eLISA : exploring the mHz regime of Gravitational Waves

Ed Porter (APC)

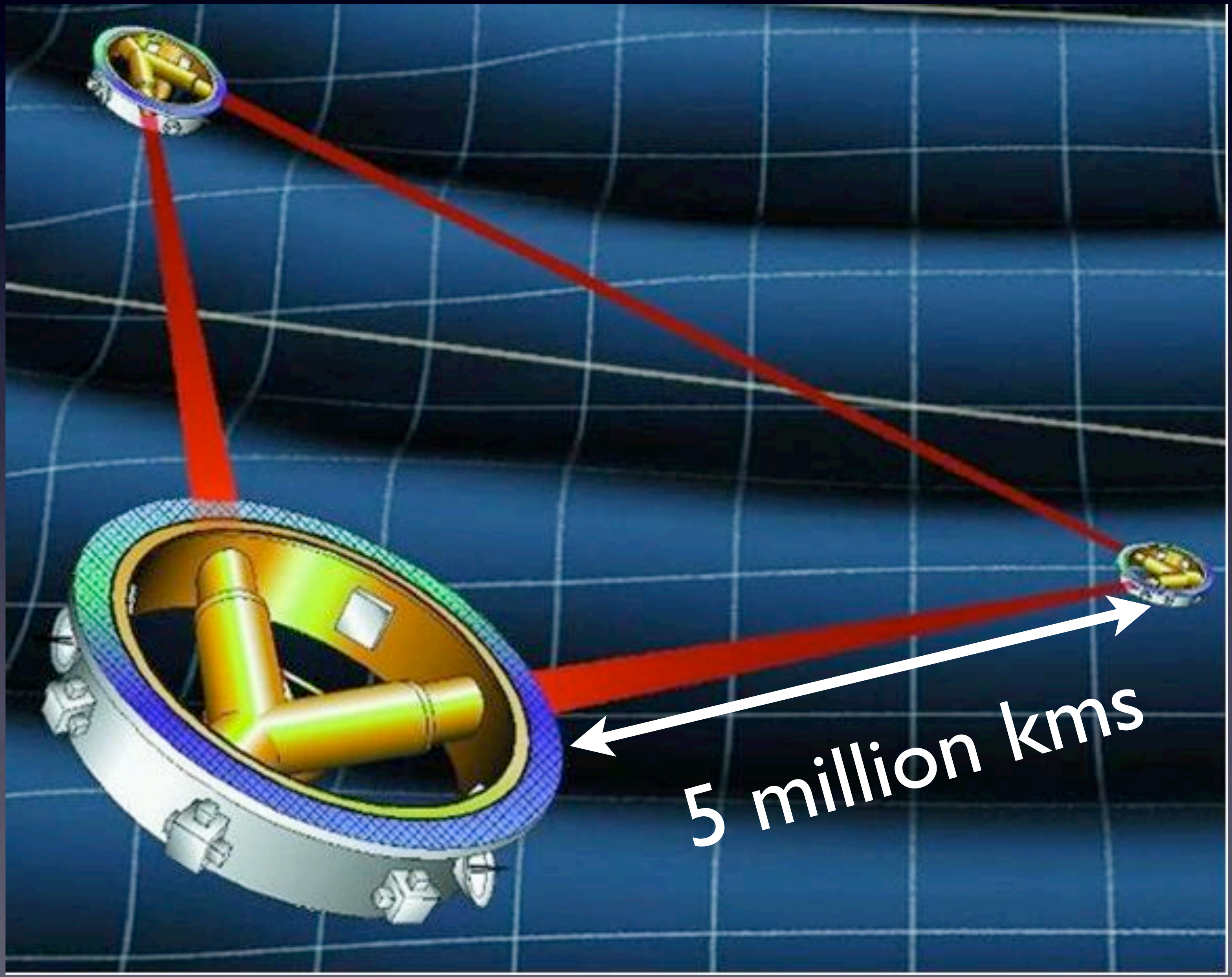
Outline

- LISA
- eLISA - mission concept, White paper and status
- Sources
- Data analysis
- What have we lost?
- What have we improved?

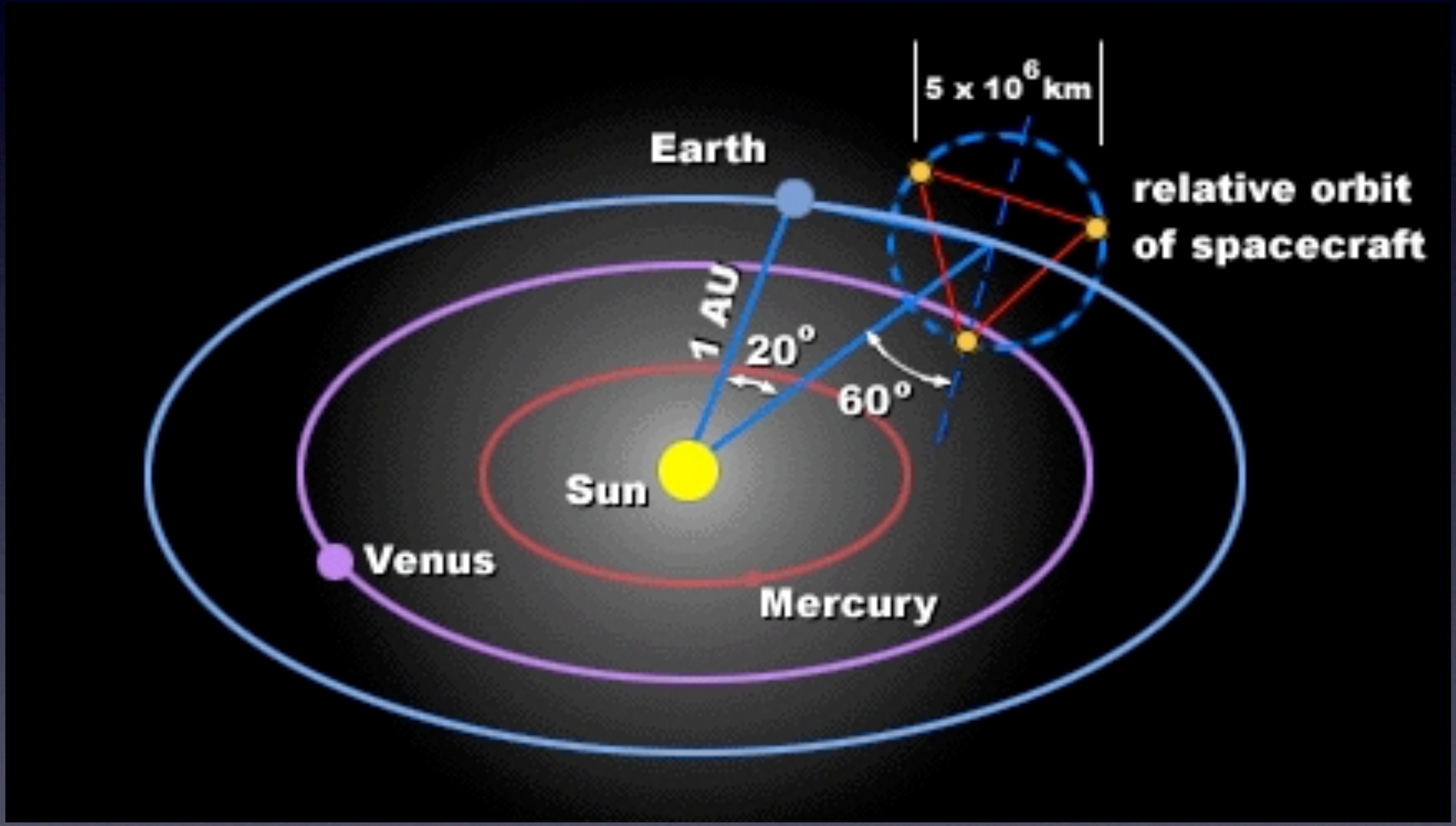
A History Lesson

LISA

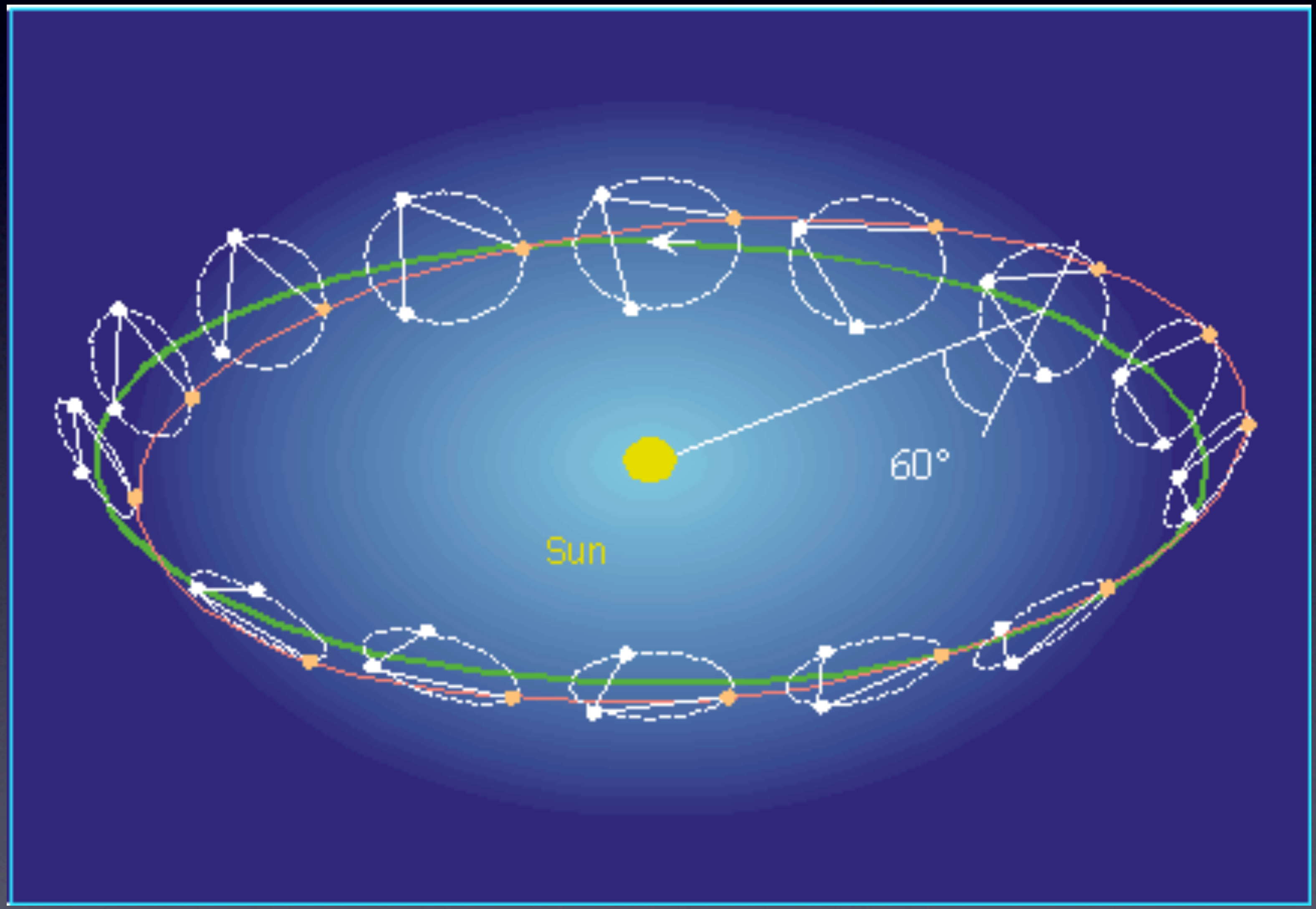
- ESA/NASA mission



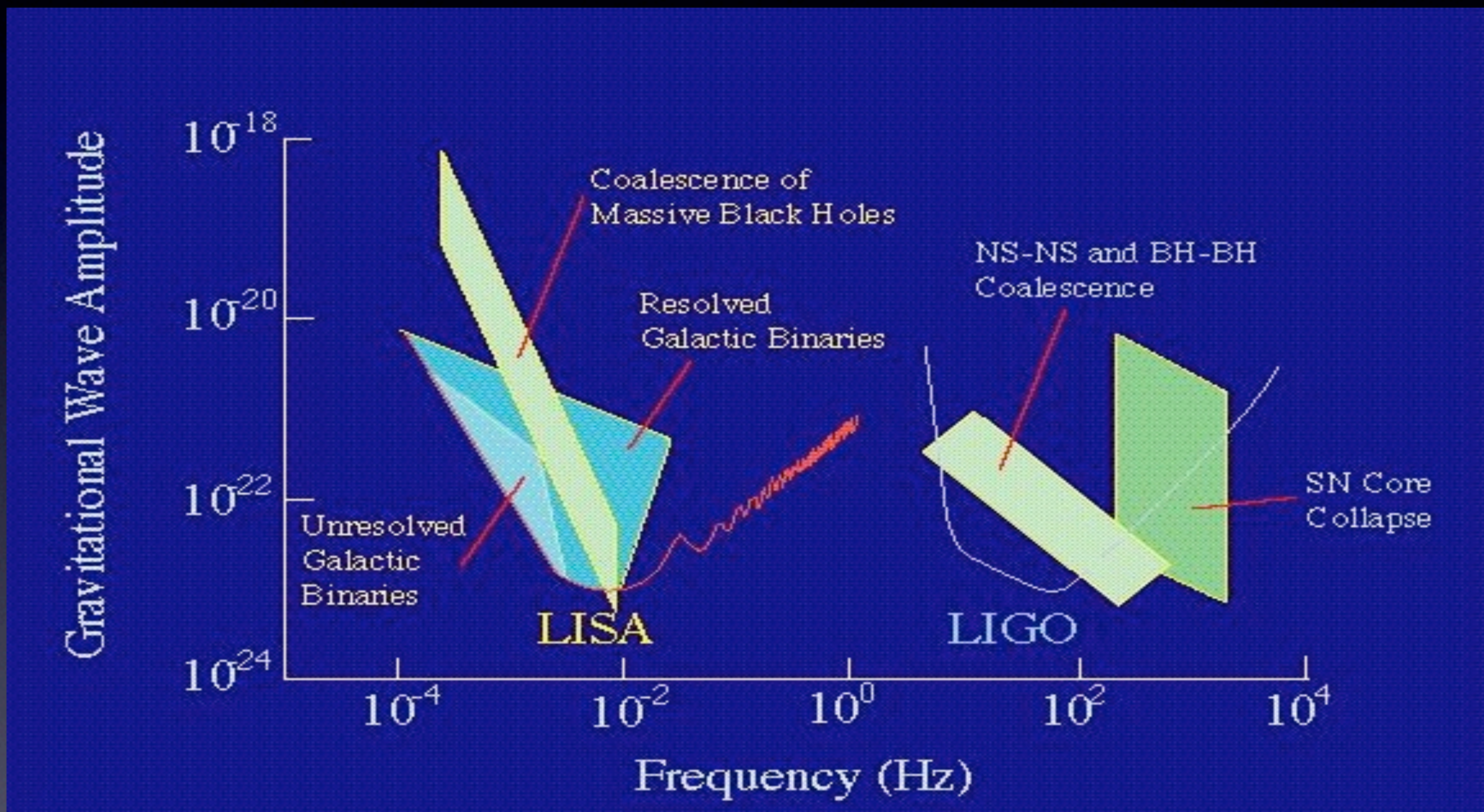
LISA


5 x 10^6 km
Earth
relative orbit
of spacecraft
1 AU
20°
60°
Sun
Venus
Mercury

LISA



LISA



Important : $f \propto m^{-1}$

LISA

High SNR sources : 10s - 1000s

Detection capabilities during the mission :

25,000 galactic binaries
100s supermassive black hole mergers
100s extreme mass ratio inspirals
10s cosmic string cusps
possible detection of the cosmological background

LISA

Financial crisis in 2010, plus the exploding budget of JWST forced NASA to end their particiaption in a number of projects...including LISA.

Decision made in Europe to continue alone.

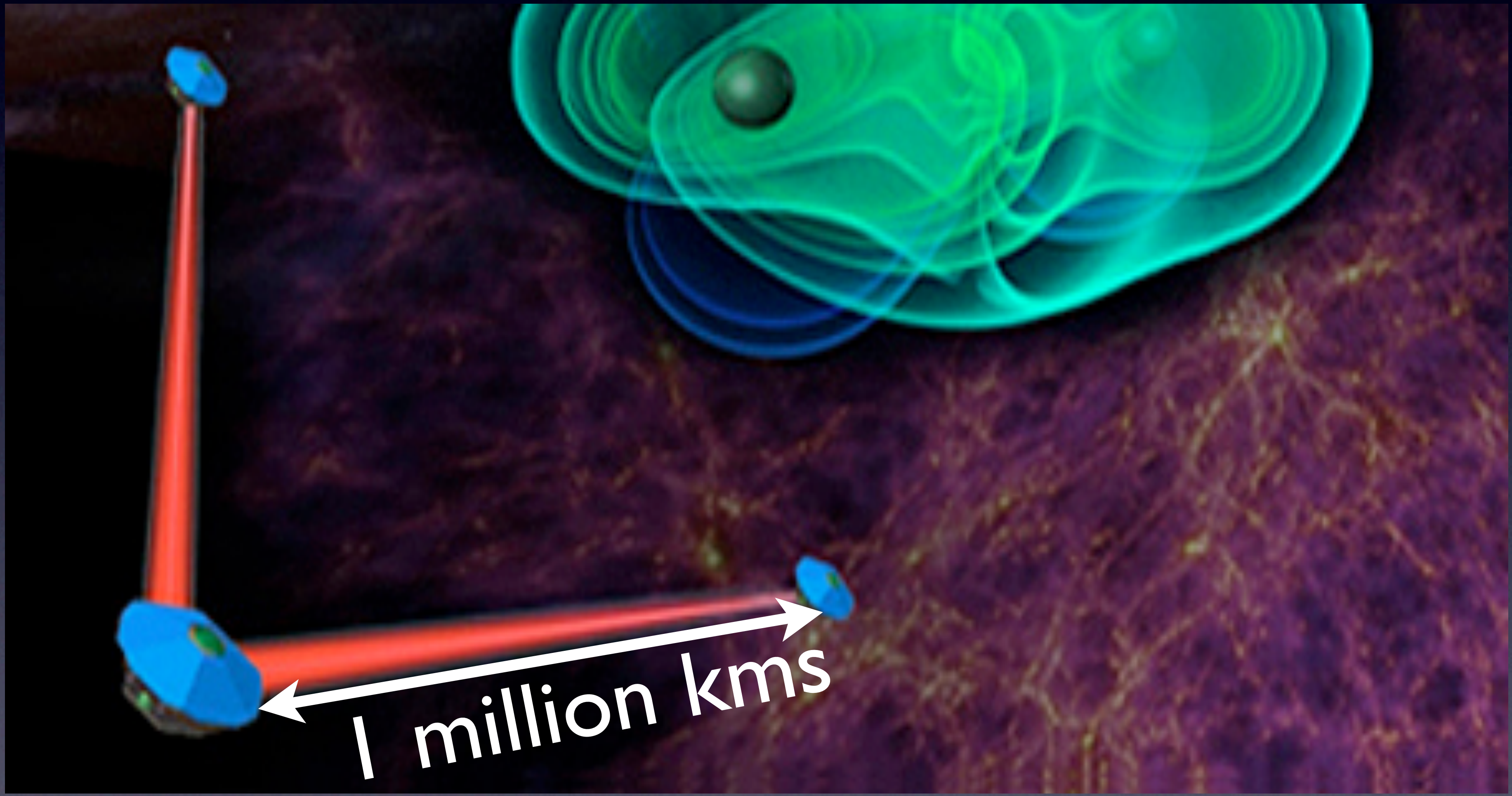
eLISA

eLISA/NGO

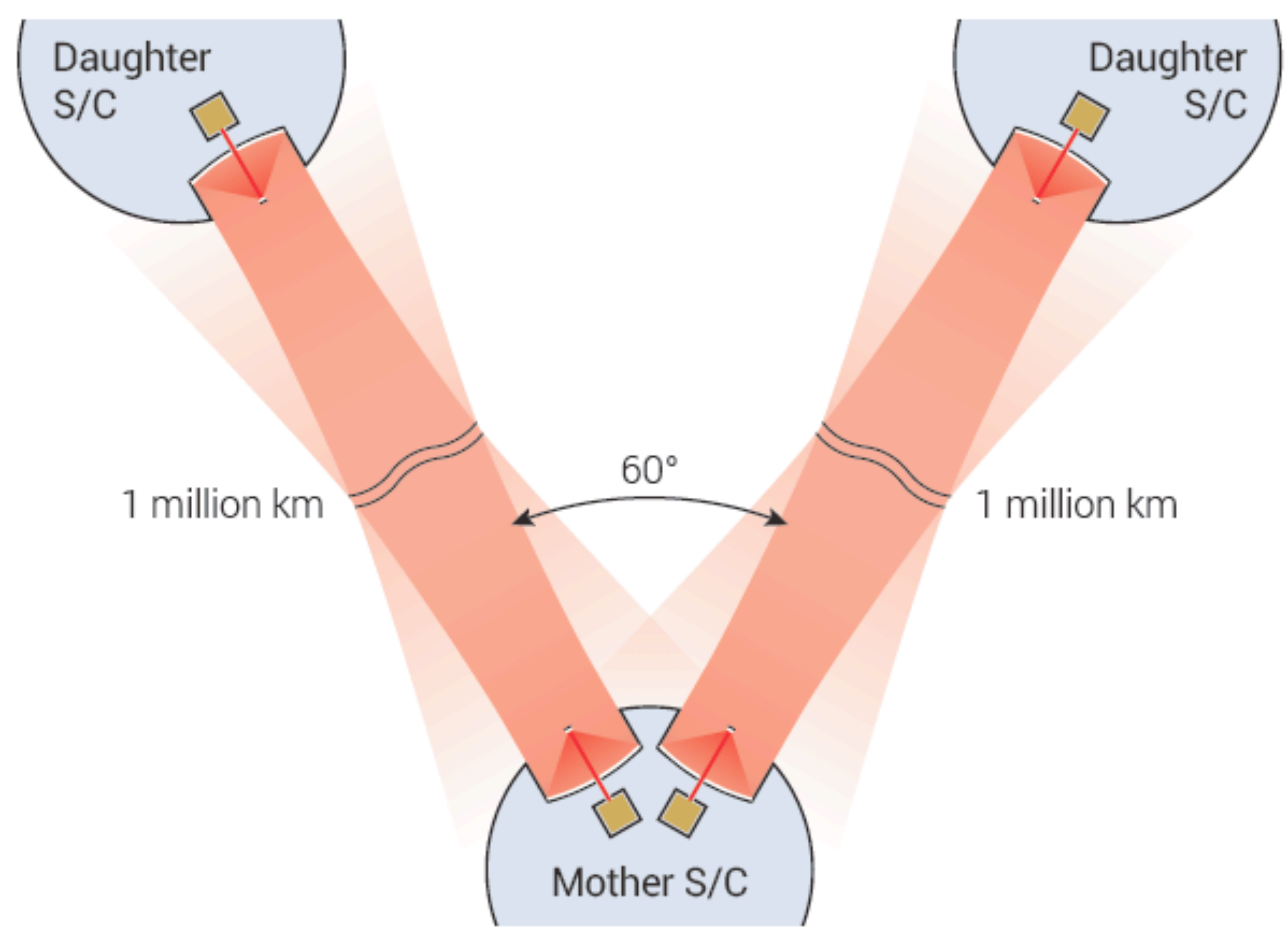
- CDF study carried out June-July 2011
- Creation of a new science team by ESA (P. Binetruy (APC-France), M. Colpi (Uni. of Milan-Italy), K. Danzmann (AEI-Germany), P. Jetzer (ITP-Switzerland), A. Lobo (IEEC-Spain), G. Nelemans (Radboud Uni-Netherlands), B. Schutz (AEI-Germany), T. Sumner(Imperial College-UK), S. Vitale (Trento-Italy), H. Ward (Glasgow-UK),)
- Creation of a science investigation taskforce (A. Petiteau (AEI-Germany) & EKP (APC-France))

Science Investigation Taskforce

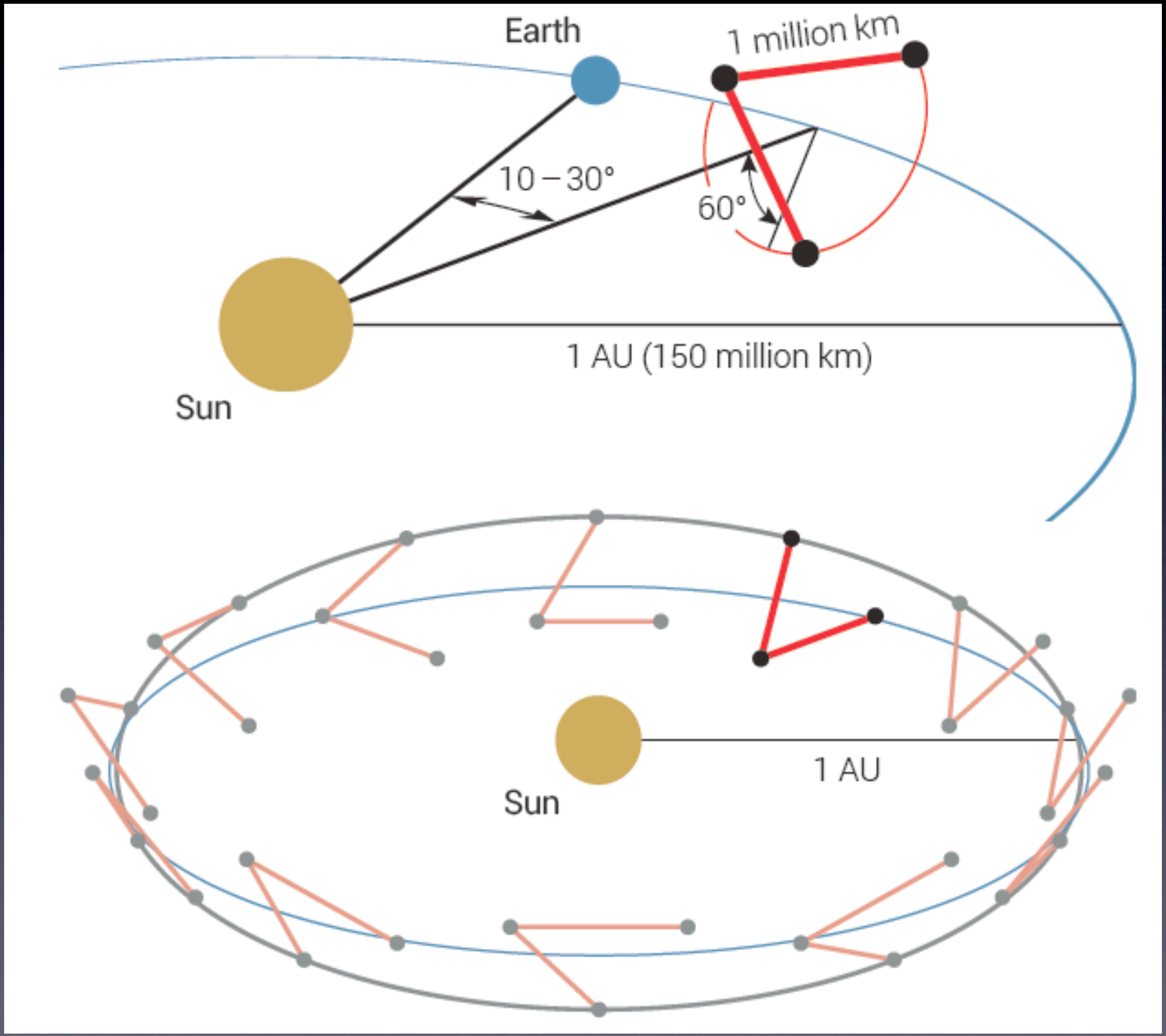
Mission Concept



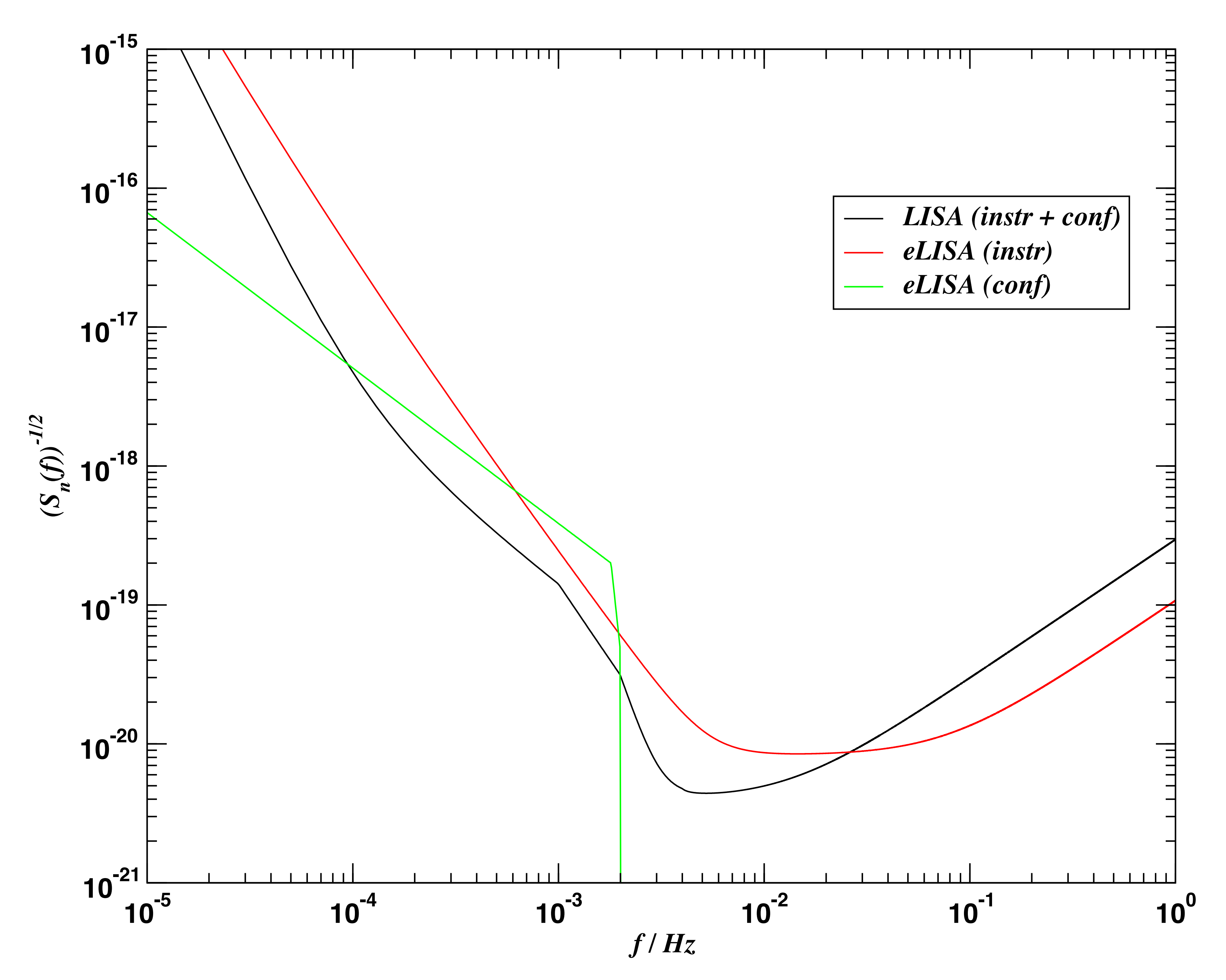
Mission Concept



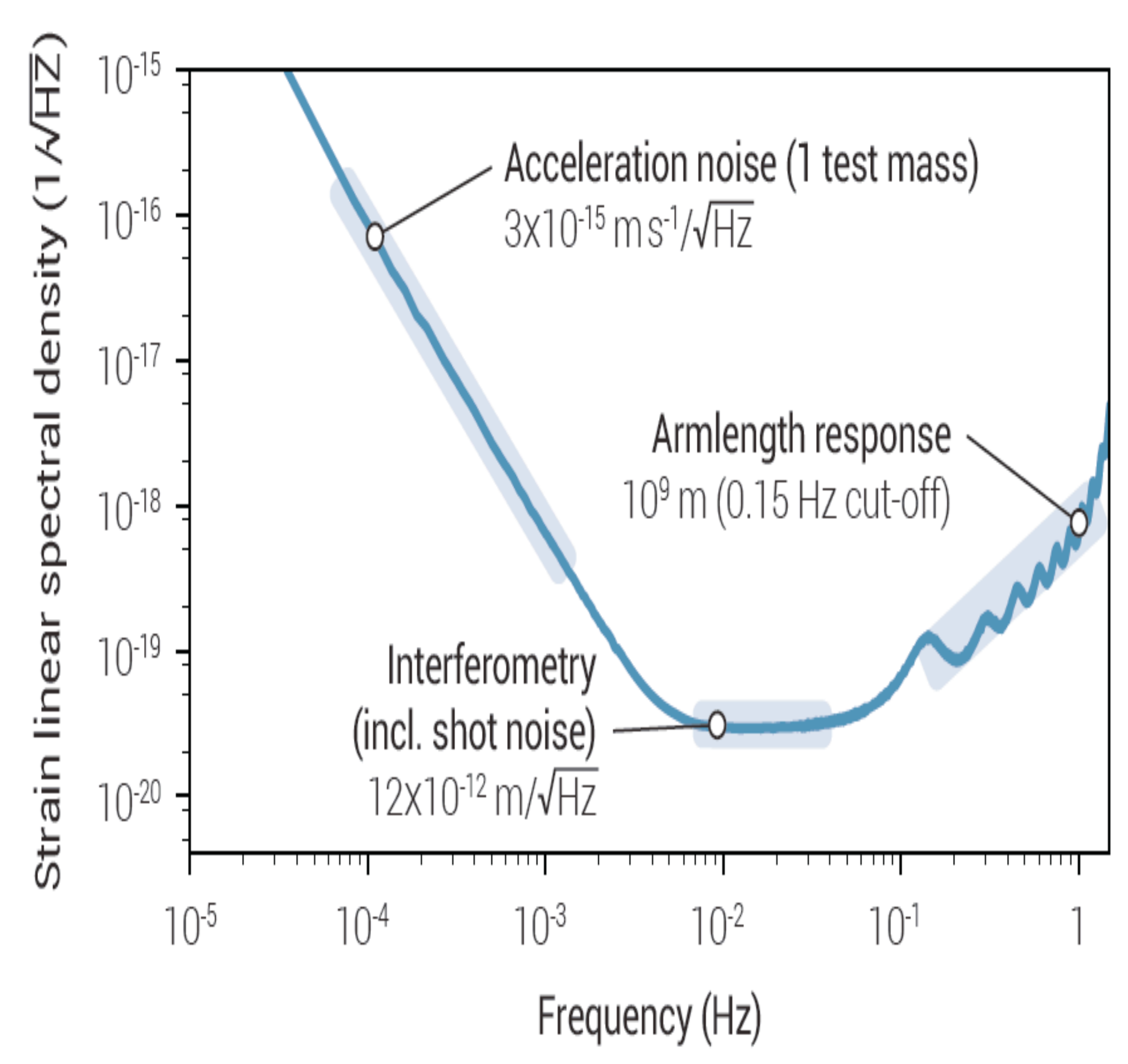
Mission Concept

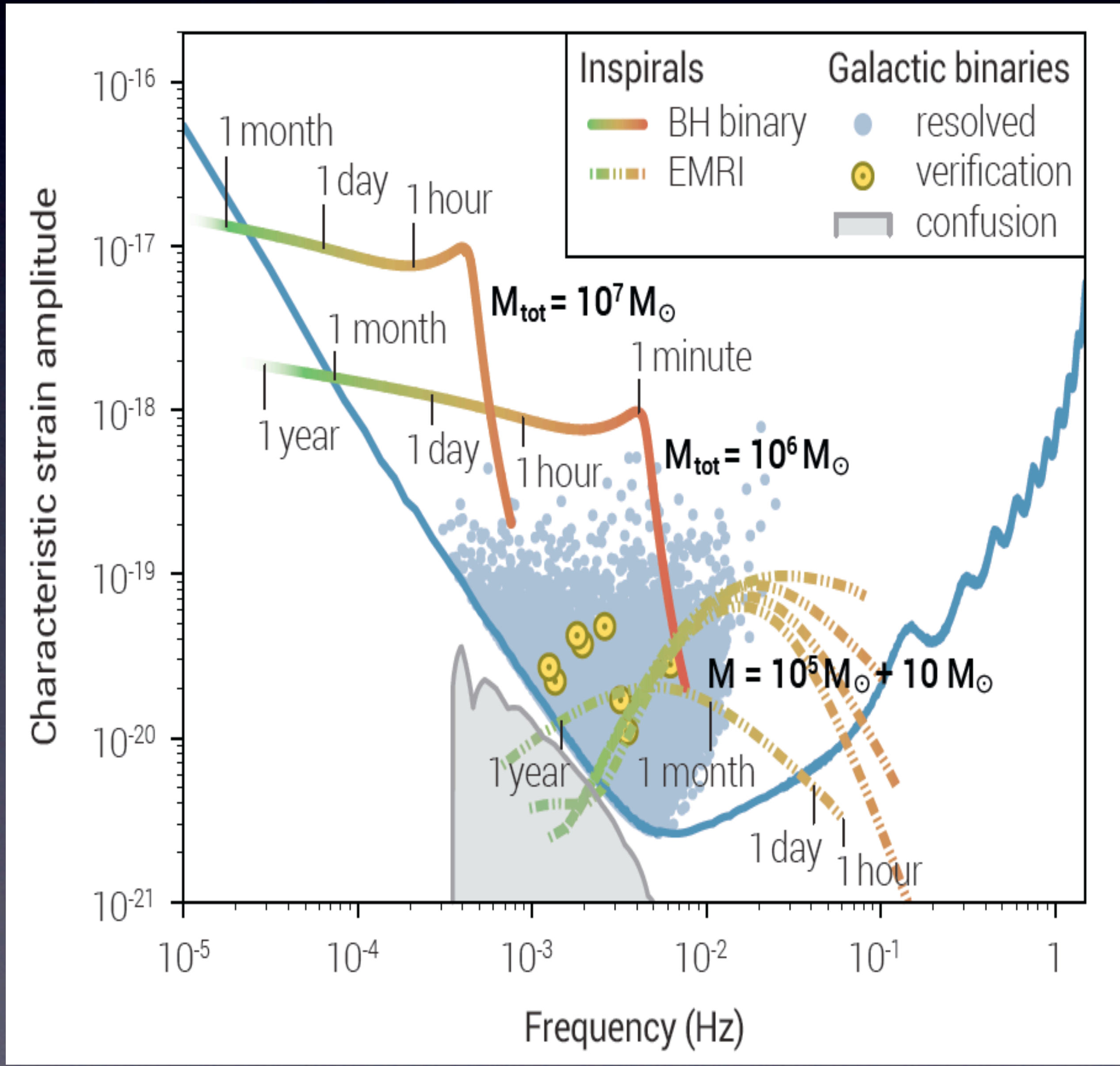


Mission Concept



Mission Concept

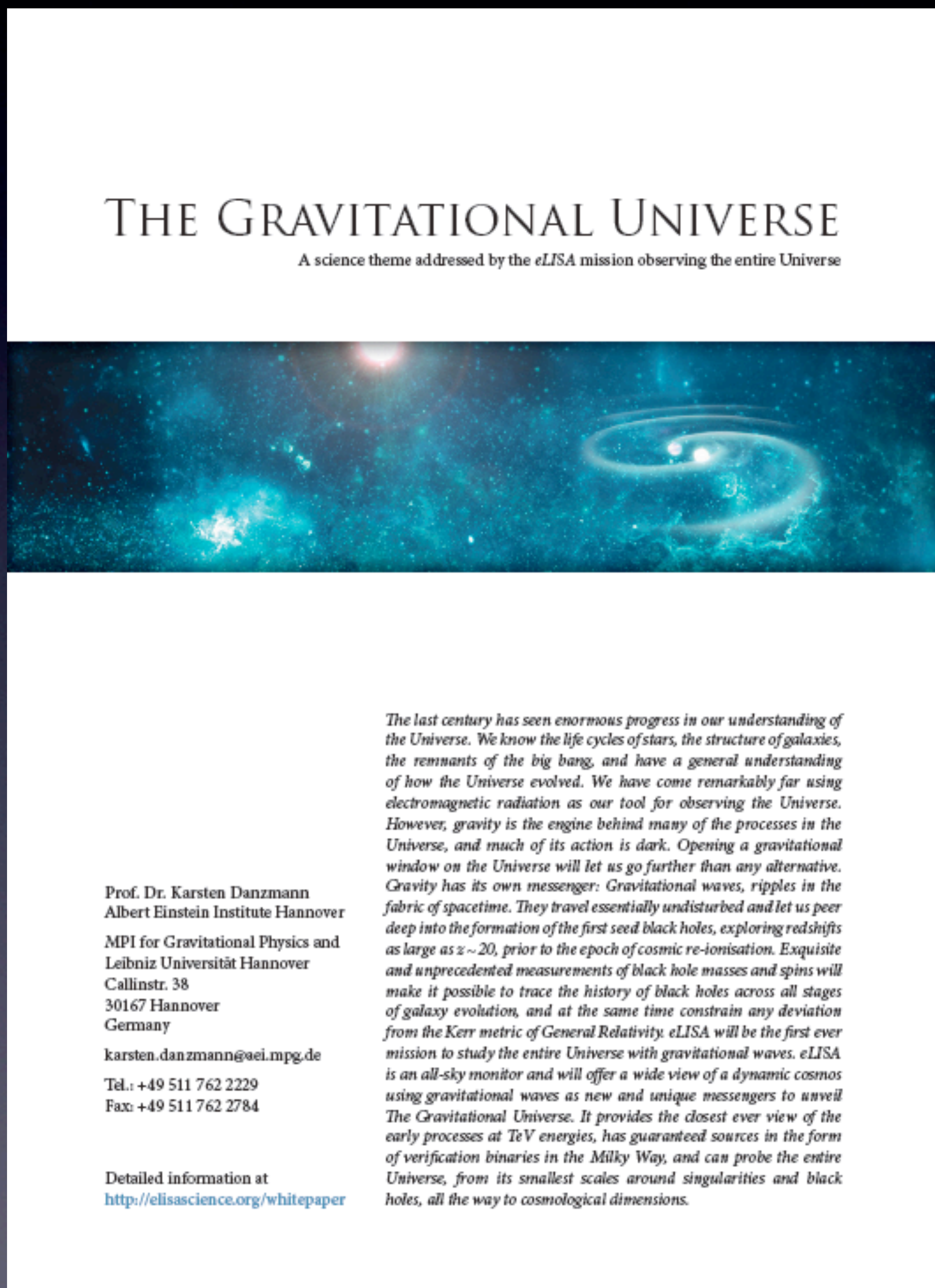




eLISA/NGO

- Yellow book submitted for L1 mission selection in 2012
- eLISA/NGO finished second behind JUICE
- October 2012, 1st eLISA consortium meeting, APC, Paris
- Formation of WGs
- Announcement by ESA of call for White Paper for L2/L3 candidates
- White Paper for eLISA submitted 24/05/2013

eLISA White Paper



THE GRAVITATIONAL UNIVERSE

A science theme addressed by the *eLISA* mission observing the entire Universe

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Detailed information at
http://elisascience.org/whitepaper

The last century has seen enormous progress in our understanding of the Universe. We know the life cycles of stars, the structure of galaxies, the remnants of the big bang, and have a general understanding of how the Universe evolved. We have come remarkably far using electromagnetic radiation as our tool for observing the Universe. However, gravity is the engine behind many of the processes in the Universe, and much of its action is dark. Opening a gravitational window on the Universe will let us go further than any alternative. Gravity has its own messenger: Gravitational waves, ripples in the fabric of spacetime. They travel essentially undisturbed and let us peer deep into the formation of the first seed black holes, exploring redshifts as large as z ~ 20, prior to the epoch of cosmic re-ionisation. Exquisite and unprecedented measurements of black hole masses and spins will make it possible to trace the history of black holes across all stages of galaxy evolution, and at the same time constrain any deviation from the Kerr metric of General Relativity. eLISA will be the first ever mission to study the entire Universe with gravitational waves. eLISA is an all-sky monitor and will offer a wide view of a dynamic cosmos using gravitational waves as new and unique messengers to unveil The Gravitational Universe. It provides the closest ever view of the early processes at TeV energies, has guaranteed sources in the form of verification binaries in the Milky Way, and can probe the entire Universe, from its smallest scales around singularities and black holes, all the way to cosmological dimensions.

http://www.elisascience.org/whitepaper/

eLISA White Paper

- 79 authors (Europe)
- 80 contributors (Europe, US and Australia)
- 979 supporters (Europe, US, South America, Asia, Australia)
- 2458 eLISA friends

eLISA White Paper

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Among the, roughly, 1000 scientific supporters of the Gravitational Universe science theme, are

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A complete list of supporters can be found at http://elisascience.org/supporters

eLISA : The Science

Sources & Science

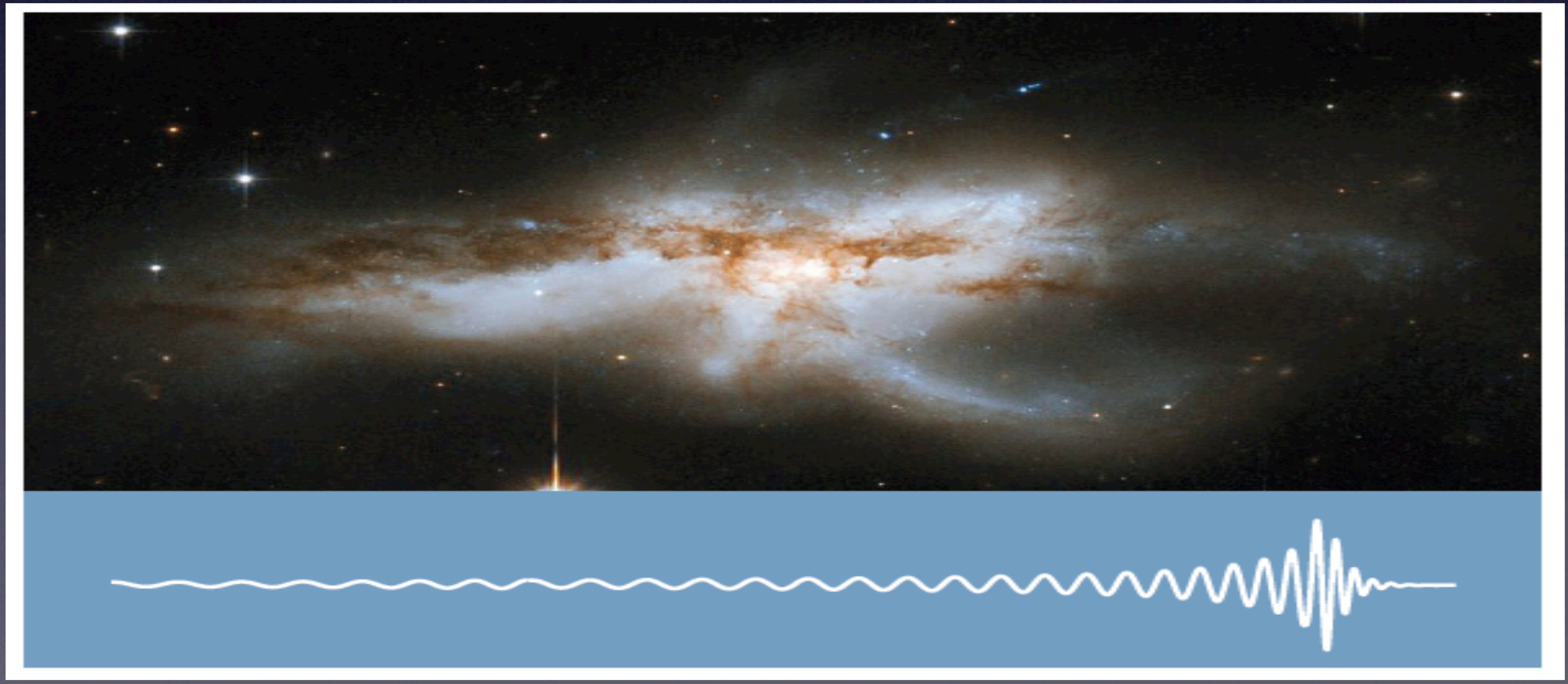
1) (Super)Massive black hole binaries

2) Extreme mass ratio inspirals

3) Galactic binaries

4) Cosmology, fundamental physics and the stochastic background

(Super)Massive Black Hole Binaries

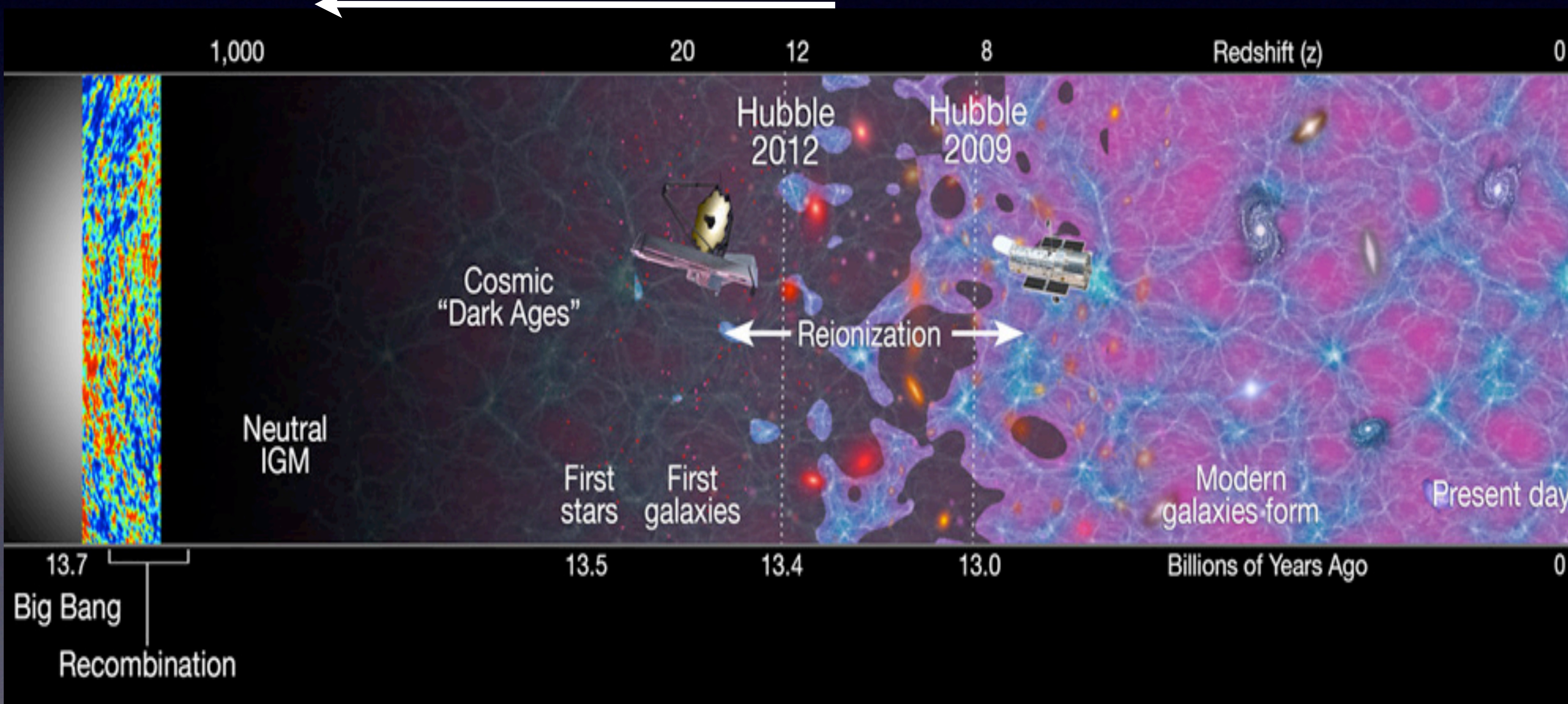


Questions

- *When did the first black holes form in pre-galactic halos, and what is their initial mass and spin?*
- *What is the mechanism of black hole formation in galactic nuclei, and how do black holes evolve over cosmic time due to accretion and mergers?*
- *What is the role of black hole mergers in galaxy formation?*

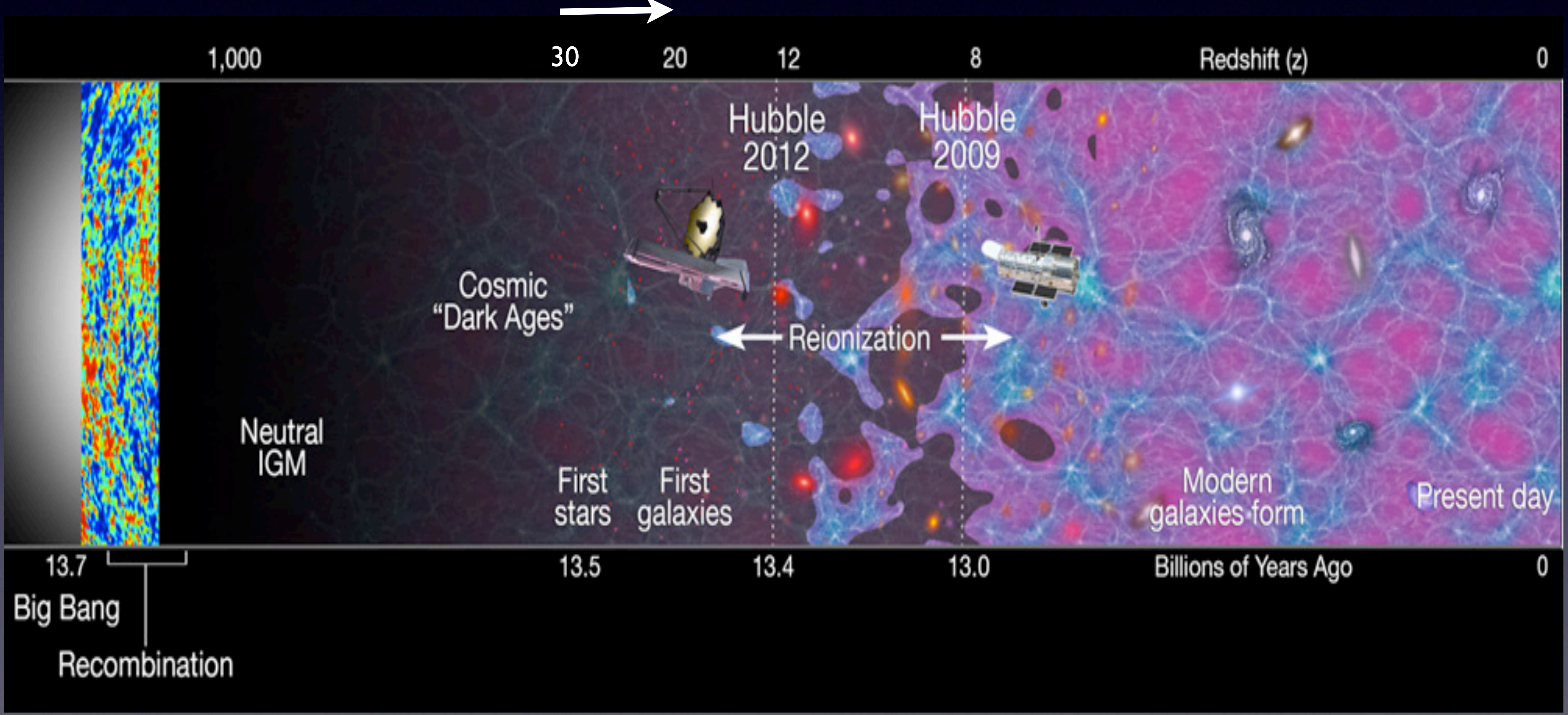
Distance scale of the Universe

"cosmic dawn"



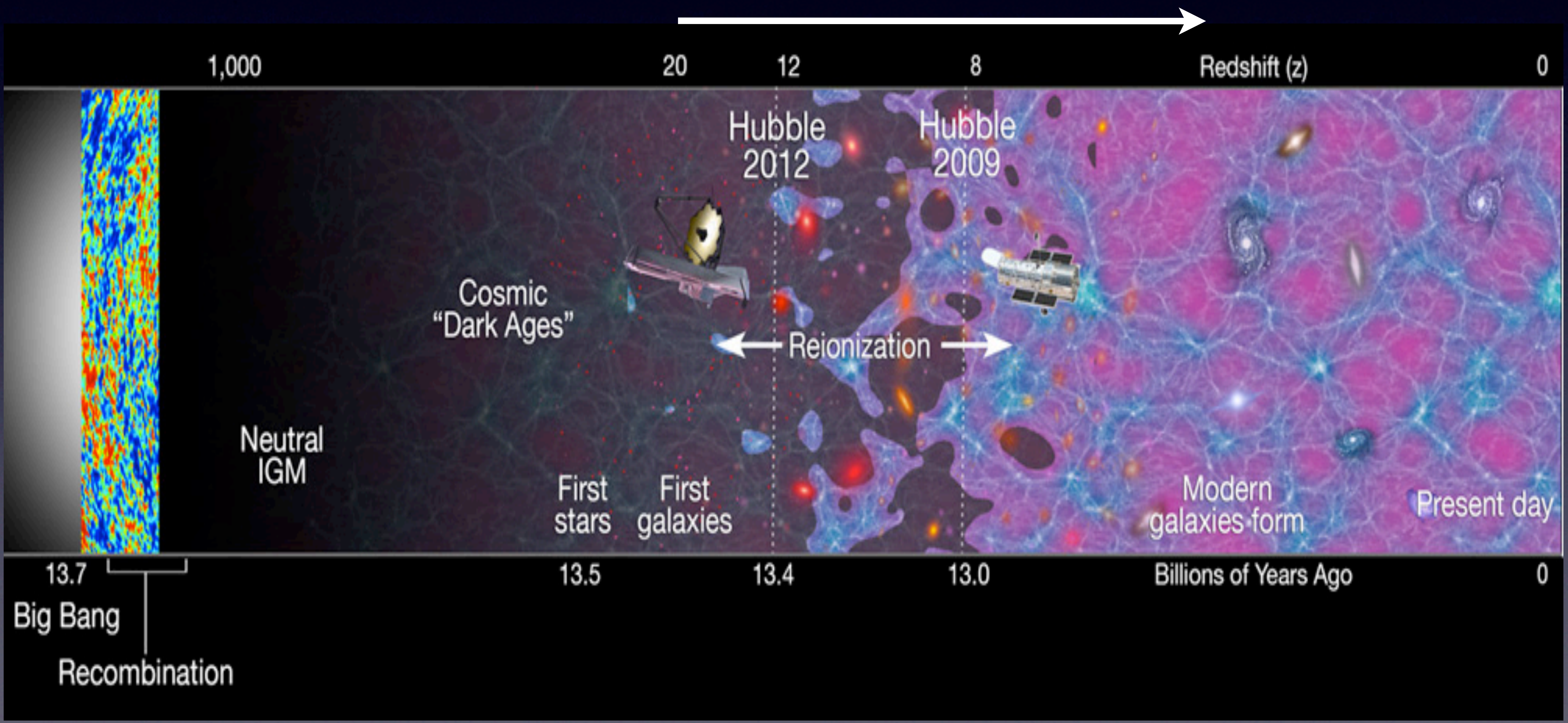
Distance scale of the Universe

Pop III stars



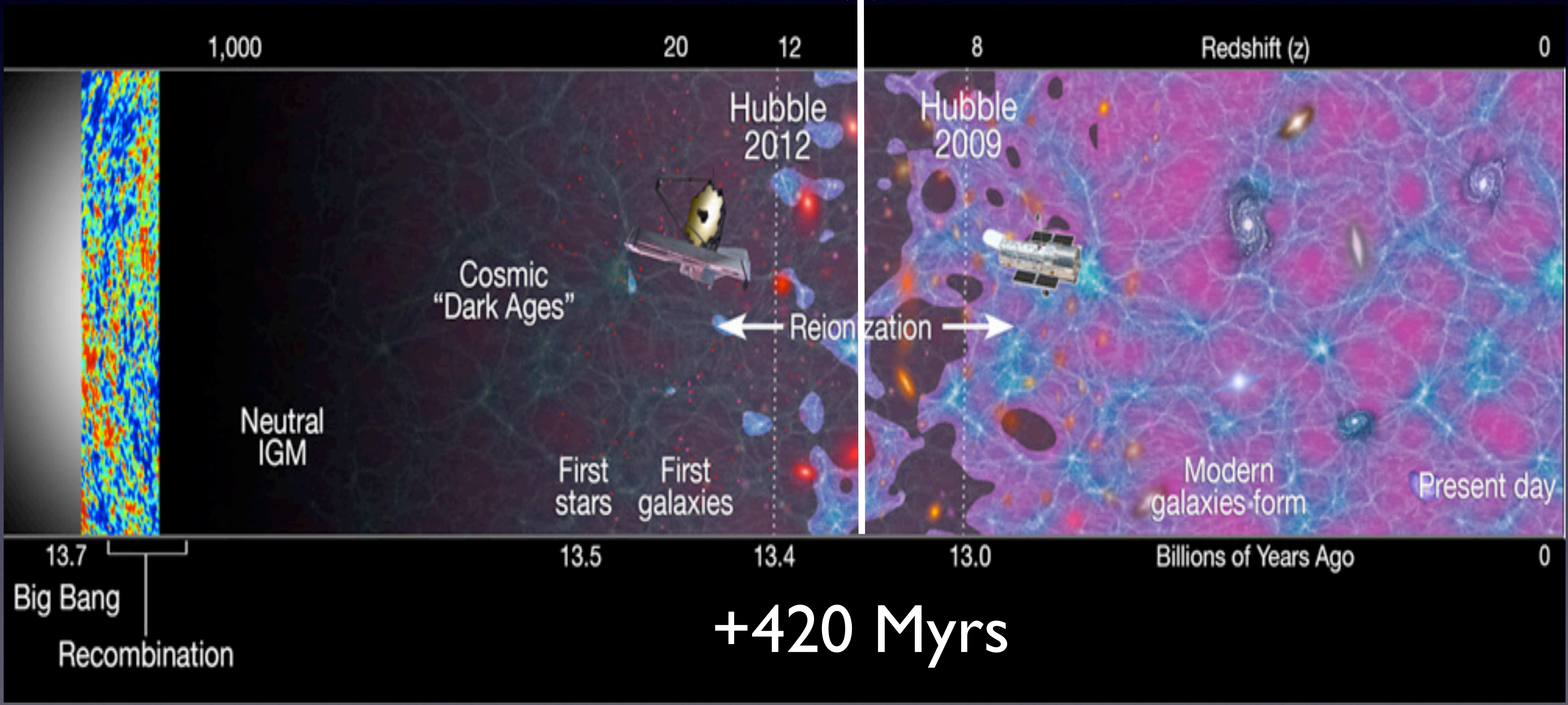
Distance scale of the Universe

galaxy formation begins



Distance scale of the Universe

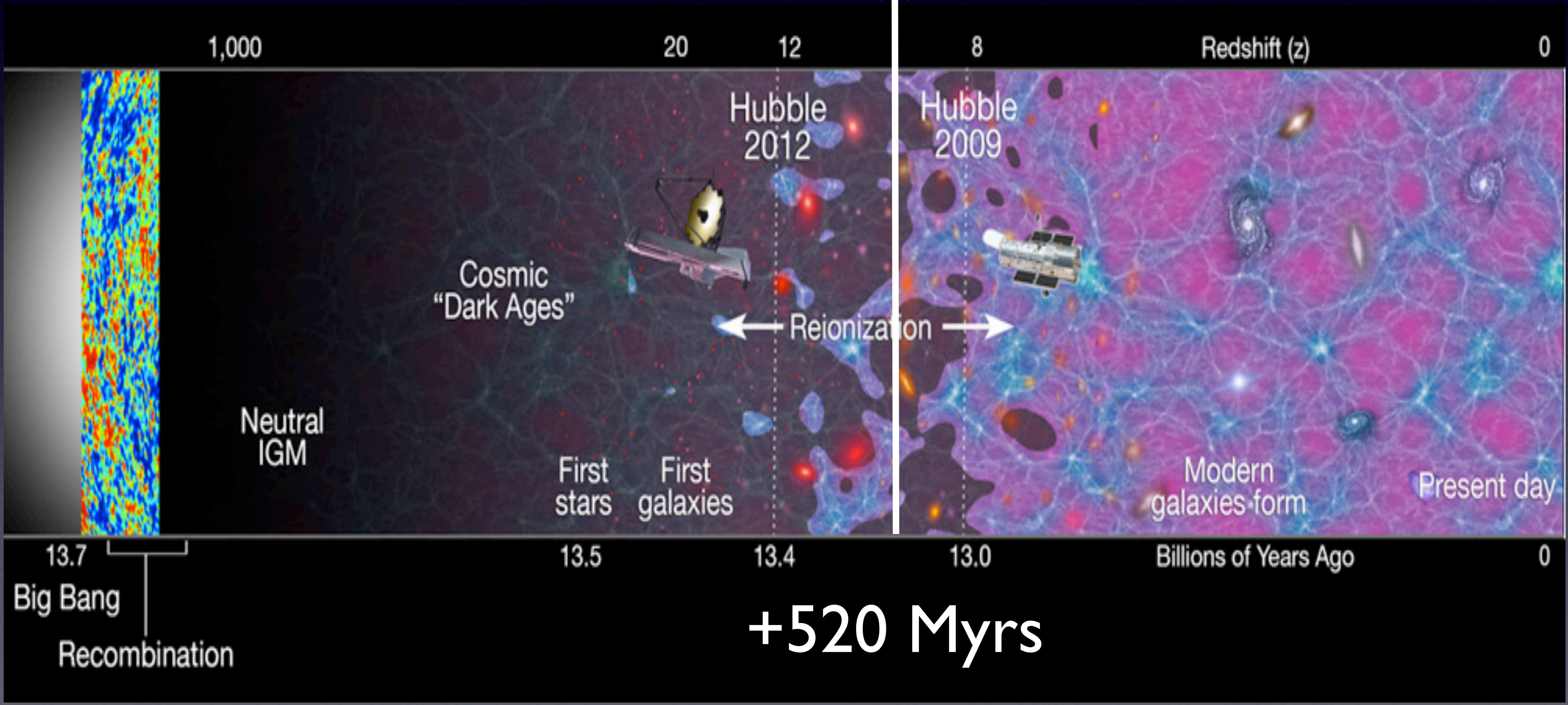
MACS0647-JD, z = 10.7



+420 Myrs

Distance scale of the Universe

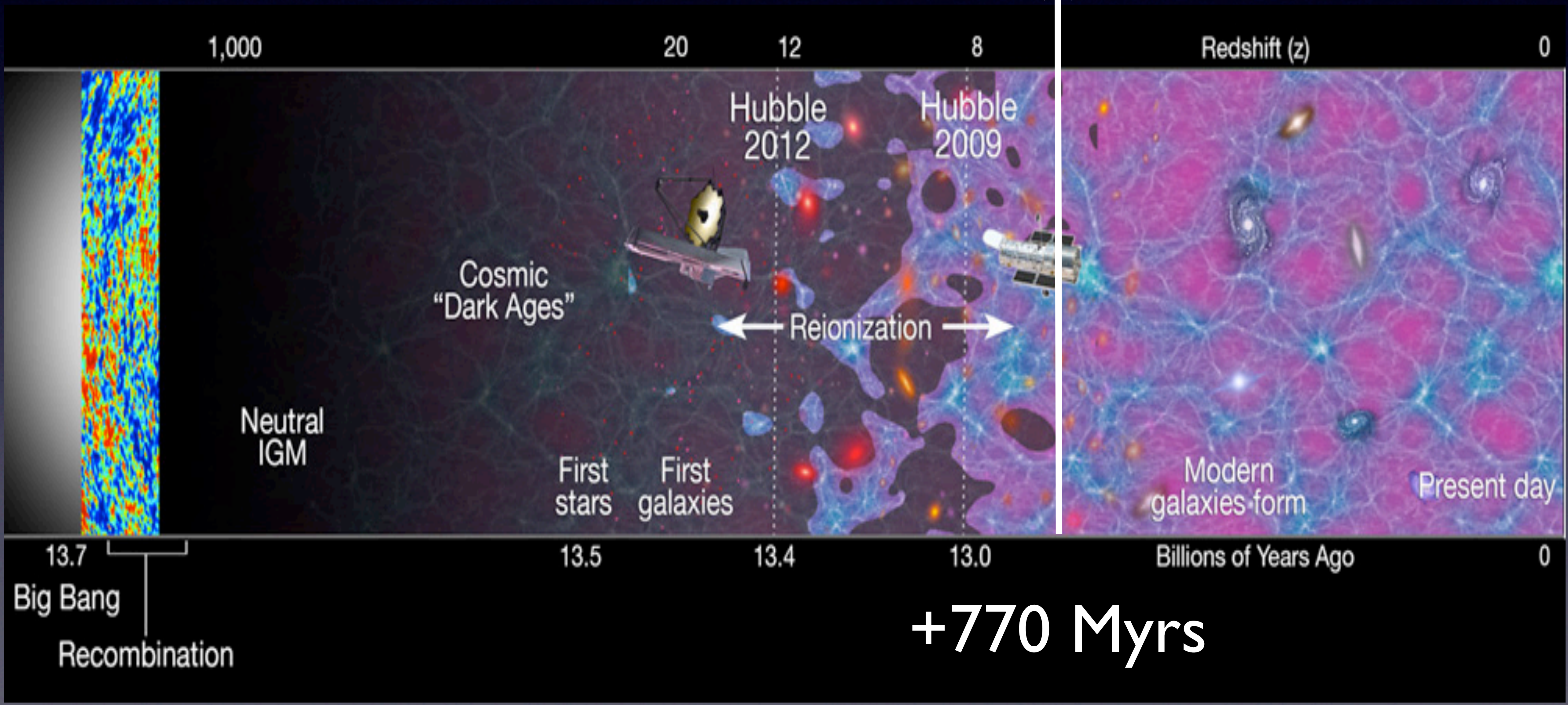
GRB090429B, z = 9.4



+520 Myrs

Distance scale of the Universe

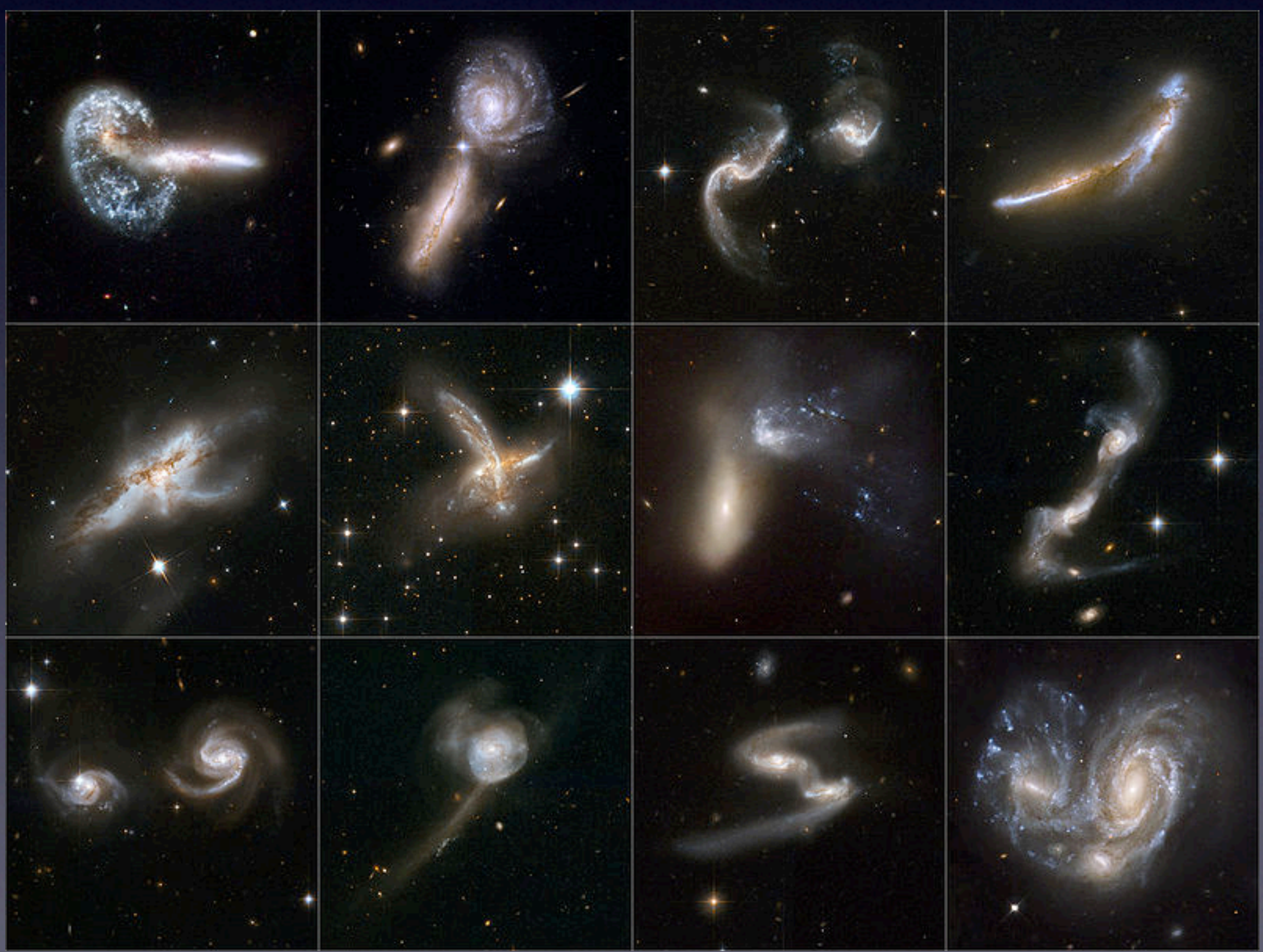
ULAS J1120+0641, z = 7.08

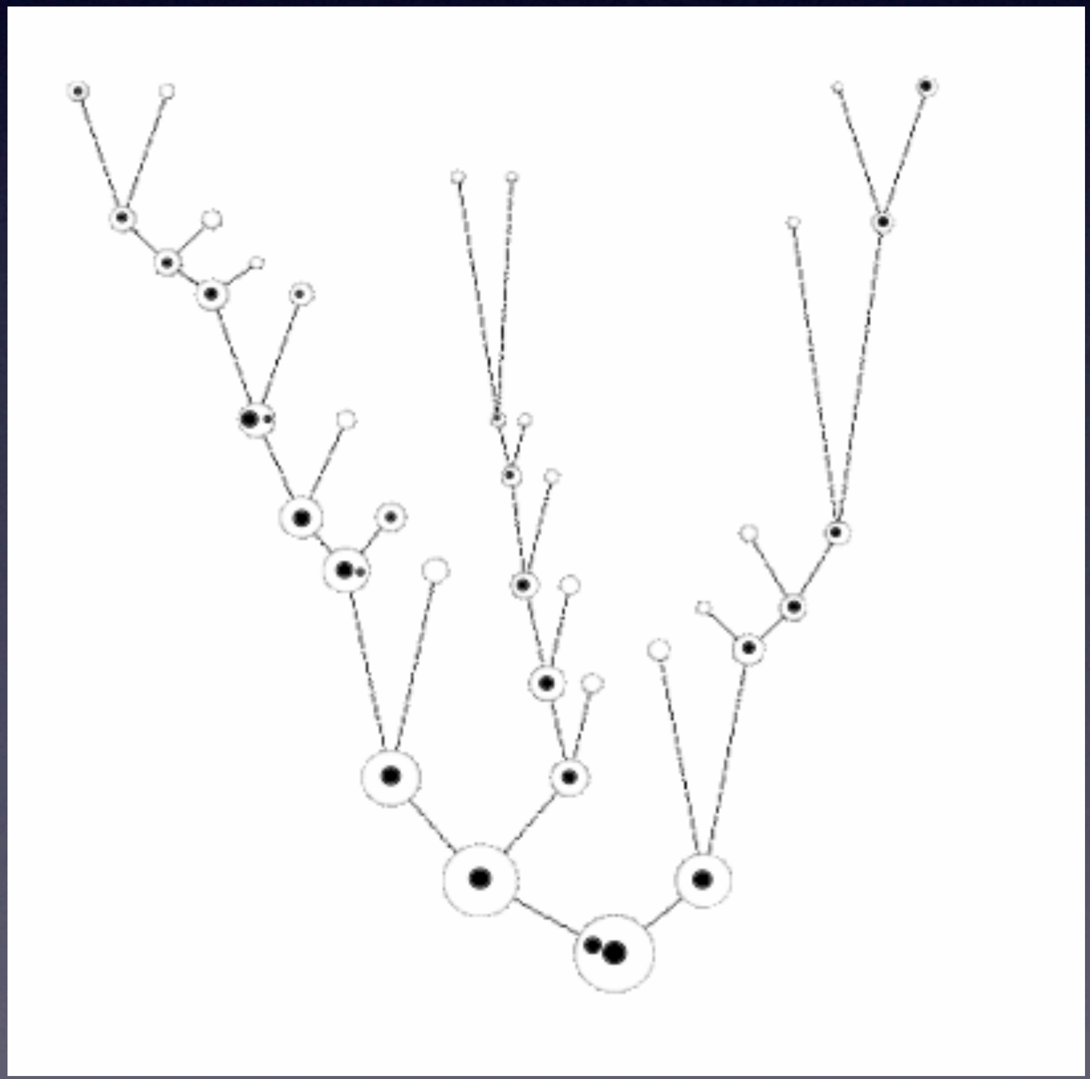


+770 Myrs

Formation

- Hierarchical formation





Formation

- Hierarchical formation
- Mechanism unknown
- 2 possibilities :

Formation

- Hierarchical formation
- Mechanism unknown
- 2 possibilities :

a) Remnants of Pop III stars
Low metalicity
Short lifespans
z ~17
No direct evidence for their existence

Formation

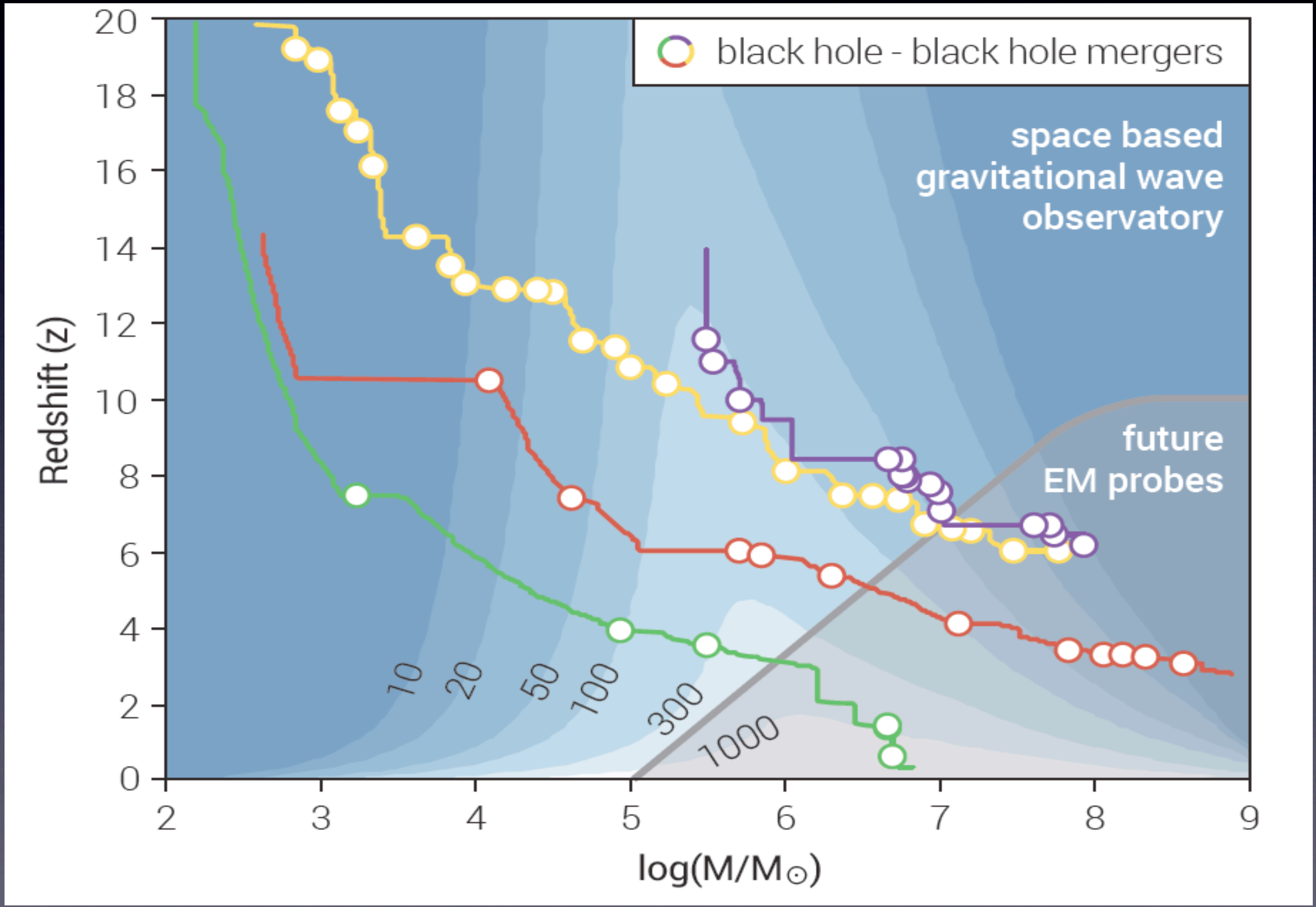
- Hierarchical formation
- Mechanism unknown
- 2 possibilities :

  b) proto-galactic collapse
  high mass remnants
  z ~ 12

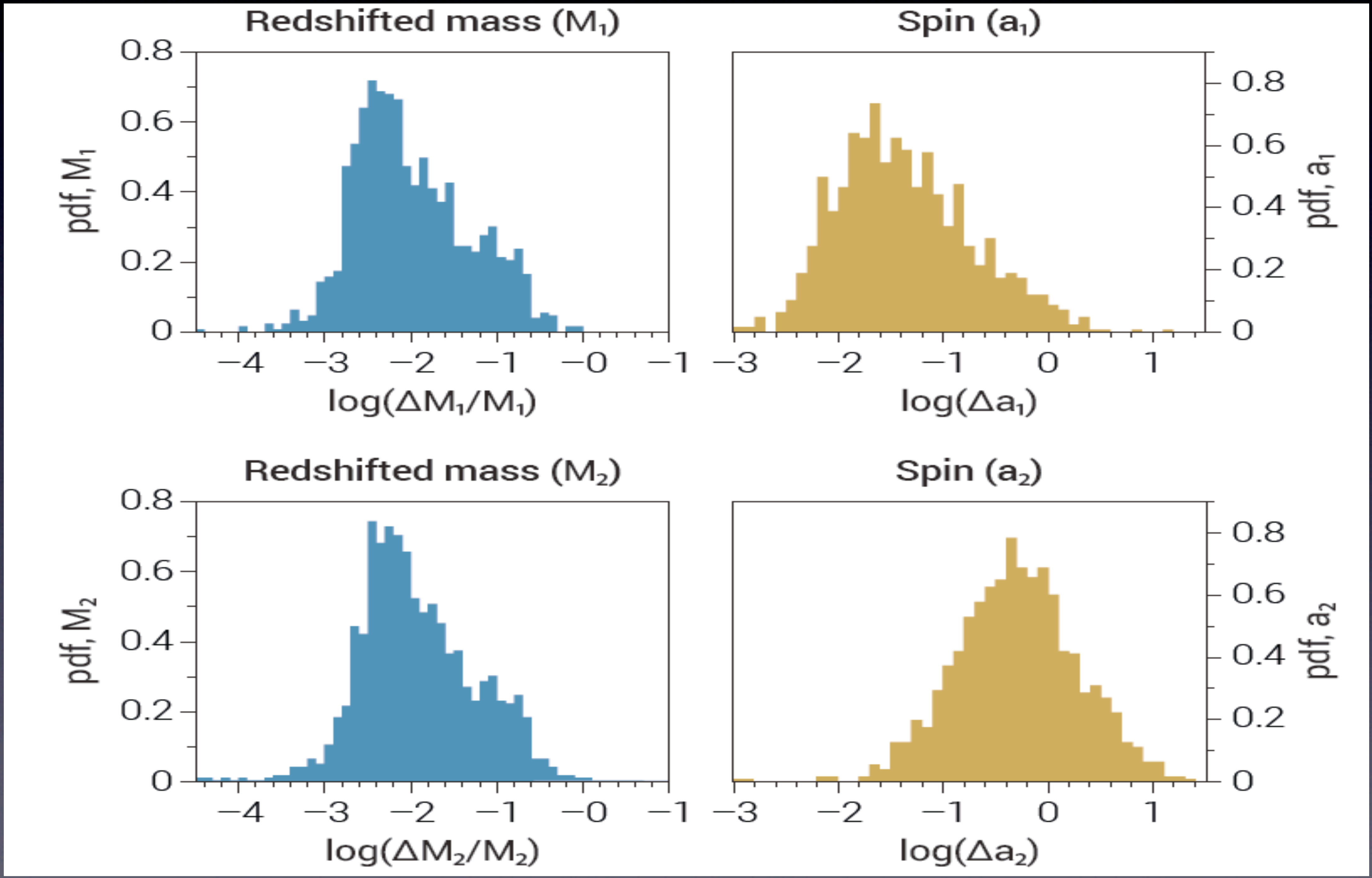
MBHBs

- Still remain the brightest sources
- A SMBHB merger releases 10^{26} solar luminosities in GWs
- Event rate : 10-100s / yr (model dependent)

Detection Horizon



Parameter Estimation



Parameter Estimation

We also expect :

A number of sources giving D_L < 10%

A number of sources with error boxes of < 10 sq. deg.

These sources should be accessible to LSST and/or SKA

Parameter Estimation

A candidate sub-parsec supermassive binary black hole system

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Abstract

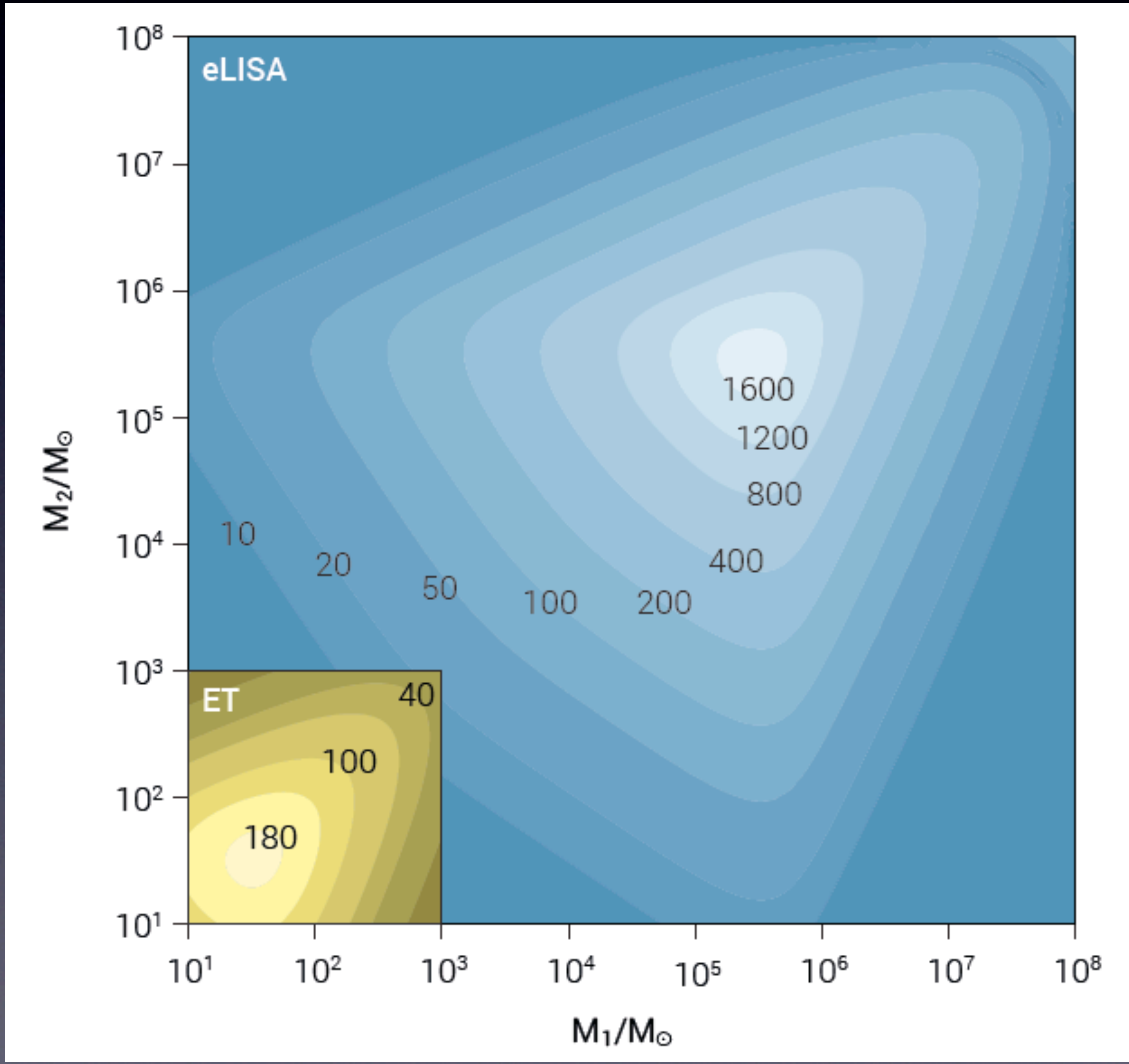
The role of mergers in producing galaxies, together with the finding that most large galaxies harbour black holes in their nuclei[1], implies that binary supermassive black hole systems should be common. Here we report that the quasar SDSS J153636.22+044127.0 is a plausible example of such a system. This quasar shows two broad-line emission systems, separated in velocity by 3,500 km s^{-1}. A third system of unresolved absorption lines has an intermediate velocity. These characteristics are unique among known quasars. We interpret this object as a binary system of two black holes, having masses of $10^{7.3}$ and $10^{8.9}$ solar masses separated by ~0.1 parsec with an orbital period of ~100 years.

N.B. : Typically no error estimate!

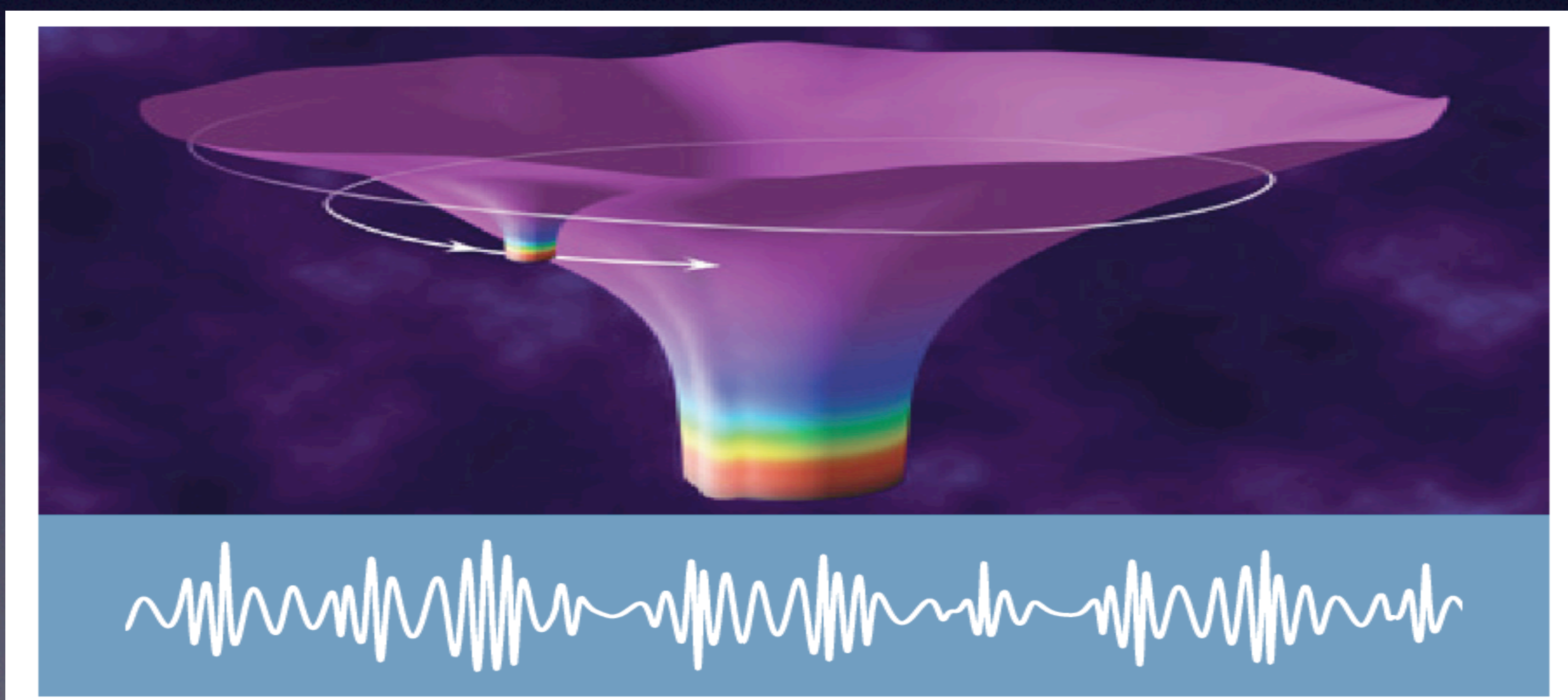
In the 2028 context

source at z = 0.5

Overlap with 3rd generation ground detectors such as ET (See Matteo's talk)



Extreme Mass Ratio Inspirals



Questions

- *What is the mass distribution of stellar remnants at the galactic centres and what is the role of mass segregation and relaxation in determining the nature of the stellar populations around the nuclear black holes in galaxies?*
- *Are massive black holes as light as* $\sim 10^5 M_{\odot}$ *inhabiting the cores of low mass galaxies? Are they seed black hole relics? What are their properties?*

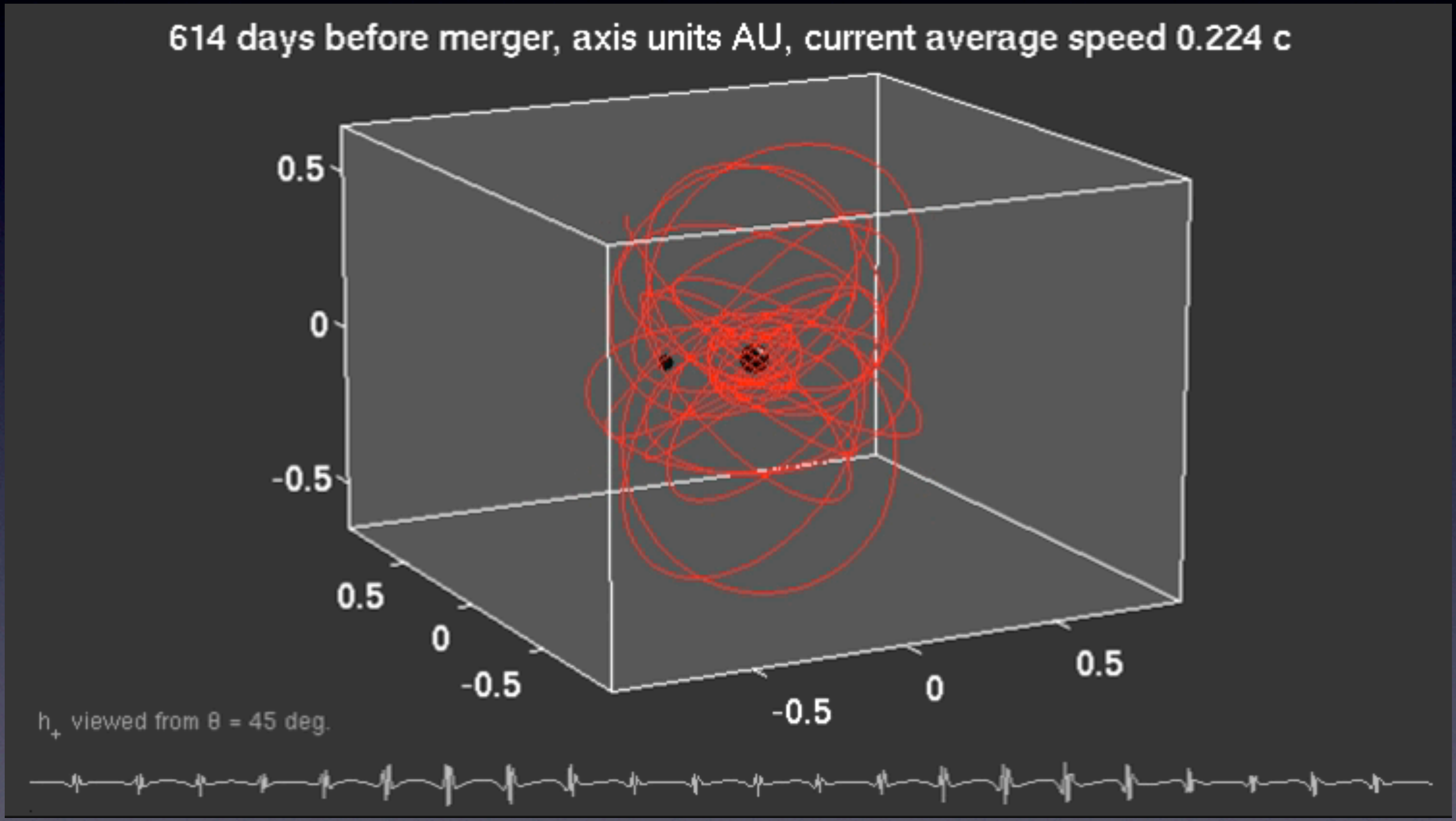
EMRIs

- Event rate : 50 per year
- However, large uncertainties in the astrophysical and waveform models
- Should see EMRIs in the last five years of their inspiral
- Even 10 events would allow us to match the observation uncertainty in the slope of the MBH mass function

EMRIs

simulation by Steve Drasco

EMRIs



simulation by Steve Drasco

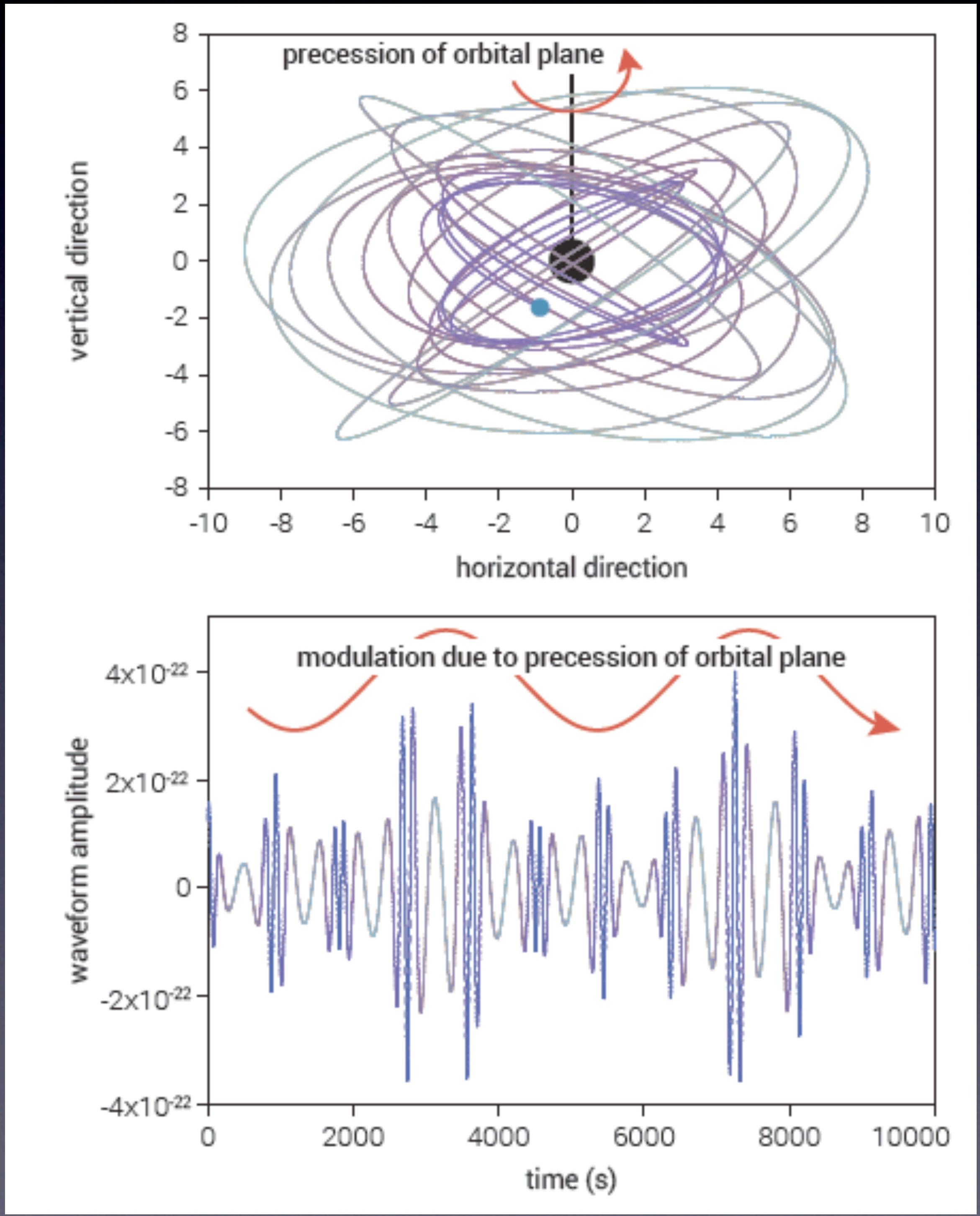
EMRIs

Very complex waveforms

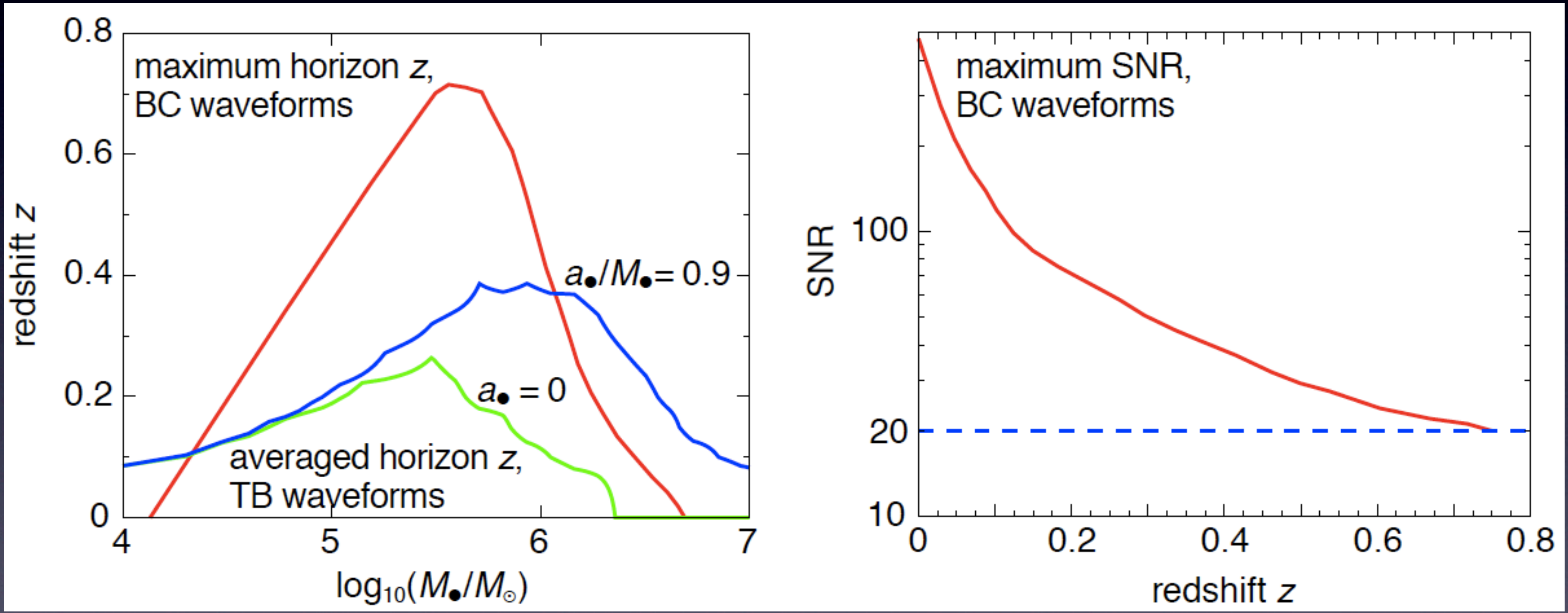
Difficult to model

Highly relativistic

10^5 orbits in the strong field regime close to the LSO, and horizon for high spin central black holes

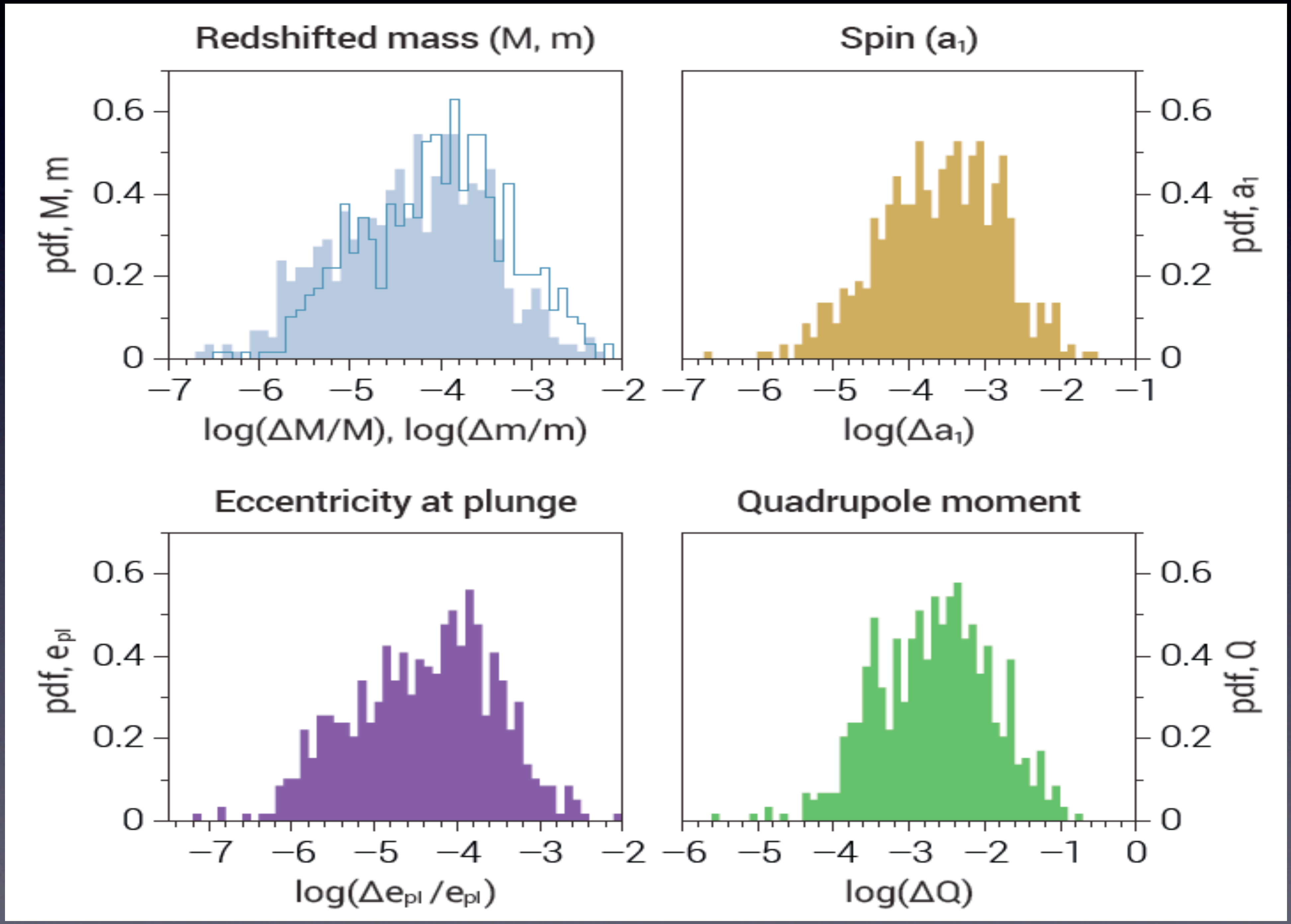


Detection Horizon

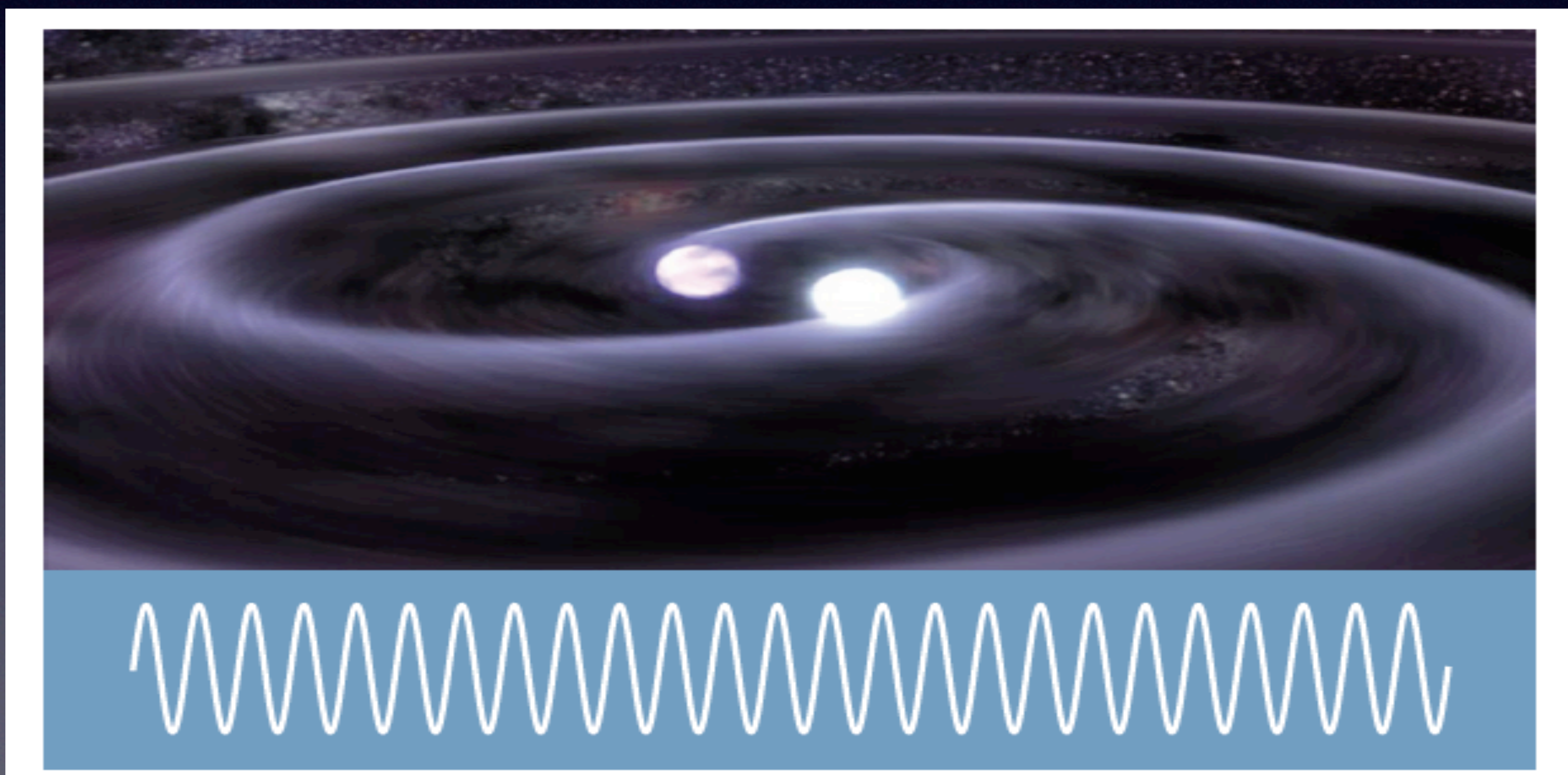


Monday, May 27, 13

Parameter Estimation



Galactic Binaries



Questions

- *How many ultra-compact binaries exist in the Milky Way?*
- *What is the merger rate of white dwarfs, neutron stars and stellar mass black holes in the Milky Way (thus better constraining the rate of the explosive events associated with these sources)?*
- *What does that imply for, or how does that compare to, their merger rates in the Universe?*
- *What happens at the moment a white dwarf starts mass exchange with another white dwarf or neutron star, and what does it tell us about the explosion mechanism of type Ia supernovae?*
- *What is the spatial distribution of ultra-compact binaries, and what can we learn about the structure of the Milky Way as a whole?*

Galactic Binaries

GBs : predominantly WD-WD

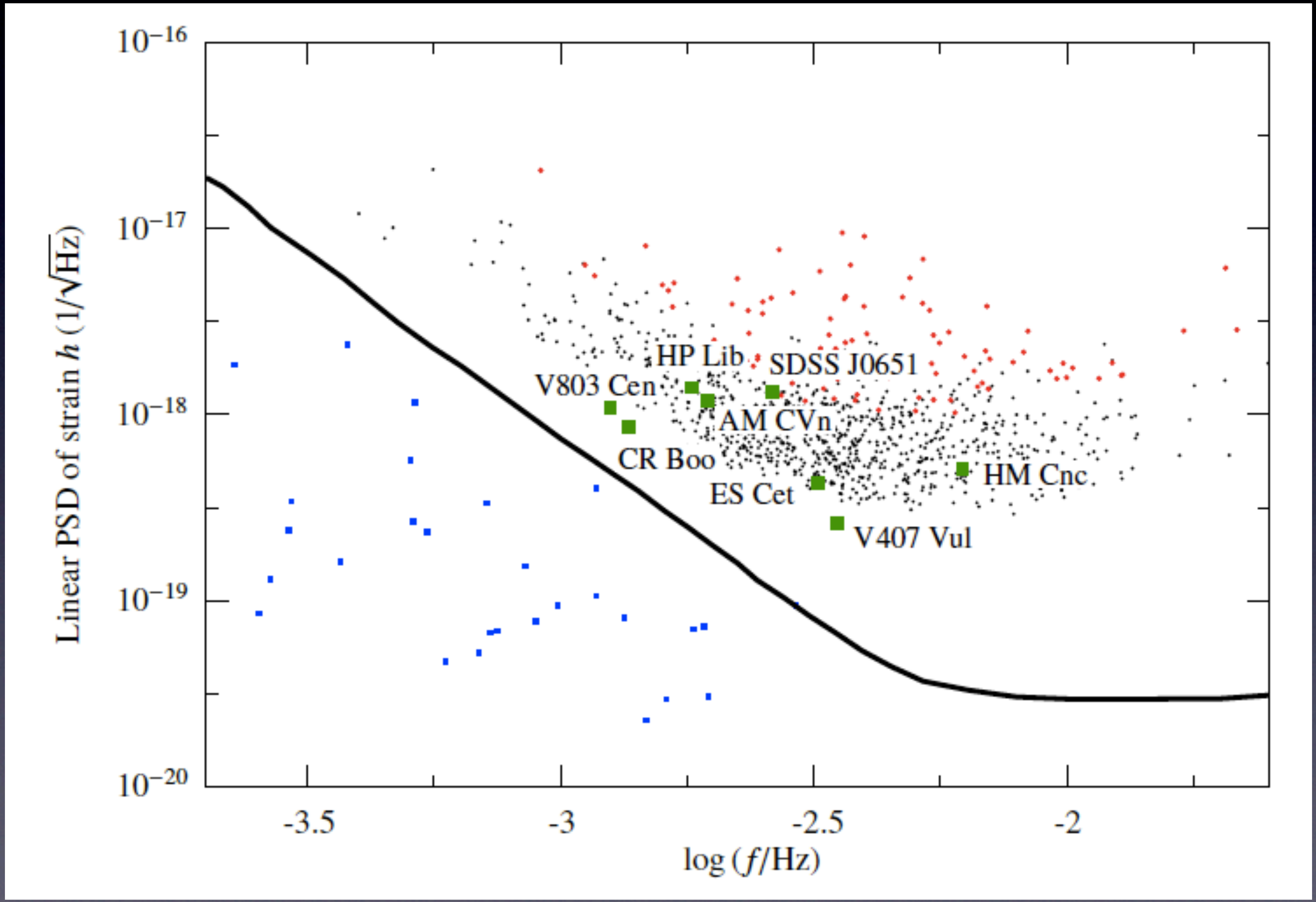
Also expect NS-NS, BH-BH, BH-NS, BH-WD, NS-WD

Expectation that there are 60×10^6 GBs in our galaxy

Galactic Binaries

- 3500-4000 detections in 2 years
- Will measure chirp mass, f and df/dt in 25% of sources
- Measuring 2nd frequency derivative will give information on tidal/mass-transfer interactions
- 500 high frequency (>10mHz) allowing sky resolution to 10 sq. deg., frequency derivative to 10%, distance to 10% and inclination to 10 degrees
- May also be able to say something on the populations of NS-NS and NS-BH binaries

Galactic Binaries



Verification Binaries

	Coordinates		f [mHz]	D [pc]	m_2 [$M_\odot$]	m_1 [$M_\odot$]
AM CVn systems						
RX J0806.3+1527	120.443557	-4.704035	6.2202766	300-1000	0.13	0.2-0.5[5]
V407 Vul	294.994600	+46.783096	3.51250	300-1000	0.068	0.7[6]
ES Cet	25.310039	-20.333218	3.22	350-1000	0.062	0.7[7]
AM CVn	171.084432	+37.441925	1.94414	606	0.14	0.85
HP Lib	235.786580	+4.959494	1.813	197	0.032	0.57
CR Boo	202.971814	+17.896456	1.360	337	0.023	0.55
KL Dra	334.830867	+78.322322	1.333	100*	0.022	0.27
V803 Cen	216.866251	-30.317527	1.241	347	0.021	1.31
SDSS J0926+3624	132.286781	+20.234177	1.177	100*	0.02*	0.6*
CP Eri	42.830979	-26.426918	1.176	100*	0.019	0.63
2003aw	140.733734	-21.234213	0.9862	100*	0.015*	0.42*
SDSS J1240-0159	190.193388	+2.225887	0.8921	350-440	0.015*	0.38*
GP Com	188.418156	+23.000197	0.7158	75	0.010	0.45
CE 315	206.451728	-14.462612	0.5120	77	0.006	0.48
(Ultra-)compact X-ray binaries						
4U 1820-30	275.841980	-7.027394[8]	2.92[9]	8100[3]	<0.1[3]	1.4[3]
4U 1543-624	251.159958	-41.352944	1.832	5000*	0.04	1.4
4U 1850-087	283.530386	+14.112497	1.618	8200	0.03	1.4
4U 1626-67	259.038082	-44.908517	0.4[10]	8000[3]	0.02-0.08[10]	1.4[10]
CC Com	174.038625	+21.775780[8]	0.105	90[3]	0.36[11]	0.62[11]
Double white dwarfs						
WD 0957-666	209.226640	-67.301935	0.379520267	135	0.32	0.37
KPD0422+4521	76.322155	+22.854567[8]	0.256690[12]	100*	0.511[13]	0.526[13]
KPD1930+2752	302.454582	+48.904889[8]	0.2434262[14]	100*	0.5[14]	0.97[14]
WD 1101+364	152.950020	+27.689153	0.15996	97	0.31[15]	0.36[15]
WD 1704+481	242.213221	+70.224728[8]	0.1598789[16]	100*	0.39[16]	0.56[16]
WD 2331+290	7.631717	+29.202332 [8]	0.1 [15]	100*	>0.32 [15]	0.39[15]
Cataclysmic variables						
EI Psc	356.370891	+8.925019	0.5195	210	0.13	0.7
SDSS J1507+5230	192.423733	+64.768925	0.4958	100*	0.13*	0.7*
GW Lib	234.794265	-6.417916	0.4341	100*	0.13*	0.7*
WZ Sge	309.727920	+36.921088	0.4065	43	<0.11	>0.7
SDSS J0903+3300	128.734149	+15.542558	0.3918	100*	0.13*	0.7*

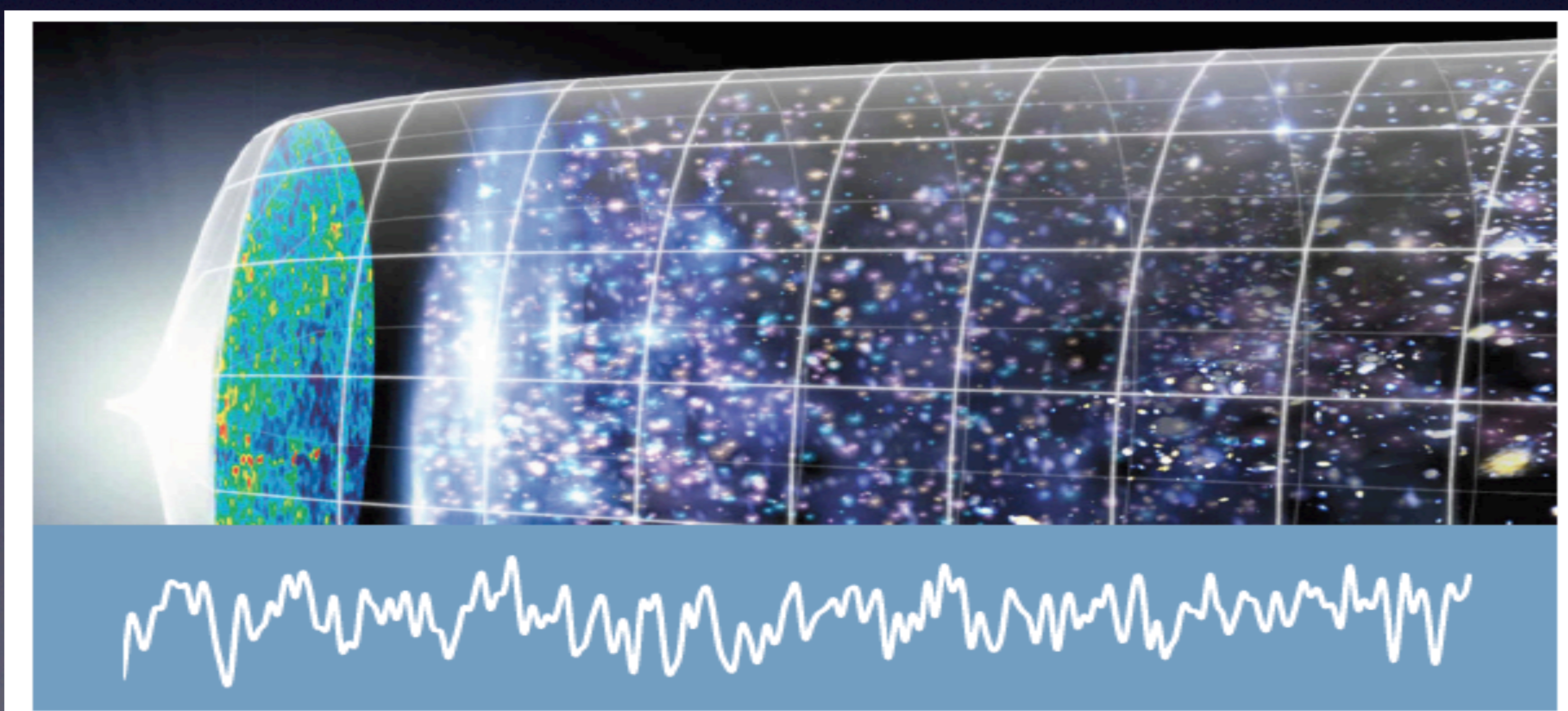
Verification Binaries

Should provide first detection within one month

Will allow calibration of the detector

Can be used to re-calibrate the detector after gaps or interruptions.

Cosmology, fundamental physics and the stochastic background

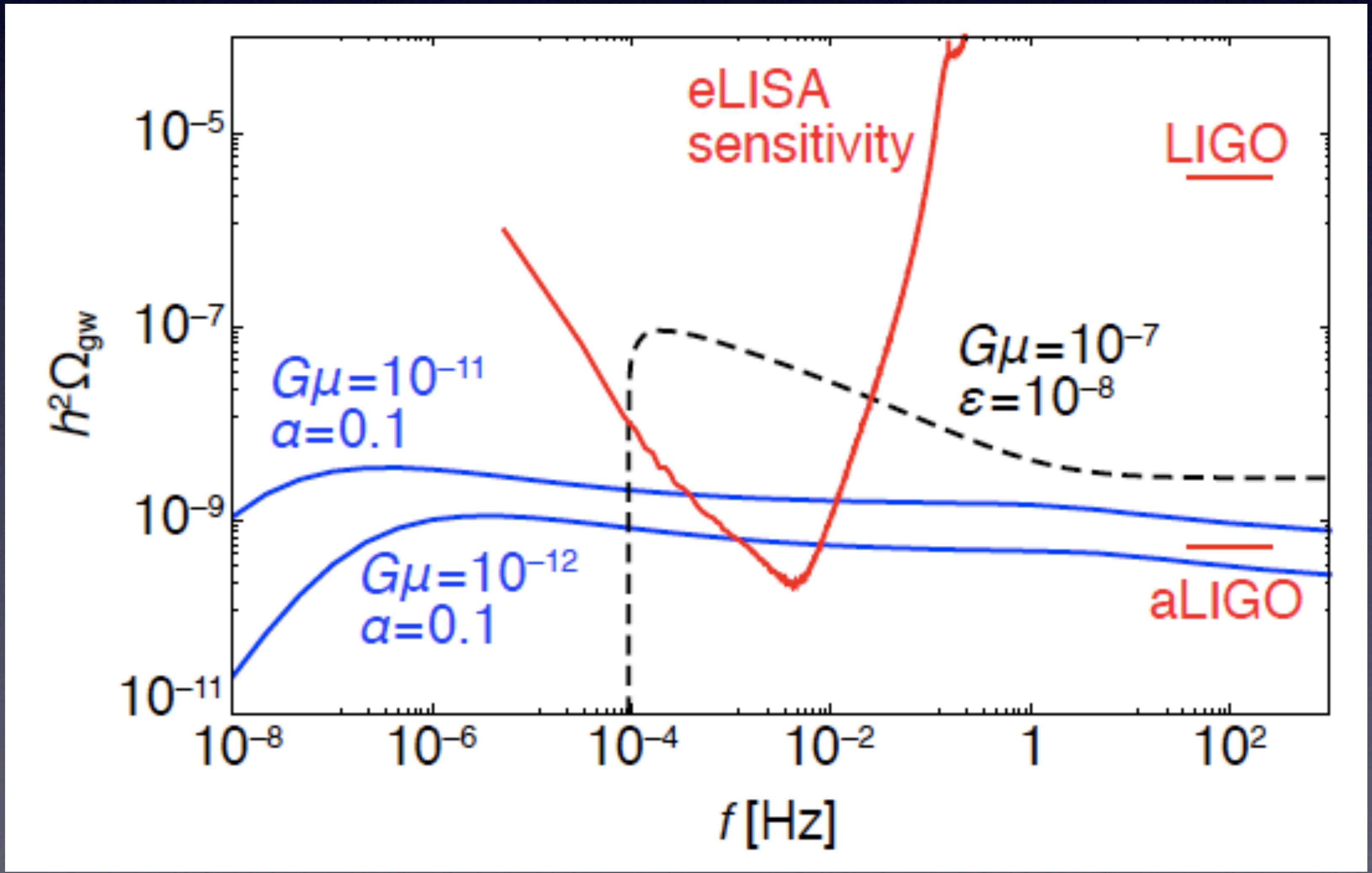


Questions

- *Does gravity travel at the speed of light ?*
- *Does the graviton have mass?*
- *How does gravitational information propagate: Are there more than two transverse modes of propagation?*
- *Does gravity couple to other dynamical fields, such as, massless or massive scalars?*
- *What is the structure of spacetime just outside astrophysical black holes? Do their spacetimes have horizons?*
- *Are astrophysical black holes fully described by the Kerr metric, as predicted by General Relativity?*

Cosmology

Background from cosmic (super)strings



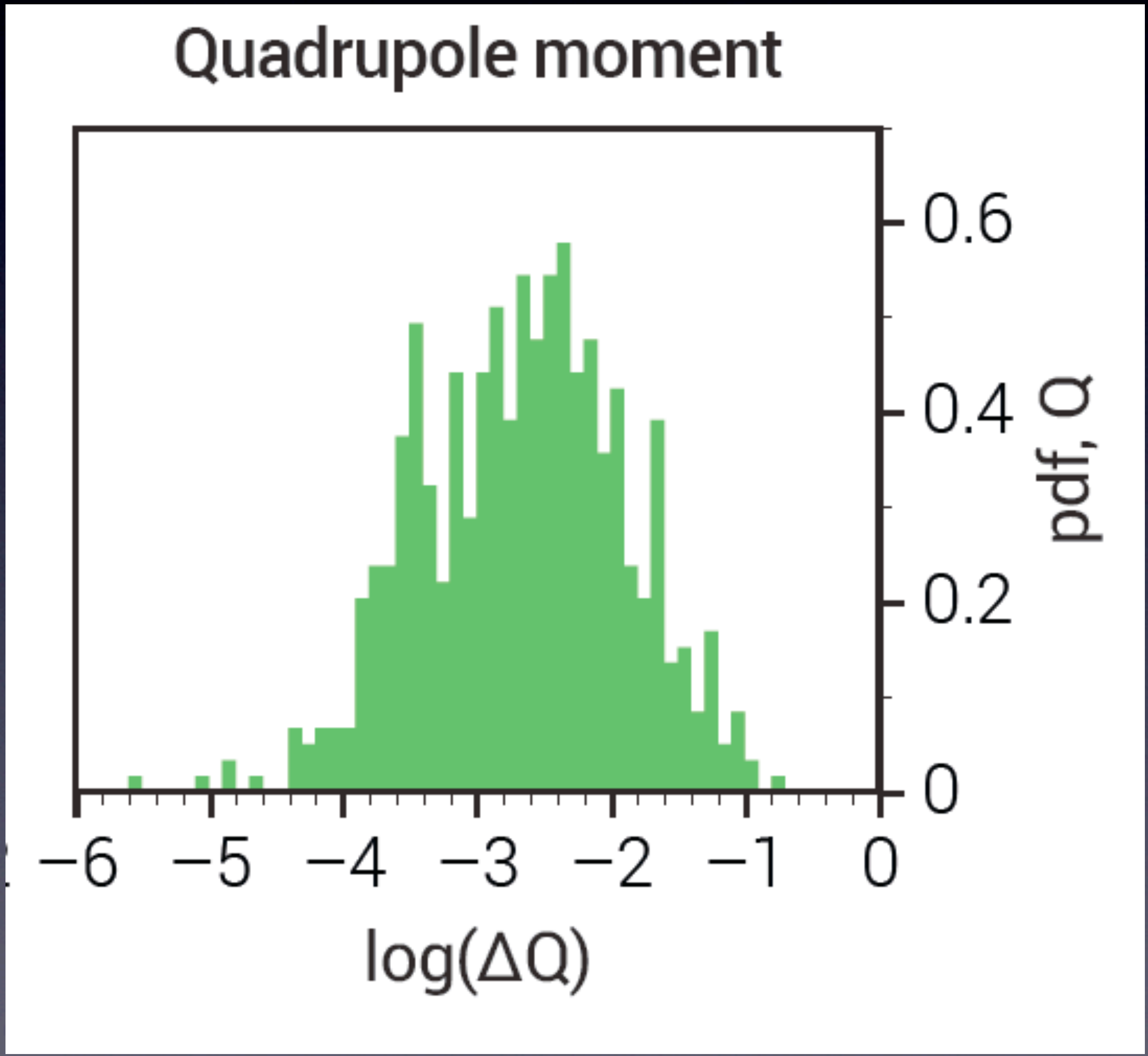
Fundamental Physics

- MBH inspirals can be used to test massive gravitons and can put constraints on theories such as Brans-Dicke, theories with evolving G etc.
- The merger can be used to compare numerical relativity and observation
- The ringdown, by measure at least two QNMs, can test the "Kerr-ness" of the background spacetime
- EMRIs can test the no-hair theorem. An EMRI with an SNR of 30 will measure the mass and spin to 1 part in 1000/10,000 and thus the mass quadrupole moment to 1 part in a 100/10,000
- EMRIs can test for boson stars, Chern-Simons theory, bumpy spacetimes etc.

Fundamental Physics

EMRIs will allow us to test deviations from GR

Do BHs exist, if not what are they - boson stars? quark stars?

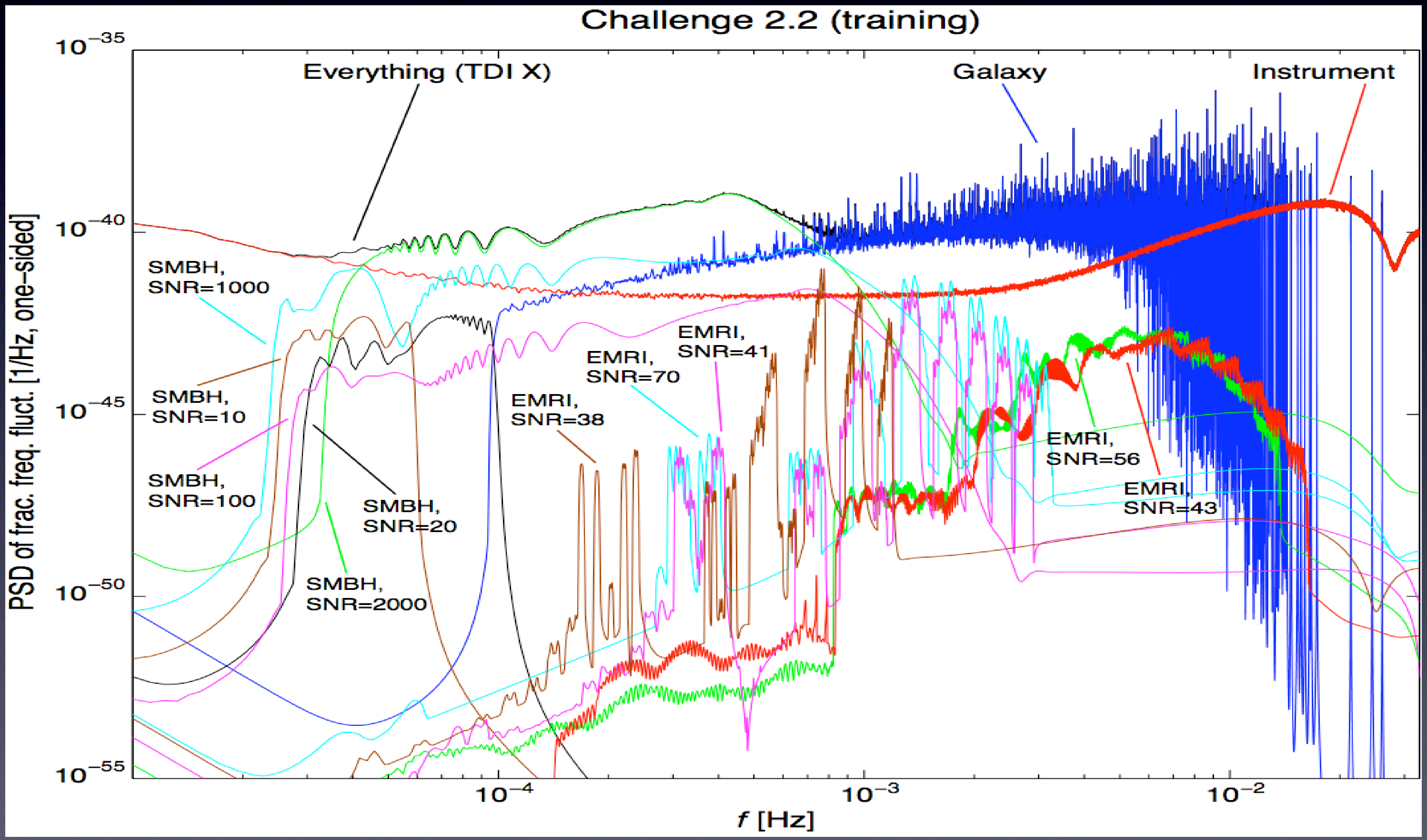


Data Analysis

eLISA vs. LIGO/Virgo

Detector	eLISA	LIGO/VIRGO
Frequencies	0.04mHz - 1 Hz	20 Hz - 2 kHz
Sources	SMBHBs, EMRIs, GBs, CSs, SB	BH-BH, BH-NS, NS-NS, SN
Source Duration	days - years	0.5 sec - minutes
Main Difficulty	Source dominated, source confusion	Noise dominated, glitches mimic GWs

eLISA

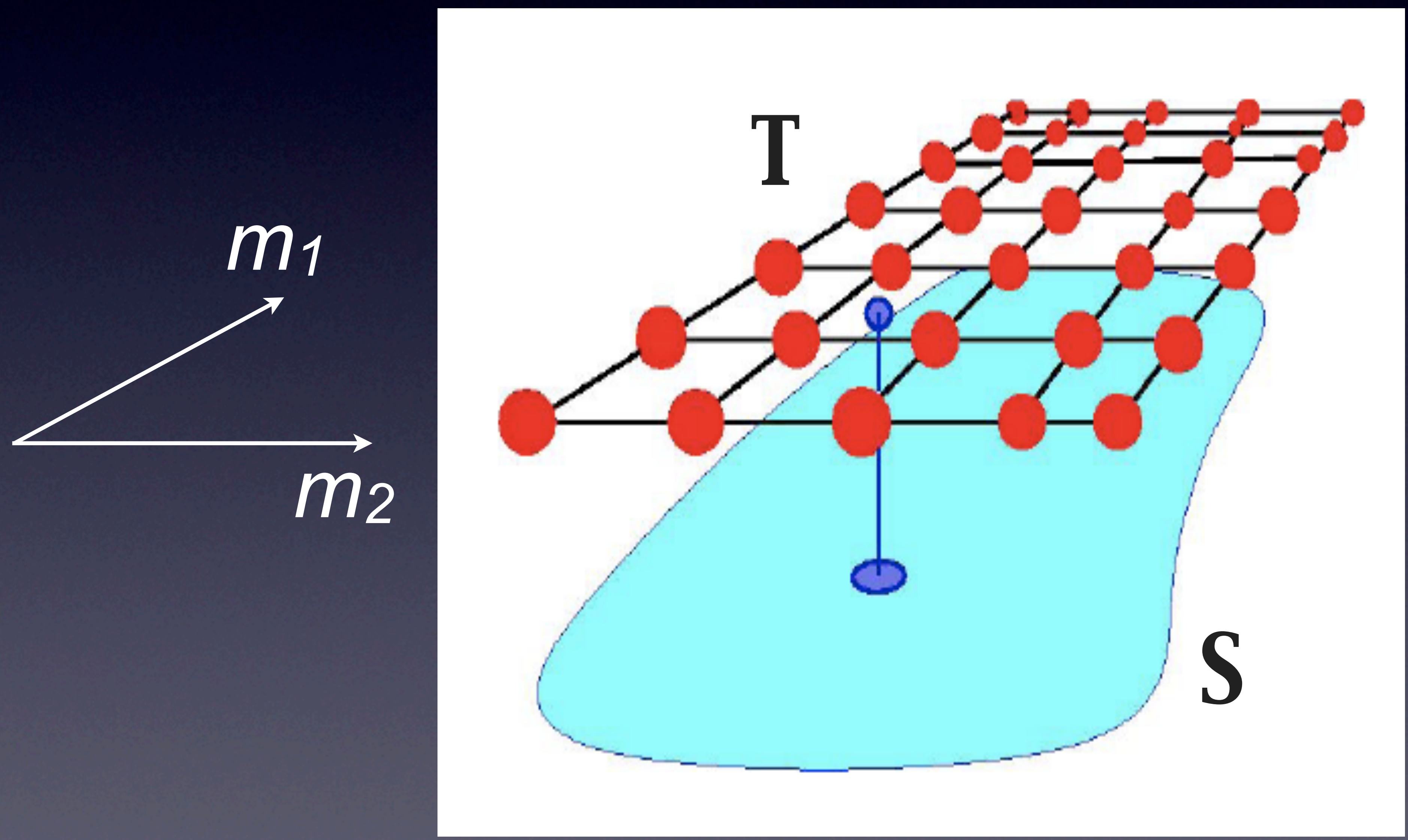

Challenge 2.2 (training)
Everything (TDI X)
Galaxy
Instrument
SMBH, SNR=1000
SMBH, SNR=10
SMBH, SNR=100
SMBH, SNR=20
SMBH, SNR=2000
EMRI, SNR=38
EMRI, SNR=70
EMRI, SNR=41
EMRI, SNR=56
EMRI, SNR=43
PSD of frac. freq. fluct. [1/Hz, one-sided]
f [Hz]
10^{-35}
10^{-40}
10^{-45}
10^{-50}
10^{-55}
10^{-4}
10^{-3}
10^{-2}

So, how do we search?

Most eLISA data analysis is based on matched filtering.

1st idea comes from ground-based data analysis

Template Grids



Problem

For :

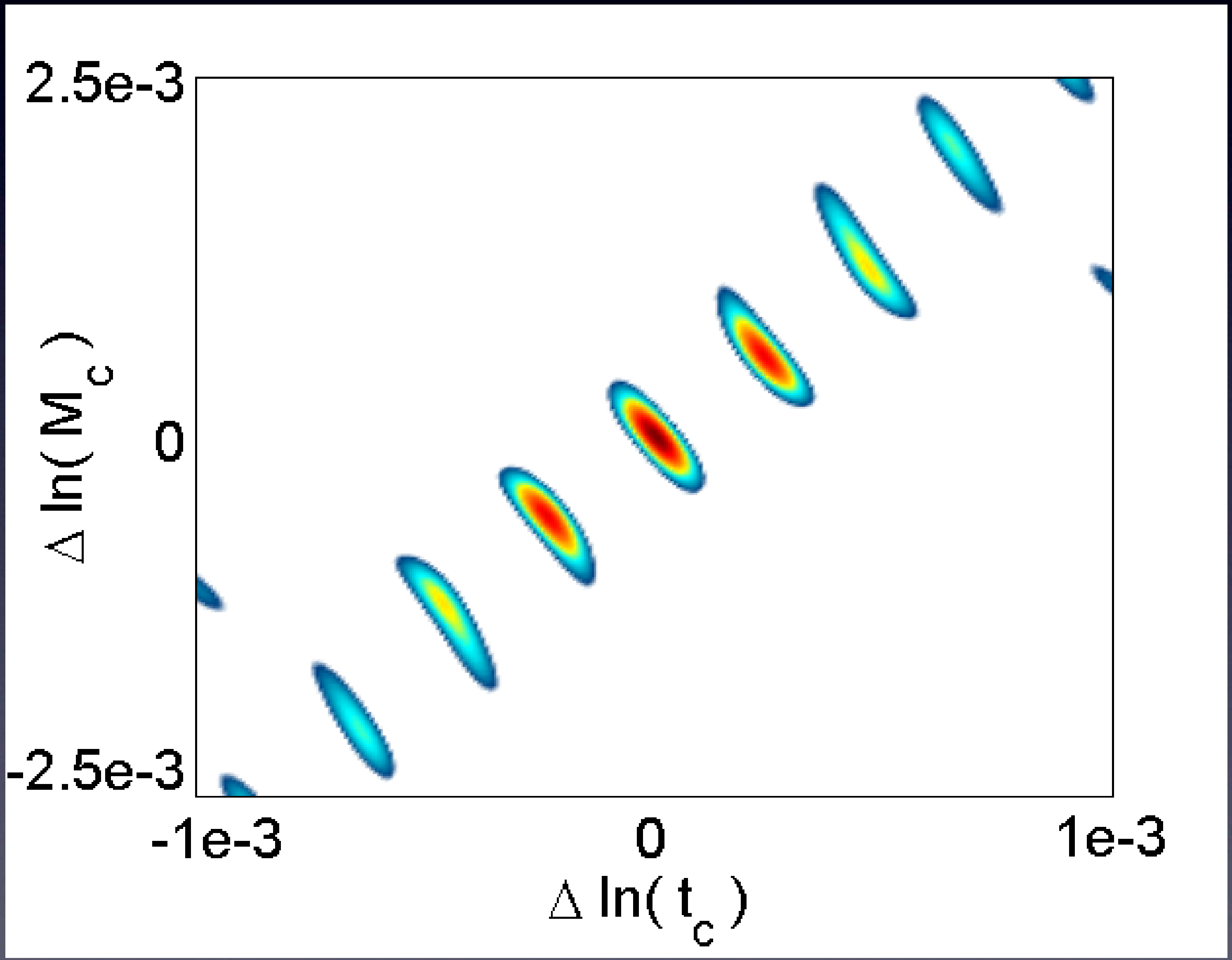
SMBHBs, we need 10^{12} templates
EMRIs, we need 10^{40} templates
GBs, we need 10^{8}-10^{10} templates

Sources are overlapping in frequency

Need more sophisticated methods as template number scales geometrically with dimension

MHMC, HEA, GA etc provide algorithms where template number scales linearly with dimension.

Advantage of high SNR



What have we lost?

MBHBs

- Detection horizon of z ~ 15 (LISA) -> z ~ 11 (eLISA/NGO)
- 10-1000 sources per year (LISA) -> 10-100 sources per year (eLISA/NGO)
- Reduced parameter estimation for short duration sources due to loss of third arm
- No instantaneous measurement of polarisation
- Reduced sky resolution for some sources

EMRIs

- Detection horizon of z ~ 2 (LISA) -> z ~ 0.7 (eLISA/NGO)
- 100 sources per year (LISA) -> 10-50 per year (eLISA/NGO)
- Parameter estimation still very good due to the nature of the source

Galactic Binaries

- 25,000 sources (LISA) -> 3,500 sources (eLISA/NGO)
- Reduced parameter estimation due to loss of arm
- Parameter estimation still quite good due to long-lived nature of the sources

Cosmology

- Possible reduction in the number of theories that can be constrained
- However, the same science should be achievable

Fundamental Physics

- Cosmography may be harder due to reduced redshift horizon and number of sources
- Testing hypotheses regarding the spacetime around a black hole is still very possible
- Impact on astrophysics, cosmology, theory, fundamental physics etc.

What have we improved?

Mock LISA Data Challenges

- Blind data challenges of increasing difficulty
- Started in 2005
- First challenges focused on individual sources
- By 2008, the challenges had moved onto mixed sources
- Also increased the complexity of the waveform models

MLDCs : Major Results

- Demonstrated it was possible to practically resolve almost 20,000 galactic binaries with correlations of > 90% with the data
- Demonstrated that not only were EMRIs detectable, but were detectable at low SNRs of ~20
- Demonstrated that MBHBs could be accurately resolved even in the presence of a full galaxy
- Demonstrated that exotic objects such cosmic (super)strings are detectable
- Rapid evolution of sophisticated algorithms since the beginning

MeLDCs : The future

- No real change to waveforms or algorithms
- Continue with MLDC 4, now with new noise curve
- First ‘full enchilada’
- New challenge every 1-2 years until launch

Conclusion

- eLISA / NGO is a strong mission
- There is a lot of new science that can be done
- Impact on astrophysics, cosmology, theory, fundamental physics etc.

Additional Slides

Sources : GBs

- 1990-98 : Confusion noise estimate : calculate density of stars in a spatial and frequency regions and extrapolate
- 2002 : Estimate of 2000 resolvable binaries per year with SNR > 10 using LISA
- 2003 : First major simulations of galaxies (Nelemans, Yungleson & Portegies Zwart - 200 million; Benacquista, DeGoes & Lunder - 90,000)
- 2005 : Estimate that with a NYZ galaxy simulation, 25,000 GBs would be resolvable with LISA
- 2005 : 10^6-10^{10} templates would be needed for a single stage template grid search with FF > 0.97

Sources : GBs

- 2006-7 : First generation of search algorithms for GB searches. Slice & Dice , Hierarchical grid search , Reverse Jump MCMC , BAM
- 2007 : MLDC 1+2. ~20,000 resolved binaries with C > 0.9
- 2009 : MLDC 3 & Second generation of search algorithms. Delayed rejection MCMC, Iterative template grid. Almost 5,000 binaries resolved with C > 0.9
- 2011 : MLDC 4 & 3rd generation algorithms - MLDC on hold, but ~10,000 sources resolved with C > 0.9

Sources : MBHs (waveforms)

- 2002 : Higher harmonics
- 2003 : Simple precession
- 2005 : Ringdown
- 2006 : Spin induced precession
- 2007- : NR, EOB
- 2007-8 : Higher harmonics
- 2009-10 : Eccentricity
- 2011 : Ringdown

Sources : MBHs (Algorithms)

- 2005 : 10^{12} templates needed for grid search with FF > 0.97
- 2006-7 : MHMC/MCMC based algorithms
- 2007 : MLDC 1-2. MHMC, TF, Grid & MCMC. First demonstration that we could approach the theoretical estimates given by PE studies. Waveforms were non-spinning
- 2008-9 : 2nd generation algorithms. HEA, Multinest, GA , PTMHMC
- 2009 : MLDC 3. algorithms "tweeked" to search for spinning MBHBs

Sources : MBHs (Astro)

- 2005 : Just about overcoming the last parsec problem
- 2006-7 : Dry inspirals
- 2009 : Gas, accretion disks introduced
- 2008-9 : last 10th of a parsec problem
- 2010 : Role of 3-body scattering, eccentricity
- 2011 : Seed model selection

Sources : EMRIs

- 2004 : 10^{40} templates needed for grid search with FF > 0.97
- 2004 : “EMRIs can’t be done...”
- 2005 : First search algorithm based on TF methods. Crude detection
- 2006 : Detection limit of EMRIs set at SNR ~ 30
- 2008 : MLDC 2. MHMC search algorithms & TF. Demonstrated detectability of strong EMRIs (SNR > 100). PE not good.
- 2009 : MLDC 3. PTMHMC, Stochastic search + MCMC & TF. Demonstrated detectability & good PE for low SNR EMRIs (SNR ~ 20)