



The Galileo Galilei Institute for Theoretical Physics
Arcetri, Florence

GGI 10th ANNIVERSARY

New Frontiers of Theoretical Physics:

Cortona GGI 2016

17-20 May 2016 GGI Arcetri, Firenze

On the occasion of the 10th anniversary since the starting of the activities of the Galileo Galilei Institute (GGI), this year the Italian National Meeting on Theoretical Physics will exceptionally take place in Arcetri, Florence.

The GGI will celebrate ten years of successful activity in the afternoon of May 17 with a scientific symposium with the participation of the President of INFN, of the Rector of the University of Florence, of the former and present GGI coordinators and of the chairman of the Advisory Committee. The scientific talks will be presented by S. Bertolucci (CERN), G. Giudice (CERN), L. Hui (Columbia) and A. Sen (Allahabad).

The regular conference "Cortona 2016" will start in the morning of May 18 and end in the afternoon of May 20. The aim of this conference, keeping its tradition, is to discuss some of the most recent advances in many areas of theoretical physics, in the pleasant early-Summer atmosphere of Galileo's hill. A good participation of young researchers including graduate students and postdoc fellows, alongside more senior researchers, is one of the characteristics of this Meeting, which we plan to maintain. There will be a number of plenary talks as well as shorter presentations by the participants. Interested people are kindly invited to register as soon as possible, providing the title and abstract of their proposed talk.

Plenary Speakers of Cortona 2016

Zvi Bern (UCLA), Denis Bernard (ENS, Paris), Pasquale Biasi (INAF, Firenze), Michele Della Morte (Odense), Christof Galtmayer (Graz), Zohar Komargoski (Weizmann), Michele Maggiore (Geneve), Enrico Pajer (Utrecht), Marco Pelin (IT, Genova), Antonio D. Polosa (Roma), Andrea Romanino (SISSA), Shirsei Ryu (Illinois).

Organizing Committee:

Bartolome Alles Salom, Francesco Bigazzi, Stefano Bolognesi, Andrea Cappelli, Daniele Dominicci, Massimo DiEia, Dario Francia, Dario Grasso, Kenichi Konishi, Enrico Moggioiario, Michele Redi, Alessandro Strumia, Enrico Trincherini.

Secretary

Paola Cecchi, Lucia Lilli (Pisa), Annalisa Anichini, Mauro Morandini (Firenze)

Galileo Galilei



Exploring fundamental physics with

gravitational waves

G.F. Giudice



based on 1605.01209 with

M. McCullough & A. Urbano



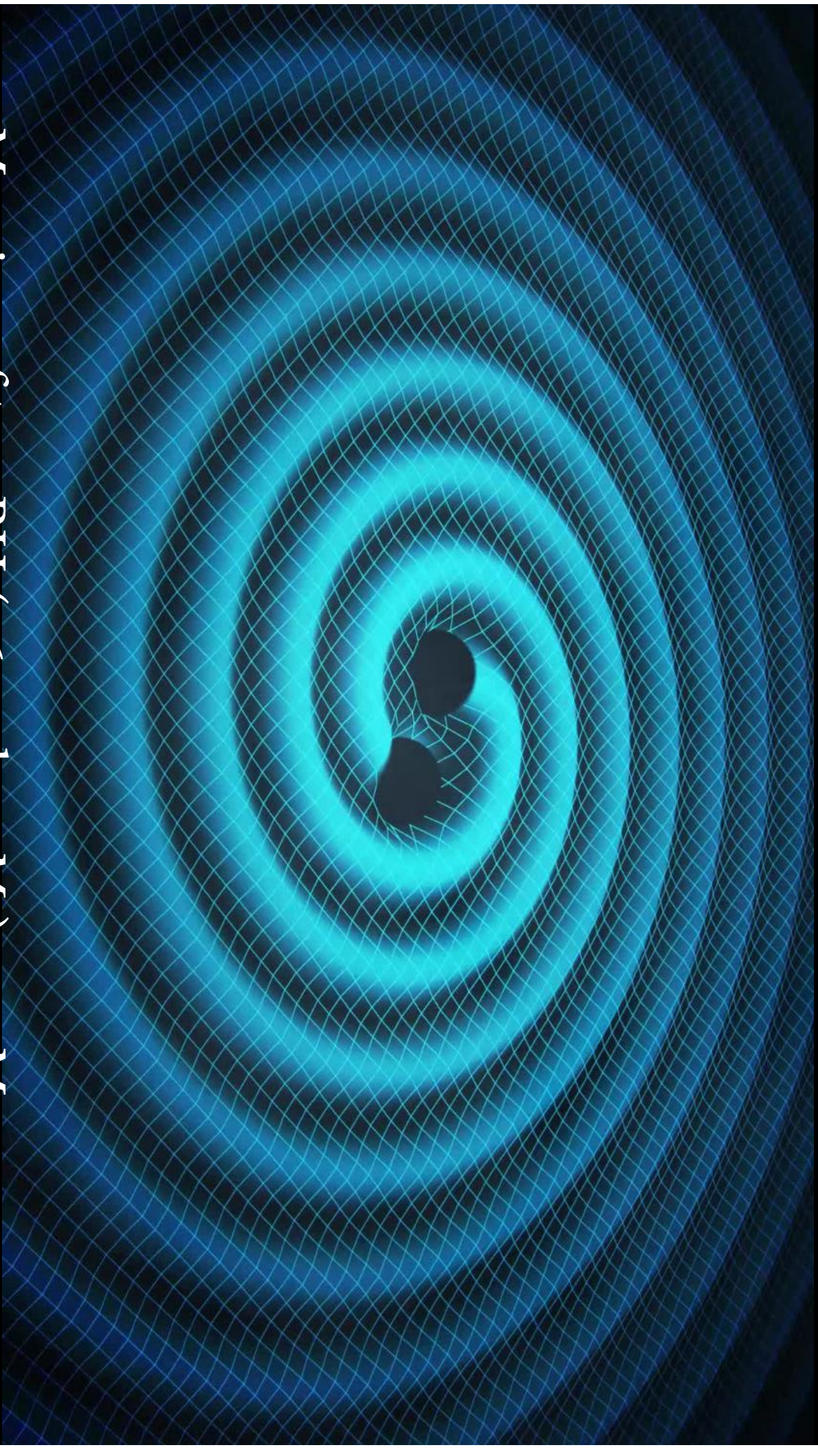
SCUOLA
NORMALE
SUPERIORE

UNIVERSITÀ DI PISA

GGI: <http://www.ggi.fi.infn.it/>

webpage:<http://www.ggi.fi.infn.it/index.php?page=events&id=230>

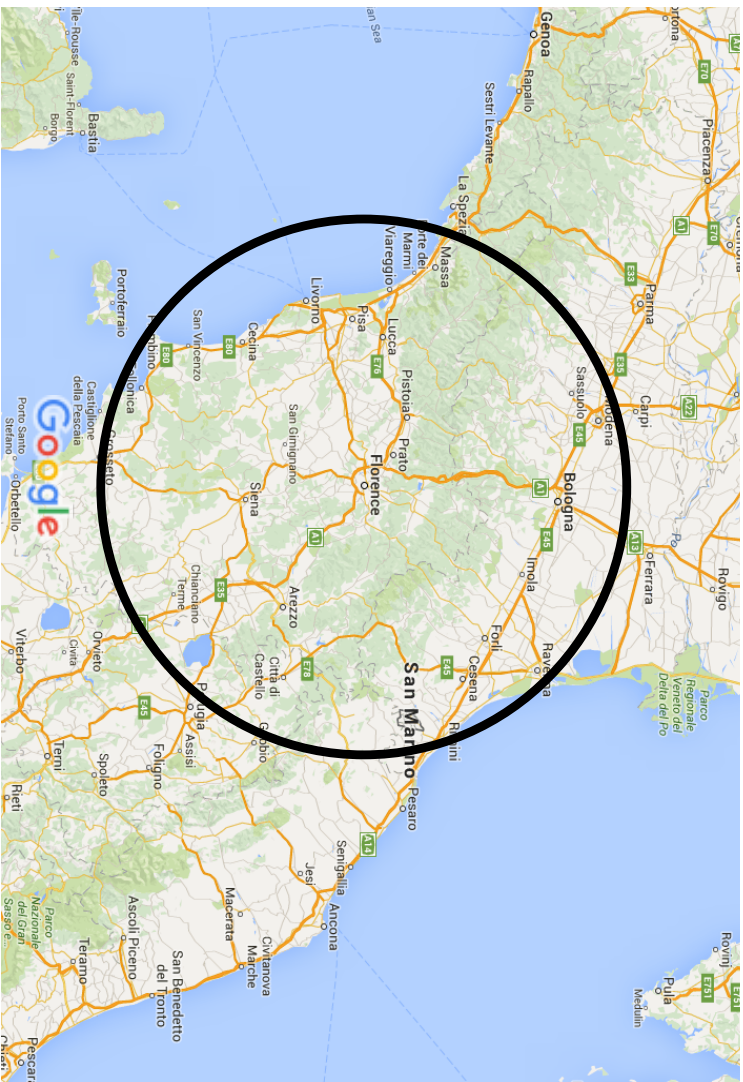
GW: science fiction come true!



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

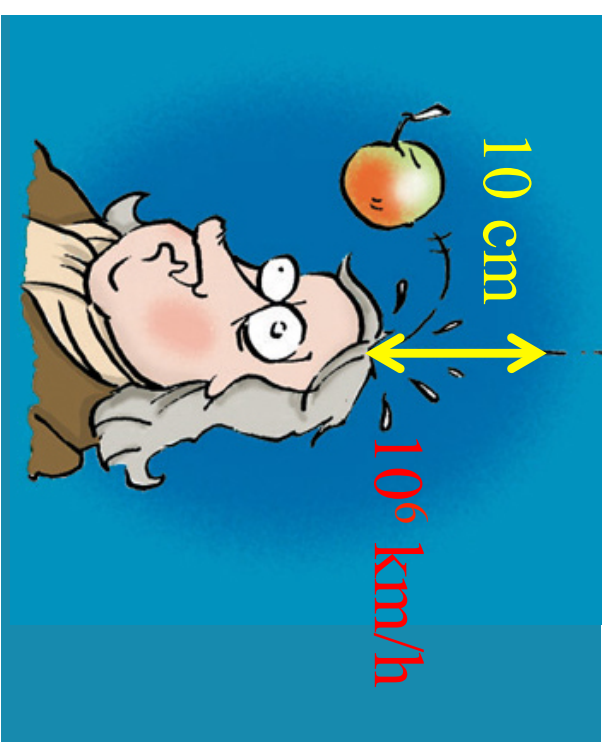
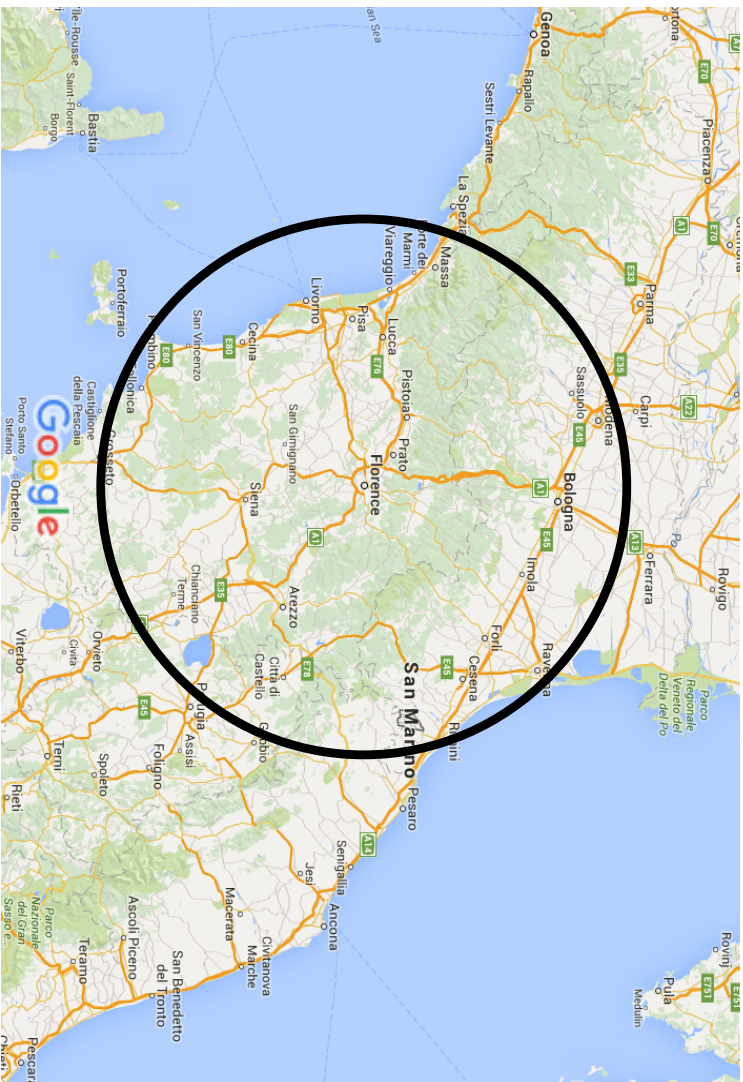
BH radius:

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

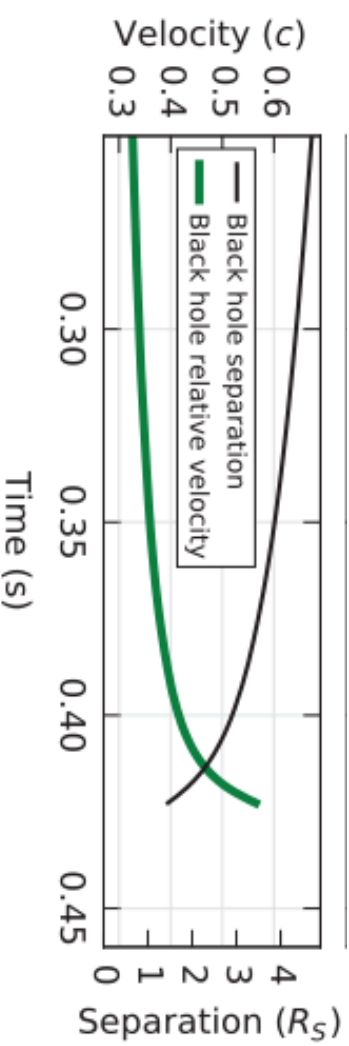


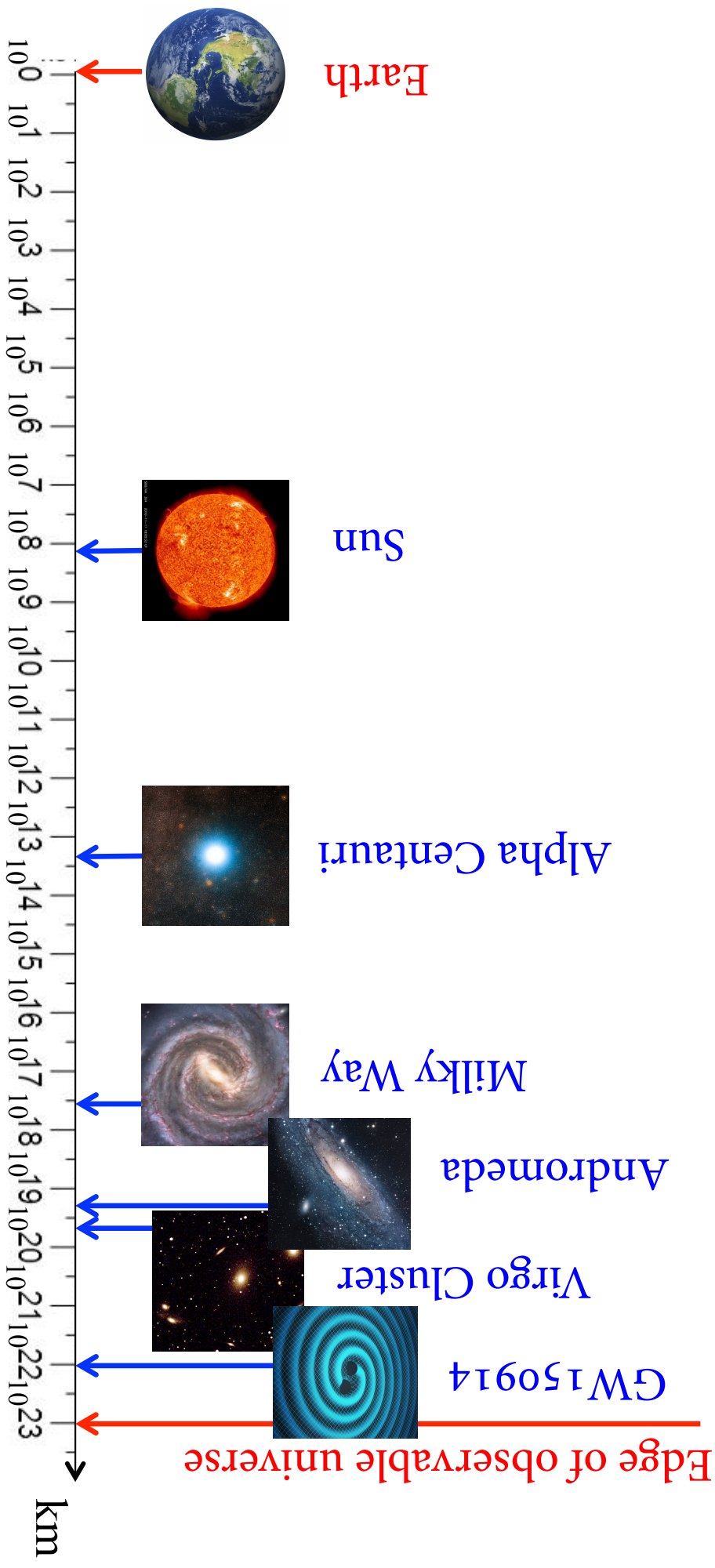
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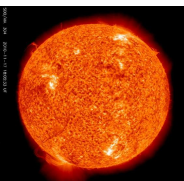


relativistic velocities!





Earth



Sun



Alpha Centauri



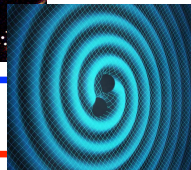
Milky Way



Andromeda



Virgo Cluster



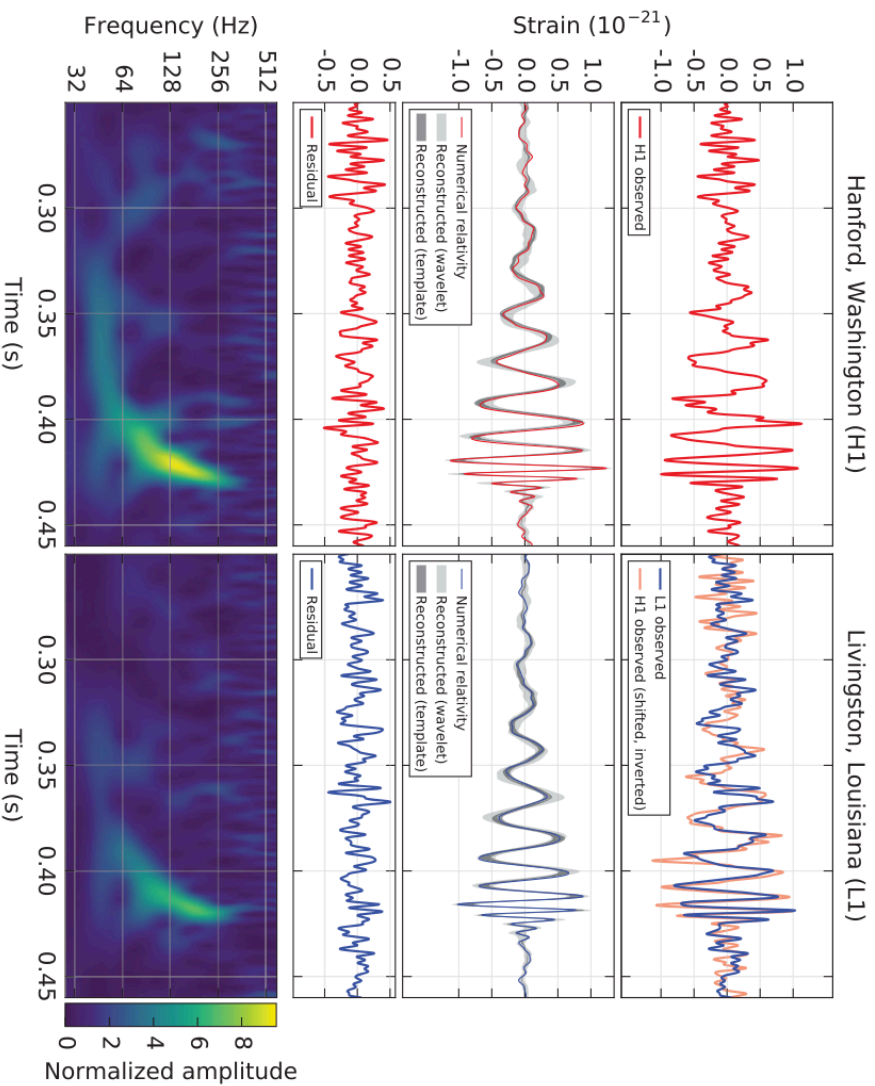
GW150914

Edge of observable universe

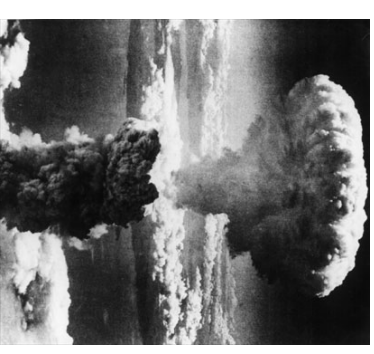
km

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}

Energetic output
 $\approx 3 M_{\odot}$ in 0.1 s



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



Power: $3 M_{\odot} / 0.1 \text{ s} = 10^{46} \text{ kW} = 3 \times 10^{22} L_{\odot}$
Stars in the universe: $10^{22} - 10^{24}$

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

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

$\Rightarrow 10^{-18} \text{ m} \approx 10^{-3}$ 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 (ECOs)

- 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

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

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

- Supported by repulsive self-interaction

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

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

- 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 ($M \lesssim M_{\text{P}}^3/m_{\text{F}}^2$)

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

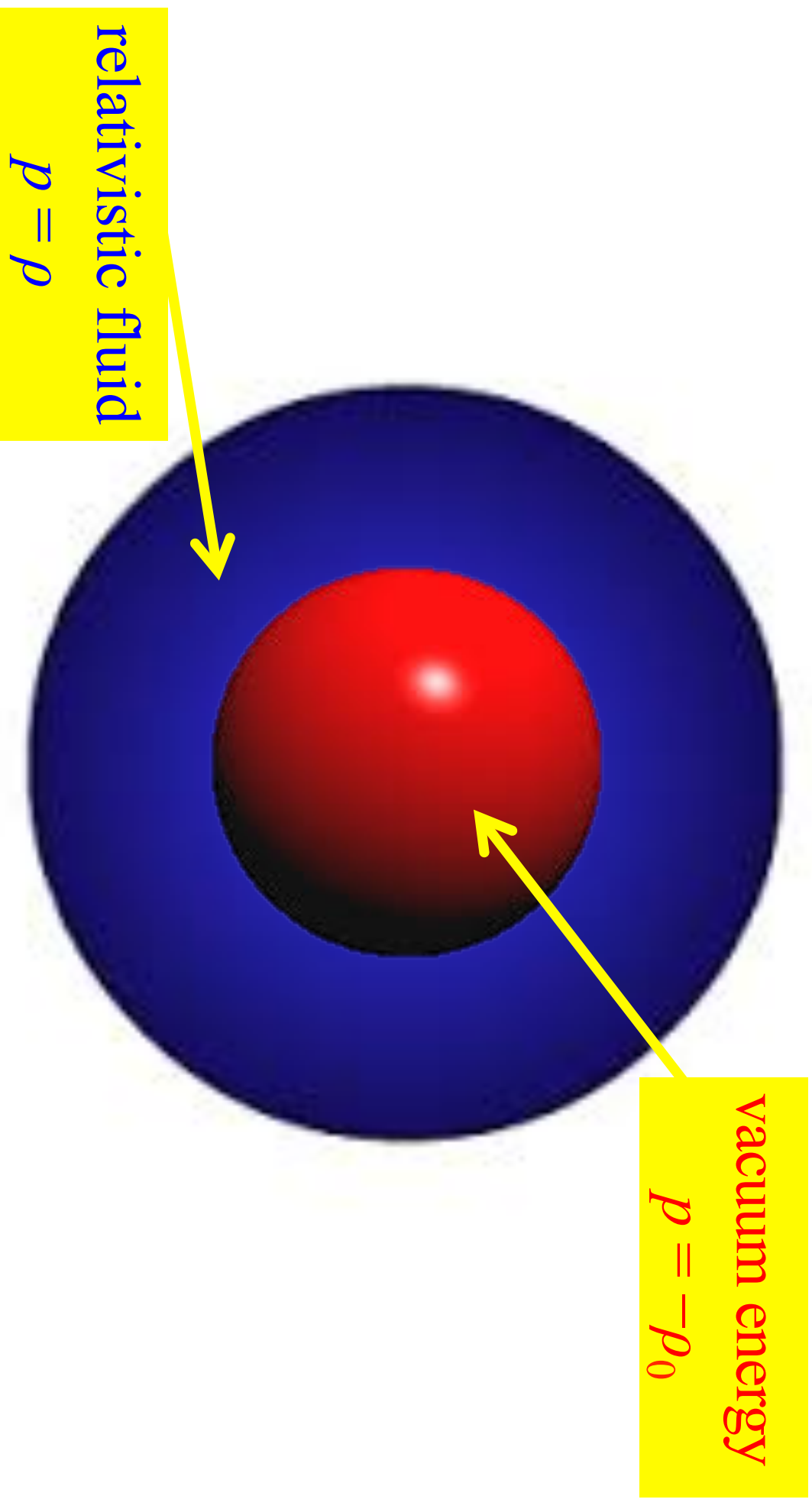
with collisionless DM:

- 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

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

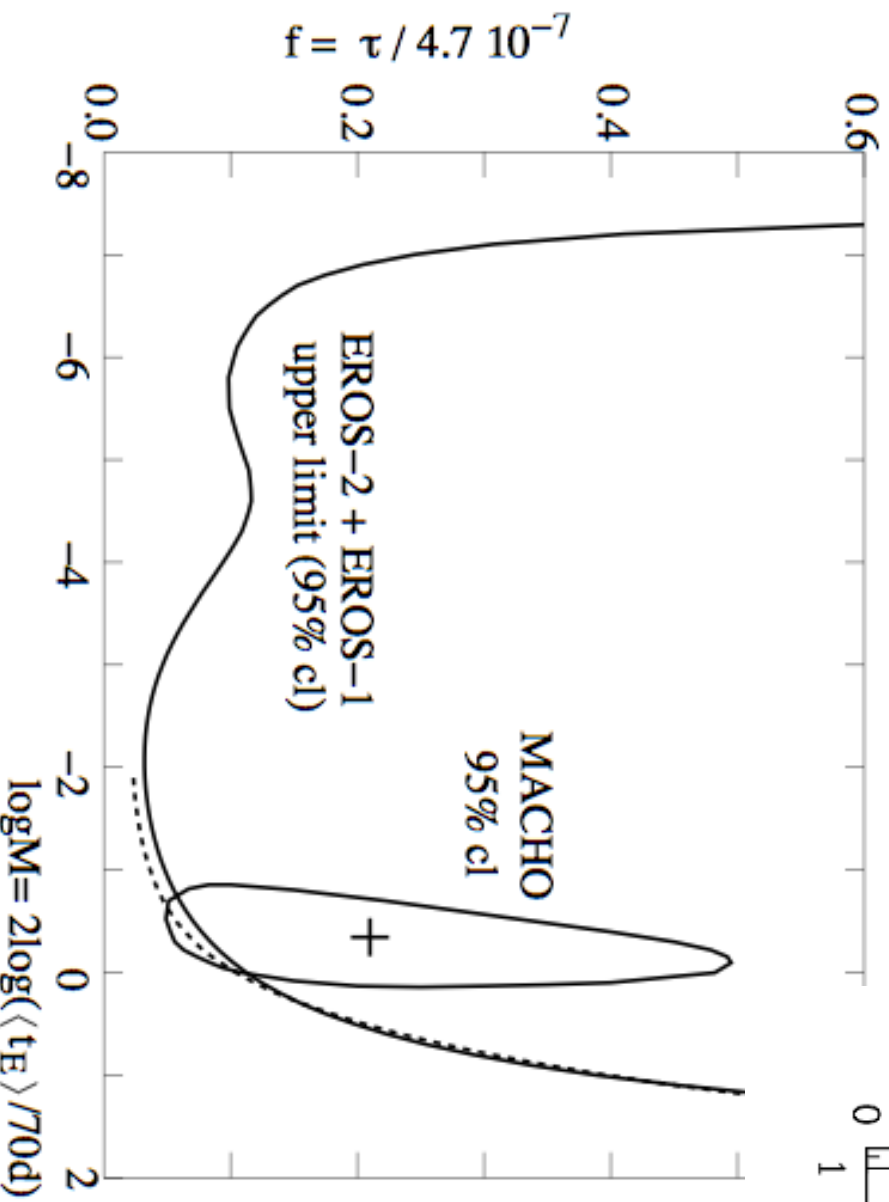
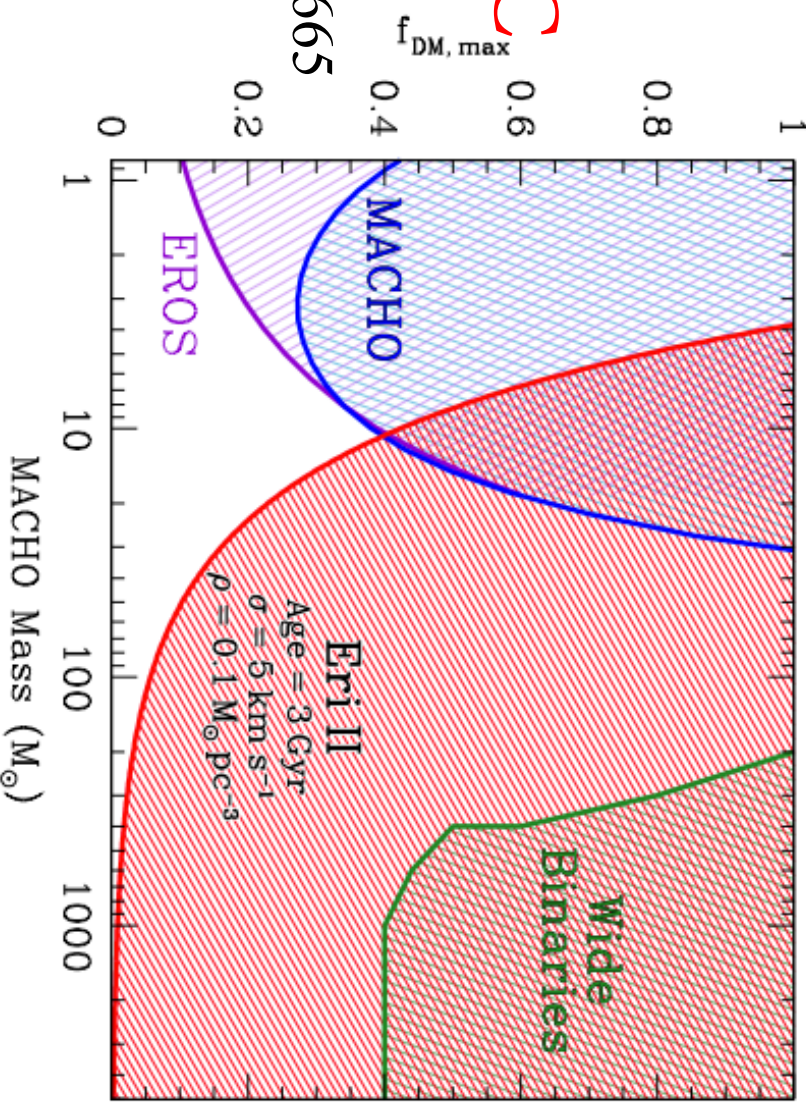
ECCO formation?

Dark-energy stars (gravastars)



Limits from microlensing in the LMC

Brandt 1605.03665



- For $M \sim 1$ 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

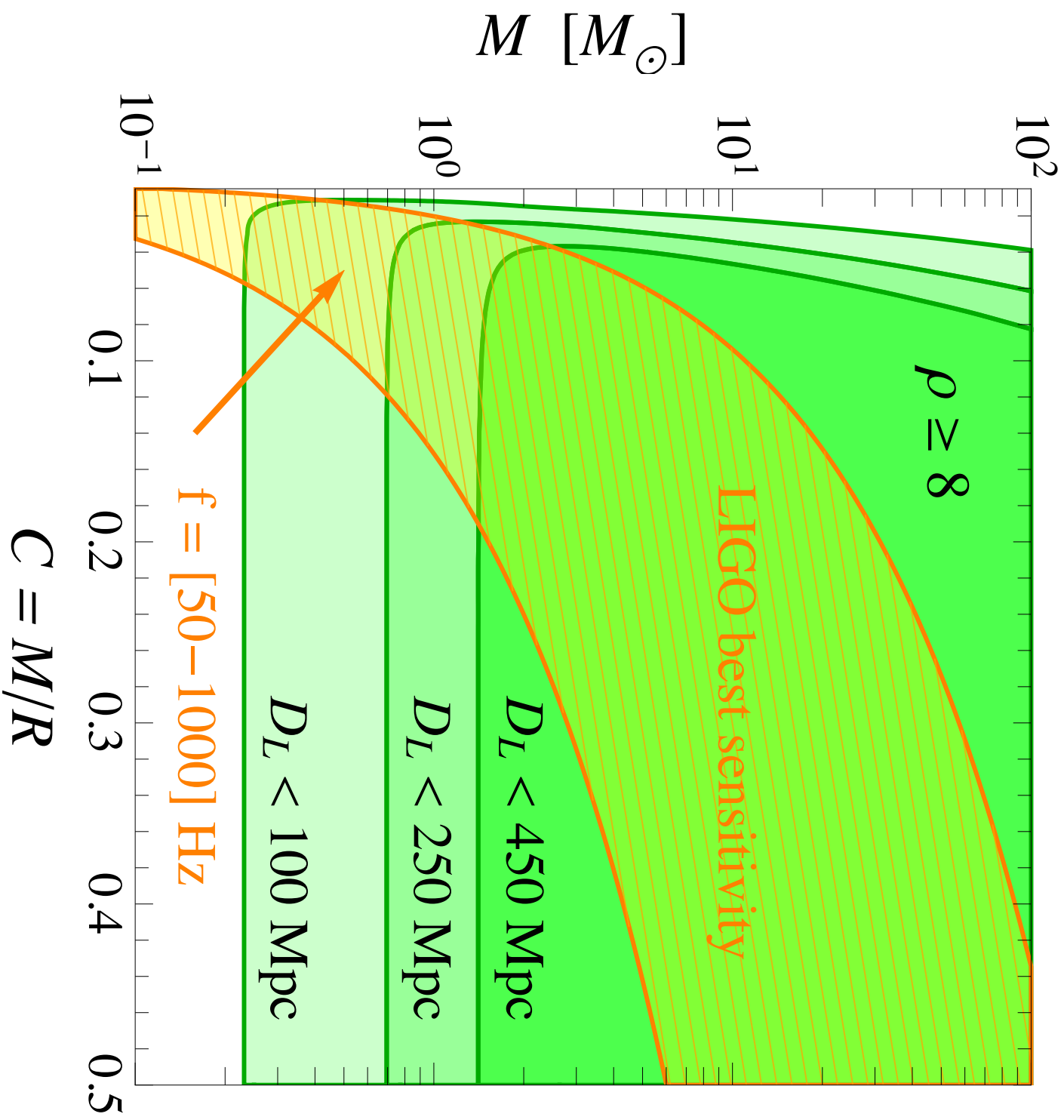
In terms of the astrophysical parameters only:

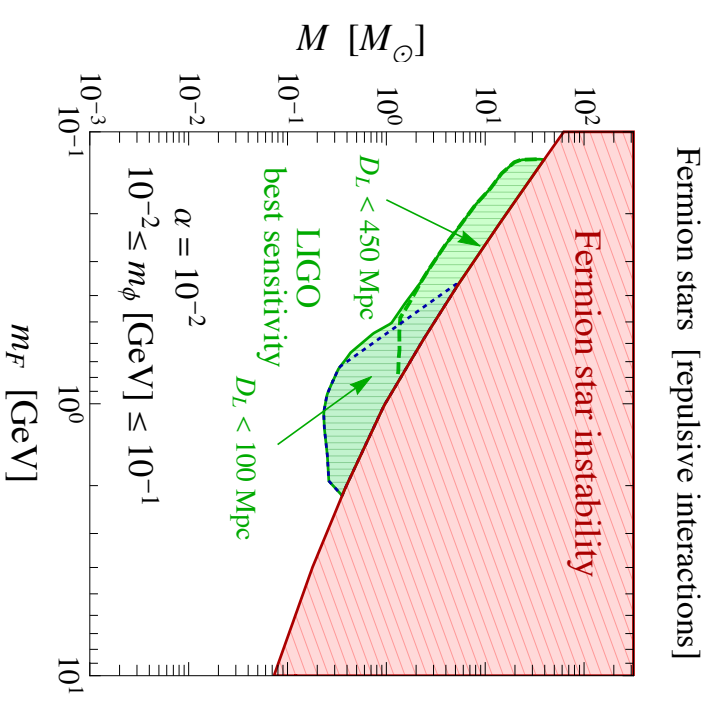
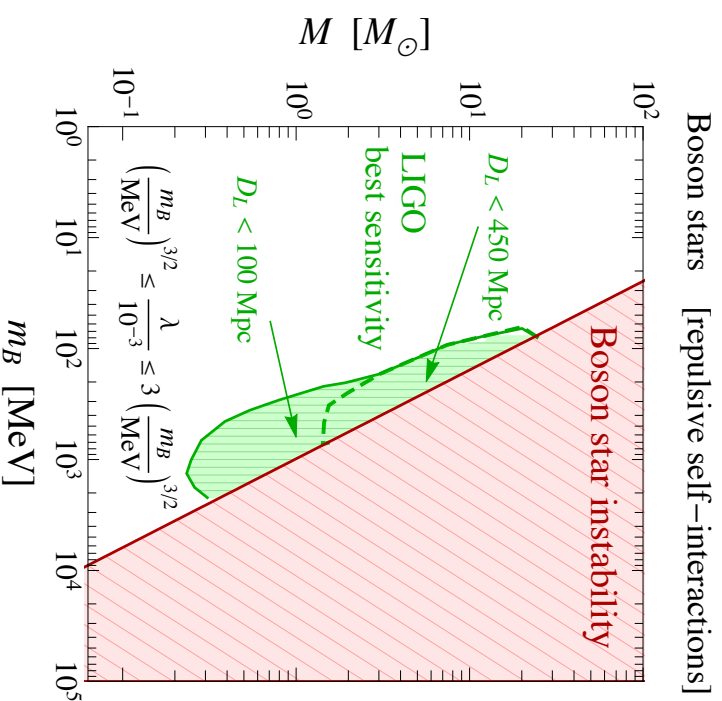
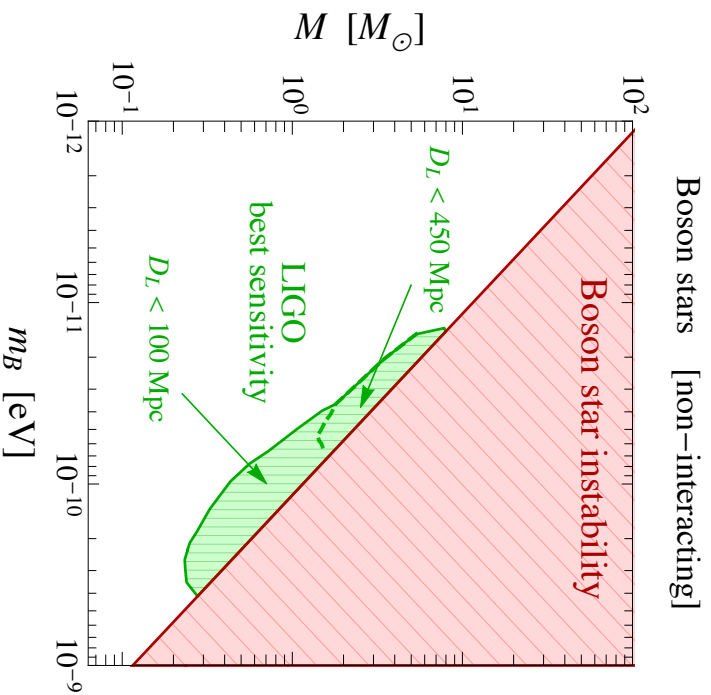
- mass M (for $M_1=M_2$)
- compactness $C = M/R$ ($C_{BH}=1/2$)

GW frequency grows as the two objects approach \Rightarrow
sensitivity to size

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

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





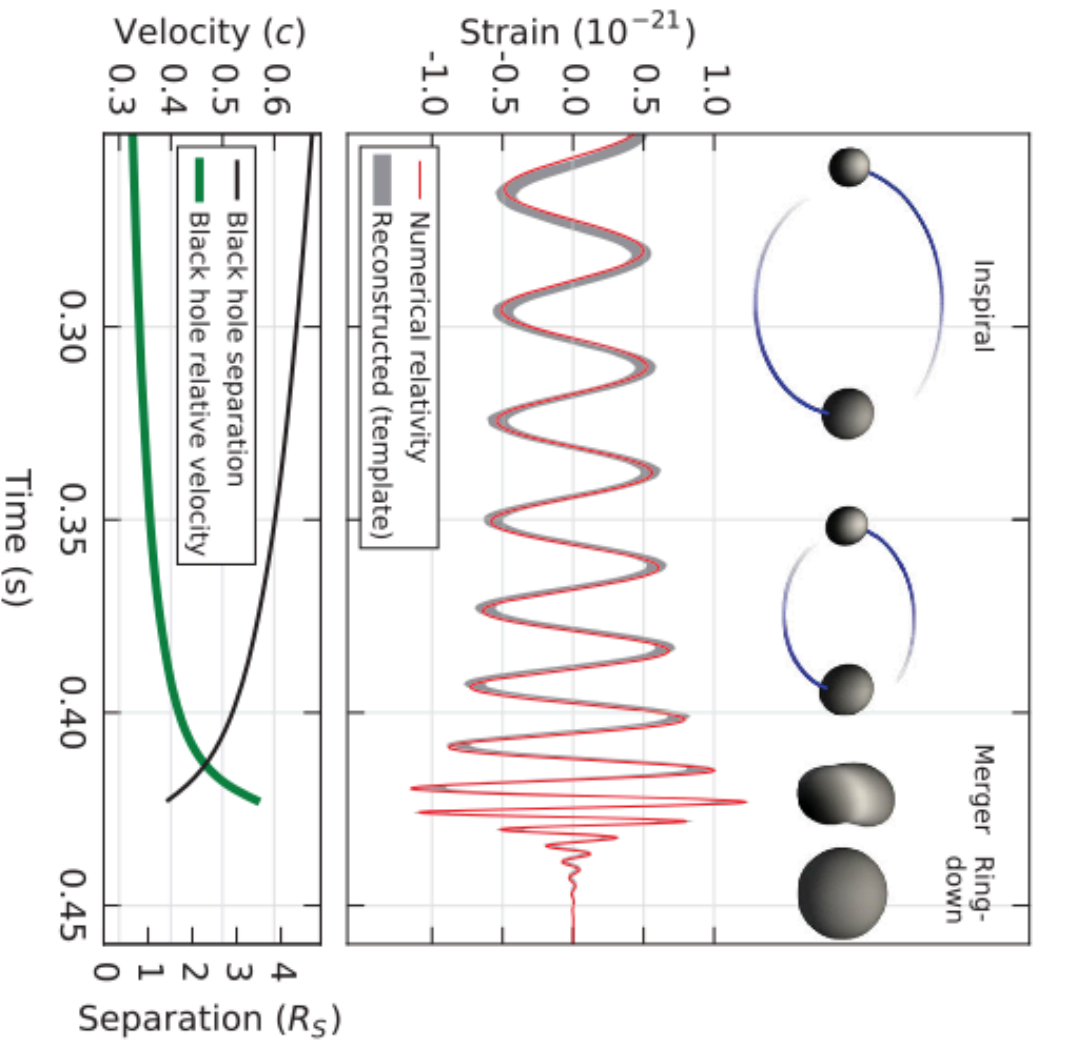
Interesting for
axion-like DM:

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

Interesting for
asymmetric DM:

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

How to detect ECO in a single GW event



Inspiral

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

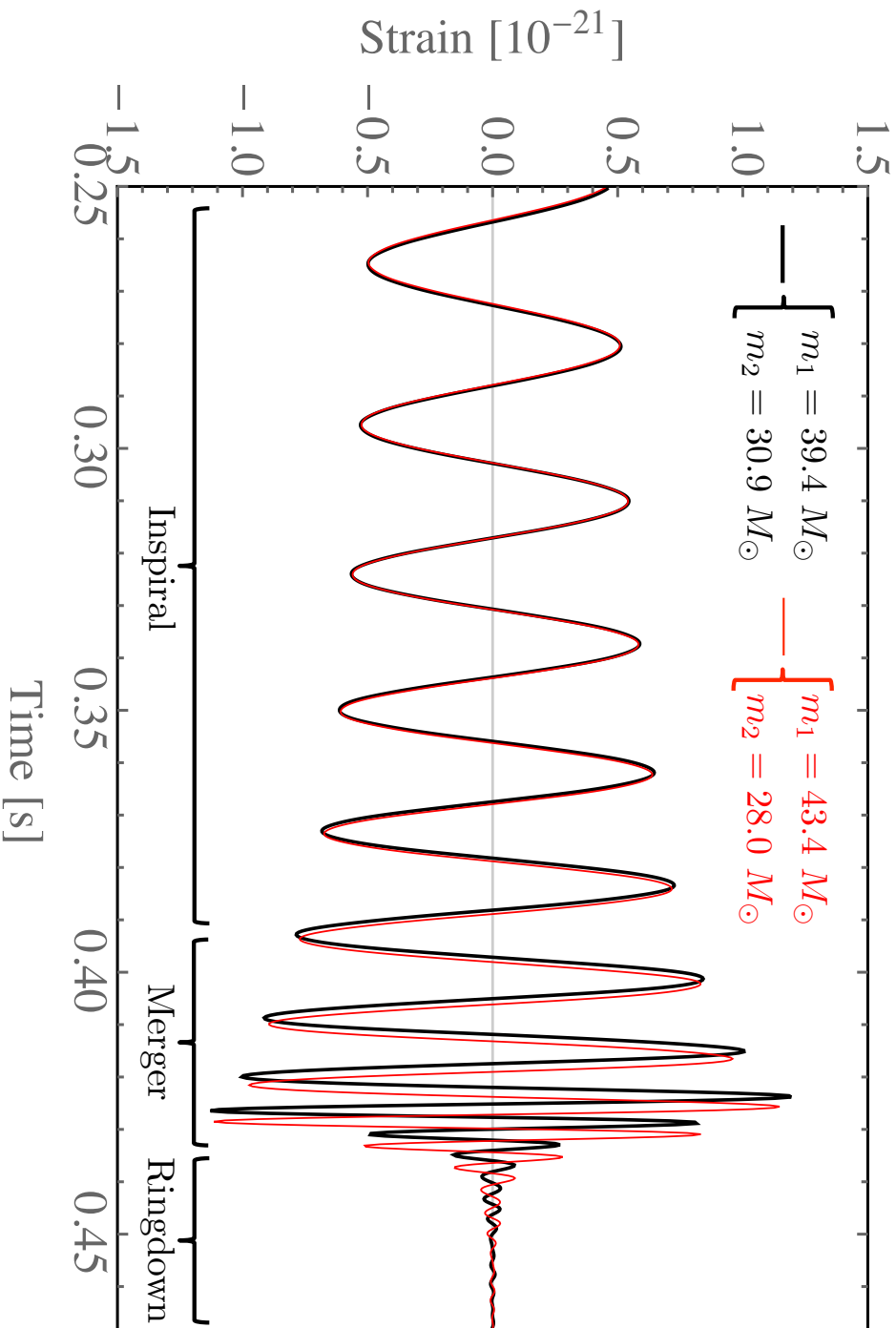
Ringdown

- 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	
Secondary black hole mass	
Final black hole mass	
Final black hole spin	
Luminosity distance	
Source redshift z	

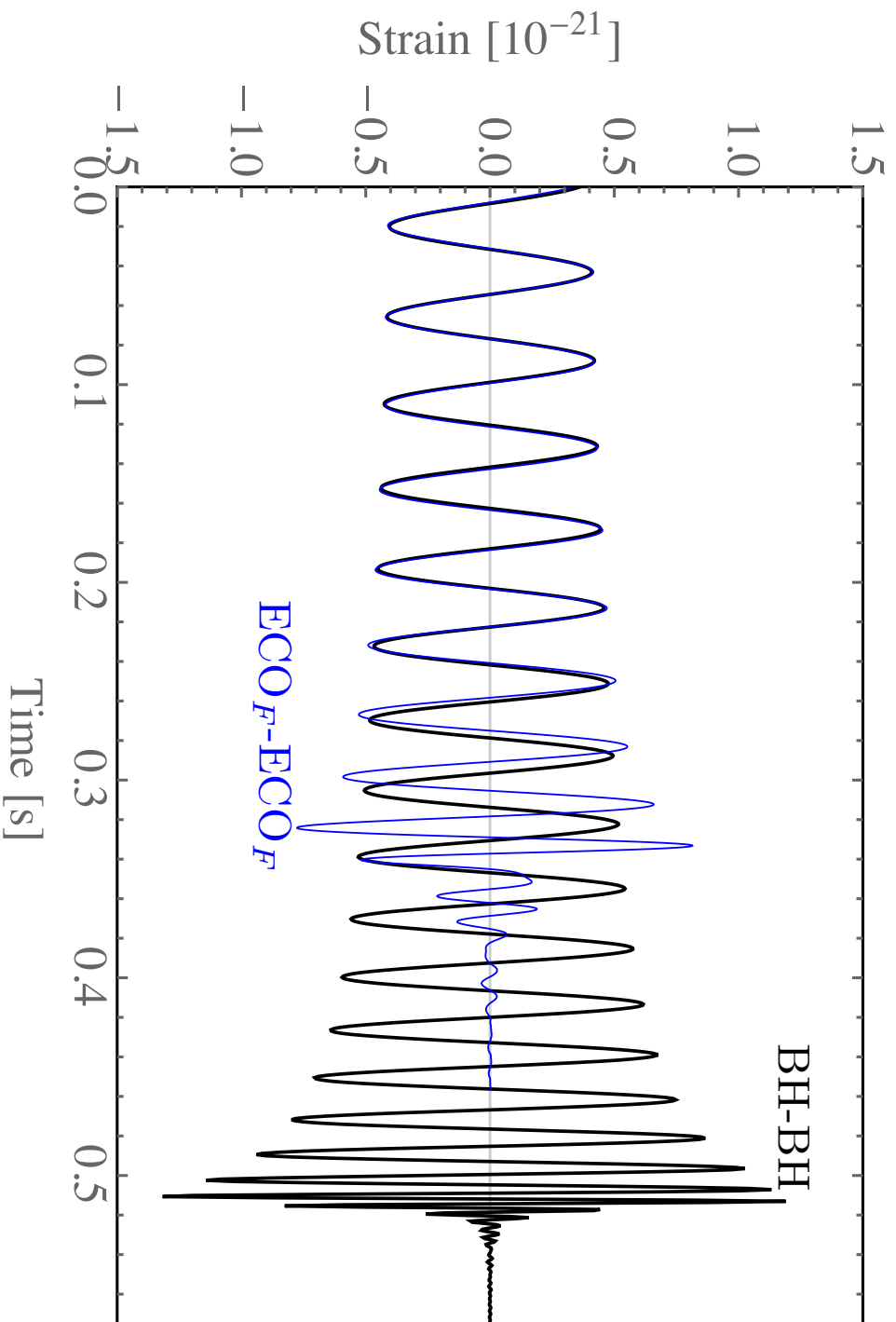
$36_{-4}^{+5} M_\odot$	
$29_{-4}^{+4} M_\odot$	
$62_{-4}^{+4} M_\odot$	
$0.67_{-0.07}^{+0.05}$	
410_{-180}^{+160} Mpc	
$0.09_{-0.04}^{+0.03}$	

From **inspiral**, we could learn about **C**

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

At innermost stable orbit

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



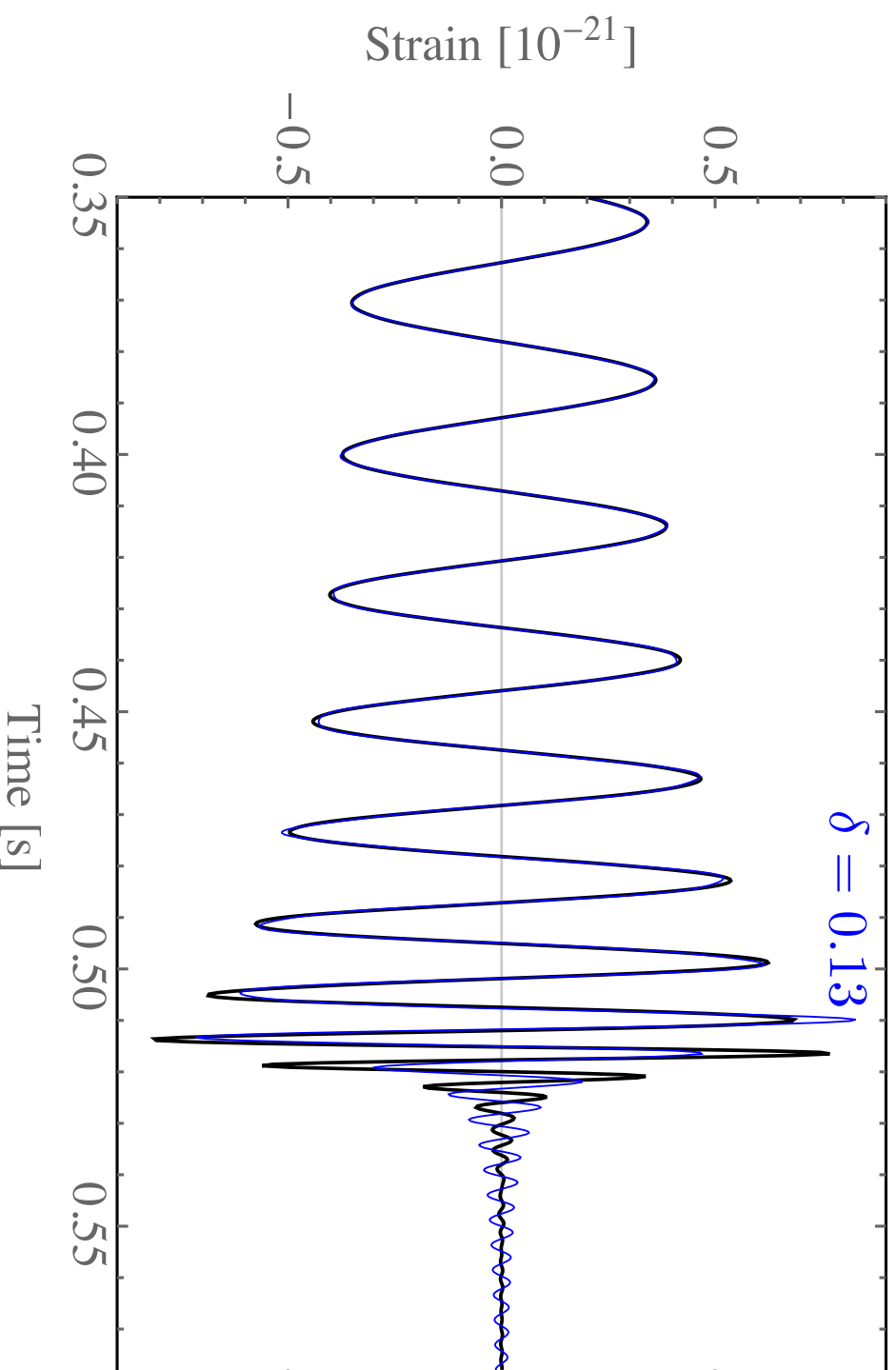
$$M_{BH} = M_{ECO} = 35 M_{\odot}$$

$$C_{BH} = 0.5$$

$$C_{ECO} = 0.16$$

Ringdown is sensitive to EOS and absence of horizon

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



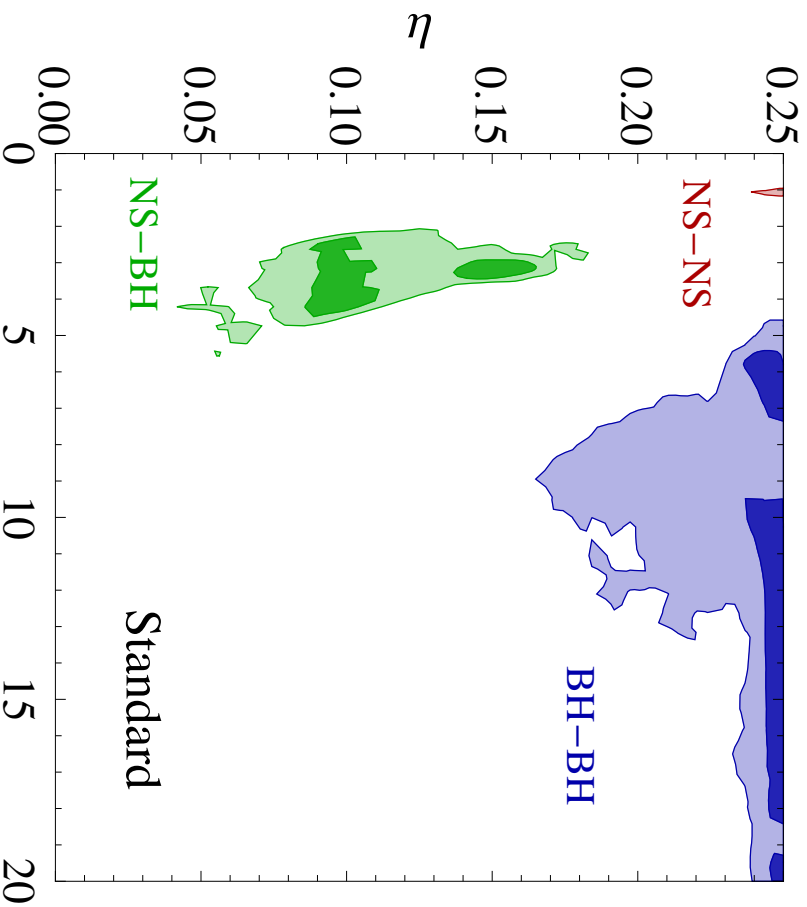
What can be learned from GW event distributions?

Conventional heavy objects:

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

Mass gap can be explained in stellar evolution models

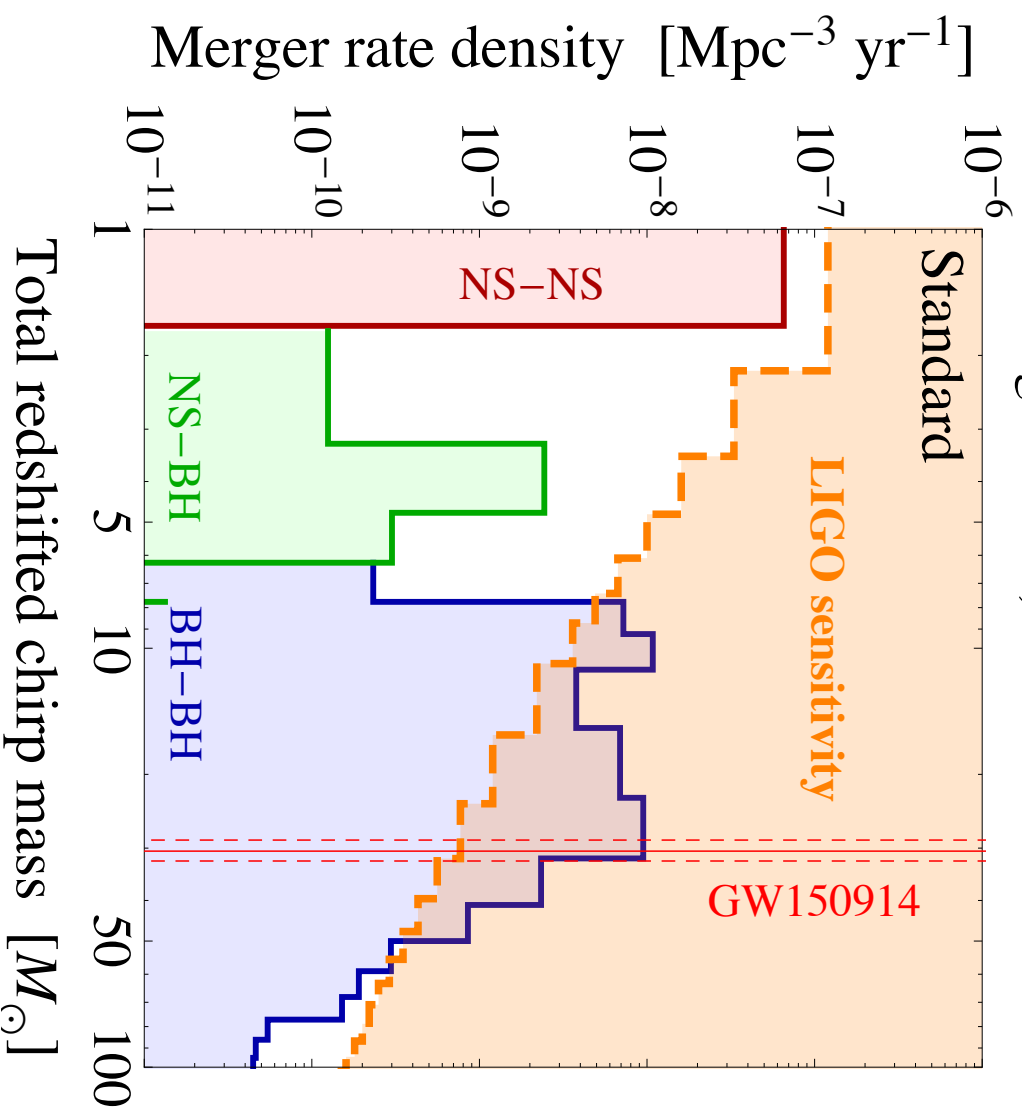
High-end Z, IMR PhenomC



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

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

High-end Z, IMR PhenomC



- 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 $\Rightarrow R$ decreases $\Rightarrow A$ decreases
Violation of the theorem?

Thermodynamics interpretation: BH temperature $T = M_{\text{p}}^2/M$

BH entropy $S = A/4$

Second law of thermodynamics \Rightarrow 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

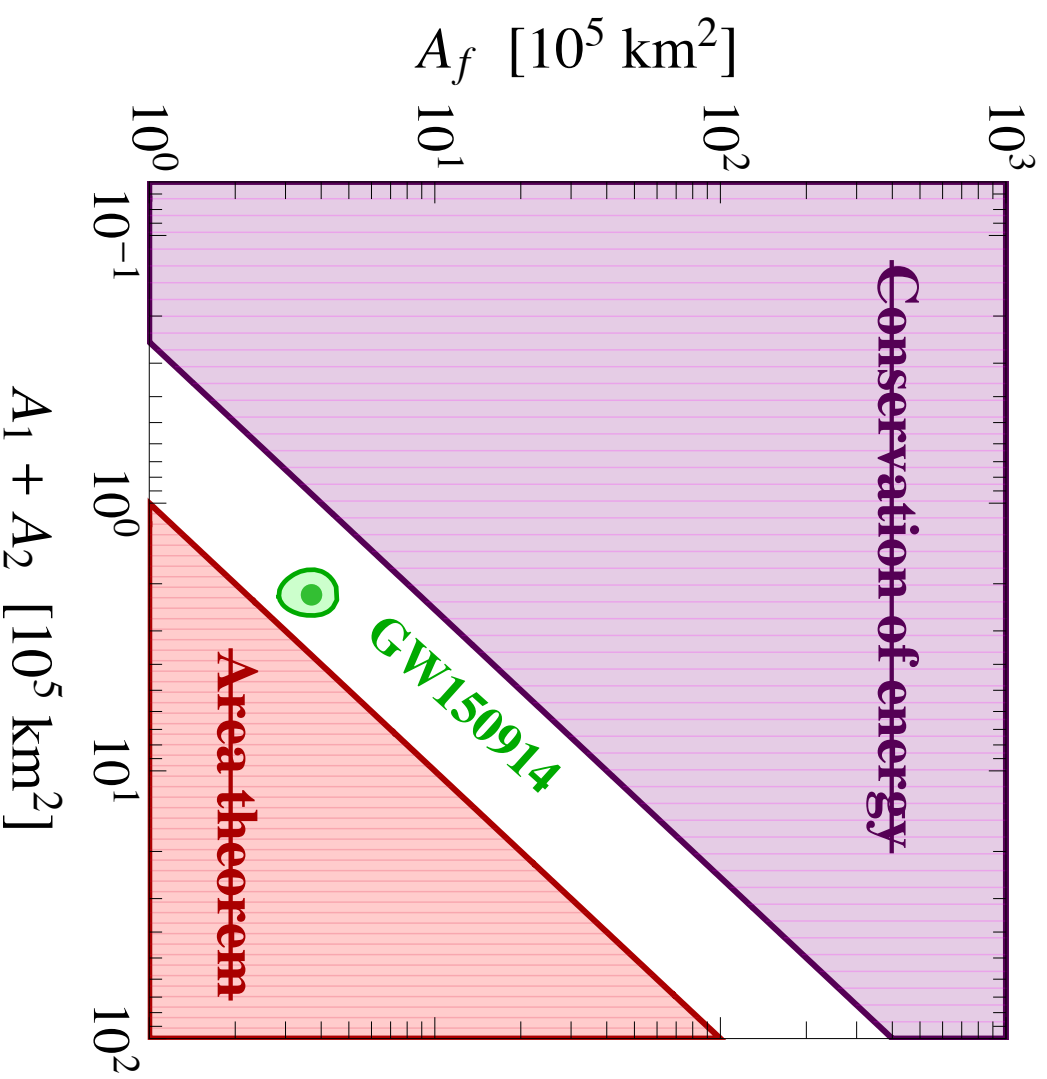
$$\text{For a Kerr BH: } A = 8\pi M^2 \left(1 + \sqrt{1 - a^2} \right) \quad a \equiv \frac{J}{M^2}$$

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

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

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