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Tweaking the expansion rate using the cosmological recombination lines with exotic physics

Copernicus Webinar Series

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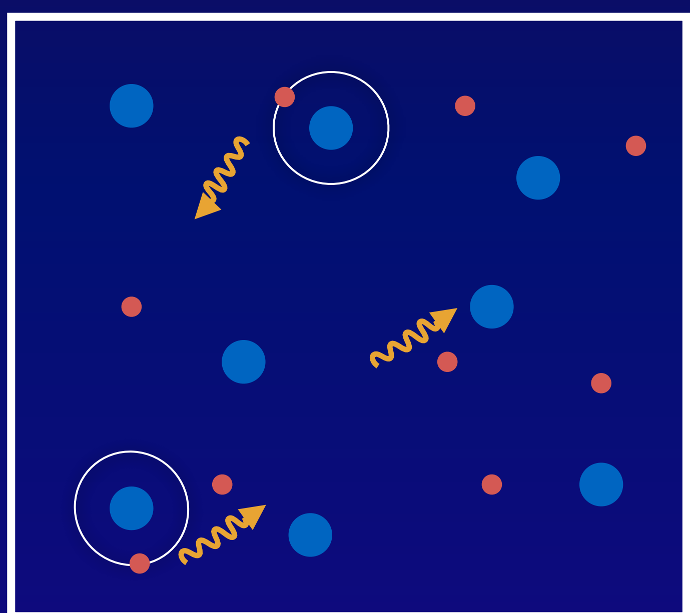
Jodrell Bank Centre for Astrophysics
Tuesday 27 July 2021

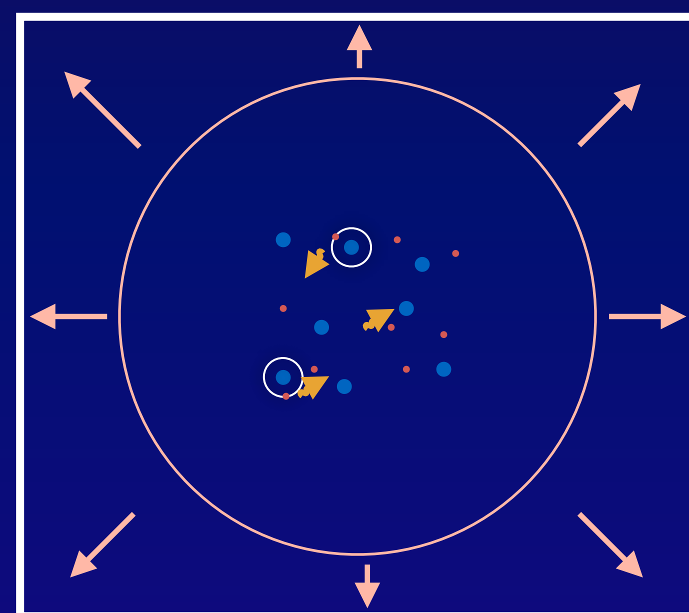
Overview

1. About recombination
2. Cosmological recombination radiation
3. Forecasts for the recombination lines
4. Exotic physics in the expansion rate
5. Future constraints and hints to wider exotic physics
6. Quick update on distortions in the community

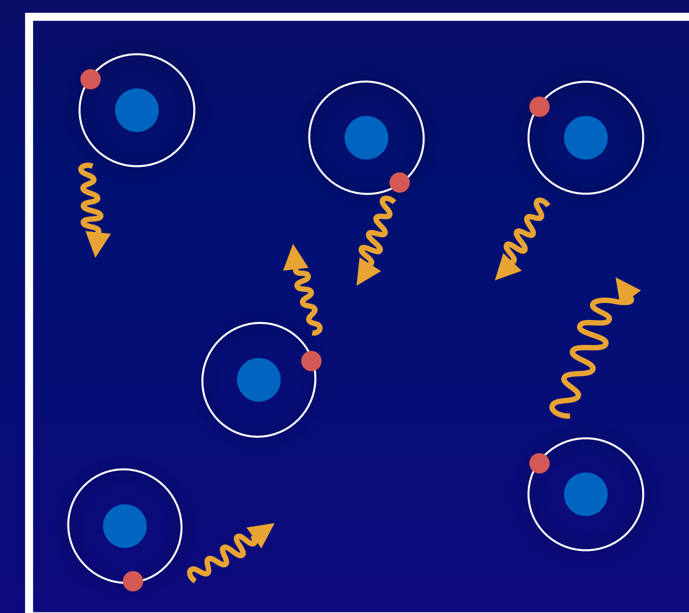
From free electrons to the CMB



Electrons and photons interact within thermal equilibrium.



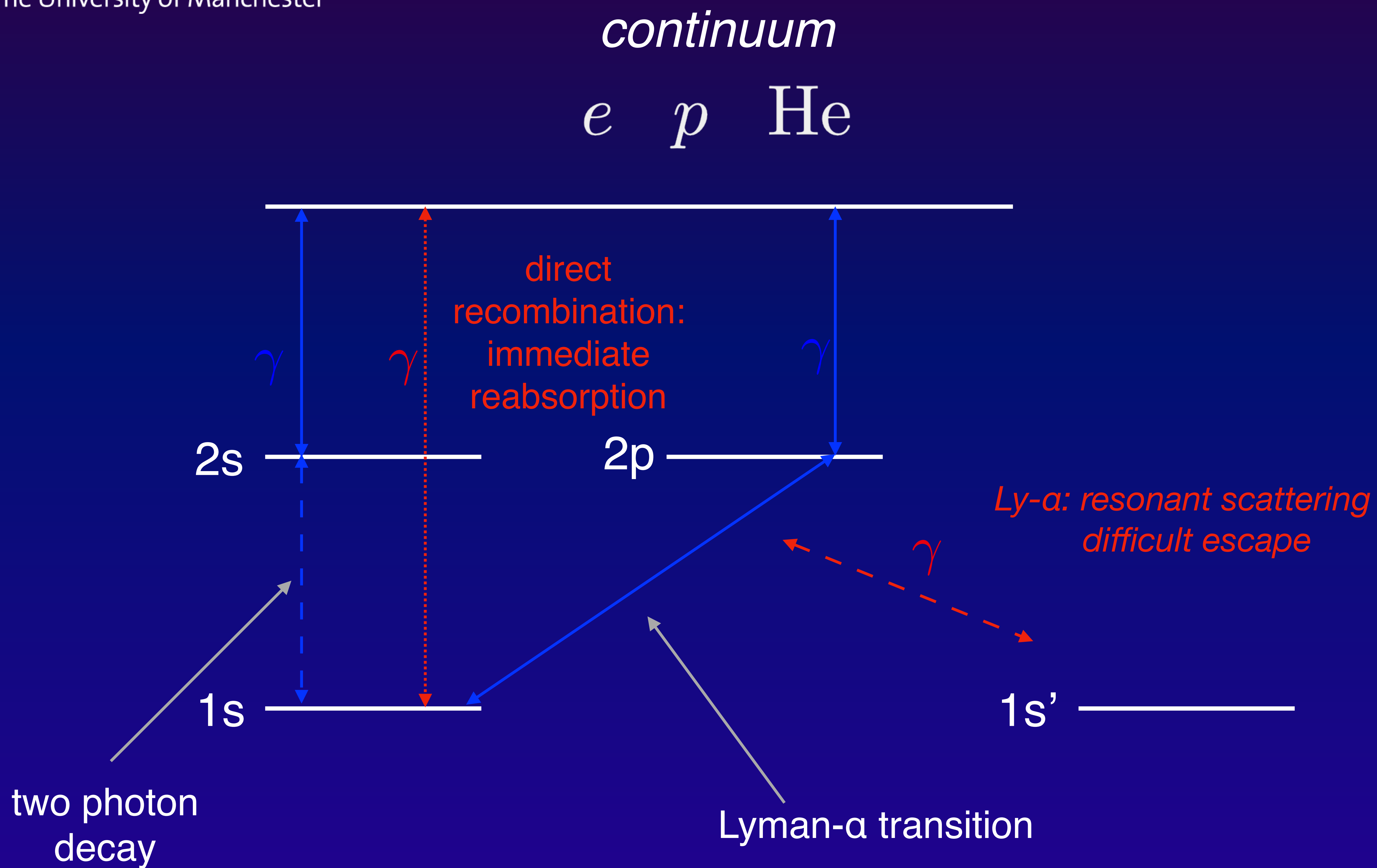
Eventually the Hubble expansion overtakes the effective energies/rates in recombination physics



Protons and electrons bind irreversibly*.
Baryons and photons decouple.
Photons free stream.

Vital for *Planck* accuracy $< 0.1\%$ on parameters like Ω_b and n_s

From free electrons to the CMB



From free electrons to the CMB

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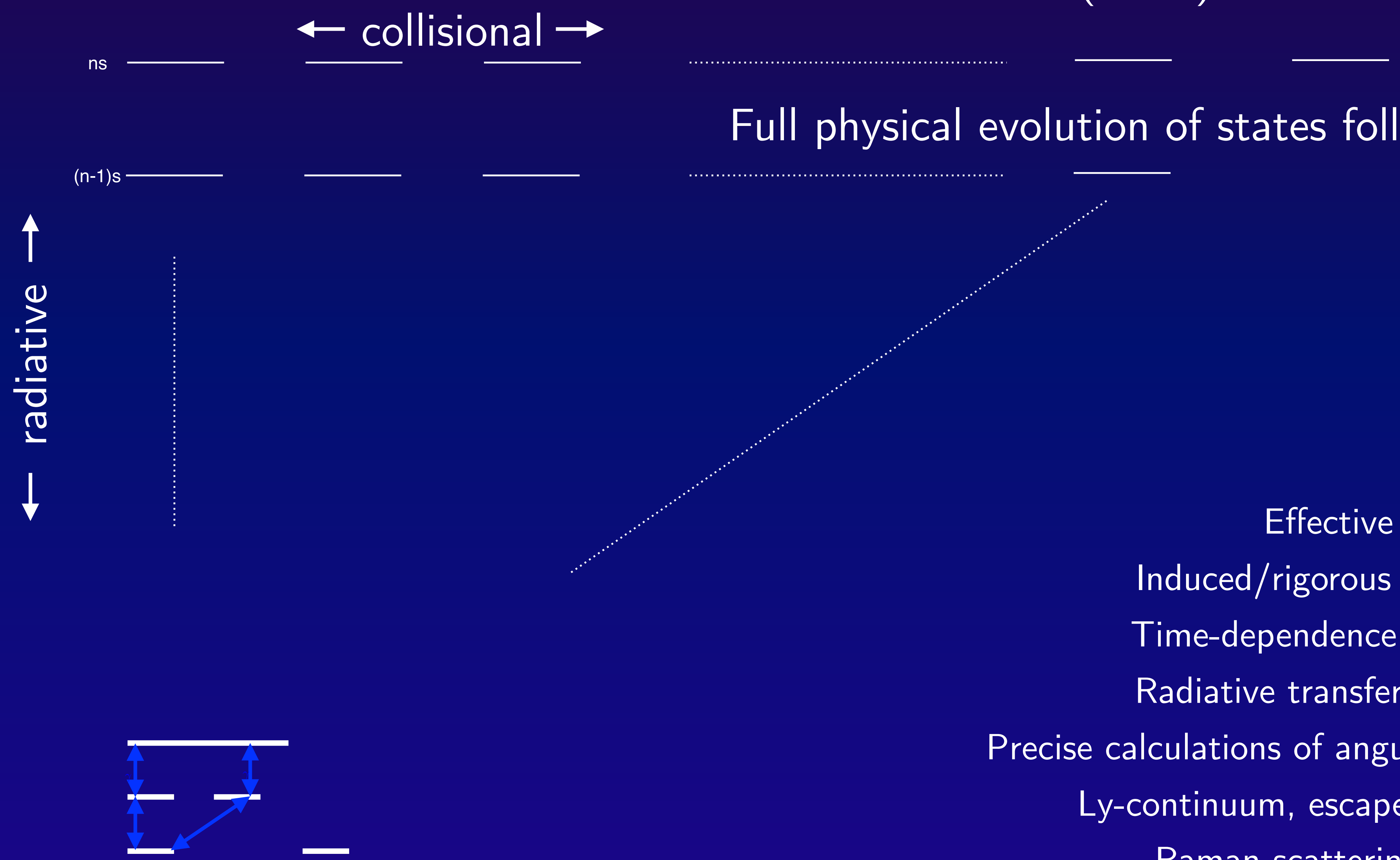
Higher statistical states are treated in equilibrium with $(2\ell+1)$ rule



Full physical evolution of states followed in *CosmoRec*

Effective multi-level atomic model
Induced/rigorous two-photon decay effects
Time-dependence of the escape probability
Radiative transfer corrections to H and He
Precise calculations of angular momentum substates
Ly-continuum, escape and Sobolev corrections
Raman scattering corrections ...and more

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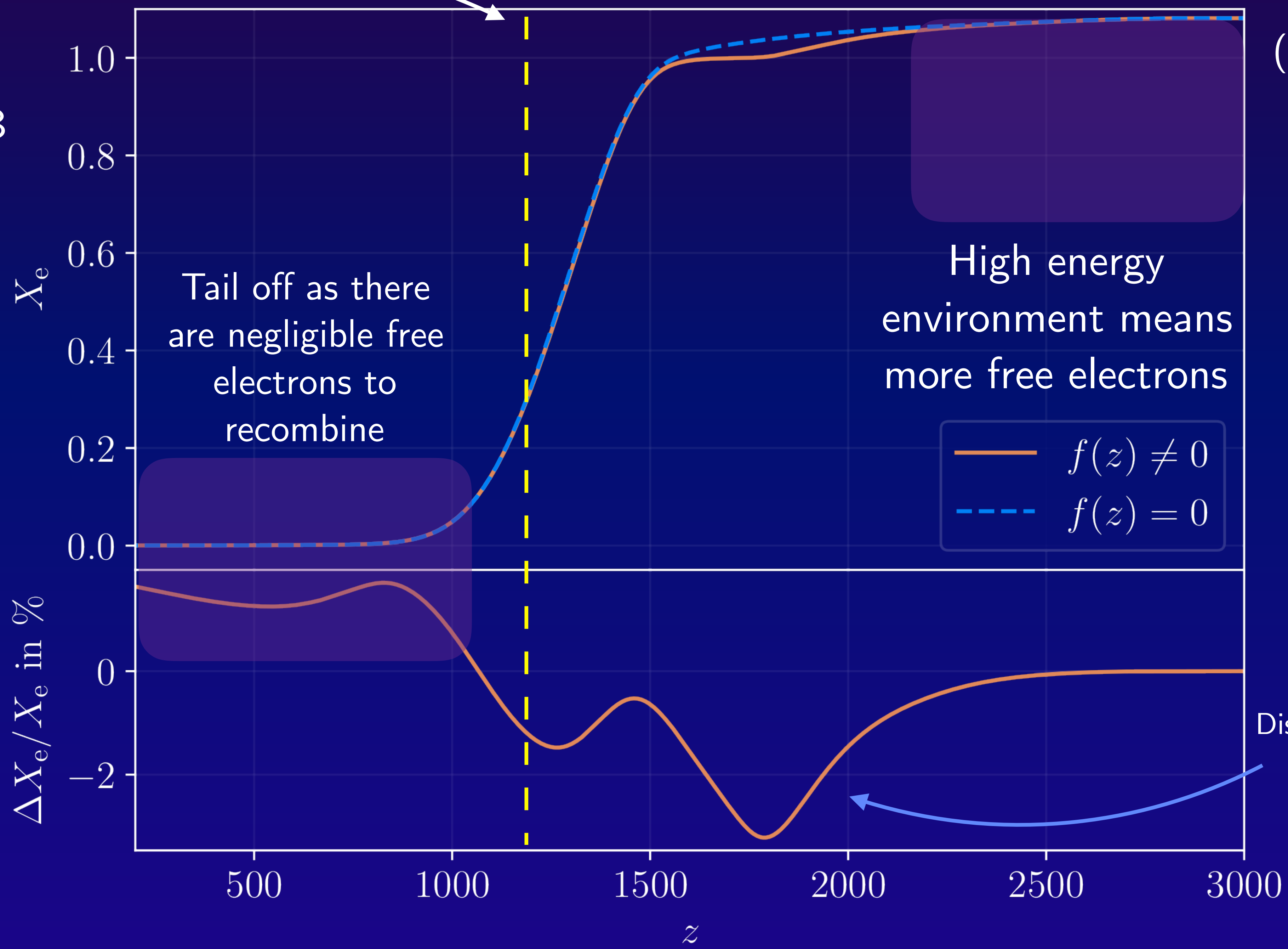
Quantifying recombination → Ionisation history

Most likely epoch for CMB photons to free-stream

(LH thesis)



Disparities between Recfast and full calculation (Rubiño-Martin 2010)

Higher values leads to more <u>ionisation</u> (free electrons)
Lower values tends to <u>recombination</u> (bound electrons)

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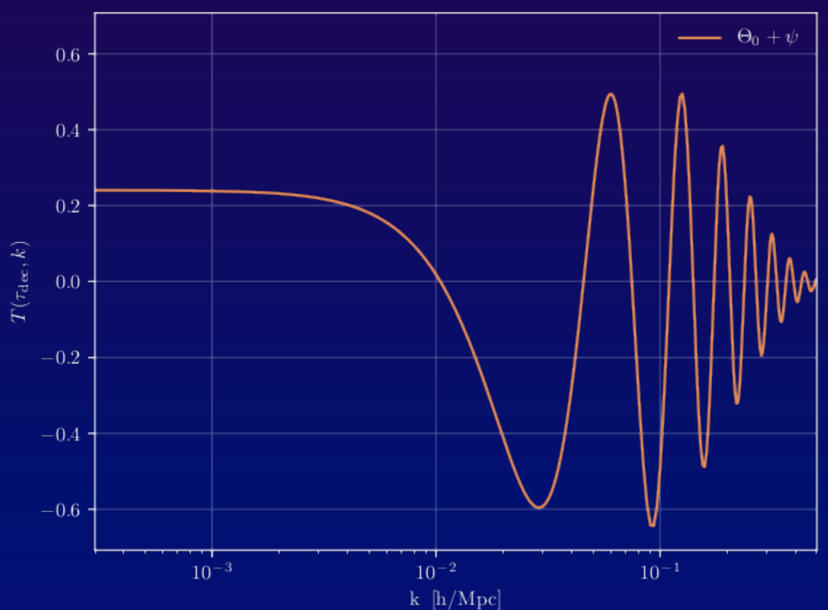
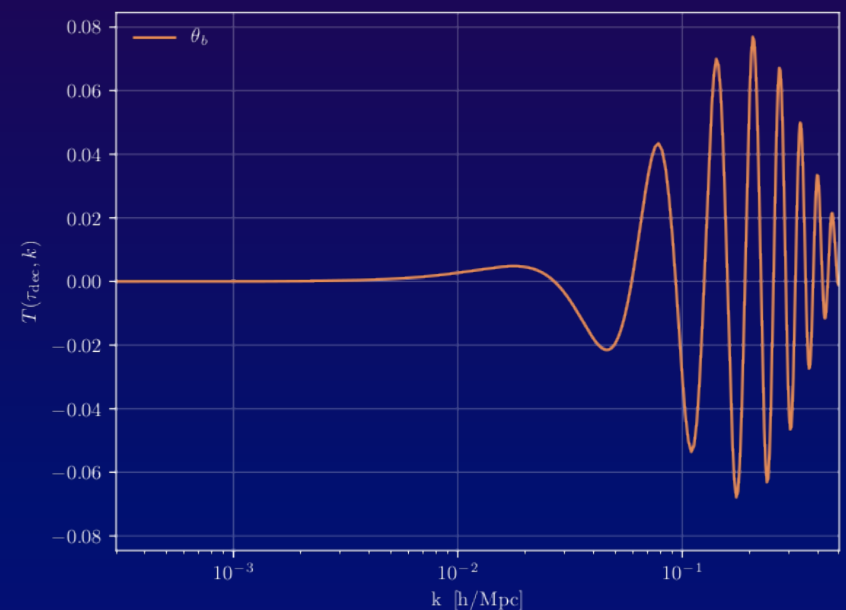
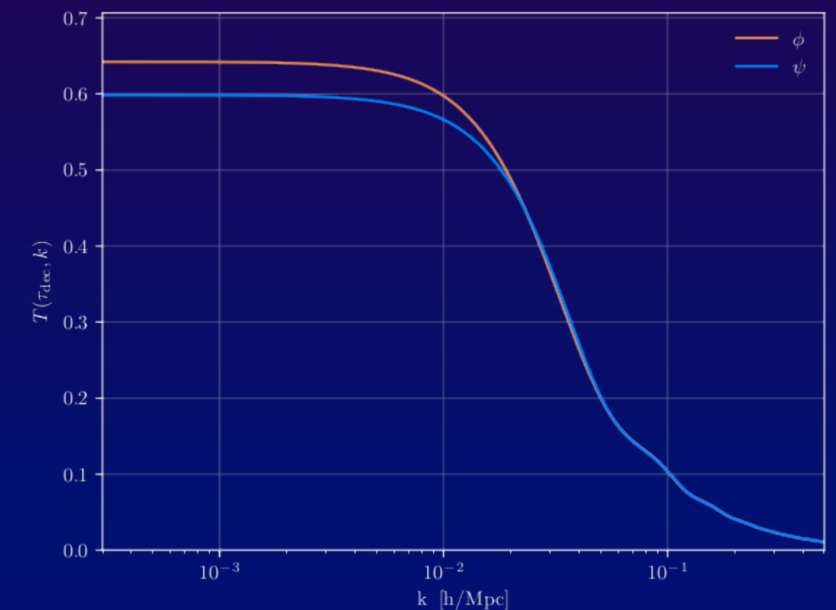
From free electrons to the CMB: Recap (detailed)







$$\Theta_0 + \Psi$$

Sachs Wolfe (monopole)

$$\Theta_1(\theta_b)$$

Doppler (dipole)

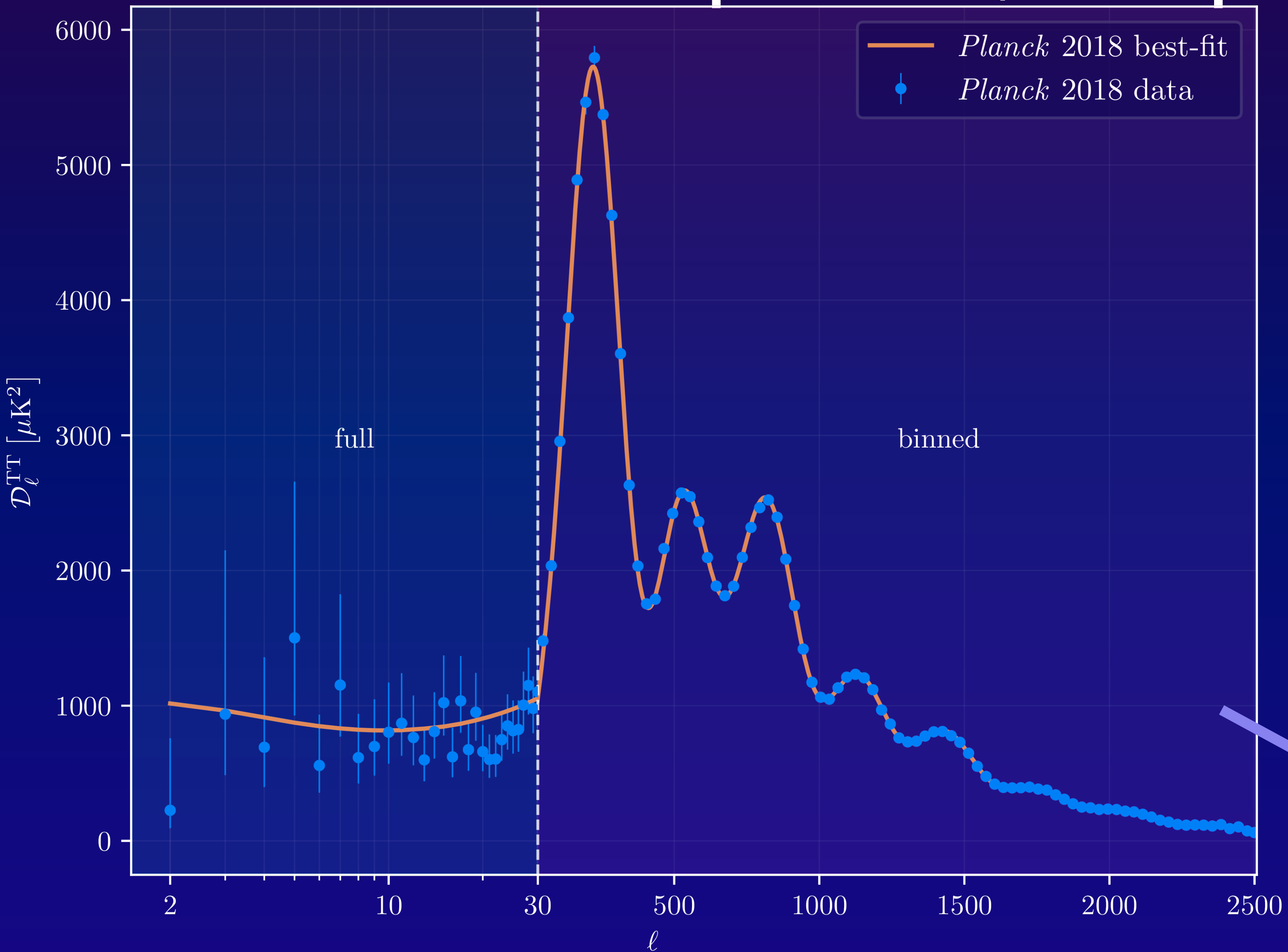
$$\dot{\Psi} - \dot{\Phi}$$

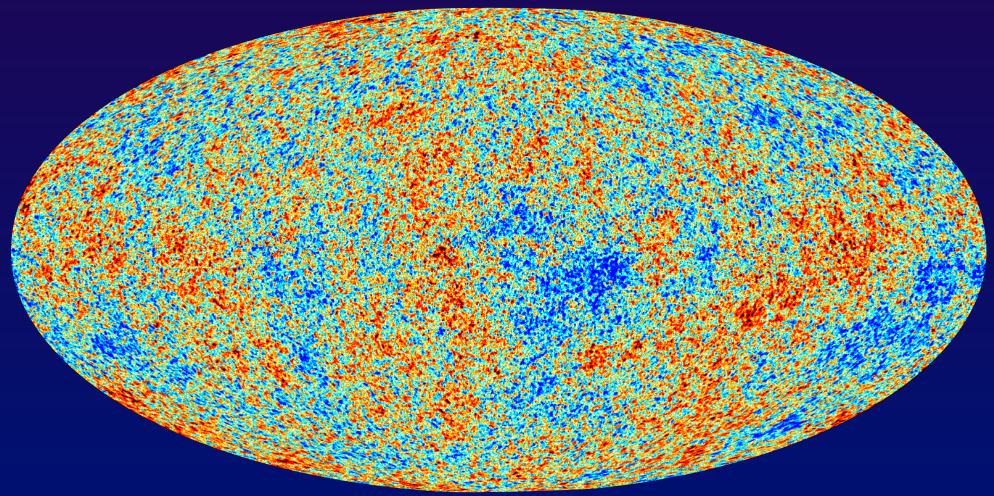
Integrated Sachs Wolfe

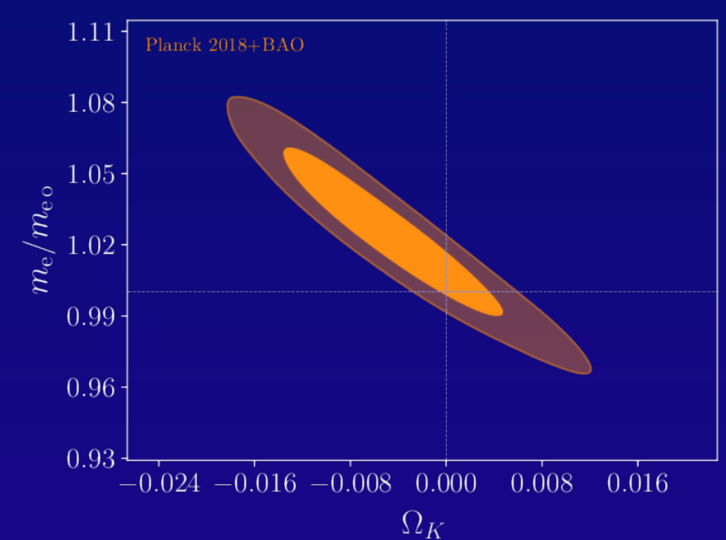
$$\frac{\mathrm{d}\tau}{\mathrm{d}z} \propto X_\mathrm{e}$$

Thomson scattering optical depth
is dependent on the ionisation history

From free electrons to the CMB: Spectra, Maps and Observables







Joint probability analysis: BAO, weak lensing etc..

Planck Collaboration et. al. (2018)
LH (thesis)

Anistropies: not the only probe for testing...

Number density/energy state evolution

$$\frac{\mathrm{d}X_{nl}^{\mathcal{H}}}{\mathrm{d}t}, \mathcal{H} \in \{\mathrm{HI}, \mathrm{HeI}, \mathrm{HeII}\}$$

Temperatures that feed the interaction rates

Number density feeds the source terms

$$\frac{1}{c}\left(\left.\frac{\partial \Delta n_\nu}{\partial t}\right|_\nu - H\nu \left.\frac{\partial \Delta n_\nu}{\partial \nu}\right|_t \right) = \mathcal{C}\left(\Delta n_\nu\right)_{\mathrm{em/abs}} + \mathcal{C}\left(\Delta n_\nu\right)_{\mathrm{scat}}{}^{*}$$

Photon field evolution

**Peebles (1968), Zeldovich and Sunyaev (1968), Chluba and Ali Haïmoud (2015)....*

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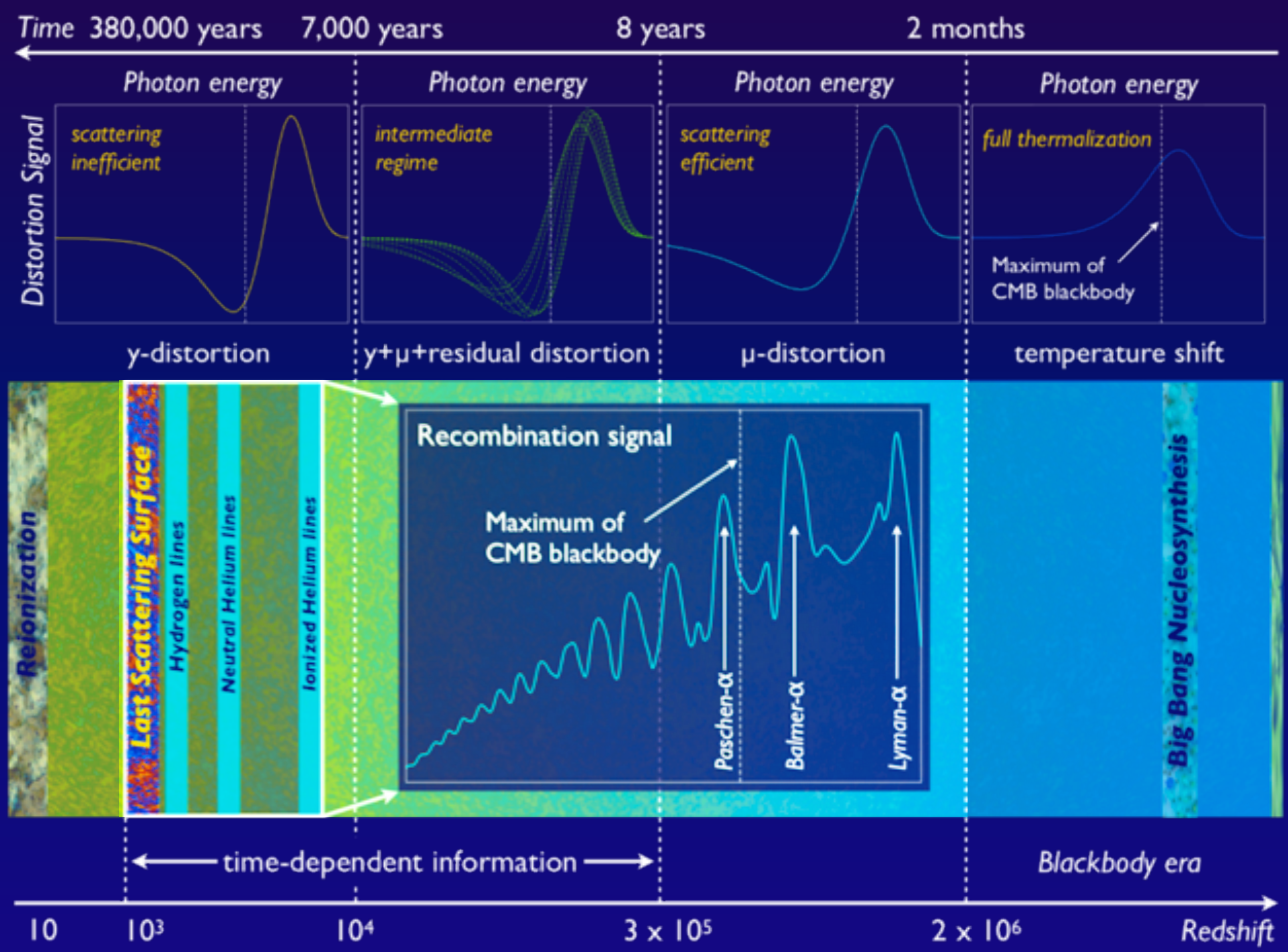
CMB Spectral distortions

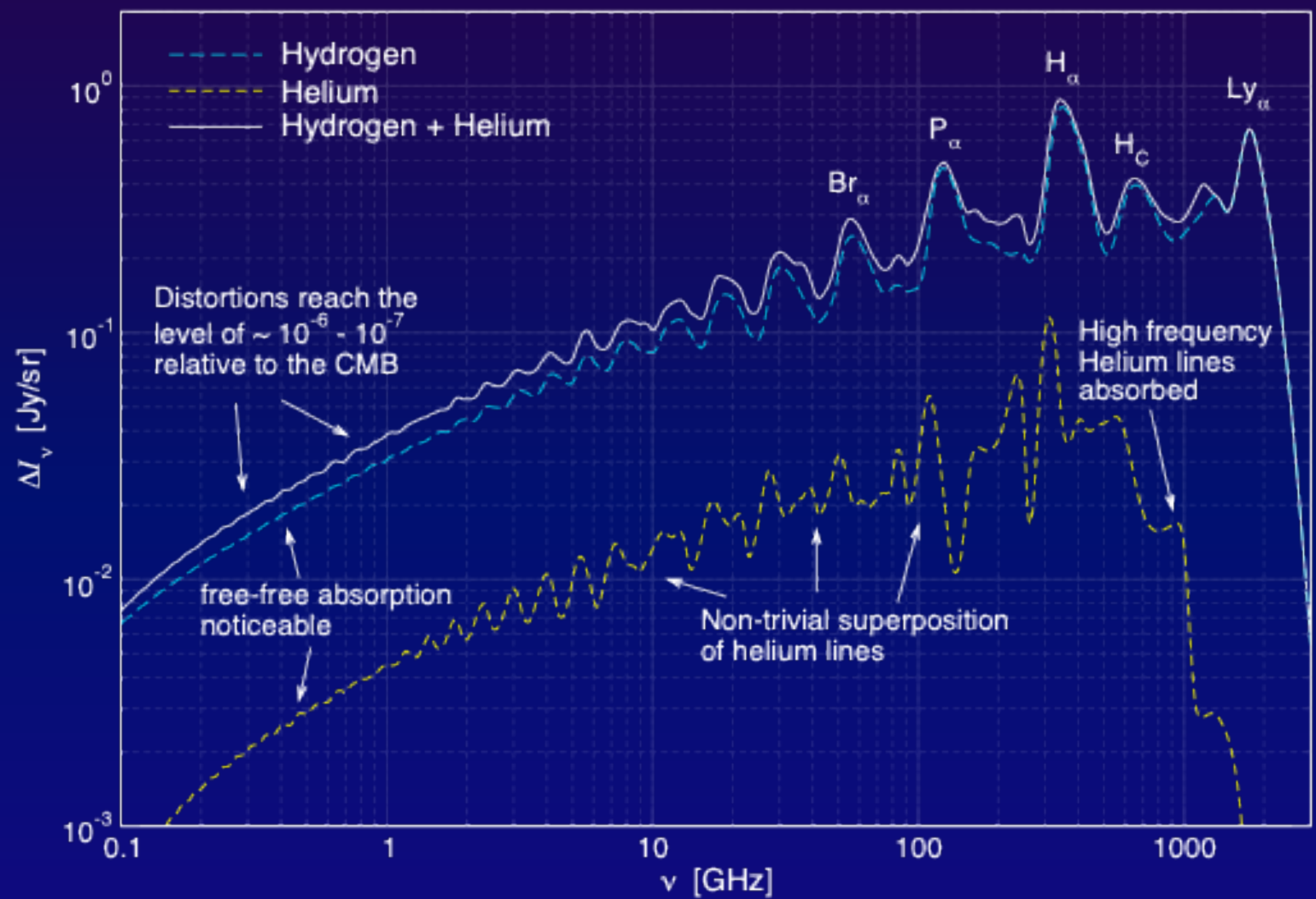


Chluba et. al. (2019, V2050)

- Generally any non-thermal process can induce SDs
- In this case: recombination dumps photons that perturb equilibrium
  → spectral distortion

The recombination lines

Chluba et. al. (2019, V2050), LH, Rotti, Chluba (2020)



- Recombination of electrons deposits energy into the CMB depending on the energy level/species
- Helium + hydrogen superposition — unique spectral shape
  [Chluba and Ali-Haimoud (2015), LH, Rotti, Chluba (2020), many more...]

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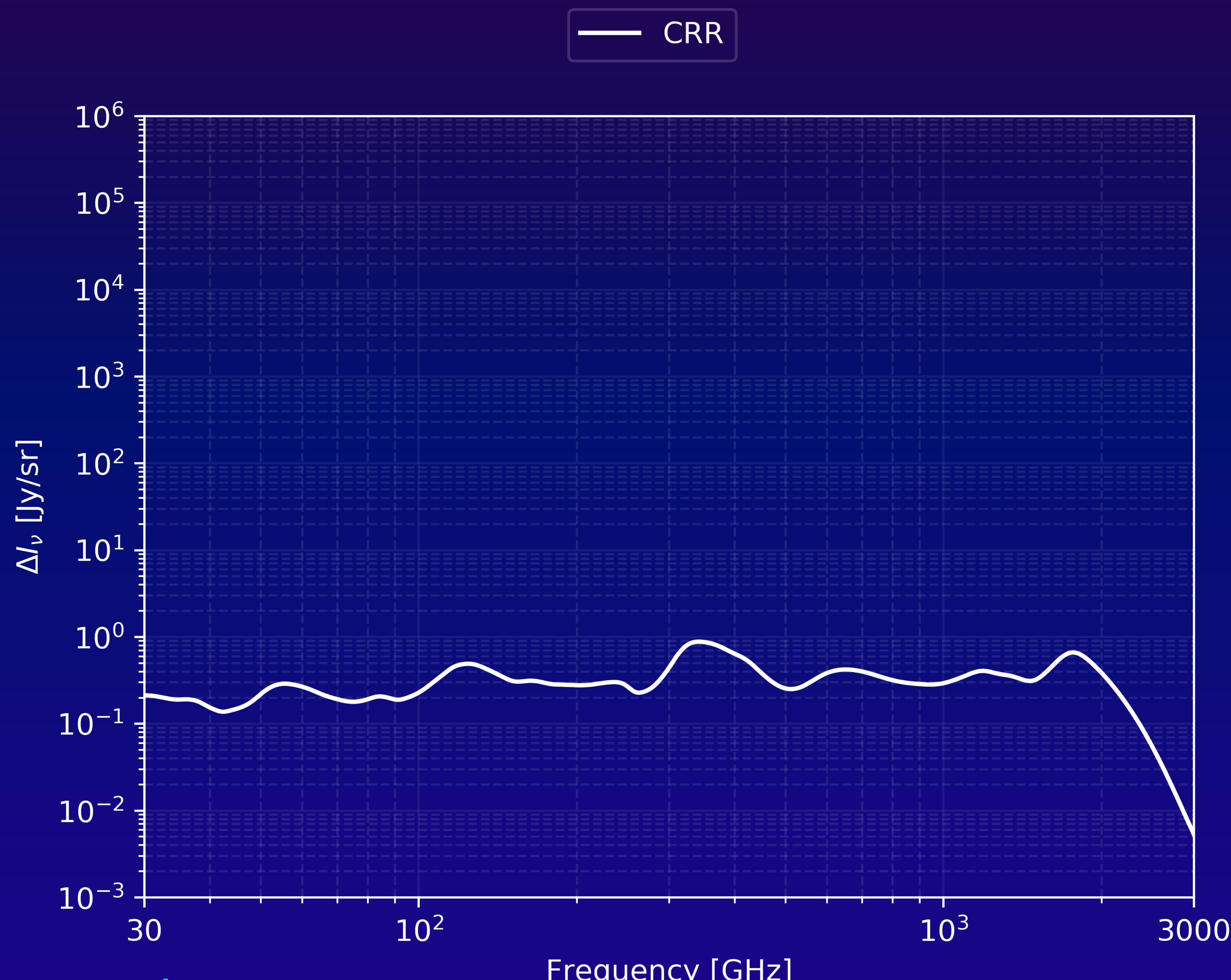
Detecting distortions

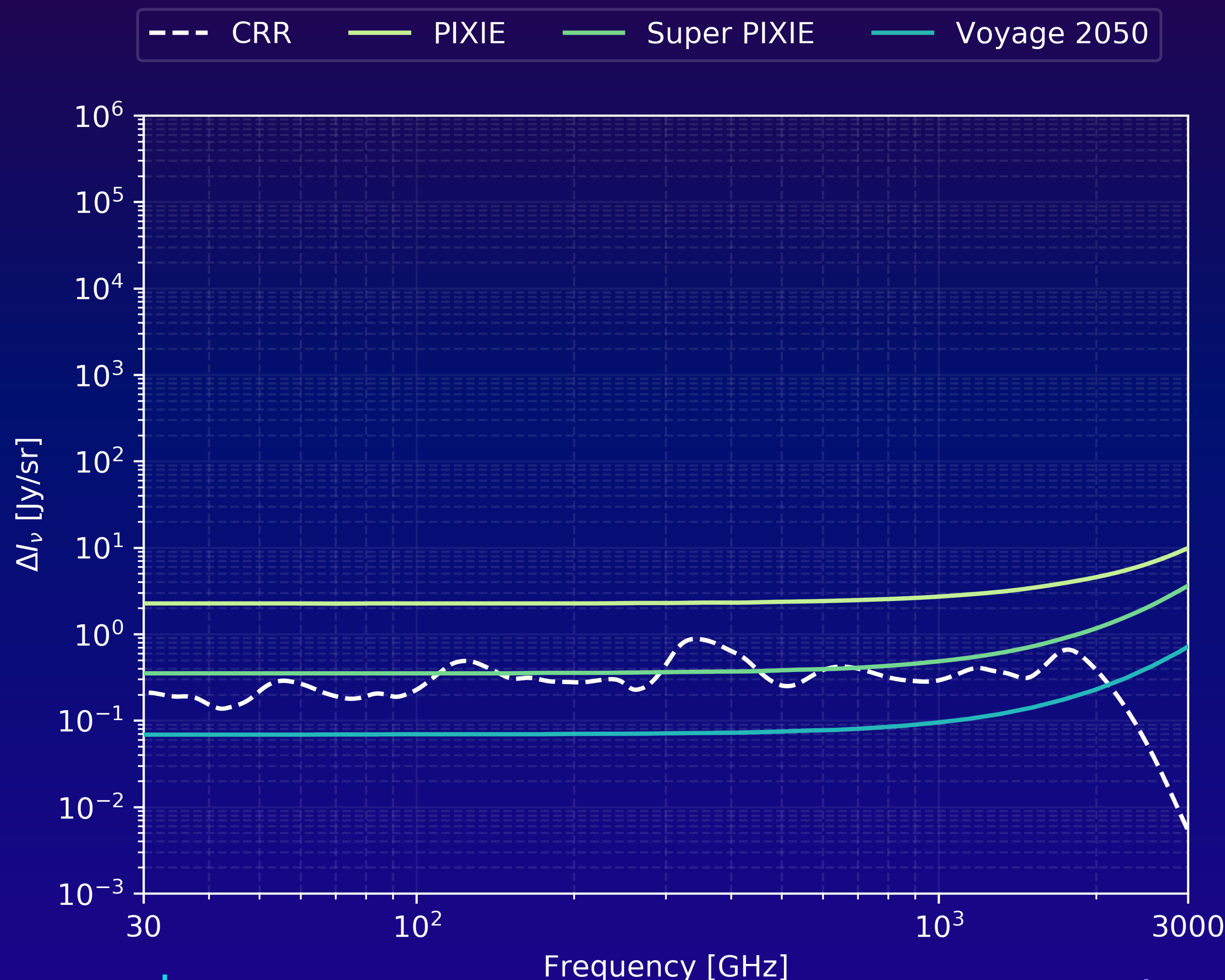


cosmology and foreground parameters

$$\mathcal{F}_{pp'} = \sum_{\nu\nu'} \frac{\partial \Delta I_\nu}{\partial p} \mathcal{C}^{-1}_{\nu\nu'} \frac{\partial \Delta I_{\nu'}}{\partial p'}$$

encodes all the noise and systematics

Detecting distortions



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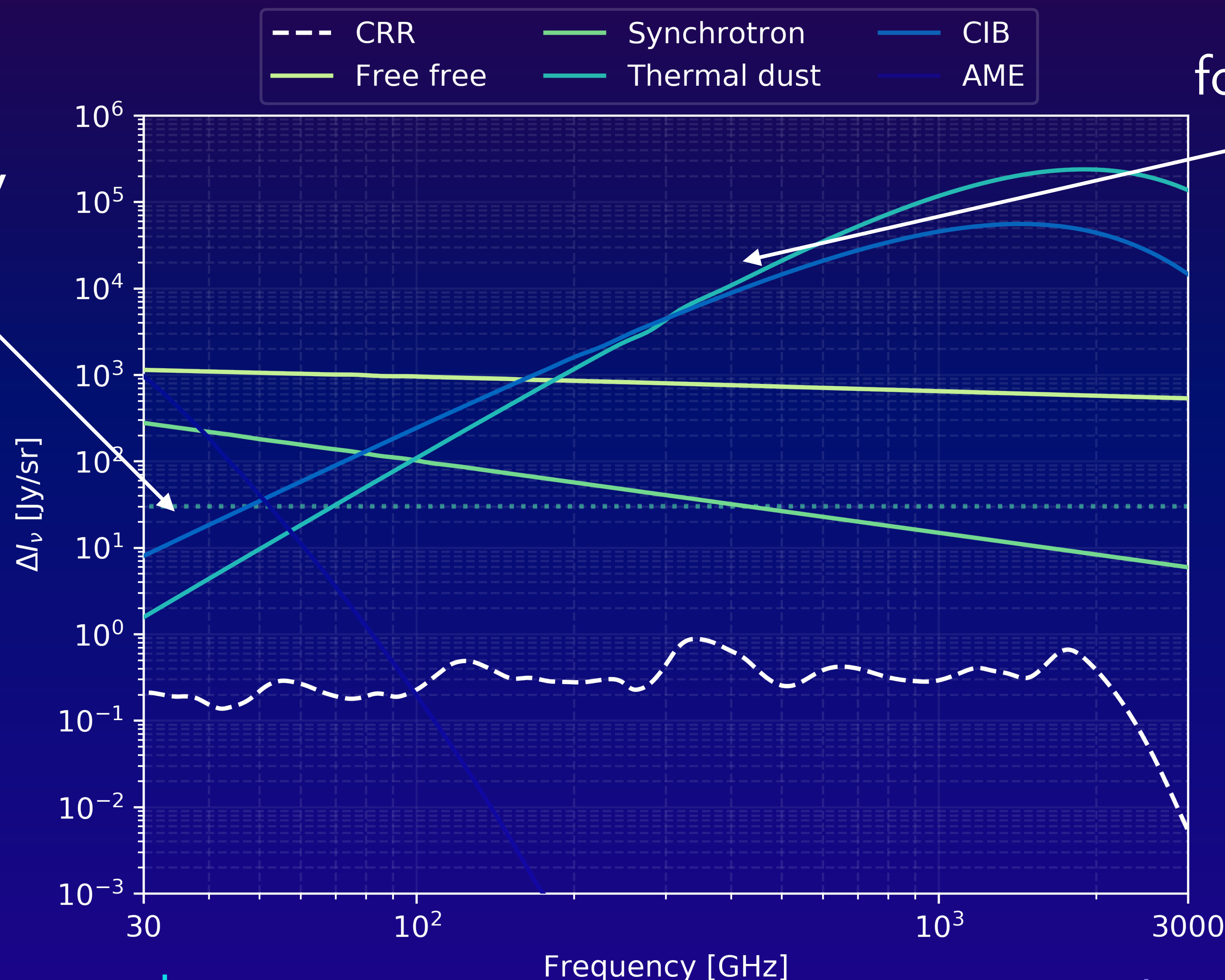
encodes all the noise and systematics

Detecting distortions

Band by frequency

+ other spectral distortion foregrounds (μ,y)

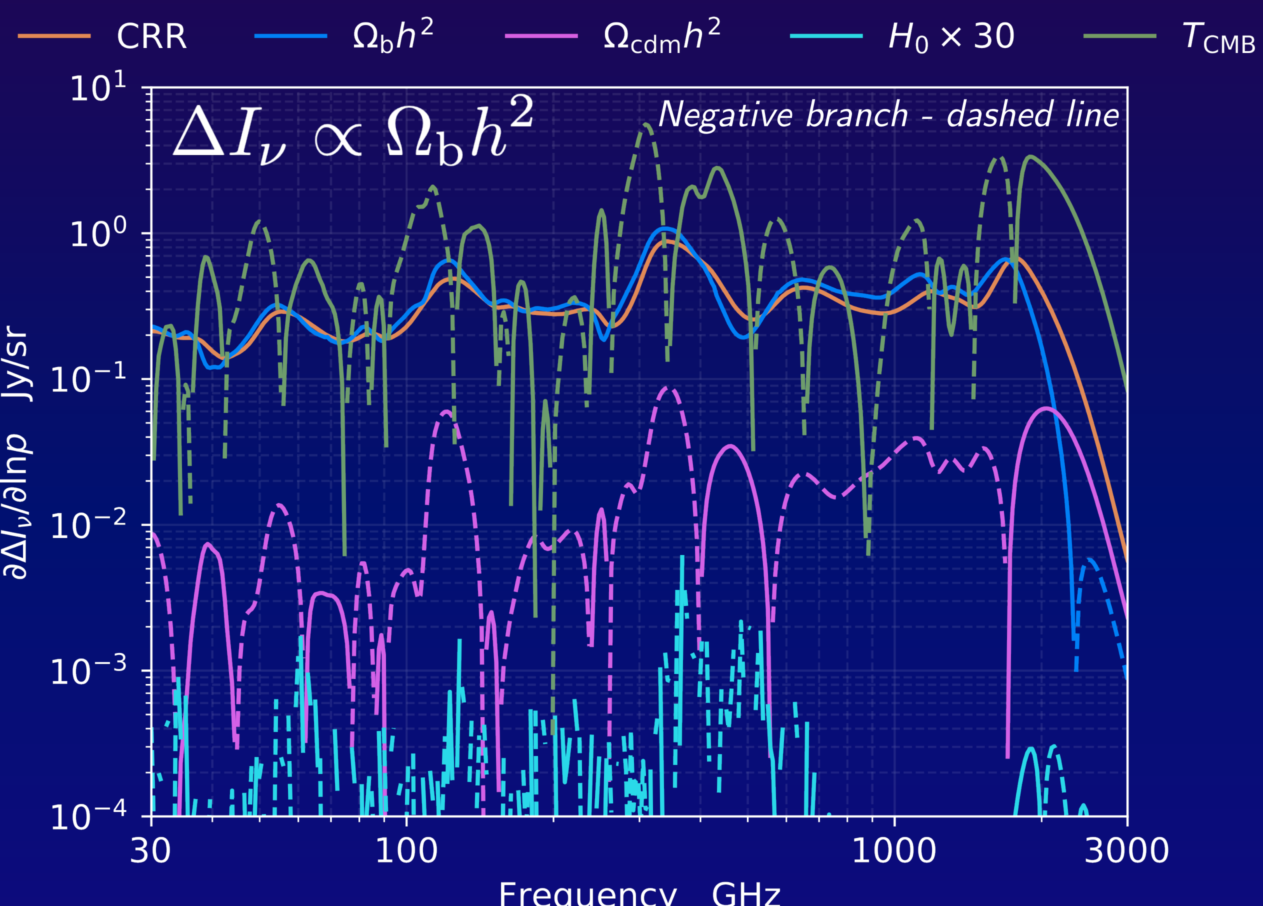


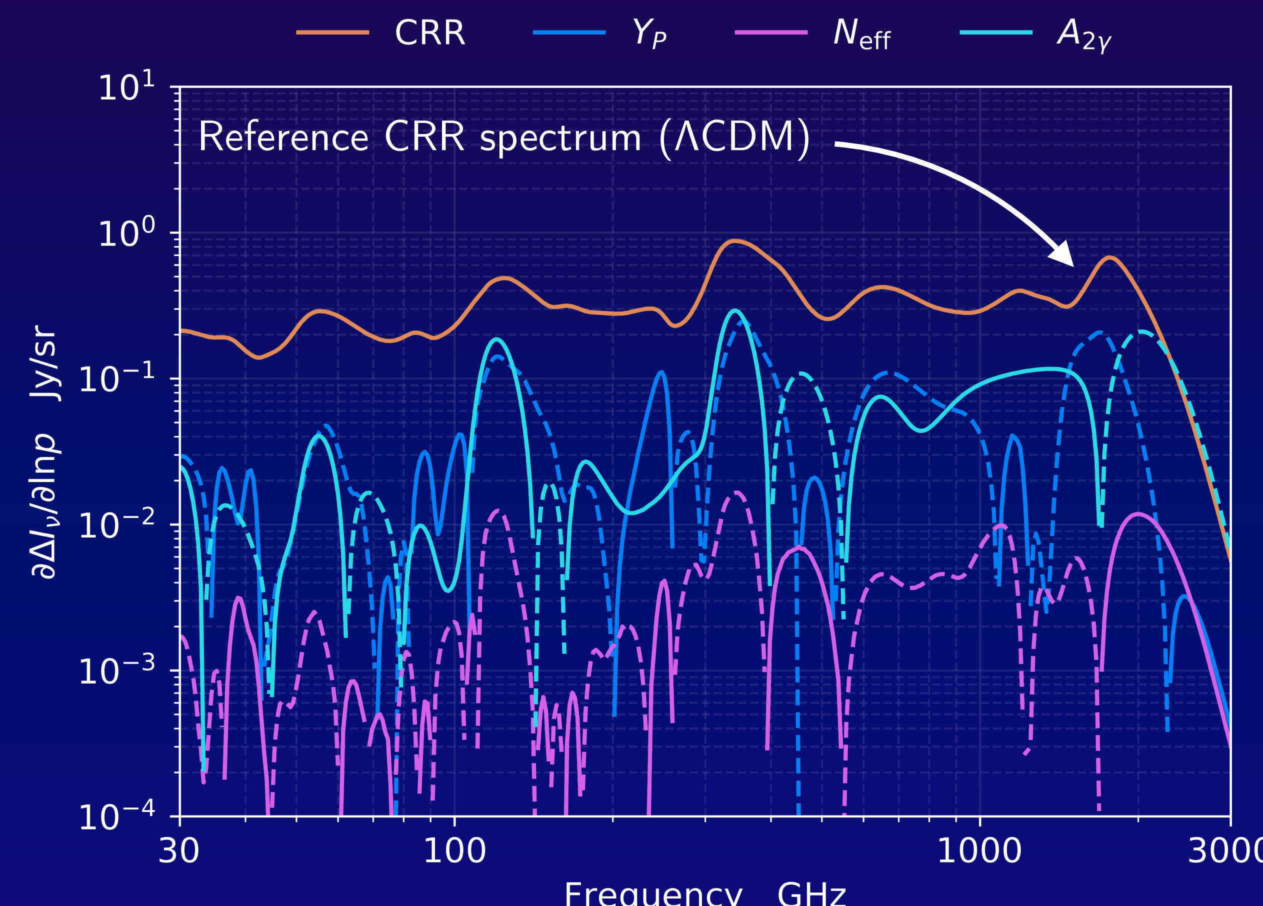
cosmology and foreground parameters

$$\mathcal{F}_{pp'} = \sum_{\nu\nu'} \frac{\partial \Delta I_\nu}{\partial p} \mathcal{C}^{-1}_{\nu\nu'} \frac{\partial \Delta I_{\nu'}}{\partial p'}$$

encodes all the noise and systematics

Cosmology with the recombination lines



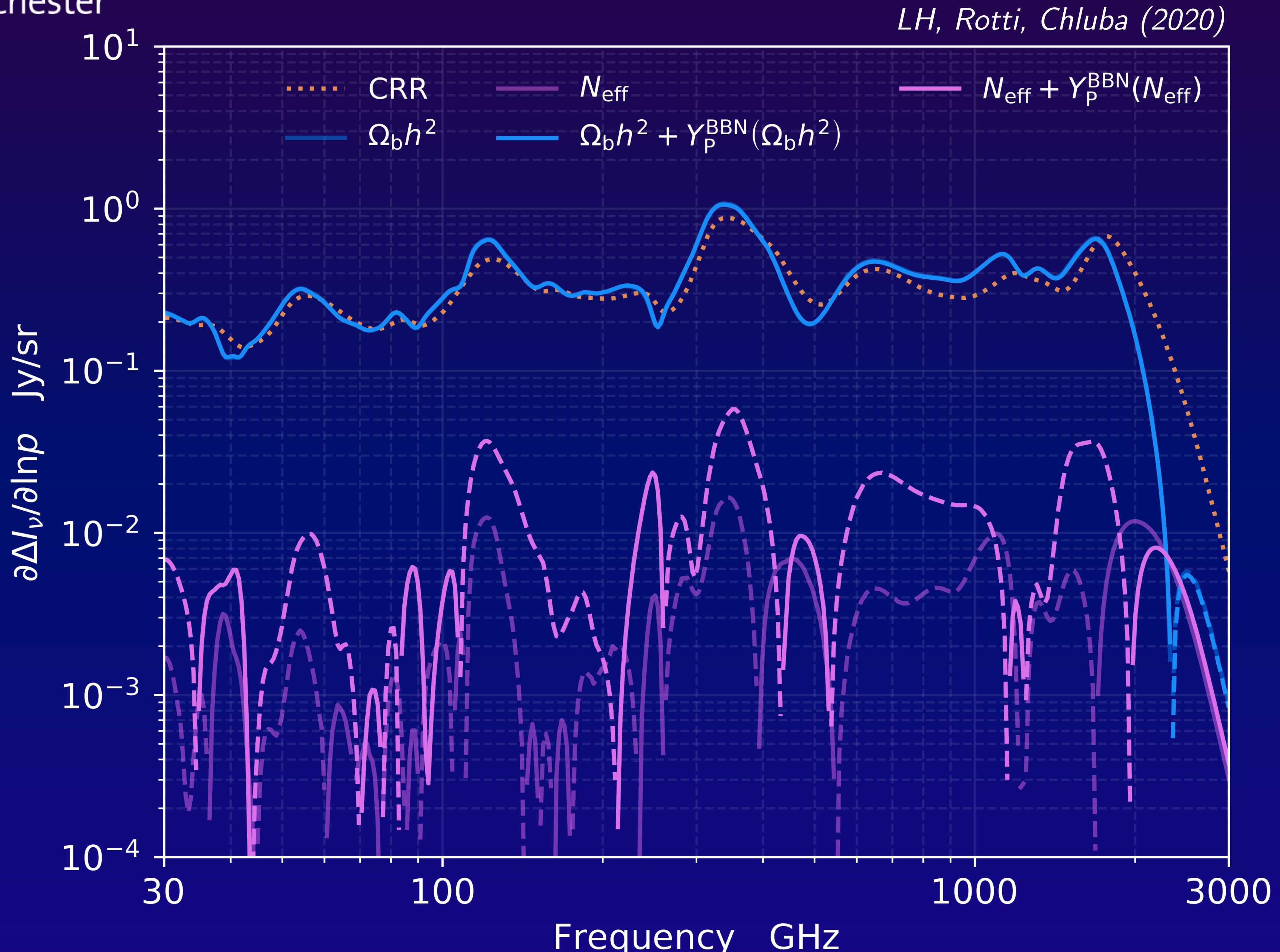


LH, Rotti, Chluba (2020)

- $\Omega_b h^2 \rightarrow$ more effective scattering
- $\Omega_c h^2 \rightarrow$ smooths out ΔI_ν features
- $T_{CMB} \rightarrow$ lower ν, translation of peaks

- $A_{2\gamma} \rightarrow$ unique spectral response (hydrogen lines)
- $N_{eff} \rightarrow$ smooths out ΔI_ν features
- $Y_P \rightarrow$ lower ν, translation of peaks

Recombination lines and BBN



- Using $Y_{\rm P} \equiv Y_{\rm P}^{BBN}\left(\Omega_{\rm b}h^2, N_{\rm eff}\right)$ leads to superposition of effects
- Modified and checked with *PArthENoPE* BBN polynomials
- Large effect on the $N_{\rm eff}$ response in the CRR

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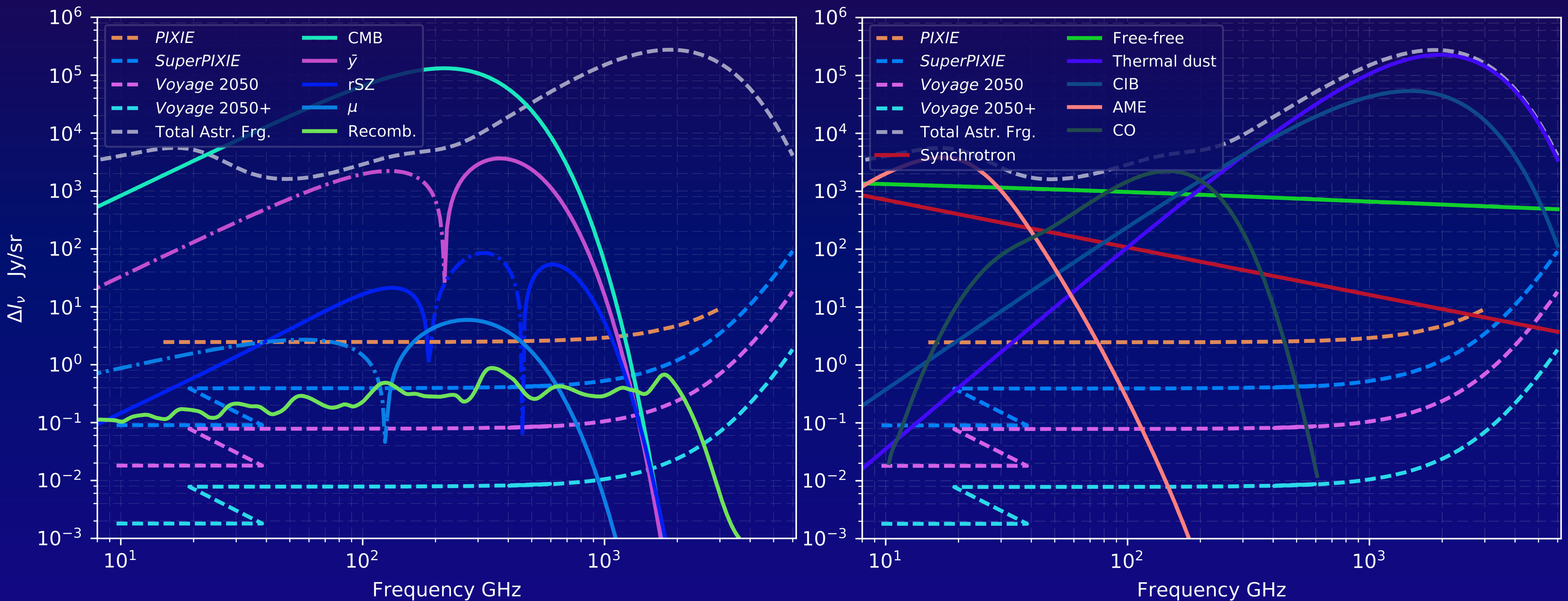
LH, Rotti, Chluba (2020)

Cosmology with the recombination lines



- First time foregrounds have been added properly
- Affects μ quite strongly, however not as frequency dependent
- Still accounted for, along with y, μ and kT_e
- Impact of <u>bandwidth averaging</u> and <u>systematic effects</u> also considered

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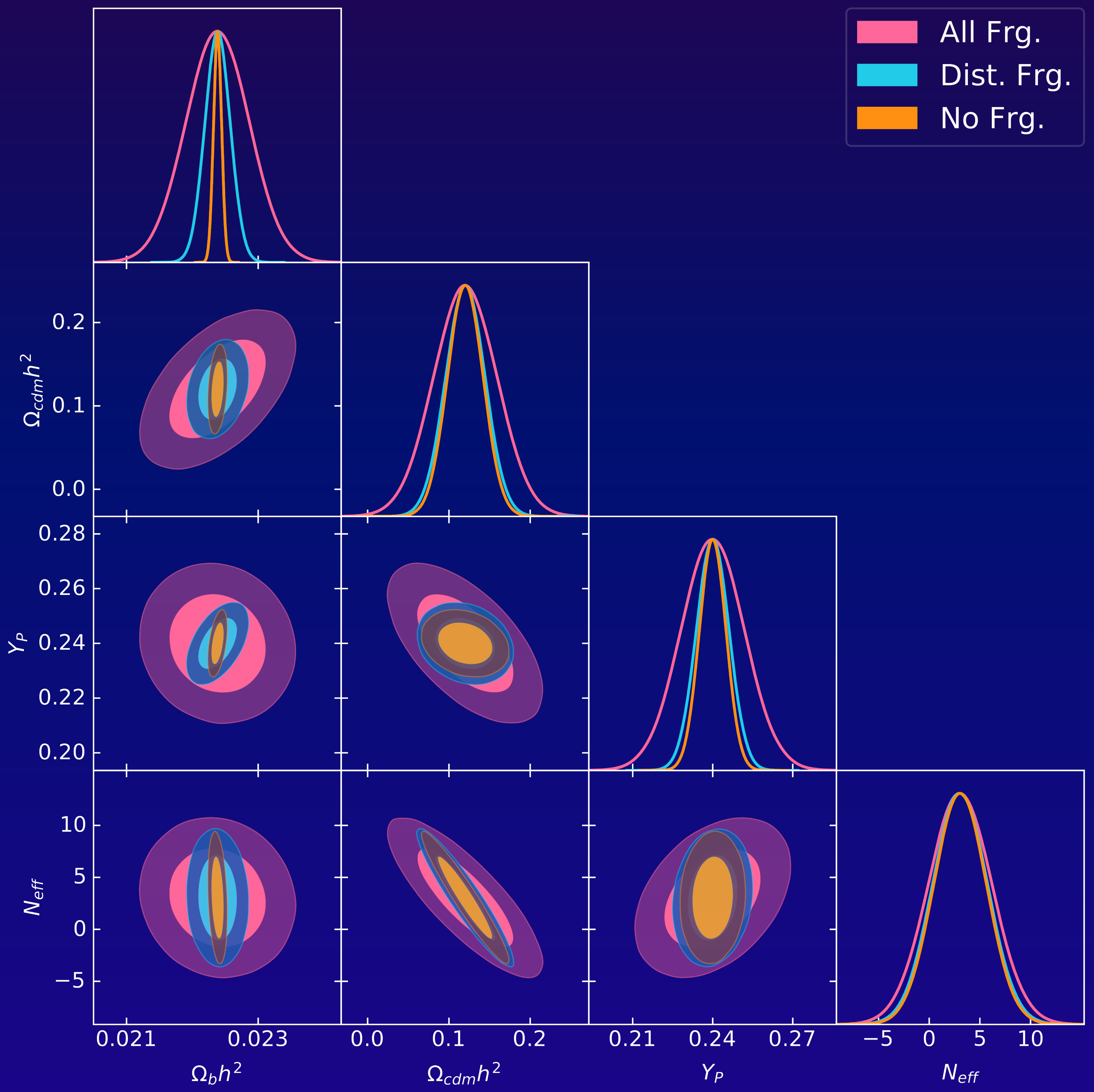
Cosmology with recombination lines

LH, Rotti, Chluba (2020)

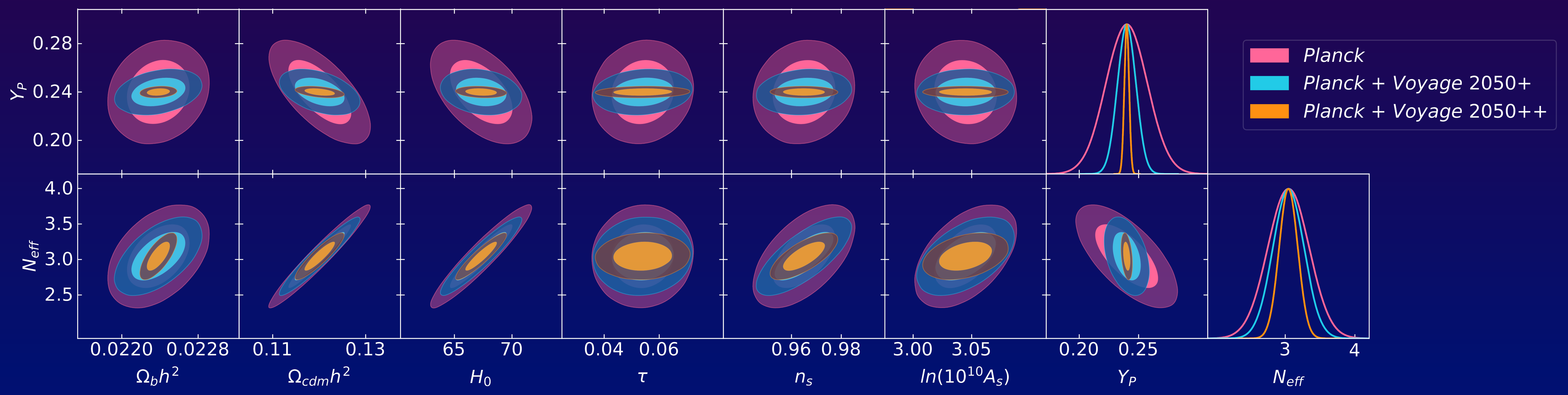


Analysis	*PIXIE*	*SuperPIXIE*	*Voyage 2050*	*Voyage 2050+*
No Frgs.	1.6	9.5	48	477
Dist. Frgs.	1.1	3.6	18	179
Astr. Frgs.	0.5	2.5	12	122
All Frgs.	0.3	1.5	7.7	77

- Degeneracy lines with N_{eff} as expected
- SNR dependent on foregrounds as expected
- PIXIE and SuperPIXIE parameter constraints hindered by foregrounds
- V2050 and V2050+ getting close to parameter constraining limits
- Main hindrance is the astro FGs but other distortions do make a difference

Cosmology with recombination lines

LH, Rotti, Chluba (2020)



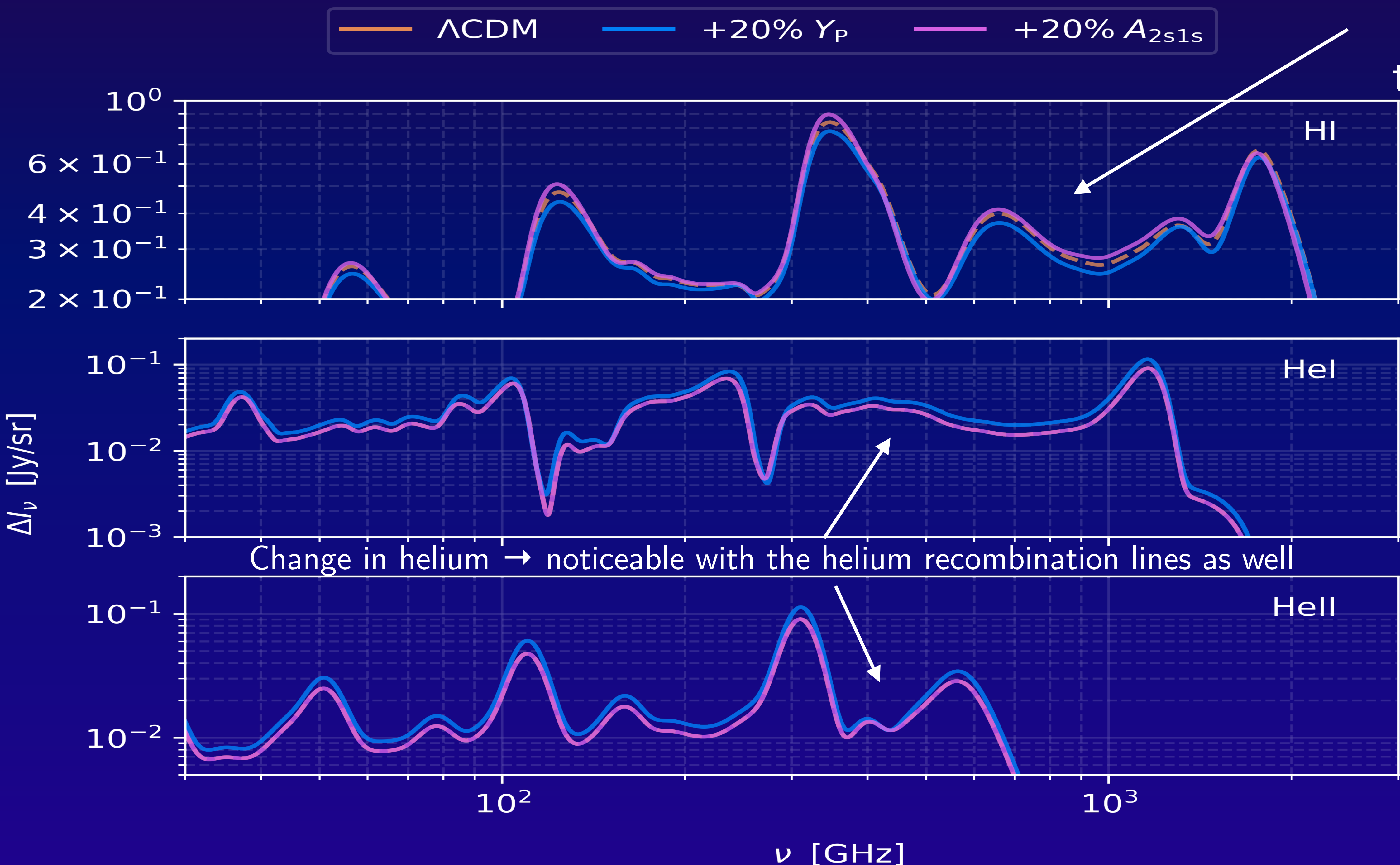
Analysis	$\Omega_b h^2$	$\Omega_{cdm} h^2$	H_0	Y_p	N_{eff}
No Frgs.	0.26	0.58	0.46	0.26	0.49
Dist. Frgs.	0.63	0.65	0.62	0.30	0.59
Astr. Frgs.	0.83	0.72	0.72	0.35	0.67
All Frgs.	0.86	0.79	0.80	0.45	0.75

$$R = \frac{\sigma_{\rm V2050+}}{\sigma_{\rm Planck}}$$

- We need a spectrometer with 10x sensitivity proposed of Voyage 2050 for above-Planck errors
- Particular future strength for Y_P

Extended cosmology with the recombination lines

Customised expansion rate will explore H and He independently



Changes in the two photon rate for hydrogen → opaque to helium

Feedback processes between helium and hydrogen :: Y_P still affects hydrogen!

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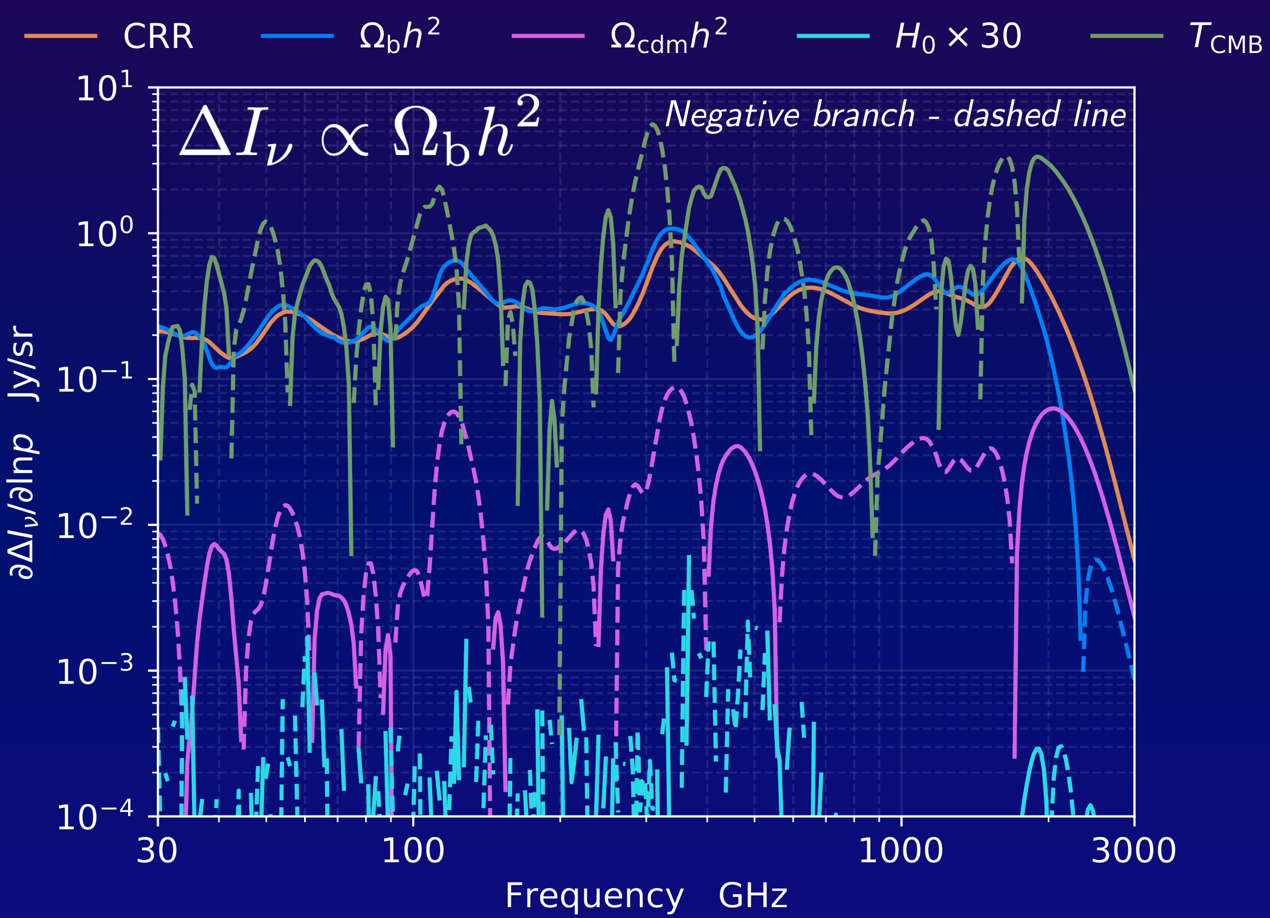
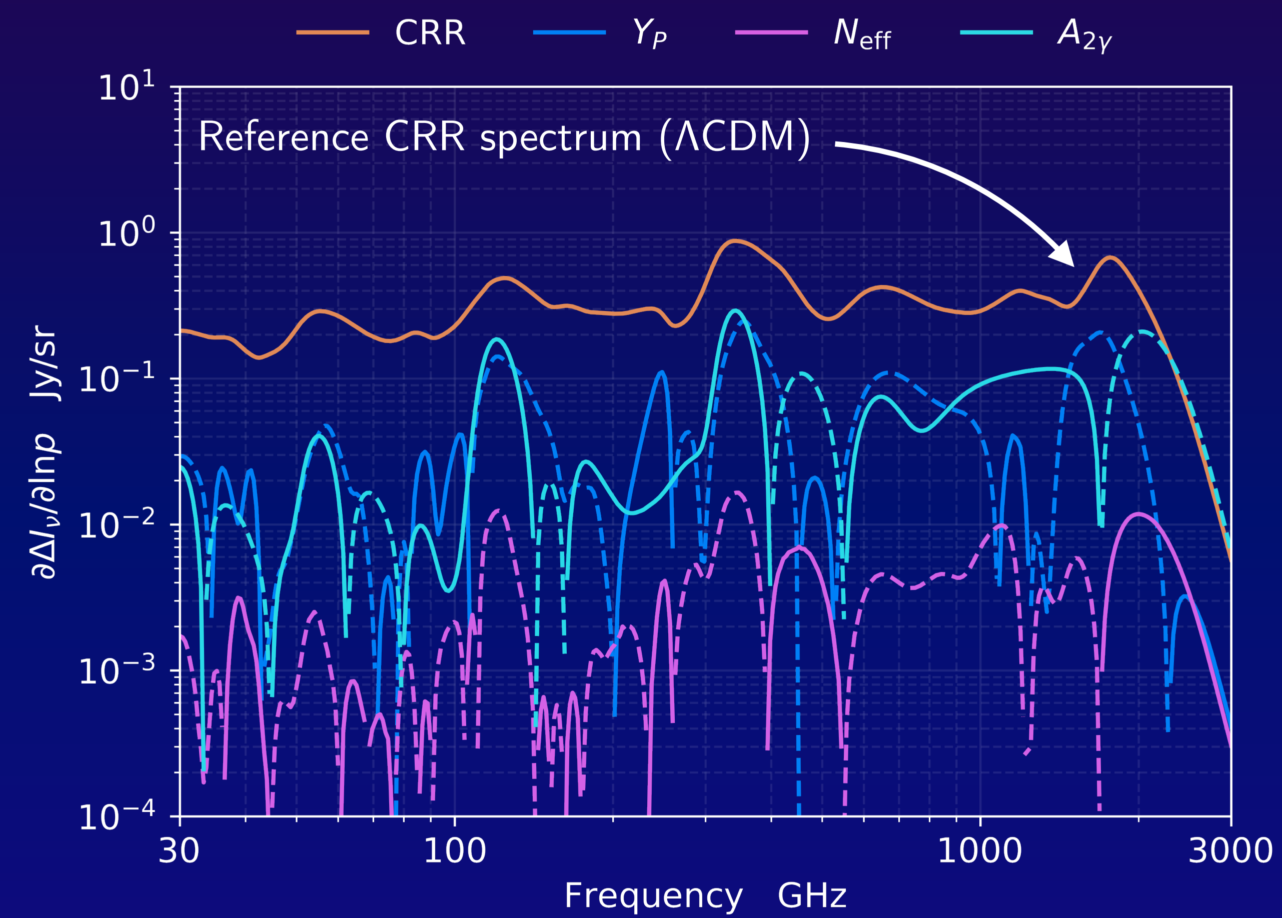
Cosmology with the recombination lines





LH, Rotti, Chluba (2020)

- $\Omega_b h^2$ → more effective scattering
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- $A_{2\gamma}$ → unique spectral response (hydrogen lines)
- N_{eff} → smooths out ΔI_ν features
- Y_P → lower ν, translation of peaks

Both parameters enter the problem through the expansion rate

N_{eff} in the recombination lines

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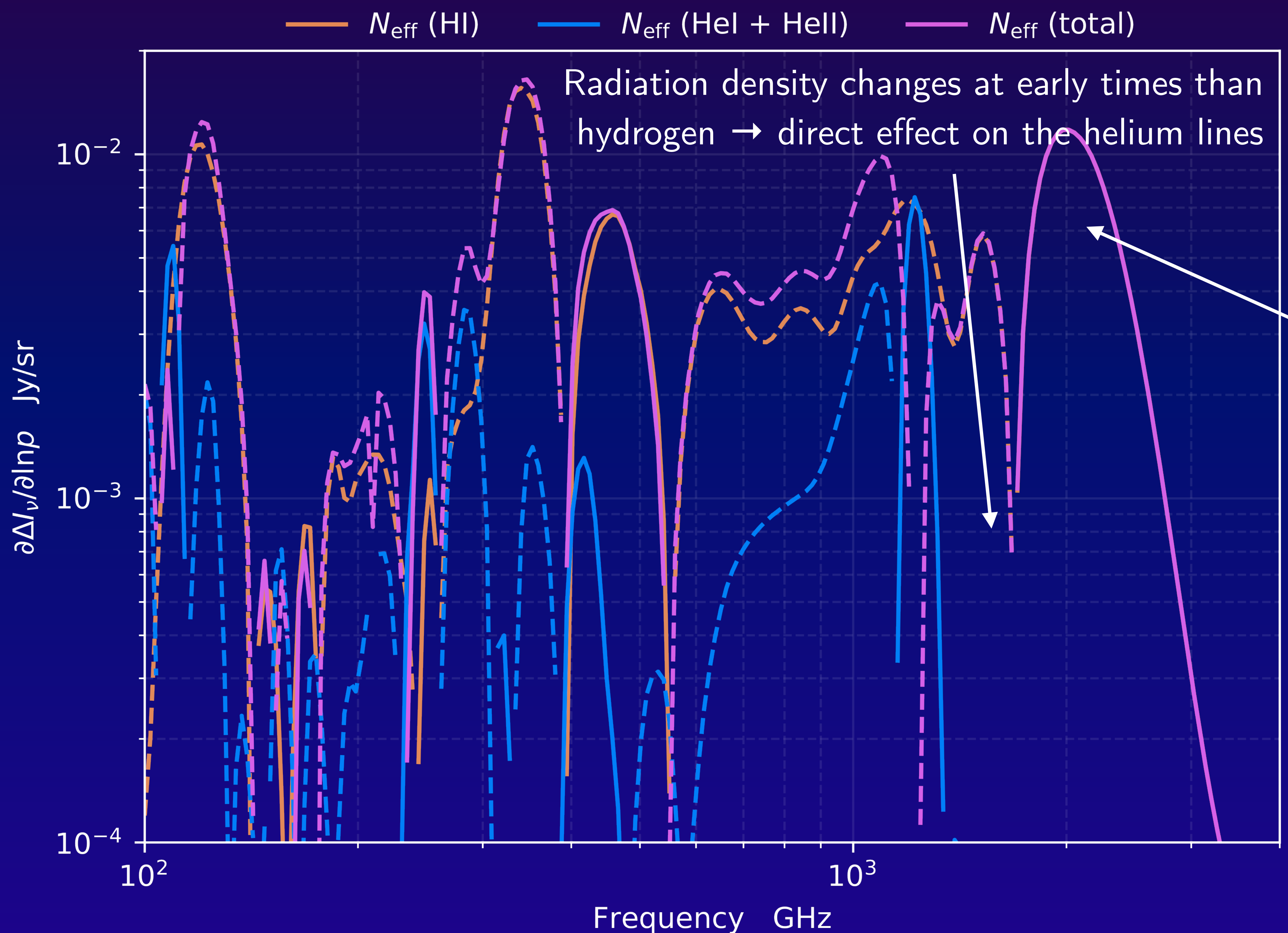


Unique impacts in distinct redshift eras → <u>could we constrain other effects in the expansion rate?</u>

Early dark energy: the basics

$$V(\phi) \propto [1 - \cos(\phi/f)]$$

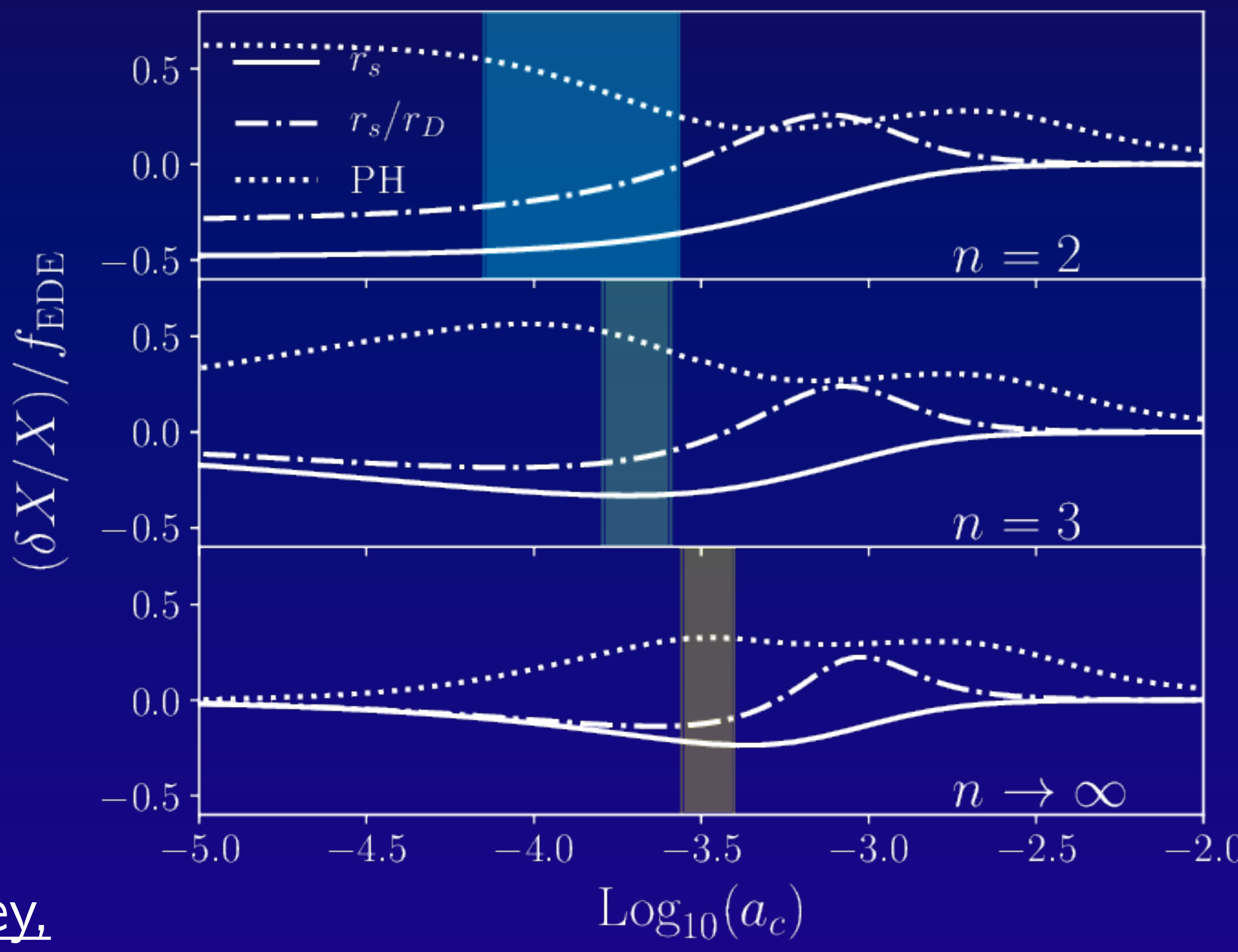
Oscillating potential

$$\Omega_\phi(z) \propto \left(a^{-3(w_n+1)} + 1\right)^{-1}$$

Energy density approximated as a fluid → constant early, dilutes faster at late times

Note: EDE is not a new idea. Doran, Huey, Kamionkowski and others have considered this idea for years...

Karwal et. al. (2016), Poulin et. al. (2018, 2019), Smith et. al. (2019)



Scale variations from EDE vs. Planck BFs (Poulin et. al. 2019)

Hubble Constant getting tense...

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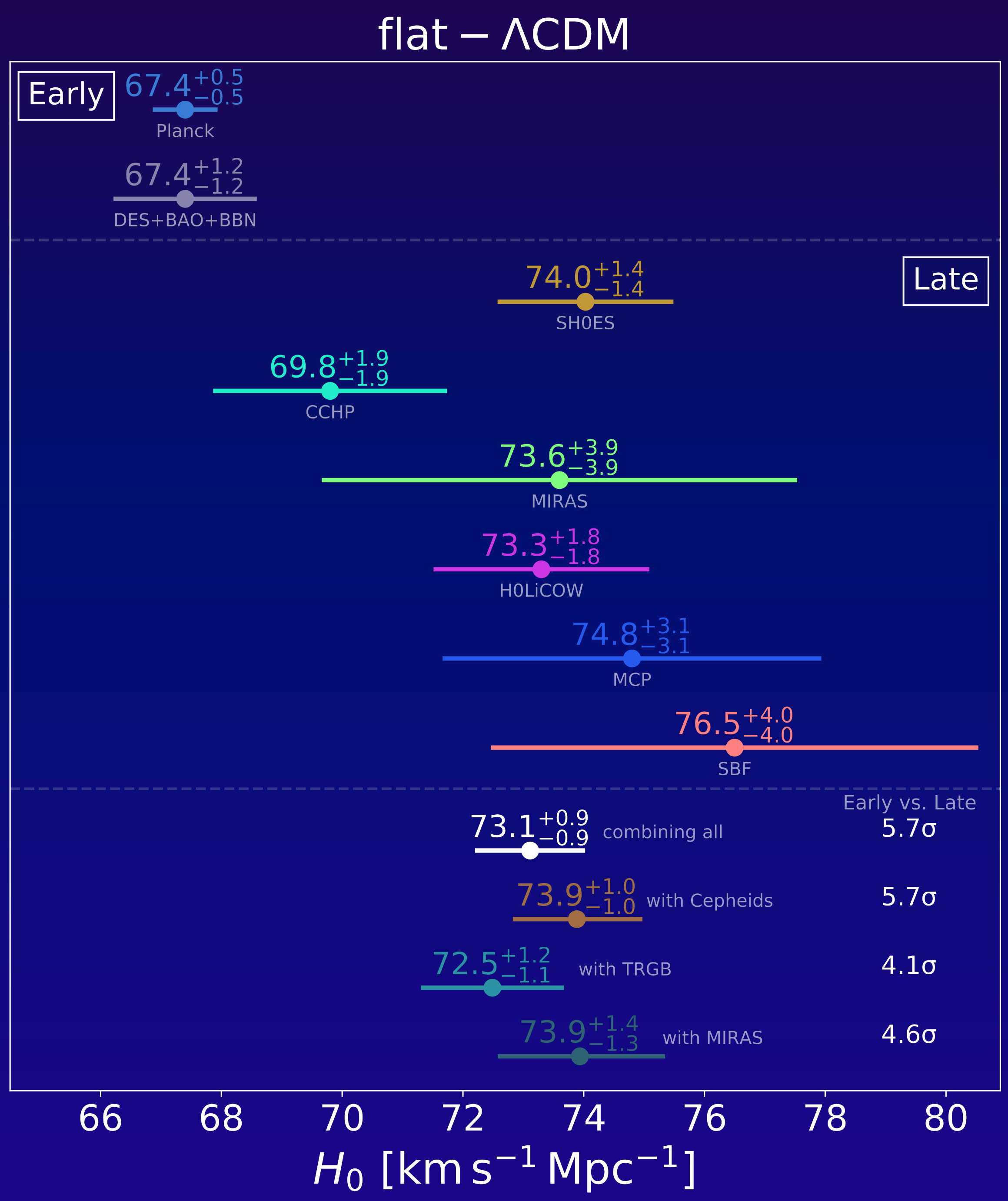
Fix with systematics

- Cepheid variable → SNe distance ladder anchors?
- Disagreement within low redshift probes (TRGB from CCHP)
- Counters suggest this relies on LMC calibration (Riess et. al. 2020)
- General agreement over low-z probes

Add in other probe ideas

- The sGWB background may help (Jeong et. al. 2019, Clarke et. al. 2020)
- Standard sirens (Feeney et. al. 2018)



Verde et. al. (2019),
Di Valentino et. al. (2020)

Fix with new physics
(modification to the sound horizon?)

- **Some early dynamical dark energy (Poulin et. al. 2018, Lin et. al. 2019, Pan et. al. 2019)**
- Toy model primordial magnetic fields (Jedamzik 2020)
- Generalised changes to recombination (Liu et. al 2019)
- Cosmological crisis: closed universe (Di Valentino et. al. 2019)
- many **many** more...

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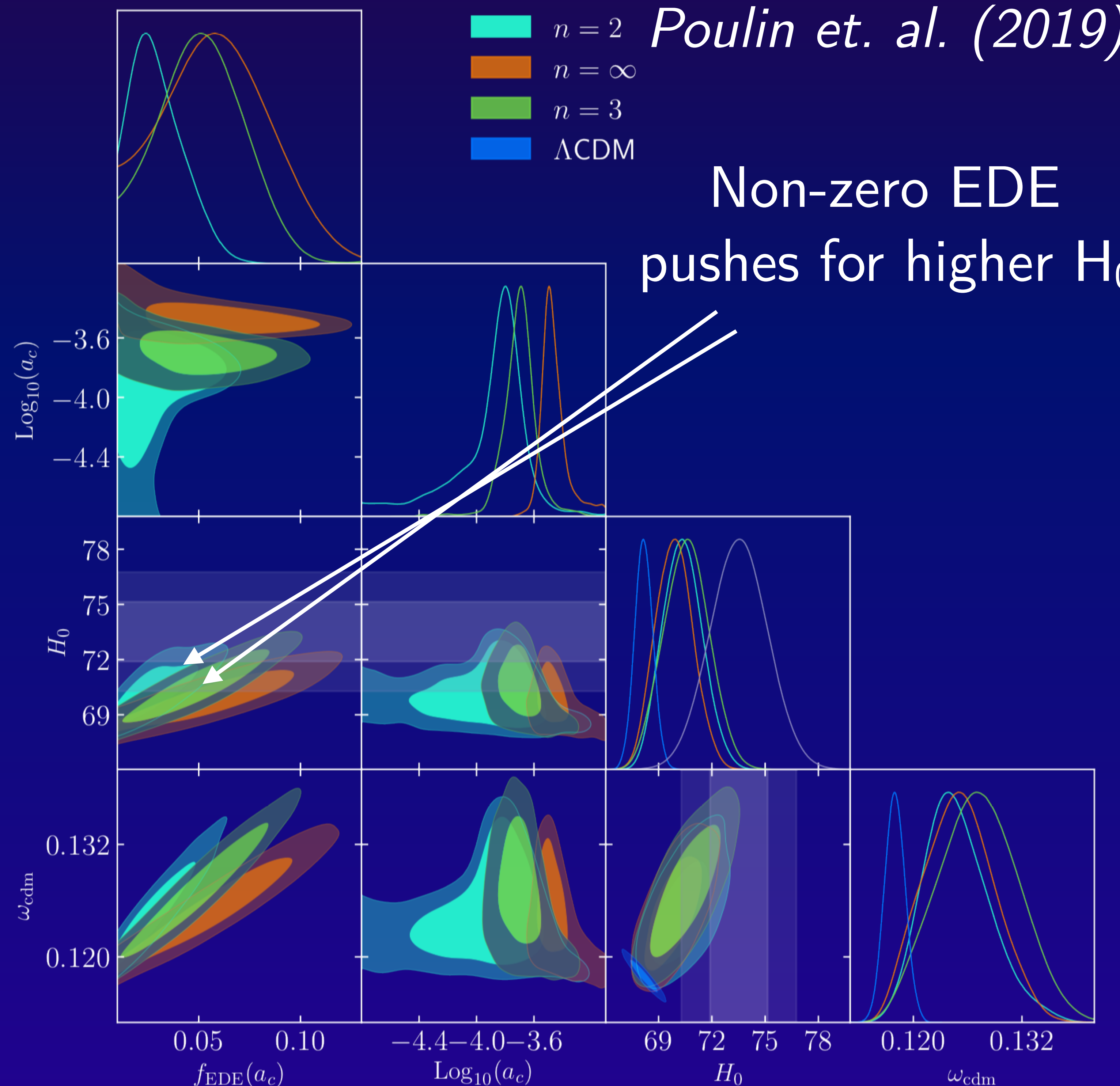
Early dark energy and the Hubble tension

Early dark energy → can alleviate the Hubble tension

More complications associated with the implications on large scale structure (Ivanov et. al. 2020)

Story is *deeper* when you try EDE with *other* distortions (Lucca et. al. 2020)

Poulin et. al. (2019)



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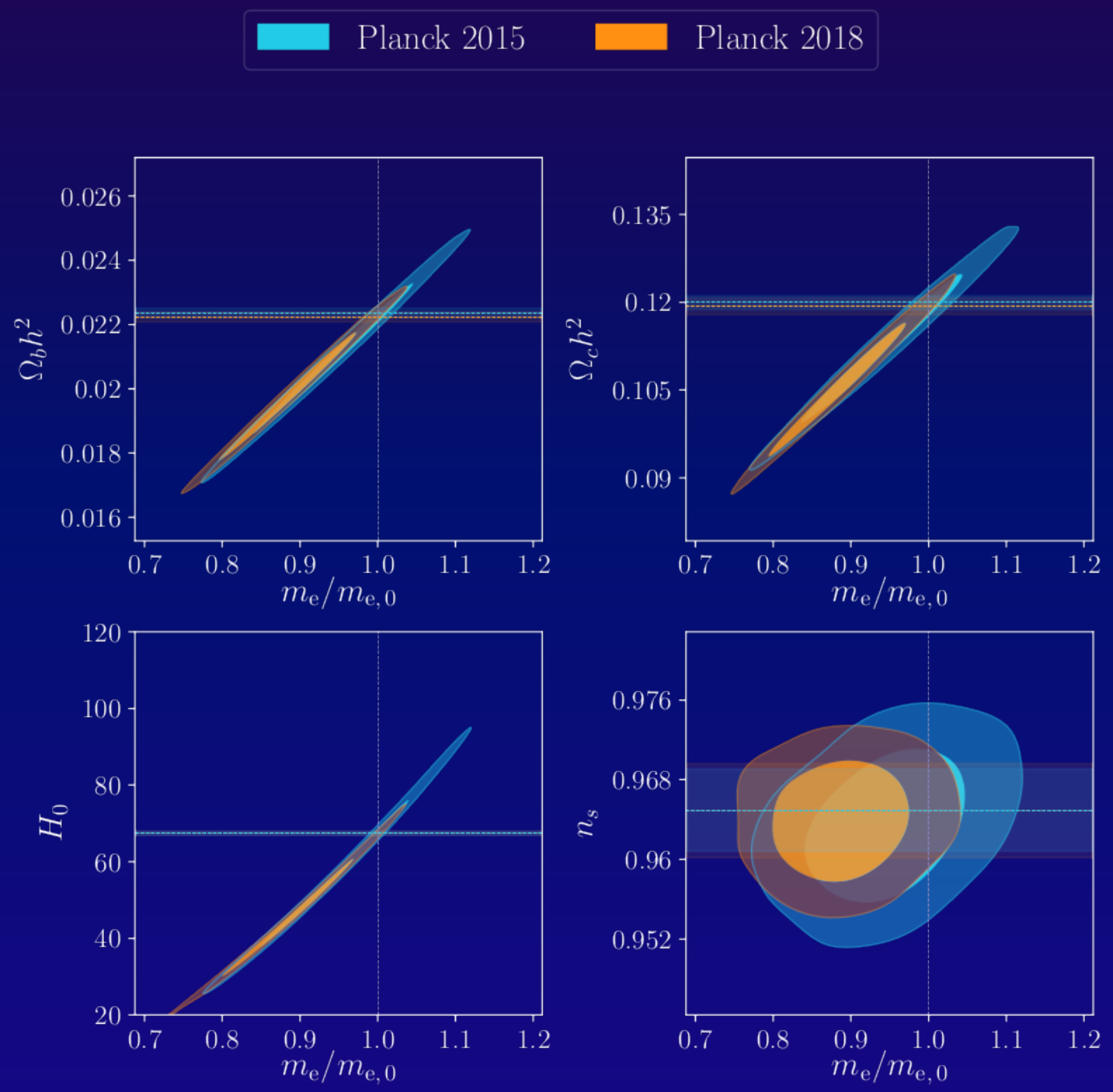

Hart and Chluba (2020) https://arxiv.org/abs/1912.03986

Other tension alleviation mechanisms can theoretically fold into EDE → such as m_e

Early dark energy: the basics

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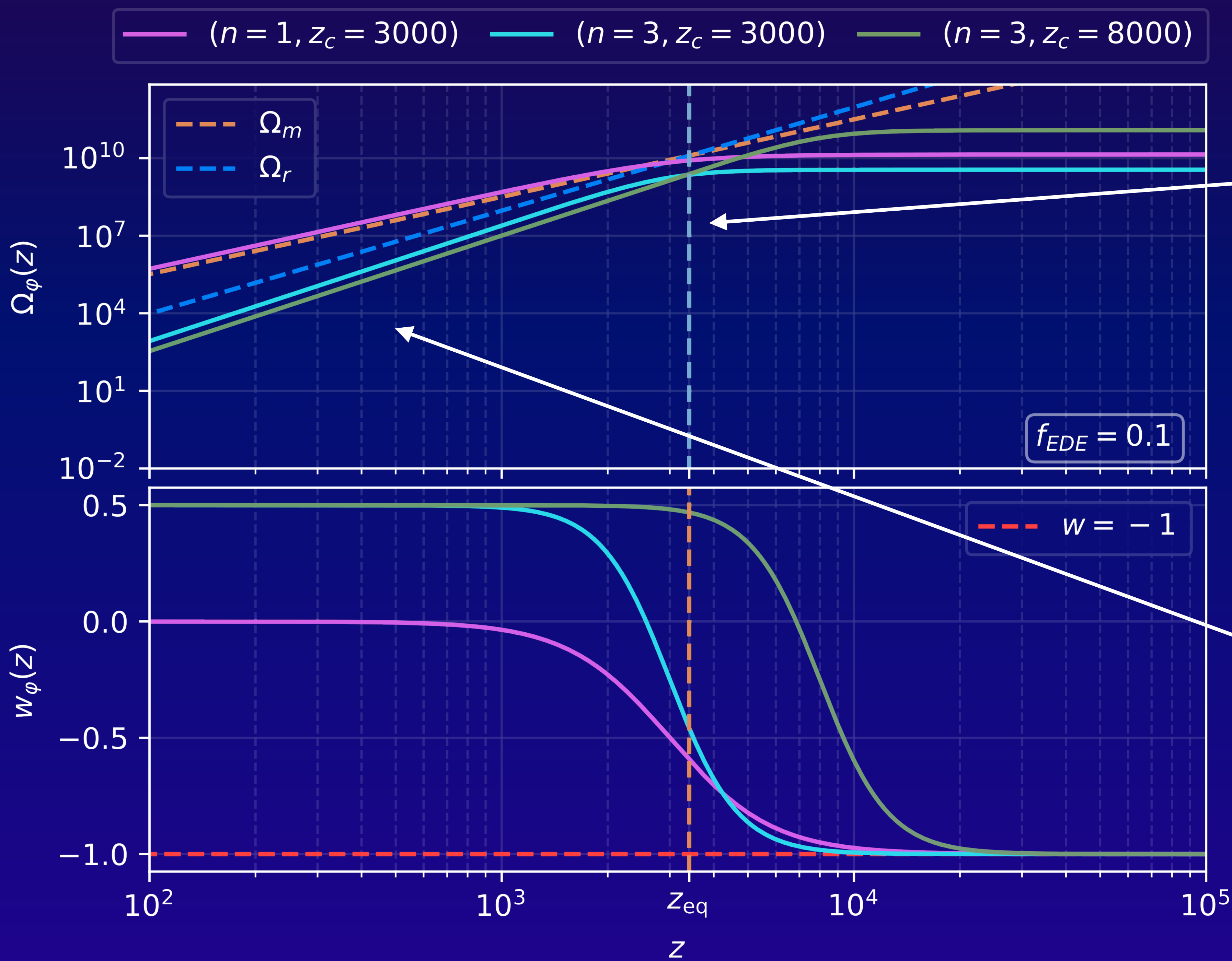
dilutes slower | fixed model | starts earlier



Energy dilutes at a dynamic time

The index denotes the steepness

LH, Chluba (2021, in final prep)

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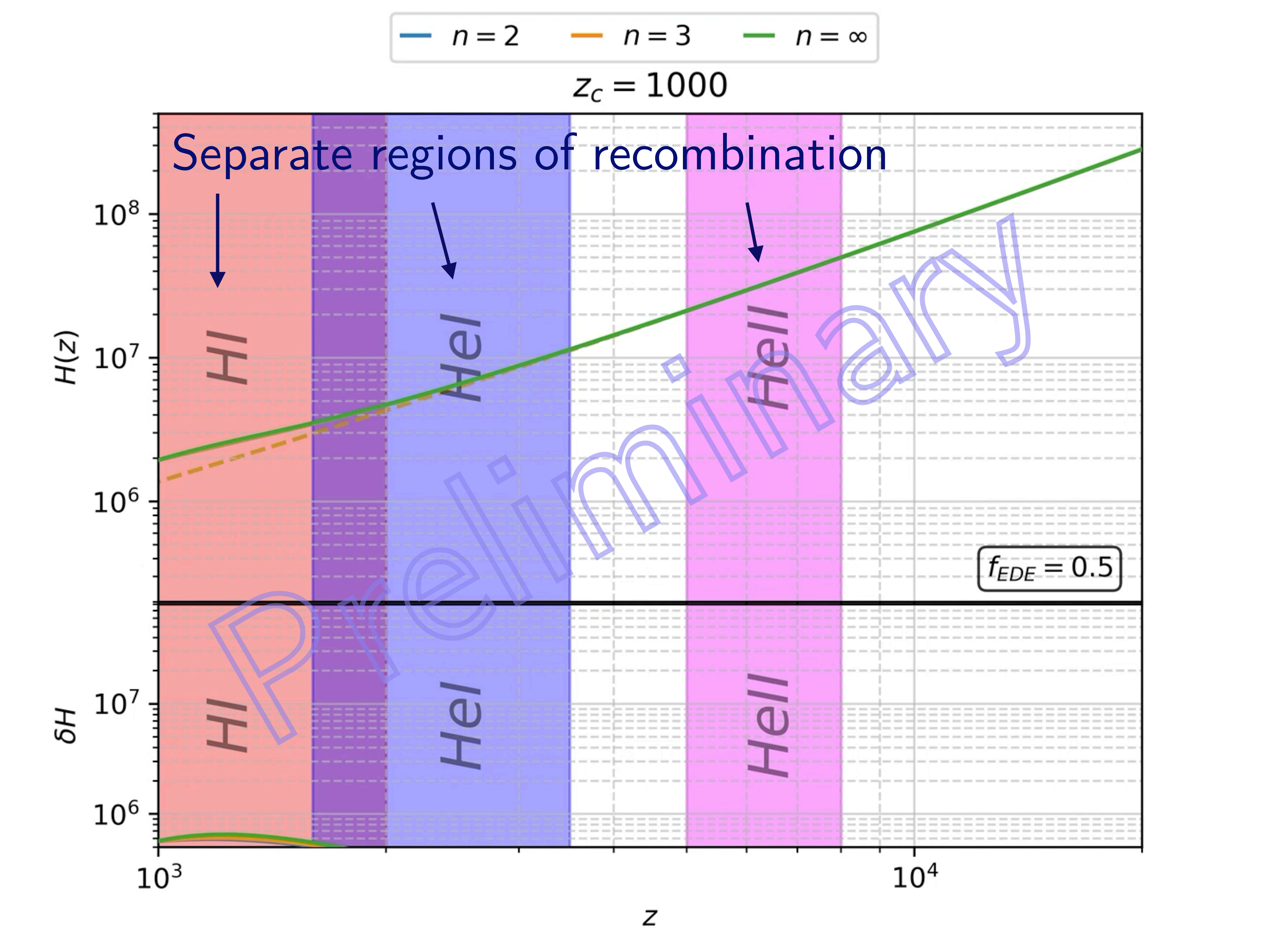
Early dark energy: the background



Redshift indicates the dynamic switch

$$z_c$$

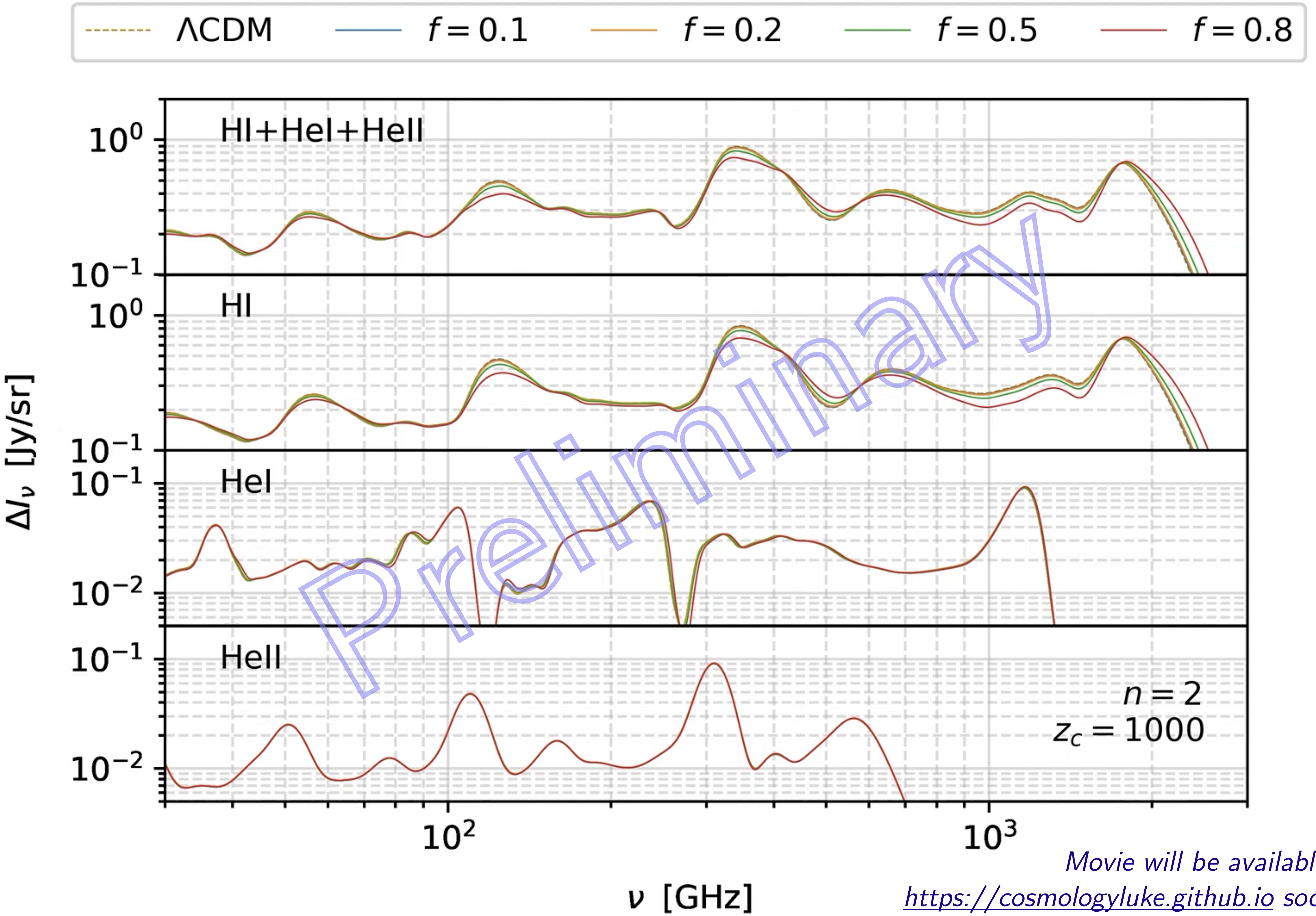
Amplitude of early dark energy at the pivot

$$f_{\rm EDE} \equiv \left.\frac{\Omega_\phi}{\Omega_{\rm tot}}\right|_{z=z_c}$$

Sharpness/tilt of dilution

$$n$$

LH, Chluba (2021, in final prep)



Movie will be available at https://cosmologyluke.github.io soon...

Later dynamic times lead to larger net density → larger apparent effect

Different spectral features isolated by different models

Very sharp cut off of all features for a radically dynamic model with an early dilution time

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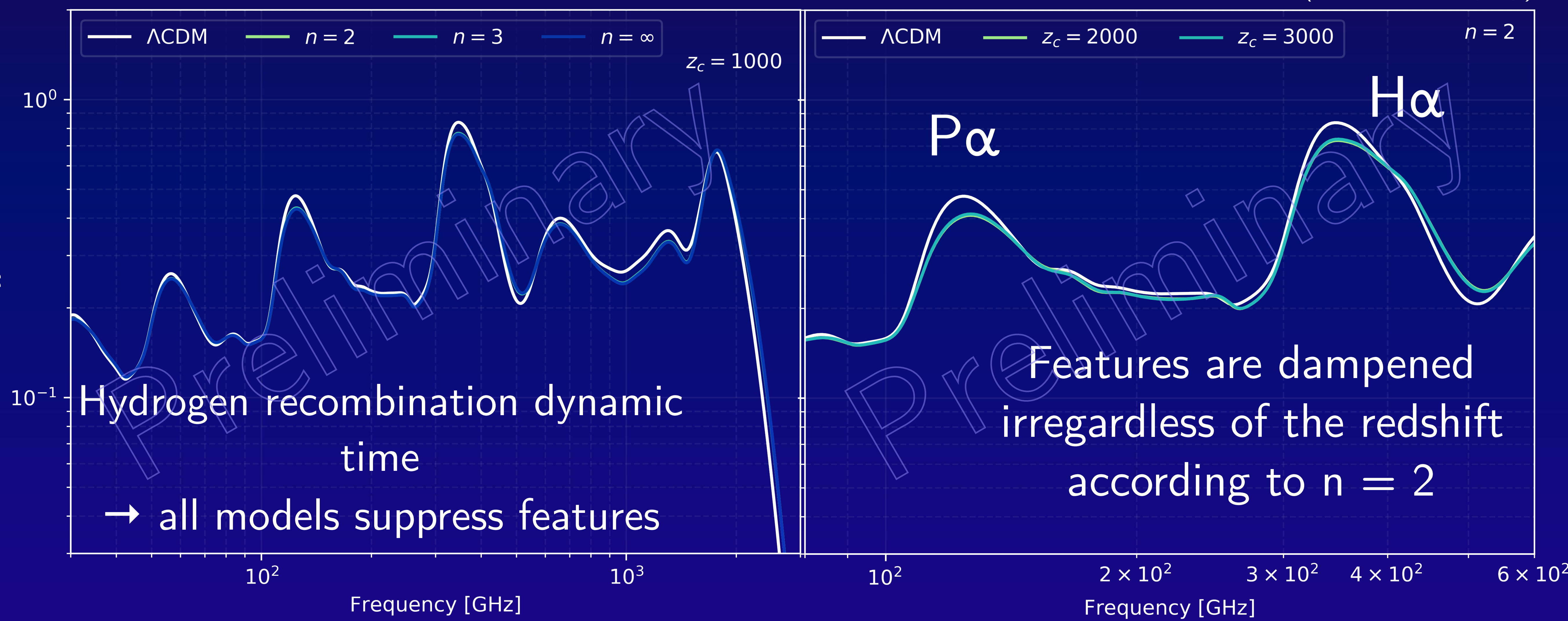
Early dark energy and the recombination radiation:

Some examples

LH, Chluba (2021, in final prep)



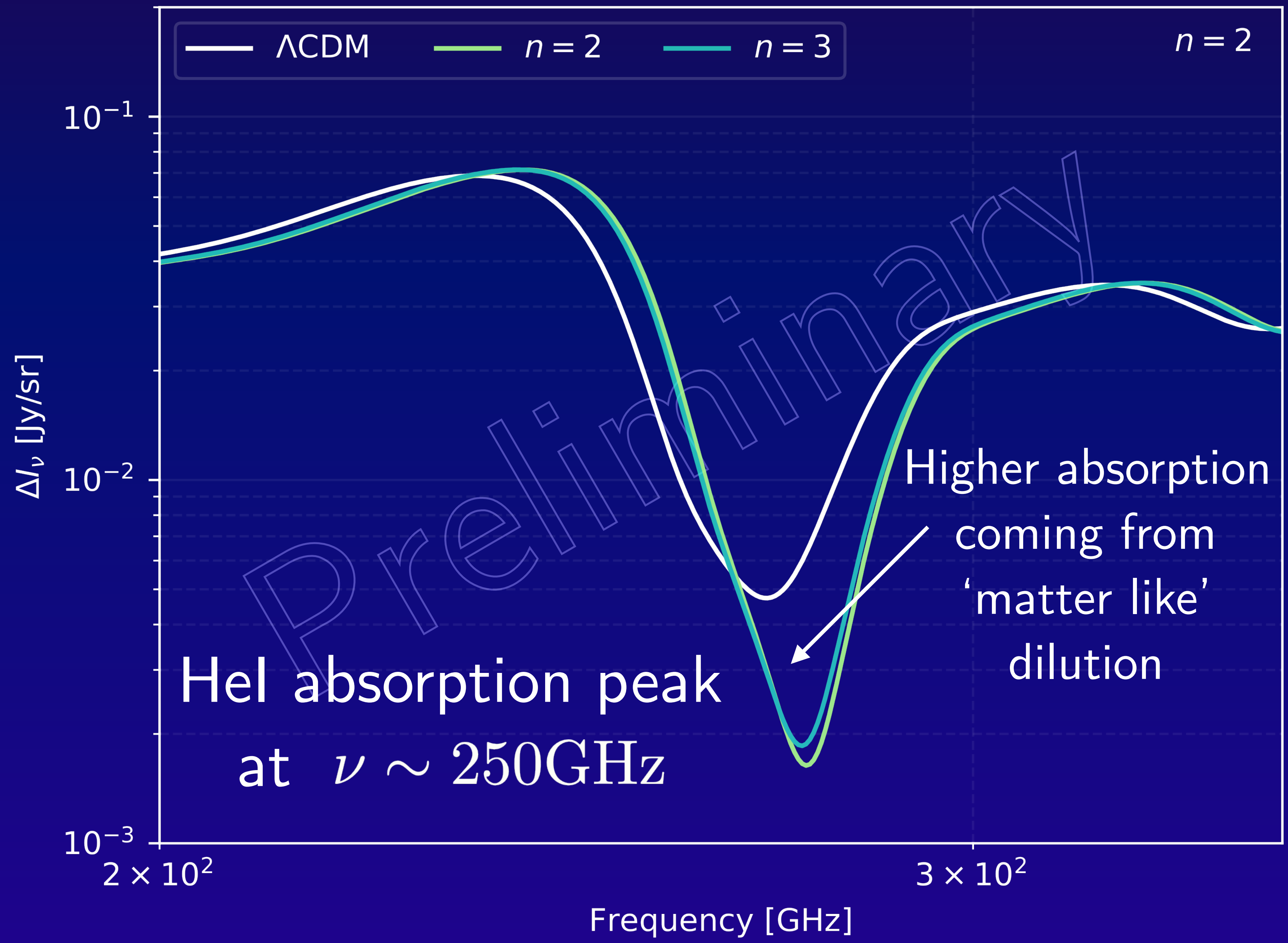
Atomic transitional line features suppressed by accelerated EDE

Early dark energy and the recombination radiation:

Does not happy for too rapid dilution ($n = \infty$)

Some examples

LH, Chluba (2021, in final prep)



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BSM in Recombination: Electromagnetic constants

Coupling to the EM field affects the atomic interactions

Effective mass of the hydrogen atom, affects the energies/interaction rates

$$\alpha_{\mathrm{EM}}$$

$$m_{\mathrm{e}}$$

For all our purposes: this approximation works

$$\mu_{\mathrm{e,p}} = \frac{m_{\mathrm{e}} m_{\mathrm{p}}}{m_{\mathrm{e}} + m_{\mathrm{p}}} \approx m_{\mathrm{e}} + \mathcal{O}\left(\frac{m_{\mathrm{e}}}{m_{\mathrm{p}}}\right)$$

What's next?
Building on the phenomenology

- Fundamental constants are... constant right?
- Any scalar field couples to EM == variations

$$\mathcal{L}_\phi = -\frac{1}{4} B_F(\phi) F_{\mu\nu} F^{\mu\nu}$$

<u>Dynamical dark energy</u>
(e.g. quintessence)

- Scalar field that couples to the dark energy variations induced by a BSM model such as k-essence in *w*

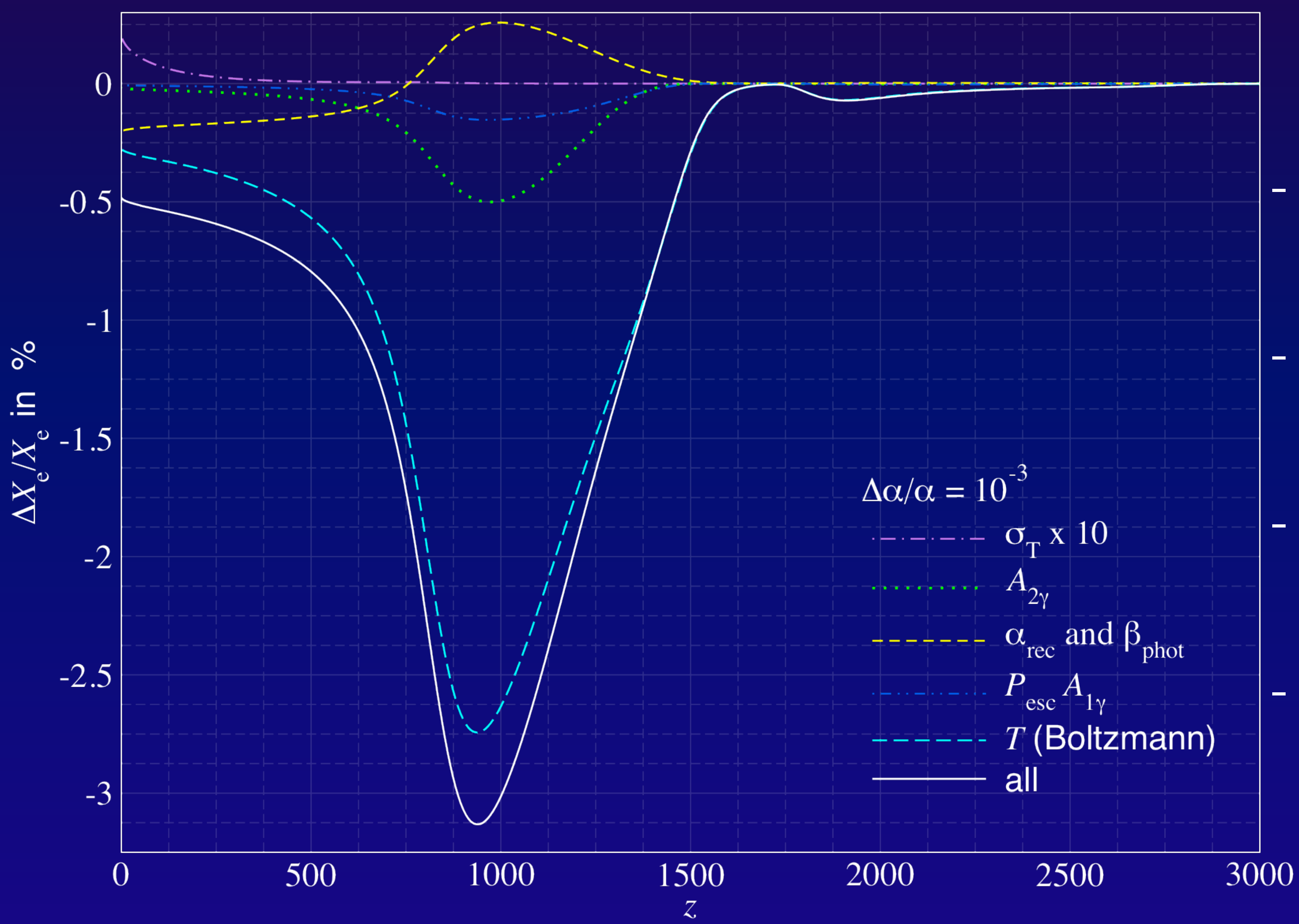
Huey et. al. (2001)
Calabrese et. al. (2011)

<u>Explicit scalar field</u>
(e.g. Bekenstein, BSBM, runaway dilation)

- Scalar field that explicitly couples to the electromagnetic field Lagrangian
- Field value posits variations in α over time

Barrow et. al. (2001)
Martins et. al. (2017, 2019)

Electromagnetic constants in recombination



(LH, Chluba 2018)

- Mainly dominated by energy levels (effective temperature)
- Secondary effect from two-photon decay rate
- Negative slope in ΔXe: acceleration of recombination
- Net rates: hinders recombination

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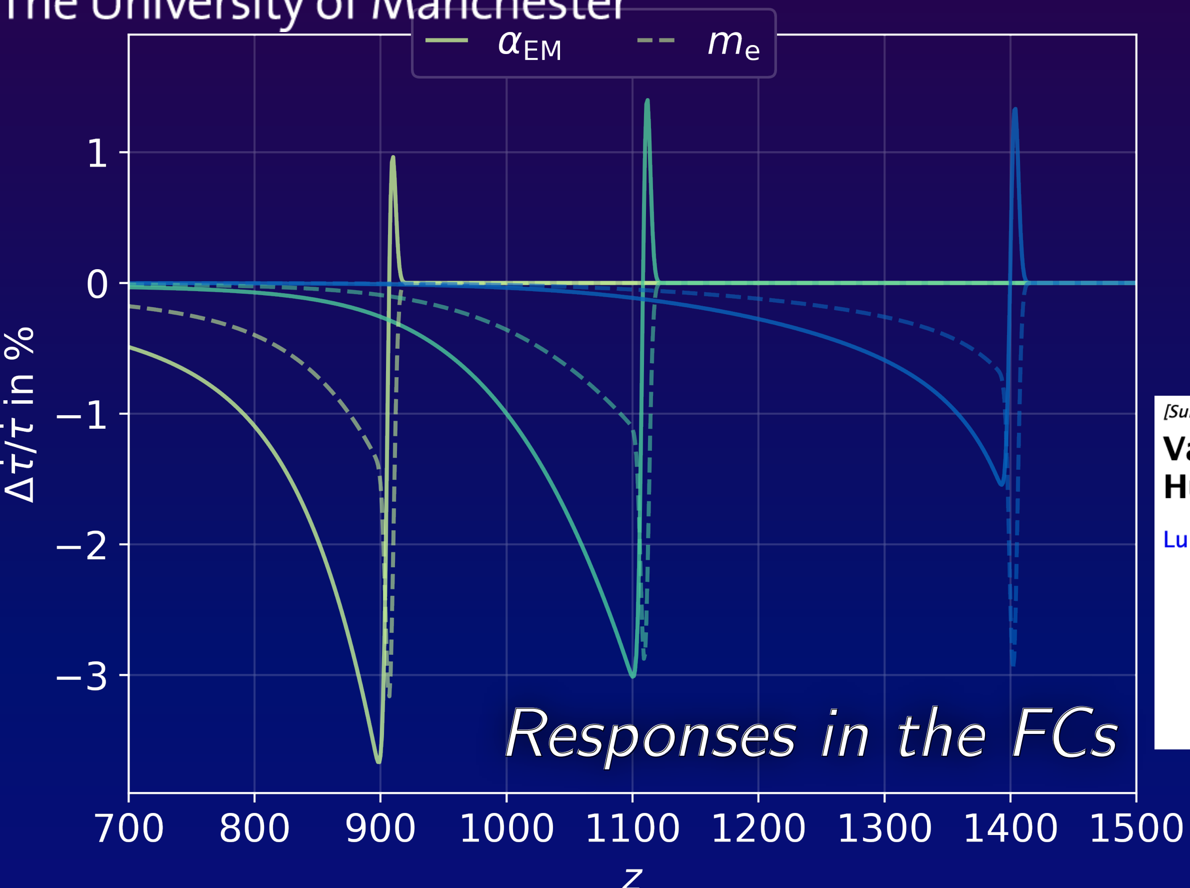
Varying fundamental constants → principal component analysis



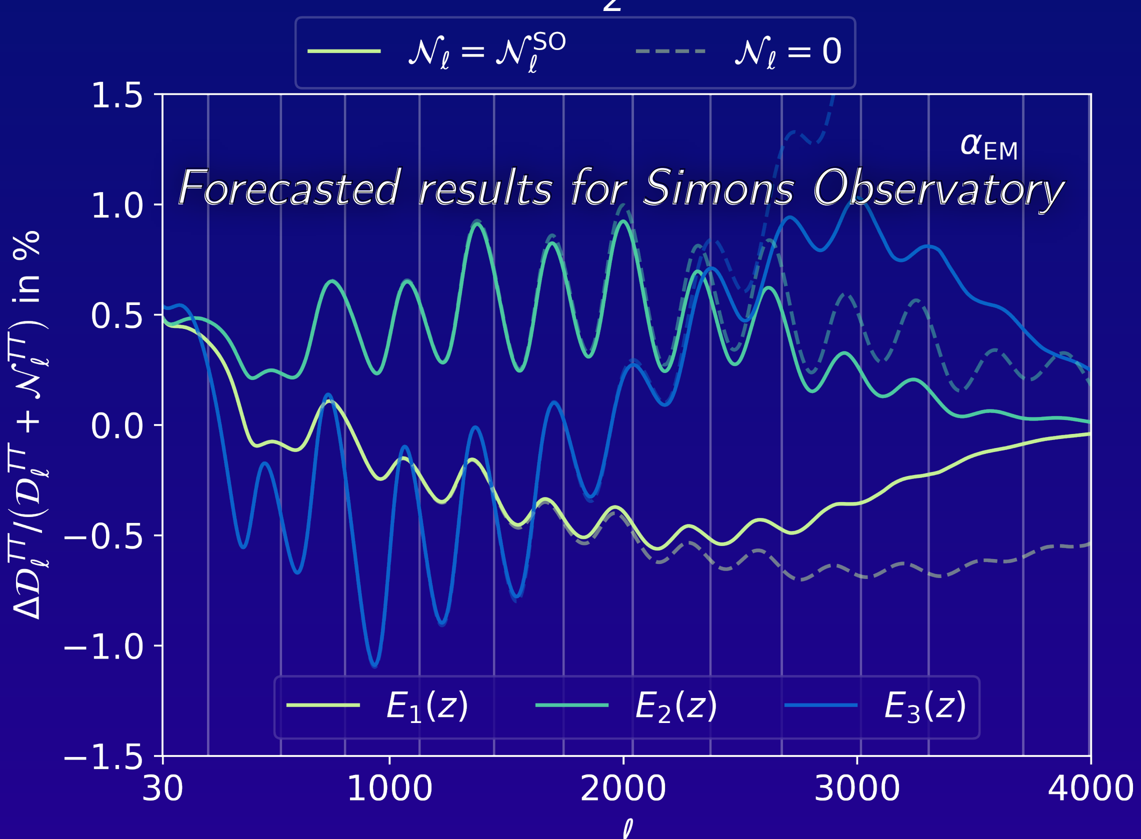
Paper on the arXiv tomorrow morning!

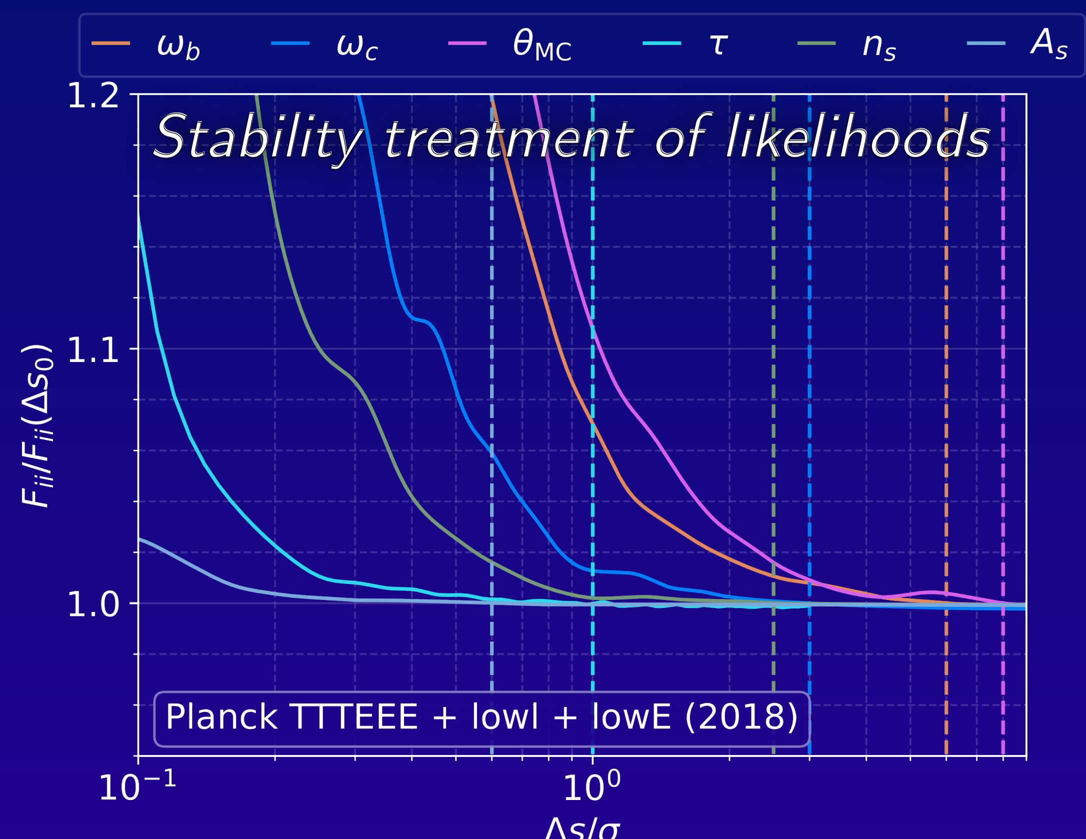
[Submitted on 26 Jul 2021]

Varying fundamental constants principal component analysis: additional hints about the Hubble tension

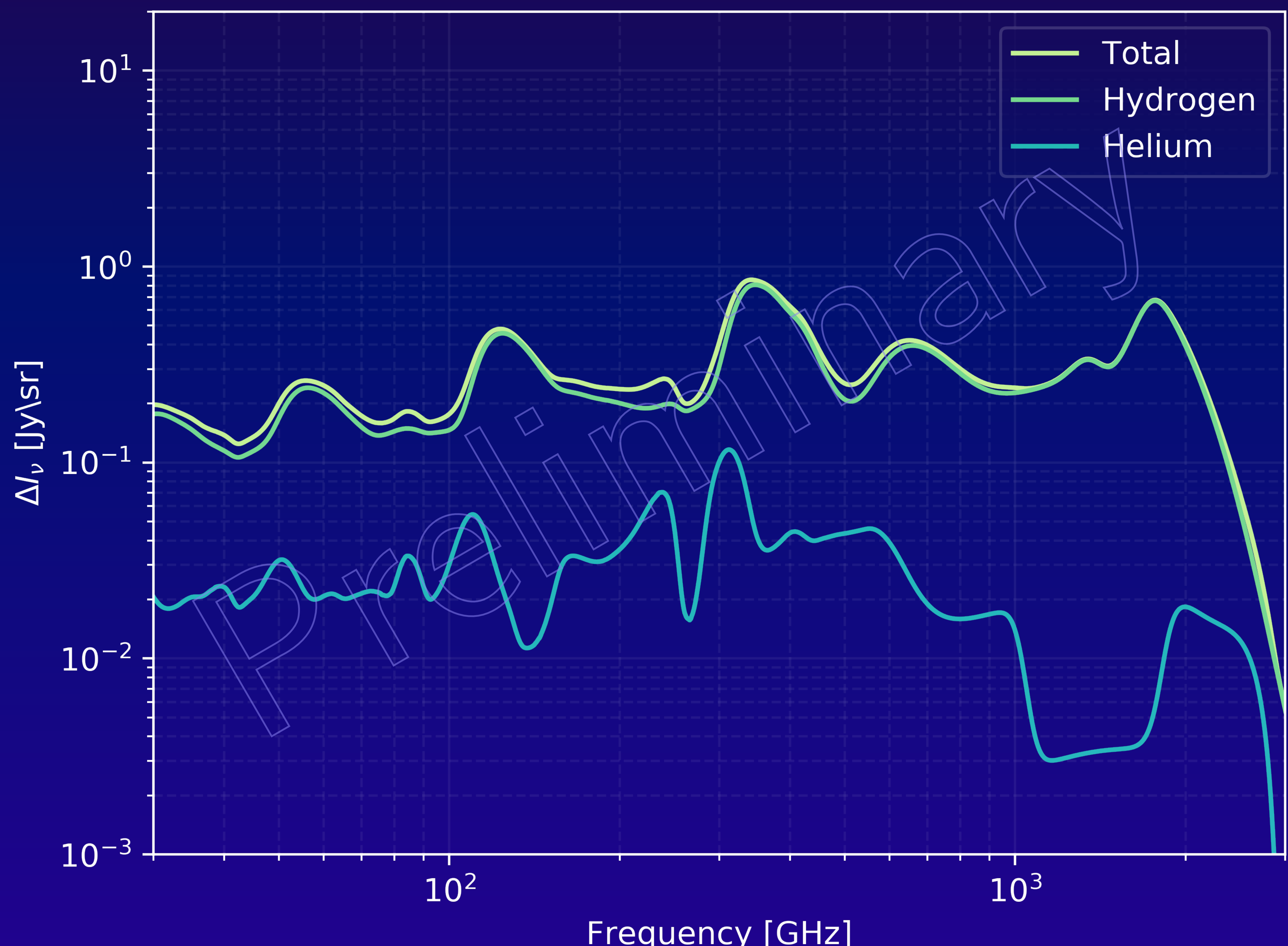
Luke Hart, Jens Chluba

Varying fundamental constants (VFC) [e.g., the fine-structure constant, α_{EM}] can arise in numerous extended cosmologies. Through their effect on the decoupling of baryons and photons during last scattering and reionisation, these models can be directly constrained using measurements of the cosmic microwave background (CMB) temperature and polarization anisotropies. Previous investigations focused mainly on time-independent changes to the values of fundamental constants. Here we generalize to time-dependent variations. Instead of directly studying various VFC parameterizations, we perform a model-independent principal component analysis (PCA), directly using an eigenmode decomposition of the varying constant during recombination. After developing the formalism, we use Planck 2018 data to obtain new VFC limits, showing that three independent VFC modes can be

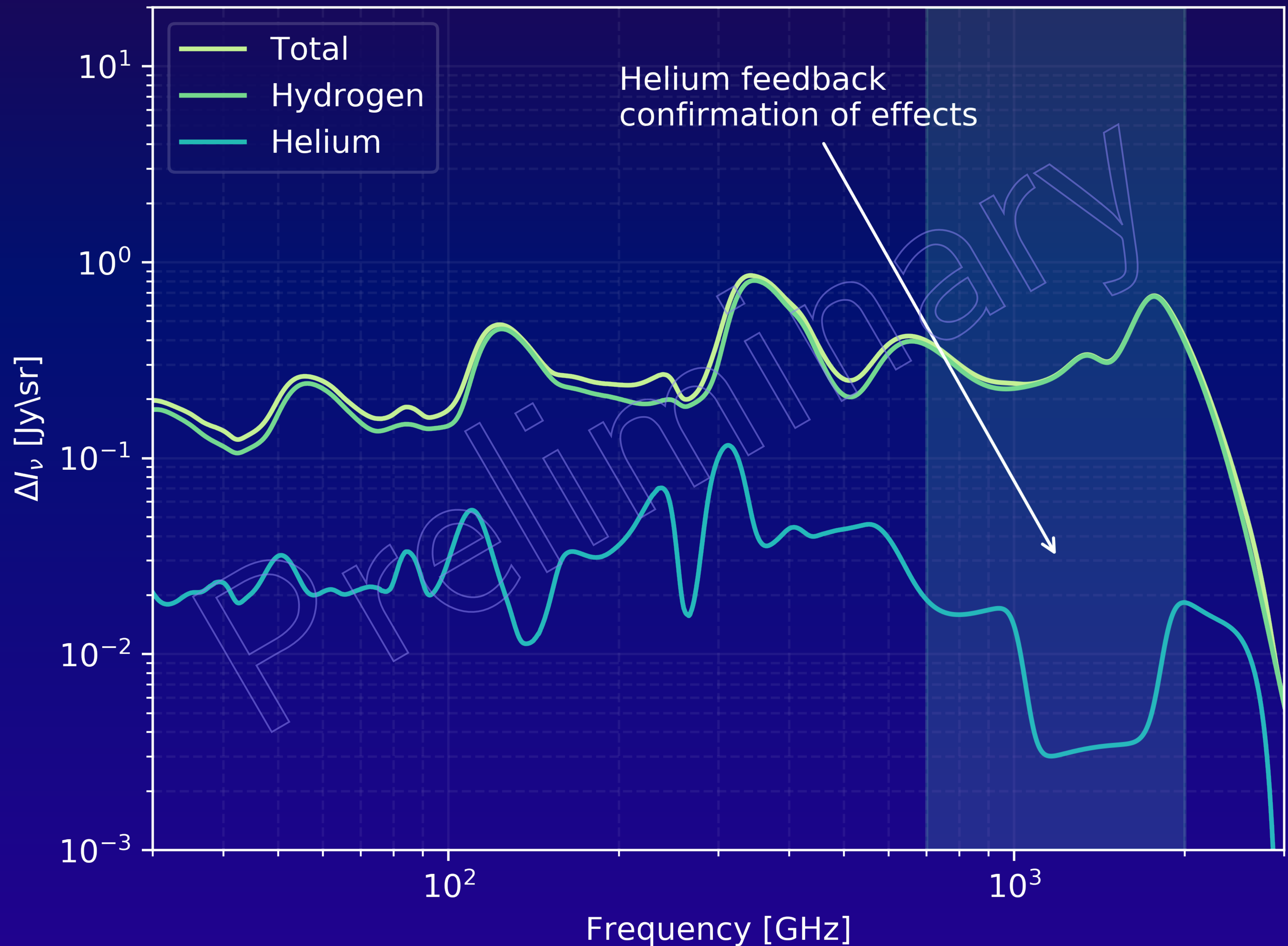




Fundamental constant variations in the distortions



Fundamental constant variations in the distortions



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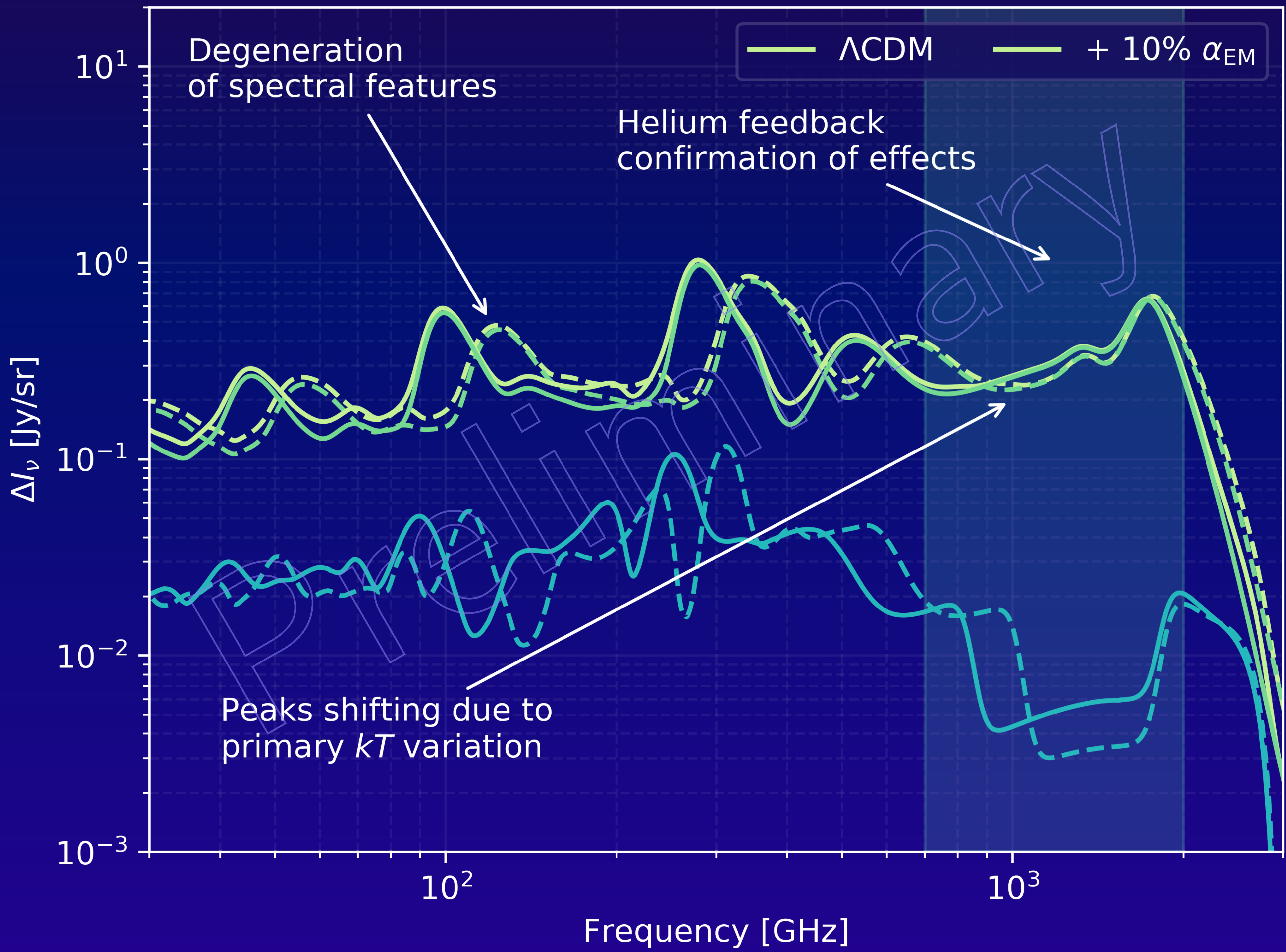
Fundamental constant variations in the distortions



Distortions with a bright

Voyage 2050 looking promising for SDs!

→ THE EUROPEAN SPACE AGENCY

esa

SCIENCE & EXPLORATION

Voyage 2050 sets sail: ESA chooses future science mission themes

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ESA / Science & Exploration / Space Science

ESA's large-class science missions for th
System planets, temperate exoplanets o

New physical probes of the early Universe

How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are outstanding questions in fundamental physics and astrophysics that could be addressed by missions exploiting new physical probes, such as detecting gravitational waves with high precision or in a new spectral window, or by high-precision spectroscopy of the cosmic microwave background – the relic radiation left over from the Big Bang. This theme follows the breakthrough science from Planckand the expected scientific return from LISA, and would leverage advances made in instrumentation to open a huge discovery space. Additional study and interaction with the scientific community will be needed to converge on a mission addressing this theme.

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otal moment for ESA's science programme, and for the future generation of
singer, ESA Director of Science.

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Distortions with a bright future!

Raising the profile: Wikipedia page approved!

Cosmic microwave background spectral distortions

From Wikipedia, the free encyclopedia

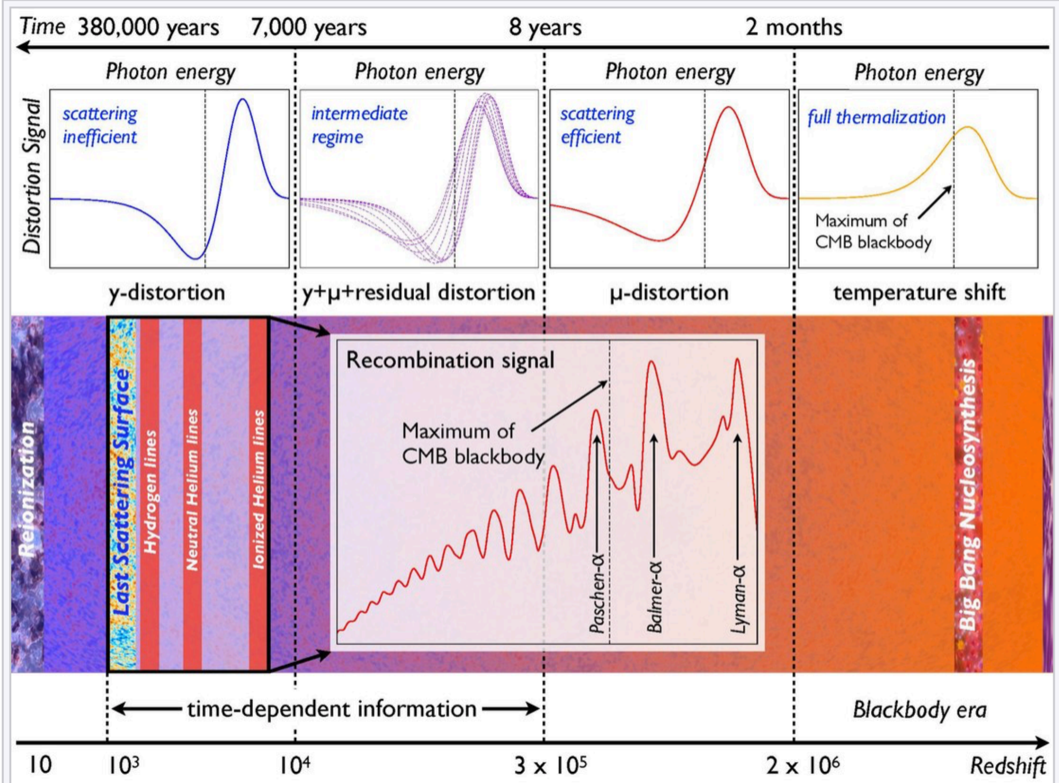
CMB spectral distortions are tiny departures of the average cosmic microwave background (CMB) frequency spectrum from the predictions given by a perfect black body. They can be produced by a number of standard and non-standard processes occurring at the early stages of cosmic history, and therefore allow us to probe the standard picture of cosmology. Importantly, the CMB frequency spectrum and its distortions should not be confused with the CMB anisotropy power spectrum, which relates to spatial fluctuations of the CMB temperature in different directions of the sky.[1]

Contents [hide]

Overview [edit]

The energy spectrum of the CMB is extremely close to that of a perfect blackbody with a temperature of $2.7255K$[3] [4]. This is expected because in the early Universe matter and radiation are in thermal equilibrium. However, at redshifts $z < 2 \times 10^6$, several mechanisms, both standard and non-standard, can modify the CMB spectrum and introduce departures from a blackbody spectrum. These departures are commonly referred to as CMB spectral distortions and mostly concern the average CMB spectrum across the full sky (i.e., the CMB monopole spectrum).

Spectral distortions are created by processes that drive matter and radiation out of equilibrium. One important scenario relates to spectral distortions from early energy



Spectral distortions at different cosmological epochs. At very early times, with redshift $z > 2 \times 10^6$, any injection of energy emerges as a *temperature shift* in the black body. As the age of the Universe increases, the processes that lead to thermalization of CMB distortions to a blackbody become less efficient (bremsstrahlung and double Compton scattering when $z < 10^6$, Compton scattering when $z < 10^4$). The spectral distortions also interplay with distinguished epochs of cosmic history such as reionization, recombination and Big Bang nucleosynthesis as shown. Specifically,

https://en.wikipedia.org/wiki/Cosmic_microwave_background_spectral_distortions

Conclusions

- Spectral distortions aren't just μ, y, r and SZ → recombination lines are there and *predicted by even ΛCDM*
- Provides a unique cosmological probe for future spectrometers
- Changing the expansion rate models → directly affects the CRR between HI and HeI/HeII epochs
- Similar EM small-scale time variations could be constrained via α_{EM} and m_e with more interesting physical implications

Thank you for listening! Any questions welcome :)