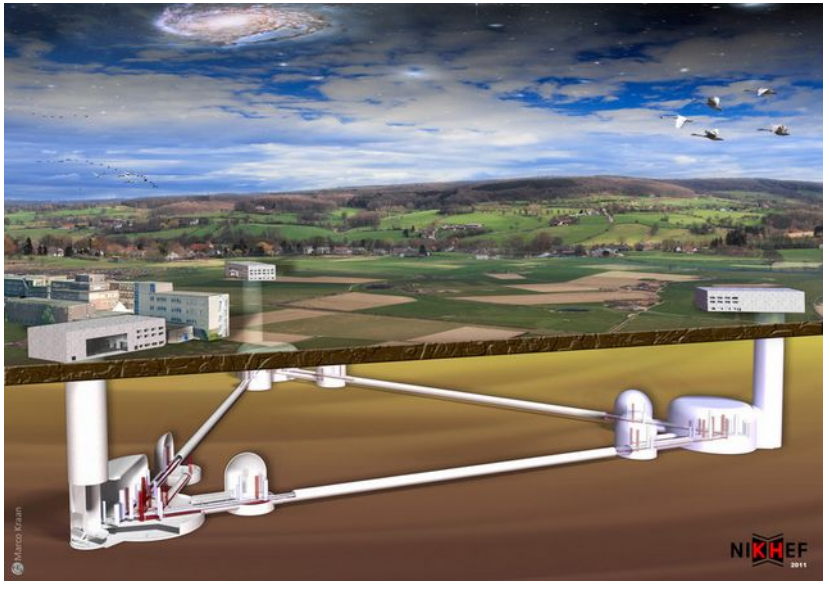
Fundamental physics with Einstein Telescope



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Gravitational Wave Center

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

KU LEUVEN

@GWC_KULeuven

This talk

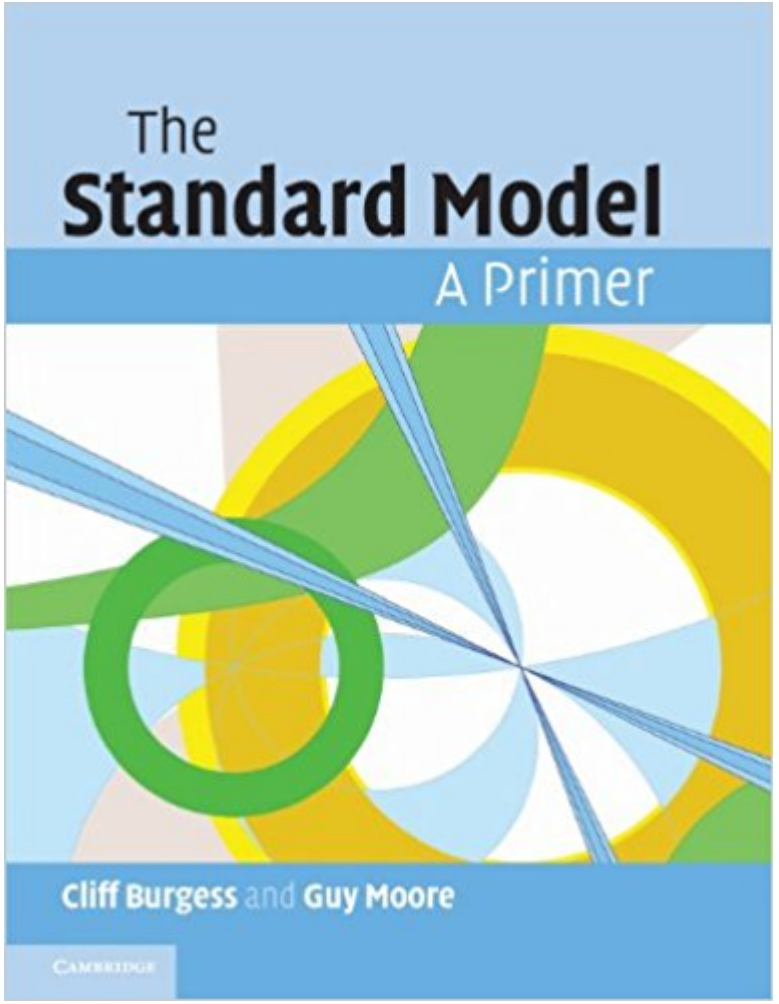
1) Motivation

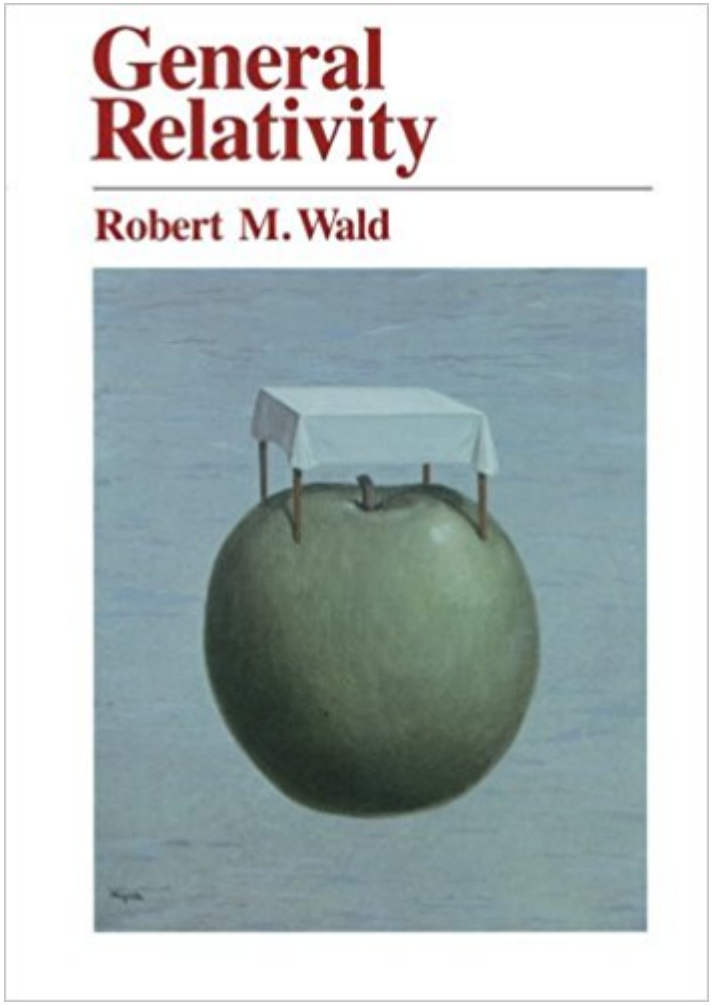
2) Fundamental physics targets

3) Example: The nature of horizons

Fundamental physics?

- New physics beyond:





Hints to new physics

Galaxy rotation curves

Gravitational lensing

CMB

"COINCIDENCES"

Strength of gravity
Dark energy density

General Relativity
non-renormalizable

Information paradox

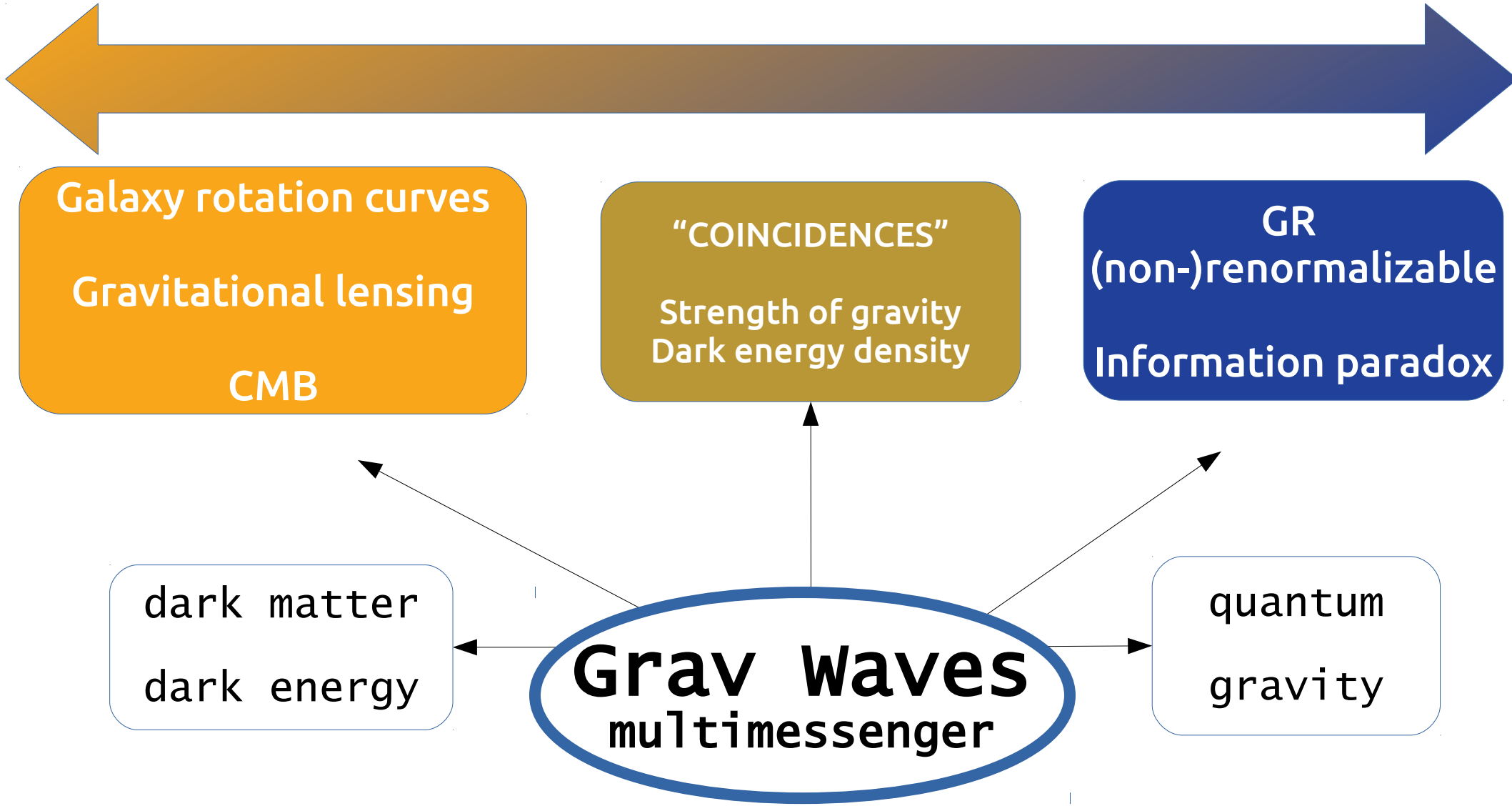
dark matter

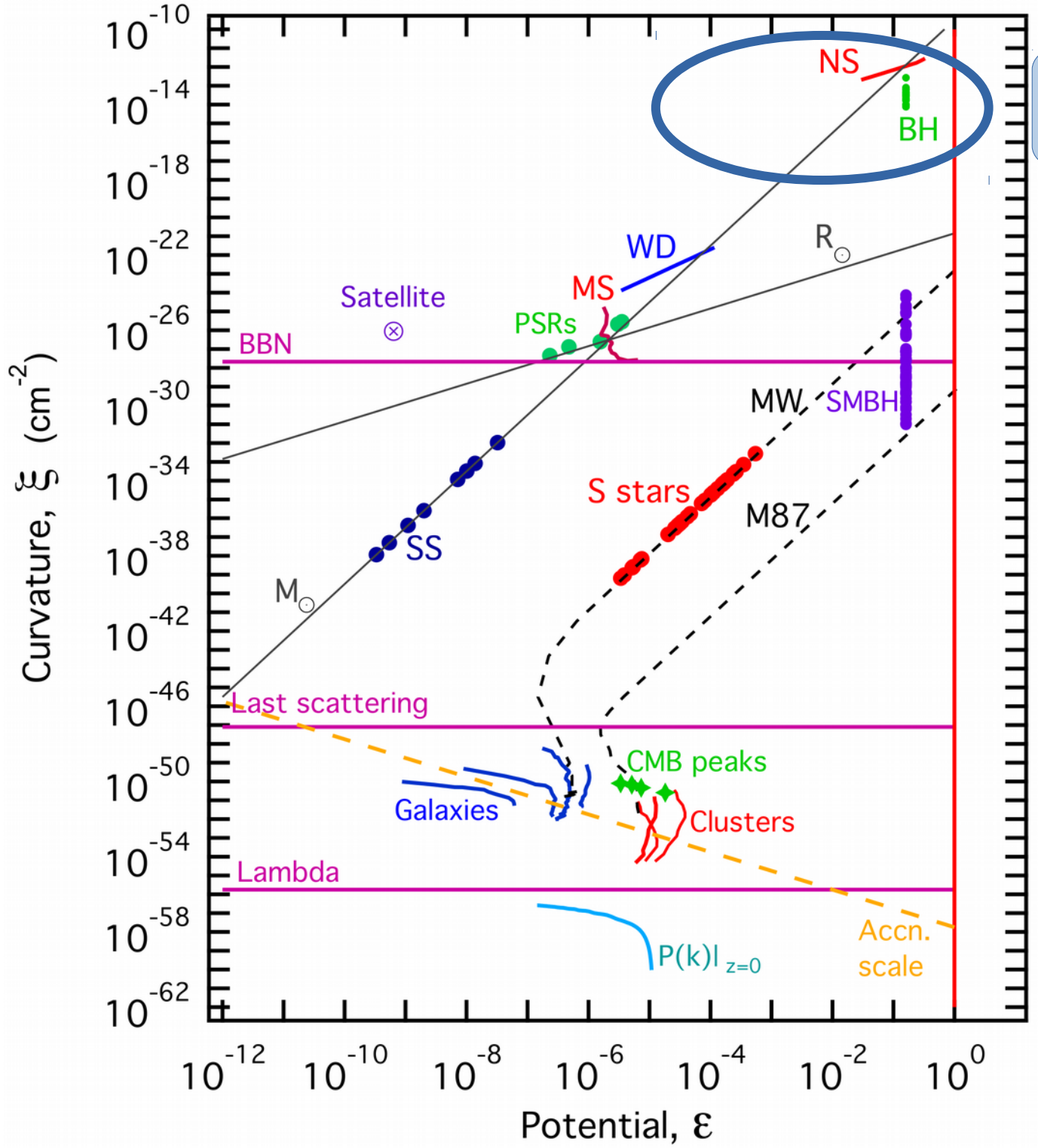
dark energy

quantum

gravity

Hints to new physics





Baker, Psaltis, Skordis 2014

Why new GW detectors?

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

$$m_g < 10^{-22} eV$$

LIGO +Virgo, PRL116, 221101 (2017)

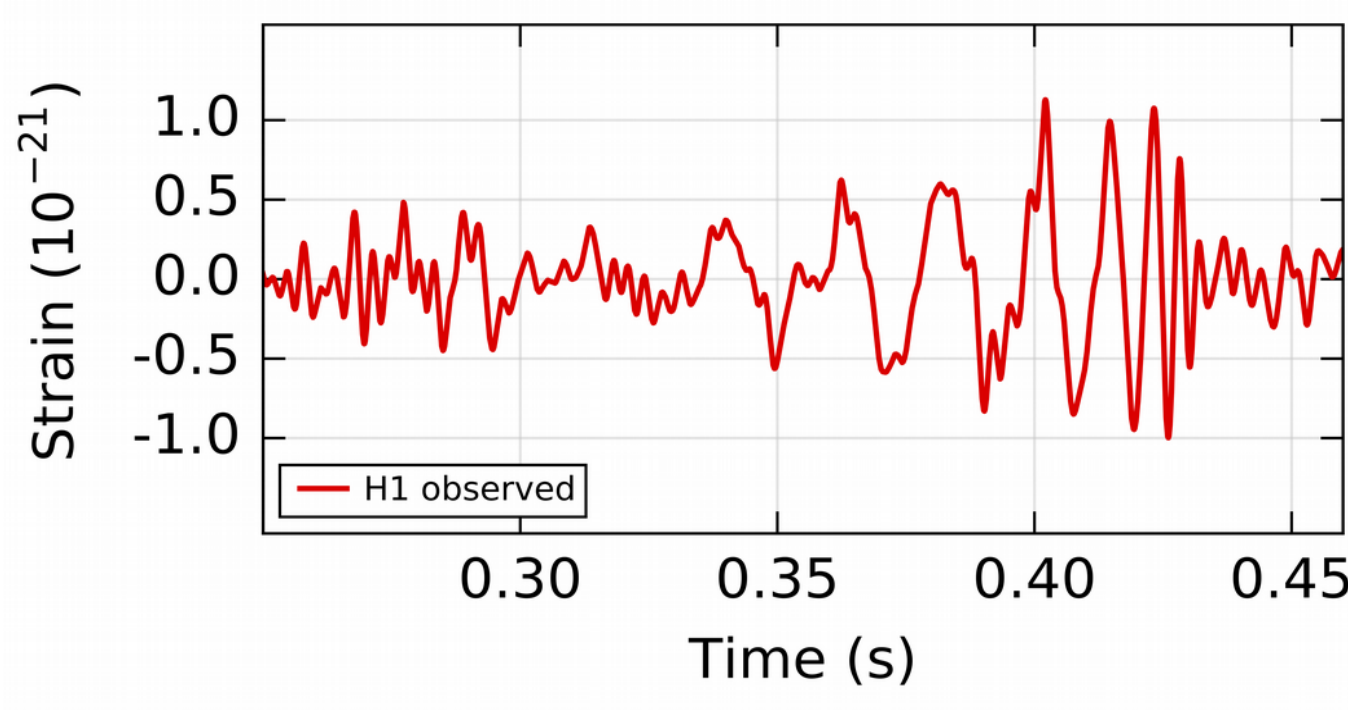
Why new GW detectors?

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

$$m_g < 10^{-22} eV$$ LIGO +Virgo, PRL116, 221101 (2017)

- Precision!

GW150914: black holes by sight?

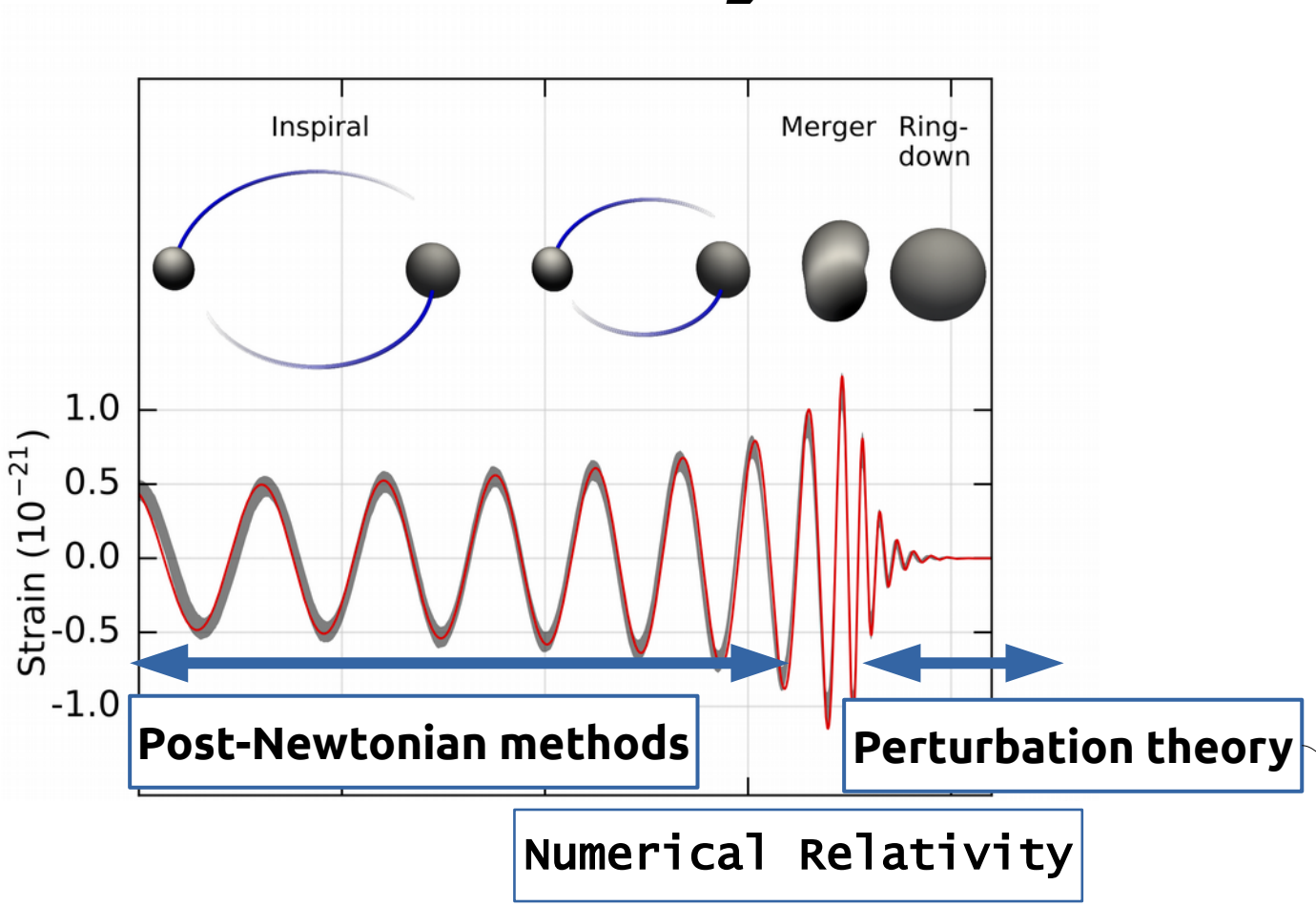


- Einstein quadrupole + Newton's laws:

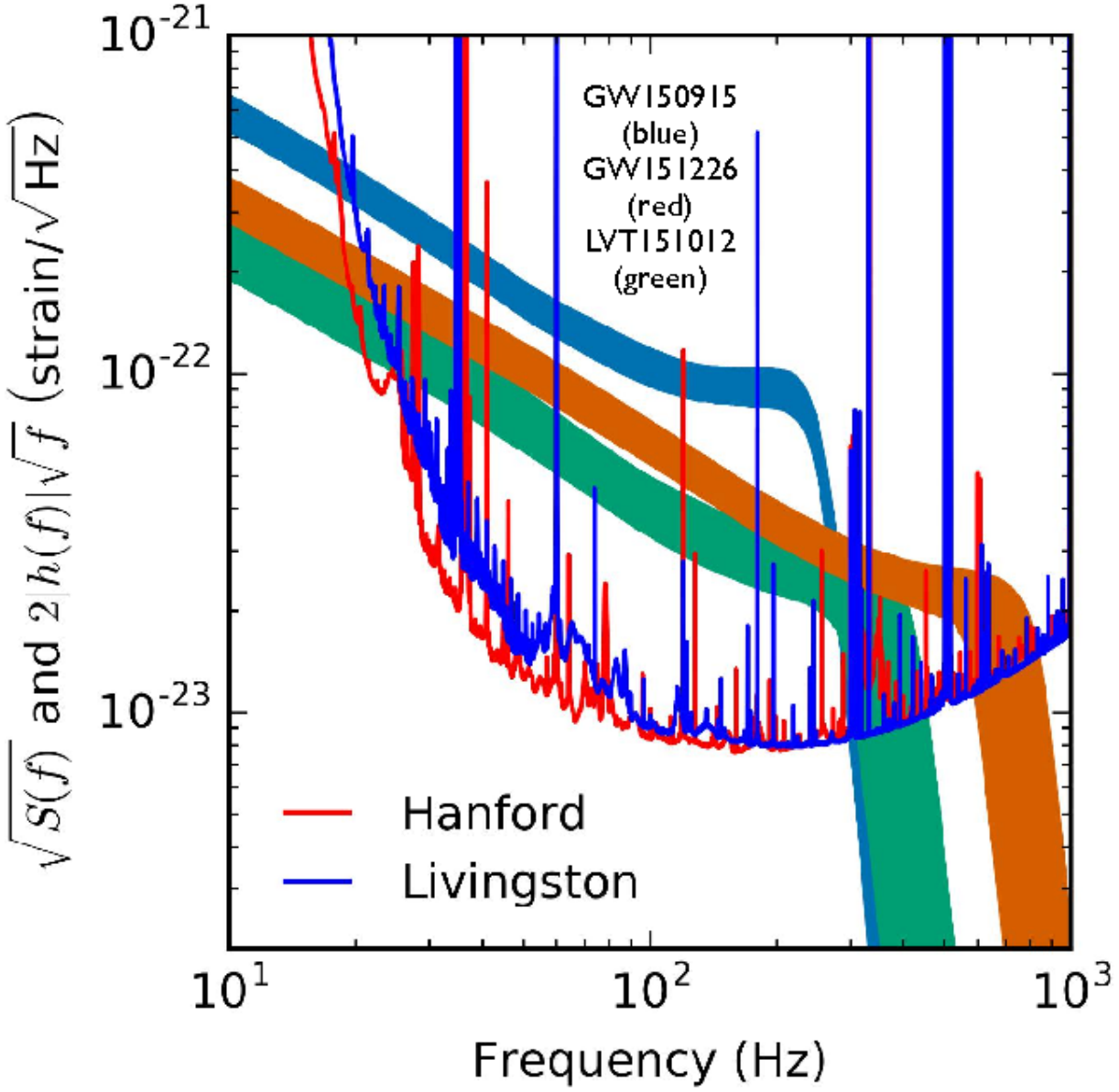
$$M_{\rm total} \sim 70 M_\odot \qquad\qquad R = \sqrt{\frac{GM}{\omega_{\rm max}}} = 350 \text{ km}$$

See also: LIGO/Virgo collaboration, *"The basic physics of the binary black hole merger GW150914"* arXiv:1608.01940

Data analysis



- No independent total mass
  - Too low SNR & GR templates



LIGO/Virgo collaboration, 2016

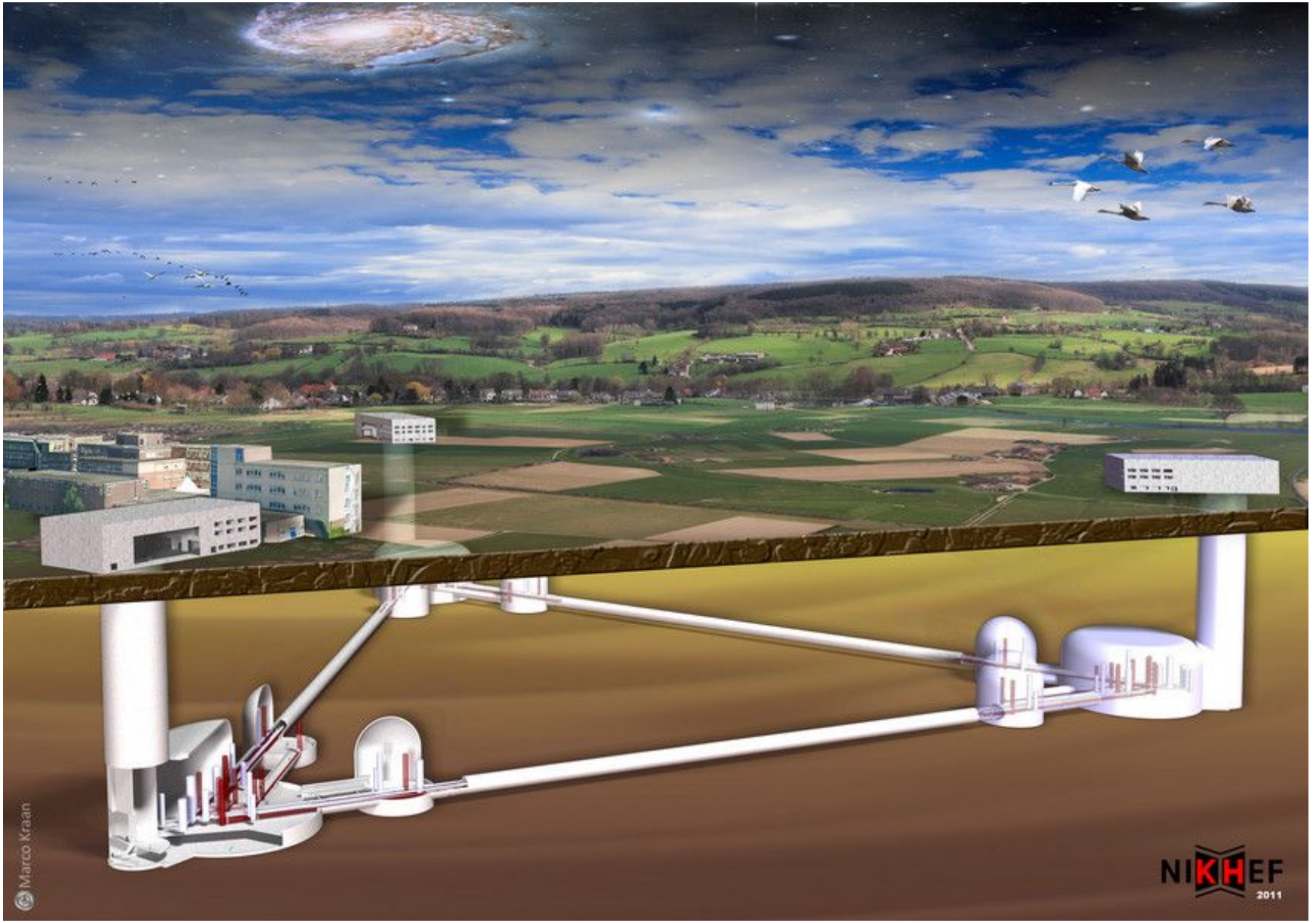
This talk

1) Motivation

2) Key targets

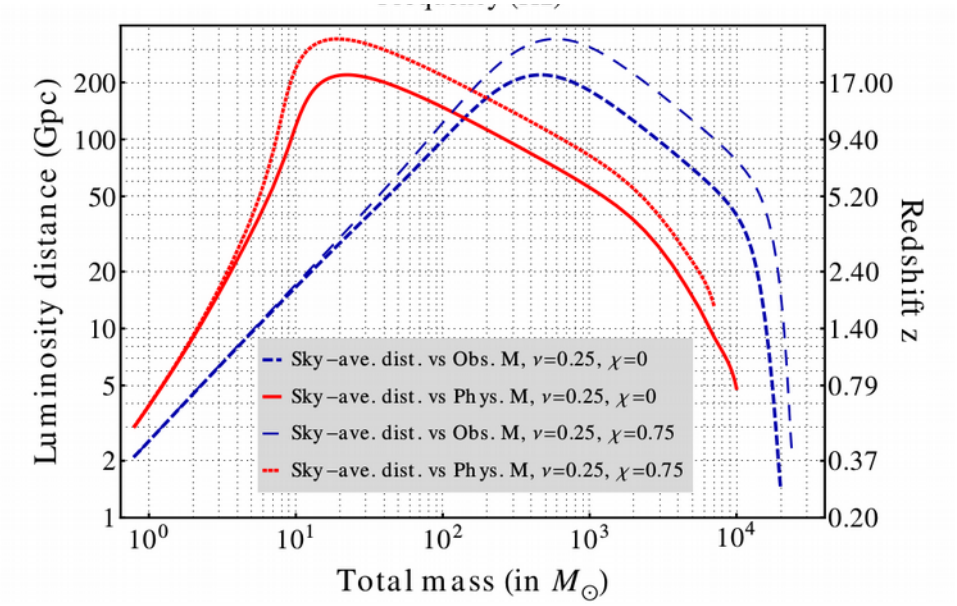
3) The nature of horizons

Einstein Telescope

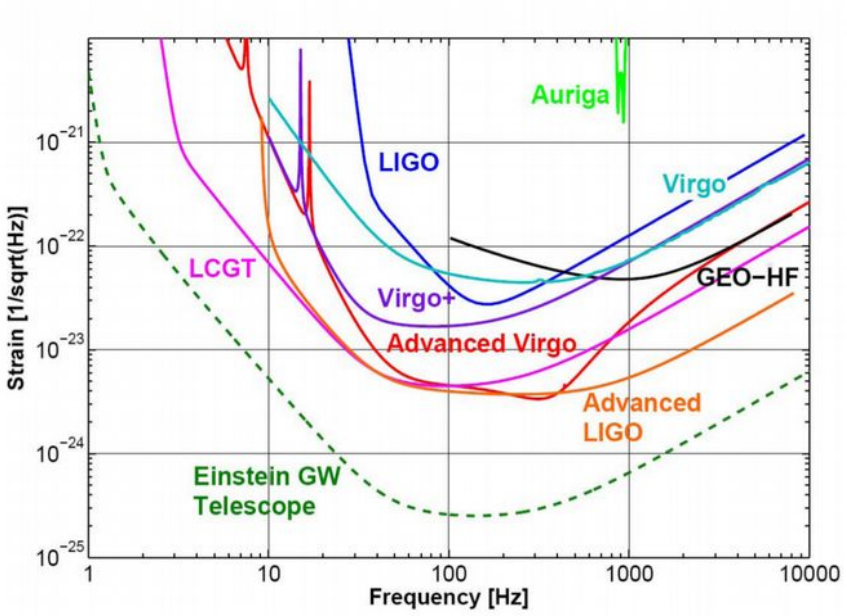


Main Target Sources

- Merging black holes and neutron stars
  - … many thousands sources per year
  - Black holes z=15 (current: z=0.5)
  - Neutron stars z=5 (current: 200Mpc)

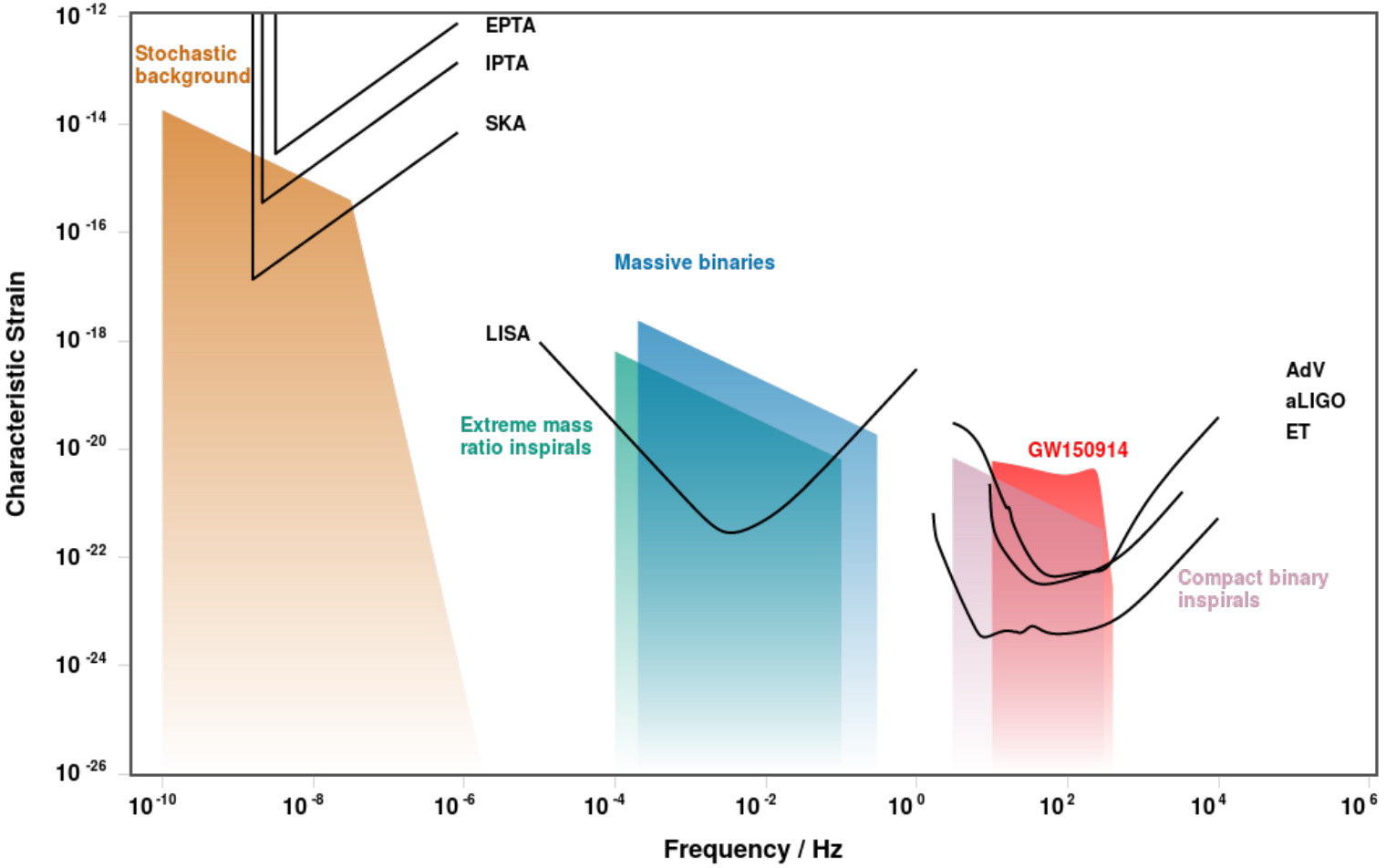


Sathyaprakash et al, “Scientific Objectives of Einstein Telescope” Arxiv:1206.0331

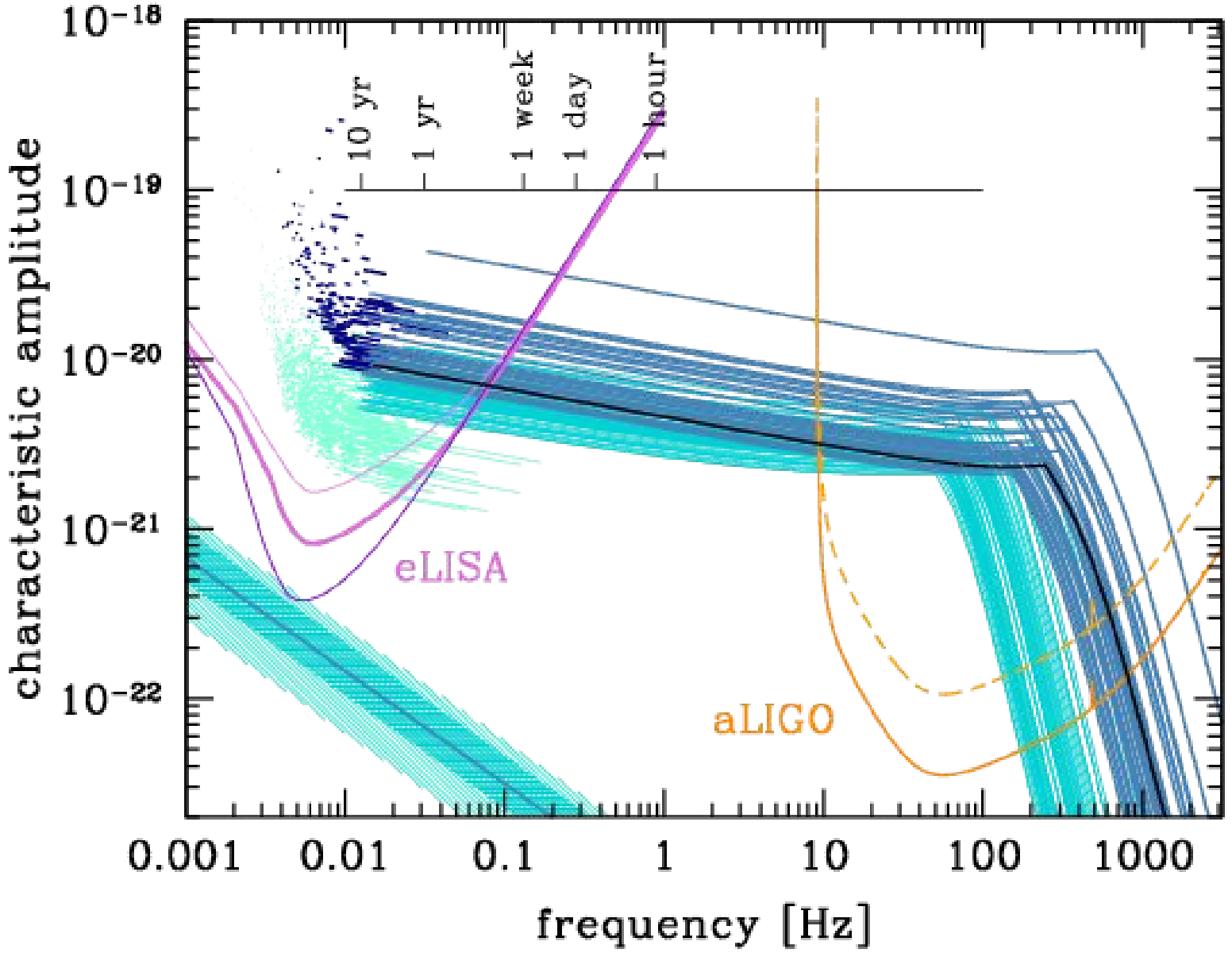


ET design study, 2011

Large spectrum



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


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

Fundamental physics targets

- Astrophysics/astronomy/neutron stars…
  see talks Vanbeveren/Van Eindhoven/van den Brand
- Cosmology see talk Clesse
- Nature of GW radiation
  - Dispersion, Lorentz violation...
- Testing gravity with black holes
  - Are black holes described by GR Kerr metric?

This talk

1) Motivation

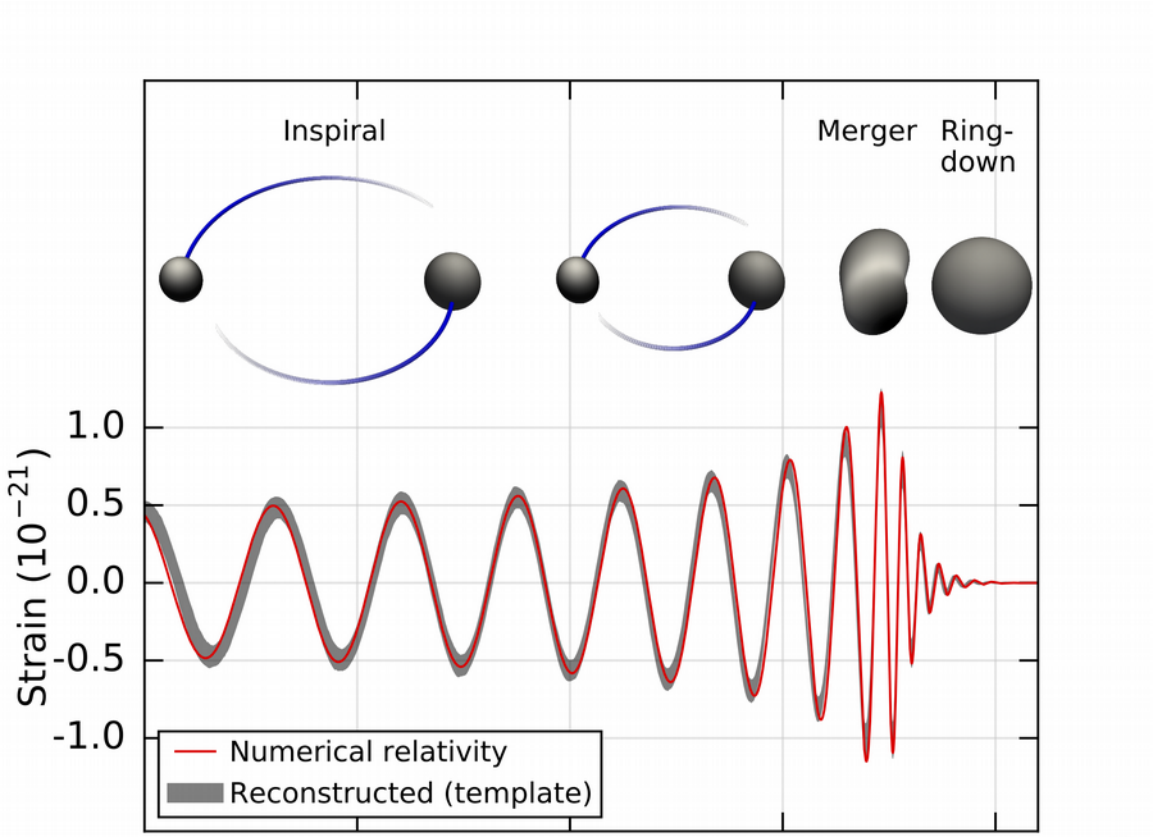
2) Key targets

3) The nature of horizons

True nature of black hole horizon

1) Tests of no-hair theorem

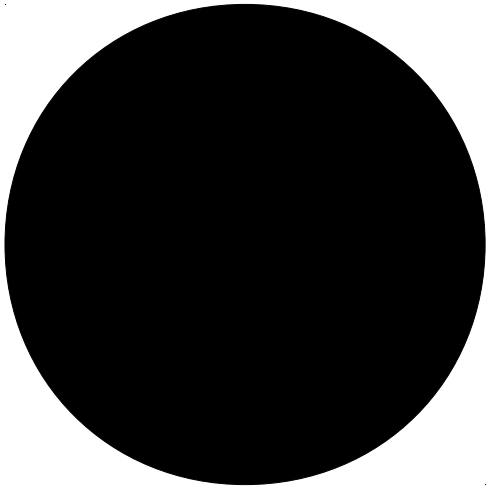
2) Quantum effects near horizons



No-hair conjecture

- Kerr black hole only depends on two parameters: *mass* and *spin*

Black hole uniqueness theorems: Israel, Carter, Hawking, Robinson ‘67-’75

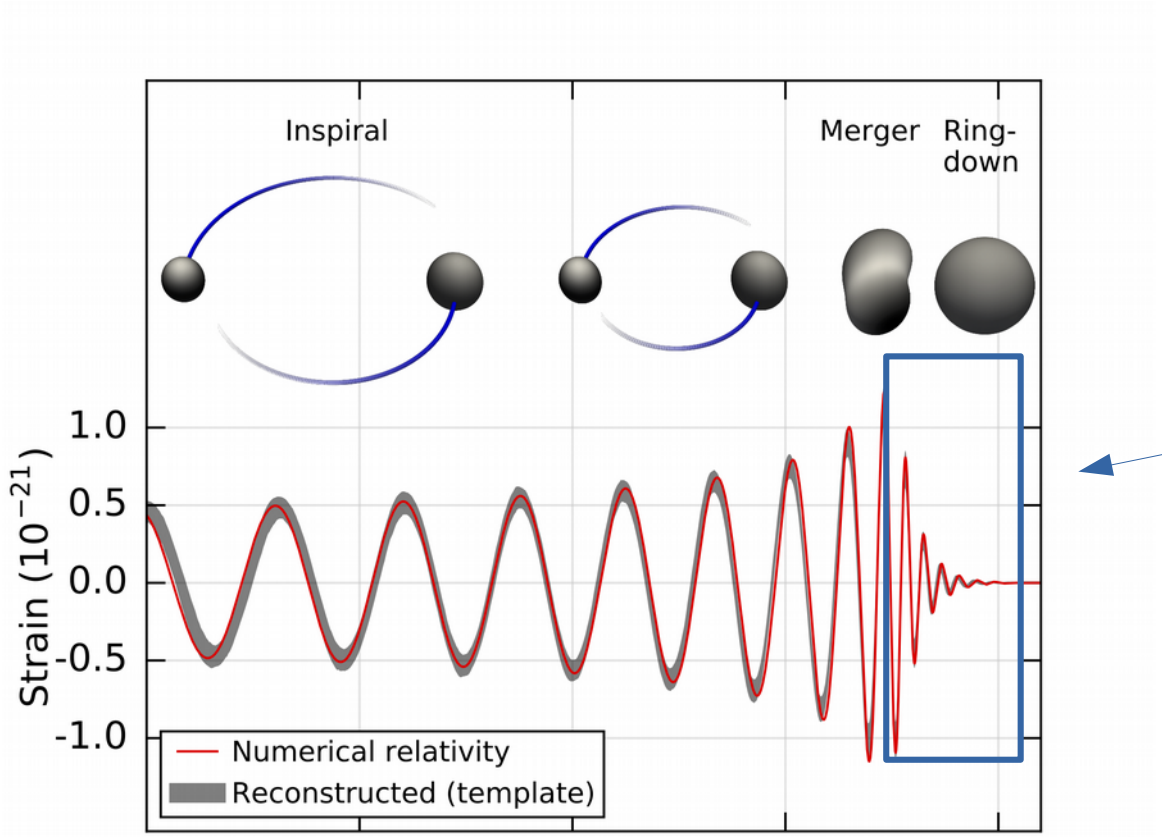


- *Astrophysical black holes too?*

Black hole spectroscopy

Ringdown: for a black hole in GR

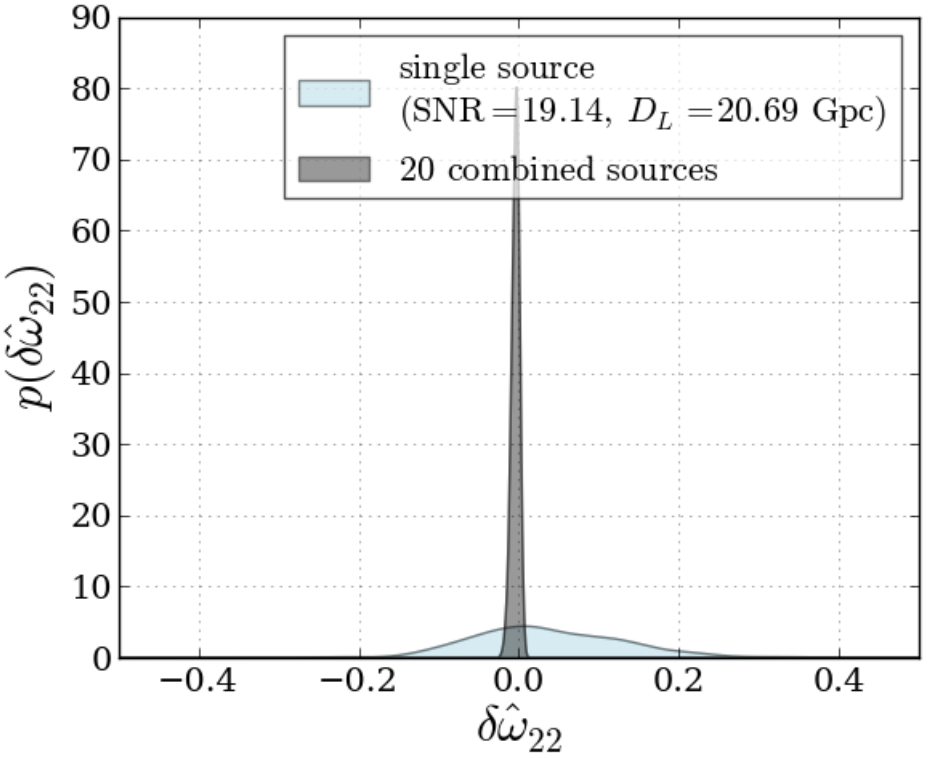
ω_n & τ_n depend on mass & spin only

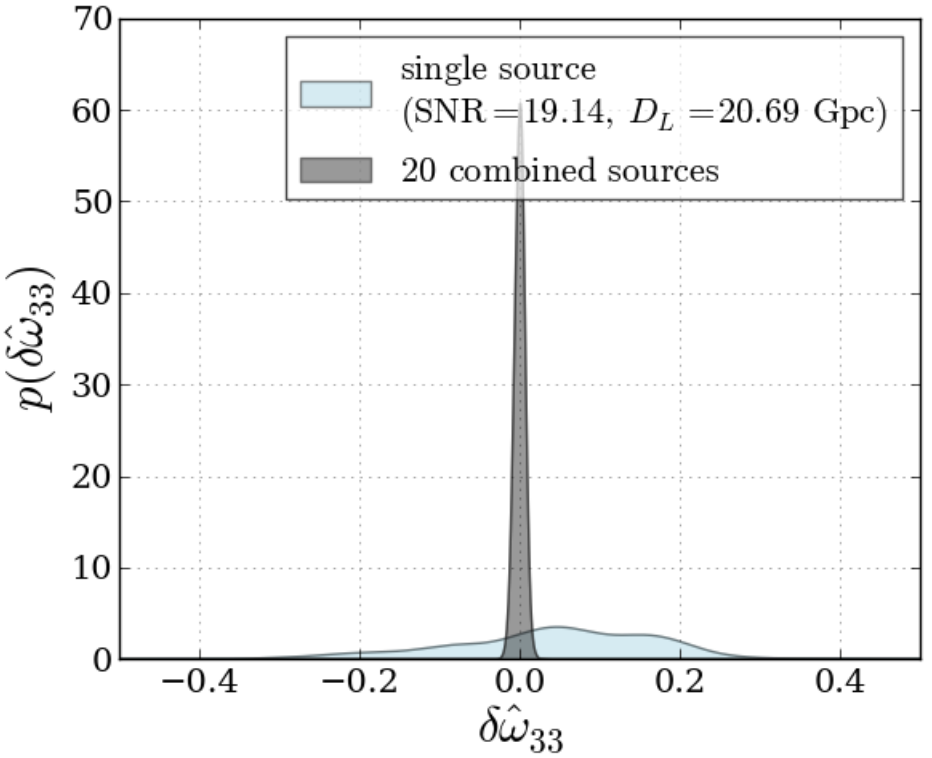


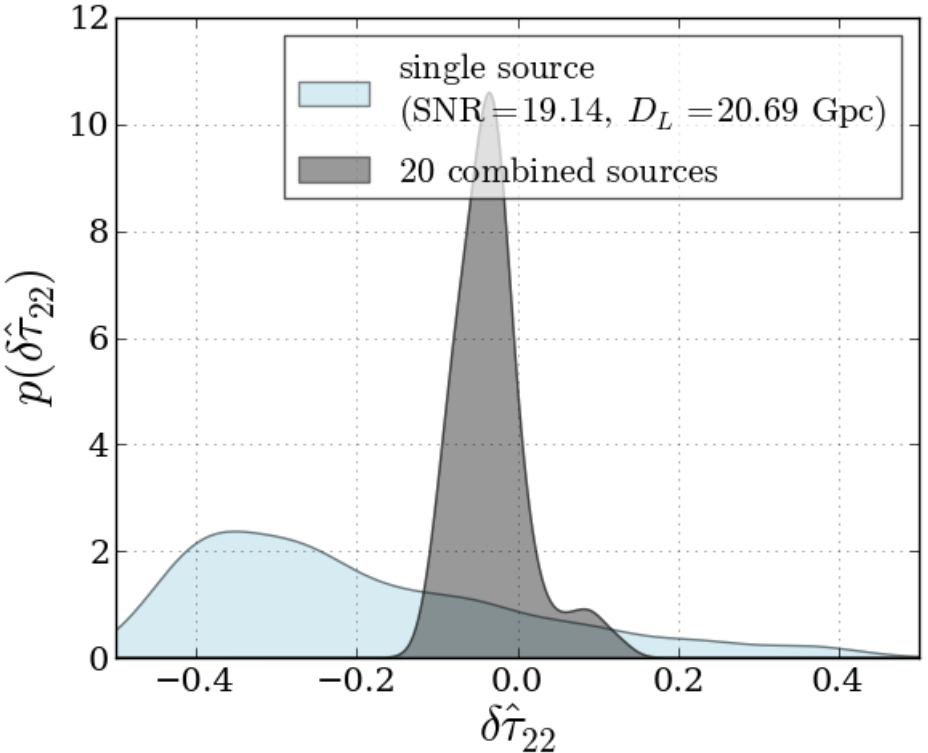
$$\sum_n c_n \sin(\omega_n t) e^{-\tau_n}$$

Damping times

Frequencies



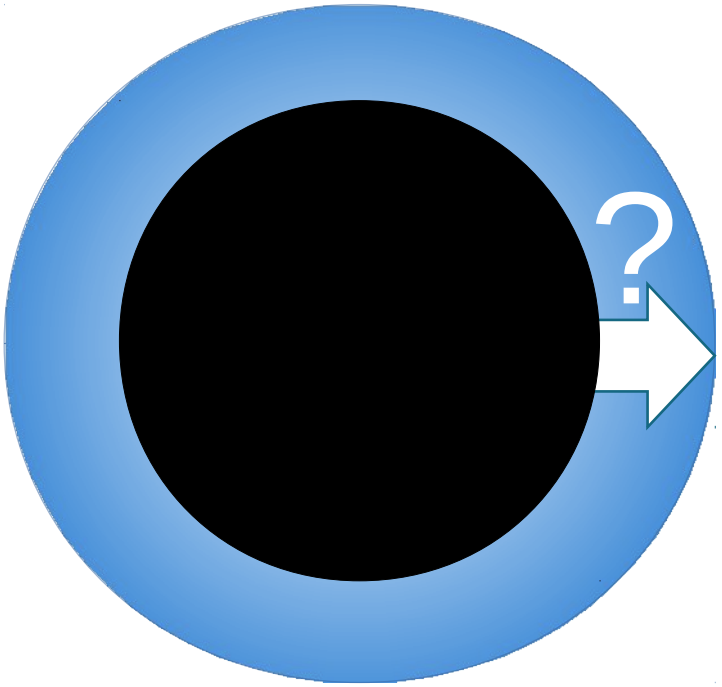




Meidam et al 2014

Quantum expectations

- Information paradox (Hawking ‘76)

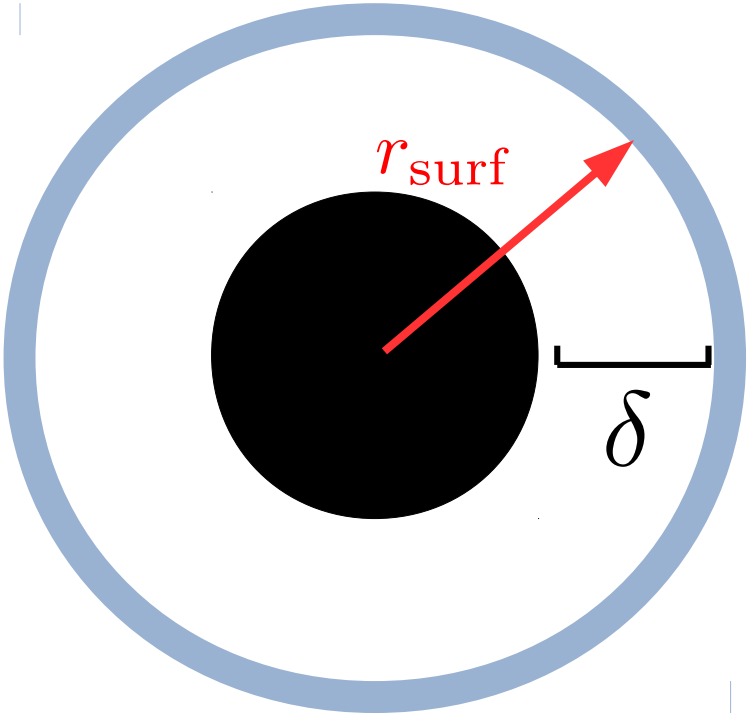


- Quantum gravity:
  - New physics/structure at horizon
  - Many **recent** proposals and ideas:
    fuzzball, firewalls, gravastars, boson stars..

Let's make a toy model

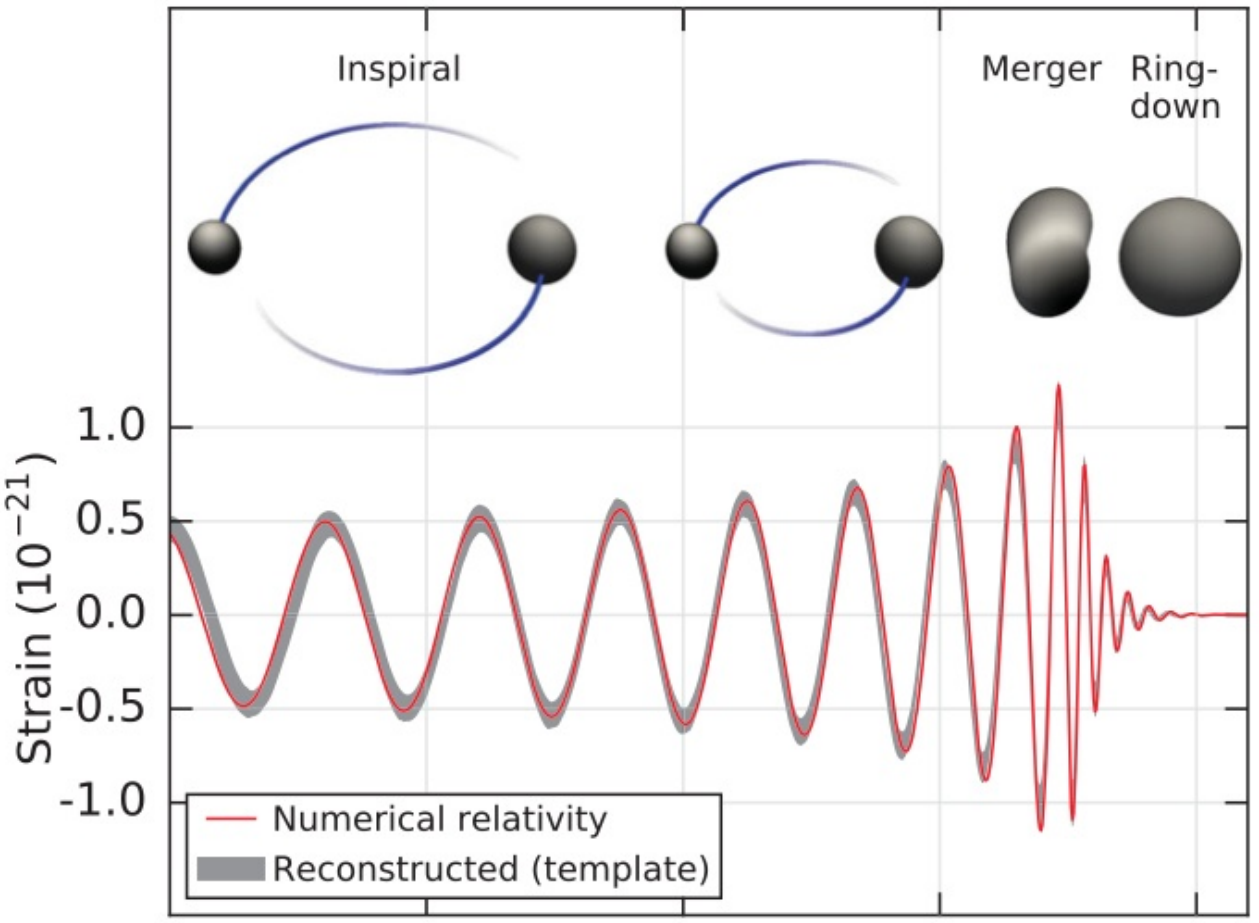
- Reflecting surface at $r_{\rm surf} = 2M + \delta$

Cardoso, Pani arXiv:1707.03021
(extended version of Nature Physics review)

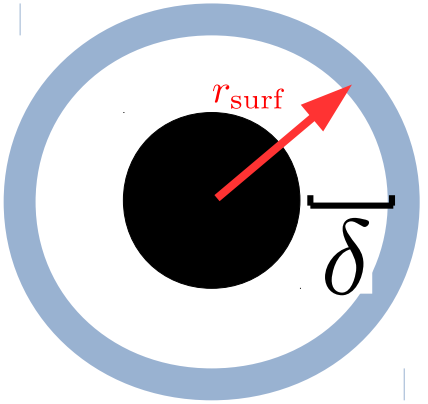


$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

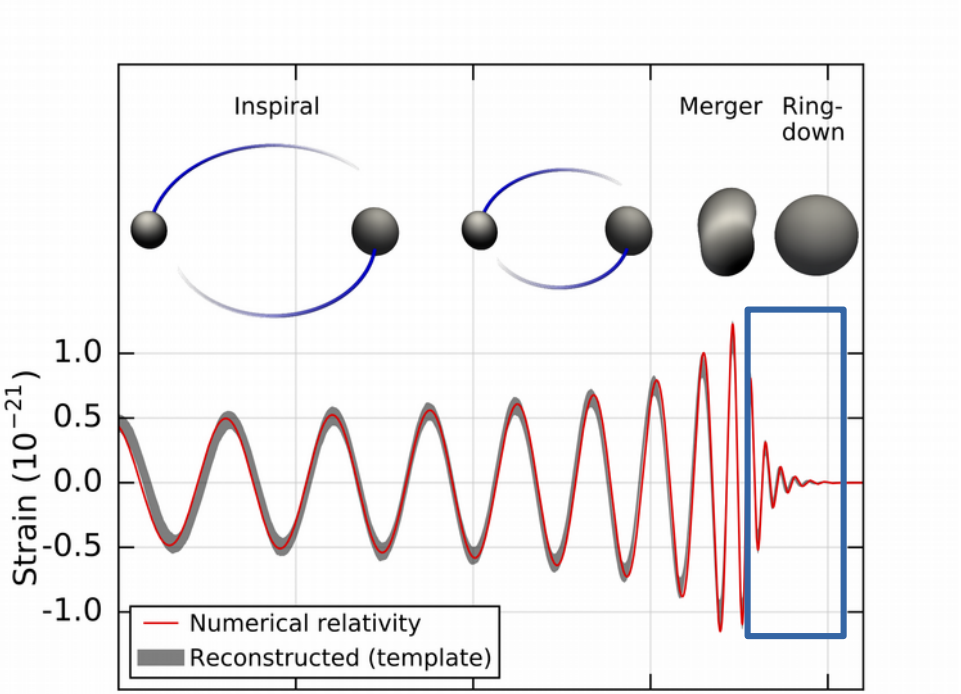
Where can quantum corrections hide?

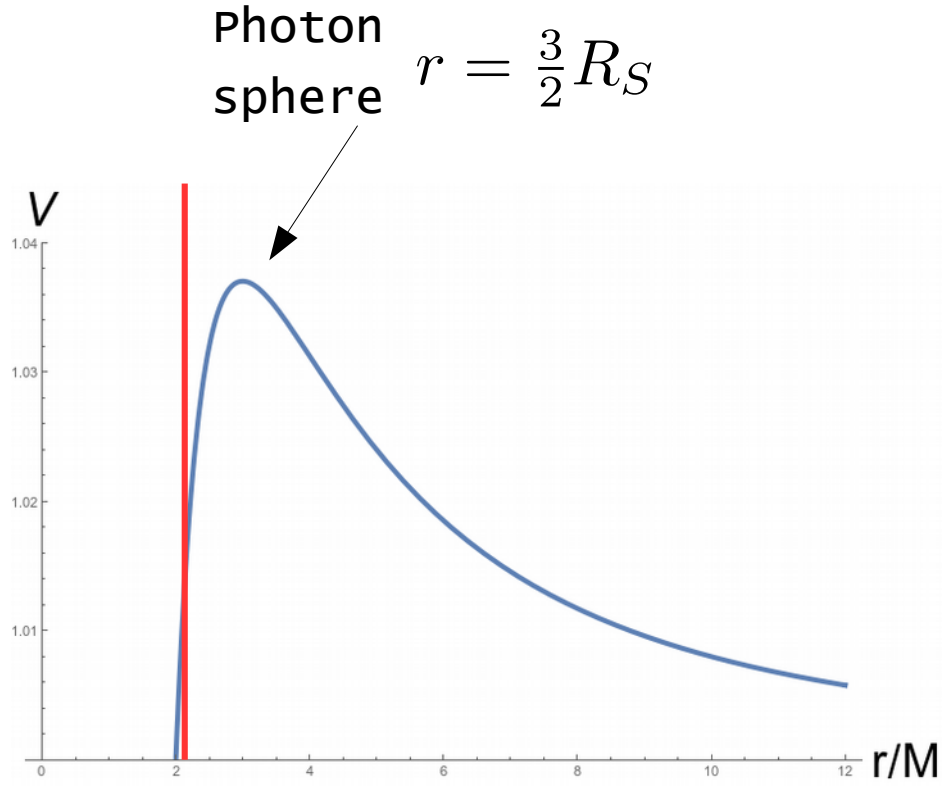


Spectroscopy?



- Prompt ringdown:
  - Not sensitive to near-horizon!
  - Determined by photon sphere

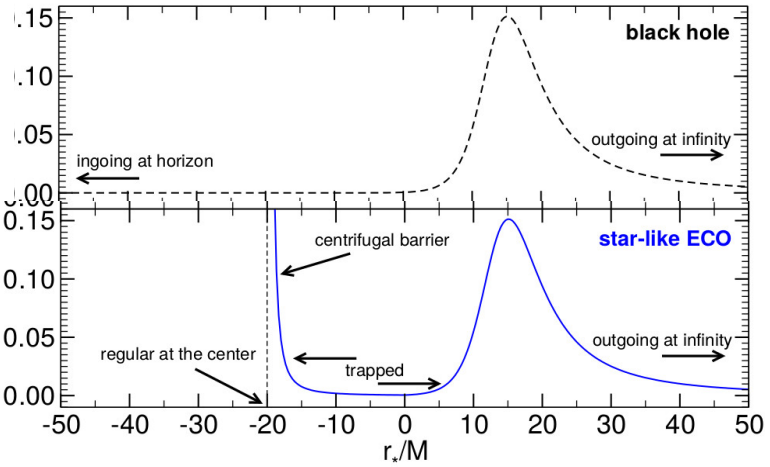




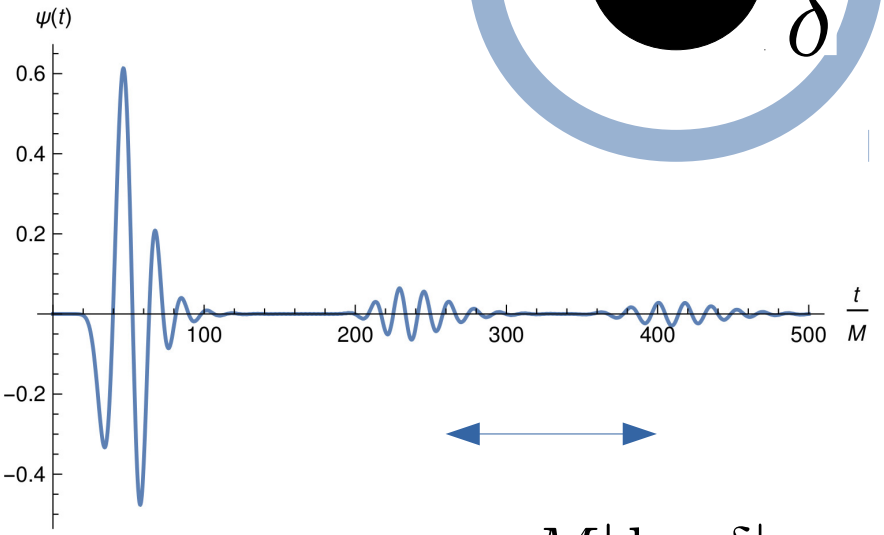
$$r_{\rm surf} = R_S + \delta$$

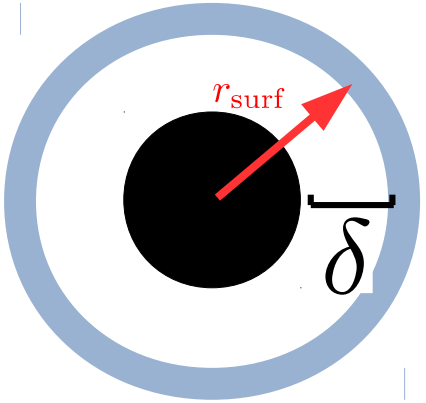
Gravitational Wave Echoes

$$\left(\frac{\partial^2}{\partial r_*^2} - \frac{\partial^2}{\partial t^2} - V_{l,s}(r_*)\right)\Psi_{l,s}(t,r) = 0$$



Cardoso+ 16



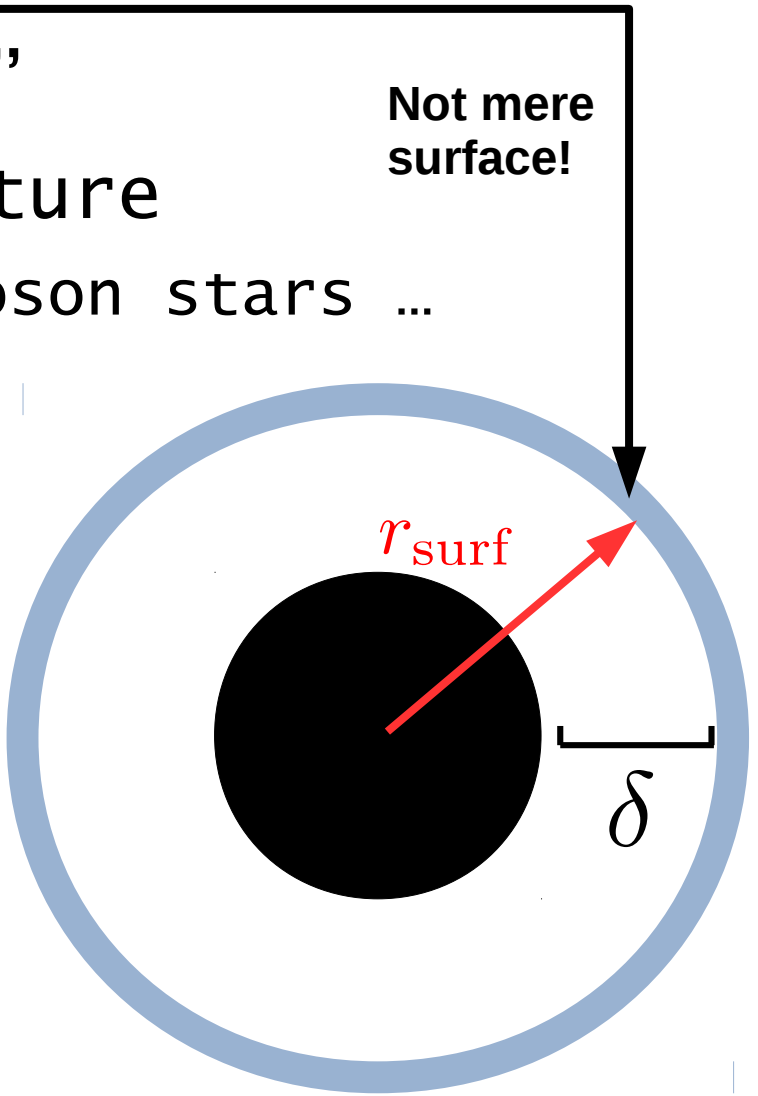


$$\tau_{\rm echoes} \sim M|\log\delta|$$

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

Rich new phenomenology

- "Exotic Compact Objects"
- Proxy for quantum structure
  - Wormholes, gravastars, boson stars …

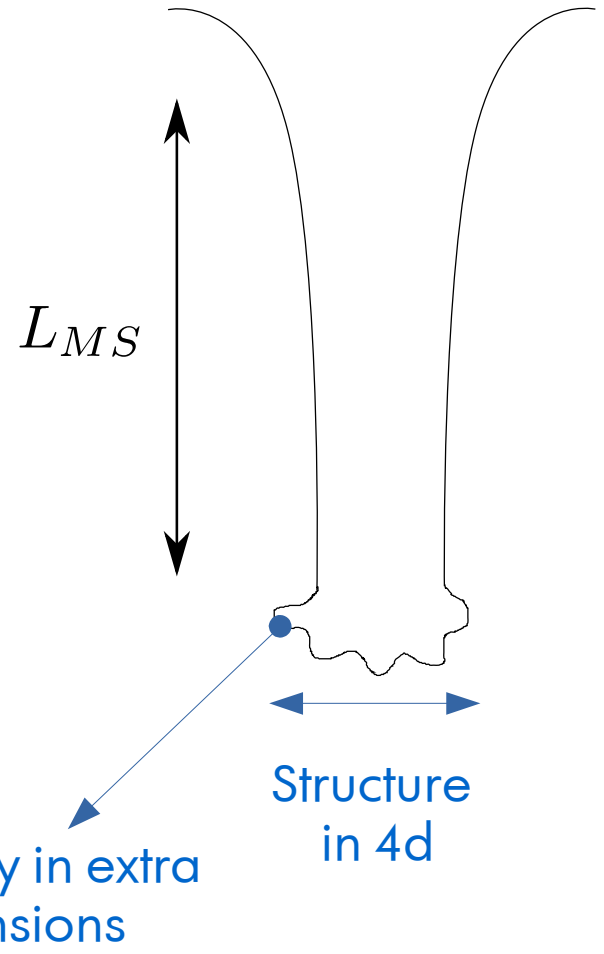


Cardoso, Pani arXiv:1707.03021
(extended version of Nature Physics review)

New "echoes"-pipeline
(LIGO/Virgo- group C. Van Den Broeck)

Better models?

- String theory:
  - "Fuzzball" solutions
  - (Semi-)classical description of Quantum Structure



Work in progress…
New field sprouting

Great new opportunities

- Interdisciplinary
- Macroscopic quantum gravity: modelling