LISA - A Mission of Discovery

Gravitational Wave Detection - Laser Interferometer Space Antenna

A Physical Cosmology-focused Overview

Scott Perrin

The LISA mission will discover and study a variety of cosmic events and systems with high sensitivity in a new era of multi-messanger astronomy…. To be described more fully in a few minutes, but first some background

Contents

1. Gravitational & Electromagnetic Radiation
2. History
3. Science
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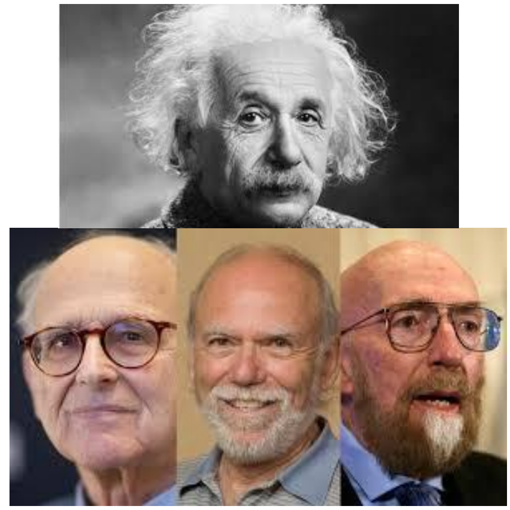
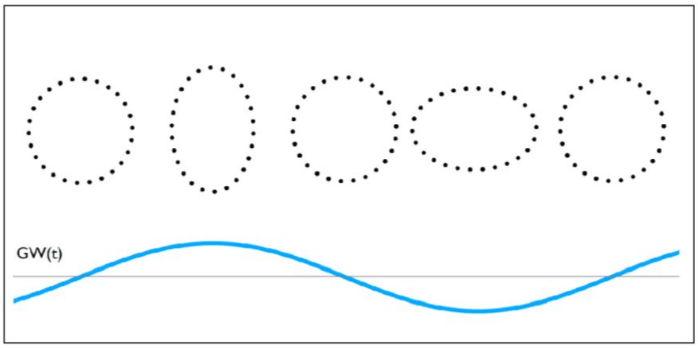
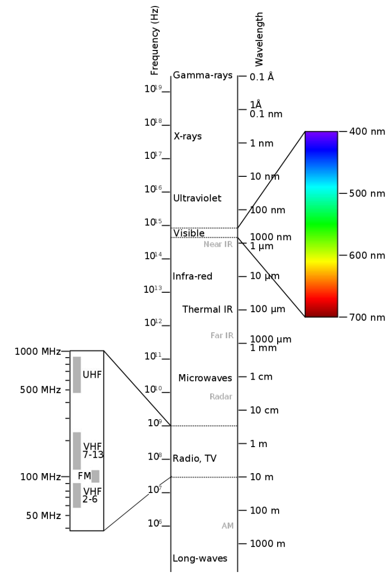


100 years in the making

Einstein Theory of General Relativity predicts Gravitational Waves - observed in 2015 (as you likely know) via LiGO, a ground based detector
2017 Nobel prize awarded to: Rai Weiss, Barry Barish, Kip Thorne for contributions to observation of gravitational waves
Not same as Gavity Waves, so not a clear abbreviation

Radiation





Emission/Transmission of Energy

Wave on ocean or pond analogy

Whereas astrophysical electromagnetic waves are typically much smaller than their sources, ranging from a few kilometres down to sub-nuclear wavelengths, gravitational waves are larger than their sources, with wavelengths starting at a few kilometres and ranging up to the size of the Universe. A gravitational perturbation larger than the Universe would not be called a wave because it would not have any detectable oscillation; in fact, it would not be detectable at all.

Spacetime distorted by effects of strain - magnitude decreases in proportion to the inverse distance from the source. Figure 1. Effect of gravitational waves on a ring of ‘test masses’. When a gravitational wave passes perpendicular to the plane of the ring, it deforms the circular ring into ellipses. In this figure, the deformation is greatly exaggerated; the actual distortion is minute, but it can be detected using a high precision laser interferometer.

➔ History - Astrophysical vs Cosmological GW Background

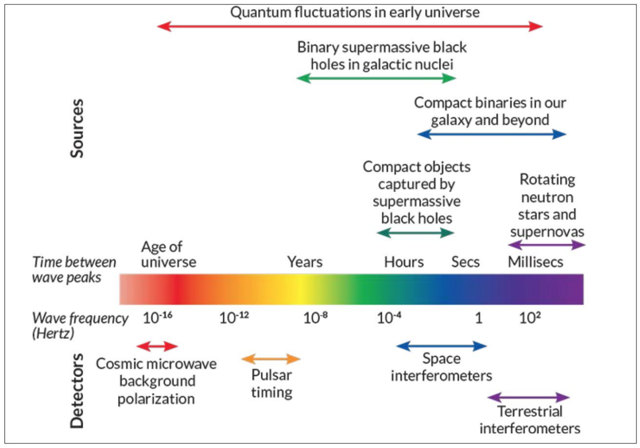


Figure 1: Gravitational-wave spectrum (credit: NASA)

How we got to where we are

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Gravitational Wave International Committee - helps coordinate all GW detection strategies and multi-messenger approaches

LISA: Third Generation of Detectors (upgrades to LIGO and others are second gen). LISA will be able to detect binaries shedding gravitational waves in wider orbits and with heavier masses than LIGO, opening up a new window on the universe to study objects such as white dwarf binaries and supermassive black holes. As soon as it's turned on, LISA will detect a "hum" of sources in all directions, giving researchers a treasure trove of data that will illuminate many new and different aspects of the universe in which we live.

The Deci-Hertz Interferometer Gravitational wave Observatory (or DECIGO) is a proposed Japanese, space-based, gravitational wave observatory.[1][2] The laser interferometric gravitational wave detector is so named because it is to be most sensitive in the frequency band between 0.1 and 10 Hz,[3] filling in the gap between the sensitive bands of LIGO and LISA. If funding can be found, its designers hope to launch it in 2027.

PTA experiments (nHz) - Multiple Radio telescopes: EPTA - European Pulse Timing Array; IPTA - International Pulsar Timing Array; SKA - Square Kilometre Array (increases the sensitivity of pulsar timing)

Source of GWs detectable in the LIGO band (100-1000 Hz early designs, 10-1000 later designs); LISA band: mili Hz to Hz

Optional Background information:
Massive black hole binaries = 1.5 - 100 solar masses

- GW Sources - LISA band
  - Galactic binaries
  - Massive Black Hole related
    - Origin of “seed” MBHs/related collisions
    - 10xSun stars/dwarfs in orbit around MBHs
    - Coalescence of MBH binaries
  - Stochastic backgrounds
  - Cosmological sources
    - Primordial gravitational waves
      - Complementary to CMB/polarity experiments
    - Early Phase transitions

If LISA will detect so many sources at once, how will astronomers ever separate them? It’s a bit, Larson says in his talk, like how one picks out individual voices in a room during a party. Amidst the background noise, you can easily focus in on the conversation you’re having because it’s happening nearby; astronomers will use several techniques to do the same, isolating signals against the background to hone in on a given source of gravitational waves.

- ➔ Science
  - ◆ Cosmology
    - Probe rate of expansion of the universe
    - Understand stochastic GW backgrounds
    - GW bursts and unforeseen sources
  - ◆ Astrophysical
    - Evolution of compact binary stars in the MW
    - History of massive BHs
    - Probe dynamics of dense nuclear clusters via EMRIs
    - Astrophysics of stellar origin BHs

Multiple Objectives

Generally, mission focus around two key questions: 1) evolution of massive black holes and 2) Nature of gravity near black holes and on cosmological scales; Missions most well funded address multiple questions and target issues…

Mission Framework: Objectives -> investigations -> observational requirements -> mission requirements

Background - cosmology ; Foreground - Astrophysical sources

Cosmology:

- relics of inflation and of the symmetry-breaking epoch directly after the Big Bang - measuring the background of inflationary gravitational waves would confirm inflation models and determine energy scale of inflation
- **Stochastic gravitational waves** arise from a large number of random, independent events combining to create a cosmic gravitational wave background. The Big Bang is expected to be a prime candidate for the production of the many random processes needed to generate stochastic gravitational waves (and the CMB), and therefore may carry information about the origin and history of the universe.

EMRI - extreme mass ratio inspirals == objects of highly different mass

Multi-Messenger strategies - A gravitational-wave observation provides the distance to the host galaxy, and an electromagnetic observation can give the redshift. From

their relationship, the Hubble constant can be inferred using current detectors, and more-sensitive detectors will be able to pin down the universe's energy content in terms of dark energy, dark matter, and baryons. And, he says, because the redshifts of binary neutron stars can be inferred from gravitational-wave observations alone, it should one day be possible to do cosmology with just gravitational-wave detectors.
Ideas -> expectations and hopes

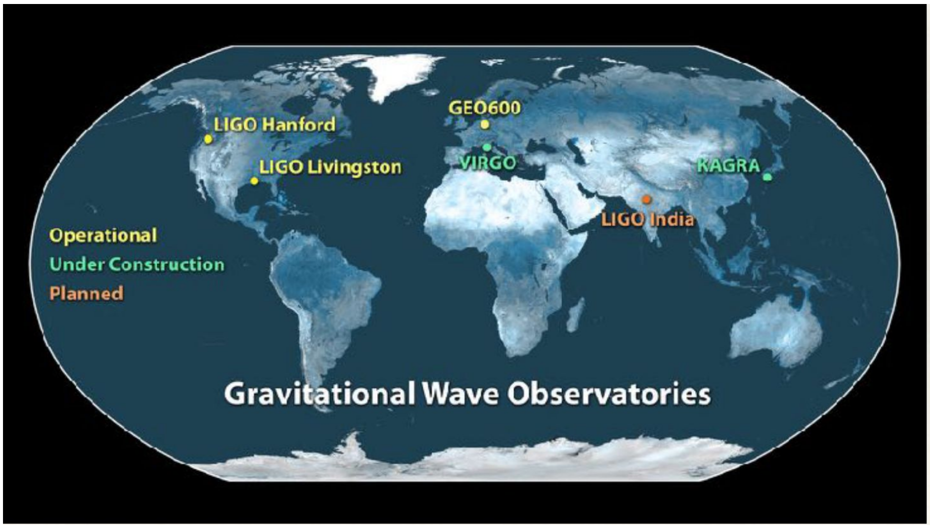
- Cosmological vs Astrophysical GW Background
  - Cosmological
    - Emitted ~10^-24 seconds after the BB
    - Test inflationary models
    - Topological phase transitions and cosmic strings
    - String Theory
  - Astrophysical - heaviest and most distant objects via LISA band
    - Compact binaries
    - Pulsars
    - Core-collapse supernovae

Massive black holes == few x mass of sun to 100 million x mass of sun
Z ~20 prior to epoch of re-ionization

- ◆ First order phase transitions?
- ◆ Detections of stochastic backgrounds
- ◆ Topological defects
- ◆ Standard sirens
- ◆ Tests of General Relativity
- ◆ Bound Inflation Models
- ◆ Primordial black holes and dark matter
- ◆ Structure formation

- ➔ Ideas - Some Details
  - ◆ Probe bulk motions at $3*10^{-19}$ - $3*10^{-10}$ secs post BB
  - ◆ 0.1 TeV - 1000 TeV, if 10^{-5} of energy density is converted to gravitational energy at production
    - First-order cosmological phase transitions
    - Dynamics of warped sub-mm extra dimensions
    - Backgrounds, bursts, harmonics from cosmic strings
    - Terascale inflationary reheating
    - Exotic inflationary quantum vacuum fluctuations

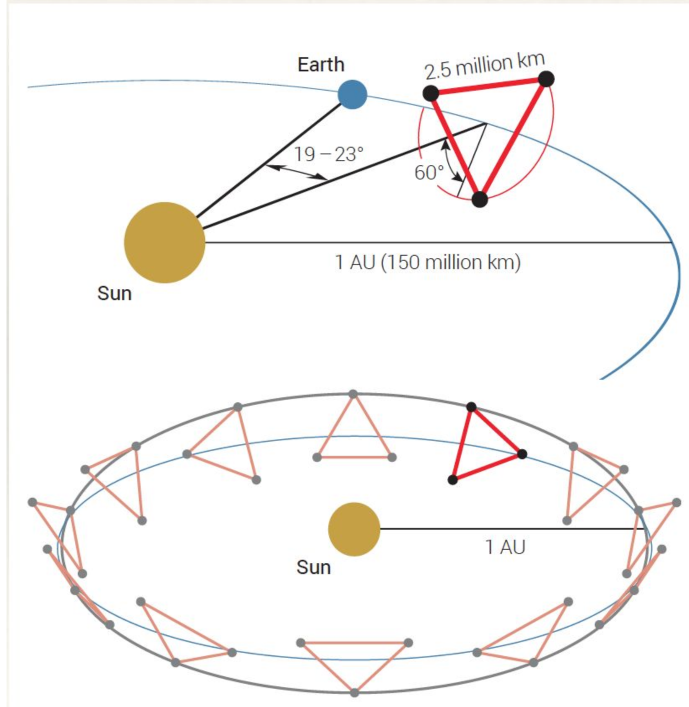
Pose objectives as questions



LIGO/VIRGO GW Detectors

➔ Mission Overview
- Pathfinder 2015
- Lisa 2032

Ariane 6



- Principle - in curved spacetime, two distant free-falling observers (test masses) exchanging a laser beam observe a time-varying difference between their respective measurements of beam frequency
- Jaw dropping moments - distance between satellites and complexity of getting (them) into orbit; test mass in free fall; data analysis
- Survey **<u>low frequency</u>** gravitational wave band (0.1 mHz to 1 Hz) - sensitivity to Z=15-20
- Identical satellites (current design - previous mother and 2 child versions) from a dedicated (vs shared) launch vehicle with propulsion to reach desired orbit… size/test mass etc. Powered by propellant and 3m solar array. 2W lasers. Distance maintained via aux modulation on laser beam
- Size and weight each? 3x3m each, 120 kg (265lbs)
- 4 year base, extensible to 10 year mission; Transfer time before start of ops, 400 days
- LISA: 5 m km arms -> **2.5m km (2017/ 1.6m miles)** -> 1m km (eLISA) arm length separation
- 50-65 million km from earth <30-40 million miles> WFO!
- Near full time observation with dynamically allocated protected mode (when predicted observations are expected) and calibrations, but communications 8 hours per day
- ~300 MB of level 1 data per day (600 MB of level 2 data) - data sent to the ground stations for processing. Single ground antenna at each of 2 data centers (US and Europe)

➔ Summary:

1. Scope: Gravitational wave detection
2. Schedule: 2032 launch
3. Budget: LISA -> NGO -> eLISA -> ?
4. Risks:
   a. Cost and mission scope reduction
   b. Data analysis, noise mitigation, equipment failure
   c. Obsolete before launch?
5. Leadership and the team

Multi-Messenger Astronomy

Scope: Gravitational wave observational science is in its infancy - started by Reiner Weiss more than 30 years or so ago

LISA staff have tried to anticipate discoveries and confirmations in related areas in the meantime…..

Schedule: How old will you be? 2032 launch + 400 days transfer time

Budget: evolution over last almost 20 years; 4 year base mission with design extensible to 10 years

Risks - at distance - not serviceable with current spacecraft like Hubble.

Cannot take leadership (to drive funding) for granted!

Plan your science - a new tool for multi-messenger detections - I believe these collaborations will continue to be the future of astronomy - GW astronomy is in its infancy

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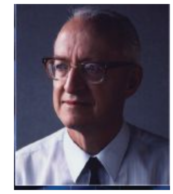
Questions?

GW observational science is in its infancy - started by Reiner Weiss more than 20 years or so ago
Plan your science - a new tool for multi-messenger detections - I believe these collaborations will continue to be the future of astronomy
Science may self-select your friends and colleagues - Peter Bender

Backup Slides

LISA

➔ Remarkable Coincidence



- "The first mission concept studies for a space-borne gravitational wave observatory can be traced back to activities in the 1980s at the Joint Institute for Laboratory Astrophysics (JILA) leading to a first full description of a mission comprising three drag-free spacecraft in a heliocentric orbit...." [1]

It's who you meet

Peter Bender here at JILA - major contribution was related to orbit that makes the mission possible…

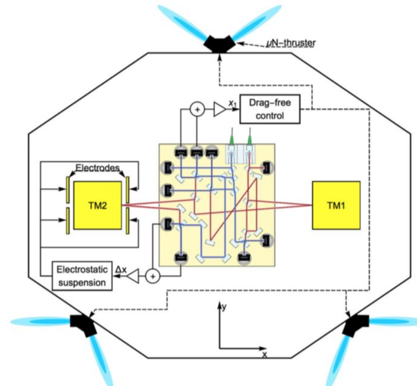
Concept to detect GWs 1970s-1980s - Rainer Wiess paper in '72; shared related Nobel prize in 2017

Bender: 6 manned moon missions from 1969-1972 via Apollo 11-17 (Apollo 13 that had an equipment failure/movie with Tom Hanks). Early missions learnings that Astronauts could not work > 30 minutes before chaffing from gloves/suits - needed experiments that were simple to setup on moon surface as proposed and finally accepted by NASA after JILA heard about the issue and persevered in getting the mirrors placement on surface accepted… result was laser-mirror distance measurement after JILA staff recommended based on chance opportunity surmised at NASA meetings.

Genesis: ICTP Cosmology Summer program - similar to TASI at CU (Theoretical Advanced Study Institute in elementary particle physics: John Noonan / Jeremy Darling / Ravi Sheth / Stas Babak / Andrew Hamilton => Peter Bende

➔ Prototype - LISA Pathfinder, Dec ‘15 - Jul ‘17

- Demonstrate free fall of test masses
- Insensitive to GW due to test length
- Prove interferometric readout of relative test mass motion with characterized noise
- Varying electrostatic forces applied to test masses
- Differential displacement of TMs



Preparation for Cosmology Science

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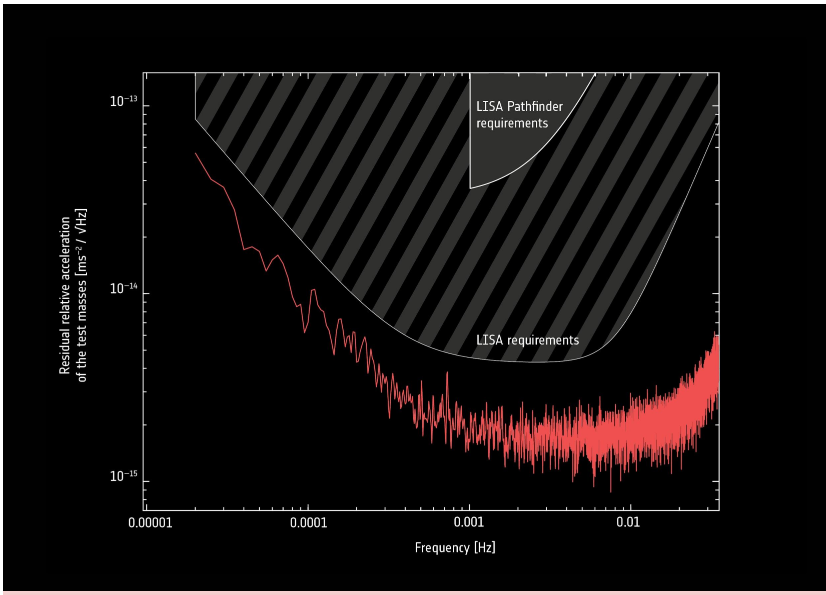
LISAPathfinder - Technological mission to prove the technical readiness of LISA - Dec 2015, final report Spring 2016: fantastic results, order of magnitude better than minimum requirement
Model catalog of mock data from multiple sources to develop signal processing techniques; Spacecraft: 580 Kg or 1000 lbs; **$600M mission**.

Orbit around L1 point - In the Earth-sun system, for example, the first point, L1, lies between Earth and the sun at about 1 million miles from Earth...A Lagrange point is a location in space where the combined gravitational forces of two large bodies, such as Earth and the sun or Earth and the moon, equal the centrifugal force felt by a much smaller third body. The interaction of the forces creates a point of equilibrium where a spacecraft may be "parked" to make observations.

Test Masses: Gold:Platinum alloy has a very high density (20,000kg/m3). This is very important as our little cubes (46mm on a side) have a mass of 2kg. The particular alloy has a very low susceptibilty to magnetic fields, which again reduces the noise of the test ass motion; microNewton thrusters/Capacitive sensors surround test mass to monitor position/orientation. A relative acceleration lower than 1 part in ten millionths of a billionth of Earth's gravity is simply unimaginable.

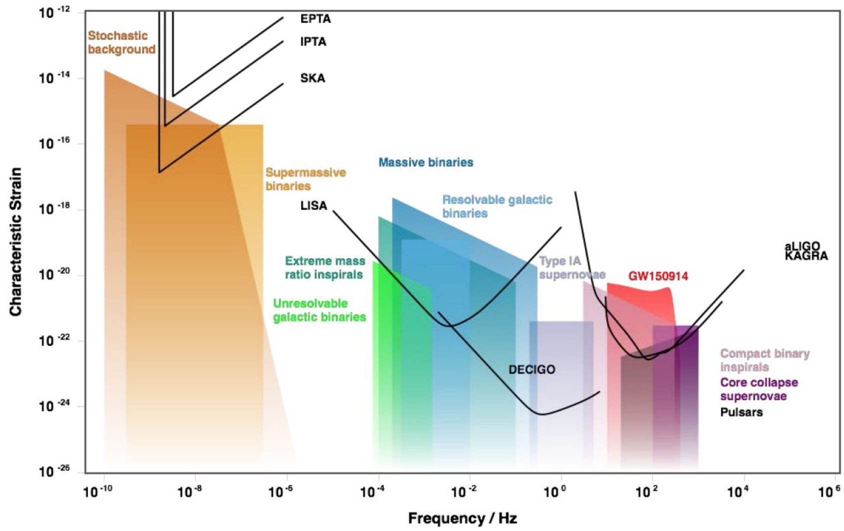
GWs change light travel time or optical path length between free falling test masses..
Laser interferometers measure distance between test masses (beryllium) -
pico-meter (10^-12) to nano-meter (10^-9) path length variations caused by GWs;
note atom is 10^-10 meter.



Get to the Next Step

➔ Future Observation

- Characteristic Strain, h_c - accumulate power in signal over a time frame
- Well-defined source:
  - $h_c^2 \approx \int h(t)^2\, f dt \approx N h_0^2/8$
- Stochastic:
  - $h^2 = \int S_h(f)\, df$



Have the Next Goal in Mind

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Teach me something new - fresh way of looking at old problems:

Whereas astrophysical electromagnetic waves are typically much smaller than their sources, ranging from a few kilometres down to sub-nuclear wavelengths, gravitational waves are larger than their sources, with wavelengths starting at a few kilometres and ranging up to the size of the Universe. A gravitational perturbation larger than the Universe would not be called a wave because it would not have any detectable oscillation; in fact, it would not be detectable at all.

The following diagram illustrates some typical amplitudes and wavelengths of gravitational waves across this entire spectrum, and the sensitivities of several detection methods. Some of these sources are quite speculative, or have highly uncertain amplitudes. There are also many more speculative sources that have not been included here.

The *h* axis is not the raw, instantaneous strain of the source. (In particular some sources are stochastic in nature and have no well-defined "instantaneous" strain.) Instead, it is the "characteristic" strain that one obtains by accumulating the signal over some timescale. For rotating sources the strain is also averaged over possible inclination angles.

- For sources with a **well-defined** $\boldsymbol{h(t)}$, one can accumulate the power in the signal over **many cycles** $\boldsymbol{N}$, giving $h_c^2 \approx \int h(t)^2\, f dt \approx N h_0^2/8$, where $\boldsymbol{h_0}$ **is the**

- **peak amplitude and 1/8 approximates the time and angle averaging**. For nearly constant-frequency sources, we use $N = f \times 1$ year. For sources that sweep through a large frequency range in one year, the number of cycles it spends near a given frequency is $N \approx f^2/(df/dt)$. In the latter case, we plot one year's worth of signal, sweeping through amplitude and frequency, from the strongest such source that one might expect in any given year.
- For sources of a stochastic nature, we do not have a well-defined $h(t)$. Instead, such signals have a ***power spectral density*** $\boldsymbol{S_h(f)}$ such that the mean squared fluctuations in h are given by $h^2 = \int S_h(f)\, df$. By correlating the signal between two detectors, one can achieve a further improvement in the signal strength, by a factor of $N^{1/2}$, where N is the number of cycles correlated. We therefore define a characteristic strain $h_c^2 \approx N^{1/2} f\, S_h(f)$, where $N = f \times 1$ year, or $N = 1$ for $f < 1$/year.
- For the various detectors, their sensitivities are defined by the power spectral density of their noise $S_n(f)$. As above we can define a characteristic noise strain $h_n = f\, S_n(f)$. A signal is detectable in a given detector if h_c exceeds h_n by a factor of a few (the *signal-to-noise ratio*).

Gravitational Wave International Committee - helps coordinate all GW detection strategies and multi-messenger approaches LISA: Third Generation of Detectors (upgrades to LIGO and others are second gen)

The Deci-Hertz Interferometer Gravitational wave Observatory (or DECIGO) is a proposed Japanese, space-based, gravitational wave observatory.[1][2] The laser interferometric gravitational wave detector is so named because it is to be most sensitive in the frequency band between 0.1 and 10 Hz,[3] filling in the gap between the sensitive bands of LIGO and LISA. If funding can be found, its designers hope to launch it in 2027.

PTA experiments (nHz) - Multiple Radio telescopes: EPTA - European Pulse Timing Array; IPTA - International Pulsar Timing Array; SKA - Square Kilometre Array (increases the sensitivity of pulsar timing)

- Follow the Money
  - ESA large project (L3)
  - NASA study team
  - LISA Consortium
  - Status - detailed schedule to 2022
    - Space System development - payload engineering
      - Phase A: contractors developing specific designs

People, Satellites, and Rockets are Expensive

On 25 October 2016, ESA issued a formal call for proposals from the scientific community. The proposal for 'LISA-2' was evaluated, and on 20 June the LISA concept was selected as ESA's next large mission, L3. Formal adoption of the mission by ESA's Science Programme Committee is expected no later than 2025, with a launch nominally scheduled for 2034.

- NASA involvement
  - US Study Team established July 2017
  - Launch support? Funding priorities are science….
- LISA Consortium
  - Bi-annual meetings

NOTE: eLISA or evolved LISA is a downscoped variant that accomplishes most of the science, 1.0 km arms (original proposal was for 5 million km arms), which could be launched by 2022

Current Status: in L3 - launch per decade

Options such as rigid organization such as 1) CERN to collaboration of collaborations (current GW detectors); unified central management to help coordinate planning for observing and data access or Cookie cutter approach or best possible facility…. Barry Barrish (shared Nobel prize in 2011).... How best to set scientific priorities with finite cash (and evolve current generation and and plan next gen detectors with limited resources).

- Follow the Money (continued)
  - Governments provide budgets for majority of (cosmology) research
  - In some countries, researchers are paid below living wage scales
  - Ideas to increase funding
    - Directed donations by university/college alumni
    - More focus on private foundations as source
    - Private enterprise motivations
    - Monetize research

People, Satellites, and Rockets are Expensive

End with showstopper - Dodelson book prop - Ilhar (Igor) Dudko from Belarus (list intellectual elite in WWII) - can't afford Cosmology by Dodleson on my postdoc salary….

- Topics - June 2018
  - First order phase transitions
  - Detection of stochastic backgrounds
  - Topological defects
  - Standard sirens
  - Testing General Relativity
  - Inflation and beyond
  - Primordial black holes and dark matter
  - Structure formation
- Work packages by the Cosmology Working Group
- Prospects to participate in multi-messenger detections
- Primordial BHs - possibly in LISA sensitivity band
- Data analysis techniques to extract events from data
- GW from cosmic strings and phase transitions

5th Cosmology Working Group Workshop

Detection of PBHs depends on mass and LISA sensitivity band
Cosmic Strings are proposed thread-like objects of concentrated energy that may have been produced in the early universe
First order phase transitions - universe may transition from one phase to another through nucleation, expansion/merger of bubbles.. Sound waves -> source gravitational waves…

In the standard model of particle physics there are no first-order phase transitions in the early universe… unless the model is extended with additional/undiscovered particles (at scale observable by LISA)
Inflation/modified theory of gravity support - range of particle physics to consider e.g. extra spectator fields during inflation -> merger of these compact objects could form a stochastic background in the LISA band

- In Standard Model of Particle Physics, there is no first-order phase transition in the early universe…. What if detected such a transition is observed by LISA? New particles?
- Inflation - some models give rise to GW that LISA could detect
  - Background GWs due to extra spectator fields
  - Primordial Black Holes from vacuum fluctuations (mergers could be detected in LISA band)
- Modified Gravity

Detection of PBHs depends on mass and LISA sensitivity band

- ➔ eLISA - launch prior to 2022; 10^9 m arms
  - ◆ Ultra-Compact Binaries
  - ◆ Astrophysical Black Holes (10^4 - 10^7 mass of sun)
  - ◆ Extreme mass ratio inspirals and astrophysics of dense stellar systems
  - ◆ GR - precision measurements of strong gravity
  - ◆ Cosmology
    - Uncertain/unpredicted sources (relics of inflation and symmetry breaking epoch after BB

Doing Science with eLISA (20120013339)

1. A stochastic background in the eLISA frequency band can be generated by less conventional sources, such as phase transitions in the very early Universe and/or cosmic strings.
2. Cosmology - eLISA will probe new physics and cosmology with gravitational waves, and search for unforeseen sources of gravitational waves. The eLISA frequency band in the relativistic early Universe corresponds to horizon scales where phase transitions or extra dimensions may have caused catastrophic, explosive bubble growth
   and efficient gravitational wave production. eLISA will be capable of detecting a stochastic background from such events from about 100 GeV to about 1000 TeV, if gravitational waves in the eLISA band were produced with sufficient efficiency.
3.

- Gravitational Waves
  - Physics of detection
    - LIGO/Virgo and network of ground-based detectors
    - LISA - space based satellites
  - Generation of GW
  - What GW can tell us about gravity
  - Black hole dynamics

Exciting new complement to electromagnetic spectrum-based observation/probes

Historically, mankind has gathered most observation about the Universe through probes via electromagnetic radiation including visible light… now
GW detection and study will open a whole new rich channel in understanding gravity and underlying physics of the universe.
New observation/detectors are under upgrade/modification or design
Arguably the most exciting area of the six areas presented during the school program, and focus of significant global research communities

- ➔ Standard Model of Cosmology - unresolved issues
  - ◆ Lithium problem
  - ◆ Form of Baryons (esp low redshift)
  - ◆ Understanding of the end of the dark age
  - ◆ Validity and precision of perturbation theory
  - ◆ Nature and properties of dark matter
  - ◆ Cosmological constant problem/dark energy
  - ◆ Microphysics behind inflation
  - ◆ Connecting inflation to the big bang
  - ◆ Fine tuning
  - ◆ Primordial singularity
  - ◆ Quantum Gravity

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➔ Peter Bender-JILA: Interview, September 19, 2018
- ◆ Insight to your interest in Gravity Waves and possible detection via LISA? Initial tech barriers a worry?
- ◆ What are the current challenges? Funding? Tech?
- ◆ What do you think NASA involvement will be in LISA mission? Study team progress?
- ◆ Current focus/Any recent papers
- ◆ What are the most important objectives in your view - related to cosmology?
- ◆ Primordial Gravity waves via LISA?

Take Away

- ICTP Summer Program - Stanislav (Stas) Babak.
  - University of Paris Diderot; 26,000 students
  - AstroParticule et Cosmologie, CNRS (Paris); Astroparticle and Cosmology lab - 200 researchers
- ESA vs NASA led?
- July 2017 - NASA LISA study team
  - Rita Sambruna - Program Scientist NASA HQ Astrophysics division
  - James Thorpe - Study Scientist, NASA Goddard Space Flight Center
  - 2020 Decadal Survey paper? Draft available?
- July 2018 12th Annual LISA Symposium, AAS - Chicago, 241 Attendees, including Bender, Alberto Roper-Pol, Tuck Stebbins
  - ?

➔ Peter Bender-JILA: Interview, September 19, 2018
- Advice for graduate students in the class?

Take Away

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- ICTP Summer Program - Stanislav (Stas) Babak.
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- ➔ Peter Bender-JILA: Interview, September 19, 2018
  - ◆ History - Bender - JILA founding scientist - estimated at 80 yrs old as was in Boulder 1962 on staff
  - ◆ Apollo 11 contingency project 1969
    - Astronauts were getting sore in space suites and NASA limited time on moon surface to 2 hours - some experiments were then cut as too long - Dicke proposed refector project. Told it was not on list, but found out about contingency projects… this became one and JILA was on the way with related experience
    - 1974 MIT's Rainer Weiss (now 85) pioneering paper on detection laid framework for laser interferometric techniques - shared Nobel prize

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- ➔ Peter Bender-JILA: Interview, September 19, 2018
    - ◆ History con't
    - ◆ Envisioned space antennae since mid-70's to early 80s
    - ◆ One of Peter's contributions was to bring help bring back by solving orbital dynamics issue to keep satellites together (plane offset gives some advantages to orbit).....
    - ◆ 90's proposed to ESA in response to middle size mission call , scored #3 - got leg's with some NASA funding
    - ◆ NASA budget woes dropped LISA participation for some time , but
    - ◆ ESA (new/2015) director/Johann-Dietrich Worner familiar. ESA mission #2 on XRAY interferometer

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- Peter Bender-JILA: Interview, September 19, 2018
    - History cont
    - Now
        - NASA may participate - ~$300M with ESA
            - 2 European private companies on preliminary and competitive so some information is harder to get now until next year when complete; then 1 will likely take lead
            - ESA awards projects in proportion to funding countries
            - ESA would like NASA to take cost/responsibiltyu for launch, but NASA mission to fund science - JPL working on updated to thrusters

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➔ Peter Bender-JILA: Interview, September 19, 2018
   - History cont
   - Now - moving forward
     - 2016 LISA pathfinder successful
     - LIGO success

Take Away

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- Peter Bender-JILA: Interview, September 19, 2018
  - History cont
  - Now
    - Decadal 2020 survey should not be delayed (some question due to JWST) and LISA support should include a dozen science aspects to LISA mission in addition to mission plan. Due by early next year and in progress… Decadal 2020 director to be named, so up in the air at this point.
    - Launch was 2034 due to funding/long lead development, but will move up perhaps 2030-32.

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- Peter Bender-JILA: Interview, September 19, 2018
  - Tech not a big issue compared to ground Interferometric requirements.. Despite test mass clearance 4mm and arms length, orbit requirements
    - Packaging and deployment and thrusters and other issues being addressed in labs
  - Top objectives
    - Growth of 10x Sun + black holes and role in LSS
      - Confirm or other new models
    - Long monitoring of event (3 months) - prove out or find issues with GR
    - Lesser GW generation events assured
    - Not likely in range for Primordial BHs

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➔ Peter Bender-JILA: Interview, September 19, 2018

9:00 AM	**400 Supermassive Black Holes and Cosmology (Chair: Laura Blecha), 9:00 AM–12:30 PM, Grand Ballroom A–B–C**
	Nicola Tamanini (AEI Potsdam): Cosmology at All Redshifts with LISA, 9:00 AM–9:20 AM
	Zoltan Haiman (Columbia): The Electromagnetic Chirp of a Supermassive Black Hole Binary, 9:20 AM–9:40 AM
	Qingjuan Yu (Kavli IAA, Peking): Evolution of massive binary black holes in realistic galaxy distributions and their gravitational wave radiation, 9:40 AM–10:00 AM
	Luke Kelley (Harvard): LISA Sources and Detection Rates from Massive Black Holes in the Illustris Simulations, 10:00 AM–10:20 AM
	Luciano Del Valle (IAP): The Effect of AGN Feedback on the Migration Timescale of Supermassive Black Holes Binaries, 10:20 AM–10:40 AM

Cosmological forecasts for LISA mission - works on
G-W

Take Away

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➔ Black holes, gravitational waves and fundamental physics: a roadmap, pg 70

Forecasts with space-based interferometers: Space-based GW interferometry will open the low-frequency window (mHz to Hz) in the GW landscape, which is complementary to Earth-based detectors (Hz to kHz) and PTA experiments (nHz). The Laser Interferometer Space Antenna (LISA) is currently the only planned space mission designed to detect GWs, as it has been selected by ESA [64]. Several new GW astrophysical sources will be observed by LISA, including SOBBHs, EMRIs and massive BBHs from 104 to 107 solar masses. These sources can not only be conveniently employed as standard sirens, but they will be detected at different redshift ranges, making LISA a unique cosmological probe, able to measure the expansion rate of the universe from local (z 0.01) to very high (z 10) redshift. The current forecasts, produced taking into account only massive BBHs [613] (for which an EM counterpart is expected) or SOBBHs [660, 661] (for which no EM counterpart is expected), estimate constraints on H0 down to 1%. However, joining all possible GW sources that can be used as standard sirens with LISA in Black holes, gravitational waves and fundamental physics: a roadmap 71 the same analysis, should not only provide better results for H0, which will likely be constrained to the sub-percent level, but it will open up the possibility to constrain other cosmological parameters. The massive BBH data points at high redshifts will, moreover, be useful to test alternative cosmological models, predicting deviations from the CDM expansion history at relatively early times [662, 663]. Finally, more advanced futuristic missions, such as DECIGO or BBO, which at the moment have only been proposed on paper, may be able to probe the cosmological parameters, including the equation of state of dark energy, with ultra-high precision [664–667]. They might also be able to detect the effect of the expansion of the universe directly on the phase of the binary GW waveform [668, 669], although the contribution due to peculiar accelerations would complicate such a measurement [277, 670].

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