Exploring the mHz Gravitational Wave Universe with eLISA

Ed Porter - APC, Paris
CEA, 22/01/2015

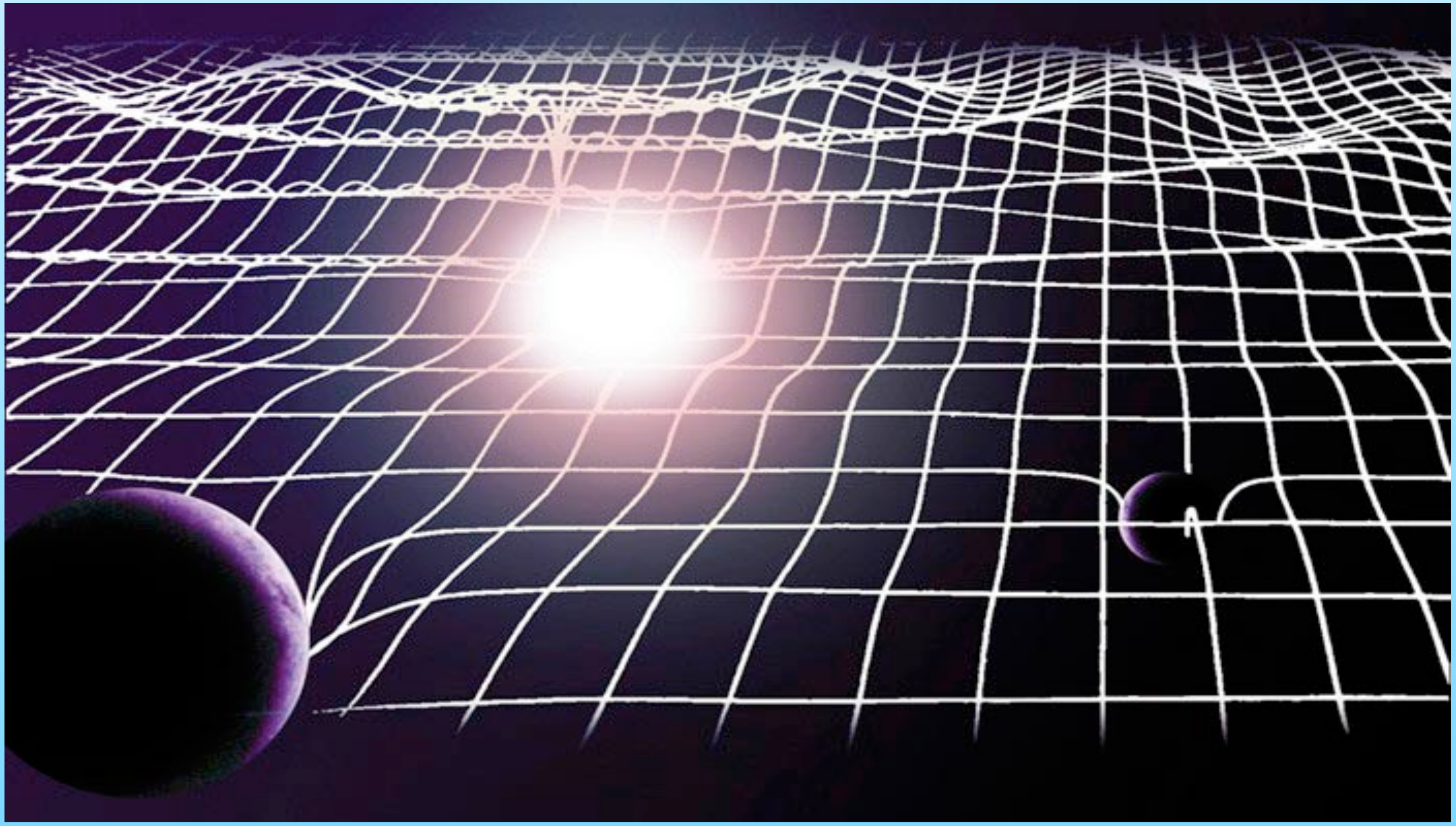
Outline :

1) Gravitational Waves
2) Ground Based Detectors and The Rumour!
3) LISA Pathfinder
4) eLISA
5) Sources of GWs for eLISA
6) How do we detect GWs?

Gravitational Waves

Gravitational Waves

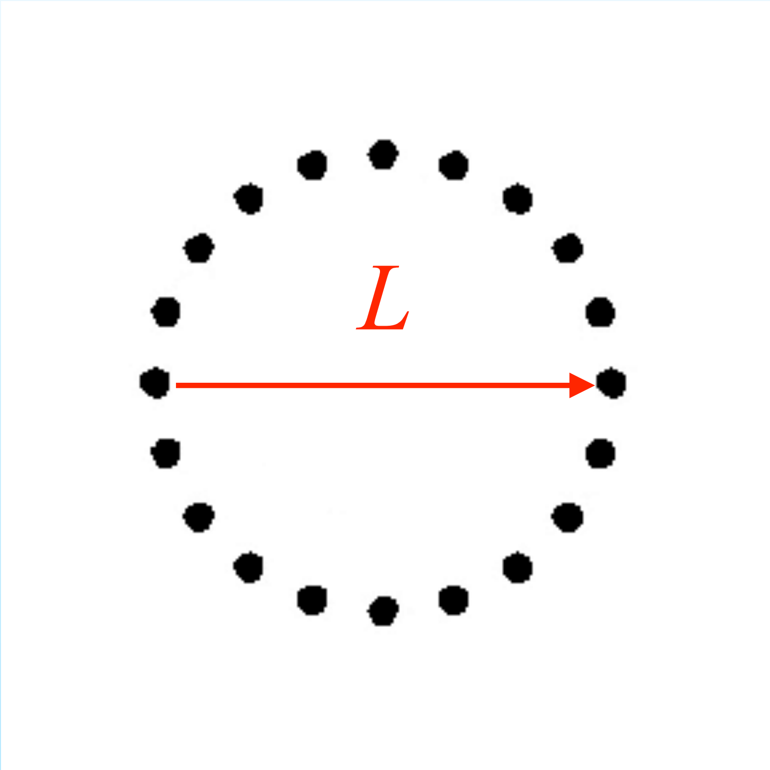
- Last untested prediction of General Relativity
- Oscillations in the curvature of spacetime
- GWs are generated by large masses and large accelerations



Comparison with EM waves

EM	GW
inverse square law	inverse square law
$v_{prop} = c$	$v_{prop} = c$
2 polarisations	2 polarisations
rotation of 90°	rotation of 45°
scattered & diffracted due to interaction with matter	virtually no interaction with matter
oscillation of the electromagnetic field	oscillation of spacetime

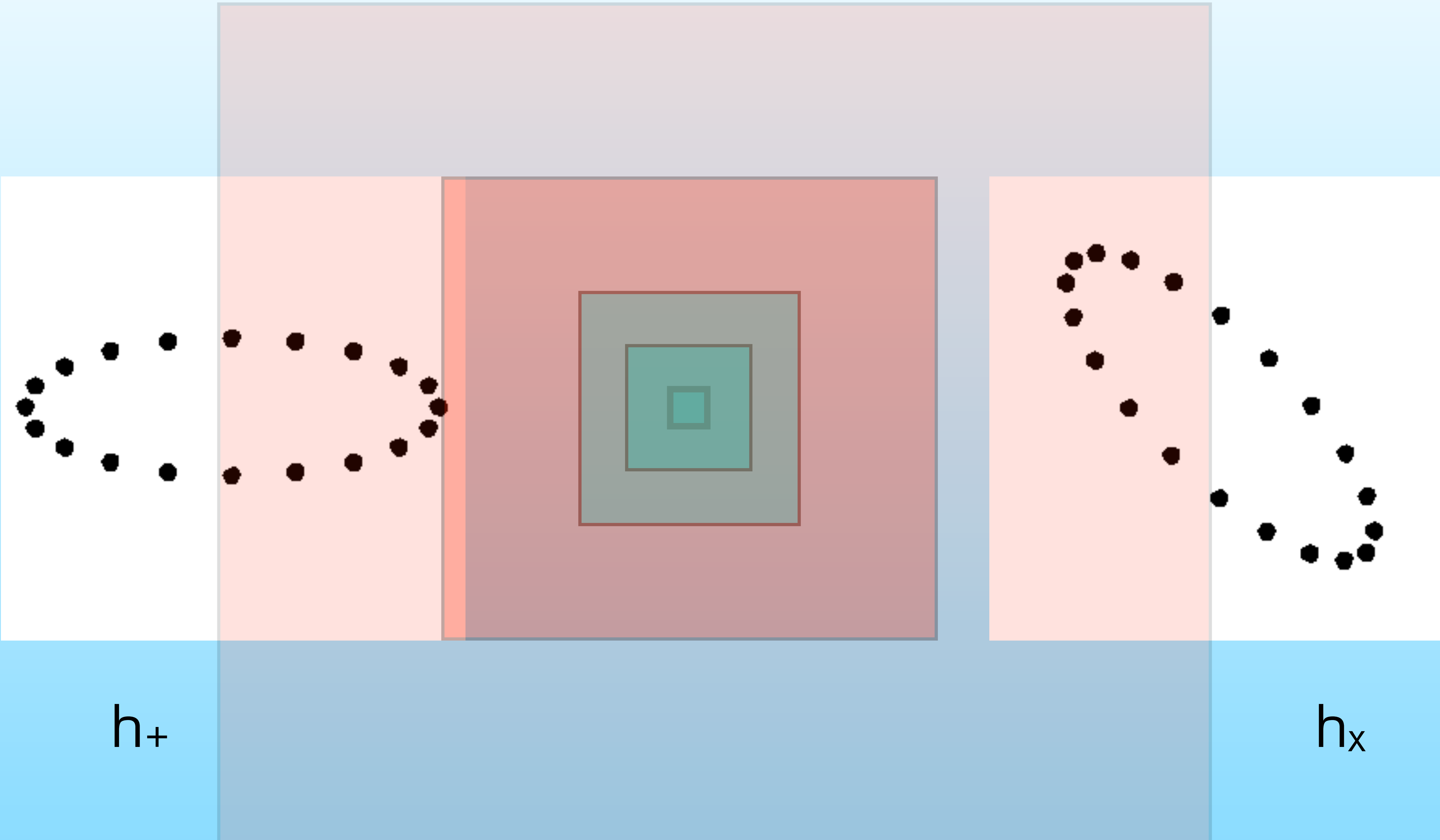
GW Polarisations



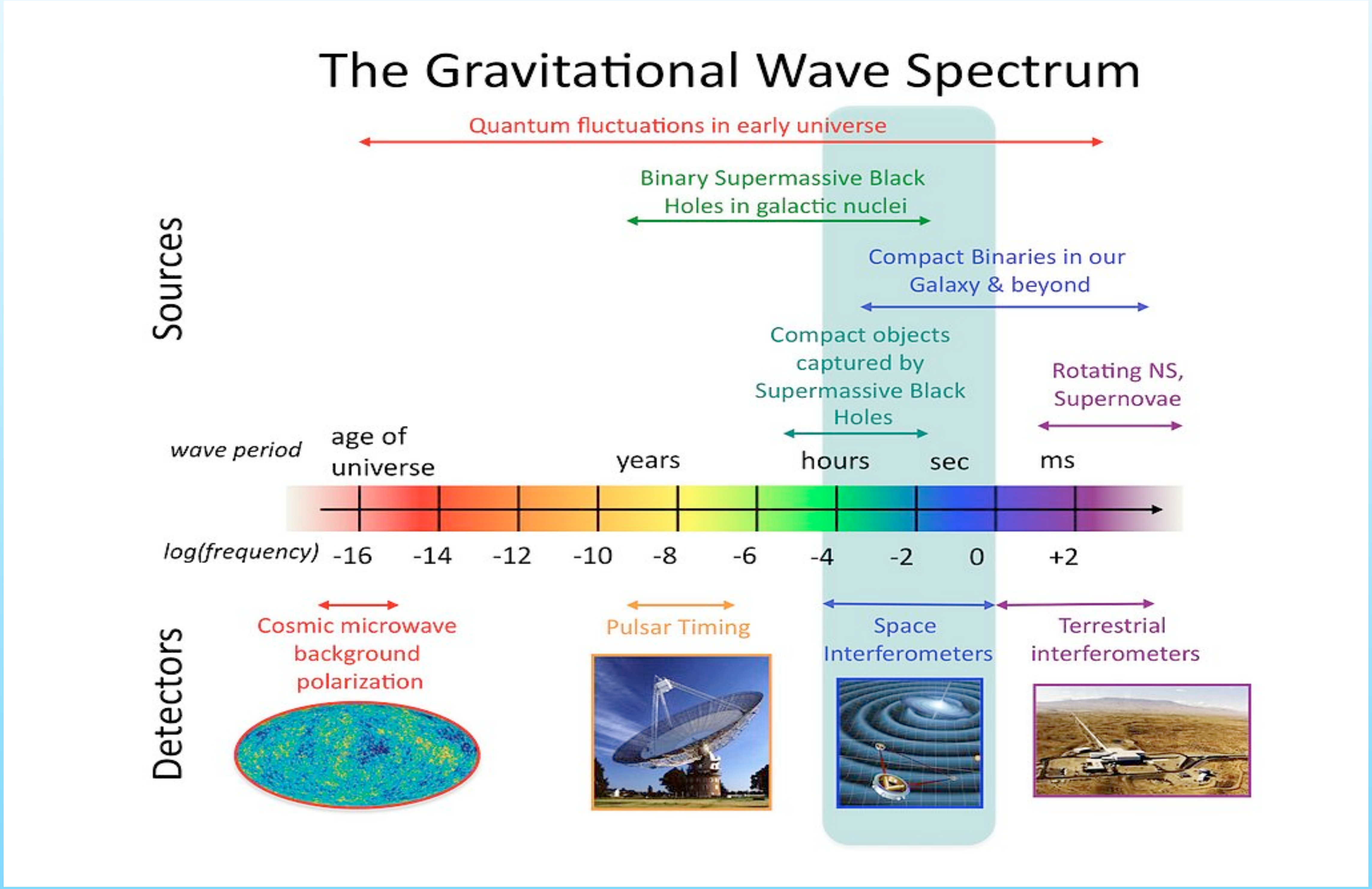
A passing GW will induce a strain h according to

$$\Delta L = h\, L$$

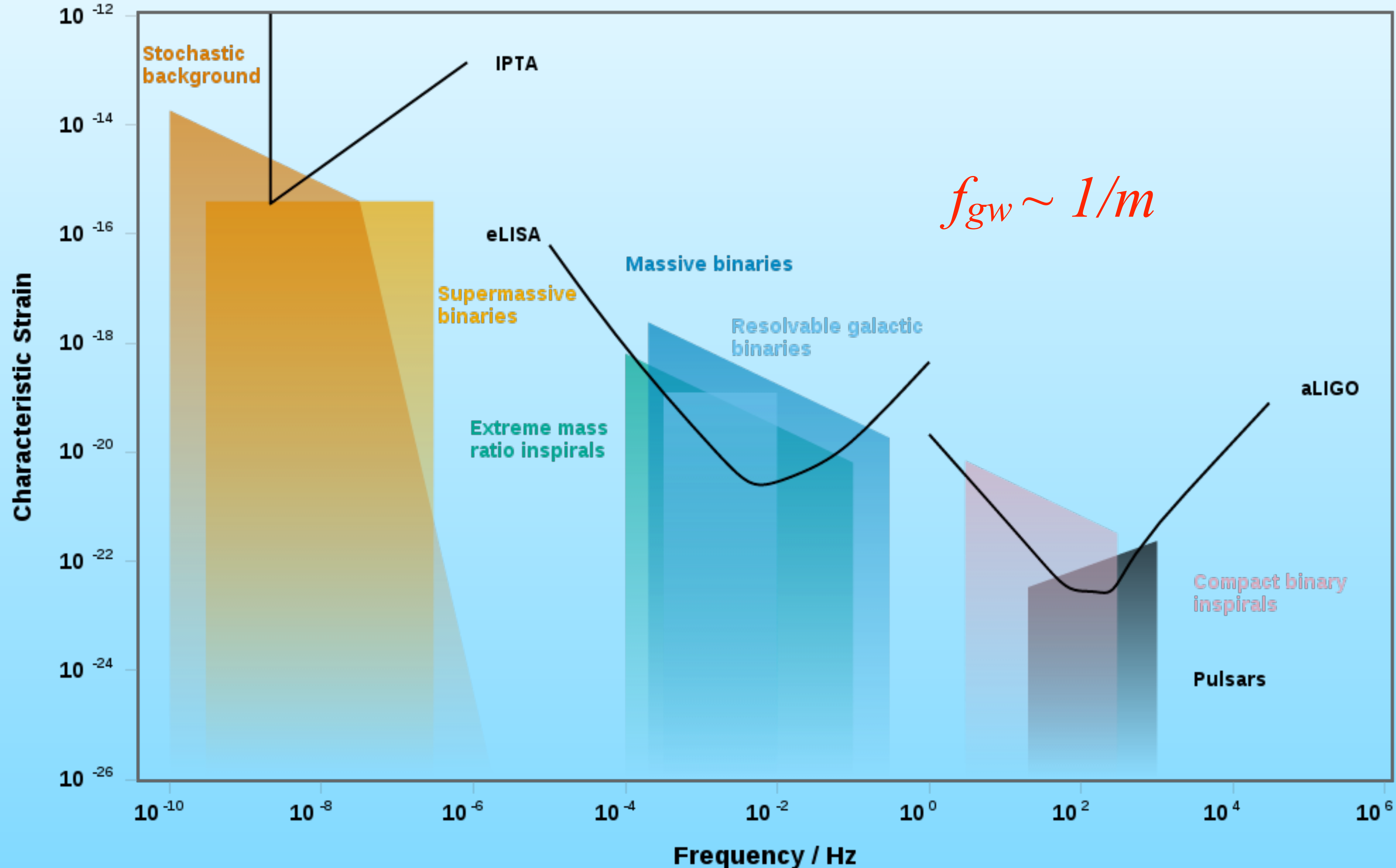
GW Polarisations



GW Spectrum


The Gravitational Wave Spectrum
Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Rotating NS, Supernovae
Sources
wave period
age of universe
years
hours
sec
ms
log(frequency)
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Detectors
Cosmic microwave background polarization
Pulsar Timing
Space Interferometers
Terrestrial interferometers

GW Spectrum



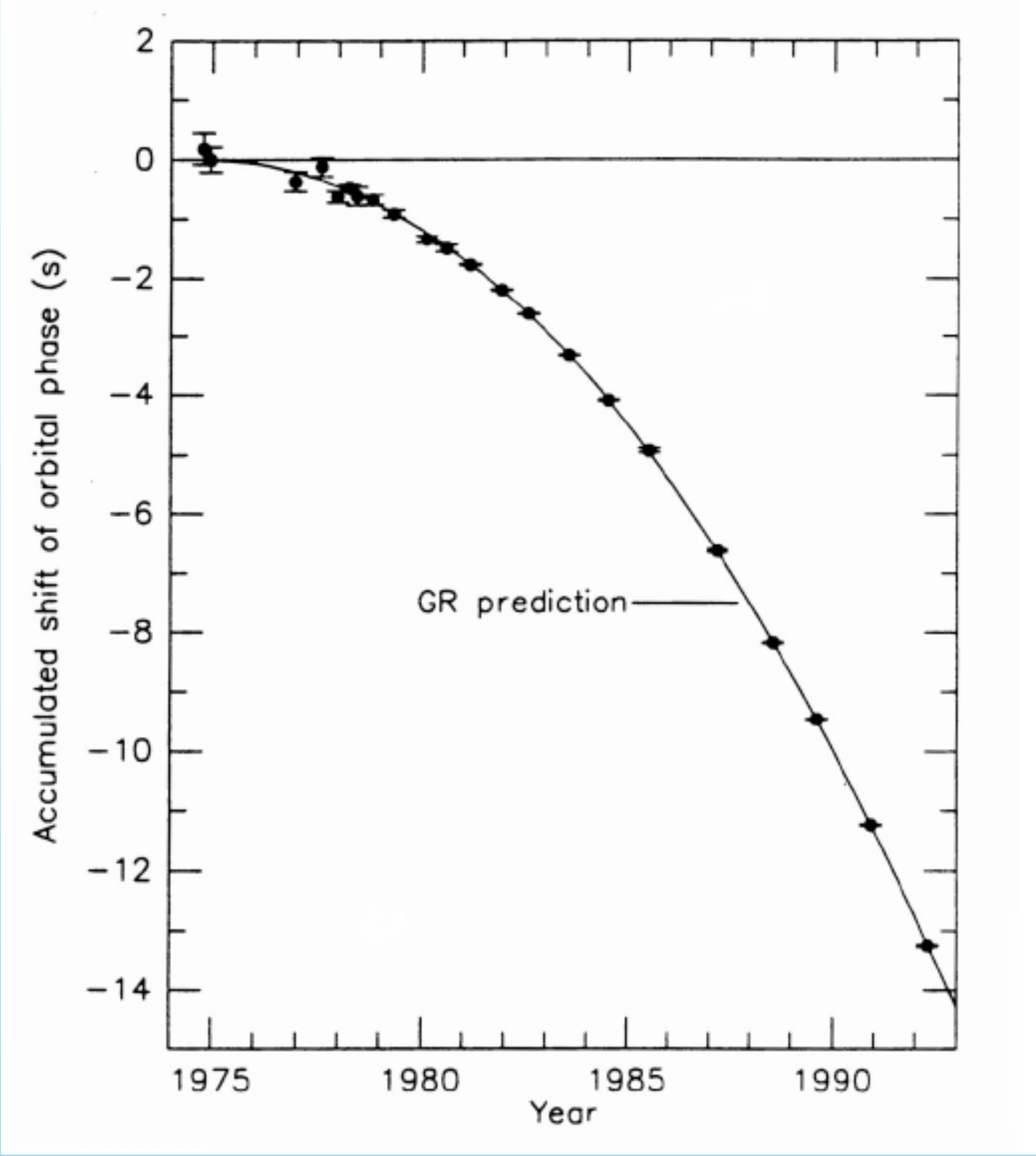
$f_{gw} \sim 1/m$

Indirect Proof of GWS

Hulse-Taylor Binary Pulsar

dP/dt = GR prediction

Other systems now known, including one who's orbit has decayed more in the last 2.5 years that the HT pulsar has in the last 30



Ground-based GW detectors

The Detection of GWs

- Detection is based on the use of laser interferometers

- Atom interferometers are a future possibility

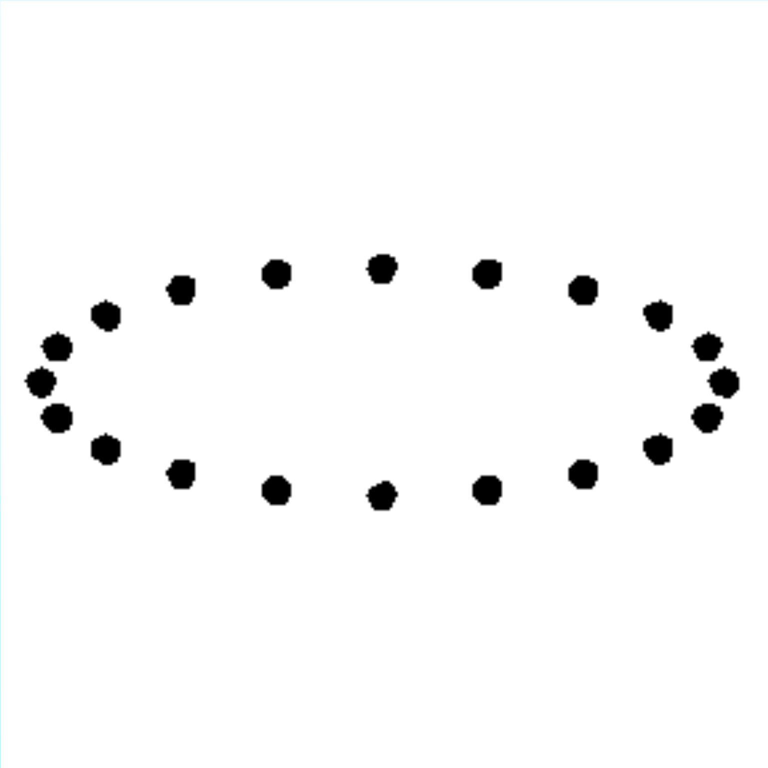
- While a number of detectors can form a network akin to long baseline interferometry, they are not true telescopes!

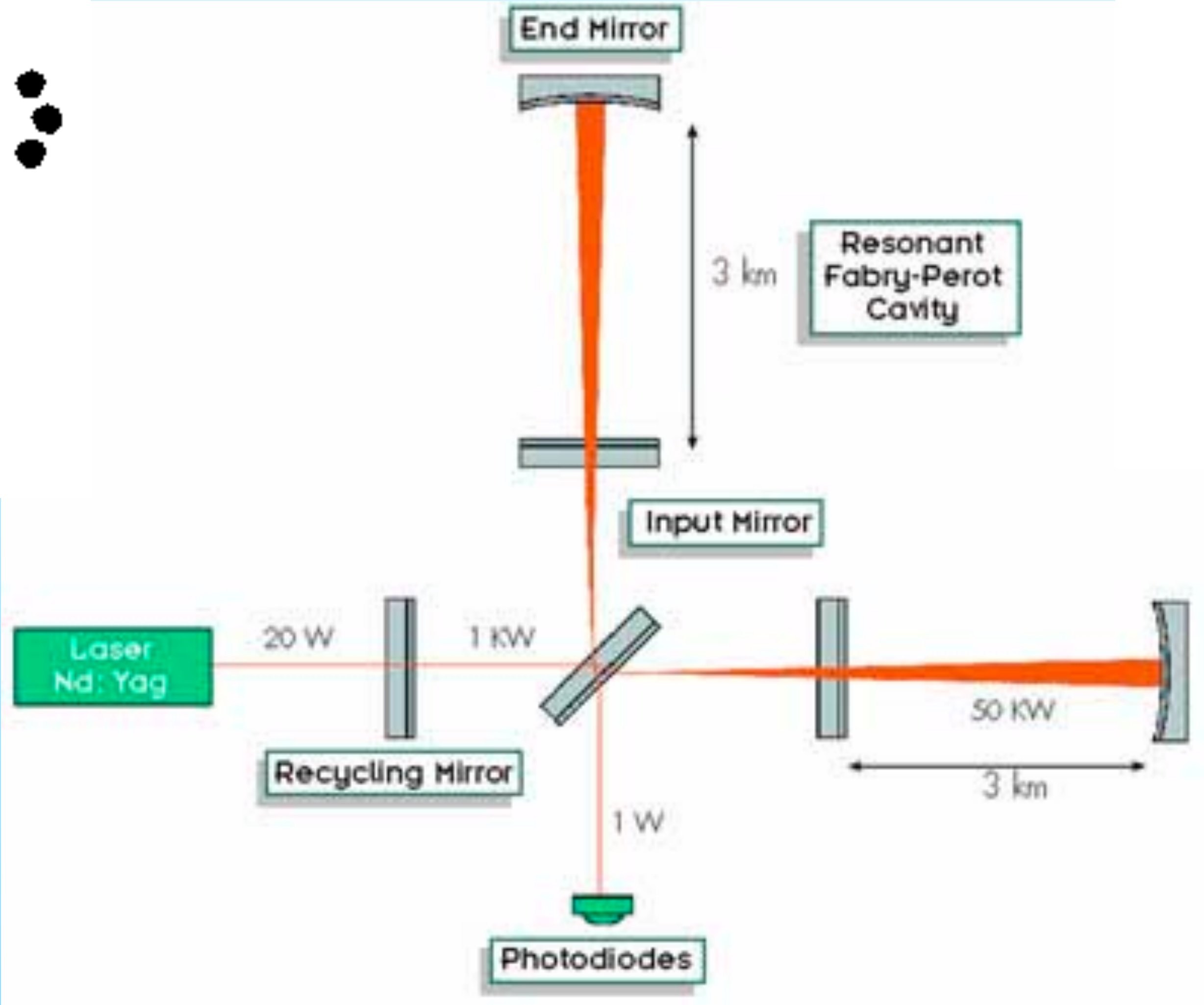
- GW detectors are complimentary to EM telescopes

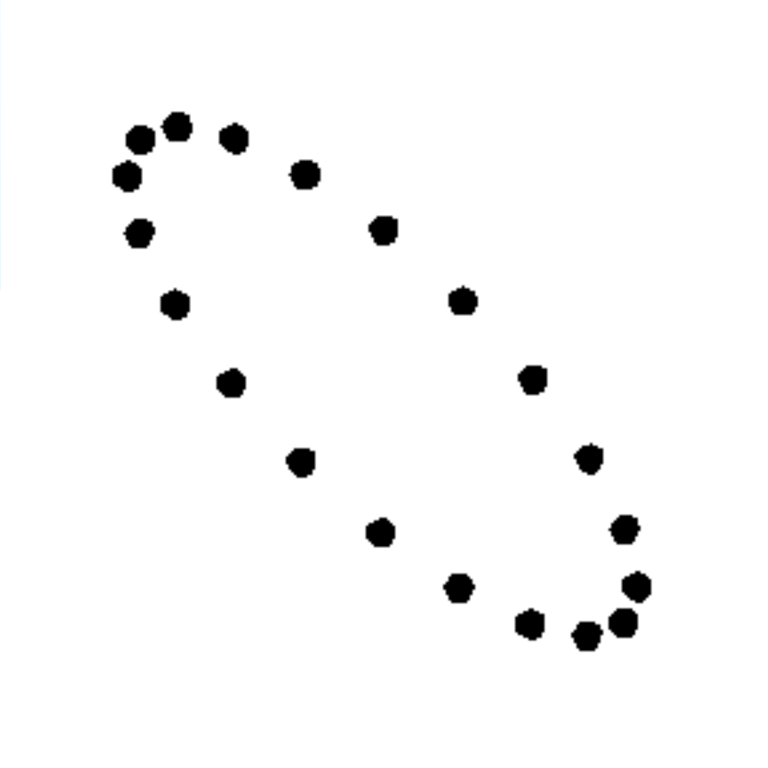
- EM telescopes do well on sky location and distance, but bad on masses, inclination etc.

- GW detectors do well on masses, inclination etc., but bad on sky location and distance.

The Detection of GWs







The Detection of GWs

- So, how large do detectors need to be?

- Ground based : $$L \sim \frac{\Delta L}{h} \sim \frac{10^{-18}}{10^{-21}} \sim 10^3 m$$

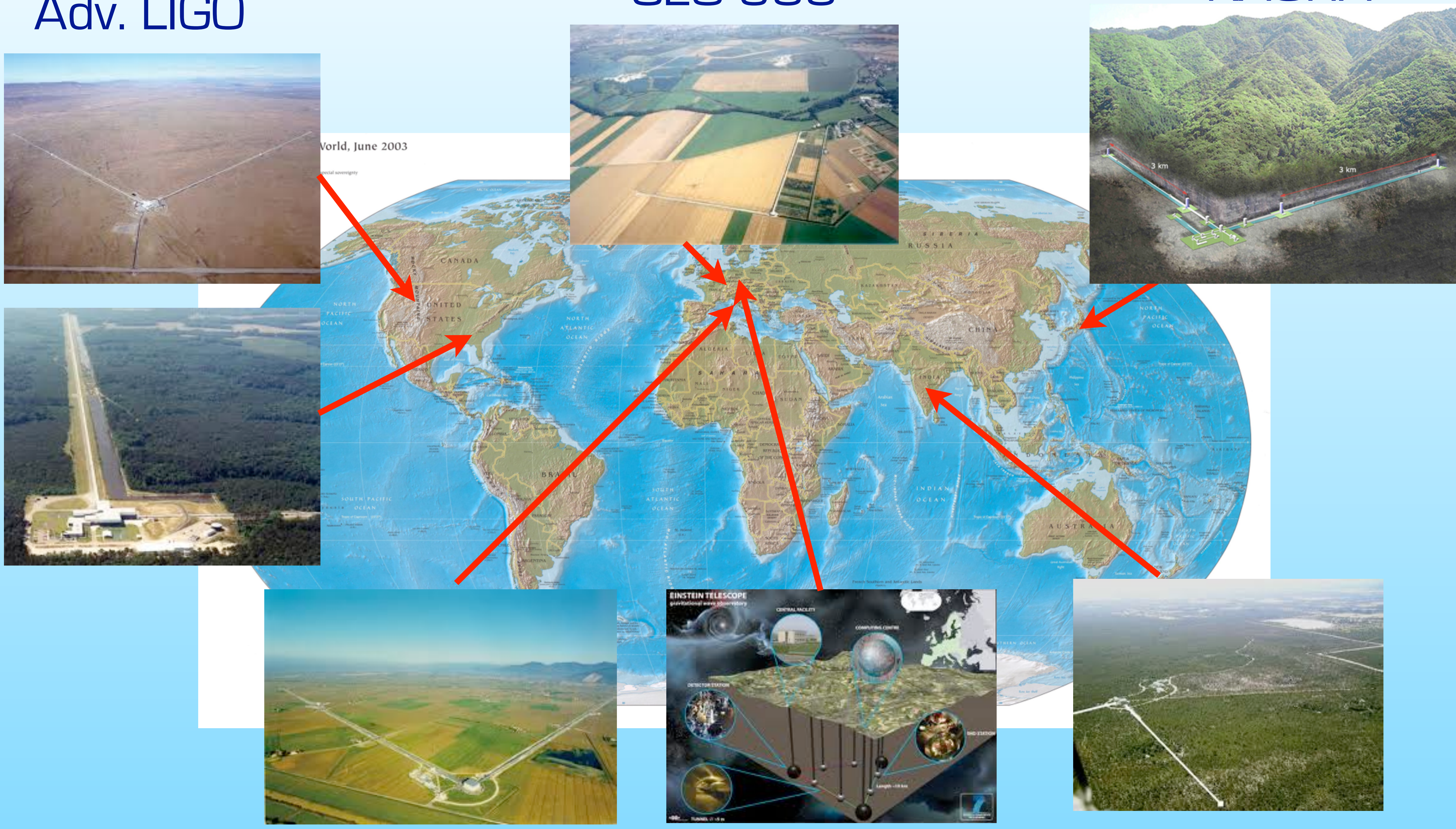
- Space based : $$L \sim \frac{10^{-12}}{10^{-21}} \sim 10^9 m$$

Detector Network

Adv. LIGO

GEO 600

KAGRA



Adv. VIRGO

ET

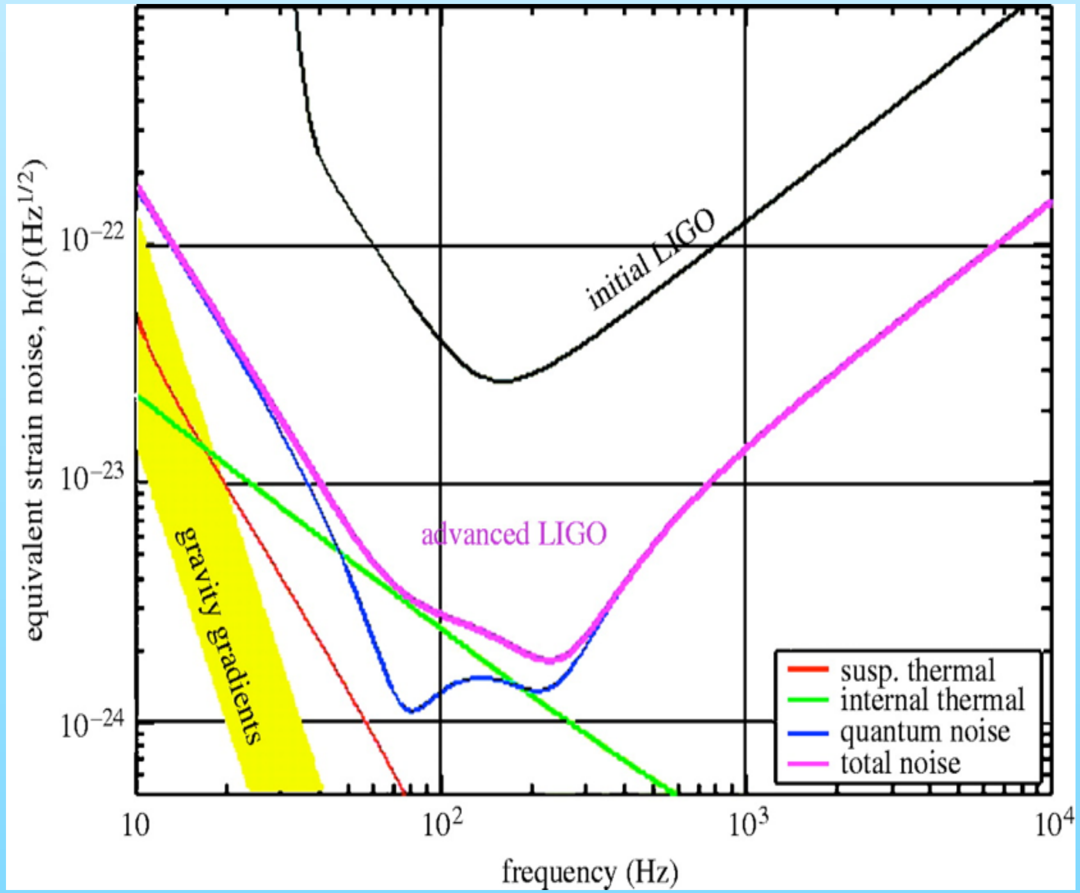
LIGO India

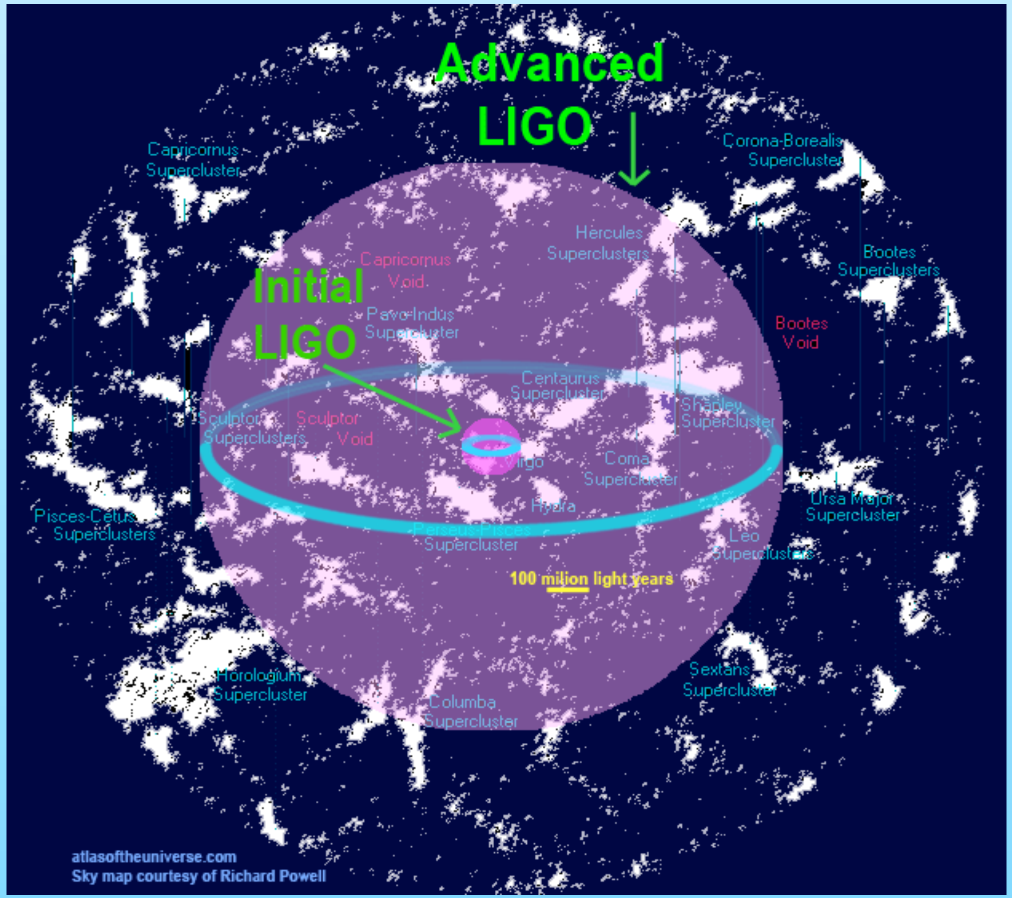
2-Gen Detectors

- Both LIGOs and Virgo have undergone significant improvement
- In September 2015, Advanced LIGO began its first observation run (O1)
- Advanced Virgo is due to come online in 2016
- First joint detector run scheduled for second half of 2016 (O2)

Advanced LIGO

- 4x sensitivity to initial LIGO
- Design sensitivity expected in 2019
- Current detection horizon is 2.5 Gpc





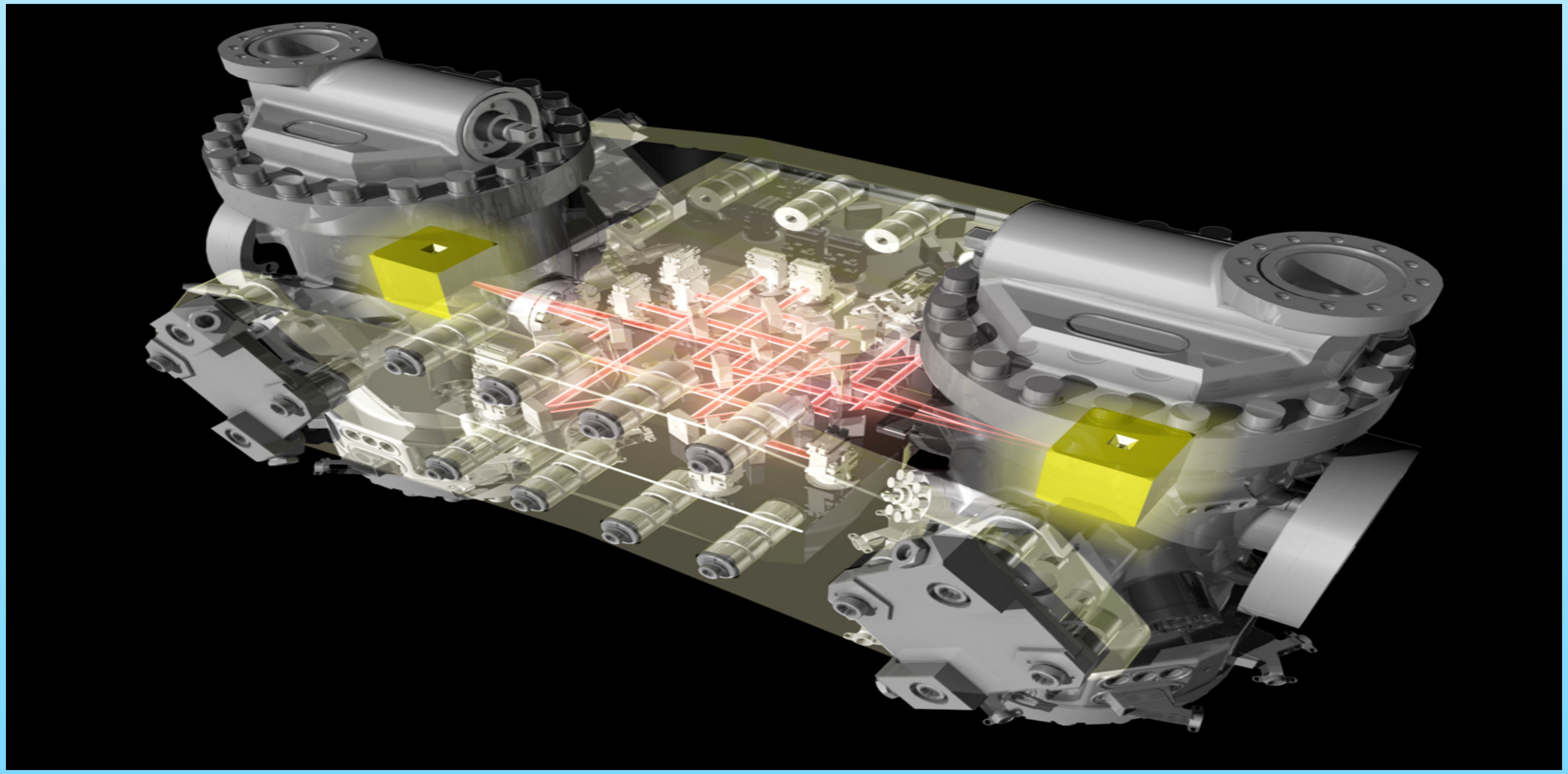
The Rumour!

- O1 began in September 2015, and finished Jan. 12 2016.
- Big data problem
- Noise transients ("glitches") can mimic GW signals
- Any "event" must be visible in both Adv. LIGO detectors
- Also a number of blind injections
- There are a number of interesting events, but the analysis is still in progress!

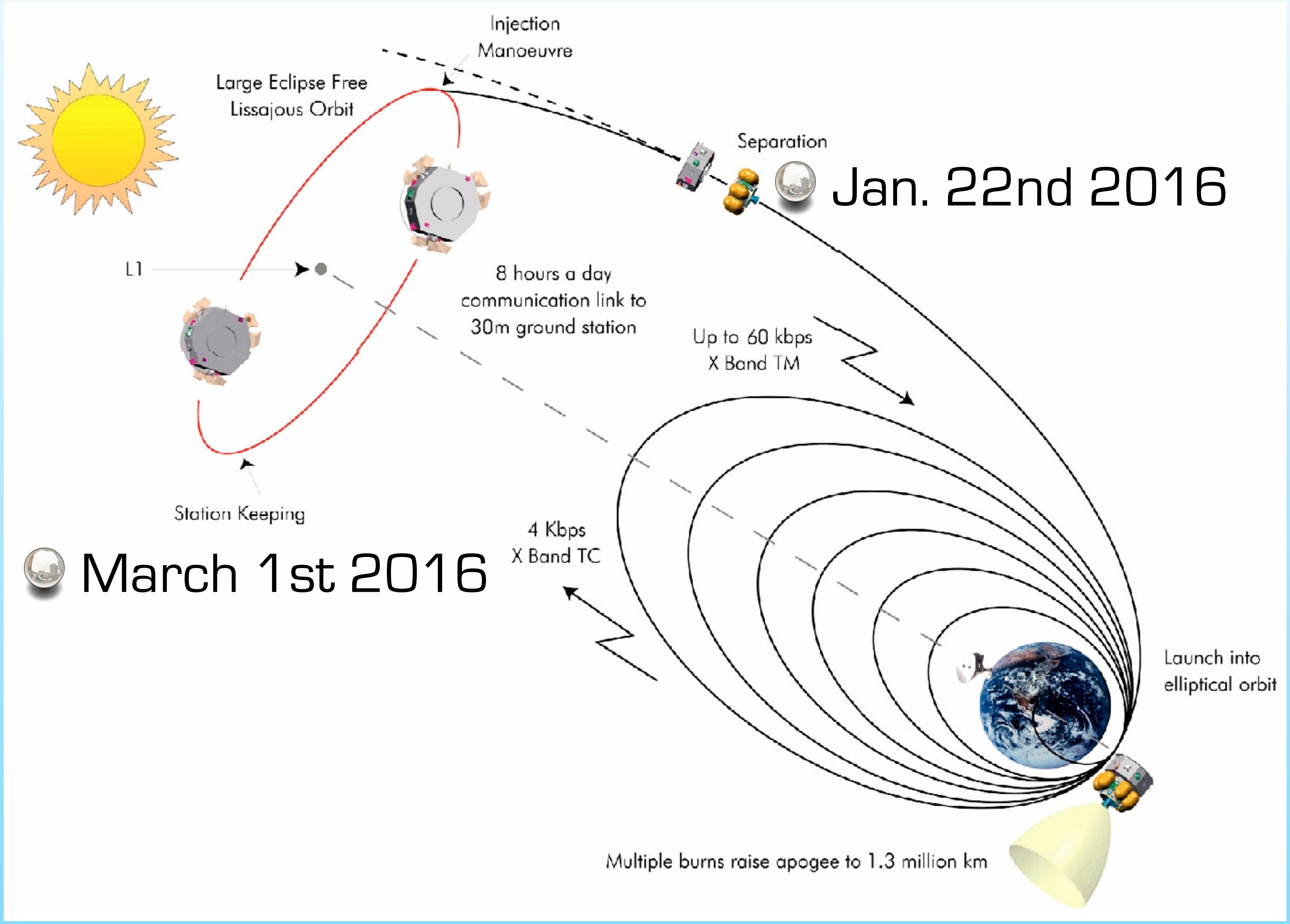
LISA Pathfinder

LISA Pathfinder

- Technology demonstration mission for a future GW detector
- Shrinks the million km arms of eLISA to 40cm
- Objective is to measure deviations from geodesic motion
- Will test drag-free control of the spacecraft, precision inteferometry on a desired scale and longevity of components



LISA Pathfinder



- Jan. 22nd 2016
- March 1st 2016
- Launched on Dec. 3rd 2015

Current Status

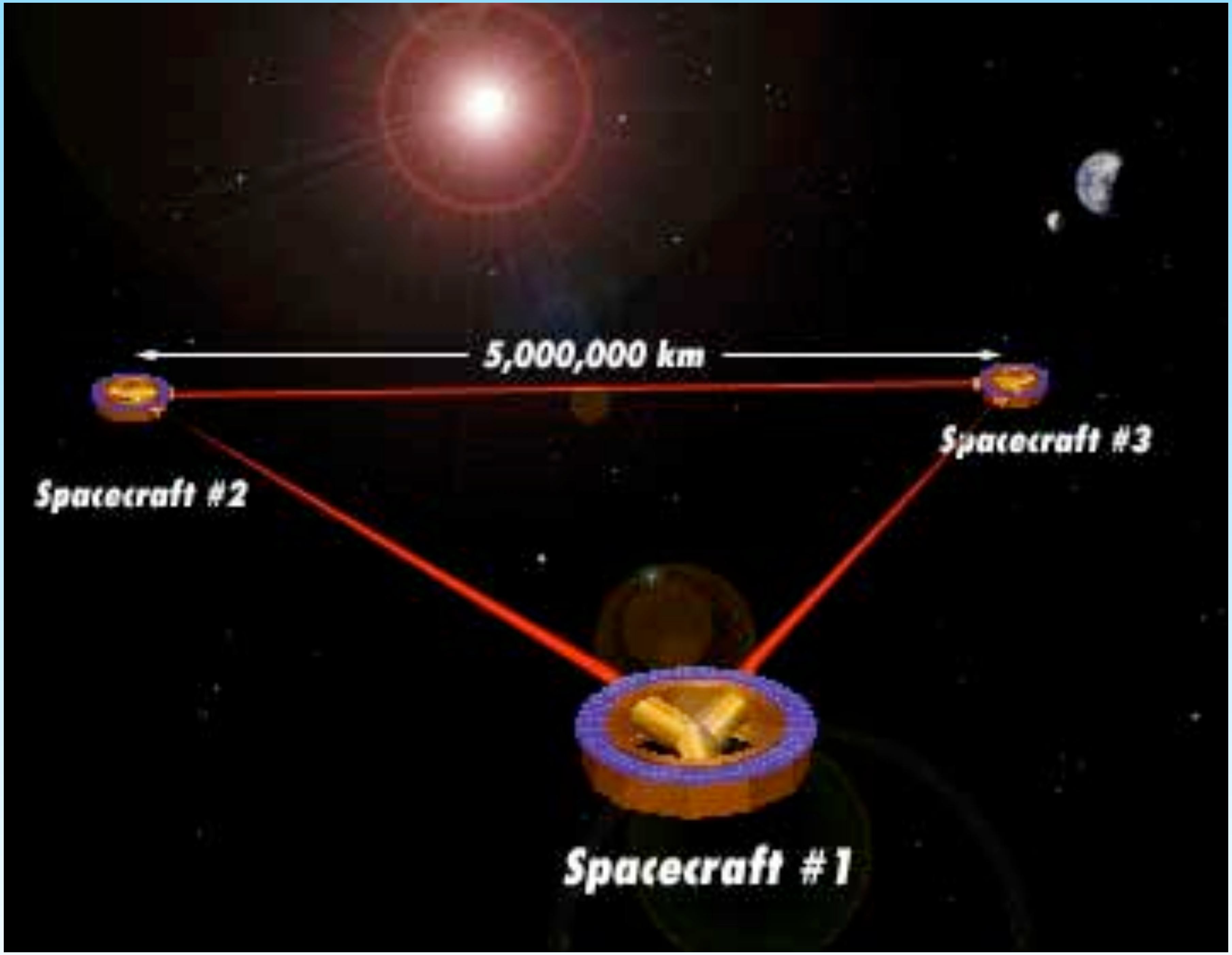
- 12 Jan - commissioning started
- 13 Jan - subsystems incl. laser initiated. Laser stabilisation ongoing
- Separation of propulsion module
- 3 Feb - "fingers" on test mass corners will be retracted
- 15/16 Feb - Test masses will be released from caging mechanism
- 16 Feb to 1 March - electrostatic actuation of test masses
- 1 March - free-fall achieved

eLISA

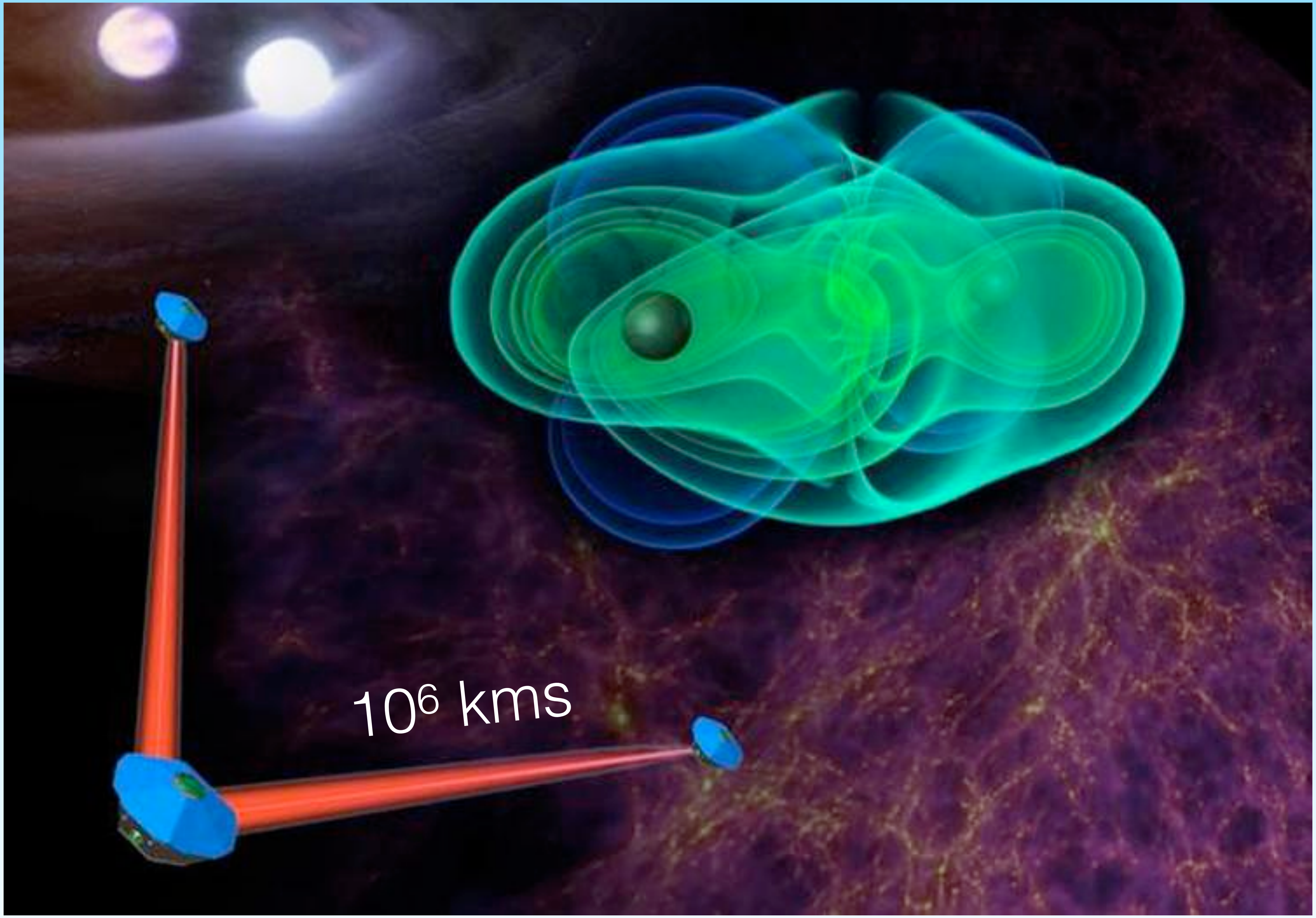
eLISA

- Mission concept currently proposed within the ESA Cosmic Vision L3 program under the theme "The Gravitational Wave Universe"
- Estimated launch date is 2034
- Mission configuration expected to be fixed by 2020

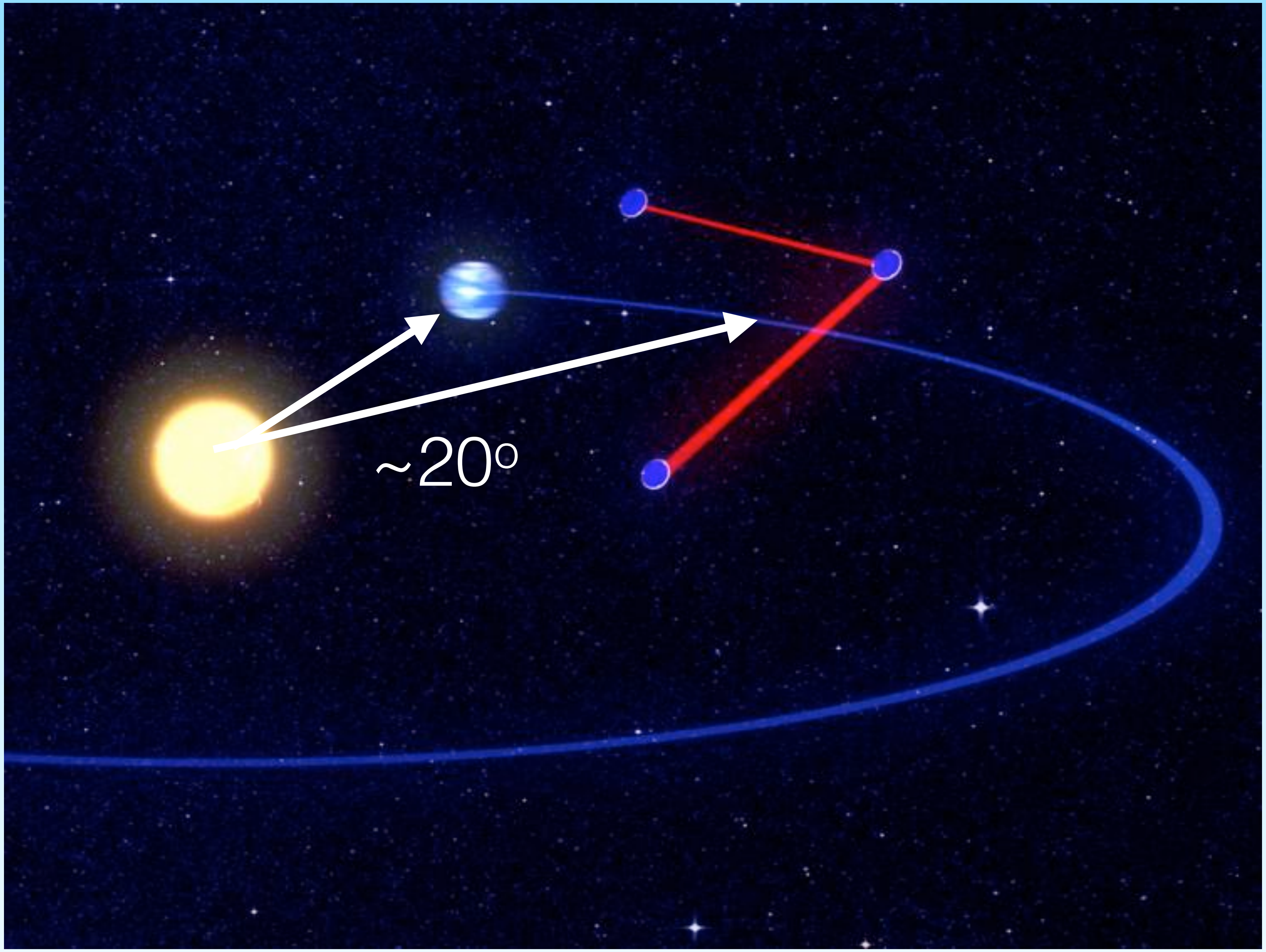
LISA to eLISA



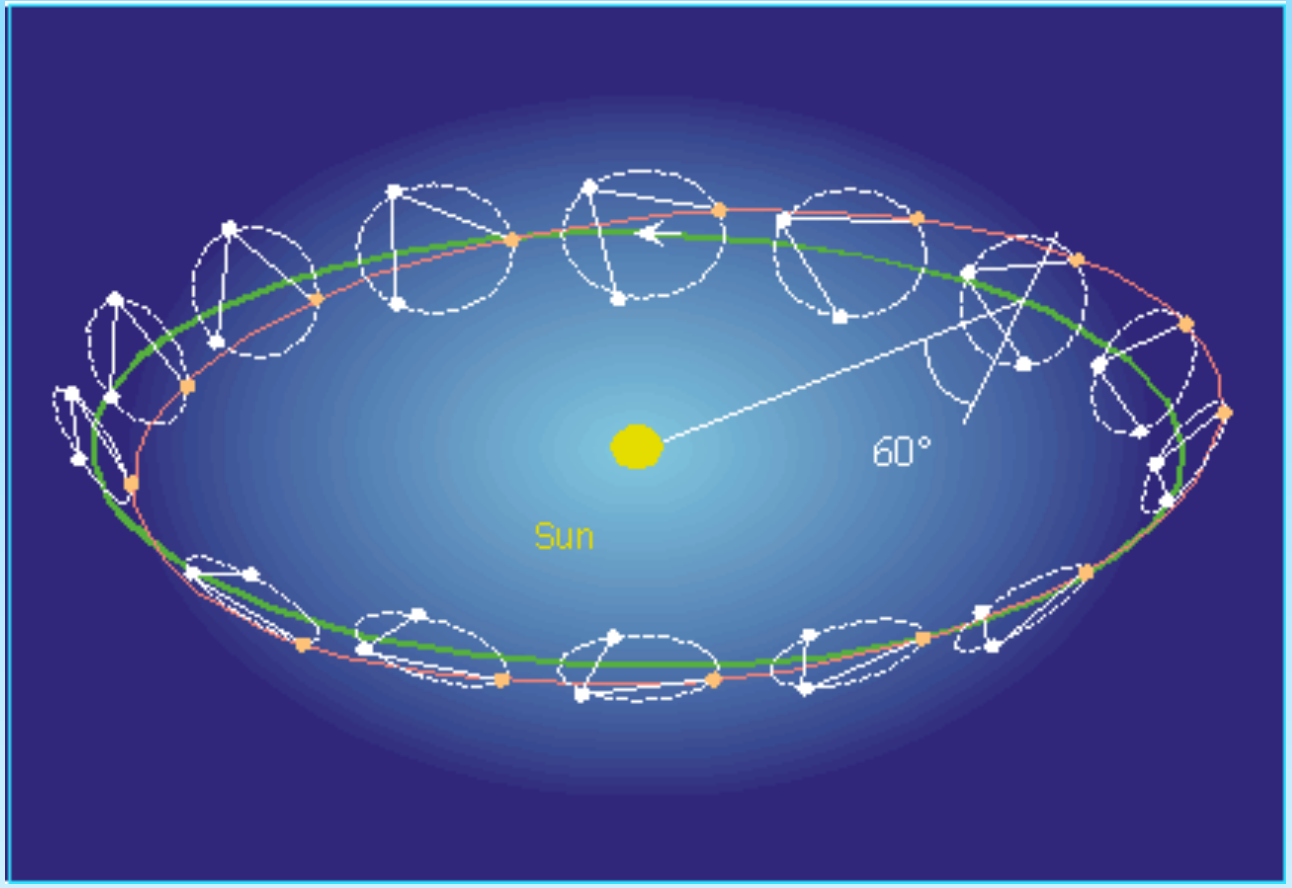
LISA to eLISA



LISA to eLISA

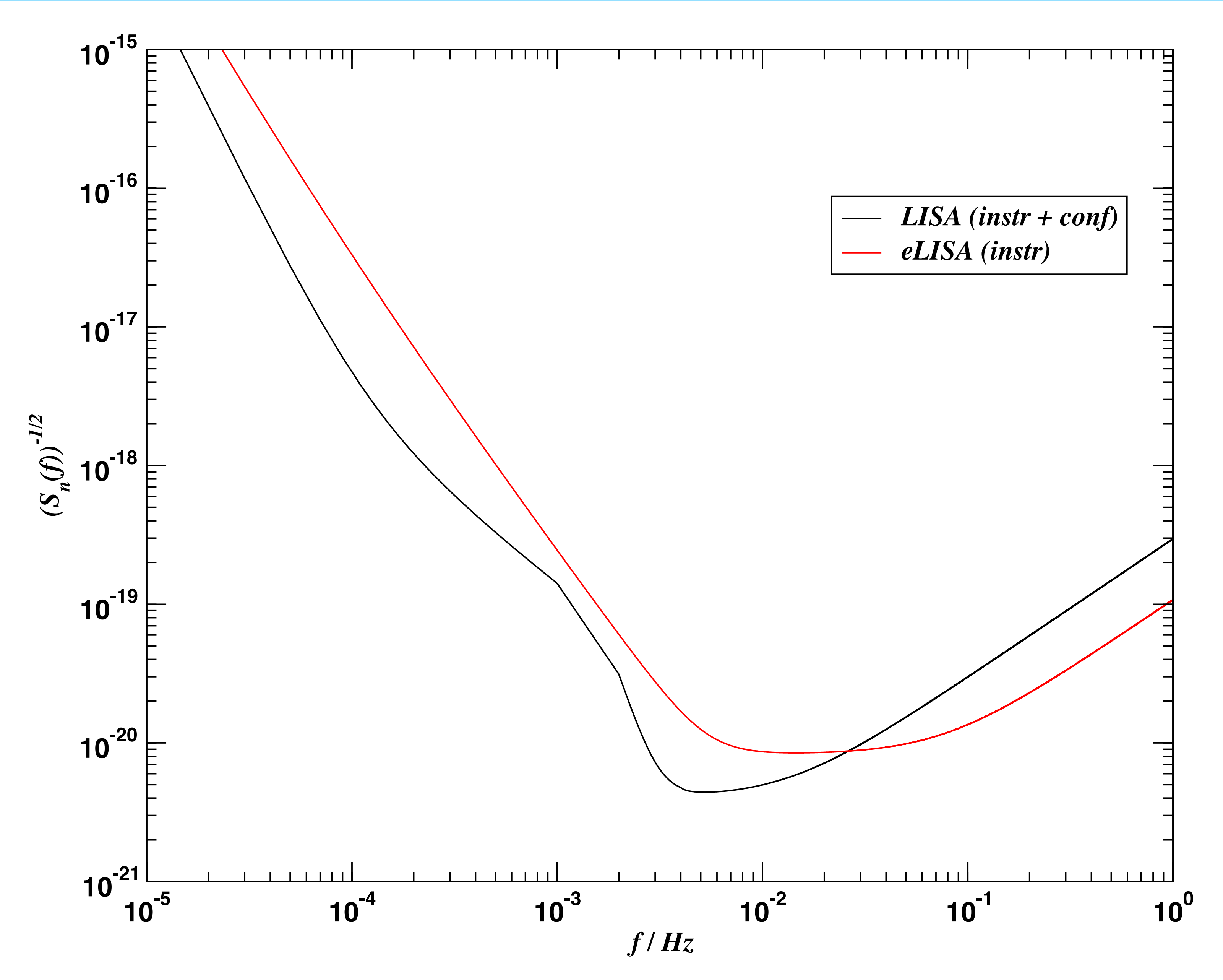


LISA to eLISA

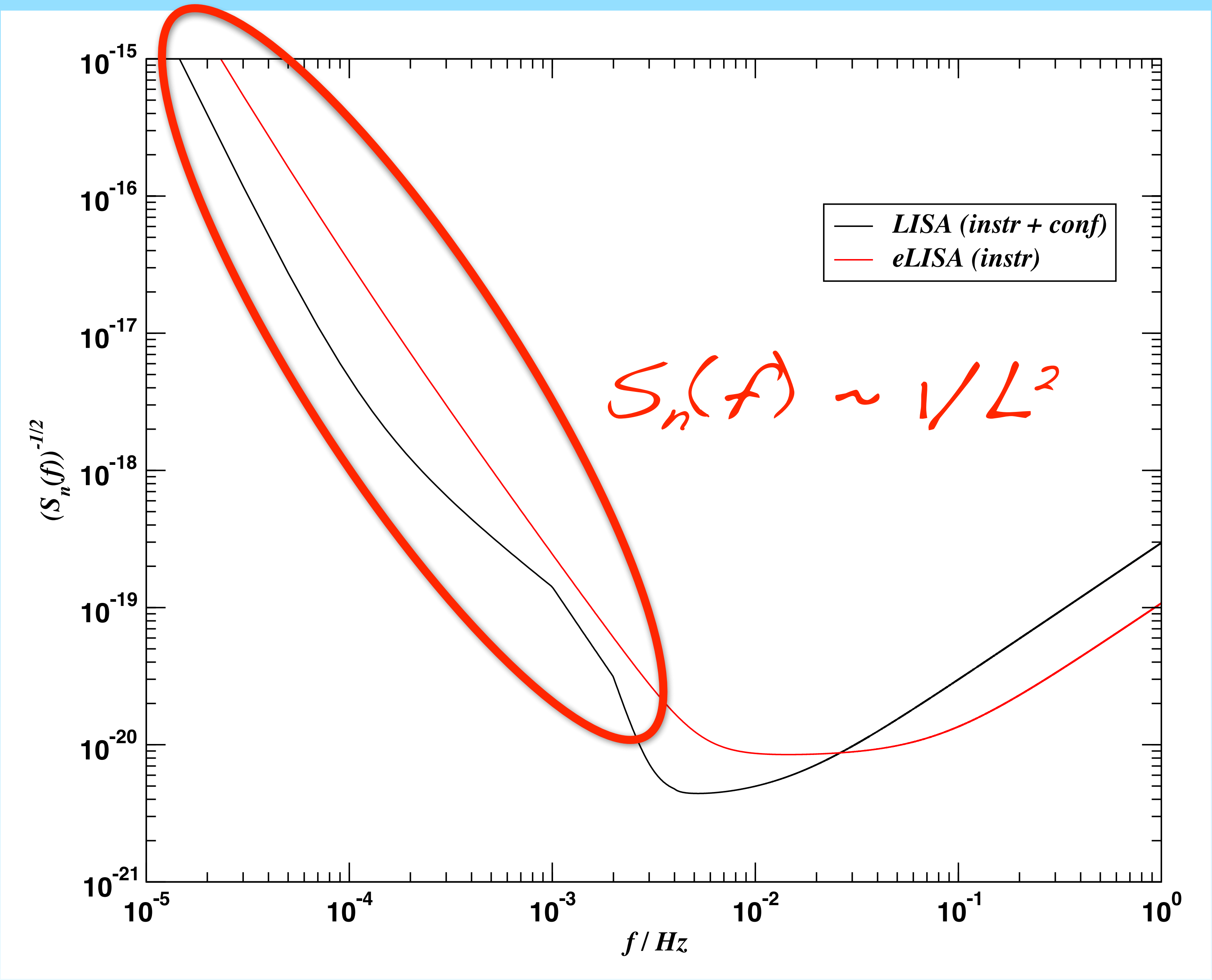


- Space-craft travel on ballistic orbits
- Induces a Doppler motion which is important for sky position resolution

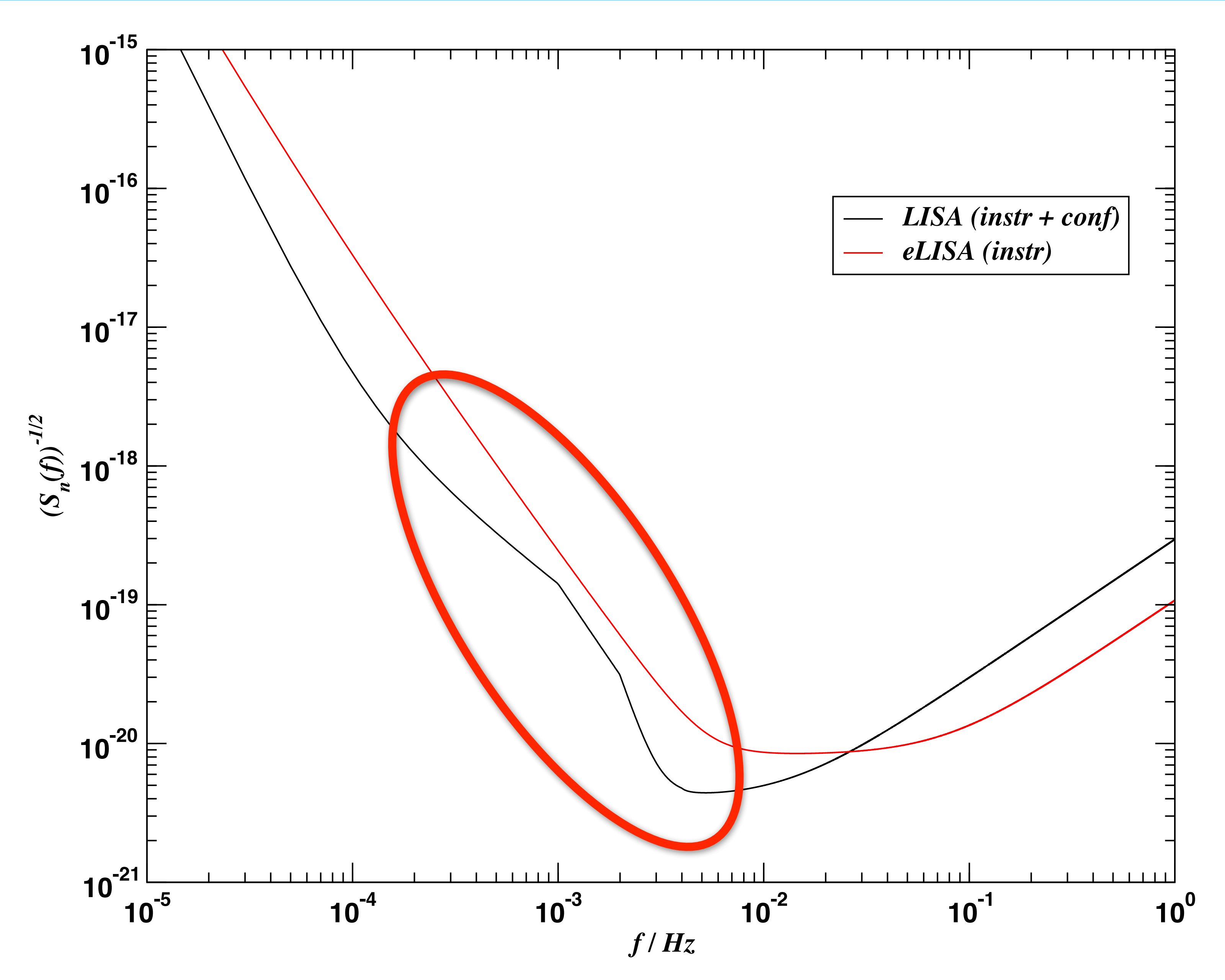
LISA to eLISA



LISA to eLISA

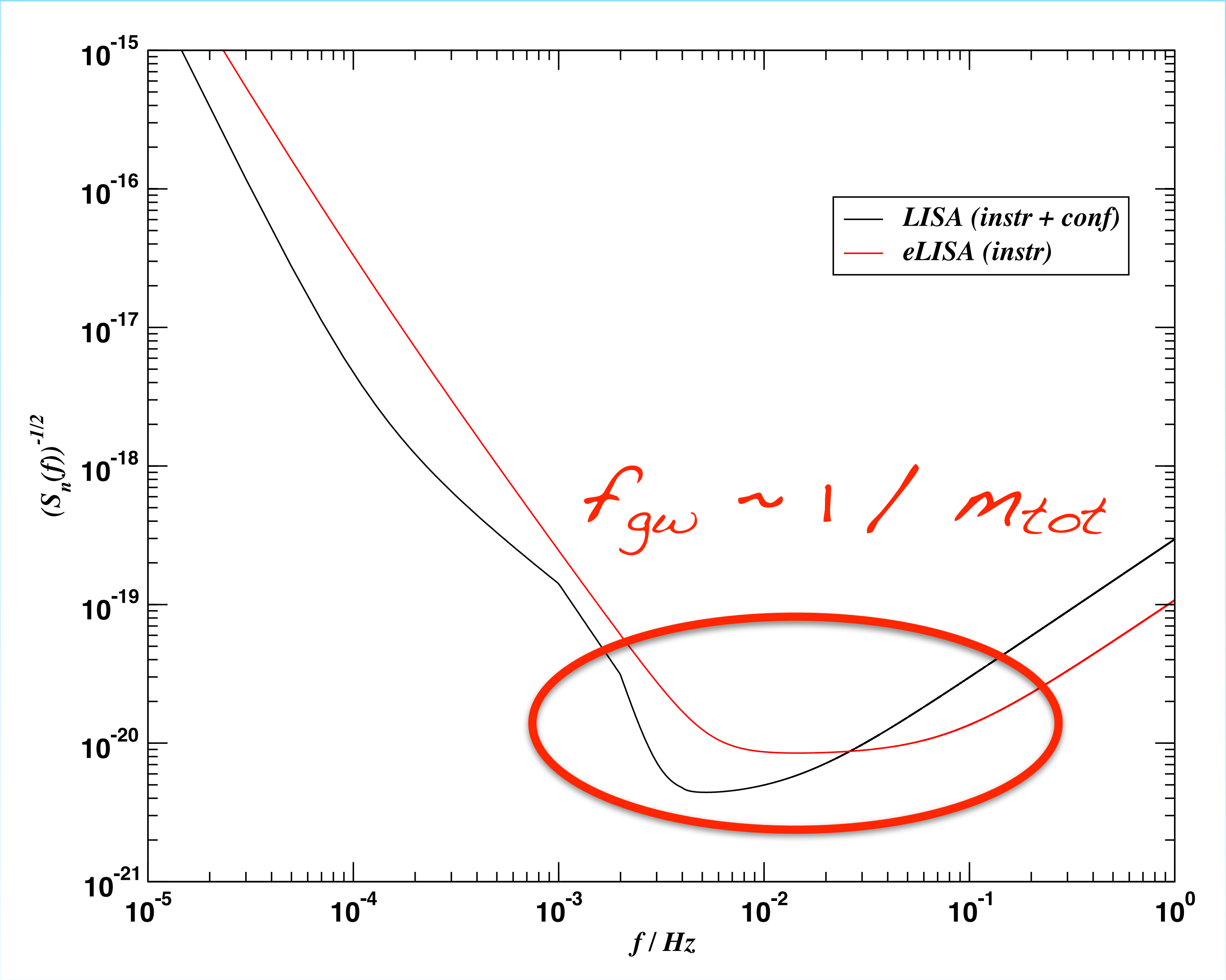


LISA to eLISA

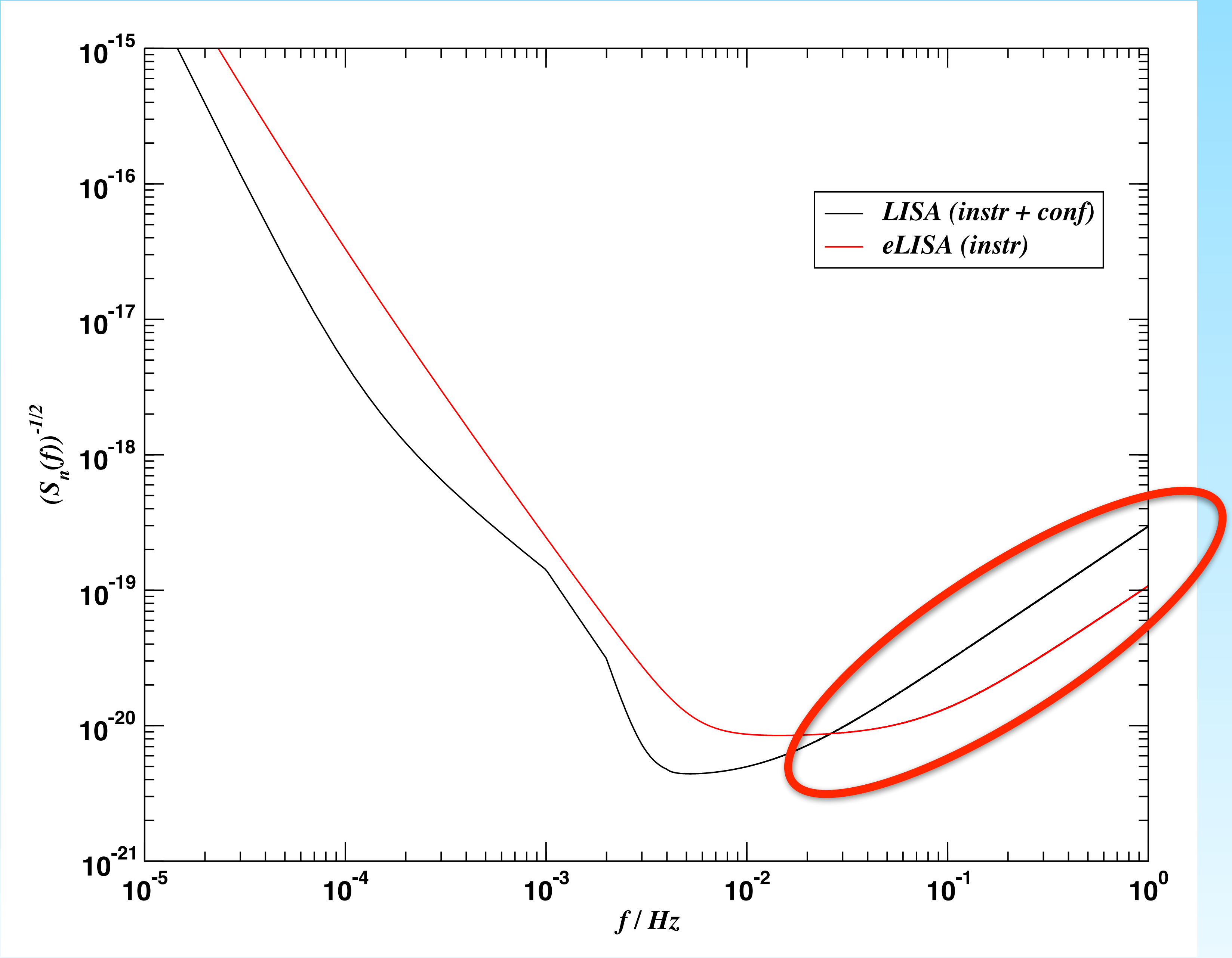


Galactic confusion suppressed!

LISA to eLISA



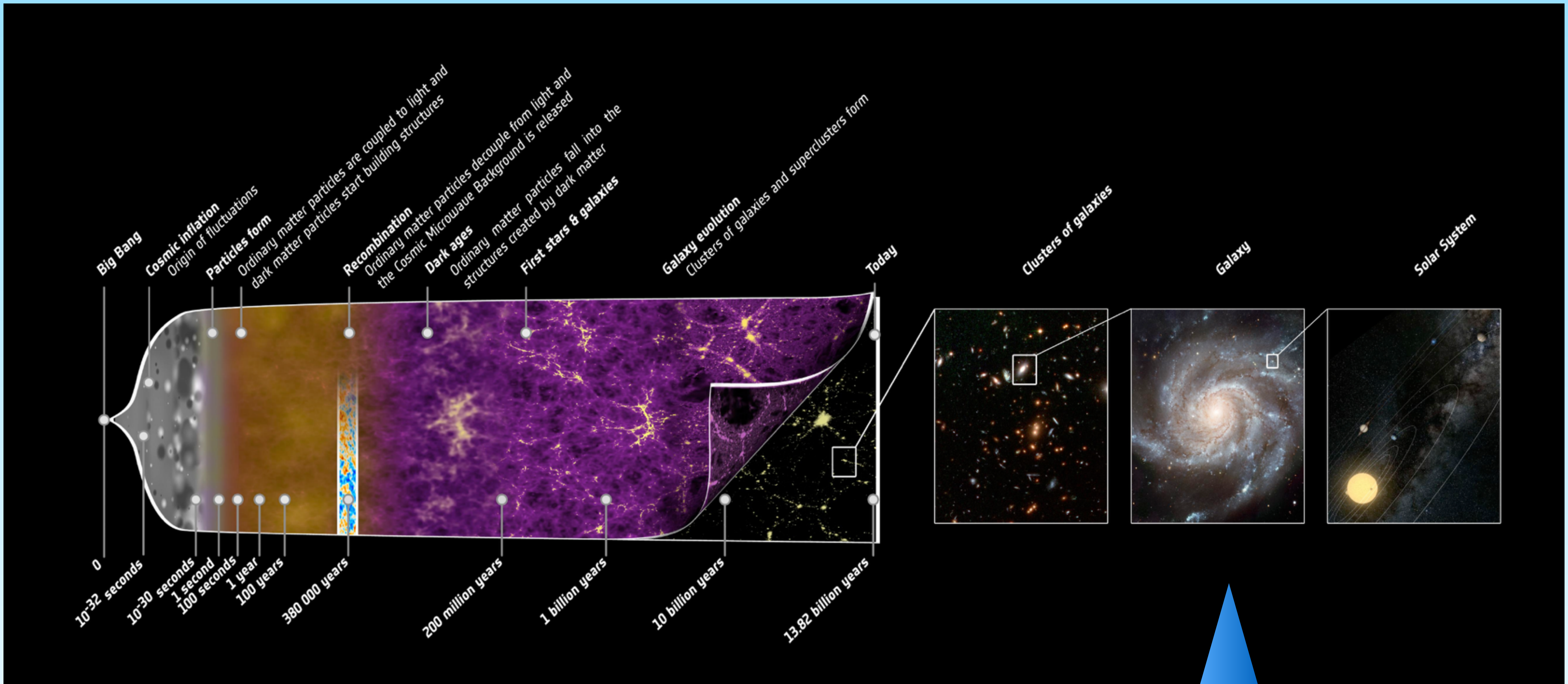
LISA to eLISA



photon shot noise reduced due to smaller L

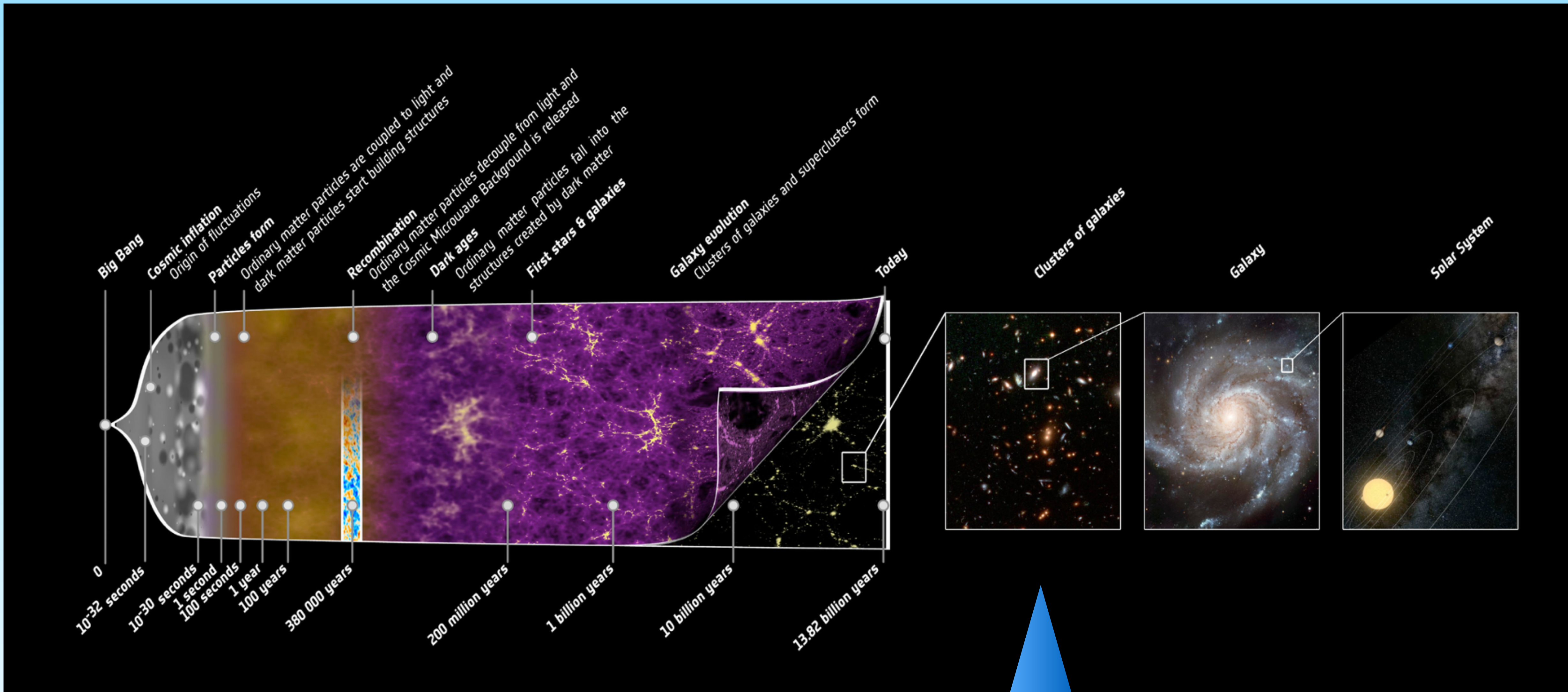
GW Sources for eLISA

eLISA Sources



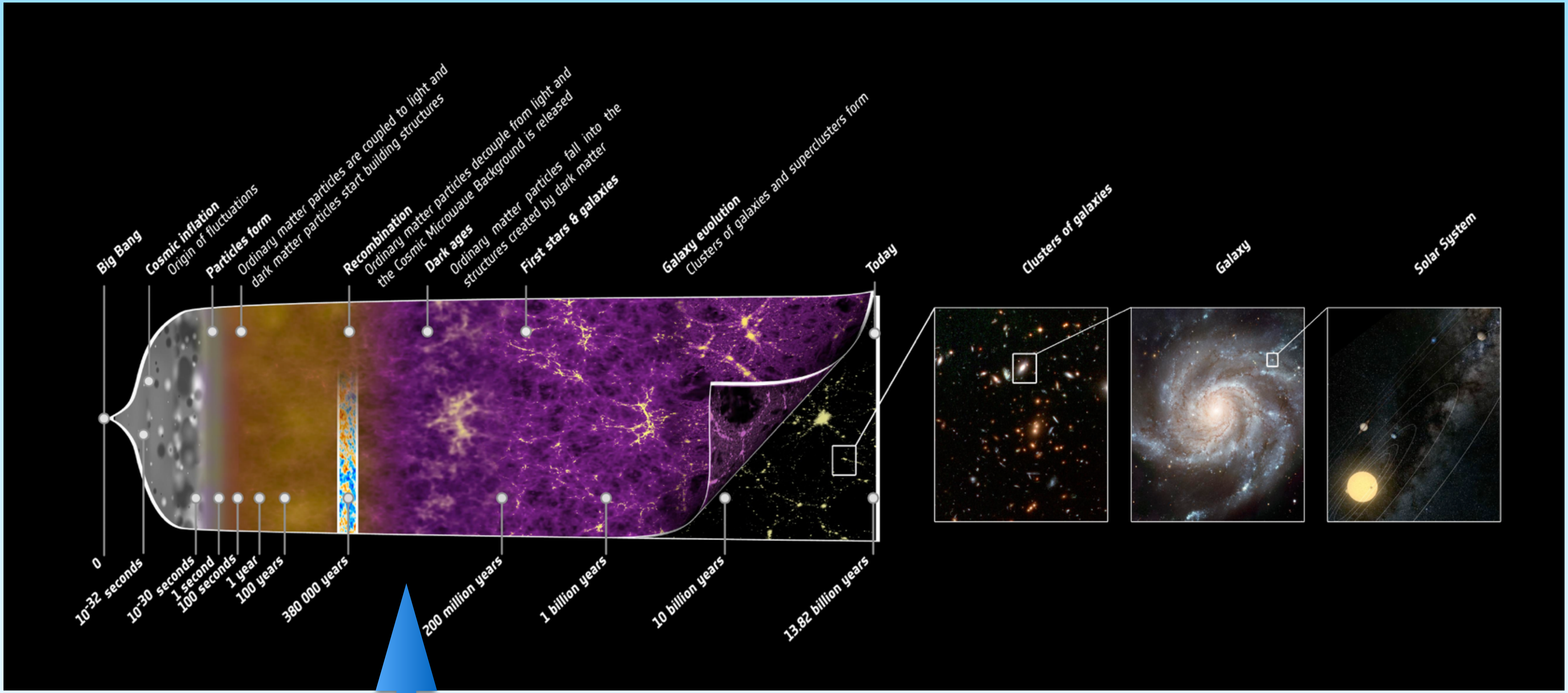
Compact galactic binaries

eLISA Sources



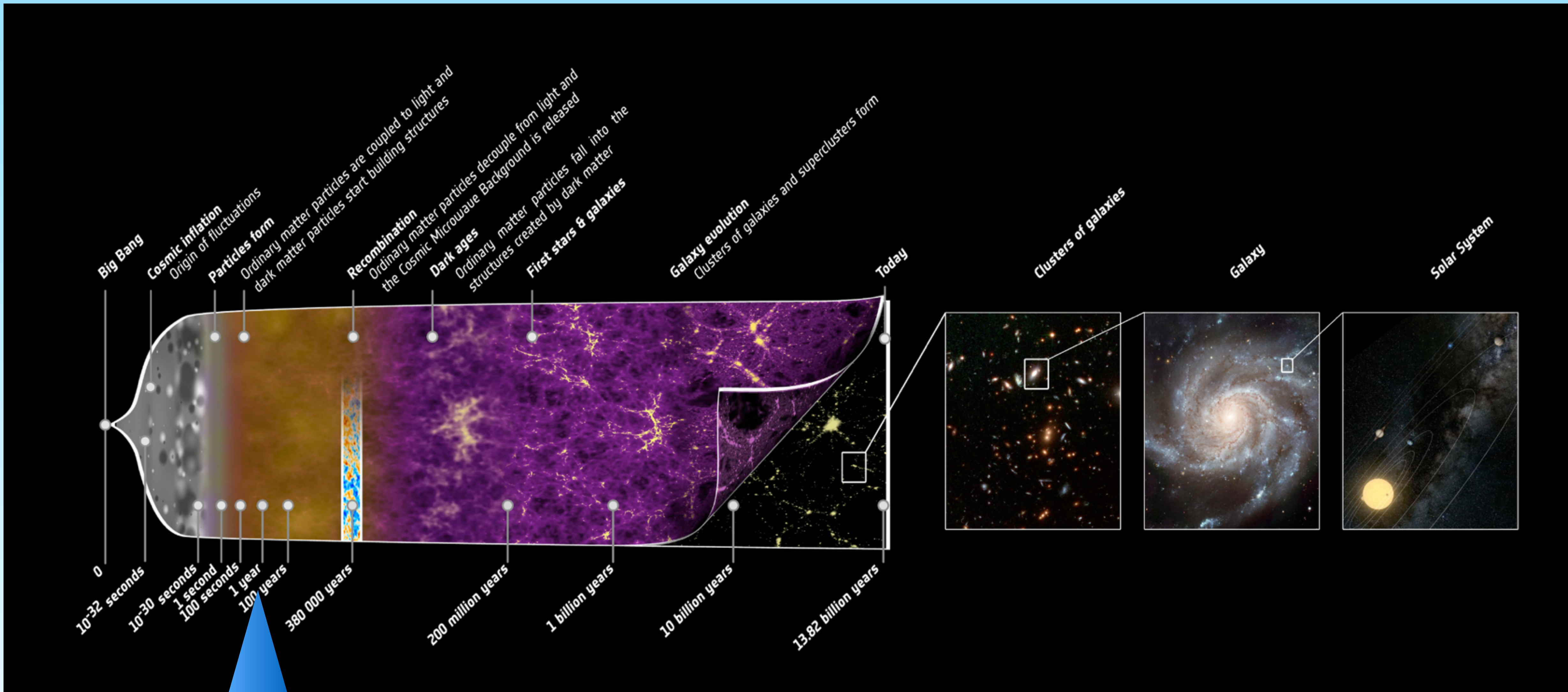
EMRIs

eLISA Sources



SMBHBs

eLISA Sources

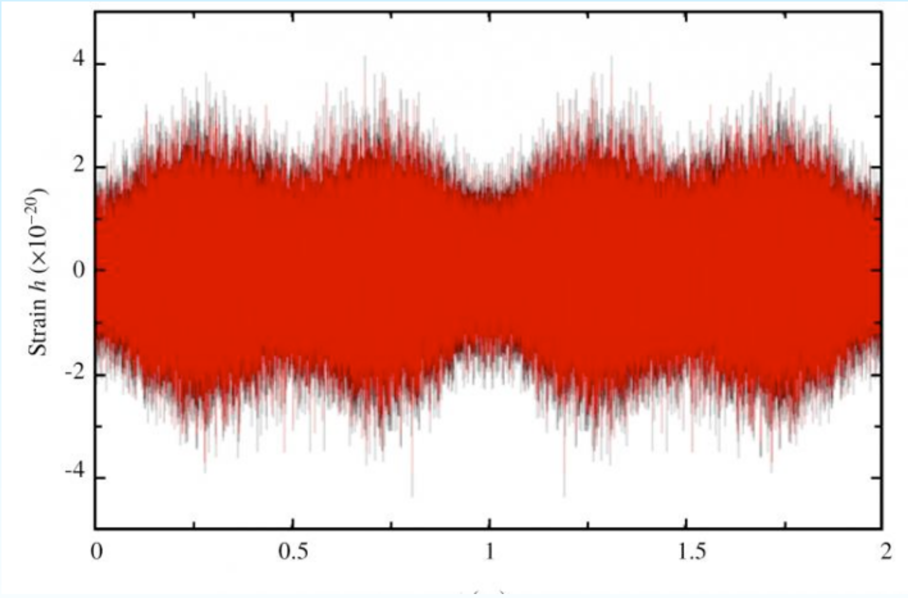


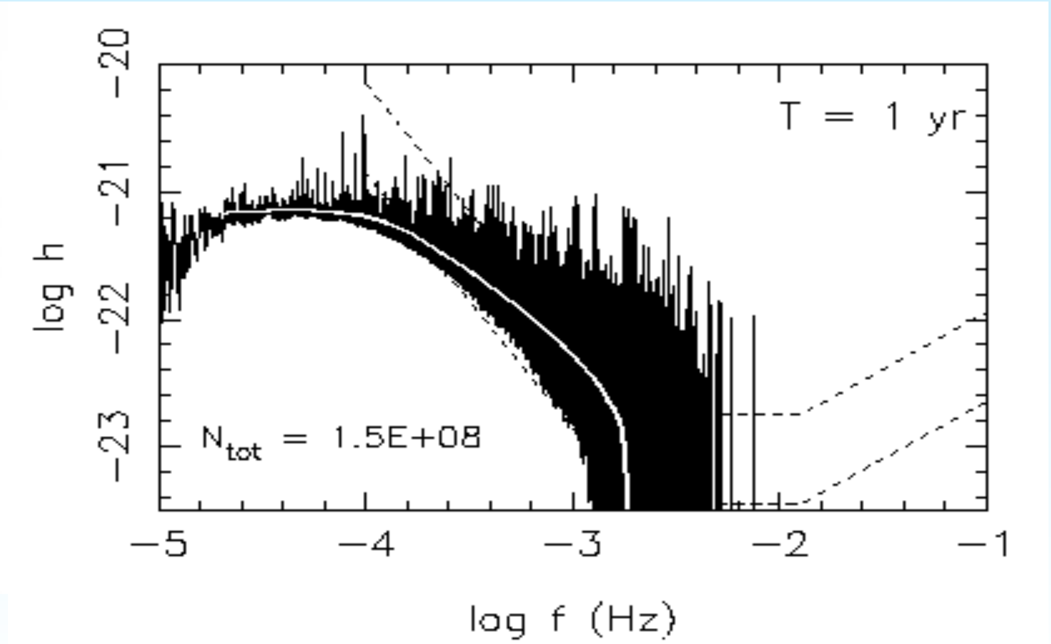
Cosmological

Galactic Binaries

Galactic Binaries

- Estimated 60 million compact binaries in our galaxy and local globular clusters
- Mostly white dwarf binaries, but also systems composed of neutron stars and stellar mass black holes
- eLISA should allow us to resolve ~4000 binaries in the first two years, +1000 binaries per each successive year





Verification Binaries

- Unlike ground-based detectors, we have guaranteed sources, i.e. the verification binaries
- A non detection of the VBs would suggest a serious problem with our understanding of GW propagation
- Projects such as GAIA, PanSTARRS,LSST, SKA, etc. should increase this number before eLISA launches

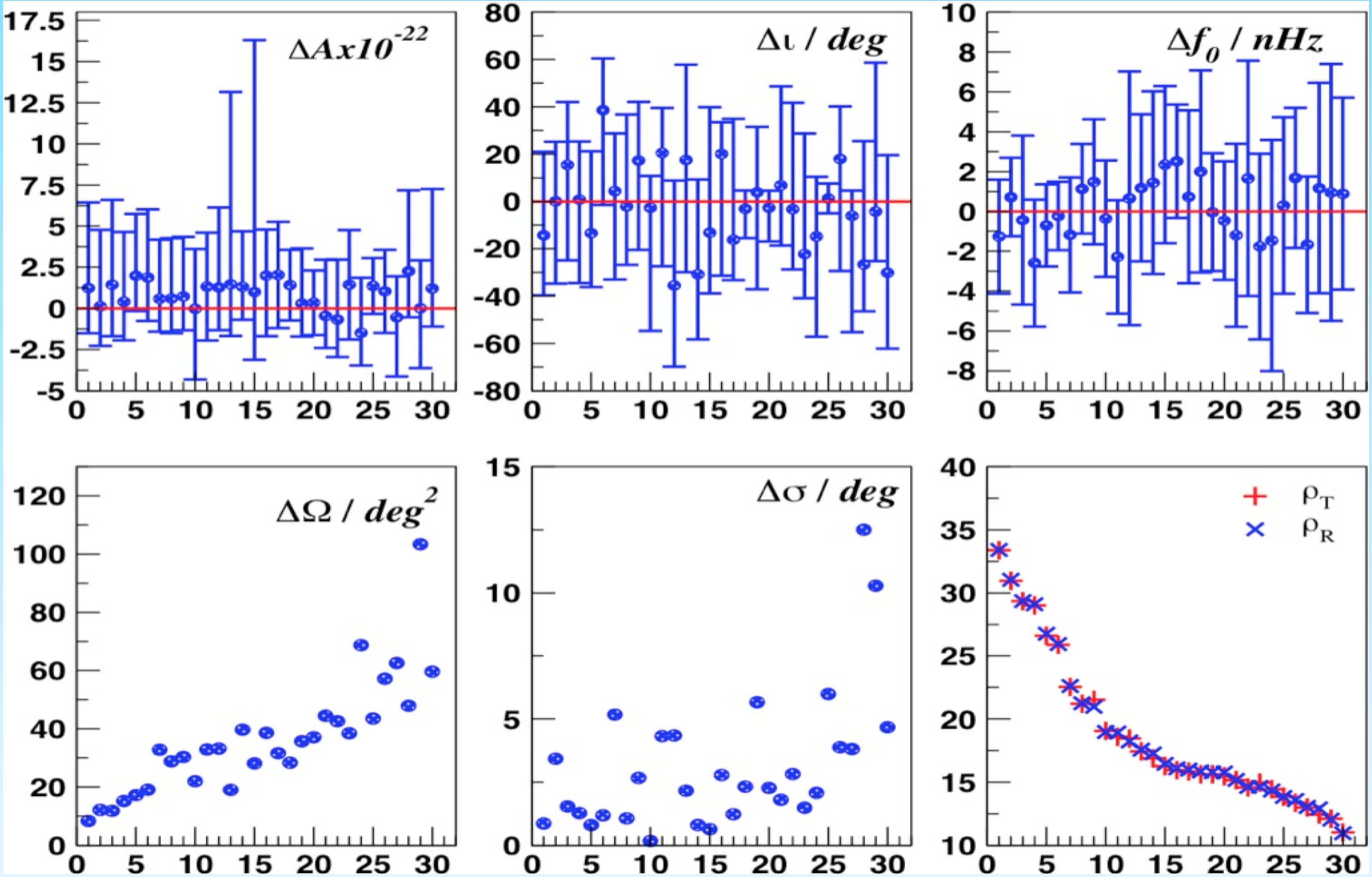
RX J0806.3+1527
V407 Vul
ES Cet
AM CVn
HP Lib
CR Boo
KL Dra
V803 Cen
SDSS J0926+3624
CP Eri
2003aw
SDSS J1240-0159
GP Com
CE 315
4U 1820-30
4U 1543-624
4U 1850-087
4U 1626-67
CC Com
WD 0957-666
KPD0422+4521
KPD1930+2752
WD 1101+364
WD 1704+481
WD 2331+290
EI Psc
SDSS J1507+5230
GW Lib
WZ Sge
SDSS J0903+3300

Galactic Binaries

eLISA should measure :

- Distance to between 1-10% for a large number of sources
- df/dt < 10%
- sky position to < 10 deg^2
- Inclination to < 10 deg

Galactic Binaries



Bouffanais & EKP 2015

Galactic Binaries

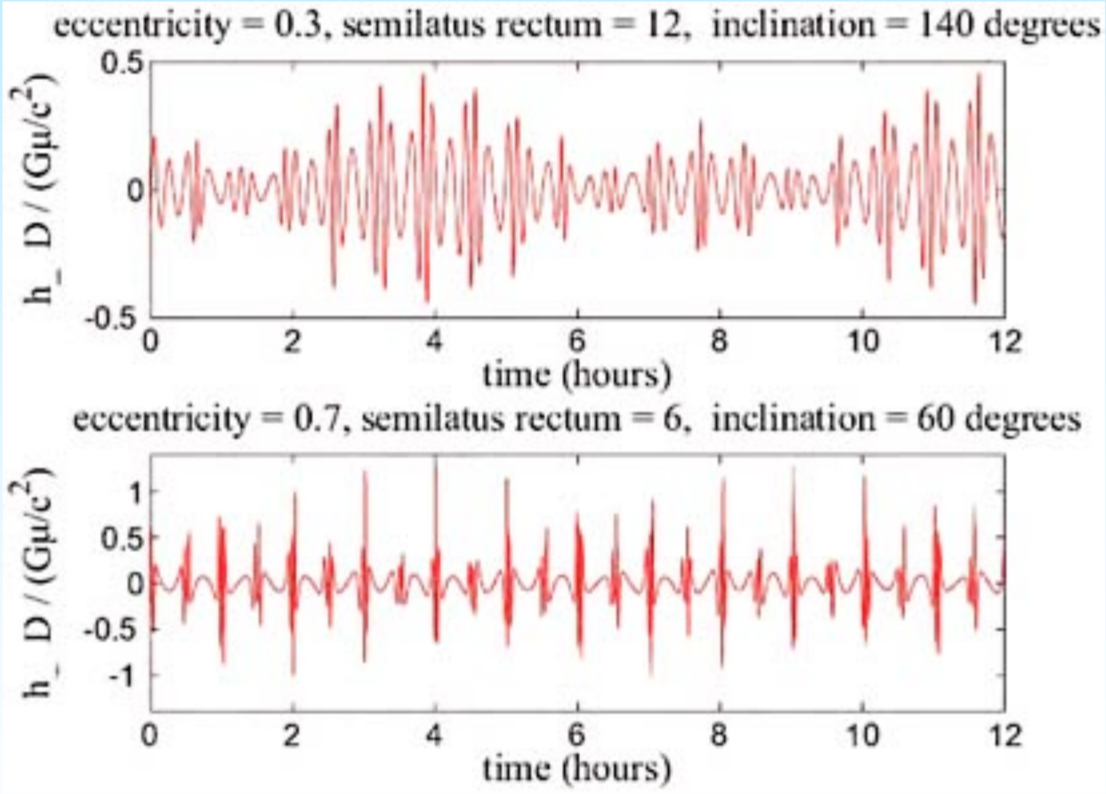
Astrophysical implications:

- Our detections will be dominated by double WDBs
- Will be able to differentiate between UCXBs and WDBs in globular clusters
- Investigate tidal interactions in CBs
- Should be able to constrain the formation rate, and the numbers of NS and stellar mass BH binaries in the galaxy

EMRIs

EMRIs

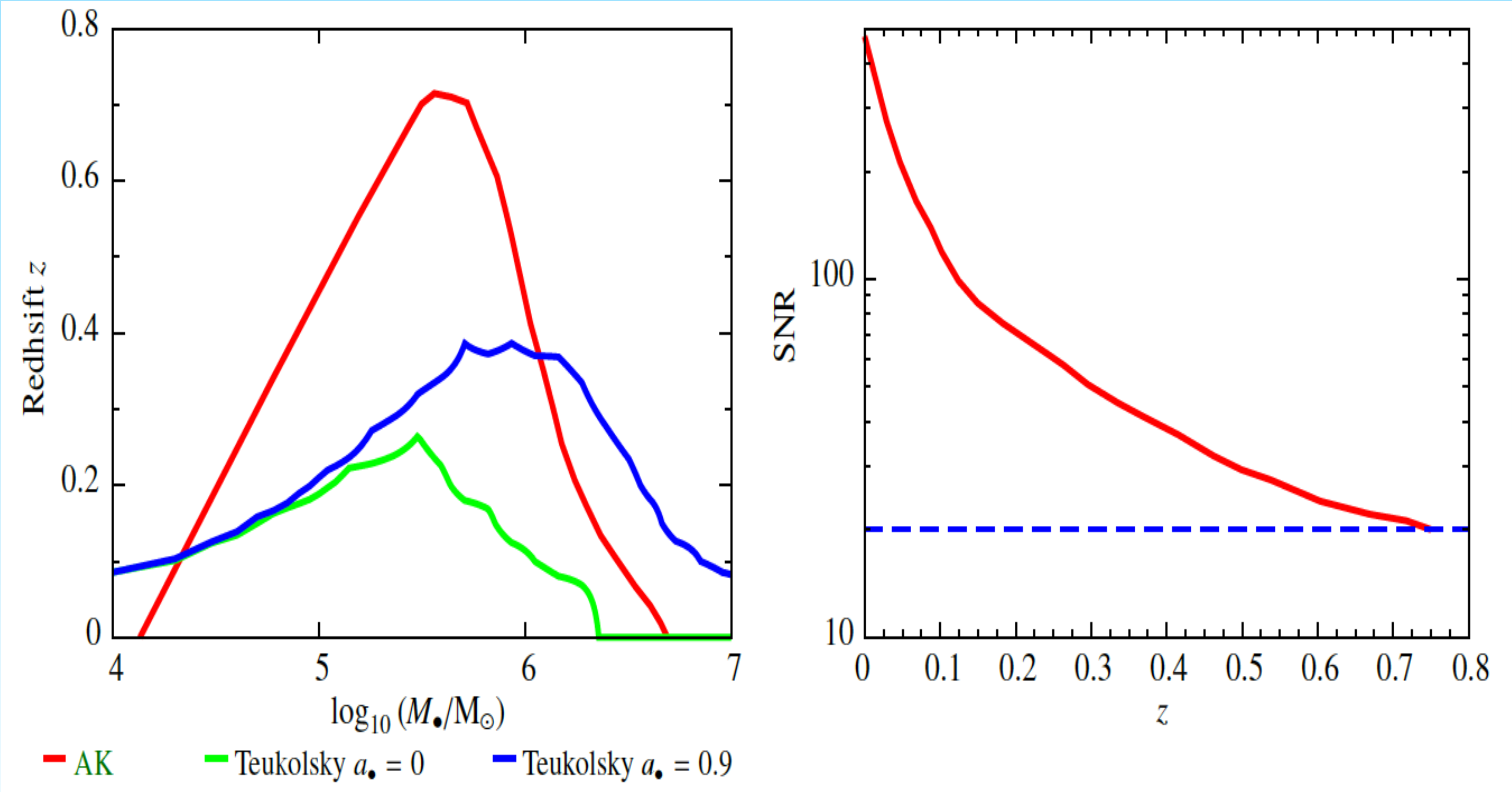
- Inspiral of a stellar mass compact object into a (super)massive black hole in galactic centres
- 1-1000 EMRIs / yr
- 10^5-10^6 cycles during last 1-2 yrs of lifetime
- In reality, we expect ~50 events/yr to z~0.7
- $M_\bullet \sim 10^5 - 10^6\ M_{sol}$



EMRIs

Detection Horizon

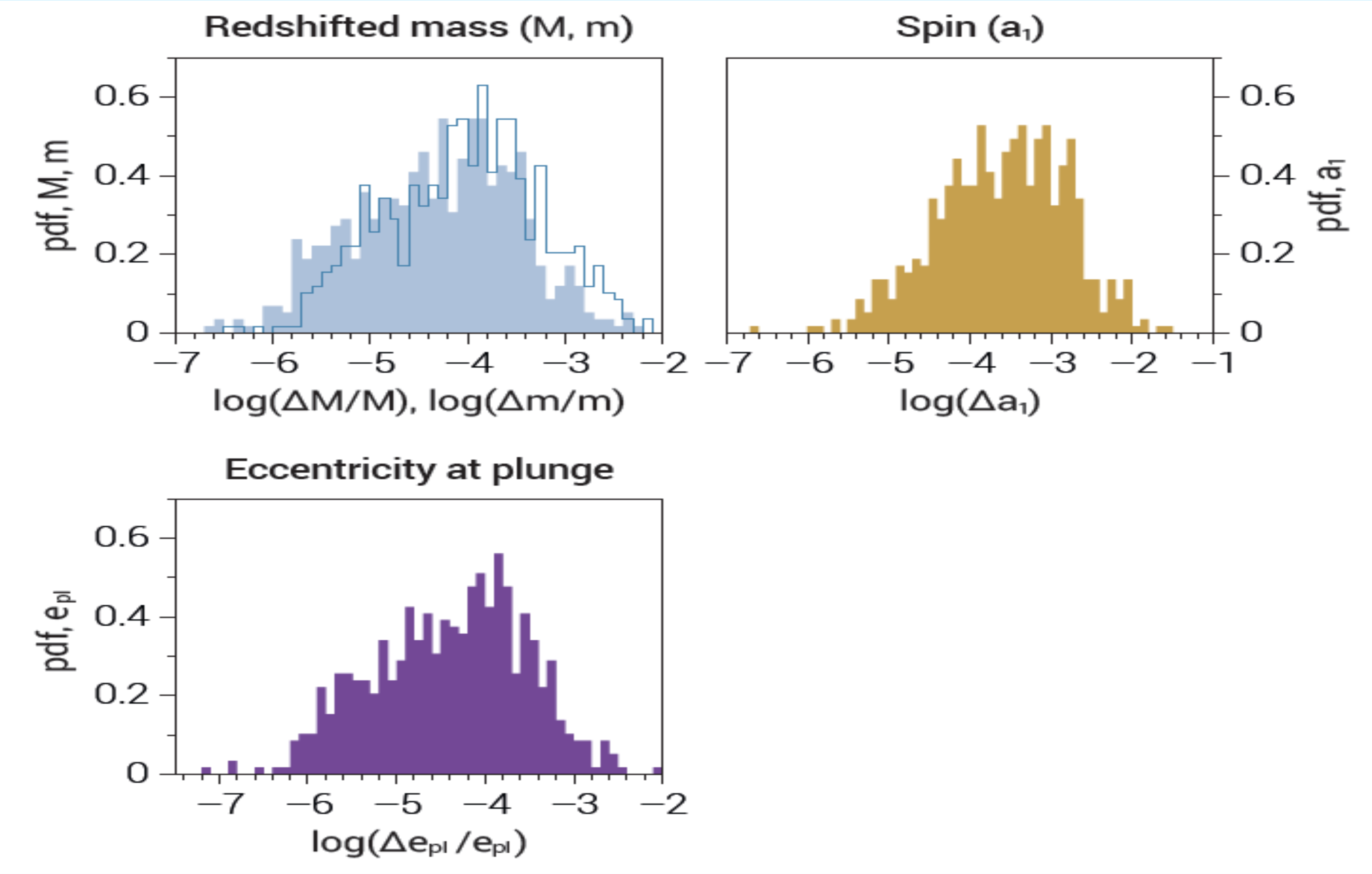
Expected SNR



J. Gair & EKP 2013

EMRIs

With proper templates, we should be able to measure the system parameters with unprecedented accuracy



EMRIs

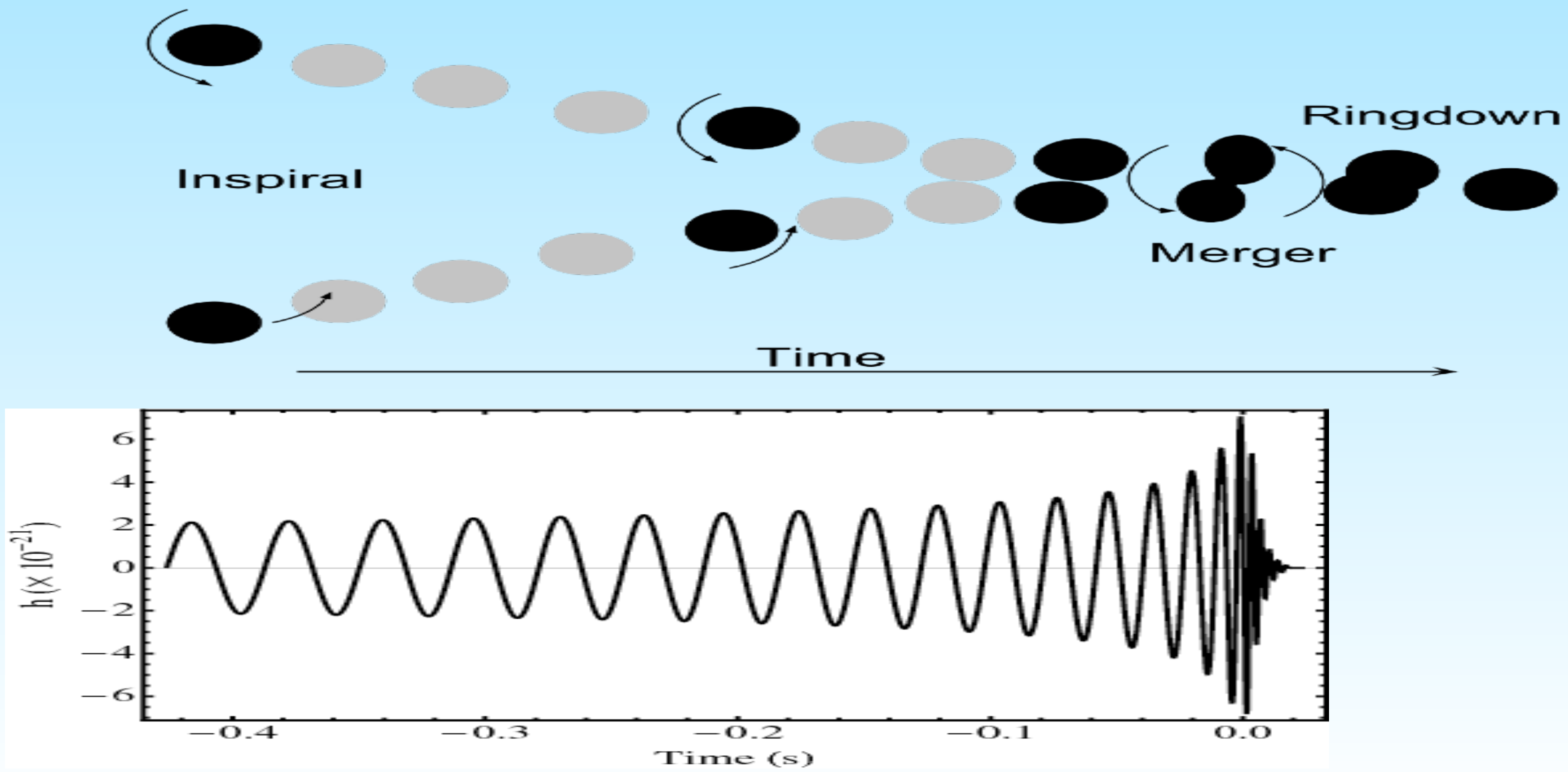
Astrophysical implications:

- Test strong field gravity and alternatives to GR
- Provide information on stellar dynamics in galactic nuclei
- Investigate the galaxy-MBH relation at the low mass end
- 10 EMRIs are needed to measure the BH mass function to a level of 0.3 (current estimate)
- Measurements of the spin of the SMBH will provide information on the growth and evolution process

Supermassive BHs

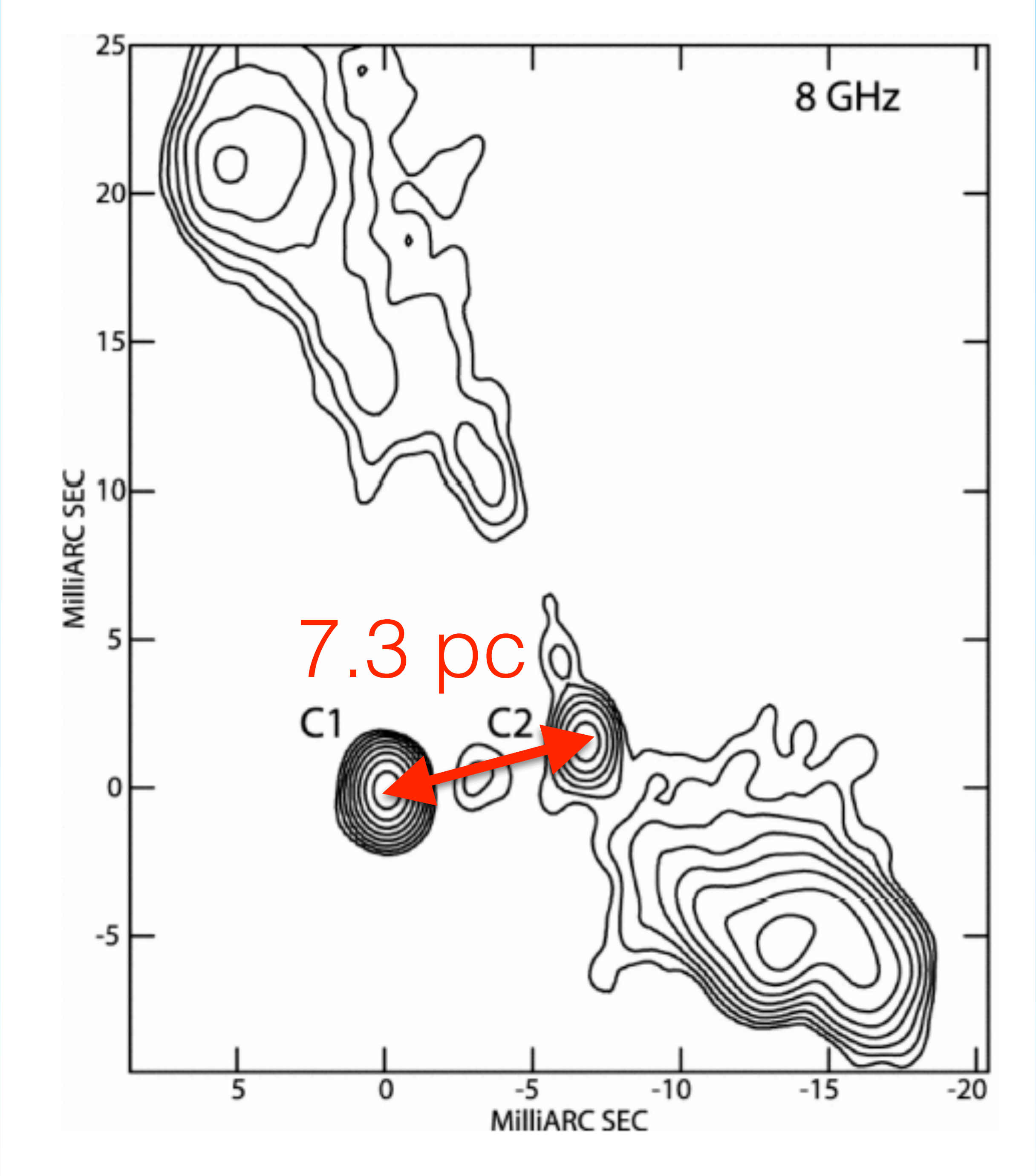
SMBHBs

- Primary sources for eLISA
- A typical SMBHB merger releases 10^{26} L_{solar} in GWs - a typical SN releases 10^{14} L_{solar} in photons



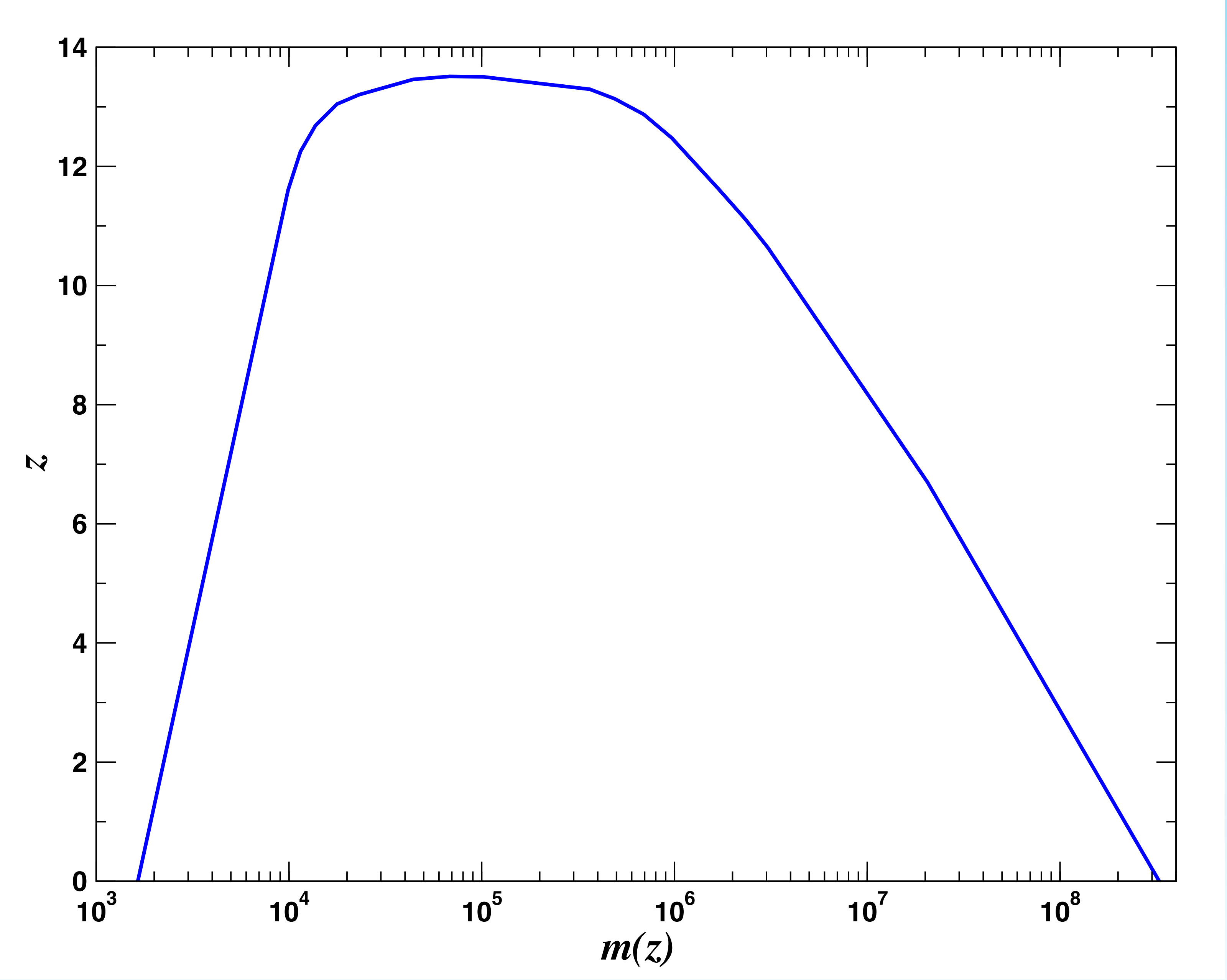
SMBHBs

- Handful of SMBHB candidates
- All at low redshift, i.e. $z < 0.3$
- e.g. Radio Galaxy 0402+379



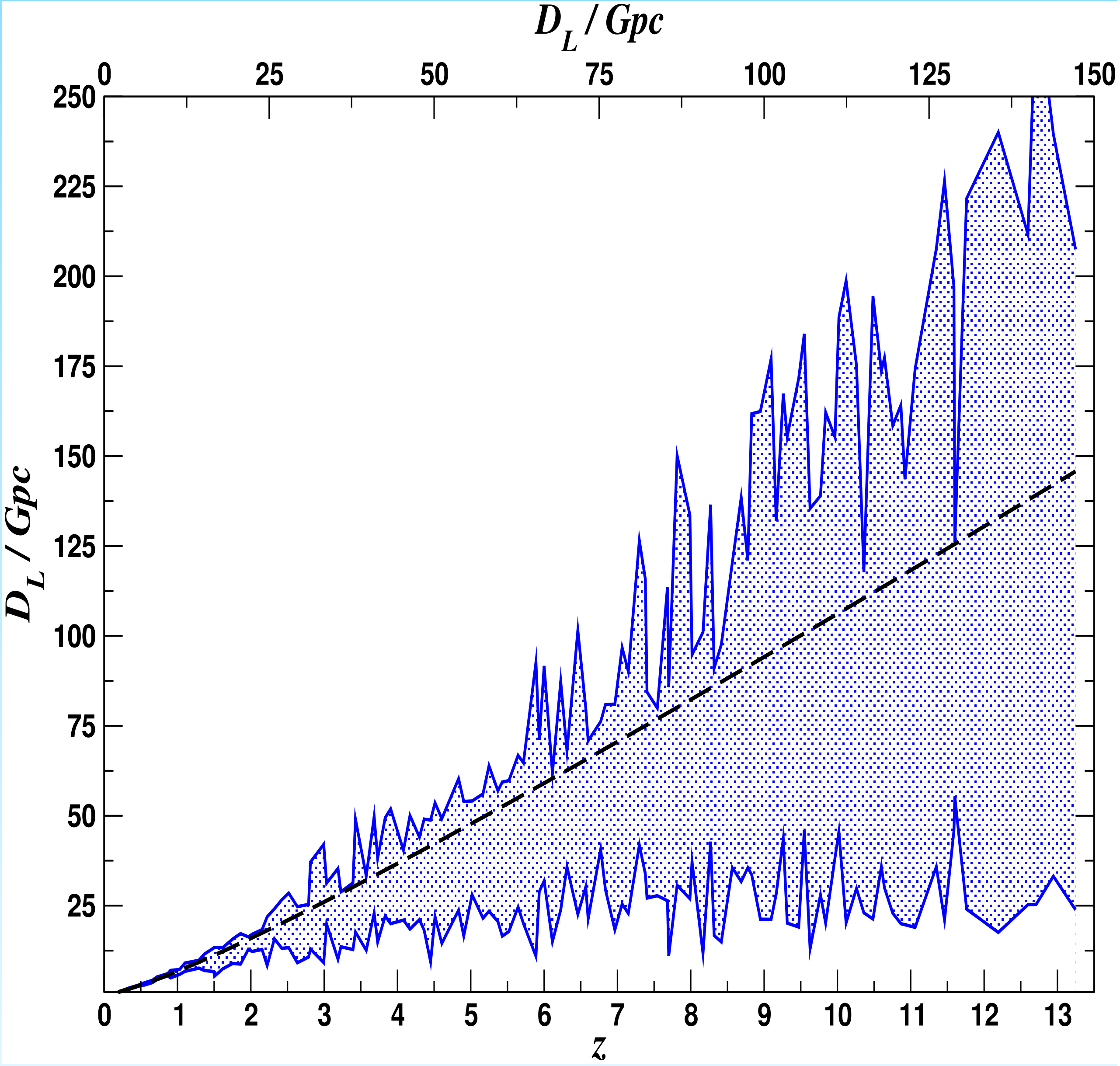
SMBHBs

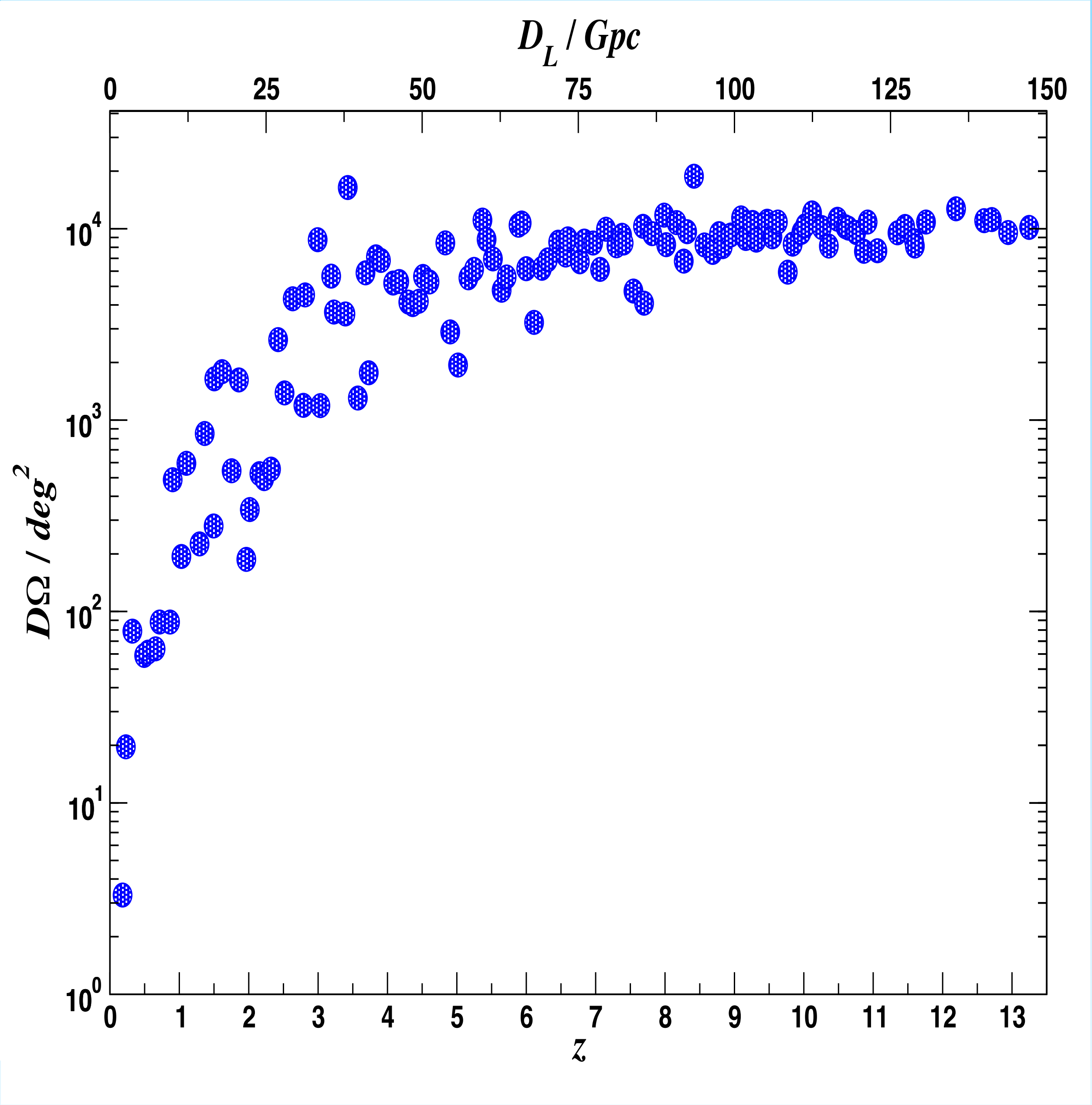
- Detection (inspiral only)



EKP & N.J.Cornish, 2015

SMBHBs





EKP & N.J.Cornish, 2015

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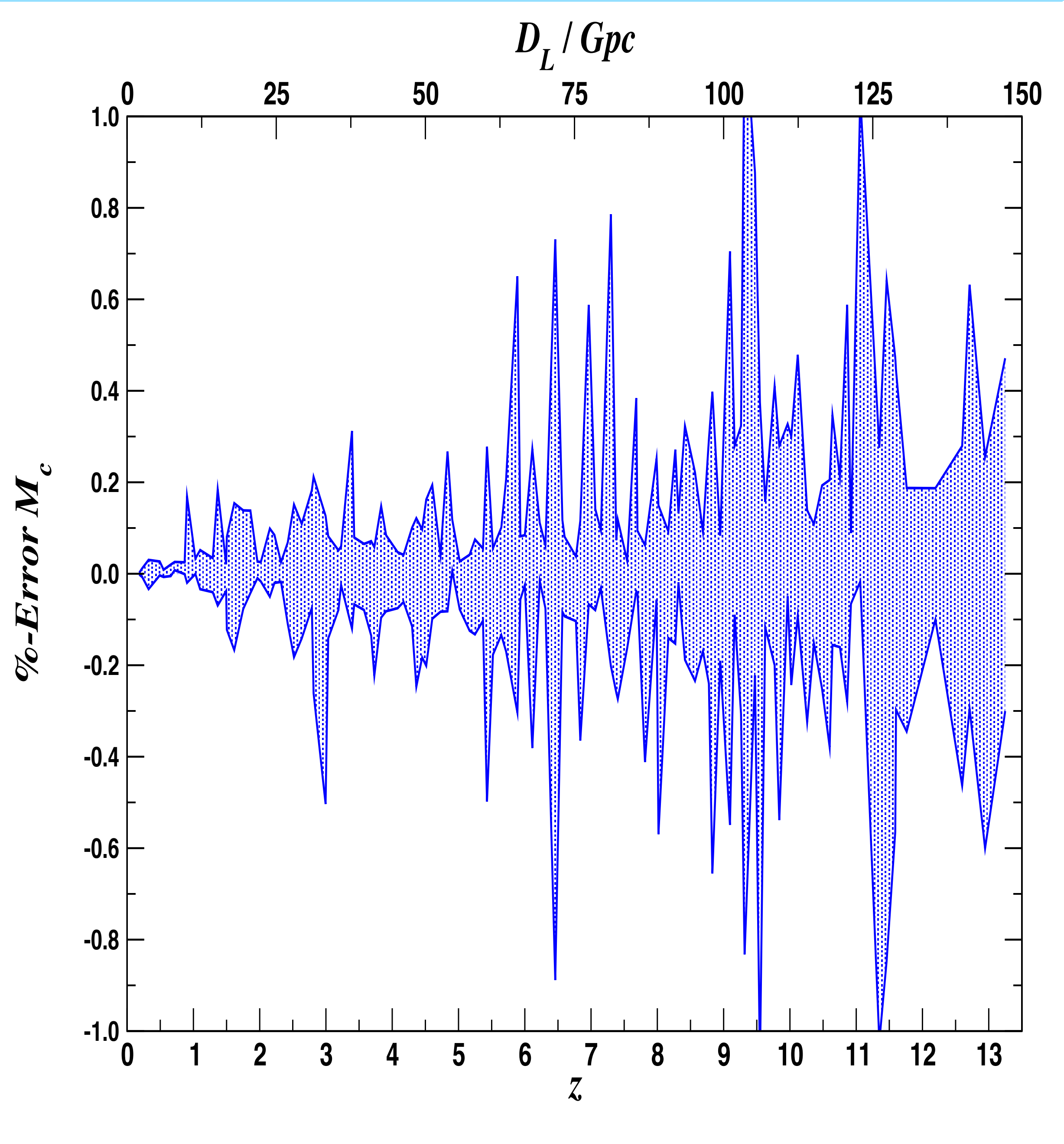

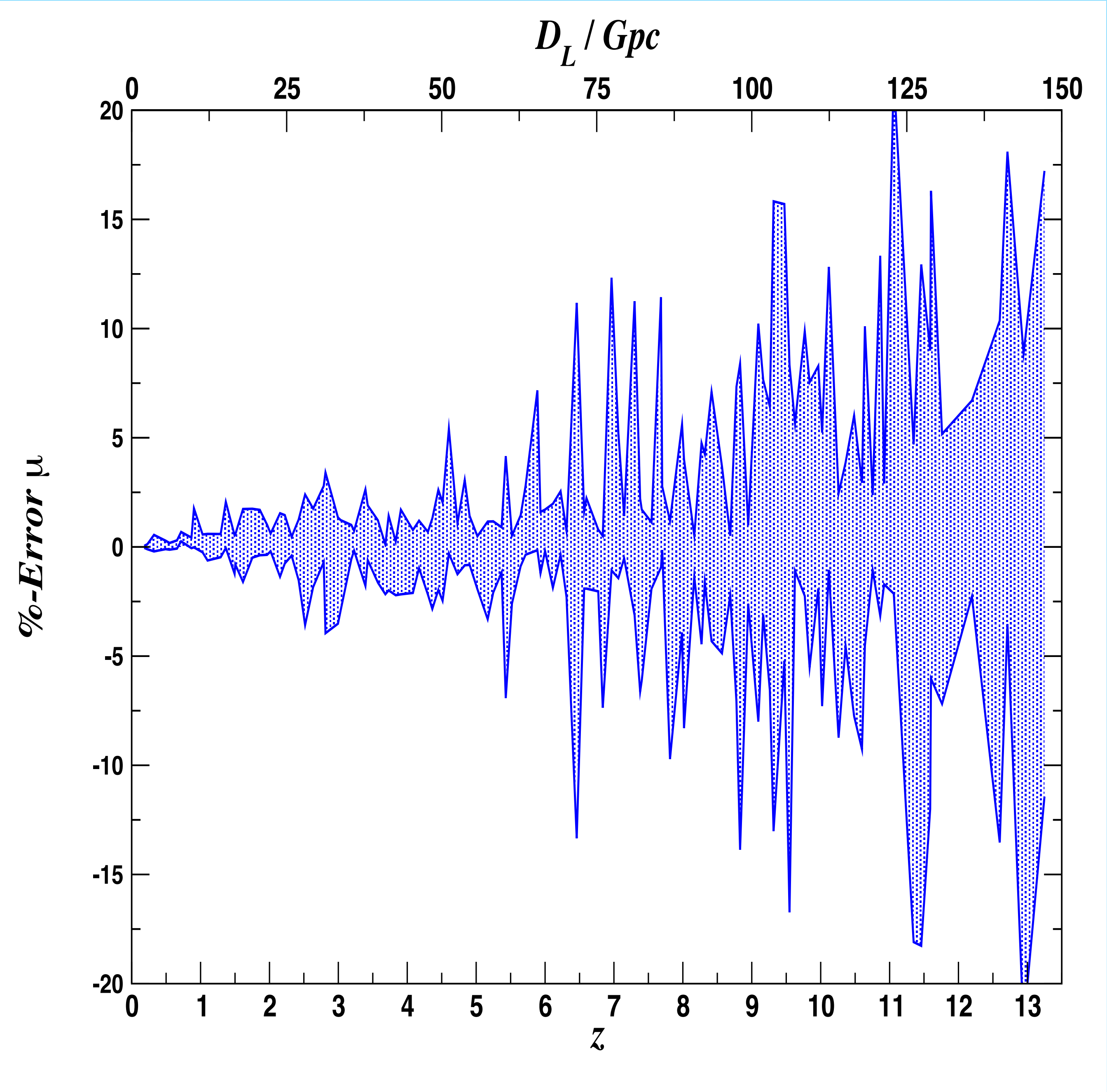

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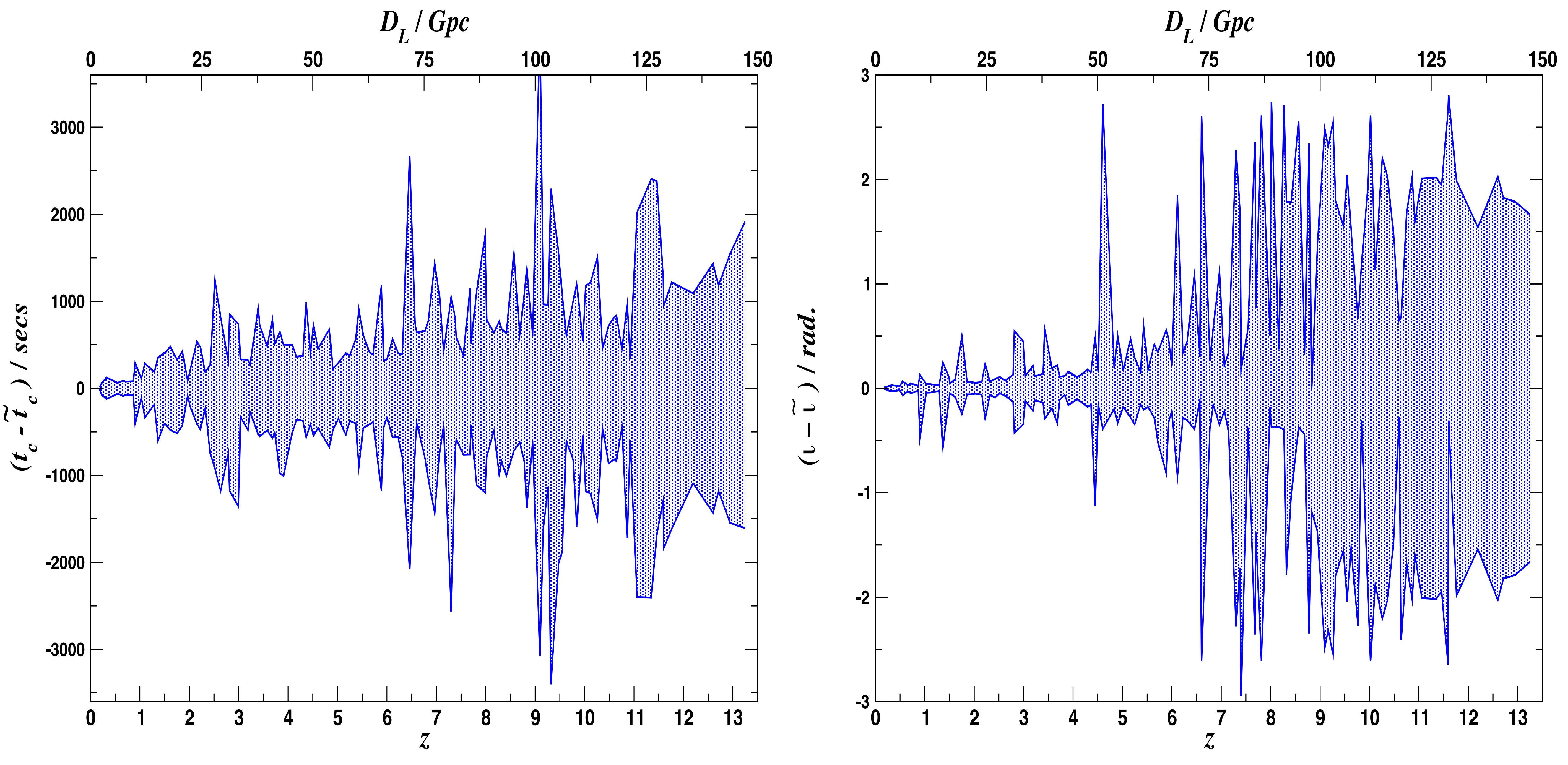

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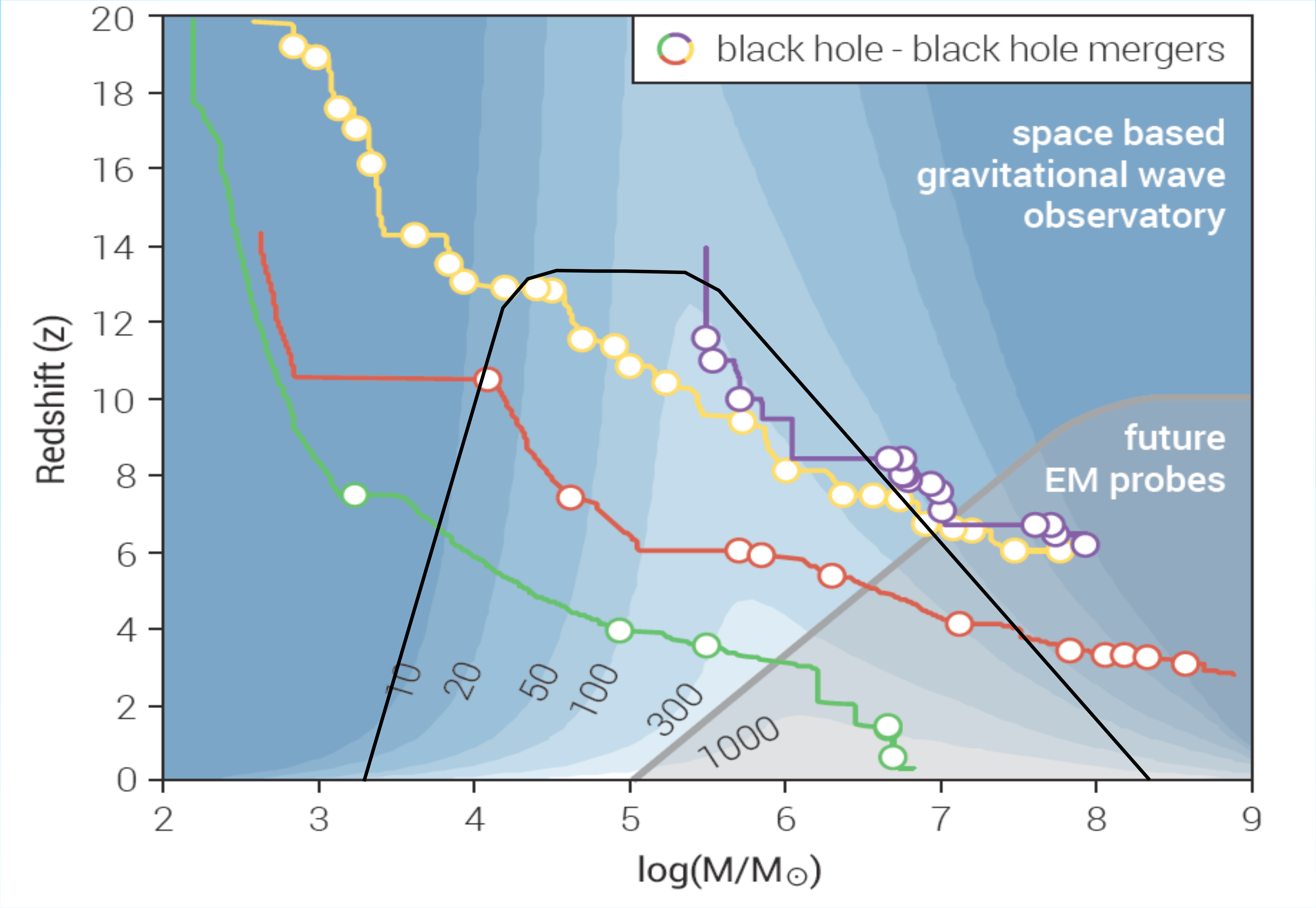
SMBHBs



black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
10
20
50
100
300
1000
Redshift (z)
log(M/M⊙)

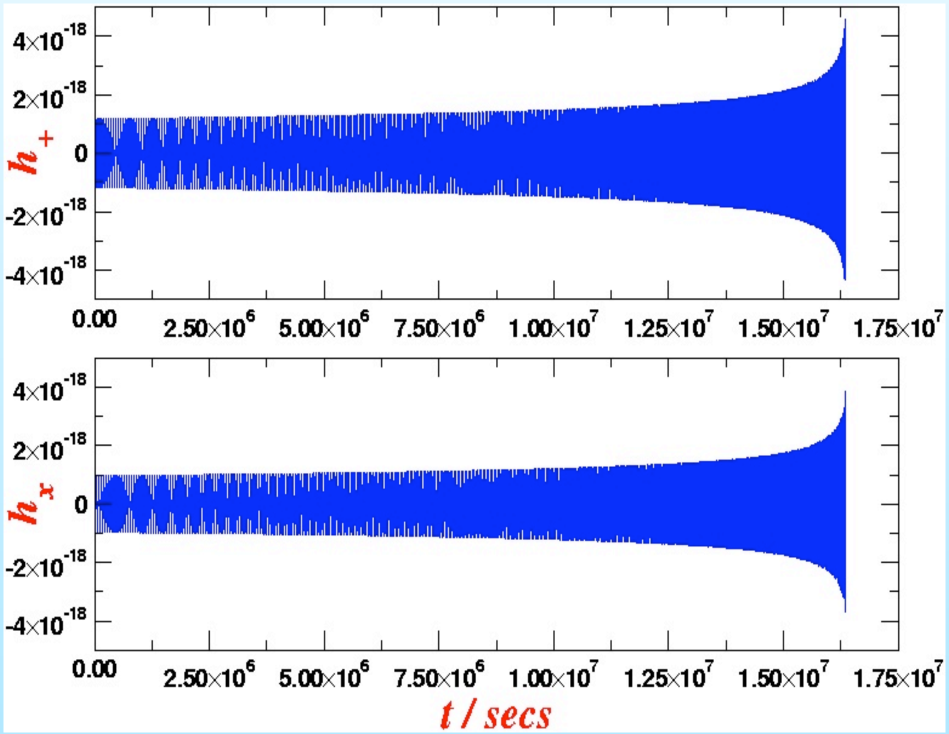
How do we detect GWs?

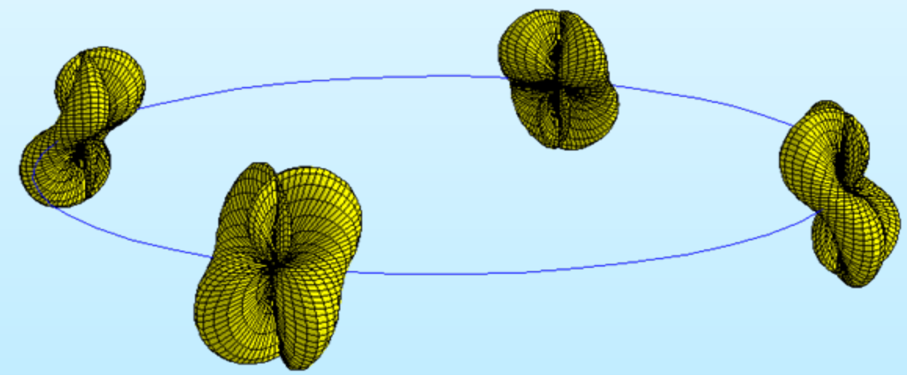
Difficult Problem

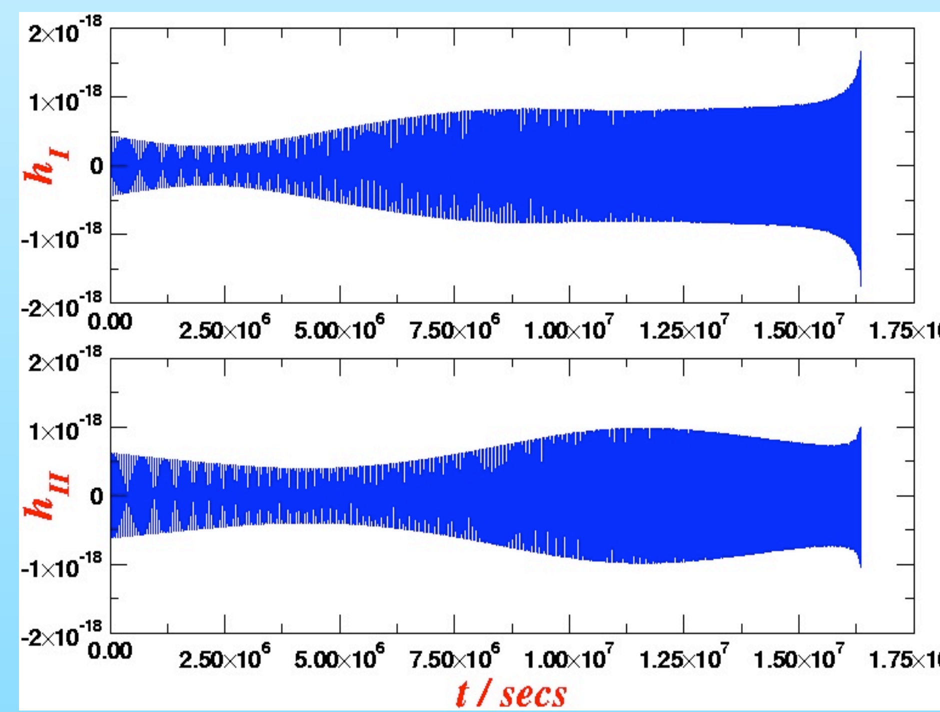
- GWs are analogous to 1D sound waves
- Each source type has a different waveform type
- Laser noise is usually orders of magnitude stronger
- Astrophysical priors are not very helpful

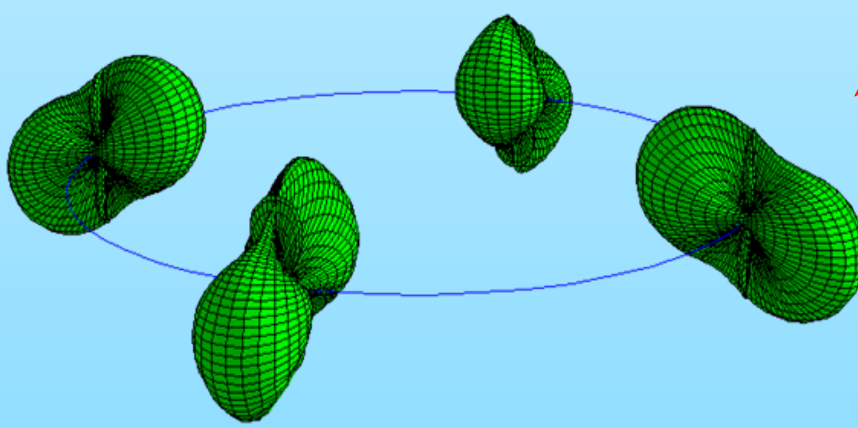
Difficult Problem

$$h_{+,\times}(t) = h_{+,\times}(t;\lambda^{\mu},\theta,\phi)$$





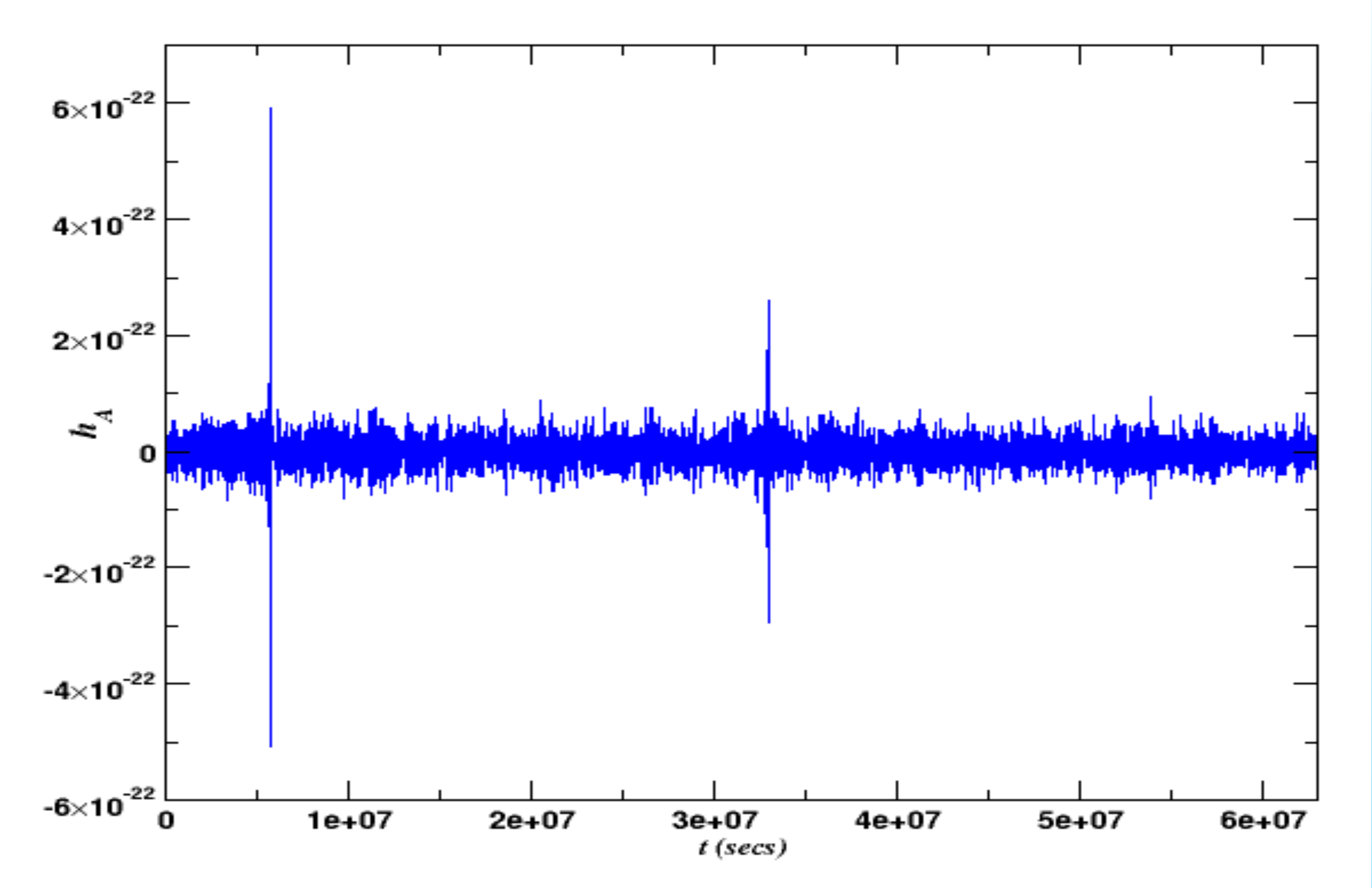




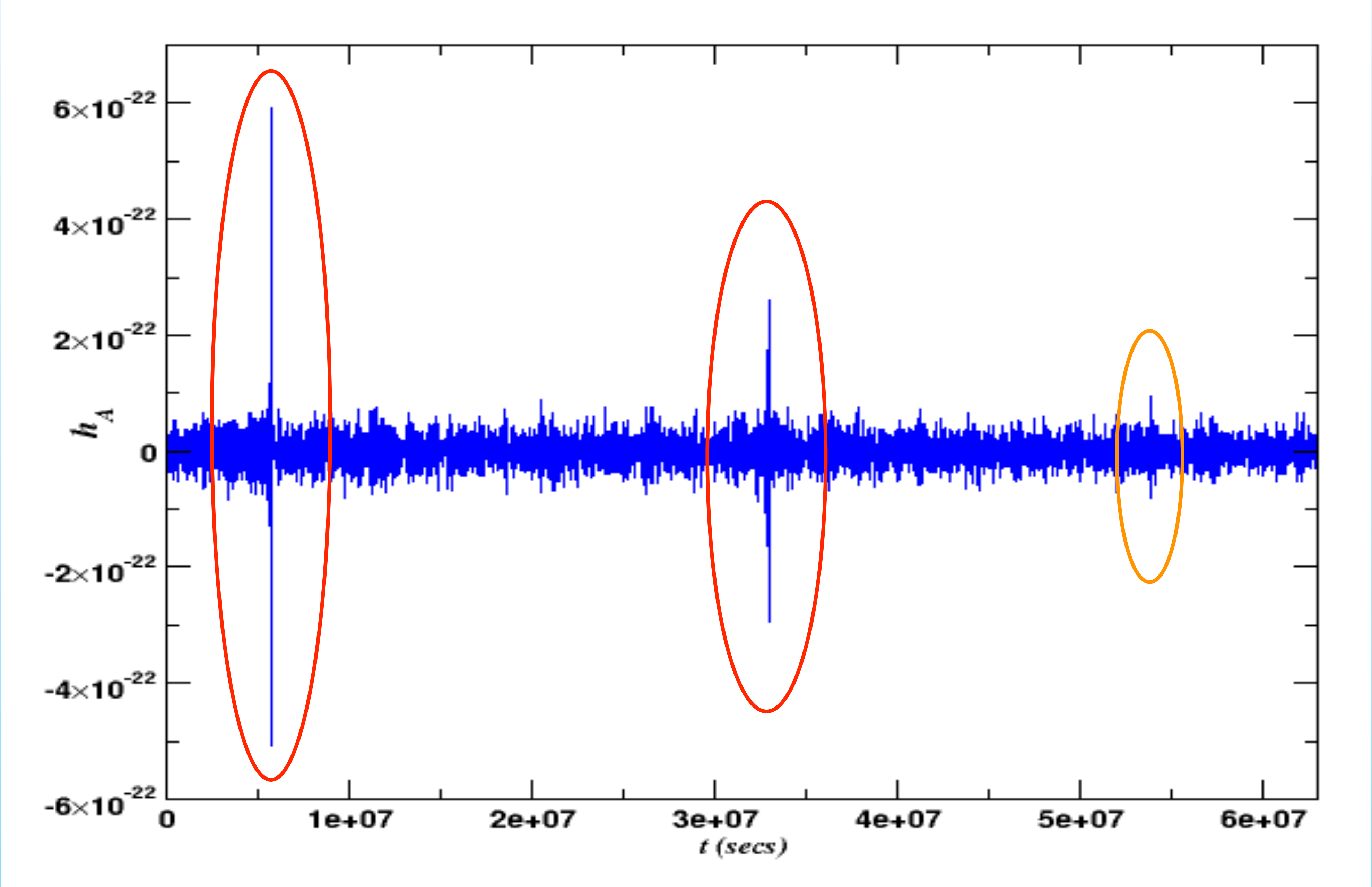
$$F^{+,\times}(t) = F^{+,\times}(t;\theta,\phi,\psi)$$

$$h(t) = h_{+}(t)F^{+}(t) + h_{\times}(t)F^{\times}(t)$$

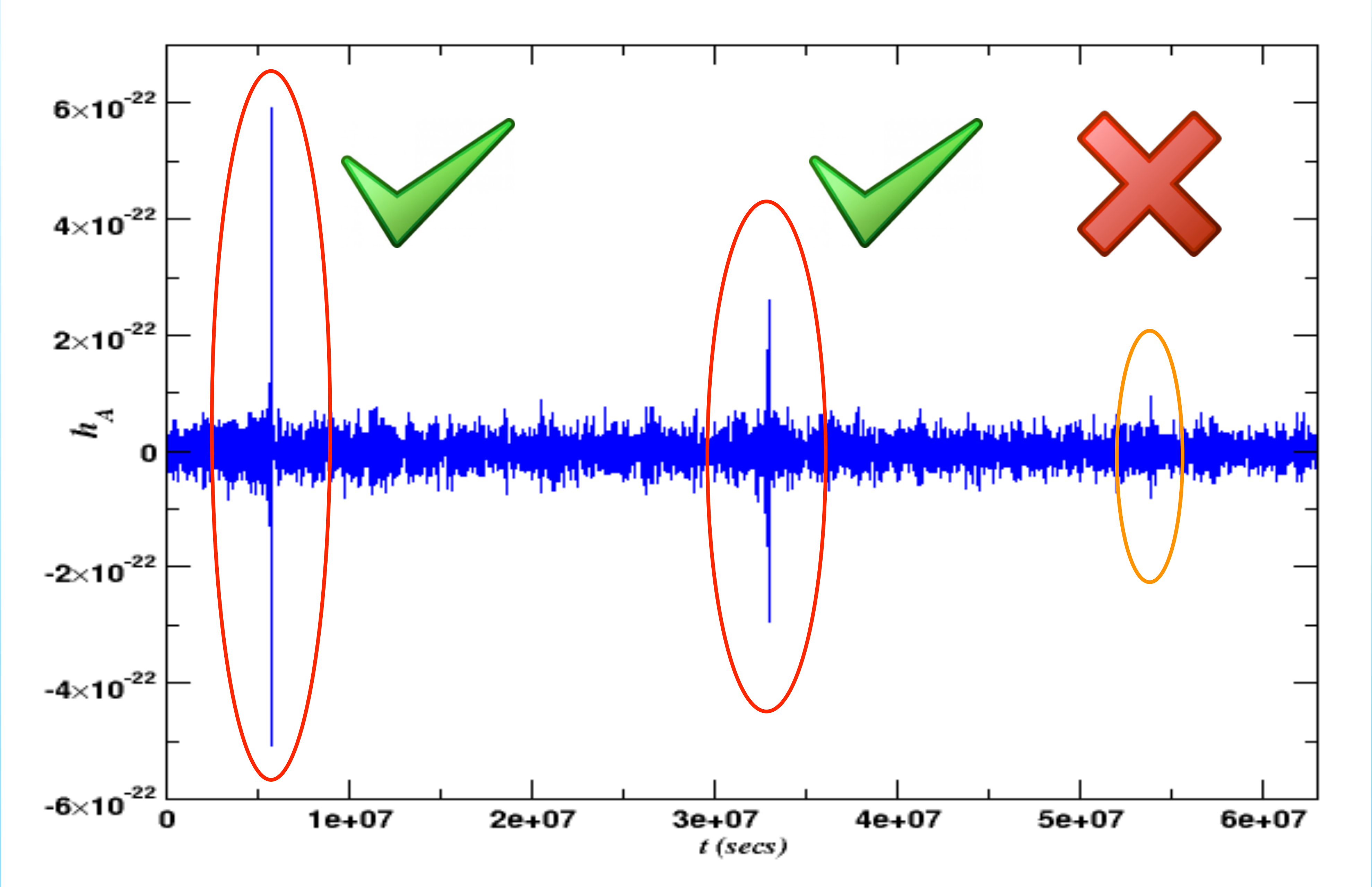
Visual Inspection



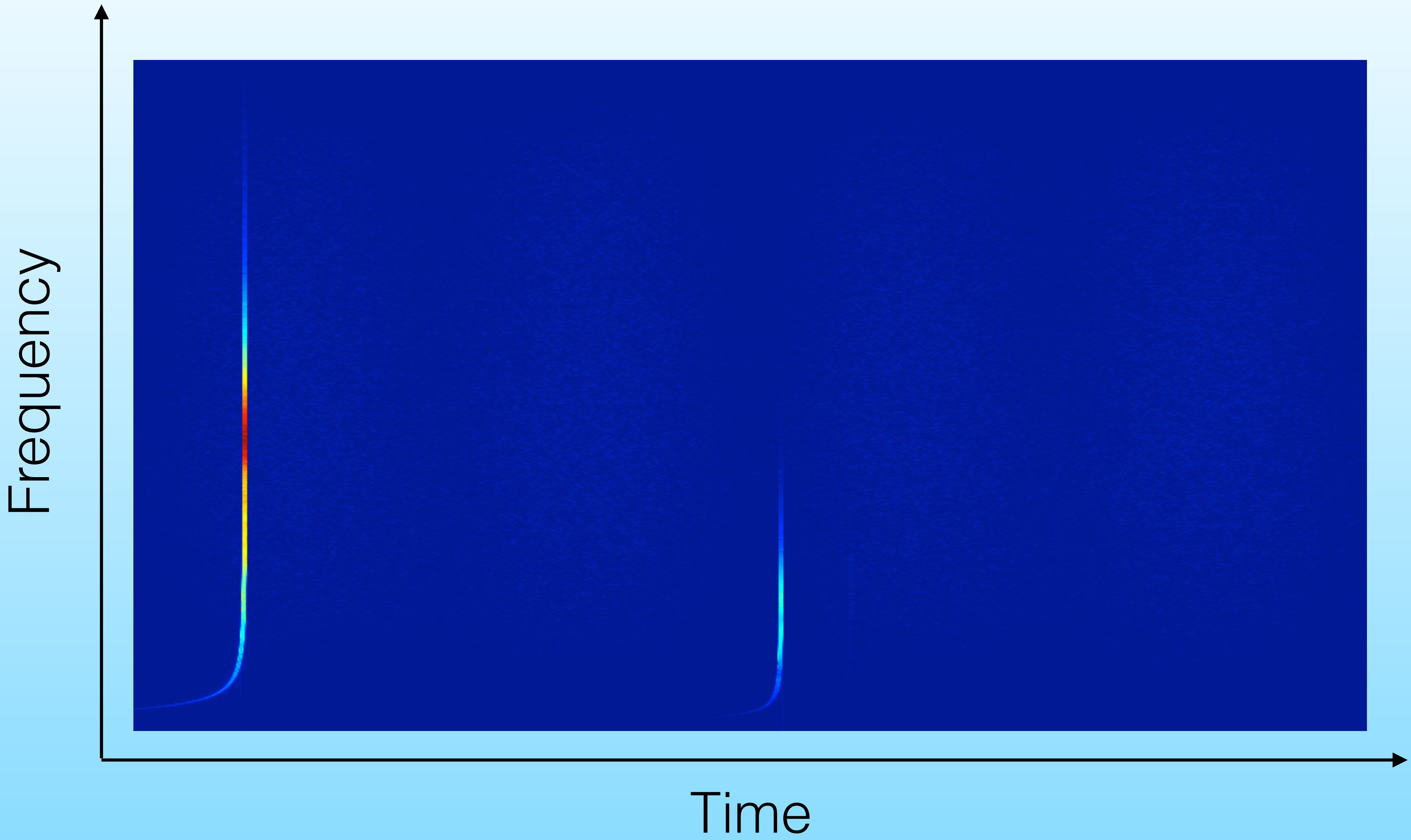
Visual Inspection



Visual Inspection



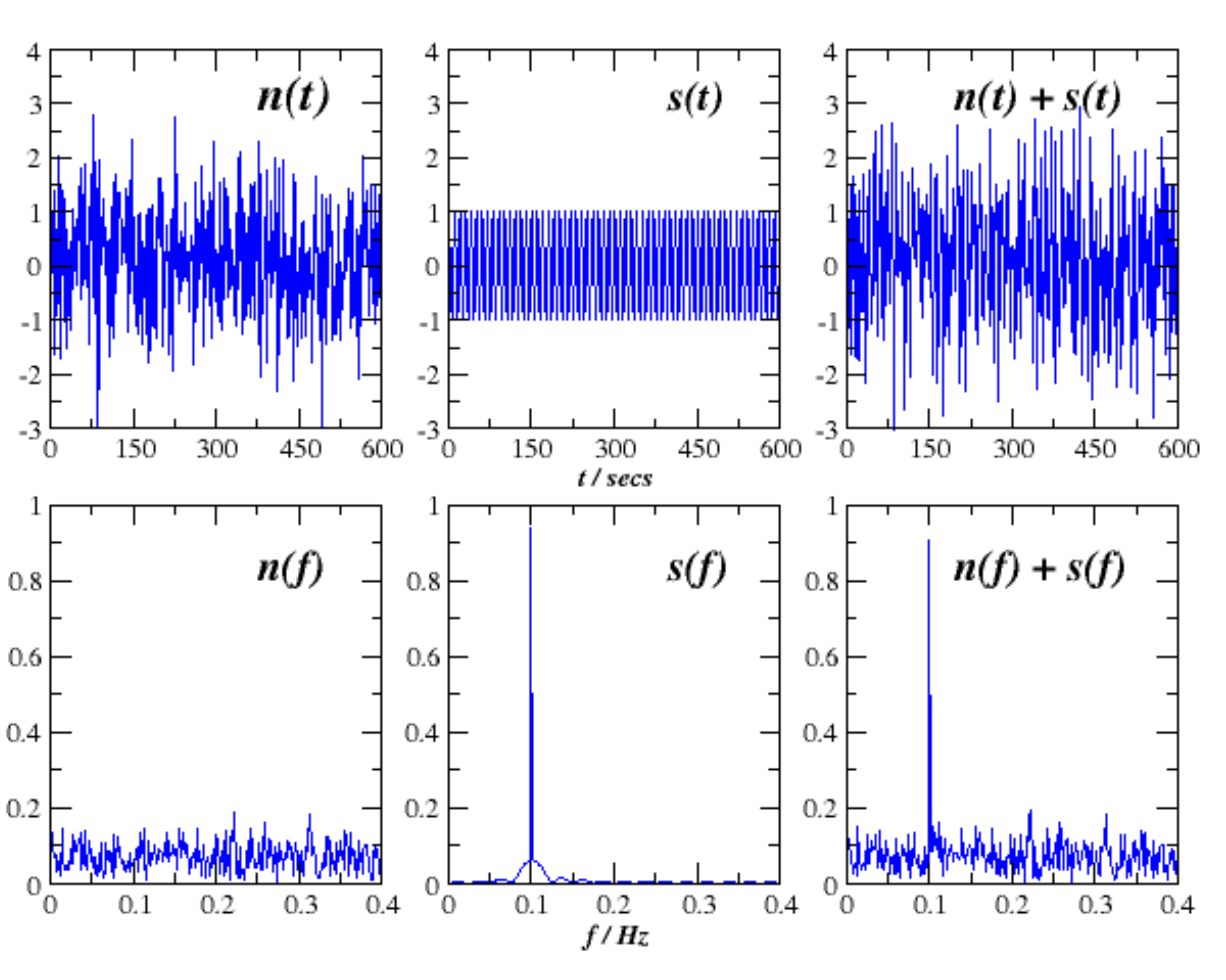
Time-Frequency Plot



Matched Filtering

- Work in Fourier domain
- Search for the optimal linear filter
- Each signal type has a different spectral signature
- Optimal methods for complex signals buried in noise
- Demonstrated to work very well for GW analysis
- Requires accurate waveform models

Matched Filtering



e.g. Galactic binary signal in noise

Conclusion

- GWs are a new window on the Universe
- A ground-based network will be operational by end of 2016
- LISA Pathfinder should begin science operations on March 1st
- eLISA is now the L3 cosmic vision mission with a launch date of 2034, and has immense scientific potential
- Still a lot of work to be done on all fronts, so….

...go to

www.elisascience.org

and join a working group!