

Title: Fundamental physics from remote velocity and quadrupole reconstruction with the cosmic microwave background and galaxy surveys

Speakers: Selim Hotinli

Series: Cosmology & Gravitation

Date: May 03, 2022 - 11:00 AM

URL: <https://pirsa.org/22050022>

Abstract: Next generation cosmic microwave background (CMB) experiments and galaxy surveys will generate a wealth of new data with unprecedented precision on small scales. Correlations between CMB anisotropies and the galaxy density carry valuable cosmological information about the largest scales, creating novel opportunities for inference. It is possible to foresee a future where reconstruction of the gravitational weak-lensing potential, velocity fields and the remote quadrupole field will provide the most precise tests of fundamental physics. The use of the second-order effects in the CMB to extract this information motivate a strong push towards low noise, high resolution frontiers of the upcoming generation CMB experiments. In this talk, I will discuss the prospects to use small-scale kinetic and polarized Sunyaev Zel'dovich effects and the moving-lens effect, in cross-correlation with ongoing galaxy surveys, to extract cosmological information.

Zoom Link: <https://pitp.zoom.us/j/91455862792?pwd=M1hFRDgyOXVKU1U4Z0pLcm1wZGdRQT09>



Selim Hotinli

Fundamental physics from CMB secondaries



Selim Hotinli

05/03/2022

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JHU Horizon Fellow



In collaboration with...



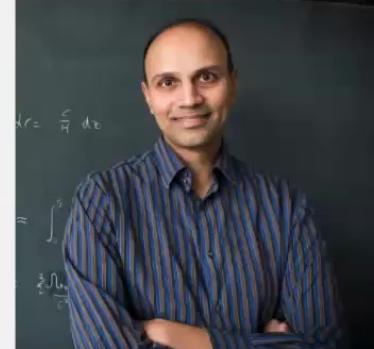
Matt Johnson
(Perimeter/York)



Gil Holder
(UIUC)



Marc Kamionkowski
(JHU)



Neal Dalal
(Perimeter)



Andrew Jaffe
(Imperial)



Moritz Munchmeyer
(Perimeter)



Kendrick Smith
(Perimeter)



Joel Meyers
(SMU)



Alex van Engelen
(CITA)



Mat Madhavacheril
(Perimeter)

Outline



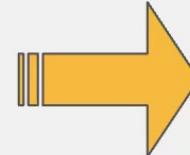
Primordial signatures

Observables

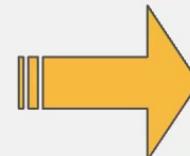
Kinetic Sunyaev Zel'dovich effect

Moving lens effect

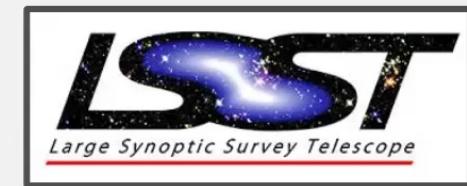
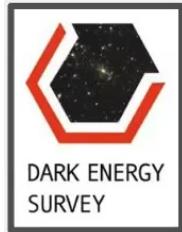
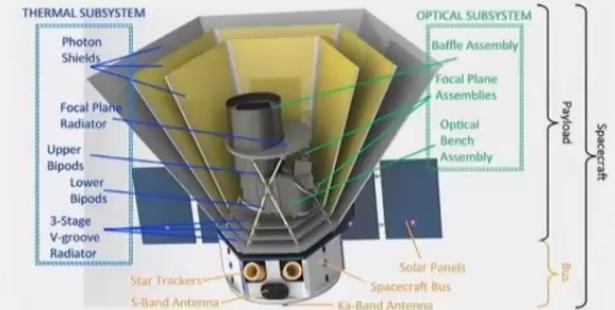
Polarized Sunyaev Zel'dovich effect



Bulk velocity field



Remote-quadrupole field





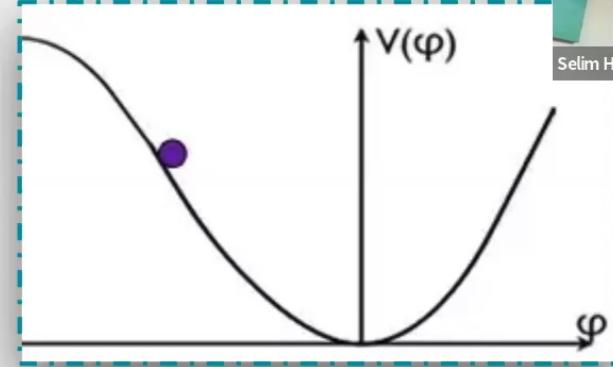
Fundamental Properties of the Universe

Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.o.F
- Isocurvature
- Scale invariance
- Parity
- Heavy particles
- ...

Fundamental Properties of the Universe

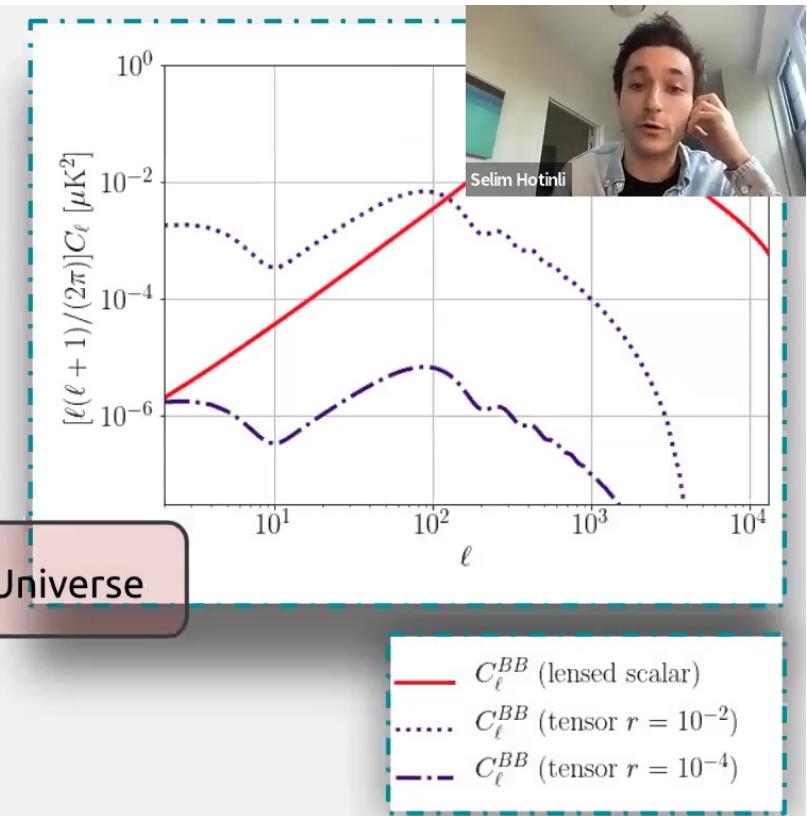


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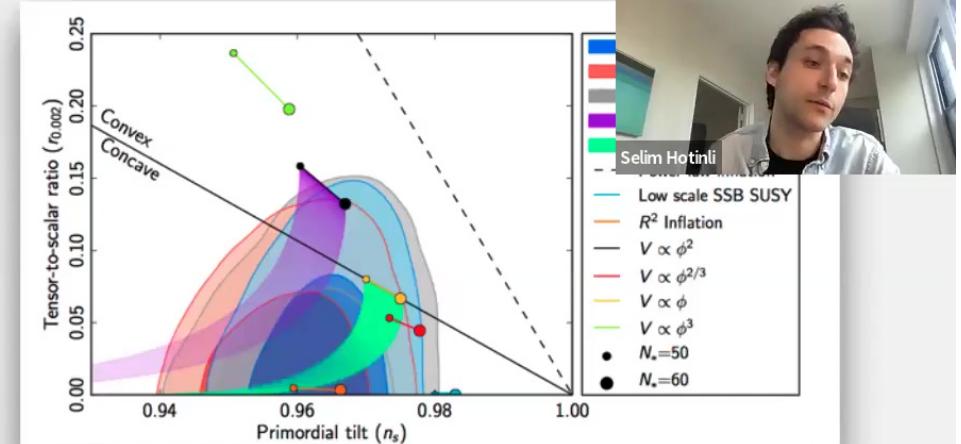


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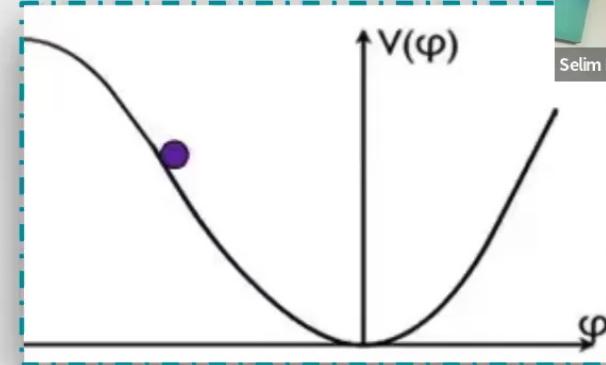


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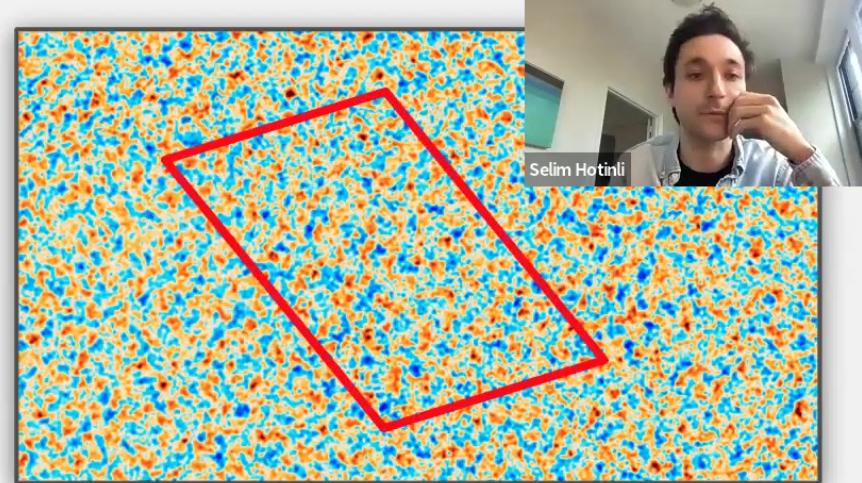


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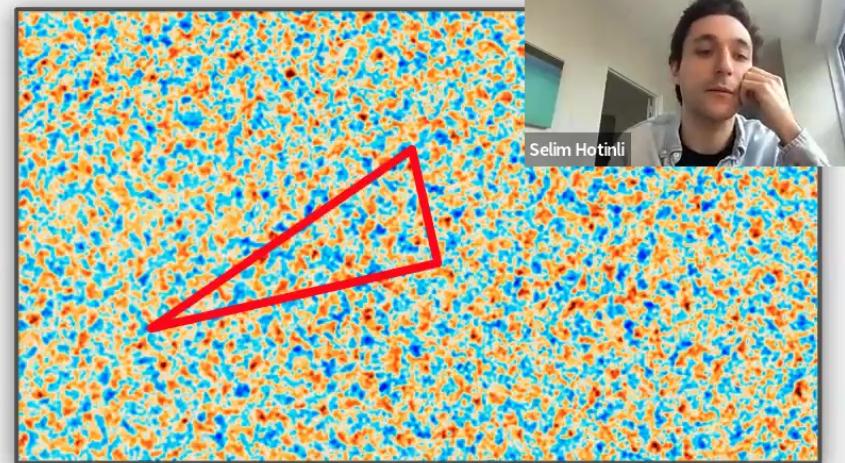


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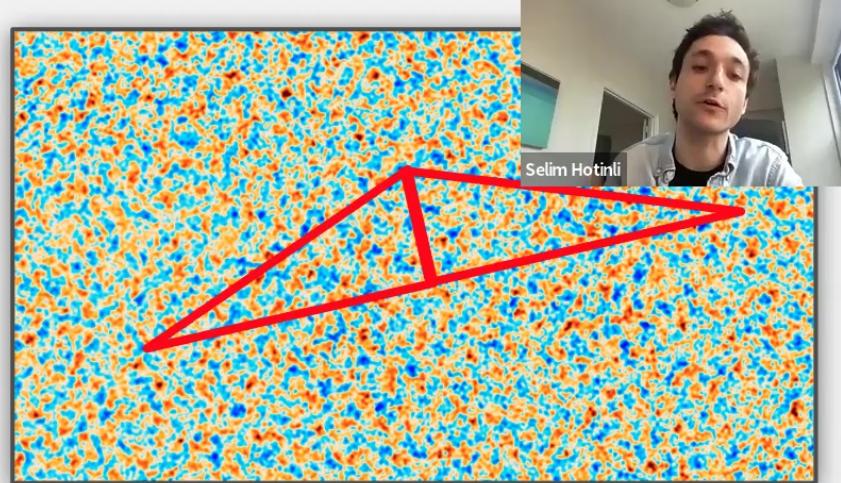
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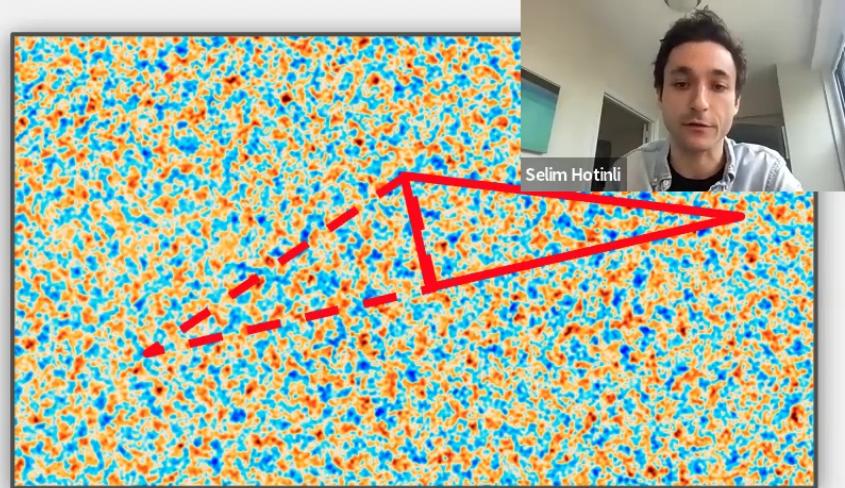
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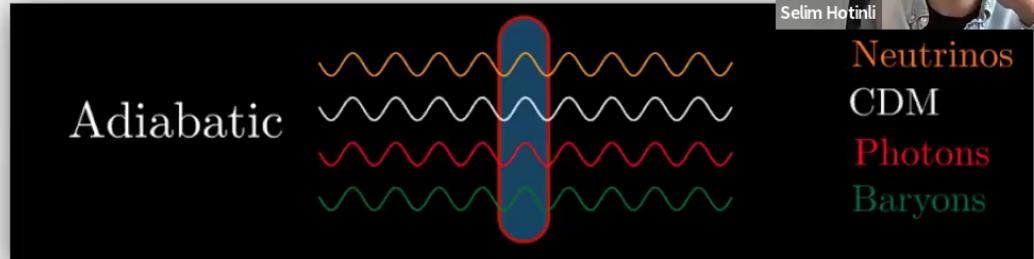


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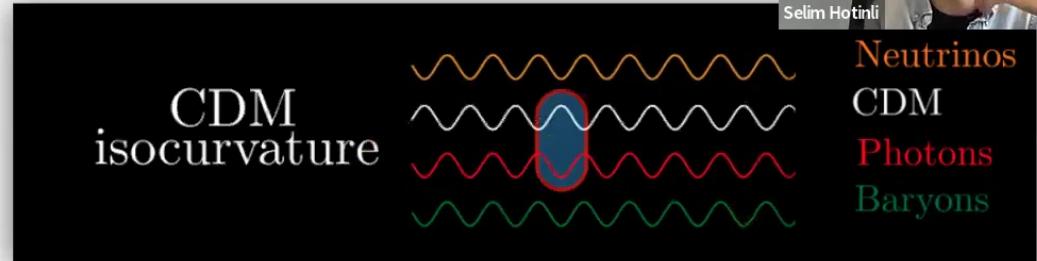


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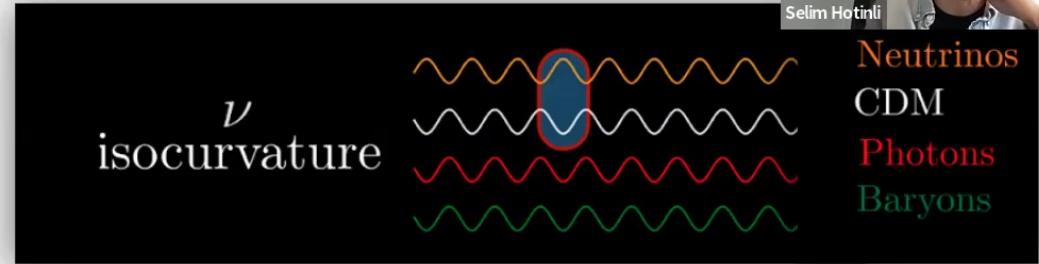
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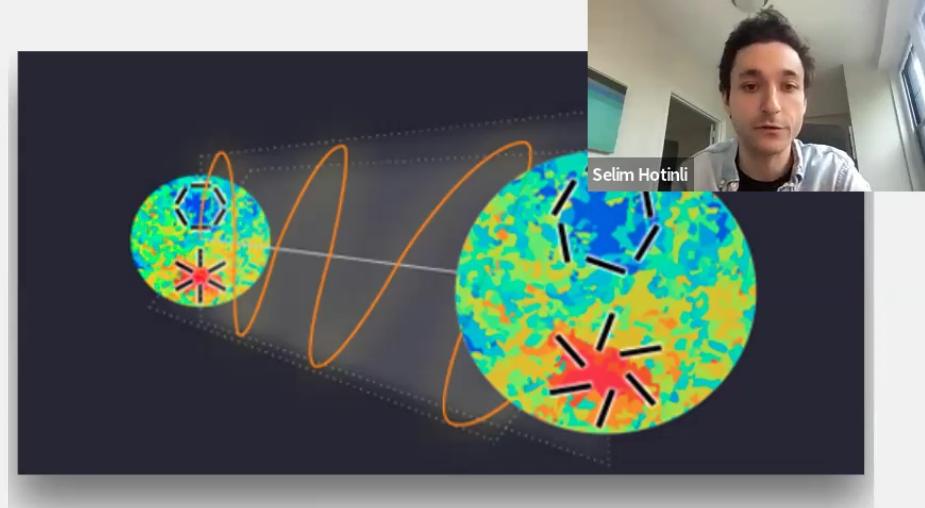
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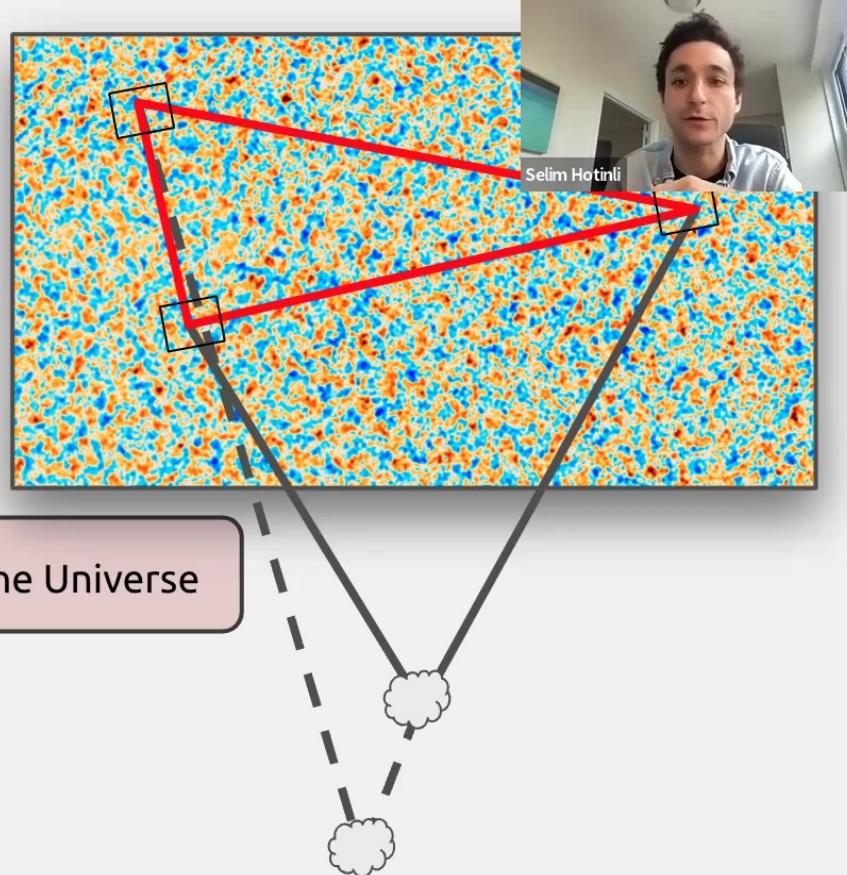


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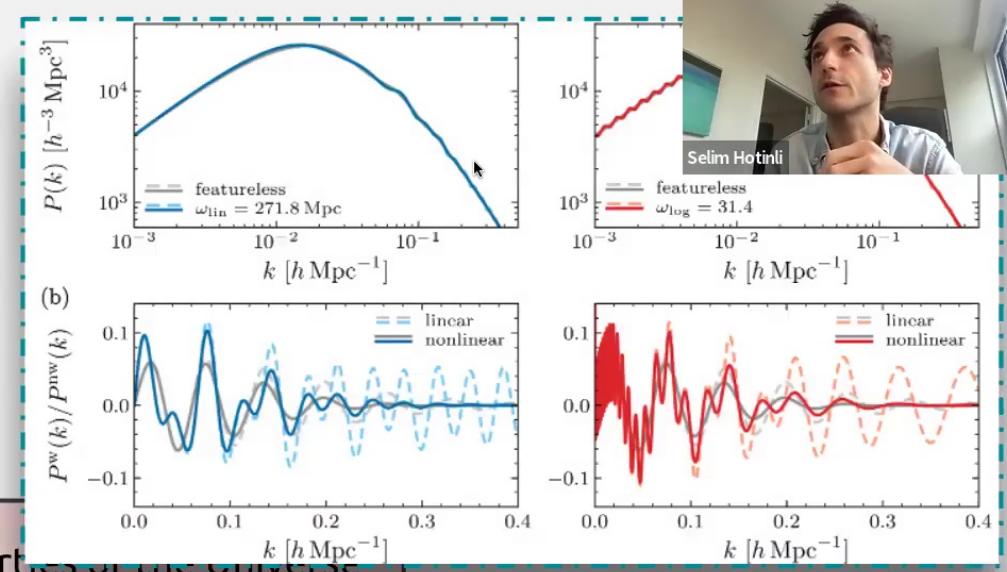
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CMB secondaries:

- Kinetic SZ
- Polarized SZ
- Moving lens
- Weak lensing
- ...



Upcoming observations

LSST

- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...

Fundamental Properties of the Universe

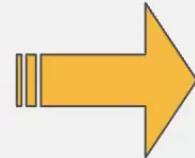
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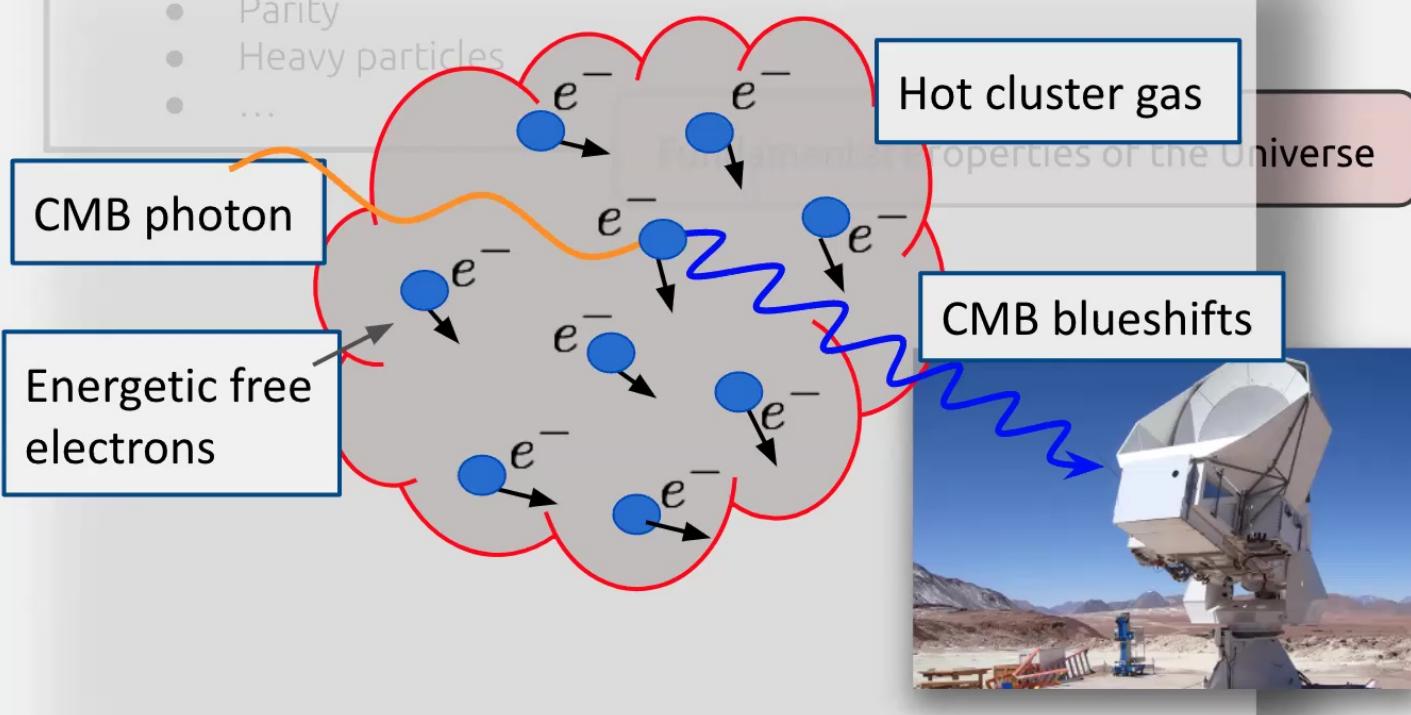
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Fundamental Properties of the Universe

websky

$$\frac{\Delta T_{\text{KSZ}}(\hat{\mathbf{n}})}{T_{\text{CMB}}} \sim \int d\chi e^{-\tau(z)} v_r \delta_e(\hat{\mathbf{n}}, \chi)$$

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Fundamental Physics

kSZ SNR*	CMB	
LSS	SO	S4
DESI	231	414
VROY1	116	210
VROY10	123	228

*from cross-correlation with galaxies

Upcoming observations

CMB secondaries:

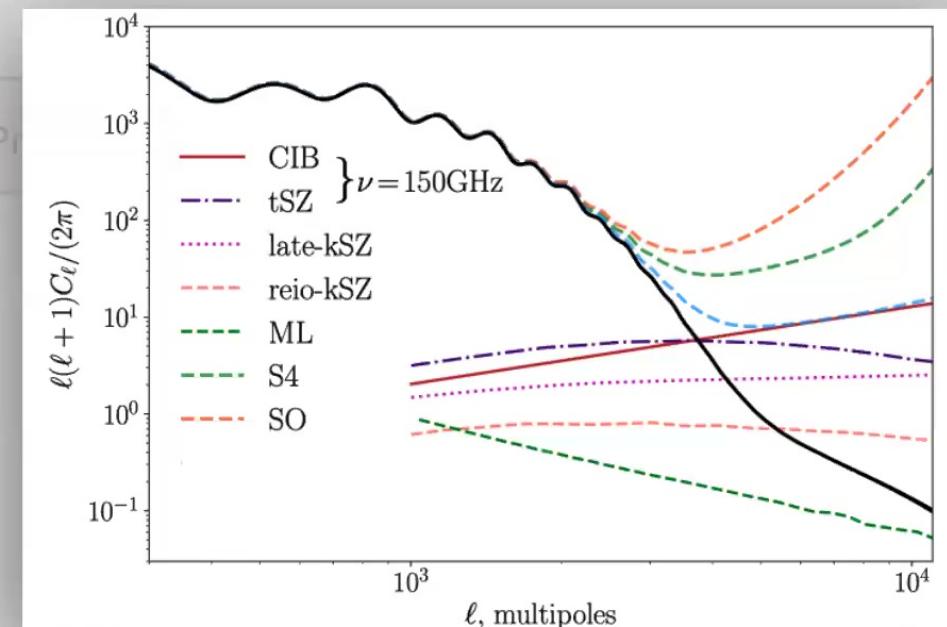
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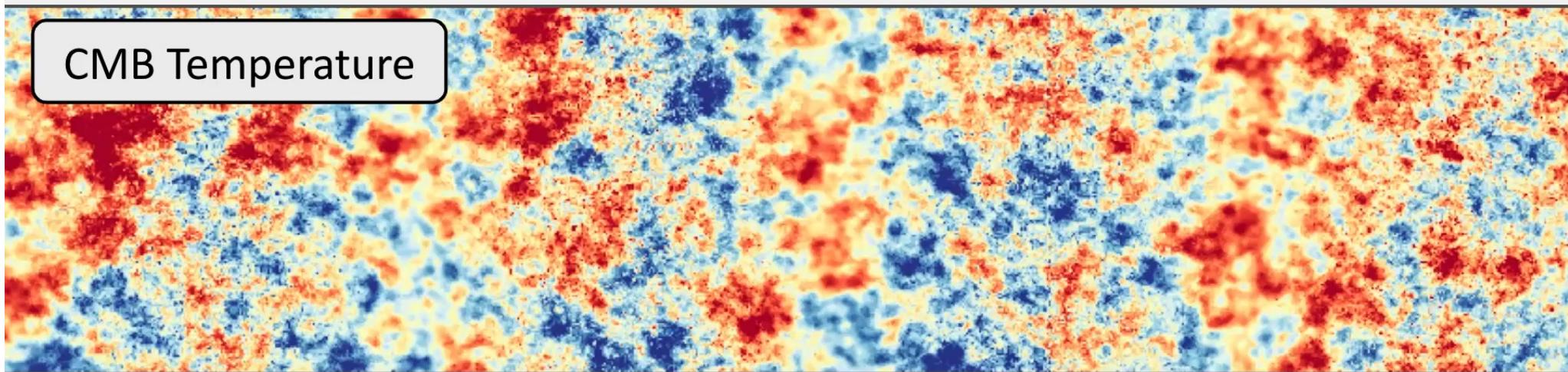


Cosmology from kSZ

$$\frac{\Delta T_{\text{kSZ}}(\hat{\mathbf{n}})}{T_{\text{CMB}}} \sim \int d\chi e$$



CMB Temperature



Cosmology from kSZ

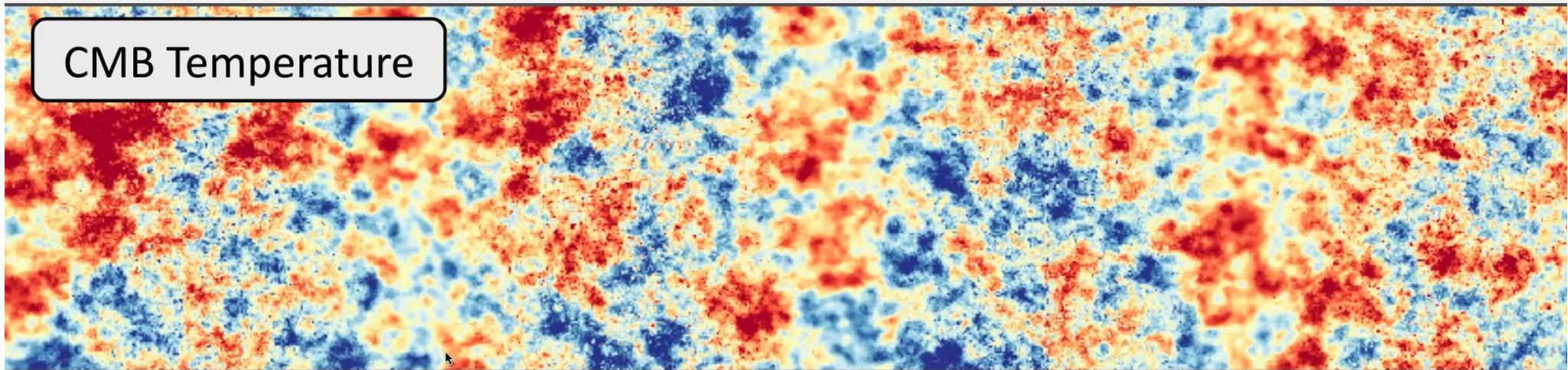
$$\frac{\Delta T_{\text{kSZ}}(\hat{\mathbf{n}})}{T_{\text{CMB}}} \sim \int d\chi e$$



Large-scale radial-velocity mode:
 $(\ell \lesssim 100)$



CMB Temperature



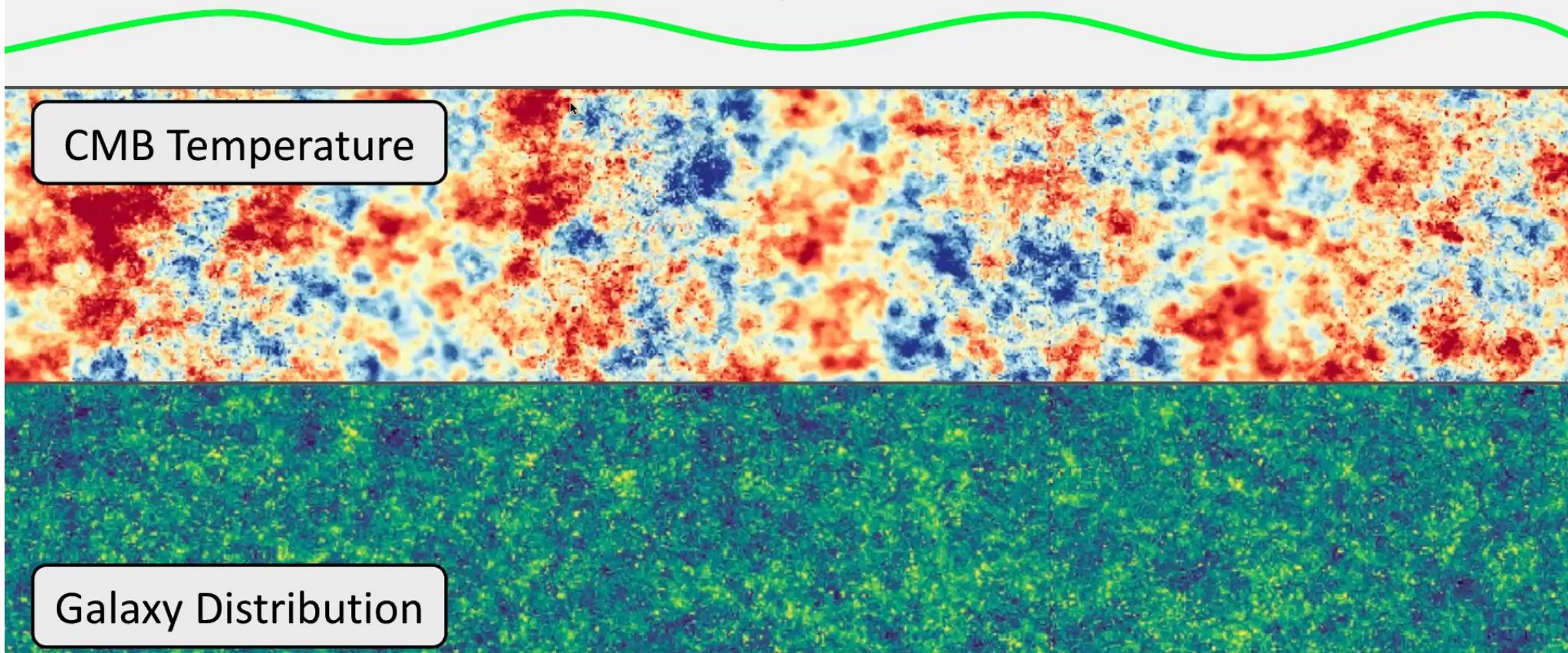
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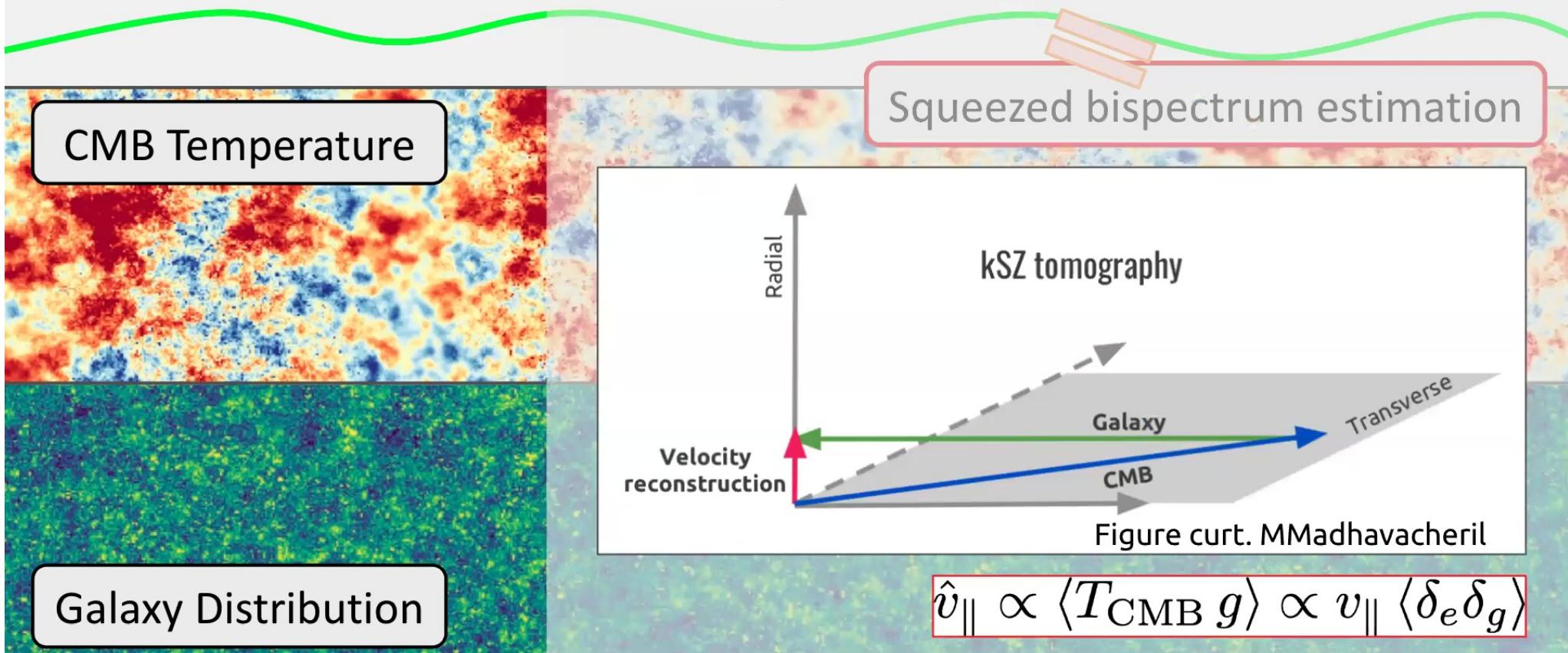
Galaxy Distribution

Cosmology from kSZ

$$\frac{\Delta T_{\text{kSZ}}(\hat{\mathbf{n}})}{T_{\text{CMB}}} \sim \int d\chi e$$



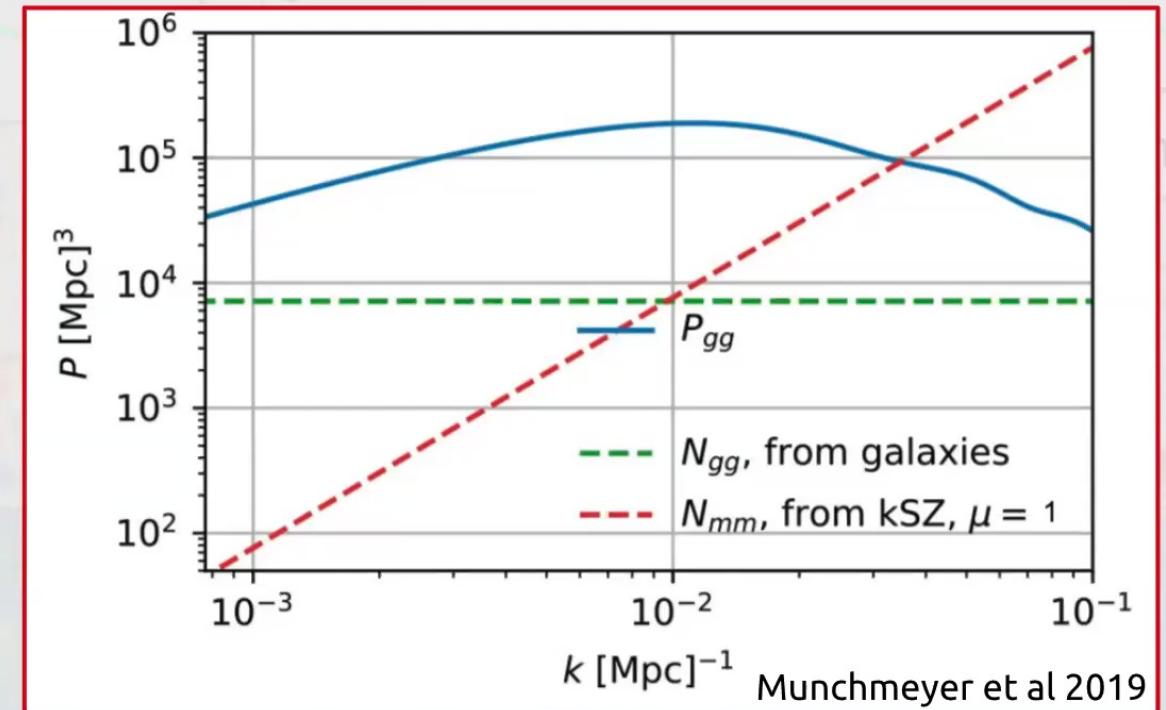
Large-scale radial-velocity mode:



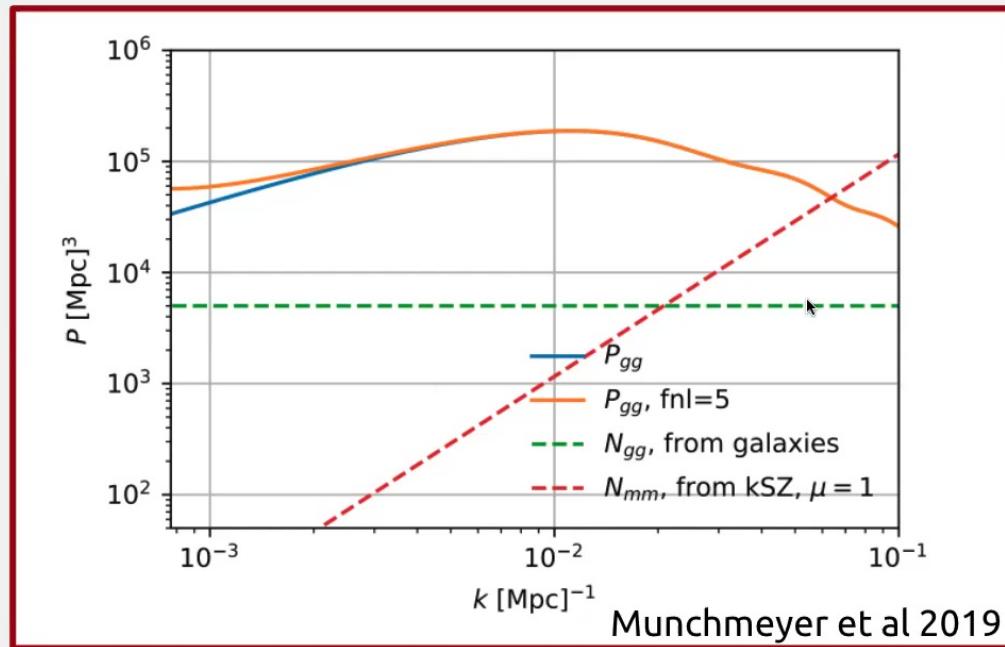
Cosmology from kSZ



$$v \simeq \frac{faH}{k} \delta_m$$



Cosmology from kSZ



Cosmology from kSZ



$$P_{gg}(k, \mu) = (b_g + b_{\text{rsd}} f \mu^2)^2 P_{mm}(k),$$

$$P_{gv}(k, \mu) = b \left(\frac{faH}{k} \right) (b_g + b_{\text{rsd}} f \mu^2) P_{mm}(k),$$

$$P_{vv}(k, \mu) = b^2 \left(\frac{faH}{k} \right)^2 P_{mm}(k),$$

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CMB secondaries:

- Kinetic SZ
- Polarized SZ
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LS

- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...

Upcoming obse



Fundamental Properties of the Universe

- Scale-dependent galaxy bias: b_g
- Cosmological growth rate: f

$$b_g \rightarrow b_g + f_{\text{NL}} \frac{\beta_f}{\alpha(k, z)}$$

Observational signatures

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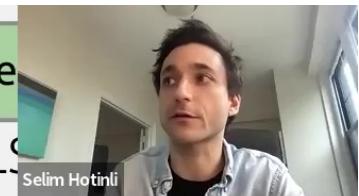
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$$\delta_m(\mathbf{k}, z) = \alpha(k, z)\Phi(\mathbf{k})$$

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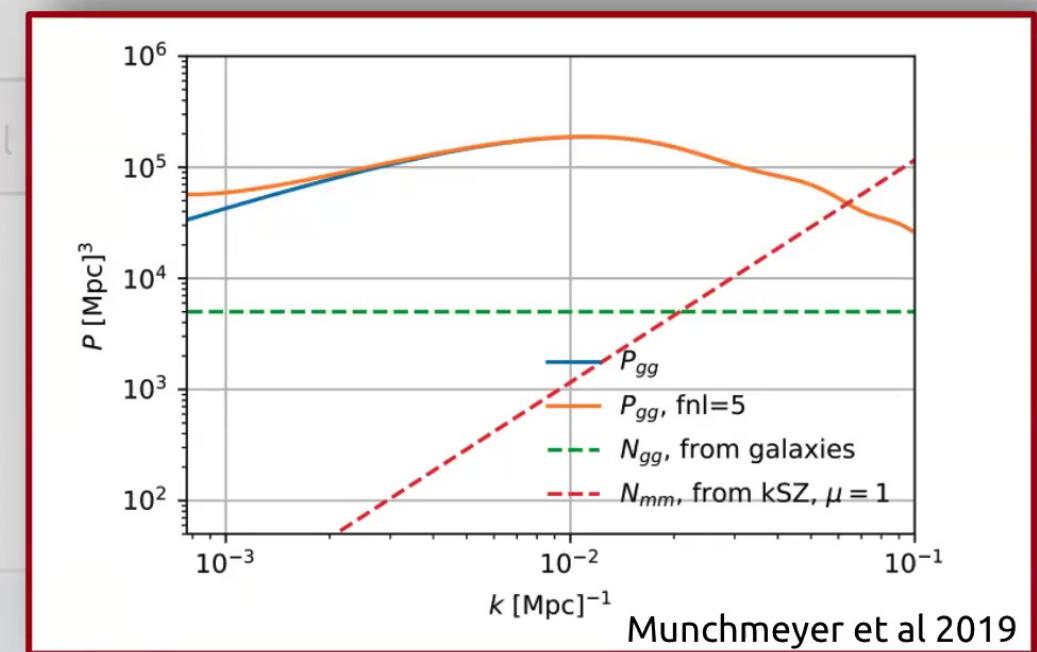
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	baseline 1	baseline 2
survey volume V	100 Gpc ³	100 Gpc ³
central redshift z	1.0	1.0
galaxy density n_g	2×10^{-4} Mpc ⁻³	10^{-2} Mpc ⁻³
halo bias b_h	1.6	1.6
photo-z error σ_z	-	0.06
CMB sensitivity	5 μK-arcmin	1 μK-arcmin
CMB resolution	1.5'	1.5'
$\sigma_{f_{NL}^{kSZ+gal}}^{\text{gal}}$	6.0	5.3
$\sigma_{f_{NL}^{kSZ+gal}}^{\text{gal}} / \sigma_{f_{NL}}^{\text{gal}}$	3.3	0.7
	1.8	7.8

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Upcoming observations



Fundamental Properties of the Universe

- Scale-dependent galaxy bias b_g
- Cosmological growth rate $\alpha(k)$

$$P_{gg}(k, \mu) = \left[b_g^2 + 2b_g\beta_f \frac{f_{NL}}{\alpha(k)} + \beta_f^2 \frac{(5/6)^2 \tau_{NL}}{\alpha^2(k)} \right] P_{mm}(k)$$

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Fundamental Properties of the Universe

Single-field slow roll

$$\tau_{NL} \equiv (6/5 f_{NL})^2$$

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Fundamental Properties of the Universe

Multi-field inflation

$$\Pi = P_\phi / P_\psi$$

$$\tau_{NL} \equiv (6/5 f_{NL})^2 (1 + \Pi)$$

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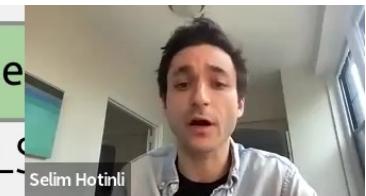
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Multi-field inflation

$$\tau_{NL} \equiv (6/5 f_{NL})^2 (1 + \Pi)$$

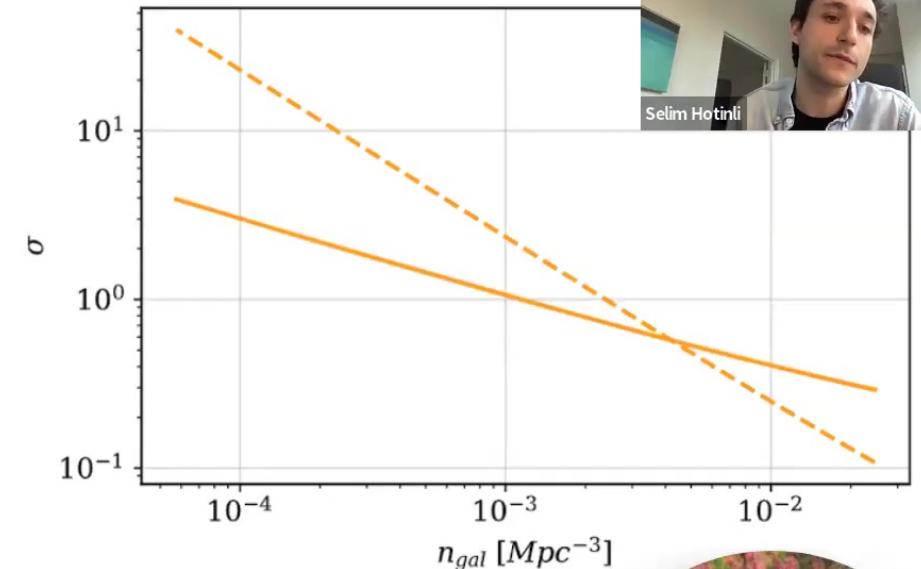
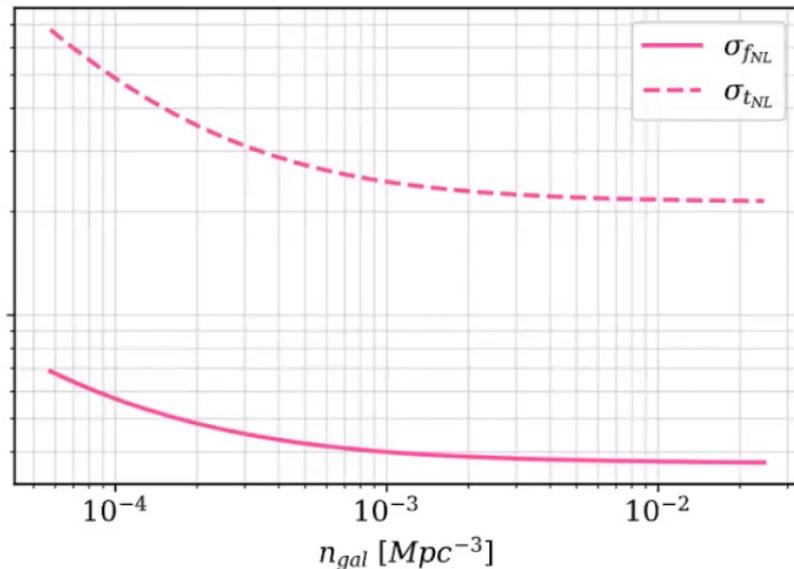
- Scale-dependent galaxy bias b_g
- Cosmological growth rate $\alpha(k)$

$$P_{gg}(k, \mu) = \left[b_g^2 + 2b_g\beta_f \frac{f_{NL}}{\alpha(k)} + \beta_f^2 \frac{(5/6)^2 \tau_{NL}}{\alpha^2(k)} \right] P_{mm}(k)$$

Observational signatures

Planck constraint:

$$\tau_{NL} \lesssim 2 \times 10^3 \text{ (68%)}$$



• Scale-dependent galaxy bias b_g

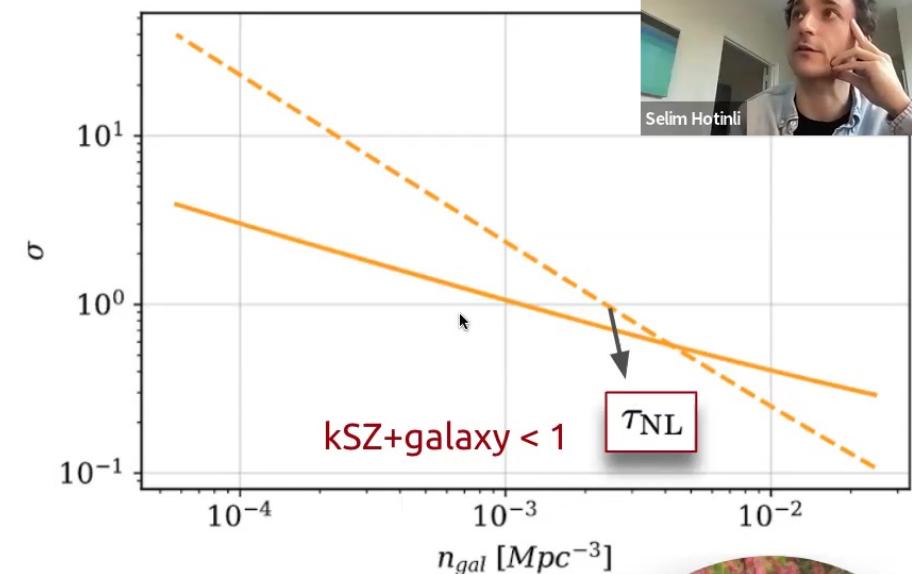
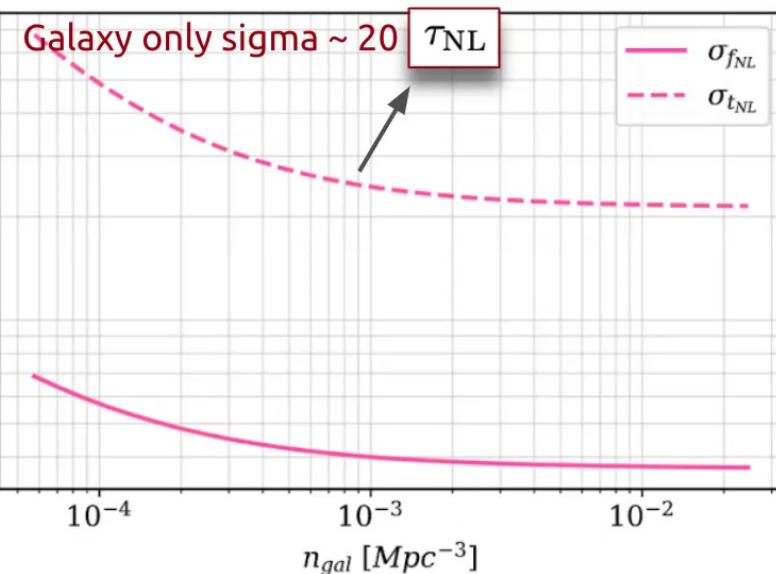
• Cosmological growth rate: \int

$$P_{gg}(k, \mu) = \left[b_g^2 + 2b_g\beta_f \frac{f_{\text{NL}}}{\alpha(k)} + \beta_f^2 \frac{(5/6)^2 \tau_{\text{NL}}}{\alpha^2(k)} \right] P_{mm}(k)$$



Observational signatures

Neha Anil Kumar (JHU) et al. to appear



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Observational signatures

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Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.o.F
- **Isocurvature**
- Scale invariance
- Parity
- Heavy particles
- ...

Growth of structure:

- Free-streaming species
- Dark energy
- Dark matter
- Gravity
- ...

CMB secondaries:

- **Kinetic SZ**
- Polarized SZ
- Moving lens
- Weak lensing

LS

- Galaxies
- Dropouts
- Quasars
- 21-cm

Upcoming obse



Fundamental properties of the Universe

$$S_{i\gamma} = \frac{\delta n_i}{\bar{n}_i} - \frac{\delta n_\gamma}{\bar{n}_\gamma}$$

baryons, CDM, neutrinos

- **Scale-dependent galaxy bias:** b_g
- Cosmological growth rate: f

Observational signatures

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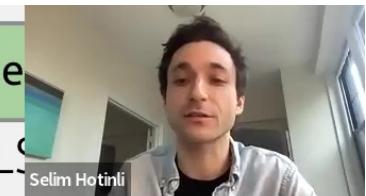
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Upcoming obse



Fundamental properties of the Universe

Baryons & CDM

$$\delta_g(\mathbf{k}, \tau) \simeq b(z)\delta_m(\mathbf{k}, \tau)$$

$$+ b_{bc}(z)[\delta_{bc}(\mathbf{k}, \tau) + f\Delta(\mathbf{k})]$$

- **Scale-dependent galaxy bias:** b_g
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Observational signatures

Beyond the standard cosmological paradigm

Initial conditions:

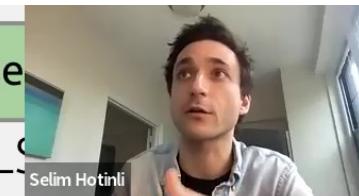
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e.g. curvaton decay

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Observational signatures

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Fundam

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Observational signatures

Upcoming obse



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Forecast ingredients

σ_A

N only	3.8
N + CMB	3.2
N + CMB + kSZ	0.25
N + CMB + kSZ + fixed cosmology	0.23
N + CMB + kSZ + variable f_{NL}	0.49

PRD 1908.08953, SCH et al

Beyond the standard cosmological paradigm

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Observational signatures

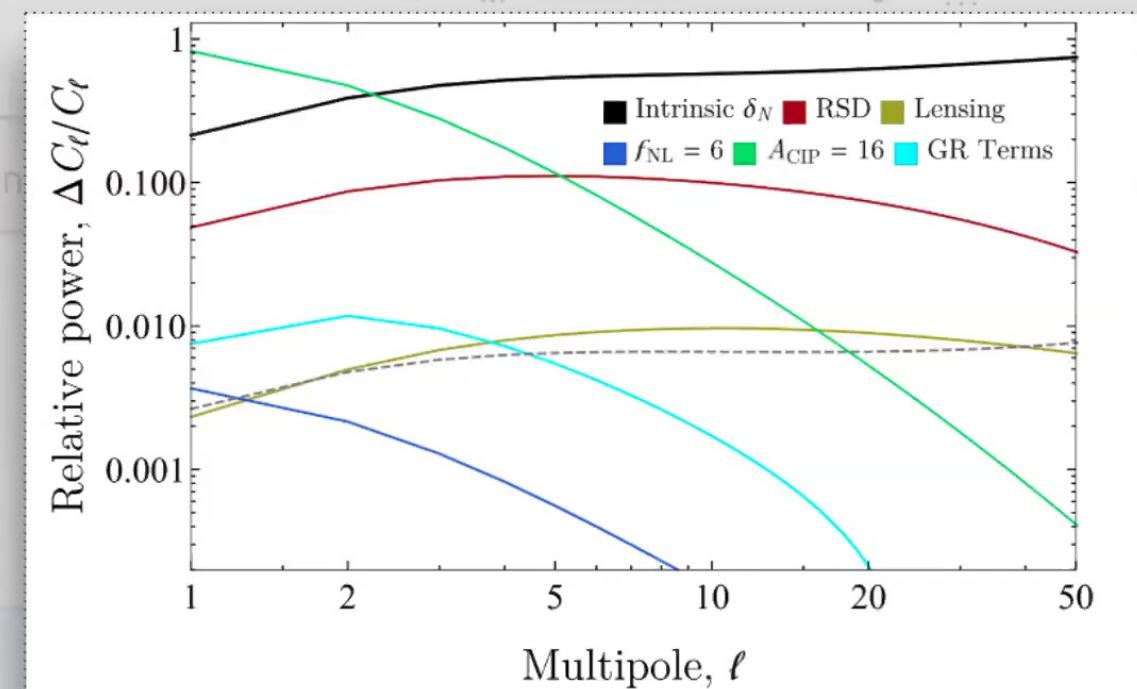
Upcoming obse

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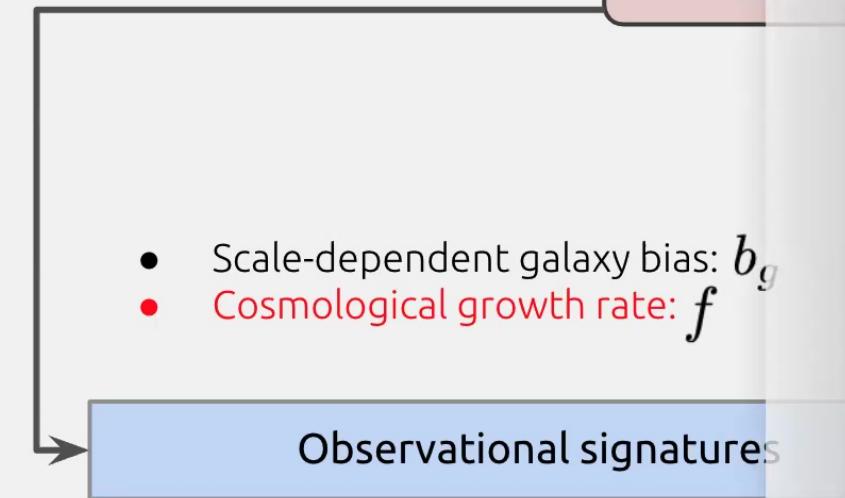
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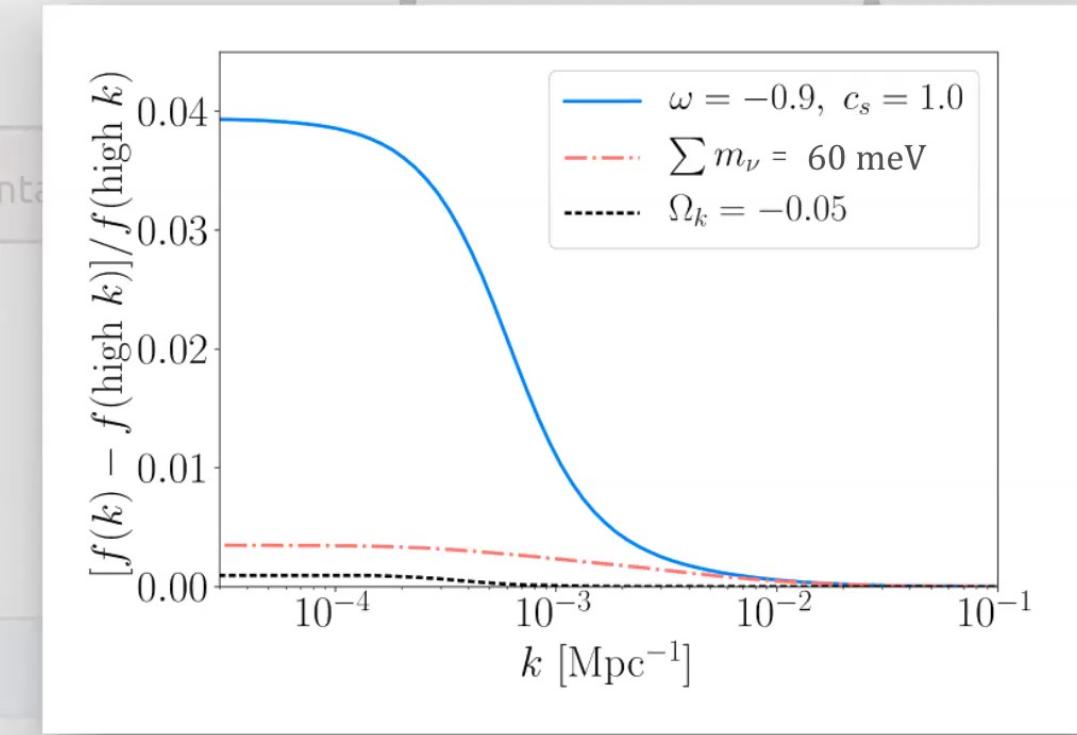
Upcoming observations

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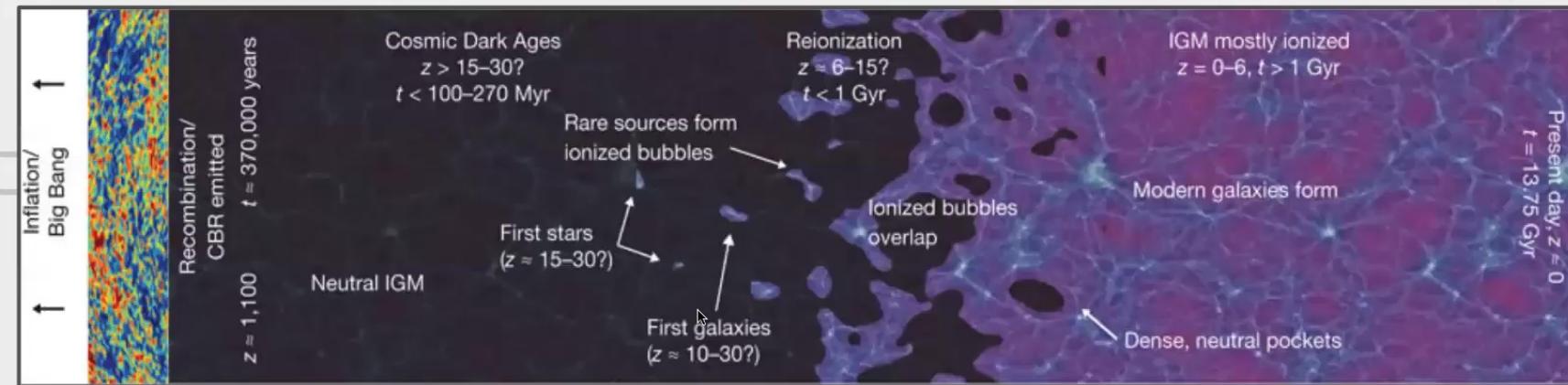
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- Scale-dependent galaxy bias: b_g
- Cosmological growth rate: f

Upcoming observations



LSS

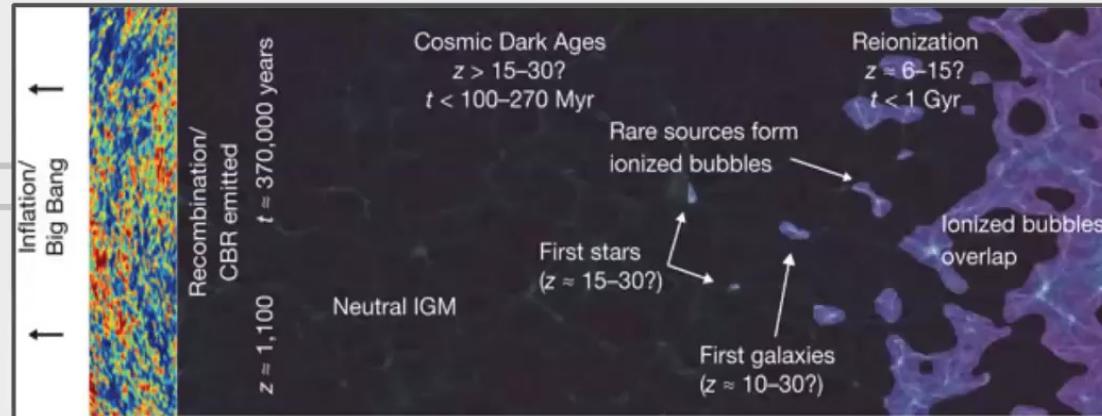
- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...

Observational signatures

Beyond the standard cosmological paradigm

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- Scale-dependent galaxy bias: b_g
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Observational signatures

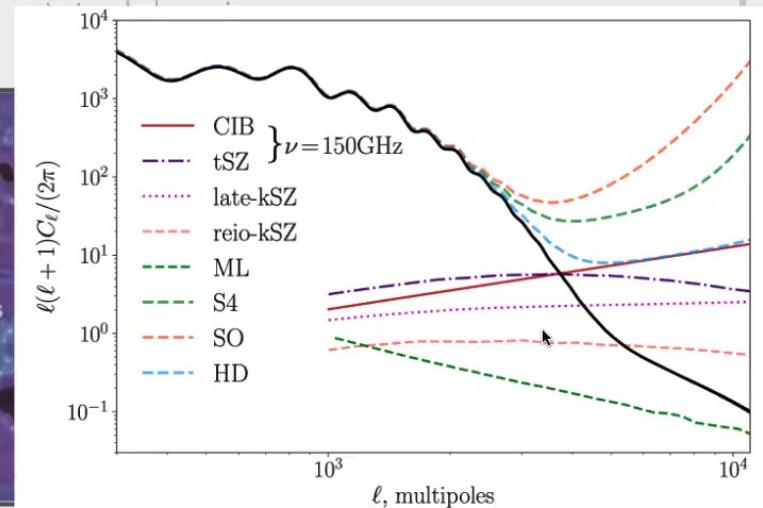
Upcoming observations

CMB secondaries:

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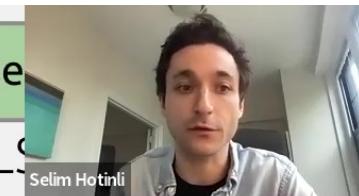
Growth of structure:

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CMB secondaries:

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Upcoming observations

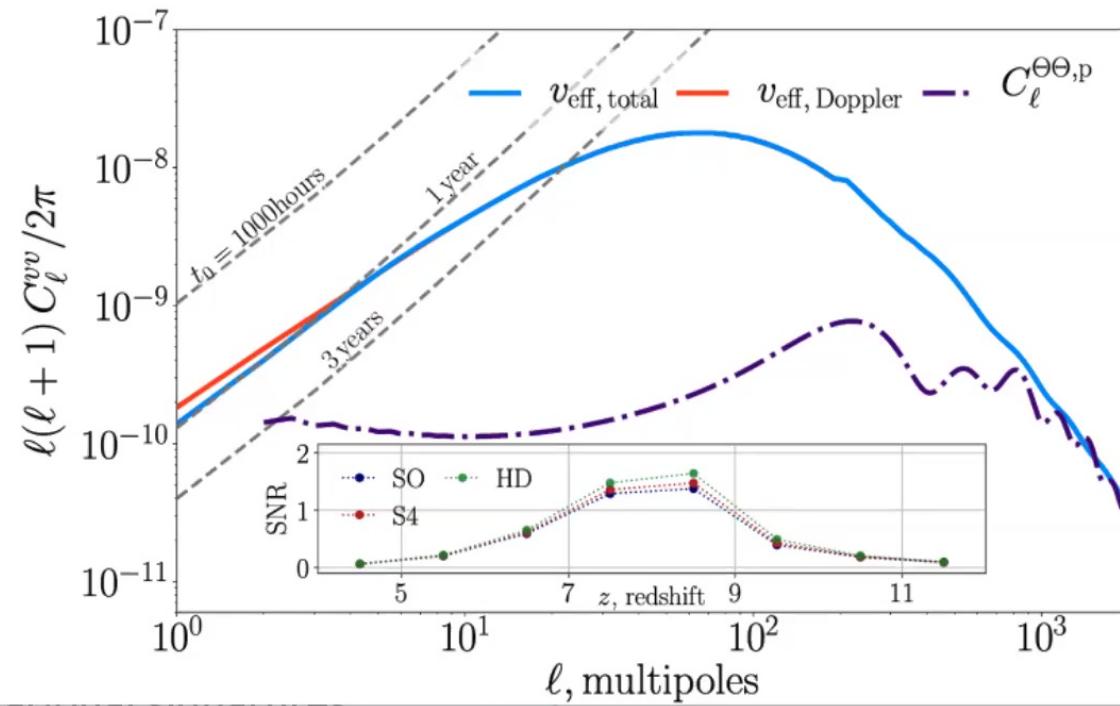


LS

- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...

(PRD) 2012.09851
SCH, M Johnson

- Scale-dependent
- Cosmological



Observational signatures

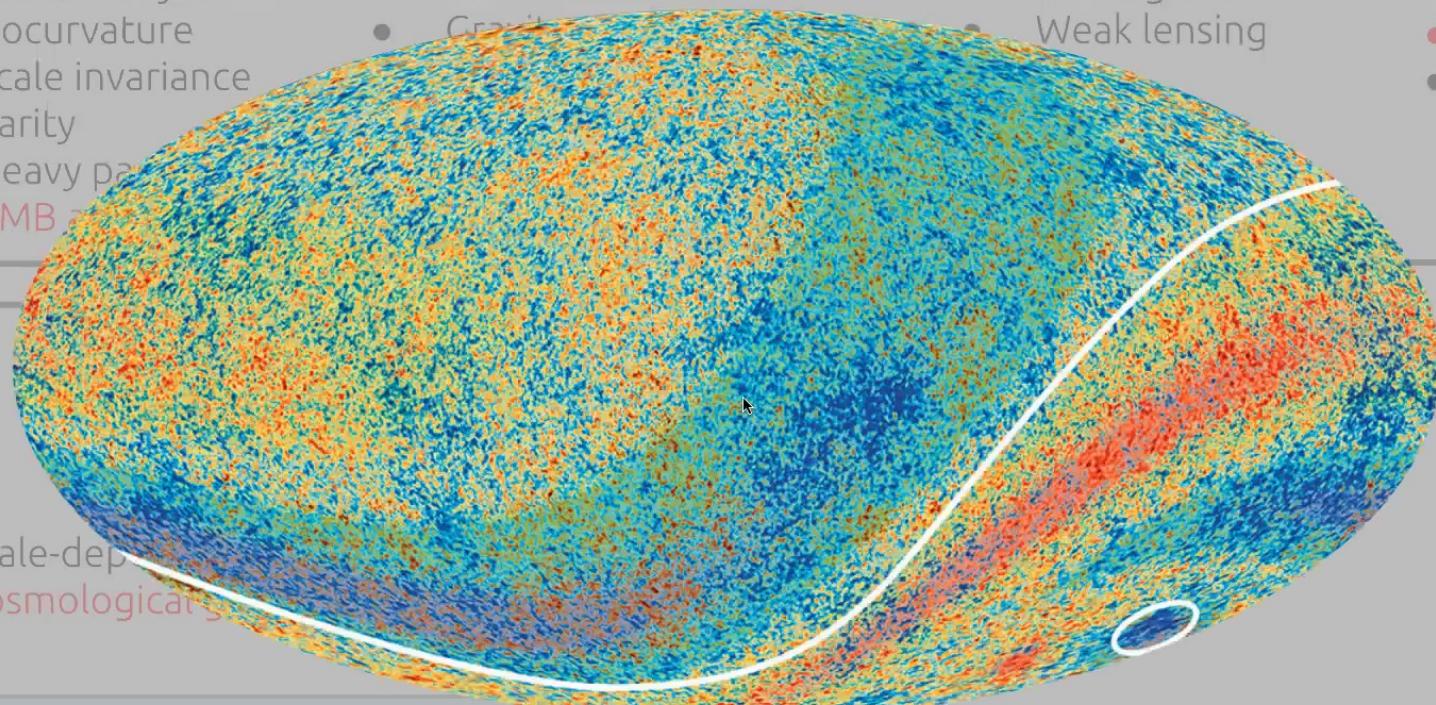
Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
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- Heavy particles
- CMB anisotropies

Growth of structure:

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Upcoming observations



CMB secondaries:

- Kinetic SZ
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LS

- Galaxies
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- ...

- Scale-dependent bias
- Cosmological parameters

Observational signatures

Beyond the standard cosmological paradigm

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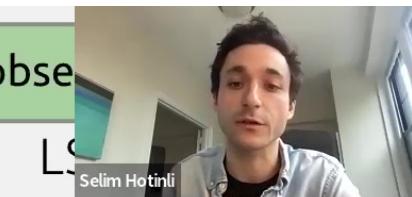
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Upcoming obse

CMB secondaries:

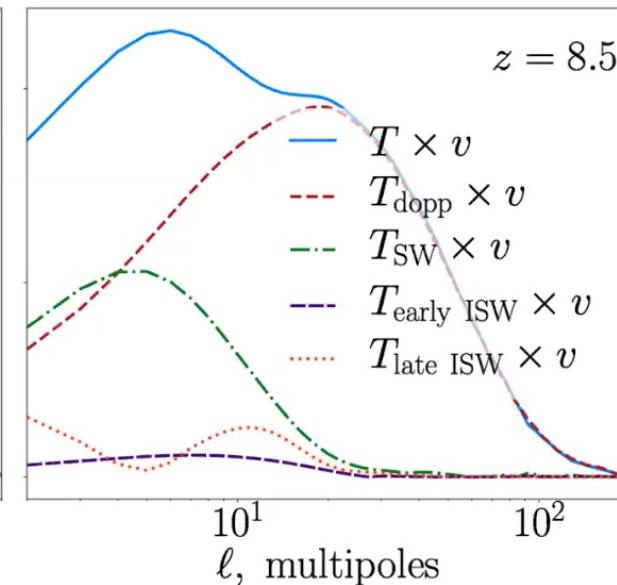
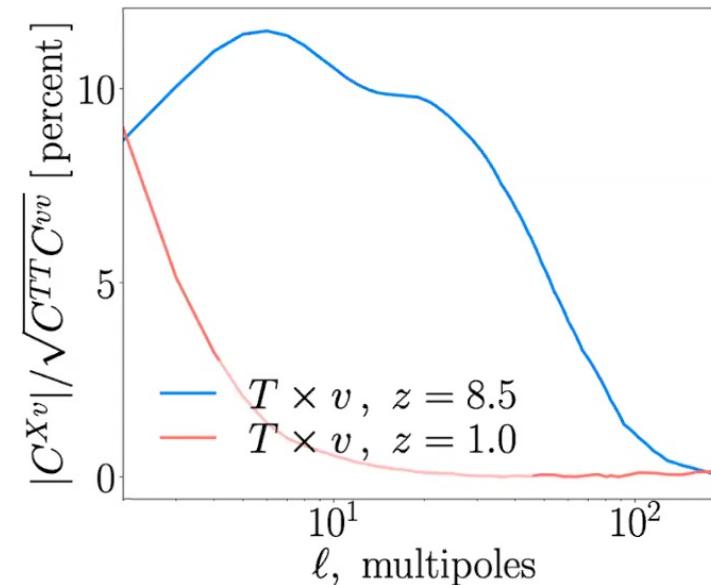
- Kinetic SZ
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- Galaxies
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(PRD)2012.09851
SCH, M Johnson

- Scale-d
- Cosmol



Observational signatures

Outline

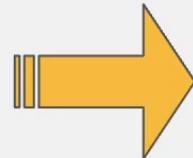


Primordial signatures

Observables

Kinetic Sunyaev Zel'dovich effect

Moving lens effect



Bulk velocity field

Beyond the standard cosmological paradigm

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Fundamental Properties of the Universe

- Scale-dependent galaxy bias: b_g
- Cosmological growth rate: f

Observational signatures

Upcoming obse

CMB secondaries:

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LS

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CMB



α

χ

Φ

Φ

v_{\perp}

v_{\perp}

β

χ^*

\hat{n}



Beyond the standard cosmological paradigm

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CMB

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Observational signatures



α

χ

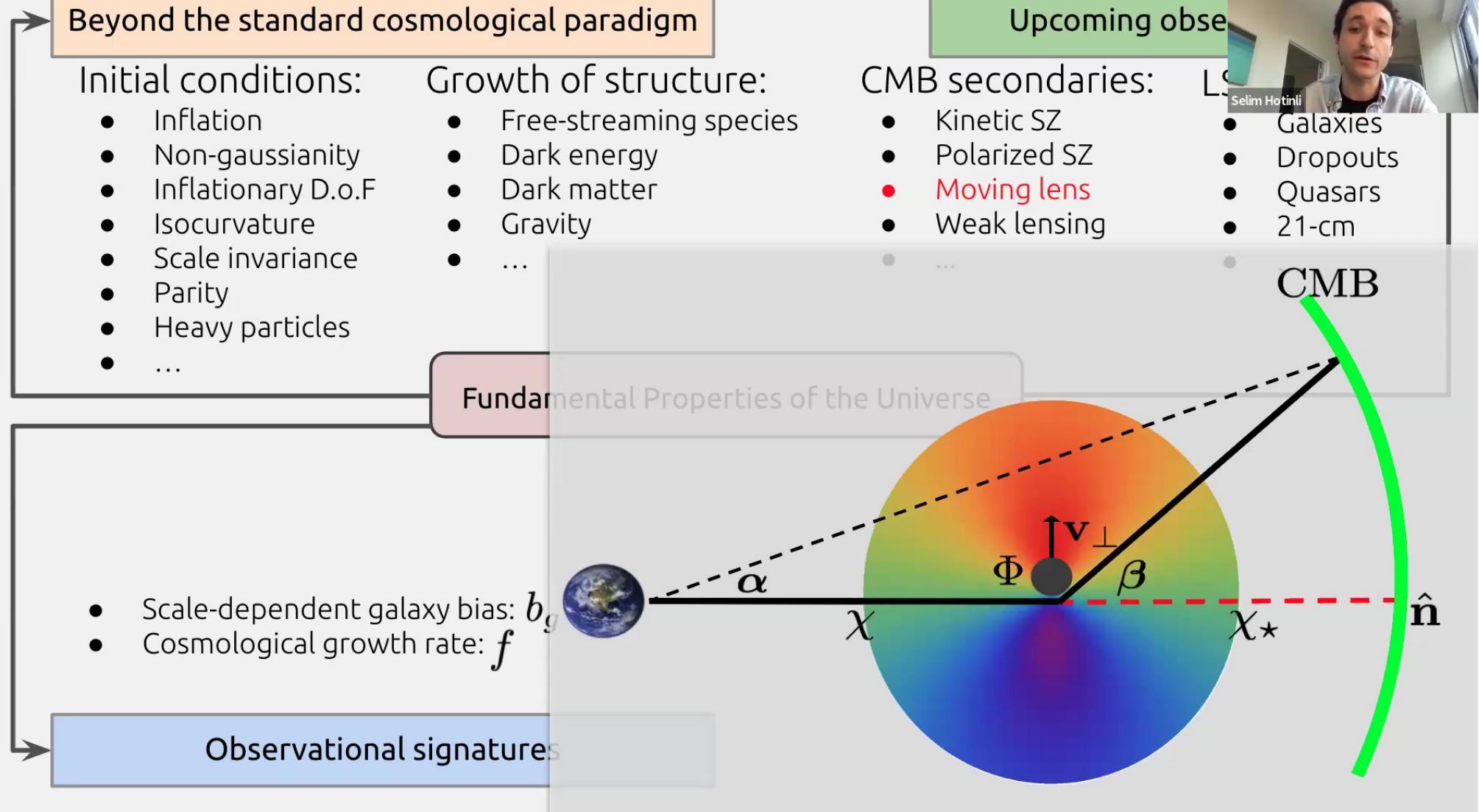
Φ

v_{\perp}

β

χ^*

\hat{n}



Beyond the standard cosmological paradigm

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Upcoming obse



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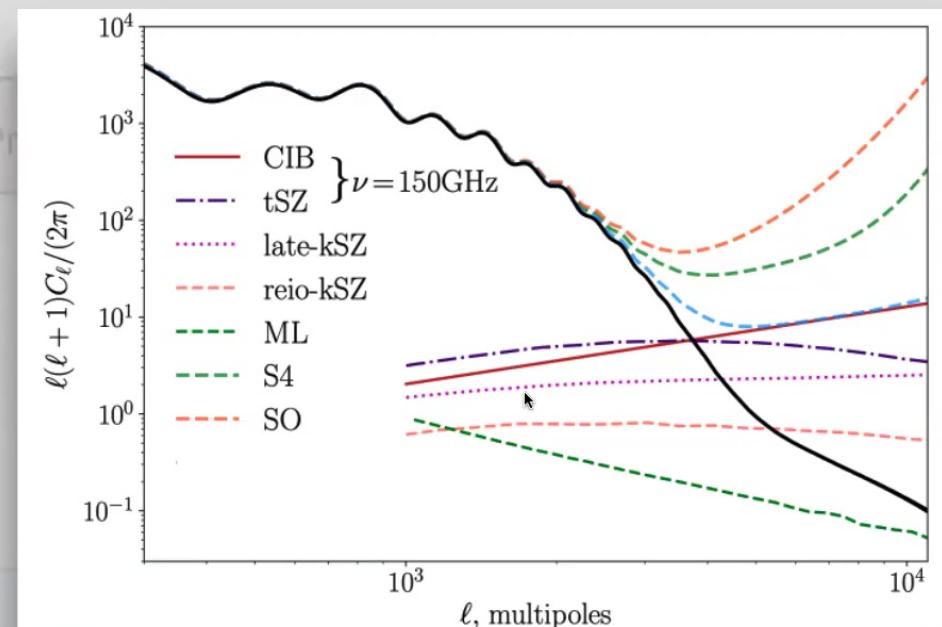


Upcoming obse

ML SNR*	CMB	
LSS	SO	S4
DESI	7	8
VROY1	16	28
VROY10	20	37

Observational signatures

*from cross-correlation with galaxies



1812.03167 (PRL) SCH et al.

Cosmology from moving lens

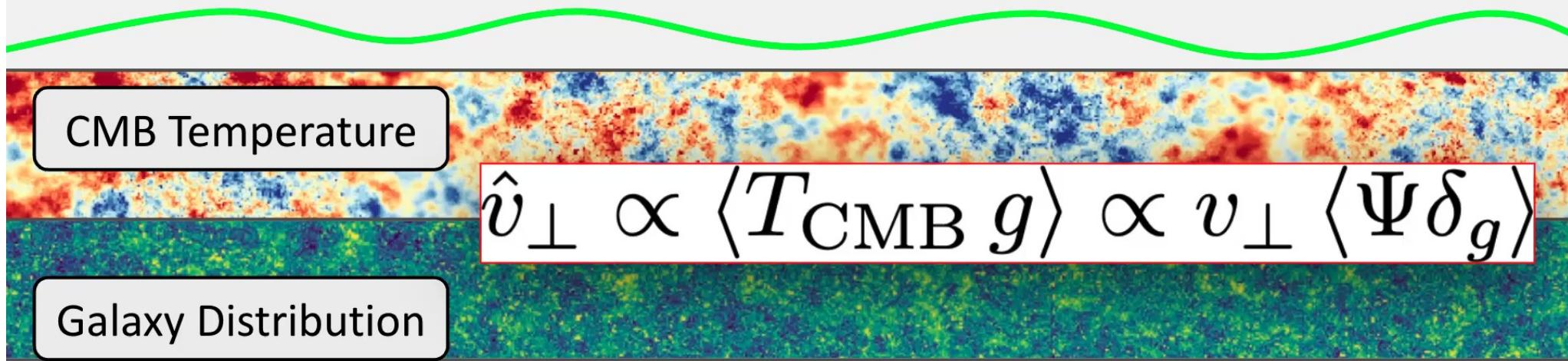
$$\langle T_{\text{CMB}} \rangle$$



$$T_{\text{CMB}} \propto v_{\parallel} \delta_e$$

$$T_{\text{CMB}} \propto \vec{v}_{\perp} \cdot \nabla \Psi$$

Large-scale transverse-velocity mode:



Cosmology from moving lens



Selim Hotinli

$$P_{gg}(k, \mu) = (b_g + b_{\text{rsd}} f \mu^2)^2 P_{mm}(k),$$

$$P_{gv}(k, \mu) = b \left(\frac{faH}{k} \right) (b_g + b_{\text{rsd}} f \mu^2) P_{mm}(k),$$

$$P_{vv}(k, \mu) = b^2 \left(\frac{faH}{k} \right)^2 P_{mm}(k),$$

Cosmology from moving lens



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moving lens : $b_{\perp} \sim \langle \Psi \delta_g \rangle$

kSZ : $b_{\parallel} \sim \langle \delta_e \delta_g \rangle$

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Fundamental Physics

- Scale-dependent galaxy bias: b_g
- Cosmological growth rate: f

Observational signatures

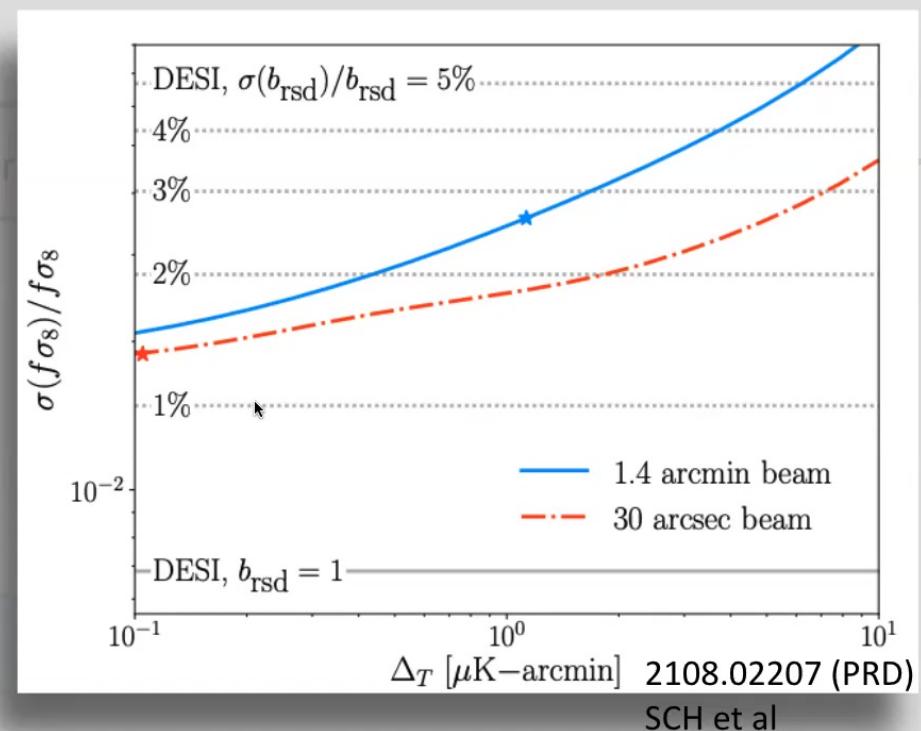
Upcoming observations

CMB secondaries:

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Outline



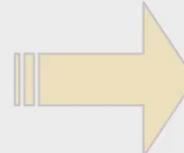
Primordial signatures

Observables

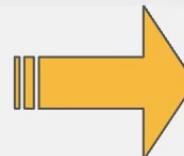
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Polarized Sunyaev Zel'dovich effect



Bulk velocity field



Remote-quadrupole field

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Observational signatures

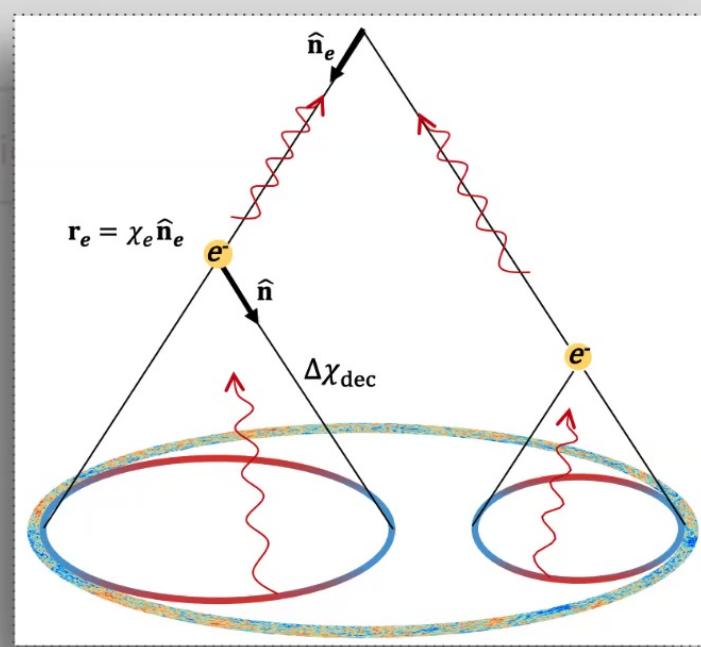
Upcoming obse

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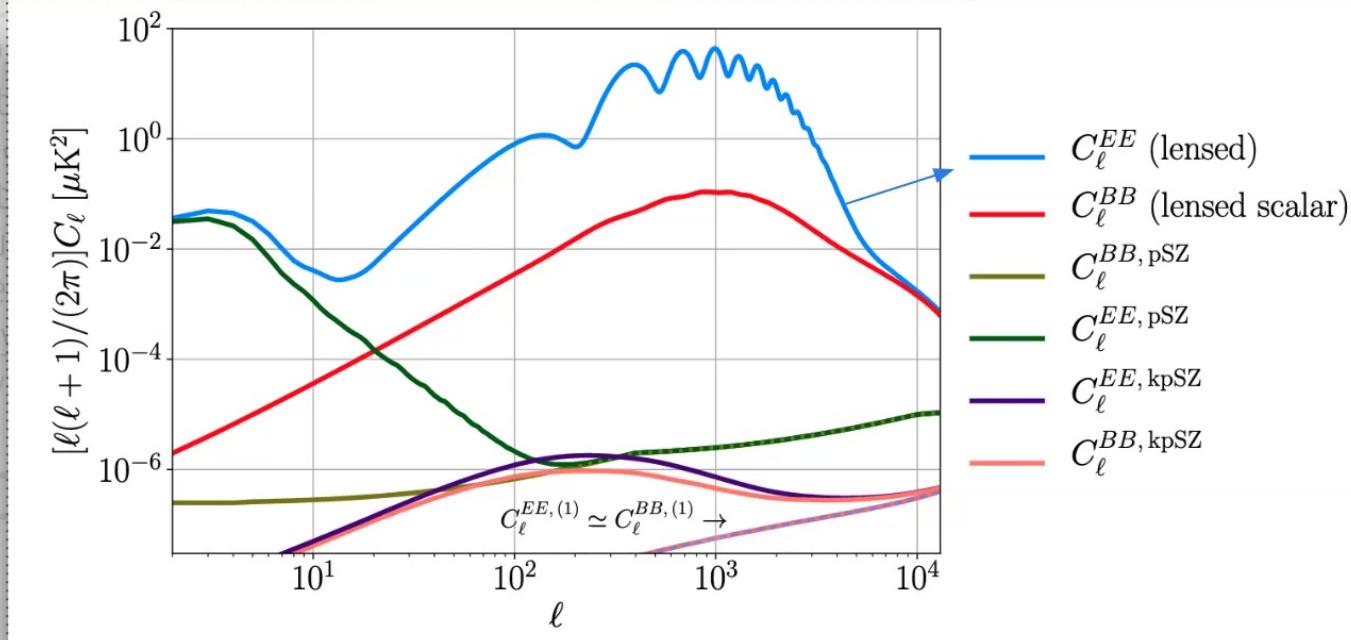
Beyond the standard cosmological paradigm

- Initial conditions
- Inflationary
- Non-inflationary
- Inflationary
- Isocurvature
- Scale-dependent
- Parity-violating
- Heavy particles
- ...

Upcoming observational



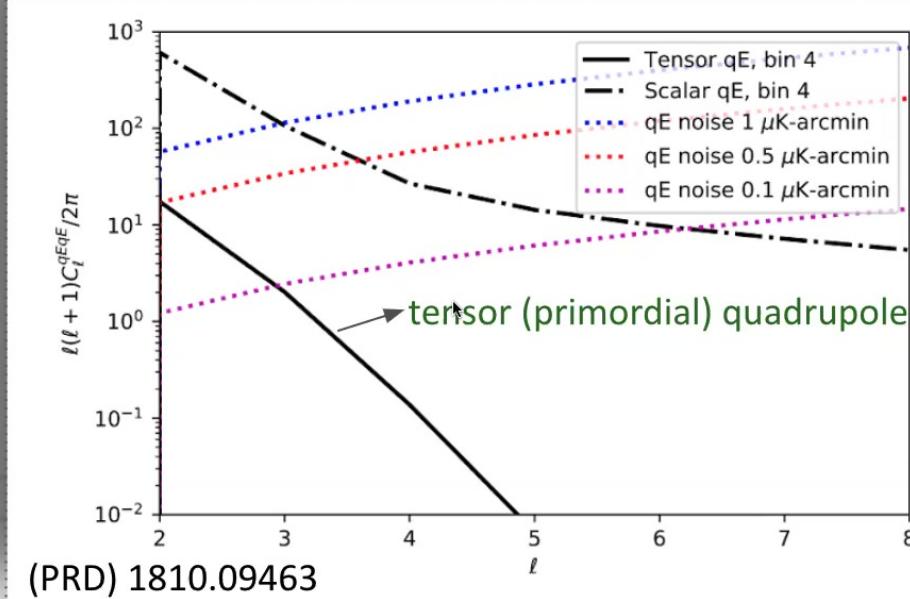
Galaxies
Dropouts
Quasars
21-cm
...



- Scale-dependent
- Cosmological growth

$$(Q \pm iU)(\hat{\mathbf{n}}) = \int_0^{\chi_*} d\chi \dot{\tau}(\chi \hat{\mathbf{n}}) e^{-\tau(\chi)} \pm p(\chi \hat{\mathbf{n}})$$

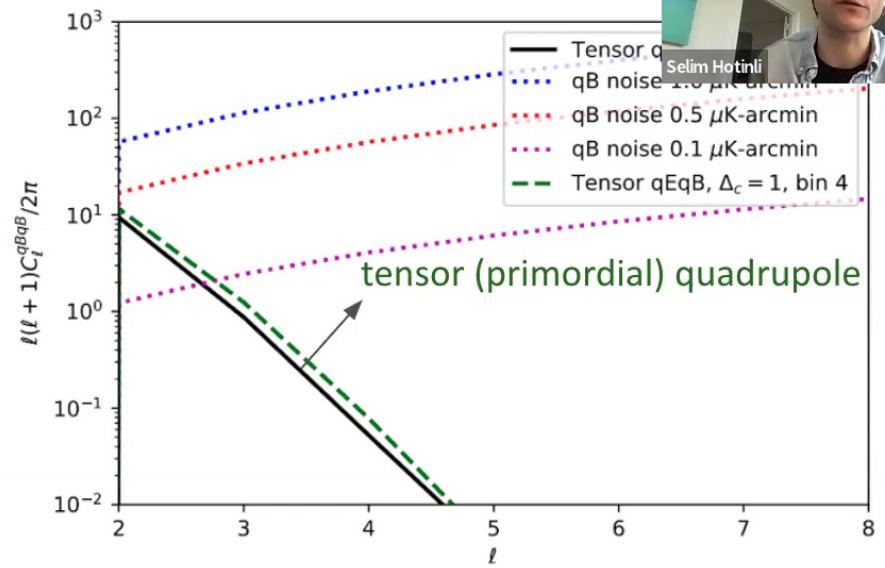
Observational signatures



$$p^E, p^B \sim \langle E\delta_g \rangle, \langle B\delta_g \rangle$$

- Scale-dependent galaxy bias: b_g
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Observational signatures



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Upcoming observations

LS

Selim Hotinli

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Fundamental Properties of the Universe

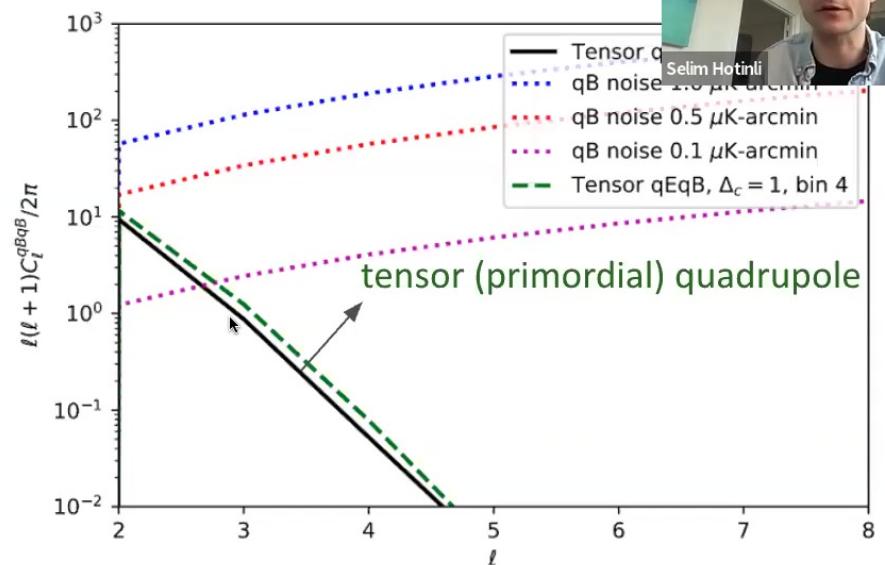
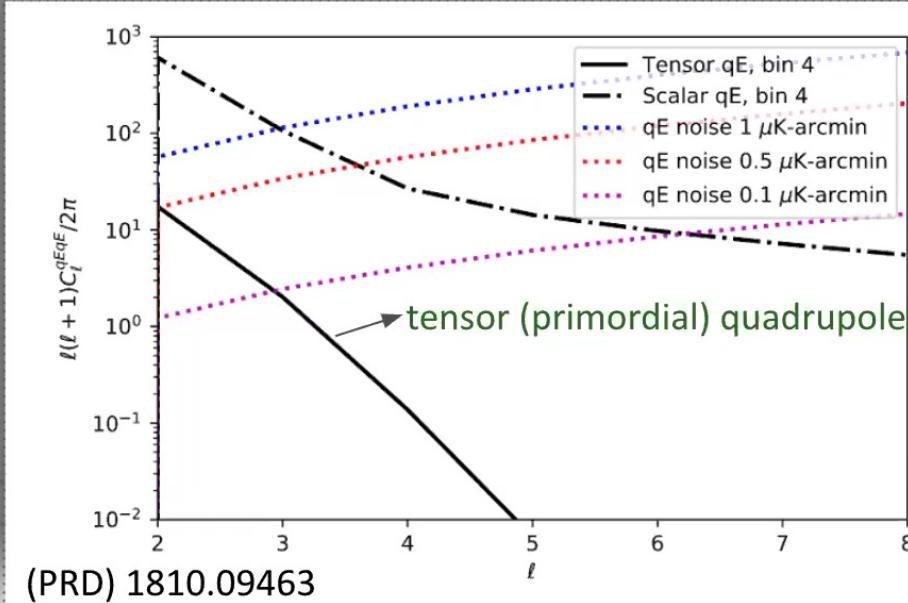
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Observational signatures

2203.05728

Beyond the standard cosmological paradigm

Upcoming observations



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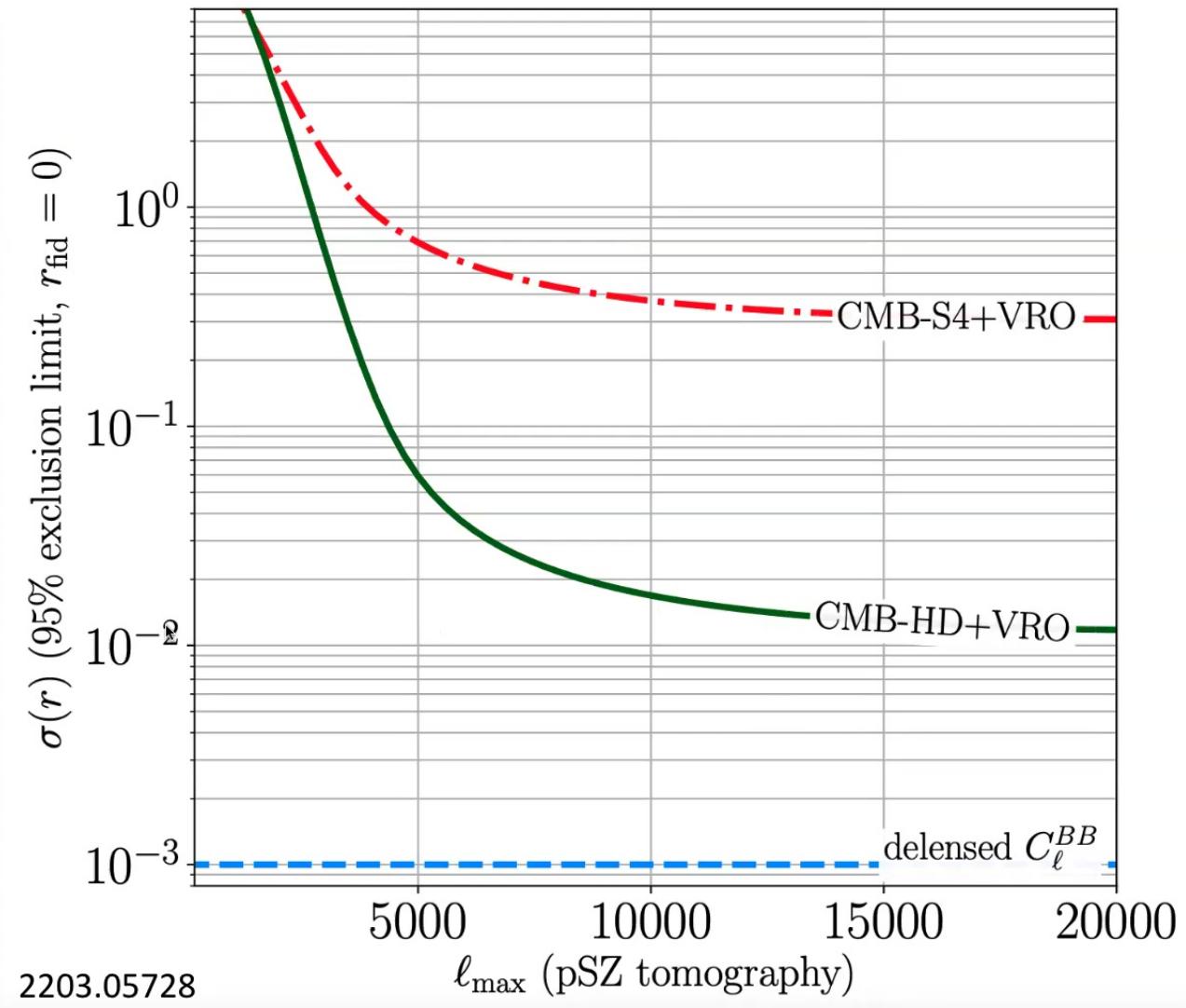
Observational signatures

Beyond the s

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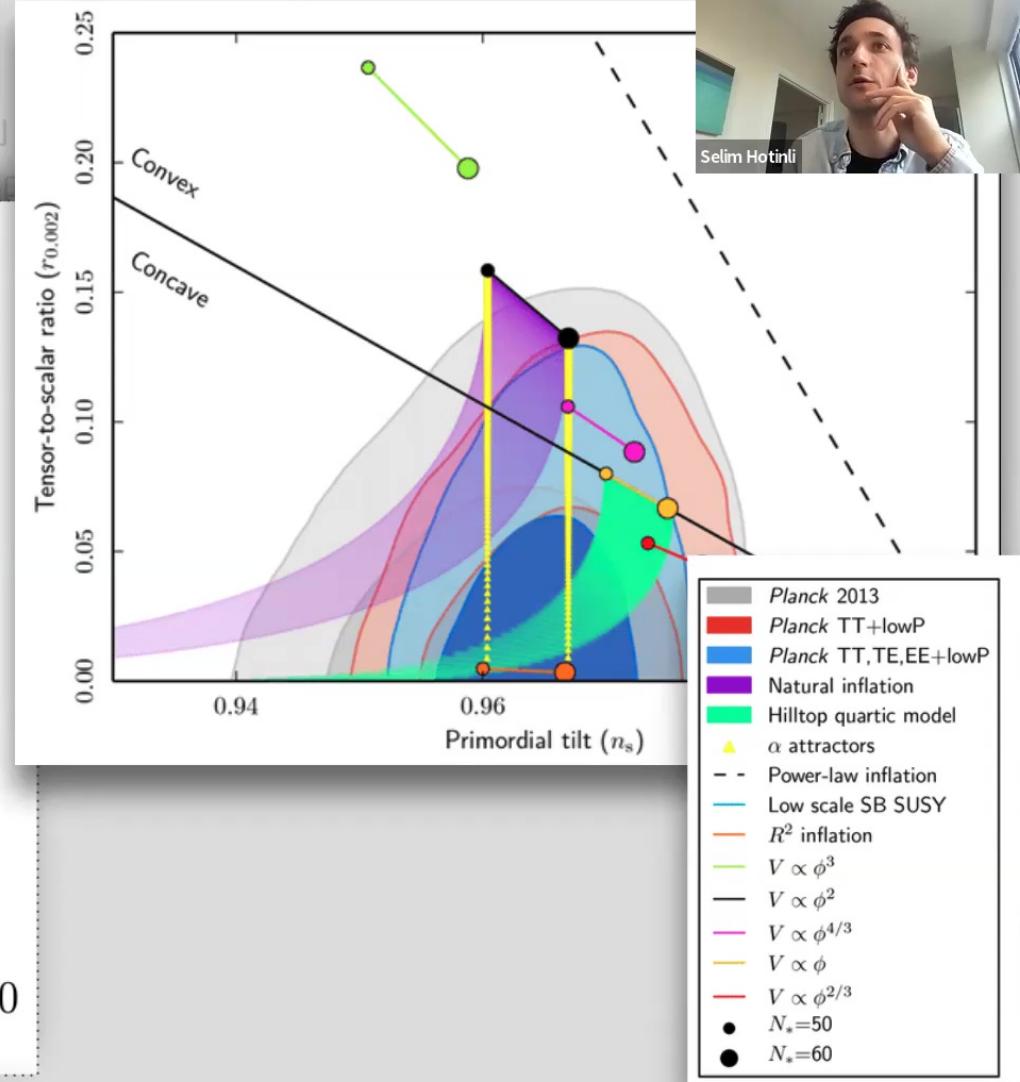
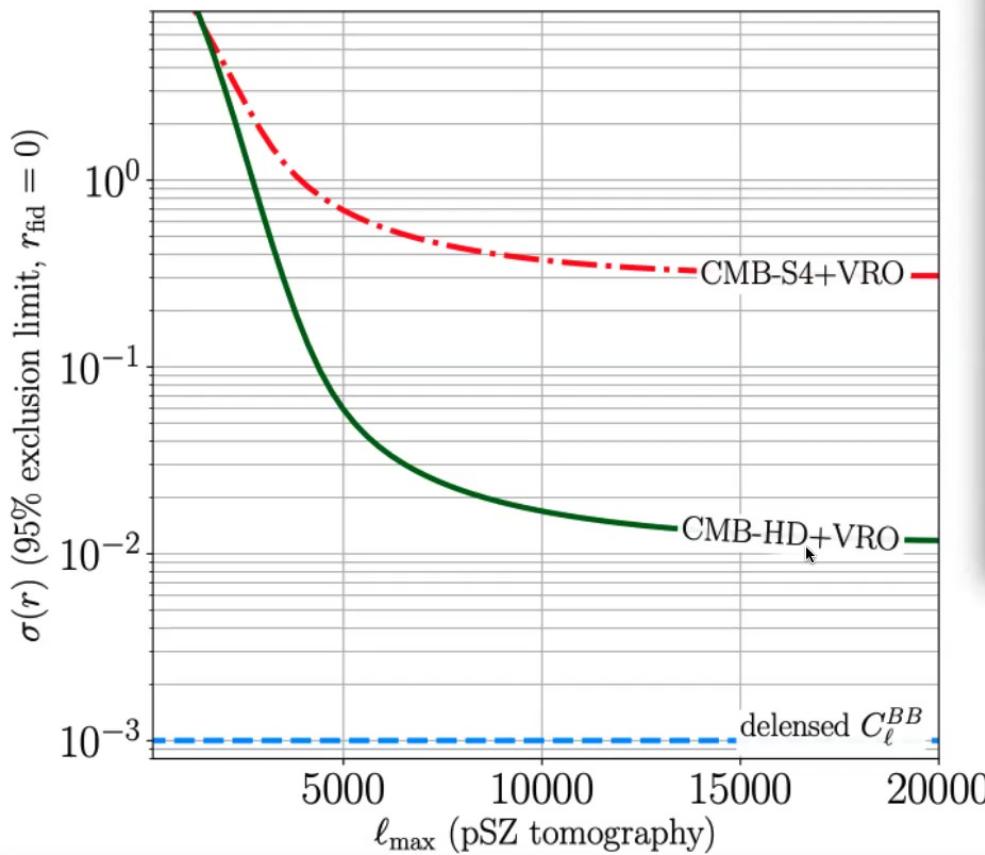
- Inflation
- Non-ga
- Inflatio
- Isocurv
- Scale in
- Parity
- Heavy p
- ...

- Scale-de
- Cosmolo



Beyond the standard cosmological paradigm

Initial conditions: Growth of structure
 • Inflation • Free-streaming sources



Beyond the standard cosmological paradigm

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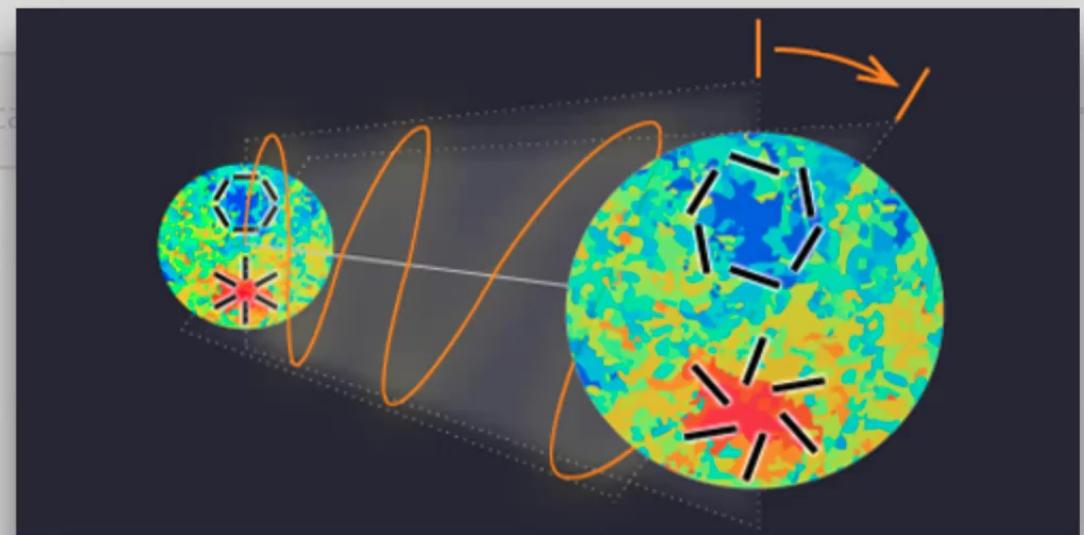


LS

CMB secondaries:

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- Inflation
- Non-gaussianity
- Inflationary D.o.F
- Isocurvature
- Scale invariance
- **Parity**
- Heavy particles
- ...

Growth of structure:

- Free-streaming species
- Dark energy
- Dark matter
- Gravity

- Scale-dependent galaxy bias
- Cosmological growth rate: $\propto \phi^{-1}$

Observational signatures

Upcoming observations

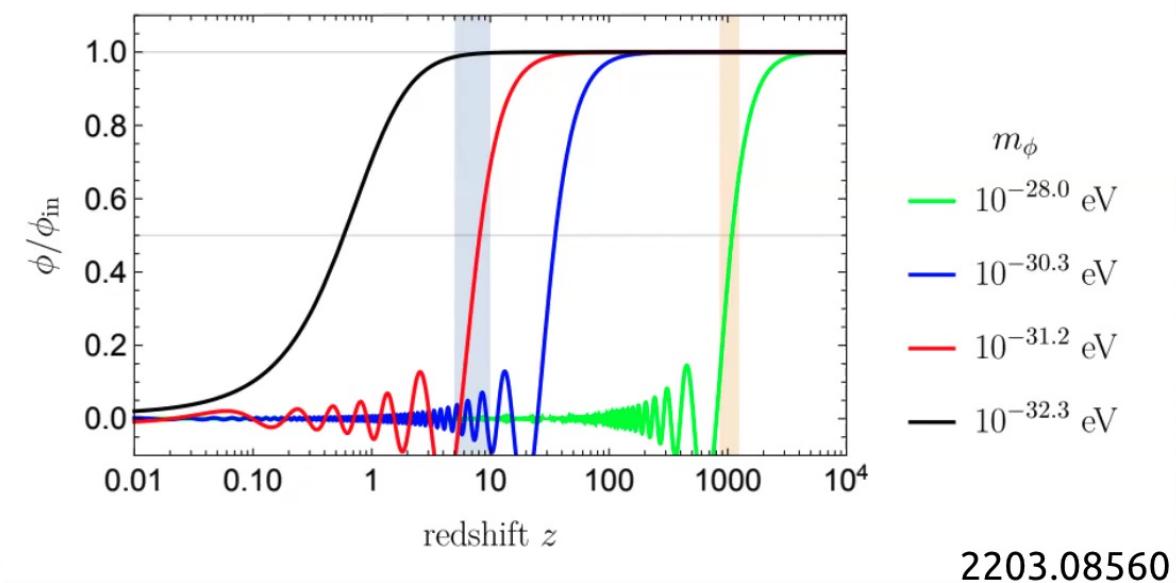


CMB secondaries:

- Kinetic SZ
- **Polarized SZ**
- Moving lens
- Weak lensing

LS

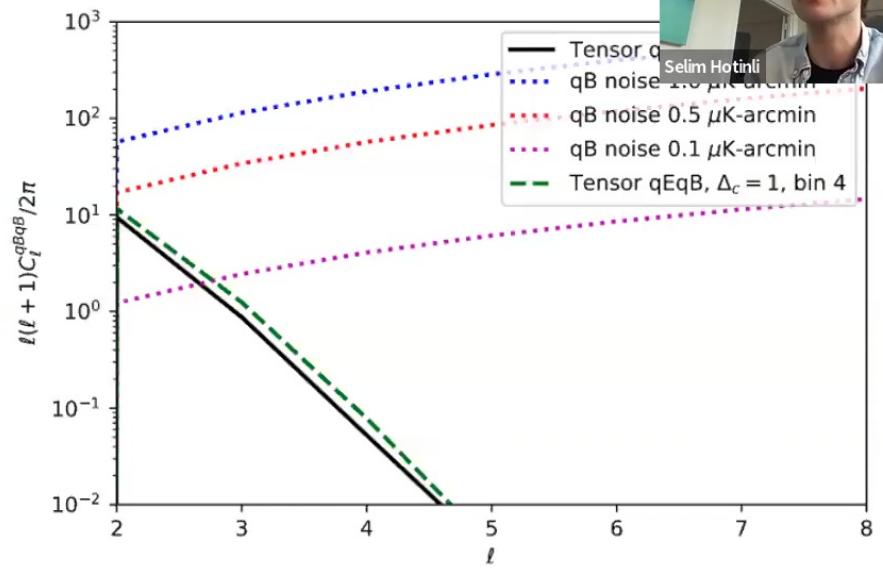
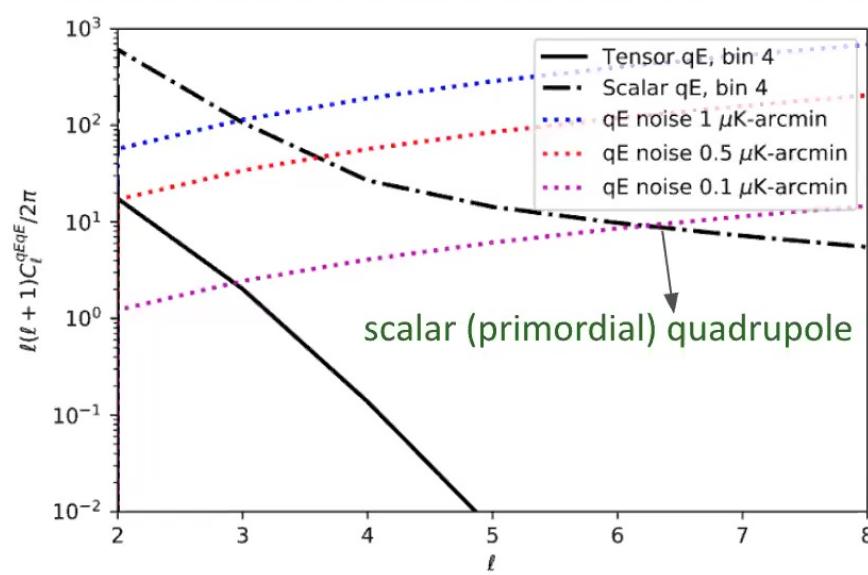
- **Galaxies**
- Dropouts
- Quasars
- 21-cm



2203.08560

Beyond the standard cosmological paradigm

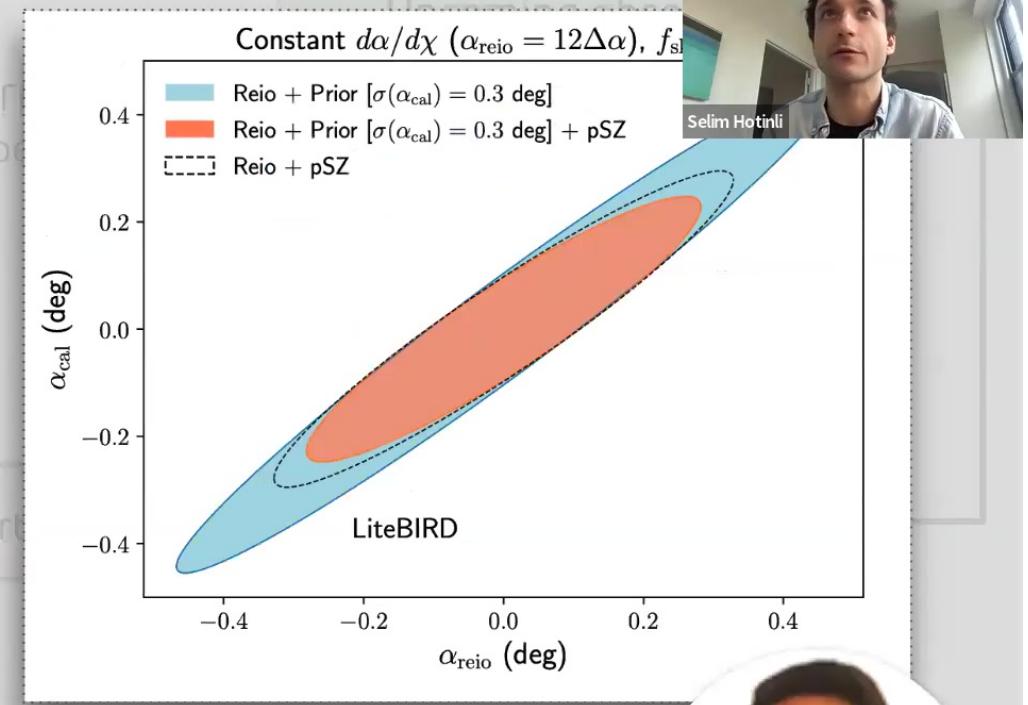
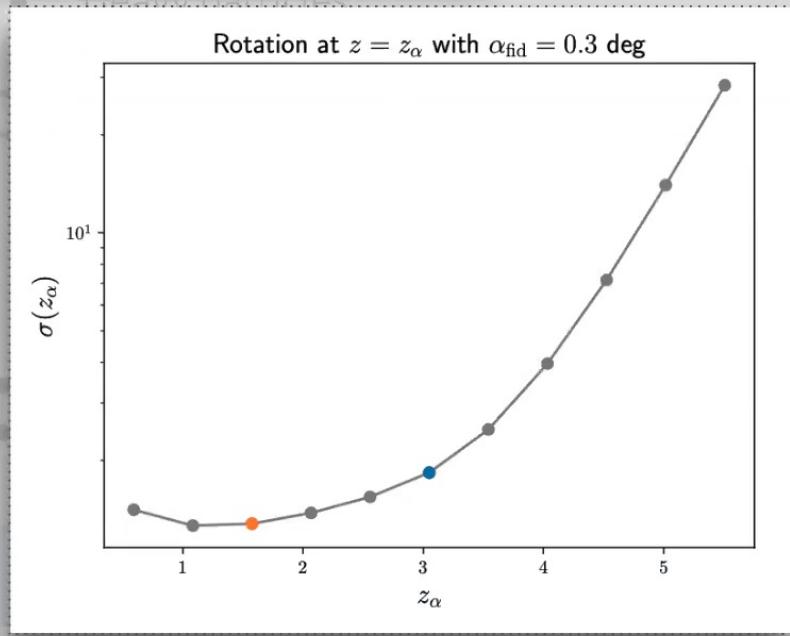
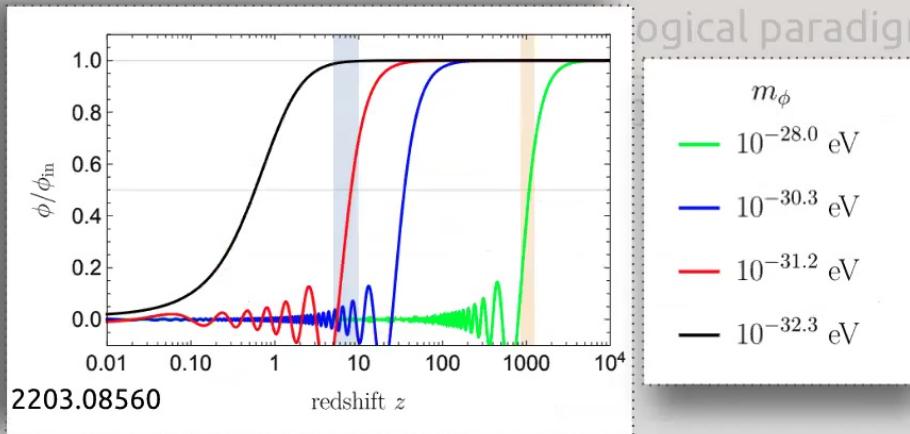
Upcoming observations



$$p^E, p^B \sim \langle E\delta_g \rangle, \langle B\delta_g \rangle$$

- Scale-dependent galaxy bias: b_g
- Cosmological growth rate: f

Observational signatures



Nanoom Lee (NYU) et al. to appear

Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.o.F
- Isocurvature
- Scale invariance
- Parity
- Heavy particles
- ...

- Scale-dependent galaxies
- Cosmological growth

Observational

Growth of structure:

- Free-streaming species
- Dark energy
- Dark matter
- Gravity
- ...

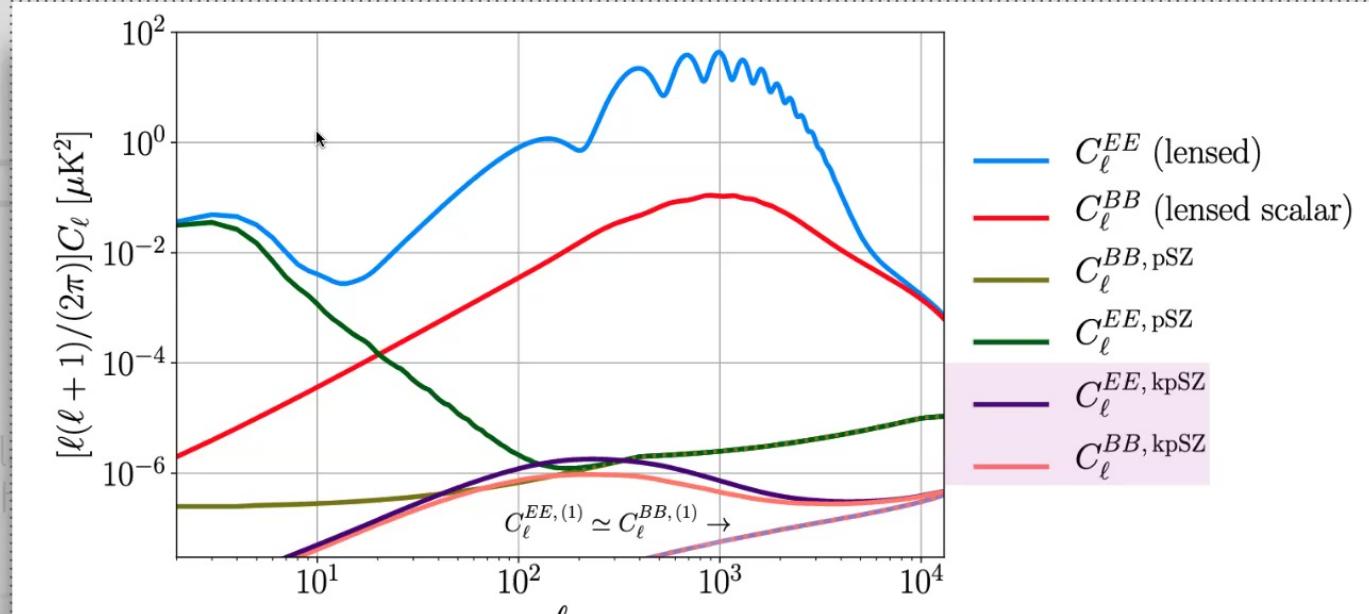
CMB secondaries:

- Kinetic SZ
- Polarized SZ
- Moving lens
- Weak lensing
- ...

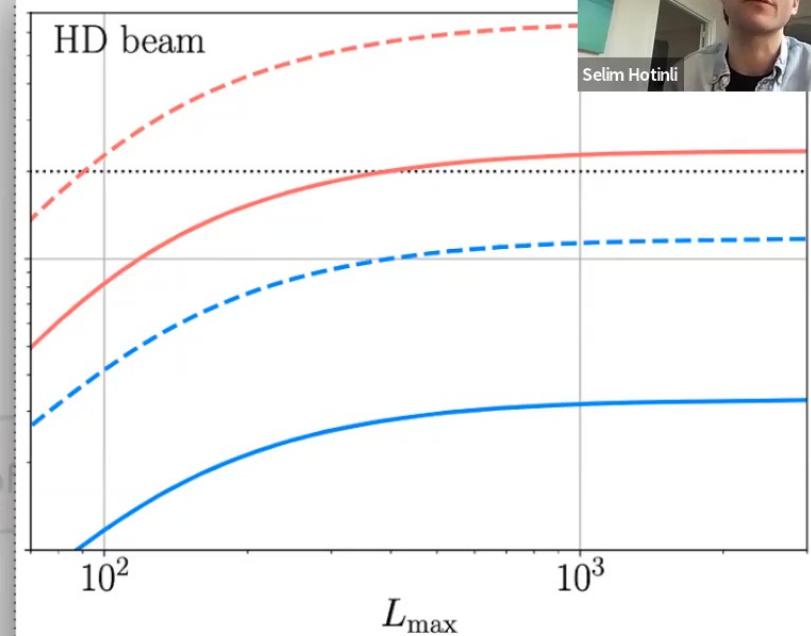
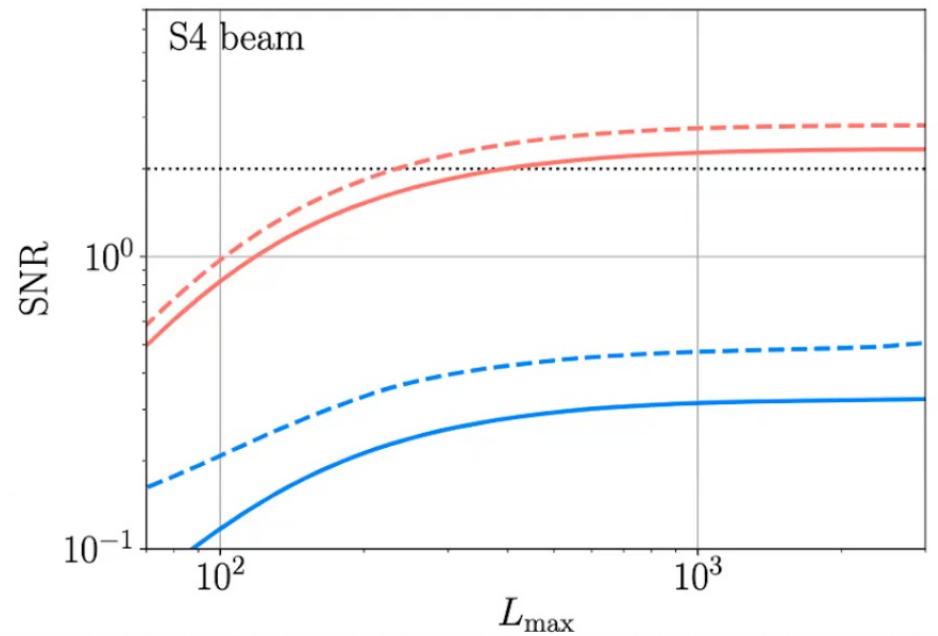
Upcoming obse



- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...



Beyond the standard cosmological paradigm



Scale-dependent galaxy bias: b

- 1: E -mode, V3R0-25 (ultra-deep patch) $f_{\text{sky}} = 0.03$
- 2: E -mode, baseline $f_{\text{sky}} = 0.5$
- 3: B -mode, V3R0-25 (ultra-deep patch) $f_{\text{sky}} = 0.03$
- 2: B -mode, baseline $f_{\text{sky}} = 0.5$

Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.o.F
- Isocurvature
- Scale invariance
- Parity
- Heavy particles
- ...

- Scale-dependent galaxies
- Cosmological growth

Observational

Growth of structure:

- Free-streaming species
- Dark energy
- Dark matter
- Gravity
- ...

CMB secondaries:

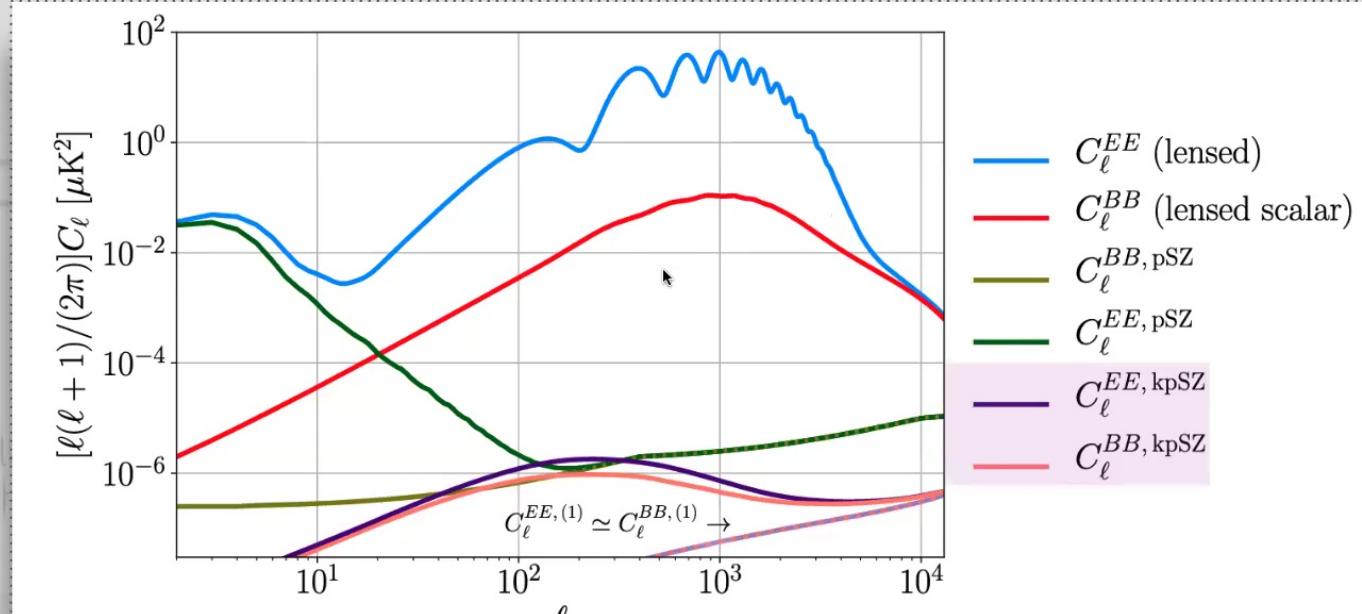
- Kinetic SZ
- Polarized SZ
- Moving lens
- Weak lensing



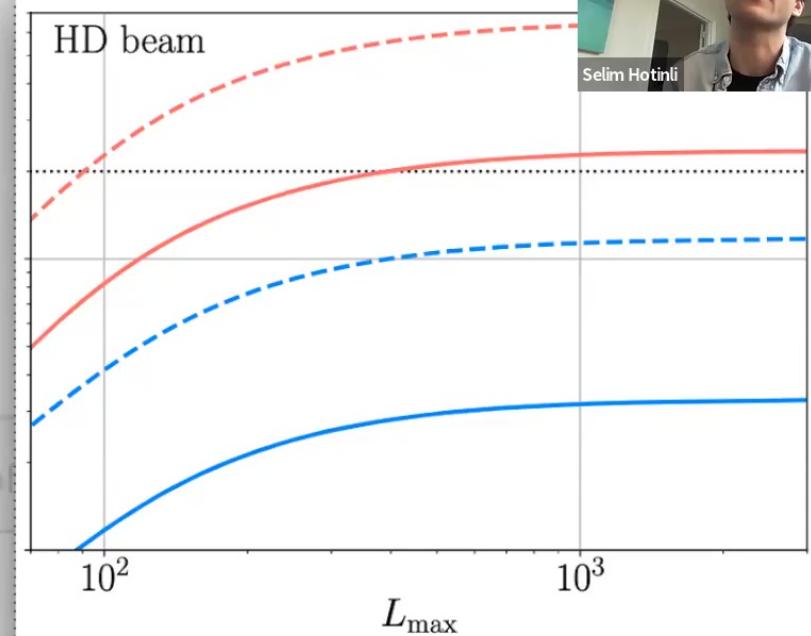
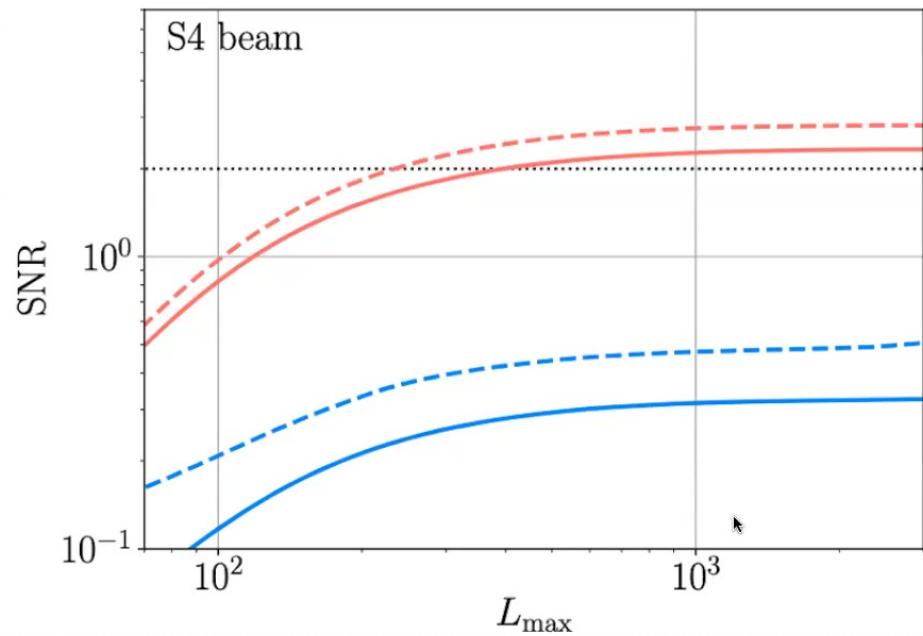
Upcoming observations

LS

- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...



Beyond the standard cosmological paradigm



Selim Hotinli

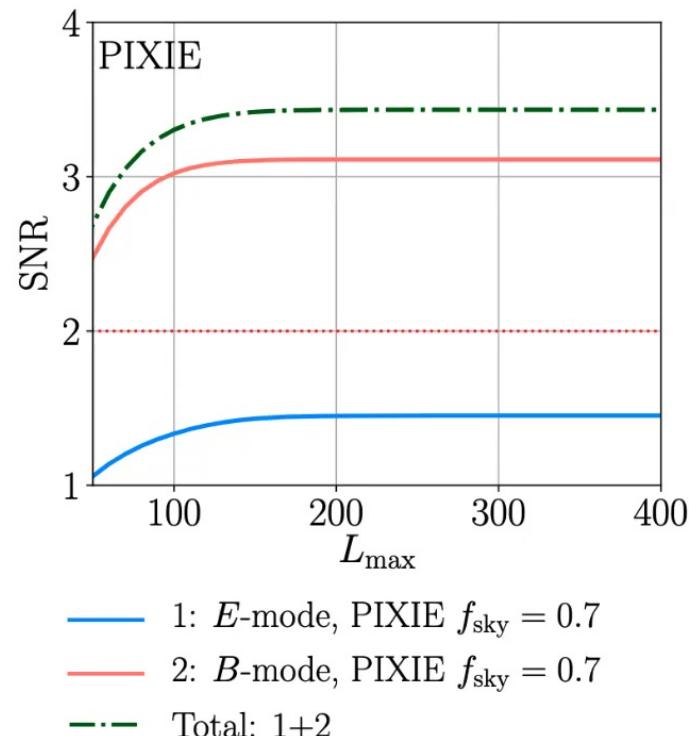
Scale-dependent galaxy bias: b

- 1: E -mode, V3R0-25 (ultra-deep patch) $f_{\text{sky}} = 0.03$
- 2: E -mode, baseline $f_{\text{sky}} = 0.5$
- 3: B -mode, V3R0-25 (ultra-deep patch) $f_{\text{sky}} = 0.03$
- 2: B -mode, baseline $f_{\text{sky}} = 0.5$

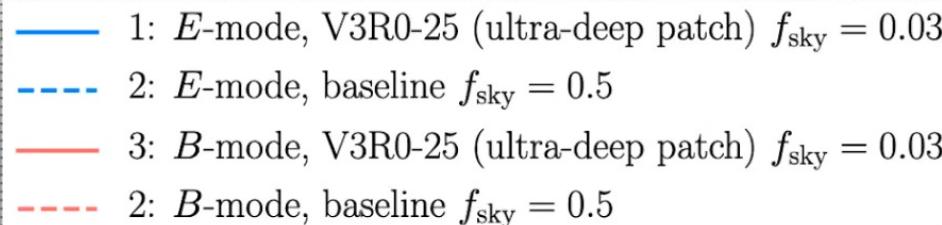
Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.o.f.
- Isocurvature
- Scale invariance
- Parity
- Heavy particles
- ...



- Scale-dependent galaxy bias: b_a
- Cosmological...



Upcoming observations

Secondaries:

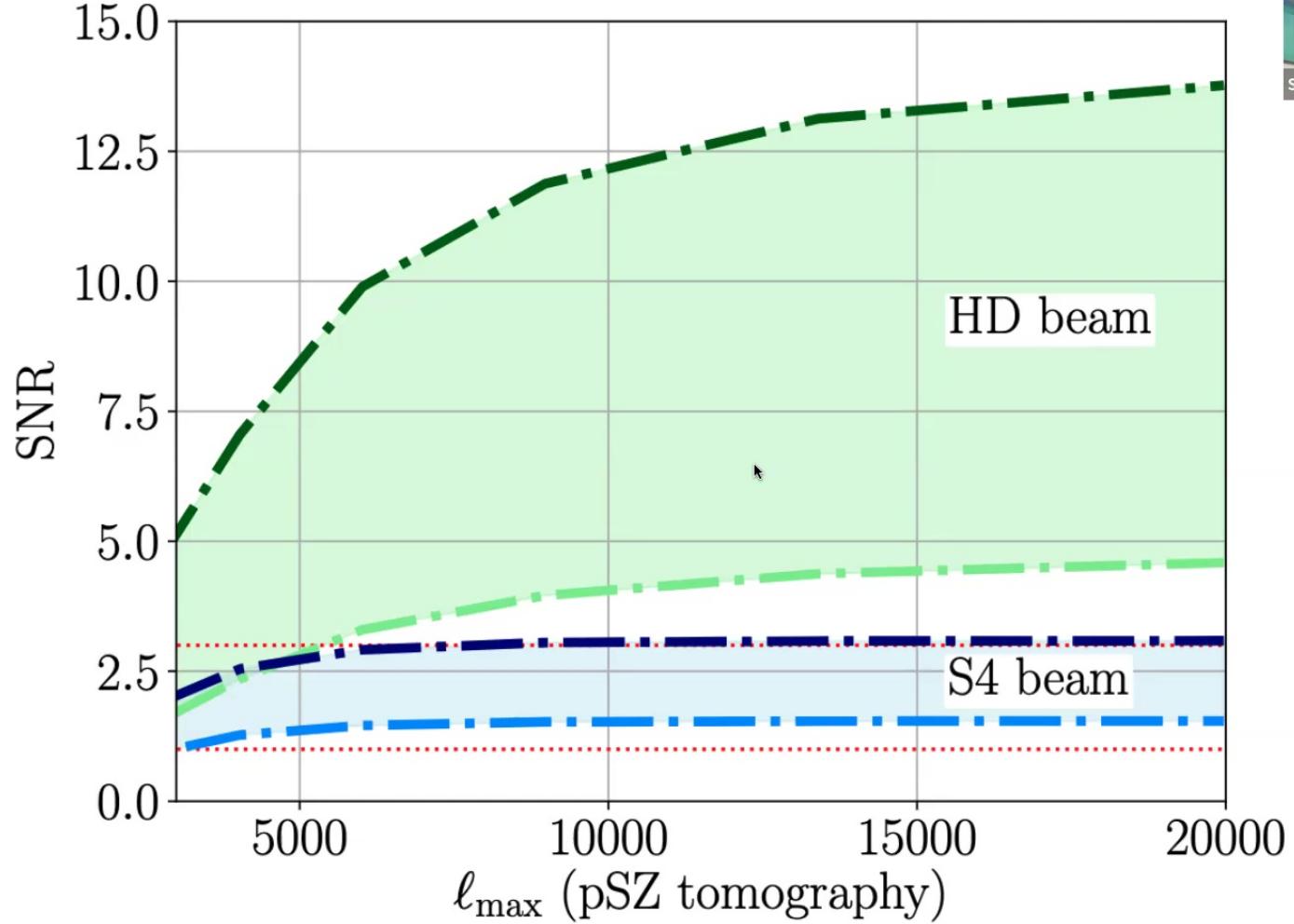
- Kinetic SZ
- Polarized SZ
- Moving lens
- Weak lensing



- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...

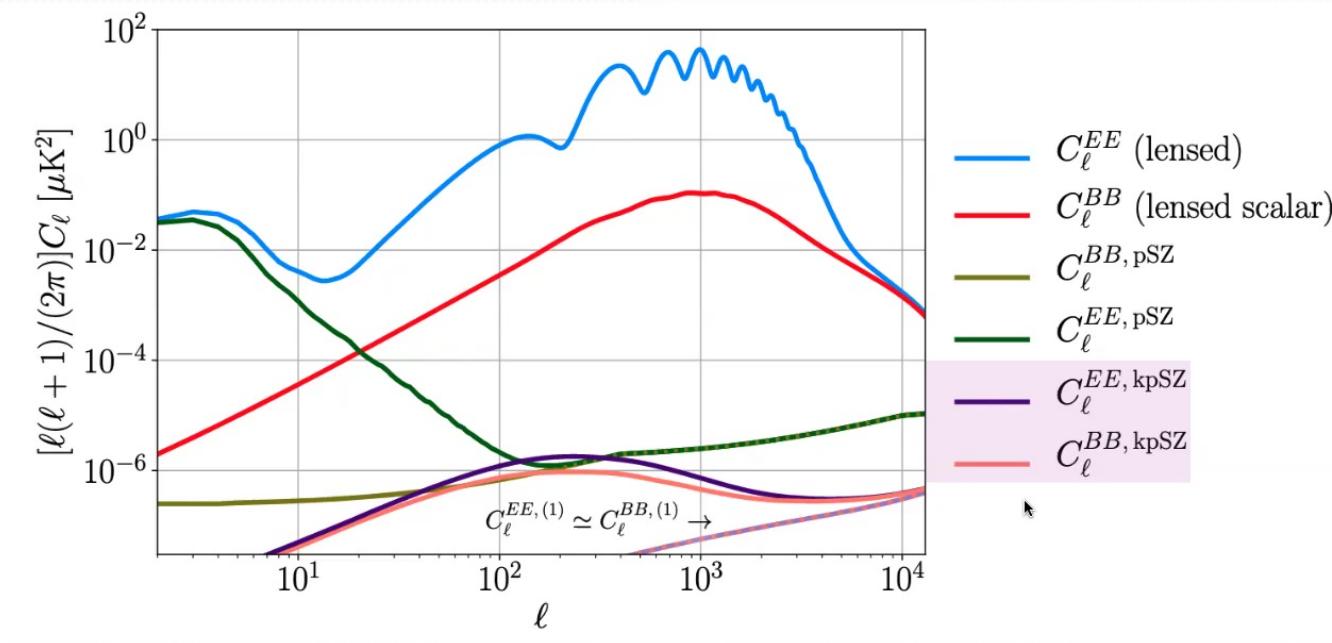


Galaxies
Dropouts
Quasars
21-cm
...



Beyond the standard cosmological paradigm

- Initial conditions
- Inflationary
- Non-inflationary
- Inflationary
- Isocurvature
- Scale invariant
- Parity violation
- Heavy neutrinos
- ...



- Scalar fields
- Cosmological parameters

$$\pm p(\chi \hat{\mathbf{n}}) = -\frac{T_{\text{CMB}}}{10} \left(\frac{x}{2} \coth \frac{x}{2} \right) (V_\theta(\chi \hat{\mathbf{n}}) \mp i V_\phi(\chi \hat{\mathbf{n}}))^2$$

Observational signatures



Cosmology from pSZ

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.C.
- Isocurvature
- Scale invariance
- Parity
- Heavy particles
- ...

- Scale-dependent
- Cosmological g

Growth of structure:

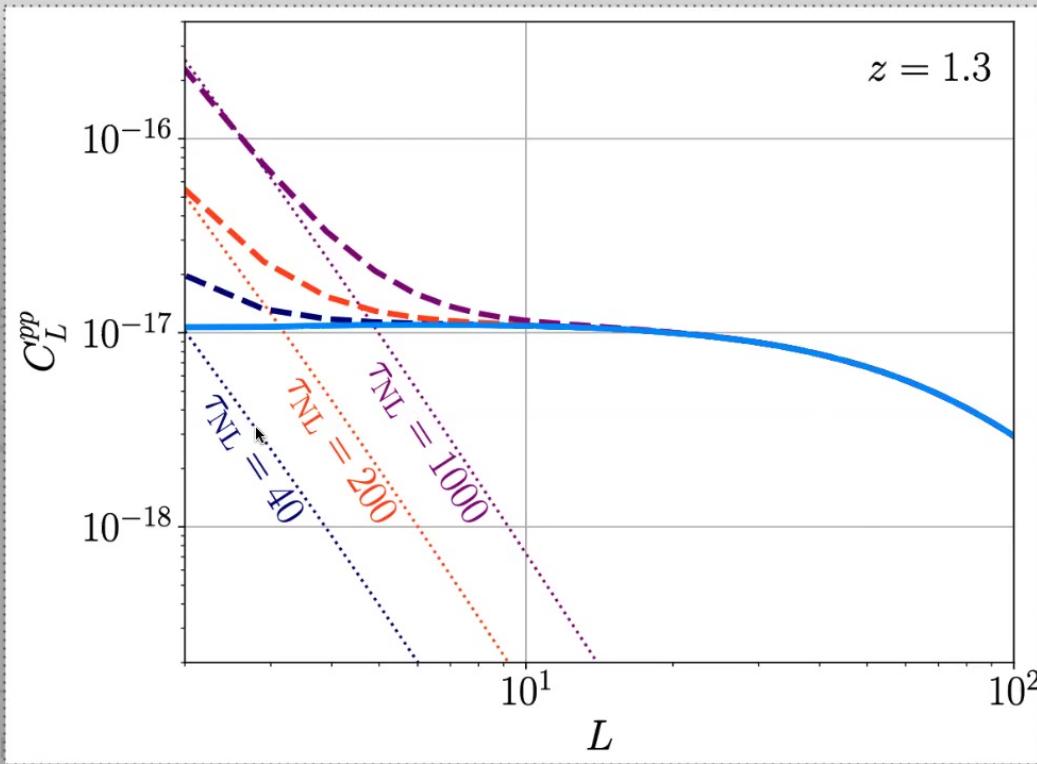
CMB secondaries:

LSS

Upcoming obse



- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...



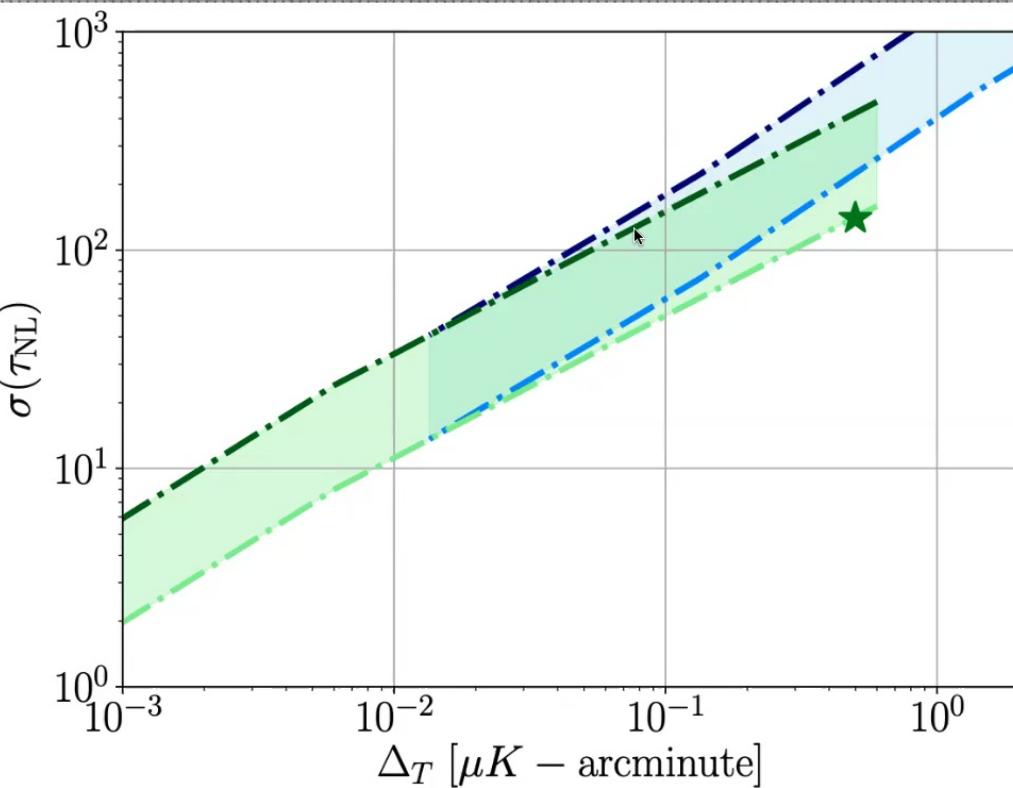
$$\langle \pm p(\mathbf{k}_L) \pm p(\mathbf{k}'_L) \rangle_{\text{NG}} = f^2(x) (100/9) \tau_{\text{NL}} \sigma_{v_\perp}^4 P_\Phi(\mathbf{k}_L) \times (2\pi)^3 \delta_D(\mathbf{k}_L + \mathbf{k}'_L)$$

Cosmology from pSZ

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary Dynamics
- Isocurvature
- Scale invariance
- Parity
- Heavy particles
- ...

- Scale-dependent
- Cosmological growth



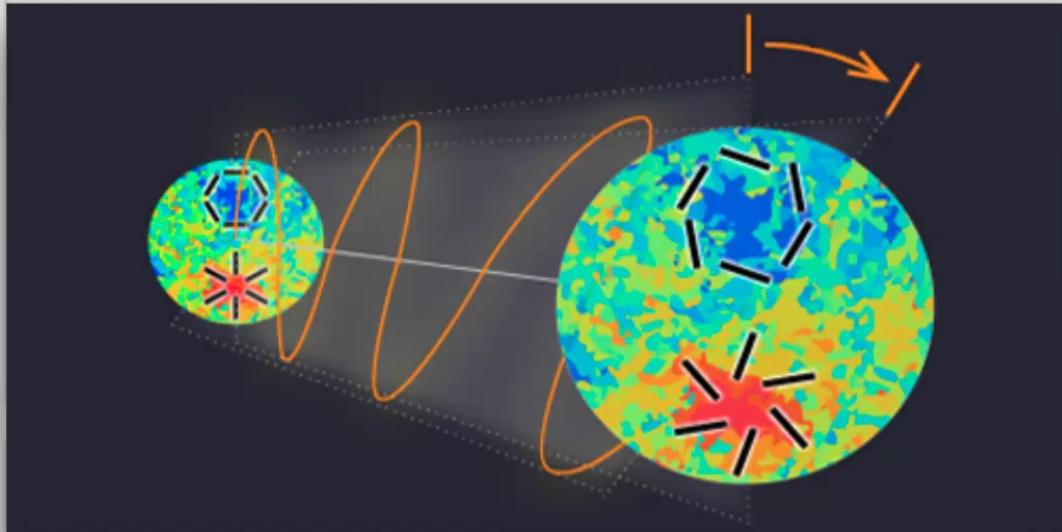
$$\langle \pm p(\mathbf{k}_L) \pm p(\mathbf{k}'_L) \rangle_{\text{NG}} = f^2(x) (100/9) \tau_{\text{NL}} \sigma_{v_\perp}^4 P_\Phi(\mathbf{k}_L) \times (2\pi)^3 \delta_D(\mathbf{k}_L + \mathbf{k}'_L)$$



Cosmology from pSZ

Initial conditions:

Growth of structure:



- Scale-dependent galaxy bias: b_g
- Cosmological growth rate: f

Observational signatures

Upcoming obse

CMB secondaries: LS



$$p_{\ell m}^E' = p_{\ell m}^E \cos 2\alpha - p_{\ell m}^B \sin 2\alpha$$
$$p_{\ell m}^B' = p_{\ell m}^B \cos 2\alpha + p_{\ell m}^E \sin 2\alpha .$$

of the Universe

Cosmology from pSZ

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary
- Isocurvature
- Scale invariance
- Parity
- Heavy particles
- ...

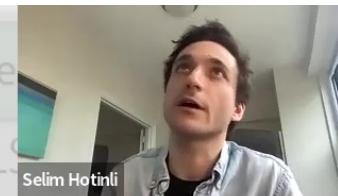
Growth of structure:

- Free-streaming species

Upcoming observations:

CMB secondaries:

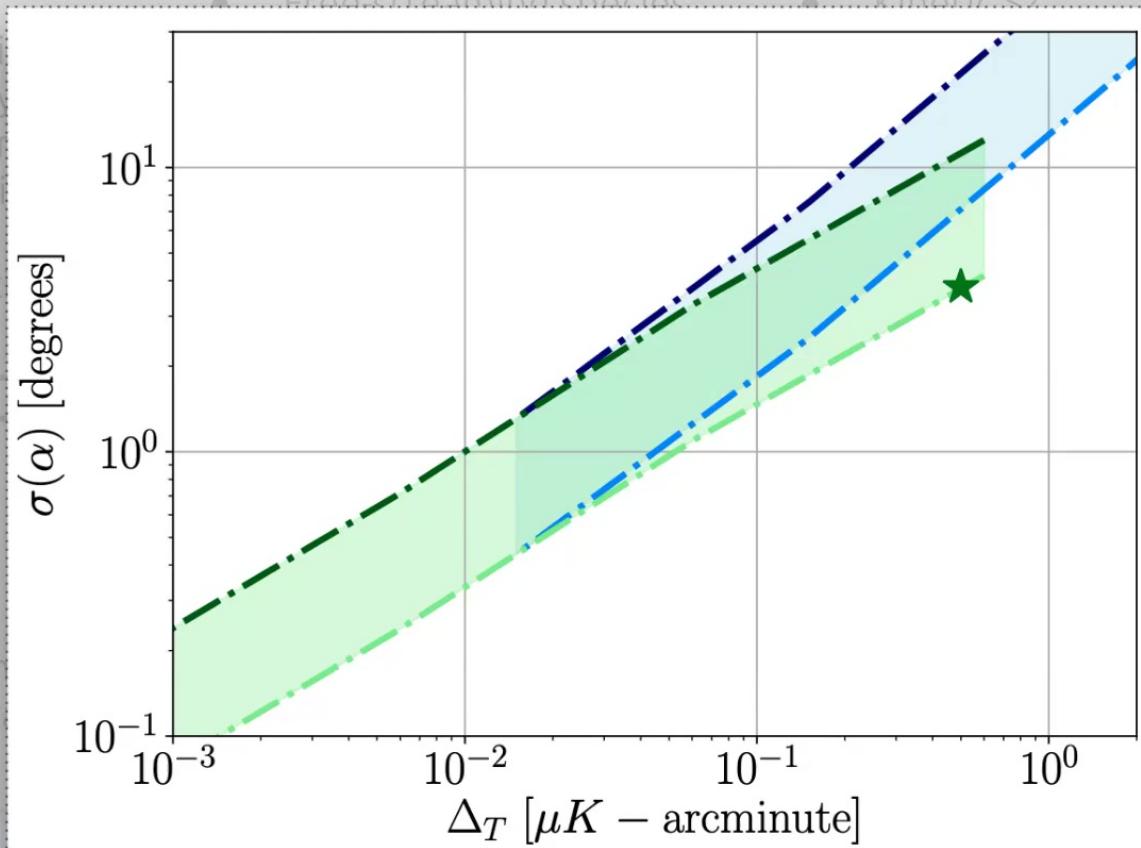
- LSST
- Kinetic SZ



- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...

- Scale-dependent
- Cosmological

Observational signatures



Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.o.F
- Isocurvature
- Scale invariance
- Parity
- Heavy particles
- ...

Growth of structure:

- Free-streaming species
- Dark energy
- Dark matter
- Gravity
- ...

CMB secondaries:

- Kinetic SZ
- Polarized SZ
- Moving lens
- Weak lensing
- ...

Upcoming obse



Selim Hotinli

L

- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...

Velocity reconstruction with the cosmic microwave background and galaxy surveys

Juan Cayuso^{1,2}, Richard Bloch³, Selim C. Hotinli⁴, Matthew C. Johnson^{1,3}, and Fiona McCarthy^{1,2,5}

¹*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

²*Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*

³*Department of Physics and Astronomy, York University, Toronto, Ontario, M3J 1P3, Canada*

⁴*Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218 USA and*

⁵*Center for Computational Astrophysics, Flatiron Institute,*

162 5th Avenue, New York, NY 10010 USA

(Dated: November 24, 2021)

- Scale-dependent
- Cosmological gro

Observational signatures

arXiv: 2111.11526

Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.o.F
- Isocurvature
- Scale invariance
- Parity
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- ...

Growth of structure:

- Free-streaming species
- Dark energy
- Dark matter
- Gravity
- ...

Fundamental

- Scale-dependent galaxy bias: b_g
- Cosmological growth rate: f

Observational signatures

arXiv: 2111.11526

Upcoming observations



Selim Hotinli

LSS

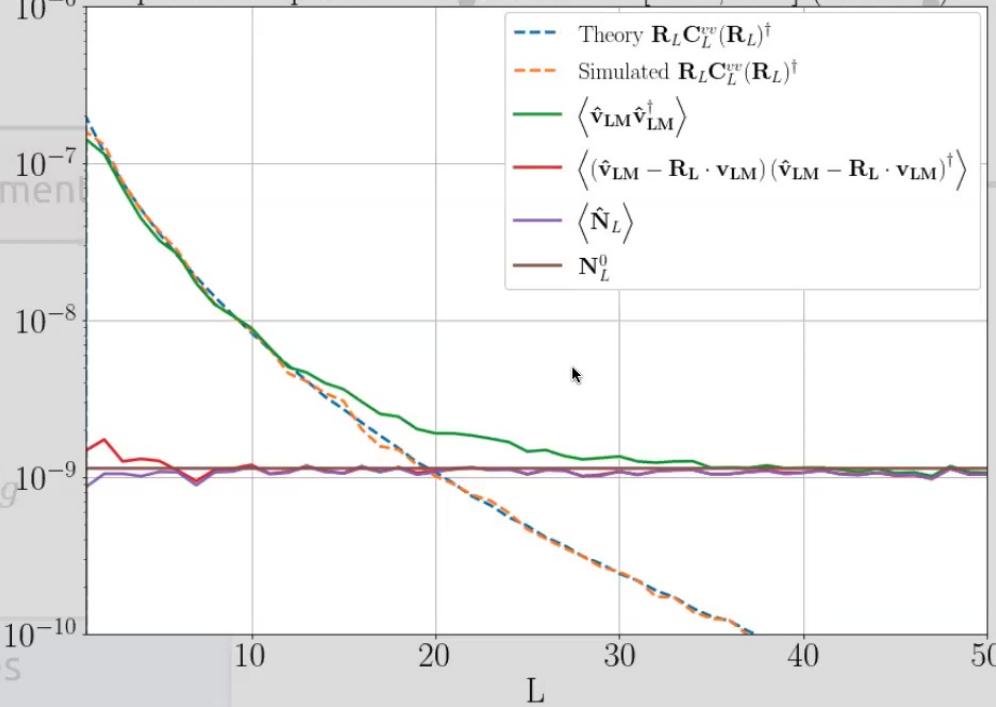
- Galaxies
- Dropouts
- Quasars
- 21-cm

...

CMB secondaries:

- Kinetic SZ
- Polarized SZ
- Moving lens
- Weak lensing

Spectra comparison in redshift bin = [0.44 ; 0.50] (no mask)



Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.o.F
- Isocurvature
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- Heavy particles
- ...

Growth of structure:

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- Dark energy
- Dark matter

CMB secondaries:

- Kinetic SZ
- Polarized SZ
- Moving lens

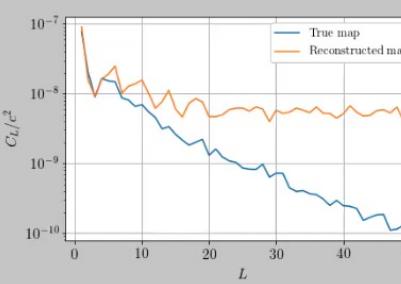
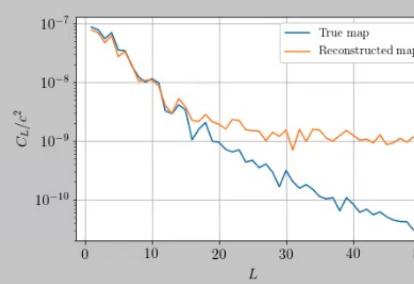
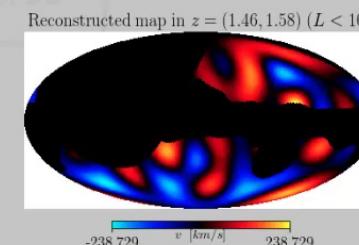
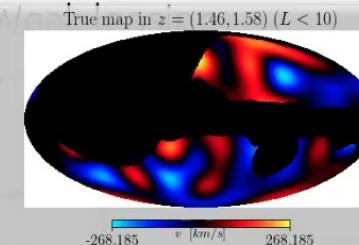
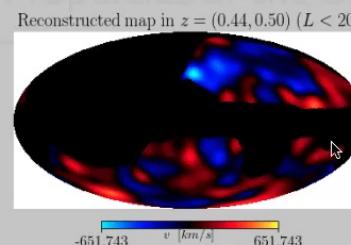
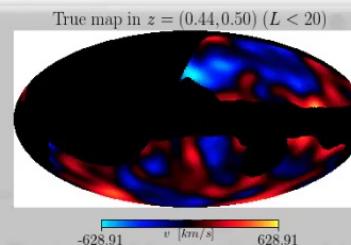
Upcoming observations



- Galaxies
- Dropouts
- Quasars

21-cm

Gravity



Observational signatures

arXiv: 2111.11526

Beyond the standard cosmological paradigm

Initial conditions:

- Inflation
- Non-gaussianity
- Inflationary D.o.F
- Isocurvature
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Growth of structure:

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- Dark matter
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- ...

CMB secondaries:

- Kinetic SZ
- Polarized SZ
- Moving lens
- Weak lensing
- ...

LS

- Galaxies
- Dropouts
- Quasars
- 21-cm
- ...

Fundamental Properties of the Universe

- Scale-dependent galaxy bias: b_g
- Cosmological growth rate: f

Observational signatures

Upcoming obse



Selim Hotinli

Thanks for
listening!