The Einstein Telescope Optical Design

Research and Development

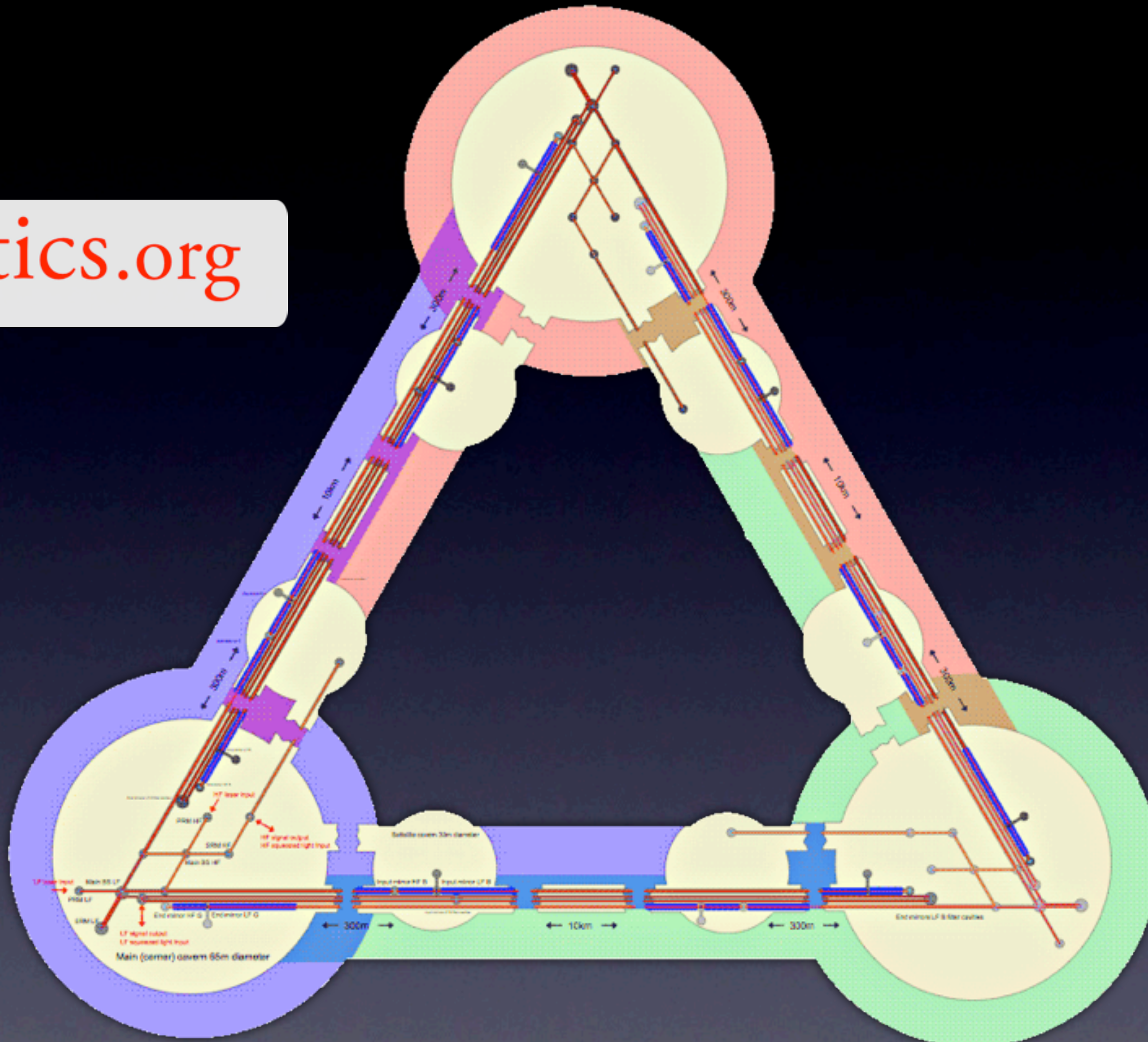
Andreas Freise 04.12.2012 ET General Meeting

Overview

- Reminder: the ET interferometers
- Baseline design is done, why do we do further research on interferometry?

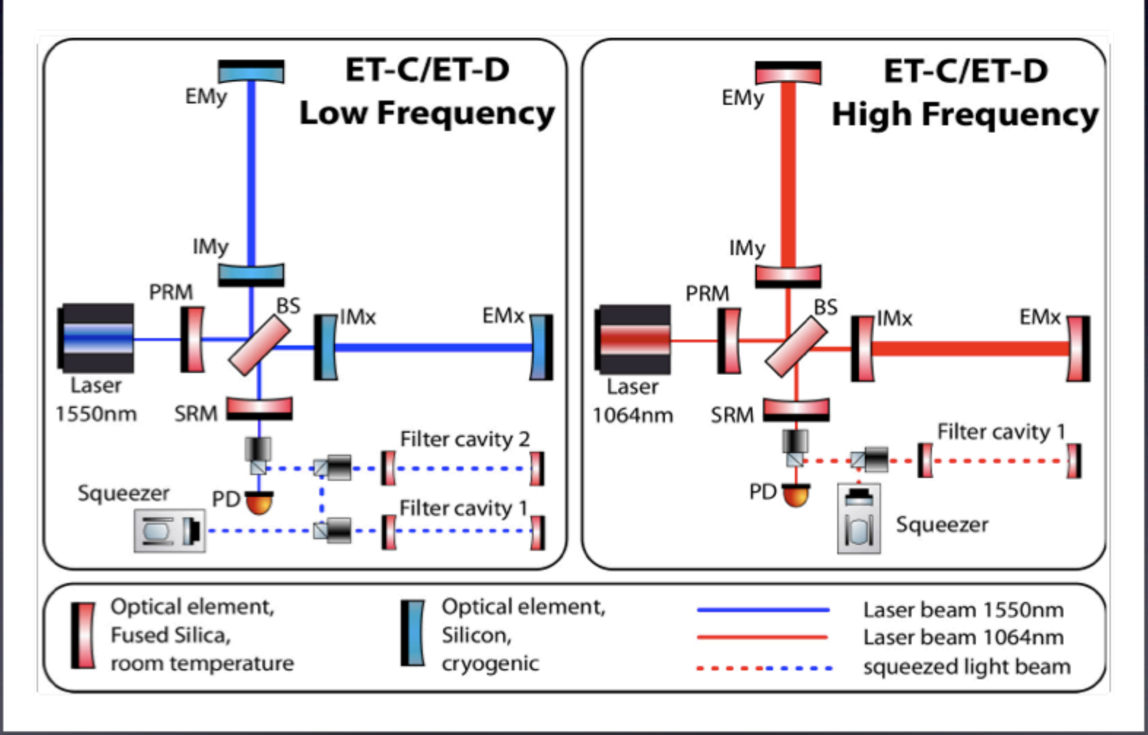
- Optics R+D towards ET

gwoptics.org



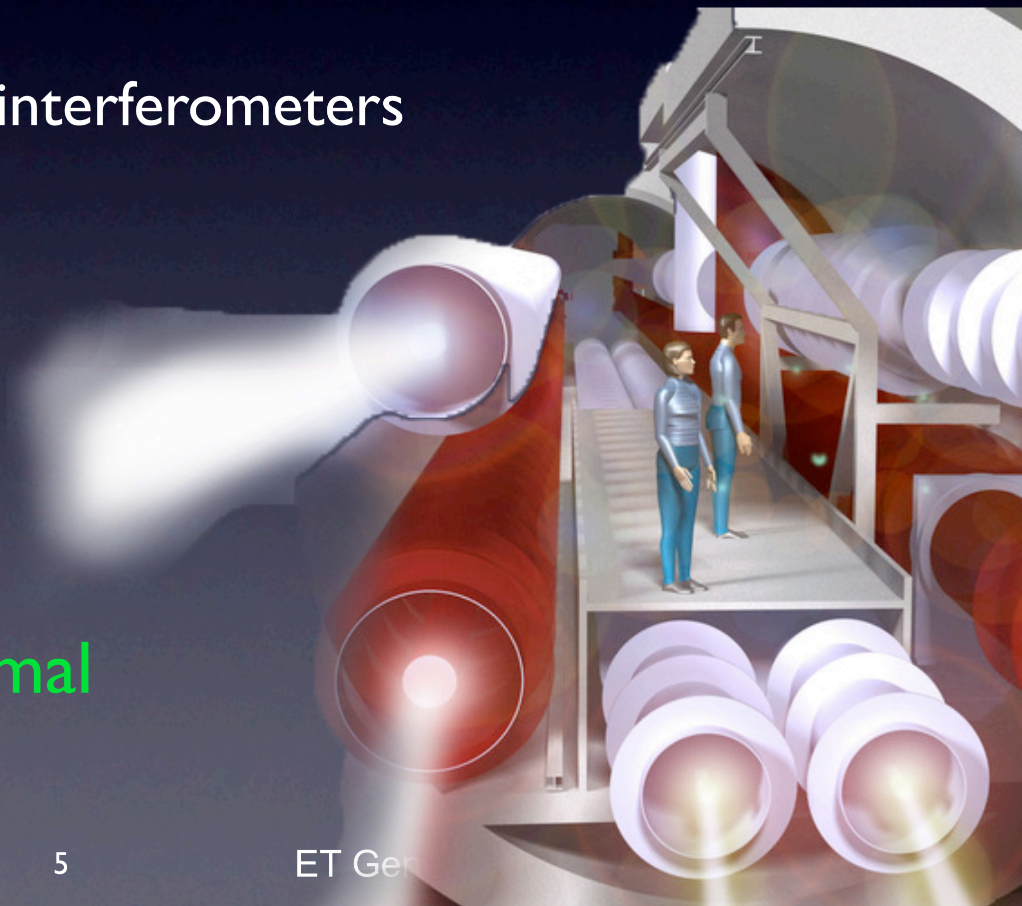
ET interferometer design

- Each detectors has two Michelson interferometers in a Xylophone configuration. The interferometers are similar to Advanced Detectors (arm cavities, plus recycling)
- `Conservative' design with a bit of magic: thermal noise reduction and quantum noise reduction



Design Concept

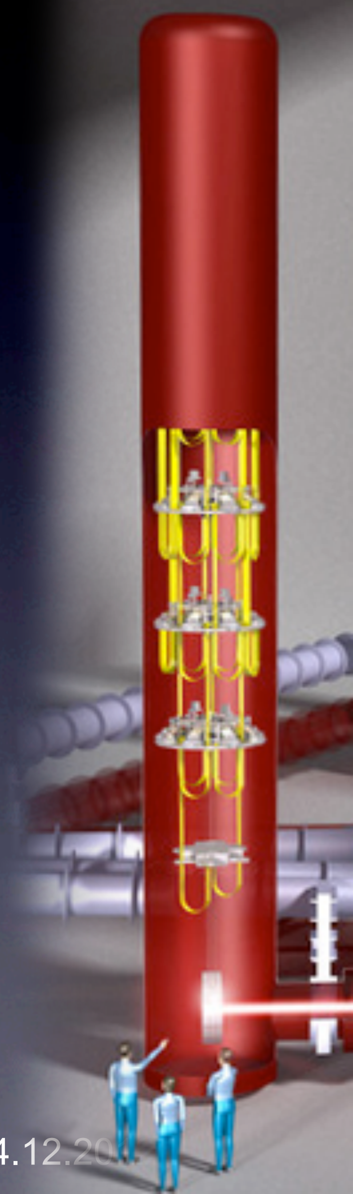
- L-shaped form fits all types of interferometers
- long distances between central optics and arm cavities
- allows for `hot’ and `cold’ interferometers side by side
- room for extra tubes (filter cavities)



Flexible design, in minimal amount of space

Technology Concepts

- Baseline design is an extension of known techniques
- combines many flexible and compatible technologies
  - Michelson, power+signal recycling
    replace by Sagnac, other topology?
  - cryogenic silicon
    use sapphire, different temperature?
  - frequency dependent squeezed light
    adapt implementation to main topology
  - LG modes
    replace by Khalili cavities, waveguide coatings?



Required R+D

In the ET Design study report we explicitly list the following technologies to be studied:

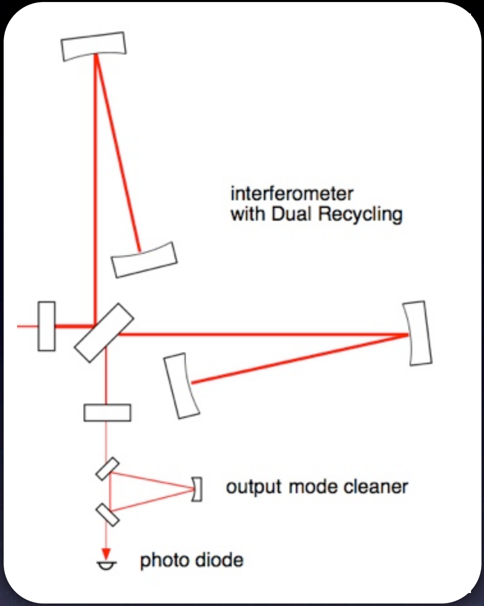
- Thermal noise reduction:
  LG modes, Khalili cavities, coating research, waveguide mirrors
- Quantum noise reduction:
  Speedmeter technologies, Michelson based and Sagnac based

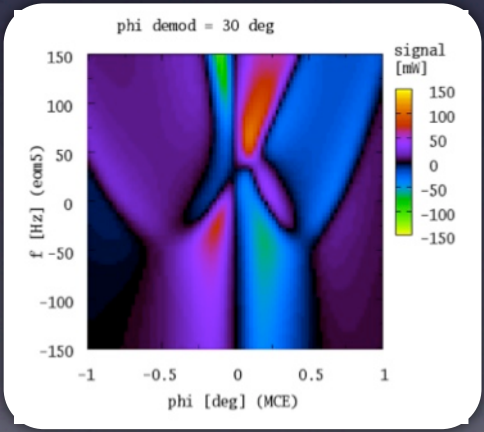
Ongoing work to study fundamental concepts as possible alternatives for baseline design and future upgrades.

Example: Signal Recycling

An incomplete, approximate history:

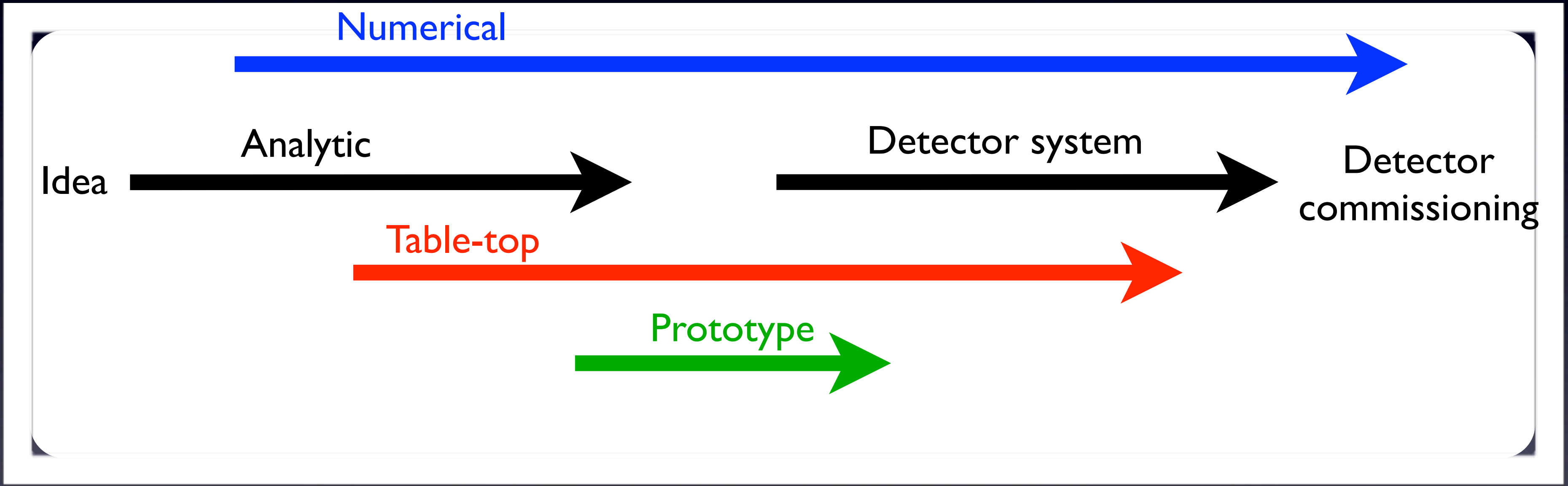
- 1980ies invented/proposed in Glasgow
- 1990ies table-top experiments in Hannover, prototype demonstrations in Garching
- 2000+ implemented in GEO, large LSC effort on aLIGO design, from RSE to DC readout, optical spring
- 2010+ implemented in Advanced Detectors
- 2020+ Implemented for ET? (Control signals for very low bandwidth, very small detuning?)





From idea to implementation

Pushing the state of tha art!



10 to 30 years is a good time scale to go from idea to an implementation/application of a new concept or technology

Conclusion so far?

- Baseline design for ET interferometers is ready!
- Thermal noise and quantum noise reduction is something to work on (technical details!)
- Technical details are fun for researchers but take a lot of time (and money!) to eliminate.
- Two threads:
  - make it work!
  - find better ideas to replace parts of the current design

ET work @ Glasgow Interferometry

Overview of finished experiments:

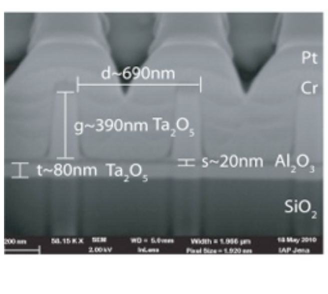
- Optical spring demonstration with 100g mirror
- First Demonstration of a waveguide mirror in a suspended cavity
- Injection of LG modes into a suspended 10m cavity *(see talk by Ludovico)*

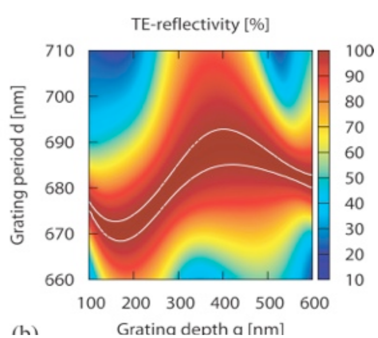
Overview of ongoing experiments:

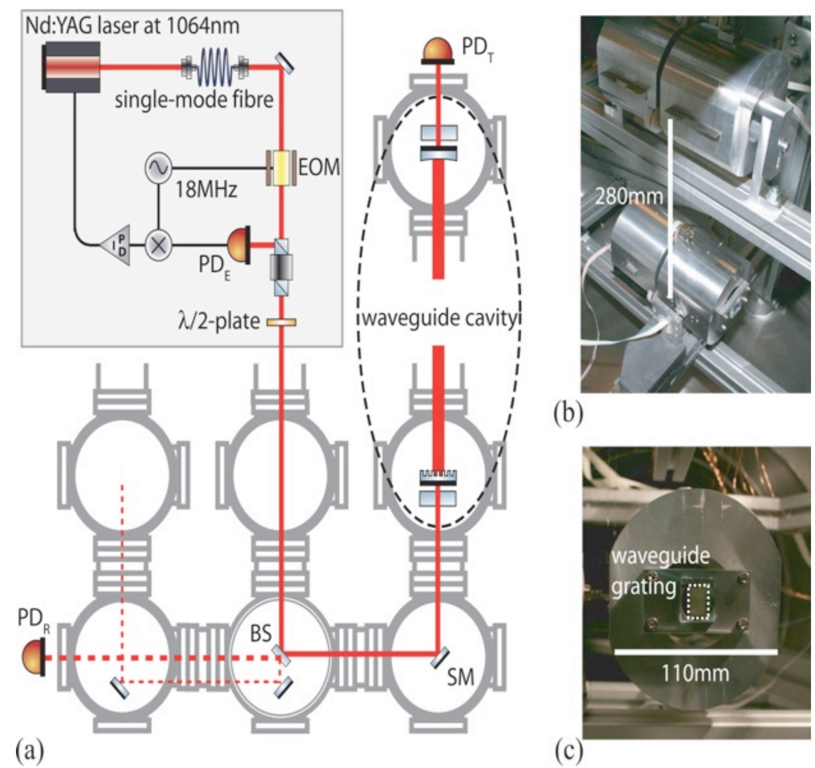
- Local Readout / Optical Bar experiment
- Dual Carrier Optical Springs and Quantum Control
- Waveguide mirror side motion noise
- Speedmeter proof of principle experiment *(see talk be Stefan)*

Waveguide demonstration in suspended

- Collaboration between Jena, Hannover and Glasgow
- First time that a waveguide mirror was used in a suspended high finesse cavity.
- New waveguide design (etch stop layer) yielded R=99.2%

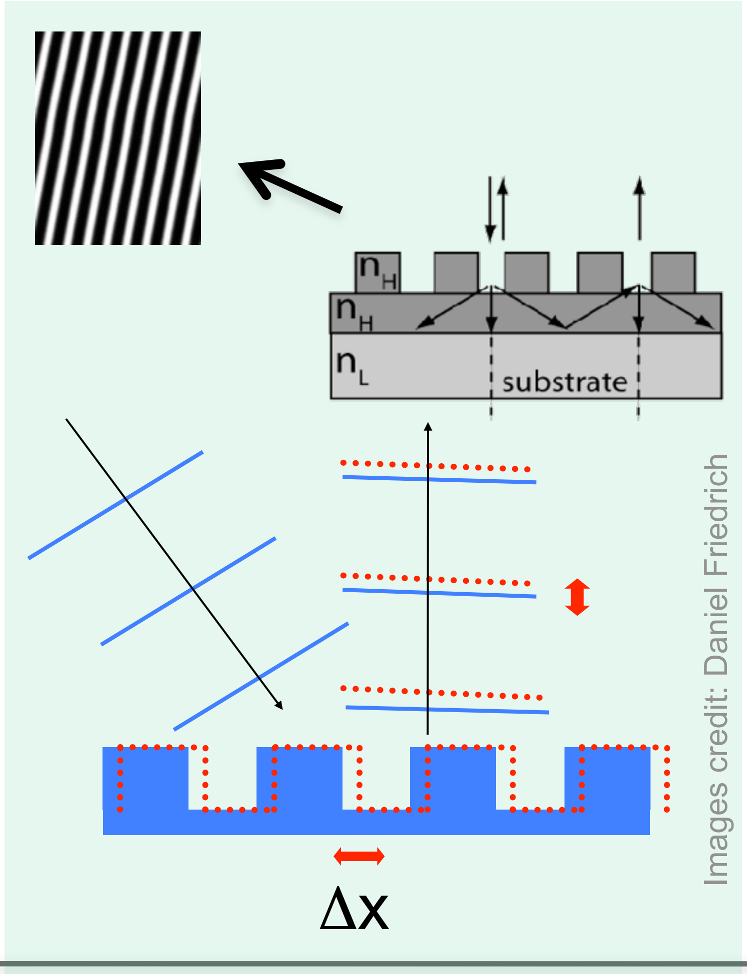






For details see: D.Friedrich et al Optics Express, Vol. 19, Issue 16, pp. 14955-14963 (2011) http://dx.doi.org/10.1364/OE.19.014955

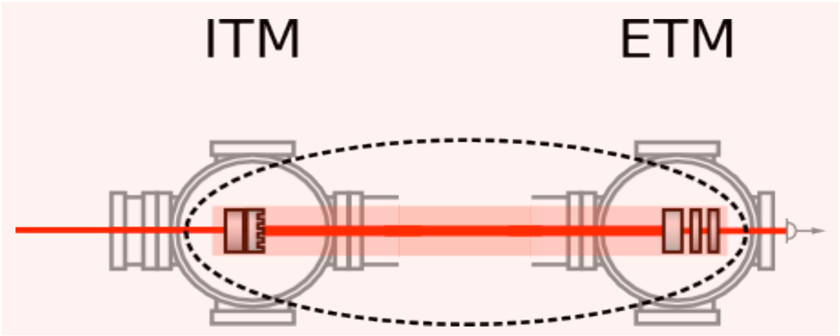
Coupling of Waveguide Sidemotion into Longitudinal Signal?



Lateral displacement of waveguide mirrors introduces a phase change on the light inside the cavity. This experiment aims to set an **upper limit** on this phase change.

Currently investigating two different options:

- Pushing the waveguide mirror (ITM) sideways
- Moving beam on ITM by misaligning ETM



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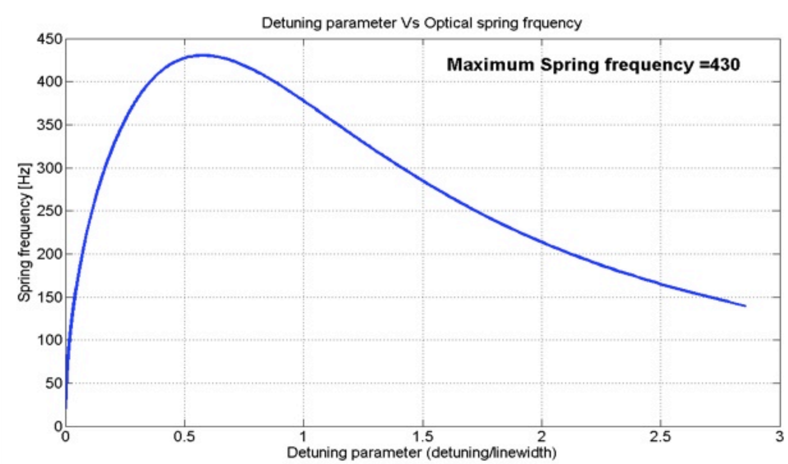
Local Readout Demonstration

LONGTERM AIM: Pinning down of optical spring features to refine models and simulations to provide deeper understanding of system dynamics and control while maintaining low noise performance.

- Cavity Finesse = 11000
- Input Power = 700mW (Laser amplifier addition will give up to 4W)
- **ETM (100g) coupled to ITM (3kg) with optical spring.**
- **ITM is then read out in local frame with an independent interferometer**
- EUCLID local readout: 10^{-13}m/sqrt(Hz) at 100Hz but poor dynamic range 633nm (limited to less than a micron)
- Beginning of Optical bar/Lever interferometer configurations



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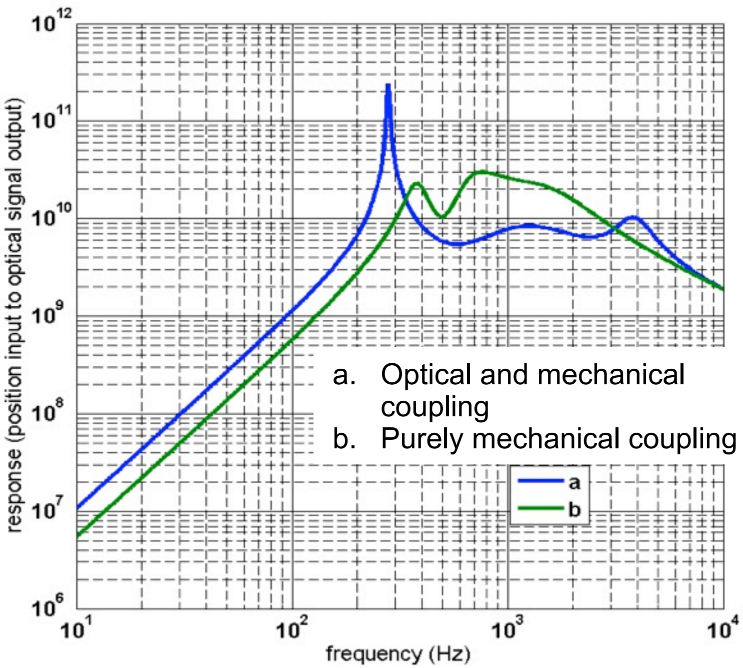
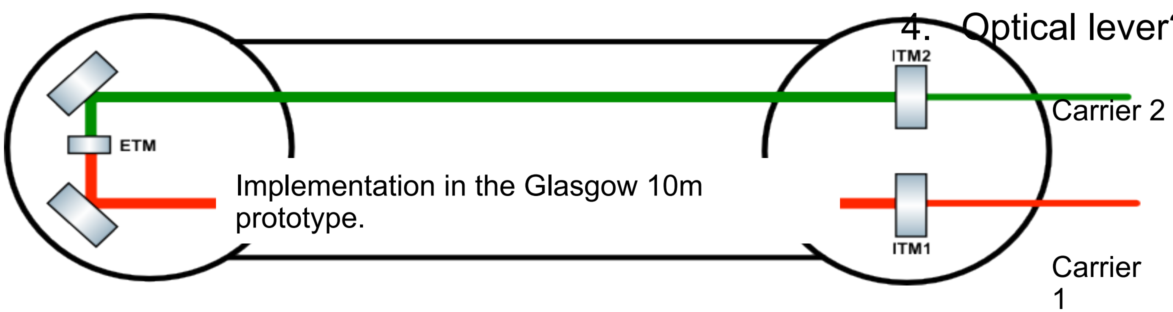
ET EINSTEIN TELESCOPE

Dual Carrier Optical Spring



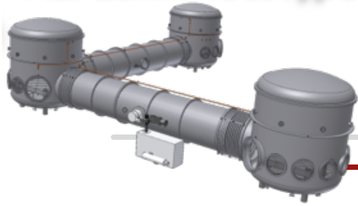
a. Optical and mechanical coupling
b. Purely mechanical coupling

- **<u>Two end-pumped, detuned cavities, coupled via radiation pressure</u>**
  - **Two independent optical springs acting on lightweight (100g) shared mirror**
  - Up to 5W input power available per carrier, with spring frequencies in the range of a few hundred Hz to a few kHz
- Several experimental configurations:
  1. Mechanically-coupled cavities
     Single carrier resonant in each cavity, coupled via interaction of springs with central mass (ETM)
  2. Optical and mechanical coupling
     Transmissive ETM allowing resonant carriers to mix between cavities
  3. Stable dual carrier configuration?
  4. Optical lever?



Implementation in the Glasgow 10m prototype.

AEI 10m Prototype



Centre for Quantum Engineering and Space-Time Research

University of Glasgow

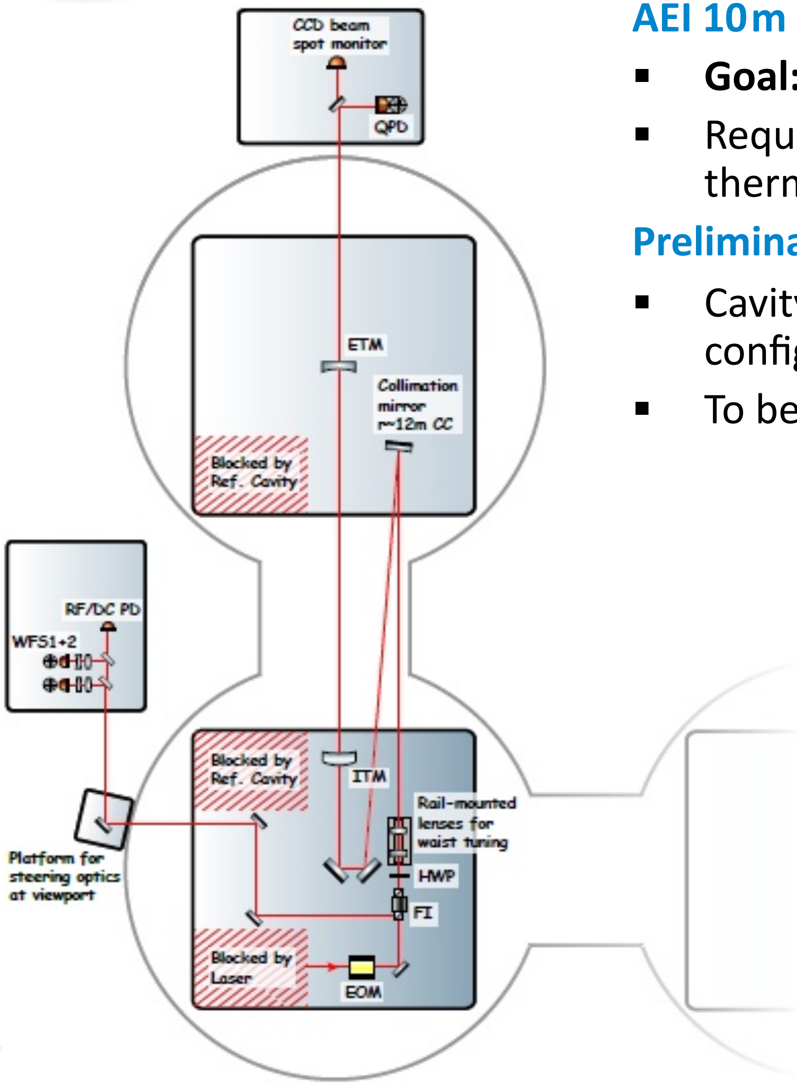
Leibniz Universität Hannover

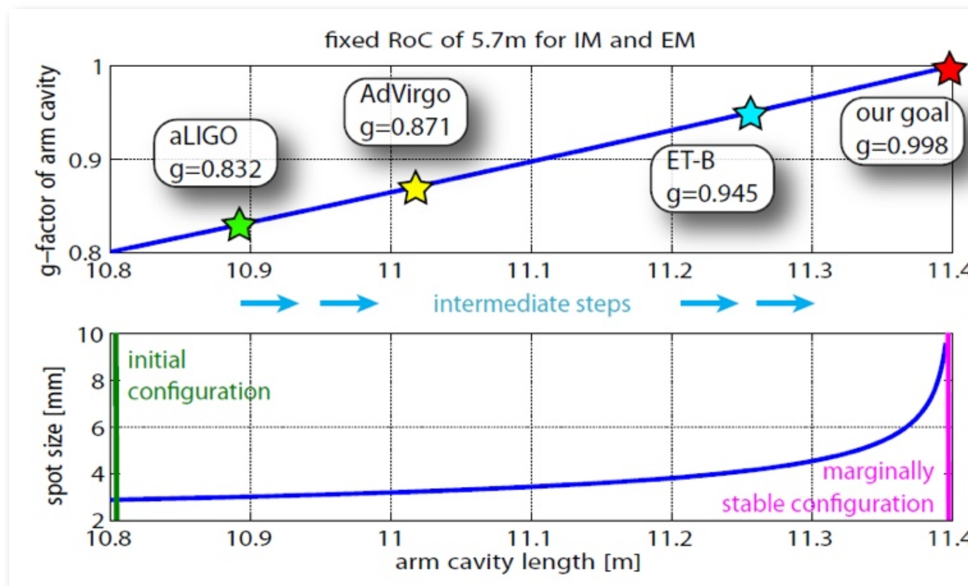
AEI 10m Prototype sub-SQL Interferometer

- **Goal:** reach the SQL at 200 Hz
- Requires extremely large beam spots to bring down coating thermal noise

Preliminary configuration: Single arm test

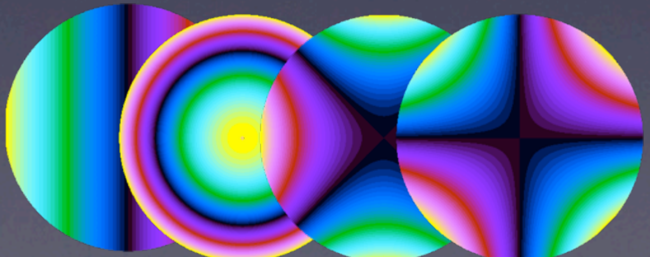
- Cavity with continuously variable g-factor from “easy“ initial configuration (g=0.8) to “challenging“ target config. (g=0.998)
- To be installed in 2013!





Overview of Birmingham work

- Laguerre-Gauss modes, theory, numerical studies, experiments, see talk by Ludovico Carbone
- Mirror surface defects, numerical studies, table-top experiments, see talk by Charlotte Bond
- Quantum noise reduction, theoretical studies, see poster by Mengyao Wang
- Further development of Finesse, mirror maps, radiation pressure, see poster by Daniel Brown
- New work: Advanced LIGO commissioning, simulation support for on-site activities: validate Finesse, knowledge transfer from aLIGO to ET design
- New work: Noise cancellation in co-located interferometers



ASPERA R+D proposal

- Task 1: Mitigation scheme for radiation pressure effects for the ET-HF interferometer.
- Task 2: Control scheme for the injection of frequency dependent squeezed light.
- Task 3: Low-frequency control scheme for the ET-LF interferometer.
- Task 4: Mitigation scheme for correlated noise in co-located interferometers.
- Task 5: Contamination of potential null stream signals by technical noises.

ASPERA
3rd common call

ET-R&D

- Networking and R&D for the Einstein Telescope -

R+D Summary

- Strong research activities in interferometry and advanced optics
- Numerical simulations, table top experiments and two versatile 10m prototypes
- Technology testing at advaned detectors (GEO HF, Advanced LIGO/Virgo, KAGRA)
- New work starting on looking into the details of control schemes and noise couplings

Summary

- Baseline design for possible optical layout is done

- R+D towards the realisation of the optics needed for that design is in it's most interesting phase

Idea

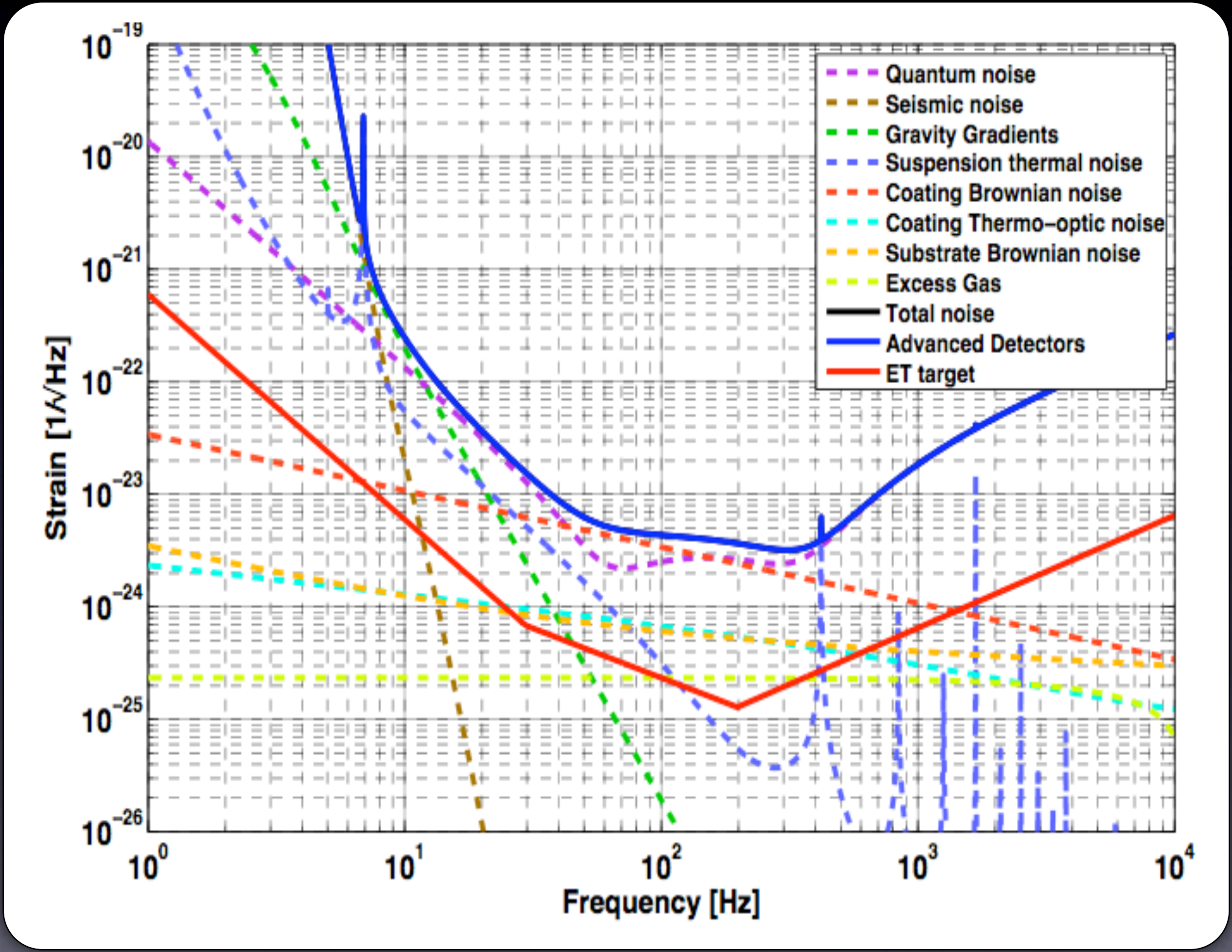
- We need the lessons from Advanced Detectors and the results of dedicated R+D to make it work

...end

ET `D' Parameters

Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ T
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×10 km	2×10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	none

Noise budget of a gravitational wave detector



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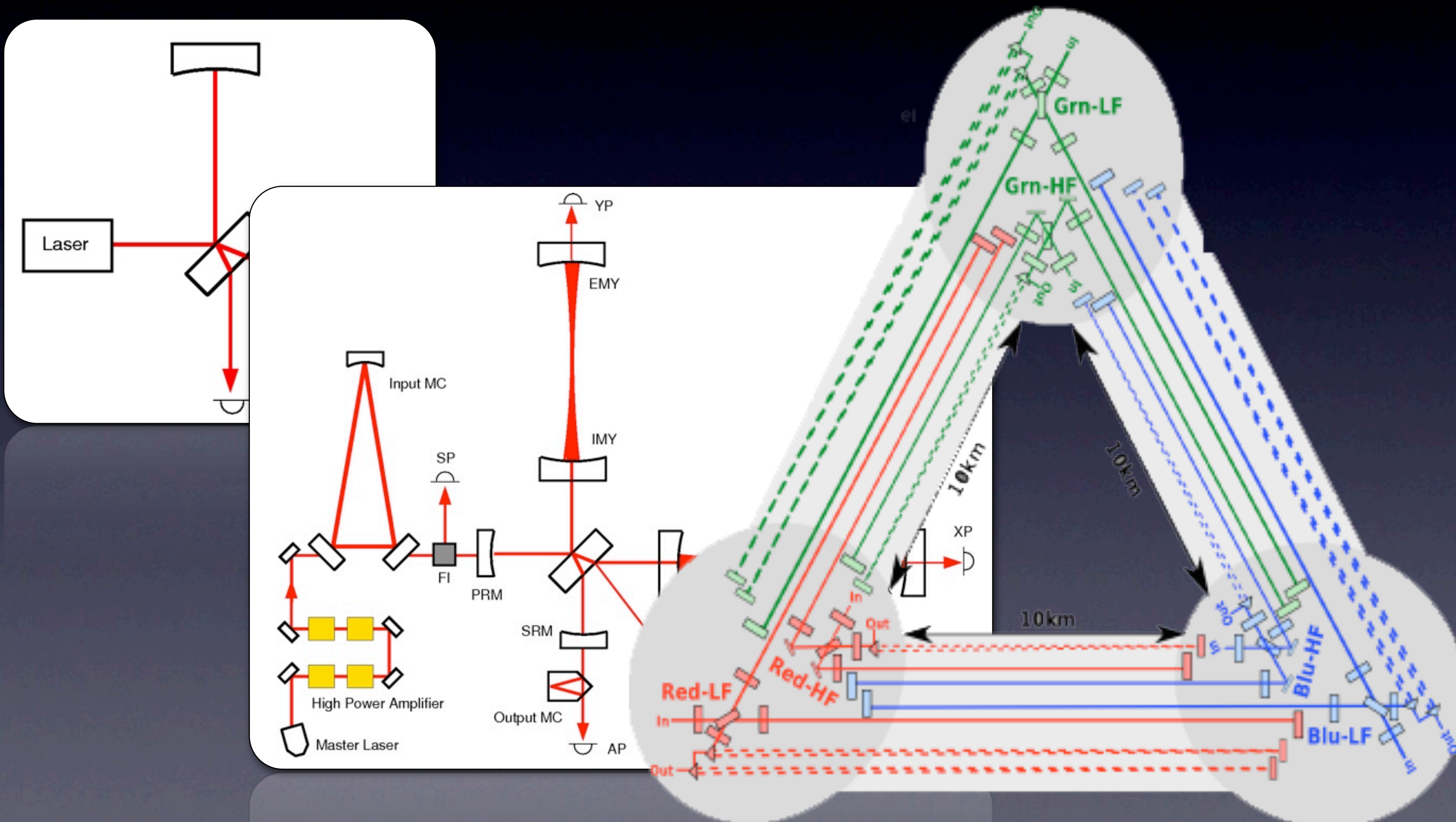
Advanced Interferometry



Waveguide Coatings and other diffractive elements

- Theoretical and numerical work to investigate alignment induced phase noise on gratings (complete)
- Development of framework for numerical simulation of this effect (complete, to be published)
- Implemented own FDTD code to show that this noise does not appear with waveguide coatings (complete to be published)