Title: Constraining Early Dark Energy with Large Scale Structure

Speakers: Evan McDonough

Series: Cosmology & Gravitation

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Abstract: The Hubble tension is conventionally viewed as that between the cosmic microwave background (CMB) and the SH0ES measurement. A prominent proposal for a resolution of this discrepancy is to introduce a new component in the early universe, which initially acts as "early dark energy" (EDE), thus decreasing the physical size of the sound horizon imprinted in the CMB and increasing the inferred H_0, bringing it into near agreement with SH0ES. However, this impacts cosmological observables beyond the CMB -- in particular, the large scale structure (LSS) of the universe across a range of redshift. The H_0 tension resolving EDE cosmologies produce scale-dependent changes to the matter power spectrum, including 10% more power at k=1 h/Mpc. Motivated by this, I will present the results of two analyses of LSS constraints on the EDE scenario. Weak lensing and galaxy clustering data (from, e.g., the Dark Energy Survey) significantly constrain the EDE model, and the resulting H_0 is in significant tension with SH0ES. Complementary to this, including data from the Baryon Oscillation Spectroscopic Survey (BOSS), analyzed using the effective field theory (EFT) of LSS, yields an EDE H_0 value that is in significant (3.6\sigma) tension with SH0ES. These results indicate that current LSS data disfavours the EDE model as a resolution of the Hubble tension, and, more generally, that the EDE model fails to restore cosmological concordance. A sensitivity forecast for EUCLID suggests that future LSS surveys can close the remaining parameter space of the model.

Constraining Early Dark Energy with Large Scale Structure

Evan McDonough
U Chicago, KICP & EFI

[Ivanov, EM, Hill, Simonovic, Toomey, Alexander, Zaldarriaga] [arXiv:2006.11235][PRD]

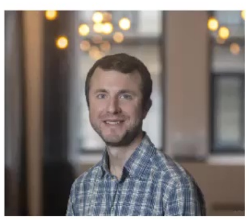
[Hill, EM, Toomey, Alexander] [arXiv:2003.07355] [PRD, Editors Suggestion]

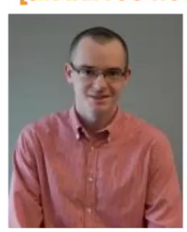
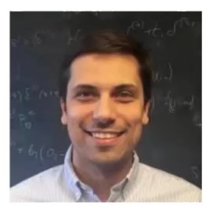
[EM, Alexander] [arXiv:1904.08912] [PLB]

Bourses postdoctorales Banting Postdoctoral Fellowships

Massachusetts Institute of Technology

"Cosmological Complementarity and the Dark Universe"



Early Dark Energy

Large Scale Structure

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EDE x LSS

Outline:

1. The Hubble Tension
2. EDE Observables beyond H0
3. EDE meets LSS
4. LSS Redux (Effective Field Theory)
5. Priors, EDE vs LCDM

See:
2003.07355: Sec. VII+App. B

VII. PRIOR DEPENDENCE

2006.11235: App. B, C

Appendix B: Likelihood profile for $f_{\rm EDE}$

Appendix C: EDE away from the ΛCDM limit 2/27

1. Best-fit EDE in fit to P18+LSS is very far from H0-resolving EDE

2. H0-resolving EDE much worse fit to data (P18+BOSS+S8) than LCDM

3. This is not all a "prior volume effect"

The Hubble tension

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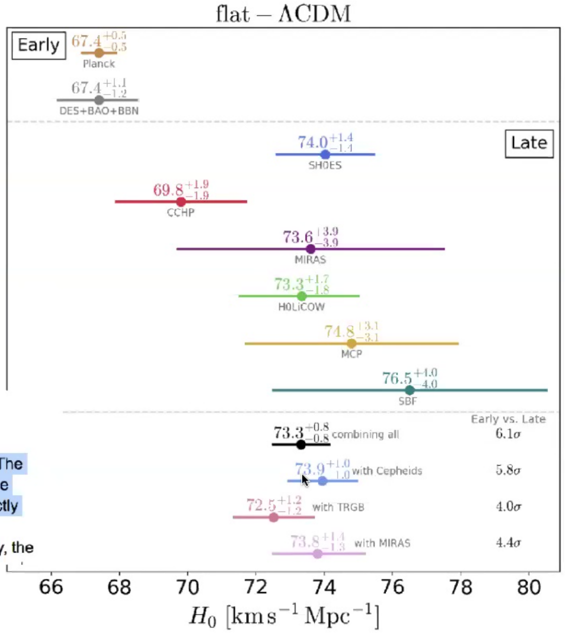
= CMB vs SH0ES? No!

Assessing Uncertainties in Hubble's Constant Across the Universe

The tension in the Hubble constant is the one of the potentially most consequential open problems of present-day astrophysics. The early-Universe H0 value inferred from high-precision measurements of the Cosmic Microwave Background (CMB) – assuming the ΛCDM concordance model – differs by 9.4 ± 2.1% (4.4σ) from the cosmology-independent present-day H0 value measured directly using a well-calibrated, empirical cosmic distance ladder composed of classical Cepheid variable stars and type-Ia supernovae (SNIa). Despite intense scrutiny, no straightforward resolutions of the Hubble tension have as yet been identified. On the contrary, the



Large Scale Structure

Combining Full-Shape and BAO Analyses of Galaxy Power Spectra: A 1.6% CMB-independent constraint on H0

Oliver H.E. Philcox (Princeton U., Astrophys. Sci. Dept.), Mikhail M. Ivanov (New York U., CCPP and Moscow, INR), Marko Simonović (CERN), Matias Zaldarriaga (Princeton, Inst. Advanced Study) (Feb 10, 2020)

Published in: *JCAP* 05 (2020) 032 • e-Print: 2002.04035 [astro-ph.CO] (Result : $H_0 = 68.6 \pm 1.1$ km/s/Mpc)

See also:
Ivanov+ 1909.05277, D'Amico+ 1909.05271, Tröster+ 1909.11006

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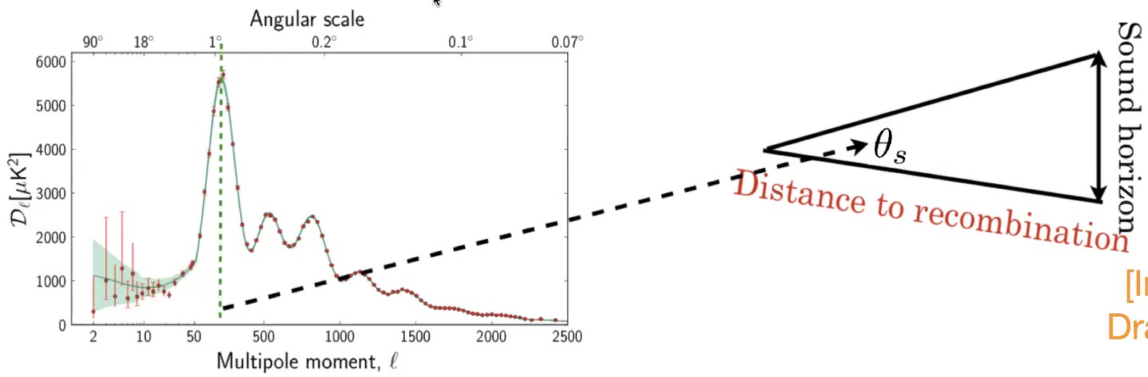
Early Universe Solutions: Appease the CMB



[Image credit: Dragan Huterer]

$$\theta_s = \frac{r_s(z_*)}{D_A(z_*)},$$

$$D_A(z_*) = \int_0^{z_*} \frac{\mathrm{d}z}{H(z)}$$

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{\mathrm{d}z}{H(z)} c_s(z)$$

Planck 2018 results. VI. Cosmological parameters

The angular acoustic scale is measured to $0.03\,\%$ precision, with $100\theta_* = 1.0411 \pm 0.0003$.

[Poulin+ 1811.04083]
[Smith+ 1908.06995]
[Walker+ 1409.0549]

Early Dark Energy

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The canonical model

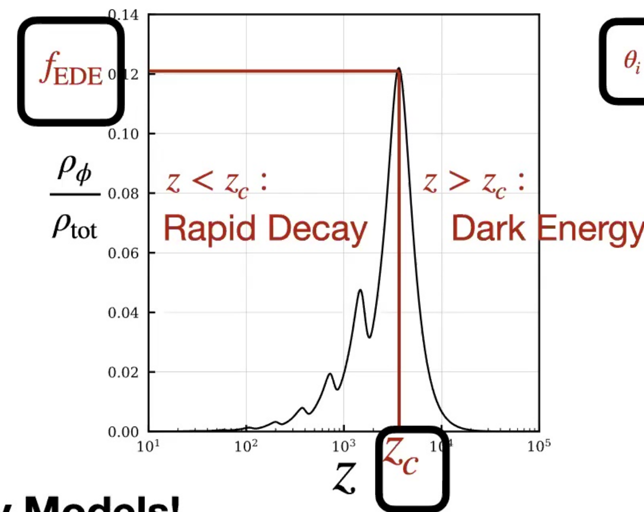
$$V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)^n$$

Ultralight: $m \sim H(z_{eq}) \sim 10^{-27}\text{eV}$

10% of the universe at $z \sim z_{eq}$: $f \lesssim M_{pl}$

Hidden from Late Universe: $n \geq 2 \;\; (w \geq 1/3)$

Parameterization



$\theta_i \equiv \frac{\phi_i}{f}$

Many Models!

Example: Trigger Field Models:

Two-field destabilization [EM, Alexander] [arXiv:1904.08912]
1st order PT [Niedermann & Sloth, 1910.10739]
Neutrinos [Sakstein & Trodden, 1911.11760)]

See also:
non-minimal coupling [Gonzalez, Mark P. Hertzberg, Rompineve]
decay into gauge fields [Ballesteros, Notari, Rompineve] [Berghaus,Karwal]

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A Recipe for the CMB

(CLASS-EDE code on GitHub)

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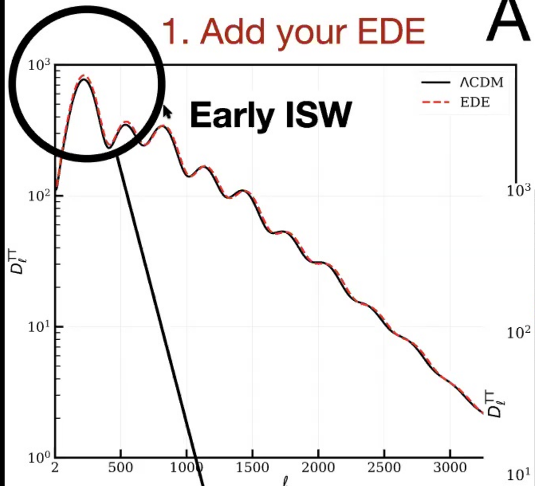
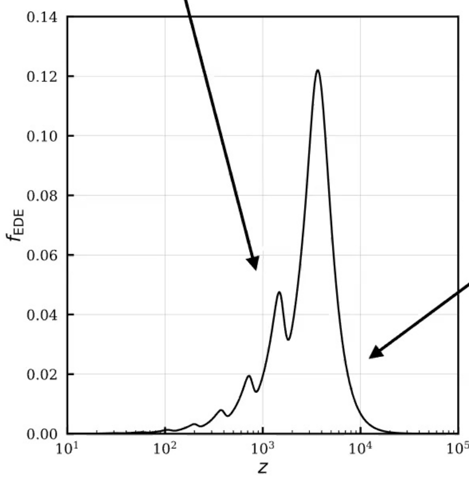
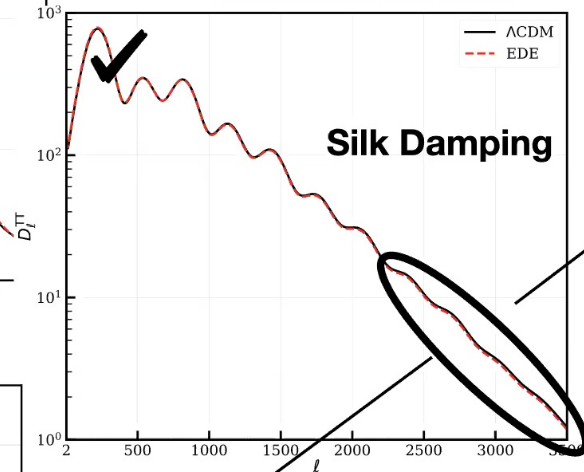
LCDM with H0=68 ,
EDE with H0=72

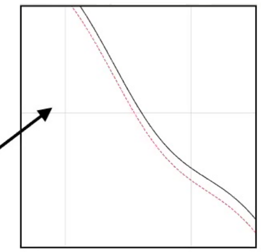
1. Add your EDE



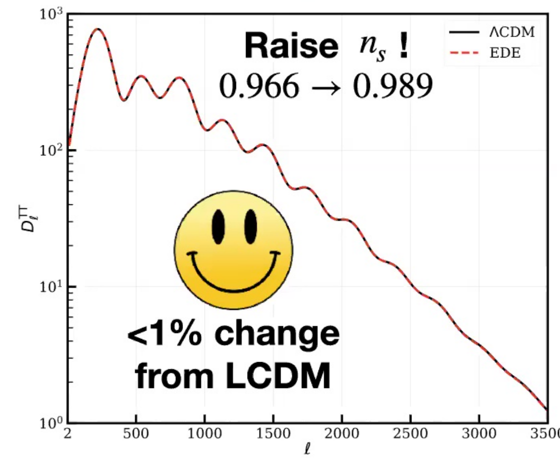


2. **Add 5% more DM**





3. Pump up small-scales



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(CLASS-EDE code on GitHub)

Large Scale Structure

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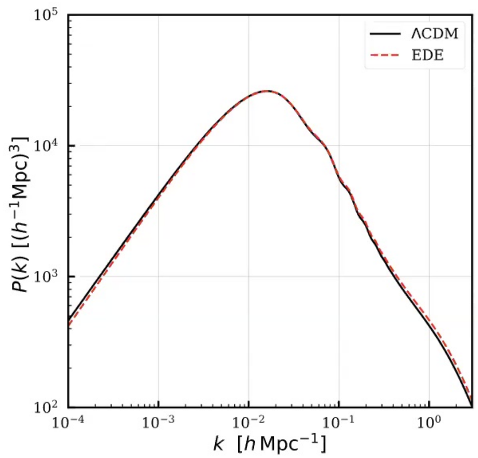
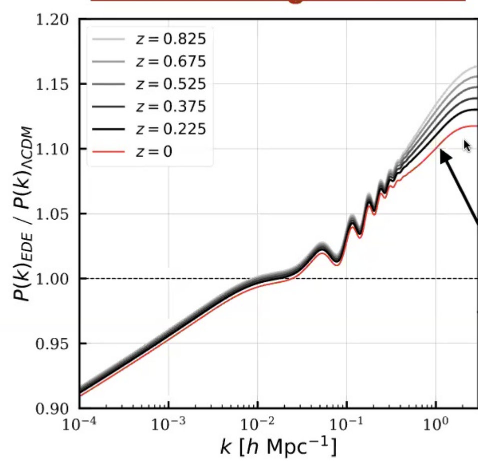
More than 1 or 2 numbers!

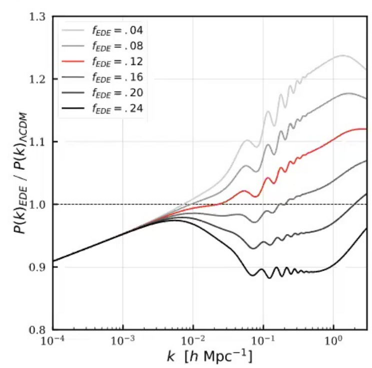
Changes in LCDM params boost P(k) on small scales.



Impact is worse at 'high' redshift



The EDE itself acts to *suppress* modes inside the horizon before EDE decays



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LSS Data
Case Study: The Dark Energy Survey

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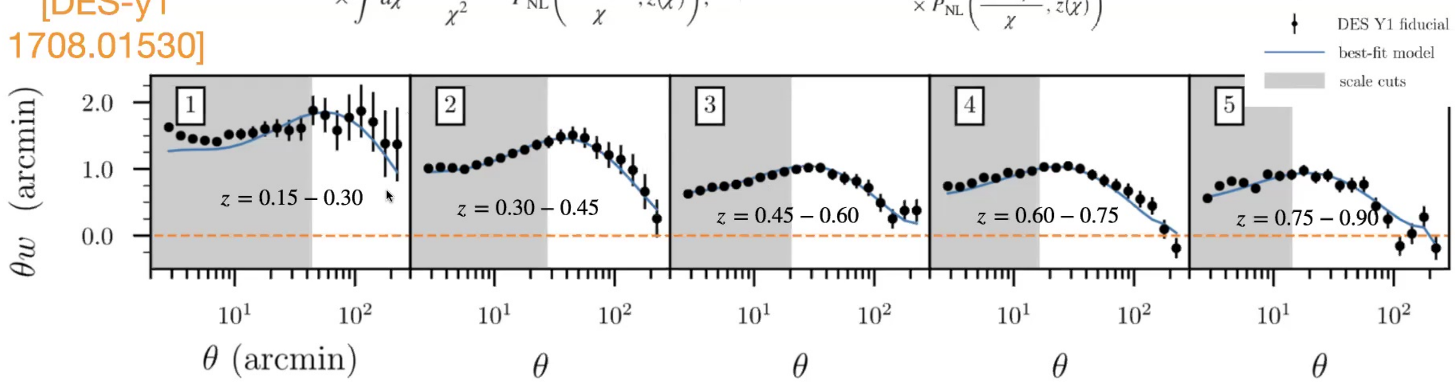
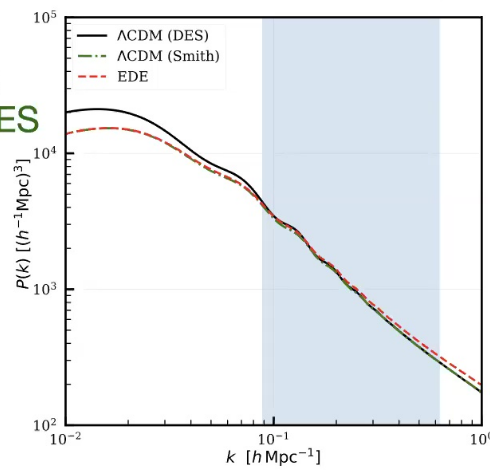
$$\xi^{ij}_{+/-}(\theta) = (1+m^i)(1+m^j)\int \frac{dll}{2\pi} J_{0/4}(l\theta) \times \int d\chi \frac{q^i_\kappa(\chi)q^j_\kappa(\chi)}{\chi^2} P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right),$$

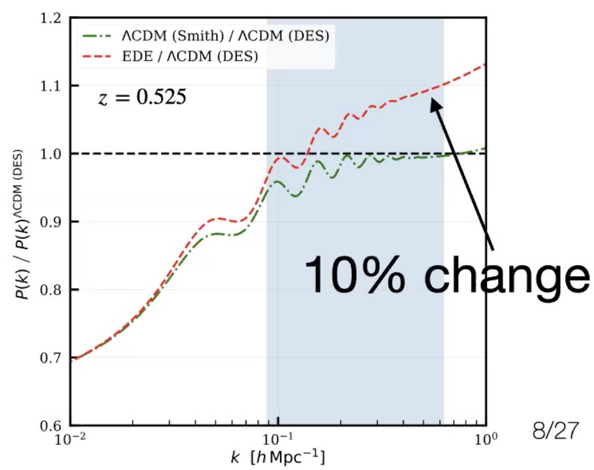
$$w^i(\theta) = \int \frac{dll}{2\pi} J_0(l\theta) \int d\chi \frac{q^i_{\delta_g}\left(\frac{l+1/2}{\chi},\chi\right) q^j_{\delta_g}\left(\frac{l+1/2}{\chi},\chi\right)}{\chi^2} \times P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right)$$

[DES-y1 1708.01530]



Compare P(k):
Inferred from DES data
LCDM fit to CMB, SH0ES
EDE fit CMB, SH0ES





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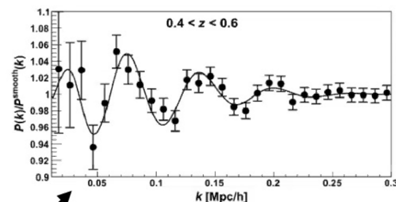
Let's get to work. Data Sets:

CMB Temperature and Polarization: Planck 2018 TT, TE, EE

Large Scale Structure:

- Planck 2018 lensing
- BAO:
  - 6dF galaxy survey
  - SDSS DR7 main galaxy sample
  - SDSS DR12 BOSS LOWZ+CMASS
- Redshift Space Distortions BOSS DR12
- Dark Energy Survey 3x2pt
- S8 from HSC, KiDS $(S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3})$

CMASS (angle averaged)



[Dodelson, Schmidt]

$$\delta_{\mathrm{g,RSD}}(\boldsymbol{k}) = \left[b_1 + f\mu_k^2\right]\delta_{\mathrm{m}}(\boldsymbol{k})$$

$$(\sigma_8)^2 = \frac{1}{2\pi^2}\int \mathrm{d}\log k\, W^2(kR)\, k^3 P(k)\,. \quad (R = 8h^{-1}\mathrm{Mpc})$$

Supernovae: Pantheon: relative luminosity of 1048 SNeIa in $0.01 < z < 2.3$

SH0ES 2019: $H_0 = 74.03 \pm 1.42\,\mathrm{km/s/Mpc}$

Priors: Follow past work, uniform EDE priors

$$f_{\mathrm{EDE}} = [0.01, 0.25] \;,\; \log_{10}(z_c) = [3.1, 4.2] \;,\; \theta_i = [0.1, 3.1]$$

[Poulin+ 1811.04083]
[Smith+ 1908.06995]

Chains available on Flatiron Servers:
https://users.flatironinstitute.org/~chill/H20_data/

Warning! Uniform EDE Priors= Effective Prior on Decay Constant

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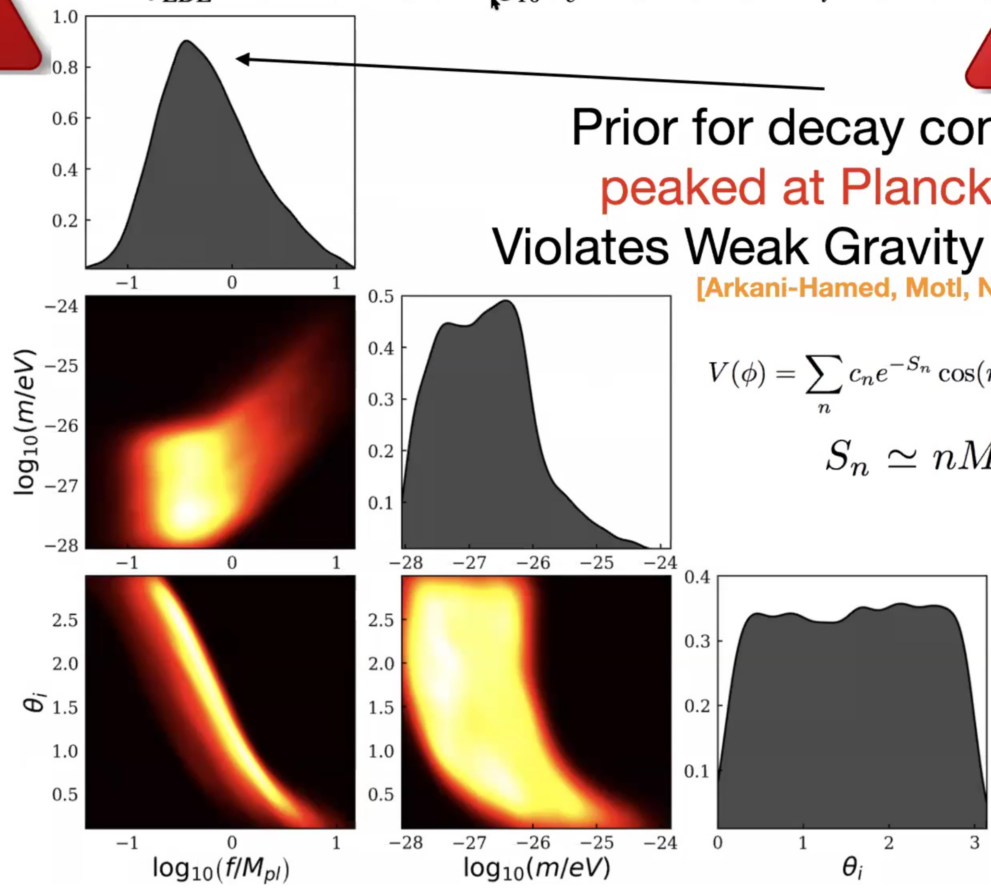
$f_{\rm EDE} = [0.01, 0.25]$, $\log_{10}(z_c) = [3.1, 4.2]$, $\theta_i = [0.1, 3.1]$



Prior for decay constant is **peaked at Planck scale**!
Violates Weak Gravity Conjecture
[Arkani-Hamed, Motl, Nicolis, Vafa]

$$V(\phi) = \sum_n c_n e^{-S_n} \cos(n\phi/f) \simeq V_0 \cos\frac{\phi}{f} + ...$$

$$S_n \simeq nM_{pl}/f$$

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What is the theory prior on f?

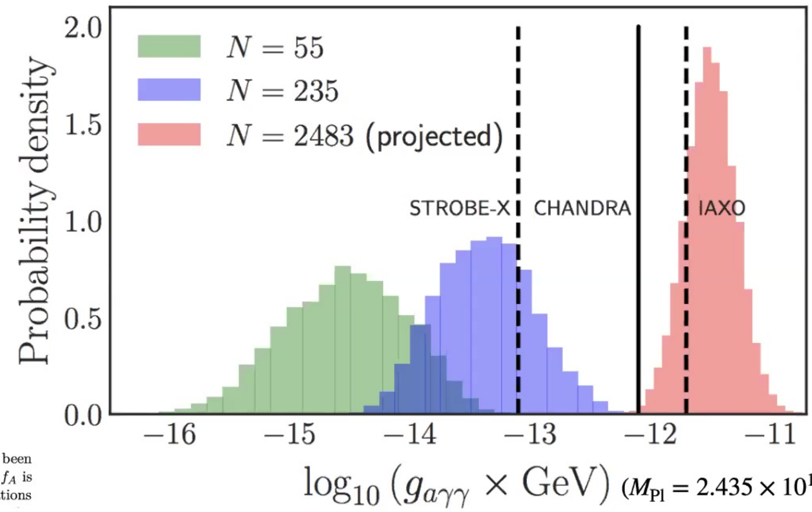
[Halverson, Long, Nelson,Salinas]
1909.05257

$$f \equiv g_{a\gamma\gamma}^{-1}$$

$$S = \int \theta F \wedge F = \int \frac{\phi}{f} F \wedge F$$

PDG:

where ϕ_A is the axion field and f_A the axion decay constant. Color anomaly factors have been absorbed in the normalization of f_A which is defined by this Lagrangian. Thus normalized, f_A is the quantity that enters all low-energy phenomena [19]. Non-perturbative topological fluctuations



$(M_{\rm Pl} = 2.435 \times 10^{18}\,\mathrm{GeV})$

study the F-theory geometry with the most flux vacua [15], which is very constrained due to the existence of only a single divisor that can support the Standard Model, given our assumptions; it yields $g_{a\gamma\gamma} = 3.47\times10^{-12}\,\mathrm{GeV}^{-1}$.

$$f \sim 10^{-6} M_{\rm Pl}$$

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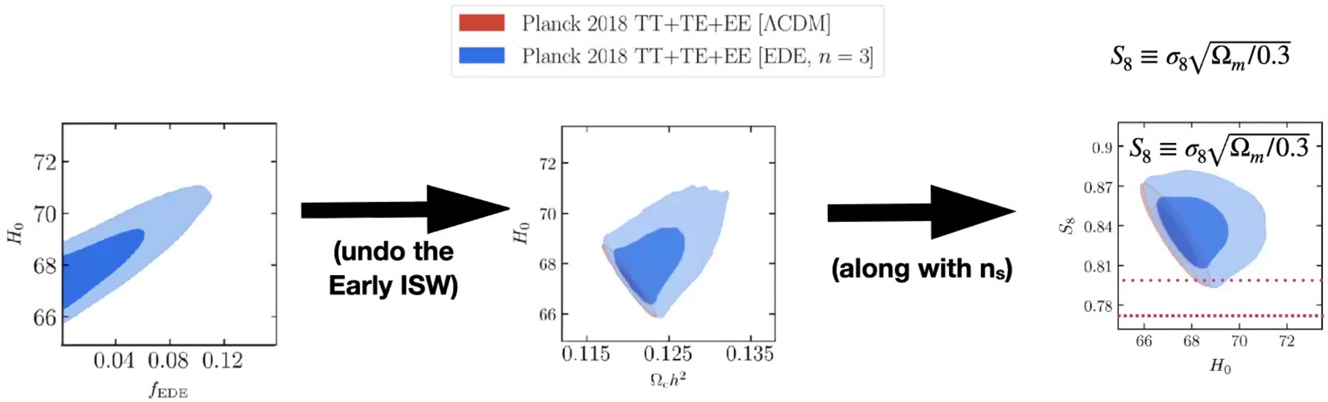
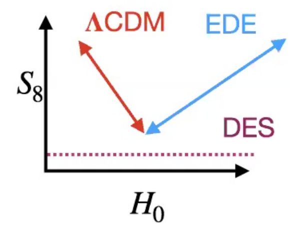
Appetizer: (The First Ever) EDE Fit To CMB:

New Degeneracies



Artists Rendering:



Chains available on Flatiron Servers:
https://users.flatironinstitute.org/~chill/H20_data/

Results: Tight Constraint, No Concordance

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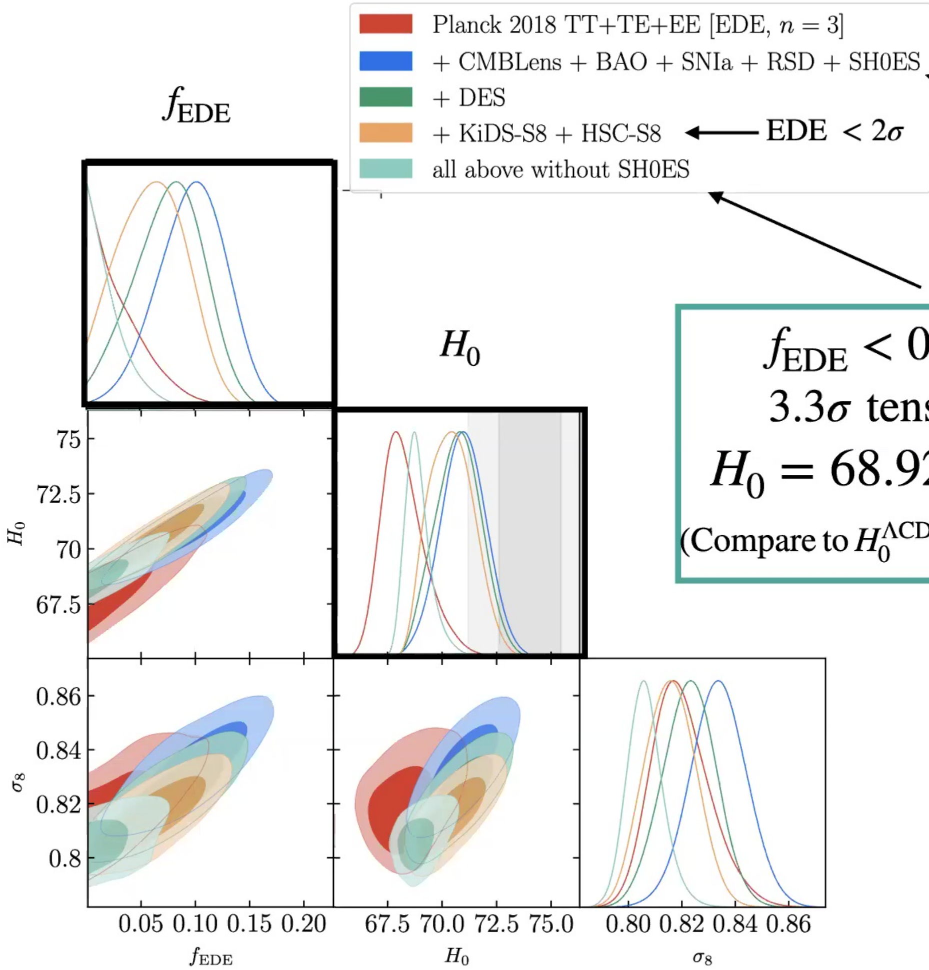

Peak "proof" of EDE:
H_0 tension $= 1.7\sigma$
$f_{\rm EDE} \sim 10\,\% > 0$ at 3.1σ

$f_{\rm EDE} < 0.060$ (95 % CL)
3.3σ tension with SH0ES
$$H_0 = 68.92^{+0.57}_{-0.59}\,\text{km/s/Mpc}$$
(Compare to $H_0^{\Lambda\rm CDM} = 68.33 \pm 0.36$ km/s/Mpc)

Chains available on Flatiron Servers:
https://users.flatironinstitute.org/~chill/H20_data/

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A more careful analysis of LSS?

Modeling of non-linear P(k):

Use of "Fitting Formulas" for Non-Linear Matter Power Spectrum?
e.g. HALOFIT, HMCODE

HALOFIT:

arXiv.org > astro-ph > arXiv:1208.2701

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 13 Aug 2012 (v1), last revised 5 Nov 2012 (this version, v2)]

Revising the Halofit Model for the Nonlinear Matter Power Spectrum

Ryuichi Takahashi, Masanori Sato, Takahiro Nishimichi, Atsushi Taruya, Masamune Oguri

Based on a suite of state-of-the-art high-resolution N-body simulations, ...

We run high-resolution N-body simulations for 16 cosmological models around the Wilkinson Microwave Anisotropy Probe (WMAP) best-fit cosmological parameters (1, 3, 5, and 7 year results), including dark energy models with a constant equation of state. ...

Calibrated to N-body simulations of LCDM!

[Note: consistency check performed for DES-y1 in EDE, see Appendix B]

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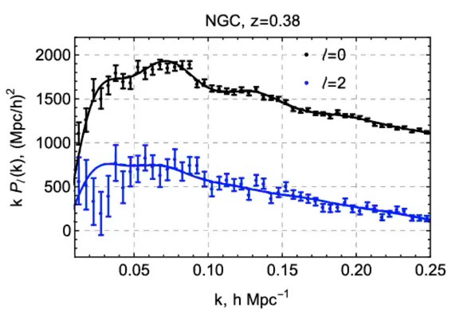
A more careful analysis of LSS?

Full Power (and Cosmology-Dependence) of BOSS Likelihood?

3D P(k) Data



Fiducial LCDM Cosmology [Planck priors on DM and baryon density]

Likelihood

sdss_DR12Consensus_FS-txt.txt

```
0.38 1528.65  DM_over_rs
0.38 81.2369  bao_Hz_rs
0.38 0.502242 f_sigma8
0.51 2007.41  DM_over_rs
0.51 88.3372  bao_Hz_rs
0.51 0.459128 f_sigma8
0.61 2274.01  DM_over_rs
0.61 95.5946  bao_Hz_rs
0.61 0.419163 f_sigma8
```

+ covariances, etc.

$$\delta_{\mathrm{g,RSD}}(\boldsymbol{k}) = \left[b_1 + f\mu_k^2\right]\delta_{\mathrm{m}}(\boldsymbol{k}) \longrightarrow f\sigma_8$$

$$f = \frac{d\ln D}{d\ln a}$$

$$(\sigma_8)^2 = \frac{1}{2\pi^2}\int d\log k\, W(kR)^2 k^3 P_{\mathrm{lin}}(k)$$

$R = 8h^{-1}\mathrm{Mpc}$

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The Effective Field Theory of Large Scale Structure "EFT of LSS"

[Carrasco, Hertzberg, Senatore, 1206.2926]
[Baumann, Nicolis, Senatore, Zaldarriaga, 1004.2488]

$$\langle [\tau^{ij}]_\Lambda \rangle_{\delta_l} = p_b \delta^{ij} + \rho_b \left[c_s^2 \delta_l \delta^{ij} - \frac{c_{bv}^2}{Ha} \delta^{ij} \partial_k v_l^k - \frac{3}{4} \frac{c_{sv}^2}{Ha} \left(\partial^j v_l^i + \partial^i v_l^j - \frac{2}{3} \delta^{ij} \partial_k v_l^k \right) \right] + \dots$$

$$\eta = 3\rho_b c_{sv}^2/(4H), \;\; \zeta = \rho_b c_{bv}^2 / H$$

[Philcox, Ivanov, Simonovic, Zaldarriaga] [2002.04035]

Nuisance Parameters, marginalized over in Bayesian analysis

$$\delta_g(\boldsymbol{x}) = b_1 \delta(\boldsymbol{x}) + \frac{b_2}{2} \delta^2(\boldsymbol{x}) + b_{\mathcal{G}_2} \mathcal{G}_2(\boldsymbol{x})$$

$$P_{g,\ell}(k) \equiv \frac{2\ell+1}{2} \int_{-1}^{1} d\mu \, P_g(k,\mu) \mathcal{P}_\ell(\mu) \,,$$

$$P_{g,\ell}(k) = P_{g,\ell}^{\text{tree}}(k) + P_{g,\ell}^{1-\text{loop}}(k) + P_{g,\ell}^{\text{noise}}(k) + P_{g,\ell}^{\text{ctr}}(k) \,.$$

Recent Successes:

1. CMB-independent measurement of DM density, H_0 ← vs DES+BAO+BBN: Swap DES for BOSS-FS
2. Neutrino Masses

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[Ivanov, Simonovic. Zaldarriaga, 1909.05277]
[D'Amico+1909.05271]

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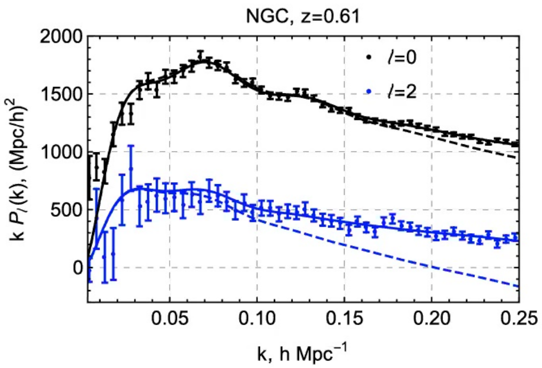
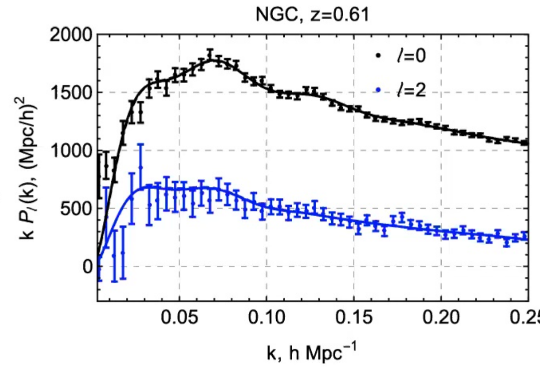
EDE Meets BOSS Data

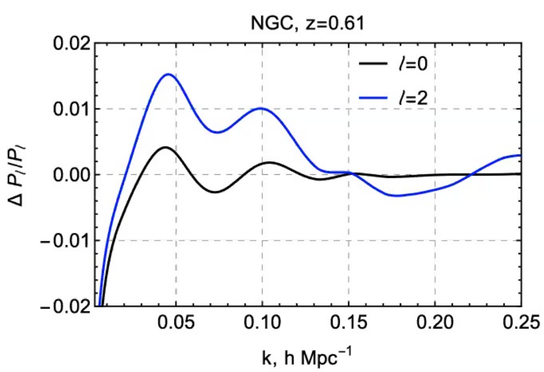


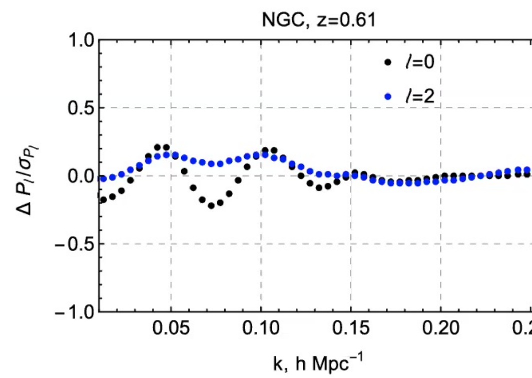
Best-fit
EFT params →



Note: $\theta_{BAO} = r_s(z_*)/D_V(z_{\rm gal})$

EDE vs LCDM: $\Delta\chi^2_{{\rm NGC},z=0.61} \sim 2.1$ $\Delta\chi^2_{\rm tot} \sim 2.5$





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Results: Planck + BOSS Data

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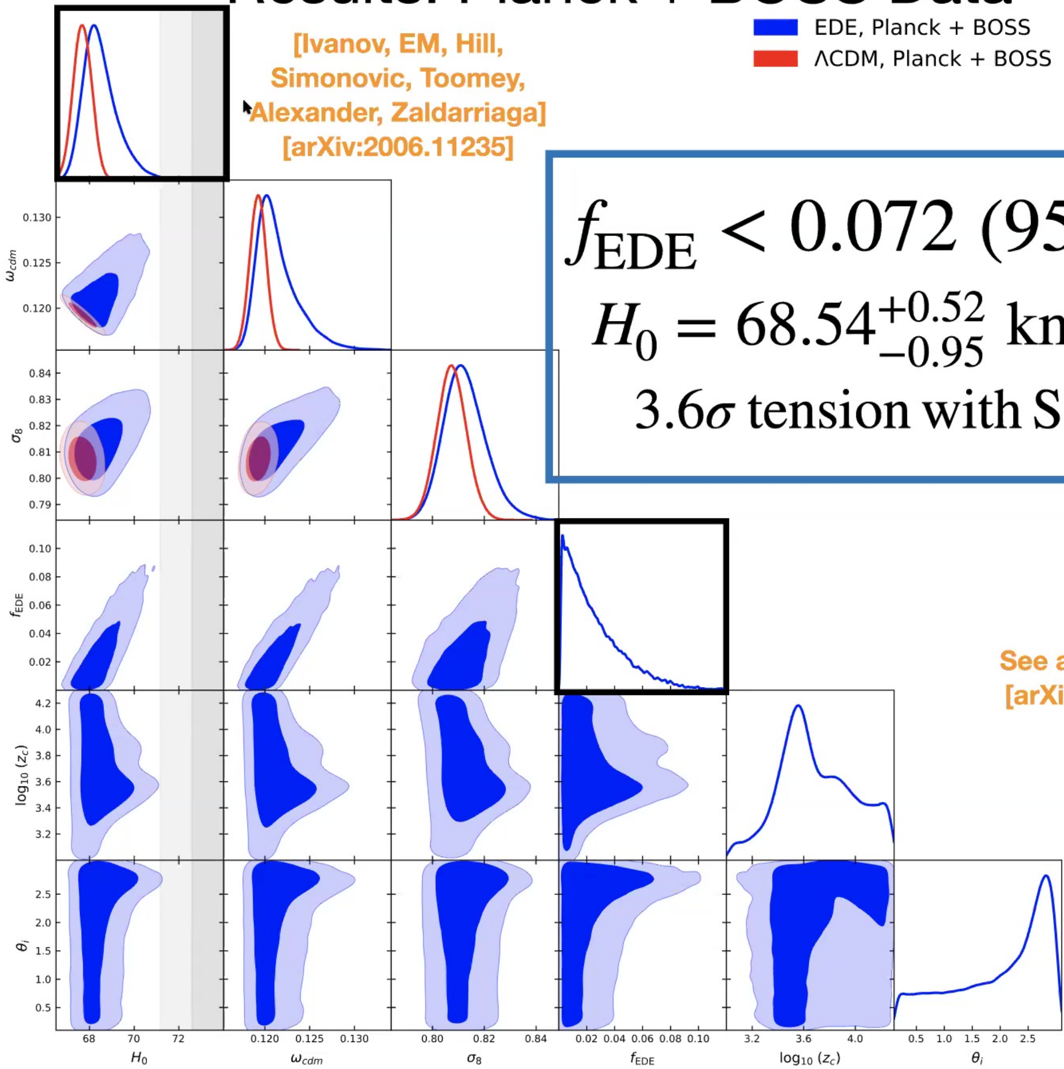
[Ivanov, EM, Hill, Simonovic, Toomey, Alexander, Zaldarriaga] [arXiv:2006.11235]



$$f_{\rm EDE} < 0.072 \ (95\,\%\ {\rm CL})$$

$$H_0 = 68.54^{+0.52}_{-0.95} \ {\rm km/s/Mpc}$$

3.6σ tension with SH0ES

See also D'Amico+ [arXiv:2006.12420]

Compare EFT vs no EFT

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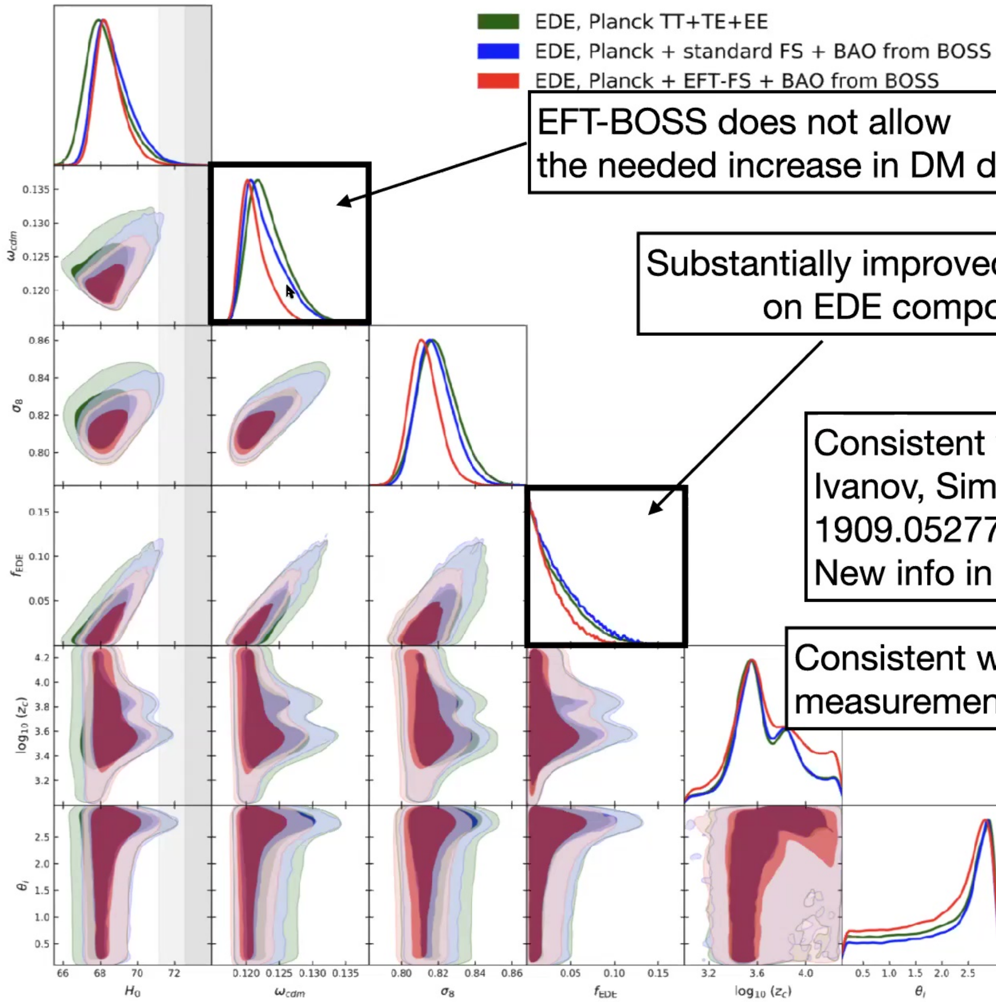

EFT-BOSS does not allow the needed increase in DM density

Substantially improved constraint on EDE component

Consistent with Ivanov, Simonovic, Zaldarriaga 1909.05277: New info in FS is DM density

Consistent with BOSS+BBN measurement of H_0 (2002.04035)

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Results 2: BOSS Data + S8 from DES, HSC, KiDS

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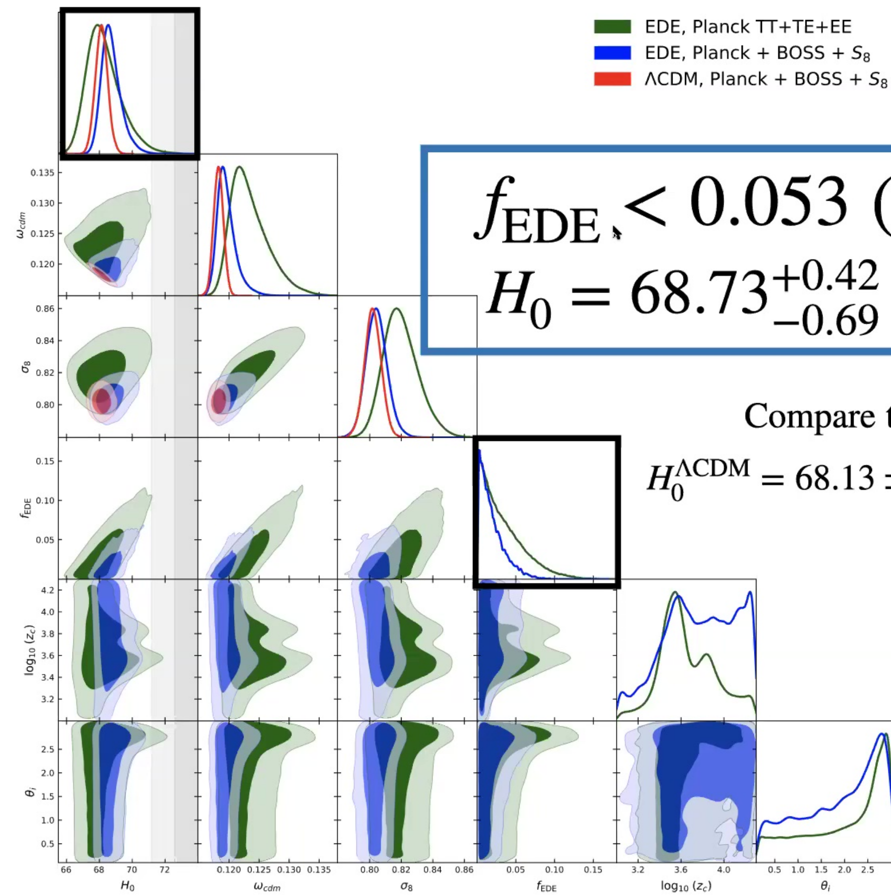

$$f_{\rm EDE} < 0.053 \; (95\,\%\,\mathrm{CL})$$

$$H_0 = 68.73^{+0.42}_{-0.69} \; \mathrm{km/s/Mpc}$$

Compare to ΛCDM :

$$H_0^{\Lambda\mathrm{CDM}} = 68.13 \pm 0.38 \; \mathrm{km/s/Mpc}$$

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2019 and 2020 in Priors

[Submitted on 17 Jul 2019 (v1), last revised 26 Jun 2020 (this version, v2)]

New physics in light of the H_0 tension: an alternative view

Sunny Vagnozzi

models the H_0 tension is addressed due to larger uncertainties rather than a genuine shift in the central value of H_0. What happens if a physical theory is able to fix the extra parameters to a specific set of non-standard values? The

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New Early Dark Energy

Florian Niedermann, Martin S. Sloth

$$V(\psi,\phi) = \frac{\lambda}{4}\psi^4 + \frac{1}{2}\beta M^2\psi^2 - \frac{1}{3}\alpha M\psi^3 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}\tilde{\lambda}\phi^2\psi^2\,,$$

=6 parameter model

The cosmological parameters are then extracted with the Monte Carlo Markov Chain code `MontePython` [39, 40], employing a Metropolis-Hastings algorithm. Compared to ΛCDM we introduce two new parameters: the fraction of NEDE before the decay, $f_{\rm NEDE} = \bar{\rho}^*_{\rm NEDE}/\bar{\rho}(t_*)$, and the logarithm of the mass of the trig-

[Submitted on 11 Jun 2020 (v1), last revised 4 Jul 2020 (this version, v2)]

Resolving the Hubble Tension with New Early Dark Energy

Florian Niedermann, Martin S. Sloth

In order to get around this technical obstruction, we perform a two-step analysis where we first vary both m and $f_{\rm NEDE}$ to obtain the best-fit values (which are of course not affected by this volume effect). Then we perform a second run where we fix m close to its best-fit value and only vary $f_{\rm NEDE}$.

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2019 and 2020 in Priors

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Resolving the Hubble Tension with New Early Dark Energy

Florian Niedermann, Martin S. Sloth

[Submitted on 22 Sep 2020]

The early dark energy resolution to the Hubble tension in light of weak lensing surveys and lensing anomalies

Riccardo Murgia, Guillermo F. Abellán, Vivian Poulin

however, we have been considering a phenomenological model whose primary characteristics is to have enough freedom to extract information from the data to resolve the tension – we will therefore make use of that information and fix Θ_i & $\mathrm{Log}_{10}(z_c)$ to their best fit value from PLANCK data only – which, we recall, are close-

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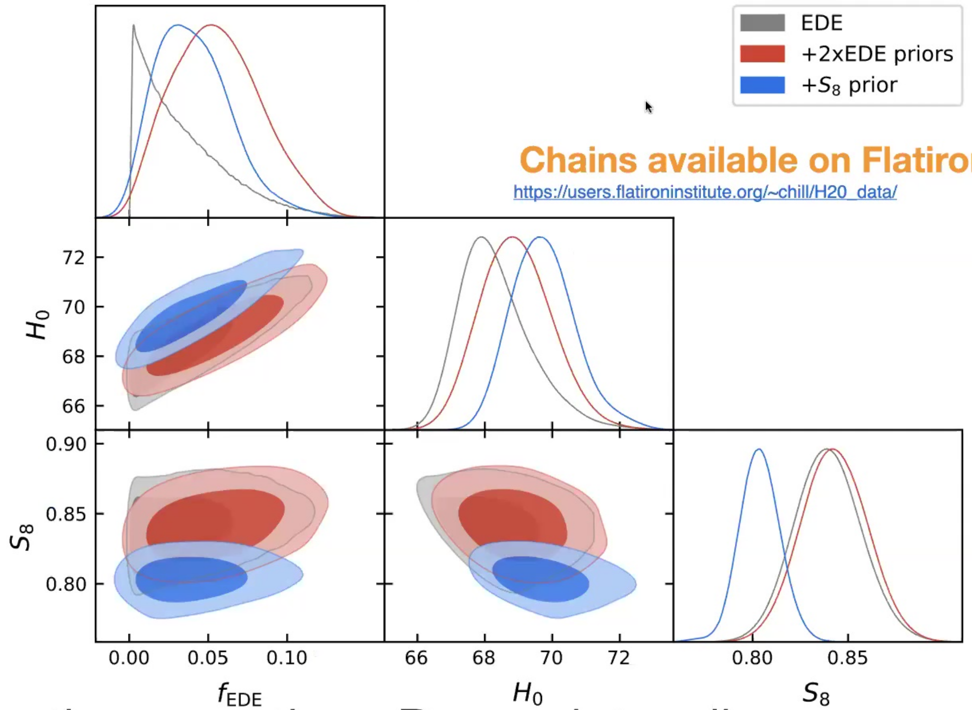
“Discovering” EDE in Planck (by reverse-engineering priors)

Fix z_c, θ_i to their best-fit values



Chains available on Flatiron Servers:

https://users.flatironinstitute.org/~chill/H20_data/

Begs the question: Does data allow or even prefer EDE?

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EDE vs LCDM

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1. Best-fit EDE not close to resolving H0:

$$f_{\rm EDE}^{\rm Best-Fit} = 1\,\% \text{ , need } 10\,\%$$

2. H0-resolving EDE is much worse fit to data than LCDM:

$$\Delta\chi^2 = +\,6.48$$

3. Constraints are not driven by prior-volume effects (which punish fine-tuning)

EDE vs LCDM

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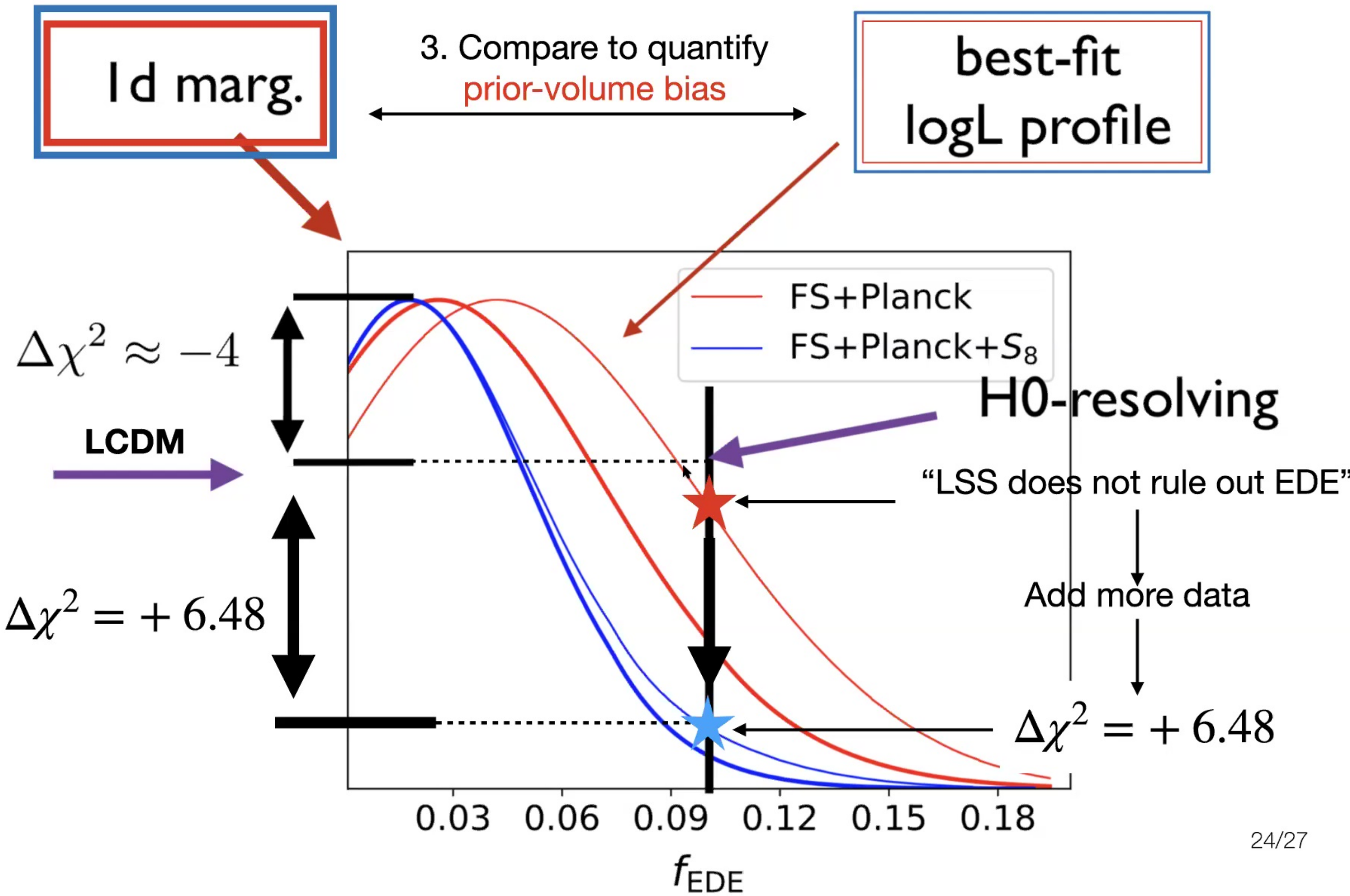
1. Best-fit EDE (fEDE=0.01) not close to resolving H0
2. H0-resolving EDE is much worse fit to data than LCDM: $\Delta\chi^2 = +6.48$



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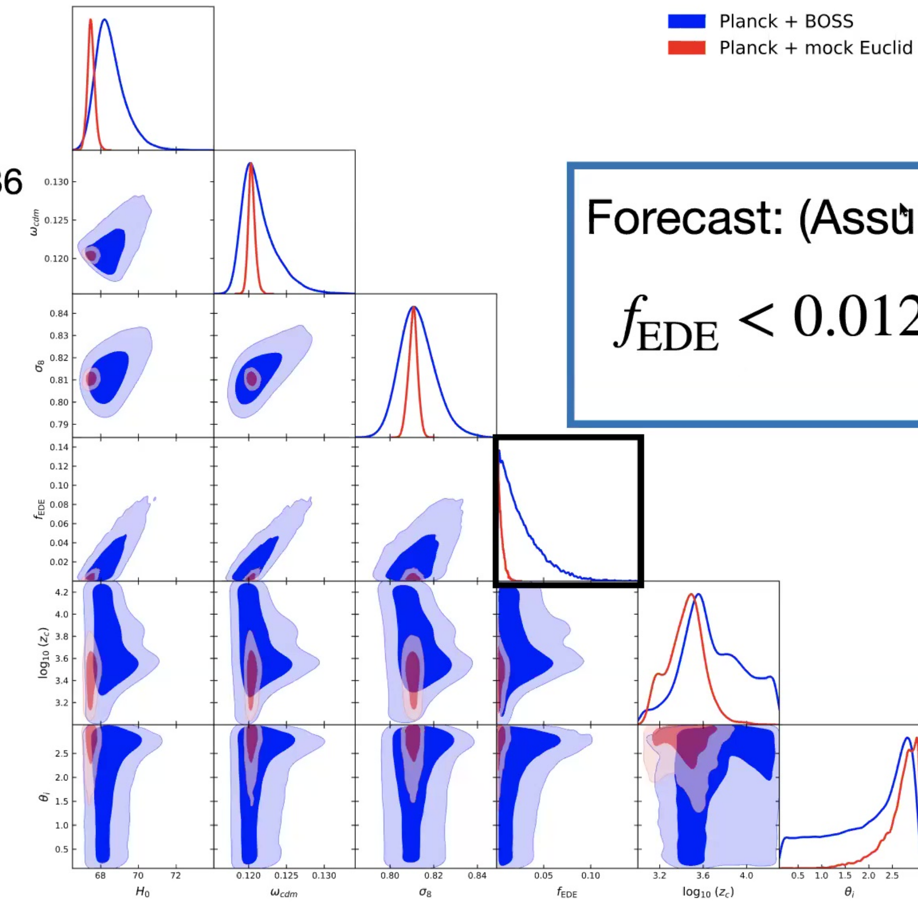
LSS: The Next Generation
Forecast for Euclid

Euclid:
5 x 10^7 galaxies,

8 redshift bins:
$0.5<z<2.1$

Sky fraction=0.3636

Total volume=
= 10 x BOSS
= 70 $(Gpc/h)^3$



Forecast: (Assuming LCDM)

$$f_{\rm EDE} < 0.012 \; (95\,\%\,{\rm CL})$$

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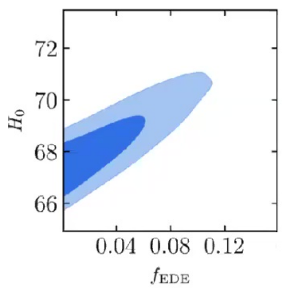
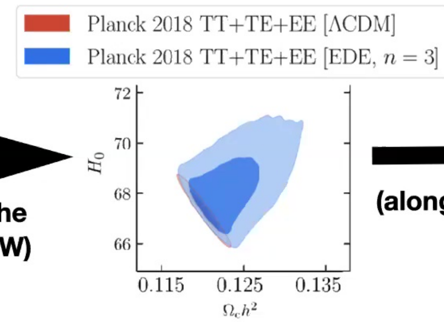
Summary

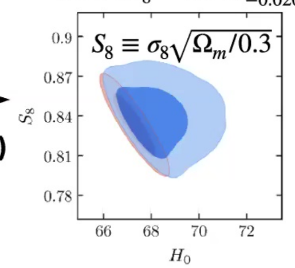


(undo the Early ISW)

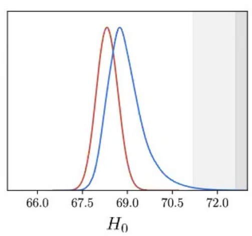


(along with n_s)

$$\mathrm{DES}: S_8 = 0.773^{+0.026}_{-0.020}$$



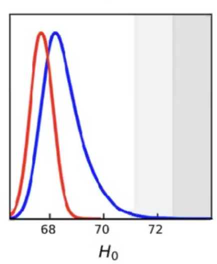
What say ye, Large Scale Structure?



P18 + CMBLens + BAO + SNIa + RSD + DES + KiDS-S8 + HSC-S8 [ΛCDM]
P18 + CMBLens + BAO + SNIa + RSD + DES + KiDS-S8 + HSC-S8 [EDE, $n=3$]

$$H_0 = 68.96^{+0.55}_{-0.58}\ \mathrm{km/s/Mpc}$$
3.3σ tension with SH0ES

[Hill, EM, Toomey, Alexander] [arXiv:2003.07355]



EDE, Planck + BOSS (EFT)
ΛCDM, Planck + BOSS (EFT)

$$H_0 = 68.54^{+0.52}_{-0.95}\ \mathrm{km/s/Mpc}$$
3.6σ tension with SH0ES

[Ivanov, EM, Hill, Simonovic, Toomey, Alexander, Zaldarriaga] [arXiv:2006.11235]

See also D'Amico+ [arXiv:2006.12420]

<u>LSS breaks the degeneracies of the EDE model</u>

See also Jedamzik, Pogosian, Zhao arXiv: 2010.04158

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Where to go from here?

Ways forward for the Hubble tension:

- Early+Late Hybrid Resolutions
- Interacting Dark Sectors

Apply New Technology to **Ultralight Axion Dark Matter**
(e.g. Constraint on fraction of DM)

LSS Constraints on BSM Physics