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Title: Gravitational-Wave Astronomy's Future Among the Stars

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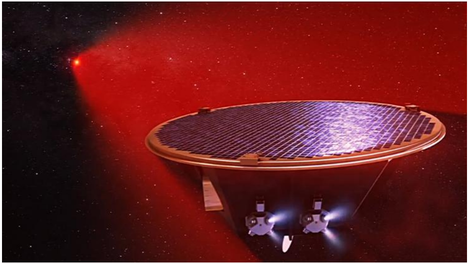
Gravitational-Wave Astronomy's Future Among the Stars

Grant David Meadors [he/him]
ISR-3, LANL

2022 February 25 (JD 2459636)
PEEC Nature Center Public Talk

Preface



Artist depiction: one of 3 **LISA** satellites in heliocentric orbit, receiving laser light to measure distance interferometrically ...
$\rightarrow$ observing gravitational waves (GWs)
Credit: AEI/MM/exozet, via NASA

LISA:
L*aser*
I*nterferometer*
S*pace*
A*ntenna*
$\therefore$ ESA-NASA mission will launch in 2037!

$\Longrightarrow$ like telescopes, GWs observatories reshape astronomy

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Outline

This evening's talk:

- Who I am
- What is a gravitational wave (GW)?
- Where LISA fits in (why it matters)
- How the future begins today

Introduction

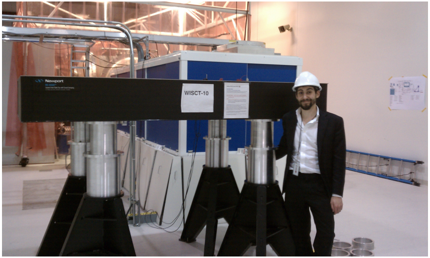
Who I am – detector characterizer/data analyst – (astro)physicist

∴ 2008 to 2019 LIGO (Laser Interferometer Gravitational-wave Observatory)

∴ PhD: UMich 2014 (Physics) + postdocs:

1. AEI Hannover 2015/2017
2. Monash 2018/2019
3. LANL postdoc 2019/2020

∴ LANL scientist (Dec 2020-)



GDM at LIGO Hanford Observatory, 2011, procuring optical table extensions for quantum-vacuum squeezer

Kip/Rai/Barry's 2017 Nobel was great, . . . "new era of astronomy" but ground-based GW science only part of astrophysical spectrum

Introduction

$>$ '40000 foot' summary $\sim$ more like 'orbital' summary

Telescopes see light from stars + hot matter (EM radiation)

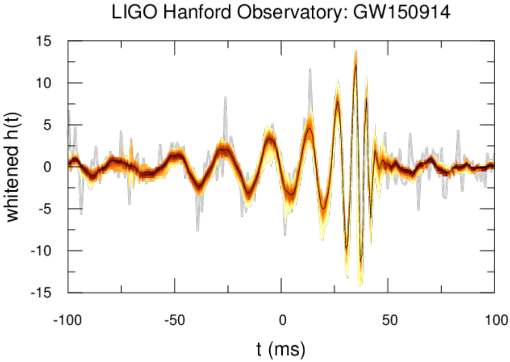
LIGO sees light (w/ interferometer),
– imprints GW signal from black holes (or neutron stars)

LISA like LIGO, but in space & BIGGER,
– bigger, slower GW signals from bigger black holes

What is a Gravitational Wave (GW)?

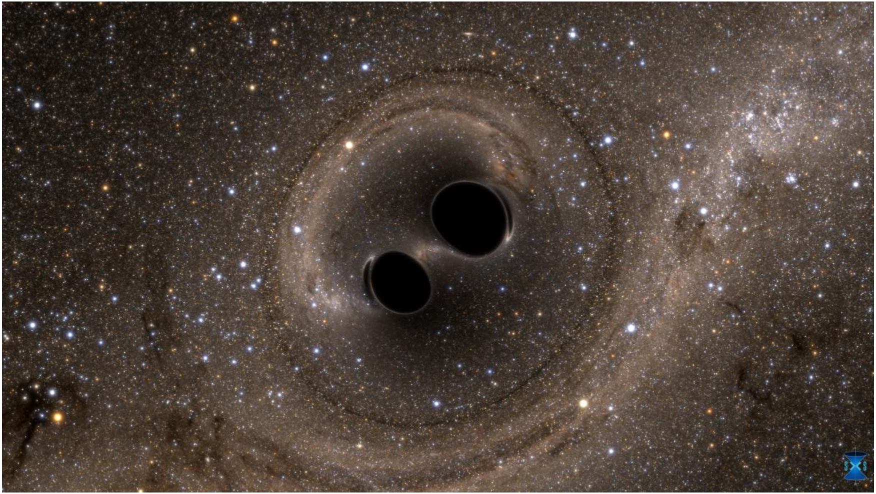
Definition

Oscillations in the metric of space ($>$ 50 mergers seen to-date)



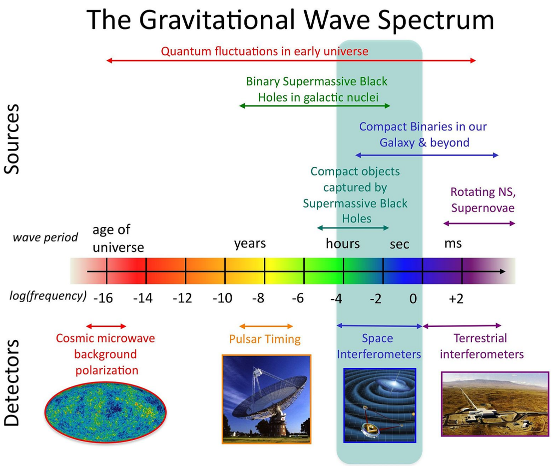
What we woke up to one Monday (credit: LIGO Scientific Collaboration)

What is a Gravitational Wave (GW)?



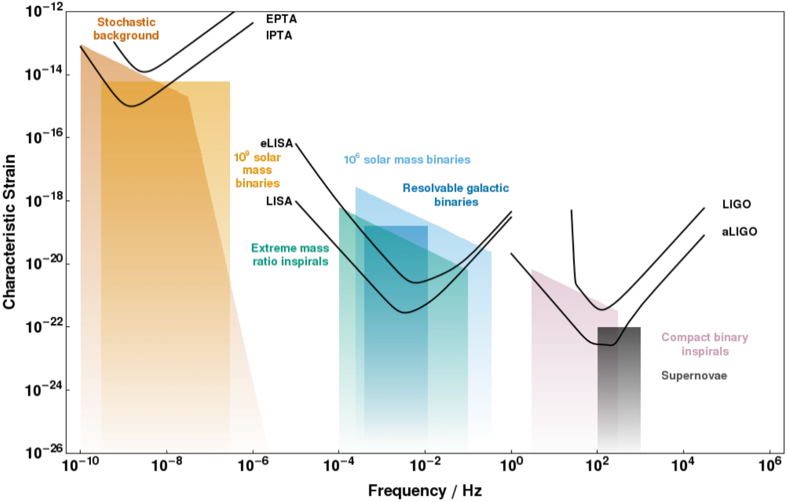
(credit: Simulating Extreme Spacetimes [SXS])

What is a Gravitational Wave (GW)? Spectrum



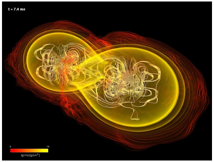
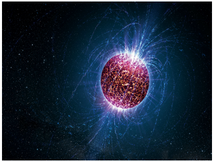
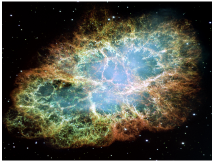
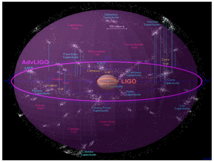
Like light: many λ/f windows (credit: NASA Goddard Spaceflight Center)

What is a Gravitational Wave (GW)? Spectrum



Pulsar-timing/LISA/LIGO sensitivity (credit: C. Moore, R. Cole, C. Berry)

What is a Gravitational Wave (GW)? Sources

	Transient	*Persistent*
Modeled	 Coalescence	 Continuous ←
Unmodeled	 Burst	 Stochastic

Credits: AEI, Penn State (C. Reed), NASA, LIGO (B. Berger)

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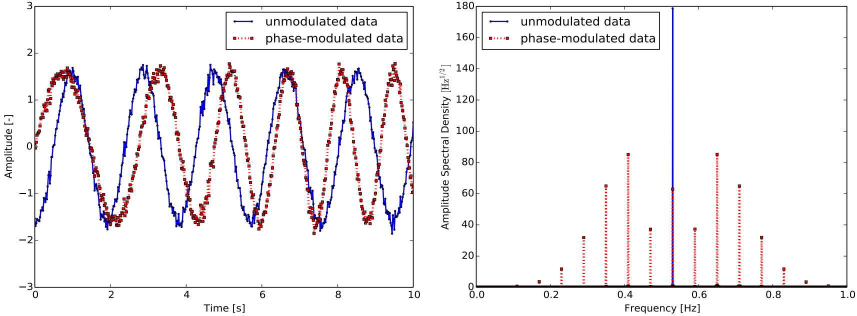
What is a Gravitational Wave (GW)? Sources

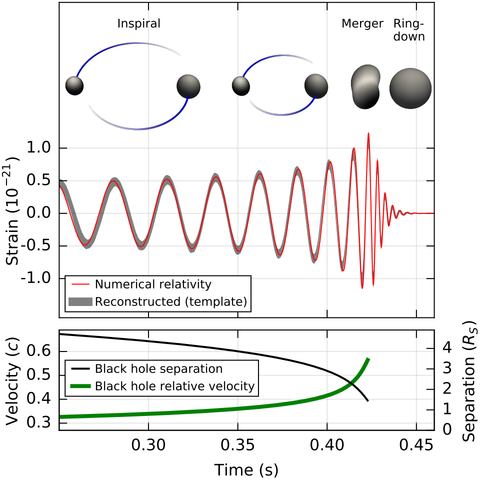
Phase modulation for long-duration GWs (simplified illustration)



Roemer/Doppler effect from orbit in time & Fourier domains

→ HPC/data-science challenge
(sub-field where I worked most: no detection yet,
but blinded data challenges prove *we have the technology*)

What is a Gravitational Wave (GW)? Sources



('Observation of gravitational waves from a binary black-hole merger', LVC, *Phys Rev Lett* 116 (2016) 061102)

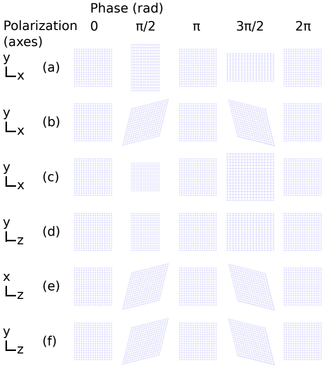
What is a... (GW)? General Relativity

Wave equation from Einstein: perturbation $h_{\mu\nu}$ to metric $g_{\mu\nu}$,

$$-\frac{1}{2}\partial_t^2 h_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$h_{\mu\nu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & -h_+ & h_\times & 0 \\ 0 & h_\times & h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\times \Re\left(e^{\mathrm{i}(k_\mu x^\mu + \phi_0)}\right)$$



6 theoretical polarizations:
conservation allows only (a) & (b) [+ & ×]

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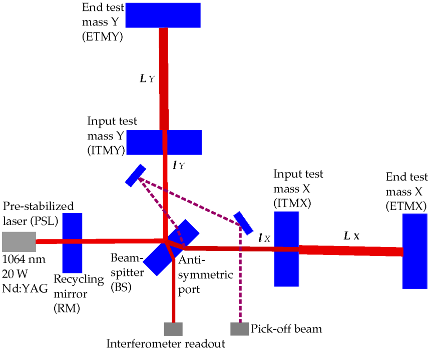
What is a... (GW)? Observatories

Infer $h(t)$: *measure* phase ϕ between times-of-flight $T_{x,y}$ (laser ω),

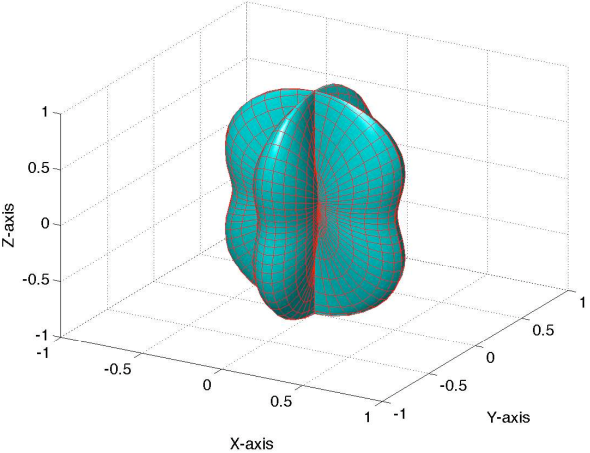
$$\phi \equiv \omega(T_y - T_x) = \omega \int_0^{\frac{2L}{c}} \frac{h_+(t, x(t)) + h_+(t, y(t))}{2} dt.$$



Initial LIGO (1997/2010): Michelson interferometer w/ Fabry-Perot arms

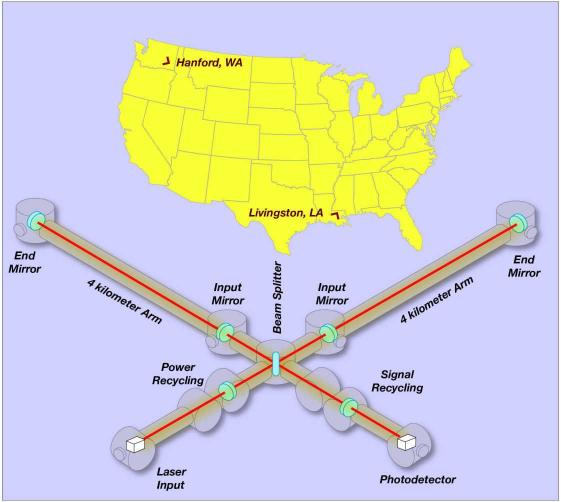
What is a... (GW)? Observatories

Amplitude modulation as Earth rotates (illustration)



AM: 'Antenna' response, h_+ pol., 0 Hz (credit: M. Rakhmanov)

What is a... (GW)? Observatories



Advanced LIGO: Hanford & Livington (credit: S. Larson, Northwestern U)

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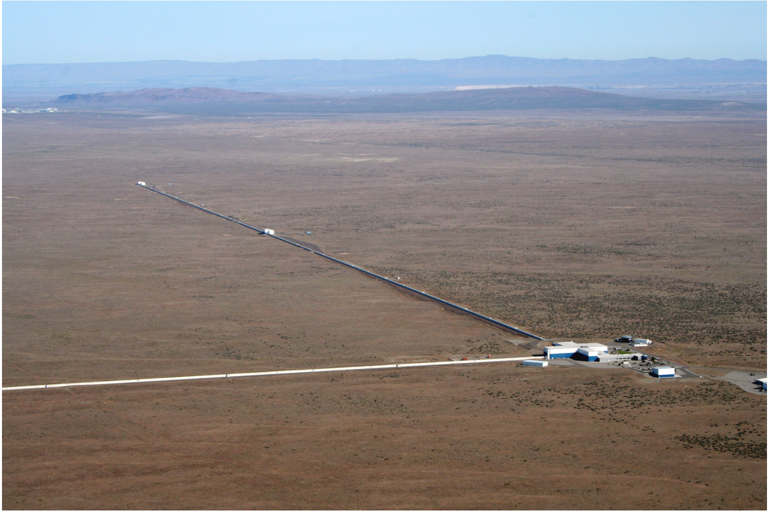
What is a... (GW)? Observatories



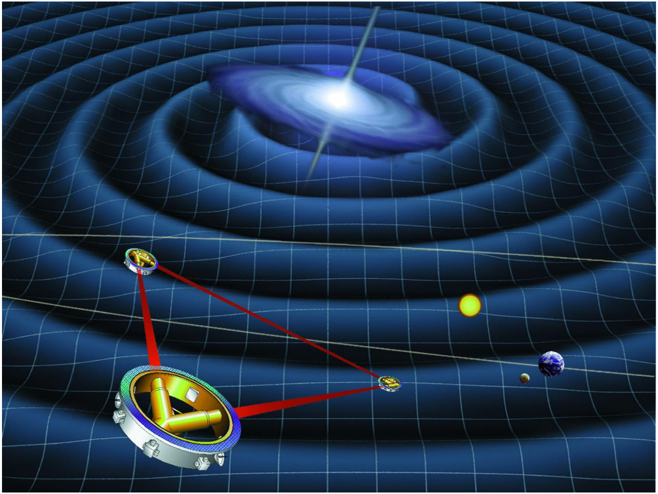
Overlooking X-arm, LIGO Hanford (credit: C. Gray)

Where LISA fits in

Impressions

- Interferometric GW ideas go back to 1960s
  Glasgow/Hughes Lab/MIT/Moscow State;
  First bar detector late 1950s, Joe Weber [Maryland]
- Bigger $=$ (except at high f) better
- Biggest: go to SPACE!

Where LISA fits in



JPL's original plan: 5 Gm, launch $\sim$ 2015. Credit: NASA/JPL

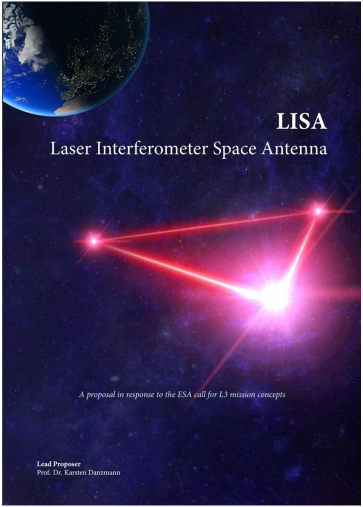
Where LISA fits in

That got cancelled in 2011,... but then ESA stepped in $\Longrightarrow$

selected for L3 misson (2037) in 2017
(following LIGO and LISA Pathfinder)

NASA back onboard

Where LISA fits in



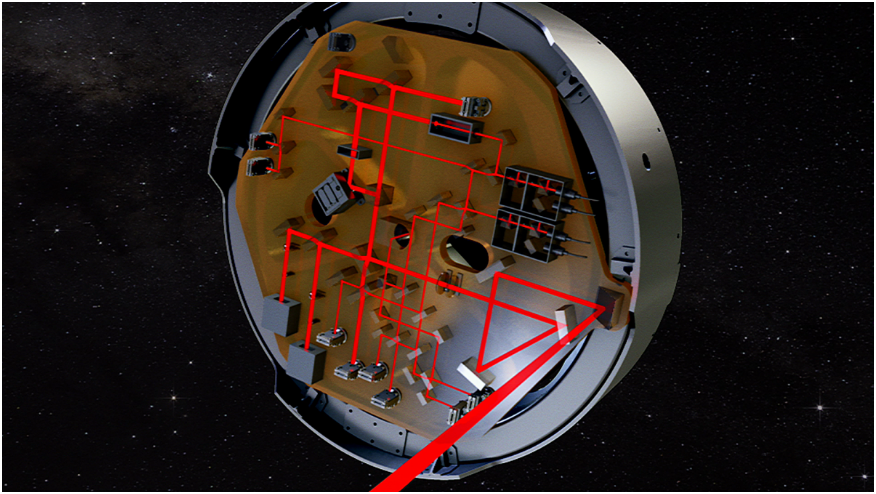
Funded 2017 ESA proposal. Credit: NASA/Simon Barke

Where LISA fits in

	Advanced LIGO	LISA
Arm length	4 km	2.5 Gm
Laser power	$\sim$ 125 W	$\sim$ 1 W
Interferometry	Michelson	Time-Delay
Resonant Arms	Fabry-Perot	(none)
Recycling	Power+Signal	(none)
Squeezing	$\sim$ 3 dB	(none)
Spectral band	$\sim 10 - 2000$ Hz	$\sim 0.1 - 100$ mHz

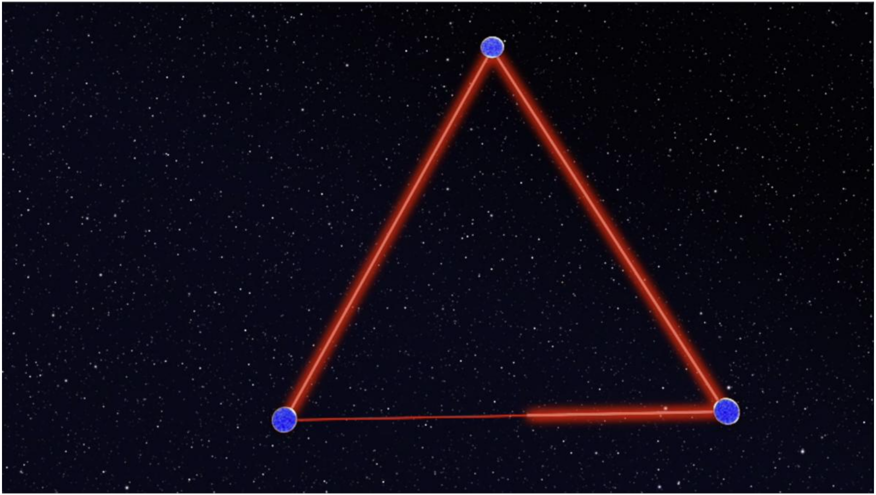
Other than being in space,
LISA is a safe, robust design
(All that extra stuff is low-hanging fruit for the next-gen)

Where LISA fits in



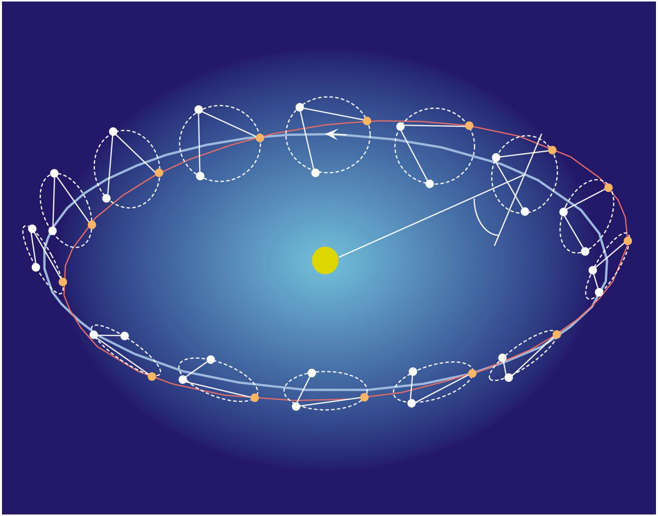
Optical bench in drag-free satellite. Credit: Max Planck/Milde/Exozet

Where LISA fits in



3 arm-pairs → polarization. Credit: Max Planck/Milde/Exozet

Where LISA fits in



Satellites (triangular formation) in heliocentric orbit. Credit: ESA

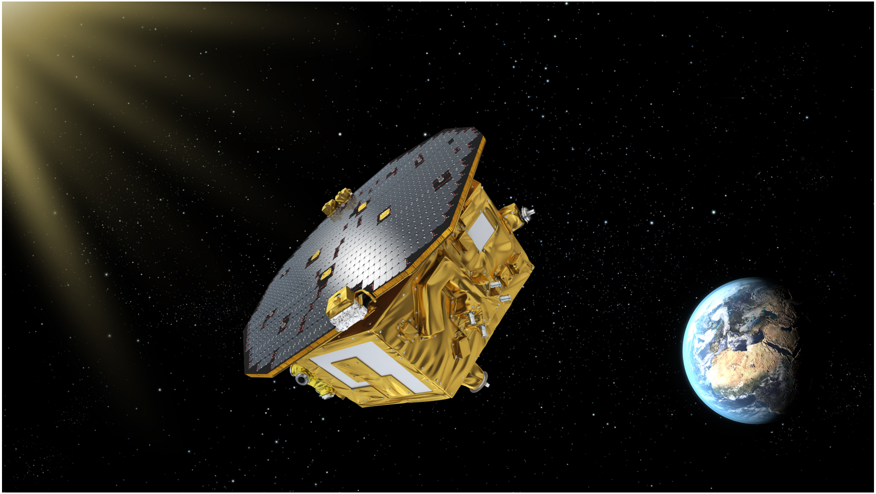
Where LISA fits in

Seem ambituous...

is it technologically ready?

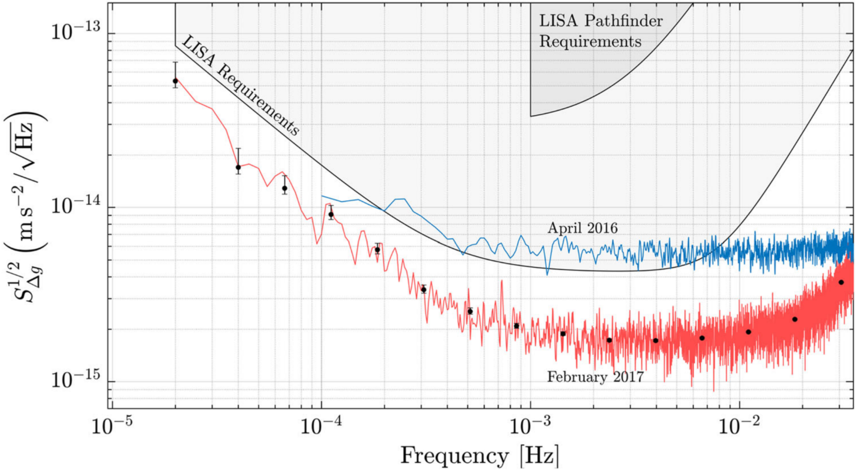
YES

Where LISA fits in



LISA Pathfinder, launched 2015. (Credit: ESA, C. Carreau)

Where LISA fits in

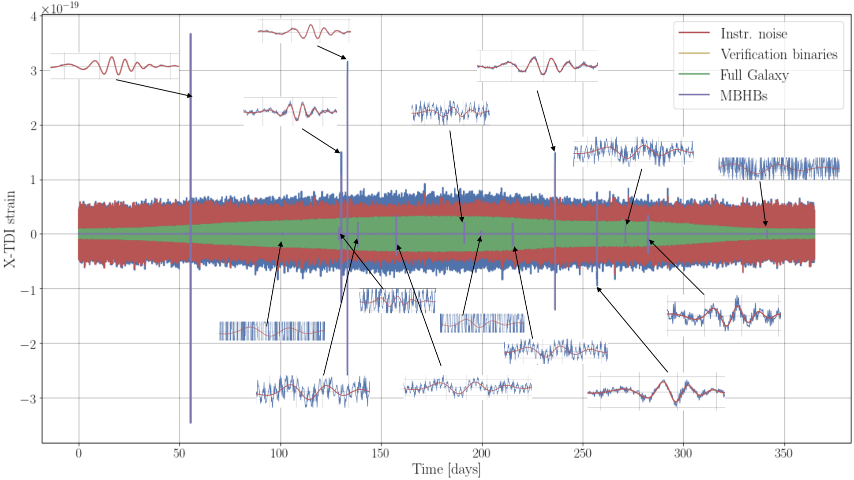


Success! Credit: ESA, c.f., Fig 1, Armano et al, PRL 120, 061101 (2018)

How the future begins

An international team is already forming! Credit: LISA Consortium

How the future begins: right now



Simulated dataset w/ signals. Credit: LISA Data Challenge, C. Cavet

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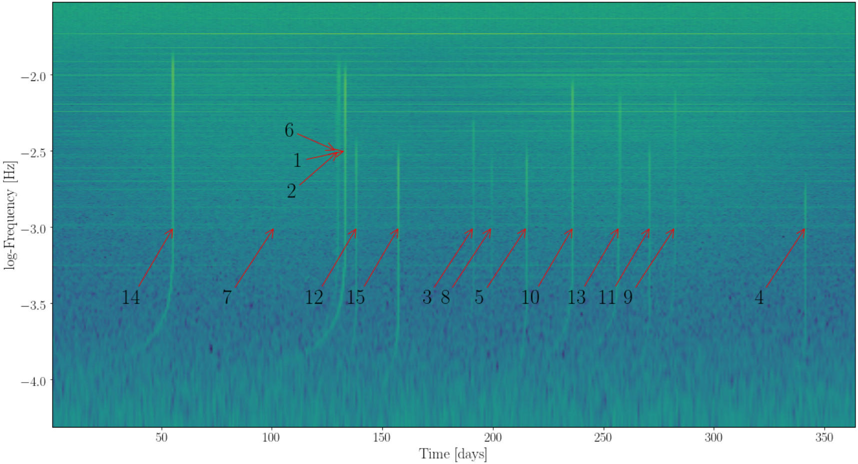
How the future begins: right now



Periodogram of simulated data. Credit: LISA Data Challenge, C. Cavet

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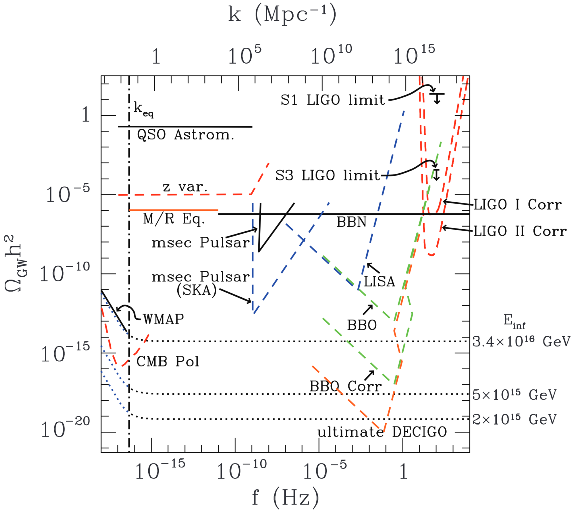
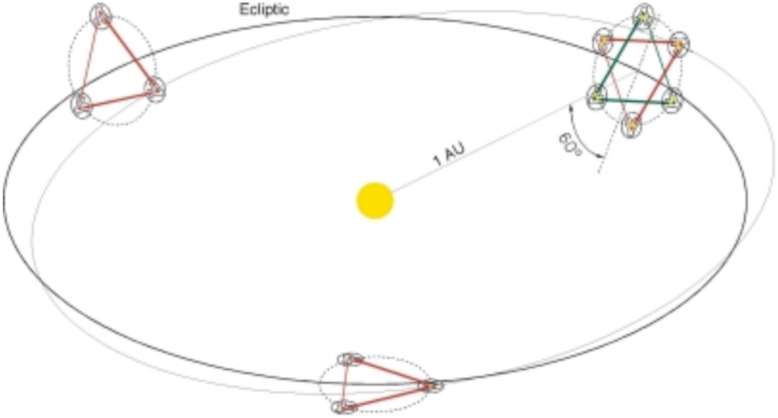
How the future begins: back to the beginning



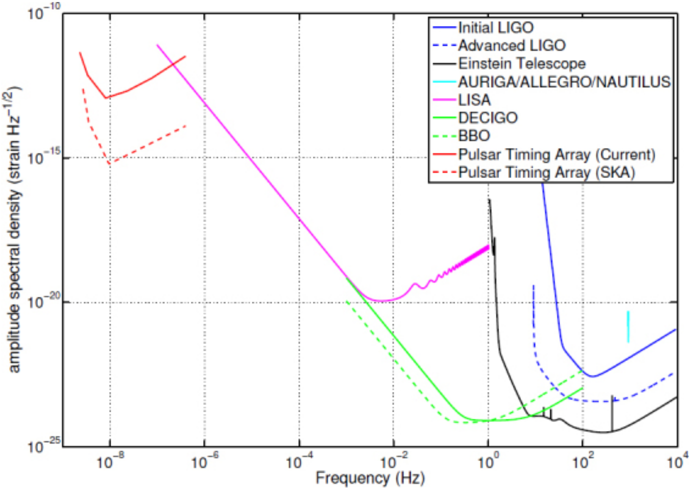
Inflation/strings. Credit: Fig. 1, Smith et al, arXiv:astro-ph/0506422v2

How the future begins: back to the beginning



12 sats in 3 sets. Credit: Fig. 3, Folkner & Seidel, Space 2005, p. 6711.

How the future begins: back to the beginning



Beyond LIGO/LISA! Credit: Fig. 1, Liv. Rev. Rel. 14 (2011) 5, Pitkin et al.

Conclusion: the future

The universe *... can be studied so many ways*

- Electromagnetic astronomy
  (optical, IR, UV, microwave, radio, X/γ-ray)
- Ground-based GW observatories
  bigger & better laser interfeometers above+below,
  w/ atom-interferometry a possible breakthough
- Pulsar-timing arrays
  using radio telescopes to track pulsars on galactic scale
- Microwave polarization
  seing the imprint of gravity on early cosmic light
- **LISA** and space-based interferometers
  what today's talk was about!

Conclusion

Even this is just the start!

- LISA is the *next generation* of (GW) astronomy
- GW sources are diverse:
  merging black holes, spinning neutron stars, the Big Bang
- Now is a great time for you too
  to get involved – everyone can be a scientist

Acknowledgments
Thanks to the Pajarito Environmental Education Center for hosting this, as well as my colleagues at Los Alamos National Laboratory. This work is assigned LA-UR-22-xxxxx.

Questions: gdmeadors@lanl.gov