BLACK HOLES IN THE COSMOS

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IAP/JHU/Oxford

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The black holes of nature are the most perfect macroscopic objects there are in the universe: the only elements in their construction are our concepts of space and time.

Subrahmanyan Chandrasekhar

PREDICTION

If the semi-diameter of a sphere of the same density as the Sun were to exceed that of the Sun in the proportion of 500 to 1, a body falling from an infinite height towards it would have acquired at its surface greater velocity than that of light, and consequently supposing light to be attracted by the same force in proportion to its vis inertiae, with other bodies, all light emitted from such a body would be made to return towards it by its own proper gravity.

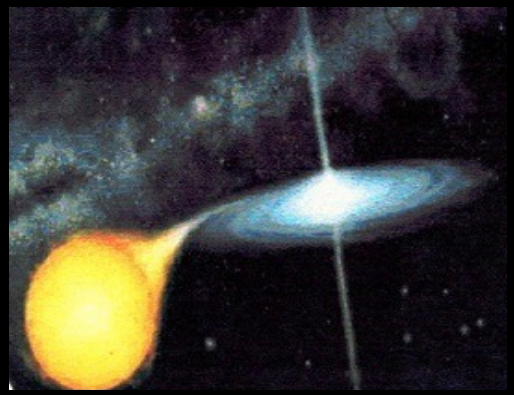
John Michell 1724-1793

John Michell 1783
Professor of Geology at Cambridge, then a Yorkshire vicar

Escape velocity from star satisfies $\frac{1}{2} v^2 = GM/r$ $v <$ speed of light c

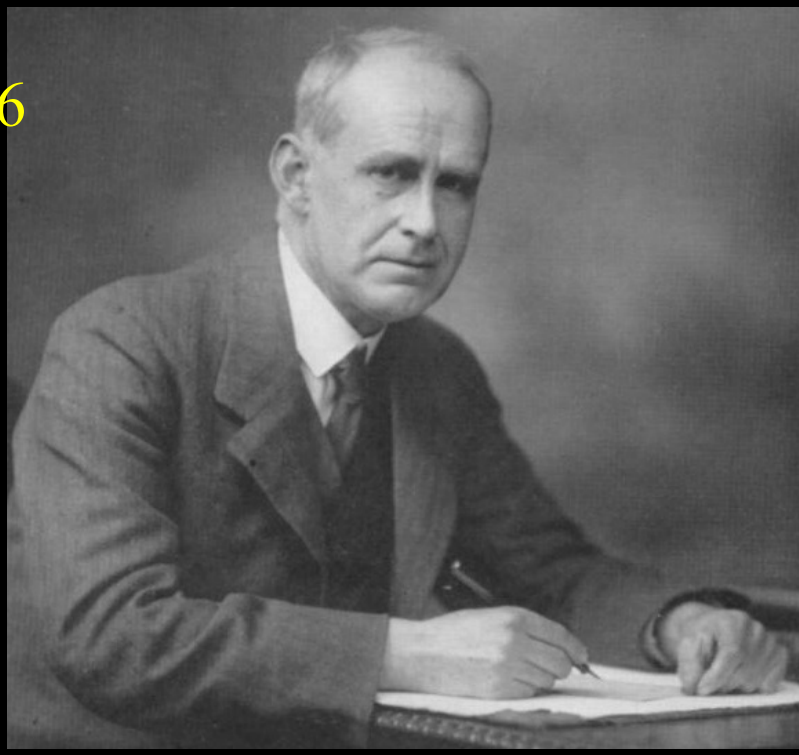
If a star is too compact, light cannot escape!

The critical size is $r=2GM/c^2$



Purpose. By the Rev. John Michell, *B. D. F. R. S.*
Letter to Henry Cavendish, *Esq. F. R. S. and A. S.*

Arthur Eddington 1882-1946



imagine a physicist calculating
on a cloud-bound planet and ending with the
dramatic conclusion, "What 'happens' is the stars."

In 1913, Einstein wrote to many astronomers
urging them tosearch for his predicted shift of 0.87”

In 1916, he changed his mind: 0.87” was the newtonian
prediction, his was double this!

Eddington avoided conscription as a conscientious objector by agreeing to lead an expedition to Principe, West Africa in 1919 to measure the deflection of light during a total eclipse. Another expedition went to Sobral, Brazil.

The results:

Einstein’s prediction: 1.74”, Newton’s theory: 0.87”

Sobral: 1.98+-0.16”; Principe: 1.61+-0.40”

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

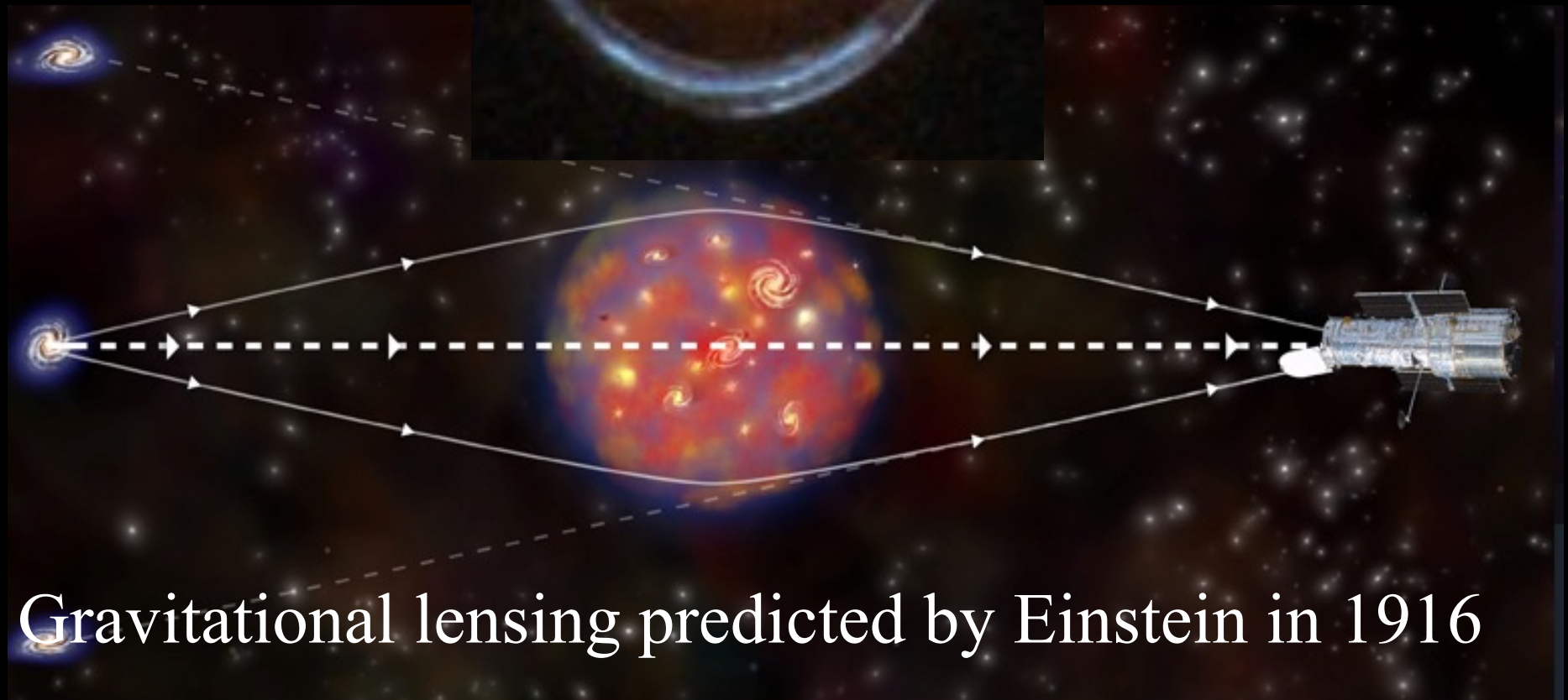
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

New York Times headline of

Albert Einstein 1879-1955

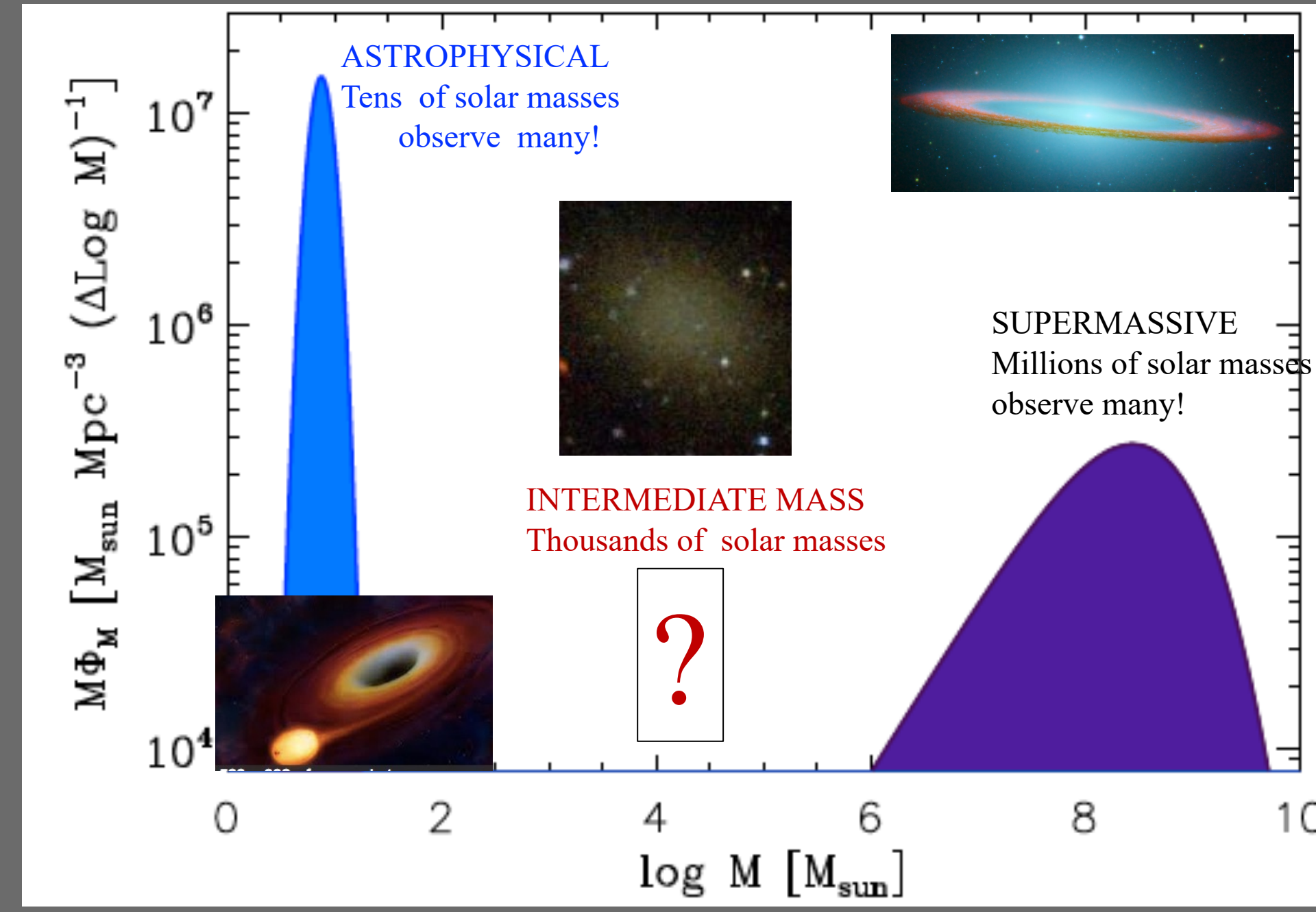
In 1916 used general relativity
correct result of $4GM/rc^2$
(time dilation + space curvature)

Gravitational lens observed

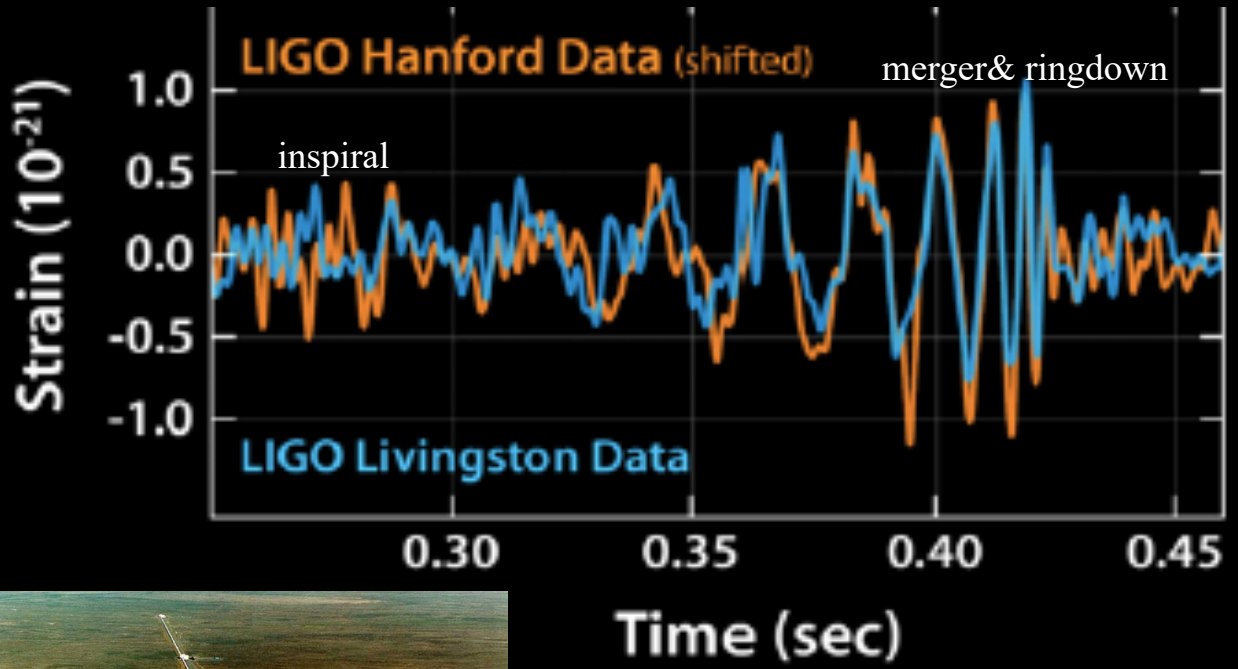


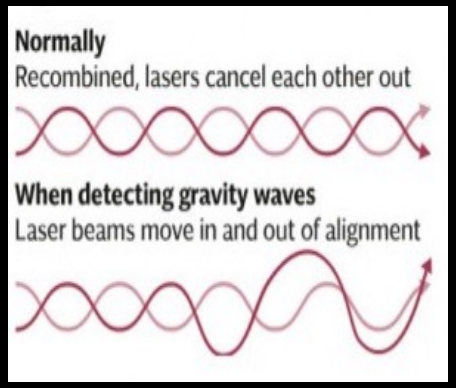
Gravitational lensing predicted by Einstein in 1916

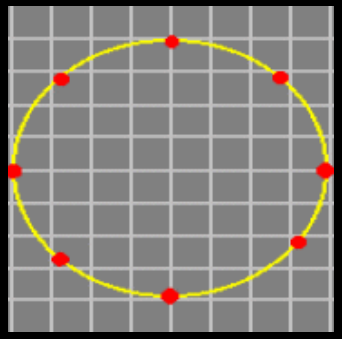
three types of astrophysical black holes

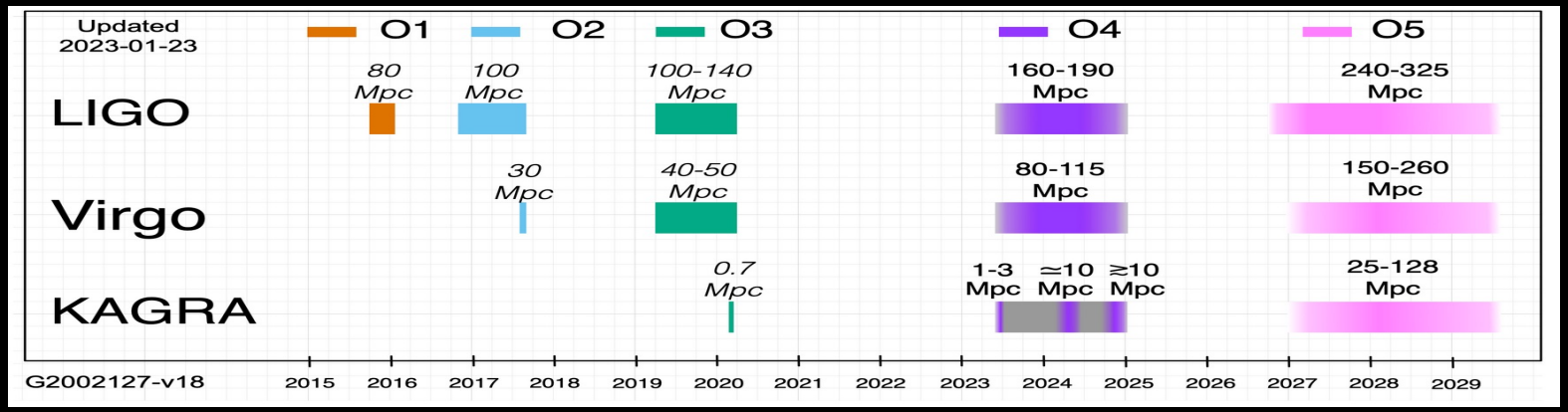


ASTROPHYSIVAL black holes observed








Updated
2023-01-23
O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
100-140 Mpc
160-190 Mpc
240-325 Mpc
Virgo
30 Mpc
40-50 Mpc
80-115 Mpc
150-260 Mpc
KAGRA
0.7 Mpc
1-3 Mpc
≃10 Mpc
≳10 Mpc
25-128 Mpc
G2002127-v18
2015
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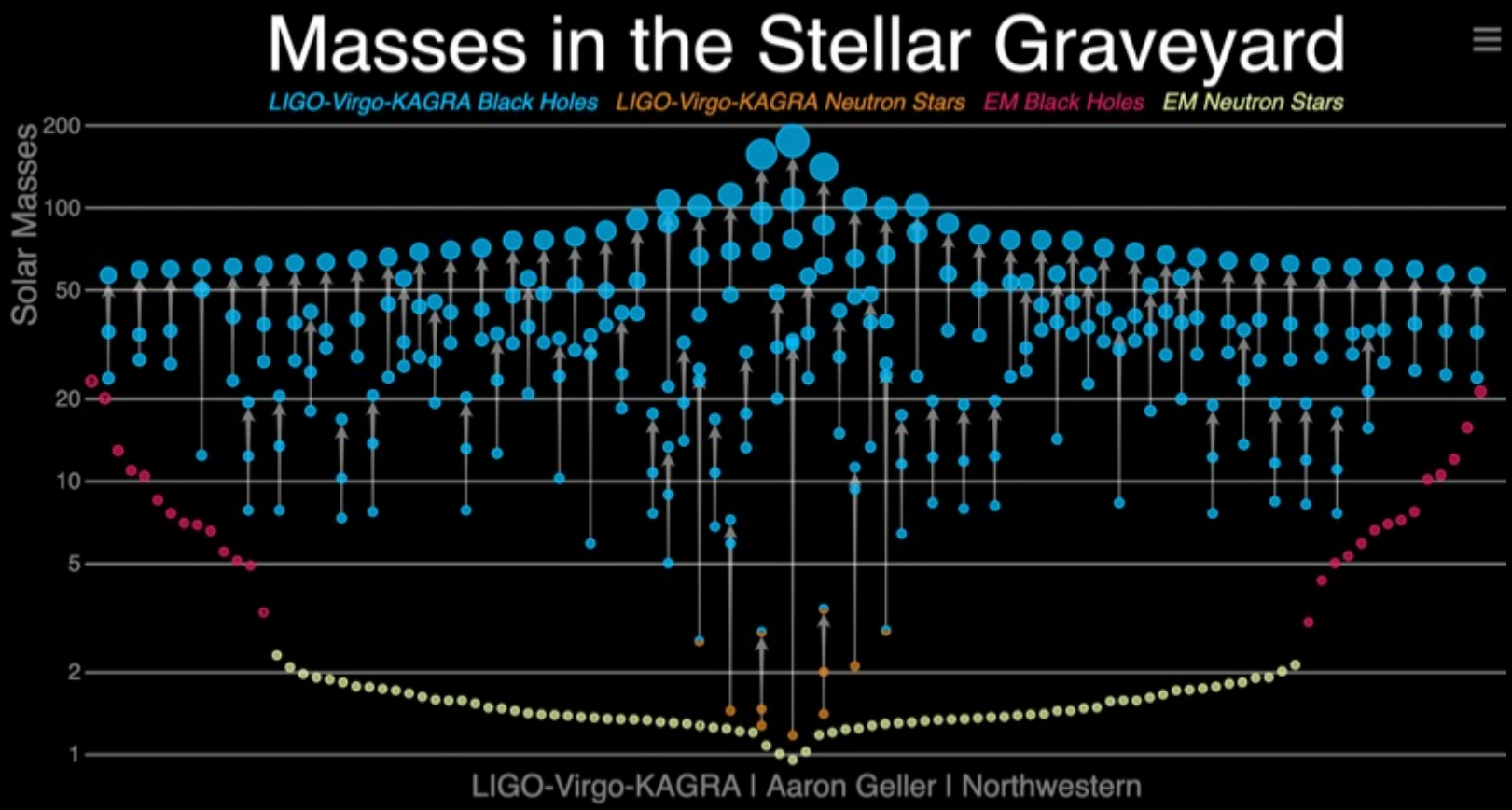
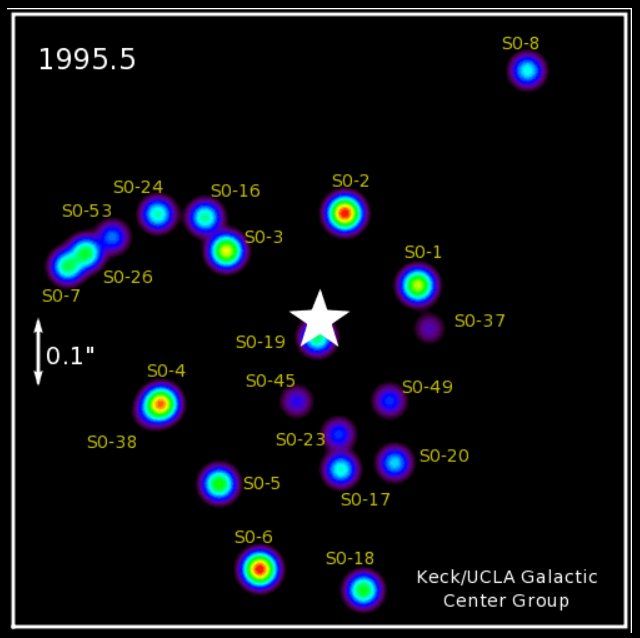

Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

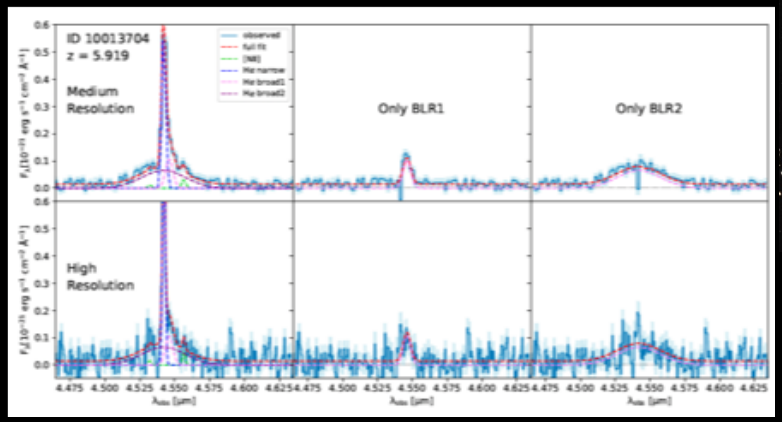
Orbits of stars tell us black hole mass

Centre of our galaxy 4.10^6 Msun

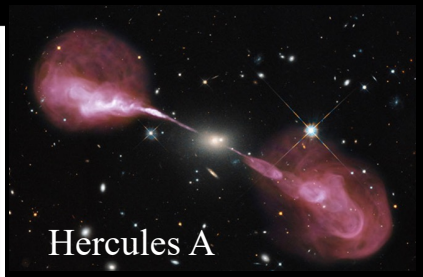


Distant massive black holes

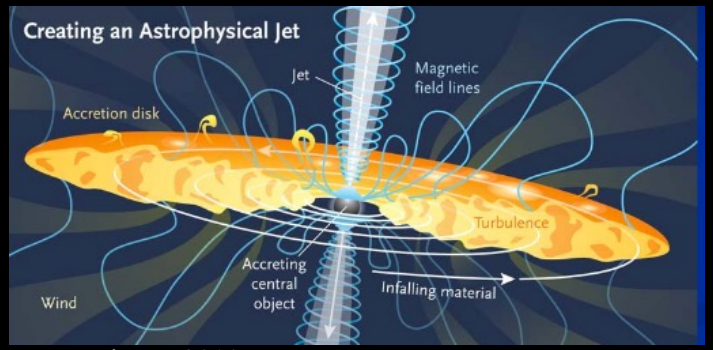
Binary SMBH pair



Maiolino 2023



Radio galaxy and jet

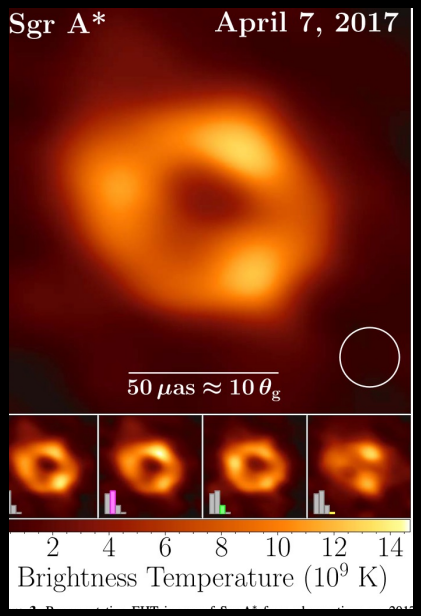


McKinney 2010

The central engine

Imaging the BH

4.10^6 M_{sun}



Black hole shadow observed

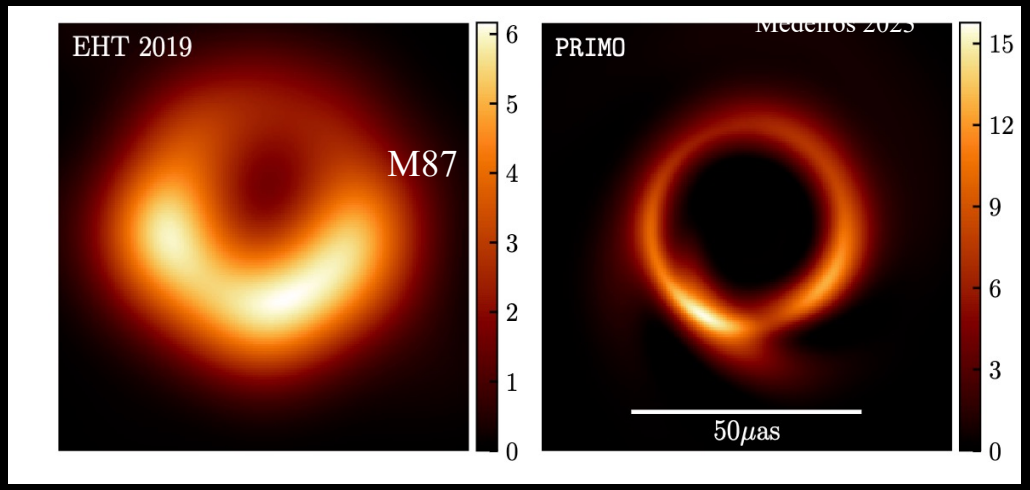
Event Horizon Telescope

Resolve black hole horizon scale

GM/c^2 at ~5 μ arcsec

M87 distance 2000 x GC but M_{BH} 1500 x SagA*

6.10^9 Msun



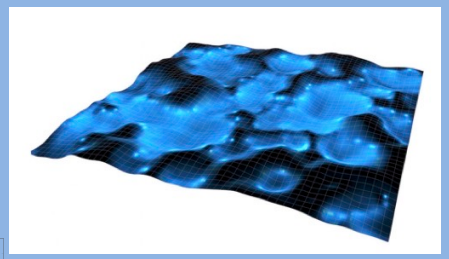
PRIMORDIAL BLACK HOLES

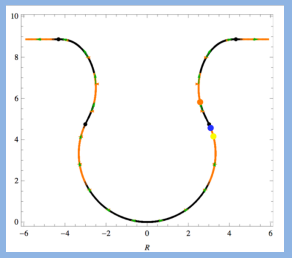
A plausible candidate for the dark matter

primordial black holes
form by known physics

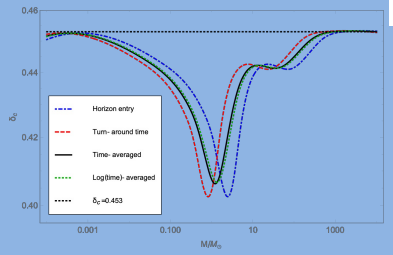
Formation Mechnisms of Primordial Black Holes

- Large density perturbations (inflation)

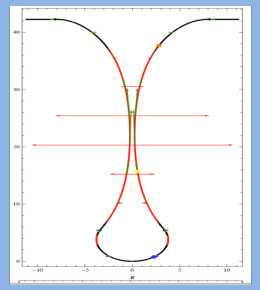




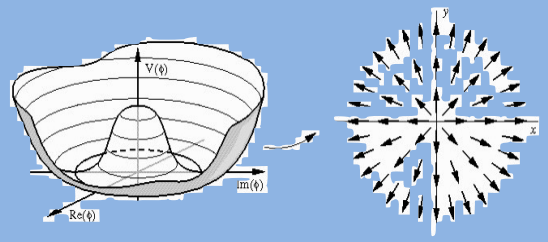
- Pressure reduction

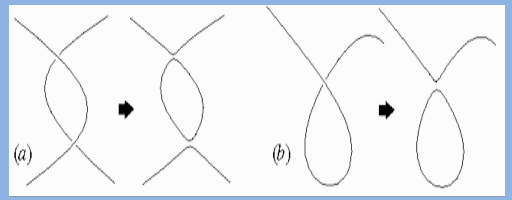


Kopp 2010

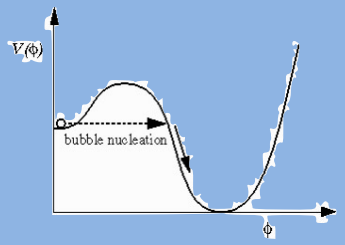


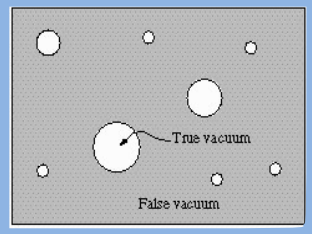
- Cosmic string loops

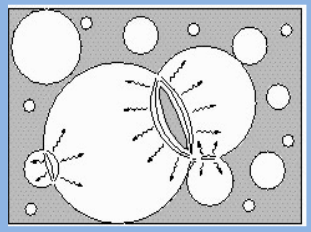




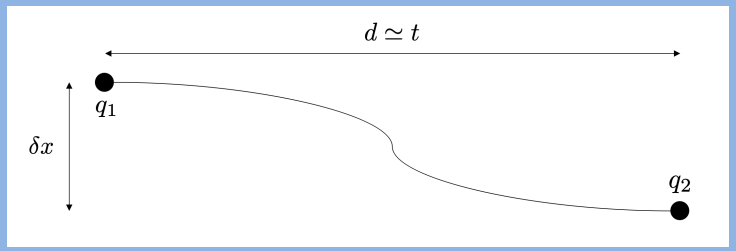
- Bubble collisions







- Quark confinement

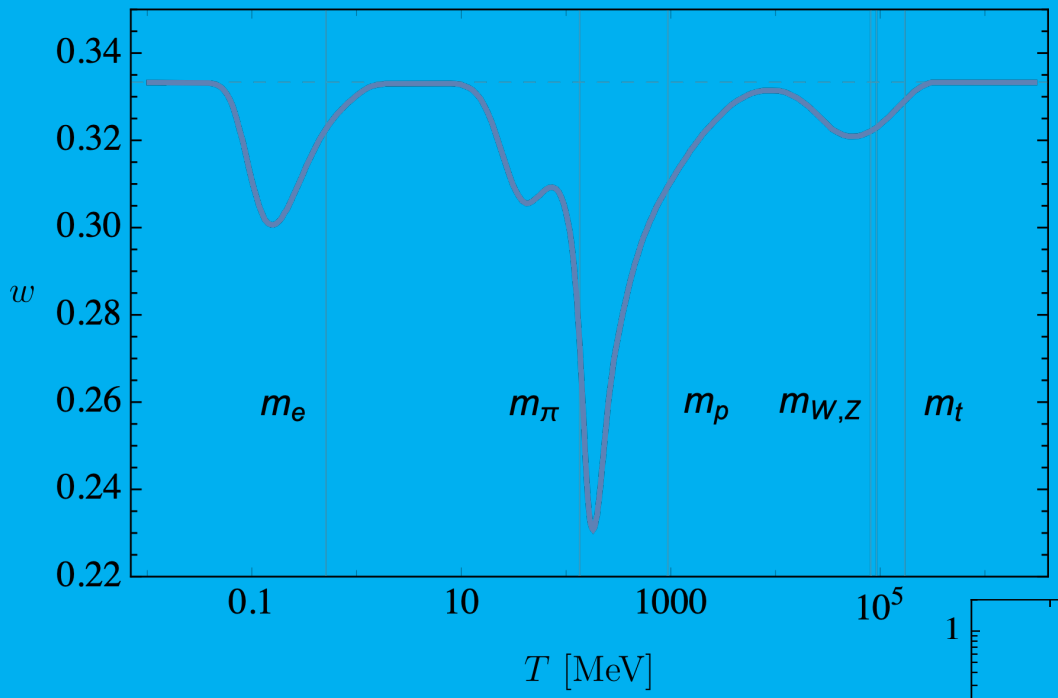


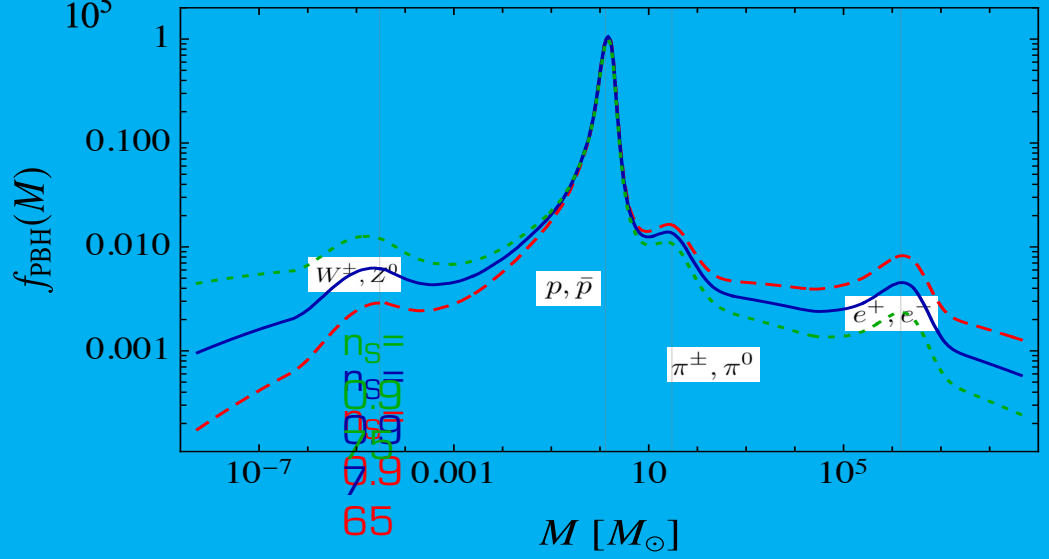
Credit: Carr and Kuhnel 2021

Thermal History of the Universe

Changes in equation-of-state parameter $w = p/\rho$ are destabilizing

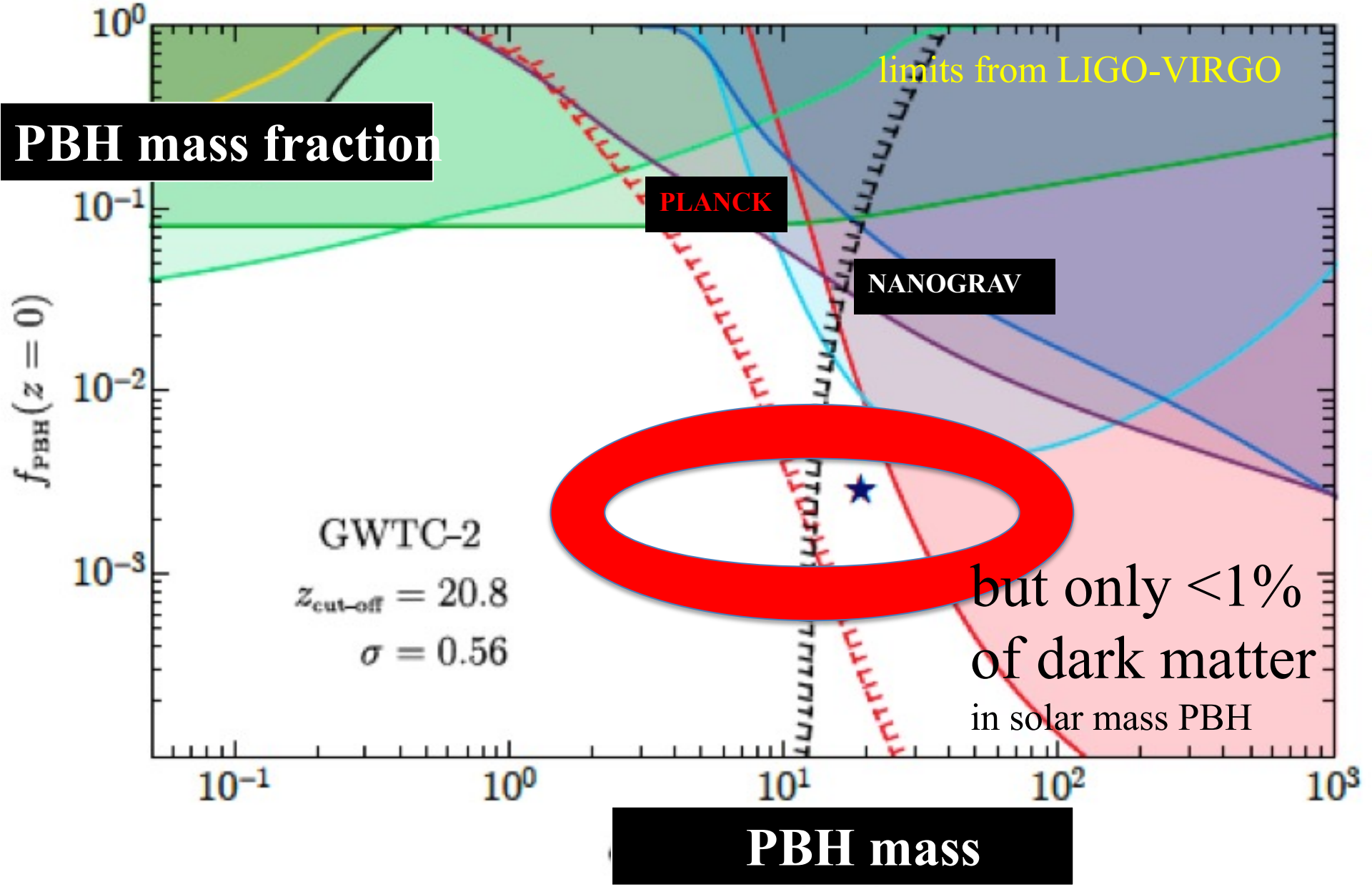
Especially at QCD epoch





Carr 2021

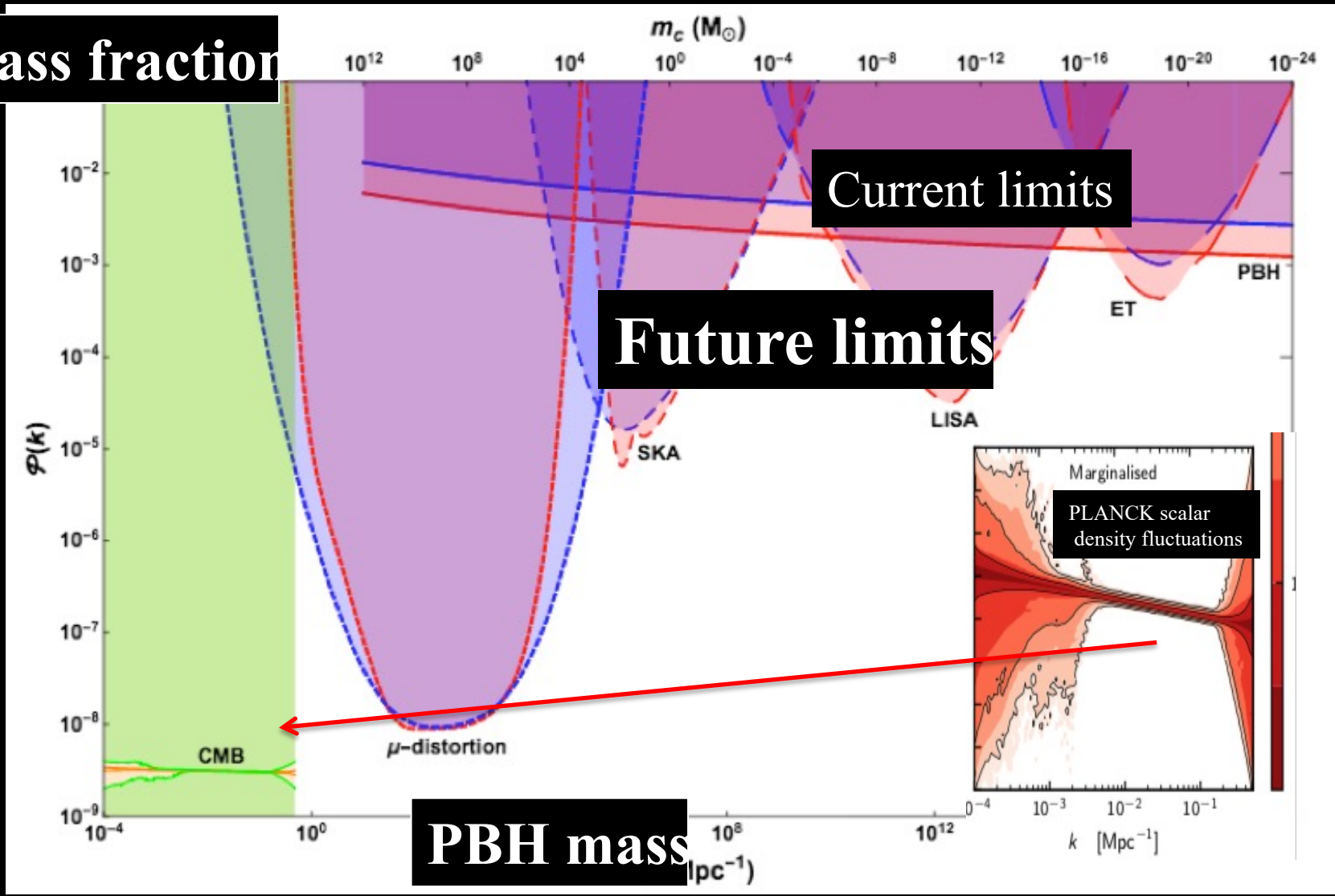
Can solar massPBH be the dark matter?



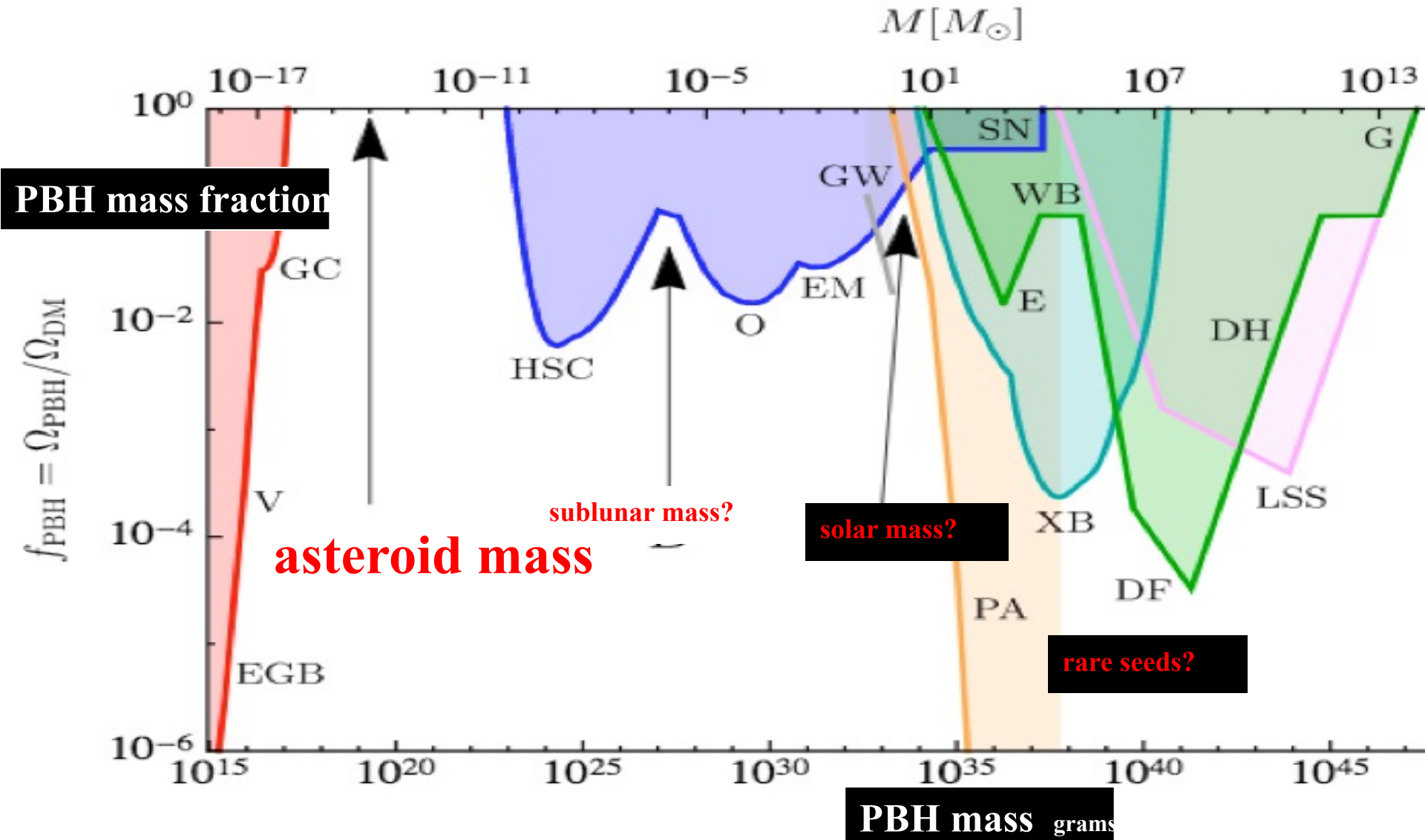
Wong + 2020

How to constrain PBH!

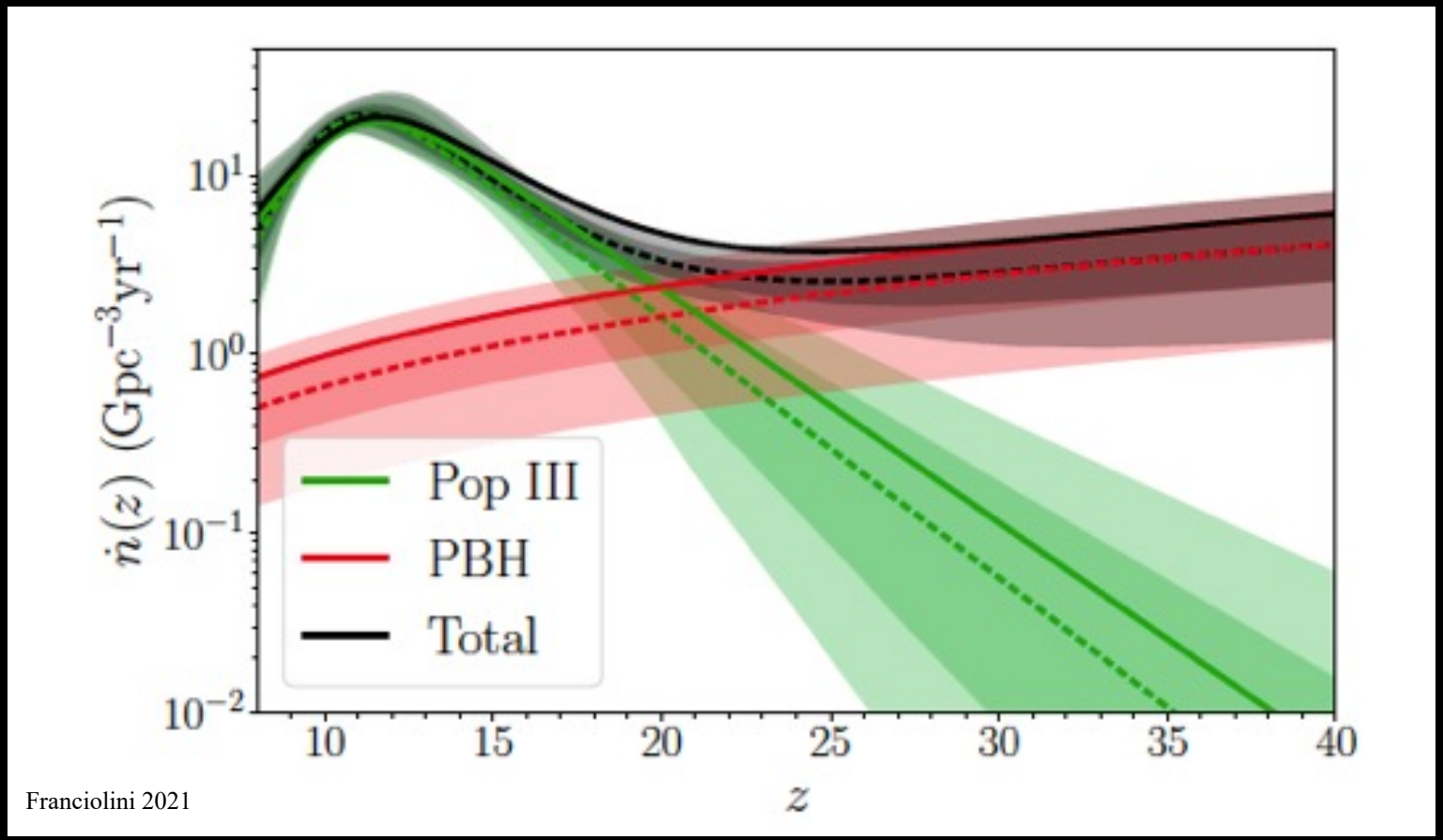
Predict stochastic gravity wave background at formation



PBH mass windows of interest but only one is a 100% dark matter option



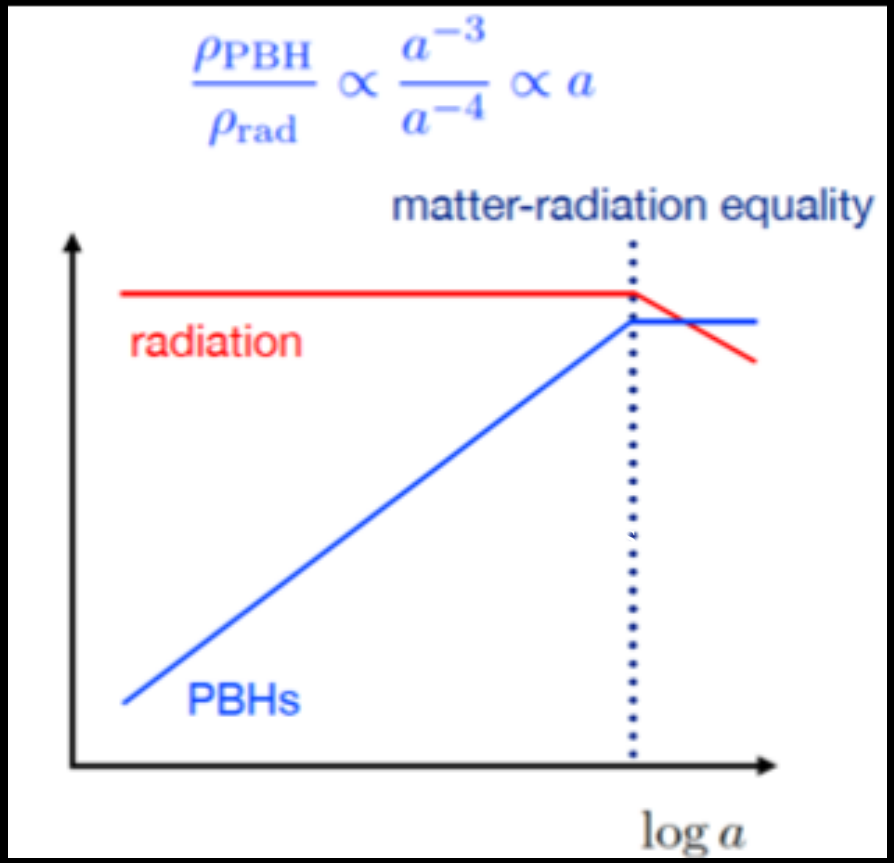
How to distinguish primordial from astrophysical BH



Franciolini 2021

PBHs are rare at formation

a tiny birth fraction dominates DM at late times



Green 2001

PBH EVAPORATION

Black holes radiate thermally with temperature

T = ~ 10^{-7} (Msun/M) K

=> evaporate completely in time $t_{evap} \sim 10^{64}$ (M/Msun

M ~ 10^{15}g => final explosion today. Multi-messenger signals

How to slow evaporation: go to higher dimension gravity!

higher dimensional black hole has T ---> 0 as Schwarzschild radius ----> dimension scale

Horizon < dimensional scale R < ~1μm ----> 5d BH

$$\varepsilon_{\rm eff}^{-4} = 3\frac{(d-3)}{(d-1)}\frac{S_4}{S_d}\left(\frac{2\pi R}{r_s}\right)^{2(d-4)}$$

$r_s >> R$ evaporates in 4d…until $r_s \sim R$.

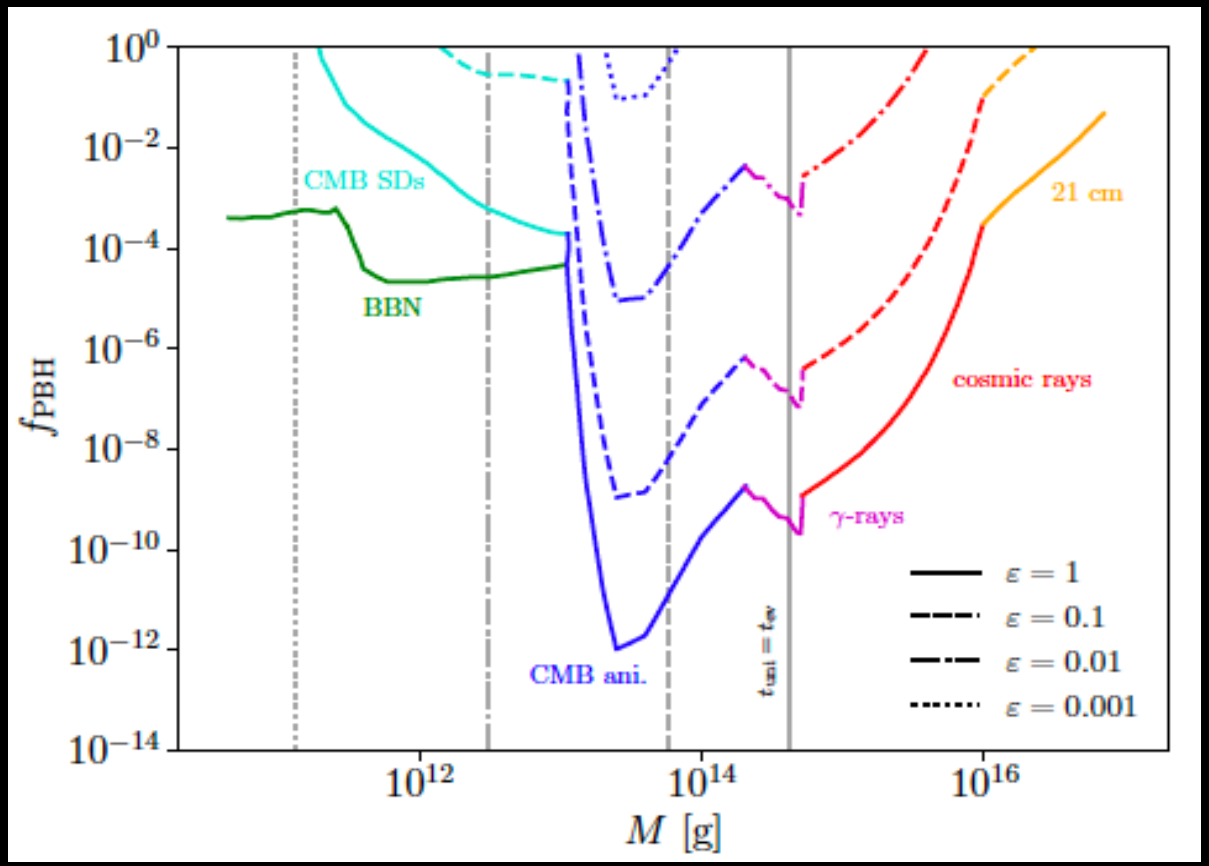
$$1-\frac{a^2}{M^2}=\varepsilon^2$$

$$T=\frac{1}{4\pi r_+}\left(1-\frac{Q^2}{r_+^2}\right)=\frac{1}{8\pi M}\frac{2^2\,\varepsilon}{(1+\varepsilon)^2}$$

$$L=A\sigma T^4\propto r_+^2T^4\propto\frac{2^6\,\varepsilon^4}{(1+\varepsilon)^6M^2}$$

$$1-\frac{Q^2}{M^2}=\varepsilon^2\ll 1$$

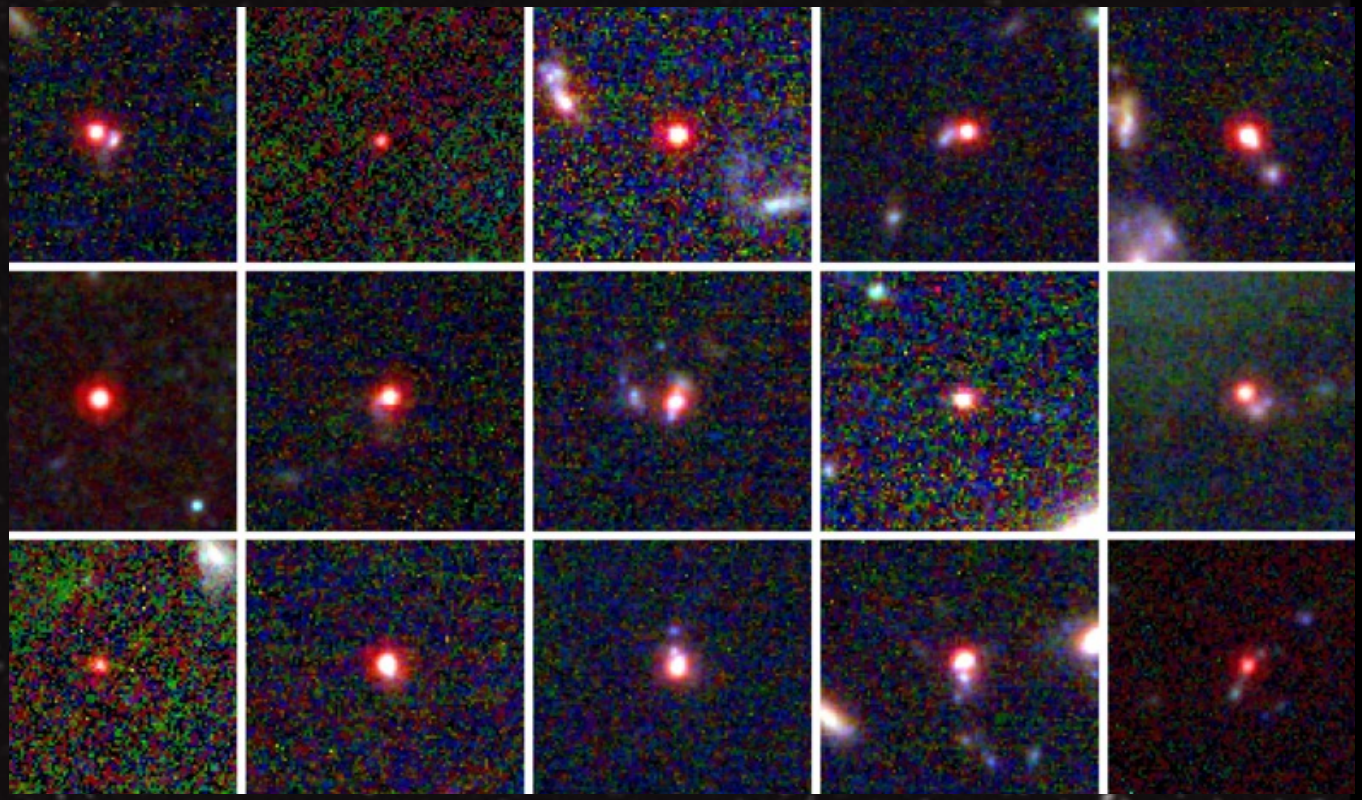
New limits on PBH masses and on extremality



Kiritsis + 2023

SMBH: Whats new from JWST

“Little red dots”



many compact red galaxiess

SMBH 10^7 -10^9 M_{sun}

Ultracompact: R_{eff} =150pc

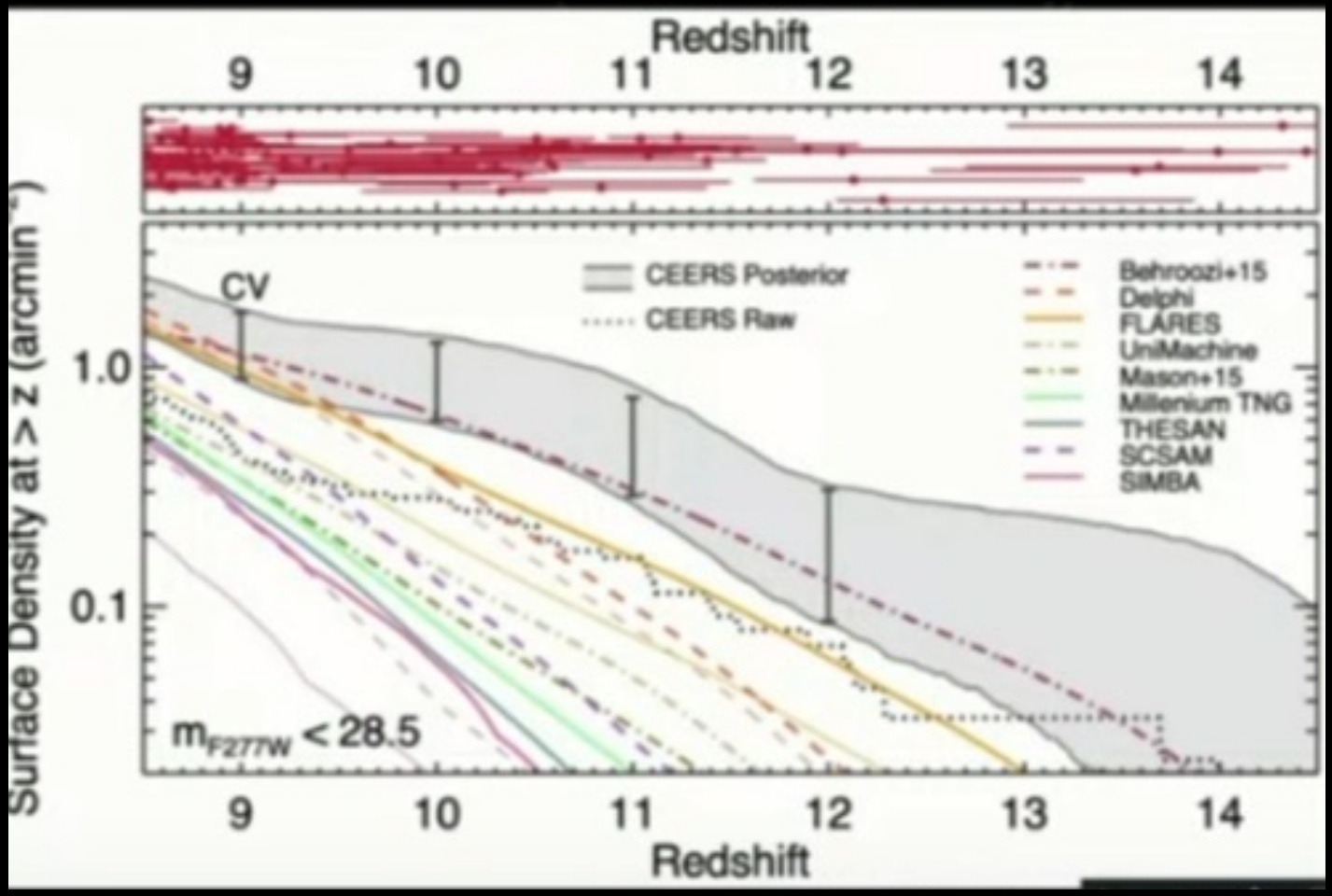
z > 7

100 x frequency of quasars

10% of “normal” galaxies

Mahhee + 2023

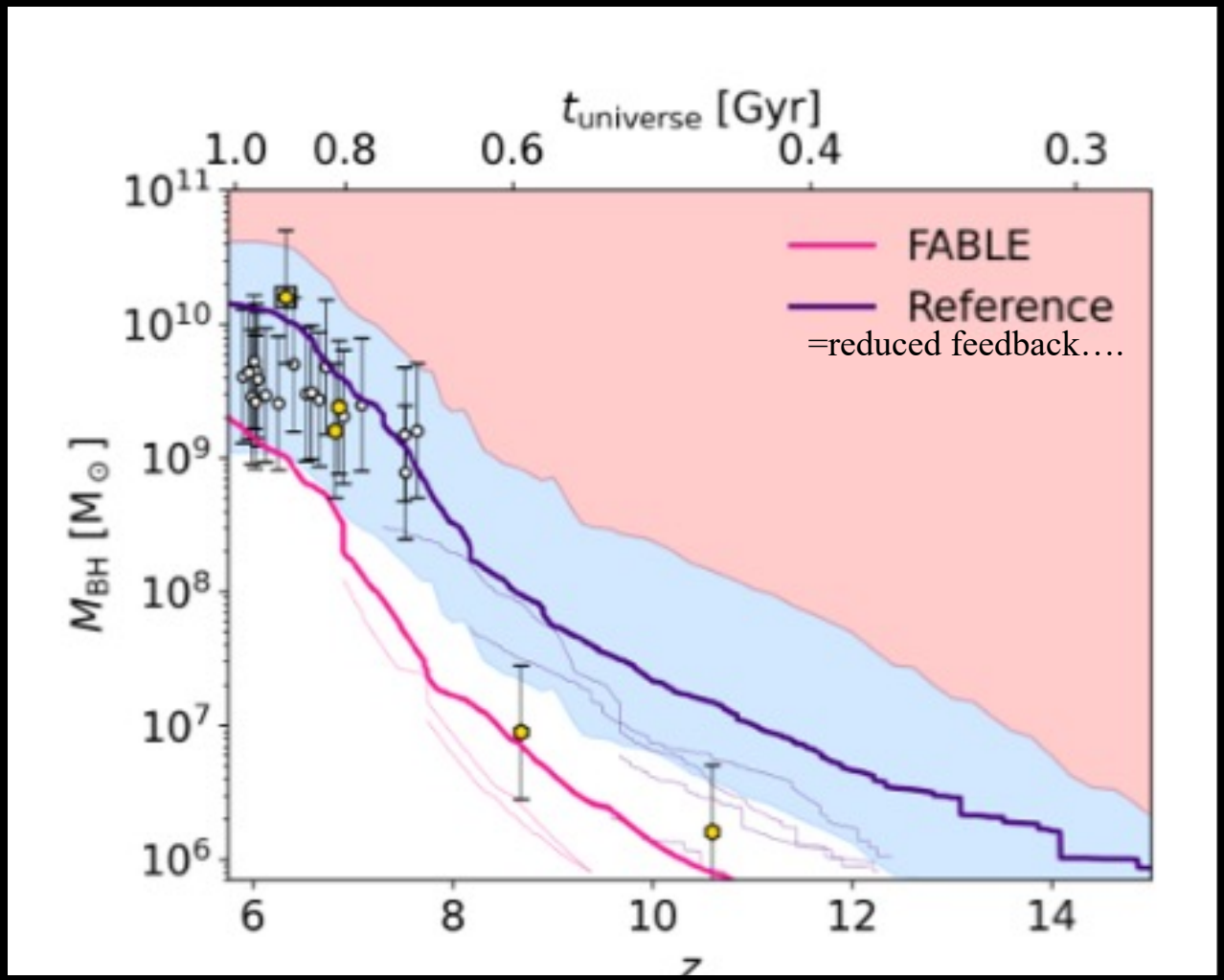
Too many galaxies, too early, too luminous



Finkelstein + 2023

Do SMBH form first?

The missing seeds?



Bennett + 2023

Origin of the seeds

a). PBH

$f_{seed} = M_{seed}/M_{BH} \times M_{BH}/M^* \times M^*/M_{halo}$

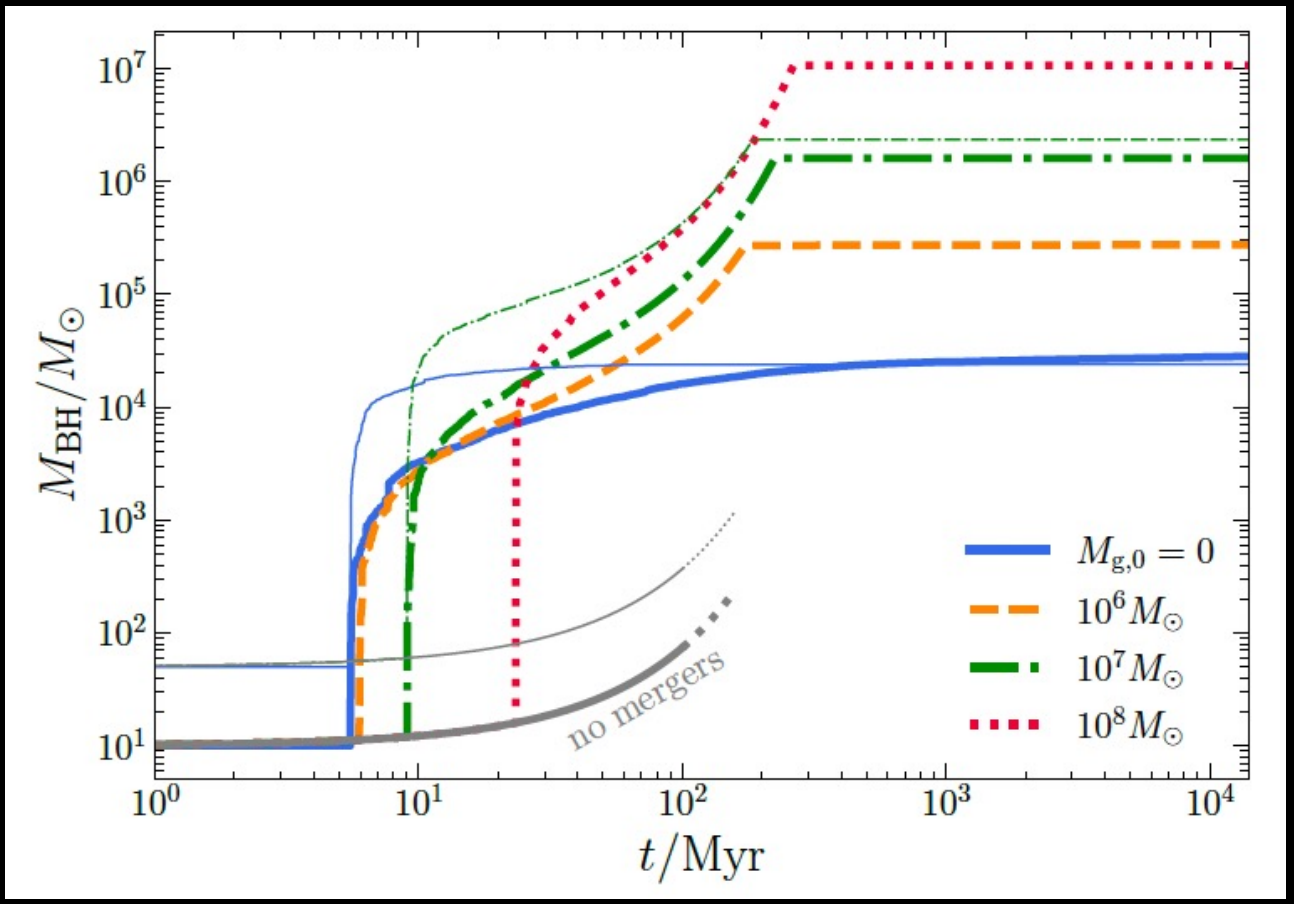
$$\sim 0.001 \times 0.01 \times 0.1 \sim 10^{-6}$$

b). Early mergers in ultradense star clusters

Astrophysical black holes sink to centre and undergo runaway mergers

Growing astrophysical BH seeds in nuclear star clusters

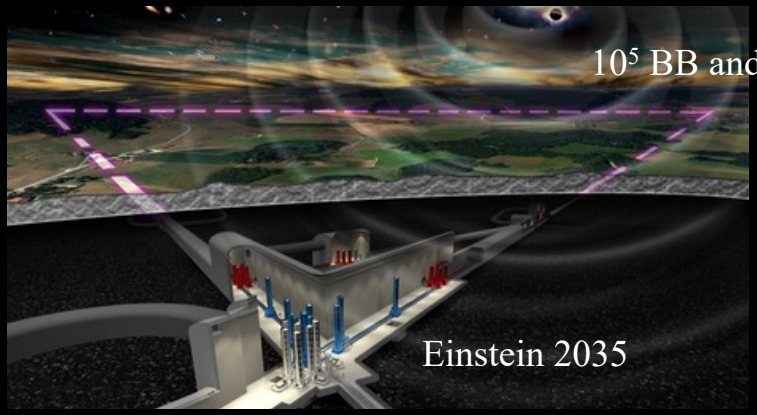
The densest star clusters in the unverse



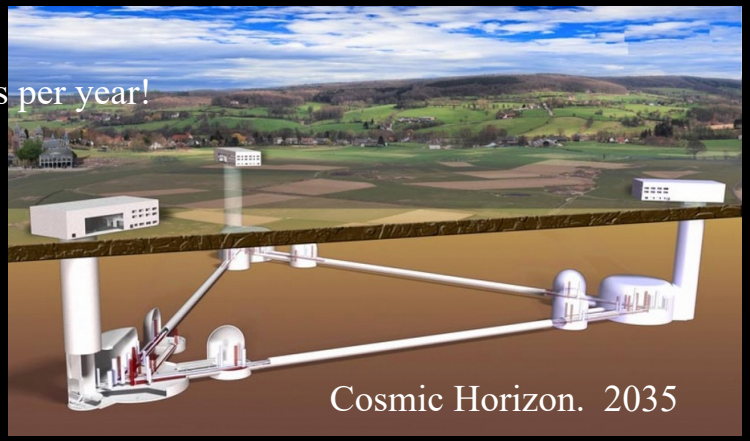
Runaway growth

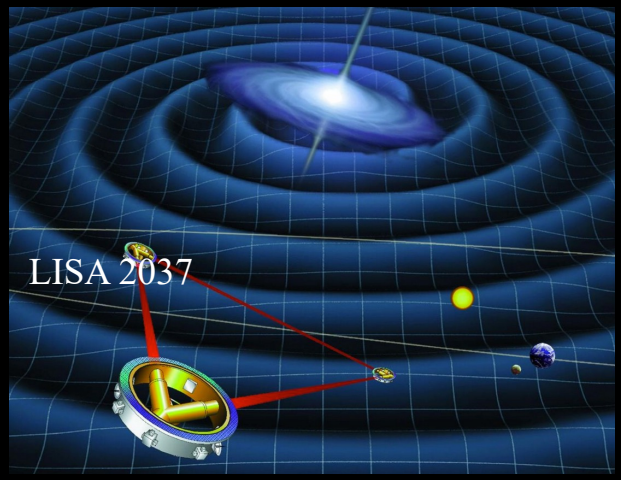
Kritos, Berti & Silk 2023

The future



10^5 BB and NS-NS mergers per year!





ありがとう