Tentative evidence for cosmological coupling of black holes and implications for dark energy

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Overview

- Oustanding astrophysical problems + theoretical problems
- Effects of the universe on black holes (reasonable)
- Effects of black holes on the universe (outrageous)
  warning: "blak holes" means "non-singular black holes" (outrageous) and discussion is non-perturbative (not backreaction).

Many details, will only give schematic view (see references, mostly work by Kevin Croker).

Observational problems with BHs

- Supermassive black holes (SMBH) have masses that are too large. Challenging to explain with
  - accretion
  - galaxy-galaxy mergers
  - combined channels
- Also many stellar mass BHs observed by LIGO are too massive.
- Galaxy scaling relations: there is an unespected disconnect between the mass in black holes M_{BH} and the mass of stellar populations $M_\star$ in galaxies.

Observational problem 1). To wit: ancient quasar SMBHs grow too fast

Consider quasar J0313-1806 at $z = 7.64$ and suppose the first stars are at $z_\star = 25$. Then it has $\Delta t = 546\ \mathrm{Myr}$ to grow.

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$$M = 10^2 M_\odot \exp\left(10\,\frac{4\pi G m_p}{\epsilon c \sigma_T}\Delta t\right)$$

SMBHs in the highest z quasars need many mergers and/or hyper-Eddington accretion.

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Assuming optimistic efficiency $\epsilon = 0.16$, then

$$\frac{4\pi G m_p}{\epsilon c \sigma_T} = 1.4 \times 10^{-8}\ \mathrm{yr}^{-1}$$

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... but the measured mass is $M = 1.6 \times 10^9\ M_\odot$
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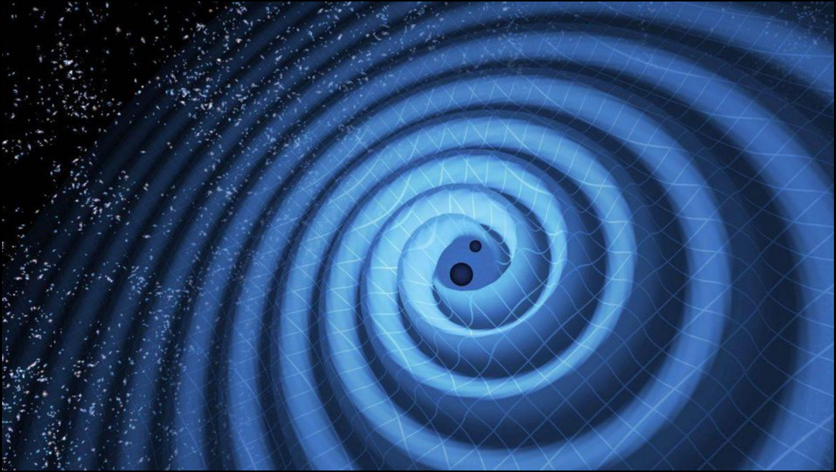
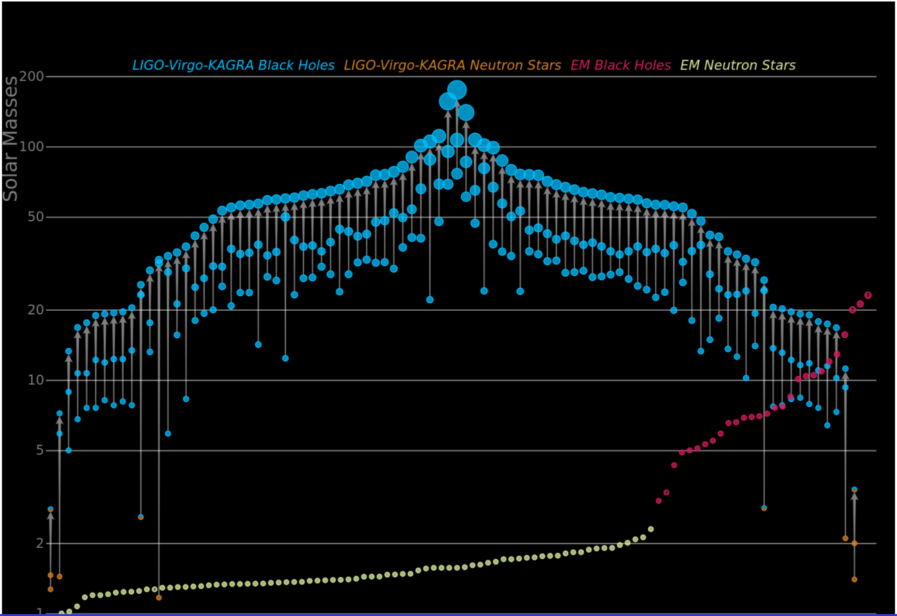
Observational problem 2). What does LIGO–Virgo observe?




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

Theoretical problems

- What is dark energy? (1998)
- Spacetime singularities inside BHs

  50+ years of literature on non-singular BHS:

  Gliner 1966; Dymnikova 1992; Bardeen 1968; Hayward 2006; Chapline + 2002; Mazur & Mottola 2004-05, 2023; Lobo 2006; Visser +; Dymnikova & Galktionov 2019; Posada & Chirenti 2019; Beltracchi & Gondolo 2019; Casadio + 2023; ...

  gravastars, de Sitter-cored BHs, Loop Quantum Gravity-corrected BHs, polymer-quantized BHs, dark energy stars, Λ-objects, ...

  There are short time scale constraints on non-singular BHs:

  Sakai + 2014; Cardoso + 2016; Uchikata + 2016; Yunes + 2016; Cardoso & Pani 2017; Chirenti 2018; Konoplya + 2019; Maggio + 2020; ...

- Global expansion vs local physics: the Kerr metric universally assumed to describe BHs in GR is only tested on:
  - $\Delta t \sim 10^{-3} - 10^{3}\,\mathsf{s} \ll cH_0^{-1}$ Hubble time
  - $\Delta \ell \sim 10^{-3}$ pc

  asymptotically Minkowski boundary conditions are unrealistic—does it matter?

What is cosmological coupling?

Phenomenologically, the BH mass varies as

$$\boxed{M_{BH}(a) = M_{BH}(a_i)\left(\frac{a}{a_i}\right)^k}$$

with $a \geq a_i, \;\; k \geq 0.$ Cosmological coupling effective only on scales comparable to cH^{-1}.

A sort of cosmological coupling of BHs was proposed in the context of gravitational æther$\neq$ GR (Afshordi 2008; Prescod-Weinstein + 2009): quantum gravity effects at BH horizon $\rightarrow$ effective Λ but no time dependence of M_{BH}

Why cosmological coupling?

Pretty much every time we attempt to find exact solutions of the Einstein equations describing a central object (hopefully, a BH) embedded in a FLRW universe $\neq$ de Sitter, the object has dynamical boundary and time-dependent mass (McVittie 1933; Faraoni & Jacques 2007; ...)

Challenging to study this kind of solution: is the object a BH (conformal structure)? Does it have an event horizon or an apparent horizon? (very rarely located analytically.) What is the "mass"? = quasilocal energy? Usually studied in spherical symmetry.

No known solution describes a non-singular BH/gravastar/dark energy star embedded in FLRW.

We decided to look in the sky instead.

OBSERVATIONAL RESULTS

D. Farrah + ApJL 944, L31 (2023)

- Direct observational test of BH mass growth.
- Cannot observe a BH for billions of years $\rightarrow$ study *populations* of BHs: compare mass M_{BH} in BHs and host galaxy stellar mass $M_\star$ in a sequence of red elliptical galaxies over 6-9 Gyr or $0 \leq z \leq 2.5$ (Farrah + ApJ 943, 133 (2023)).
- Result: M_{BH} increases over this time by a factor 8–20 *relative to the stellar mass* $M_\star$; larger growth factor at high z.
- This increase in $M_{BH}/M_\star$ is very challenging to explain via standard galaxy assembly pathways, but is compatible with cosmological coupling with $k \simeq 3$. Accretion expected to be insignificant in red-sequence ellipticals; galaxy-galaxy mergers, on average, increase M_{BH} at the same rate as $M_\star$.

METHODS

6 samples of elliptical galaxies (~ 1600)

- 2 high-z samples
  - 2 in WISE survey ($z_1 = 0.75$, $z_2 = 0.85$)
  - 2 from SDSS ($z_3 = 0.75$, $z_4 = 0.85$)
  - 1 from COSMOS ($z_5 = 1.6$)
- $+$ 1 local sample

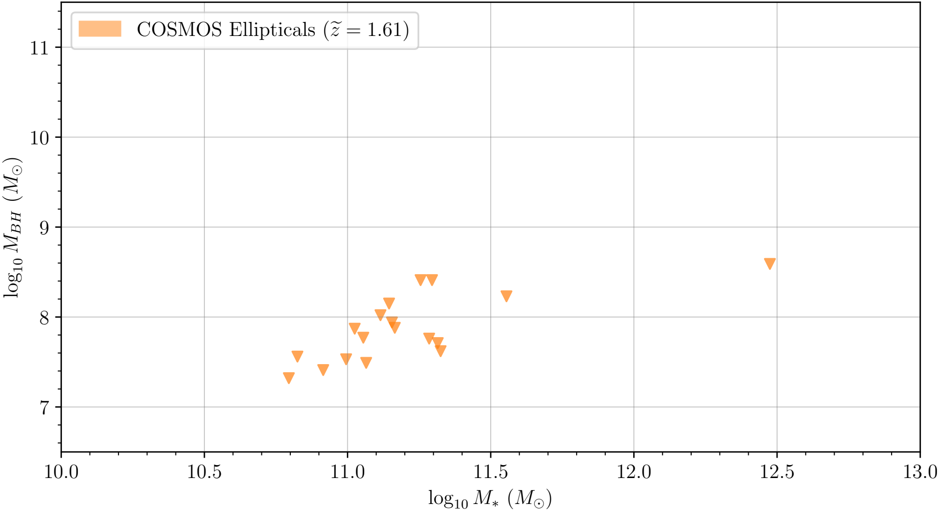
Plot $(M_\star, M_{BH})$ plane and find the value of k needed to align each high-z sample with the local sample. The same value of k should be found for all samples if cosmological coupling is the culprit. Compute posterior distribution of k.

The redshift dependence of mass growth translates to the same value across all 5 comparisons:

$$\boxed{k = 3.11^{+1.19}_{-1.33} \quad \text{(90\% confidence level)}}$$

$k = 0$ is excluded with 99.98% confidence.

Elliptical galaxies in $M_{BH} - M_*$



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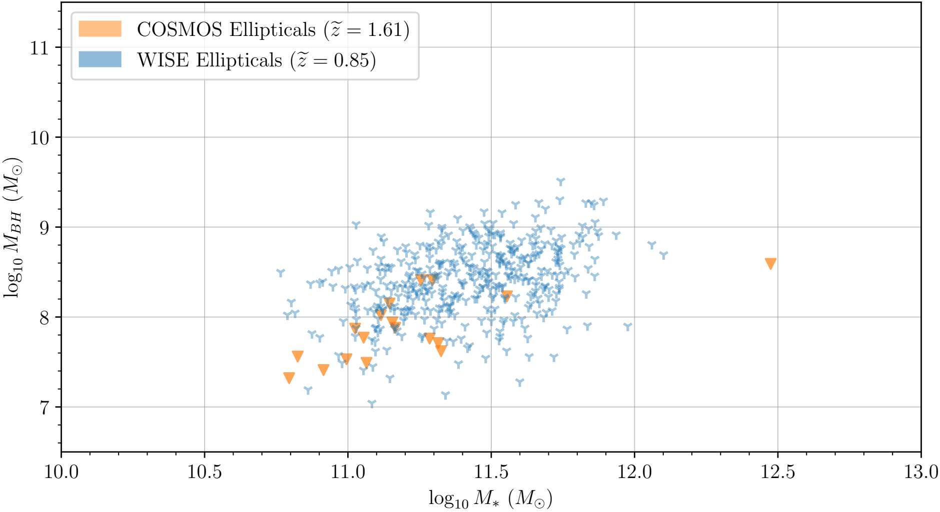

Data: D. Farrah, S. Petty, **KC**, et al. *ApJ* 943 (2023): 133

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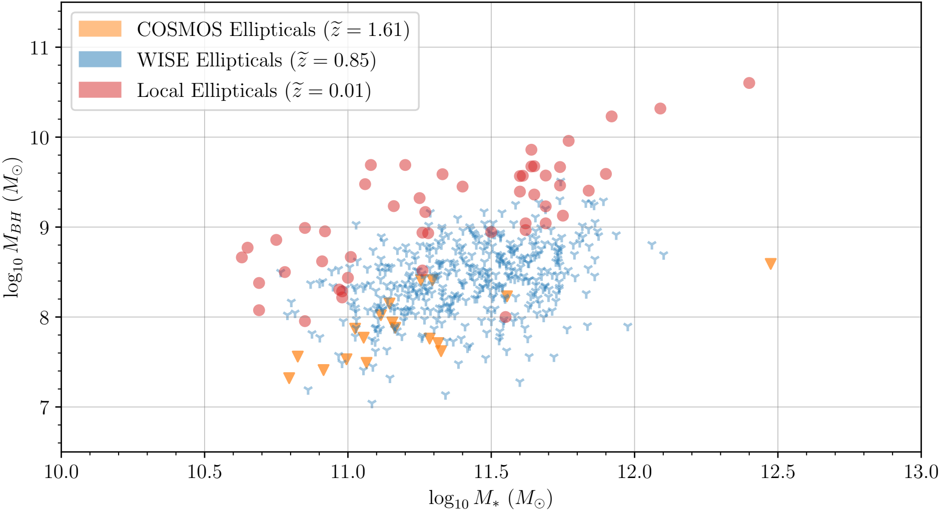

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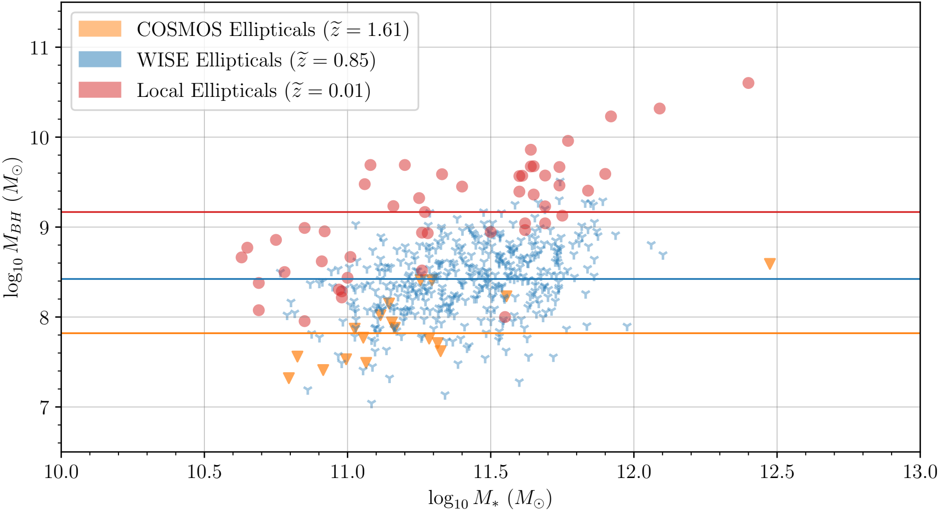

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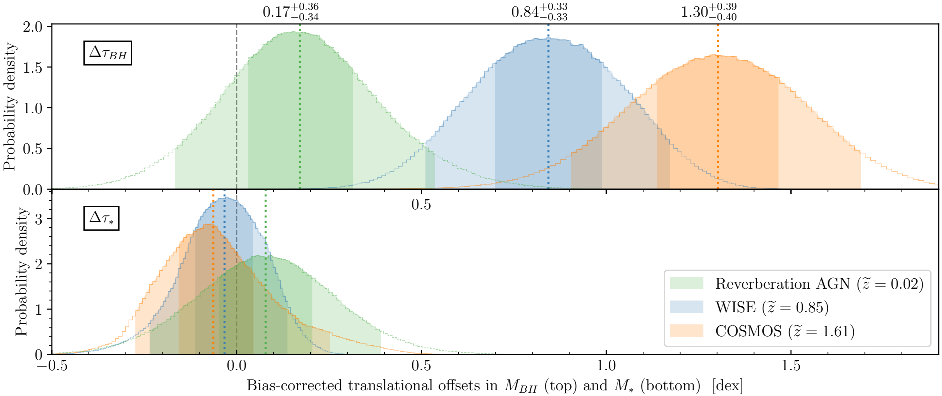
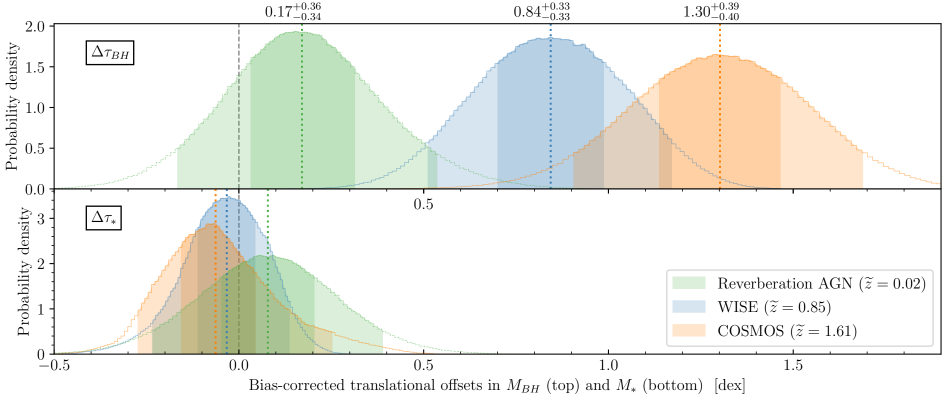
Elliptical galaxy SMBHs grow too fast (relative to M_*)



Data: No evolution in M_*...

Elliptical galaxy SMBHs grow too fast (relative to M_*)



Data: *strong* preferential evolution in M_{BH}

Elliptical galaxy SMBH growth gives $k \sim 3$, repeatedly

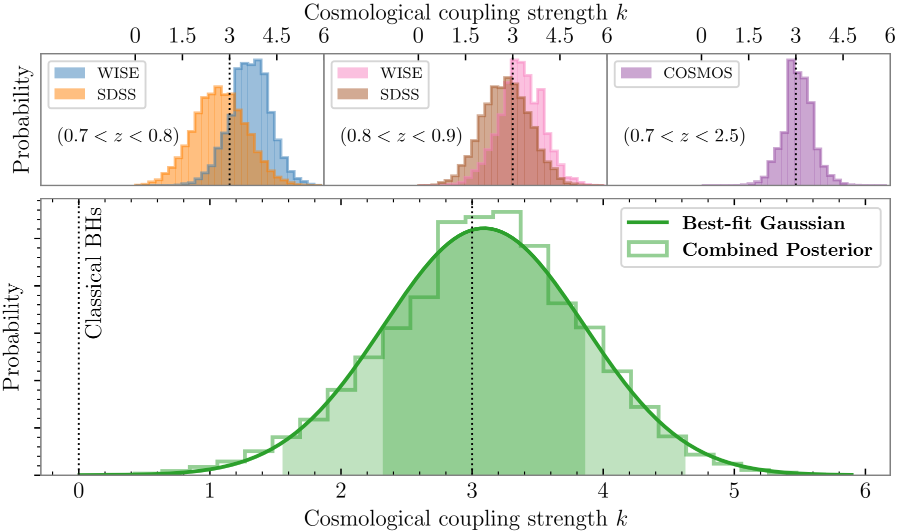


Figure: D. Farrah *et al.* *ApJL* 944, L31 (2023)

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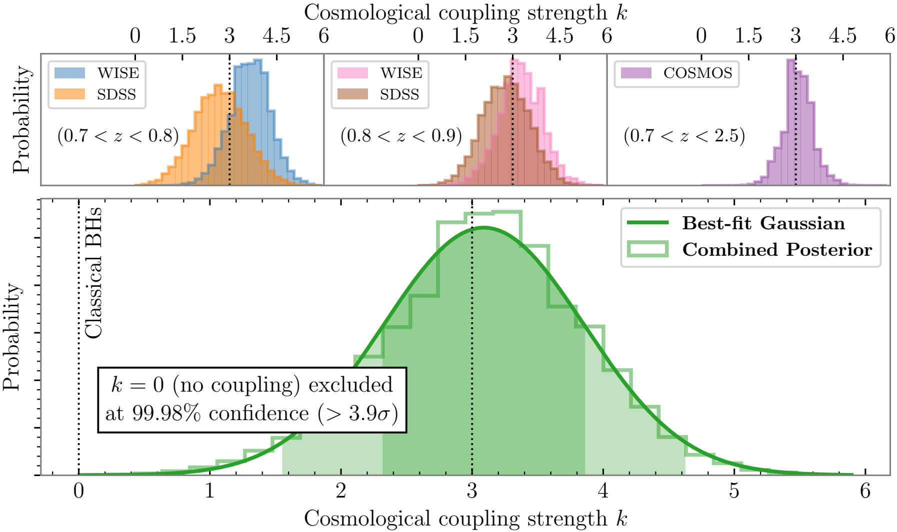

Figure: D. Farrah *et al.* *ApJL* 944, L31 (2023)

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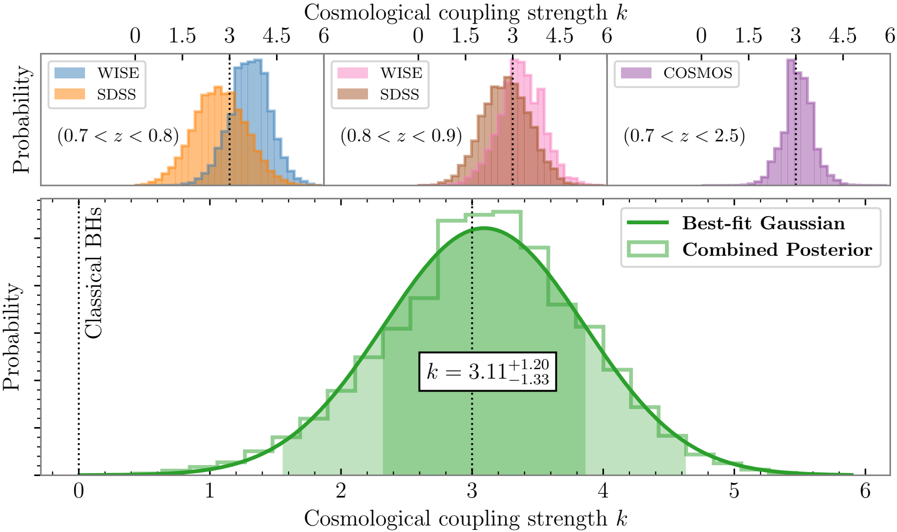

Figure: D. Farrah *et al.* *ApJL* 944, L31 (2023)

THEORY

Assumptions:

- BHs couple cosmologically with $k \simeq 3$;
- there is no dark energy outside BHs;
- BHs form solely from stellar collapse;
- ("BHs" means "non-singular BHs" $\rightarrow$ generically, they have internal stresses).

Key ingredients

1. When stars collapse to BHs, baryons are converted into BH, *i.e.*, into dark energy in their interiors (microphysics unknown—have fun!).
2. Stars form at $z \sim 25$ collapse, form BHs and Ω_Λ formed at that time is $\gg \Omega_{BH}$ today
3. We need only $\sim 3\%$ of all baryons to form BHs at $z \sim 25$.

Figure: D. Farrah *et al.* *ApJL* 944, L31 (2023)

Examine cosmic star formation rate density (SFRD) using

- various combinations of stellar production rate
- stellar initial mass function
- accretion history

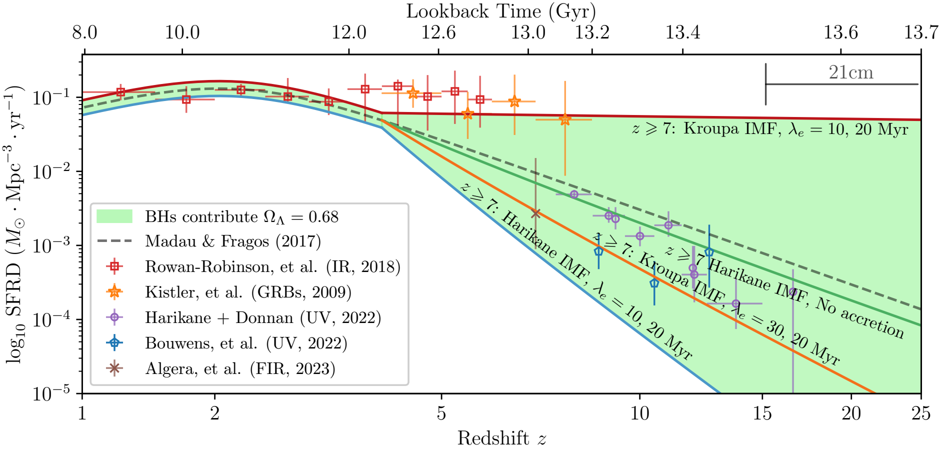

Figure: D. Farrah *et al.* *ApJL* 944, L31 (2023)

(compatible with Macquart *et al.*, *Nature* 581, 391 (2020))

The entire range of scenarios deduced from the literature is capable of producing the necessary $k \simeq 3$ BH density to give $\Omega_{BH} = \Omega_\Lambda \simeq 0.68$ today (Aghanim + 2020)

At most 3% of baryons are consumed around $z \simeq 25$, so that $\Omega_{baryons}$ left agrees with the value measured at low z.

The scenarios produced are consistent with MACHO constraints (population of MAssive Compact Halo Objects) — these constraints will improve.

THEORY

Obtain Einstein-Friedmann eqs. from Einstein-Hilbert variational principle with *non-local* (Fourier space) constraint $\rightarrow$ correct usual acceleration equation from stresses inside (regular) BHs.

$$S = S_G + S_M = \int d^4x\sqrt{-g}\,(\mathcal{L}_G + \mathcal{L}_M)$$

Idea: "zero order" is FLRW; introduce inhomogeneities (not perturbations, allow for BHs); we average mass-energy distributions on time slices, over a spatial volume $\mathcal{V}$ of scale ~ 180 Mpc (Nadathur + 2023) $\rightarrow$ introduce a *constraint in Fourier space*.

How do we obtain the Einstein eqs. from $\delta S = 0$ with this constraint? Unconventional variational principle

K.S. Croker, J.L. Weiner, D. Farrah PRD 105, 084042 (2022)

K.S. Croker, J. Runburg, D. Farrah Ap. J. 900, 57 (2020)

K.S. Croker, J.L. Weiner, Ap. J. 882, 19 (2019)

$$S = \int_{\mathcal{M}} \mathcal{L}\sqrt{-g}\, d^{N+1}x\,, \quad \mathcal{L} = \mathcal{L}\left(A, \partial_\mu A, \underbrace{...}_{\text{sources}}\right)$$

impose variations δA satisfy the same constraint in Fourier space as the fields A, then

$$\int_{\mathcal{M}} \delta A \left\{ \frac{\delta\left(\mathcal{L}\sqrt{-g}\right)}{\delta A} \right\} d^{N+1}x \quad \not\Rightarrow \frac{\delta\left(\mathcal{L}\sqrt{-g}\right)}{\delta A} = 0$$

but $\int_{\mathcal{M}} \delta A \left\{ \frac{\delta(\mathcal{L}\sqrt{-g})}{\delta A} \right\} d^{N+1}x \;\Rightarrow$

$$\boxed{\frac{\delta\left(\mathcal{L}\sqrt{-g}\right)}{\delta A} * \mathcal{F}^{-1}\left[\mathbb{I}_V\right] = 0}$$

where

$*$ convolution

$\mathcal{F}^{-1}$ inverse Fourier transform

$\mathbb{I}_V$ indicator of V

or (in less compact form)

$$\left[\frac{\partial}{\partial x^\mu}\left(\frac{\partial\left(\mathcal{L}\sqrt{-g}\right)}{\partial(\partial_\mu A)}\right) - \frac{\partial\left(\mathcal{L}\sqrt{-g}\right)}{\partial A} + \underbrace{\ldots}_{\text{sources}}\right] * \mathcal{F}^{-1}\left[\mathbb{I}_V\right] = 0$$

K.S. Croker, J.L. Weiner, D. Farrah, PRD 105, 084042 (2022); reduces to usual Euler-Lagrange eqs. if constraints are local.

Apply to FLRW with BHs: $\rightarrow$

$$\boxed{\frac{d^2 a}{d\eta^2} = \frac{4\pi G}{3}\, a^3 \langle \bar{\rho} - 3\bar{P}_{(isotropic)} \rangle \mathcal{V}}$$

Contrary to folklore, internal stresses contribute! (Note: this is a zero-order equation).

For "ordinary" BHs = vacuum GR solutions, there are no internal stresses/densities and we recover the usual acceleration equation (in conformal time).

Do such objects contributing to the FLRW source exist?

If BHs are non-singular BHs, they typically have anisotropic stresses (Cattoen, Faber, Visser CQG 22, 4189 (2005))

Conclusions

We report a *correlation* (not causation). Major observational + theoretical work needed:

- independent tests, better statistics; improved accuracy in measuring M_{SMBH} and $M_\star$.
- Cosmological coupling should have other effects, *e.g.*:
  - Cosmic Microwave Background (low ℓ, due to different clustering of non-singular BHs $\rightarrow$ different integrated Sachs-Wolfe effect)
  - strong lensing of γ-ray bursts by BHs ($\rightarrow$ density of BH lenses along line of sight)
  - stellar mass BH-BH merger rates in LIGO (long) orbital period decay
  - stellar mass BH and stellar evolution

overall, falsifiable fairly easily ("strong" model in the Popperian sense).

- Theory: currently no exact GR solution is known that described an asymptotically FLRW non-singular BH.
- What "mass"? Quasilocal? Event or apparent horizon, or none at all? Comoving boundary? Dark energy interior matched to FLRW exterior. Is there a lower mass limit to these objects?

If any of this is confirmed, it's very intriguing.

THANK YOU