Space-based Gravitational-wave Observatories (SGOs)

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Outline

- Why are SGOs important?
- Basic GW physics
- Science
- Mission description
- How it works – more detail
- Program status
- Summary
Why is this important?

The Gravitational Wave Spectrum

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Sources

- **Richest set of sources**
  - ESA L3 (2034 launch)

- **GW imprint on inflation**
  - age of universe

- **Stochastic background**
  - years

- **Compact objects captured by Supermassive Black Holes**
  - hours

- **Compact Binaries in our Galaxy & beyond**
  - sec

- **Rotating NS, Supernovae**
  - ms

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Detectors

- **Cosmic microwave background polarization**
- **Pulsar Timing**
- **Space Interferometers**
- **Terrestrial interferometers**

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**BICEP-2/Planck** Detection 2018-20?

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Image credit: NASA
Measurement Challenge

- **Lowest order radiator is a quadrupole**
  - Dipole radiation forbidden by conservation of momentum
  - Simplest quadrupole is a pair of masses rotating around their common center of mass (a “dumbell”)

- **What is to be measured**
  - Time-varying strain ($\Delta L/L$) in spacetime typically $\sim 10^{-21}/\sqrt{\text{Hz}} = 10\, \text{pm}/10\, \text{Gm}/\sqrt{\text{Hz}}$
  - Variations are periodic or quasi-periodic between $10^{-4}$ and 1 Hz, observable for months to centuries

- **Measurement concept**
  - Measure distance changes between free-falling mirrors
    - Test masses are the mirrors
    - Interferometric measurement of distance changes
  - Preferred measurement conditions
    - A long measurement path to make $\Delta L$ large
    - A very quiet place to avoid disturbances to the test masses: SPACE!
Binary Black Hole Merger
Science Overview

- $\log_{10}[S_{\nu}/\text{Hz}^{-1/2}]$
- $\log_{10}[f/\text{Hz}]$

- $(10^6+10^6) M_\odot$ MBH, $z=1$
- $(10^5+10^5) M_\odot$ MBH, $z=1$
- (10+10^6) M_\odot EMRI, $z=0.2$

sensitivity
verification binaries
SGO High
Science Overview

- Formation and growth of massive black holes: galaxy mergers
- Dynamical strong-field gravity
- Merger rates of 10s -100s yr\(^{-1}\) expected

Supermassive Black Hole Mergers

\[(10^6 + 10^6) M_\odot \text{ MBH, } z=1\]

\[(10^5 + 10^5) M_\odot \text{ MBH, } z=1\]

\[(10+10^6) M_\odot \text{ EMRI, } z=0.2\]

sensitivity
verification binaries
SGO High
Science Overview

Formation and growth of massive black holes: galaxy mergers
- Dynamical strong-field gravity
- Merger rates of 10s - 100s yr\(^{-1}\) expected

Supermassive Black Hole Mergers
- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
- $>10^4$ sources expected

Galactic close compact binaries
- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
- $>10^4$ sources expected

![Graph showing science overview](https://example.com/graph.png)
Science Overview

- Formation and growth of massive black holes: galaxy mergers
- Dynamical strong-field gravity
- Merger rates of 10s -100s yr⁻¹ expected

Supermassive Black Hole Mergers
- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
- >10⁴ sources expected

Galactic close compact binaries
- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
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Extreme Mass Ratio Inspirals (EMRIs)
- Precision tests of GR in strong-field regime
- Event rates uncertain
Science Overview

Formation and growth of massive black holes: galaxy mergers
Dynamical strong-field gravity
Merger rates of 10s -100s yr⁻¹ expected

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Galactic close compact binaries
- Population of galactic ultra-compact binaries
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Extreme Mass Ratio Inspirals (EMRIs)
- Cosmological gravitational wave background
- Superstring bursts
- Precision tests of GR in strong-field regime
- Event rates uncertain

New Physics / Unexpected Sources
- Cosmological gravitational wave background
- Superstring bursts
Not just detection...

- Detection already happened (direct + indirect…)
- Study growth of cosmic structure
- Test of GR in strong field limit
- Precise parameter estimation, including distances

<table>
<thead>
<tr>
<th>Number of Sources Observed</th>
<th>Classic LISA</th>
<th>SGO-Mid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive Black Hole Mergers</td>
<td>108-230</td>
<td>41-52</td>
</tr>
<tr>
<td>Detected @ Z&gt;10</td>
<td>3-57</td>
<td>1-4</td>
</tr>
<tr>
<td>Both mass errors &lt; 1%</td>
<td>67-171</td>
<td>18-42</td>
</tr>
<tr>
<td>One spine error &lt; 1%</td>
<td>49-130</td>
<td>11-27</td>
</tr>
<tr>
<td>Both spin errors &lt; 1%</td>
<td>1-17</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Distance error &lt; 3%</td>
<td>81-108</td>
<td>12-22</td>
</tr>
<tr>
<td>Sky location &lt; 1 deg^2</td>
<td>71-112</td>
<td>14-21</td>
</tr>
<tr>
<td>Sky location &lt; 0.1 deg^2</td>
<td>22-51</td>
<td>4-8</td>
</tr>
<tr>
<td>Extreme-Mass-Ratio-Inspirals</td>
<td>800</td>
<td>35</td>
</tr>
<tr>
<td>Resolved Ultra Compact Binaries</td>
<td>40,000</td>
<td>7,000</td>
</tr>
<tr>
<td>Interacting UCB's</td>
<td>1,300</td>
<td>100</td>
</tr>
<tr>
<td>Detached UCB's</td>
<td>40,000</td>
<td>8,000</td>
</tr>
<tr>
<td>Sky location &lt; 1 deg^2</td>
<td>13,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Sky loc &lt; 0.1 deg^2 + distance error &lt; 10%</td>
<td>8,000</td>
<td>800</td>
</tr>
<tr>
<td>Stochasitic Bkgrnd relative to LISA</td>
<td>1.00</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table courtesy Robin T. Stebbins
With assistance from R. Lang, N. Cornish, and S. Larson
SGO Mission Concepts

SGO High

LISA concept with single-agency costing and all know cost reductions.

SGO Mid

Minimum-cost three arm design with acceptable Decadal-survey science return.

SGO Low

Two-arm version of SGO Mid

SGO Lowest

Minimum two-arm mission

Study final report is available here:
http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php
How the science instrumentation works

- **The Constellation is the instrument**
  - Orbits passively maintain formation
  - “Sciencecraft” house test masses and interferometry

- **Interferometer Measurement System (IMS)**
  - Active transponder, phase-locked laser ranging system
  - Phasemeter records fringe signal
  - Laser frequency noise correction by pre-stabilization and post processing

- **Disturbance Reduction System (DRS)**
  - Free-falling test masses don’t contact the sciencecraft
  - Drag-free stationkeeping reduces sciencecraft test mass relative motion and force gradients
  - Design to limit thermal, magnetic, electrostatic, mechanical, self-gravity disturbances
Payload Integrated with Bus

Payload systems
- Interferometer Measurement System (IMS)
  - Laser
  - Telescope
  - Optical bench
- Disturbance Reduction System (DRS)
  - Gravitational Reference Sensor (GRS)
  - µN thrusters
  - Control laws

Full Spacecraft Bus

(Note: solar array not shown)
Prop Module/Cruise Configuration

**Propulsion Module:**
- Bi-prop design
- $\Delta v \sim 200$ m/sec capability
- 6 coarse sun sensors
- 2 star tracker heads
- 2 omni antennas
Mission Timeline

Falcon Heavy EELV

Cruise Trajectories

Science Orbits

Doppler/Arm length changes

Stack in Falcon 5 m PLF

Acquisition

Mission Timeline

24 months science operations: orbits optimized for 48 months

Pre-Launch

18 month cruise

Science Operations
• Test-mass to test-mass measured in 3 parts:
  • $2 \times$ test-mass to spacecraft measurements (short-arm: LPF tests this)
  • $1 \times$ spacecraft to spacecraft interferometer (long-arm)
Interferometry Measurement System

**LASER**
- Seed laser with LPF heritage
- Cavity pre-stabilization
- Same noise with tuning
  - US Patent 7,970,025
- TDI demonstrated with realistic delays using electronic signals

**OPTICAL BENCH**
- Optical bench with LPF heritage
- Low noise quad detector
  - US Patent 8,598,673 B2
- LISA Phasemeter development meets multiple requirements
- Pointing mechanisms tested
- Prototype telescope spacer demonstrates dimensional stability and for studying scattered/stray light
**Front-end Phasemeter Architecture**

- Low noise quad photodiode* serves two functions
  - Differential wavefront sensing of quadrant pairs determines S/C pointing
  - Sum is main science signal

100 pW from far spacecraft

100 μW from local oscillator

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Weak Light Phase Locking

SGO received power budget:
\[ \theta \sim 2.4 \frac{\lambda}{D} \sim 13 \, \mu \text{radian} \]

- \[ \lambda = 1064 \, \text{nm} \]
- \[ D = 20 \, \text{cm} \]

\[ \text{PTX} = 0.5 \, \text{W} \rightarrow \text{PRX} \sim 125 \, \text{pW} \]

\[ (20 \, \text{cm}/13 \, \text{km})^2 \sim 2.5 \times 10^{-10} \]

- Phase lock Successful at lower power than requirements
  - Master Oscillator = 1 mW vs 3-10 mW
  - Slave laser power = 13pW vs ~ 100 pW
  - Laser power step attenuated– not variable
- Shot noise limit for 13pW = 1.3x10^{-4} \, \text{rad/\sqrt{Hz}}

Paul W McNamara 2005 *Class. Quantum Grav.* 22 S243-S247

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IEEE AVFOP Conference: Atlanta, GA 11 Nov 2014
Frequency Noise Suppression:
Time Delay Interferometry (TDI)

• An interferometer arm length mismatch $\Delta L$ will allow frequency noise to mimic a displacement noise, $\delta x$.

• A sensitivity requirement of $\delta x < 10 \text{ pm}/\sqrt{\text{Hz}}$ implies that the interferometer arm lengths must be equal to better than 100 m.

• LISA arm lengths may differ by as much as 1% or 10,000 km!

$$\delta x = \frac{\delta \nu}{\nu} \Delta L$$

1. Unequal-arm Michelson interferometer
2. Equal-arm (Sagnac) interferometer (TDI combination X)
3. Constant spacecraft velocity introduces an arm length mismatch to the synthesized interferometer.

- $\Delta L \sim 20\text{m/s} \times 6.7 \text{ s} \sim 130 \text{ m}$
- Output immune to laser frequency noise: synthesized equal arms

Laser frequency noise can be reduced with margin

• Laser frequency noise suppression of \(~10^9\)
• Clock noise suppression of \(~6 \times 10^4\)

Mitryck, et al. PRD 86, 122006 (2012) testbed with electronic delays

de Vine, et al. PRL 104, 211103 (2010) static test bed
Inter-Sciencecraft Signaling: Clock noise and ranging

- **Requirement 1:**
  - **Implementation:** clock-coherent side tone
    - 8 GHz nominal sidetones (~2 MHz offsets in send vs receive)
    - 1% of power in sidebands
    - Sideband-sideband beat detection

- **Requirement 2:**
  - **Implementation:** inter-spacecraft comm
    - 1% modulation on main science beam (carrier)
    - Manchester encoding (2 Mchips/s)
    - 13-bit Gold code yields 2 m range accuracy
    - ~100 bps required (400 kbps capable)

Phase modulator supports clock noise rqmts

Using sideband-sideband beatnotes (instead of carrier-sideband) allows high modulation frequency and low photoreceiver BW
Instrument Performance

• The instrument performance is determined by:
  – Displacement noise from the Interferometric Measurement System (IMS)
  – Acceleration noise from the Disturbance Reduction System (DRS)
  – Arm Length ($1 \times 10^6$ km)

• The arm length also determines the instrument response function and is optimized for the science requirements.

Summary of DRS Subsystem allocations

<table>
<thead>
<tr>
<th>Effect</th>
<th>Total per group</th>
<th>Per group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Acceleration noise Budget</td>
<td>30.0</td>
<td></td>
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<tr>
<td>Total of subsystem allocations</td>
<td>19.5</td>
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<tr>
<td>Disturbance Groups</td>
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<td></td>
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<tr>
<td>Electrostatics</td>
<td>12.0</td>
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</tr>
<tr>
<td>Brownian</td>
<td>9.1</td>
<td></td>
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<tr>
<td>Spacecraft magnetic</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Spacecraft coupling</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>Spacecraft cross coupling</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Interplanetary Magnetic</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Mise small effects</td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

Summary of IMS subsystem noise allocations

<table>
<thead>
<tr>
<th>Effect</th>
<th>Total per group (pm/√Hz)</th>
<th>Sub-Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total IMS Error/Noise Budget</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>Total of subsystem allocations</td>
<td>11.7</td>
<td></td>
</tr>
<tr>
<td>Subsystem Allocations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shot noise</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>Pathlength noise</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Pointing Errors</td>
<td>5.3</td>
<td></td>
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<tr>
<td>Telescope pathlength stability</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Optical bench pathlength stability</td>
<td>4.5</td>
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</tr>
<tr>
<td>Measurement noise</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Photoreceiver errors</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Residual laser frequency noise</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Residual clock frequency noise</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Phasemeter noise</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Intensity noise</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Phase reconstruction</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>straylight</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
Instrument Performance

- The instrument performance is determined by:
  - Displacement noise from the Interferometric Measurement System (IMS)
  - Acceleration noise from the Disturbance Reduction System (DRS)
  - Arm Length ($1 \times 10^6$ km)
- The arm length also determines the instrument response function and is optimized for the science requirements.

LISA Pathfinder to validate noise model
LPF Status

- Propulsion module complete
- Spacecraft bus near complete
  - cold-gas thruster system currently being integrated
- Major system tests complete
  - thermal
  - electro-magnetic
  - vibration/shock
- On-track for July 2015 launch
  - Lissajous orbit around L1
  - 90 days LTP Ops
  - 90 days DRS Ops
Summary

• Space-based gravitational-wave work continues
  – Science receives top ratings in reviews
  – LPF is progressing for launch in July 2015
  – Issue is funding, not technology

• Current opportunity is partnership with ESA on an L3 mission for 2034 launch
  – 20+ year scientific collaboration on both sides of the Atlantic

• Successful LISA Pathfinder technology demo required

• US technology development targeted at TRL-5 level for ~ 2020 for key technologies
Context and Status of SGO-Mid

- No official project office at NASA
  - Study team under Physics of the Cosmos Program office
- No LISA International Science Team (LIST)
  - University engagement is critical
  - Community engagement through PhysPAG
- Technology development for L3 mission contribution
  - laser -- photoreceiver
  - telescope -- micro-newton thruster
  - phasemeter
- Participation on LPF science team
  - ST-7 experiments -- mission data analysis operations
- Developing a reference mission and science case
SGO-High vs Mid (vs LISA baseline)

- **SGO High differs from LISA by:**
  - Preserves all LISA performance parameters
  - Single agency cost model (not joint mission)
  - Lower cost launch vehicle (shared launch on a Falcon Heavy)
  - Demonstrated improvements in photoreceiver performance
  - More economical trajectories to the operational orbits

- **SGO Mid differs from LISA by:**
  - Detector arm length reduced from 5 Gm to 1 Gm
  - Science operations reduced from 5 to 2 years.
  - Nominal starting distance from Earth is reduced by about a factor of 2.5 to a 9-degree trailing orbit.
  - Telescope diameter is reduced from 40 to 25 cm, and the laser power out of the telescope is reduced from 1.2 to 0.7 W (end of life).
  - In-field guiding is used instead of articulating the entire optical assembly

High

Mid
## LISA vs SGO-high vs SGO-mid

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LISA Concept</th>
<th>SGO High</th>
<th>SGO Mid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm length (meters)</td>
<td>$5 \times 10^9$</td>
<td>$5 \times 10^9$</td>
<td>$1 \times 10^9$</td>
</tr>
<tr>
<td>Constellation</td>
<td>Triangle</td>
<td>Triangle</td>
<td>Triangle</td>
</tr>
<tr>
<td>Orbit</td>
<td>$22^\circ$ heliocentric, earth-trailing</td>
<td>$22^\circ$ heliocentric, earth-trailing</td>
<td>Heliocentric, earth-trailing, drifting-away $9^\circ$ - $21^\circ$</td>
</tr>
<tr>
<td>Trajectory</td>
<td>Direct injection to escape, 14 months</td>
<td>Direct injection to escape, 14 months</td>
<td>Direct injection to escape, 18 months</td>
</tr>
<tr>
<td>Interferometer configuration</td>
<td>3 arms, 6 links</td>
<td>3 arms, 6 links</td>
<td>3 arms, 6 links</td>
</tr>
<tr>
<td>Launch vehicle</td>
<td>Medium EELV (e.g., Atlas V 431)</td>
<td>Medium EELV (e.g., Falcon Heavy shared launch)</td>
<td>Medium EELV (e.g., Falcon 9 Block 3)</td>
</tr>
<tr>
<td>Baseline/Extended Mission Duration (years)</td>
<td>5/3.5</td>
<td>5/3.5</td>
<td>2/2</td>
</tr>
<tr>
<td>Telescope Diameter (cm)</td>
<td>40</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>Laser power out of telescope end of life (W)</td>
<td>1.2</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Measurement system modifications</td>
<td>Baseline/Reference</td>
<td>Baseline/Reference (Same as LISA Concept)</td>
<td>In-field guiding, UV-LEDs, no pointing</td>
</tr>
<tr>
<td>Motivation:</td>
<td>Science performance, two agencies</td>
<td>LISA performance with all known economies</td>
<td>Lowest cost 6 links</td>
</tr>
<tr>
<td>Approximate Cost (FY12 $B)</td>
<td>$1.82$</td>
<td>$1.66$</td>
<td>$1.40$</td>
</tr>
</tbody>
</table>
Orbits/trajectory

- **2 year drift-away**
  - ~6 deg/year drift rate starting at 9 degrees
  - 2 year end of mission similar to nominal SGO-high orbital station (but orbit optimized for 4 years)
  - EOL communications requirements similar to SGO-high

- **Stable constellation geometry simplifies measurement**
  - $\Delta L/L \sim 0.010$, relative to $10^6$ km
  - $\Delta \alpha \sim +/- 0.6^\circ$ relative to 60°
  - $\Delta v \sim +/- 1.6$ m/s

- **18 month trajectory from escape**
  - For shared launch, second stage has 2 restarts
  - Drop off shared package at GTO, then go to escape
  - Optimized $\Delta V \sim 130$ m/s (each), ~200 m/s for extended launch window and margin
Operations / Science Data

- **Simple Operations**
  - No instrument pointing or scheduling of observation time
  - LISA observes “all the sky, all the time”
    - Scheduled interruptions approximately every 2 weeks for HGA re-pointing and to switch laser offset frequencies

- **Routine Communications Strategy**
  - Ka-Band downlink every 2 days with one spacecraft (6 days for the constellation)
  - Up to 8-hr contacts with DSN 34m at 90 kbps (allows downlink of 6 days telemetry generated at 5 kbps)
  - Special merger events may require more frequent contact and continuous operation for up to ~ 4 days to preempt schedule interruptions and com

- **Science Data**
  - 5 kbps = 1 kbps science data + 4 kbps science housekeeping and engineering data, 15 kbps total for the constellation
  - **No on-board science processing**
  - Mission Ops Team forwards downlinked data to Science Data Centers
Countering Solar Radiation Pressure

Drag-free control

Thrusters

Satellite

Control loop

Position sensor

Test mass

X

Courtesy K. Danzmann