Exploring fundamental physics with gravitational waves

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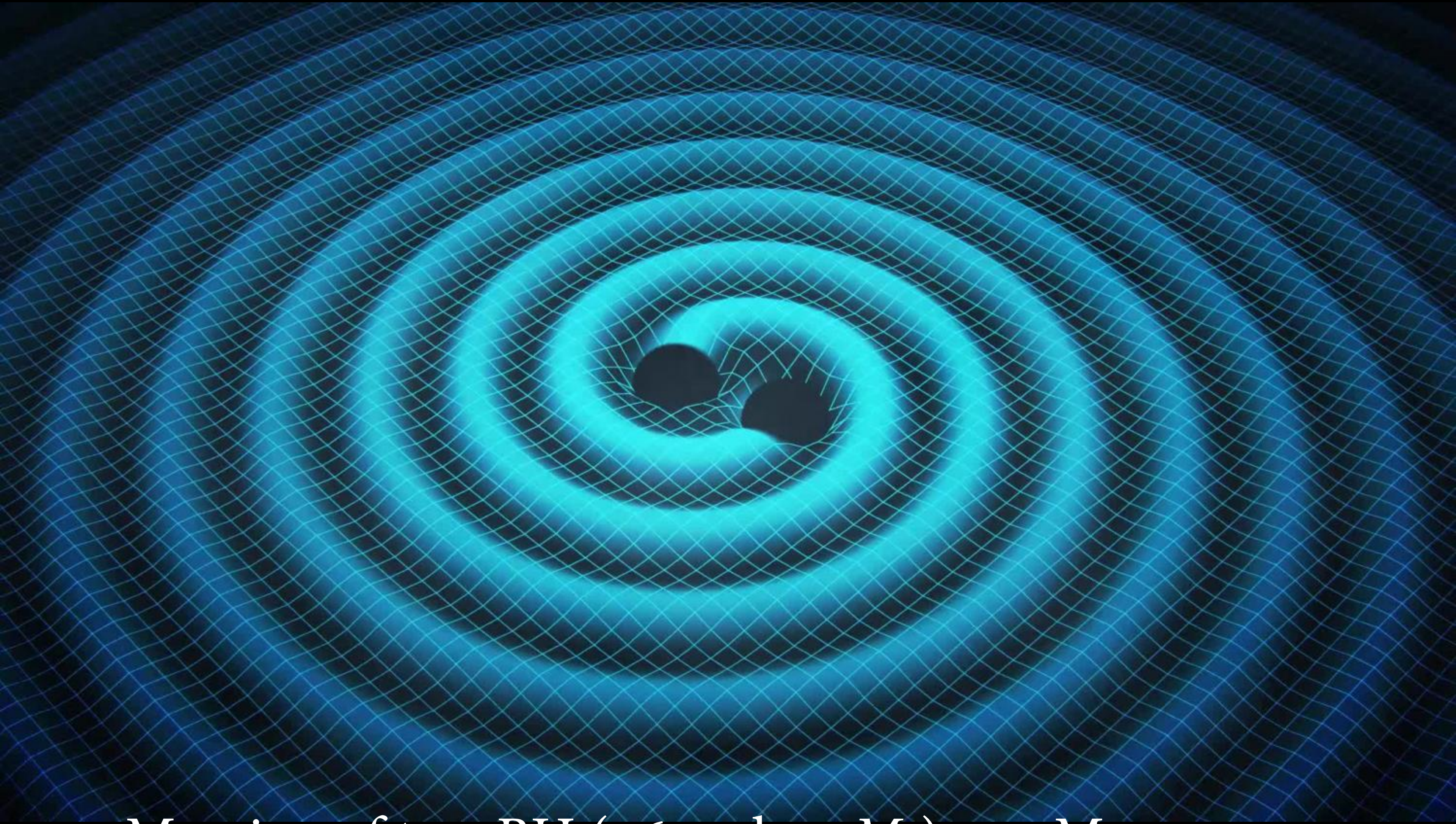
based on 1605.01209 with M. McCullough & A. Urbano

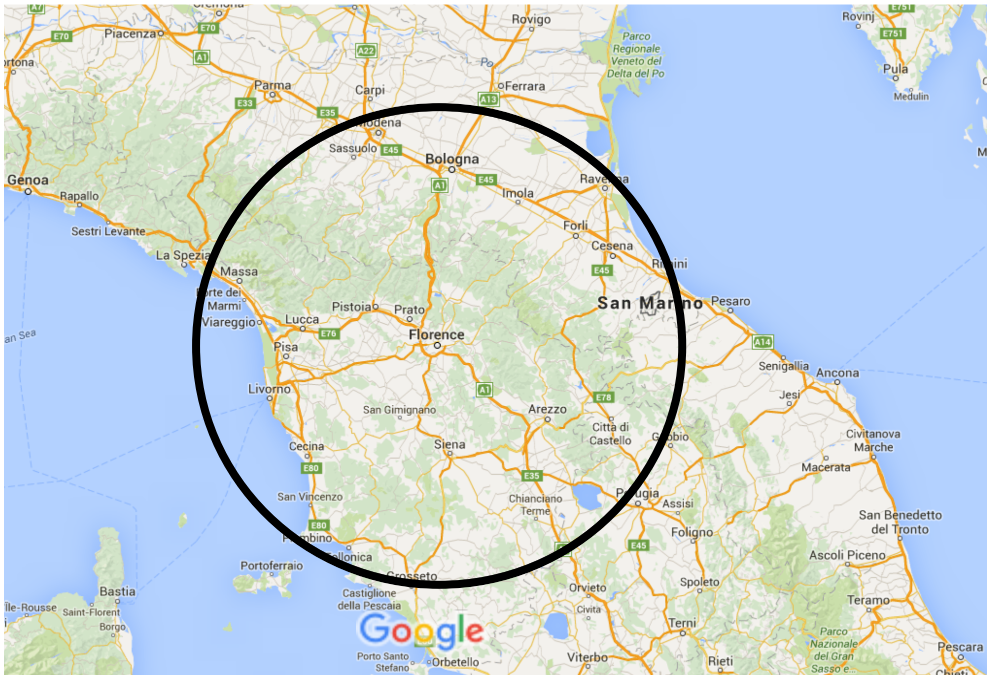
GW: science fiction come true!



Merging of two BH (36 and 29 $M_\odot$) 410 Mpc away, emitting 3 $M_\odot$ in GW

BH radius:

$$R_{BH} = \frac{2 M_{BH} G_N}{c^2} = 106 \text{ km } \frac{M_{BH}}{36 M_{\oplus}}$$



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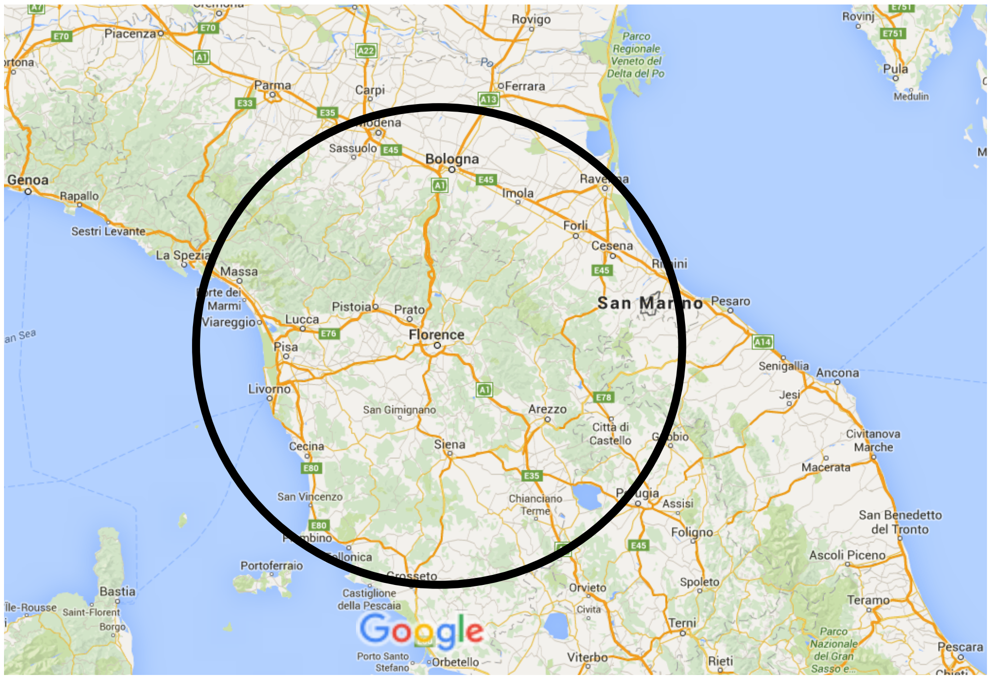
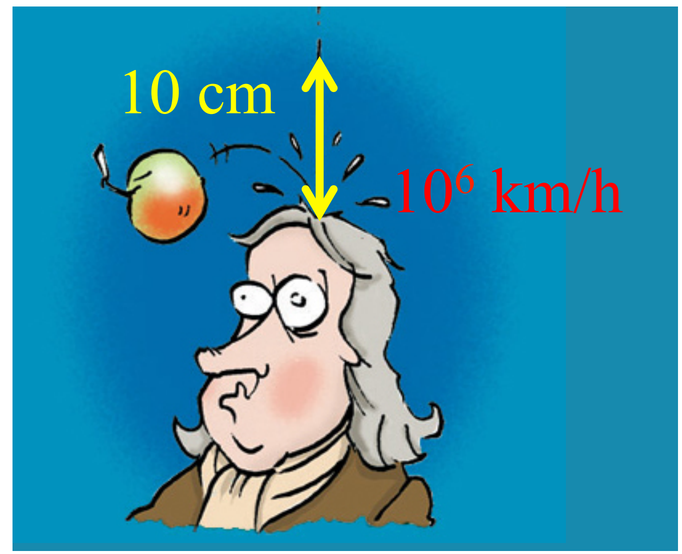
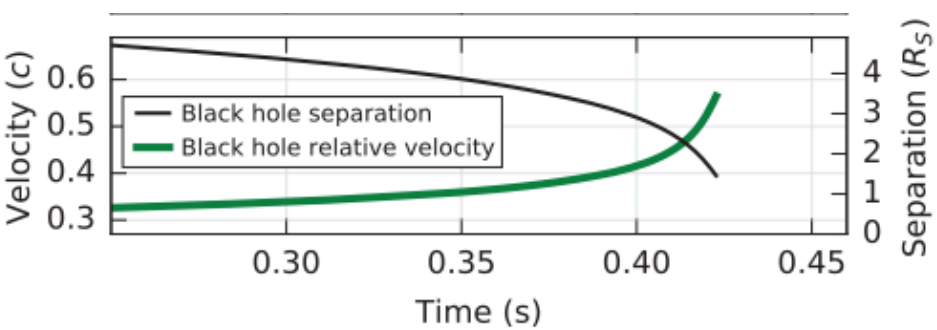
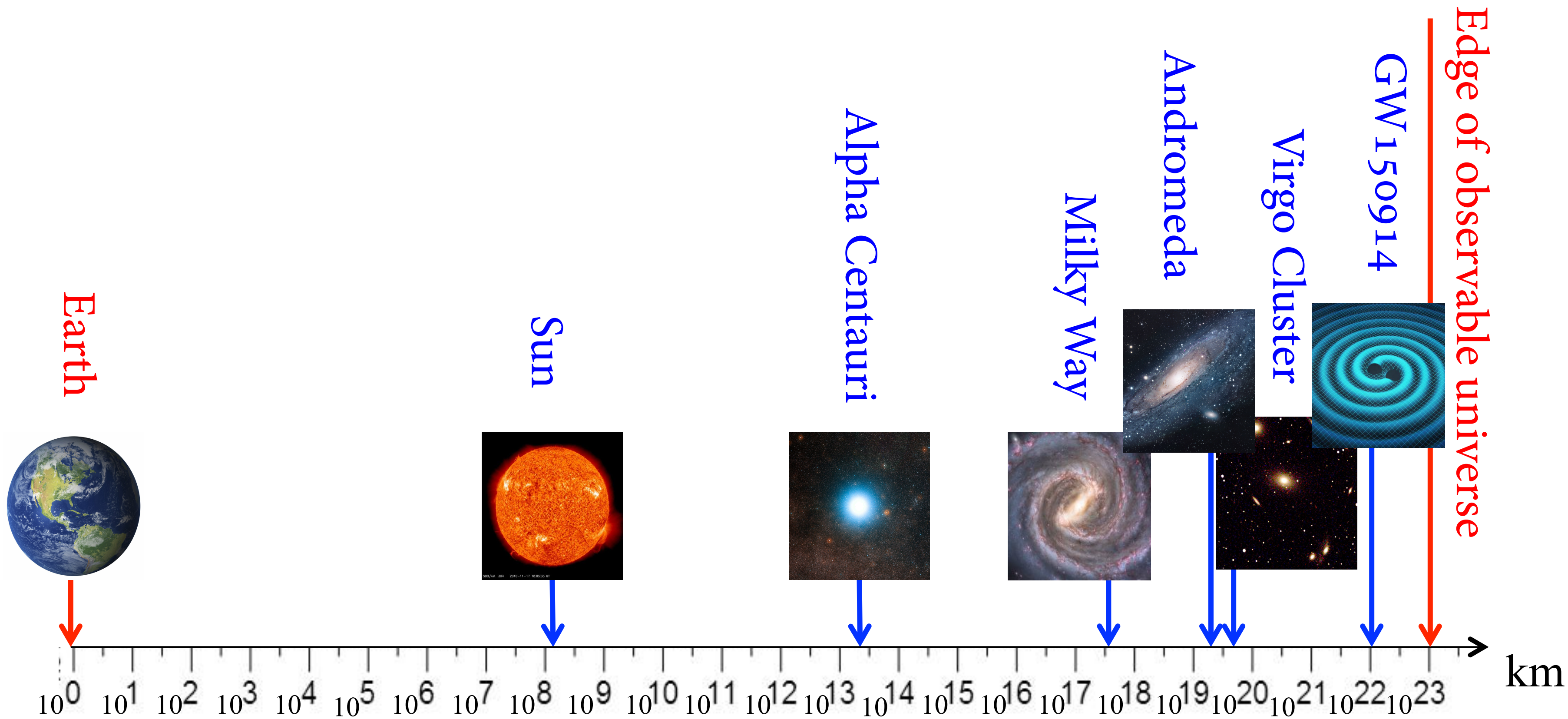


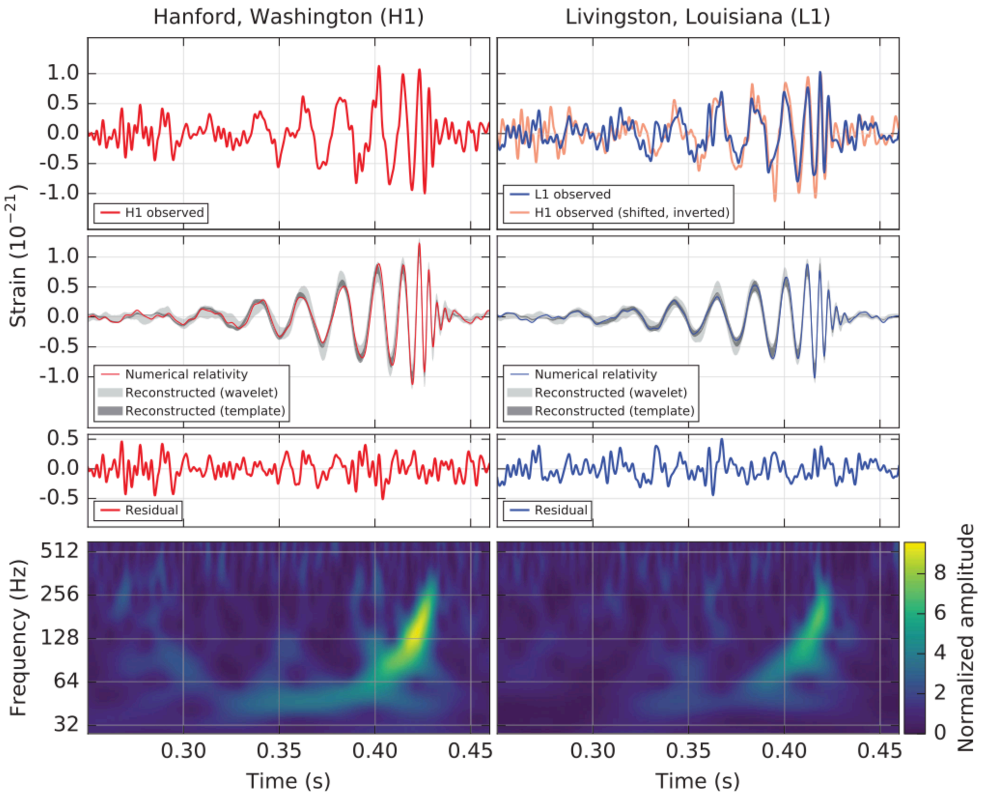




relativistic velocities!



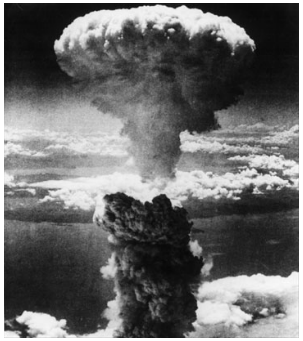
Earth
Sun
Alpha Centauri
Milky Way
Andromeda
Virgo Cluster
GW150914
Edge of observable universe
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20 10^21 10^22 10^23
km



Energetic output

$\approx 3\ M_\odot$ in 0.1 s

$3\ M_\odot = 2 \times 10^{41}$ kWh $\approx 10^{34}$ Hiroshima



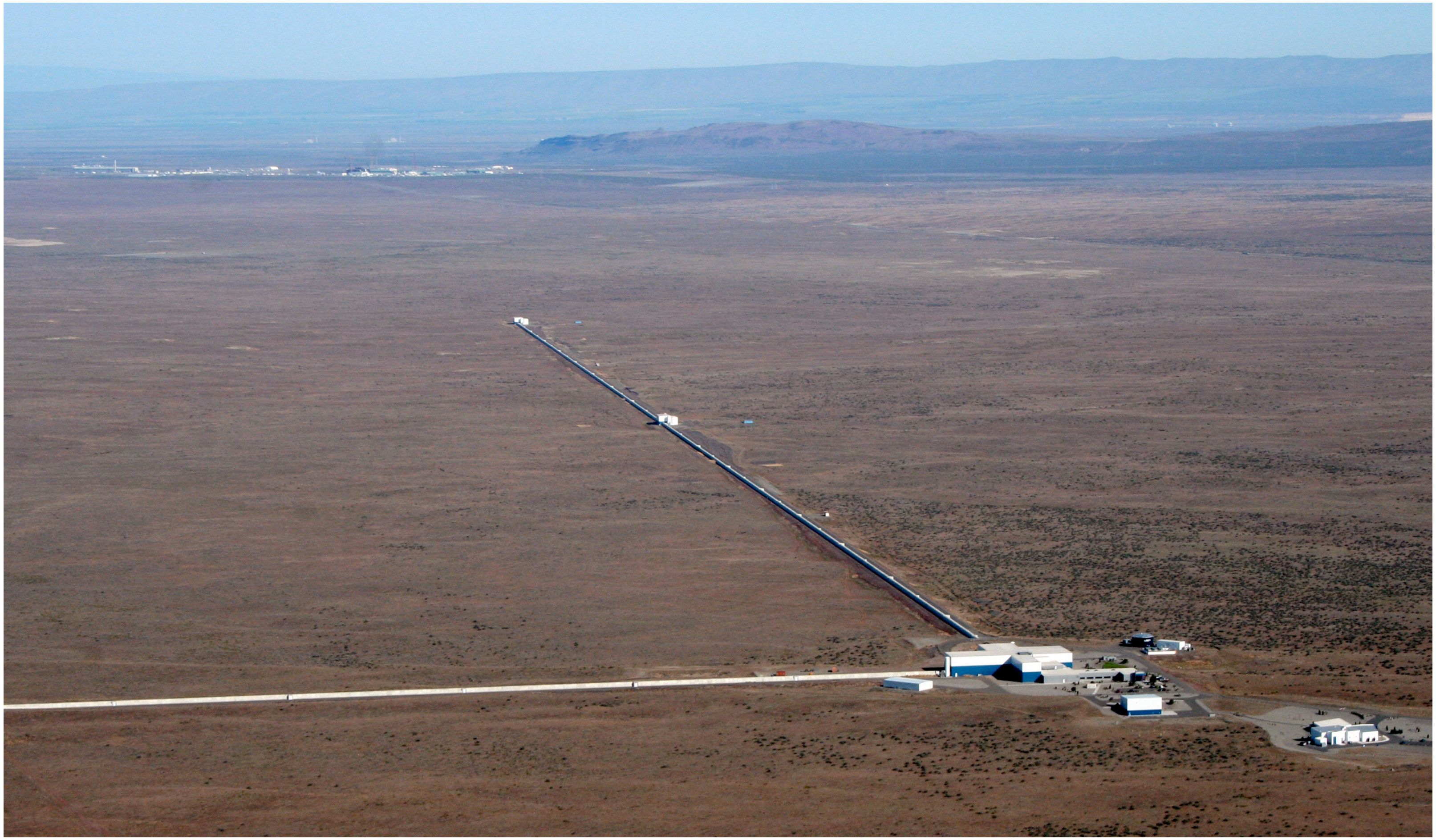
Power: $3\ M_\odot$ / 0.1 s $= 10^{46}$ kW $= 3 \times 10^{22}\ L_\odot$

Stars in the universe: 10^{22}-10^{24}

Flux: 5×10^{-3} W/m^2 = 4×10^{-6} $F_\odot$

Strain: 10^{-21}-10^{-22} of 4 km arms

$\Rightarrow 10^{-18}$ m $\approx 10^{-3}$ proton radius



Not only a fantastic tool for astronomy,
but a new testing ground for fundamental physics

Testing gravity under extreme conditions

- gravitational field is strong and rapidly changing
- curvature of spacetime in large
- dynamics of event horizons
- velocities are relativistic

GW150914 can be used to test:

equivalence principle, modifications of gravity, quantum structure of BH, propagation of GW, ...

Search for new physics in the form of Exotic Compact Objects (ECO)

- DM primary motivation
- New light elusive particles that can coalesce into ECOs
- GW offer unique tool for probing the existence of ECOs

Boson stars

- Supported by Heisenberg's principle

$$R \sim \frac{\hbar}{m_B c} \quad \text{no gravitational collapse if } R > R_{BH} = \frac{2G_N M}{c^2} \quad \Rightarrow$$

$$M_{\max} = 0.633\,\frac{M_P^2}{m_B} \approx \left(\frac{10^{-10}\ \mathrm{eV}}{m_B}\right) M_\odot$$

- Supported by repulsive self-interaction

$$V(\phi) = m_B^2|\phi|^2 + \frac{\lambda}{2}|\phi|^4$$

$$M_{\max} = 0.06\sqrt{\lambda}\,\frac{M_P^3}{m_B^2} \approx \sqrt{\lambda}\left(\frac{100\ \mathrm{MeV}}{m_B}\right)^2 10\ M_\odot$$

- Non-topological solitons (localized solutions of EoM in presence of a conserved charge Q and with trivial asymptotic behaviour)

Fermion stars

Supported by Fermi pressure

Chandrasekhar limit ($M \lesssim M_P^3/m_F^2$)

Multi-component stars

Mixtures of exotic or ordinary/exotic matter components

Dark-matter stars

- Strongest motivation for exotic matter
- Is DM collisionless?

Problems of simulations with collisionless DM:

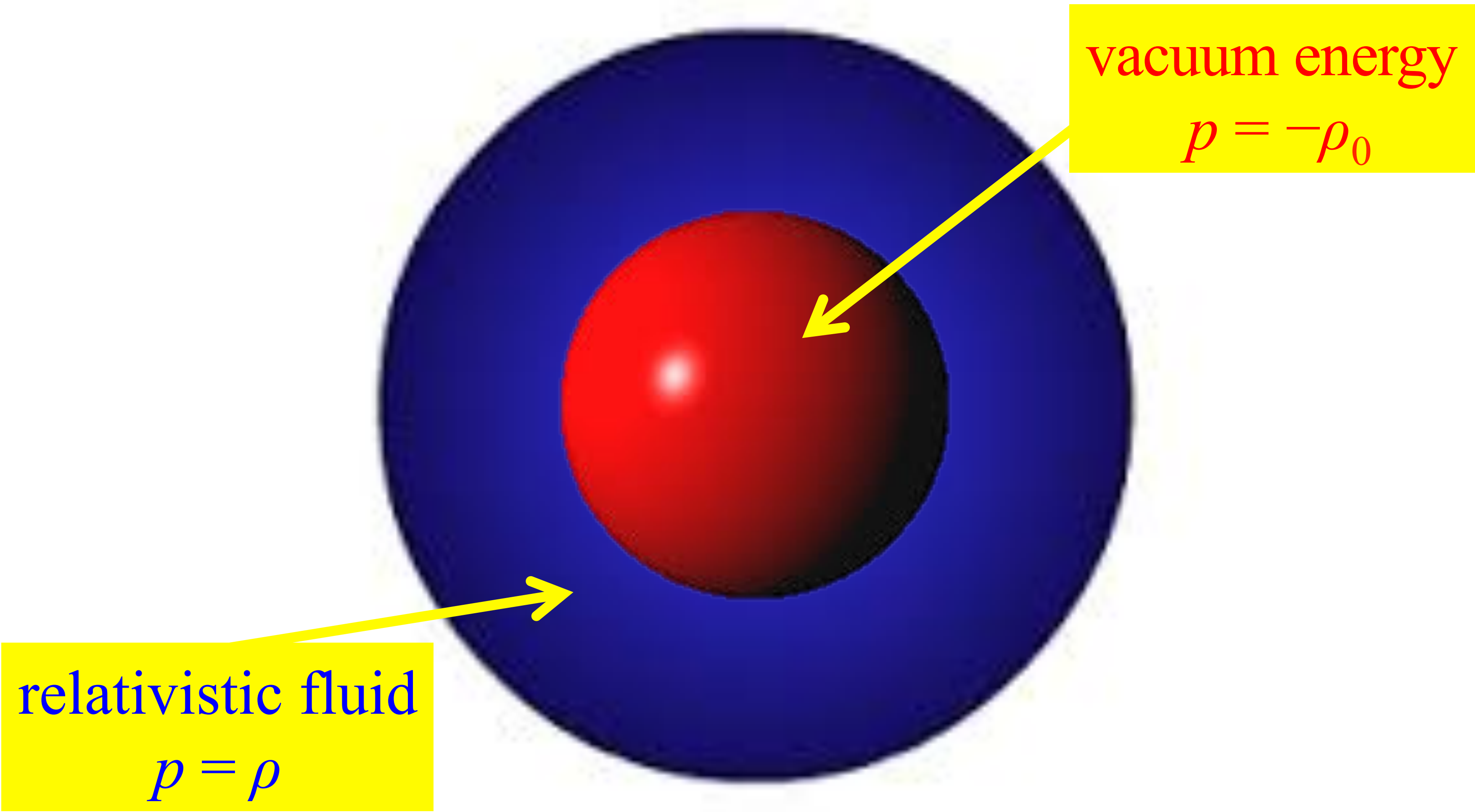
- profiles of dwarf galactic haloes too cuspy
- too many satellite galaxies
- dwarf galaxies too massive

+ indications from gravitational lensing of elliptical galaxies falling into Abell 3827 cluster

$$\Rightarrow \frac{\sigma}{m_{DM}} \approx 0.1 - 1 \ \frac{\text{cm}^2}{\text{g}}$$

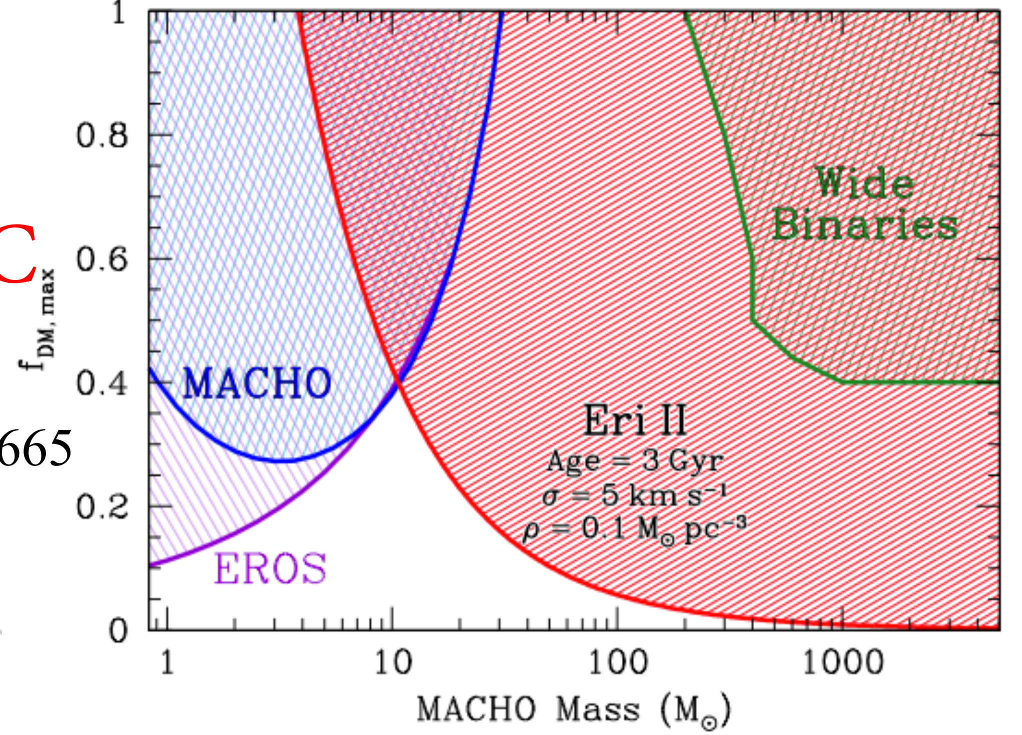
ECO formation?

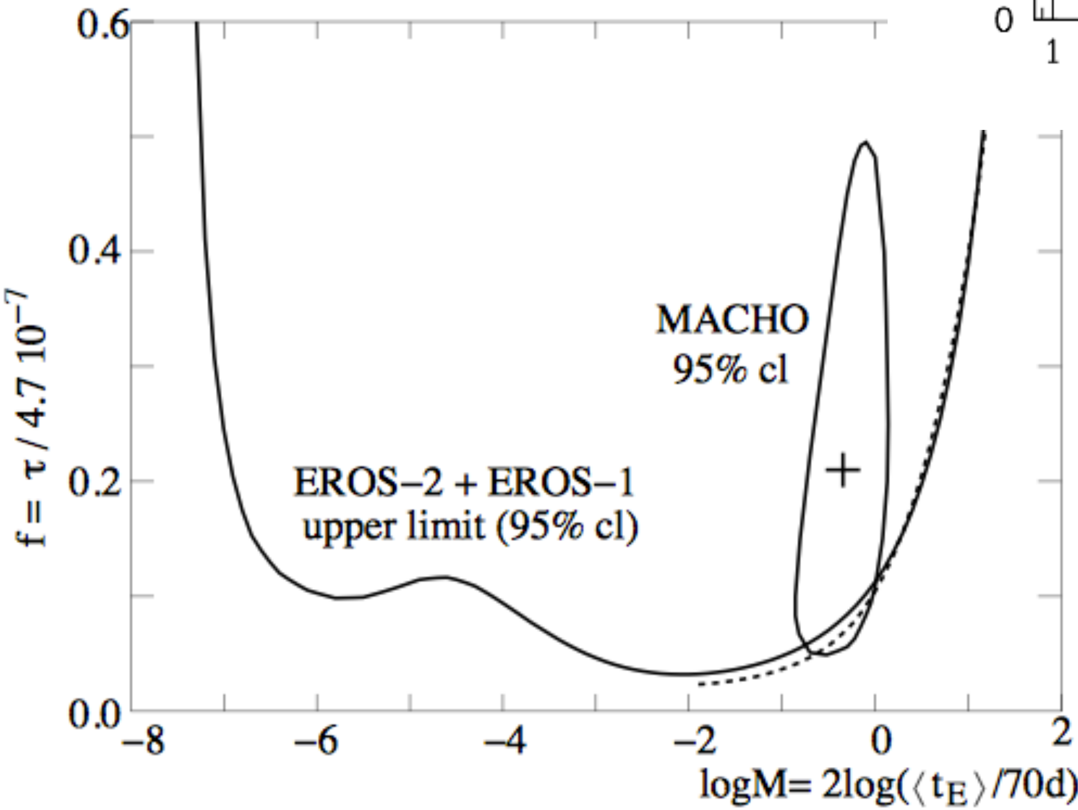
Dark-energy stars (gravastars)



Limits from microlensing in the LMC

Brandt 1605.03665





For M ~ 1 to tens of $M_\odot$ 20-40% of halo DM is allowed:

- ECO can be as numerous as ordinary stars
- ECO could be made of DM, if DM is both in dust and compact objects

LIGO sensitivity to ECO binary mergers

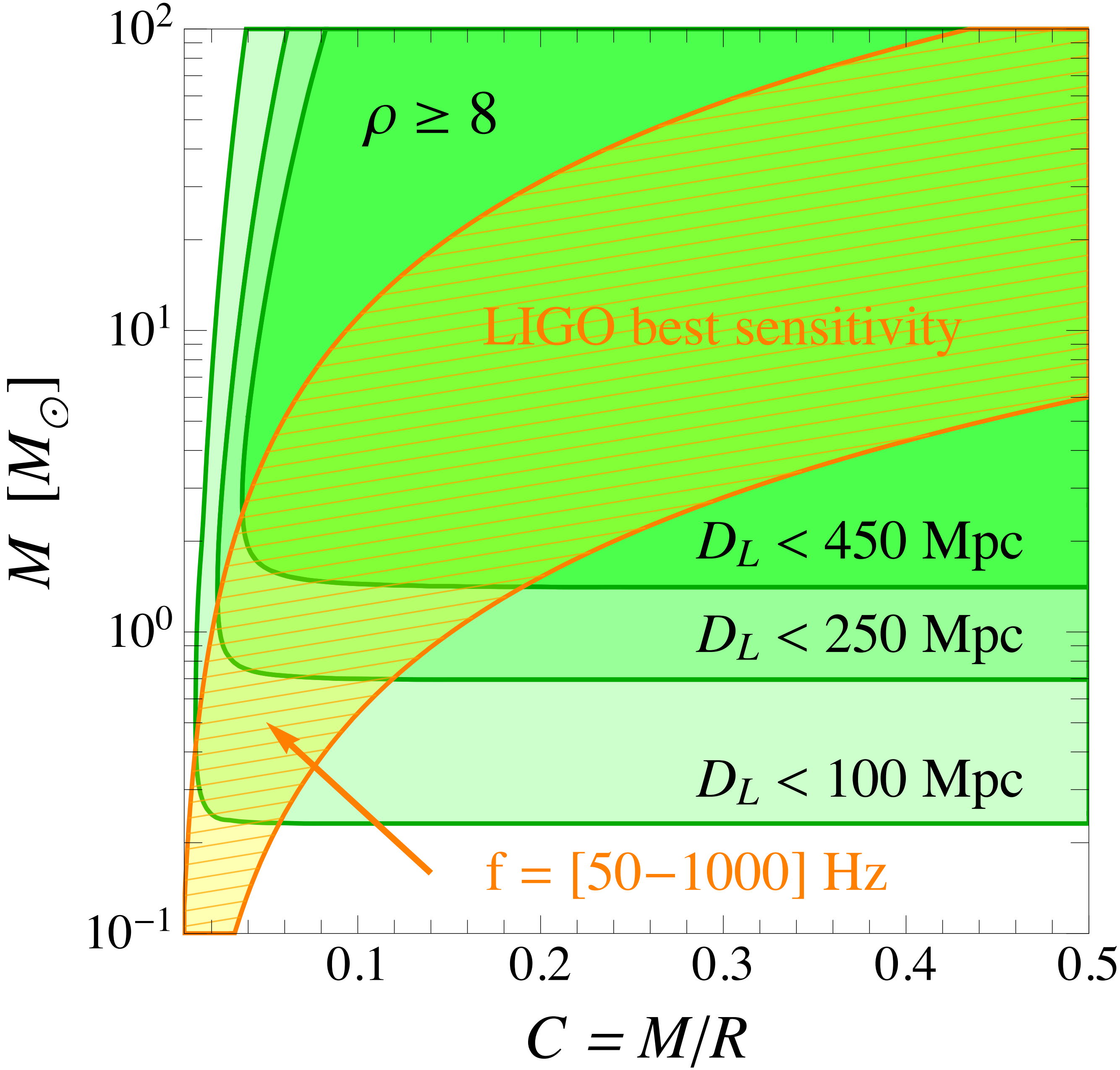
In terms of the astrophysical parameters only:

- mass M (for M_1=M_2)
- compactness $C = M/R$ (C_{BH}=1/2)

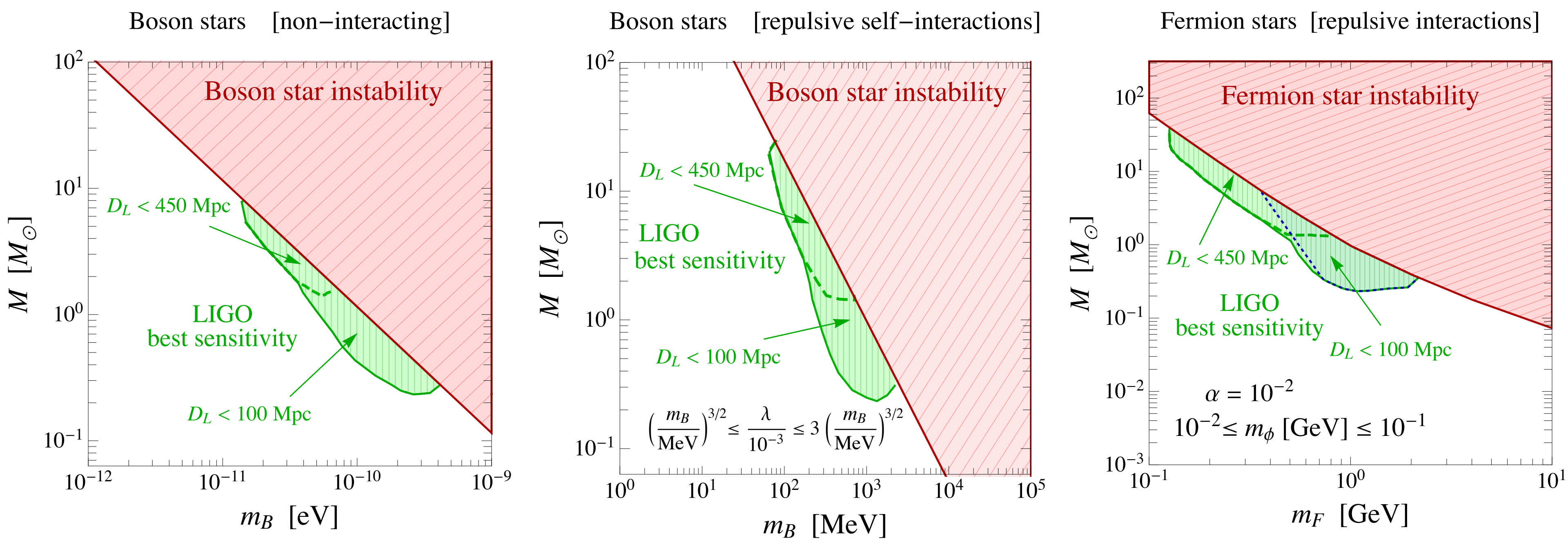
GW frequency grows as the two objects approach ⇒ sensitivity to size

At innermost stable orbit: $f = \dfrac{\sqrt{2}\,C^{3/2}}{3\sqrt{3}\,\pi M}$ $\qquad f_{LIGO} \sim 50 - 1000$ Hz

Signal/noise must be sufficiently large (depends on D_L)



$\rho \geq 8$
LIGO best sensitivity
$D_L < 450$ Mpc
$D_L < 250$ Mpc
$D_L < 100$ Mpc
f = [50−1000] Hz
10^2
10^1
10^0
10^{-1}
$M\ [M_\odot]$
0.1
0.2
0.3
0.4
0.5
$C = M/R$



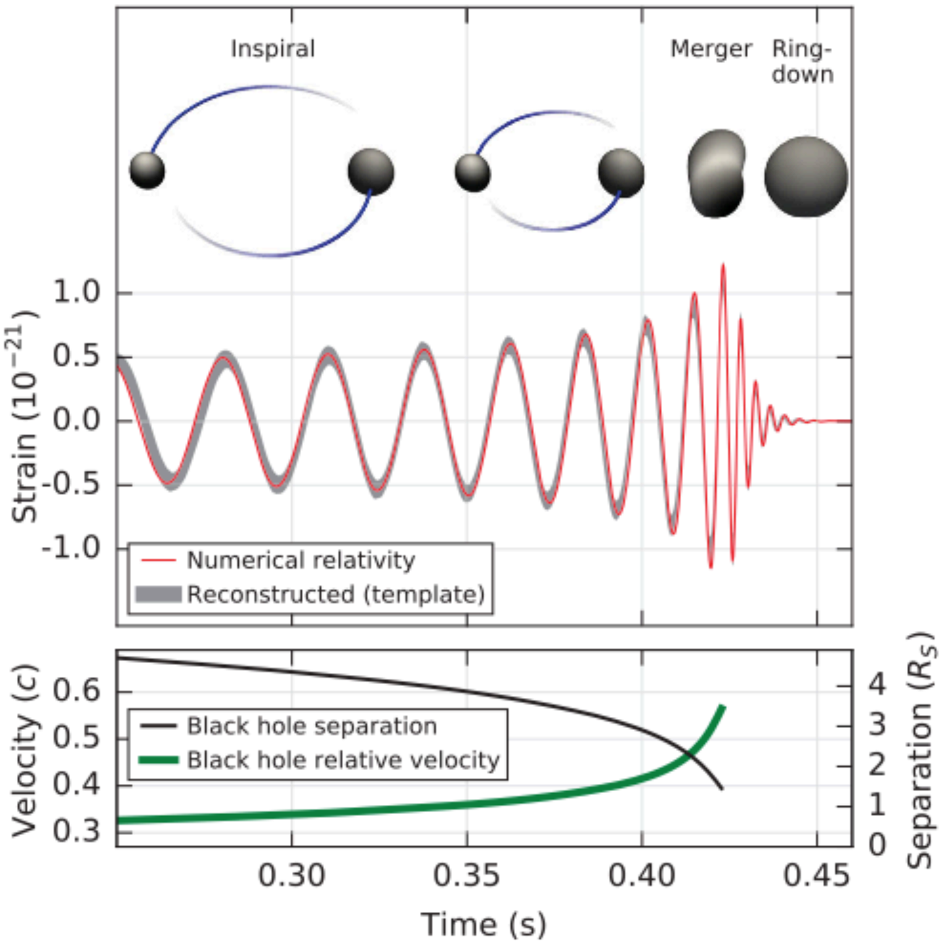
Interesting for asymmetric DM:

$$m_{DM} = \frac{\eta_b}{\eta_{DM}}\, 5 \text{ GeV}$$

Interesting for axion-like DM:

$$m_a = \left(\frac{10^{17} \text{ GeV}}{f_a}\right) 0.6 \times 10^{-10} \text{ eV}$$

How to detect ECO in a single GW event



Inspiral

- post-Newtonian expansion
- chirp mass $M_c = \dfrac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$
- redshift (from the way frequency and amplitude change)

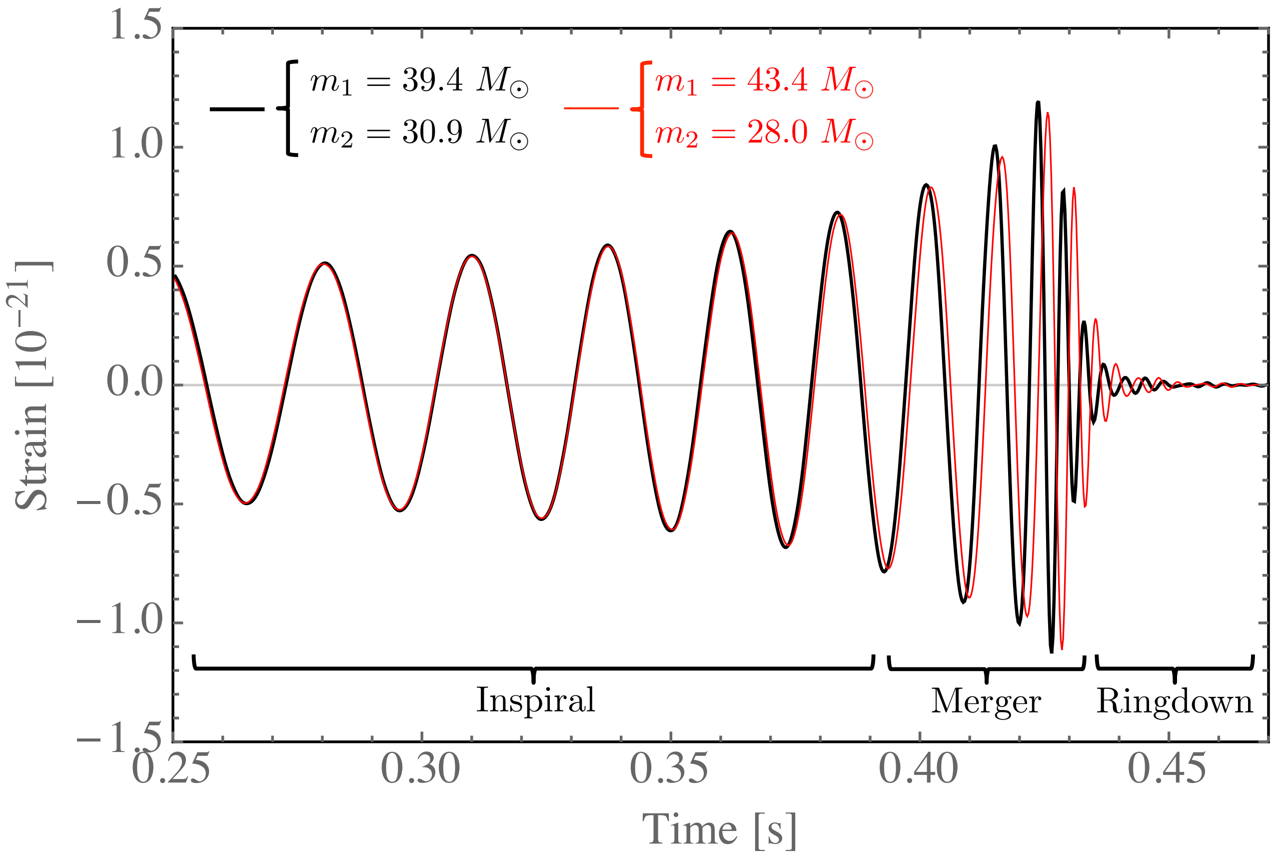
Ringdown

- QNM as perturbations of Kerr BH solution

Merger

- numerical relativity (progress in the last 10 yrs)
- need to develop ECO simulations

Extraordinary sensitivity



Black: LIGO best fit

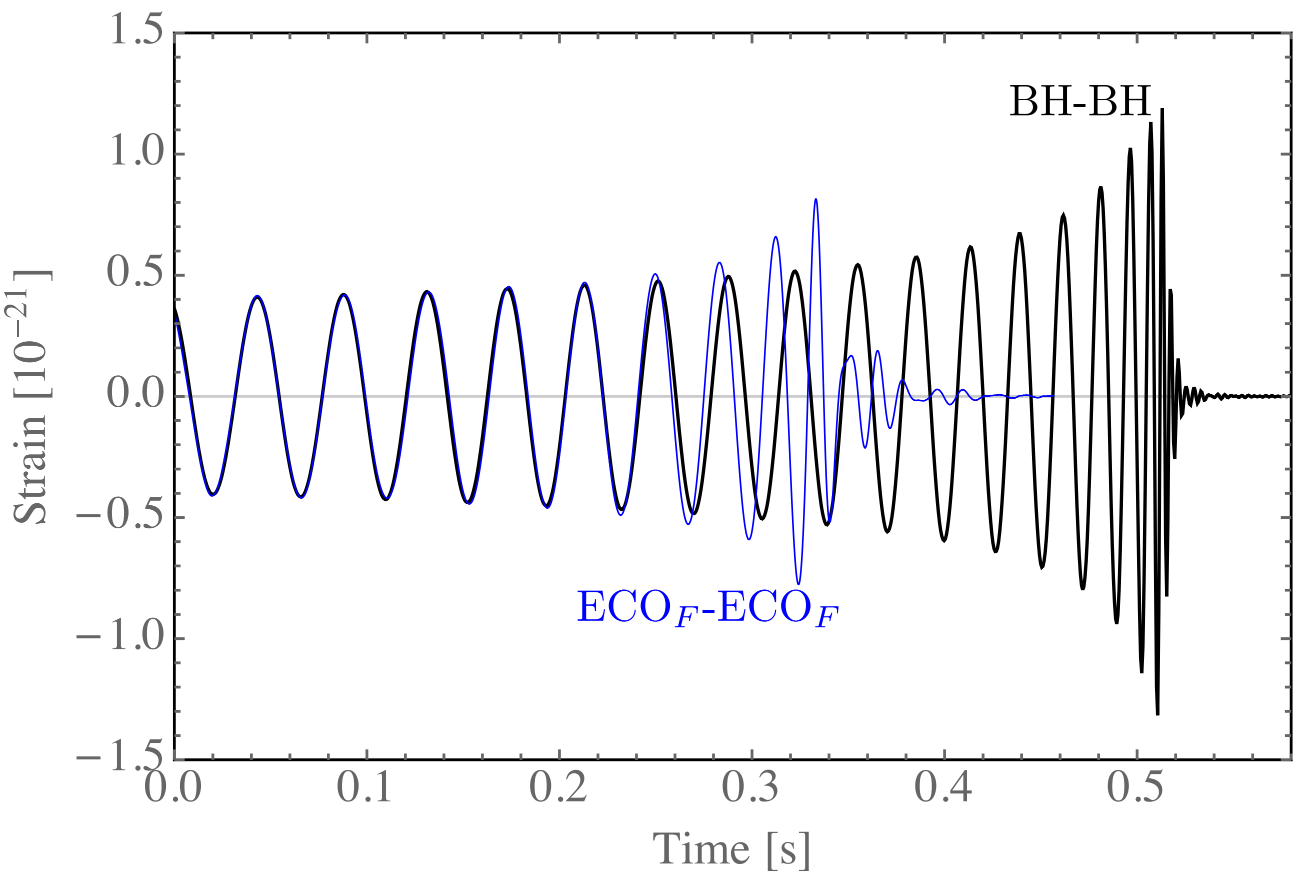
Red: same chirp mass, but mass ratio excluded @ 90% CL

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

From inspiral, we could learn about C

(GW150914 must come from BH merger as objects come very close)

At innermost stable orbit $\frac{f_{BH}}{f_{ECO}} = 5.5\left(\frac{0.16}{C}\right)^{3/2}$



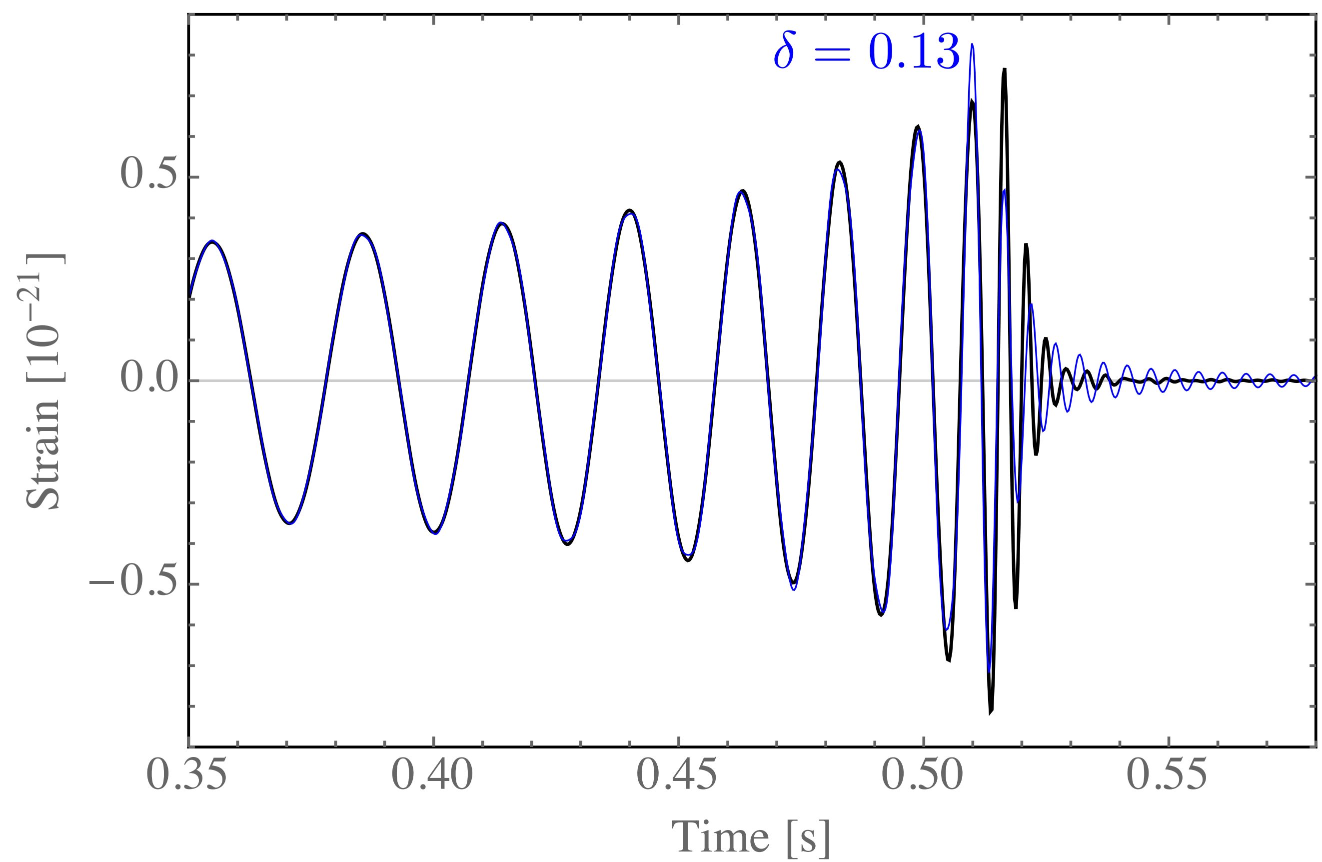
$M_{BH} = M_{ECO} = 35\ M_\odot$

$C_{BH} = 0.5$

$C_{ECO} = 0.16$

Ringdown is sensitive to EoS and absence of horizon

For a gravastar with $M_{BH} = M_{ECO} = 35\ M_{\odot}$ $C_{ECO} = 0.44$

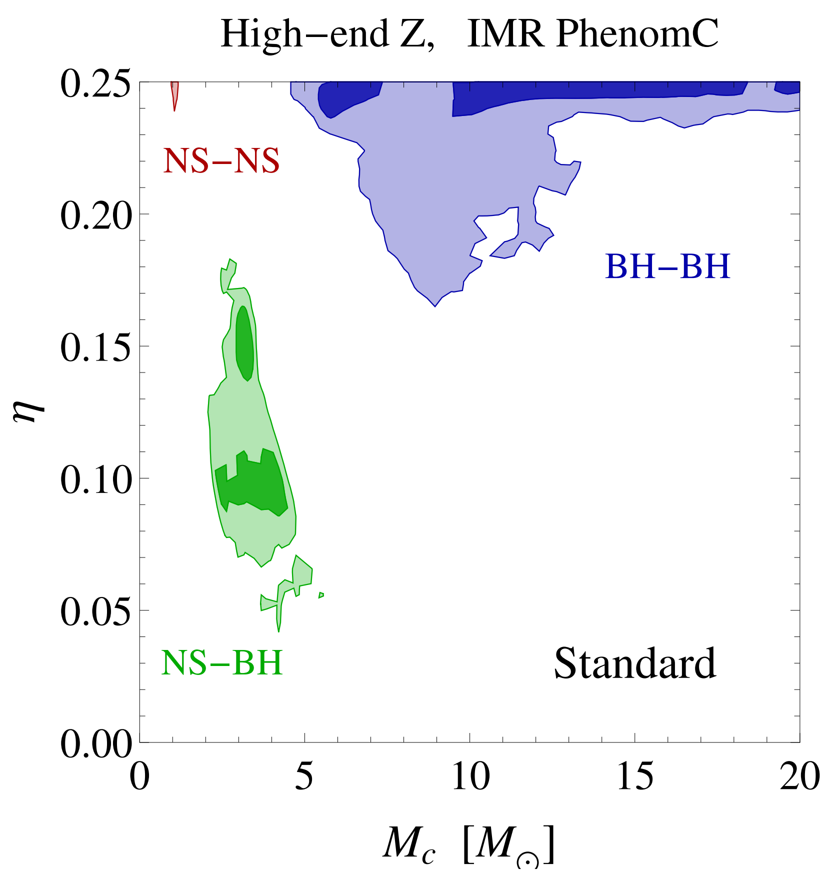


What can be learned from GW event distributions?

Conventional heavy objects:

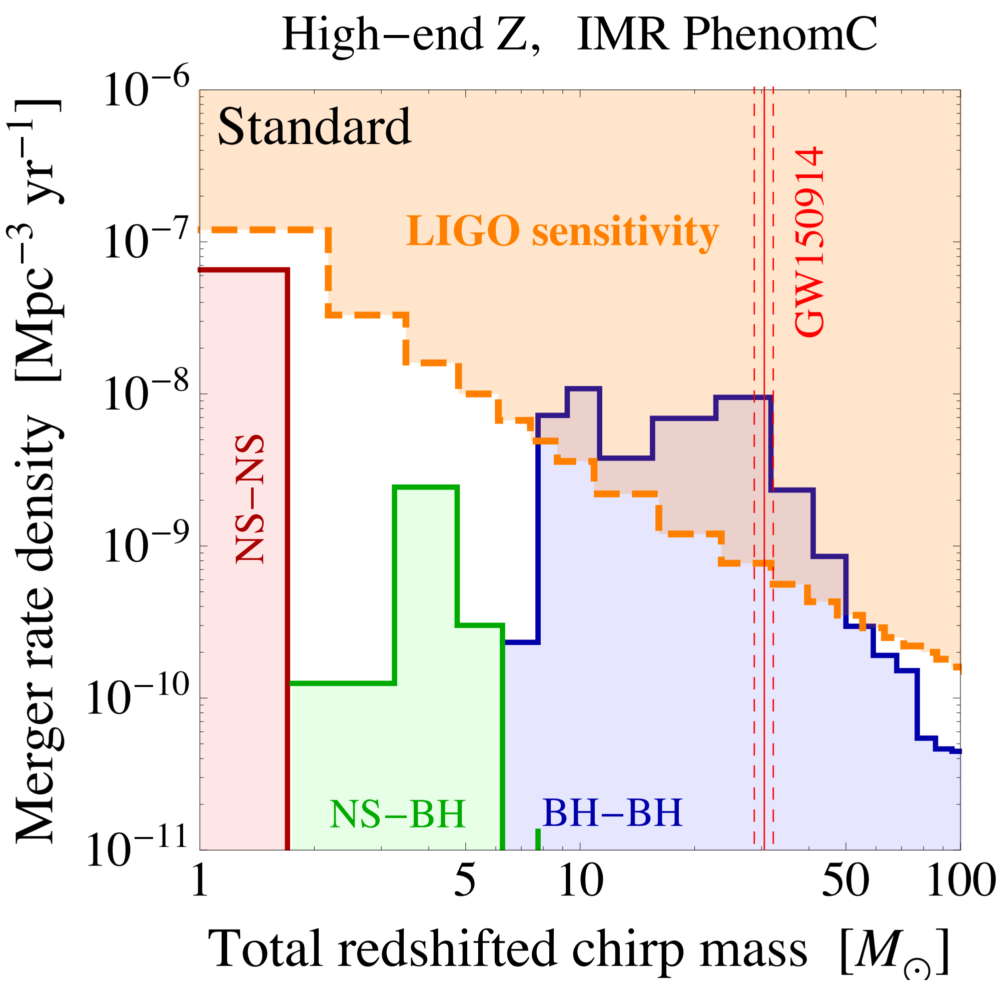
- NS: most massive observed M=2.01±0.04 $M_\odot$ and most models hardly exceed 2 $M_\odot$ (0.13≤C≤0.23)
- Stellar BH: mass distribution expected to start at 5 $M_\odot$ (C=0.5)

Mass gap can be explained in stellar evolution models



$$M_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

$$\eta = \frac{M_1 M_2}{(M_1 + M_2)^2}$$



- Filling the gap is evidence of a new population of exotic objects
- Distribution is an essential tool to understand ECO mass function and formation process

Test of Area Theorem

Hawking's Area Theorem: the sum of the horizon areas of a system of BHs never decreases

It follows from GR + null energy condition

Hawking's radiation: M decreases ⇒ R decreases ⇒ A decreases

Violation of the theorem?

Thermodynamics interpretation: BH temperature $T = M_P^2/M$

BH entropy $S = A/4$

Second law of thermodynamics ⇒ Area Theorem

Once the entropy of the emitted radiation is taken into account, no violation of the "generalized" second law of thermodynamics

Test of Area Theorem in BH mergers

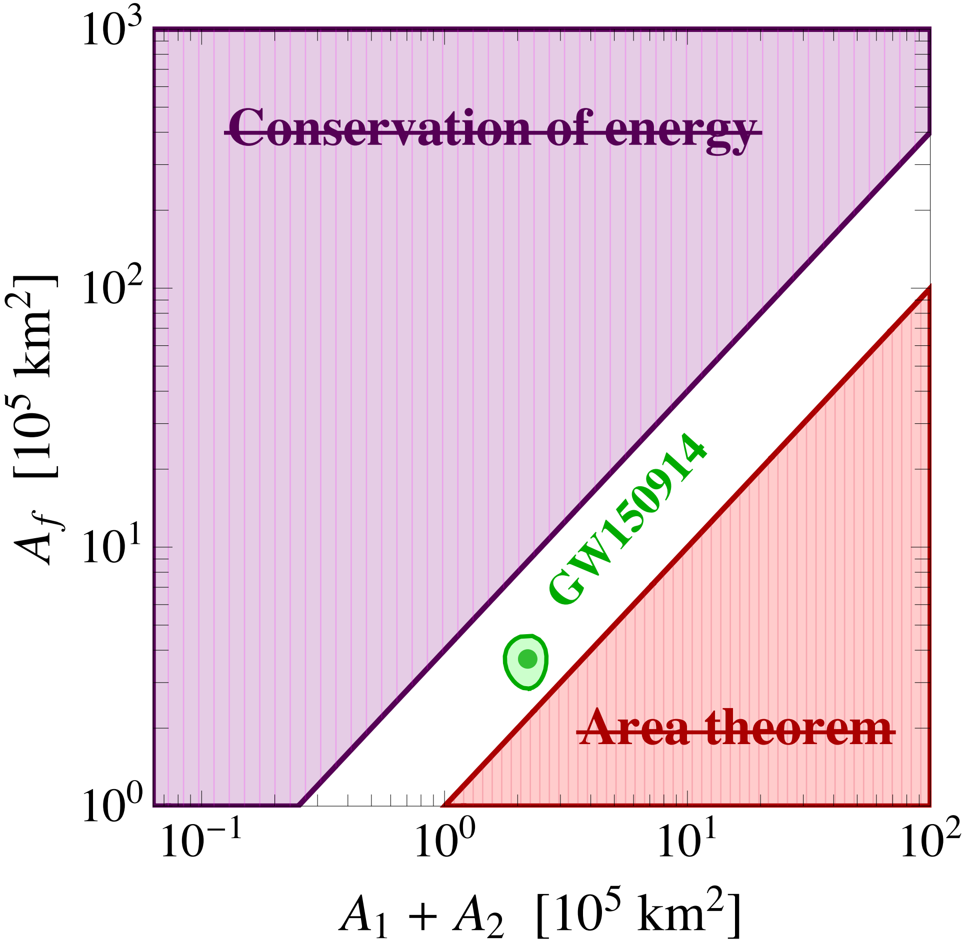
For a Kerr BH: $A = 8\pi M^2 \left(1 + \sqrt{1 - a^2}\right)$ $\qquad a \equiv \frac{J}{M^2}$

Hawking's Area Theorem: $A_f > A_1 + A_2$

$$M_f > \sqrt{M_1^2\, s_1 + M_2^2\, s_2}\,, \qquad s_{1,2} \equiv \frac{1 + \sqrt{1 - a_{1,2}^2}}{1 + \sqrt{1 - a_f^2}}$$

Hawking's Area Theorem:

lower bound on $M_f \Rightarrow$ upper bound on efficiency of GW emission



What if the Area Theorem is observed to be violated?

A BH-mimicker ECO can violate it by emitting dark radiation

- Test of fundamental principles
- Test of undetected radiation

Conclusions

- GW observations have opened a new avenue in astronomy
- A unique tool to test gravity in the regime of strong and rapidly-changing field, and relativistic velocities
- Search for new forms of matter in compact objects
- Probing DM clumping in astronomical bodies
- Probing a variety of new-physics ideas
- Information in single GW events and event distribution
- Testing Hawking's Area Theorem can probe dark radiation