Primordial Black Holes as DM
Entropic Acceleration as DE

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Summary

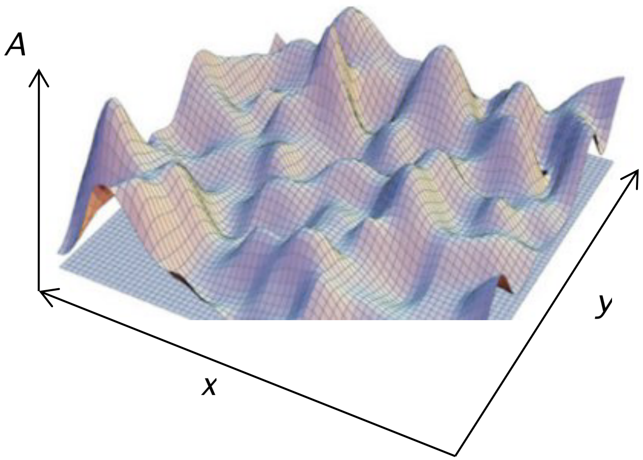
Primordial Black Holes have become a hot topic since the detection by LIGO/Virgo of BBH mergers of spinless massive BH in the range 1-100 Msun.

Their existence and their contribution to the Dark Matter budget is still uncertain. For the moment they are consistent with being 100% DM, only if clustered and wide-mass distributed.

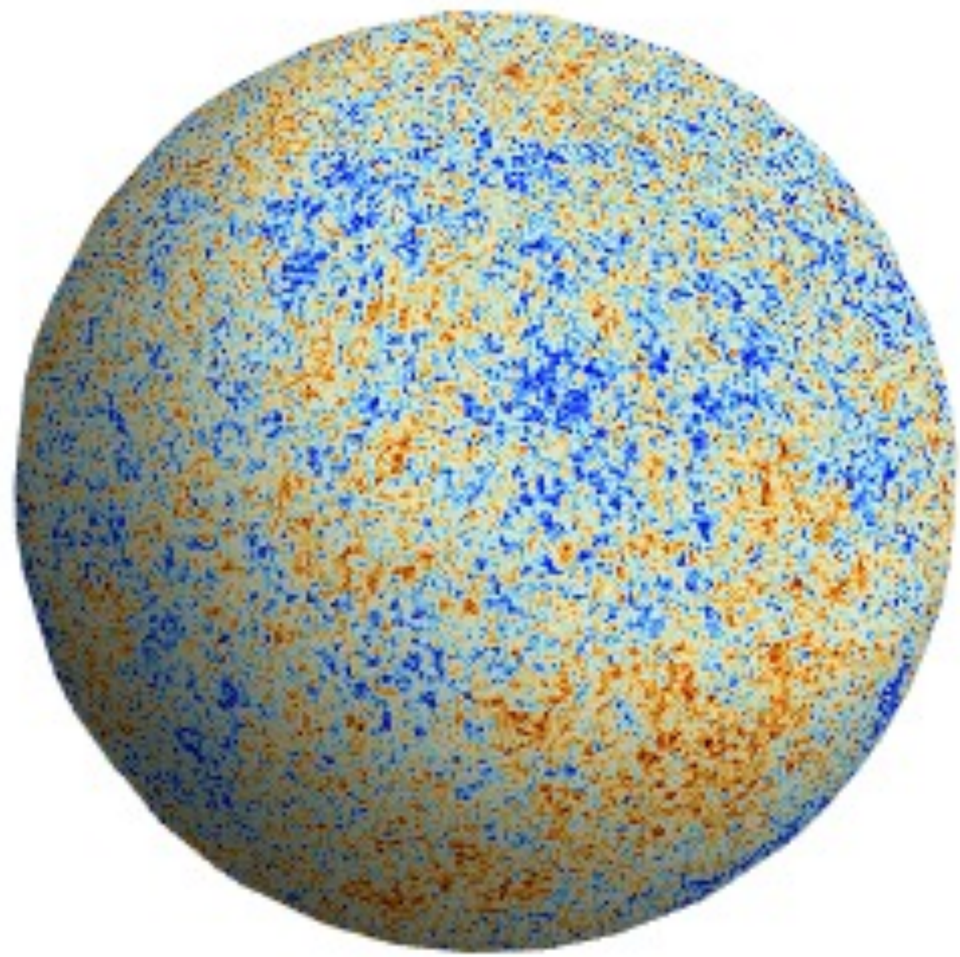
In the next few years the mass and spin distribution of BH will be known from LIGO/Virgo/KAGRA mergers and microlensing surveys, and their clustering properties inferred from next generation LSS and GW – 3G detectors like Einstein Telescope

Present cosmic acceleration could arise from relativistic entropic forces. Dynamics very similar to LCDM, except H0 = 74 km/s/Mpc.

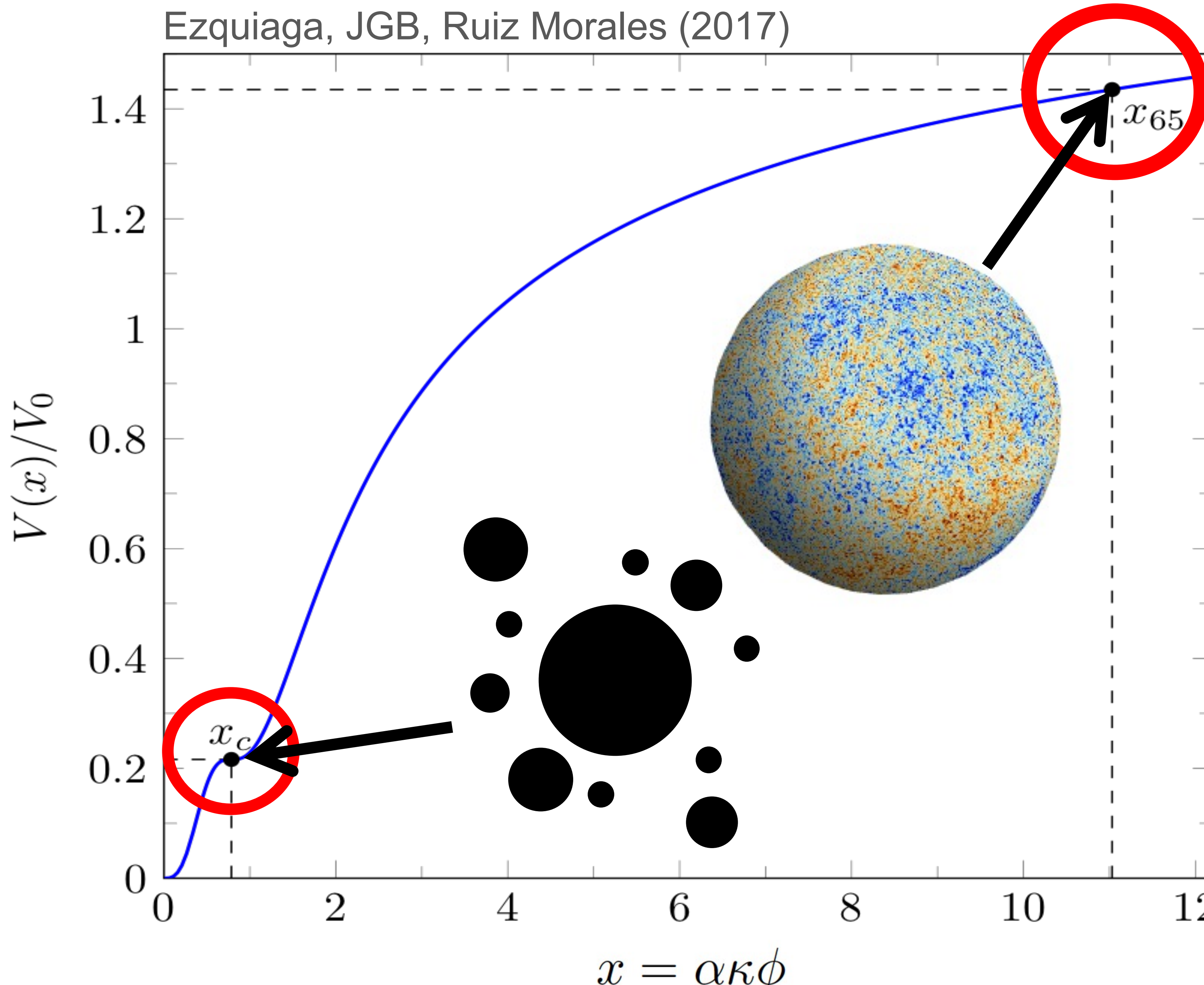
Inflation

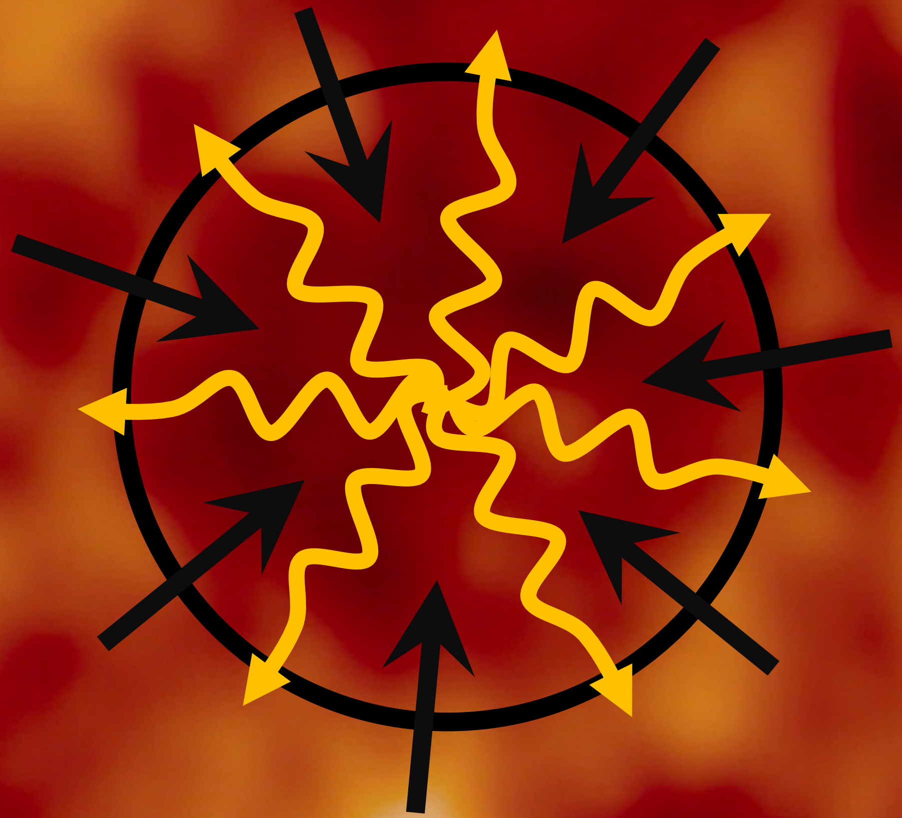


Quantum Fluctuations=
Ripples in Space-Time



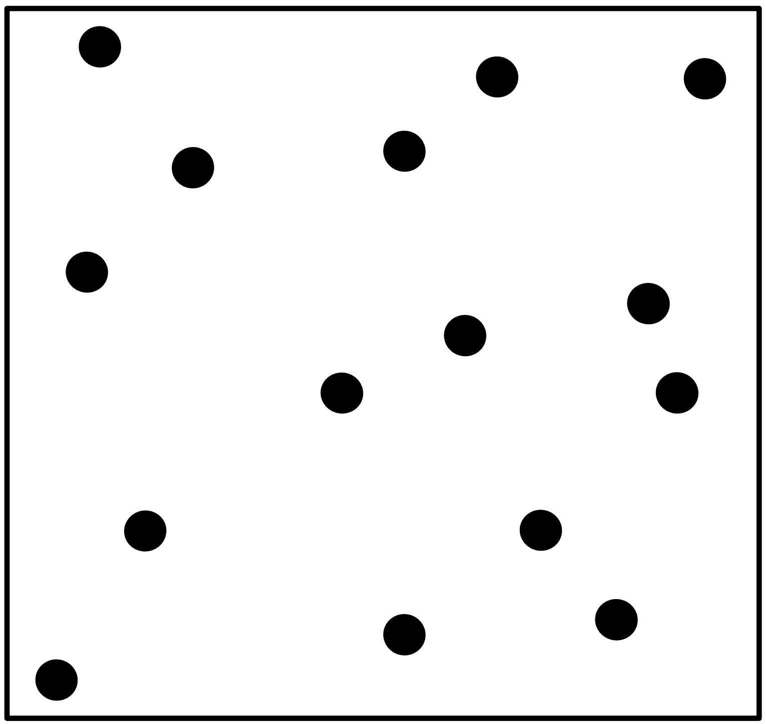
Stretched to cosmological distances


Ezquiaga, JGB, Ruiz Morales (2017)
$V(x)/V_0$
$x = \alpha\kappa\phi$
x_c
x_{65}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
2
4
6
8
10
12

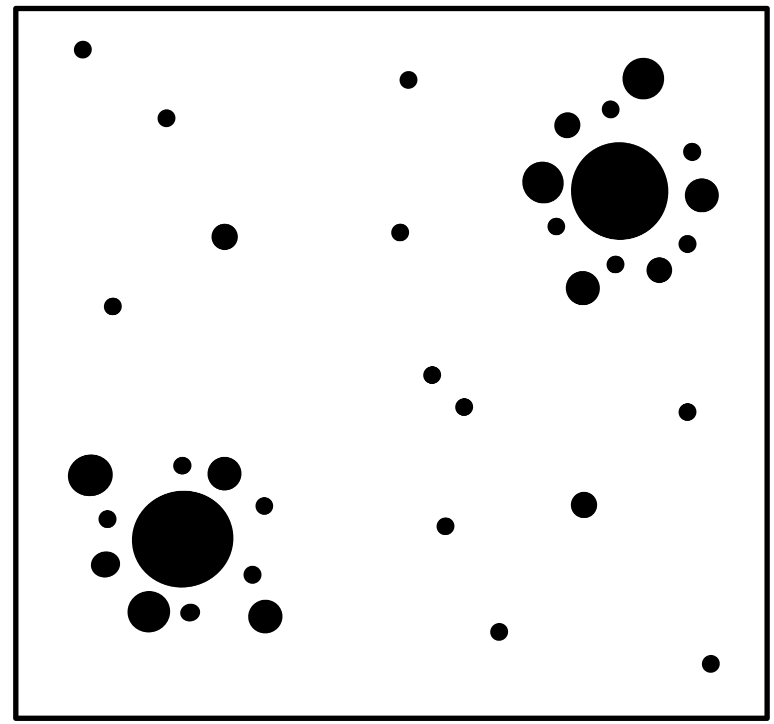


Primordial plasma

Spatial Distribution PBH



- Monochromatic
- Uniformly distributed

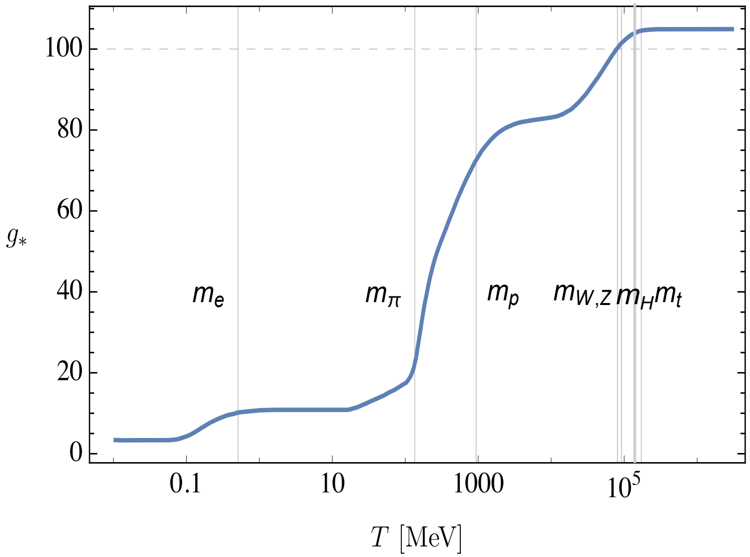


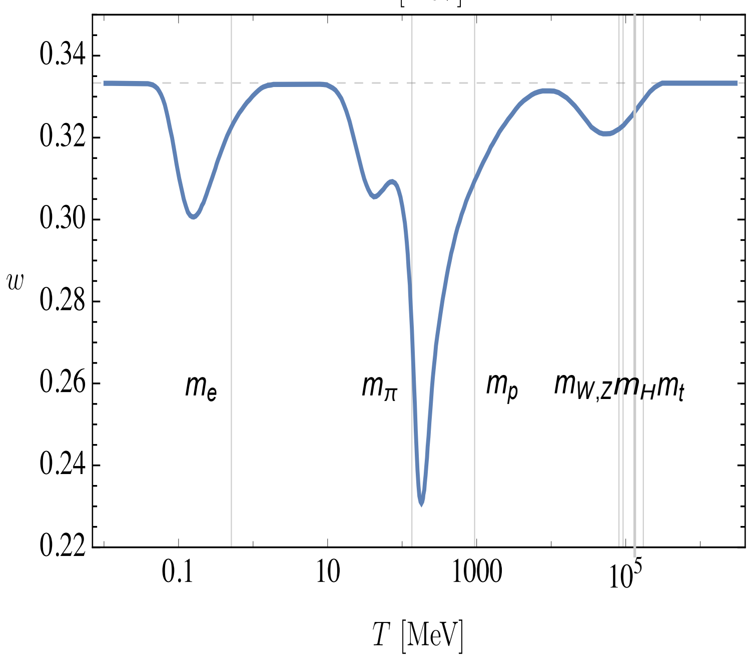
- Broad range of masses
- PBH in clusters

JGB (2017)

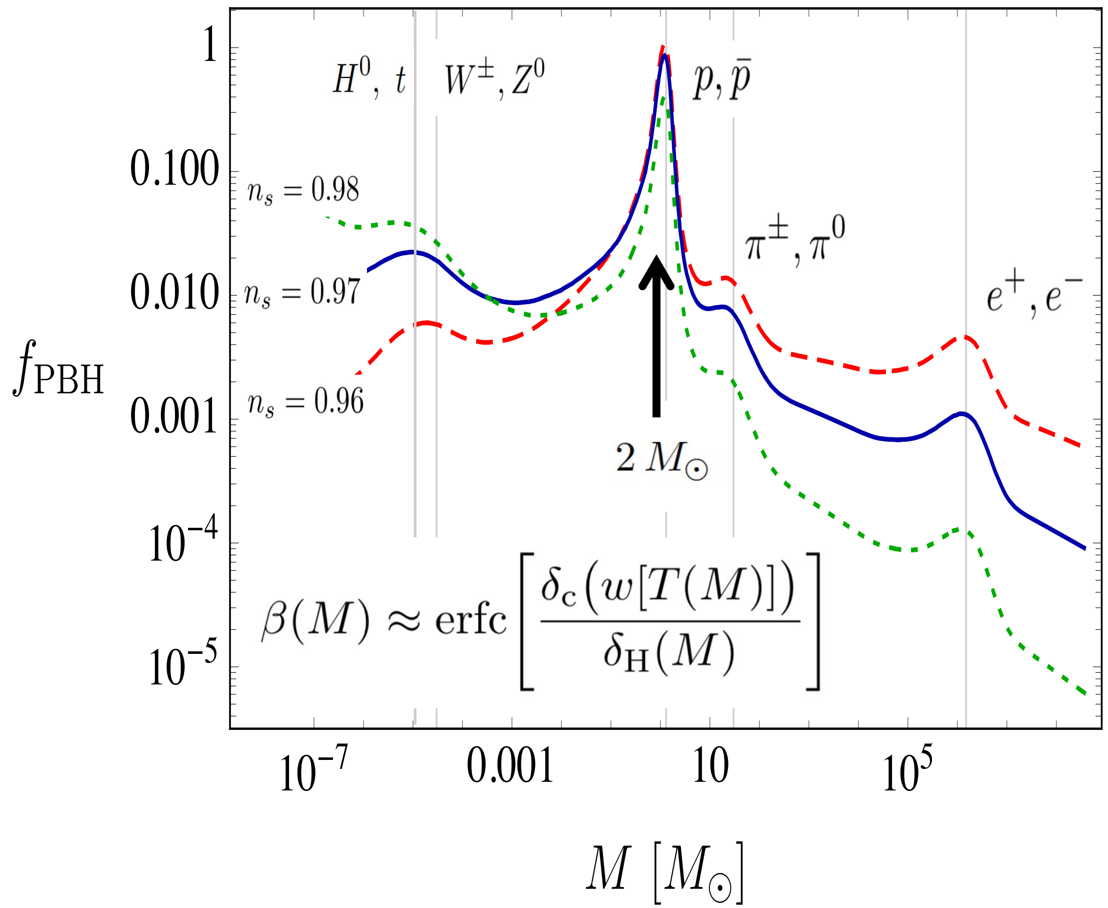
Thermal history of the universe

Carr, Clesse, JGB, Kühnel (2019)

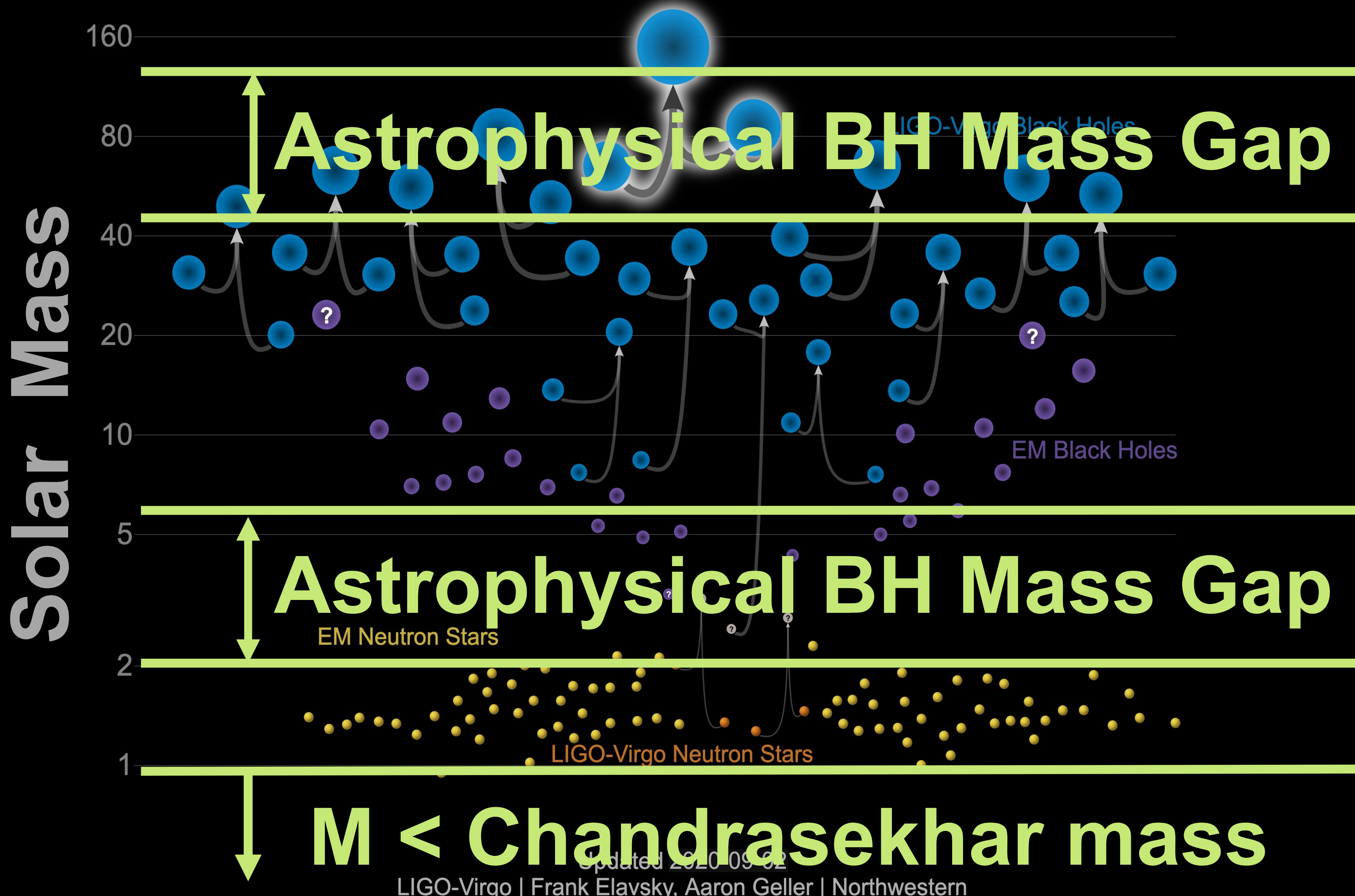




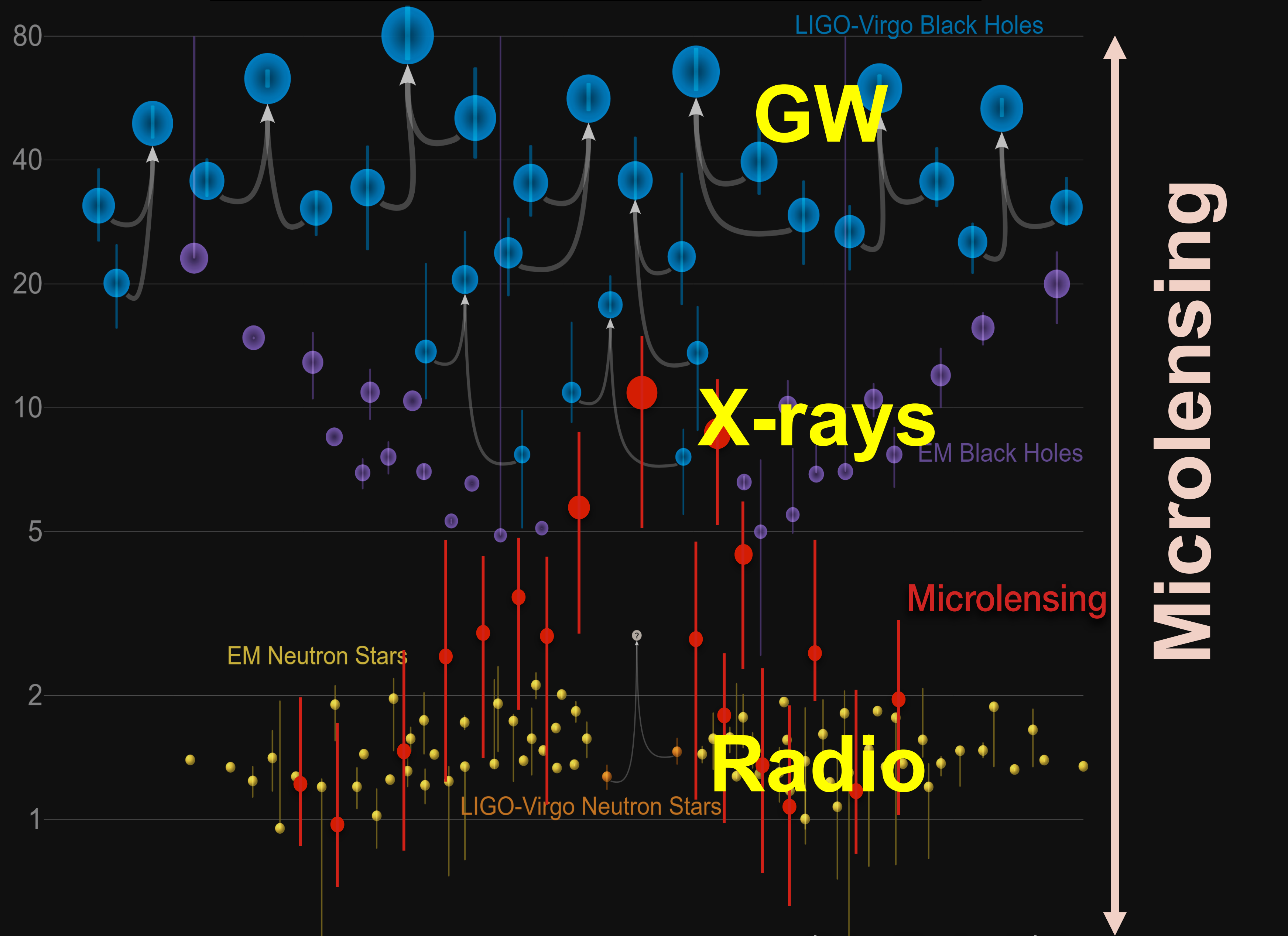
PBH mass spectrum



Black Holes and Neutron Stars

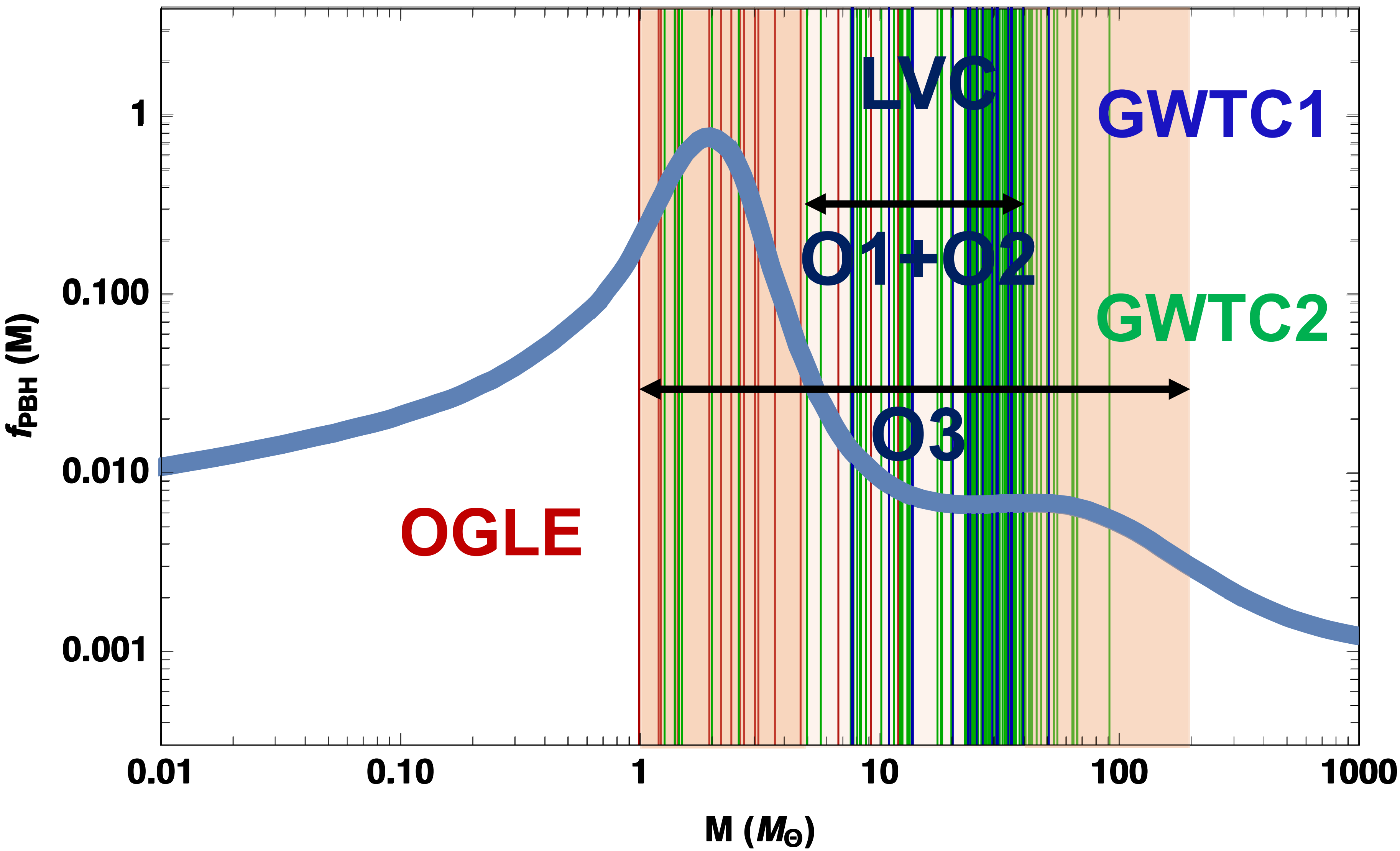


Black Holes and Neutron Stars

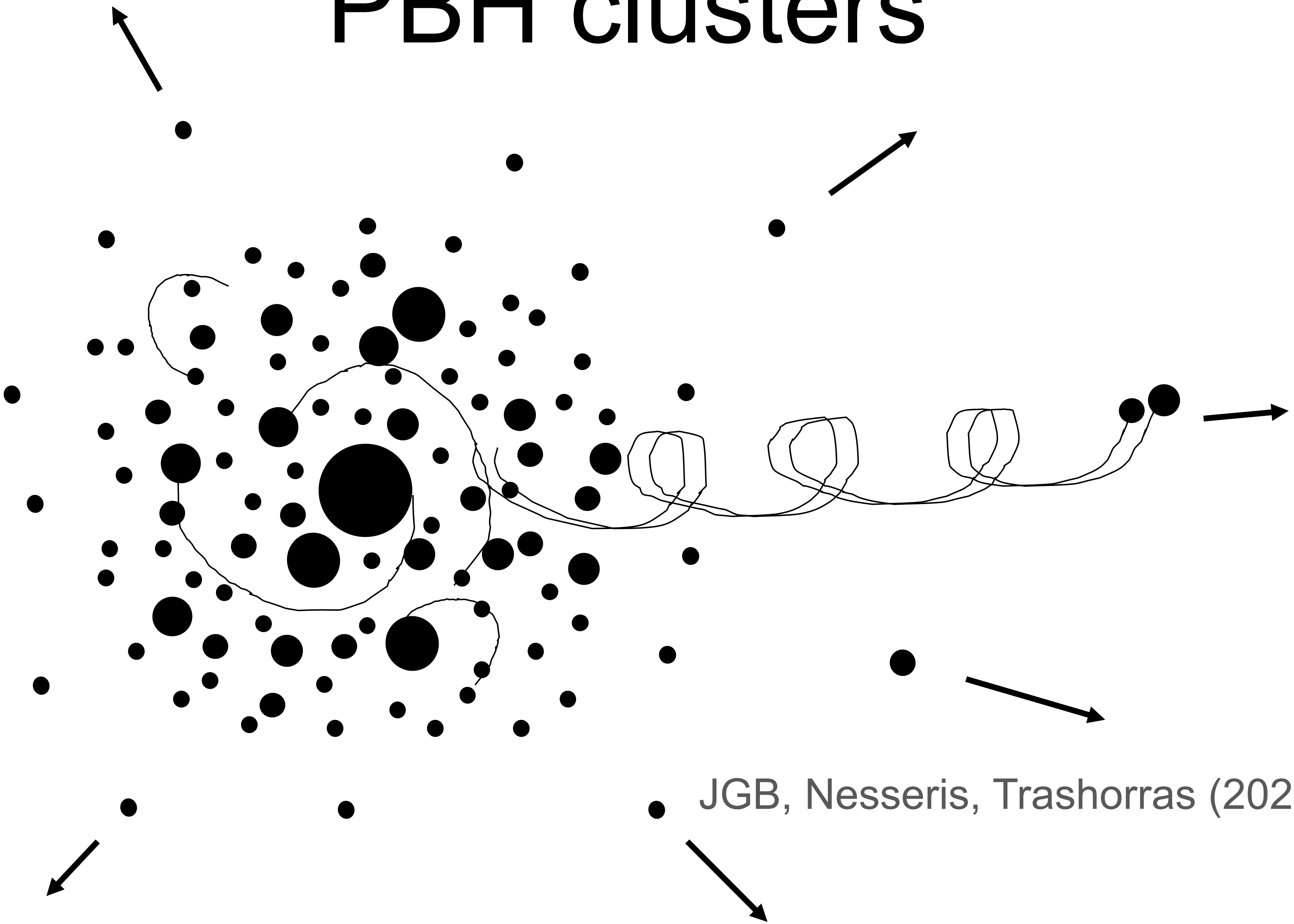


Model prediction: mass spectrum

JGB, Clesse (2020)

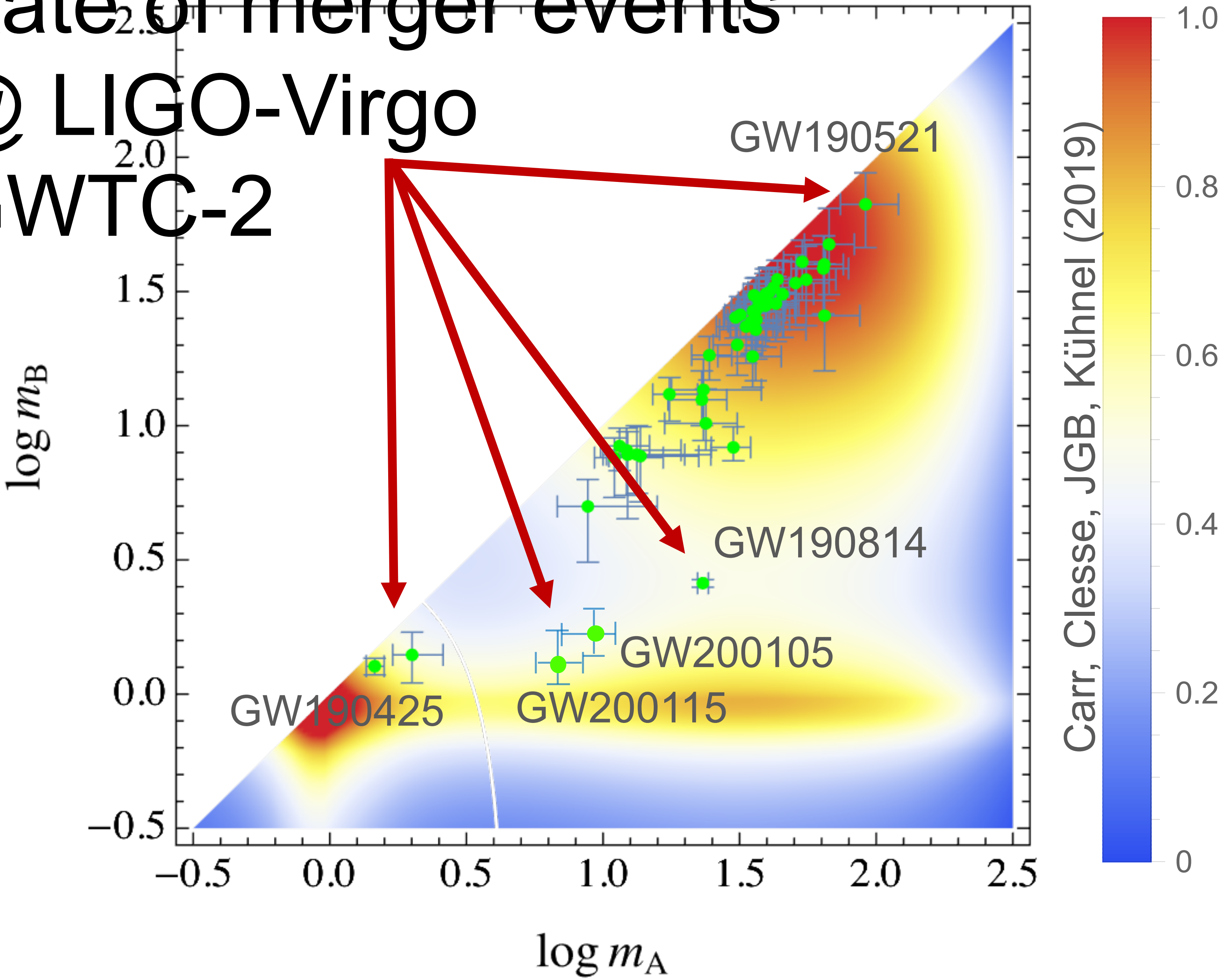


PBH clusters

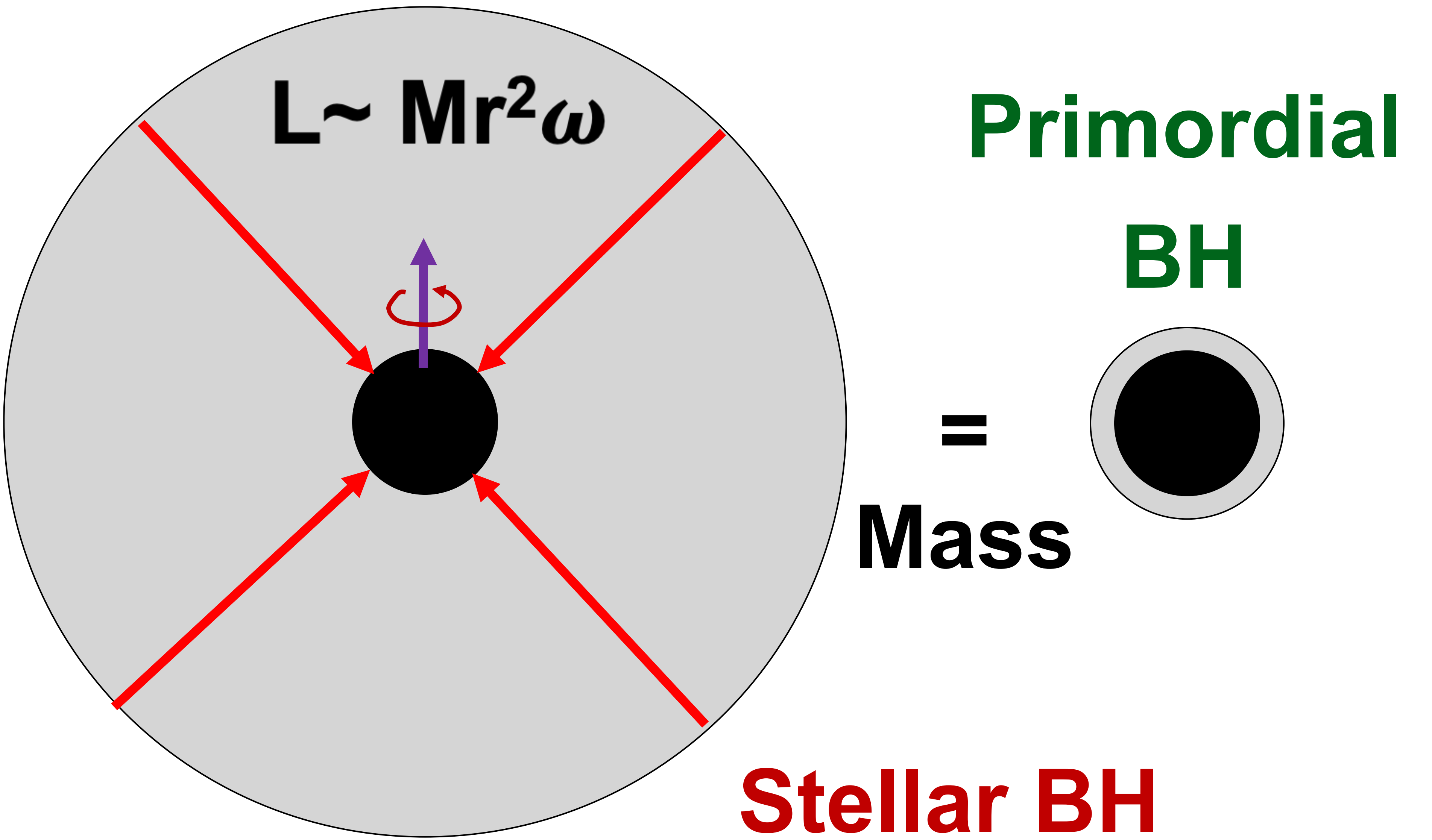


JGB, Nesseris, Trashorras (2020)

Rate of merger events @ LIGO-Virgo GWTC-2

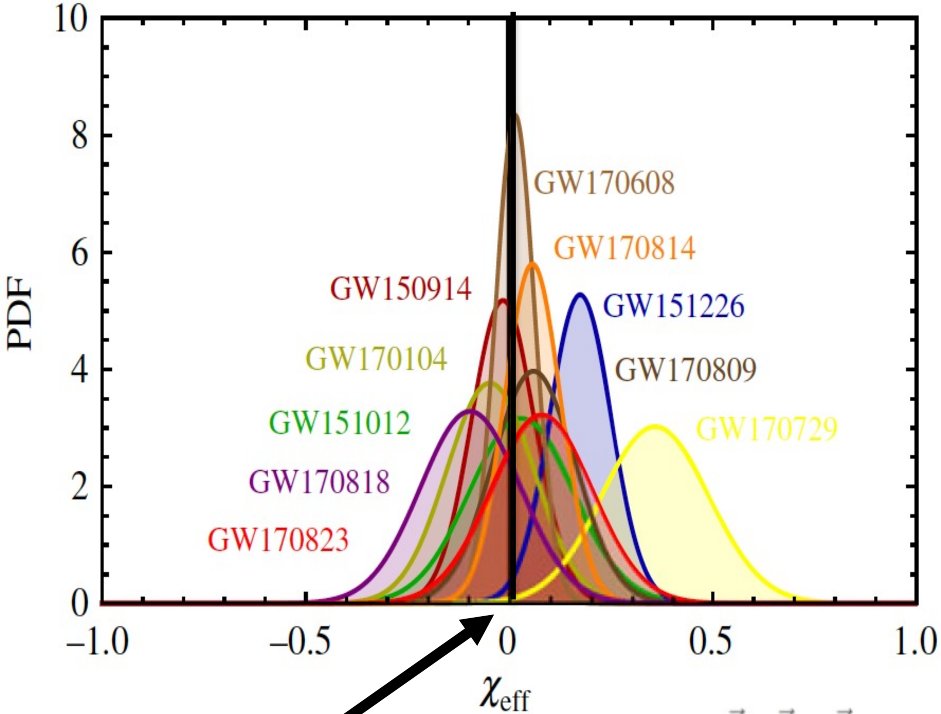


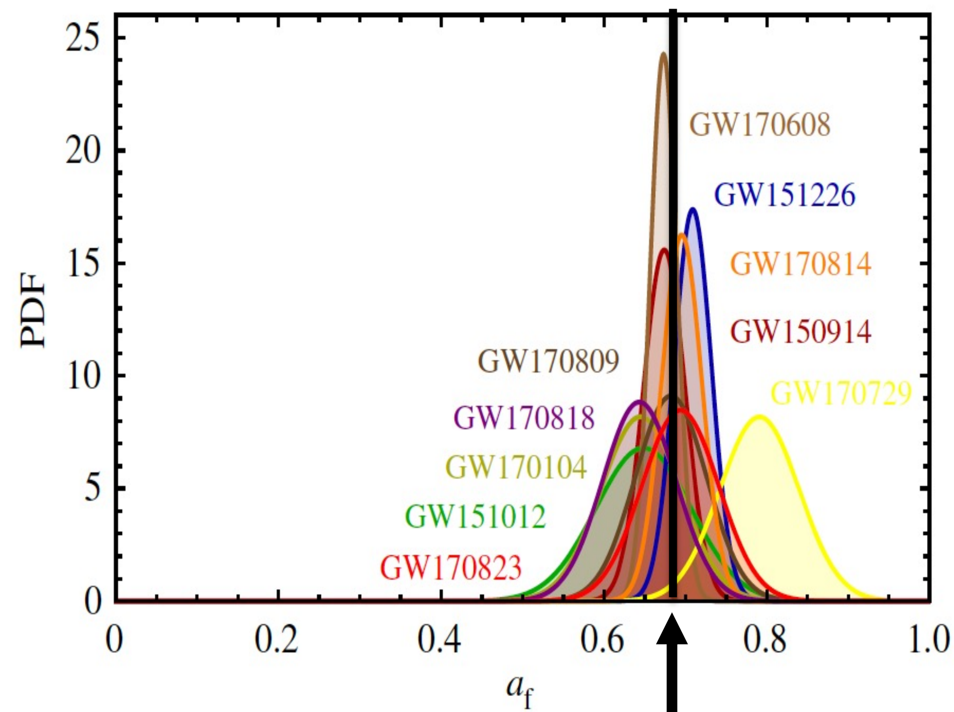
PBH are ~ spinless



Effective & Final Spin

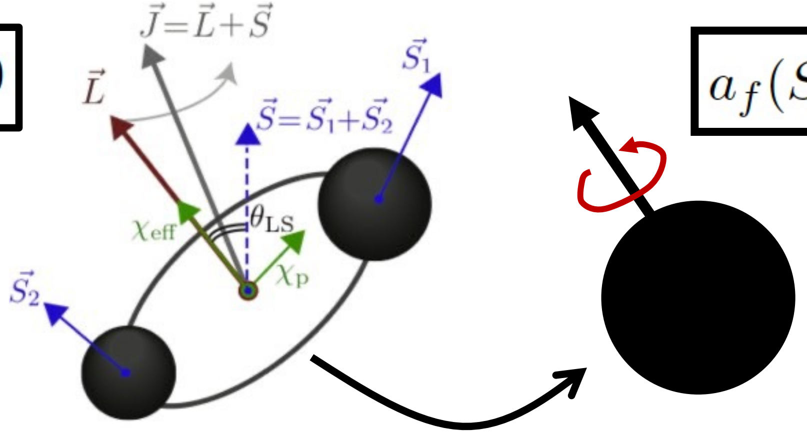
JGB, Nuño Siles, Ruiz Morales (2020)



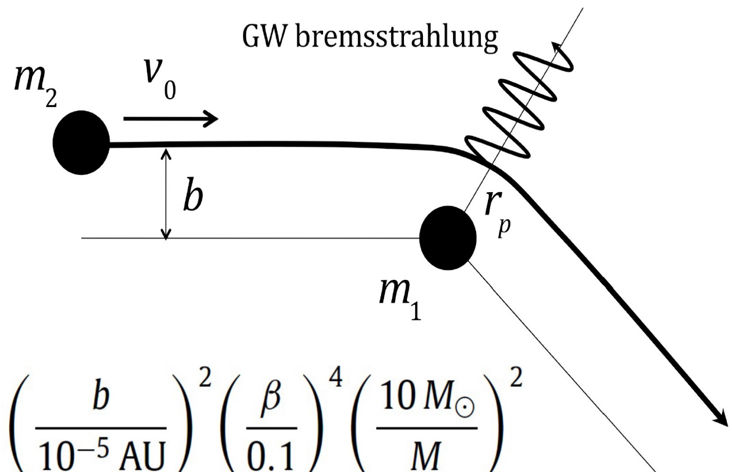


$$\chi_{\rm eff}(S_1 = S_2 = 0) = 0$$

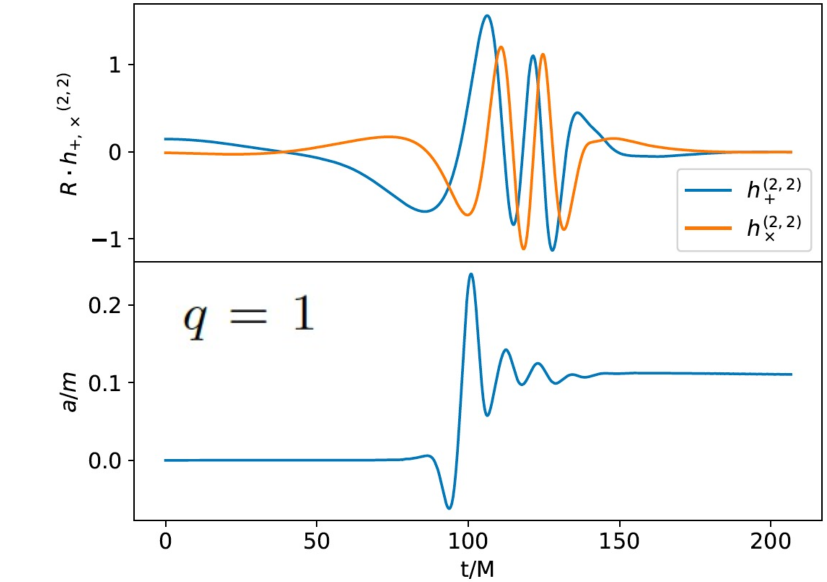
$$a_f(S_1 = S_2 = 0) = 0.686$$



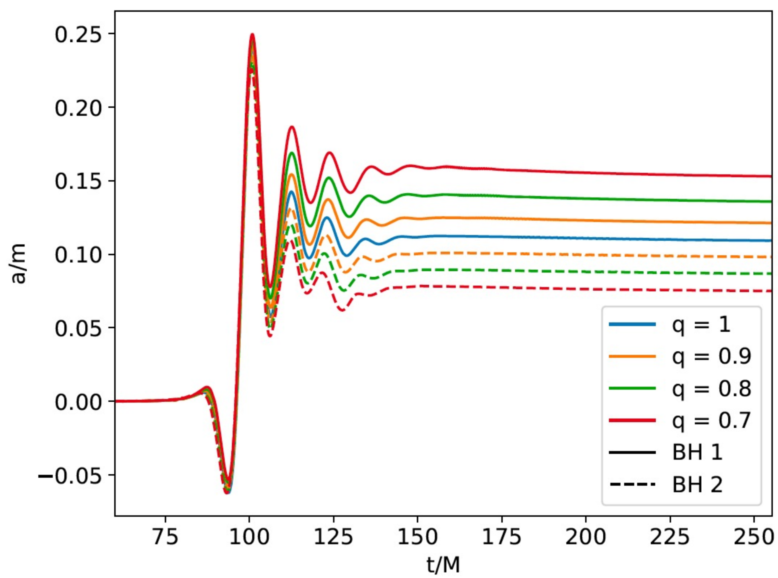
PBH spin-up by CHE

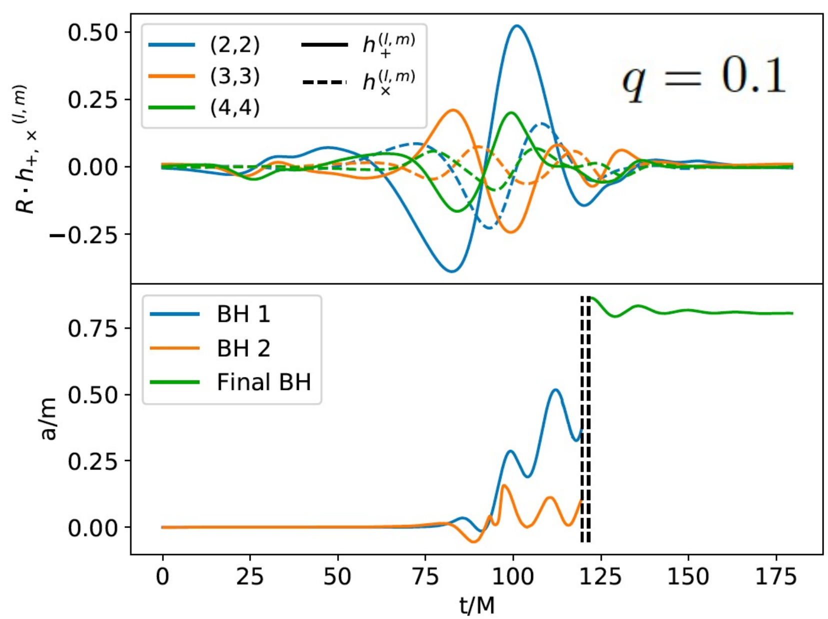


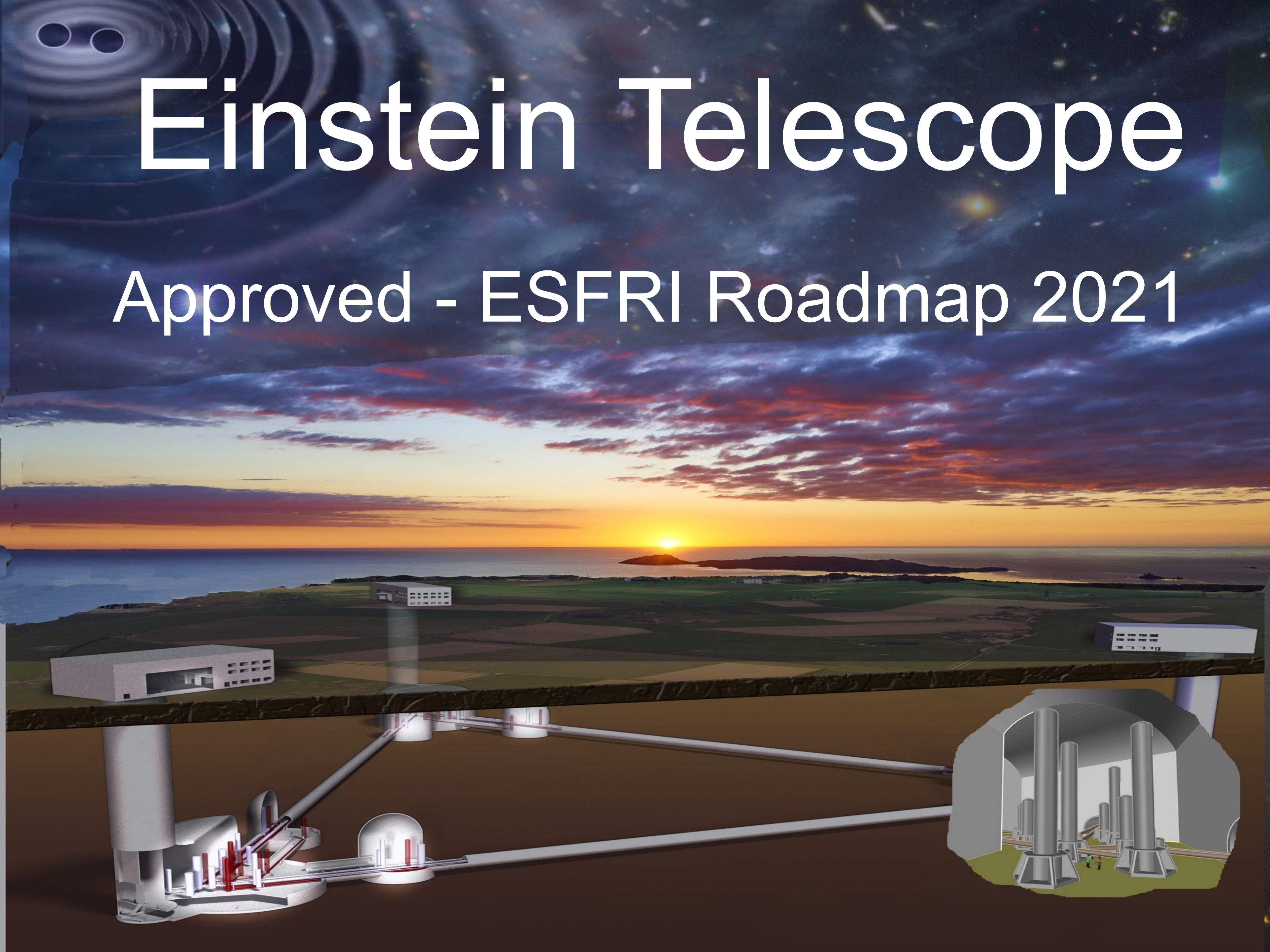
$$e^2 = 1 + \left(\frac{b}{10^{-5}\,\mathrm{AU}}\right)^2 \left(\frac{\beta}{0.1}\right)^4 \left(\frac{10\,M_\odot}{M}\right)^2$$



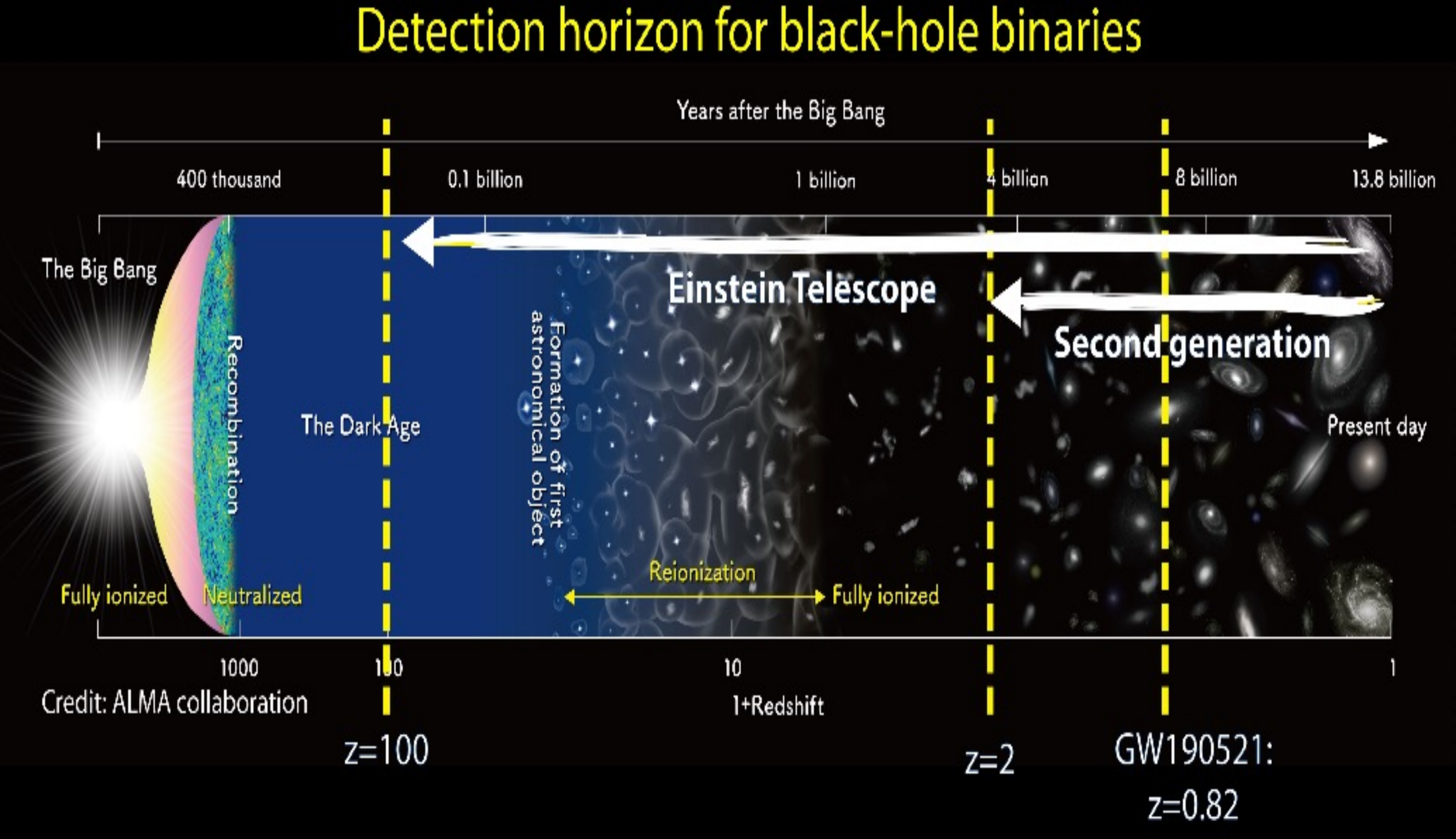
Jaraba, JGB (2021)






Einstein Telescope
Approved - ESFRI Roadmap 2021

The future of GW (G3)



Entropic forces in GR

Espinosa, JGB (2021)

$$\frac{1}{2\kappa}\int d^4x\sqrt{-g}R + \int d^4x\mathcal{L}_m(g_{\mu\nu}, S)$$

non-equilibrium thermodynamics

$$\int d^4x\left(\frac{1}{2\kappa}\frac{\delta(\sqrt{-g}R)}{\delta g^{\mu\nu}} + \frac{\delta\mathcal{L}_m}{\delta g^{\mu\nu}}\right)\delta g^{\mu\nu} + \int d^4x\frac{\partial\mathcal{L}_m}{\partial S}\delta S = 0$$

the second law of thermodynamics: variational constraint

$$\frac{\partial\mathcal{L}_m}{\partial s}\delta s = \frac{1}{2}\sqrt{-g}f_{\mu\nu}\delta g^{\mu\nu}$$

$$\boxed{R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \kappa\left(T_{\mu\nu} - f_{\mu\nu}\right)}$$

$$D^\mu T_{\mu\nu} = D^\mu f_{\mu\nu}$$

ADM Formalism

(3+1)- splitting of space-time

$$ds^2 = -(N dt)^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

Lie derivative $\pounds_n$ along the normal vector n as a generalization of the time derivative

$$n_\alpha = (-N, 0, 0, 0)$$

$$h_{\mu\nu} = g_{\mu\nu} + n_\mu n_\nu$$

$$K_{ij} = \frac{1}{2}\pounds_n h_{ij} = \frac{1}{2N}\left(\partial_0 h_{ij} - \nabla_i N_j - \nabla_j N_i\right)$$

$$\frac{\partial \mathcal{L}}{\partial s}\pounds_n s = \frac{1}{2} N\sqrt{h}\tilde{f}_{ij}\pounds_n h^{ij} \qquad \tilde{f}_{ij} = h_i^\mu h_j^\nu f_{\mu\nu}$$

Hamilton equations

$$\frac{\delta \mathcal{H}_G}{\delta \Pi^{ij}} = \dot{h}_{ij}$$

$$\frac{\delta \mathcal{H}_G}{\delta h_{ij}} = -\dot{\Pi}^{ij} - 2\kappa\frac{\delta \mathcal{L}_m}{\delta h_{ij}} - \kappa N\sqrt{h}\tilde{f}^{ij}$$

Hamiltonian and momentum constraints

$$\frac{\delta \mathcal{H}_G}{\delta N} = \mathcal{H} = 2\kappa\frac{\partial \mathcal{L}_m}{\partial N}$$

$$\frac{\delta \mathcal{H}_G}{\delta N_i} = \mathcal{H}^i = 2\kappa\frac{\partial \mathcal{L}_m}{\partial N_i}$$

Raychaudhuri Eq.

congruence of worldlines

$$\Theta_{\mu\nu} = D_\nu n_\mu = \frac{1}{3}\Theta h_{\mu\nu} + \sigma_{\mu\nu} + \omega_{\mu\nu} - a_\mu n_\nu$$

$$\pounds_n \Theta = -\frac{1}{3}\Theta^2 - \sigma_{\mu\nu}\sigma^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} - R_{\mu\nu}n^\mu n^\nu + D_\mu a^\mu$$

$\sigma_{\mu\nu}\sigma^{\mu\nu} > 0$ and $\Theta^2 > 0$. vorticity vanishes $\omega_{\mu\nu} = 0$.

$$R_{\mu\nu}n^\mu n^\nu = 8\pi G\left(T_{\mu\nu}n^\mu n^\nu + \frac{1}{2}T - f_{\mu\nu}n^\mu n^\nu - \frac{1}{2}f\right)$$

If the strong energy condition is satisfied, then: $T_{\mu\nu}n^\mu n^\nu \geq -\frac{1}{2}T$

and, in the absence of intrinsic acceleration, $a_\mu = 0$, we can establish the bound:

$$\pounds_n \Theta + \frac{1}{3}\Theta^2 \leq 8\pi G\left(f_{\mu\nu}n^\mu n^\nu + \frac{1}{2}f\right)$$

a positive and sufficiently large entropic contribution can avoid recollapse.

FLRW Universe

The effect of non-equilibrium thermodynamics in an expanding FLRW universe

$$ds^2 = -N(t)^2 dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega_2^2\right)$$

$$T^{\mu\nu} = (\rho + p)u^\mu u^\nu + p g^{\mu\nu} \qquad D^\mu T_{\mu\nu} = D^\mu f_{\mu\nu}$$

the second law of thermodynamics:

$$T dS = d(\rho a^3) + p\, d(a^3) \qquad \dot{\rho} + 3H(\rho + p) = \frac{T\dot{S}}{a^3}$$

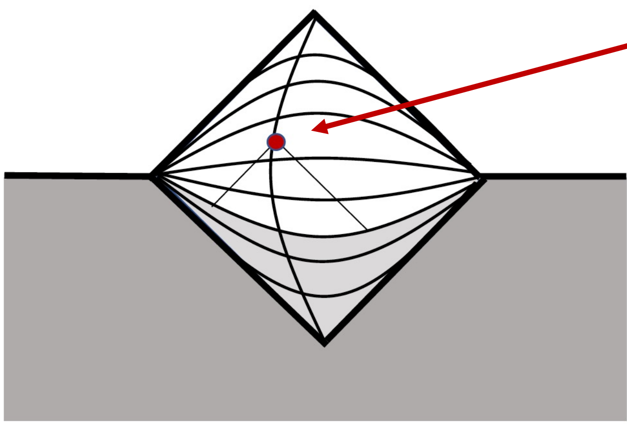
Hamiltonian constraint $\quad \dot{a}^2 + k = \frac{8\pi G}{3}\rho\, a^2$

Friedmann/Raychaudhuri equation

$$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{4\pi G}{3}\frac{T\dot{S}}{a^3 H}}$$

Cosmic Acceleration

JGB, Espinosa (2021)



consider a causal horizon satisfying

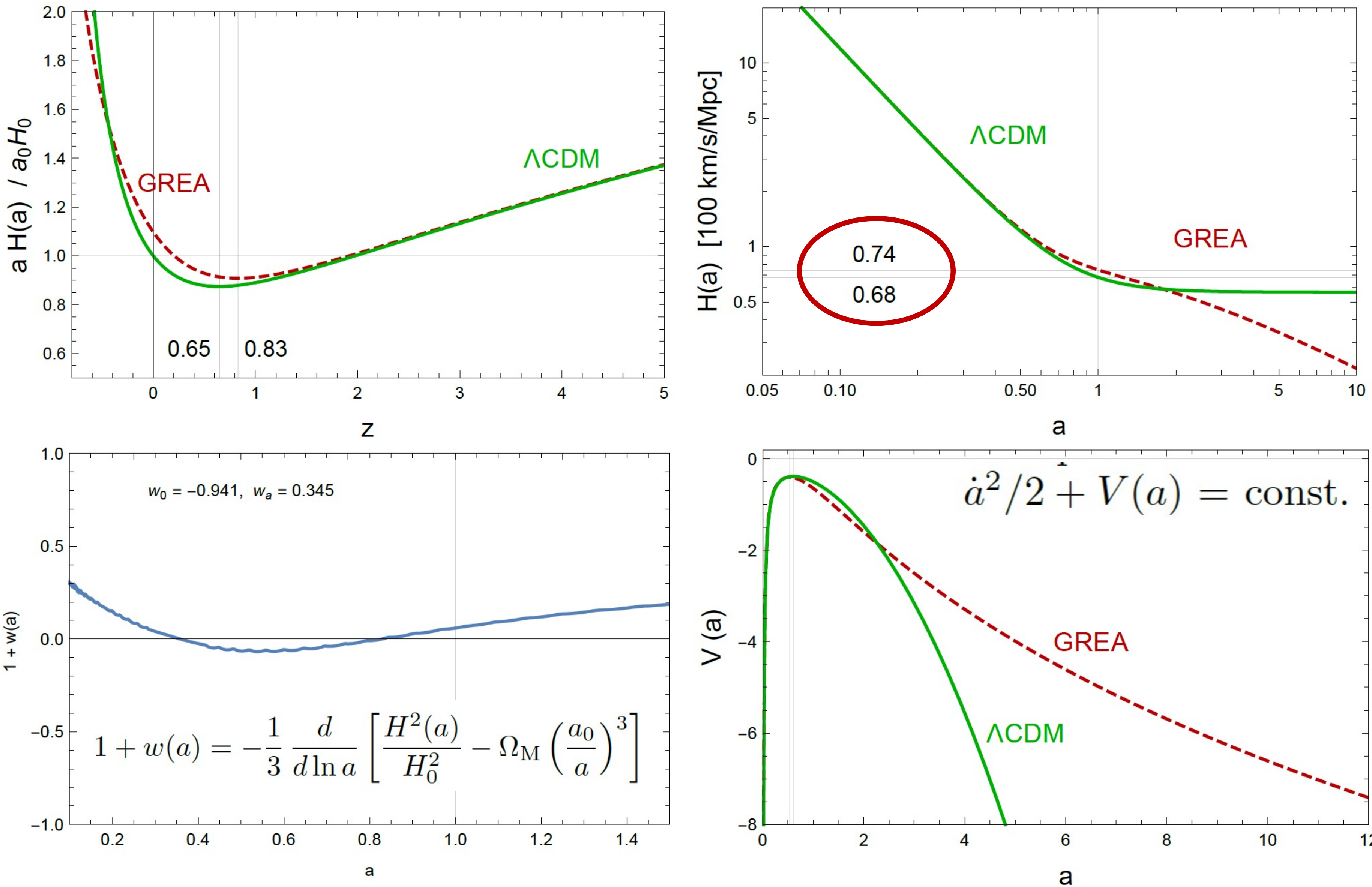
$$\rho_H\, a^2 = \frac{T_H S_H}{a} = \frac{x_0}{2G}\sinh(2a_0 H_0 \eta)\,,$$

$$x_0 \equiv \frac{1-\Omega_0}{\Omega_0} = e^{-2N}\left(\frac{T_{\rm rh}}{T_{\rm eq}}\right)^2 (1+z_{\rm eq})\,.$$

Hamiltonian constraint ($\boxed{3.1}$) in conformal time (where primes denote derivatives w.r.t. $\tau = a_0 H_0 \eta$) as

$$\left(\frac{a'}{a_0}\right)^2 = \Omega_{\rm M}\left(\frac{a}{a_0}\right) + \Omega_{\rm K}\left(\frac{a}{a_0}\right)^2 + \frac{4\pi}{3}\Omega_{\rm K}\left(\frac{a}{a_0}\right)^2\sinh(2\tau)\,.$$

Cosmic Acceleration



Conclusions

- Thermal history predicts PBH have multimodal mass distribution ~ 1E-5, 1, 100, 1E5 Msun (1E-10 also?)
- The predicted PBH spin and mass distribution has been measured by LIGO/Virgo + OGLE around 1-100 Msun (features: peak+plateau)
- Paradigm shift in Structure Formation of Universe

- Non-equilibrium phenomena in GR: entropic forces
- ADM (3+1) slicing: Raychaudhuri eq. grav. collapse
- Cosmic acceleration from first principles
- No need for a Cosmological Constant