Smoke, Mirrors, Big Bangs and Big Scientific Payoffs:

An outline in using an interferometer network to conduct astronomy.

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Outline of Talk

- Historical Perspective
- Gravitational Waves
  - Intro physics
  - GW Sources
  - “Vivisble” GW sources
- GW Detectors
  - Essential Idea
  - Pioneering technology
  - Current technology
- GW Detection
  - Signal Identification
    - Types
    - Instrument networks
  - Analysis methods
  - Instrumentation consideration
- GW Astronomy
  - Source localization
  - Understanding astrophysics
  - Complimentary observations

But, first!!!

Our Goal is to:

Detect Gravitational Waves!

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Historical Perspectives

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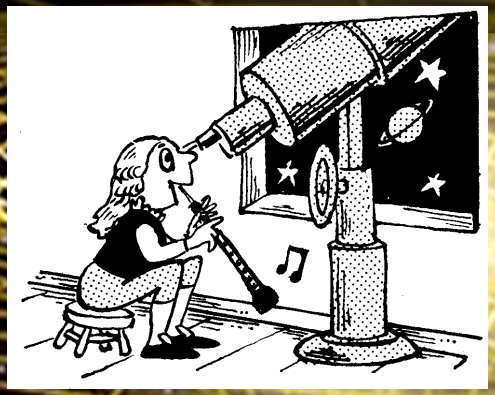
Astronomy Snapshot

- Observations by ancient cultures
- 85 AD: Ptolemy, first theory built on known observations
- 1564 AD: Galileo births observational astronomy
- 1905 AD: Jansky fathers radio astronomy
- . . .



McDonald Observatory(NASA)

Arecibo Radio Telescope

. . .

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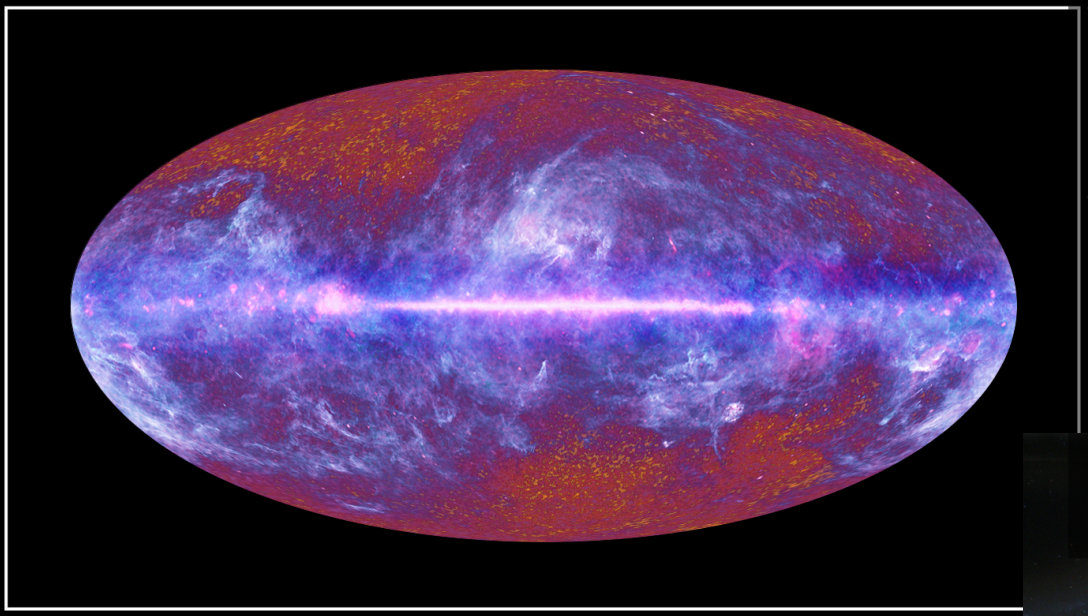
+ Much much more, astronomy is a content rich field

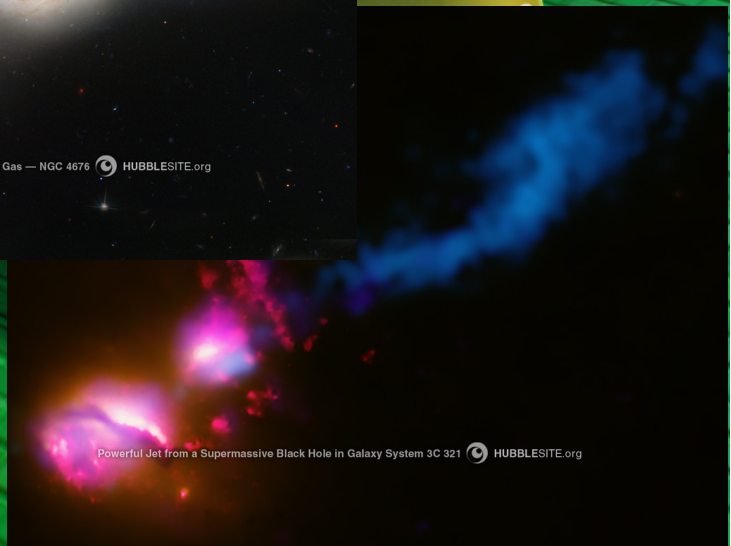
Astronomical “Observables”

Stellar Dust to Stellar Cores



- Stellar formation/reactions are gravity powered...
- Motion induced ionization causes electromagnetic radiation

- Bulk masses are also accelerating..
  - *Is there a gravitational analogue to radiation emission from accelerated charges?*



Gravitational Waves: What are they?

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General Relativity
Down the rabbit hole

curiouser and curiouser views of gravity

If I had a world of my own, everything would be nonsense. Nothing would be what it is because everything would be what it isn't. And contrary-wise; what it is it wouldn't be, and what it wouldn't be, it would. You see?

Alice, Alice in Wonderland, Lewis Carroll

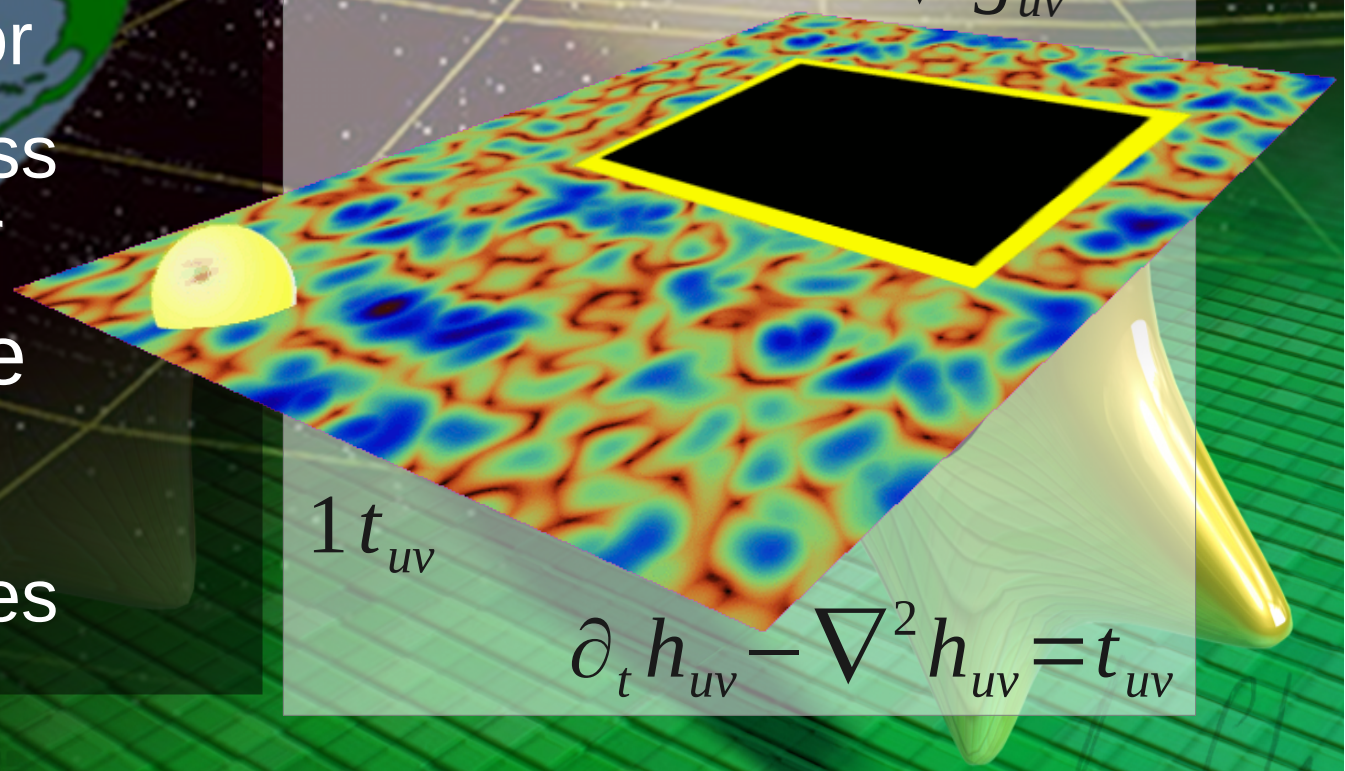
- Newton's Gravity
  - Instantaneous (action at a distance)
  - A force (mechanical)
- Einstein's Gravity
  - Limited by speed of light!
  - Geometrical
- What about every day gravity?

Gravitational Radiation 101

- Einstein Equation
- Universe Content
  - "Action/Shape" Einstein Tensor
  - "Content" Stress Energy Tensor
- Linear Regime
  - Point Sources
  - Flat space times

$$G_{uv} = \frac{8\pi G_n}{c^4} T_{uv}$$

$$\eta_{uv} + h_{uv} = g_{uv} \qquad \nabla g_{uv} = 0$$

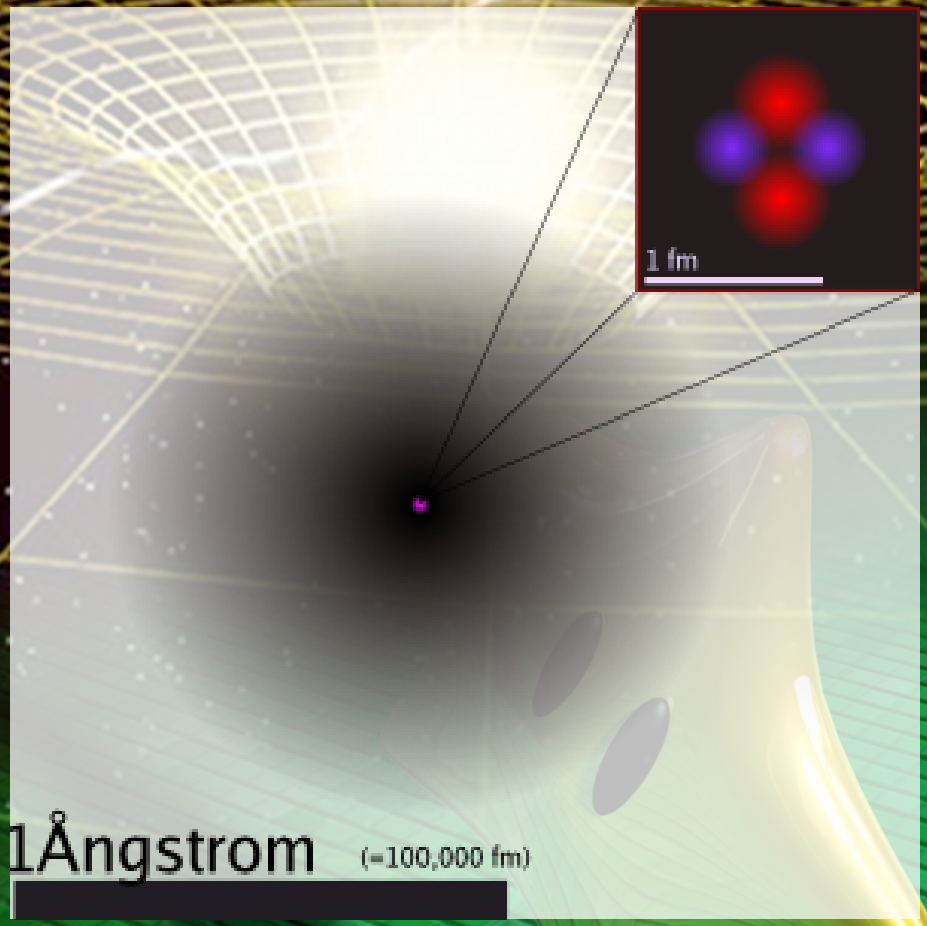


$$1 t_{uv}$$

$$\partial_t h_{uv} - \nabla^2 h_{uv} = t_{uv}$$

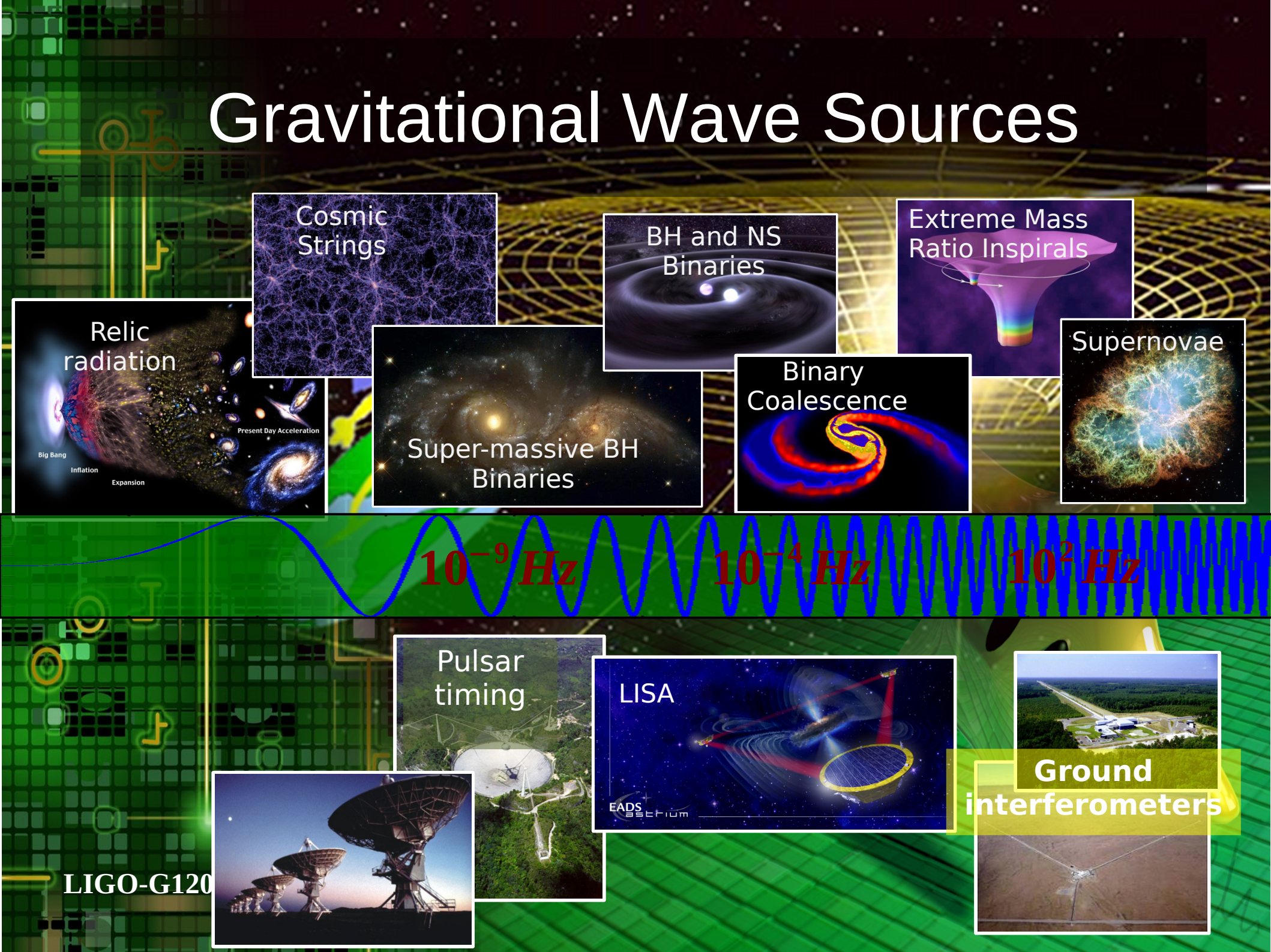
Gravitational Radiation

- How big is this wave?
  - As expected on earth 1e-18m
- Wave has two polarizations!
  - Cross "x"
  - Plus "+"



0.00000000000000000001m

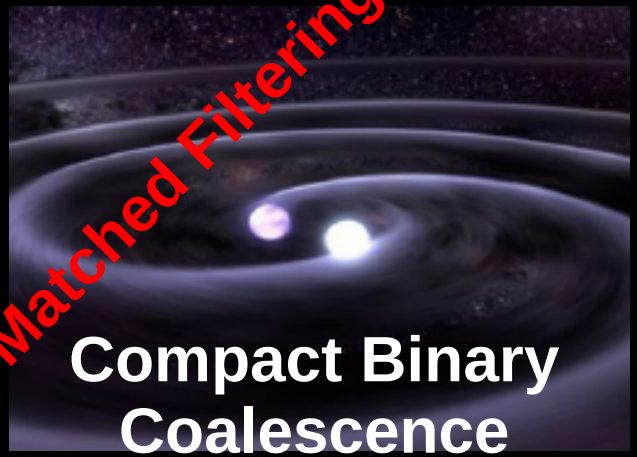
Gravitational Wave Sources

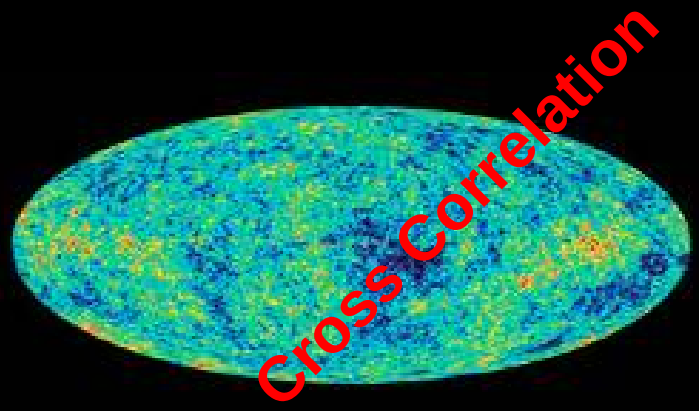


Sources for ground based detectors

Short Duration to Long Duration Signals

Unknown Waveform to Known Waveform





Gravitational Wave Detectors: The Nuts & Bolts

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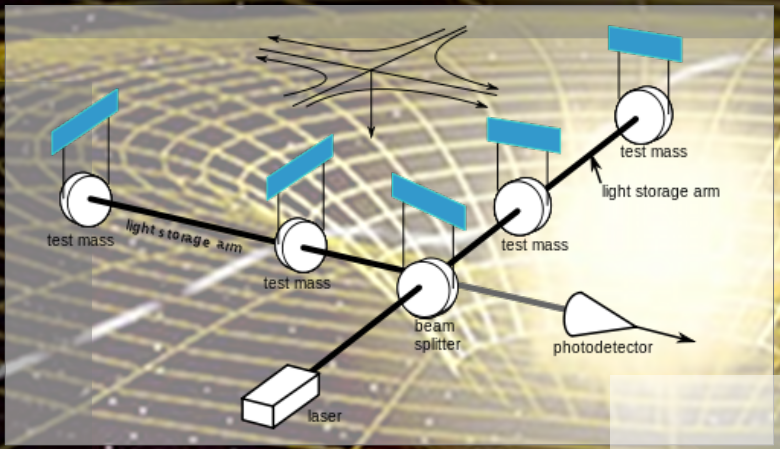
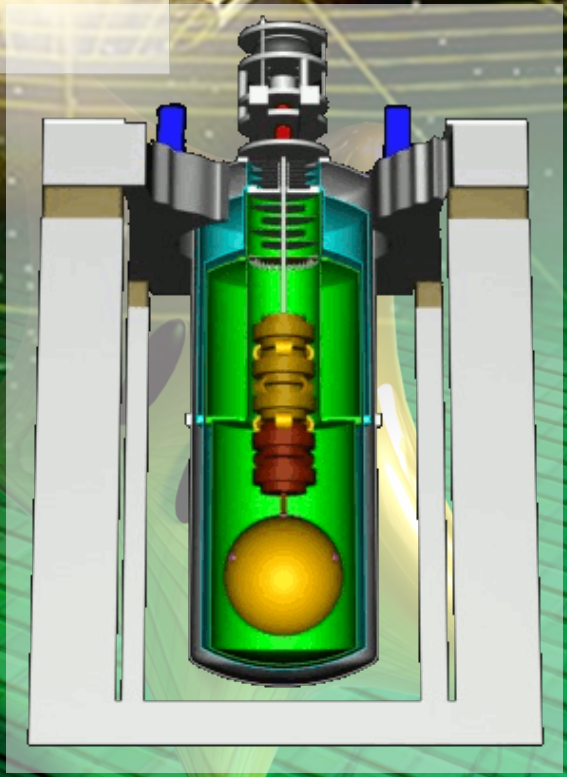
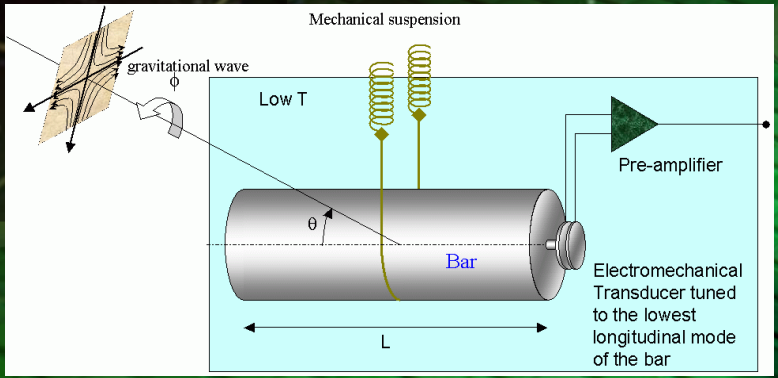
GW Telescopes

- Interferometric
  - Michaelson
  - Fabry Perot Michaelson
- Resonant Mass Detectors
  - Cylindrical
  - Spherical
- Others



Courtesy of LIGO



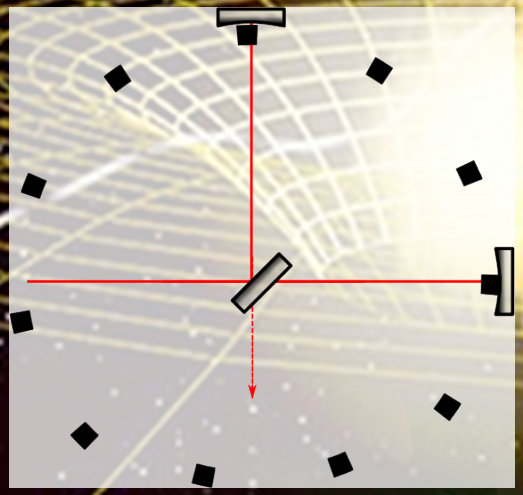


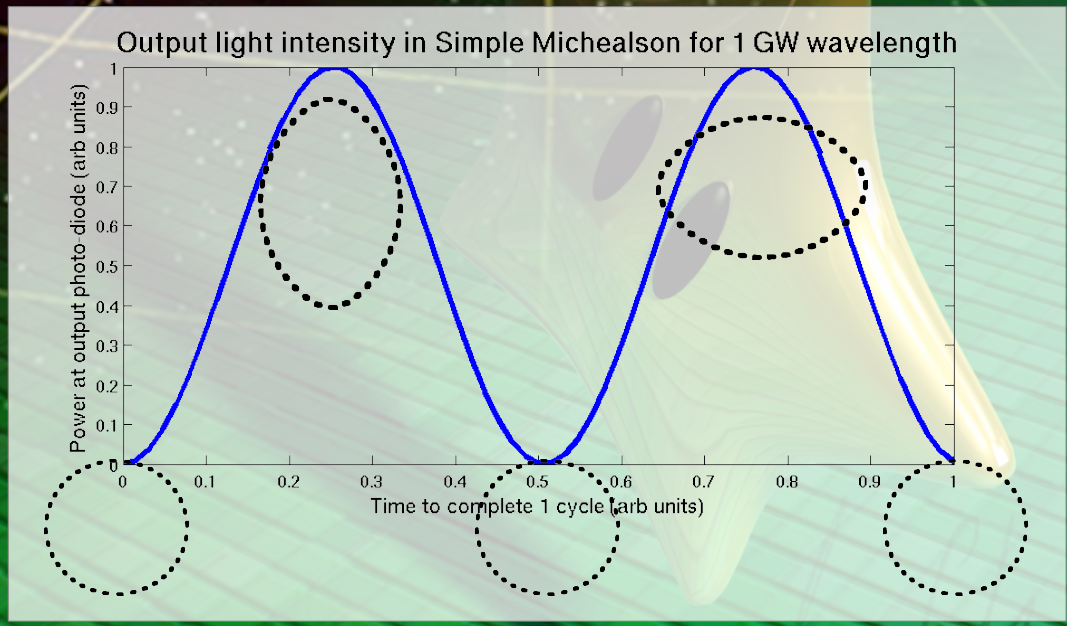
Courtesy of Auriga Group

Courtesy of INPE Group

Designing an Interferometic GW Detector

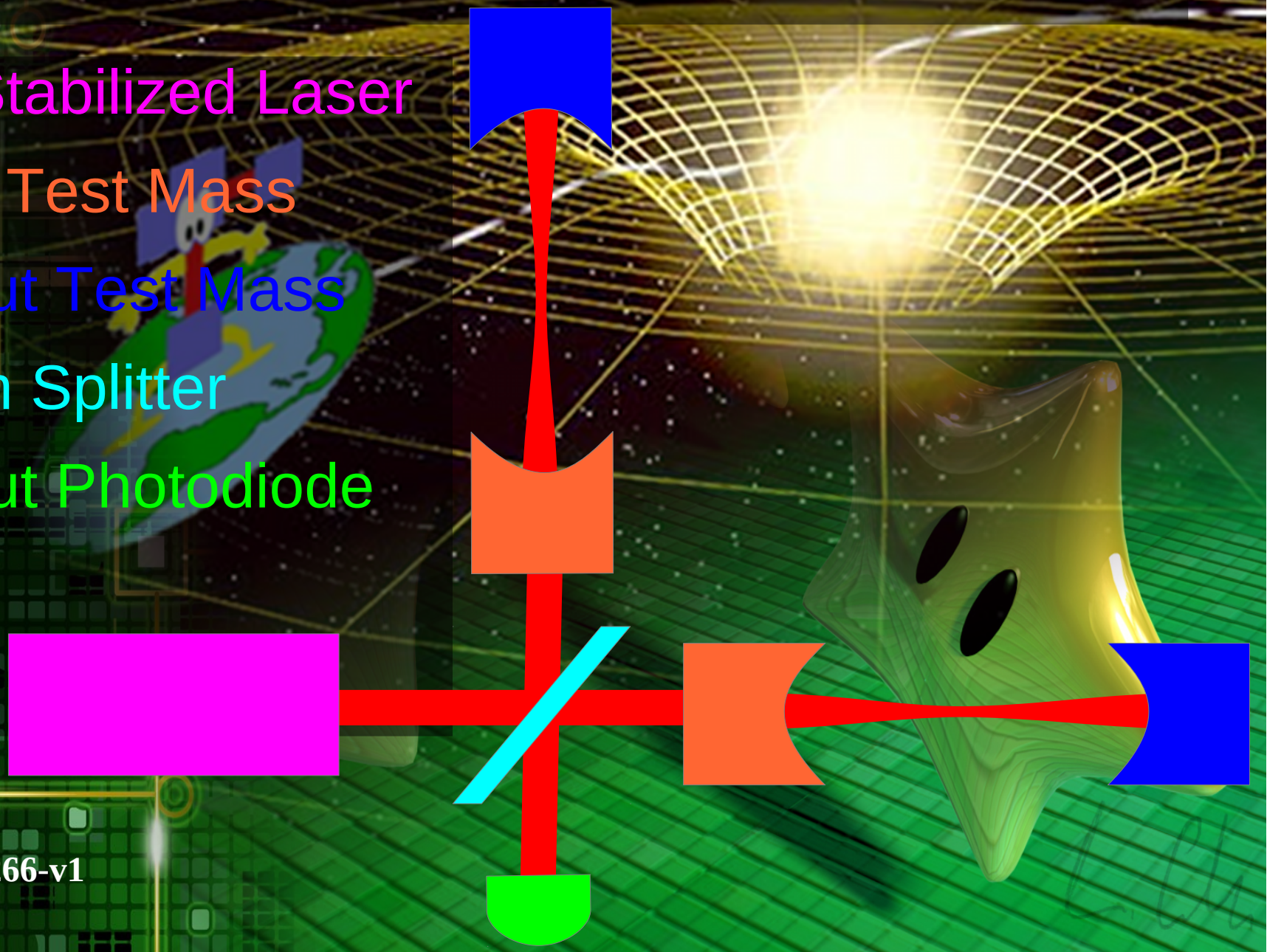
- GW Signals cause *differential* space-time distortion
- Polarizations
  - Cross “x”
  - Plus “+”
- Wave Properties
  - Transverse
  - Speed of light





Interferometric GW Antenna

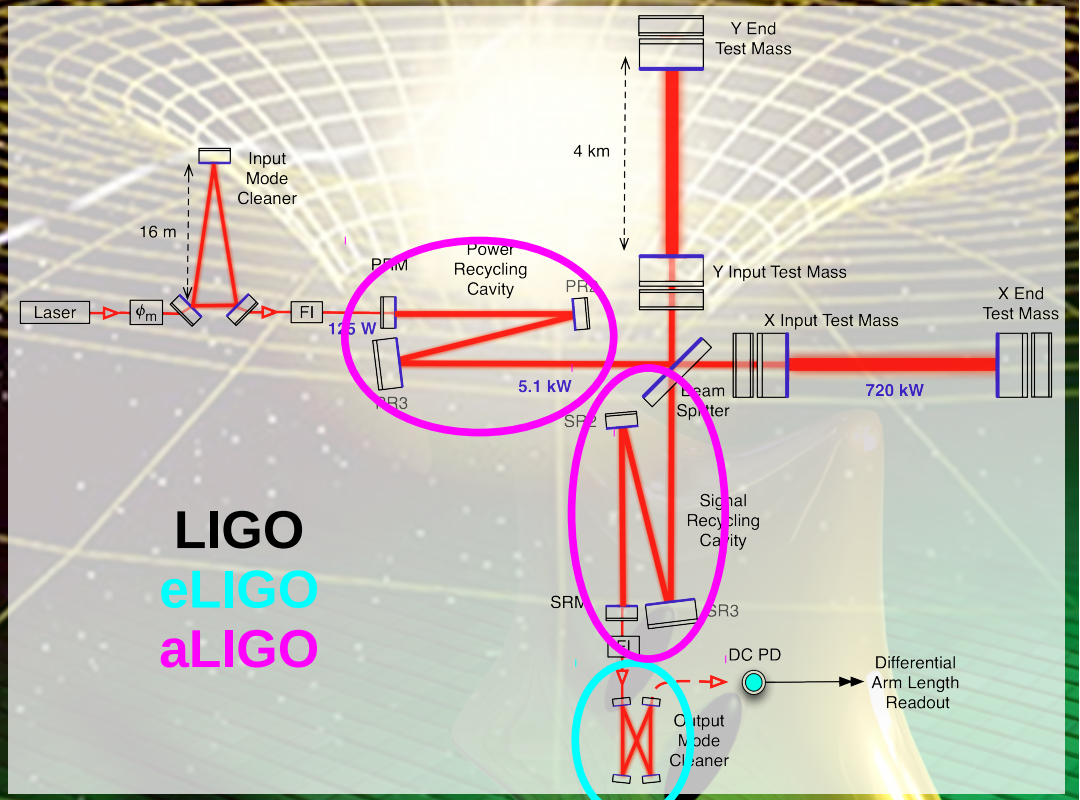
- Pre Stabilized Laser
- Input Test Mass
- Output Test Mass
- Beam Splitter
- Output Photodiode



More realistic detector

Fabry-Perot Michelson

- Instrument arms
  - Fabry-Perot cavities
  - Store light, increasing sensitivity
- Signal Recycling Optic
  - Increase power of resonant light
- Input mode cleaner
- Sensing differential motion has evolved



$$\frac{\Delta L}{L} \propto 10^{-23}, f \approx 100\text{Hz}$$

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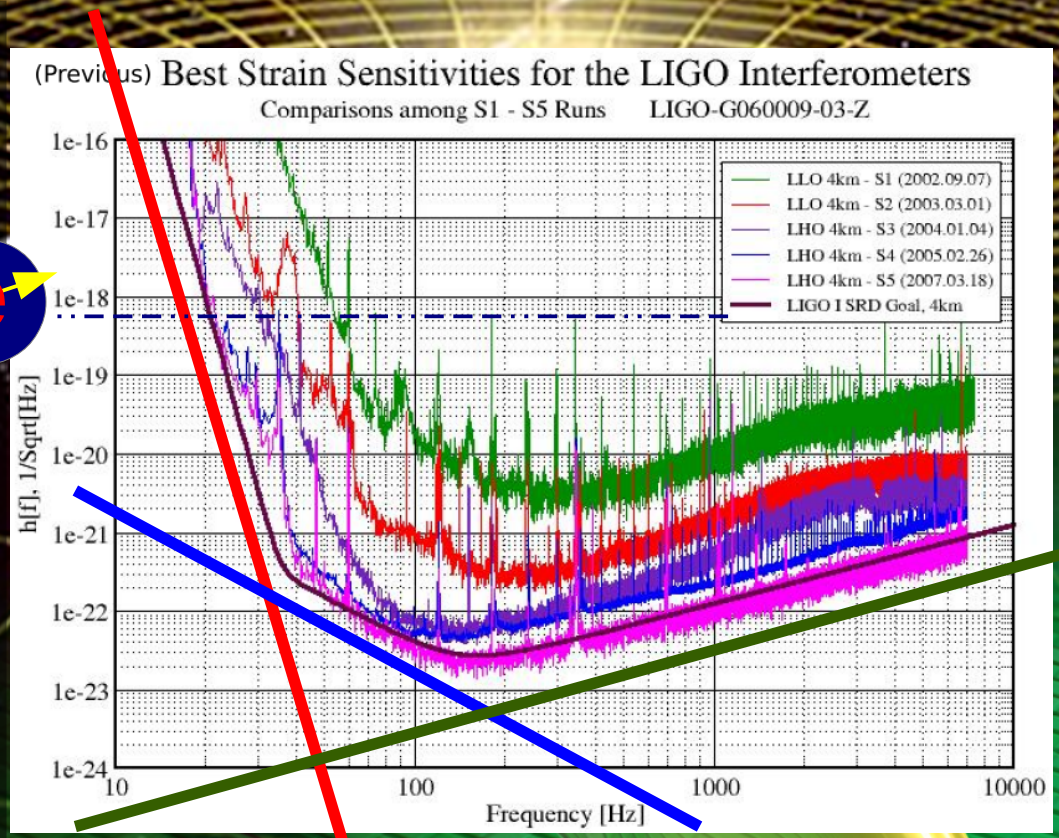
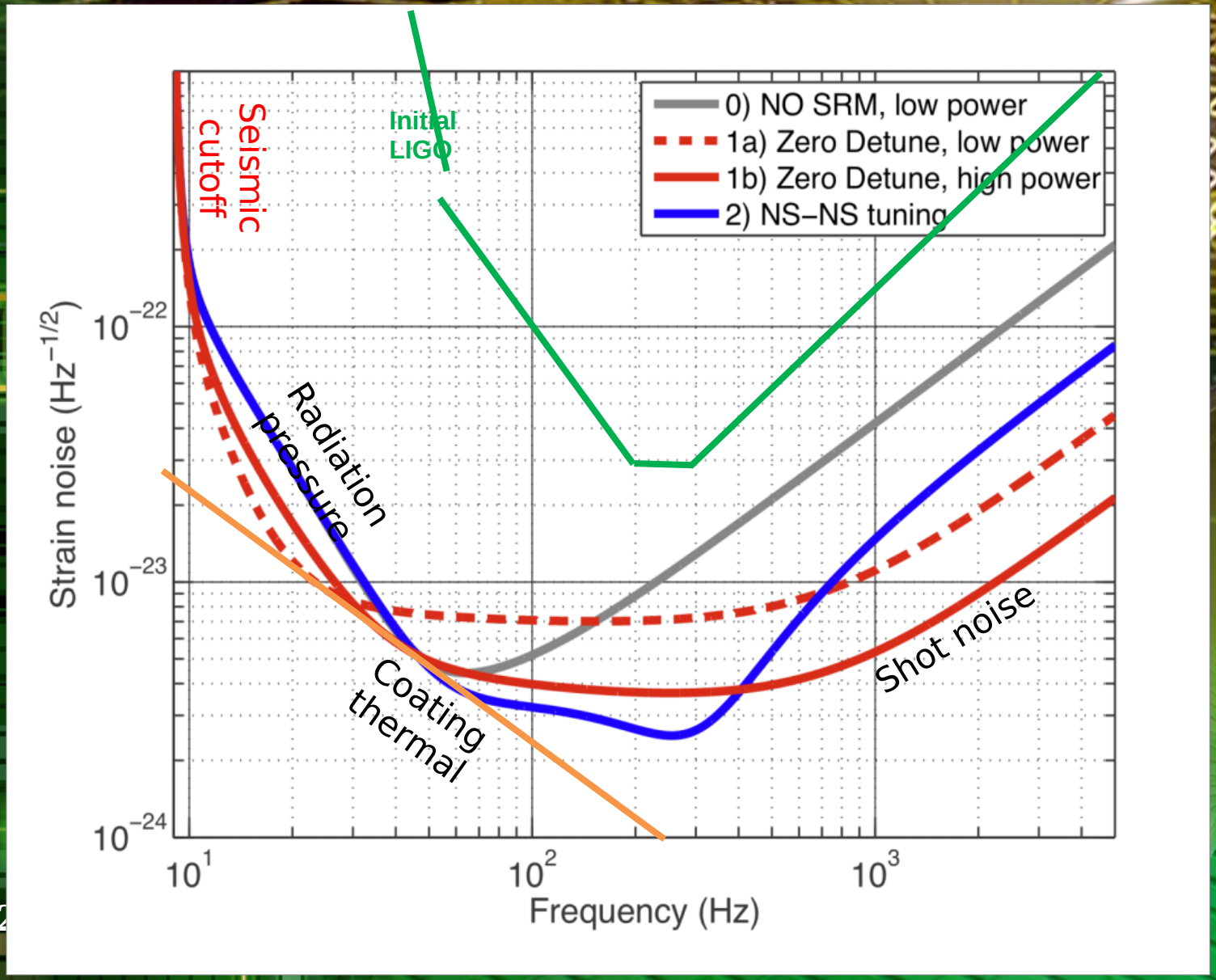
Detector Performance: Historical Perspectives

- Seismic Noise mechanical transmission of local ground motion to optics motion
- Suspension/Thermal Noise thermally induced vibration agitation affecting optic motion
- Shot Noise randomized photo arrival times

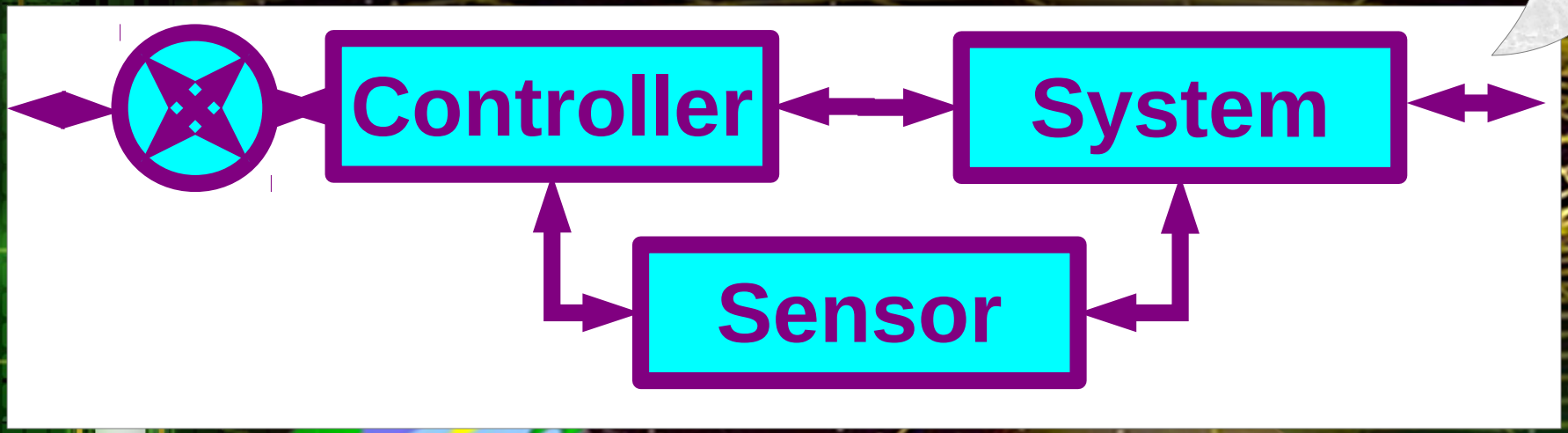


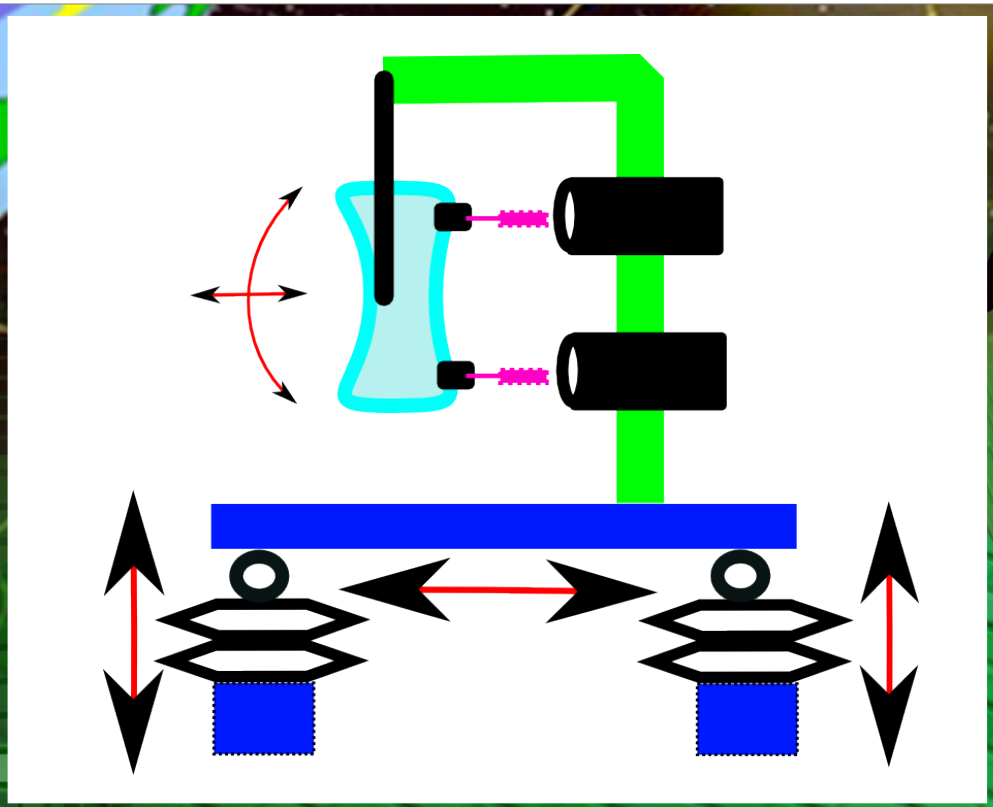
Milestones: 1999 Inauguration, S1 2003, Design Sensitivity 2005, eLIGO 2007, aLGIO Components Install Completed 2014, .., ?

Detector Evolution: Historical Perspectives

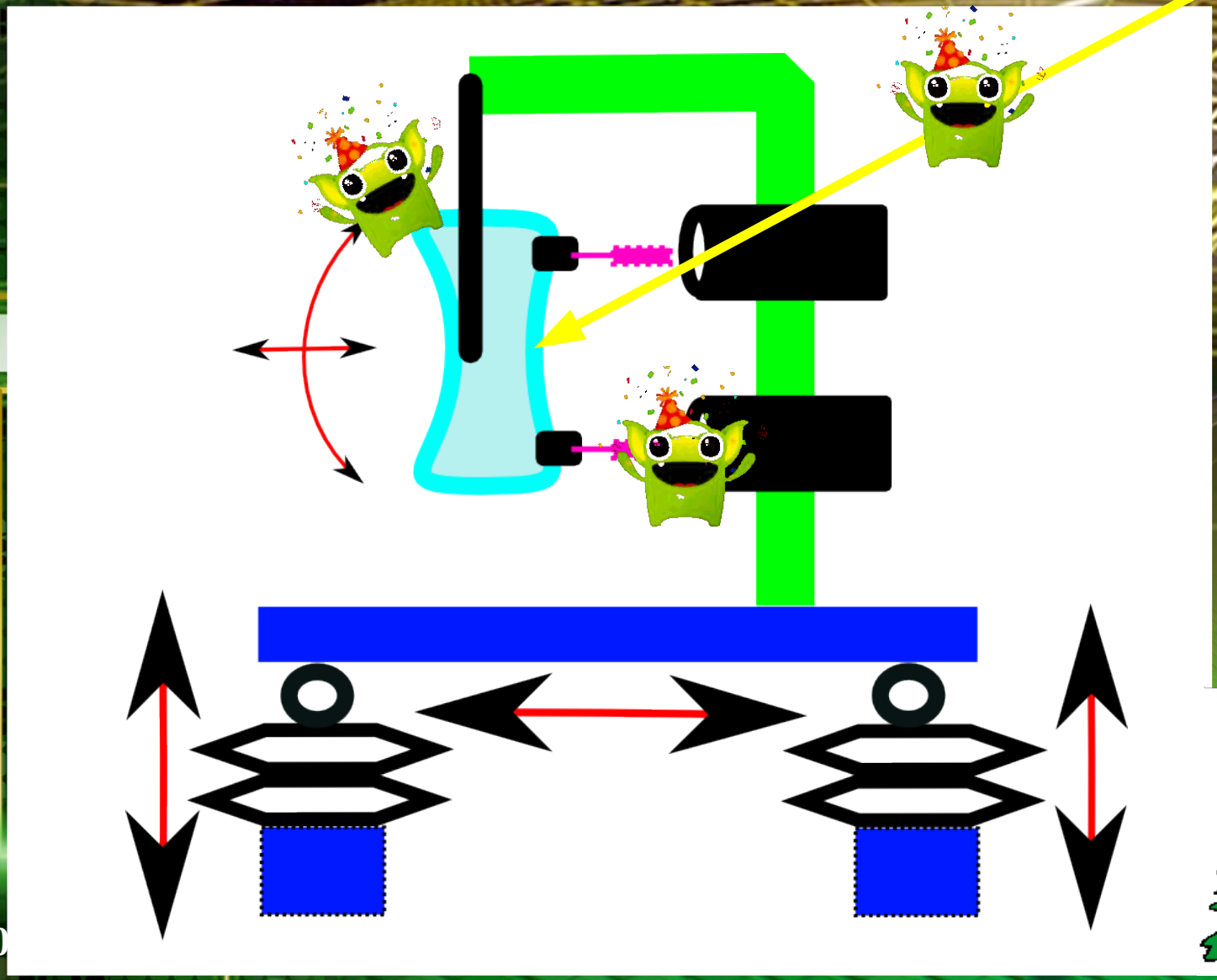


Instrumental Controls

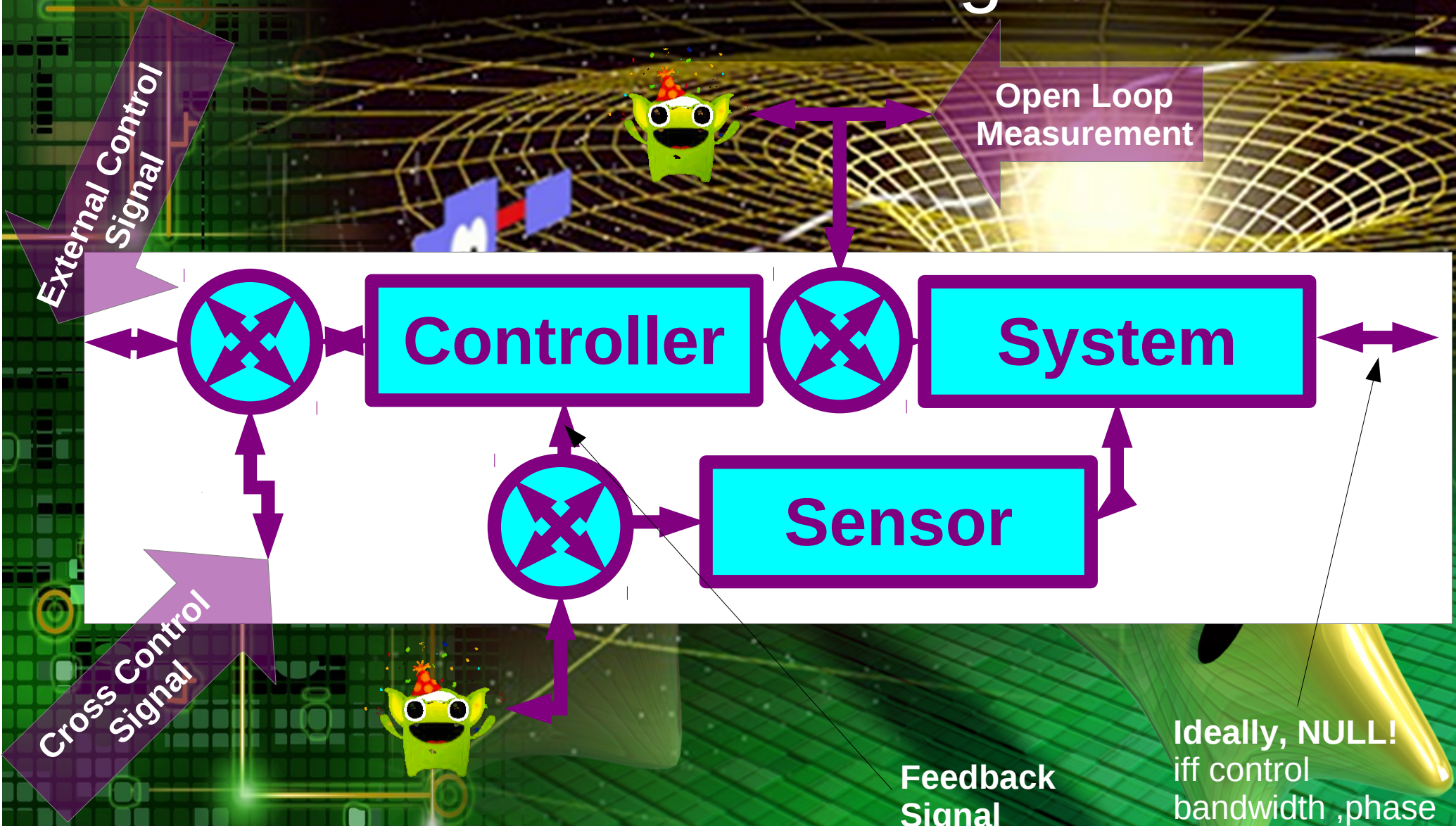




Real Instrumental Controls

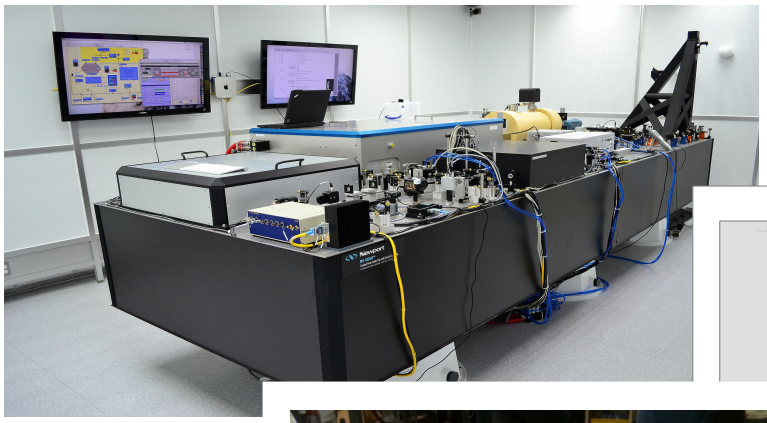


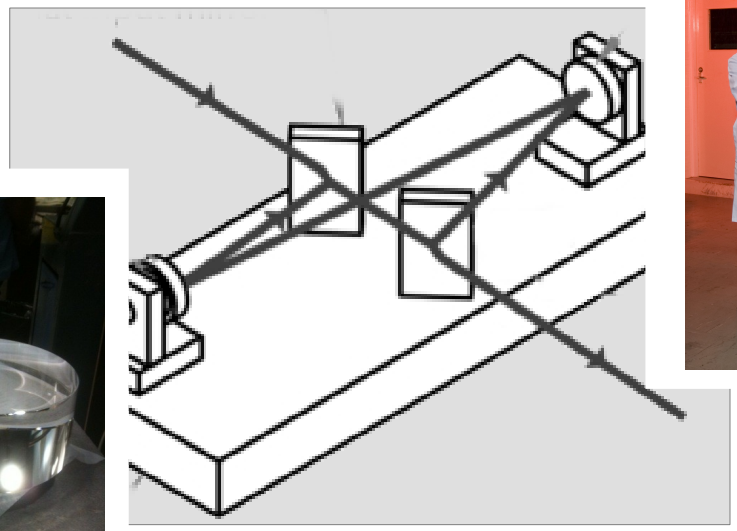
Real Controller Configurations



Cutting Edge Detector Technology

	Laser	Mirrors	Layout	Readout	Seismic	Software
iLIGO	10 W 10 kW	10 kg	Power Recycling	Hetero-dyne RF	Single Pendulum	Off-line analysis
aLIGO	180 W 700 kW	40 kg	Dual Recycling	Homo-dyne DC	FF + Multi Pendulum	Real-time^{+} analysis





Gravitational Wave Detection Theory vs Practice

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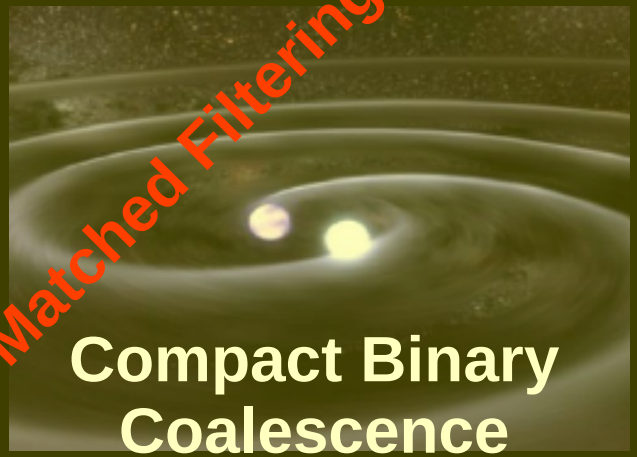
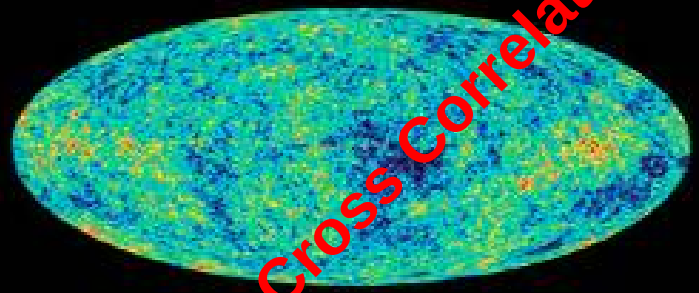
Sources for ground based detectors

Short Duration to Long Duration Signals

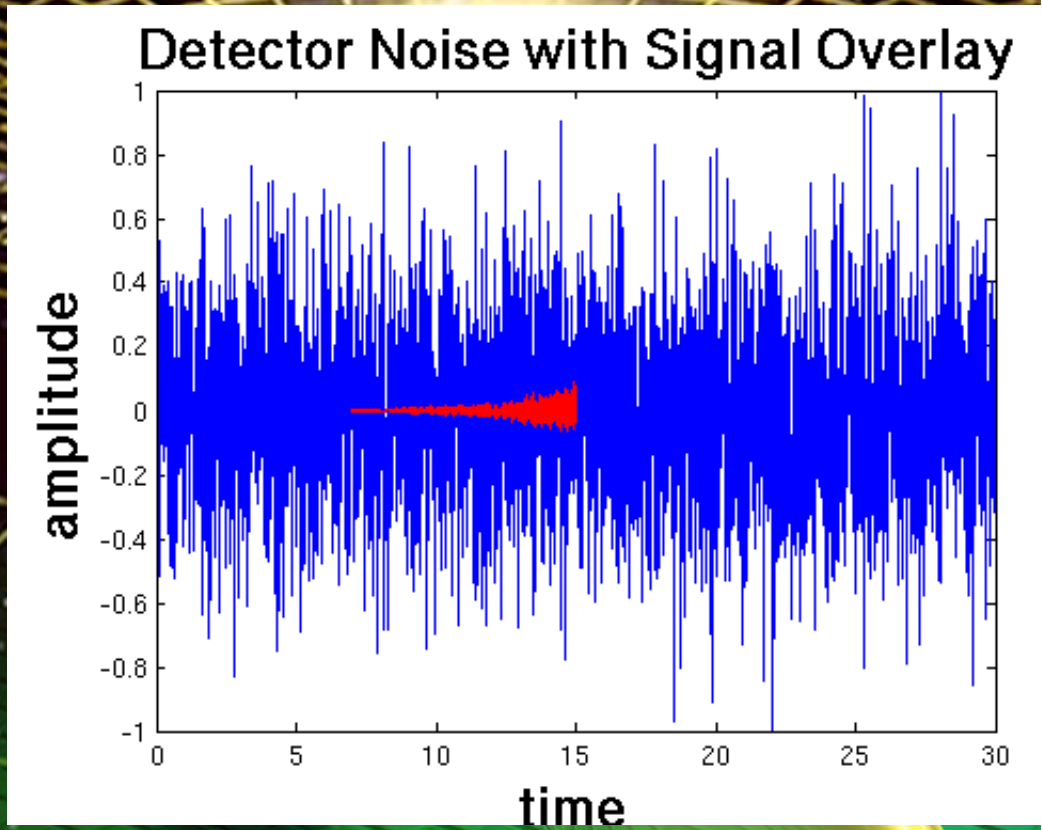
Unknown Waveform to Known Waveform





Compact Binary Coalescence

- Use theoretical knowledge to construct signal models
- Compare models to observatory data
- Account for environment
- Compare common interesting events
- If events pass criteria...



DETECTION

Matched filtering

- Is waveform in data?
- Stationary noise
  - SNR direct measure of significance
  - Integral maximum if $\tilde{s}(f)=\tilde{h}(f)$
- Non-stationary noise
  - Significance measures function of time

$$z_m(t)=4\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} e^{(2\pi f t)} df$$

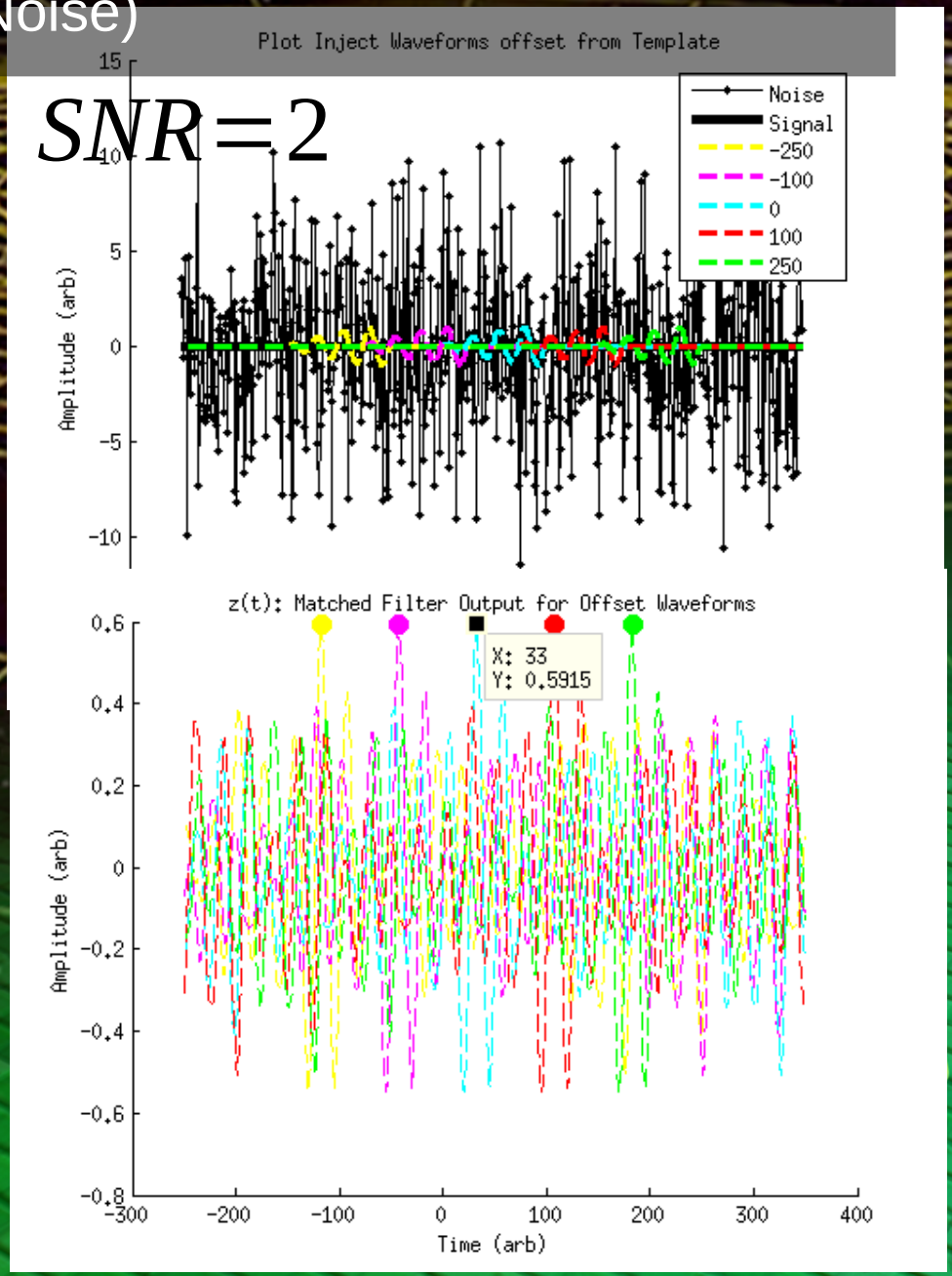
$$\sigma_m^2=4\int_0^\infty \frac{|h_{1\,Mpc,m}(f)|^2}{S_n(f)\,df}$$

$$\rho_m(t)=\frac{|z_m(t)|}{\sigma_m}$$

Filtering Complications

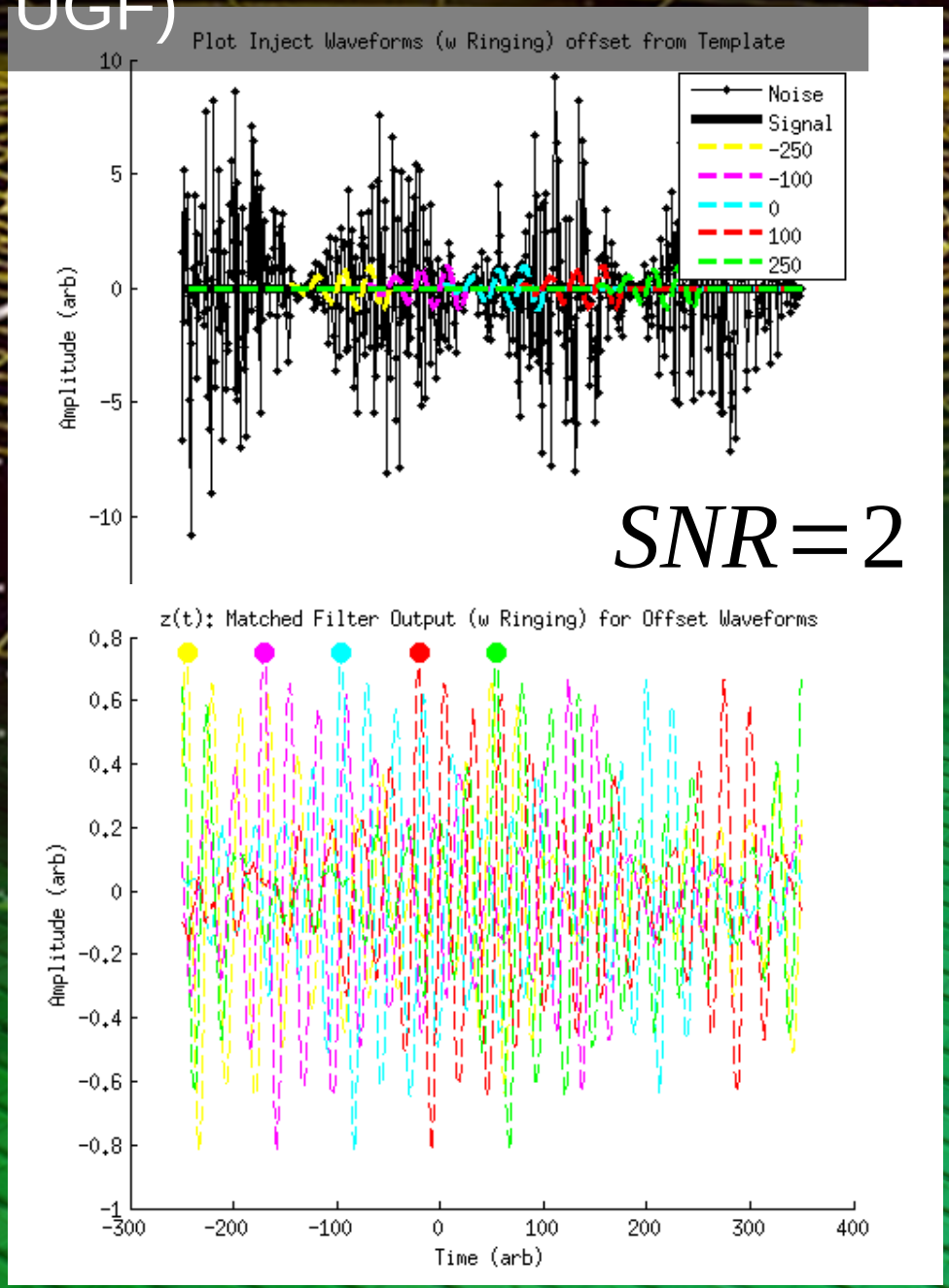
(White Noise)

- Critical Assumptions
  - Stationary Noise
  - Signal properties well understood
- Real Noise
  - Limited stationarity epochs
  - Noise impulses, "ring"
  - Unknown "color"
- Signal
  - Signal waveforms "discretized" (gaps)
  - Initial phasing unknown



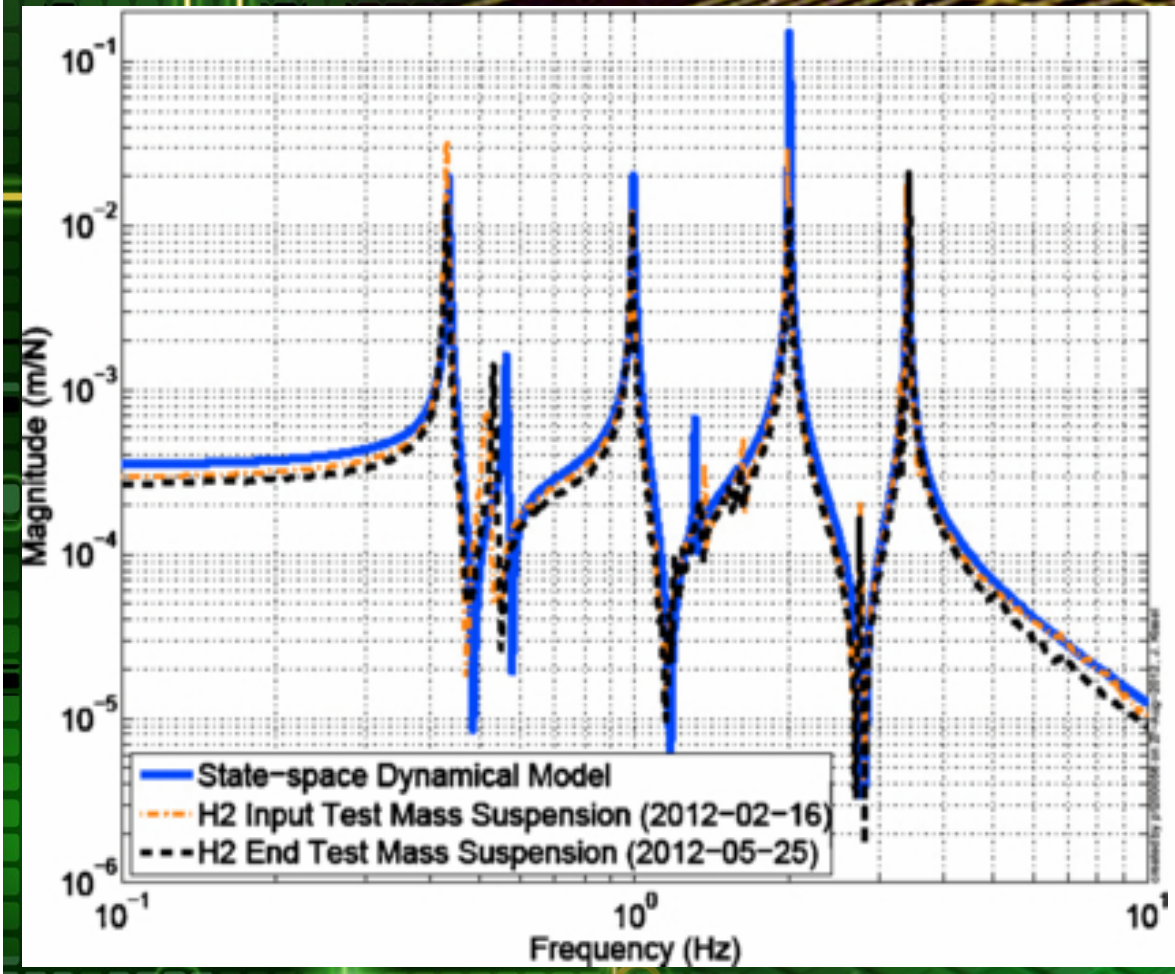
Filtering Complications
(Unstable UGF)

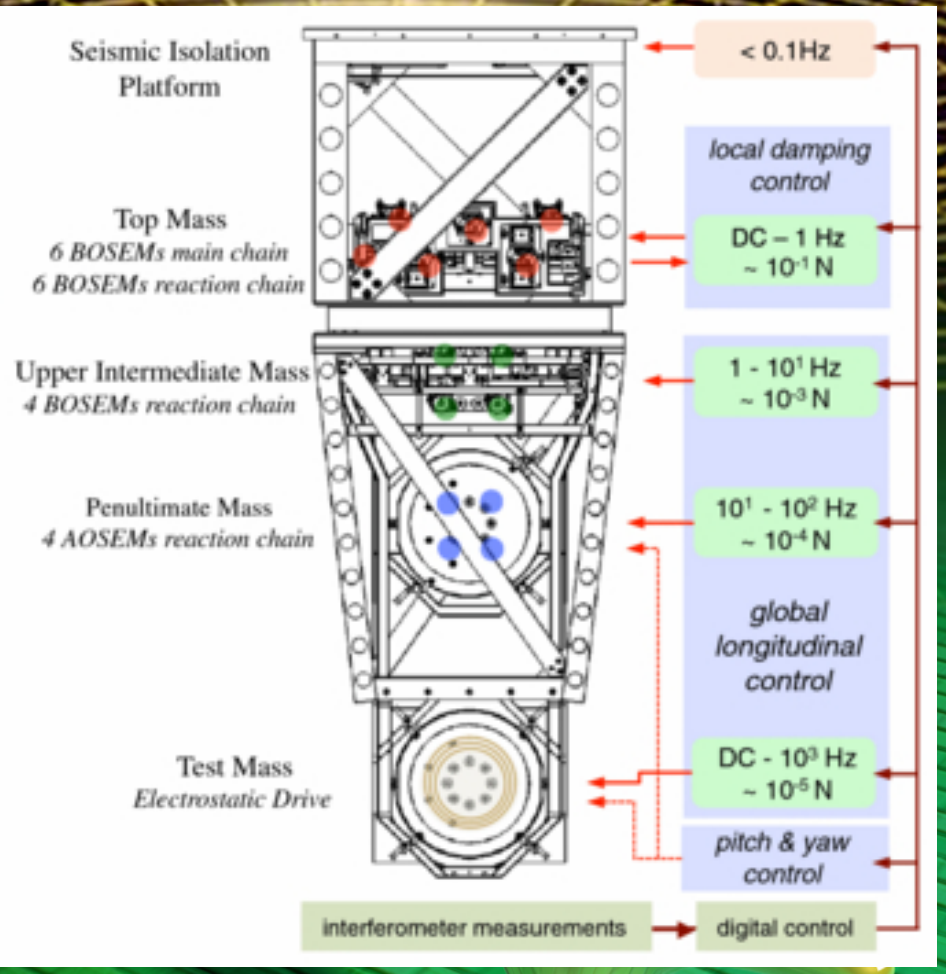
- Critical Assumptions
  - Stationary Noise
  - Signal properties well understood
- Real Noise
  - Limited stationarity epochs
  - Noise impulses, "ring"
  - Unknown "color"
- Signal
  - Signal waveforms "discretized" (gaps)
  - Initial phasing unknown



Detector Characterization

Understanding “real” noise sources





L. Carbone et al (CQG, 2012)

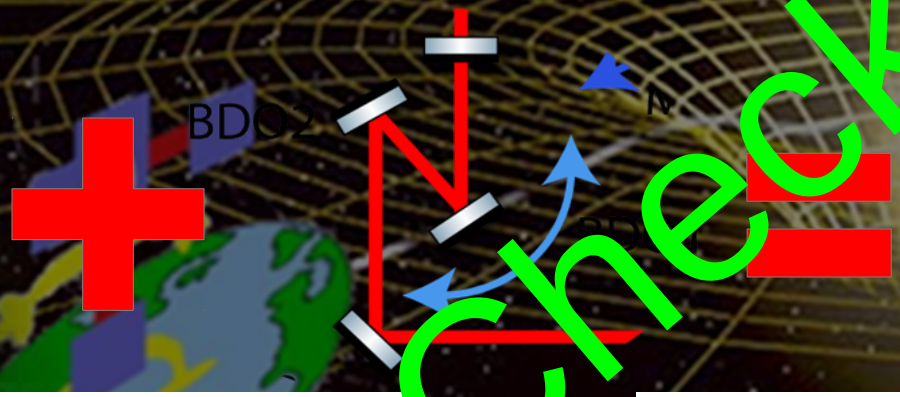
Detector Characterization

Understanding “real” noise sources

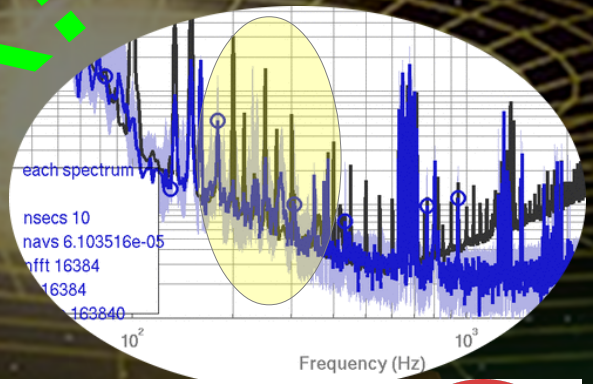
- Techniques:
  - Automatic monitoring
    - Identifying damping loop limits/stability
    - Monitoring external correlations to output
  - Manual monitoring
    - **Onsite instrument scientists**
    - Instrumentalist and analyst electronic logbook

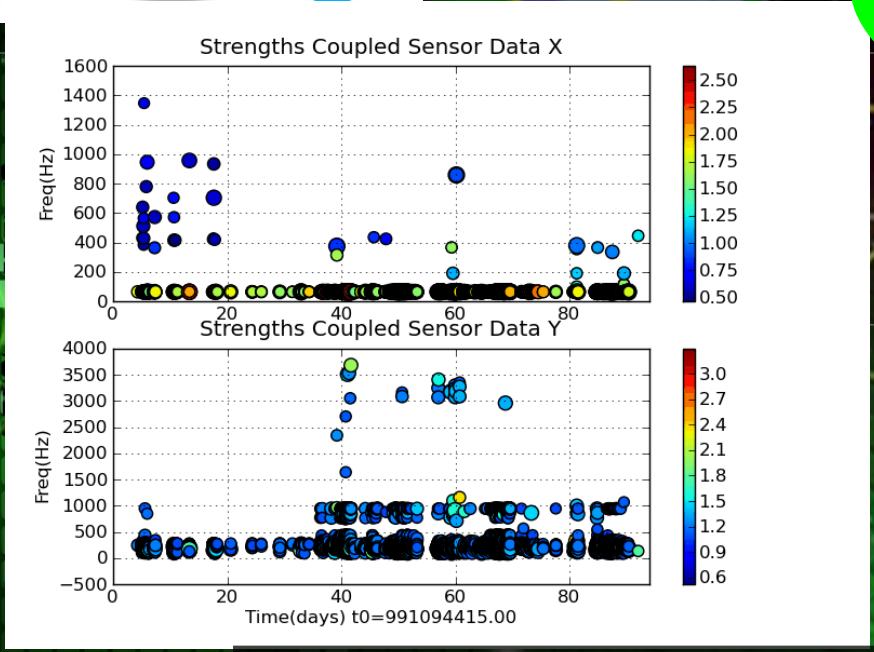
- 10,000s degrees of freedom for Advanced detectors
- Existence of correlated noises?
- Physical intuition still key component of work!

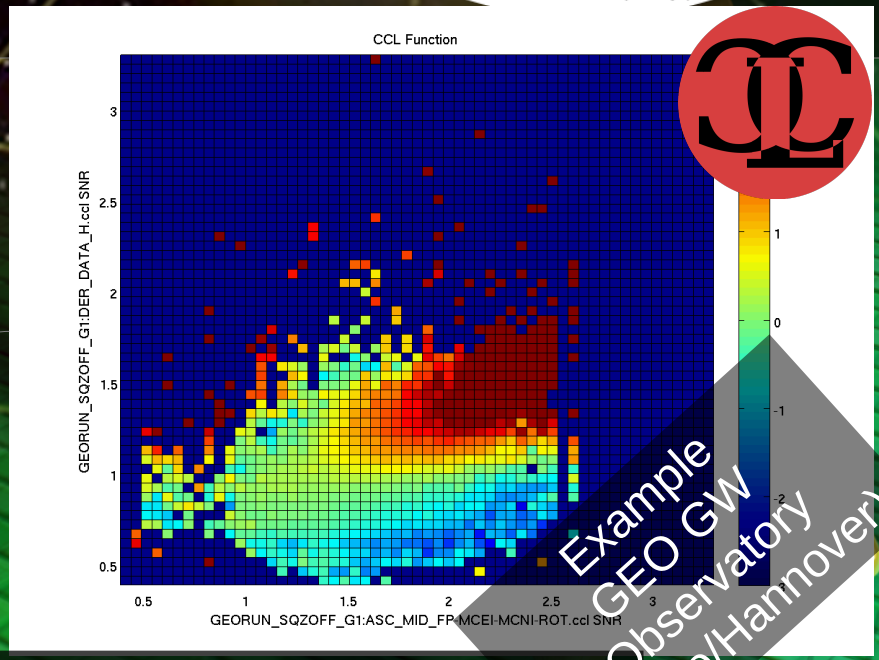
“Practicing” Detector Characterization



Check!







Example GEO GW Observatory (Ruthe/Hannover)

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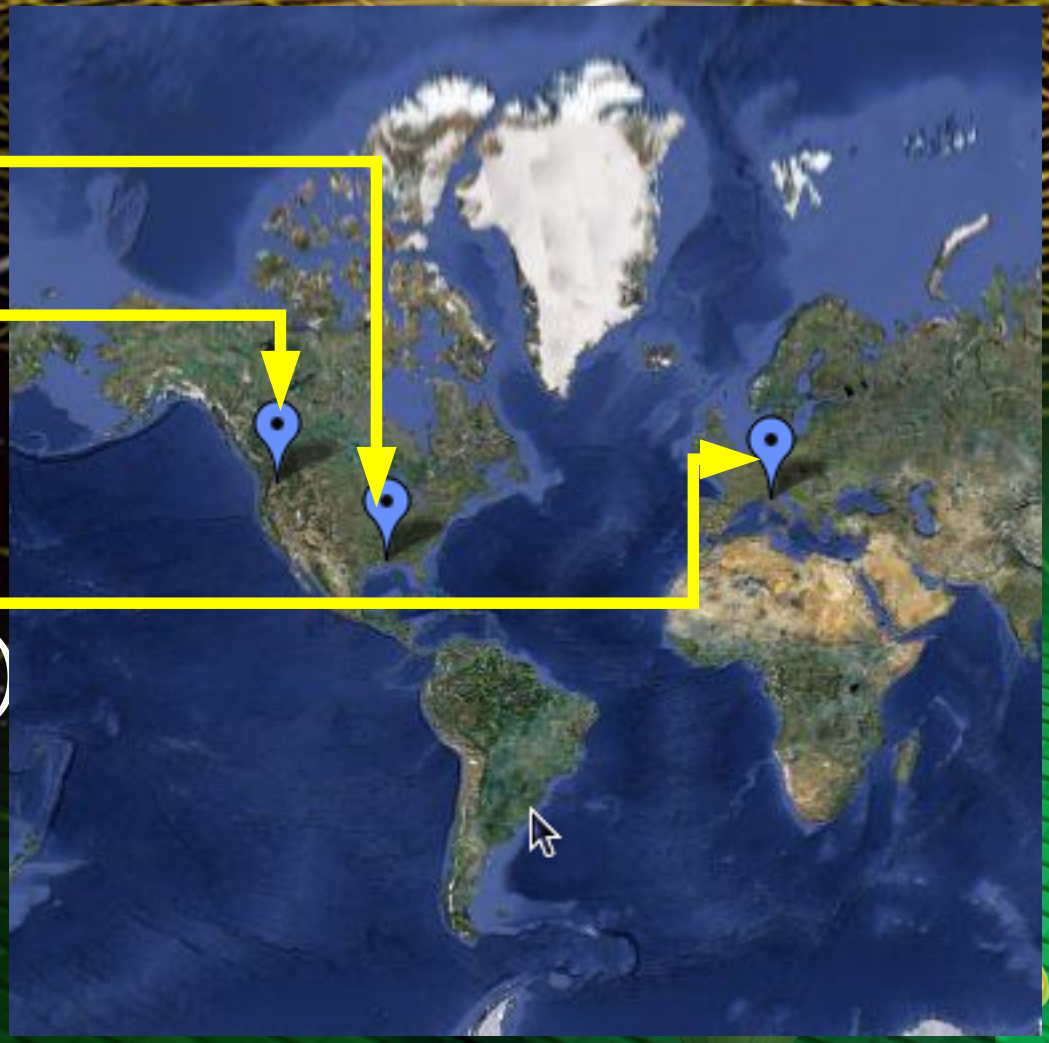
Pseudo-Transfer Function :abs(T(f))

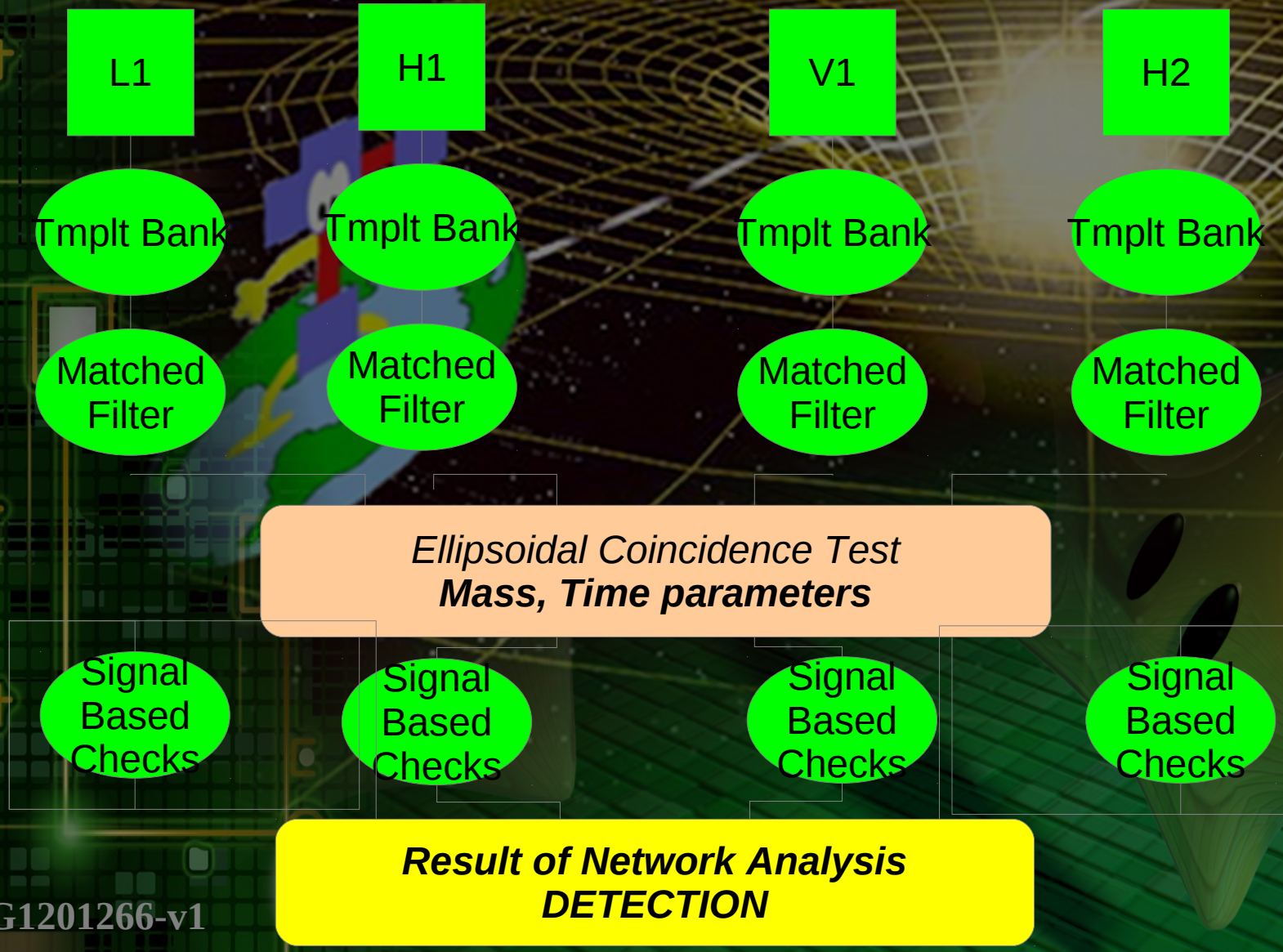
Global GW Detector Network

- LIGO (United States)
  - 4km (Livingston)
  - (4km & 2km) Hanford
- Virgo (French/Italian)
  - 3km (Cascina)
- GEO (German/British)
  - 600m (Sarstedt)
- TAMA (Japan)
  - 300m (Tokyo)
  - LCGT

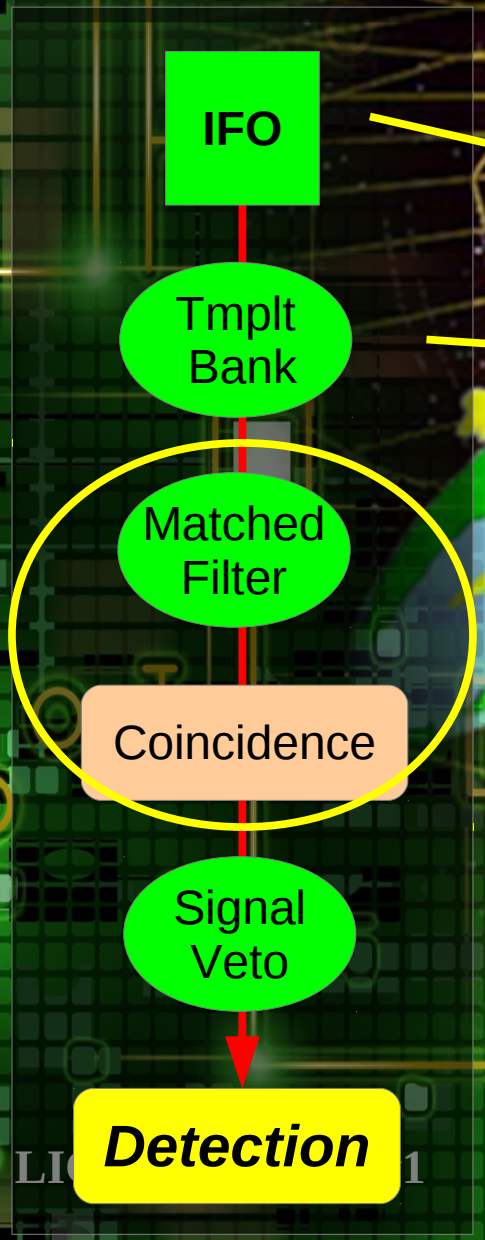


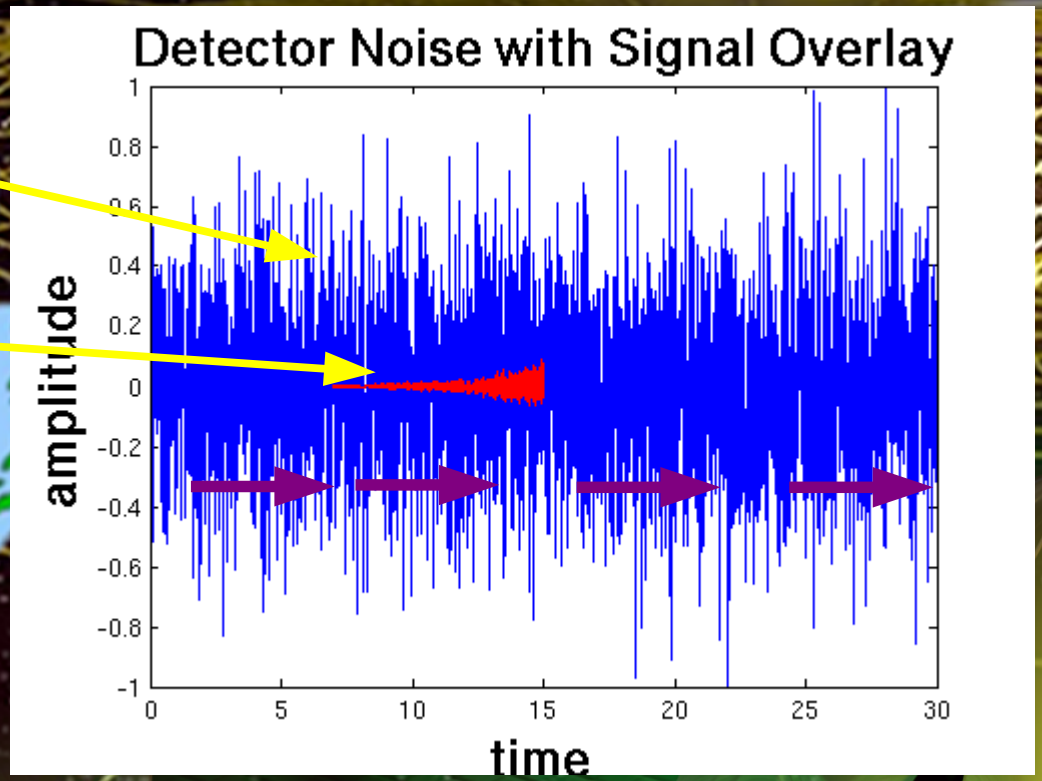
High Performance Computing

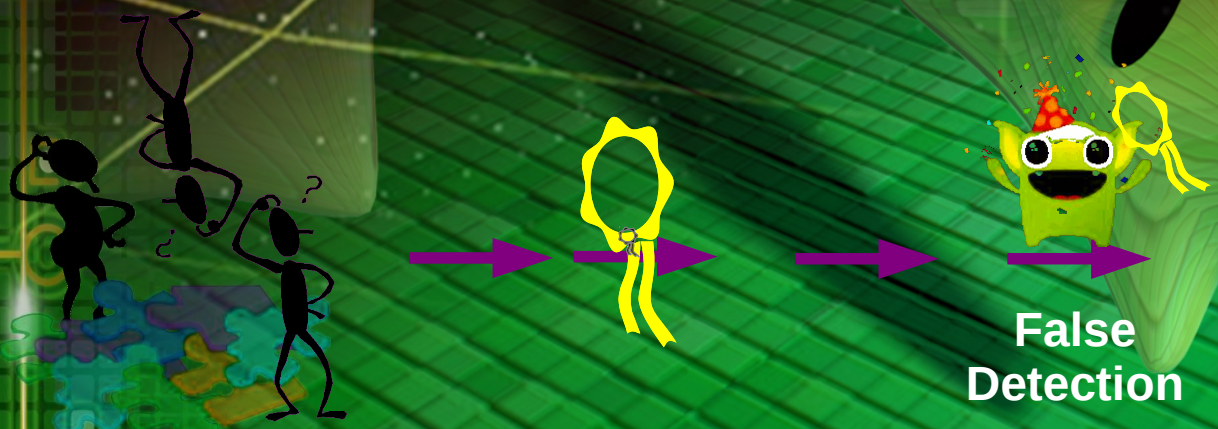
LIGO Data Grid



Example search infrastructure: IFO







Gravitational Wave Astronomy: Climbing through that newly opened window

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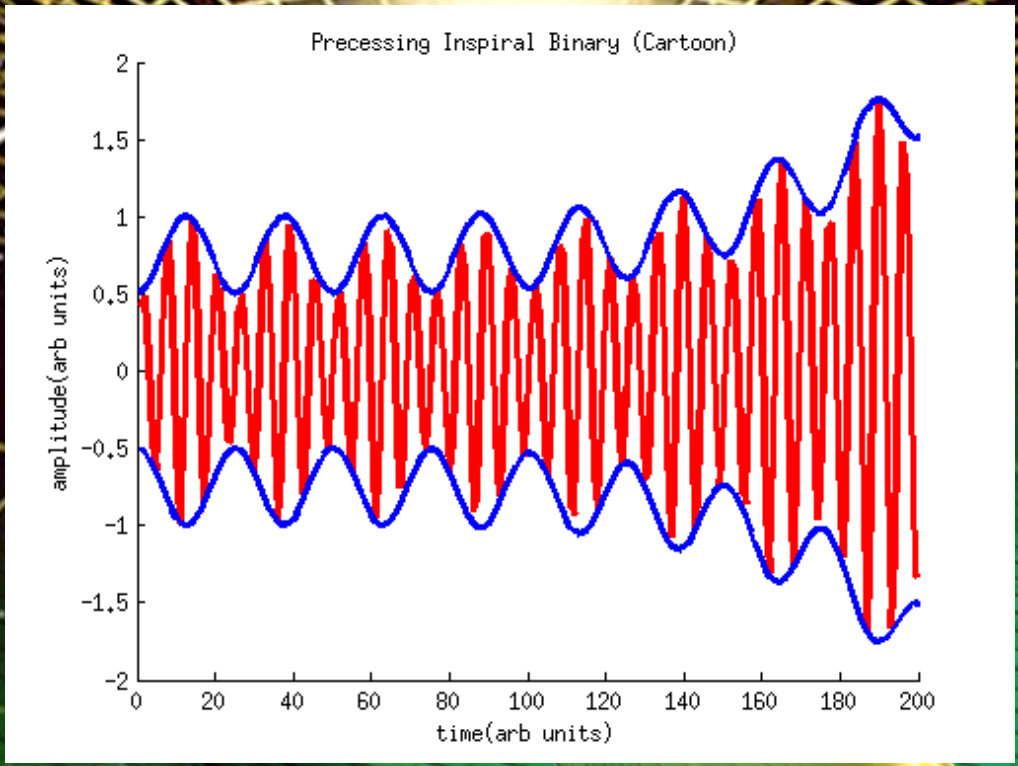
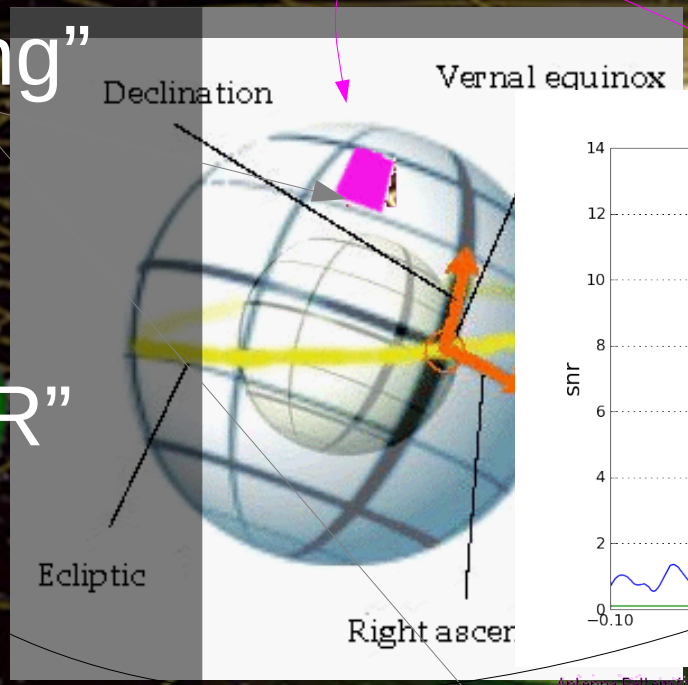
Astrophysics: Parameter Estimation

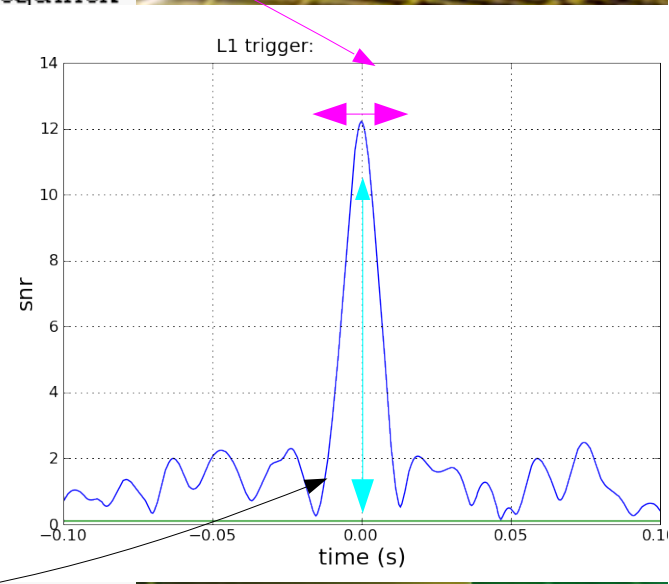
- Talk about CBC estimations
  - X-Ray Binary
    - Microquasar (radio)
    - HMXB
  - NS NS mergers
- Impacts Stellar Dynamics
- Test of GR, or alternate theories

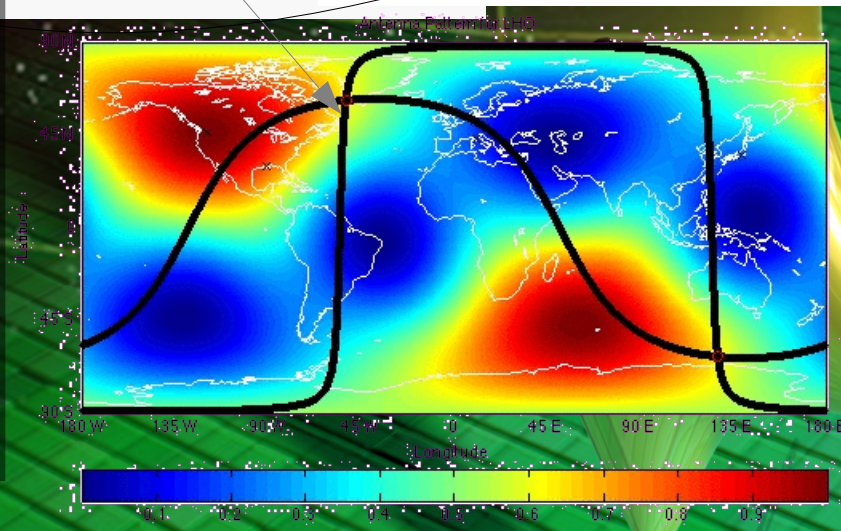


Errors in Sky Pointing and Distance

- Sky Pointing: “timing”
  - Template choice
  - Initial phase
- Est. Distance: “SNR”
  - Data quality
  - PSD estimates
- “Ignored” errors
  - Source polarization
  - “Simple” search assumptions







L1H1:H1V1
Effective Network Antenna Response

Sources for EM Counterparts

- Coalescing binaries
  - Neutron Stars Binary
  - NS – Black Hole
  - BH – BH
- Electromagnetic emission
  - accretion
  - kilonova
  - Unknown

Coordinating GW and EM Astronomy

- Transients
  - Visible afterglow
  - Post-facto wide field survey searches (think LSST archives)
- Fuller astrophysics
  - Internal dynamics (EoS)
  - Useful for constraining stellar dynamical models
- aLIGO
  - Real-time alerts (think GCN circular)
  - On-line source DB 'GraceDB'

TORUS

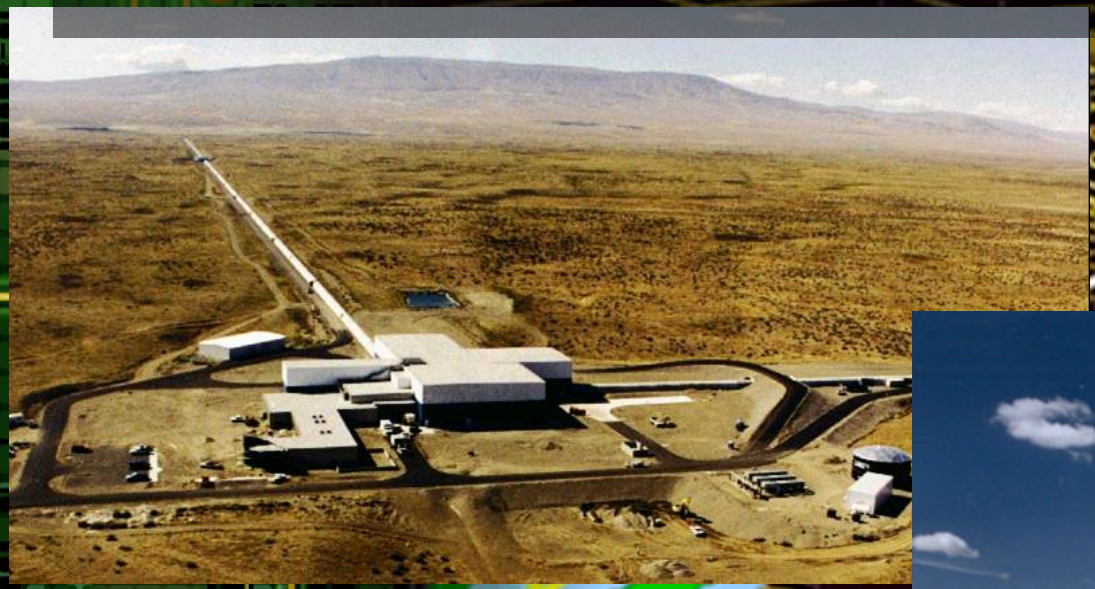
M45, The Pleiades
Baton Rouge Astronomical Society

STOP

Extra
Slides
Follow
Here

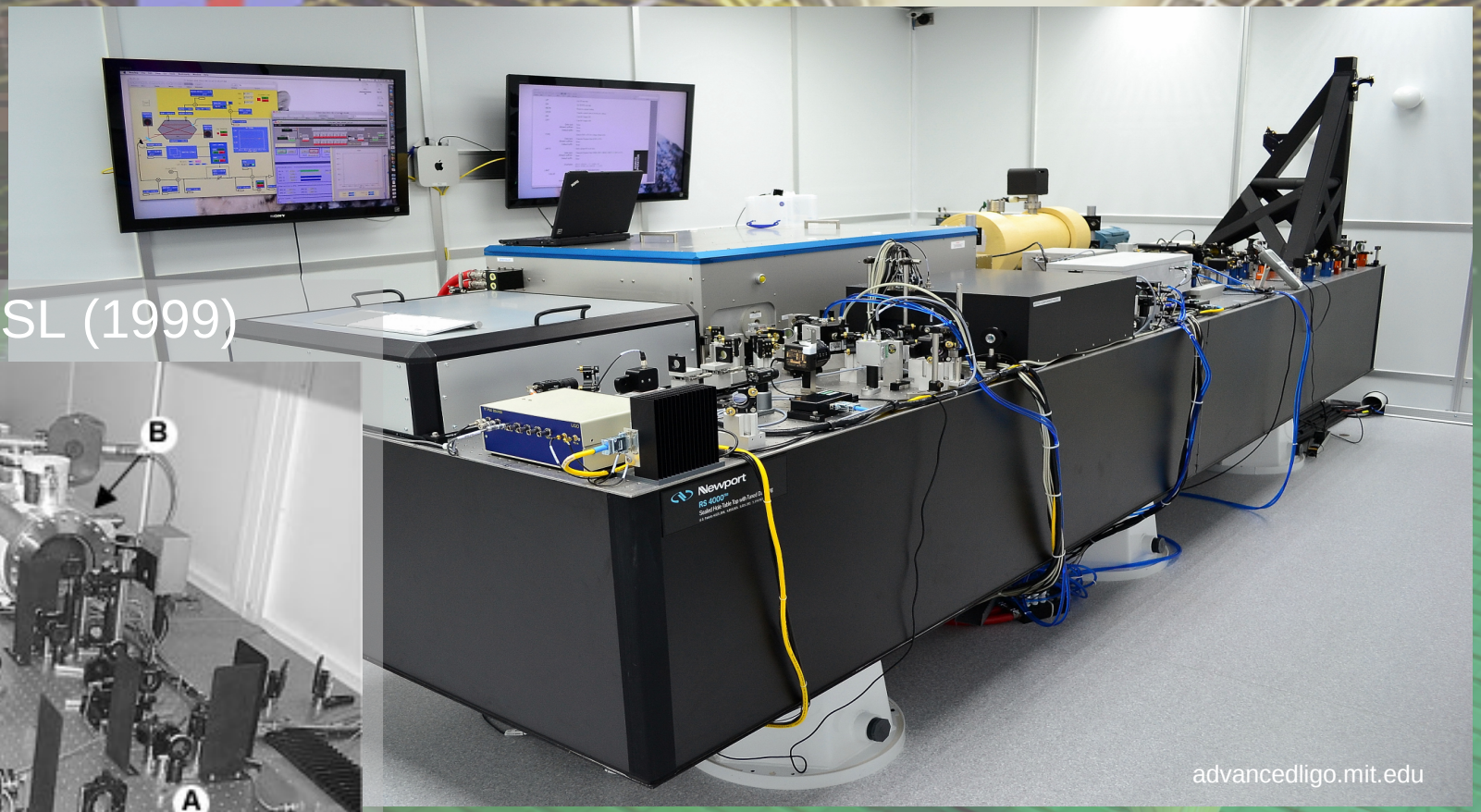
LIGO Livingston Observatory

LIGO Hanford Observatory

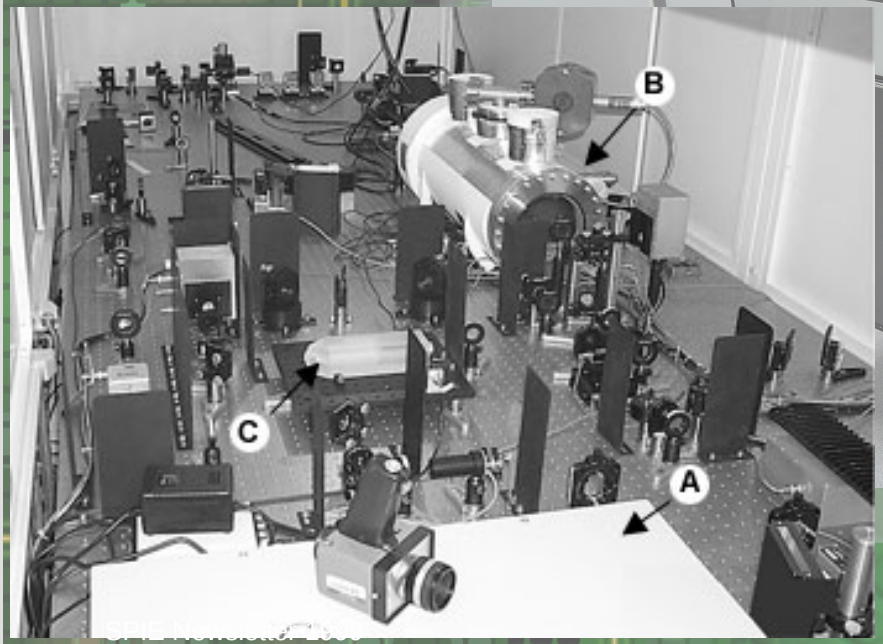


	Laser	Mirrors	Layout	Readout	Seismic	Software
iLIGO	10 W 10 kW	10 kg	Power Recycling	Hetero-dyne RF	Single Pendulum	Off-line analysis
aLIGO	180 W 700 kW	40 kg	Dual Recycling	Homo-dyne DC	FF + Multi Pendulum	Real-time^{+} analysis

Livingston 2k PSL (2011)



Hanford 2k PSL (1999)



	Laser	Mirrors	Layout	Readout	Seismic	Software
iLIGO	10 W 10 kW	10 kg	Power Recycling	Hetero-dyne RF	Single Pendulum	Off-line analysis
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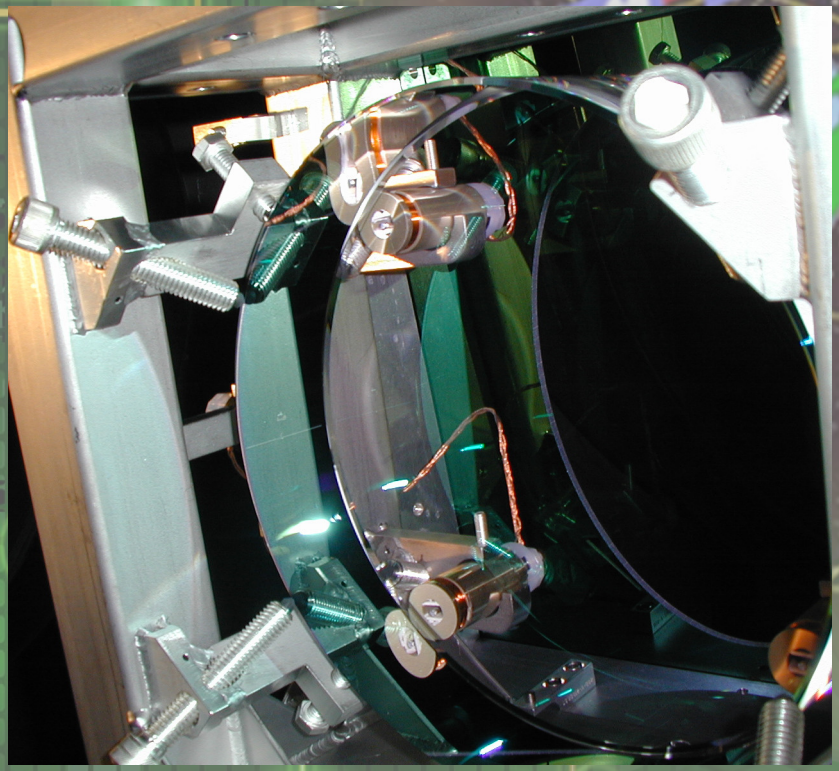
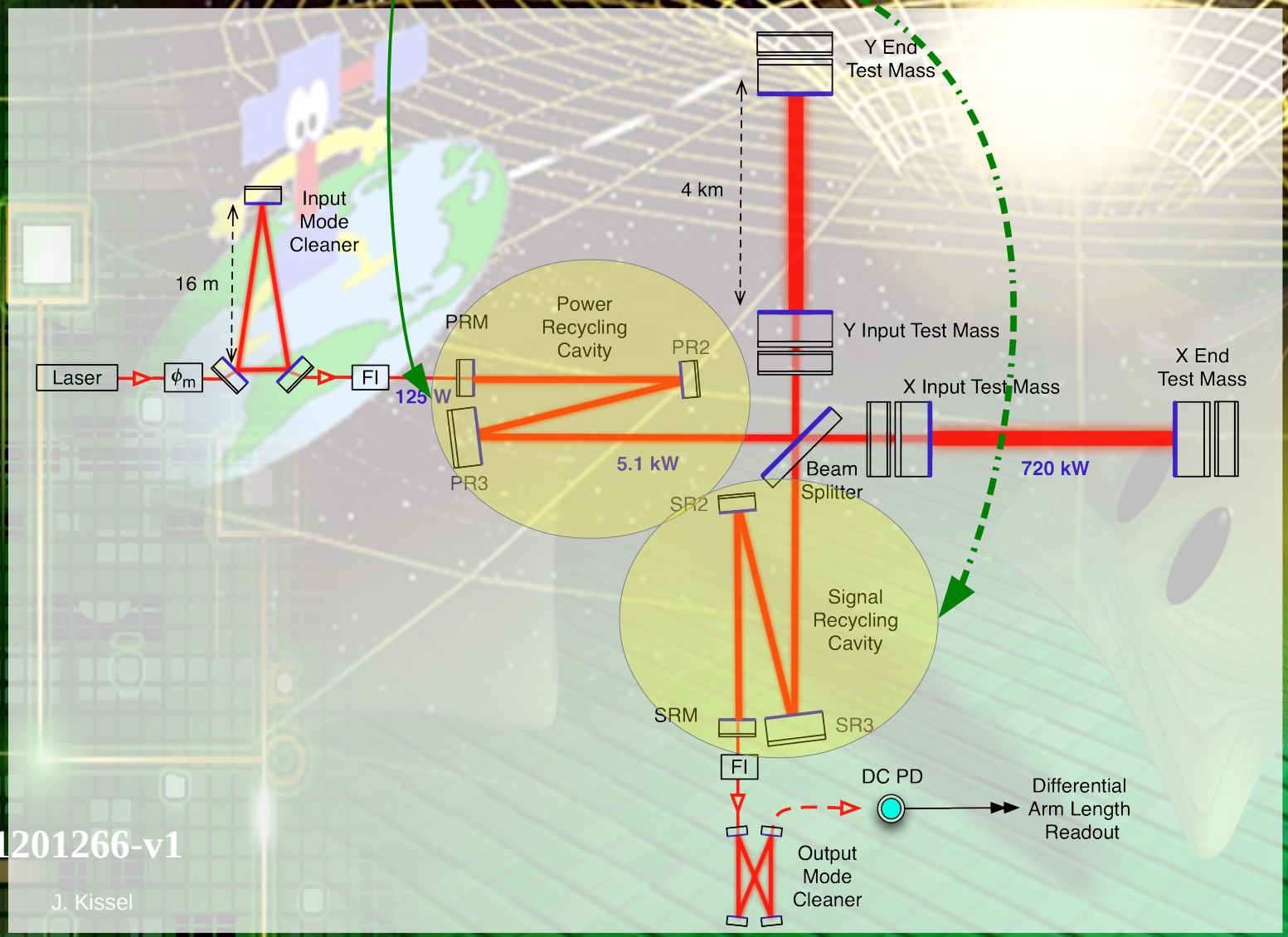
ITM Hanford iLIGO



aLIGO
ETM
Livingston

LIGO-G1201266-v1

	Laser	Mirrors	Layout	Readout	Seismic	Software
iLIGO	10 W 10 kW	10 kg	Power Recycling	Hetero-dyne RF	Single Pendulum	Off-line analysis
aLIGO	180 W 700 kW	40 kg	Dual Recycling	Homo-dyne DC	FF + Multi Pendulum	Real-time+ analysis



LIGO-G1201266-v1

J. Kissel

	Laser	Mirrors	Layout	Readout	Seismic	Software
iLIGO	10 W 10 kW	10 kg	Power Recycling	Hetero-dyne ★ RF	Single Pendulum	Off-line analysis
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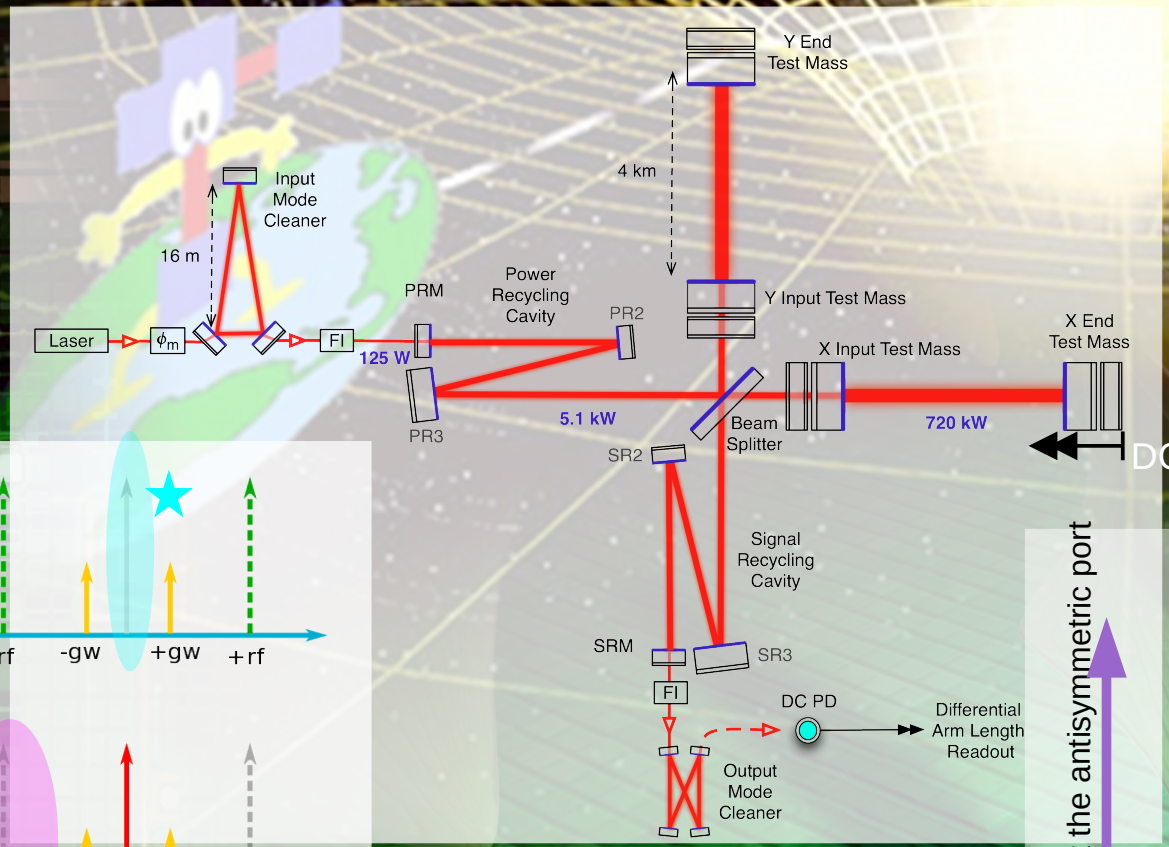

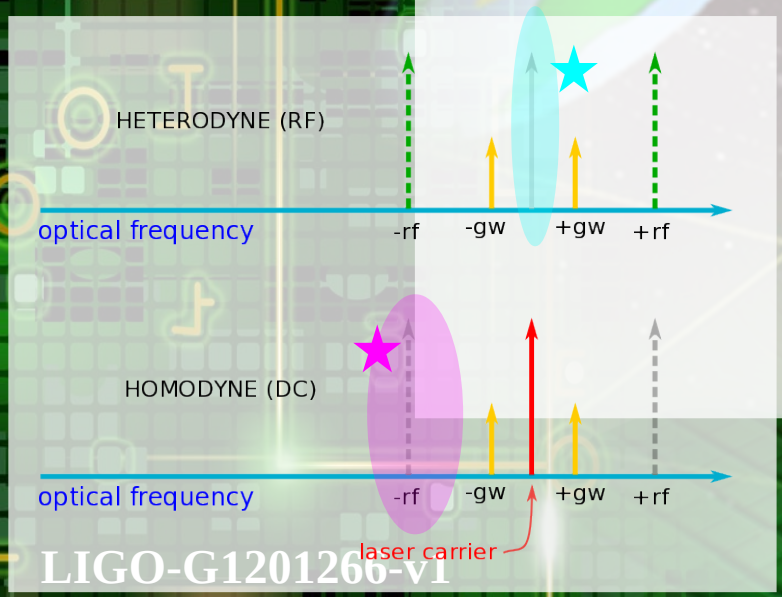

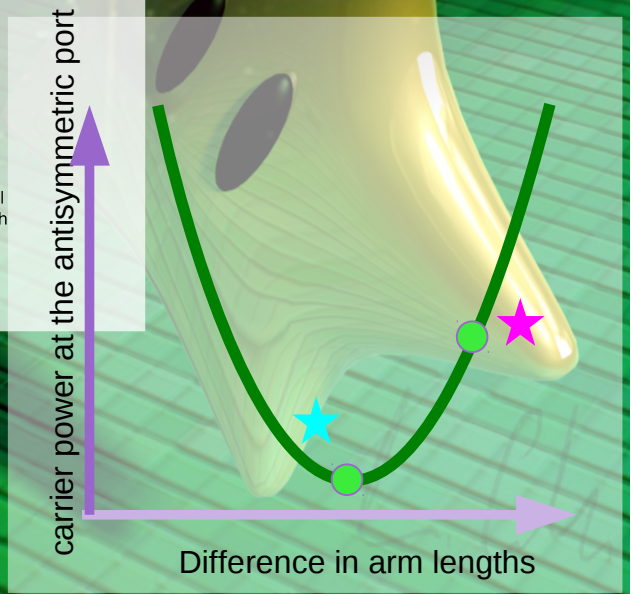

LIGO-G1201266-v1

	Laser	Mirrors	Layout	Readout	Seismic	Software
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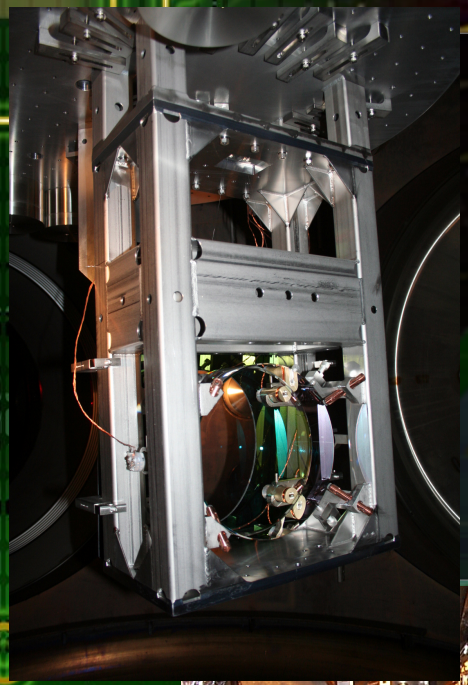
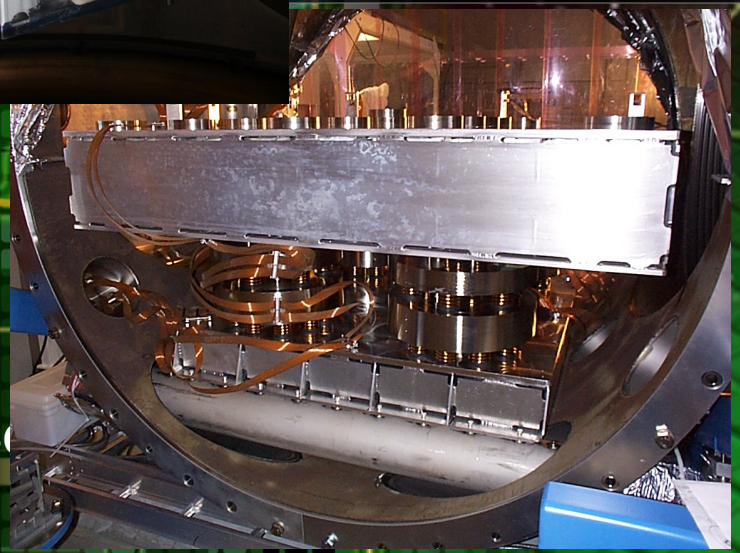


Single Stage
Pendulum
Active
Control

$$\propto \frac{1}{f}$$

Passive
Mass Spring
Damping Stacks



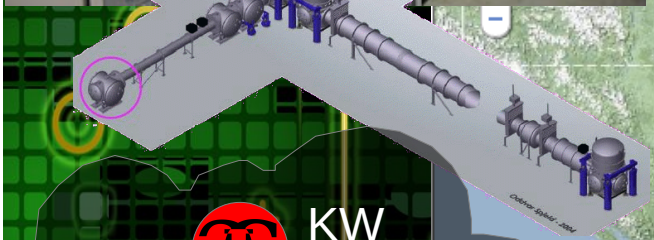
4 Stage
Pendulum
Mixed
Control

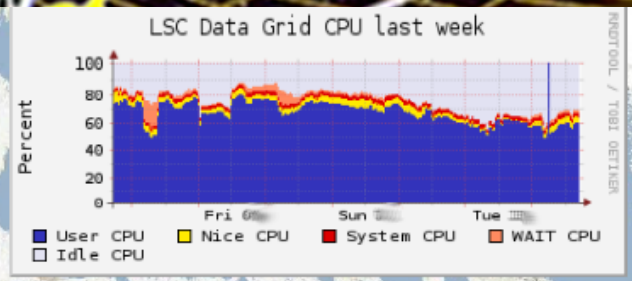
$$\propto \frac{1}{f^4}$$

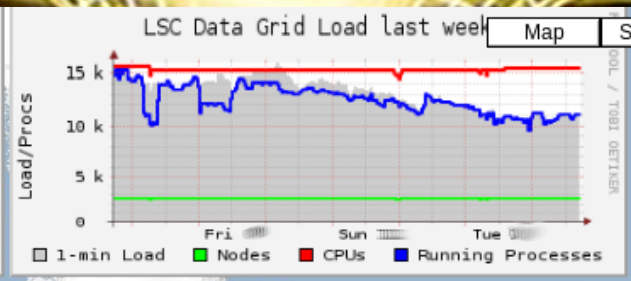
Active Payload
Isolation Table

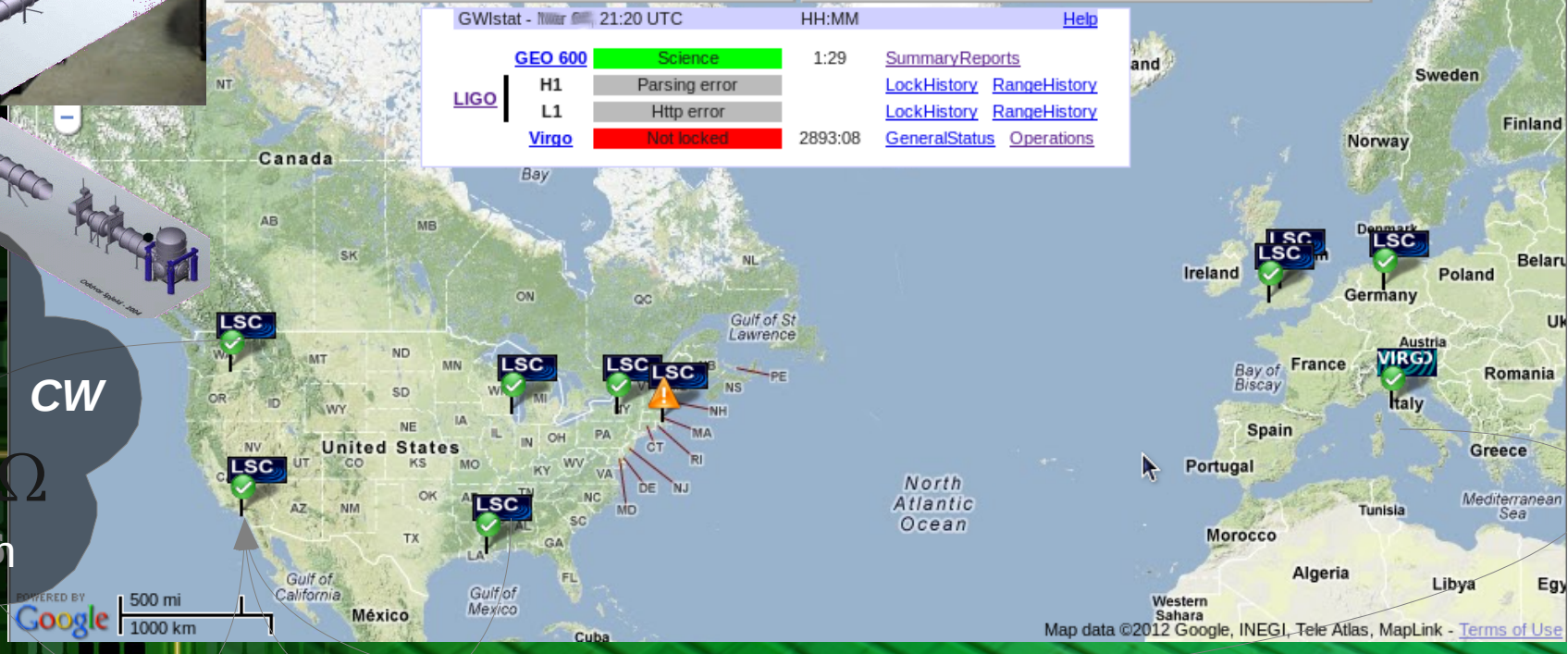
	Laser	Mirrors	Layout	Readout	Seismic	Software
iLIGO	10 W 10 kW	10 kg	Power Recycling	Hetero-dyne RF	Single Pendulum	Off-line analysis
aLIGO	180 W 700 kW	40 kg	Dual Recycling	Homo-dyne DC	FF + Multi Pendulum	Real-time+ analysis

Search Groups (4), Detector Characterization (1), Instrument Groups(3+)









KW

MVSC

. . .

cWB

CW

hVeto

iHope

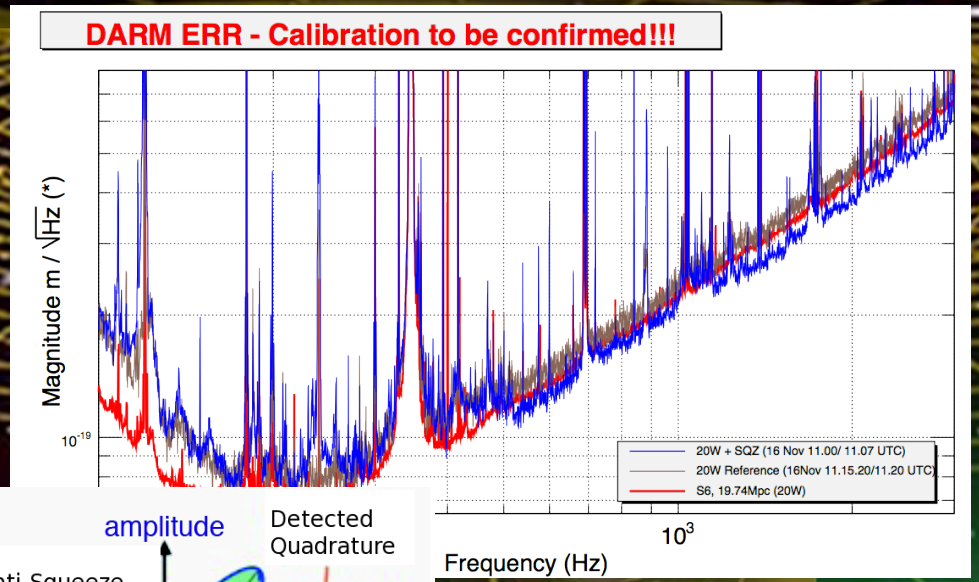
Ω

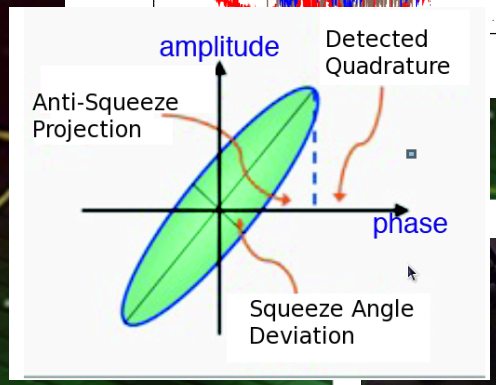
Ann

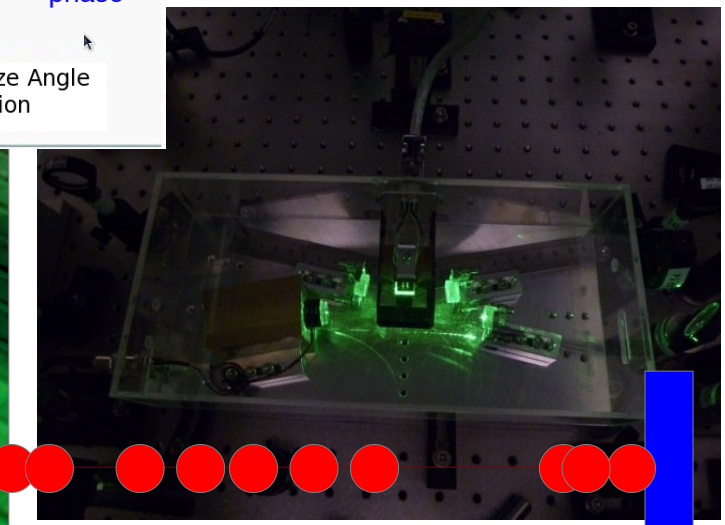
LIGO-G120[illegible]

Tweaking the Detectors

- Squeezing
  - Supress Counting Noise (Poisson)
  - Overcome 'quantum' uncertainties; trading
    - Phase noise
    - Amplitude noise
    - Requires 2nd laser
- Prototypes completed
- Tested at 600m GEO observatory



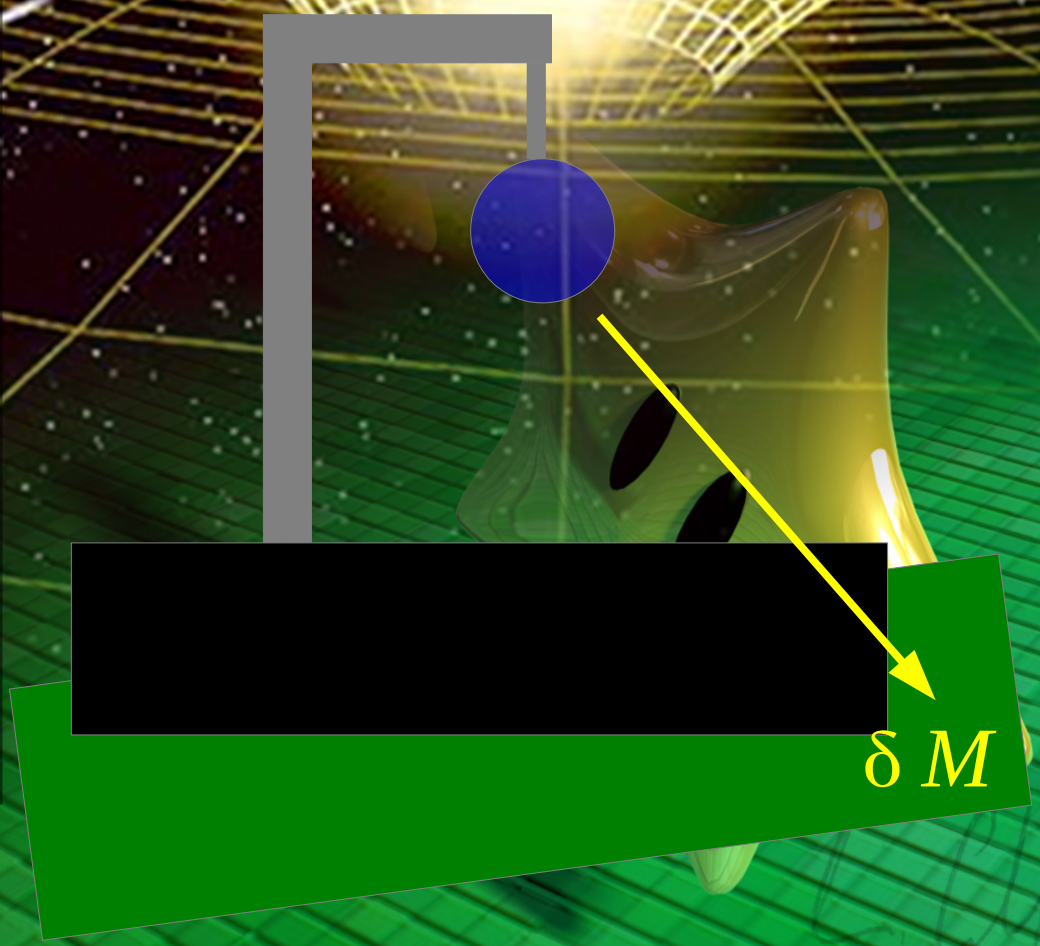




Tweaking the Detectors

- Newtonion Noise
  - Noise from localized mass distributions (not gravitational radiation)
  - Control systems reflexively feed back to optics suspensions

$$x(f) \propto \frac{\delta M(f)}{r^2 f^2}$$

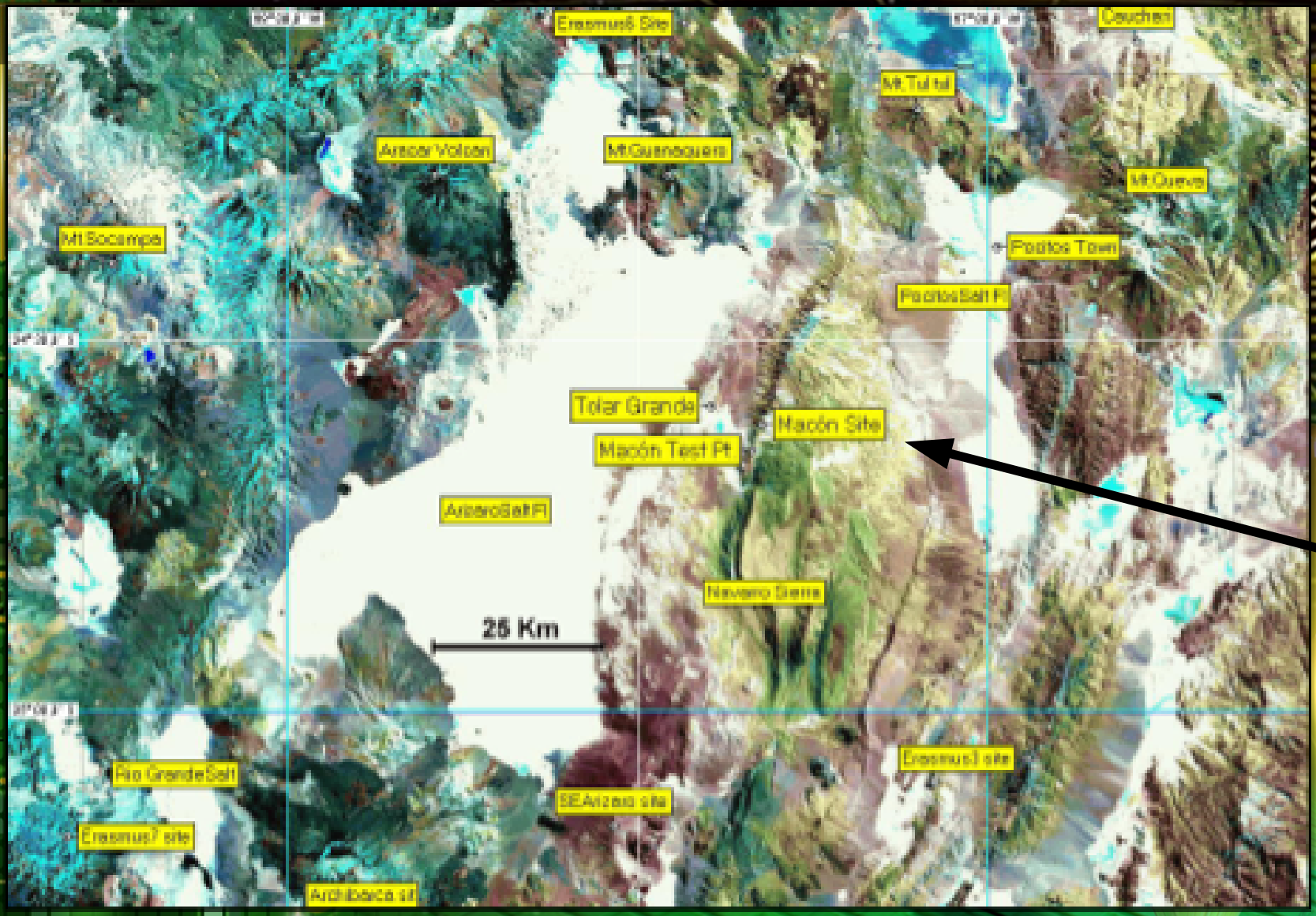


The road ahead!

Some items already completed!

iLIGO component removal
aLIGO components under construction
DAQ system installed and running
Major components being installed
Seismic,Tubes,Laser,...
Cleaning of components and chambers

TORUS Site


Erasmus8 Site
Cauchari
Mt.Tul tul
Aracar Volcan
Mt.Guanacoqueno
Mt.Quevar
Mt.Socompa
Pastos Town
Pastos Salt Fl
Tolar Grande
Macón Site
Macón Test Pit
Arizaro Salt Fl
Navarro Sierra
25 Km
Erasmus1 site
Rio Grande Salt
SE Arizaro site
Erasmus7 site
Archibarca sit

Torus Site

Antofagasta
Chajnantor
Jujuy
379 km
Paranal
Salta
Tolar Grande
CHILE
Aprox. 1468 Km
ARGENTINA
La Serena
La Silla
Córdoba
Santiago
Buenos Aires