DM & DE from 1st Principles

How PBH define a new paradigm for a unified view of the evolution of the Universe

[arXiv: 2306.03903, 2306.10593 & 2310.19857]

PBH & GW, Paris, 27th November 2023

Juan García-Bellido
IFT-UAM/CSIC

Early Universe

Inflation

- **Critical Higgs Inflation (Standard Model + ξ)**
- Generation of fluctuations for PBH
  - Large amplitude $P(k)$ 2-point function
  - Large PNG tails from Quantum Diffusion
- Signatures in CMB & LSS (LiteBird + JWST)

- **Coupling to gauge fields (axion-gauge model)**
- Signatures in GW (chirality and PNG)

Early Universe

Radiation era

- Gravitational collapse to PBH
  - Radiation pressure – Thermal history (SM)
- Baryon asymmetry at QCD – PBH collapse
- ISGWB from PBH collapse/non-collapse
- CMB spectral distortions and anisotropies

Late Universe

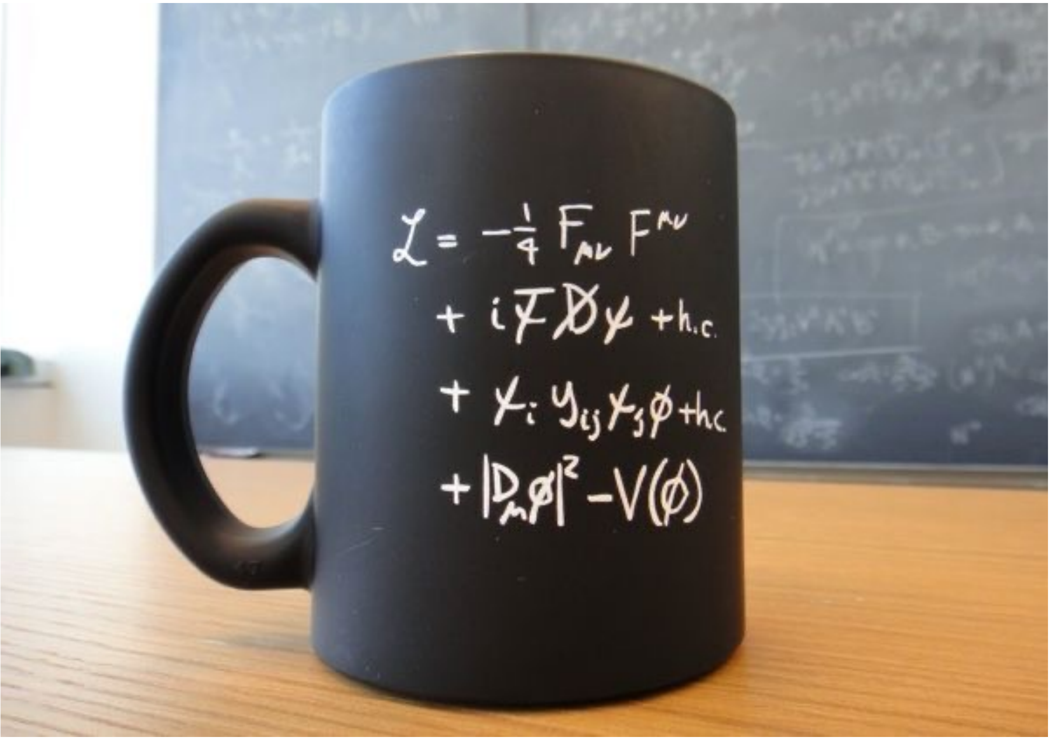
Matter era

- **Early Structure formation** ($z>30$, JWST)
  - Poisson/seed effect + PBH clustering
  - First Stars and X-ray/CIR backgrounds
- **GW emission** from BHBC – GWTC-3
  - Spin + mass + redshift distributions
- **Microlensing events** – OGLE/GAIA
- **SMBH growth via accretion** – Entropic forces
- **Cosmic acceleration** GREA = DE

Observational Prospects

- Gaia + LSST : microlensing surveys
- LVK + ET + LISA : SSMBH + IMBH (PISN)
- IPTA : SGWB from SMBH-PBH
- JWST : high-z SMBH seed + growth
- Euclid + DESI : $H(z)$ Not ΛCDM

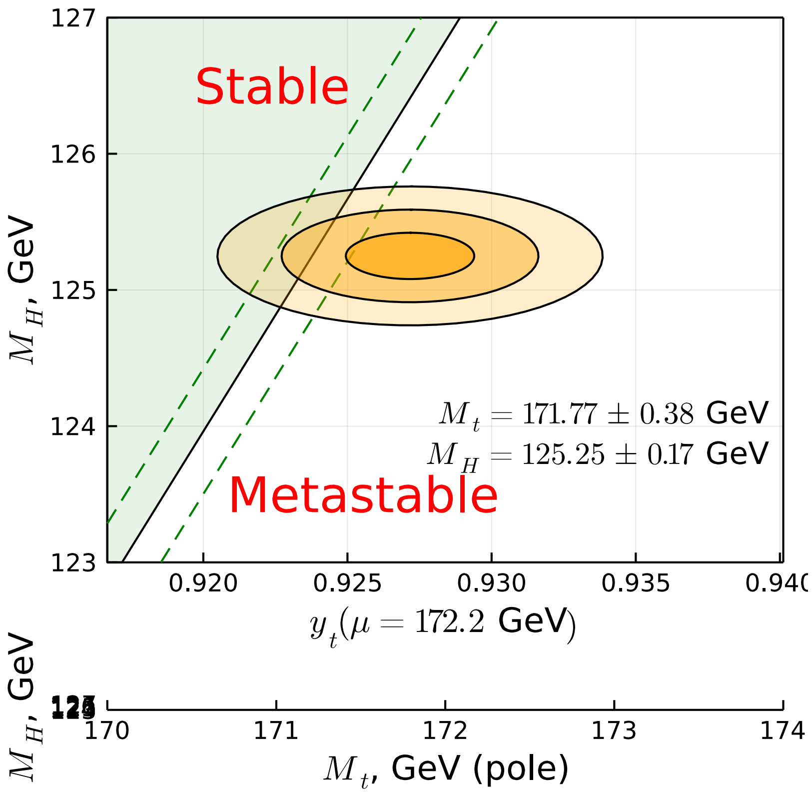
Standard Model Lagrangian



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$
$$+ \xi |\phi|^2 R$$

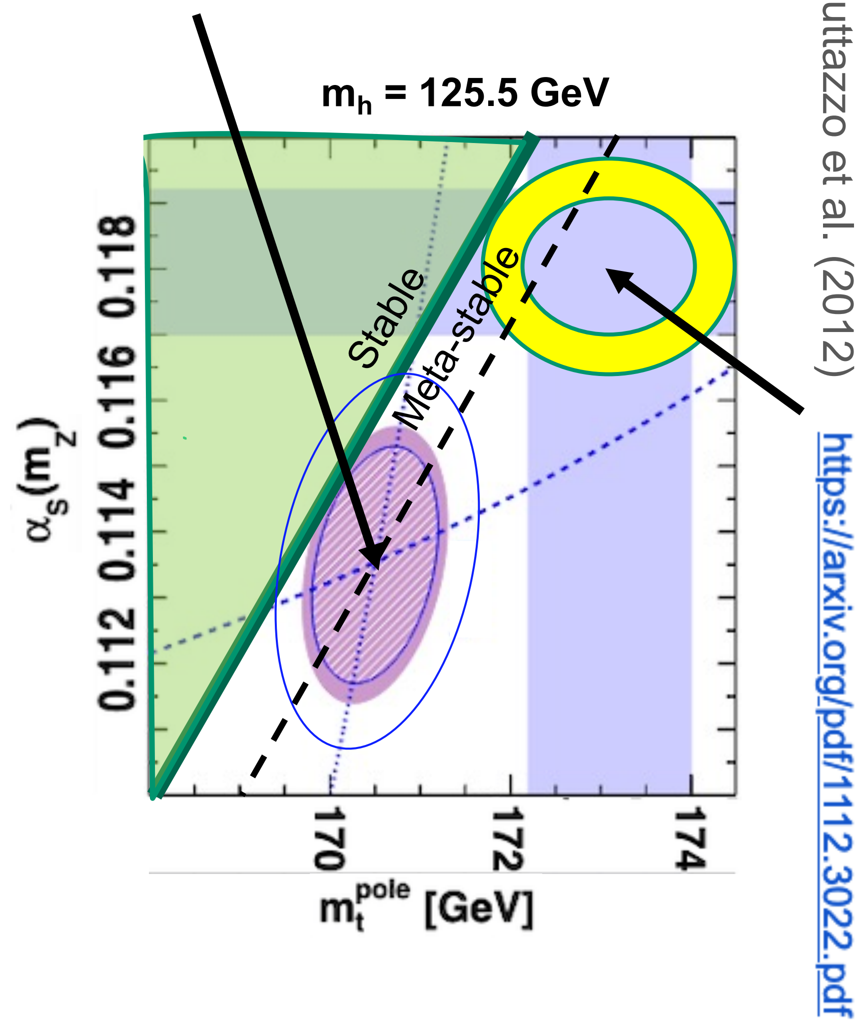
$$R = 12H^2 + 6\dot{H} \rightarrow R_0 = 9.2\, H_0^2 \rightarrow m_H = \sqrt{\xi R_0} = 2 \times 10^{-32}\ \mathrm{eV}$$

EW vacuum metastability



LHC-CMS Collab. (2020)

https://arxiv.org/abs/1904.05237



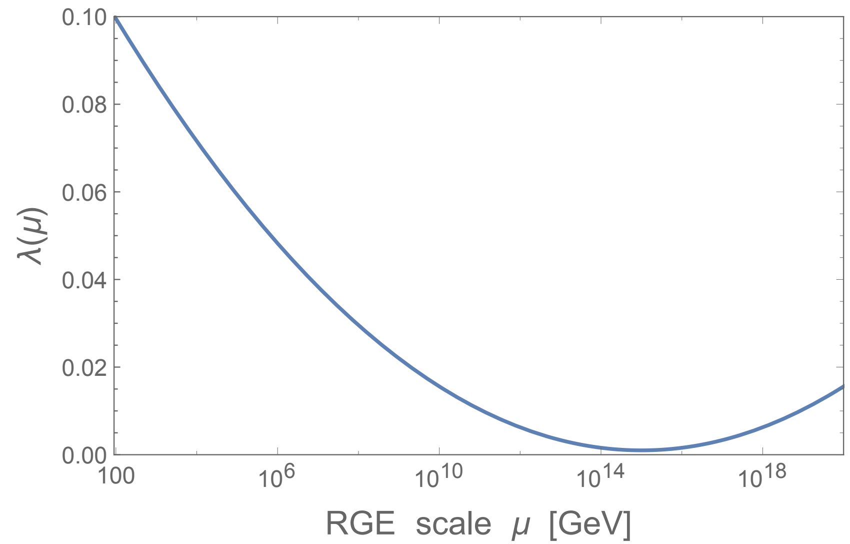
$$m_t^{pole} = 170.5 \pm 0.8\,\text{GeV}$$

$$\alpha_S(m_Z) = 0.1135^{+0.0021}_{-0.0017}$$

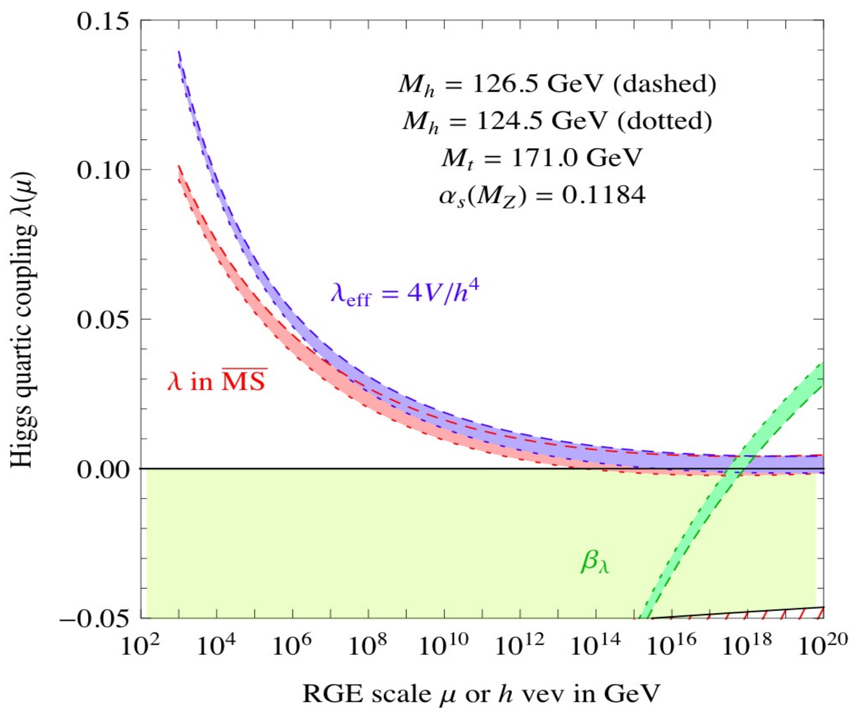
Renormalization of Higgs couplings

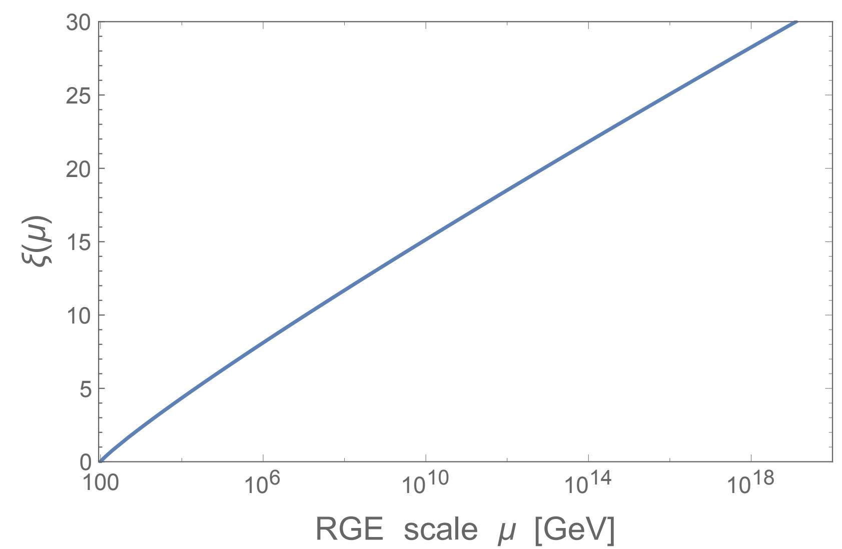
$$\lambda(\phi) = \lambda_0 + b_\lambda \ln^2(\phi/\mu) ,$$

$$\xi(\phi) = \xi_0 + b_\xi \ln(\phi/\mu) ,$$



Buttazzo et al (2014)





Critical Higgs Inflation

Ezquiaga, JGB, Ruiz Morales (2017)

$$S = \int d^4x\sqrt{g}\left[\left(\frac{1}{2\kappa^2} + \frac{\xi(\phi)}{2}\phi^2\right)R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda(\phi)\phi^4\right]$$

$$\lambda(\phi) = \lambda_0 + b_\lambda \ln^2(\phi/\mu) \,,$$

$$\xi(\phi) = \xi_0 + b_\xi \ln(\phi/\mu) \,,$$

$$\frac{d\varphi}{d\phi} = \frac{\sqrt{1+\xi(\phi)\,\phi^2 + 6\,\phi^2\,(\xi(\phi)+\phi\,\xi'(\phi)/2)^2}}{1+\xi(\phi)\,\phi^2}$$

$$V(x) = \frac{V_0\,(1 + a\,\ln^2 x)\,x^4}{(1 + c\,(1 + b\,\ln x)\,x^2)^2} \qquad x = \phi/\mu$$

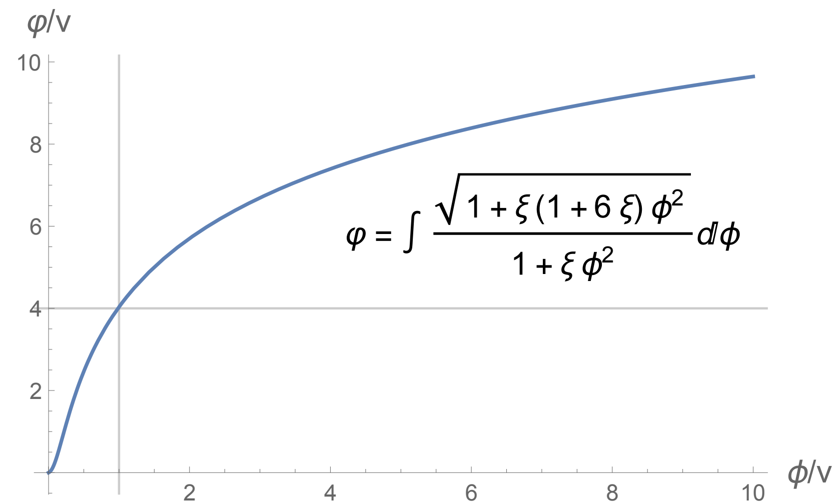
$V_0 = \lambda_0\mu^4/4$, $a = b_\lambda/\lambda_0$, $b = b_\xi/\xi_0$ and $c = \xi_0\,\kappa^2\mu^2$

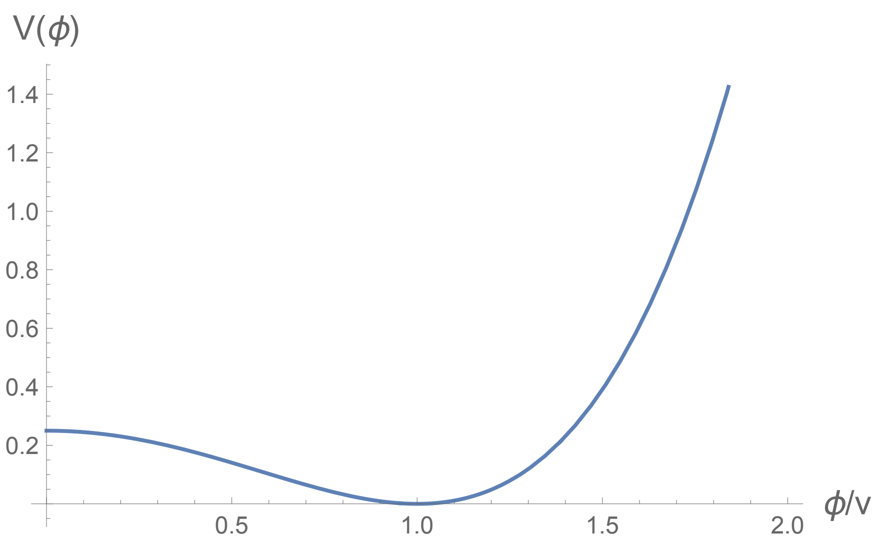
Conformal redefinition of metric and Higgs

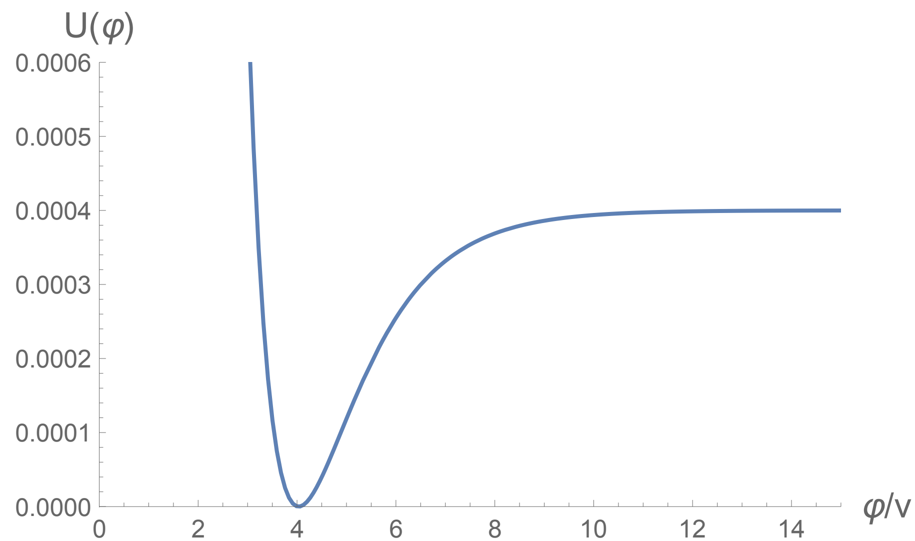
$$g_{\mu\nu} \to (1+\xi\phi^2)\, g_{\mu\nu}$$

$$\phi \to \varphi$$

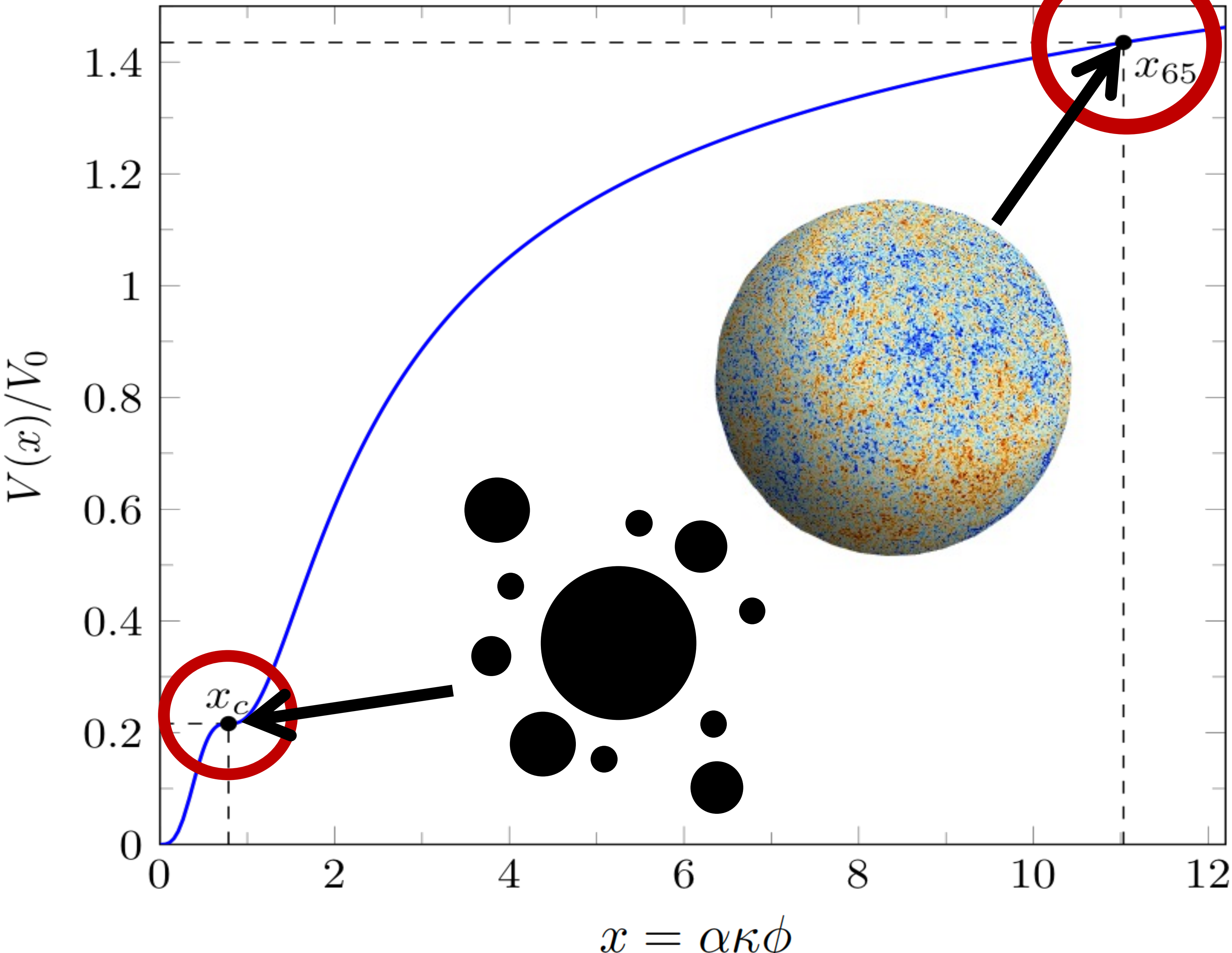
$$V(\phi) \to \frac{V(\phi)}{(1+\xi\phi^2)^2}$$



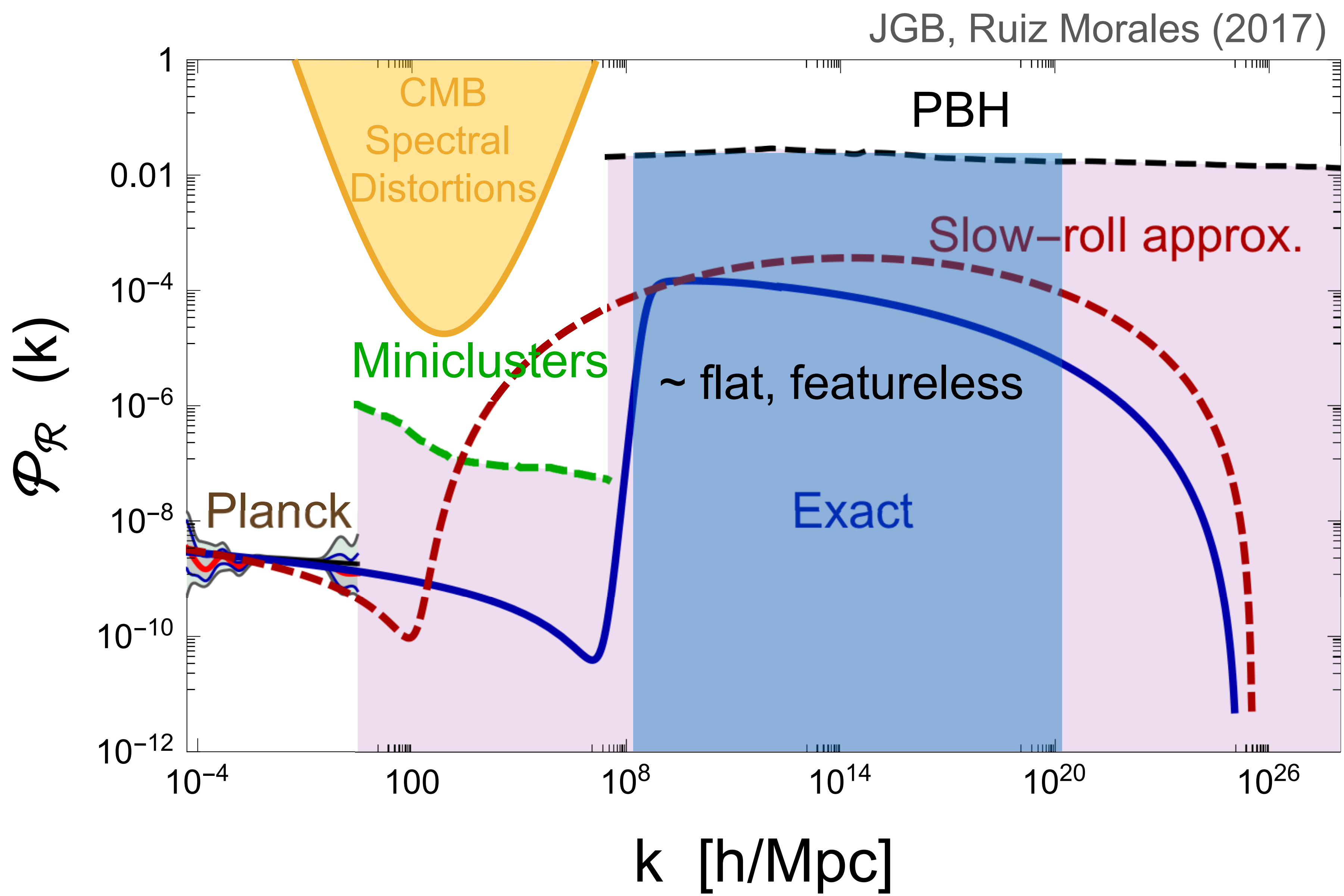




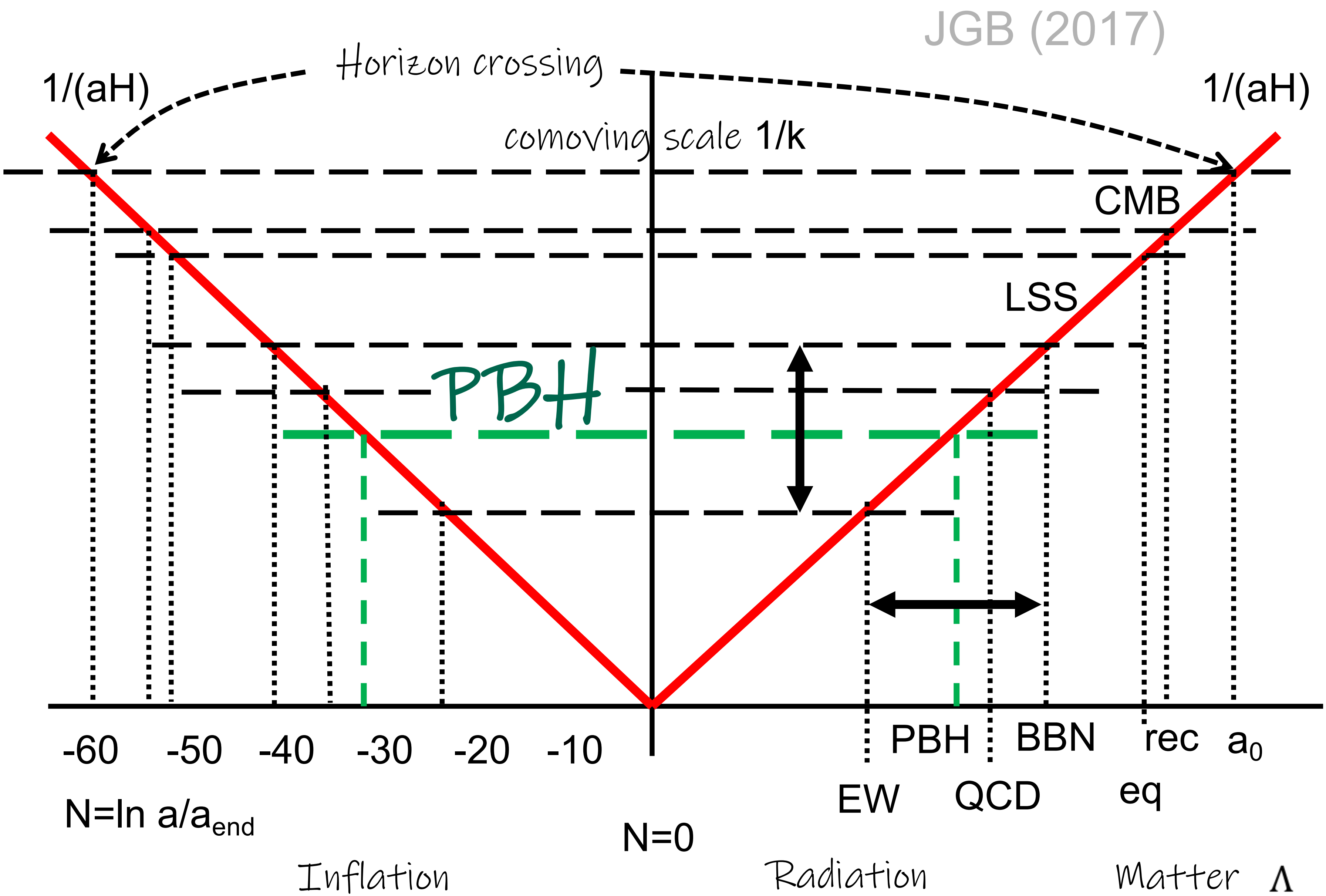
Ezquiaga, JGB, Ruiz Morales (2017)



Primordial Power Spectrum



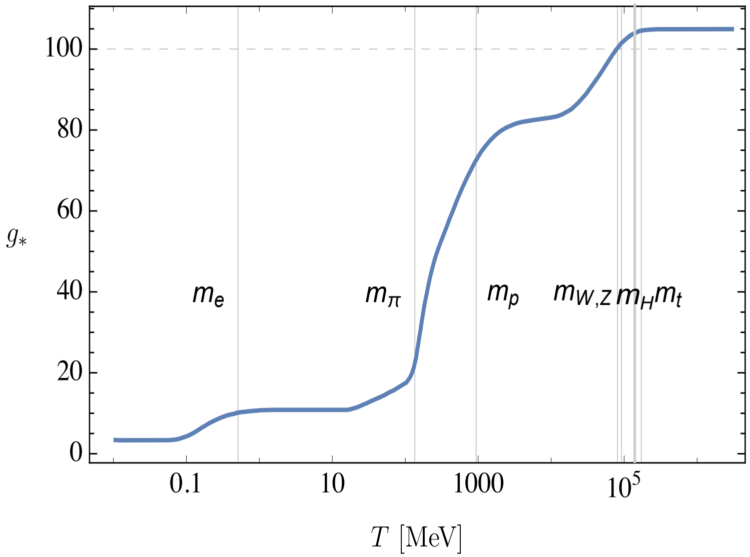
Inflation

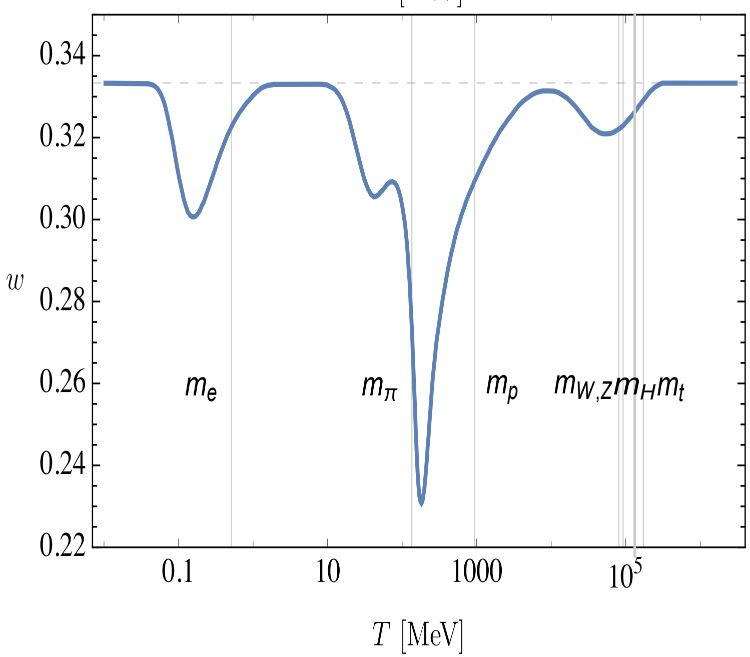


JGB (2017)
Horizon crossing
1/(aH)
1/(aH)
comoving scale 1/k
CMB
LSS
PBH
-60
-50
-40
-30
-20
-10
N=ln a/a_end
N=0
PBH
BBN
rec
a_0
EW
QCD
eq
Inflation
Radiation
Matter
Λ

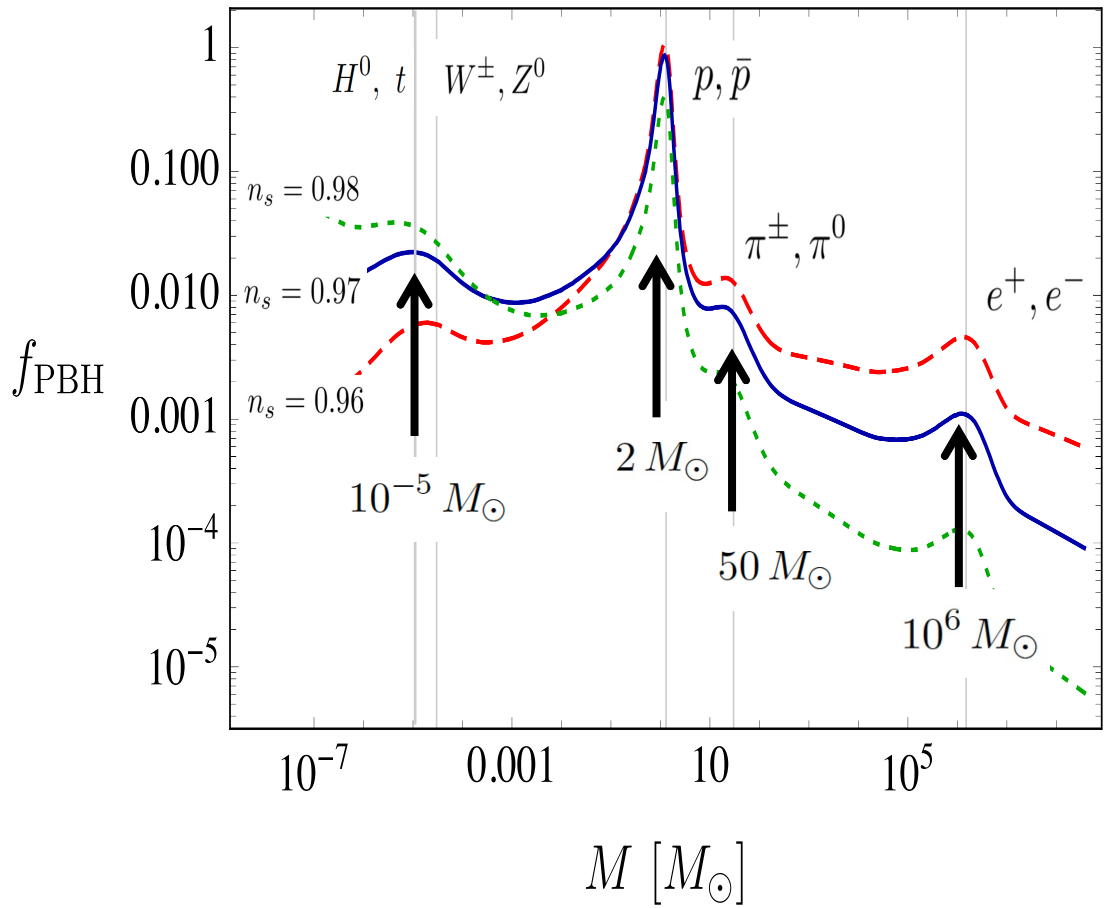
Thermal history of the universe

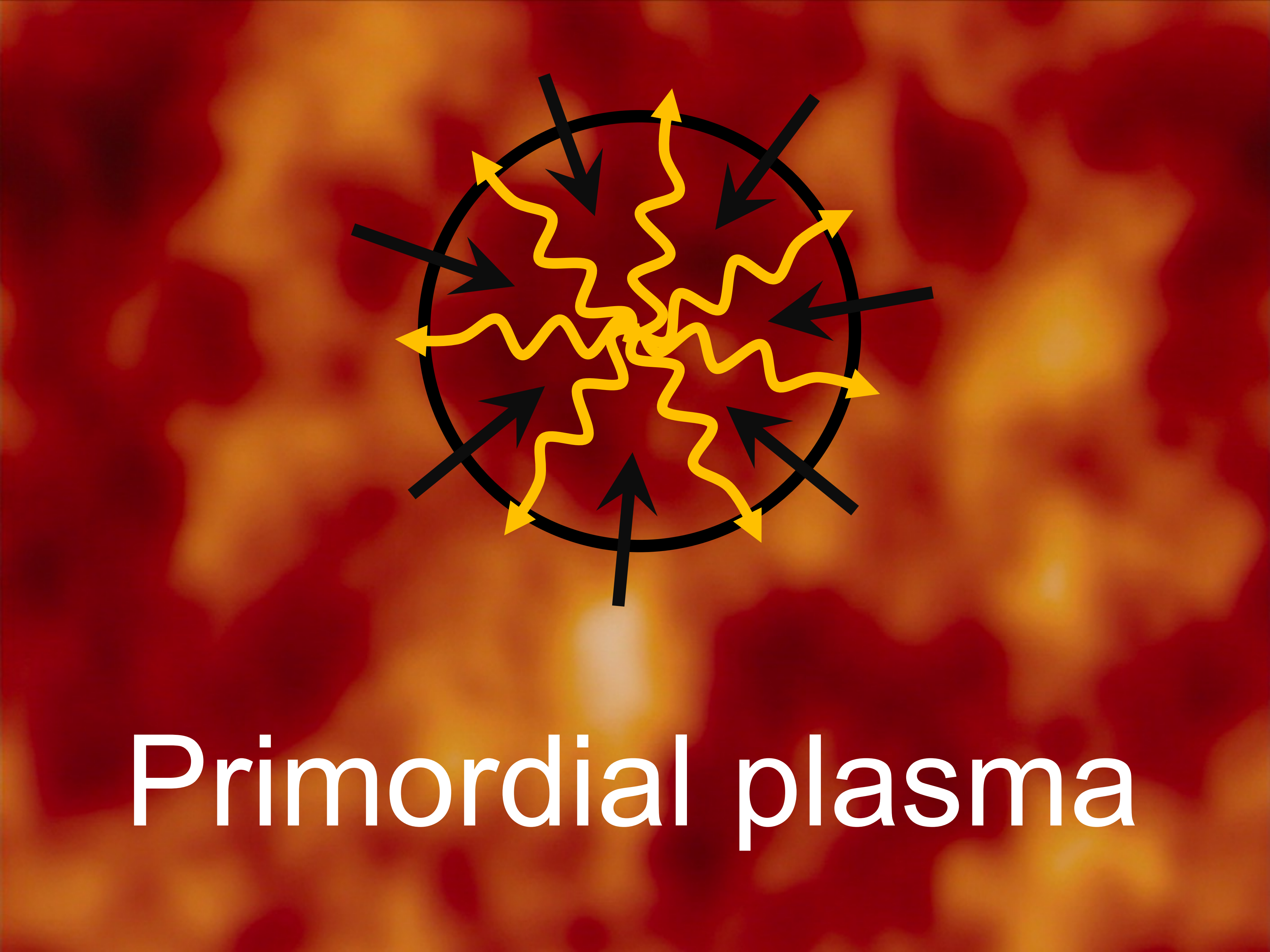
Carr, Clesse, JGB, Kühnel (2019)



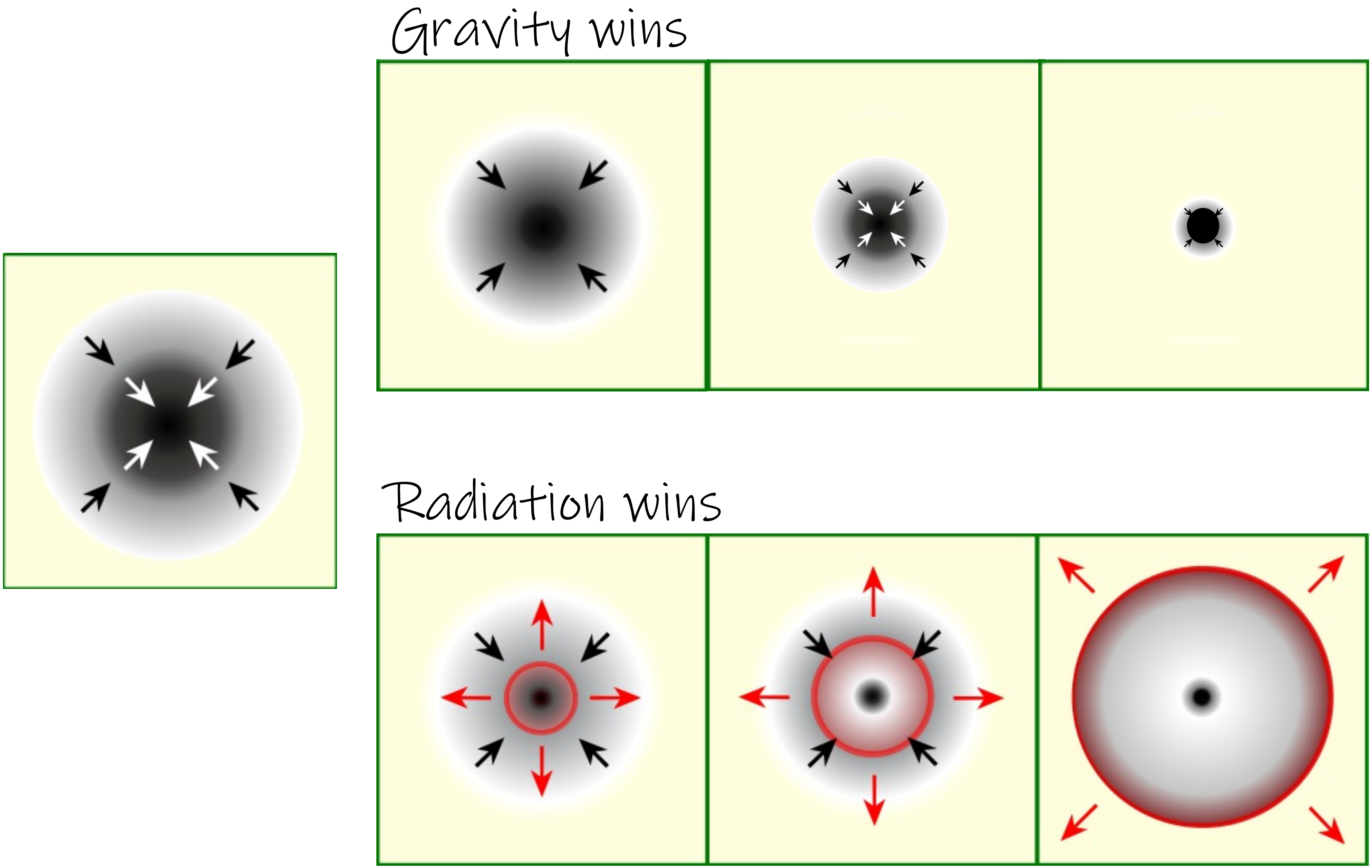


PBH mass spectrum




Primordial plasma

Gravitational Collapse



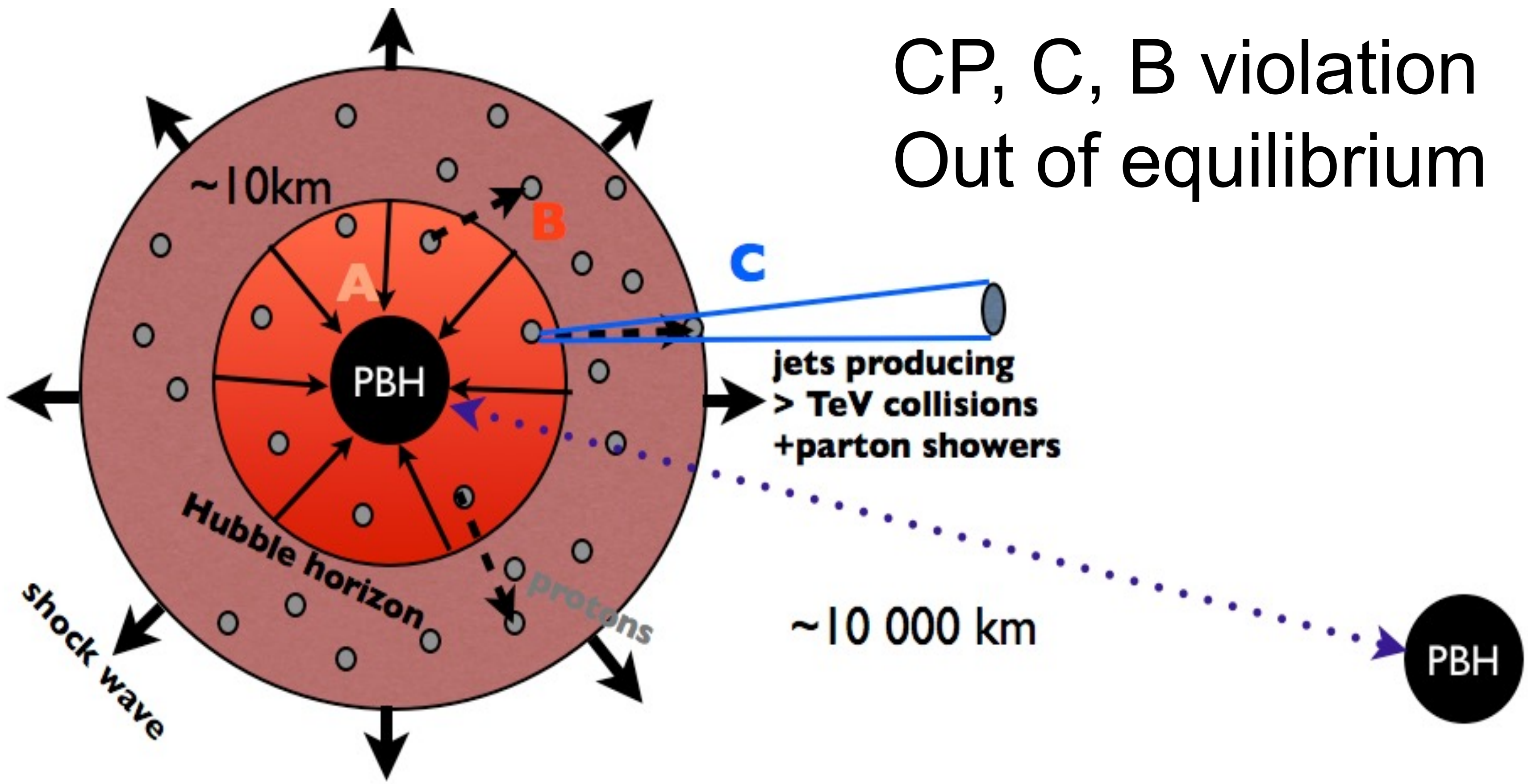
Hot Spot Electroweak baryogenesis

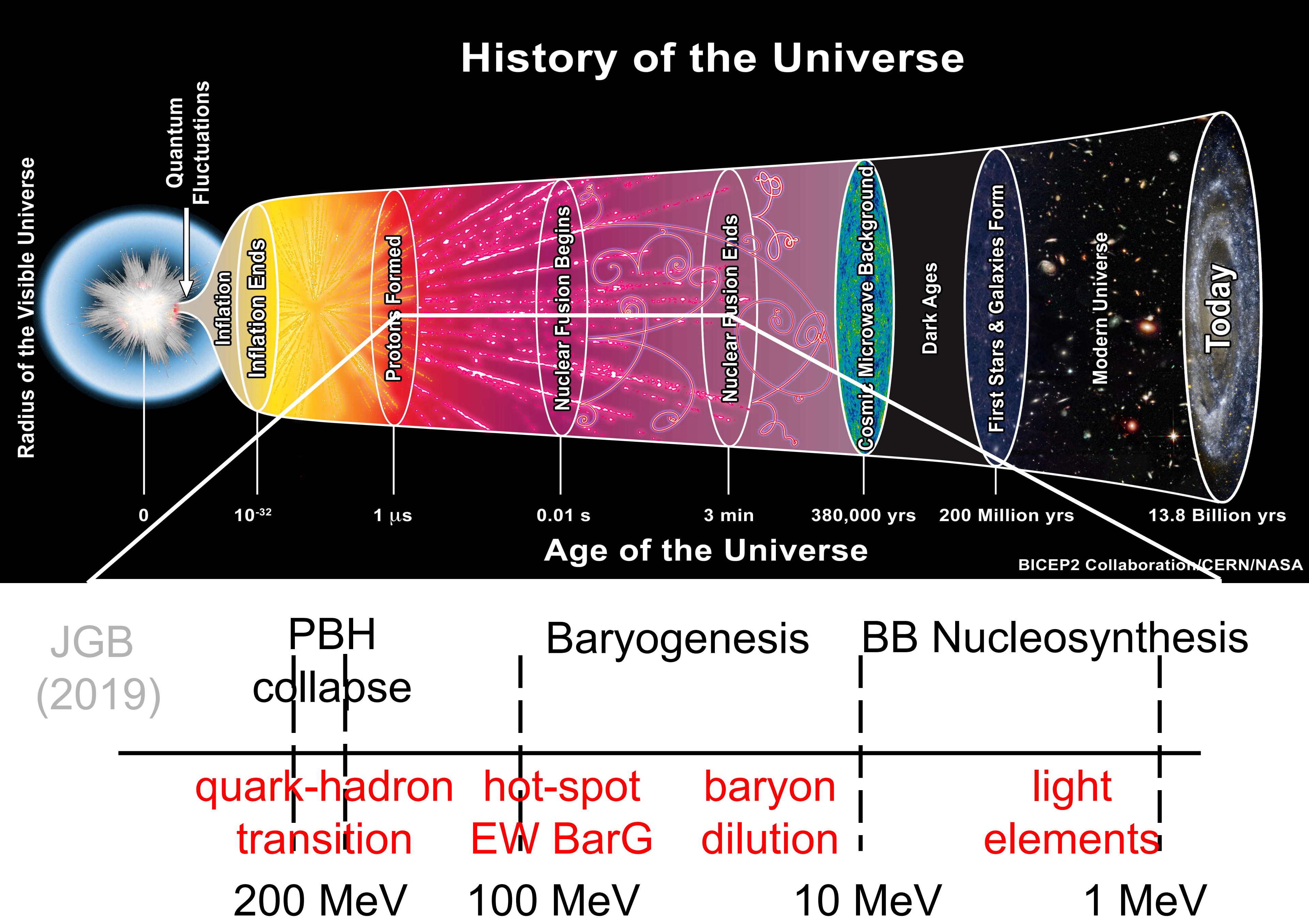
“Primordial supernova”

JGB, Carr, Clesse (2019)

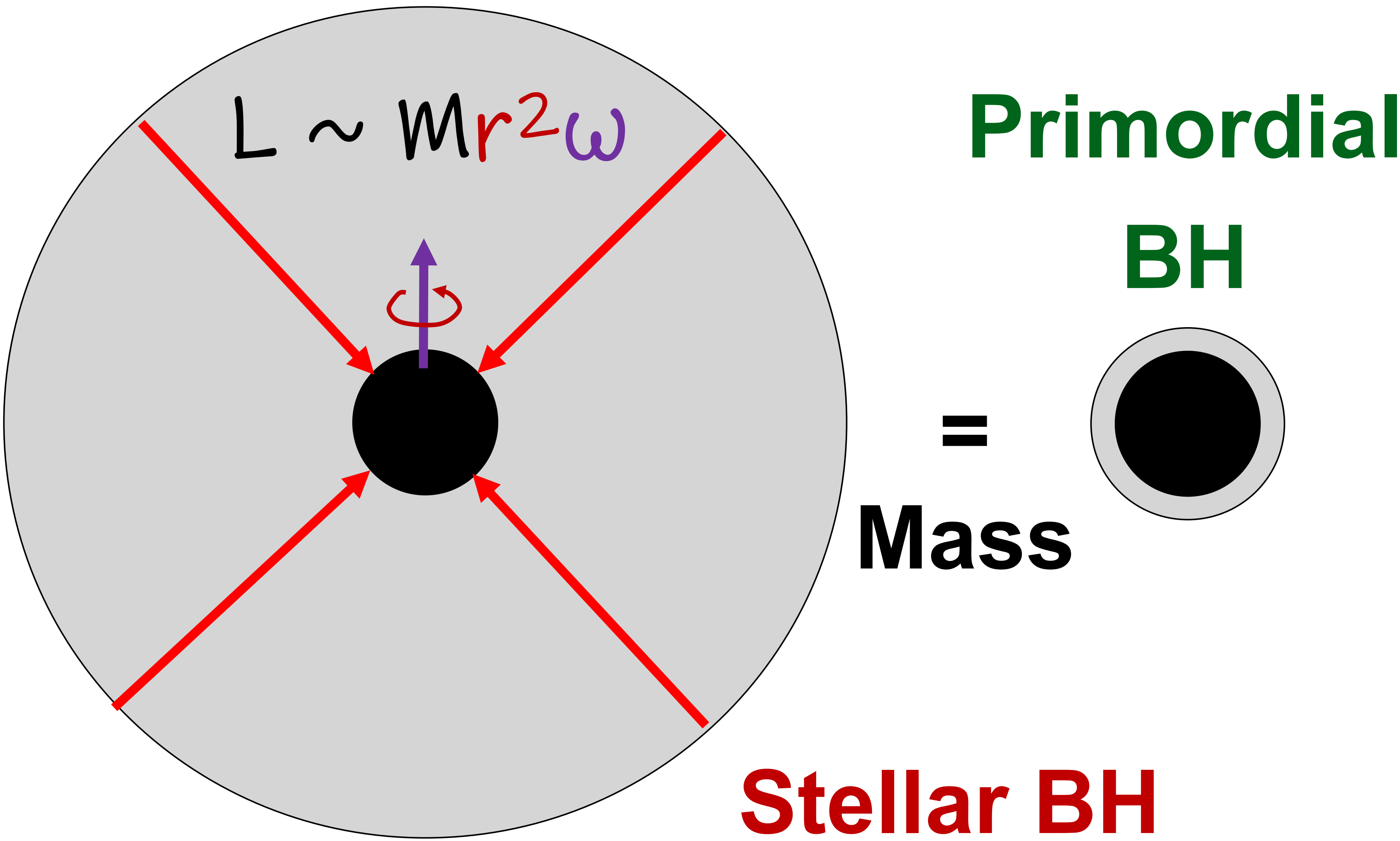
Sakharov conditions:

CP, C, B violation
Out of equilibrium

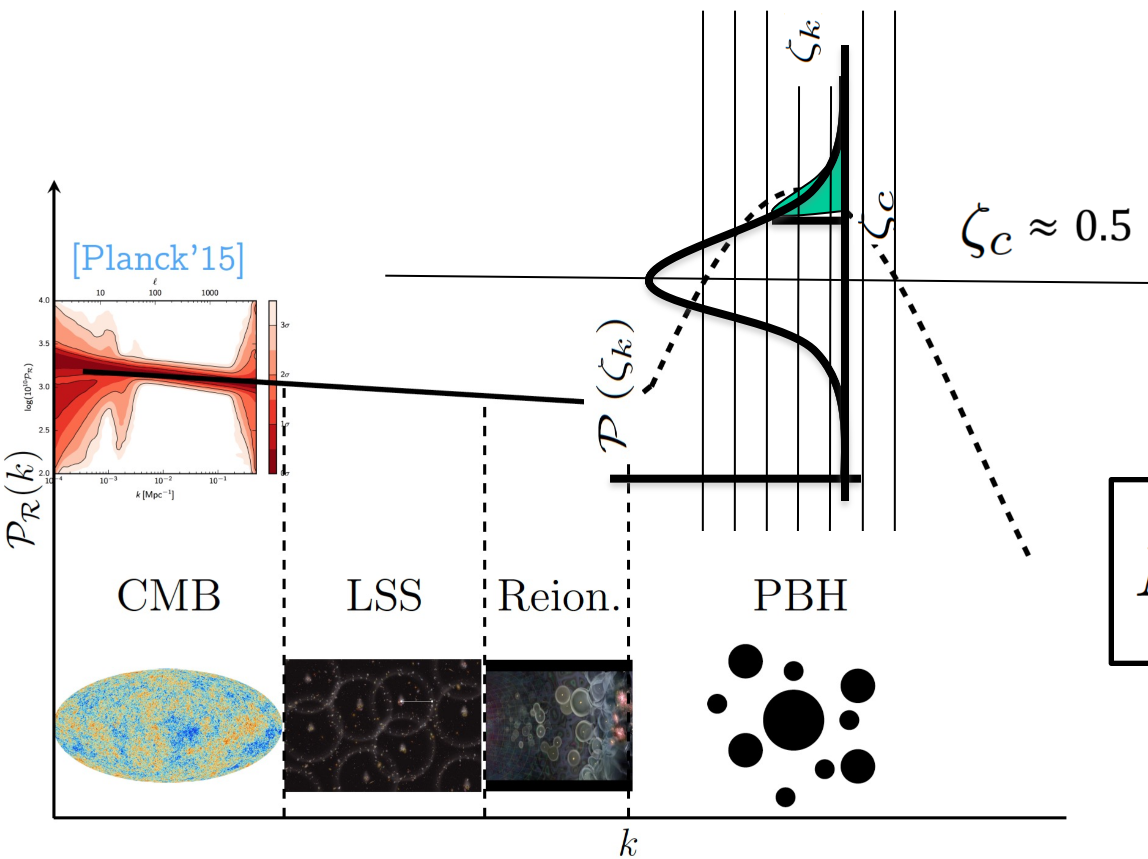


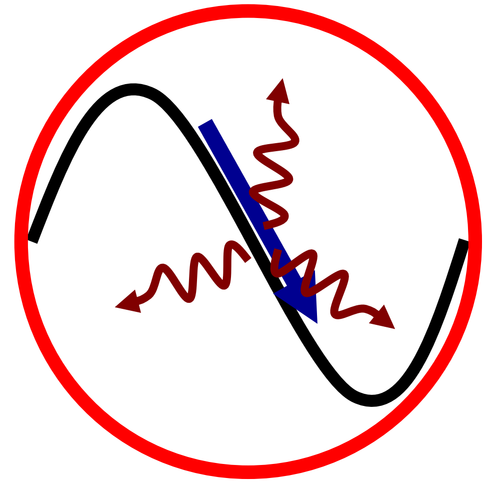

History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10^{-32}
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA
JGB (2019)
PBH collapse
Baryogenesis
BB Nucleosynthesis
quark-hadron transition
hot-spot EW BarG
baryon dilution
light elements
200 MeV
100 MeV
10 MeV
1 MeV

PBH are ~ spinless



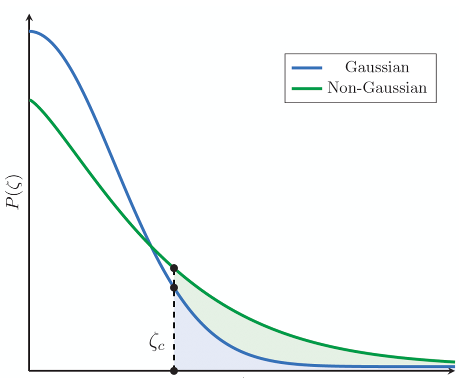
Gravitational Collapse of PBH





$$M_{\rm PBH} \simeq 30\, M_\odot\, e^{2(N-36)}$$

$$\beta^{\rm form}\left(M_k\right) = \int_{\zeta_c}^{\infty} \mathcal{P}\left(\zeta_k\right)\, d\zeta_k$$



$$\beta\left(N\right) = \begin{cases} {\rm Erfc}\left(\dfrac{\zeta_c}{\sqrt{2P_\zeta(N)}}\right)\,, & \text{Gaussian statistics}\,, \\ {\rm Erfc}\left(\sqrt{\dfrac{1}{2}+\dfrac{\zeta_c}{\sqrt{2P_\zeta(N)}}}\right)\,, & \chi^2 \ \text{statistics} \end{cases}$$

Stochastic δN - formalism

Coarse-grained curvature perturbation

$$ds^2 = -dt^2 + a^2(t)e^{2\zeta(t,\mathbf{x})}\delta_{ij}dx^i dx^j \qquad \zeta_{\rm cg}(\mathbf{x}) = \delta N_{\rm cg}(\mathbf{x}) = \mathcal{N}(\mathbf{x}) - \langle\mathcal{N}\rangle$$

$$\frac{1}{M_{\rm pl}^2}\frac{d}{d\mathcal{N}}P_{\mathbf{\Phi}}(\mathcal{N}) = \left(-\sum_i \frac{v_{\phi_i}}{v}\frac{\partial}{\partial\phi_i} + v\sum_i \frac{\partial^2}{\partial\phi_i^2}\right)\cdot P_{\mathbf{\Phi}}(\mathcal{N})$$

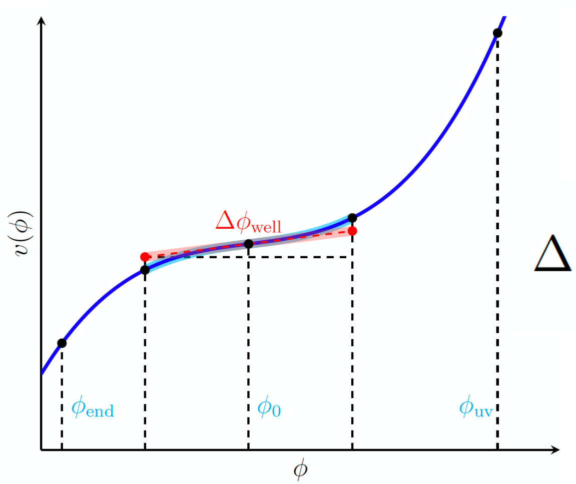
Fokker-Planck Diffusion Eq.

Determined by the poles of the characteristic function

$$P_\phi(\mathcal{N}) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-it\mathcal{N}}\chi_{\mathcal{N}}(t,\phi)dt = \sum_n a_n(\phi)\, e^{-\Lambda_n \mathcal{N}}$$

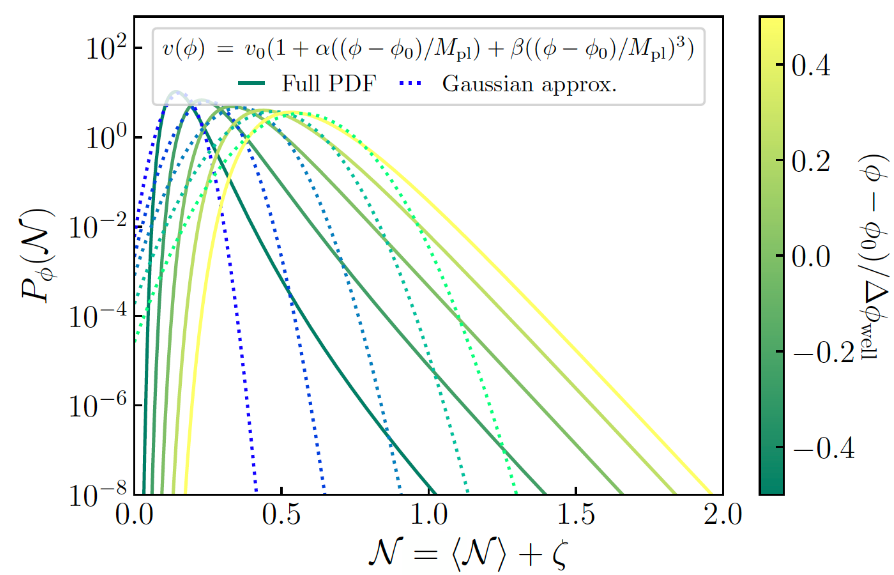
$$\chi_{\mathcal{N}}(t,\phi) = \sum_n \frac{a_n(\phi)}{\Lambda_n - it} + \text{regular func}$$

Ezquiaga, JGB, Vennin (2019)



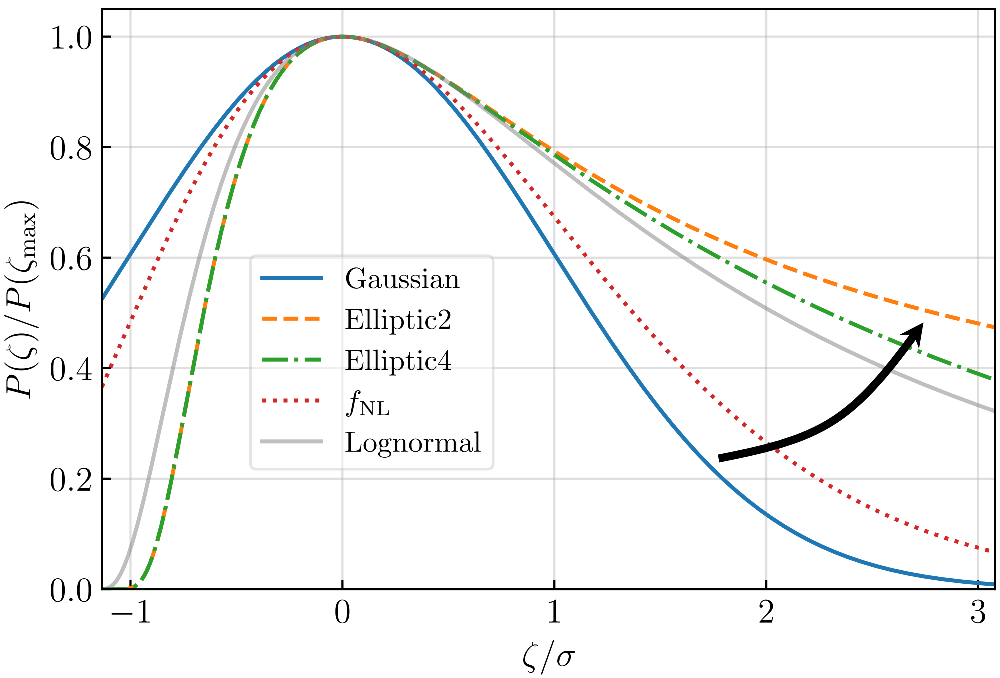
$$\alpha \gg (v_0^2\beta)^{1/3}$$

$$\Delta\phi_{\rm well} \simeq 2M_{\rm pl}\sqrt{\frac{\alpha}{3\beta}}$$



Quantum Diffusion @ CMB & LSS

Ezquiaga, JGB, Vennin (2022)



$$P_2(\zeta_k) = -\frac{\pi}{2\mu^2}\vartheta_2'\left(\frac{\pi\alpha_k}{2}, e^{-\frac{\pi^2}{\mu^2}\mathcal{N}_k}\right)$$

$$P_4(\zeta_k) = \frac{\pi}{2\mu^2\alpha_k}\vartheta_4'\left(\frac{\pi\alpha_k}{2}, e^{-\frac{\pi^2}{\mu^2}\mathcal{N}_k}\right)$$

$$\zeta(x) = \zeta_{\rm G}(x) + \frac{3}{5}f_{\rm NL}\left[\zeta_{\rm G}^2(x) - \sigma_{\rm G}^2(x)\right]$$

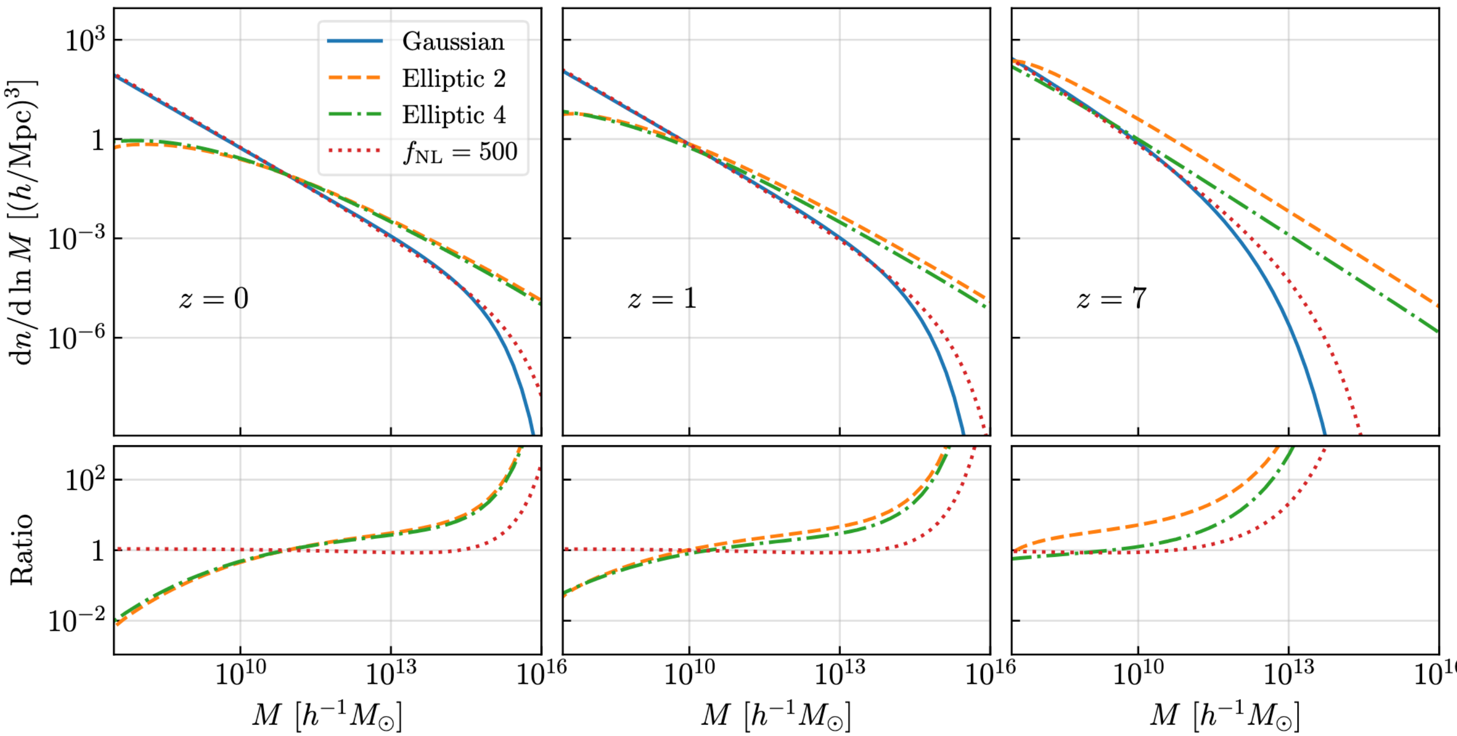
$$\mathrm{LN}(x,\,\rho,\,\sigma) = \frac{1}{\rho\,\sigma\sqrt{2\pi}}\exp\left[-\frac{\ln(x/\rho)^2}{2\sigma^2} - \frac{\sigma^2}{2}\right]$$

$$\mathrm{G}(x,\,\rho,\,\sigma_{\rm G}) = \frac{1}{\sigma_{\rm G}\sqrt{2\pi}}\exp\left[-\frac{(x-\rho)^2}{2\sigma_{\rm G}^2}\right]$$

$$P_{\rm NL}(\zeta) = \frac{1}{\sqrt{2\pi\sigma_{\rm G}^2\Delta}}\left[e^{-\frac{25(\sqrt{\Delta}-1)^2}{72 f_{\rm NL}^2\sigma_{\rm G}^2}} + e^{-\frac{25(\sqrt{\Delta}+1)^2}{72 f_{\rm NL}^2\sigma_{\rm G}^2}}\right]$$

$$\text{where}\quad \Delta(\zeta) = 1 + \frac{12}{5}f_{\rm NL}\zeta + \frac{36}{25}f_{\rm NL}^2\sigma_{\rm G}^2.$$

Quantum Diffusion @ CMB & LSS

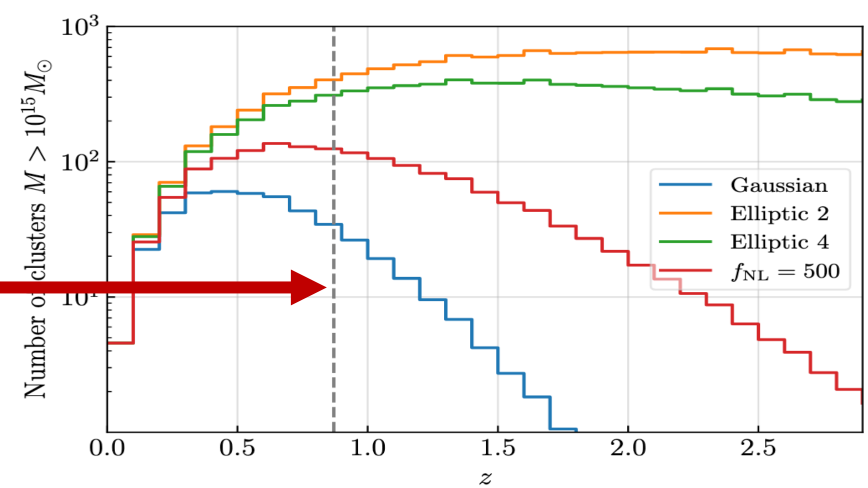


Halo Mass Function

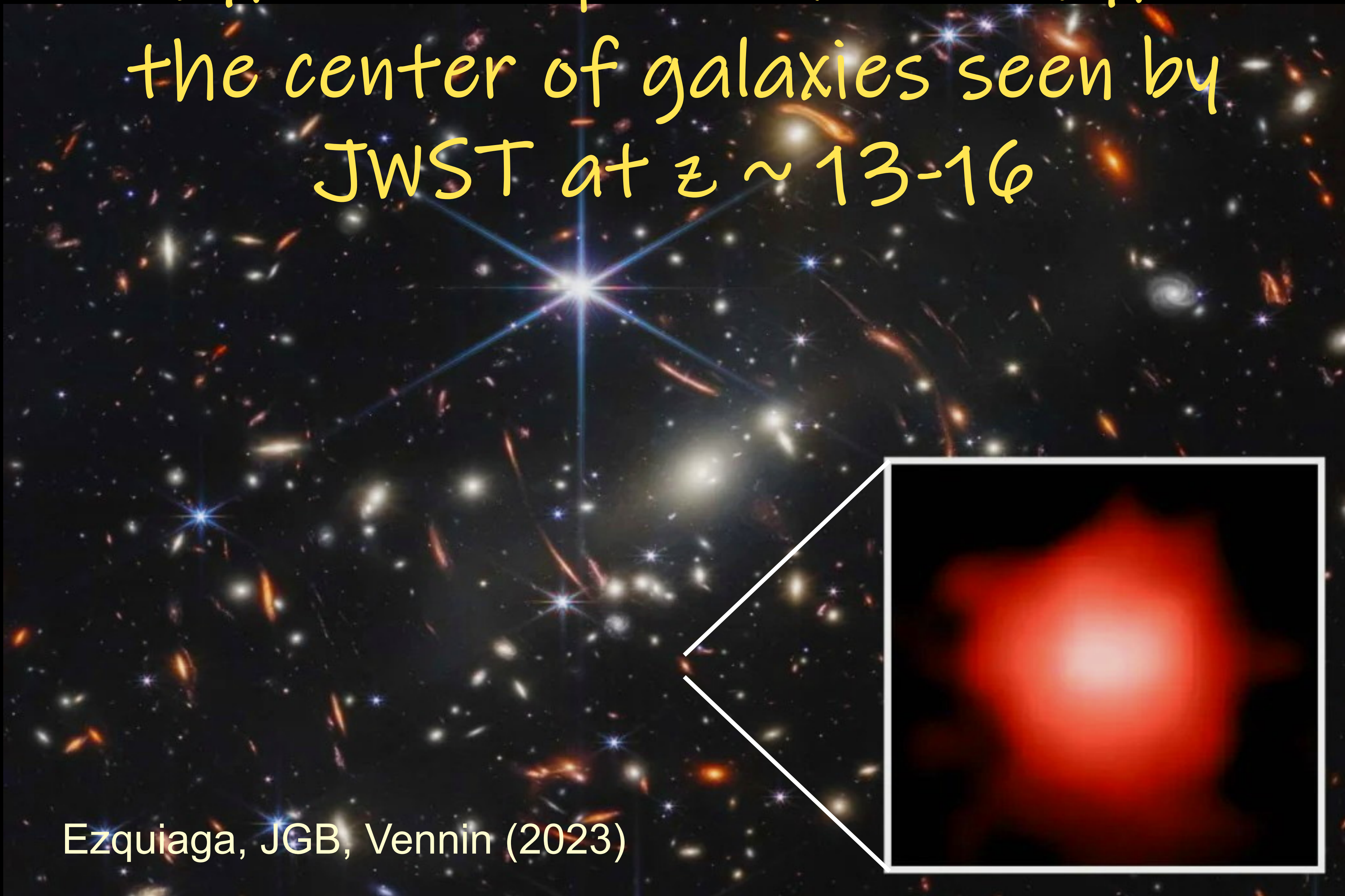
Ezquiaga, JGB, Vennin (2023)

El Gordo

$$M \sim 3 \cdot 10^{15} M_\odot \text{ at } z = 0.87$$



PBH could explain the SMBH in the center of galaxies seen by JWST at z ~ 13-16



Ezquiaga, JGB, Vennin (2023)

PBH could explain SMBH in AGN seen by JWST+Chandra at z ~ 10

The Astrophysical Journal Letters, 955:L24 (8pp), 2023 September 20 Goulding et al.

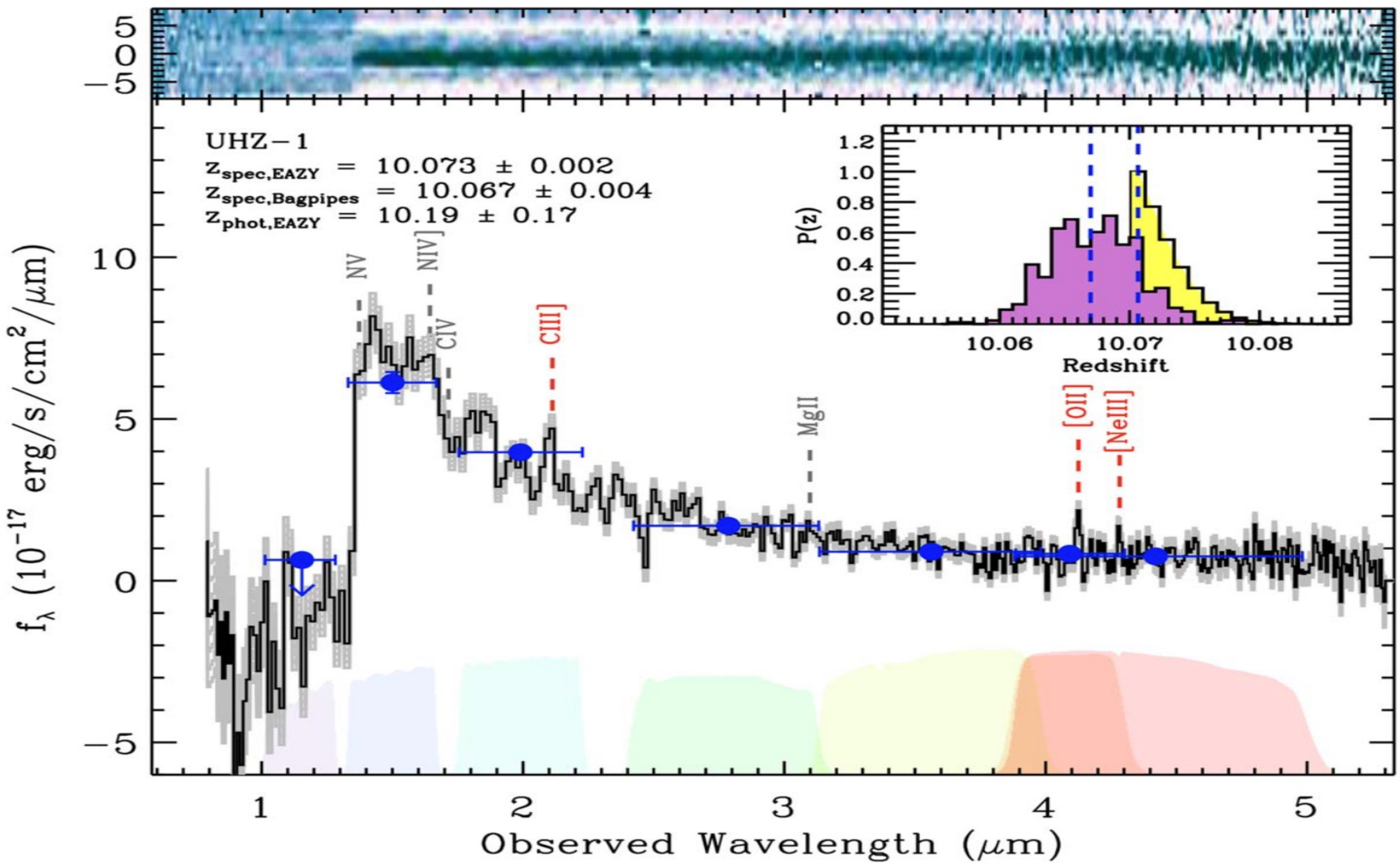


Figure 2. JWST/NIRSpec Prism spectroscopy of UHZ-1. Upper panel: 2D MSA Prism spectroscopy produced by msaexp. Lower panel: 1D spectral extraction in f_λ (in units of 10^{-17} erg s^{-1} cm^{-2} μm^{-1}) with associated statistical uncertainties (gray shaded region). Slit-loss corrections are defined by convolution of the JWST photometry with the Prism spectrum (see Section 2). Prominent and/or expected emission features are highlighted assuming $z_{spec} = 10.07$ with significant $>3\sigma$ detections and nondetections labeled in red and gray, respectively. Overlaid are the JWST/NIRCam photometry (blue circles) with associated filter responses highlighted. Inset panel: redshift probability distributions for fits to the NIRSpec spectroscopy produced by EAZY (yellow) and BAGPIPES (purple) packages.

Cappelutti+ (2022)

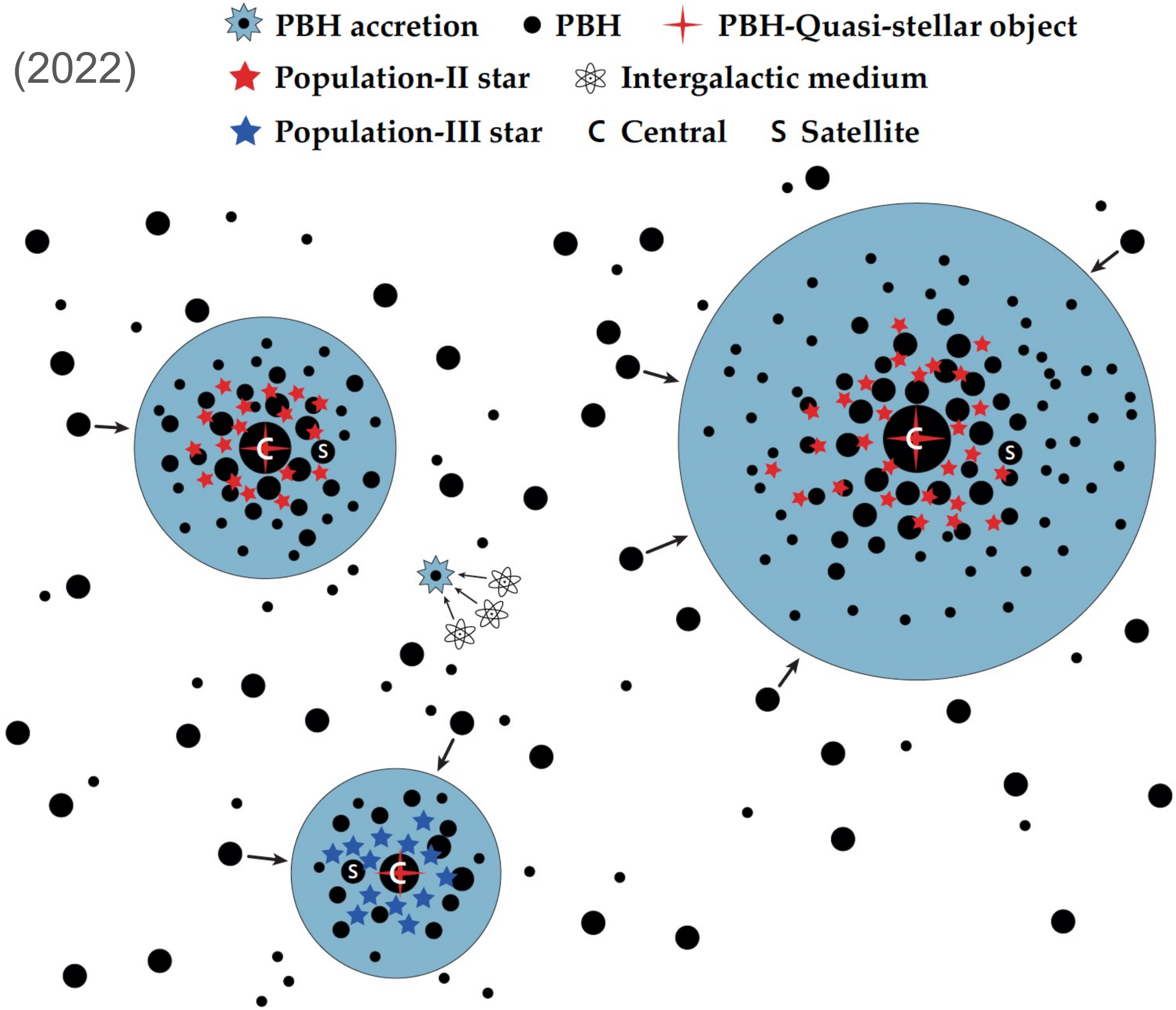
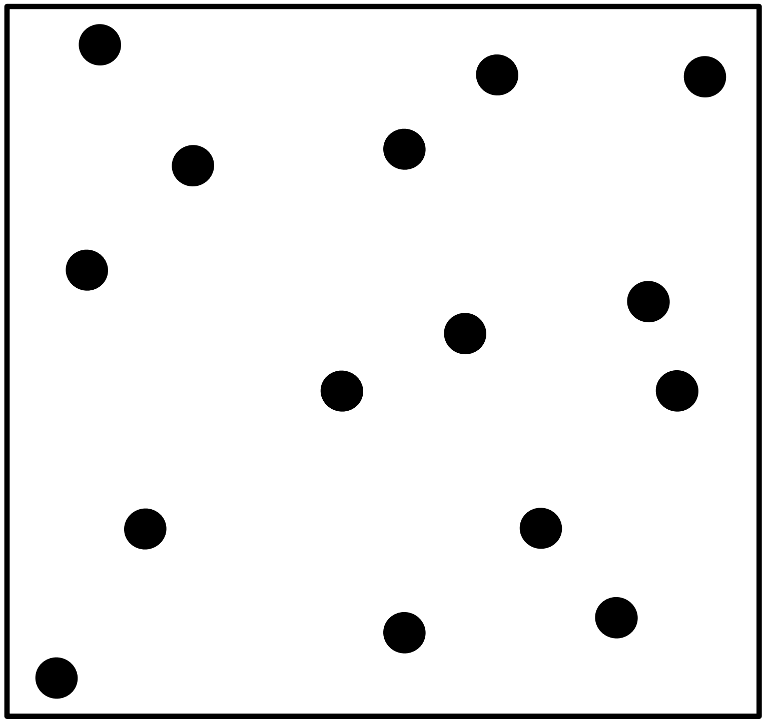
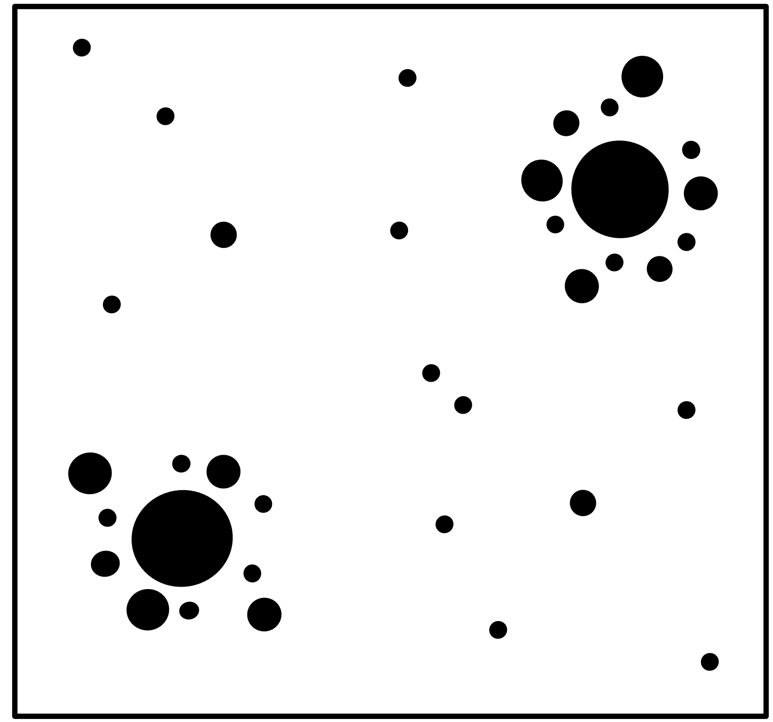


Figure 22. Illustration of PBH clustering at redshifts 10 – 15. Initially, PBHs (black dots) capture baryons while accreting, thereby contributing to the cosmic X-ray background. Lighter PBHs later form halos around more massive ones and initiate star formation; the lowest mass halos first form Population III stars, which generate a faint cosmic infrared background, and the higher mass ones then yield Population II stars. The most massive (central) supermassive PBH continues to accrete and merge with other PBHs. It appears as the central source in the infrared and X-ray emission, with the smaller PBHs and stars filling the halo as satellites.

Spatial Distribution PBH





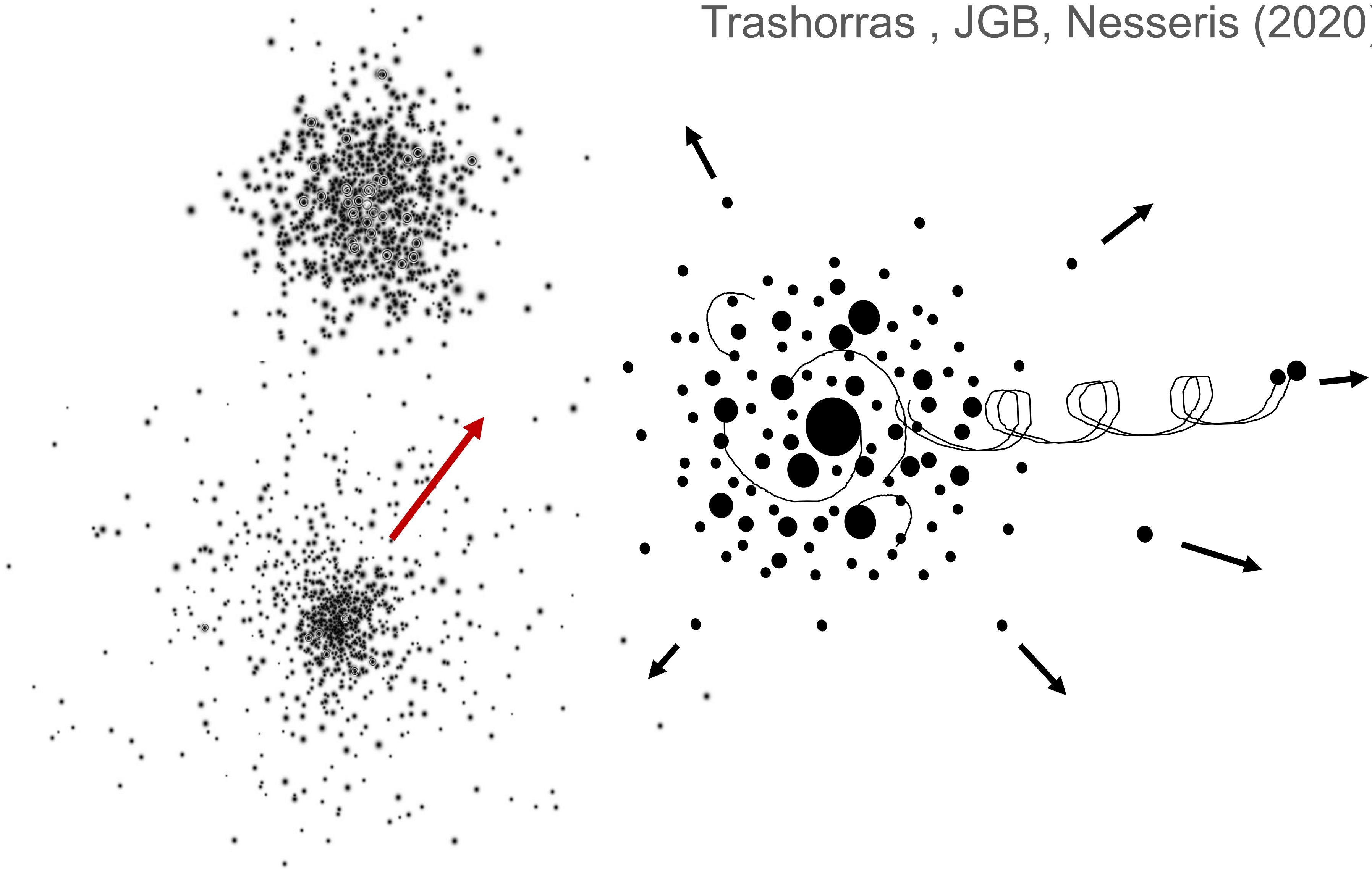
- Monochromatic
- Uniformly distributed

- Broad range of masses
- PBH in clusters

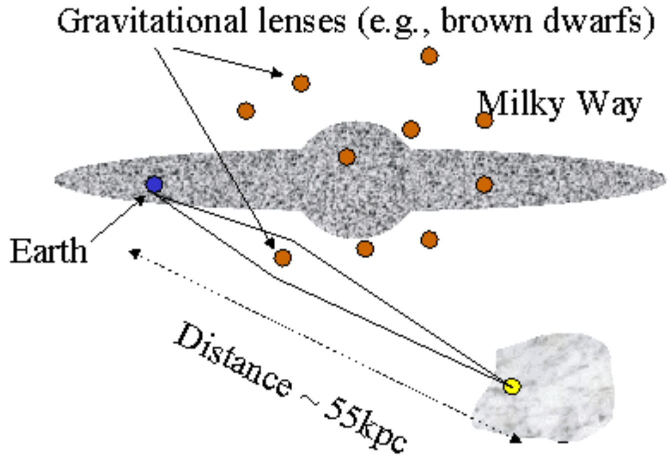
JGB (2017)

PBH clusters

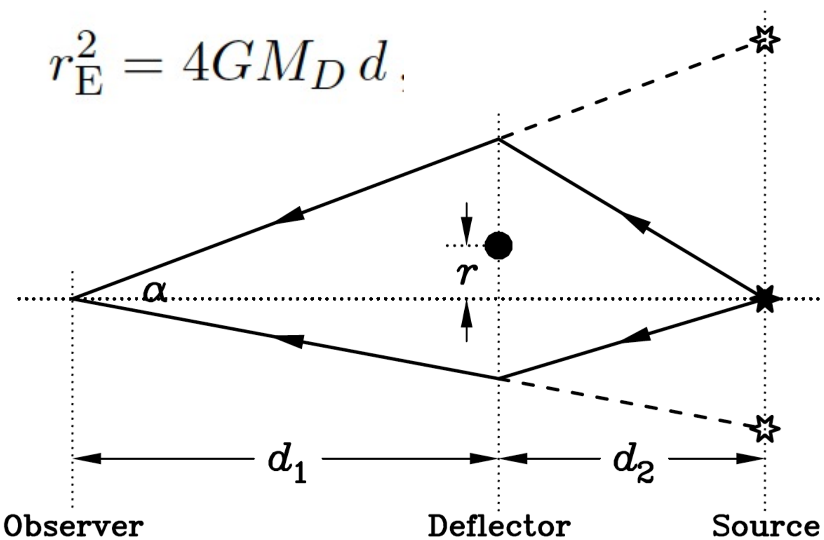
Trashorras , JGB, Nesseris (2020)



Microlensing



$$r_E^2 = 4GM_D\, d$$



$$d = \frac{d_1 d_2}{d_1 + d_2}$$

$$A = \frac{2+u^2}{u\sqrt{4+u^2}} \qquad u = \frac{r}{r_E} \quad \text{amplification}$$

$$\overline{Dt} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v} \quad \text{average } \frac{1}{2} \text{ crossing}$$

$M_D = 100\,M_\odot$ => $\overline{Dt} = 4$ years

$M_D = 10\,M_\odot$ => $\overline{Dt} = 1.23$ years

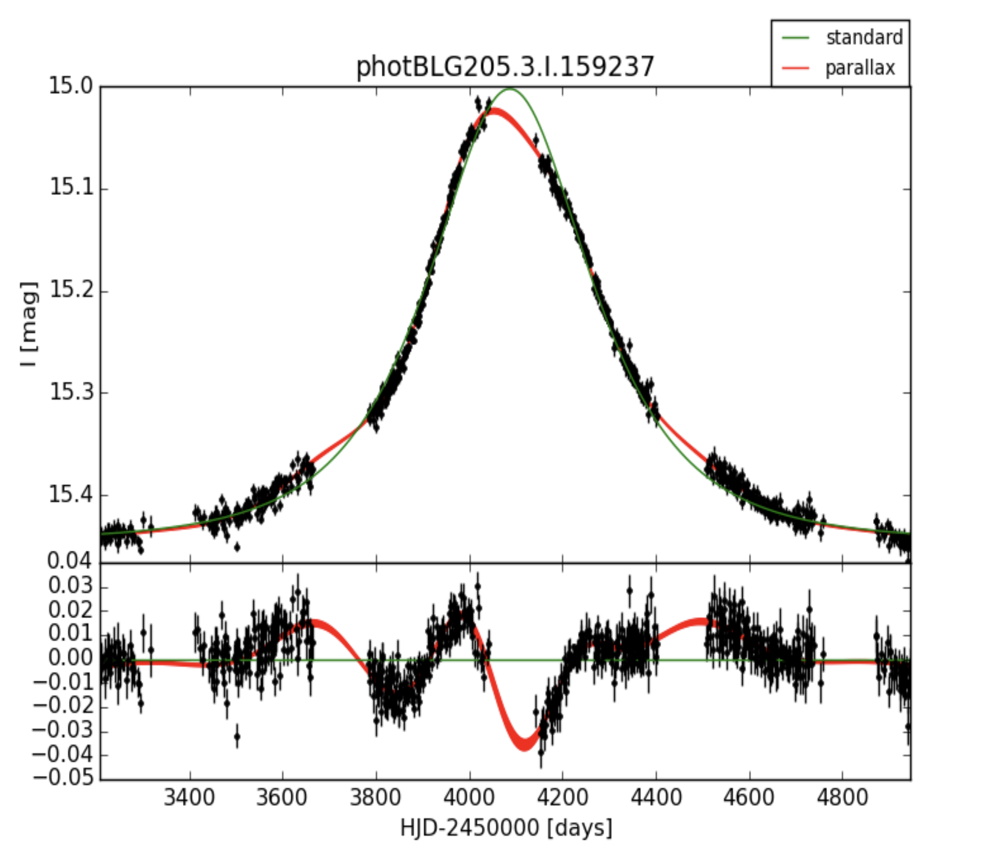
$M_D = 1\,M_\odot$ => $\overline{Dt} = 5$ months

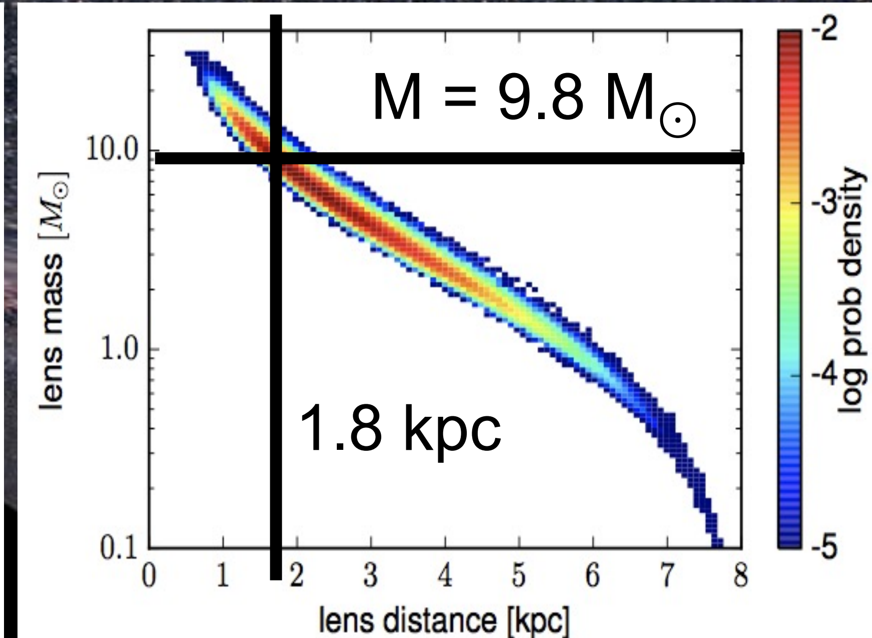
$M_D = 0.1\,M_\odot$ => $\overline{Dt} = 1.5$ months

$M_D = 0.01\,M_\odot$ => $\overline{Dt} = 2$ weeks

OGLE3-UL-PAR-02 - candidate BH

Wyrzykowski (2016)



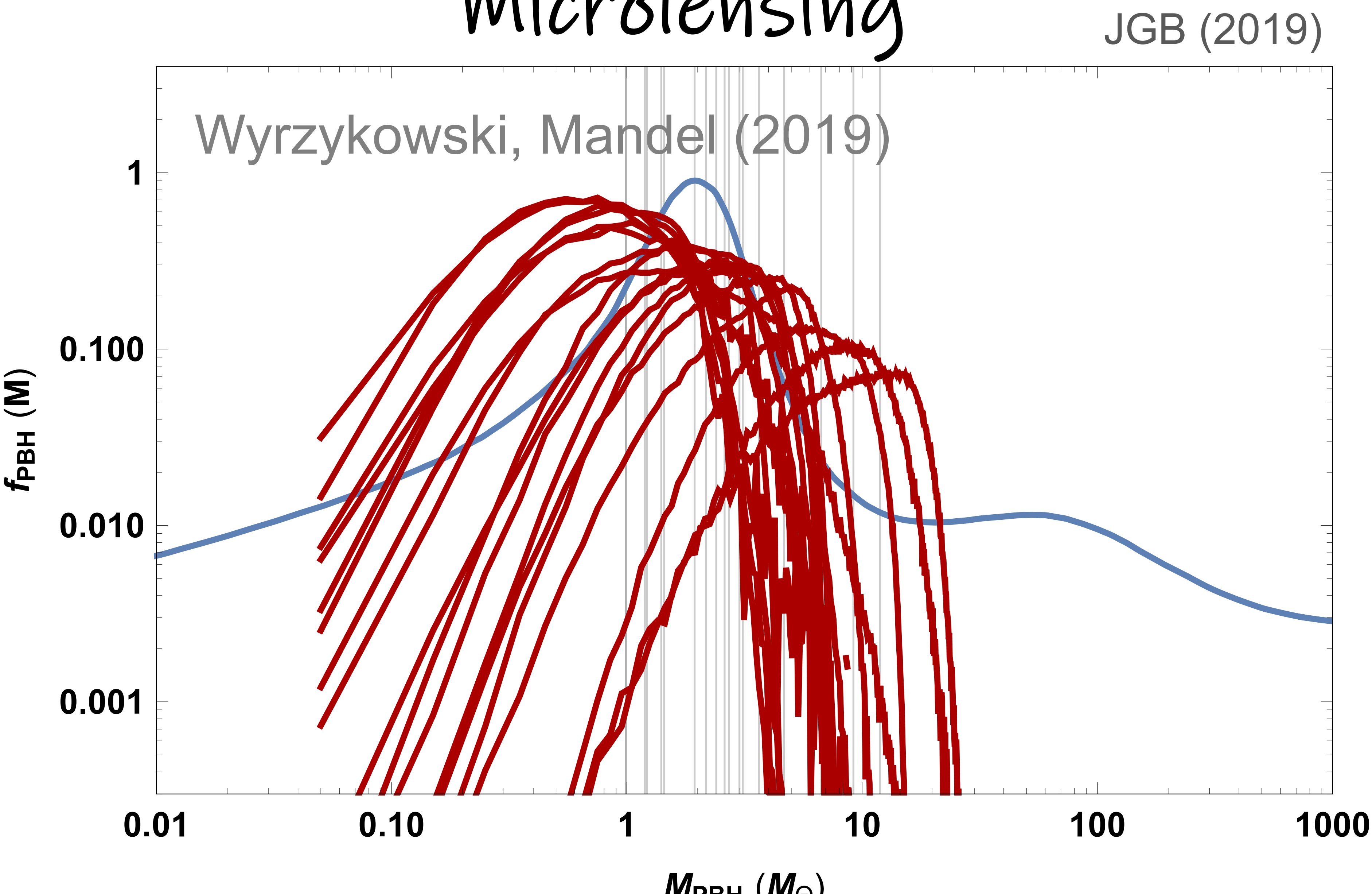


$$\overline{Dt} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v}$$

OGLE photometry from 2001-2008 and microlensing model

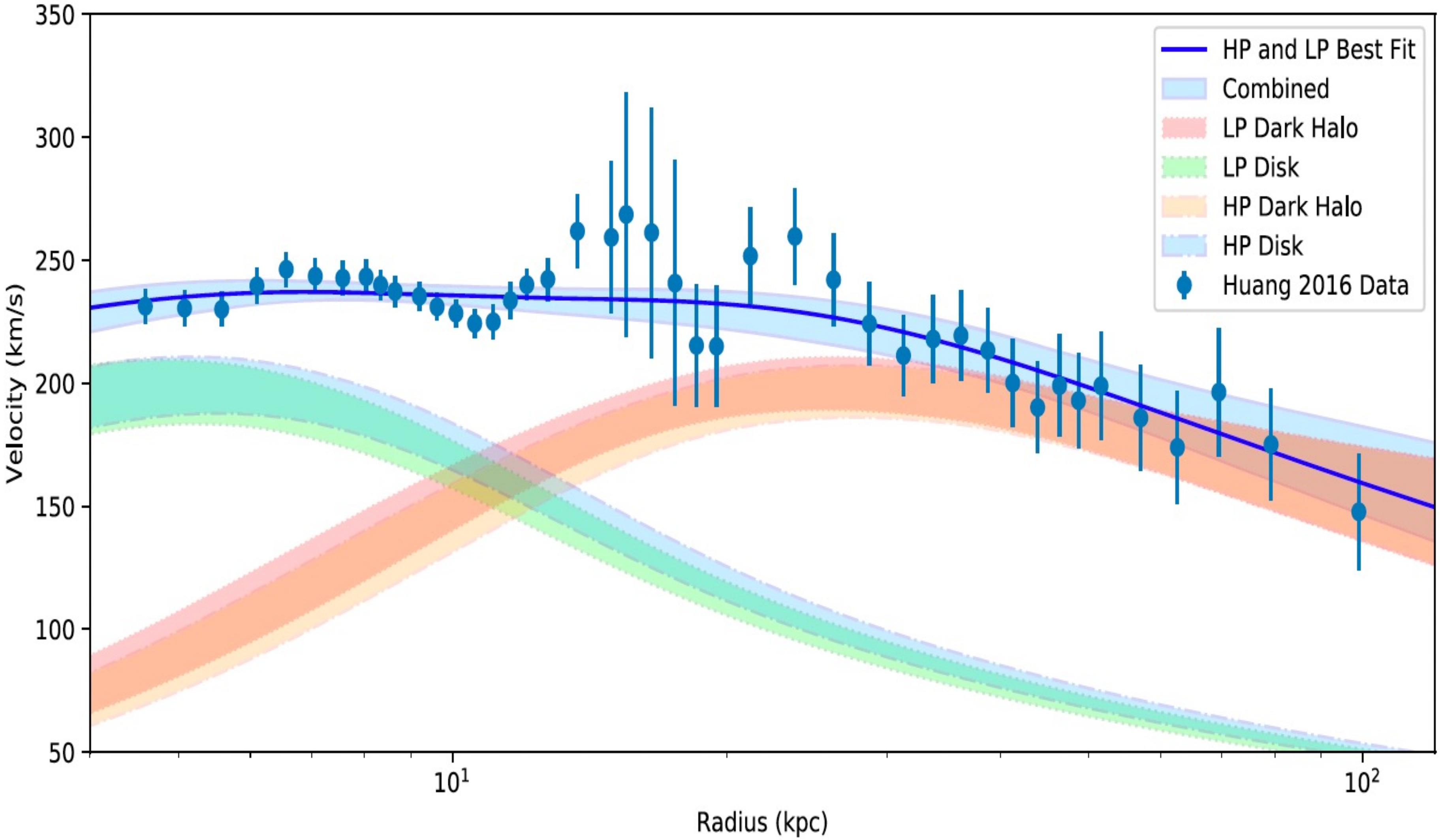
Mass, Distance (degenerated estimate)

Microlensing



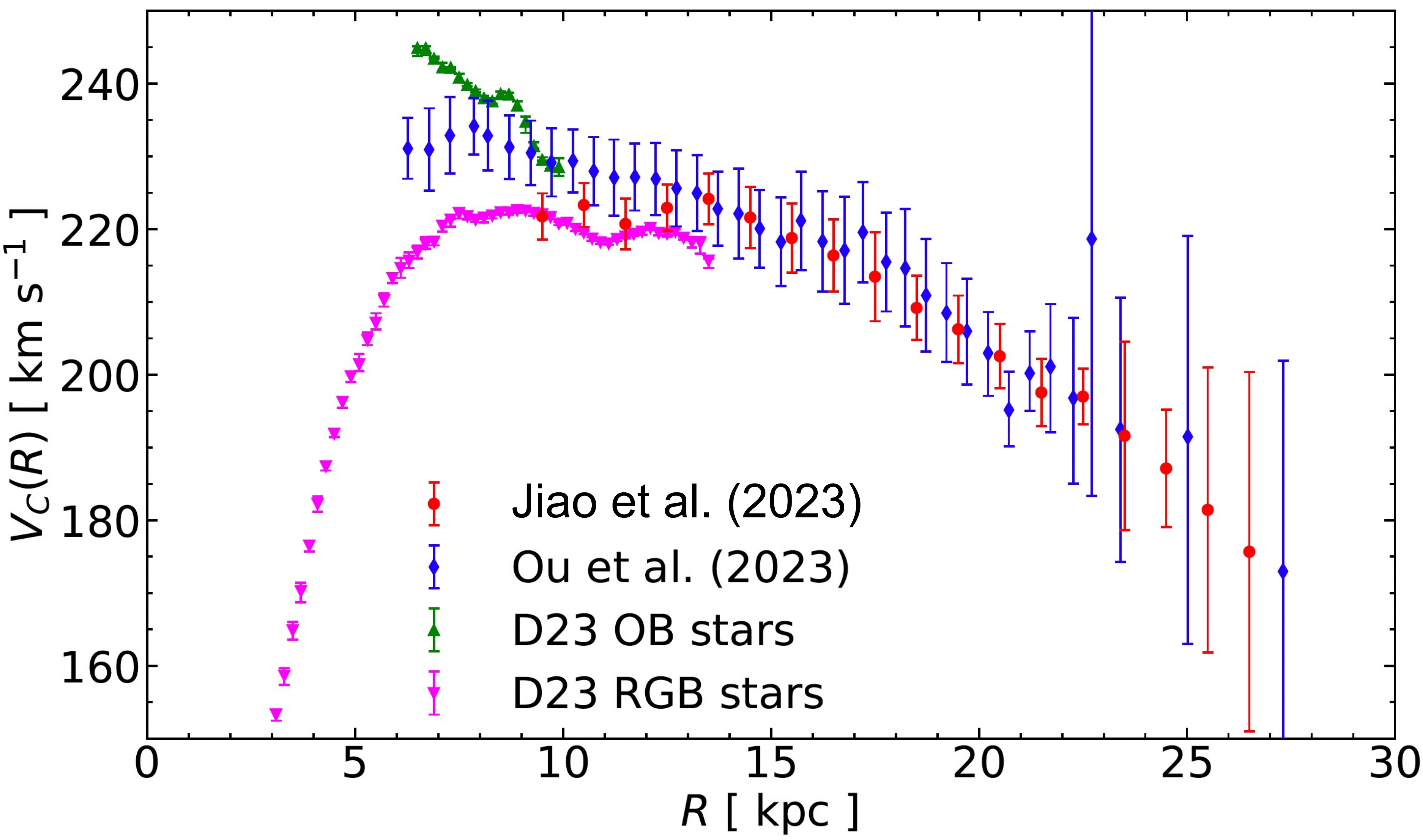
Rotation curves MW

J. Calcino et al (2018)

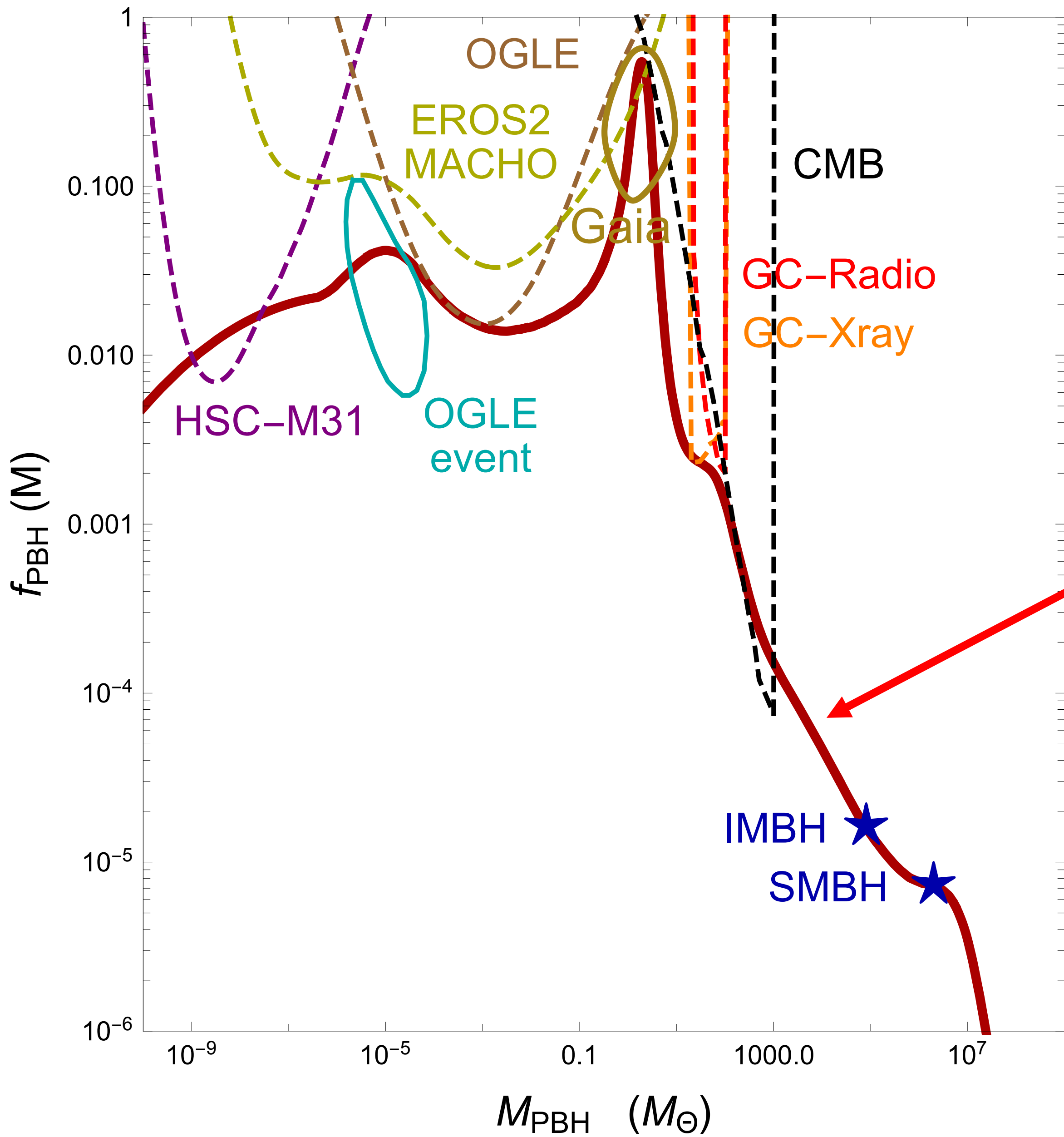


Rotation curves MW

J. Jiao et al. (2023)
X. Ou et al. (2023)



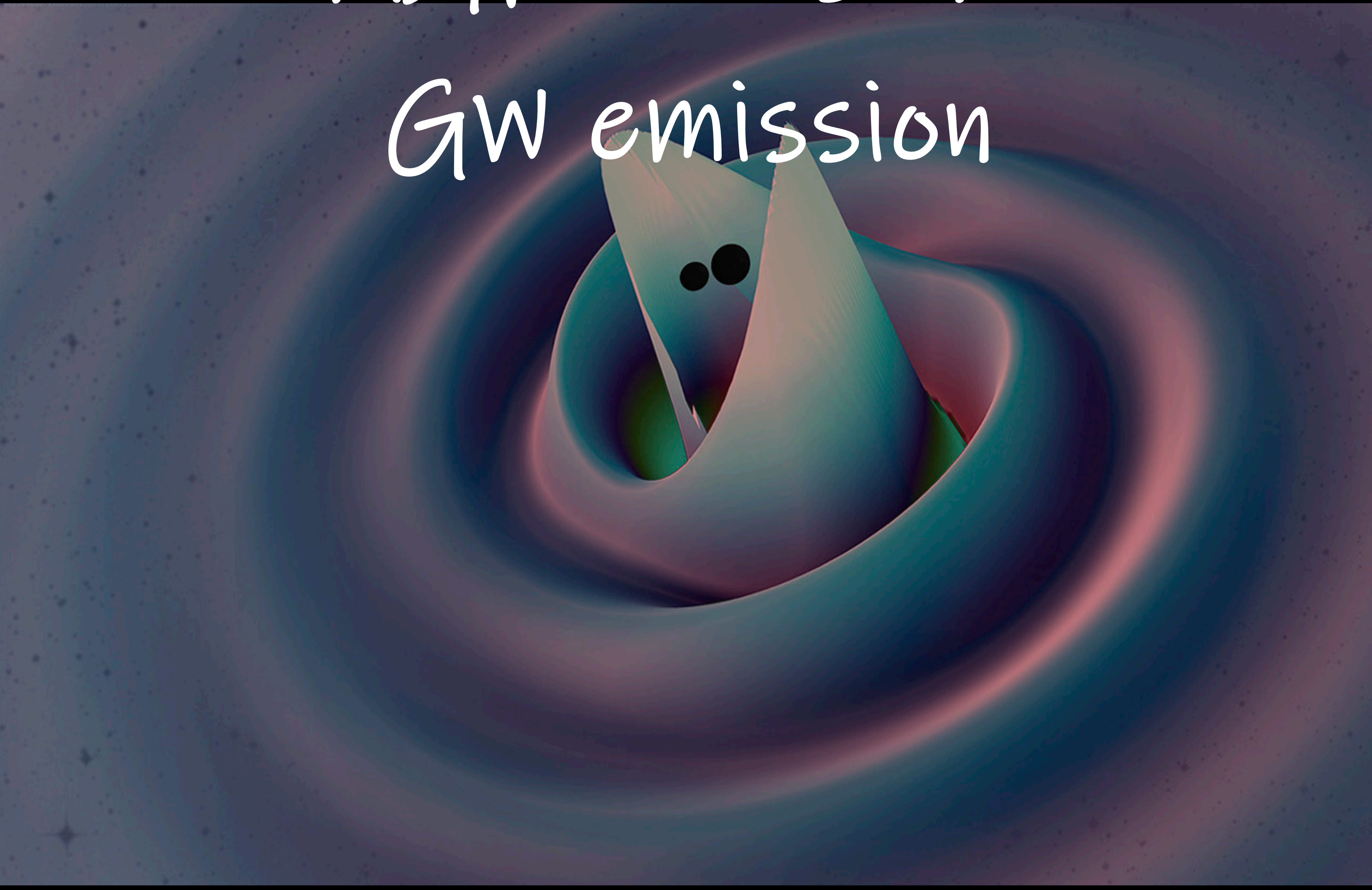
PBH could be all of the DM



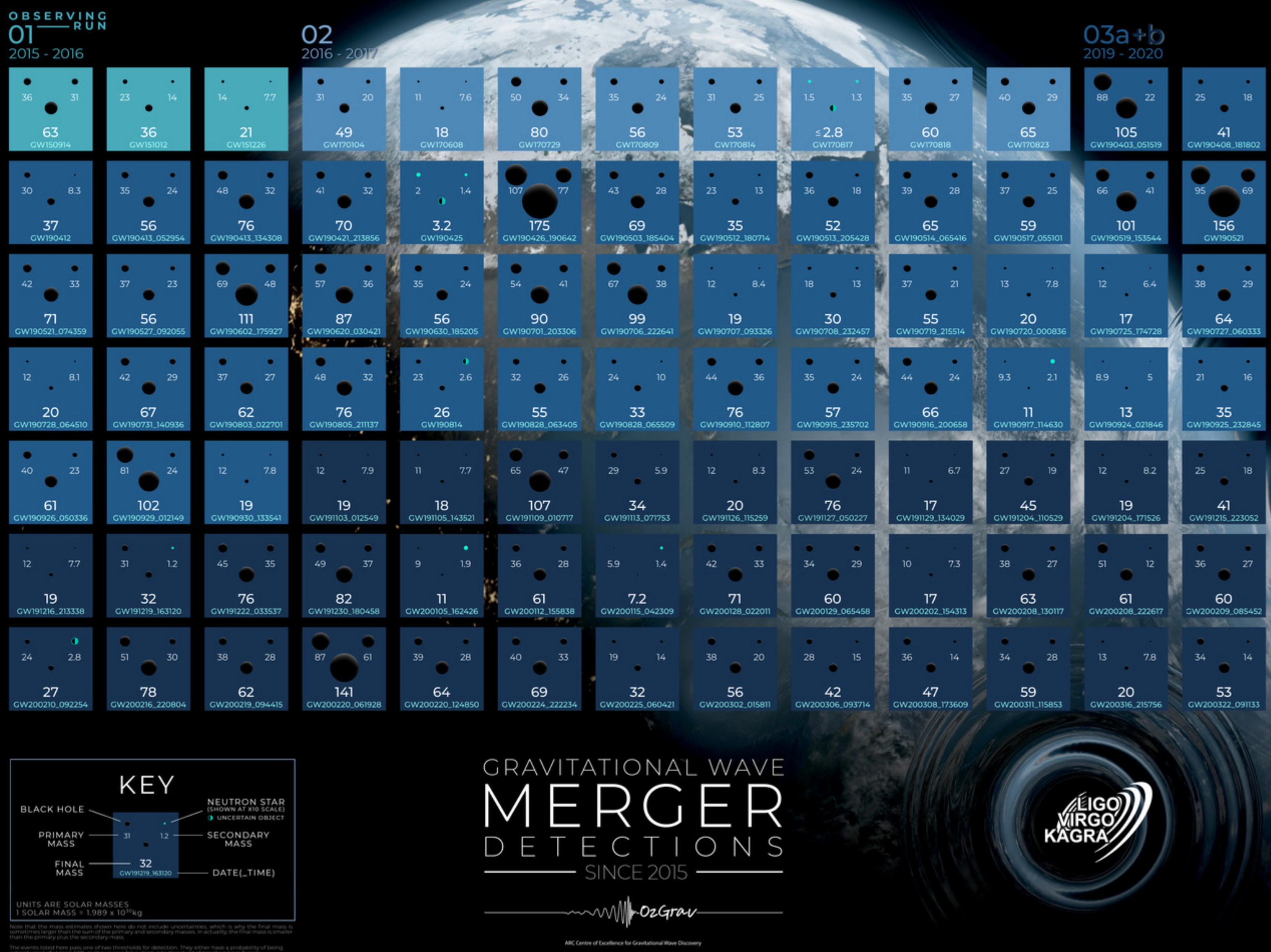
Cappelluti
Hasinger
Natarajan
(2022)

Based on
JGB (2021)

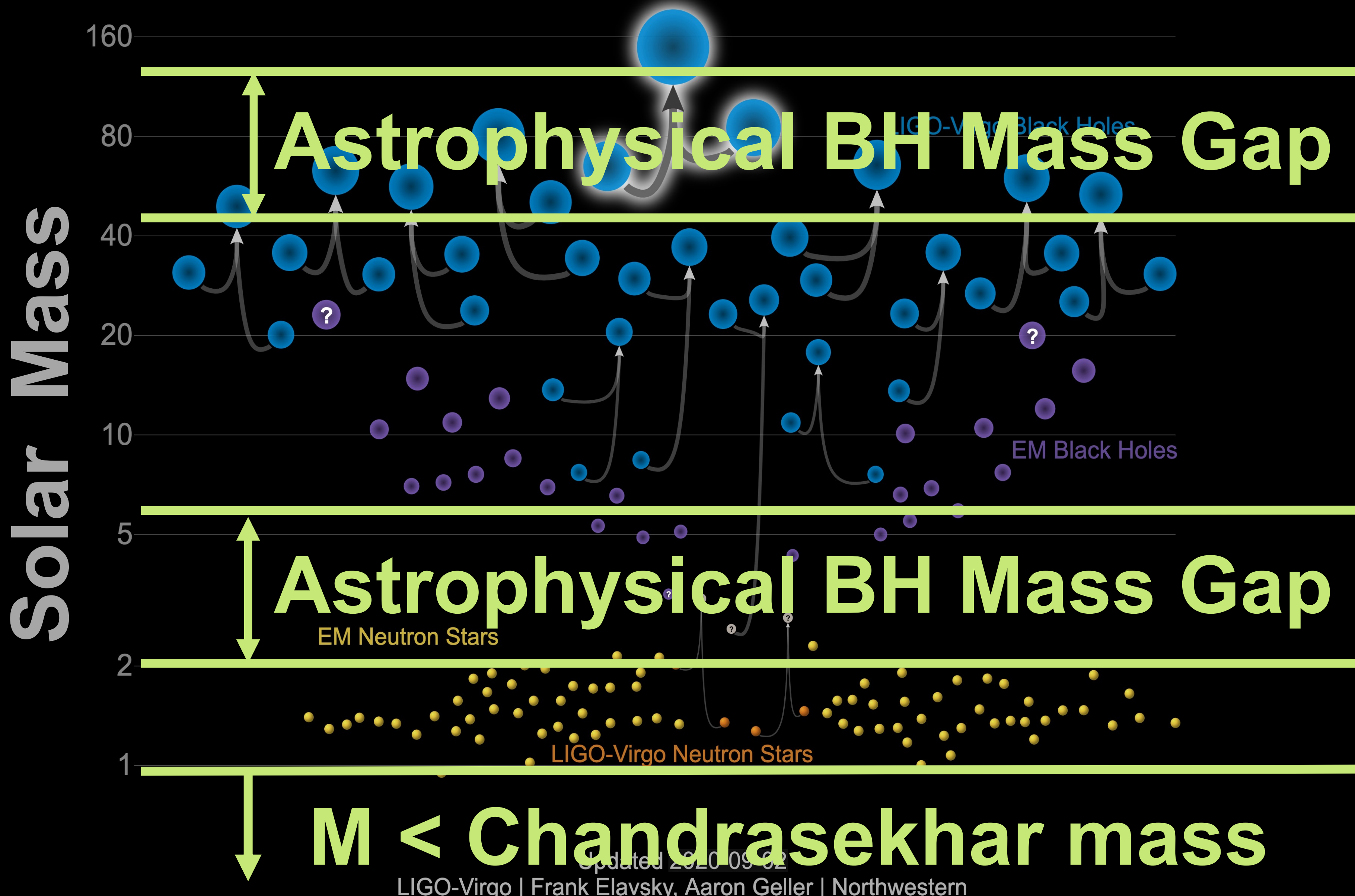
PBH coalesence



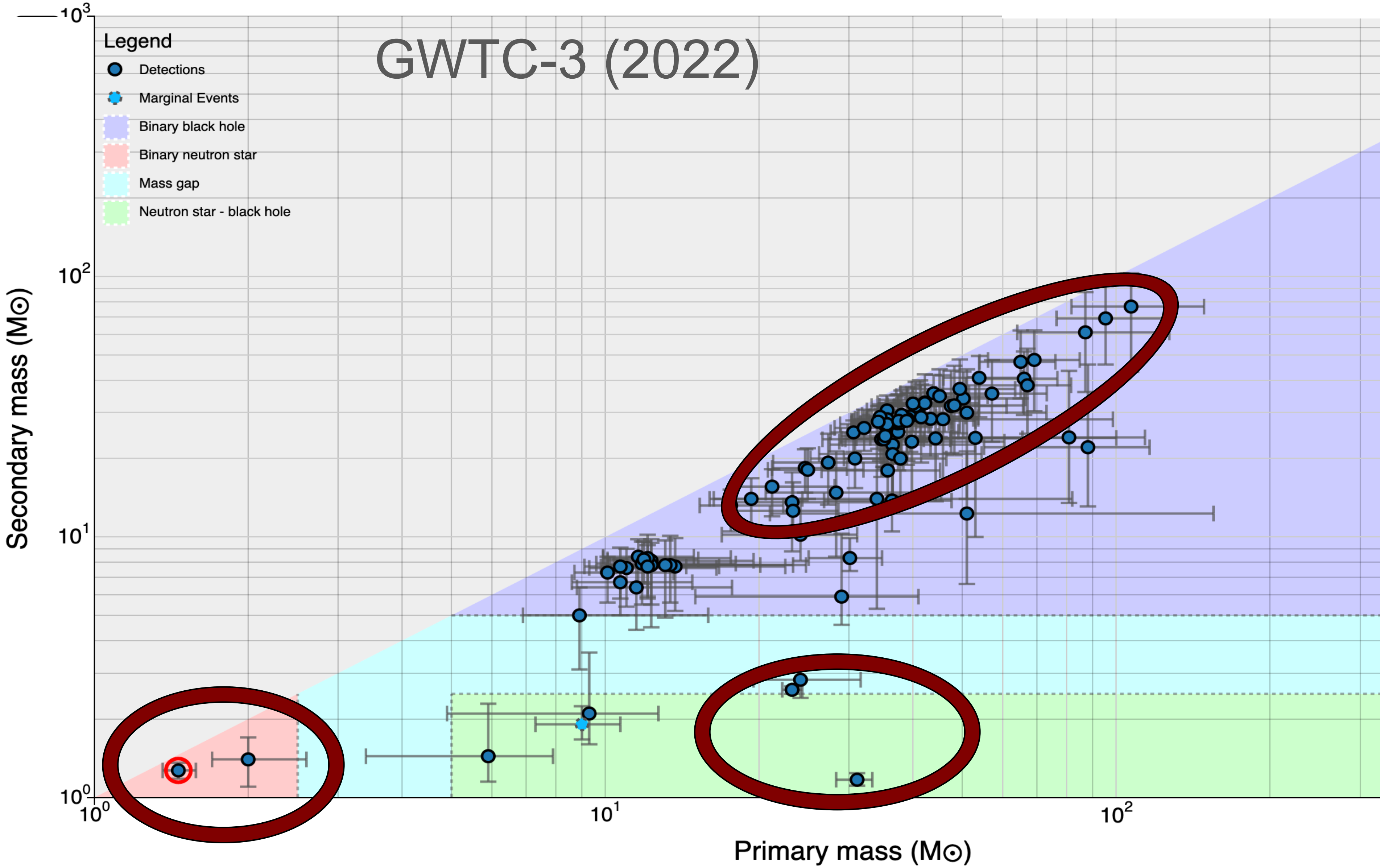
GWTC-3 LVK Coll. (2022)



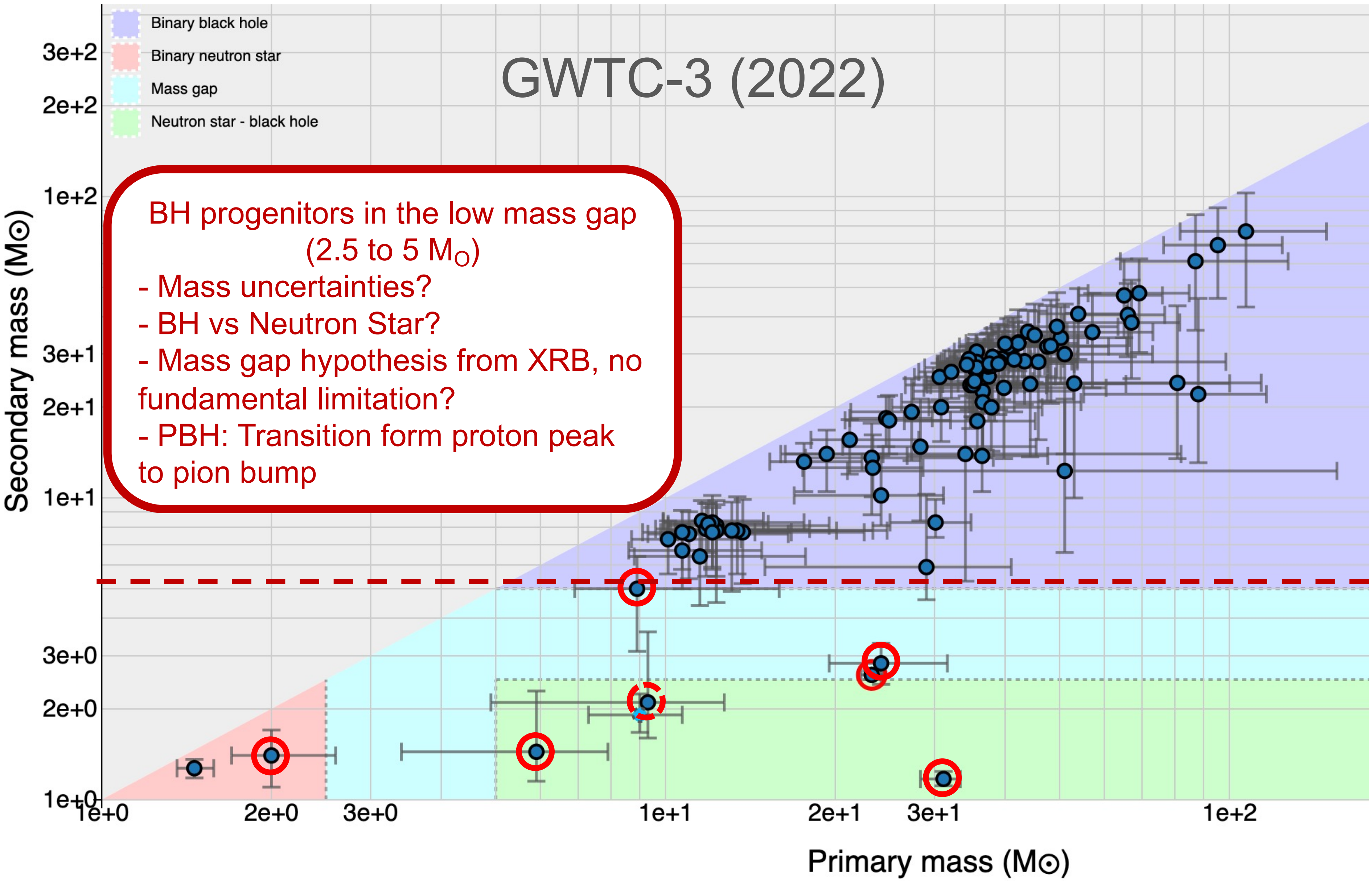
Black Holes and Neutron Stars



Primary and secondary masses



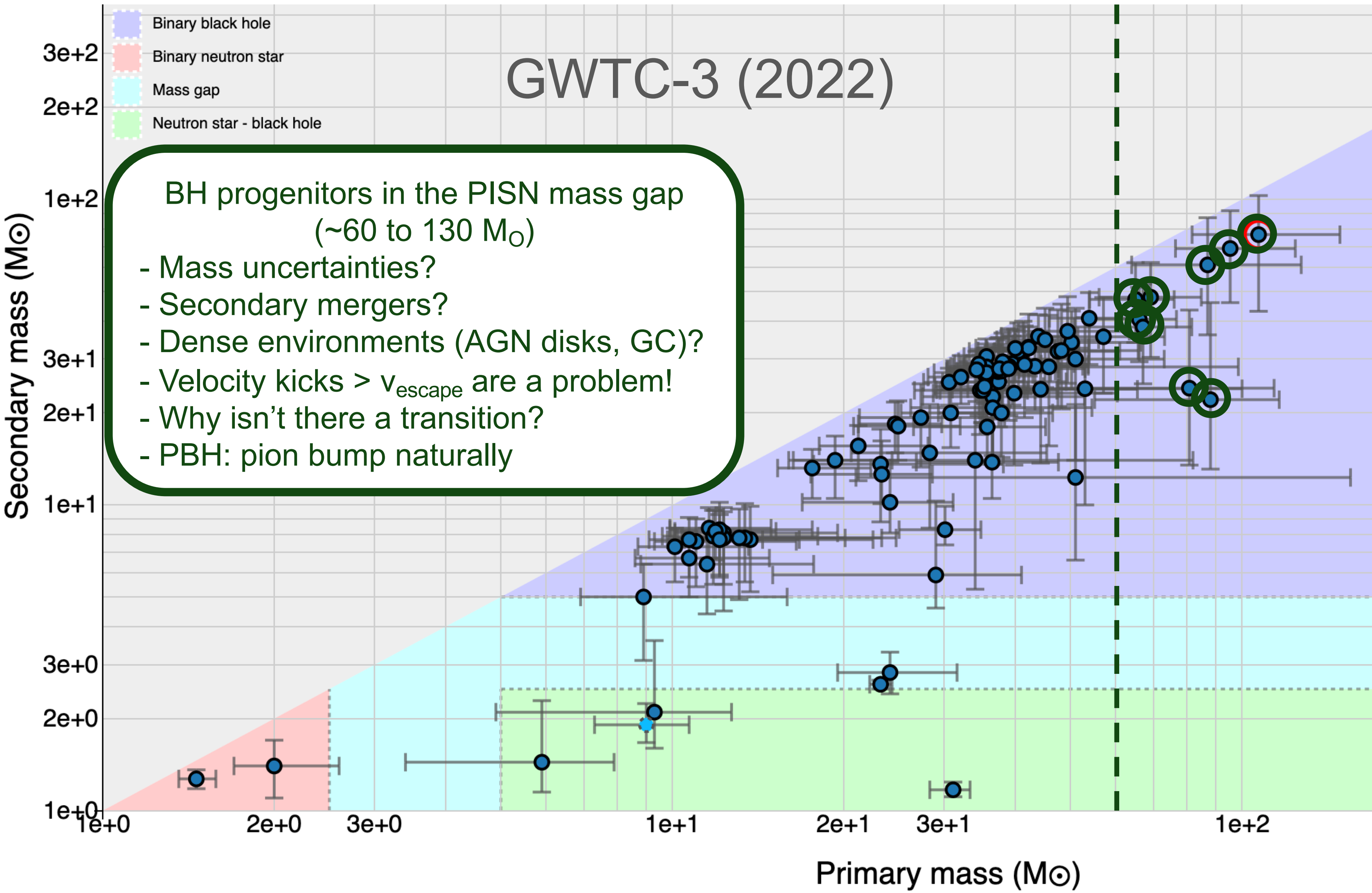
Are LIGO/Virgo BH Primordial?



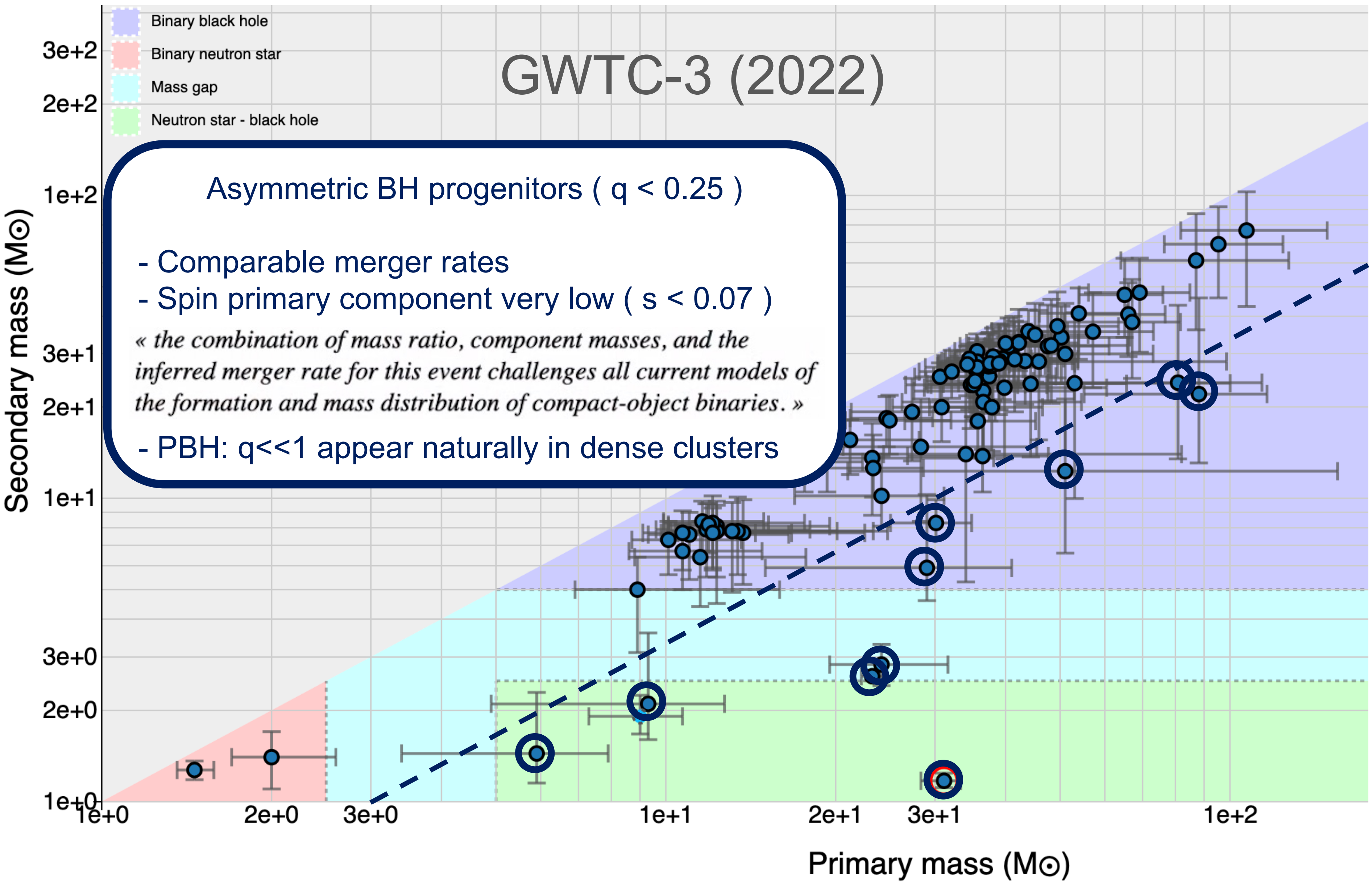
BH progenitors in the low mass gap (2.5 to 5 M_{O})

- Mass uncertainties?
- BH vs Neutron Star?
- Mass gap hypothesis from XRB, no fundamental limitation?
- PBH: Transition form proton peak to pion bump

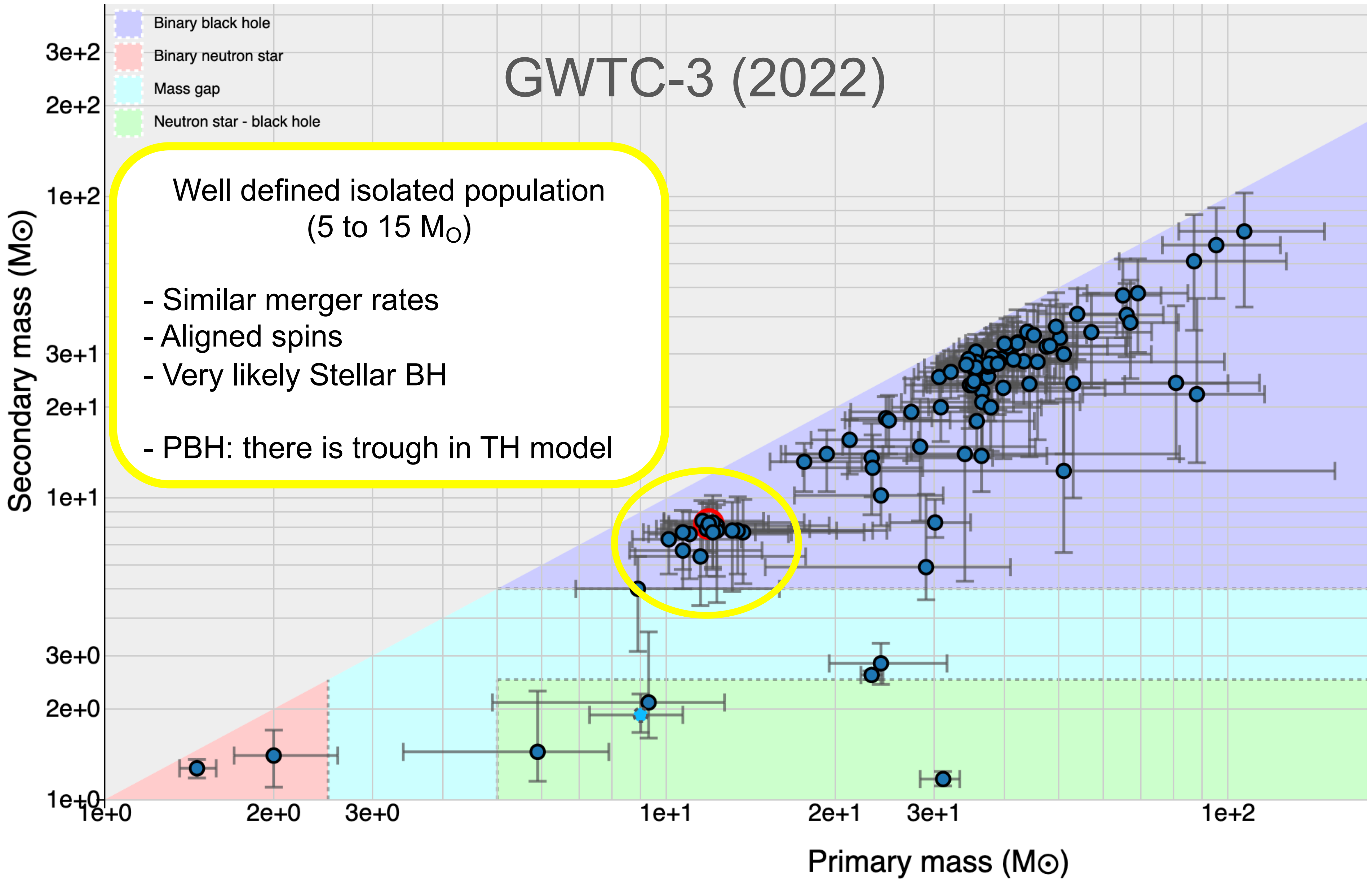
Are LIGO/Virgo BH Primordial?



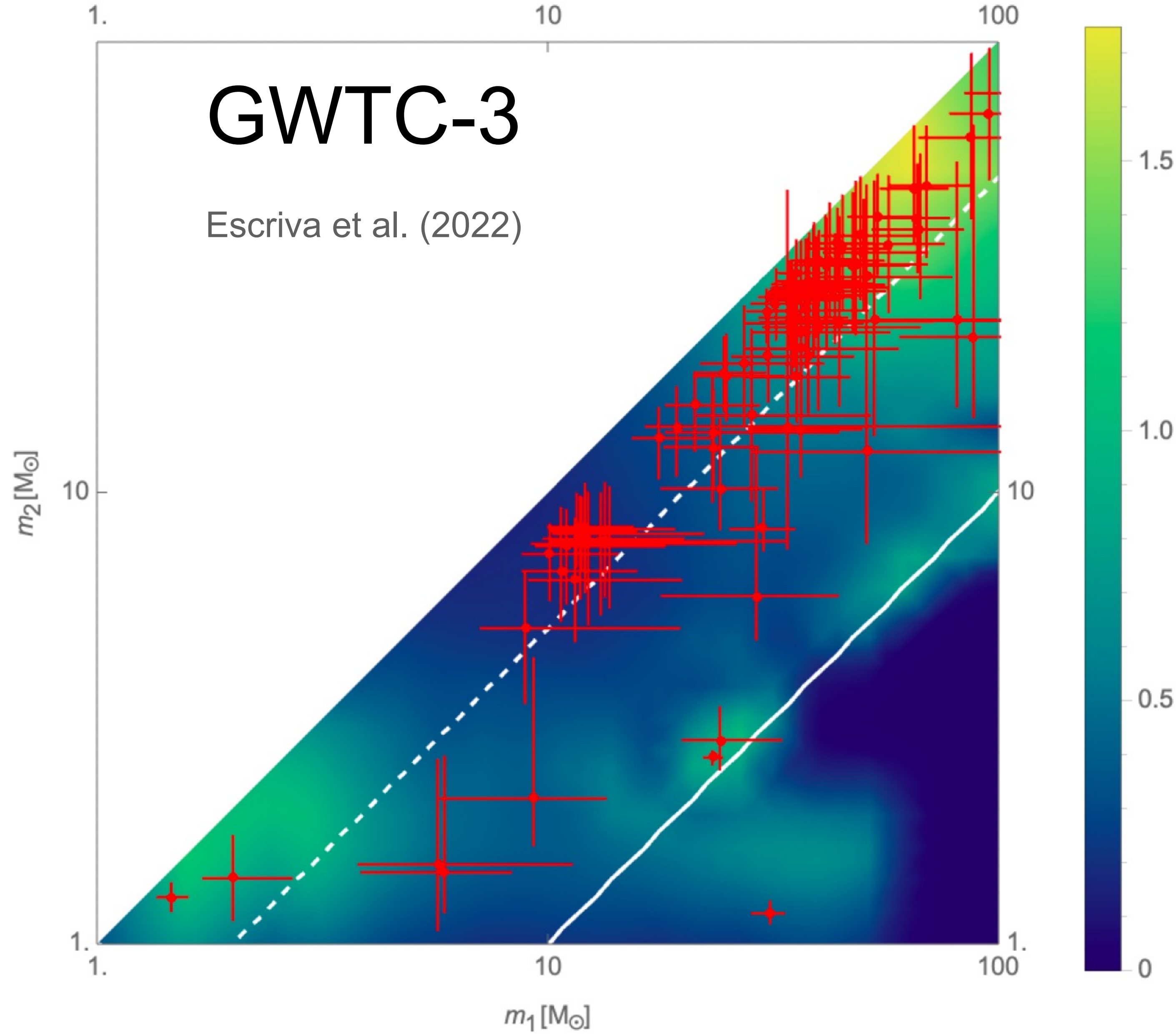
Are LIGO/Virgo BH Primordial?



Are LIGO/Virgo BH Primordial?

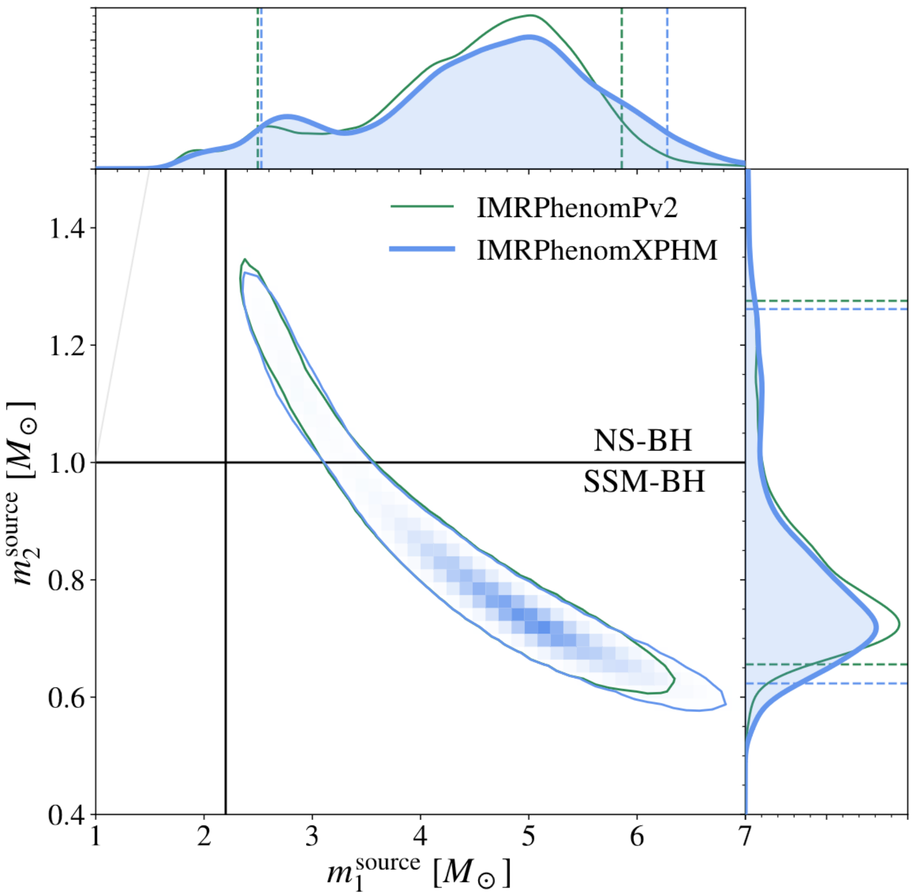


Are LIGO/Virgo BH Primordial?



Are LIGO/Virgo BH Primordial?

SSM170401



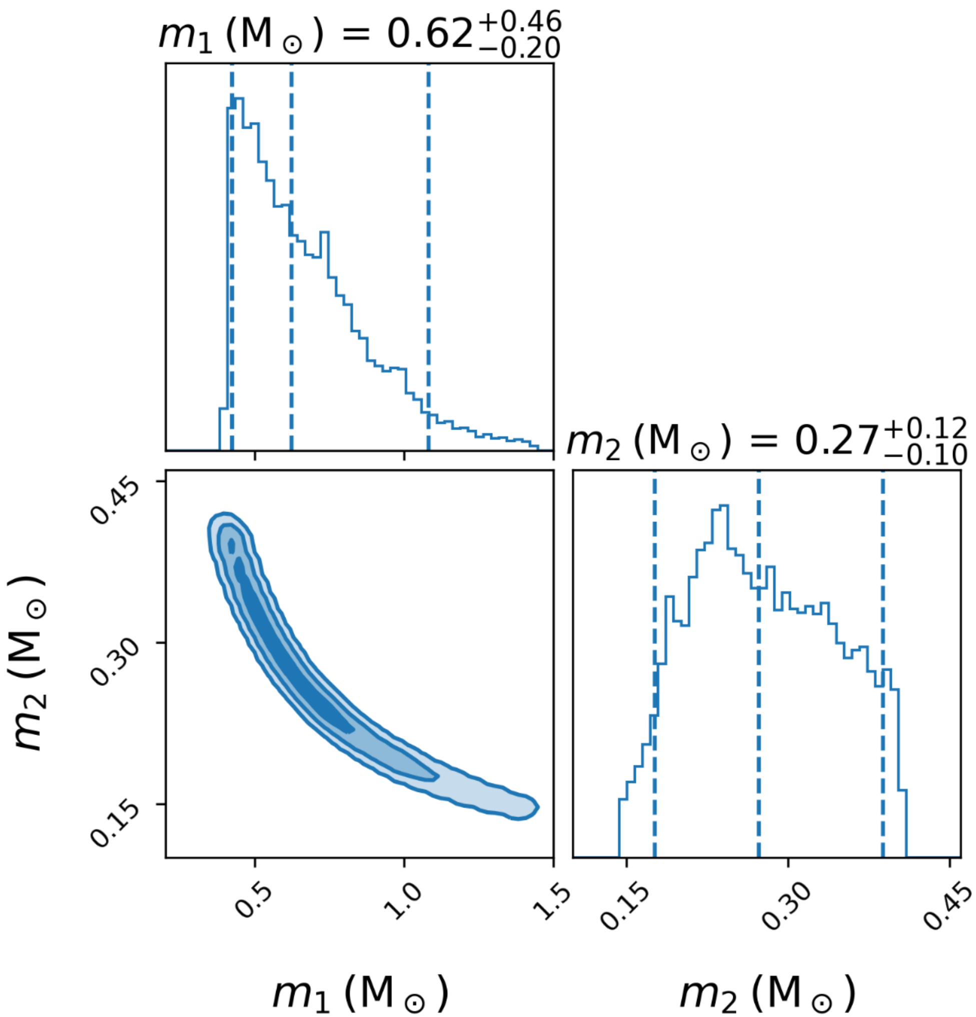
Morras et al. (2023)

Parameter	IMRPhenomPv2	IMRPhenomXPHM
Signal to Noise Ratio	$7.98^{+0.62}_{-1.03}$	$7.94^{+0.70}_{-1.05}$
Primary mass ($M_\odot$)	$4.65^{+1.21}_{-2.15}$	$4.71^{+1.57}_{-2.18}$
Secondary mass ($M_\odot$)	$0.77^{+0.50}_{-0.12}$	$0.76^{+0.50}_{-0.14}$
Primary spin magnitude	$0.32^{+0.47}_{-0.26}$	$0.36^{+0.46}_{-0.30}$
Secondary spin magnitude	$0.48^{+0.46}_{-0.43}$	$0.47^{+0.46}_{-0.42}$
Total mass ($M_\odot$)	$5.42^{+1.10}_{-1.65}$	$5.47^{+1.43}_{-1.68}$
Mass ratio ($m_2/m_1 \leq 1$)	$0.17^{+0.34}_{-0.05}$	$0.16^{+0.34}_{-0.06}$
$\chi_{\rm eff}$ [51, 52]	$-0.06^{+0.17}_{-0.32}$	$-0.05^{+0.22}_{-0.35}$
$\chi_{\rm p}$ [53]	$0.28^{+0.34}_{-0.21}$	$0.33^{+0.33}_{-0.26}$
Luminosity Distance (Mpc)	119^{+82}_{-48}	124^{+82}_{-48}
Redshift	$0.028^{+0.018}_{-0.010}$	$0.028^{+0.017}_{-0.011}$
Ra (°)	-2^{+34}_{-35}	-1^{+34}_{-37}
Dec (°)	47^{+14}_{-26}	46^{+14}_{-29}
Final mass ($M_\odot$)	$5.34^{+1.11}_{-1.70}$	$5.40^{+1.45}_{-1.73}$
Final spin	$0.39^{+0.24}_{-0.07}$	$0.42^{+0.22}_{-0.10}$
$P(m_2 < 1\ M_\odot)$	85%	84%

Are LIGO/Virgo BH Primordial?

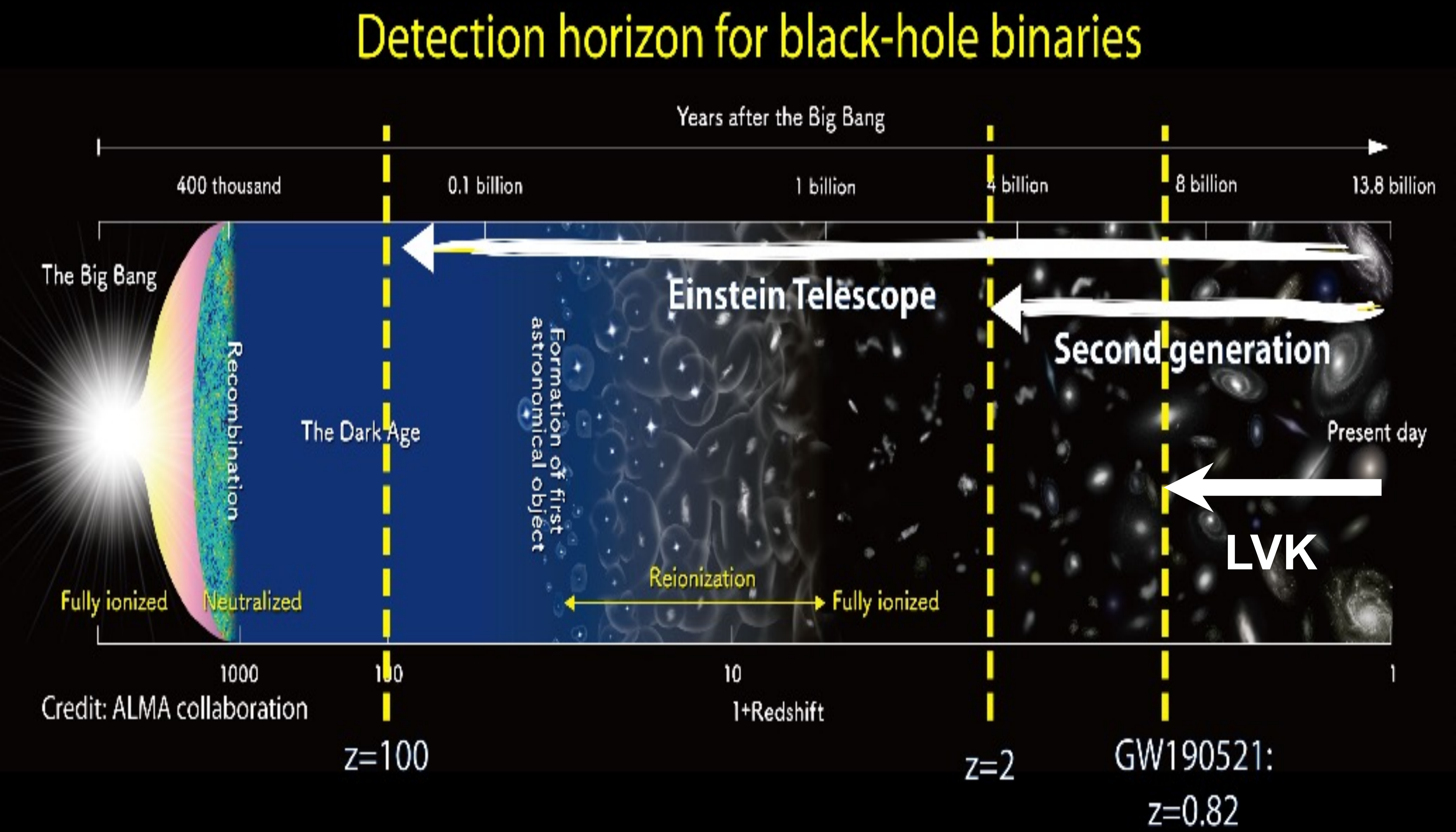
SSM200308

Prunier et al. (2023)

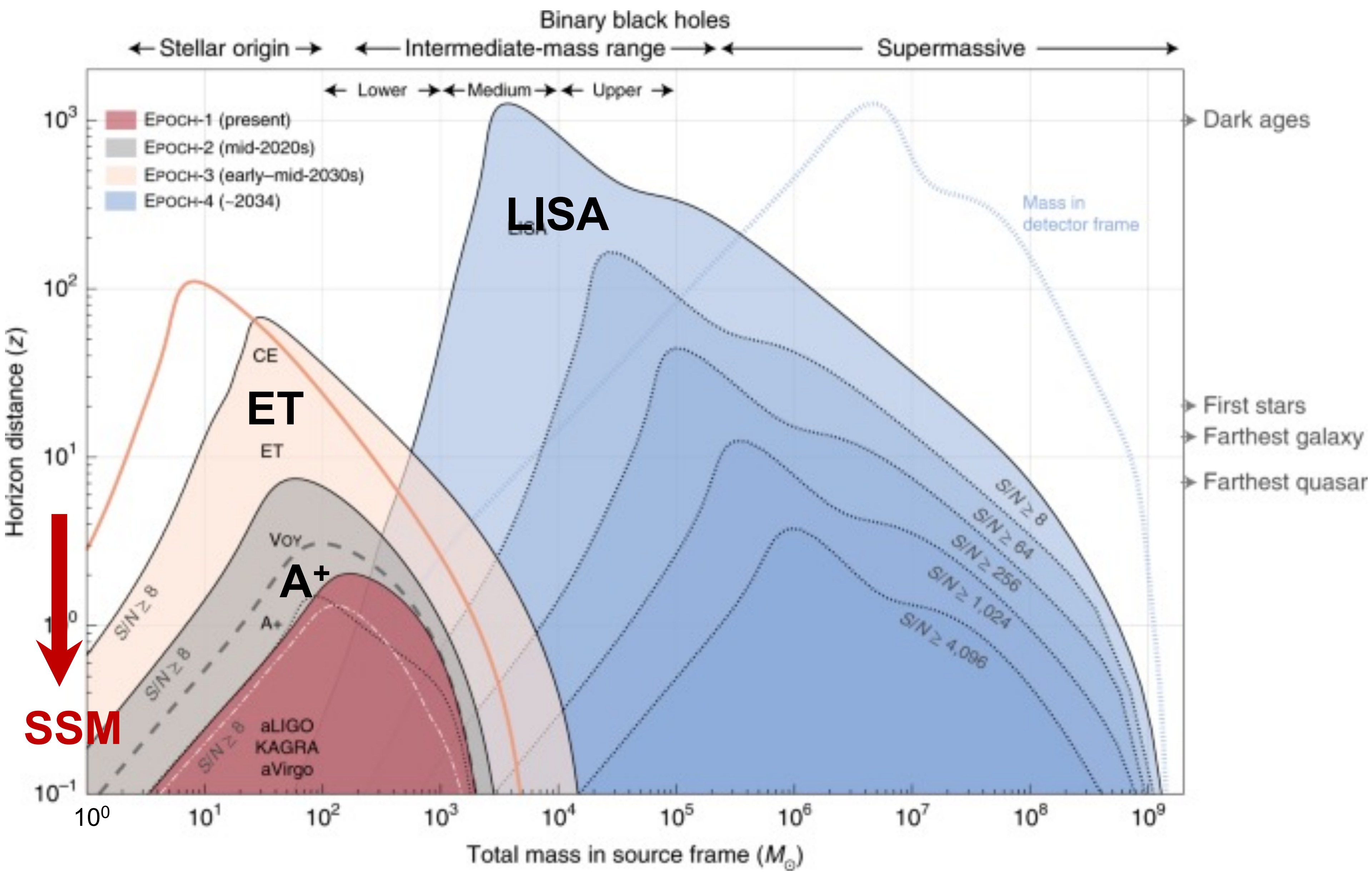


Parameter	
Matched Filter SNR	$8.02^{+0.49}_{-0.85}$
Primary mass ($M_\odot$)	$0.62^{+0.46}_{-0.20}$
Secondary mass ($M_\odot$)	$0.27^{+0.12}_{-0.10}$
Primary spin magnitude	$0.66^{+0.13}_{-0.25}$
Secondary spin magnitude	$0.44^{+0.33}_{-0.39}$
Total mass ($M_\odot$)	$0.88^{+0.35}_{-0.08}$
Detector-frame chirp mass ($M_\odot$)	$0.3527^{+0.0003}_{-0.0001}$
Mass ratio ($m_2/m_1 \leq 1$)	$0.44^{+0.48}_{-0.28}$
$\chi_{\rm eff}$ [27, 28]	$0.41^{+0.08}_{-0.04}$
$\chi_{\rm p}$ [29]	$0.37^{+0.24}_{-0.24}$
Luminosity Distance (Mpc)	90^{+43}_{-39}
Redshift	$0.02^{+0.01}_{-0.01}$
$P(m_1 < 1\ M_\odot)$	92%
$P(m_2 < 1\ M_\odot)$	100%

The future of GW (G3)



BBH sensitivity in future G3 GW



Partial Summary

- Quantum diffusion inevitably generates PBH
- Thermal history predicts PBH have multimodal mass distribution $\sim 10^{-5}, 1, 100, 10^{5}\ M_\odot$ ($10^{-10}\ M_\odot$ also?)
- The predicted PBH spin and mass distribution has been measured by LIGO/Virgo + OGLE around 1-100 $M_\odot$ (features: peak & plateau)
- Other peaks could be explored with microlensing
- PBH scenario can explain various cosmic conundra
- Paradigm shift in Structure Formation of Universe
- Very rich phenomenology: multiscale, multiepoch, multiprobe => Future G3 detectors (ET, LISA, GAIA)

Forces in Physics

- **Fundamental Forces**

  Gravitation, Strong, Weak, E.M.

- **Residual Forces**

  Molecular, Nuclear, Surface Tension

- **Collective Forces**

  Brownian motion, Entropic Forces

$$F\,dx = dW = -dU + T\,dS \;\Rightarrow\; F = -\frac{dU}{dx} + T\frac{dS}{dx}$$

Entropic forces in mechanics

General mechanical system with two components:

- **Slow** d.o.f. described with **canonical coordinates** (q, p)
- **Fast** d.o.f. **coarsegrained** as a thermodynamical system with macroscopic quantities (S, T)
- The interaction between the slow and fast d.o.f. are described by the Thermodynamical constraint: the First Law of Thermodynamics

Entropic forces in GR

JGB, Espinosa (2021)

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

Entropy

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

Variational constraint: **First law thermodynamics**

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

Non-equilibrium Einstein field equations

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

Entropic force

<u>Entropy (anti)gravitates !</u>

GREA = General Relativistic Entropic Acceleration

Gravitational Collapse

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \kappa \left(T_{\mu\nu} - f_{\mu\nu} \right) \equiv \kappa \, \mathcal{T}_{\mu\nu}$$

Variational constraint: **First law thermodynamics**

$$-dW = -\vec{F} \cdot d\vec{x} \; = \; dU + \left(P - T \frac{dS}{dV} \right) dV$$

Effective Pressure

$$\equiv \; dU + \tilde{P} \, dV$$

Coeff. viscosity

$$f_{\mu\nu} = \zeta \, D_\lambda u^\lambda \left(g_{\mu\nu} + u_\mu u_\nu \right) = \zeta \, \Theta \, h_{\mu\nu}$$

$$\begin{aligned} \mathcal{T}^{\mu\nu} \; &= \; P \, g^{\mu\nu} + (\epsilon + P) u^\mu u^\nu - \zeta \, \Theta \, h^{\mu\nu} \\ &= \; \tilde{P} \, g^{\mu\nu} + (\epsilon + \tilde{P}) u^\mu u^\nu \, , \end{aligned}$$

$$\zeta = \frac{T}{\Theta} \frac{dS}{dV}$$

Maintains the perfect fluid form

Gravitational Collapse

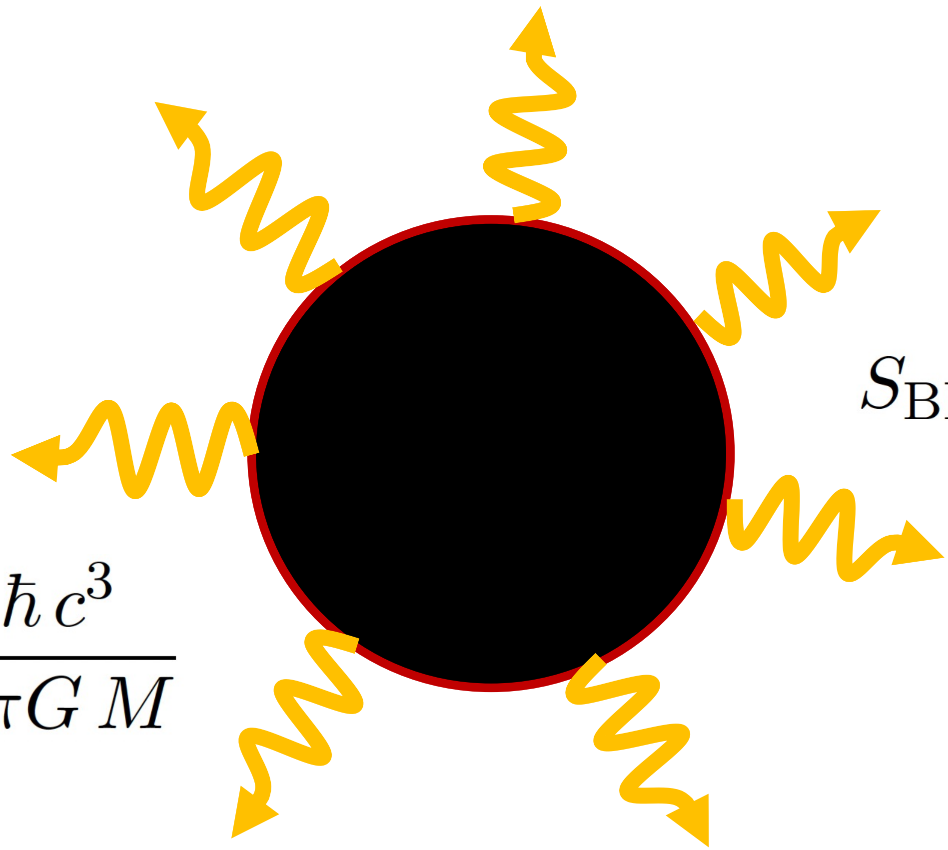
Raychaudhuri equation for geodesic motion

$$\begin{aligned}\frac{D}{d\tau}\Theta + \frac{1}{3}\Theta^2 &= -\sigma_{\mu\nu}\sigma^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} - R_{\mu\nu}u^\mu u^\nu \\ &= -\kappa\left(T_{\mu\nu}u^\mu u^\nu + \frac{1}{2}T^\lambda_{\ \lambda} - \frac{3}{2}\zeta\Theta\right) \\ &= -\frac{\kappa}{2}(\epsilon + 3\tilde{P}) = -\frac{\kappa}{2}\left(\epsilon + 3P - 3T\frac{dS}{dV}\right).\end{aligned}$$

Due to the extra entropic term in the effective pressure, even for matter that satisfies the strong energy condition, $\epsilon + 3P > 0$, it's possible to prevent gravitat. collapse, $\dot{\Theta} + \Theta^2/3 > 0$, as long as entropy production is significant, i.e. $3TdS/dV > (\epsilon + 3P) > 0$

Hawking Radiation

Temperature & Entropy of a black hole horizon



$$S_{\mathrm{BH}} = k_{\mathrm{B}} \frac{4\pi G\, M^2}{\hbar\, c}$$

$$k_{\mathrm{B}} T_{\mathrm{BH}} = \frac{\hbar\, c^3}{8\pi G\, M}$$

$$(\hbar,\ c,\ G,\ k_{\mathrm{B}})$$

Bekenstein (1973)
Hawking (1974)

Entropic forces in GR

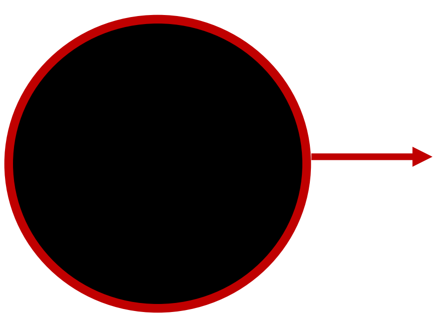
Temperature and Entropy from the gravity sector

- Horizon $\mathcal{H}$ with induced metric h

$$\mathcal{S}_{\text{GHY}} = \frac{1}{8\pi G}\int_H d^3y\,\sqrt{h}\,K = \frac{1}{8\pi G}\int_H dt\,\sin\theta d\theta\,d\phi\,\sqrt{h}\,K$$

- Schwarzschild black hole

$$ds^2 = -\left(1-\frac{2GM}{r}\right)dt^2 + \left(1-\frac{2GM}{r}\right)^{-1}dr^2 + r^2 d\Omega_2^2\,.$$



$$n = -\sqrt{1-\frac{2GM}{r}}\partial_r$$

normal vector to S_2 of radius r

Entropic forces in GR

$$\mathcal{S}_{\rm GHY} = \frac{1}{8\pi G}\int_H d^3y\,\sqrt{h}\,K = \frac{1}{8\pi G}\int_H dt\,\sin\theta d\theta\,d\phi\,\sqrt{h}\,K$$

$$\sqrt{h}K = (3GM - 2r)\sin\theta$$ at event horizon $r = 2GM$

$$\mathcal{S}_{\rm GHY} = -\frac{1}{2}\int dt\,Mc^2 = -\int dt\,T_{\rm BH}S_{\rm BH}$$

$$T_{\rm BH} = \frac{\hbar c^3}{8\pi GM}$$

$$S_{\rm BH} = \frac{A\,c^3}{4G\hbar} = \frac{4\pi GM^2}{\hbar c}$$

Classical (emergent)

quantum origin

Entropic forces in FLRW

Non-equilibrium thermodynamics in expanding universe

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

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

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

2nd law thermodynamics

$$T dS = d(\rho a^3) + p\, d(a^3)$$

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

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

Friedmann/Raychaudhuri equation

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

Entropic forces in SMBH

Accretion onto black holes from the gas around them will change their mass and therefore their entropy, inducing an entropic force on space-time around them, according to Raychaudhuri equations.

At the Eddington limit, the mass of SMBH grows like

$$\dot{M} = \frac{4\pi G\, m_p}{0.1 c\, \sigma_T}\, M \simeq \frac{M}{40\,\mathrm{Myr}} = \frac{2}{t(z_*)}\, M \qquad (z_* \simeq 35)$$

<u>Assumption:</u> SMBH continue to accrete mass at Eddington limit with a rate that decreases with the available gas over cosmological timescales,
at least since 80 Myr

$$M \propto t^2 \propto a^3 = V$$

Entropic forces in SMBH

Growth of BH entropy associated with this mass growth

$$S \propto M^2 \propto V^2 \quad \Rightarrow \quad \frac{dS}{S} = 2\frac{dV}{V}$$

Contributes with a **constant & negative entropic pressure**

$$p_S = -T\frac{dS}{dV} = -2\frac{TS}{V} = -\frac{N_{\rm SMBH} M_{\rm SMBH}}{V} = -\rho_{\rm SMBH}$$

where the total entropy is $S = \sum_i S^{(i)}_{\rm SMBH} = N_{\rm SMBH} S_{\rm SMBH}$

$N_{\rm SMBH}$ is the total number of SMBH in the Universe,

assumed constant (i.e. without SMBH mergers)

Acceleration from SMBH

The Raychaudhuri equation in this case becomes

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p + \rho_{\rm SMBH} + 3p_S)$$
$$= -\frac{4\pi G}{3}(\rho + 3p) + \frac{8\pi G}{3}\rho_{\rm SMBH}\,.$$

The entropic force term can be interpreted as an **effective cosmological constant** term $\Lambda = 8\pi G\,\rho_{\rm SMBH}$

Consequence: Primordial seeds of SMBH, rather than contributing as DM, they behave as DE, due to their rapid growth, until accretion stops.

DE from SMBH

Only a small fraction of DM in the form of PBH constitute the seeds of SMBH at the centers of galaxies, and their rapid growth induces GREA that we interpret as DE.

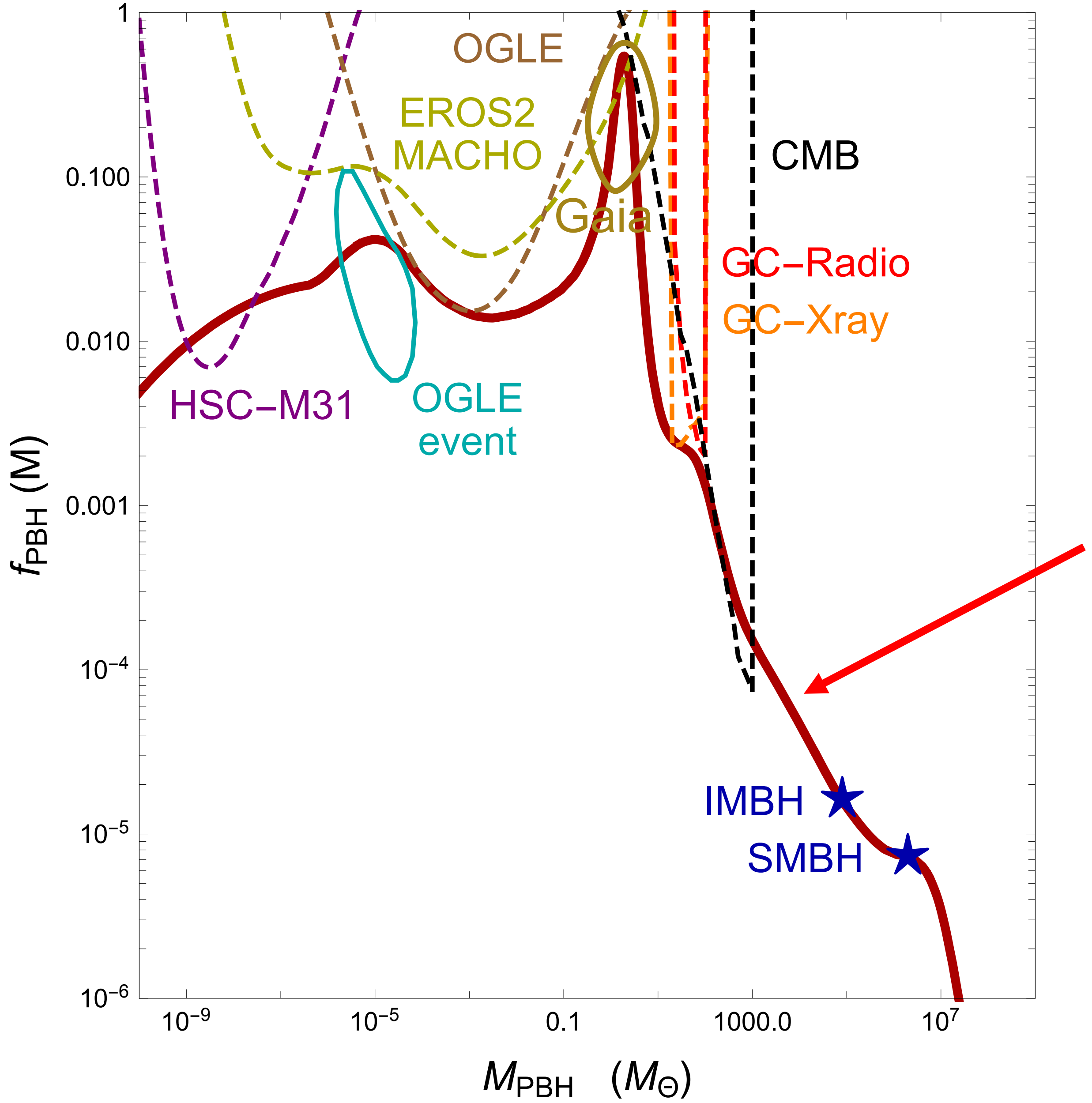
$$\Omega_{\rm DE} = f_{\rm SMBH}\,\Omega_{\rm DM}\,(1+z_*)^3 = 0.69\,,$$

$$f_{\rm SMBH} = 5\times 10^{-5} \qquad \Omega_{\rm DM} = 0.26.$$

A more sophisticated computation is needed for the case of a broad mass distribution f(M) of PBH, and possibly different rates of accretion, M(z)

$$\Omega_{\rm DE} = \Omega_{\rm DM} \int \frac{f(M)}{M}\,\frac{dM}{dz}\,dz$$

PBH could be all the DM

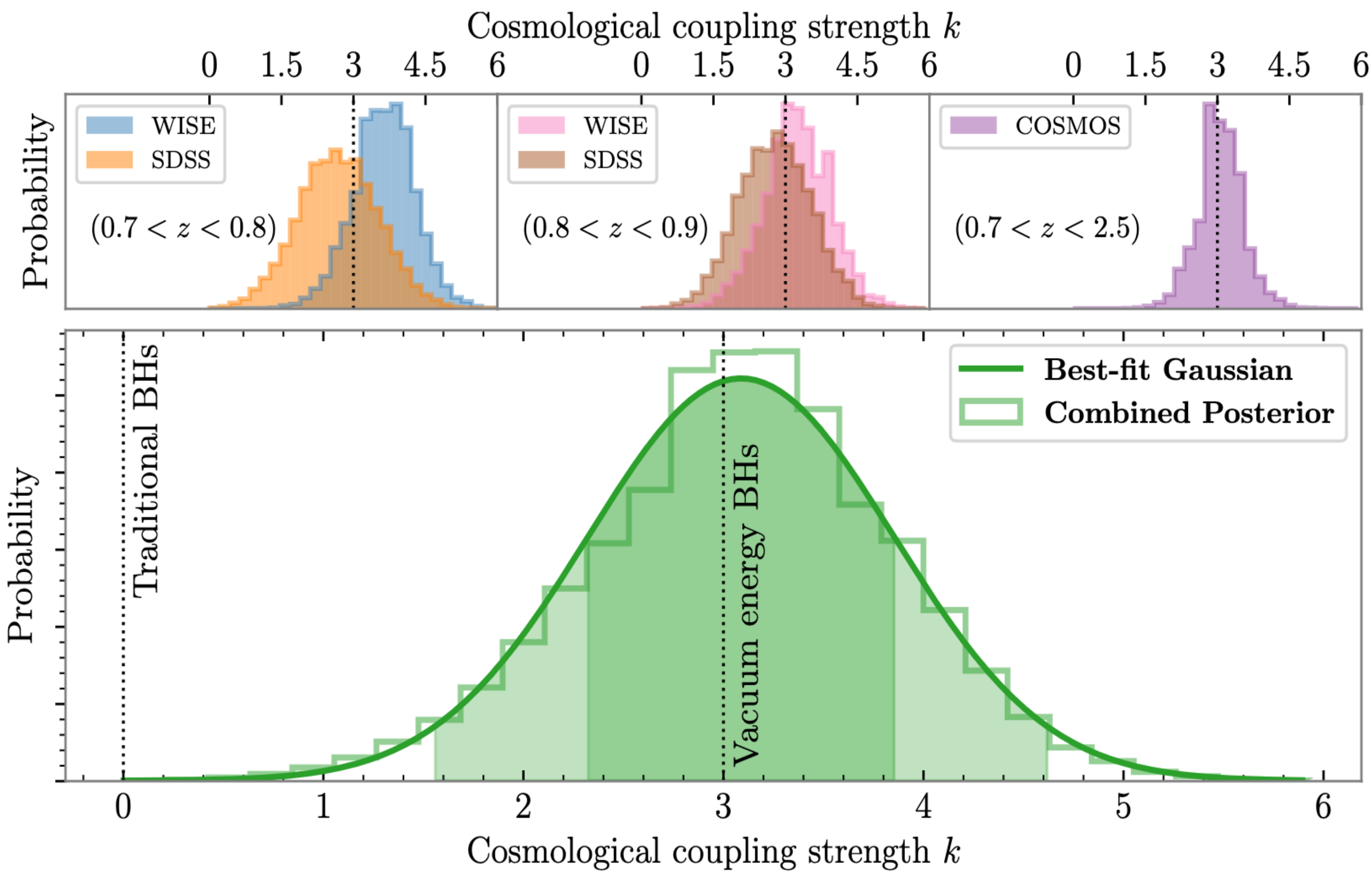


Cappelluti
Hasinger
Natarajan
(2022)

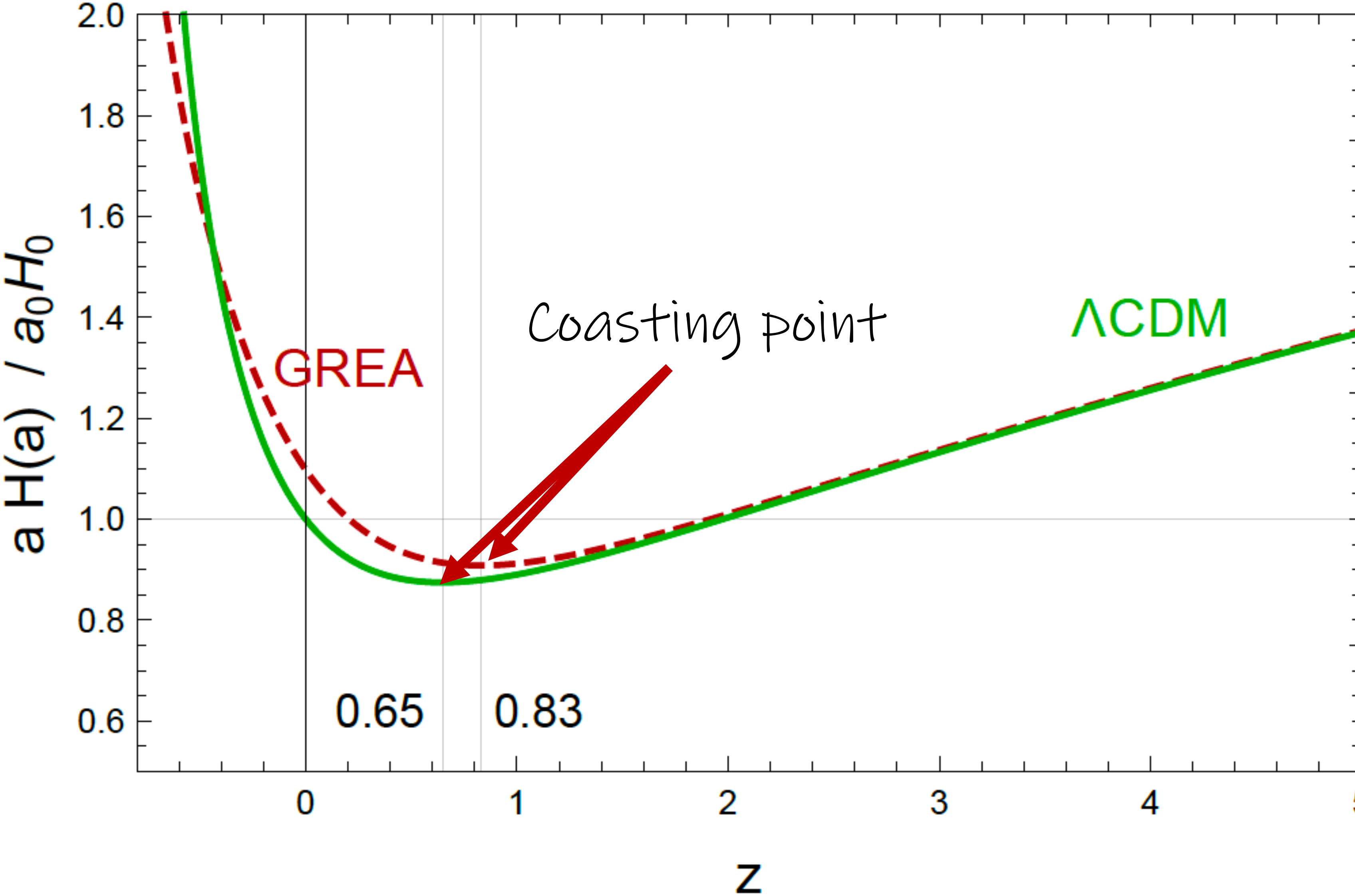
Based on
JGB (2021)

SMBH growth

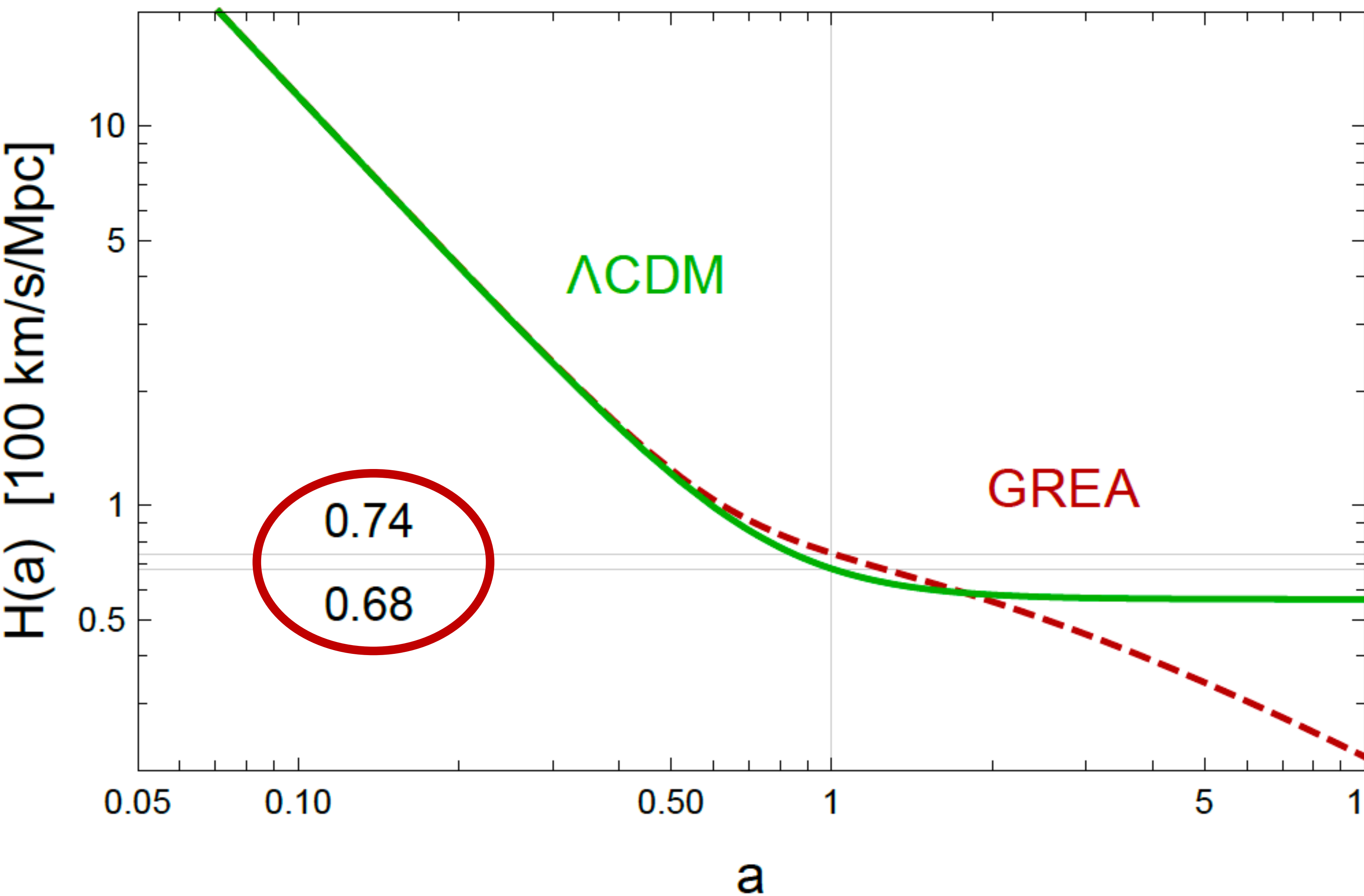
Farrah+ (2023)



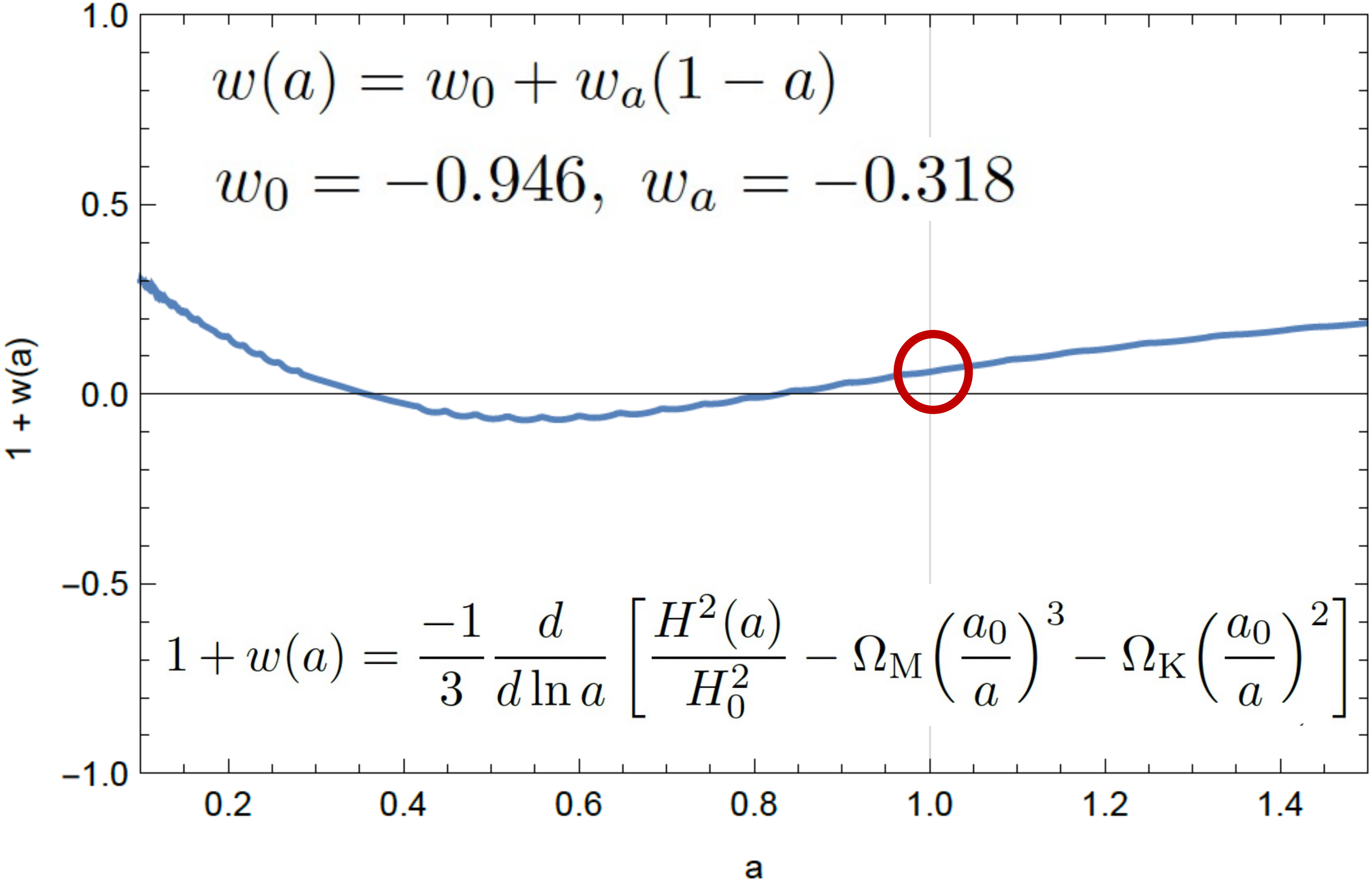
Cosmic Acceleration



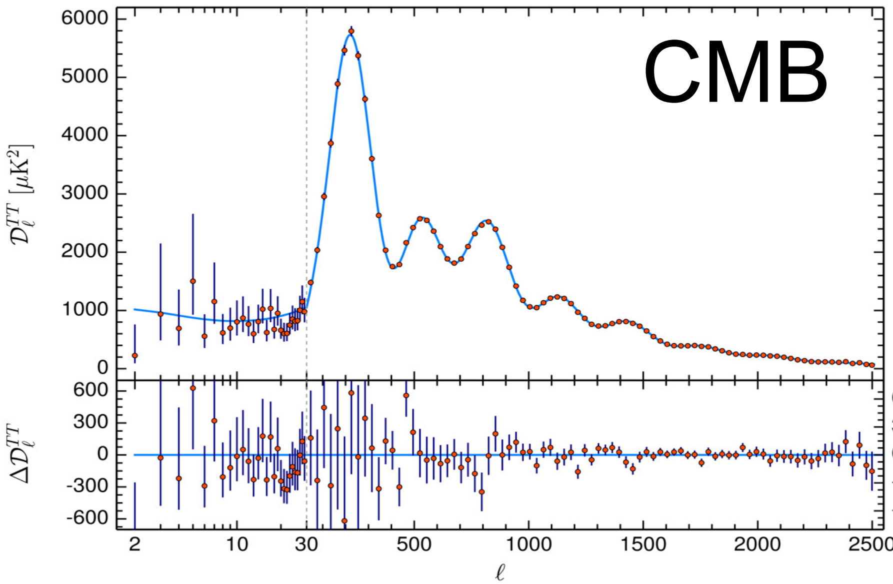
Cosmic Acceleration

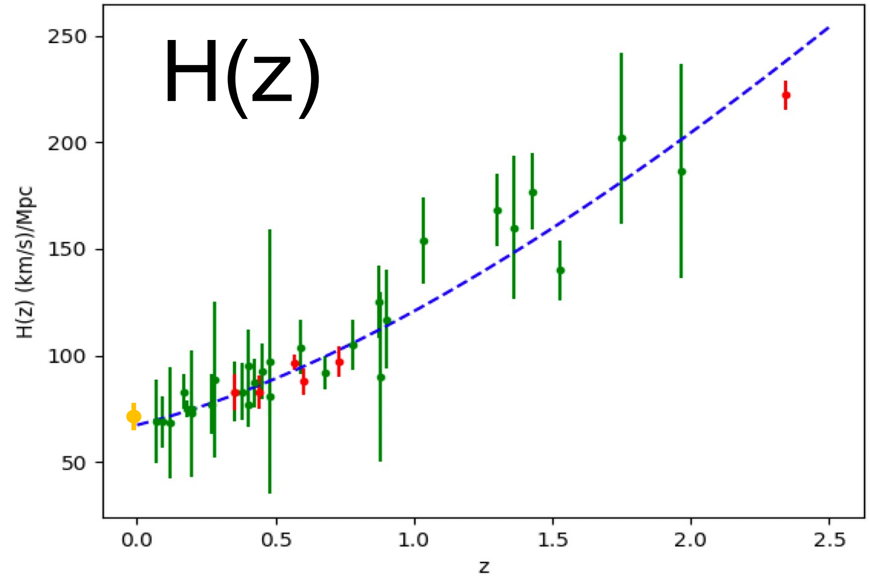


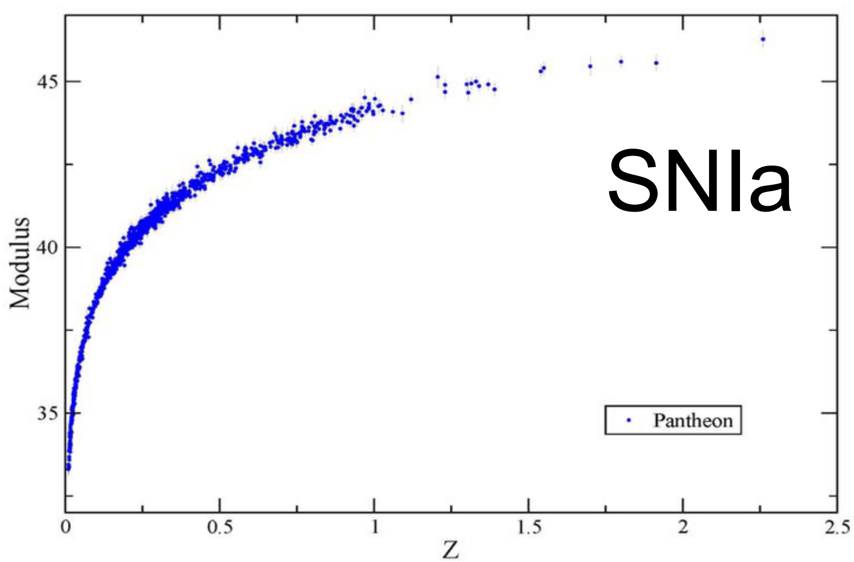
Cosmic Acceleration

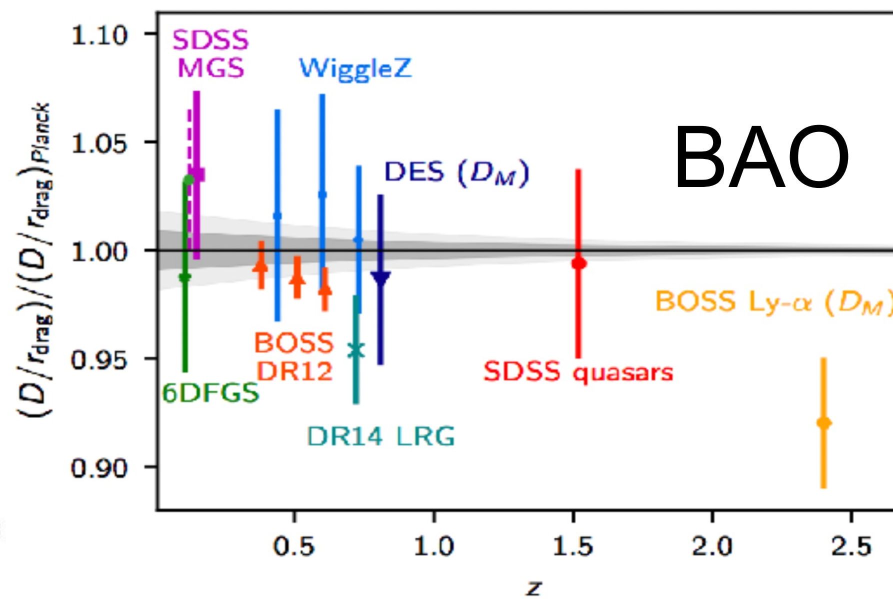


Cosmo Observations









Cosmic Constraints

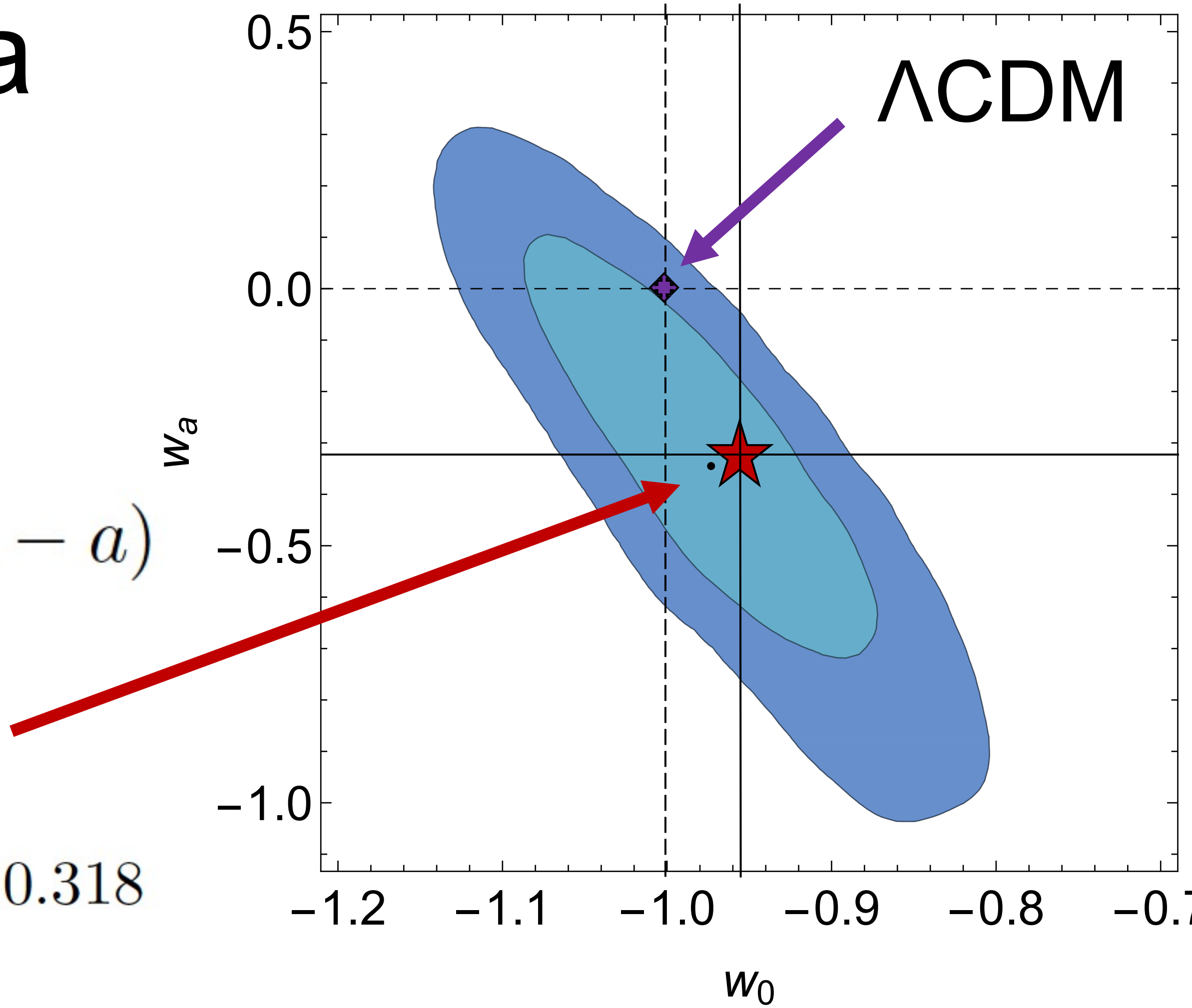
Arjona, Espinosa, JGB & Nesseris (2021)

Same data but with $(w_0,\, w_a)$ free:

$$w(a) = w_0 + w_a(1-a)$$

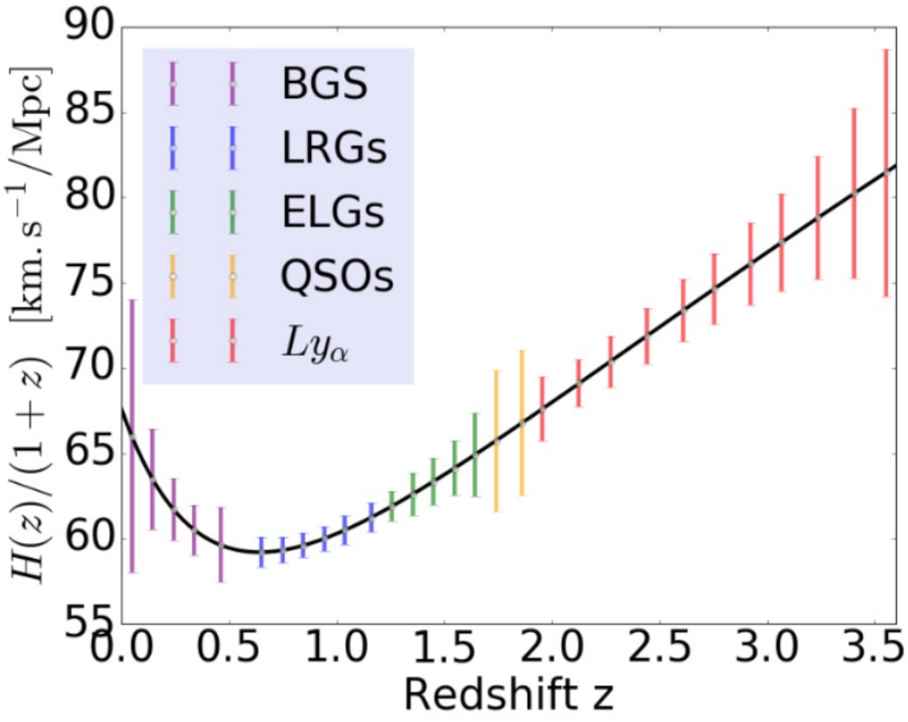
GREA

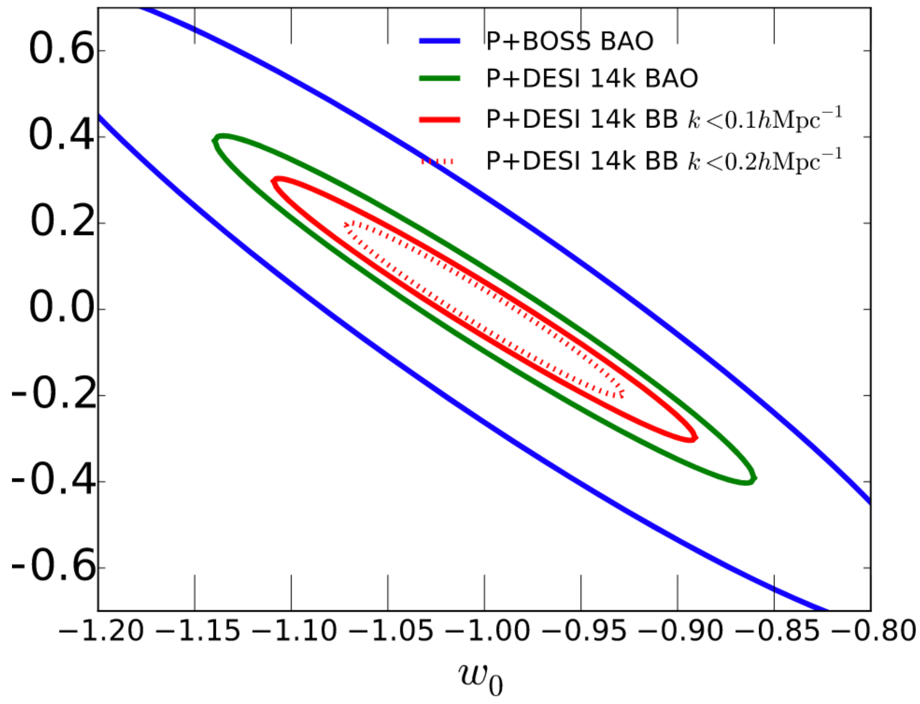
$$w_0 = -0.946,\ w_a = -0.318$$



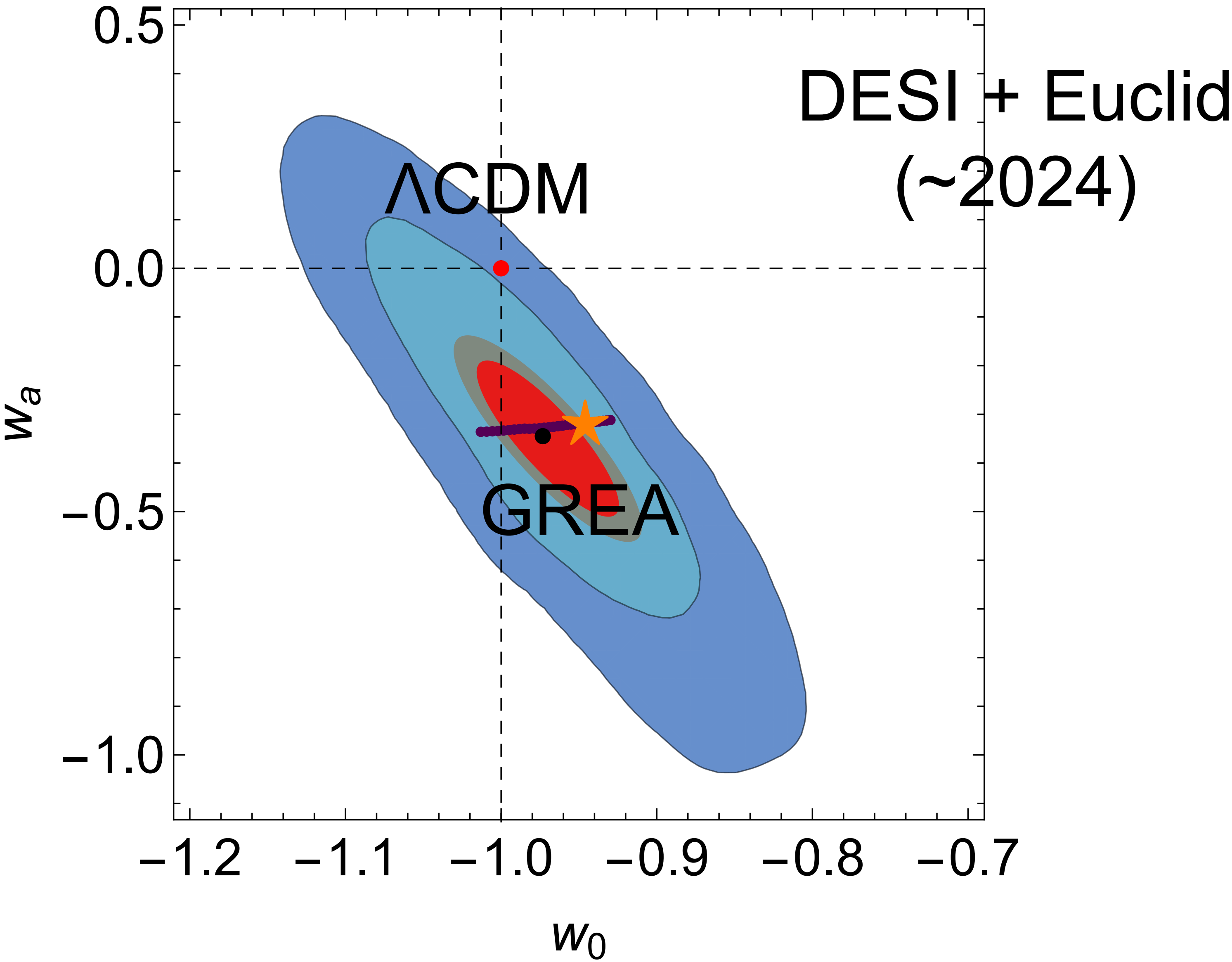
Future Constraints

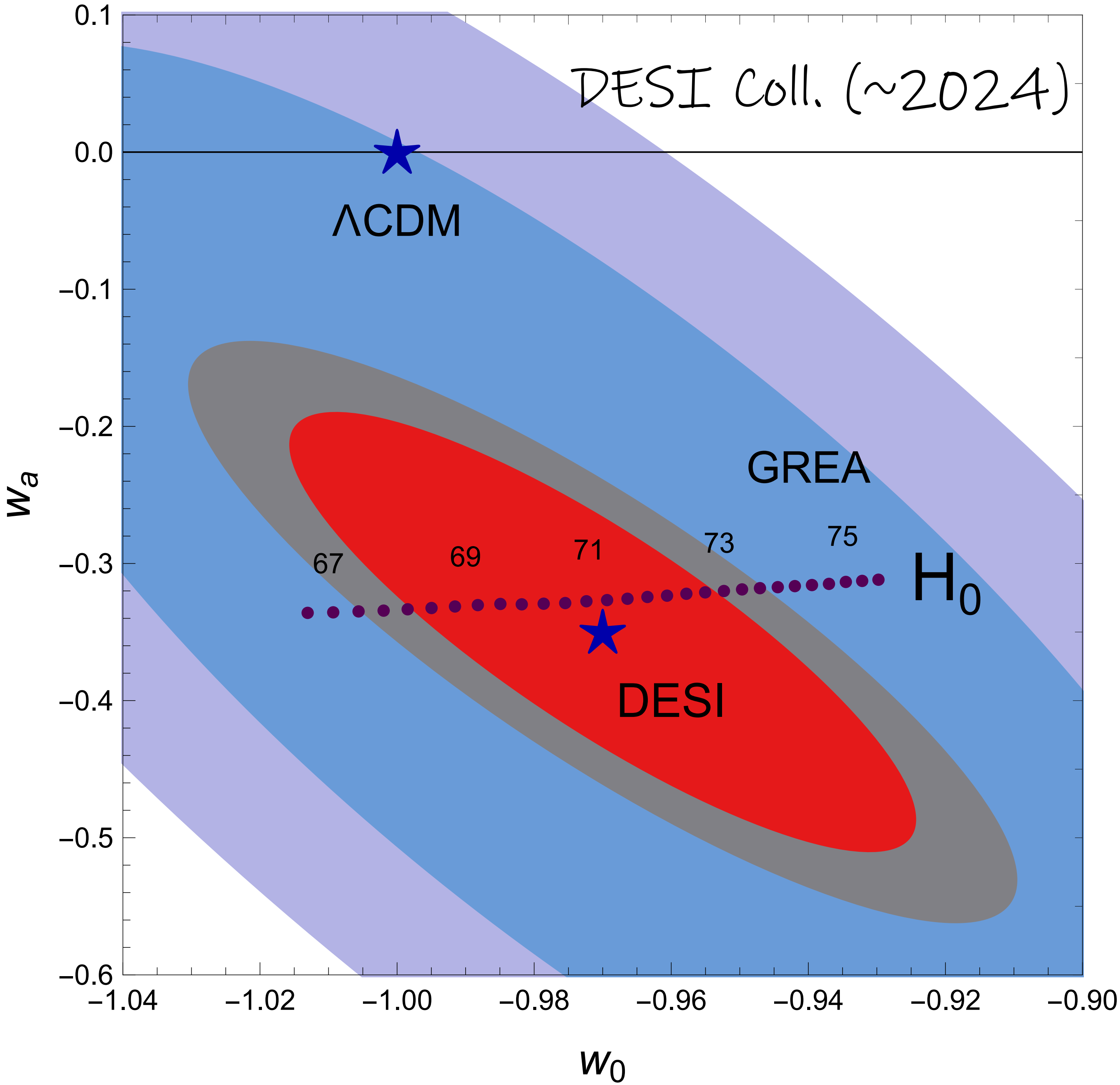
DESI Coll. (2016)





Future Parameters

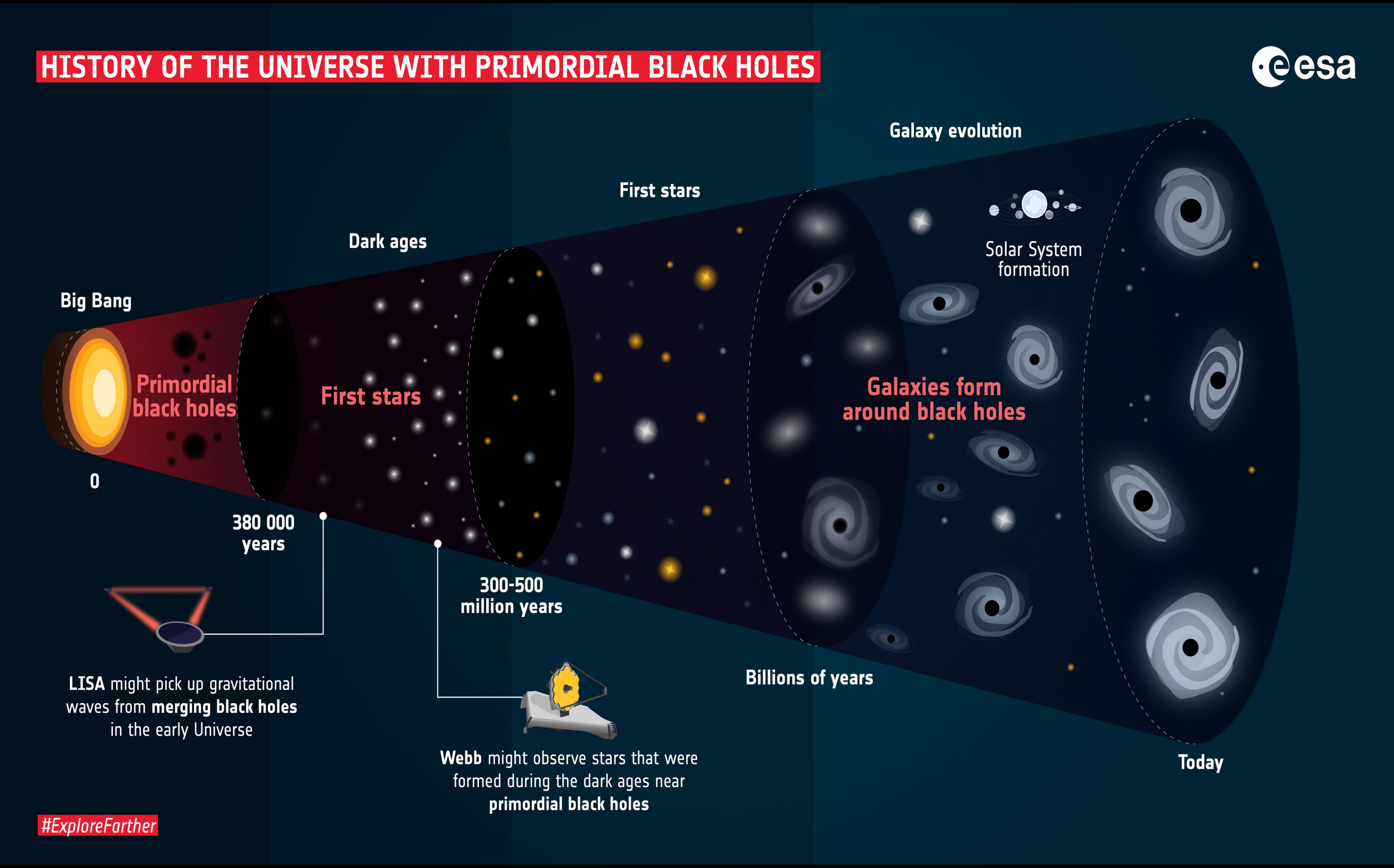




DESI Coll. (~2024)
ΛCDM
GREA
67
69
71
73
75
H_0
DESI
w_a
w_0
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−1.04
−1.02
−1.00
−0.98
−0.96
−0.94
−0.92
−0.90

Conclusions

- Quantum diffusion inevitably generates PBH
- Thermal history predicts PBH have multimodal mass distribution $\sim 10^{-5}, 1, 100, 10^5\ M_\odot$ ($10^{-10}\ M_\odot$ also?)
- Very rich phenomenology: multiscale, multiepoch, multiprobe => Future G3 detectors (ET, LISA, GAIA)
- Non-equilibrium phenomena in GR: entropic forces
- FLRW: Cosmic acceleration from first principles
- SMBH growth through Eddington accretion
- BH entropy production generates GREA
- No need for a Cosmological Constant
- Precise knowledge of $M(z)$ & $f(M)$ will give (w_0, w_a)


HISTORY OF THE UNIVERSE WITH PRIMORDIAL BLACK HOLES
esa
Galaxy evolution
First stars
Dark ages
Big Bang
Primordial black holes
First stars
Solar System formation
Galaxies form around black holes
0
380 000 years
300-500 million years
Billions of years
Today
LISA might pick up gravitational waves from merging black holes in the early Universe
Webb might observe stars that were formed during the dark ages near primordial black holes
#ExploreFarther