**Title:** Cosmological Coupling in the Era of the Dark Energy Spectroscopic Instrument

**Speakers:** Kevin Croker

**Collection/Series:** Cosmology and Gravitation

**Subject:** Cosmology

**Date:** October 01, 2024 - 11:00 AM

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**Abstract:**

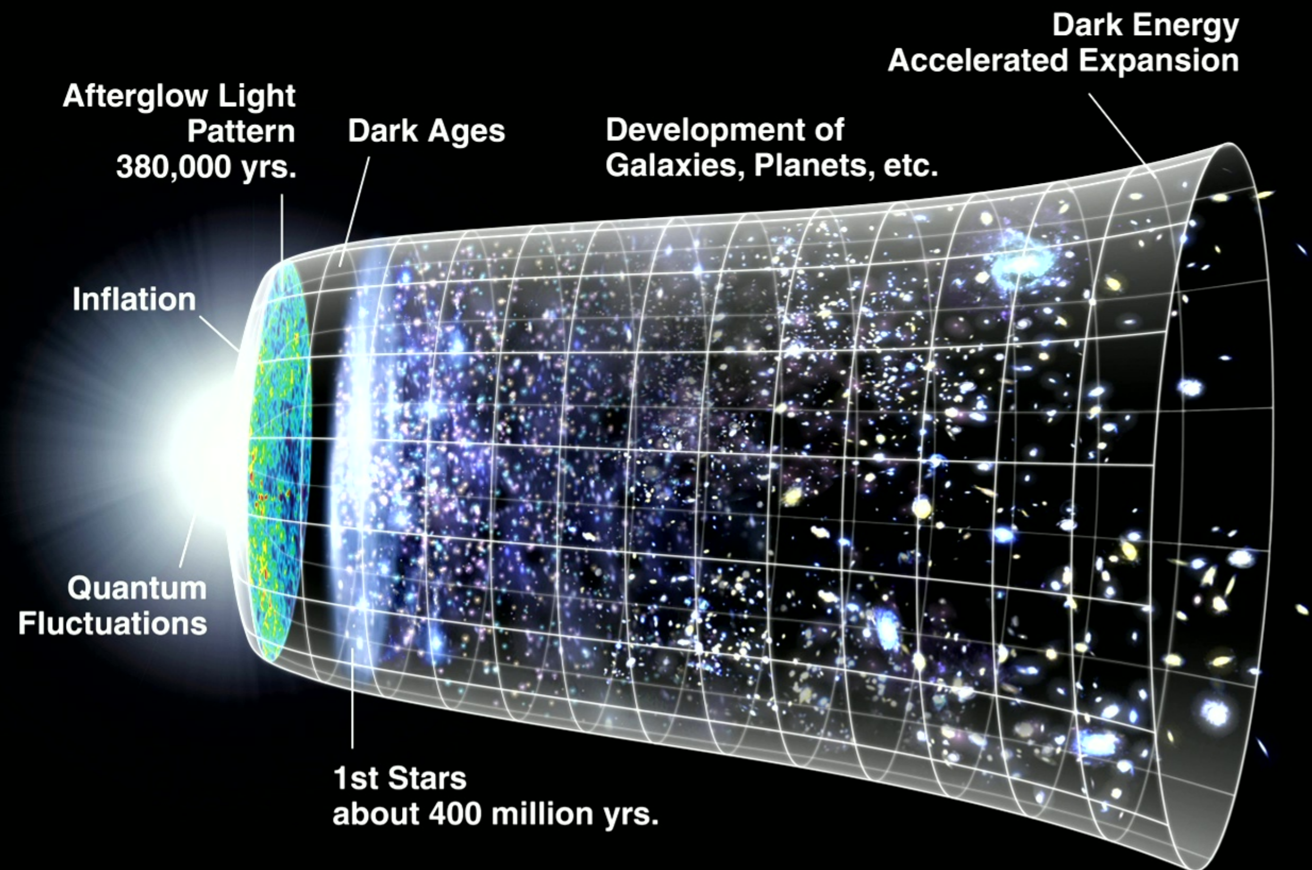
Recent advances in General Relativity point toward unanticipated, and dynamic, relations between ultracompact objects and the universe they inhabit. The possibility for strongly gravitating systems, like astrophysical black holes (BHs) and their embedding cosmology, to directly interact has been dubbed "cosmological coupling." We focus on recent results from the DOE Stage IV Dark Energy (DE) Spectroscopic Instrument (DESI), which strongly suggest that DE is dynamical. Using typical empirical models for the cosmic star-formation rate density as a proxy to BH production, we show that the DESI-inferred time-evolution of DE is consistent with cosmologically coupled stellar-collapse BHs as the source of DE. The predicted cosmological expansion rate today, H_0 = 69.94 +/- 0.81 km/Mpc/s, is in excellent agreement with H_0 = 69.58 +/- 1.58 km/Mpc/s recently reported by the Chicago-Carnegie Hubble Program using Cepheid, Tip of the Red Giant Branch, and J-Region Asymptotic Giant Branch stellar distance-ladder calibrations. With DESI Redshift Space Distortions and Year 3 datasets on the horizon, we highlight exciting prospects for further observational confrontation in the near term.

# Cosmological Coupling in the Era of the Dark Energy Spectroscopic Instrument

**Kevin Croker**[1,2], Gregory Tarlé[3], Steve P. Ahlen[4], Brian G. Cartwright[5], Duncan Farrah[2,6], Nicolas Fernandez[7], Rogier A. Windhorst[1]

Black Hole Models
Astrophysical Black Holes

$a \to 0$
(Big Bang)




$a := 1$
(Today)

SOVIET PHYSICS JETP VOLUME 22, NUMBER 1 JANUARY, 1966

# *THE INITIAL STAGE OF AN EXPANDING UNIVERSE AND THE APPEARANCE OF A NONUNIFORM DISTRIBUTION OF MATTER*

A. D. SAKHAROV

Submitted to JETP editor March 2, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) **49**, 345-358 (July, 1965)

A hypothesis of the creation of astronomical bodies as a result of gravitational instability of the expanding universe is investigated. It is assumed that the initial inhomogeneities arise as a result of quantum fluctuations of cold baryon-lepton matter at densities of the order of $10^{98}$ baryons/cm$^3$. It is suggested that at such densities gravitational effects are of decisive importance in the equation of state and the dependence of the energy density $\epsilon$ on the baryon density n can qualitatively be described by graphs a of b of Fig. 1. $\epsilon$ vanishes at a certain density $n = n_0$. A theoretical estimate (containing some vague points) yields initial inhomogeneities in the distribution of matter which can explain the origin of clusters of $10^{62}$—$10^{63}$ baryons ($10^5$—$10^6$ $M_\odot$). The calculated mass is smaller than that of the galaxies by a factor of $10^5$—$10^6$; it is in fact closer to the masses of globular clusters. The hypothesis is pro-

the condition $\mu$ = const, plays the role of the cosmological constant, which accordingly can be interpreted in the framework of the ordinary formalism of the general theory of relativity. If, on the other hand, we cannot neglect the matter other than the $\mu$-vacuum, the analogy of the $\mu$-vacuum density with the cosmological constant can be maintained only in so far as the interaction of this matter with the $\mu$-vacuum is unimportant. Otherwise the condition $\mu$ = const does not hold, and the analogy with the cosmological constant is destroyed.

The differences between the structure of the energy-momentum tensor of $\mu$-vacuum and that for ordinary matter, and the consequent differences between its equations of motion and its properties and the equations of motion and properties for ordinary matter show that if the $\mu$-vacuum is real, then it is a specific form of matter. Since the equations of the general theory of relativity do not contain adequate information about the conditions of transition between different forms of matter, within the framework of this theory we cannot describing of particles of matter are annulled.

This situation is not utterly unrealistic. An attempt to describe phenomenologically the structure of an elementary charged particle would lead to the conclusion that inside the particle there must be a negative pressure which balances the electrostatic repulsion. This raises the thought that in an ultradense state of matter, with the baryons so compressed that the meson fields which provide the interaction between them (repulsion!) cannot be produced, a continuous medium is formed in which the conditions correspond to an attraction between material elements and are described phenomenologically by a negative pressure. For example, such a state might be reached in gravitational collapse.

It would seem that a negative pressure should lead to an internal instability, and that if there are no volume forces of the type of the electrostatic repulsion it would lead to a contraction without limit. This is not true, however. Let us assume that compression actually leads to a negative pres-

*General Relativity and Gravitation, Vol. 24, No. 3, 1992*

# Vacuum Nonsingular Black Hole†

**Irina Dymnikova**[1]

The spherically symmetric vacuum stress-energy tensor with one assumption concerning its specific form generates the exact analytic solution of the Einstein equations which for large $r$ coincides with the Schwarzschild solution, for small $r$ behaves like the de Sitter solution and describes a spherically symmetric black hole singularity free everywhere.

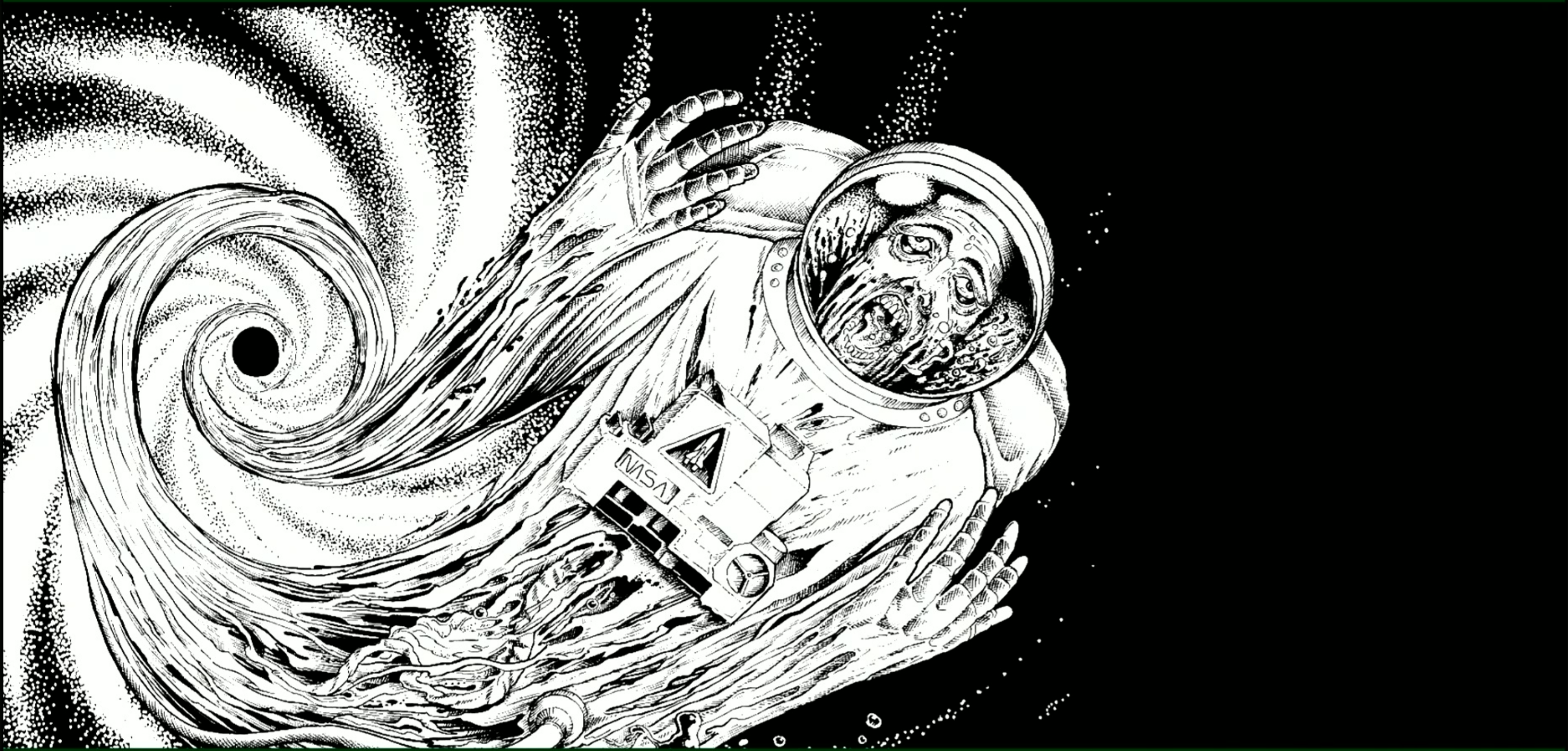
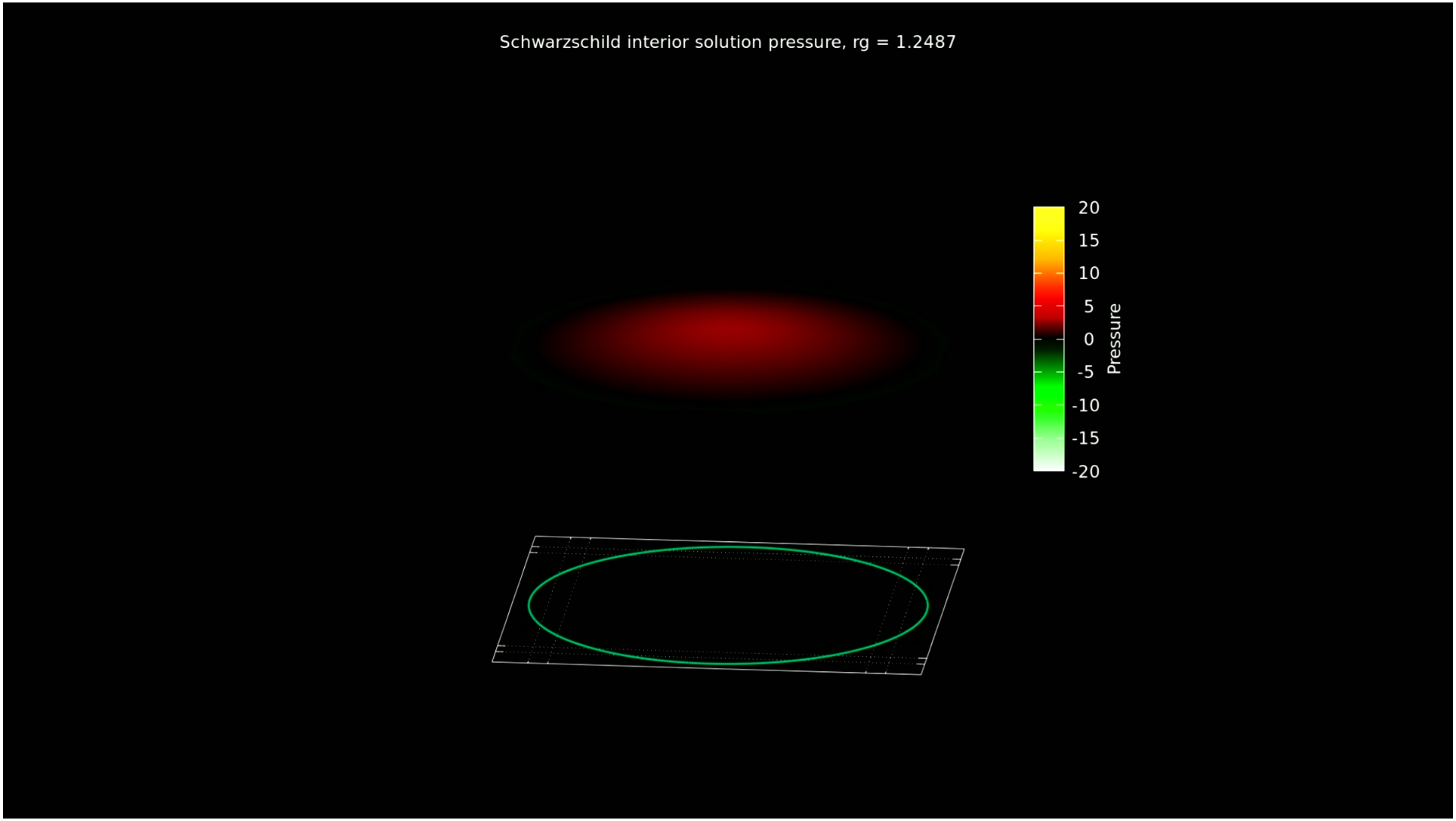
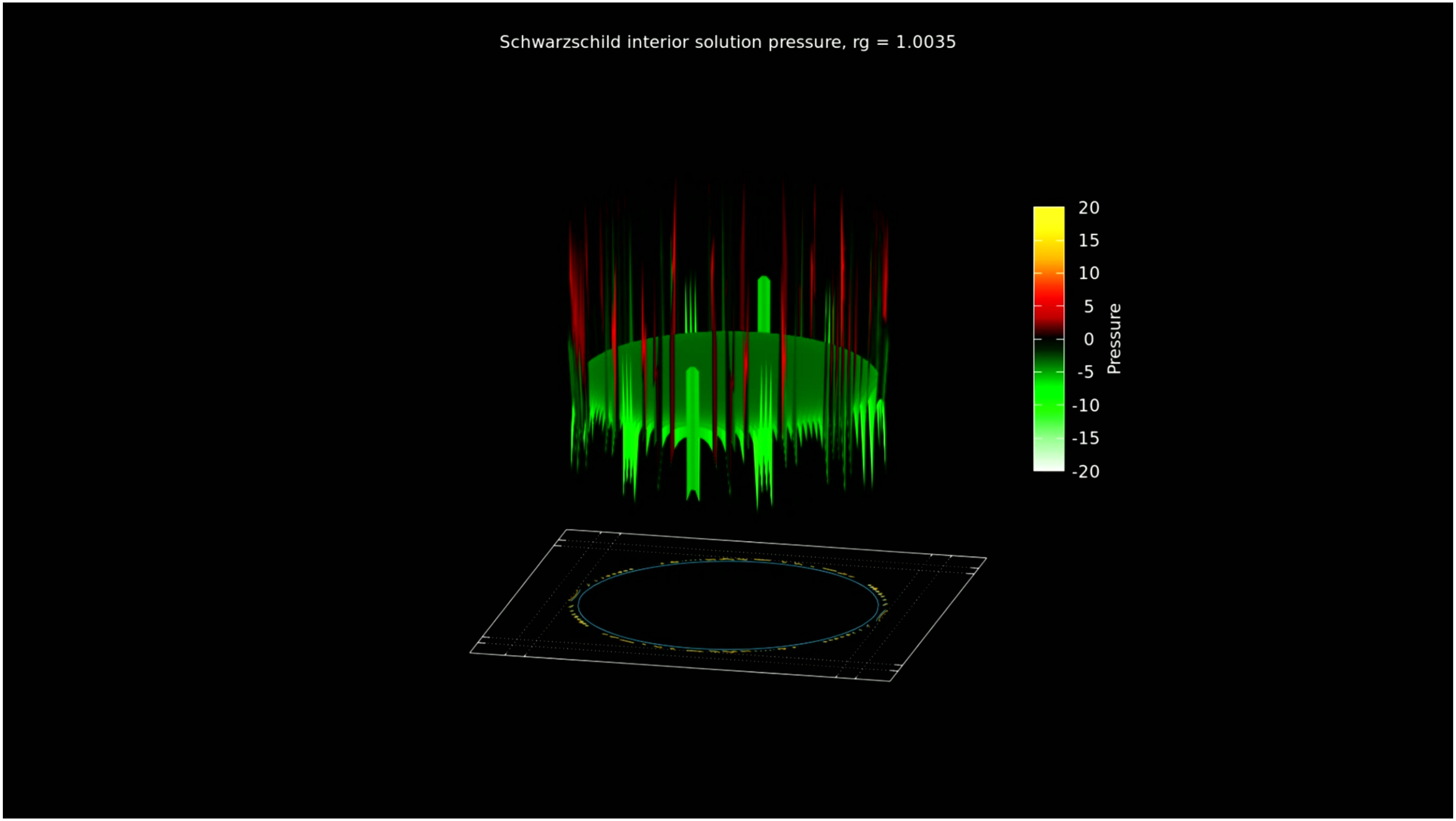


Image Credit: Maeghan LeMay Art, 2015


Schwarzschild interior solution pressure, rg = 1.2487
20
15
10
5
0
-5
-10
-15
-20
Pressure


Schwarzschild interior solution pressure, rg = 1.0035
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15
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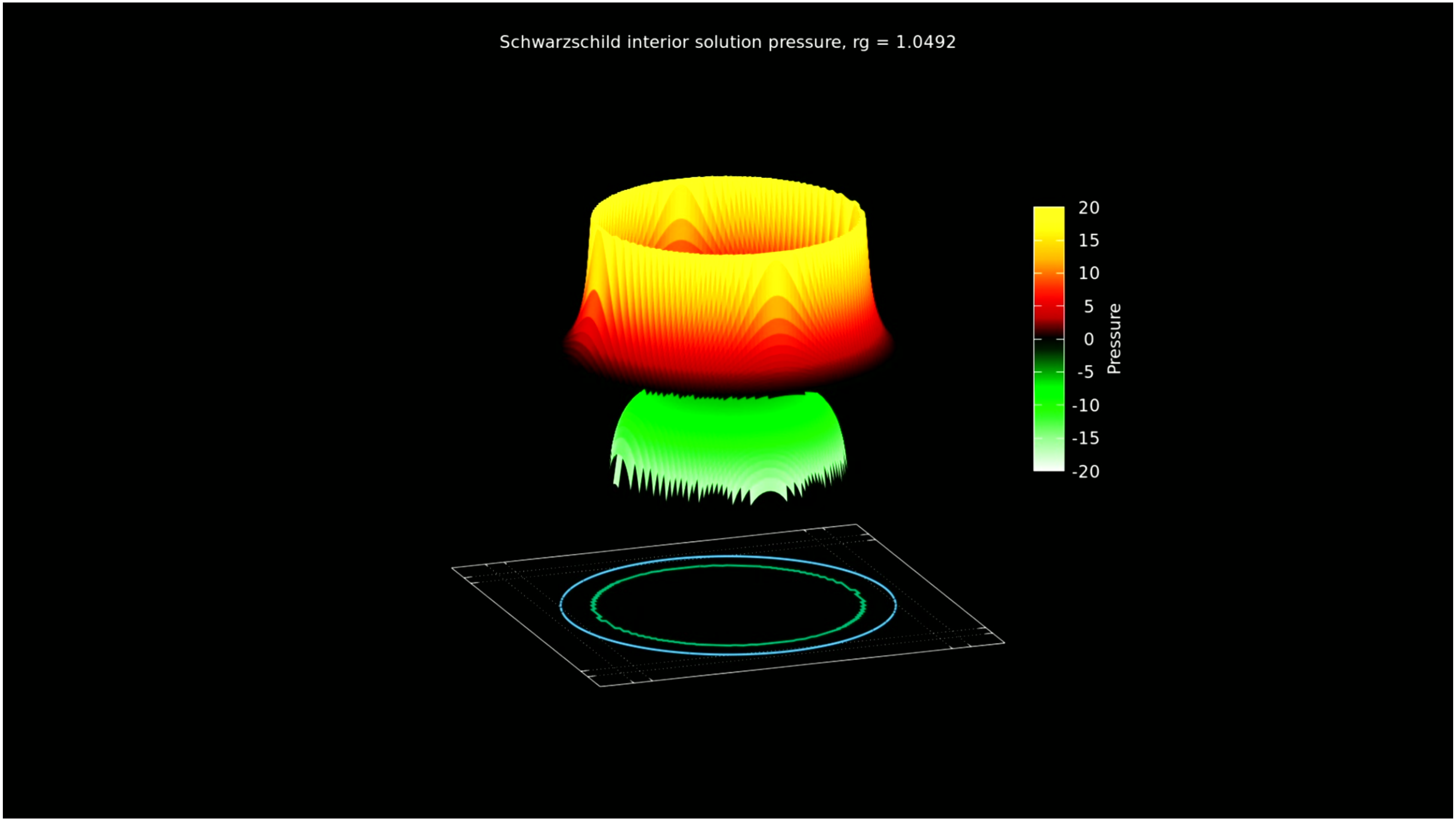
-15
-20
Pressure


Schwarzschild interior solution pressure, rg = 1.0492
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15
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5
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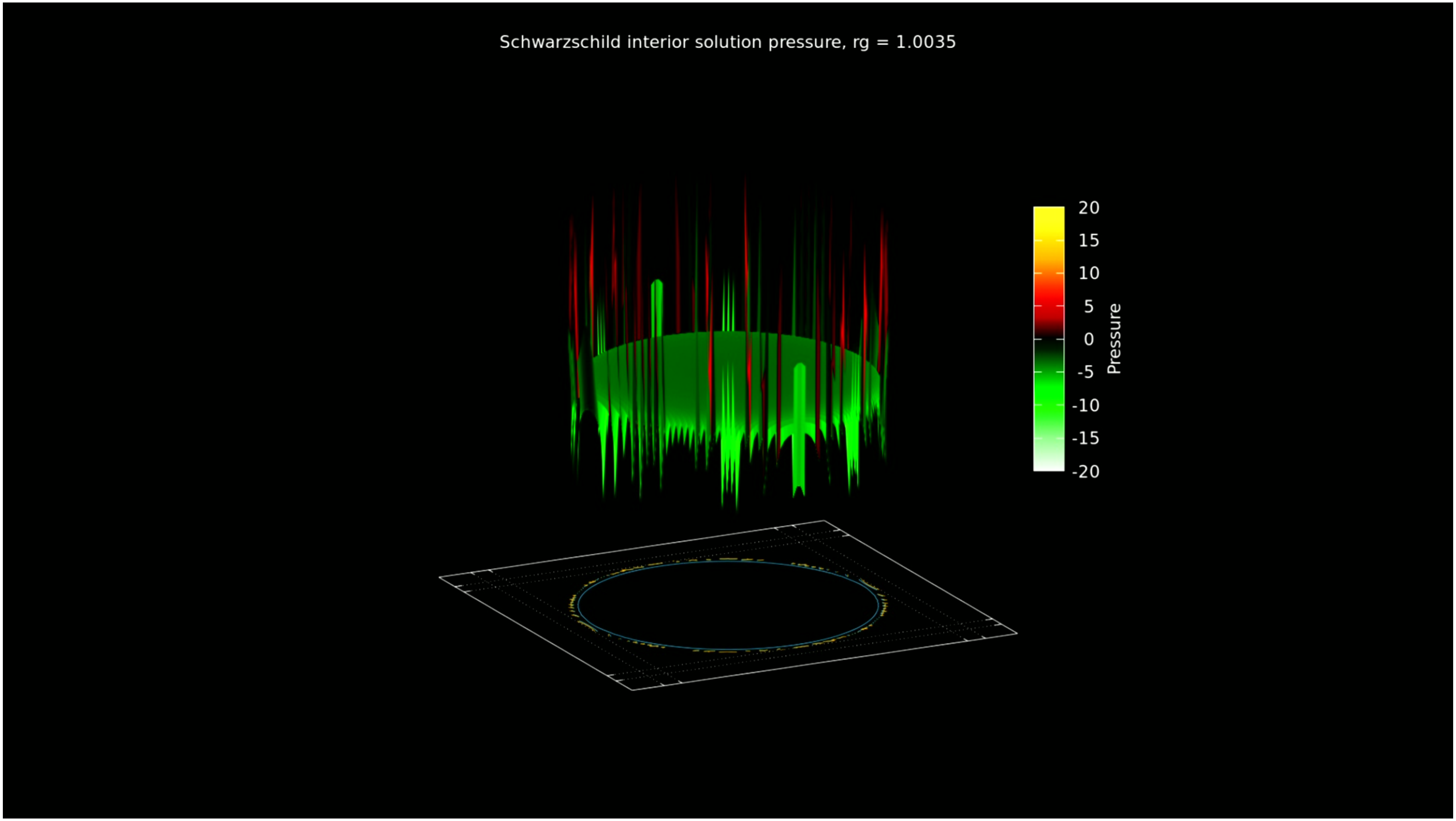
-5
-10
-15
-20
Pressure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20
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10
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-10
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# Surprise! There's a zoo of Black Hole Models

Non-singular GR black hole solutions with pressure $P = -\rho c^2$ interiors studied for decades:

- **Junctionless and Junctioned**: Bardeen (1968), Dymnikova (1992), Visser et al. (2004), Lobo (2006)
- **QFT (Horizon free)**: Chapline, Laughlin, et. al (2002); Mazur & Mottola (2015)
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**LIGO/Virgo consistent:** Mimic or indistinguishable from Schwarzschild/Kerr on the outside

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PHYSICAL REVIEW D **76,** 063510 (2007)

# Cosmological expansion and local physics

Valerio Faraoni* and Audrey Jacques†
*Physics Department, Bishop's University, 2600 College Street, Sherbrooke, Québec, Canada J1M 0C8*
(Received 7 June 2007; published 24 September 2007)

The interplay between cosmological expansion and local attraction in a gravitationally bound system is revisited in various regimes. First, weakly gravitating Newtonian systems are considered, followed by various exact solutions describing a relativistic central object embedded in a Friedmann universe. It is shown that the "all or nothing" behavior recently discovered (i.e., weakly coupled systems are comoving while strongly coupled ones resist the cosmic expansion) is limited to the de Sitter background. New exact solutions are presented which describe black holes perfectly comoving with a generic Friedmann universe. The possibility of violating cosmic censorship for a black hole approaching the big rip is also discussed.

DOI: 10.1103/PhysRevD.76.063510 PACS numbers: 98.80.−k, 04.50.+h

## I. INTRODUCTION

issue of whether a planet, a star, or a galaxy expands ing the rest of the universe is a problem of principle eral relativity that still awaits a definitive answer.

perturbed by a transient and does not expand [22]. This work breaks free of the standard assumption of previous literature that the coupling (of a gravitationally, instead of electrically, bound system) is weak. However, it has two fundamental limitations: first, the cosmological back-

$$\mathcal{A}_{\Sigma_0}(t) = \iint_{\Sigma_0} d\theta d\varphi \sqrt{g_{\Sigma_0}} = 4\pi a^2(t)\bar{r}_0^2\left(1 + \frac{m(t)}{2\bar{r}_0}\right)^4, \tag{47}$$

where $g_{ab}|_{(\Sigma_0)}$ is the metric on $\Sigma_0$ at a fixed time $t$ and $g_{\Sigma_0}$ is its determinant. By using the Schwarzschild curvature coordinate $r \equiv \bar{r}(1 + \frac{m}{2\bar{r}})^2$, one has

$$\mathcal{A}_{\Sigma_0}(t) = 4\pi a^2(t) r_0^2. \tag{48}$$

The star surface is comoving with the cosmic substratum and the proper curvature radius of the star is $r_{\text{phys}}(t) = a(t)\bar{r}_0(1 + \frac{m}{2\bar{r}_0})^2$. Therefore, we have a local relativistic object with strong field which is perfectly comoving at all times: in this case the cosmic expansion wins over the local dynamics.

It is interesting to compute the generalized Tolman-

$$\frac{\partial P}{\partial r} + (P + \rho)\ldots$$

In the Newtonian ... equation reduces ...

where $\rho = m(\frac{4\pi}{3}\ldots$ ... potential. This e... obtained from E... curvature radius. ... of hydrostatic eq... uniform density s...

$$\frac{dP}{\ldots} + \frac{d\Phi_N}{\ldots}$$

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Models with realistic, cosmological, boundary conditions exhibit new phenomena

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Models with realistic, cosmological, boundary conditions exhibit new phenomena:

- **Dynamical radius**: Faraoni & Jacques (2007), Faraoni & Rinaldi (2024)

ion (40) was imposed by McVittie to
he accretion of cosmic fluid onto the
umption $e$) of Ref. [1]). It corresponds
in turn implies that the stress-energy
$T_0^1 = 0$ and there is no radial flow. In
Eq. (40) corresponds to the constancy of
vard mass, $\dot{m}_H = 0$. It is important to
he physically relevant mass (eventually
cal size of the horizon or of the central
o avoid making coordinate-dependent
mass and size (cf., e.g., Refs. [18,55]),
] of the central object. $m(t)$ is just a
n a particular coordinate system.
little doubt that the McVittie metric
nd of strongly gravitating central object,
etation is not completely clear and is
[10,12,15,16]. This metric reduces to
solution in isotropic coordinates when
FLRW metric if $m \equiv 0$. However, in
(39) can not be interpreted as describing
dded in a FLRW universe because it is
sphere $\bar{r} = m/2$ (which reduces to the

## FLRW universe and its Newtonian limit

It is of interest to study the behavior of a relativistic star embedded in a FLRW background with respect to the problem of local physics versus cosmological expansion. The Nolan interior solution [33] describes a relativistic star of uniform density in such a background. The metric is

$$ds^2 = -\left[\frac{1 - \frac{m}{\bar{r}_0} + \frac{m\bar{r}^2}{\bar{r}_0^3}\left(1 - \frac{m}{4\bar{r}_0}\right)}{\left(1 + \frac{m}{2\bar{r}_0}\right)\left(1 + \frac{m\bar{r}^2}{2\bar{r}_0^3}\right)}\right]^2 dt^2 + a^2(t)\frac{\left(1 + \frac{m}{2\bar{r}_0}\right)^6}{\left(1 + \frac{m\bar{r}^2}{2\bar{r}_0^3}\right)^2}\left(d\bar{r}^2 + \bar{r}^2 d\Omega^2\right) \qquad (43)$$

in isotropic coordinates, where $\bar{r}_0$ is the star radius, $\frac{\dot{m}}{m} = -\frac{\dot{a}}{a}$ (the condition forbidding accretion onto the star surface), and $0 \leq \bar{r} \leq \bar{r}_0$. The interior metric is regular at the center and is matched to the exterior McVittie metric at $\bar{r} = \bar{r}_0$ by imposing the Darmois-Israel junction conditions. The energy density is uniform and discontinuous at the surface $\bar{r} = \bar{r}_0$, while the pressure is continuous. These quantities are given by [33]

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- **Dynamical mass**: Guariento et al. (2012), Cadoni et al. (2023)

# Cosmological Coupling

**GR Prediction**: if a species of compact objects contributes $P \neq 0$ to Einstein's equations, the individual masses will observably shift, analogous to the photon redshift:

$$m(a) := m_i \left(\frac{a}{a_i}\right)^k \qquad a \geqslant a_i$$

Here

- $a_i$ is the scale factor at the time of coupling
- $m_i$ is the mass when the body becomes cosmologically coupled
- $k = -3P/\rho c^2$ is the strength of the cosmological coupling

**KC** & J. Weiner. *ApJ* 882.1 (2019): 19.; **KC**, M. Zevin, D. Farrah, K. Nishimura, G. Tarlé, *ApJL* 921.2 (2021): L22.

# Local searches for cosmological coupling

Our teams have led the search for the effect in astrophysical BH populations

- LIGO-Virgo-KAGRA merging BBHs: $k \sim 0.5$ (**KC** et al., *ApJL* 2021)
- Early-type Galaxies: $k = 3.11^{+1.20}_{-1.33}$ at $90\%$ confidence (Farrah et al., *ApJL* 2023)

Many other groups have begun to search, e.g.

- Globular clusters: $k \lesssim 0.5$ (Rodriguez *ApJL* 2023)
- *Gaia* DR3 BH1 and BH2: $k \lesssim 1$ (Andrae & El-Badry, *A&A Let.* 2023)
- LVK BBHs: $k \lesssim 0.5$ or initial $m \sim 0.5 M_\odot$ for $k = 3$ (Amendola et al. *MNRAS* 2023)
- Accretion + NANOgrav: $k > 2$ preferred (Lacy, Engholm et al., *ApJL* 2024)

**Current picture**: SMBHs prefer larger $k$, stellar mass BHs prefer smaller $k$.

**KC** & J. Weiner. *ApJ* 882.1 (2019): 19.; **KC**, M. Zevin, D. Farrah, K. Nishimura, G. Tarlé, *ApJL* 921.2 (2021): L22.

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# Global searches for cosmological coupling

If $k \sim 3$, then each black hole satisfies

$$M_{BH}(a) \propto a^3$$

BHs are objects inside a cosmology, so their number density

$$\frac{\mathrm{d}N_{BH}}{\mathrm{d}\mathcal{V}} \propto \frac{1}{a^3}.$$

$\therefore$ the total energy density of BHs

$$\rho_{BH} = M_{BH}\frac{\mathrm{d}N_{BH}}{\mathrm{d}\mathcal{V}} = \text{constant}$$

**KC** & J. Weiner. *ApJ* 882.1 (2019): 19.

# Global searches for cosmological coupling

Cosmological conservation of stress-energy requires

$$\frac{\mathrm{d}\rho_{BH}}{\mathrm{d}\eta} + \frac{3}{a}\frac{\mathrm{d}a}{\mathrm{d}\eta}\left(\rho_{BH} + P_{BH}\right) = 0$$

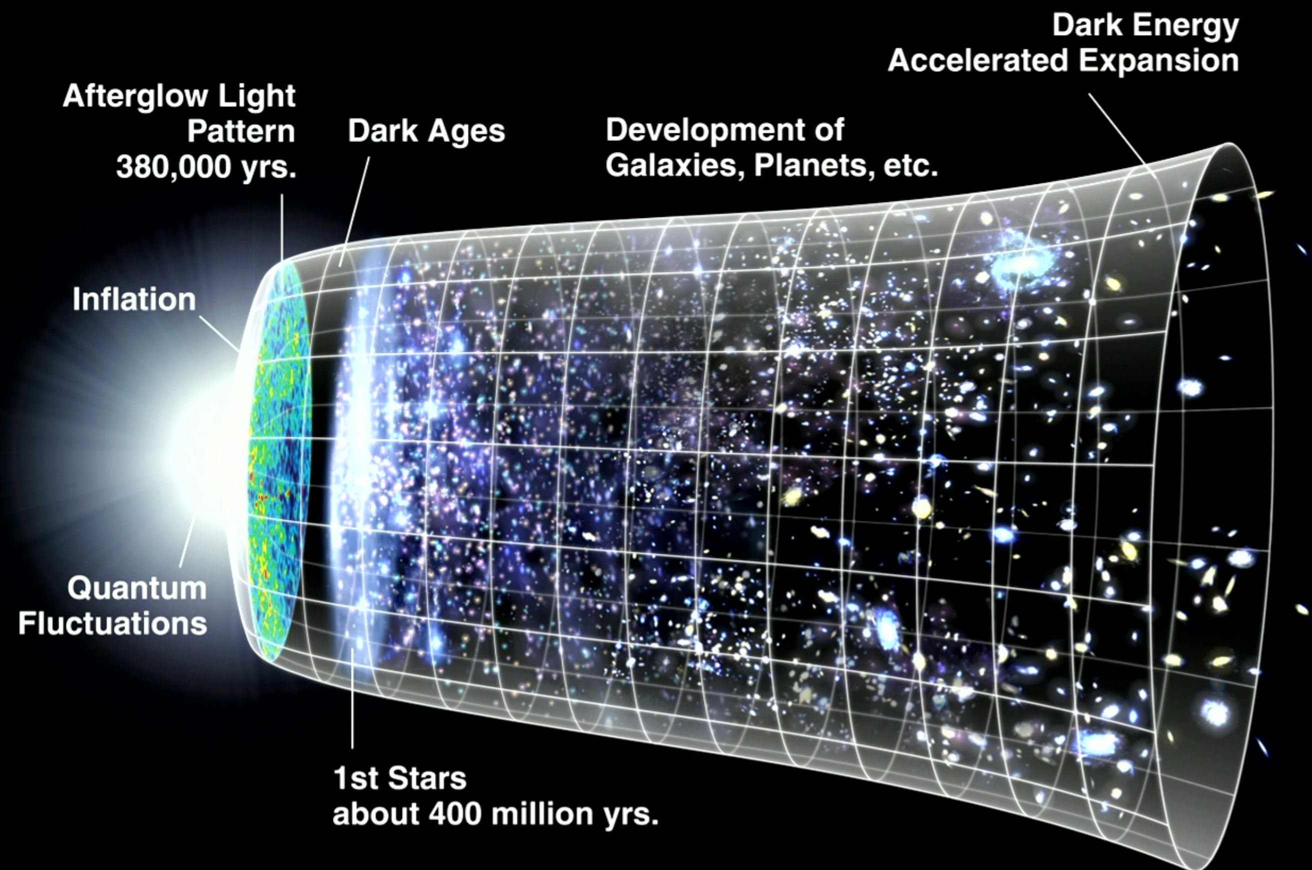
If $\rho_{BH}$ is constant, then

$$\boxed{P_{BH} = -\rho_{BH}}$$

$\therefore$ and black holes, in aggregate, contribute as a **dark energy species**.

**KC** & J. Weiner. *ApJ* 882.1 (2019): 19.

$a \to 0$
(Big Bang)




$a := 1$
(Today)

-4. The LRG sample should therefore out- by a factor of 2 in fractional errors on large ar surveys cover much more volume than but their effective volumes are worse, even ) shot noise.

-SPACE CORRELATION FUNCTION

*-elation Function Estimation*

ıalyze the large-scale clustering using the function (Peebles 1980, § 71). In recent trum has become the common choice on ver in different Fourier modes of the linear cally independent in standard cosmology ıl. 1986). However, this advantage breaks due to nonlinear structure formation, while ıte methods are required to recover the sta- in the face of survey boundary effects (for ark et al. 1998). The power spectrum and ontain the same information in principle, ınsforms of one another. The property of different Fourier modes is not lost in real encoded into the off-diagonal elements of via a linear basis transformation. One must

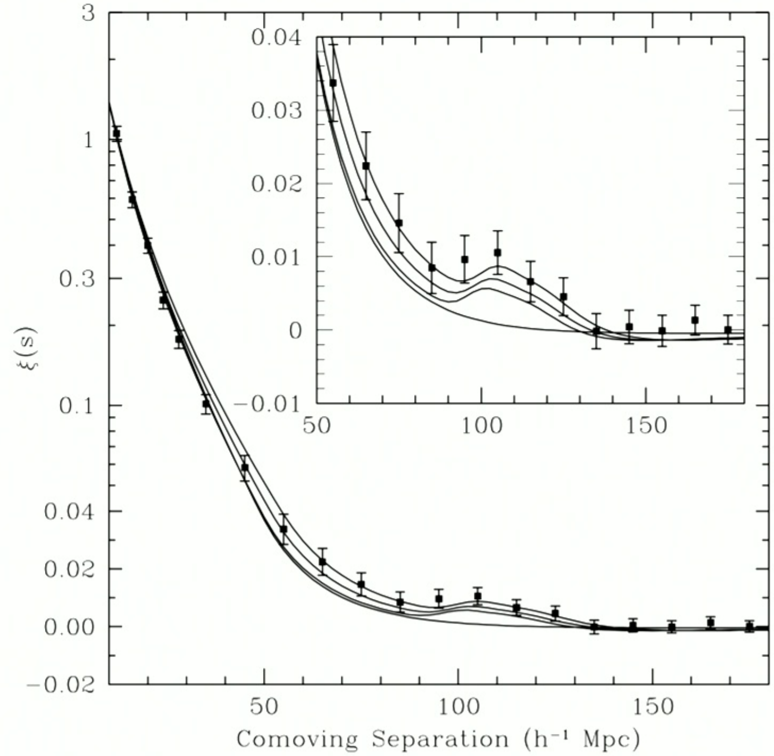
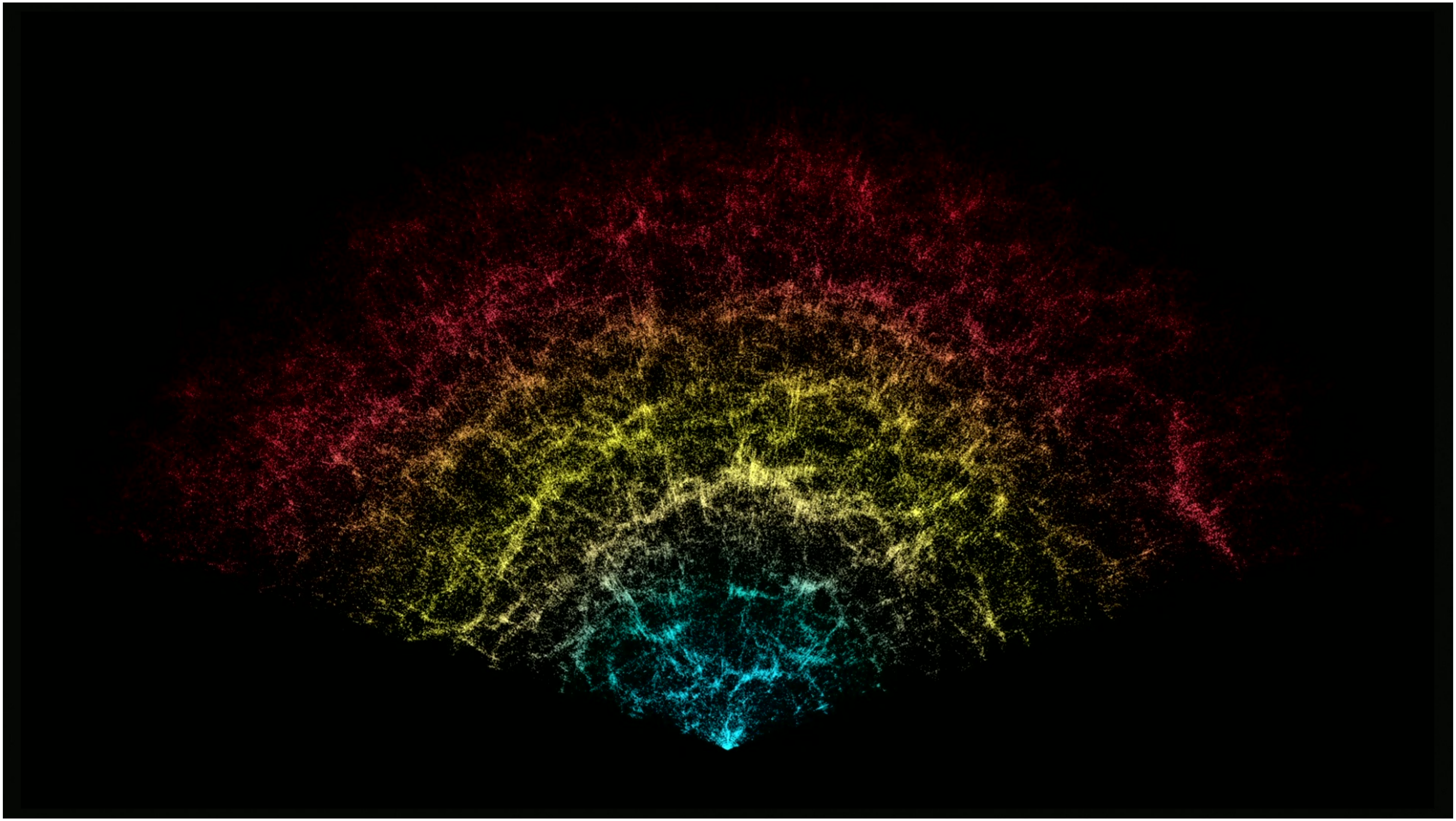
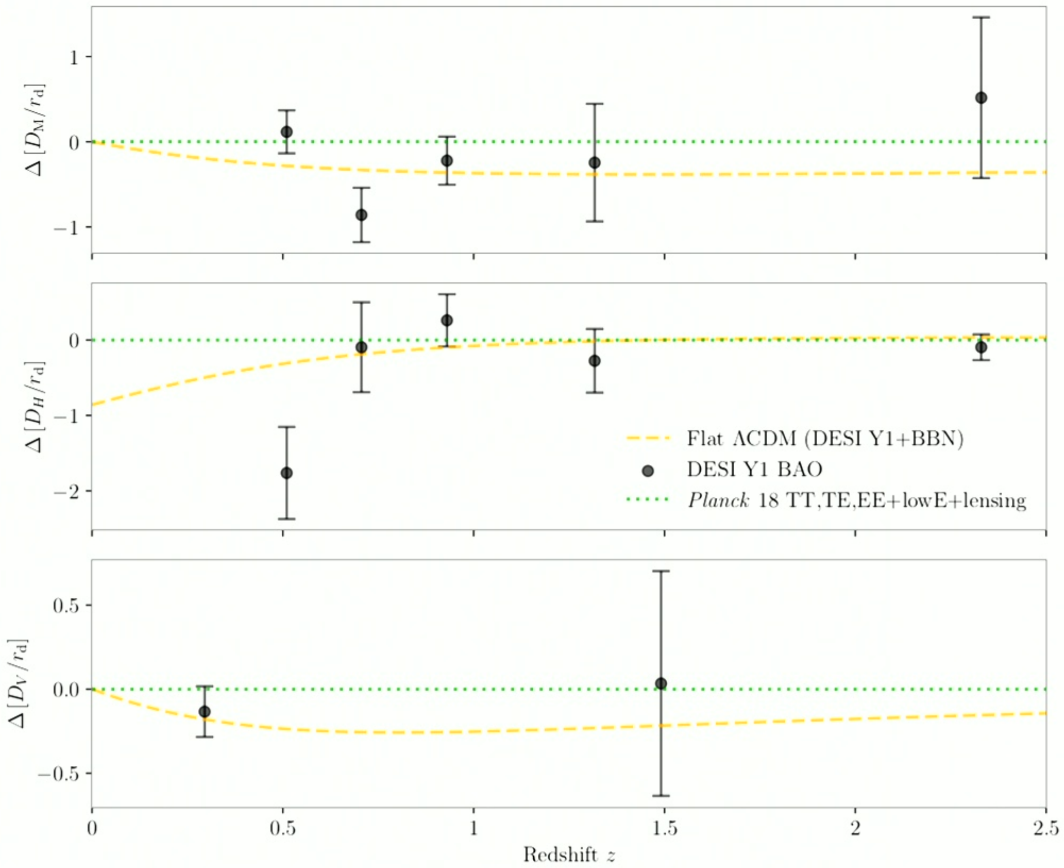



FIG. 2.—Large-scale redshift-space correlation function of the SDSS LRG sample. The error bars are from the diagonal elements of the mock-catalog co-

D. Eisenstein, et al. *ApJ* 633 560 (2005)



DESI measures distances, relative to the BAO $r_d$

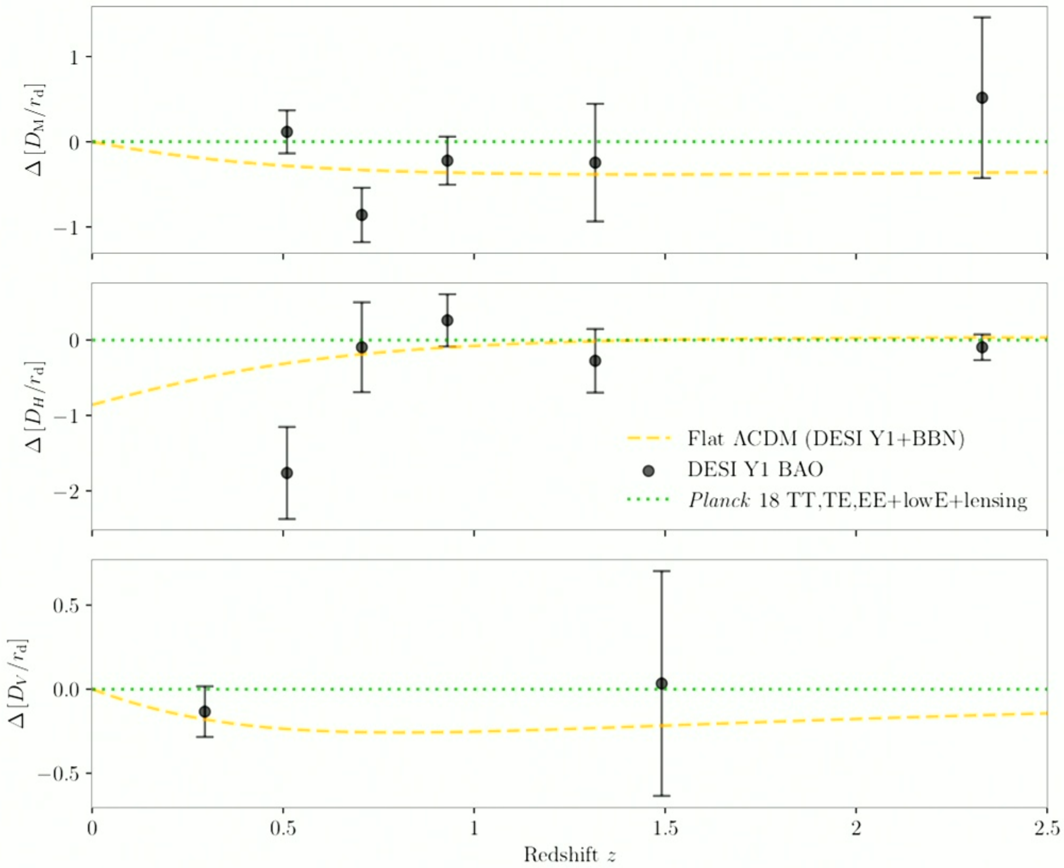



**KC**, G. Tarlé, S. Ahlen, B. Cartwright, D. Farrah, N .Fernandez, R. A. Windhorst *JCAP* (In Press, `arXiv:2404.03002`)

DESI measures distances, relative to the BAO $r_\mathrm{d}$

- Transverse: Angular diameter distance $D_\mathrm{M}$
- Line-of-sight: Hubble distance $D_\mathrm{H} := c/H(z)$
- Angle-averaged combination $D_\mathrm{V} := (zD_\mathrm{H}D_\mathrm{M}^2)^{1/3}$

**Tension?** $\sim 2\sigma$ tension

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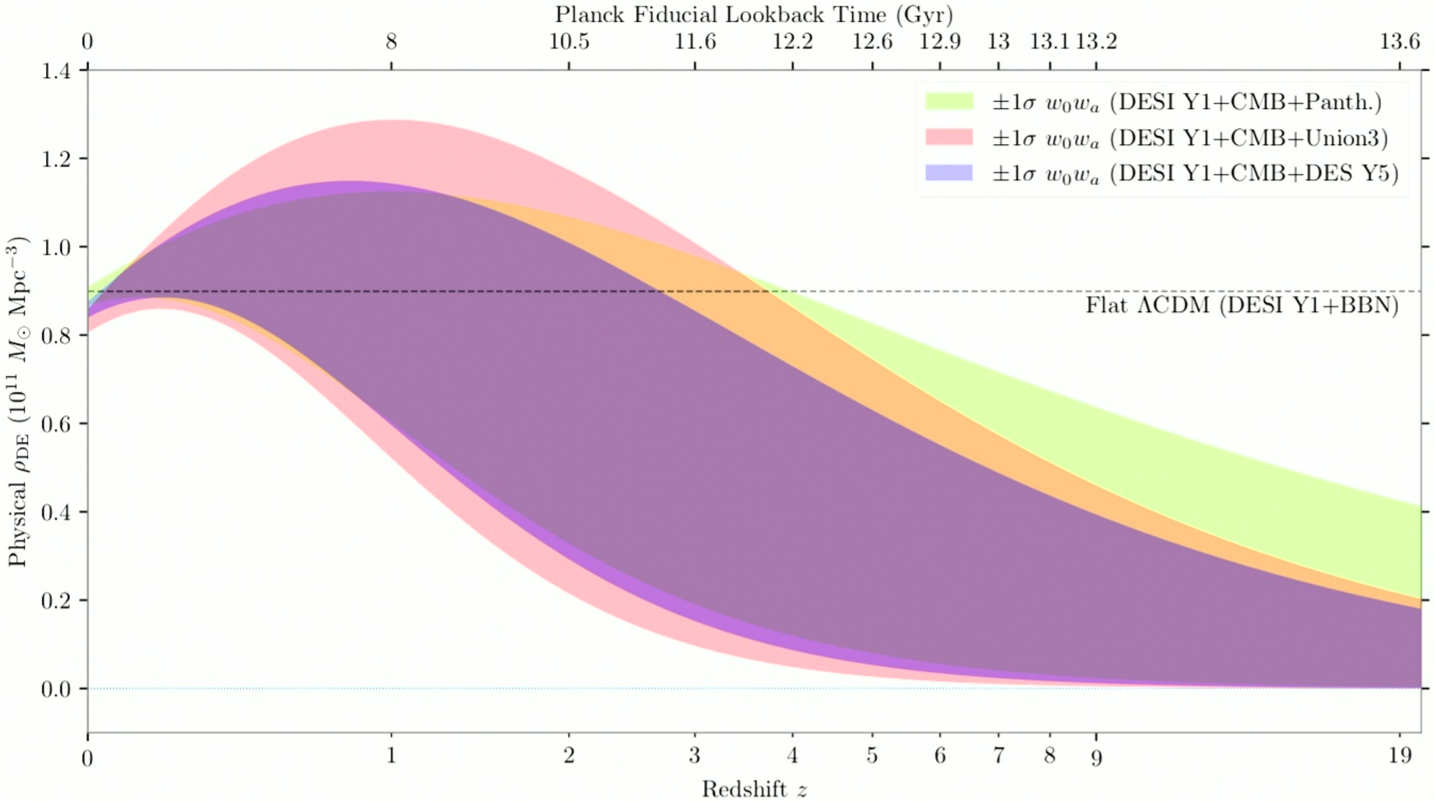
# DESI BAO + *Planck* + Supernovae: Time-dependence favored at $3.9\sigma$

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# Dark Energy from Cosmologically Coupled BHs

**Hypothesis**: all DE comes from stellar-collapse BHs

$$\rho_b := \begin{cases} \dfrac{C\omega_b^{\mathrm{proj}}}{a^3} & a < a_i \\ \dfrac{C\omega_b^{\mathrm{proj}}}{a^3} - \dfrac{\Xi}{a^3}\displaystyle\int_{a_i}^{a} \psi \frac{\mathrm{d}a'}{Ha'} & a \geqslant a_i \end{cases}$$

Evolution of DE density follows directly from conservation of stress-energy $\nabla_\mu T^\mu{}_\nu = 0$

$$\frac{\mathrm{d}\rho_{\mathrm{DE}}}{\mathrm{d}a} = \frac{\Xi}{Ha^4}\psi \qquad \rho_{\mathrm{DE}}(a_i) := 0$$

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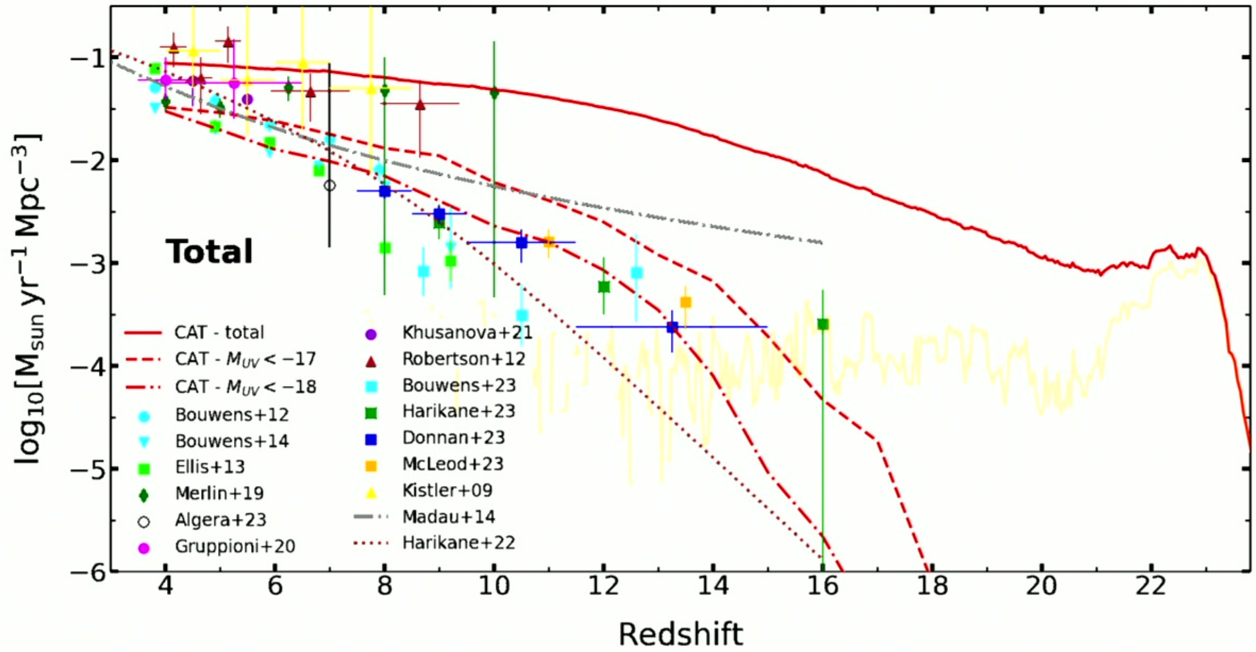
# Cosmic star-formation rate density (SFRD) $\psi$

We use Trinca, et al. for $z > 4$ SFRD

- Accounts for faint sources




Figures: A. Trinca, et al. *MNRAS* 529.4 (2024): 3563; P. Madau & M. Dickinson *ARA&A* 52 (2014): 415

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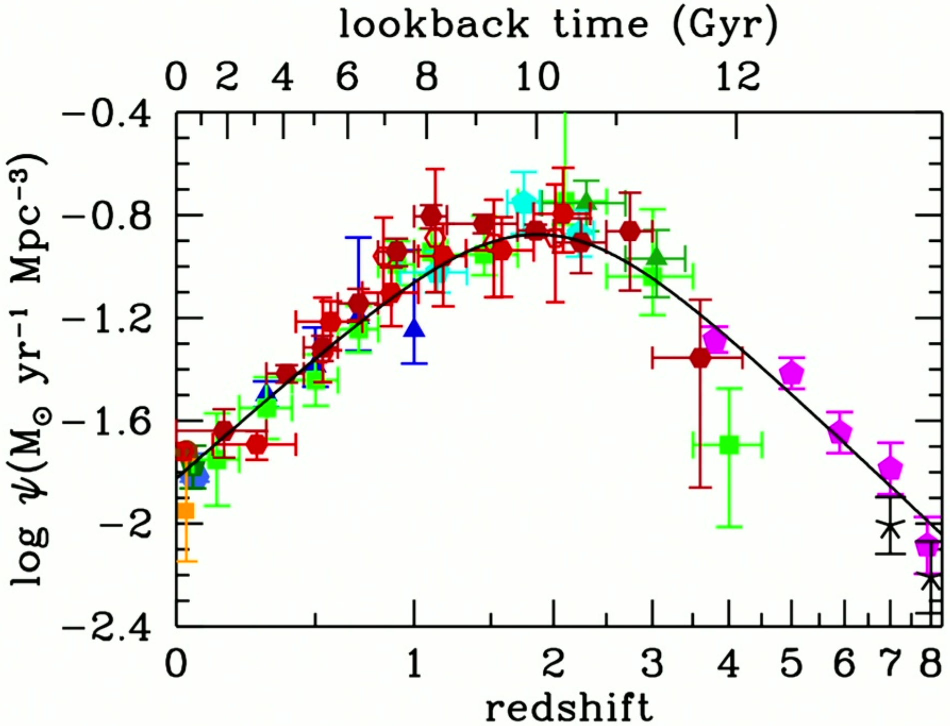
We use Trinca, et al. for $z > 4$ SFRD

- Accounts for faint sources
- Calibrated to JWST $M_{UV} < -18$

We use Madau & Dickinson for $z < 4$ SFRD

- Madau & Fragos update
- Consistent normalization via Hopkins & Beacom




Figures: A. Trinca, et al. *MNRAS* 529.4 (2024): 3563; P. Madau & M. Dickinson *ARA&A* 52 (2014): 415

# Consistent time-evolution using 2 fewer parameters than $w_0 w_a$

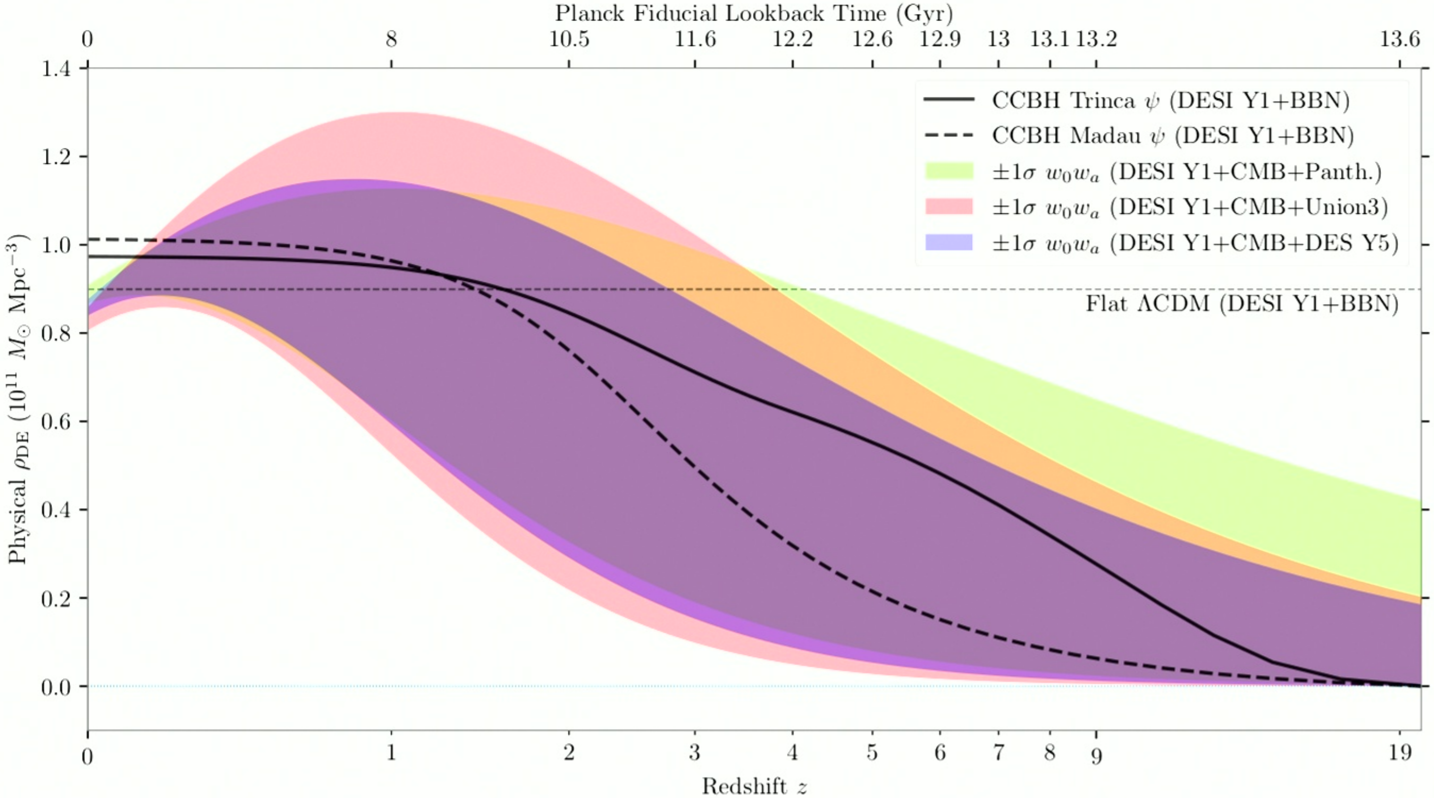
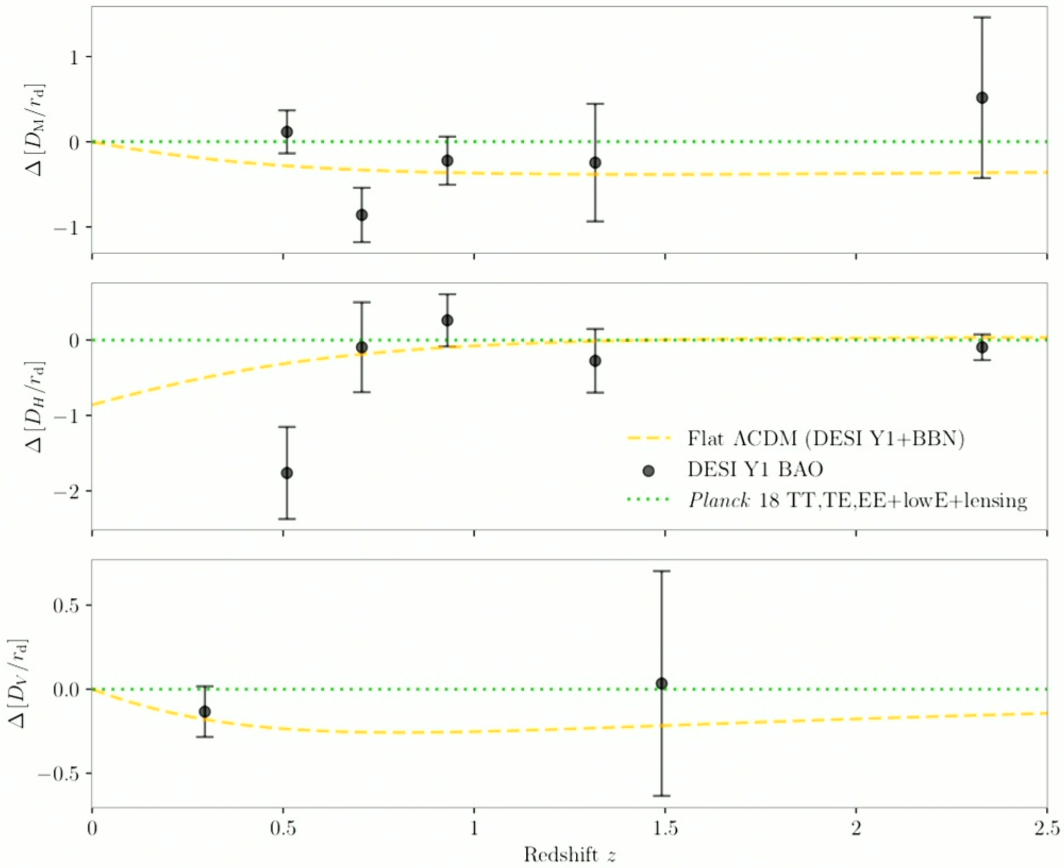



Figure: **KC**, G. Tarlé, S. Ahlen, B. Cartwright, D. Farrah, N .Fernandez, R. A. Windhorst *JCAP* (In Press, arXiv:2404.03002)

DESI measures distances, relative to the BAO $r_\mathrm{d}$

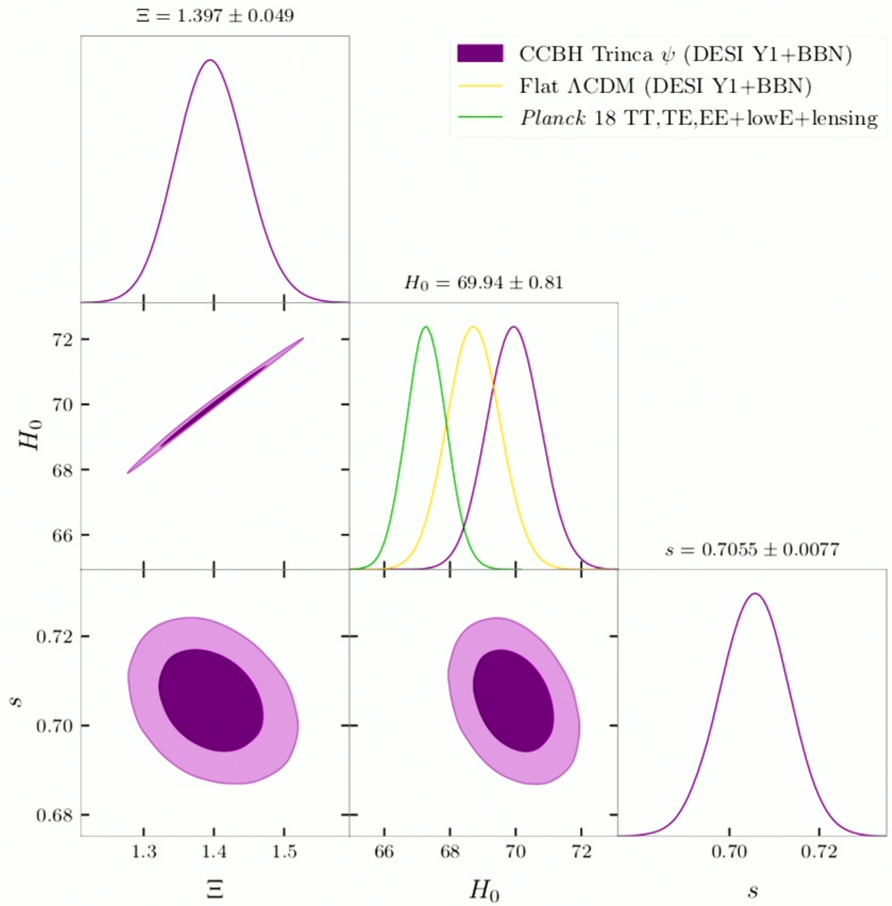
- Transverse: Angular diameter distance $D_\mathrm{M}$
- Line-of-sight: Hubble distance $D_\mathrm{H} := c/H(z)$
- Angle-averaged combination $D_\mathrm{V} := (zD_\mathrm{H}D_\mathrm{M}^2)^{1/3}$




**KC**, G. Tarlé, S. Ahlen, B. Cartwright, D. Farrah, N .Fernandez, R. A. Windhorst *JCAP* (In Press, `arXiv:2404.03002`)

Assuming a Big Bang Nucleosynthesis prior on $\omega_b^{\rm proj}$, we find

- $\Xi = 1.4$ vs. naive $\Xi = 0.4$ from Chabrier IMF $\mathrm{d}N/\mathrm{d}m \propto m^{-2.3}$
  $\implies$ some accretion, floor, or GR
- $H_0 = 69.94 \pm 0.81$ only $2.7\sigma$ $SH0ES$ tension vs. $5.6\sigma$ *Planck*




**KC**, G. Tarlé, S. Ahlen, B. Cartwright, D. Farrah, N .Fernandez, R. A. Windhorst *JCAP* (In Press, arXiv:2404.03002)

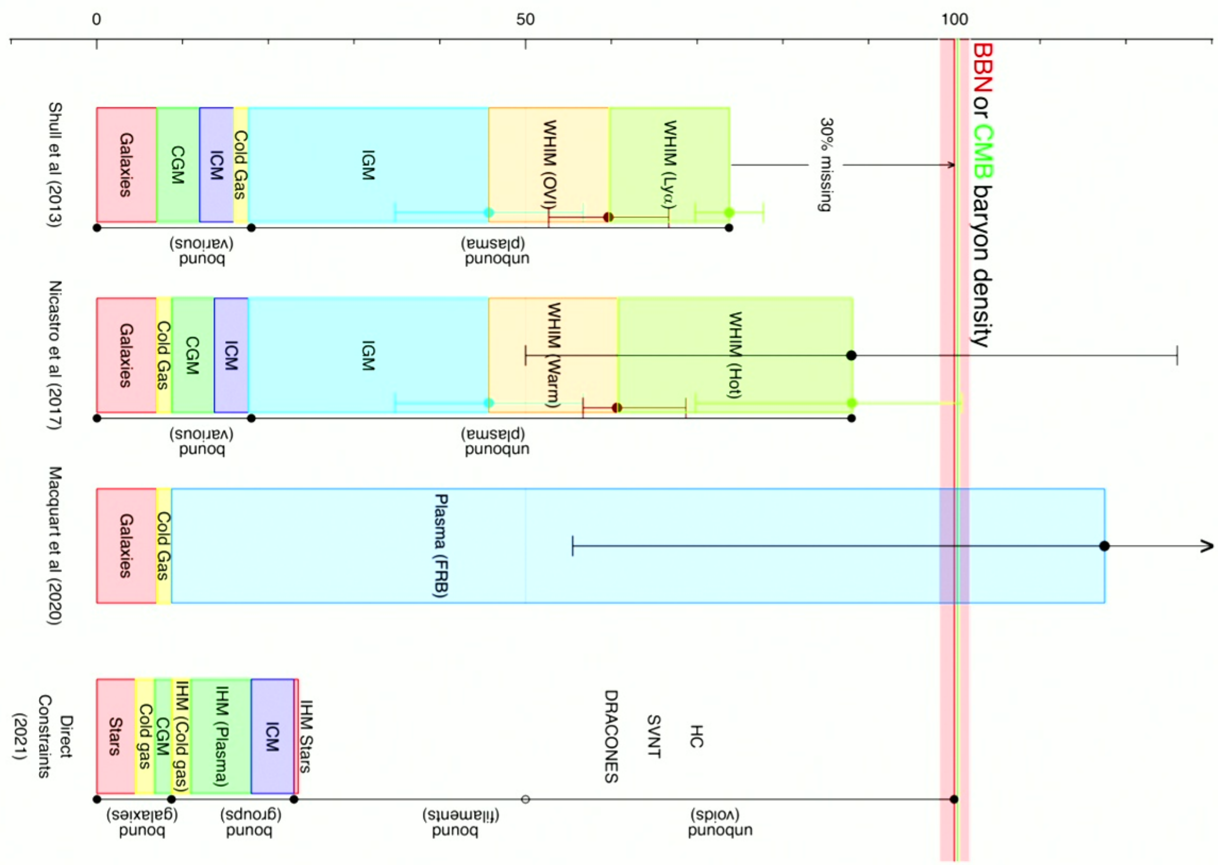



Figure: Driver, Simon. Nature Astronomy (2021) 5, 852–854

Assuming a Big Bang Nucleosynthesis prior on $\omega_b^{\text{proj}}$, we find

- $\Xi = 1.4$ vs. naive $\Xi = 0.4$ from Chabrier IMF $\mathrm{d}N/\mathrm{d}m \propto m^{-2.3}$ $\implies$ some accretion, floor, or GR
- $H_0 = 69.94 \pm 0.81$ within $0.5\%$ of Chicago-Carnegie Hubble Group Cepheid+TRGB+JAGB measurement
- $30\%$ of baryons are consumed by BHs... $\implies$ room for the summed neutrino masses to increase toward physical $\sum m_\nu > 0.059$ eV...

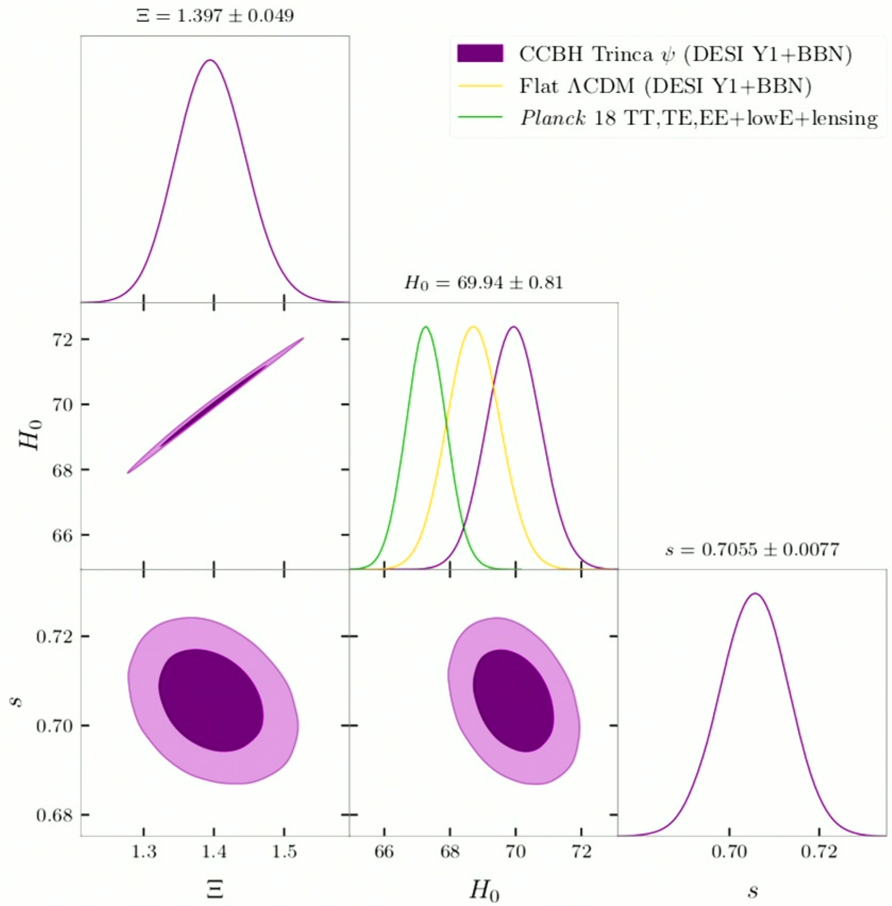
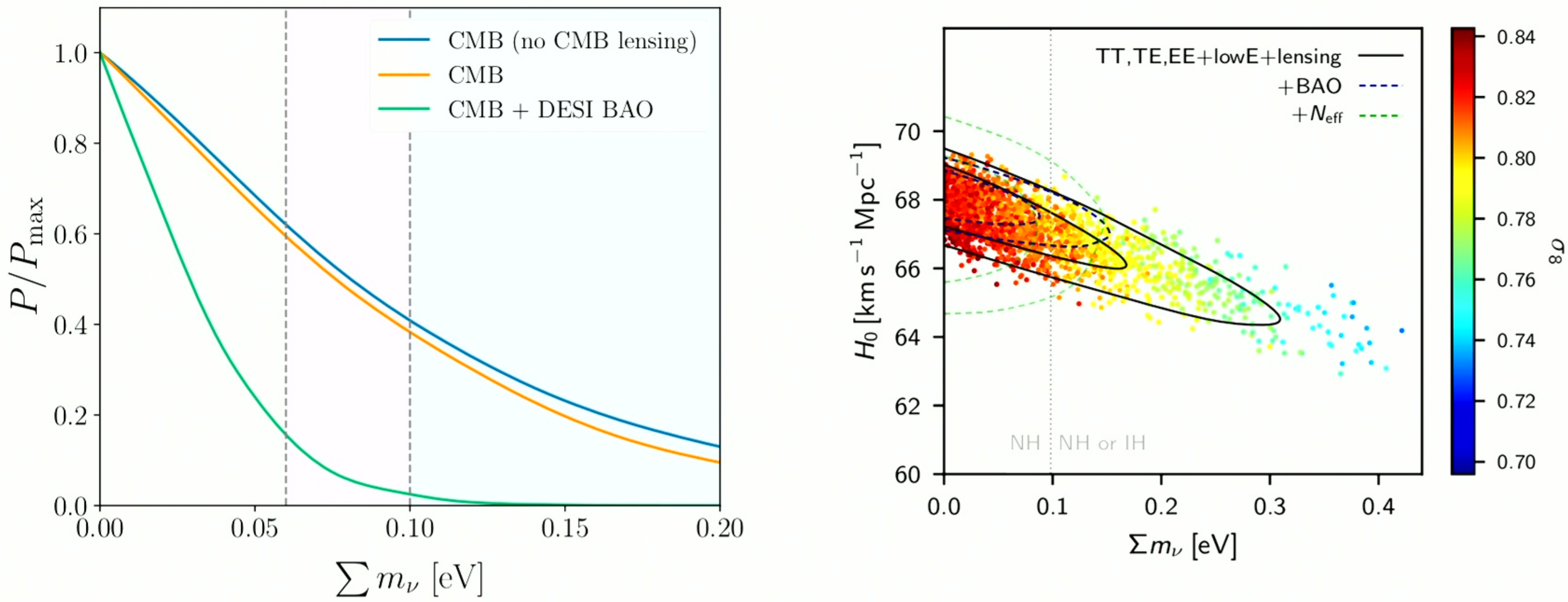



Figure: Driver, Simon. Nature Astronomy (2021) 5, 852–854

# DESI Preferred Neutrino masses are zero




Figures: DESI 2024 VI, https://arxiv.org/abs/2404.03002; Aghanim, Nabila, et al. A&A 641 (2020): A5.

# Summary

- Known BH models suggest, and Einstein's equations allow, BHs to cosmologically couple and gain mass $\propto a^k$
- Experimental evidence from multiple sources: BBH mergers, Early-type galaxies, *Gaia* BHs, pulsar-timing stochastic GW background, high-precision BAO measurements
- Preferred theoretical model ($k = 3$) for stellar-collapse BHs gives consistent $\rho_{\rm DE}$ time-dependence with data-driven SFRD
- Expansion rate $H_0 = 69.94 \pm 0.81$ decreases tension with S$H0$ES $5.6 \to 2.7\sigma$
- Baryons depleted (converted into DE) consistent with "missing baryons problem" $\sim 30\%$ and allows larger $\sum m_\nu$
- Near-term DESI data: Y1 RSD (December 2024) and Y3 release (April 2025) will sharpen the picture

Figures: DESI 2024 VI, `https://arxiv.org/abs/2404.03002`; Aghanim, Nabila, et al. A&A 641 (2020): A5.

Image: EHT Collaboration

# Cosmological equations describe effective fluids

## Lemma

*Let* $A(\mathbf{k},\eta)$ *be the Fourier transform of some field* $A(\mathbf{x},\eta)$ *that appears in* $\mathcal{L}$*. Let* $V$ *denote the support of* $A(\mathbf{k},\eta)$*. Then the Euler-Lagrange equations of motion for* $A$ *are*

$$\frac{\delta \mathcal{L}}{\delta A}(\mathbf{x},\eta) * \mathcal{F}^{-1}\left[\mathbf{1}_V\right] = 0,$$

*where* $*$ *denotes convolution,* $\mathcal{F}^{-1}$ *denotes the inverse Fourier transform, and* $\mathbf{1}$ *denotes the indicator function.*

If $A(\mathbf{x},\eta)$ is unconstrained in Fourier-space,

$$V := \operatorname{supp} A(\mathbf{k},\eta) = \mathbb{R}^3$$

Proved: **KC**, J. Weiner, & D. Farrah. *PRD* 105.8 (2022): 084042.

# Cosmological metric is Fourier constrained

By definition of the model,

$$g_{\mu\nu} := a^2(\eta)\left[\eta_{\mu\nu} \qquad\qquad\qquad\qquad \right].$$

- The zero-order dynamical DOF $a(\eta)$ only depends on time
- $\therefore$ $a$, a scalar DOF in a 3+1 dimensional theory, is subject to derivative constraint

$$\partial_j a := 0$$

- In Fourier space

$$\operatorname{supp} a(\mathbf{k}) = \{(0,0,0)\}$$

**KC** & J. Weiner. *ApJ* 882.1 (2019): 19.

# Apply the Lemma to the Einstein-Hilbert action

Gravitational DOF is unaltered by convolution:

$$\frac{\delta \mathcal{L}_{\mathrm{EH}}}{\delta a} * \mathcal{F}^{-1}\left[\mathbf{1}_{(0,0,0)}\right] \propto \int_{\mathcal{V}} \partial^{\mu}\partial_{\mu} a(\eta)\ \mathrm{d}\mathbf{x}' = -\mathcal{V}\frac{\mathrm{d}^2 a}{\mathrm{d}\eta^2}$$

but unapproximated stress-tensor DOFs are necessarily filtered by the EL convolution:

$$\frac{\delta \mathcal{L}_{M}}{\delta a} * \mathcal{F}^{-1}\left[\mathbf{1}_{(0,0,0)}\right] \propto a^3 \frac{4\pi G}{3}\int_{\mathcal{V}} T^{\mu}{}_{\mu}\left(\mathbf{x}', \eta\right)\ \mathrm{d}\mathbf{x}'$$

Trace is frame invariant $\Longrightarrow$ these are **microphysical** degrees of freedom:

$$a^3 \frac{4\pi G}{3}\left\langle \underbrace{-\rho(\mathbf{x},\eta) + \sum_i \mathcal{P}_i(\mathbf{x},\eta)}_{\text{Microphysical eigenvalues!}} \right\rangle_{\mathcal{V}} = -\frac{\mathrm{d}^2 a}{\mathrm{d}\eta^2}$$

**KC** & J. Weiner. *ApJ* 882.1 (2019): 19.