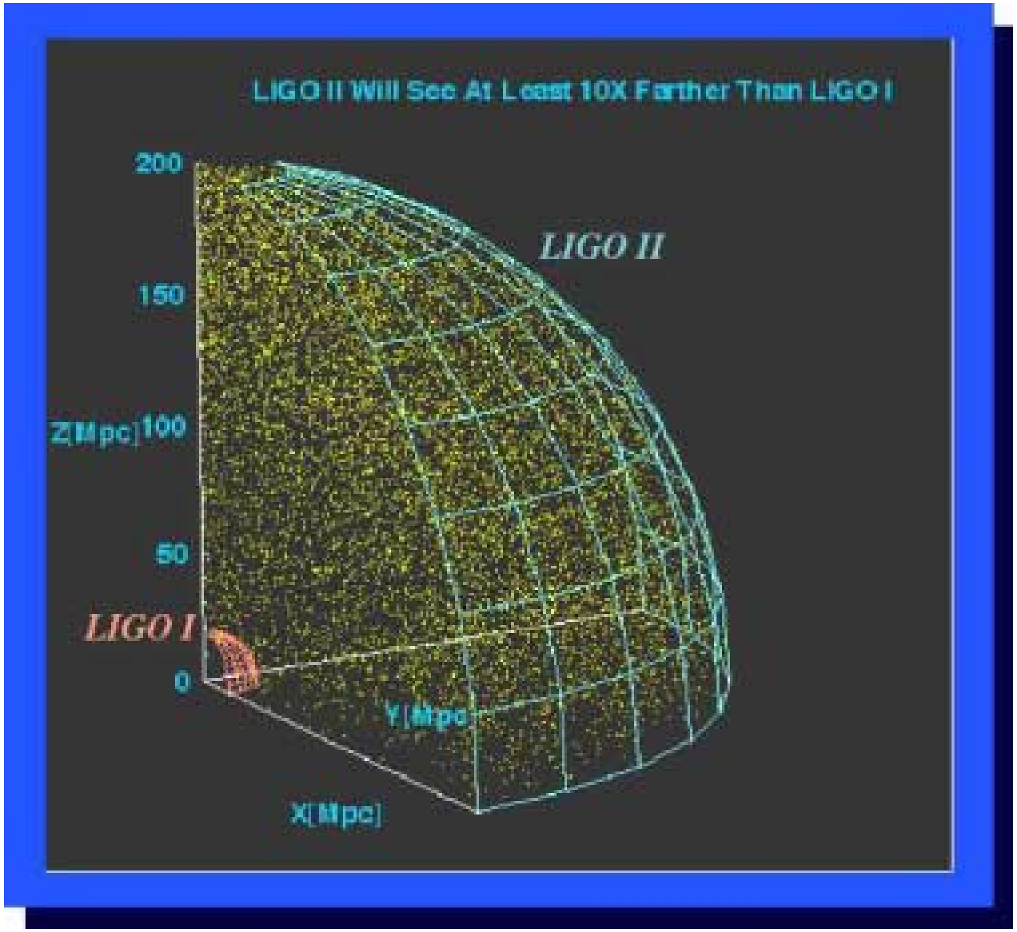
Second Generation LIGO Interferometers



Peter Fritschel, *LIGO/MIT*

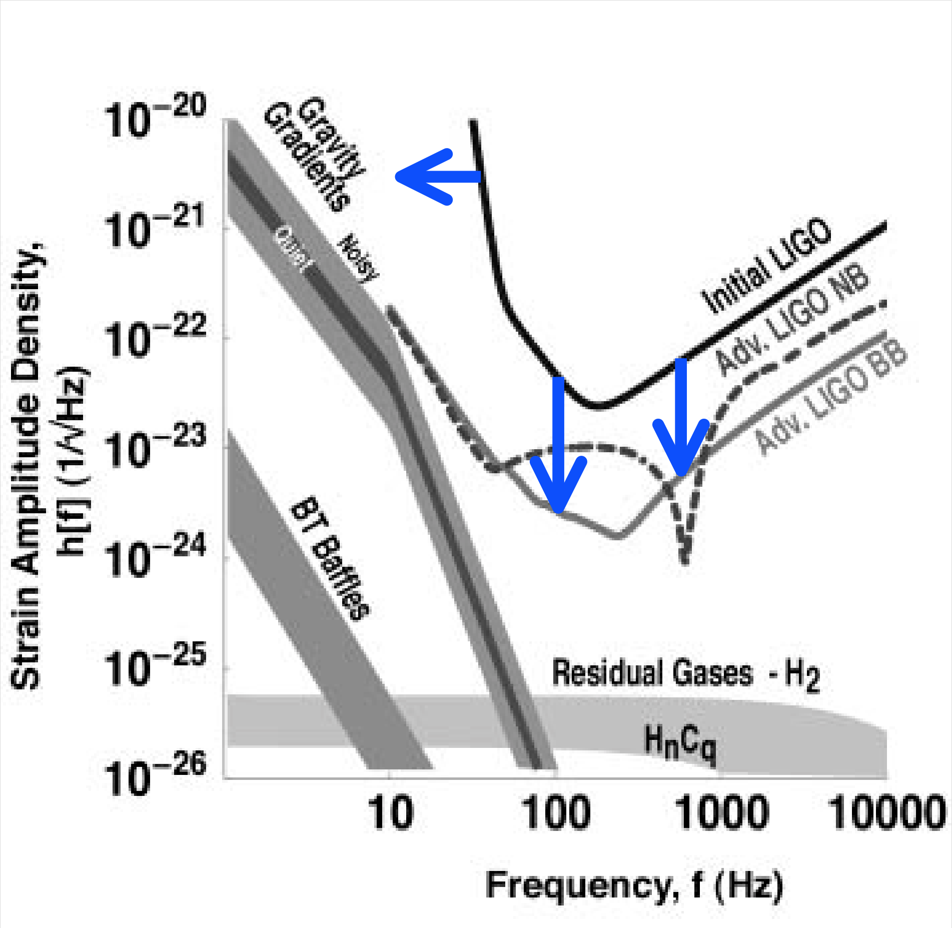
SPIE Astronomical Telescopes & Instrumentation Conference

25 August, 2002, Waikoloa, HI

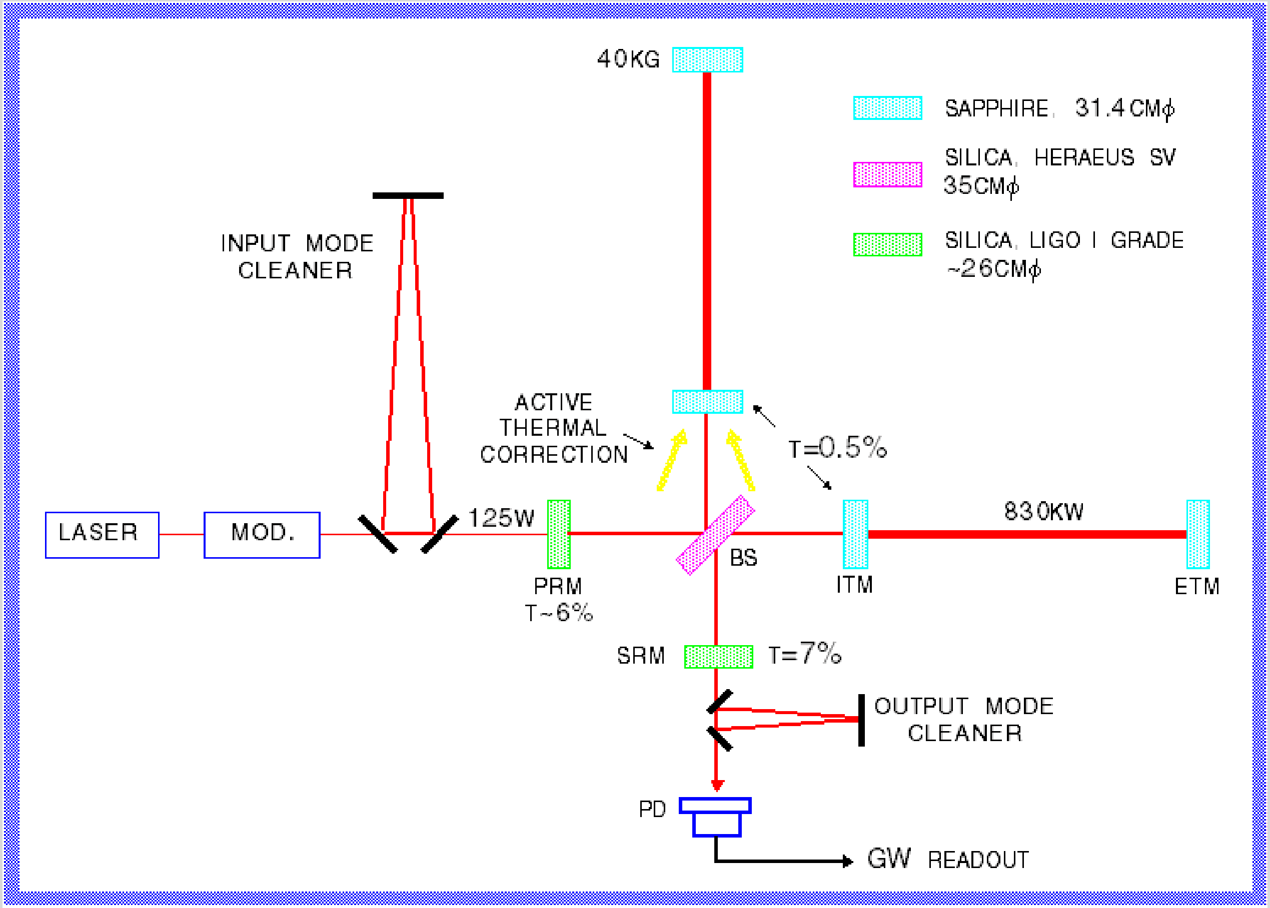
LIGO-G020345-00-D

Present and future limits to sensitivity

- Facility limits
  - Gravity gradients
  - Residual gas
  - (scattered light)
  - Leaves lots of room for improvement
- Advanced LIGO
  - Seismic noise 40→10 Hz
  - Thermal noise 1/15
  - Shot noise 1/10, tunable
- Beyond Adv LIGO
  - Thermal noise: cooling of test masses
  - Quantum noise: quantum non-demolition



Advanced Interferometer Concept



» Signal recycling

» 180-watt laser

» 40 kg Sapphire test masses

» Larger beam size

» Quadruple suspensions

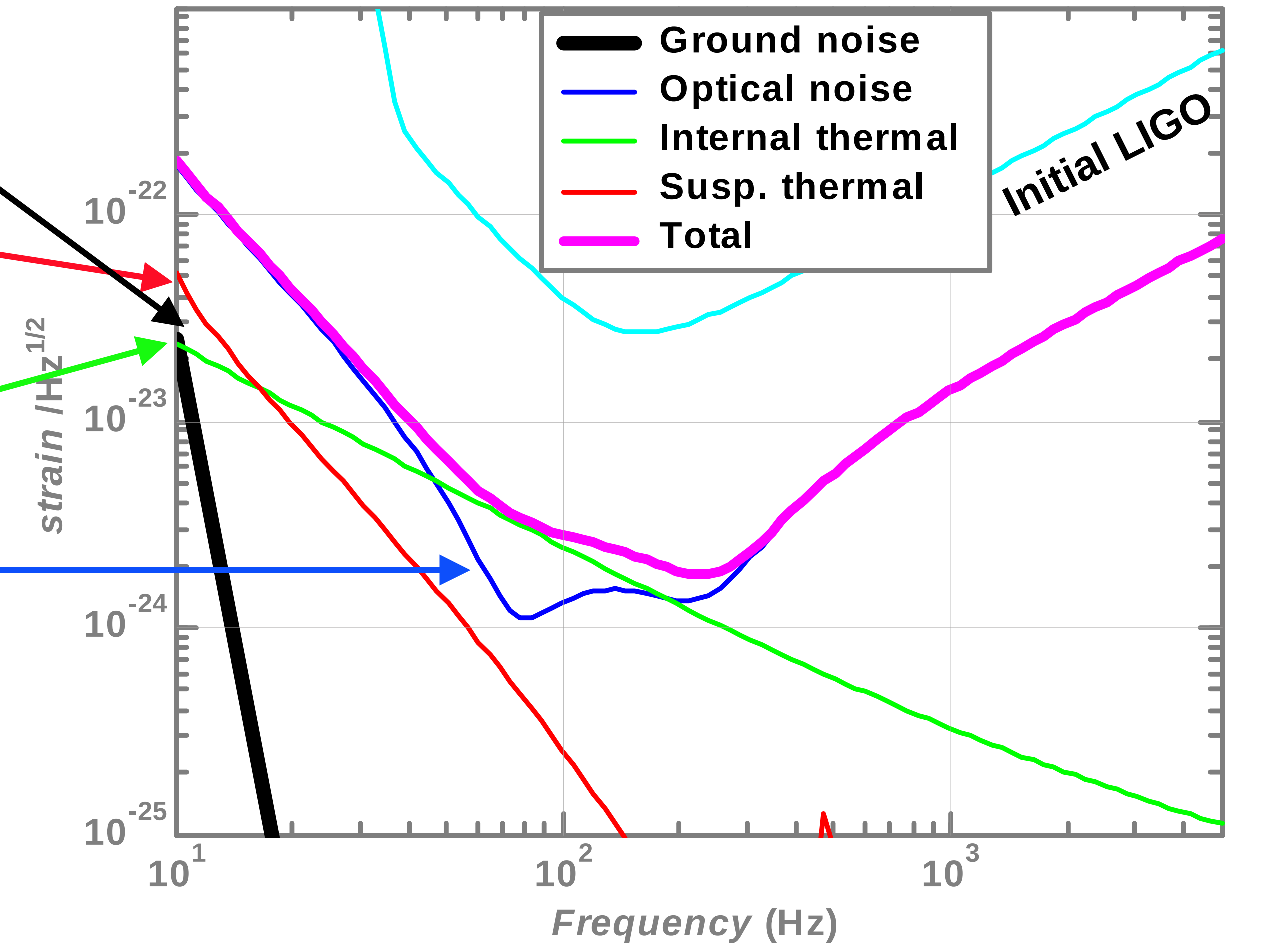
» Active seismic isolation

» Active thermal correction

» Output mode cleaner

Anatomy of Projected Performance

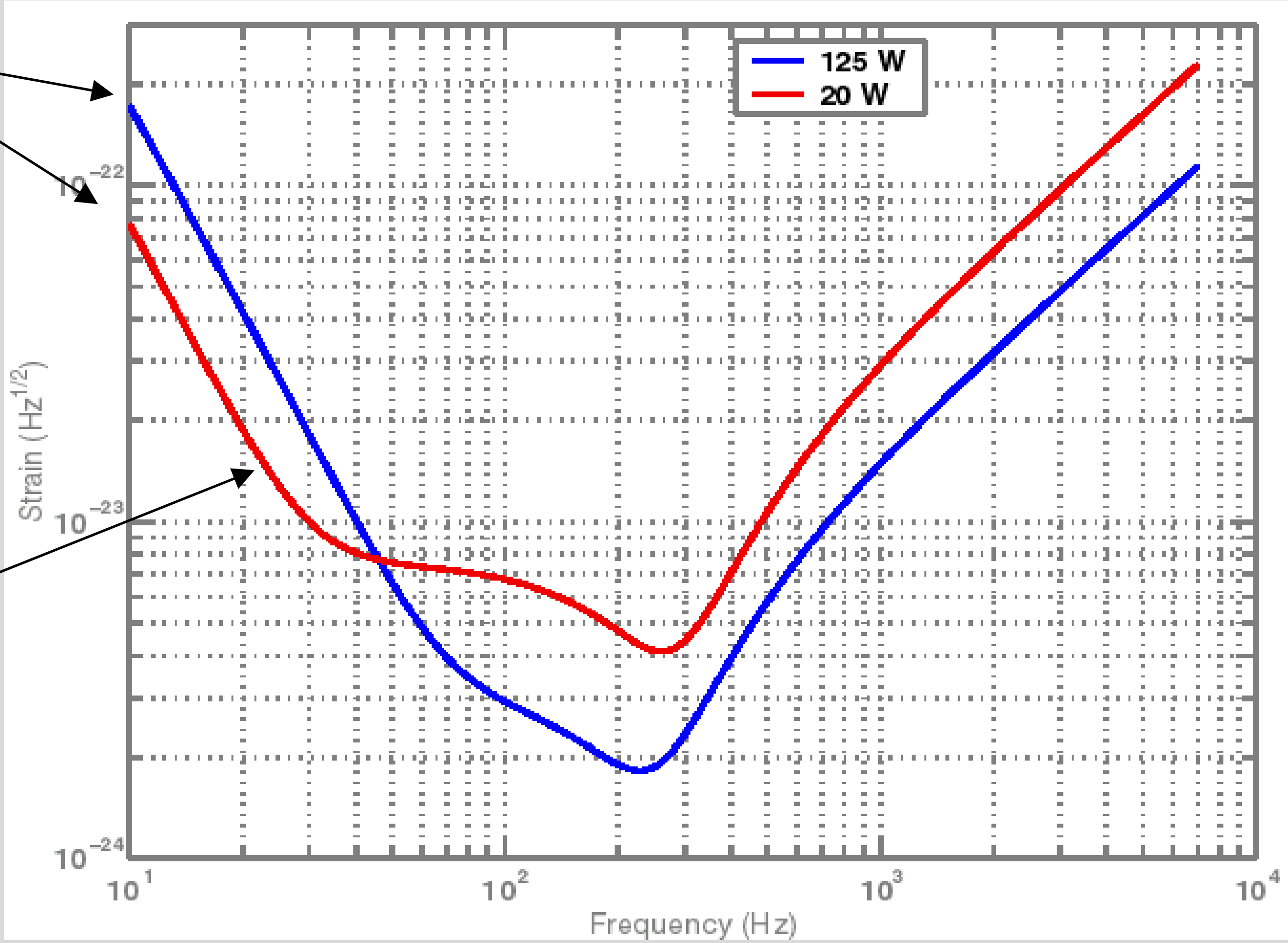
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- 'technical' noise (e.g., laser frequency) levels held in general well below these 'fundamental' noises



Low & High power modes

Factor of 3 difference at low frequencies

Quantum radiation pressure roughly equal to suspension thermal noise



Top level performance: Initial to Advanced LIGO

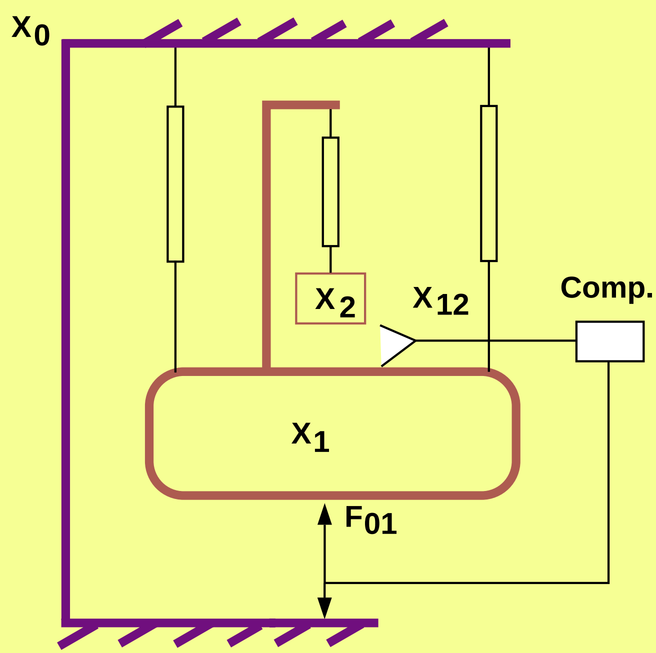
Parameter	LIGO I	Adv LIGO
Equivalent strain noise, minimum	$3x10^{-23}$/rtHz	$2x10^{-24}$/rtHz
Neutron star binary inspiral range	19 Mpc	300 Mpc
Stochastic backgnd sens.	$3x10^{-6}$	$1.5\text{-}5x10^{-9}$
Interferometer configuration	Power-recycled MI w/ FP arm cavities	LIGO I, plus signal recycling
Laser power at interferometer input	6 W	125 W
Test masses	Fused silica, 11 kg	Sapphire, 40 kg
Seismic wall frequency	40 Hz	10 Hz
Beam size	3.6/4.4 cm	6.0 cm
Test mass Q	Few million	200 million
Suspension fiber Q	Few thousand	~30 million

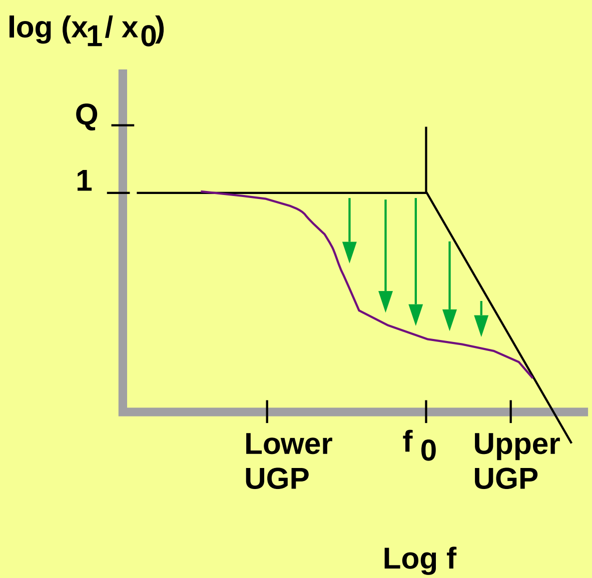
Advances in Seismic Isolation

- Goal: 10^{-19} m/√Hz at 10 Hz
  - Corresponds to level of suspension thermal noise
  - Very close to gravity-gradient noise around 10 Hz
  - Ground noise attenuation of 10^{10} required

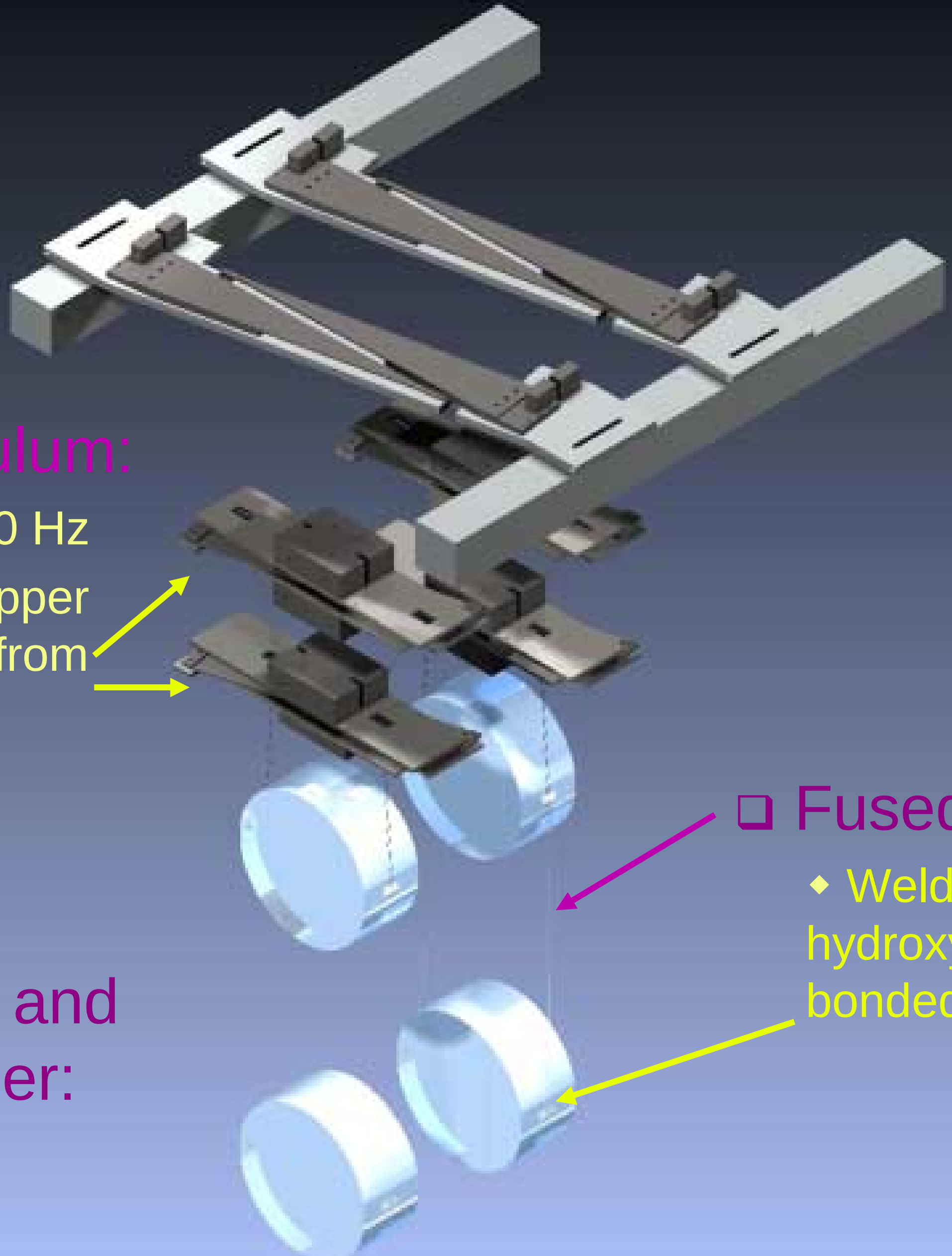
Active Seismic Isolation

- 2 in-vacuum stages, each w/ sensors & actuators for 6 DOF
- provides ~1/3 of the required attenuation
- provides ~10^3 reduction of rms in the *1-10 Hz band*, crucial for controlling technical noise sources





Advances in Suspensions



- Quadruple pendulum:
  - ~10^7 attenuation @10 Hz
  - Controls applied to upper layers; noise filtered from test masses
- Seismic isolation and suspension together:
  - 10^{-20} m/rtHz at 10 Hz
  - Factor of 10 margin
- Fused silica fiber
  - Welded to 'ears', hydroxy-catalysis bonded to optic

Advances in Thermal Noise

- Suspension thermal noise
  - Fused silica fibers, ~10^4x lower loss than steel wire
  - Ribbon geometry – more compliant along optical axis
  - Another trick – cancel the linear thermal expansion term with the Young's modulus temperature dependence
- Internal thermal noise

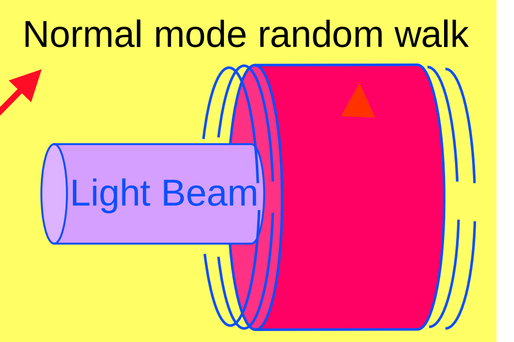
Sapphire test masses:

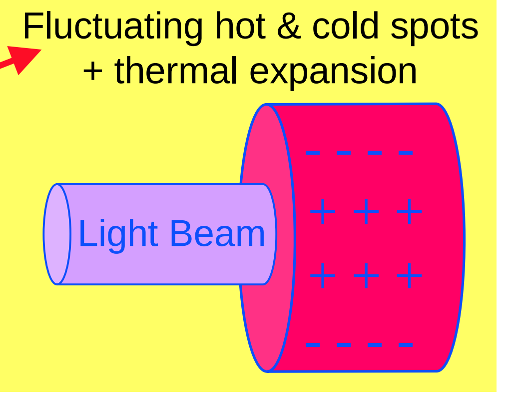
- Much higher Q: 2e8 vs 2-3e6 for LIGO I silica
- BUT, higher *thermoelastic damping* (higher thermal conductivity and expansion coefficients); can counter by increasing beam size
- Requires development in size, homogeneity, absorption

Fused silica test masses:

- Intrinsic Q can be much higher: ~5e7 (avoid lossy attachments)
- Low absorption and inhomogeneity, but expensive

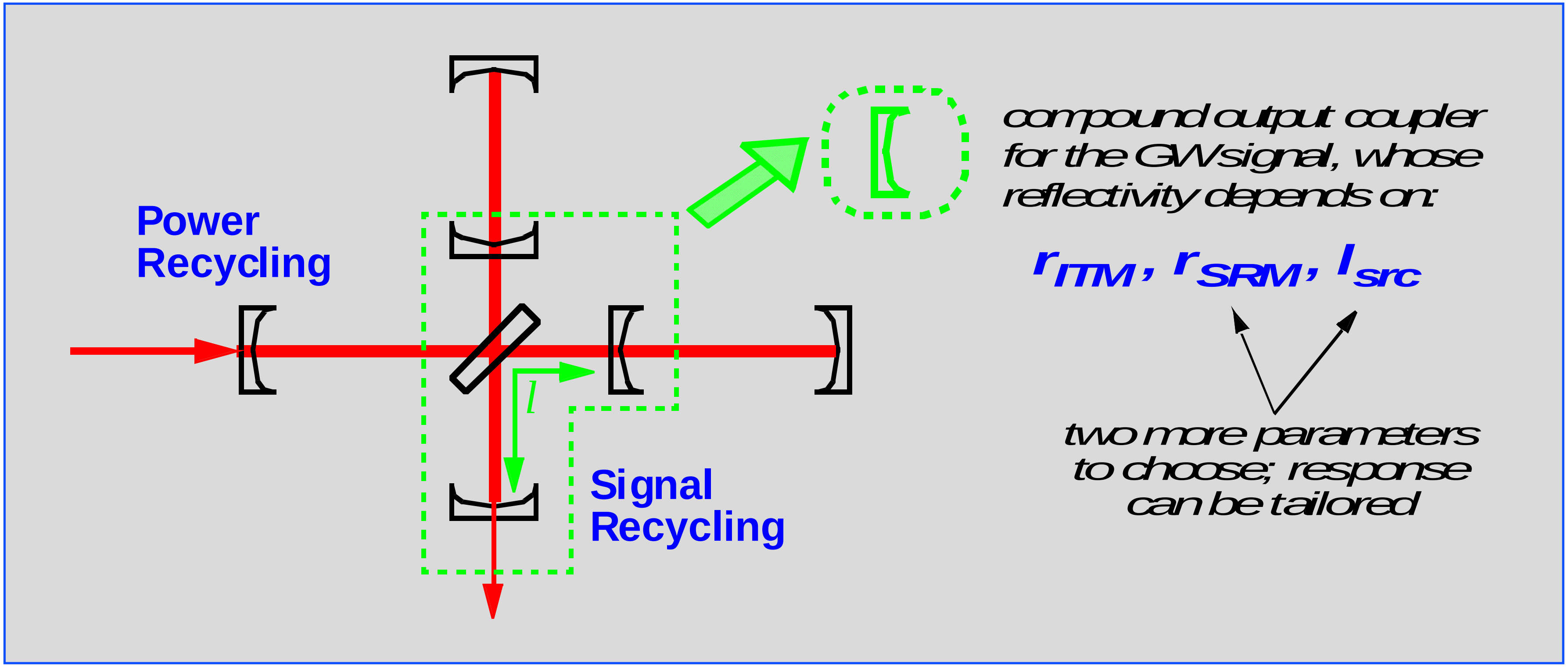
Both materials: mechanical loss from polishing and dielectric coatings is being studied, and must be controlled



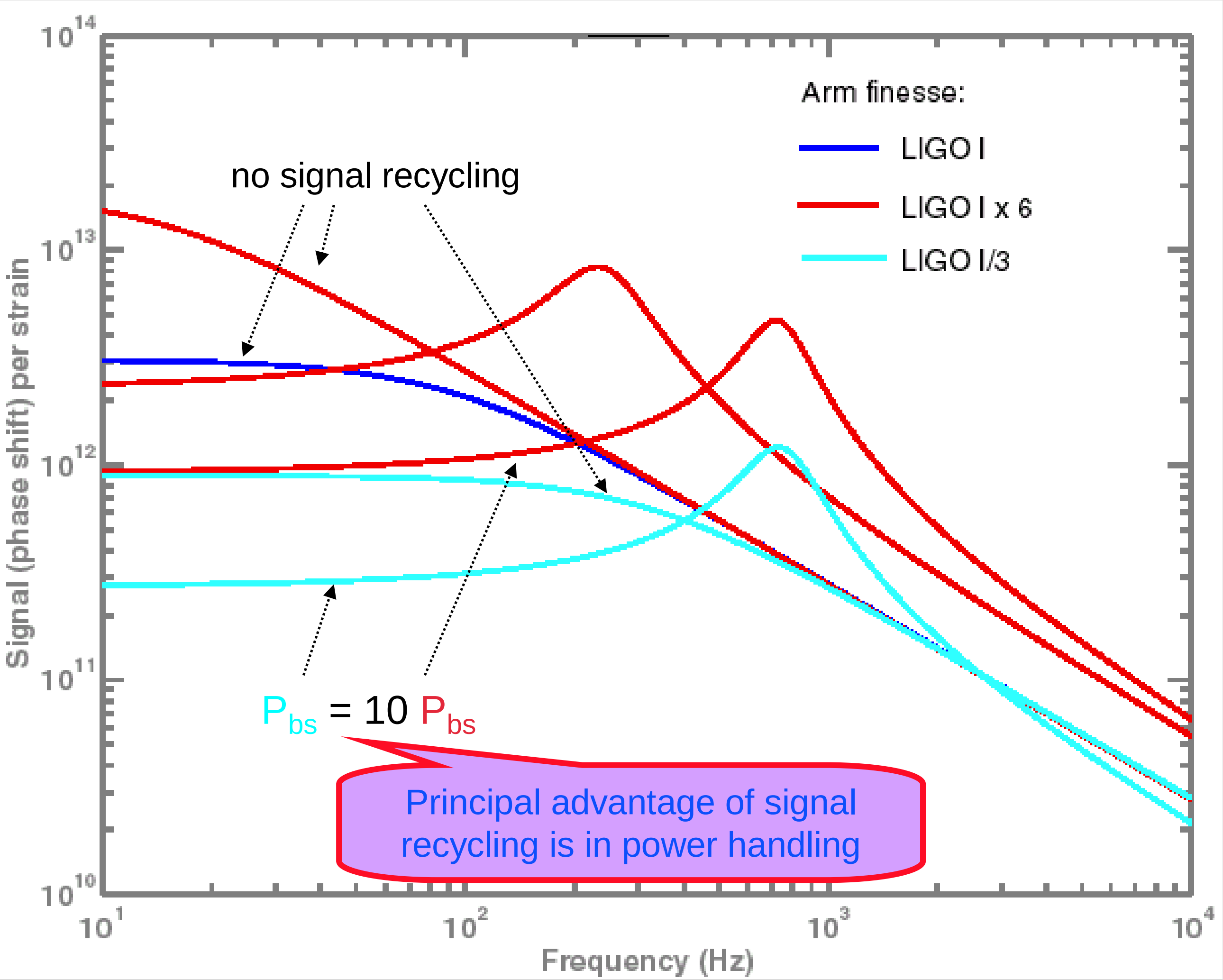


Advances in Sensing

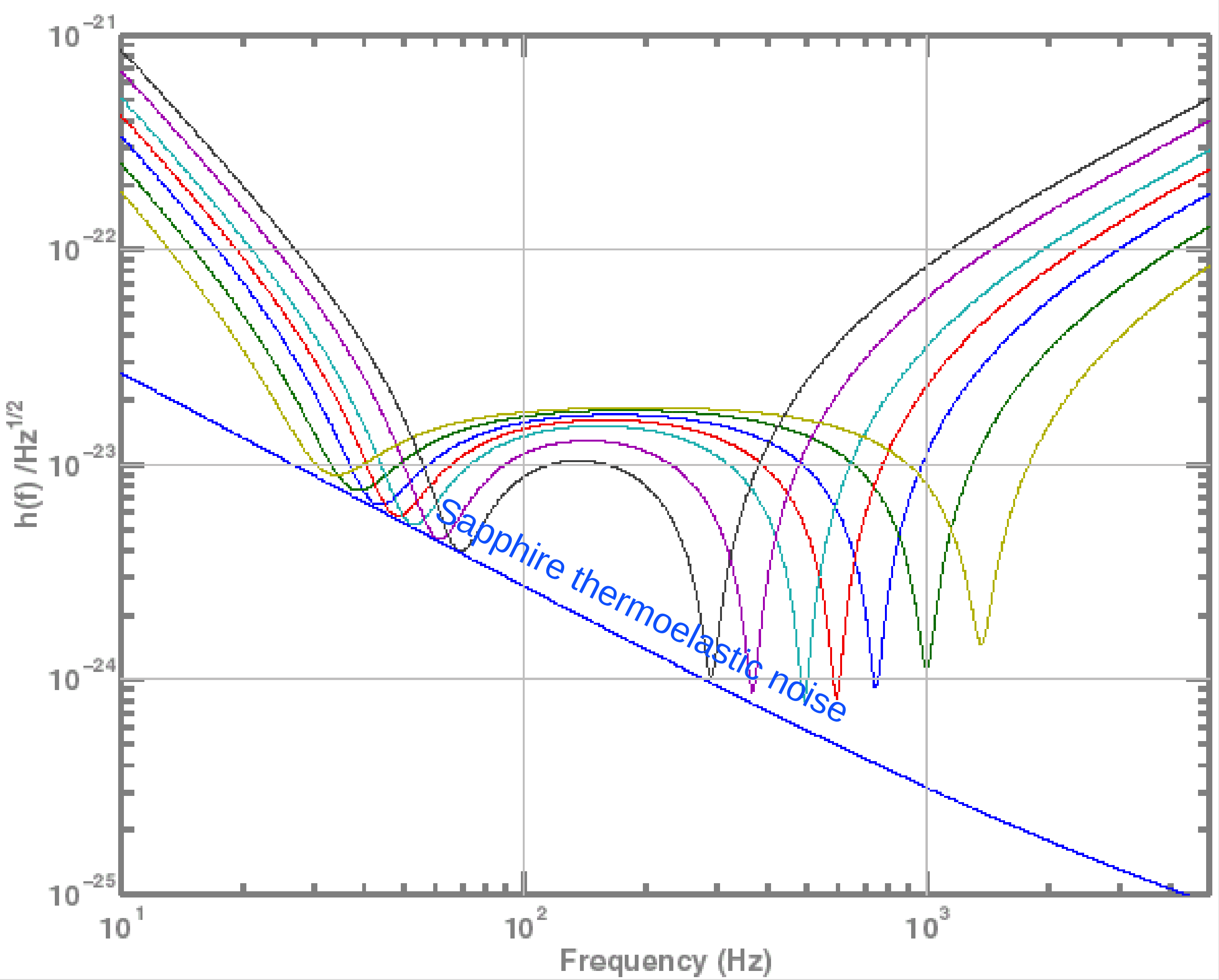
- Input laser power: 120 W
  - Incremental progress in laser technology
  - Thermal management in the interferometer become a big issue!
- Optimizing interferometer response



Response functions



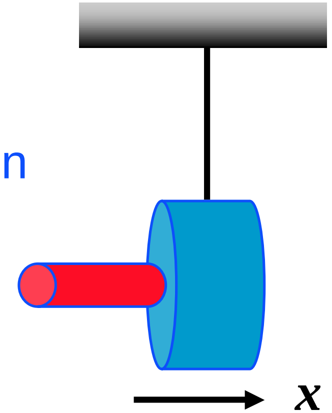
A Narrowband Interferometer



Example tuning curves for a fixed transmission signal recycling mirror

LIGO

Nature of Optical Noise



- Standard Quantum Limit:
  - ‘A 20 year misunderstanding’, K Thorne
  - Δx ~ Δp ❍ $\leftarrow$ naively applied to the test mass position
- Output of the interferometer:
  - $x_{OUT} = x_{FREE} + x_{SH} + x_{RP}$

Shot noise & radiation pressure of the light source

  - Commutes with itself at different times!

$$[x_O^0, x_O^\tau] = [x_F^0, x_F^\tau] + [x_{SH}^0, x_{SH}^\tau] + [x_{RP}^0, x_{RP}^\tau] = 0$$

$i \leftarrow \tau/m$ $\qquad$ $-i \leftarrow \tau/m$

SH & RP arise from The same vacuum Fluctuations (Caves`81)

• *State reduction has no influence on the LIGO data!*

LIGO

Nature of Optical Noise, cont'd

- $x_{OUT} = x_{FREE} + x_{SH} + x_{RP}$ ⇨ Noise spectral density

$$S_x = S_F + S_{SH} + S_{RP} + S_{SH,RP} + S_{RP,SH}$$

Noise in
$x_F = x_0 + (p_0/m)\tau$
is at low frequency,
not part of data

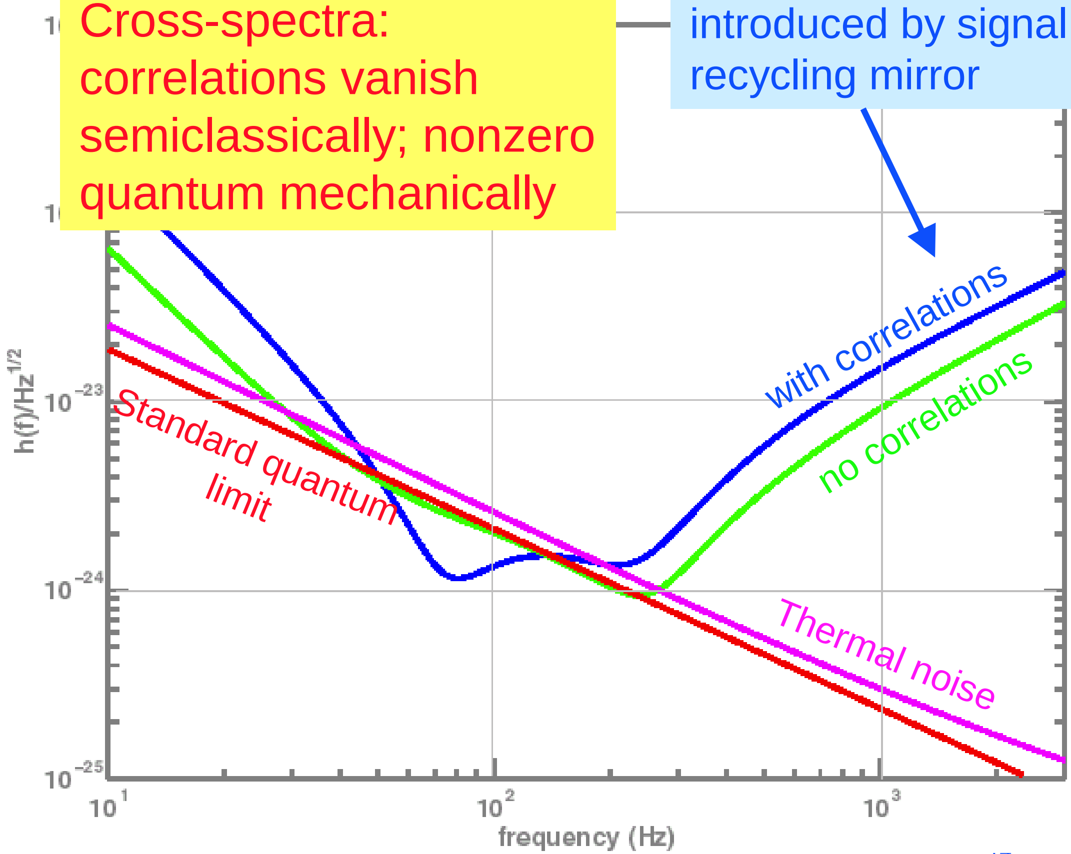
Cross-spectra:
correlations vanish
semiclassically; nonzero
quantum mechanically

Correlations between
vacuum fluctuations
introduced by signal
recycling mirror

- In absence of correlations:

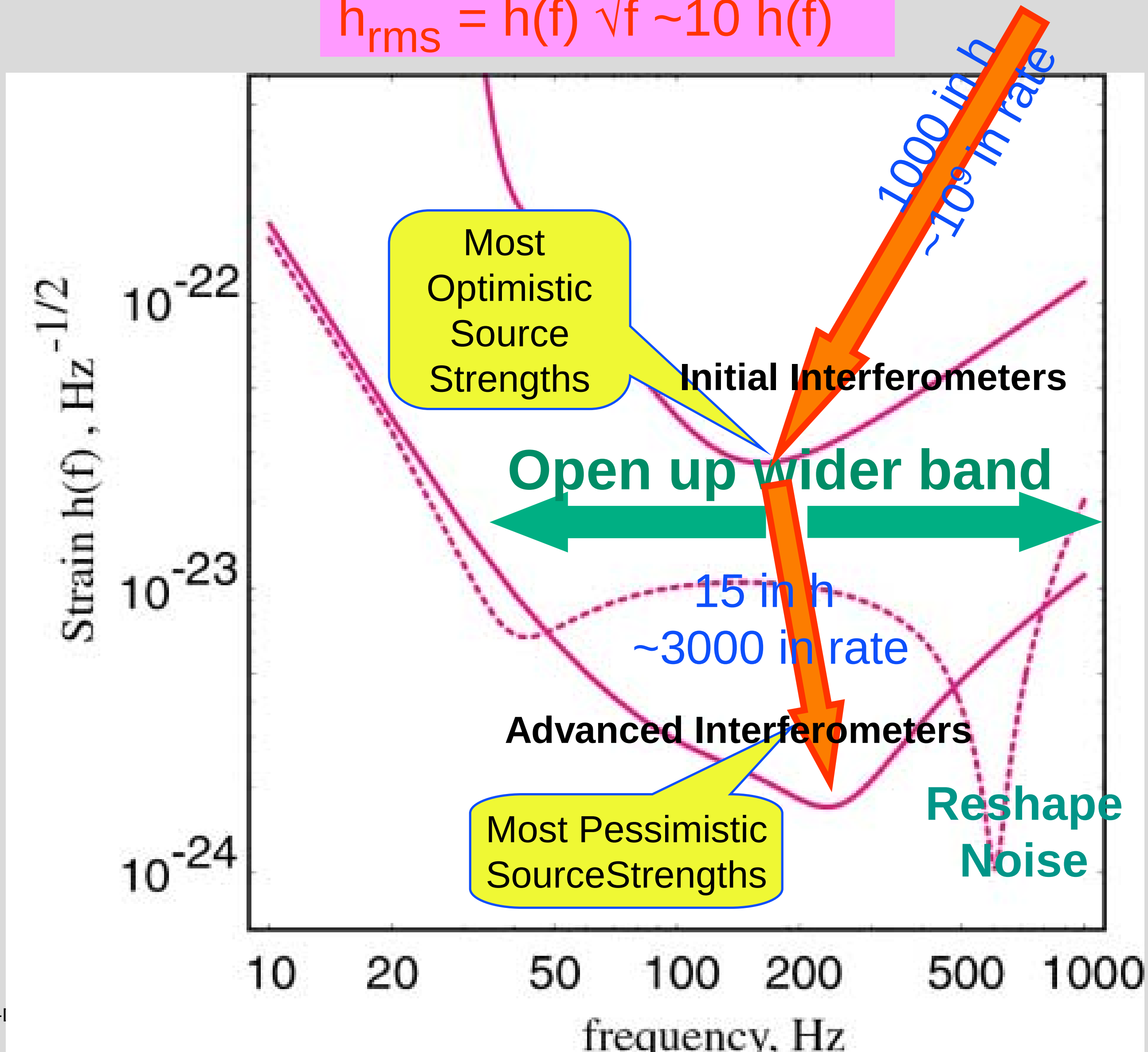
$S_{SH} + S_{RP}$ ❍ SQL

- correlations enable SQL to be beat, but can worsen noise elsewhere



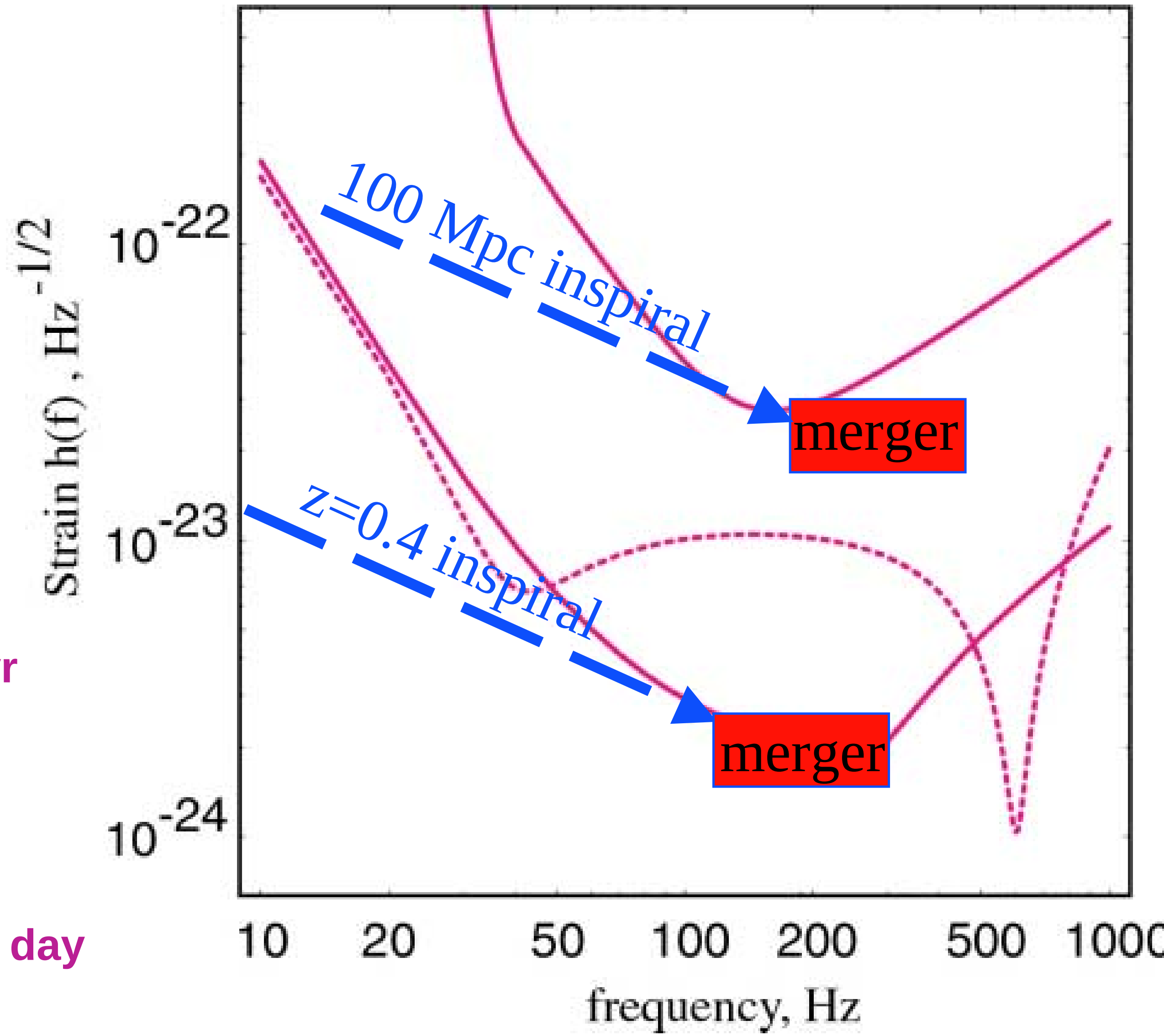
Source Detection: from Initial to Advanced Interferometers

$h_{rms} = h(f)\sqrt{f} \sim 10\,h(f)$



Black Hole / Black Hole Inspiral and Merger

- 10M✍ / 10 M✍ BH/BH Binaries
- Event rates
  - Based on population synthesis [Kalogera's summary of literature]
- Initial IFOs
  - Range: 100 Mpc
  - ≲ 1 / 300yrs to **~1 / yr**
- Advanced IFOs -
  - Range: z=0.4
  - ≲ **2 / month to ~10 / day**

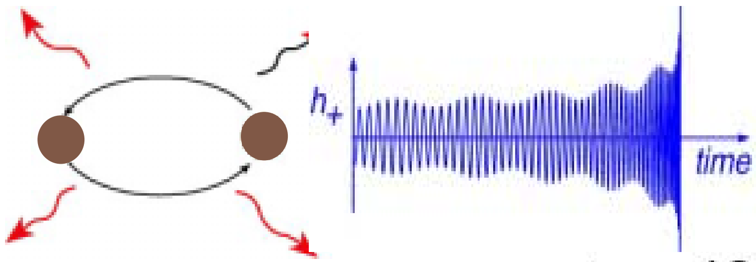


Advanced LIGO Summary

- Goal: quantum-noise-limited interferometer
  - Nearly so (thermal noise not completely beaten)
  - SQL should be forgotten!
- Advanced LIGO interferometers: 15x increase in sensitivity over initial LIGO
  - *First 2-3 hours of Advanced LIGO is equivalent to initial LIGO's 1 year science run!*
- Now being designed by the LIGO Scientific Collaboration (~25 institutions, worldwide)
  - Major design challenges:
  - Begin installation: end 2006
  - Begin data run: 2009

LIGO

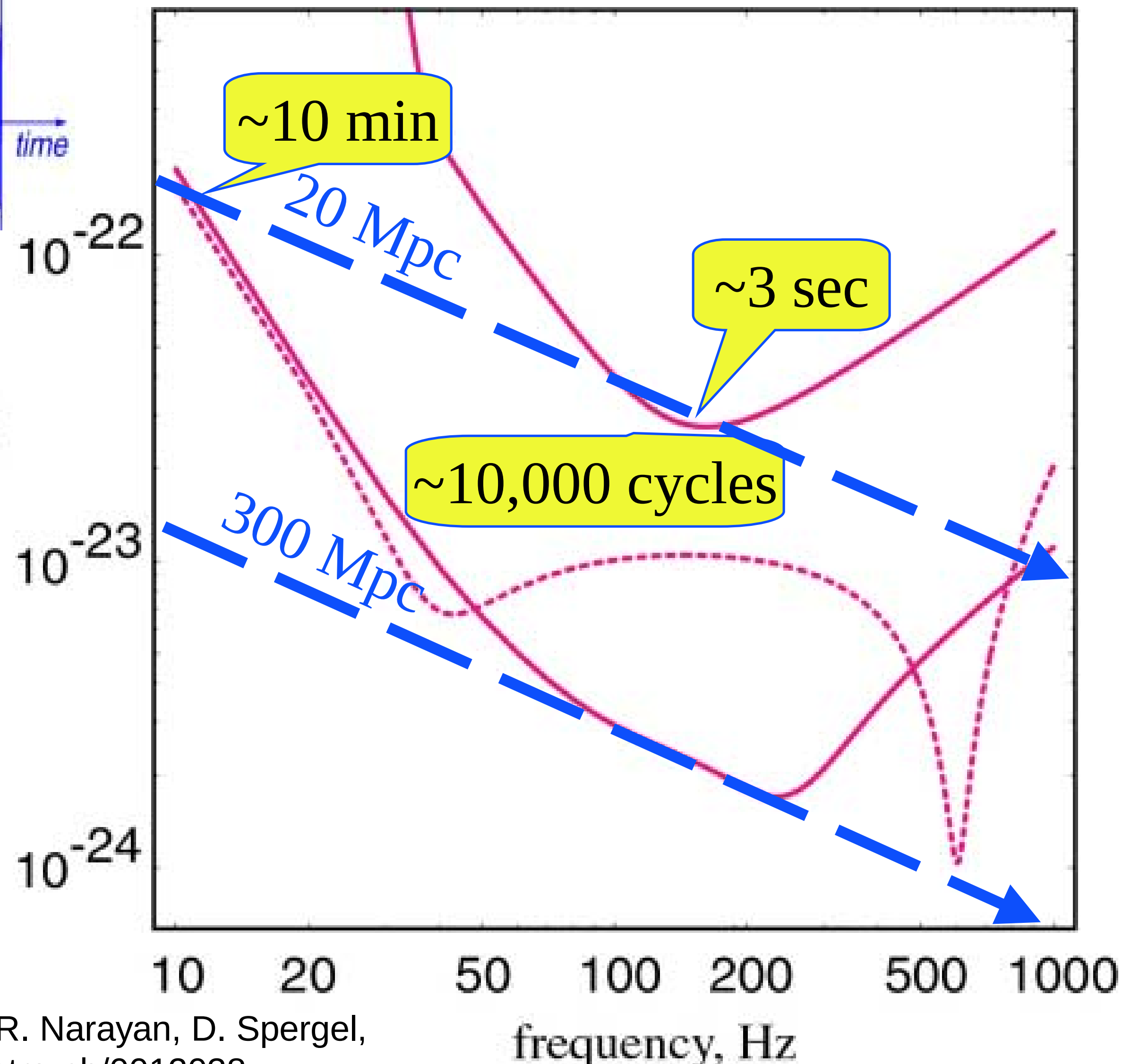
Neutron Star / Neutron Star Inspiral
(our most reliably understood source)



- 1.4 M✍ / 1.4 M✍ NS/NS Binaries

Event rates:*

- Initial IFOs
  - Range: 20 Mpc
  - 1 / 3000 yrs to **1 / 3yrs**
- Advanced IFOs -
  - Range: 300Mpc
  - **1 / yr to 2 / day**



*V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor, astro-ph/0012038