Goddard Space Flight Center
November 18, 2004

Synthetic LISA: simulating the future of LISA data analysis

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Tasting menu

- The LISA response: geometric TDI
- Simulating TDI: Synthetic LISA (w/Armstrong)

Adventures in detector characterization with SynthLISA

- The effects of noisy armlengths
- Post-processed TDI (w/Shaddock, Ware, Spero)
- TDI ranging (w/Tinto, Armstrong)

A quick survey of LISA sources: status and wishlist

- Massive-BH binaries
- Extreme-mass ratio inspirals
- The removal of galactic binaries

- A conclusion on simulation for LISA

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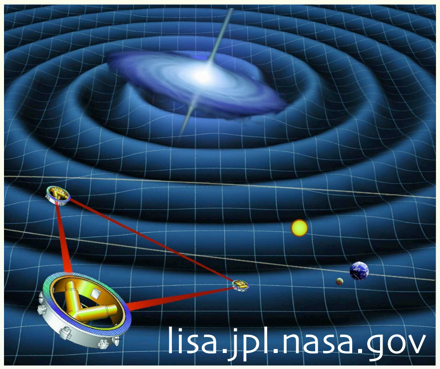
How is LISA an Interferometer?

LISA:



- A constellation of three drag-free spacecraft, separated by 5×10^6 km and flying on an Earth-trailing solar orbit
- Gravitational waves detected in 10^{-5}–10^{-1} Hz band as modulation of distance between spacecraft by picometer interferometry
- Sources: compact binary-star systems in our galaxy, massive and super-massive BH mergers, compact stellar objects captures by massive BHs

Interferometer:

- (Noun) a device that combines signals radiating from a common source [*or multiple sources*], and received at different locations [*or at a common location, but after traveling different paths*]

TDI:

Armstrong+Estabrook+ Tinto, Hellings, …

- Six laser beams are exchanged between the spacecraft; each spacecraft compares the phase of the incoming and local lasers; these measurements are delayed and combined to synthesize interferometric observables

The basic GW observable

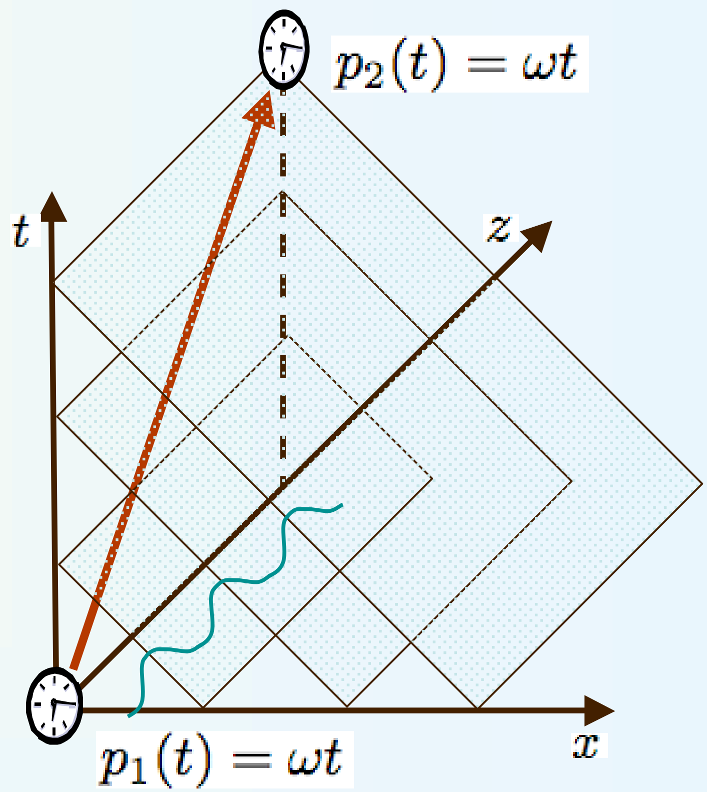
In fact, with good clocks, any
time transport link is a GW detector

$$h_{\mu\nu}^{\mathrm{TT}} = h_+(t+x)[\mathrm{e}_{zz} - \mathrm{e}_{yy}]$$ ← plane GW prop. along x

$$p_2(t) - p_1(t - L_{12}(t)) = \omega L_{12}(t)$$

$$L_{12}(t) = L_{12}^{\mathrm{no\,gw}} + \frac{1}{2}\int_1^2 h_+(t)dt$$

$$[\dot{p}_2(t) - \dot{p}_1(t - L_{12}(t))]/\omega = \tfrac{1}{2}[h_+(2) - h_+(1)]$$



and in general
(Estabrook-Wahlquist two-pulse response)

$$[\dot{p}_2(t) - \dot{p}_1(t - L_{12}(t))]/\omega = \frac{1}{2}\frac{\mathbf{n}\cdot[\mathsf{h}(2) - \mathsf{h}(1)]\cdot\mathbf{n}}{1 - \mathbf{k}\cdot\mathbf{n}}$$

← link dir. vector

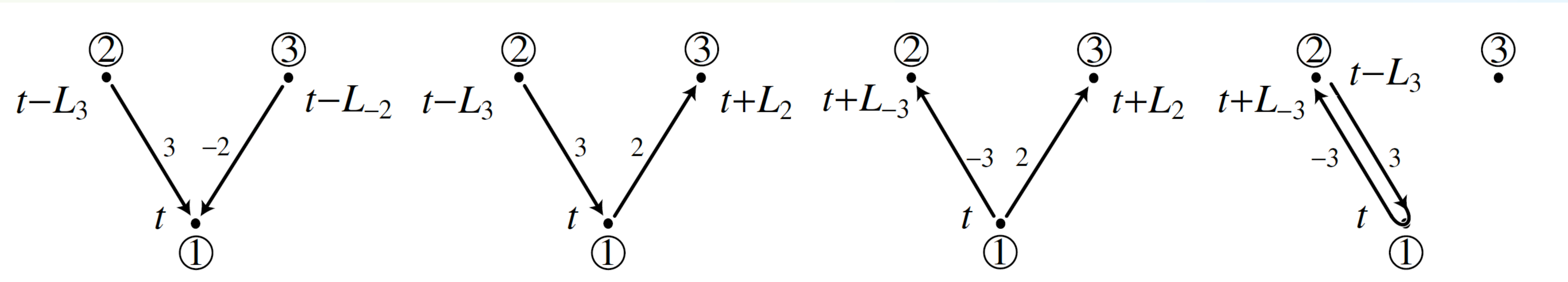
wave propagation dir.

Introducing TDI

But LISA's clocks (lasers) are not perfect: rms $\Delta f/f = 10^{-13}\ \mathrm{Hz}^{-1/2}$ (160 dB louder than proof-mass noise)

$$\dot{p}_i(t) = \omega + C_i(t) + \mathrm{g.w.}$$

Then we can add (or subtract) single-link observables $y_{\text{send (link) recv}}$ to cancel laser noise at common events (with six LISA lasers, we will need also backplane measurements)

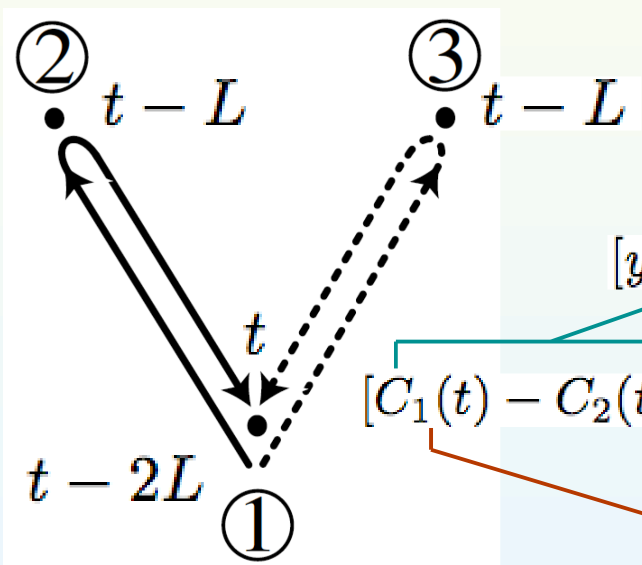


The geometric TDI principle: add/subtract single-link obs. to create a closed loop that cancels laser noise at all send/recv events

Synthesized interferometers

The TDI combination of single-link observables can synthesize the phase-difference output of laser beams sent along standard interferometer paths:

- The head-to-tail sum of observables [e.g., $y_{12}(t)+y_{21}(t+L)$, or $y_{12}(t)+y_{23}(t+L)$] replaces a perfect phase-locked transponder (mirror)
- The head-to-head or tail-to-tail difference of two such sums computes their total phase difference (replacing the photodetector)



$$[y_{21}(t) + y_{12}(t-L)] - [y_{31}(t) + y_{13}(t-L)]$$

$$[C_1(t) - C_2(t-L) + C_2(t-L) - C_1(t-2L)]$$

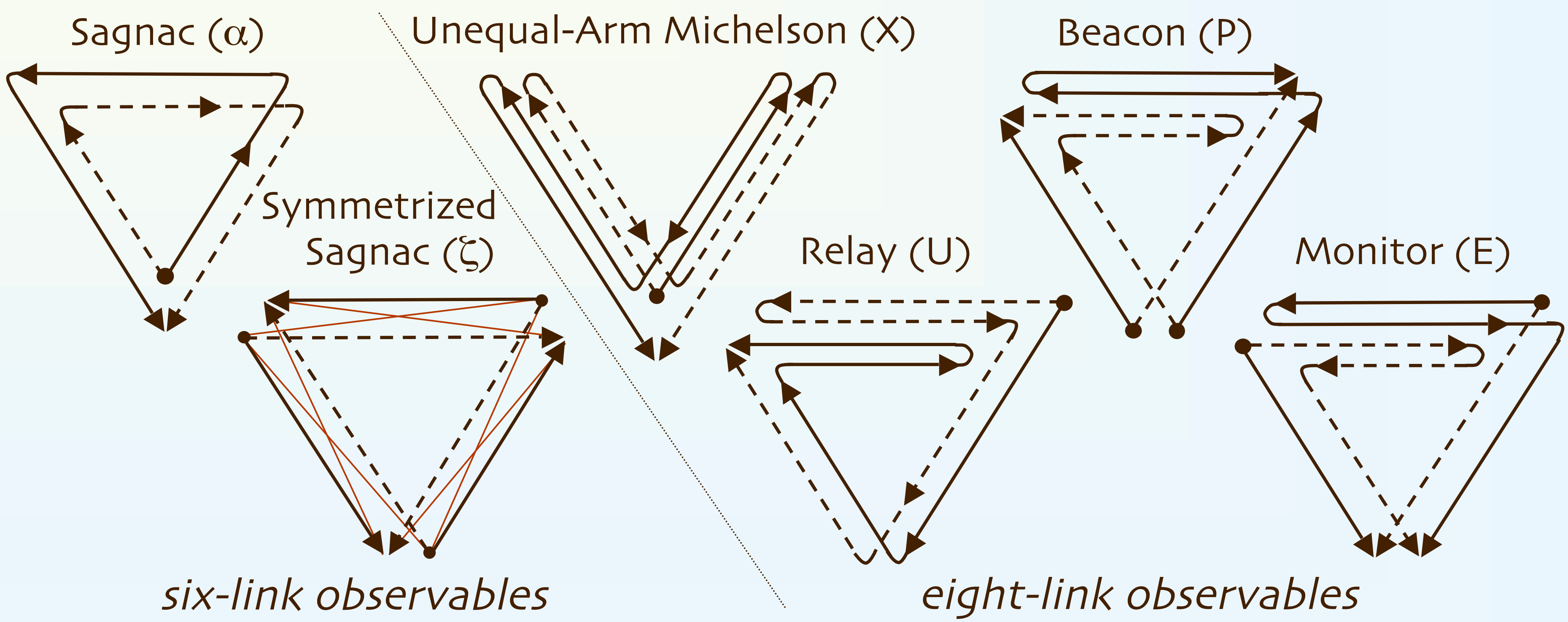
$$-[C_1(t) - C_3(t-L) + C_3(t-L) - C_1(t-2L)]$$

Synthesized equal-arm Michelson interferometer

The garden of TDI observables

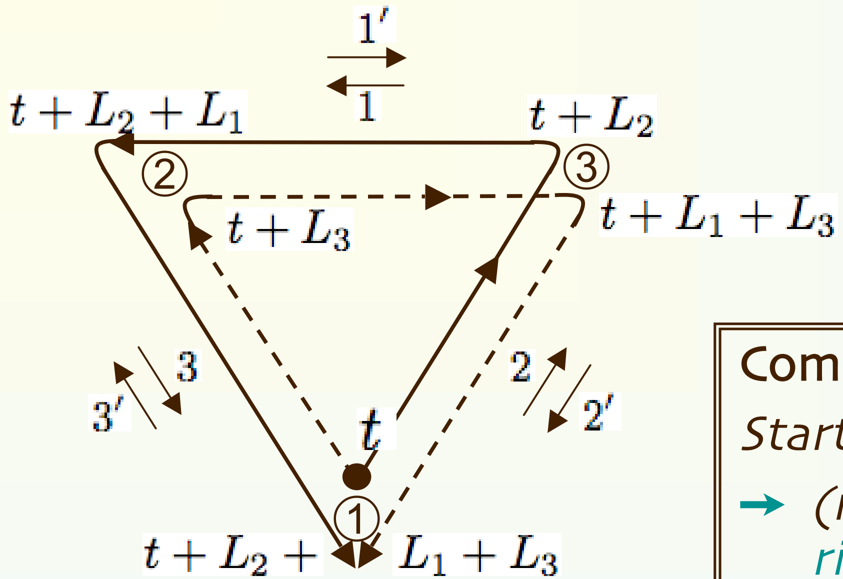
The first-generation TDI observables, discovered algebraically by AET:

- cancel laser noise in stationary unequal-arm LISA configurations
- are built with 6 single-link obs. (using all links), or 8 single-link obs. (using 4 out of 6 links); Dhurandar et al. (2002) give generators
- can all be interpreted geometrically as synthesized interferometers with 2, 4, or 6 beams!



TDI *à la* Feynman-Wheeler

The F-W TDI principle: a 2N-beam combination can be seen as a single beam that travels forward and backward in time to meet itself back at its origin



$$1\,\overrightarrow{\mathrm{R}}\,\overrightarrow{\mathrm{R}}\,\overrightarrow{\mathrm{R}}\,\overleftarrow{\mathrm{L}}\,\overleftarrow{\mathrm{L}}\,\overleftarrow{\mathrm{L}} \equiv \overrightarrow{213}\overleftarrow{2'1'3'}$$

Combinatorial recipe for n-link combinations:

Starting at arbitrary spacecraft, repeat n times:

→ *(randomly or exhaustively) choose left or right, choose future or past, lay down arrow*

For n links, 3×2^{2n} combinations possible

Closure rules to verify laser noise cancellation:

|L|-closure (first-generation TDI, unequal-arm LISA):
#(1 or 1'), #(2 or 2'), #(3 or 3') must be same under → and ←

L-closure (modified TDI, rotating unequal-arm LISA):
#(1), #(1'), #(2), #(2'), #(3), #(3') must be same under → and ←

$\dot{\mathrm{L}}$-closure (second generation TDI, flexing LISA; actual dL/dt=10^{-8} s/s):
even more restrictive, will fit in a few lines of code

Geometric TDI!

[MV, in preparation]

- Geometric TDI is a powerful (and pedagogical!) way to understand TDI
- It provides the first systematic method to explore the space of 2nd-gen. TDI observables. For instance:
  - the shortest 2nd-gen. obs. has length 16
  - there is no ζ-type obs. up to (at least) length 20
  - the search recovers TEA's 16-link, 2-beam X_1, X_2, X_3 but also news 4-beam and 6-beam X-type obs.

$$\overrightarrow{22'3'33'322'}\overleftarrow{33'2'22'233'}$$

$$\overrightarrow{22'3'322'}\;\overleftarrow{33'2'2}\;\overrightarrow{3'3}\;\overrightarrow{2'233'}$$

$$\overrightarrow{3'322'}\;\overleftarrow{33'}\;\overrightarrow{22'}\;\overrightarrow{33'}\;\overrightarrow{22'3'3}\;\overrightarrow{2'22'22'2}$$

- The new combinations have the same sensitivity, but employ both time delays and advancements, with reduced temporal footprint

links	combination space	unique observables	X	P,E	U	α	2 beam	4	6	8
16	4×10^9	45	9	18	18	0	3	24	0	18
18	7×10^{10}	168	0	12	12	144	6	24	90	48
20	1×10^{12}	618	24	12	18	564	12	114	264	84
24	3×10^{14} (4% done)	6,534 (160,000?)	29	24	40	6,440	48	536	1,540	…

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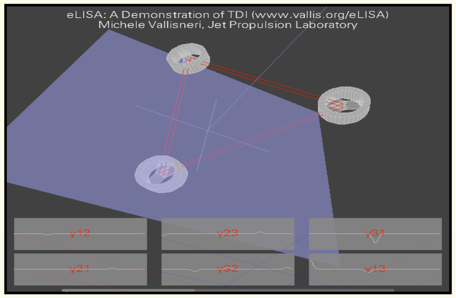
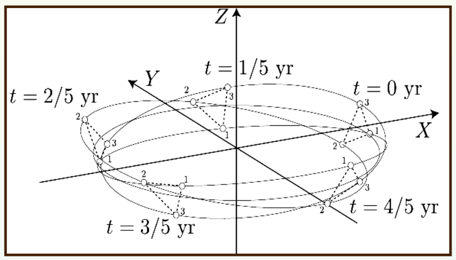
Why simulate TDI?



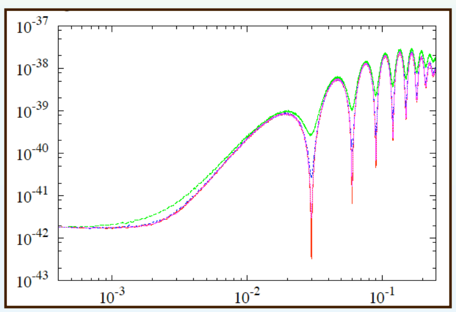
The time-delay structure of the TDI observables generates complicated **many-pulse responses** to GW signals, making for burdensome analytical signal models



The LISA **orbital motion** modulates GW signals:

→ by changing the orientation of the LISA plane

→ by Doppler shifting incoming signals



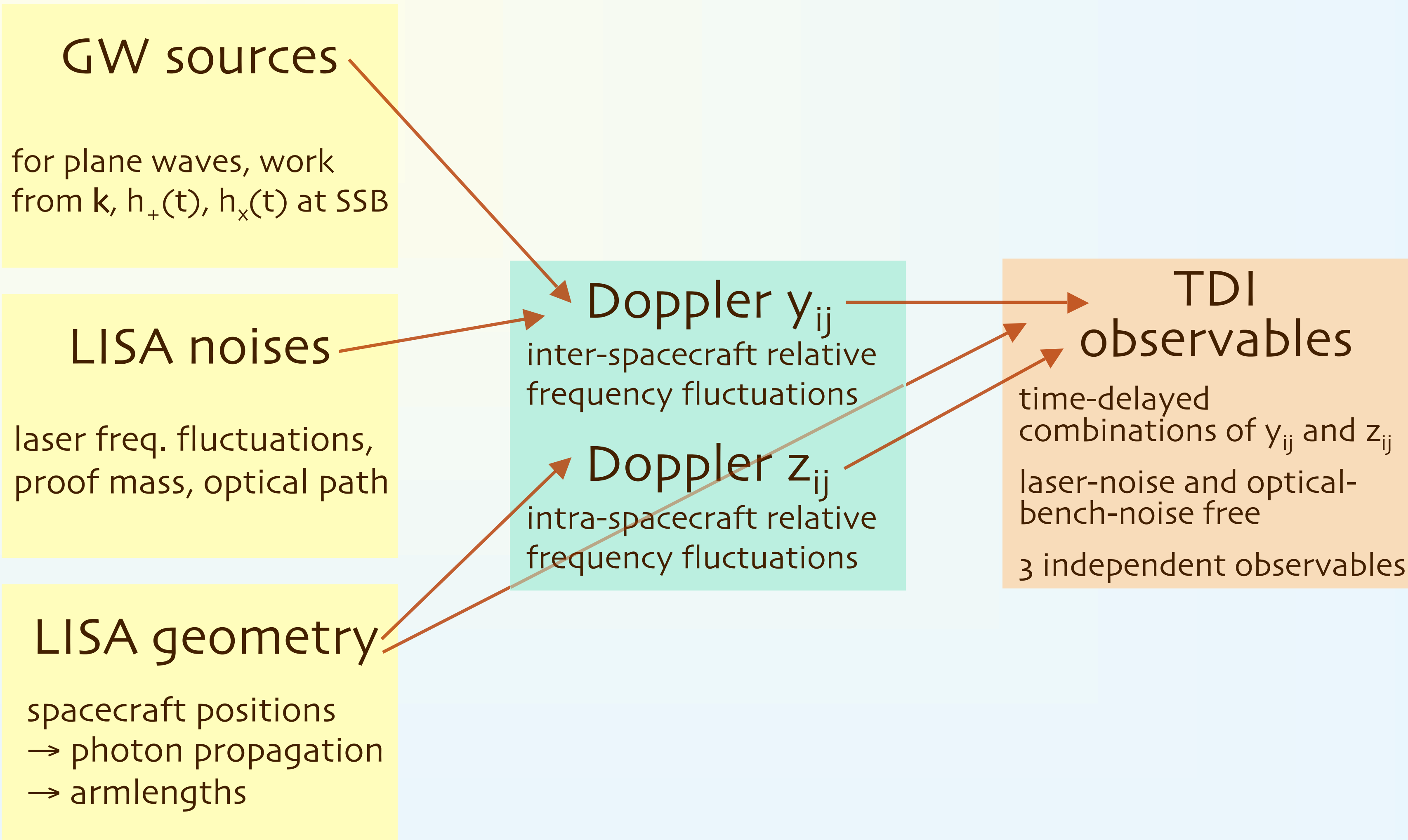
The successful **subtraction of laser phase noise** must be verified w.r.t. the practical implementation of TDI and the realistic time dependence of the armlengths

Synthetic LISA

[by MV & J. W. Armstrong; MV, *PRD*, in review, gr-qc/0407102]

- Simulates the LISA fundamental noises and GW response at the level of science/technical requirements; can be adapted and extended to the analysis of systems-engineering questions
- Includes a full model of the LISA science process (shearing LISA motion, causal light propagation, second-generation TDI, laser-noise subtraction, phase locking)
- Contains standard noise and GW-signal objects, but it's easy to implement or load new ones
- Is conceived as a modular and steerable package, to allow easy interfacing to extended modeling and data-analysis applications
- Is user-friendly, and extensible (C++, Python, XML), to allow easy interfacing to extended modeling and data-analysis applications
- Is award-winning (NASA Space Act) software, (to be) released in the public domain

A Synthetic LISA Block Diagram



The Synthetic LISA Package

Implements the LISA science process as a collection of C++ classes

Class **LISA**

Defines the LISA time-evolving geometry (positions of spacecraft, armlengths)

OriginalLISA: static configuration with fixed (arbitrary) armlengths

ModifiedLISA: stationary configuration, rotating with T=1yr; different cw and ccw armlengths

CircularRotating: spacecraft on circular, inclined orbits; cw/ccw, time-evolving, causal armlengths

EccentricInclined: spacecraft on eccentric, inclined orbits; cw/ccw, time-evolving, causal armlengths

NoisyLISA (use with any **LISA**): adds white noise to armlengths used for TDI delays

...

Class **Wave**

Defines the position and time evolution of a GW source

SimpleBinary: GW from a physical monochromatic binary

SimpleMonochromatic: simpler parametrization

InterpolateMemory: interpolate user provided buffers for h_+, $h_\times$

...

Class **TDI**(LISA,Wave)

Return time series of noise and GW TDI observables (builds causal y_{ij}'s; includes first- and second-generation observables)

TDInoise: demonstrates laser-noise subtraction

TDIsignal: causal, validated vs. *LISA Simulator*

TDIfast: cached for multiple sources (Edlund)

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Check the sensitivity of alternate LISA configurations

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...

Class **Wave**

V

on

...

Demonstrate laser-noise subtraction

- 1st-generation TDI
- modified TDI
- 2nd-generation TDI
- degradation of subtraction for imperfect knowledge of arms

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Implements the LISA science process as a collection of C++ classes

Class **LISA**

Defines the LISA time-evolving geometry

Produce synthetic time series to
test data-analysis algorithms

(arbitrary) armlengths

ModifiedLISA: stationary configuration, rotating with T=1yr: different cw and ccw armlengths

CircularRotating: spacecraft on circular, inclined orbits, cw/ccw, time-evolving, causal armlengths

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Running Synthetic LISA

Synthetic LISA is steered with simple Python scripts
What can we do with ten lines of code?

Import SynthLISA library

```
from lisaswig import *
from lisautils import *
```

Create LISA geometry object

Init. LISA pos. and orientation

```
lisa    = EccentricInclined(0.0, 0.0)
```

Create noise object

Noise sampling rate and spectral density

```
noise   = TDInoise(lisa, 1.0, 2.5e-48,
                   1.0, 1.8e-37, 1.0, 1.1e-26)
```

Create GW object

Source freq., init. phase, incl.

```
wave    = SimpleBinary(1e-3, 0.0, 0.0,
                       1e-20, 1.57, 0.0, 0.0)
```

Source ampl., eclipt. lat. & lon., polarization

Create TDI object

```
signal  = TDIsignal(lisa, wave)
```

Get X noise and X signal

Requested samples, sampl. rate, observable

```
noiseX  = getobsc(2**16, 1.0, noise.Xm)
signalX = getobsc(2**16, 1.0, signal.Xm)
```

Write spectra to disk

Output file — Observable, sampl. rate, avg. periods

```
writearray('noise.txt',  spect(noiseX, 1.0, 64))
writearray('signal.txt', spect(signalX,1.0))
```

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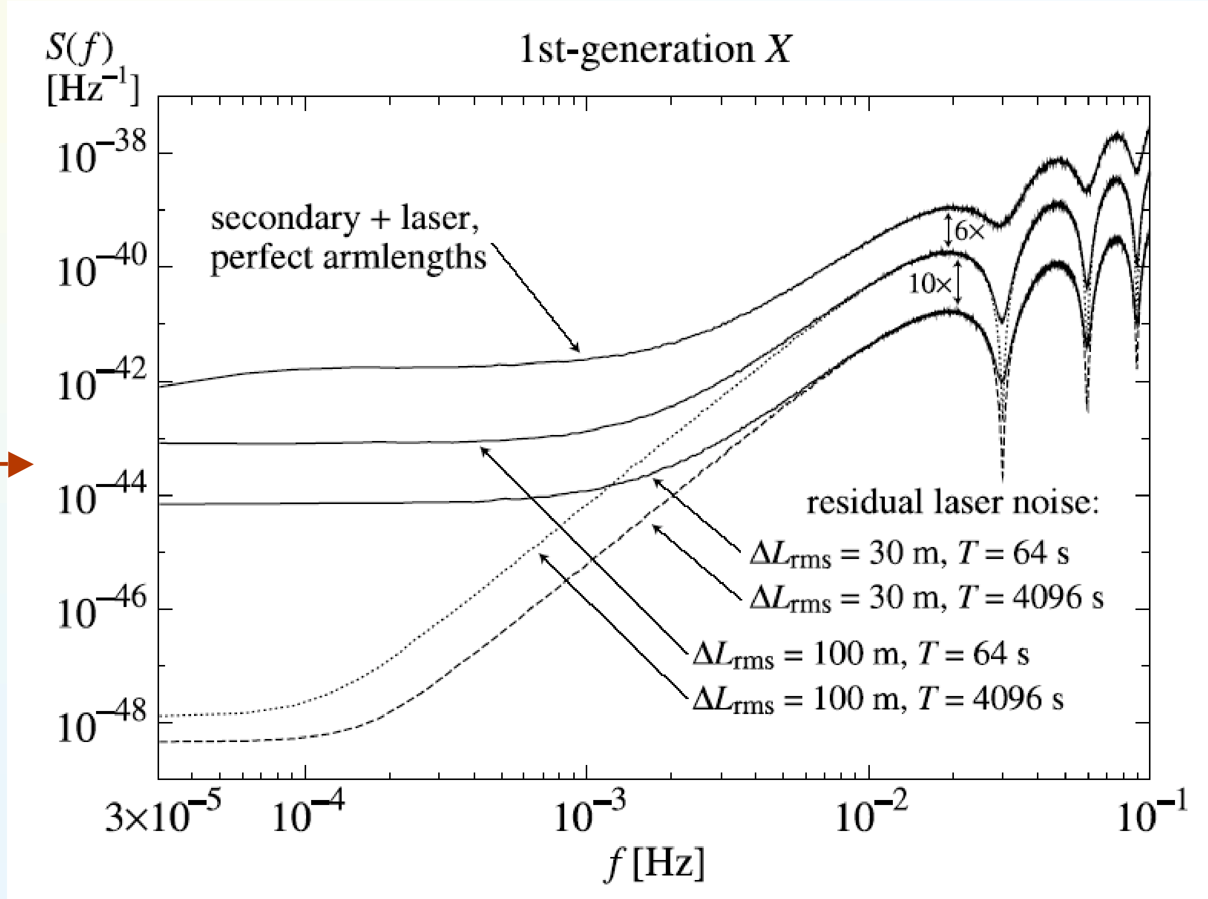
Case study: laser-noise cancellation for noisy armlengths

In accordance with analytical estimates, the armlength-measurement tolerance needed for first-generation TDI is ~ 50 m, or 1.7×10^{-7} s (residual laser noise is still present because of flexing).

But much depends on the model of the armlengths used to assemble the TDI observables.

Using only linear extrapolation from the last two measurements…

Paradoxically, it's bad to measure too often!



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Signal Interpolation for TDI!

[D. Shaddock, B. Ware, B. Spero, MV, *PRD* **70**, 081101(R) (2004)]

Suppression of laser noise to 1 part in 10^8 with TDI requires armlength delays to be specified with a precision of 100 ns. How do we get phase measurements at the right times?

The current approach is to **trigger the phasemeters** at the TDI delays:

- Knowledge of the armlengths is needed on the spacecraft and in real time
- Spacecraft clocks must be synchronized to 100 ns
- Errors in armlength knowledge or synchronization lead to irreversible corruption of TDI combination

Interpolation/post-processing is the way:

- Sample phase measurements at (low) uniform rate; transmit the time series to Earth; apply the TDI delays by interpolating the time series; Assemble the TDI combinations in postprocessing
- Combining n~20 Lagrange interpolation with oversampling (10 Hz for 2.5 Hz-bandlimited phasemeter output), only 2 s of data needed to form observables
- Ranging information not needed in real time
- TDI implemented in postprocessing allows flexibility to choose TDI schemes
- Might require higher data rates (larger dynamical range)

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Time-Delay Interferometric Ranging

[M. Tinto, MV, J. W. Armstrong, gr-qc/0410122]

- As we said, the effective suppression of laser noise with TDI (to 1 part in 10^8) requires knowledge of the armlength delays to 100 ns
- The current LISA baseline assumes that a dedicated inter-spacecraft ranging subsystem will provide the armlengths with the required precision
- Enter **TDIR**: since laser noise cancels in the TDI combinations assembled with the correct armlengths, find them by minimizing noise power in the TDI combinations!
- From a similar idea by Gürsel and Tinto [1989]
- TDIR is made possible by post-processed (interpolated) TDI

$$X_1 = \Big[(y_{31} + y_{13;\hat{2}}) + (y_{21} + y_{12;\hat{3}'})_{;\hat{2}'\hat{2}} + (y_{21} + y_{12;\hat{3}'})_{;\hat{3}\hat{3}'\hat{2}'\hat{2}} + (y_{31} + y_{13;\hat{2}})_{;\hat{3}\hat{3}'\hat{3}\hat{3}'\hat{2}'\hat{2}}\Big] + \cdots$$

TDI-imposed delays: for good noise removal, must match the physical propagation delays

$$1 \xrightarrow{L_2} 3$$

$$y_{31} = C_{13;2} - C_{31} + S_{31}$$

A TDIR algorithm

- Choose a TDI observable:

Everything else

$$X_1 = X_1^{(0)} + X_1^{(n)}$$

Laser noise

- The minimum of the laser-noise-only X_1 power gives the physical delays:

$$I^{(0)}(\hat{L}_k) = \frac{1}{T}\int_0^T [X_1^{(0)}(\hat{L}_k)]^2\, dt$$

- The presence of secondary noise (and GWs)…

Near the physical delays, sec. noise variations are negligible w.r.t. laser noise

$$I^{(n)}(\hat{L}_k) = \frac{1}{T}\int_0^T [X_1(\hat{L}_k)]^2\, dt$$

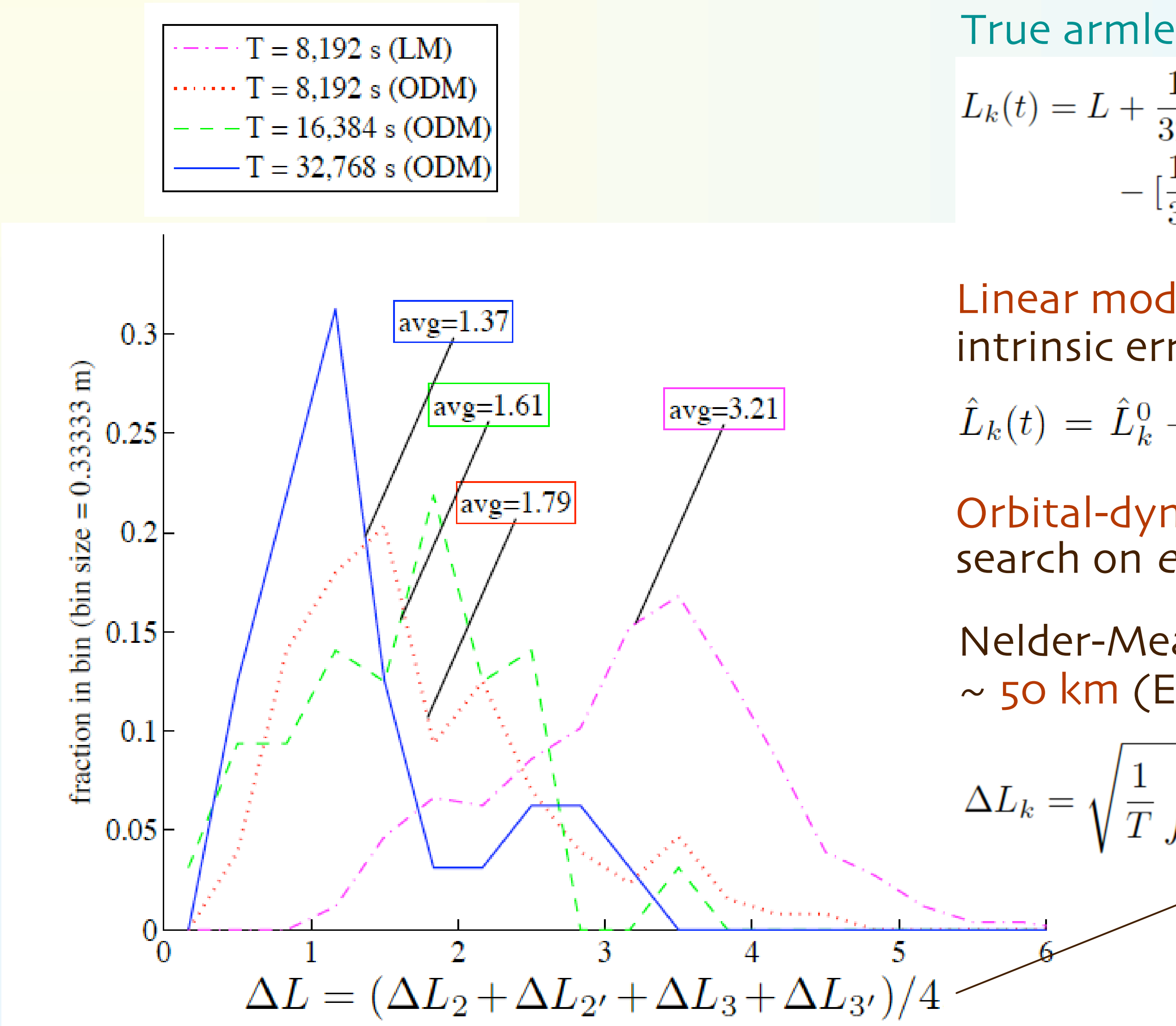
$$= I^{(0)}(\hat{L}_k) + \frac{1}{T}\int_0^T [X_1^{(n)}]^2\, dt + \frac{2}{T}\int_0^T X_1^{(n)} X_1^{(0)}(\hat{L}_k)\, dt$$

…introduces an error ~ 30 ns = 9 m for T = 10,000 s

$$\delta L_k \sim \left(\sigma_{X_1^{(n)}} / \sigma_{\dot{X}_1^{(0)}}\right) \sqrt{\rho/T}$$

rms power

TDIR: simulation results



True armlengths:

$$L_k(t) = L + \frac{1}{32}(eL)\sin(3\Omega t - 3\xi_0) - [\frac{15}{32}(eL) \pm (\Omega R L)]\sin(\Omega t - \delta_k)$$

Linear model (LM):
intrinsic error 0.25-2.60 m

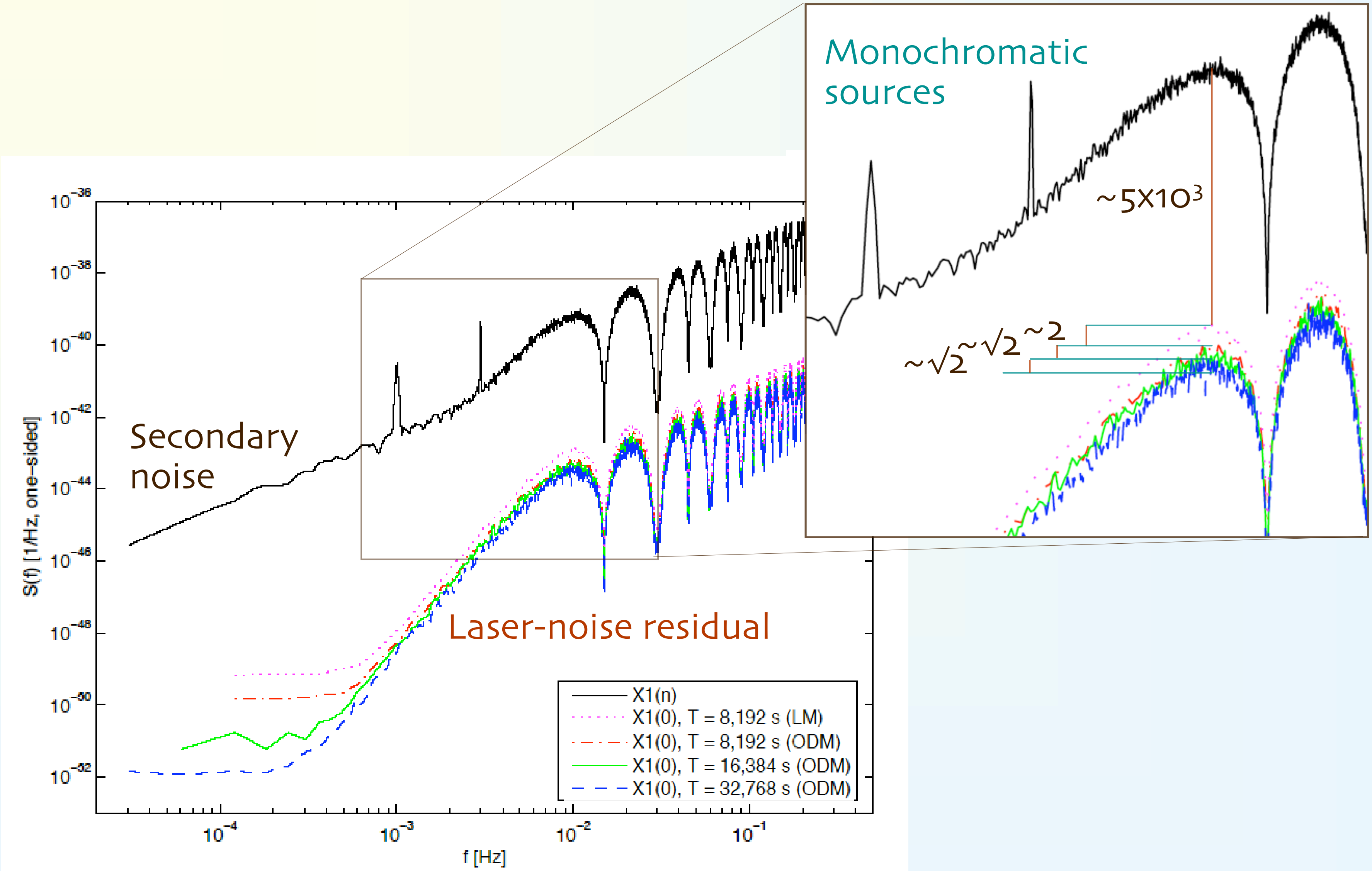
$$\hat{L}_k(t) = \hat{L}_k^0 + \hat{L}_k^1(t - t_0)$$

Orbital-dynamics model (ODM):
search on eL, ΩRL, ξ_0

Nelder-Mead search, initial errors ~ 50 km (Earth-based ranging)

$$\Delta L_k = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T}\left(\hat{L}_k(t) - L_k(t)\right)^2 dt}.$$

TDIR: simulation results



TDIR: conclusions

- With T ~ 10,000 s, TDIR allows the determination of the armlength delays with accuracy sufficient to suppress the laser noise ~ 10^3 below the secondary noises
- The error induced in the reconstruction of GWs and secondary noises is

$$\sim dX_1^{(n)}/dt \times \delta L \;\; = (2\pi\, f\, \delta L) \times X_1^{(n)}$$
$$\sim 2 \times 10^{-8}\, X_1^{(n)}\, (f\, /\, 1\ \mathrm{Hz})\, (\delta L\, /\, 1\ \mathrm{m})$$

- Although an independent ranging system will probably be included in the LISA design, TDIR provides backup and fault tolerance
- The armlength-delay determination can be optimized over the space of TDI observables
- TDIR is conceptually distinct from conventional one-way and two-way ranging: it employs a phase-closure relation between the measurements of three spacecraft
- Applicable in other missions that rely on formation flying?

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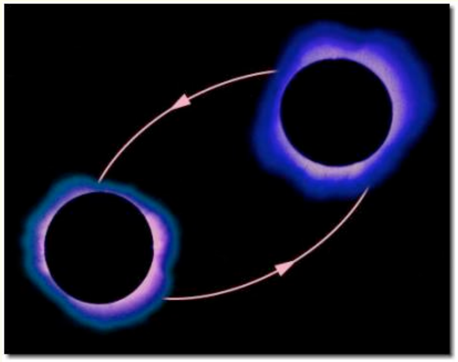
Black-hole binaries

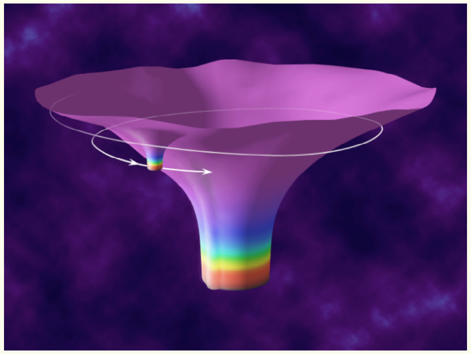


- Total mass 10^3–10^6 $M_\odot$, detectable out to $z \sim 5$–10
- In conjunction with EM detection, provide standard candle to measure equation of state of dark energy [Holz and Hughes, 2003]; accuracy limited by lensing
- If cosmological params well determined, study galaxy-MBH coevolution [Hughes, 2002]; "golden binaries" (insp.+ringdown) yield E_{GW} [Hughes and Menou, 2004]
- Post-Newtonian inspiral and perturbative ringdown well understood, at least for nonspinning binaries
- Spin effects in adiabatic inspiral: Buonanno, Chen, Pan, Vallisneri [PRD, 2004 (two papers)] developed a family of physical signal templates to search for precessing, strongly spin-influenced NS-BH and BH-BH inspirals

Desiderata

- Merger waveforms! In the meantime: robust merger analysis algorithms [Brady and Majumdar 2004]; attention to reliability of waveforms [Miller 2003, 2004]
- Study entanglement of spin and distance measurements [MV+PBC, in progress]
- Study practicality of coherent matched-filtering detection: watch out for response modulation and confusion noise

Extreme-mass-ratio inspirals



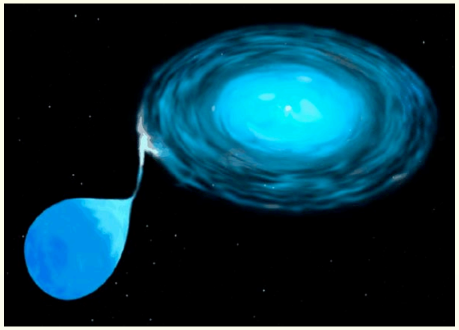
- Very complicated waveforms (10^5 cycles/y, 14 params) to be computed using BH perturbation theory, and event rates exceedingly uncertain
- Very rich science payoff: map curvature of black-hole spacetimes, test no-hair theorems, get census of galactic cusp population

- Study of detection prospects [Gair et al. incl. MV, CQG **21** (2004)] :
  - assume matched filtering detection, evaluate CPU burden using kludge waves
  - coherent search not possible: $>10^{13}$ templates for one month of integration
  - stacked search: eliminate phases, thread dynamical parameters through stacks
  - conclude ~ 1000 detections/lifetime probable out to z = 1

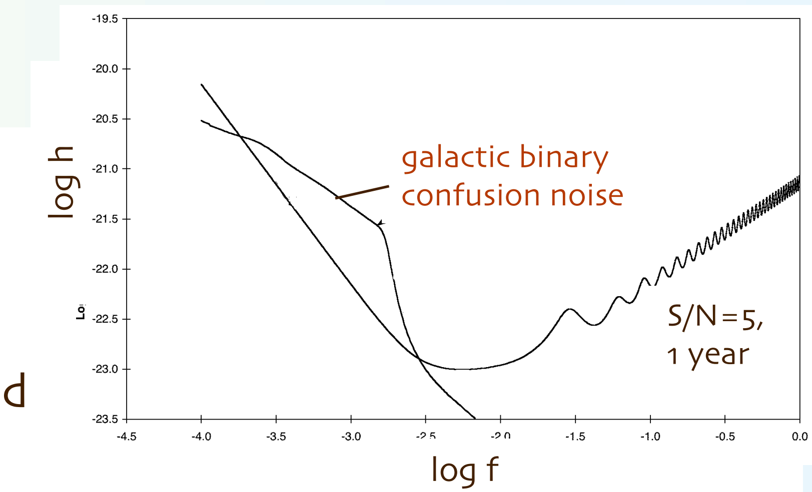
Recent developments

- Simpler TF power-excess detection for strongest events [Gair+Wen, in progress]
- IMBHs from runaway mergers in young stellar mass clusters [C. Miller, 2004]: IMBH-SMBH mergers (few/year?) visible without templates, test strong gravity
- Confusion noise from unresolved inspirals [Barack and Cutler, 2004]: weak to modest reduction of LISA sensitivity

Galactic binaries



- Guaranteed verification source, but their ensemble generates confusion noise between 10^{-4}–$10^{-2.5}$ Hz
- Low number of cycles/year: when sources resolvable, coherent detection possible
- Analytical expression of the TDI responses and ML detection scheme available [Królak, Tinto, and MV 2004]



- Rule of thumb: confusion limit at one binary/bin ($f \sim 2 \times 10^{-3}$ Hz)
- gCLEAN [Larson and Cornish 2003]
- In practice: parameter uncertainty grows exponentially with # of binaries in bin; five-bin rule [Crowder and Cornish 2004]
- However: directionality of WD background [Seto and Cooray 2004, Tinto et al. 2004]

Desiderata

- Problem of orthogonality (baby/bathwater) in background subtraction
- Information-theoretical understanding of LISA resolving power
- Maximum-entropy/Bayesian methods

Tasting menu

- The LISA response: geometric TDI
- Simulating TDI: Synthetic LISA (w/Armstrong)

Adventures in detector characterization with SynthLISA

- The effects of noisy armlengths
- Post-processed TDI (w/Shaddock, Ware, Spero)
- TDI ranging (w/Tinto, Armstrong)

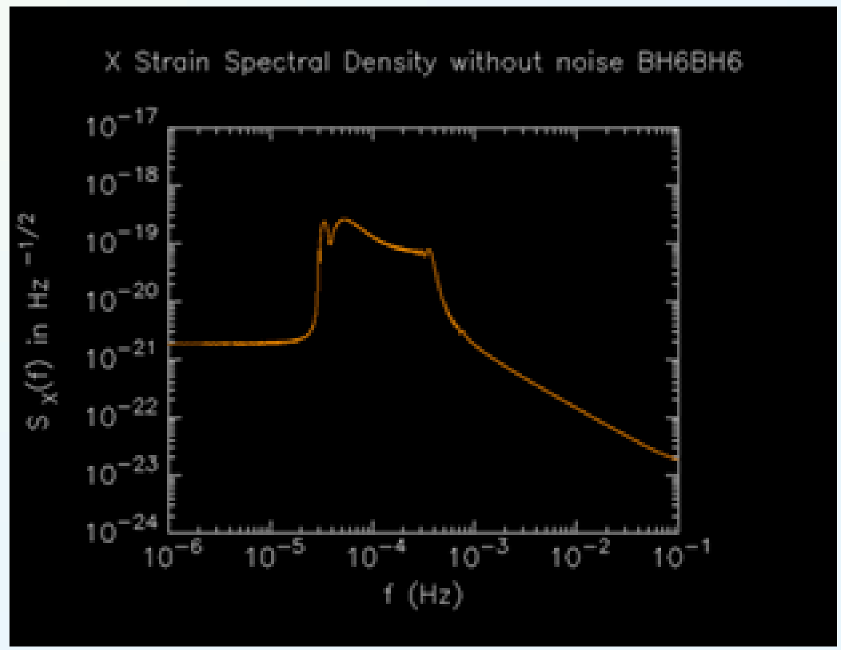
A quick survey of LISA sources: status and wishlist

- Massive-BH binaries
- Extreme-mass ratio inspirals
- The removal of galactic binaries

- A conclusion on simulation for LISA

Mock LISA Data Archive

- Hosted at astrogravs.nasa.gov (GSFC)
- Steering Committee: N. Cornish, J. Baker, M. Benacquista, J. Centrella, S. Hughes, S. Larson, M. Vallisneri
- Collect realistic time series of GW strains and of the LISA outputs, for use in developing and testing data-analysis algorithms
- Formulate standard parameter conventions:
  - Where is the source?
  - Whence the LISA orbits?
  - Which is the plus polarization?
  - What is X?
- As more contributions become available, will develop DB search and indexing capabilities
- Organize mock data challenges



The Mock LISA Data Input Format

```xml
<?xml version="1.0"?>
<!DOCTYPE XSIL SYSTEM "xsil.dtd">

<XSIL Name="GWPlaneWaveSource">
  <Param Name="EclipticLatitude"   Unit="Degree">40.0</Param>
  <Param Name="EclipticLongitude"  Unit="Degree">180.0</Param>
  <Param Name="SourcePolarization" Unit="Degree">0.0</Param>

  <Time  Name="StartTime" Type="ISO-8601">2004-07-15 06:30:00.0</Time>
  <Param Name="Cadence"   Unit="s">1.0</Param>
  <Param Name="Duration"  Unit="s">65536.0</Param>
```

Optional parameters go here

```xml
  <Array Name="hp" Type="double">
    <Dim Name="Length">65536</Dim>
    <Dim Name="Records">1</Dim>

    <Stream Type="Remote"
      Encoding="Bigendian">
      hp.bin</Stream>
  </Array>
</XSIL>
```

- An application of XSIL (extensible scientific interchange language; also used as LIGO_LW)
  - Easily parsed by machine and human (web browsers, DBs)
  - Inline or externally linked data
- Read/written by LISA Simulator and Synthetic LISA

Why simulations?

- The LISA response is complex
- Honest time-domain simulations can:
  - Take over where analytical treatments become unwieldy
  - Increase our trust in analytical insights
  - Point out the unexpected
- Uses of simulation:
  - Development and testing of data-analysis schemes and algorithms
  - Performance characterization and architecture tradeoffs
  - Interface between scientific and technical mission requirements
  - Time-domain studies of noise and vetos
- The future of simulation:
  - Waveform repositories (astrogravs), data formats, mock data challenges
  - Interface/incorporate technical simulations, experimental measurements
  - Requirement flowdown automation?
  - LISA stand in: prototyping of data-management system
  - Investigate other missions and geometries