Sixteenth Marcel Grossmann Meeting - Parallel session

The Early Universe

Constraining beyond ΛCDM models with 21cm intensity mapping forecast observations combined with latest CMB data

SISSA

Maria Berti

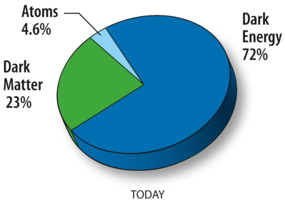
Astroparticle PhD student

07 July, 2021

Introduction

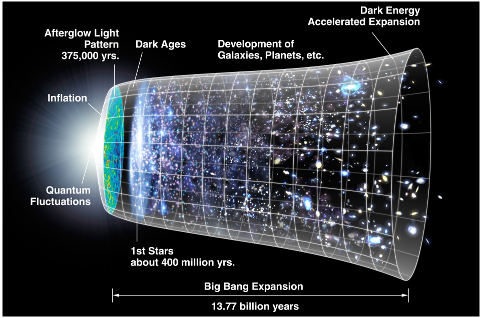
ΛCDM model

Credit: *NASA*



↪ **Cosmological Constant** Λ

$$p_\Lambda = -\rho_\Lambda$$

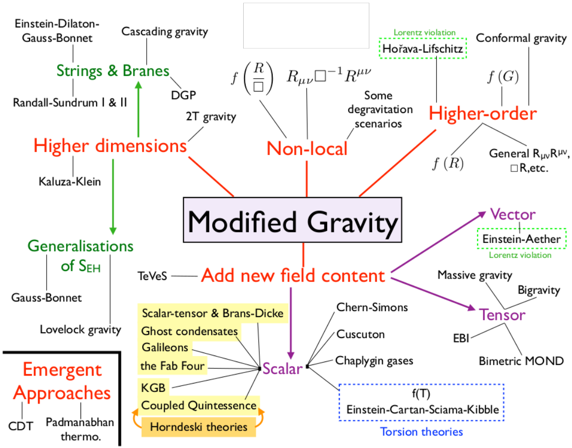


Credit: *NASA/WMAP Science Team*

Is it enough?

- What are Dark Matter and Dark Energy?
- Tensions on H_0, σ_8/S_8, A_L
- Cosmological Constant problem
- Coincidence problem

State-of-the-art



Bull et al., 2016

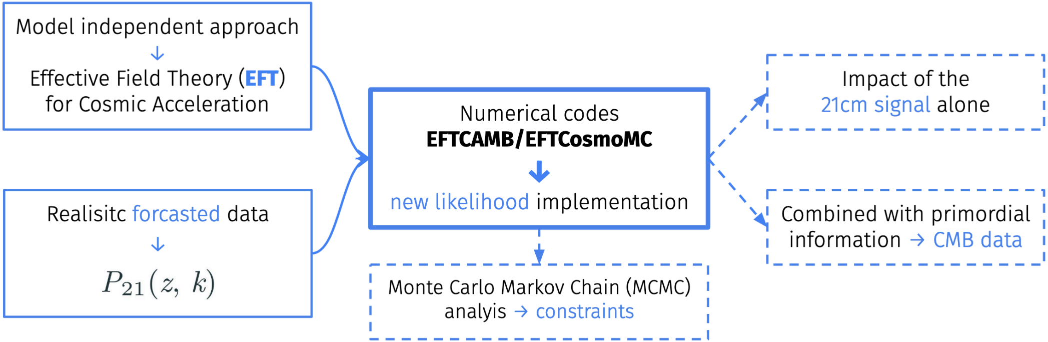
- All the results are broadly compatible with ΛCDM
- Future observations (*Euclid*, SKAO, . . .) → improve constraints
- New observables → 21cm signal power spectrum

Overview

Constraining beyond ΛCDM models with 21cm intensity mapping forecast observations combined with latest CMB data

Supervisor: **M. Viel**

Collaborators: M. Spinelli, B. S. Haridasu, A. Silvestri



Effective Field Theory for Cosmic Acceleration

Effective Field Theory - The idea behind

Introduced for INFLATION (*Creminelli et al., 2006, Cheung et al., 2008*) → applied to the LATE TIME COSMIC ACCELERATION (*Creminelli et al., 2009, Gubitosi, Piazza, and Vernizzi, 2013, Bloomfield et al., 2013*)

→ description of Large Scale Structure (EFTofLSS, *Carrasco et al., 2012*)

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$\longrightarrow$ description of Large Scale Structure (EFTofLSS, *Carrasco et al., 2012*)

Construct the most general

ACTION

Effective
easily interfaced
with observations

Unifying
includes as many DE-MG
models as possible

Up to second order in perturbations in the Jordan frame:

$$
\begin{aligned}
S = \int \mathrm{d}^4x\sqrt{-g}\Bigg\{ &\frac{m_0^2}{2}\left[1+\Omega^{\mathrm{EFT}}(\tau)\right]R + \Lambda(\tau) - c(\tau)a^2\delta g^{00} \\
&+ \frac{M_2^4(\tau)}{2}\left(a^2\delta g^{00}\right)^2 - \frac{\bar{M}_1^3(\tau)}{2}a^2\delta g^{00}\delta K \\
&- \frac{\bar{M}_2^2(\tau)}{2}(\delta K)^2 - \frac{\bar{M}_3^2(\tau)}{2}\delta K^\mu_\nu \delta K^\nu_\mu \\
&+ m_2^2(\tau)(g^{\mu\nu}+n^\mu n^\nu)\partial_\mu\left(a^2 g^{00}\right)\partial_\nu\left(a^2 g^{00}\right) \\
&+ \frac{\hat{M}^2(\tau)}{2}a^2\delta g^{00}\delta R^{(3)} + \dots \Bigg\} + S_m
\end{aligned}
$$

EFT action

Up to second order in perturbations in the Jordan frame:

$$S = \int \mathrm{d}^4x\sqrt{-g}\Bigg\{ \frac{m_0^2}{2}\left[1+\Omega^{\mathrm{EFT}}(\tau)\right]R + \Lambda(\tau) - c(\tau)a^2\delta g^{00} + \frac{M_2^4(\tau)}{2}\left(a^2\delta g^{00}\right)^2 - \frac{\bar{M}_1^3(\tau)}{2}a^2\delta g^{00}\delta K - \frac{\bar{M}_2^2(\tau)}{2}(\delta K)^2 - \frac{\bar{M}_3^2(\tau)}{2}\delta K^\mu_\nu \delta K^\nu_\mu + m_2^2(\tau)(g^{\mu\nu}+n^\mu n^\nu)\partial_\mu\left(a^2 g^{00}\right)\partial_\nu\left(a^2 g^{00}\right) + \frac{\hat{M}^2(\tau)}{2}a^2\delta g^{00}\delta R^{(3)} + \dots \Bigg\} + S_m$$

Full EFT is described by 9 time-dependent **EFT functions**

- $\{\Omega^{\mathrm{EFT}}, \Lambda, c\}$ first order $\rightarrow$ also background evolution
- $\{M_2^4, \bar{M}_1^3, \bar{M}_2^2, \bar{M}_3^2, m_2^2, \hat{M}^2\}$ second order $\rightarrow$ only perturbations
- ΛCDM limit $\rightarrow$ all EFT functions are 0

Testing MG/DE models in the EFT formalism

S_{EFT} →
- Einstein eqs.
- Fluid eq.
- Boltzmann eqs.
- ...

→ EffectiveFieldTheory with CAMB

by B. Hu, M. Raveri, N. Frusciante and A. Silvestri

→ Theoretical predictions for observables

↓

constraints

statistical MCMC analysis

Latest constraints

- studied in *Raveri et al., 2014*, *Planck Collaboration et al., 2016*, *Planck Collaboration et al., 2018*
- constraints from Planck, Weak Lensing, BAO, RSD data
- no significant evidence beyond ΛCDM

Testing MG/DE models in the EFT formalism

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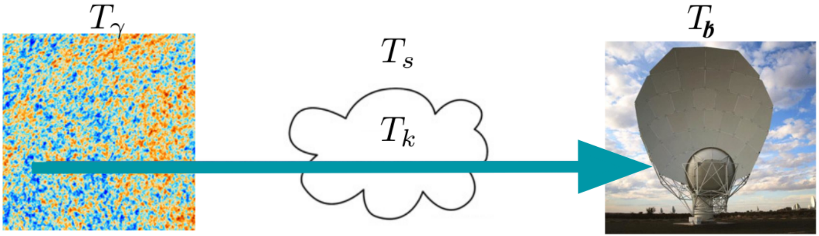
→ Could a new observable such as $P_{21}(k, z)$ help constrain such models beyond ΛCDM?

21cm intensity mapping

The 21cm signal

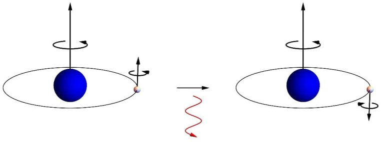


3 fundamental temperatures:

- T_γ the CMB temperature
- T_k the gas (IGM) temperature
- T_s the spin temperature $\rightarrow$ sets the population of the hyperfine level with respect to the ground state

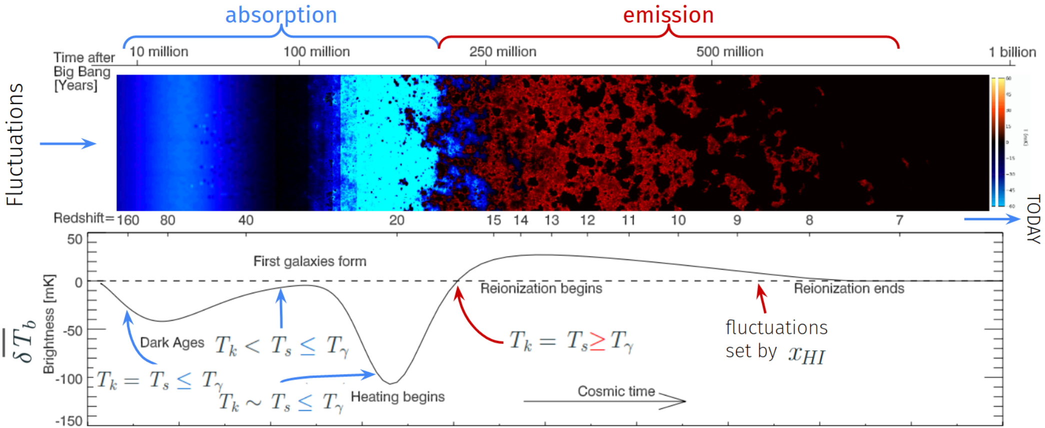
$\rightarrow$ T_b the brightness temperature

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-h\nu_{21}/kT_s}$$



Evolution of the 21cm signal

$\delta T_b \propto x_{HI}(1+\delta)(1-\frac{T_\gamma}{T_s})$ mK[1]



[1] *Mesinger, Greig & Sobacchi, 2016*

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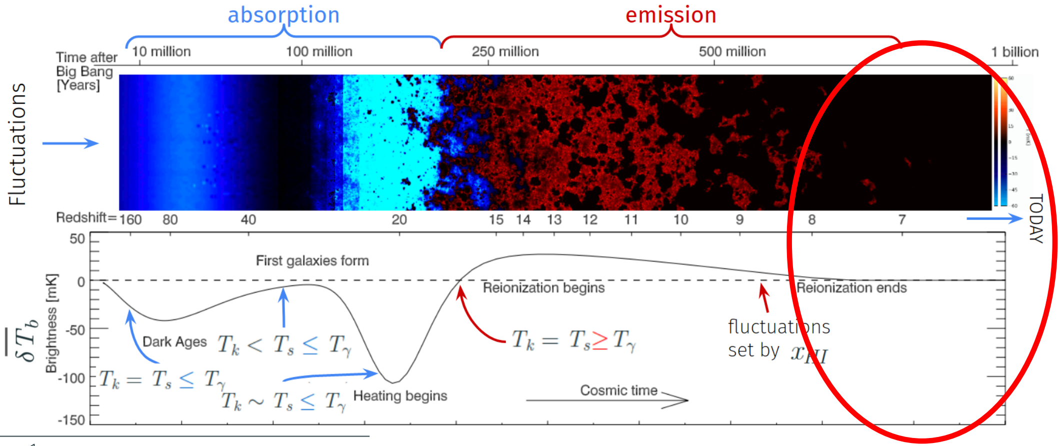

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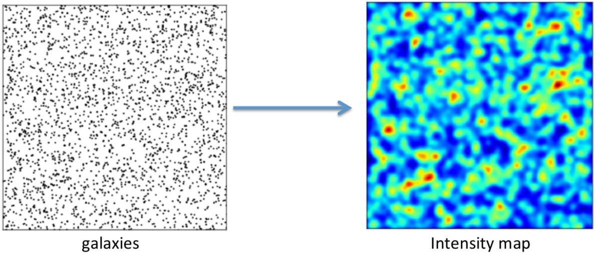
Line intensity mapping



- Look at the total intensity of the emission line in a large 3d pixel (angle and frequency)
- Pixel will have integrated emission from multiple galaxies
- relatively low-budget technique
- Challenging foreground cleaning
- wide redshift range $1 + z = \frac{\nu_{em}}{\nu_{obs}}$

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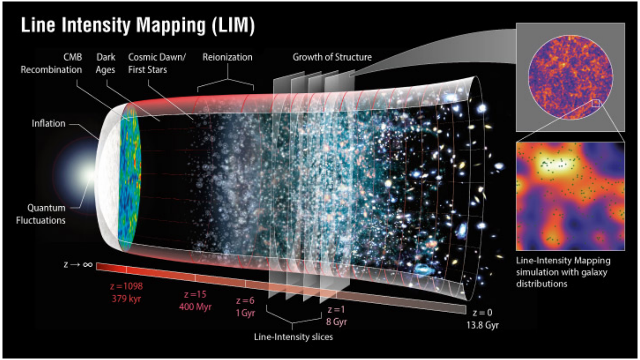

Credit: *NASA / LAMBDA Archive Team*

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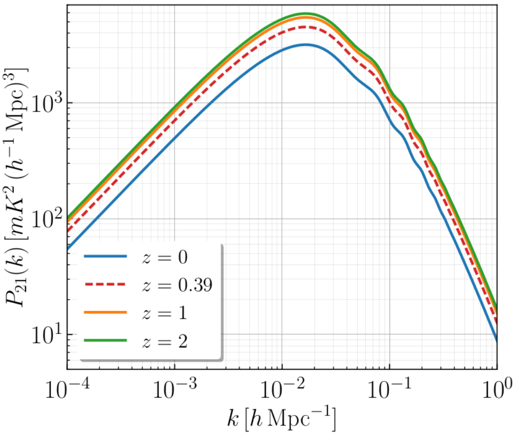
We can model it as[2]

$$P_{21}(z,\, k) = \bar{T}_b^2(z)(b_{\rm HI}(z) + f(z))^2 P_m(z,\, k)$$

where

- $\bar{T}_b^2(z)$ is the mean brightness temperature
- $b_{\rm HI}(z)$ is the HI bias
- $f(z)$ is the linear growth rate
- $P_m(z,\, k)$ is the matter power spectrum

→ in good agreement with hydro-dynamical simulation results (*Villaescusa-Navarro et al., 2018*)



[2] *Kaiser, 1987, Bacon et al., 2019*

Present and future instruments

Currently taking data (some examples):

- CHIME (Canada) $\rightarrow$ interferometer array
- FAST (China) $\rightarrow$ single dish
- MeerKAT (South Africa) $\rightarrow$ single dish

The Square Kilometer Array Organization (SKAO):

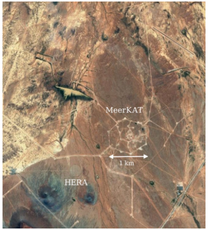
- SKAO-MID: ~ 200 dishes (South Africa)
- SKAO-LOW: $> 10^5$ simple dipole antennas (Western Australia)

$\rightarrow$ more dishes and possibly higher redshifts

Credit: *www.skatelescope.org/*

Intensity mapping with MeerKAT

Credit: *www.sarao.ac.za*



MeerKLASS (*Santos et al., 2017*)

- 4000 deg^2, 4000 h
- IM for Cosmology
- *Radio Continuum HI galaxies*

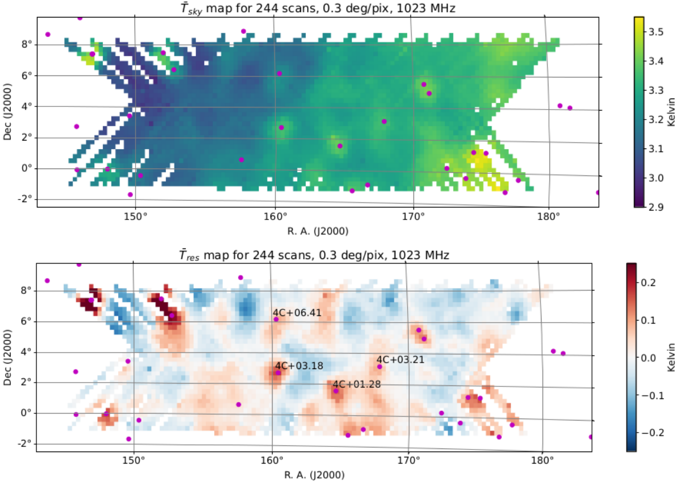
Science Verification Data (*Wang et al., 2021*)

Antennas	All 64 MeerKAT dishes
Observation mode	Single-dish
Frequency range	0.856-1.712 GHz

$\rightarrow$ already taking data

$\rightarrow$ we build a very realistic data set of future MeerKAT observations at $z = 0.39$

First results with MeerKAT



Wang et al., 2021

Likelihood implementation

Bayes theorem

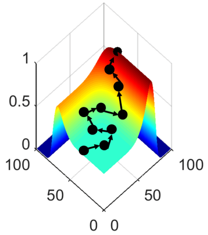
$$\mathcal{P}(\boldsymbol{\alpha}|D) \propto \mathcal{L}(D|\boldsymbol{\alpha})\,\mathcal{P}(\boldsymbol{\alpha})$$

$\boldsymbol{\alpha}$ set of parameters, D set of observations

$\mathcal{L}(D|\boldsymbol{\alpha})$ LIKELIHOOD function $\rightarrow$ *compute*

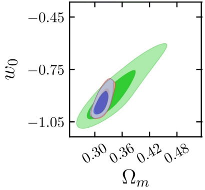
$\mathcal{P}(\boldsymbol{\alpha})$ PRIOR distribution $\rightarrow$ *guess*

$\mathcal{P}(\boldsymbol{\alpha}|D)$ POSTERIOR distribution $\rightarrow$ *sample*

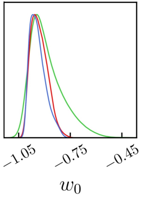


Monte-Carlo Markov-Chains (MCMC) sampling

1. Confidence Regions (68%, 95%)



2. Marginalized posterior



3. Confidence levels (68%)

Parameter	Planck
Ω_m	$0.341^{+0.022}_{-0.043}$
w_0	$-0.892^{+0.055}_{-0.11}$

Ingredients to compute constraints from a new data set

To compute constraints on model parameters for a generic cosmological model we need:

- compute theoretical predictions $\boldsymbol{\alpha} \rightarrow$ *CAMB/EFTCAMB*[3]
  $\hookrightarrow$ model with P_{21} $P_{21}(z,\, k) = \bar{T}_b^2(z)(b_{\rm HI}(z) + f(z))^2 P_m(z,k)$
- observations $D \rightarrow$ construct a mock data set
- compute $\mathcal{L}(D|\boldsymbol{\alpha}) \rightarrow$ multivariate Gaussian
- a MCMC code to sample the parameter space $\rightarrow$ *CosmoMC/EFTComsoMC*[4]

EFTCAMB/EFTComsoMC $\rightarrow$ new module twentyonepk.f90 (**Fortran 2008** language)

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[3] *Hu et al., 2014a, Hu et al., 2014b*

[4] *Raveri et al., 2014*

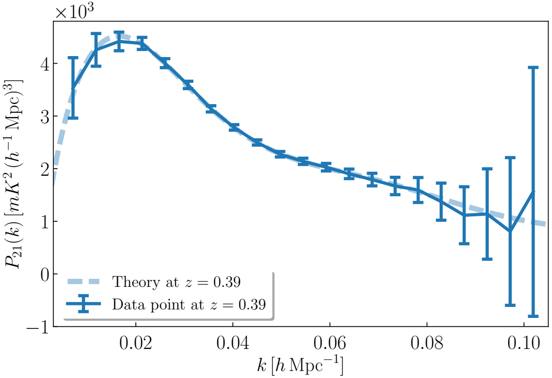
Mock data set

Errors

- assume MeerKAT observation
- 64 single dishes, 2000 deg^2 sky area
- at redshift $z = 0.39$

Central points

- ΛCDM theory prediction randomly scattered

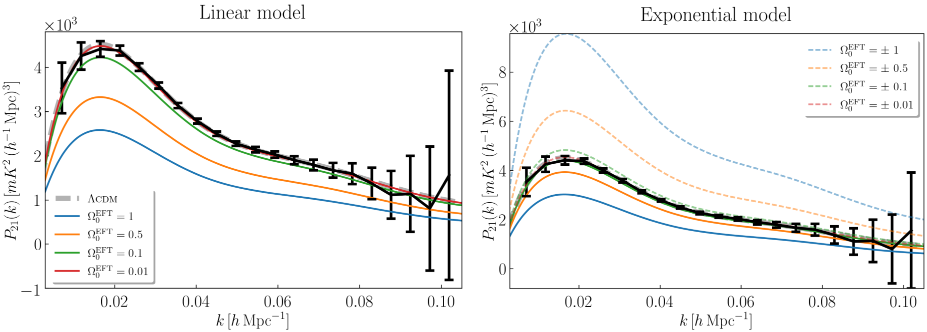


Results

Studied Models

We test the P_{21} likelihood in the following frameworks:

- reference ΛCDM constraints
- we study the effect of P_{21} alone and combined with CMB Planck data
- two different *pure* EFT models described only by the function $\Omega^{\rm EFT}(a)$

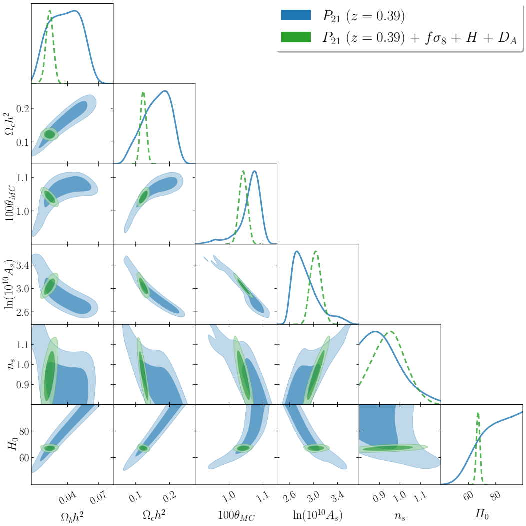


Data sets

Label	Description
Planck 2018	**CMB** data from **Planck 2018**:[5] **TT, TE, EE** power spectra + low polarization (**lowE**) data + **lensing**
$P_{21}\ (z = 0.39)$	mock data set of MeerKAT forecast observations at redshift $z = 0.39$
$f\sigma_8 + H + D_A$	or background, additional background and structure formation mock data sets at $z = 0.39$ inferred from higher redshift IM forecast

[5] http://pla.esac.esa.int/pla/#home

ΛCDM reference simulation - I



Par.	P_{21} $(z = 0.39)$	+ $f\sigma_8 + H + D_A$
$\Omega_b h^2$	0.038 ± 0.015	0.0226 ± 0.0035
$\Omega_c h^2$	$0.162^{+0.050}_{-0.033}$	0.1227 ± 0.0081
n_s . . .	< 0.959	$0.951^{+0.072}_{-0.085}$
H_0 . .	> 73.6	67.1 ± 1.3

Remarks

- cannot constrain all the cosmological parameters, we fixed τ

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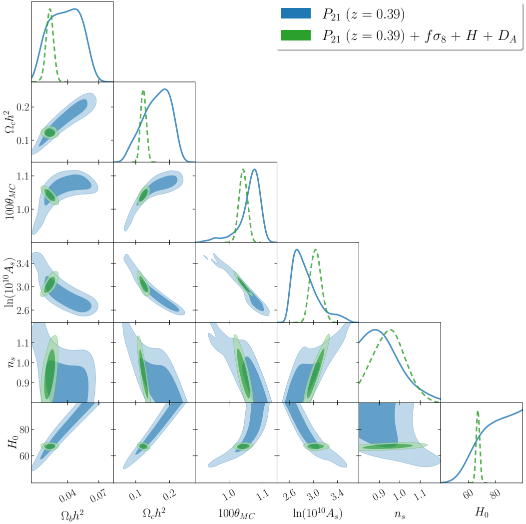

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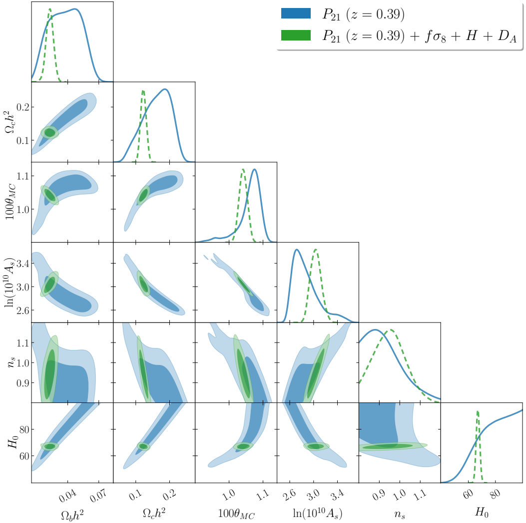

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- adding the background data significantly improve the constraints

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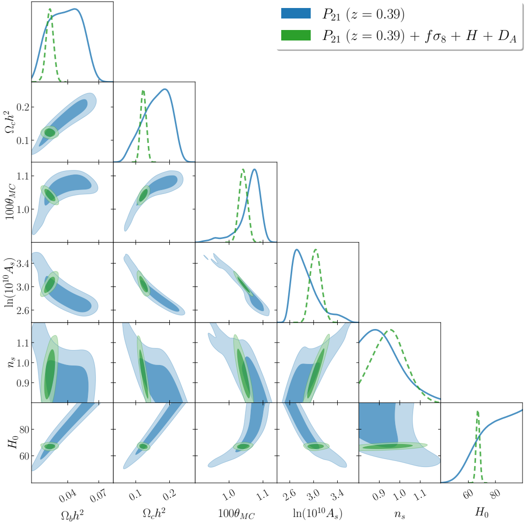

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Remarks

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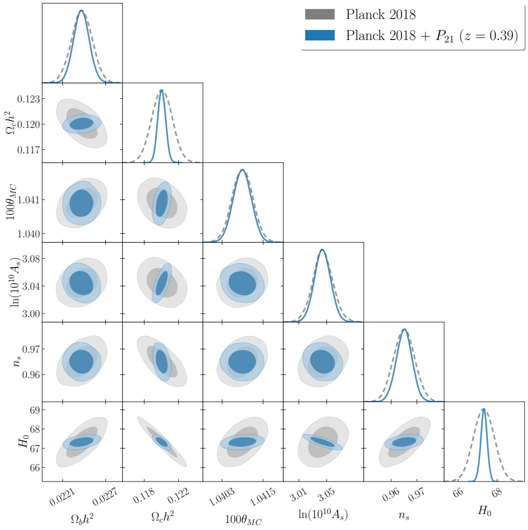
- marked degeneracy between $\Omega_c h^2$ and H_0
- adding the background data significantly improve the constraints
- with only 21 + 3 points we get a competitive constraints on H_0

ΛCDM reference simulation - II



Par.	Planck 2018	+ P_{21} $(z = 0.39)$
$\Omega_b h^2$	0.02237 ± 0.00014	0.02236 ± 0.00011 (-24%)
$\Omega_c h^2$	0.1201 ± 0.0012	0.12004 ± 0.00046 (-61%)
n_s ...	0.9650 ± 0.0041	0.9651 ± 0.0031 (-25%)
H_0 ..	67.32 ± 0.53	67.32 ± 0.16 (-69%)

Remarks

- significant improvement on $\Omega_c h^2$ and H_0

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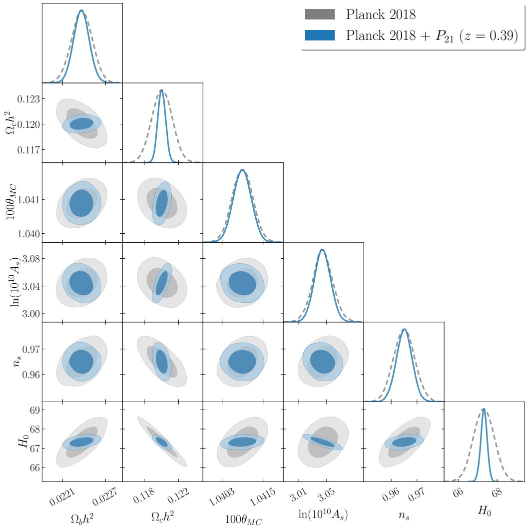

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- $\Omega_c h^2$ and H_0 anti-correlated from Planck 2018 data

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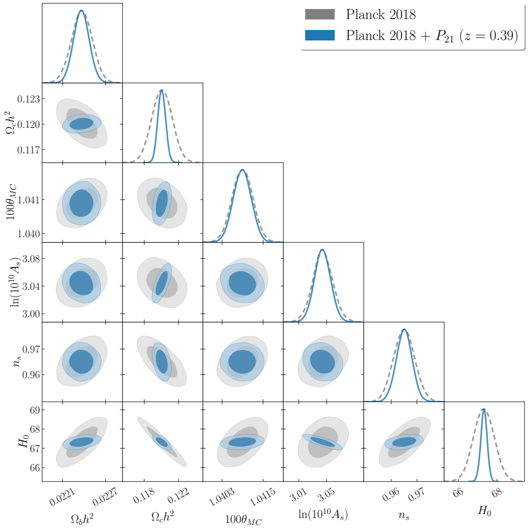

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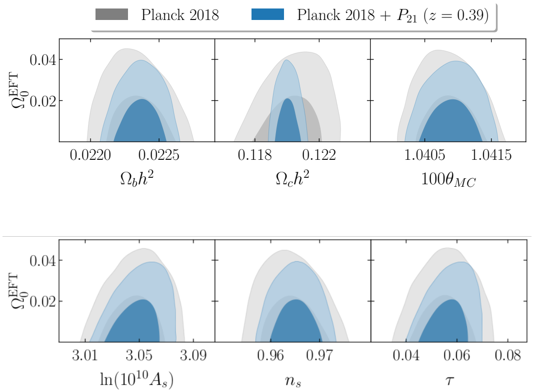
Remarks

- significant improvement on $\Omega_c h^2$ and H_0
- $\Omega_c h^2$ and H_0 anti-correlated from Planck 2018 data
- adding BAO data does not produce relevant effects

EFT results - Linear evolution of $\Omega^{\rm EFT}(a)$



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H_0 ...	67.21 ± 0.55	67.33 ± 0.17 (-70%)
$\Omega_0^{\rm EFT}$	< 0.0147	< 0.0135 (-11%)

Remarks

- P_{21} $(z = 0.39)$ alone has no significant constraining power on EFT parameters

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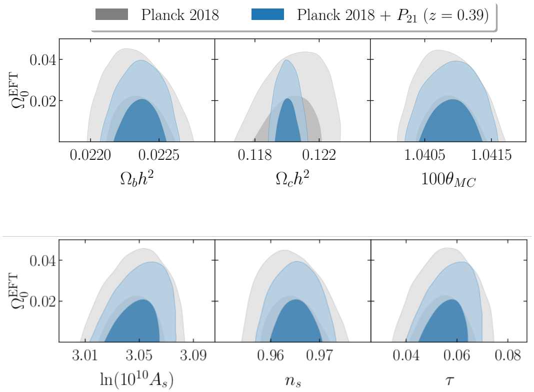

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- constraints on cosmological parameters remain unaffected

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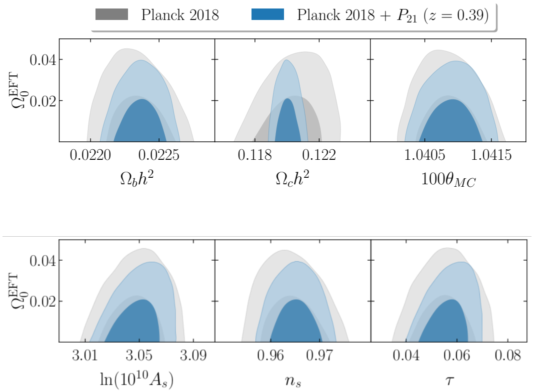

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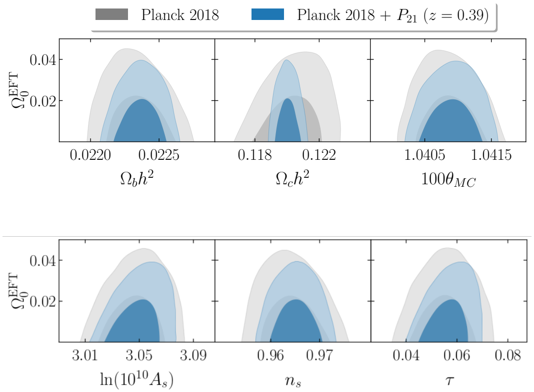
Remarks

- P_{21} $(z = 0.39)$ alone has no significant constraining power on EFT parameters
- constraints on cosmological parameters remain unaffected
- results compatible with results in literature

EFT results - Linear evolution of $\Omega^{\rm EFT}(a)$



Par.	Planck 2018	+ P_{21} $(z = 0.39)$
$\Omega_b h^2$.	0.02234 ± 0.00015	0.02237 ± 0.00011 (-26%)
$\Omega_c h^2$.	0.1203 ± 0.0012	0.12003 ± 0.00046 (-63%)
H_0 ...	67.21 ± 0.55	67.33 ± 0.17 (-70%)
$\Omega_0^{\rm EFT}$	< 0.0147	< 0.0135 (-11%)

Remarks

- P_{21} $(z = 0.39)$ alone has no significant constraining power on EFT parameters
- constraints on cosmological parameters remain unaffected
- results compatible with results in literature
- Planck 2018 + P_{21} $(z = 0.39)$ improvement at the 10% level on errors of EFT parameters

Conclusions

Summary

Work done

- We extended the EFTCAMB/EFTCosmoMC codes by implementing a likelihood module fully integrated with original codes to test forecast 21cm Intensity Mapping observations
- We constructed a realistic data set at $z = 0.39$ from future MeerKAT observation settings
- We tested the impact of P_{21} likelihood on DE/MG models in the EFT framework

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The road ahead

- Add observations from other redshift bins
- Cross-correlation exploitation of intensity mapping and galaxy clustering observations
- extend the likelihood other beyond ΛCDM models, e.g. decaying dark matter