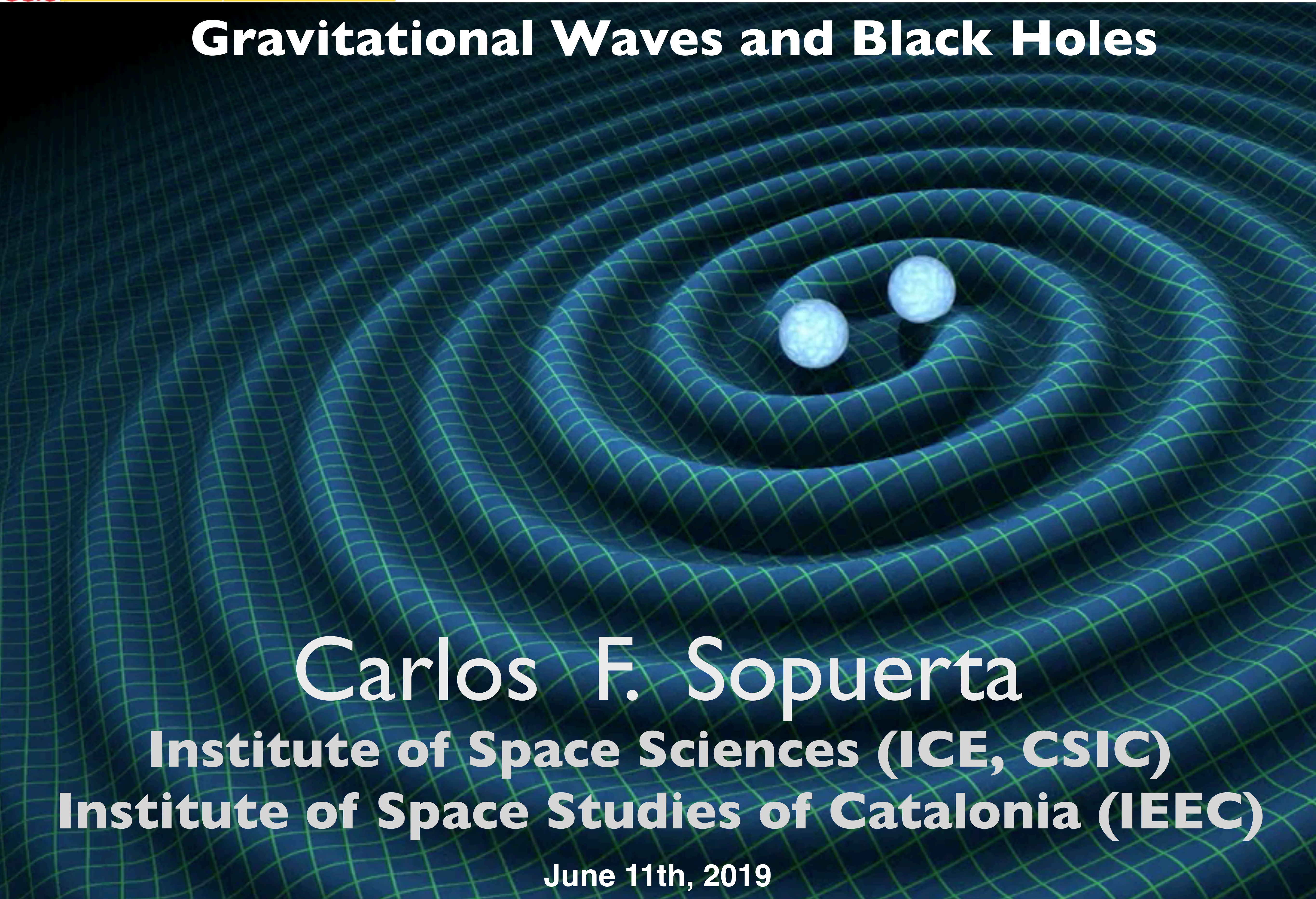
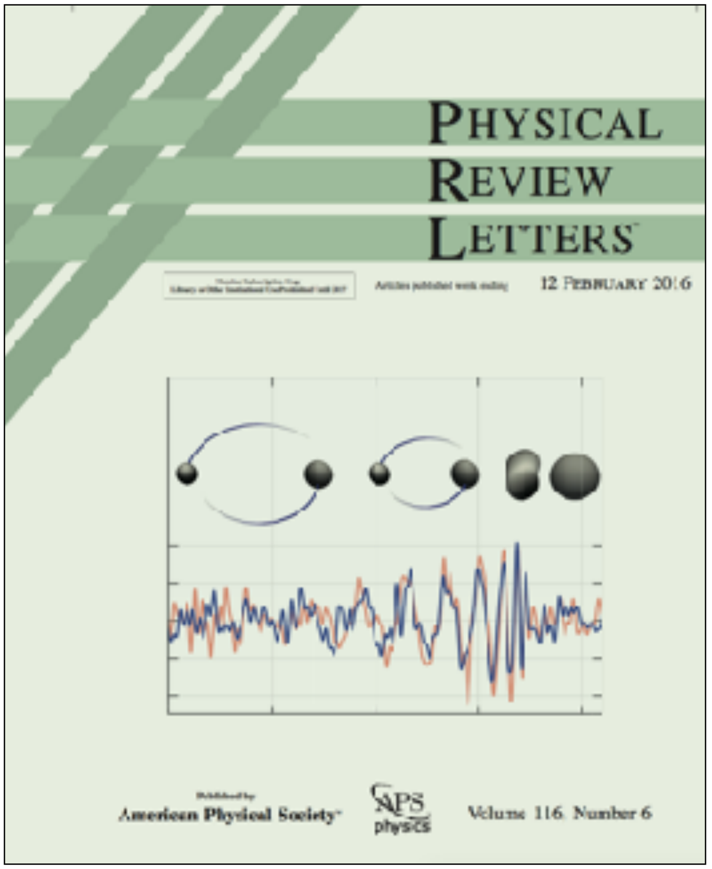
Gravitational Waves and Black Holes



Carlos F. Sopuerta
Institute of Space Sciences (ICE, CSIC)
Institute of Space Studies of Catalonia (IEEC)

June 11th, 2019

The Beginning of Gravitational Wave Astronomy



Selected for a Viewpoint in *Physics*
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

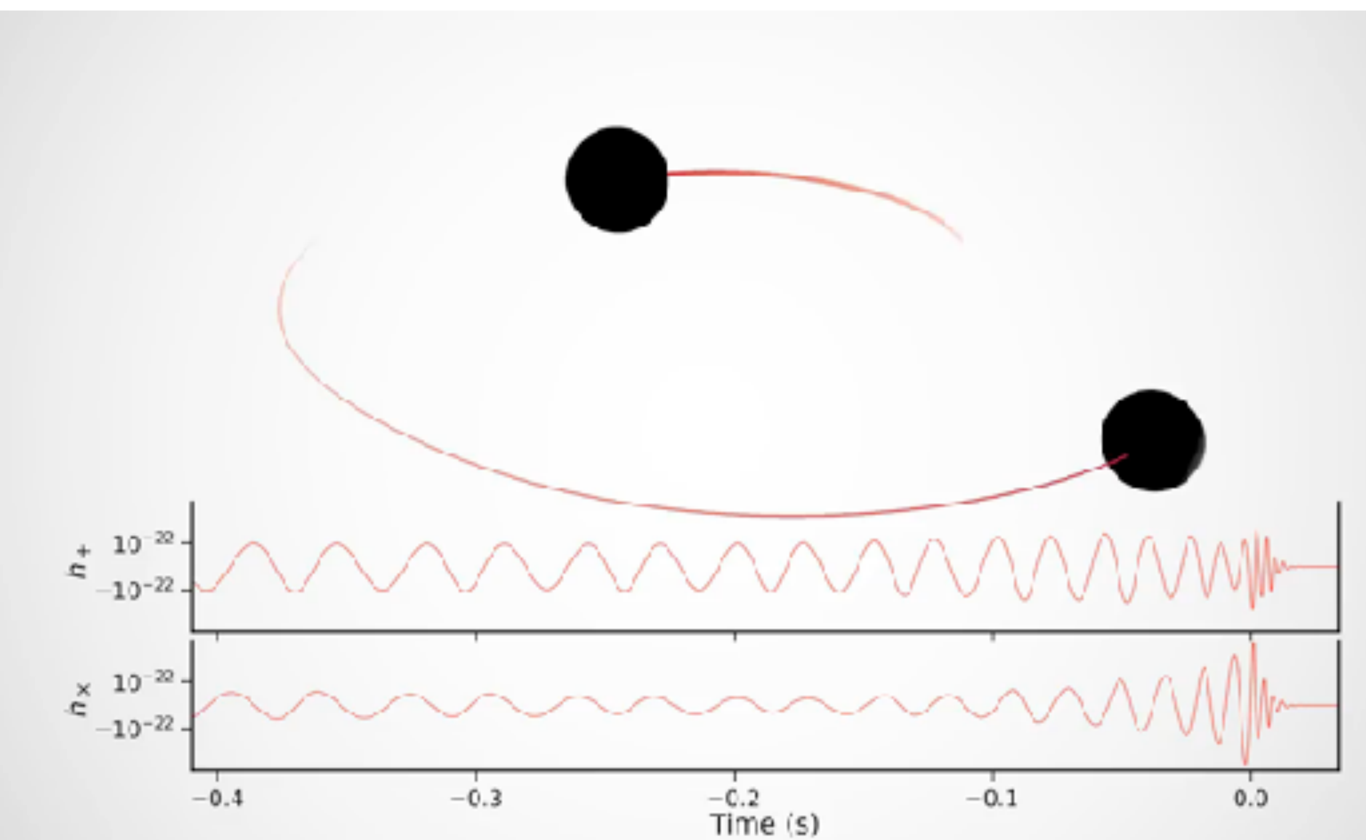
Observation of Gravitational Waves from a Binary Black Hole Merger

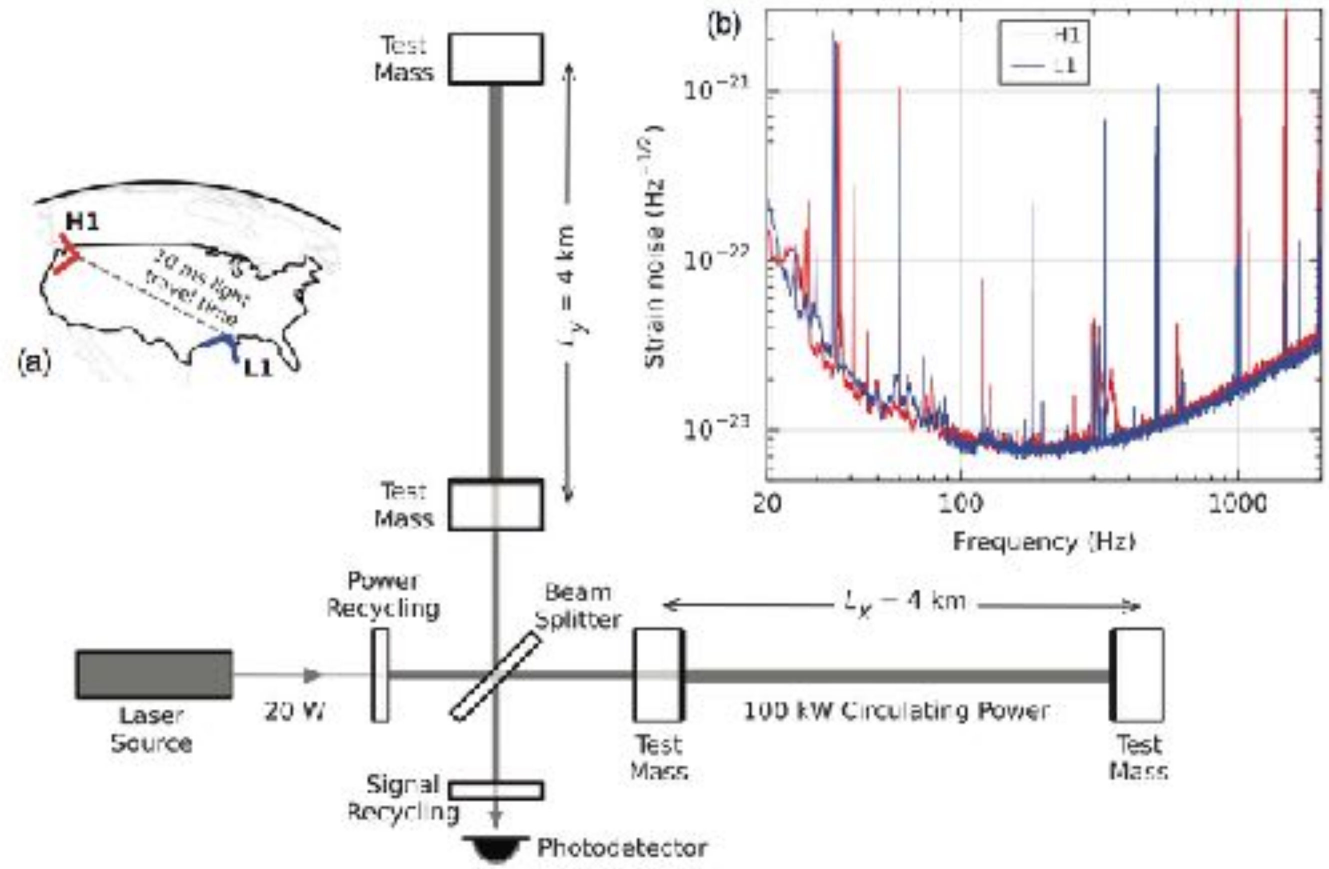
B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

LIGO

EGO - Virgo





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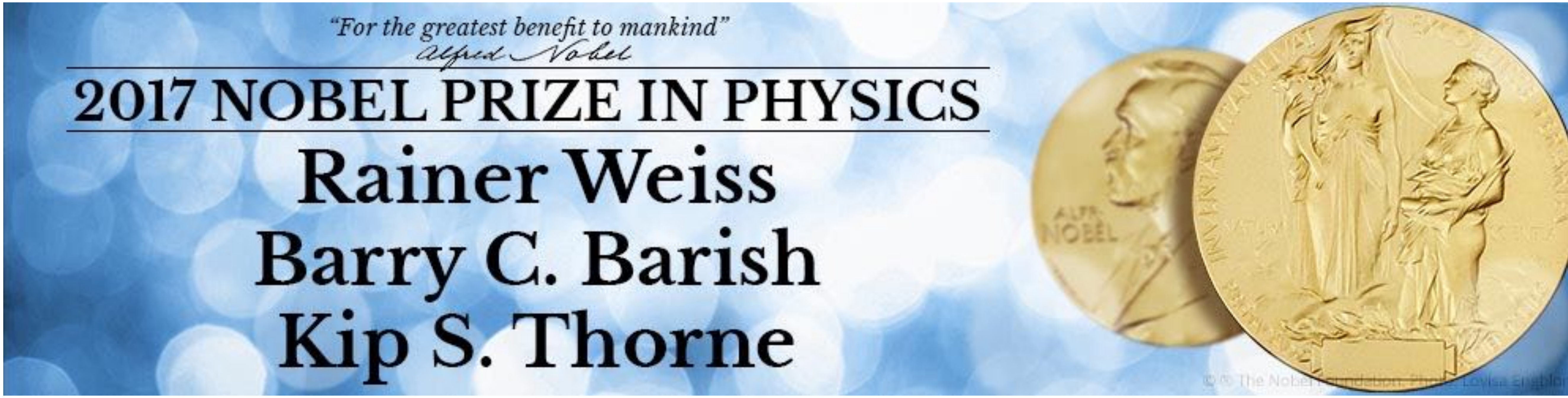
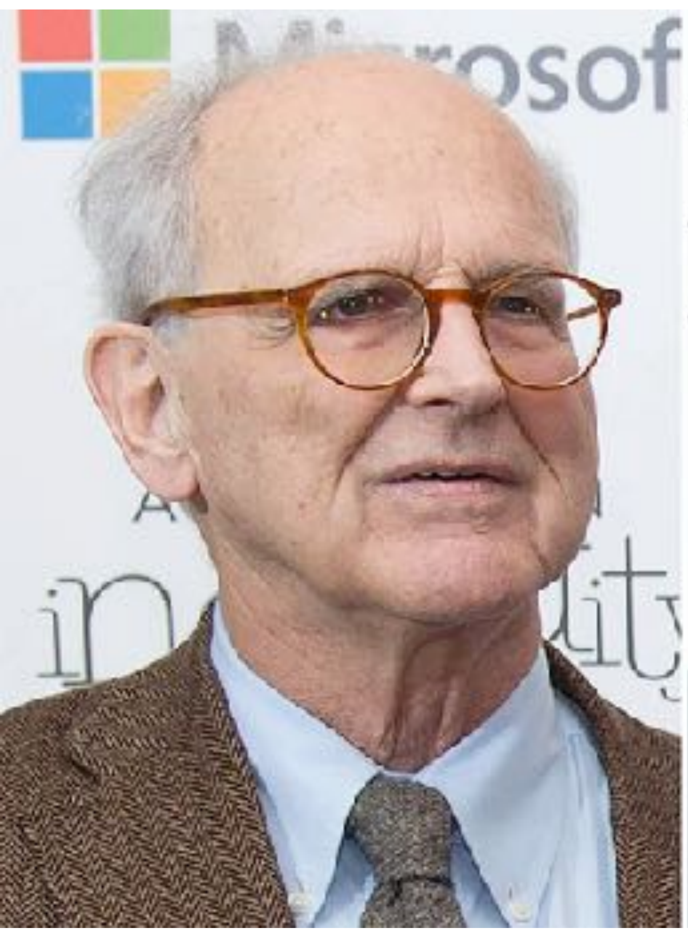
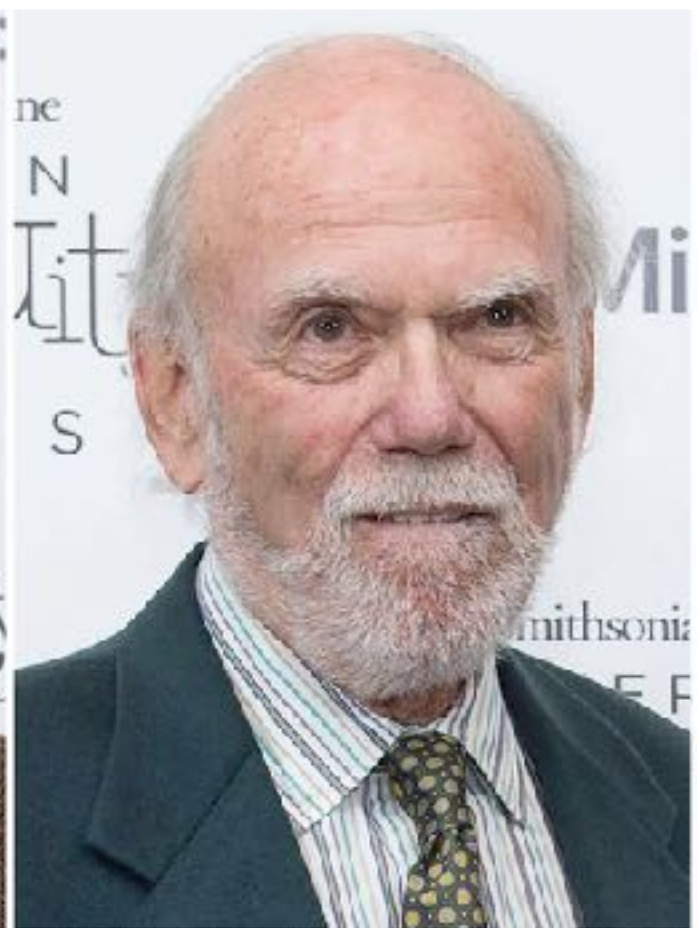






"For decisive contributions to the LIGO detector and the observation of gravitational waves".

Carlos F. Sopuerta
June 11th, 2019
Institute of Space Sciences (ICE, CSIC)
Institute of Space Studies of Catalonia (IEEC)

OUTLINE

I. The Black Hole Spectrum

II. The Gravitational Wave Spectrum

III. Black Hole Science with Gravitational Waves

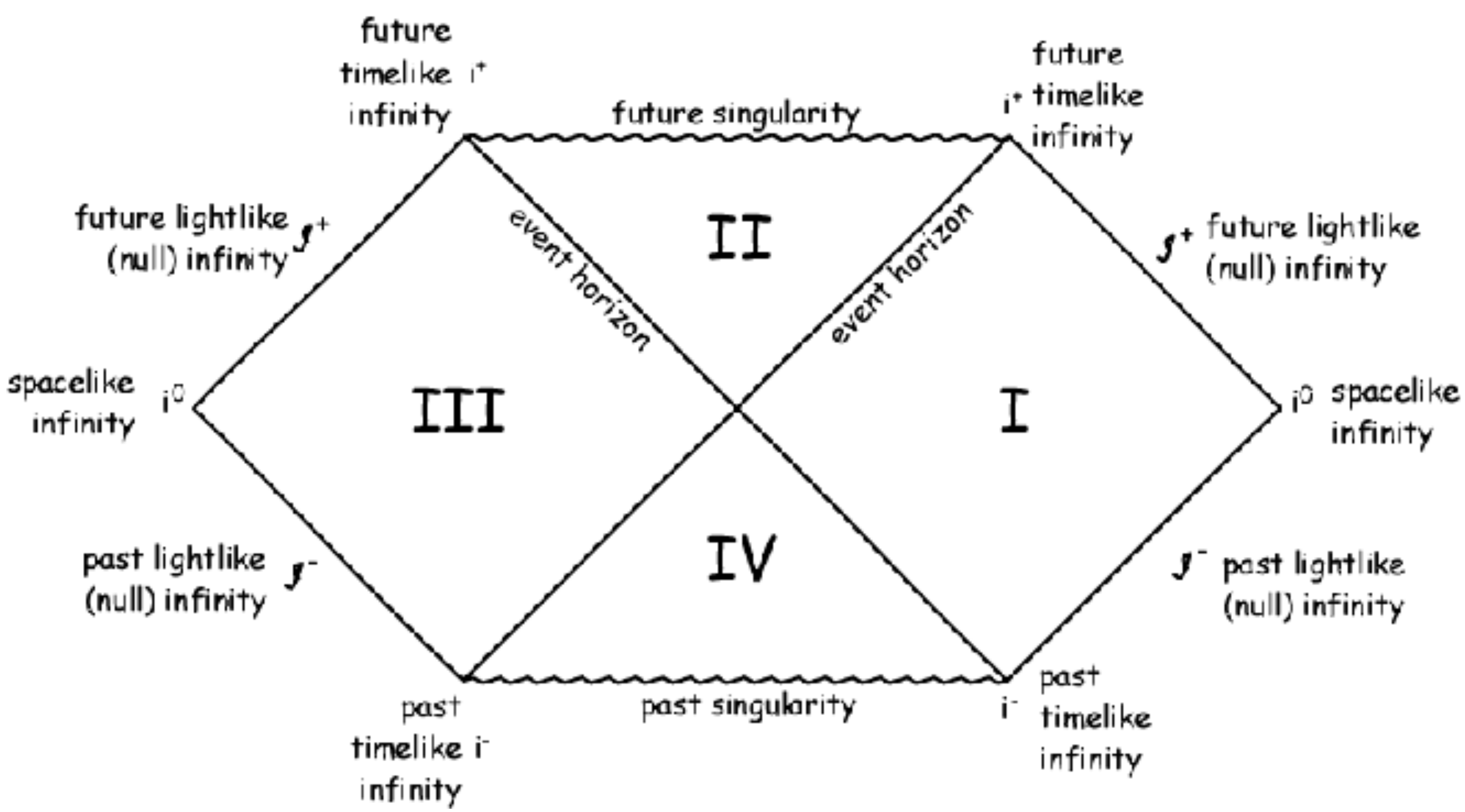
IV. Conclusions

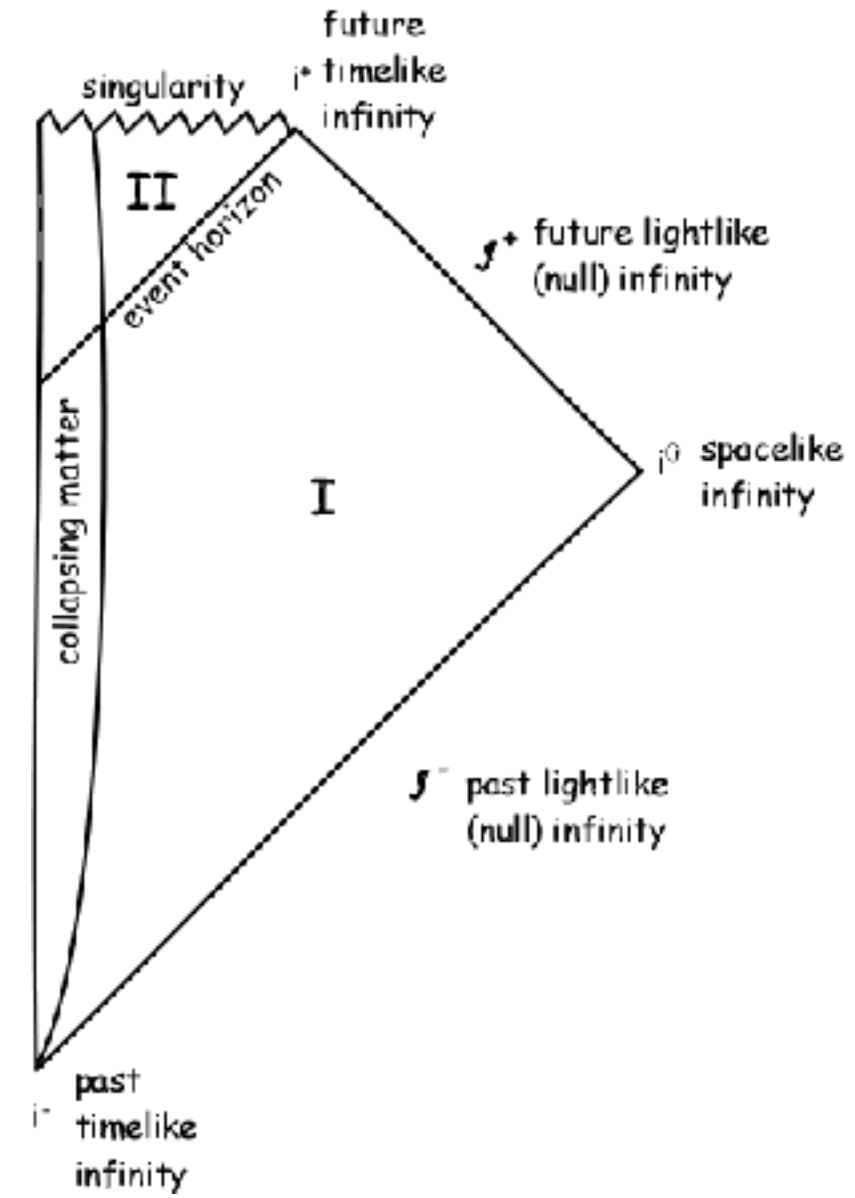
The Black Hole Spectrum

Black Holes

✳ Black Holes are becoming central objects in different wide areas of research in Physics. They originate from General Relativity:

- A Black Hole is a region of the spacetime of no escape. From this region, no physical signals/interactions can propagate outside. The BH horizon is the boundary of this region.





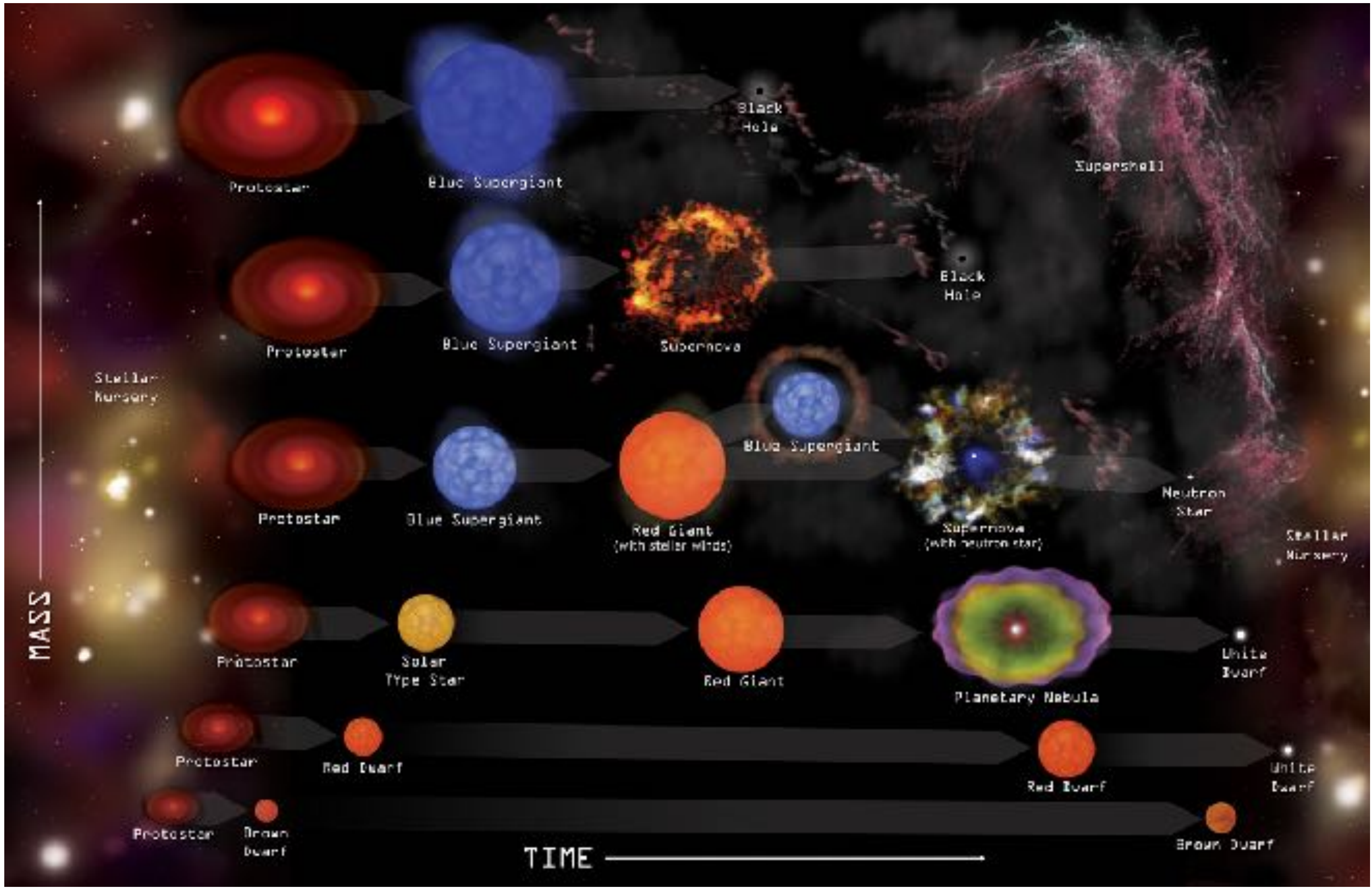
Black Holes

✳ Black Holes are becoming central objects in different wide areas of research in Physics.

✳ **Astrophysics:**

- End point of Gravitational Collapse [Critical Phenomena, Mass gap between Neutron Stars (NSs) and Stellar Black Holes (SBHs)?, maximum mass of SBHs, etc.]

- Understanding stellar synthesis: (Mass, Spin) distribution of SBHs in (the) Galaxy.



Carlos F. Sopuerta
June 11th, 2019
Institute of Space Sciences (ICE, CSIC)
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Black Holes

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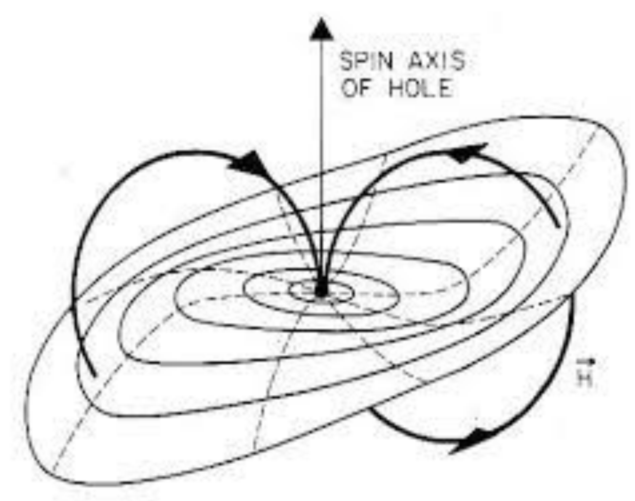
* **Astrophysics:**
  - End point of Gravitational Collapse [Critical Phenomena, Mass gap between Neutron Stars (NSs) and Stellar Black Holes (SBHs)?, maximum mass of SBHs, etc.]
  - Understanding stellar synthesis: (Mass, Spin) distribution of SBHs in (the) Galaxy.
  - Globular Clusters and Intermediate-Mass Black Holes.
  - Micro-quasars and quasars [mechanism of the engine powering these systems, Bardeen-Petterson effect on accretion disks around black holes, etc.]

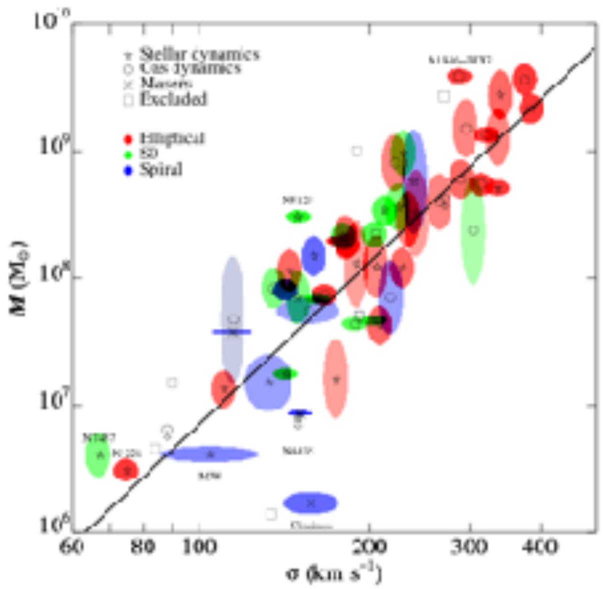


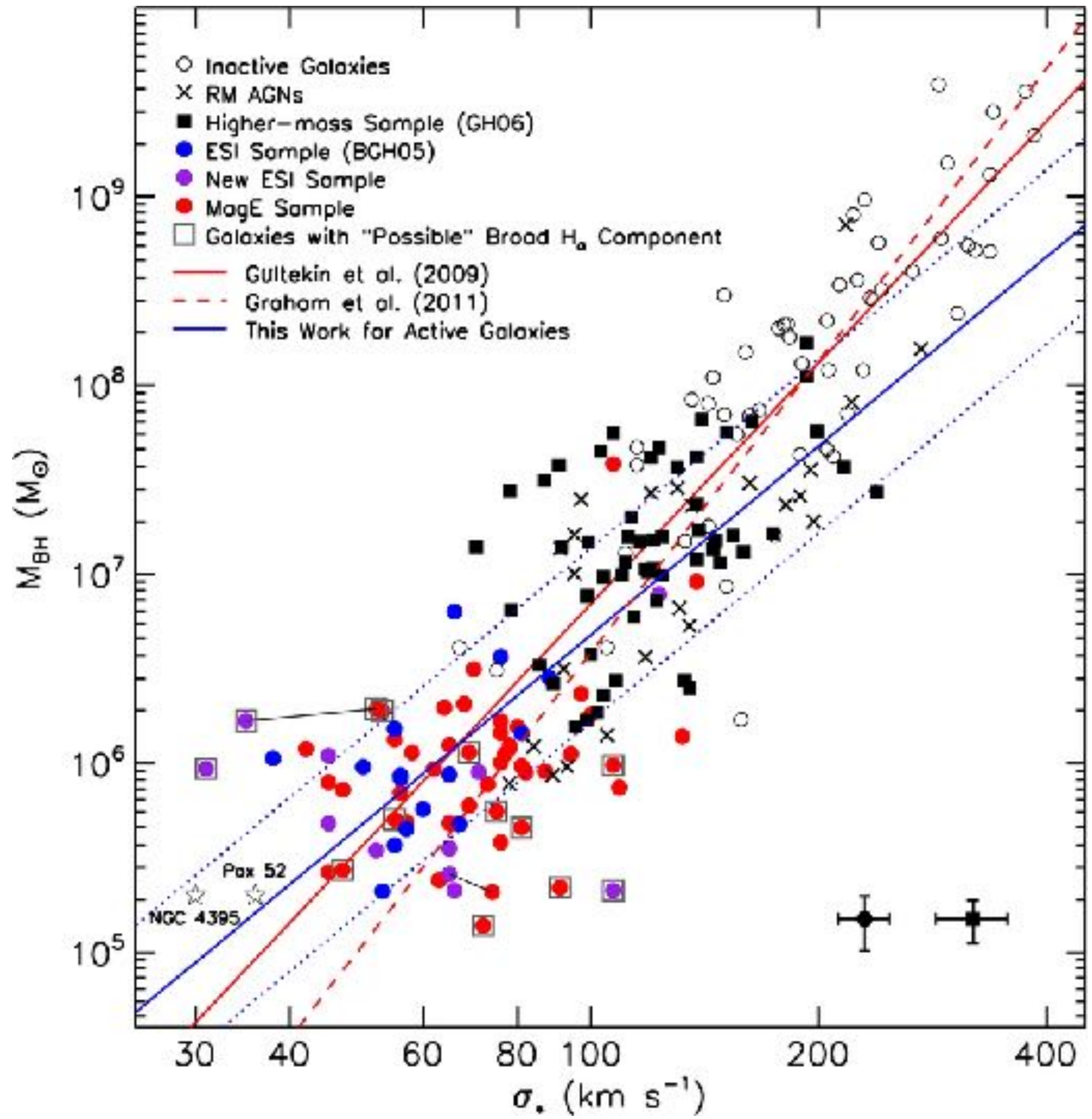
Black Holes

✳ Black Holes are becoming central objects in different wide areas of research in Physics.

✳ **Cosmology:**

• Supermassive Black Holes and the origin and evolution of Galaxies [the $M_{\rm BH} - \sigma$ relation and other connections between the central (super)massive black hole and the bulge of the galaxy and local dark matter halo].





Black Holes

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* **Cosmology:**

  • Supermassive Black Holes and the origin and evolution of Galaxies [the $M_{\rm BH} - \sigma$ relation and other connections between the central (super)massive black hole and the bulge of the galaxy and local dark matter halo].

  • Supermassive Black Hole Binaries in the coalescence phase (emitting gravitational waves in the low and very-low frequency bands) as standard sirens for cosmography.

  • Primordial Black Holes.

  • Black Holes and higher-dimensional cosmological scenarios.

Black Holes

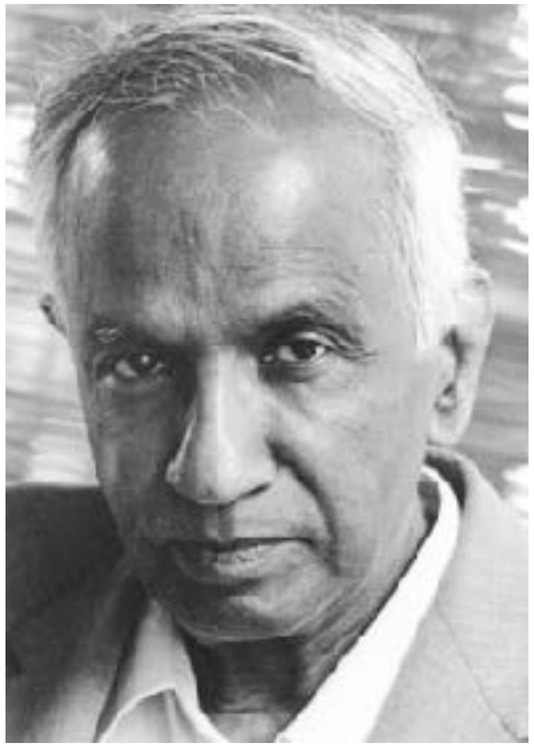
✳ Black Holes are becoming central objects in different wide areas of research in Physics.

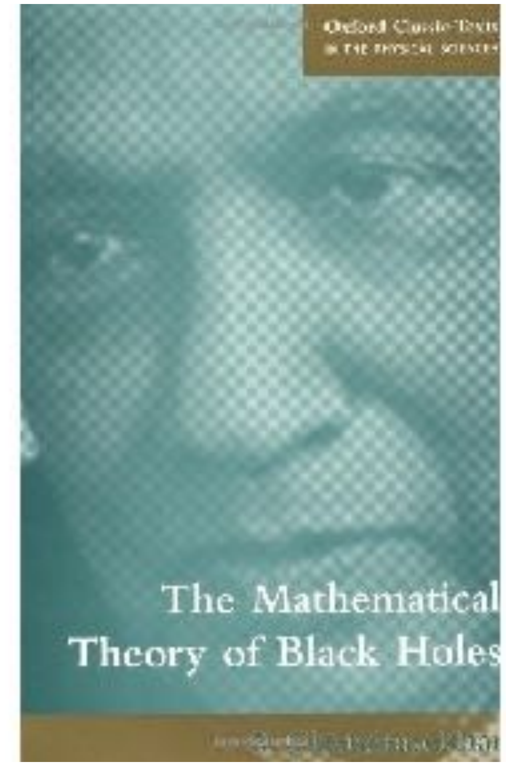
✳ **Fundamental Physics:**

- The Black Hole paradigm [no-hair conjecture/cosmic censorship]: Are the "black objects" we see in Nature well described by the Kerr family of vacuum solutions of Einstein field equations?

Black Holes in General Relativity

- Subrahmanyan Chandrasekhar (Nobel Prize in Physics 1983)





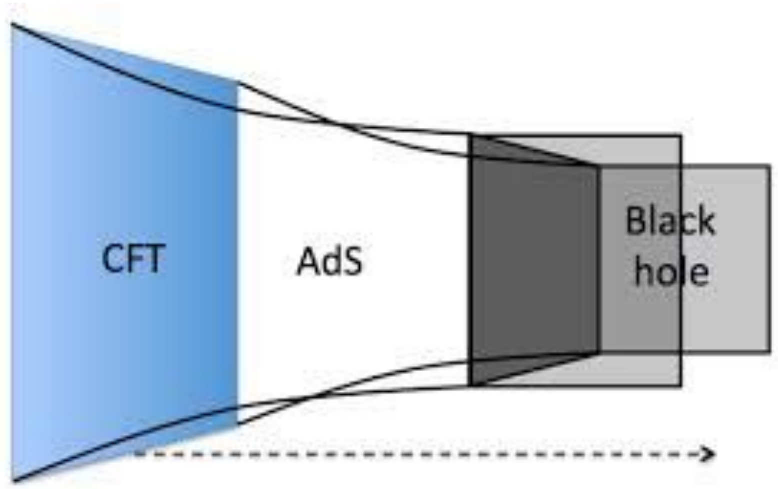
"The Black Holes of Nature are the most perfect macroscopic objects there are in the Universe: The only elements in their construction are our concepts of space and time. And since the General Theory of Relativity provides only a single unique family of solutions for their description, they are the simplest objects as well".

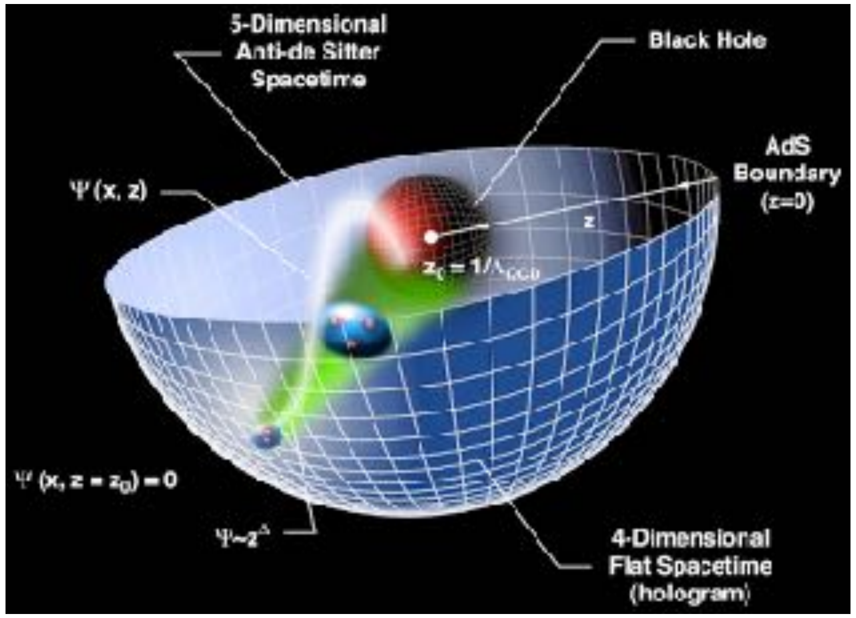
Black Holes

✴ Black Holes are becoming central objects in different wide areas of research in Physics.

✴ **Fundamental Physics:**

- The Black Hole paradigm [no-hair conjecture/cosmic censorship]: Are the "black objects" we see in Nature well described by the Kerr family of vacuum solutions of Einstein field equations?
- Tests of General Relativity and other alternative theories of Gravity.
- Towards quantum gravity [Black Hole Information paradox, holography, etc.]



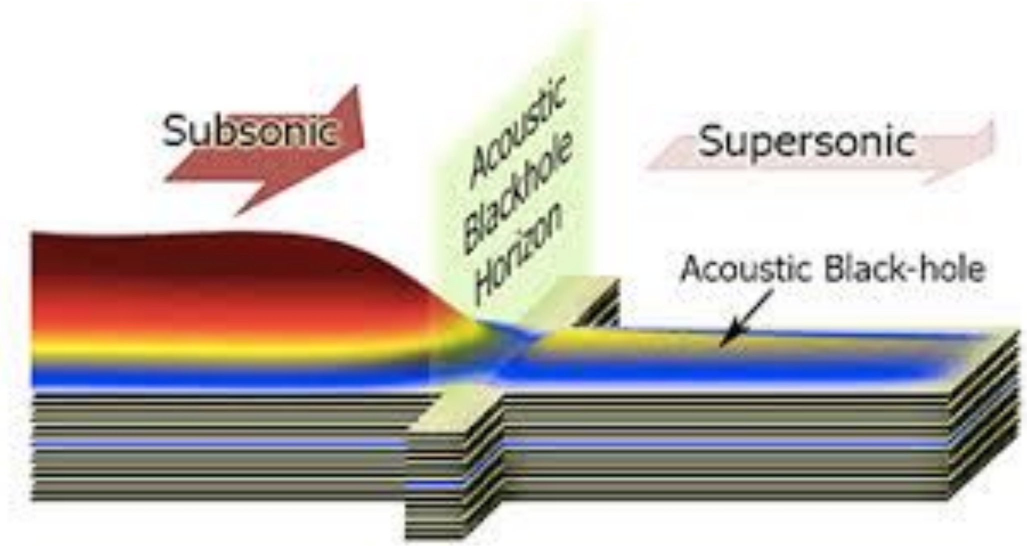


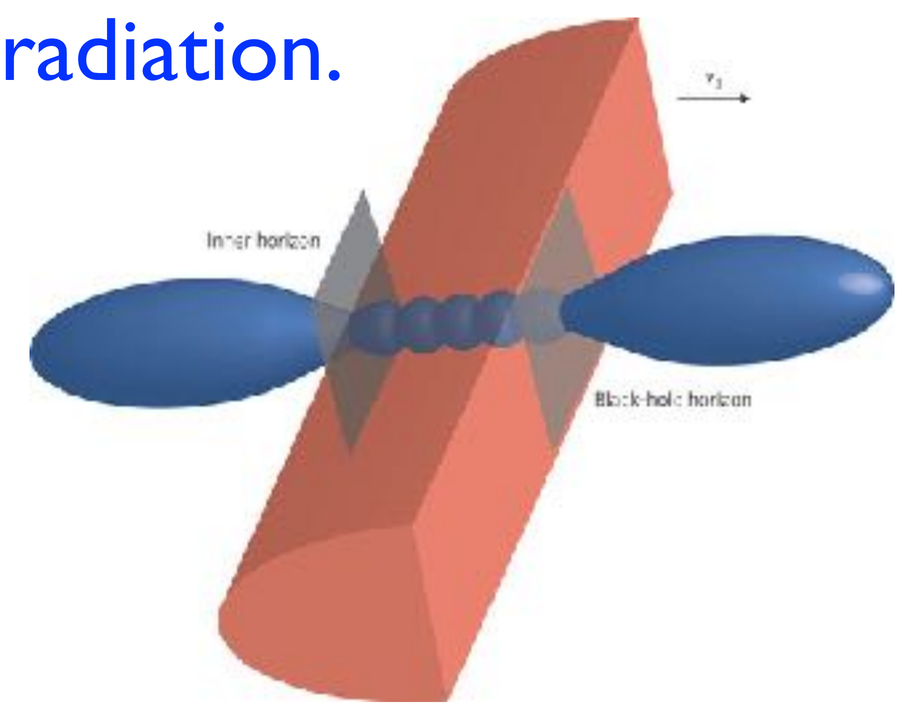
Black Holes

✳ Black Holes are becoming central objects in different wide areas of research in Physics.

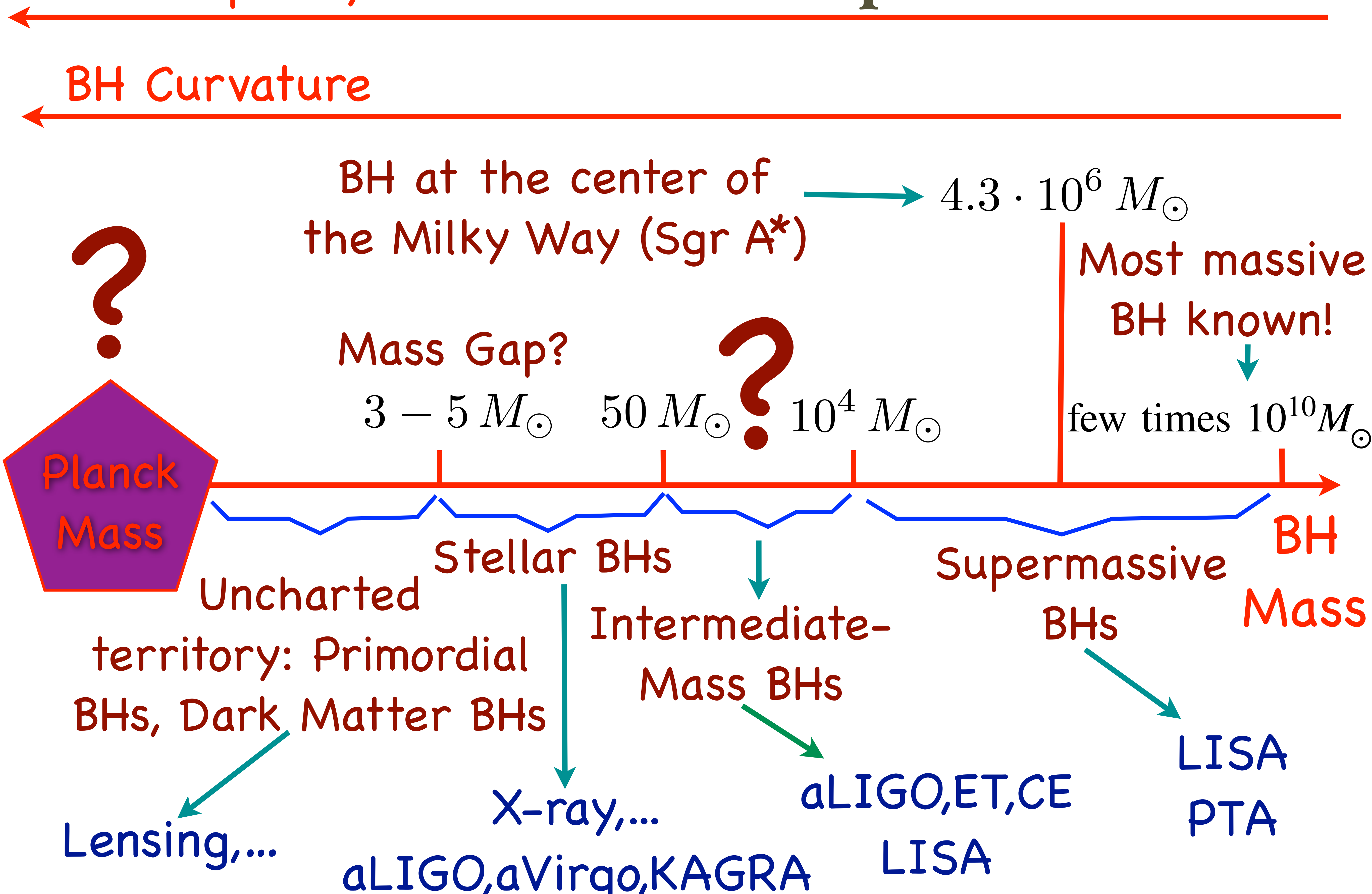
✳ **Condensed Matter Physics:**

- Black Holes and gravity as emerging (collective) phenomena.
- Extensions of the Gauge/Gravity duality to condensed matter physics.
- Analogues of Black Holes and Hawking radiation.





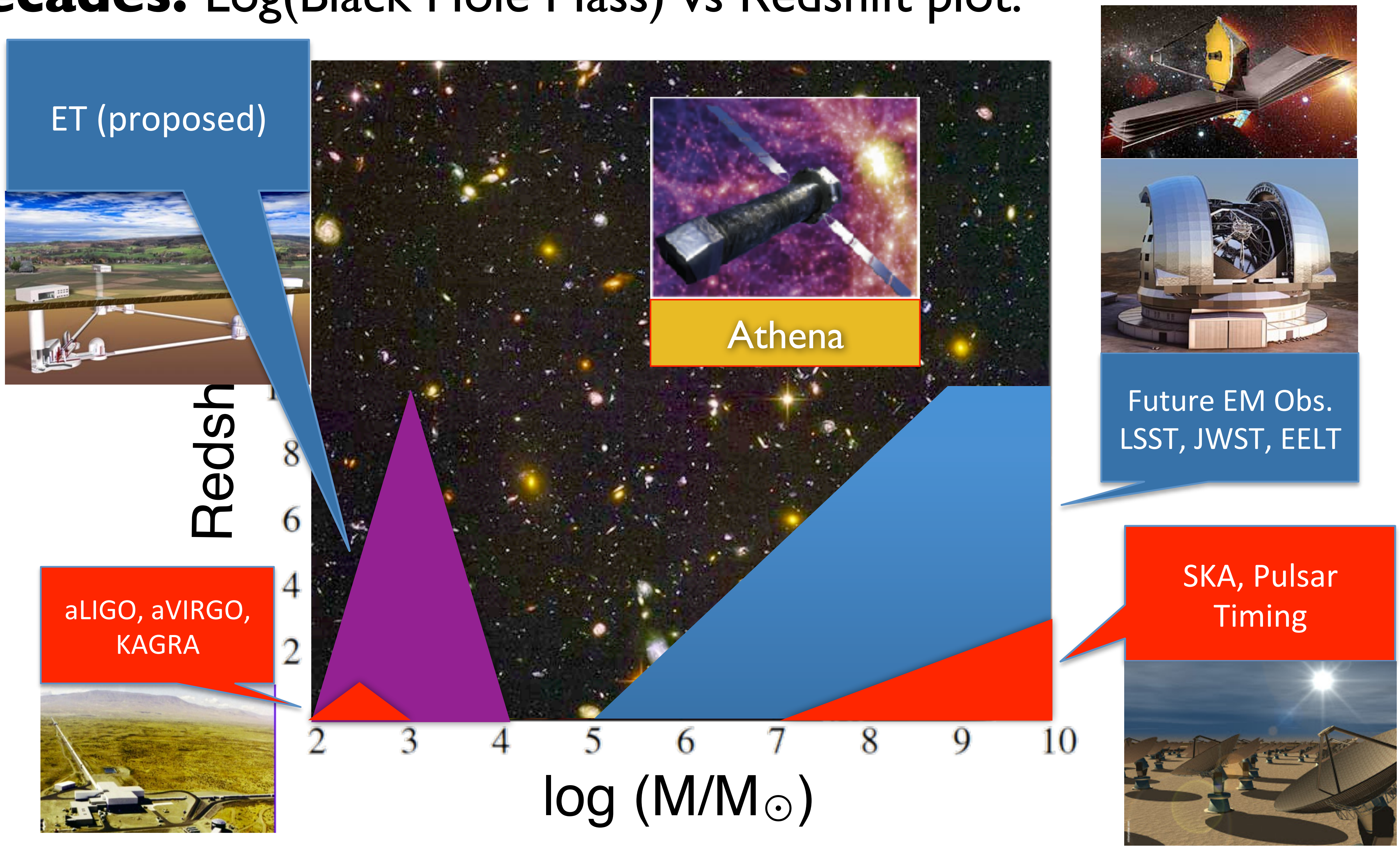
The Black Hole Spectrum



Carlos F. Sopuerta
June 11th, 2019
Institute of Space Sciences (ICE, CSIC)
Institute of Space Studies of Catalonia (IEEC)

Black Hole Observations by ~2030

- **Landscape of Black Hole Observations in the next decades:** Log(Black Hole Mass) vs Redshift plot.



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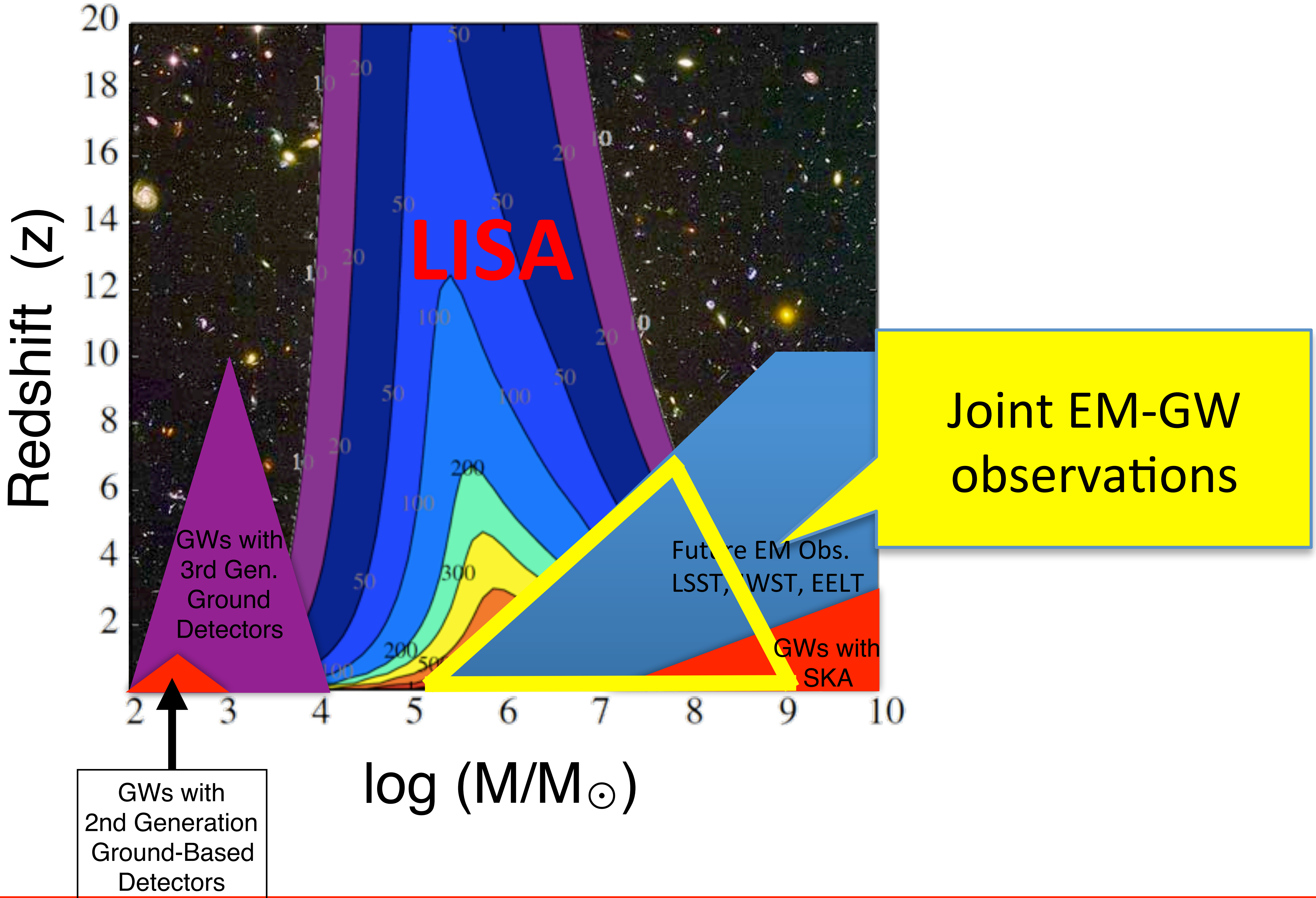


The Gravitational Wave Spectrum

Fact Sheet on Gravitational Waves

* Gravitational Waves are ripples in the spacetime geometry produced by time-varying distributions of energy and momentum, that propagate (locally) at the speed of light.

* Gravitational Waves are transverse waves with two independent polarization states (in General Relativity).

* They are generated by the bulk of the energy-momentum distribution so their wavelengths are bigger than the source size. So the **cannot** be use to do images. We "*listen*" to them.

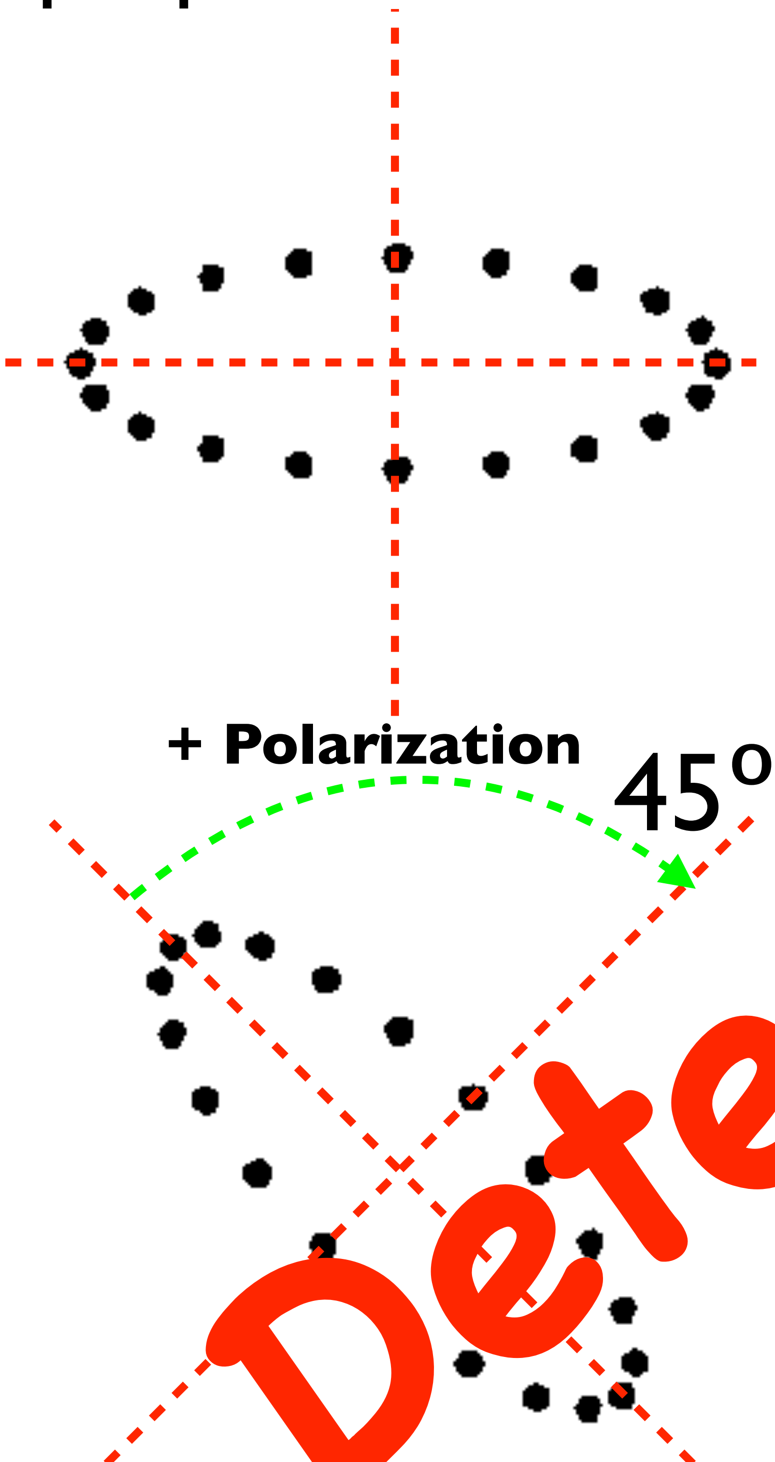
* Detection is based on the inference of the radiative gravitational field ($h \sim 1/r$), not on the energy flux ($dE/dt \sim 1/r^2$).

* GWs from cosmological sources at $z > 1$ suffer significantly from lensing). Affects Luminosity distance estimation.

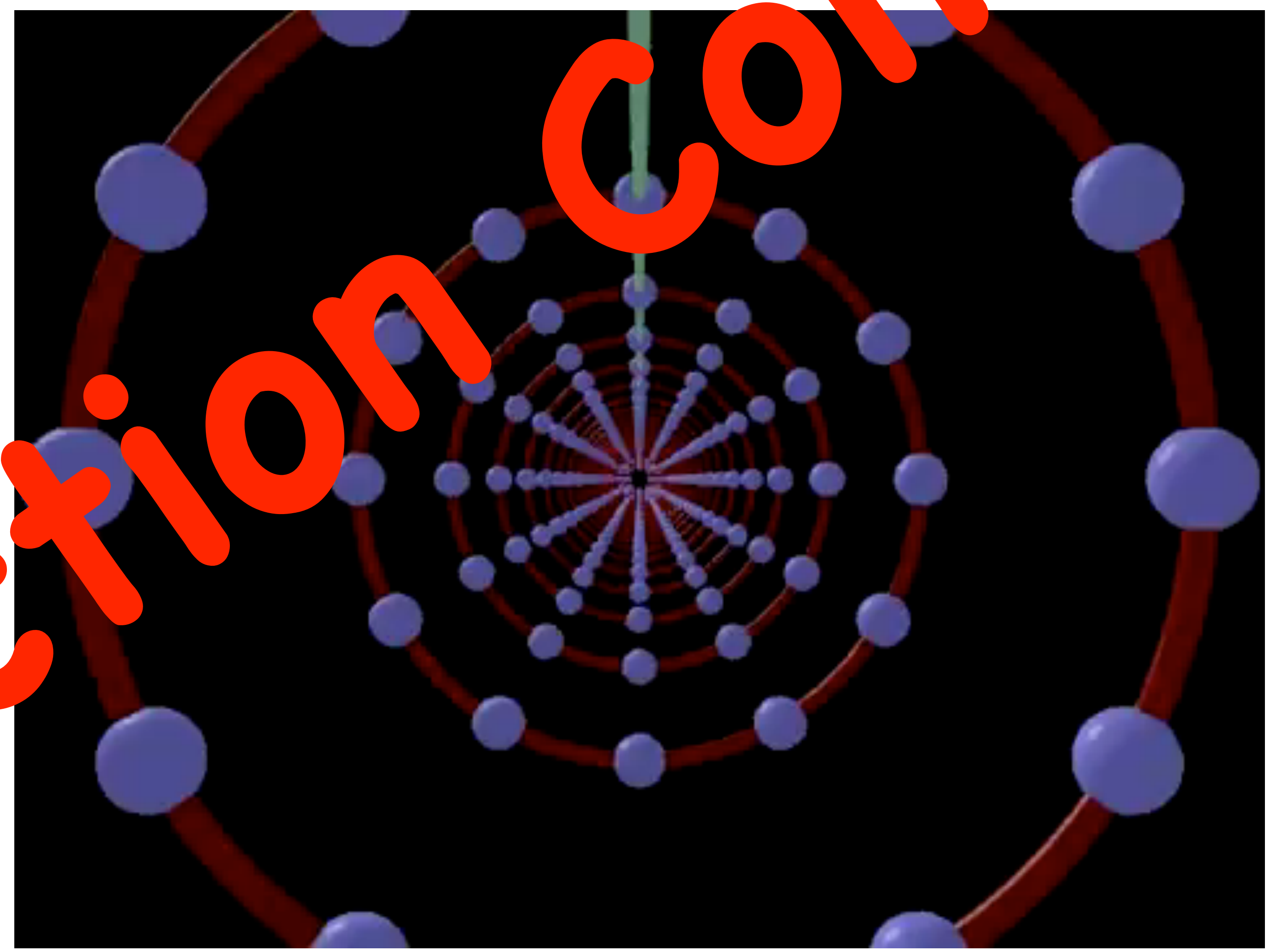
* Degeneracy with redshift: $M(z) = (1+z)M$

Detection of Gravitational Waves

- The effect of gravitational waves on matter is to change the proper distance between the matter constituents:



$$\Delta L \sim (\text{GW strain amplitude}) \times L$$
$$= \qquad h \qquad \times L$$



L : Proper distance between "test" bodies

GWs in GR have 2 independent polarizations!

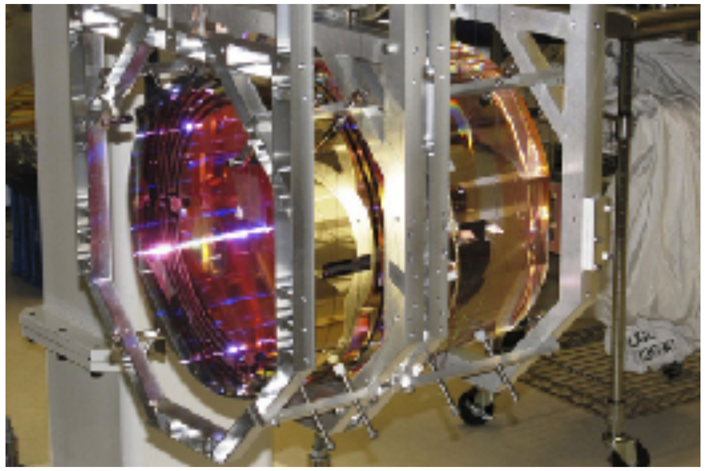
Detection concept!

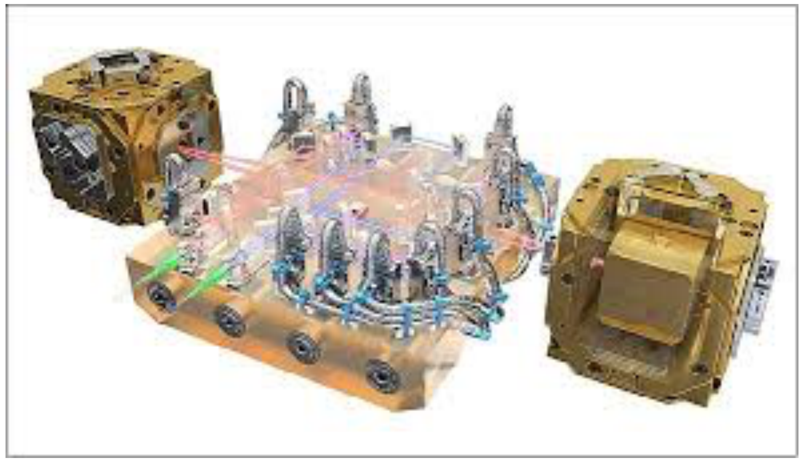
CSIC
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Carlos F. Sopuerta
June 11th, 2019
Institute of Space Sciences (ICE, CSIC)
Institute of Space Studies of Catalonia (IEEC)
IEEC

Detection of Gravitational Waves

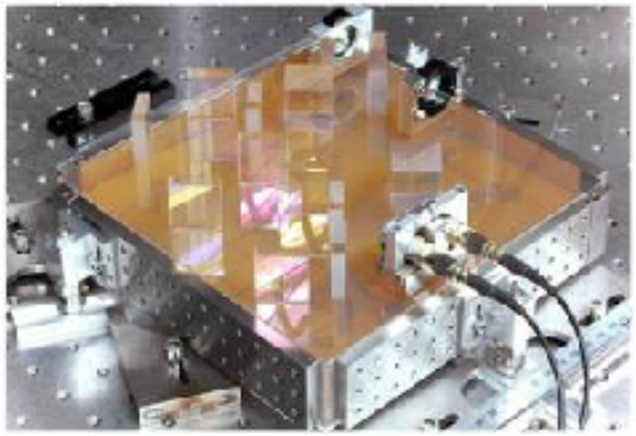
* Therefore, to detect Gravitational Waves we need:

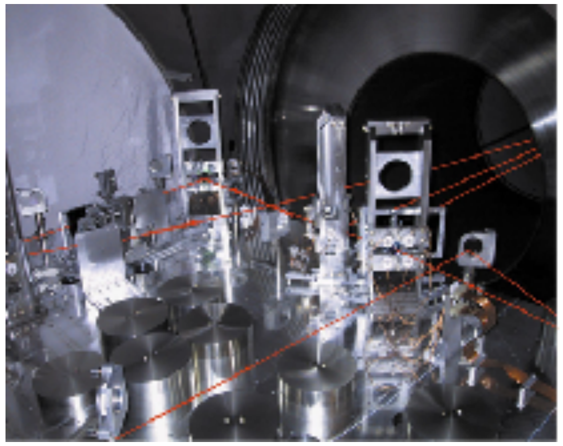
• Masses in almost perfect free-fall (no subject to non-gravitational forces).





• A highly precise and stable device for length/ time measurements.



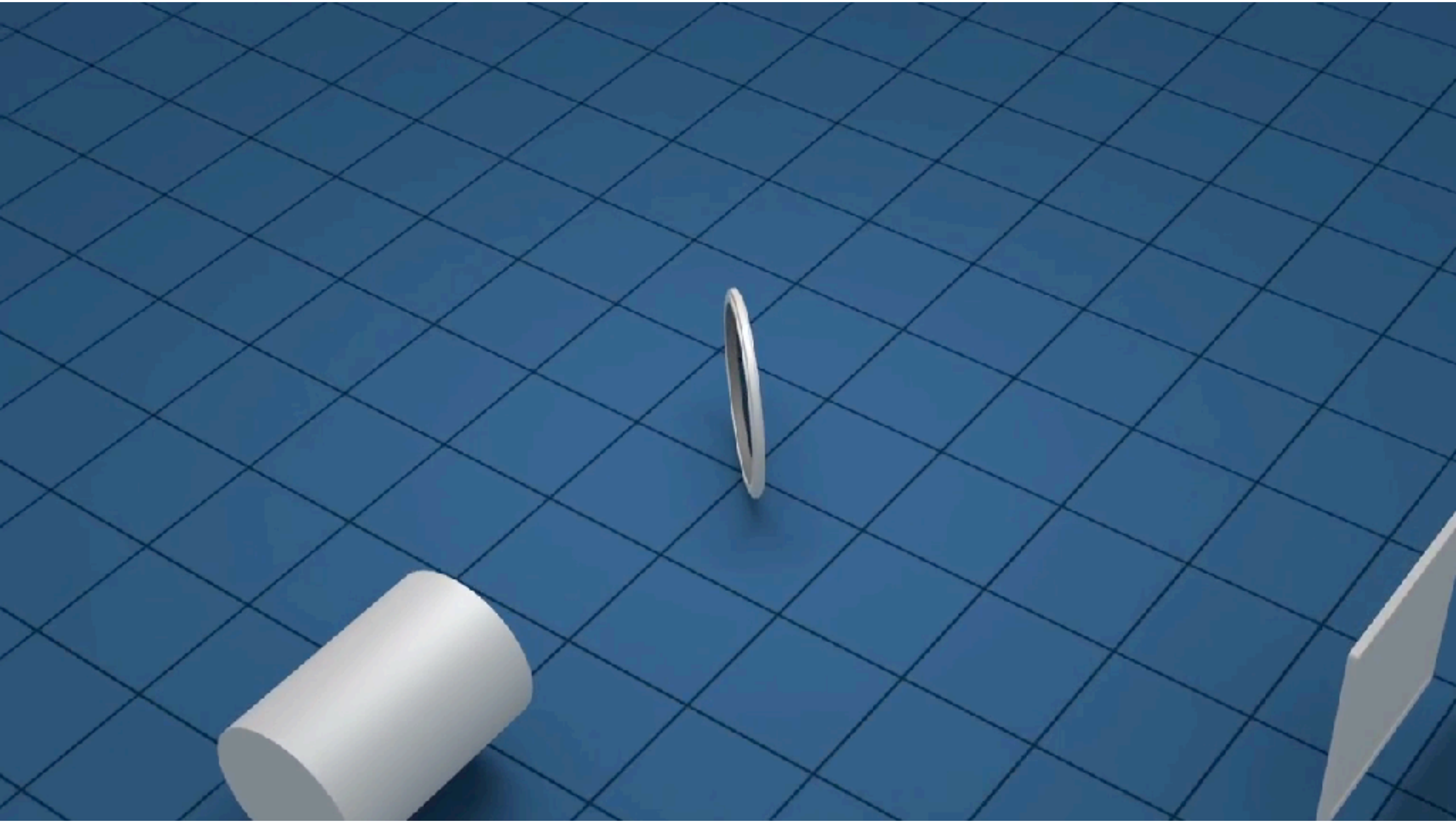


Detection of Gravitational Waves

- Resonant Detectors **(Pioneer Technology)**

- Laser Interferometric Detectors **(Current Technology for Ground-Based Detectors)**

Principle of LIGO Detector



dL/L ~ 1/1000 size of a typical atomic nucleus

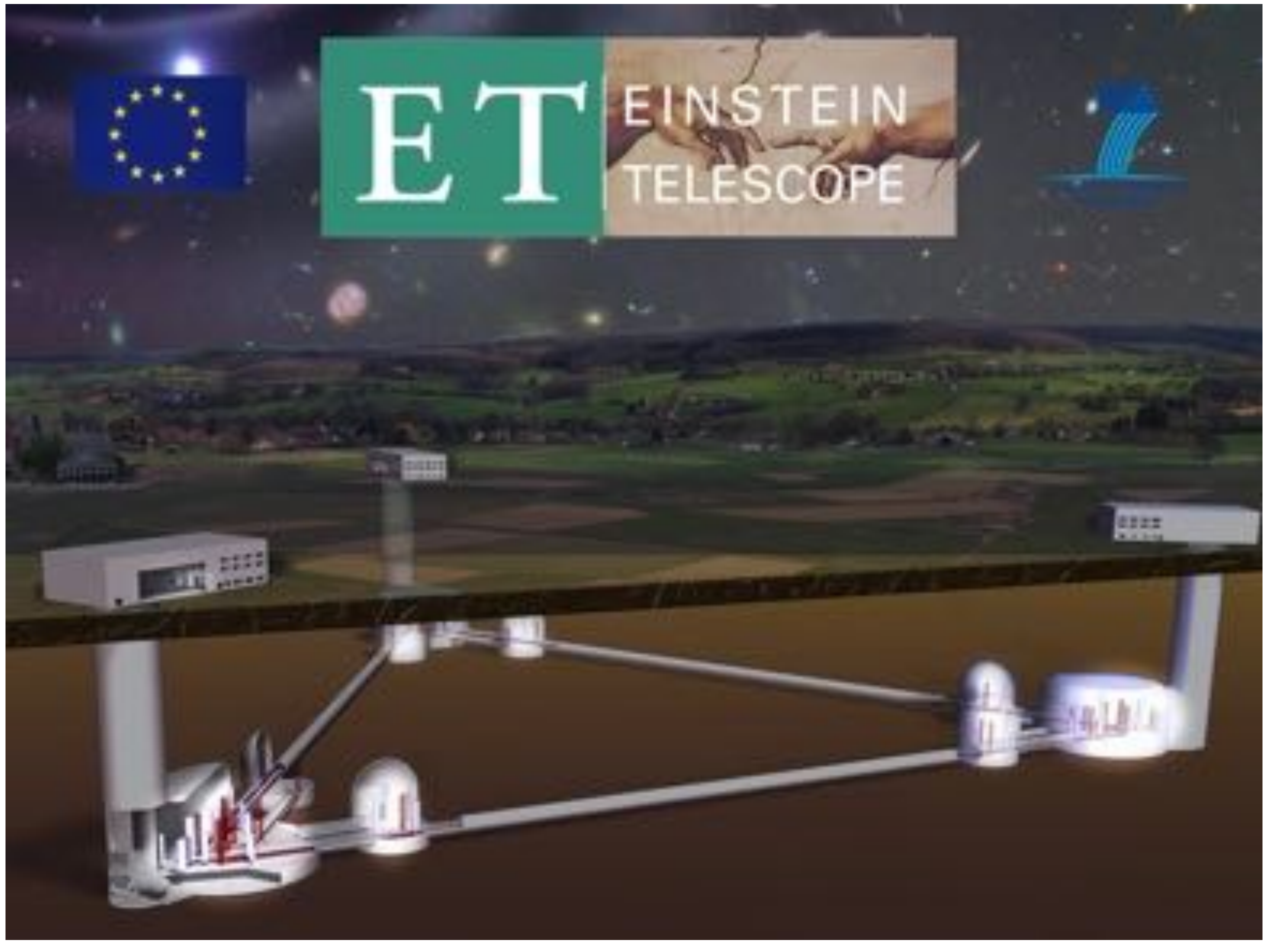
Ground-Based Laser Interferometer Detectors

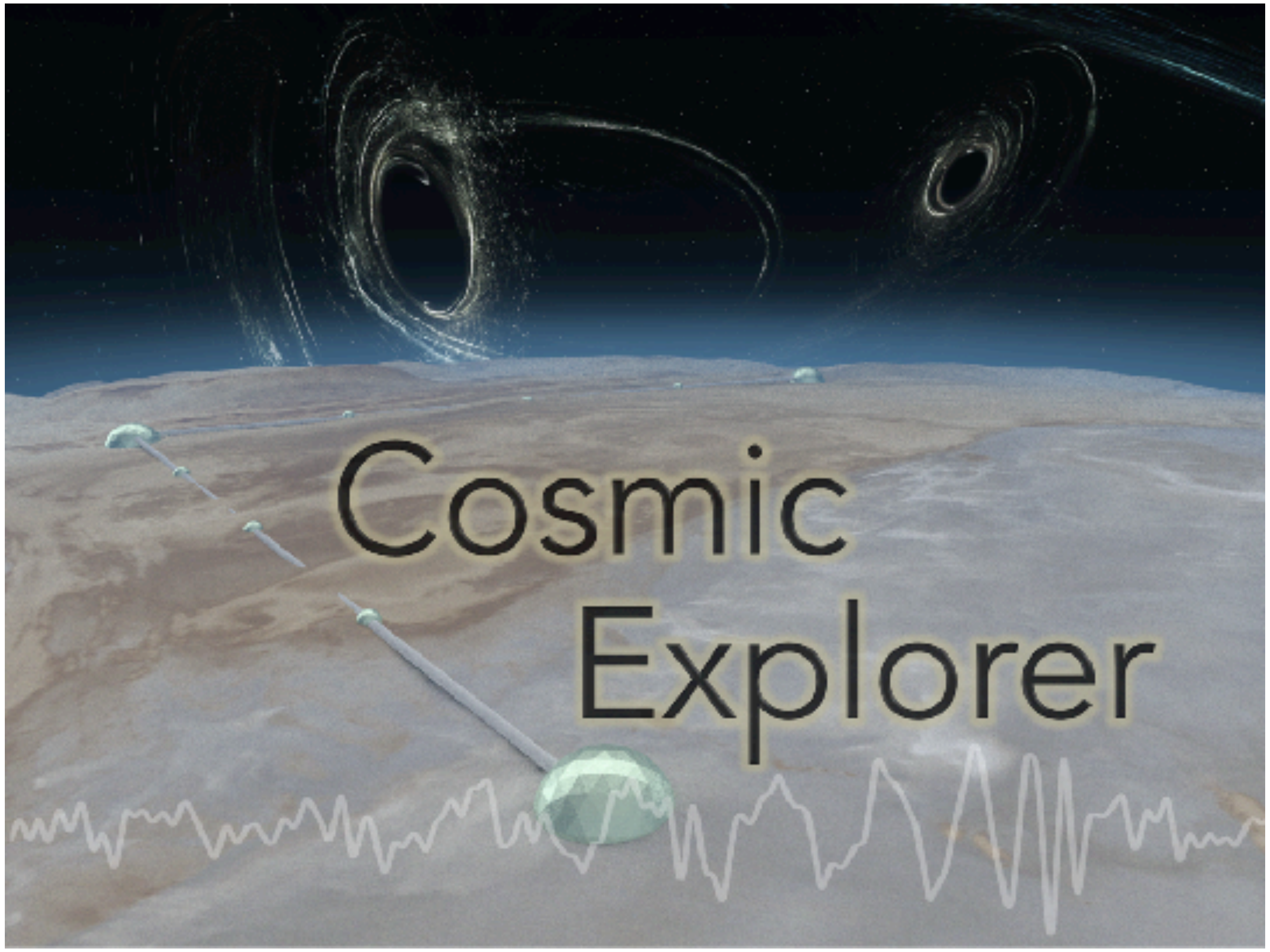
• LIGO showed that Gravitational Waves affect our (laser interferometric) detectors as expected (by most people...)!

• Ground-Based second-generation detectors LIGO (USA) and Virgo (Italy, France, The Netherlands, Hungary, Poland, Spain, …) have just started their third observation run (O3). KAGRA (Japan) is second-1/2 generation detector currently in engineering runs.

Ground-Based Laser Interferometer Detectors

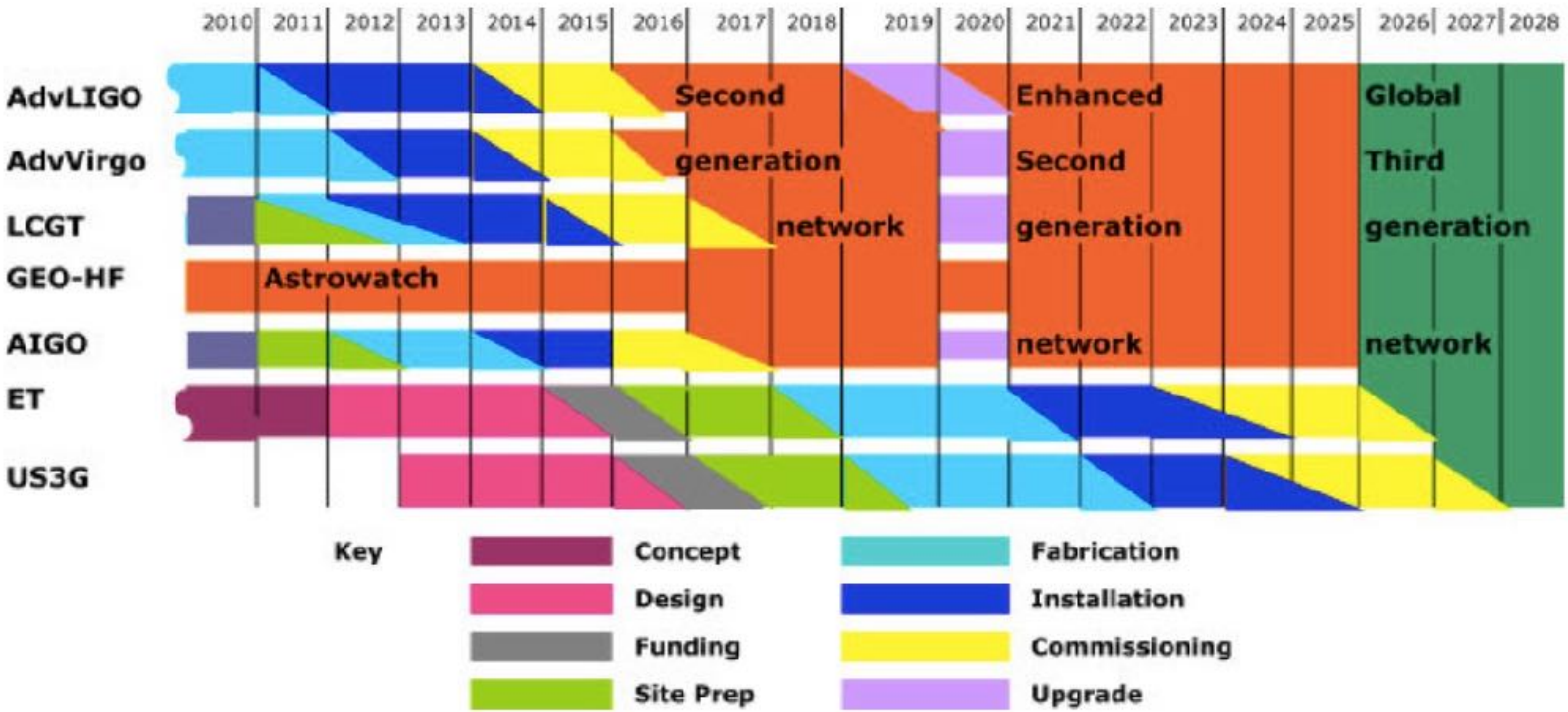
• There are plans for Ground-Based third-generation detectors: Einstein Telescope (Europe), LIGO Voyager and LIGO Cosmic Explorer (USA).





Ground-Based Laser Interferometer Detectors

✴ Status and Future Plans:



LCGT = KAGRA (Japan)

LIGO India was approved!

Detection of Gravitational Waves

- Resonant Detectors **(Pioneer Technology)**
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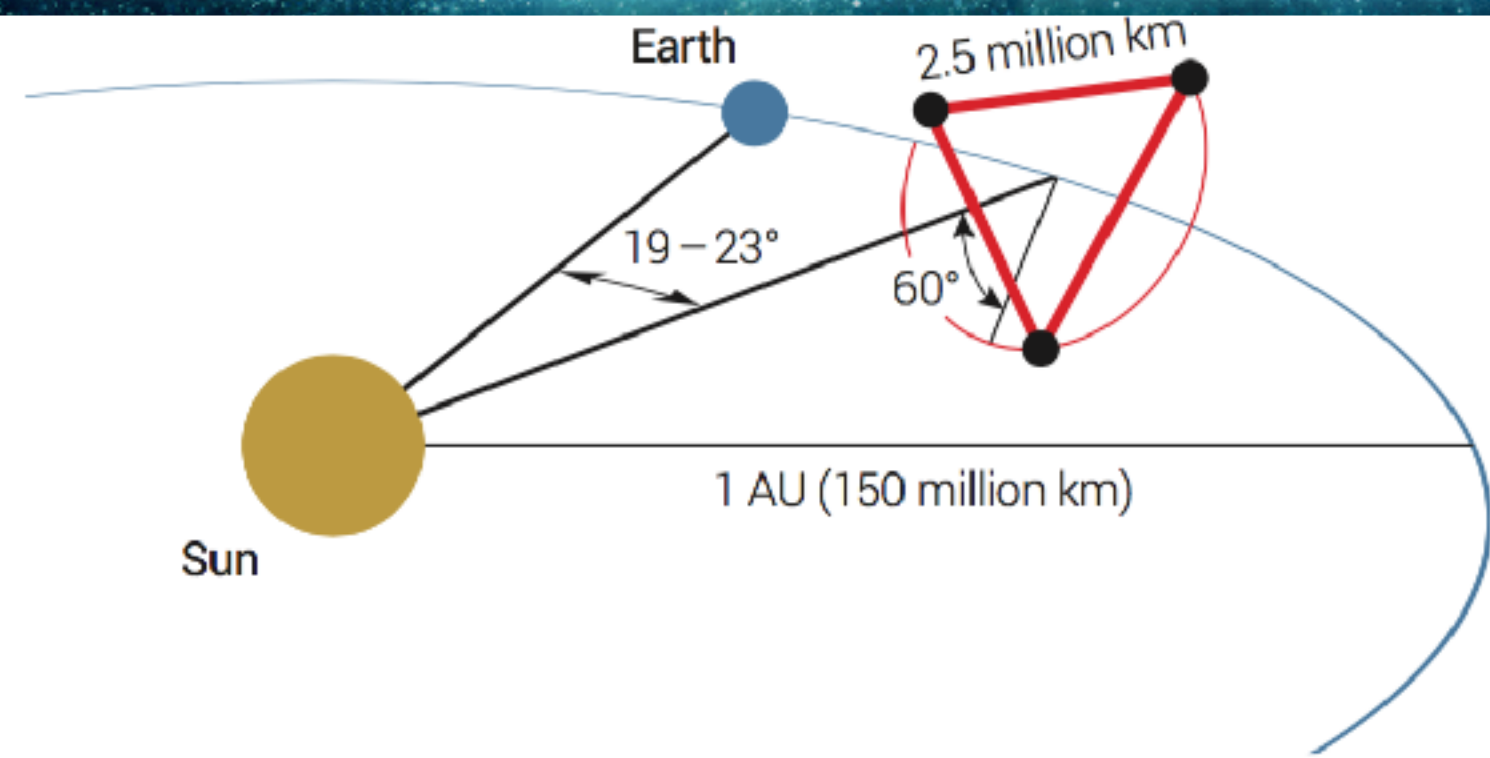
- Long-Arm Laser Interferometric Detectors **(Technology for the first Space-Based Observatory)**

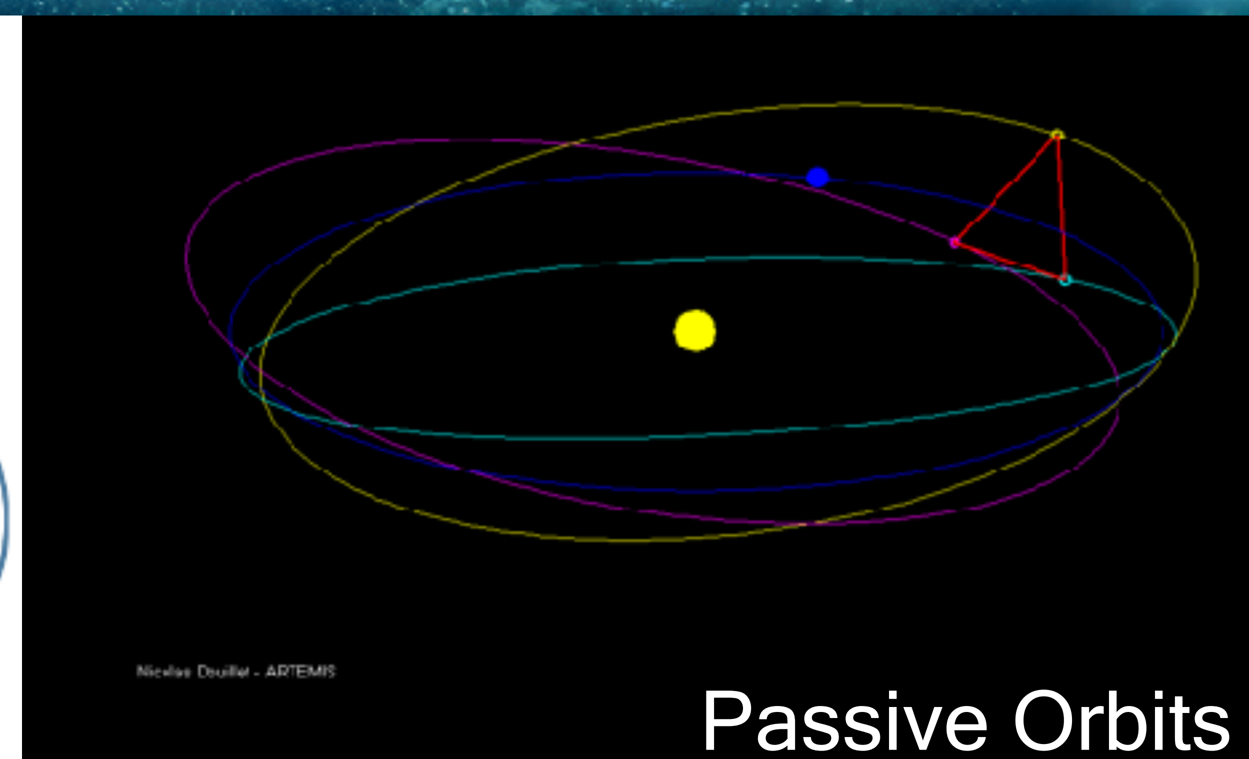
Gravitational Wave Detection from Space

Ground-Based are noise dominated detectors

$0.1\,\mathrm{mHz} < f < 1\,\mathrm{Hz}$

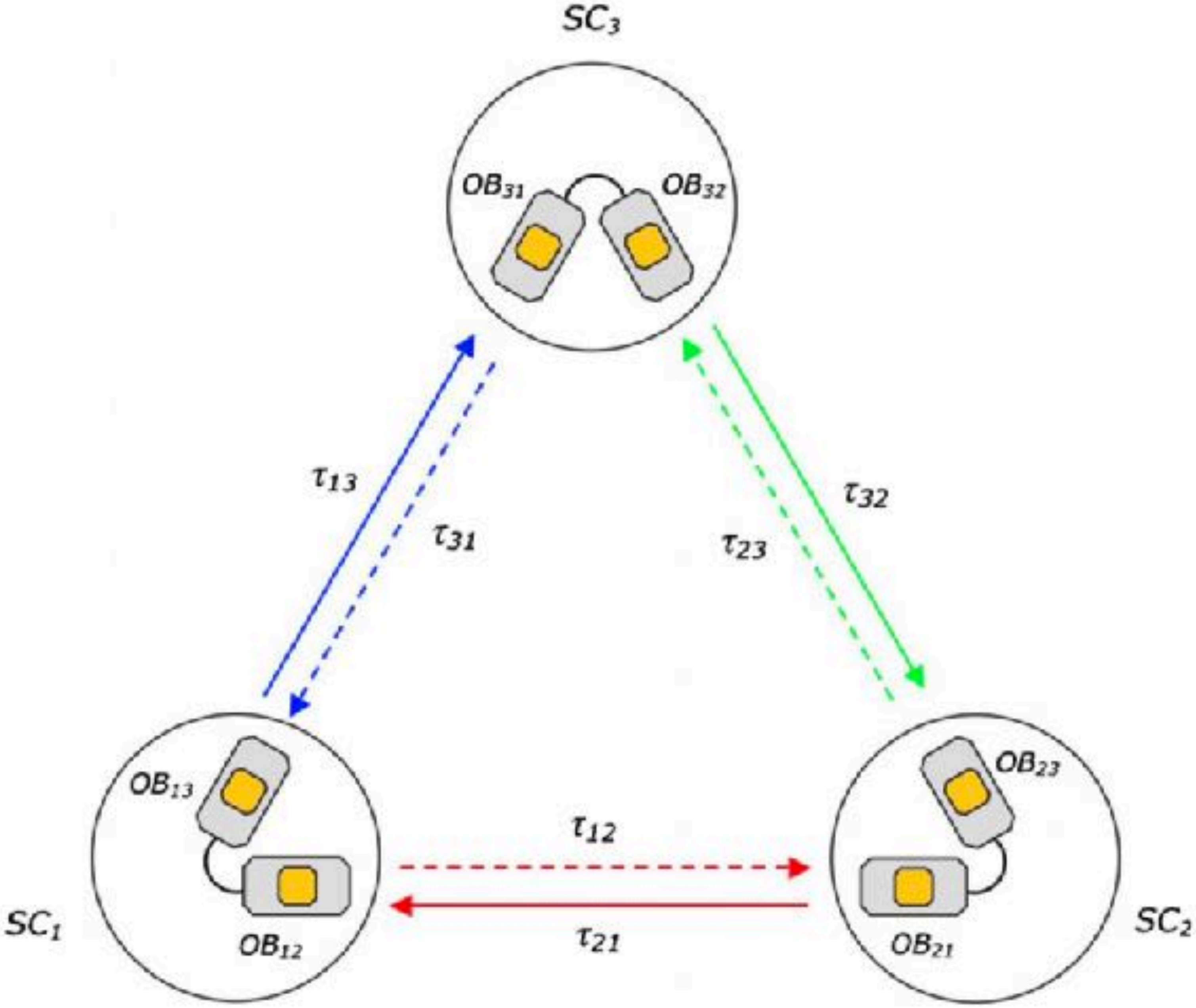
Space-Based are signal-dominated detectors

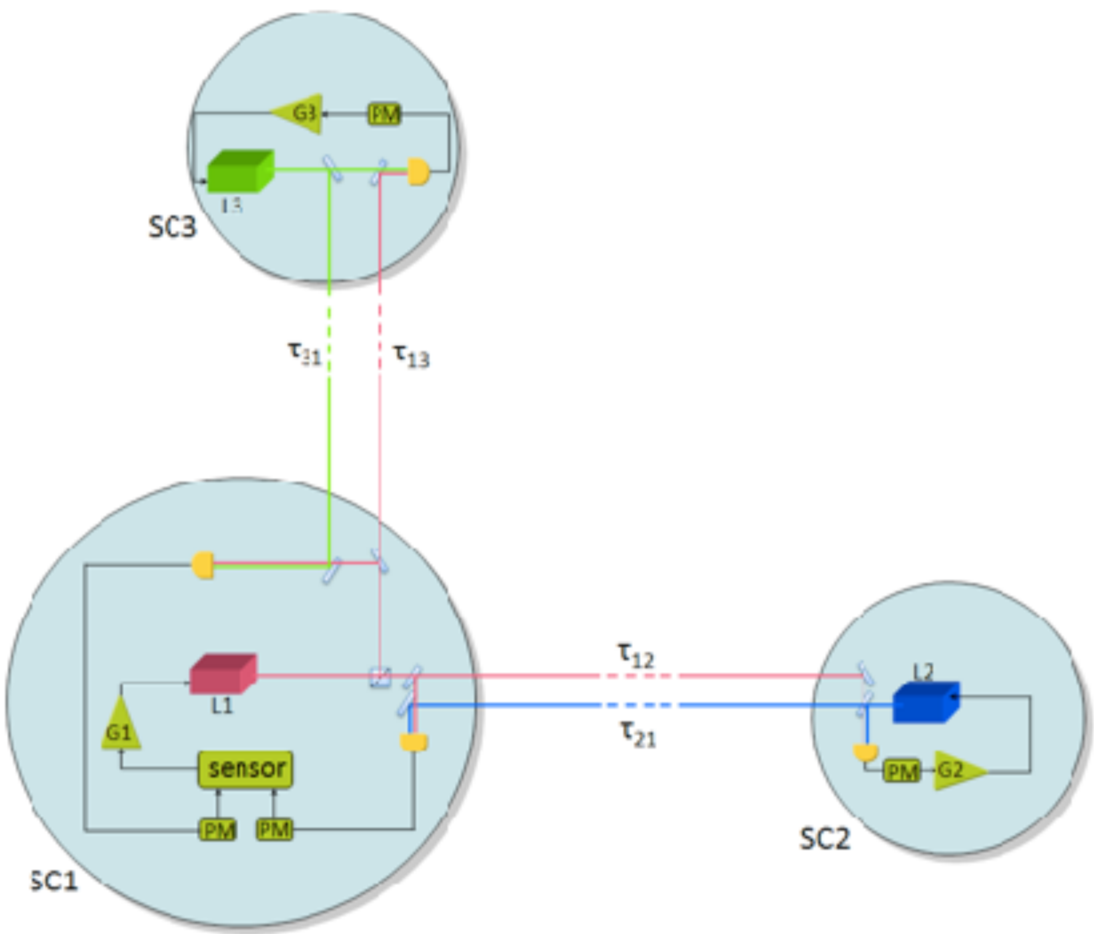




Gravitational Wave Detection from Space

* With such baselines we cannot use mirrors for reflection (LISA ≠LIGO in Space). Instead, active mirrors with phase locked laser transponders on the spacecraft will be implemented.

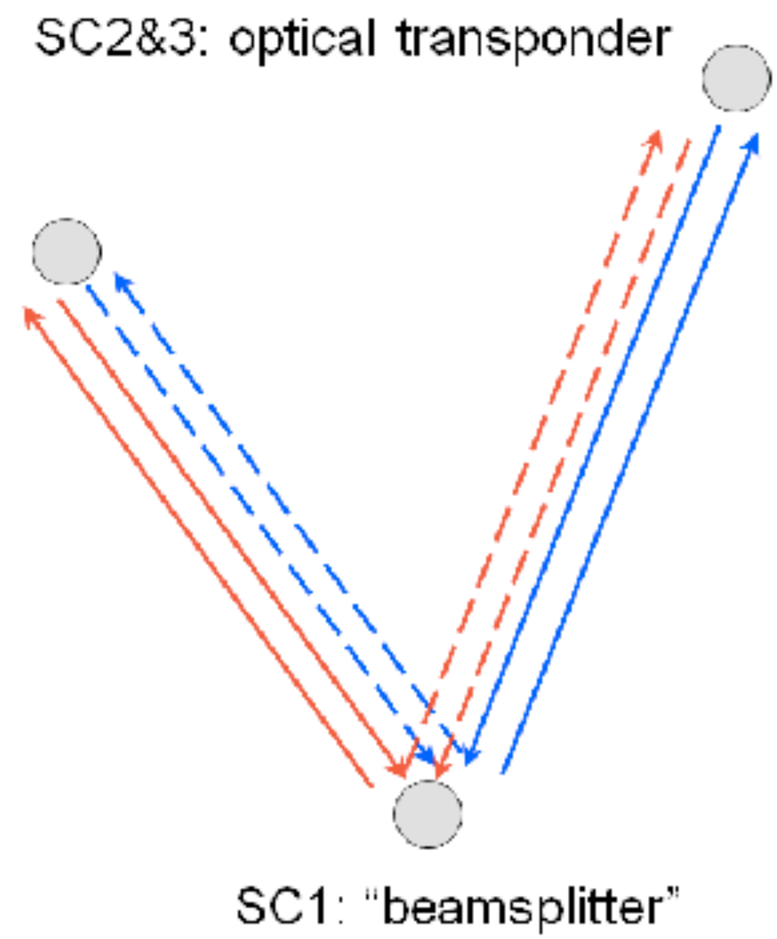


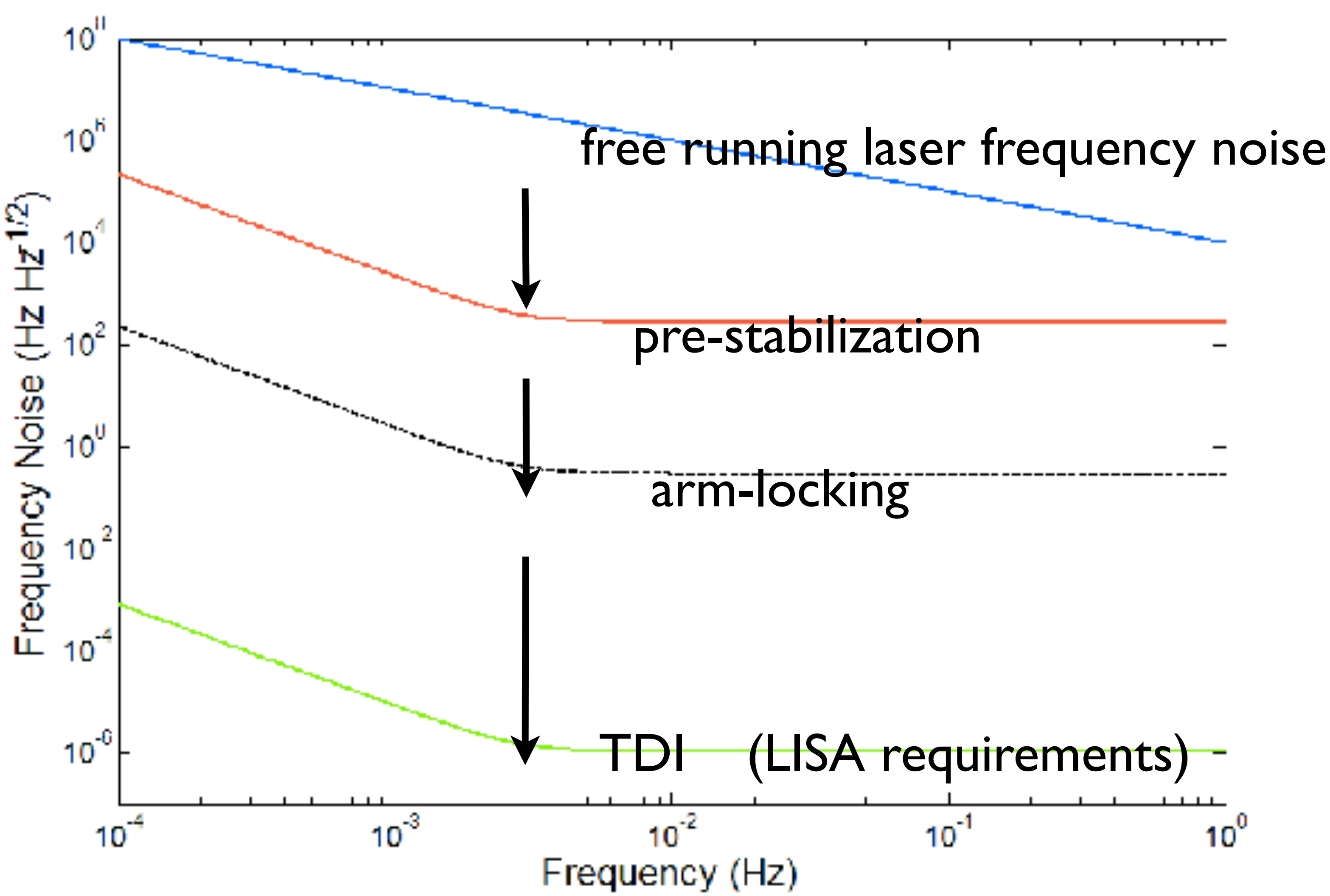


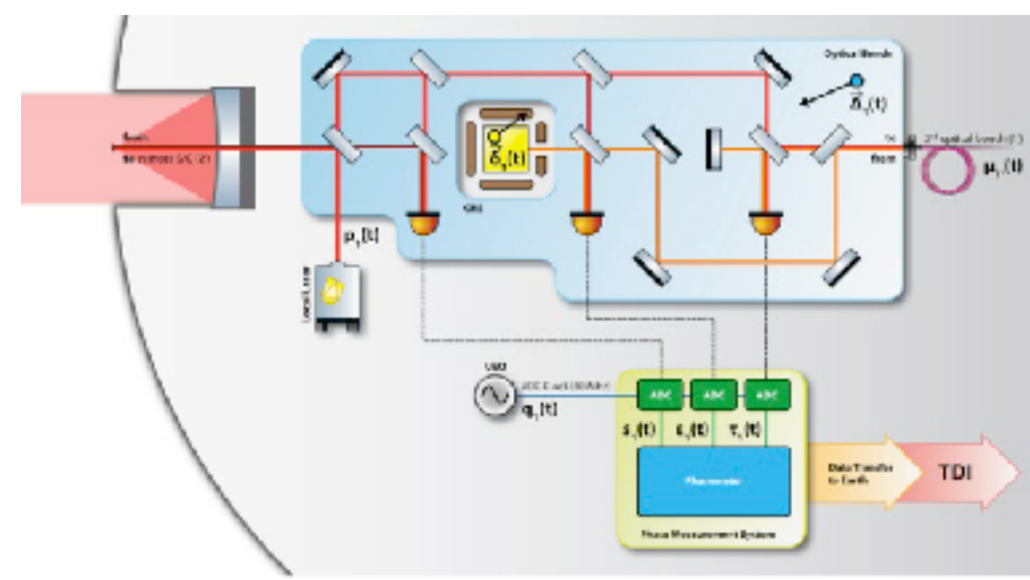
Thorpe, CQG, **27**, 084008 (2010)

Gravitational Wave Detection from Space

- Time-delay interferometry (TDI): Correlations in the frequency noise can be calculated and subtracted by algebraically combining phase measurements from different craft delayed by the multiples of the time delay between the spacecrafts.







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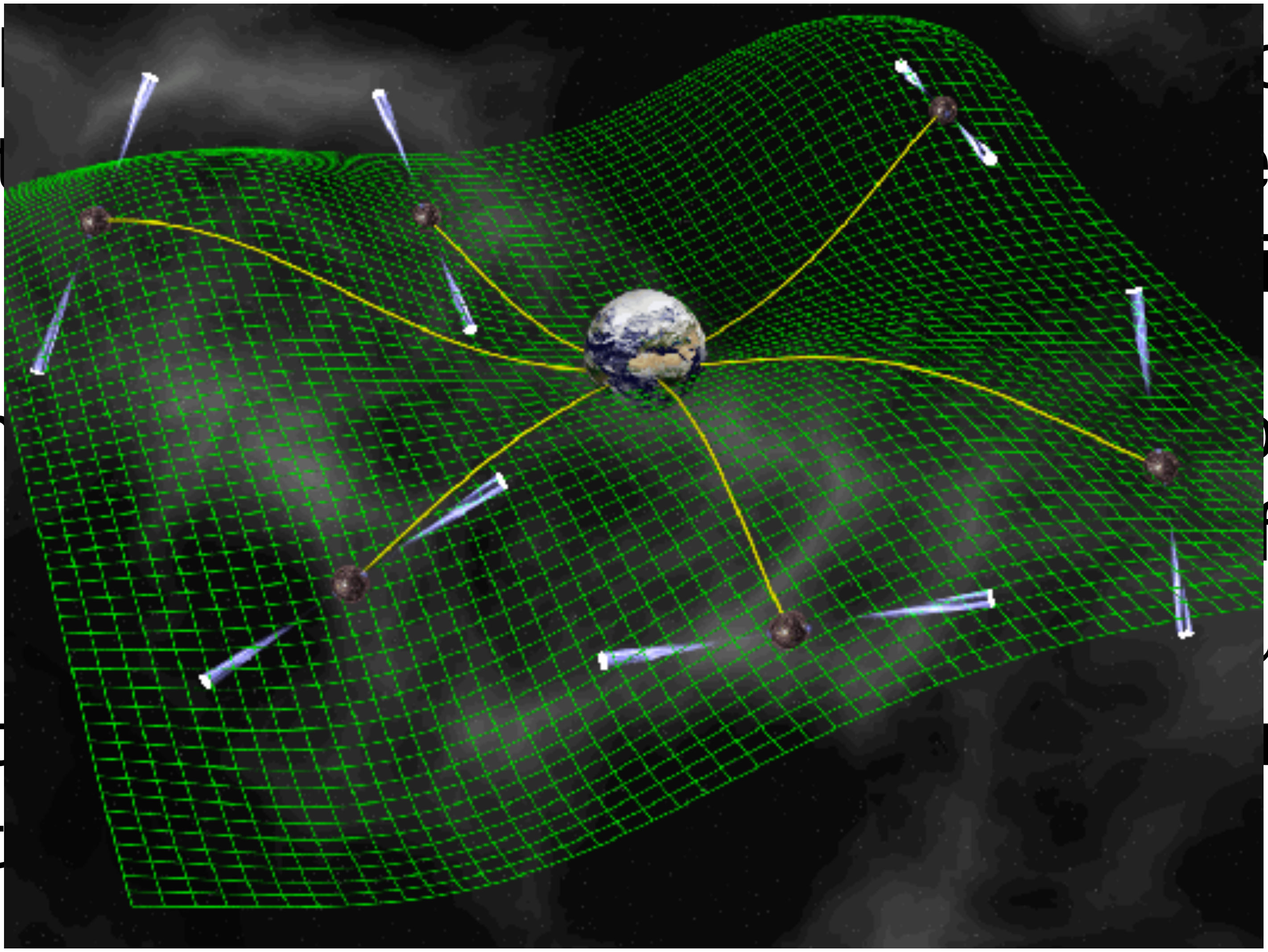
- Long-Arm Laser Interferometric Detectors **(Technology for the first Space-Based Observatory)**
- Pulsar Timing Arrays **(Radiotelescopes)**

Pulsar Timing Arrays



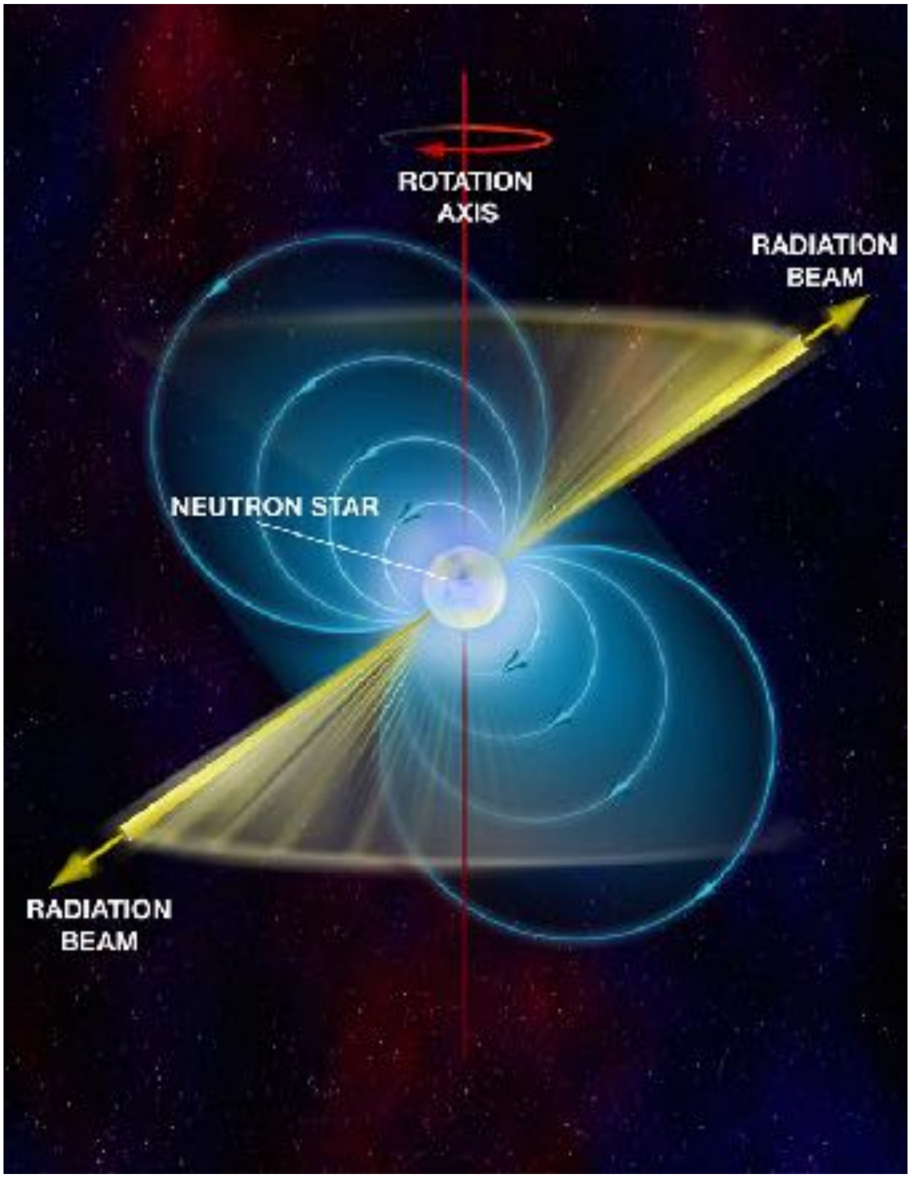
* It has been s… …onal waves will induce pulsar t… …ectable with high-precision … …imes.

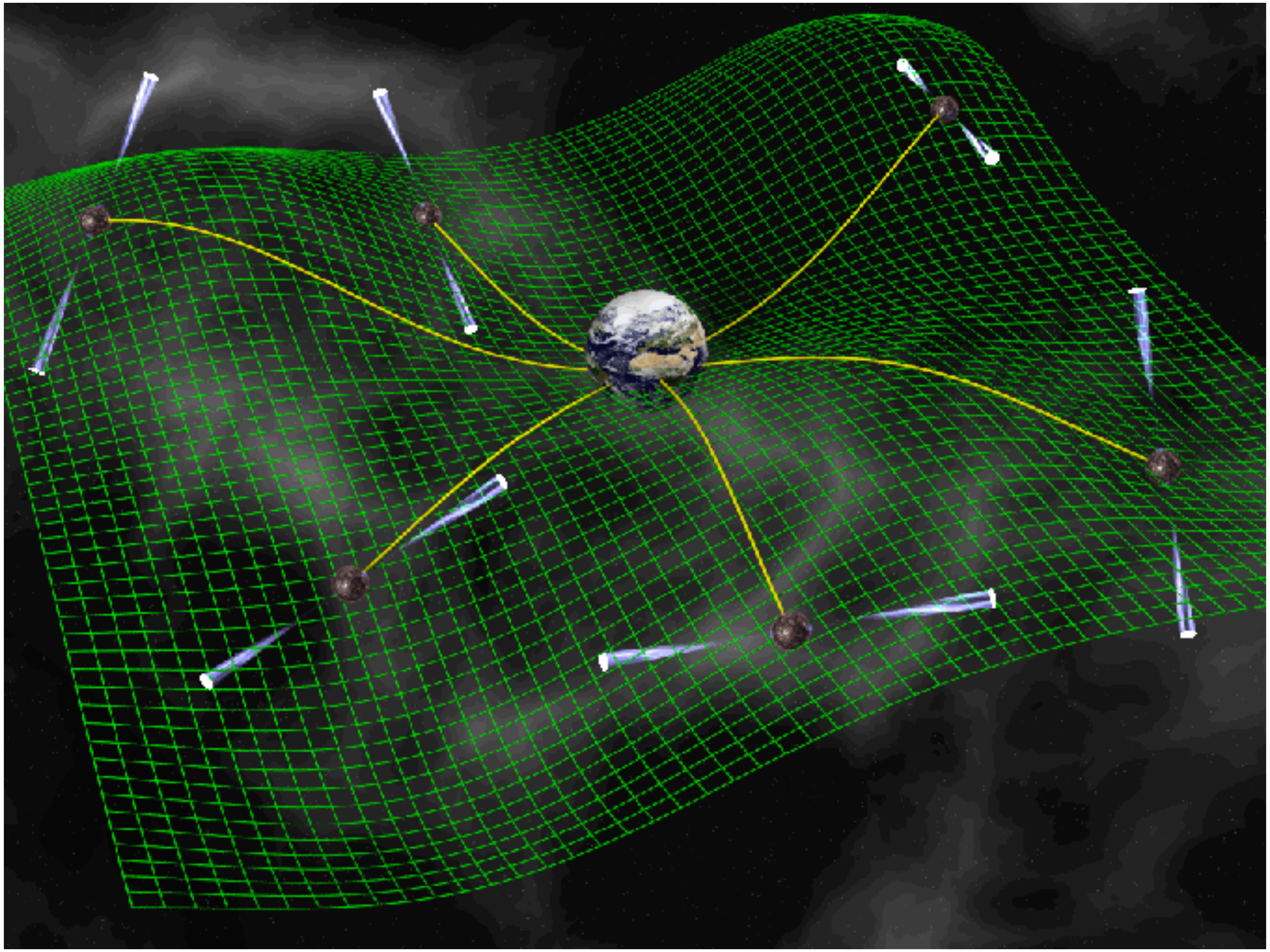
* However, with… …perhaps impossible, to … …f gravitational waves and ma… …ular rotation of the neutron st… …n effects or in accuracies in t…

* It has been shown that such effects could be distinguished by looking for correlated behaviour in the timing residuals of many pulsars: The timing residuals caused by irregular rotation or propagation effects should be uncorrelated between different pulsars.

Pulsar Timing Arrays

- Pulsar Timing Arrays have achieved a sensitivity in the discovery region of the expected parameter-space for GW backgrounds produced by supermassive black hole binaries





Detection of Gravitational Waves

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- Long-Arm Laser Interferometric Detectors **(Technology for the first Space-Based Observatory)**
- Pulsar Timing Arrays **(Radiotelescopes)**
- Cosmic Microwave Background Radiation Polatization Detectors
- Atom Interferometric Detectors **(Future Technology)**

The Gravitational-Wave Spectrum

- The Ultra-low Frequency Band:

$$10^{-18}\ \mathrm{Hz} \lesssim f \lesssim 10^{-13}\ \mathrm{Hz}$$

- The very Low Frequency Band:

$$10^{-9}\ \mathrm{Hz} \lesssim f \lesssim 10^{-7}\ \mathrm{Hz}$$

- The Low Frequency Band:

$$10^{-5}\ \mathrm{Hz} \lesssim f \lesssim 1\ \mathrm{Hz}$$

- The High Frequency Band:

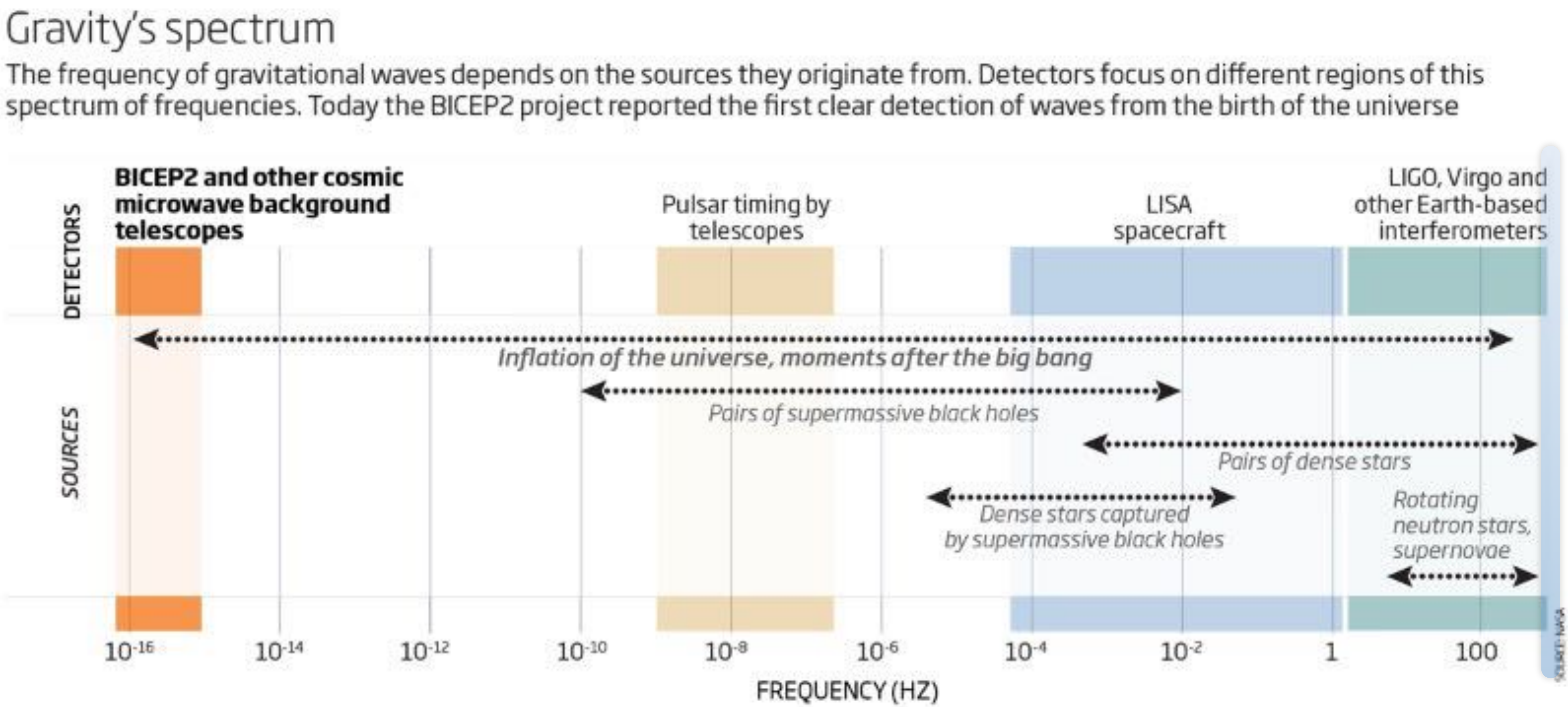
$$1\ \mathrm{Hz} \lesssim f \lesssim 10^{4}\ \mathrm{Hz}$$

- The very High Frequency Band:

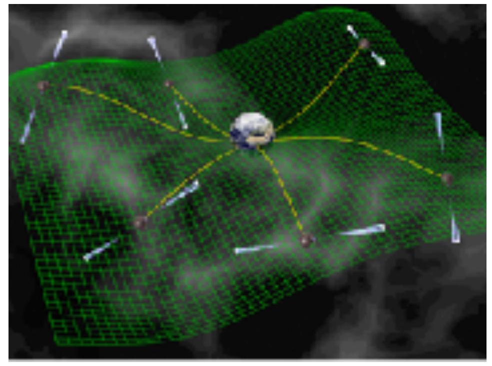
$$f > 10^{4}\ \mathrm{Hz}$$

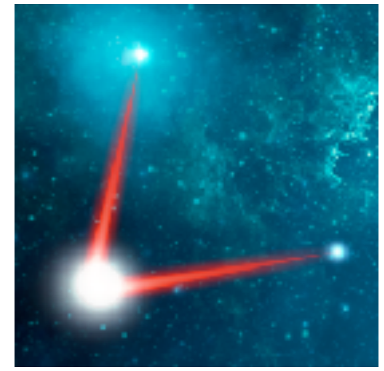
Gravitational Wave Spectrum (with Detectors & Sources)

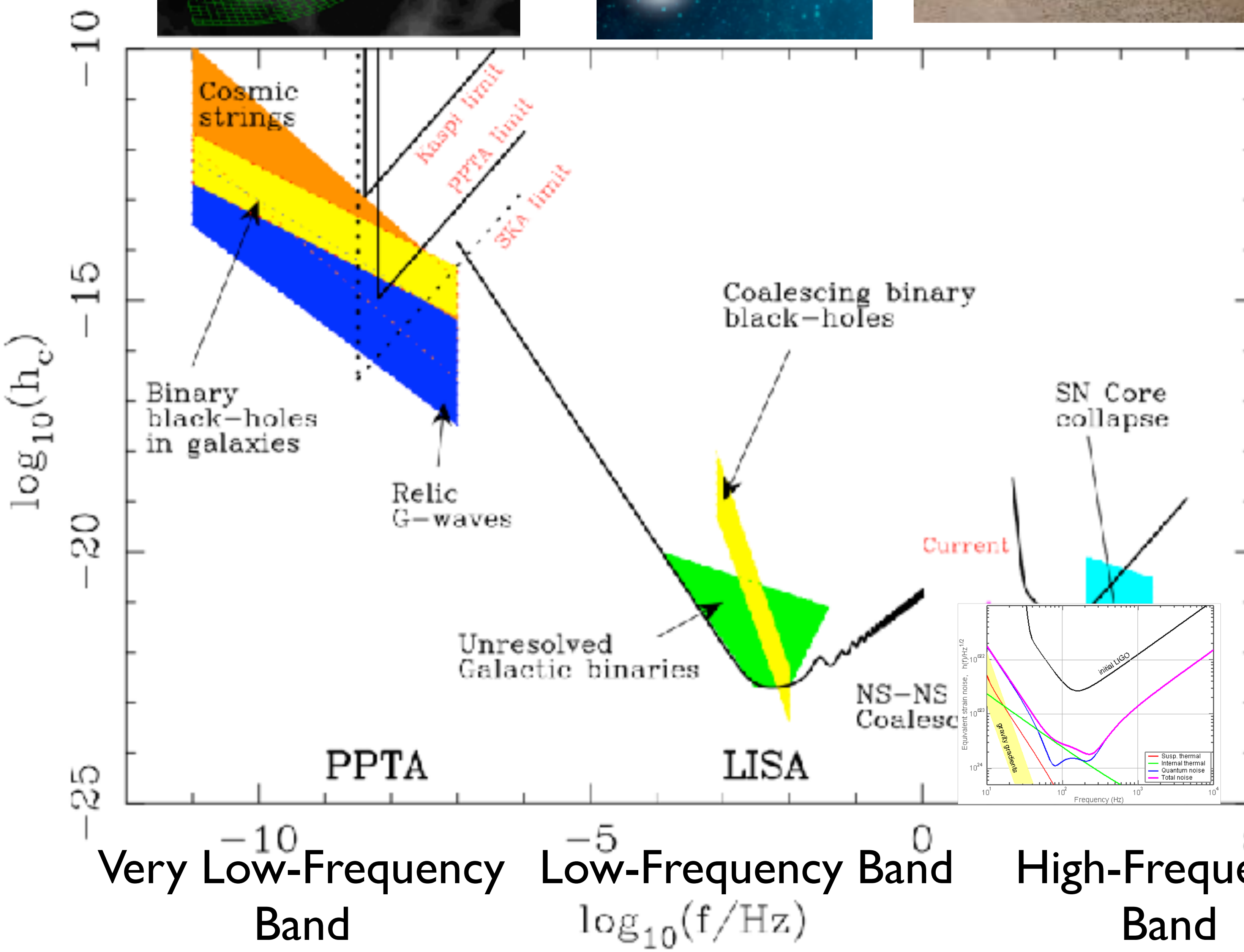
<- GW Detector "Size"



Gravitational Wave Spectrum (with Sources & Detectors)







Very Low-Frequency Band

Low-Frequency Band

High-Frequency Band

$$f_{\rm GW} \downarrow \ (\lambda_{\rm GW} \uparrow) \quad \Rightarrow \quad L_{\rm arm} \uparrow$$

Carlos F. Sopuerta
June 11th, 2019
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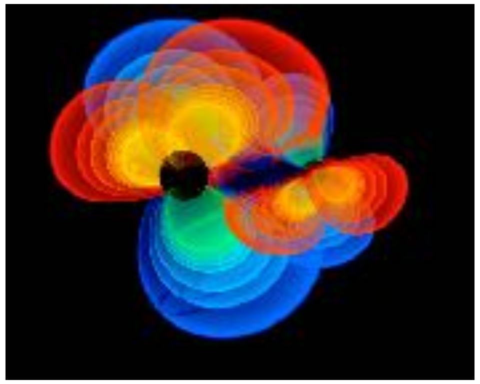
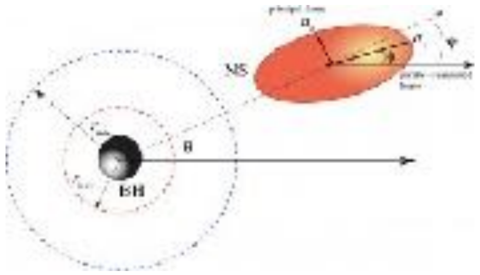
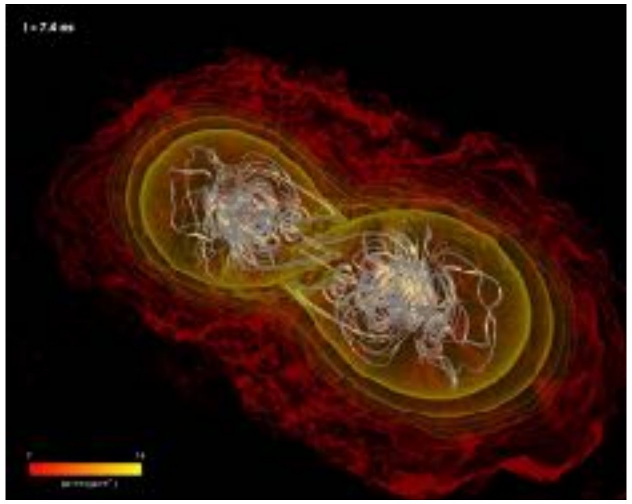
Black Hole Science with Gravitational Waves

Gravitational Wave Sources (HF Band)

Compact Binary System Coalescence

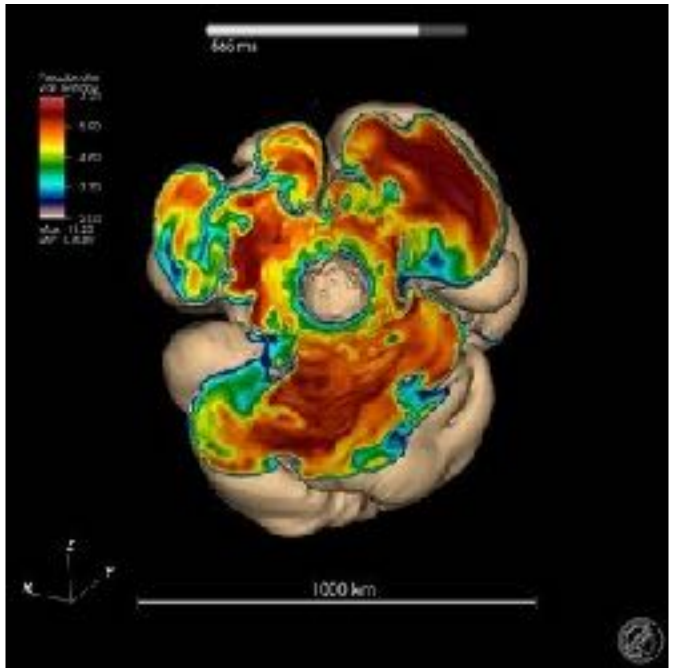




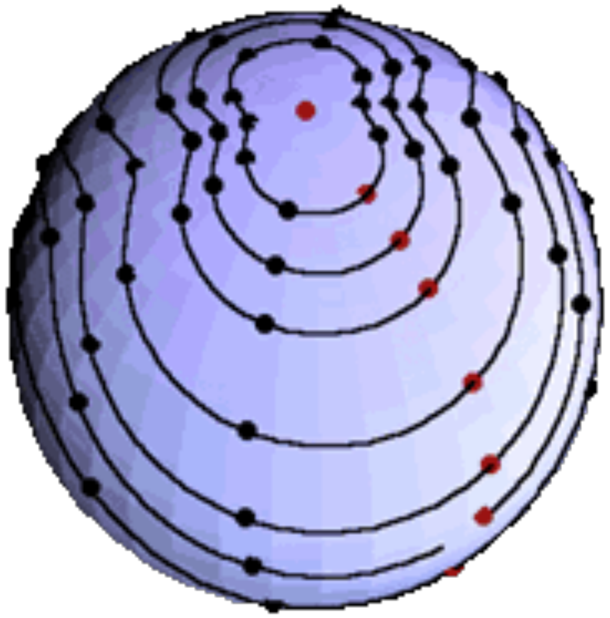


NS-NS, BH-BH, BH-NS

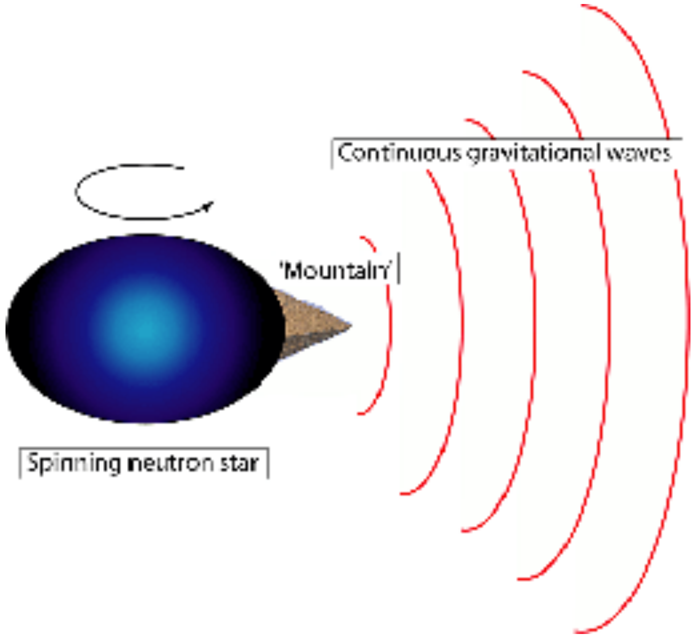
Core Collapse Supernovae



Oscillations of Relativistic Stars

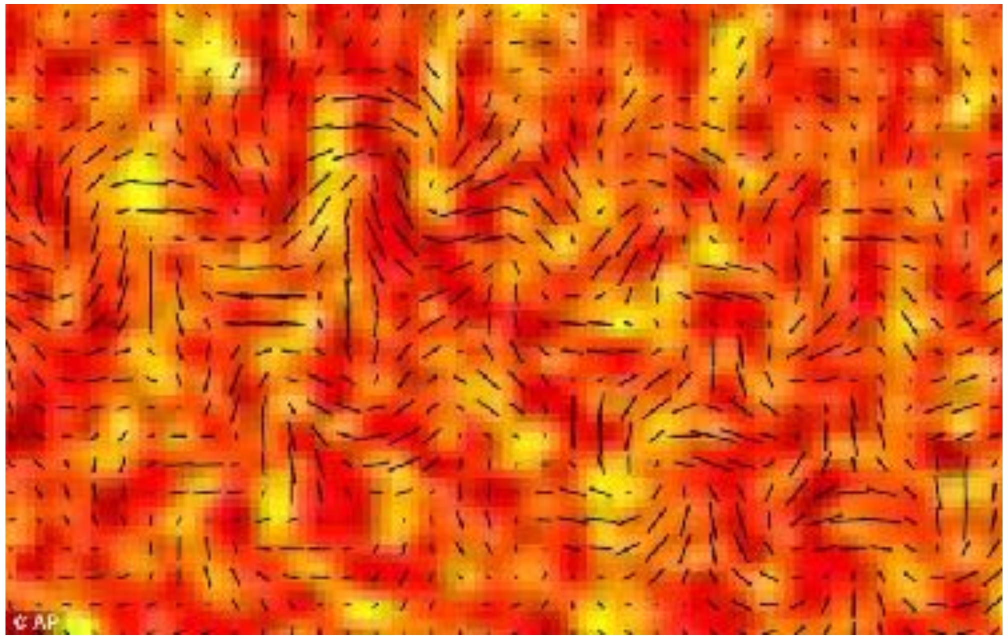


r-Modes



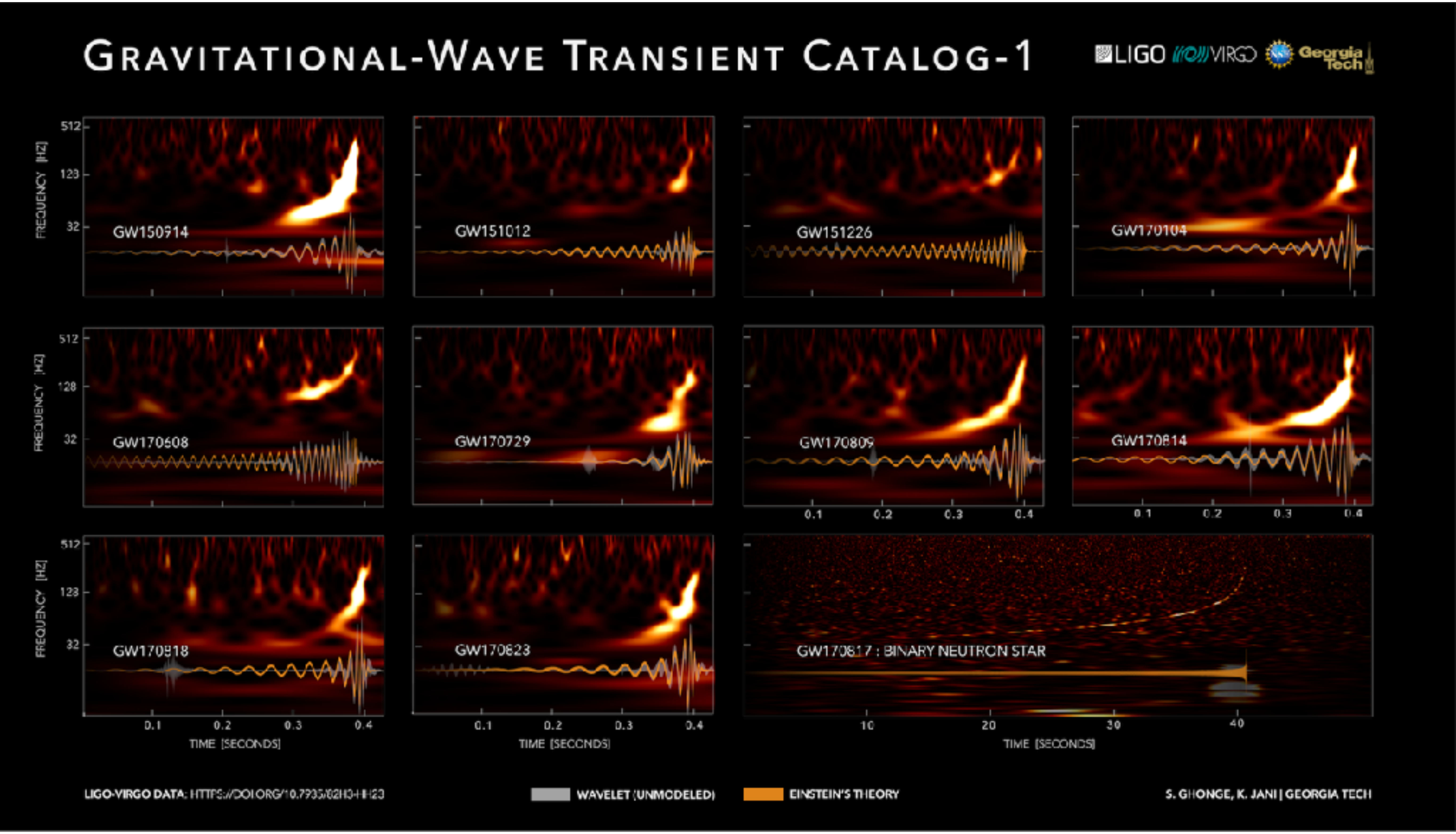
“mountains” in Neutron Stars

Stochastic Signals/
Gravitational Wave Backgrounds



Carlos F. Sopuerta
June 11th, 2019
Institute of Space Sciences (ICE, CSIC)
Institute of Space Studies of Catalonia (IEEC)

2018 (Dec 1st): First catalog of the O1 (Sep 2015 to Jan 2016) and O2 (Nov 2016 to Aug 2017) Observing Runs released:



Summary of Discoveries in the O1 & O2 Science Runs

- Stellar-Mass Binary Black Holes exist (first evidence), they merge and form another (bigger) black hole!
- Stellar-Mass Black Holes with masses above 30 $M_{\odot}$ exist!
- The LIGO-Virgo collaboration has detected the coalescence and merger of 10 Binary Black Holes and a Binary Neutron Star (with lots of electromagnetic counterparts).
- The BNS is the first known outside our galaxy.
- First direct association of a BNS merger with a short gamma-ray burst (GRB), the closest known so far.
- First measurement of the Hubble constant using gravitational waves (for the determination of the luminosity distance).
- First confirmation of the Kilonova mechanism for the formation of the heaviest elements.

Parameter estimation for GW150914

✳ From the estimation of the initial and final masses we have an estimation of the energy radiated:

$$E_{GW} = (3.0 \pm 0.5) M_{\odot} c^2$$

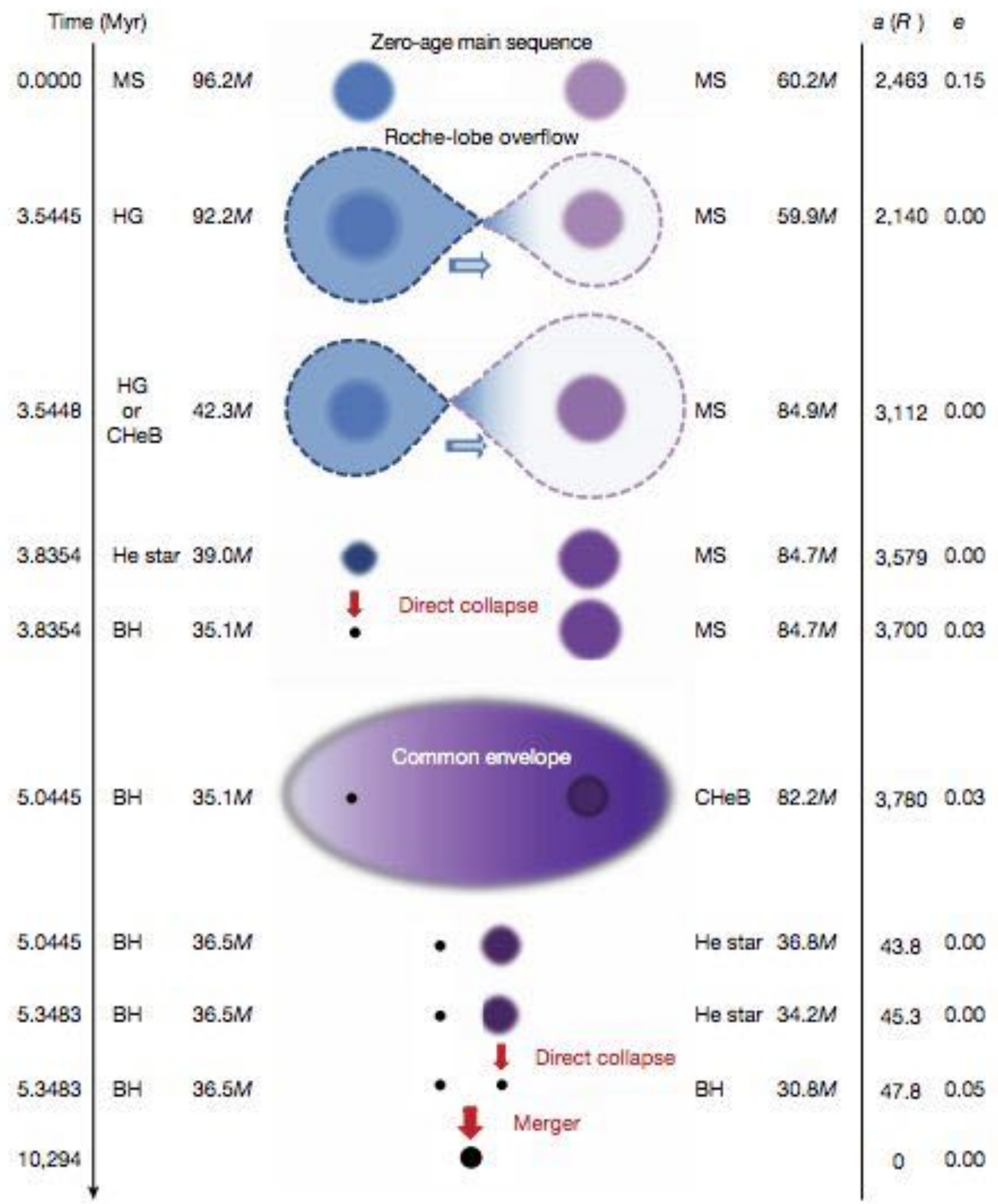
✳ The source maximum GW luminosity during the merger phase has been estimated:

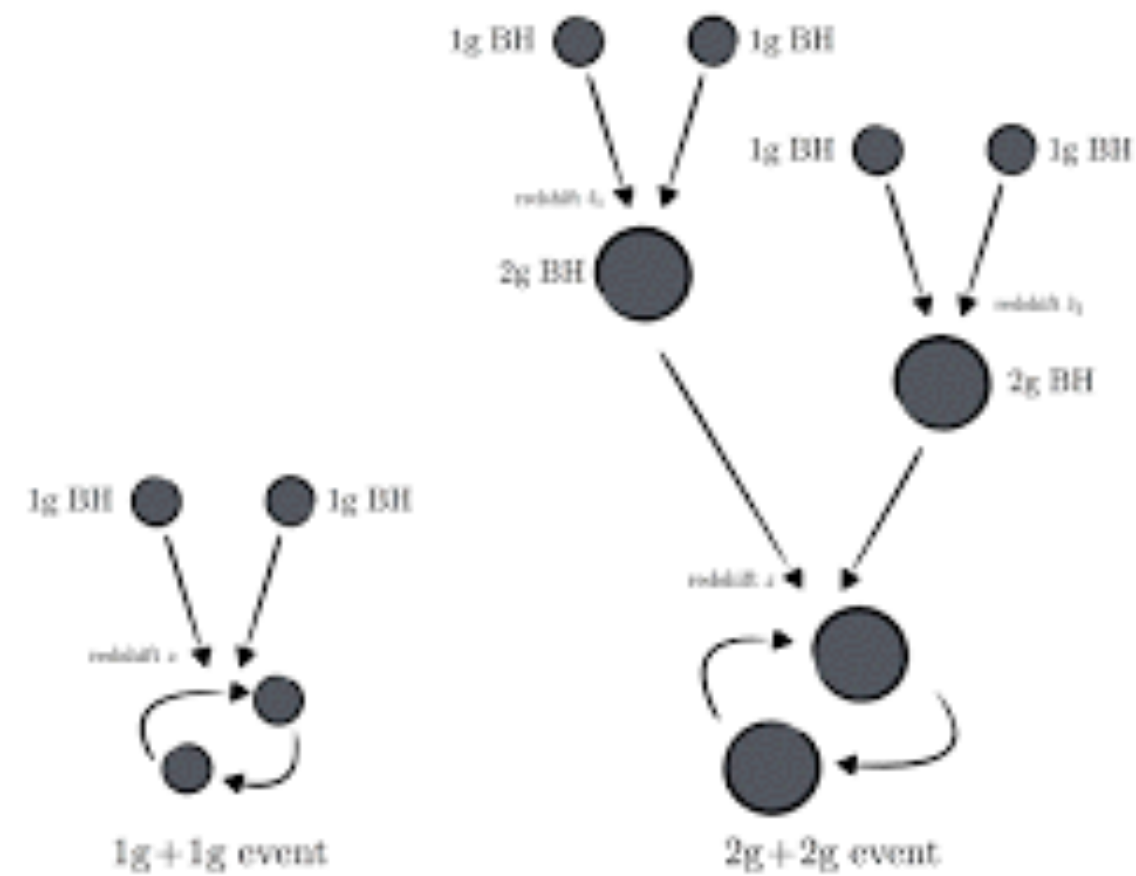
$$\dot{E}_{GW} = 3.6^{+0.5}_{-0.4} \times 10^{56}\, \mathrm{erg}/s = 200^{+30}_{-20} M_{\odot} c^2/s$$

✳ The ultraluminous GRB 110918A reached a peak isotropic-equivalent luminosity:

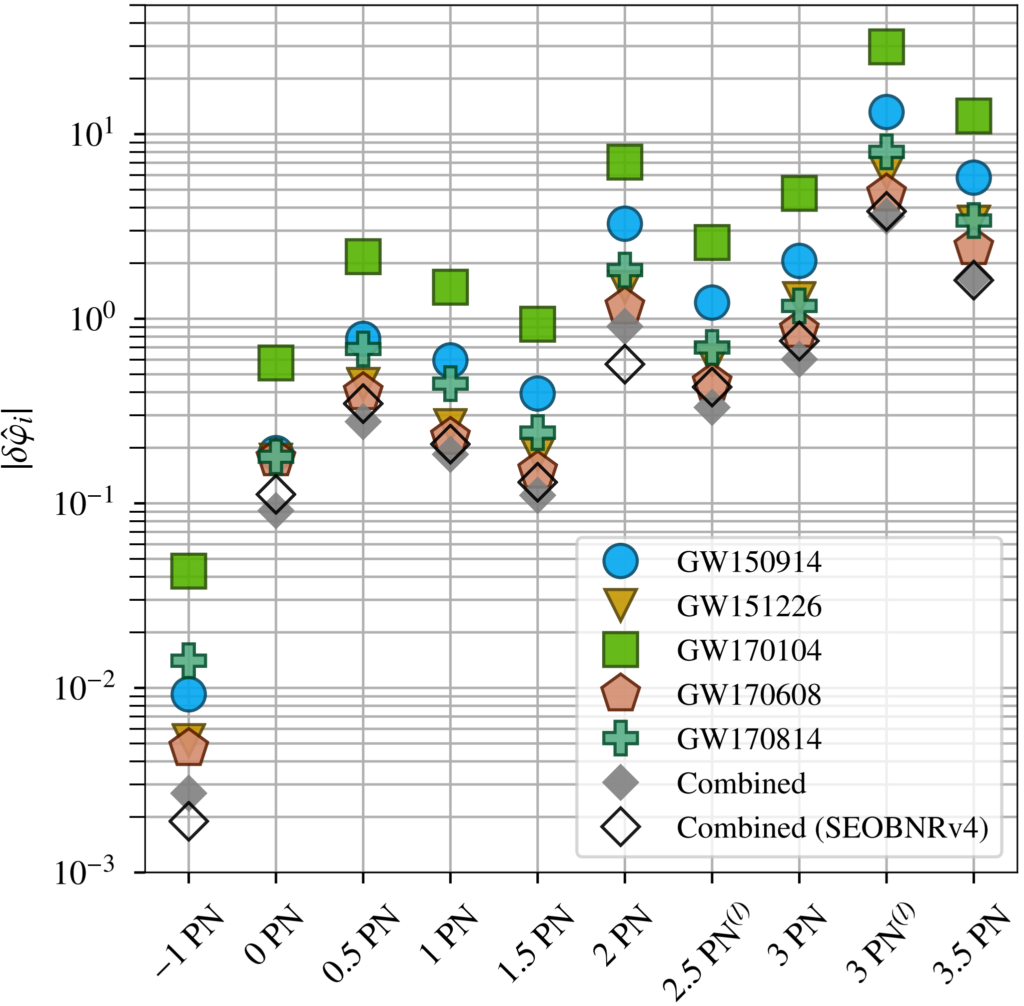
$$L = (4.7 \pm 0.2) \times 10^{54}\, \mathrm{erg}/s$$

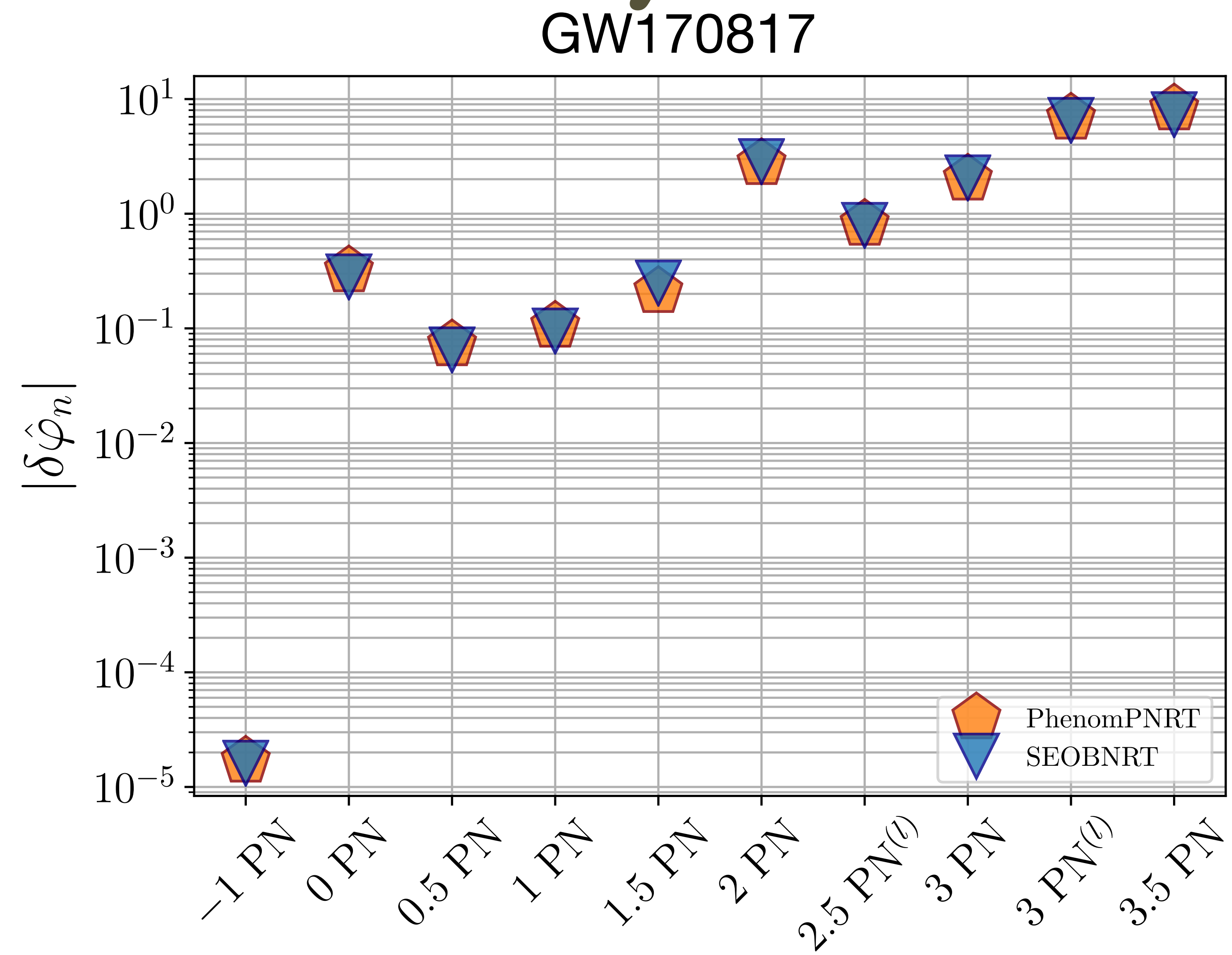
Origin of the LIGO-Virgo Black Holes

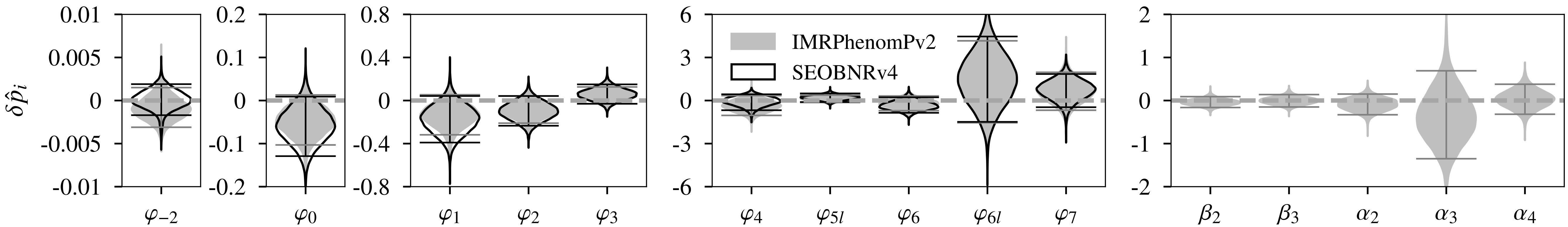




Tests of General Relativity







From: N. K. Johnson-McDaniel (for the LIGO Scientific Collaboration and Virgo Collaboration)
arXiv: **1905.05565**

Tests of General Relativity

Event	Properties D_L [Mpc]	Properties M_{tot} [$M_\odot$]	SNR	GR tests performed RT	IMR	PI	PPI	MDR
GW150914	430^{+150}_{-170}	$66.2^{+3.7}_{-3.3}$	$25.3^{+0.1}_{-0.2}$	✓	✓	✓	✓	✓
GW151012	1060^{+550}_{-480}	$37.3^{+10.6}_{-3.9}$	$9.2^{+0.3}_{-0.4}$	✓	–	–	✓	✓
GW151226	440^{+180}_{-190}	$21.5^{+6.2}_{-1.5}$	$12.4^{+0.2}_{-0.3}$	✓	–	✓	–	✓
GW170104	960^{+440}_{-420}	$51.3^{+5.3}_{-4.2}$	$14.0^{+0.2}_{-0.3}$	✓	✓	✓	✓	✓
GW170608	320^{+120}_{-110}	$18.6^{+3.1}_{-0.7}$	$15.6^{+0.2}_{-0.3}$	✓	–	✓	✓	✓
GW170729	2760^{+1380}_{-1340}	$85.2^{+15.6}_{-11.1}$	$10.8^{+0.4}_{-0.5}$	✓	✓	–	✓	✓
GW170809	990^{+320}_{-380}	$59.2^{+5.4}_{-3.9}$	$12.7^{+0.2}_{-0.3}$	✓	✓	–	✓	✓
GW170814	580^{+160}_{-210}	$56.1^{+3.4}_{-2.7}$	$17.8^{+0.3}_{-0.3}$	✓	✓	✓	✓	✓
GW170818	1020^{+430}_{-360}	$62.5^{+5.1}_{-4.0}$	$11.9^{+0.3}_{-0.4}$	✓	✓	–	✓	✓
GW170823	1850^{+840}_{-840}	$68.9^{+9.9}_{-7.1}$	$12.1^{+0.2}_{-0.3}$	✓	✓	–	✓	✓

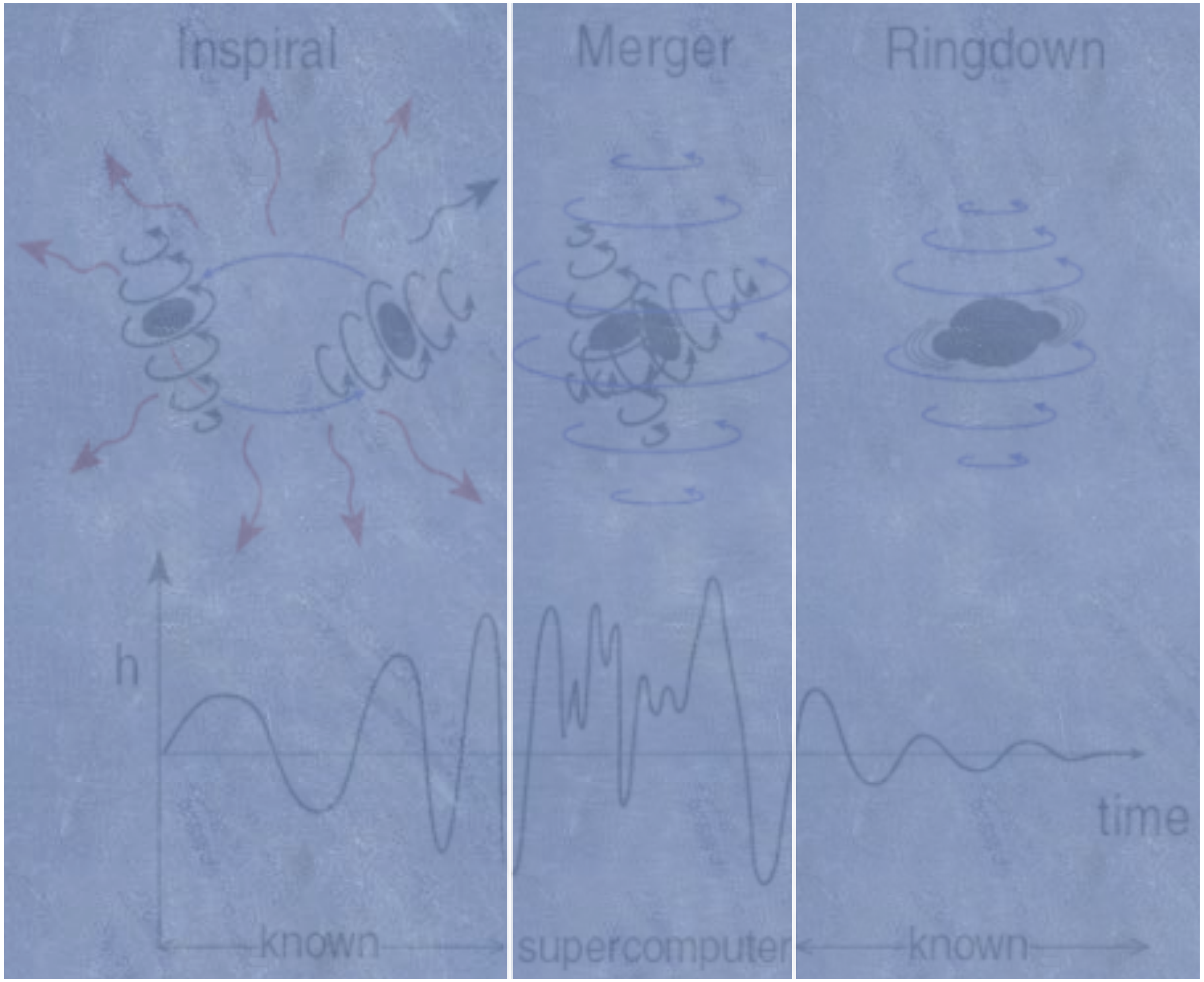
GR tests performed: **RT** = residuals test; **IMR** = inspiral-merger-ringdown consistency test; **PI** & **PPI** = parameterized tests of GW generation for inspiral and post-inspiral phases; **MDR** = modified GW dispersion relation

From: N. K. Johnson-McDaniel (for the LIGO Scientific Collaboration and Virgo Collaboration). arXiv:**1905.05565**

Massive Black Hole Mergers

- The last stages of the evolution of a Black Hole Binary will be driven by gravitational-wave emission:

The system here resembles a perturbed single Black Hole. The evolution can be followed using BH perturbation theory (evolution of damped sinusoids, i.e. Quasi-normal modes).



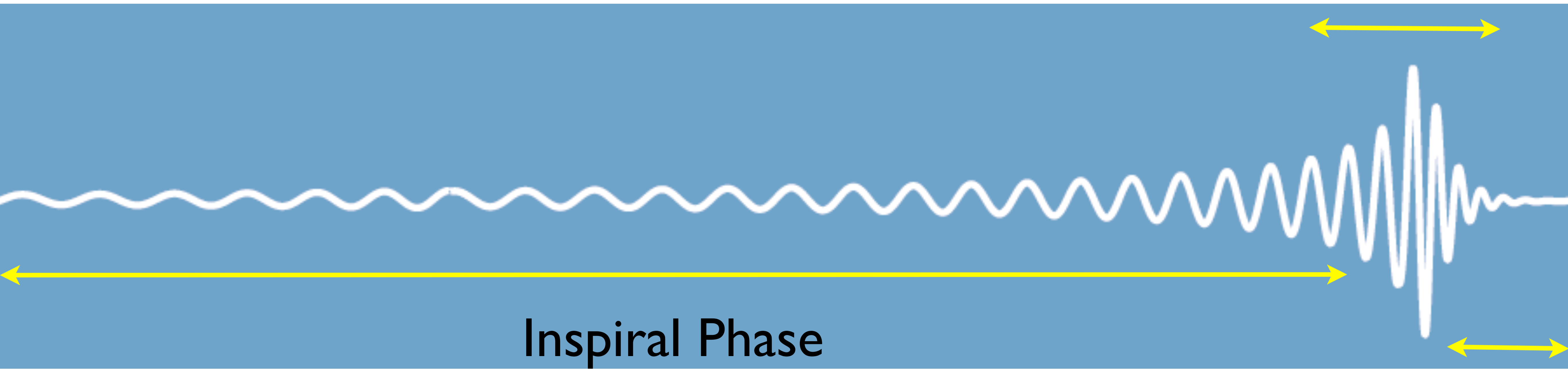
From: Kip Thorne

Carlos F. Sopuerta
June 11th, 2019
Institute of Space Sciences (ICE, CSIC)
Institute of Space Studies of Catalonia (IEEC)

Fundamental Physics with Massive Black Hole Mergers

- High precision measurements of Strong Gravity

Merger
(Numerical Relativity)



(post-Newtonian)

Ringdown
(Perturbation Theory)

The phase carries information about the propagation of the Gravitational Waves

Can test theories of gravity that predict massive gravitations, improving present bounds.

Short bursts of Gravitational Waves in the non-linear regime of General Relativity.

It is a very energetic event with a power corresponding to ~ 10^{22} times the power of the Sun.

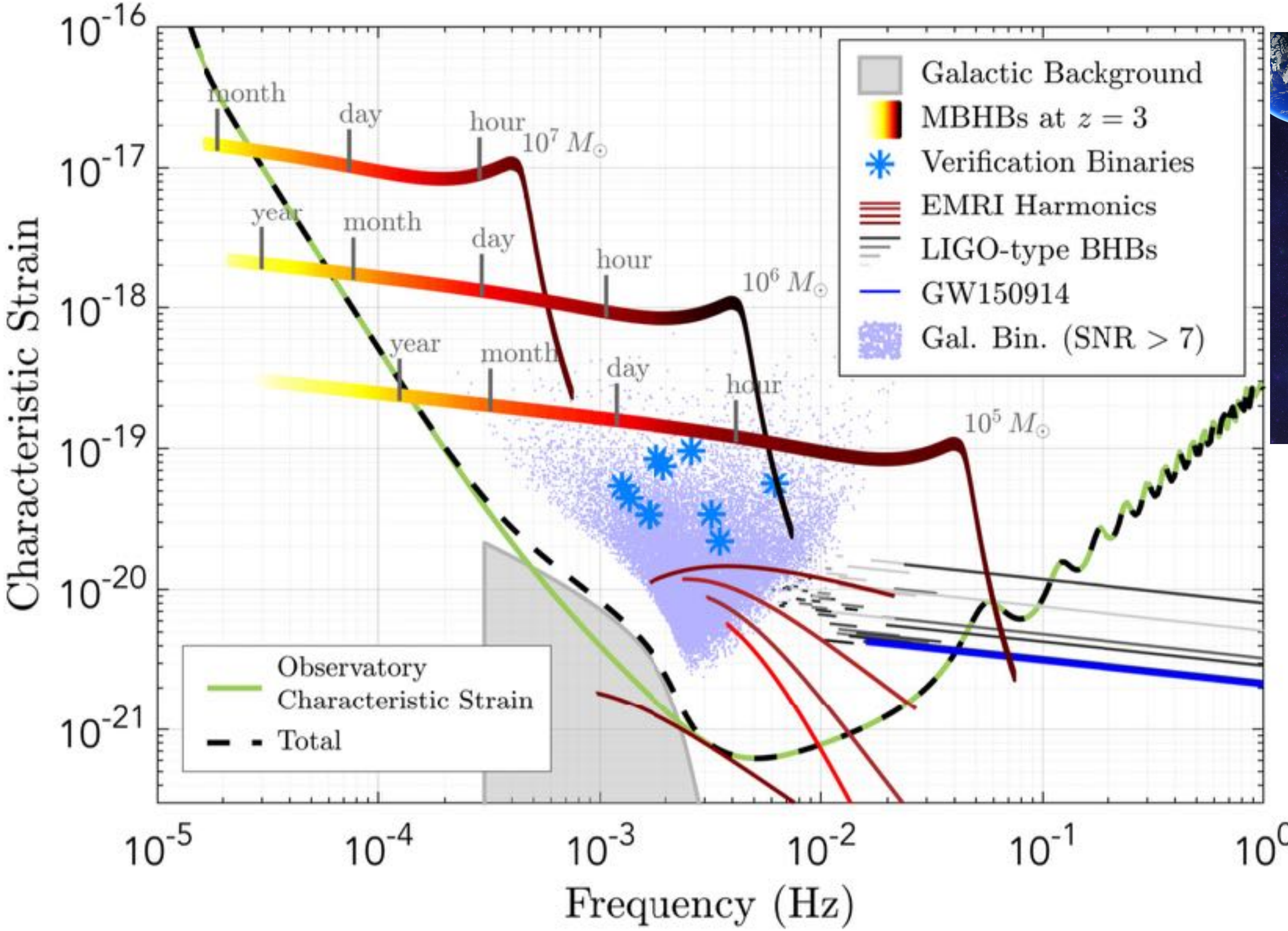
The asymmetric remnant after the merger settles down to a single (Kerr) Black Hole. In this "relaxation" process the system emits Gravitational Waves that are combinations of the QuasiNormal Modes (QNMs) of the final Black Hole.

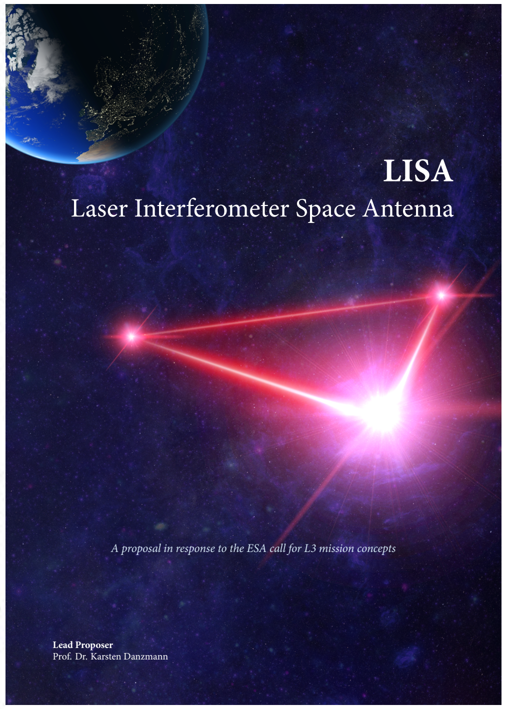
The QNMs, according to General Relativity, only depend on the Mass and Spin of the Black Hole (*no hair* conjecture).

The identification of two QNMs provides a test of the geometry of Black Holes (are they really Kerr Black Holes?). The QNM spectrum is sufficiently rich to allow for distinction of different object.

The Science of LISA

- Expected Sensitivity and Sources:





Carlos F. Sopuerta
June 11th, 2019
Institute of Space Sciences (ICE, CSIC)
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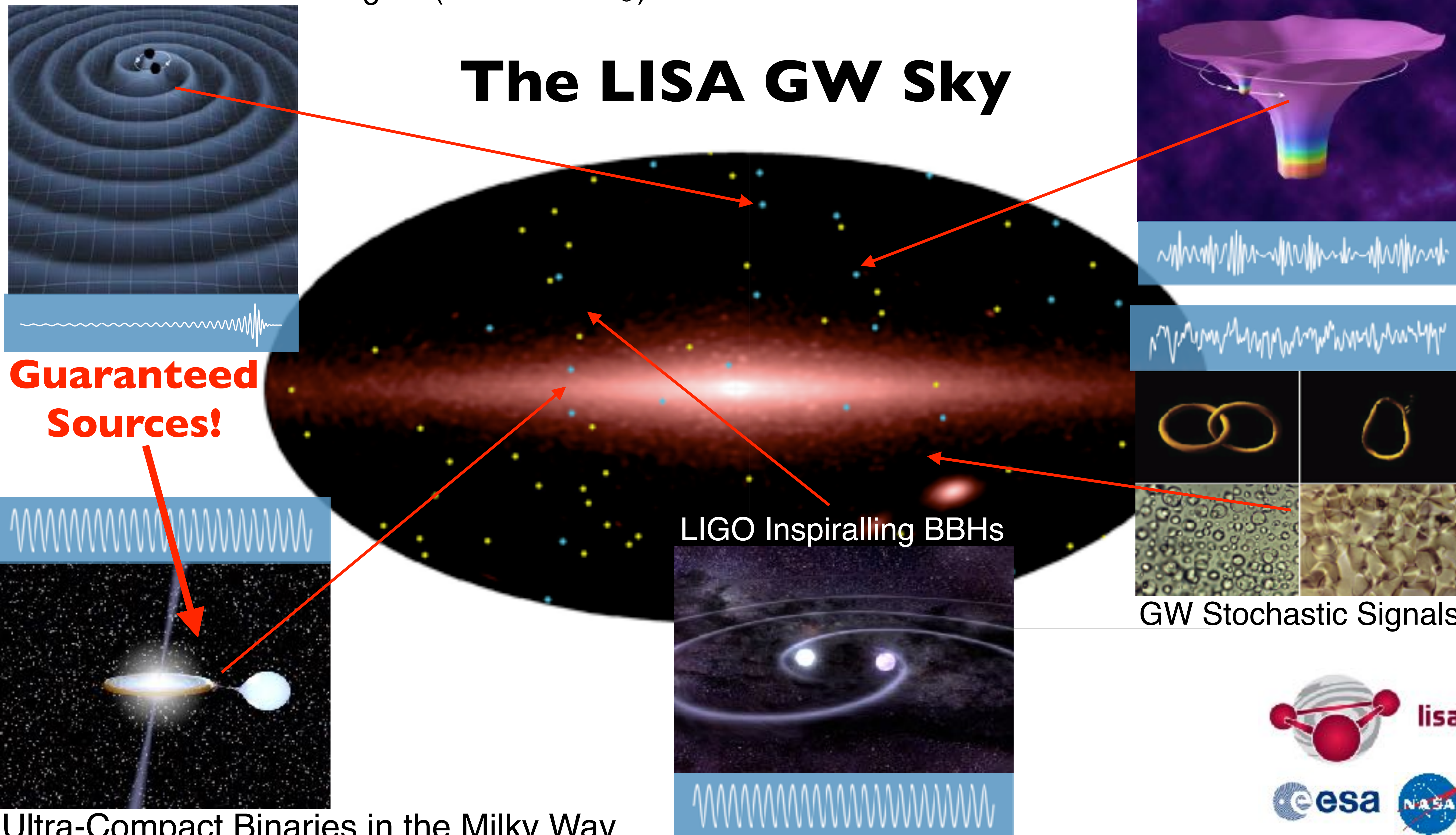
The Science of LISA

✳ The Low-Frequency Band (0.1 mHz - 1 Hz):

Massive Black Holes mergers (10^4 to 10^7 $M_\odot$)

Extreme Mass Ratio Inspirals, EMRIs (1 to 10 $M_\odot$ into 10^4 to 5×10^6 $M_\odot$)



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CSIC

Carlos F. Sopuerta

June 11th, 2019

Institute of Space Sciences (ICE, CSIC)
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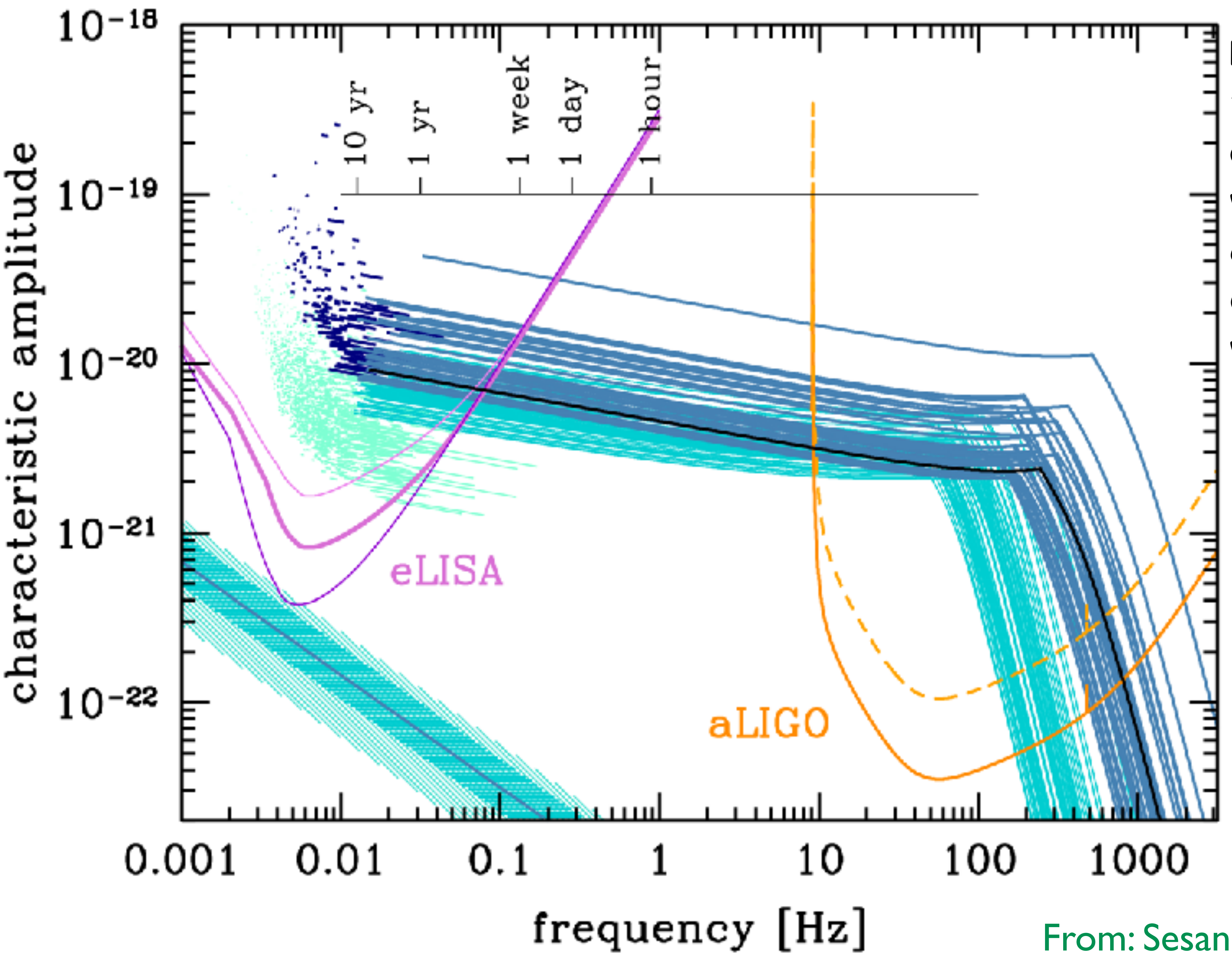
The Science of LISA

- Expected Sensitivity and Sources:



LISA observations will tell LIGO and all electromagnetic probes weeks in advance when and where these BHB coalescences will occur with uncertainties of:

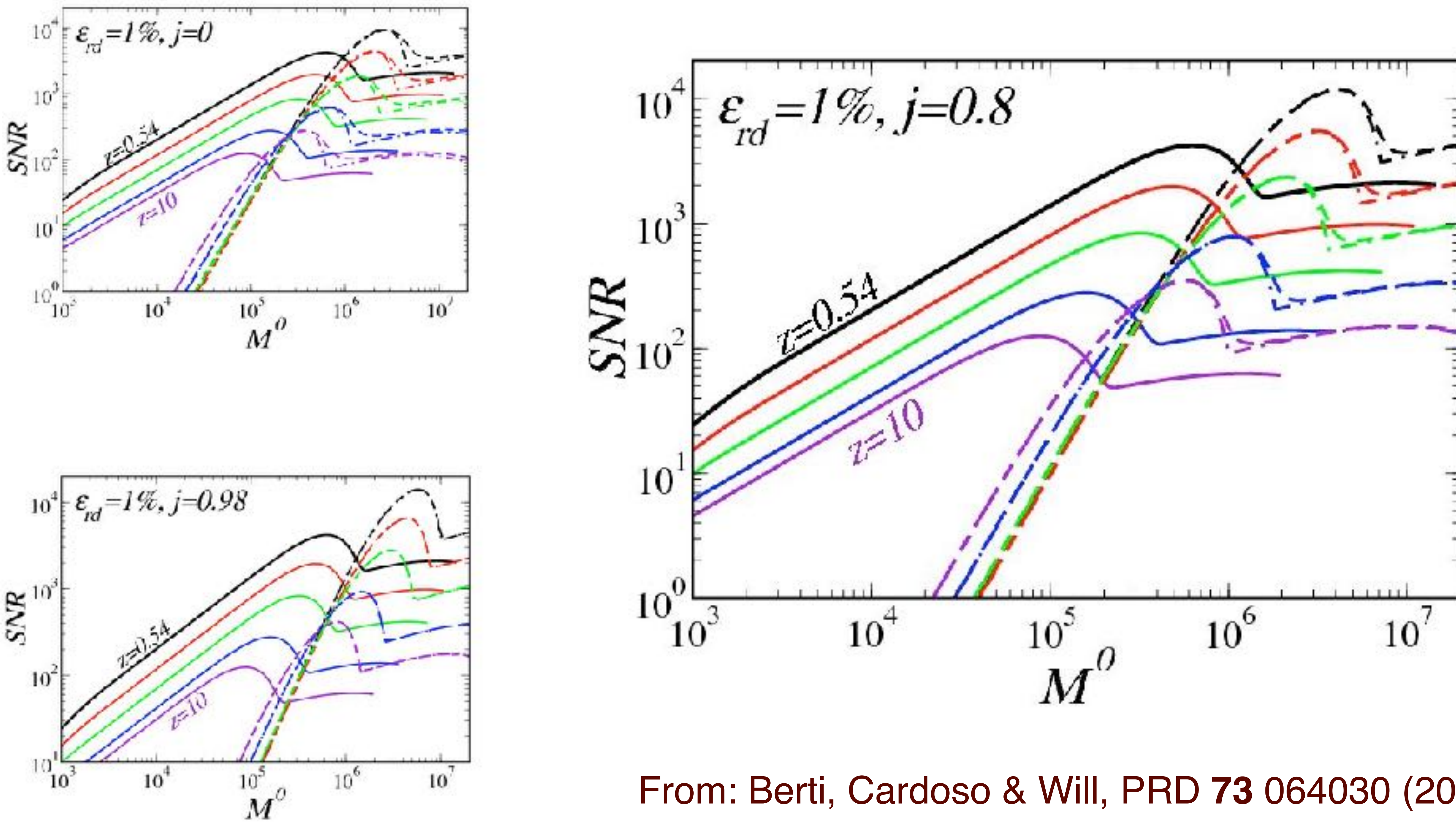
$$t_{coalescence} < 10\,\mathrm{sec}$$

$$d\Omega < 1\,\mathrm{deg}^2$$

From: Sesana, PRL, **116**, 231102 (2016)

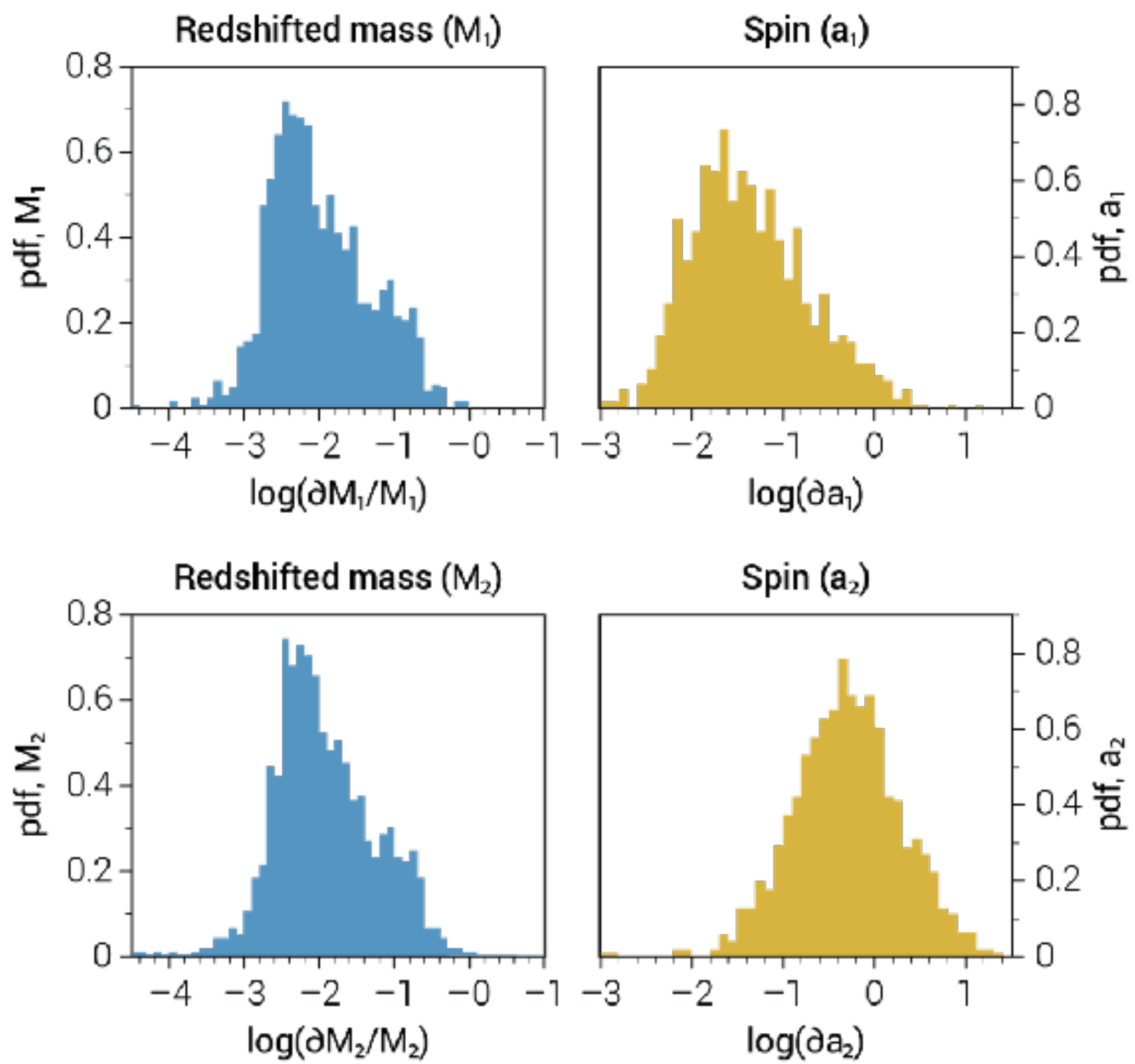
The Science of LISA

✴ **Massive Black Holes: LISA SNR for inspiral and ringdown:**



From: Berti, Cardoso & Will, PRD **73** 064030 (2006)

✳ **Parameter estimation accuracy for LISA for Massive Black Hole mergers:**

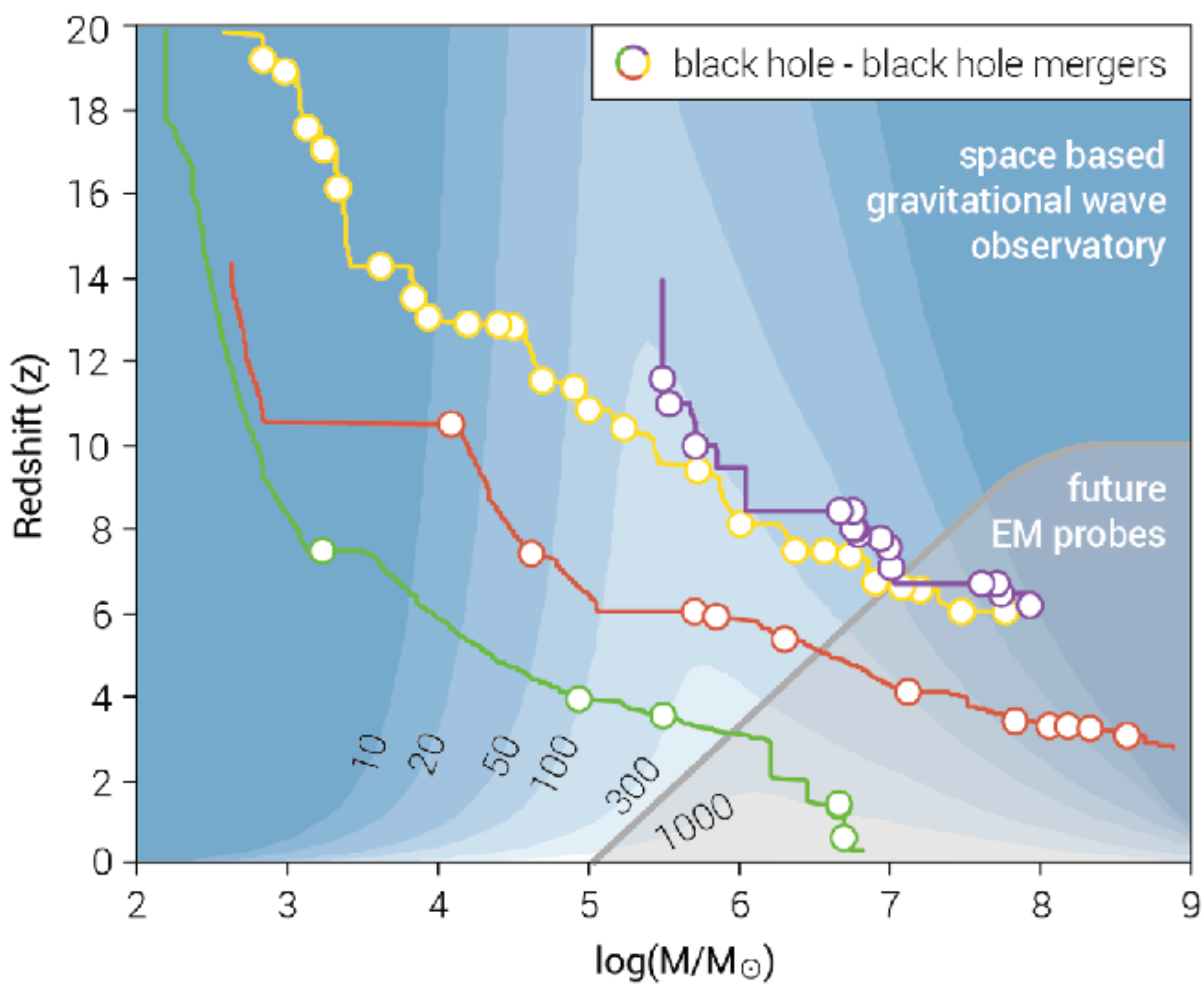


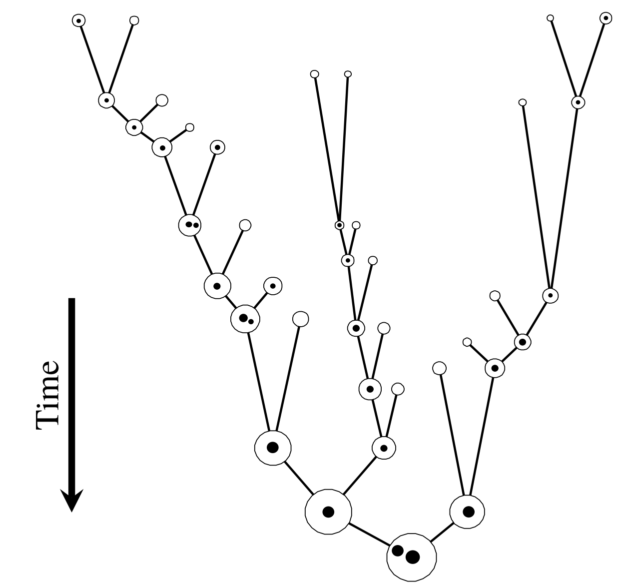
Error distributions estimated from a synthetic catalogue of ~ 1500 sources.

The catalogue has been constructed from different cosmological models of BH formation and evolution.

The Science of LISA

- **Science Objective 2**: Trace the origin, growth and merger history of massive black holes across cosmic ages.





The tracks show the mass-redshift evolution of selected supermassive black holes:

- BH powering a QSO at z=6 starting from a massive seed (blue).

- BH powering a QSO at z=6 starting from a collapsed Pop III seed (yellow).

- Typical 10^9 M⊙ in a giant elliptical galaxy (red).

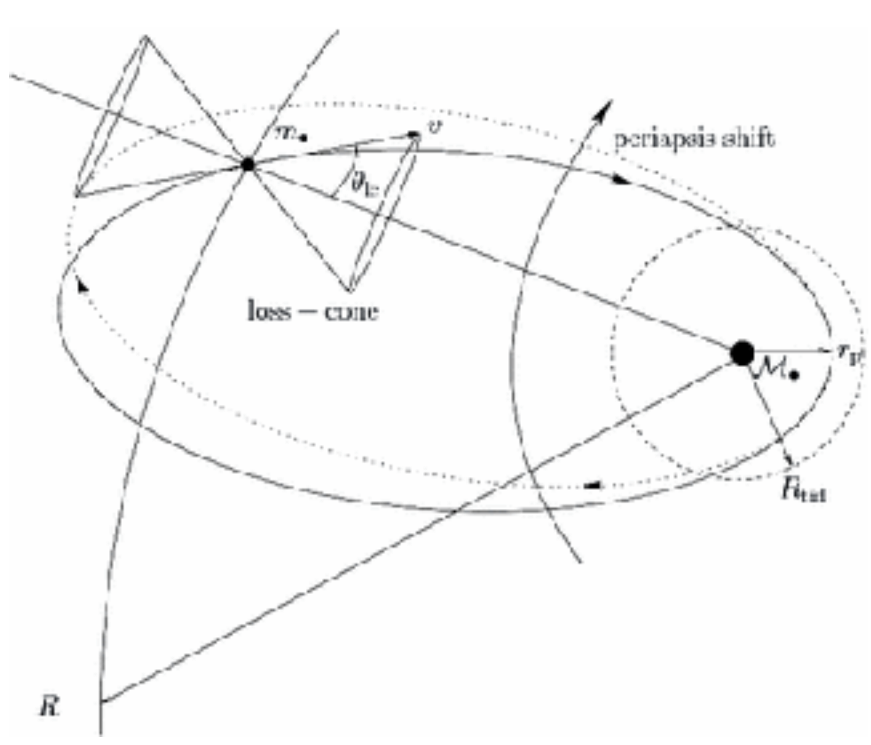
- A Milky Way type black hole (green).

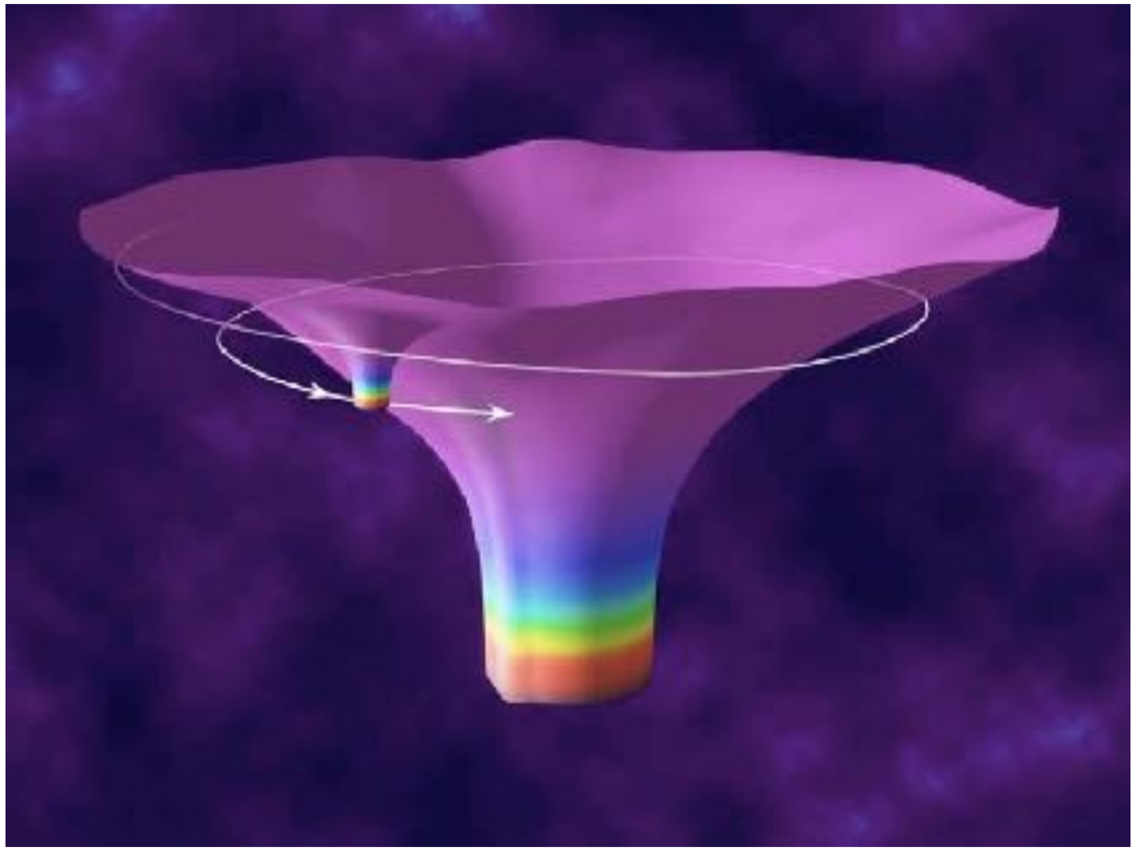
The Science of LISA

- **Science Objective 3**: Probe the dynamics of dense nuclear clusters using EMRIs.

- Extreme Mass Ratio Inspirals (EMRIs) describe the long-lasting inspiral (from months to a few years) and plunge of Stellar Origin Black Holes (SOBHs), with mass range 10−60 M⊙, into MBHs of 10^5−10^6M⊙ in the centre of galaxies.

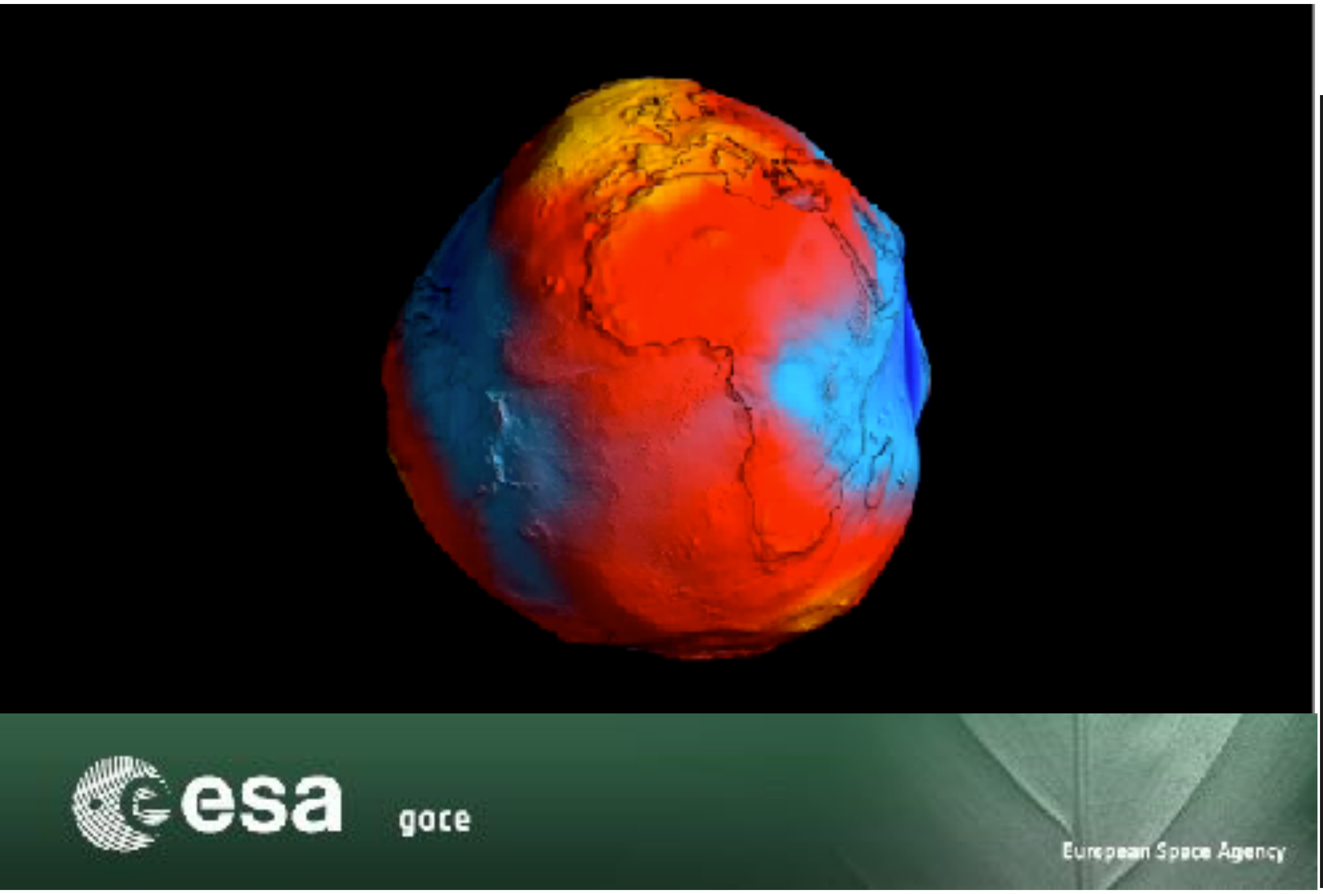
- **SI3.1**: Study the immediate environment of Milky Way like MBHs at low redshift.



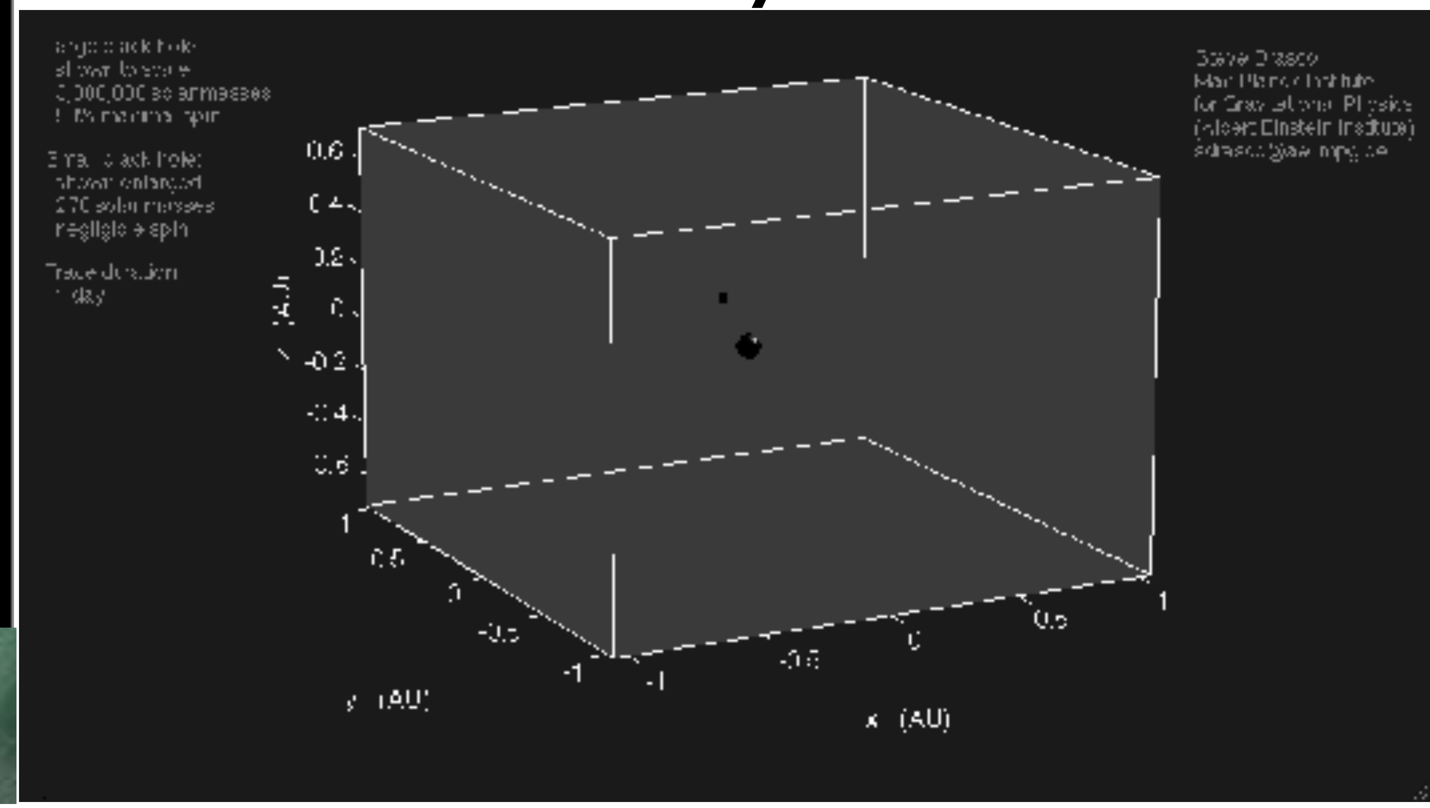


The Science of LISA

- **SI5.2**: Use EMRIs to explore the multipolar structure of MBHs.



EMRI System



$$V(\vec{r}) = -G \sum_{\ell\,,m} \frac{M_{\ell m}}{r^{\ell+1}}\, Y_{\ell m}(\theta,\varphi)$$

$M_{\ell m}$: Multipole moments

GOCE can measure up to

$\ell_{\rm MAX} \sim 200$

$\ast$ For a Kerr BH in GR:

$$M_\ell + i\, J_\ell = M_\bullet \left(i\, \frac{S_\bullet}{M_\bullet\, c} \right)^\ell$$

Tests of the Kerr geometry and/or theory of Gravity!

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MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Carlos F. Sopuerta
June 11th, 2019
Institute of Space Sciences (ICE, CSIC)
Institute of Space Studies of Catalonia (IEEC)
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The Science of LISA

- This program was pioneered by Ryan [Ryan, PRD, **52**, 5707 (1995); **56**, 1845 (1997)]

TABLE IV. The error $\delta\theta^i$ for each parameter θ^i, when fitting up to the l_{max}th moment, using LISA. We use the abbreviation $L(\cdots)\equiv\log_{10}(\cdots)$. We assume $\mu=10M_\odot$, $M=10^5M_\odot$, $r=3M$, and $S/N=100$.

l_{max}	$L(\delta t_*/\mathrm{sec})$	$L(\delta\phi_*)$	$L(\delta\mu/\mu)$	$L(\delta M/M)$	$L(\delta s_1)$	$L(\delta m_2)$	$L(\delta s_3)$	$L(\delta m_4)$	$L(\delta s_5)$	$L(\delta m_6)$	$L(\delta s_7)$	$L(\delta m_8)$	$L(\delta s_9)$	$L(\delta m_{10})$
0	0.74	−0.25	−5.90	−5.80										
1	1.71	0.33	−4.92	−4.70	−4.53									
2	2.37	1.41	−4.17	−4.01	−3.89	−2.82								
3	2.73	2.52	−3.49	−3.28	−2.94	−2.27	−1.66							
4	4.54	3.80	−2.40	−2.23	−1.97	−0.81	0.07	0.72						
5	5.99	4.74	−0.73	−0.55	−1.12	0.47	0.59	0.95	2.35					
6	6.05	4.87	−0.68	−0.50	−1.00	0.54	0.94	1.53	2.35	2.58				
7	6.07	4.88	−0.66	−0.48	−0.99	0.56	0.94	1.53	2.35	2.81	2.68			
8	6.07	4.88	−0.65	−0.47	−0.98	0.57	0.96	1.56	2.35	2.81	3.16	3.68		
9	6.08	4.91	−0.65	−0.47	−0.96	0.58	1.04	1.67	2.35	2.82	3.20	3.74	4.10	
10	6.08	4.92	−0.64	−0.46	−0.95	0.58	1.05	1.69	2.35	2.82	3.20	3.75	4.17	4.70

- This uses quasi-circular and quasi-equatorial orbits. The conclusion is that a LISA-like detector may be able to estimate 3-5 moments (1-3 tests of the Kerr hypothesis).

Carlos F. Sopuerta

June 11th, 2019

Institute of Space Sciences (ICE, CSIC)

Institute of Space Studies of Catalonia (IEEC)

The Science of LISA

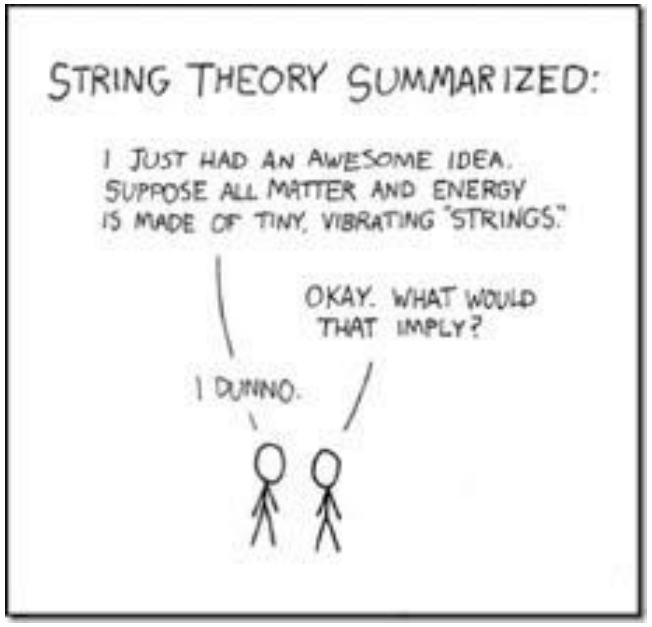
- Barack & Cutler extended their study [PRD, **75**, 042003 (2007)] to consider a central object with a mass quadrupole. The error estimations for this parameter (using generic orbits) are in the range:

$$\Delta\left(\frac{M_2}{M_0^3}\right) \sim 10^{-(2-4)}$$

which is a considerably better error estimate than Ryan's estimate.

The Science of LISA

- Again, to test General Relativity, we must use models that consider non-GR dynamics for EMRIs.
- The Landscape of Theories of Gravity is very rich...

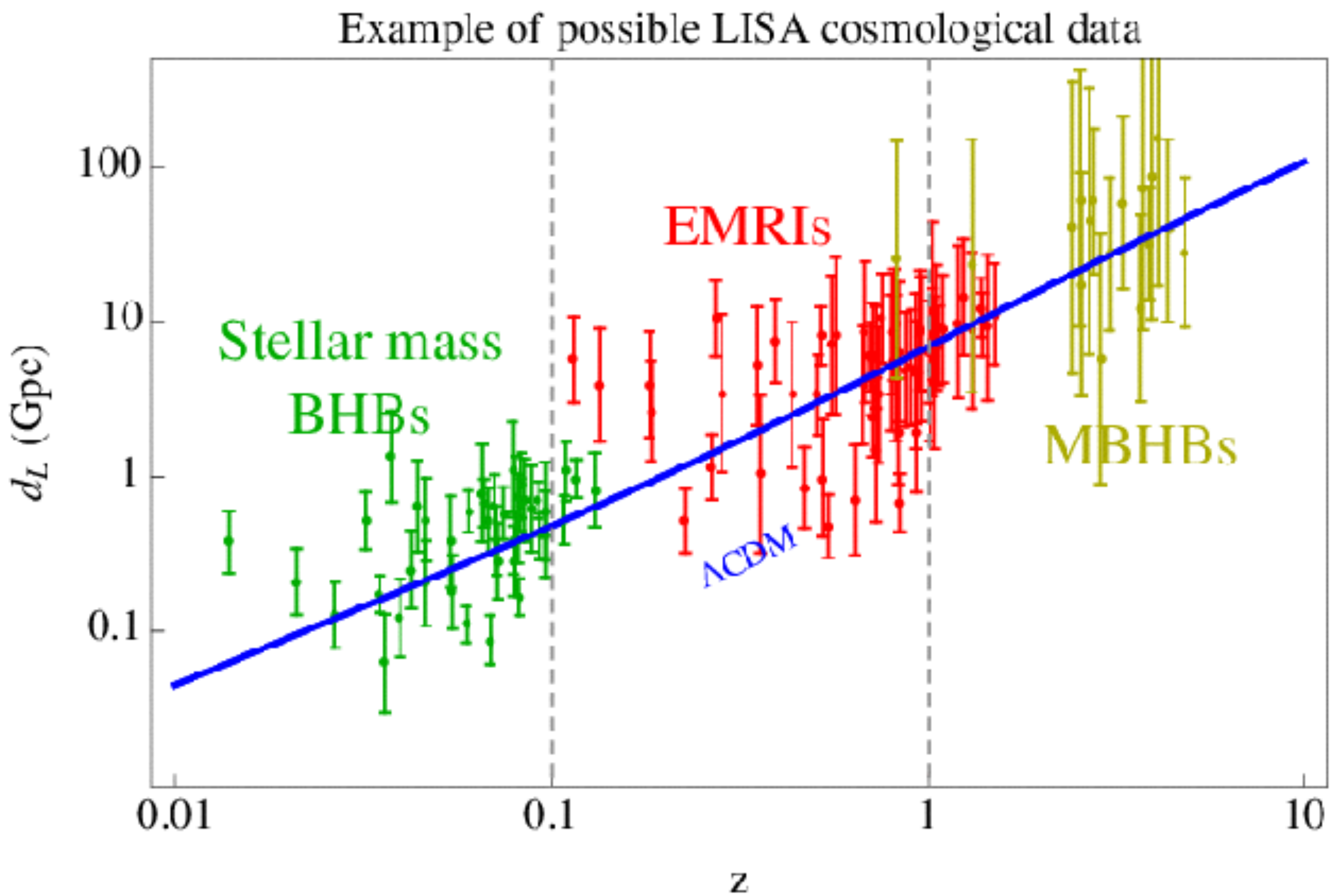


- Not all theories are suitable to consistently study EMRIs.

The Science of LISA

- **Science Objective 6**: Probe the rate of expansion of the Universe.

- LISA will probe the expansion of the Universe using GW sirens at high redshifts: SOBH binaries (z < 0.2), EMRIs (z < 1.5), MBHBs (z < 6).



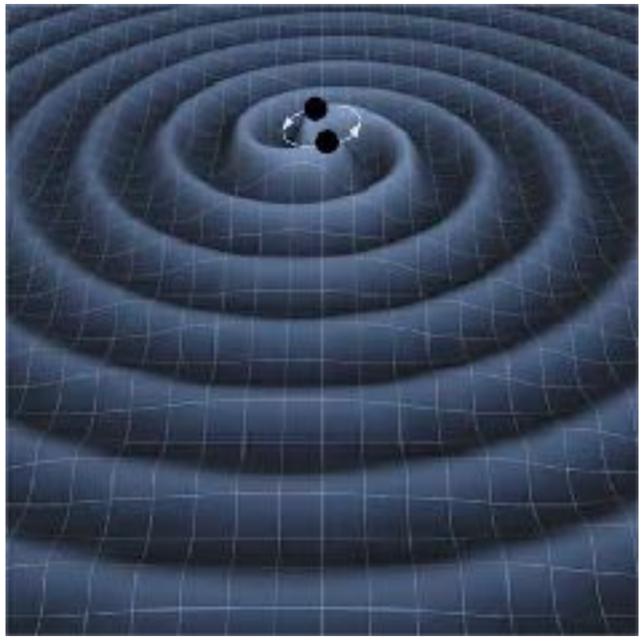
Tamanini et al, JCAP, 04(2016)002

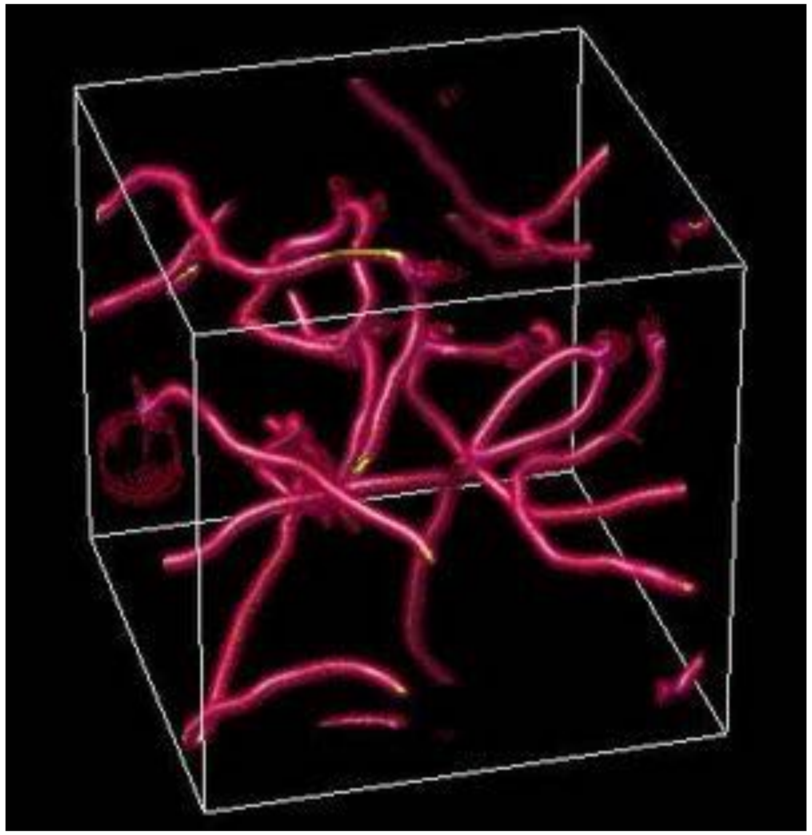
- **SI6.1**: Measure the dimensionless Hubble parameter by means of GW observations only.

- **SI6.2**: Constrain cosmological parameters through joint GW and EM observations.

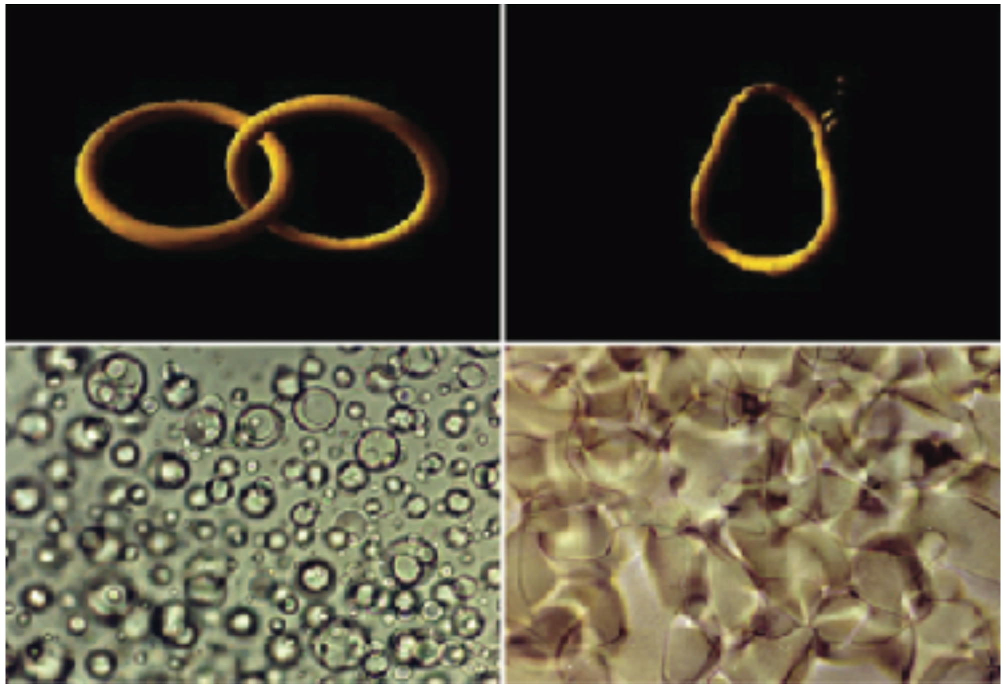
Gravitational Wave Sources (VLF Band)

Stochastic Background from Supermassive Black Holes mergers (10^8 to 10^{10} $M_\odot$)





Cosmic Strings



GW Stochastic Signals

Conclusions

Conclusions

- LIGO has inaugurated the Era of Gravitational Wave Astronomy in the High-frequency Band.

- There are great expectations for the direct detection of Gravitational Waves within the present decade (Ground Based detectors and PTAs).

- The L3 mission of ESA will be devoted to Gravitational Wave Astronomy in the Low-frequency Band. LISA Pathfinder has demonstrated the technology.

- The potential of GW discoveries to impact Black Hole Physics is very high!

Conclusions

- All these is very exciting but:

"We get what we put in"

All the strong field tests of gravity require a lot of theoretical developments. There is a lot of work to be done…

Many Thanks for your attention!