UNIVERSITY OF BIRMINGHAM

EGO

The ET sensitivity curve with ‘conventional‘ techniques

Stefan Hild and Andreas Freise

University of Birmingham

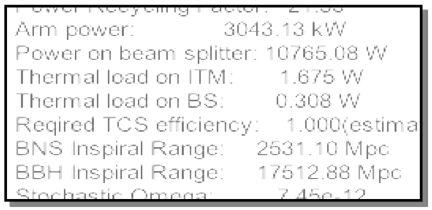
1st ET General meeting, Pisa, November 2008

UNIVERSITY OF BIRMINGHAM

EGO

Overview

How close can we get to the ET target sensitivity conventional methods?

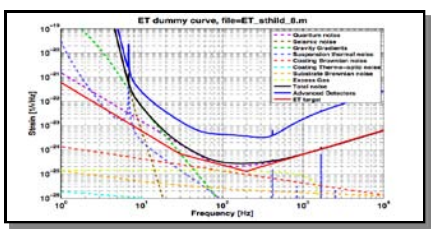


Arm power: 3043.13 kW
Power on beam splitter: 10765.08 W
Thermal load on ITM: 1.675 W
Thermal load on BS: 0.308 W
Reqired TCS efficiency: 1.000(estima
BNS Inspiral Range: 2531.10 Mpc
BBH Inspiral Range: 17512.88 Mpc

Developed a GWINC (former Bench) model for ET.

3km => 10km ?
200W => 800W ?
42kg => 200kg ?

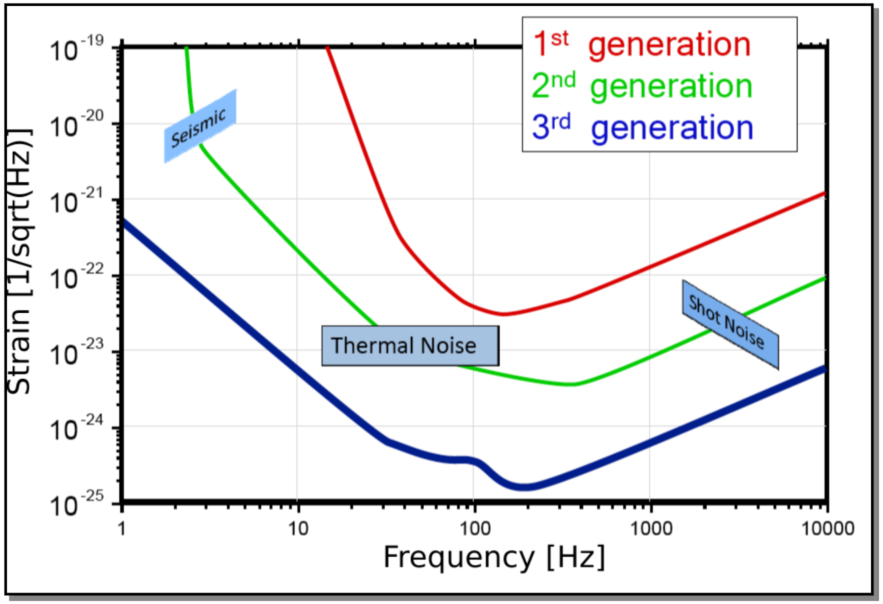
How much would we have to boost conventional technology?



What can we learn from this toy-analysis?

The Context of this analysis

- How close can we get to ET target sensitivity employing only available (conventional) techniques?
- Educational exercise: Push conventional techniques to - or maybe beyond - their limits.
- Our method: Start from a 2nd Generation detector. Then make step-by-step modifications to reach ET target.



Definition of *conventional* and *non-conventional* techniques

Conventional:

- Successfully demonstrated on table-tops and prototypes:
  - Squeezed light
  - Cryogenic optics
  - ...
- Up-scaling of current technology without major change in involved physics:
  - 30m long suspensions
  - 200kg test masses
  - ...

Non-Conventional:

- So far only existent on paper:
  - Optical levers
  - Higher order Laguerre Gauss modes
  - ...
- Proof-of-principle experi-ments exist, but deviate from targeted interferometery:
  - Displacement noise free interferometry (Mach Zehnder)
  - ...

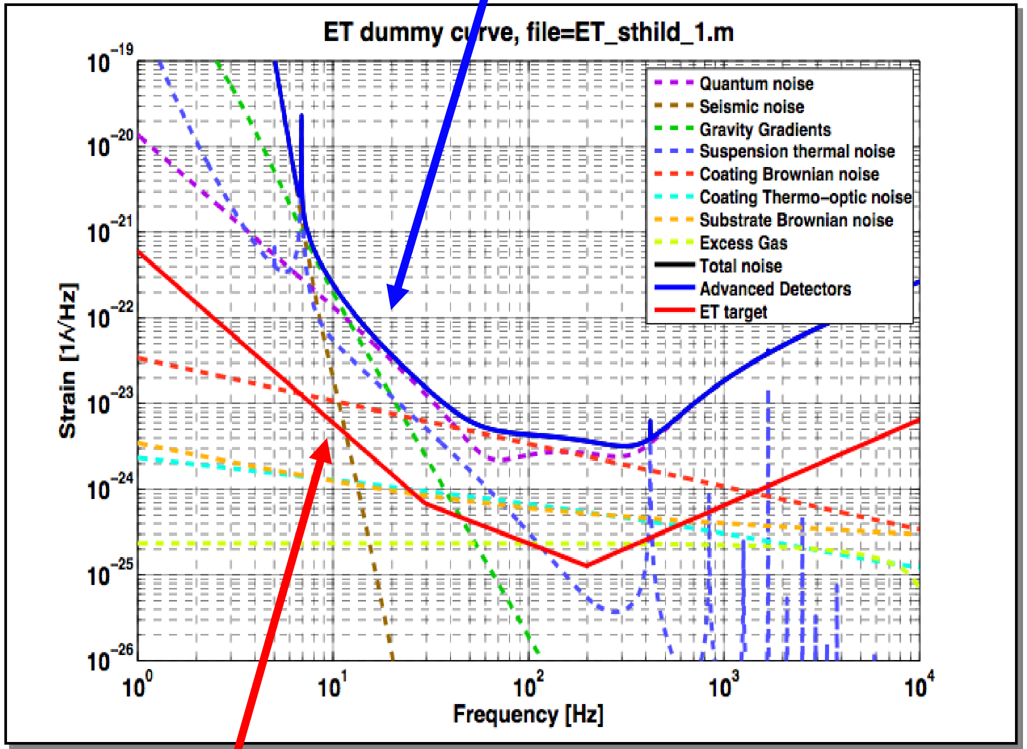
Not considered in our analysis

The starting point

- We consider:
  - Michelson topology with dual recycling.
  - One detector covering the full frequency band
  - A single detector (no network)
- Start from a 2nd Generation instrument.
- Each fundamental noise at least for some frequencies above the ET target.

  => OUR TASK:
  All fundamental noises have to be improved !!

2nd Generation design sensitivity

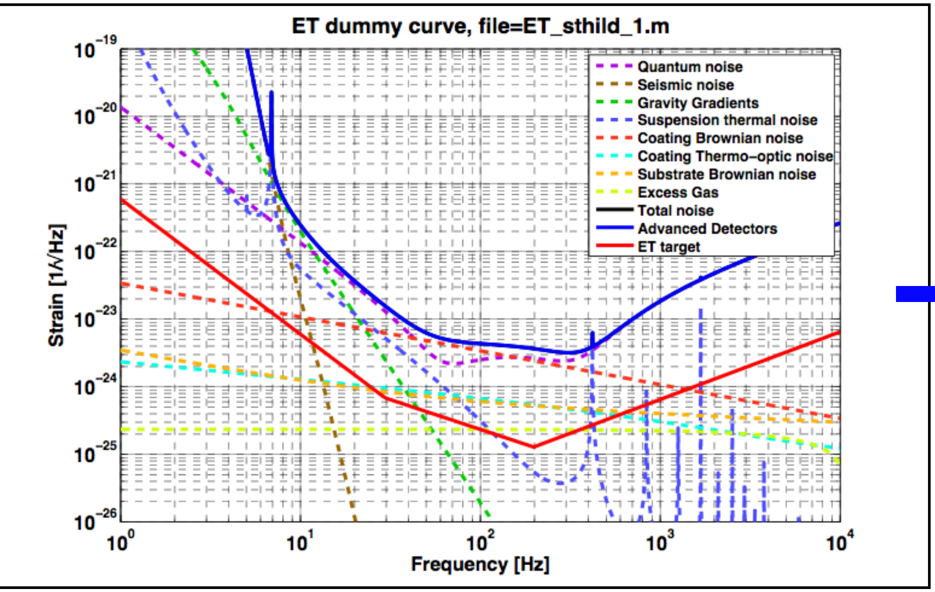


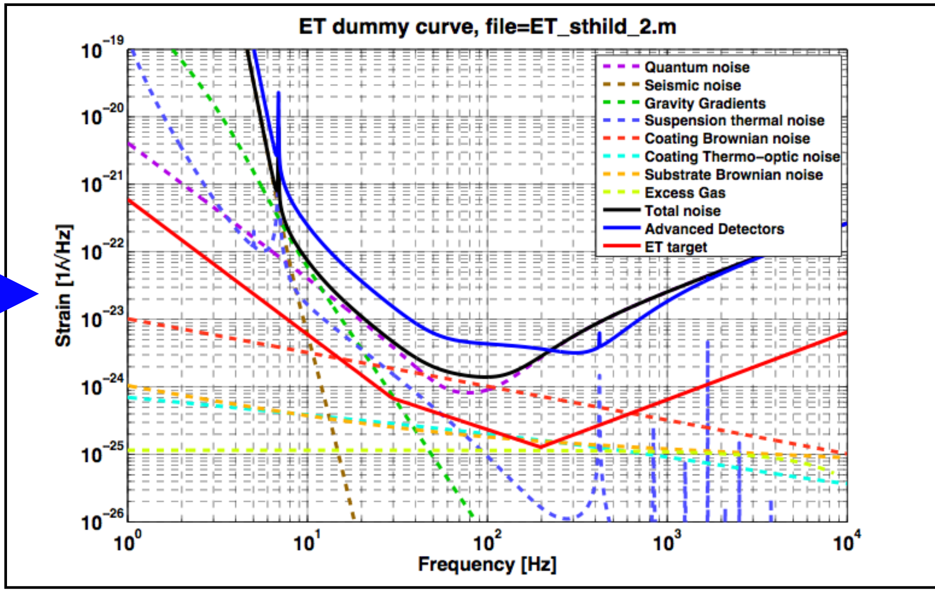
ET target sensitivity (approximated)

UNIVERSITY OF BIRMINGHAM

EGO

Step 1: Increasing the arm length



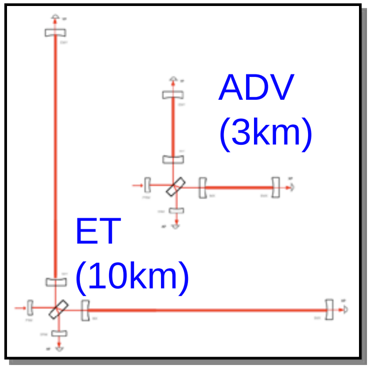


DRIVER: All displacement noises

ACTION: Increase arm length from 3km to 10km

EFFECT: Decrease all displacement noises by a factor 3.3

SIDE EFFECTS:
- Decrease in residual gas pressure
- Change of effective Signal recycling tuning

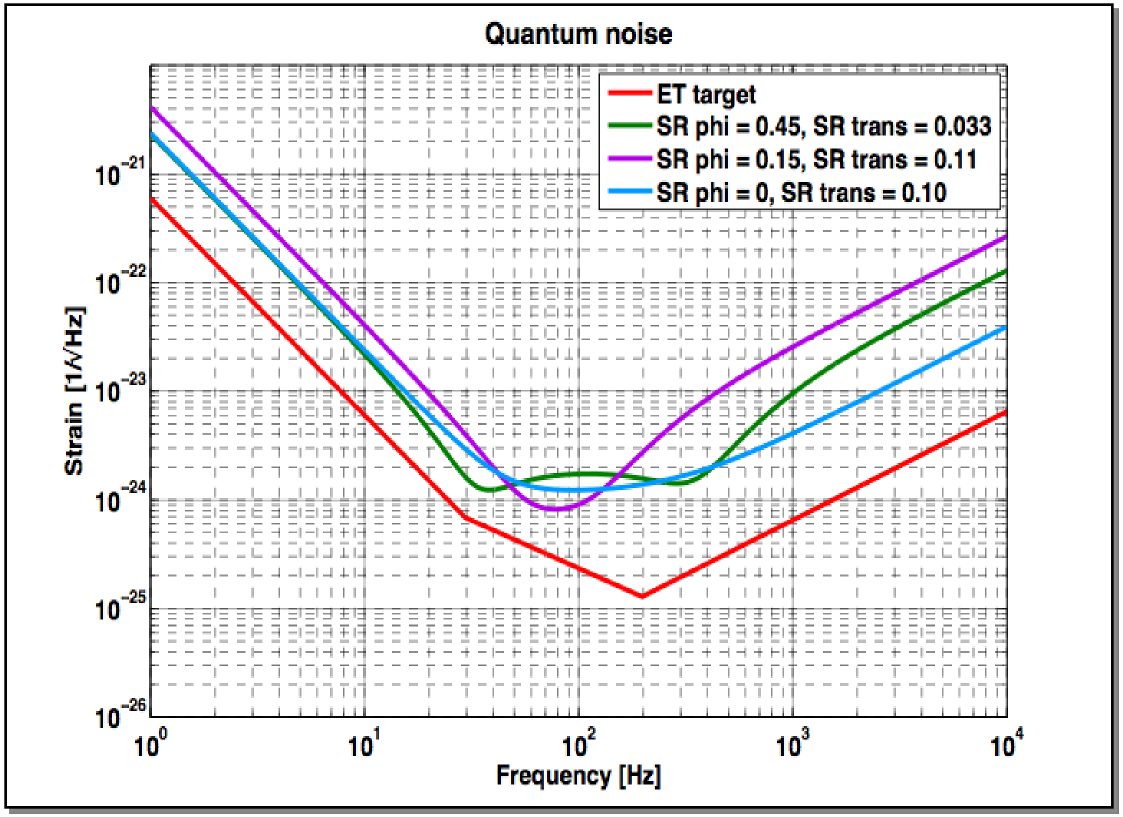


UNIVERSITY OF BIRMINGHAM

EGO

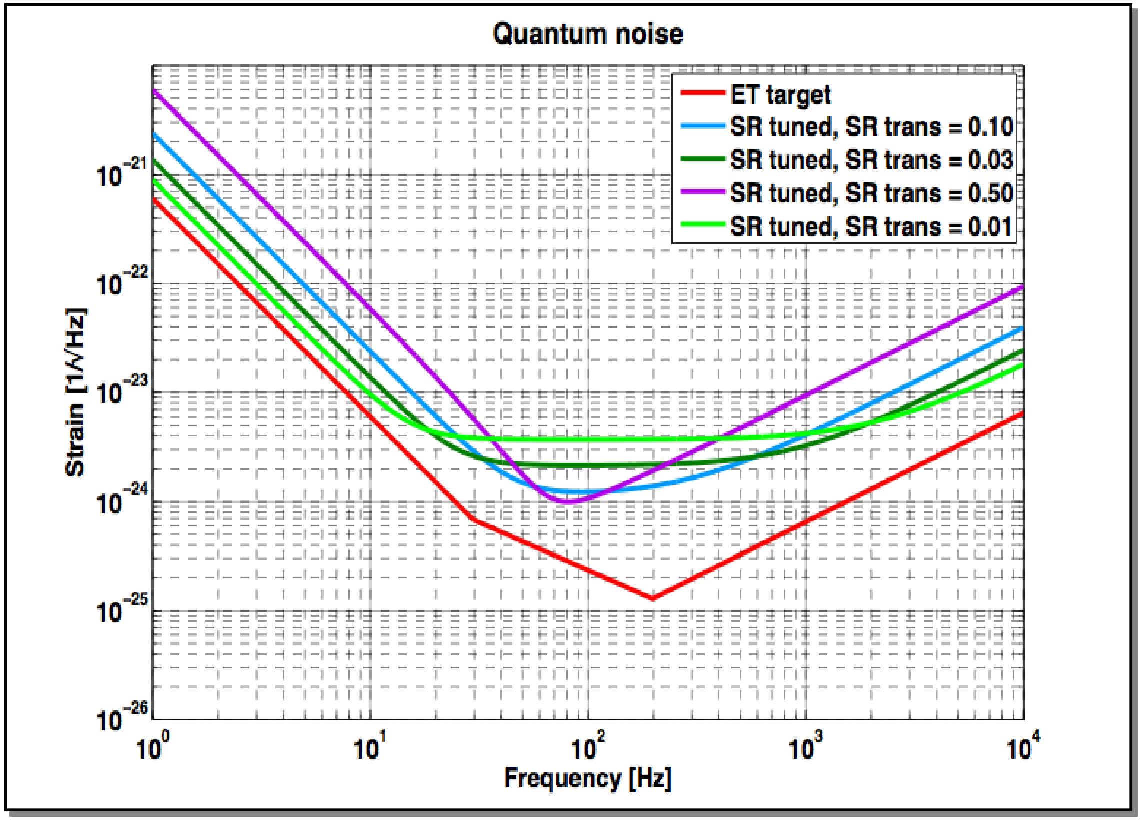
Optimising the signal recycling detuning

- Detuned SR is used in Advanced Virgo and Advanced LIGO
- For ET **tuned SR** seems to be more promising:
  - Optimal trade-off between peak sensi-tivity and bandwidth
  - Recycle both signal sidebands.



Optimising the signal recycling transmittance

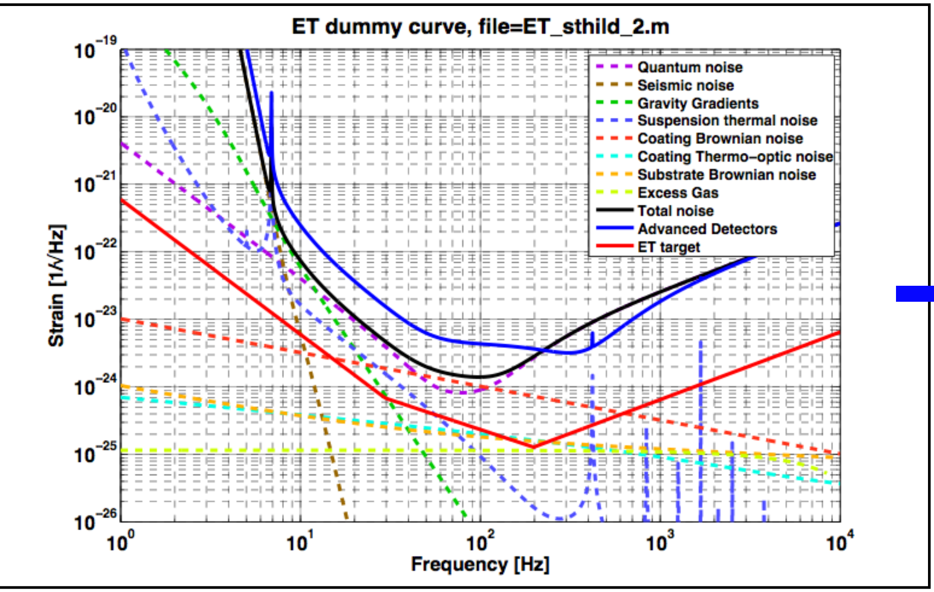
- Optimal trade-off between peak sensi-tivity and bandwidth for 10% transmittance.

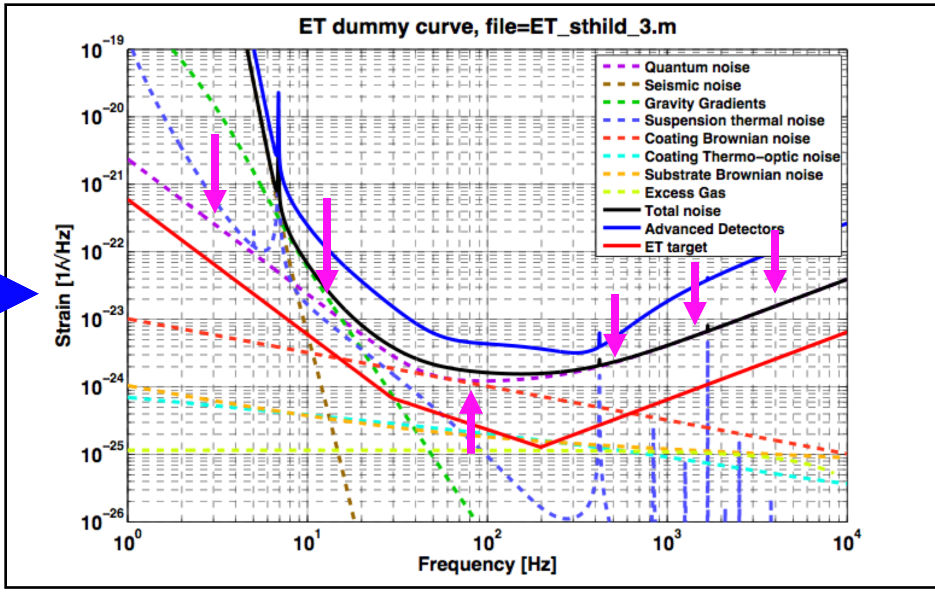


UNIVERSITY OF BIRMINGHAM

EGO

Step 2: Optimising signal recycling

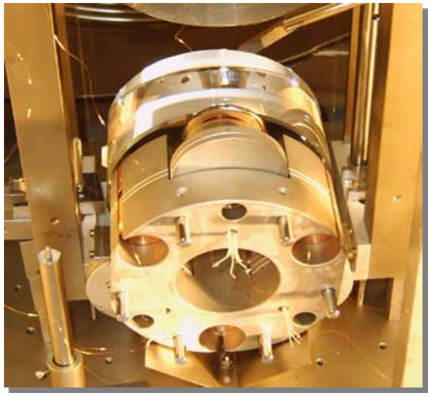




DRIVER: Quantum noise

ACTION: From detuned SR to tuned SR (with 10% transmittance)

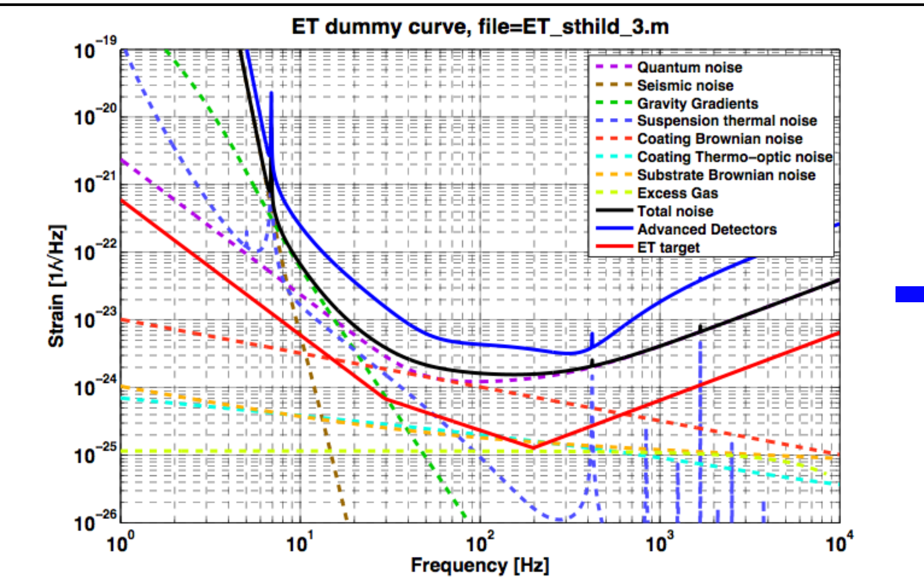
EFFECTS:
- Reduced shot noise by ~ factor 7 at high freqs
- Reduced radiation pressure by ~ factor 2 at low freqs
- Reduced peak sensitivity by ~ factor sqrt(2) :(

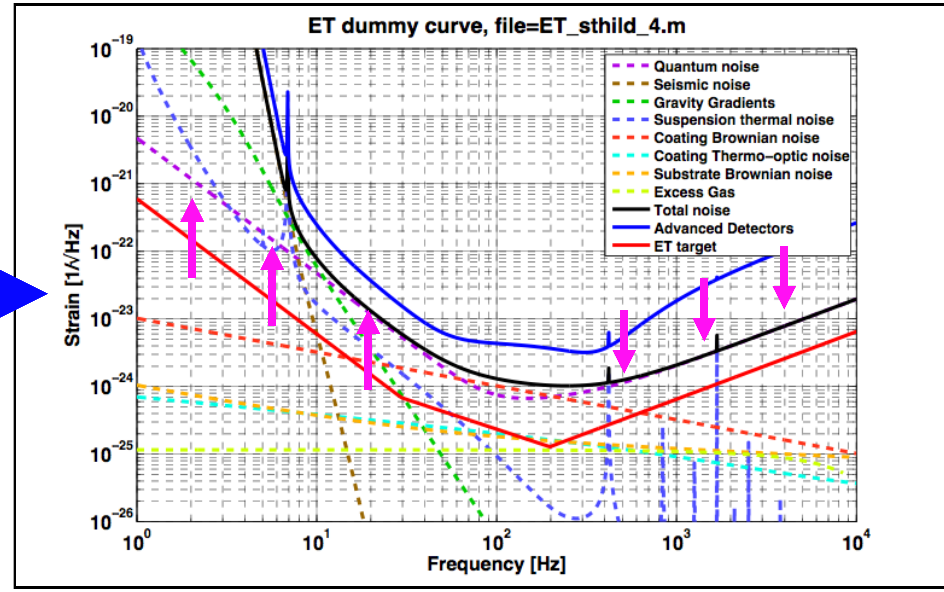


UNIVERSITY OF BIRMINGHAM

EGO

Step 3: Increasing the laser power



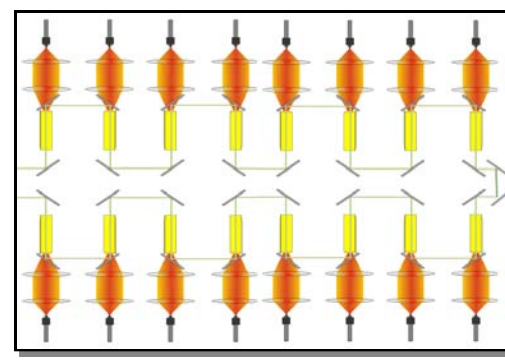


DRIVER: Shot noise at high frequencies

ACTION: Increase laser power (@ ifo input) from 125W to 500W

EFFECT: Reduced shot noise by a factor of 2

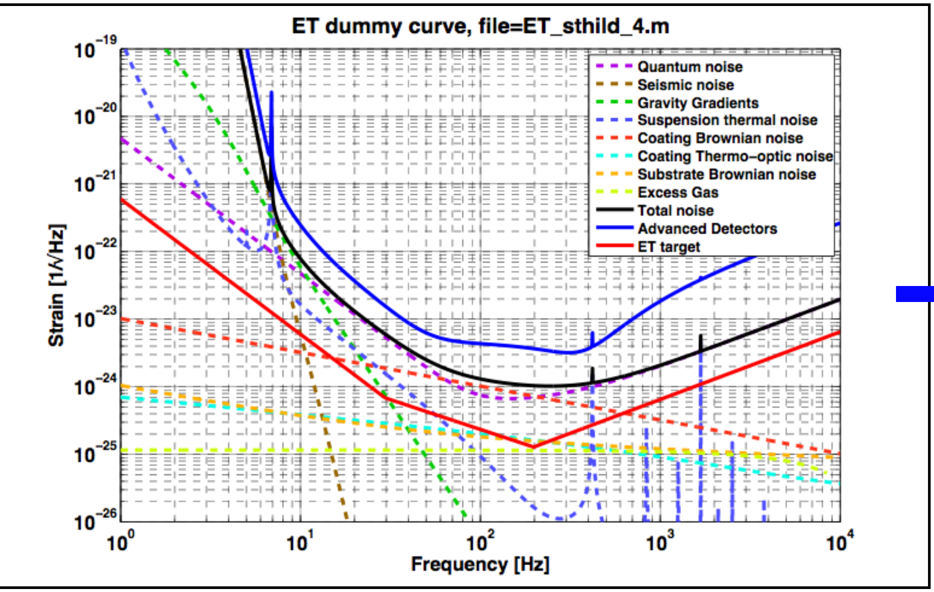
SIDE EFFECTS: Increased radiation pressure noise by a factor 2

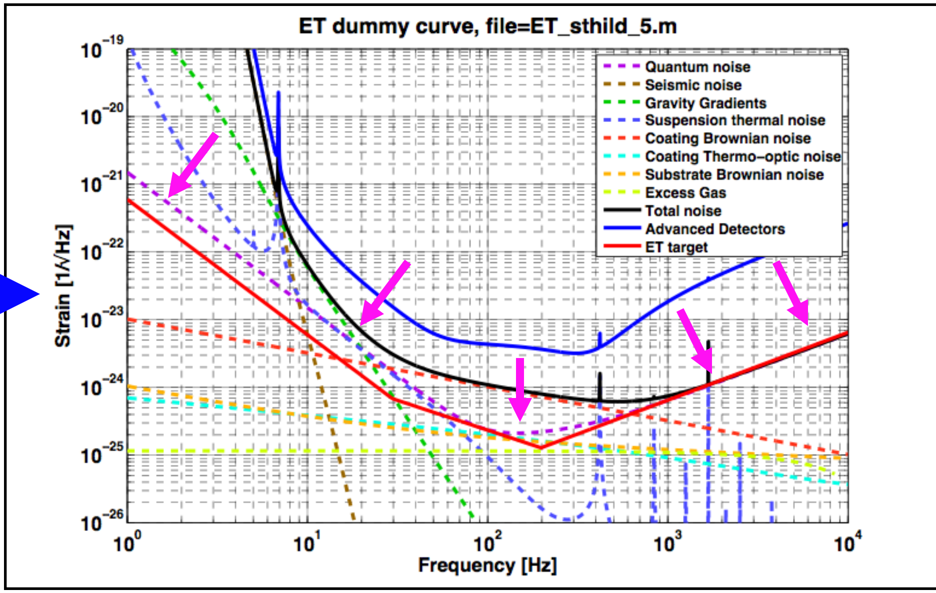


UNIVERSITY OF BIRMINGHAM

EGO

Step 4: Quantum noise suppression



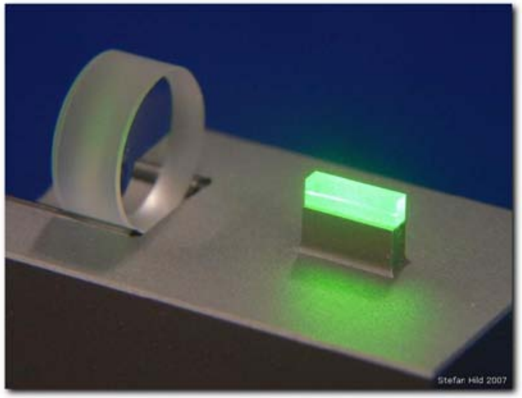


DRIVER: Shot noise at high frequencies

ACTION: Introduced 10dB of squeezing (frequency depend angle)

EFFECT: Decreases the shot noise by a factor 3

SIDE EFFECTS: Decreases radiation pressure noise by a factor 3



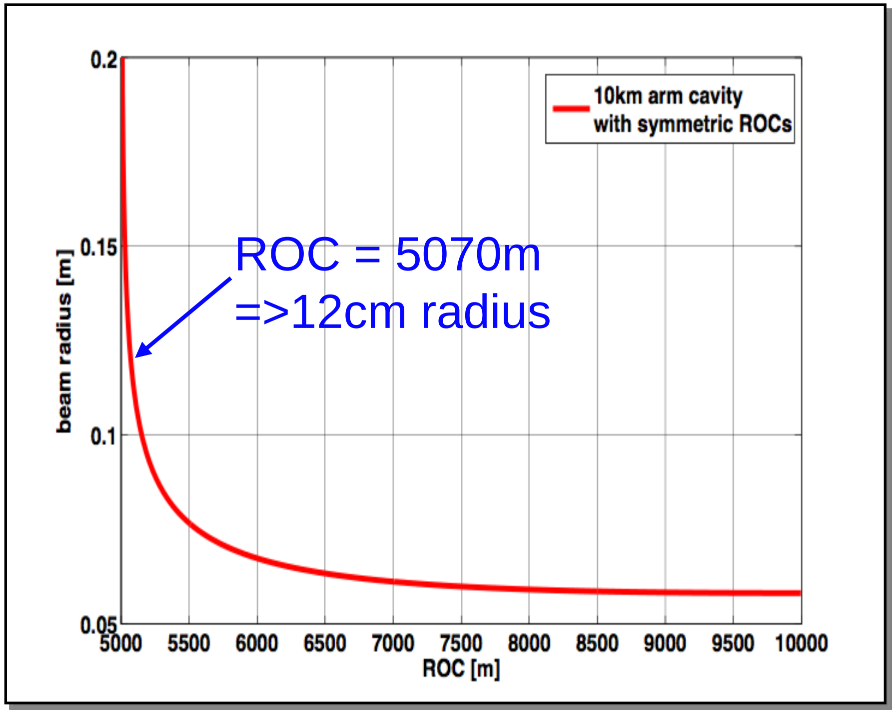
Increasing the beam size to reduce Coating Brownian noise

Increasing the beam size at the mirrors reduces the contribution of Coating Brownian.

Coating Brownian noise of one mirror:

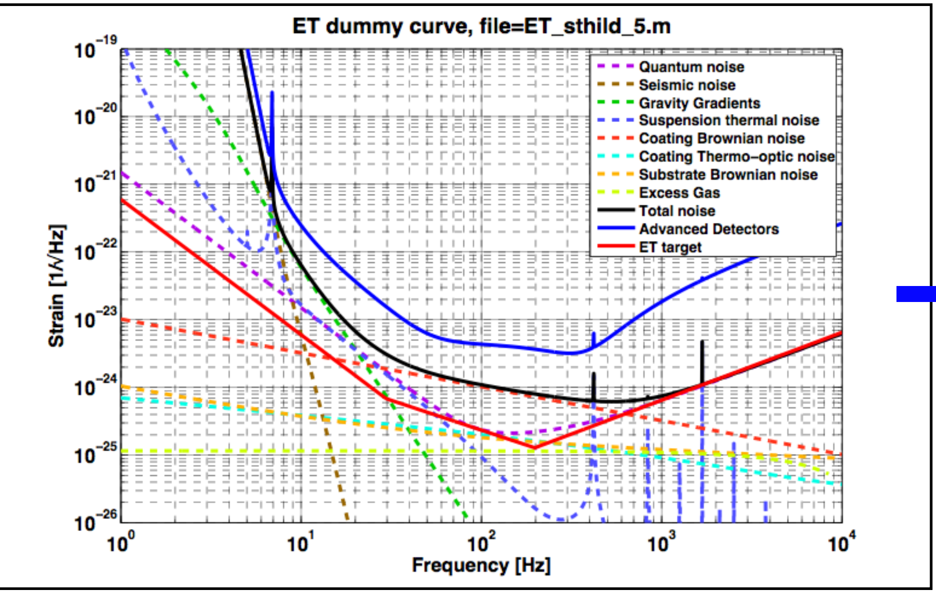
$$S_x(f) = \frac{4k_B T}{\pi^2 f Y}\frac{d}{r_0^2}\left(\frac{Y'}{Y}\phi_{||} + \frac{Y}{Y'}\phi_\perp\right)$$

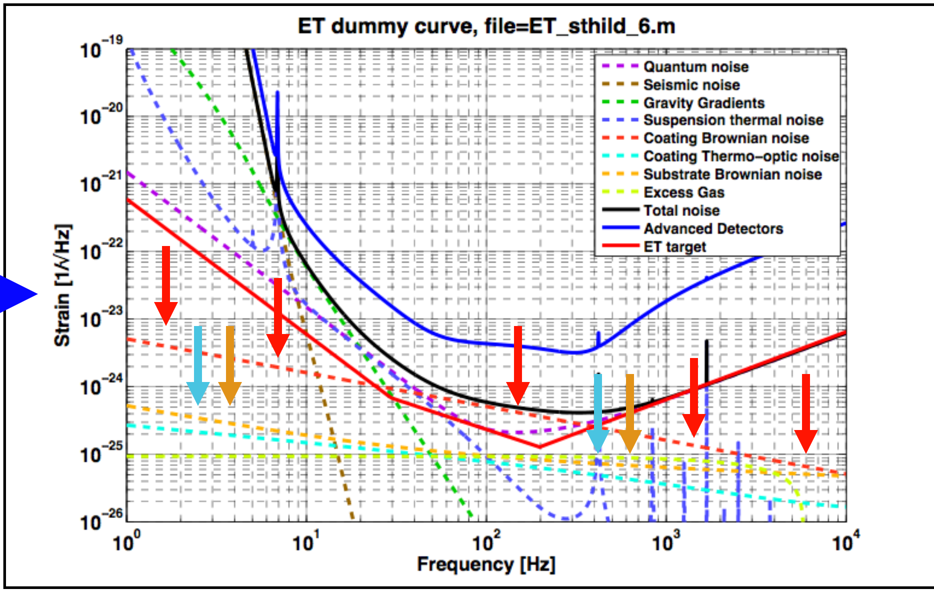
beam radius on mirror



Please note: a beam radius of 12cm requires mirrors of 60 to 70cm diameter

Step 5: Increasing the beam size





DRIVER: Coating Brownian noise

ACTION: Increase of beam radius from 6 to 12cm

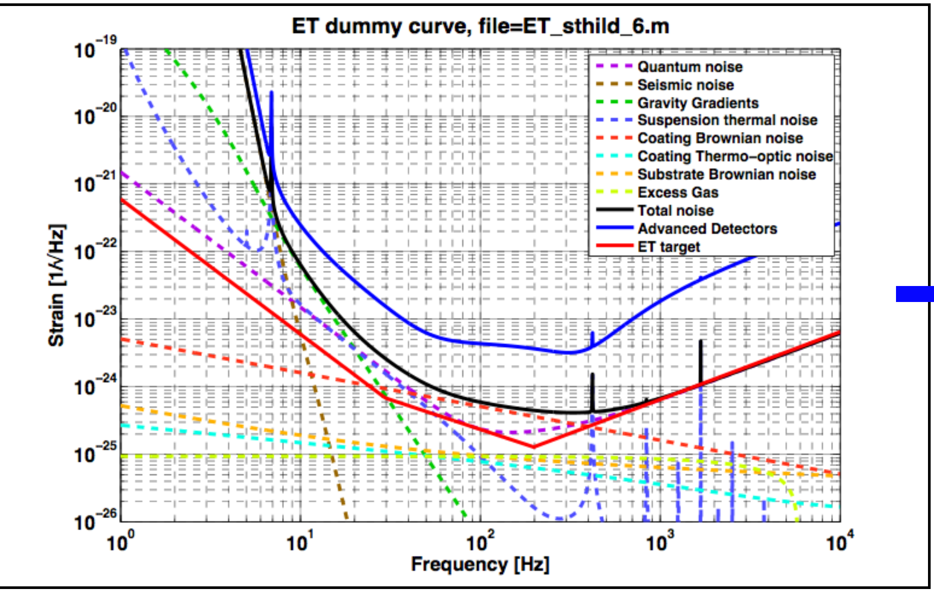
EFFECT: Decrease of Coating Brownian by a factor 2

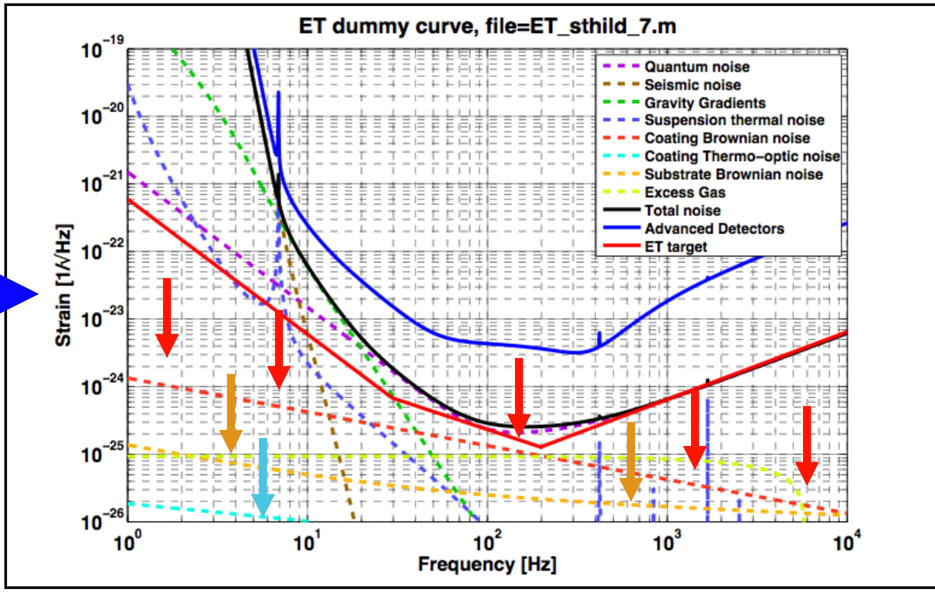
SIDE EFFECTS:
- Decrease of Substrate Brownian noise (~factor 2)
- Decrease of Thermo-optic noise (~factor 2)
- Decrease of residual gas pressure noise (~10-20%)

UNIVERSITY OF BIRMINGHAM

EGO

Step 6: Cooling the test masses



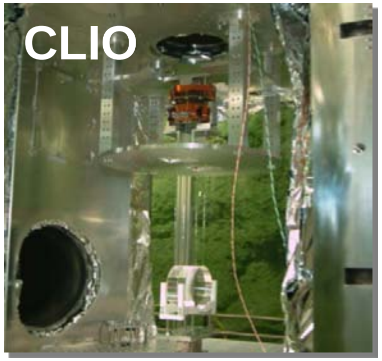


DRIVER: Coating Brownian noise

ACTION: Reduce the test mass temperature from 290K to 20K

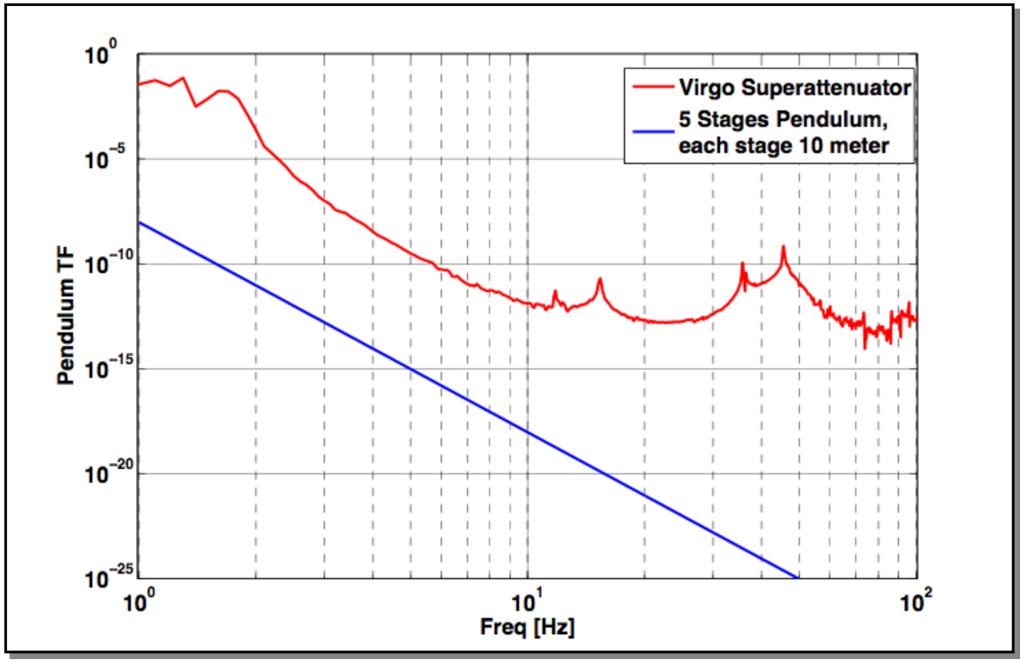
EFFECT: Decrease Brownian by ~ factor of 4

SIDE EFFECTS:
- Decrease of substrate Brownian
- Decrease of thermo-optic noise



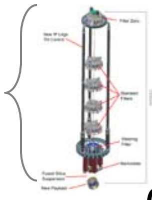
Kuroda 2008
LIGO-G080060

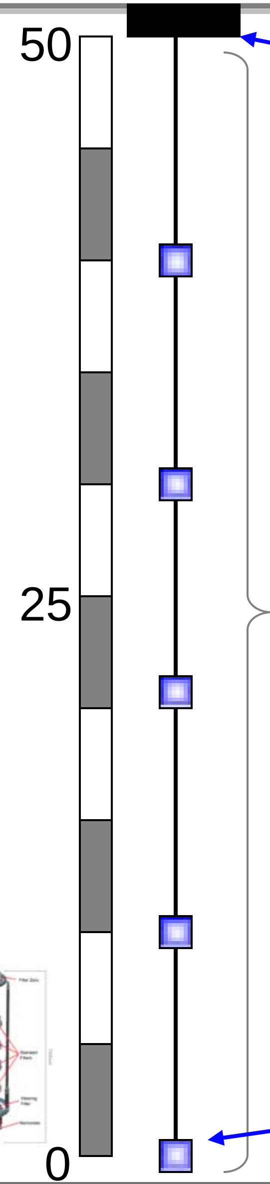
Seismic Isolation / Suspension



SA-data: G.Ballardin et al, Rev. Sci. Instrum., Vol.72, No.9 (2001)

Virgo Superattenuator (height ~ 8 meter)

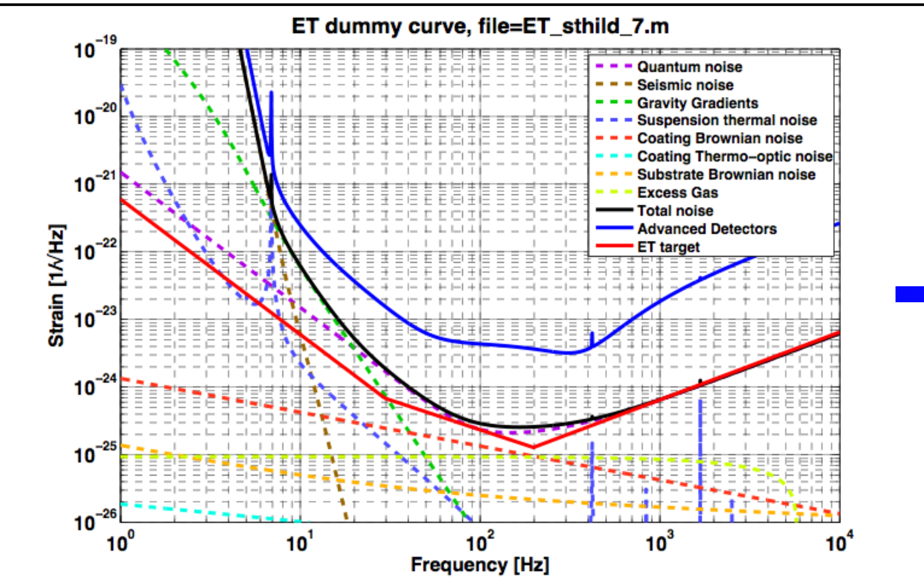


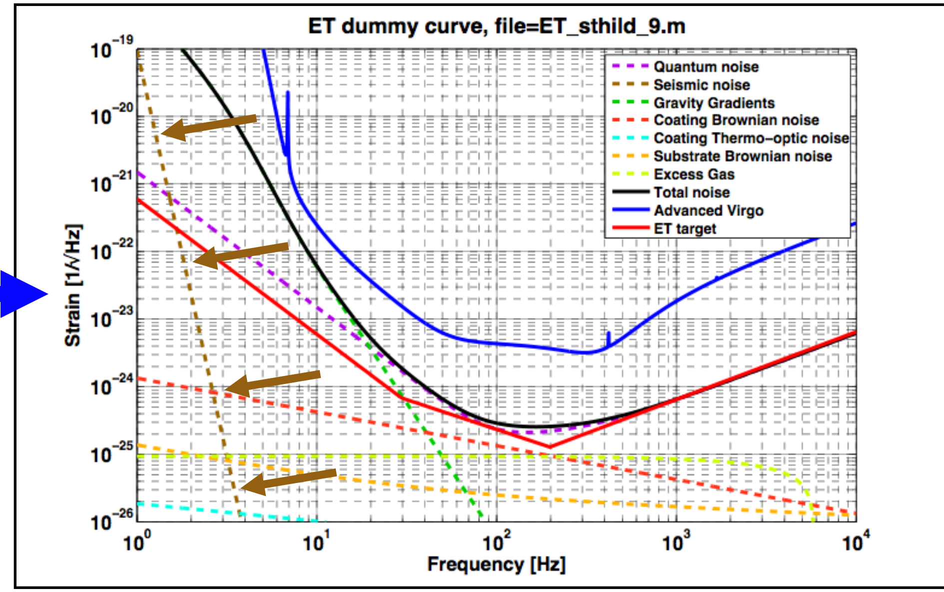


5 Stages of each 10 m height

corner freq = 0.158Hz

Step 7: Longer Suspensions



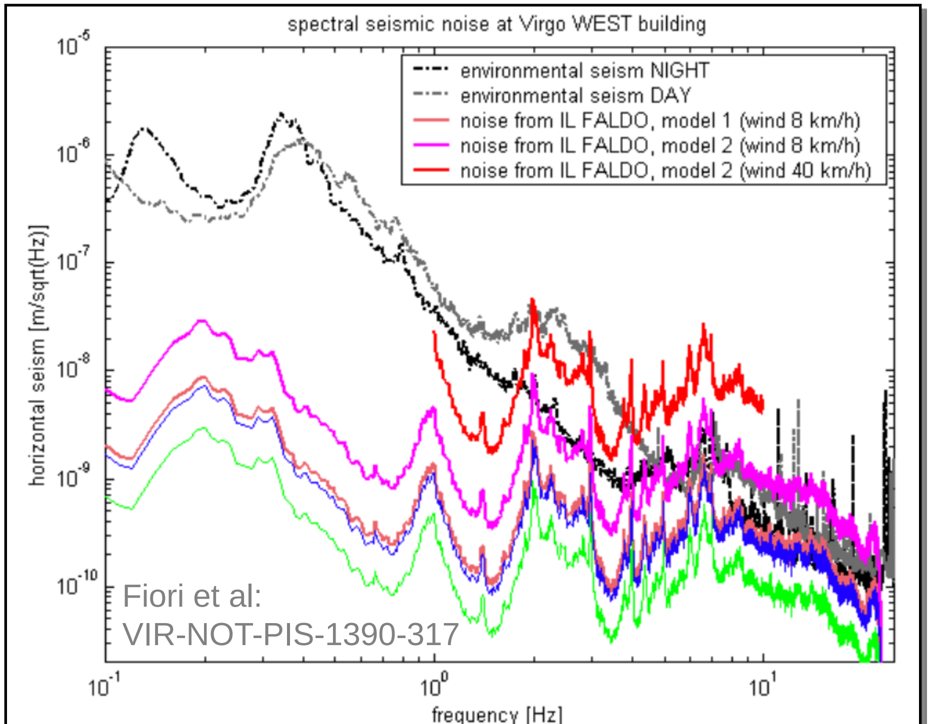


DRIVER: Seismic noise

ACTION: Build 50m tall 5 stage suspension (corner freq = 0.158 Hz)

EFFECT: Decrease seismic noise by many orders of magnitude
or pushes the seismic wall from 10 Hz to about 1.5 Hz

Tackling Gravity Gradient noise: going underground



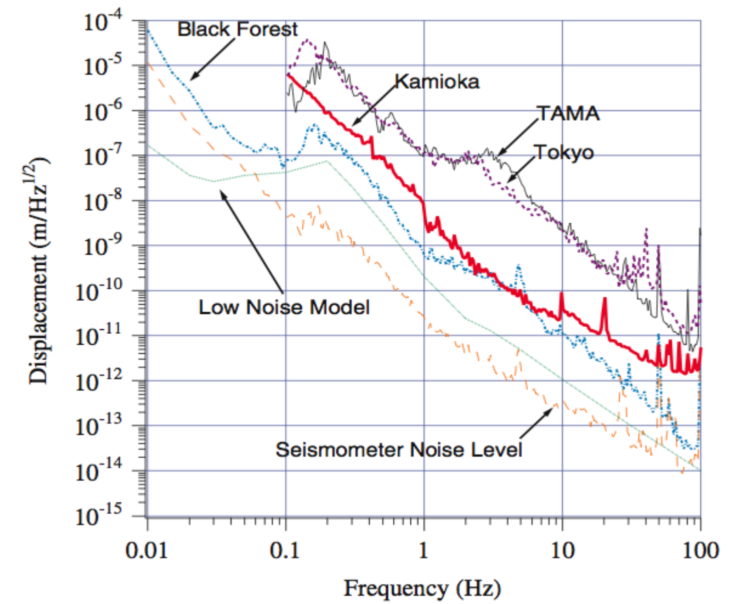


Figure 7. Low seismic noise environment at the Kamioka site. Displacement noises at Kamioka, TAMA site, Tokyo, Black Forest Geophysical Observatory (Germany) and a low noise model (a hybrid spectrum of quiet sites in the world) are described.

Ohasi et al: Class. Quantum Grav. **20** (2003) S599-607

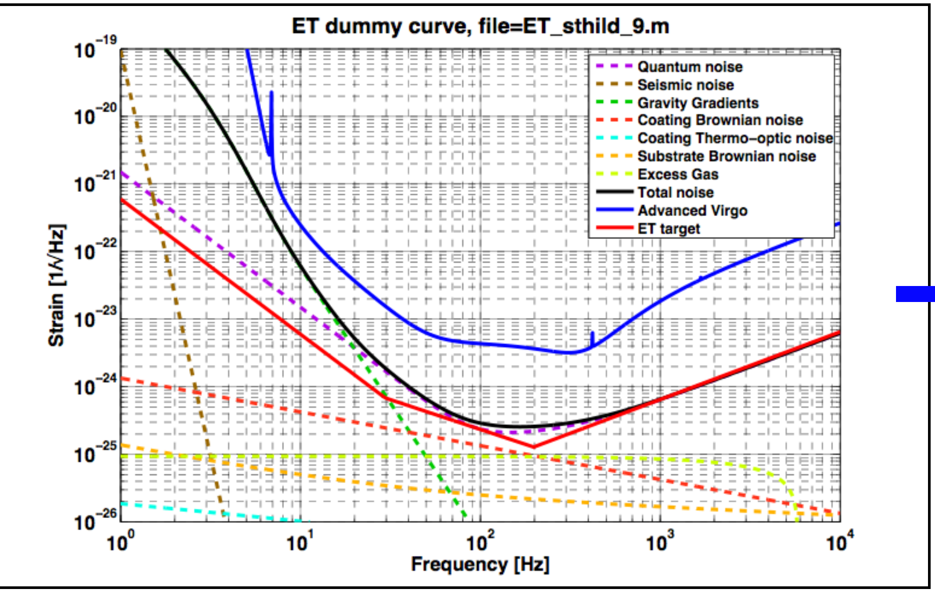
Surface (Cascina)

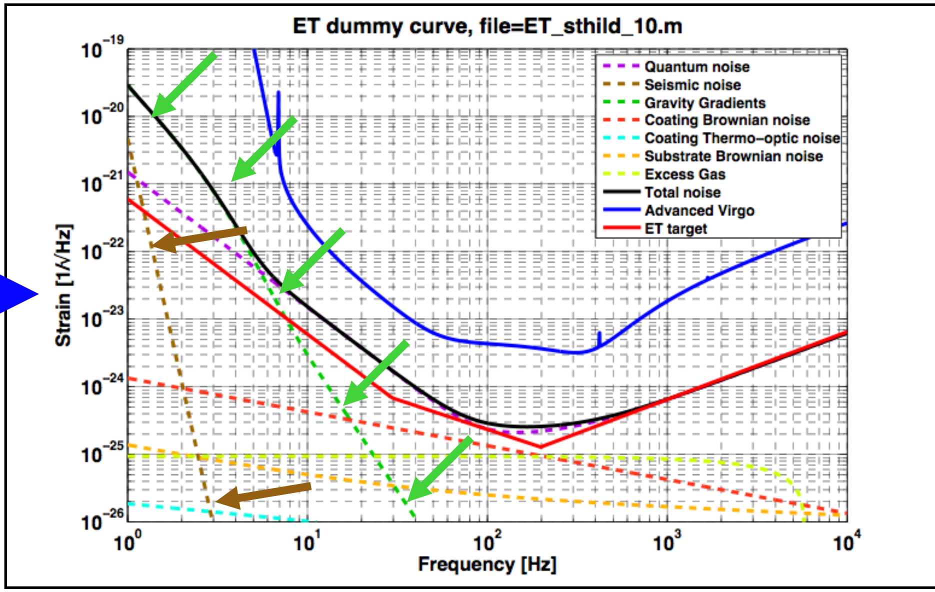
about $1 \cdot 10^{-7}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$

Underground (Kamioka)

about $5 \cdot 10^{-9}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$

Step 8: Going underground





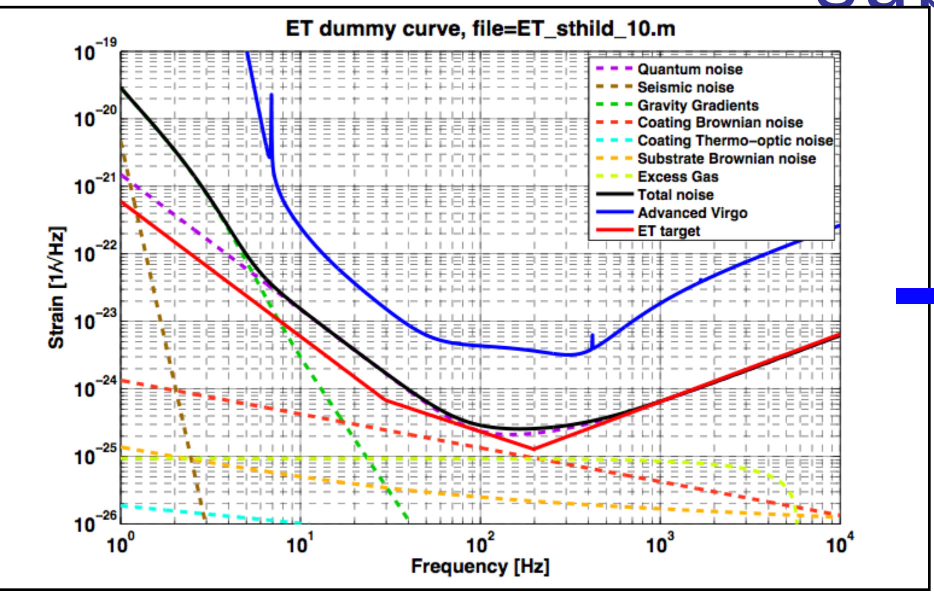
DRIVER: Gravity gradient noise

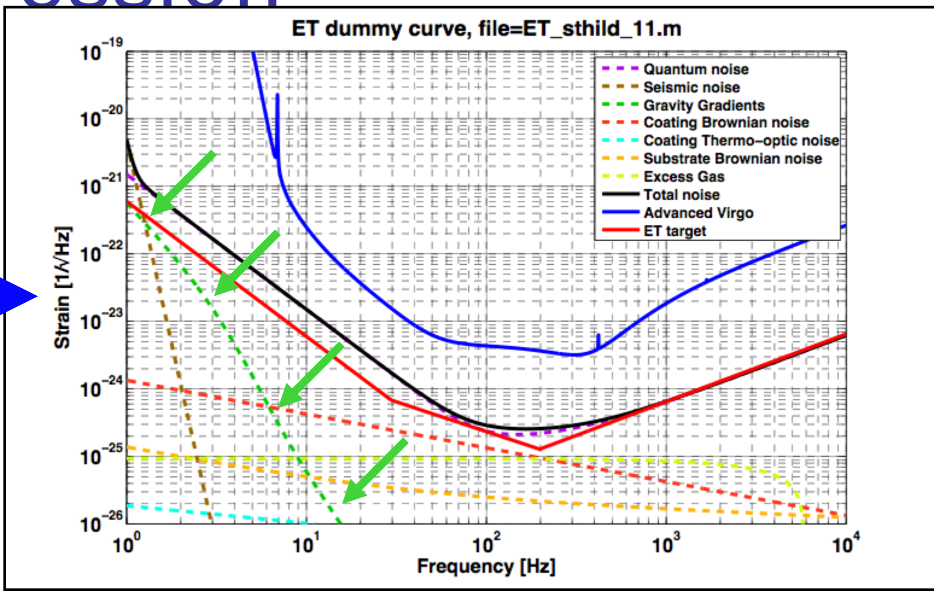
ACTION: Go from the surface to underground location

EFFECT: Decrease gravity gradients by a factor 20

SIDE EFFECTS: Decrease in seismic noise by a factor 20

Step 9: Gravity gradient supression



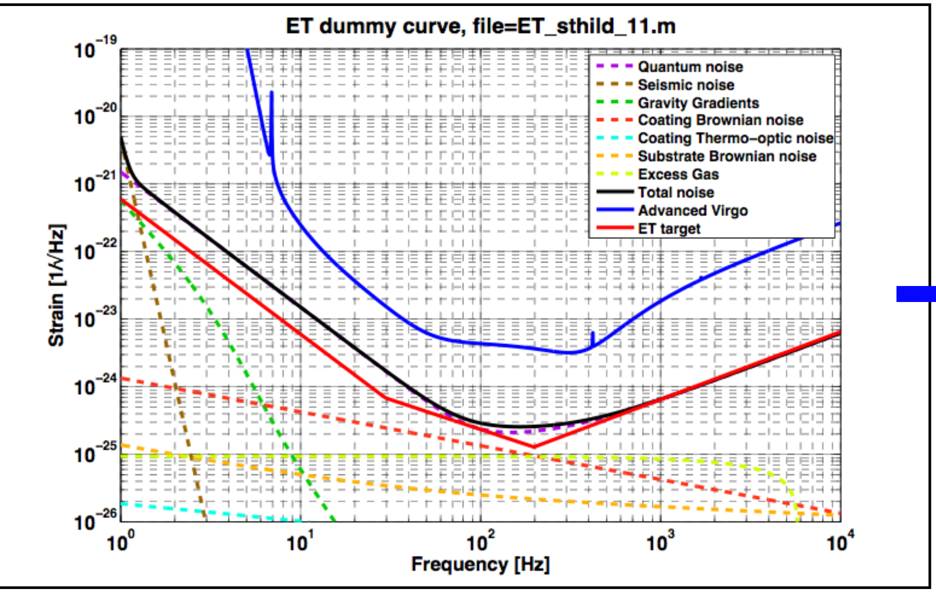


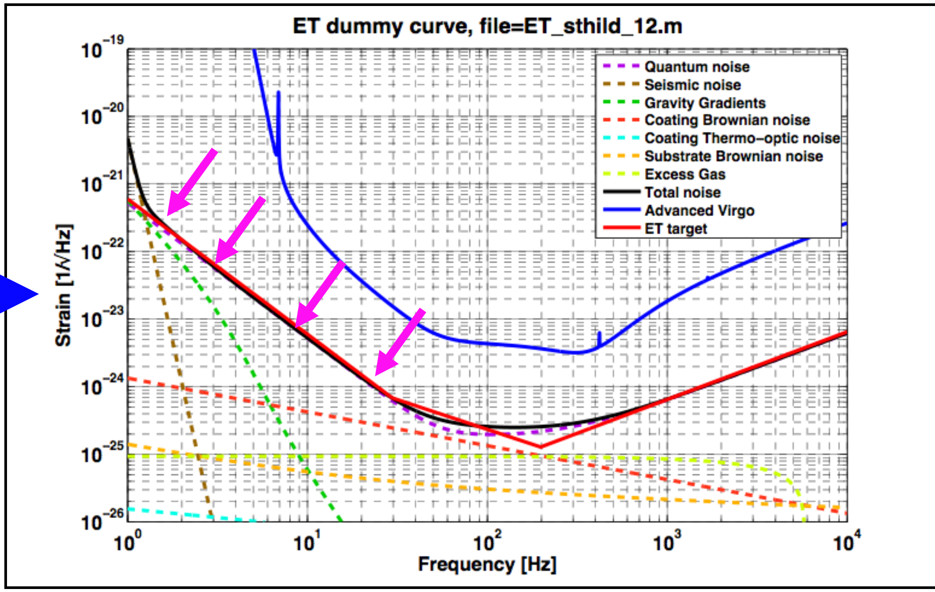
DRIVER: Gravity gradient noise

ACTION: M A G I C

EFFECT: Decrease gravity gradient noise by a factor 50.

Step 10: Heavier mirrors

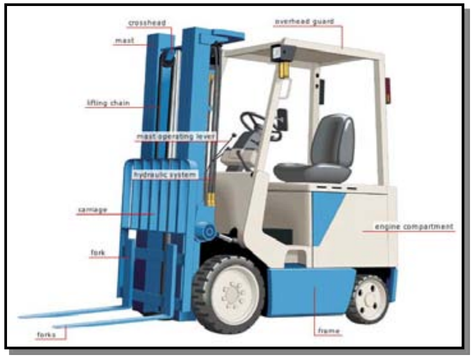


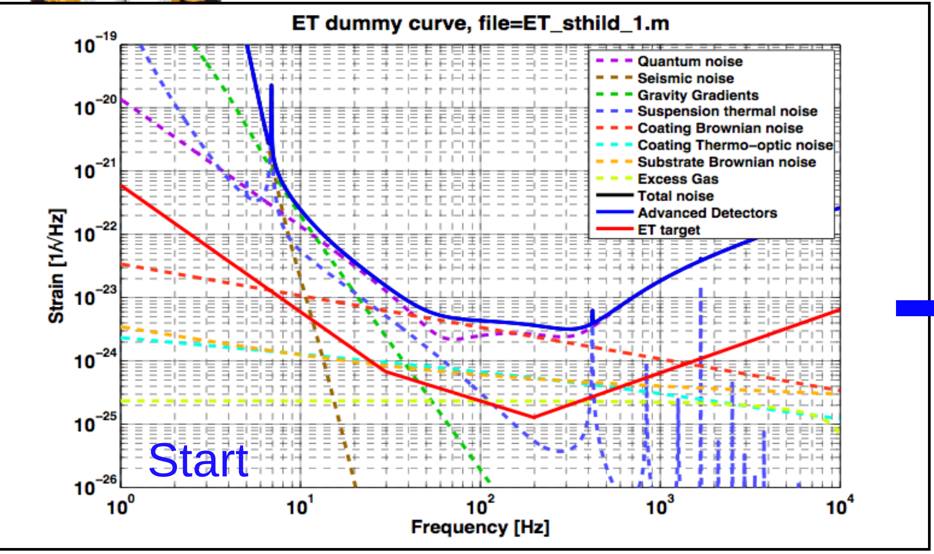


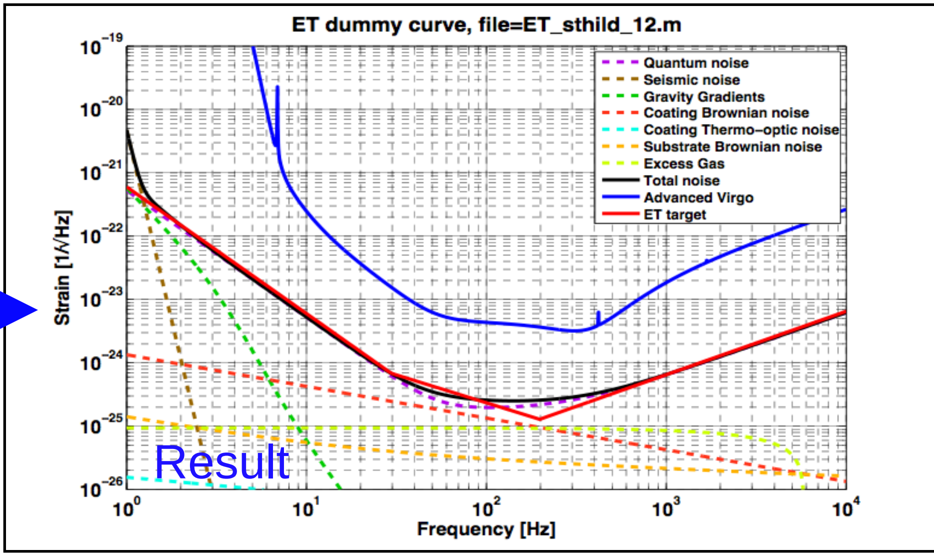
DRIVER: Quantum noise at low frequencies

ACTION: Increase test mass weight from 42 kg to 120 kg

EFFECT: Decrease of radiation pressure noise







	advanced detector	potential ET design
Arm length	3 km	10 km
SR-phase	detuned (0.15)	tuned (0.0)
SR transmittance	11 %	10 %
Input power (after IMC)	125 W	500 W
Arm power	0.75 MW	3 MW
Quantum noise suppression	none	10 dB
Beam radius	6 cm	12 cm
Temperature	290 K	20 K
Suspension	Superattenuator	5 stages of each 10 m length
Seismic	$1 \cdot 10^{-7}\,\mathrm{m}/f^2$ for $f > 1$ Hz (Cascina)	$5 \cdot 10^{-9}\,\mathrm{m}/f^2$ for $f > 1$ Hz (Kamioka)
Gravity gradient reduction	none	factor 50 required (cave shaping)
Mirror masses	42 kg	120 kg
BNS range	150 Mpc	2650 Mpc
BBH range	800 Mpc	17700 Mpc

Our analysis can be seen as the ...

Brute Force Approach

+

a little bit
of magic

What can we learn from our analysis?

- The brute-force approach we presented:
  - It is just one of many approaches (values are mostly arbitrary chosen)
  - Not a very brave or innovative approach
  - Definetly high costs...
  - ..., but in principle possible. :)

- Approaches also using non-convential techniques:
  - Definitely more elegant
  - Probably smaller costs

- Our brute-force approach can be used as reference scenario, allowing cost-benefit comparisons for evaluating 'new' (non-conventional) techniques.
  - Example: Using LG33 modes needs larger mirrors, but allows to operate ET at room temperature. Costs for larger mirrors = xxx. Cost for cryogenic test masses = yyy.

Summary

- Using only conventional techniques it is possible to get close to the ET target sensitivity.

	advanced detector	potential ET design
Arm length	3 km	10 km
SR-phase	detuned (0.15)	tuned (0.0)
SR transmittance	11 %	10 %
Input power (after IMC)	125 W	500 W
Arm power	0.75 MW	3 MW
Quantum noise suppression	none	10 dB
Beam radius	6 cm	12 cm
Temperature	290 K	20 K
Suspension	Superattenuator	5 stages of each 10 m length
Seismic	$1 \cdot 10^{-7}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$ (Cascina)	$5 \cdot 10^{-9}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$ (Kamioka)
Gravity gradient reduction	none	factor 50 required (cave shaping)
Mirror masses	42 kg	120 kg
BNS range	150 Mpc	2650 Mpc
BBH range	800 Mpc	17700 Mpc

- We developed a GWINC model for such an ET detector. This model can be used as reference for evaluation of benefit of more elegant / innovative approaches.

- More details can be found in:
  S. Hild et al, http://arxiv.org/abs/0810.0604

E N D