Title: TBA

Speakers: Benjamin Wallisch

Series: Cosmology & Gravitation

Date: January 10, 2022 - 11:00 AM

URL: https://pirsa.org/22010080

Abstract: Abstract: TBD

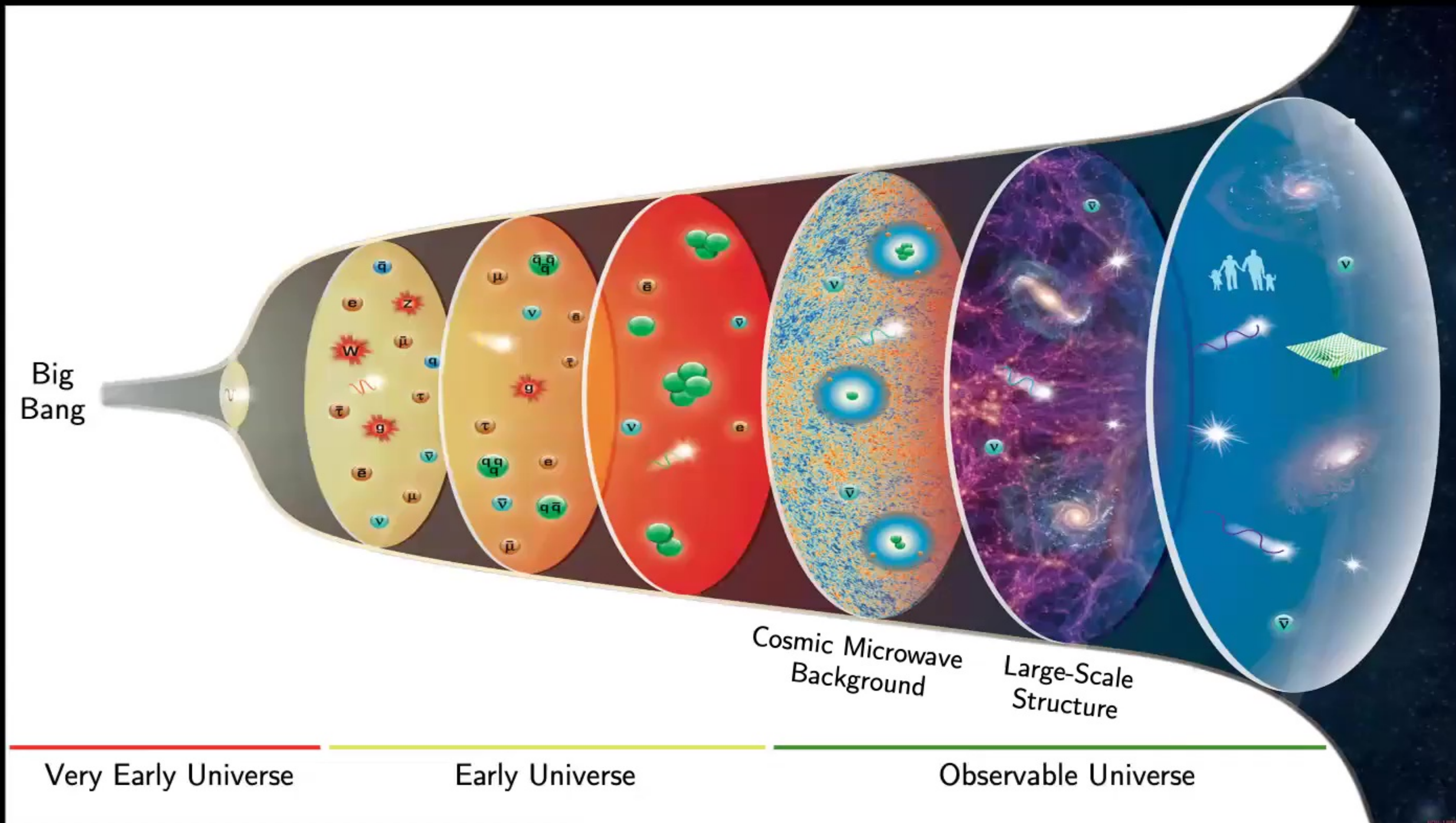
Zoom Link: https://pitp.zoom.us/j/92363291452?pwd=bXJ6L0REQklGcGk0MEk4NGVocElqUT09

Constraining Dark Matter Interactions Throughout Cosmic History

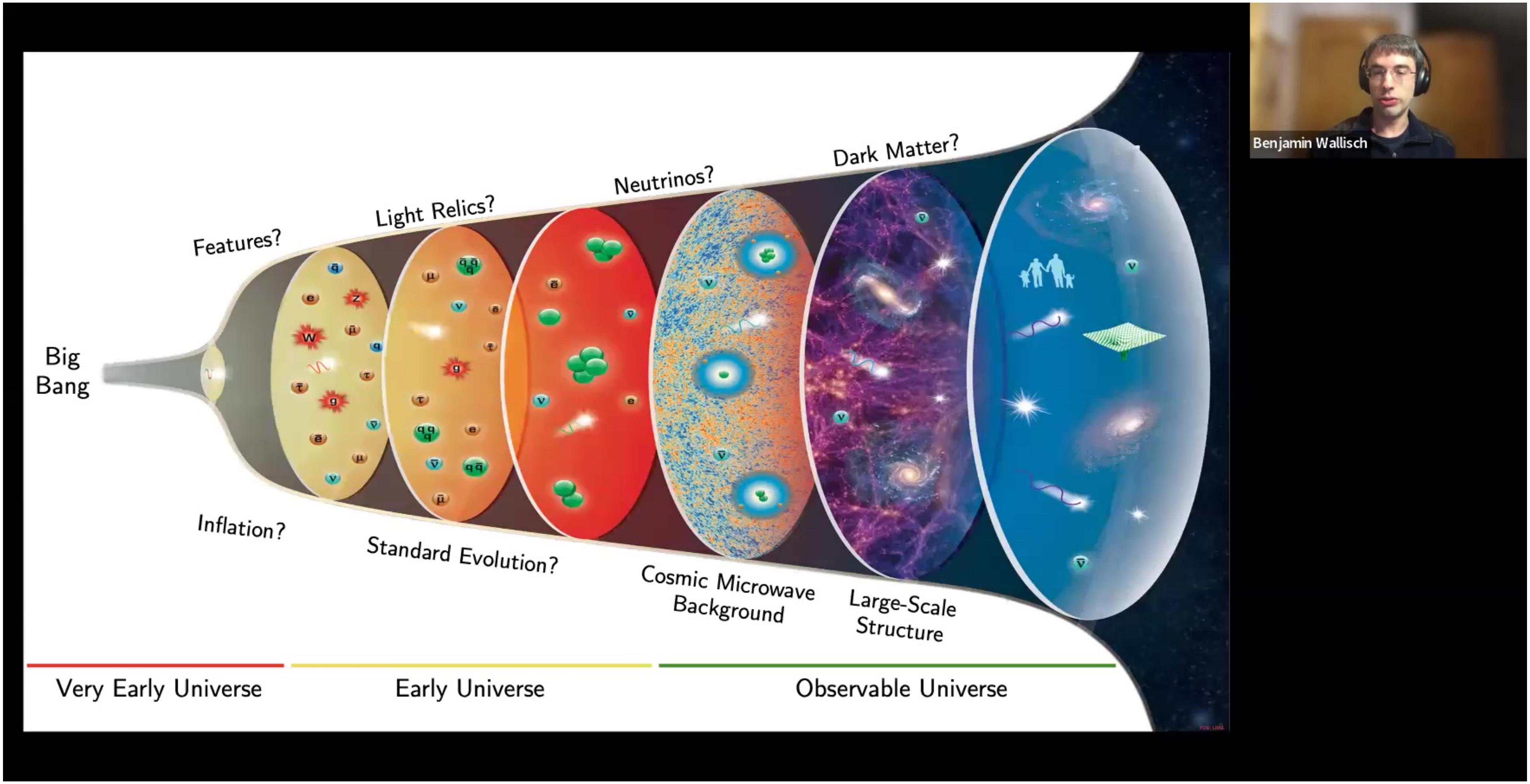
Benjamin Wallisch
Institute for Advanced Study & UC San Diego

Based on ongoing work with Daniel Green

Perimeter Institute, January 2022


Big
Bang
Cosmic Microwave
Background
Large-Scale
Structure
Very Early Universe
Early Universe
Observable Universe


Benjamin Wallisch


Big Bang
Features?
Light Relics?
Neutrinos?
Dark Matter?
Inflation?
Standard Evolution?
Cosmic Microwave Background
Large-Scale Structure
Very Early Universe
Early Universe
Observable Universe
Benjamin Wallisch

Plan of the Talk

- Cosmic Microwave Background and Large-Scale Structure
- Highlights on Primordial Features, Neutrinos and Light Relics
- Dark Matter-Baryon Interactions in the CMB and LSS
- Probing Dark Matter-Baryon Interactions in the Nonlinear Universe
- Conclusions

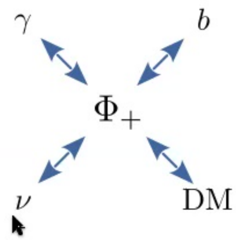
Cosmic Sound Waves

In the early universe, photons and baryons were strongly coupled.

Perturbations excited sound waves in the photon-baryon fluid:

$$\ddot{\delta}_\gamma - c_\gamma^2 \nabla^2 \delta_\gamma = \nabla^2 \Phi_+$$

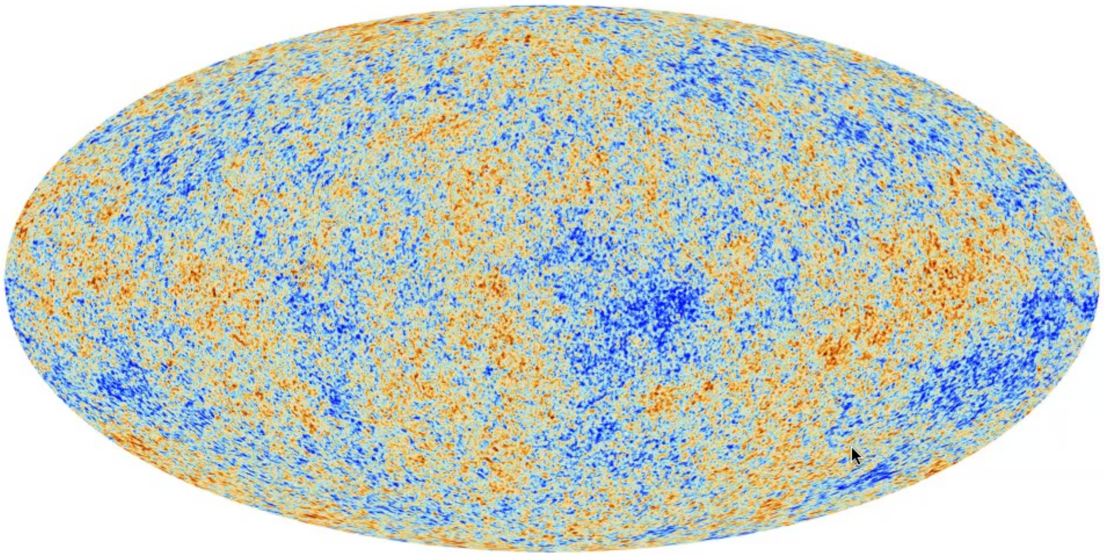
sound waves — pressure — gravity



These acoustic oscillations have been observed...

Cosmic Sound Waves

... in the correlations of the cosmic microwave background (CMB) anisotropies:



Planck (2015)

Cosmic Sound Waves

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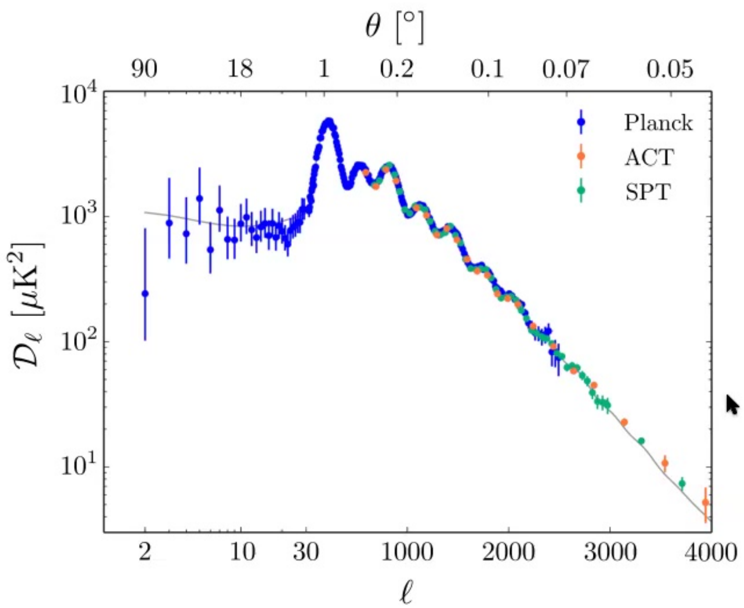
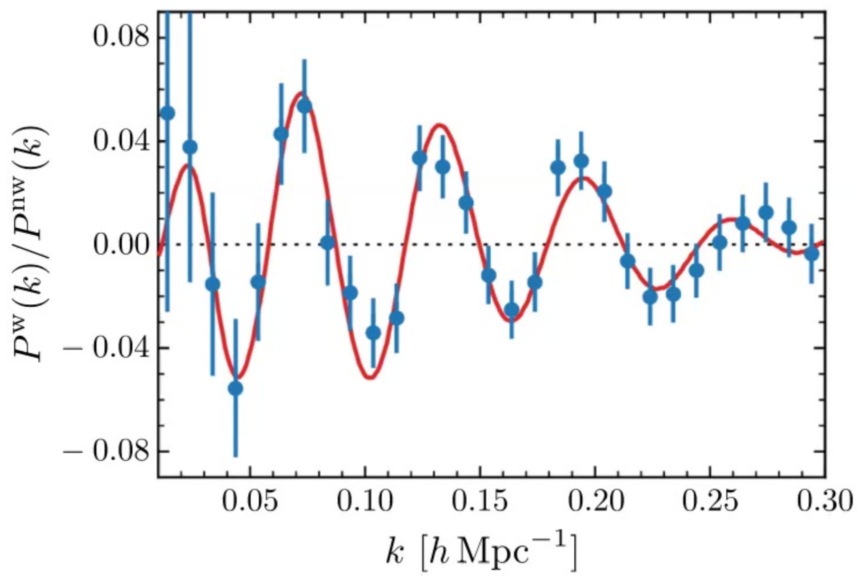


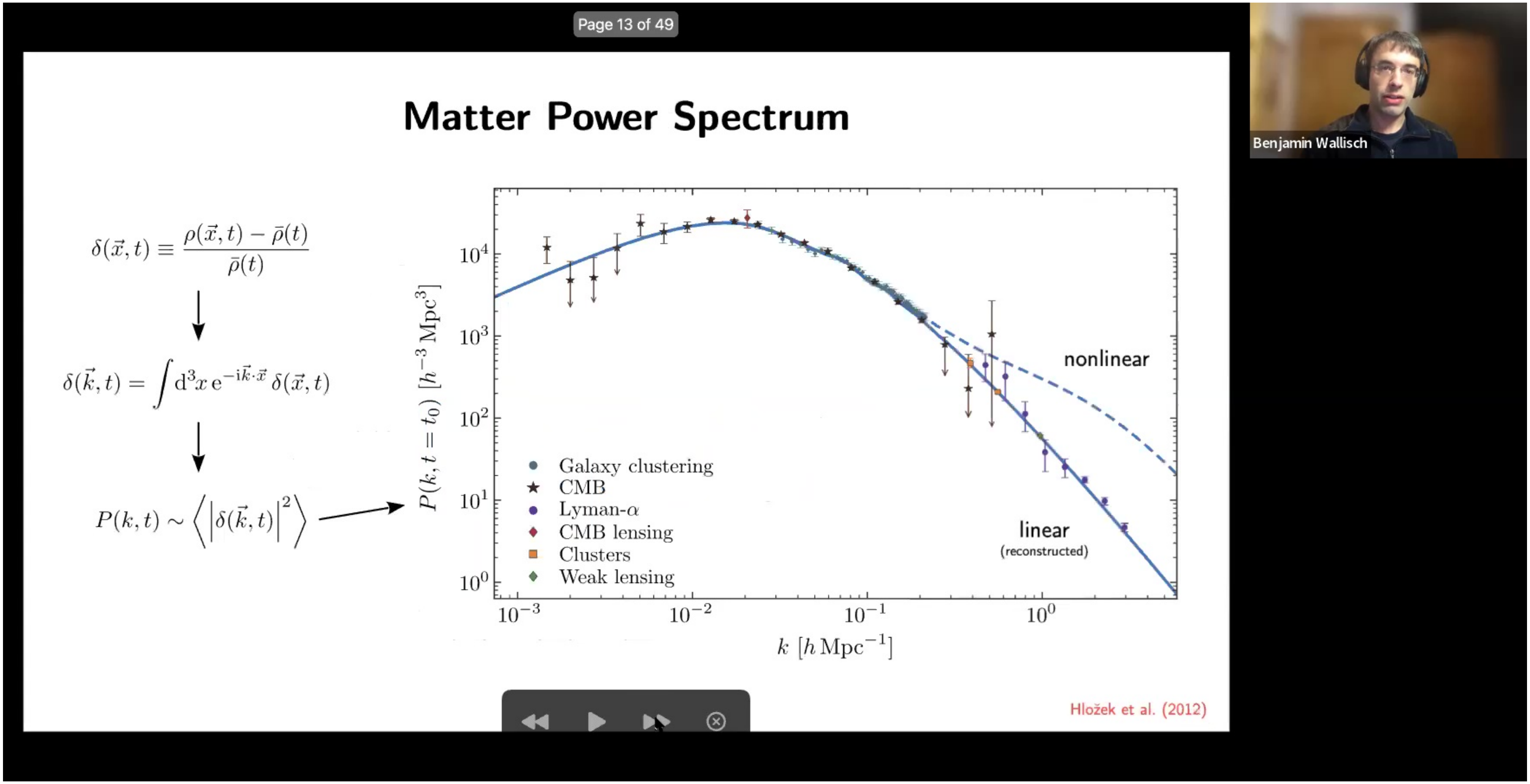
Planck (2015)

Cosmic Sound Waves

… and in the distribution of galaxies in the universe via the spectrum of baryon acoustic oscillations (BAO):



BOSS (2016)


Page 13 of 49
Benjamin Wallisch
Matter Power Spectrum
$\delta(\vec{x},t) \equiv \frac{\rho(\vec{x},t)-\bar{\rho}(t)}{\bar{\rho}(t)}$
$\delta(\vec{k},t) = \int \mathrm{d}^3x\, \mathrm{e}^{-\mathrm{i}\vec{k}\cdot\vec{x}}\, \delta(\vec{x},t)$
$P(k,t) \sim \left\langle \left|\delta(\vec{k},t)\right|^2 \right\rangle$
$P(k, t=t_0)\ [h^{-3}\,\mathrm{Mpc}^3]$
$k\ [h\,\mathrm{Mpc}^{-1}]$
Galaxy clustering
CMB
Lyman-α
CMB lensing
Clusters
Weak lensing
nonlinear
linear
(reconstructed)
Hložek et al. (2012)

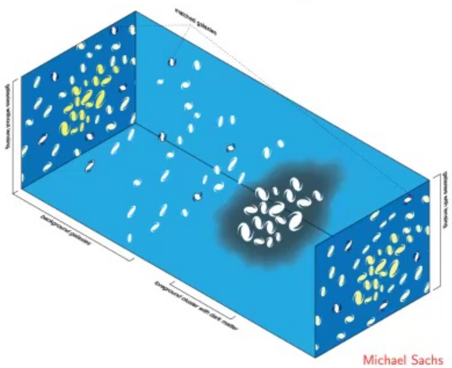
Why Consider Large-Scale Structure?

- Additional observational information.
- Complementary to cosmic microwave background observations.
- More observable modes: 2d (CMB) versus 3d (LSS).
- More statistical power (in principle).
- Accessibility of smaller scales (in principle).
- Vast observational effort in next few years:
  DES, DESI, LSST, Euclid, SPHEREx, WFIRST, ...

$\rightarrow$ Another window onto our universe!

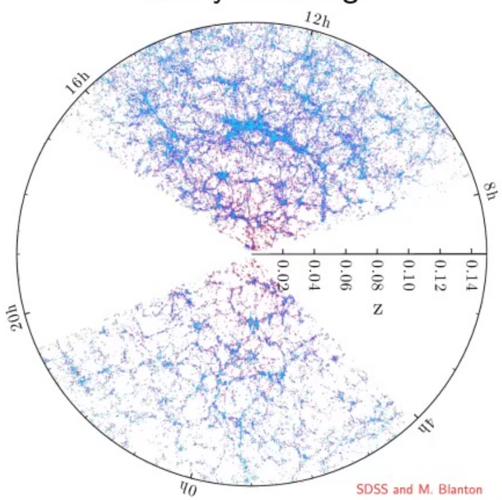
Some Large-Scale Structure Observables

Weak lensing



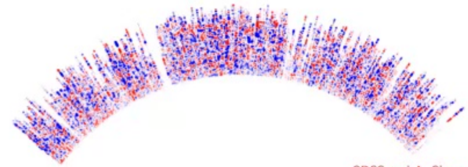
Michael Sachs

Galaxy clustering



SDSS and M. Blanton

Lyman-α forest



SDSS and A. Slosar

Galaxy clusters

NASA, ESA and M. Brodwin

Primordial Features

Several inflationary (and other primordial) scenarios predict additional features:

$$P_\zeta(k) = P_{\zeta,0}(k) + \Delta P_\zeta(k)$$

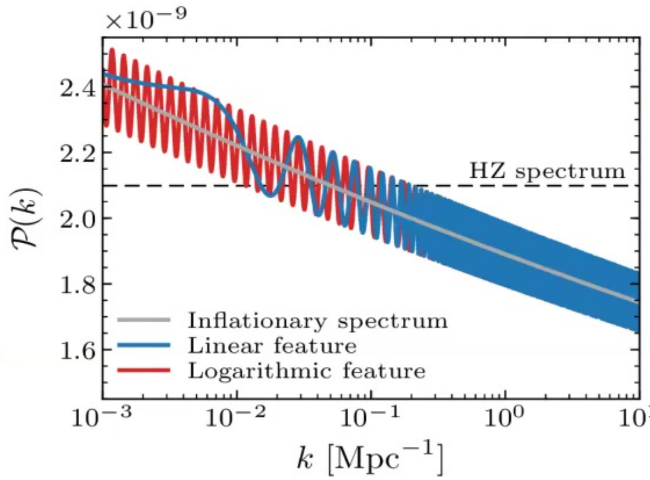
such as

- linearly-spaced oscillatory features:

$$\frac{\Delta P_\zeta(k)}{P_{\zeta,0}} = A_{\mathrm{lin}}\, \sin(\omega_{\mathrm{lin}} k + \phi_{\mathrm{lin}})\,,$$

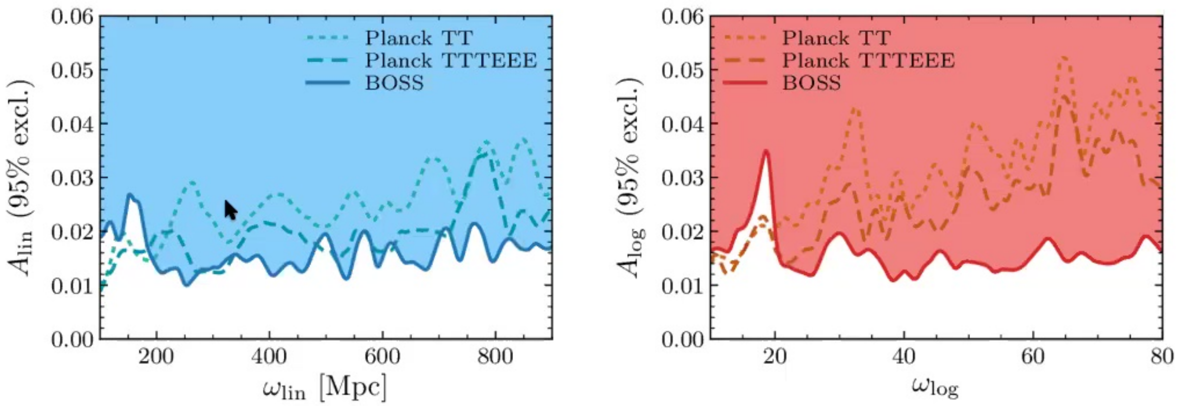
- logarithmically-spaced oscillatory features:

$$\frac{\Delta P_\zeta(k)}{P_{\zeta,0}} = A_{\mathrm{log}}\, \sin(\omega_{\mathrm{log}} \log(k/k_\star) + \phi_{\mathrm{log}})\,.$$



Upper Limits from LSS and CMB

Thanks to our theoretical advances, upper limits from the BOSS DR12 dataset compared to Planck 2015:



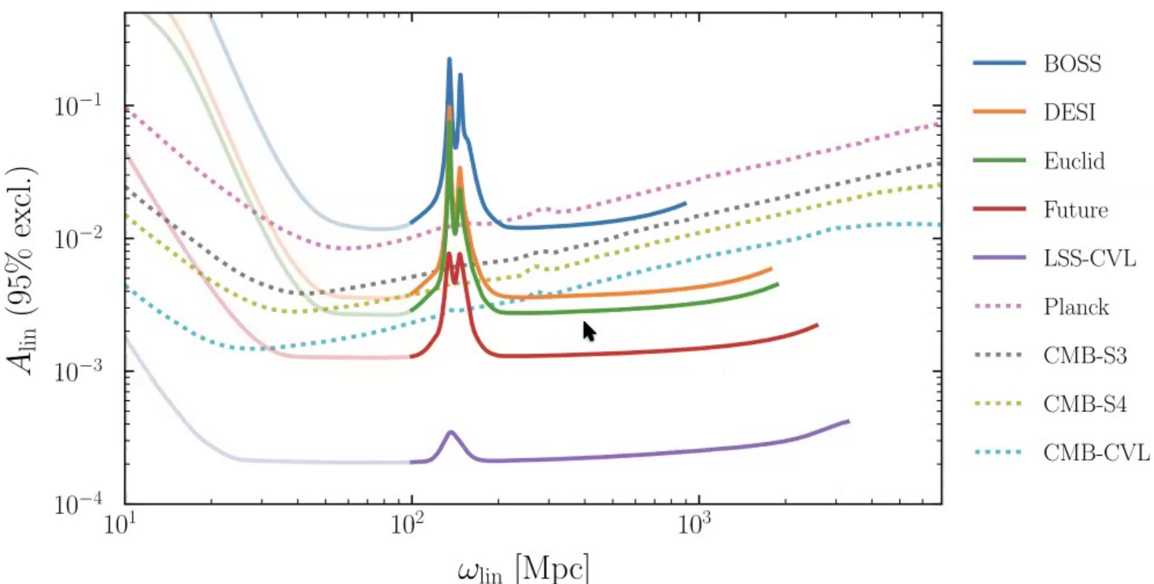
→ Feature amplitudes are limited to $\mathcal{O}(1\%)$ relative to the primordial amplitude.

→ Competitive with current CMB constraints in available frequency range.

Beutler, Biagetti, Green, Slosar & BW (2019)

Future Prospects for Primordial Features

The sensitivity to primordial features will greatly improve with future observations:



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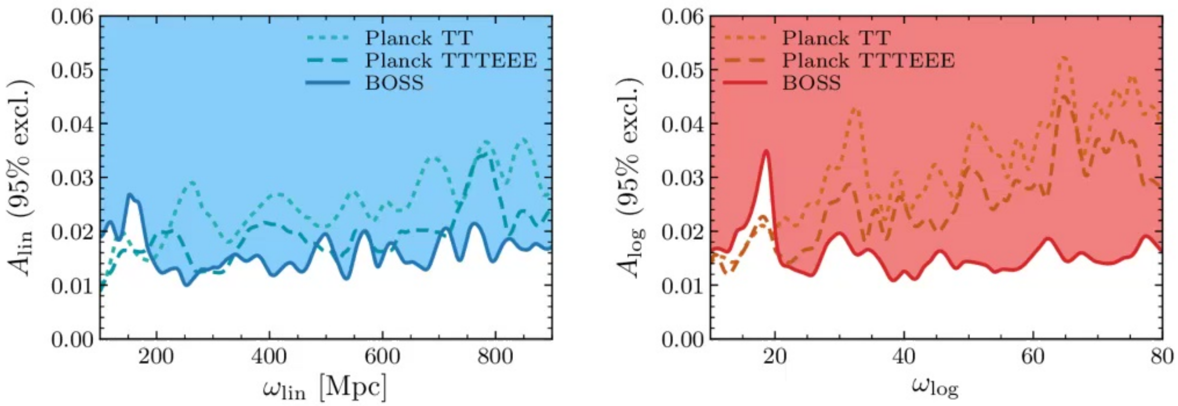

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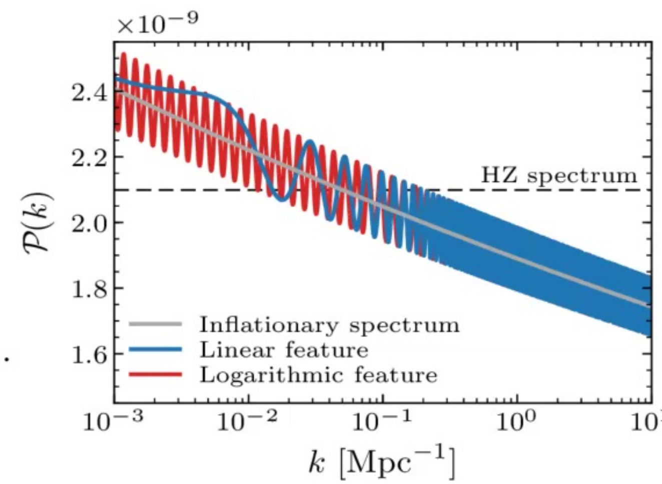


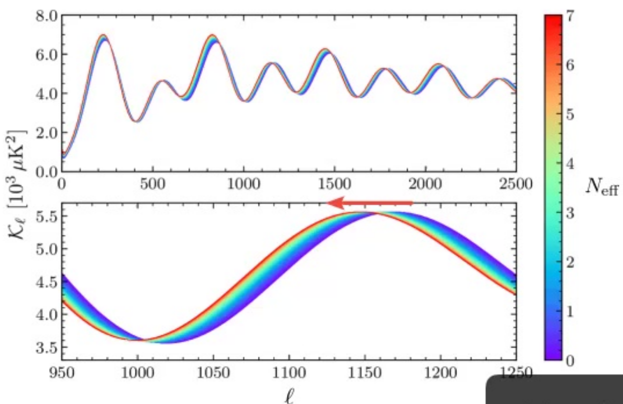
Cosmic Neutrinos

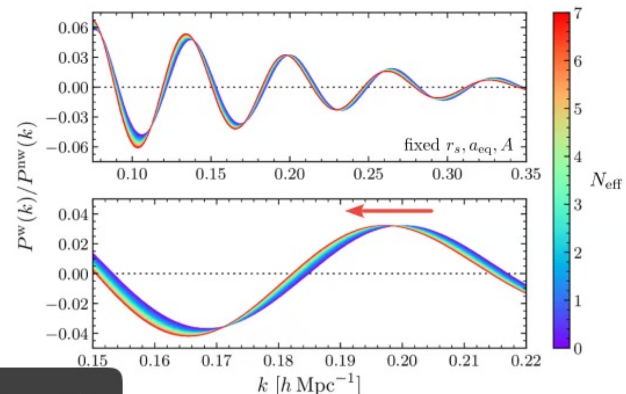
- 41% of the radiation density in the universe:
  - → Leave gravitational imprint,
  - → Can detect their energy density.

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

$$N_{\rm eff}^{\rm SM} = 3.044$$

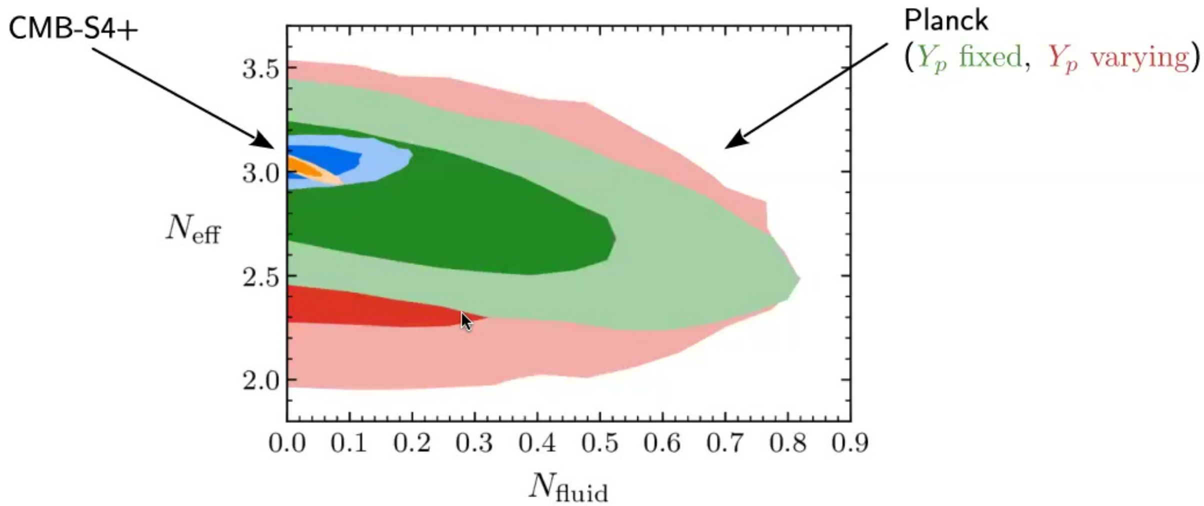
- Free-streaming since their decoupling at $T \sim 1\,\mathrm{MeV}$.
- Free-streaming neutrinos overtake the photons and pull them ahead of the sound horizon.





Constraining Free-Streaming Neutrinos with the CMB

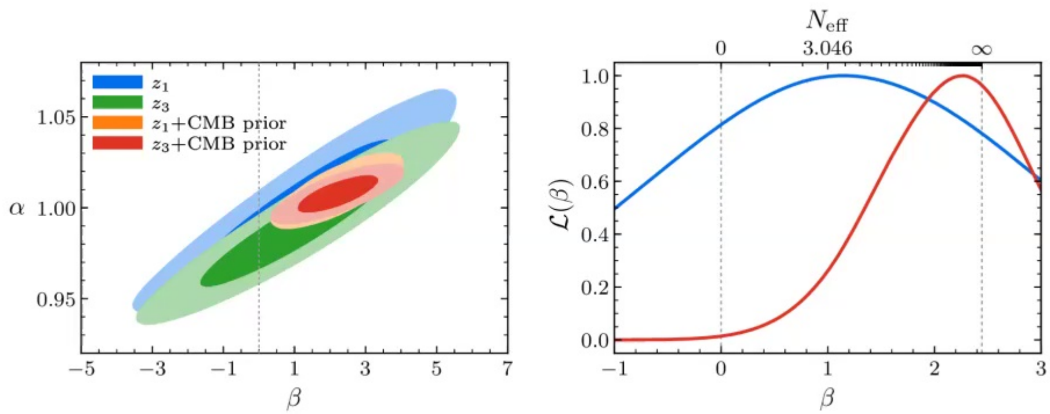
The neutrino-induced phase shift allows to distinguish free-streaming from fluid-like dark radiation/neutrinos:



Baumann, Green, Meyers & BW (2015); see also Follin, Knox, Millea & Pan (2015)

First Constraint on Phase Shift from LSS

The neutrino-induced phase shift can be measured in the BOSS DR12 dataset:



$\beta = 2.22 \pm 0.75$

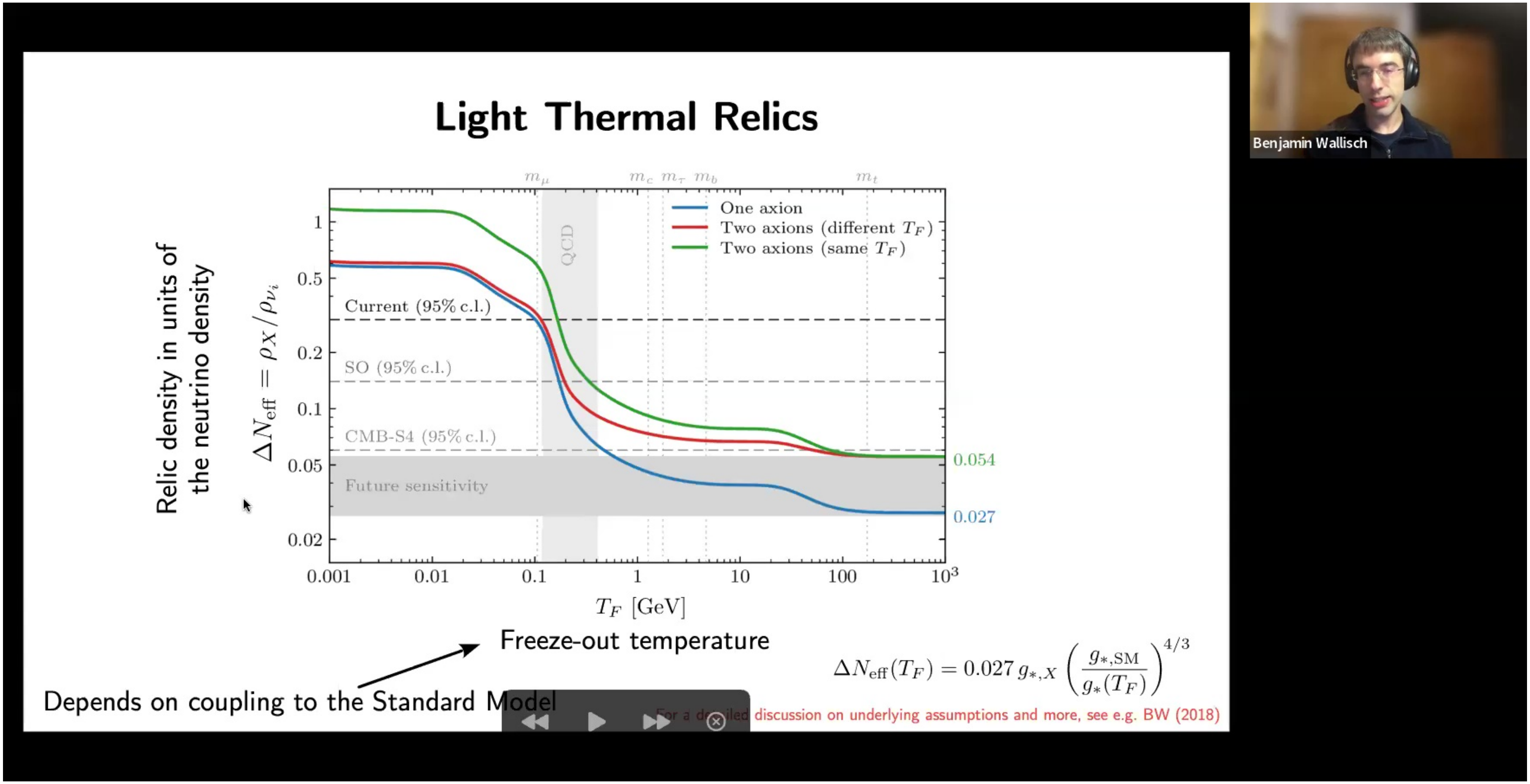
$\beta > 0$ at $> 99\%$ c.l.

(CMB prior from Planck 2018)

This is a proof of principle for directly extracting information on neutrinos (and other light relics) from galaxy clustering data.

Future observations will greatly improve on this first measurement.

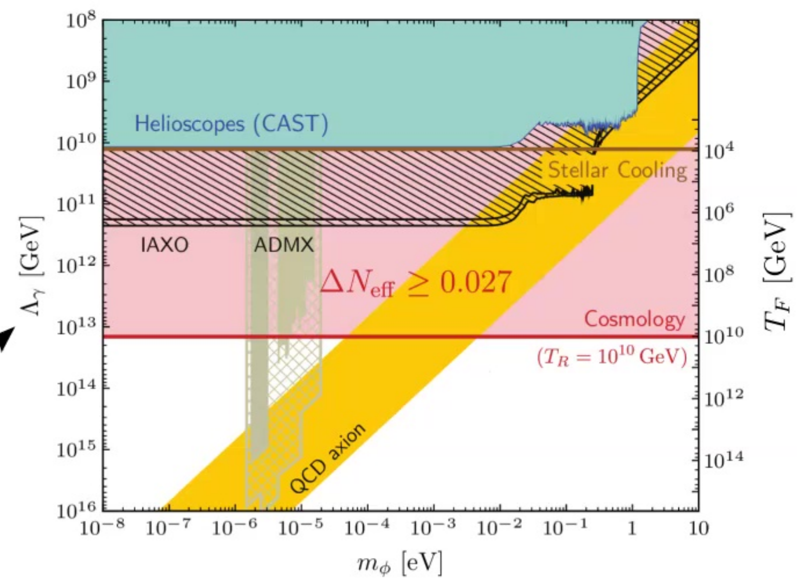
Baumann, Green & BW (2018); Baumann, Beutler, ..., BW, ... (2019)


Light Thermal Relics
Benjamin Wallisch
Relic density in units of the neutrino density
$\Delta N_{\rm eff} = \rho_X / \rho_{\nu_i}$
One axion
Two axions (different T_F)
Two axions (same T_F)
QCD
m_μ m_c m_τ m_b m_t
Current (95% c.l.)
SO (95% c.l.)
CMB-S4 (95% c.l.)
Future sensitivity
0.054
0.027
T_F [GeV]
Freeze-out temperature
Depends on coupling to the Standard Model
$\Delta N_{\rm eff}(T_F) = 0.027\, g_{*,X} \left(\frac{g_{*,\rm SM}}{g_*(T_F)}\right)^{4/3}$
discussion on underlying assumptions and more, see e.g. BW (2018)

Constraints on the Axion Coupling to Photons

Exclusion of $\Delta N_{\rm eff} = 0.027$ implies strong constraints on couplings to the Standard Model:

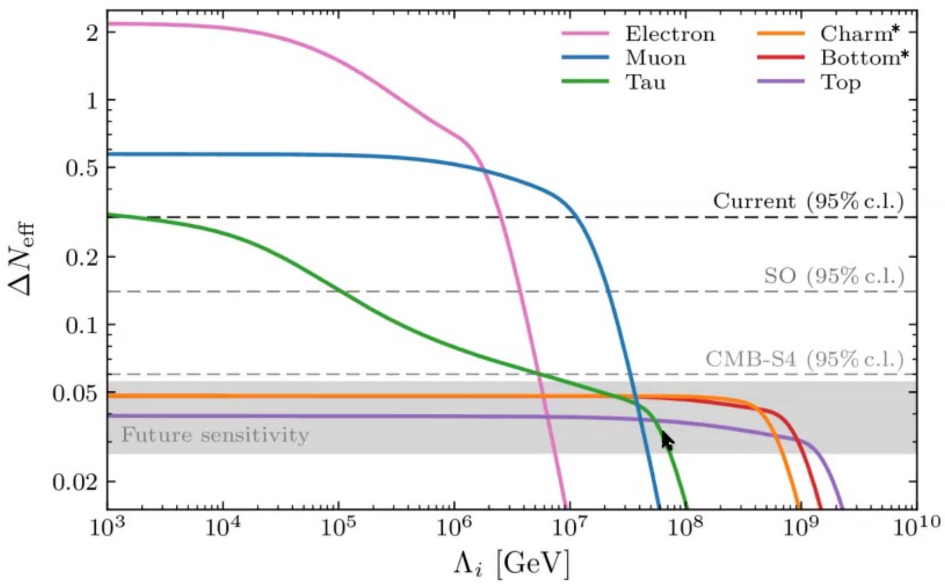
$$-\frac{\phi}{4\Lambda_\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Baumann, Green & BW (2016)

Predictions for ΔN_{eff}

Our predictions in comparison to current and future constraints from avoiding freeze-in:

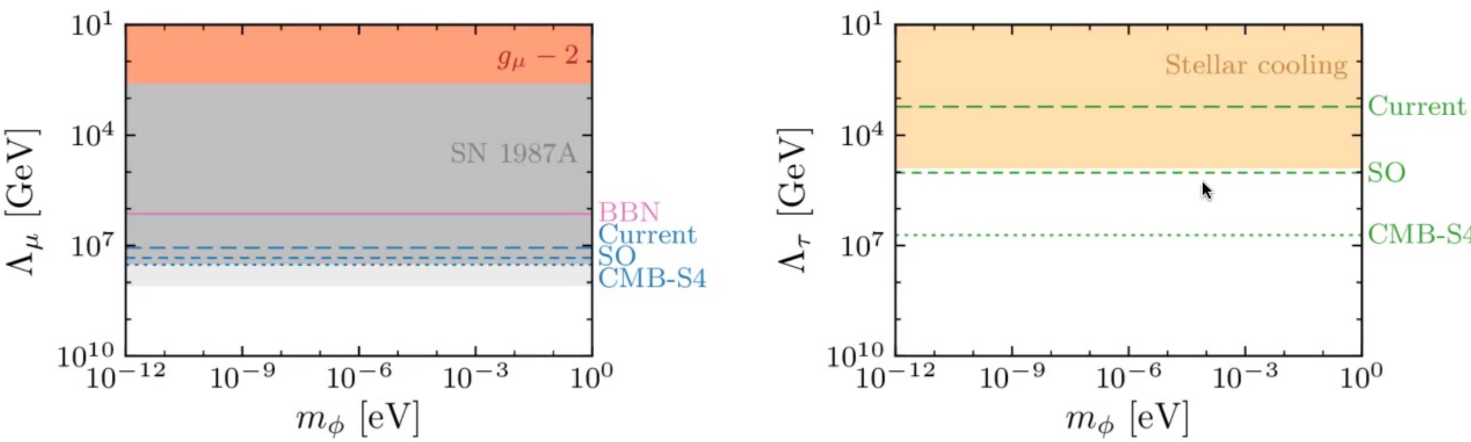


* Calculations for charm and bottom couplings are impacted by the QCD phase transition. Here: conservative estimate, might be larger.

Green, Guo & BW (2021)

Comparison to Astrophysical and Terrestrial Constraints

Current and upcoming CMB surveys (including CMB-S4) can put complimentary and competitive constraints on axion-fermion couplings by avoiding freeze-in:

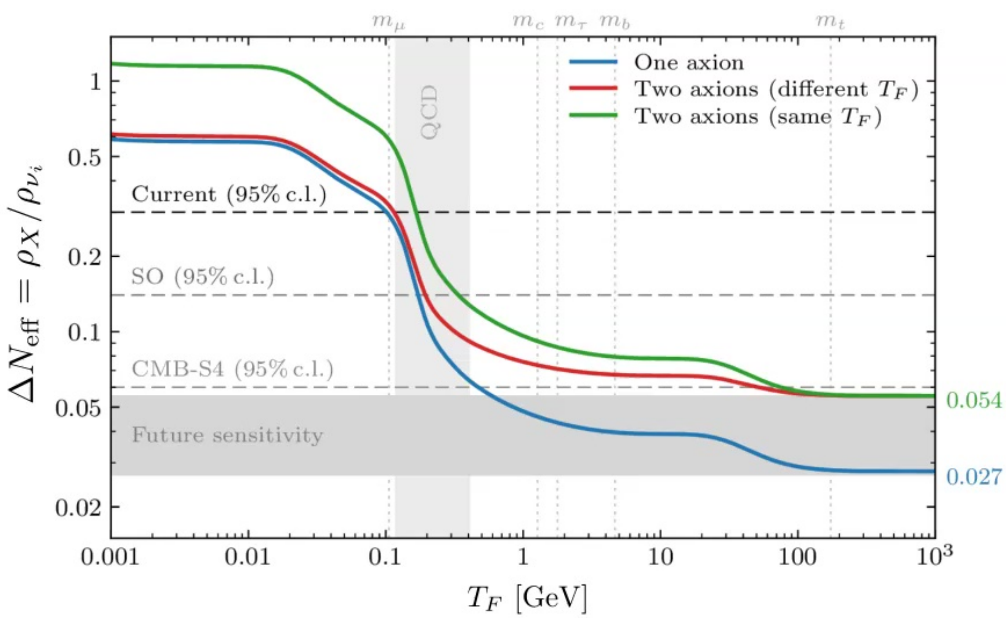


cf. Feng et al. (1998); Andreas et al. (2010); Bollig et al. (2020); Croon et al. (2021)

Green, Guo & BW (2021)

Light Thermal Relics

Relic density in units of the neutrino density



Freeze-out temperature

Depends on coupling to the Standard Model

$$\Delta N_{\mathrm{eff}}(T_F) = 0.027\, g_{*,X} \left(\frac{g_{*,\mathrm{SM}}}{g_*(T_F)} \right)^{4/3}$$

For a detailed discussion on underlying assumptions and more, see e.g. BW (2018)

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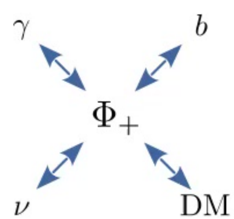
Dark Matter Properties in LCDM

- Distinct from baryons/Standard Model particles,
- Cold/non-relativistic,
- Collisionless,
- Abundance: about 6x of baryons.



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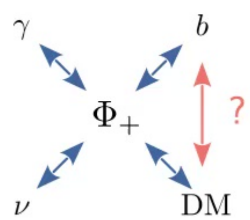
? →



Dark Matter-Baryon Interactions

- Effective field theory:

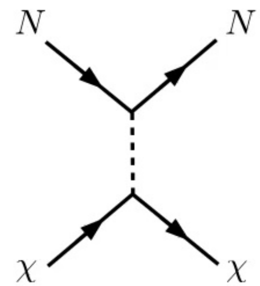
$$\mathcal{L} \sim O_\chi \, O_N$$

operator with dark matter fields

$\bar{\chi}\,\chi$

$\mathrm{i}\bar{\chi}\,\gamma^5\,\chi$

$\vdots$



operator with baryon/nucleon fields

$\bar{N}\,N$

$\mathrm{i}\bar{N}\,\gamma^5\,N$

$\vdots$

- Effective description in terms of velocity-dependent cross-section:

$$\sigma(v) = \sigma_0 v^n$$

Linear Perturbation Theory

- Effective description in terms of velocity-dependent cross-section:

$$\sigma(v) = \sigma_0 v^n$$

- Boltzmann equations:

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}\,, \qquad \dot{\theta}_\chi = -\mathcal{H}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)\,,$$

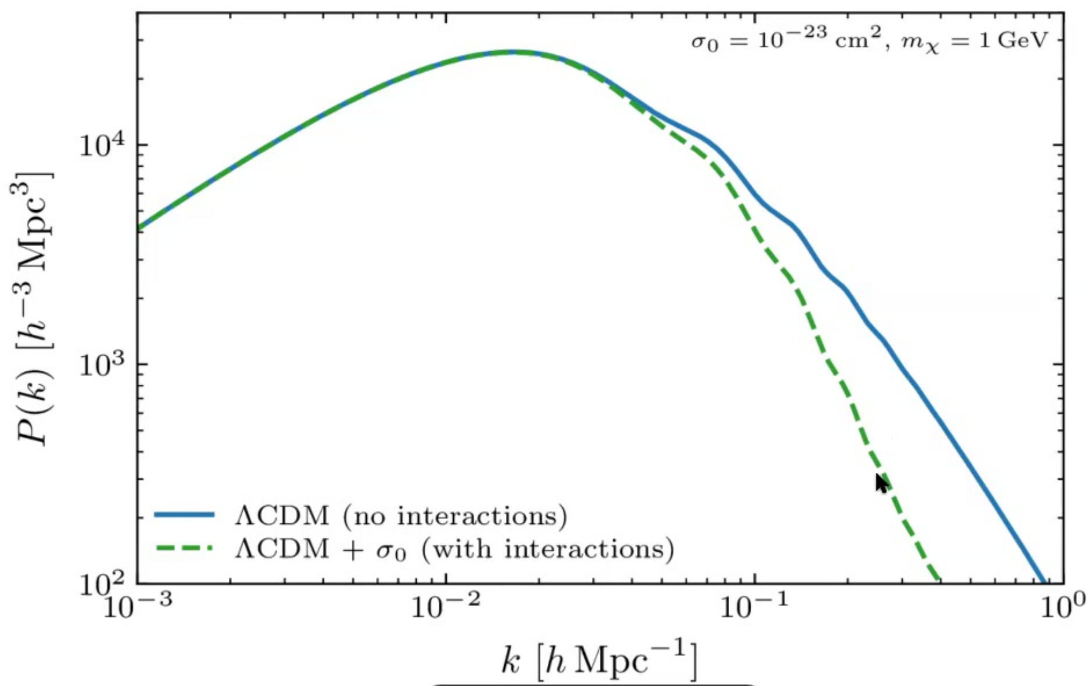
$$\dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2}\,, \qquad \dot{\theta}_b = -\mathcal{H}\theta_b + c_b^2 k^2 \delta_b + R_\gamma(\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b} R_\chi(\theta_\chi - \theta_b)\,.$$

- Dark matter-baryon momentum exchange rate:

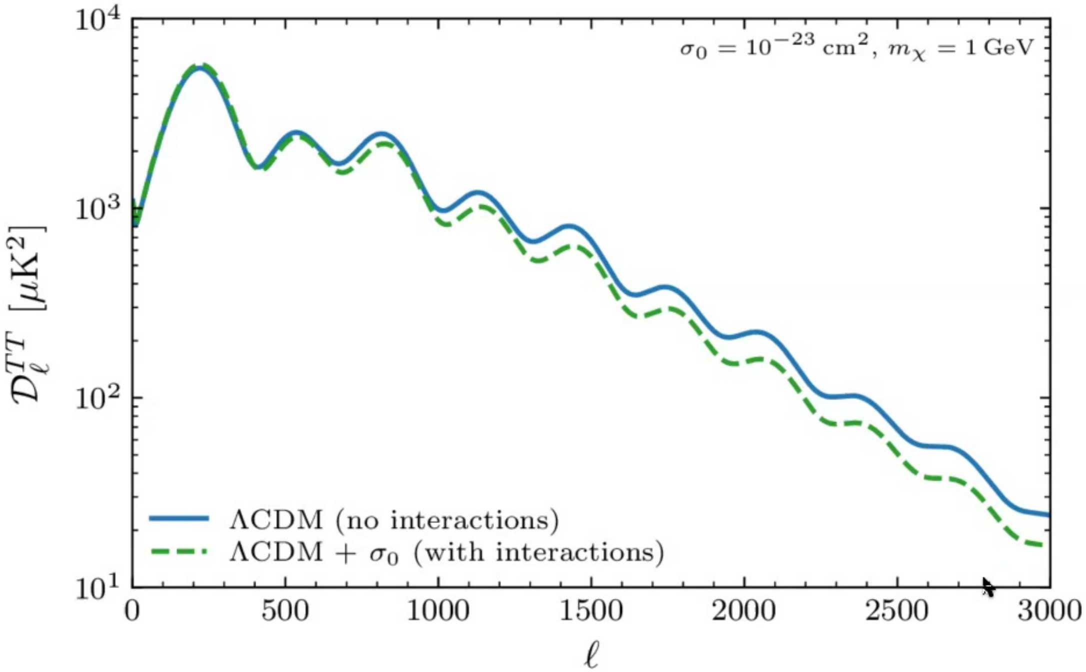
$$R_\chi = \frac{a c_n \rho_b \sigma_0}{m_\chi + m_H} \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} \right)^{\frac{n+1}{2}} F_{\mathrm{He}}$$

cf. Ma & Bertschinger (1995), Chen et al. (2002), Sigurdson et al. (2004), Dvorkin et al. (2014), Gluscevic & Boddy (2018), ...

Matter Power Spectrum

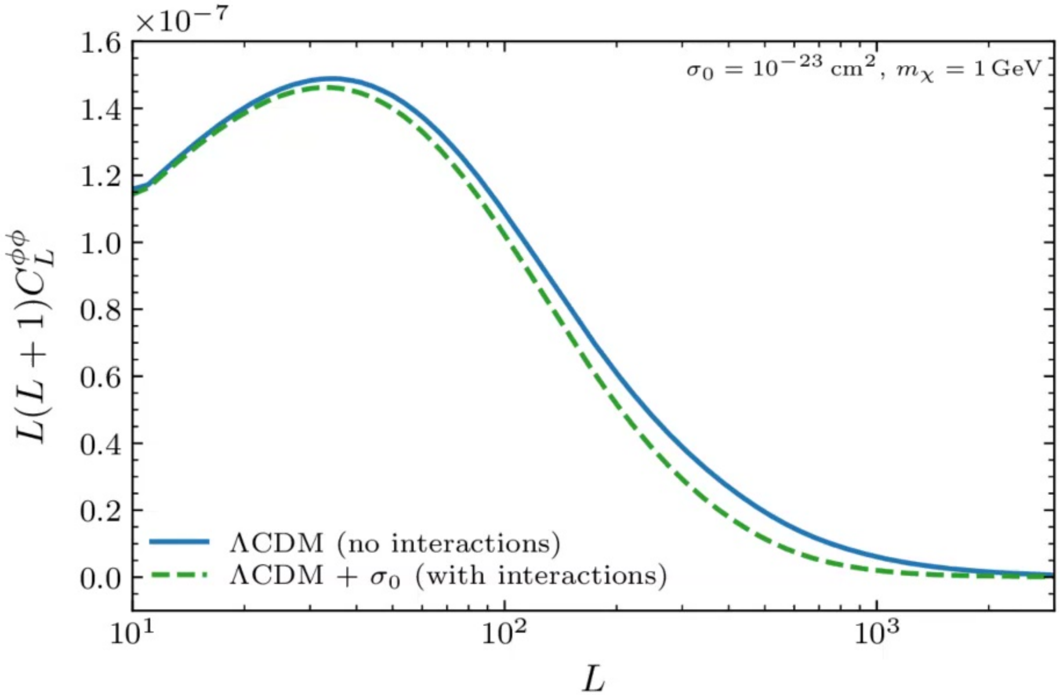


CMB Temperature Power Spectrum

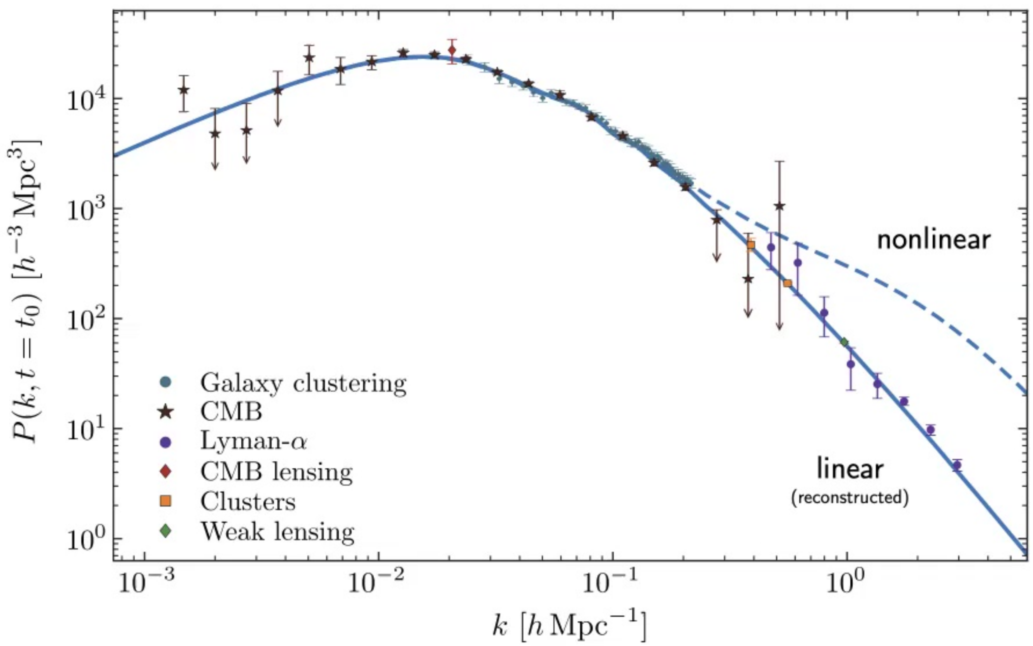


→ Planck constraints by Dvorkin (2014), Boddy & Gluscevic (2018), ...

Linear CMB Lensing Power Spectrum



But Remember: Gravitational Nonlinearities...



Hložek et al. (2012)

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Nonlinear Modeling of the Galaxy Power Spectrum

- Effective field theory of large-scale structure at 1-loop:

$$P_{\text{1-loop}}(k,z) = P_{\text{1-loop,SPT}}(k,z) + P_{\text{ctr}}(k,z)$$

$$P_{\text{1-loop,SPT}} \sim P_{\text{lin}} \int P_{\text{lin}} + \int P_{\text{lin}}^2 \qquad\qquad P_{\text{ctr}} \sim c_s k^2 P_{\text{lin}}$$

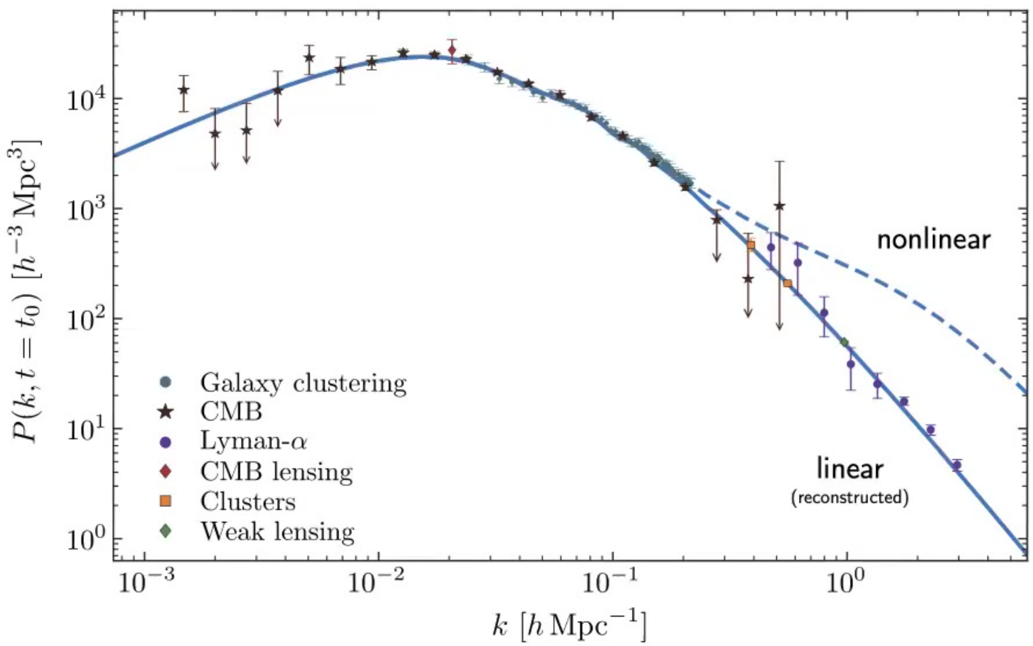
- Bias expansion:

$$P_g(k,z) = b_1^2(z)\left[P_{\text{lin}}(k,z) + P_{\text{1-loop,SPT}}(k,z)\right] + b_1(z) b_2(z) \mathcal{I}_{\delta^2}(k,z)$$
$$+ \{b_1, b_2, b_3, b_{\mathcal{G}_3}, \ldots\}$$

- Express in redshift space

cf. Baumann et al., Senatore et al., Baldauf et al.; following CLASS-PT implementation [Chudaykin et al.]

But Remember: Gravitational Nonlinearities...



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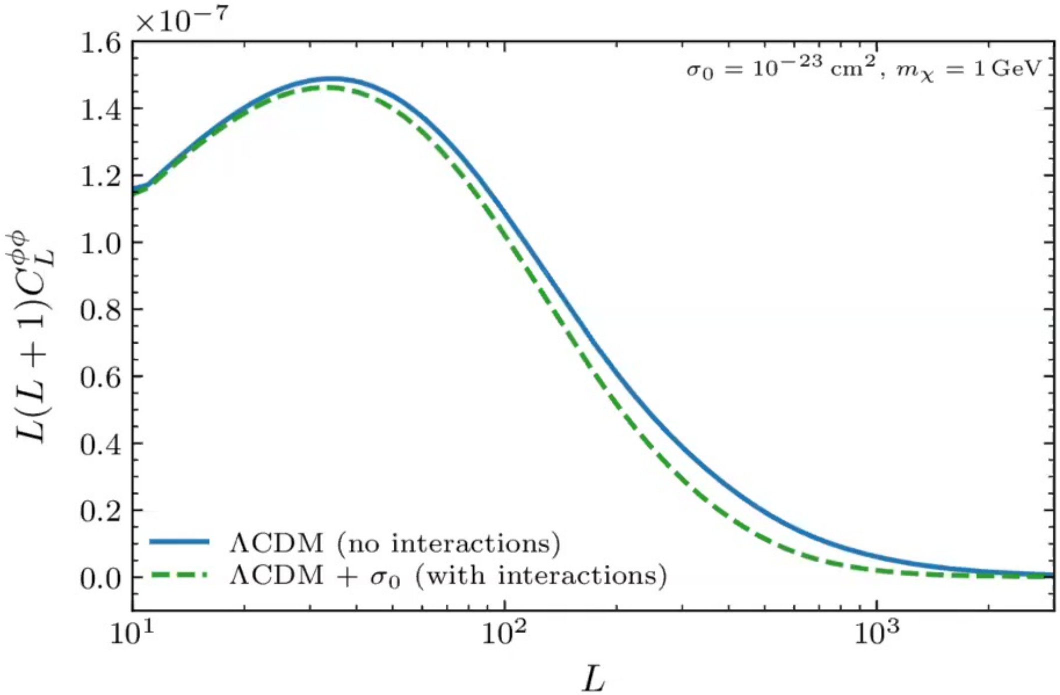

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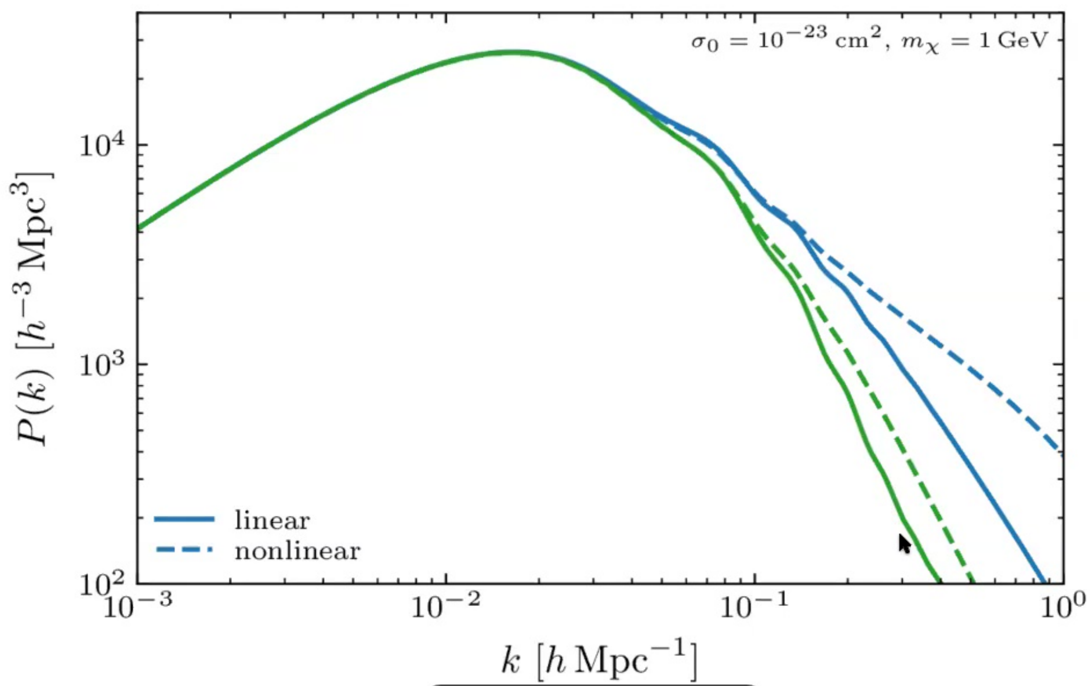
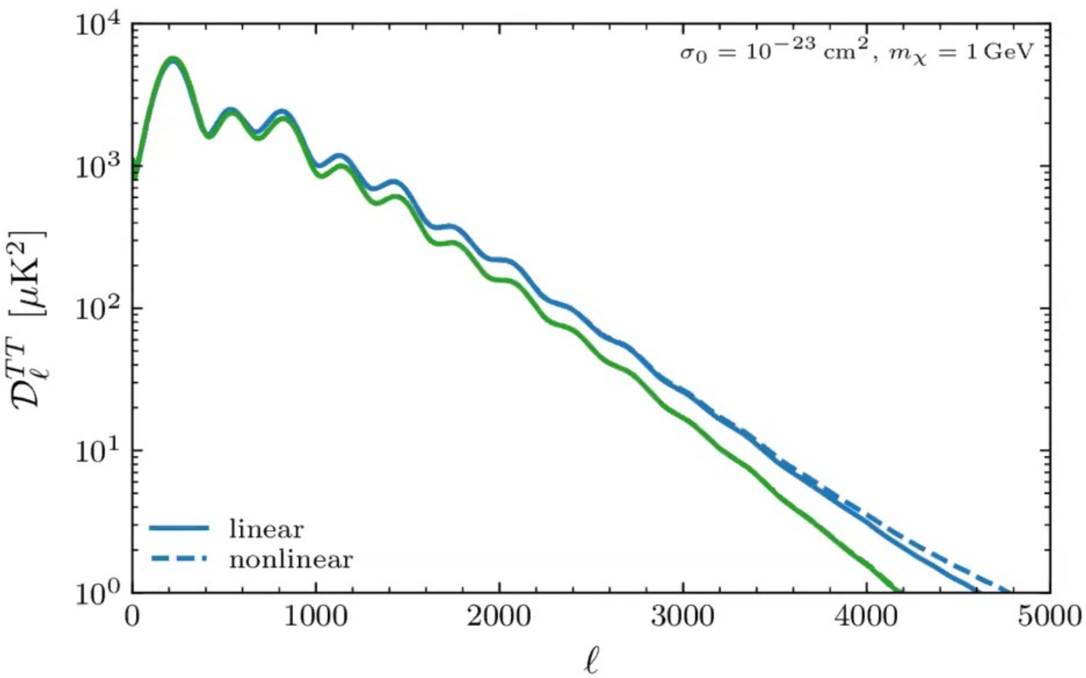
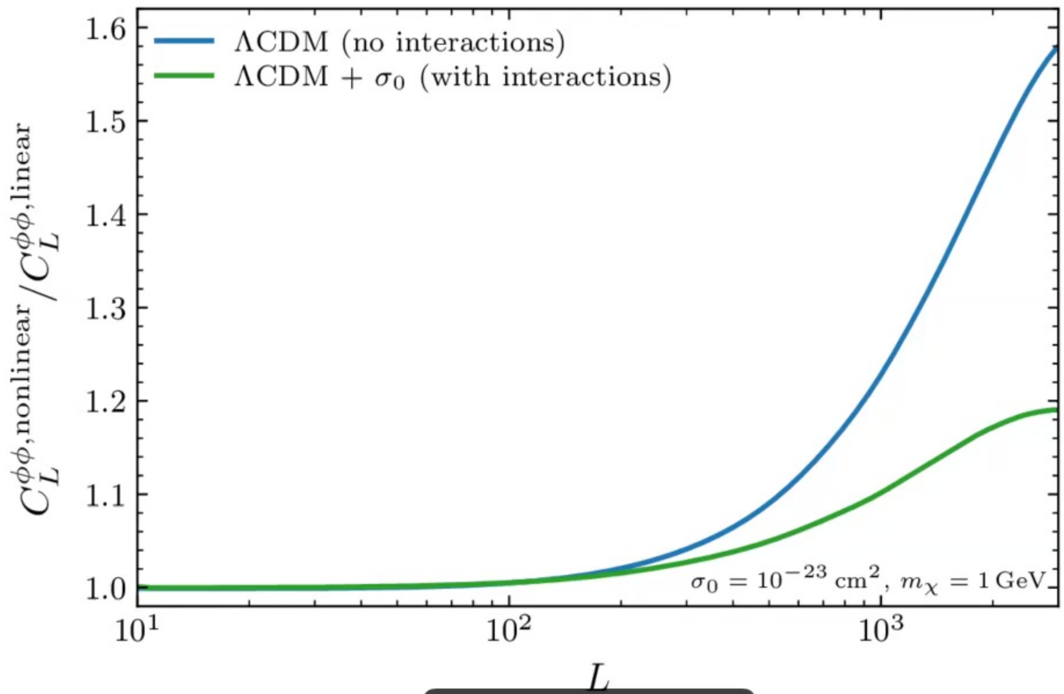


CMB Temperature Power Spectrum



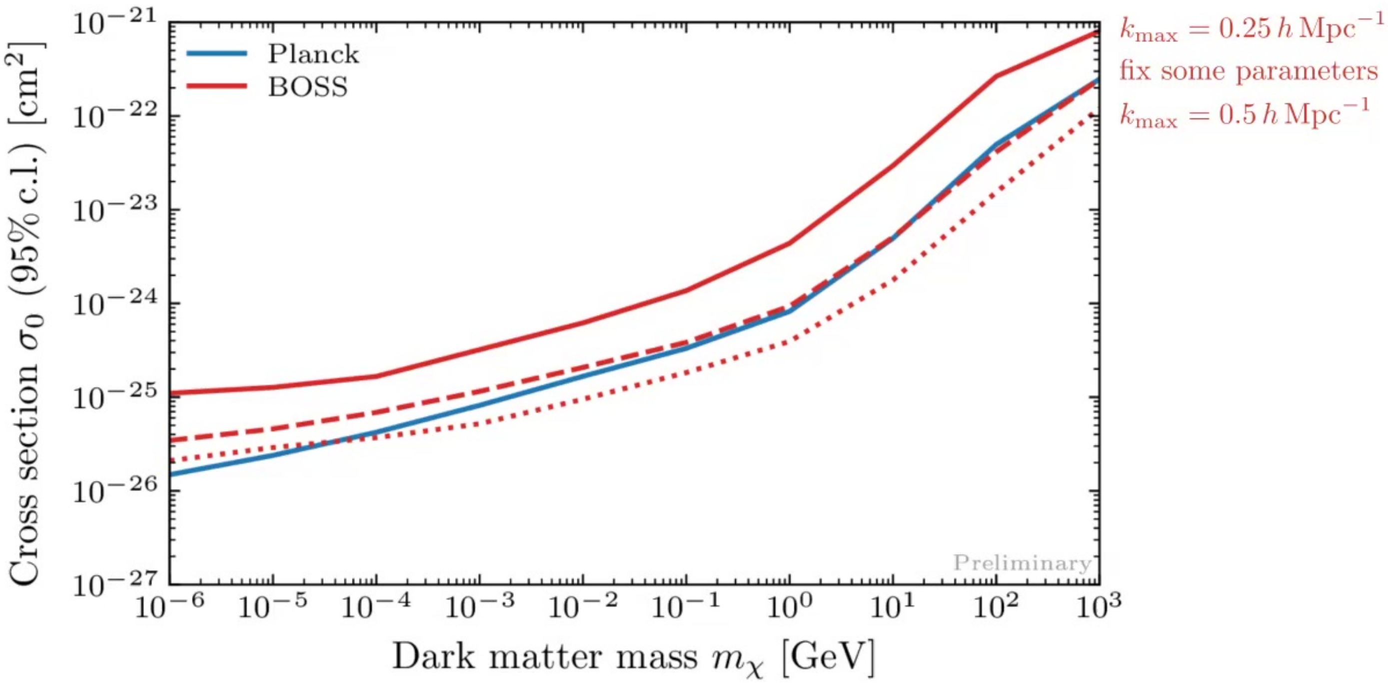
Nonlinear CMB Lensing Power Spectrum



Take-Aways from the Nonlinear Calculation

- Matter power spectrum:
  - clearly affected (unsurprising)
  - appropriately take nonlinearities into account
- CMB power spectrum:
  - barely affected (unsurprising)
  - current analyses unaffected and future ok, too
- Lensing power spectrum:
  - affected, but less than in LCDM
  - percent-level accuracy will require nonlinear treatment

Forecasts for Planck and BOSS

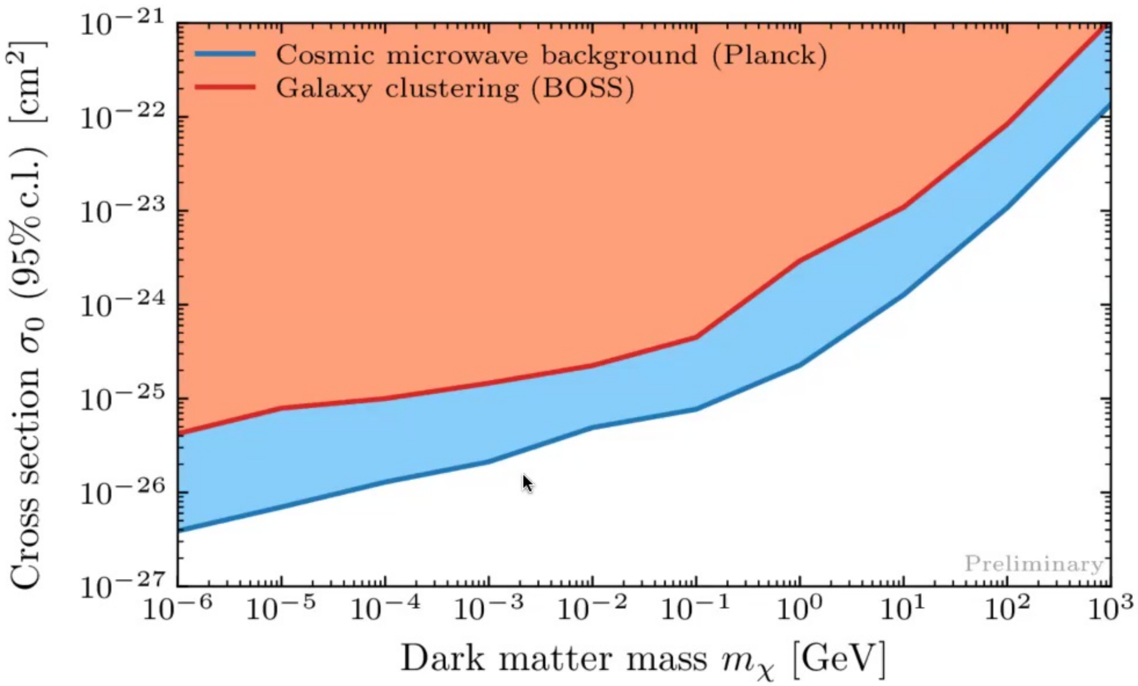


*Cosmology with half of the dark matter interacting with baryons; the other half is collisionless

Analysis of BOSS DR12 Data

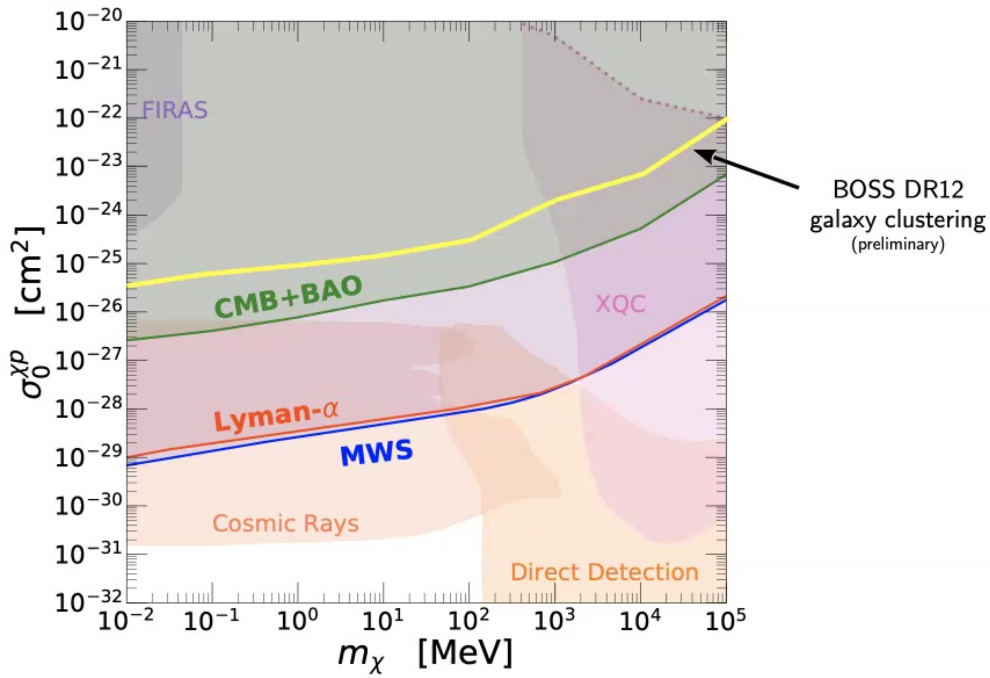
- Data based on spectra of 1.2 million galaxies.
- Two redshift bins in $0.2 < z < 0.75$, effective redshifts of $z_1 = 0.38$, $z_3 = 0.61$.
- Two sky regions: North galactic cap and south galactic cap with total of 10 252 deg^2.
- Total parameters: $\omega_c + H_0 + A_s + \sigma_0 +$ 4 x 7 nuisance parameters.
- Cosmology with half of the dark matter interacting with baryons.
- Modified version of CLASS with dark matter-baryon interactions and EFT-of-LSS.

First Preliminary Bounds from BOSS DR12



*Cosmology with half of the dark matter interacting with baryons; the other half is collisionless

Preliminary Projection on the Comparison Plot



Adapted from Buen-Abad et al. (2021); see also Maamari et al. (2021)

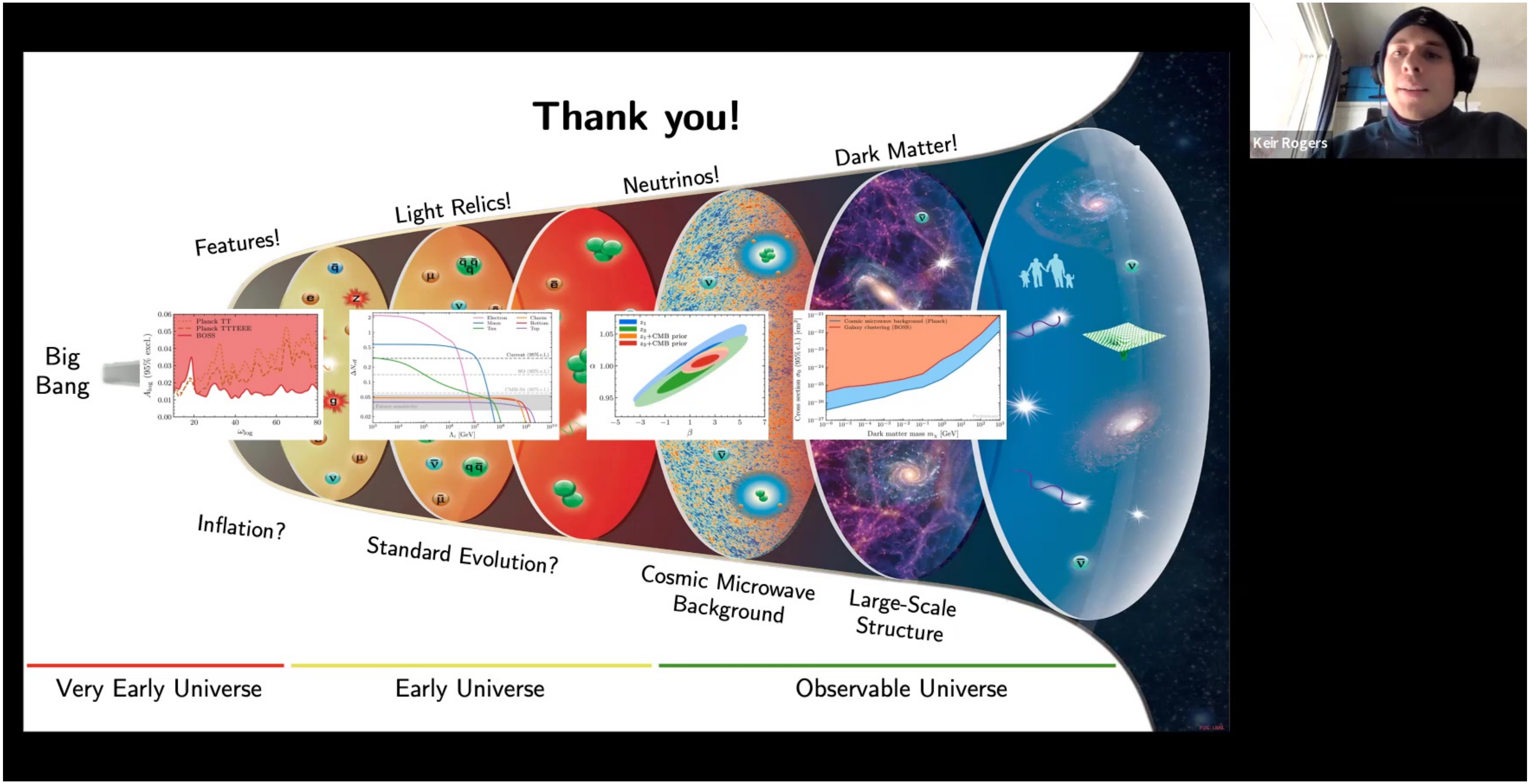
Preliminary Forecasts for Future CMB and LSS Surveys

- **CMB**, i.e. Simons Observatory and CMB-S4:
  - could potentially improve the bounds by about 1-2 orders of magnitude,
  - with nonlinear CMB lensing contributing O(1) in sensitivity to linear CMB lensing
  - and a factor of up to 6 over linear unlensed TTTEEE-only.

- **LSS**, i.e. DESI, Euclid and more futuristic surveys:
  - may lead to sizable improvements, at least similar to CMB-S4,
  - details to be verified.

Conclusions

- CMB and LSS observations (and underlying theory) are now precise enough to put interesting constraints on fundamental physics, e.g. inflation, neutrinos, light relics and dark matter.
- EFT-of-LSS treatment allows for first bounds on dark matter-baryon scattering from BOSS galaxy clustering.
- With the next generation of cosmological surveys, we will be able to place constraints through CMB primaries, CMB lensing and galaxy clustering.
- Avenue to explore: cross-correlations, including Sunyaev-Zel'dovich effect.
- These constraints will be complementary and potentially competitive with astrophysical probes.


Thank you!
Features!
Light Relics!
Neutrinos!
Dark Matter!
Big Bang
Inflation?
Standard Evolution?
Cosmic Microwave Background
Large-Scale Structure
Very Early Universe
Early Universe
Observable Universe
Keir Rogers