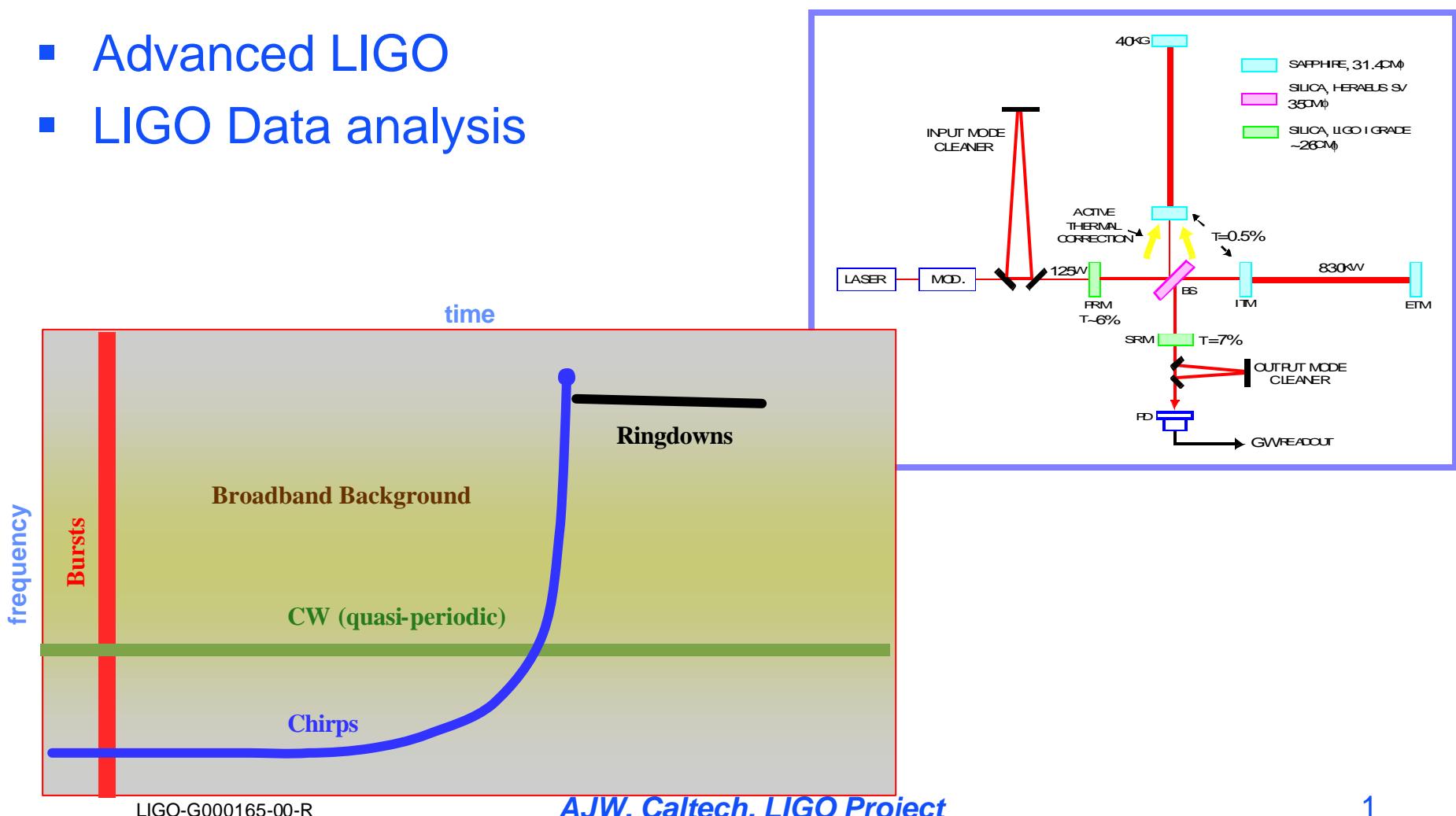




Physics of LIGO

Lecture 4

- Advanced LIGO
- LIGO Data analysis





Initial LIGO \Rightarrow Advanced LIGO schedule

1995	NSF Funding secured (\$360M)
1996	Construction Underway (mostly civil)
1997	Facility Construction (vacuum system)
1998	Interferometer Construction (complete facilities)
1999	Construction Complete (interferometers in vacuum)
2000	Detector Installation (commissioning subsystems)
2001	Commission Interferometers (first coincidences)
2002	Sensitivity studies (initiate LIGO I Science Run)
2003+	Initial LIGO data run (one year integrated data at $h \sim 10^{-21}$)
2007	Begin Advanced LIGO installation
2008	Advanced LIGO science run (2.5 hours ~ 1 year of Initial LIGO)



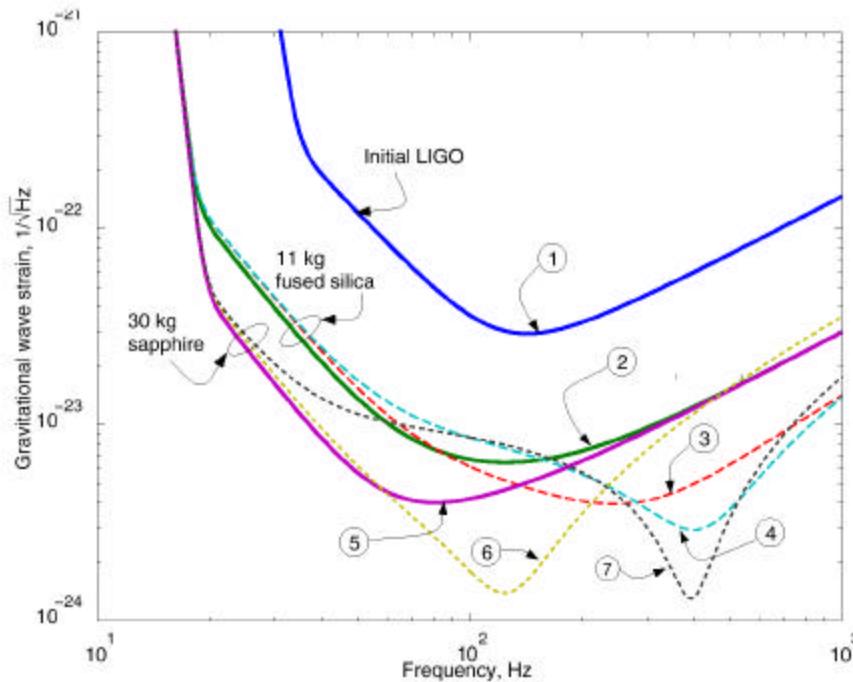
Advanced LIGO

incremental improvements

- Reduce shot noise: higher power CW-laser: 12 watts \Rightarrow 120 watts
- Reduce shot noise: Advanced optical configuration: signal recycling mirror (7th suspended optic) to tune shot-noise response in frequency
- Reduce seismic noise: Advanced (active) seismic isolation. Seismic wall moved from 40 Hz \Rightarrow \sim 12 Hz.
- Reduce seismic and suspension noise: Quadrupal pendulum suspensions to filter environmental noise in stages.
- Reduce suspension noise: Fused silica fibers, silica welds.
- Reduce test mass thermal noise: Last pendulum stage (test mass) is controlled via electrostatic or photonic forces (**no magnets**).
- Reduce test mass thermal noise: High-Q material (**40 kg sapphire**).
- To handle thermal distortions due to beam heating: advanced mirror materials, coatings, **thermal de-lensing compensation** (heating mirror at edges)

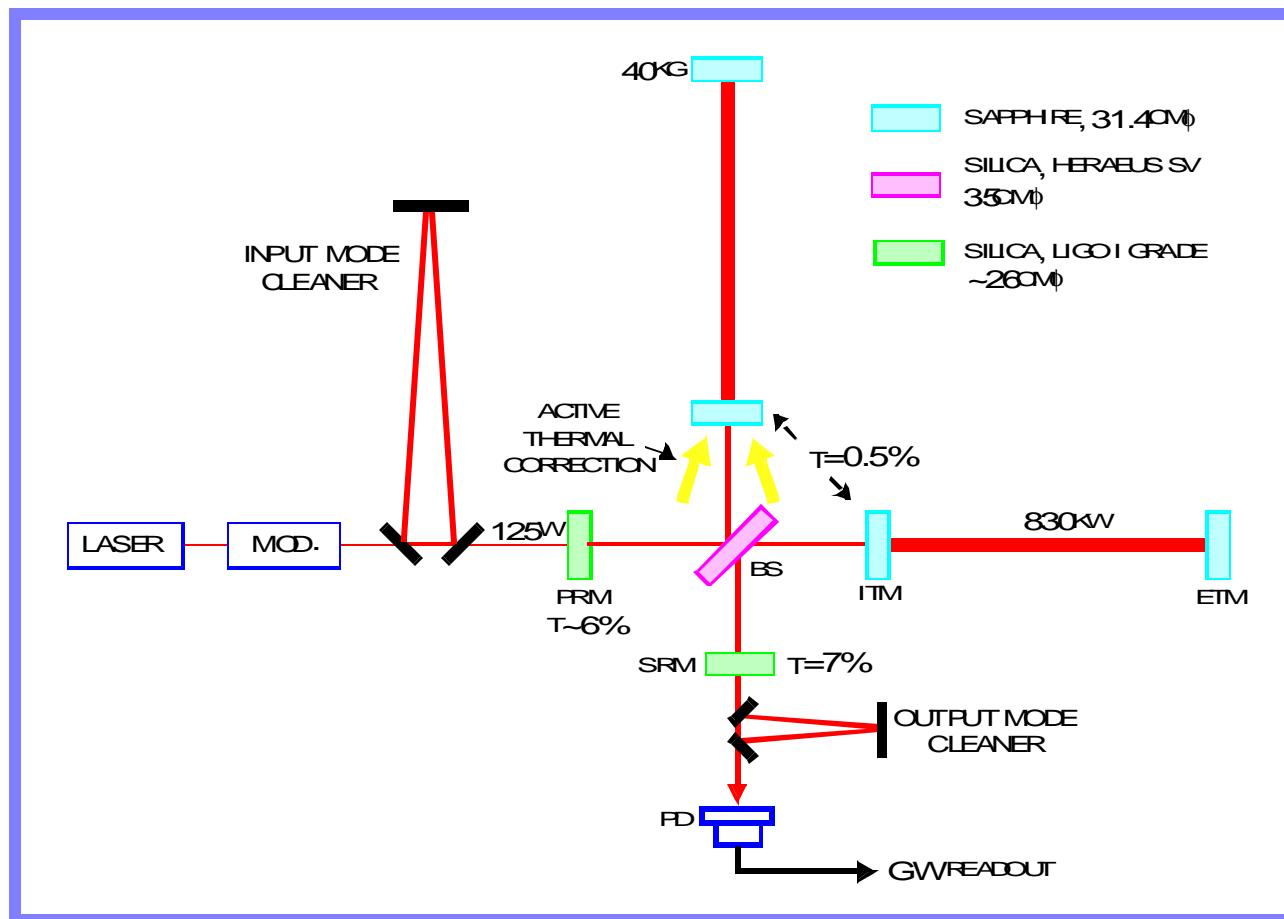
LIGO II

predicted noise curves



Parameter	Curve 1	Curve 2	Curve 3, 4	Curve 5, 6, 7
Parameter	Initial LIGO I value	Double suspension, 100 W laser, thermal de-lensing	Signal tuned configuration	Alternative test mass material
Input power to recycling mirror	6w	62w	140w	
Mirror loss (transmission+scatter)	50 ppm		20 ppm	
Effective power recycling	30		93	
Substrate absorption	5ppm/cm	0.4 ppm/cm	17 ppm/cm	
Thermal lensing correction	(none)		factor 10	
Suspension fiber	steel wire, $Q = 1.6 \times 10^5$	fused silica $Q = 3 \times 10^7$		
Test mass	fused silica, 10.8 kg, $Q = 1 \times 10^5$	fused silica, 10.8 kg, $Q = 3 \times 10^7$	sapphire, 30 kg, $Q = 2 \times 10^8$	
Signal recycling mirror transmission	(none)	T=0.6 (curve 3) T=0.15 (curve 4)	Curve 5: none T=0.3 (curve 6) T=0.09 (curve 7)	
Tuning phase		0.7 rad (curve 3) 0.45 rad (curve 4)	1.3 rad (curve 6) 0.45 rad (curve 7)	

AdvLIGO configuration

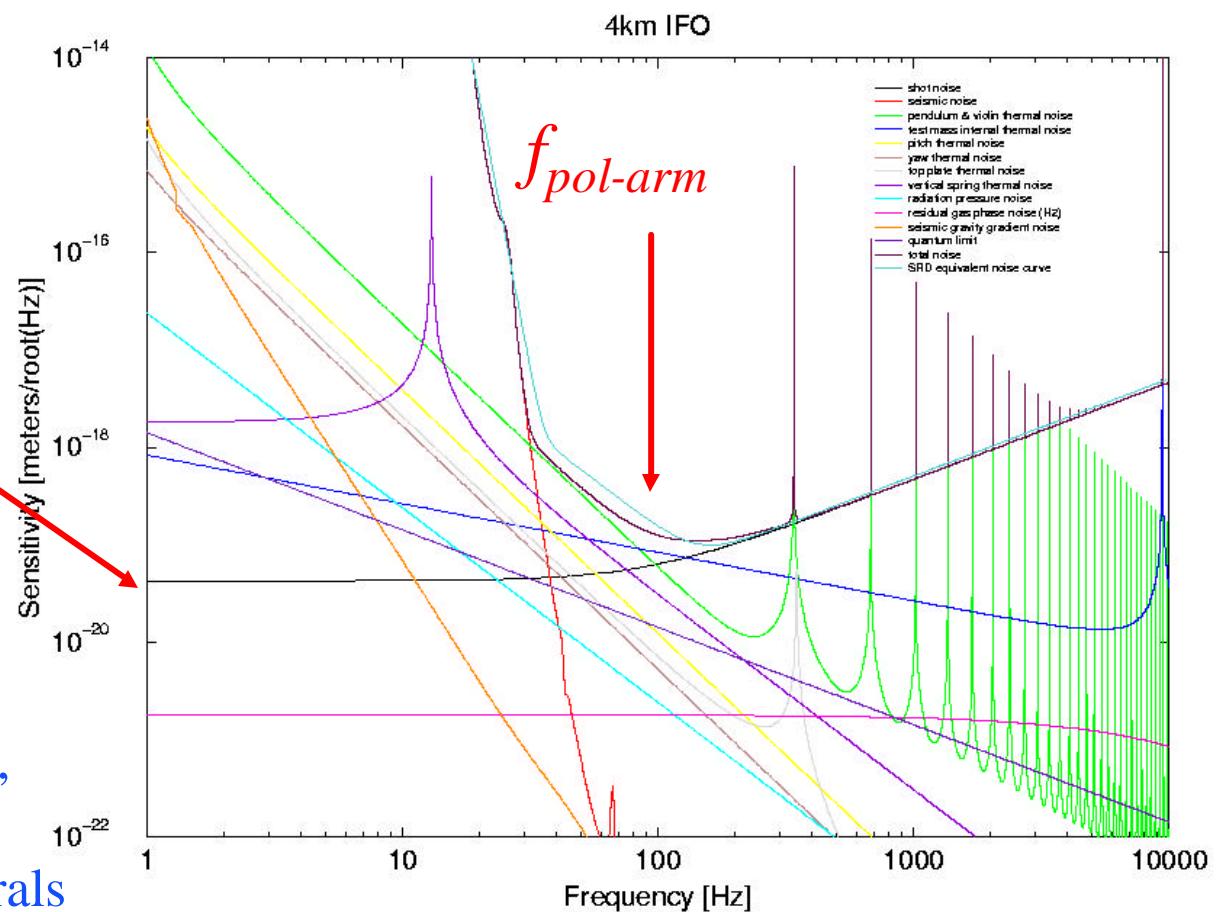


Arm cavity parameters and LIGO sensitivity

As r_{ITM} is increased,
 G_{arm} is increased,
 $f_{pol-arm}$ is decreased.

$$h_{dc} \sim 1 / \sqrt{G_{arm} P_{laser}}$$

Given other noise
sources (seismic, thermal),
choose r_{ITM} to optimize
Sensitivity to binary inspirals





Signal recycling, RSE

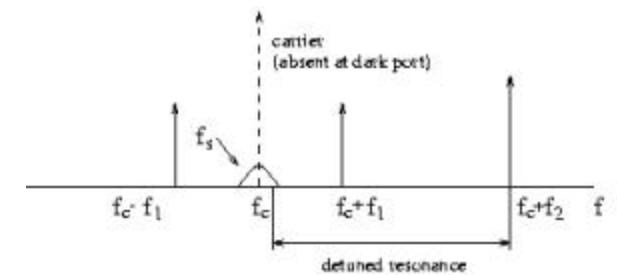
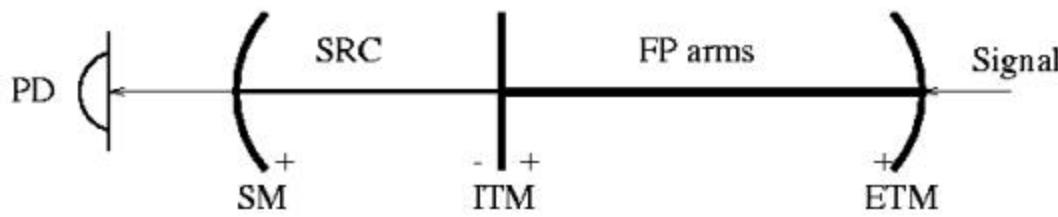
- Problem: the transmissivity of the ITM (T_{ITM}) governs *both* the arm cavity gain (power available for sensing *DL* at $f=0$) *and* the light storage time / cavity pole f_{arm}
- Need the ability to optimize these independently
- The shot noise frequency dependence can be optimized (for fixed laser power) by adding one (or more) suspended optics at the dark port (signal recycling or RSE)
- This permits independent control of cavity gain for the carrier and for the *signal sidebands* (audio frequencies of GW signal)
- Make the arms *high* finesse to store lots of carrier light (allowing one to reduce gain in PRC), but *low* finesse for the GW signal sidebands to increase bandwidth: RSE
- Combine power recycling (PR) and signal recycling (SR): Dual recycling (DR)

Coupled cavity response

Simplified analysis:

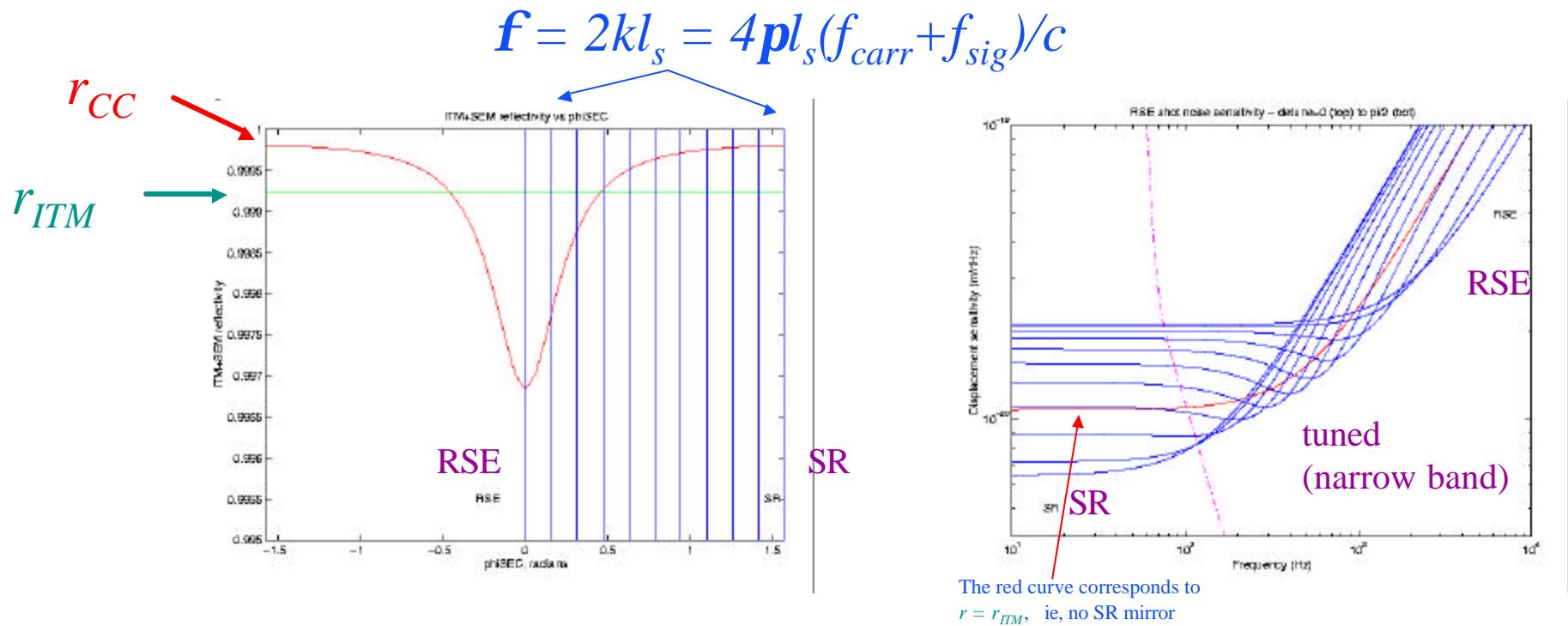
- fold beam splitter + arms together
- model as a single FP cavity
- adding SM produces a coupled cavity
- ITM+SM forms a *compound mirror*, with reflectivity

$$r_{cm} = r_{ITM} - \frac{t_{ITM}^2 r_{SM} e^{-if}}{1 - r_{ITM} r_{SM} e^{-if}} \quad \text{With } f = 2kl_s = 4pl_s(f_{carr} + f_{sig})/c$$



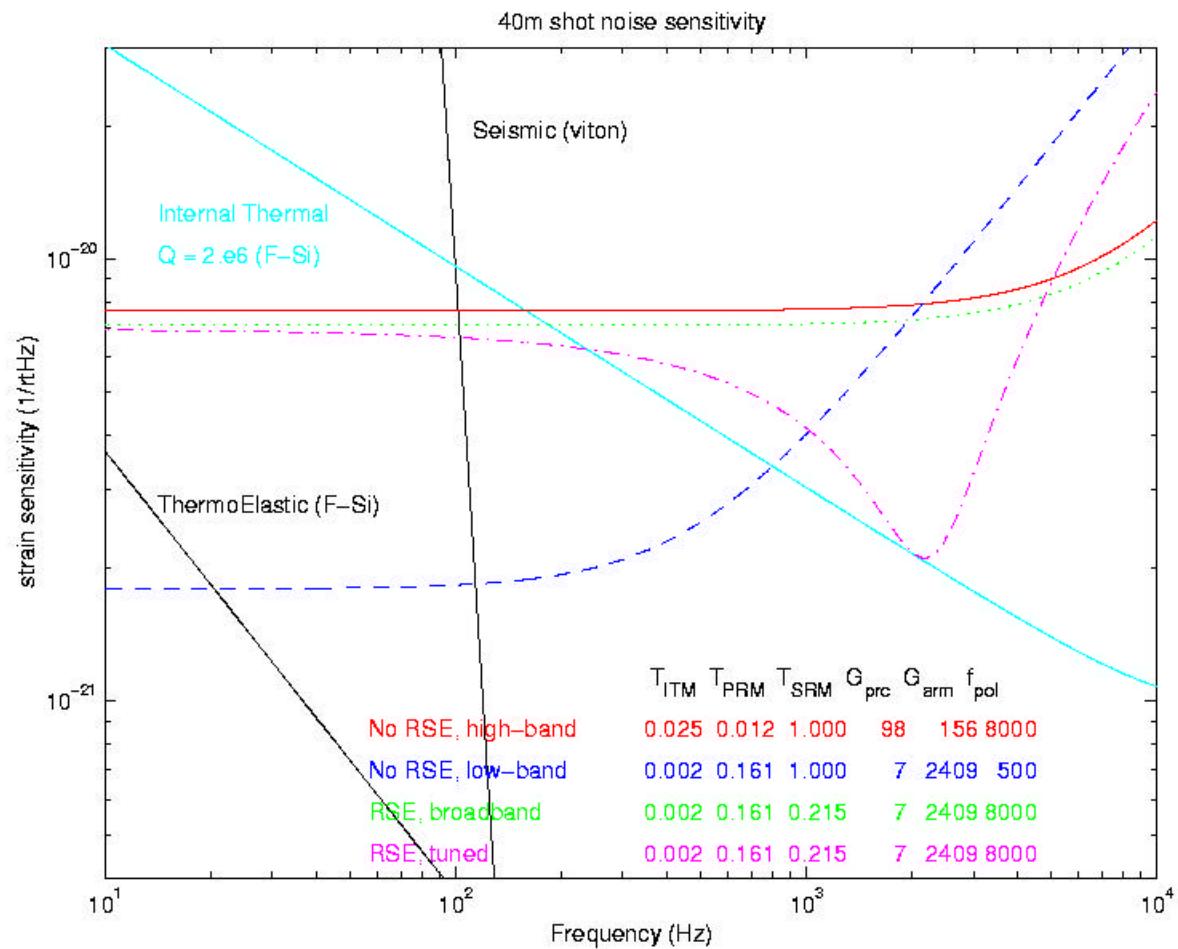
Tuning the signal response

By choosing the phase advance of the signal ($f_{carr} + f_{sig}$) in the signal recycling cavity, can get longer (SR) or shorter (RSE) storage of the signal in the arms:



Using DR to optimize sensitivity

Now we can independently tune h_{DC} and f_{polarm} to optimize sensitivity (eg, hug the thermal noise curve)

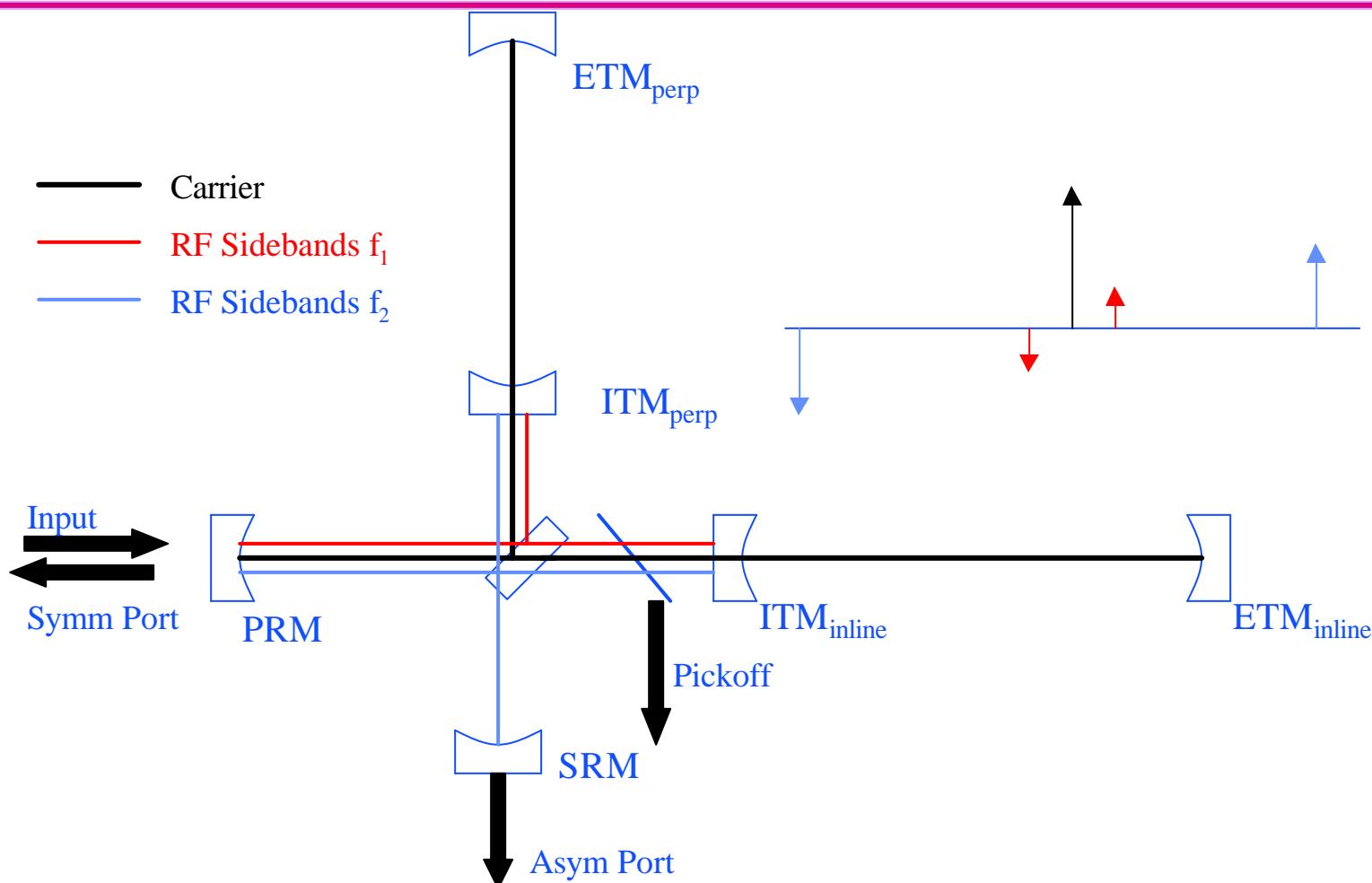




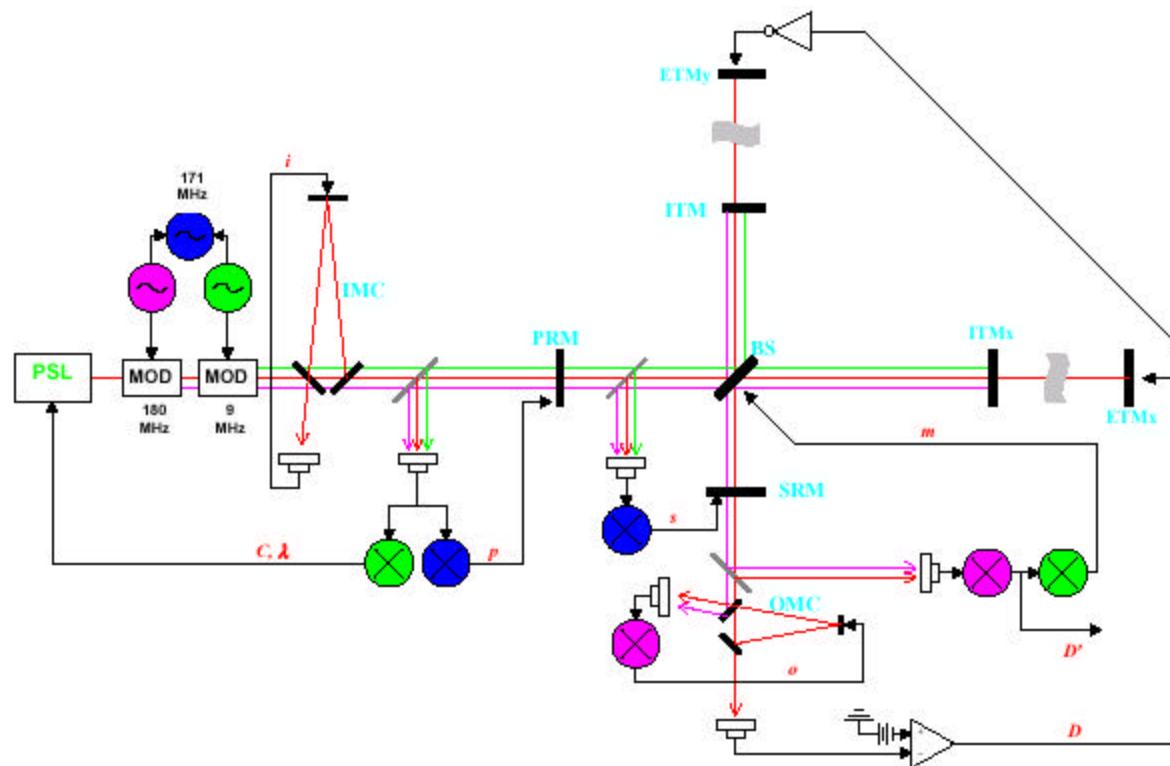
Controlling the signal mirror

- The other 6 mirrors (LIGO-I configuration) are controlled by reflection-locking: beat carrier (resonant in all cavities) off of RF sidebands
- Here, with no GW, there is no carrier in signal cavity!
- One solution: add another RF sideband; make one RF sideband resonant in signal cavity, the other isn't; then, reflection locking will work.
- Both RF sidebands must be resonant in PRC; and both must pass through the MC
- Want to change the tune $f = 2kl_s$ at will
- This is a difficult, constrained problem. One reasonable solution will be prototyped at Glasgow and at the 40m.

Control topology for Advanced LIGO



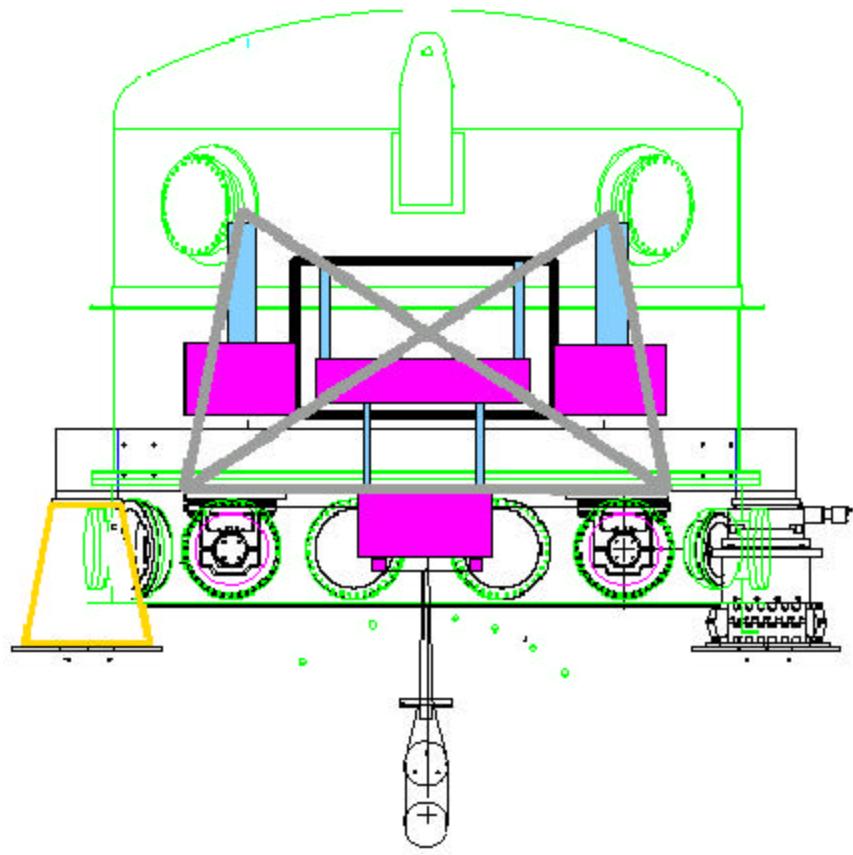
AdvLIGO controls



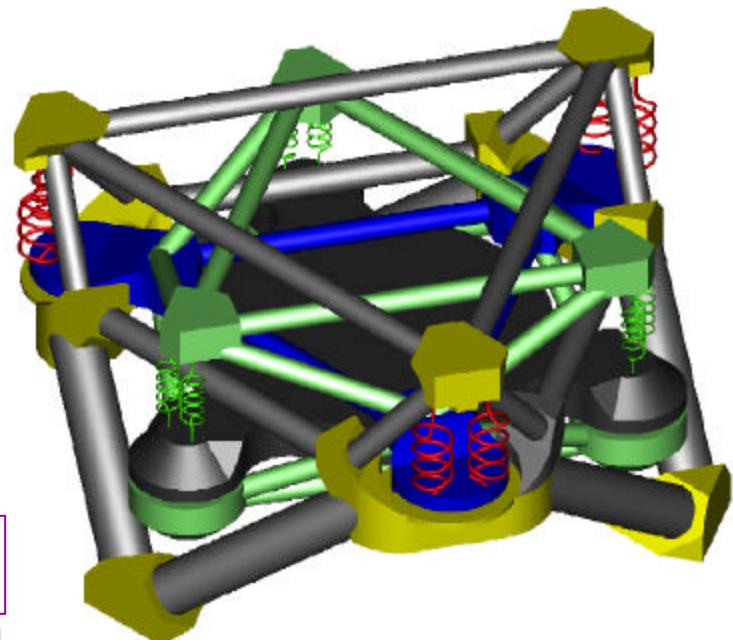
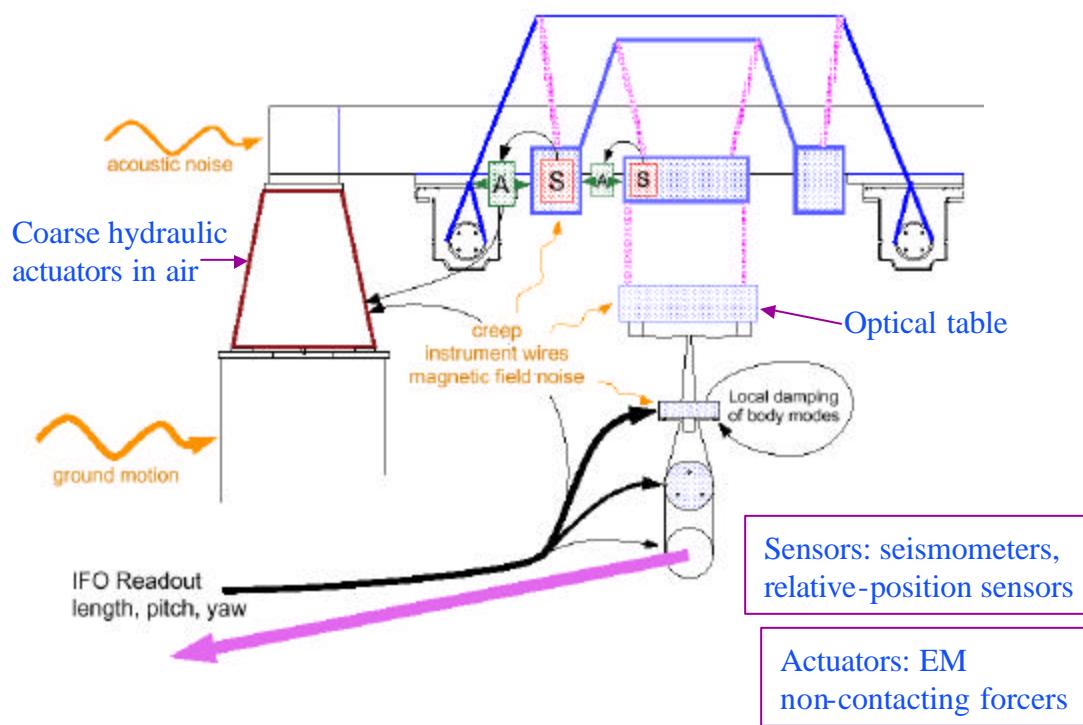
LIGO II Active seismic isolation and multiple pendulum suspension

- Must support LIGO test mass optic at the beamline.
- Must fit inside existing vacuum chambers, and be fully vacuum compatible.
- Must provide full control system.
- Must satisfy specs:

Optics Payload, (Chamber type)	Optic Axis (X-direction)				Y & Z directions		Pitch, Yaw
	Freq. (Hz)	Noise (m/ $\sqrt{\text{Hz}}$)	Motion (m rms)	Velocity (m/s)	Noise (m/ $\sqrt{\text{Hz}}$)	Motion (m rms)	
ITM, ETM, BS, FM (BSC)	10	10^{-19}	10^{-14}	10^{-9}	10^{-16}	10^{-11}	10^{-26}
RM, SRM (HAM)	10	10^{-17}	10^{-13}	10^{-8}	10^{-14}	10^{-10}	10^{-26}
MC (HAM)	10	3×10^{-18}	10^{-12}	10^{-7}	3×10^{-15}	10^{-9}	10^{-26}
Ancillary Optics (HAM, BSC)	10						



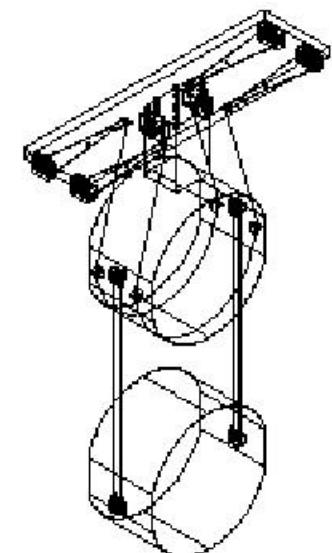
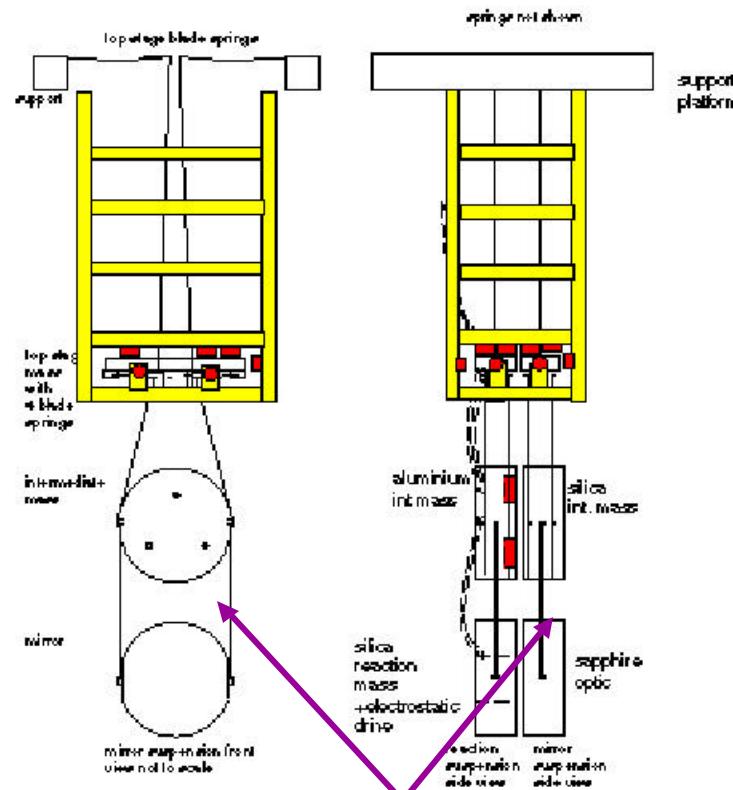
Active control of SEI system



Two active stages: cages, masses, springs, S/A pairs.
All DOF under active control.

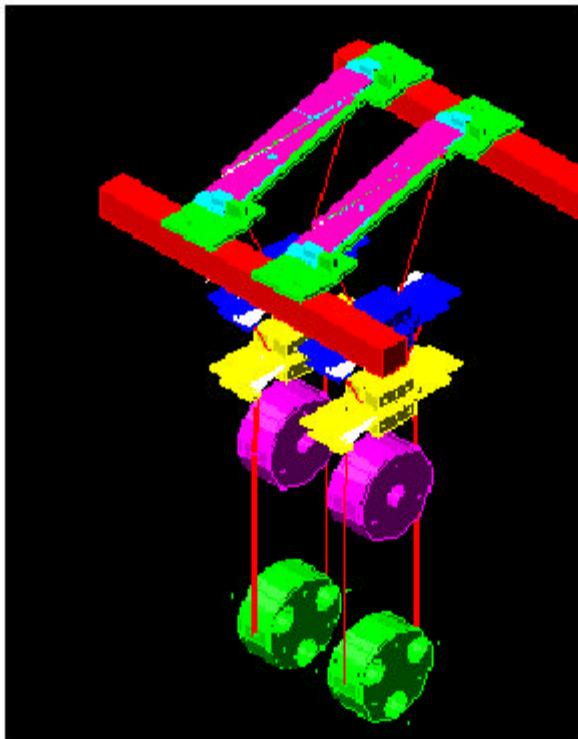
GEO multiple pendulum design

- 3 or 4 pendulum stages; each provides $1/f^2$ filtering for $f > f_0$
- Top stage has 6 OSEMs for 6-dof control (“marionetta”), relative to support cage.
- Normal modes of the multiple pendulum (~24) must not have nodes at the top, so they can be controlled from the top.
- Blade springs at the very top provide tuned vertical isolation.
- Lower stages must control w.r.t. stage above it; so the actuators must push against a “reaction mass” which is as quiet as the stage above it
- lowest stage (test mass optic) is attached to stage above it with fused silica fibers.



Fused silica fibers

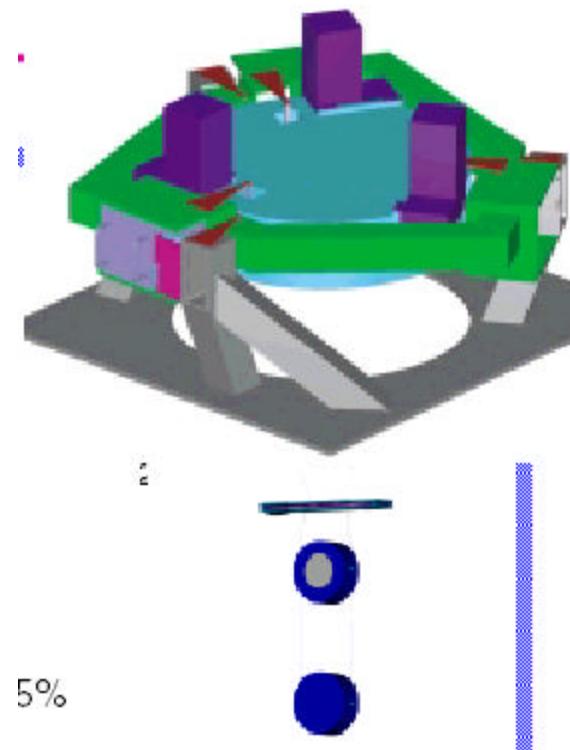
COC, SEI, SUS R&D



- Core Optics
 - » sapphire material development with Crystal Systems & SIOM
 - » joint mechanical & optical material test matrix in development
 - » spot polishing to compensate for inhomogeneity
 - » coating facility development & low absorption research (MLD & Virgo/Lyon)
- Seismic Isolation
 - » Full scale, HAM-type technology demonstrator @ ETF, Stanford
 - » Full scale prototypes (HAM & BSC types) @ LASTI, MIT
- Suspension
 - » U. of Glasgow/GEO takes the lead to PDR, LIGO Lab leads in Final Design
 - » Triple & quad pendulum 'controls' & 'noise' prototypes tested with the SEI prototypes at LASTI

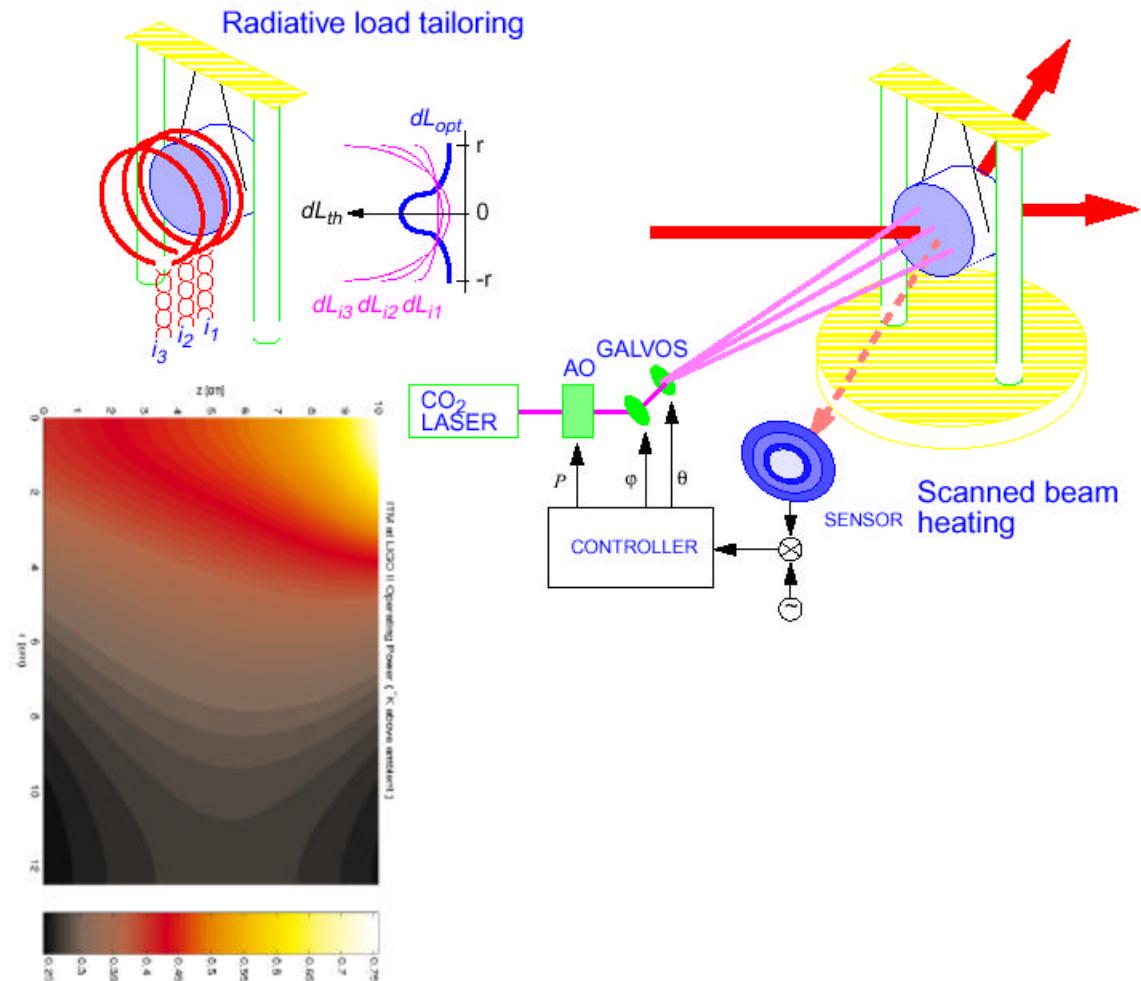
SEI + SUS

Put them together;
Test in LASTI



Thermal compensation (de-lensing) methods

- Beam heating at center of optic distorts the optic due to thermal expansion, changing ROC, index of refraction, etc.
- Compensate by heating the optic from the circumference in, to give uniform and constant-in-time thermal loading as the IFO is operated.



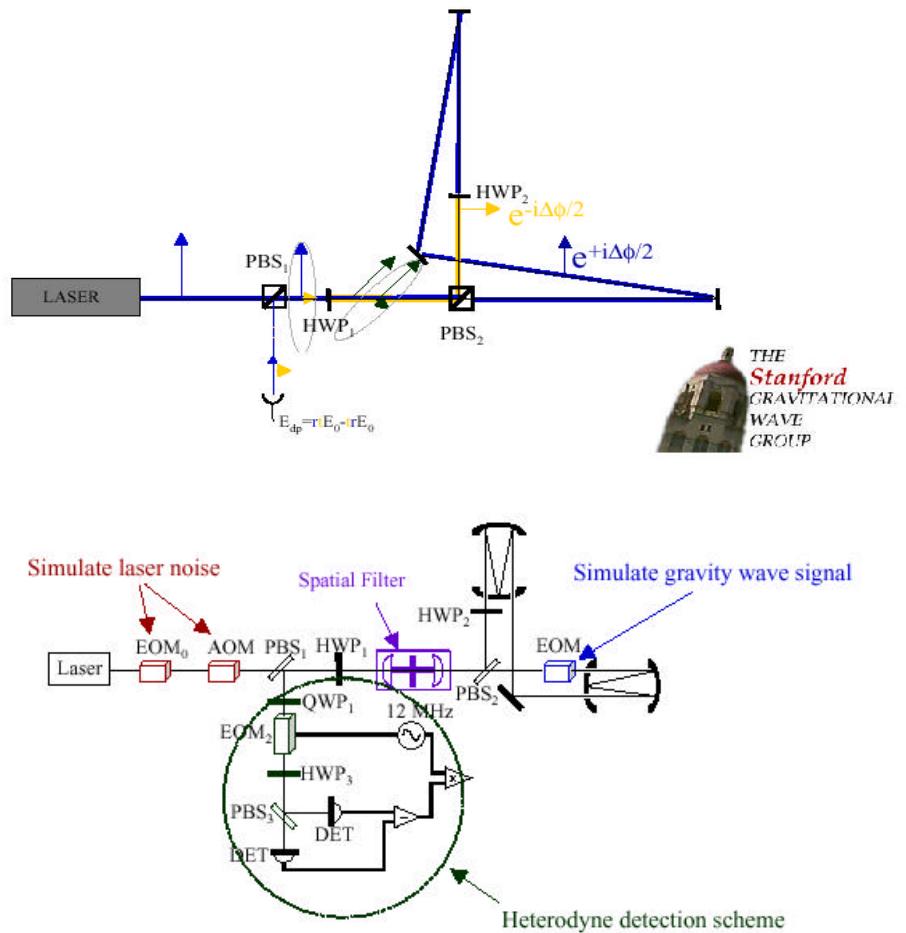


LIGO III...

- More advanced optical design (Sagnac?)
- non-transmissive optics (Sagnac)?
- Cryogenically-cooled mirrors?
- Different IFOs optimized for different frequency bands?
- Beating the standard quantum limit: squeezed light;
speed meter; frequency-dependent demodulation phase
- Photon drive mirror actuation?

The polarization Sagnac IFO

- All reflective optics to minimize thermal distortions
- Common path for interfering beams
- Grating beam splitter (double-pass, to null dispersion)
- Delay line arms
- Heroic efforts to minimize noise due to scattered light
- Polarization allows the light to exit the IFO at the symmetric port of the beam splitter
- Many clever tricks to ensure robust control, low noise





Prototype IFOs

- Several **table-top (non-suspended) IFOs** for development of RSE/DR – Caltech (Jim Mason), UFla, ANU, TAMA 3
- **40 meter (Caltech)** : full engineering prototype for optical and control plant for AdvLIGO
- **Thermal Noise Interferometer (TNI, Caltech)** : measure thermal noise in AdvLIGO test masses (sapphire)
- **LIGO Advanced Systems Testbed IFO (LASTI, MIT)** : full-scale prototyping of AdvLIGO seismic isolation & suspensions
- **Engineering Test Facility (ETF, Stanford)** : Initial seismic isolation prototype; advanced IFO configs (Sagnac)
- **10 meter IFO at Glasgow** : prototype optics and control of RSE
- **TAMA 30 meter (Tokyo)** : Advanced technologies (SAS, RSE, control schemes, sapphire, cryogenic mirrors)
- **AIGO 80m IFO at Gingin** : high powered laser, thermal effects, control stability



LIGO Data analysis

- LIGO is a broad-band amplitude detector, measures **waveforms**.
- The experimentalist thinks not in terms of astrophysical sources, but in terms of **waveform morphologies**.
- Specific astrophysical sources suggest specific waveforms, but **we don't want to miss the unexpected!**
- **Waveform morphologies being considered:**
 - » Bursts (of limited duration), for which we have models (chirps, ringdowns)
 - » Bursts, for which we have no reliable models (supernovas, ...)
 - » Continuous waves, narrow bandwidth - periodic (pulsars)
 - » Continuous waves, broad bandwidth - stochastic (BB background)
- Each requires radically different data analysis techniques.
- Algorithms, implementation development is in its infancy.

Waveforms of Gravitational Waves

- “Chirps” (reasonably known waveforms)
 - » Neutron star (NS/NS) binary pairs
 - » Black hole (BH/BH) binaries; NS/BH binaries
- Periodic (well defined waveforms)
 - » Pulsars with ellipticity, in our galaxy
 - » R-modes (neutron stars spinning up, with instabilities)
- Impulsive (unknown waveforms)
 - » Supernova bursts, BH mergers
- Stochastic (random, indistinguishable from noise)
 - » Background from primordial cosmological event (Big Bang)
- Unknown???
 - » Rates, signal sizes, waveforms for all the above are *very* uncertain
 - » Surprises are *certain!*



If we don't have a well-modeled waveform: Detection Confidence

**With all the noise faking
GW signals,
How can we be sure
we've seen the real thing
(*for first time!*)?**

Multiple interferometers – coincidence!

- three interferometers within LIGO
 - 4 km at Hanford, 4 km at Livingston
 - also 2 km at Hanford
- absolute timing accuracy of 10 microsec
 - 10 msec light travel time between sites
- AND: other detectors (interferometers, bars)

VETO Environmental noise

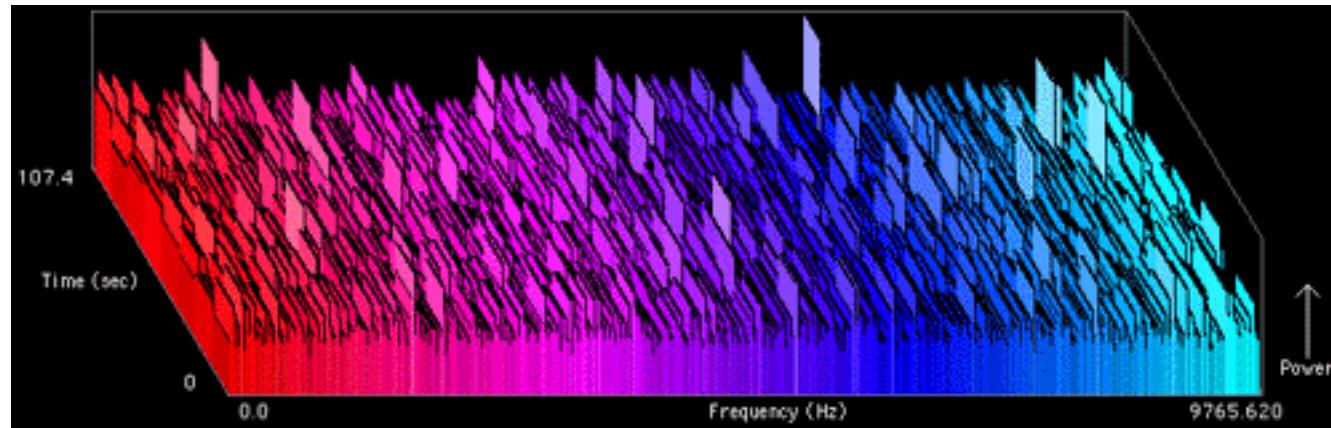
- Try to eliminate locally all possible false signals
- Detectors for many possible sources
 - seismic, acoustic, electromagnetic, muon
- Also trend (slowly-varying) information
 - tilts, temperature, weather

Detection computation

- coincidences (lack of inconsistency) among detectors
 - also non-GW: e.g., optical, X-ray, GRB, neutrino
- matched filter techniques for 'known' signals
- correlations for broad-band suspects
- deviations from explicable instrumental behavior

Frequency-Time Maps (“Images”)

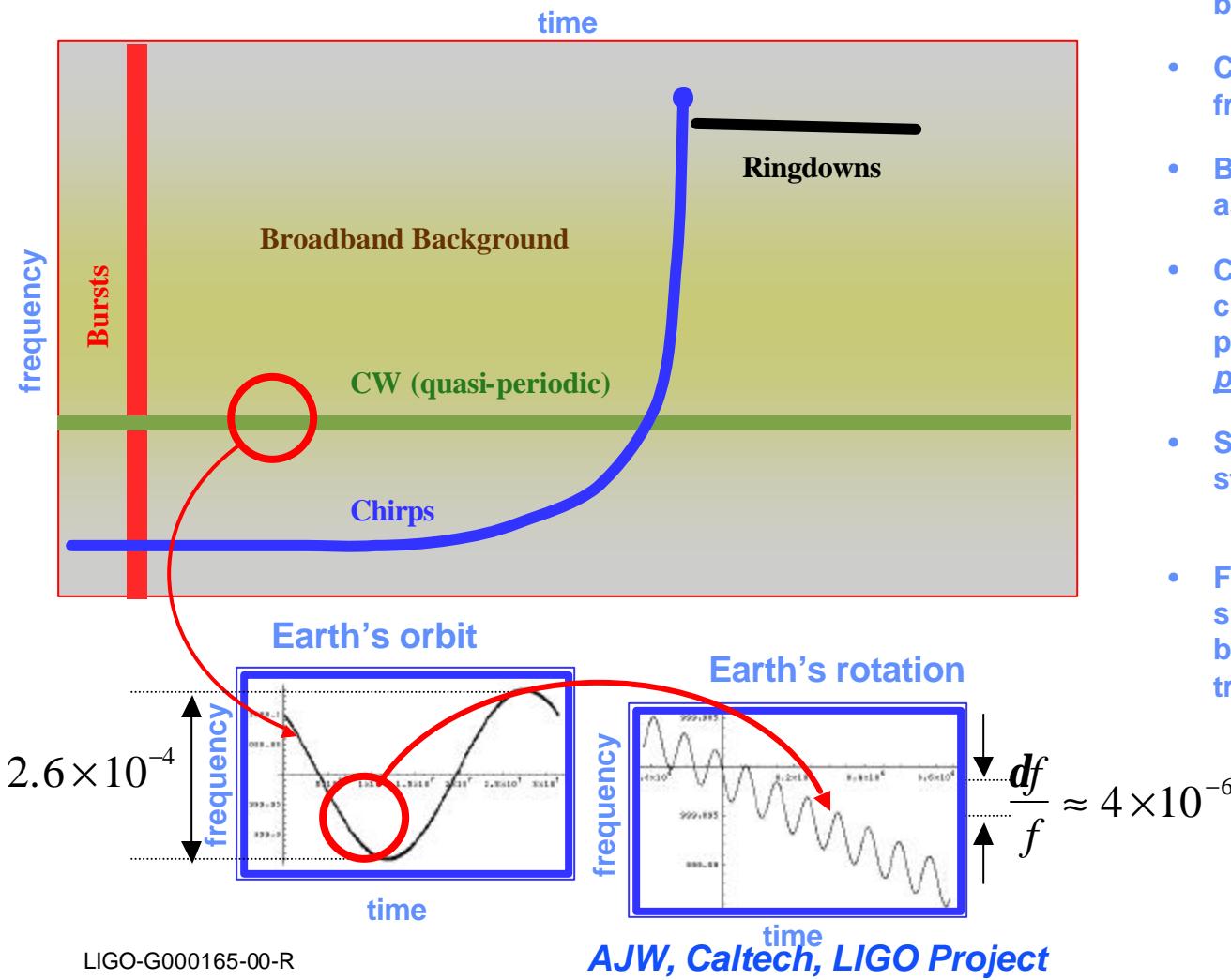
- your PC may already be doing them!



SETI@home uses frequency-time analysis methods to detect *unexpected* or *novel* features in otherwise *featureless “hiss”*



Frequency-Time Characteristics of GW Sources

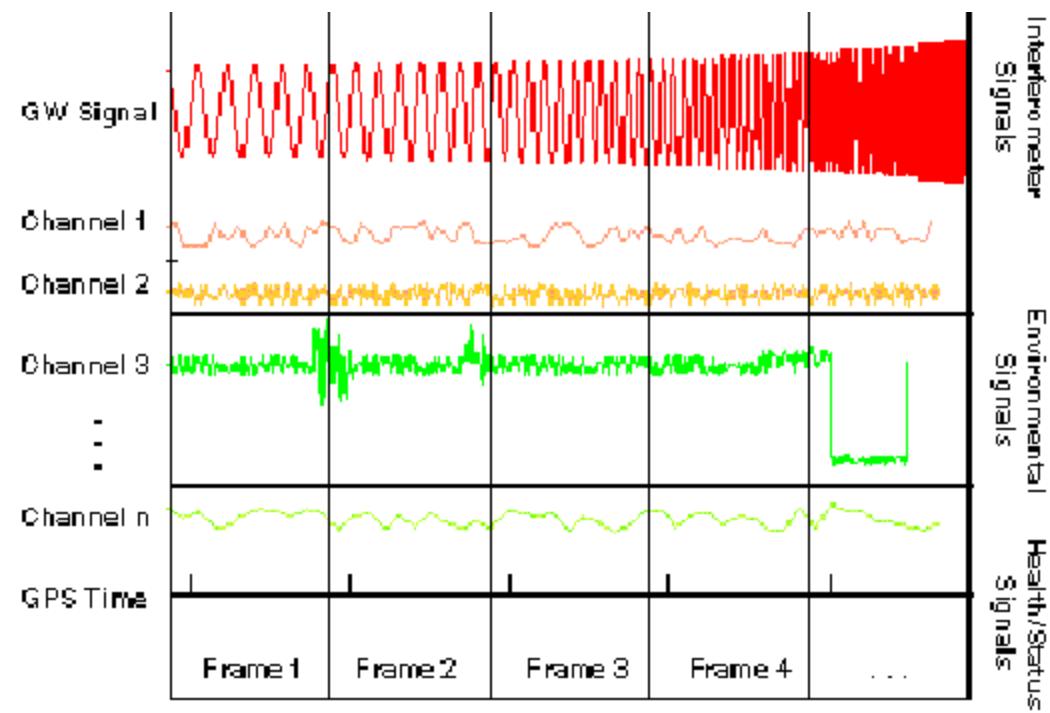


- Bursts are short duration, broadband events
 - Chirps explore the greatest time-frequency area
 - BH Ringdowns expected to be associated with chirps
 - CW sources have FM characteristics which depend on position on the sky (and source parameters)
 - Stochastic background is stationary and broadband
 - For each source, the optimal signal to noise ratio is obtained by integrating signal along the trajectory
 - If $\text{SNR} \gg 1$, kernel $\propto |\text{signal}|^2$
 - If $\text{SNR} \leq 1$, kernel $\propto |\text{template} * \text{signal}|$ or $|\text{signal}_j * \text{signal}_k|$
 - Optimal filter:
kernel $\propto 1/(\text{noise power})$

Interferometer Data Channels

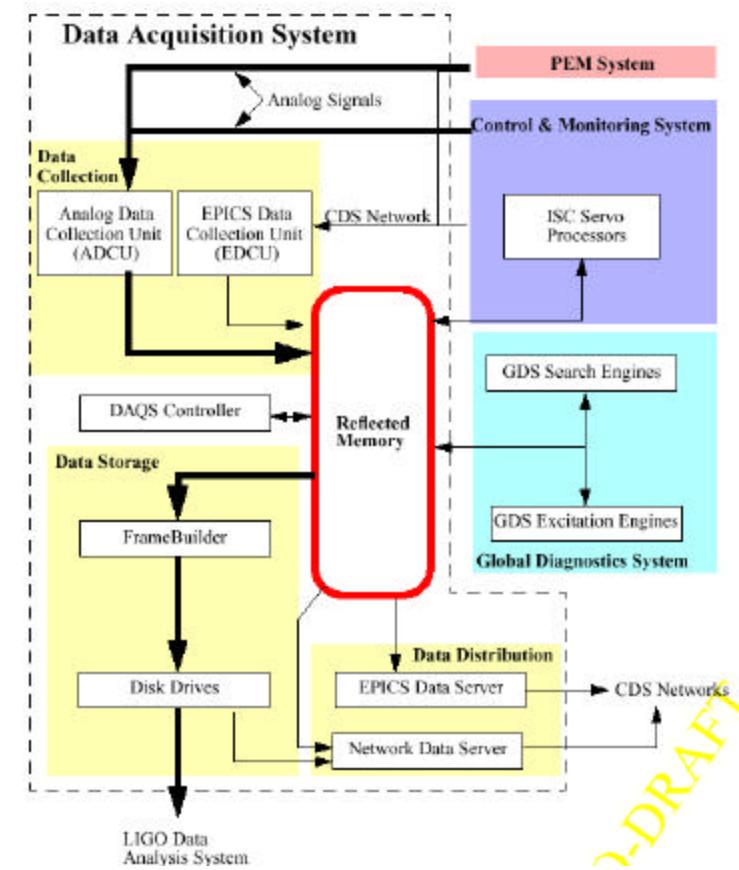


- All interferometric detector projects have agreed on a standard data format
- Anticipates joint data analysis
- LIGO Frames for 1 interferometer are ~3MB/s
 - 32 kB/s strain
 - ~2 MB/s other interferometer signals
 - ~1MB/s environmental sensors
 - **Strain is ~1% of all data**



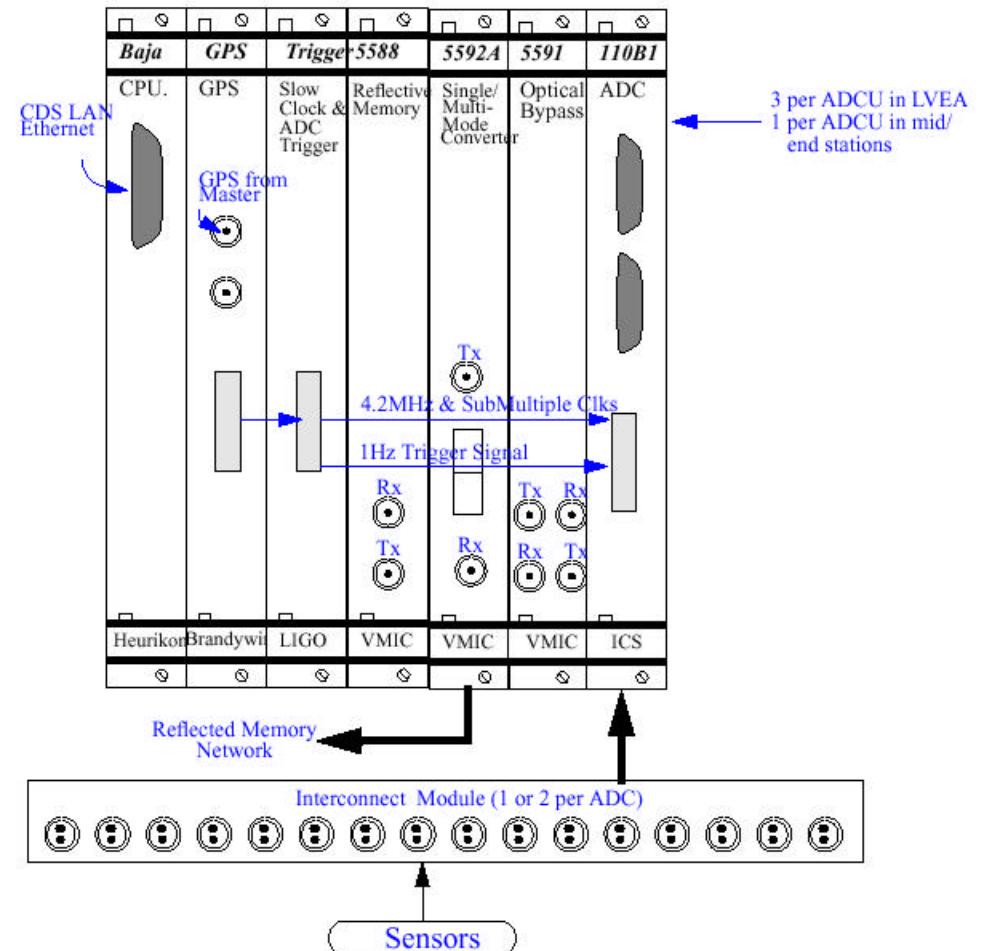
DAQS overview

- Inputs: Analog signals from sensors, to actuators; digital signals from control systems (LSC, ASC, etc)
- Signals needed for LSC, ASC, etc, get digitized in a separate path.
- All information stored in reflective memory, visible to all the cpus in the system that need it.
- I/O to GDS
- Output to frame builder, thence to RAID disk array
- Monitored and controlled via EPICS screens



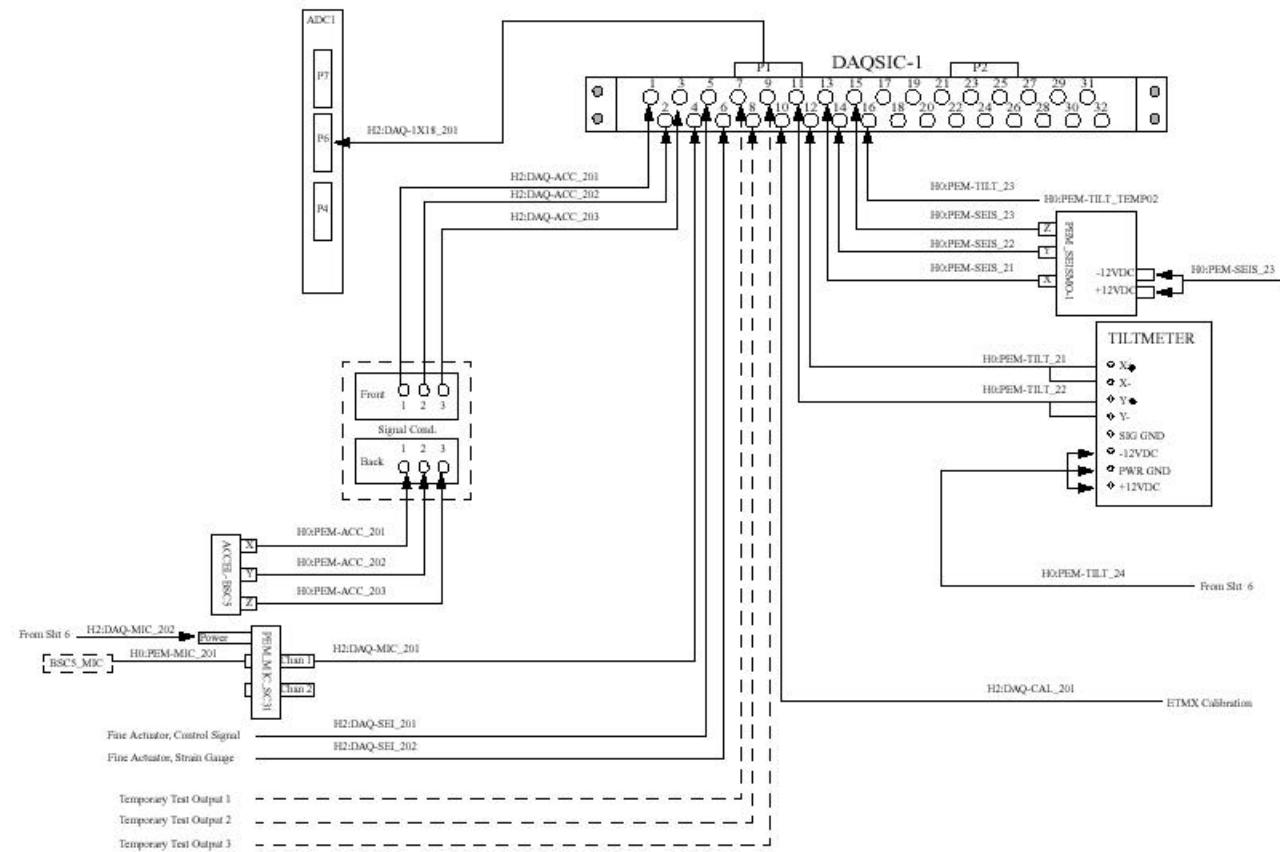
Analog Data Collection Unit (ADCU)

- Fast CPU
- ADC (up to 16 bit, 16 kHz, 32 ch)
- GPS receiver for ADC trigger
- Reflective memory

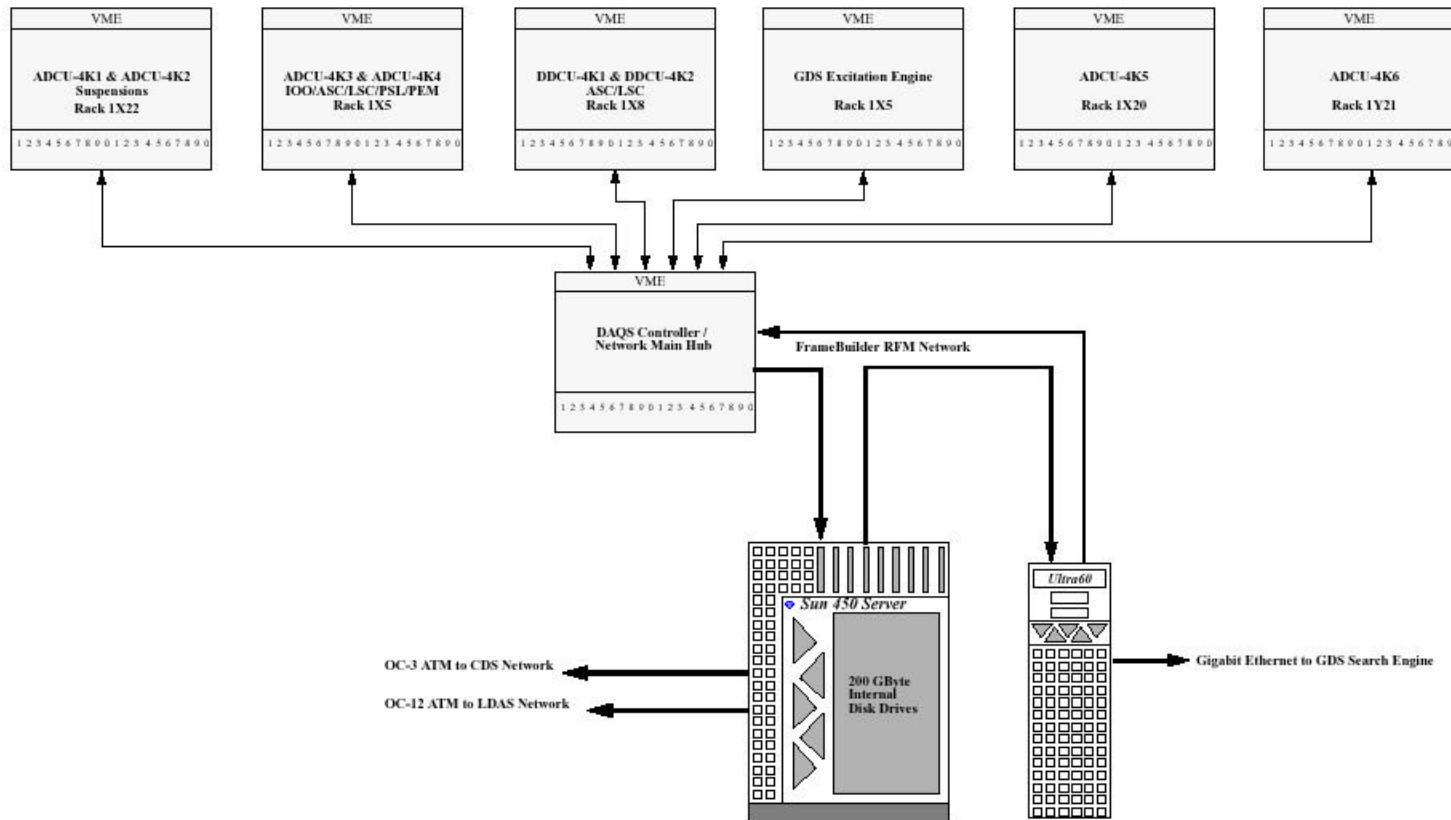


Typical example of what's in an ADCU

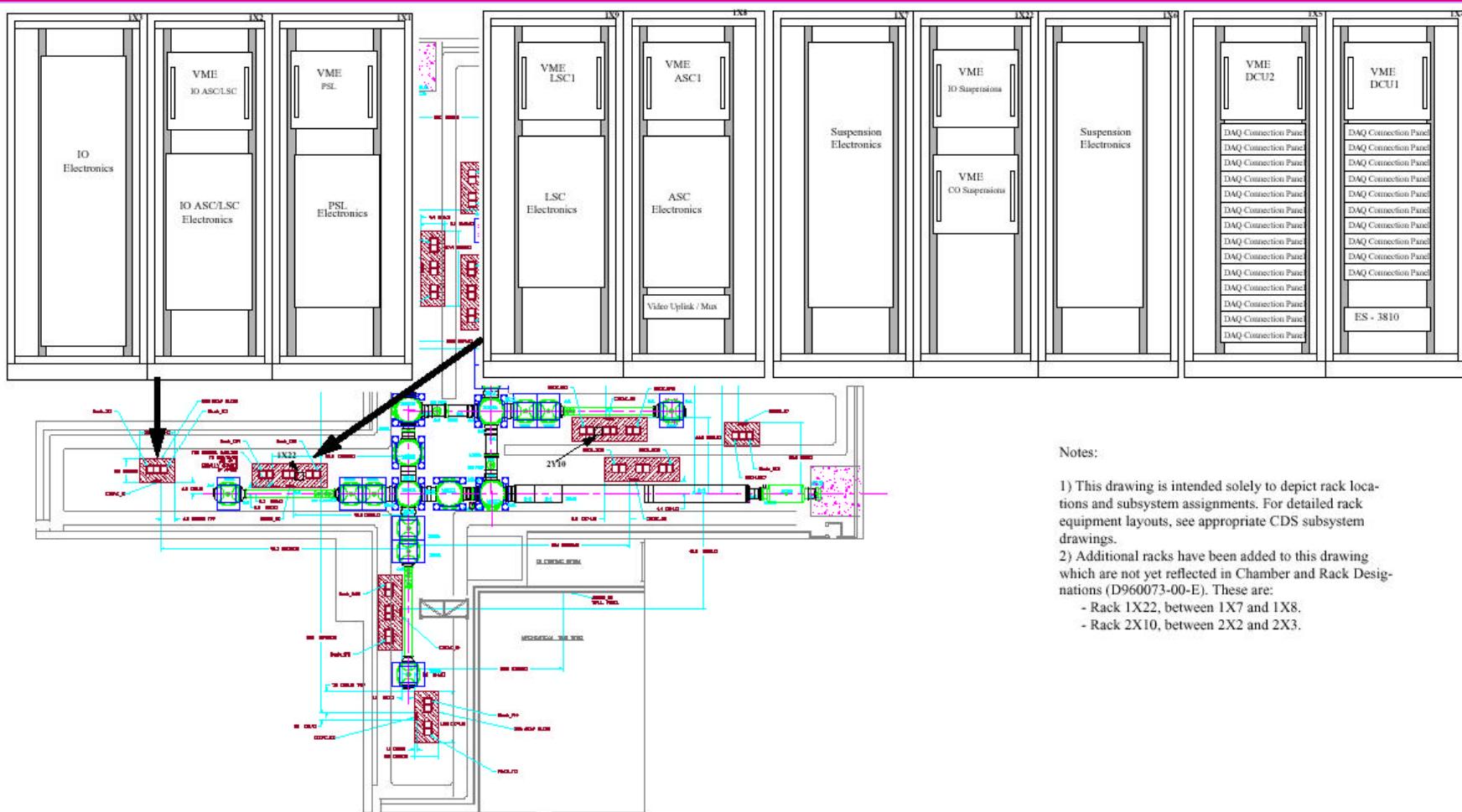
Chan	Name	Rate
00	H0:PEM-BSC5_ACCX	2048
01	H0:PEM-BSC5_ACCY	2048
02	H0:PEM-BSC5_ACCZ	2048
03	H0:PEM-BSC5_MIC	2048
04	H2:SEL-BSC5_FINE1	256
05	H2:SEL-BSC5_FINE2	256
06	H0:GDS-MX_TO1	16384
07	H0:GDS-MX_TO2	2048
08	H0:GDS-MX_TO3	2048
09	H2:SLC-ETMX_CAL	16384
10	H0:PEM-MX_TILT_X	256
11	H0:PEM-MX_TILT_Y	256
12	H0:PEM-MX_SEISX	256
13	H0:PEM-MX_SEISY	256
14	H0:PEM-MX_SEISZ	256
15	H0:PEM-MX_TEMP2	16
16	H2:SUS-BSC5_SENSOR_SIDE	256
17		
18	H2:SUS-BSC5_COIL_UL	2048
19	H2:SUS-BSC5_COIL_LL	2048
20	H2:SUS-BSC5_COIL_LR	2048
21	H2:SUS-BSC5_COIL_RL	2048
22	H2:SUS-BSC5_COIL_SIDE	2048
23	H2:SUS-BSC5_COIL_SUM	16384
24	H2:SUS-BSC5_SENSOR_UL	256
25	H2:SUS-BSC5_SENSOR_LL	256
26	H2:SUS-BSC5_SENSOR_LR	256
27	H2:SUS-BSC5_SENSOR_RL	256
28		
29		
30	H2:GDS-MX_RAMP3	16384
31	H2:GDS-MX_TRIGGER	16384
TOTAL (BTYES/SEC)		215056



DAQS crates for one IFO



Racks and racks of electronics



Notes:

- 1) This drawing is intended solely to depict rack locations and subsystem assignments. For detailed rack equipment layouts, see appropriate CDS subsystem drawings.
- 2) Additional racks have been added to this drawing which are not yet reflected in Chamber and Rack Designations (D960073-00-E). These are:
 - Rack 1X22, between 1X7 and 1X8.
 - Rack 2X10, between 2X2 and 2X3.

DAQS data channels and rates

- Each IFO has dozens of fast (16 kHz) and hundreds of slow (< 1 kHz) channels; equivalent of ~ 150 fast channels/IFO.
- $(16 \text{ kHz}) \times (2 \text{ bytes}) \times (3 \text{ IFOs}) \times (150 \text{ ch/IFO}) \times (3 \times 10^7 \text{ sec/year}) \times (2 \text{ years}) \times (50\% \text{ duty cycle}) = 500 \text{ Tbytes!}$
- Store full data stream on disk for ~ 1 day.
- Archive 10% of data to tape: 50 Tbytes!
- GW stream alone, decimated to 1 kHz: 200 GB
- Data stored in **Frames** and in **Meta-Database**

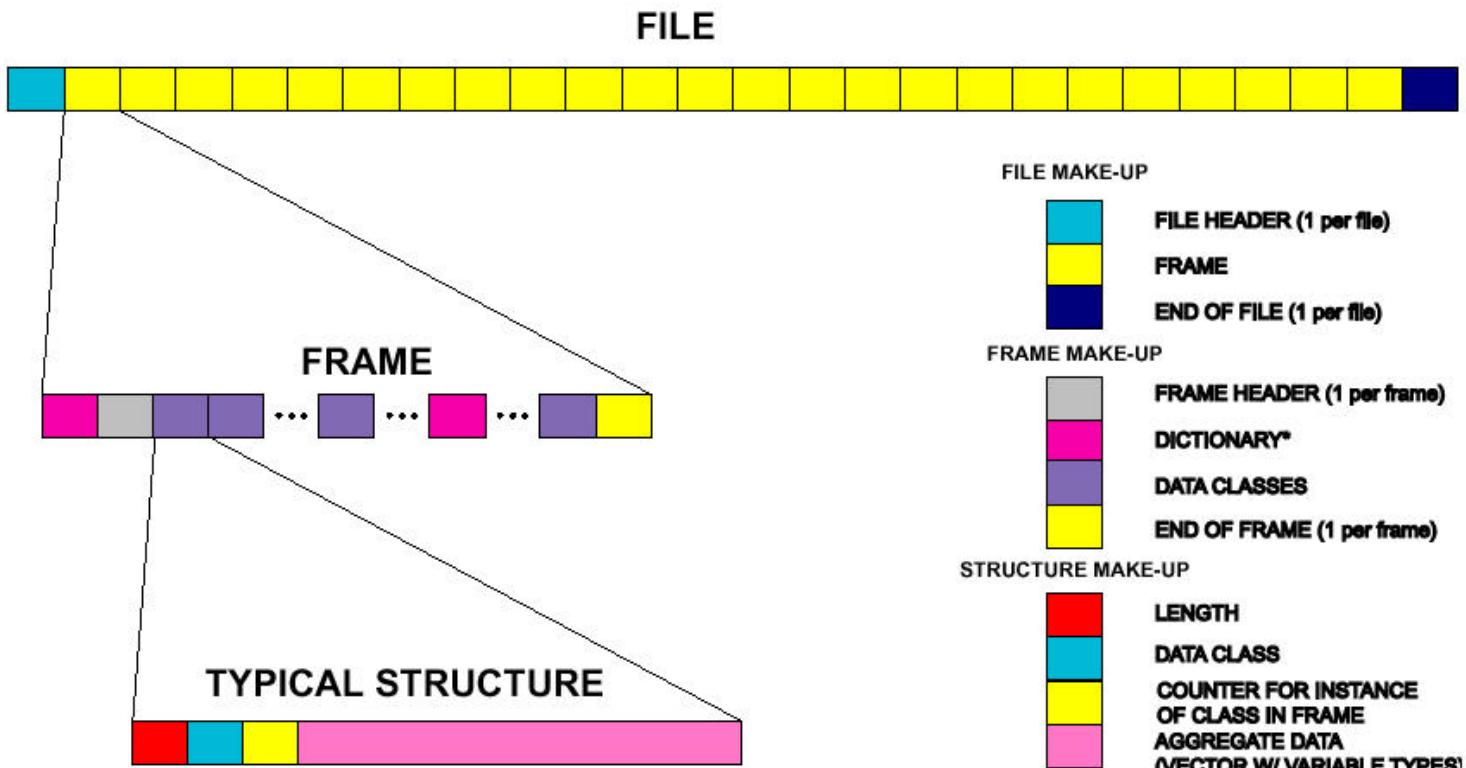
System	DAQS Network		Data Storage	
	Channels	Rate (MByte/sec)	Channels	Rate (MByte/sec)
LHO-4K	510	4.22	300	1.88
LHO-2K	548	4.37	332	1.99
LHO-PEM	204	0.89	204	0.89
LHO-VAC	500	0.01	500	0.01
LHO-GDS	133	2.45		
LLO-4K	515	4.22	305	1.89
LLO-PEM	95	0.46	95	0.46
LLO-VAC	300	0.01	300	0.01
LLO-GDS	76	0.89		



Frames

- **Frame** is a common data format developed and adopted by the **LIGO, VIRGO, GEO, TAMA** gravitational wave detectors.
- The predominant type of data stored in Frames is **time series data** of arbitrary duration. It is possible, however, to encapsulate in Frames other types of data, e.g., spectra, lists, vectors or arrays, etc. A Frame contains data for a specified epic in time.
- **Frame Class Library (fcl)** is a set of c++ OO-tools for creating, manipulating, and reading frames.

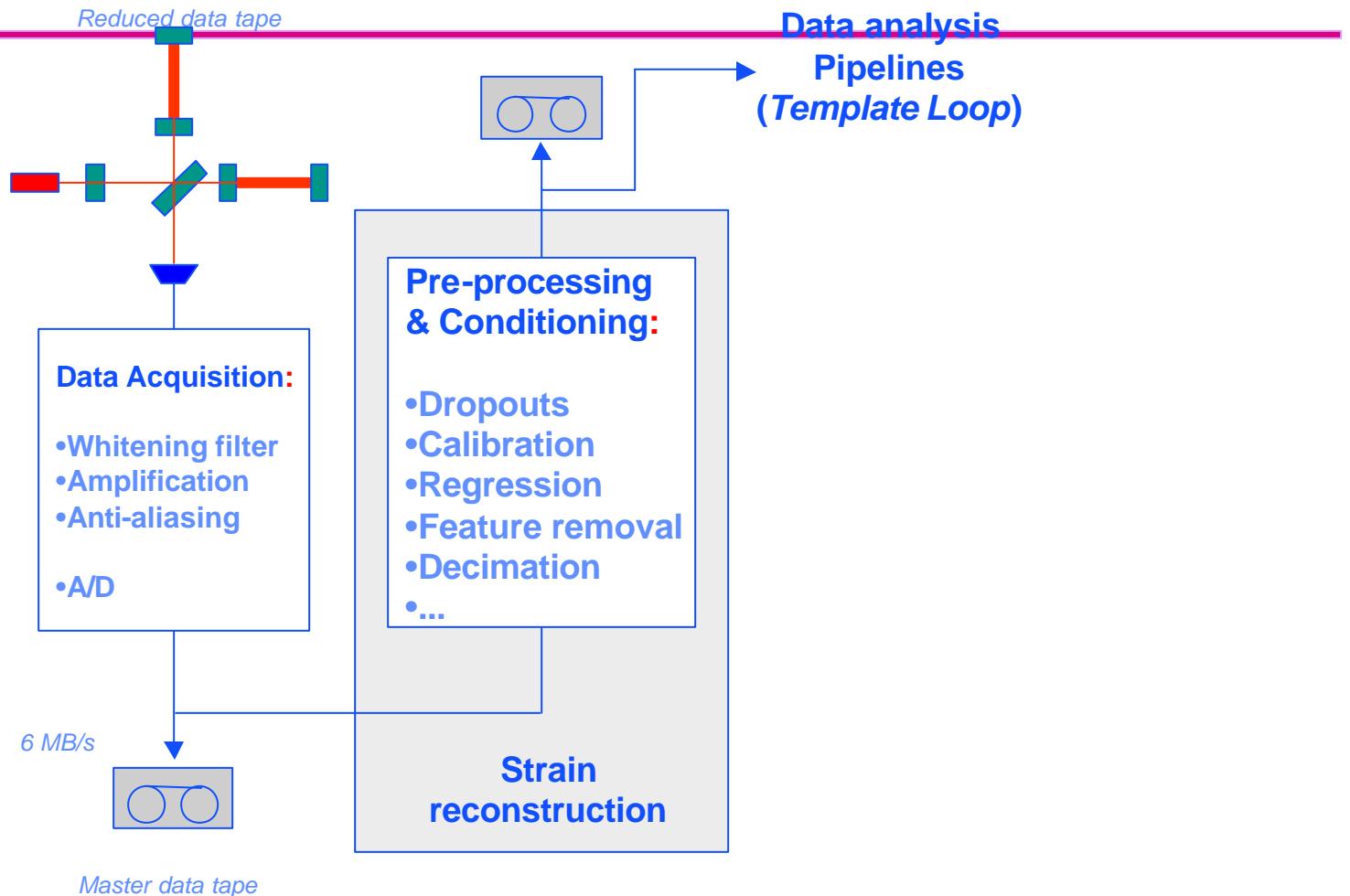
Frame structure



LIGO-T970130-B-E: VIRGO-SPE-LAP-5400-102

- * Dictionary structure behavior is unique in that:
1. It precedes header for first frame of file;
 2. Dictionary is built up incrementally as additional structures are incorporated into frame
 3. It is valid for entire file (persistent)

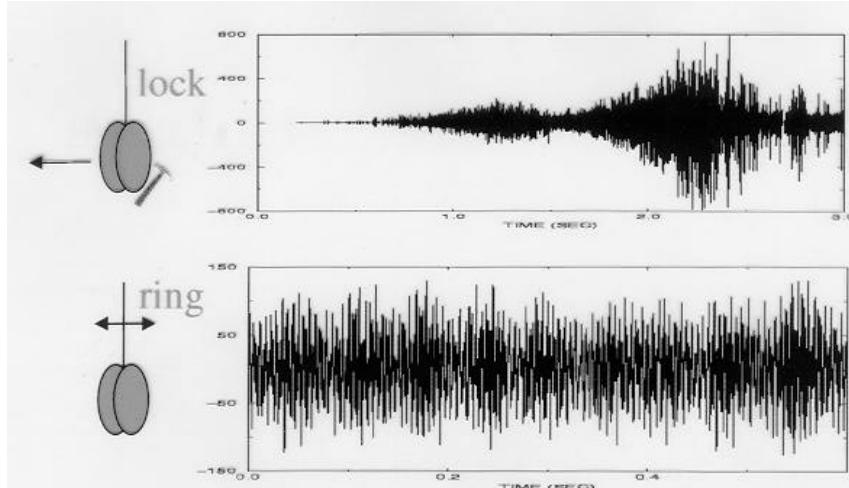
Data Flow: Pre-processing



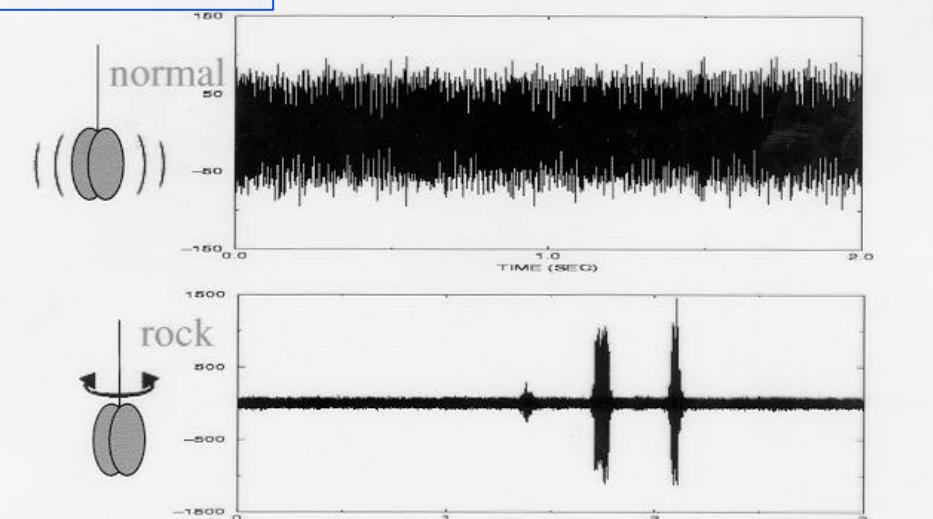
Interferometer Transients -- Examples from 40m Data

Real interferometer data is UGLY!!!
(Glitches - known and unknown)

LOCKING

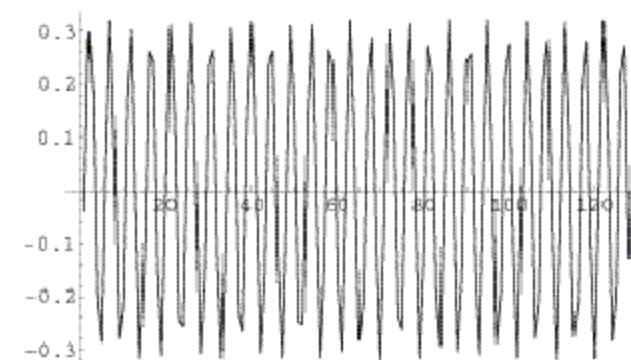
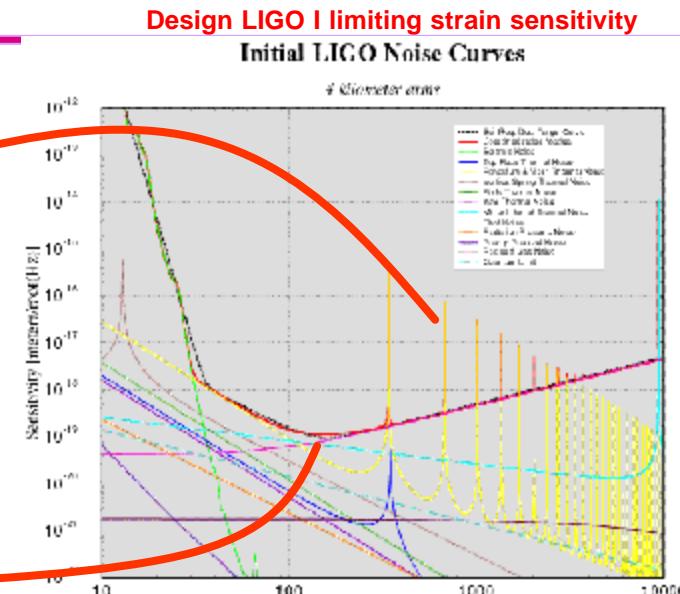
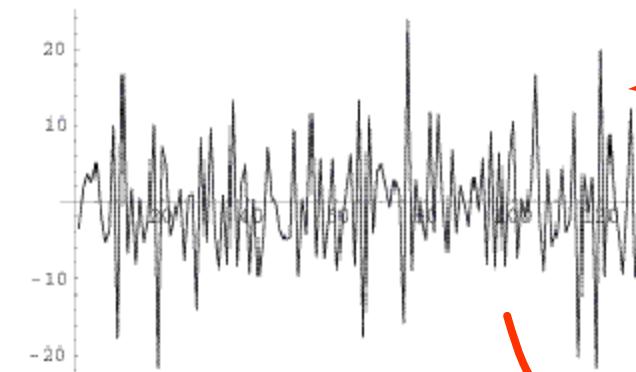
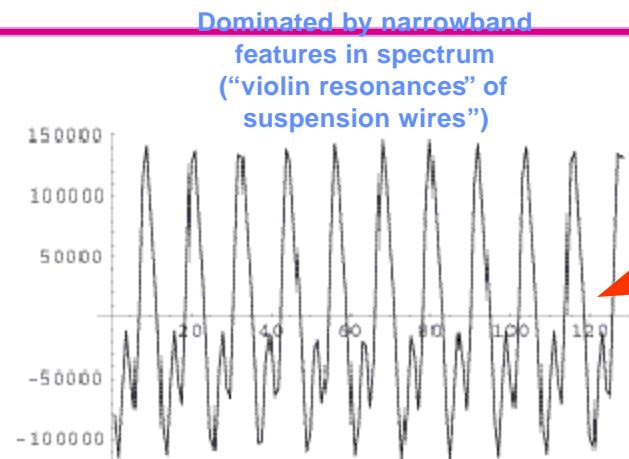


NORMAL

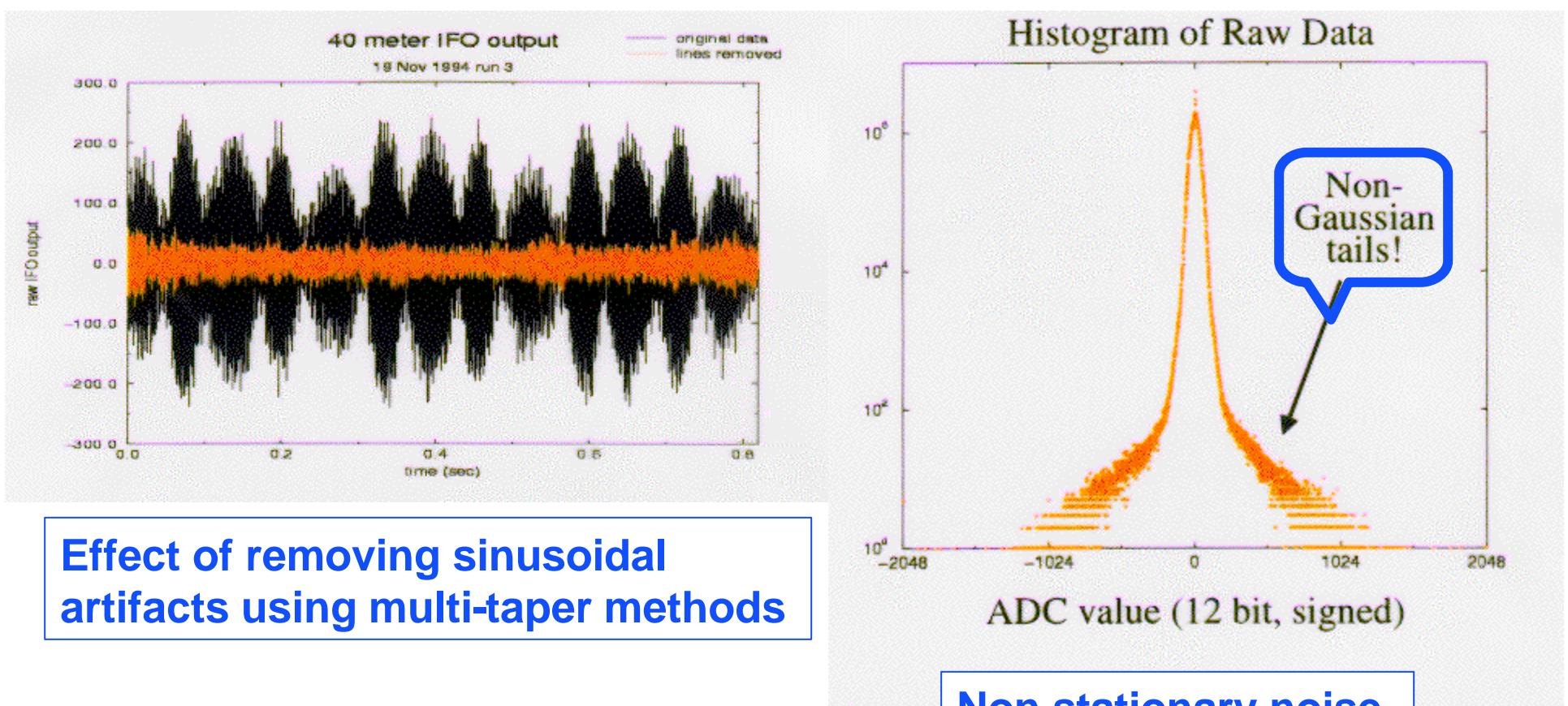


RINGING

Interferometer Strain Signal (Simulated)



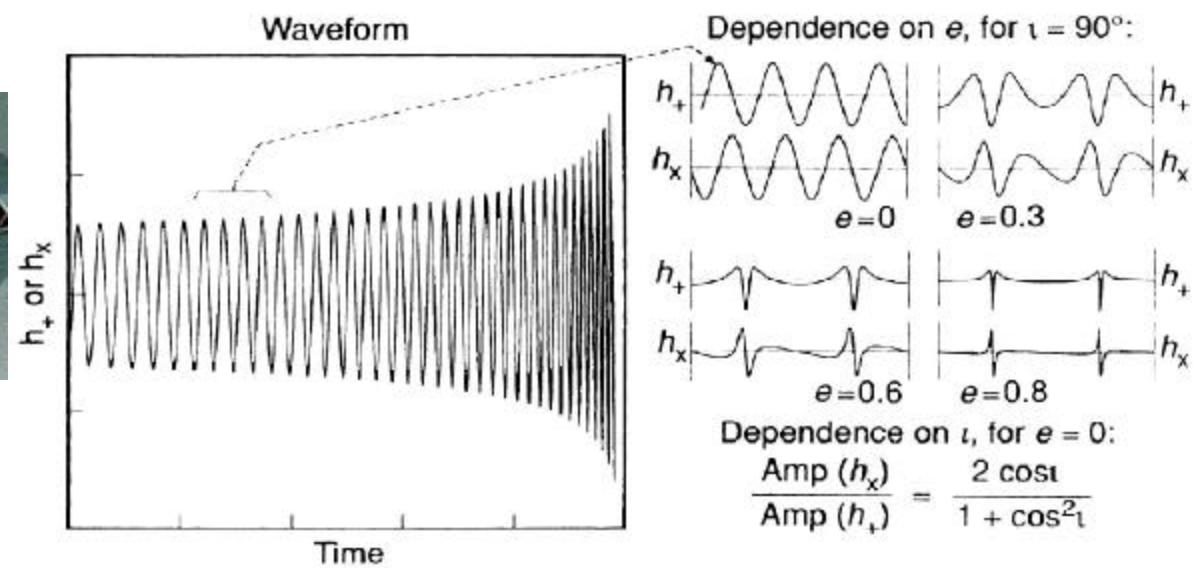
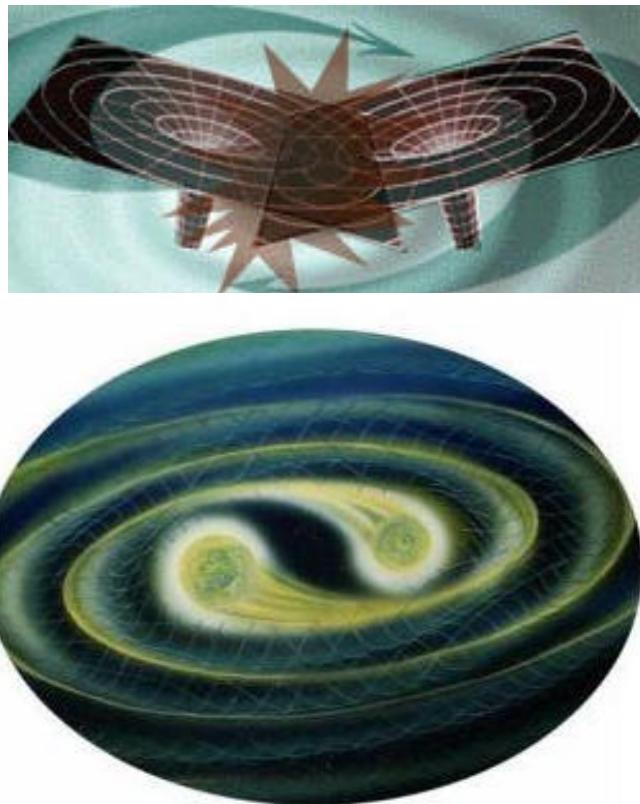
“Clean up” data stream



Effect of removing sinusoidal artifacts using multi-taper methods

**Non stationary noise
Non gaussian tails**

Chirp signal from Binary Inspiral

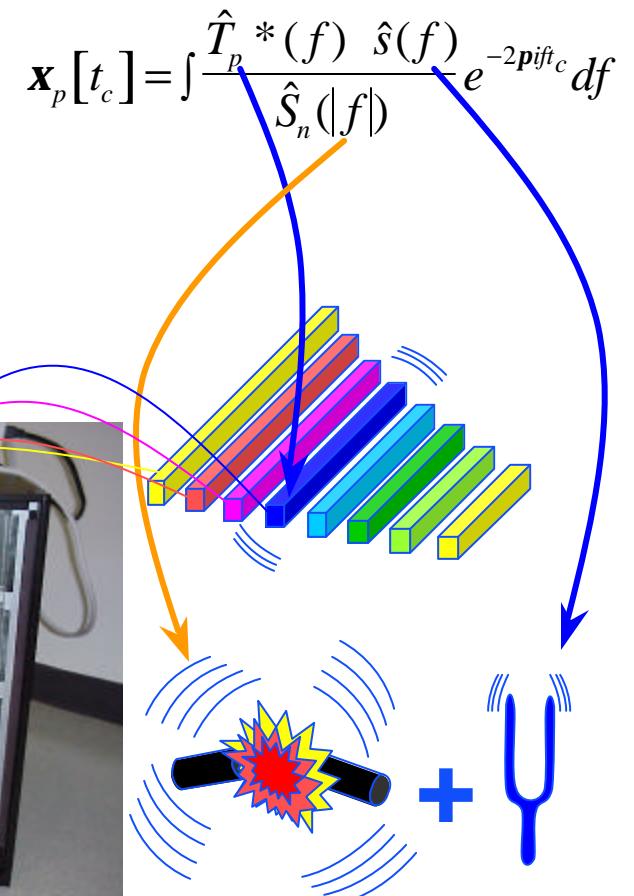
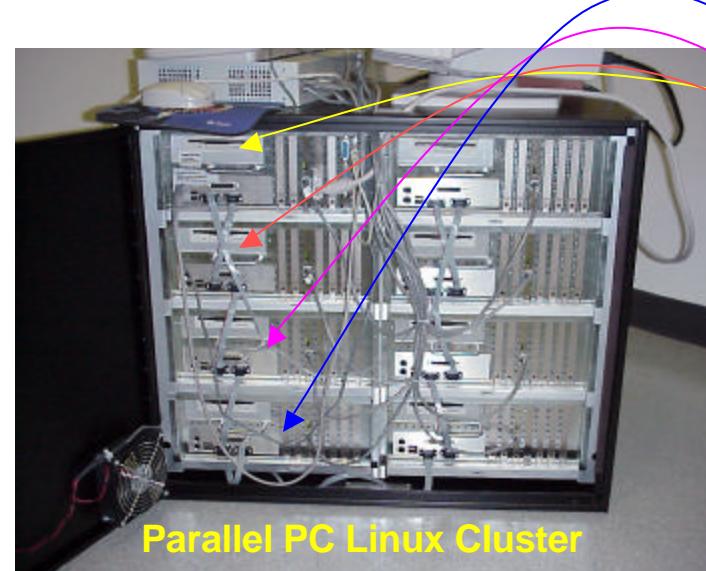


determine

- distance from the earth r
- masses of the two bodies
- orbital eccentricity e and orbital inclination ι

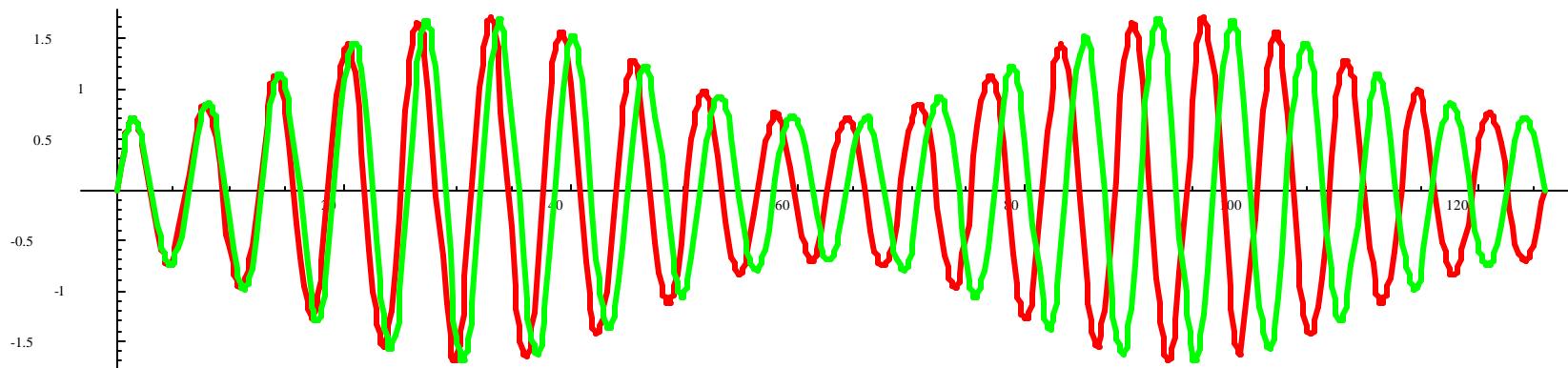
Optimal Wiener Filtering

- Matched filtering (optimal) looks for best overlap between a signal and a set of expected (template) signals in the presence of the instrument noise -- correlation filter
- Replace the data time series with an SNR time series
- Look for excess SNR to flag possible detection



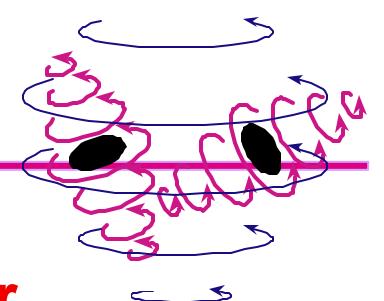
Got to get the templates **RIGHT**

- **Compute the dynamics of sources and their emitted waveforms**
 - » **Why we need waveforms:**
 - As templates to use in searches for waves via matched filtering



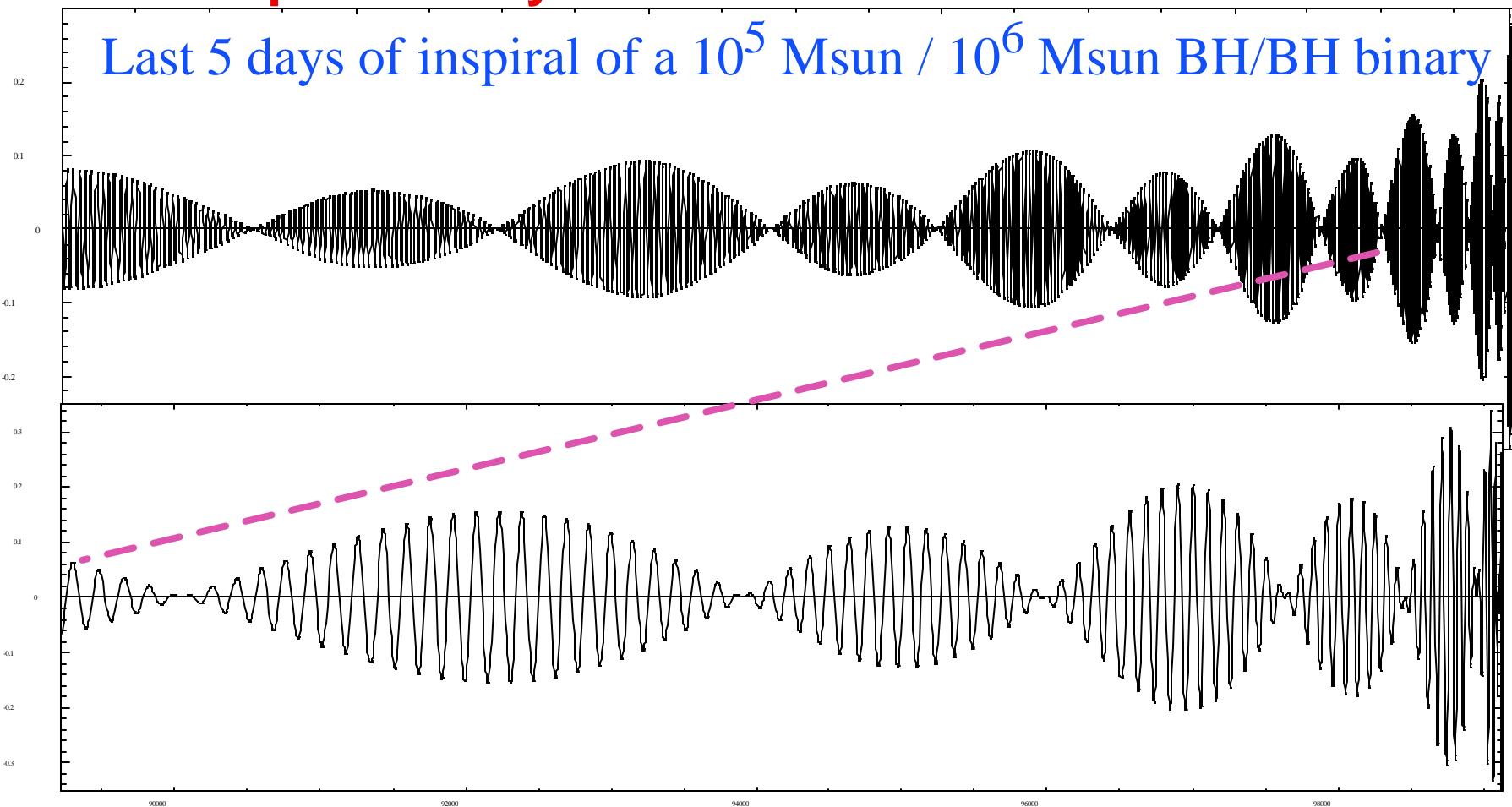


Lots to learn from the waveforms!

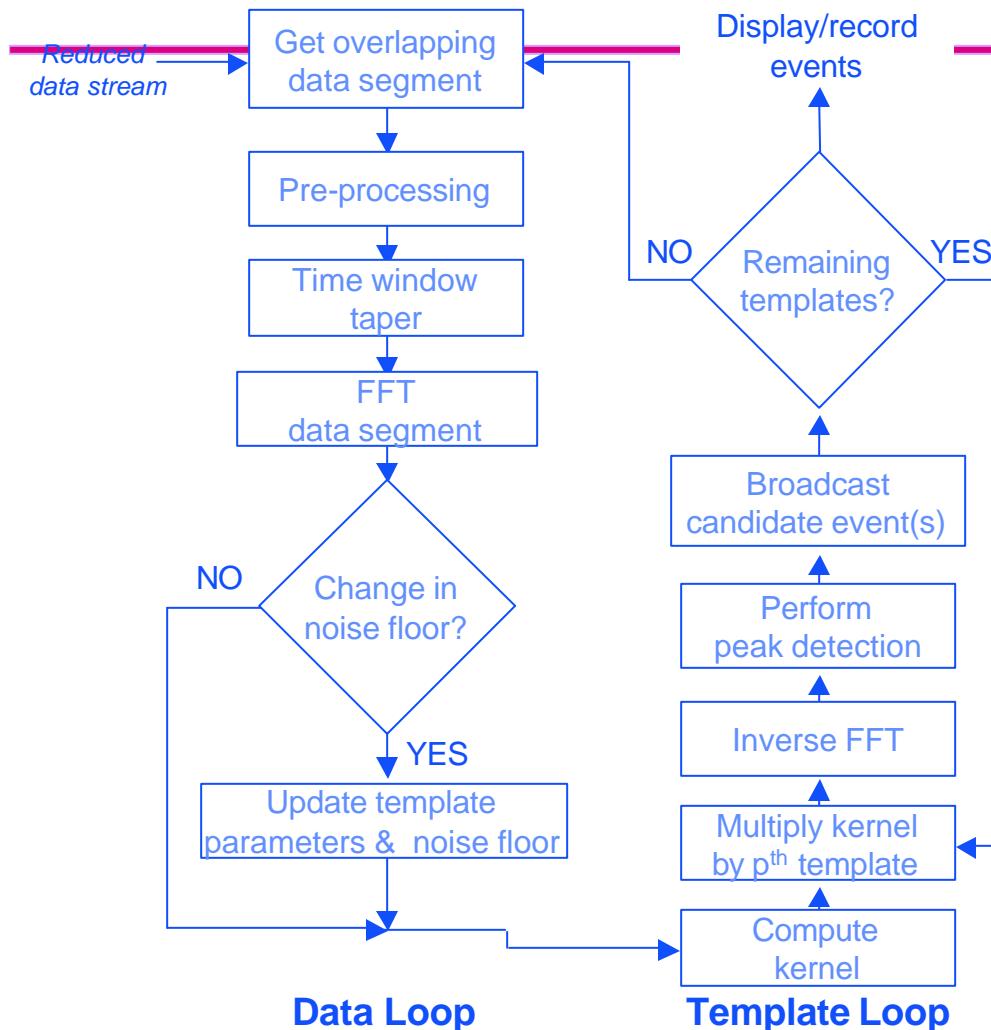


- Compute the dynamics of sources and their

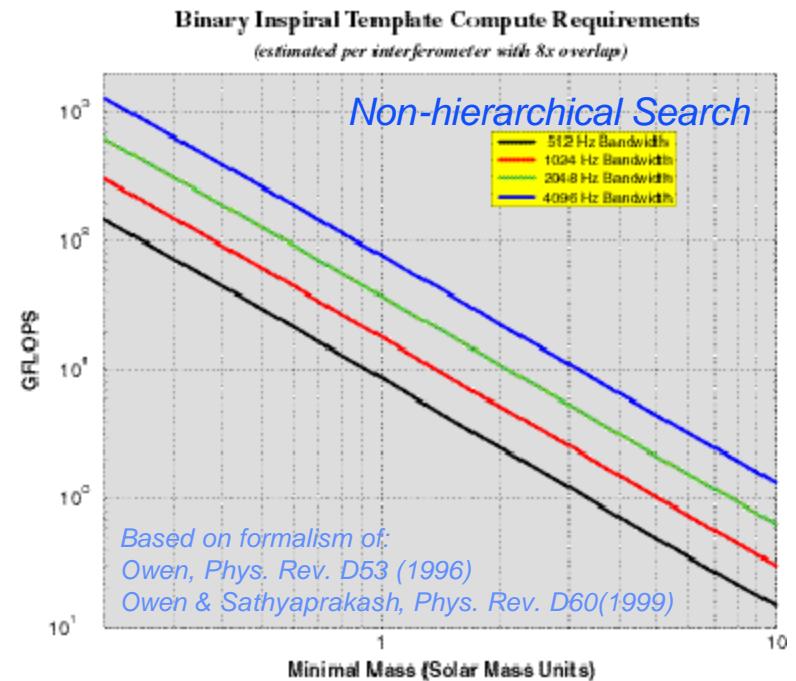
Last 5 days of inspiral of a 10^5 Msun / 10^6 Msun BH/BH binary



Compact Binary Inspirals Data Analysis Flow



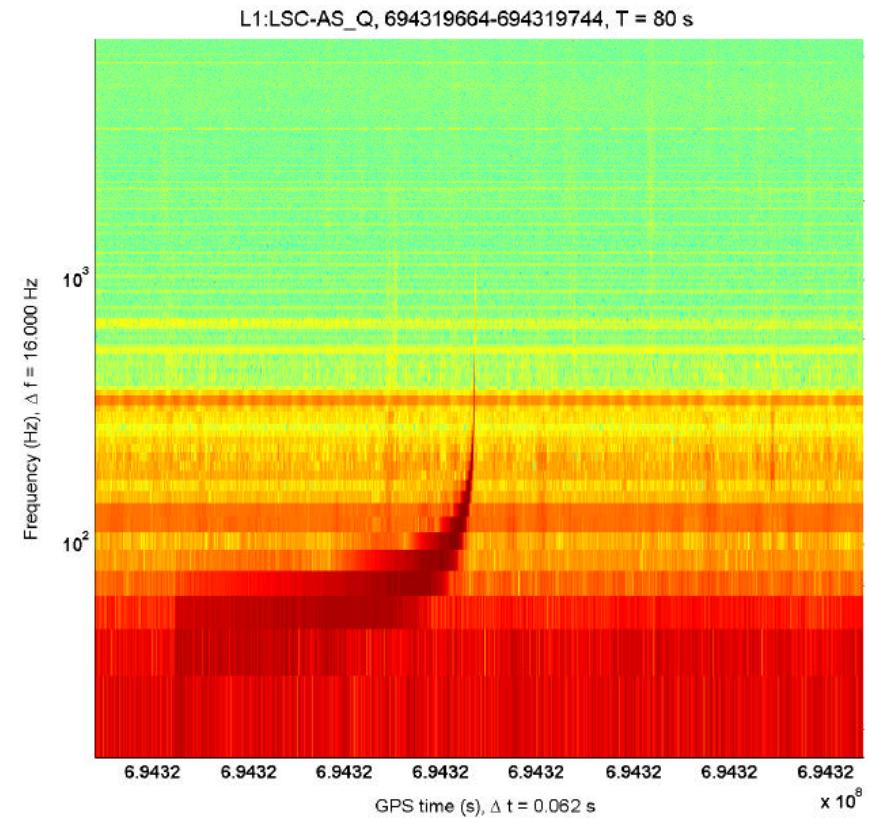
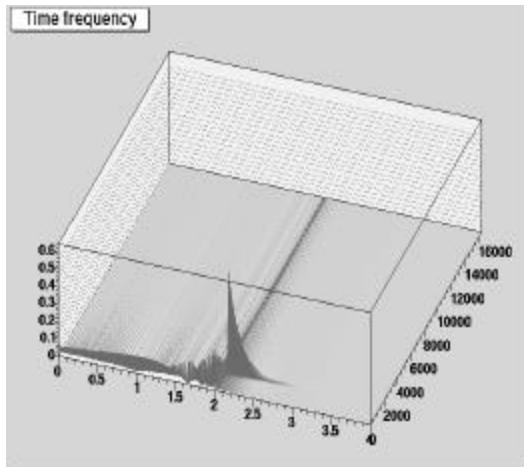
$$\mathbf{x}_p[t_c] = 2 \int \frac{\hat{T}_p(f) \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2\pi f t_c} df$$



- Process data at real time rate
- Improvements:
 - » Hierarchical searches developed
 - » Phase coherent analysis of multiple detectors (Finn, in progress)

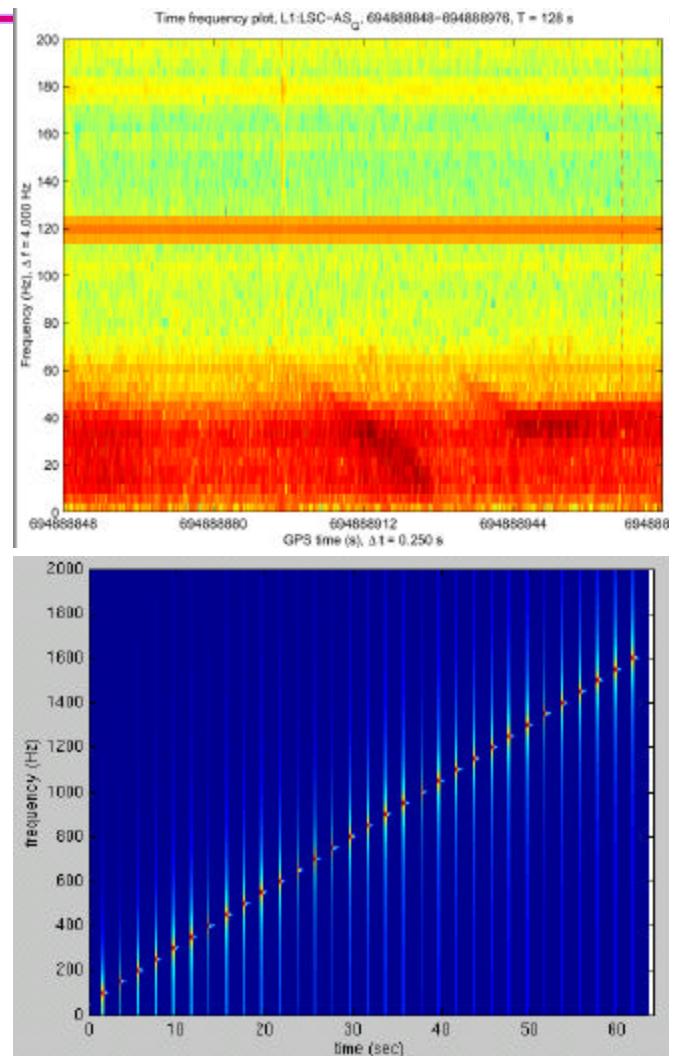
Simulations

- Test search codes with simulated inspirals and bursts added to the noisy data stream.
- Can also inject arbitrary waveform signals directly into the IFO, by moving the end mirrors.
- This also tests the interferometer response function, as measured through calibration procedure.
- It also tests the detailed E2E simulations of IFO performance.



Unmodeled bursts

- Look for excess power in time-frequency plane.
- Unfortunately, there are MANY noise bursts.
- Set excess power thresholds carefully; noise is NOT (yet) Gaussian and stationary!
- Veto on ones that correlate with environmental or non-GW-related IFO signals.
- Try not to veto away all the live time!
- Trade-off between efficiency and live-time.
- Must rely on in-time coincidences between sites
- Study correlations between sites very carefully!
- Can also look for coincidences with other IFOs, bars, GRBs, etc.

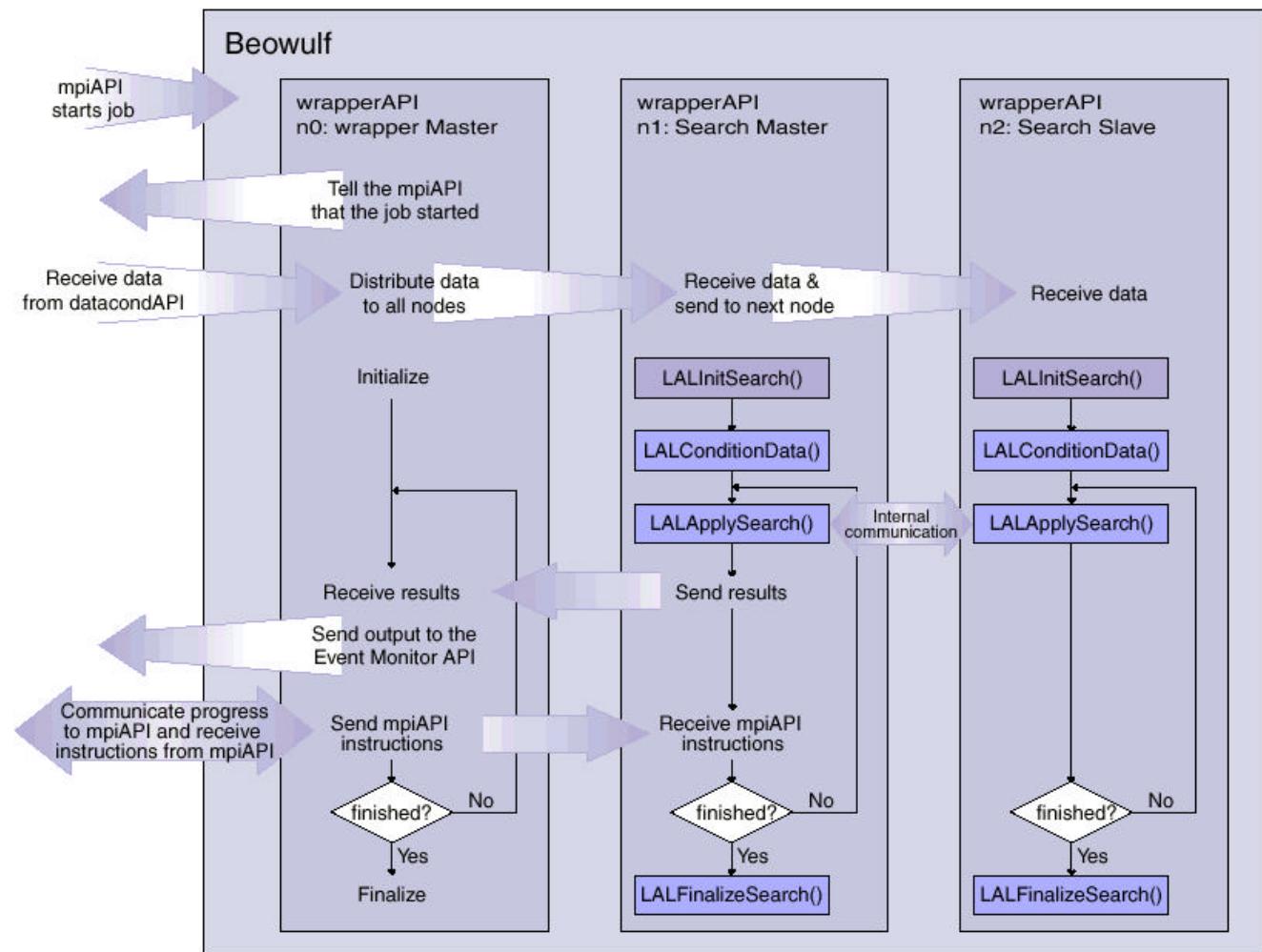




Perform CPU-intensive searches near real-time on parallel compute farms

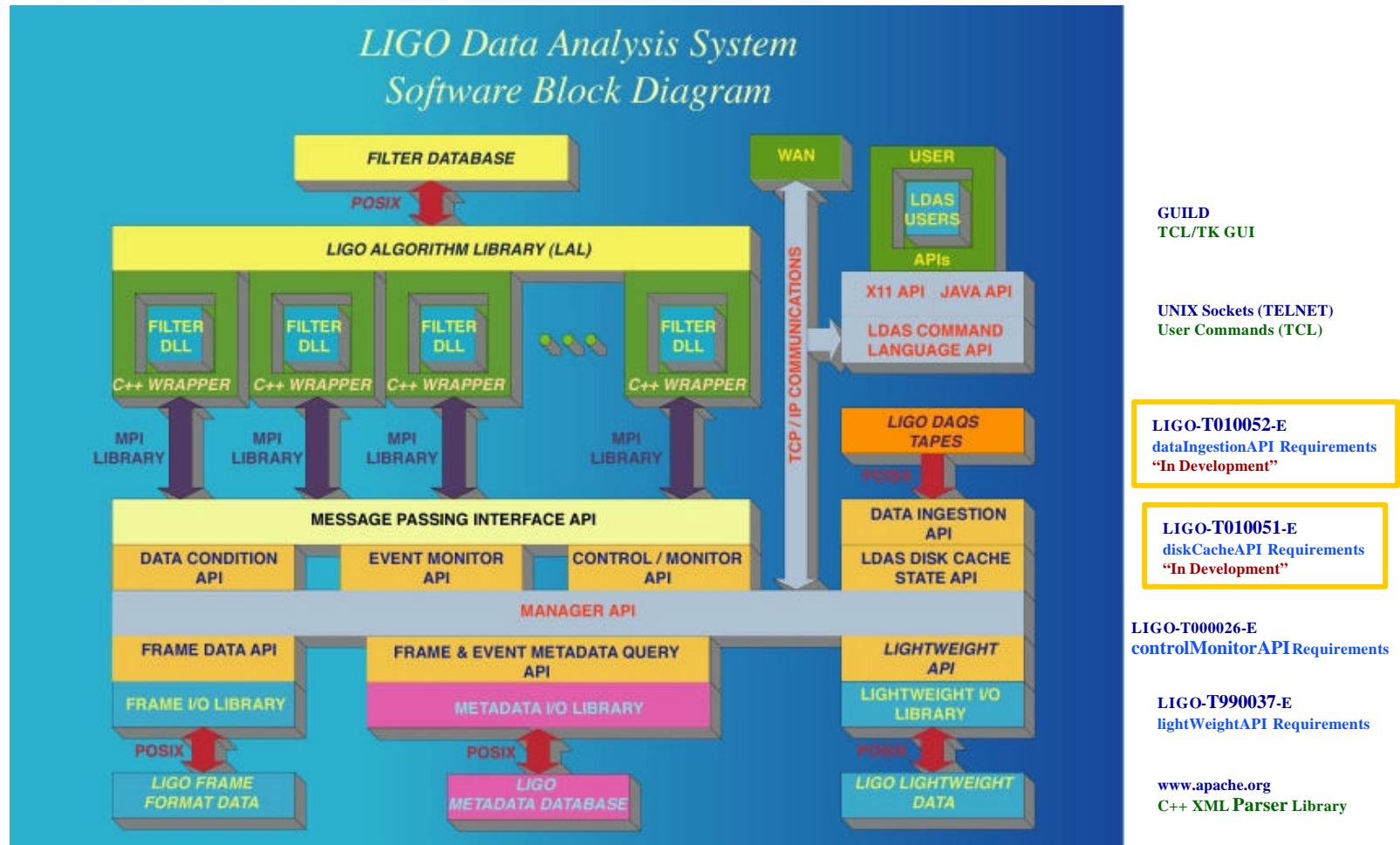
LIGO labs and LSC institutions maintain 6 (and growing) LDAS installations with Beowulf PC/linux/MPI-based search engines.

Also involved in GRID computing initiatives (CACR, Harvey's group).





Software Block Diagram



LIGO-T990101-E
LAL Specification

LIGO-T990097-E
wrapperAPI Requirements

www.lam.org
LAM version 5.6.1

LIGO-T990086-E
mpiAPI Requirements

LIGO-T990002-E
dataConditionAPI Requirements
FFTW version 2.3.1
CLAPACK version

LIGO-T980115-E
managerAPI Requirements

LIGO-T980117-E
frameAPI Requirements

LIGO-T970130-E
LIGO-VIRGO Frame Specification
FrameCPP Version 4

LIGO-T980119-E
metaDataAPI Requirements

dbEasy Library
ODBC Level 3

LIGO-T990101-E
LDAS Database Tables

LIGO-T990023-E
LIGO-Lightweight Format

GUILD
TCL/Tk GUI

UNIX Sockets (TELNET)
User Commands (TCL)

LIGO-T010052-E
dataIngestionAPI Requirements
"In Development"

LIGO-T010051-E
diskCacheAPI Requirements
"In Development"

LIGO-T000026-E
controlMonitorAPI Requirements

LIGO-T990037-E
lightWeightAPI Requirements

www.apache.org
C++ XML Parser Library

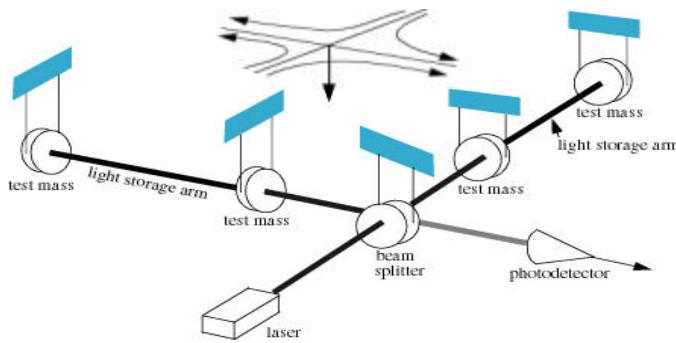
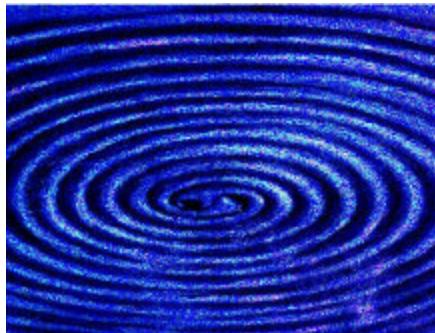


When will physics results be available?

- We have hundreds of hours of E7 data in the can
 - » LLO4K, LHO2K, LHO4K, GEO600, ALLEGRO, GRB alerts
- Work on improving detectors is ongoing.
- First science run (S1) in summer 2002.
- Currently working towards a pile of papers (Various inspiral, burst, periodic, stochastic searches) based on E7 data.
- *It is not yet clear whether this will bear fruit before the first science run!*
- If so, first papers might appear this summer.
- Else, papers based on S1 should be available by the end of 2002.

In parallel with science running,
Intense R&D on AdvLIGO – aim to install in 2007-9

Einstein's Symphony



- Space-time of the universe is (presumably!) filled with vibrations: Einstein's Symphony
- LIGO will soon 'listen' for Einstein's Symphony with gravitational waves, permitting
 - » Basic tests of General Relativity
 - » A new field of astronomy and astrophysics
- A new window on the universe!