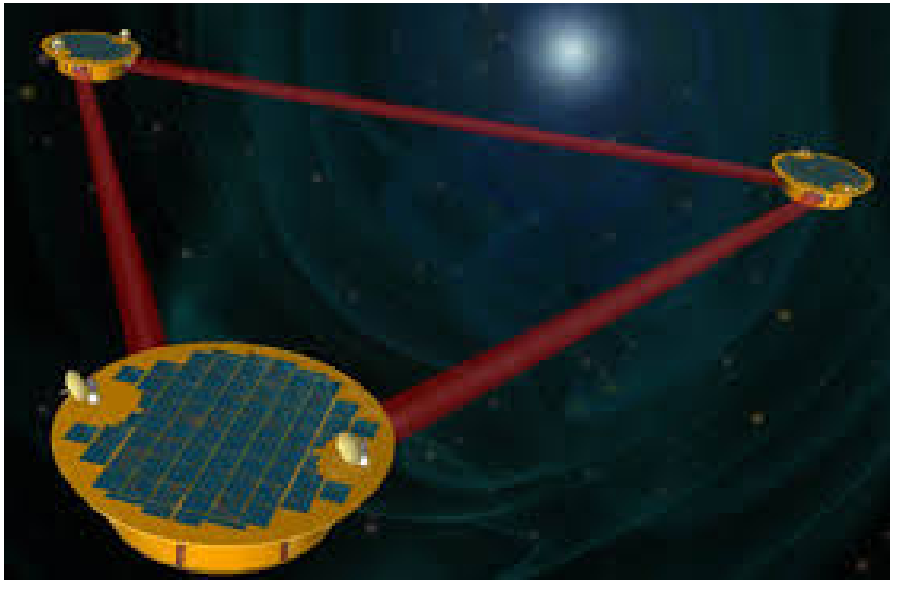
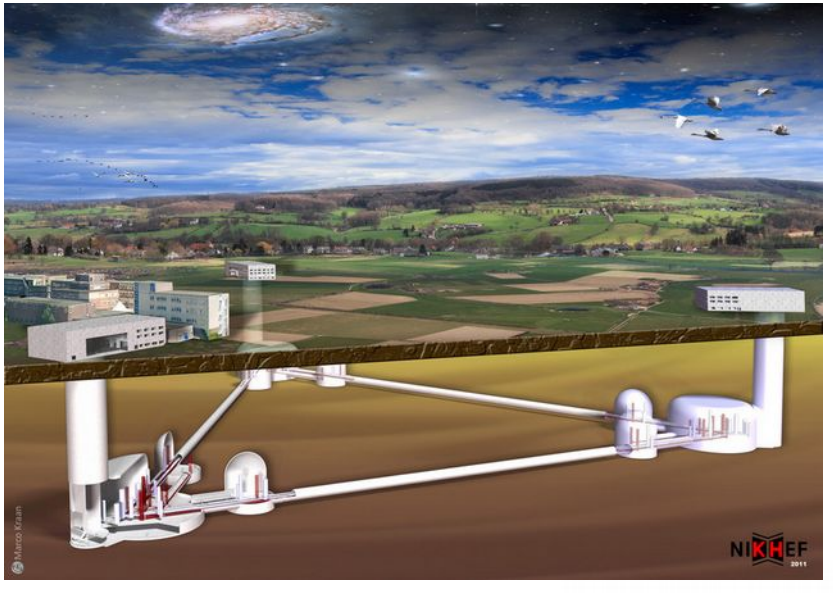
Fundamental physics with LISA and Einstein Telescope





Bert Vercnocke (KU Leuven)

Gravitational Wave Center

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

KU LEUVEN

@GWC_KULeuven

This talk

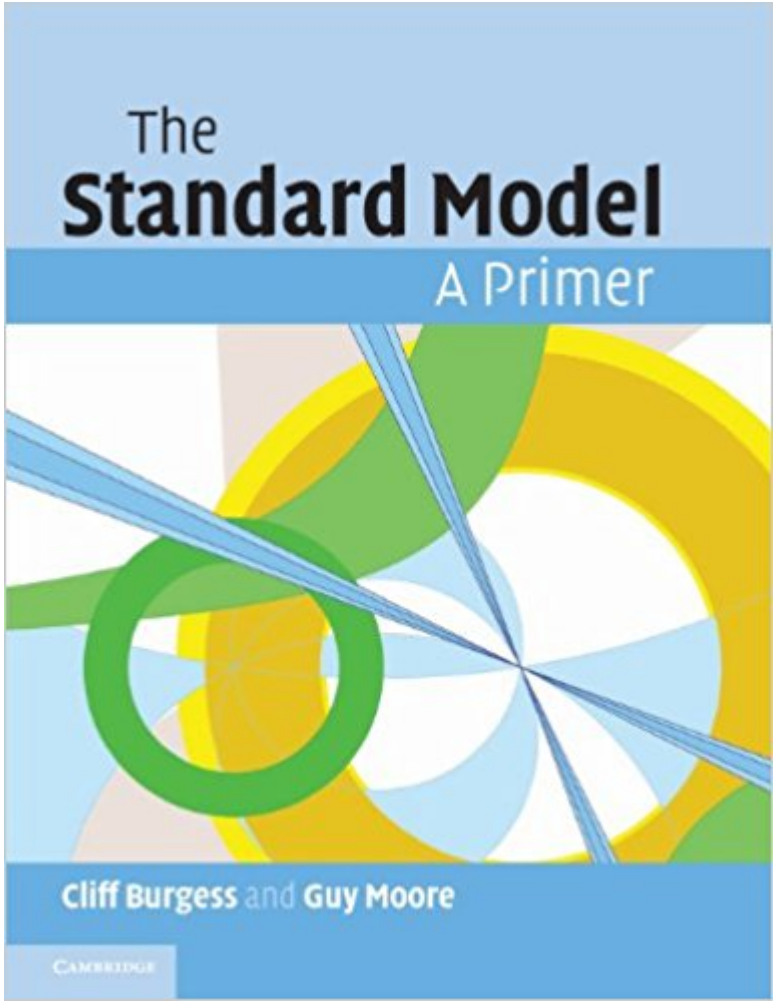
1) Motivation

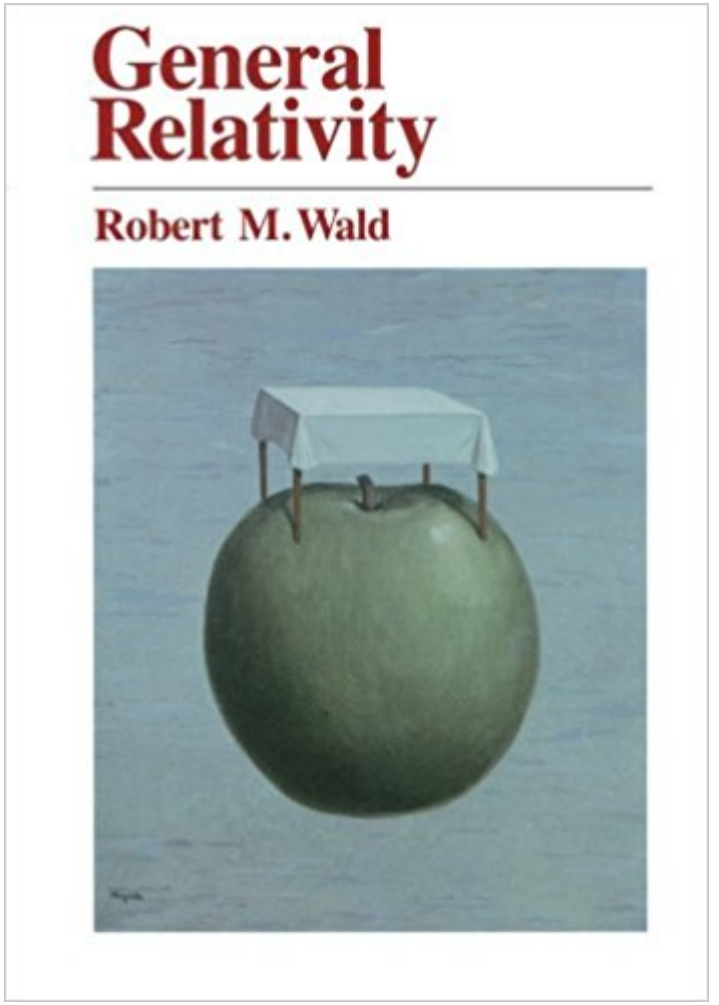
2) LISA & Einstein Telescope

3) Prospects

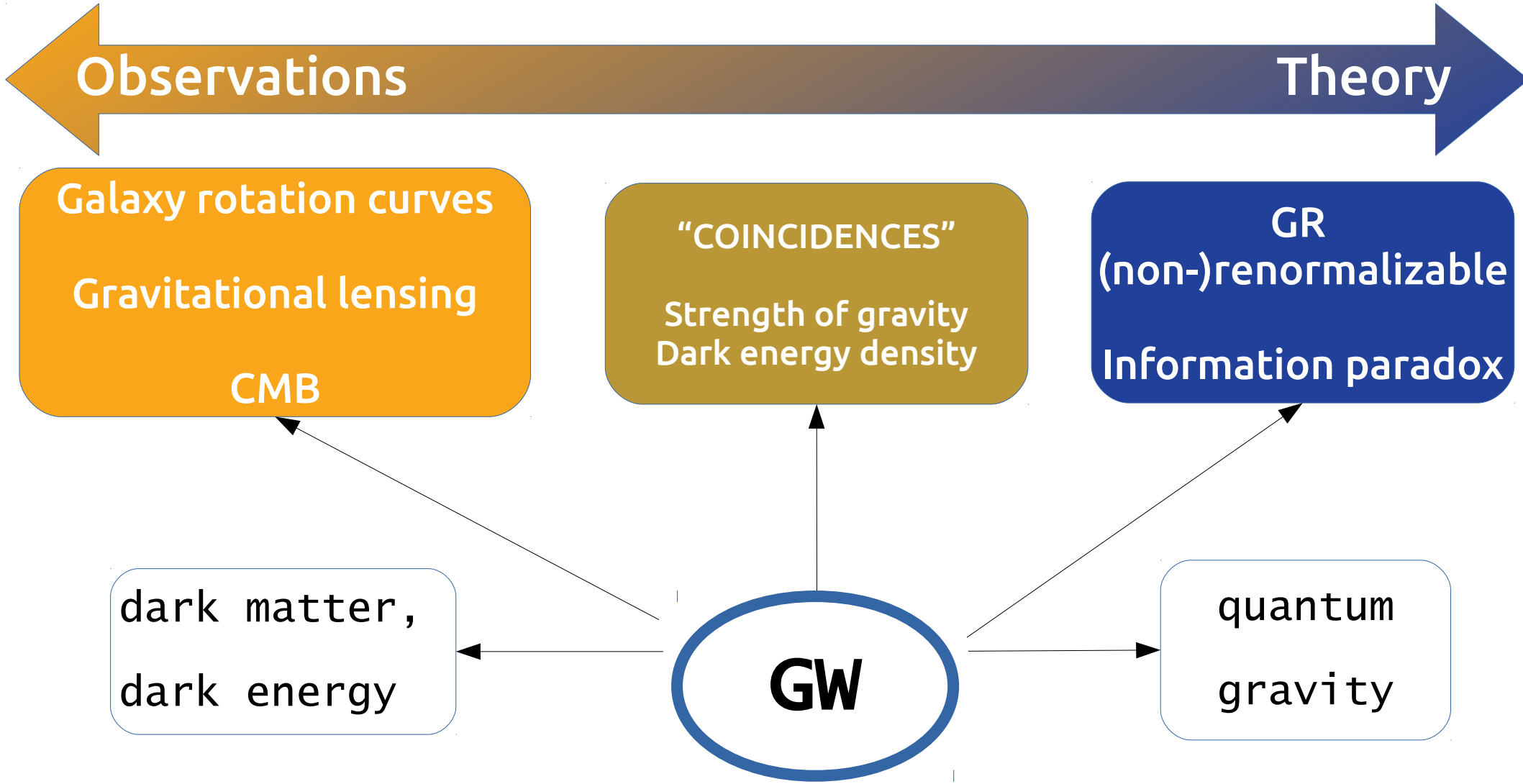
Fundamental physics?

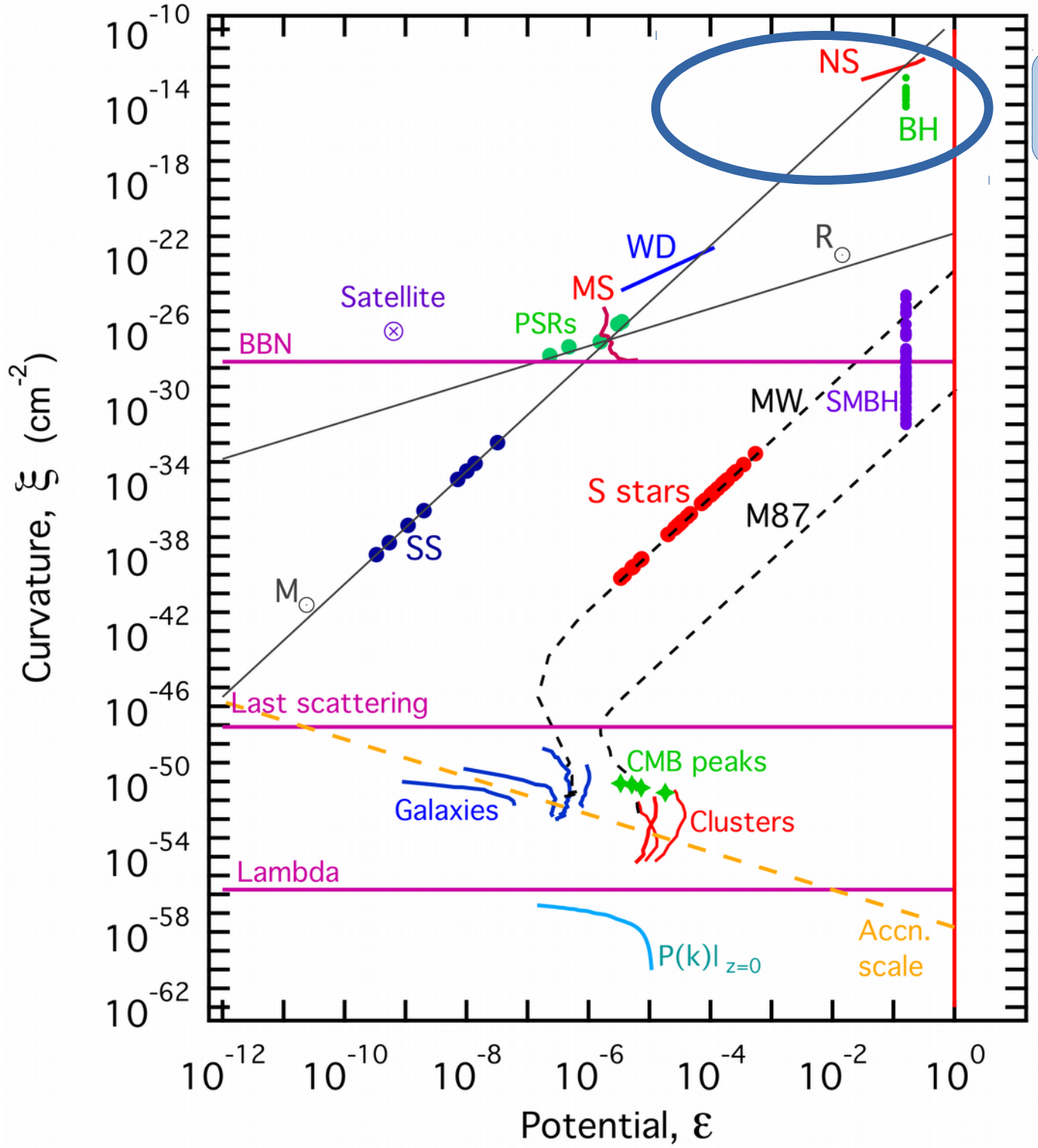
- New physics beyond:





Hints to new physics




Current GW detectors
NS
BH
WD
MS
PSRs
Satellite
BBN
R⊙
M⊙
SS
MW
SMBH
S stars
M87
Last scattering
CMB peaks
Galaxies
Clusters
Lambda
P(k)|z=0
Accn. scale
Curvature, ξ (cm-2)
Potential, ε
10-10
10-14
10-18
10-22
10-26
10-30
10-34
10-38
10-42
10-46
10-50
10-54
10-58
10-62
10-12
10-10
10-8
10-6
10-4
10-2
100

Why new GW detectors?

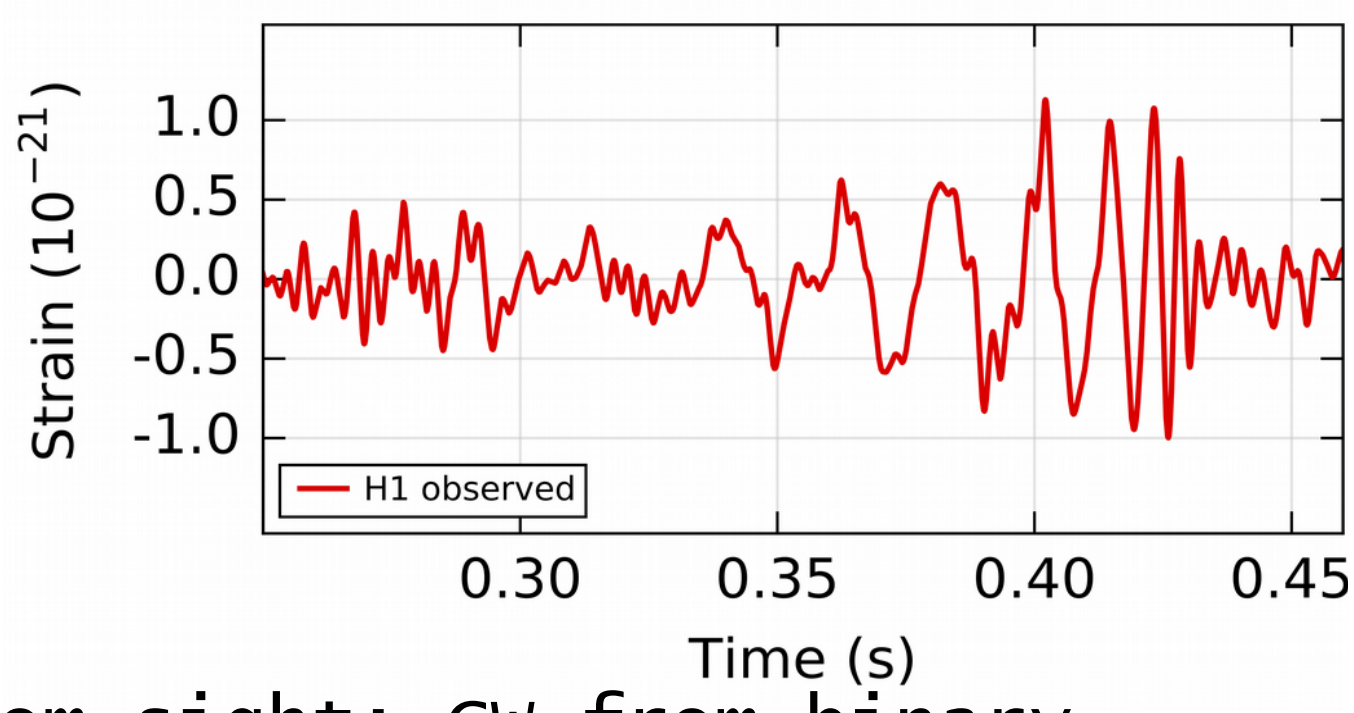
- Why haven't we ruled out everything already (beyond GR)?

Why new GW detectors?

- Why haven't we ruled out everything already (beyond GR)?

- Precision!

GW150914: black holes by sight?



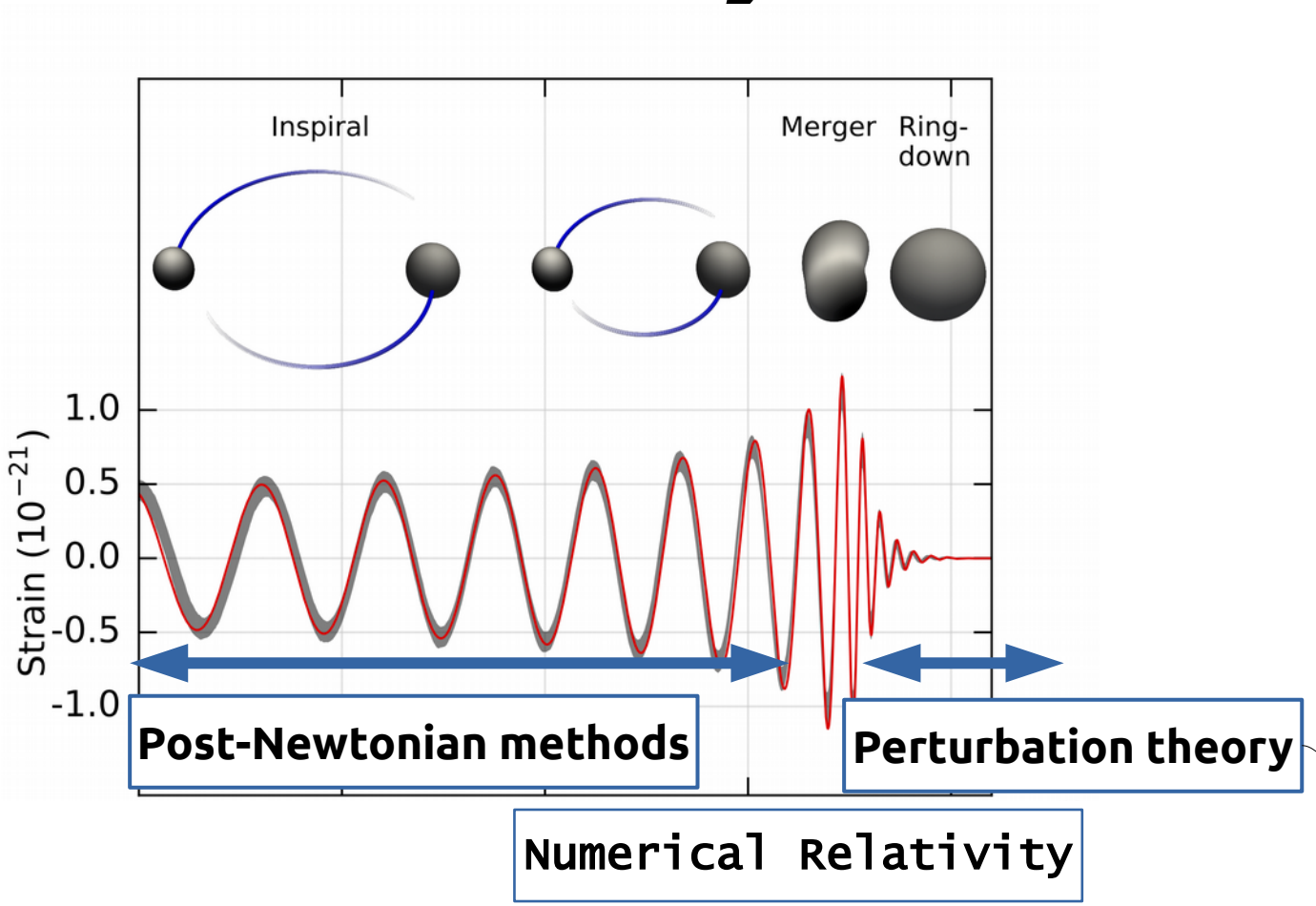
From sight: GW from binary

Einstein quadrupole + Newton's laws:

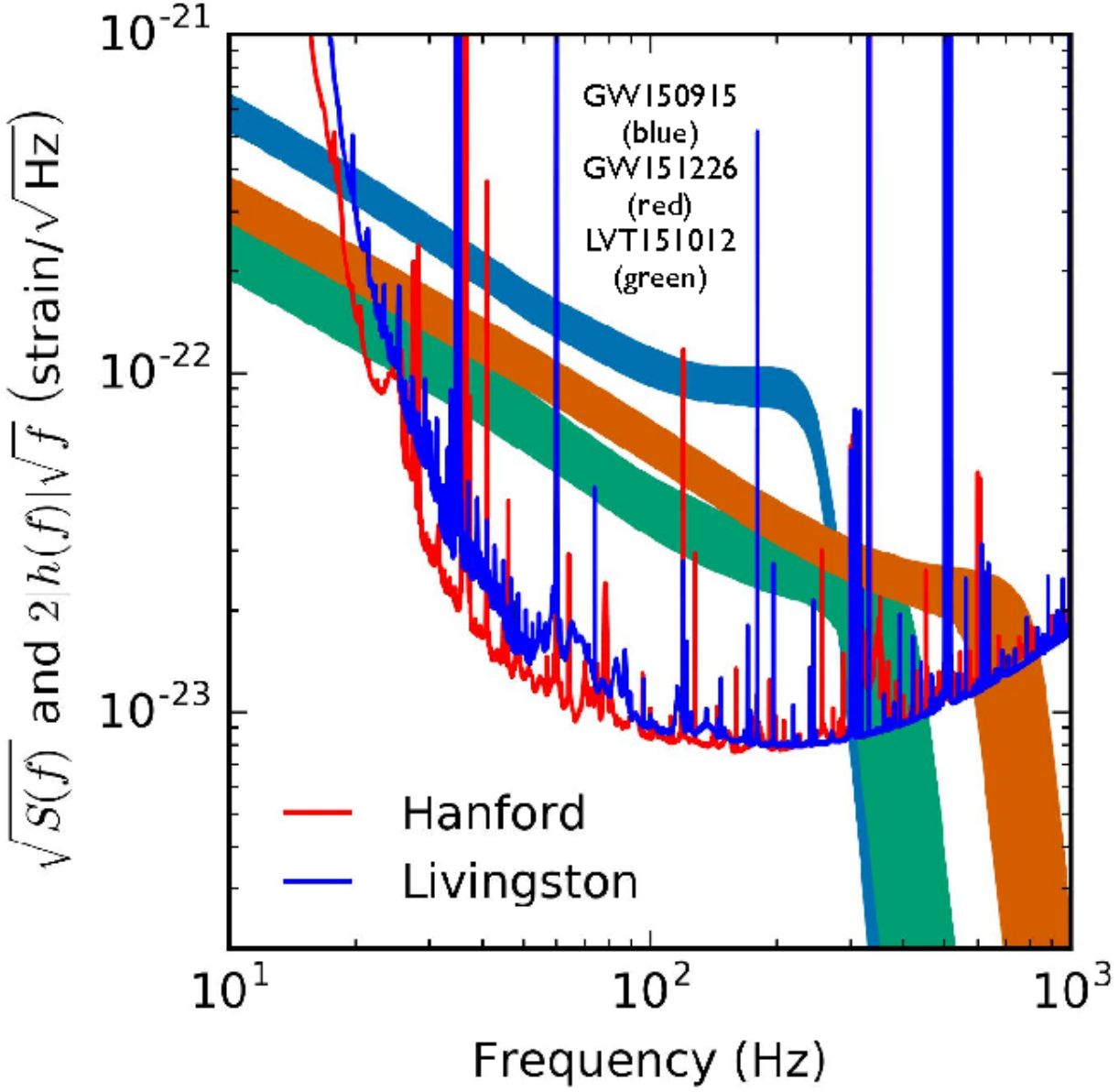
$$M_{\rm total} \sim 70 M_\odot \qquad\qquad R = \sqrt{\frac{GM}{\omega_{\rm max}}} = 350 \text{ km}$$

See: LIGO/Virgo collaboration, *"The basic physics of the binary black hole merger GW150914"* GW150914

Data analysis



- Too low SNR for independent total mass
- LIGO/Virgo analysis assumes GR!

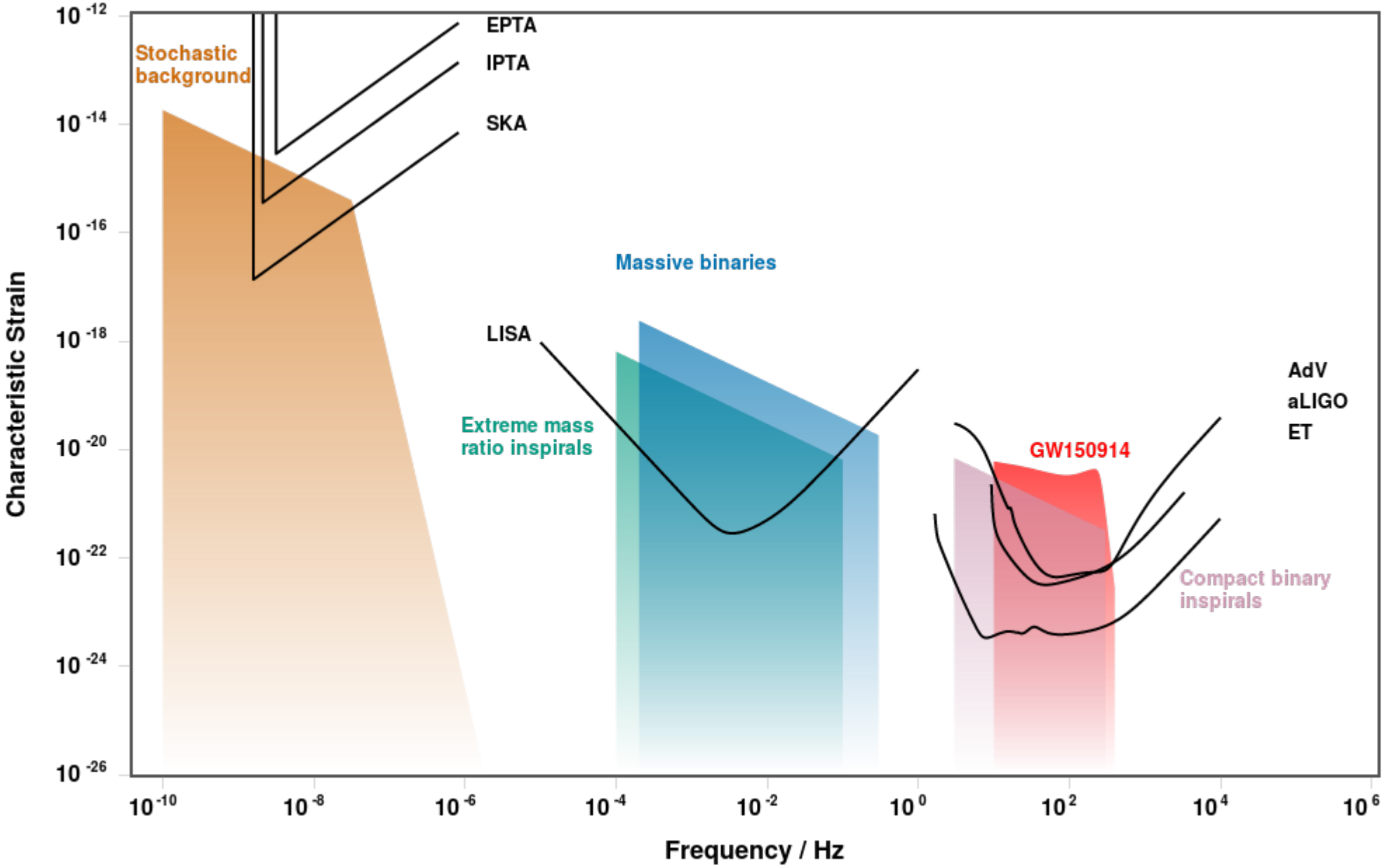

10^{-21}
10^{-22}
10^{-23}
$\sqrt{S(f)}$ and $2|h(f)|\sqrt{f}$ (strain/$\sqrt{\text{Hz}}$)
GW150915
(blue)
GW151226
(red)
LVT151012
(green)
Hanford
Livingston
10^{1}
10^{2}
10^{3}
Frequency (Hz)

This talk

1)Motivation

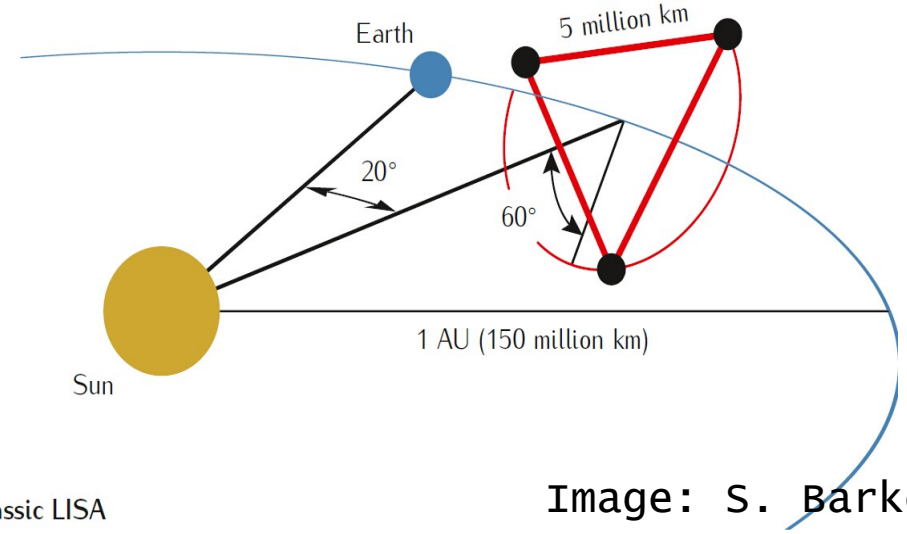
2)LISA & Einstein Telescope

3)Prospects



From Moore, Cole, Berry (2014)
http://rhcole.com/apps/GWplotter/

LISA (Laser Interferometer Space Antenna)



Classic LISA

Image: S. Barke

- Design
  - Triangle, 2.5M km arms
  - >= 4 years operation
  - Low frequency $10^{-5} - 10^{-1}$ Hz

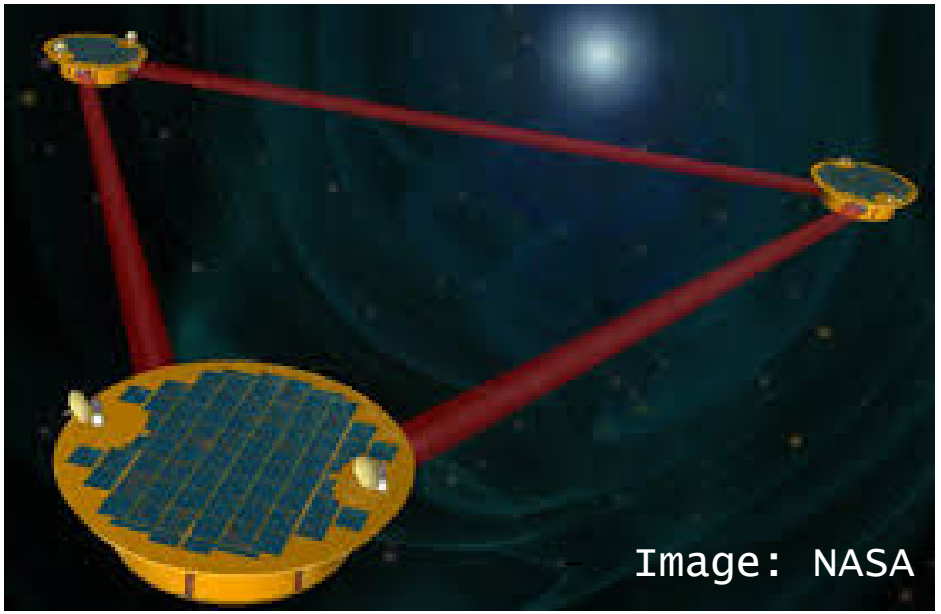
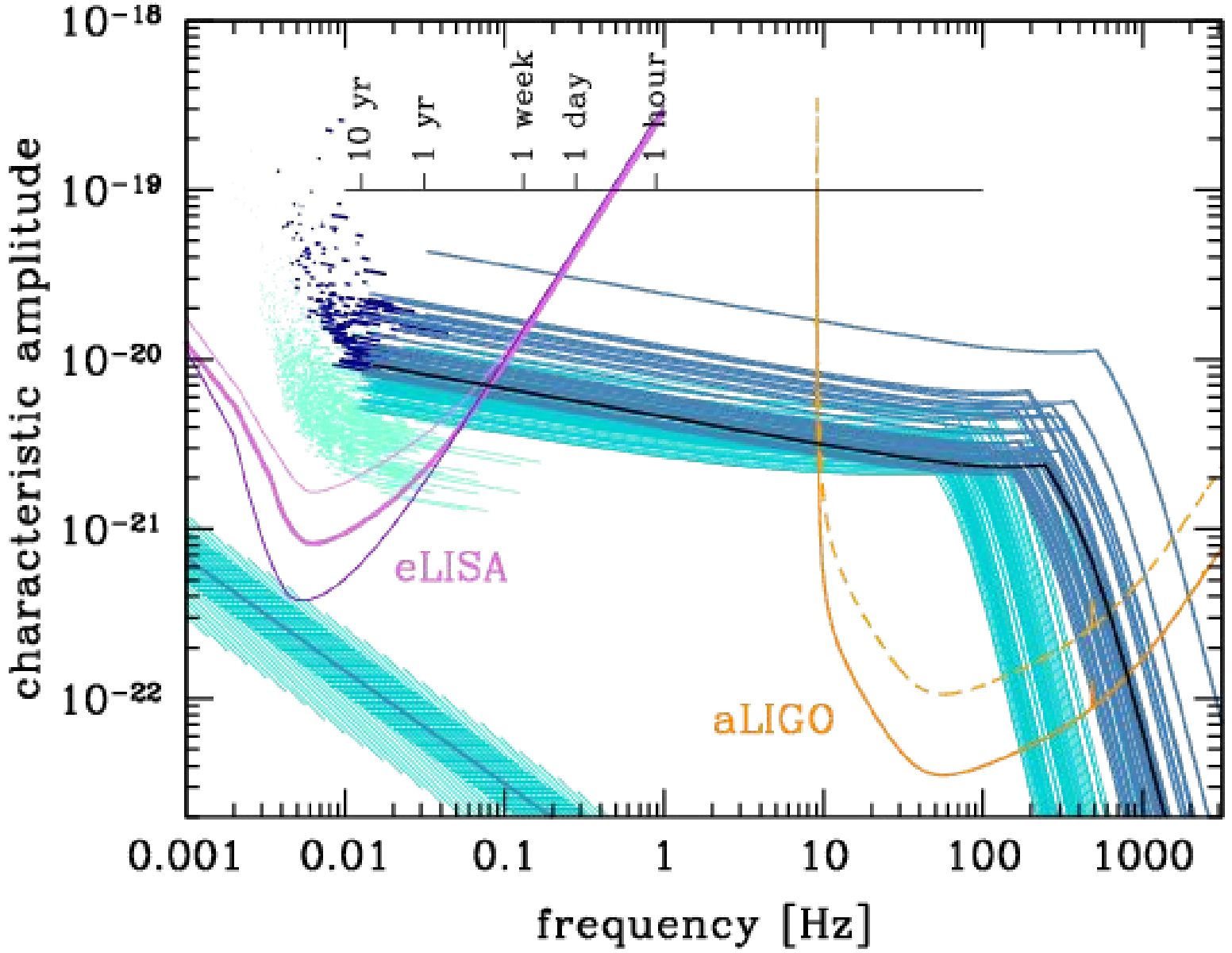
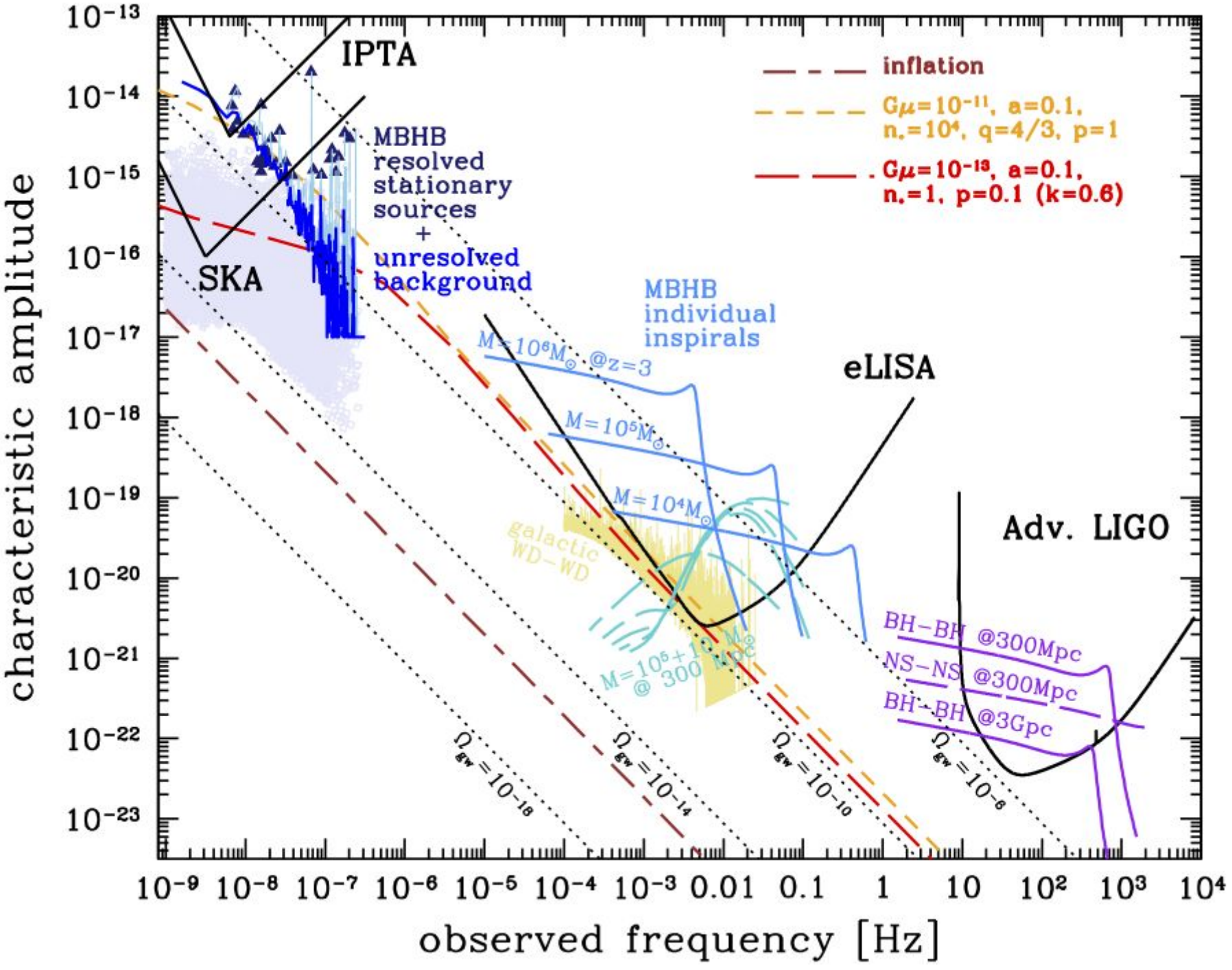


Image: NASA

- Timeline:
  - 2017 ESA/NASA approval
  - Consortium: science goals
  - Launch 2034


characteristic amplitude
frequency [Hz]
eLISA
aLIGO
10 yr
1 yr
1 week
1 day
1 hour
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
0.001
0.01
0.1
1
10
100
1000

Sesana 2016


IPTA
SKA
MBHB
resolved
stationary
sources
+
unresolved
background
MBHB
individual
inspirals
eLISA
Adv. LIGO
inflation
Gμ=10⁻¹¹, a=0.1,
n_t=10⁴, q=4/3, p=1
Gμ=10⁻¹³, a=0.1,
n_t=1, p=0.1 (k=0.6)
M=10⁶M⊙ @z=3
M=10⁵M⊙
M=10⁴M⊙
galactic
WD−WD
M=10⁵+10⁴M⊙
@ 300 Mpc
BH−BH @300Mpc
NS−NS @300Mpc
BH−BH @3Gpc
Ω_gw=10⁻¹⁸
Ω_gw=10⁻¹⁴
Ω_gw=10⁻¹⁰
Ω_gw=10⁻⁶
characteristic amplitude
observed frequency [Hz]
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
10⁻²¹
10⁻²²
10⁻²³
10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 0.01 0.1 1 10 10² 10³ 10⁴

LISA: Main Target Sources

- Supermassive Black hole binaries

$$10^4 - 10^7 M_\odot$$

- EMRI: Extreme Mass Ratio Inspirals

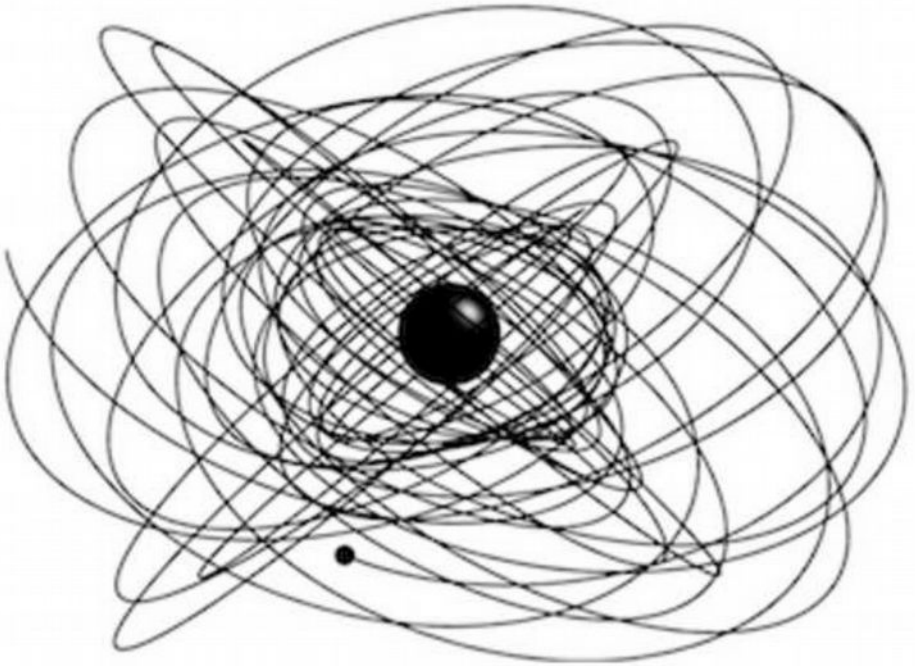
$$10^4 - 10^7 M_\odot$$

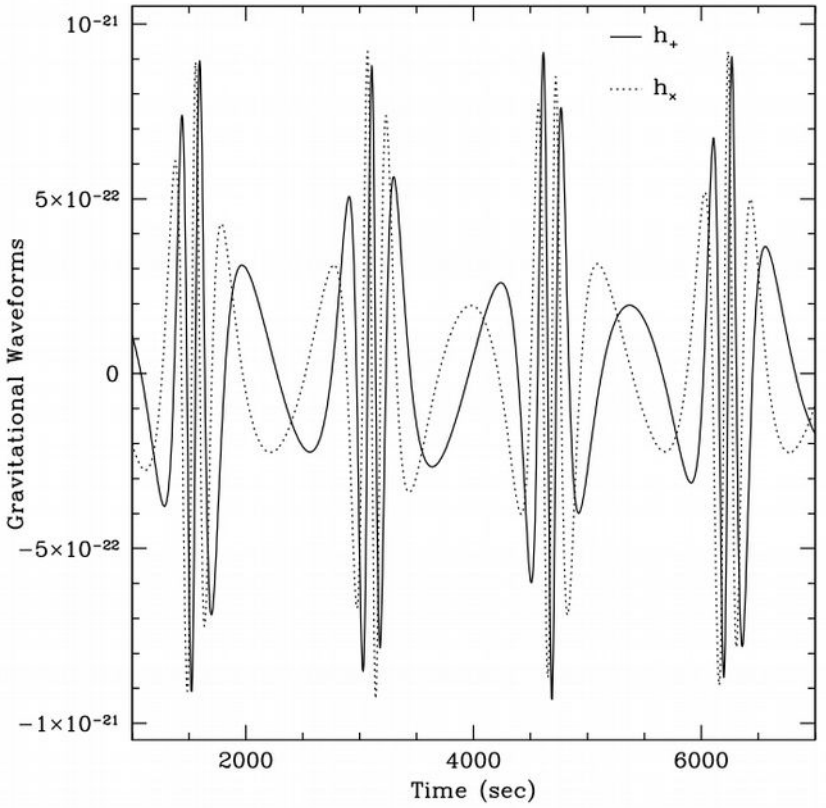
- Stochastic background
  - Primordial, inflation, phase transitions

- + Galactic binaries

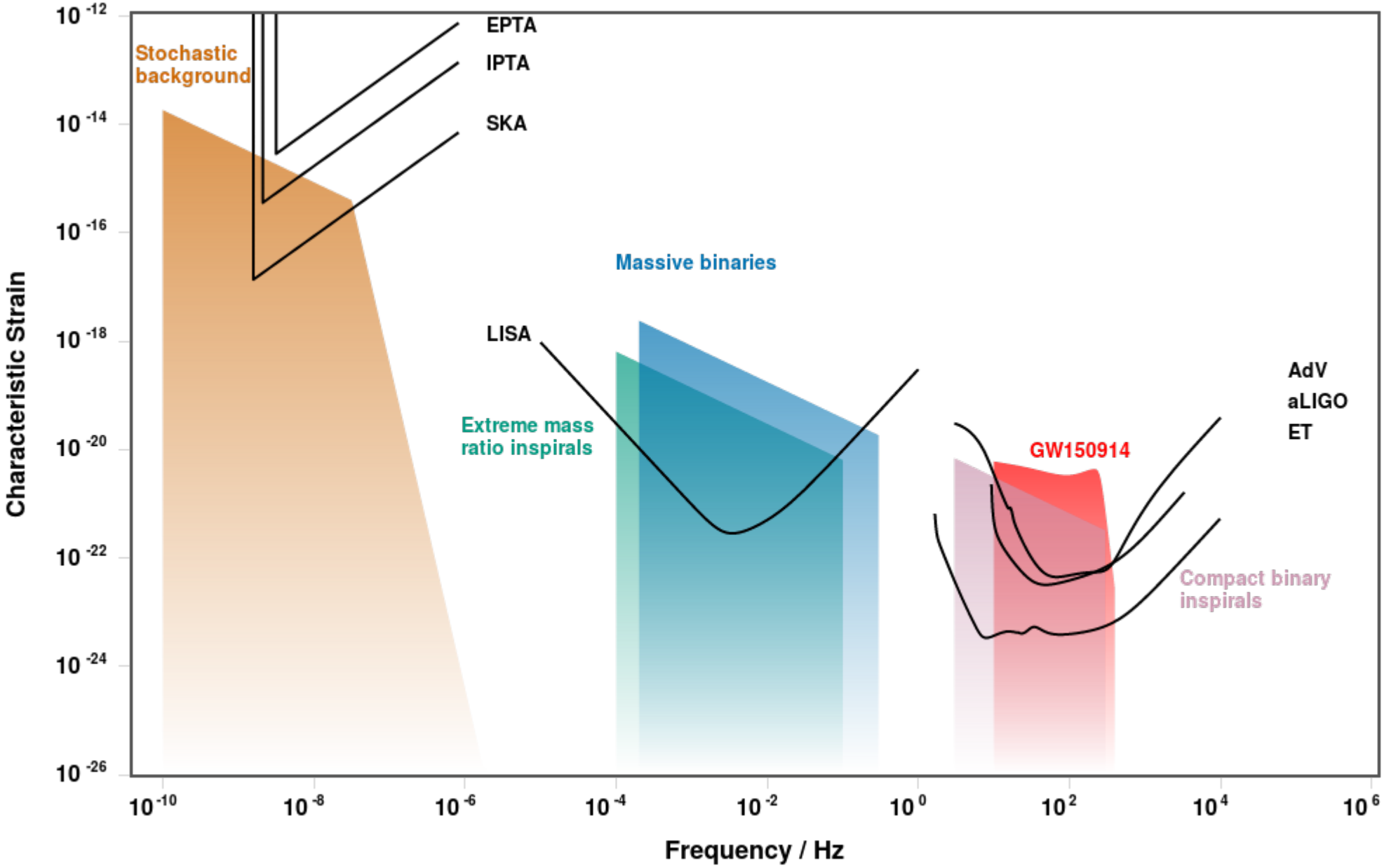
Extreme Mass Ratio Inspirals

Detailed mapping of region around BH's



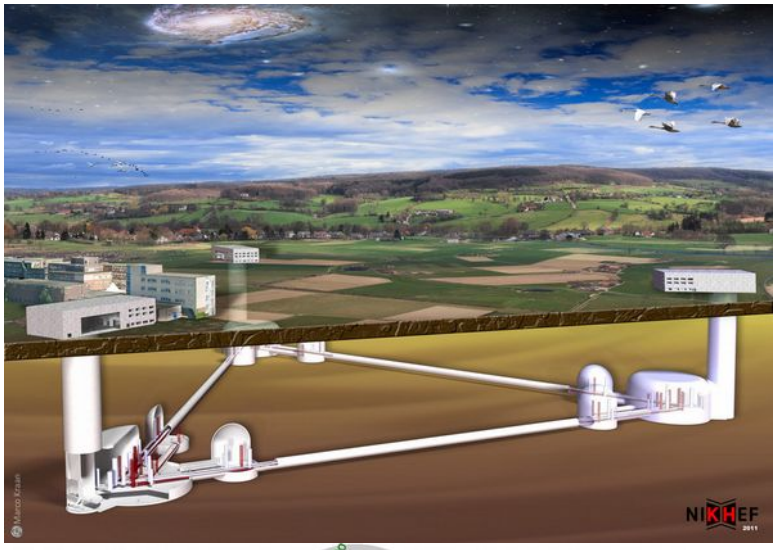


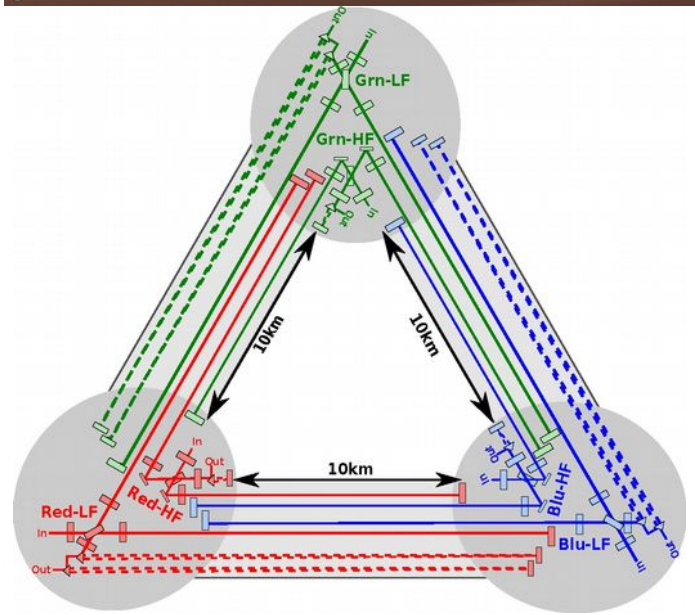
Sopuerta 2012



- Moore, Cole, Berry (2014)
- http://rhcole.com/apps/GWplotter/

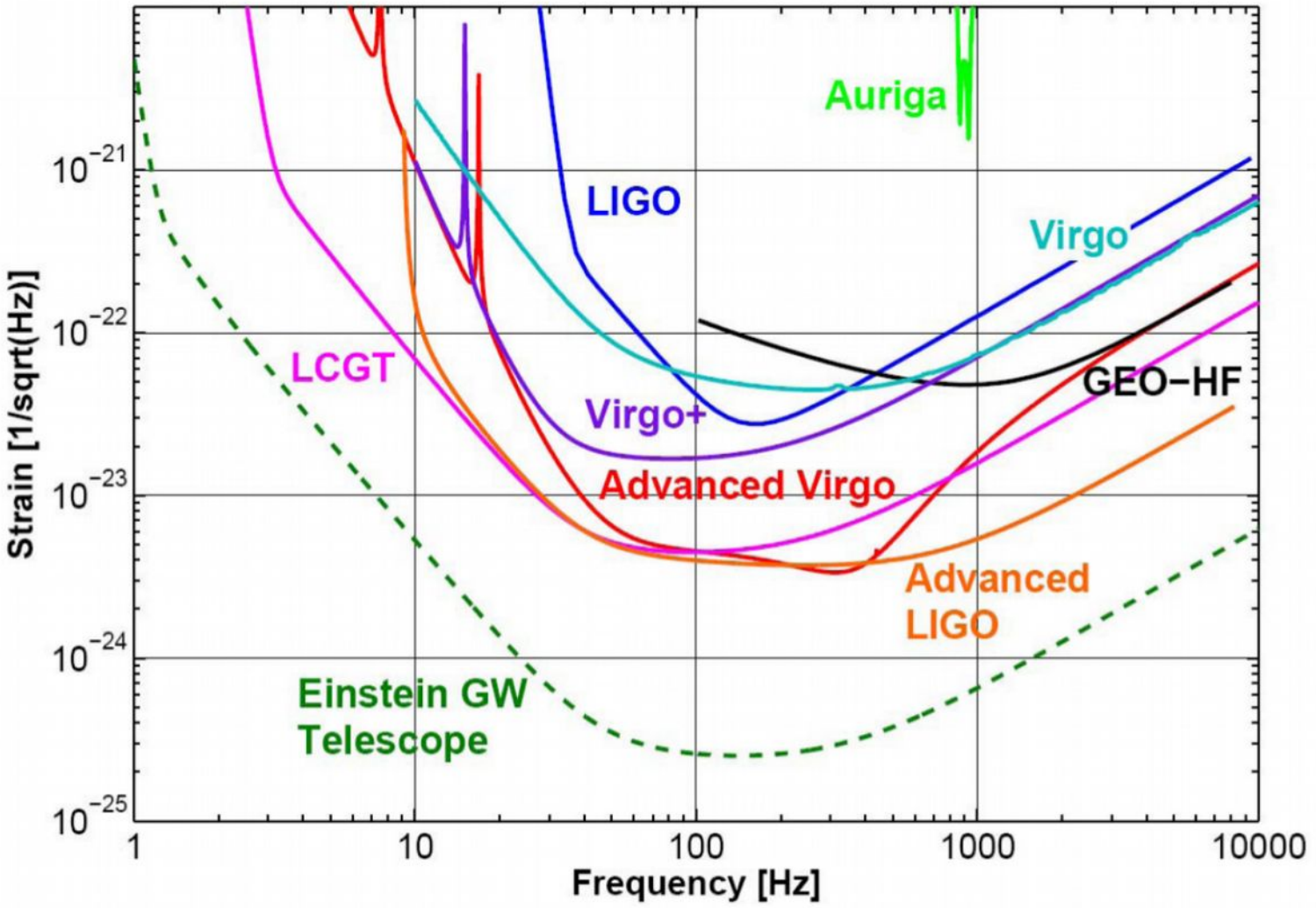
Einstein Telescope (ET)

- 



- Design:
  - 10 km arms
  - Low & high frequency
- Timeline:
  - Design study 2011
  - ESFRI proposal ~2019
  - Operational 2030s

Wednesday 31/01: ULiège ET conference/9th COSPA meeting
https://events.uliege.be/telescope-einstein/



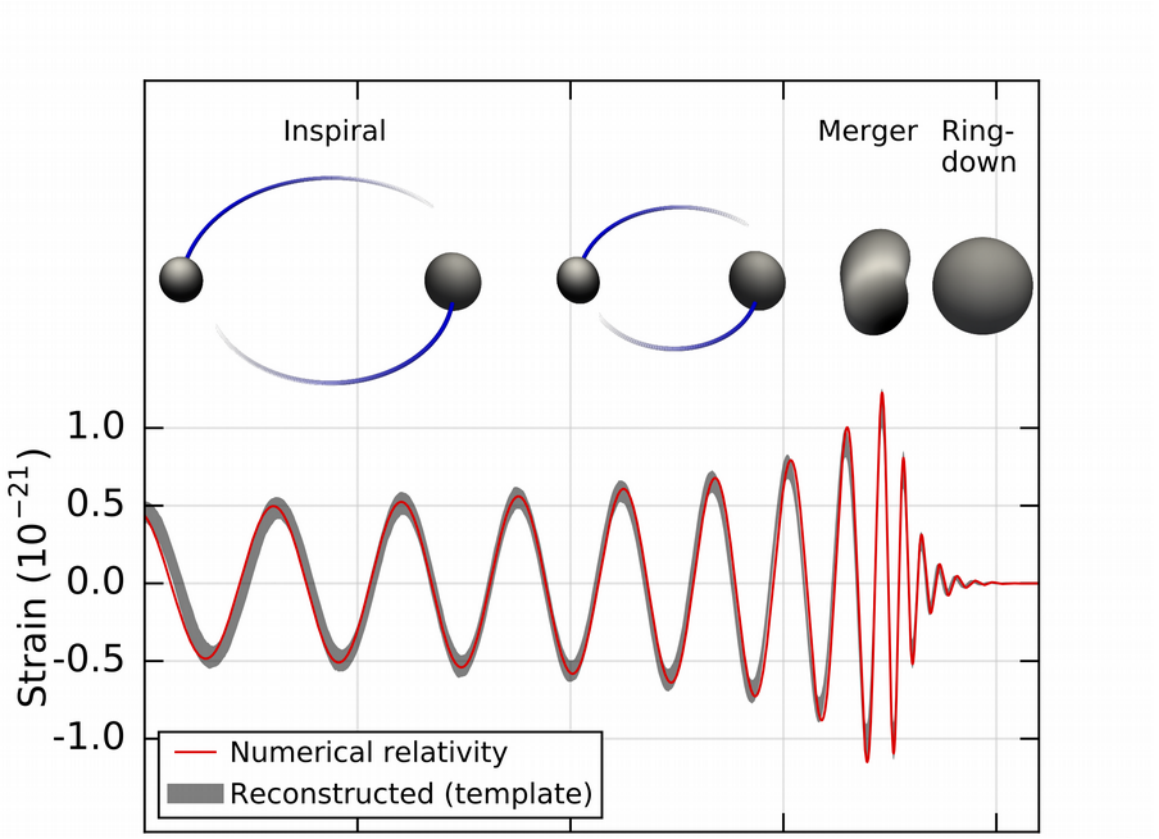
Einstein Telescope Conceptual Design Study (2011)

ET Main Target Sources

- Stellar Mass Binaries
  - Black holes: (z=15) (AdV,ALIGO: z=0.5)
  - Neutron stars (z=5) (AdV,ALIGO: 200Mpc)
- Supernovae
- Intermediate Mass BH's ($10^2 - 10^4 M_\odot$)

No-hair tests

- "Black hole spectroscopy"
  - Frequencies & Damping times
  - Depend on mass and spin only?



This talk

1) Motivation

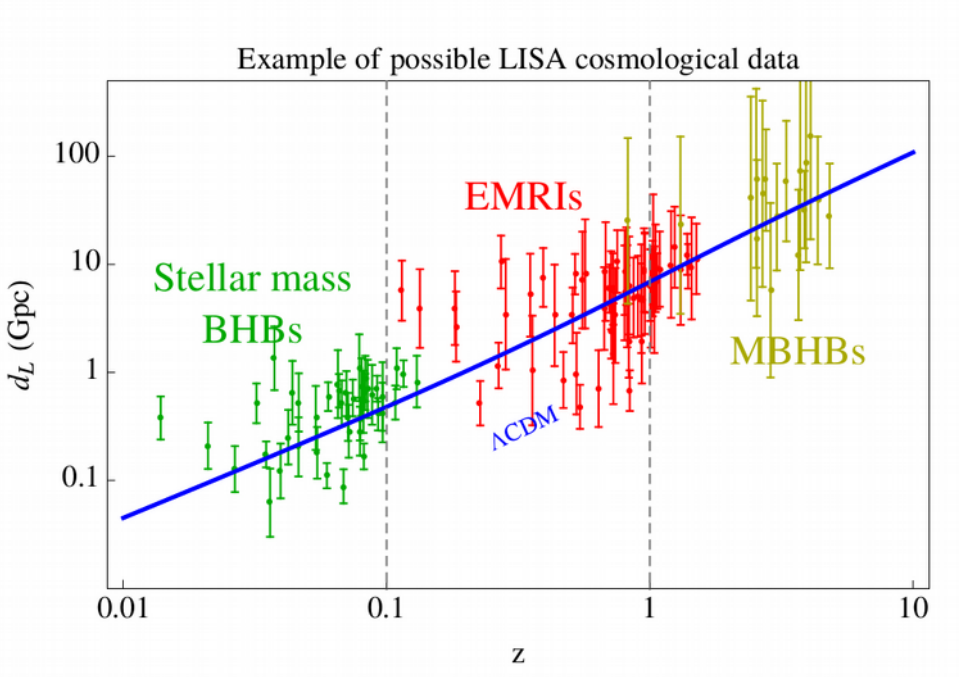
2) LISA & Einstein Telescope

3) Prospects
   - Cosmology
   - Dark matter
   - Nature of black holes

1. Cosmology

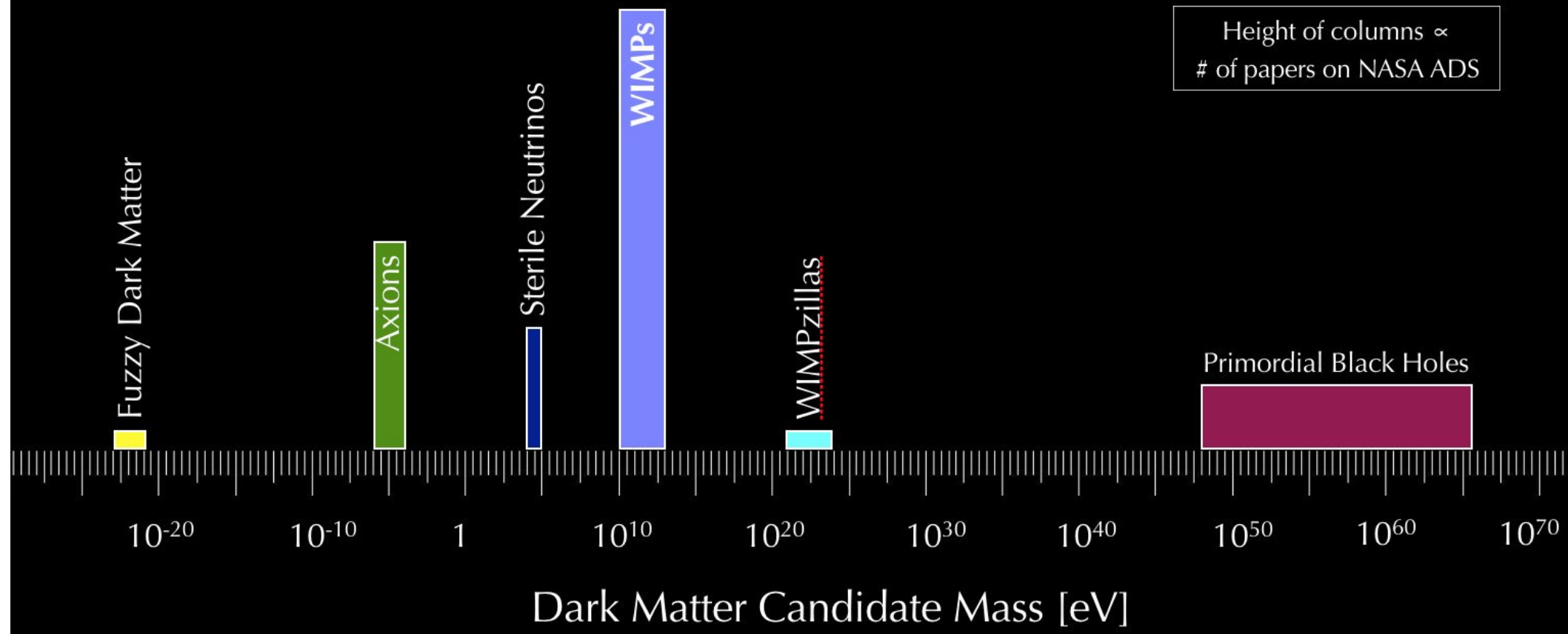
- Stochastic backgrounds:
  - Inflation
  - After inflation
    - Phase transitions
    - Formation scenarios Primordial BH's

- Cosmography
  - "Standard sirens" LISA & ET
  - Hubble parameter to percent level



What is dark matter?

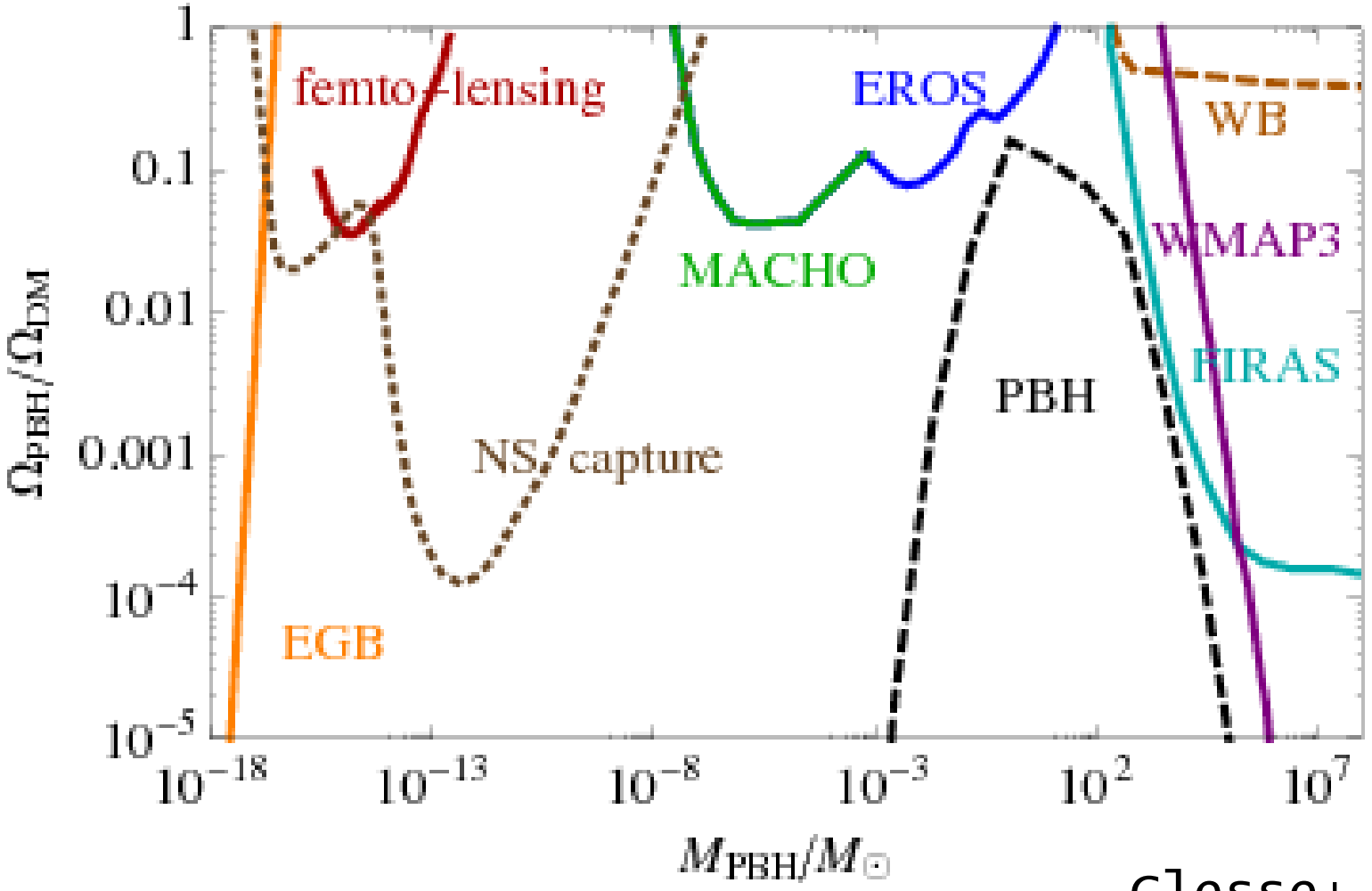
- No shortage of ideas..
- Tens of dark matter models, each with its own phenomenology
- Models span 90 orders of magnitude in DM candidate mass!



Slide by Gianfranco Bertone

2. Dark matter

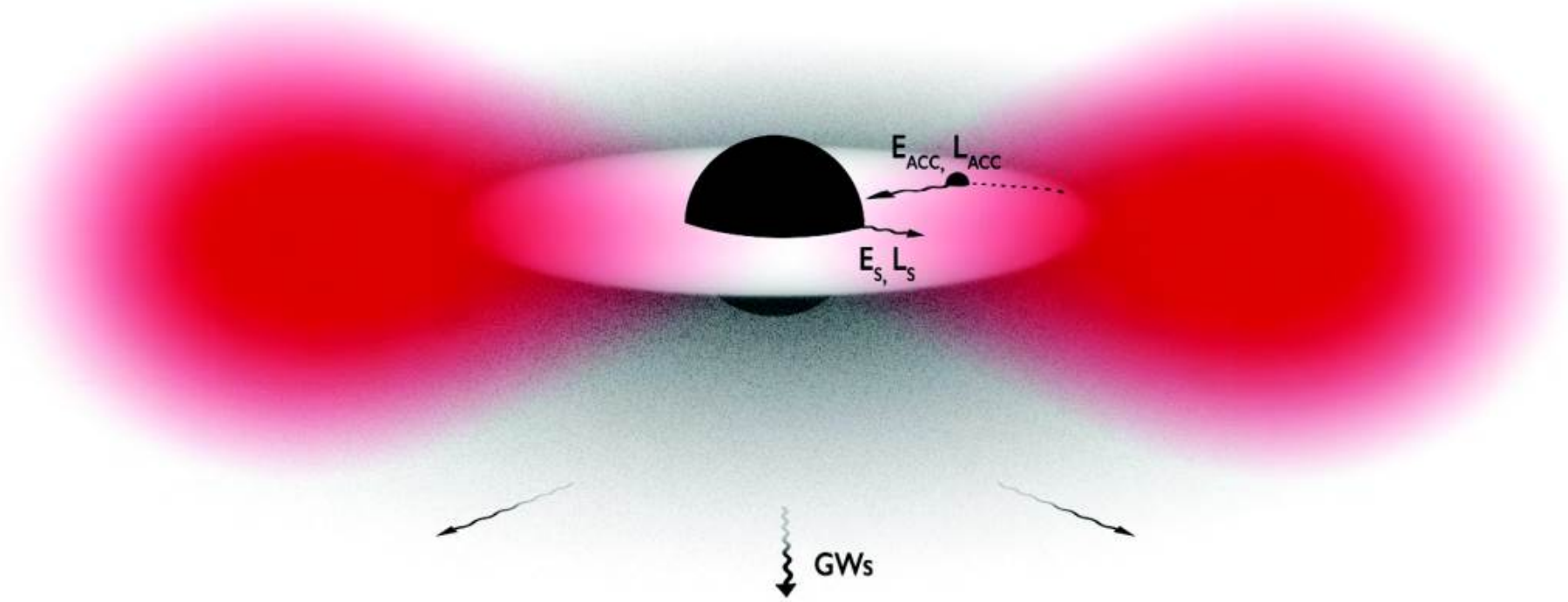
- Primordial black holes?



Clesse+ 2015

Black holes with DM Clouds

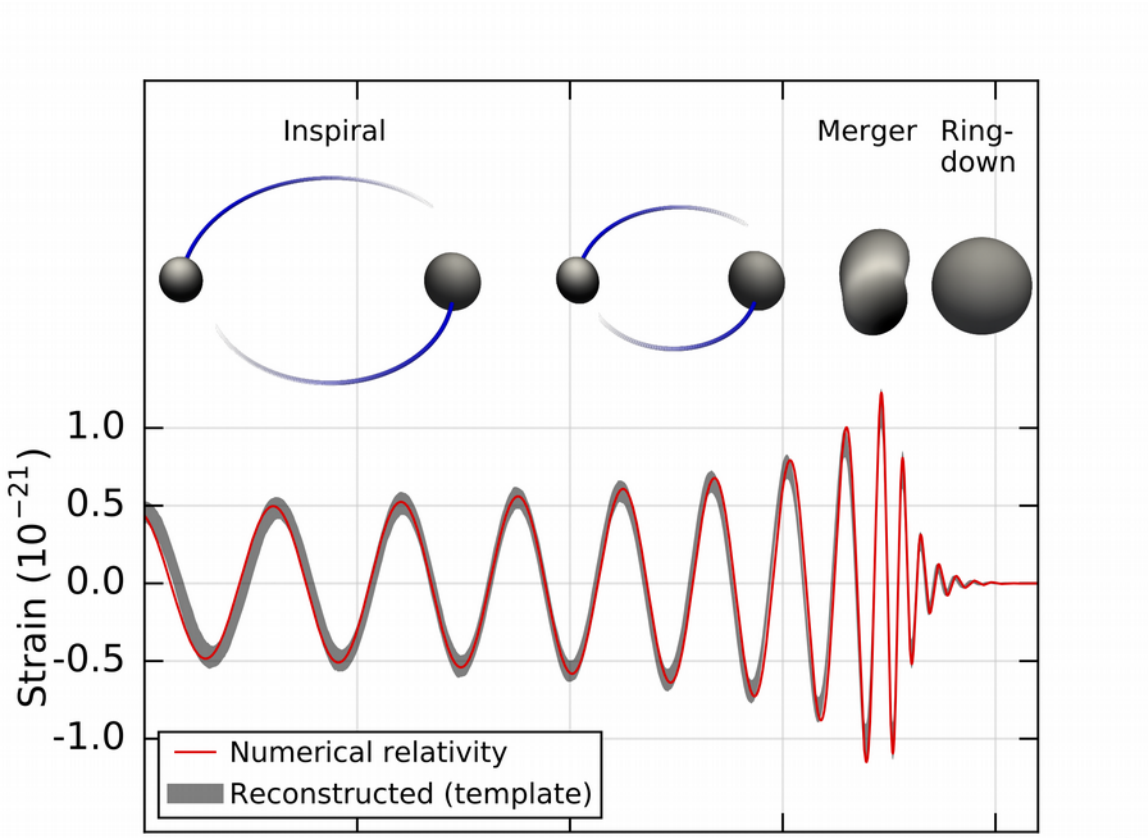
- Ultra-light bosons
  - Super-radiant instability $\omega/m < \Omega_{\rm BH}$
  - Axions, dark photons ...



R. Brito, V. Cardoso, P. Pani - 1501.06570

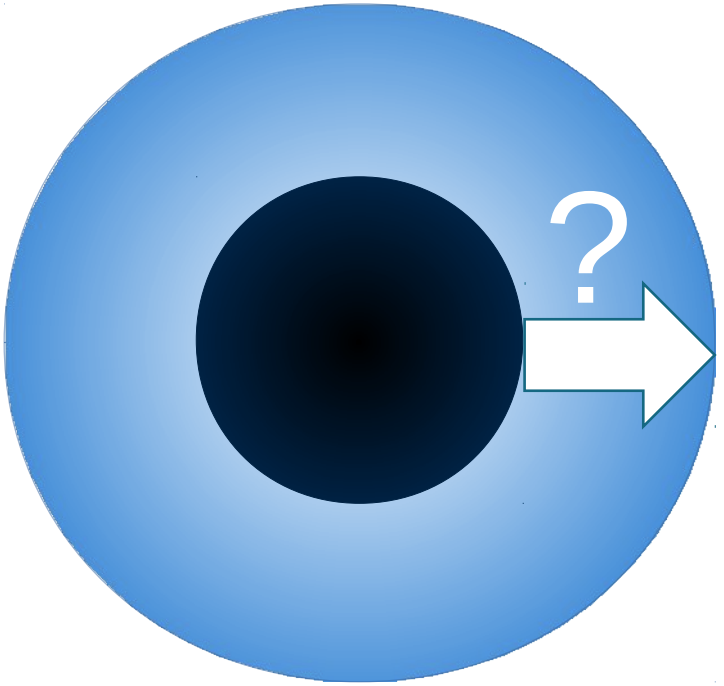
3. Nature of black holes

- Black holes, the atoms of 21st century?



Quantum expectations

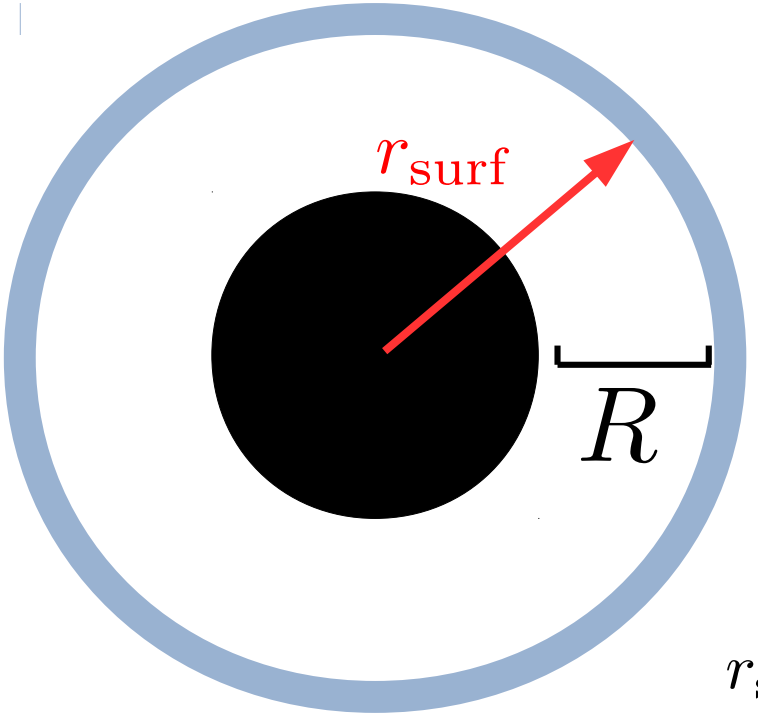
- Information paradox (Hawking /76)



- Quantum gravity:
  - New physics/structure at horizon

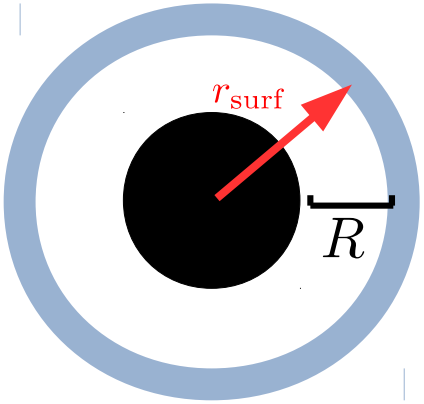
Exotic Compact Objects

- Proxy for quantum structure
  - Wormholes, gravastars, boson stars …

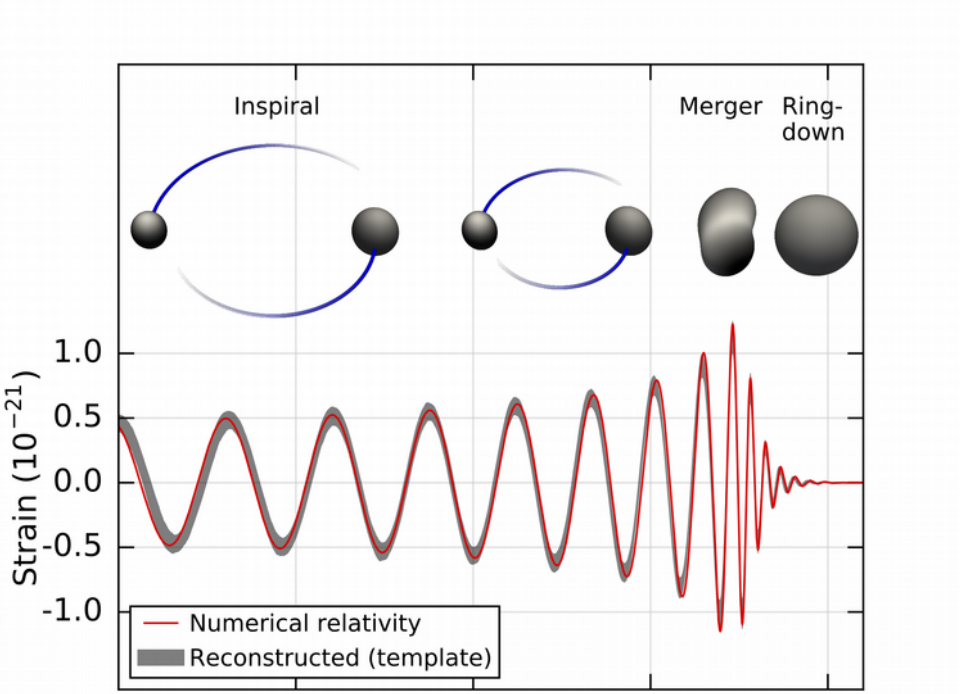


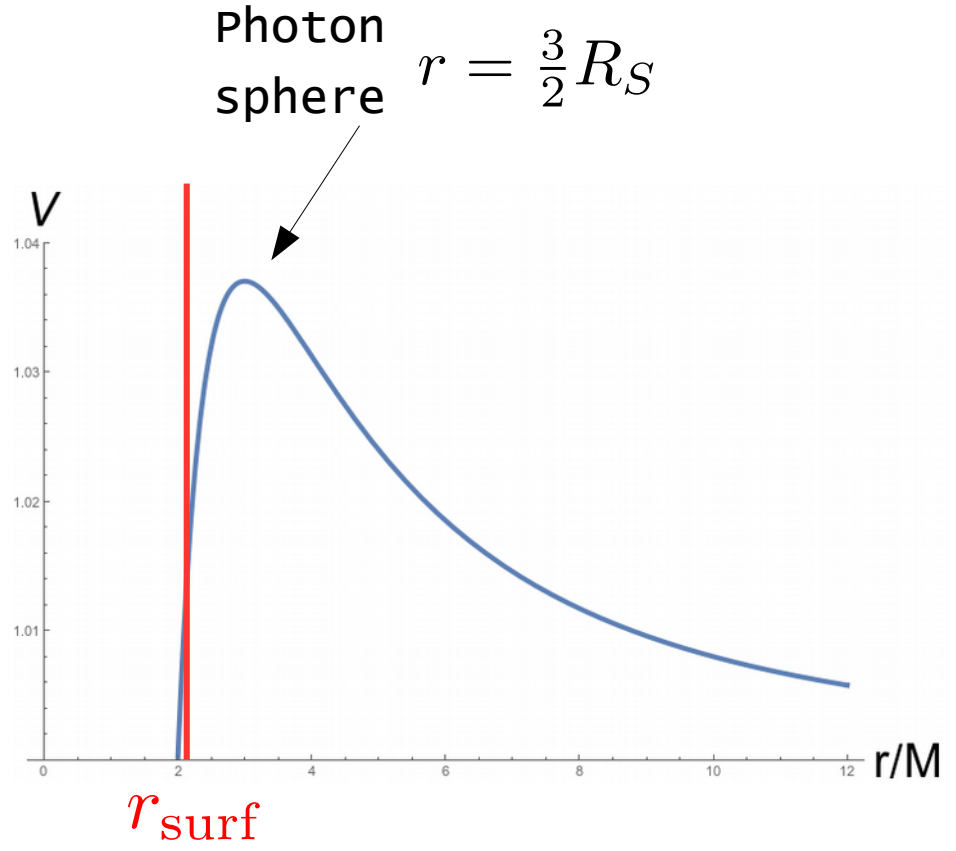
$$r_{\rm surf} = 2M\left(1+\frac{R}{R_S}\right)$$

Spectroscopy?



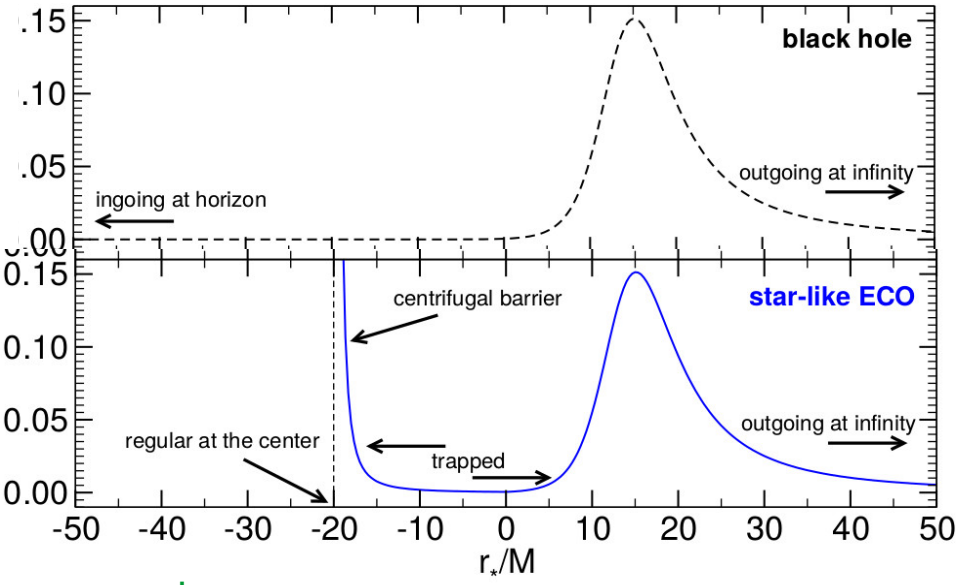
- Promt ringdown:
  - not sensitive to near-horizon!
  - Sensitive to photon sphere



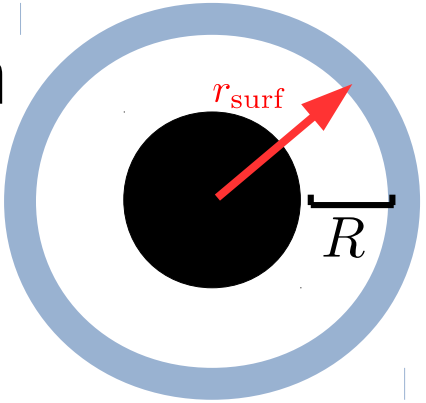


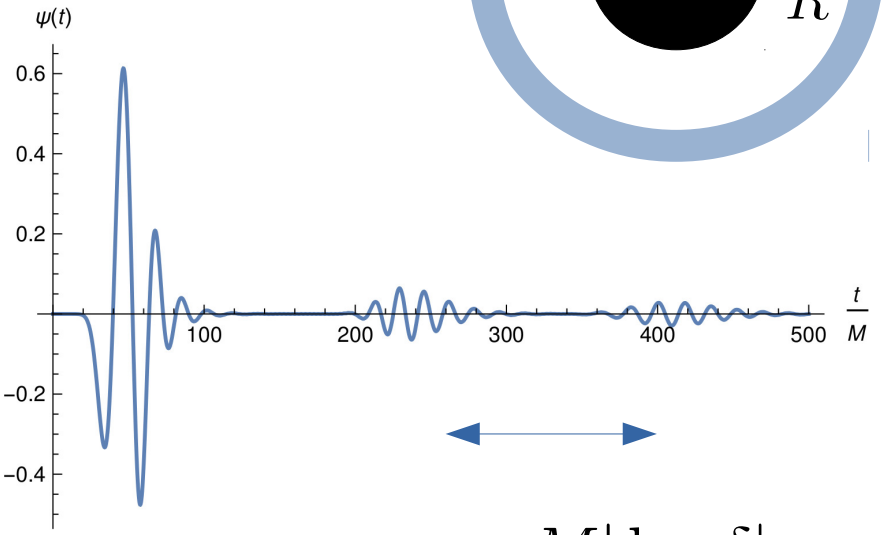
Gravitational Wave Echoes

- Can see up to Planc distance from horizon!



Cardoso+ 16





$$\tau_{\rm echoes} \sim M|\log\delta|$$

Further modeling: [Price+ 17, Nakano+ 17, Barcelo+ 17]
[Bueno, Cano, Goelen, Hertog, BV '17]
Search in LIGO data: [Abedi, Dykaar, Afshordi '16] [Westerweck+ 17]

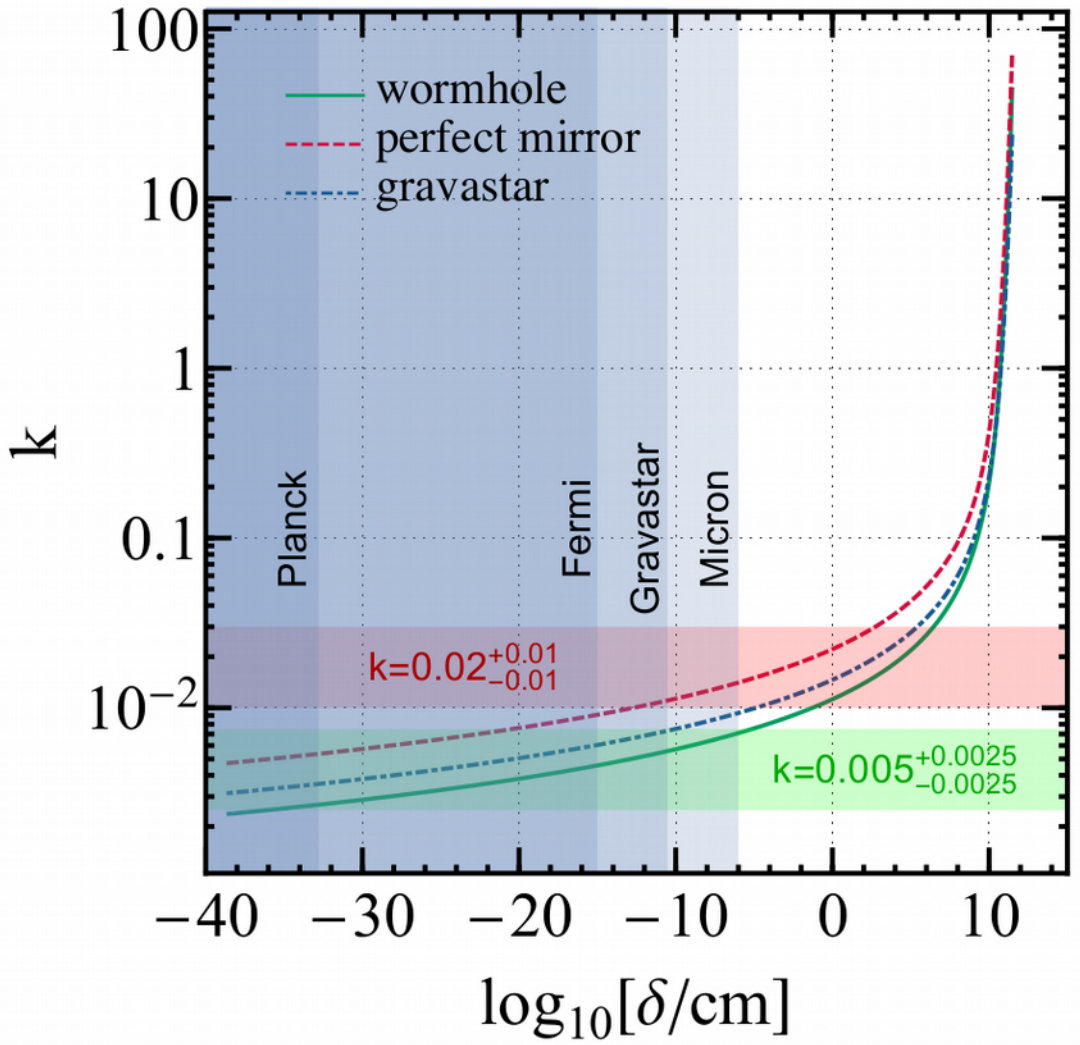
Inspiral (EMRI, LISA)

- Tidal Love numbers
- Maselli++ 2017

$$h(f) = A(f)e^{i(\psi_{\text{black hole}}+\psi_{\text{tidal}})}$$

$$k = 0(\text{black hole})$$

$$k = \log(\delta)(\text{ECO})$$



Conclusions

- Great new opportunities
  - Interdisciplinary!

- Expect the unexpected