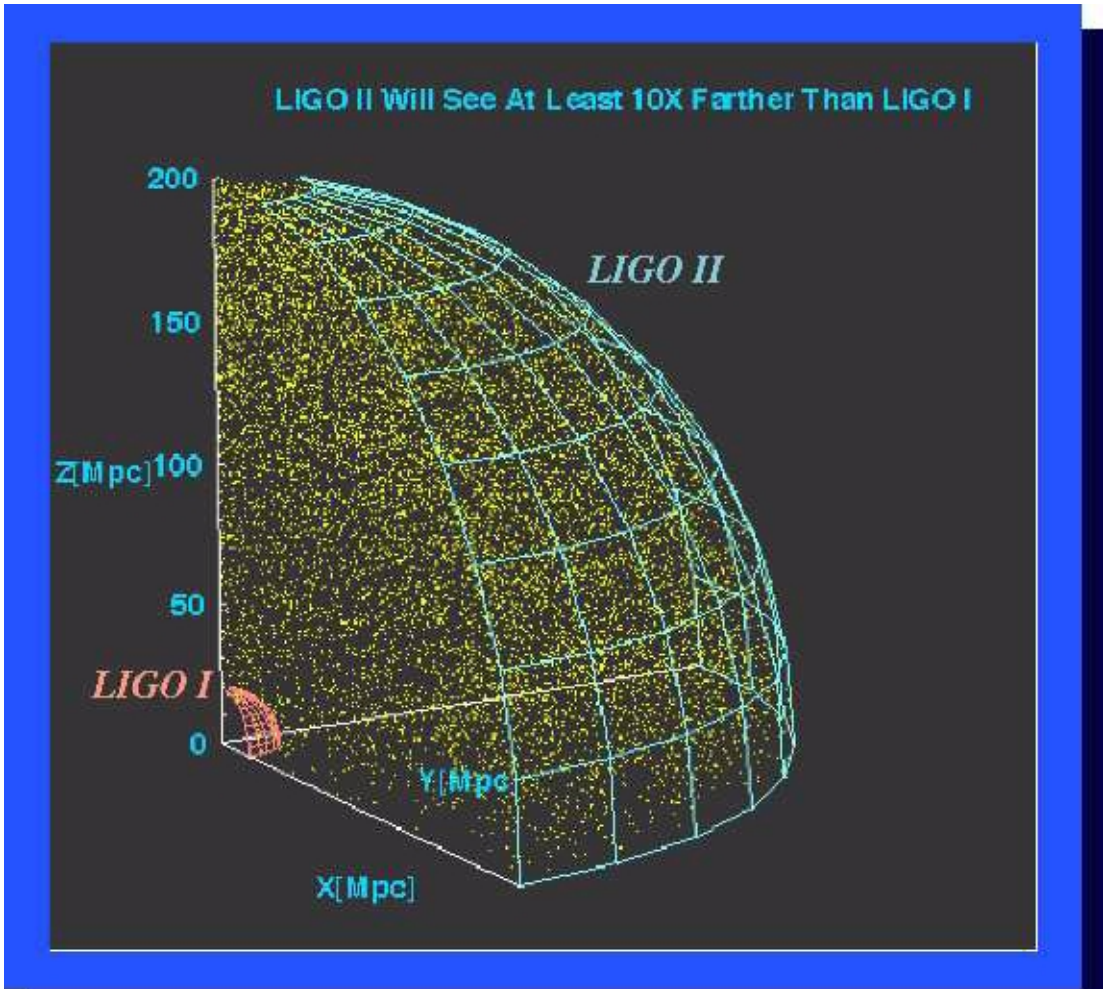
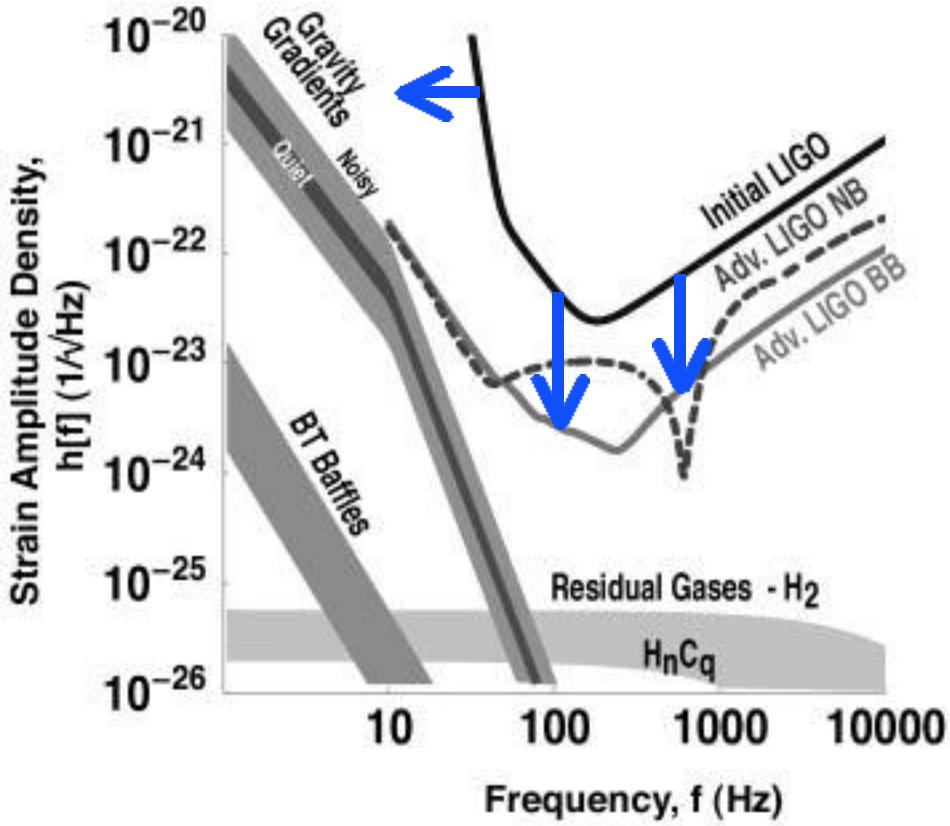
The Second Generation LIGO Interferometers



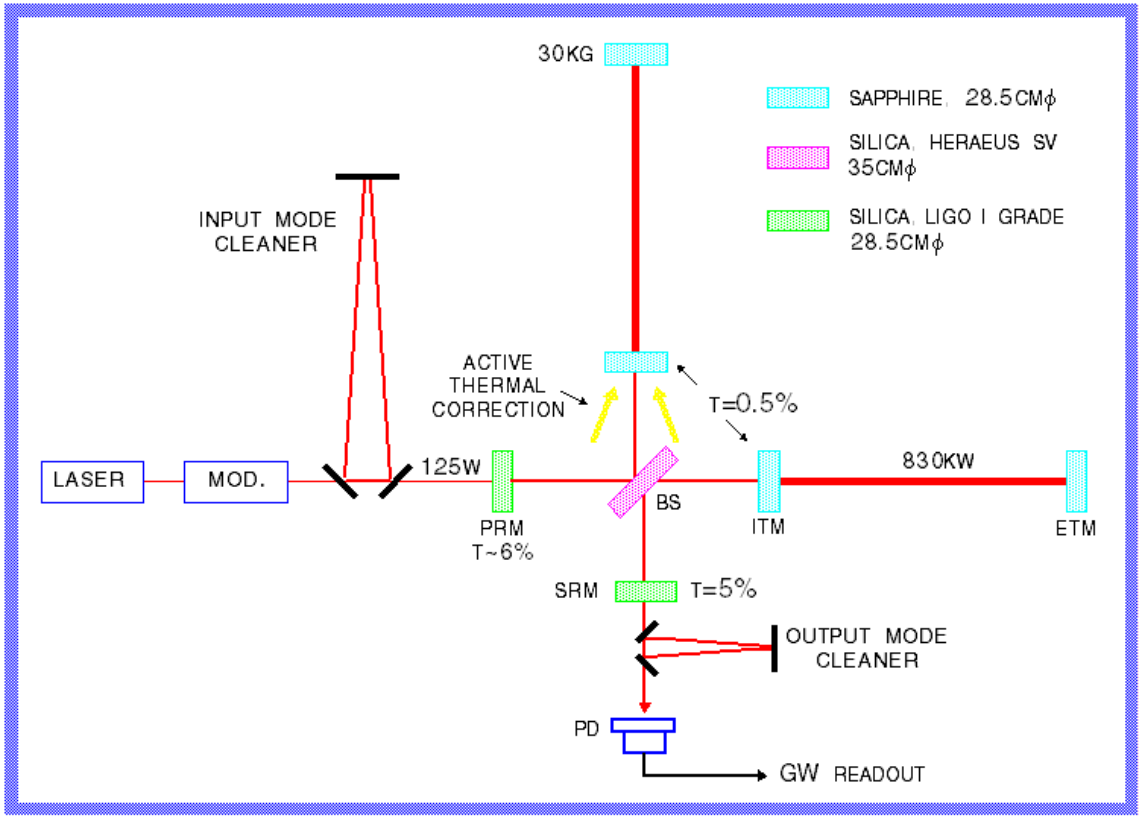
LIGO-G010201-00-D

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

» Sapphire test masses

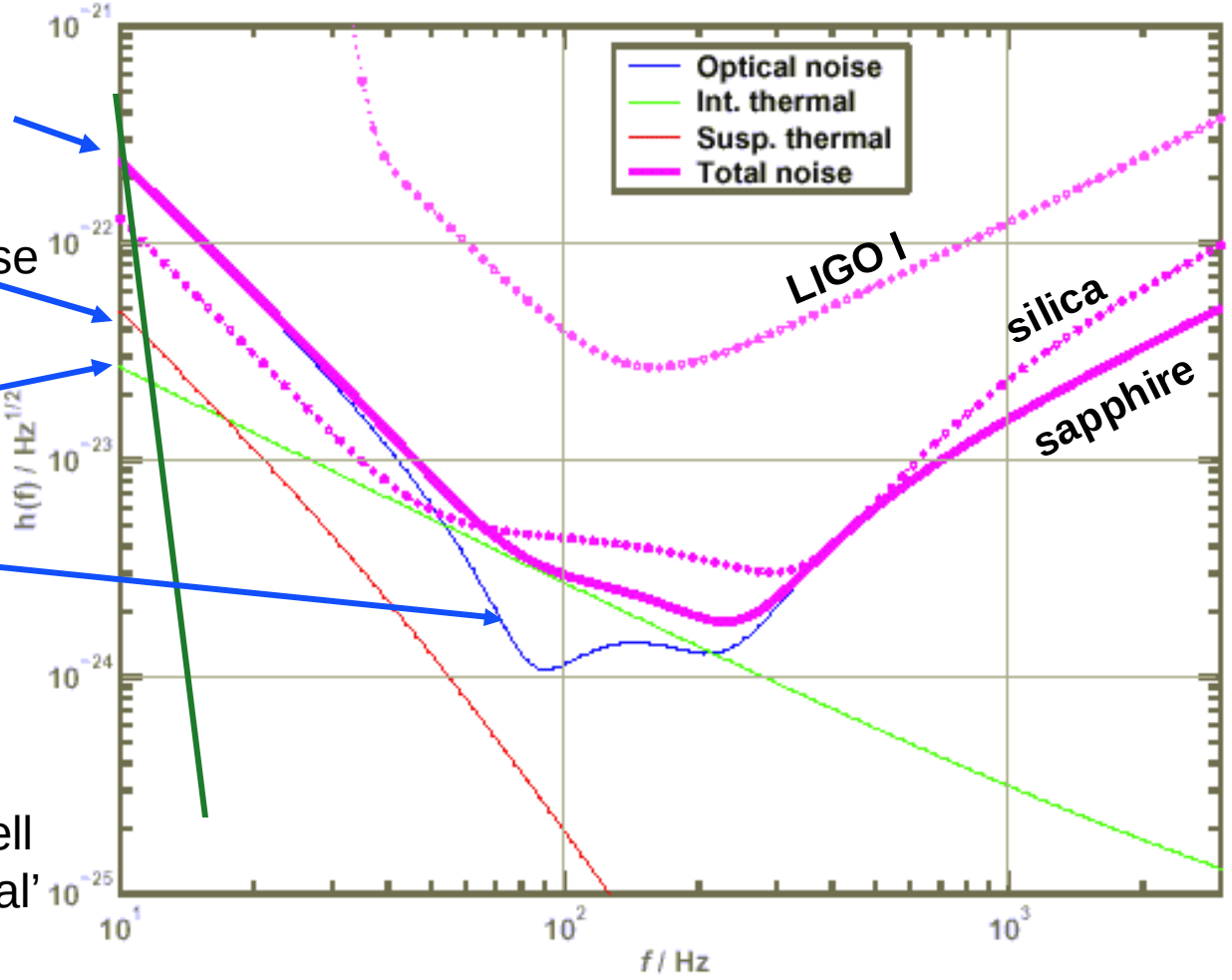
» Quadruple suspensions

» Active seismic isolation

» Active thermal correction

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



From Initial to Advanced LIGO

Parameter	LIGO I	LIGO II
Equivalent strain noise, minimum	3×10^{-23}/rtHz	2×10^{-24}/rtHz
Neutron star binary inspiral range	19 Mpc	285 Mpc
Stochastic backgnd sens.	3×10^{-6}	$1.5\text{-}8\times10^{-9}$
Interferometer configuration	Power-recycled Michelson w/ FP arm cavities	LIGO I, plus signal recycling
Laser power at interferometer input	6 W	120 W
Test masses	Fused silica, 11 kg	Sapphire, 40 kg
Suspension system	Single pendulum, steel wires	Quad pendulum, silica fibers/ribbons
Seismic isolation system, type	Passive, 4-stage	Active, 2-stage
Seismic wall frequency	40 Hz	10 Hz

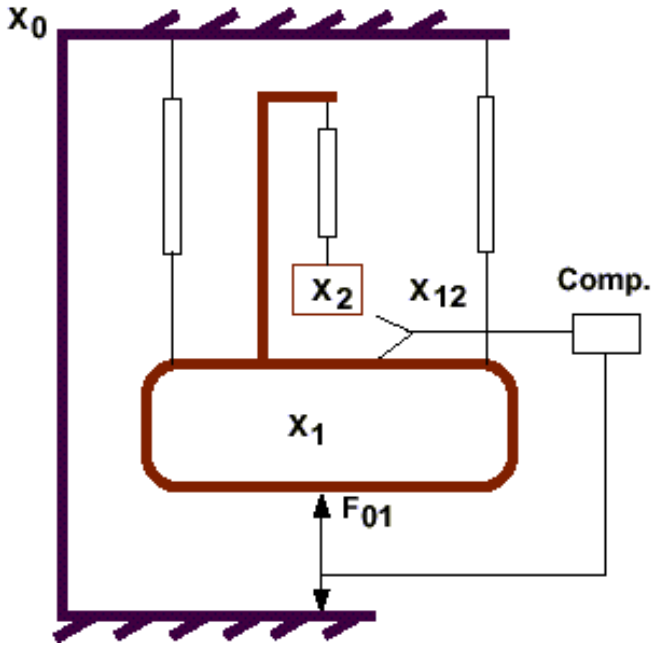
Advances in Seismic Isolation

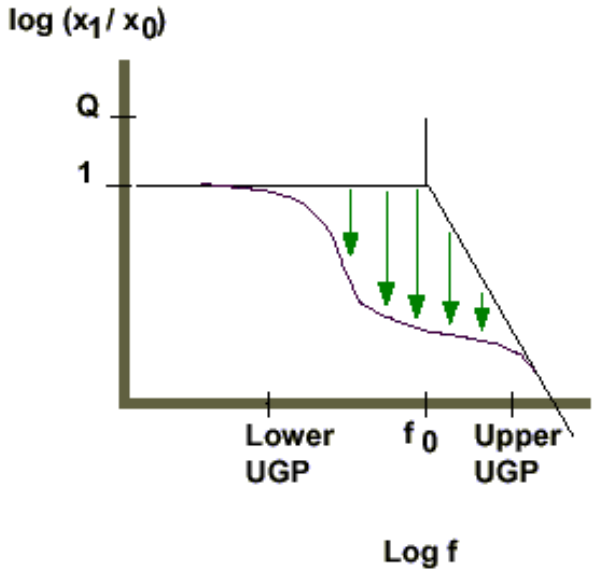
- Goal taken as 10^{-19} m/rtHz at 10 Hz
  - Corresponds to level of suspension thermal noise
  - Very close to gravity-gradient noise around 10 Hz
  - Ground noise attenuation of 10^{10} required
- Active seismic isolation

• 2 in-vacuum stages, each w/ sensors & actuators for 6 DOF

• provides ~1/3 of the required attenuation

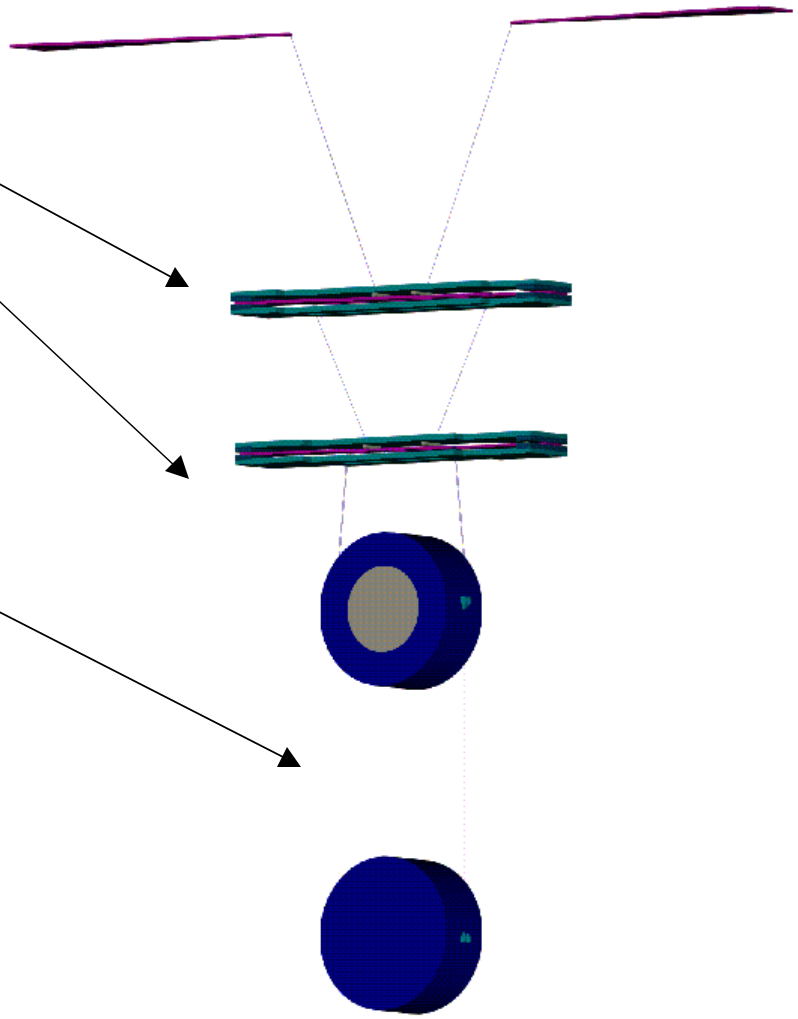
• provides ~10^3 reduction of rms at lower frequencies, crucial for controlling technical noise sources





Advances in Suspensions

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



Advances in Thermal Noise

- Suspension thermal noise
  - Fused silica fibers, ~10^4x lower loss than steel wire
  - Ribbon geometry – more compliant along optical axis
- 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 coeff); can counter by increasing beam size
- Requires development in size, homogeneity, absorption

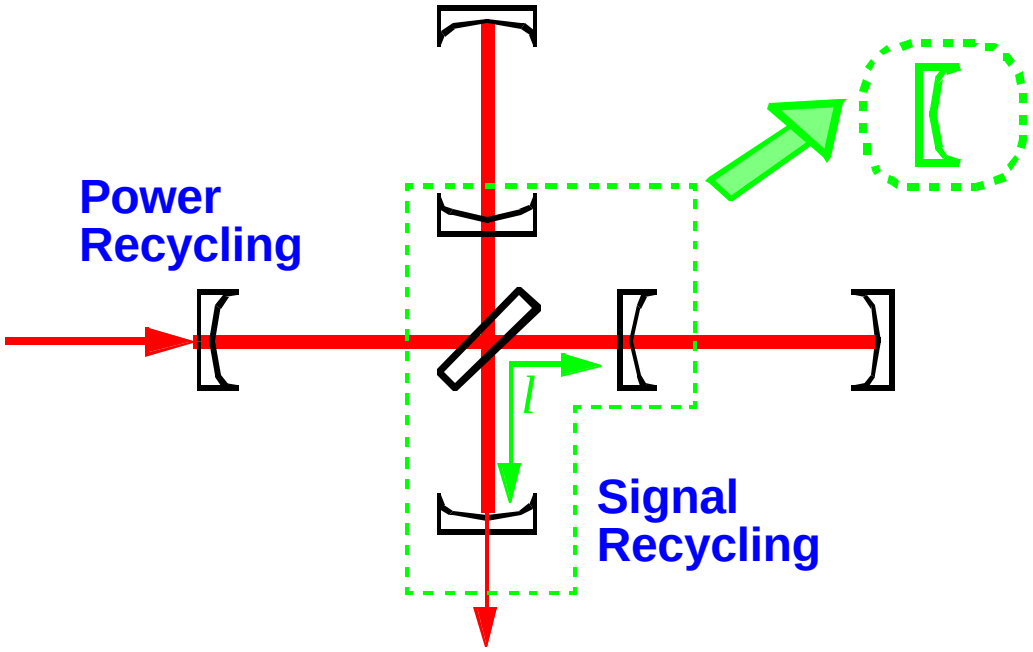
Fused silica test masses:

- 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 must be studied and 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



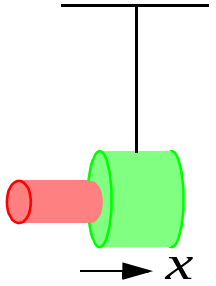
compound output coupler for the GW signal, whose reflectivity depends on:

r_{ITM}, r_{SRM}, l_{src}

two more parameters to choose; response can be tailored

Nature of Optical Noise

- Standard Quantum Limit:
  - 'A 20 year misunderstanding', K Thorne
  - $\Delta x \cdot \Delta p \geq \hbar$ naively applied to test mass positior
- Output of interferometer:
  - $x_{\mathrm{OUT}} = x_{\mathrm{FREE}} + x_{\mathrm{SH}} + x_{\mathrm{RP}}$



shot noise & radiation pressure of the light source

SH & RP arise from the same vacuum fluctuations (Caves '81)

  - commutes with itself at different times!

$$[x_{\mathrm{O}}^{0}, x_{\mathrm{O}}^{\tau}] = [x_{F}^{0}, x_{F}^{\tau}] + [x_{\mathrm{SH}}^{0}, x_{\mathrm{RP}}^{\tau}] + [x_{\mathrm{RP}}^{0}, x_{SH}^{\tau}] = 0$$

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

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

[Braginsky, Gorodetsky, Khalili, Matsko, Vyatchanin & Thorne, in prep.; Kimble, Levin, Matsko, Vyatchanin, Thorne gr-qc/0008026; Buonanno & Chen gr-qx/0010011]

Nature of Optical Noise

❑ $x_{OUT} = x_{FREE} + x_{SH} + x_{RP}$ ⟶ 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

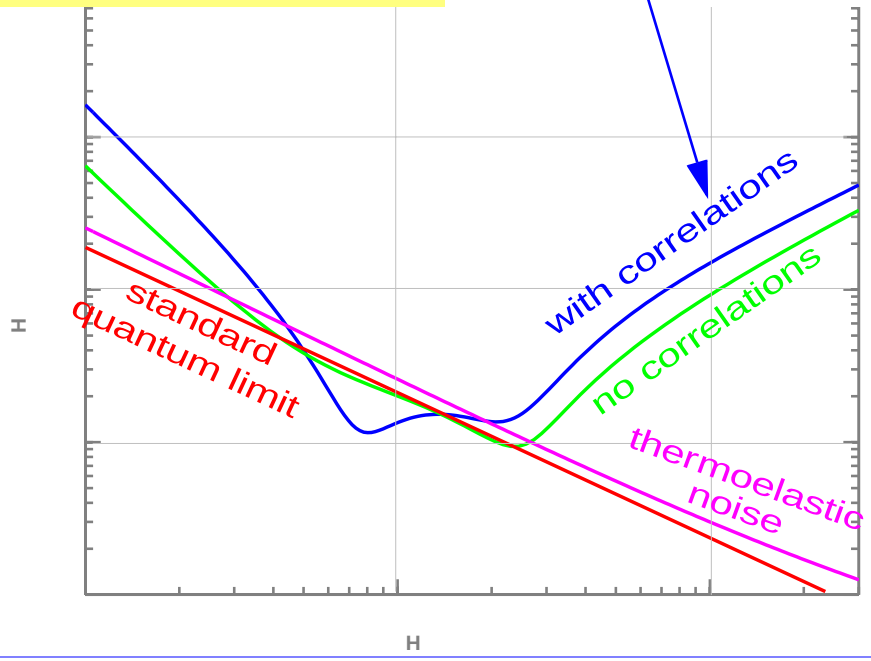
cross-spectra: correlations vanish semiclassically; nonzero quantum mechanically

correlations between the vacuum fluctuations are introduced by the signal recycling mirror

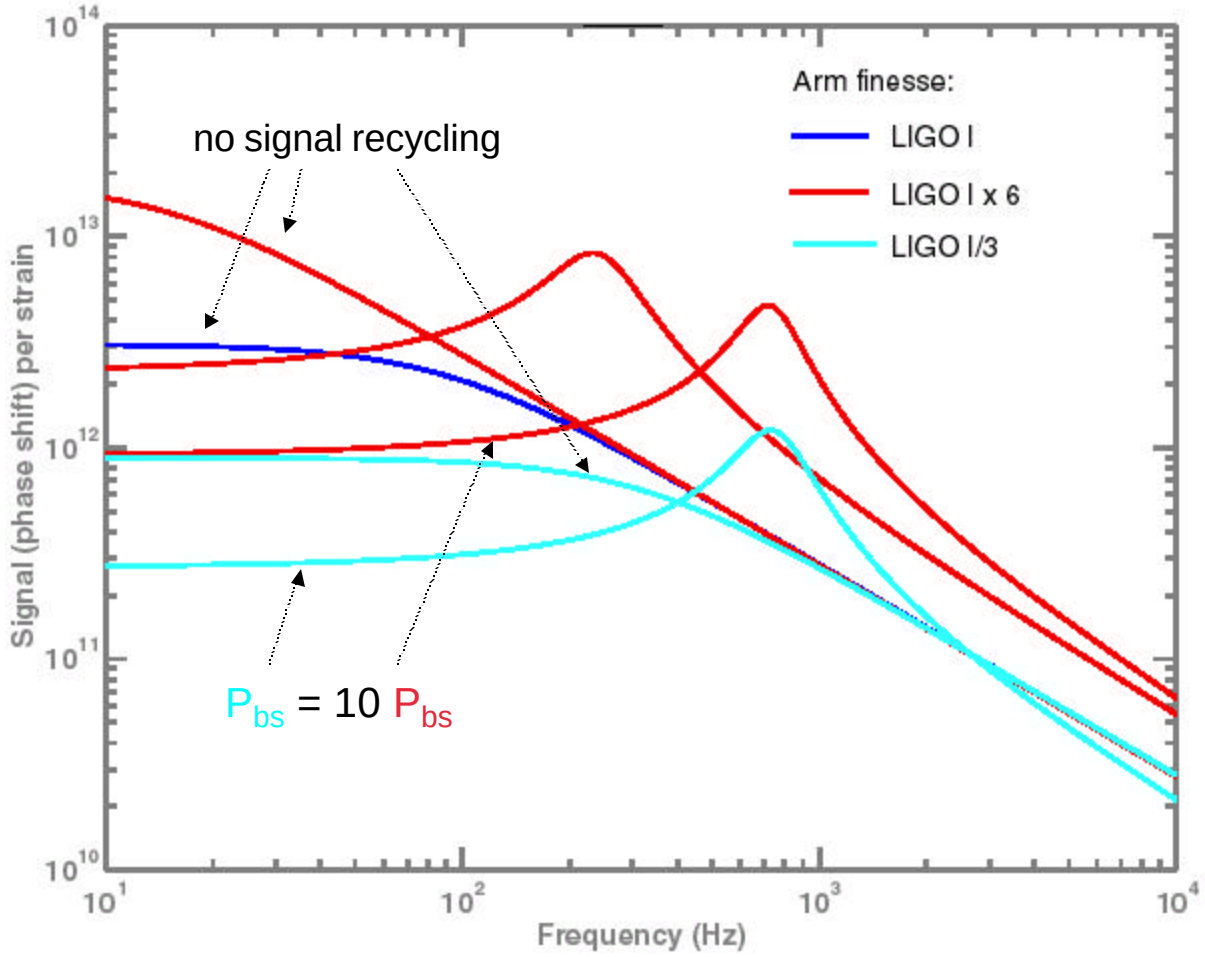
➤ In absence of correlations:

$$S_{SH} + S_{RP} \geq \mathrm{SQL}$$

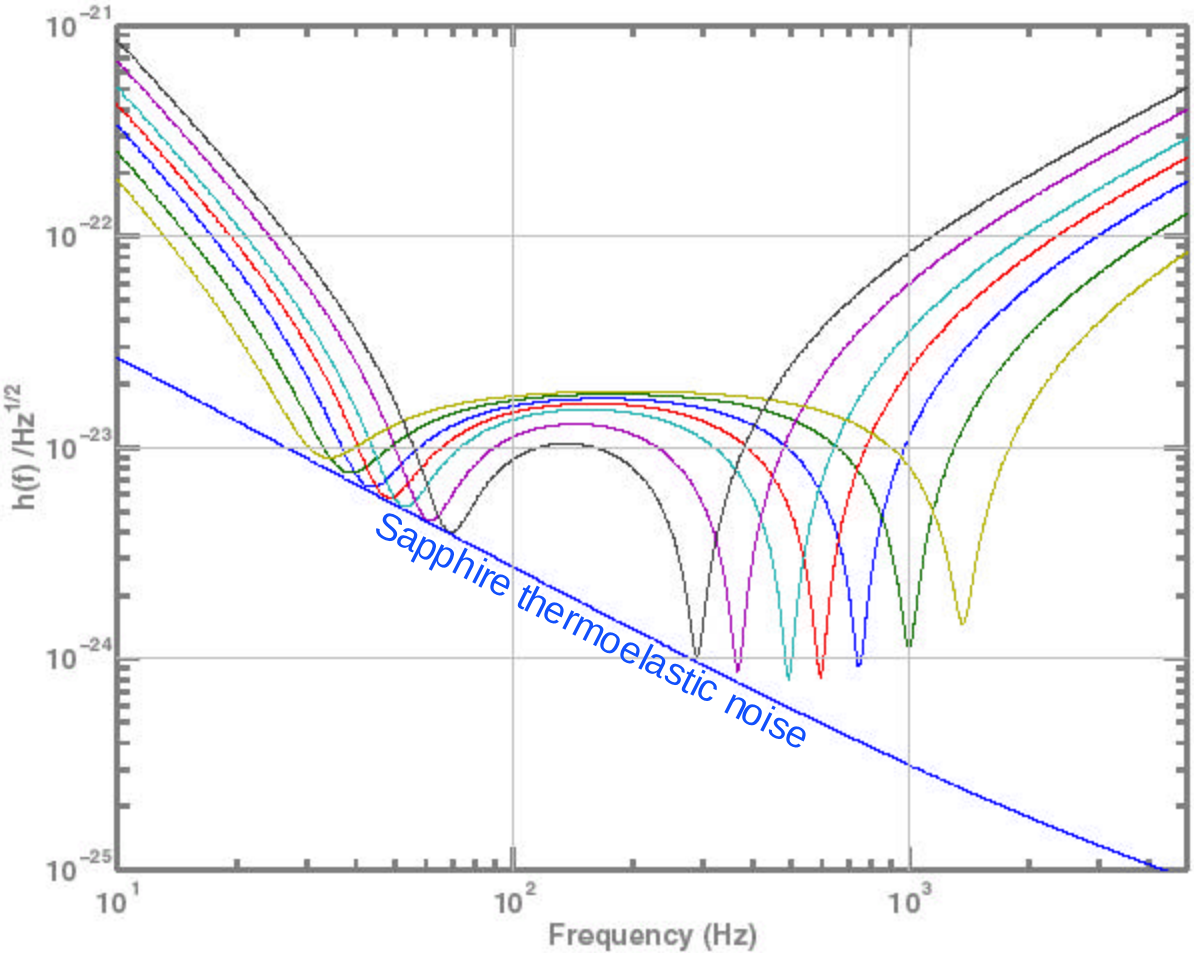
➤ The correlations enable SQL to be beat, but can worse noise elsewhere



Response functions



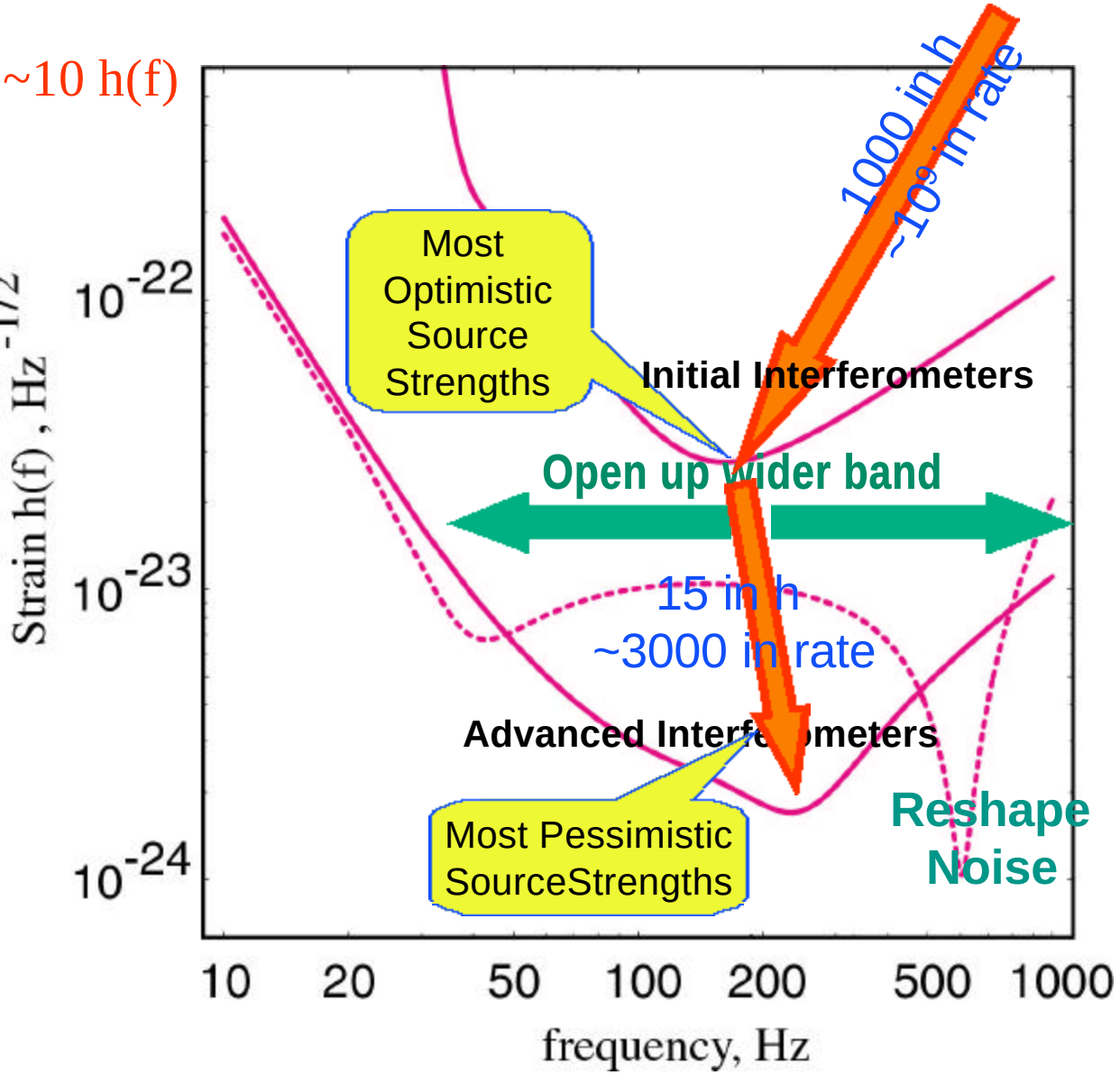
A Narrowband Interferometer



Example tuning curves for a fixed transmission signal recycling mirror

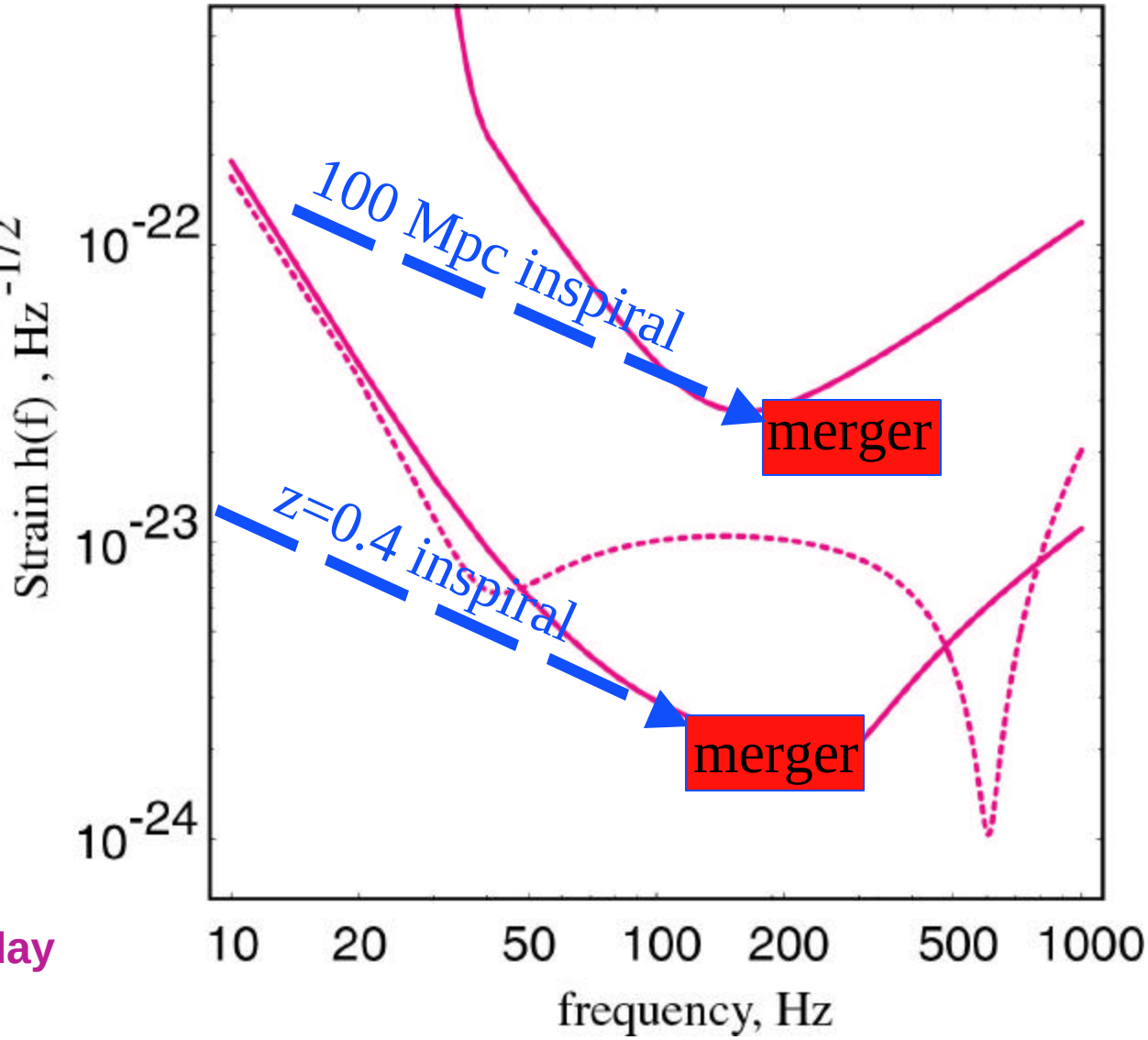
Source Detection: from Initial Interferometers to Advanced

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



Black Hole / Black Hole Inspiral and Merger

- 10Msun / 10 Msun 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**



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)
  - major design challenges: *sapphire development, operation at high power (thermal compensation), mirror coatings*
  - begin installation: 2006
  - begin data run: 2008