The challenge of Gravitational Wave Astronomy

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Soon : one century of GR

Metric tensor $ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu$

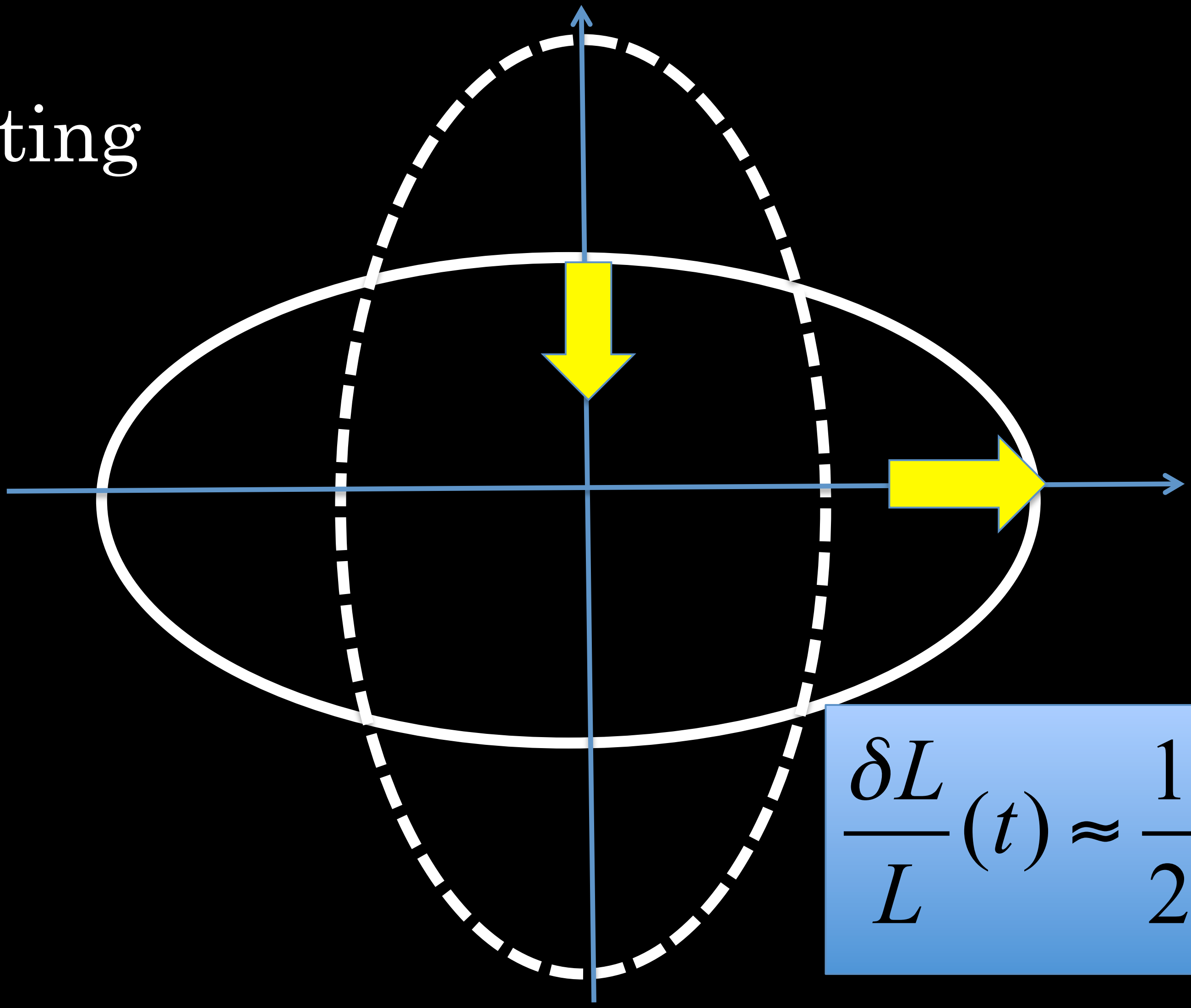
Einstein equation (1916) $G_{\mu\nu}(g, \partial g, \partial^2 g) = \frac{8\pi G}{c^4} T_{\mu\nu}$

Linearisation $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

Wave equation $\Box h_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$ → **Gravitational waves**

Spacequakes

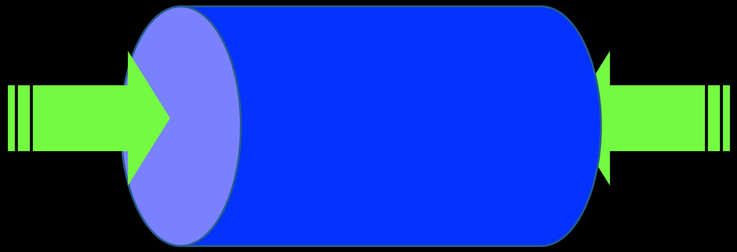
Oscillating
Shear
strain



$$\frac{\delta L}{L}(t) \approx \frac{1}{2} h(t)$$

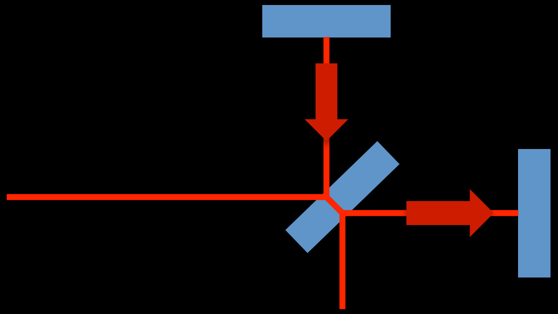
Physical effects of a GW

« Bar » detectors



Tidal stresses
In a solid

Interferometers



Modulation
of optical paths

Vibrating space-time

Light propagation : $\boxed{g_{\mu\nu}dx^{\mu}dx^{\nu}=0}$

➡ $$\boxed{0=ds^2=c^2dt^2-(1+h(t))dx^2}$$

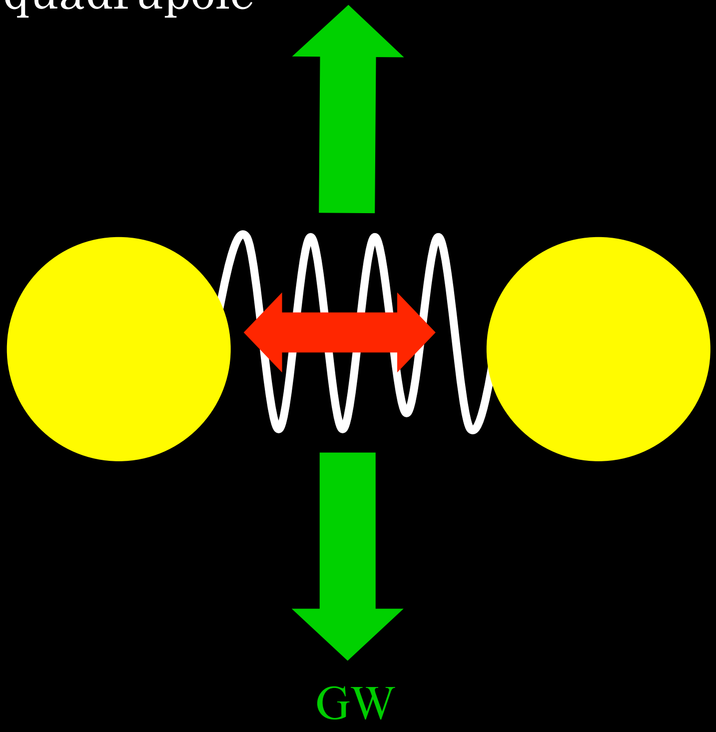
$$\boxed{dt=\frac{dx}{c}+\frac{1}{2}h(t)dt}$$

Modulated
Retarded
time

$$\boxed{t_R=t-\frac{L}{c}\pm\frac{1}{2}\int_{t-L/c}^{t}h(u)\,du}$$

Sources of GW

Fast varying mass quadrupole

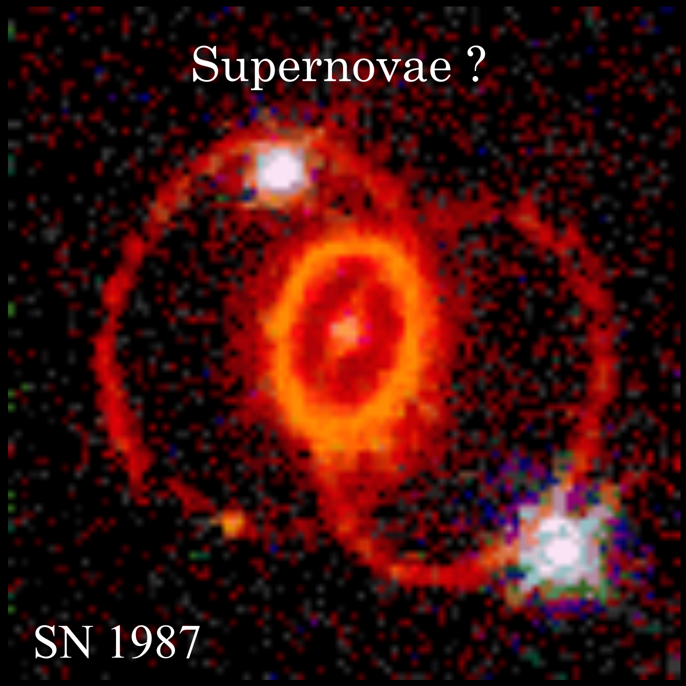


Mass quadrupole :

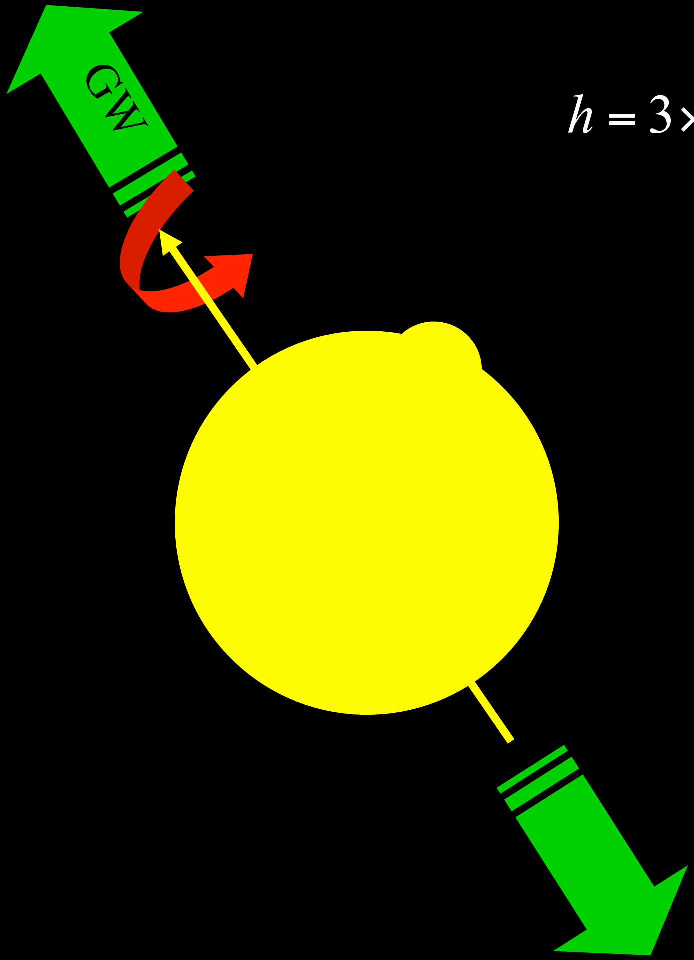
$$\Xi^{jk}(t) = \int \rho(t,\vec{x})\left[x^j x^k - \frac{1}{3}\delta^{jk}x^2\right]d^3x$$

$$h_{jk}(\boldsymbol{r},t) = -\frac{2G}{c^4}\frac{1}{r}\partial_t^2\Xi_{jk}^{TT}(t-\boldsymbol{r}/c)$$

Asymmetry ?



Rapidly rotating neutron stars



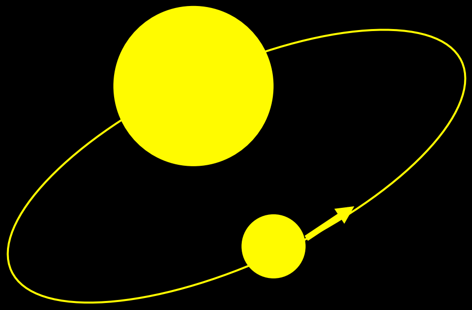
$$h = 3\times 10^{-25}\,\frac{\varepsilon}{10^{-6}}\,\frac{I_{zz}}{10^{38}\ \mathrm{kg.m^2}}\,\frac{100\mathrm{pc}}{d}\left(\frac{\nu}{100\ \mathrm{Hz}}\right)^2 \qquad (*)$$

Asymmetry $\varepsilon = \dfrac{I_{xx} - I_{yy}}{I_{zz}}$

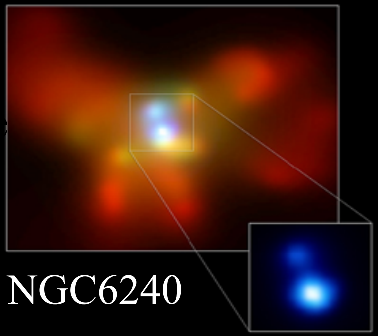
(*) Jaranowski, Krolak, Schutz
ArXiv:gr-qc/9804014v1

Coalescing compact binaries (CBC)

Binary neutron stars



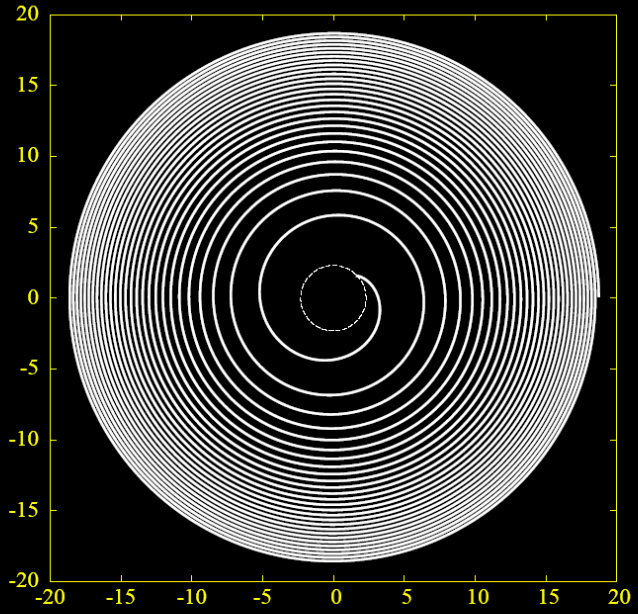
Binary Black Holes



NGC6240

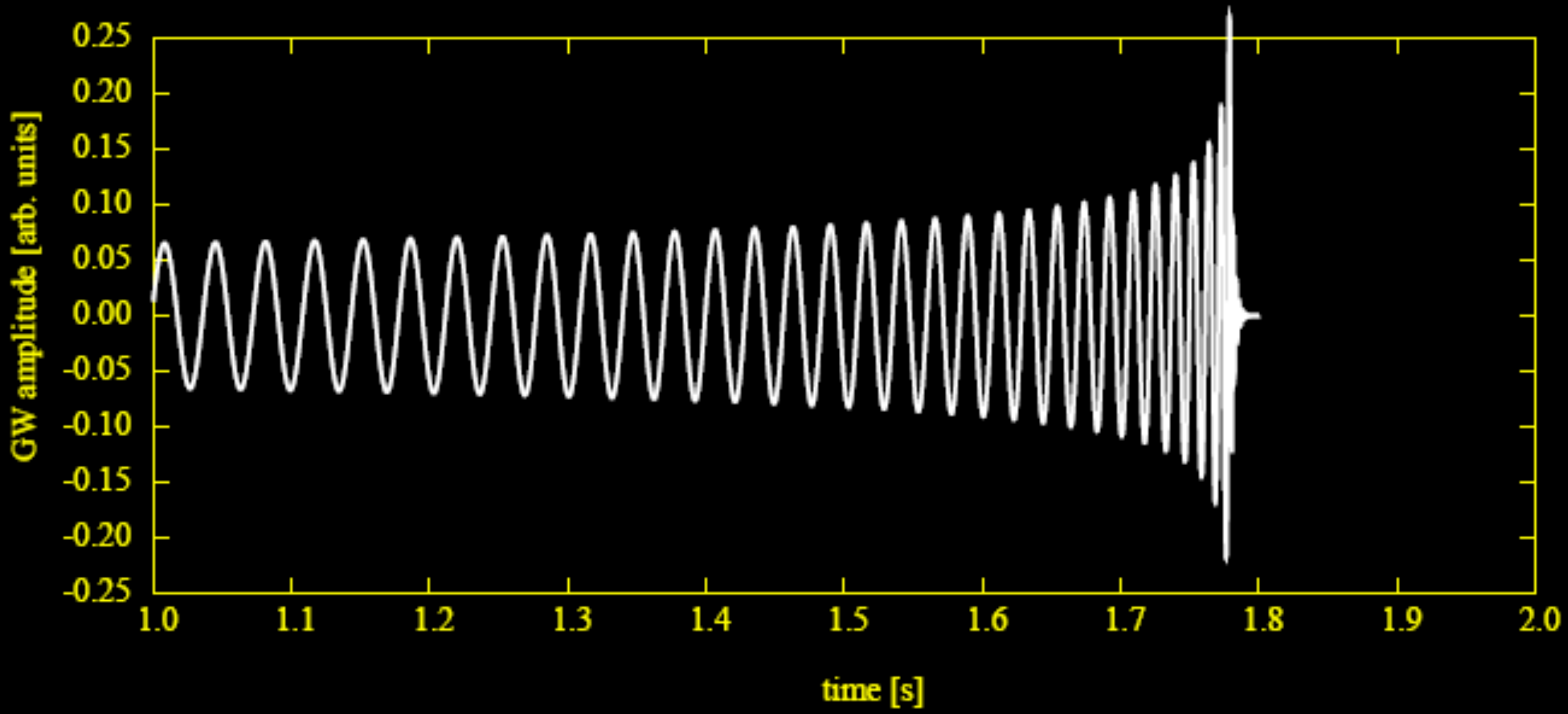
Radiative
Energy loss

Inspiral
And
coalescence

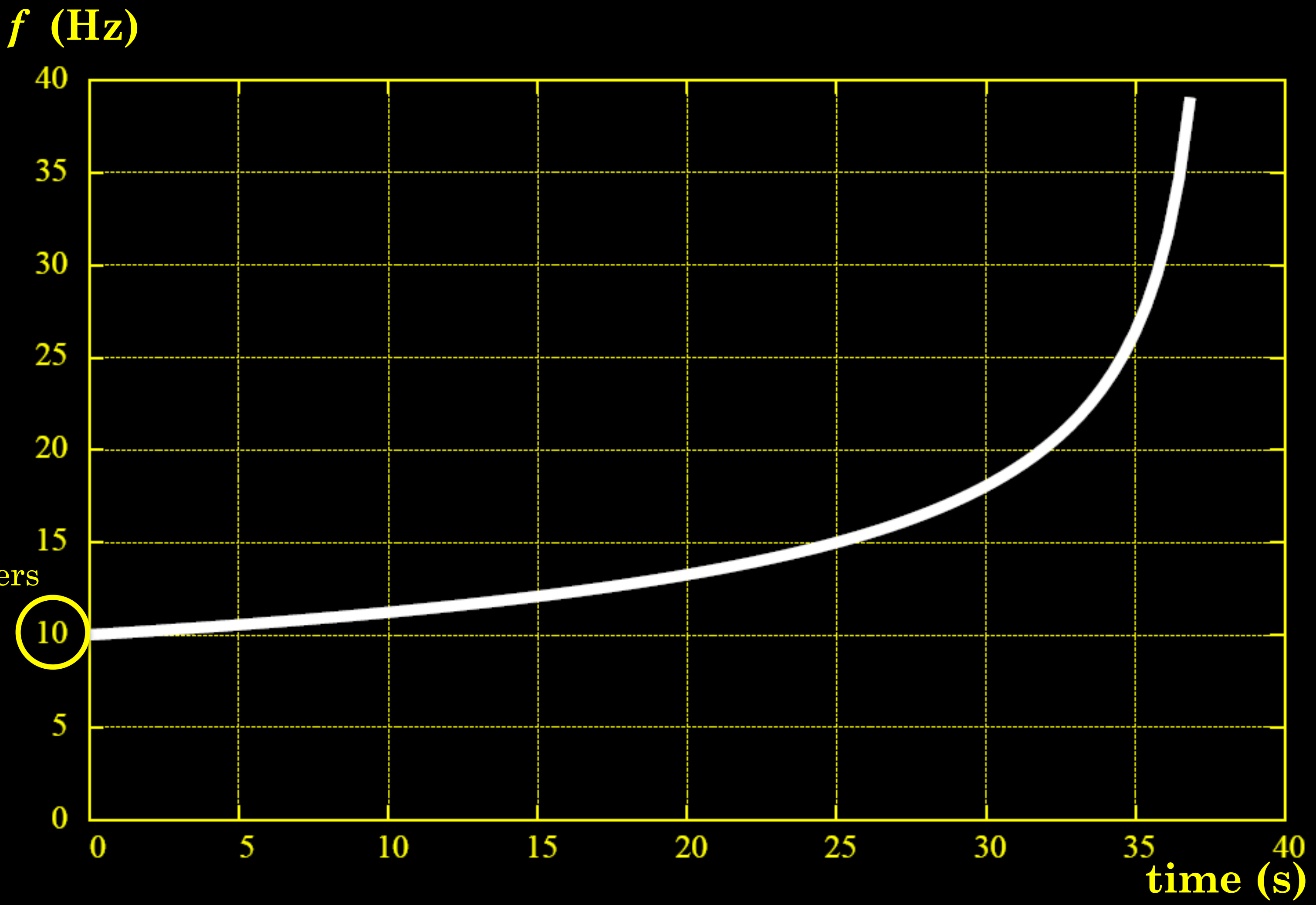


waveforms

Chirp produced by a black hole binary inspiral:
theory « Effective One Body »



A « chirp » from a [10,10] SM Bin.BlackH coalescence



Chirp enters the detection band

Coalescing compact binaries (CBC)

Chirp mass : $\mathcal{M} = \dfrac{(m_1 m_2)^{3/5}}{\left(m_1 + m_2\right)^{1/5}}$

Lowest detectable frequency : $f_<$

smallest amplitude

$$h_< \sim \frac{4}{d}\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\pi f_<}{c}\right)^{2/3}$$

Chirp duration $\tau = \dfrac{5}{256}\left(\pi f_<\right)^{-8/3}\left(\dfrac{G\mathcal{M}}{c^3}\right)^{-5/3}$

$m_1 = m_2 = 1.5\,M_\odot$
$d = 100$ Mpc
$f_< = 10$ Hz

$h_< \approx 9\times 10^{-24}$ **τ~15’**

$m_1 = m_2 = 10 M_\odot$
$d = 100$ Mpc

$h_< \approx 2\times 10^{-22}$ **τ~40”**

Interferometers

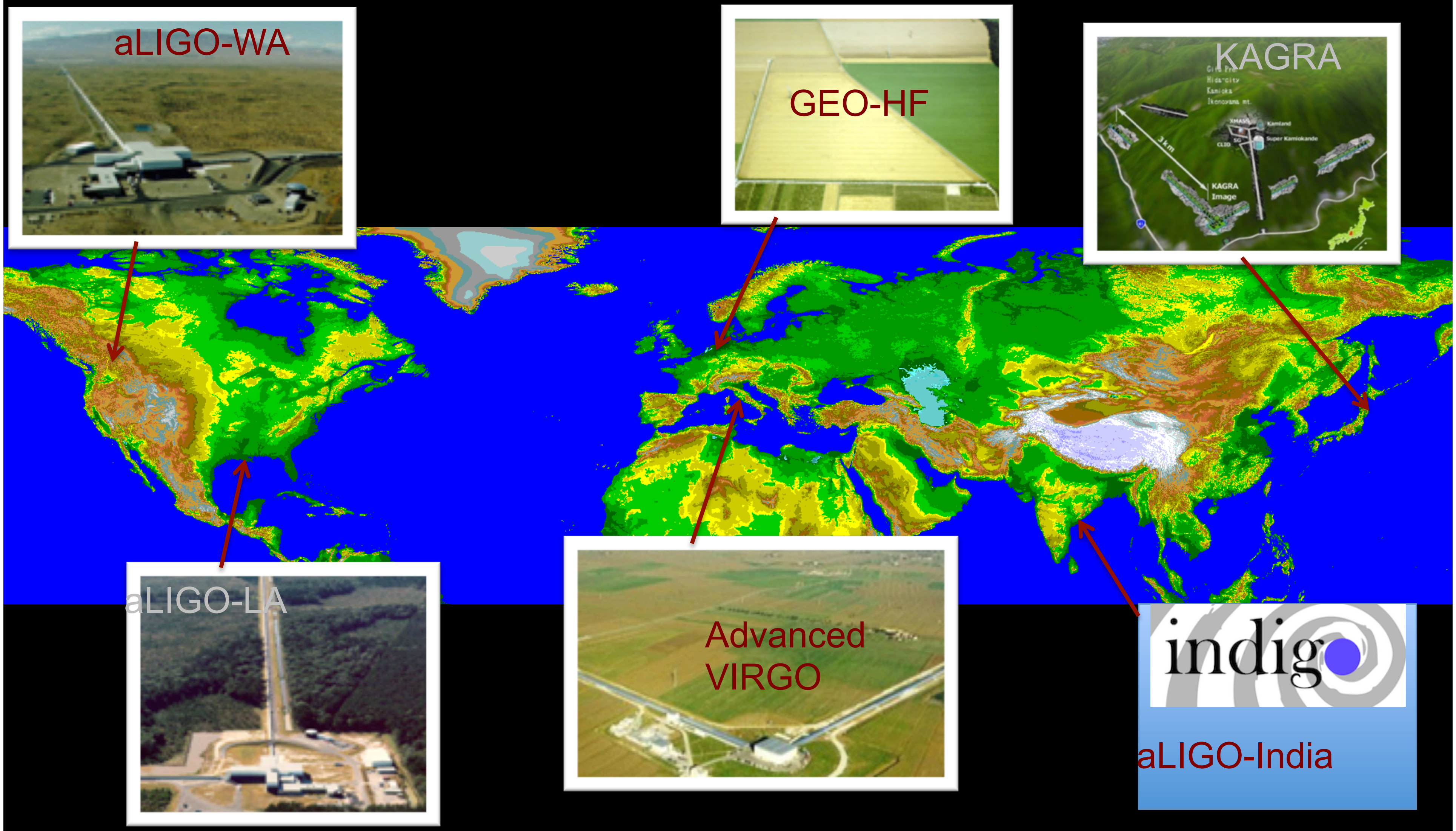
Large antennas currently in the construction phase after 1st generation successfully operated


Virgo Observatory
Cascina, Italy


LIGO Hanford Observatory
Hanford, WA USA


LIGO Livingston Observatory
Livingston, LA USA

Network


aLIGO-WA
GEO-HF
KAGRA
XMASS
Kamland
Super Kamiokande
CLIO
3km
KAGRA Image
aLIGO-LA
Advanced VIRGO
indigo
aLIGO-India

The Virgo Collaboration :
18 European teams

EGO Council (CNRS, INFN, NIKHEF)

EGO Site Cascina

NIKHEF, Amsterdam
Radboud University , Nijmegen
The NETHERLANDS

RMKI,
Academy of sciences
Budapest
HUNGARY

Institute of Mathematics
Polish Academy of Sciences
Varsaw
POLAND

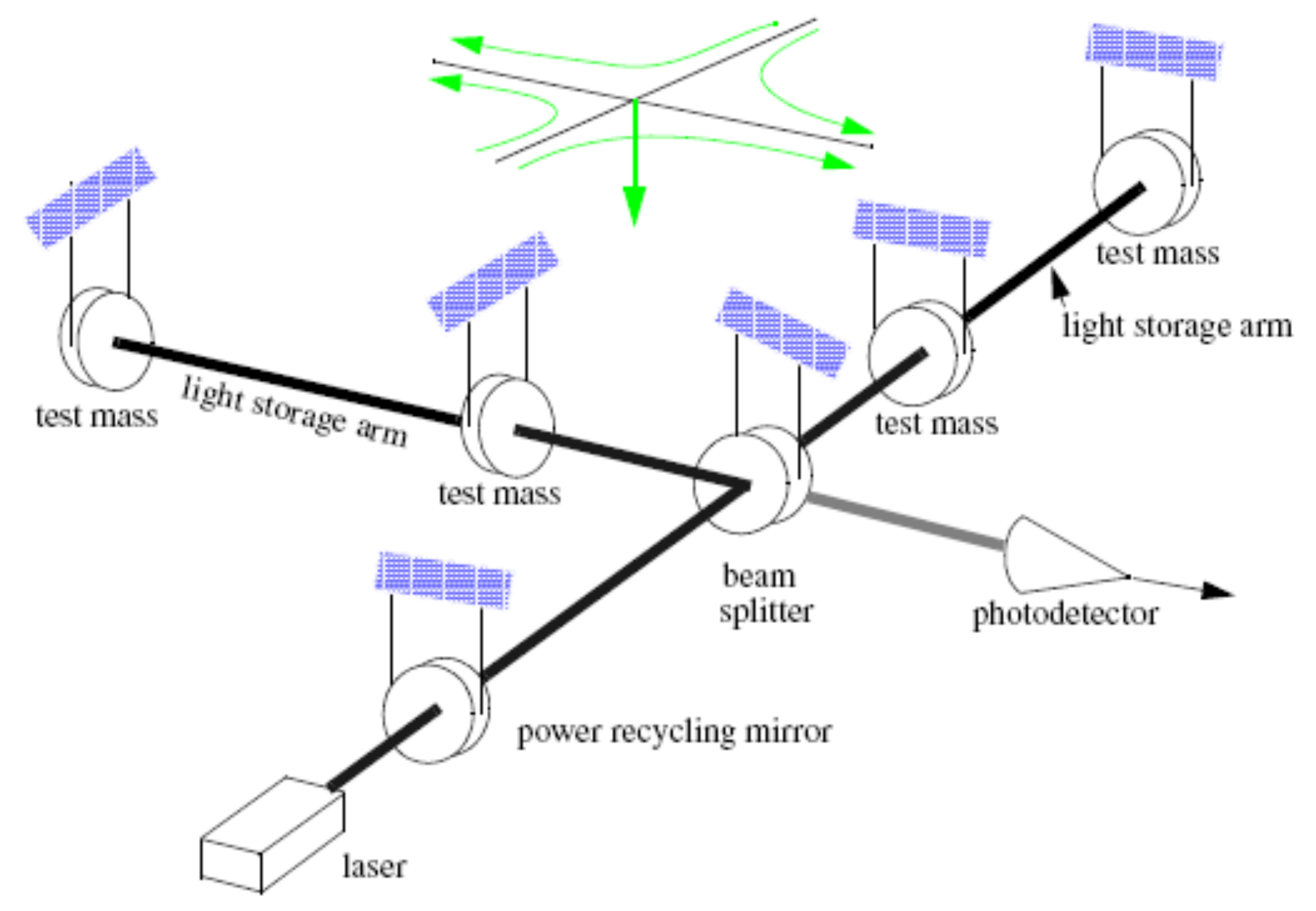
ITALY:

INFN + Universities of
Firenze-Urbino
Genova
Napoli
Perugia
Roma La Sapienza
Roma Tor Vergata
Pisa
Padova-Trento

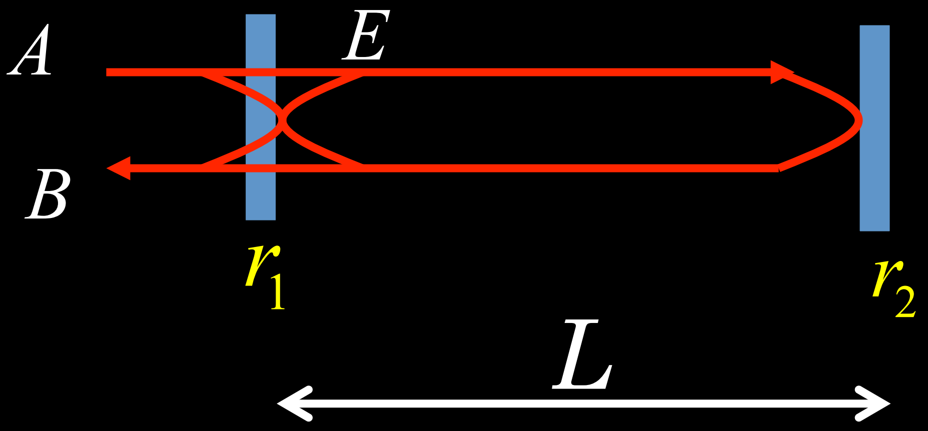
FRANCE :
Laboratoire de l'Accélérateur Linéaire (U. Paris-Sud+CNRS)
Laboratoire d'Annecy de Physique des Particules (CNRS)
Astroparticules et Cosmologie (U. Paris 7+CNRS)
Laboratoire des Matériaux Avancés (Lyon-CNRS)
Laboratoire Kastler-Brossel (ENS – U. Paris 6 - CNRS)
Observatoire de la Côte d'Azur (CNRS, Nice)
ESPCI (Paris)

Virgo Collaboration : the cloud

Generic interferometer



Fabry-Perot cavities

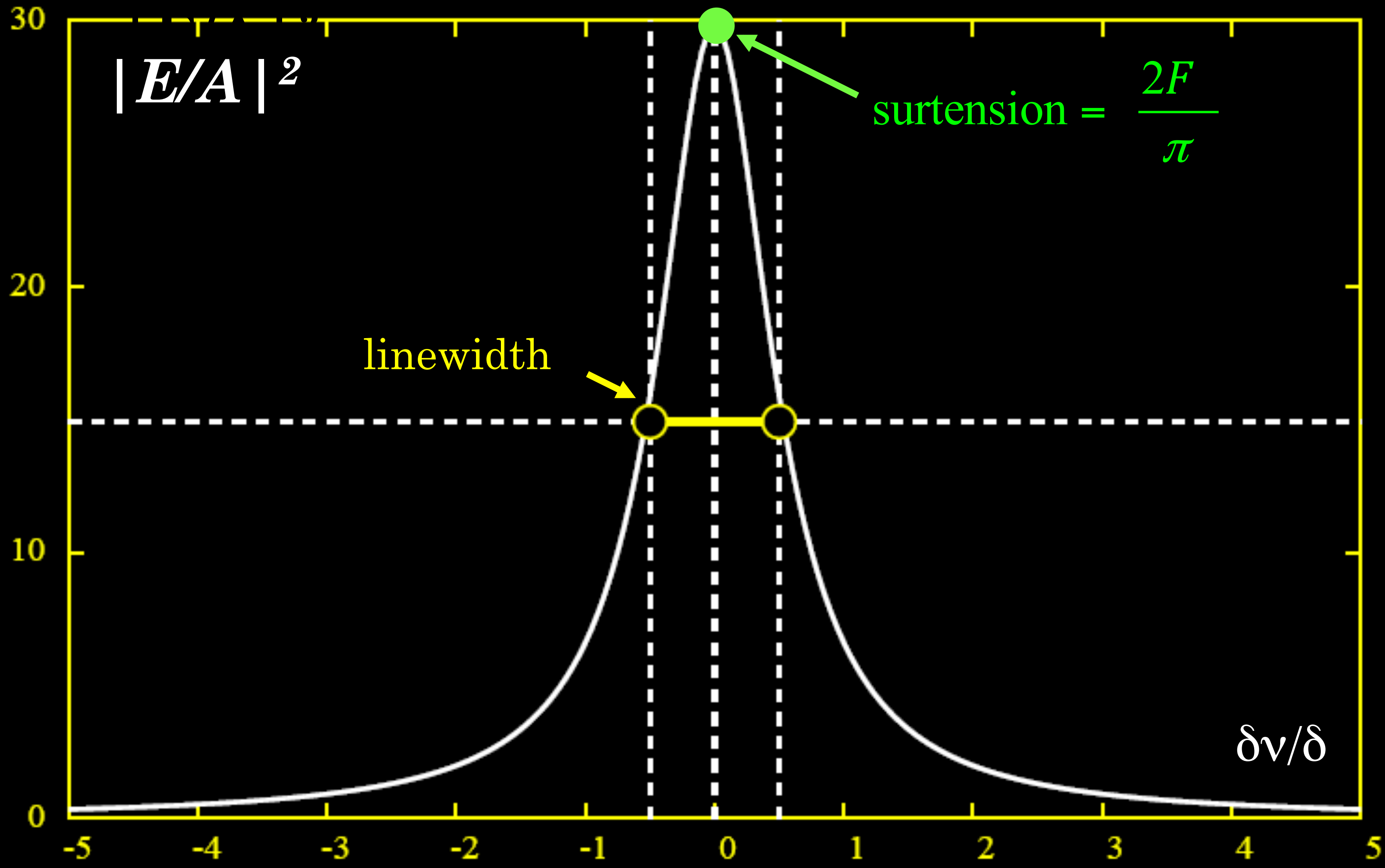


Free Spectral Range : $\Delta\nu = c/2L$ (Virgo : 50 kHz)

Finesse : $F = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$ (Virgo ~ 450)

Linewidth : $\delta = \Delta\nu / F$ (Virgo ~ 100 Hz)

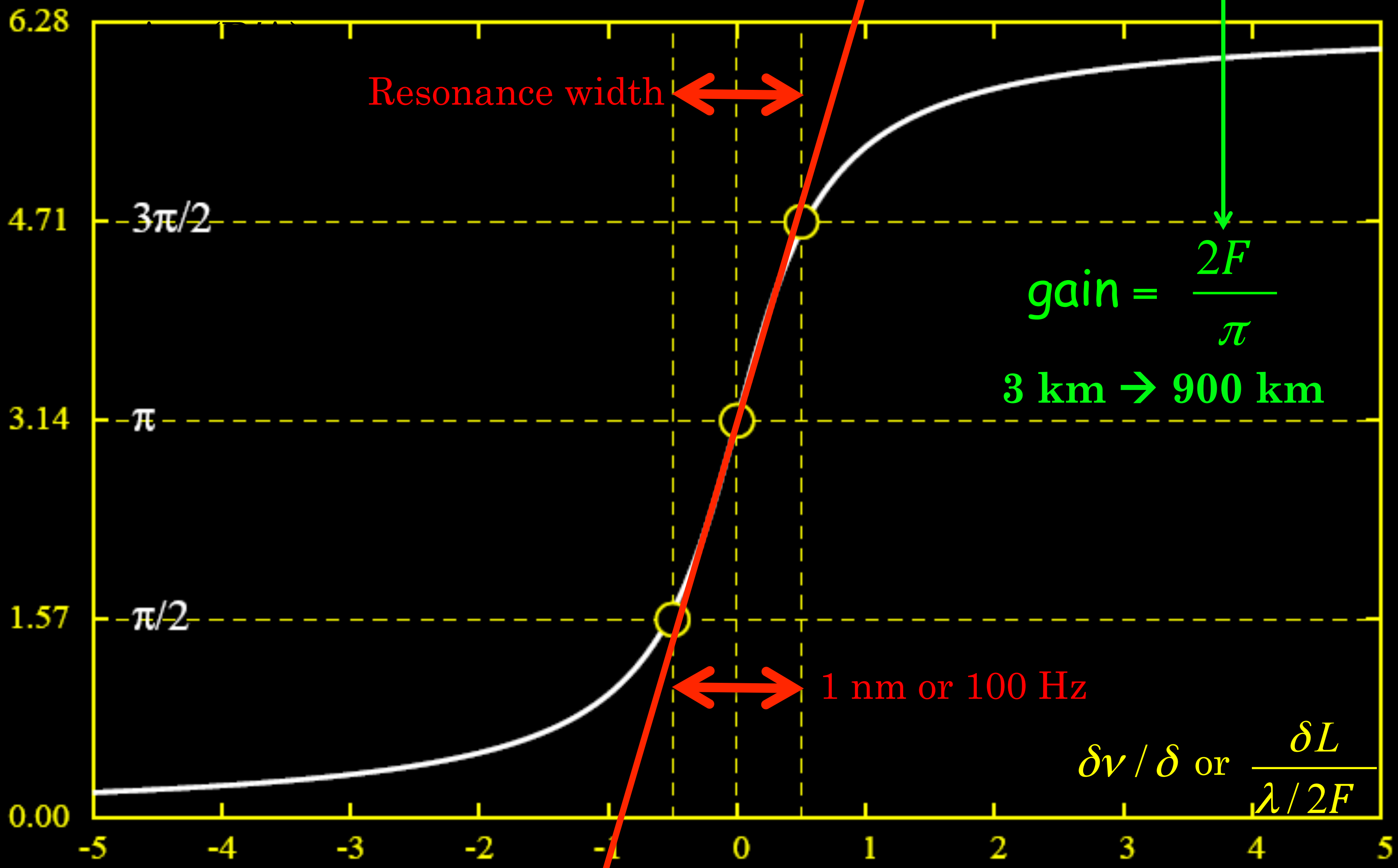
Resonance: Airy peak



surtension = $\frac{2F}{\pi}$

Phase reflectance

$$\frac{d\Phi}{d\delta L} = \frac{8F}{\lambda} = \frac{2F}{\pi} \times \frac{4\pi}{\lambda}$$



Resonance width

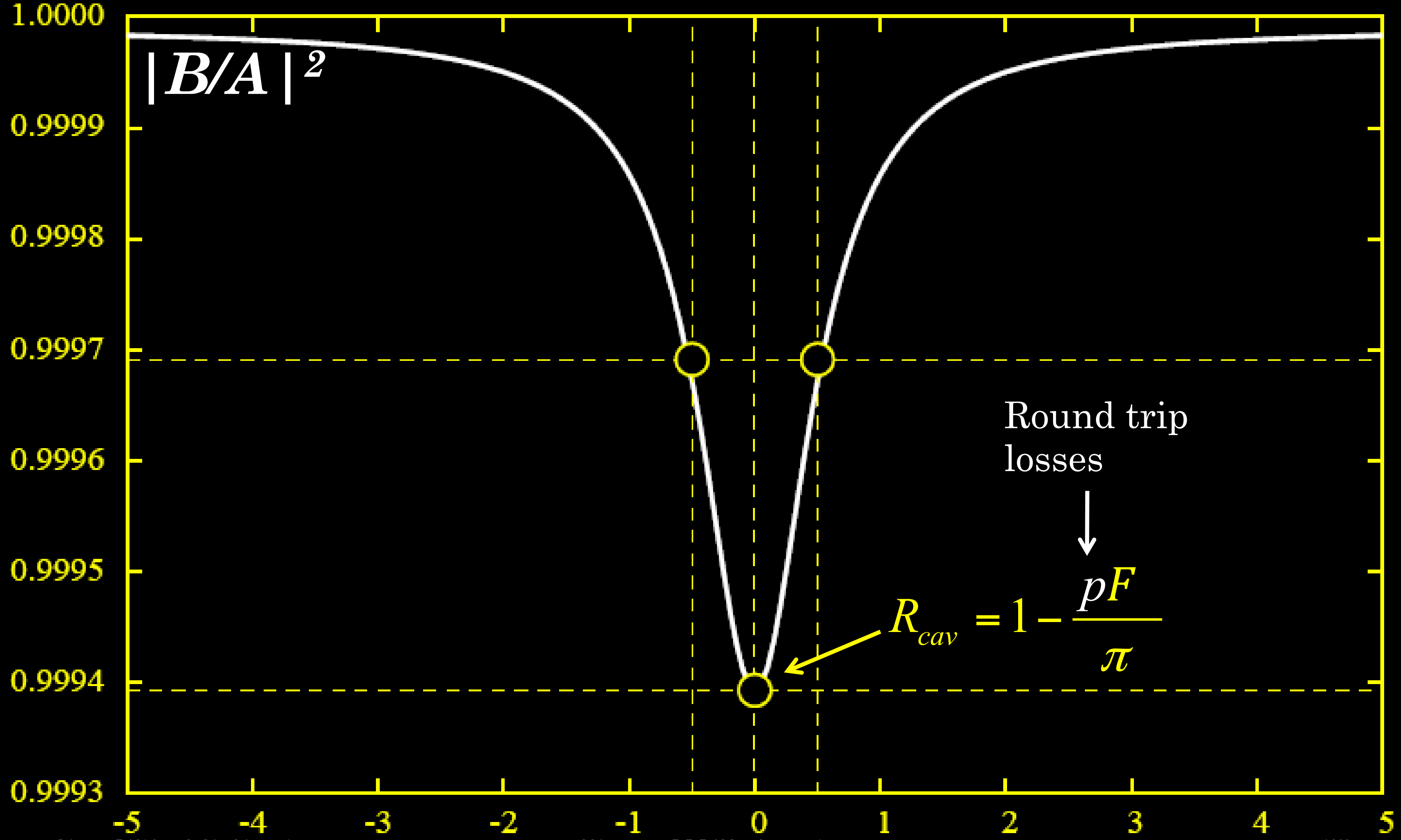
1 nm or 100 Hz

$$\text{gain} = \frac{2F}{\pi}$$

3 km → 900 km

$$\delta\nu / \delta \text{ or } \frac{\delta L}{\lambda / 2F}$$

Resonance : absorption peak

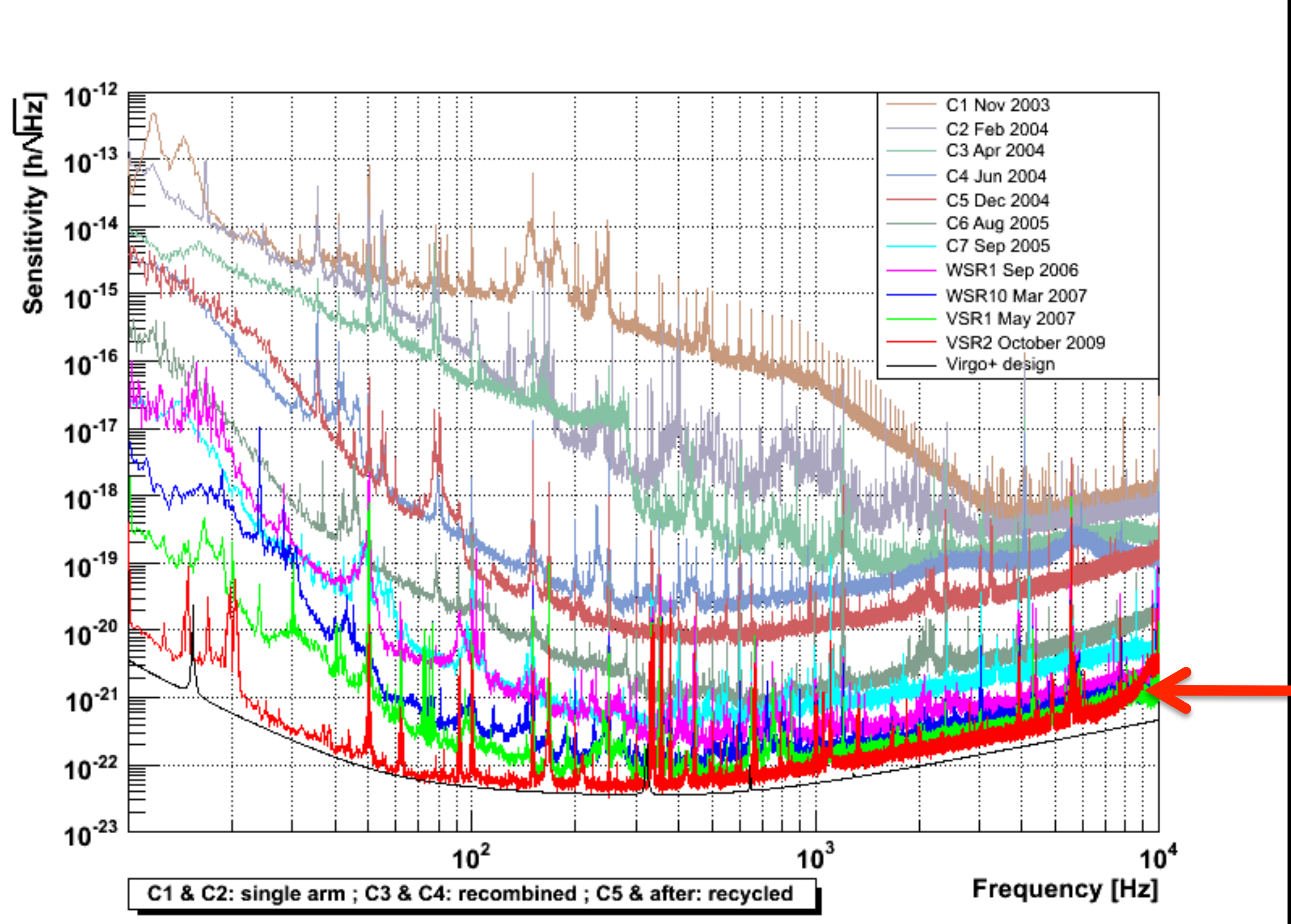


Round trip losses

$$R_{cav} = 1 - \frac{pF}{\pi}$$

Sensitivity of 1st generation

$h \sim [\,(10^{-44}\ \mathrm{Hz}^{-1}) \times (1\ \mathrm{kHz})\,]^{1/2} \sim 3 \times 10^{-21}$

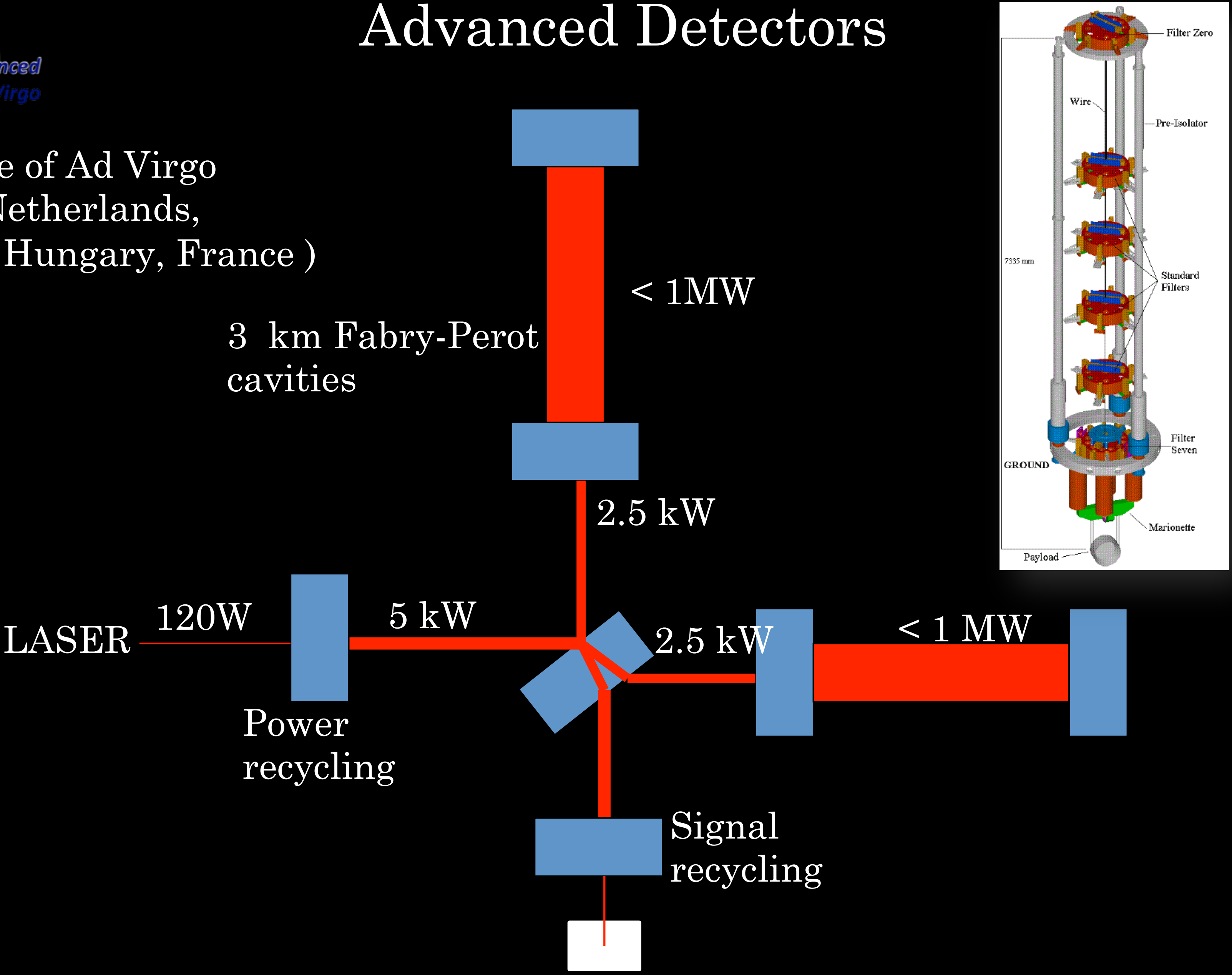


One order
Of magnitude
Missing →
« Advanced
Virgo »

4 years
ago …

Advanced Detectors

Example of Ad Virgo
(Italy, Netherlands,
Poland, Hungary, France)



3 km Fabry-Perot cavities

< 1MW

2.5 kW

LASER

120W

5 kW

Power recycling

2.5 kW

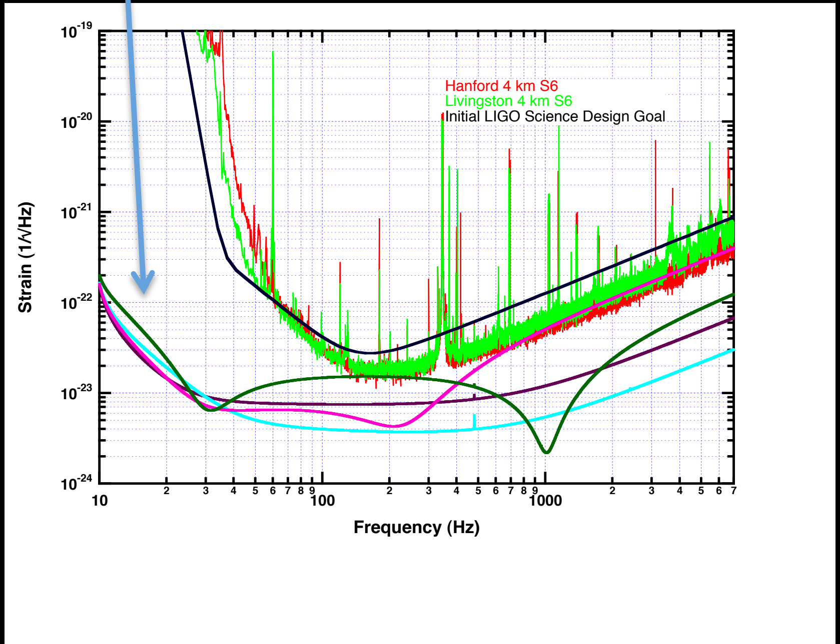
< 1 MW

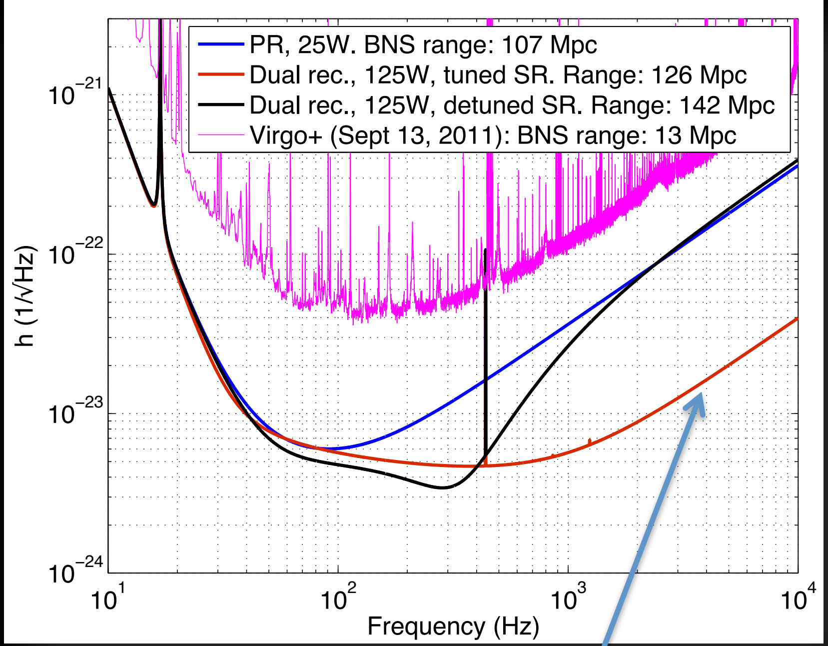
Signal recycling

New spectral sensitivities

Thermal
Noise
Low frequencies

LIGO





Virgo

Quantum
(shot)
Noise
High frequencies

Power recycling

Spectral density of shot noise

$$S_h(f) = \frac{\lambda}{8F\ L}\,\frac{1}{g}\sqrt{1+\left[\frac{4F\ Lf}{c}\right]^2}\,\sqrt{\frac{P_L}{h_P\nu}}$$

Laser power

Finesse

Recycling gain

Increasing the finesse and the recycling gain simultaneously : high quality mirror coatings, low absorption, low scattering, excellent surface quality

Increasing the laser power : extremely low absorption, thermal compensation

Thermal noise mitigation

Spectral density of noise (mirrors, bulk)

$$S_x(f) = \frac{4k_BT}{\pi f}\Phi\frac{1-\sigma^2}{2\sqrt{\pi}Yw}$$

Width of the
optical beam

Loss angle :
internal mechanical
losses

1) Large mirrors
2) High Q materials

Spectral density of noise (mirrors, coatings)

$$S_x(f) = \frac{4k_BT}{\pi f}\Phi_C\delta_C\frac{\pi(1+\sigma_C)(1-2\sigma_C)}{Y_C w^2}$$

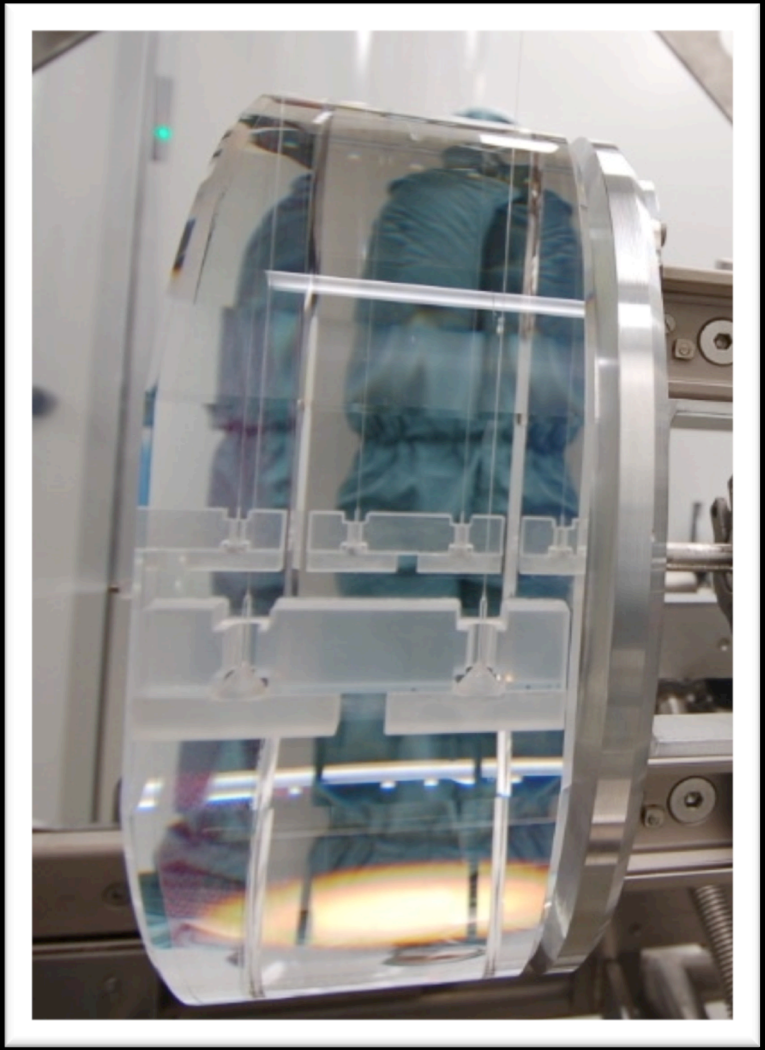
Thermal noise mitigation

Very large optical components

Beam splitter : 55cm diameter
10cm thickness, 52 kg

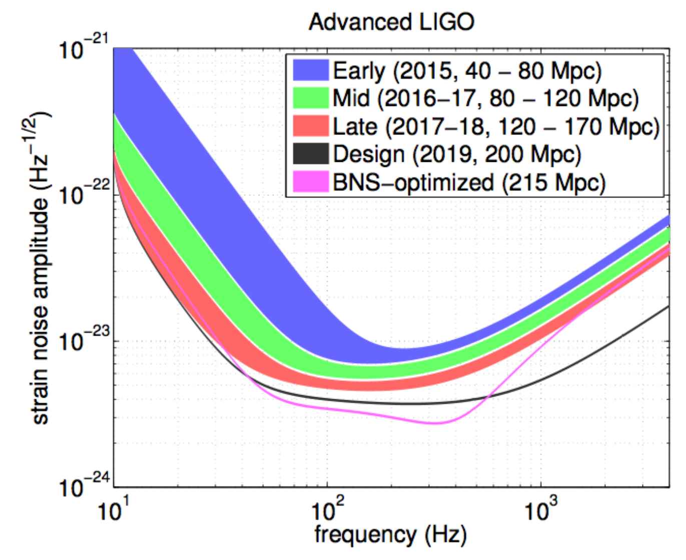
Test mass : 35cm diameter
20cm thickness, 42kg

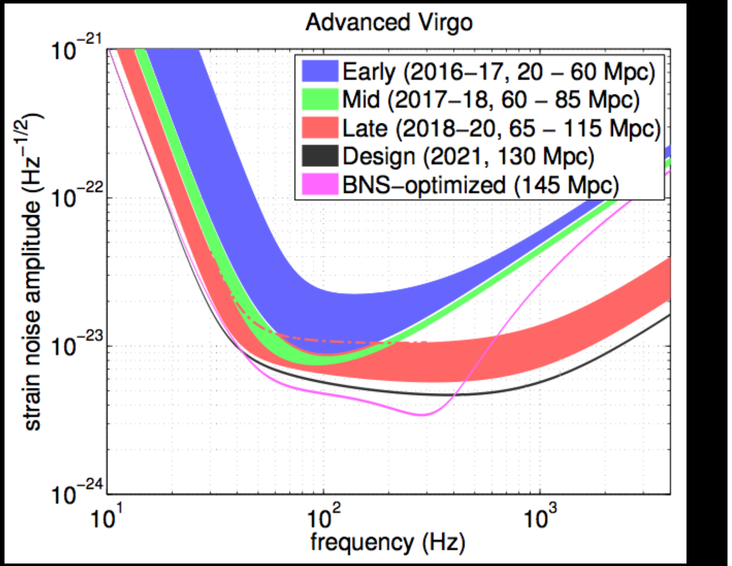
Thermal noise mitigation

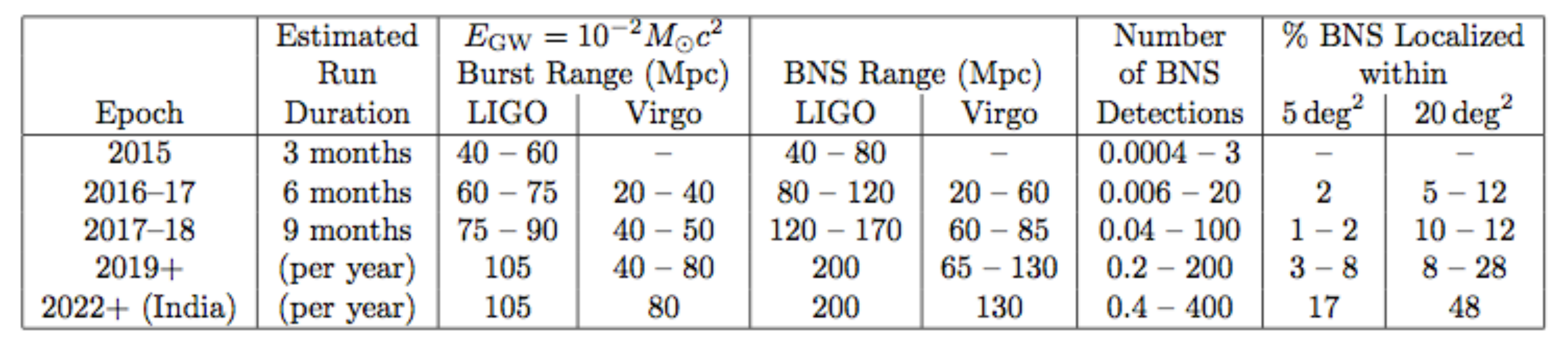


Monolithic
Suspensions
➔
High Q

Perspectives of Advanced detectors







Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

summary

- 1st generation successfull technically but below the threshold for detection
- 2d generation of LIGO/Virgo currently being constructed
- Taking data : LIGO 2015, Virgo 2016
- Network LIGO-Virgo
- KAGRA (Jap) & LIGO India will join the network later