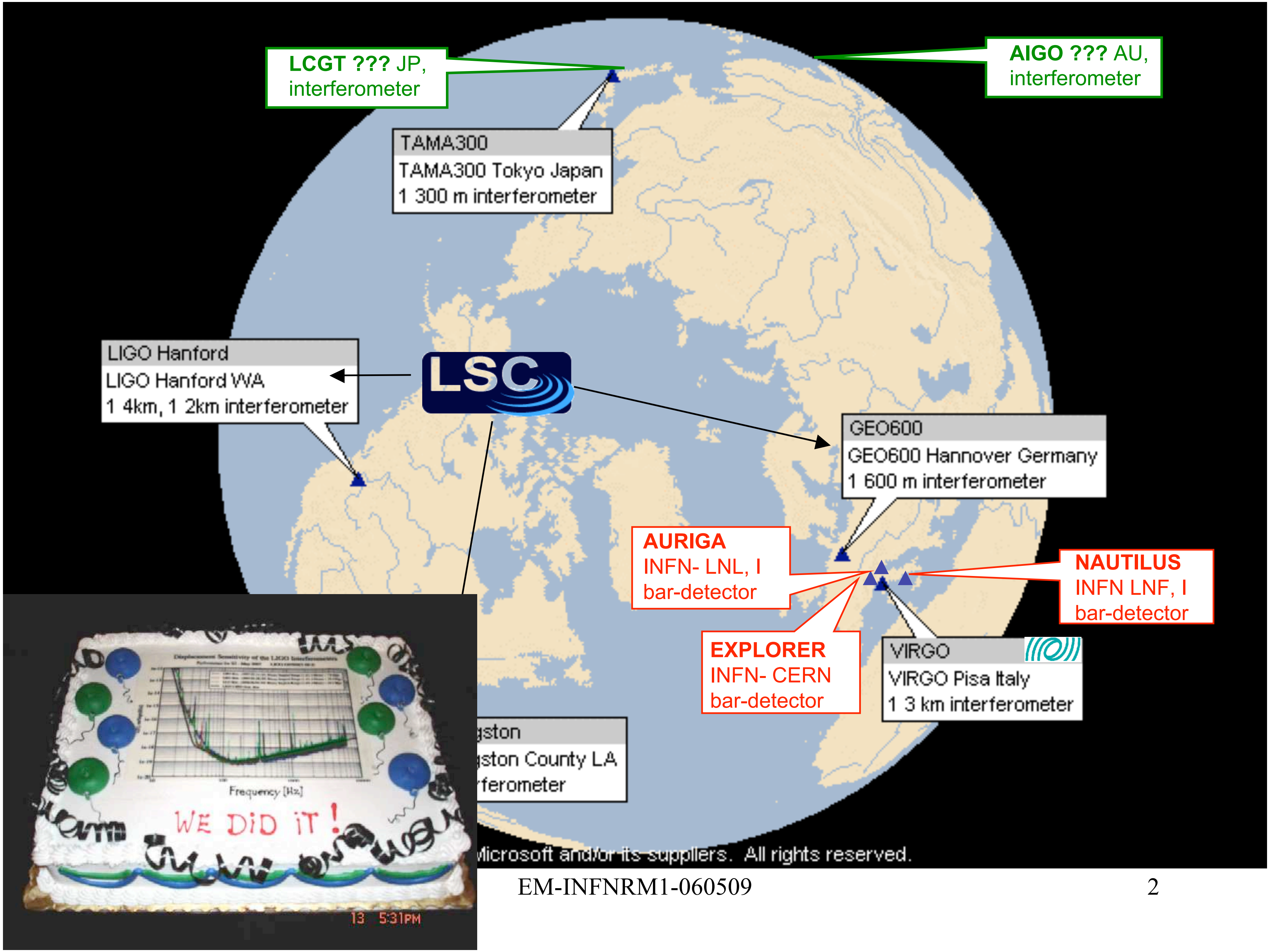
Rivelatori di onde gravitazionali:

prospettive presso la Sezione INFN di Roma

E. Majorana

Roma - 6 Maggio, 2009



LCGT ??? JP, interferometer
AIGO ??? AU, interferometer
TAMA300
TAMA300 Tokyo Japan
1 300 m interferometer
LIGO Hanford
LIGO Hanford WA
1 4km, 1 2km interferometer
LSC
GEO600
GEO600 Hannover Germany
1 600 m interferometer
AURIGA
INFN- LNL, I
bar-detector
NAUTILUS
INFN LNF, I
bar-detector
EXPLORER
INFN- CERN
bar-detector
VIRGO
VIRGO Pisa Italy
1 3 km interferometer
gston
gston County LA
ferometer
Microsoft and/or its suppliers. All rights reserved.
Frequency [Hz]
WE DiD iT !
13 5:31PM

Outline

I) GW detection basics / interferometers

II) VIRGO & Co.

Why ?

advanced VIRGO

Basics: transversal tidal waves

$$R^{\alpha\beta} - \frac{1}{2} g^{\alpha\beta} R = \frac{8\pi G}{c^4} T^{\alpha\beta}$$

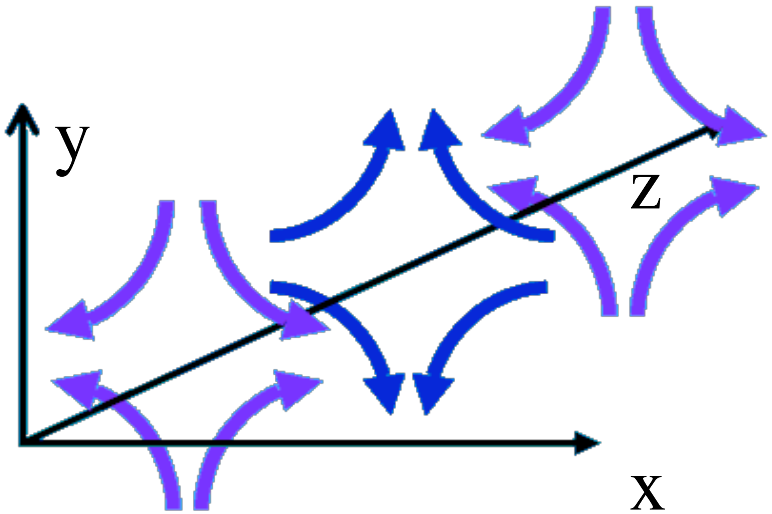
A. Einstein 1916

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta} \qquad \left| h_{\alpha\beta} \right| << 1$$

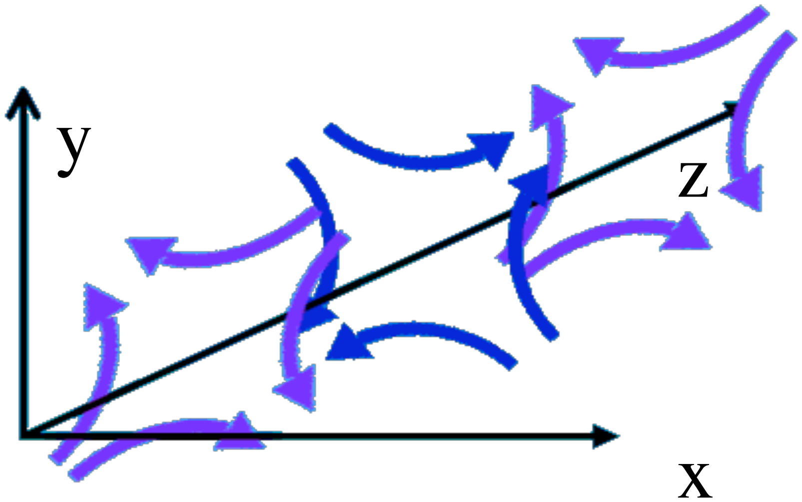
Linearization and gauge choice

$$R^{\alpha\beta} - \frac{1}{2} g^{\alpha\beta} R = -\frac{\Box h^{\alpha\beta}}{2}$$

Wave equation set



$$\hat{k} = \hat{z}$$

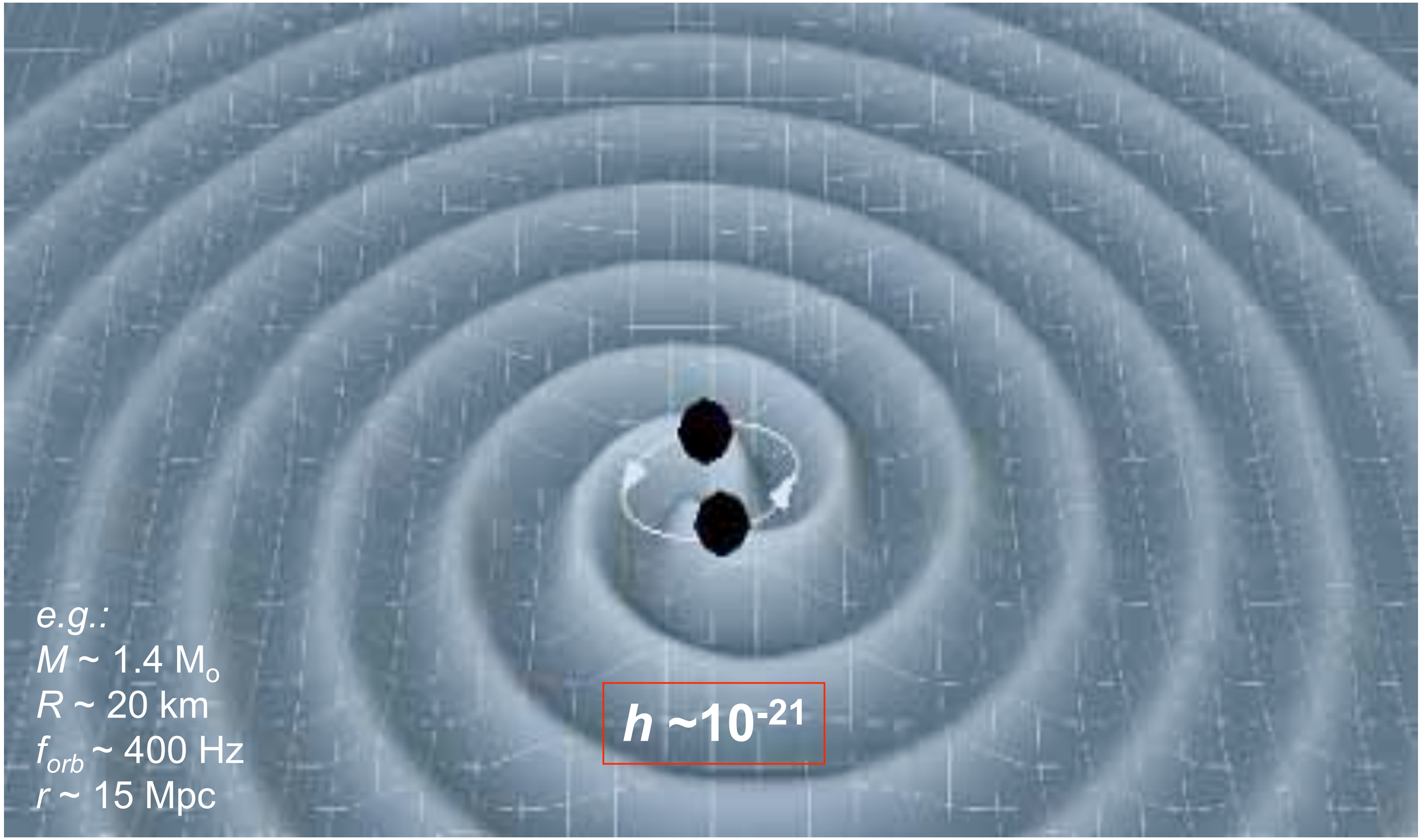


Basics: energetics

$$L = \frac{G}{5c^5}\left|\dddot{Q}_{\mu\nu}\right|^2$$

$$h_{\mu\nu} = \frac{2G}{c^4}\frac{1}{r}\ddot{Q}_{\mu\nu}$$

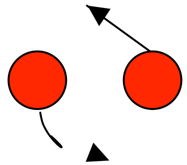
Very weak interaction with matter
=> astrophysics

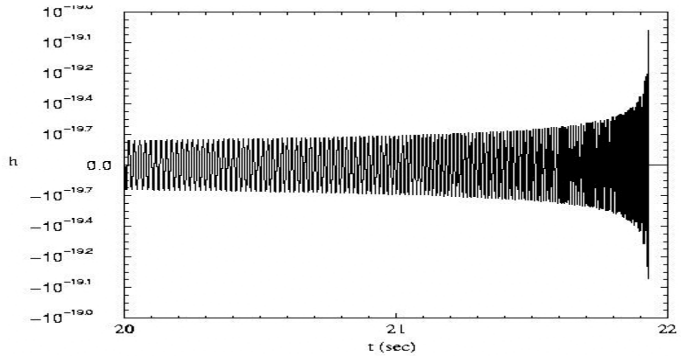


GW sources

1) Coalescing Binary Systems: NS and Black Holes

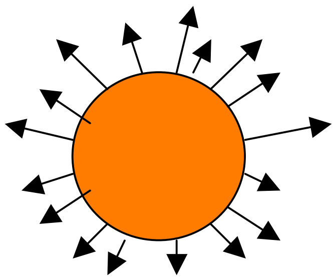
Event rate:
1~2/year in a 50Mpc sphere





2) Supernovae Explosions

Event rate:
The Galaxy (h~10^{-20}) 1/30 years
Virgo Cluster (h~10^{-23}) 1~2/year



if symmetrical: h=0

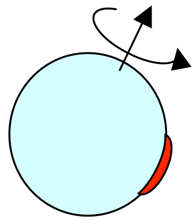
3) Periodic Sources: 10^9 Galactic rotating Neutron Stars emitting in the Hz region

Note: Earth Doppler shift

$$e^{i\omega t} \Rightarrow e^{i\omega(t-\vec{n}\cdot\vec{R}/c)}$$

n **is the NS direction**
R is the Earth radius

h< 10^{-25}

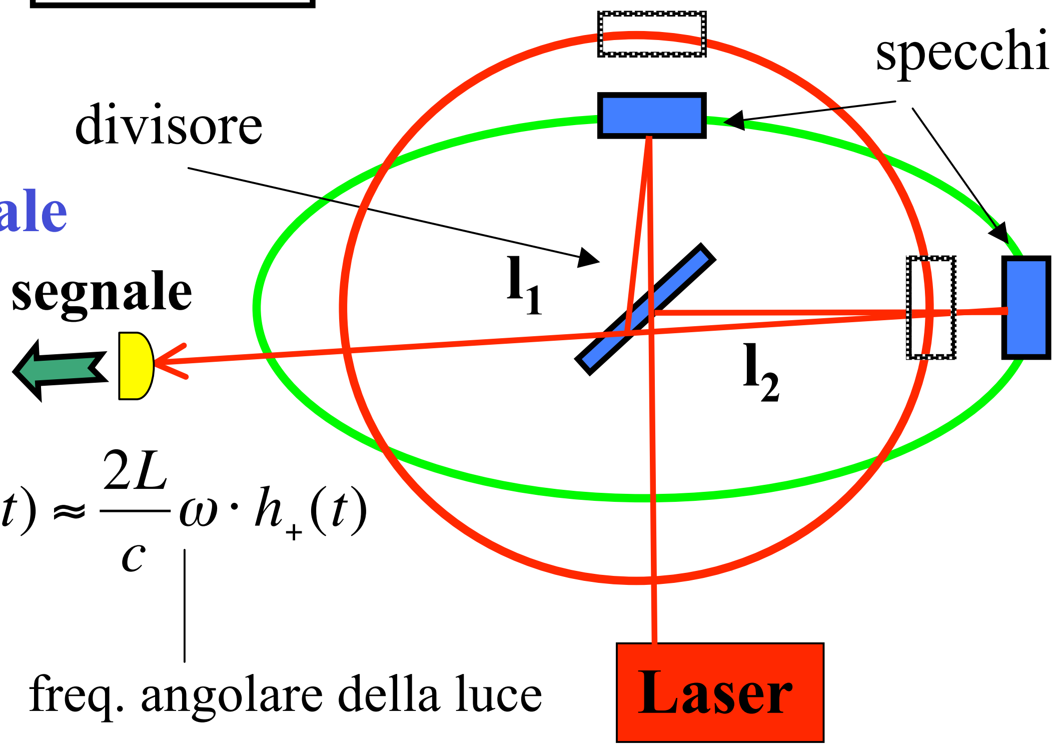


4) Cosmological BKG: to investigate the Big-Bang evolution at Planck's Era time.

Rivelatori a distribuzione di massa discreta: principio

Il segnale d'uscita di un interferometro Michelson dipende dalla differenza dei tempi di transito della luce nei due bracci, ovvero dalla differenza di lunghezza dei due bracci. La variazione di lunghezza di un braccio è $\Delta L = h * L$

A parità di *h*, più è grande *L*, tanto più grande è il segnale

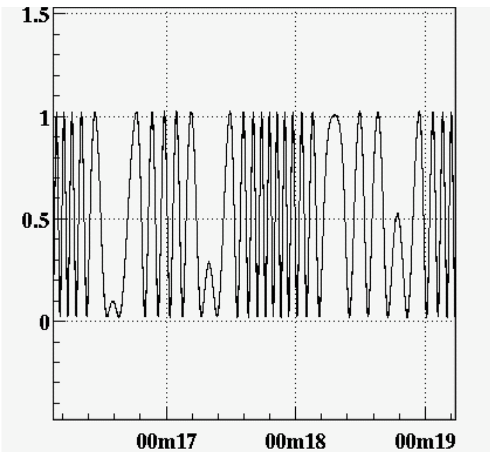


$$\delta\varphi(t) \approx \frac{2L}{c}\omega \cdot h_+(t)$$

freq. angolare della luce

Sfasamento dei due treni d'onda

Interference fringes



Michelson ITF (basics-I)

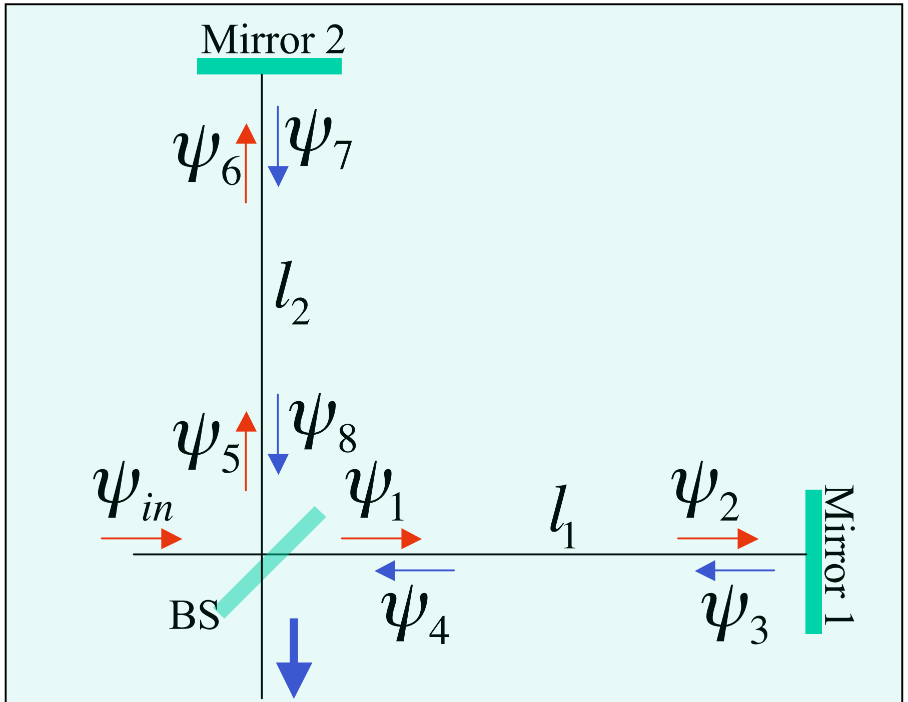
$$\psi_{in} = K e^{i\chi}$$

$$\psi_1 = t_{BS}\psi_{in} \qquad \psi_5 = i r_{BS}\psi_{in}$$

$$\psi_2 = e^{-ikl_1}\psi_1 \qquad \psi_6 = e^{-ikl_2}\psi_5$$

$$\psi_3 = i r_1 \psi_2 \qquad \psi_7 = i r_2 \psi_6$$

$$\psi_4 = e^{-ikl_1}\psi_3 \qquad \psi_8 = e^{-ikl_2}\psi_7$$



$$\psi_{out} = i r_{BS}\psi_4 + t_{BS}\psi_8$$

$$|\psi_{out}|^2 = P_{in} r_{BS}^2 t_{BS}^2 (r_1^2 + r_2^2)\left(1 + \frac{2 r_1 r_2}{r_1^2 + r_2^2}\cos(2k \cdot \Delta l)\right) \qquad (1)$$

$\Delta l = l_1 - l_2$

$$C = contrast = \frac{2 r_1 r_2}{r_1^2 + r_2^2} = \frac{P_{out}^{max} - P_{out}^{min}}{P_{out}^{max} + P_{out}^{min}} \qquad (2)$$

Michelson ITF (basics-II)

$$l_1 \rightarrow l_1\left(1+\frac{1}{2}h_+\right) \qquad l_2 \rightarrow l_2\left(1-\frac{1}{2}h_+\right) \qquad (3)$$

$$P_{out} = \frac{P_{in}}{2}\left(1 + C\cos(2k\cdot\Delta l) + h_+ Ck(l_1+l_2)\cdot\sin(2k\cdot\Delta l)\right) \qquad (4)$$

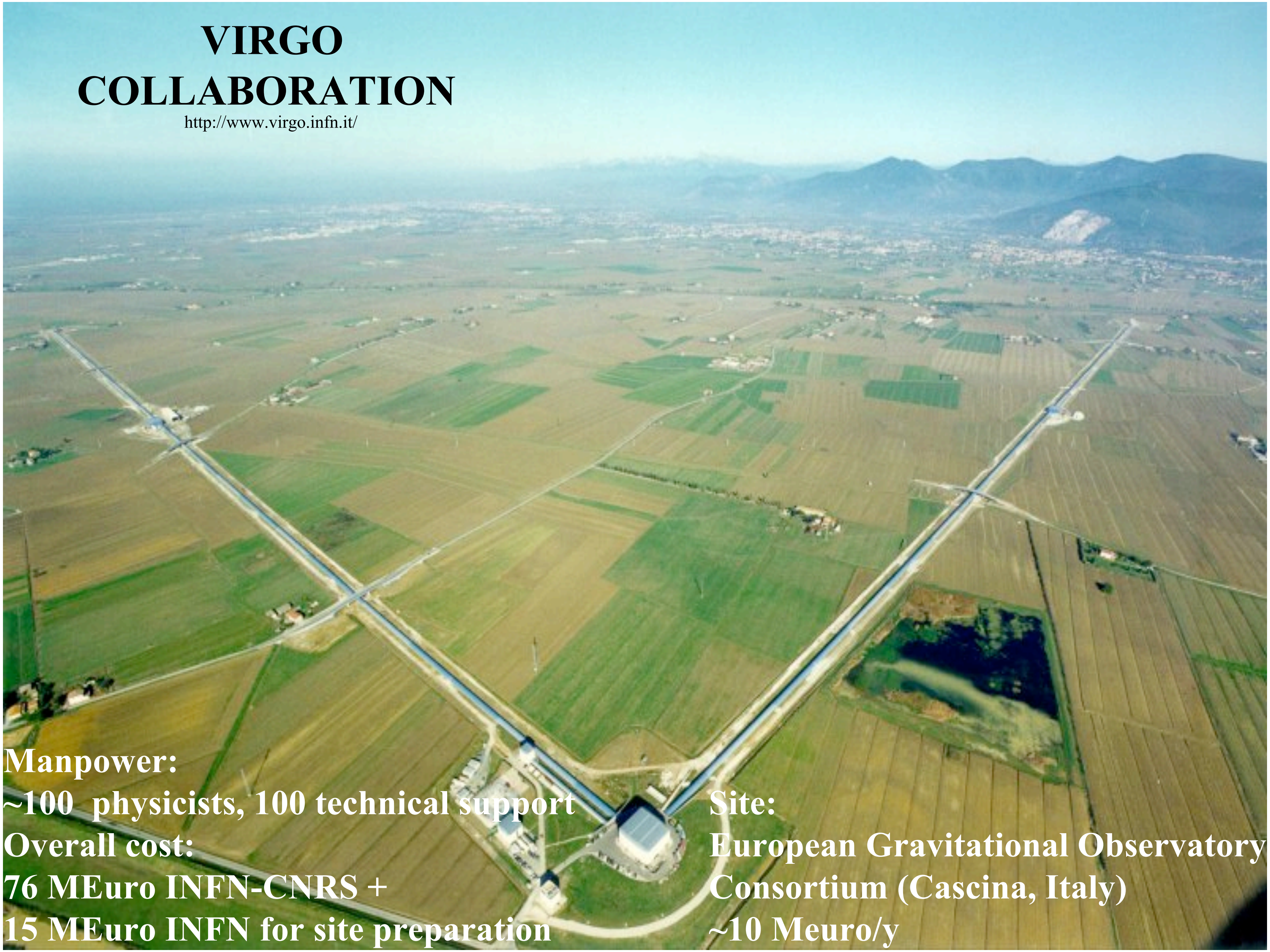
$$= P_{Mich.} + \delta P_{GW}$$

$$\delta P_{GW} \propto Amplitude_{GW}$$

The ITF **power** signal is sensitive to the **amplitude** of gravitational waves (and not to their **power**, as in electromagnetic wave detection).

The source signal fades as 1/r and not as $1/r^2$ as in e.m. telescopes: the number detectable sources grows as **ΔSensitivity³**

GW detector read-out is intrinsically limited by the noise affecting the power at the ITF output port: the **shot noise** . It follows that $P_{out}^{min} = 0$ (dark-fringe) ensures the best SNR


VIRGO
COLLABORATION
http://www.virgo.infn.it/
Manpower:
~100 physicists, 100 technical support
Overall cost:
76 MEuro INFN-CNRS +
15 MEuro INFN for site preparation
Site:
European Gravitational Observatory
Consortium (Cascina, Italy)
~10 Meuro/y

Designing Sensitivity requirements: initial Virgo

Pushing on the development of all the edge-technology solutions it is possible in principle to reach 10^{-21}-10^{-23} $Hz^{-1/2}$ strain sensitivity over a quite large bandwidth

Expected rate of coalescences:

3/yr within 40 ÷ 200 Mpc

[Grishchuk et al. Astro-ph/0008481]

Coalescence event rate

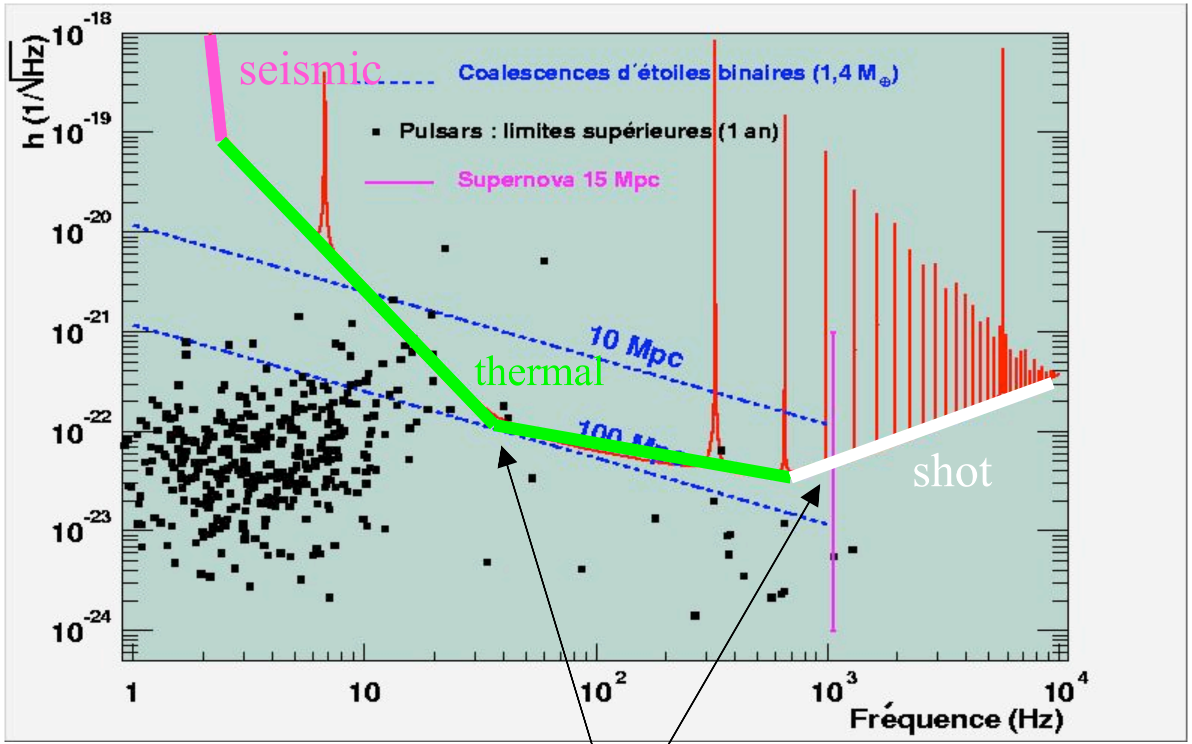
at ~ 20 Mpc

[Kalogera et al. ApJ. 601, L 179, 2004]

– 0.3/yr for NS/NS

– 0.6/yr for BH/BH

INITIAL VIRGO !!!!



Intrinsic test-mass and readout noise sources

Estimated rate of SNe:

several /yr in the Virgo cluster (20 Mpc).

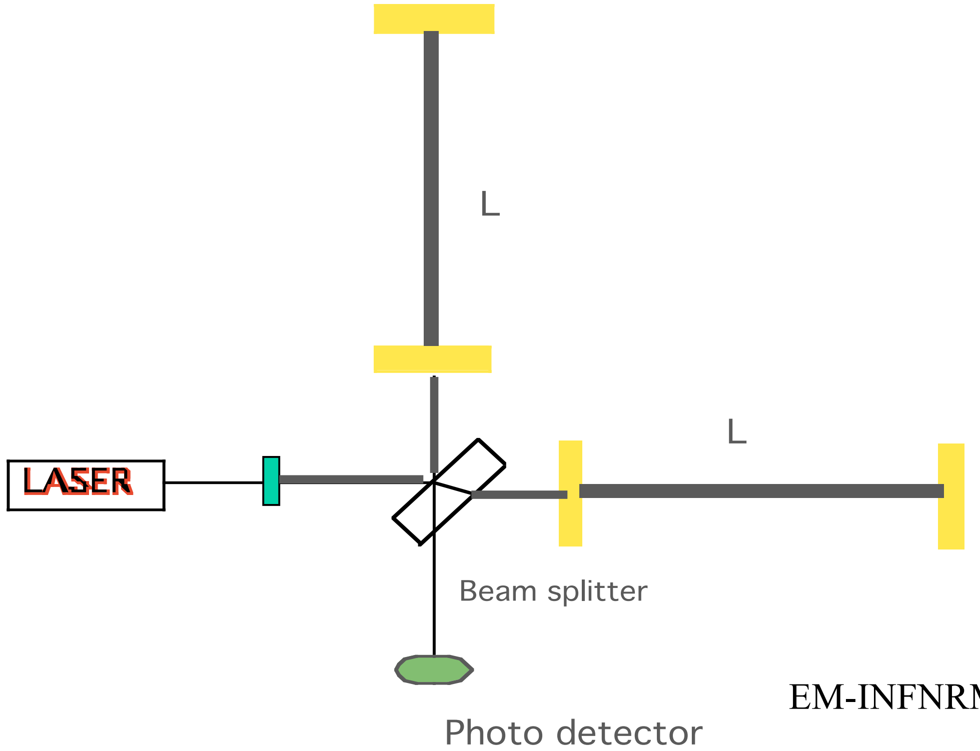
Metodo standard per aumentare la sensibilità dei rivelatori interferometrici terrestri

I) Il tempo di permanenza della luce nei bracci viene allungato disponendo lungo i bracci cavità ottiche Fabry-Perot.

II) L'ITF rivela in frangia scura.

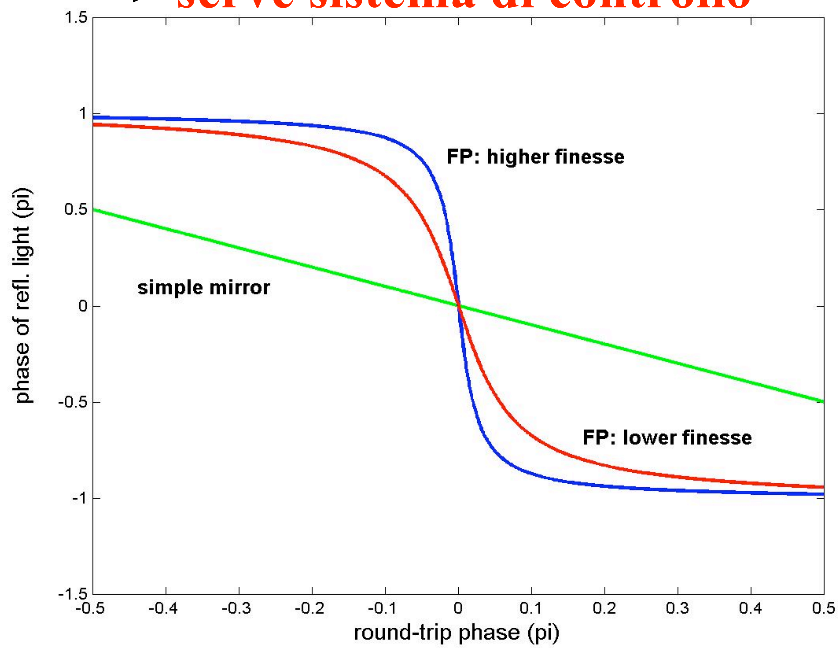
III) si usa uno specchio di ricircolo di potenza.

Lunghezza efficace =120 km



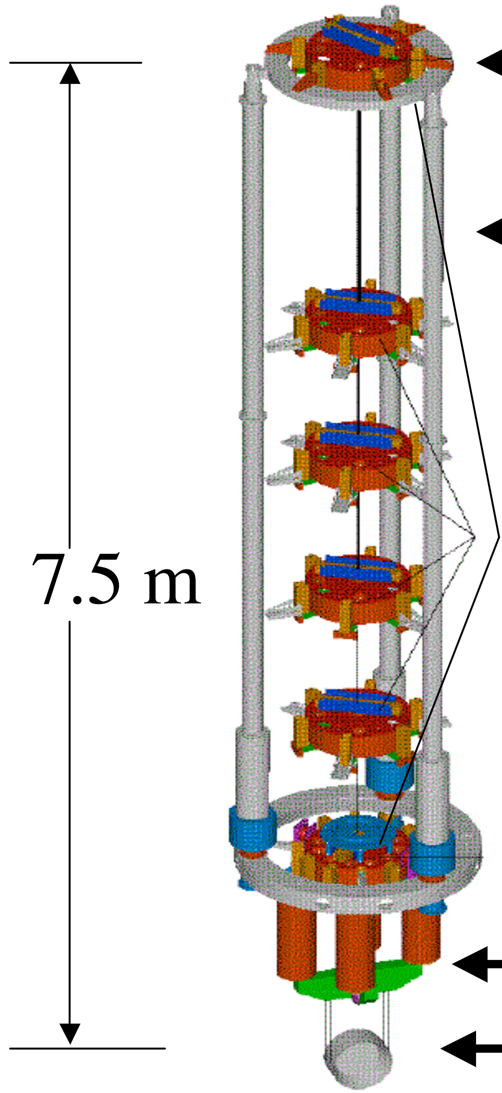
EM-INFNRM

La risposta dell'ITF aumenta molto, ma si riduce il range => serve sistema di controllo



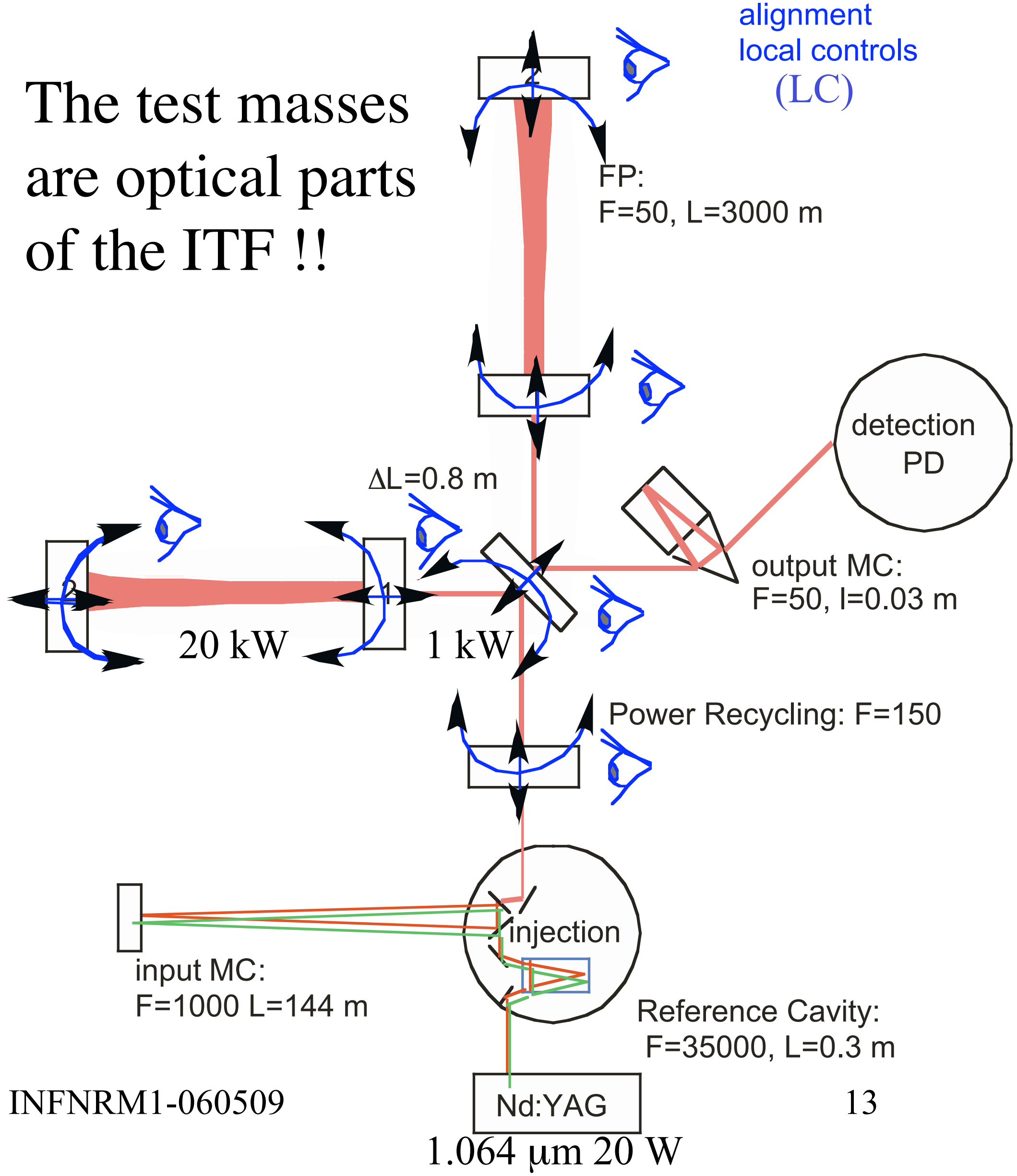
Demanding seismic isolation system

test masses



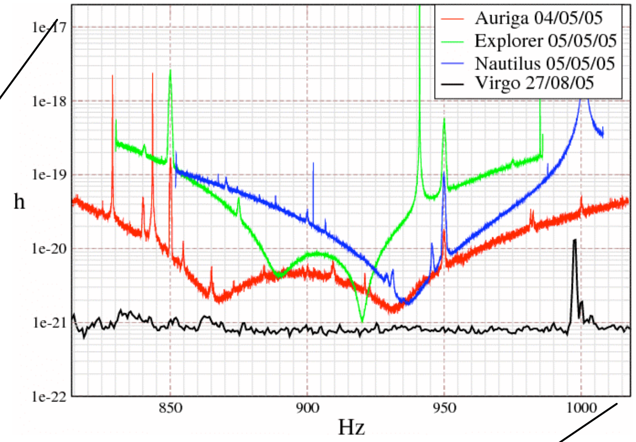
$$A = 10^{-14}$$
$$@10Hz$$

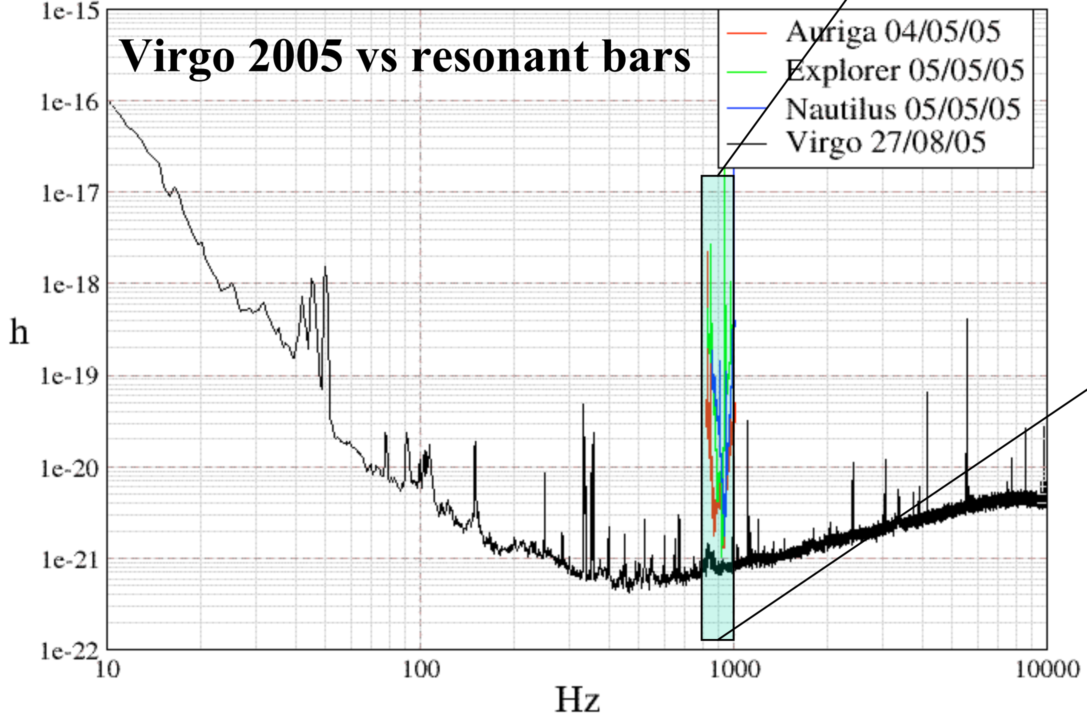
The test masses are optical parts of the ITF !!



Comparison with resonant detectors

- Continuous-mass distribution ("resonant body")
- Discrete mass distribution ("free test masses")

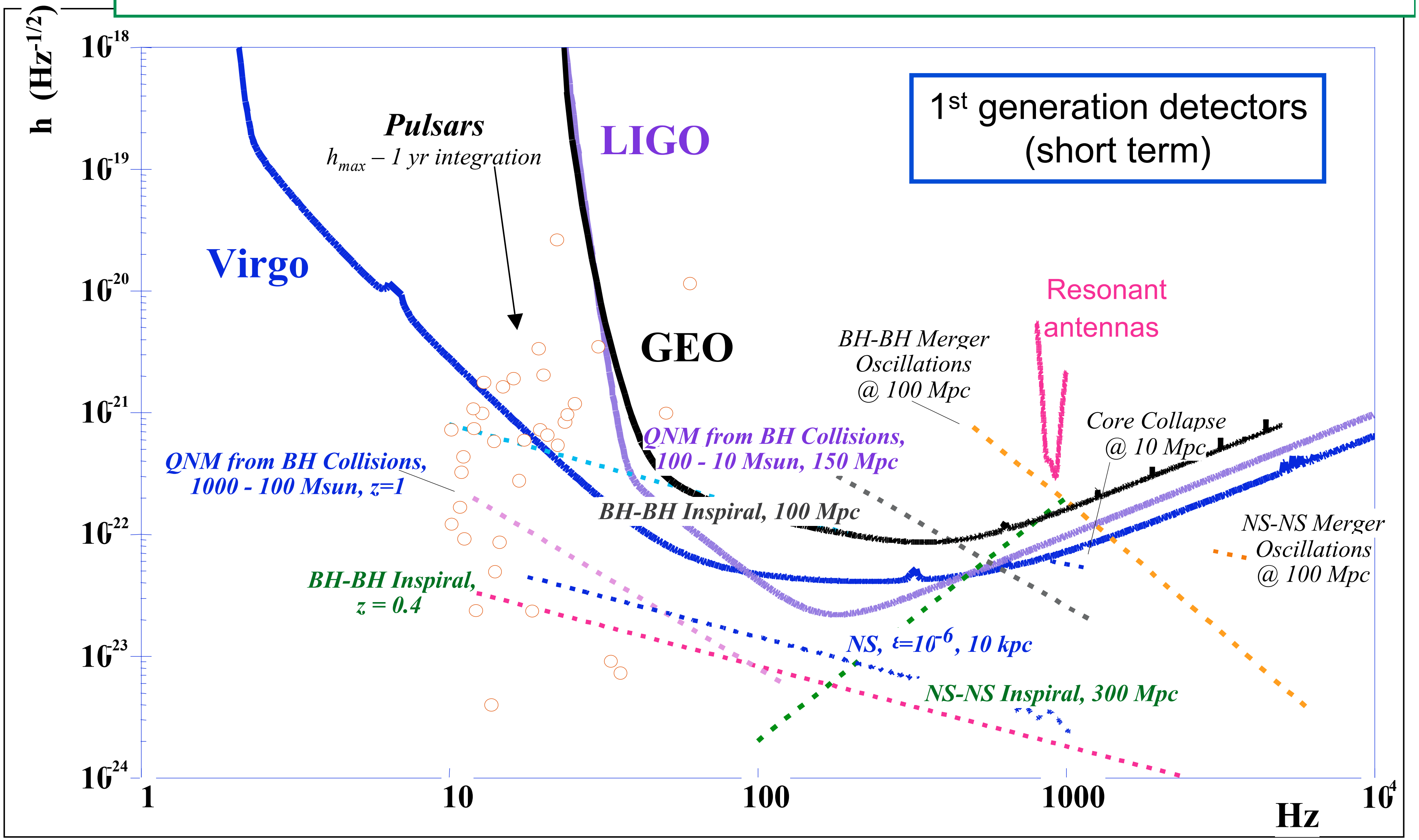




Note:
they are **not just two different classes** of detectors.
Resonant detectors in operation were **not meant to reach the Virgo Cluster**.
They are maintained in **stable operation for Galactic** event detection backup.

The European roadmap was delineated to concentrate resources on GW interferometers

1st generation GW detectors sensitivities: few and rare events



Interferometric Network	NS-NS	NS-BH	BH-BH	SNe
Event Rate (per year)	$3\ 10^{-4}$ - 0.3	$4\ 10^{-4}$ - 0.5	10^{-3} - 3	0.05
Range (Mpc)	30	60	145	0.1

The intermediate step V+ towards Advanced Virgo

Virgo ⟹ Virgo+ ⟹ AdvVirgo

The evolution of the Virgo collaboration towards Advanced-Virgo project

- The collaboration is open and new groups join VIRGO collaboration

INFN

- **Sez. Firenze/Un.Urbino**
- **Sez. Genoa**
- **Sez. Napoli/Un. Federico II**
- **Sez.Perugia/Un. Perugia**
- **Sez. Pisa/Un. Pisa**
- **Sez. Roma/Un. Sapienza**
- **Sez.Roma 2/Un. Tor Vergata**
- **Saz. Padova/ Un. Trento**
- **EGO Physics group**

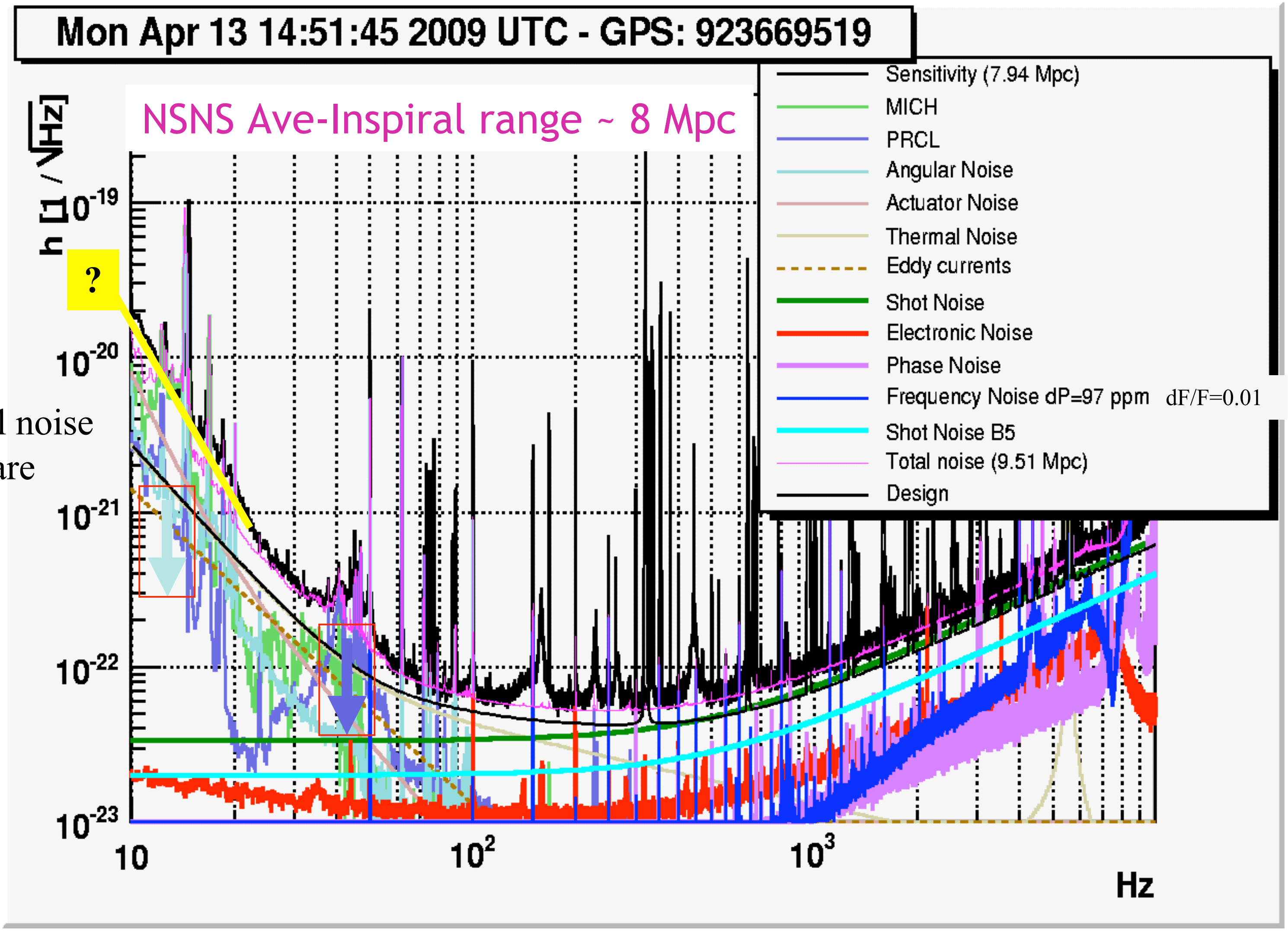
CNRS

- **APC – Paris**
- **ESPCI – Paris**
- **LMA – Lyon**
- **LAL – Orsay**
- **LAPP – Annecy**
- **OCA – Nice**
- **NIKHEF –Amsterdam**
- **POLGRAV – Warsaw (Polish Ac. Sci.)**
- **RMKI (Hungarian Ac. Sci. Budapest**
- **Birmingham Un. –UK (MOU GEO-VIRGO)**

The collaboration is fully engaged in Virgo upgrades (V+) and Advanced Virgo project

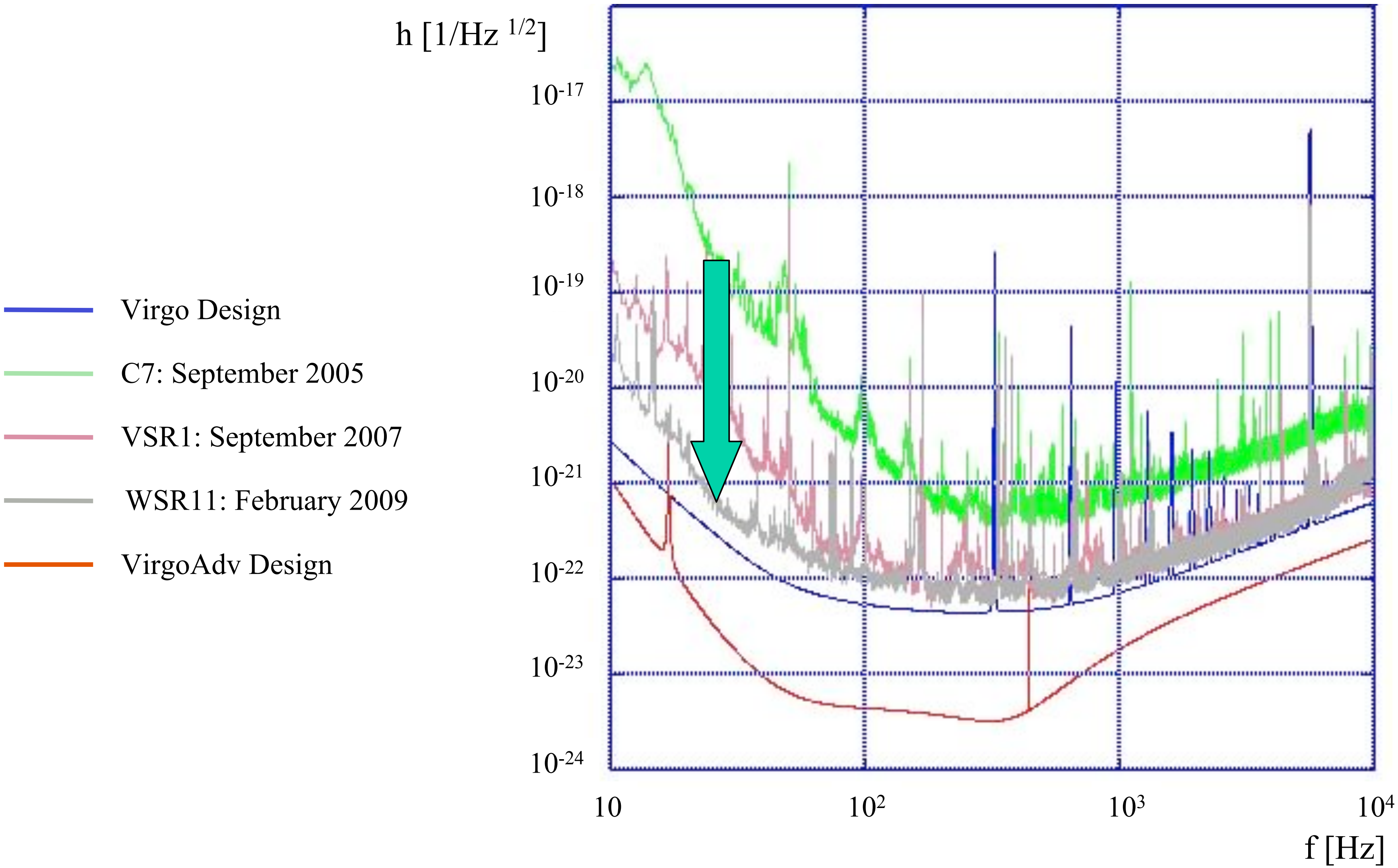
Present staus of noise hunting: few ununderstood noise sources

Note: here locking control noise MICH/PRCL are not otimized



Virgo+ is being implemented gradually:
its commissioning is interlaced with coincidence operation of *enhanced*-LIGO

Recent sensitivity improvements during commissioning and scientific runs

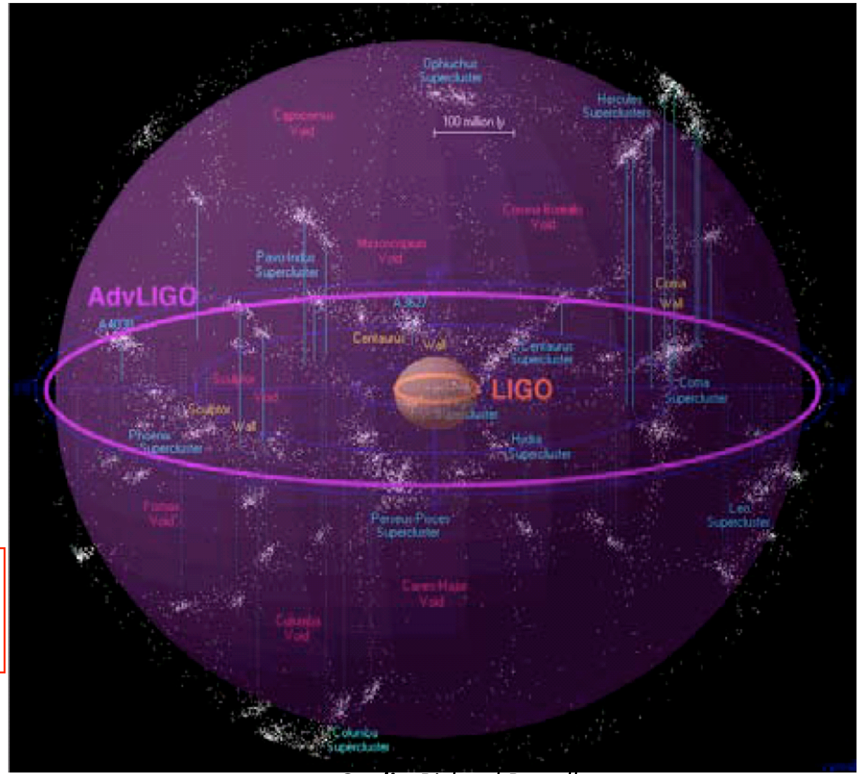


Background activity: four years spent to prepare preliminary Advanced Virgo design

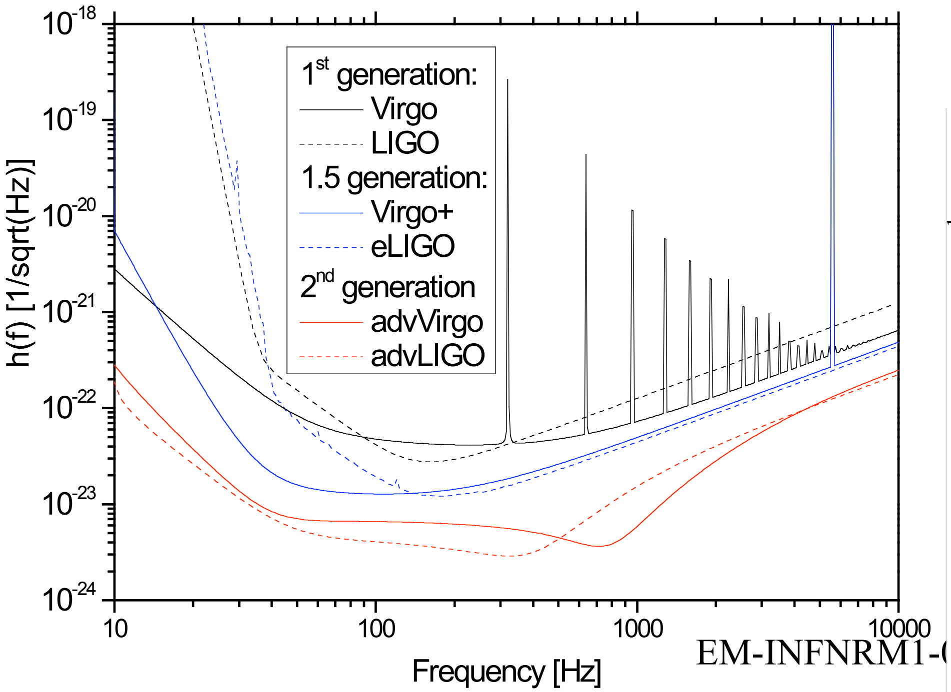
Advanced detectors target: few events/year

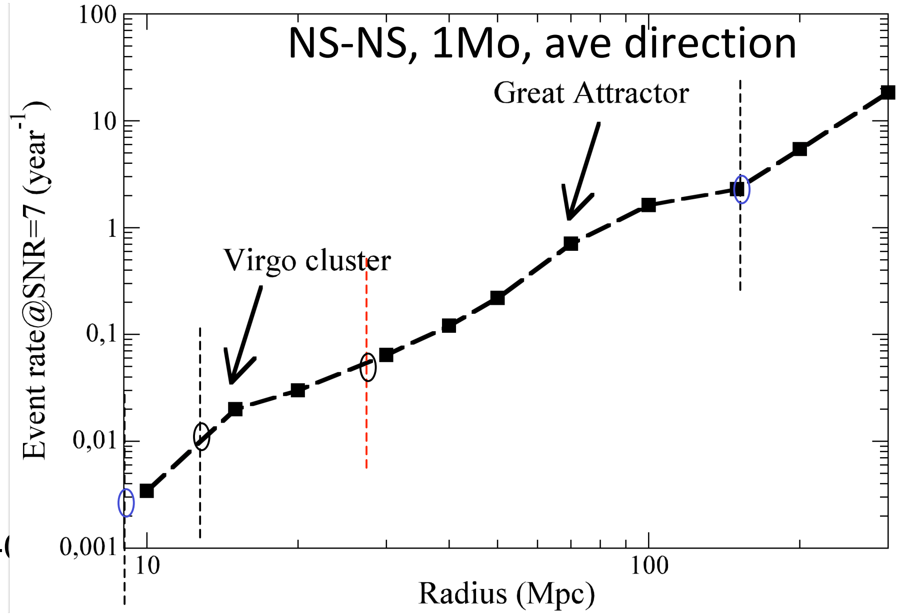
Several sensitivity improvements are possible using present imfrastructures of Virgo and LIGO in two steps :

Enhanced Interferometers => **no major hardware changes**
Advanced Interferometers => **major hardware changes**



Credit: Richard Powell





INFN Roadmap
A Proposal
for the Gravitational Wave Experiments

The CSN2 GW Working Group:
M. Bonaldi (Auriga, DUAL), S.Braccini (CSN2), R.Dolesi (LISA), V. Fafone (ROG, SFERA), M. Punturo (Virgo), P. Rapagnani (CSN2, Convener)

Contents:

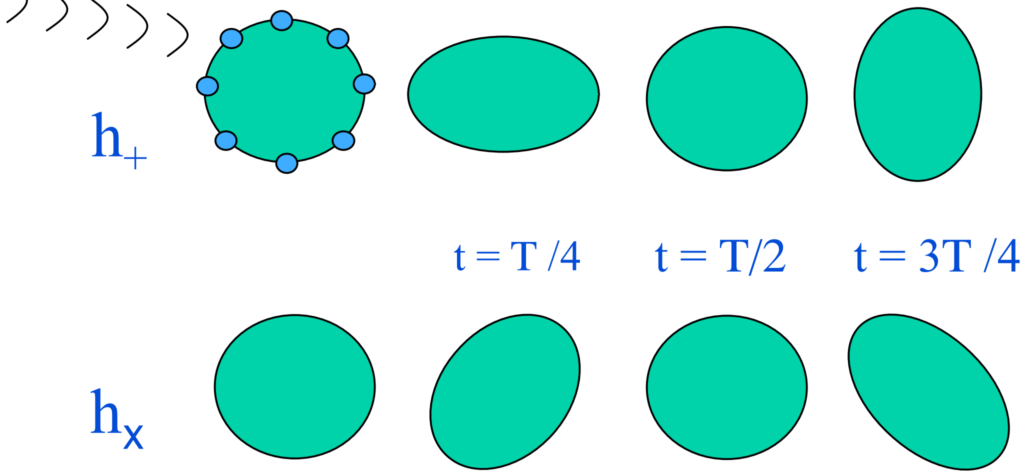
2006 – 2007: Near Term Network
2008 – 2012: Medium Term Network
2012 – 2018: Long Term Network

<u>Risorse potenziabili, ma limitate:</u>
necessario concentrarle !
I Analisi dello stato attuale
II Analisi delle prospettive nel tempo
III Analisi dei costi

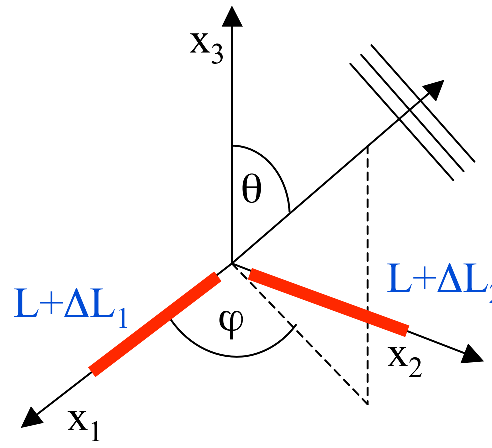
EM-INFNRM1-060509

The Network of Gravitational Detectors as a Global Instrument

Coherent analysis with several detectors:
crucial to detect the signal and to reconstruct the 5 parameters of the wave

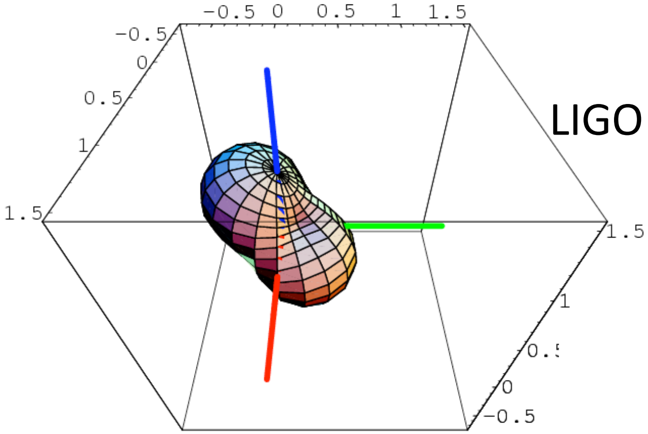


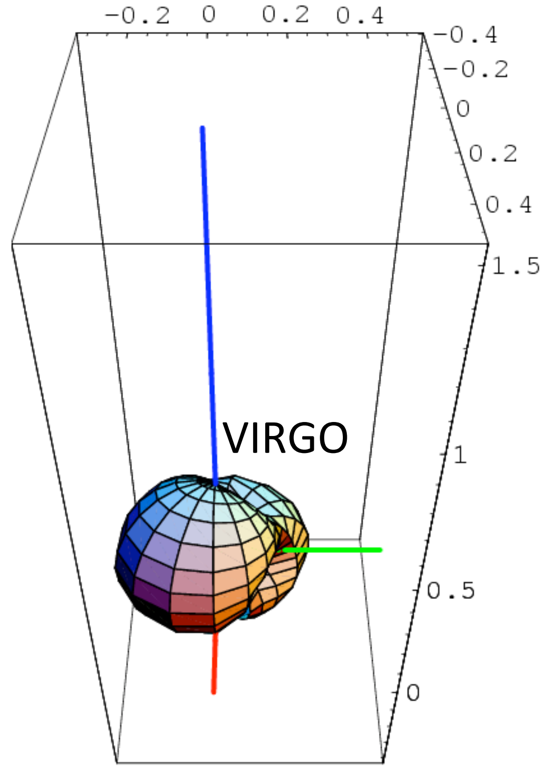
2 polarization states and initial phase
(h_+, h_x, ϕ_0)



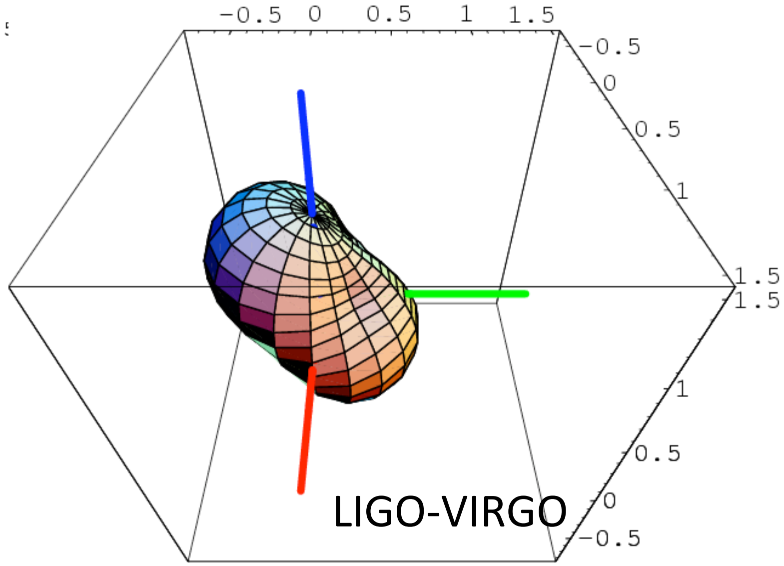
incidence direction
(φ, θ)

I diagrammi d’antenna e la rete





La rete è cruciale per la reiezione degli eventi spuri, ma non solo per questo.



Credits A. Viceré

Combinando in modo coerente i dati della rete LIGO-Virgo Advanced la distanza d’esplorazione (SNR=8, eff. 90%) per eventi del tipo BNS cresce da 150-170 Mpc per i singoli rivelatori fino a <u>270 Mpc</u>

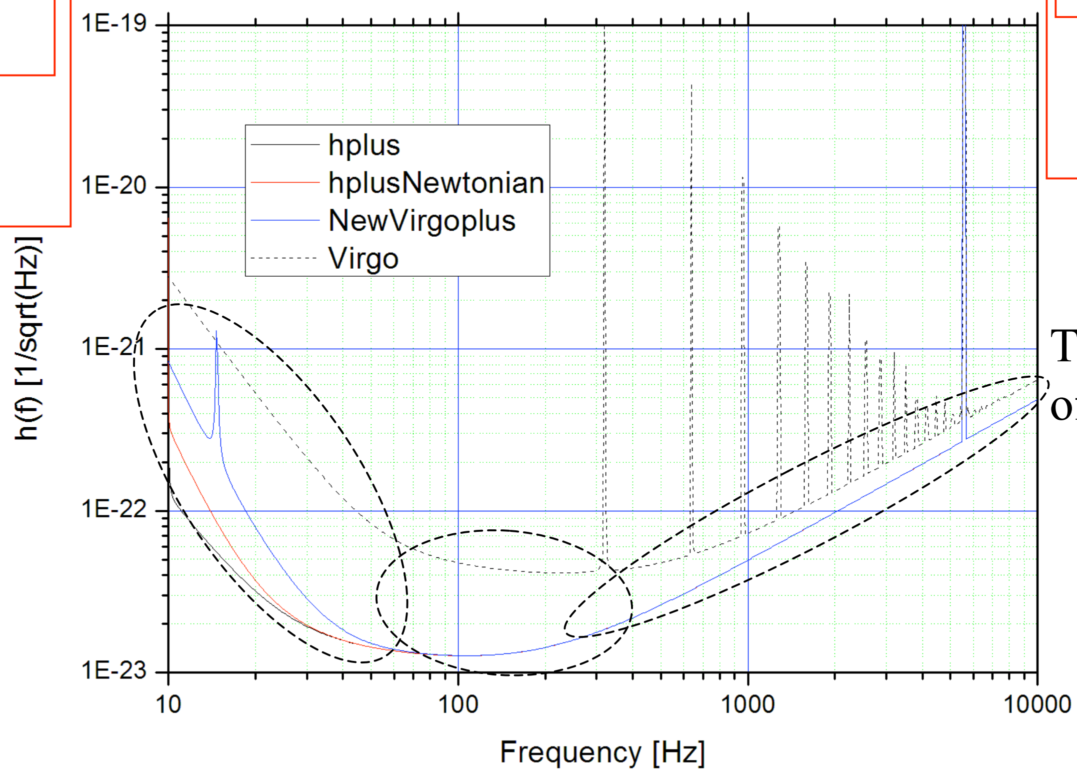
Some details about relevant hardware changes

Virgo+, first step towards Vadv: main improvements (many others underlaying)

Monolithic suspension (marionette-mirror)

new mirrors (Hi-Q)

Dedicated R&D to validate new test-mass payload (done!)



Powered injection

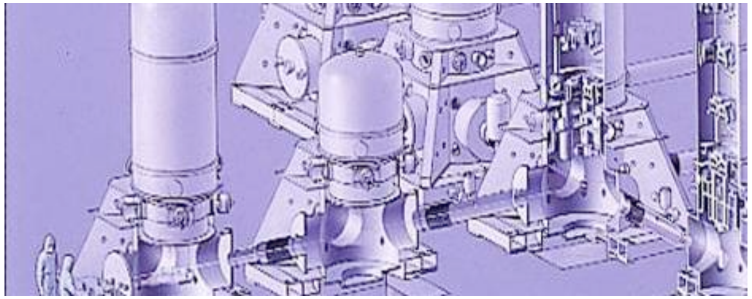
new mirrors (Hi-Finesse)

Thermal deformation of FP cavity mirrors

Thermal Compensation System needed

Schedule: Virgo+ with monolithic suspension in 2010

Da Virgo ad AvancedVirgo: cosa è necessario fare

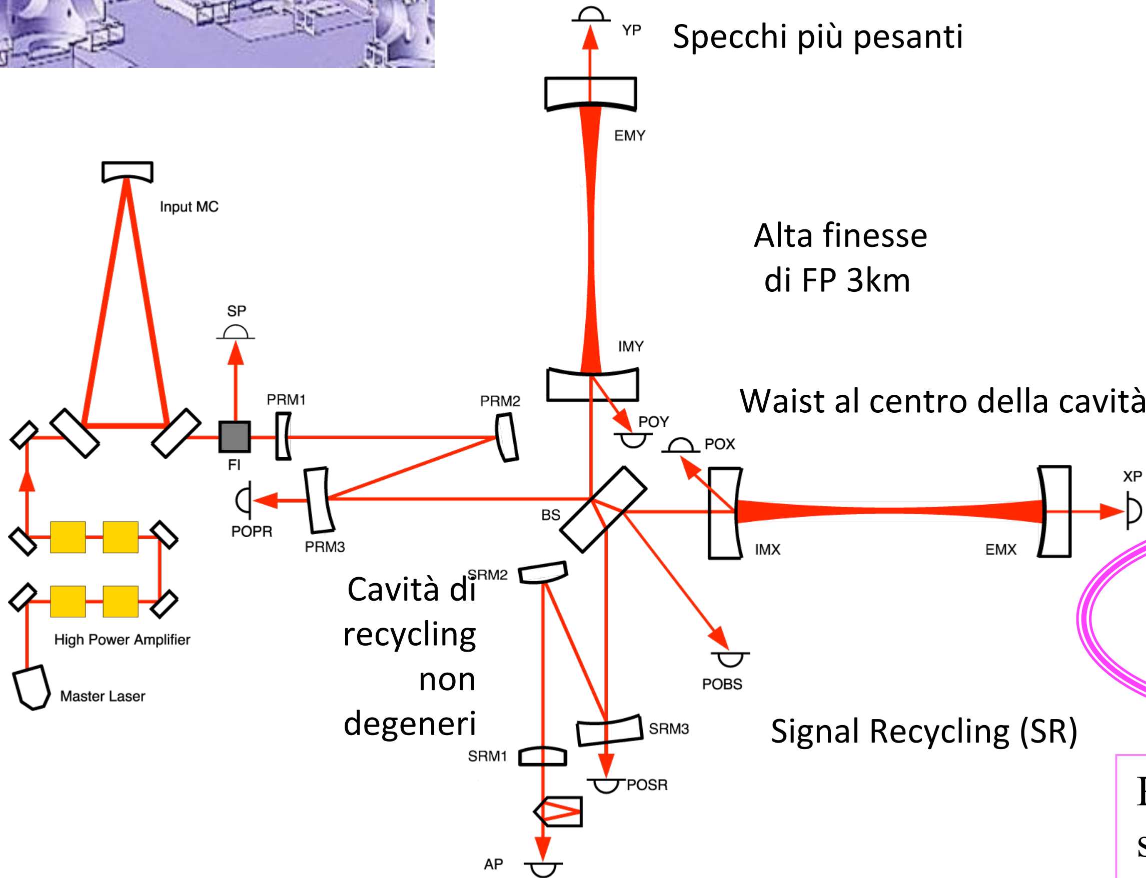


Link area centrale più grandi

Specchi più pesanti

Alta finesse
di FP 3km

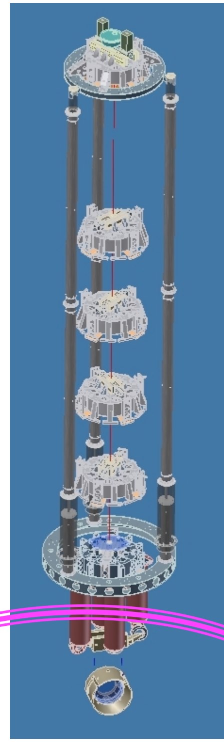
Waist al centro della cavità



Laser 200 W
e nuova
ottica di
iniezione

Cavità di
recycling
non
degeneri

Signal Recycling (SR)

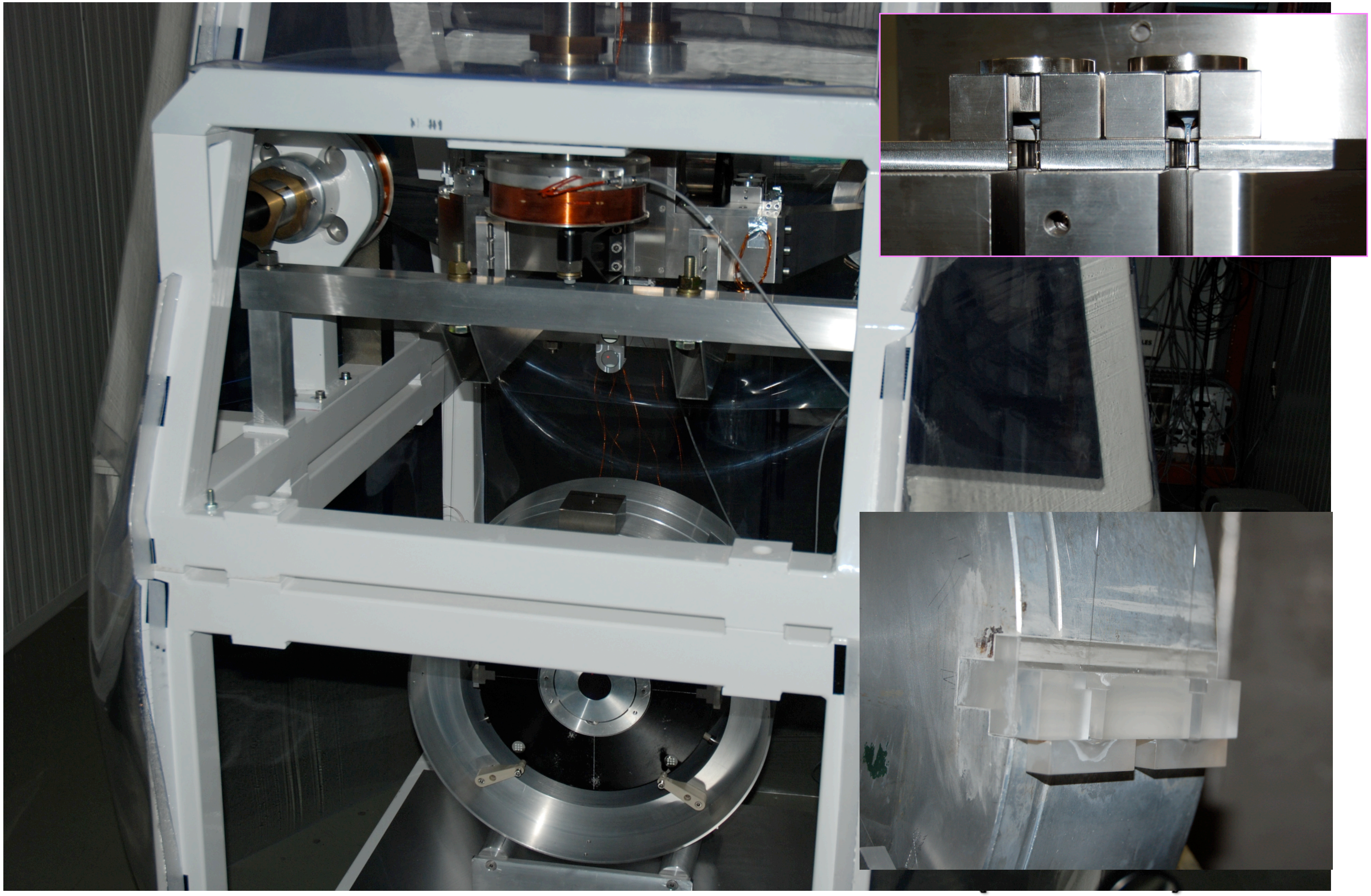


Sospensioni Monolitiche

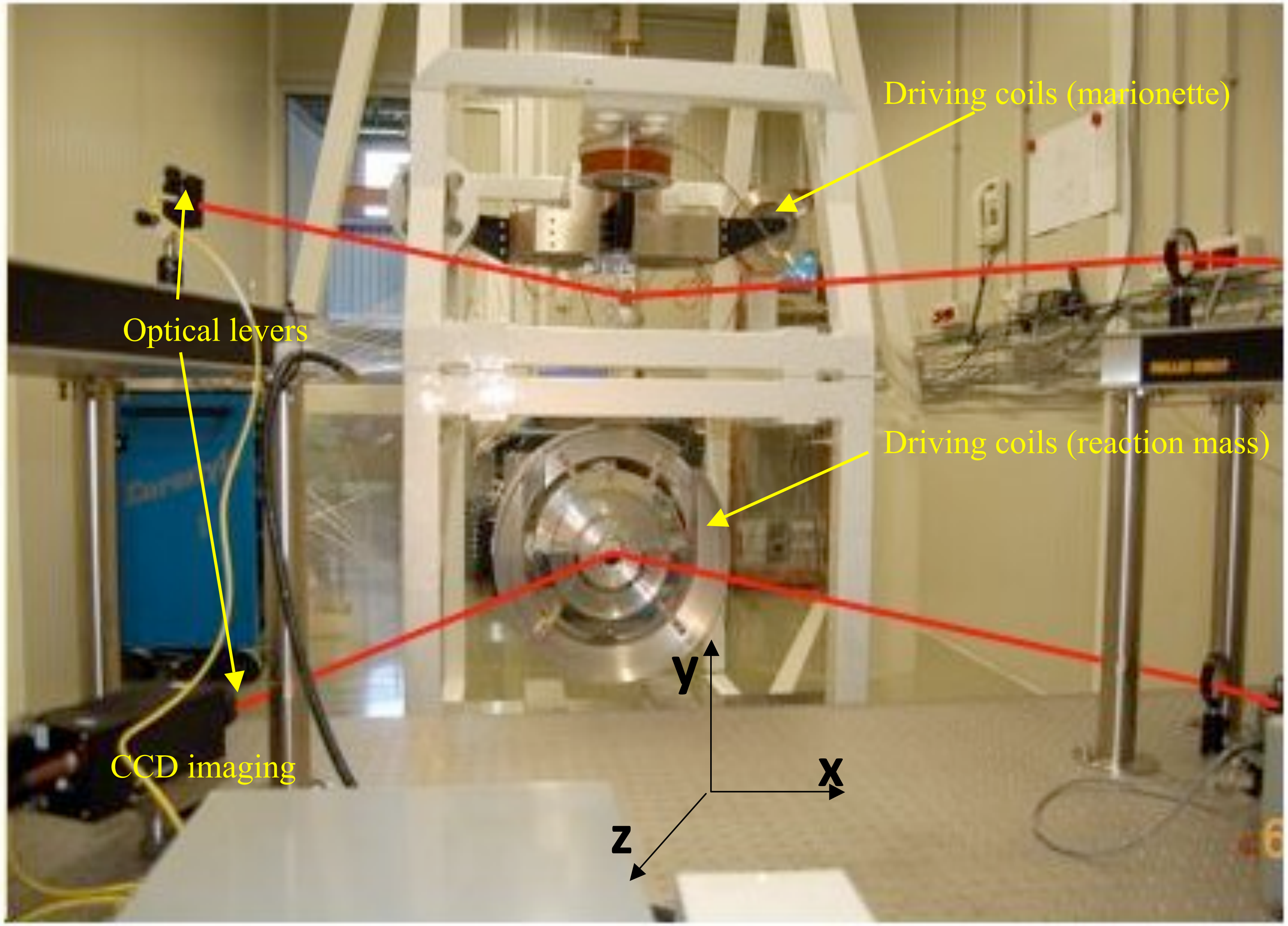
Roma1: responsabilità
sviluppo e installazione
dei nuovi payload

EM-INFNRM1-060509

Thermal noise/monolithic suspension: a key feature for low frequency sensitivity improvement (V+ payload prototype)

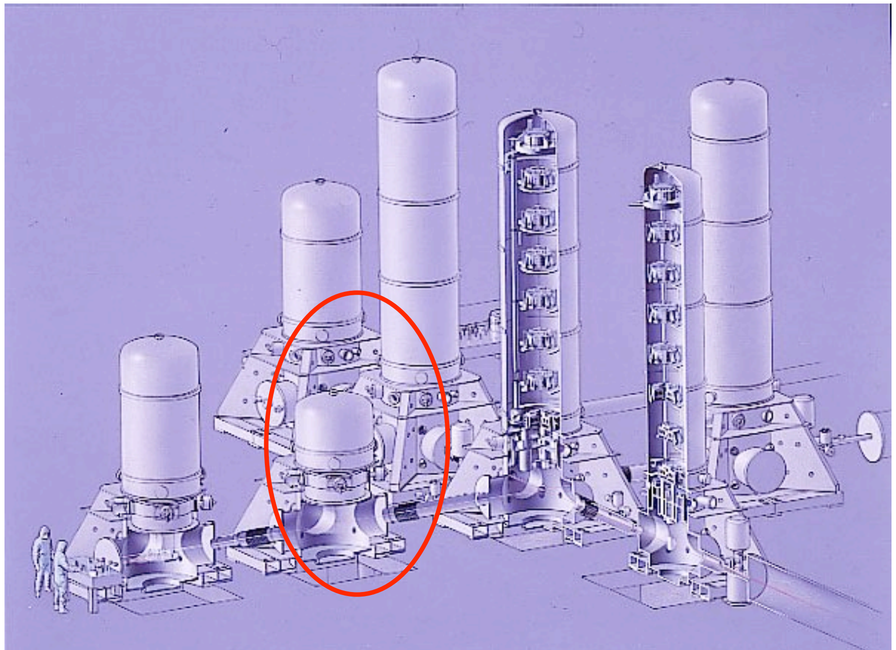


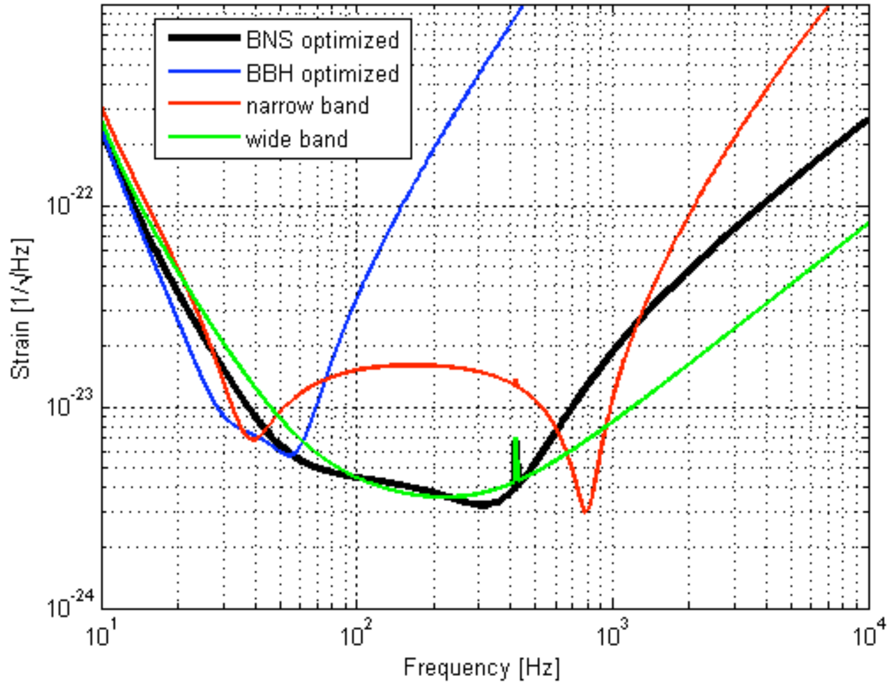
Thermal noise/monolithic suspension: a key feature for low frequency sensitivity improvement (V+ payload prototype)



nota: ricircolo del segnale

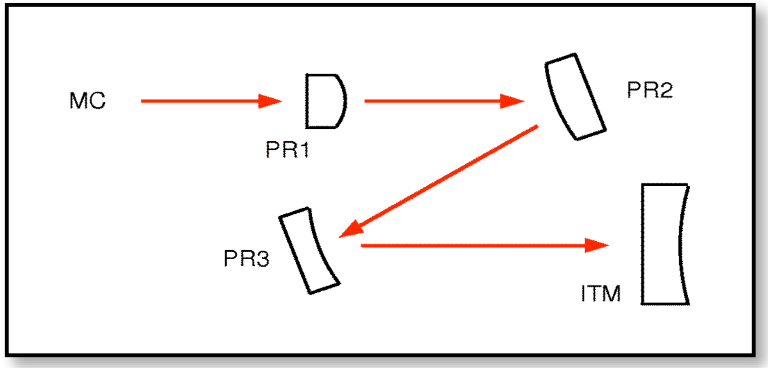
- Un ulteriore superattenuatore da implementare.
- Un’altra cavità da tenere in sul punto di lavoro

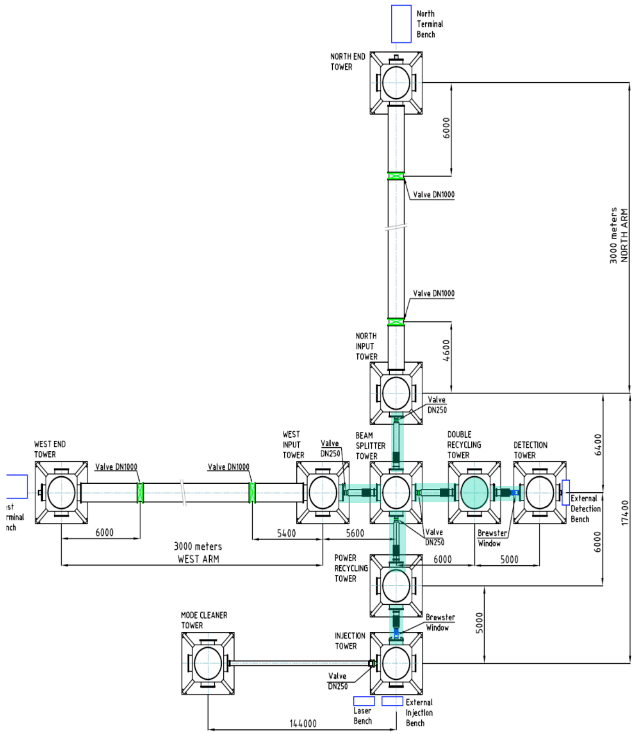




Cavità centrali non degeneri (Area centrale dell'interferometro)

Scopo:
rendere le bande laterali usate per il segnale di errore delle **2 cavità centrali** (ricircolo di potenza e di segnale) meno dipendenti dai contributi di altri modi parzialmente risonanti
➡ necessarie cavità centrali più lunghe !!





- Vantaggi:
  - Incremento della dinamica dell' Interferometro.
  - Minore sensibilità al disallineamento.
  - Ridotti effetti termici durante la transizione ad alta potenza.
- Implicazioni:
  - Link da vuoto tra le torri di diametro maggiore.
  - Modificare la performance di attenuazione sismica per i banchi ottici di iniezione e rivelazione.
  - Modifica sostanziale di alcuni payload (composti da più specchi).
  - Sistema di controllo della posizione per payload con più specchi sospesi.

Roma1

nota: sezione dei fasci sugli specchi delle cavità da 3 km

$$h_{coat}(f) = \frac{1}{r_0}\sqrt{\frac{4k_B T d}{\pi^2 f Y}\phi_{eff}}$$

Aumento delle dimensioni del fascio sugli specchi

Vantaggio:

- Riduzione del rumore termico degli specchi e degli effetti termici sullo specchio d'ingresso

Implicazioni:

- Luce diffusa: grande attenzione nella progettazione del del beam-splitter

readout/mechanics: back-action

$$< \tilde{x}_{RP} >^2 = \frac{1}{m \cdot \omega_0^{\ 2}} \frac{P_{shot}}{c}$$

displacement spectral density due
to radiation pressure on suspended mirrors

$$\tilde{h}_{readout} = \frac{1}{L_{FP}} \sqrt{\frac{c_{shot}}{F^2 P} + \frac{c_{RP}}{(m\omega_0^{\ 2})^2} F^2 P}$$

m = suspended mirror mass; $c_{shot} = c_{shot}(const_{shot}); c_{RP} = c_{RP}(const_{RP})$

Finesse and **Power cannot** be increased without mechanical reaction.

Massive mirrors **can** be used to reduce radiation pressure noise.

thermal noise

$$h_{TN} \geq h_{readout}$$

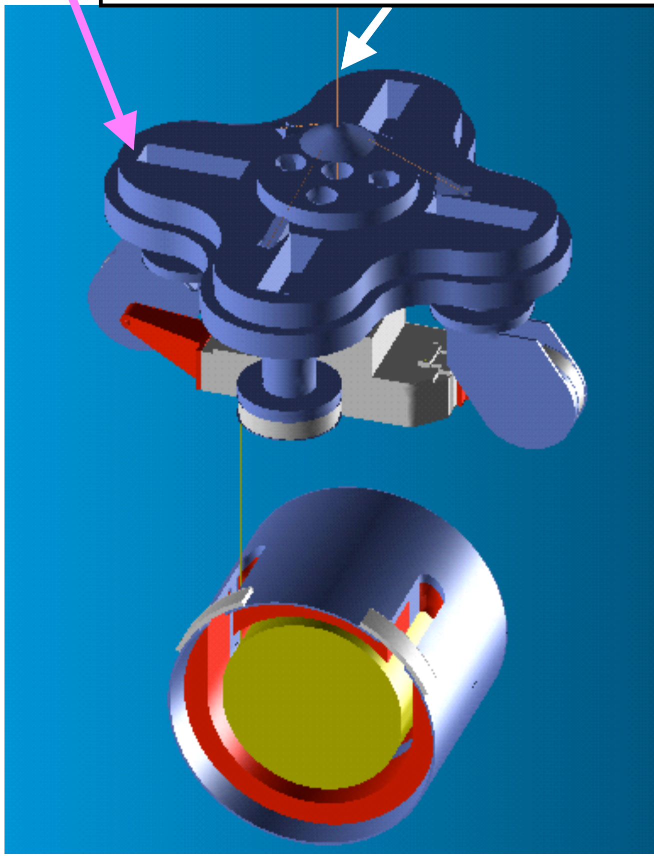
Trade-off reference solution :
35 cm Ø, 20 cm thick, 42 Kg

Significant changes in Virgo+ monolithic payload design towards AdvVirgo.

AdvVirgo payload prototype

A **second reaction mass to actuate marionette** control

Lumped to the last suspension module



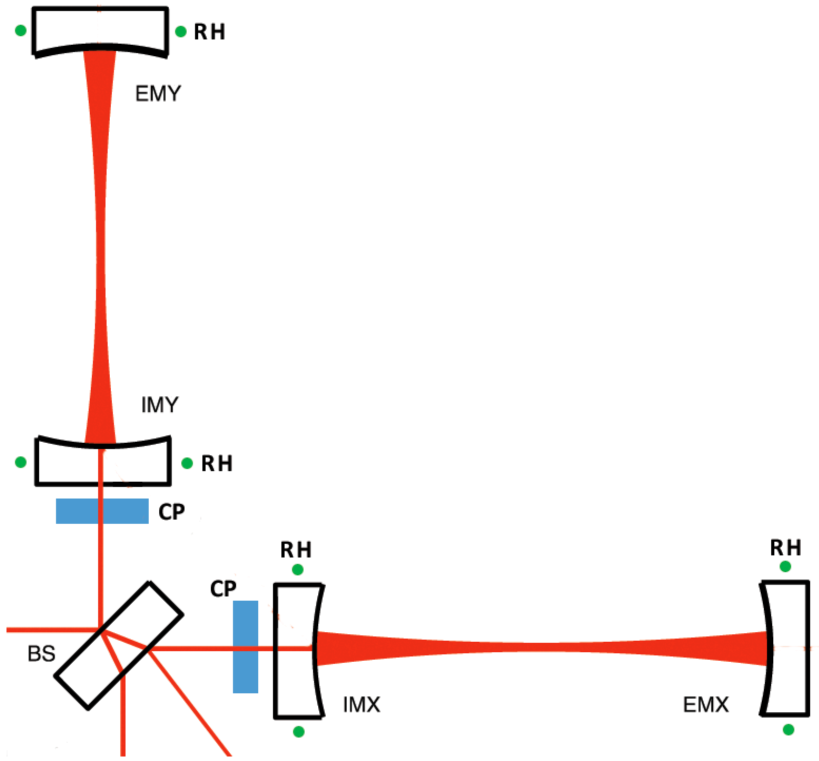
NUOVA COMPENSAZIONE TERMICA

Soluzione di riferimento:

1) Anello riscaldante attorno alle masse di test.

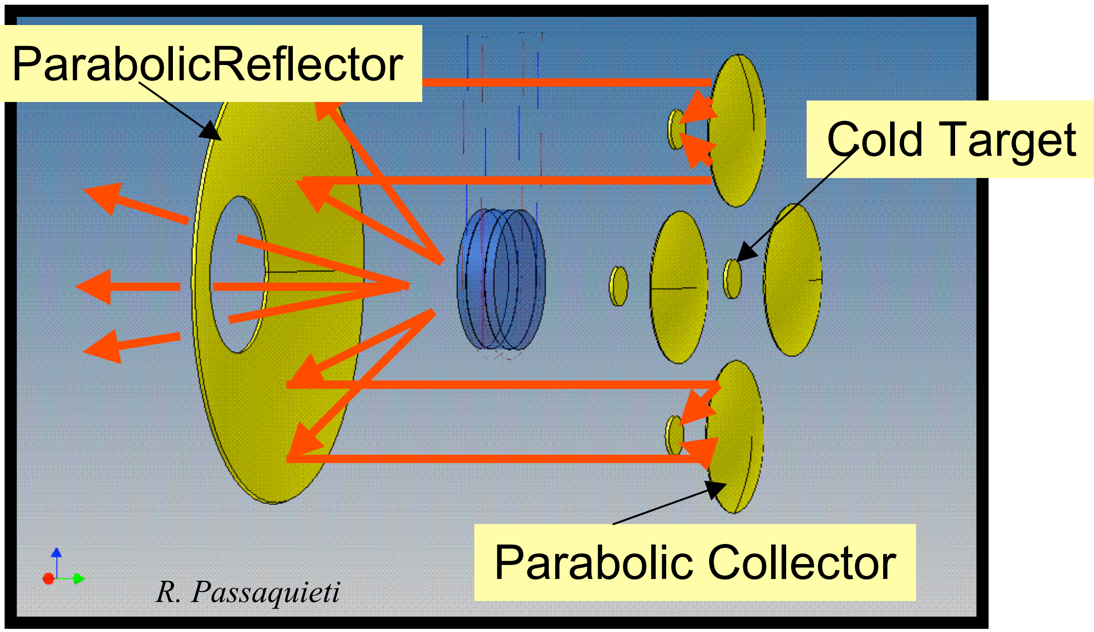
2) Ulteriore sistema di compensazione delle deformazioni termiche sullo specchio di ricircolo di potenza.

3) Elemento ottico extra (*compenstion plate*) di fronte alle masse di test d'ingresso e poste lungo il cammino ottico principale.



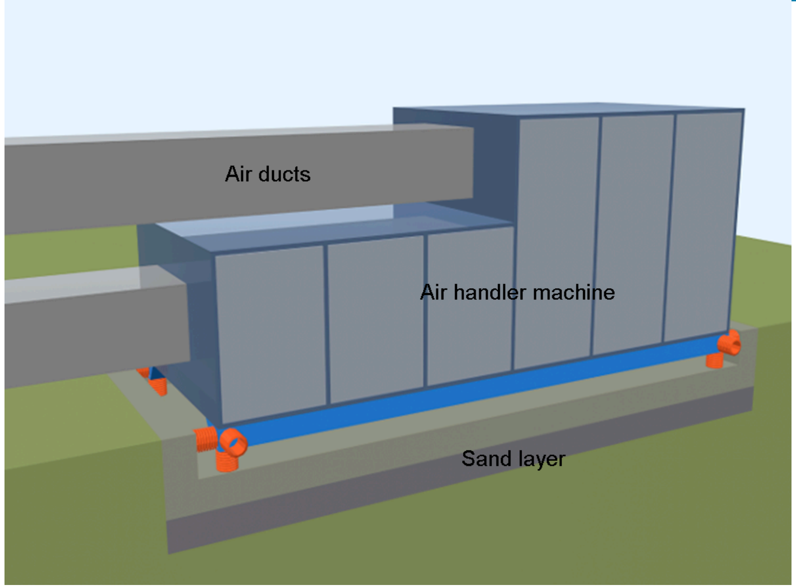
R&D proposto:

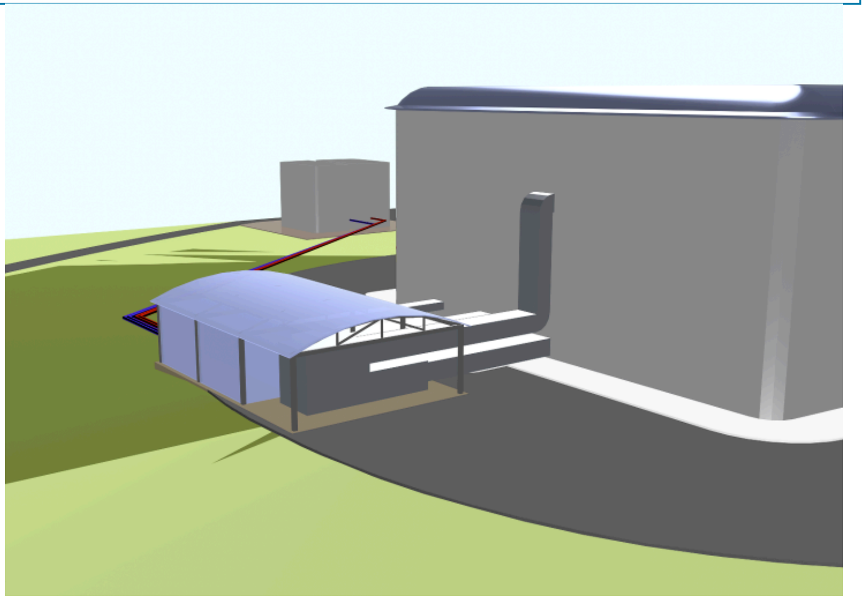
Raffreddamento radiativo degli specchi



INFRASTRUTTURA

- L'aumento di sensibilità di Ad VIRGO (10 x VIRGO) implica maggiore attenzione alla riduzione del rumore ambientale.
- Grande sforzo per la comprensione dei meccanismi d'accoppiamento e la loro riduzione. Ulteriore sperimentazione prevista con VIRGO+.
- Isolamento delle macchine industriali e loro collocazione lontano dalle masse di test, ovvero in edifici separati, fuori dalle sale sperimentali.





COST & milestones

20 MEuro (Nikhef will contribute by ~10%)

Year	2009	2010	2011	2012	2013
FTE	19	35	25	27	20

Virgo + EGO personnel fulfill this request.

1. July 2009 The Project starts with the mirror bulk order.

2. July 2011 Shutdown of Virgo+ for Advanced Virgo installation.

3. Dec 2013 Completion of assembly and integration phases.

4. July 2014 First one-hour-long operation
   (i.e. needed degrees of freedom controlled).

Conclusioni

Gli attuali rivelatori hanno una tenue ma significativa possibilità di rivelare eventi astrofisici.

↓

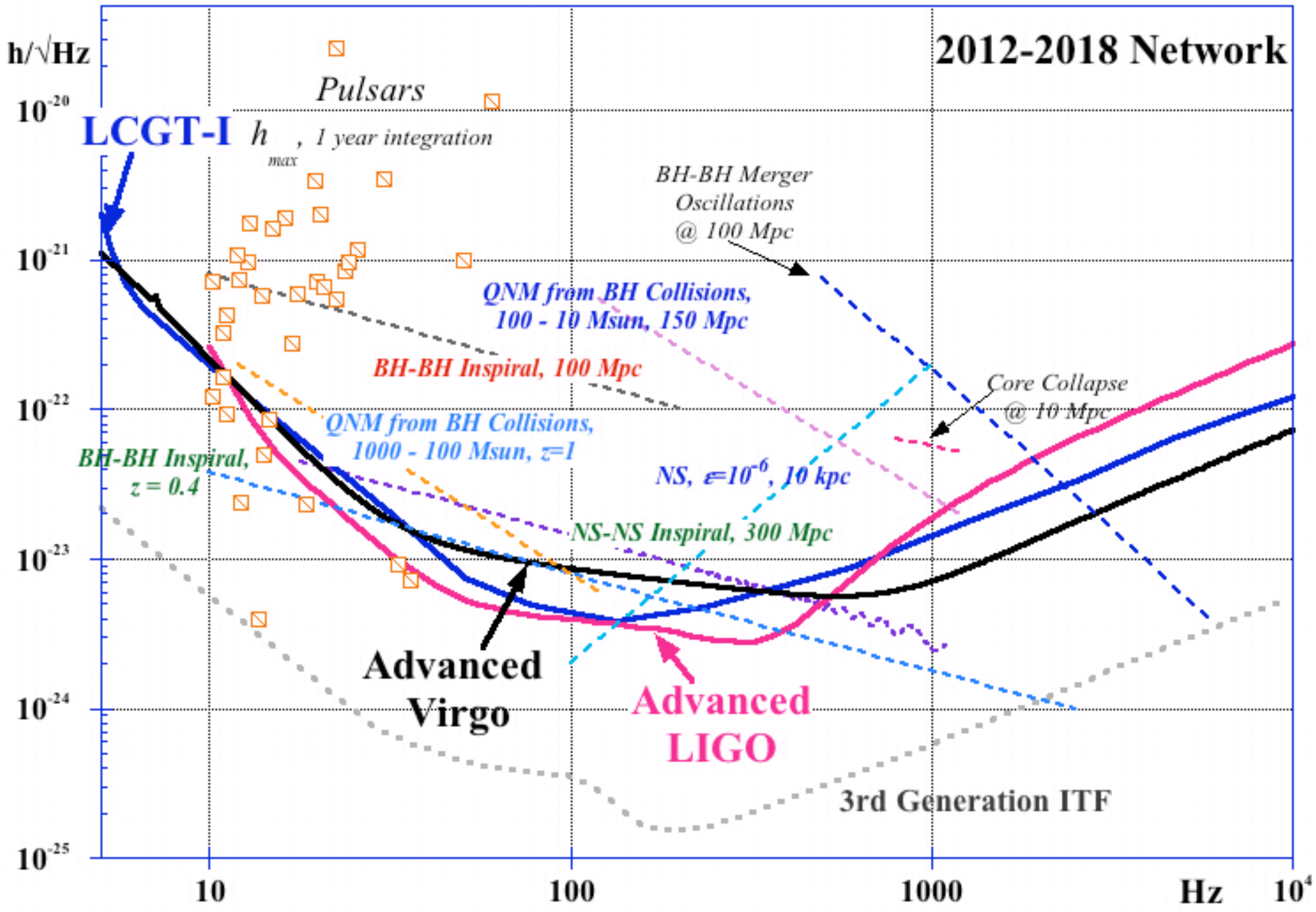
I rivelatori "Enhanced" vanno considerati come fasi intermedie verso "Advanced".

Lo sviluppo di Virgo+ e LIGOe deve essere intervallato da periodi di funzionamento in coincidenza:
(VSR1 18 Maggio 2007+4.5 mesi,
VSR2 26 Giugno 2009+6 mesi).

I rivelatori Advanced sono concepiti per esplorare un volume che ha un volume 1000 maggiore di quello accessibile tramite gli attuali rivelatori e permetteranno di fare osservazioni astrofisiche:
BNS: 2-30 events/y,150 Mpc; BBH: 20 events/y, 700 Mpc.

La rivelazione coerente Virgo-LIGO fornisce all'osservatorio composto dai 2 interferometri LIGO un aumento della profondità del 40% e permette la ricostruzione della polarizzazione dei segnali gravitazionali e la distanza delle sorgenti.

Conclusioni (annexe)



END

la solita domanda, please …

Il VUOTO

La pressione residua in VIRGO è 10^{-7} mbar (H_2O+H_2+HC) senza bake-out,

La pressione residua in Advanced VIRGO deve essere 10^{-9} mbar (bake-out necessario)

Il rumore dovuto alla pressione residua può limitare la sensibilità di Ad VIRGO

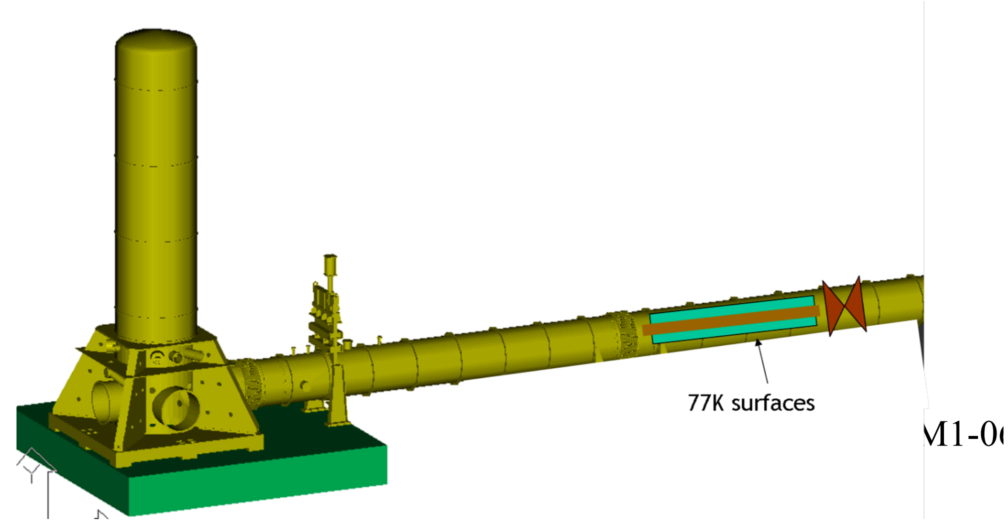
Conseguenza :

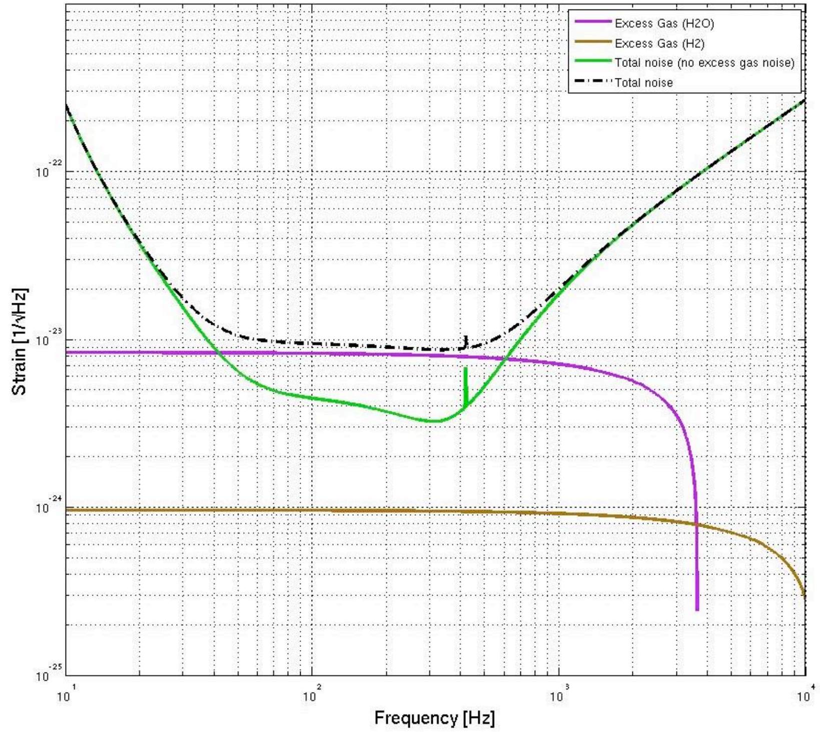
Ogni volta che si cicla da pressione atmosferica a vuoto il bake-out è necessario

Il bake-out di 6 km di tubo costa !!

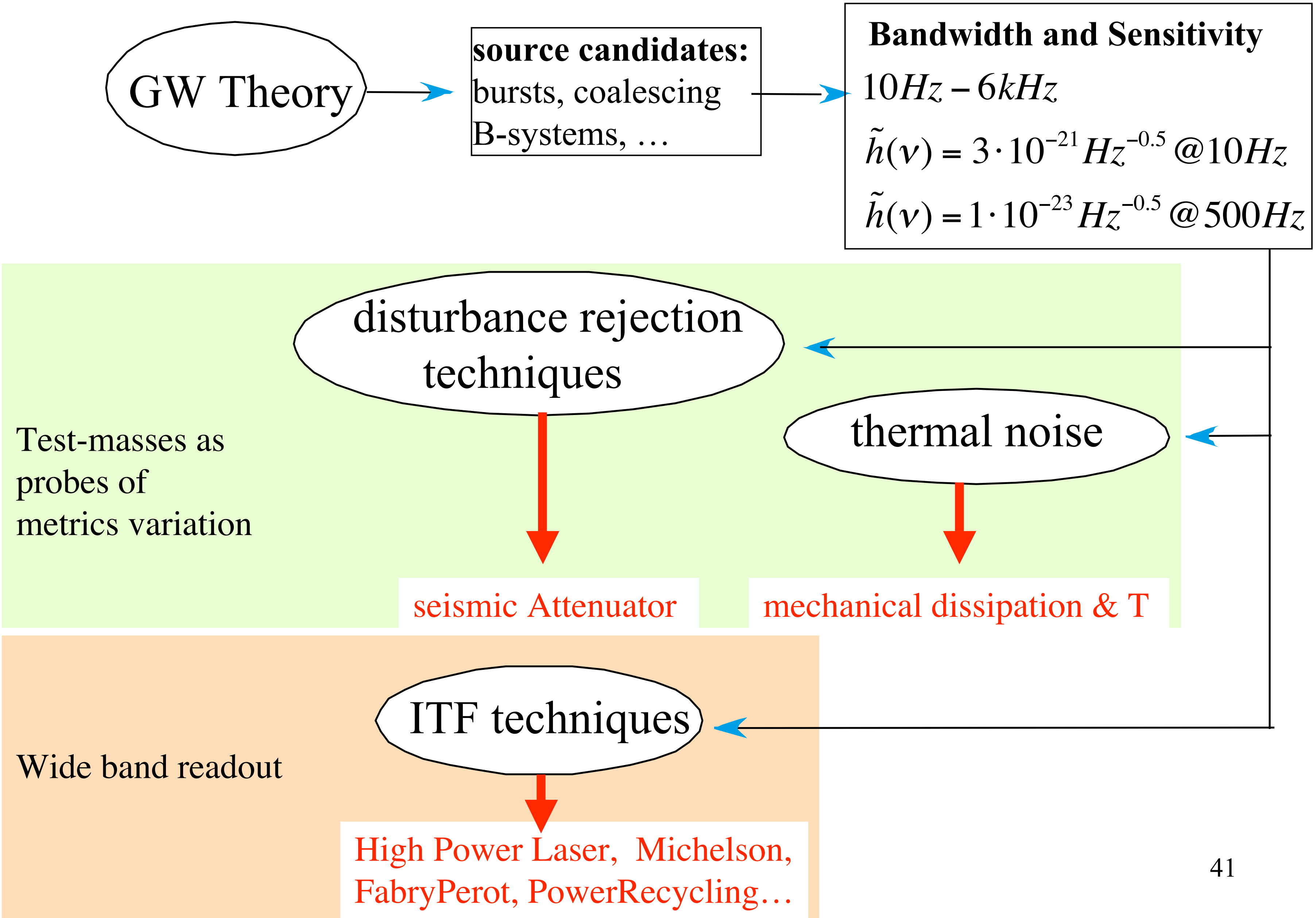
Soluzione

Separare il vuoto delle Torri da quello dei Tubi , introducendo delle trappole criogeniche





Design of a wide-band ground-based GW detector



EM vs G waves - Spectral investigation

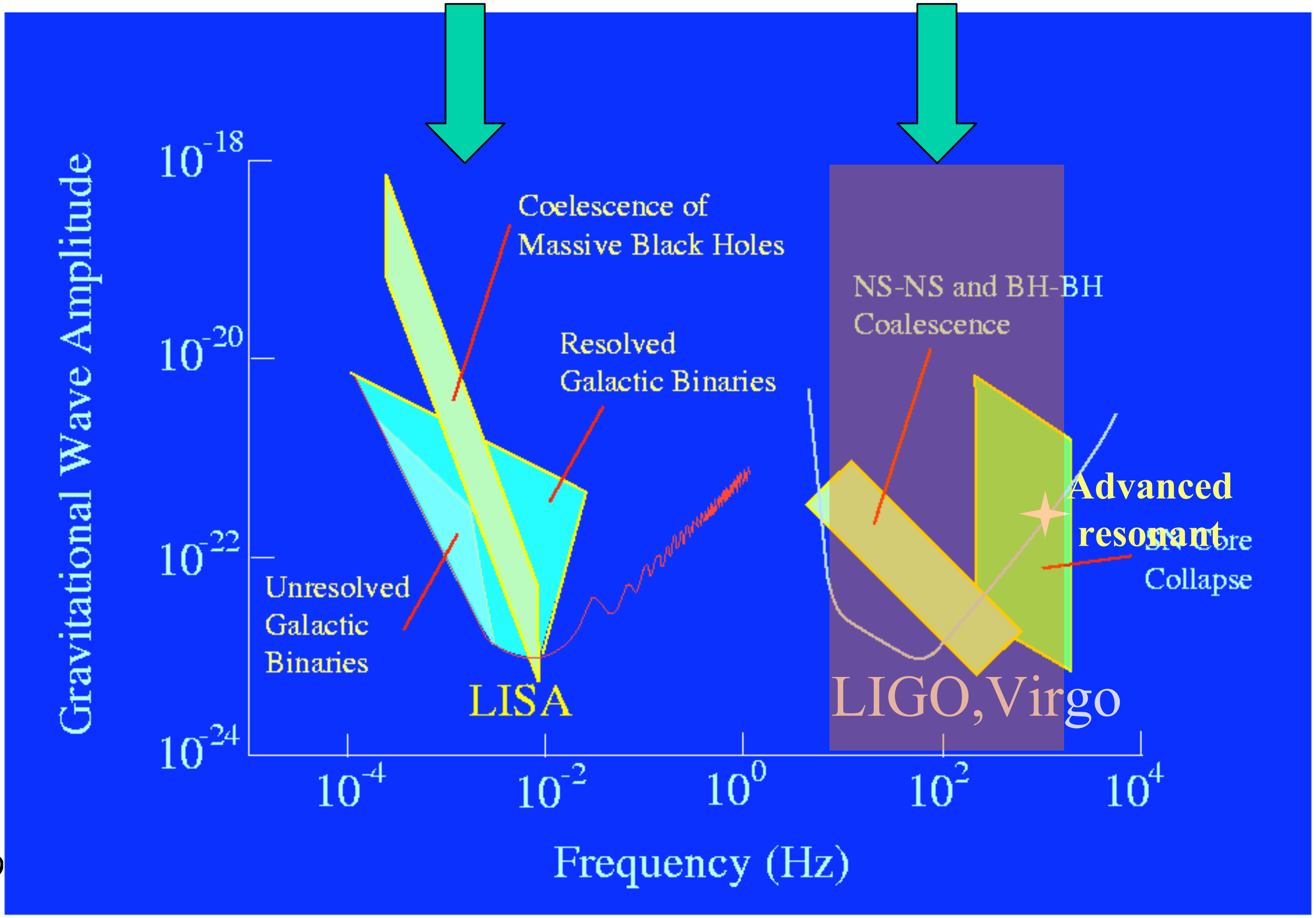
EM: 20 decades (ULF radio - HE γ)

GW: 8 decades (aimed..)

GW: ~ 3 decades (actual)

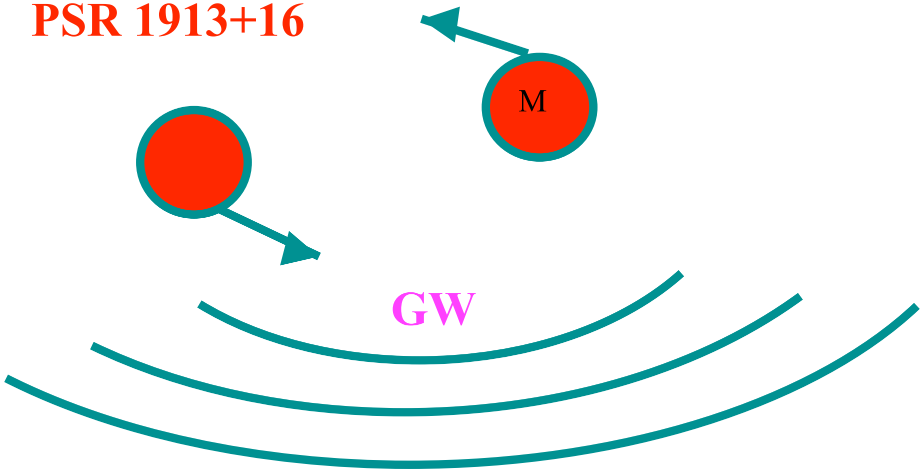
SPACE

TERRESTRIAL



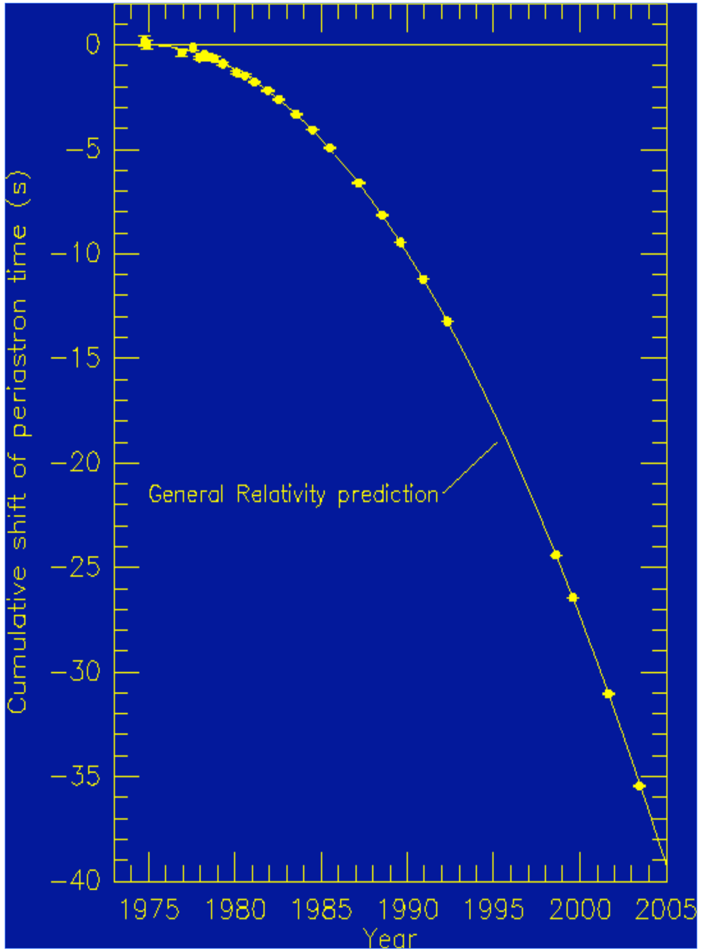
GW existence demonstration

Neutron Star System
PSR 1913+16



$$\dot{P}_{MEAS} / \dot{P}_{GTR} = 1.0023 \pm .0047$$

Taylor and Hulse
(Nobel 1993)



Orbital period decreasing changes periastron time in agreement with GRT

 Merger…too far (~300 My)

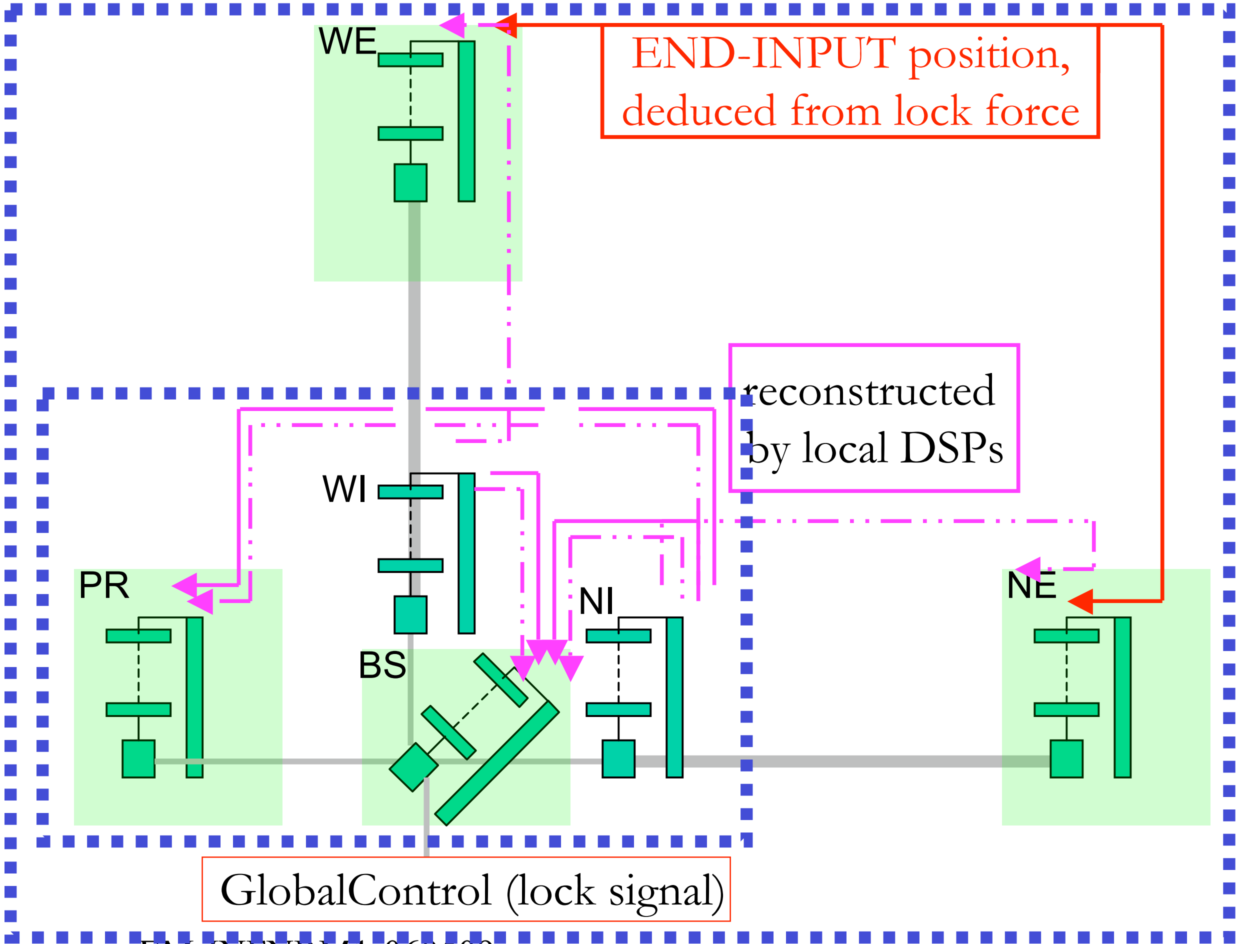
Suspension quasi-inertial damping: a too-short-blanket recently improved (VSR1-2007)

<u>The problem of top-stage control</u>:
avoiding wind-tilt noise (through accelerometers, f < 70 mHz) and
µseism sea disturbance (through position control, 0.15-0.6 Hz)

µseism is **incoherent** along the arm baseline =>µSeism reduced at **END suspension top-stages** by using position referred to **INPUT mirrors**;

Also the Acceleration !

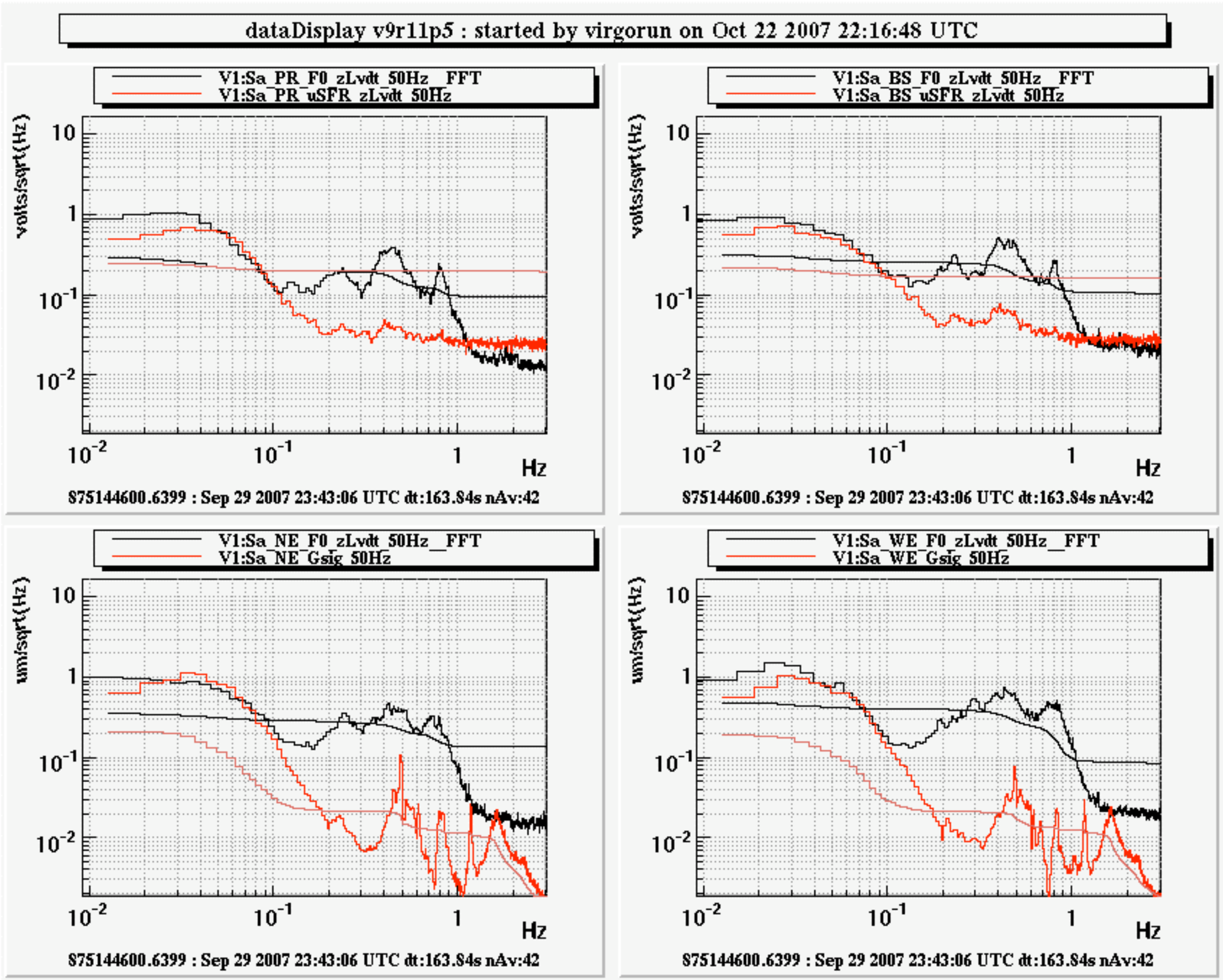
µseism is **coherent** in the central area µSeism-Free control signals reconstructed with respect to **INPUT mirrors**



µseism rejection: VSR1start-VSR1stop

quiet

INPUT mirror suspensions used as reference

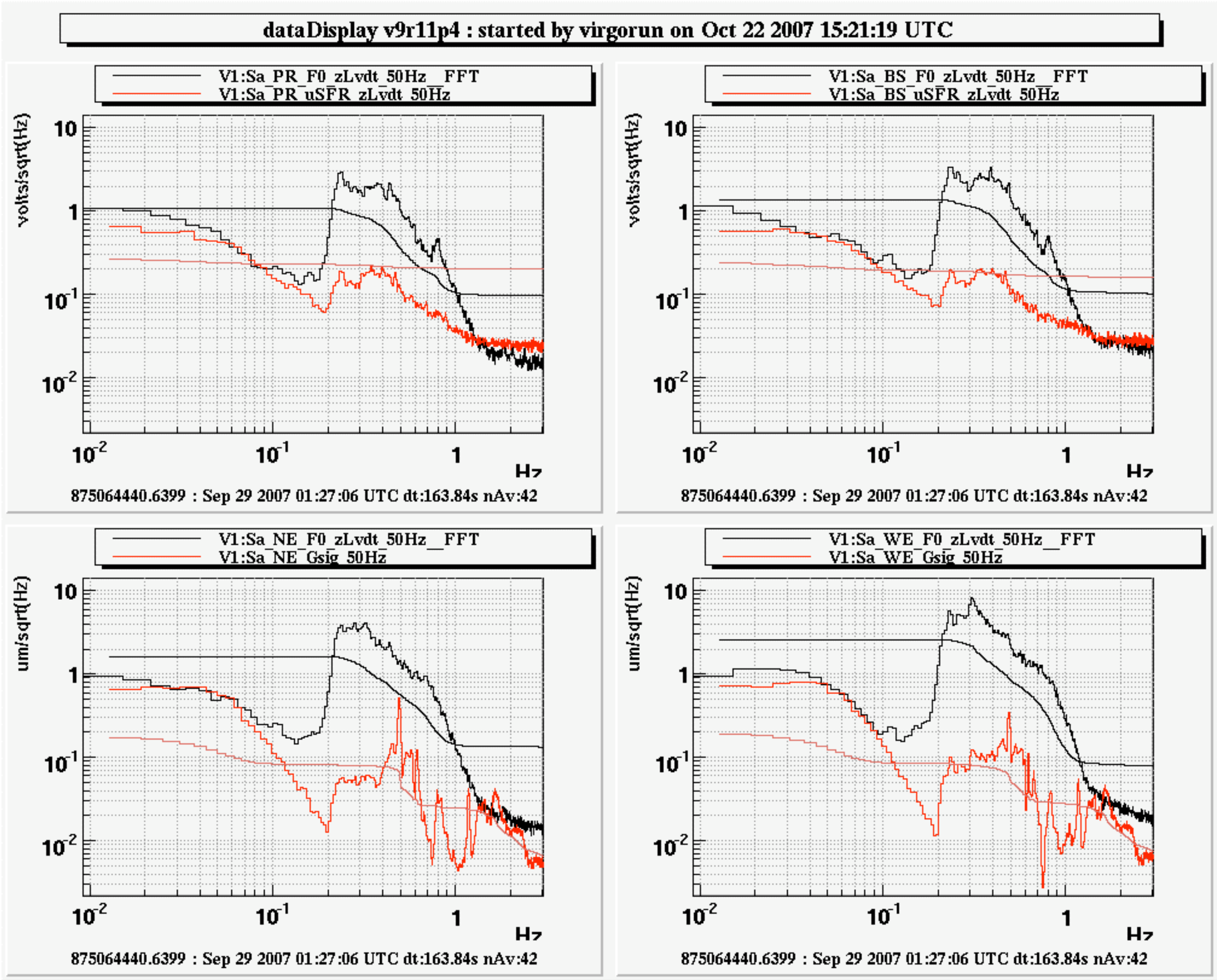


Monitoring of channels used for top-stage control at VSR1 start setup.

Combined channels used at VSR1 stop: **µSFR** (µSeism-Free Reconstruction) and **GIPC** (Global-Inverted-Pendulum Control)

µseism: rejection VSR1start-VSR1stop

INPUT mirror suspensions used as reference



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