GW from a BSM perspective

Alfredo Urbano
CERN

From quarks to gravitational waves: Neutron stars as a laboratory for fundamental physics

Introduction

Introduction

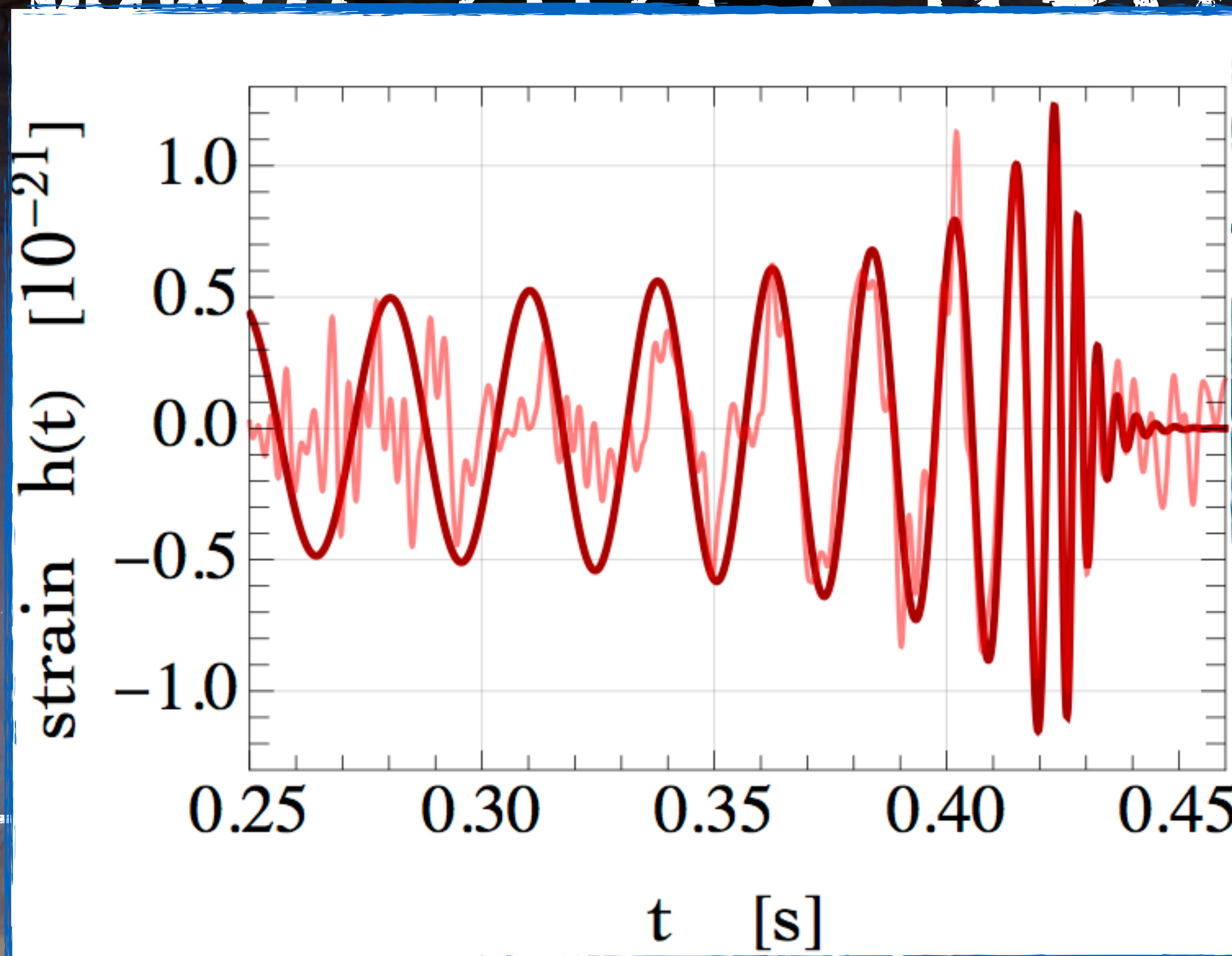
"The real voyage of discovery consists not in seeking new landscapes,
but in having new eyes"

Marcel Proust

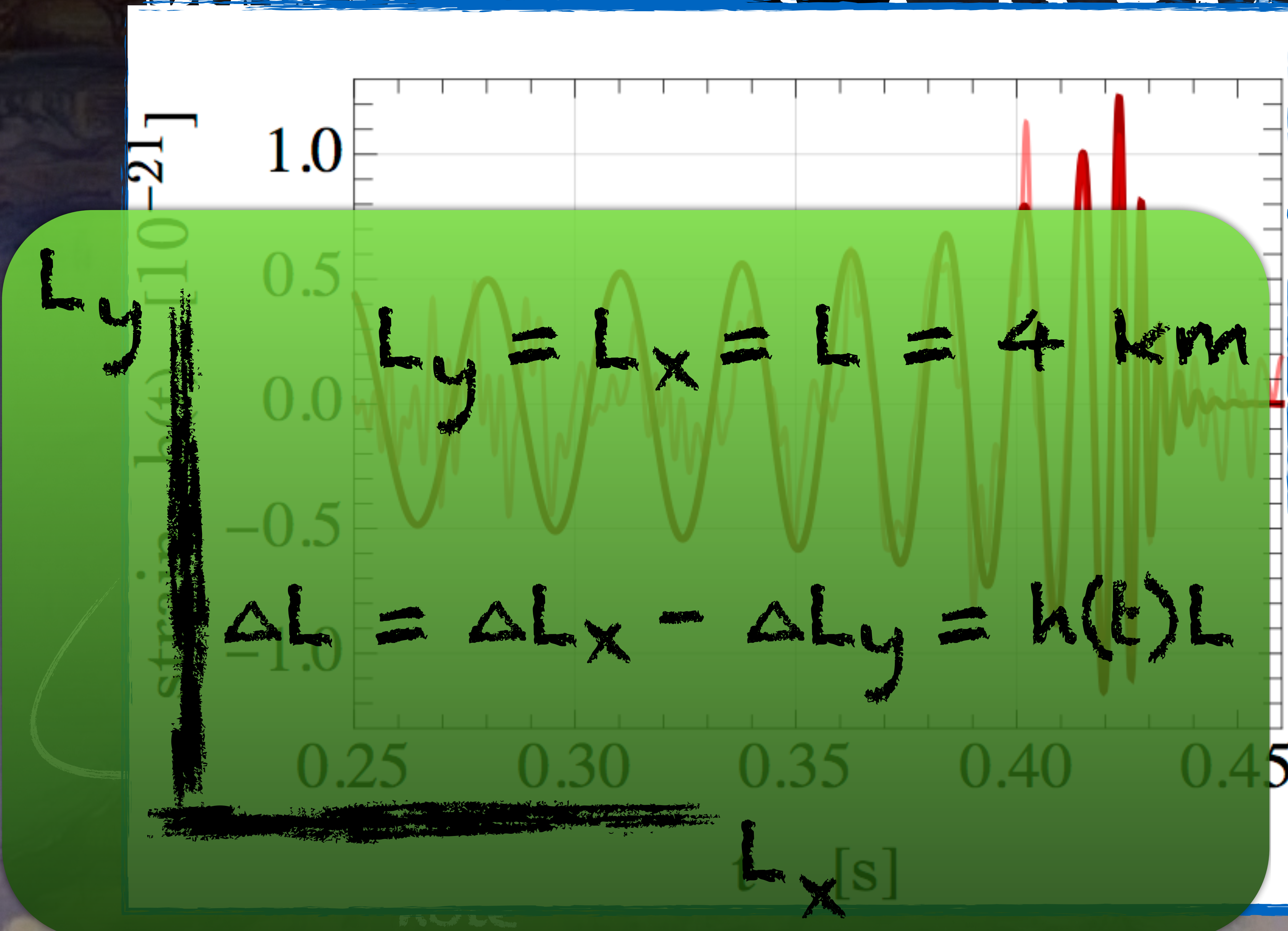
What did LIGO detect ?

What did LIGO detect ?

The GW signal emitted in the merger of compact objects with mass in the range of 10's solar masses and compactness comparable to a black hole


strain h(t) [10^−21]
1.0
0.5
0.0
−0.5
−1.0
0.25
0.30
0.35
0.40
0.45
t [s]

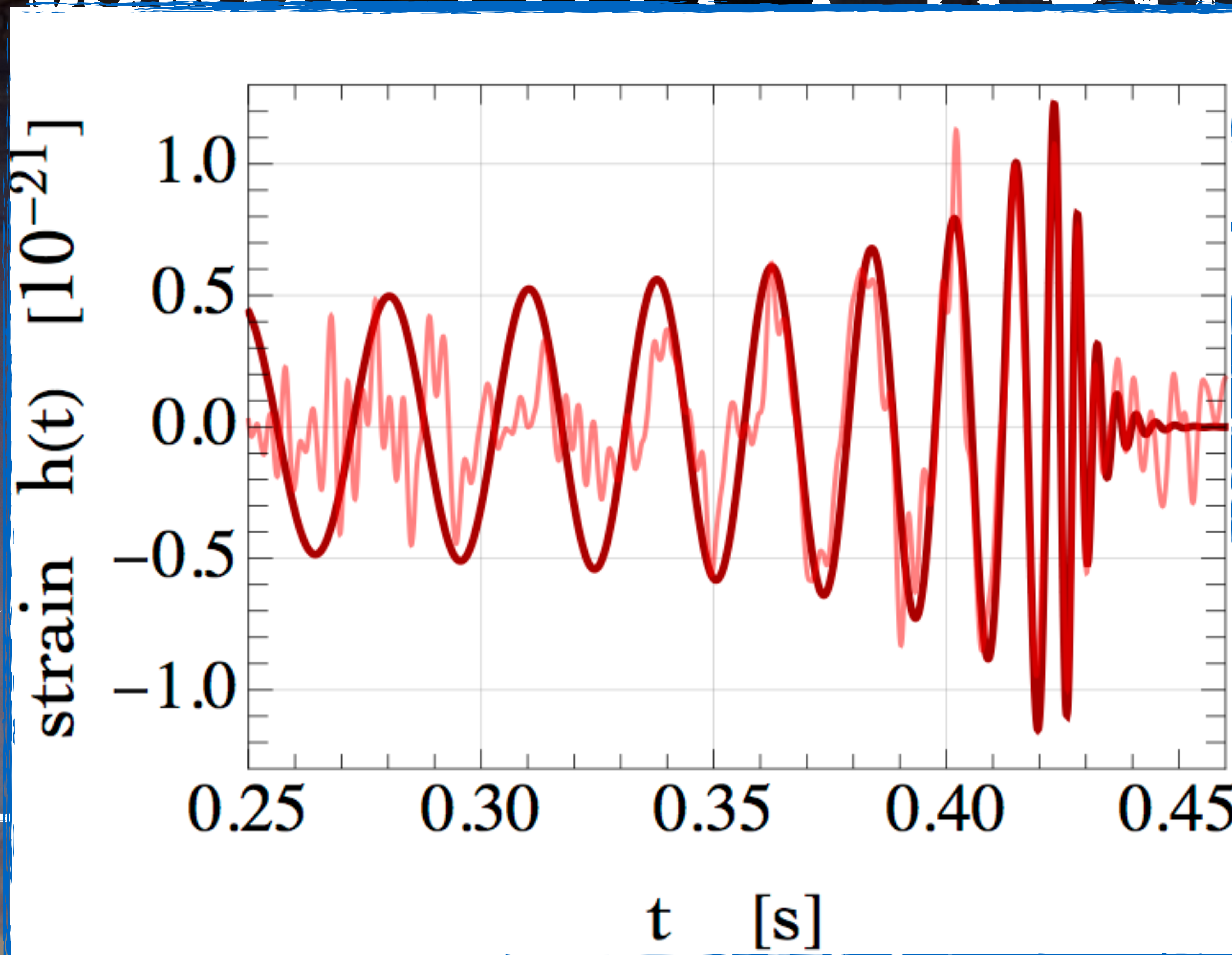
What did LIGO



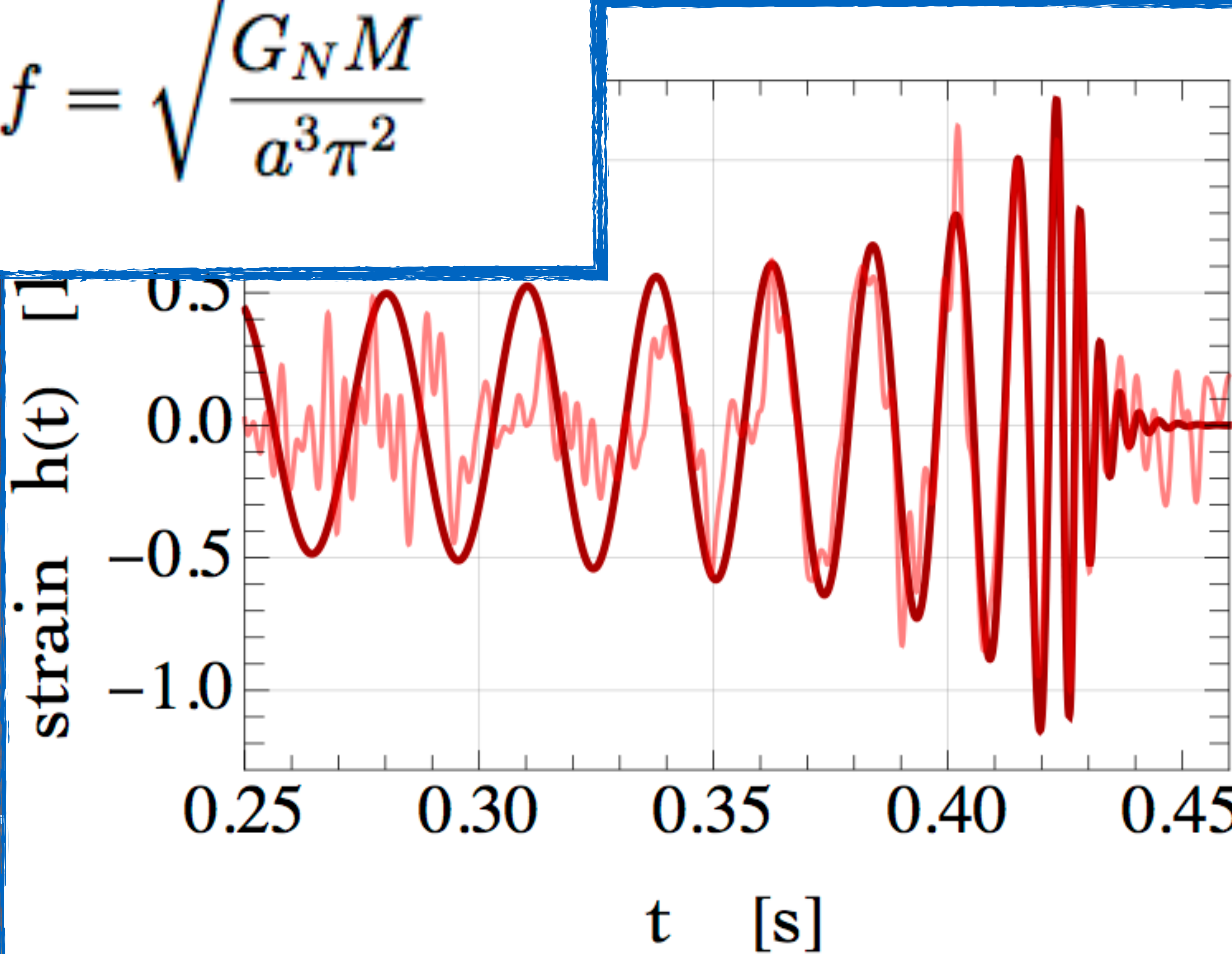
$$L_y = L_x = L = 4\ \text{km}$$

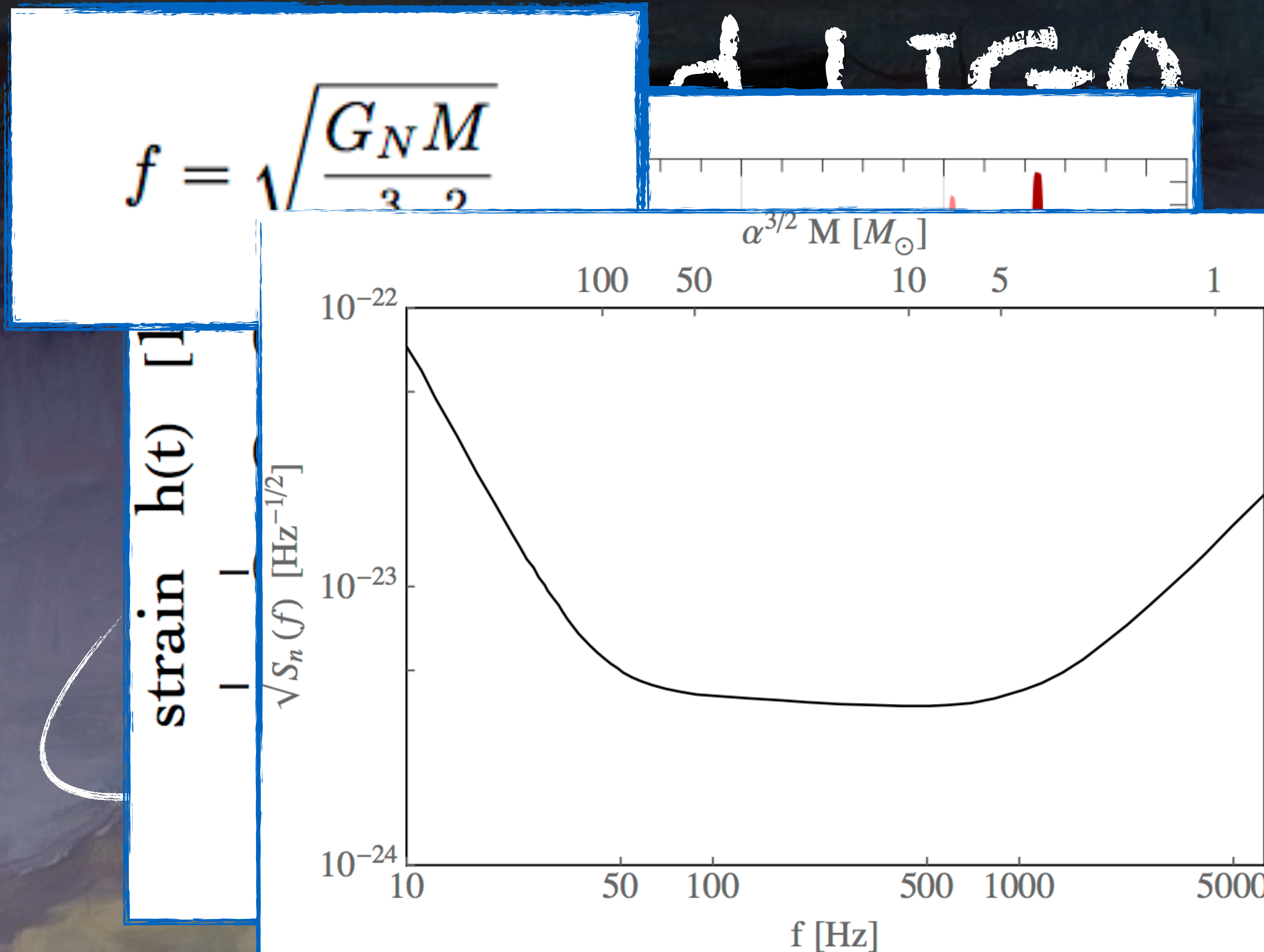
$$\Delta L = \Delta L_x - \Delta L_y = h(t)L$$

What did LIGO



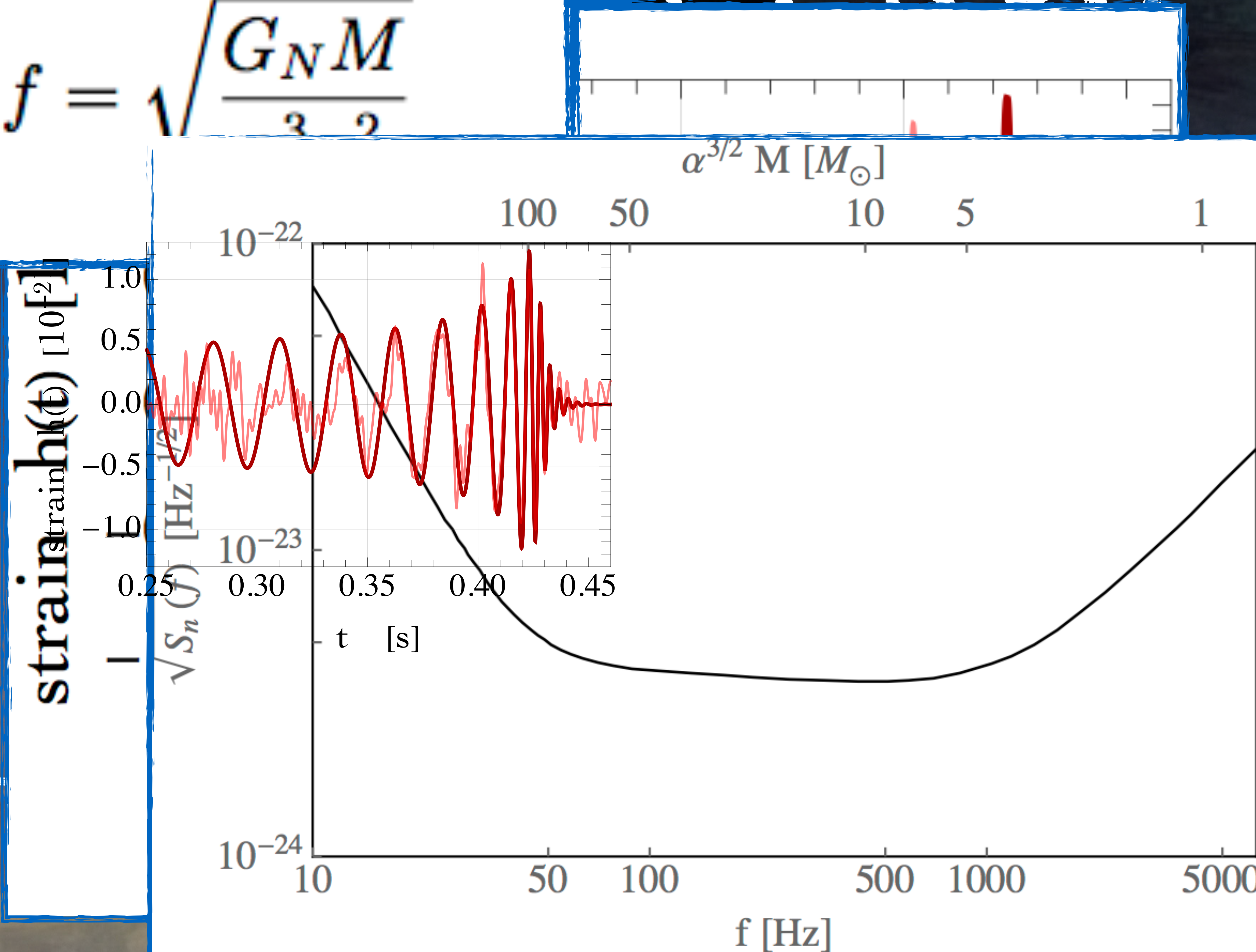
$$f = \sqrt{\frac{G_N M}{a^3 \pi^2}}$$

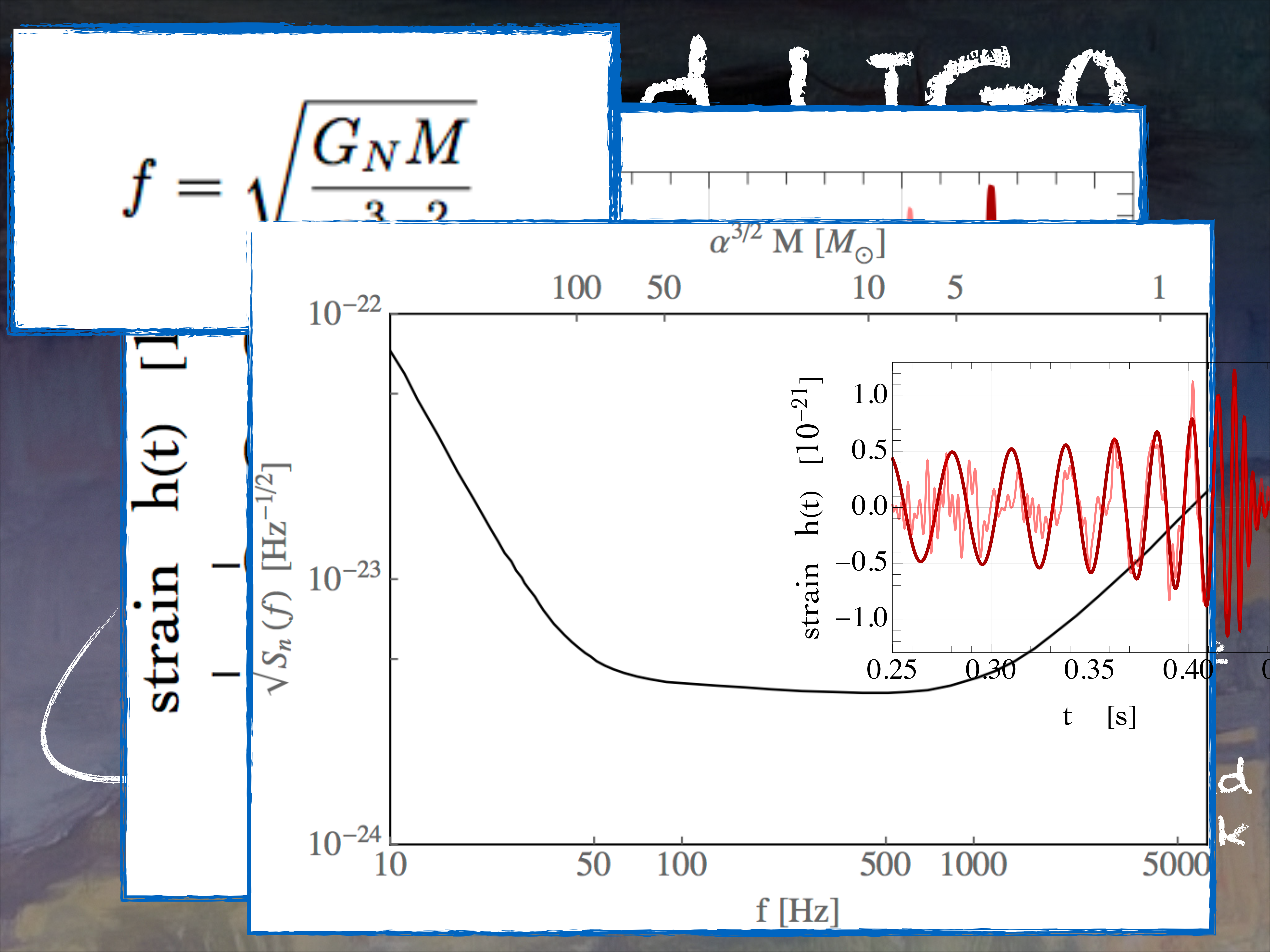




$f = \sqrt{\frac{G_N M}{\ldots}}$
strain h(t) [
$\alpha^{3/2}$ M [$M_\odot$]
100
50
10
5
1
10^{-22}
10^{-23}
10^{-24}
$\sqrt{S_n}(f)$ [$Hz^{-1/2}$]
10
50
100
500
1000
5000
f [Hz]

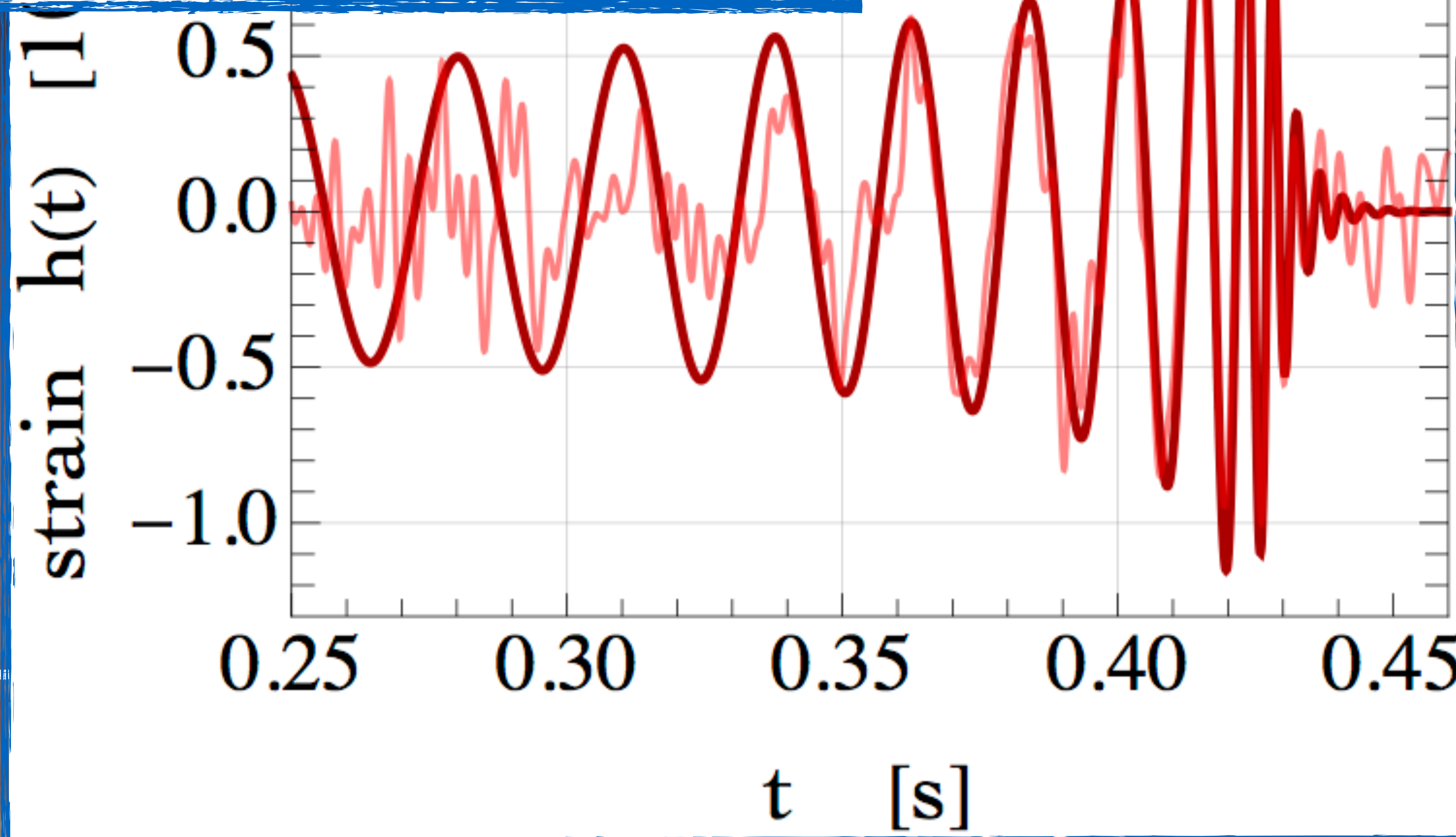
$$f = \sqrt{\frac{G_N M}{\ldots}}$$





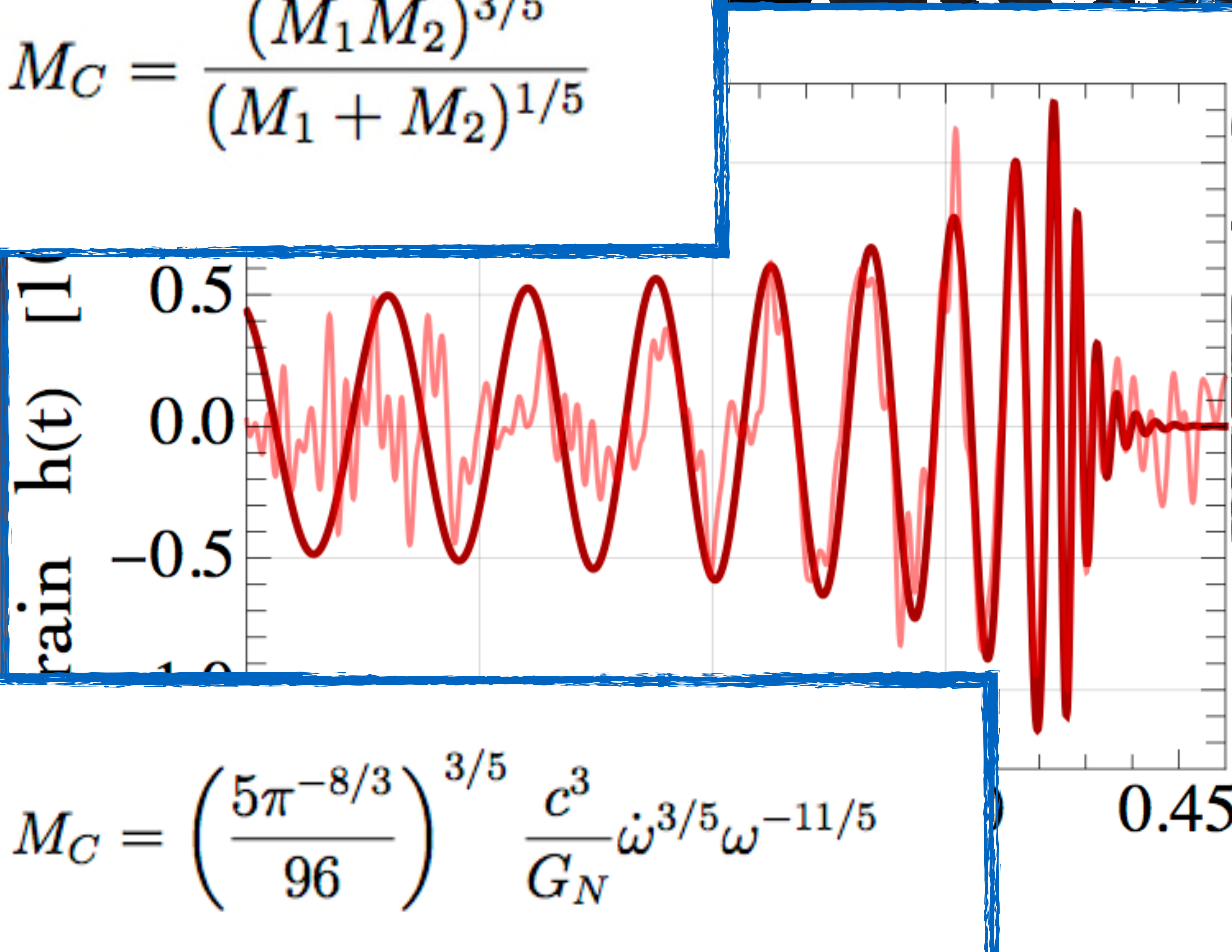
$f = \sqrt{\frac{G_N M}{\ldots}}$
strain h(t) [1
α^{3/2} M [M_⊙]
100 50 10 5 1
10^{-22}
10^{-23}
10^{-24}
√S_n(f) [Hz^{-1/2}]
10 50 100 500 1000 5000
f [Hz]
strain h(t) [10^{-21}]
1.0 0.5 0.0 −0.5 −1.0
0.25 0.30 0.35 0.40
t [s]

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



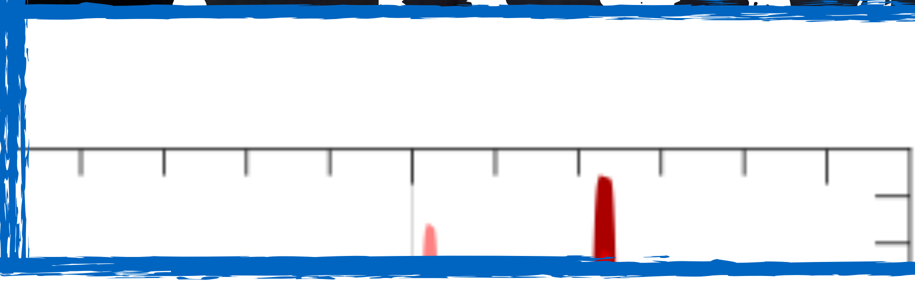
LIGO

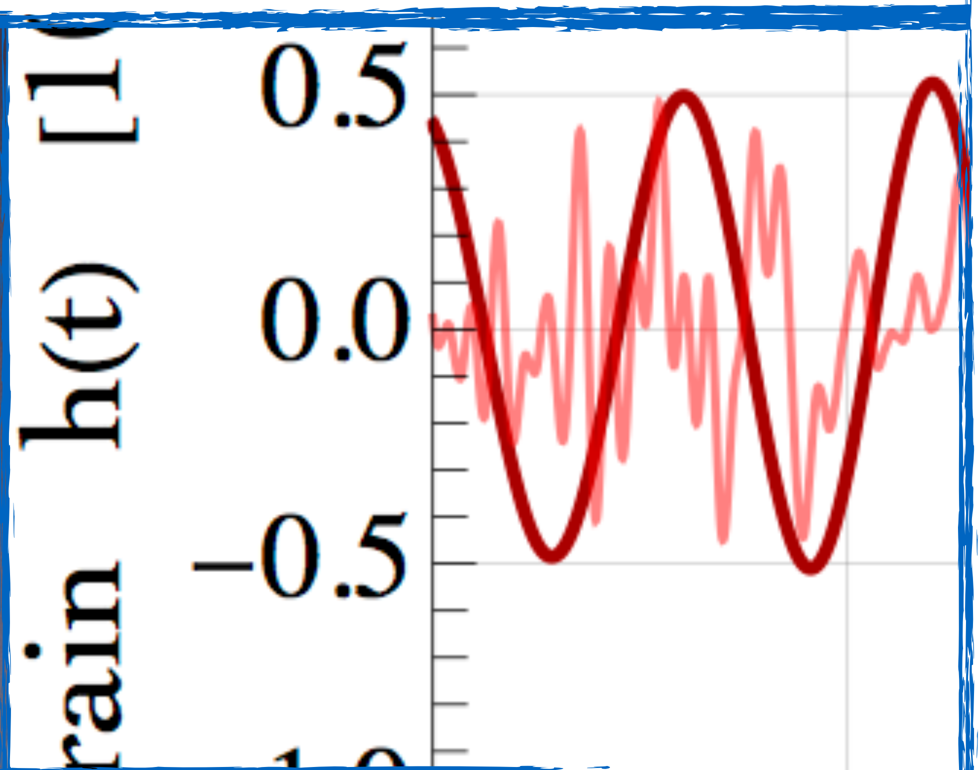
$$M_C = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

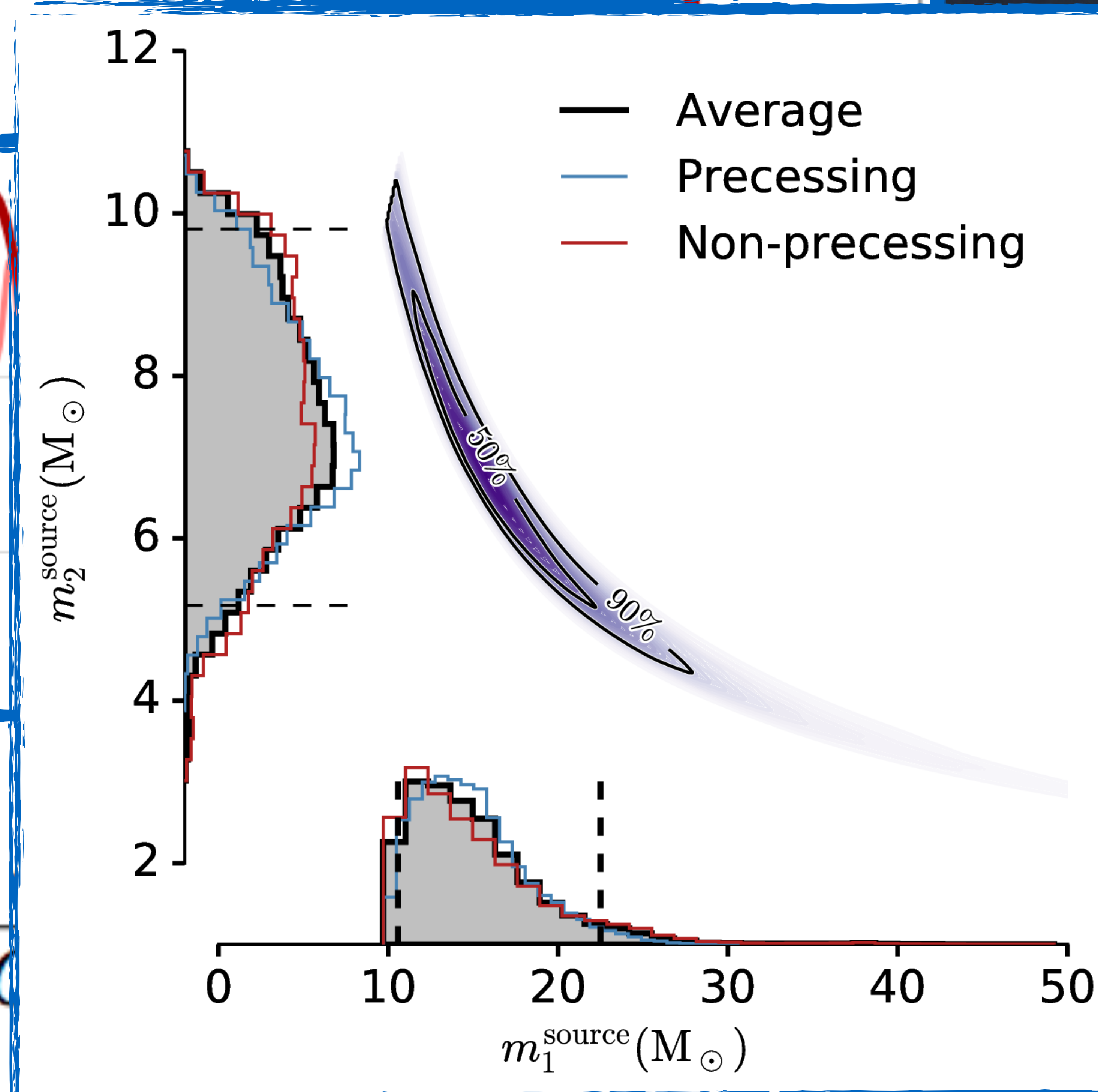


$$M_C = \left(\frac{5\pi^{-8/3}}{96}\right)^{3/5} \frac{c^3}{G_N} \dot{\omega}^{3/5} \omega^{-11/5}$$

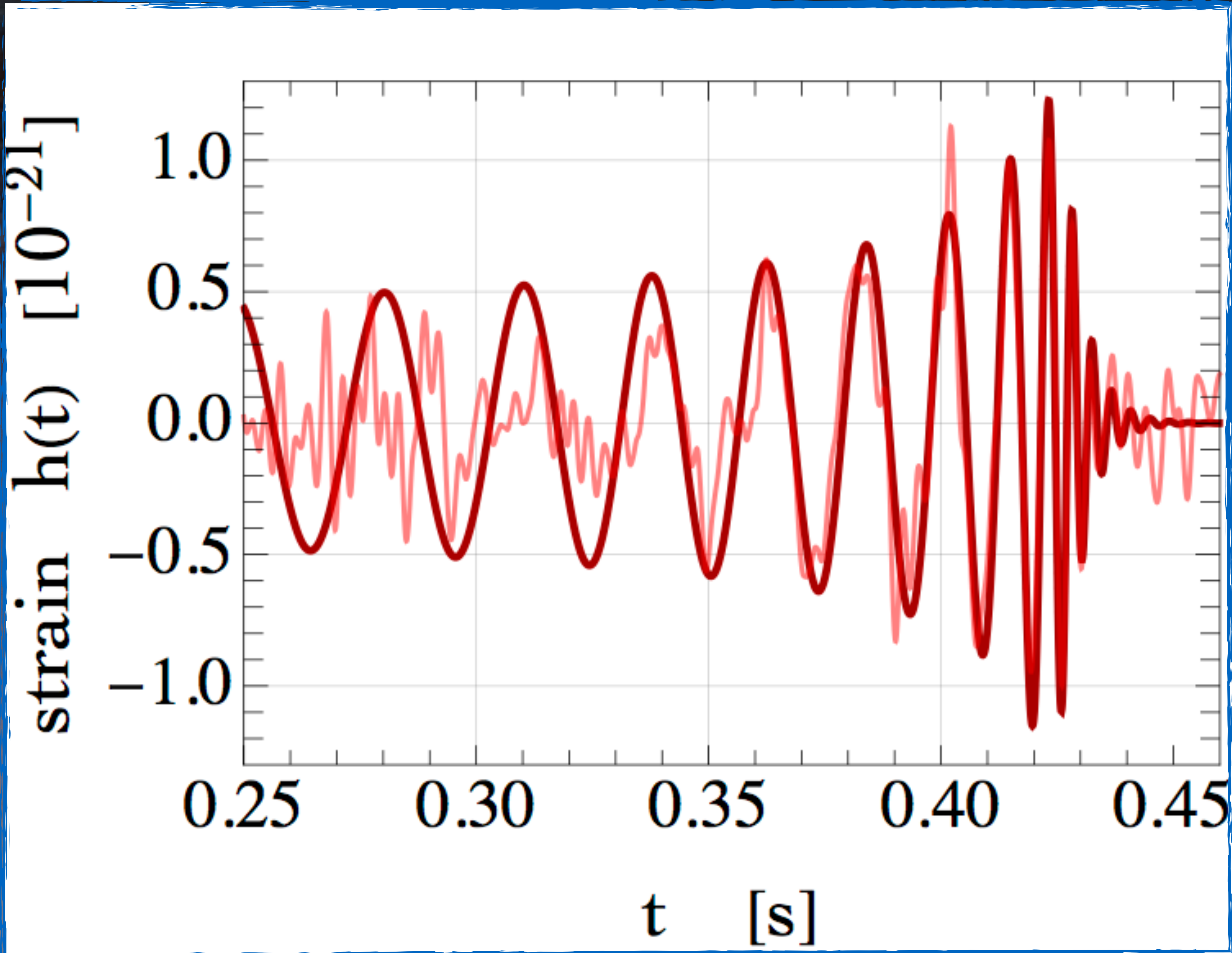
$$M_C = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$



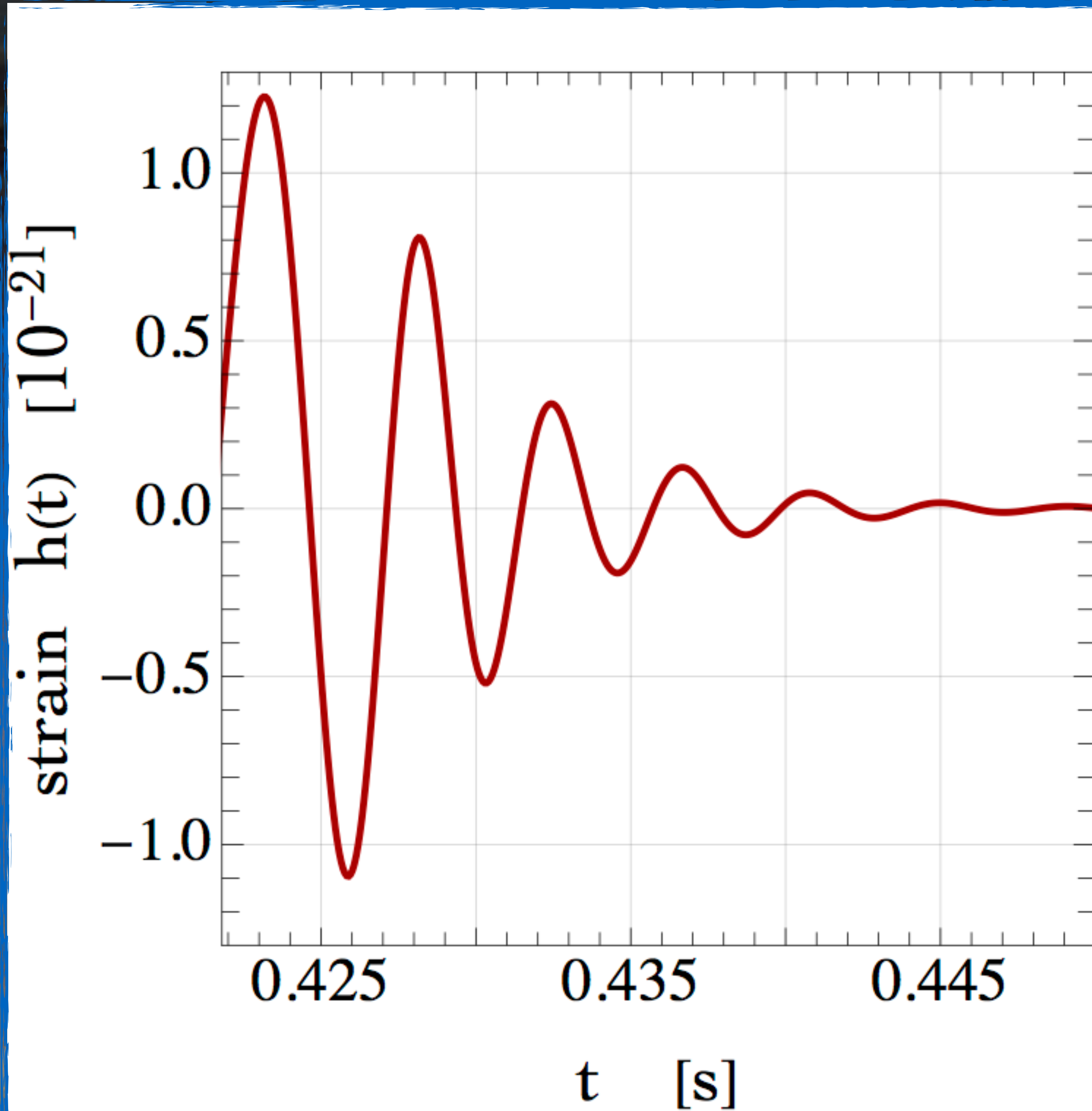




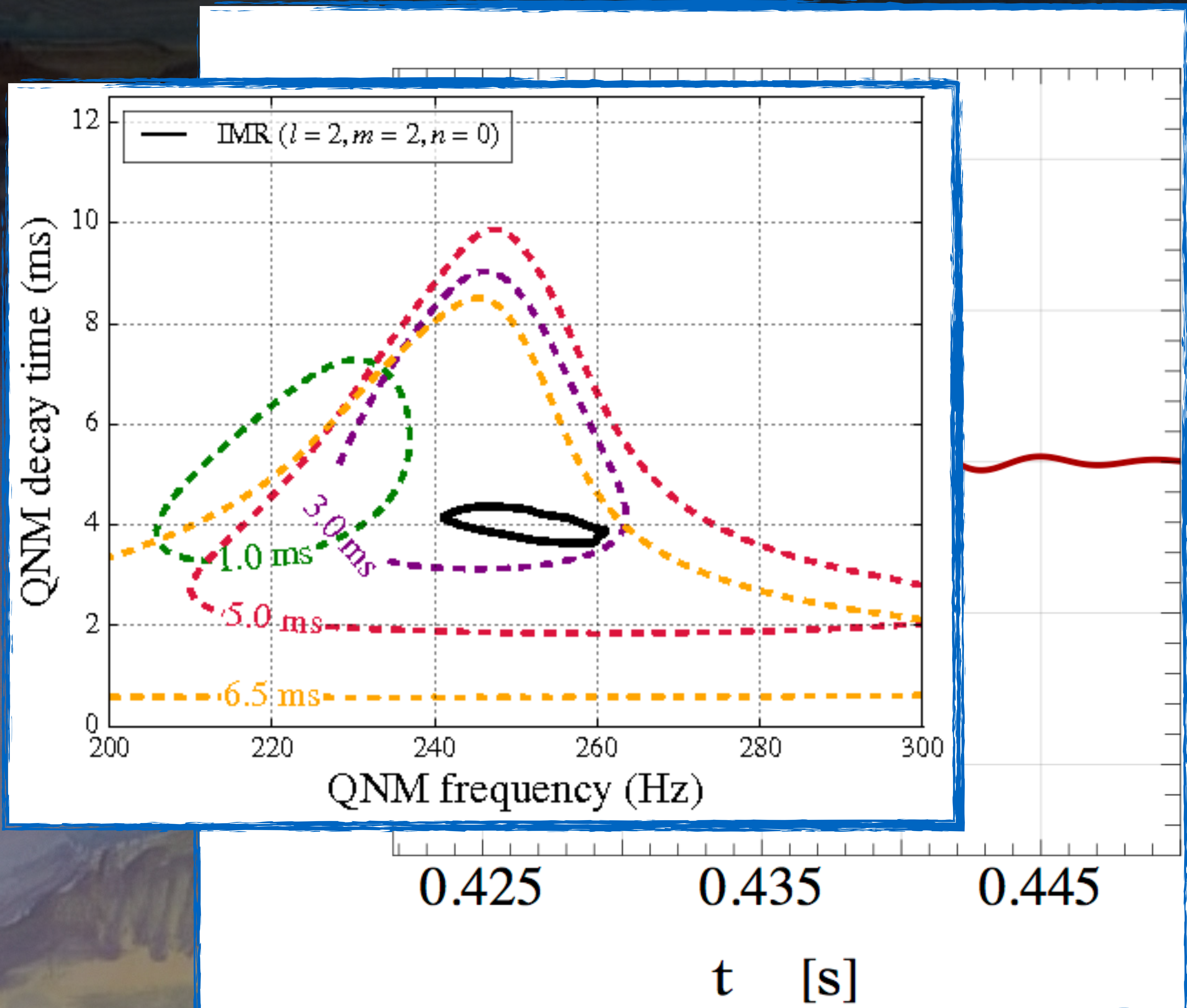
$$M_C = \left(\frac{5\pi^{-8/3}}{96}\right)^{3/5}$$

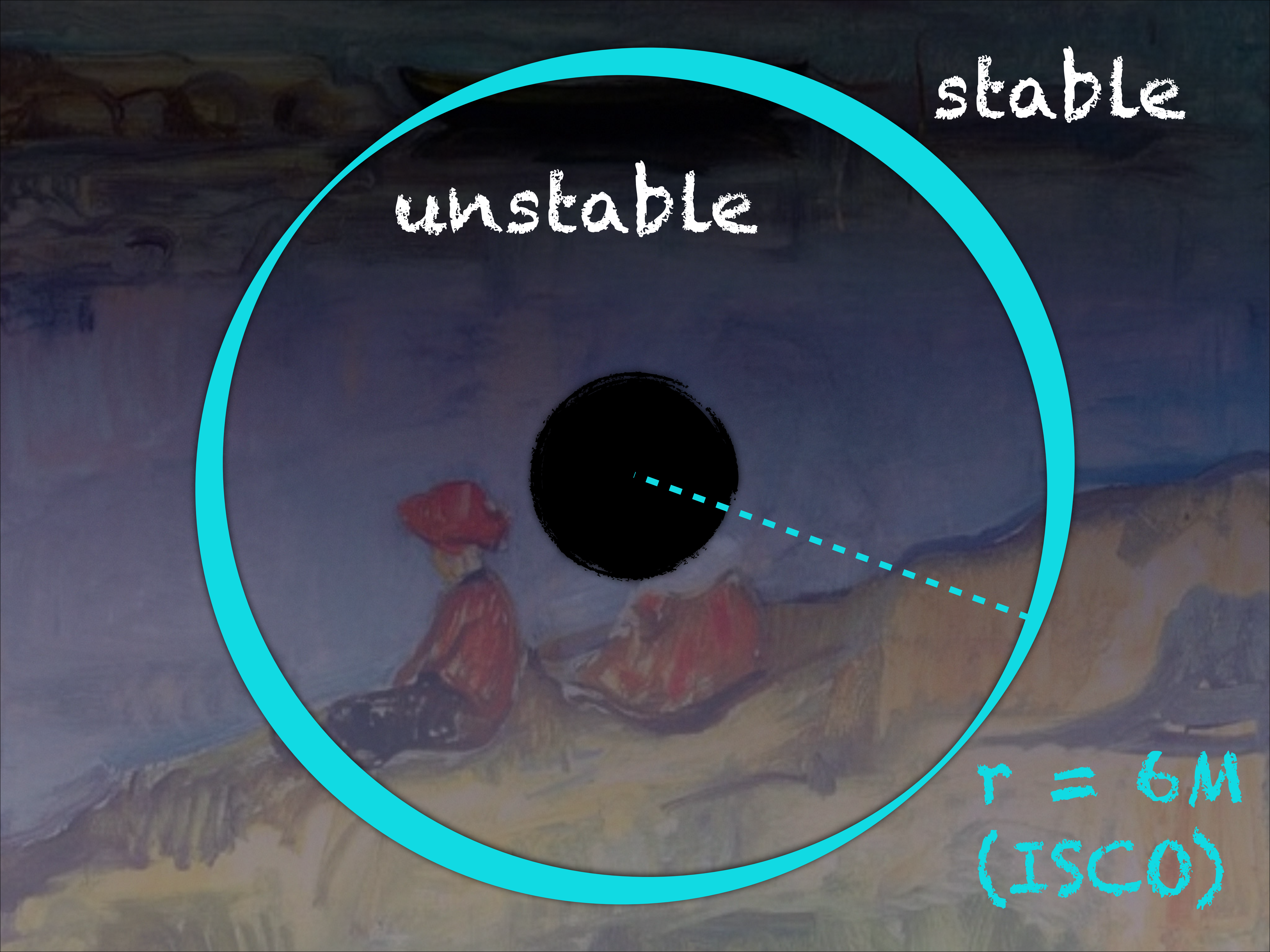


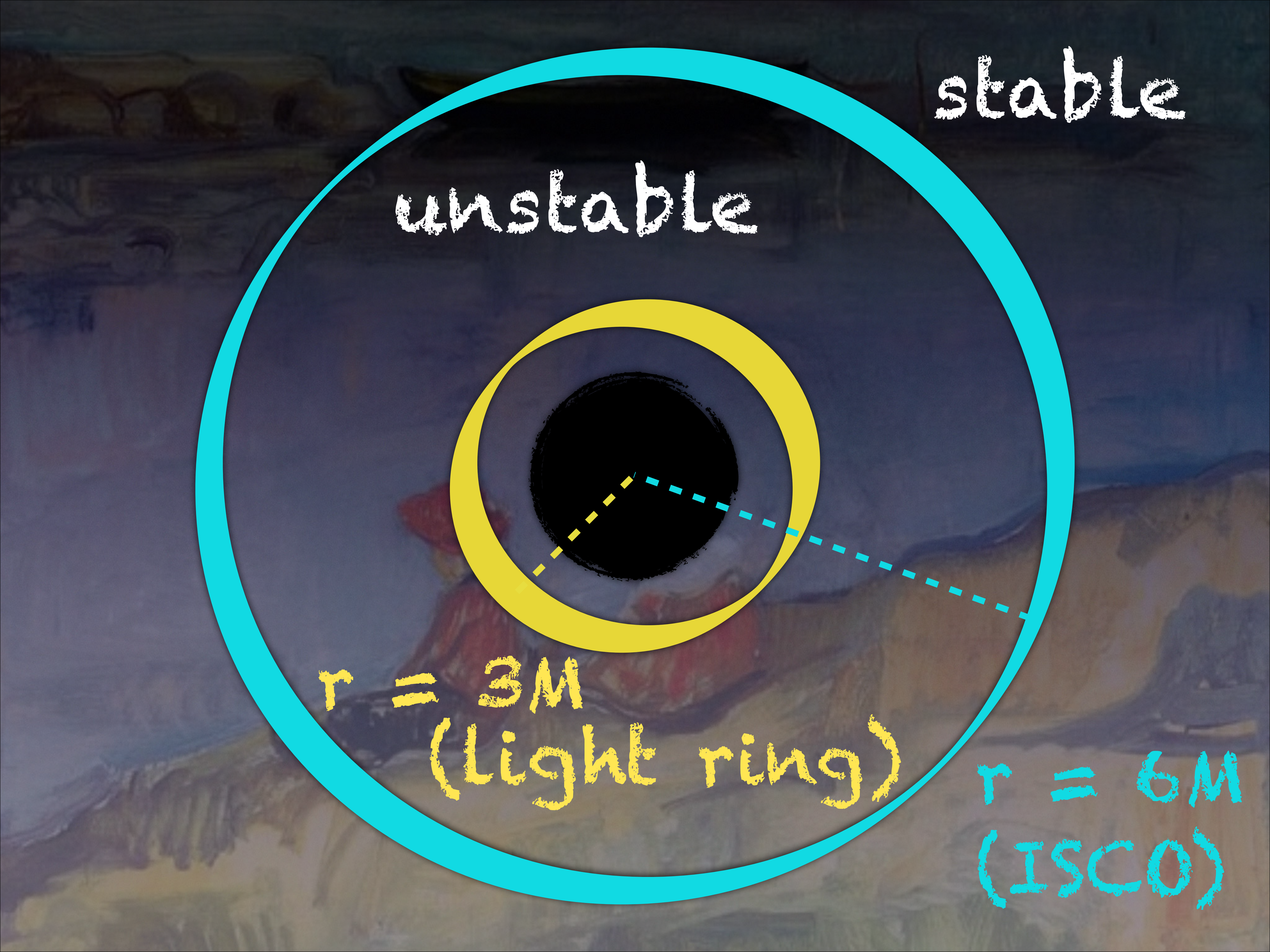
strain h(t) [10⁻²¹]
1.0
0.5
0.0
−0.5
−1.0
0.25
0.30
0.35
0.40
0.45
t [s]



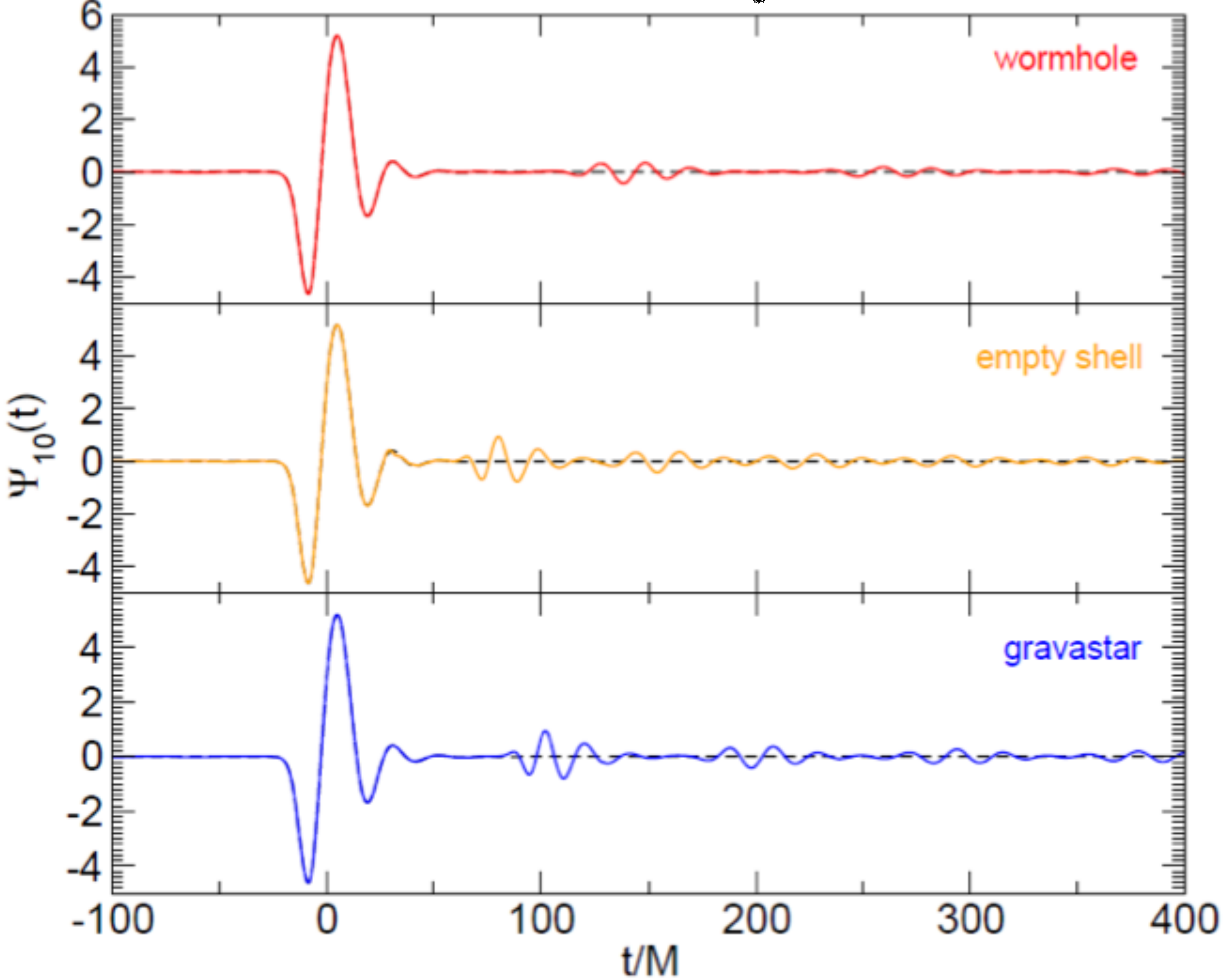
1.0
0.5
0.0
−0.5
−1.0
strain h(t) [10−21]
0.425
0.435
0.445
t [s]


IMR ($l = 2, m = 2, n = 0$)
QNM decay time (ms)
QNM frequency (Hz)
1.0 ms
3.0 ms
5.0 ms
6.5 ms
0
2
4
6
8
10
12
200
220
240
260
280
300
0.425
0.435
0.445
t [s]

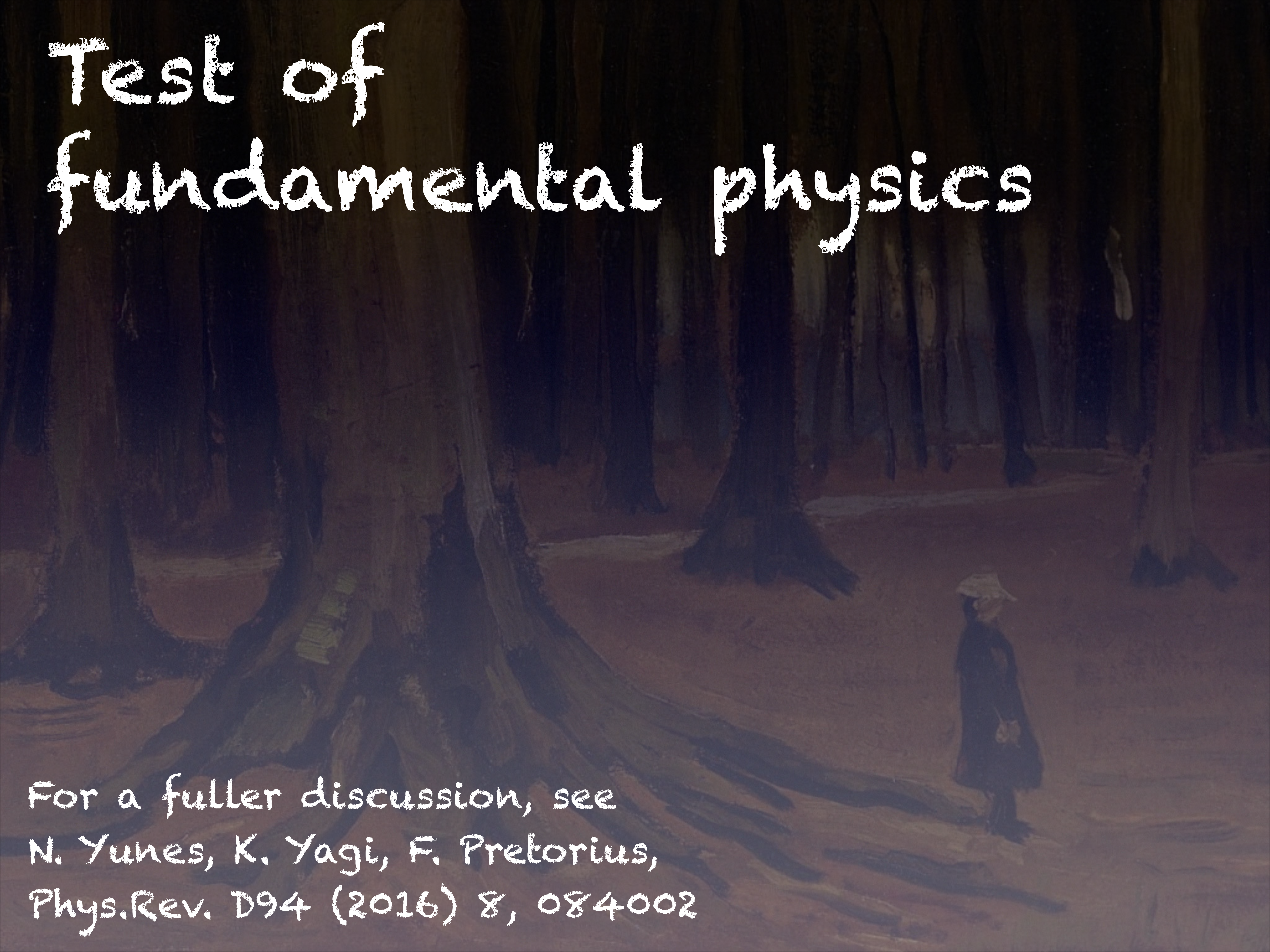

stable
unstable
r = 6M
(ISCO)


stable
unstable
r = 3M
(Light ring)
r = 6M
(ISCO)

V. Cardoso, E. Franzin, P.Pani, Phys.Rev.Lett. 116 (2016)



Test of fundamental physics



For a fuller discussion, see
N. Yunes, K. Yagi, F. Pretorius,
Phys.Rev. D94 (2016) 8, 084002

Test of fundamental physics

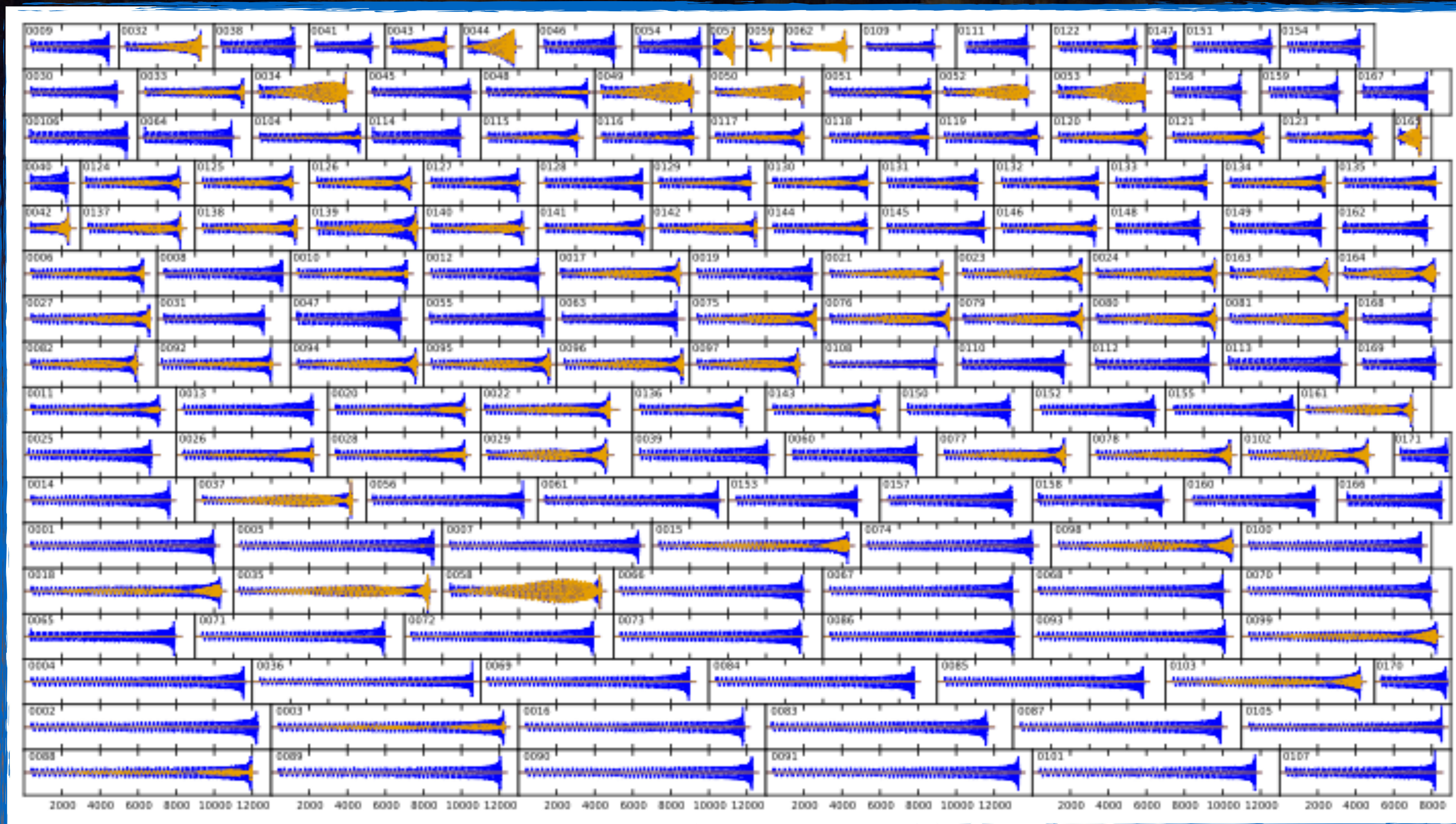
* Production mechanism

* Propagation mechanism

* Production mechanism

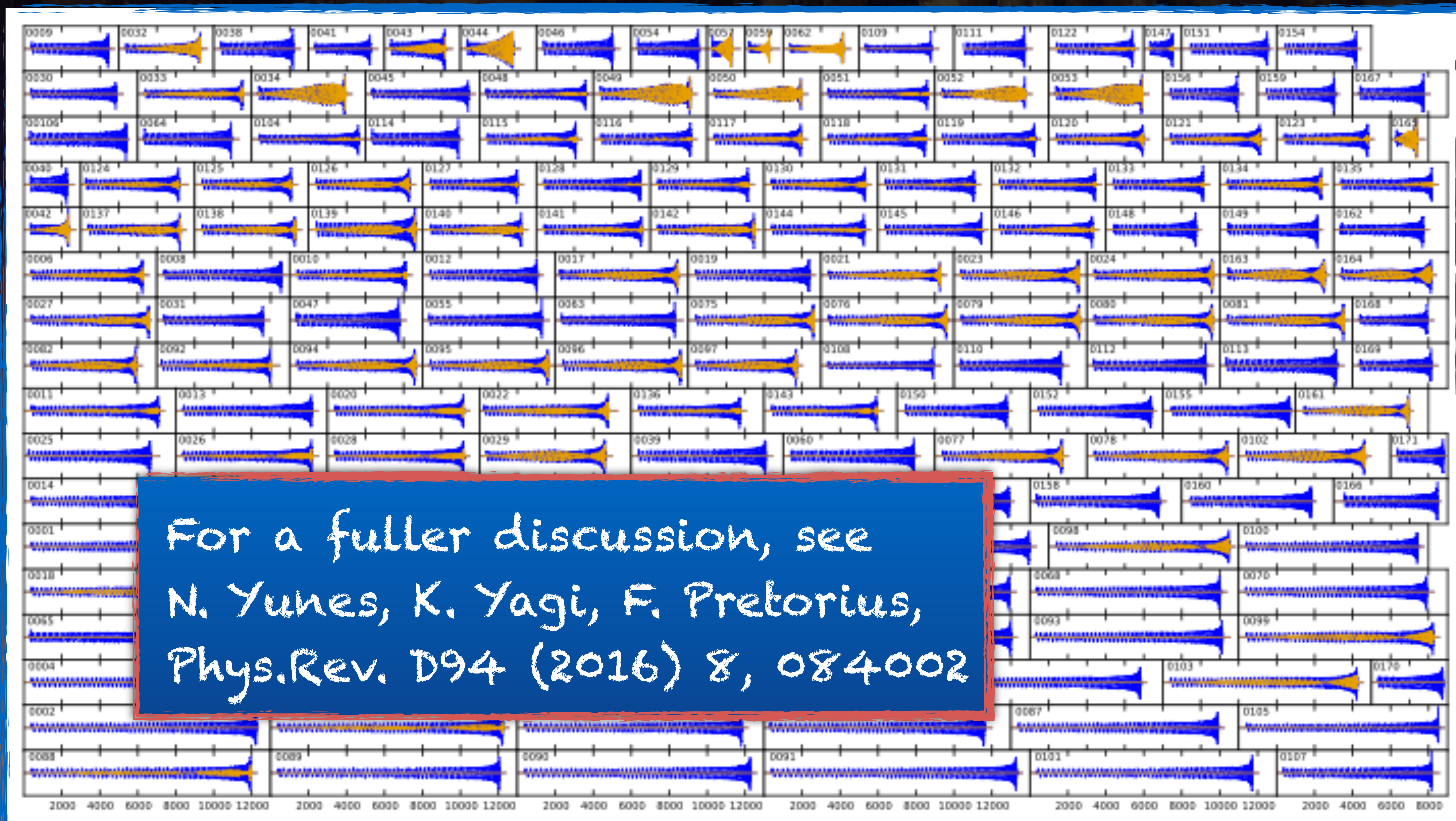
* Production mechanism

https://www.black-holes.org/waveforms/



* Production mechanism

https://www.black-holes.org/waveforms/



For a fuller discussion, see
N. Yunes, K. Yagi, F. Pretorius,
Phys.Rev. D94 (2016) 8, 084002

* Propagation mechanism

* Propagation mechanism

$$\omega^2 = m_g^2 + c_g^2 k^2$$

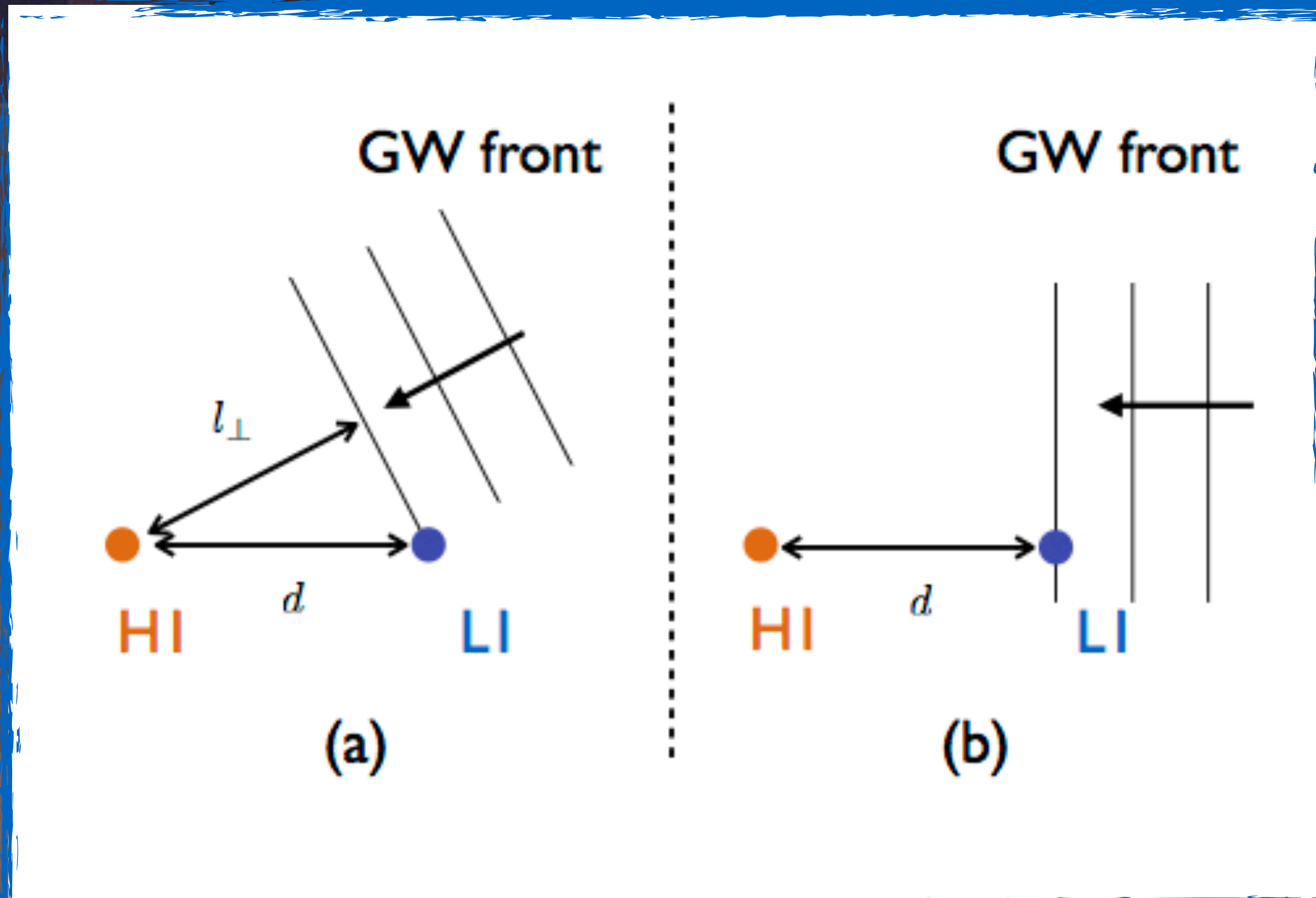
$m_g < 1.2 \times 10^{-22}$ eV

Phys.Rev.Lett. 116 (2016) no.22, 221101

* Propagation mechanism

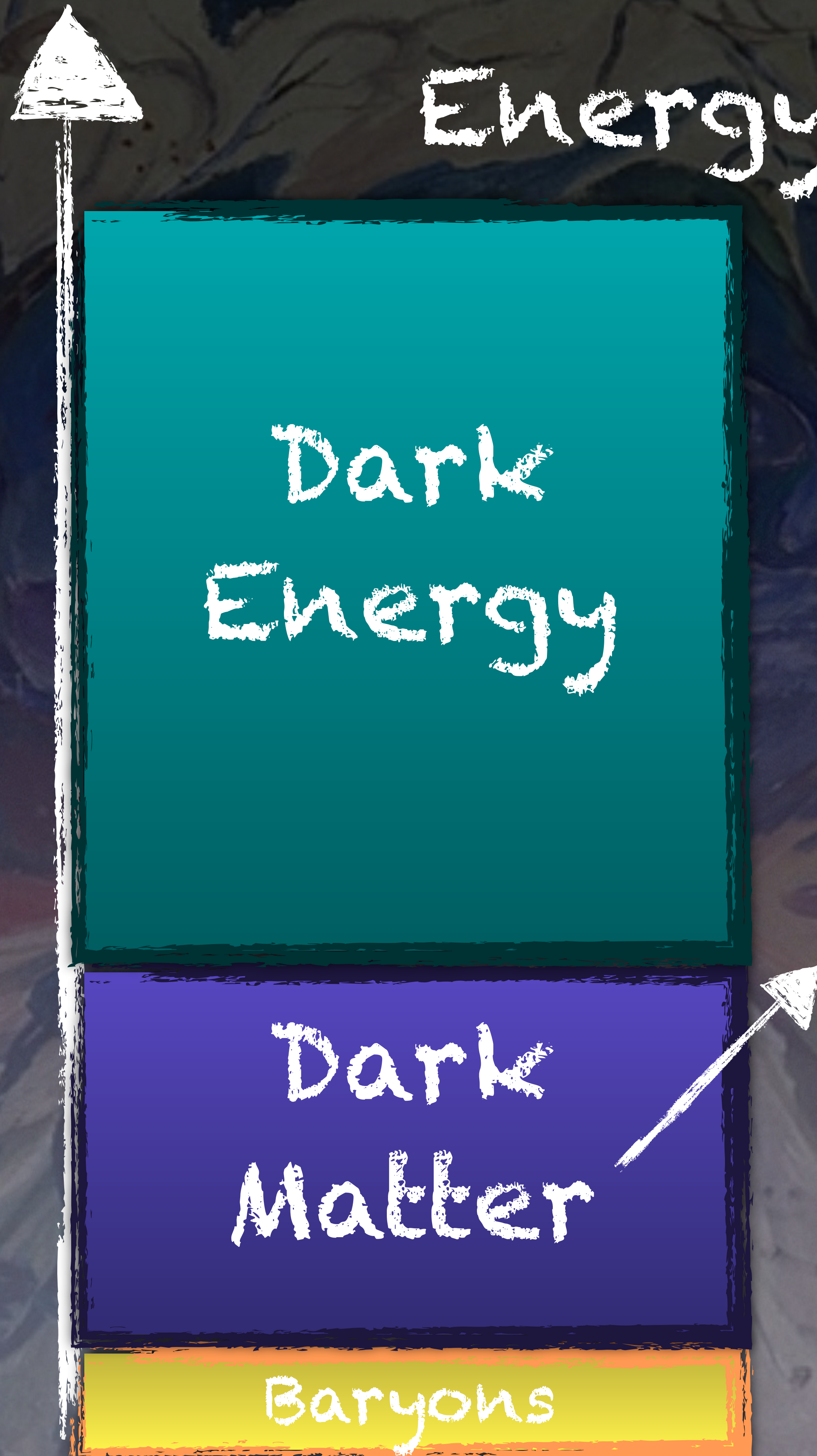
$$\omega^2 = m_g^2 + c_g^2 k^2$$

D. Blas, M. Ivanov,
I. Sawicki, S. Sibiryakov
JETP Lett. 103, 10, 624

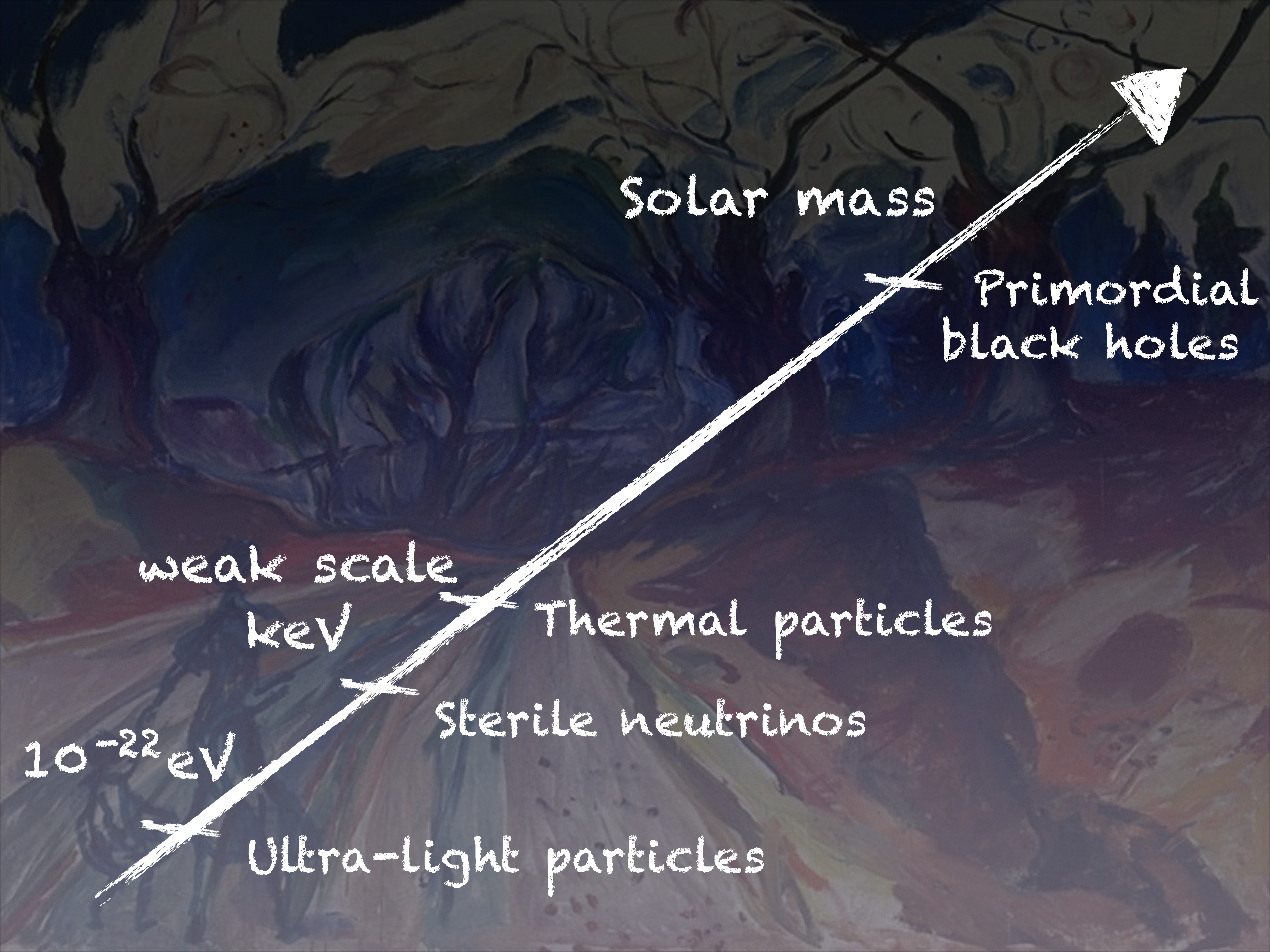



BSM

Energy budget of the Universe



Cold, collisionless matter.
Evidences from:
Rotation curves,
Galaxy clusters,
Gravitational lensing
CMB,
Structure formation,
...



Solar mass
Primordial black holes
weak scale
keV
Thermal particles
Sterile neutrinos
10^{-22}eV
Ultra-light particles

Did LIGO detect Dark Matter ?

S. Bird et al., Phys.Rev.Lett. 116 (2016) no.20

Did LIGO detect Dark Matter ?

$$\sigma = \pi \left(\frac{85\pi}{3}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$$
$$= 1.37 \times 10^{-14} M_{30}^2 v_{\rm pbh-200}^{-18/7}\,{\rm pc}^2,$$

The GW emission must exceed the initial kinetic energy

Did LIGO detect Dark Matter ?

$$\begin{aligned} M &= 10^{12}\, M_\odot \\ \rho &= 0.002\, M_\odot \mathrm{pc}^{-3} \\ v_{\mathrm{PBH}} &= 200\,\mathrm{km\,s^{-1}} \end{aligned}$$

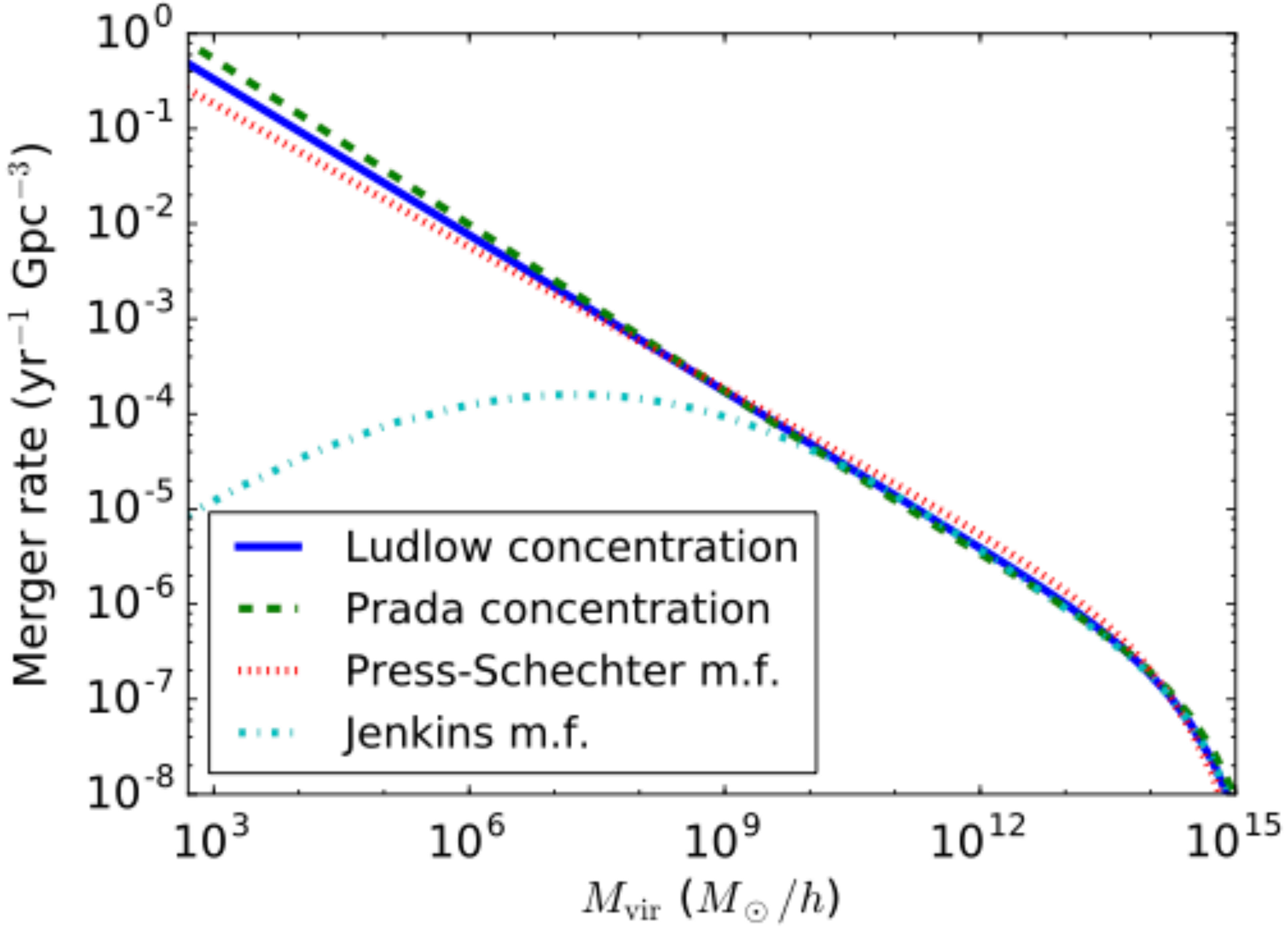
$$\Gamma \simeq 1.1 \times 10^{-4} \rho_{0.002} v_{\mathrm{pbh-200}}^{-11/7}\ \mathrm{Gpc^{-3}\,yr^{-1}}.$$

Did LIGO detect Dark Matter ?

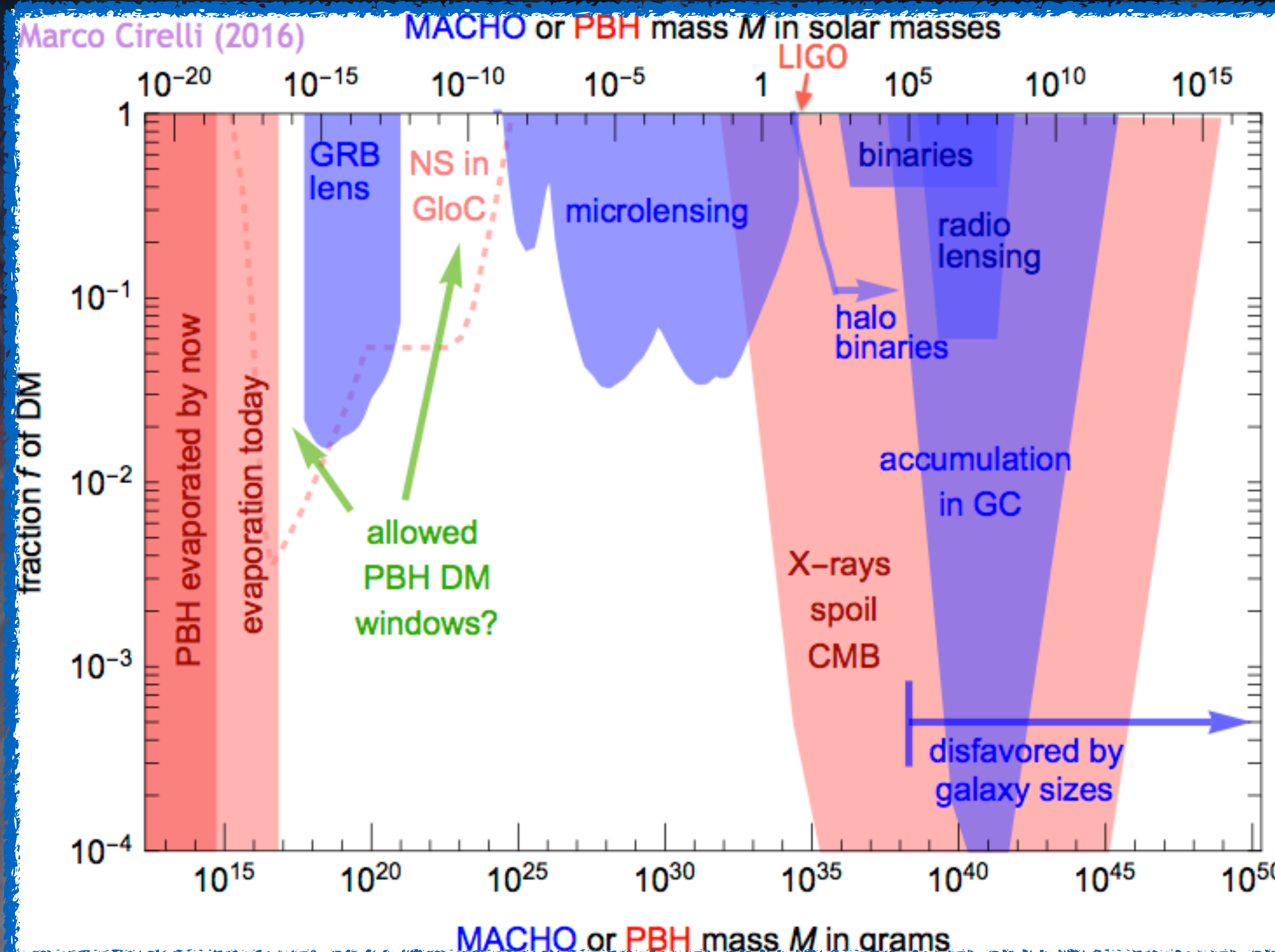
* Low dispersion velocity
* High dark matter density

$$\Gamma \simeq 1.1 \times 10^{-4} \rho_{0.002} v_{\mathrm{pbh}-200}^{-11/7} \ \mathrm{Gpc}^{-3}\, \mathrm{yr}^{-1}.$$

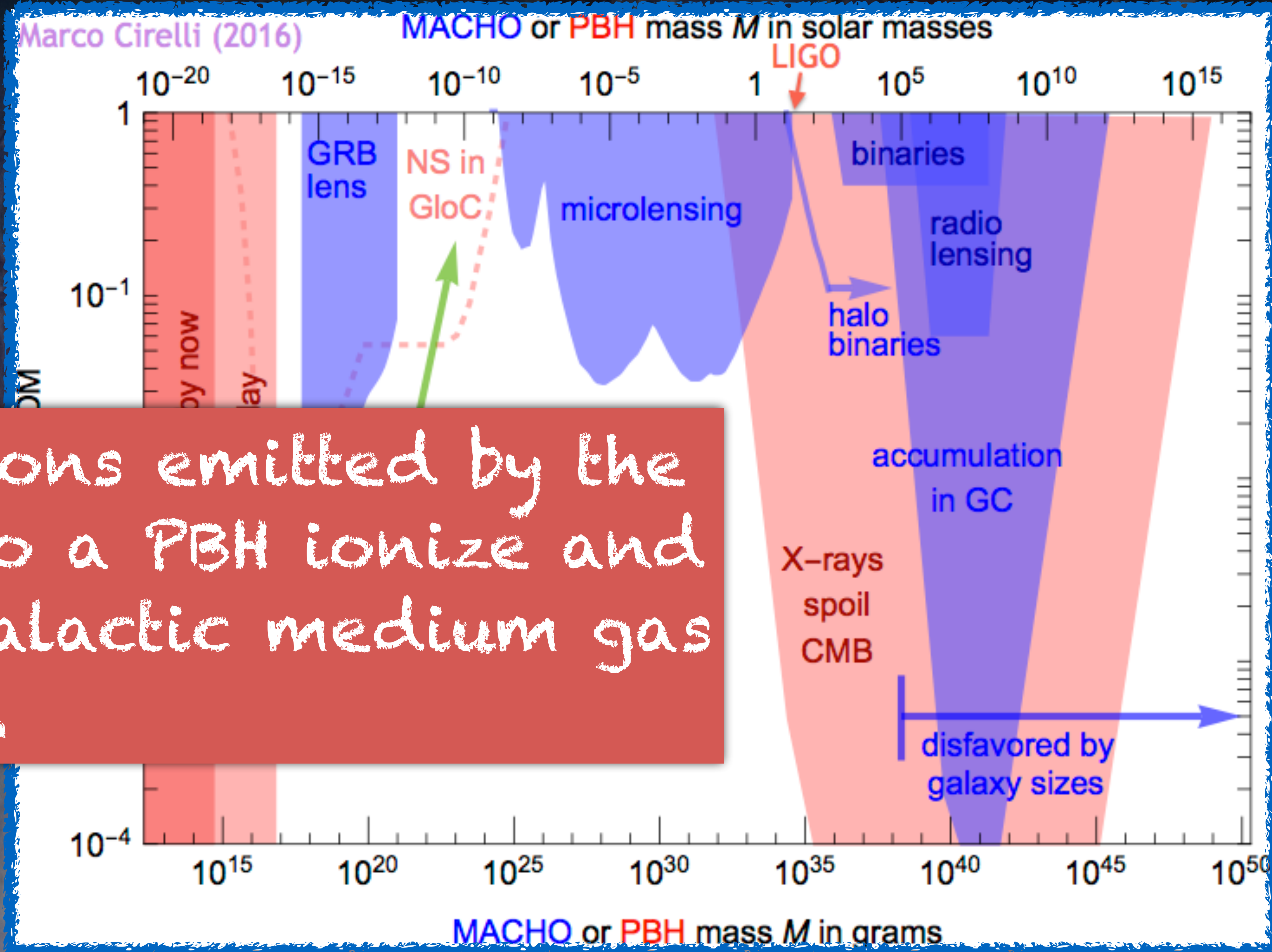
Did LIGO detect Dark Matter ?



Did LIGO detect Dark Matter ?

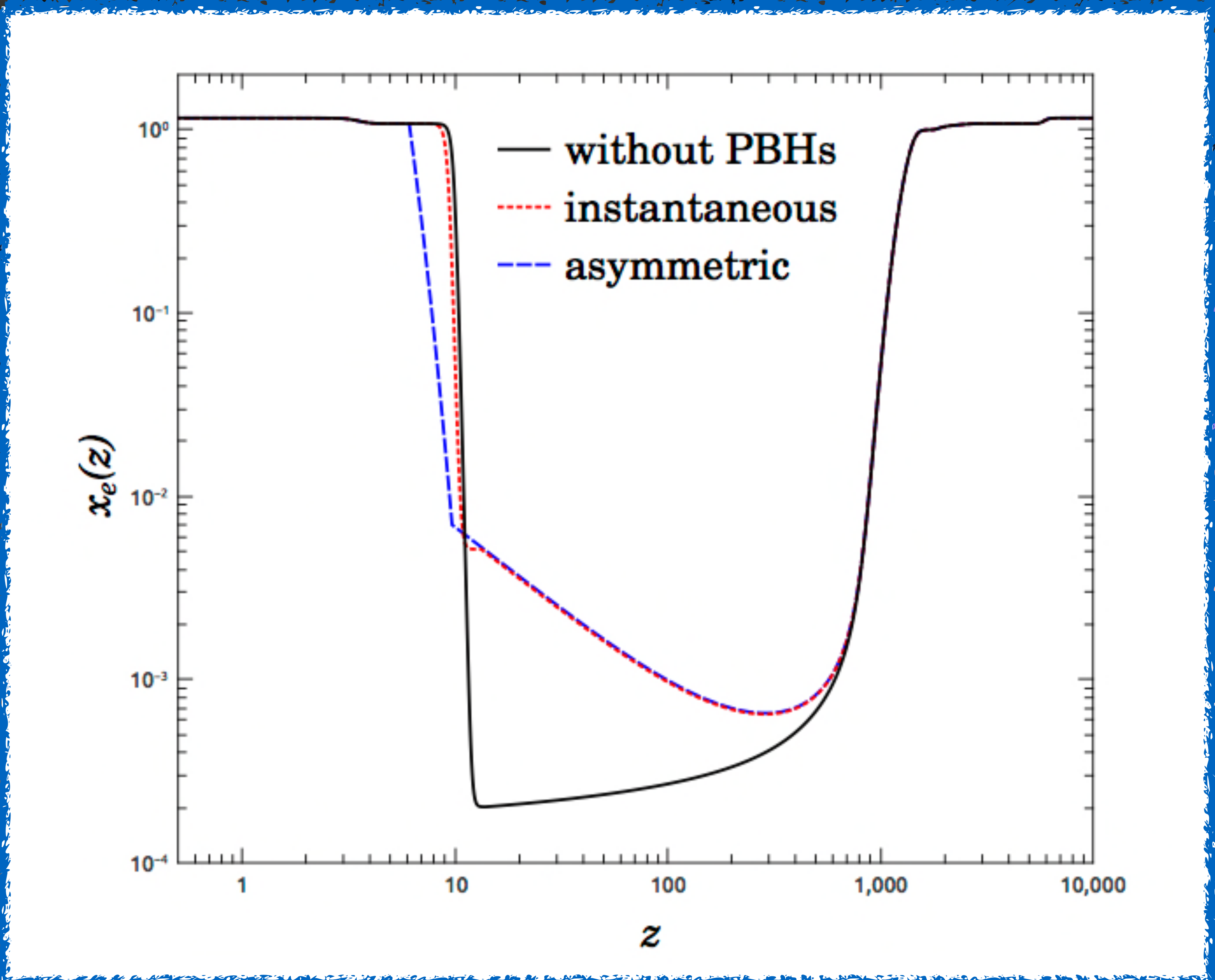


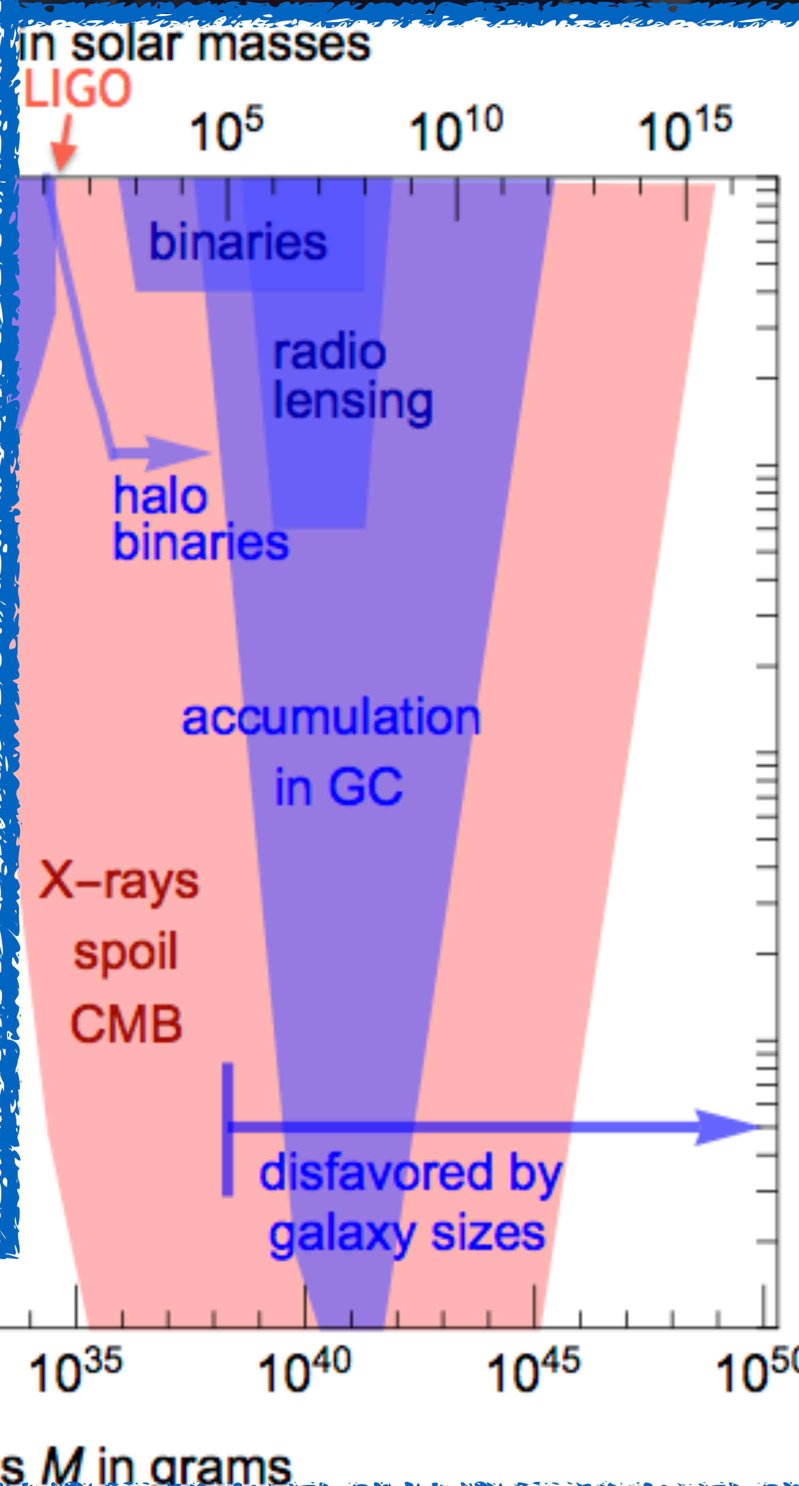
Did LIGO detect Dark Matter ?



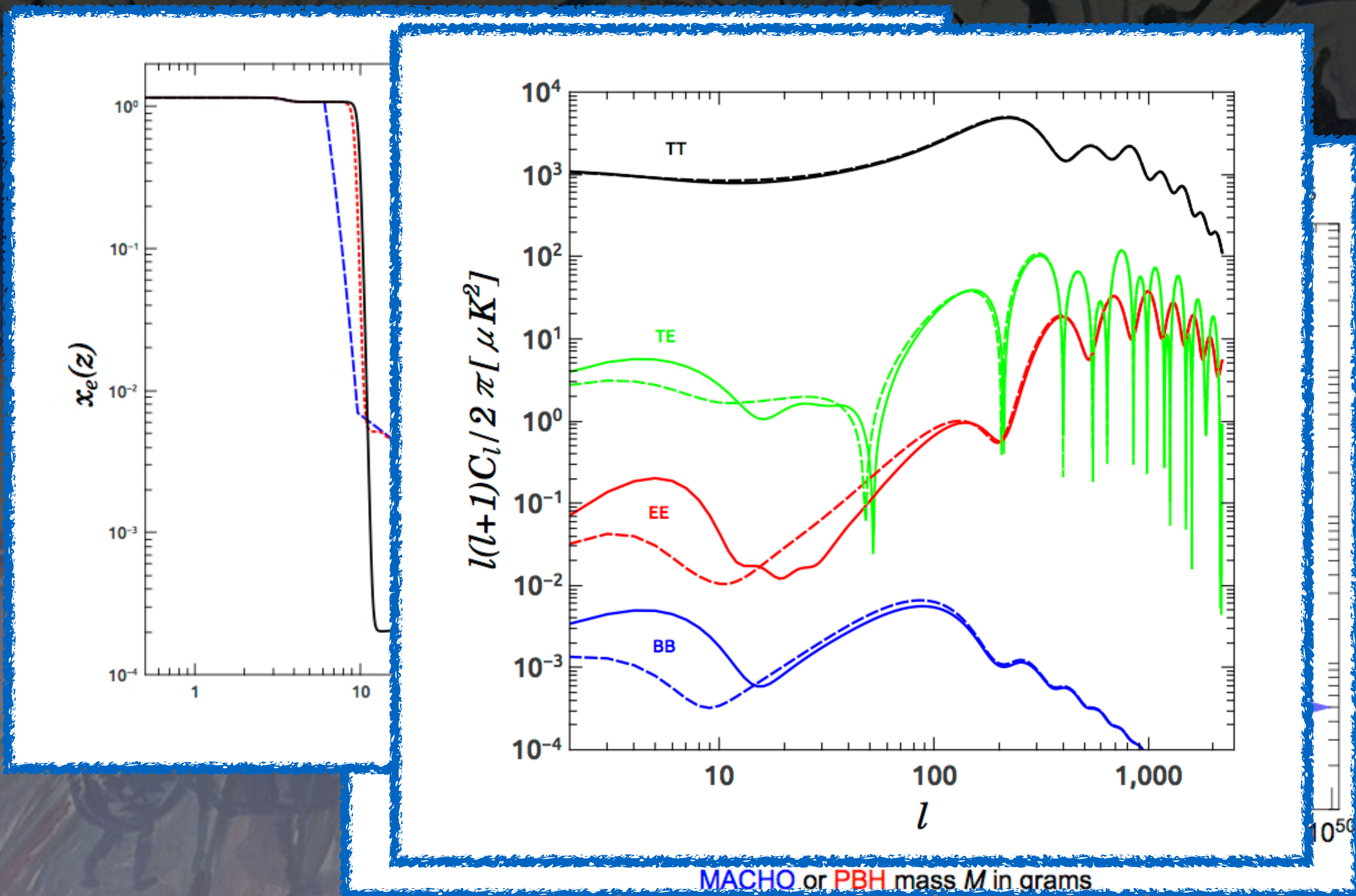
X-ray photons emitted by the accretion to a PBH ionize and heat intergalactic medium gas near a PBH.

L. Chen, Q.-G. Huang, K. Wang, 1608.02174

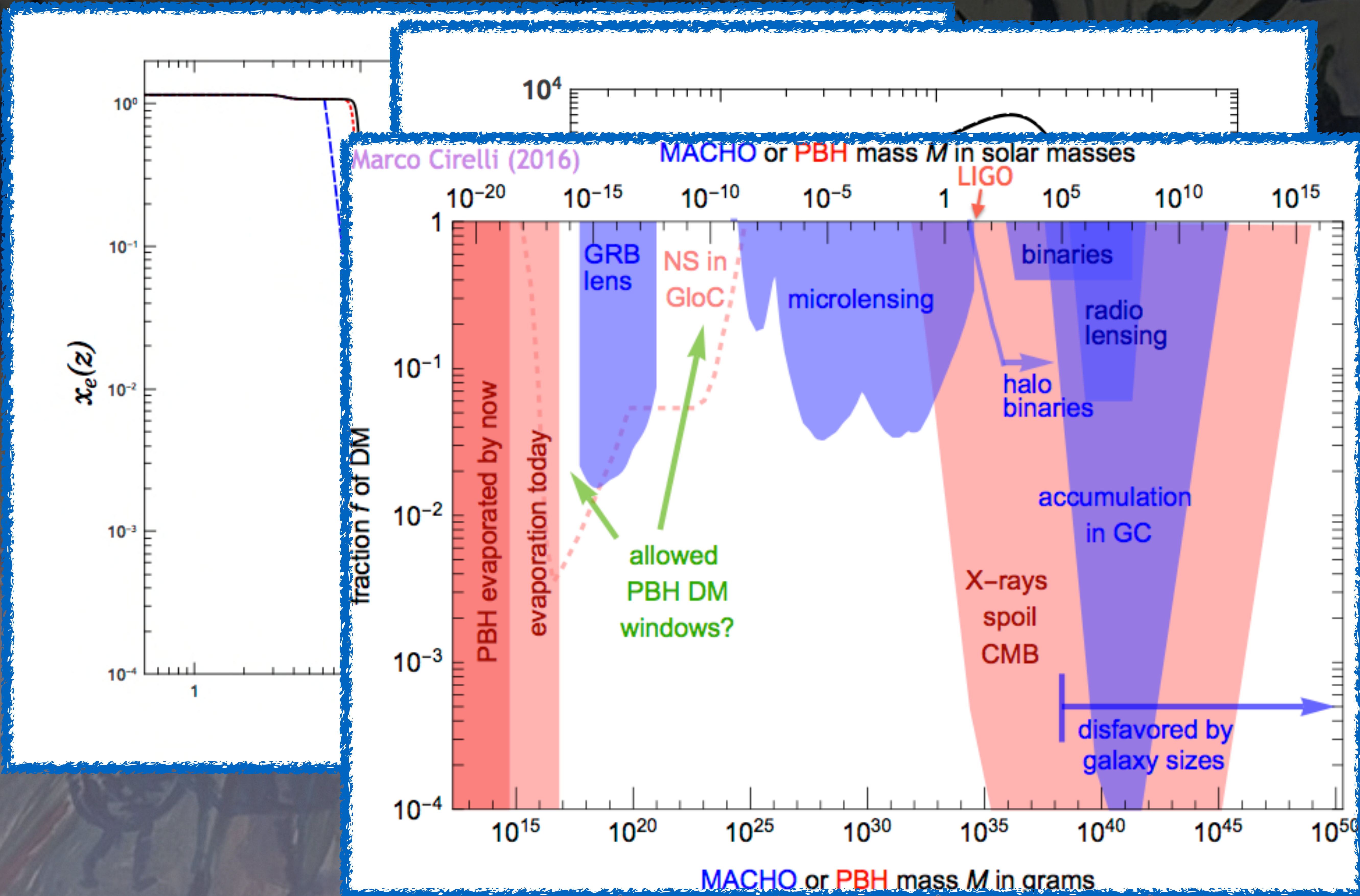




L. Chen, Q.-G. Huang, K. Wang, 1608.02174

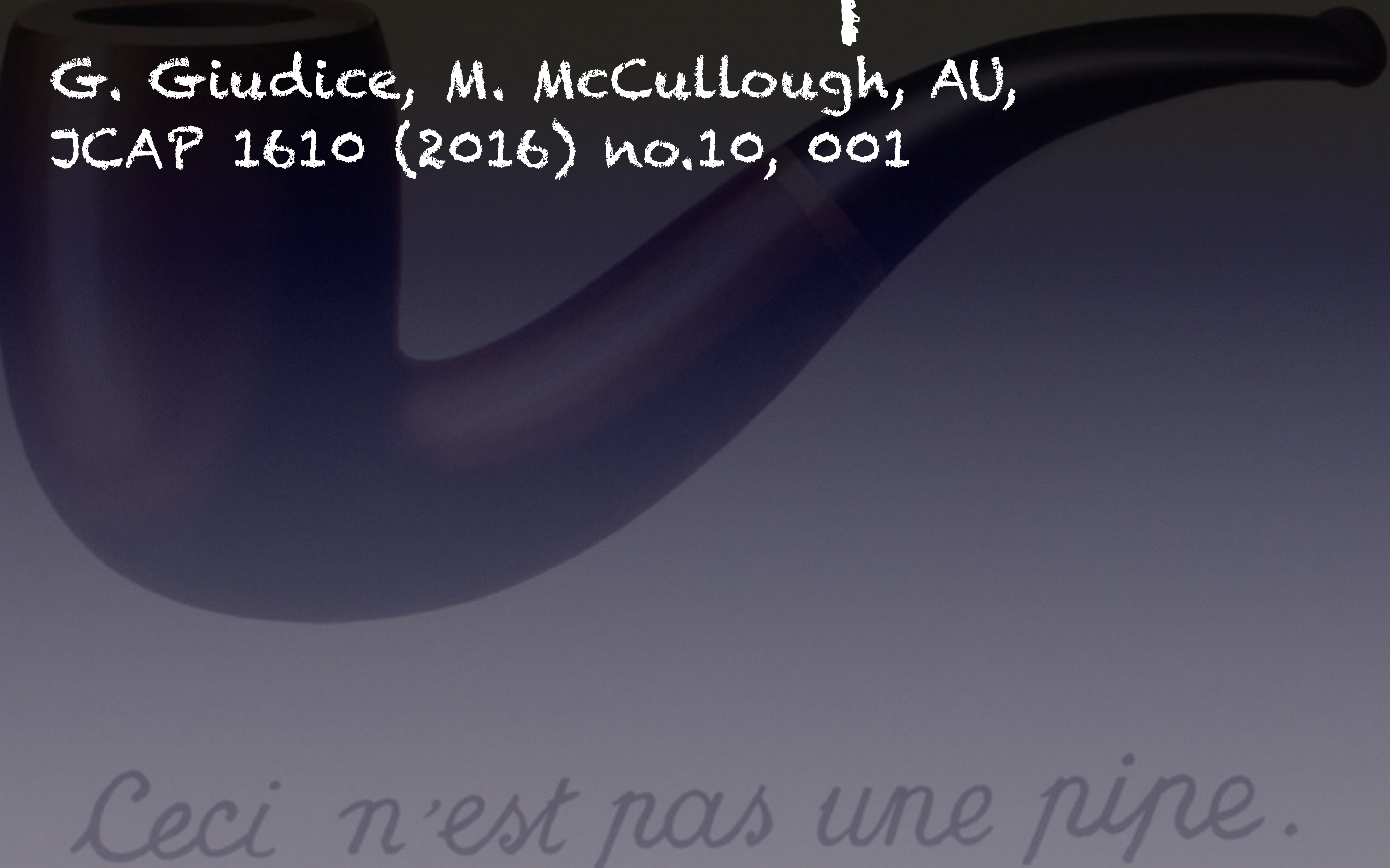


L. Chen, Q.-G. Huang, K. Wang, 1608.02174

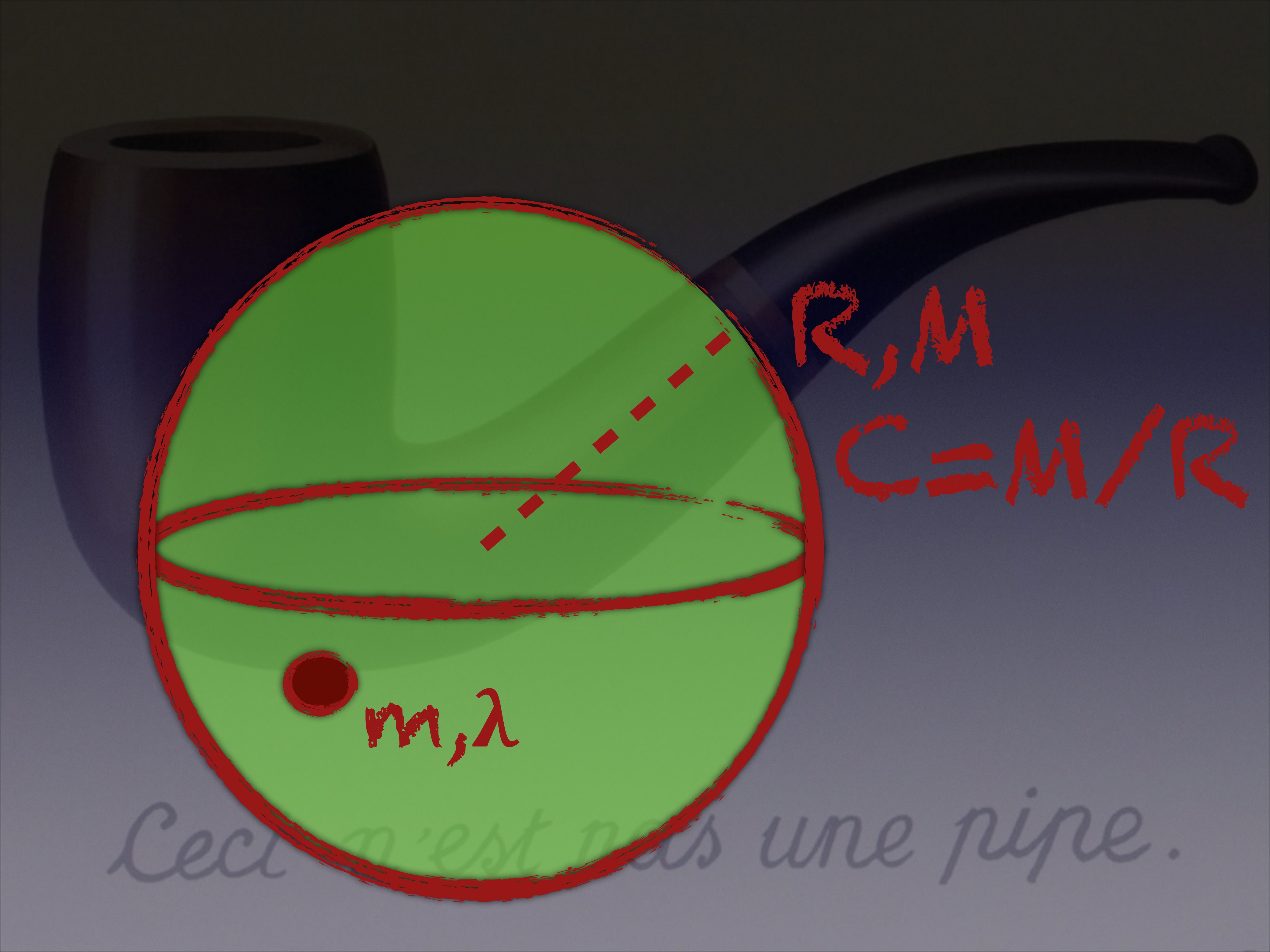


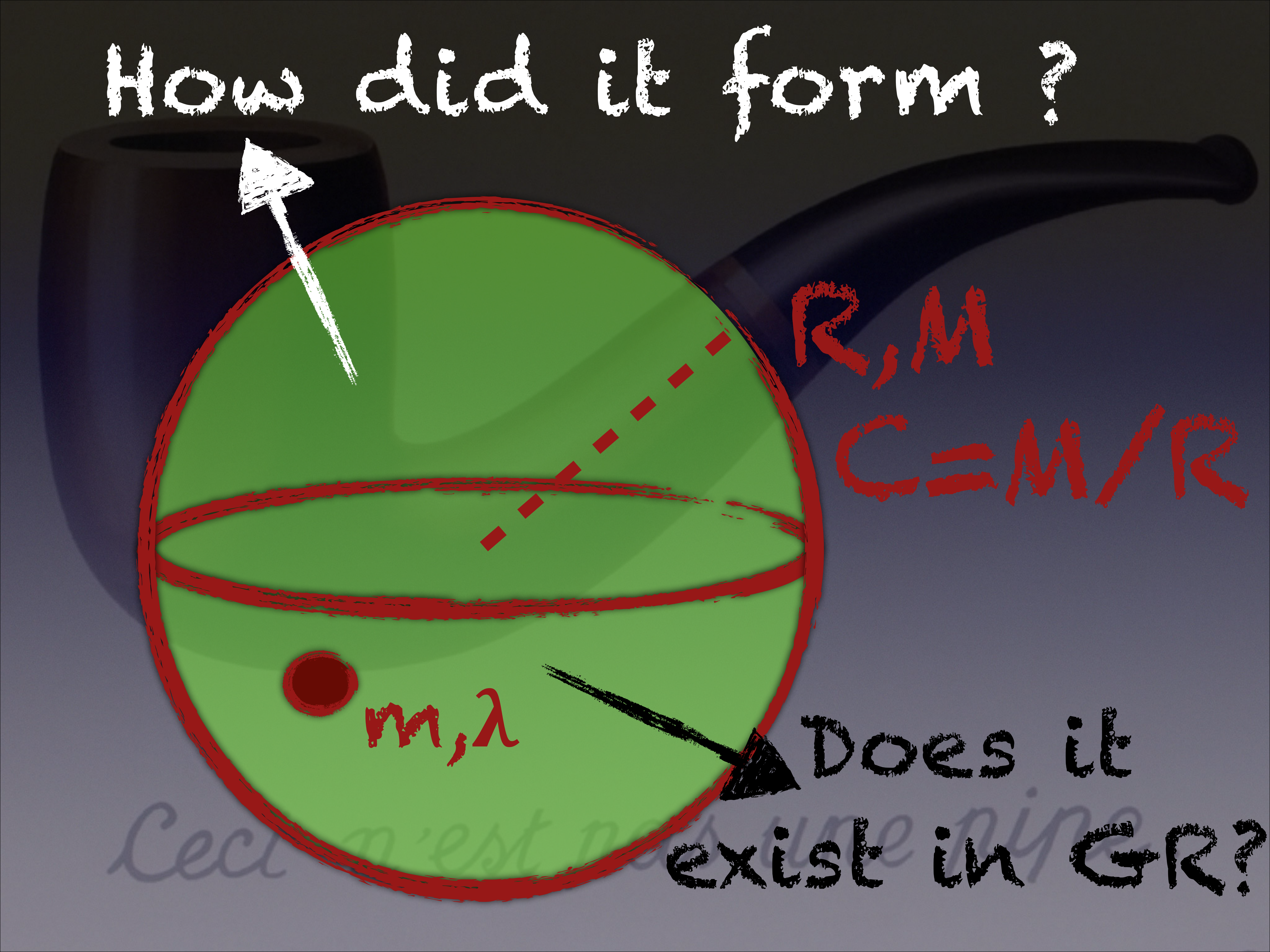
The unexpected

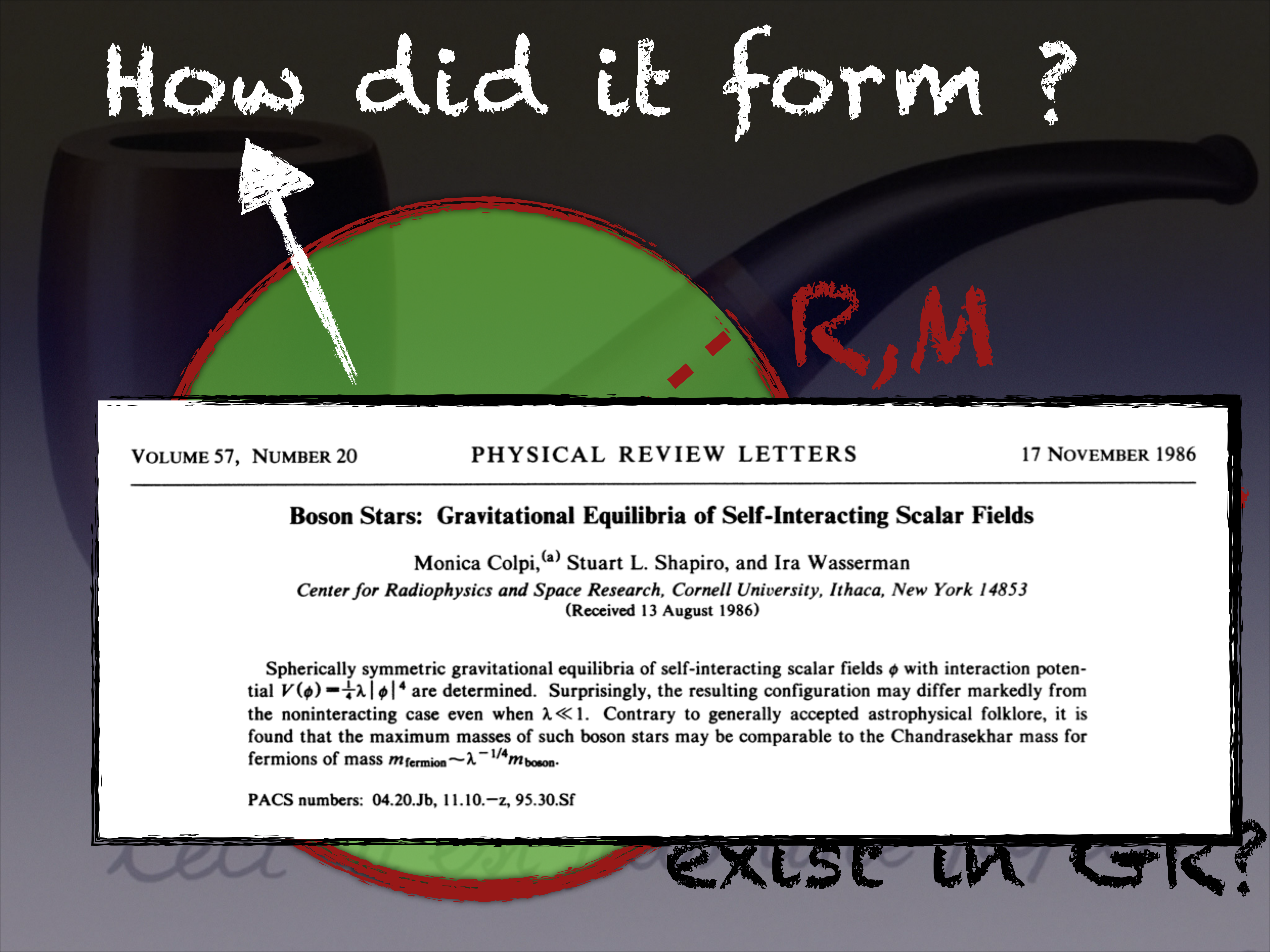
G. Giudice, M. McCullough, AU,
JCAP 1610 (2016) no.10, 001




m,λ
Ceci n'est pas une pipe.


R,M
C=M/R
m,λ
Ceci n'est pas une pipe.


How did it form ?
R,M
C=M/R
m,λ
Does it exist in GR?
Ceci n'est pas une pipe



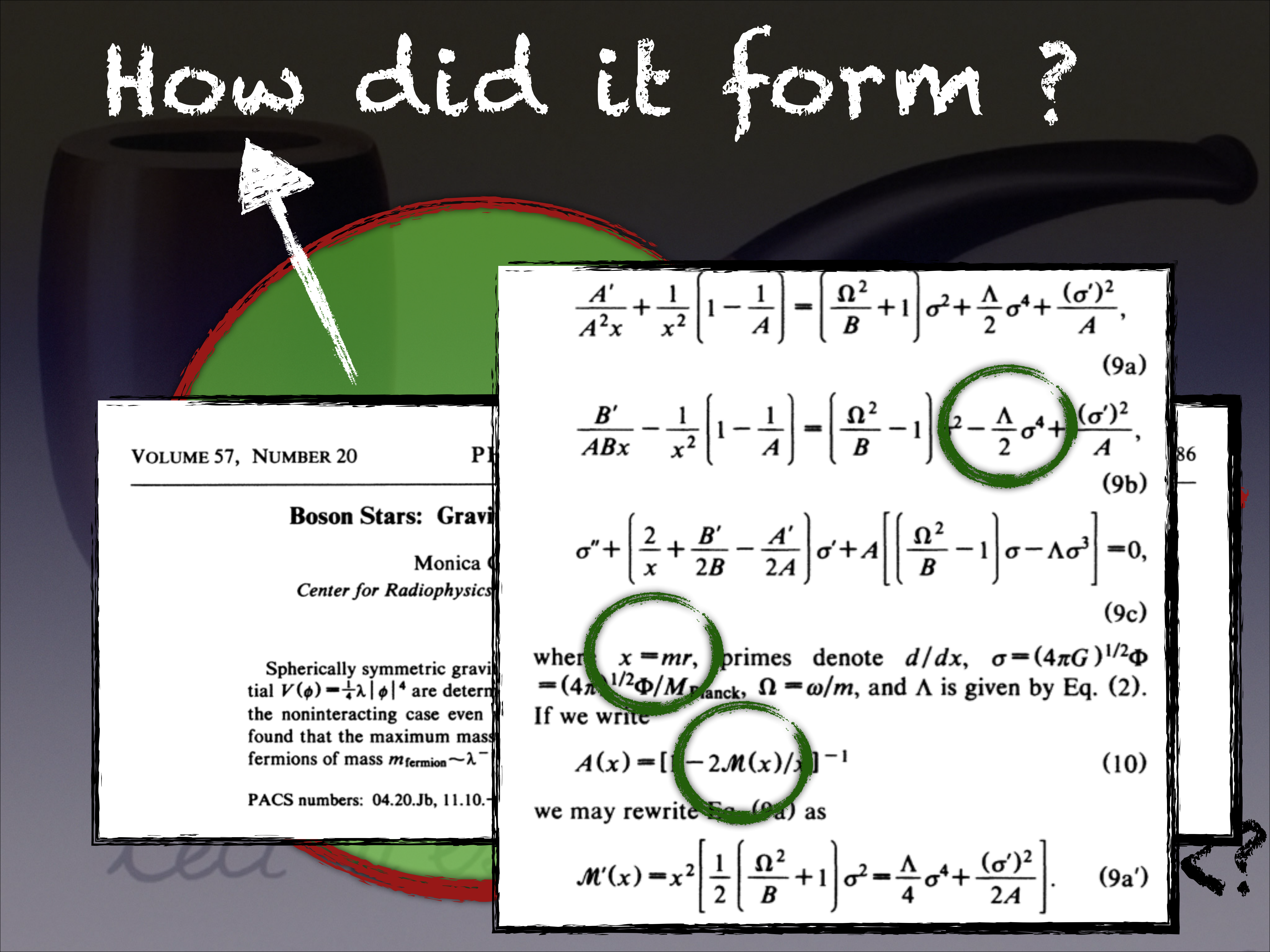
VOLUME 57, NUMBER 20 PHYSICAL REVIEW LETTERS 17 NOVEMBER 1986

Boson Stars: Gravitational Equilibria of Self-Interacting Scalar Fields

Monica Colpi,[a] Stuart L. Shapiro, and Ira Wasserman
Center for Radiophysics and Space Research, Cornell University, Ithaca, New York 14853
(Received 13 August 1986)

Spherically symmetric gravitational equilibria of self-interacting scalar fields ϕ with interaction potential $V(\phi)=\frac{1}{4}\lambda|\phi|^4$ are determined. Surprisingly, the resulting configuration may differ markedly from the noninteracting case even when $\lambda \ll 1$. Contrary to generally accepted astrophysical folklore, it is found that the maximum masses of such boson stars may be comparable to the Chandrasekhar mass for fermions of mass $m_{\text{fermion}} \sim \lambda^{-1/4} m_{\text{boson}}$.

PACS numbers: 04.20.Jb, 11.10.−z, 95.30.Sf



How did it form ?

VOLUME 57, NUMBER 20 PH
86

Boson Stars: Gravi

Monica C
Center for Radiophysics

Spherically symmetric gravi
tial $V(\phi)=\frac{1}{4}\lambda|\phi|^4$ are detern
the noninteracting case even
found that the maximum mass
fermions of mass $m_{\rm fermion}\sim\lambda^{-}$

PACS numbers: 04.20.Jb, 11.10.-

$$\frac{A'}{A^2x}+\frac{1}{x^2}\left(1-\frac{1}{A}\right)=\left(\frac{\Omega^2}{B}+1\right)\sigma^2+\frac{\Lambda}{2}\sigma^4+\frac{(\sigma')^2}{A}, \quad (9a)$$

$$\frac{B'}{ABx}-\frac{1}{x^2}\left(1-\frac{1}{A}\right)=\left(\frac{\Omega^2}{B}-1\right)\sigma^2-\frac{\Lambda}{2}\sigma^4+\frac{(\sigma')^2}{A}, \quad (9b)$$

$$\sigma''+\left(\frac{2}{x}+\frac{B'}{2B}-\frac{A'}{2A}\right)\sigma'+A\left[\left(\frac{\Omega^2}{B}-1\right)\sigma-\Lambda\sigma^3\right]=0, \quad (9c)$$

where $x=mr$, primes denote d/dx, $\sigma=(4\pi G)^{1/2}\Phi=(4\pi)^{1/2}\Phi/M_{\rm Planck}$, $\Omega=\omega/m$, and Λ is given by Eq. (2). If we write

$$A(x)=[1-2\mathcal{M}(x)/x]^{-1} \quad (10)$$

we may rewrite Eq. (9a) as

$$\mathcal{M}'(x)=x^2\left[\frac{1}{2}\left(\frac{\Omega^2}{B}+1\right)\sigma^2+\frac{\Lambda}{4}\sigma^4+\frac{(\sigma')^2}{2A}\right]. \quad (9a')$$

How did it form ?

PRL **112,** 221101 (2014) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2014

Kerr Black Holes with Scalar Hair

Carlos A. R. Herdeiro and Eugen Radu
Departamento de Física da Universidade de Aveiro and I3N, Campus de Santiago, 3810-183 Aveiro, Portugal
(Received 13 March 2014; revised manuscript received 23 April 2014; published 2 June 2014)

We present a family of solutions of Einstein's gravity minimally coupled to a complex, massive scalar field, describing asymptotically flat, spinning black holes with scalar hair and a regular horizon. These hairy black holes (HBHs) are supported by rotation and have no static limit. Besides mass M and angular momentum J, they carry a conserved, continuous Noether charge Q measuring the scalar hair. HBHs branch off from the Kerr metric at the threshold of the superradiant instability and reduce to spinning boson stars in the limit of vanishing horizon area. They overlap with Kerr black holes for a set of (M, J) values. A single Killing vector field preserves the solutions, tangent to the null geodesic generators of the event horizon. HBHs can exhibit sharp physical differences when compared to the Kerr solution, such as $J/M^2 > 1$, a quadrupole moment larger than J^2/M, and a larger orbital angular velocity at the innermost stable circular orbit. Families of HBHs connected to the Kerr geometry should exist in scalar (and other) models with more general self-interactions.

DOI: 10.1103/PhysRevLett.112.221101 PACS numbers: 04.70.Bw, 03.50.-z

PACS numbers: 04.20.Jb, 11.10.

we may rewrite Eq. (9a) as

$$\mathcal{M}'(x) = x^2\left[\frac{1}{2}\left(\frac{\Omega^2}{B}+1\right)\sigma^2 = \frac{\Lambda}{4}\sigma^4 + \frac{(\sigma')^2}{2A}\right]. \qquad (9a')$$

?

How did it form ?

VOLUME 72, NUMBER 16 PHYSICAL REVIEW LETTERS 18 APRIL 1994

Formation of Solitonic Stars through Gravitational Cooling

Edward Seidel[1] and Wai-Mo Suen[2]

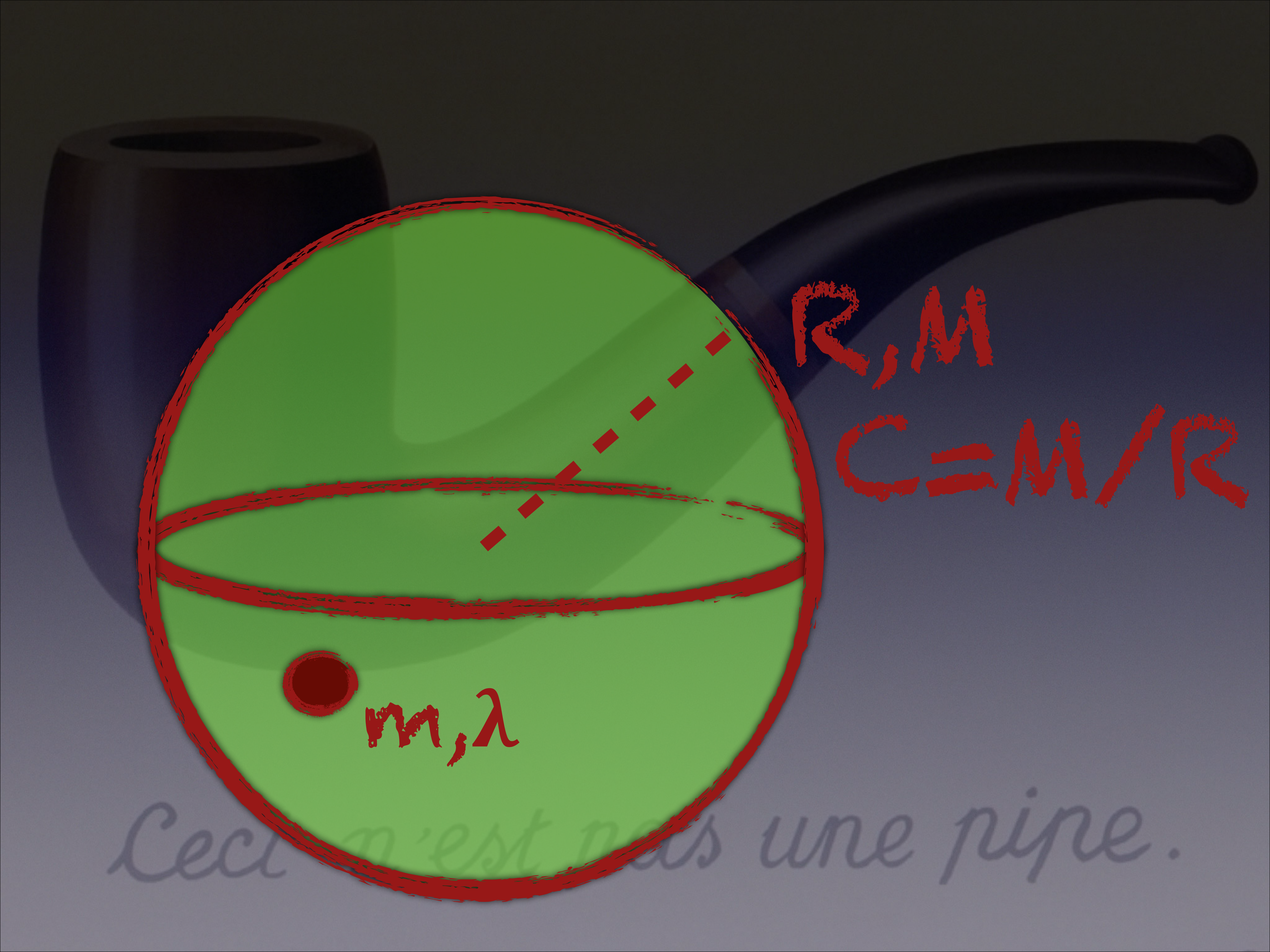
[1]*National Center for Supercomputing Applications, Beckman Institute, 405 N. Mathews Avenue, Urbana, Illinois 61801*
[2]*McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri 63130*

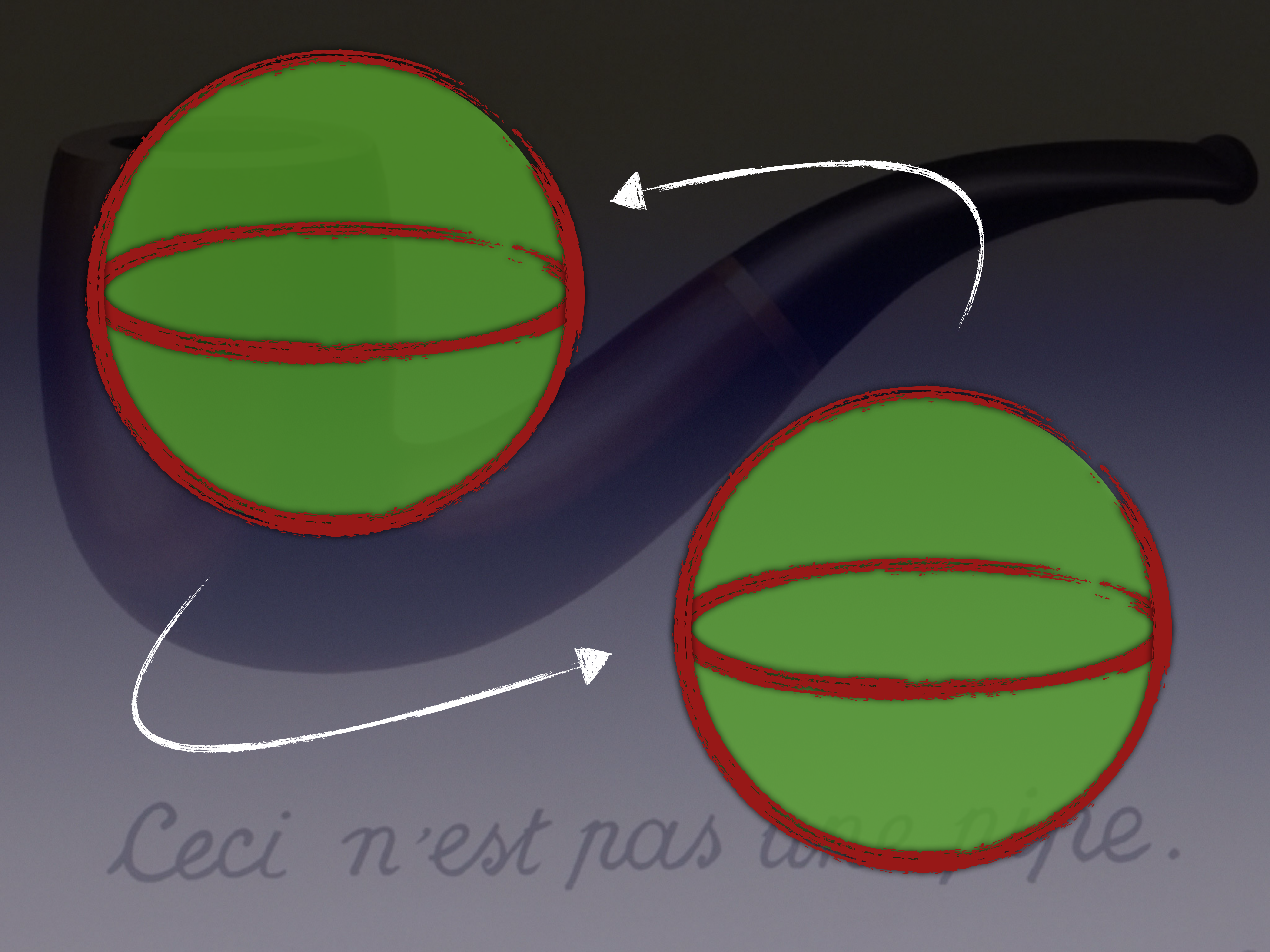
(Received 26 July 1993)

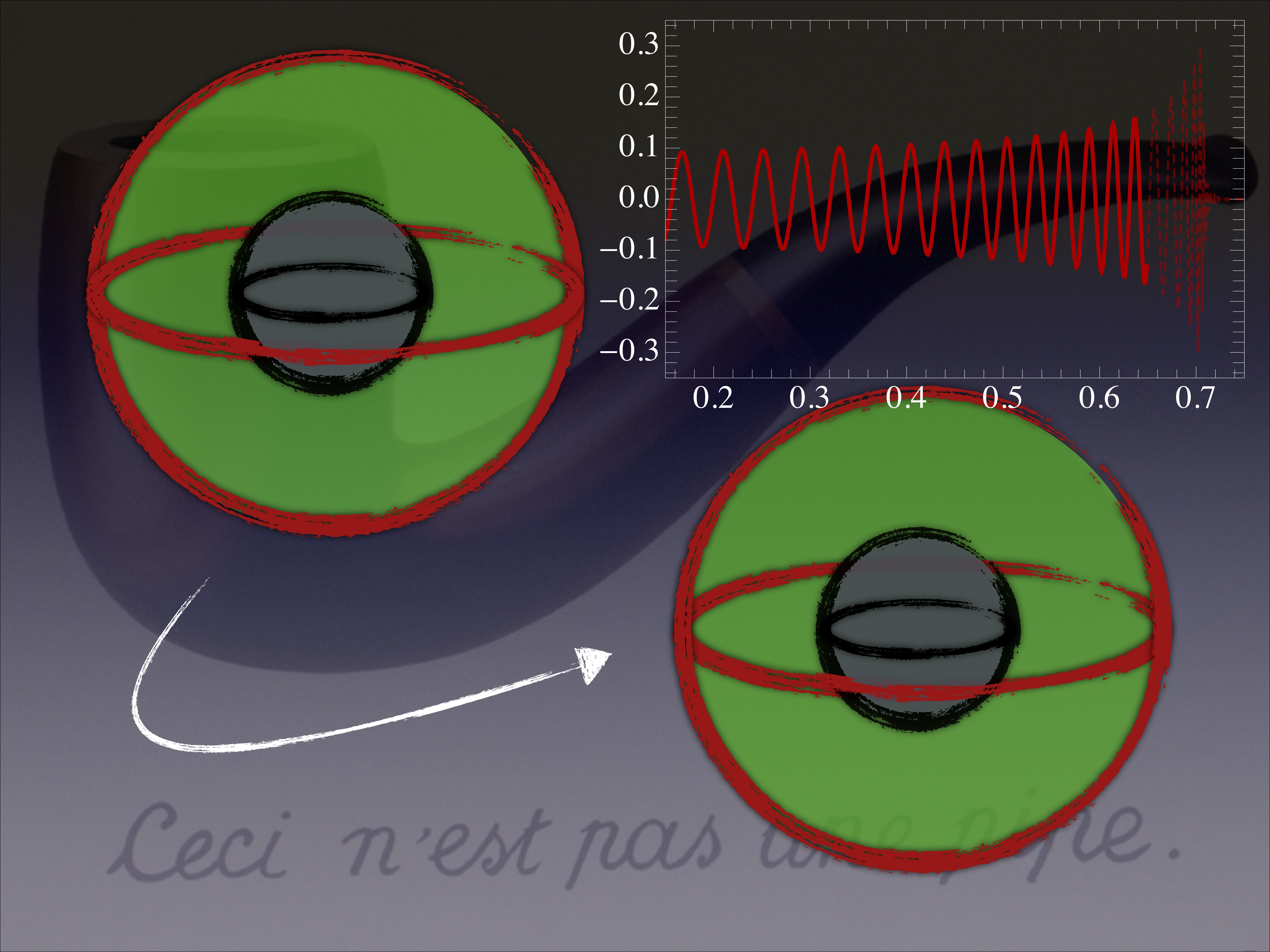
We studied the formation of compact bosonic objects through a dissipationless cooling mechanism. Implications of the existence of this mechanism are discussed, including the abundance of bosonic stars in the Universe, and the possibility of ruling out the axion as a dark matter candidate.

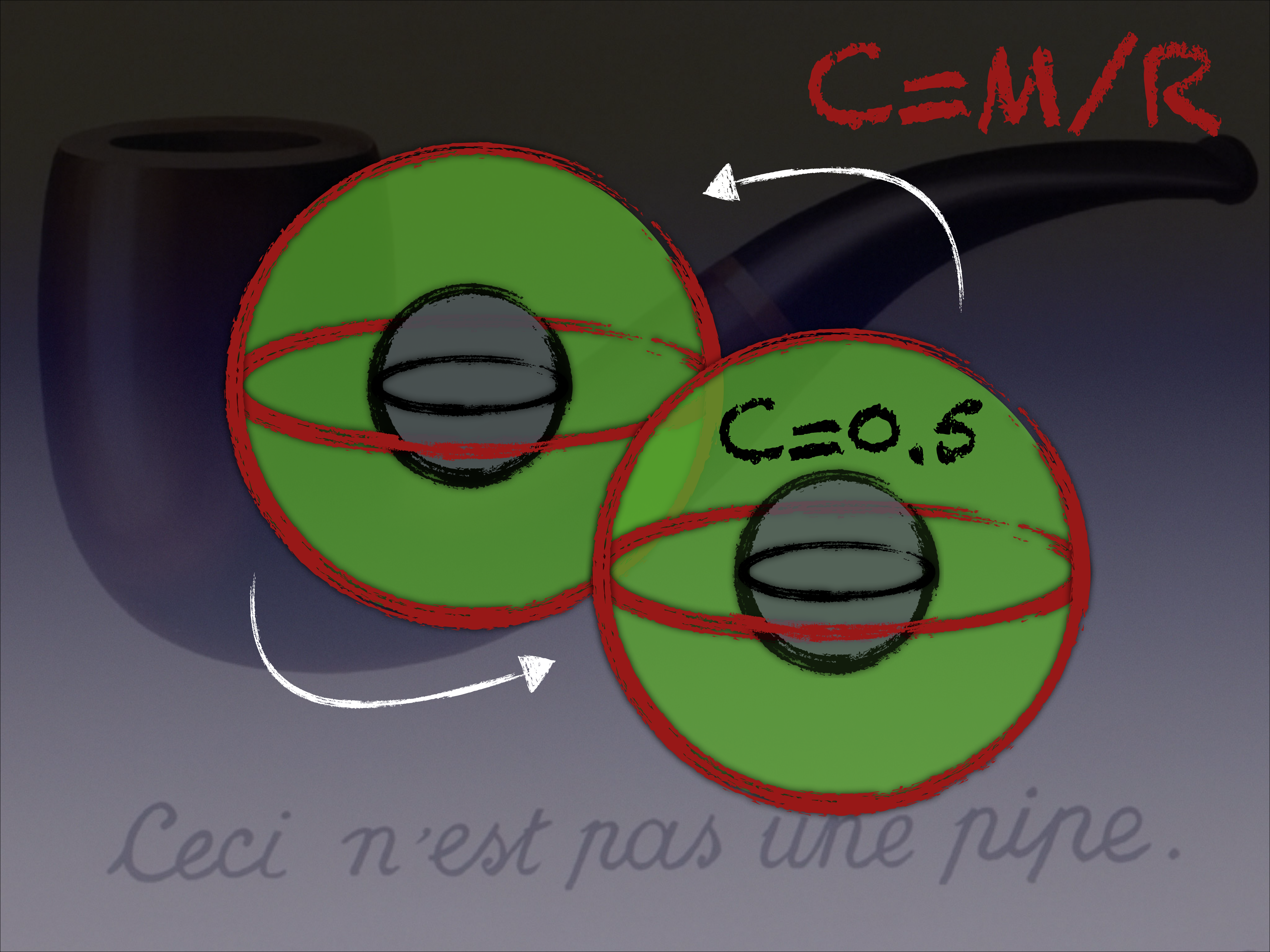
PACS numbers: 95.30.Sf, 04.40.Dg, 95.35.+d, 98.80.Cq

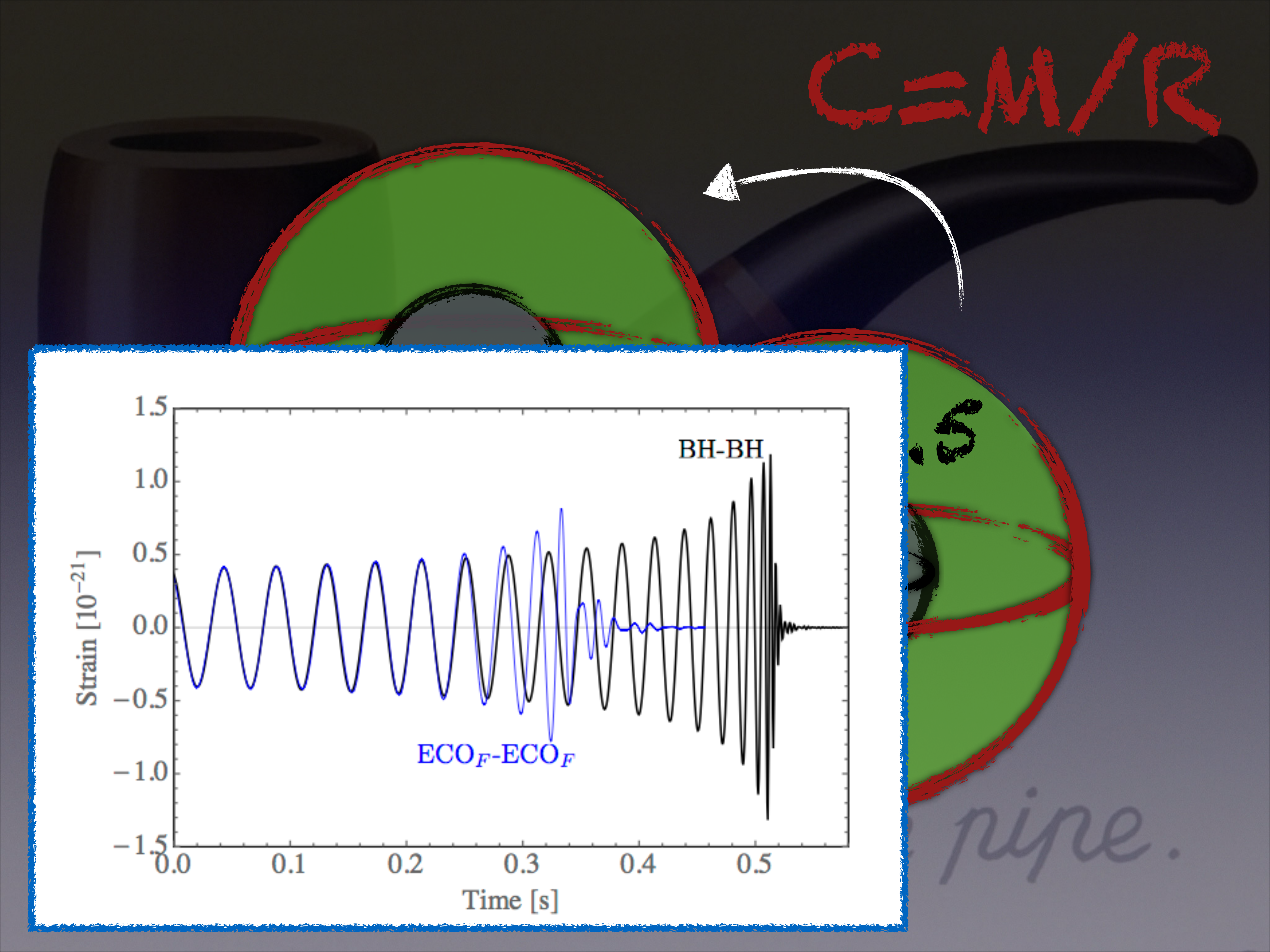
Does it exist in GR?


R,M
C=M/R
m,λ
Ceci n'est pas une pipe.

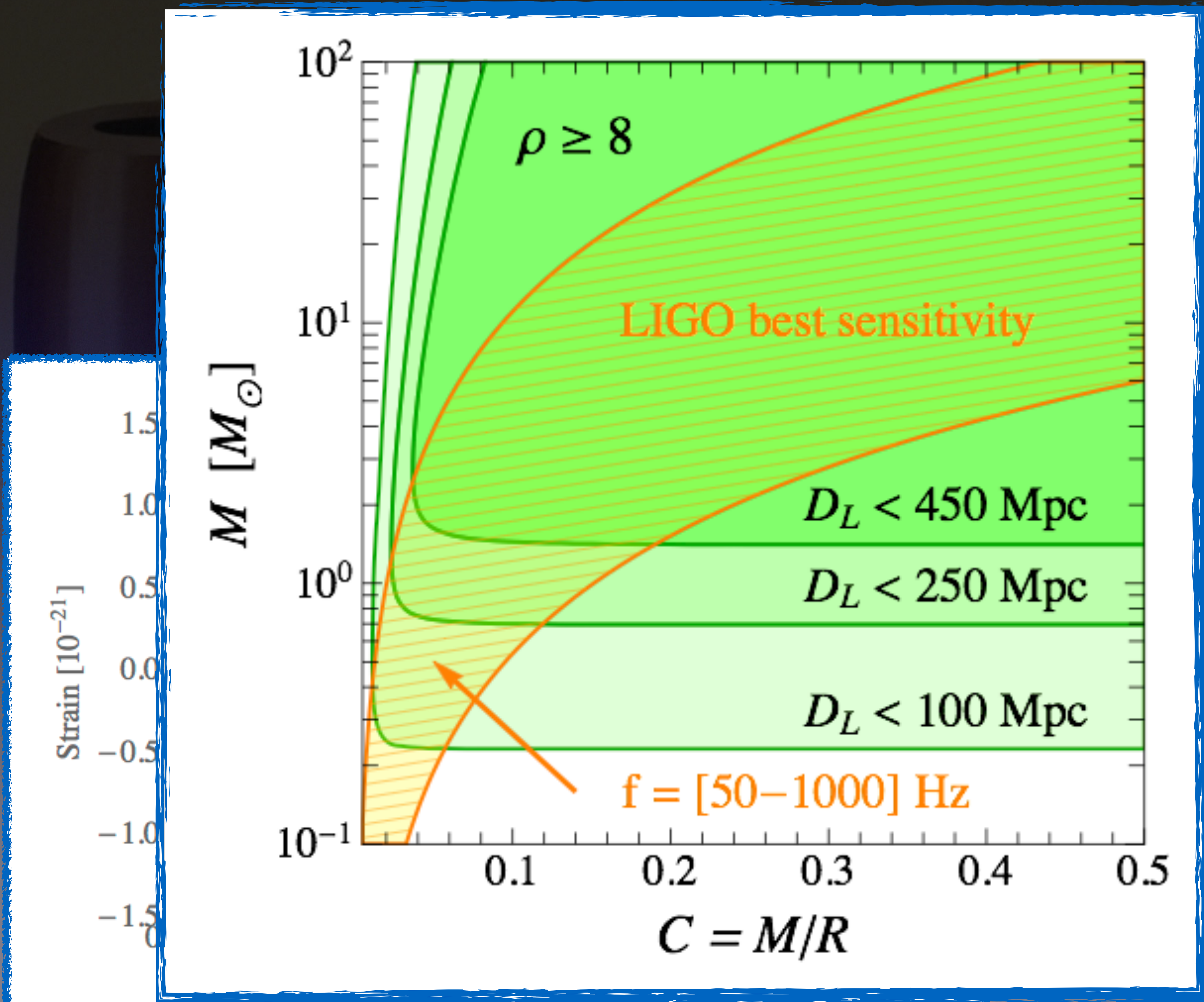

Ceci n'est pas


0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.2
0.3
0.4
0.5
0.6
0.7
Ceci n'est pas

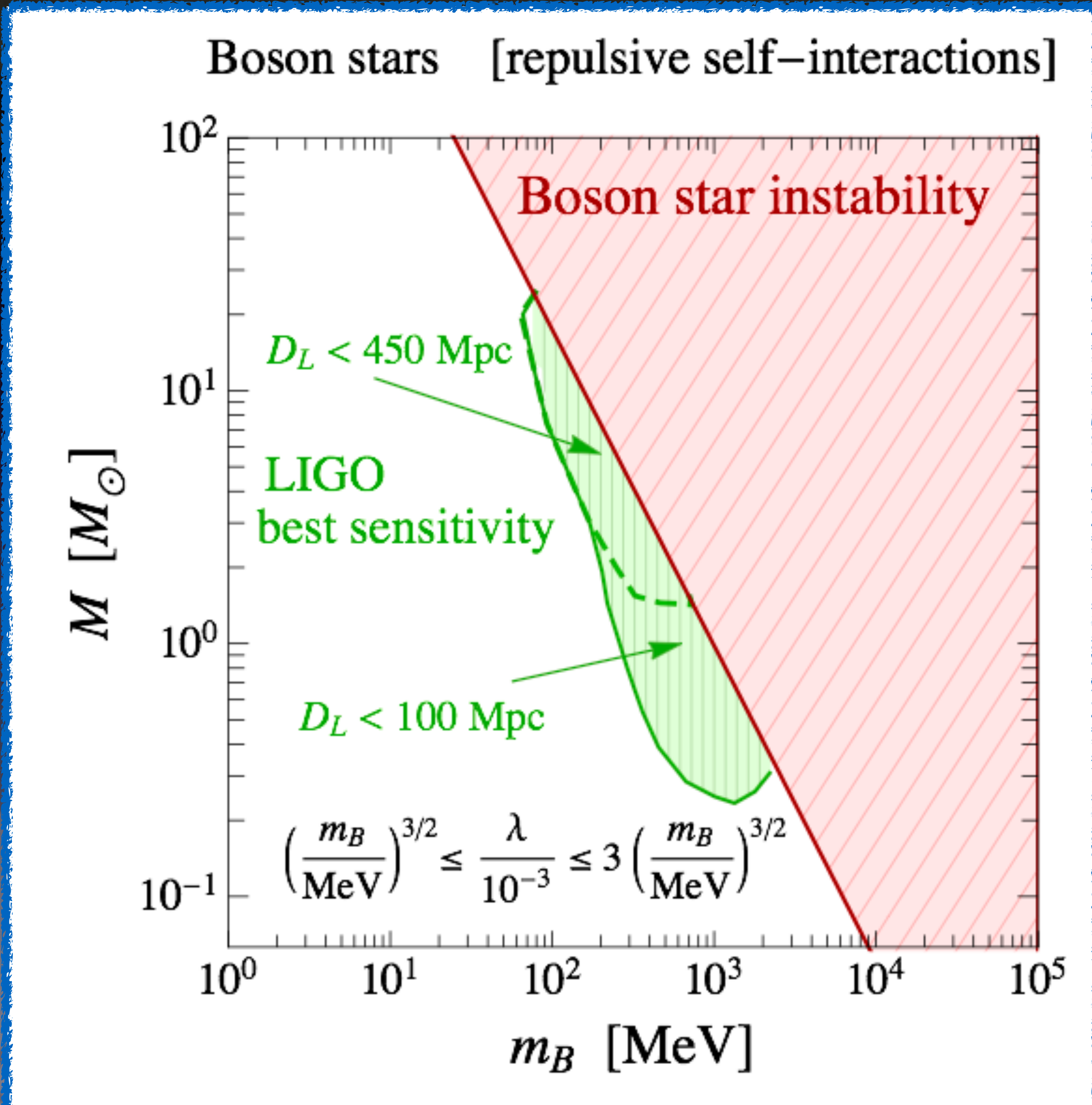

C=M/R
C=0.5
Ceci n'est pas une pipe.

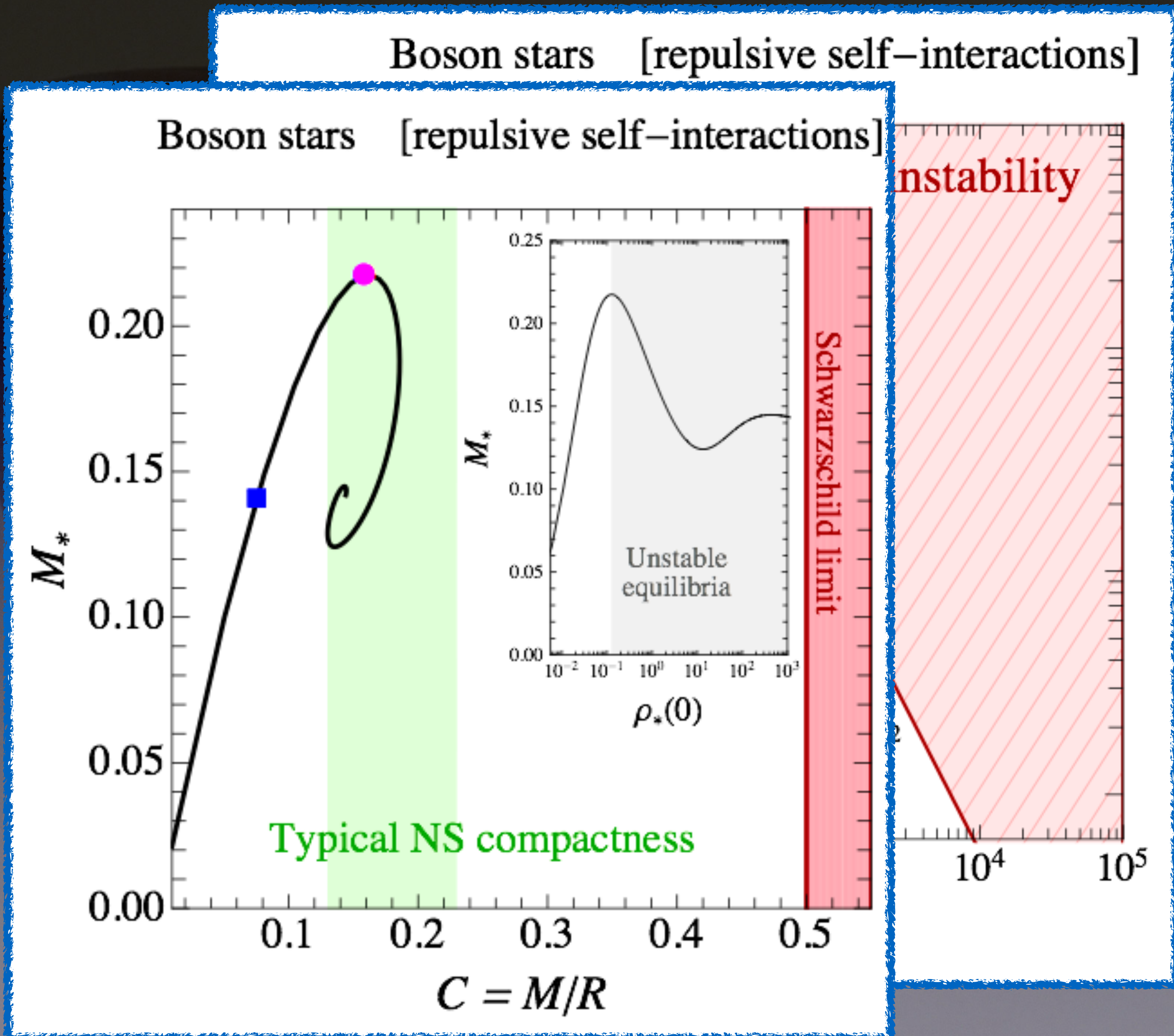


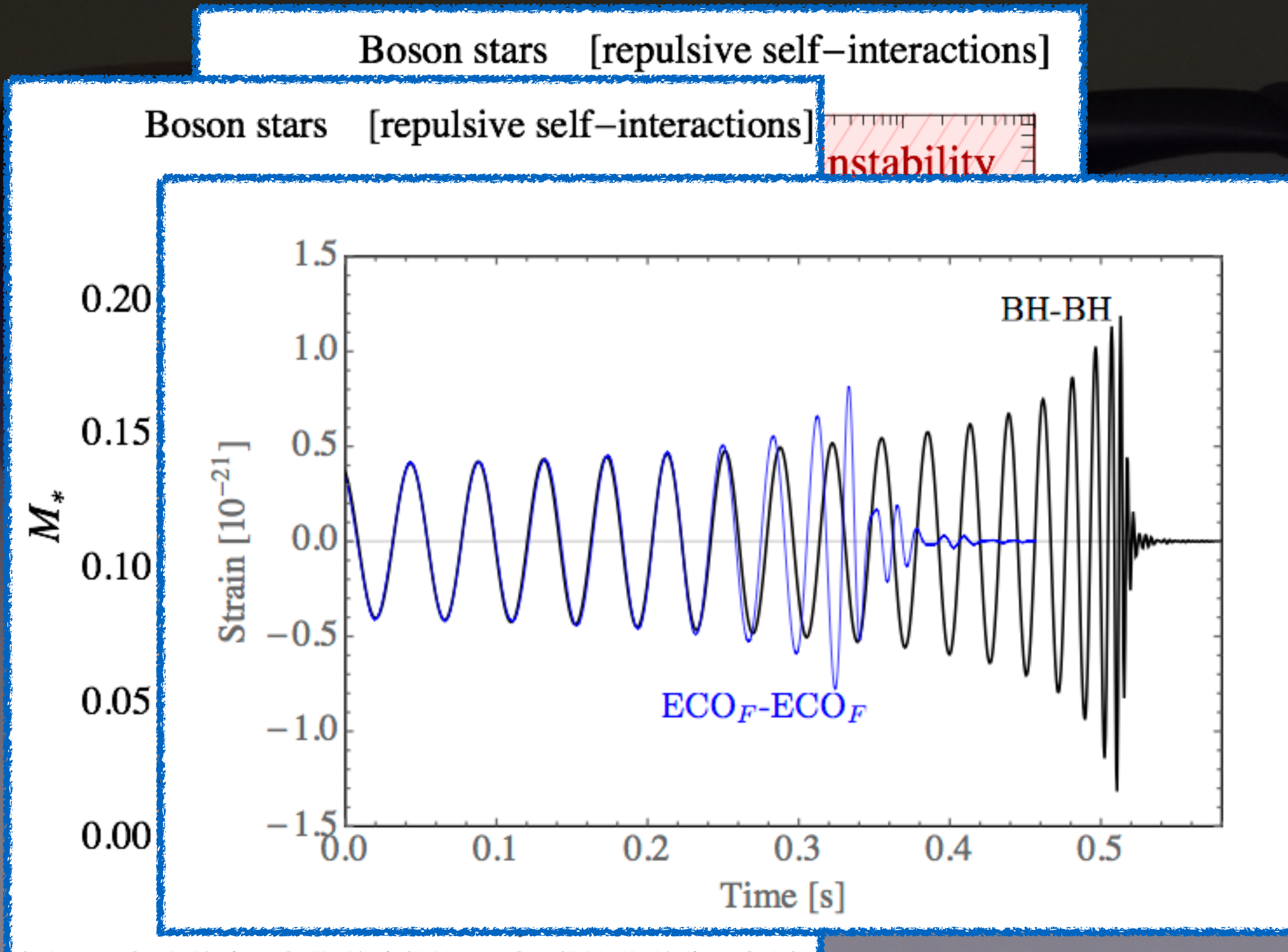
C=M/R
.5
pipe.
BH-BH
ECO_F-ECO_F
Strain [10^-21]
Time [s]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.0
0.1
0.2
0.3
0.4
0.5

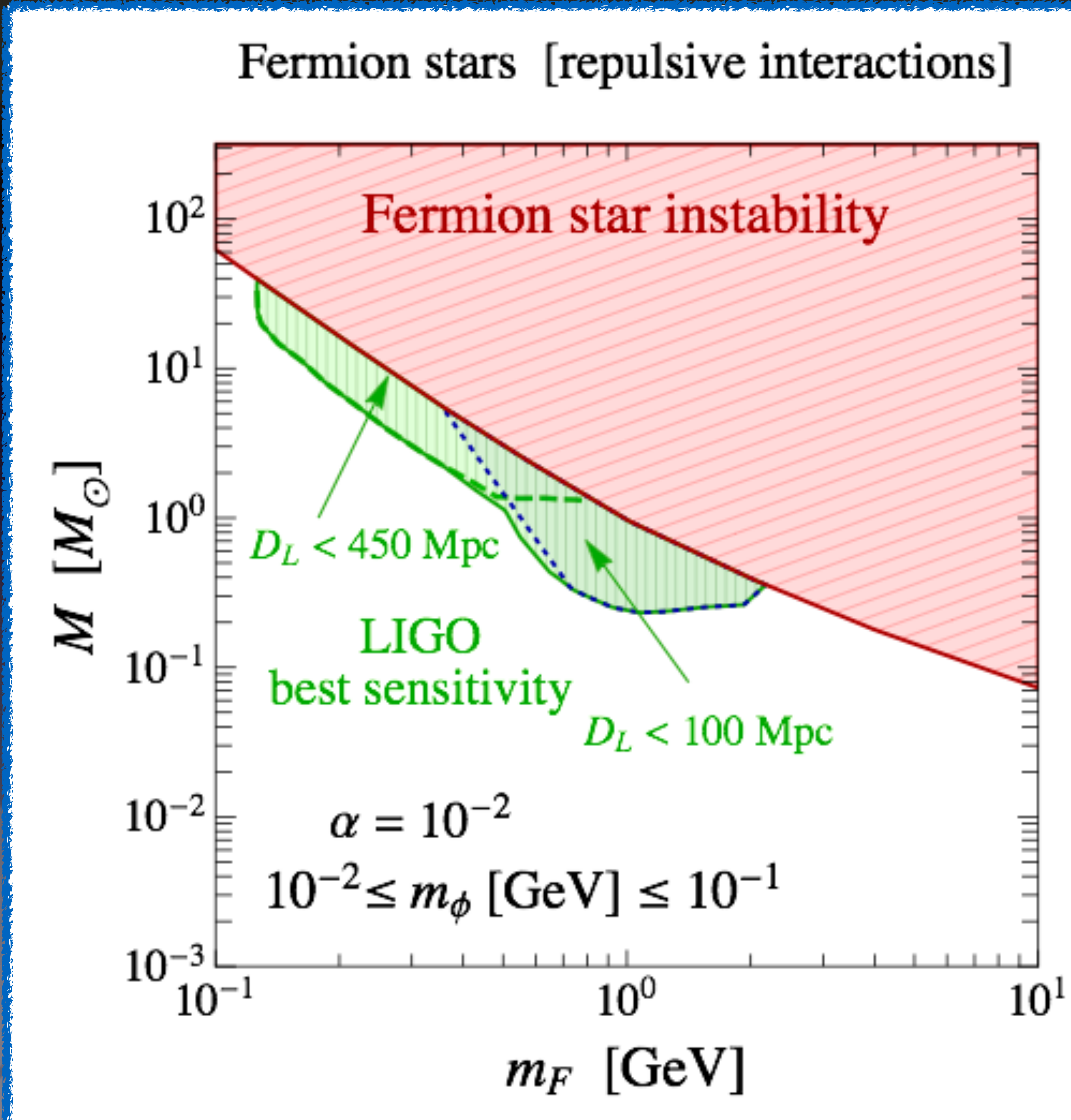


ρ ≥ 8
LIGO best sensitivity
D_L < 450 Mpc
D_L < 250 Mpc
D_L < 100 Mpc
f = [50–1000] Hz
M [M_⊙]
C = M/R
10^2
10^1
10^0
10^-1
0.1
0.2
0.3
0.4
0.5

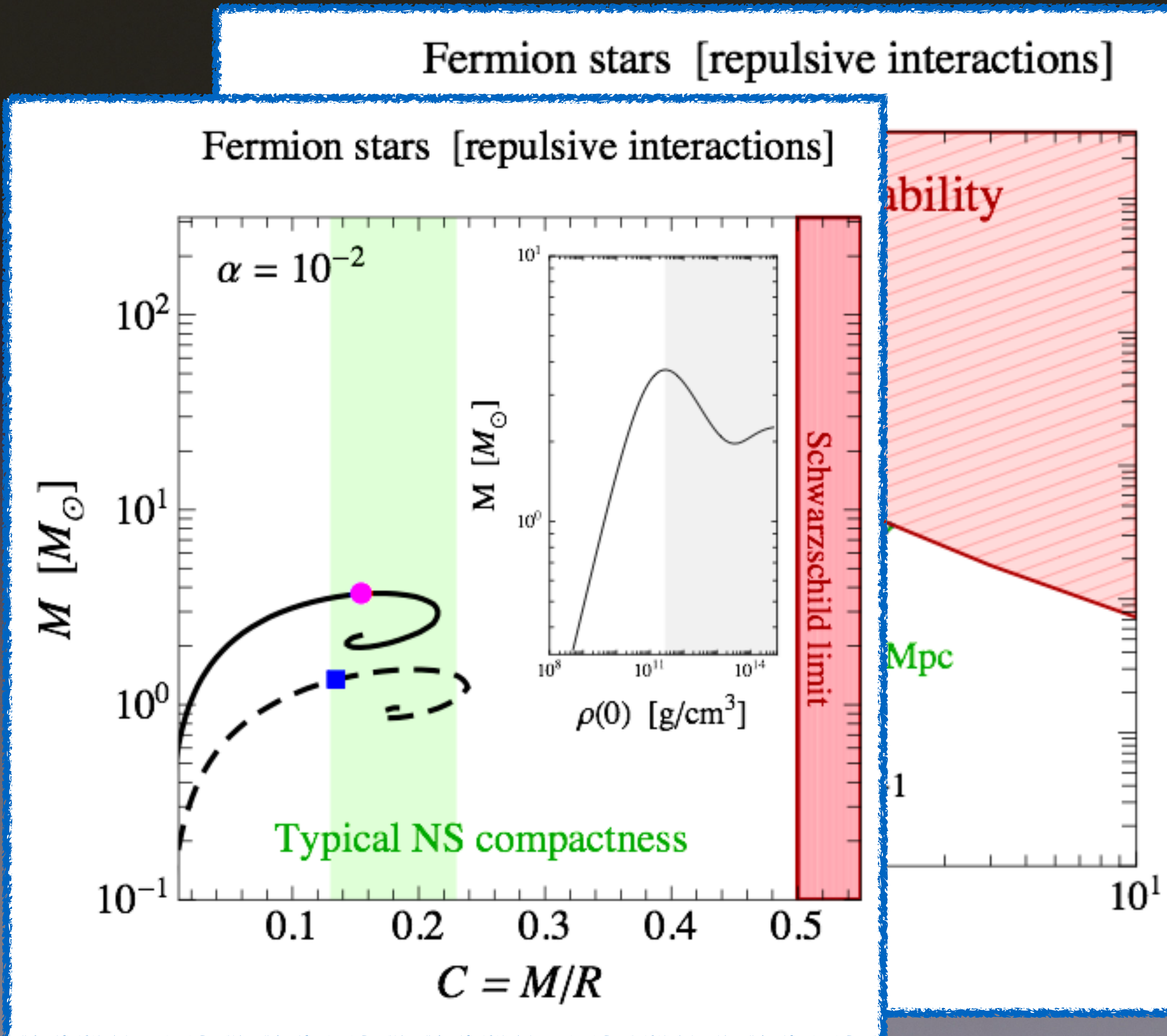

Boson stars [repulsive self−interactions]
Boson star instability
$D_L < 450$ Mpc
LIGO
best sensitivity
$D_L < 100$ Mpc
$\left(\frac{m_B}{\mathrm{MeV}}\right)^{3/2} \leq \frac{\lambda}{10^{-3}} \leq 3\left(\frac{m_B}{\mathrm{MeV}}\right)^{3/2}$
$M\ [M_\odot]$
m_B [MeV]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}


Boson stars [repulsive self−interactions]
nstability
10^4
10^5
Boson stars [repulsive self−interactions]
0.20
0.15
0.10
0.05
0.00
M_*
0.1
0.2
0.3
0.4
0.5
C = M/R
Typical NS compactness
Schwarzschild limit
0.25
0.20
0.15
0.10
0.05
0.00
M_*
Unstable equilibria
10^-2
10^-1
10^0
10^1
10^2
10^3
ρ_*(0)


Boson stars [repulsive self−interactions]
Boson stars [repulsive self−interactions]
nstability
M*
0.20
0.15
0.10
0.05
0.00
Strain [10−21]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.0
0.1
0.2
0.3
0.4
0.5
Time [s]
BH-BH
ECOF-ECOF



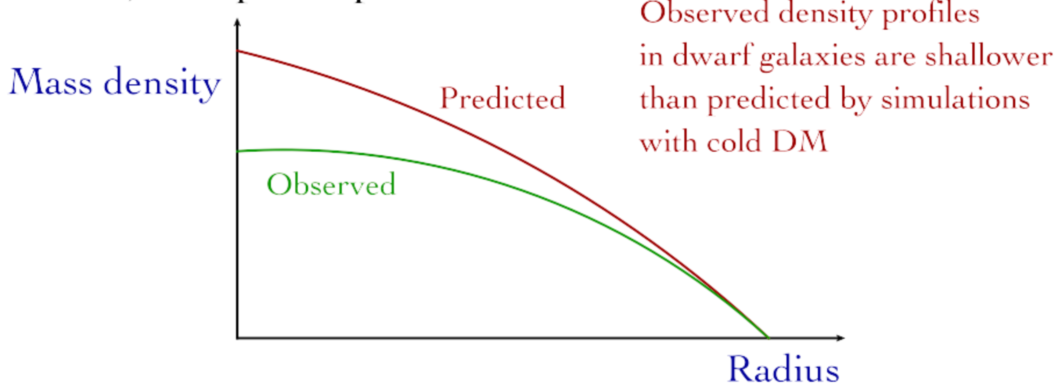
Fermion stars [repulsive interactions]
Fermion star instability
D_L < 450 Mpc
LIGO
best sensitivity
D_L < 100 Mpc
$\alpha = 10^{-2}$
$10^{-2} \leq m_\phi$ [GeV] $\leq 10^{-1}$
M [$M_\odot$]
m_F [GeV]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^{0}
10^{1}

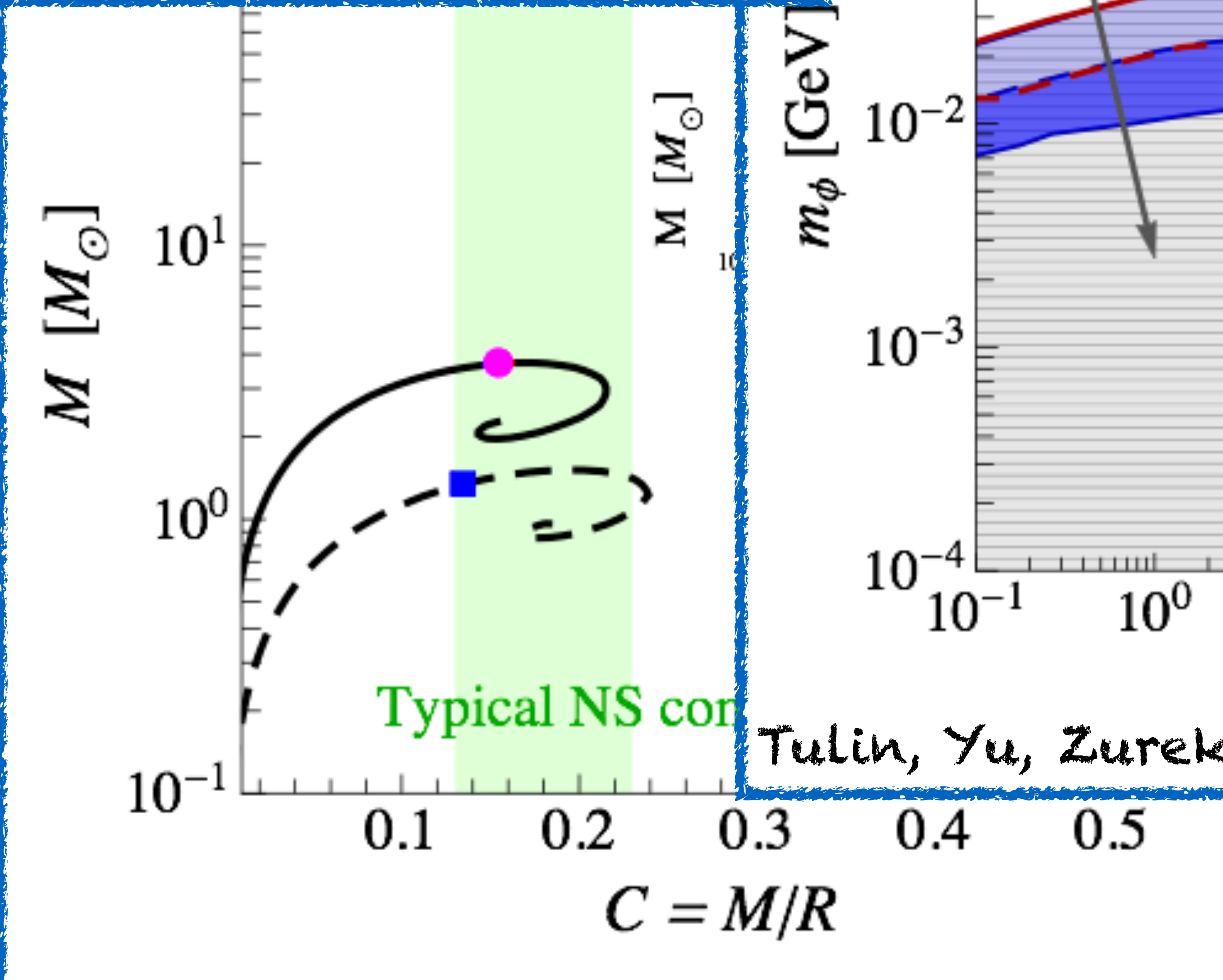

Fermion stars [repulsive interactions]
ability
Mpc
1
10^1
Fermion stars [repulsive interactions]
$\alpha = 10^{-2}$
$M\ [M_\odot]$
10^2
10^1
10^0
10^{-1}
0.1
0.2
0.3
0.4
0.5
$C = M/R$
Typical NS compactness
Schwarzschild limit
$M\ [M_\odot]$
10^1
10^0
10^8
10^{11}
10^{14}
$\rho(0)$ [g/cm^3]

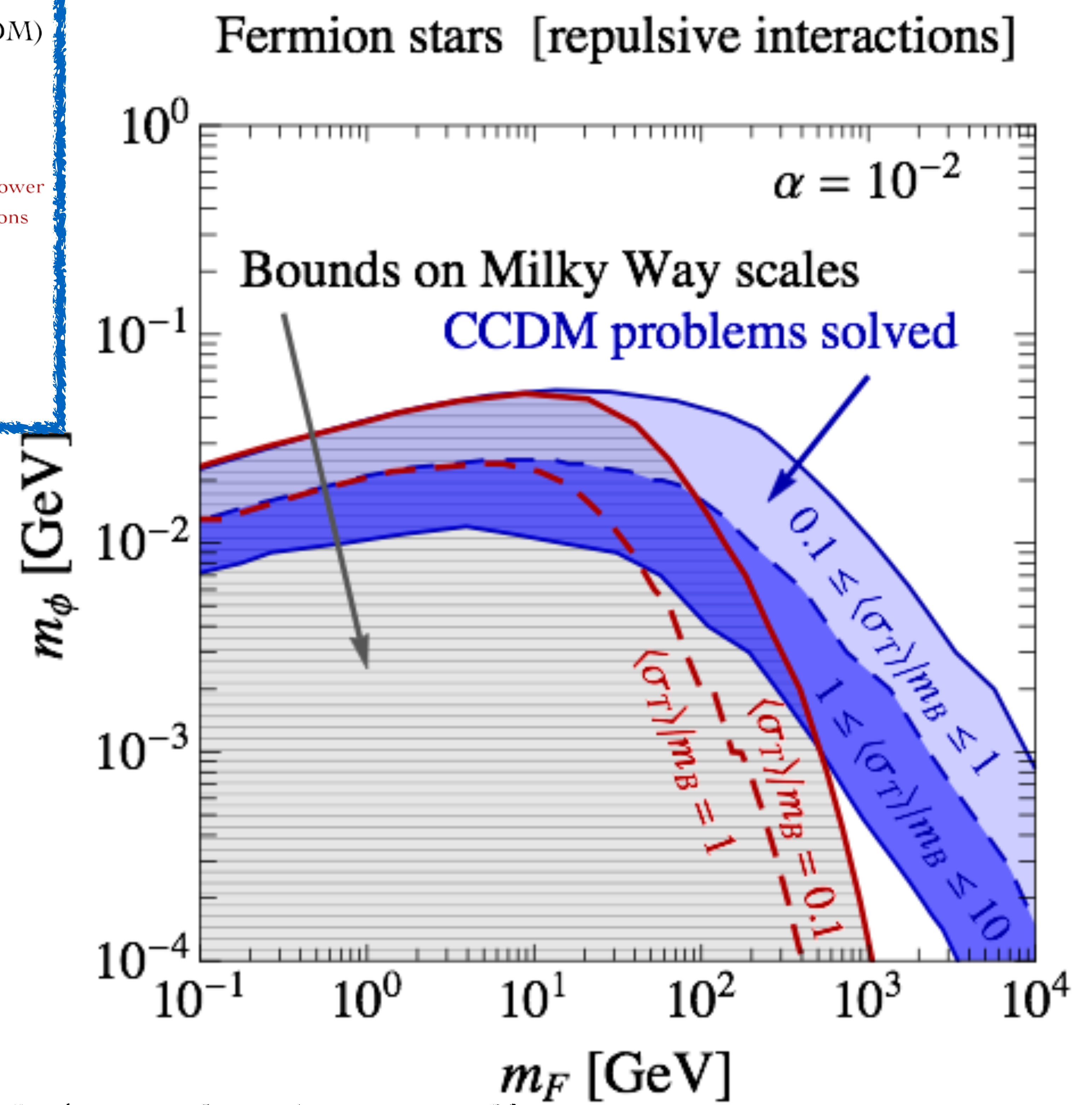
MOTIVATIONS

- Numerical N-body simulations with cold Dark Matter (DM) do not match observations at small galactic scales

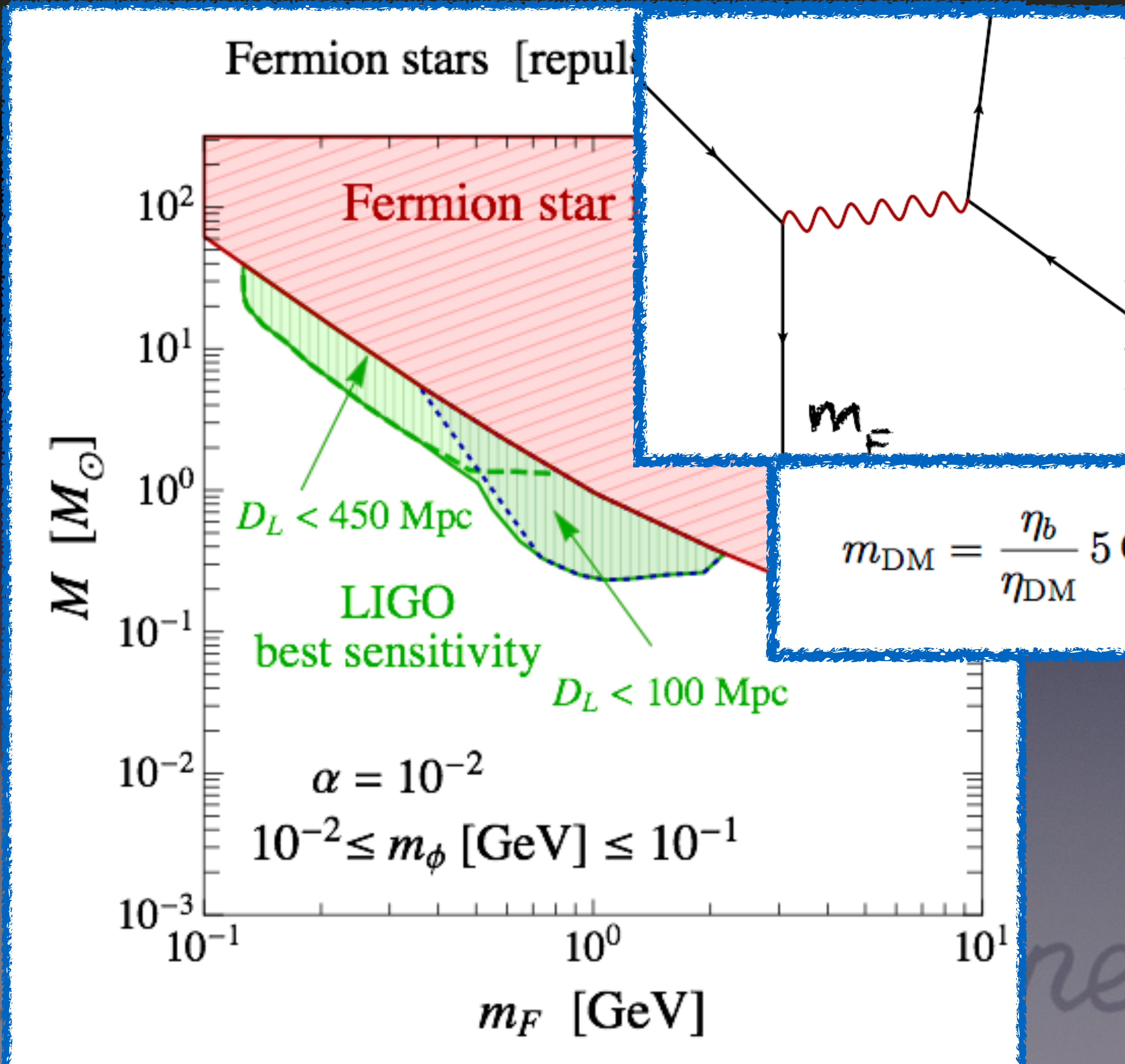
1) "Cusp/core problem"



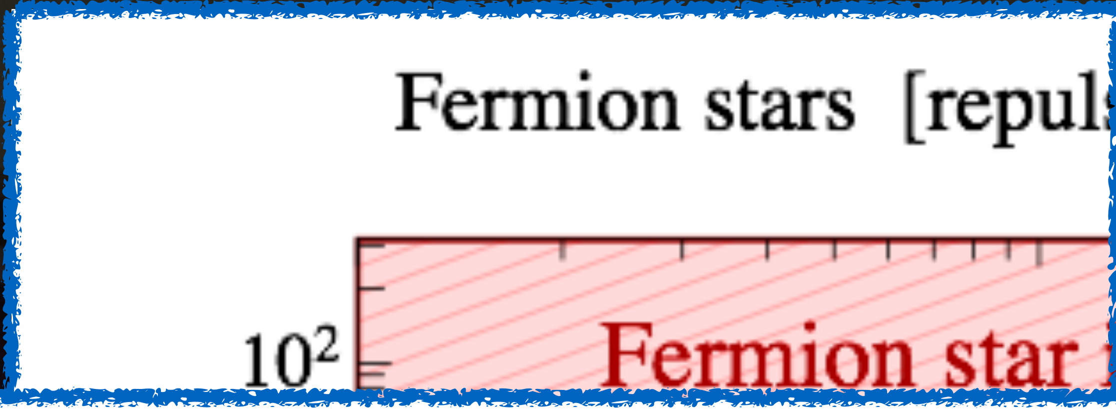


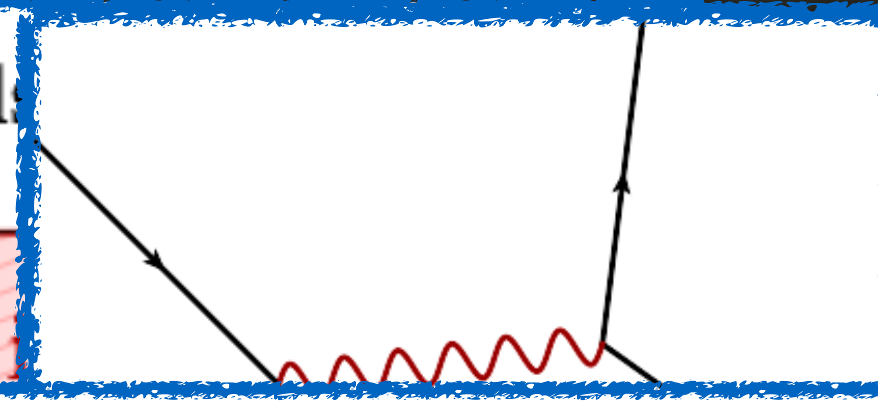


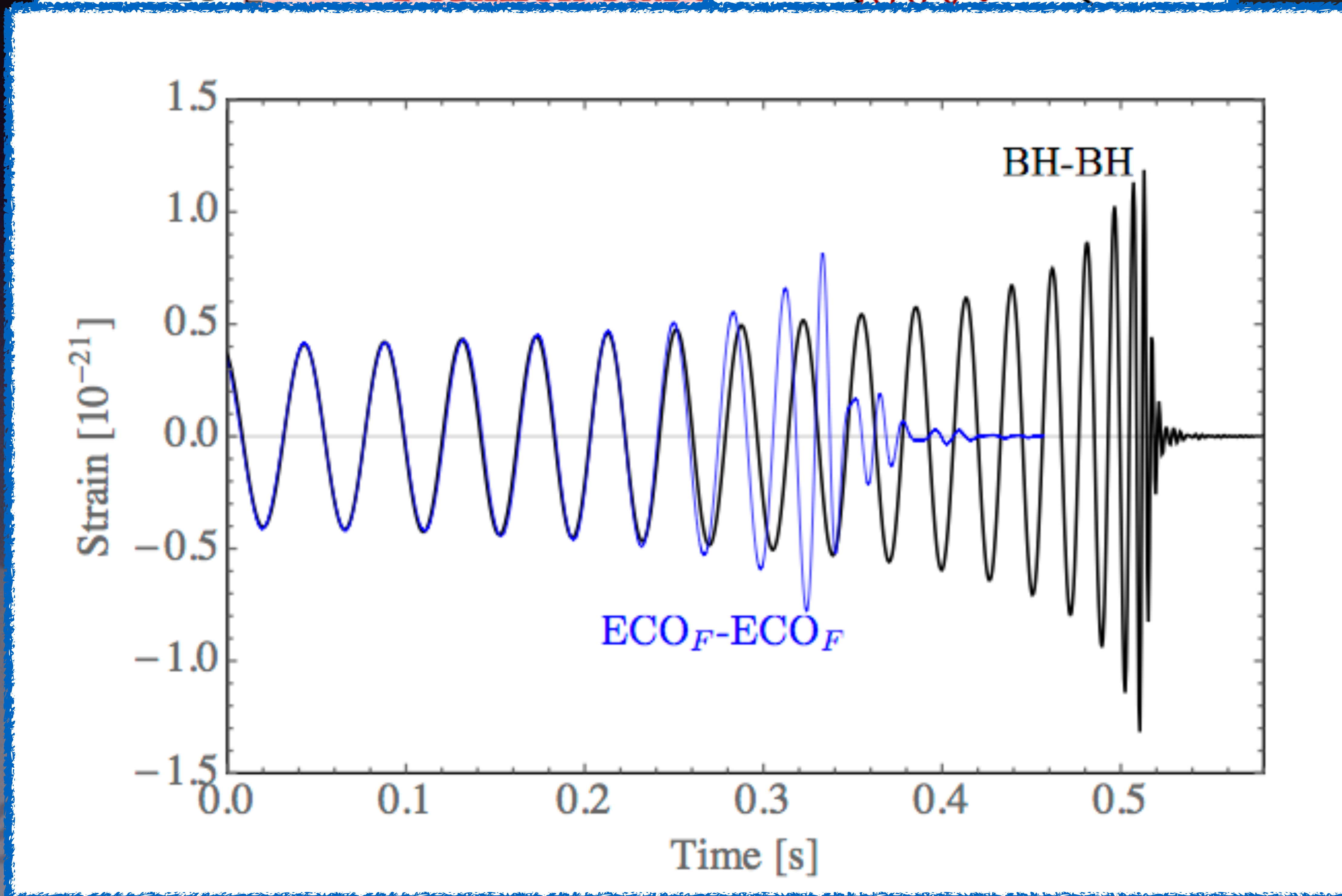
Tulin, Yu, Zurek, Phys.Rev.D87,11,115007



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


Fermion stars [repul
10^2
Fermion star




BH-BH
ECO_F-ECO_F
Strain [10^{-21}]
Time [s]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.0
0.1
0.2
0.3
0.4
0.5

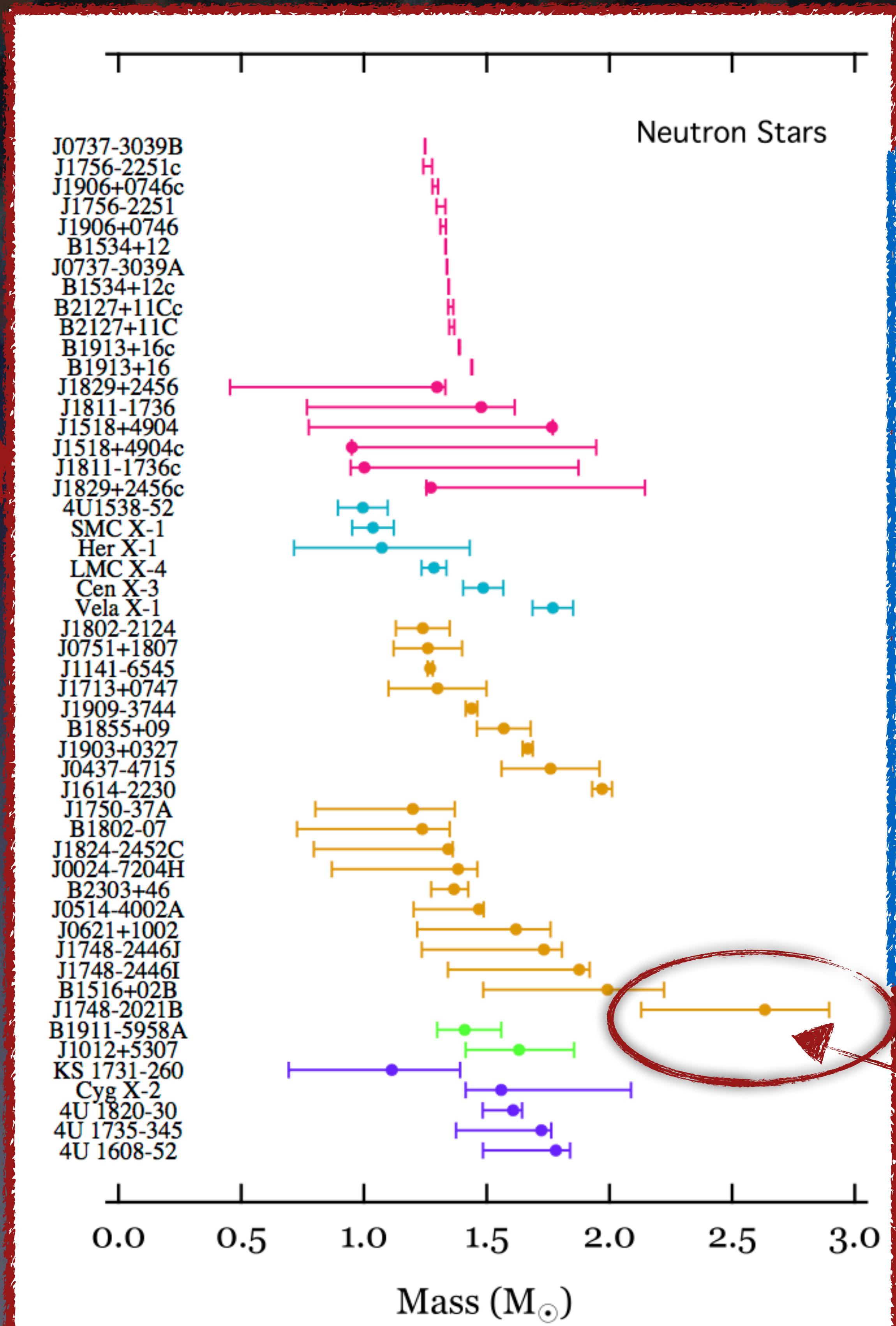
Statistical distributions

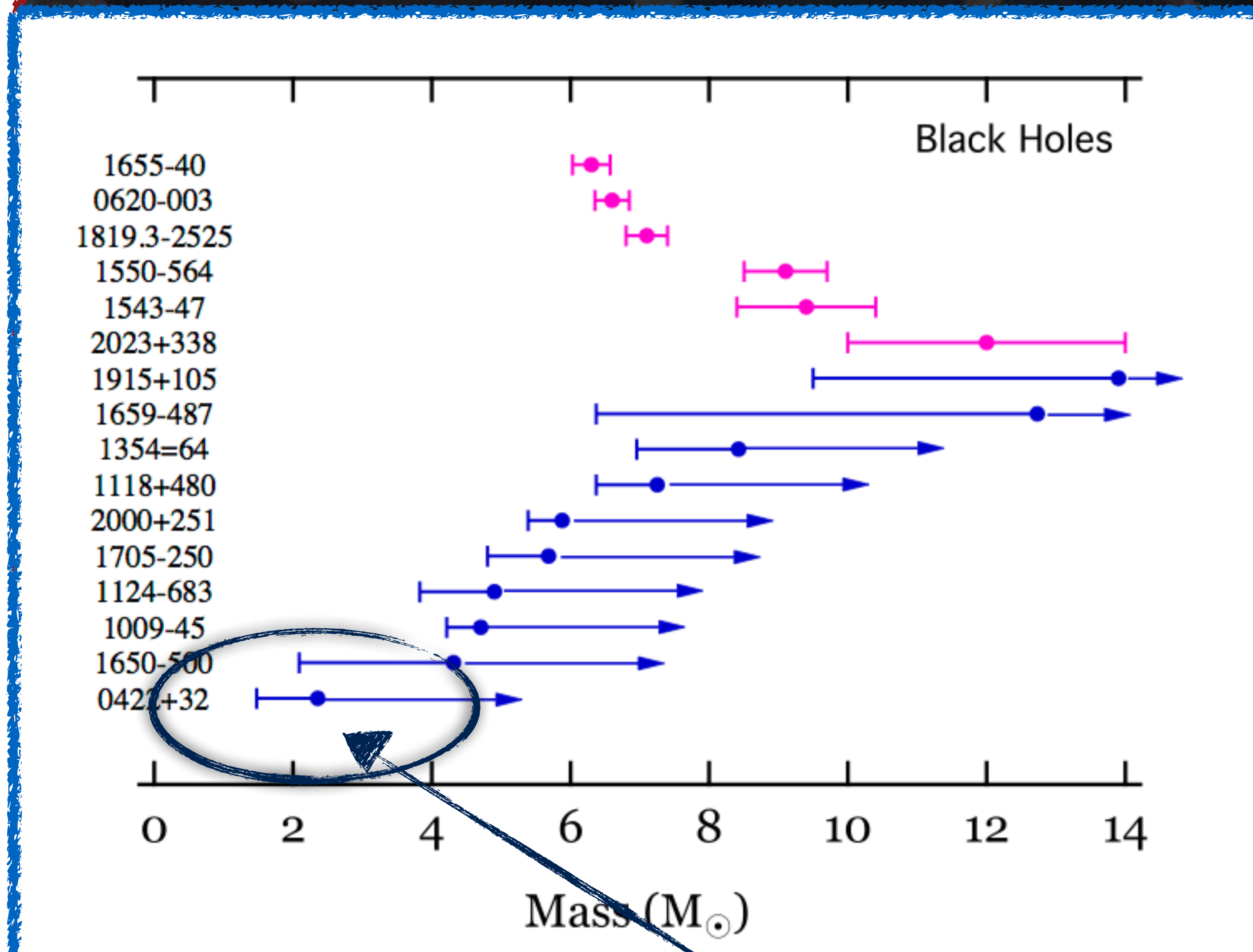
Simulations from "The Synthetic Universe project",
http://www.syntheticuniverse.org/

Statistical distributions

Typical compactness
$C = M/R = [0.1-0.2]$
($C = 0.5$ for a Schw. BH)

Statistical distributions





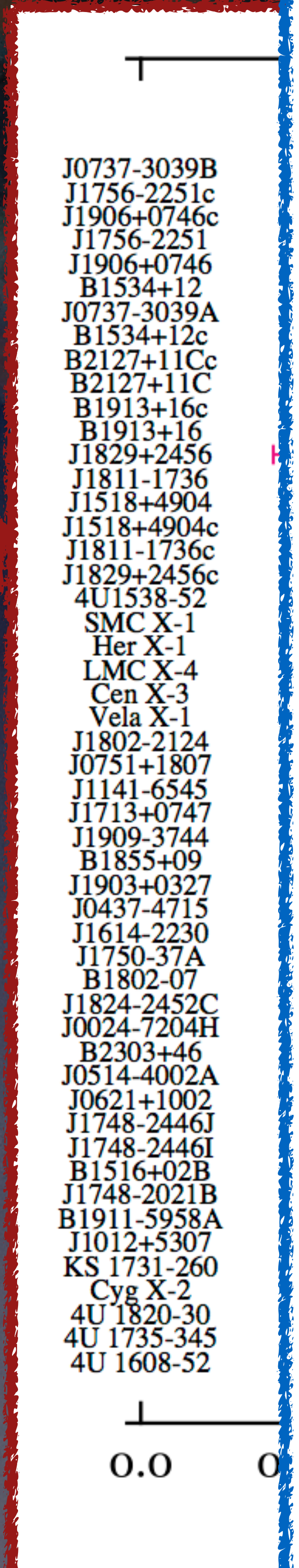
tness

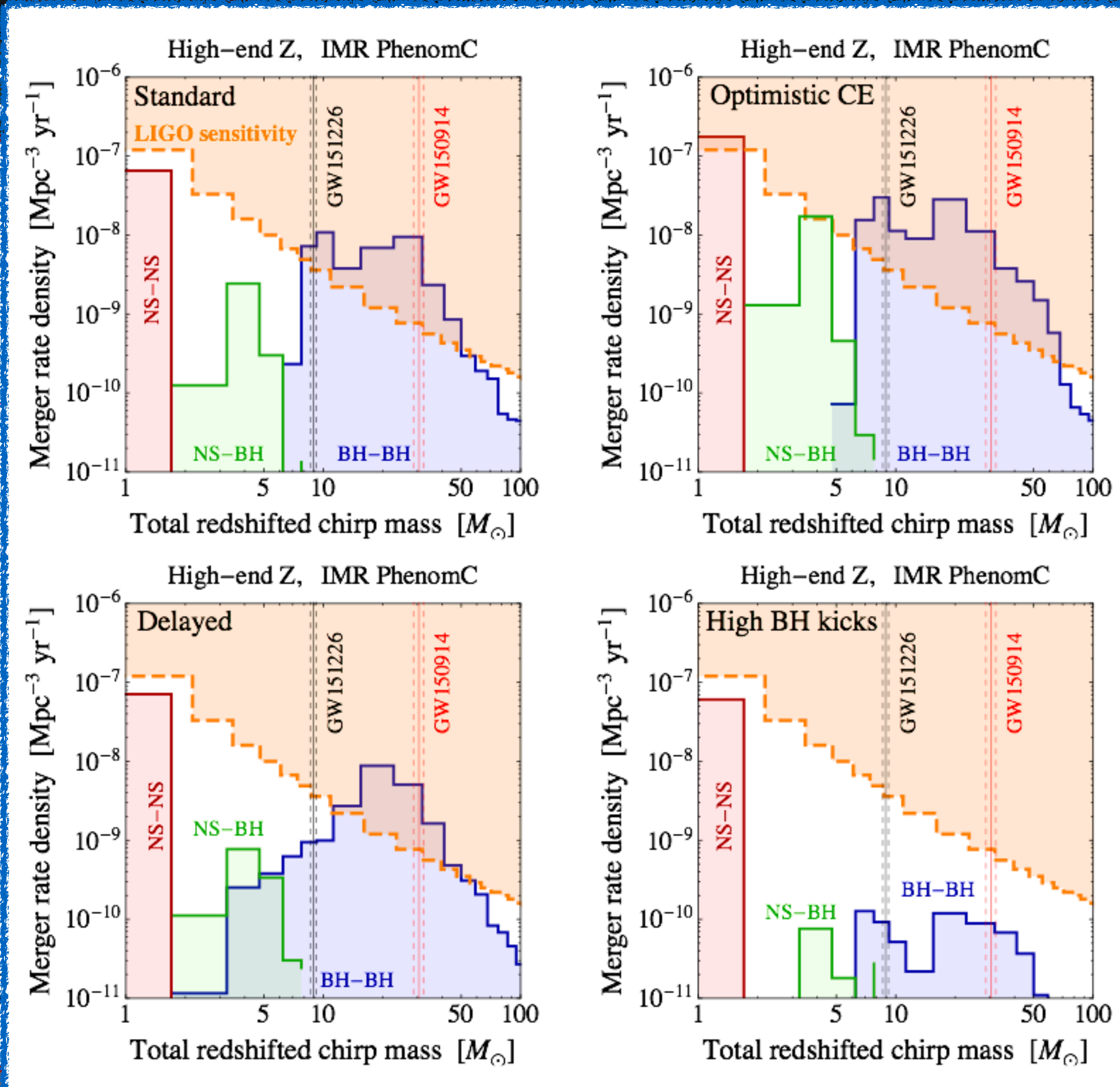
-0.2]

chw. BH)

"soft" X-ray transient

Inclination unknown


J0737-3039B
J1756-2251c
J1906+0746c
J1756-2251
J1906+0746
B1534+12
J0737-3039A
B1534+12c
B2127+11Cc
B2127+11C
B1913+16c
B1913+16
J1829+2456
J1811-1736
J1518+4904
J1518+4904c
J1811-1736c
J1829+2456c
4U1538-52
SMC X-1
Her X-1
LMC X-4
Cen X-3
Vela X-1
J1802-2124
J0751+1807
J1141-6545
J1713+0747
J1909-3744
B1855+09
J1903+0327
J0437-4715
J1614-2230
J1750-37A
B1802-07
J1824-2452C
J0024-7204H
B2303+46
J0514-4002A
J0621+1002
J1748-2446J
J1748-2446I
B1516+02B
J1748-2021B
B1911-5958A
J1012+5307
KS 1731-260
Cyg X-2
4U 1820-30
4U 1735-345
4U 1608-52
0.0


High−end Z, IMR PhenomC
Standard
Optimistic CE
Delayed
High BH kicks
LIGO sensitivity
GW151226
GW150914
NS−NS
NS−BH
BH−BH
Merger rate density [Mpc^{-3} yr^{-1}]
Total redshifted chirp mass [$M_\odot$]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
1
5
10
50
100

Outlook

* Exotic signature
  - Formation
  - Computation of the merger rate density