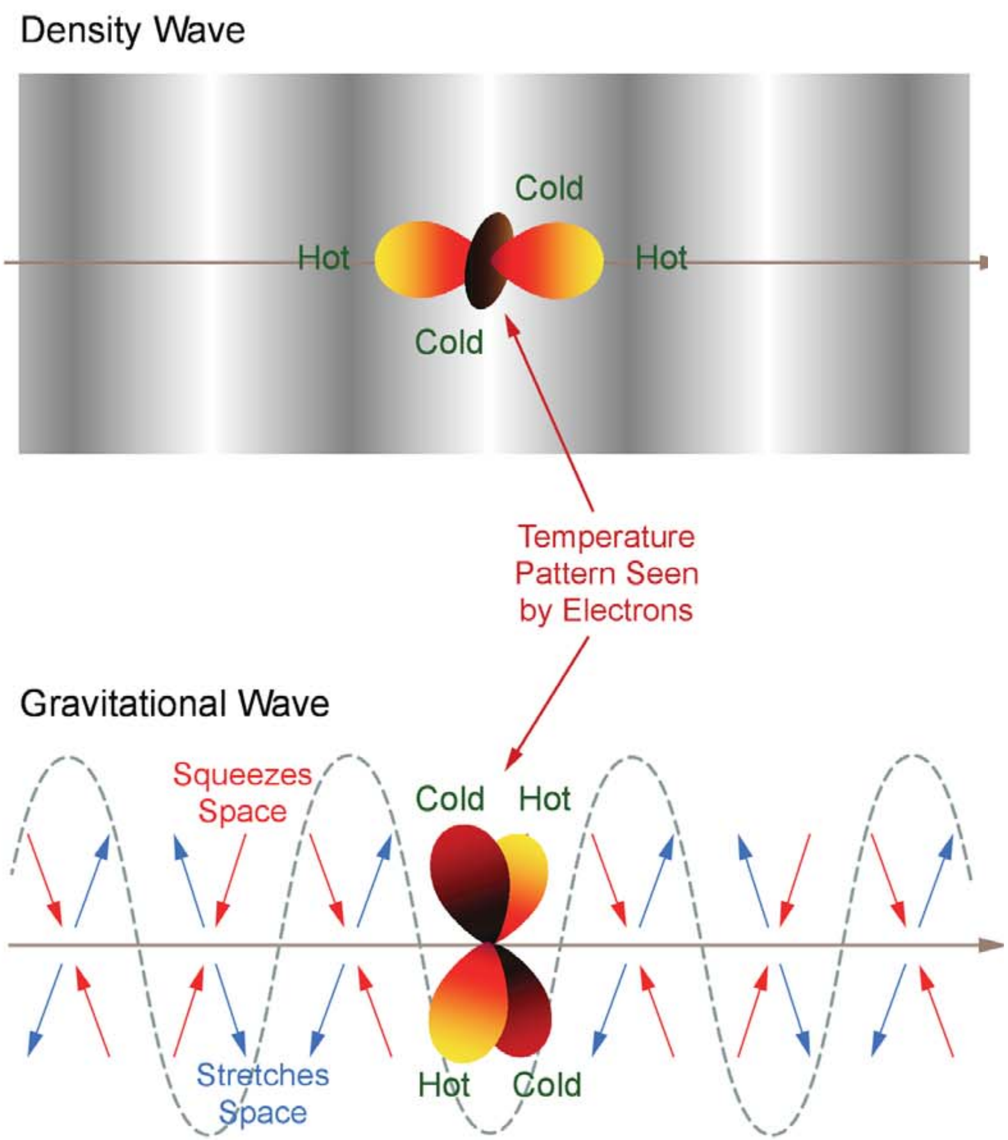
History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^-32 s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

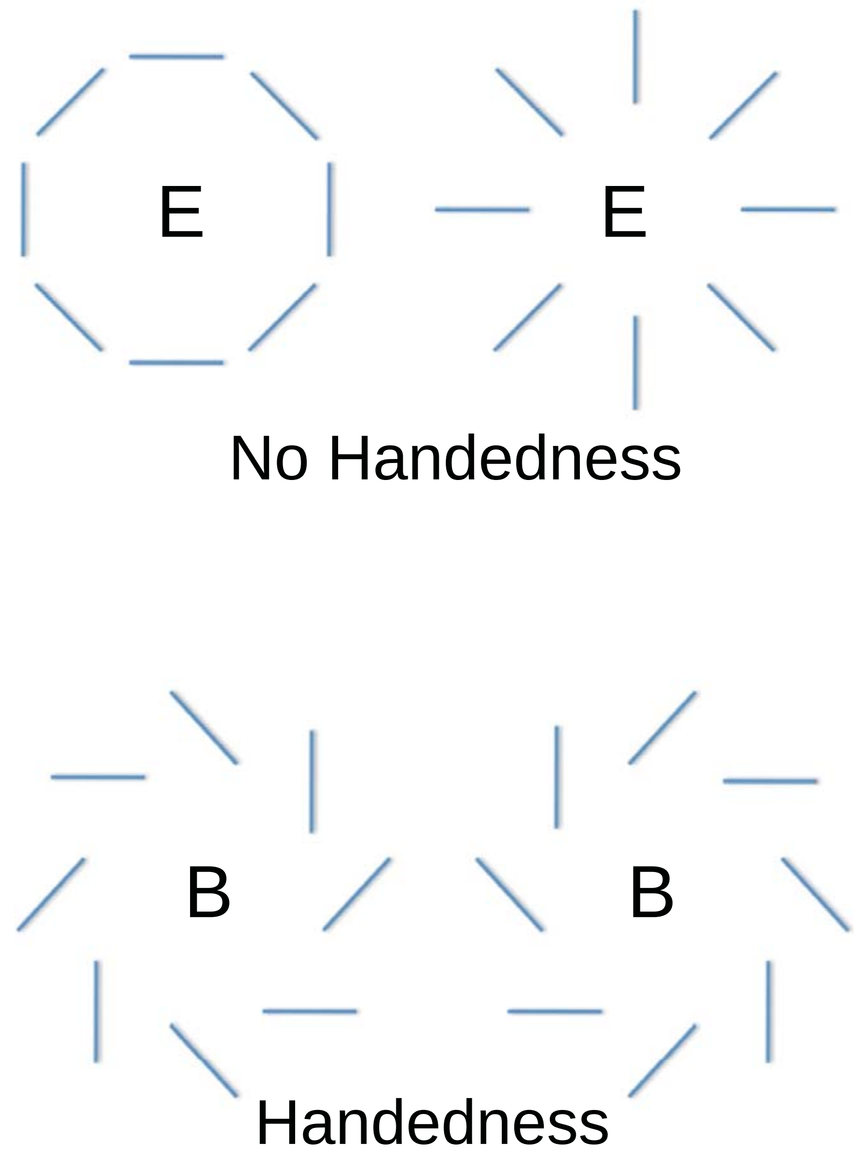
Why is the CMB Polarized?

- Thomson scattering cross section depends on polarization
- Quadrupole anisotropy (as seen by electron) @ last scattering → net linear polarization



E-Modes & B-Modes

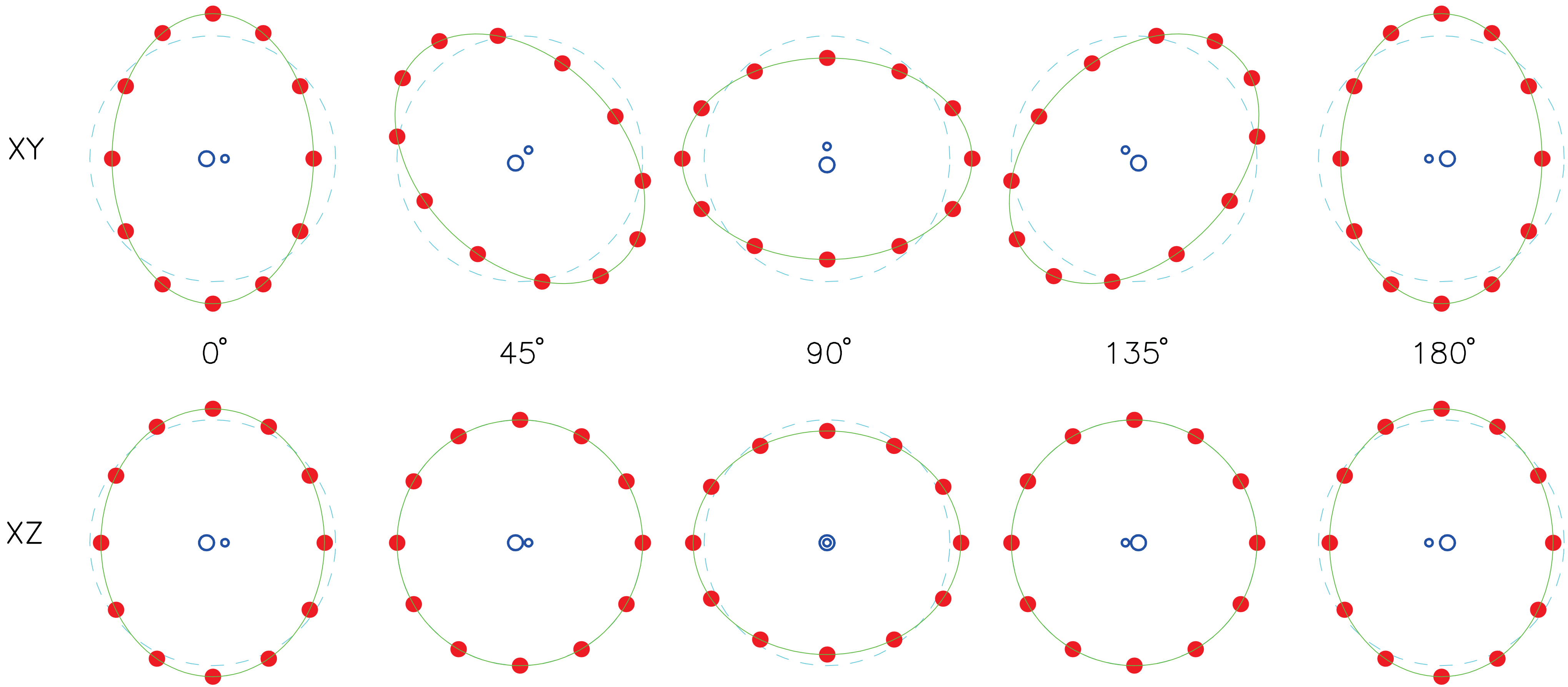




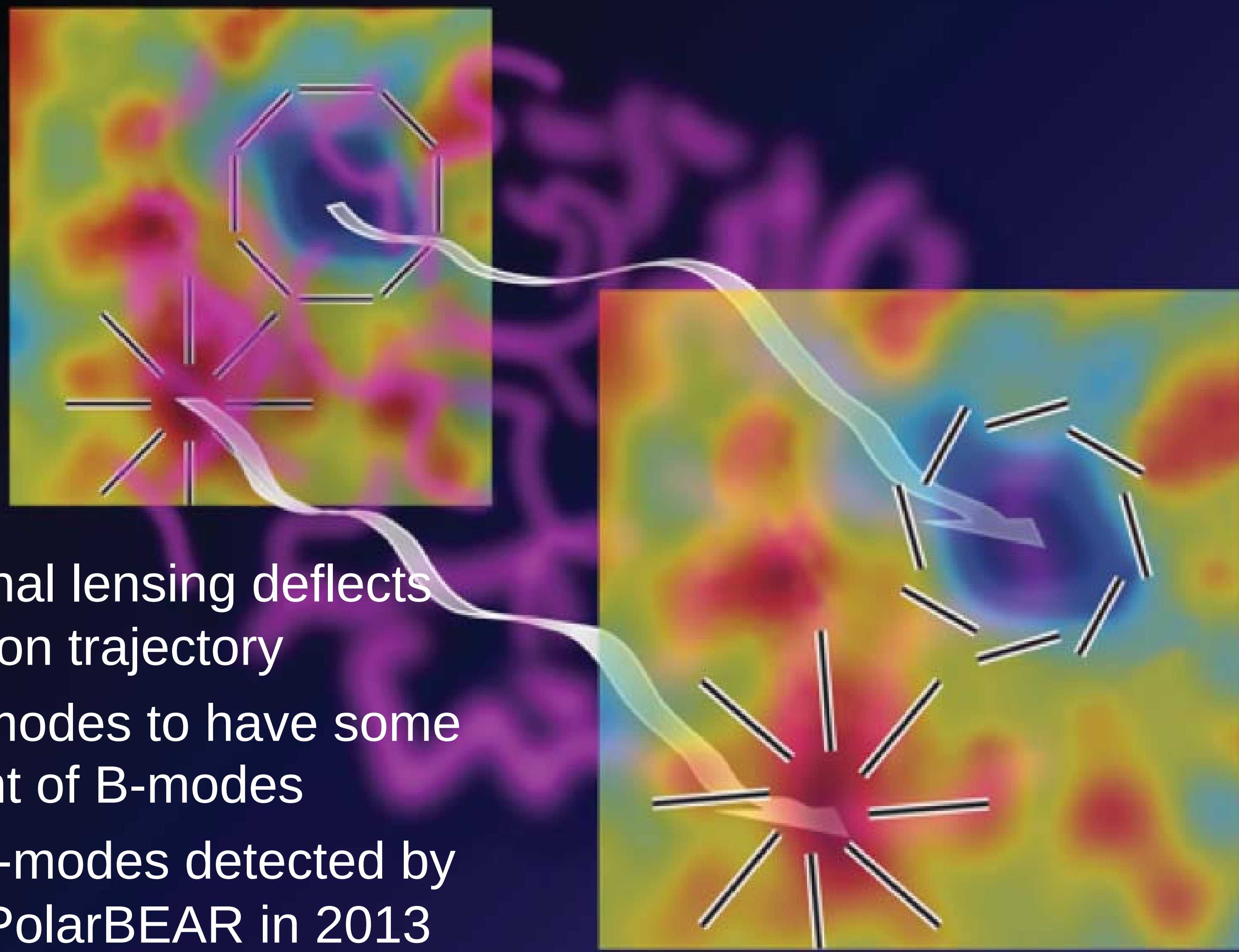
E mode can be generated by density perturbations and by gravitational waves

B mode can be generated only by gravitational waves or by gravitational lensing

Gravitational waves from orbiting double-star



Gravitational Lensing: Converting E to B



- Gravitational lensing deflects CMB photon trajectory
- Twists E-modes to have some component of B-modes
- Lensing B-modes detected by SPT and PolarBEAR in 2013

$$\hat{n} \rightarrow \hat{n} + \nabla\phi(\hat{n})$$

Features of the CMB Spectrum

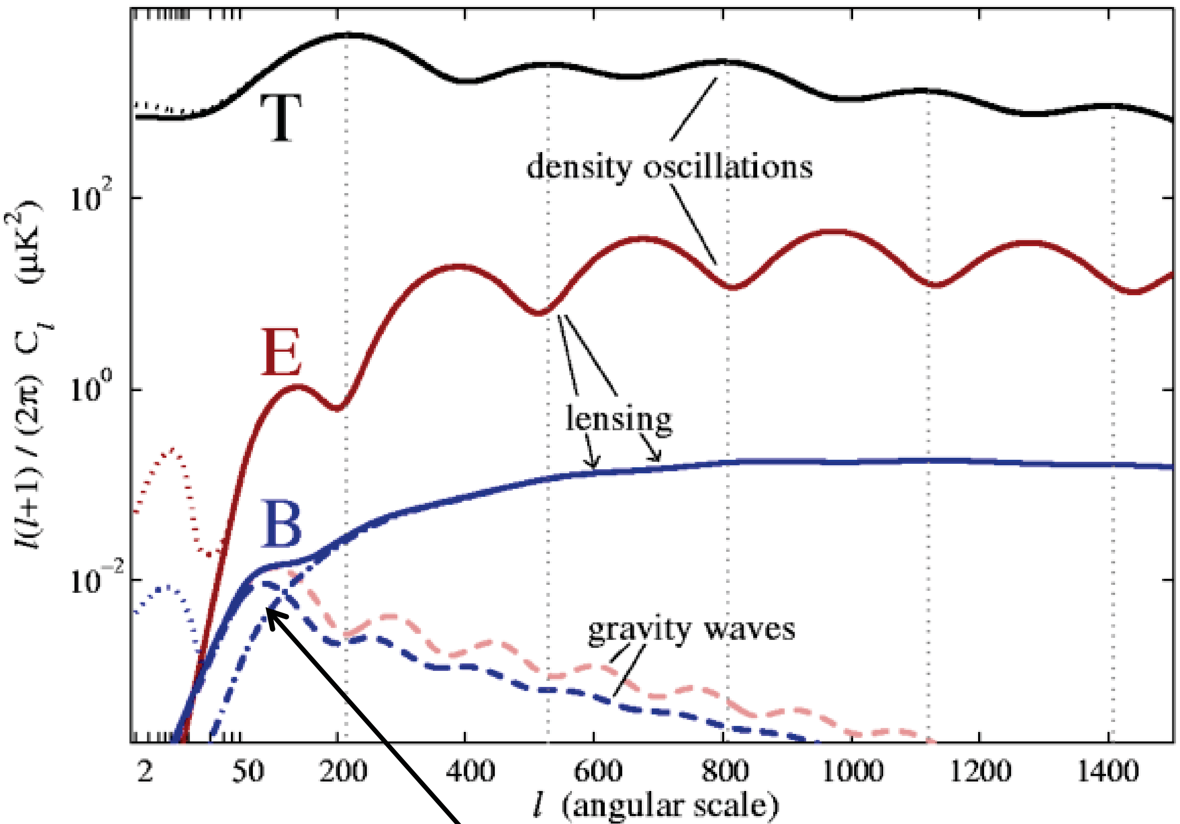
Temperature spectrum traces density evolution of acoustic oscillations in early universe.

E-polarization spectrum (first measured by DASI, Kovac et al. 2002) :

- 10^2 lower
- correlated with T
  but out of phase

B-polarization spectrum:

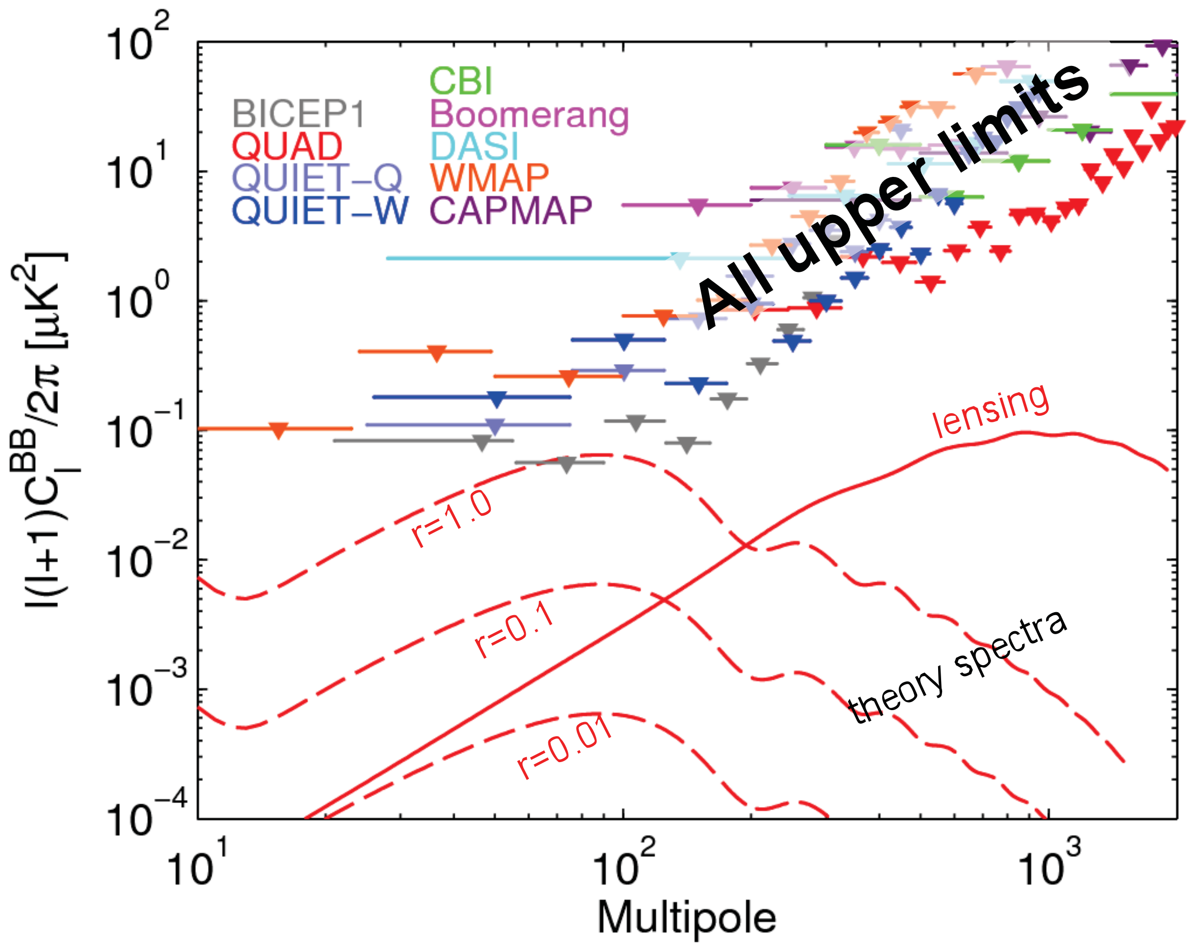
- 10^2 - 10^3 lower still!
- gravitational waves:
  large angular scale
- lensing: small angular scale



reasonable GUT-scale inflation models

B-modes are a teeny signal! Hard to detect!

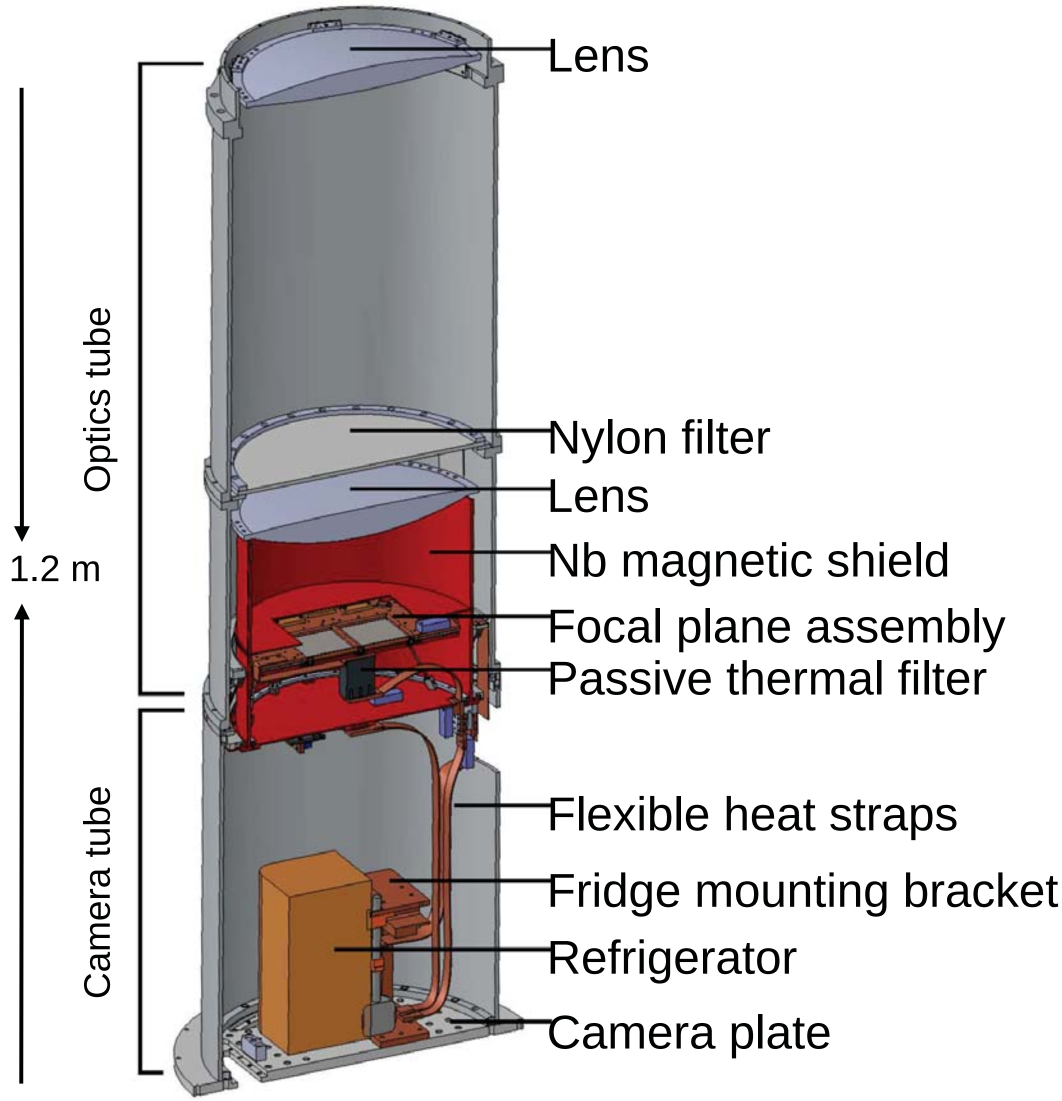
The Hunt for B-modes

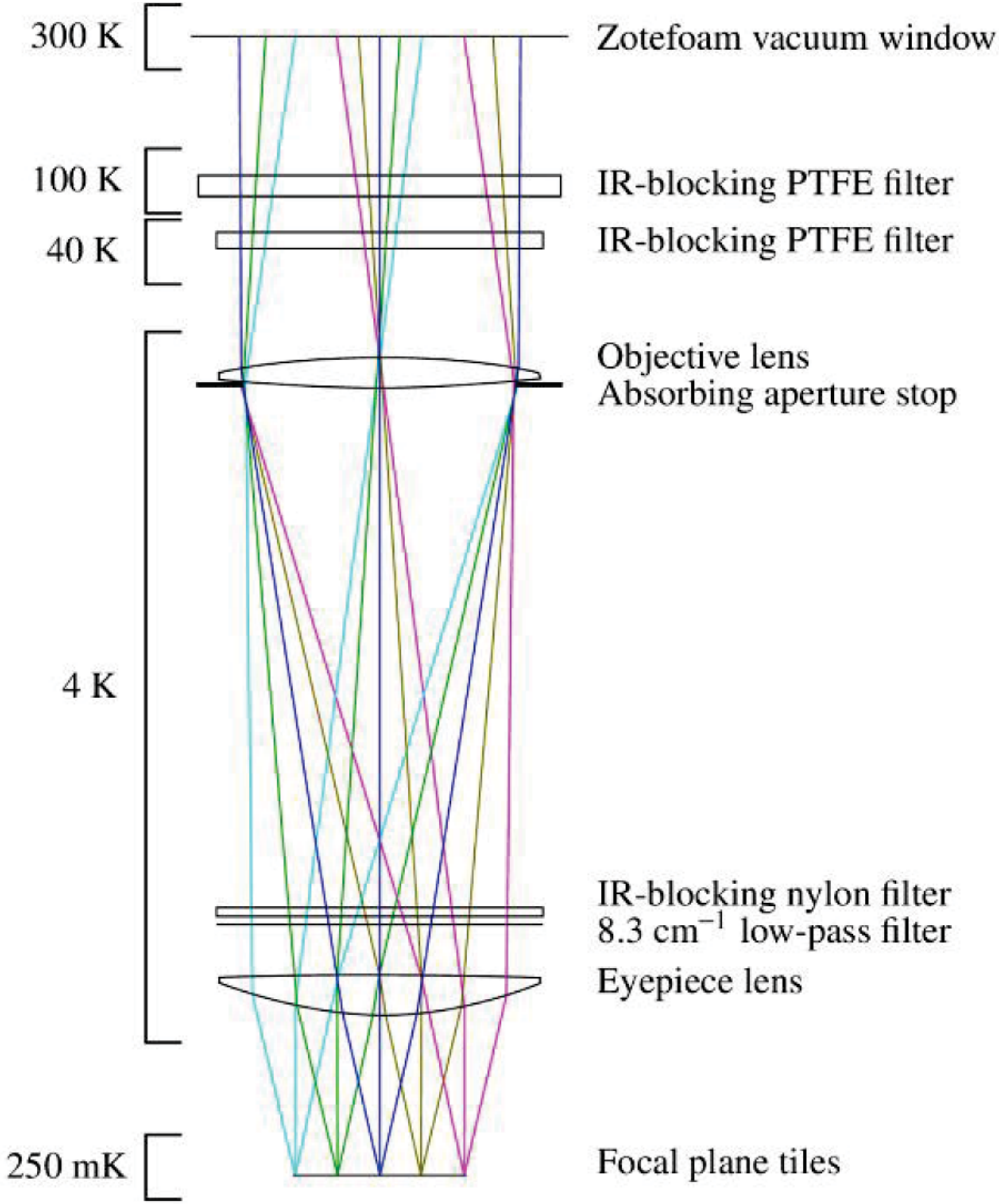


- Characterize the strength of the inflationary signal by the tensor-to-scalar ratio, **r**
- Up to now: upper limits from searches for B-modes
  - Best limit on **r** from BICEP1: **r < 0.7 (95% CL)**
- At high multipoles, lensing B-mode signal dominant

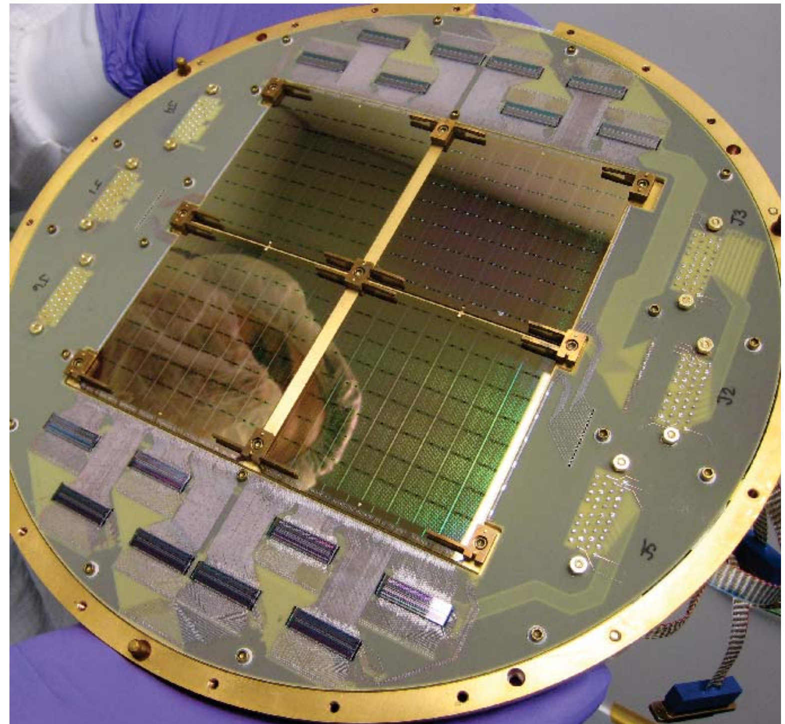
The BICEP2 Telescope

- Cold (4K), on-axis, refractive optics
- 12” aperture → 0.5 degree beams
- Compact telescope for tight systematics control and ability to rotate around optical axis
- Detectors cooled to 250 mK using a helium sorption refrigerator




300 K
Zotefoam vacuum window
100 K
IR-blocking PTFE filter
40 K
IR-blocking PTFE filter
Objective lens
Absorbing aperture stop
4 K
IR-blocking nylon filter
8.3 cm^{-1} low-pass filter
Eyepiece lens
250 mK
Focal plane tiles

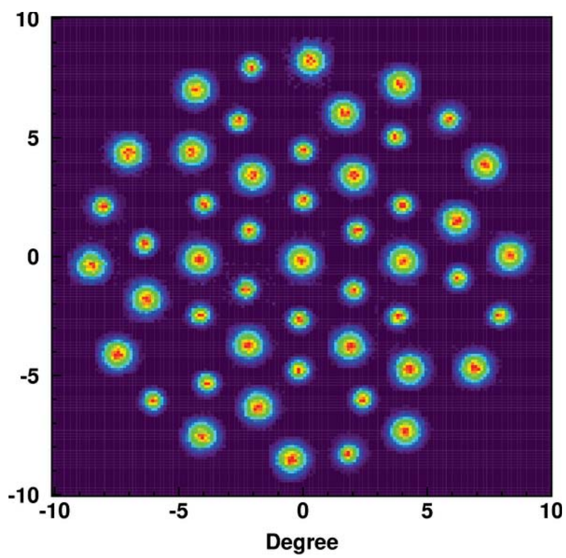
BICEP2: 10-fold increase in mapping speed:

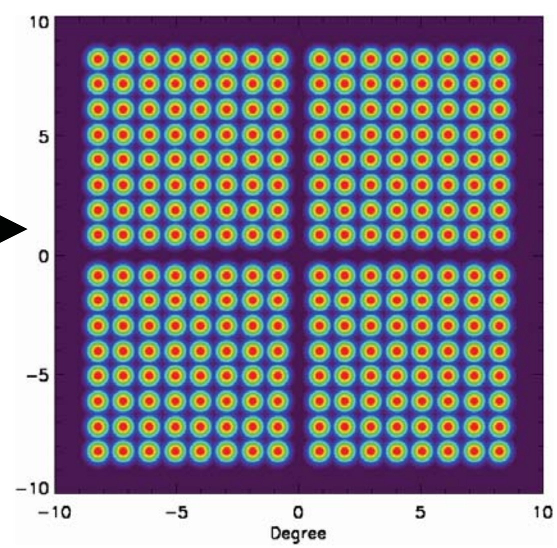


JPL : antenna-coupled TES arrays

BICEP1

48
150 GHz
detectors

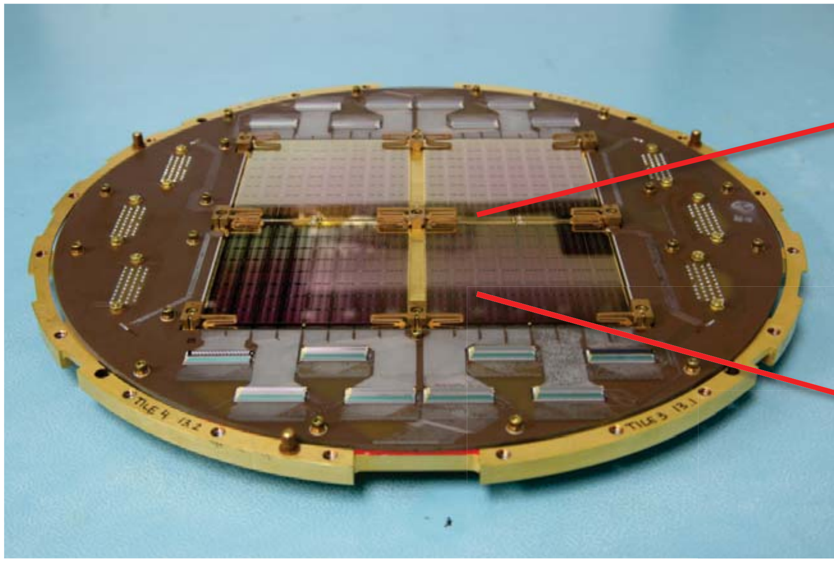


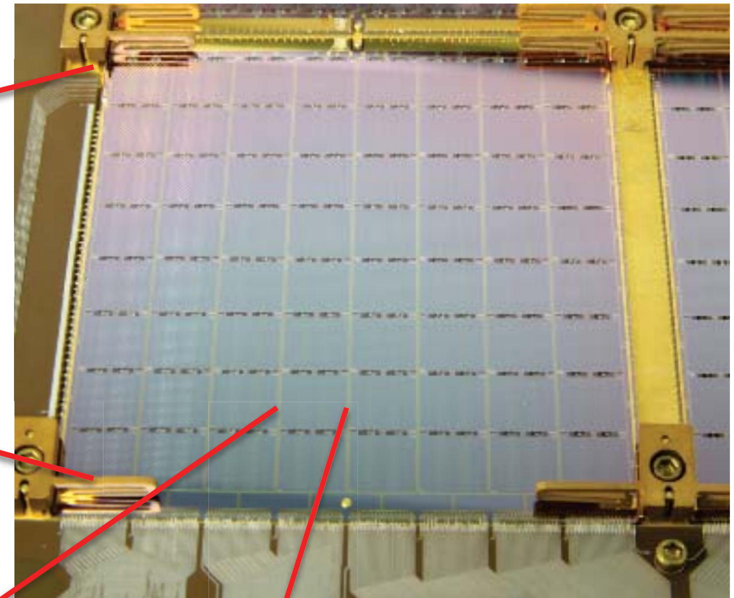


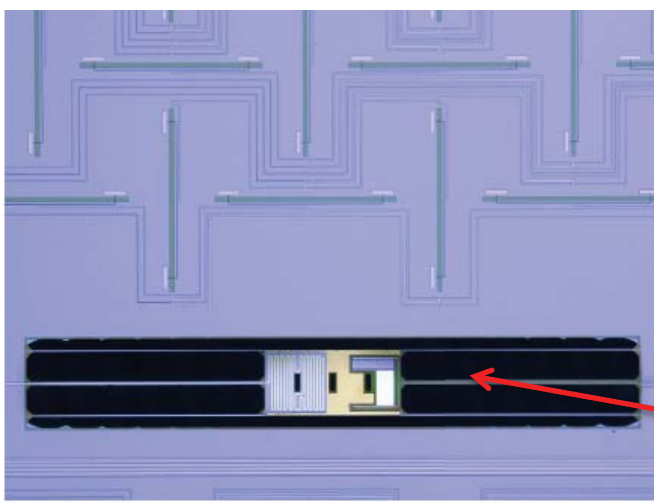
BICEP2

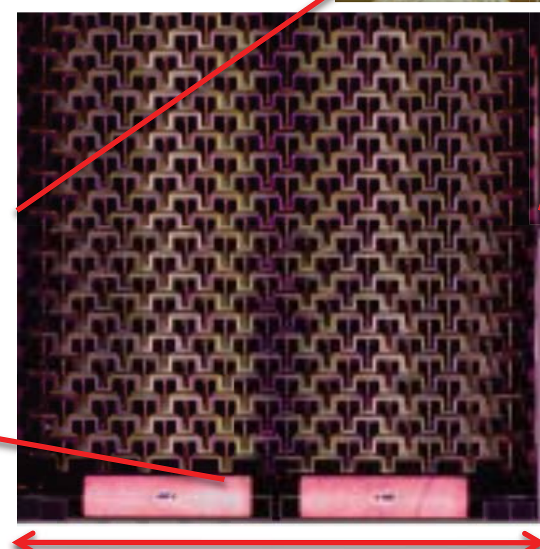
512
150 GHz
detectors

Anatomy of A BICEP2/Keck Focal Plane



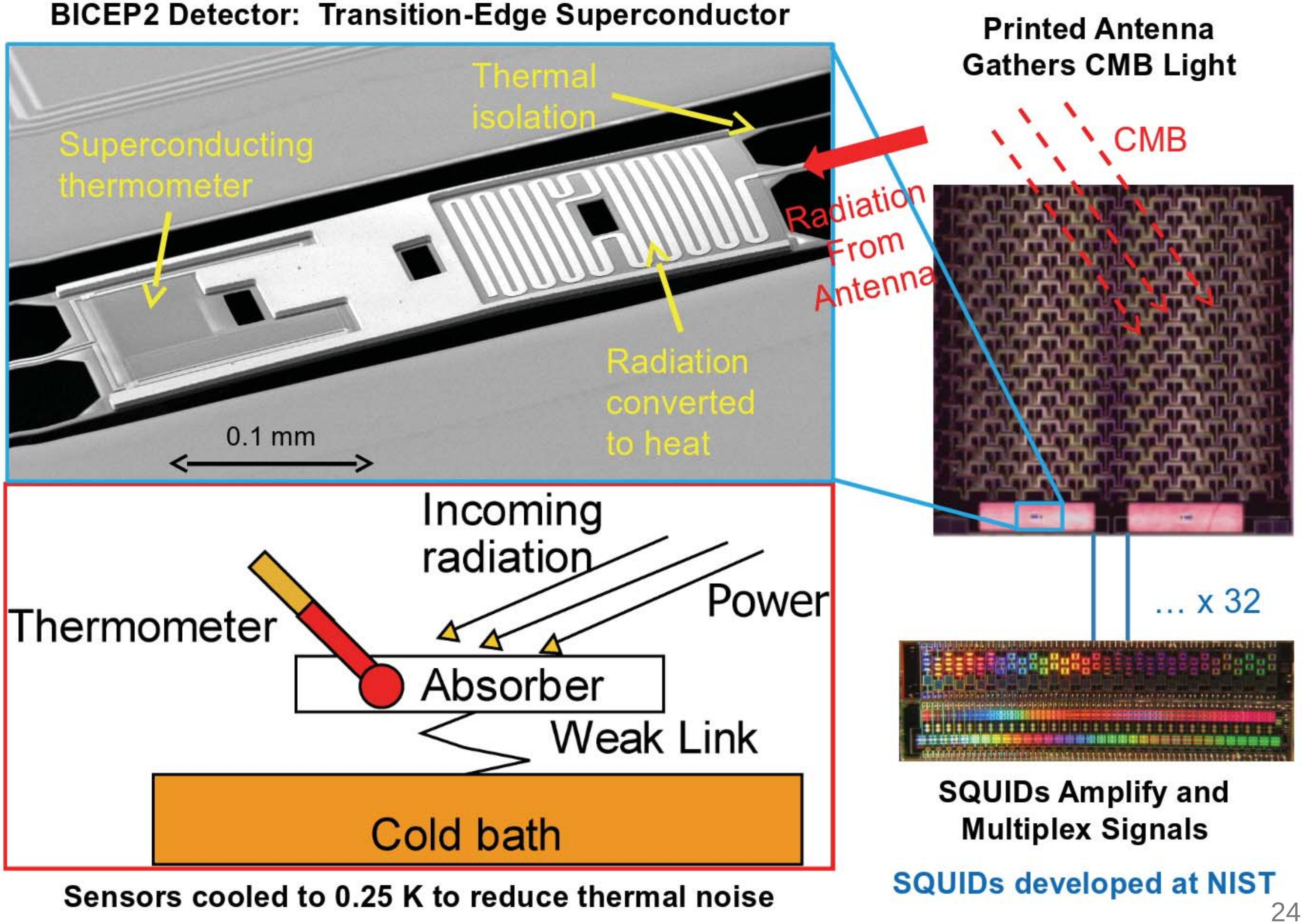






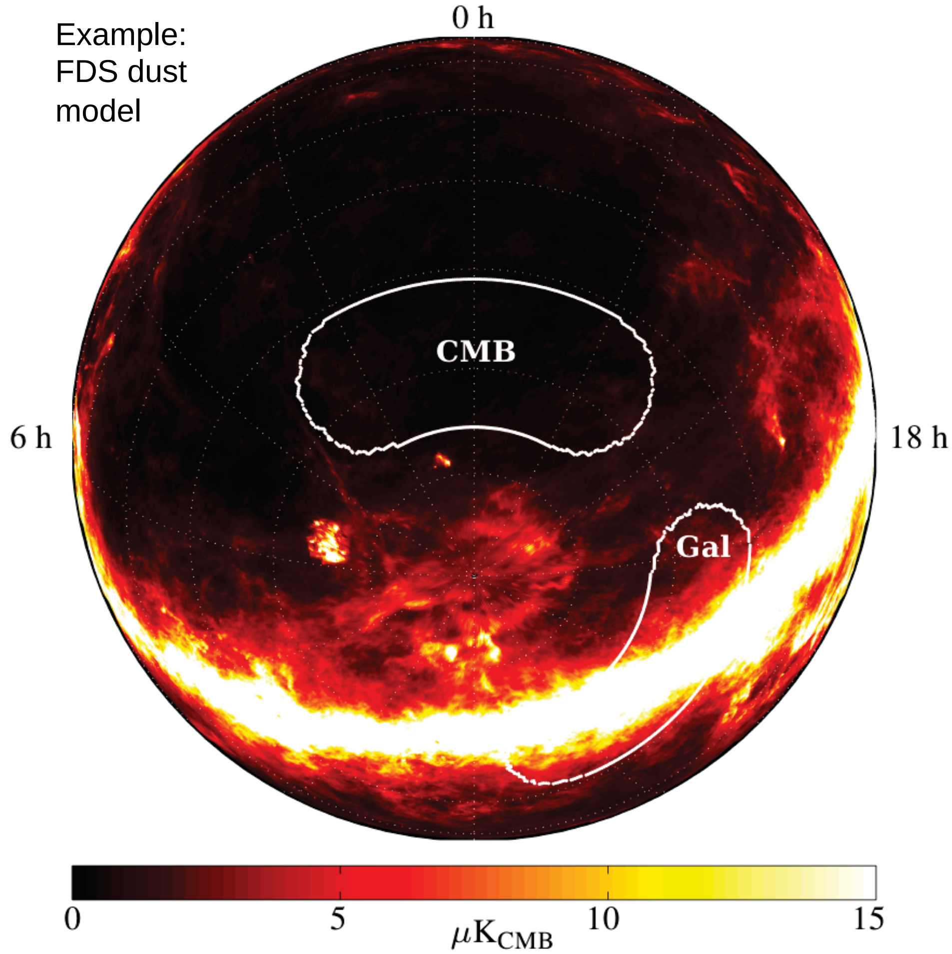
- 256 pixels per focal plane
- Slot antenna array per polarization per pixel
- Ti Transition Edge Sensor (TES) Bolometers

Detecting CMB Radiation



Observational Strategy

Example: FDS dust model



Target the "Southern Hole" – an exceptionally clean region of the sky

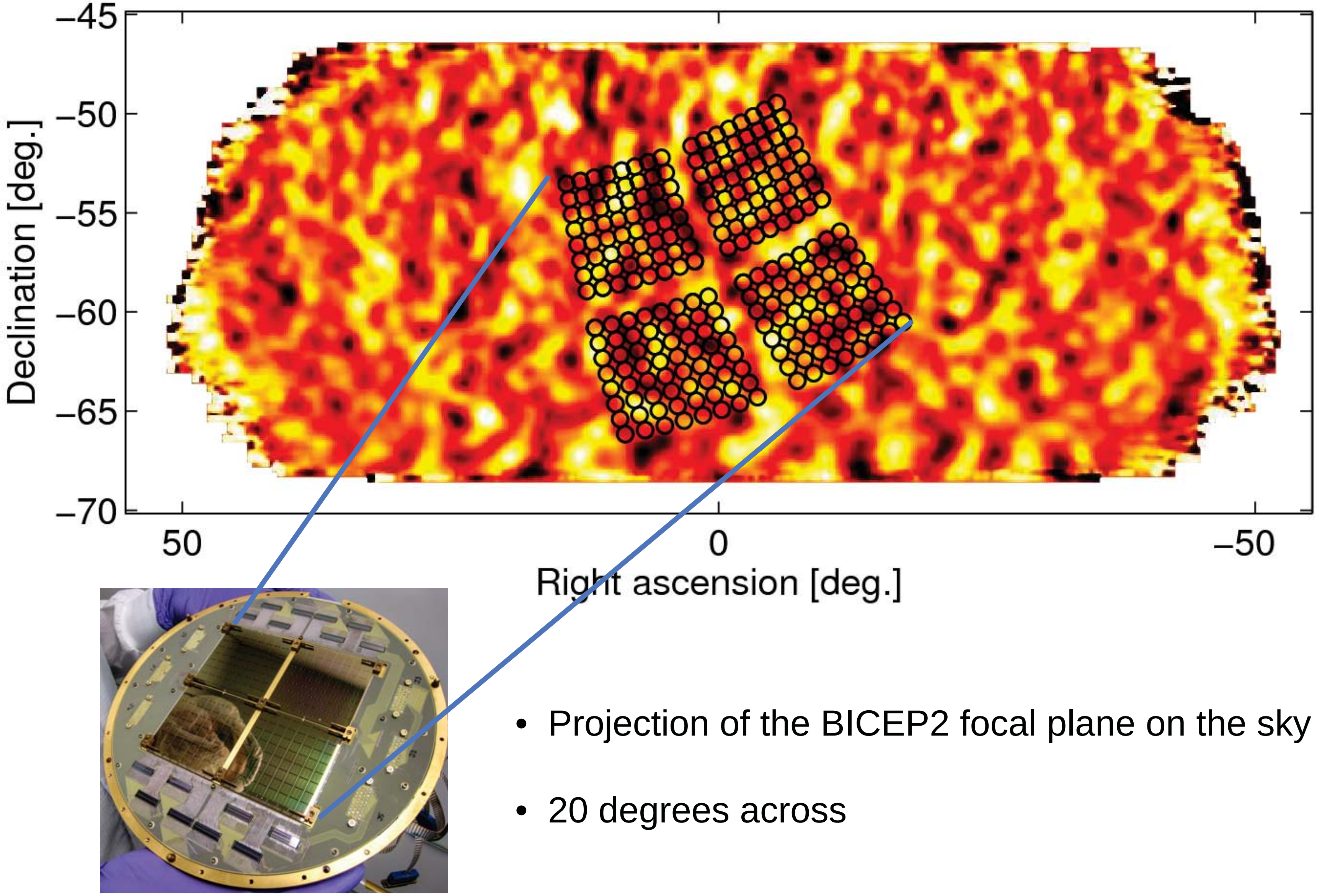
Observe @ 150 GHz until you see B-modes

→ Near peak of CMB spectrum

→ Dust + synchrotron predicted to be at a minimum

Expected foreground contamination of the B-mode power: r ≤ ~0.01

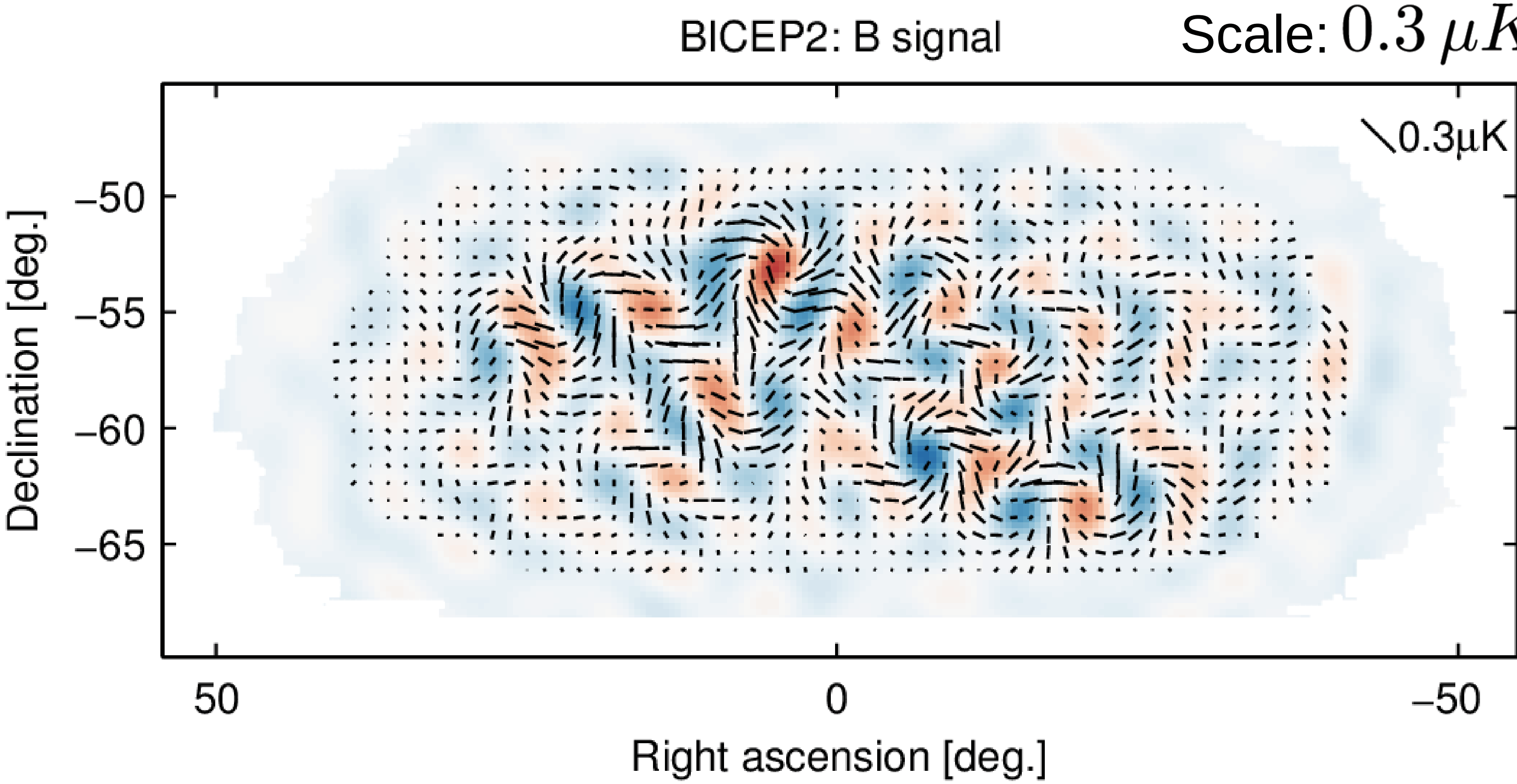
BICEP2 on the Sky



- Projection of the BICEP2 focal plane on the sky
- 20 degrees across

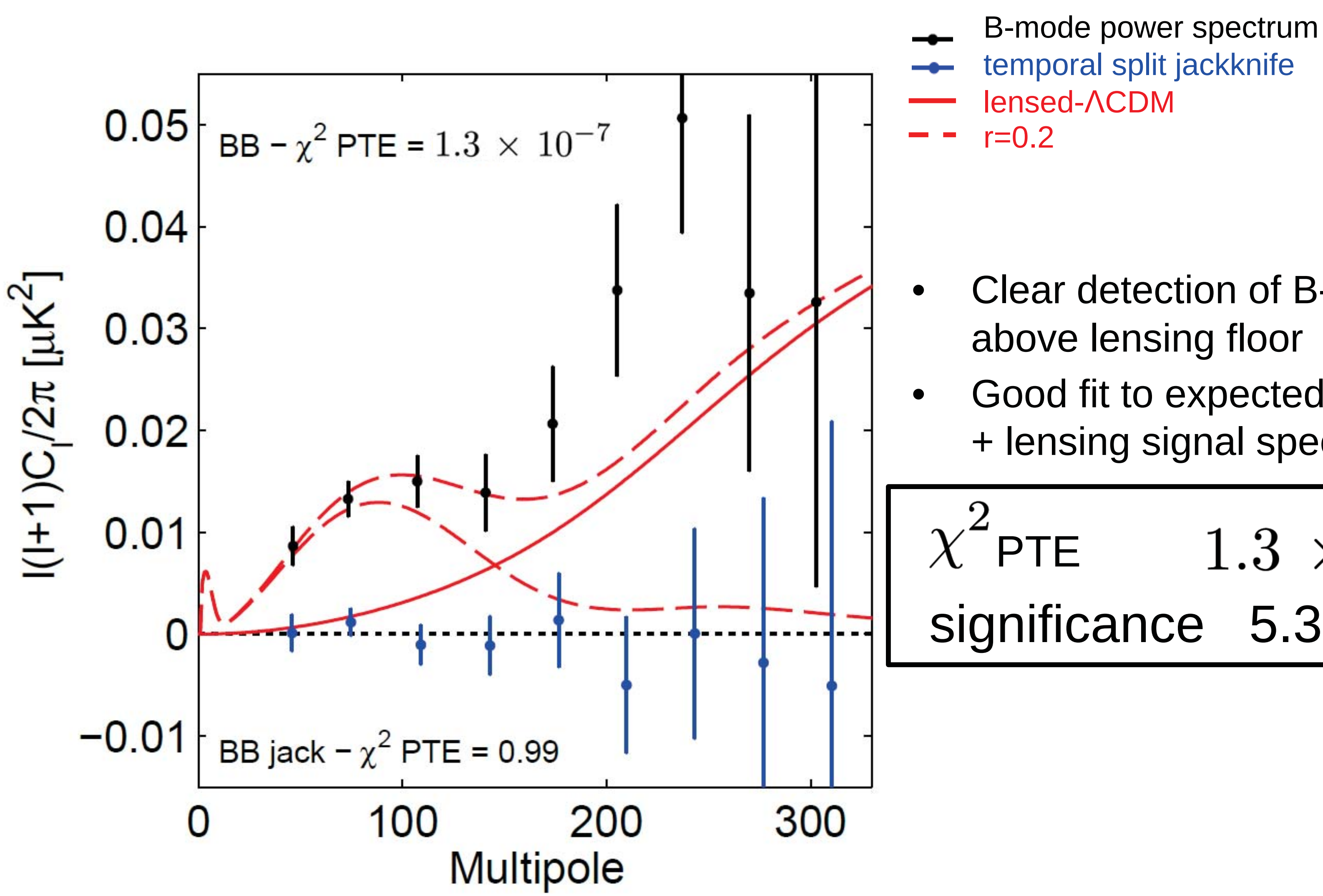
B-mode Contribution

Scale: $0.3\ \mu K$



B-modes of **r** = 0.1 contribute ~1/10 of the total polarization amplitude at ℓ=100

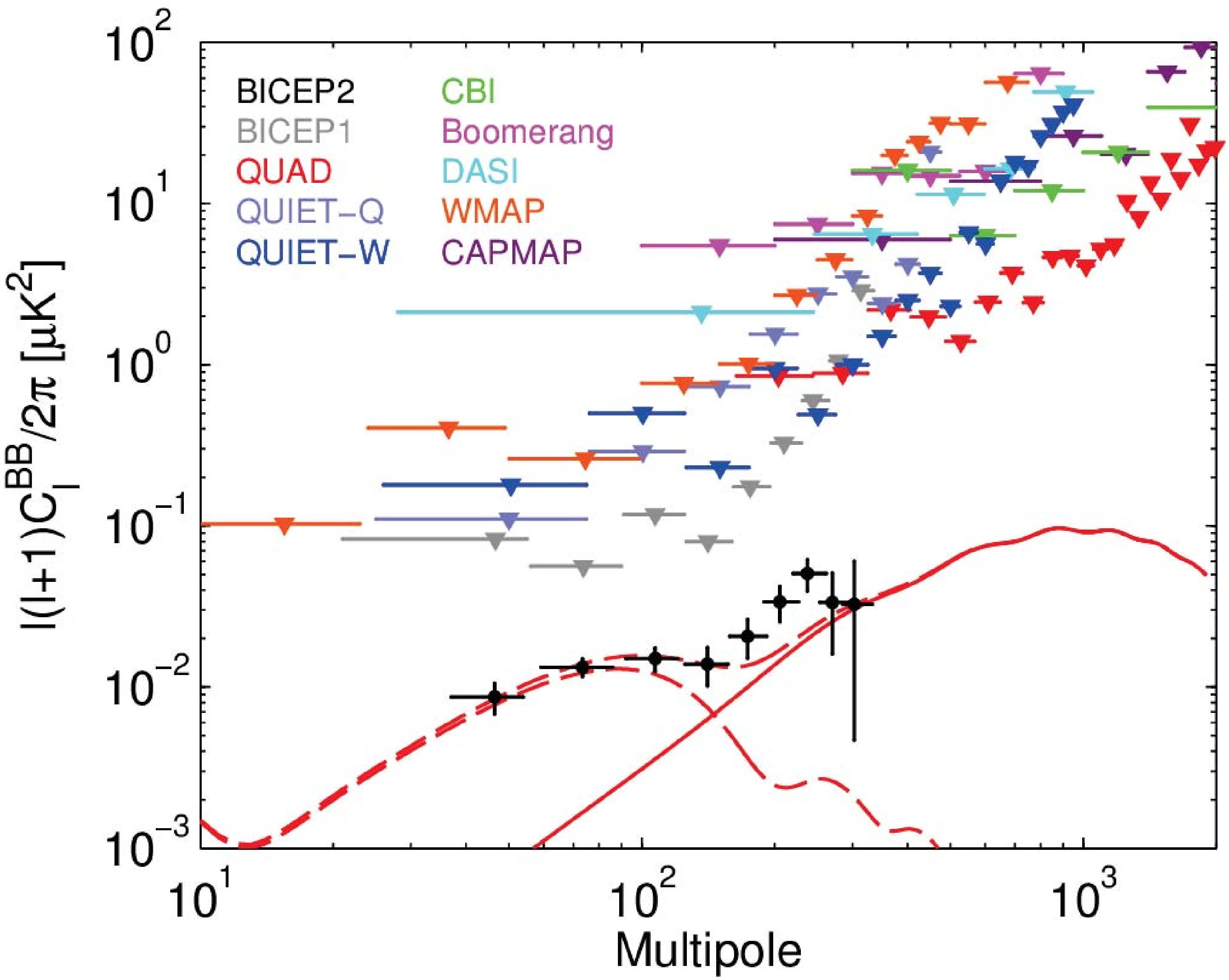
BICEP2 B-mode Power Spectrum



- Clear detection of B-modes above lensing floor
- Good fit to expected inflationary + lensing signal spectrum

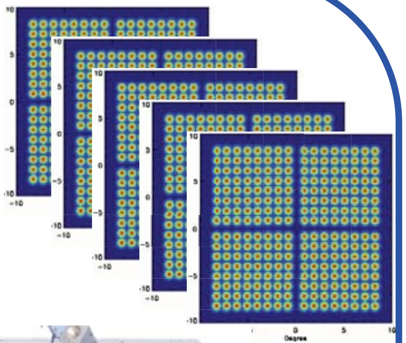
χ^2 PTE	1.3×10^{-7}
significance	5.3σ

BICEP2 Results



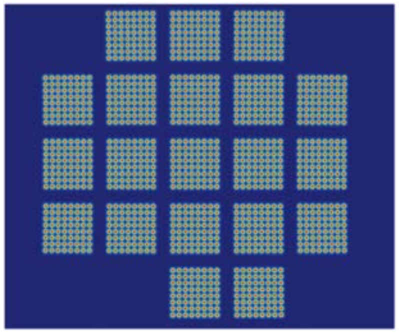
What comes next for us?

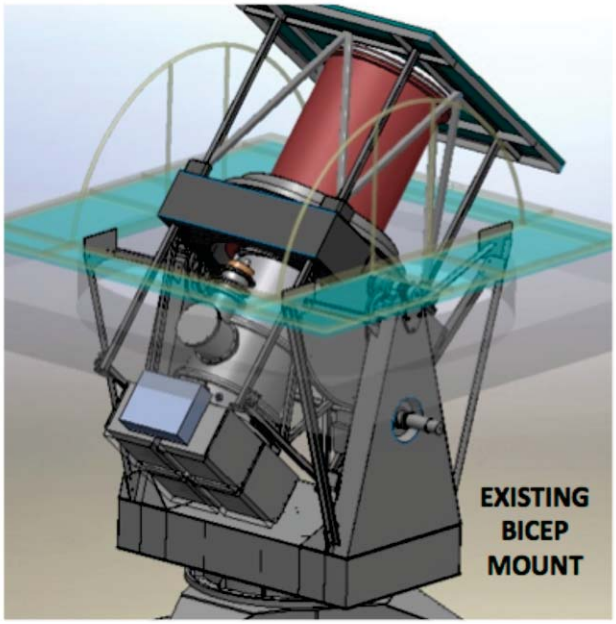
Keck Array
3 x deployed Jan 2011
2 x deployed Jan 2012
5 Years of Observation



5 x 512 @ 150 GHz (2012-2013)
Upgraded 2014: 2 x 512 @ 100 GHz

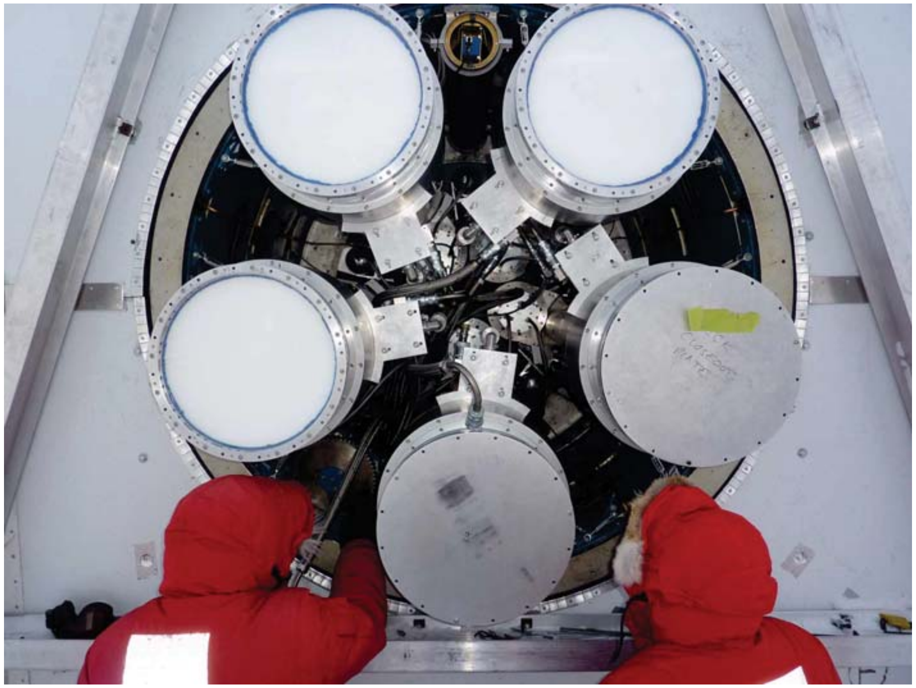
BICEP3
Will Deploy in 2014

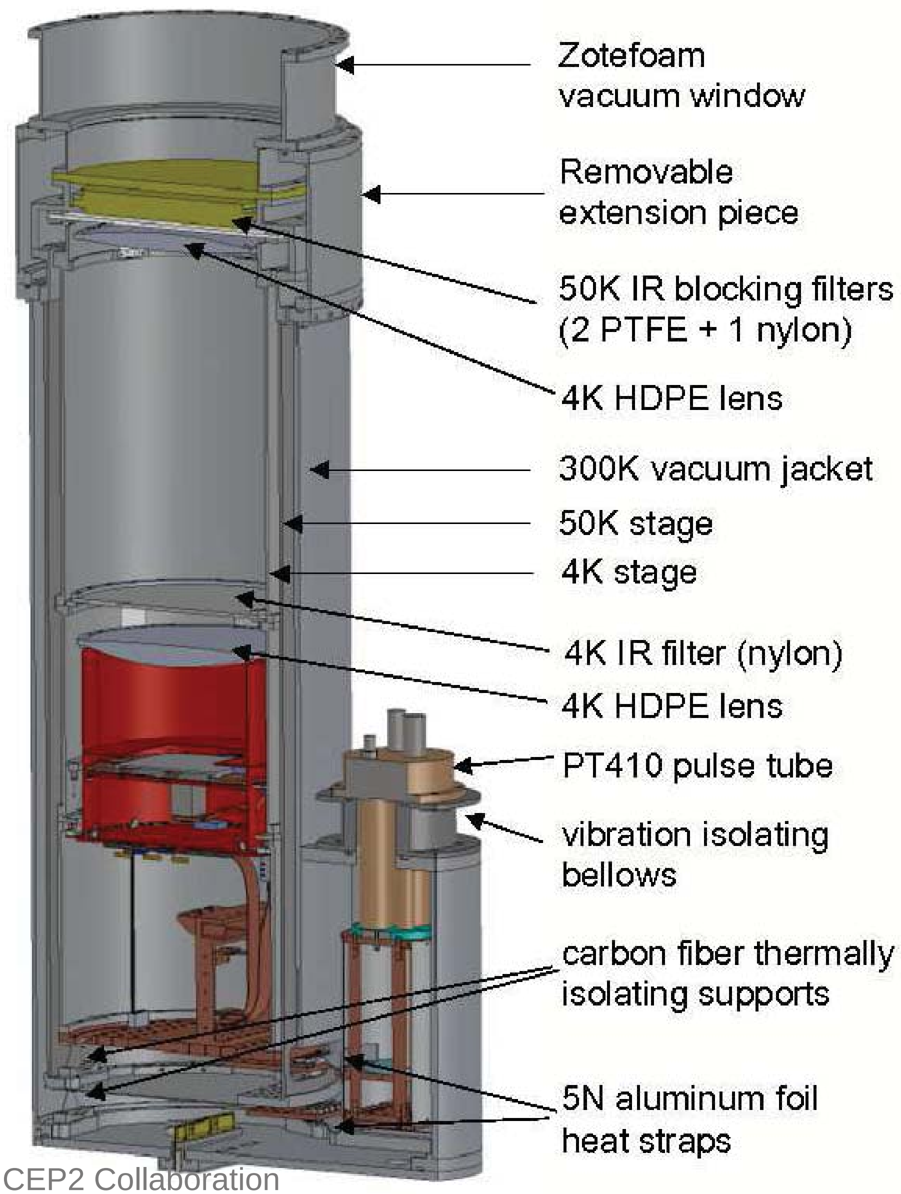




2056 @ 100 GHz

The Keck Array (2011 -)



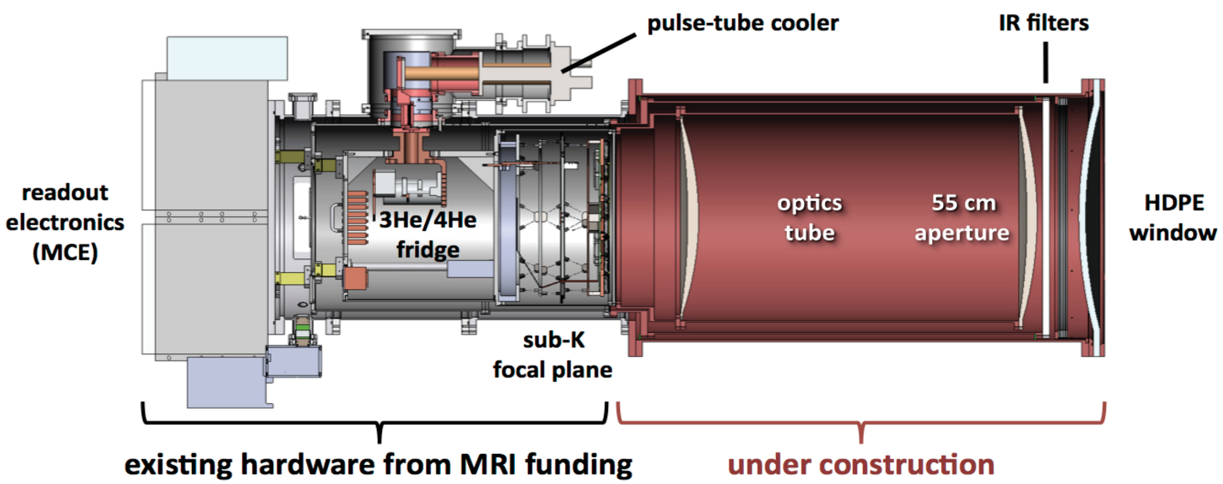


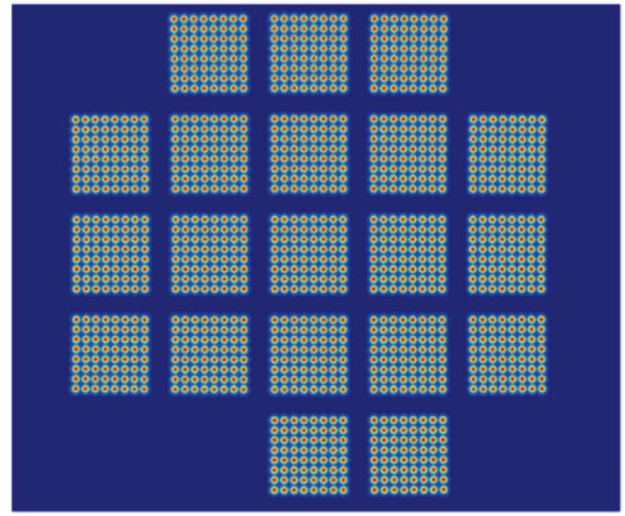
- 5x BICEP2
- New: pulse tube coolers
- 2012-13: 5 @ 150 GHz


Winter Overs:
Robert Schwarz
and Steffen Richter

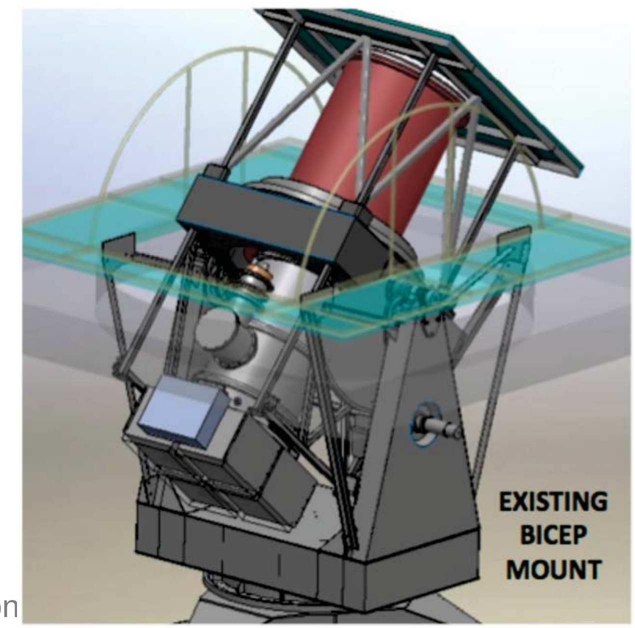
BICEP3 (2015 -)

Will deploy in December 2014: 2056 Detectors @ 100 GHz

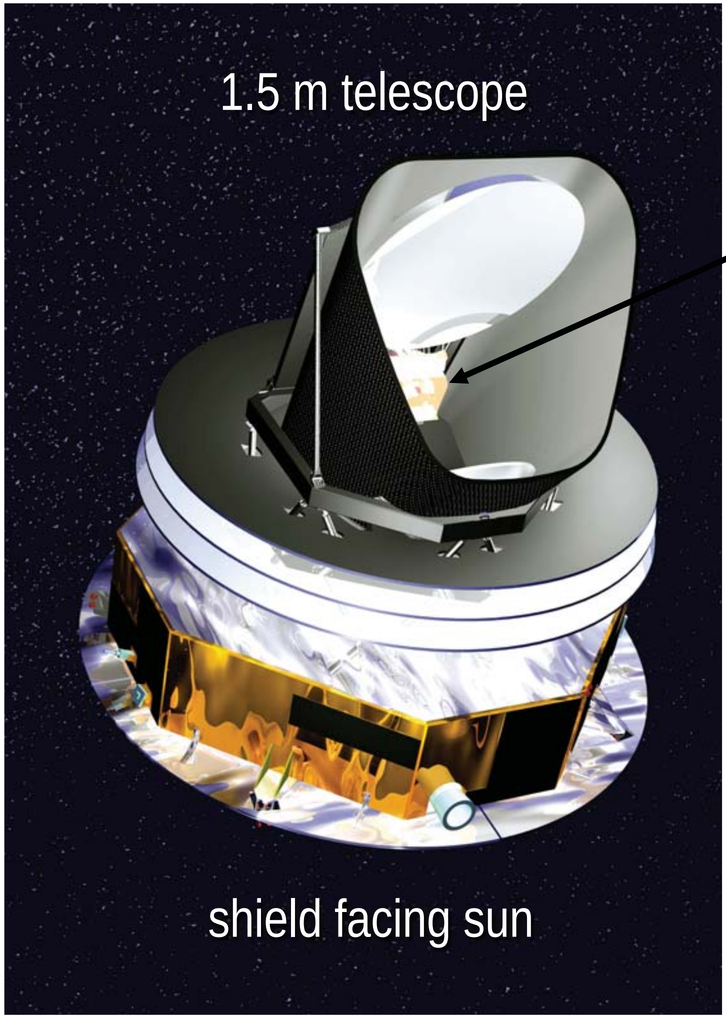




- Larger aperture, faster optics → 10x BICEP2's optical throughput
- Doubles the program's survey speed
- Important for foreground separation



The Planck satellite



2 instruments:

- LFI (led by Italy)
  - HEMTs (transitors)
  - cooled at 20K
  - sensitive to 30-100 GHz

- HFI (led by France/UK)
  - bolometer array
  - cooled at 0.1K
  - sensitive to 100-857 GHz

The Planck satellite

- Launched by ESA and placed in L2 orbit in 2009. Full scan every 6 month.
- 75 detectors cover 9 frequency channels

- Planck strengths: large and redundant sky coverage, number of channels & detectors, low detector noise (25 x better than WMAP). Resolution intermediate between WMAP (3 x better) and ACT, SPT.

- HFI requires complex cryogenic cooling at 0.1K (dilution of ^3He in ^4He). Designed for > 2 scans, achieved 5. Turned off in Jan 2012 (due to ^3He level).
- LFI requires cooling at 20K with ^4He only and proceeded until few weeks ago (8 scans).

- 2013 release restricted to "nominal mission", 15 months, > 2 scans. Further temperature data + polarization maps differed to 2014 - 2015.