Gravitational Wave Astrophysics
The Next Frontier in Understanding the Universe
An Experimentalist's View

LISA-2020 an Intermediate-Scale Space Gravitational Wave Observatory for This Decade

Hot topics in Modern Cosmology
Spontaneous Workshop VII
Cargèse, 6 - 11 May 2013
<table>
<thead>
<tr>
<th>Stanford</th>
<th>NASA ARC</th>
<th>Lockheed Martin</th>
<th>KACST of Saudi Arabia</th>
<th>SRI International</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science</td>
<td>Science orbit,</td>
<td>Telescope,</td>
<td>Science payload,</td>
<td>μN thrusters</td>
</tr>
<tr>
<td>Payload lead</td>
<td>Orb. injection,</td>
<td>Spacecraft</td>
<td>Tech. development</td>
<td></td>
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<tr>
<td>GRS / IMS</td>
<td>Prop. mod.</td>
<td></td>
<td></td>
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</tbody>
</table>
Outline

- Why Gravitational Wave (GW) Astronomy?
- What Is the Status of GW Astronomy?
- How Do We Go From Here for LISA 2020?
Today’s ‘DARK’ Universe

The Universe as seen by EM

- **Dark Energy** ~ 73%
- **Dark Matter** ~ 23%
- **Luminous matter**
  - stars &
  - luminous gas 0.4%
  - radiation 0.005%
- Other non-luminous components
  - intergalactic gas 3.6%
  - neutrinos 0.1%
  - SBHs 0.04%

What do we really know?

- Universe known by EM; only ~0.5% of matter
- Continuous ‘model improvements’ last 30 years
- GW sees and interacts with 100% of matter
- GR used for converting EM to Universe picture has ‘issues’

Seen in EM “understood” in GR
Why GW Astronomy

- Gravitational Wave (GW) Astronomy Will Give the Answers About the Universe That EM Cannot Provide
- The $10^{-4}$ Hz to 1 Hz is the ‘Richest’ GW Range
  This Range Requires a Space GW Observatory
- A Laser Interferometer Space Antenna (LISA) Is Necessary and Possible by 2020:
  - Will Achieve the Most Important GW Science
  - At “Affordable Cost” ($500M)
- Support of Science Community is Critical for LISA 2020
GW in General Relativity

- Two independent polarizations oriented at 45
- Transverse to direction of wave
- Area preserving
- Orthogonal changes in length at wave frequency

\[
\omega = \frac{\delta}{l}
\]

\[
h = \frac{\delta l}{l}
\]

\[
\mathbf{h}_{\mu\nu} = \frac{2G}{c^4} \frac{1}{r} \mathbf{Q}_{\mu\nu}
\]

\[
h < 0 - 8
\]

- Space is “stiff” \((2G/c^4 = 1.7 \times 10^{-44} \text{ s}^{-2} \text{ kg}^{-1} \text{ m}^{-1})\)
- The GW perturbation \(h_{\mu\nu}\) propagates as \(1/r\)
GW Through Time

Big Bang

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-44}$ s</td>
<td>Superstring (?) Era</td>
</tr>
<tr>
<td>$10^{-35}$ s</td>
<td>GUT Era</td>
</tr>
<tr>
<td>$10^{-32}$ s</td>
<td>Inflation Era</td>
</tr>
<tr>
<td>$10^{-10}$ s</td>
<td>Electro-weak Era</td>
</tr>
<tr>
<td>300 s</td>
<td>Particle Era</td>
</tr>
<tr>
<td>$3 \times 10^5$ yr</td>
<td>Recombination Era</td>
</tr>
<tr>
<td>$1 \times 10^9$ yr</td>
<td>Galaxy and Star Form.</td>
</tr>
<tr>
<td>$15 \times 10^9$ yr</td>
<td>Present Era</td>
</tr>
</tbody>
</table>

GW

EM
Galactic Binaries including future type Ia supernovae

Compact Objects Orbiting Massive Black Holes high precision probes of strong-field gravity EMRI

Formation of Massive Black Holes cores of galactic active nuclei, formed before most stars MBHB

Fluctuations from Early Universe, before recombination formed CMB
**MBHB Massive Black Holes Binaries**

**Answers to basic questions in physics and astrophysics**

- The role of MBH in galaxy evolution
- Fraction of galactic mergers forming MBH
- Timing of the earliest MBH mergers
- Precision tests of dynamical non-linear gravity

New physics & astrophysics

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**Graph:**

- **Frequency (Hz)**
- **Gravitational Wave Amplitude $h$**
- **LISA Instrumental Threshold 1 year, S/N=5**
- **Binary Confusion Noise Threshold Estimate 1 year, S/N=5**
- **MBHB-MBHB at z=1**
- $10^7/10^7 M_\odot$
- $10^6/10^6 M_\odot$
- $10^5/10^5 M_\odot$

---

**Images:**

- Merging galaxies NGC4038 & NGC4039. Hubble Space Telescope; Courtesy by B. Whitmore, STSI & NASA
- Chandra image of NGC6240 a super MBHB
Probing the Region Near MBH

LISA will observe compact stars scattering near MBH

Orbits of compact stars near MBH will evolve rapidly and emit gravitational waves

The warping of space-time caused by a black hole spiraling into a MBH. Courtesy of K. Thorne, Caltech

Stellar-mass black holes orbiting MBH provide precision tests of gravitational theory in the high-field limit
Galactic Sources

*LISA will observe thousands of galactic sources*

1) Compact Galactic Binary Systems
   ➢ White dwarfs
   ➢ Neutron stars
   ➢ Black holes

   **LISA measurements**
   ➢ Direction, distance, orbital period, and masses of ‘strong’ binaries.
   ➢ Thousands of systems; most unresolved

2) Type Ia Supernovae
White dwarf binaries lose energy to gravitational waves and collide (Supernova 2002ic – hydrogen blown off by partner onto WD)

   **LISA measurements**
   ➢ Direction and time of collision, for the ~ 500 type Ia supernovae

Physics, Astrophysics and Calibration
## Known Binary Calibration Sources for LISA

<table>
<thead>
<tr>
<th>class</th>
<th>source</th>
<th>dist pc</th>
<th>$f = 2/P_b$ mHz</th>
<th>$M_1$ $M_\odot$</th>
<th>$M_2$ $M_\odot$</th>
<th>$\tau_{mrg}$ $10^8$y</th>
<th>$h$</th>
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<tr>
<td>WD+WD</td>
<td>WD 0957-666</td>
<td>100</td>
<td>0.38</td>
<td>0.37</td>
<td>0.32</td>
<td>2</td>
<td>$4 \times 10^{-22}$</td>
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<tr>
<td></td>
<td>WD 1101+364</td>
<td>100</td>
<td>0.16</td>
<td>0.31</td>
<td>0.36</td>
<td>20</td>
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<tr>
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<td>WD 1704+481</td>
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<td>0.16</td>
<td>0.39</td>
<td>0.56</td>
<td>13</td>
<td>$4 \times 10^{-22}$</td>
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<td></td>
<td>WD 2331+290</td>
<td>100</td>
<td>0.14</td>
<td>0.39 $&gt; 0.32$</td>
<td>$&lt; 30$</td>
<td>$&gt; 2 \times 10^{-22}$</td>
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<tr>
<td>WD+sdB</td>
<td>KPD 0422+4521</td>
<td>100</td>
<td>0.26</td>
<td>0.51</td>
<td>0.53</td>
<td>3</td>
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<td></td>
<td>KPD 1930+2752</td>
<td>100</td>
<td>0.24</td>
<td>0.5</td>
<td>0.97</td>
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<tr>
<td>AM CVn</td>
<td>RXJ0806.3+1527</td>
<td>300</td>
<td>6.2</td>
<td>0.4</td>
<td>0.12</td>
<td>–</td>
<td>$4 \times 10^{-22}$</td>
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<tr>
<td></td>
<td>RXJ1914+245</td>
<td>100</td>
<td>3.5?</td>
<td>0.6</td>
<td>0.07</td>
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<tr>
<td></td>
<td>KUV05184-0939</td>
<td>1000</td>
<td>3.2</td>
<td>0.7</td>
<td>0.092</td>
<td>–</td>
<td>$9 \times 10^{-23}$</td>
</tr>
<tr>
<td>AM CVn</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>LMXB</td>
<td>4U1820-30</td>
<td>8100</td>
<td>3.0</td>
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<td>4U1626-67</td>
<td>3-8000</td>
<td>0.79</td>
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<tr>
<td>W UMa</td>
<td>CC Com</td>
<td>90</td>
<td>0.105</td>
<td>0.7</td>
<td>0.7</td>
<td>–</td>
<td>$6 \times 10^{-22}$</td>
</tr>
</tbody>
</table>
How Do We Measure the GW Spectrum?

- **Astronomy** <10^{-7} Hz, ~2017
  - **Pulsar Timing**
  - **CMB Polarization: WMAP, Boomerang**

- **Earth** 10 Hz - 1 kHz, ~2016
  - Gravitational Wave Observatories
    - **LIGO, VIRGO, GEO 600, Other..**

- **Space** 10^{-4} Hz - 1 Hz > 2030
  - Gravitational Wave Observatories
    - **LISA, LISA-2020**
### Three Elements for Maximizing GW Detection

1. **Free Floating Test Masses (TM) \( \geq 2 \)**
2. **Minimize \( \delta l \rightarrow \) by best sensitivity measurement**
3. **Maximize \( l \rightarrow \) by largest ‘baseline’**

<table>
<thead>
<tr>
<th></th>
<th>TM</th>
<th>( \delta l )</th>
<th>( l )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Astronomy</strong></td>
<td>Pulsars</td>
<td>( \sim 10 \text{m} )</td>
<td>( &gt; 10^{17} \text{m} )</td>
</tr>
<tr>
<td><strong>Space</strong></td>
<td>Drag-free TM</td>
<td>( \sim 10^{-11} \text{m} )</td>
<td>( \sim 10^{9} \text{m} )</td>
</tr>
<tr>
<td><strong>Earth</strong></td>
<td>Seismically Isolated TM</td>
<td>( \sim 10^{-18} \text{m} )</td>
<td>( \leq 4\times 10^{3} \text{m} )</td>
</tr>
</tbody>
</table>
The GW Spectrum

Pulsar Timing

Gravitational Wave Amplitude

Coalescence of Massive Black Holes
Resolved Galactic Binaries
Unresolved Galactic Binaries
LISA
NS-NS and BH-BH Coalescence
SN Core Collapse
LIGO

Frequency (Hz)
Physics & Astrophysics are in a 'DARK' period; GW Astronomy is a very plausible SOLUTION

Status and prospects for GW Astronomy
Resolution and Sources of GW

- Earth 10 Hz to 1000 Hz, ~2016
  Local (100 MPc range) Medium Resolution

- Astronomical Observations <10^{-7} Hz, ~2017
  TBD Sources & Resolution

- Space Experiments 10^{-4} Hz - 1 Hz, >2030
  Large # of Sources & Excellent Resolution
With many caveats which are about 50% probable:

- eLISA launch *NOT BEFORE* 2028 (means maybe after 2035)
- NASA - LISA launch *NOT BEFORE* 2030 (means maybe after 2035)

*(Plan to Mission >10 years; Hubble, GP-B, LPF, WST …)*

Implications:

- Delay in ‘best’ information required to understand the Universe
- Difficulty motivating students and scientists to join the field
- Old technology and lack of program continuity
- Loss of opportunity to perform in conjunction with LIGO/VIRGO/etc

*Few in this audience will have any chance to see LISA type science*
GW Interferometers

LISA Strain Sensitivity

\[ \propto \frac{\delta F_{TM}}{M_{TM} \omega_W l_{IN}} \]

\[ \propto \frac{l_W}{l_{IN}} \]

\[ \propto \frac{s l_{IN}}{l_{IN}} \]

\[ n \lambda_W = l_{IN} \]

Frequency (Hz)

10\(^{-20}\) - 10\(^{-18}\) - 10\(^{-16}\)

LISA Strain Sensitivity (Hz\(^{1/2}\))
Space ‘Mirror’: Drag-Free TM Performance

1. Control Spacecraft to follow TM
2. Reduce External Disturbances
   - Aerodynamic Drag
   - Magnetic Torques
   - Radiation Pressure
   - Gravitational Torques

10^{-11} \text{ m s}^{-2} \text{ RMS over 3 days (4 \mu Hz)}

Drag-free: flight data
---

Triad flight data

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Drag-free: design goal

10^{-13} \text{ m s}^{-2} \text{ / Hz}

GP-B Flight Gyroscope 2004

TRIAD Sensor 1972
# Applications of Drag-free Technology

<table>
<thead>
<tr>
<th>Category</th>
<th>Application</th>
<th>Drag-free Performance (m/sec^2Hz^{1/2}), frequency (Hz)</th>
<th>Metrology (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Navigation</strong></td>
<td>Autonomous, fuel efficient orbit maintenance</td>
<td>( \leq 10^{-10} ), near zero frequency (^a,b)</td>
<td>( \leq 10 ) absolute</td>
</tr>
<tr>
<td></td>
<td>Precision real-time on-board navigation</td>
<td>( \leq 10^{-10} ), near zero frequency (^a)</td>
<td>( \leq 10^{-9} ) differential (^a)</td>
</tr>
<tr>
<td></td>
<td>Formation flying</td>
<td>( \leq 10^{-10} ), near zero frequency (^a)</td>
<td>( \leq 10^{-9} ) differential (^a)</td>
</tr>
<tr>
<td><strong>Earth &amp; Planetary Science</strong></td>
<td>Aeronomy</td>
<td>( \leq 10^{-10}, 10^{-2} ) to 1 Hz (^a)</td>
<td>1 absolute (^a)</td>
</tr>
<tr>
<td></td>
<td>Geodesy, GRACE</td>
<td>10^{-10}, 10^{-2} to 1 Hz (^a,b,c)</td>
<td>10^{-6} differential (^a)</td>
</tr>
<tr>
<td></td>
<td>Future Earth geodesy</td>
<td>( \leq 10^{-12}, 10^{-2} ) to 1 Hz (^a)</td>
<td>( \leq 10^{-9} ) differential (^a)</td>
</tr>
<tr>
<td><strong>Fundamental Physics</strong></td>
<td>Equivalence Principal tests</td>
<td>( \leq 10^{-10}, 10^{-2} ) to 1 Hz (^a)</td>
<td>( \leq 10^{-10} ) differential (^a)</td>
</tr>
<tr>
<td></td>
<td>Tests of general relativity</td>
<td>( \leq 10^{-10}, ) near zero frequency (^a)</td>
<td>( \leq 1 ) absolute (^a)</td>
</tr>
<tr>
<td><strong>Astrophysics</strong></td>
<td>Gravitational waves</td>
<td>( 3 \times 10^{-15}, 10^{-4} ) to 1 Hz</td>
<td>( \leq 10^{-11} ) differential</td>
</tr>
</tbody>
</table>

Notes: \(^a\) Performance to be demonstrated by the drag-free CubeSat; \(^b\) demonstrated; \(^c\) non-drag-free
LISA Concept

- Three spacecraft in triangular formation separated by 5 million km
- Spacecraft have constant solar illumination
- Formation trails Earth by 20°

Orbit position and velocity modulate GW amplitude and phase

From amplitude and phase LISA determines direction to <1
LISA Systems
Geocentric Orbit: ~ 50% Heliocentric cost

Reduced Requirements ~ ×30

Small sat approach to tech demonstrations

- 2013-2017 technology (LISA technology is older than 2000)
- Parallel, low cost, low risk, on small and cube satellites
- ~6 technologies at 1 M$ - 4 M$ each
- Multiple institutions and international partners

Simplified Robust Inertial Sensor (LPF back-up)

- Spherical, fully drag-free, optical sensing

Metrology

- Optical Reflective with Gratings
Dodecagon ring with spacecraft avionics $\times 3$

Long-arm interferometer $\times 3$

Short-arm interferometer $\times 6$

35mm gap size

Test Mass $\times 3$

$\varnothing=70\text{mm}, \ M\approx 3\text{kg}$

Optics Bench $\times 3$

Two-sided grating $\times 6$
Overview of LISA-2020 Orbits

Lunar retrograde Orbit

Geocentric Orbits in Lunar Plane; Arm ~ 1 Gm
## Data Rate Estimate for Space Antennas

<table>
<thead>
<tr>
<th></th>
<th>GP-B</th>
<th>1 LISA or LISA-2020 SC</th>
<th>3 LISA SC vs GPB</th>
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<tbody>
<tr>
<td><strong>Plan</strong></td>
<td>0.35 GB/day</td>
<td>0.011 GB/day (NASA)</td>
<td>0.033 GB/day (NASA)</td>
</tr>
<tr>
<td></td>
<td>(actual data rate)</td>
<td>0.004 GB/day (ESA)</td>
<td>0.013 GB/day (ESA)</td>
</tr>
<tr>
<td><strong>System</strong></td>
<td>SC (GPB 6 deg ctrl)</td>
<td>SC (LISA-2020 7 deg ctr) (LISA 7)</td>
<td>≈ (GPB)×3</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>Cryogenics</td>
<td>µK control</td>
<td>≈ (GPB)×3</td>
</tr>
<tr>
<td><strong>Propulsion</strong></td>
<td>He thrusters</td>
<td>µN thrusters</td>
<td>≈ (GPB)×3</td>
</tr>
<tr>
<td><strong>Pointing</strong></td>
<td>1 telescope</td>
<td>2 telescopes</td>
<td>≈ (GPB)×3×2</td>
</tr>
<tr>
<td><strong>Test Masses</strong></td>
<td>4 TM × 3 deg ctrl.</td>
<td>2 TM × 6 deg control (coupled)</td>
<td>≈ (GPB)×3×2</td>
</tr>
<tr>
<td><strong>Read-out</strong></td>
<td>4 SQUID systems</td>
<td>4 pm interferometers</td>
<td>≈ (GPB)×3</td>
</tr>
<tr>
<td><strong>BW</strong></td>
<td>Meas BW 12.9 mHz</td>
<td>Meas. BW 0.1-100 mHz</td>
<td>≥ (GPB)×3</td>
</tr>
<tr>
<td><strong>Formation</strong></td>
<td>None</td>
<td>N/A</td>
<td>3 SC ???</td>
</tr>
</tbody>
</table>

GPB data rate ≤ 1 LISA/LISA-2020 SC data rate

**LISA/LISA-2020 data rate ≥ 3 × GP-B data rate ≥ 1 GB/day**

Estimated LISA/LISA-2020 data rate / Planned LISA data rate (ESA)* ≥ 77

*7 kbit/s for 8 hours every 2 days = 0.013 MB/day | ESA web site

Comm Link Increase > 100
**LISA & LISA 2020**

**LISA:** $10^{-4} – 1$ Hz GW in Space  
Laser Interferometer Space Antenna  
“Standard” since 1995
- Based on 20 yrs of studies by LISA team
- Heliocentric Orbit with Three 5 Gm Arms
- $\delta h/h \approx 10^{-20}$
- **Cost > 2 G€**
- **Launch AFTER 2030**

**LISA 2020:** $10^{-4} – 1$ Hz GW in Space
- Based on 10 yrs of studies by SU team
- Geocentric Orbit with Three ~1 Gm Arms
- $\delta h/h \approx 3\times10^{-19}$
- **Cost ≈ 1/2 G$**
- **Launch Around 2020**
### LISA & LISA-2020

<table>
<thead>
<tr>
<th>Metric</th>
<th>LISA</th>
<th>LISA-2020</th>
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<tbody>
<tr>
<td>Total MBHB</td>
<td>110-220</td>
<td>20-40</td>
</tr>
<tr>
<td>MBHB $z &gt; 10$</td>
<td>3-60</td>
<td>1-4</td>
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<tr>
<td>EMRIIs</td>
<td>800</td>
<td>$\leq 10$</td>
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<tr>
<td><strong>Total WDB</strong></td>
<td>$4 \times 10^4$</td>
<td>$\leq 3 \times 10^3$</td>
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<tr>
<td>WDB with 3D</td>
<td>$8 \times 10^3$</td>
<td>$\leq 10^2$</td>
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<tr>
<td>Stochastic Background</td>
<td>1.0</td>
<td>$\leq 0.2$</td>
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</table>

<table>
<thead>
<tr>
<th>Orbit (Gm)</th>
<th>TM (ms$^{-2}$Hz$^{-1/2}$)</th>
<th>Metrology (pm Hz$^{-1/2}$)</th>
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</thead>
<tbody>
<tr>
<td><strong>LISA 2020</strong></td>
<td>0.7-1.0 Geocentric</td>
<td>$10^{-13}$ Sphere $\times 1$</td>
</tr>
<tr>
<td><strong>LISA</strong></td>
<td>5.0 Heliocentric</td>
<td>$3 \times 10^{-15}$ Cube $\times 2$</td>
</tr>
</tbody>
</table>
Principal Cost Savings Relative to LISA

1. Orbit change: Geocentric (0.7 Gm – 1.0 Gm arm length)
   - Requires 1 small propulsion module instead of 3
   - Launch mass savings: ~ 3,000 kg
   - Reduced operations & communications complexity

2. Reduced S/C mass from reduced payload components
   - 1 GRS, 1 Laser, 1 optics bench, smaller (20 cm) telescopes
     - 2 Lasers budgeted for redundancy (4 in LISA)
     - No credible TM failure mechanism
     - TM sensing, charge control, spin-up, and drag-free have redundancy
   - Launch mass savings: ~ 150 kg \( \times \) 3 spacecraft

3. LISA-2020 wet launch mass: ~2,000 kg (~5,000 kg for LISA)
   - Historic trends show cost scales with mass
   - Complex payloads are hard to cost
Advantages of a Spherical TM

1. No TM forcing or torquing
   - Neither electrostatic support nor capacitive sensing required, reducing disturbances & complexity

2. Large gap (35 mm)
   - Disturbances reduced and/or spacecraft requirements relaxed

3. Long flight heritage
   - Honeywell gyros, Triad I ($5\times10^{-11}$ m/sec$^2$), GP-B ($4\times10^{-11}$ m/sec$^2$ Hz$^{1/2}$)

4. Scalability
   - Performance can be scaled up or down by adjusting TM and gap size

5. Simplicity
   - No cross coupling of degrees of freedom

6. Simple flight-proven caging mechanism (DISCOS)
Micronewton Thrusters Design

- Drag-free & attitude via $\mu$N thrusters
- No existing thruster meets LISA noise, max thrust, and lifetime requirements
  - LPF evaluating alternates to FEEPsb
- MIT & SRI micro-fabricated ion thrusters as attractive alternative to Busek CMNT or Italian/Austrian FEEPsb
  - Micro-fabricated emission sites produce ions & electrons
  - “Digital propulsion”: 100’s – 1,000’s of independent emitters / cm$^2$
    - Single unit can produce forces + torques
  - Huge dynamic range: ion production physics unchanged over $10^{-9}$ to 1 N
  - Up to 10,000 sec Isp
  - Prototype: 1 nN to 5 $\mu$N thruster ion source tested to 40 hr of operation
  - Can be demonstrated on a 1U CubeSat
  - MIT – uses capillarity; no moving parts

Thrusters are a problem
LISA-2020 concept with heritage
Honeywell, DISCOS, LPF, ST-7, GP-B, STAR

- 3 drag-free spacecraft in geocentric orbit
- Minimized payload: 1 test-mass (sphere), 1 laser, 2 telescopes
- Small sat approach to tech demonstrations

LISA-2020 maintains LISA science ~ 50%

- 50% Complexity
- 30% Cost
- 10,000% Communications Band
For and Against LISA 2020

- **Advantages**
  - GW Science ~2020
  - Technology
  - GW Community

- **Obstacles**
  - Funding
  - Competition
    - EM Astronomy has **Data**
    - Planetary Science
  - Inadequate EPO
Spacecraft & Mission Design by LM

Off the shelve but too large

S/C based on existing LM S/C, TRL >6

- ~3 m × 0.7 m, 300 kg, 500 W
- Fixed 10 W antenna between telescopes
- Thermal design: GRS 10 μK at 1 mHz
- ±50 K at exterior at 27.3 period
- Thermal load radiated top/bottom
- Payload at center
- Launch mass: 2,070 kg

- 4-7 month cruise
- 5 year lifetime

Concept of 3 SC & 1 Propulsion module In Launch Fairing
1. Physics & Astrophysics are in a 'DARK' period; GW Astronomy is a very plausible SOLUTION

2. A LISA-2020 Type Geocentric Medium GW Antenna Can Provide Excellent GW Data ~2020

3. Technology Development on Small Satellites
Science & Technology Implementation on Small Satellites

- **Science**
  - Special/General Relativity
  - Gravitational waves
  - Earth Geodesy/Aeronomy

- **Technology**
  - Gravitational Reference Sensors
  - Ultra-stable optics
  - Precision navigation
  - Formation flying

- **Education**
  - Grad, Undergrad
  - 3-5 year projects
  - Student led tasks

- **Science & Technology on Small Satellites**
  - Education driven
  - International collaborations
**Small Sats Technology Program**

1. **UV LED Sat - 2013**
   - Image of a CubeSat for gravitational science.

2. **Shadow Sat - 2014 (partially-funded)**
   - Image of a CubeSat for gravitational science.

3. **Drag-Free CubeSat - 2014 NEXT ARC-SU-KACST Flight**
   - Image of a Drag-Free CubeSat.

4. **Optical Sat – 2015 (Lab development)**
   - Image of an Optical Sat for gravitational science.

5. **Mini STAR– 2015 (Lab development)**
   - Image of a Mini STAR CubeSat for gravitational science.

6. **Laser Ranging – 2016 (Lab development)**
   - Image of a Laser Ranging CubeSat.

7. **UV LED Sat - 2013**
   - Image of a Mini clock Sat.

8. **Mini clock Sat – 2016 (Lab development)**
   - Image of a Mini clock Sat for gravitational science.

9. **GRACE follow-on With Cube-sats**
   - Image of a GRACE follow-on satellite.

10. **STAR With miniSTAR Geodesy, Aeronomy Gravitational Science**
    - Image of a STAR CubeSat.

11. **LISA-2020**
    - Image of a LISA-2020 satellite.

12. **10 years, 0.5G$, NASA< 0.2G$ Gravitational Waves**
    - Image of a LISA-2020 satellite with details on its specifications.
Caging System - April 2013 Parabolic Flight

MGRS, 2.5 cm TM, for Parabolic Flight Caging Test

Caging System Schematics

3 U Caging Fixture
Housing
MGRS, Mechanical
Caging System - April 2013 Parabolic Flight

Flight Team (from left)
April 22\textsuperscript{nd} – 25\textsuperscript{th}
\begin{itemize}
  \item Andreas Zoellner
  \item Kirk Ingold
  \item Eric Hultgren
\end{itemize}
**Technology Objectives**
- Raise TRL levels (4/5 → 8/9) for
  - Deep UV LEDs
  - ac charge control
- Beneficiaries:
  - LISA
  - GRACE follow-on
  - Drag-free CubeSat

**Mission Design**
- Spacecraft: Saudi Sat
- Russian launch Nov 2013
- 2 month mission
- Fully funded ($1.5M)

**Payload**
- Isolated “test mass”
- 16 UV LEDs & photodiodes
- Charge amp
- Voltage bias plates
- ac charge control electronics

**Management**
- NASA Ames: Flight payload, PM, SE, SMA
- Stanford: Payload design, SOC
- KACST: Spacecraft, Launch, MOC

**Demonstrates unconventional international collaboration**
UV LED Instrument Integration and Test

Integration of Flight Model at ARC

Thermovac chamber testing
UV LED Instrument Components; 2013 Launch

- Payload completion: May 2013
- Spacecraft CDR: May 2013
- Payload Integration: Jun 2013
- Russian launch: Nov 2013
DOSS & ADCS on 3U Cubesat; 2014 Launch

- Secondary Payload
  - ADCS Evaluation
  - Electrical Power System
  - Volume Margin
- Main Payload
  - Differential Optical Shadow Sensor
  - Motor Drive
  - Payload Processor
- Bus
  - Motherboard, CPU, Radio, Antenna
Technology Objectives

- Raise TRL level for miniature high-sensitivity displacement sensor
  - nm/Hz^{1/2} sensitivity
- No forcing
- Non-contact

Mission Design

- 3U CubeSat
- Any orbit
- Launch ~ 2014
- 1 month ops
- Payload funded

Payload

- Light source:
  - SLED, 1545 nm
- InGaAs quad-photodiode
- Ultra-low current Difet amp

Management

- Stanford & KACST: Payload, CubeSat structure
- I&T & Launch: pending
The Drag-free CubeSat

4 kg
6 W
3U Cube
The Drag-free CubeSat

Science
- Aeronomy, space weather
- Demo < $10^{-10}$ m/sec$^2$ for future
  - Planetary Geodesy
  - Earth observation
  - Gravity science
  - Gravity-waves

Payload (back-up version)
- Drag-free sensor + micro-thrusters

Mission Design
- 3U CubeSat
- Secondary launch via P-POD
- Launch ready ~ 2015
- 1-2 month drag-free ops in low g environment < $10^{-8}$ m/s$^2$

Management
- NASA ARC: PM, SE, SMA, MO
- Stanford: Payload design, drag-free control, data analysis
Conclusions

1. Physics & Astrophysics are in a 'DARK' period; GW Astronomy is a very plausible SOLUTION

2. A LISA-2020 Type Geocentric Medium GW Antenna Can Provide Excellent GW Data ~2020

3. Technology Development on Small Sats Provides the Road to LISA-2020 & Significant Science
Thank you for your attention