# LISA - A Mission of Discovery


## Gravitational Wave Detection - Laser Interferometer Space Antenna

### A Physical Cosmology-focused Overview

Scott Perrin

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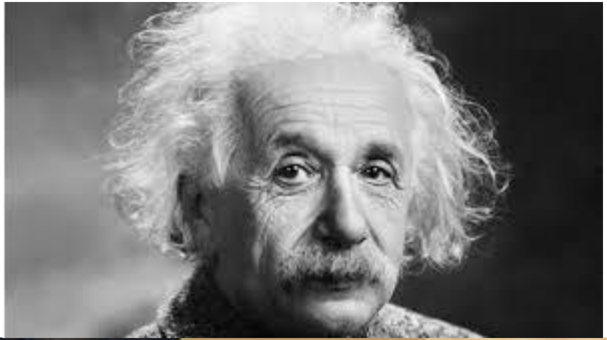
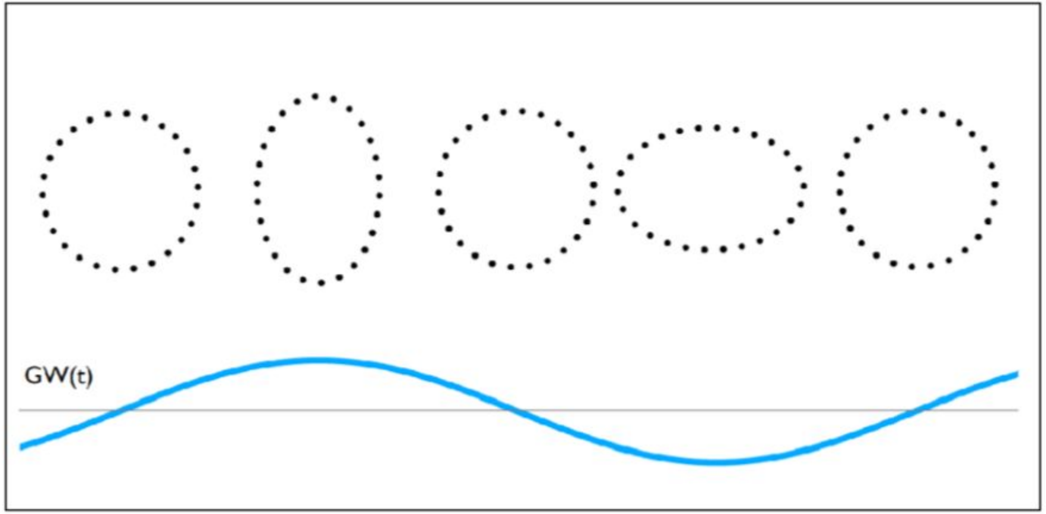
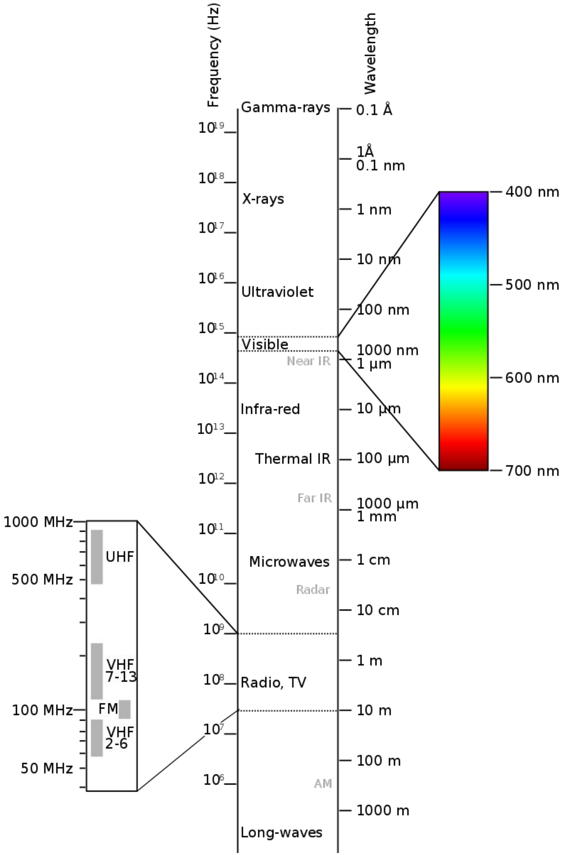


100 years in the making

# Radiation




Emission/Transmission of Energy

# ➔ History - Astrophysical vs Cosmological GW Background

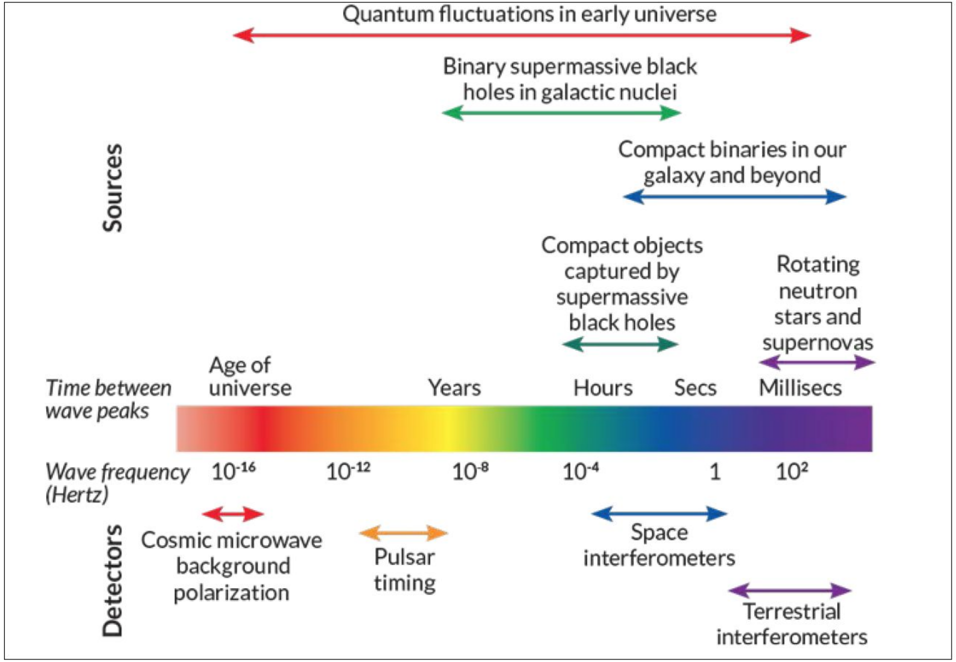
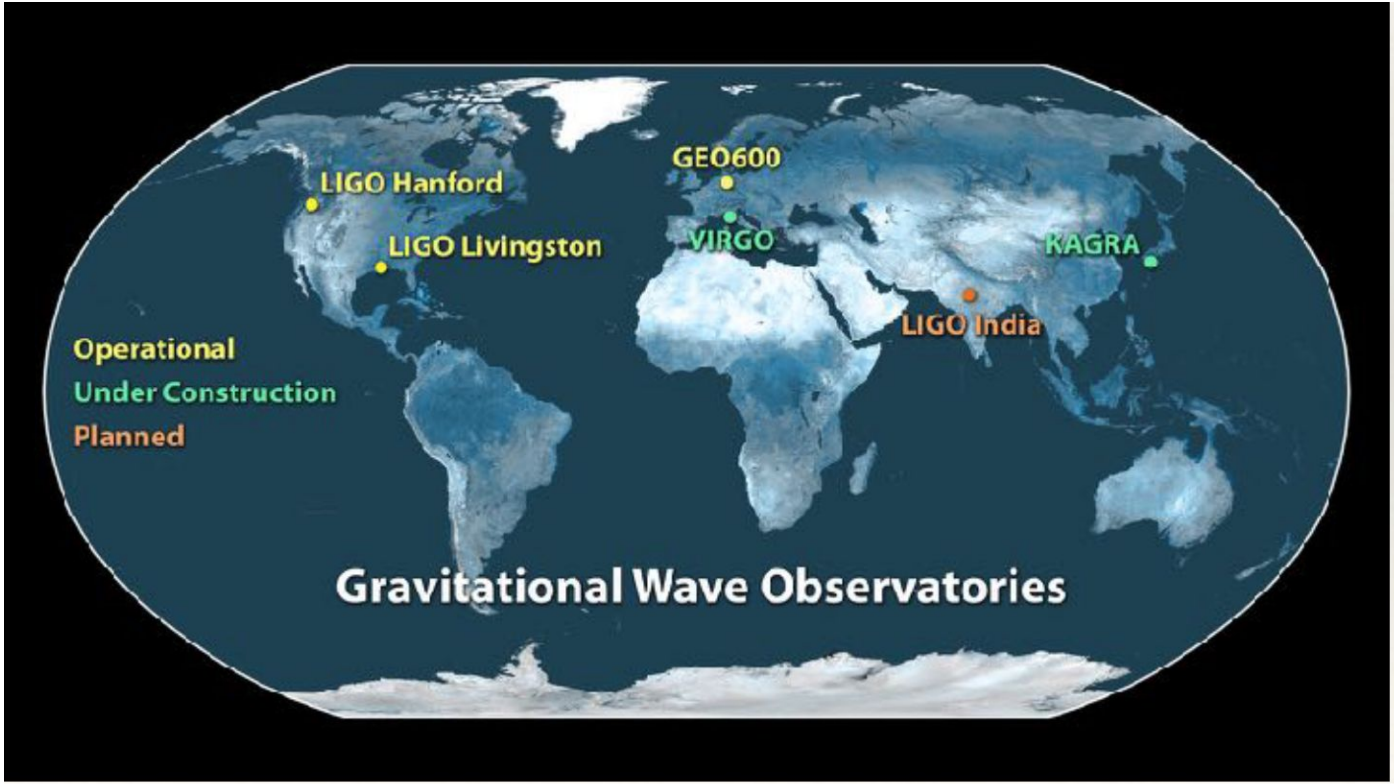



*Figure 1: Gravitational-wave spectrum (credit: NASA)*

How we got to where we are

- 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

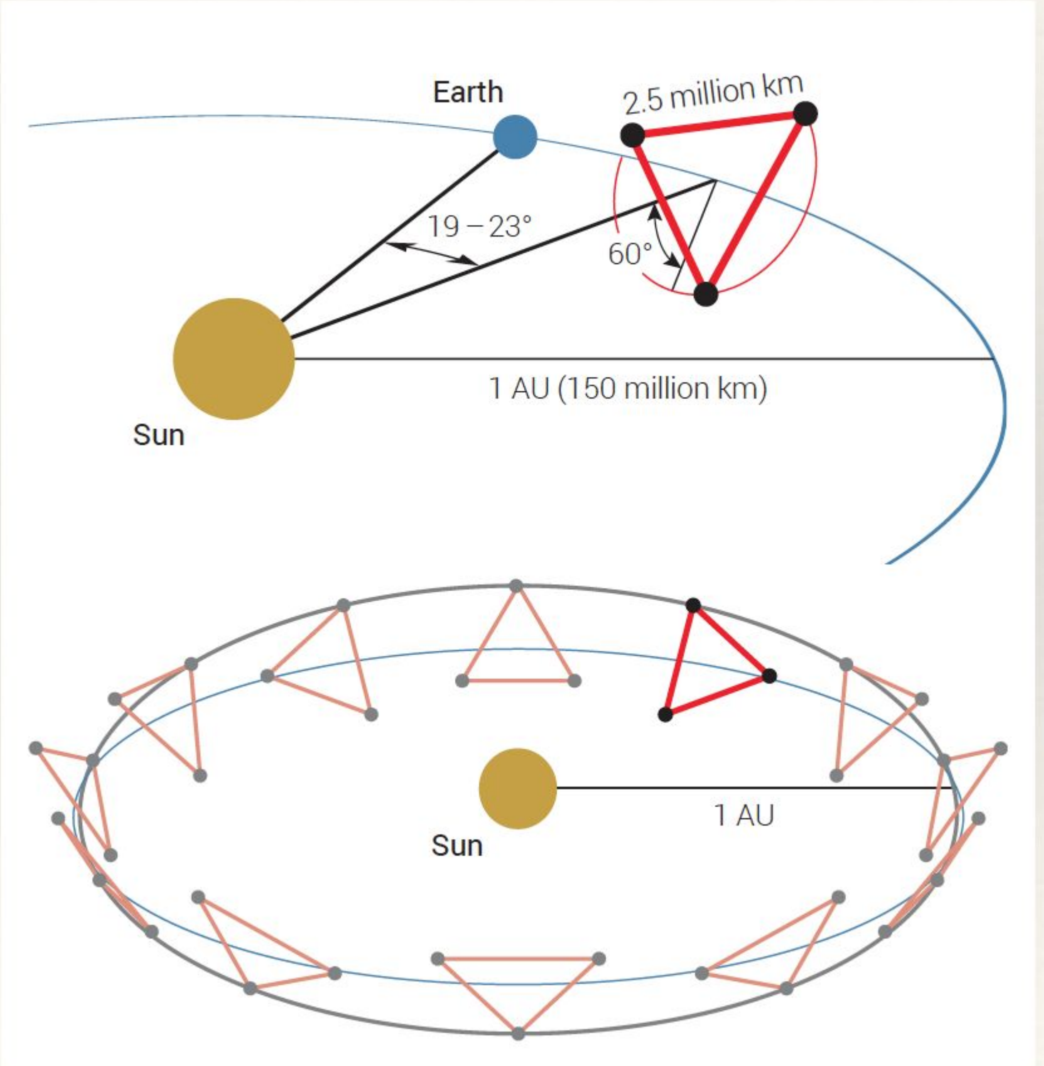



# LIGO/VIRGO GW Detectors

➔ Mission Overview

- Pathfinder 2015
- Lisa 2032

**Ariane 6**



➔ 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

# ➔ References

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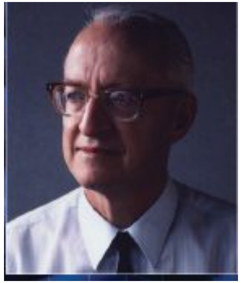
# Questions?

# Backup Slides

LISA

## ➔ Remarkable Coincidence

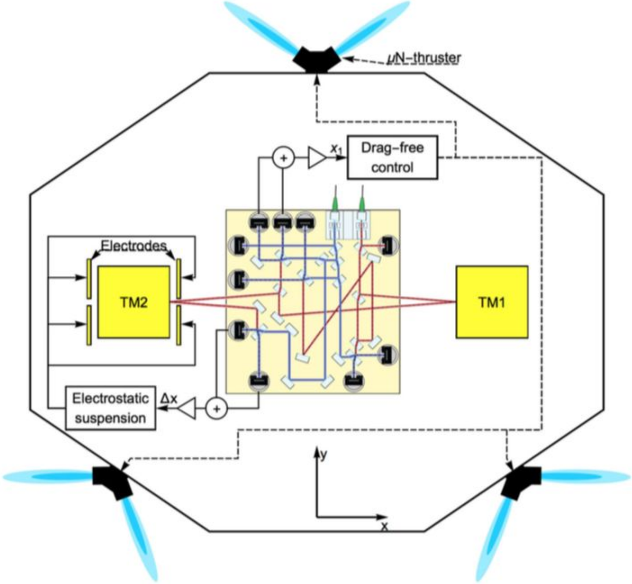


- "The first mission concept studies for a space-borne gravitational wave observatory can be traced back to activities in the 1980s at the Joint Institute for Laboratory Astrophysics (JILA) leading to a first full description of a mission comprising three drag-free spacecraft in a heliocentric orbit...."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

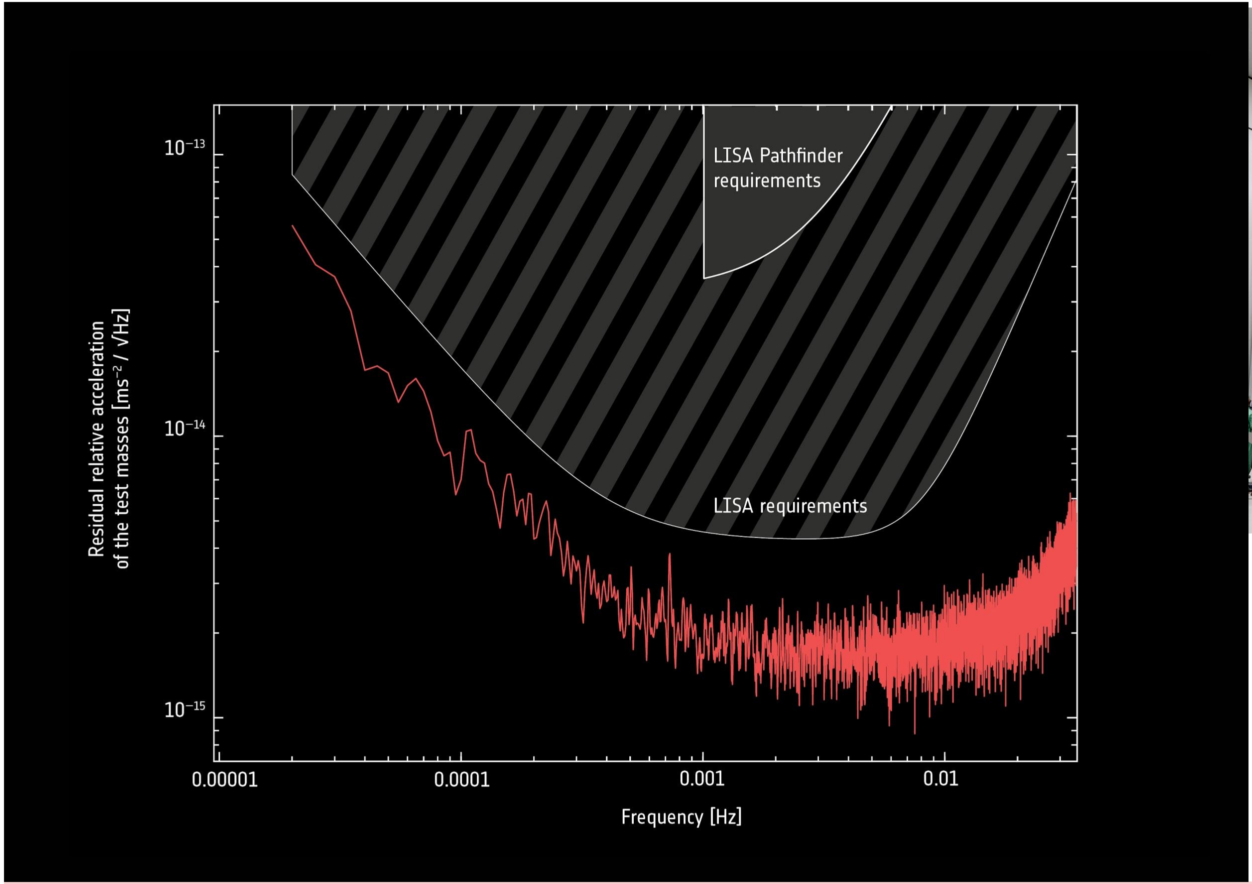
It's who you meet

# ➔ 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



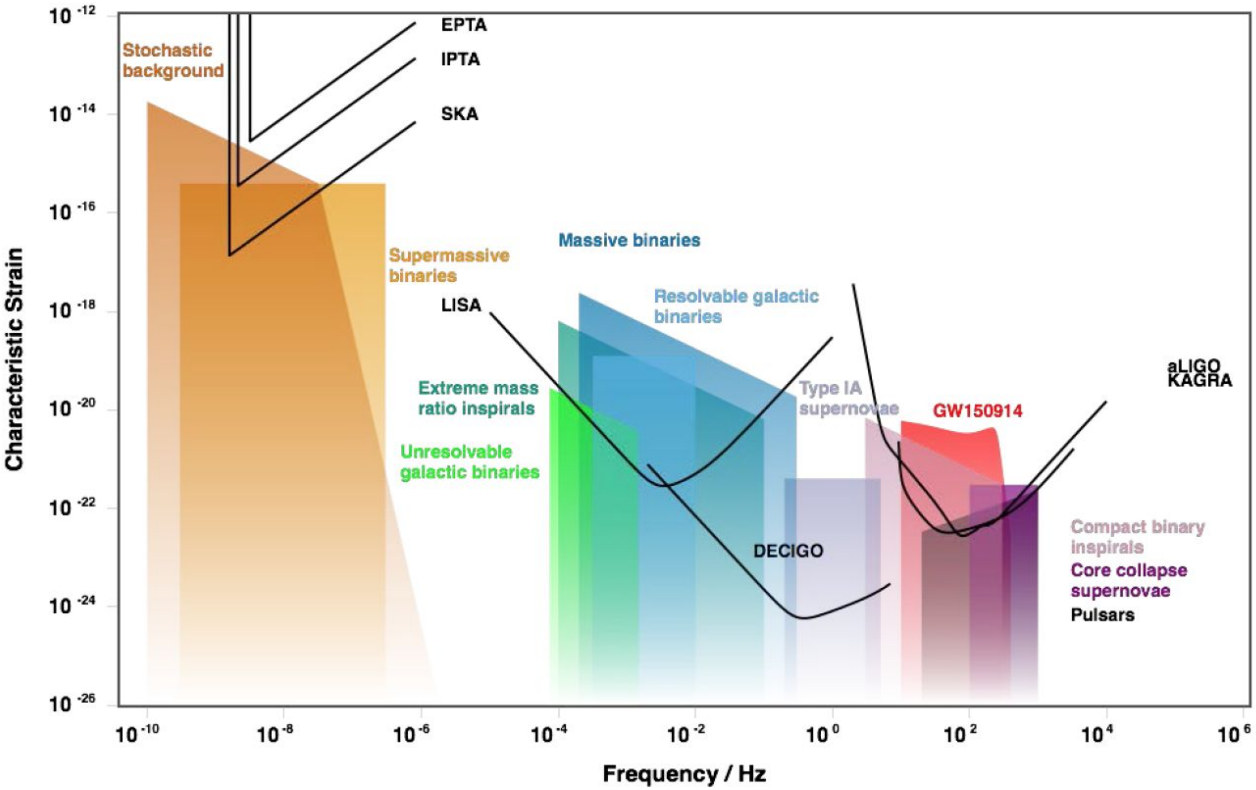

Preparation for Cosmology Science




# 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

- 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

- 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

- 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

- 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

- 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)

- 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

- 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

- ➔ 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

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

Take Away

- 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

Take Away

➔ 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

Take Away

- 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

Take Away

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

Take Away

- 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.

Take Away

- 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

Take Away

# ➔ 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

# ➔ 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].

Take Away