GRAVITATIONAL WAVES: A NEW TOOL FOR OBSERVING THE COSMOS

IAGRG, Indian Institute of Technology, Guwahati, India, 18-20 May 2017

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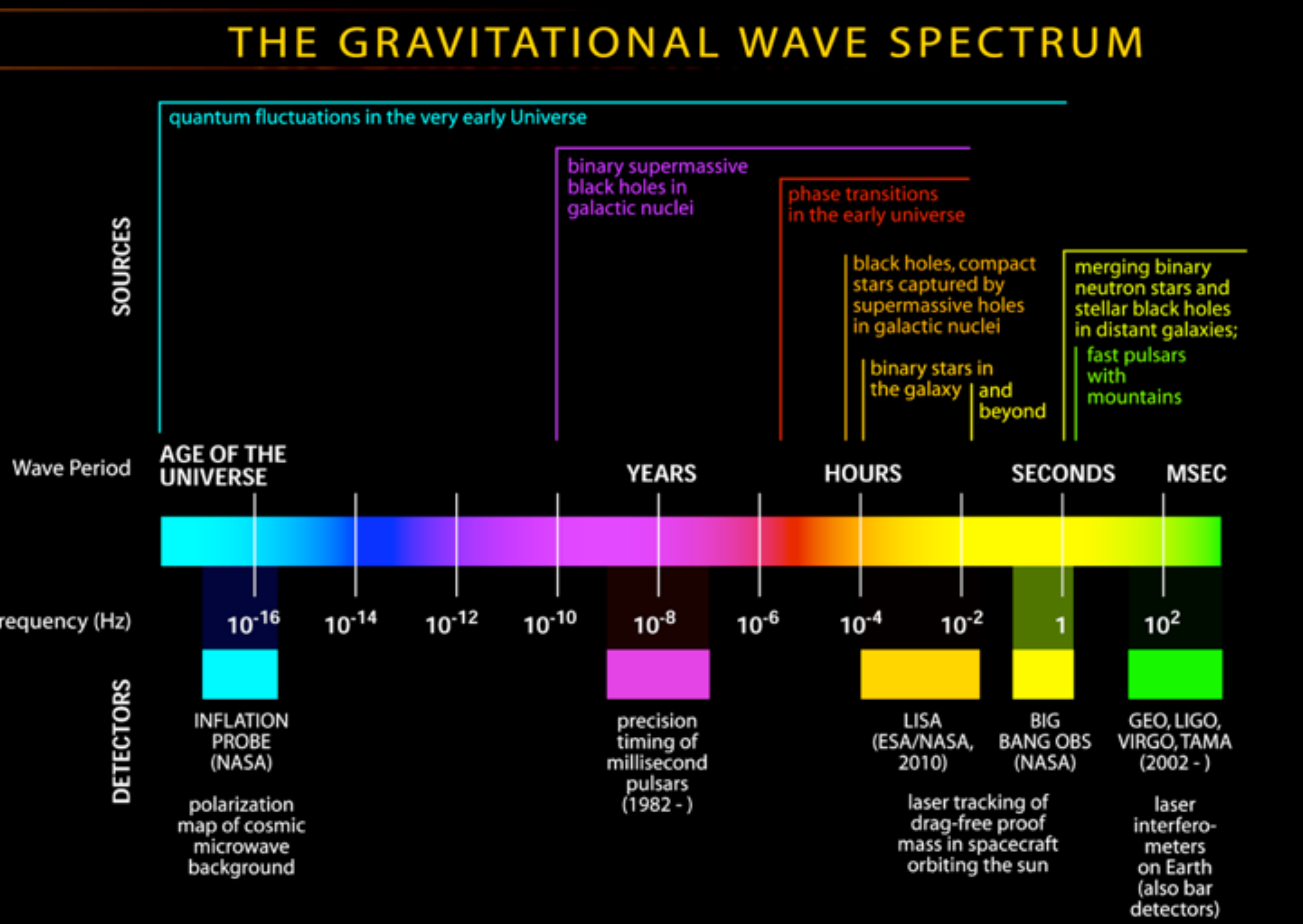
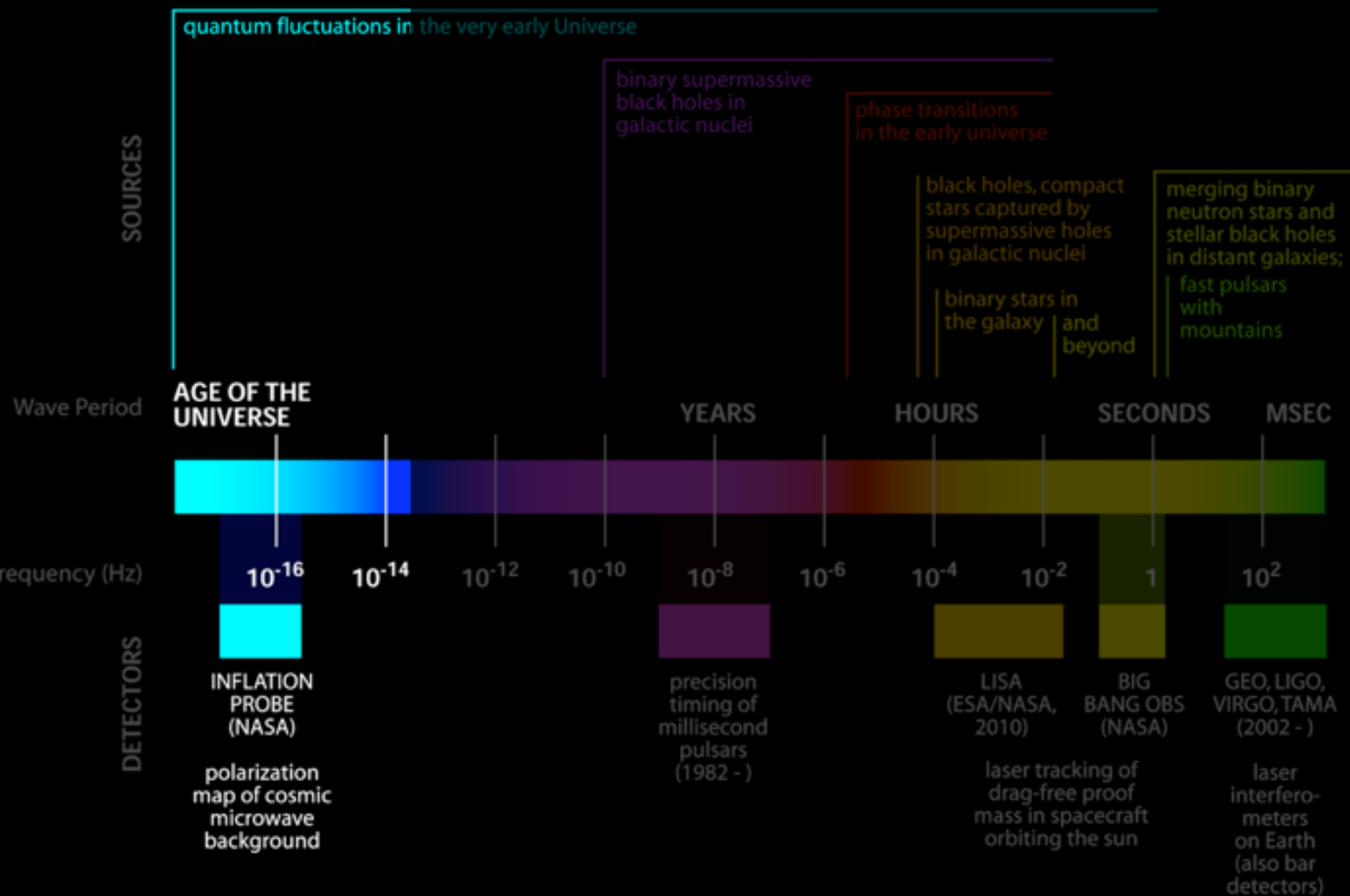
Bert Elsbach Professor of Physics Penn State
and
Professor of Physics Cardiff University

GW DISCOVERY - TRULY COLLABORATIVE WORK

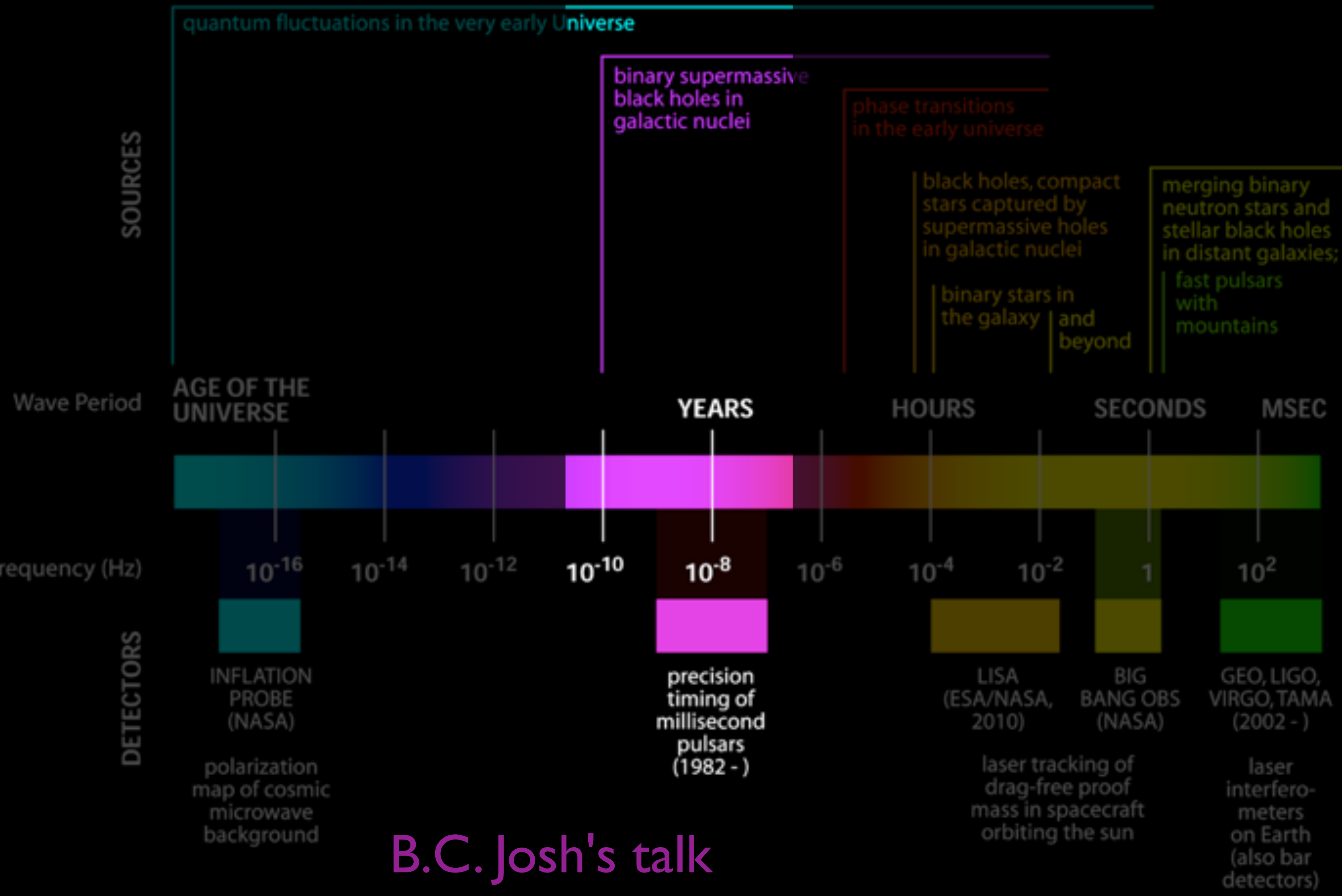
- The discovery is the work of ~1000 scientists and engineers across the globe
  - 3 different collaborations: LIGO, GEO600, Virgo
  - 15 countries, 80 institutions
  - 100's of graduate students and postdocs
- It is an engineering marvel, as much as it is a scientific discovery
- Many thanks to hundreds of colleagues from the three collaborations who have made this possible


THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
requency (Hz)
10^-16
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
1
10^2
DETECTORS
INFLATION PROBE (NASA)
polarization map of cosmic microwave background
precision timing of millisecond pulsars (1982 -)
LISA (ESA/NASA, 2010)
laser tracking of drag-free proof mass in spacecraft orbiting the sun
BIG BANG OBS (NASA)
GEO, LIGO, VIRGO, TAMA (2002 -)
laser interfero-meters on Earth (also bar detectors)

Ultra Low Frequency

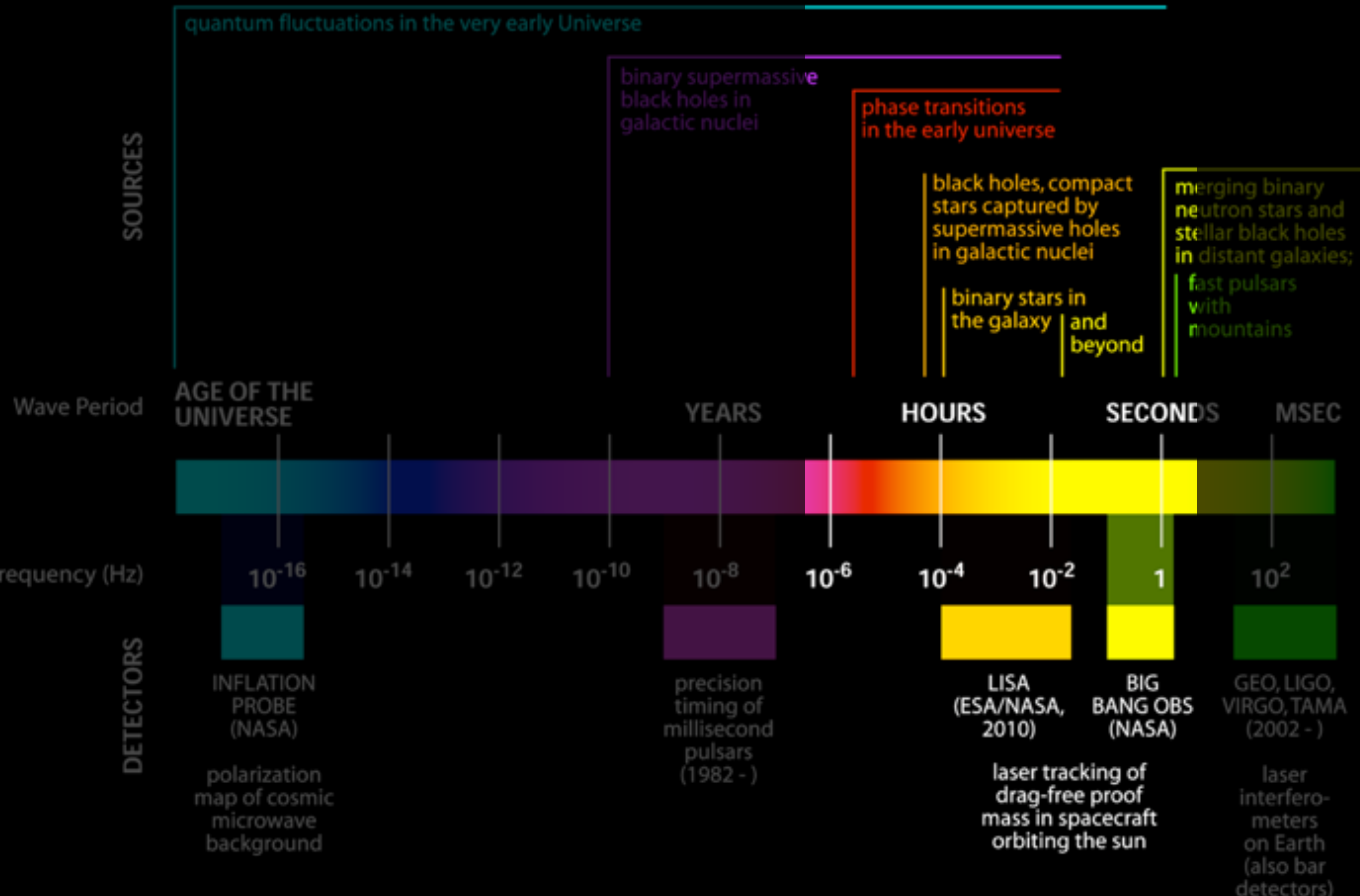


Very Low Frequency

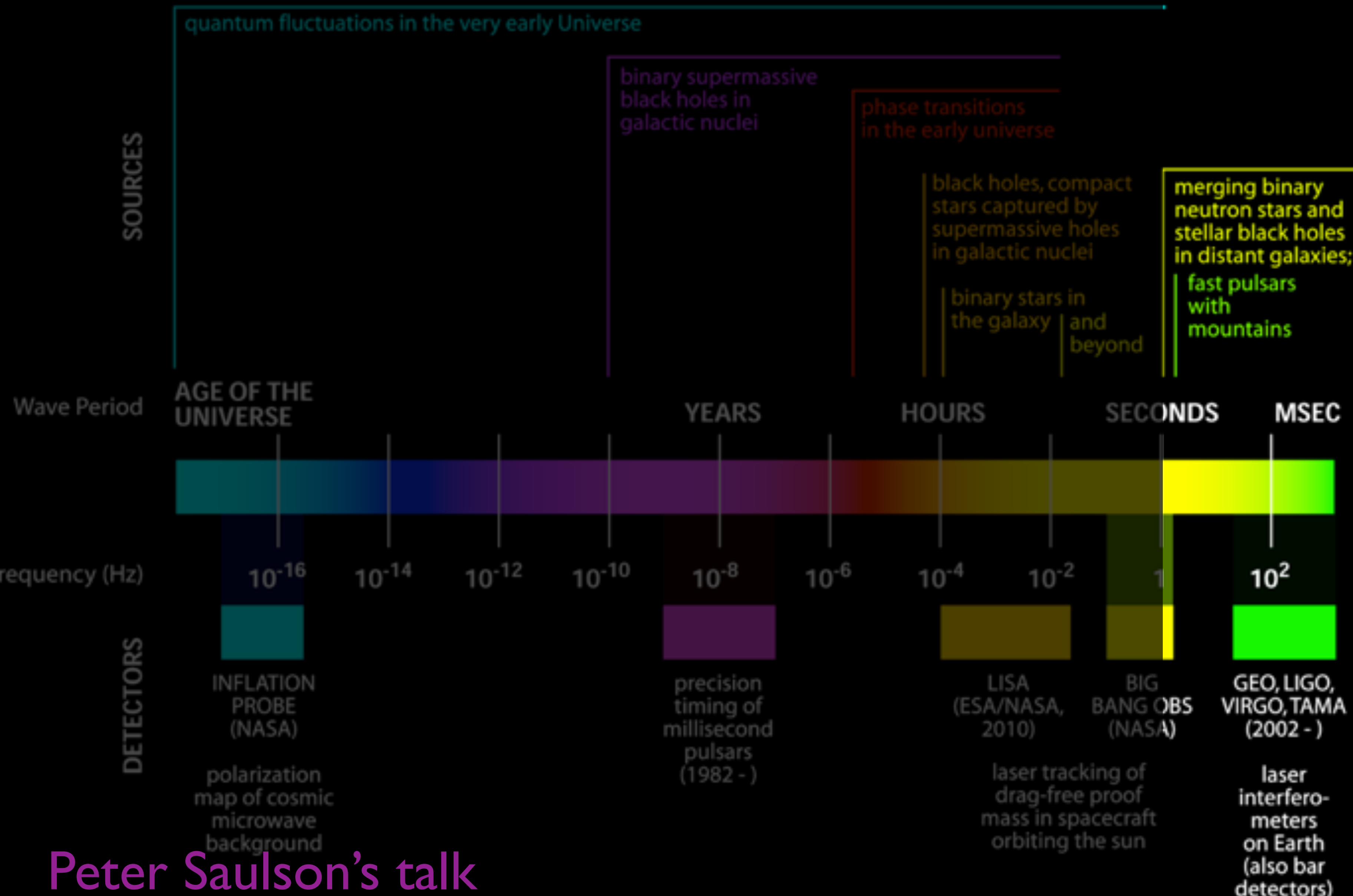


B.C. Josh's talk

Low Frequency



High Frequency



Peter Saulson's talk

OUTLINE

- compact binary mergers
  - importance of modeling for detection and inference
- detections so far
  - properties of sources
- inference from gravitational wave observations
  - astrophysics
    - evolutionary models of binary black holes
  - fundamental physics:
    - tests of general relativity
- what next for gravitational wave observations

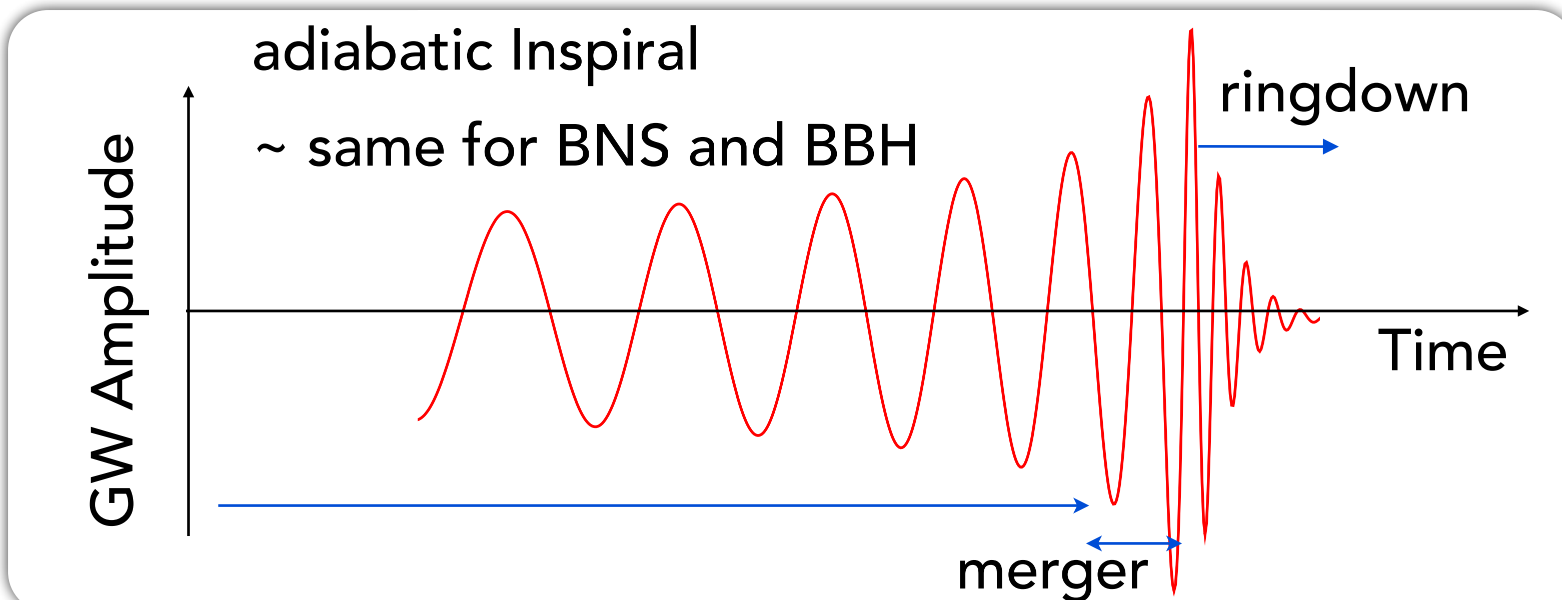
modelling compact binary mergers

Badri Krishnan's talk

K.G. Arun's talk

BINARY BLACK HOLE WAVEFORMS

- waveform characterized by
  - slow adiabatic inspiral, fast and luminous merger, rapid ringdown
- very large parameter space
  - mass ratio, large BH spins misaligned with orbit, eccentricity
- waveform shape can tell us about component masses, spins and eccentricity
- waveform amplitude (in a detector network) can tell us about source's orientation, sky position, polarization and distance



PROGRESS IN TWO-BODY PROBLEM

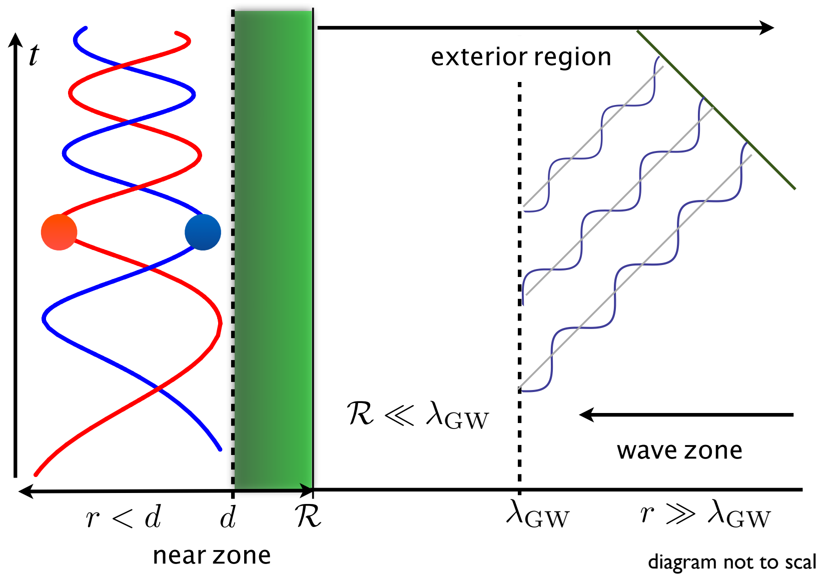
- Caltech group pointed out the importance of computing phasing beyond leading order, followed by very impressive progress in post-Newtonian computation of two-body dynamics

- construction of LIGO, Virgo, GEO600 and TAMA brought theory and observations closer

- effective one-body approach developed: bold prediction for the late inspiral, merger and ringdown

- first successful NR simulations broke conventional wisdom - a far simpler merger than anyone predicted

- phenomenological waveform models developed for GW data analysis



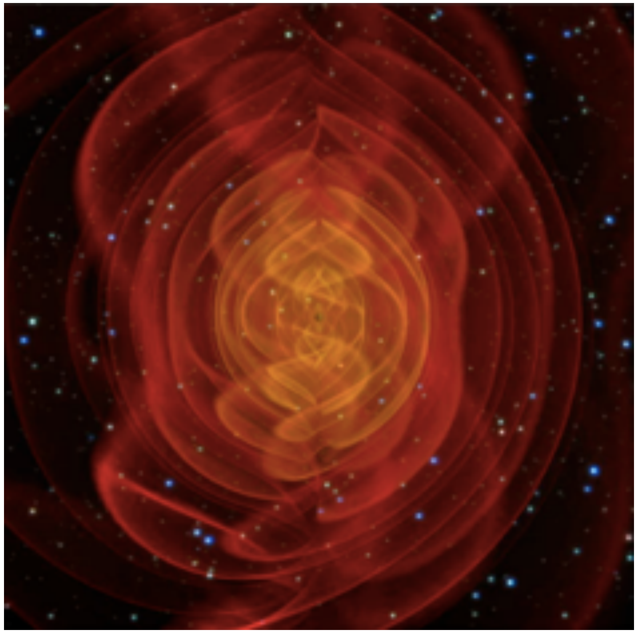
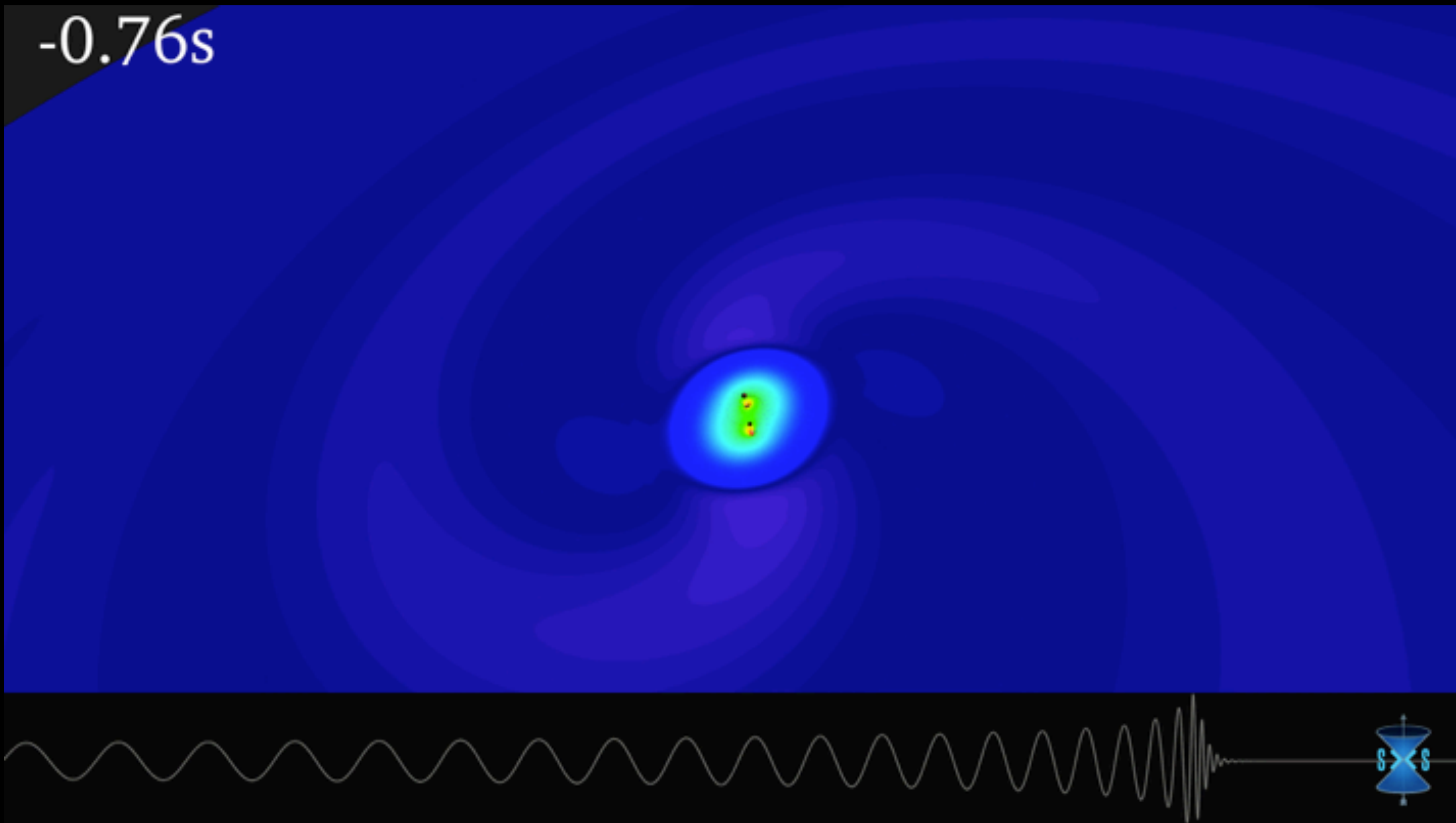
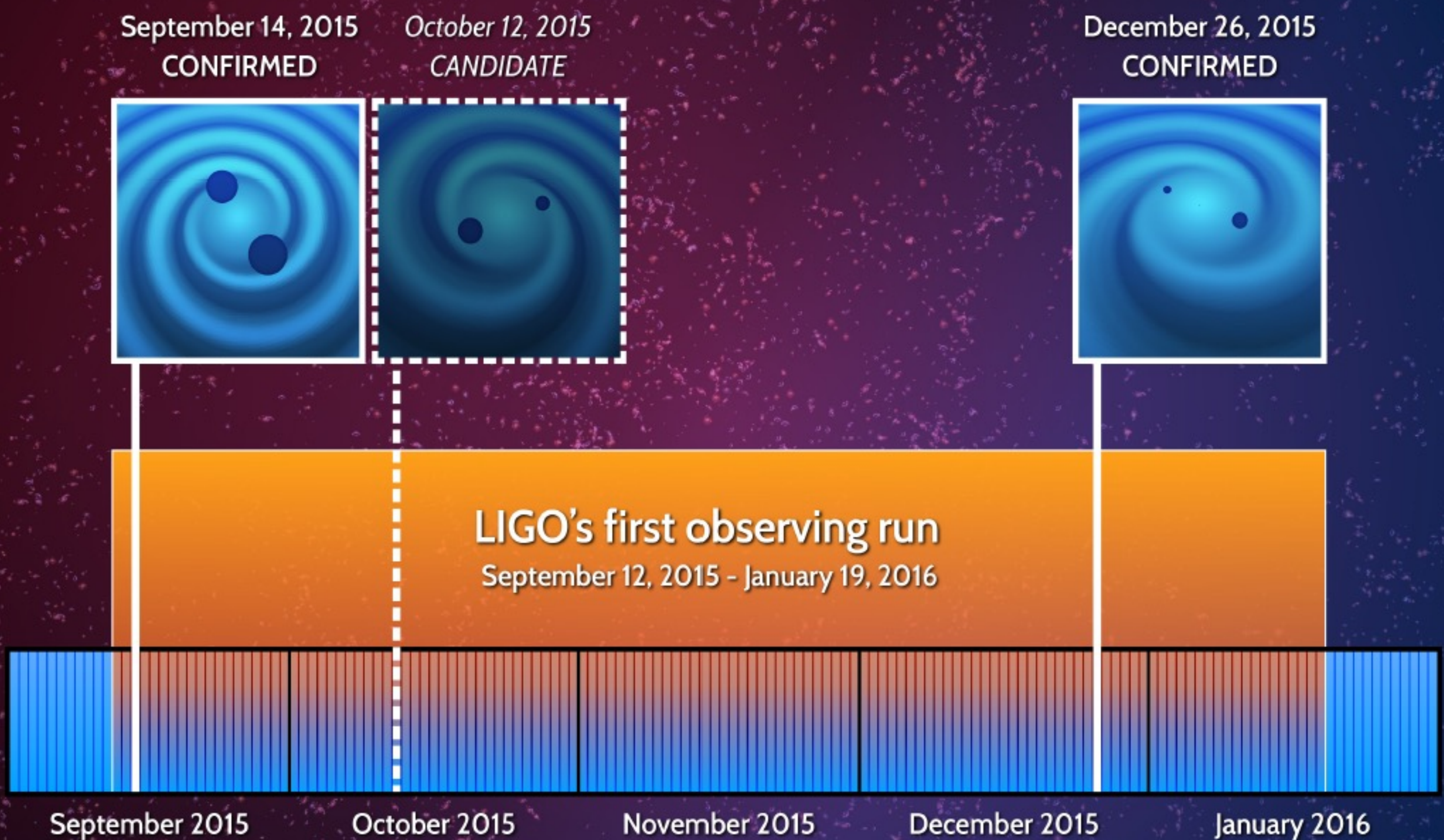


image curtsey NASA/C. Henze


-0.76s

Detections so far

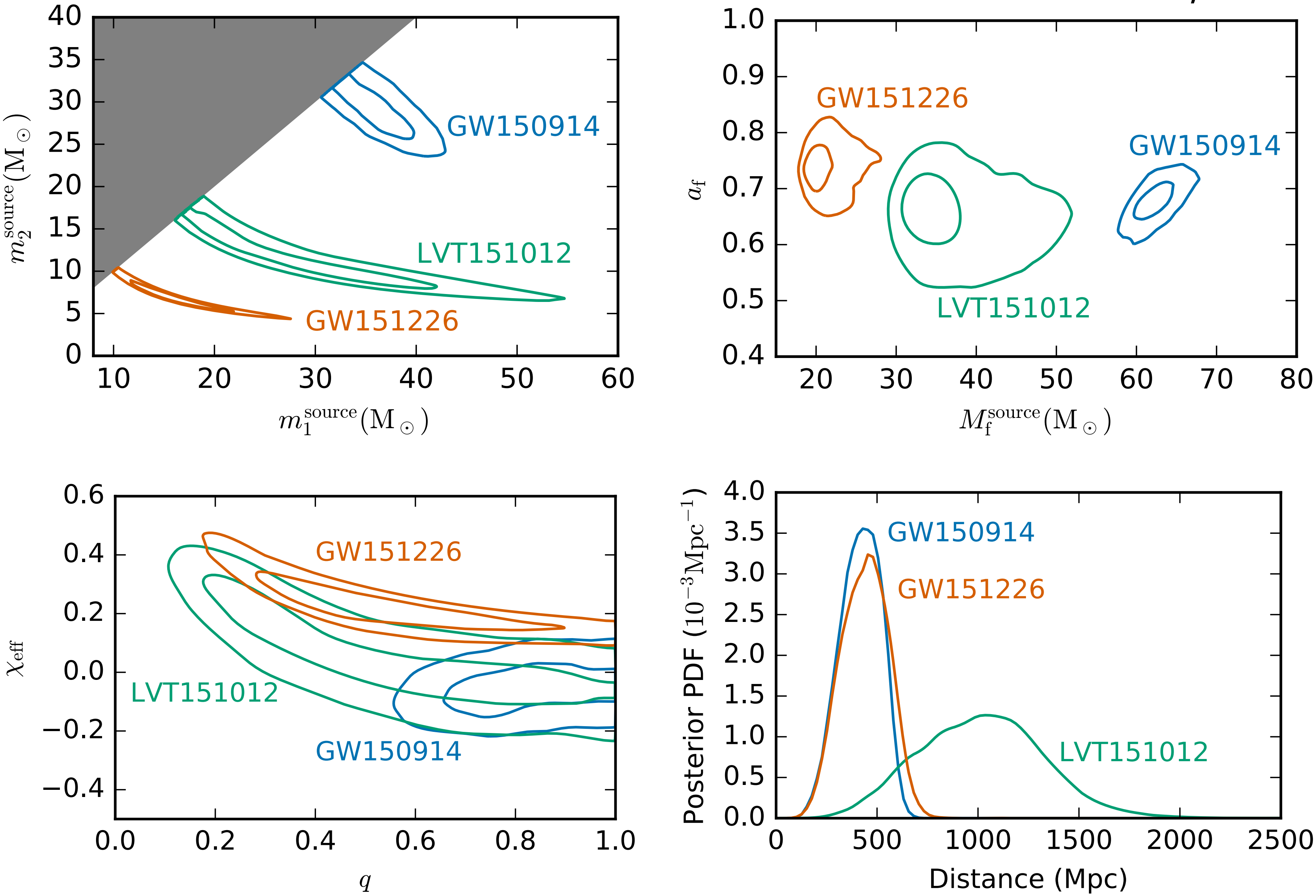
LIGO DETECTIONS SO FAR



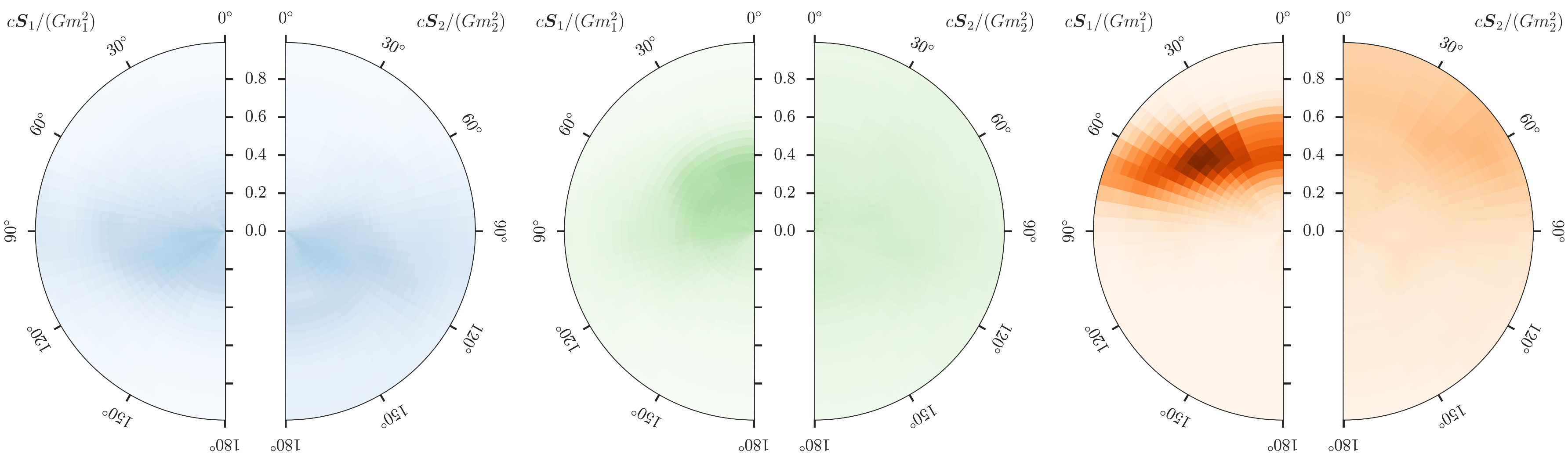
PROPERTIES OF EVENTS

50% AND 90% CREDIBLE INTERVALS

Abbott+ PRD, 2016



SPINS OF COMPONENT BLACK HOLES



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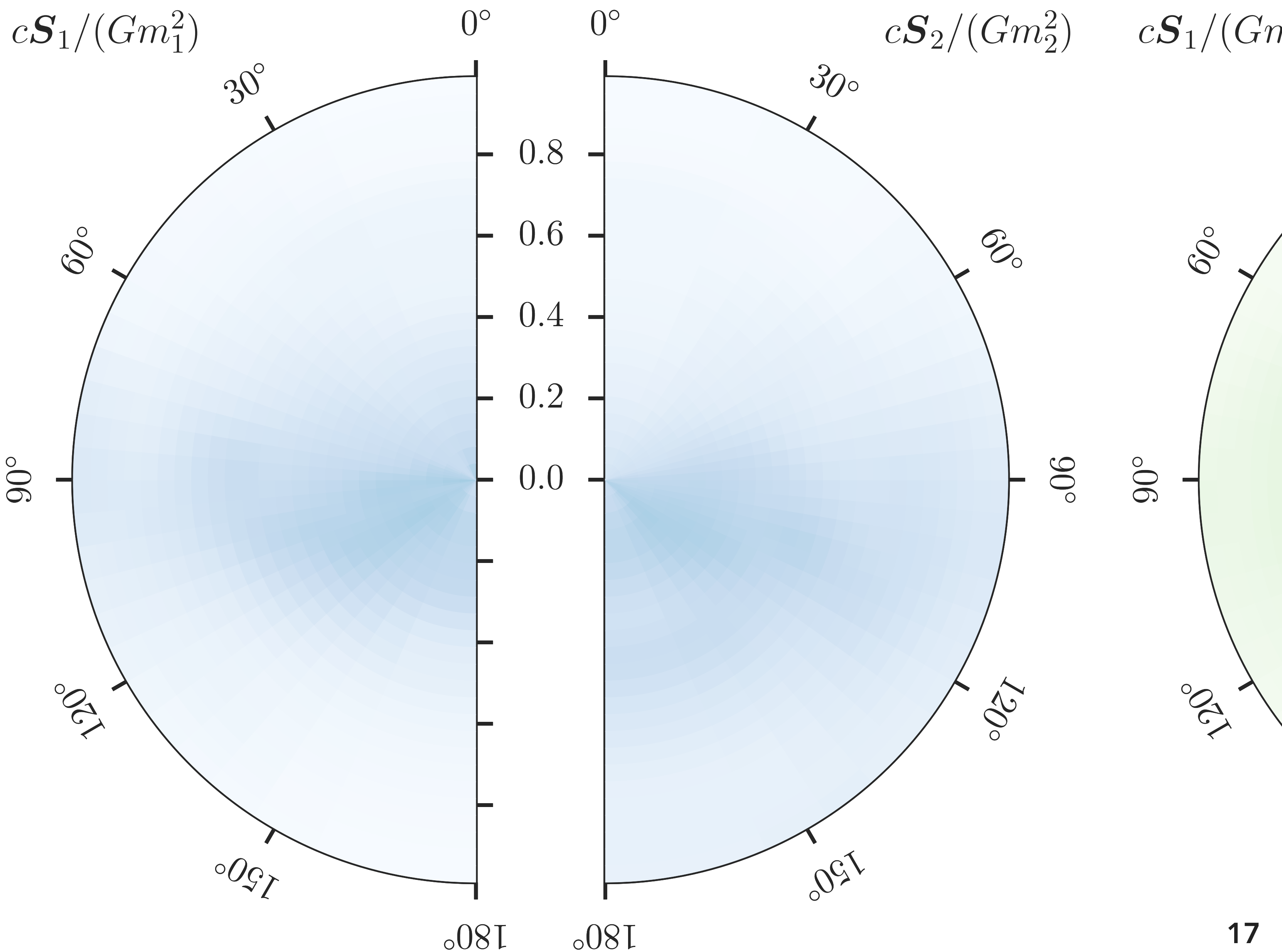

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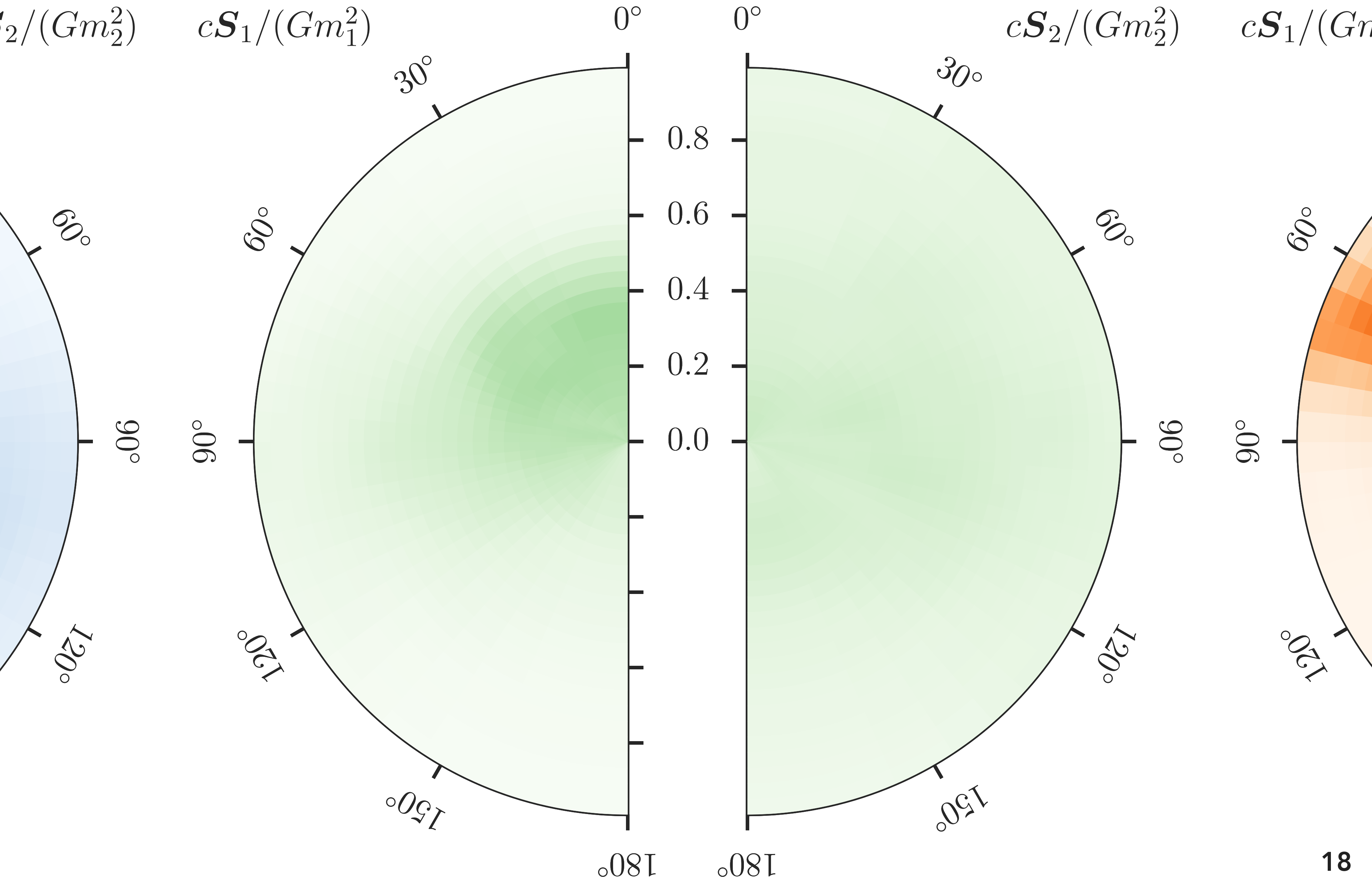

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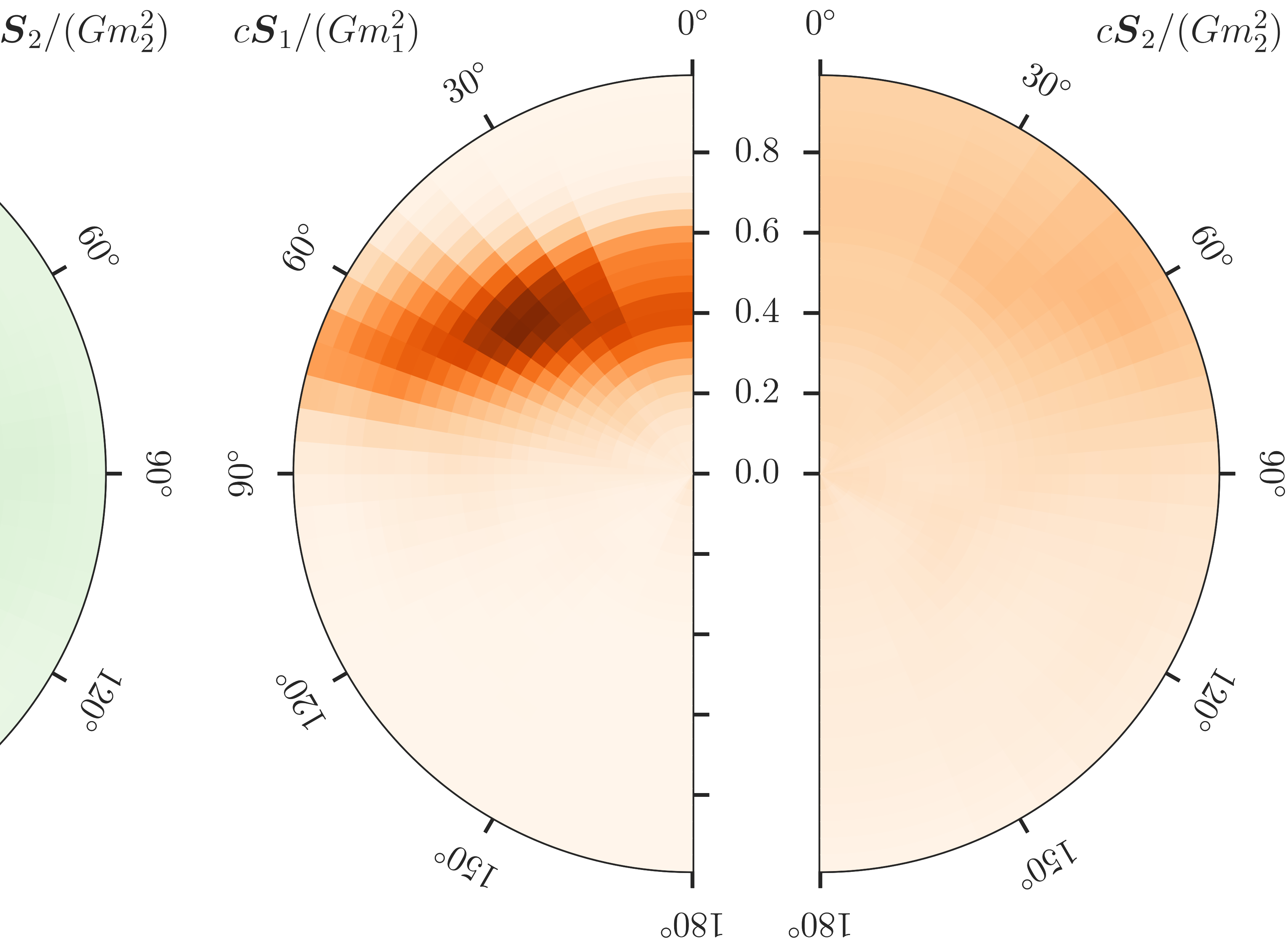
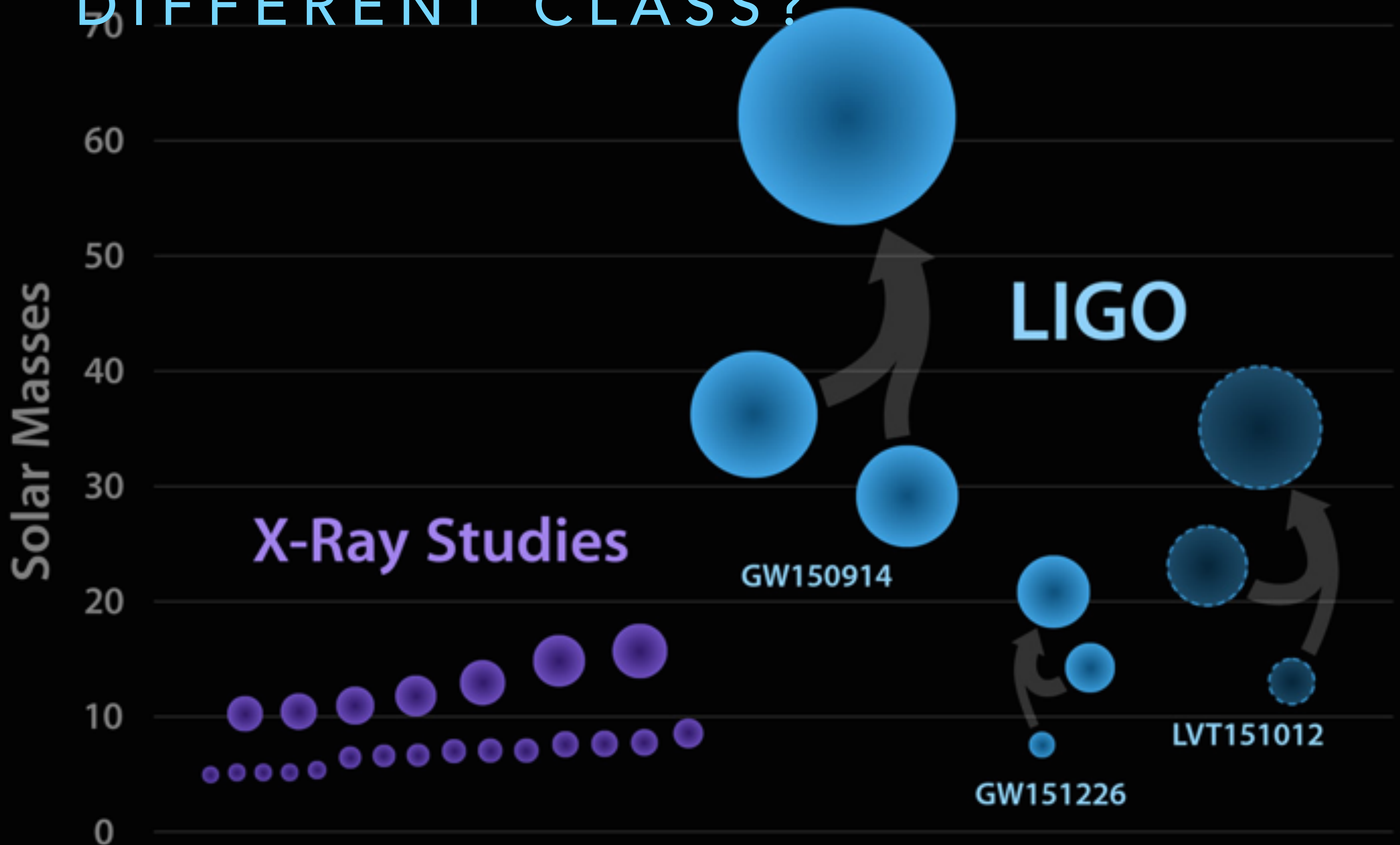


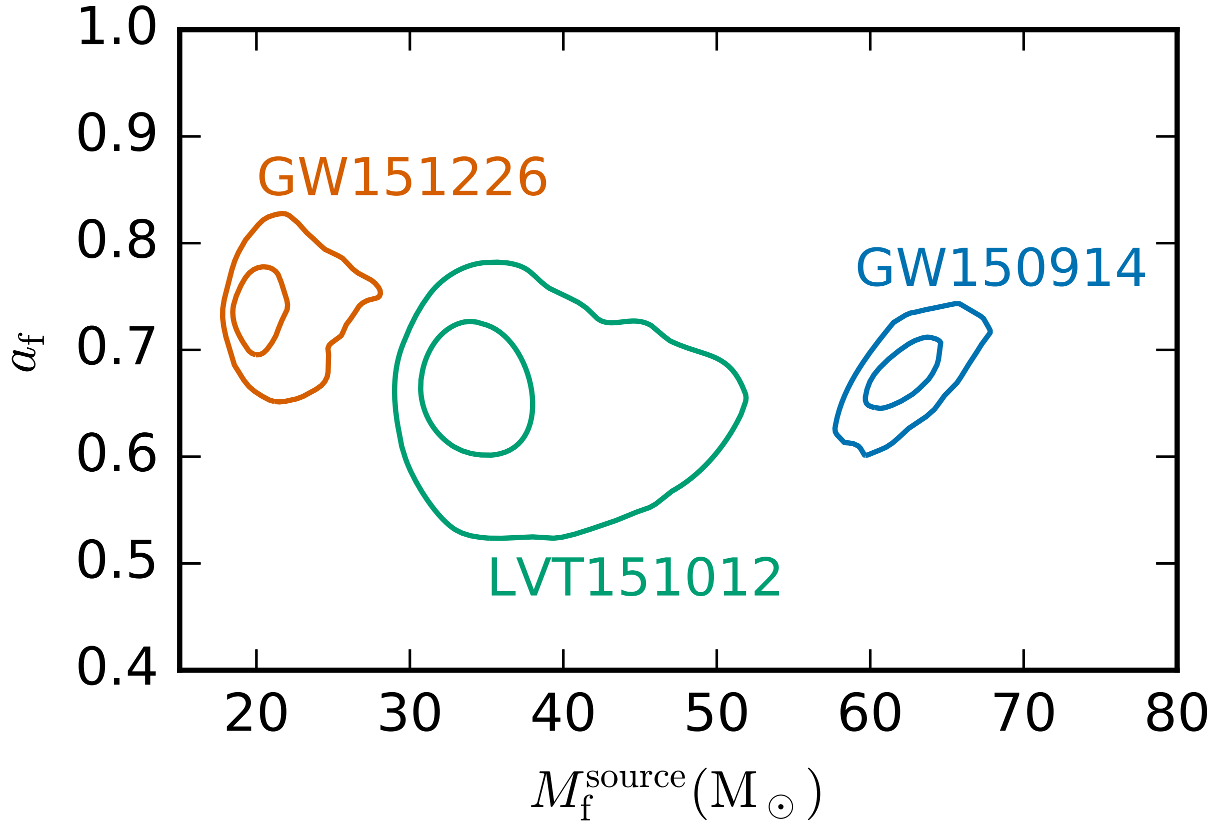
astrophysical implications of LIGO detections

ARE LIGO BLACK HOLES A DIFFERENT CLASS?



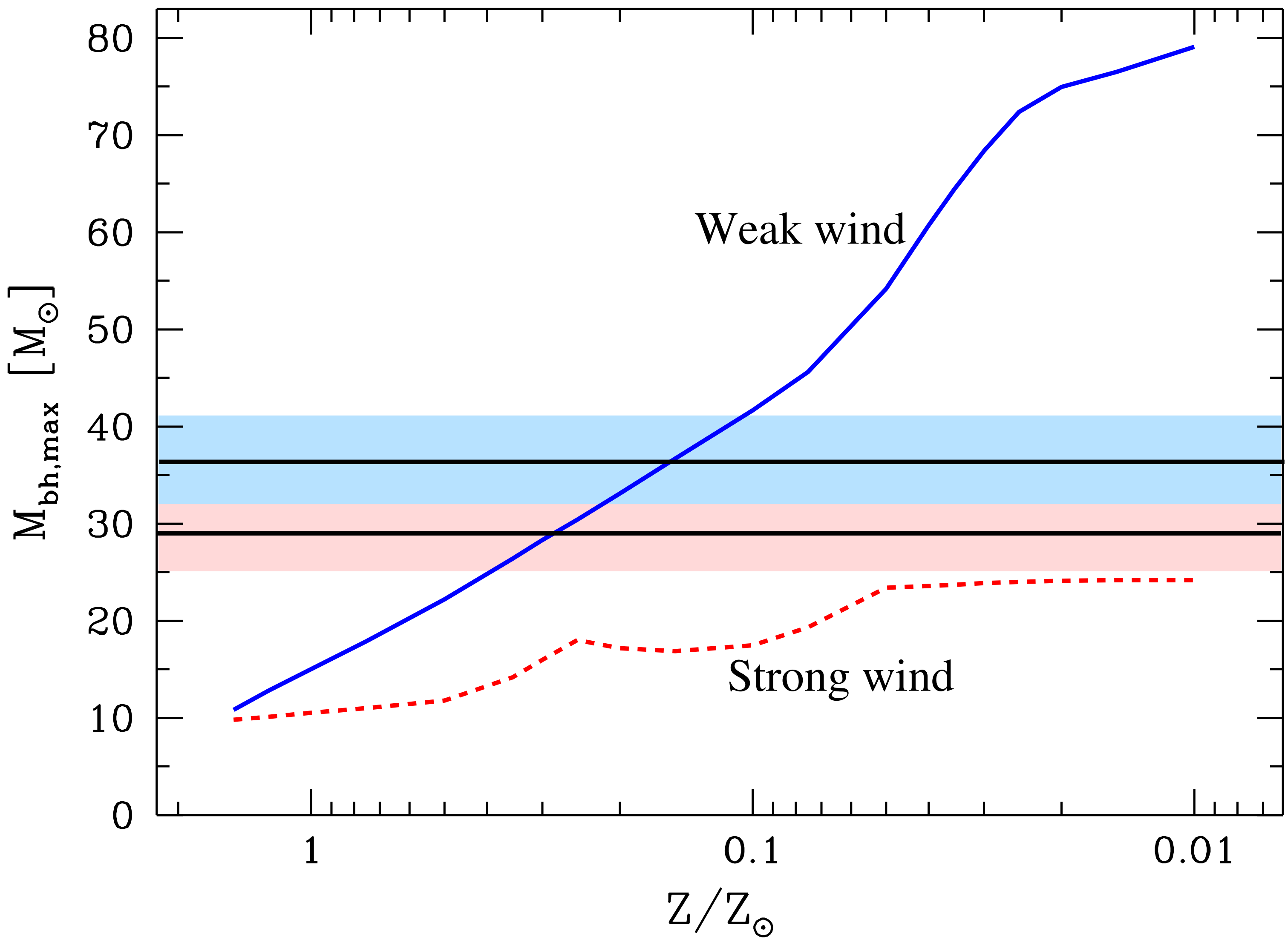
ligo.caltech.org

LIGO'S BLACK HOLES ARE THE LARGEST "STELLAR MASS" BLACK HOLES WE KNOW OF



Abbott+ PRD, 2016

HOW CAN SUCH BLACK HOLES FORM?



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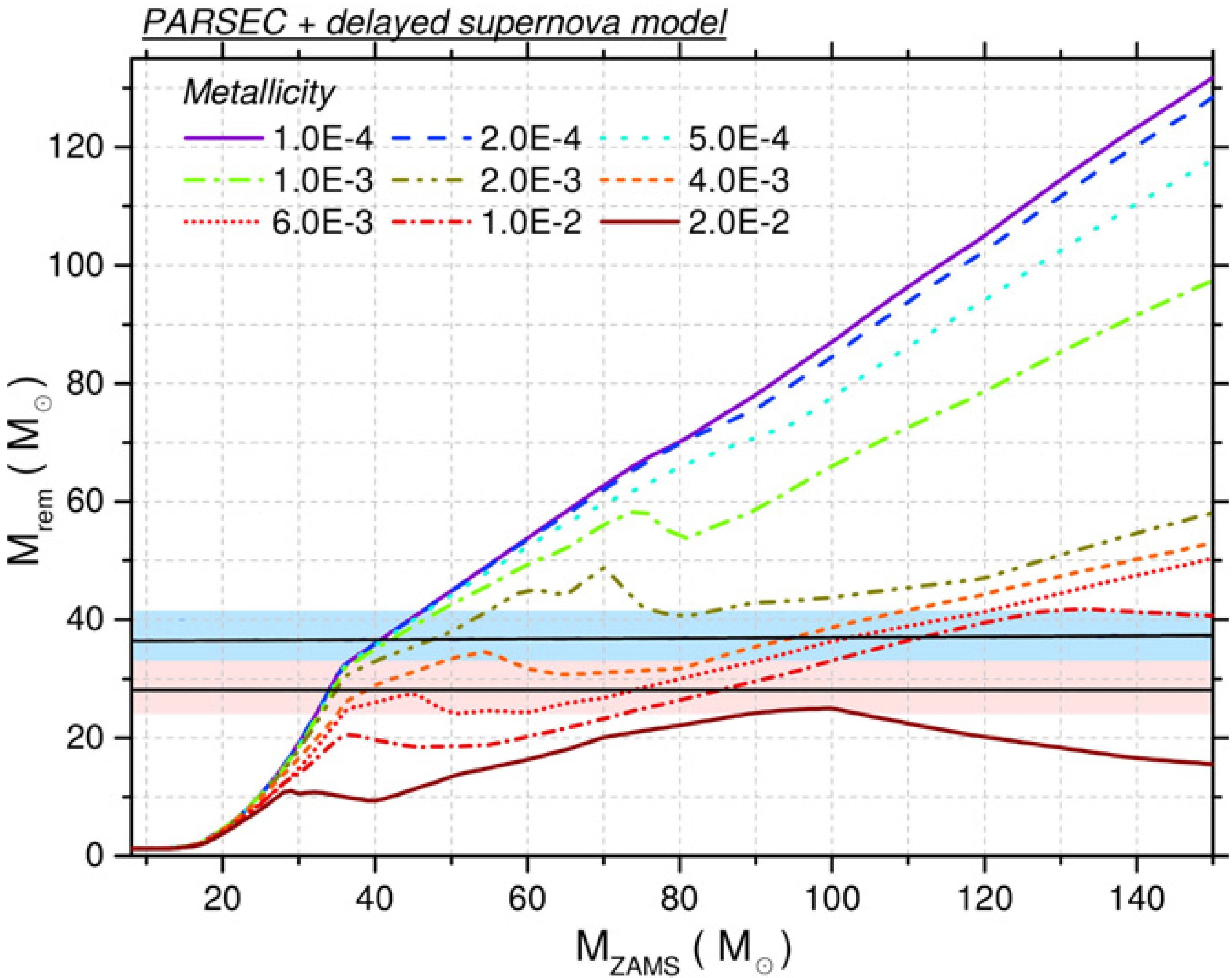
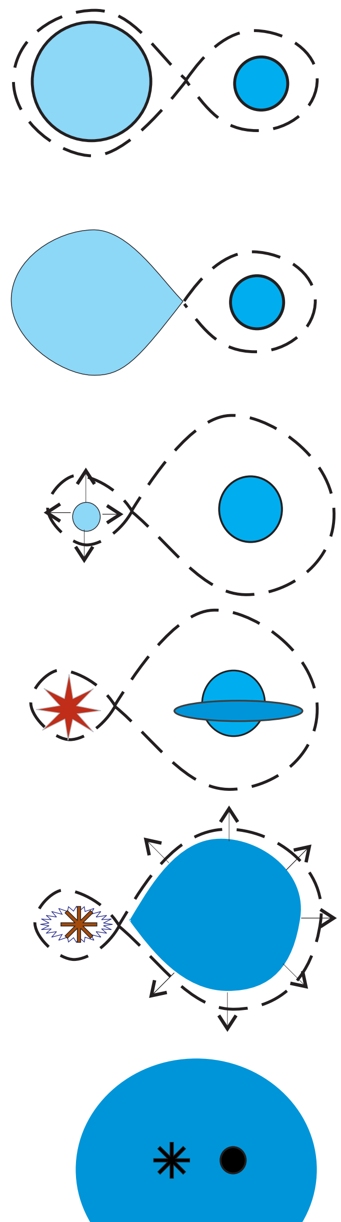


FORMATION AND EVOLUTION COMPACT BINARIES

- in isolated binaries
- in dense stellar clusters

(Lipunov+ 1997, Belczynski+ 2010, Dominik+ 2015, Belczynski+ 2015, Nelemans+ 2001, Rodriguez+ 2016, de Mink+ 2009, Marchant+ 2016, de Mink & Mandel 2016, Belczynski+ 2016)

FORMATION OF BINARY BLACK HOLES- ISOLATED BINARY



$T \sim 3$ Myr, $N \sim 10^4$ — **Two OB main-sequence stars**

$T \sim 10^4$ yr, $N \sim 30$ — **More massive star (primary) overfills Roche lobe. Stable or unstable nonconservative mass exchange**

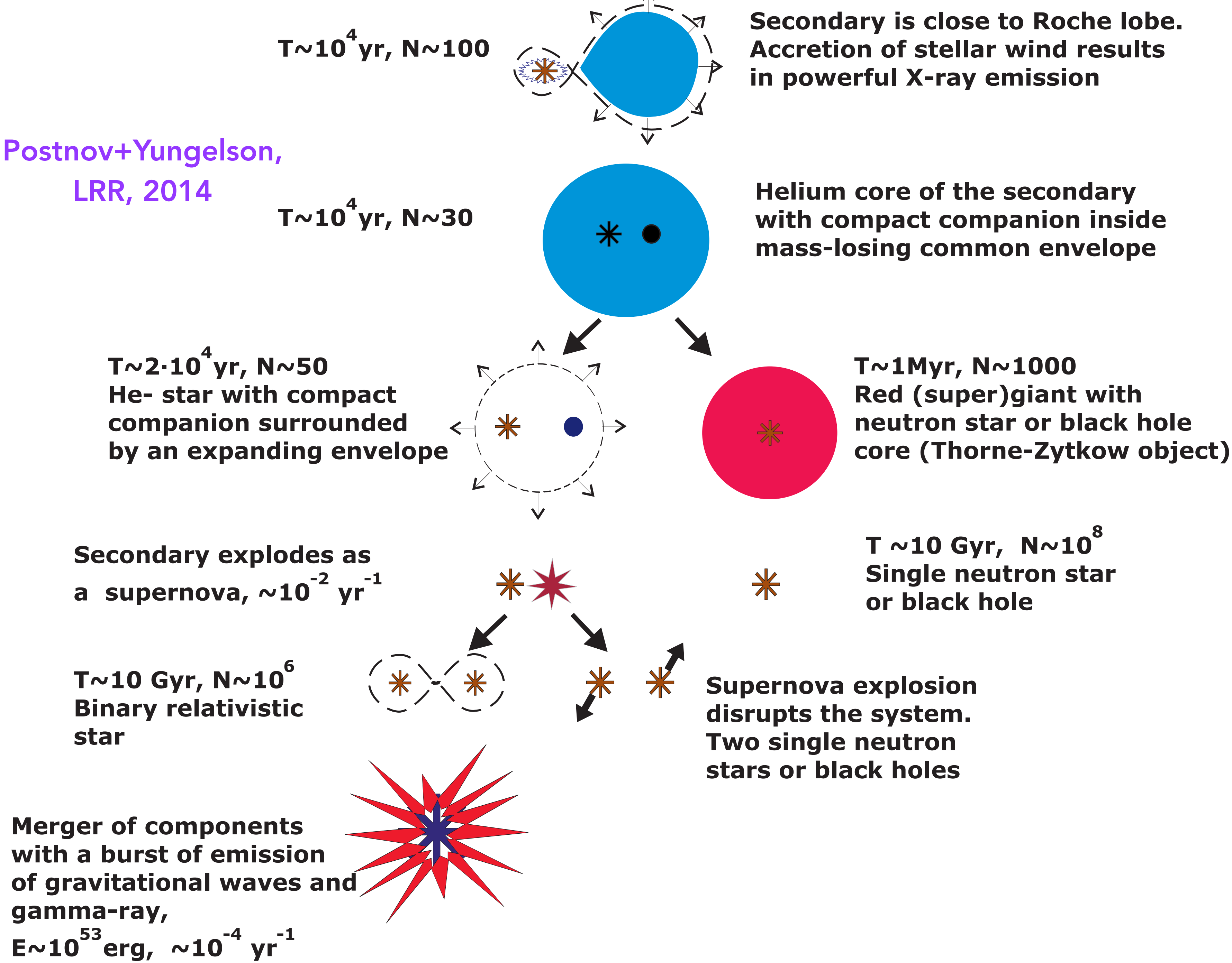
$T \sim 2 \cdot 10^5$ yr, $N \sim 500$ — **Helium-rich star with OB-companion**

$\sim 10^{-2}$ yr^{-1} — **Primary explodes as core-collapse SN or ECSN and becomes a neutron star or black hole**

$T \sim 10^4$ yr, $N \sim 100$ — **Secondary is close to Roche lobe. Accretion of stellar wind results in powerful X-ray emission**

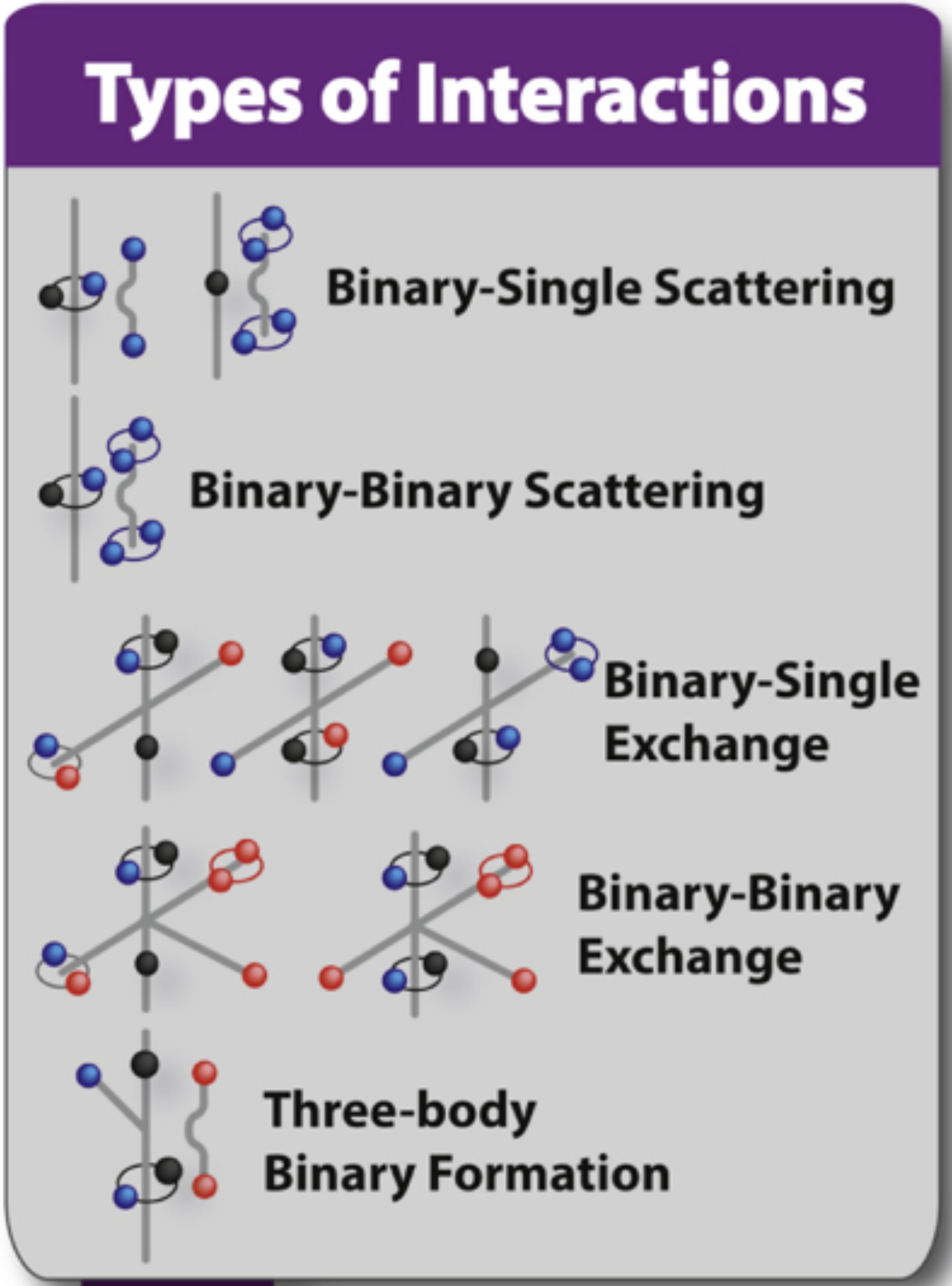
$T \sim 10^4$ yr, $N \sim 30$ — **Helium core of the secondary with compact companion inside mass-losing common envelope**

Postnov+Yungelson, LRR, 2014



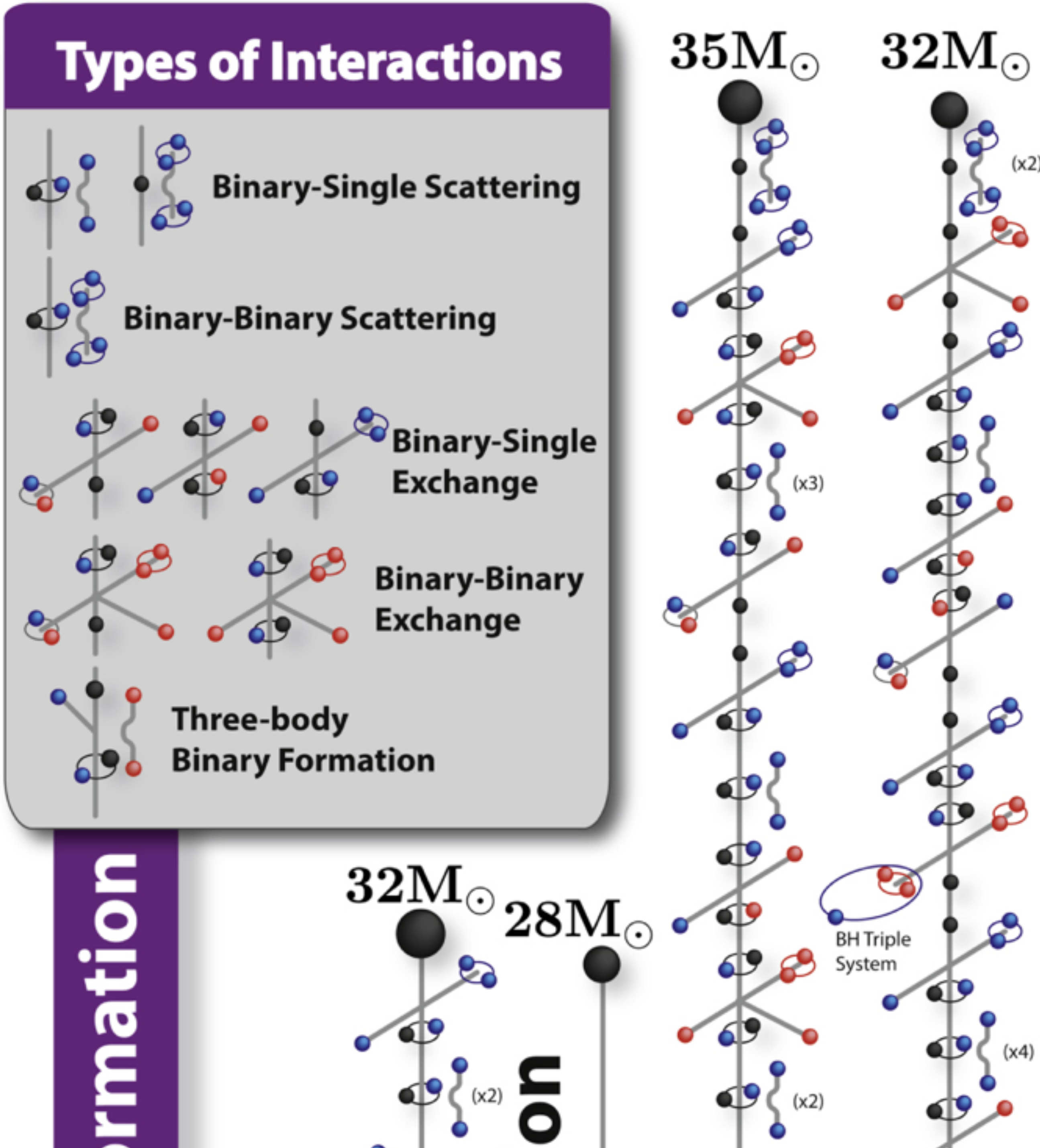
T~10^4 yr, N~100
Secondary is close to Roche lobe. Accretion of stellar wind results in powerful X-ray emission
Postnov+Yungelson, LRR, 2014
T~10^4 yr, N~30
Helium core of the secondary with compact companion inside mass-losing common envelope
T~$2\cdot10^4$ yr, N~50
He- star with compact companion surrounded by an expanding envelope
T~1Myr, N~1000
Red (super)giant with neutron star or black hole core (Thorne-Zytkow object)
Secondary explodes as a supernova, ~10^{-2} yr^{-1}
T ~10 Gyr, N~10^8
Single neutron star or black hole
T~10 Gyr, N~10^6
Binary relativistic star
Supernova explosion disrupts the system. Two single neutron stars or black holes
Merger of components with a burst of emission of gravitational waves and gamma-ray,
E~10^{53} erg, ~10^{-4} yr^{-1}

BINARY BLACK HOLE FORMATION VIA DYNAMICAL PROCESSES



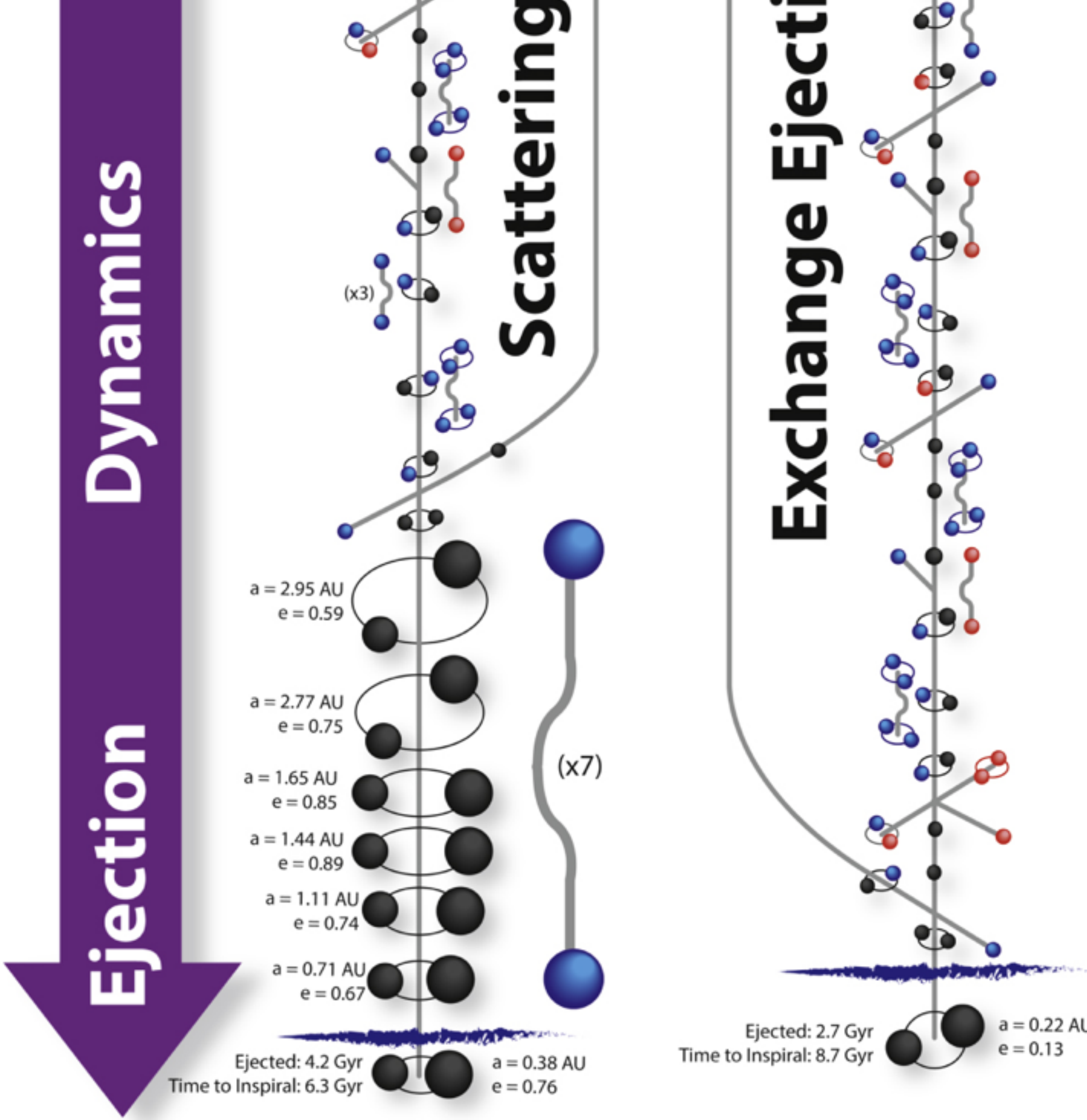
Rodriguez+, ApJL, 2016

BINARY BLACK HOLE FORMATION VIA DYNAMICAL PROCESSES



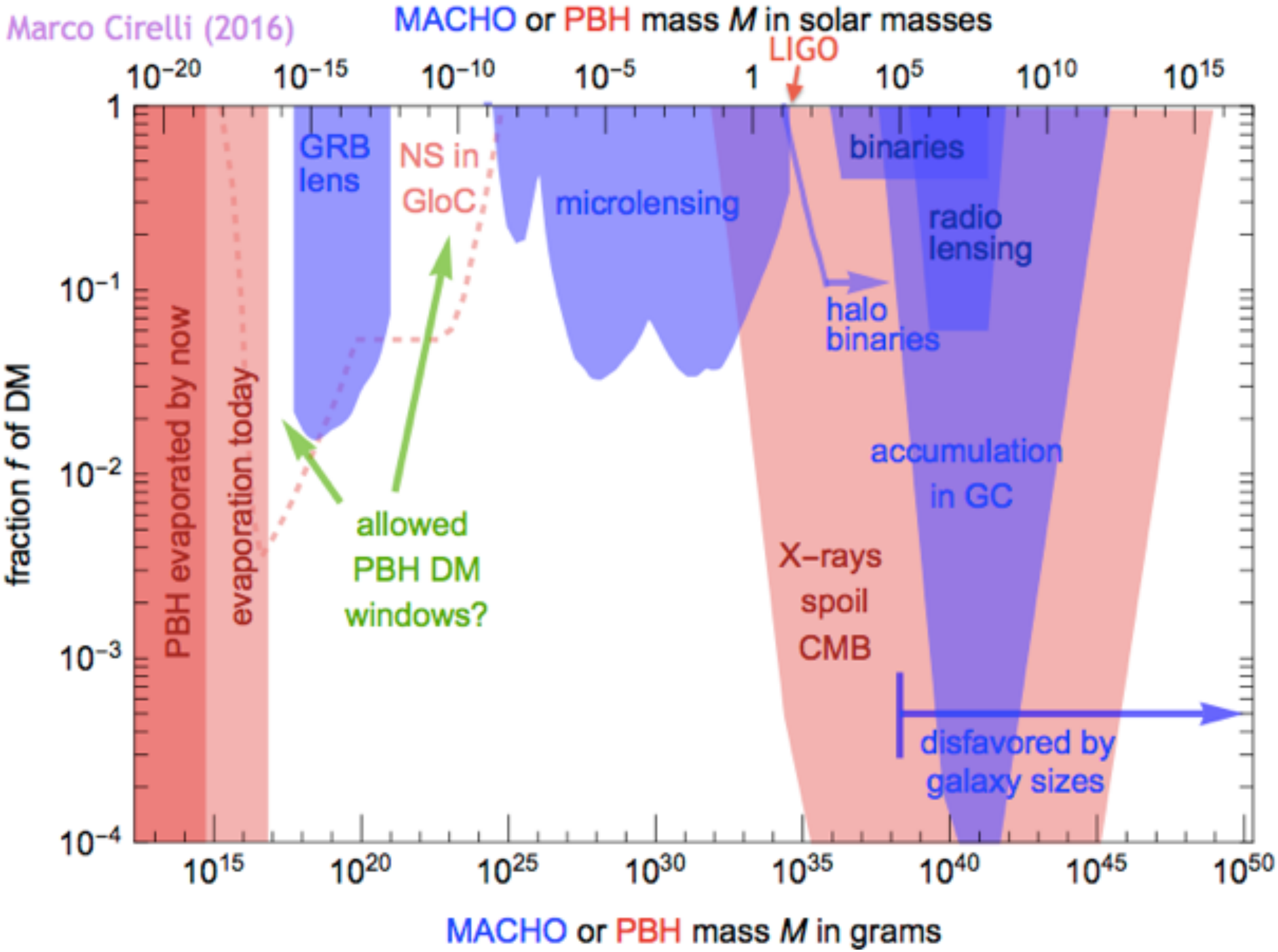
Rodriguez+, ApJL, 2016

BINARY BLACK HOLE FORMATION VIA DYNAMICAL PROCESSES

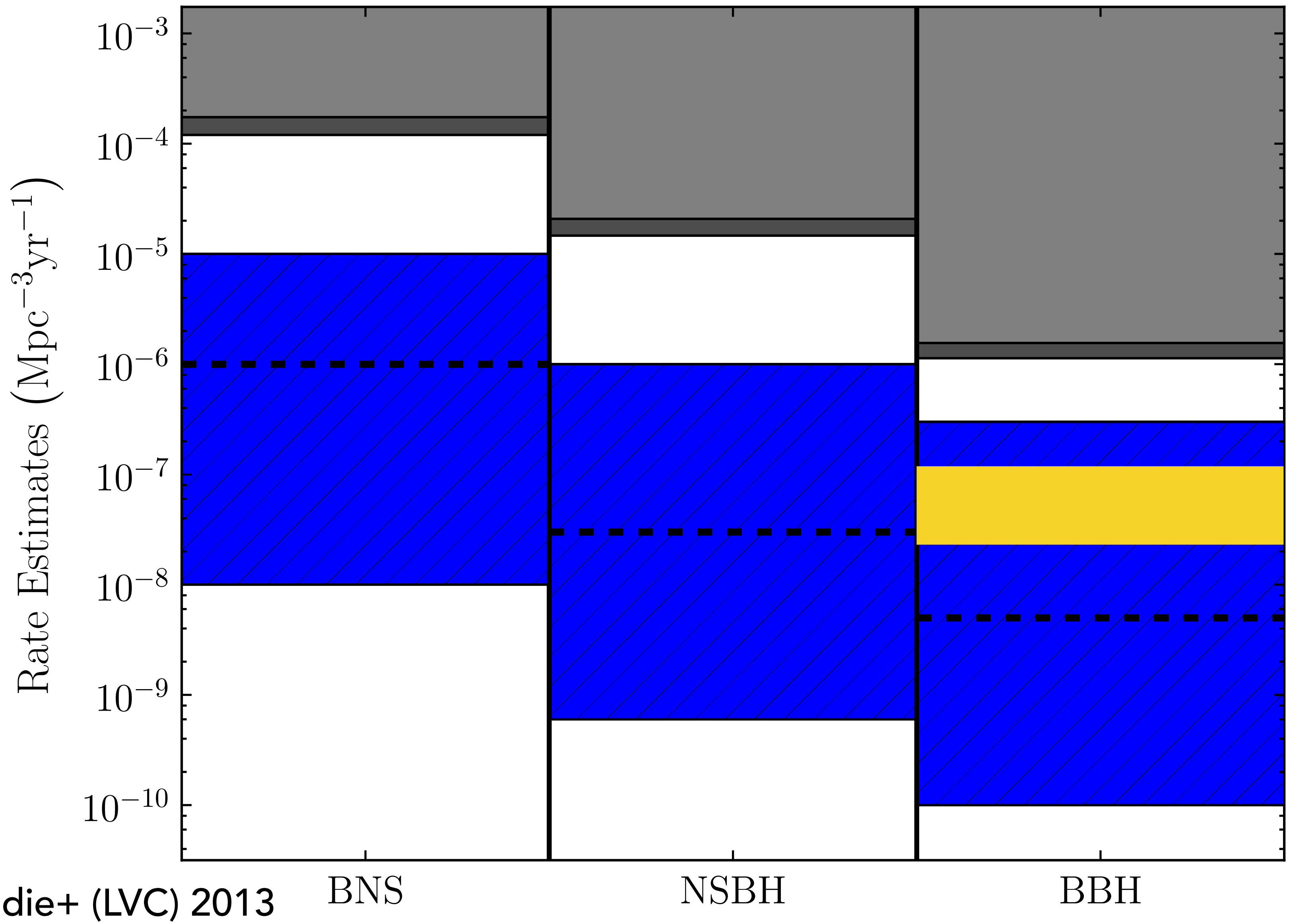


Rodriguez+, ApJL, 2016

WHAT PBH ARE ALLOWED?

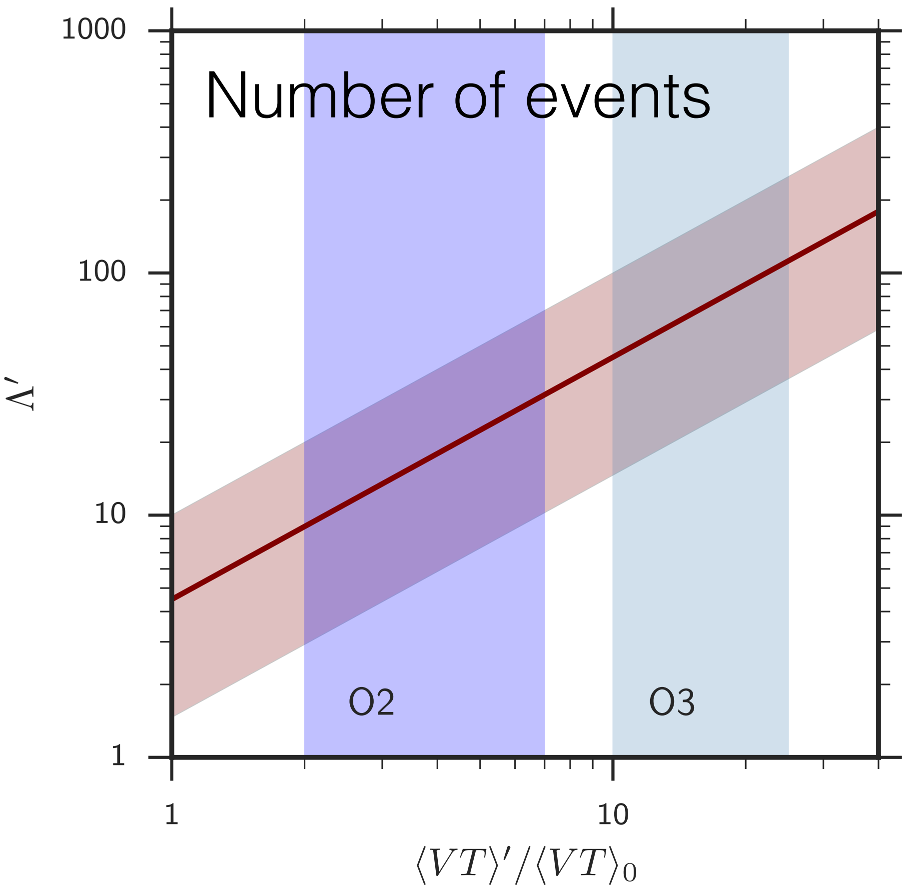


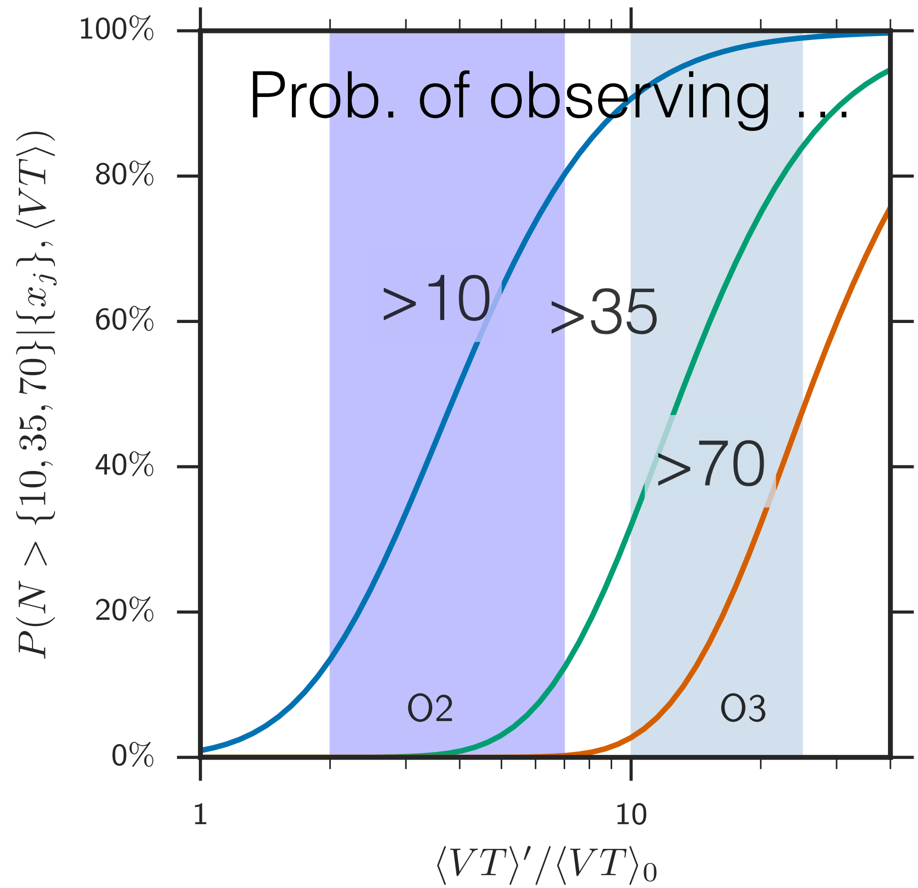
LIGO-VIRGO BEST UPPER LIMITS AND IMPLICATIONS FOR DETECTION



Abadie+ (LVC) 2013

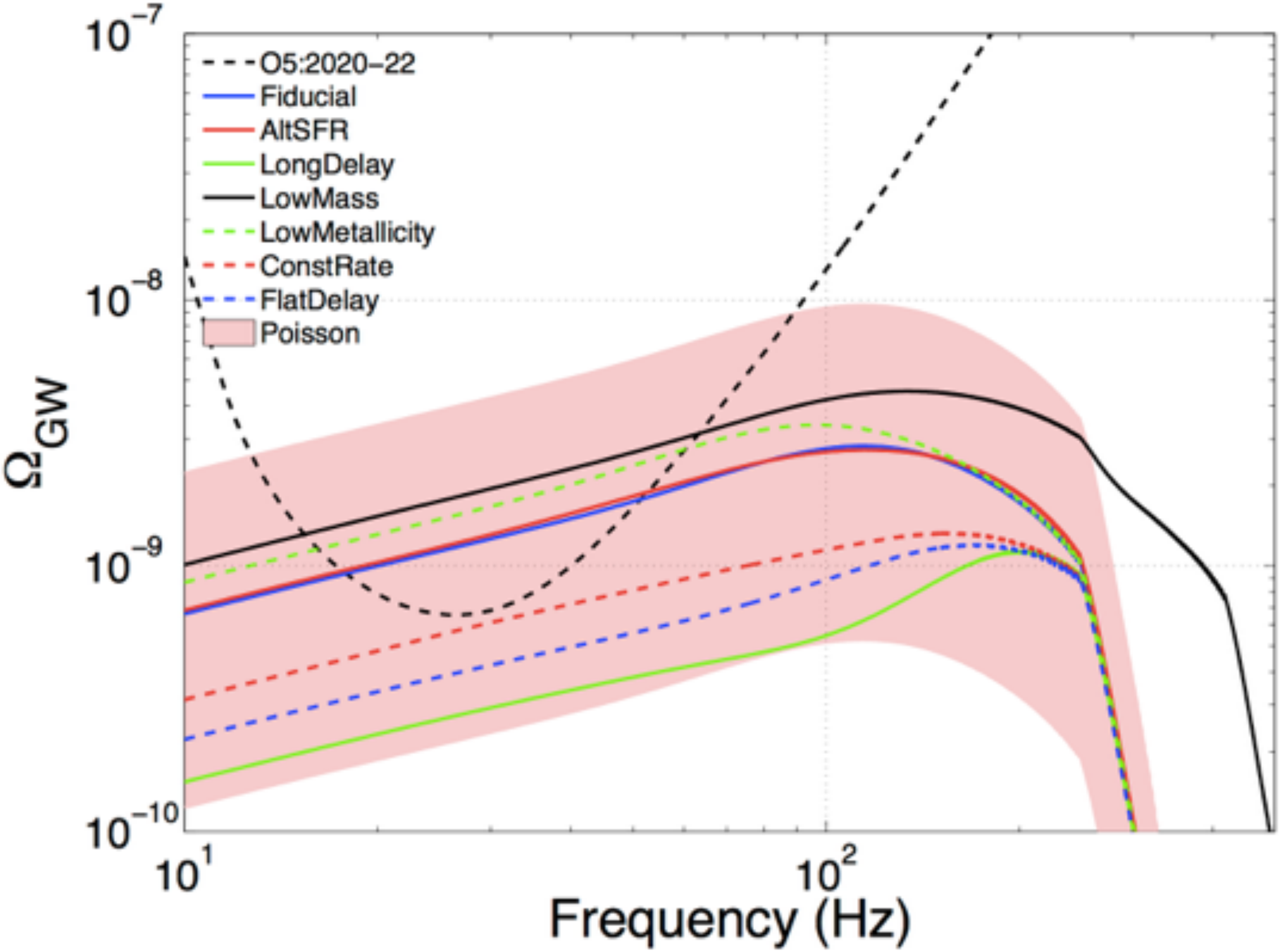
EXPECTED HIGH CONFIDENCE DETECTIONS IN FUTURE RUNS





Abbott+ arXiv:1602.03842, arXiv:160603939

STOCHASTIC BACKGROUND



arXiv:1602.03847

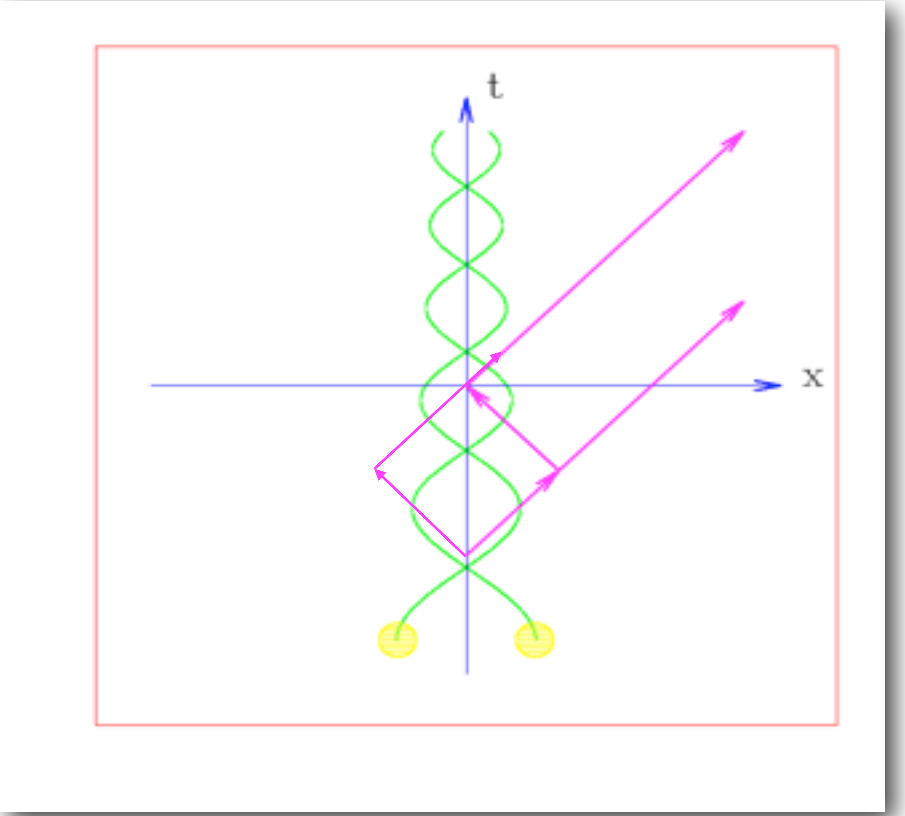
tests of general relativity

BINARY BLACK HOLES AS TESTBEDS OF GENERAL RELATIVITY

- Gravity gets ultra-strong during a BBH merger compared to any observations in the solar system or in binary pulsars
  - in the solar system: $\Phi/c^2 \sim 10^{-6}$
  - In a binary pulsar: $\Phi/c^2 \sim 10^{-4}$
  - Near a black hole: $\Phi/c^2 \sim 0.5$
- Dissipative predictions of gravity are not even tested at the 1st post-Newtonian order
  - In binary black holes even $(v/c)^7$ post-Newtonian terms might not be adequate for high SNR (~100) events expected to be observed by Advanced LIGO, Virgo and KAGRA

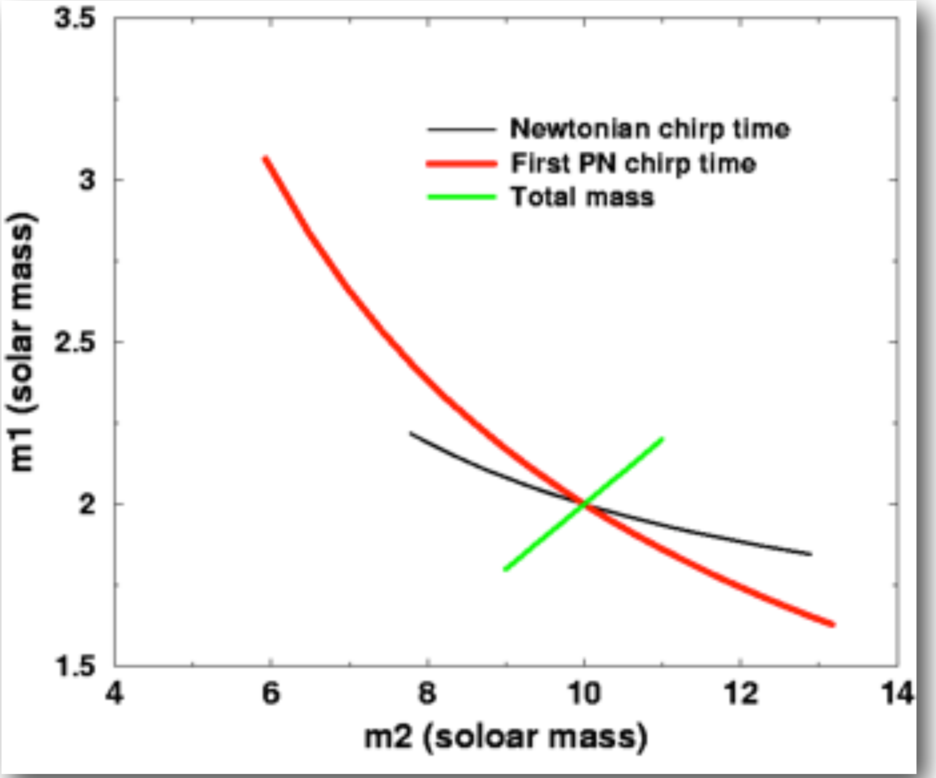
LOOKING FOR TAILS OF GRAVITATIONAL WAVES

Gravitational wave tails



Blanchet and Schaefer (1994)

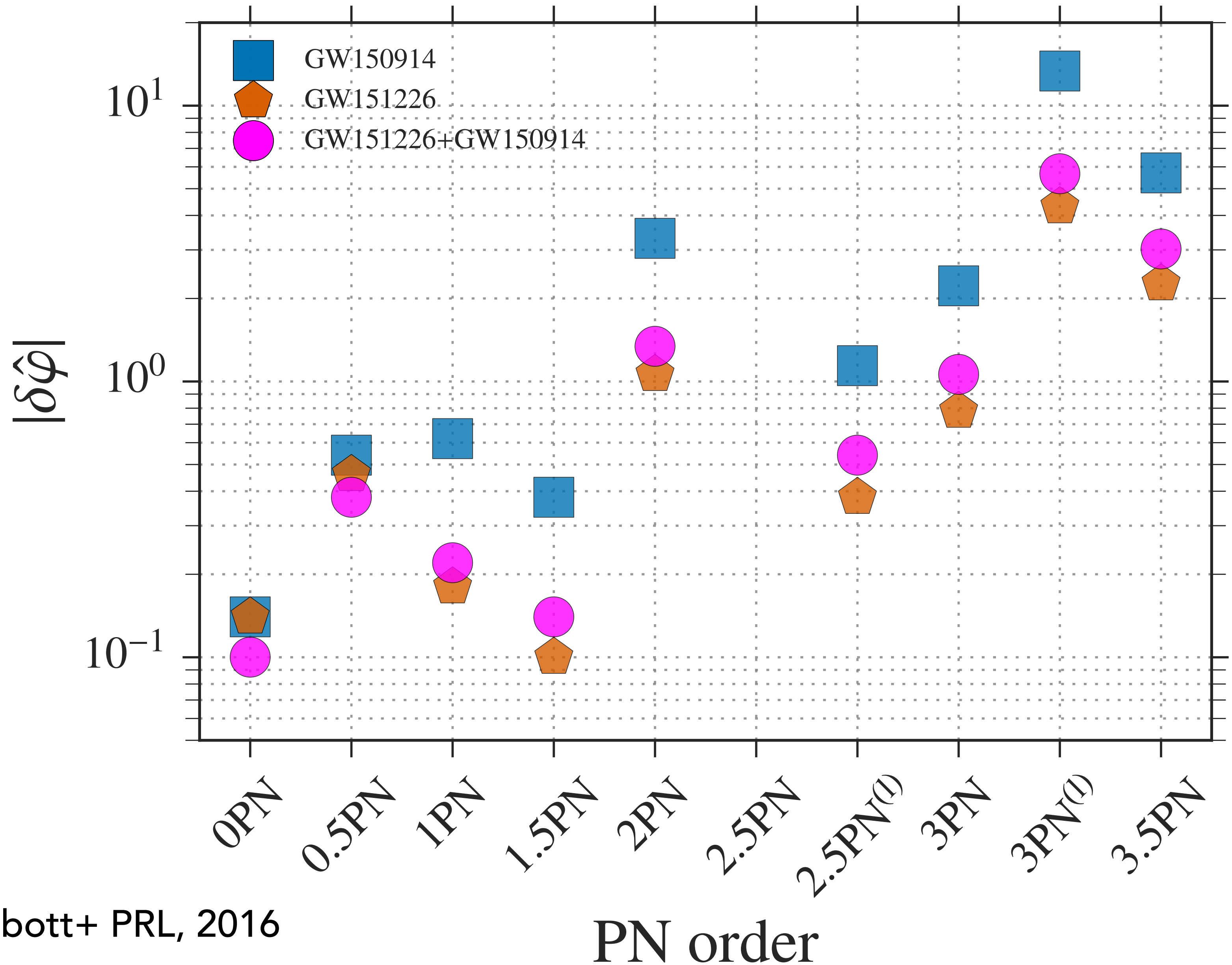
Testing the presence of tails



Blanchet and Sathyaprakash (1995)

IS THE SIGNAL CONSISTENT WITH GENERAL RELATIVITY?

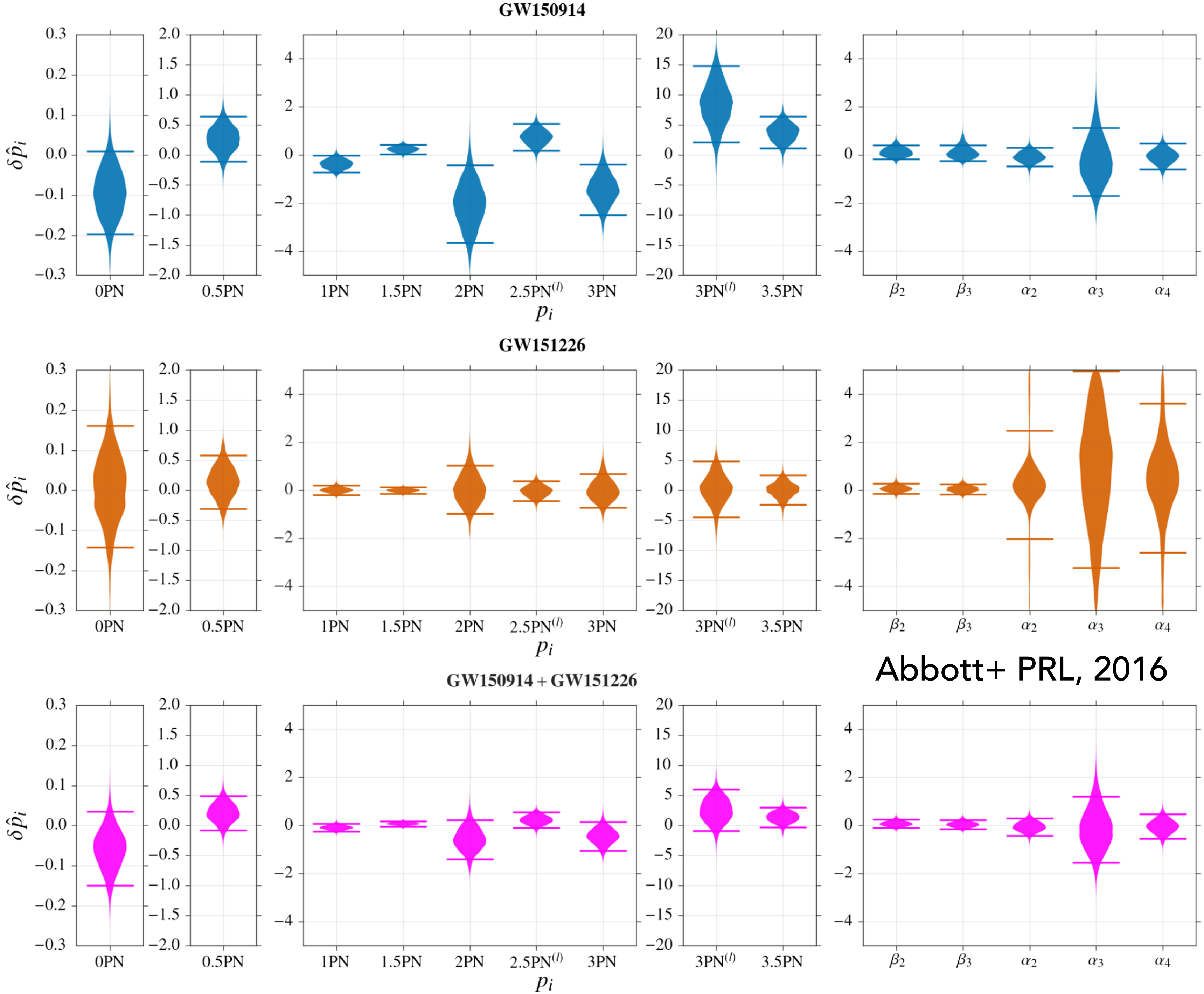
TESTS OF THE POST-NEWTONIAN THEORY



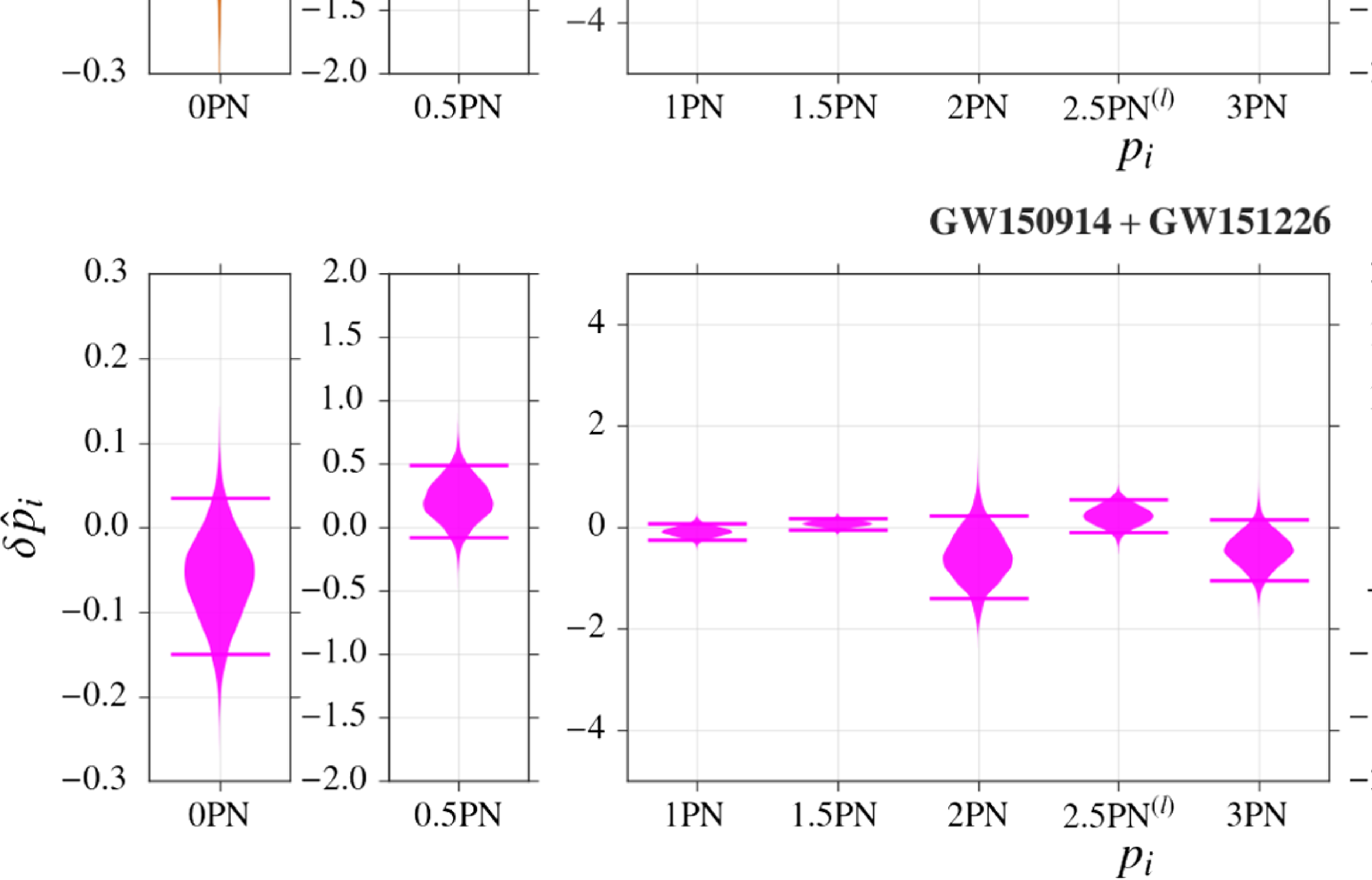
Abbott+ PRL, 2016

IS THE SIGNAL CONSISTENT WITH GENERAL RELATIVITY?

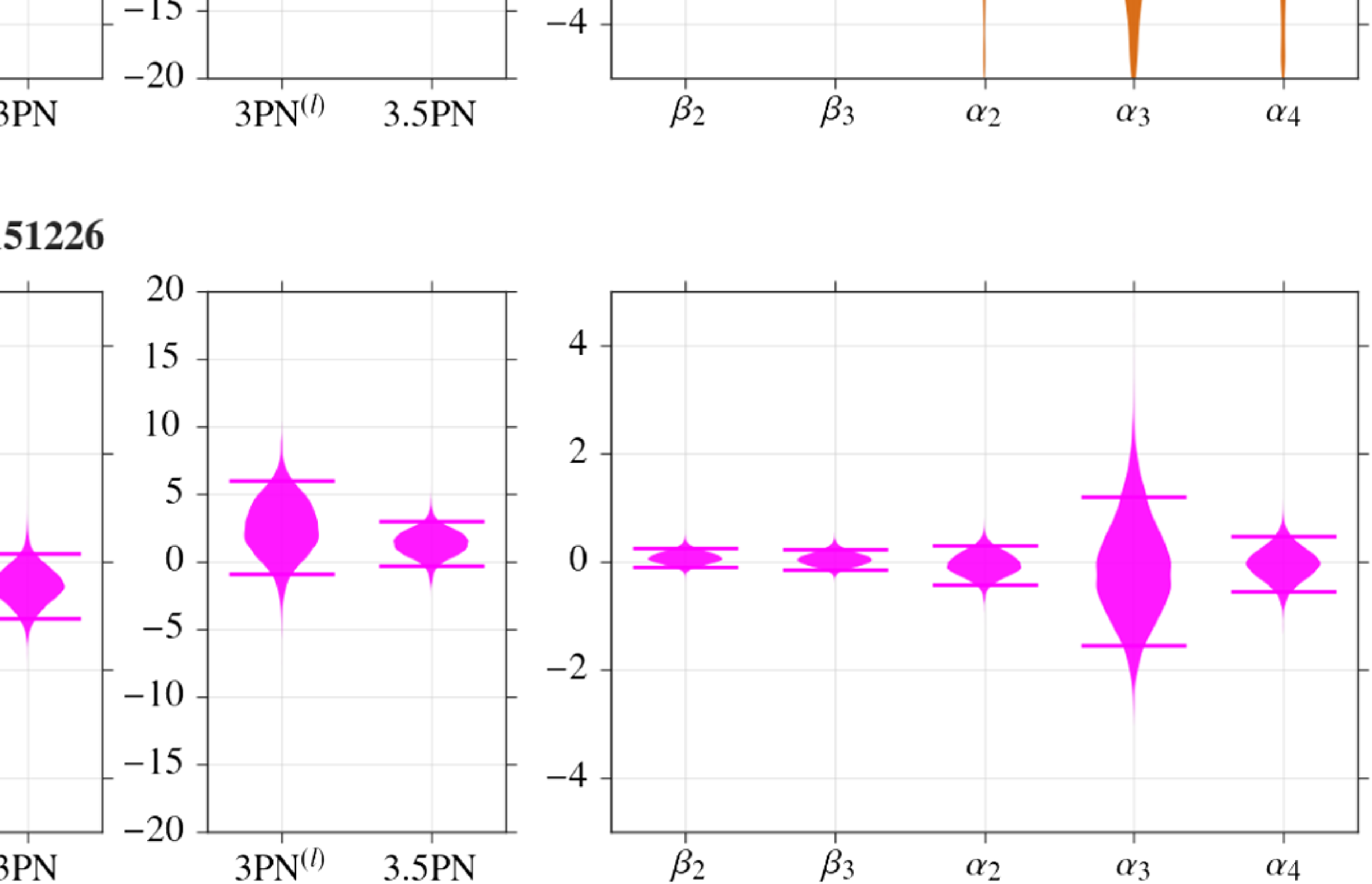
DEVIATIONS OF THE SIGNAL FROM GENERAL RELATIVITY



Abbott+ PRL, 2016



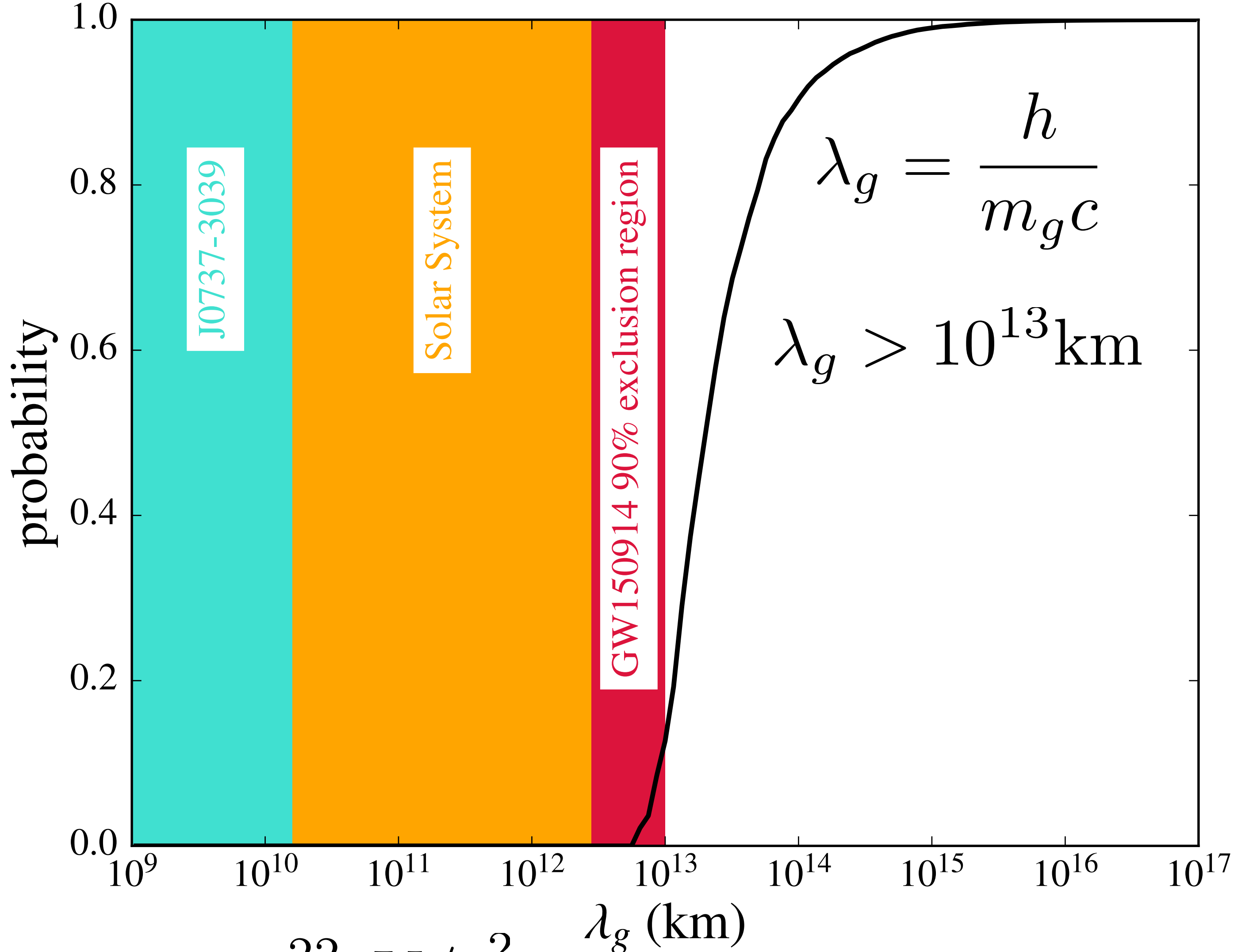
Abbott+ PRL, 2016



Abbott+ PRL, 2016

GRAVITON MASS

LIMIT ON GRAVITON MASS

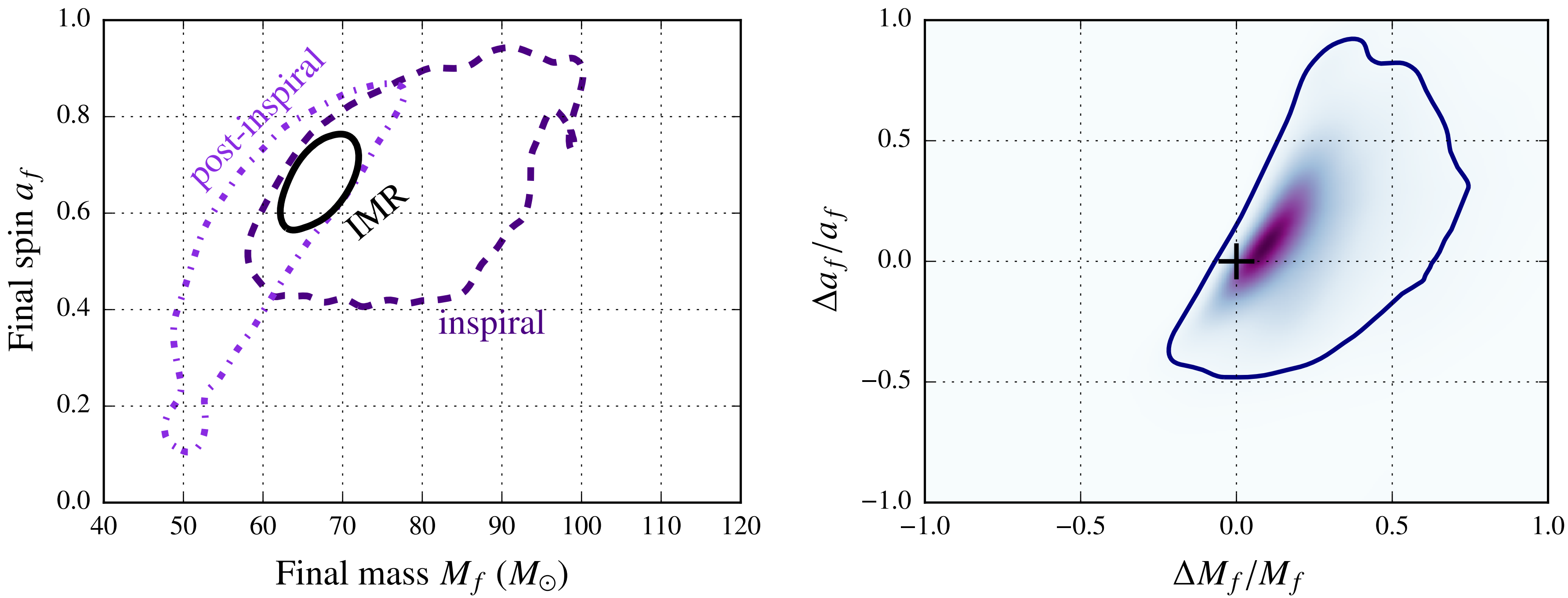


$$m_g < 1.2 \cdot 10^{-22}\mathrm{eV/c^2}$$

Abbott+ PRL, 2016

IS THE SIGNAL CONSISTENT WITH A BLACK HOLE REMNANT

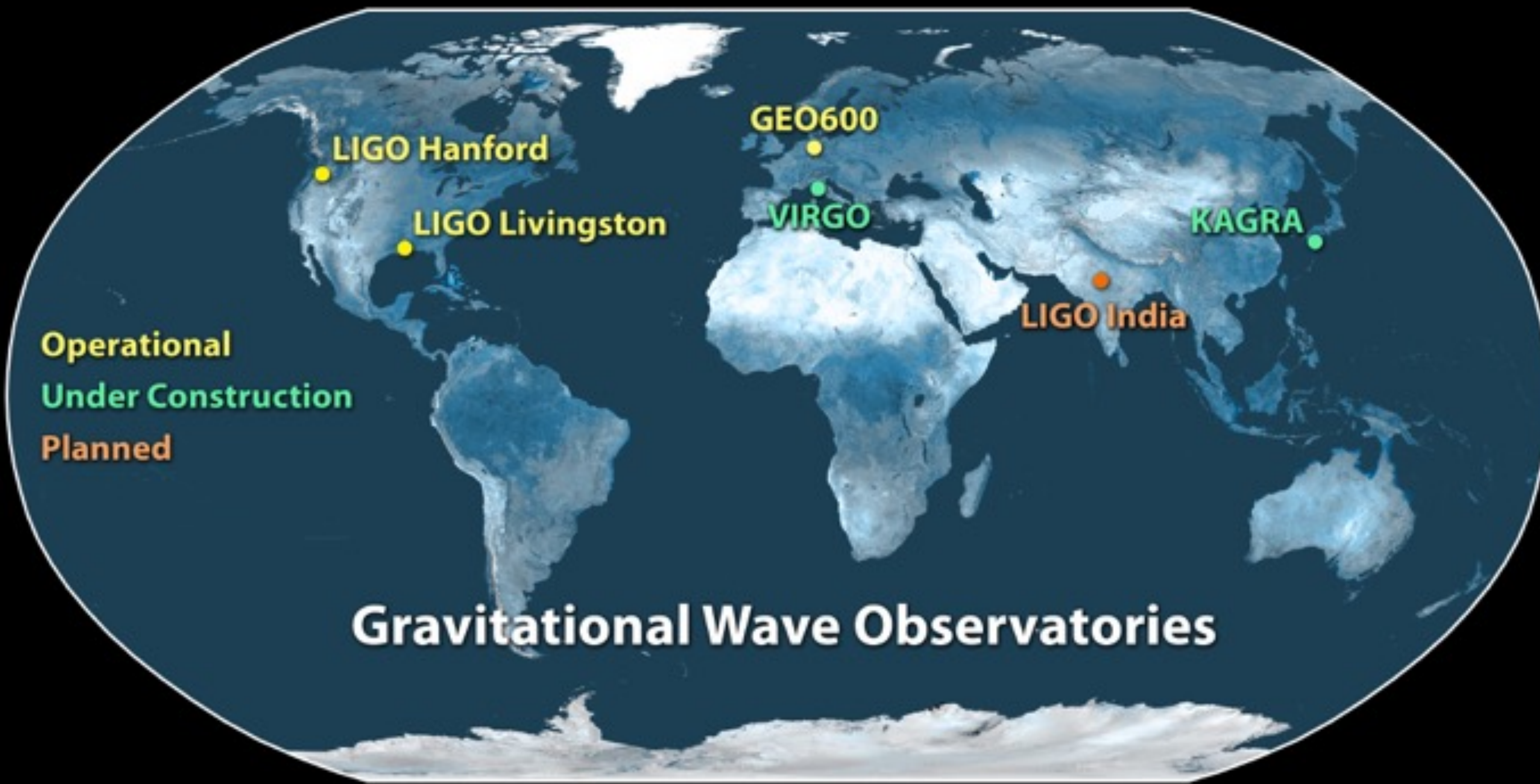
FINAL BH MASS AND SPIN



Abbott+ PRL, 2016

developments expected within the next 10 years

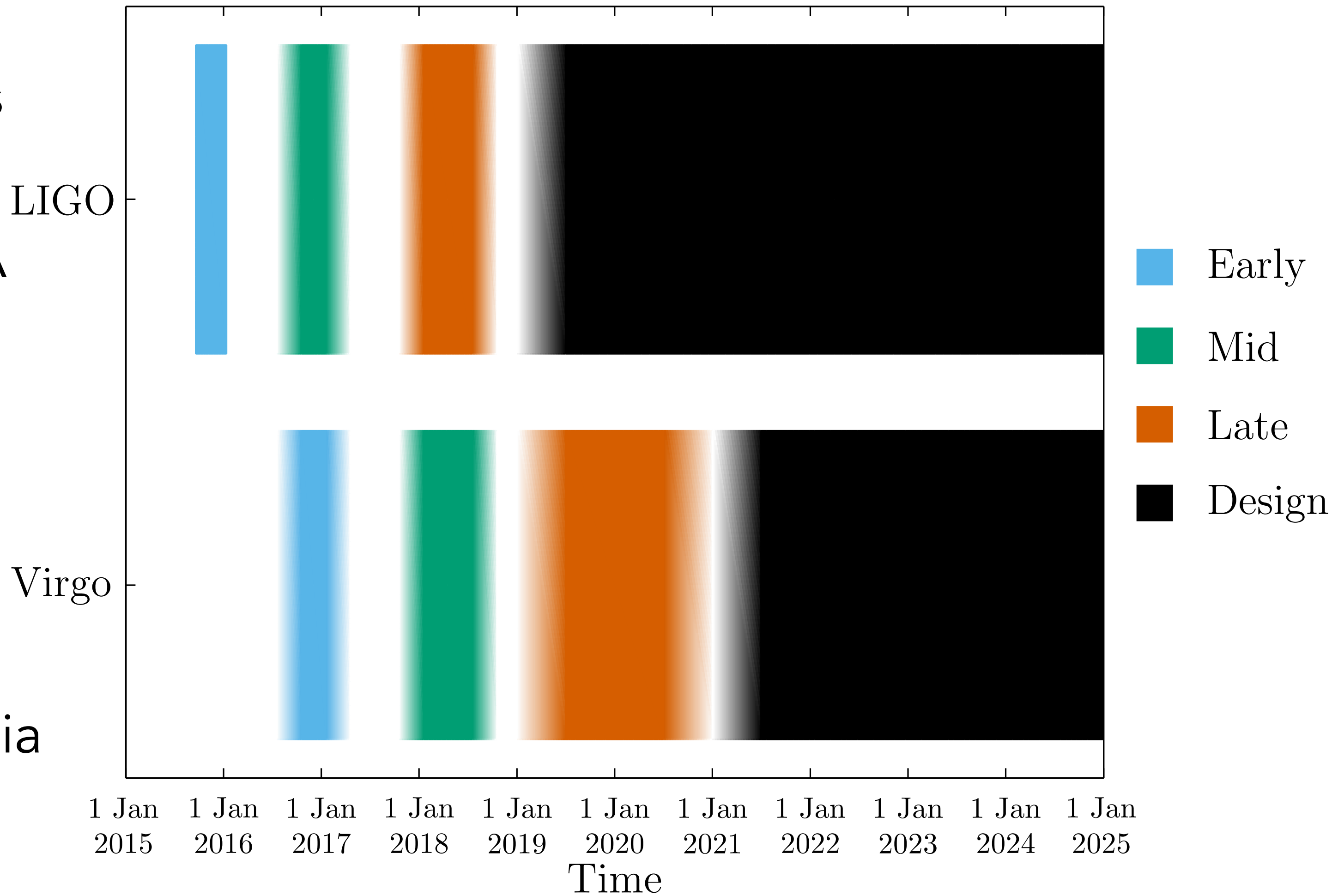
A GLOBAL NETWORK OF GRAVITATIONAL WAVE DETECTORS

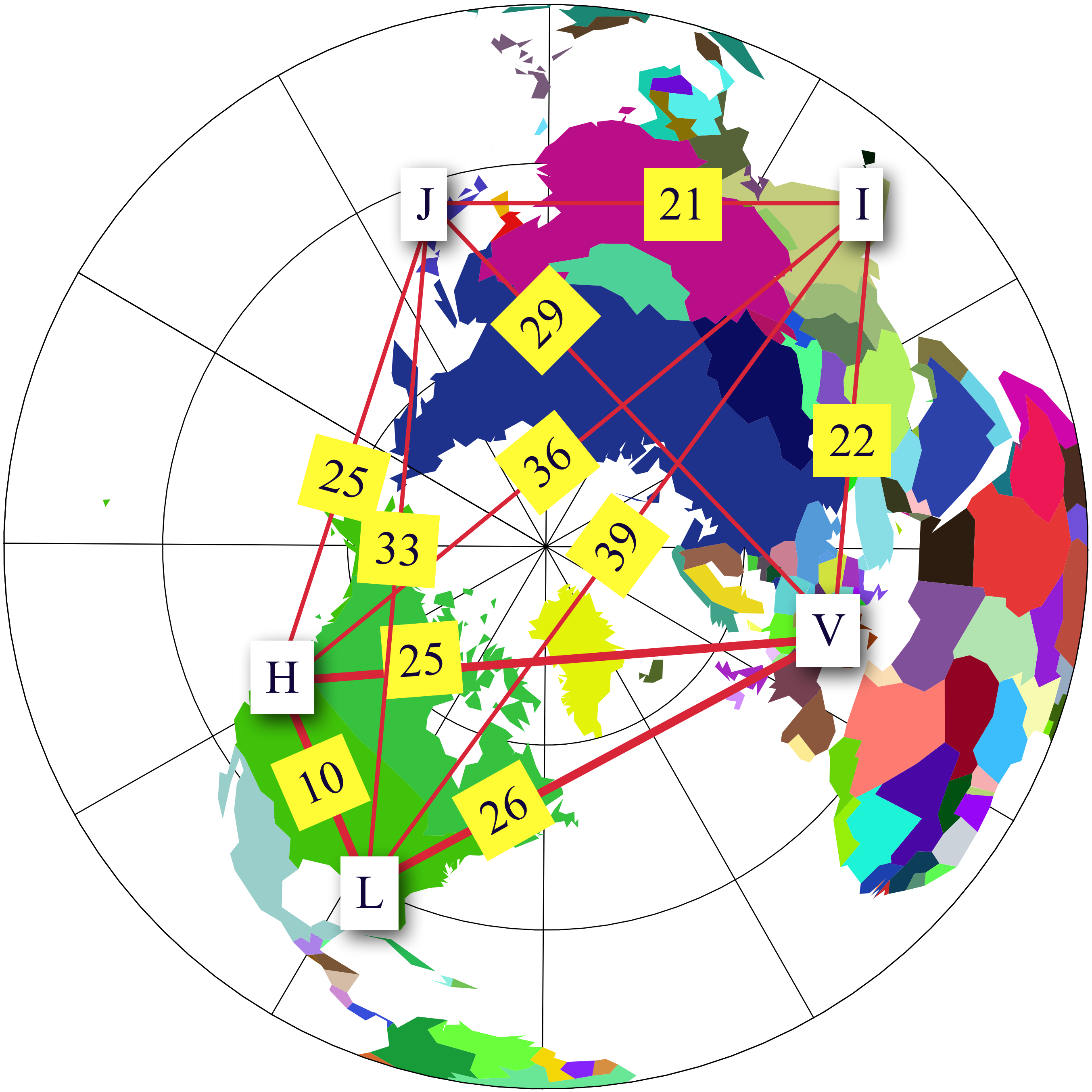


GW NETWORK

LVC, Living Rev. Relativity 19 (2016), 1

- O2: 6 months 2016-2017
- O3: 9 months 2017-2018
- 2018: KAGRA operational
- 2019+: LIGO full sensitivity
- 2022+: Virgo full sensitivity and LIGO India operational



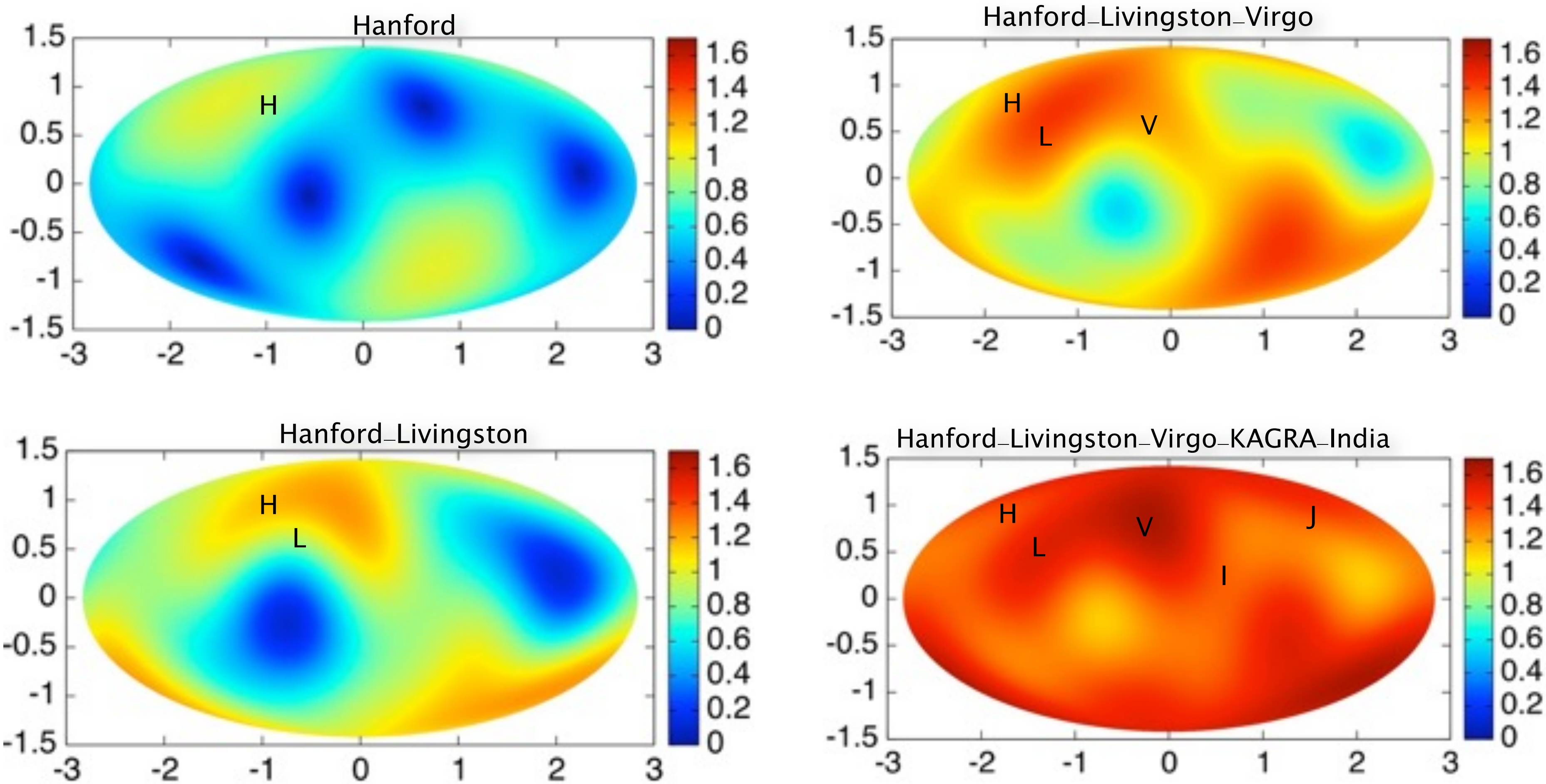


Detector Networks 2024+

Baselines

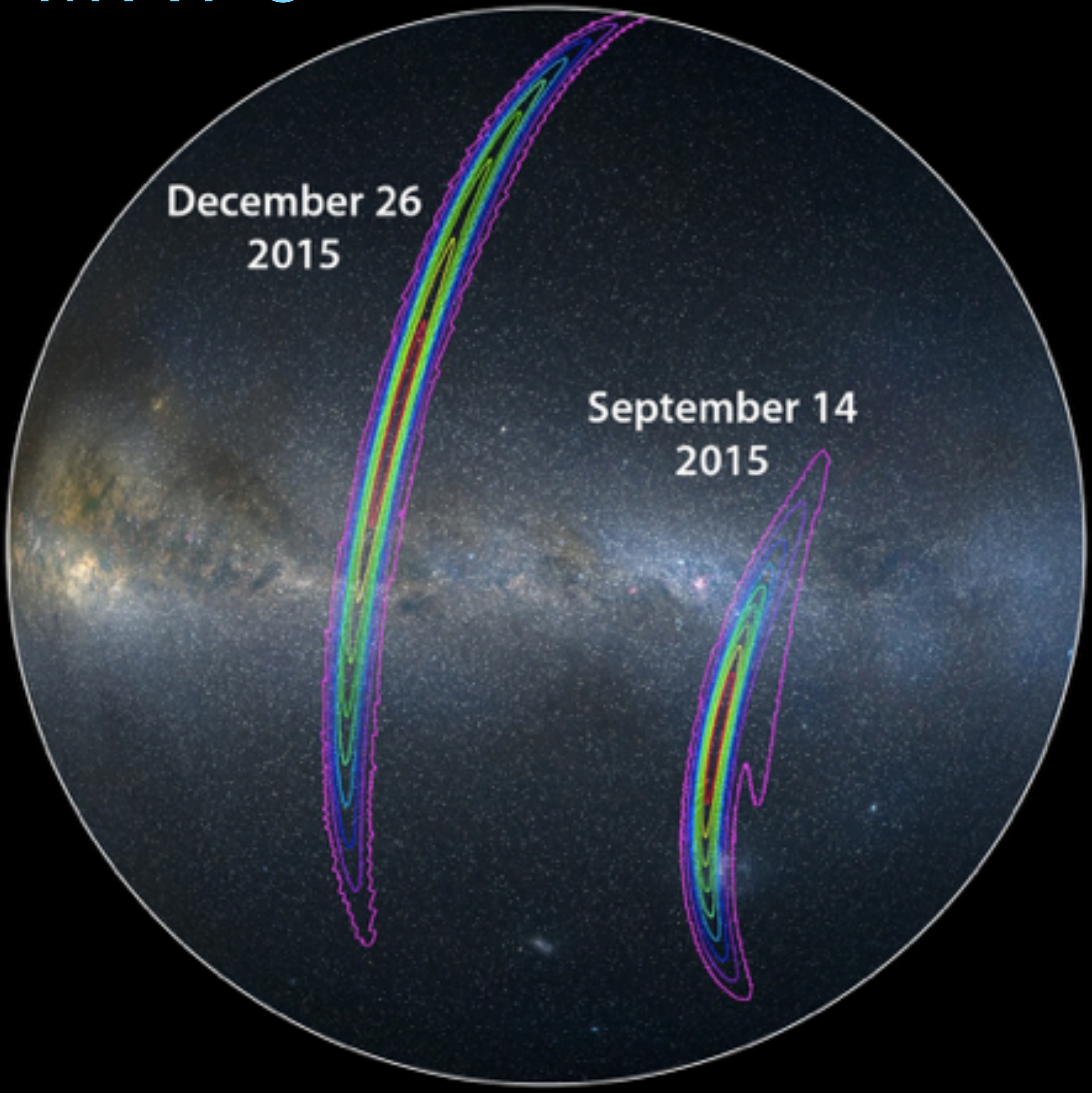
in light travel time (ms)

BEAM PATTERNS OF NETWORKS



SKY MAPS

Abbott+ PRD, 2016



ERROR ELLIPSES WITH HILV

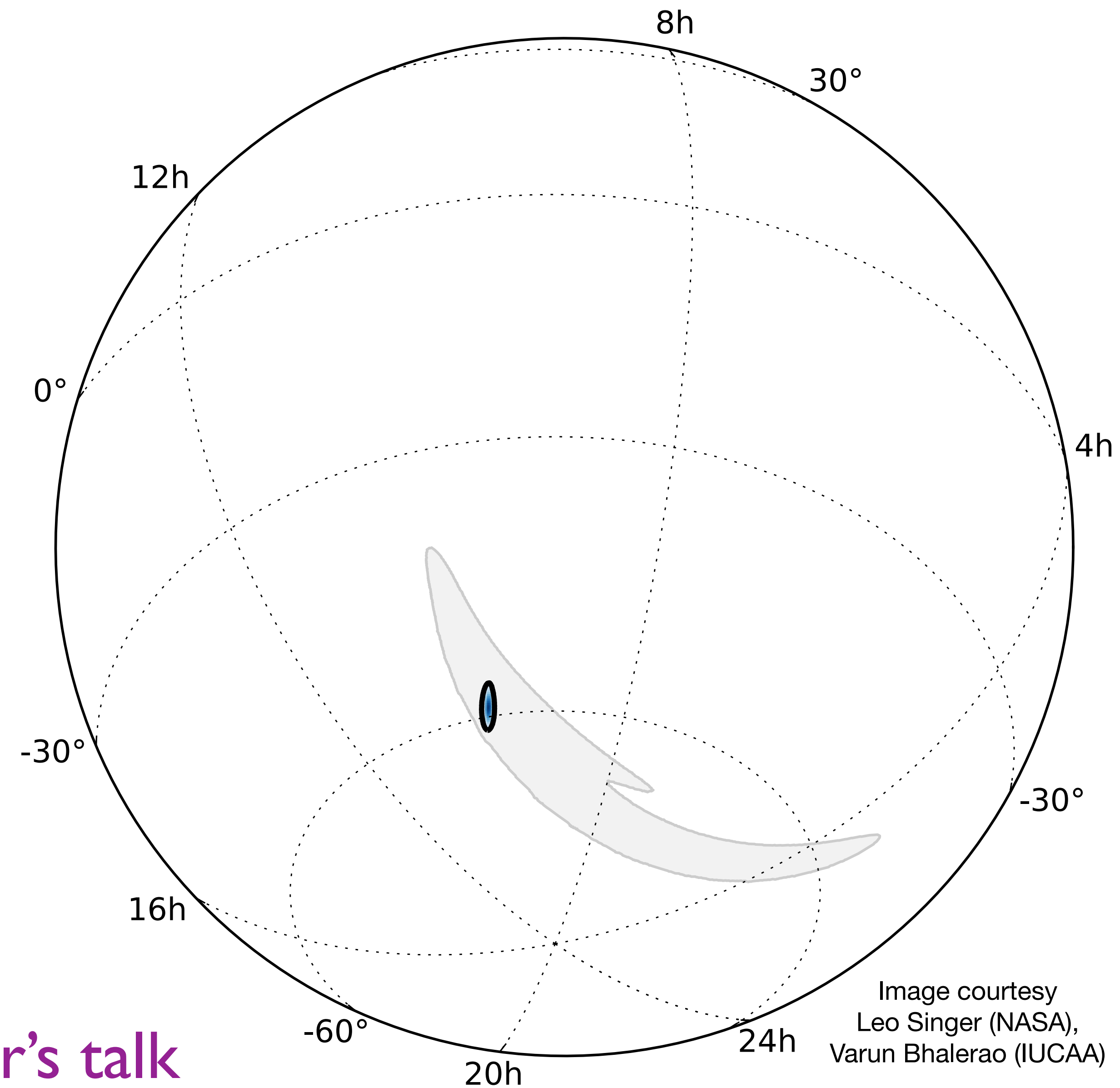
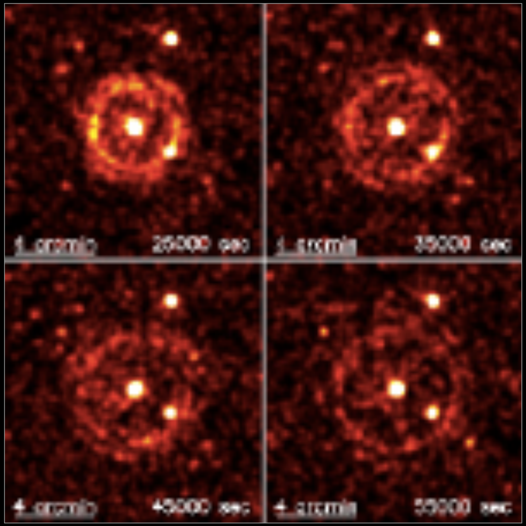


Image courtesy
Leo Singer (NASA),
Varun Bhalerao (IUCAA)

Leo Singer's talk

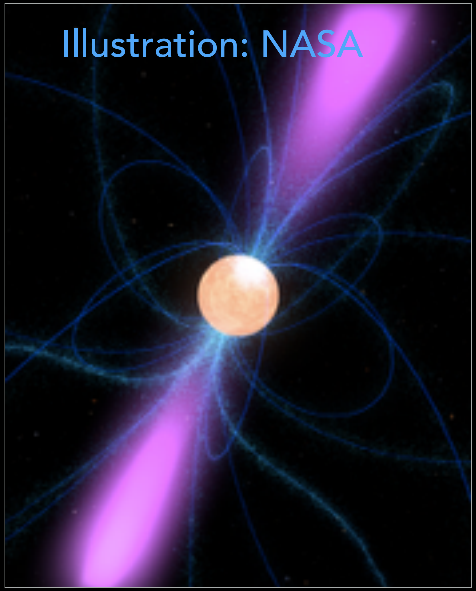
WHAT ELSE DO WE EXPECT TO OBSERVE

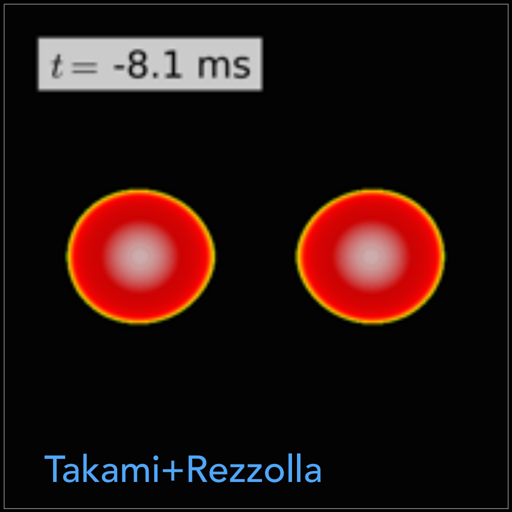
Supernovae and GRBs



XMM Newton

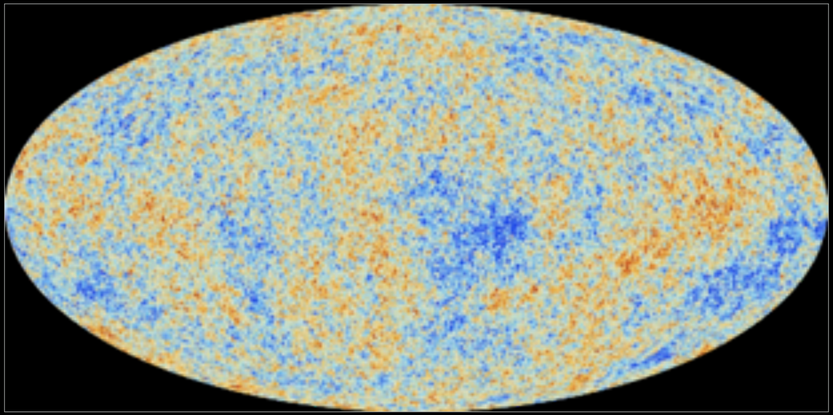
SpinningNeutron stars





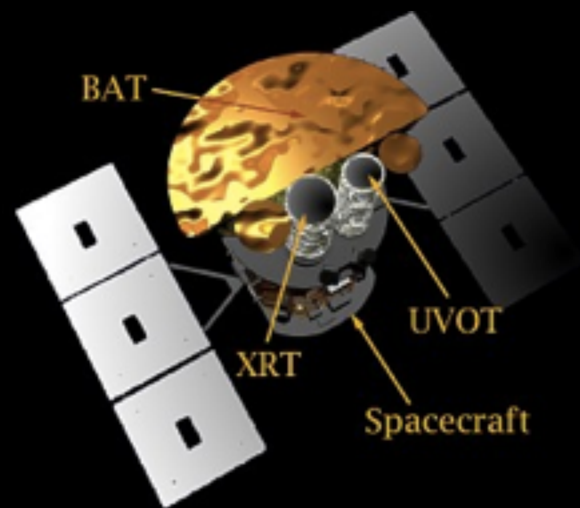
Binary neutron stars and black holes

Primordial background



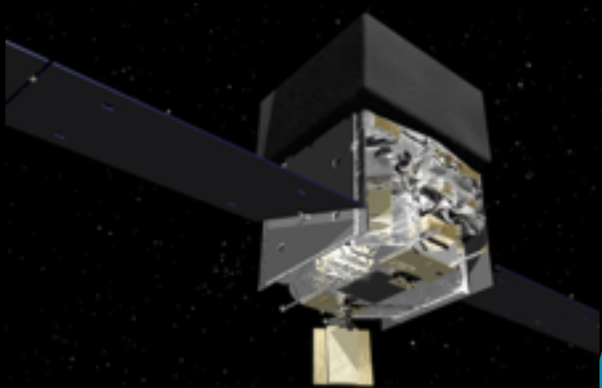
Credit: Planck Team

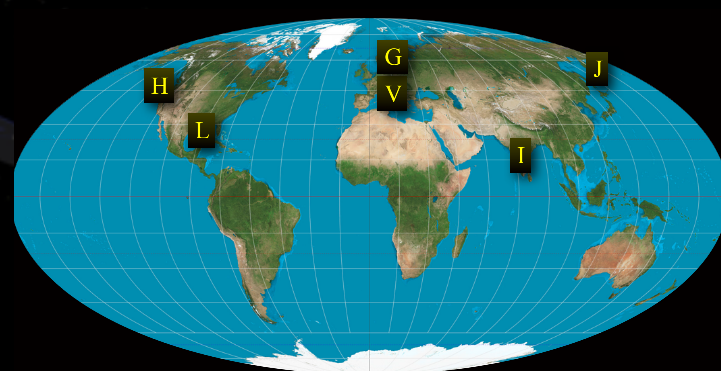
MULTIMESSENGER ASTRONOMY



SWIFT - BAT: WIDE FIELD DETECTOR THAT PRODUCES SUB-ARC SECOND RESOLUTION WITHIN MINUTES

FERMI GBM - ALL SKY





GW NETWORK - ALL SKY

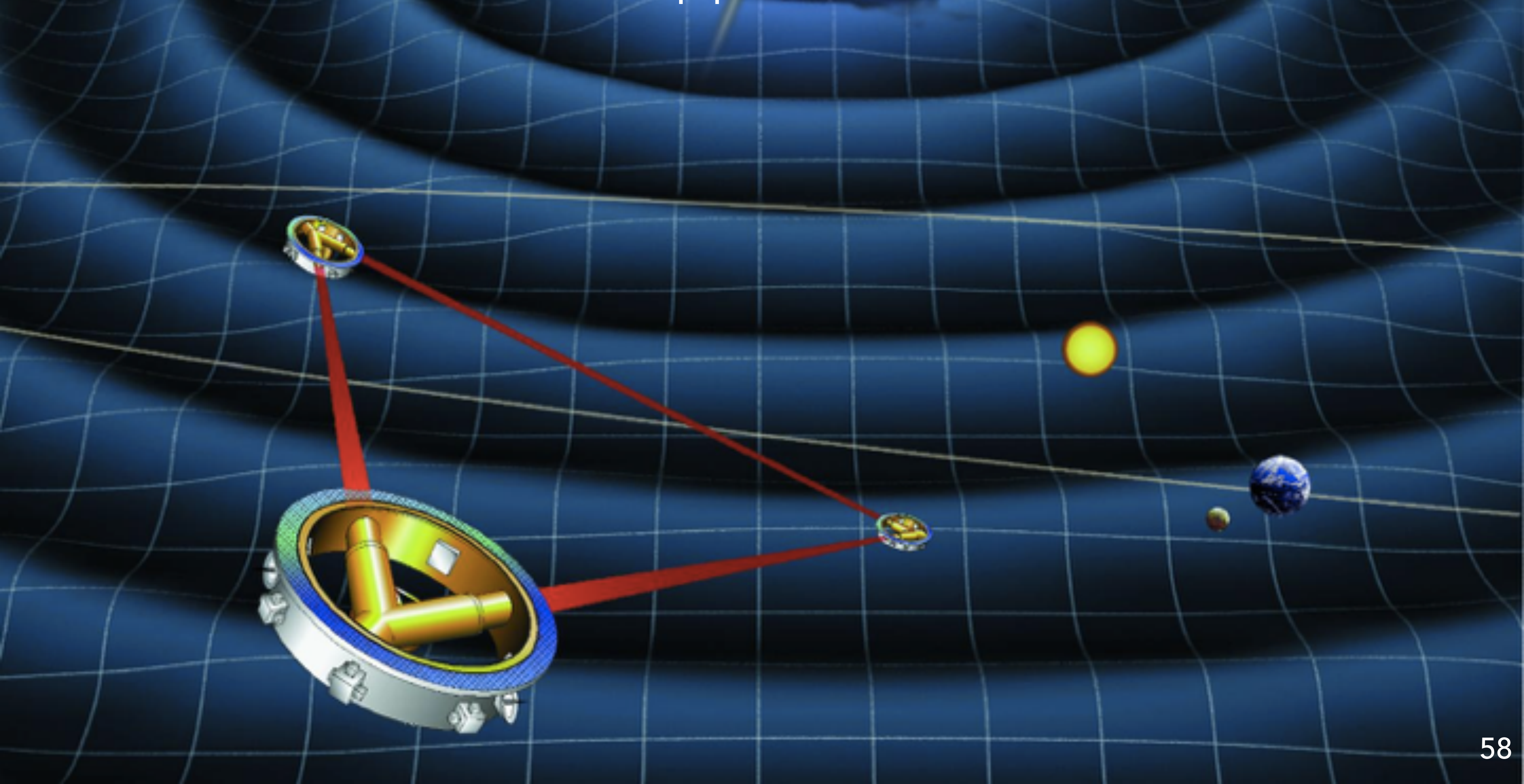
Dipankar Bhattacharya's talk

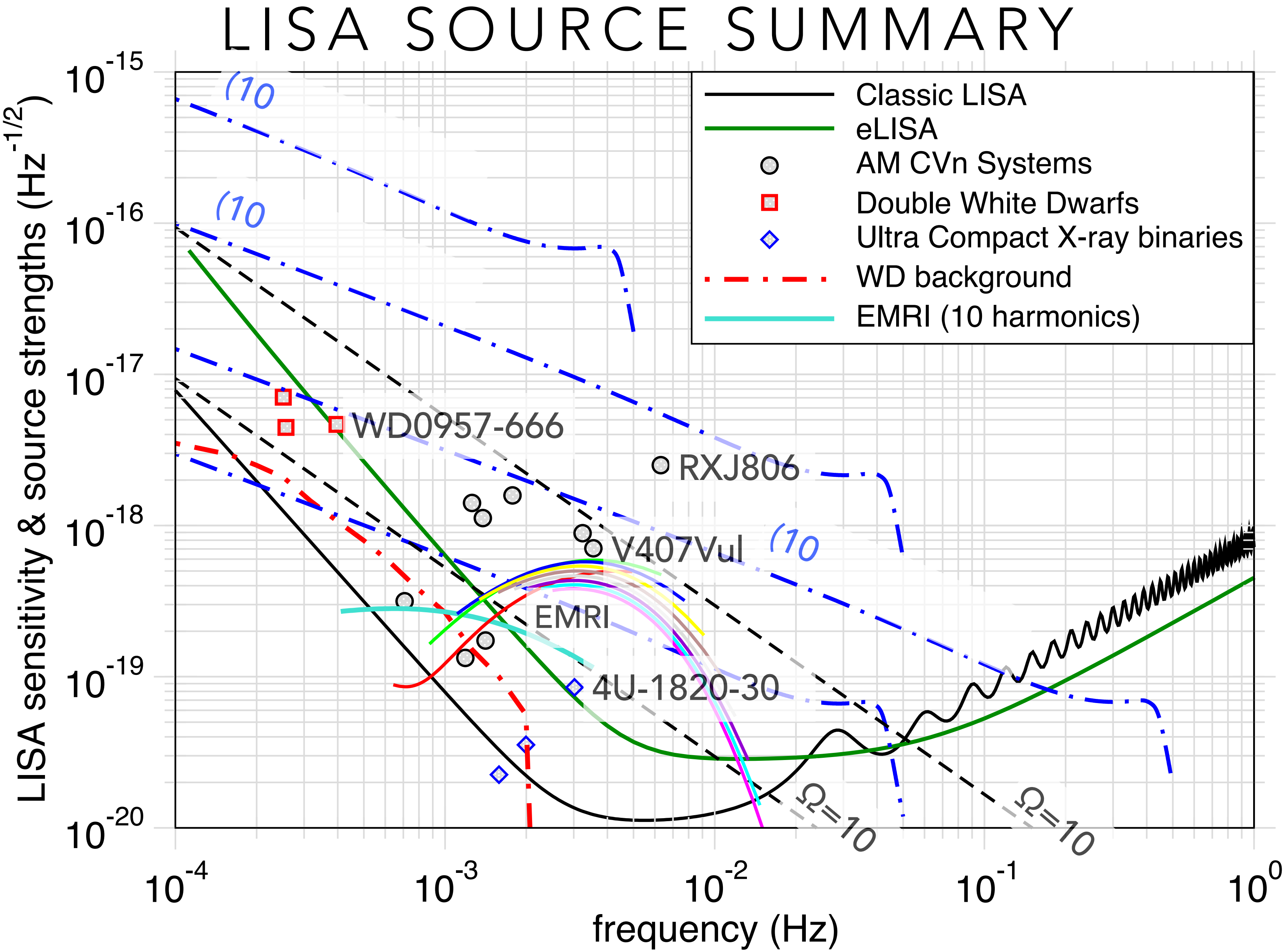
Leo Singer's talk

what can we expect in the next 2-3 decades?

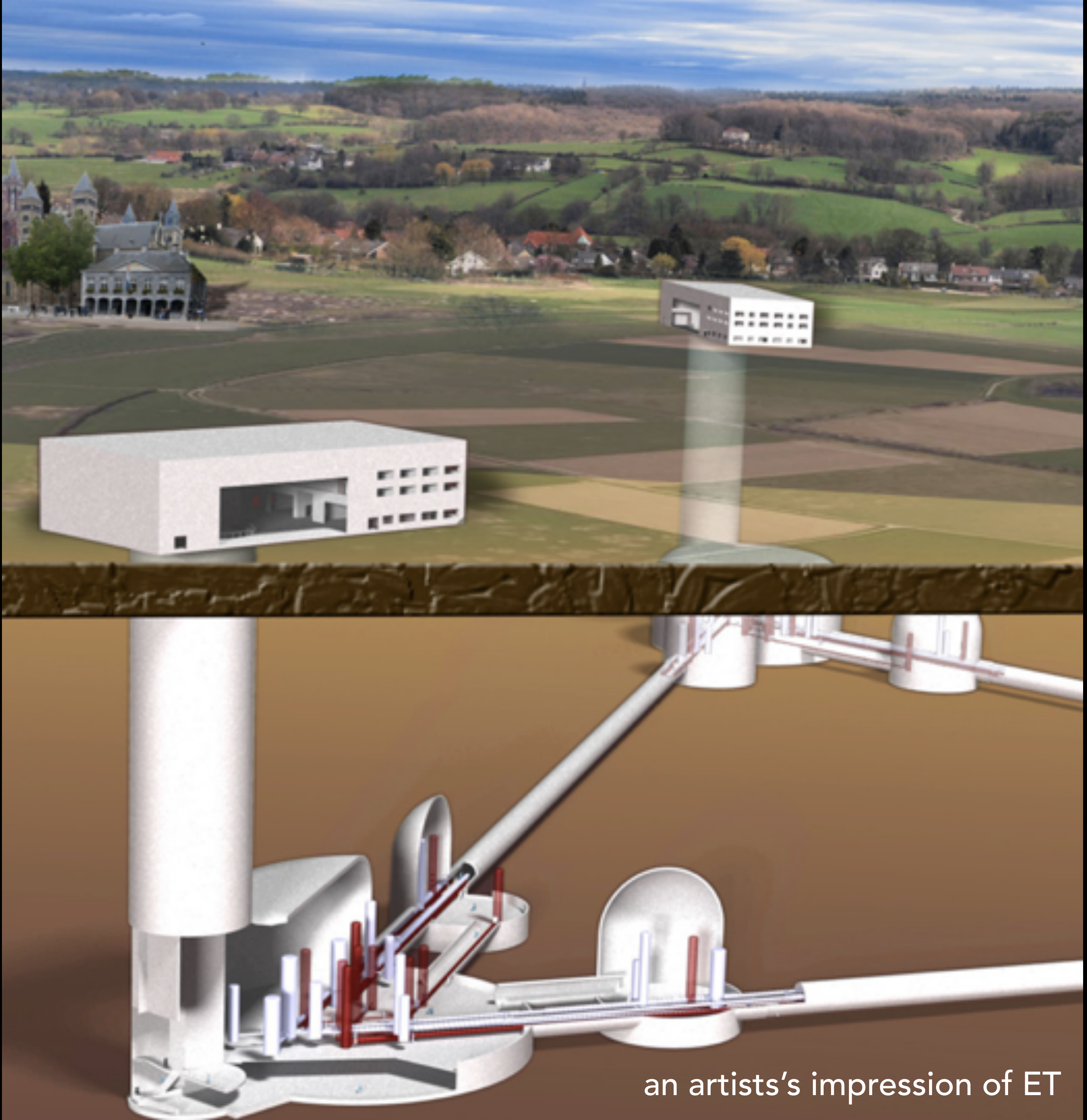
LASER INTERFEROMETER SPACE ANTENNA (LISA)

❖ L-class ESA mission approved for launch in 2034





LISA SOURCE SUMMARY
Classic LISA
eLISA
AM CVn Systems
Double White Dwarfs
Ultra Compact X-ray binaries
WD background
EMRI (10 harmonics)
WD0957-666
RXJ806
V407Vul
EMRI
4U-1820-30
Ω=10
Ω=10
(10
(10
(10
LISA sensitivity & source strengths (Hz$^{-1/2}$)
frequency (Hz)
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}



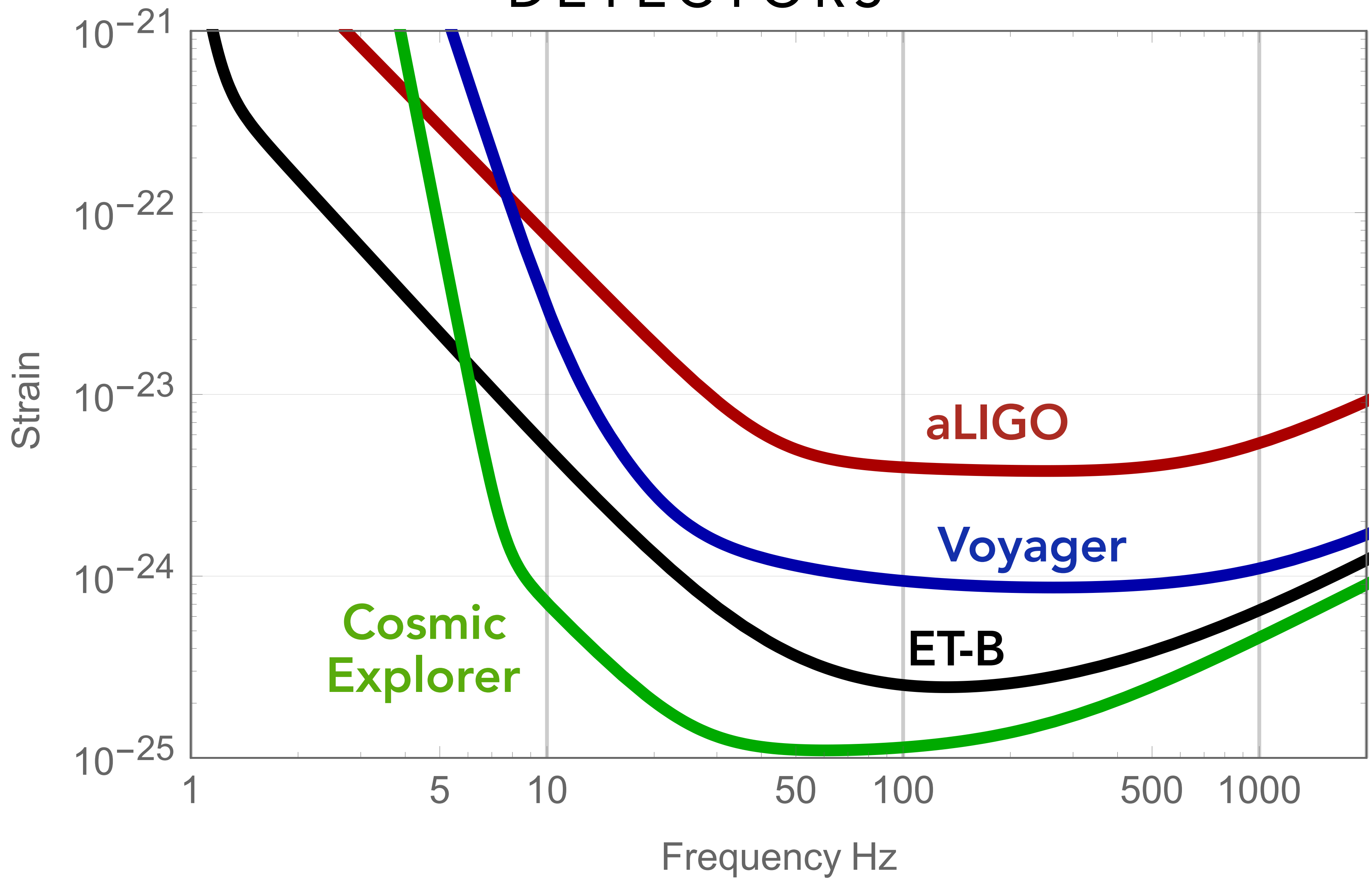
an artists's impression of ET

VOYAGER:
x 3
improvement in
aLIGO strain
sensitivity

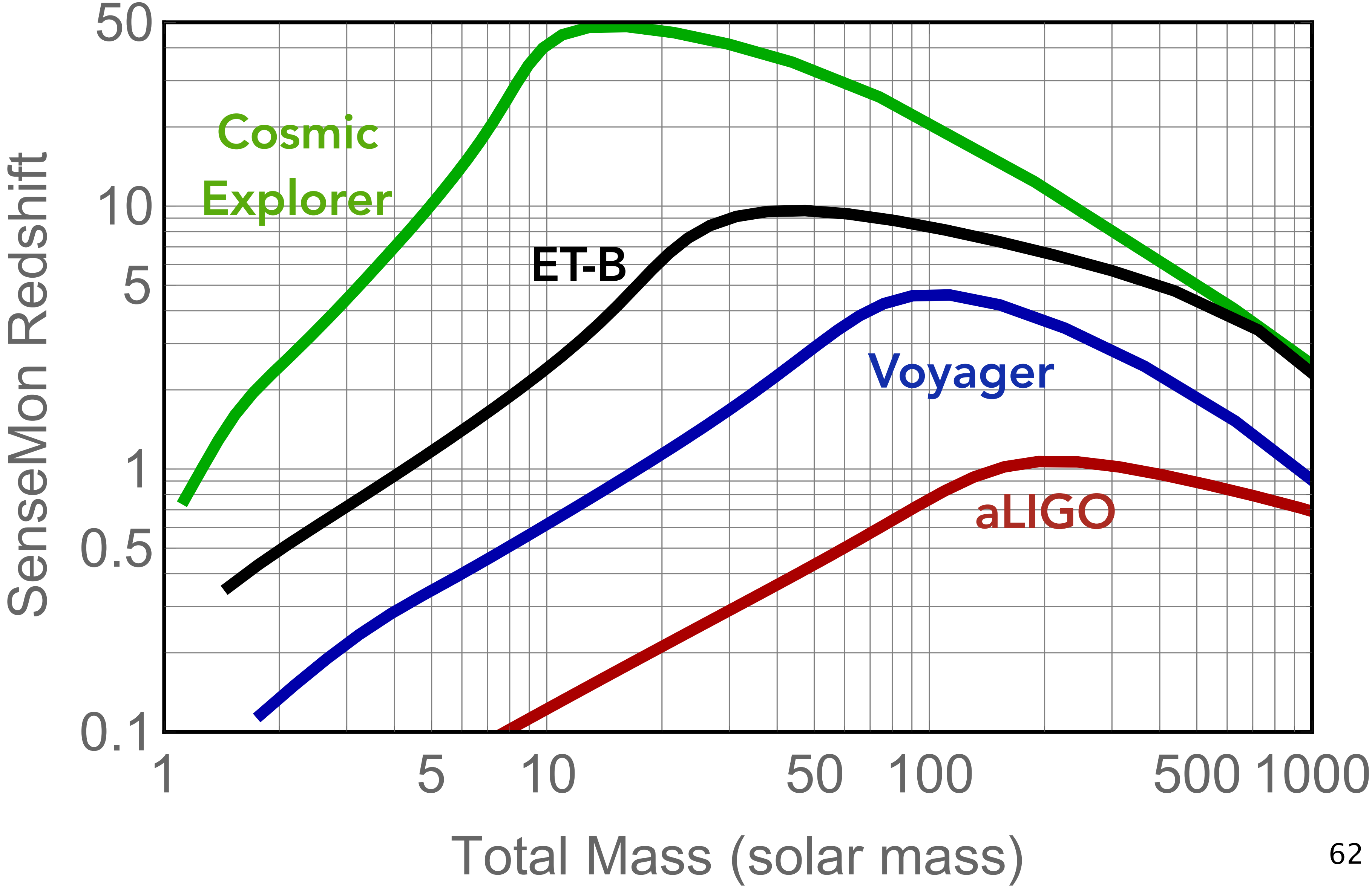
EINSTEIN TELESCOPE:
Triangular, 10 km
arm length,
underground,
cryogenic
detectors

COSMIC EXPLORER:
40 km arm length,
cryogenic,
overground
interferometer

STRAIN SENSITIVITIES OF FUTURE DETECTORS



HOW FAR CAN SEE SOURCES?



3G SCIENCE DRIVERS

Extreme gravity

Extreme matter

Cosmic history

EXTREME GRAVITY

Quasi-normal modes and the no-hair theorem

Dynamical spacetime: Higher modes, precessing orbits, Extremal spins…

GR violations and alternative gravity theories

Bursts and stochastic background from cosmic strings

Gravitational collapse, supernova

EXTREME MATTER

What are the most compact object in Nature

Equation of state of neutron star cores

GRB physics from Binary neutron star observations

Dynamics of neutron star interiors, tidal instabilities

Nature of Low-mass x-ray binaries

COSMIC HISTORY

Mapping the history of black hole formation

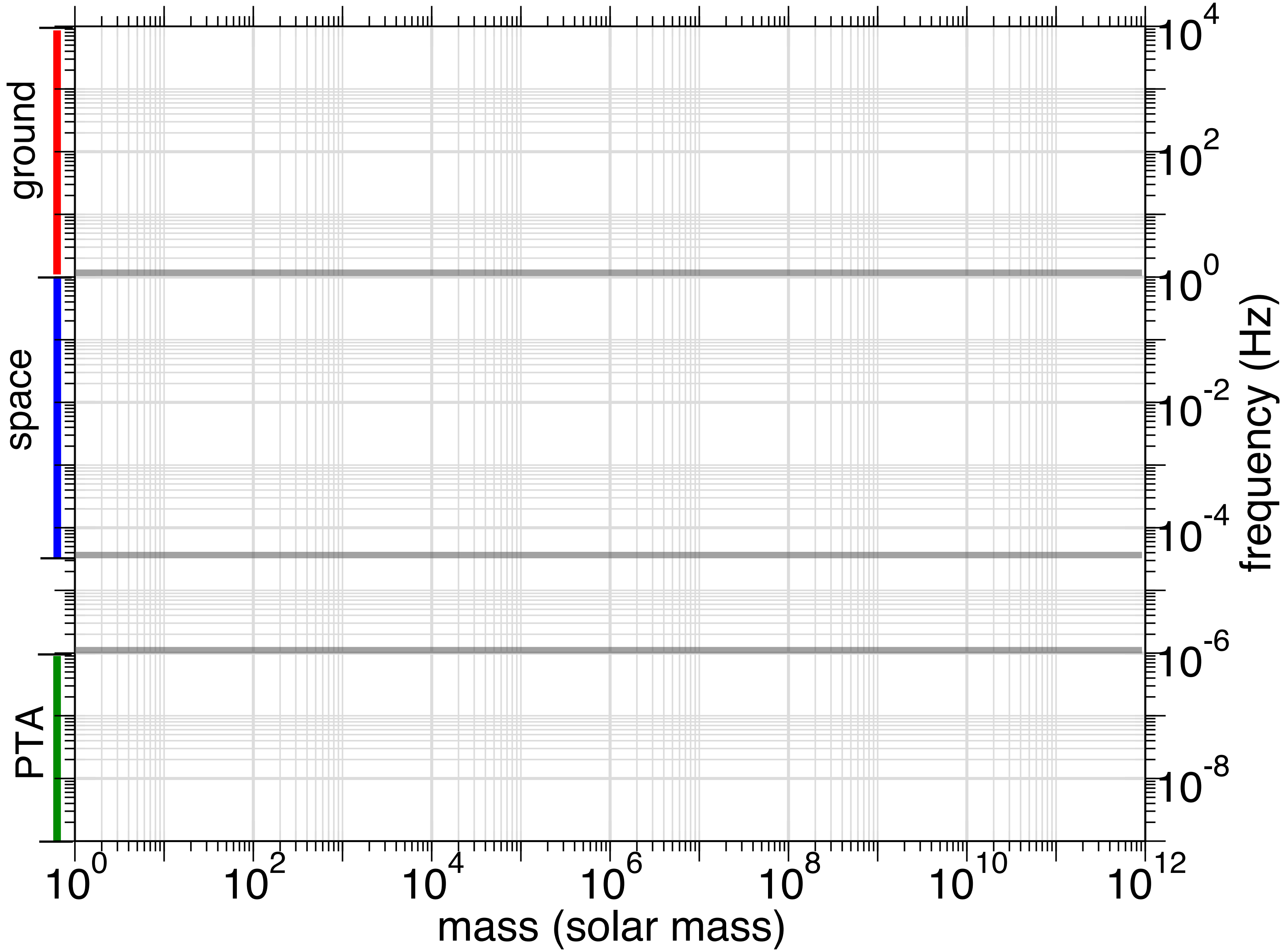
Do gravitational waves see the same universe as light

Formation and evolution of compact objects throughout the Universe

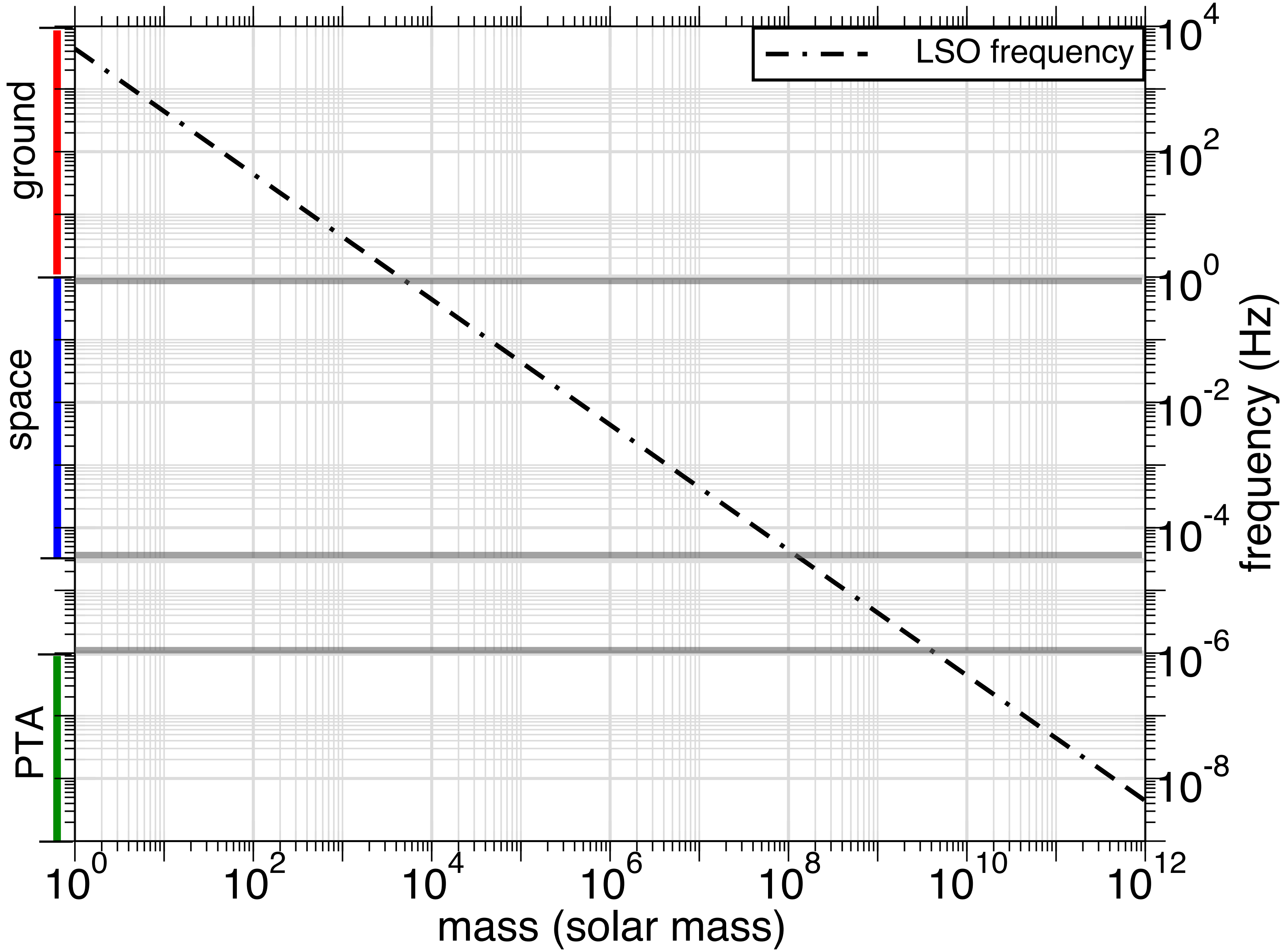
The chemical content of the Universe from NS-NS and NS-BS

Cosmic string bursts and backgrounds

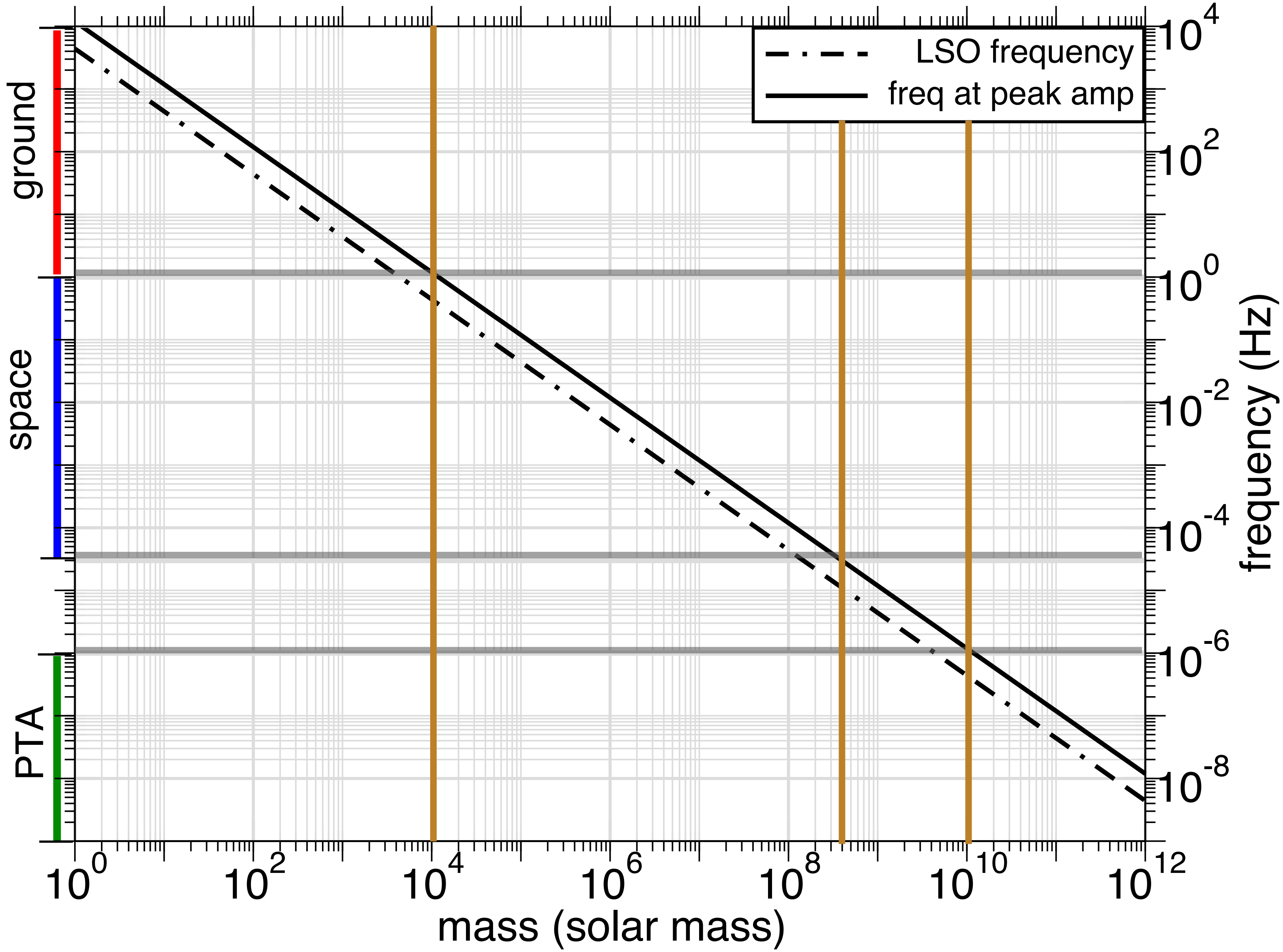
FREQUENCY SPAN OF VARIOUS DETECTORS



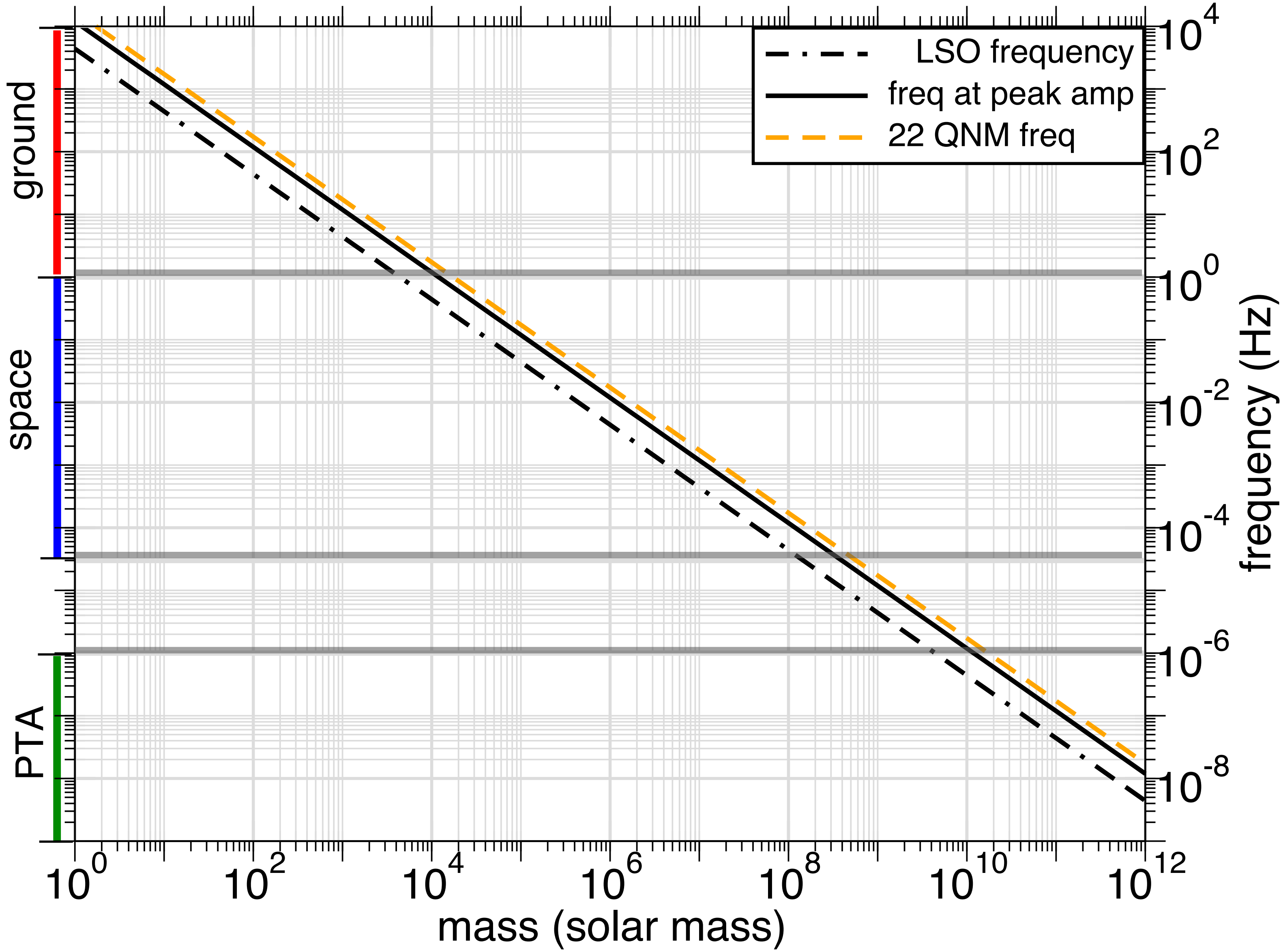
LAST STABLE ORBIT FREQUENCY: SCHWARZSCHILD BLACK HOLE



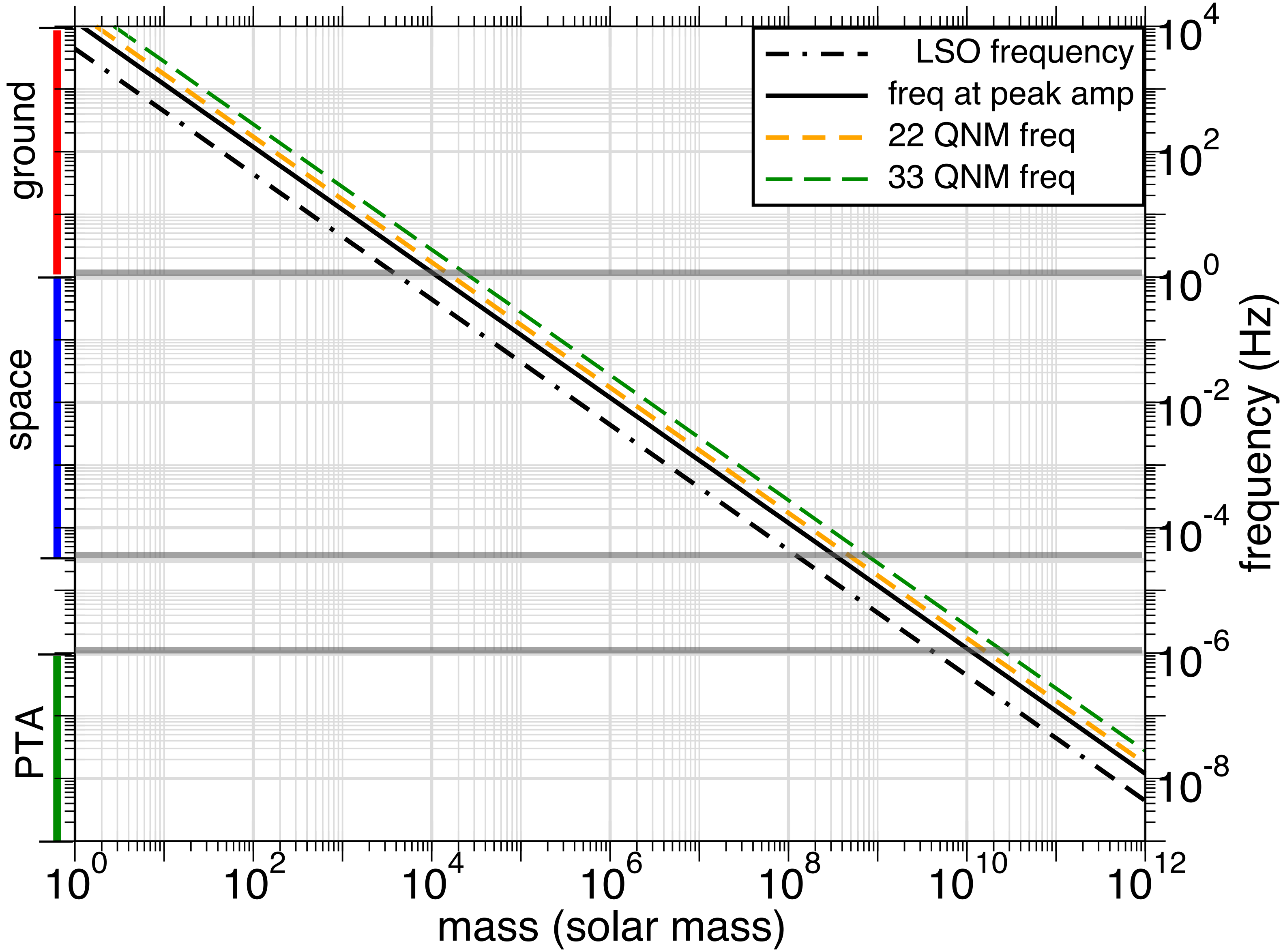
BINARY MASSES TO WHICH DETECTORS ARE MOST SENSITIVE



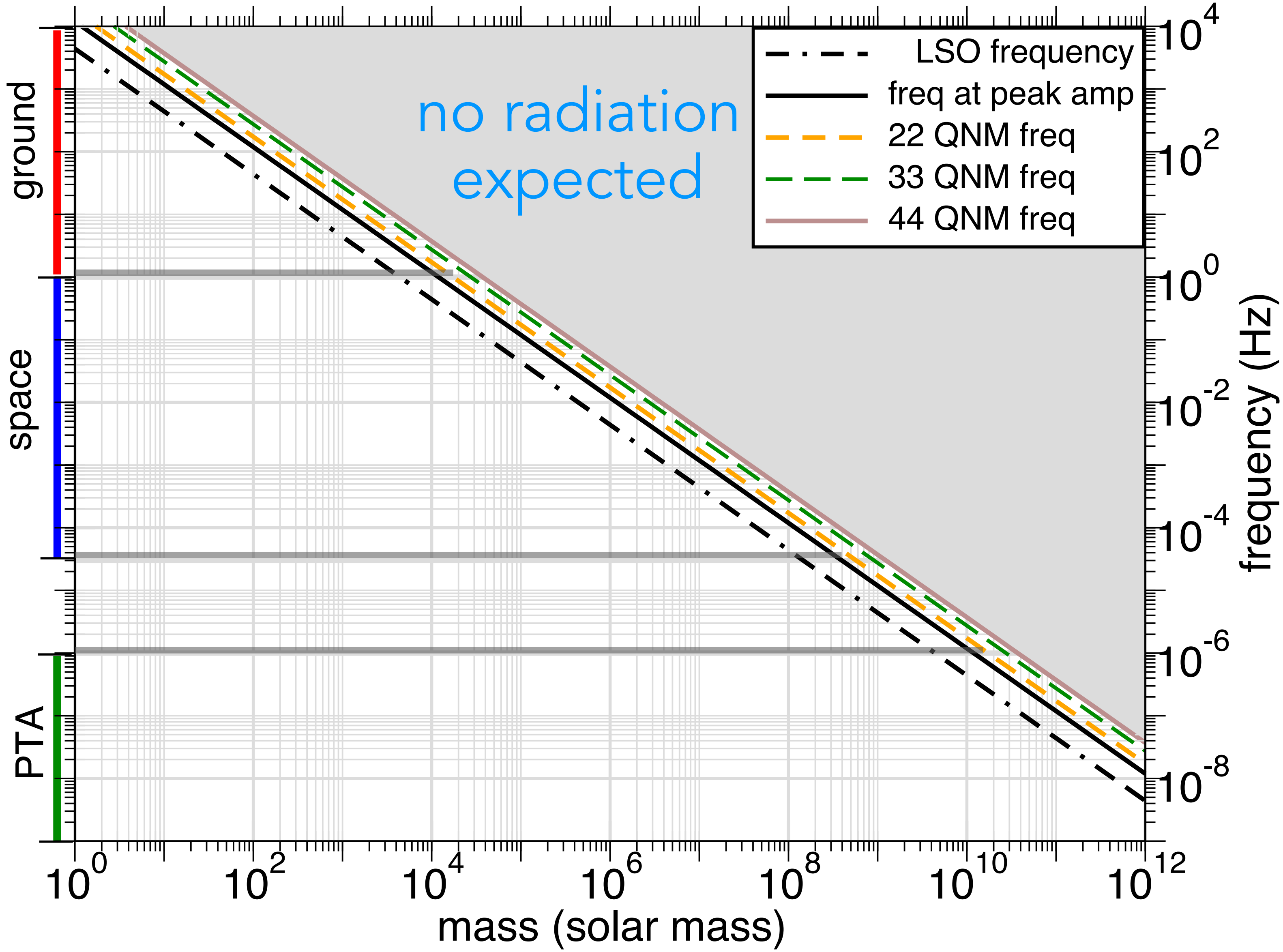
DOMINANT QUASI-NORMAL MODE FREQUENCY



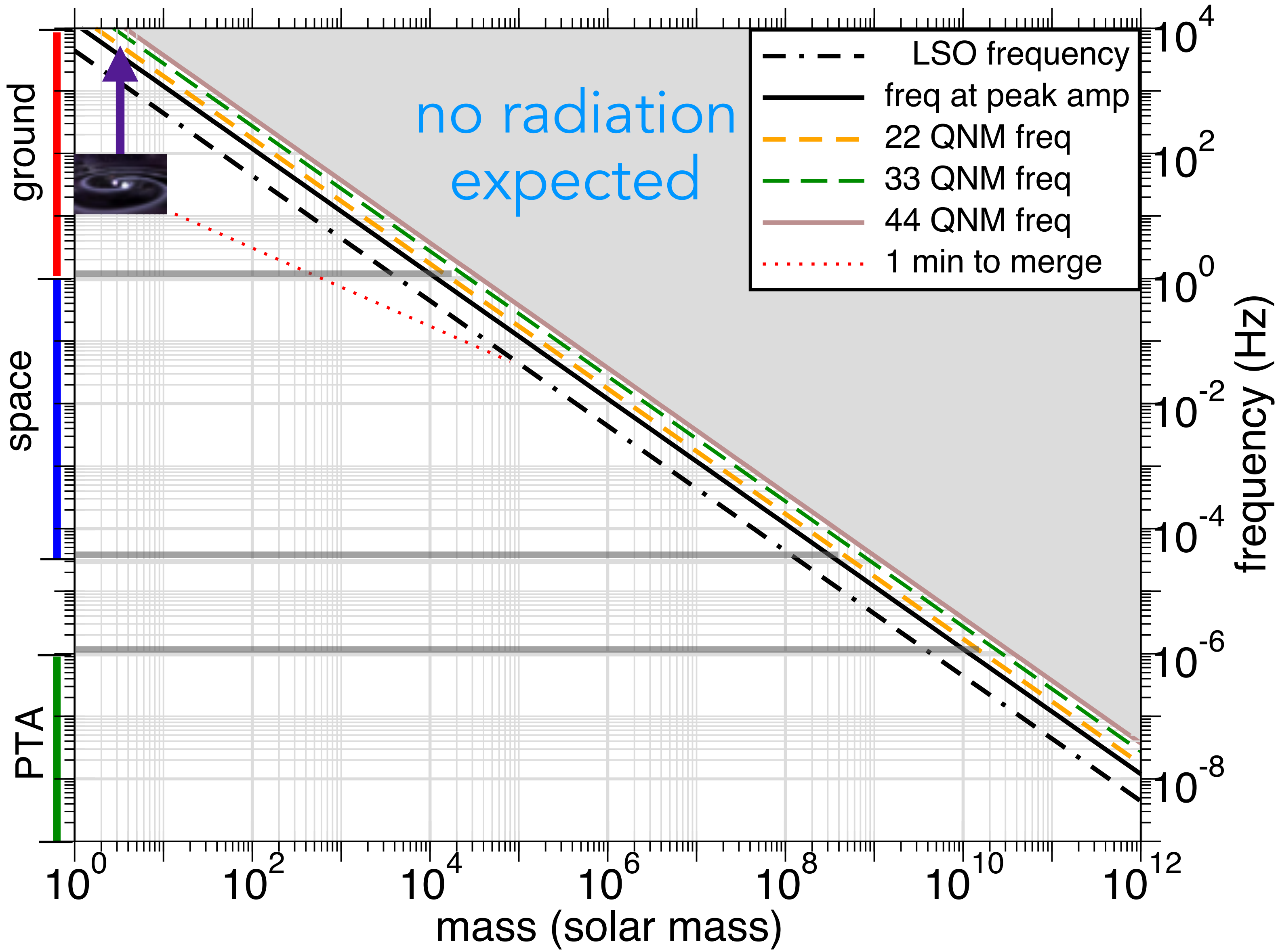
HIGHER ORDER QUASI-NORMAL MODES: SUB-DOMINANT



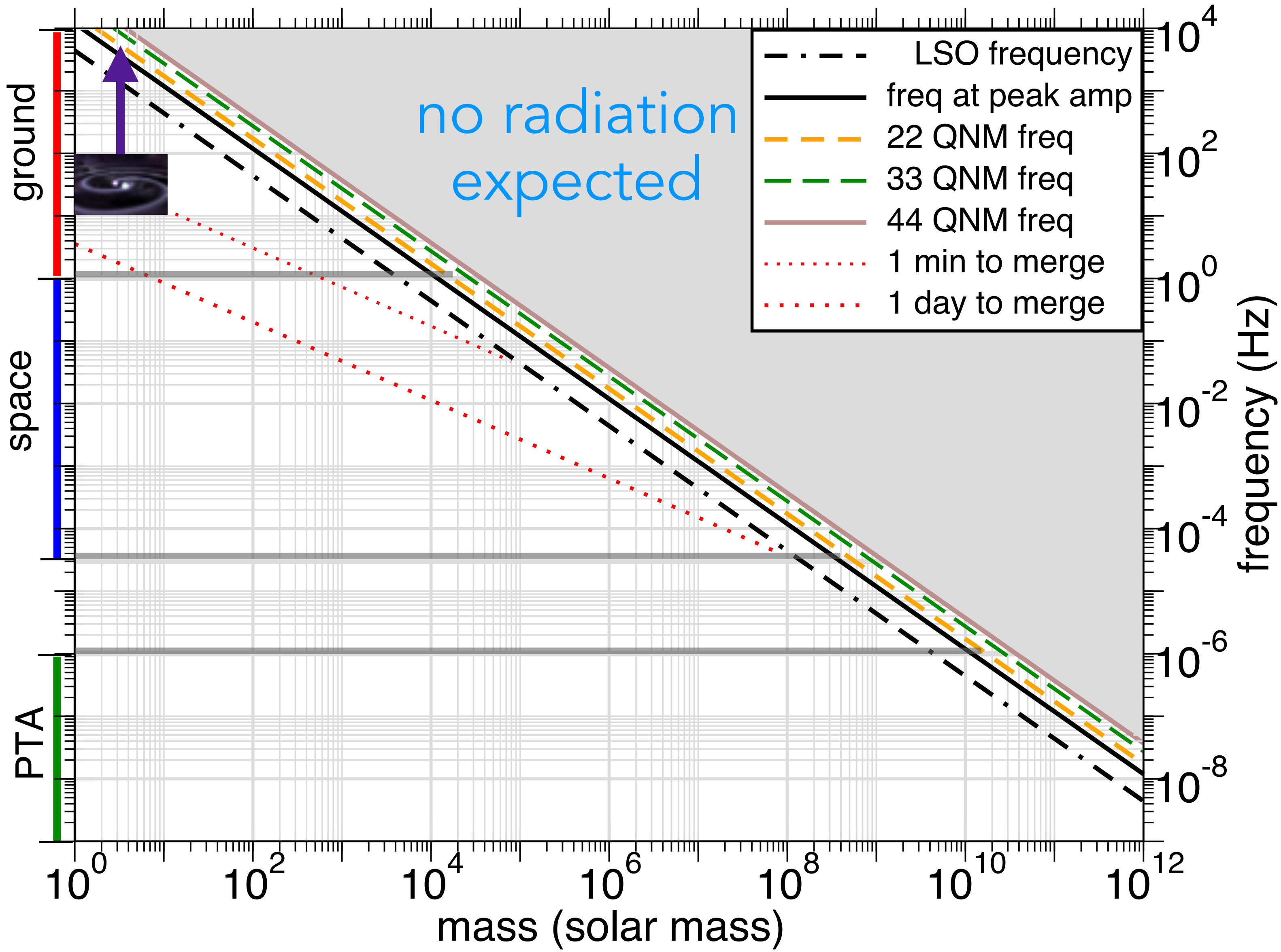
NO RADIATION FROM INSIDE A BLACK HOLE



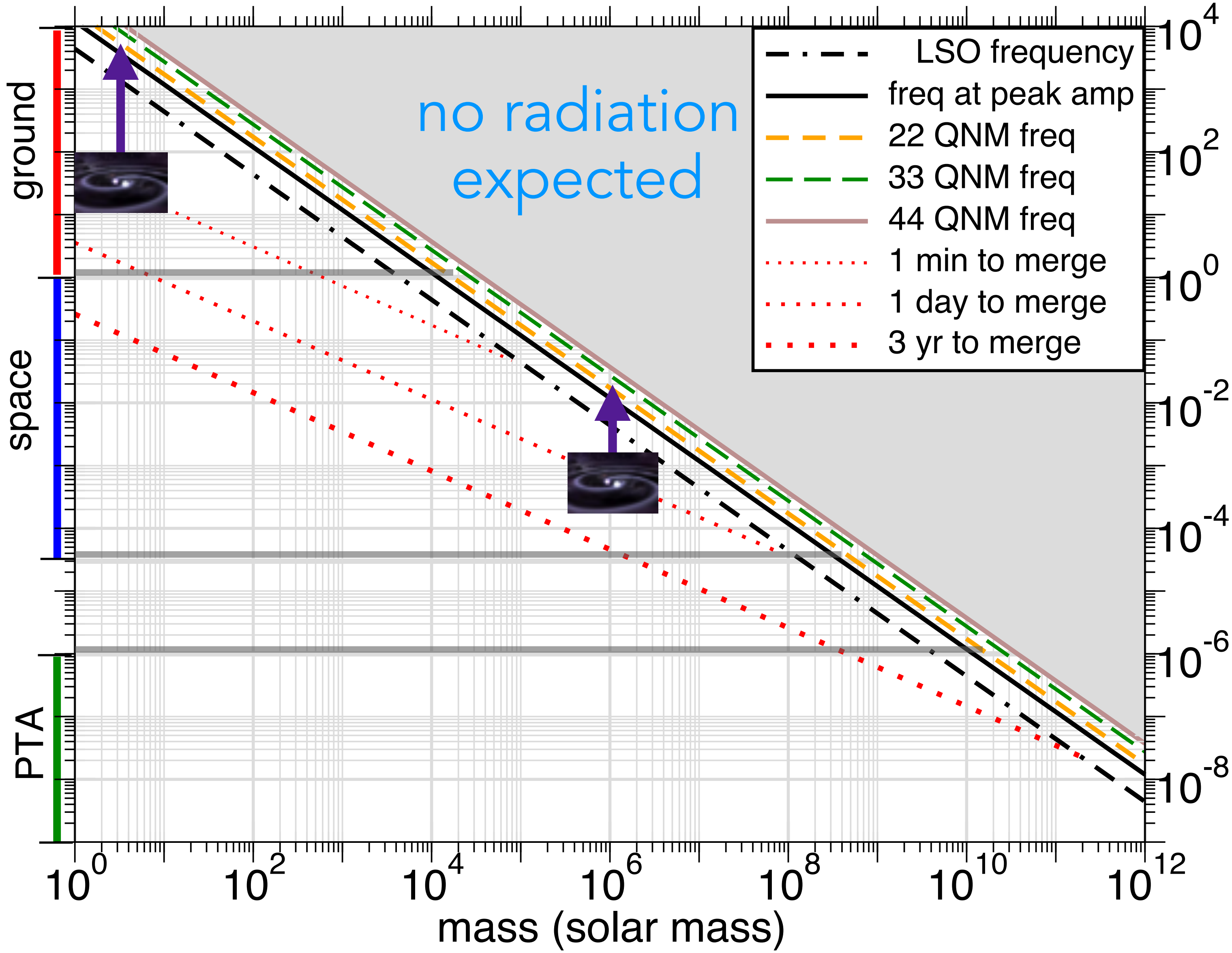
BINARIES OBSERVED BY LIGO/VIRGO MERGE WITHIN A FEW MINS OR ...



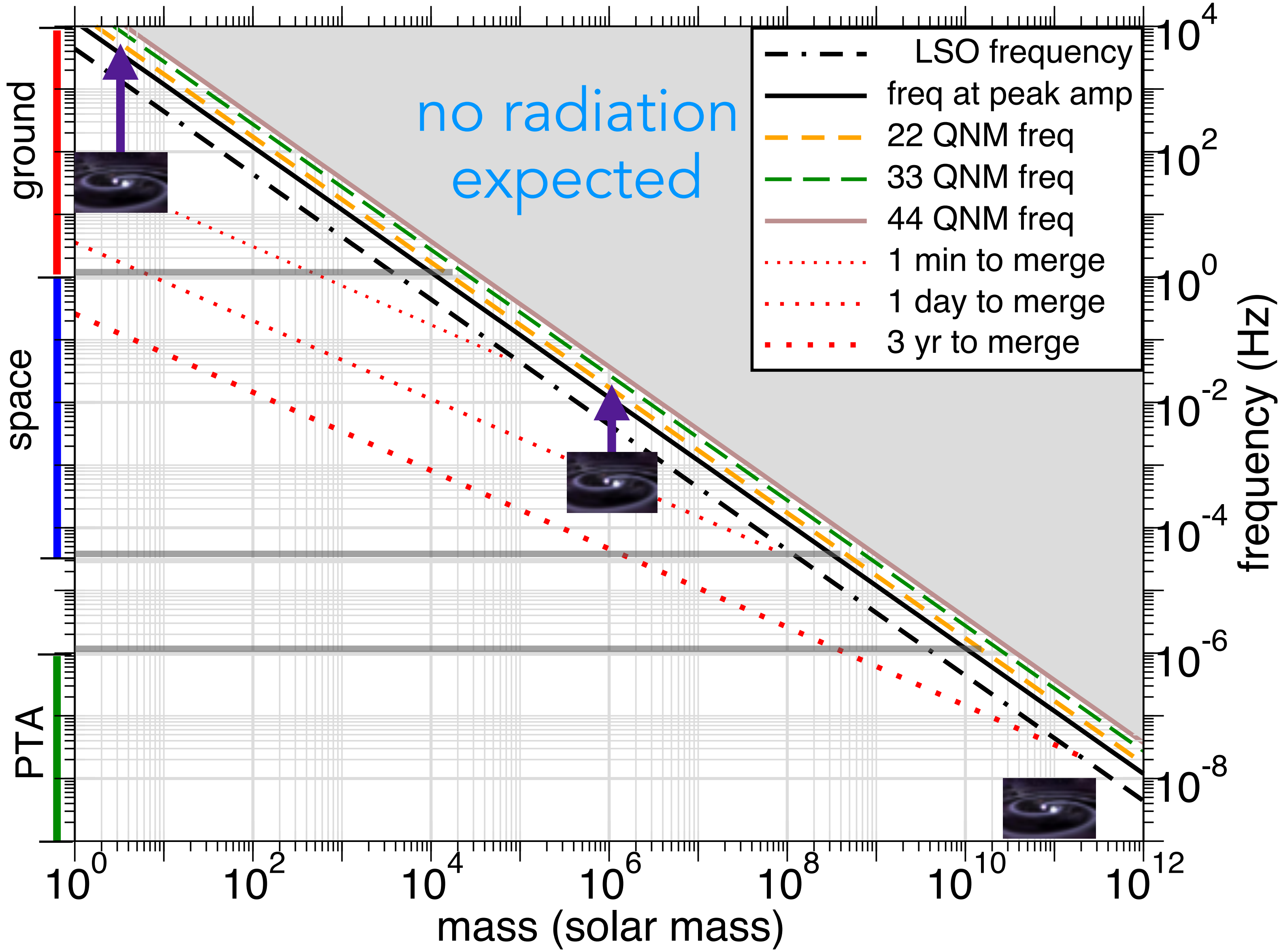
… WITHIN A FEW DAYS



MASSIVE BLACK HOLE BINARIES WILL BE VISIBLE ~ YEARS BEFORE THEY MERGE

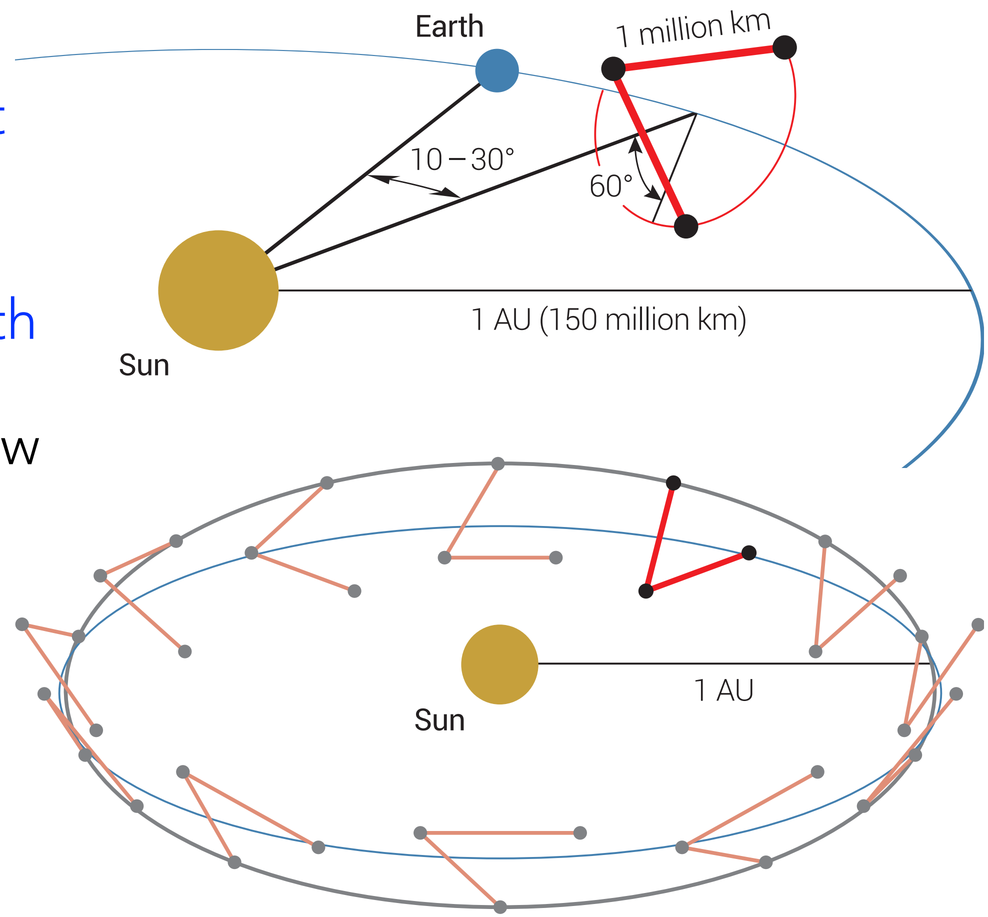


PULSAR TIMING ARRAYS OBSERVE CONTINUOUS WAVES FROM SMBBH

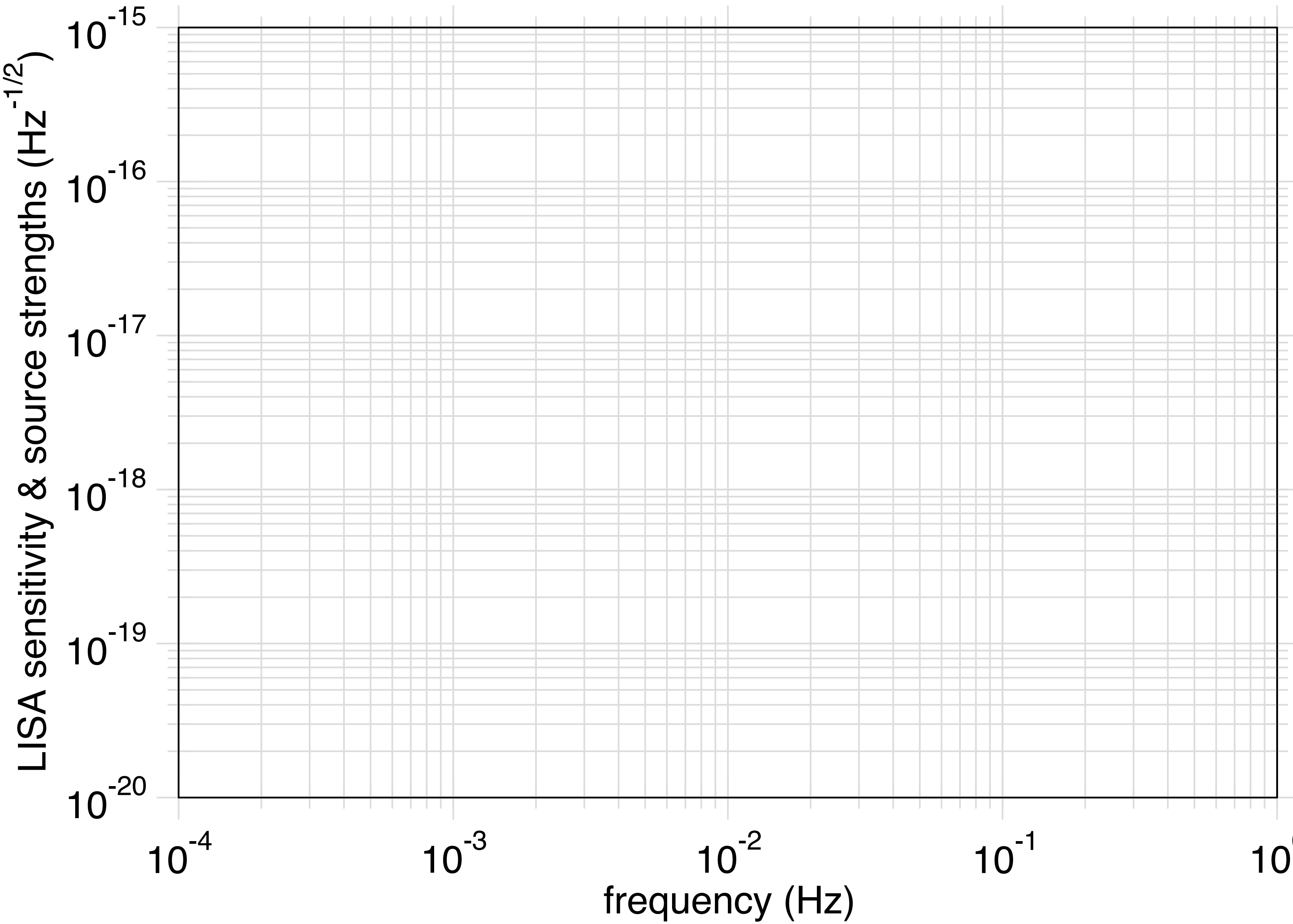


ELISA: L3 MISSION IN ESA'S COSMIC HORIZON PROGRAMME

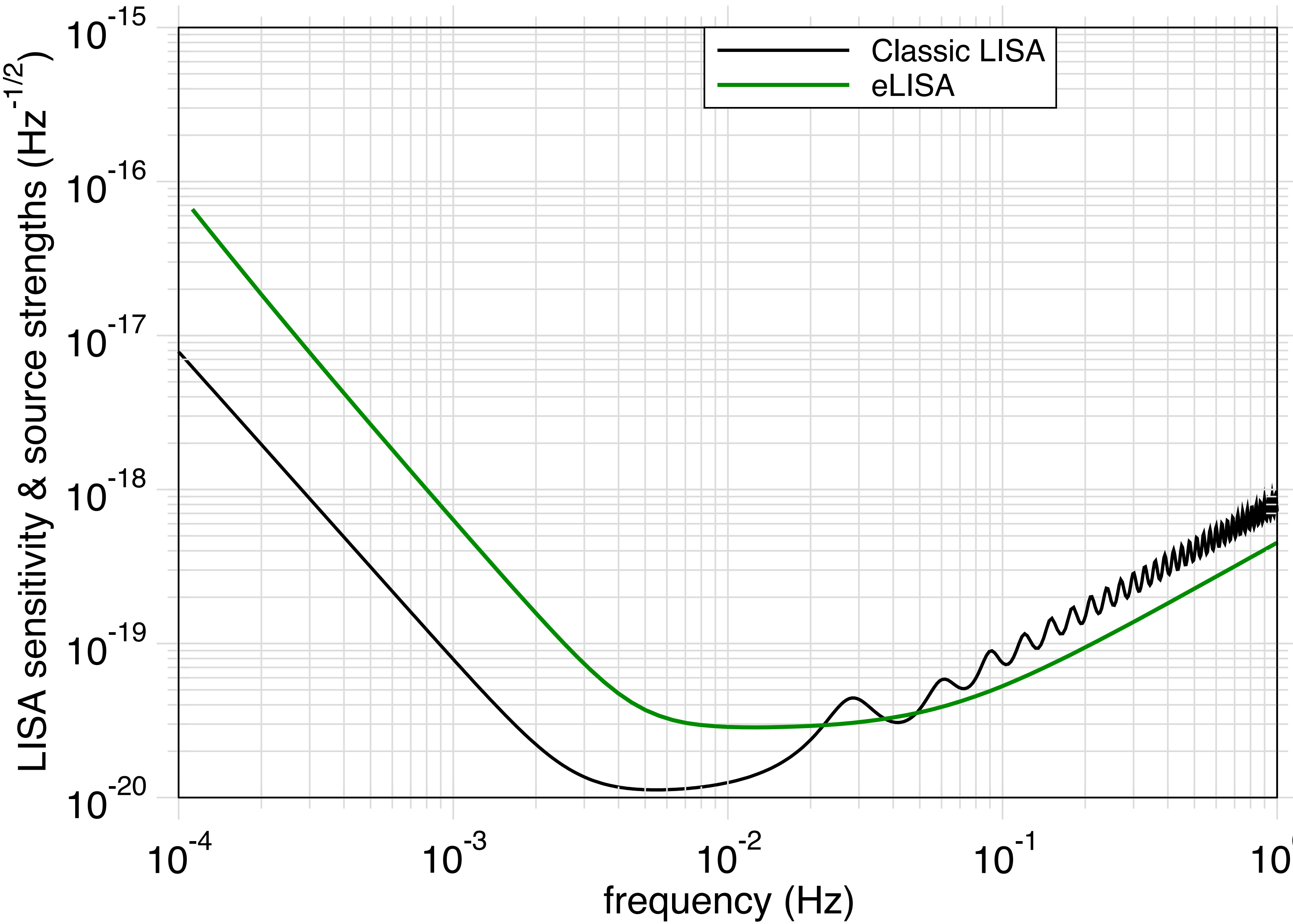
- Consists of 3 spacecraft in heliocentric orbit
  - Distance between spacecraft ~ 1 million km
  - 10 to 30 degrees behind earth
- The three eLISA spacecraft follow Earth almost as a rigid triangle entirely due to celestial mechanics
  - The triangle rotates like a cartwheel as craft orbit the sun



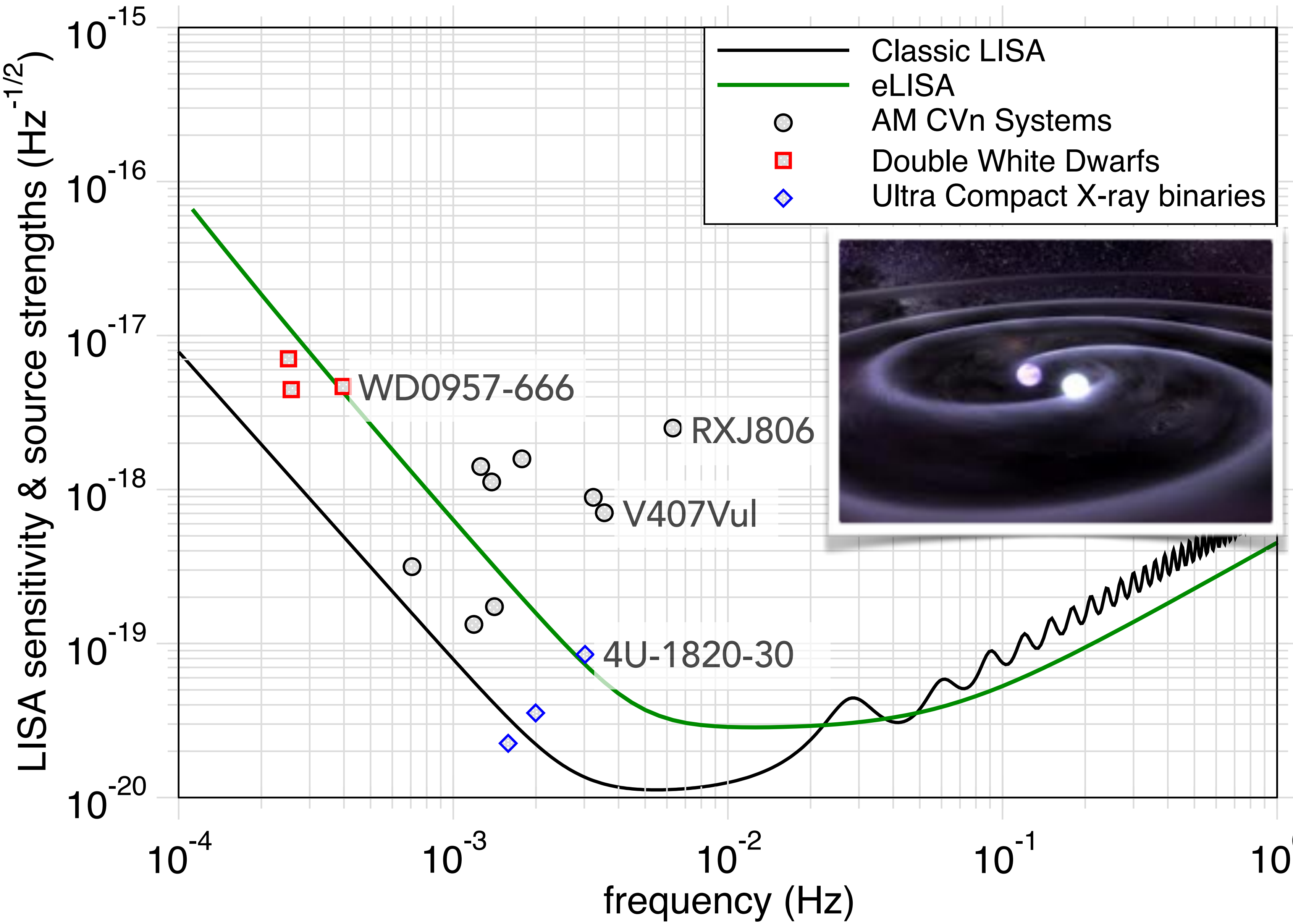
LISA: FREQUENCY RANGE



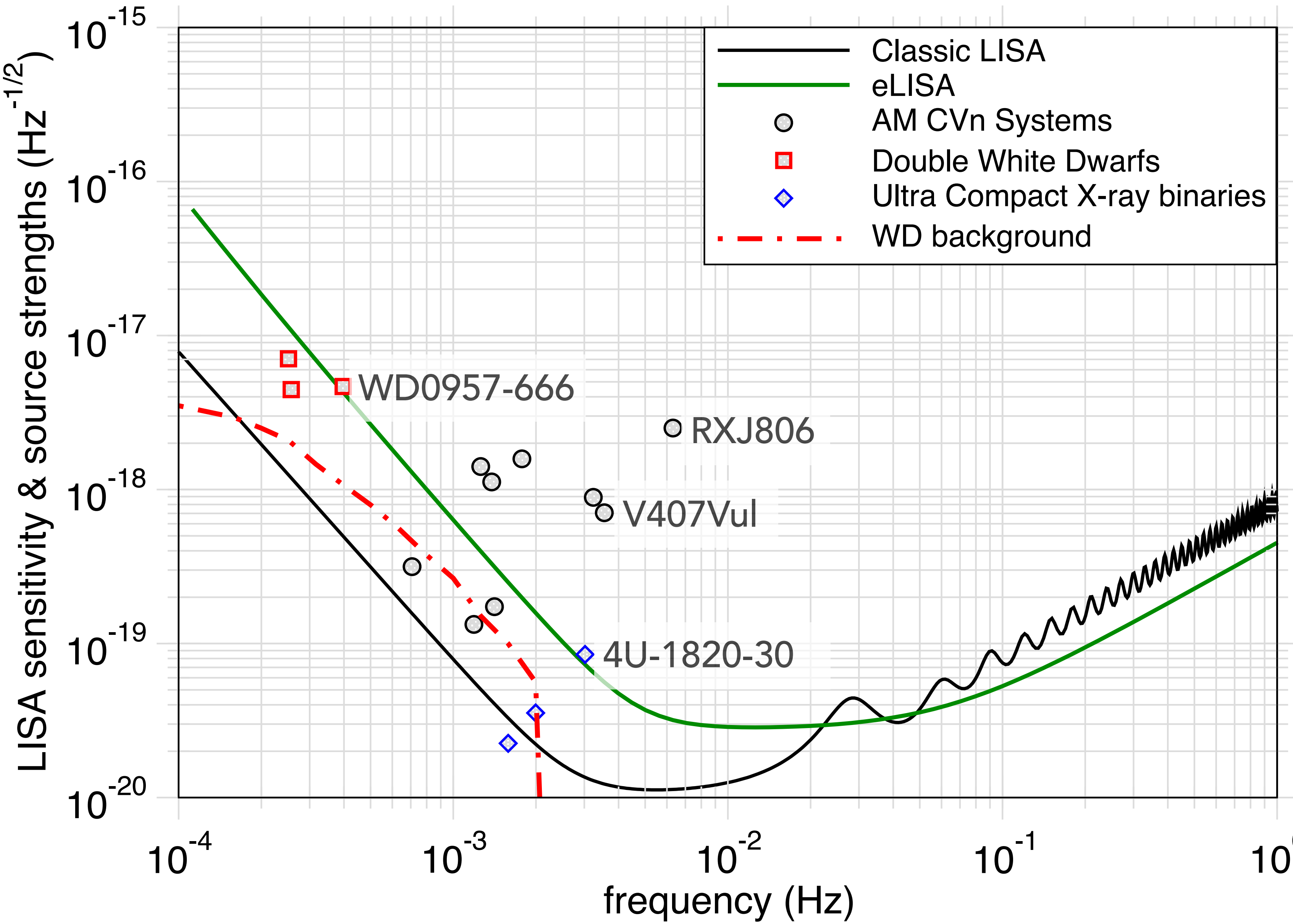
LISA SENSITIVITY



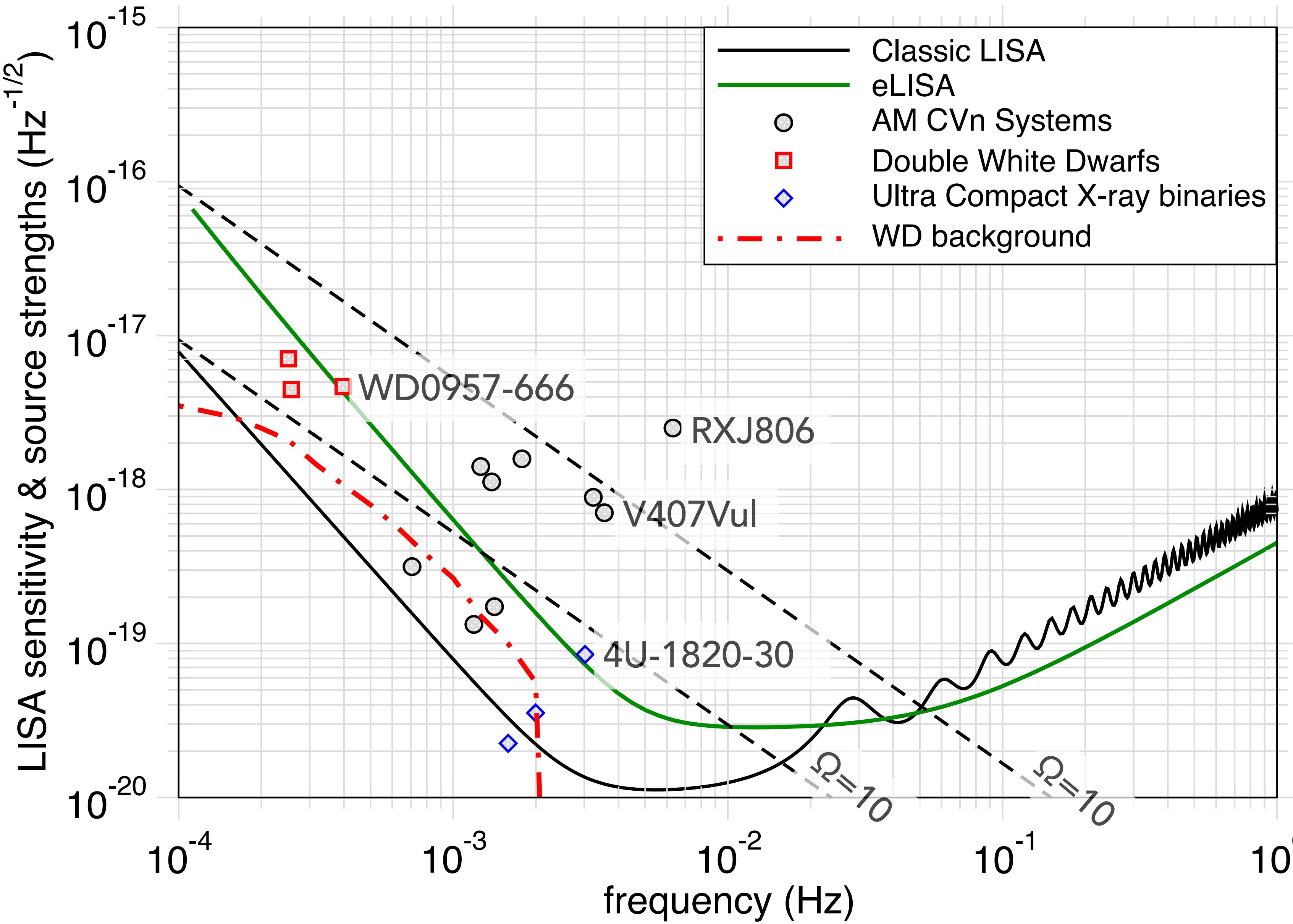
KNOWN SOURCES IN LISA BAND



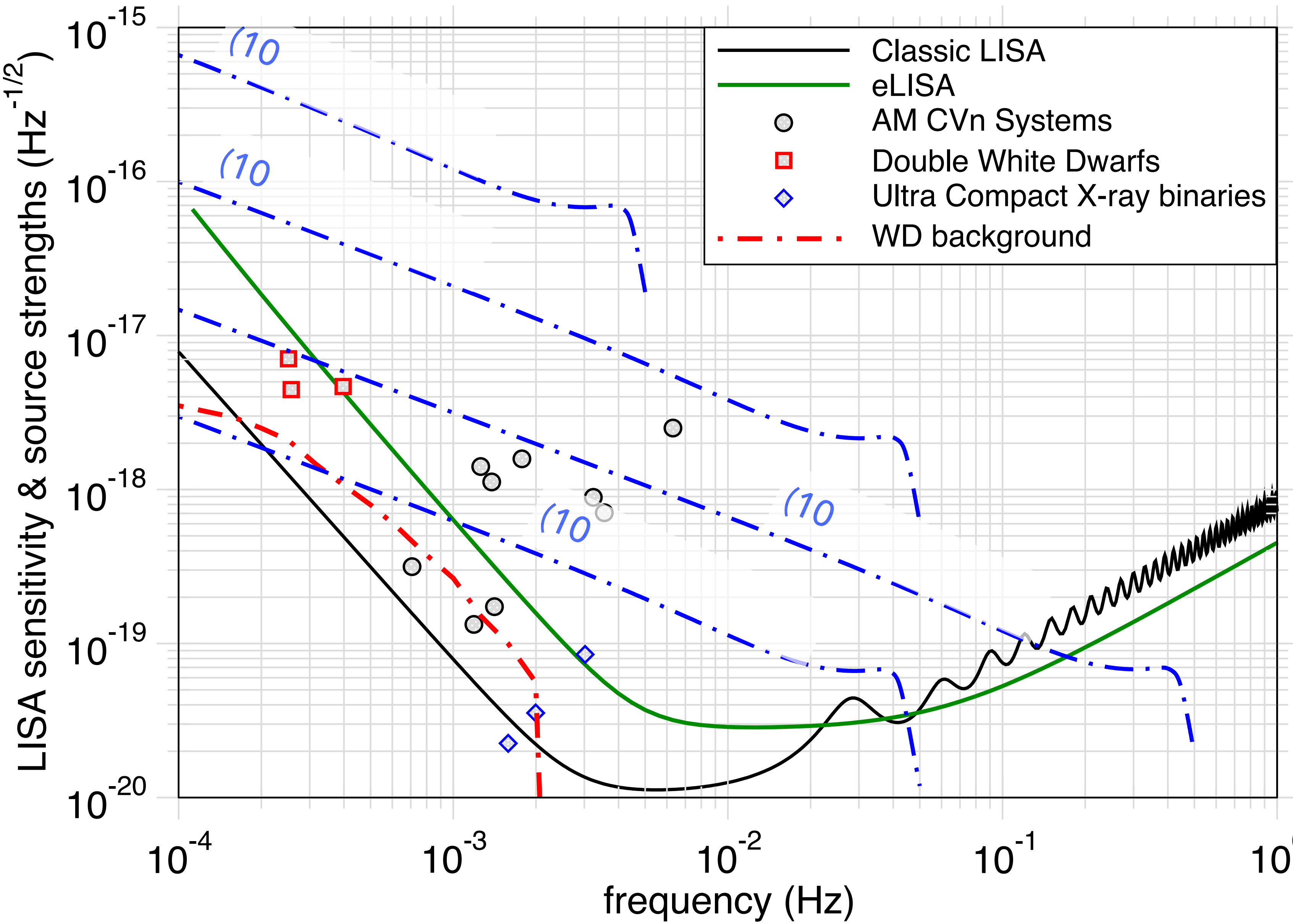
LISA WHITE DWARF BACKGROUND



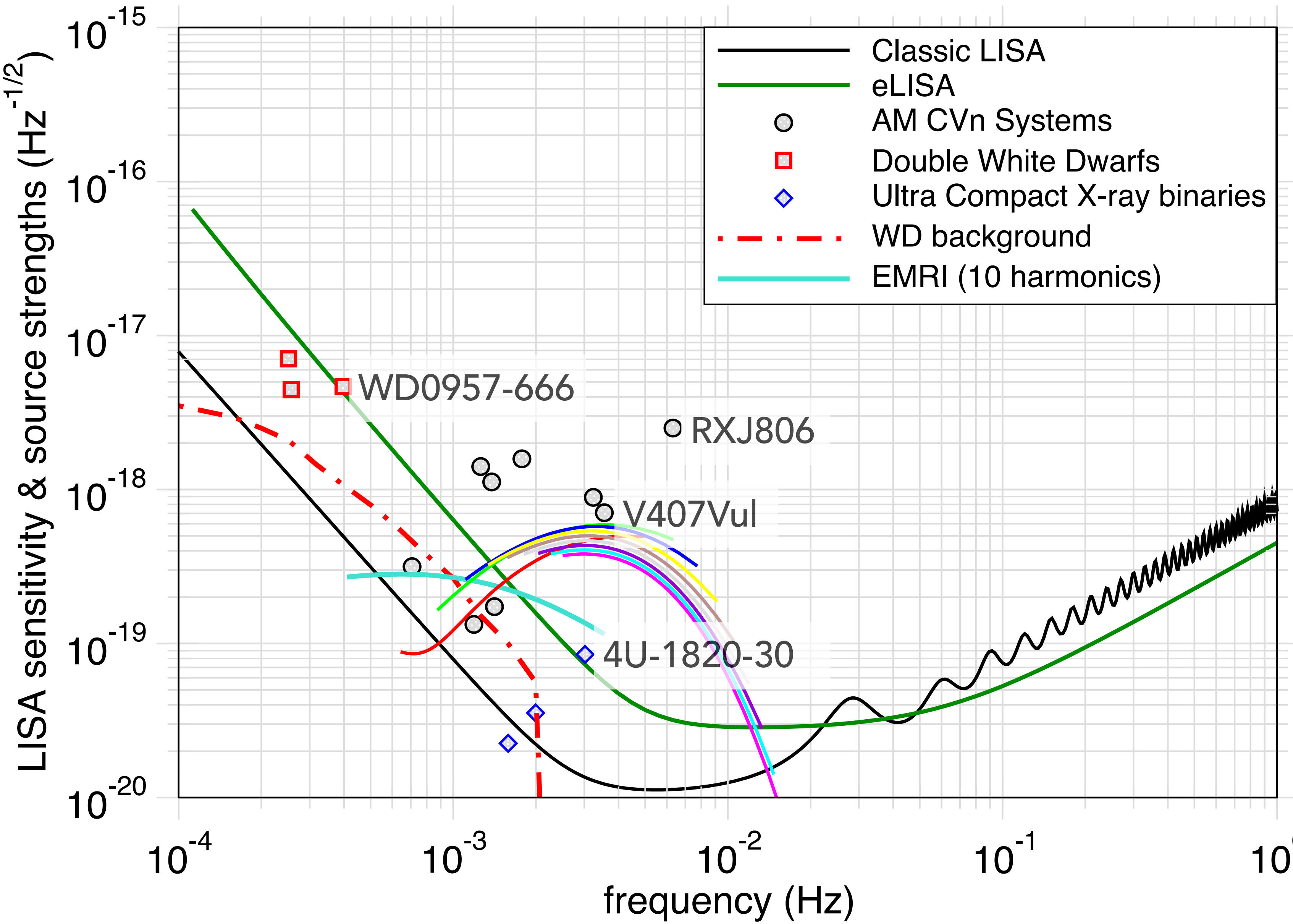
STOCHASTIC BACKGROUNDS



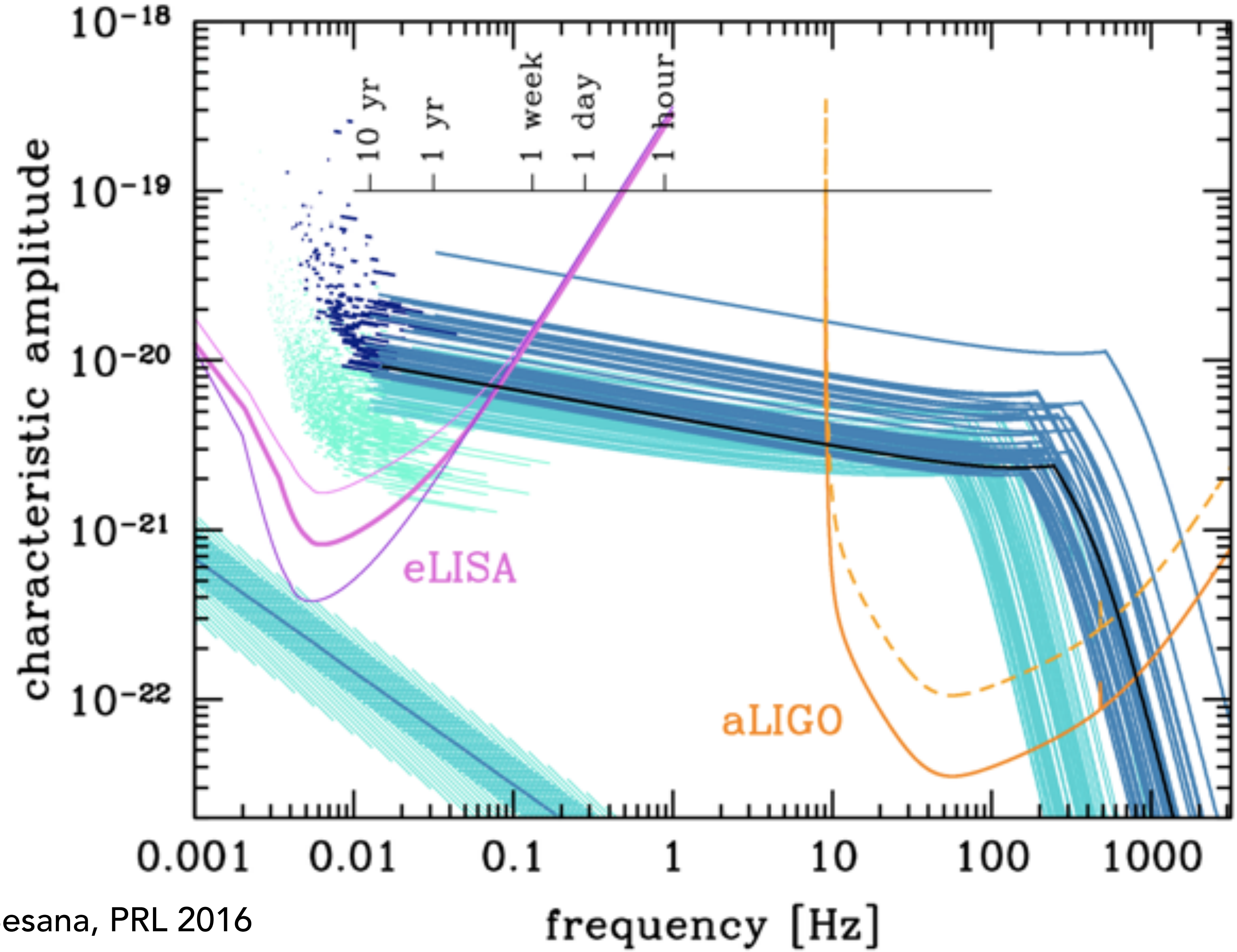
SUPERMASSIVE BLACK HOLES



EXTREME MASS RATIO INSPIRALS



BLACK HOLE BINARIES ACROSS THE GW SPECTRUM



Sesana, PRL 2016