Cosmological Tensions Lecture 4
Other tensions and challenges for ΛCDM

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Beyond the Hubble tension

The Hubble tension is not the only "issue" ($\geq 2\sigma$) with ΛCDM

ELSEVIER

New Astronomy Reviews

Volume 95, December 2022, 101659

Challenges for ΛCDM: An update

L. Perivolaropoulos, F. Skara

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Journal of High Energy Astrophysics

Volume 34, June 2022, Pages 49-211

Review

Cosmology intertwined: A review of the particle physics, astrophysics, and cosmology associated with the cosmological tensions and anomalies

Elcio Abdalla [a], Guillermo Franco Abellán [b], Amin Aboubrahim [c], Adriano Agnello [d], Özgür Akarsu [e], Yashar Akrami [f g h i], George Alestas [j], Daniel Aloni [k], Luca Amendola [l], Luis A. Anchordoqui [m n o], Richard I. Anderson [p], Nikki Arendse [q], Marika Asgari [r s], Mario Ballardini [t u v w], Vernon Barger [x], Spyros Basilakos [y z], Ronaldo C. Batista [aa], Elia S. Battistelli [ab ac], Richard Battye [ad], Micol Benetti [ae af]...Miguel Zumalacárregui [gw]

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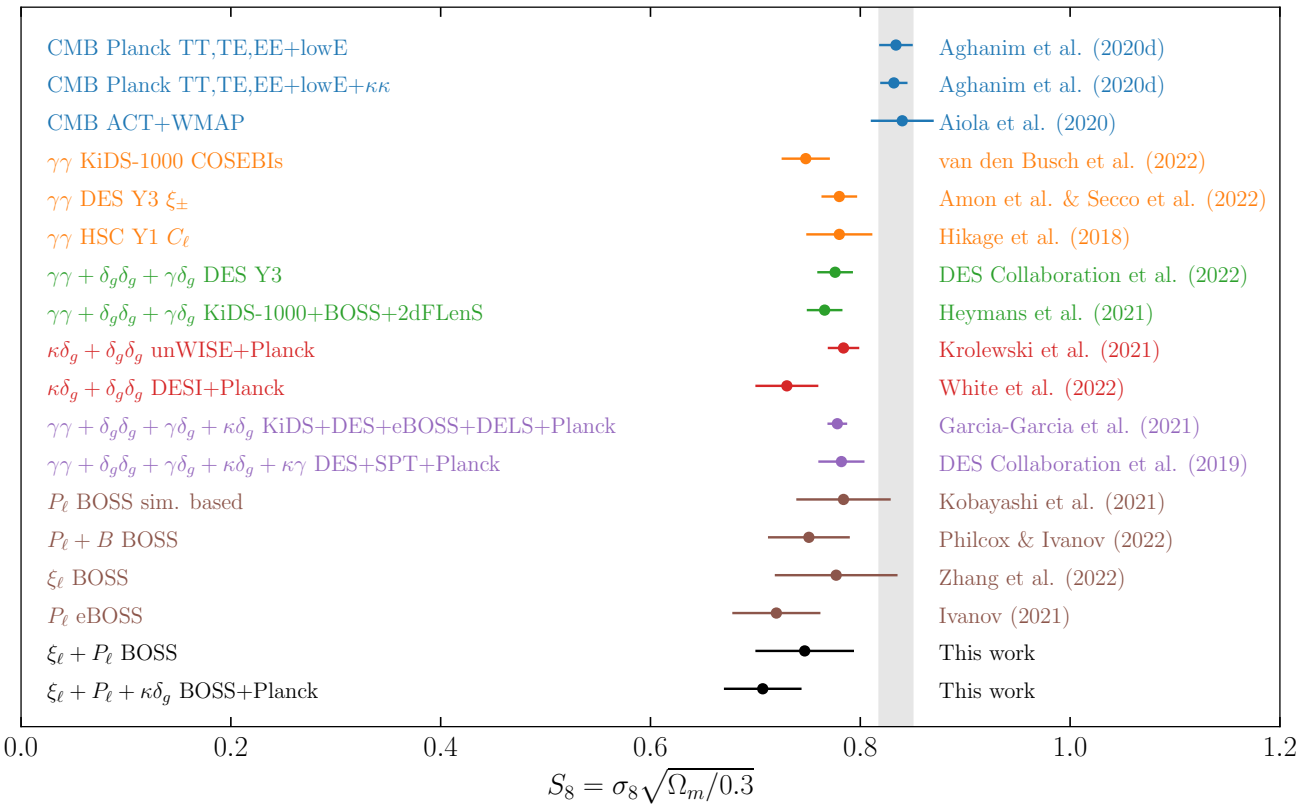
Perivolaropoulos & Skara, New Astron. Rev. 95 (2022) 101659; Abdalla *et al.*, JHEAp 34 (2022) 49

- 0σ =too good to be true, go check your error bars
- 1σ =agreement
- 2σ =curiosity
- 3σ =tension
- 4σ =discrepancy
- $\geq 5\sigma$ =crisis (disaster, calamity, catastrophe, cataclysm,...?)

S_8 tension (and more generally "growth tension")

Curiosity – Tension: S_8 from *Planck* and ACT higher than value inferred from cosmic shear, RSD, galaxy-galaxy lensing,...

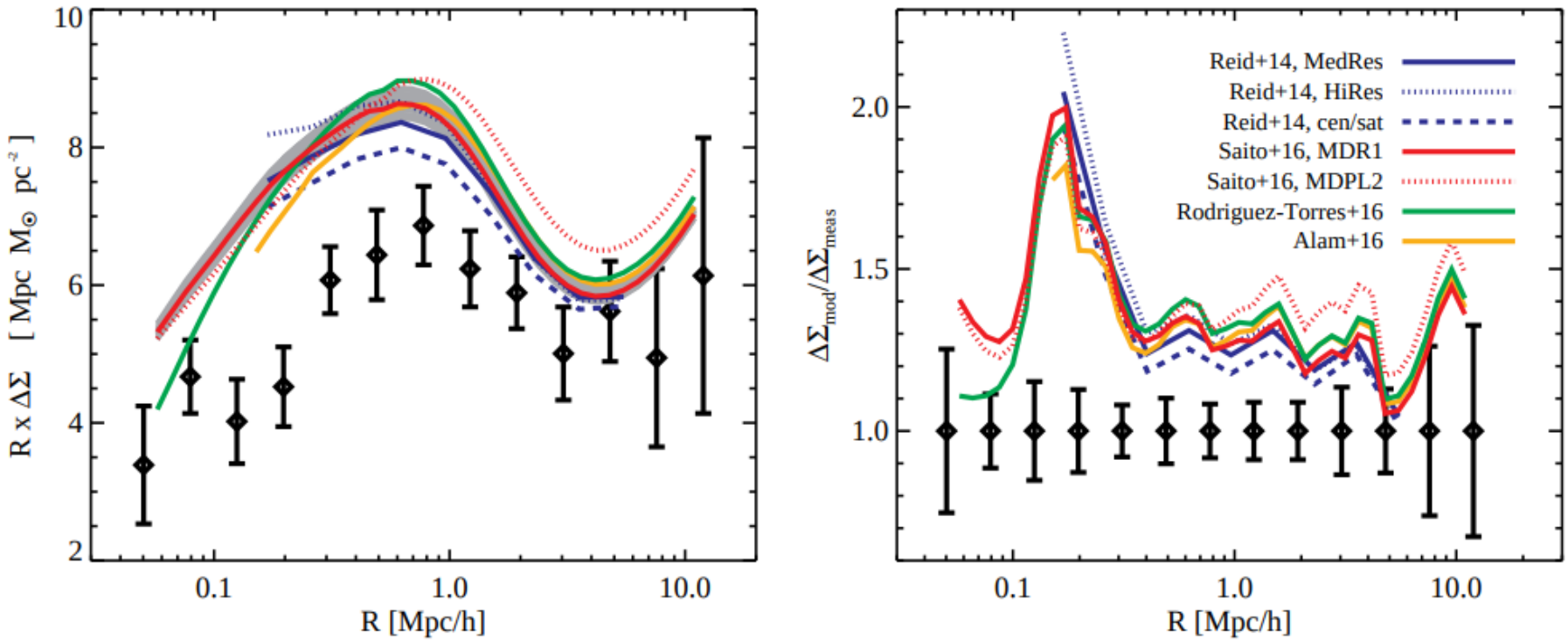


Chen *et al.*, JCAP 2207 (2022) 041

Solutions: massive neutrinos, dark scattering, NL $P(k)$ suppression, stronger galactic feedback/baryonic physics...?

"Lensing is low" problem

Curiosity: predicted galaxy-lensing ($g \times \kappa$) low given measured clustering ($g \times g$) – another manifestation of the S_8 tension?

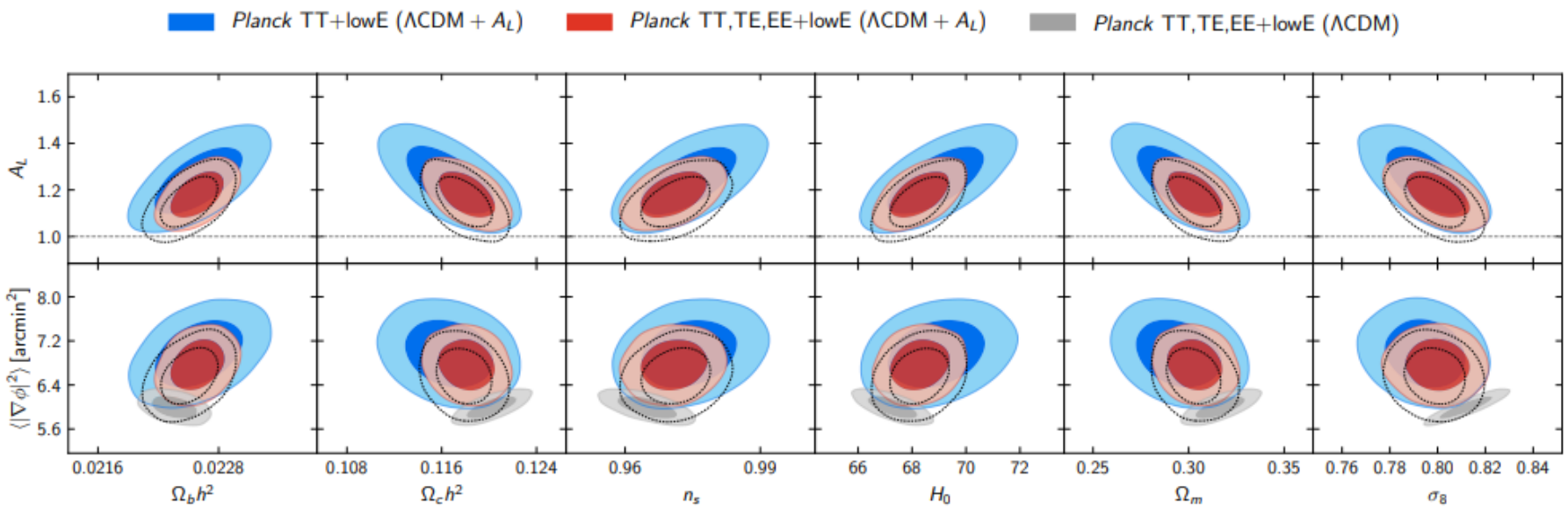


Leauthaud *et al.*, MNRAS 467 (2017) 3024

Solutions: HOD, baryonic physics, massive neutrinos, modified gravity...?

Planck lensing anomaly ("$A_{\rm lens}$ tension")

Curiosity – Tension: $A_{\rm lens} = 1.180 \pm 0.065$ (*Planck* TTTEEE+lowE)

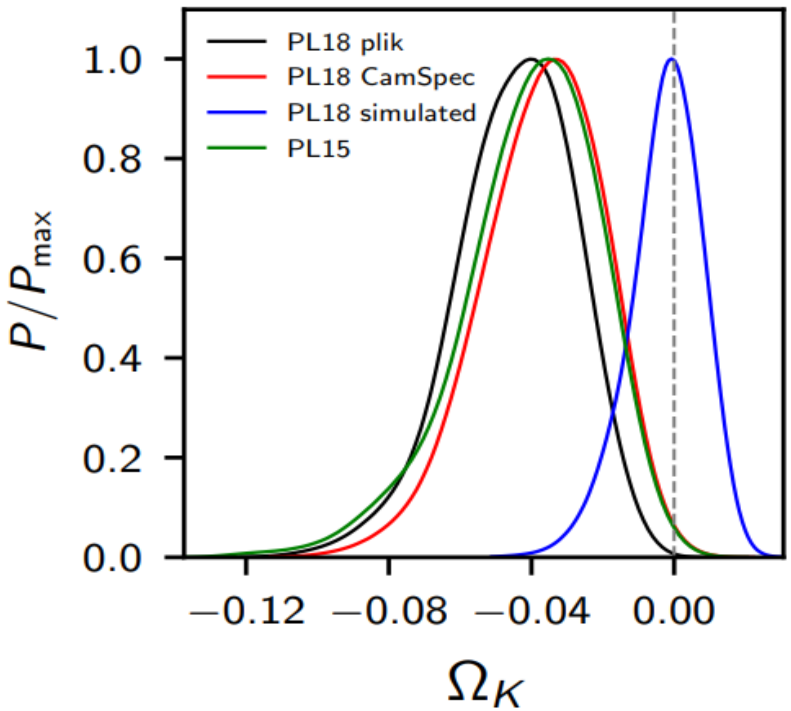


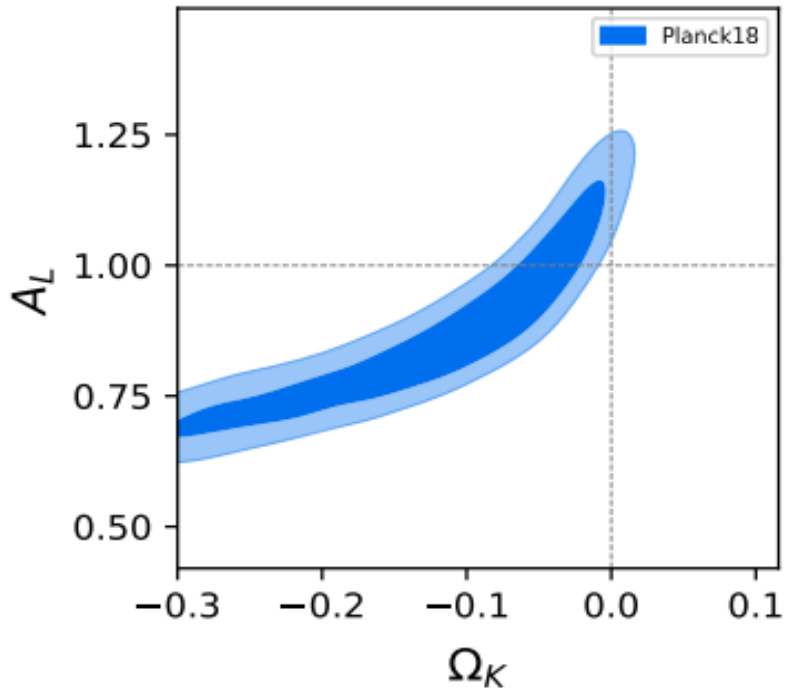
Planck collaboration, A&A 641 (2020) A6

Solutions: modified gravity, isocurvature perturbations, curvature...?

Planck closed Universe preference ("curvature tension")

Curiosity – Tension: $\Omega_K = -0.044^{+0.018}_{-0.015}$ (*Planck* TTTEEE+lowE) partially but not entirely connected to the $A_{\rm lens}$ tension



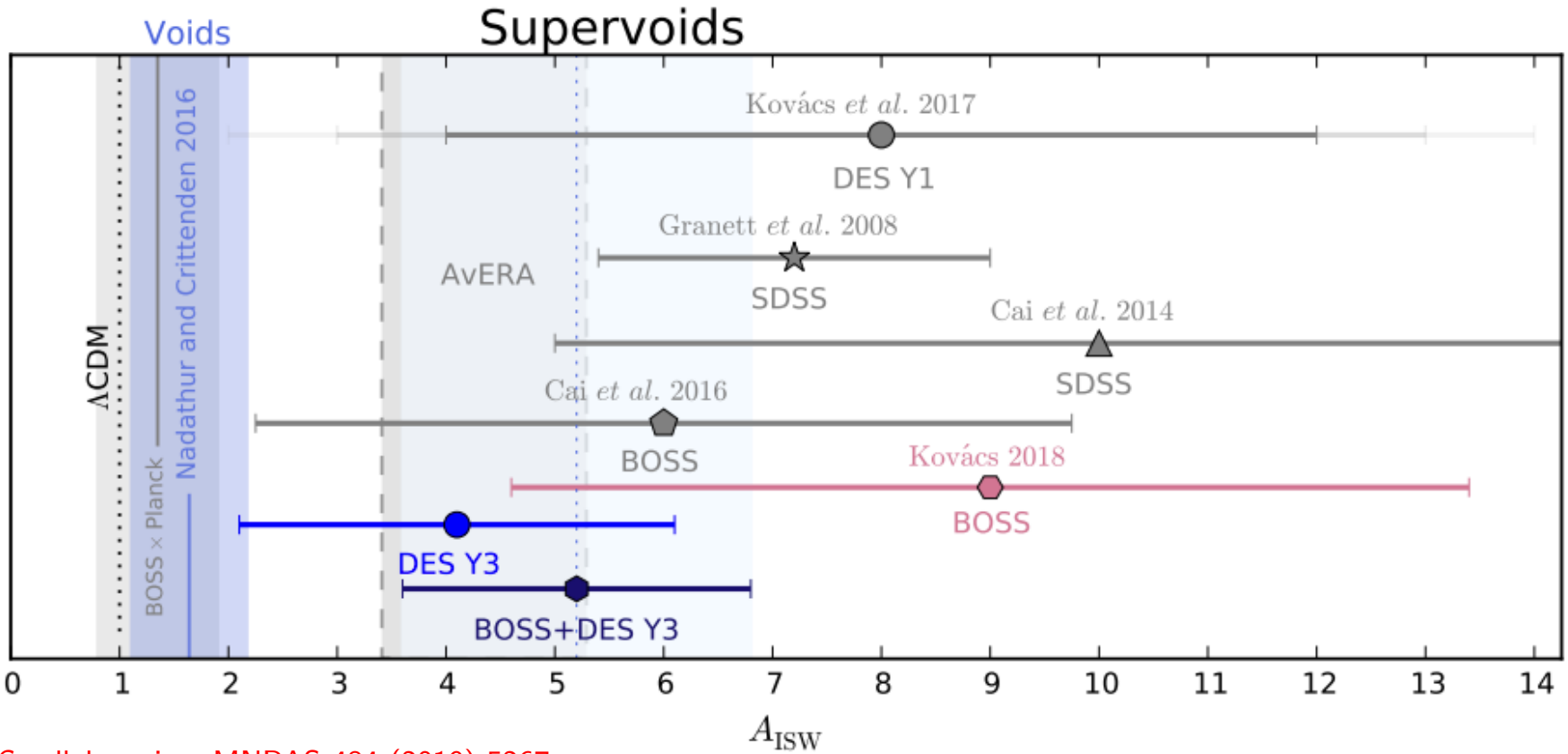


Di Valentino, Melchiorri & Silk, Nat. Astron. 4 (2019) 196

Solutions: not totally clear what to make of it due to tension with BAO, but non-flat Universe most likely cannot be the end of the story...

Anomalously strong ISW effect

Curiosity – Tension: from (stacked) supervoids and superclusters

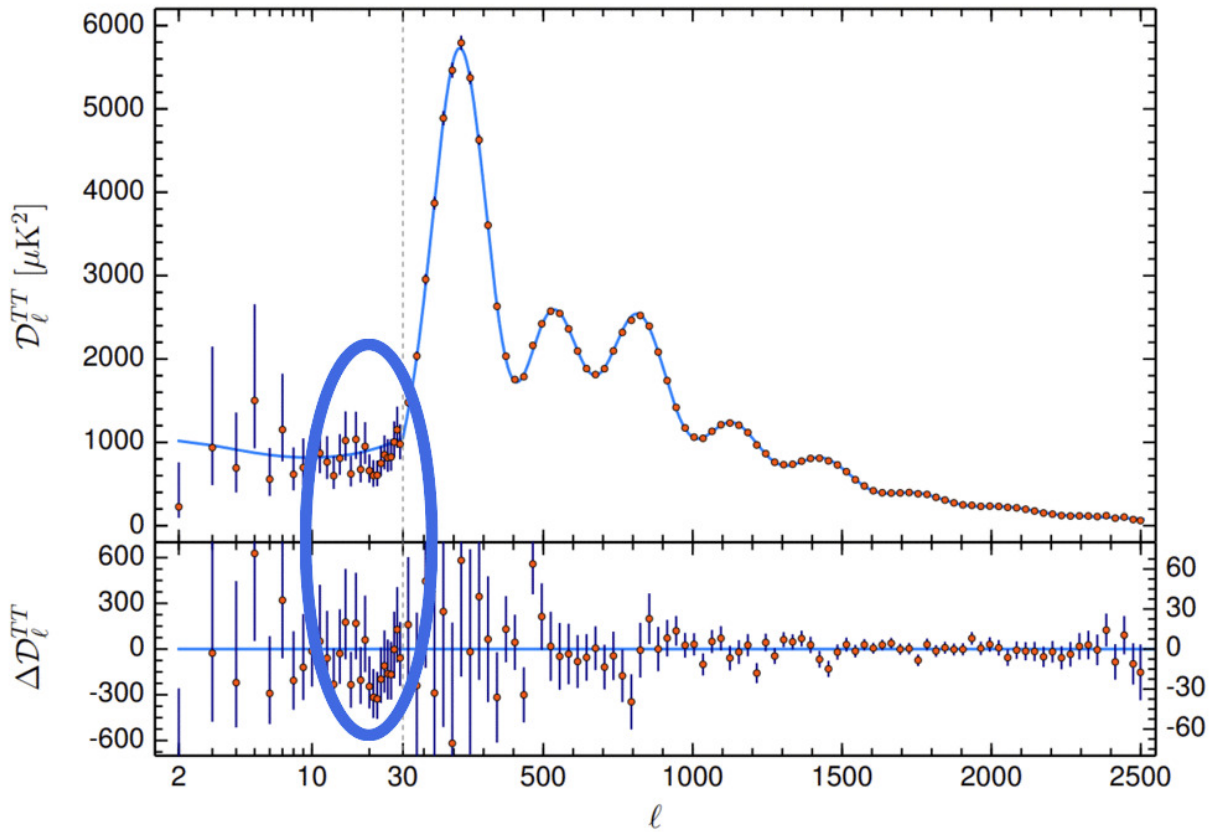


DES collaboration, MNRAS 484 (2019) 5267

Solutions: elongated void structure, supervoids and superclusters are more common than previously thought,...?

Low-ℓ dips

Curiosity: seen consistently by *Planck* and WMAP – **this is real**!

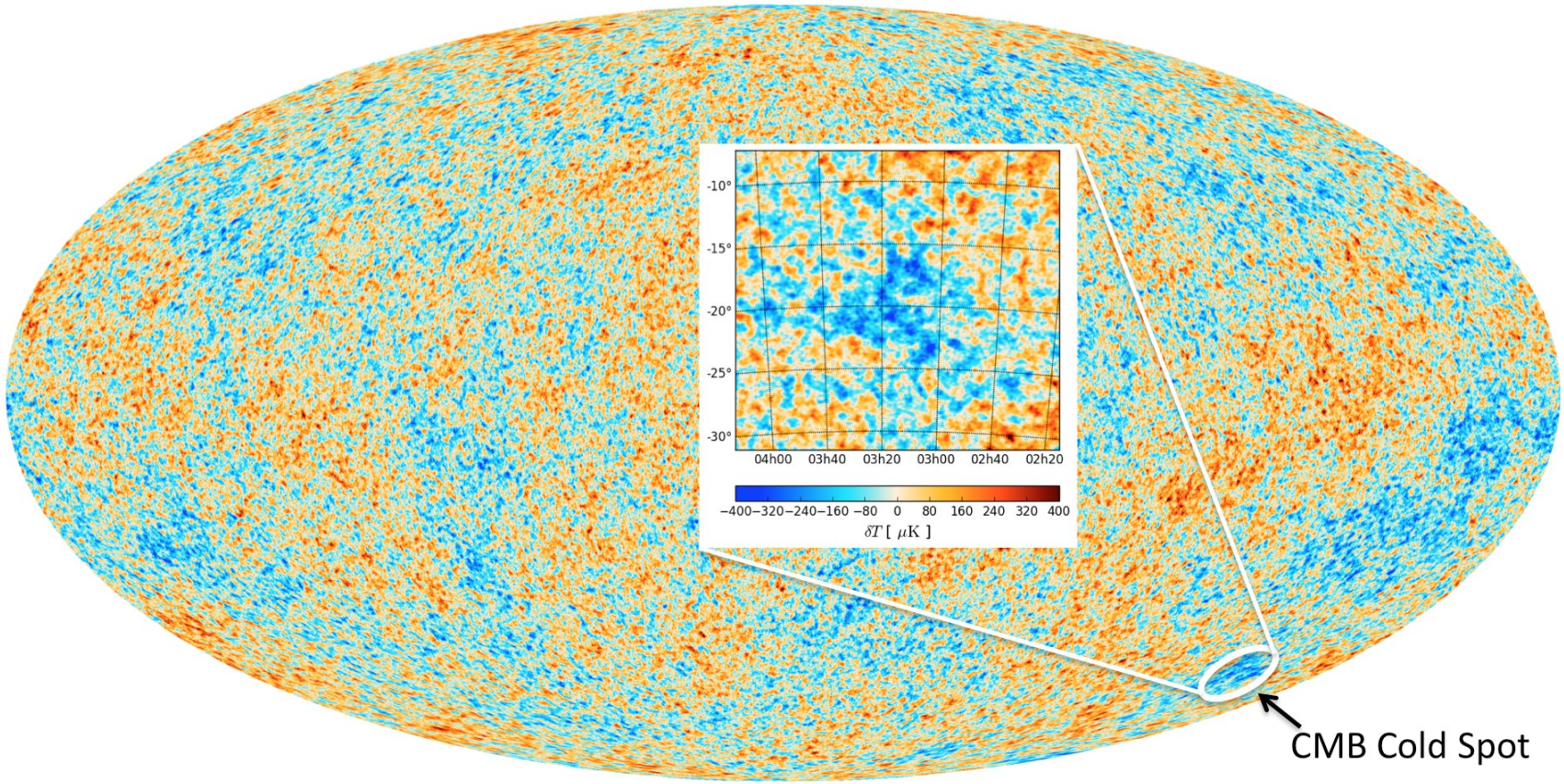


Planck collaboration, A&A 641 (2020) A6

Solutions: inflation with a step in the potential, short inflation, xresonant particle production, non-standard topology...?

CMB cold spot

Curiosity: unusually large region of low temperature ($\Delta T \approx -100\,\mu$K)

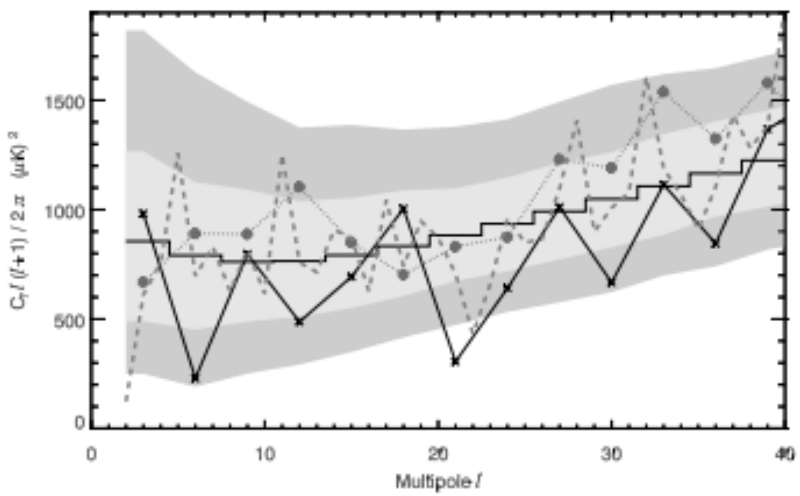


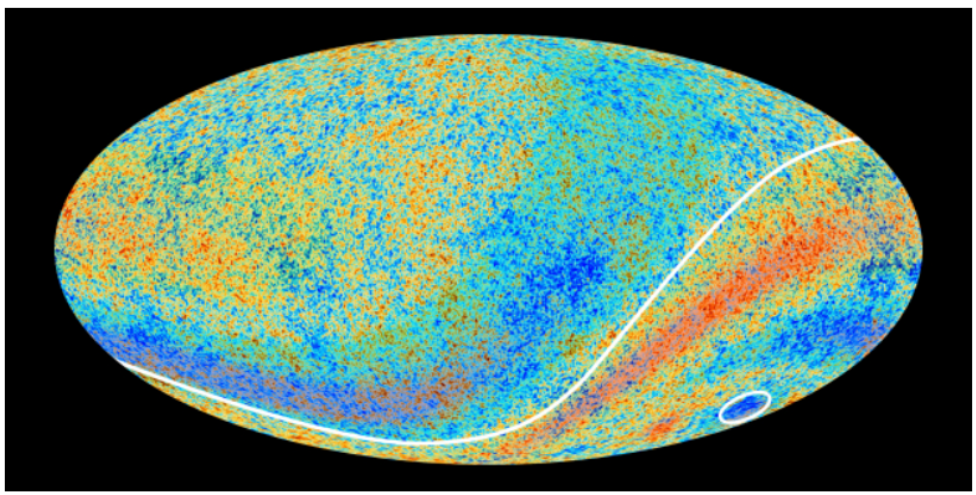
Credits: ESA and *Planck* collaboration

Solutions: Eridanus supervoid, non-Gaussian feature, foreground contamination, cosmic textures, entangled parallel Universe,...?

Cosmic hemispherical power asymmetry

Curiosity: Northern CMB hemisphere appears to have less power than Southern CMB hemisphere (North and South defined with respect to the ecliptic), observed also in higher correlators



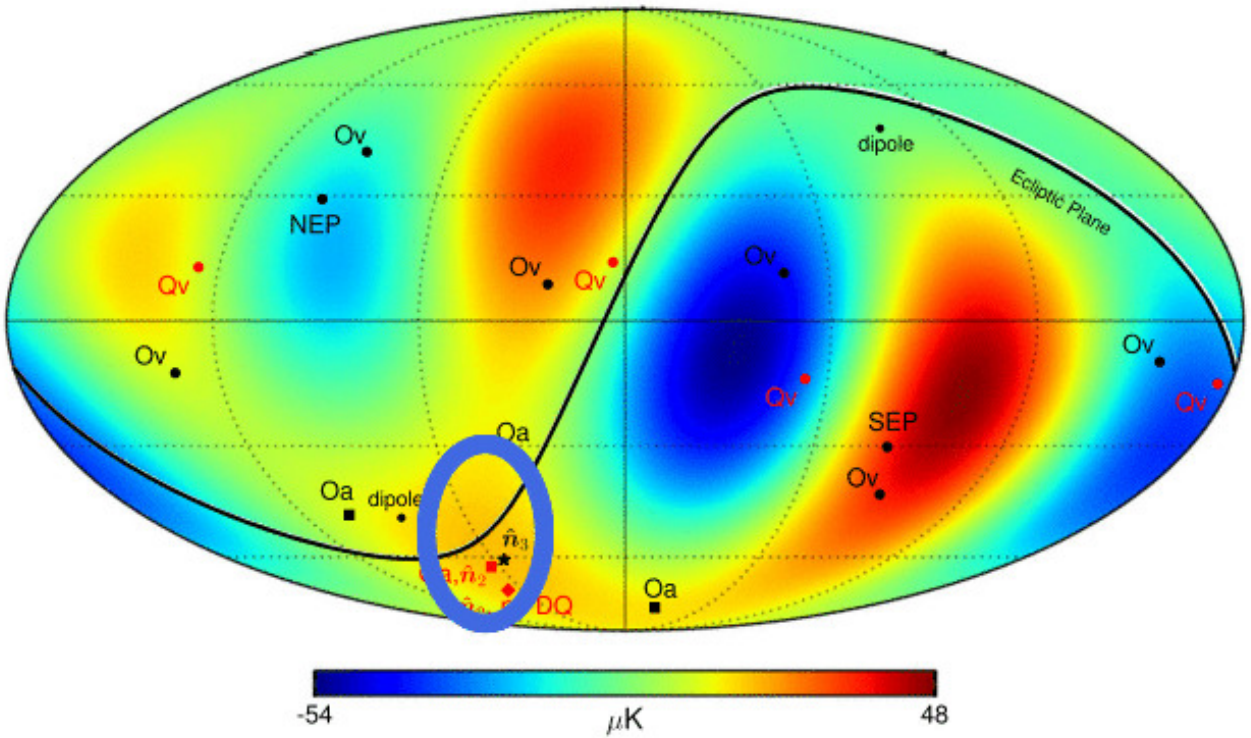


Eriksen *et al.*, ApJ 605 (2004) 14 (left) ; Credits: ESA and *Planck* collaboration (right)

Solutions: anisotropic dipolar-modulated primordial $P(k)$, mask effects, non-standard topology,...?

Quadrupole–octopole alignment

Curiosity: anomalous a_{2m}-a_{3m} correlations ($\langle a^\star_{\ell m} a_{\ell' m'} \rangle \propto \delta_{\ell\ell'}\delta_{mm'}$?), quadrupole and octupole almost aligned ($\hat{n}_2 \cdot \hat{n}_3 \simeq 0.98$)

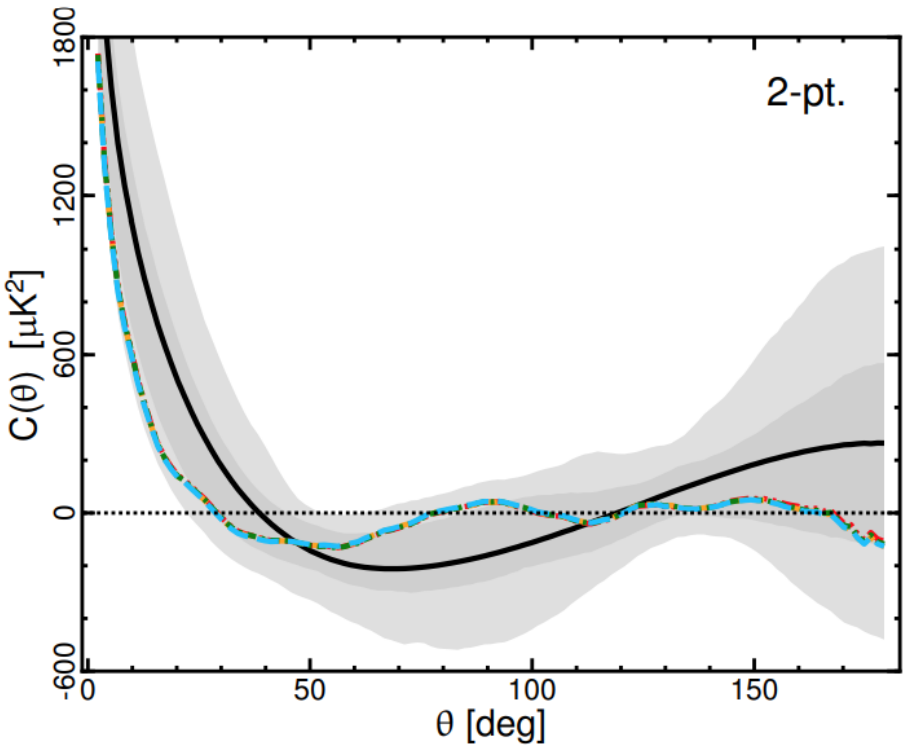


Schwarz *et al.*, ApJ 33 (2016) 184001

Solutions: residual contamination due to foregrounds, non-standard topology, ISW from local structure, anisotropic primordial $P(k)$,...?

Lack of large-angle CMB temperature correlations

Curiosity – Tension: unusually low two-point angular correlation function $\mathcal{C}(\theta) \equiv \overline{T(\hat{e}_1)T(\hat{e}_2)} = \sum_\ell C_\ell P_\ell(\cos\theta)$ for $\theta \gtrsim 60^\circ$

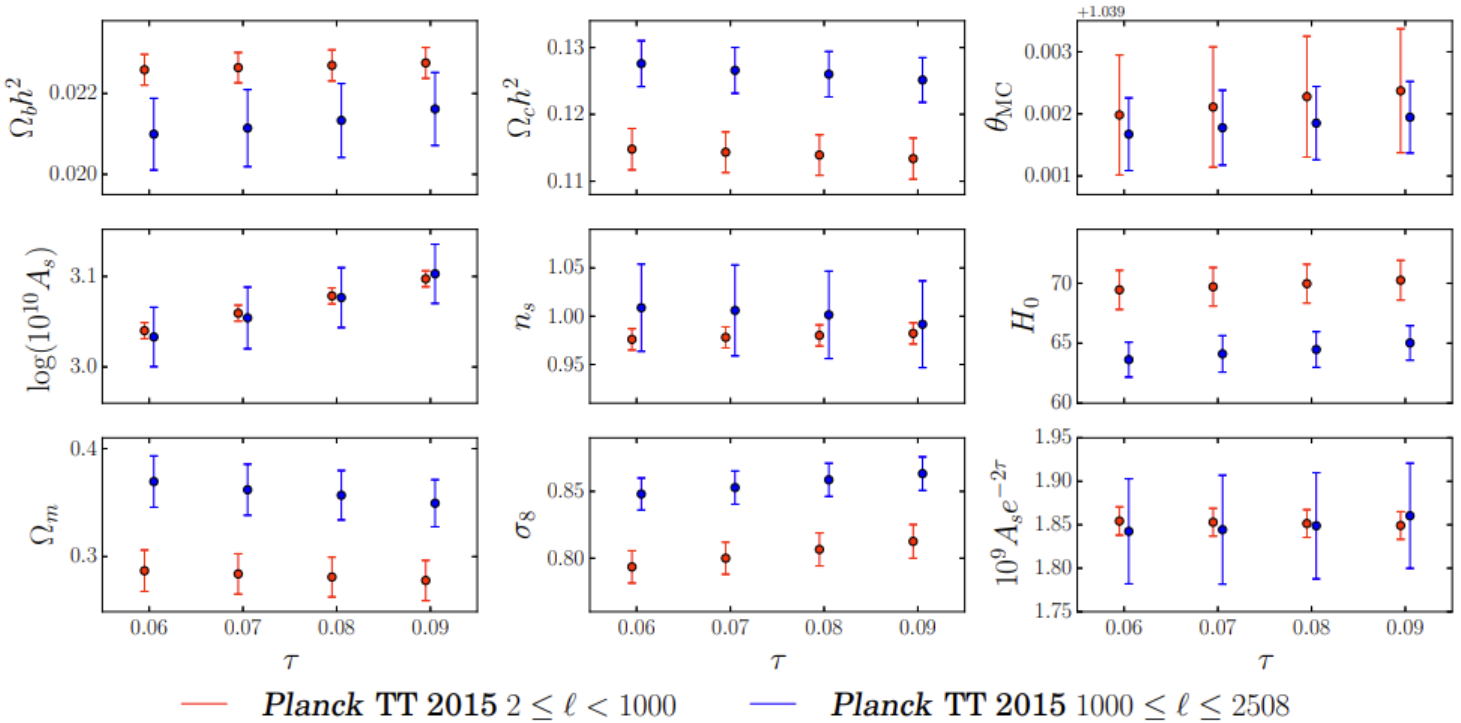


Schwarz *et al.*, ApJ 33 (2016) 184001

Solutions: residual contamination due to foregrounds, non-standard topology,...?

Planck high- vs low-ℓ consistency

Curiosity – Tension: inconsistency between parameters inferred from $\ell \geq 1000$ and $\ell < 1000$ in *Planck* data

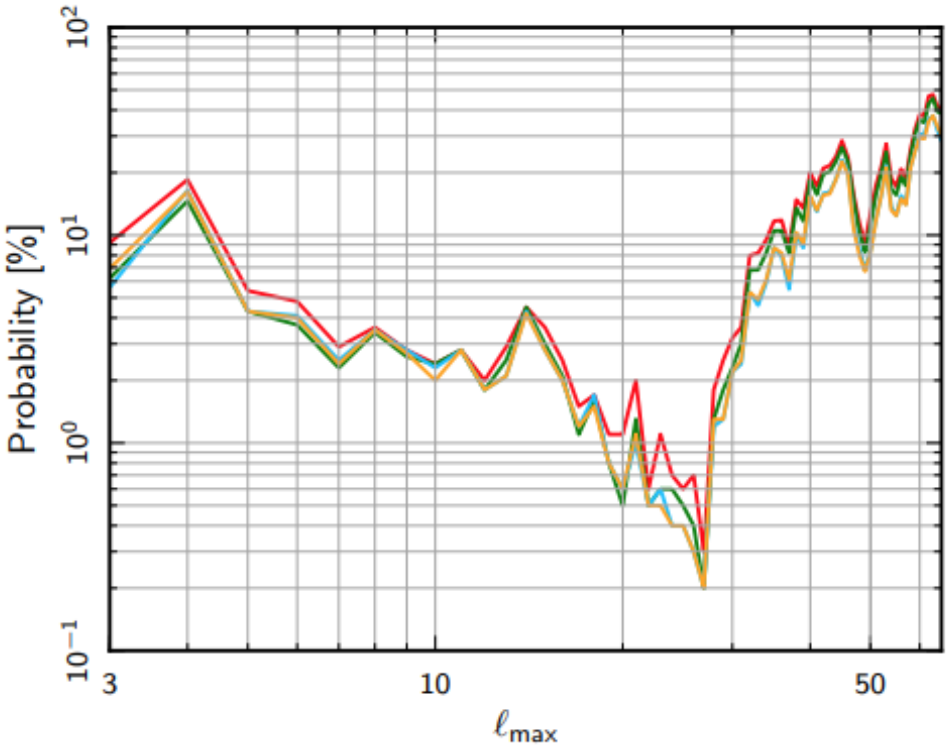


Addison *et al.*, ApJ 818 (2016) 132

Solutions: probably closely related to $A_{\rm lens}$, but new physics which alters the shape of the radiation-driving envelope may improve the situation...

Point-parity anomaly

Curiosity – Tension: more power in odd multipoles compared to even ones

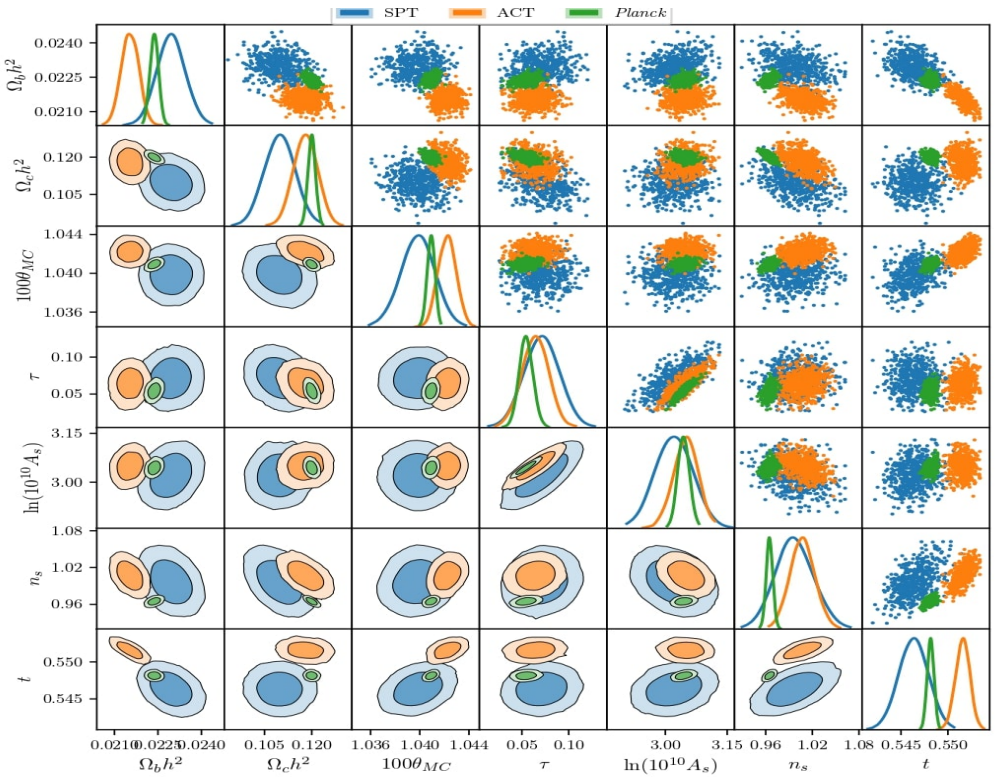


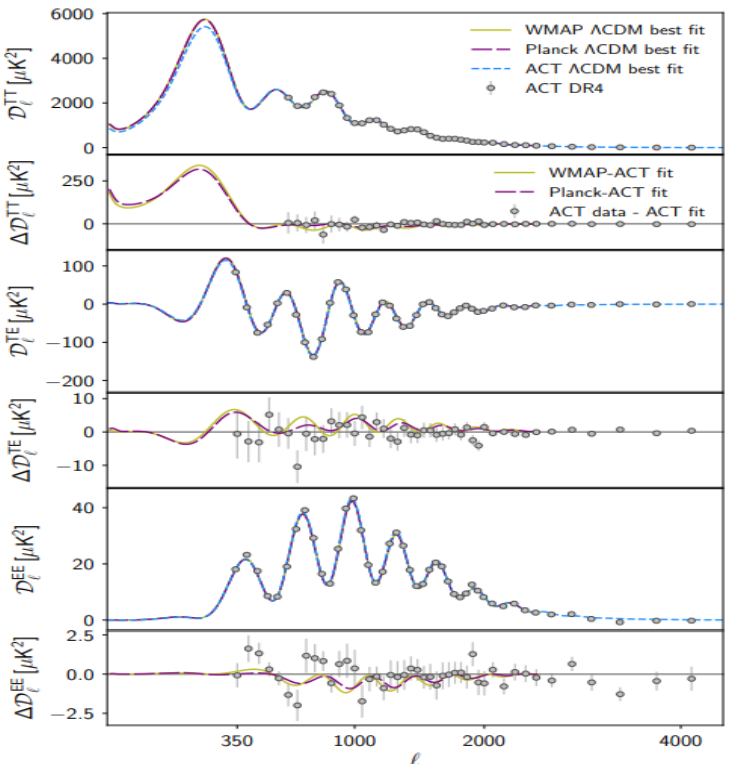
Schwarz *et al.*, ApJ 33 (2016) 184001

Solutions: residual contamination due to foregrounds, signature of parity violation, non-standard topology,...?

ACT vs Planck tension

Curiosity – Tension: ACT prefers (at face value) lower ω_b, (much) lower $N_{\rm eff}$ and Y_P, $n_s \sim 1$, non-zero $dn_s/d\ln k$ and $f_{\rm EDE}$,...



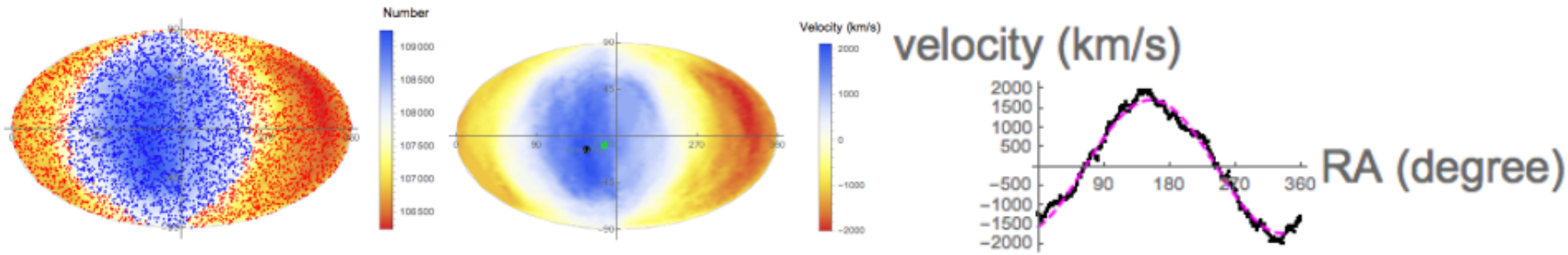


Handley & Lemos, PRD 103 (2021) 063529 (left); *ACT* collaboration, JCAP 2012 (2020) 047 (right)

Solutions: systematics in either or both, not clear whether extended models can work (they really just hide the problem)...

Velocity radio dipole

Discrepancy: dipole in radio galaxy number counts, implied velocity and direction does not match CMB dipole

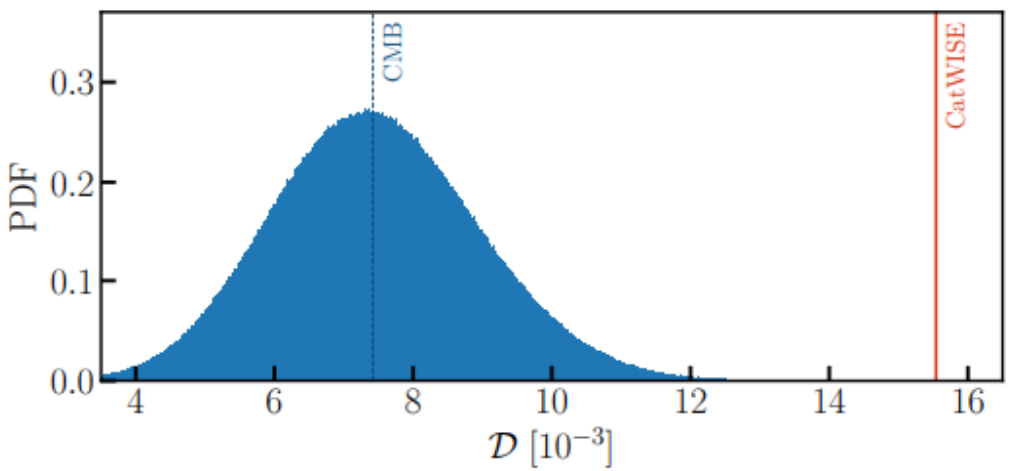


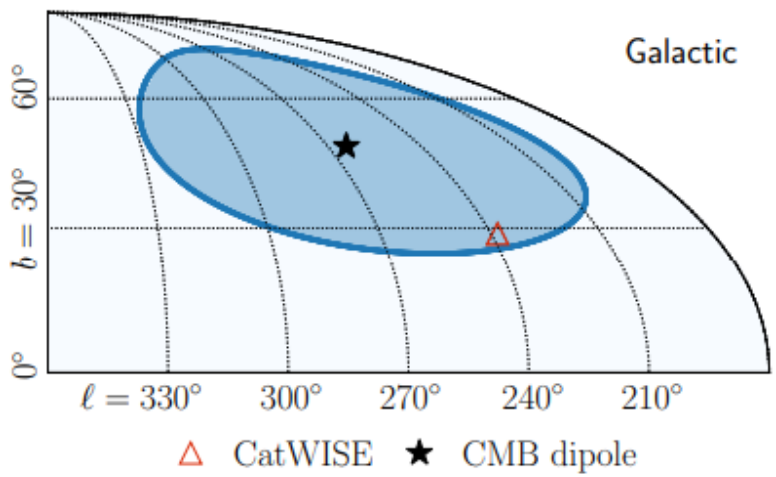
Colin *et al.*, MNRAS 471 (2017) 1045

Solutions: incomplete sky coverage, intrinsic LSS dipole, local structure bias, pre-inflationary remnants, superhorizon perturbations...

Quasar dipole

Discrepancy: dipole in radio galaxy number counts, implied velocity and direction does not match CMB dipole



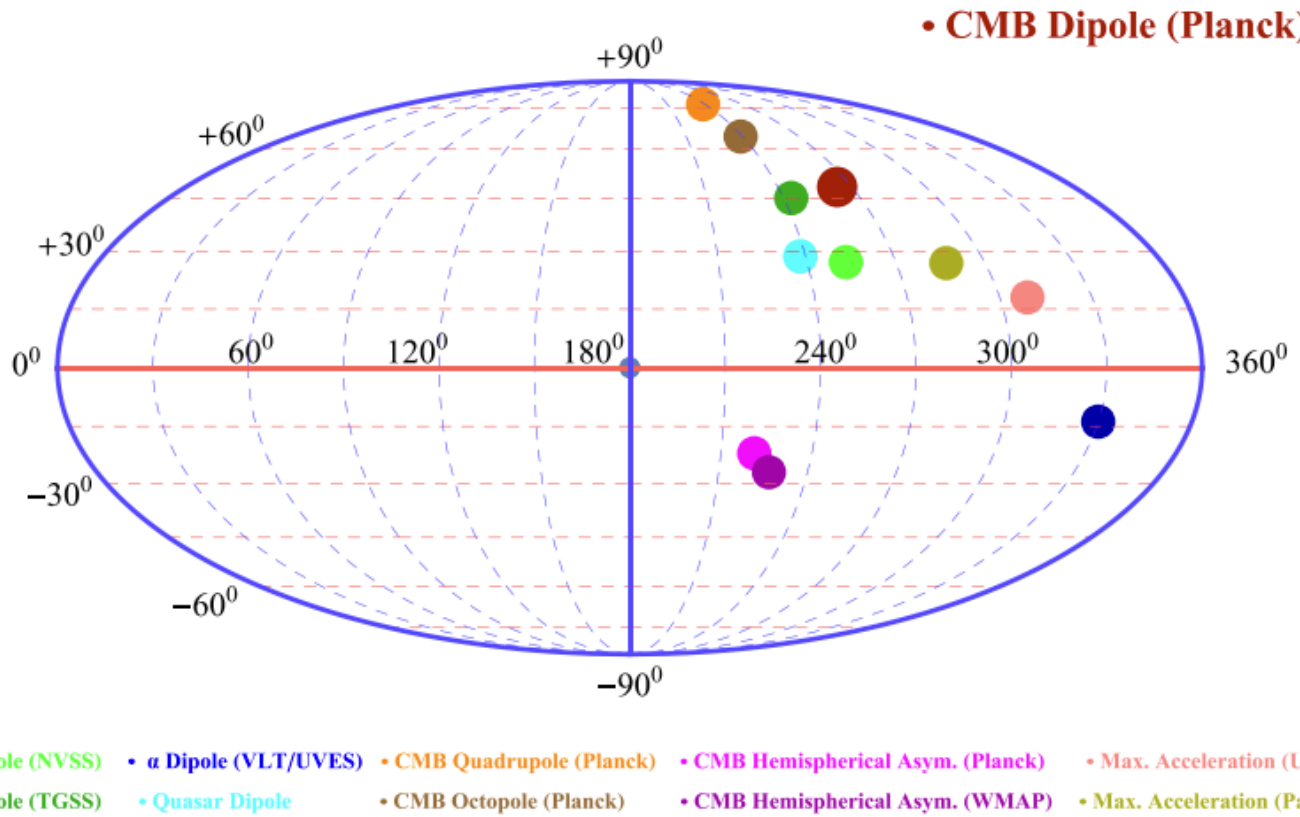


Secrest *et al.*, ApJ Lett. 908 (2021) L51

Solutions: incomplete sky coverage, intrinsic LSS dipole, local structure bias, pre-inflationary remnants, superhorizon perturbations...

Other dipoles

Curiosities – Discrepancies: other dipoles in H_0/M_B from various observations (SNeIa, cluster scaling relations), α from VLT/UVES, etc.

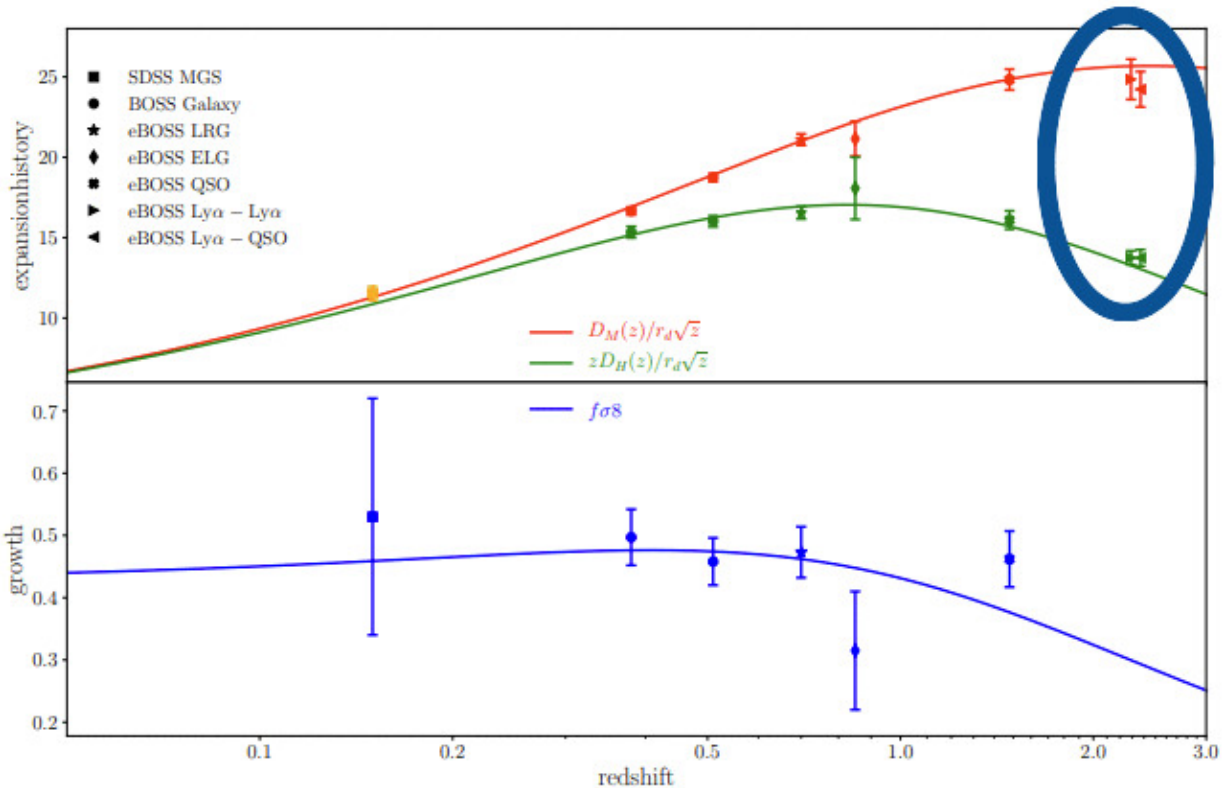


Perivolaropoulos & Skara, New Astron. Rev. 95 (2022) 101659

Solutions: really unclear as they point somewhat in different directions...

Lyman-α BAO tension (and other BAO curiosities)

Curiosity: Lyα-Lyα and Ly$\alpha\times$QSO BAO measurements of $D_H/r_s = cr_s/H$ ($z_{\rm eff} \sim 2.40$) high compared to ΛCDM expectations from *Planck* bestfits

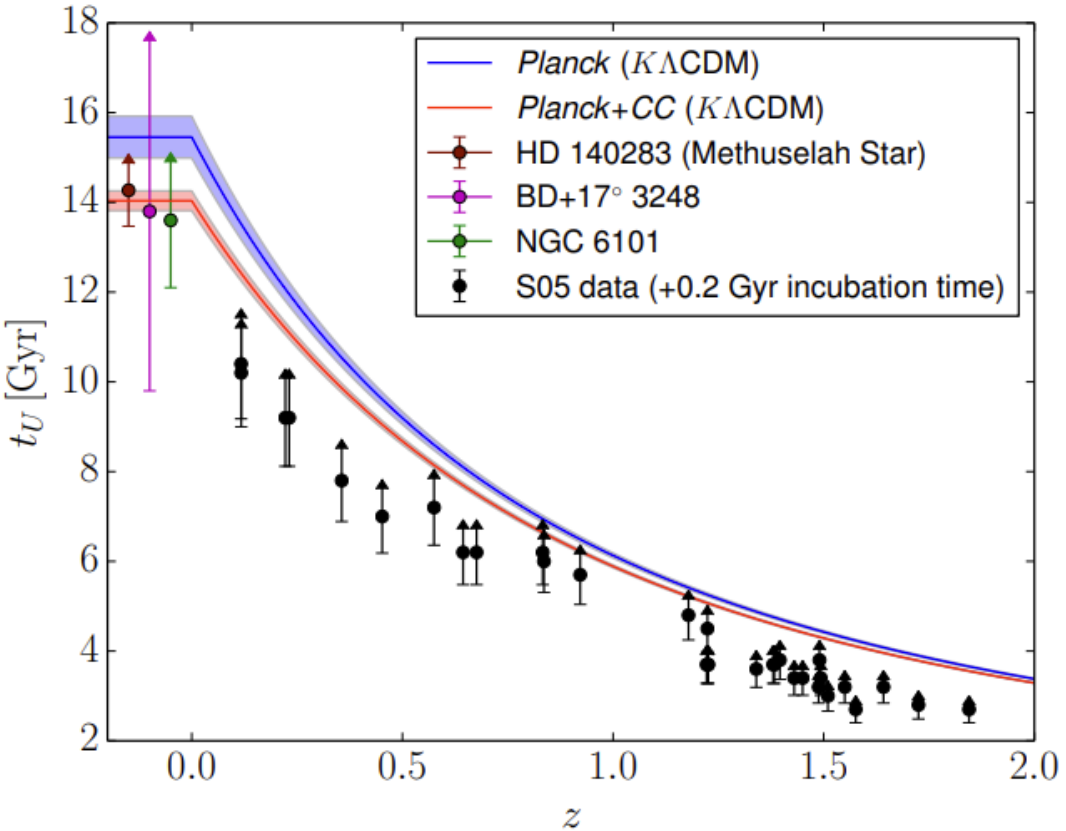


eBOSS collaboration, PRD 103 (2021) 083533

Solutions: something which lowers $H(z)$ at $z \gtrsim 2$, e.g. transition to negative values of $\rho_{\rm DE}$ (concrete example: Λ_sCDM model)

Age problem

Curiosity: a few objects appear older than the best-fit ΛCDM Universe, e.g. Methuselah star $t_\star \sim 14.46 \pm 0.31\,\mathrm{Gyr}$ vs $t_U = 13.800 \pm 0.024\,\mathrm{Gyr}$

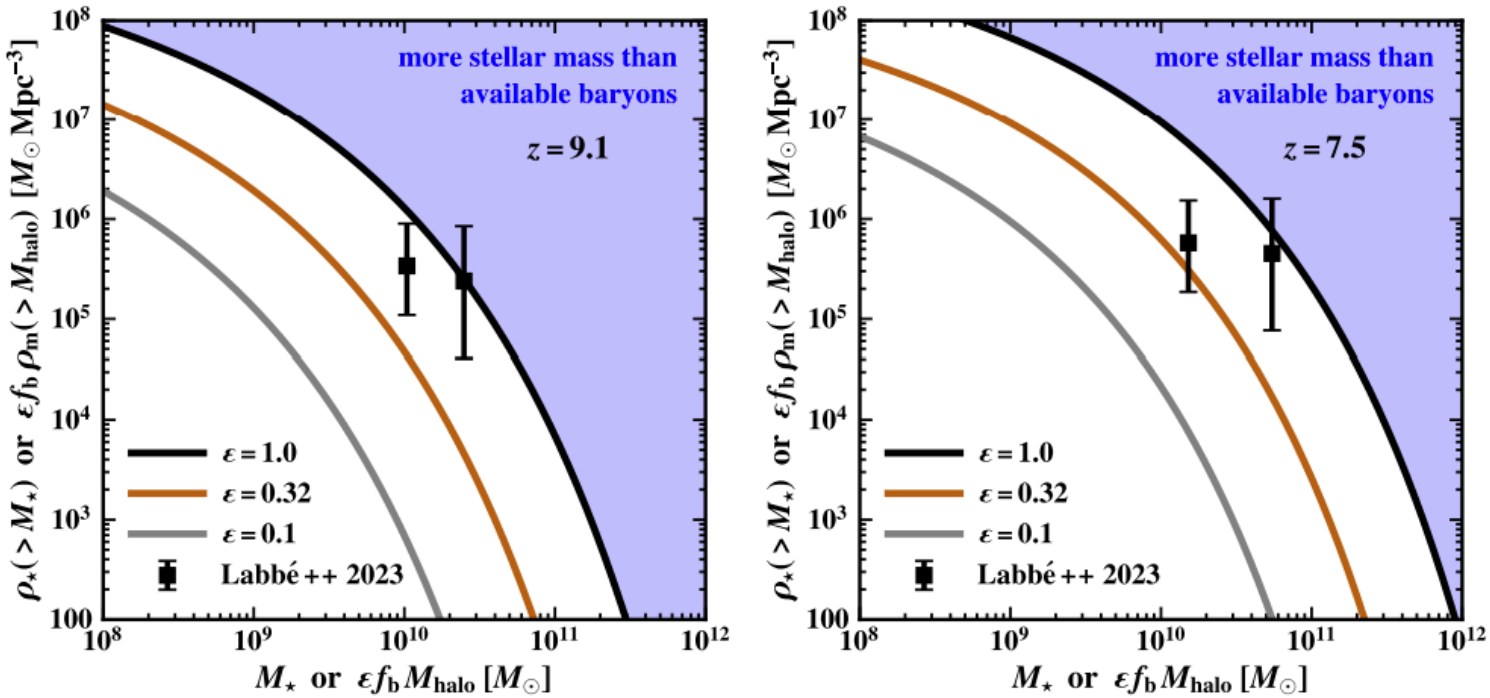


Vagnozzi, Loeb & Moresco, ApJ 908 (2021) 84

Solutions: systematics, new late-time physics ($\Omega_K < 0$, $w < -1$)...?

JWST tension

Curiosity – Tension: too many galaxies, too massive, at too high redshift

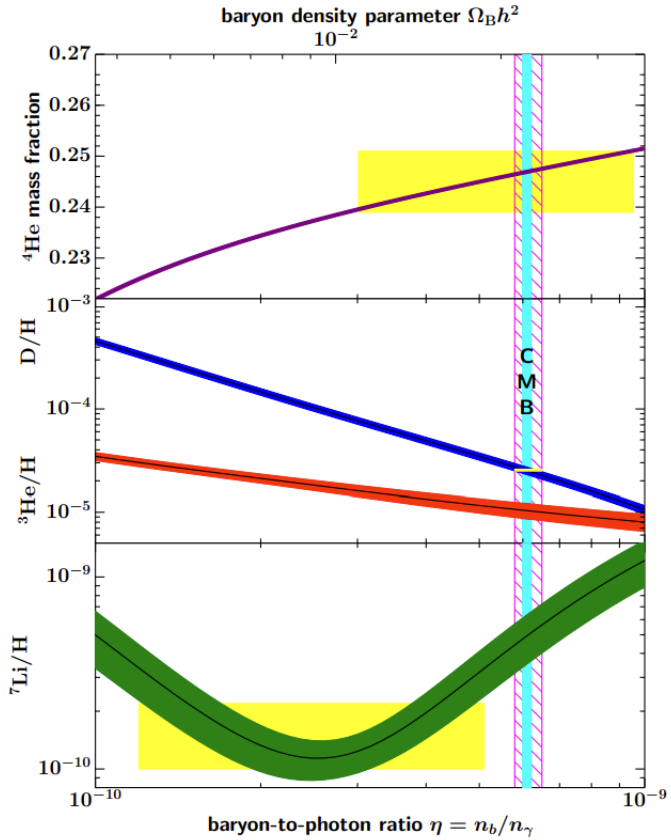


Boylan-Kolchin, Nat. Astron. 7 (2023) 731

Solutions: wrong redshifts, unusually efficient galaxy formation, primordial non-Gaussianity, enhanced small-scale power spectrum, PBHs...?

Lithium problem

Discrepancy (Crisis?): ^{7}Li abundance too low given ω_b from CMB

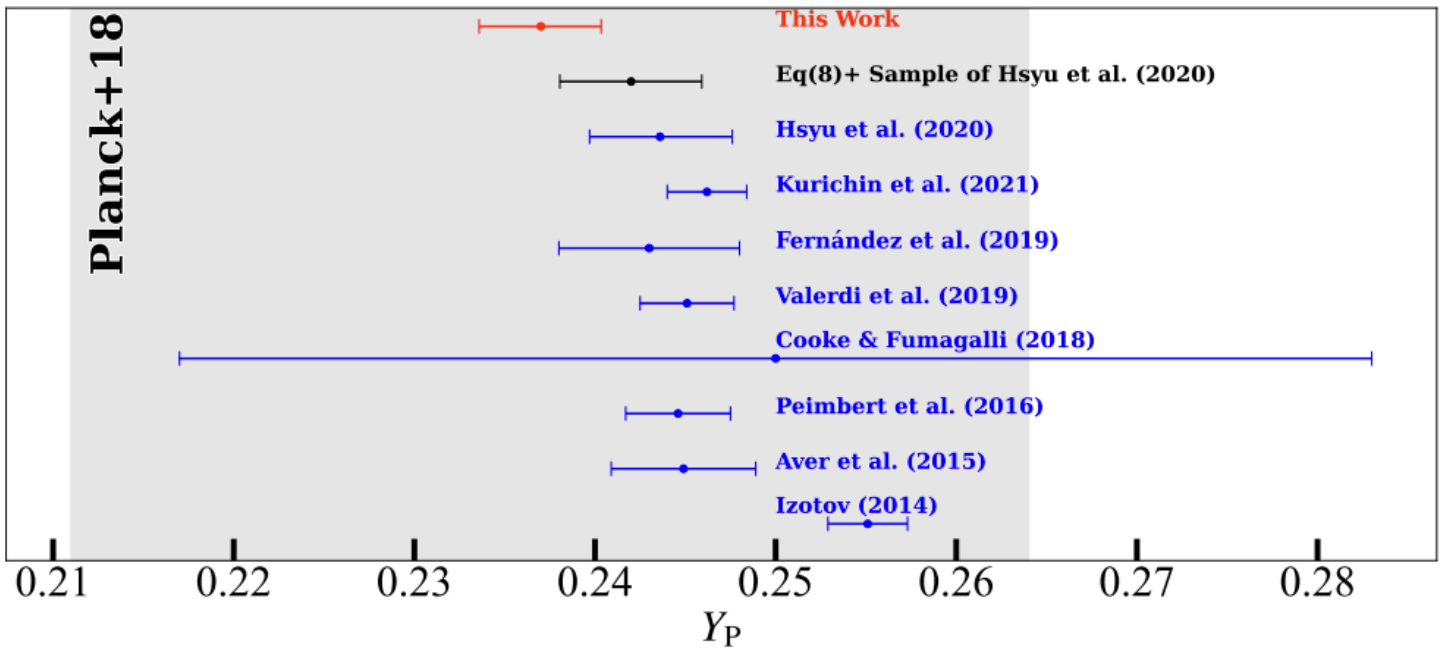


PDG collaboration, 2018 PDG, PRD 98 (2018) 030001

Solutions: stellar depletion, non-Maxwellian statistics, revised values of cross-sections, decaying DM, sterile νs, varying fundamental constants...?

"BBN tension"

Curiosity: Low value of Y_P from extremely metal-poor galaxies

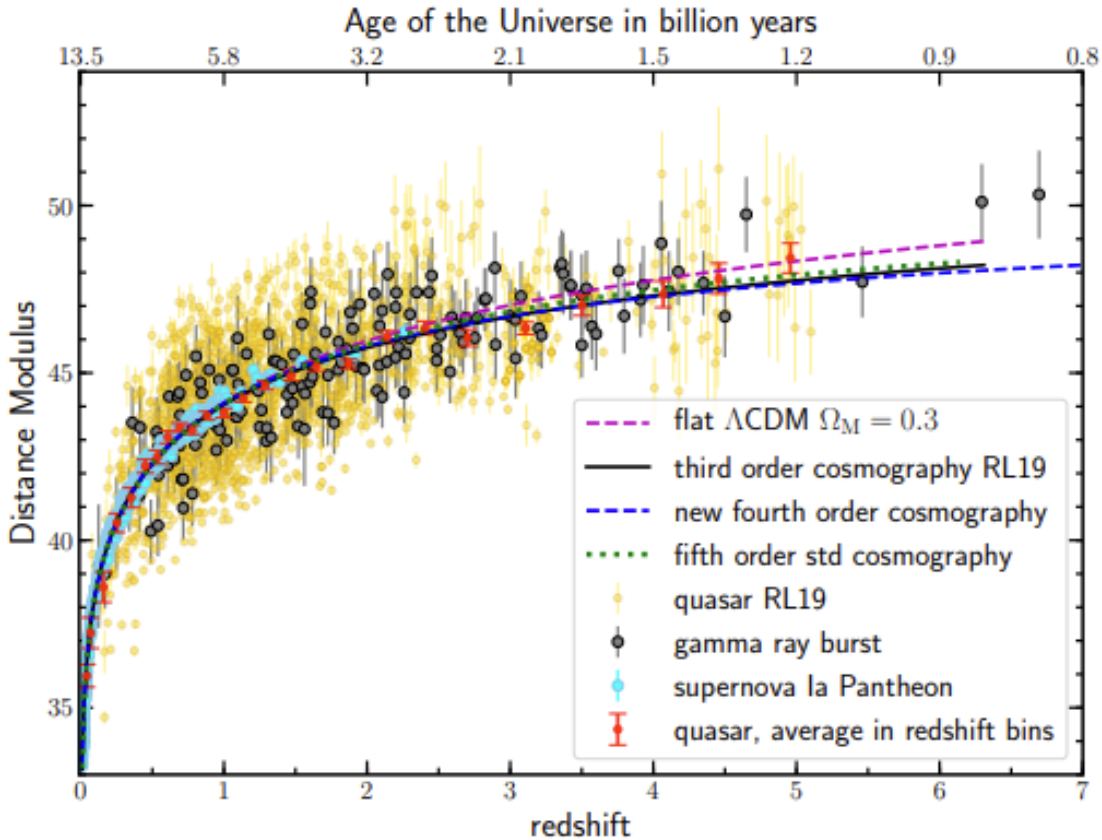


EMPRESS collaboration, ApJ 941 (2022) 167

Solutions: assuming other Y_P measurements are wrong (unlikely), could be due to lepton asymmetry ξ_e, higher $N_{\rm eff}$, (very) early dark energy,...?

Quasars Hubble diagram

Discrepancy: 1598 QSOs at $0.5 \lesssim z \lesssim 5.5$ show evidence for $w < -1$ and larger Ω_m, especially at high redshift (consistent with GRBs)

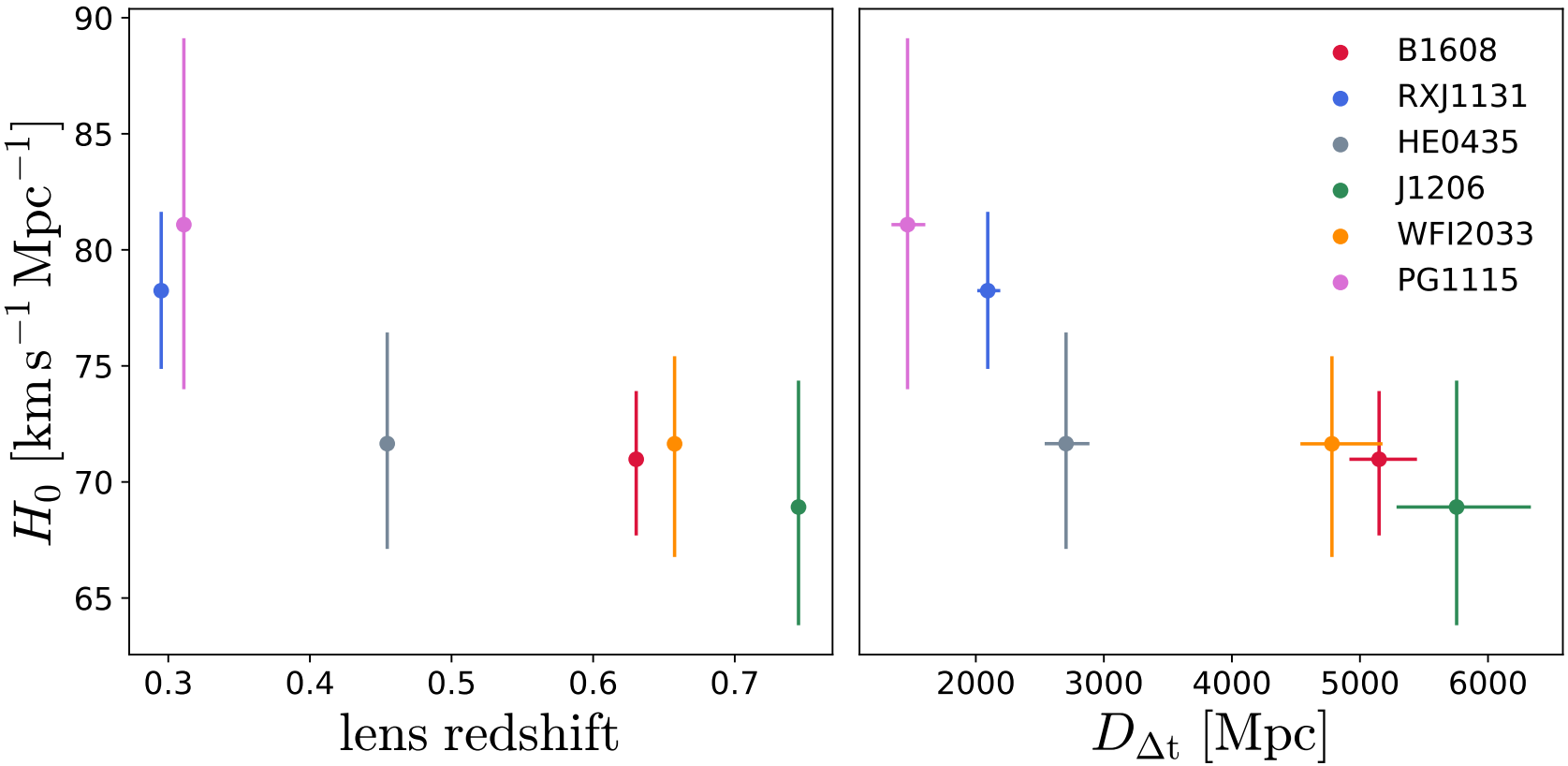


Lusso *et al.*, A&A 628 (2019) L4

Solutions: phantom DE, negative DE density, spatially closed Universe,...?

Evolving parameter trends

Curiosity – Tension: trends of parameters (H_0, Ω_m, S_8) inferred within ΛCDM evolving as a function of redshift seen in various late-time datasets

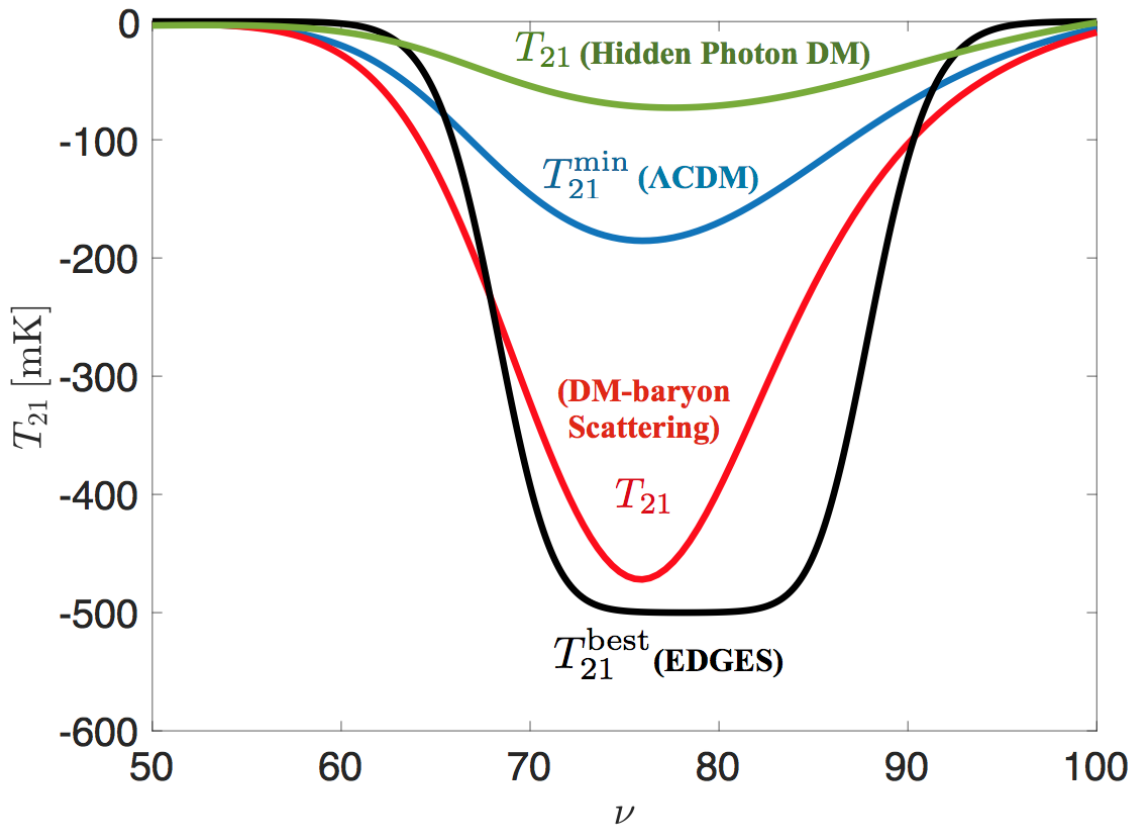


H0LiCOW collaboration, MNRAS 498 (2019) 1420

Solutions: beyond-ΛCDM late-time new physics going in the opposite direction so as to "absorb" the trend, e.g. $w < -1$,...?

EDGES tension

Curiosity – Tension: $T_{21} = -0.5^{+0.2}_{-0.5}\,\mathrm{K}$ (expectation is $\simeq -0.2\,\mathrm{K}$), appears excluded by latest SARAS results

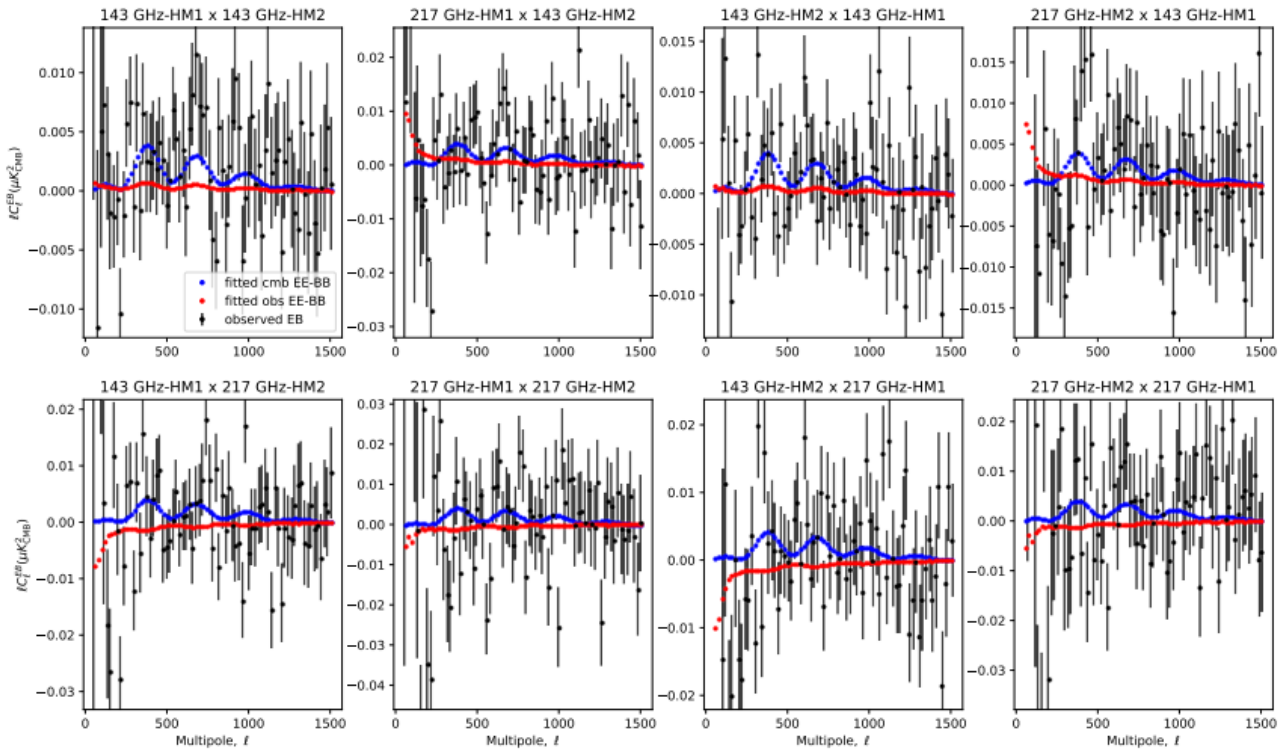


Credits: Ely Kovetz

Solutions: cooler gas (e.g. due to baryon-millicharged DM scattering), hotter CMB photons (unlikely), lower Hubble rate at $z \sim 18$,...?

Hints of parity violation

Curiosity – Tension: detection of non-zero EB correlations in CMB (2.4σ), corresponding to $\beta = (0.35 \pm 0.14)$ deg; detection of non-zero parity-odd 4PCF in galaxy surveys (up to 7σ)

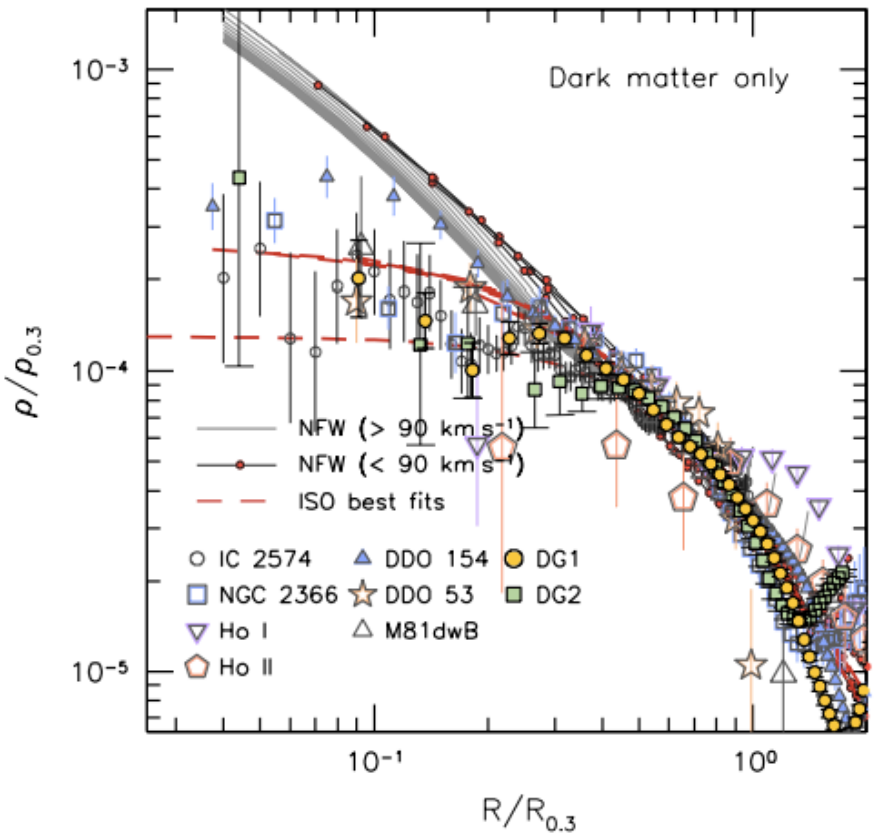


Minami & Komatsu, PRL 125 (2020) 221301

Solutions: new pseudoscalar field (for birefringence – is this DE or EDE?), parity-violating inflaton couplings (for non-zero parity-odd 4PCF),...?

Core-cusp problem

Curiosity: density profiles of low surface brightness and dwarf galaxies appear cored, collisionless CDM simulations predict cuspy NFW profile

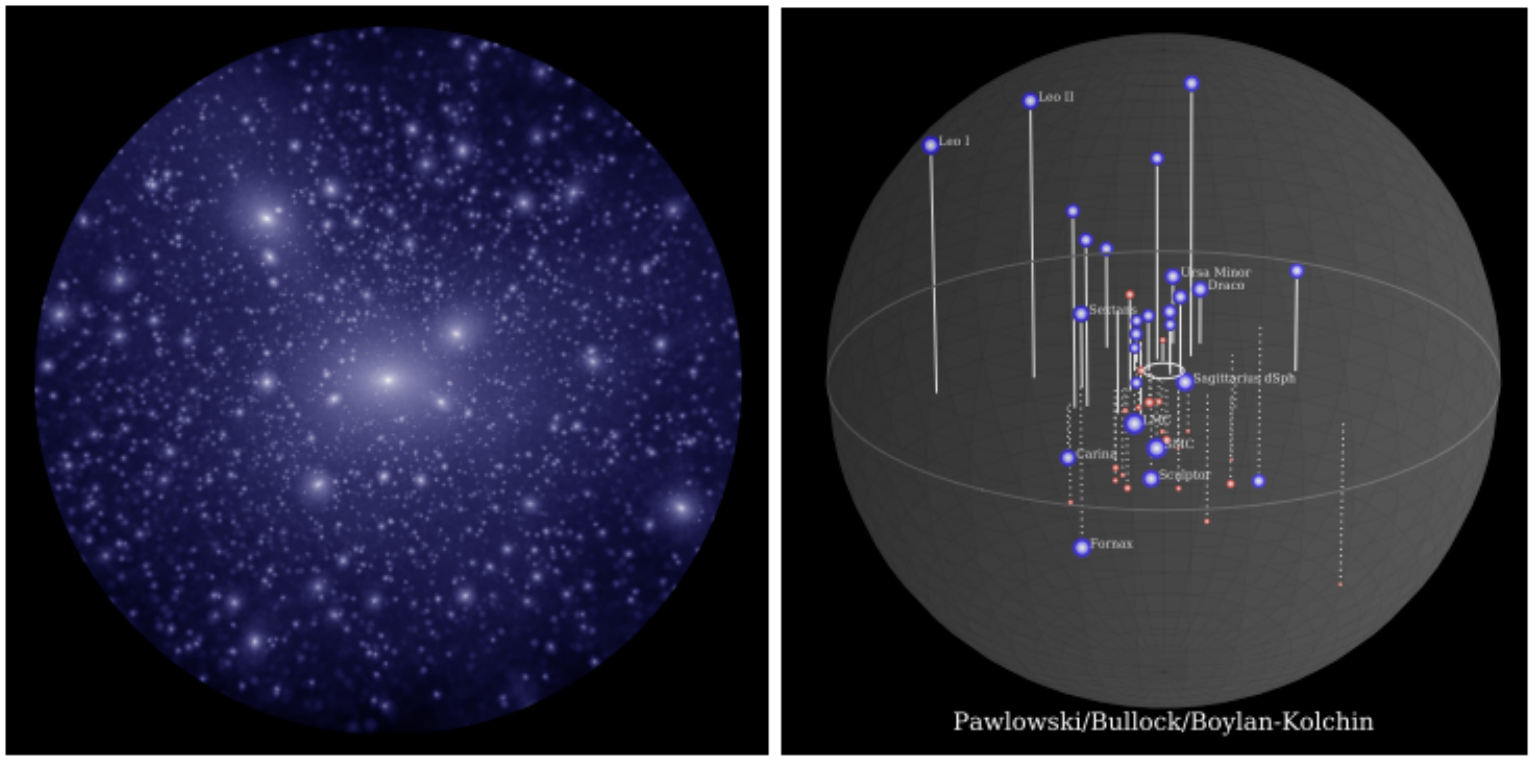


Oh *et al.*, AJ 142 (2011) 24

Solutions: baryonic feedback, central BH dynamics, DM self-interactions, fuzzy/warm/scalar field DM, baryons-DM dynamical friction,...?

Missing satellites problem

Unclear significance: number of observed dwarf (satellite) galaxies an order of magnitude lower compared to expectations from simulations

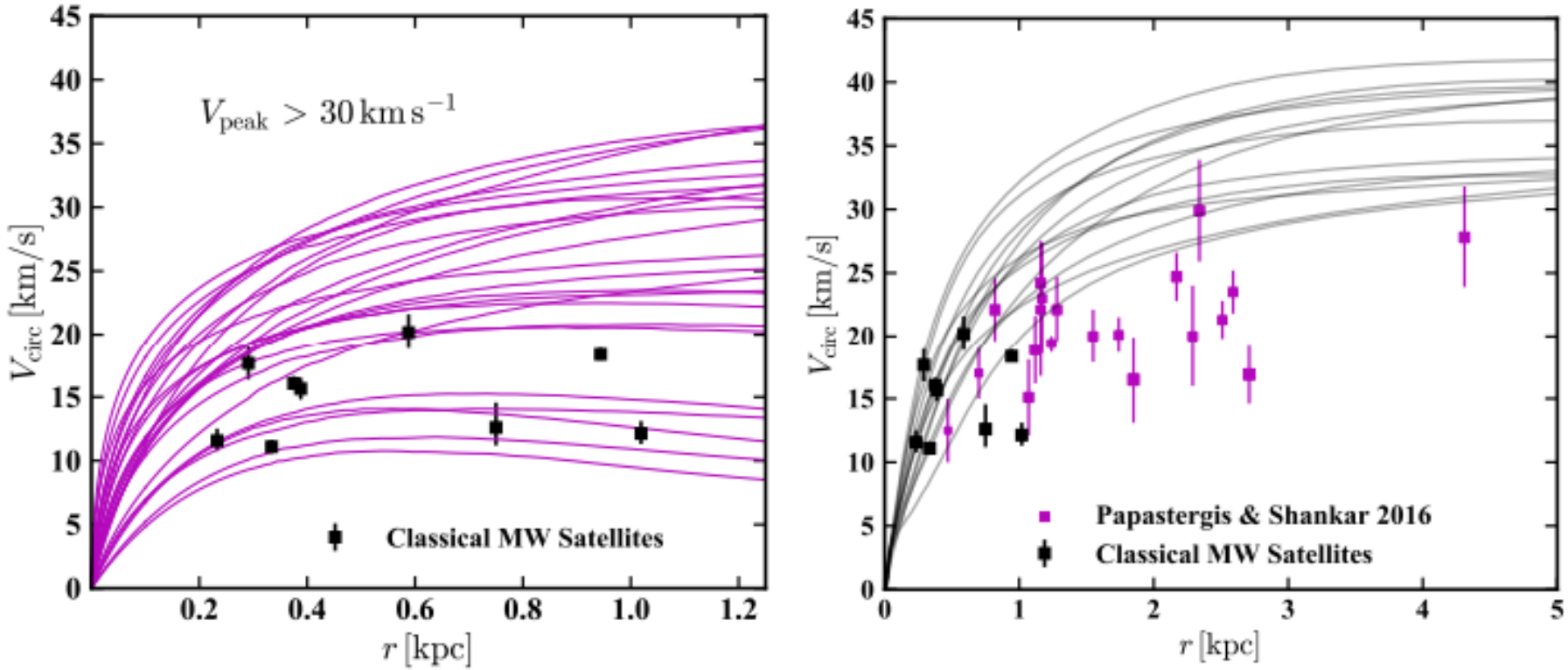


Bullock & Boylan-Kolchin, ARAA 55 (2017) 343

Solutions: baryonic feedback, dwarf galaxies are there but too faint (account for detection efficiency of surveys), tidal stripping, warm DM,...?

Too-big-to-fail problem

Unclear significance: masses of MW satellites do not match masses of most massive subhalos in ΛCDM simulations of MW-mass haloes

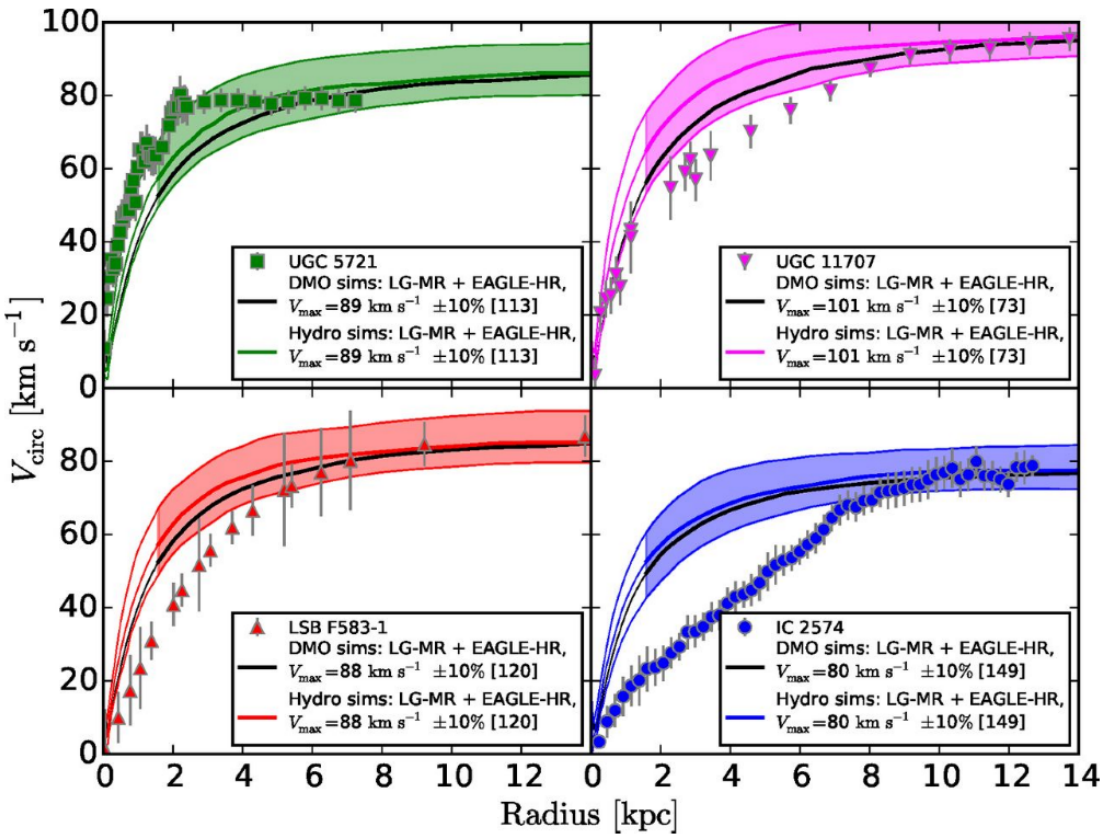


Bullock & Boylan-Kolchin, ARAA 55 (2017) 343

Solutions: baryonic feedback, non-trivial DM physics, MW-satellite interactions (tidal stripping, disk shocking, ram pressure stripping),...?

Diversity problem

Unclear significance: if halo formation is self-similar, why do galaxy rotation curves at fixed $v_{\rm max}$ show huge scatter in inner slopes?

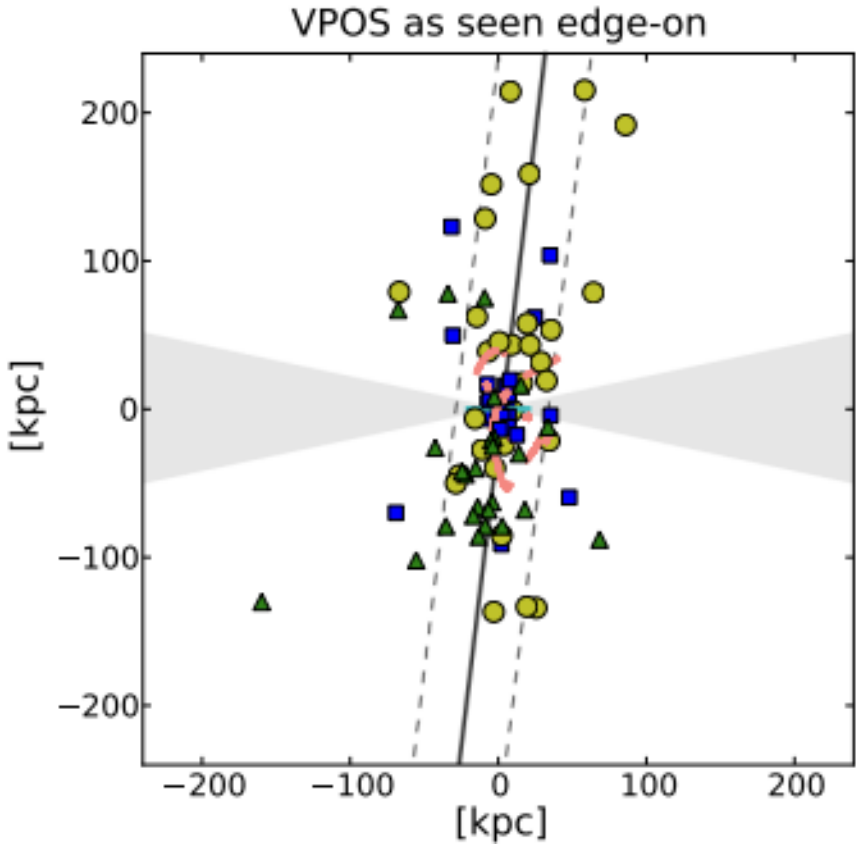


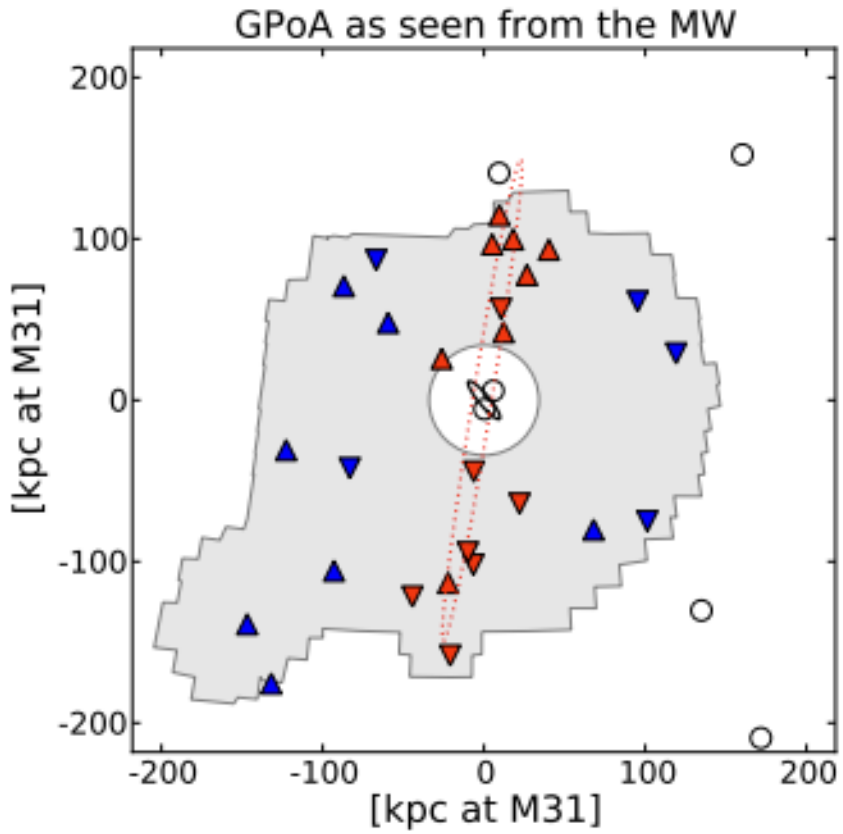
Oman *et al.*, MNRAS 452 (2015) 3650

Solutions: baryonic feedback, non-trivial DM physics,...?

Satellite planes problem

Unclear significance: several satellites of MW, M31, and CenA are part of a very thin plane almost perpendicular to the Galactic disk



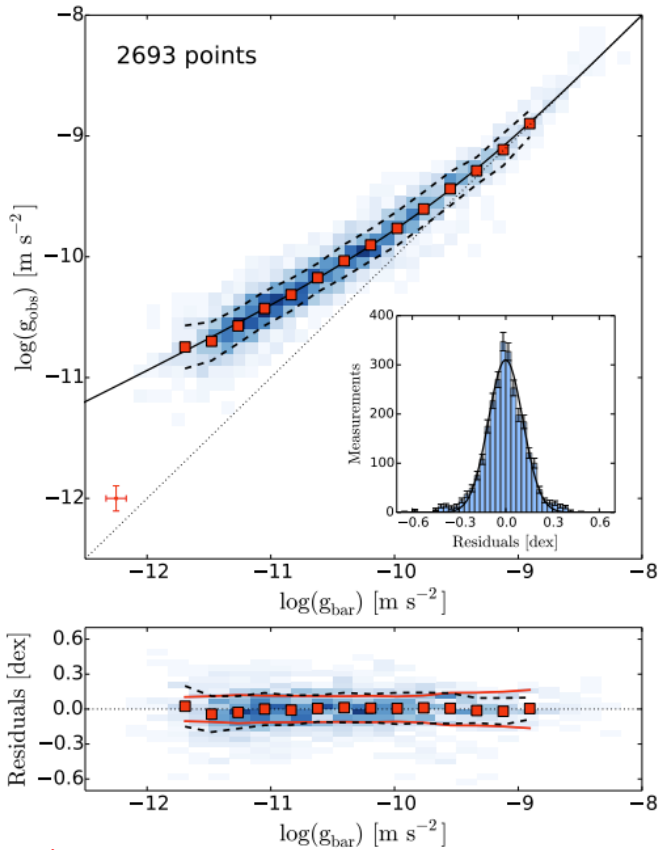


Bullock & Boylan-Kolchin, ARAA 55 (2017) 343

Solutions: filamentary accretion, non-trivial (dissipative) DM physics,...?

Radial acceleration relation

Unclear significance: observed very tight correlation between total radial acceleration g_{obs} and acceleration due to baryons g_{bar}

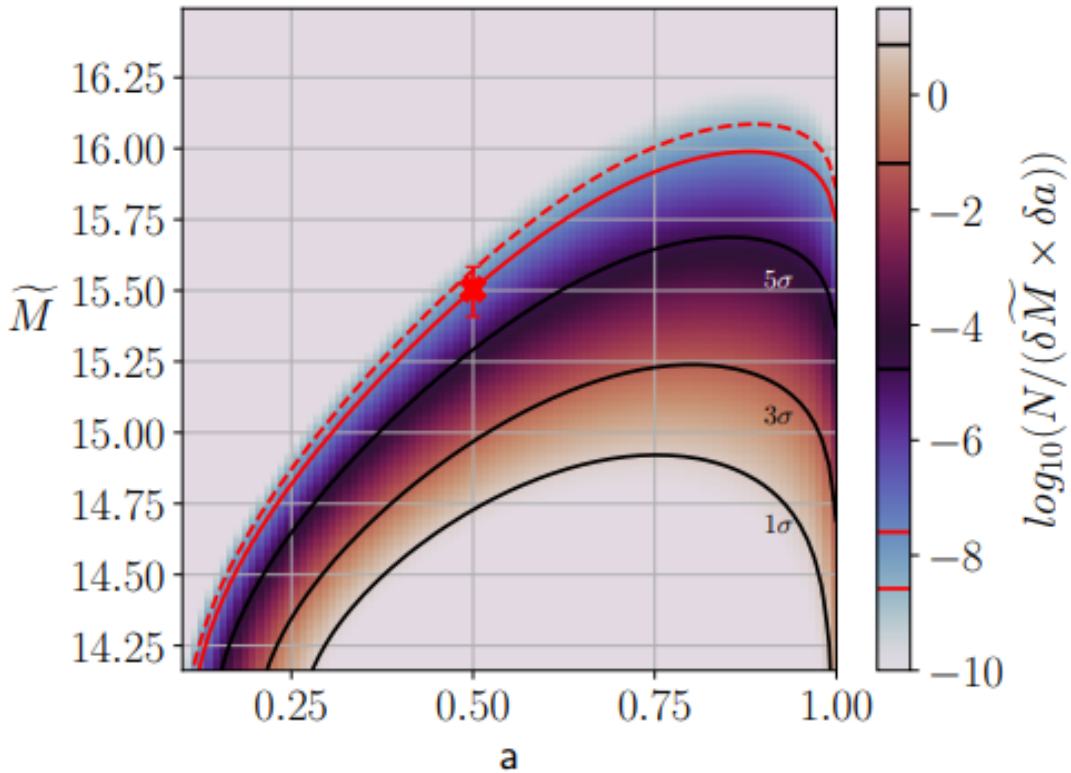


McGaugh, Lelli & Schombert, PRL 117 (2016) 201101

Solutions: baryonic feedback, non-trivial dark sector physics, new dynamical laws (e.g. MOND)...?

High-velocity colliding clusters

Crisis: clusters such as the Bullet Cluster and El Gordo colliding with very high relative velocity, suggesting they formed too early



Asencio *et al.*, MNRAS 500 (2020) 5249

Solutions: accelerated structure formation, new dynamical laws (e.g. MOND with light sterile neutrinos)...?

Conclusions