The history of reionisation : peering through the dark ages with the CMB

Stéphane Ilić
IJCLab (Orsay, France)

From Planck to the future of CMB
@ Ferrara, 23/05/2022

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Outline

I. What is the reionisation

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II. What does it have to do with the CMB

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III. How do we model it

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III. How do we model it

IV. What do we know about it so far

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II. What does it have to do with the CMB

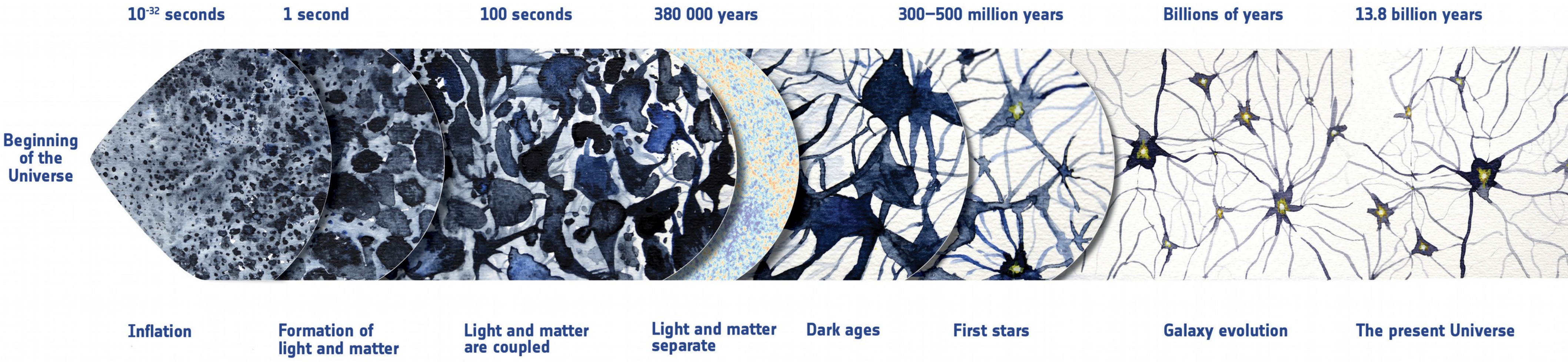
III. How do we model it

IV. What do we know about it so far

V. What we hope to learn in the future

I) The standard model of cosmology

- The ΛCDM paradigm: a (relatively) simple model, with many successes…



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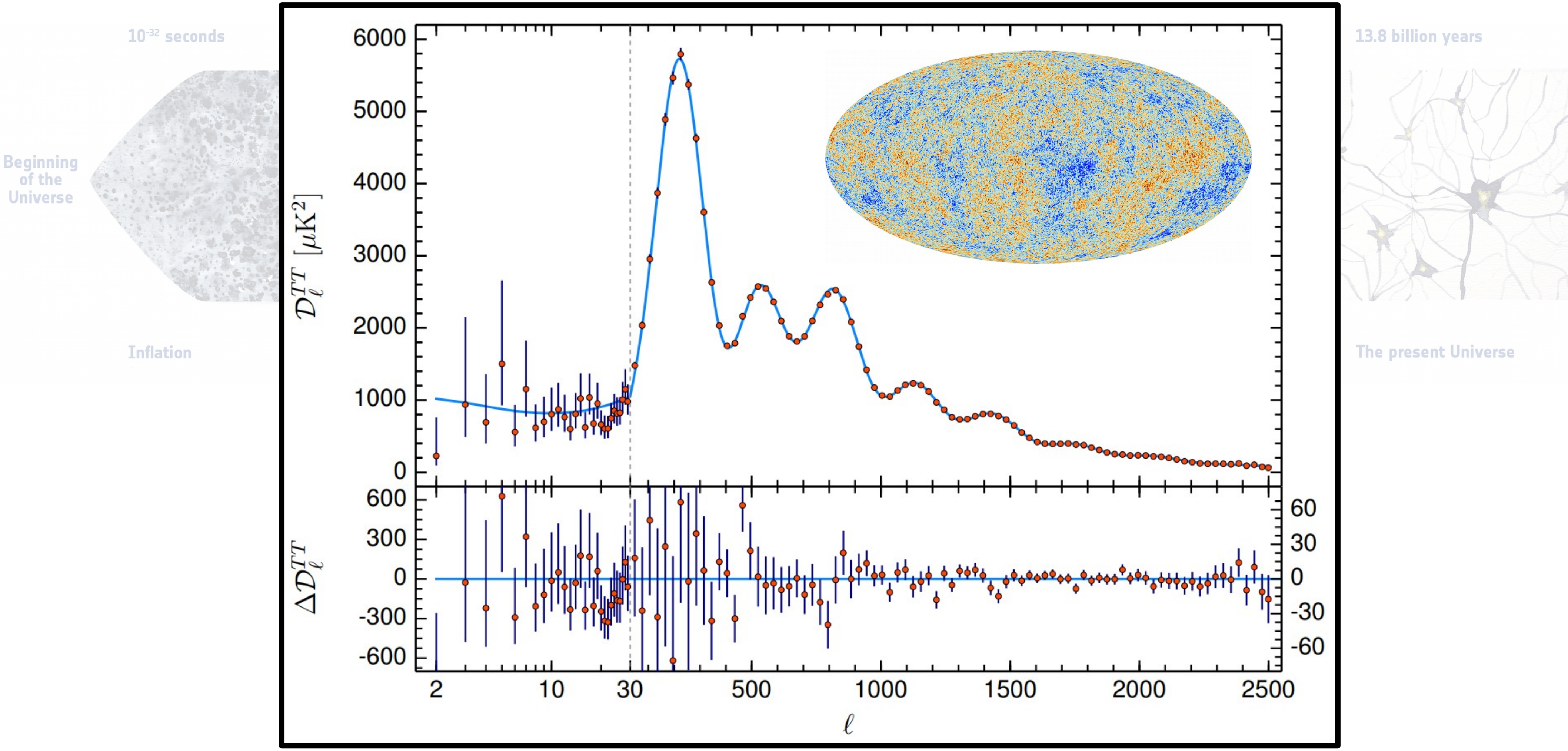

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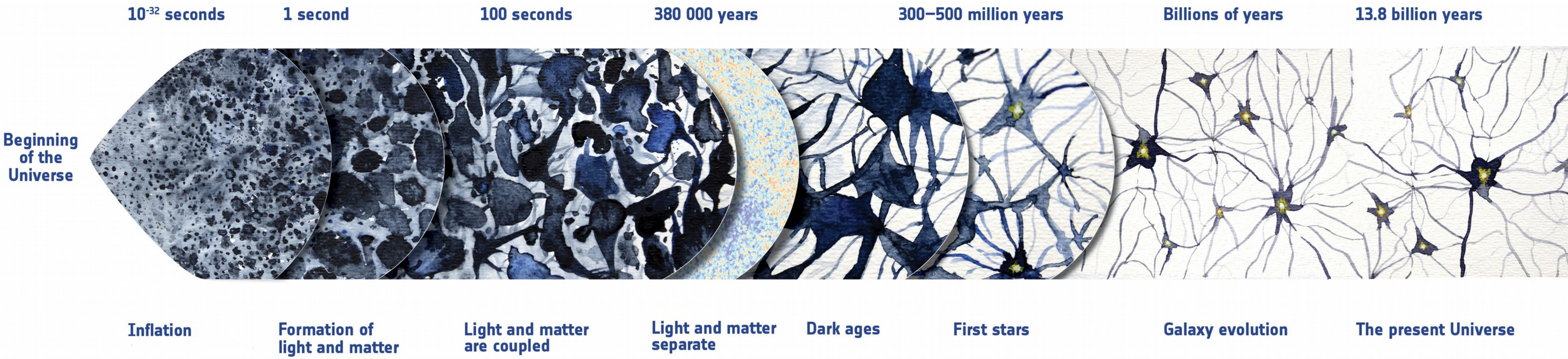

- … but rests on some pillars that are “shrouded in darkness”:
  - Primordial Universe, inflation
  - Dark matter (''CDM'')
  - Dark ages & reionisation
  - Dark energy (''Λ'')
- … and is shaken by some persistent tensions :
  - H_0 discrepancies
  - σ_8 tensions
  - ISW excesses
  - CMB “anomalies”

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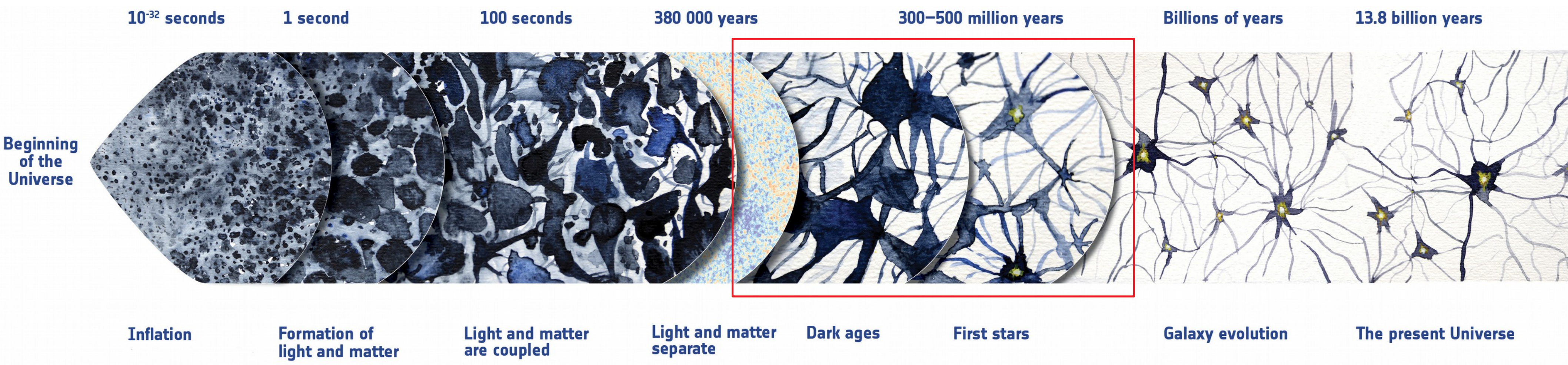

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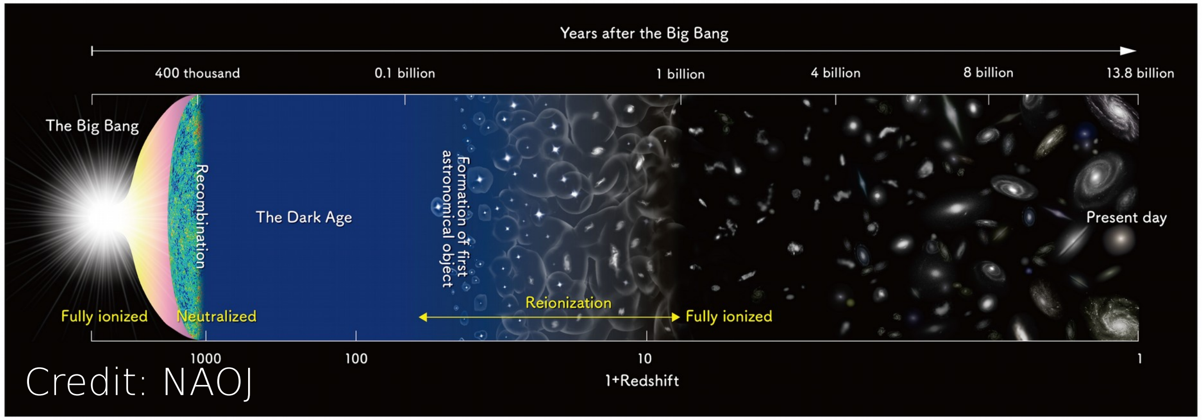

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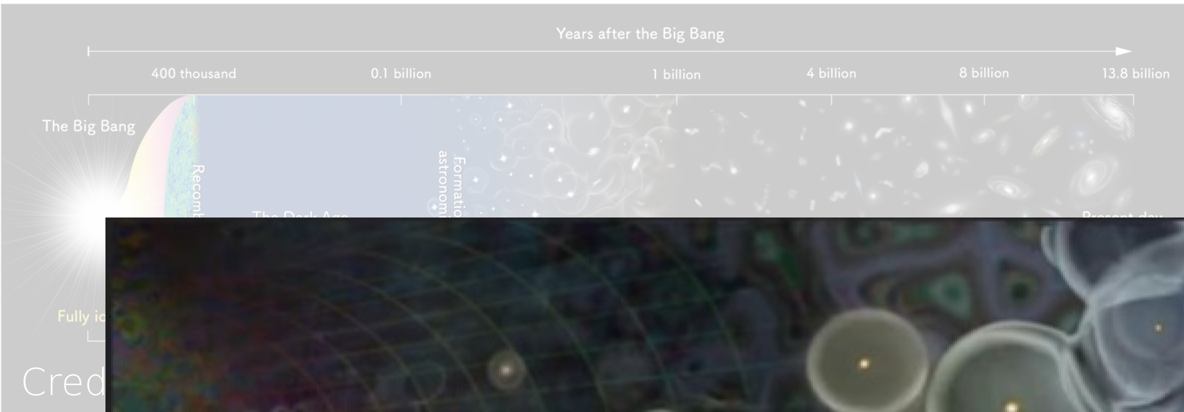

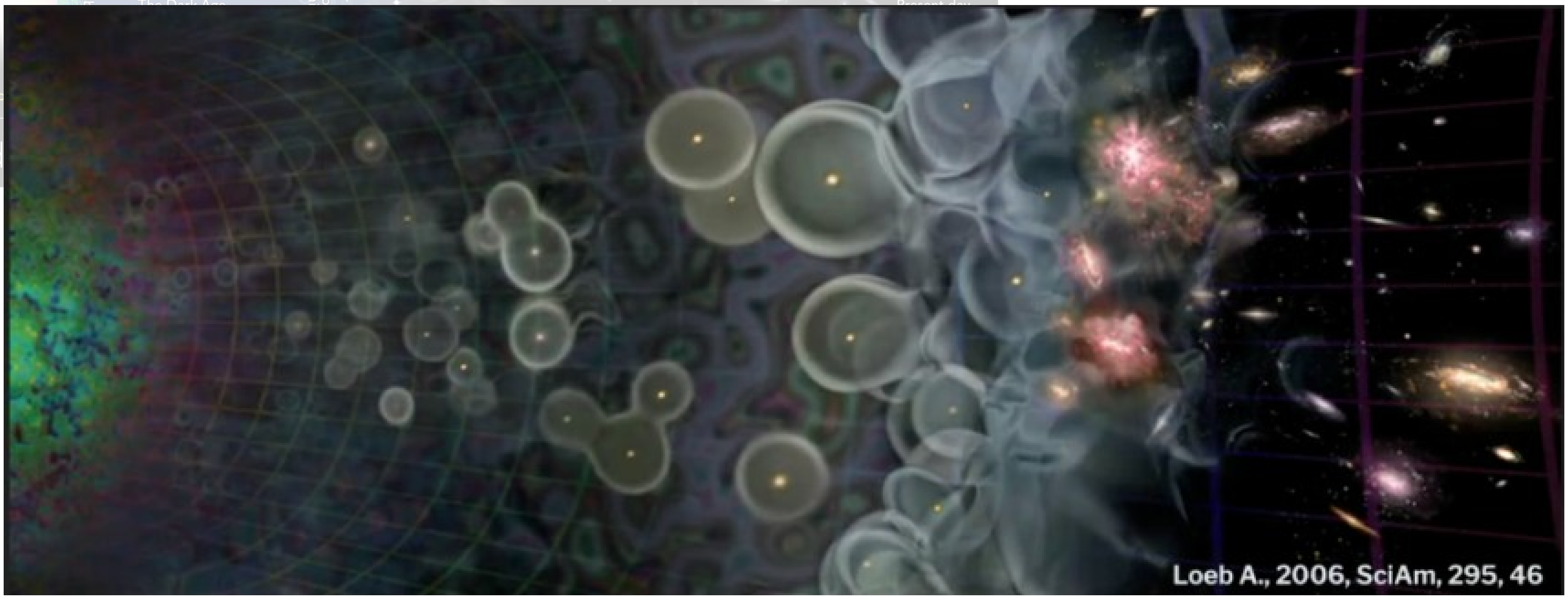

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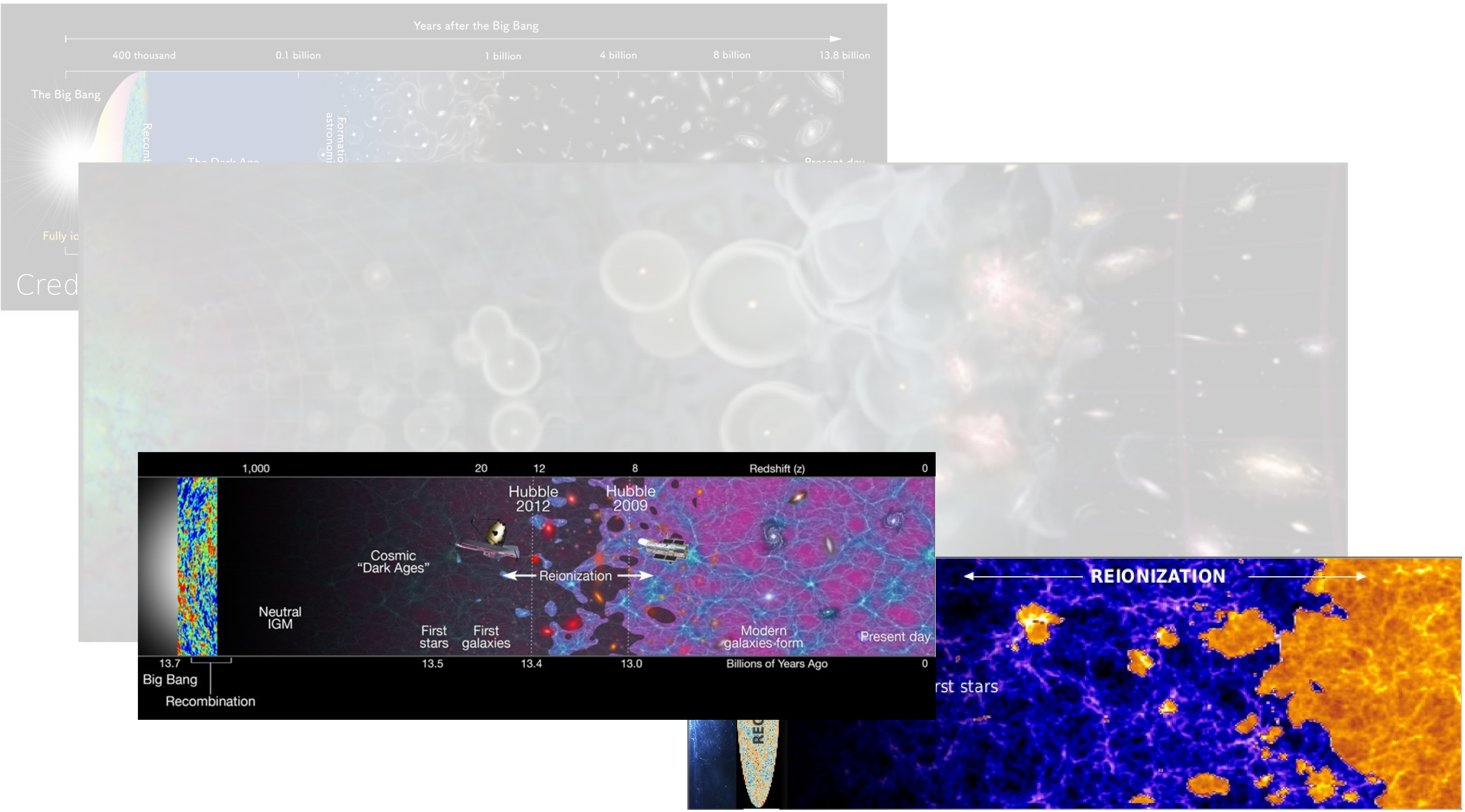

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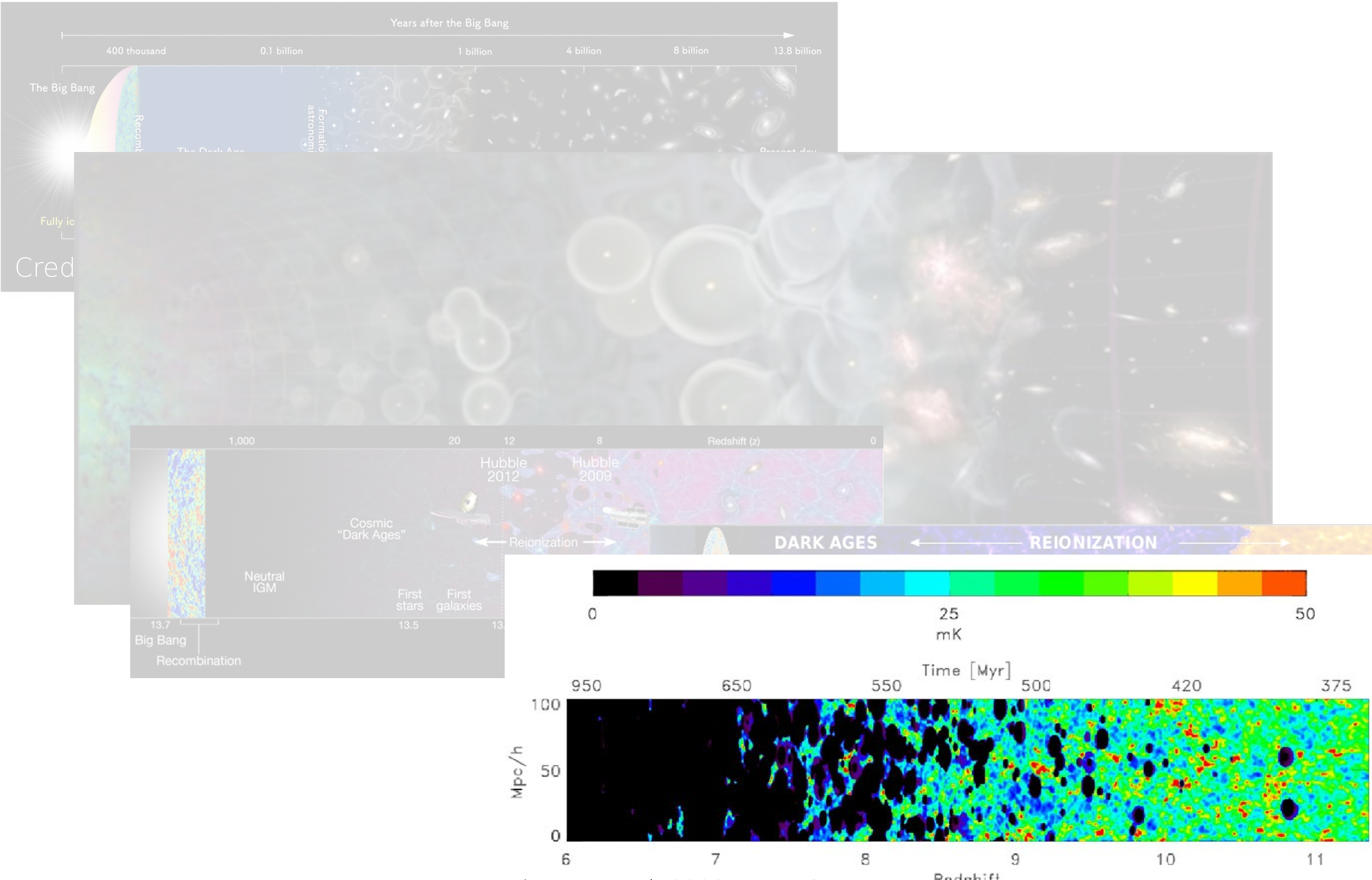

Thomas et al. 2009, MNRAS

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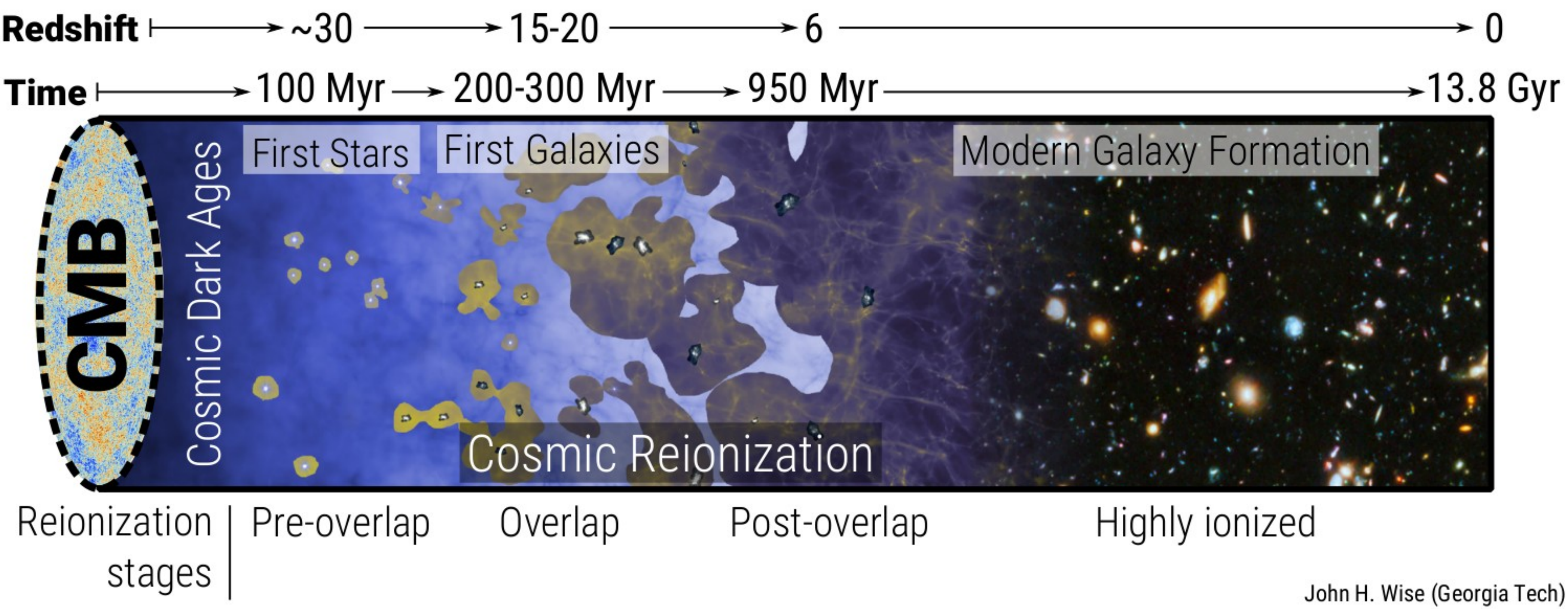

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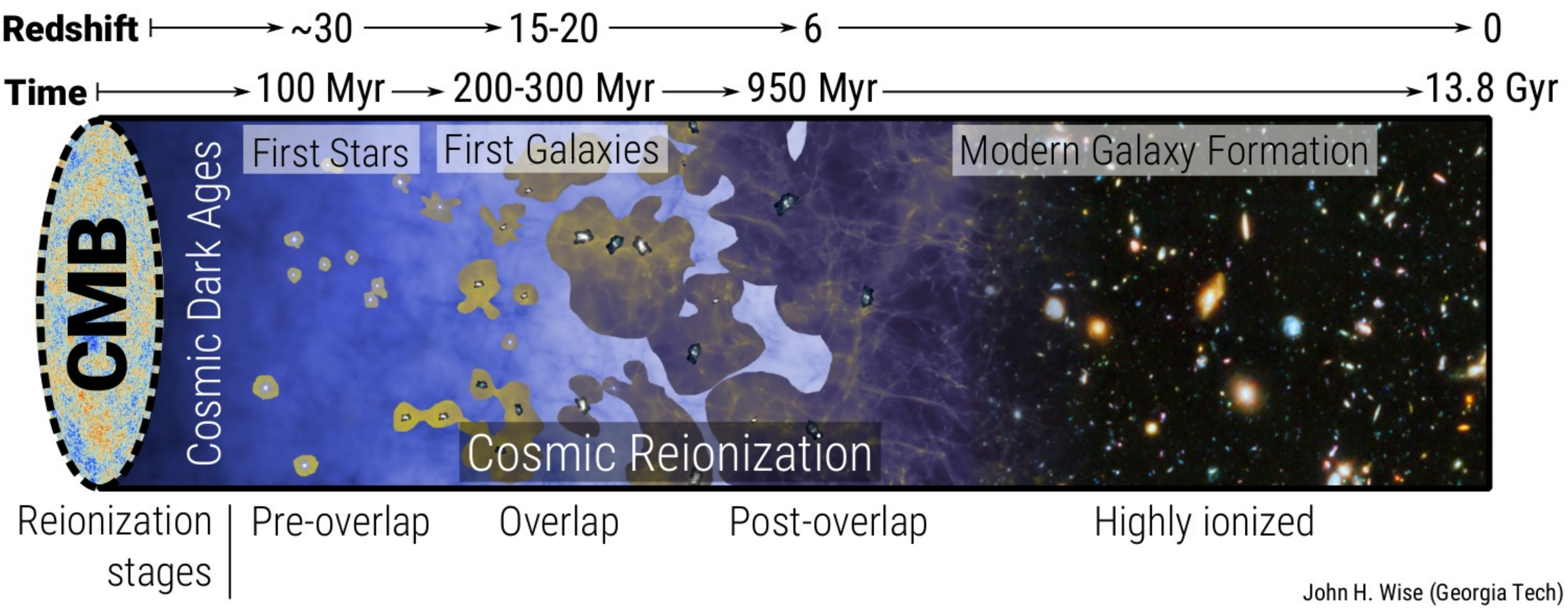
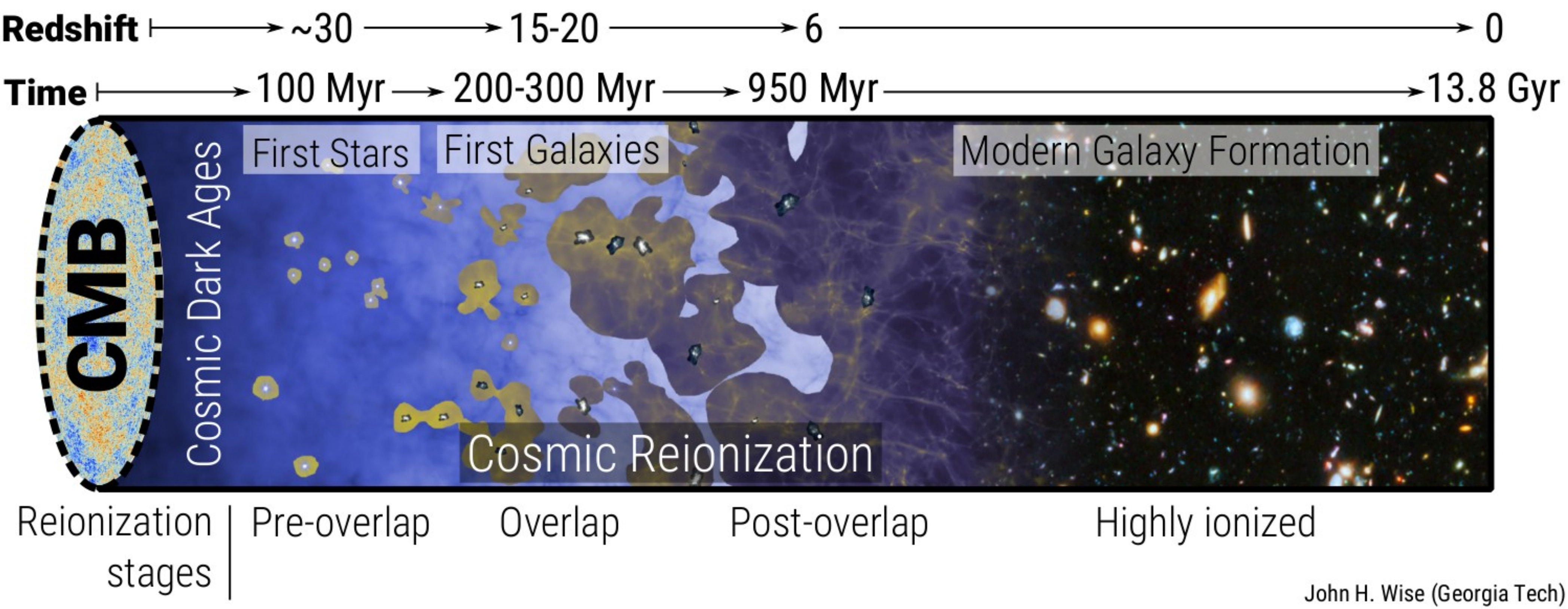
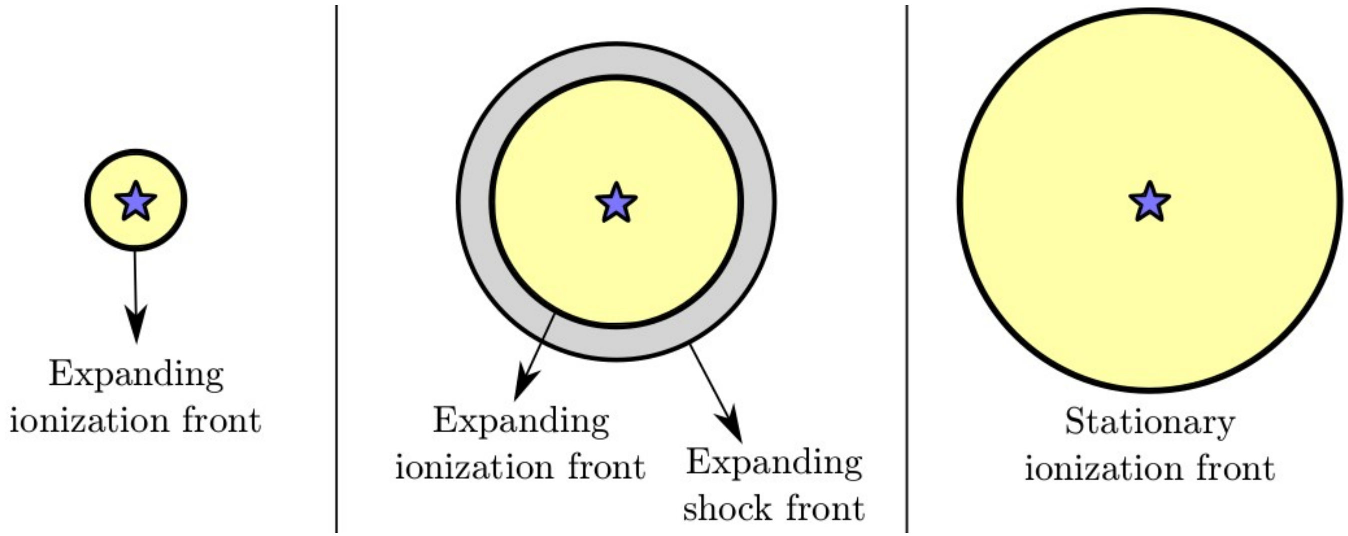


The transition from the neutral intergalactic medium (IGM, H + He) left after the universe recombined at z~1100 to the fully ionized IGM observed today

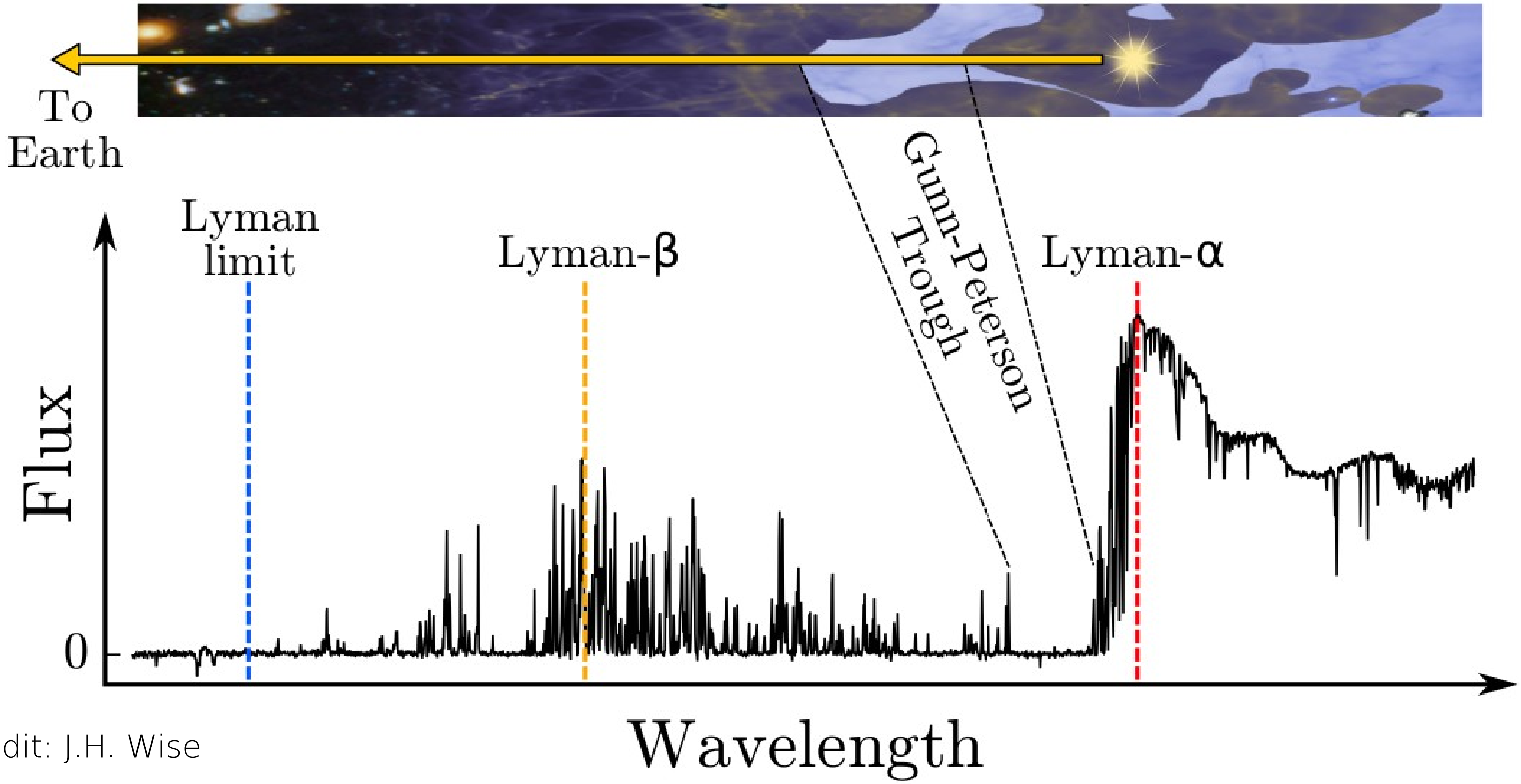
I) The epoch of reionisation





I) The epoch of reionisation

First evidence from distant quasars (Gunn & Peterson 1965)

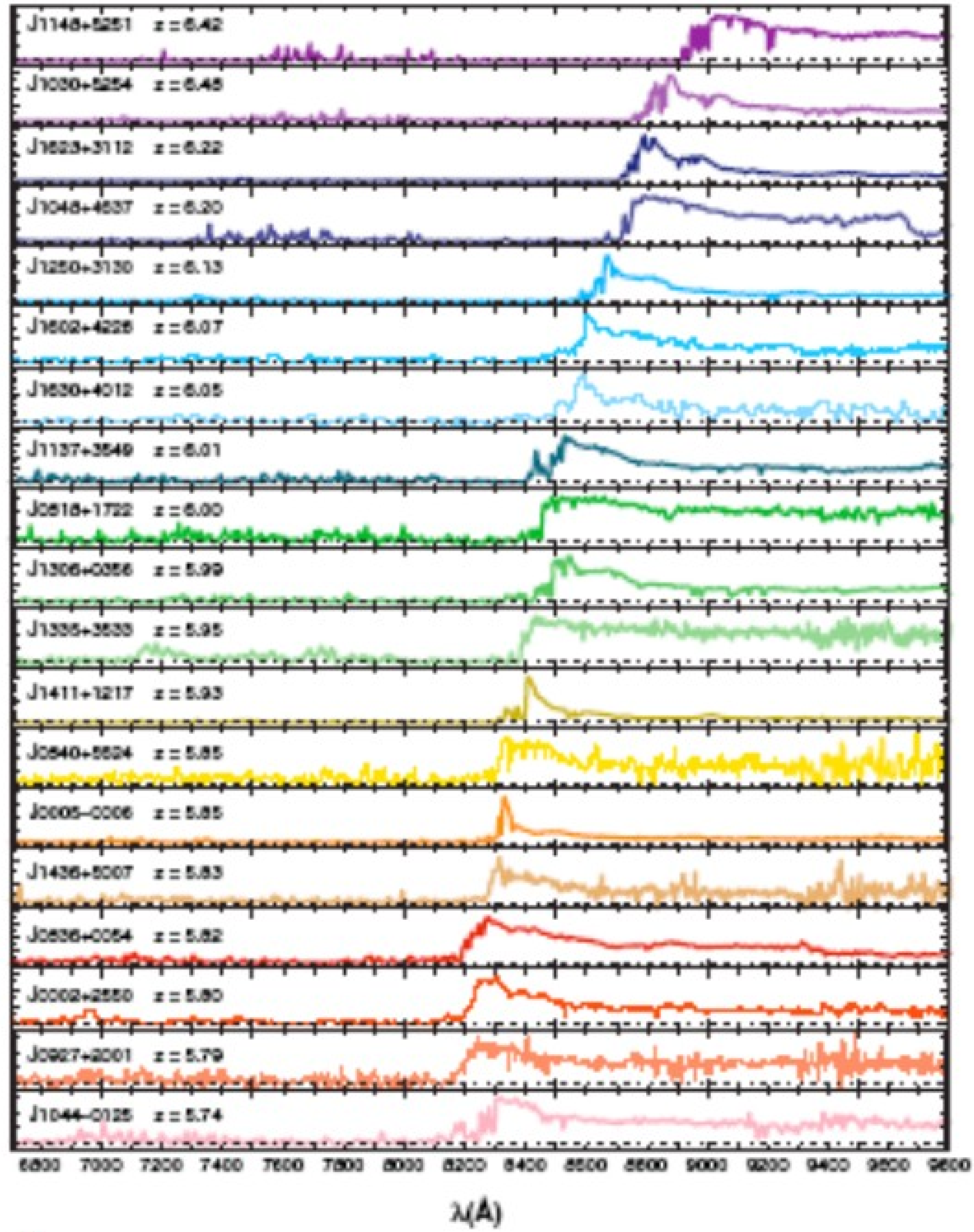


Credit: J.H. Wise

I) The epoch of reionisation

z =

6.42
6.48
6.22
6.20
6.13
6.07
6.05
6.01
6.00
5.99
5.95
5.93
5.85
5.85
5.83
5.82
5.80
5.79
5.74



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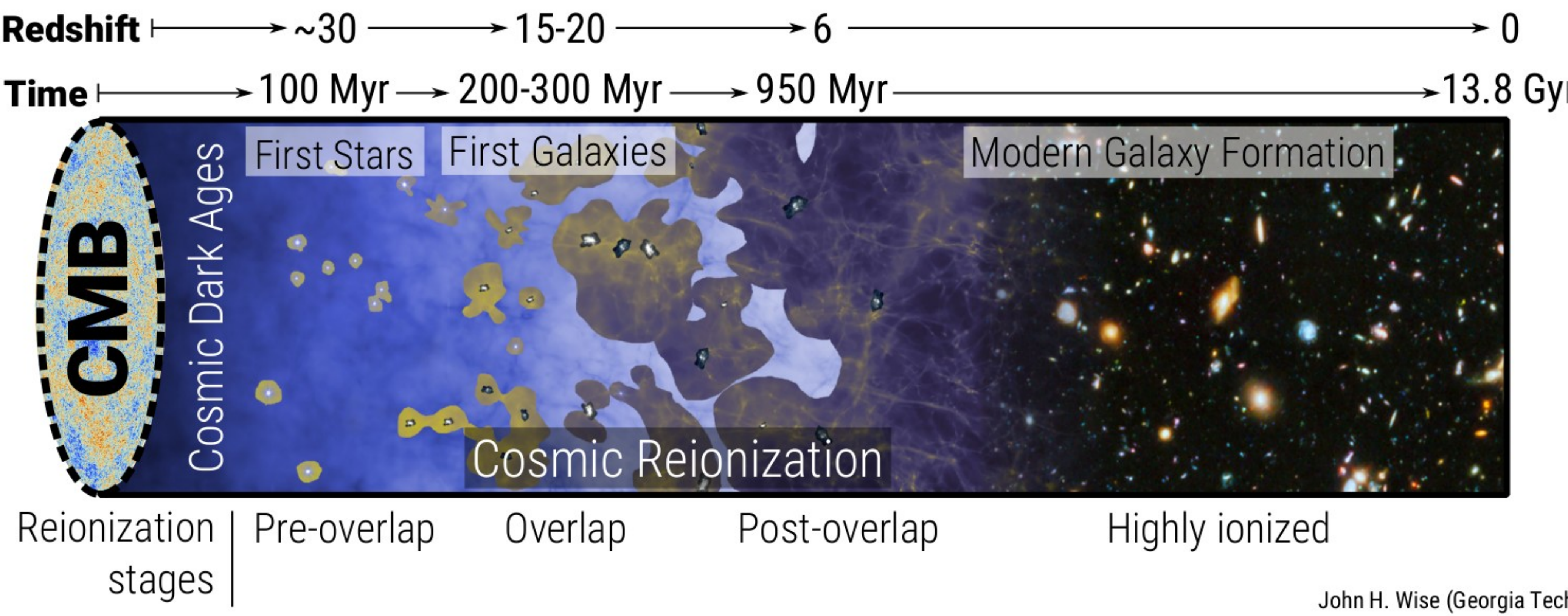

John H. Wise (Georgia Tech)

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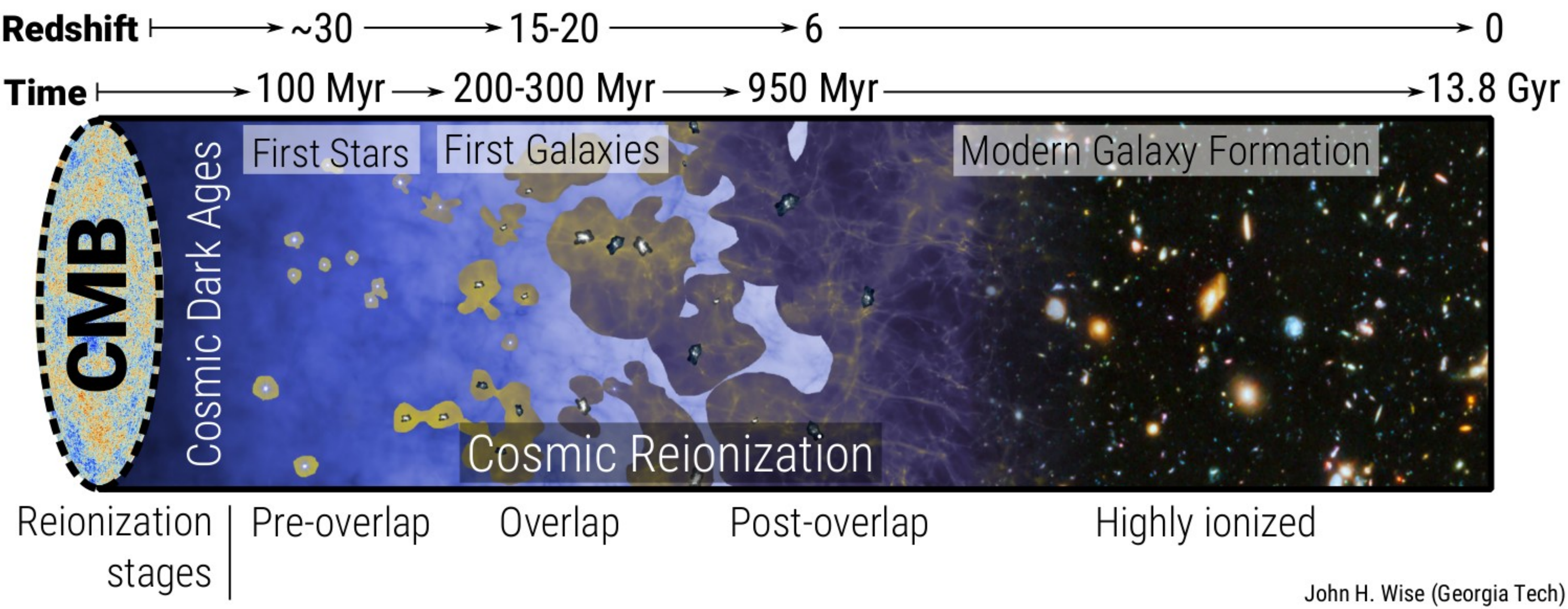

<u>Decades later, still many open questions:</u>

- WHEN: When did it happen? How long did it last?
- WHO: What were the sources responsible?
- HOW: How did it proceed? Was it gradual or sudden?
  What was its topology? Was it homogeneous or patchy?

II) Reionisation & the CMB

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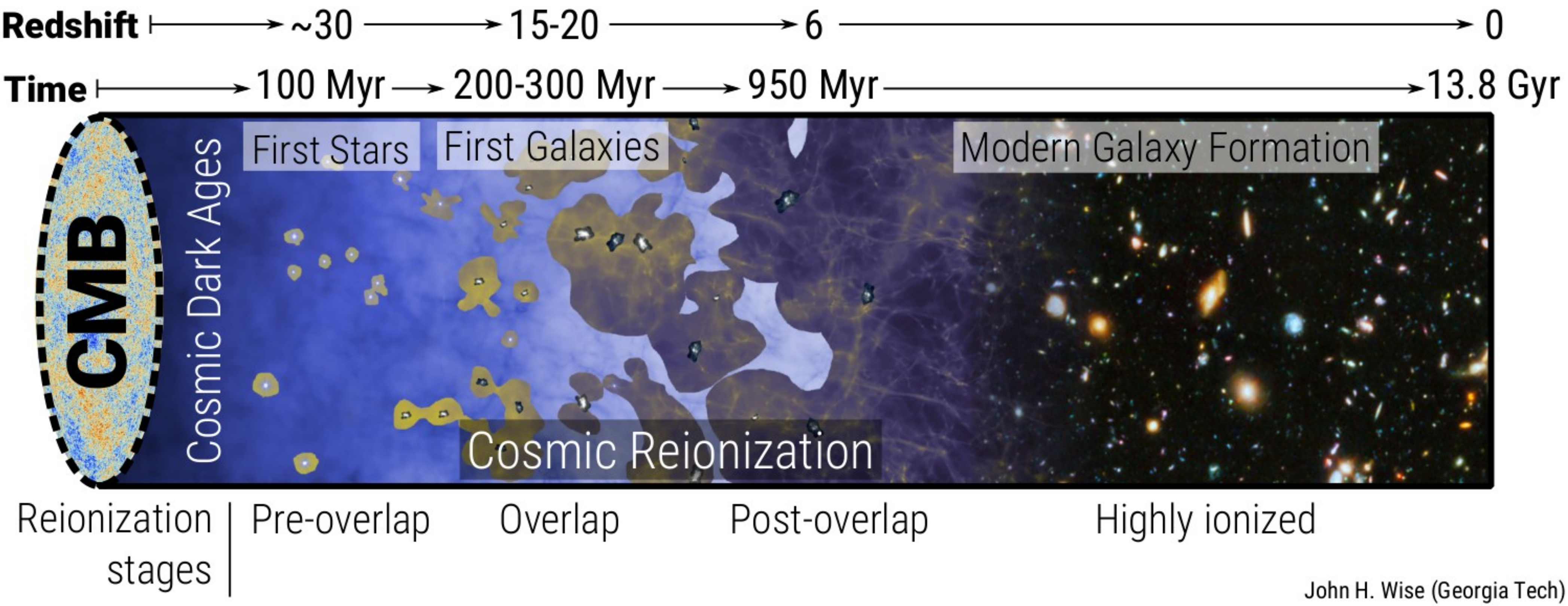

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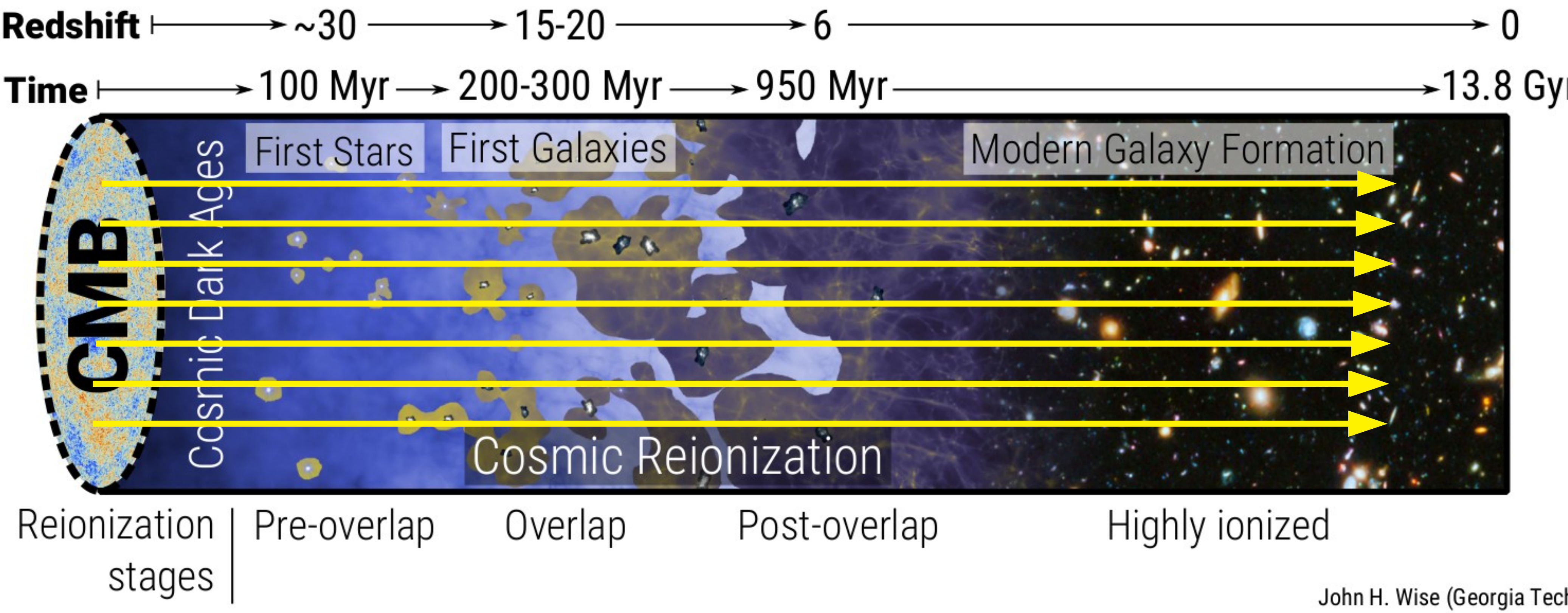

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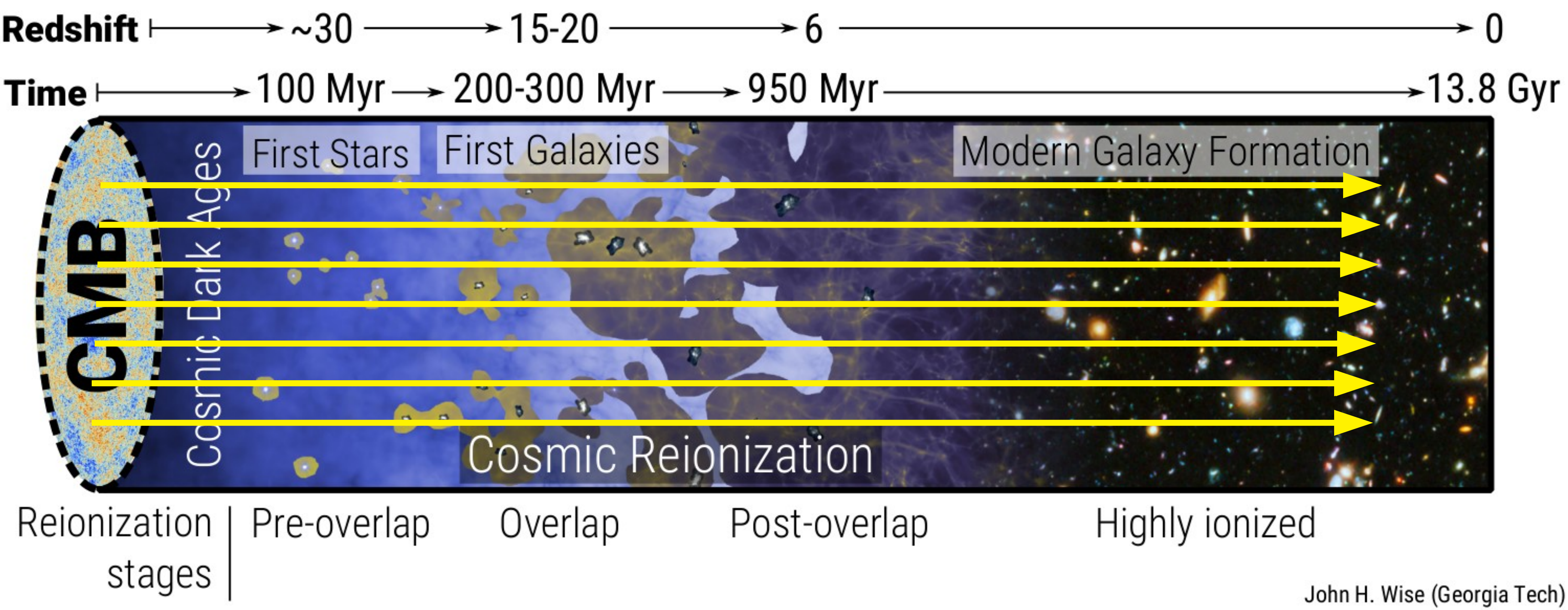

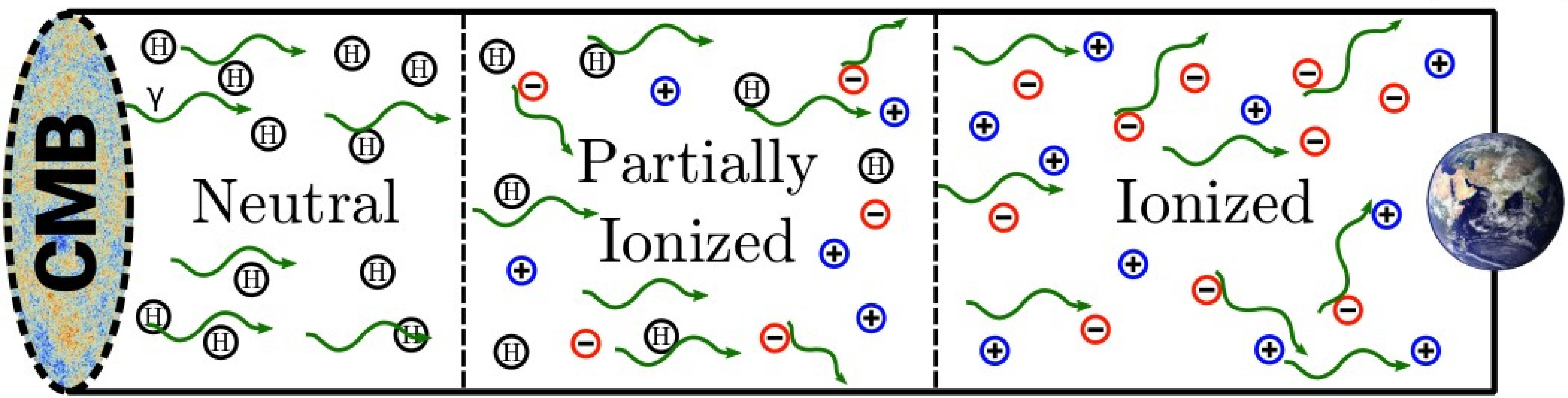

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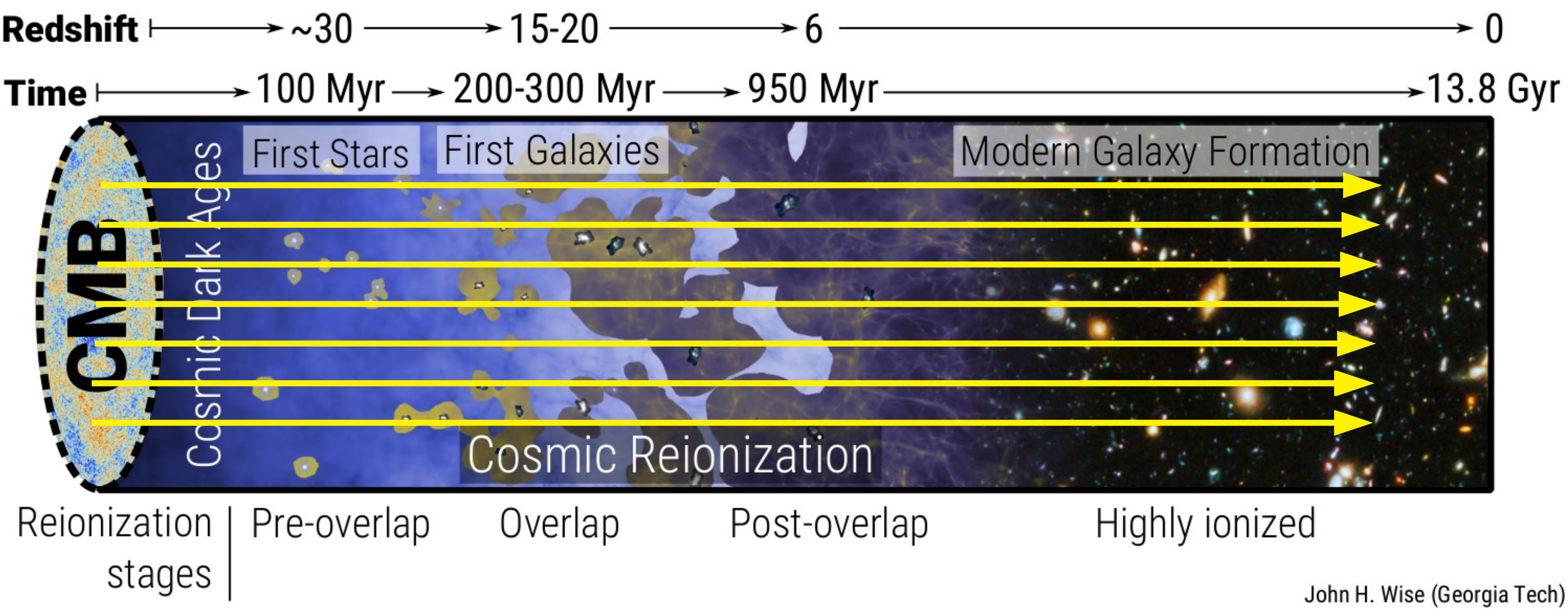

$$\tau = \int_0^{\eta_0} a n_e \sigma_T d\eta$$

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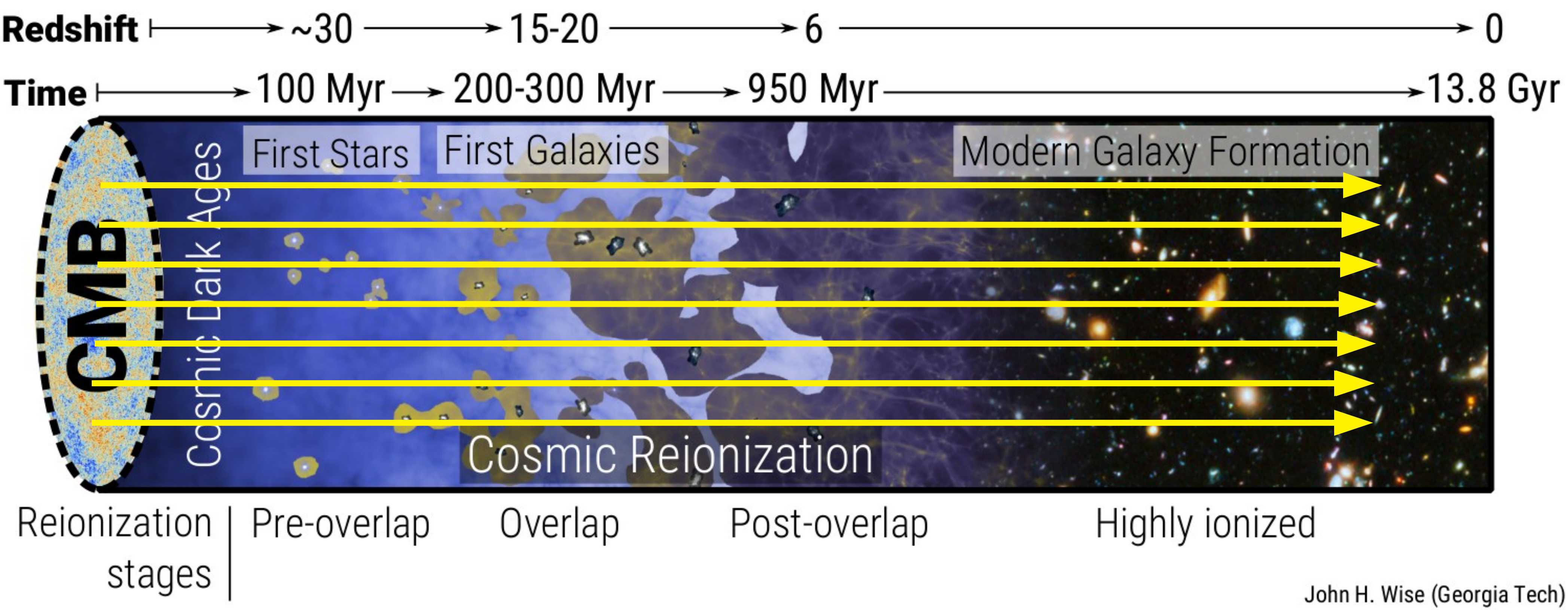

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Earlier and/or longer reionisation → τ++

II) Reionisation & the CMB

Impact on CMB angular power spectra:

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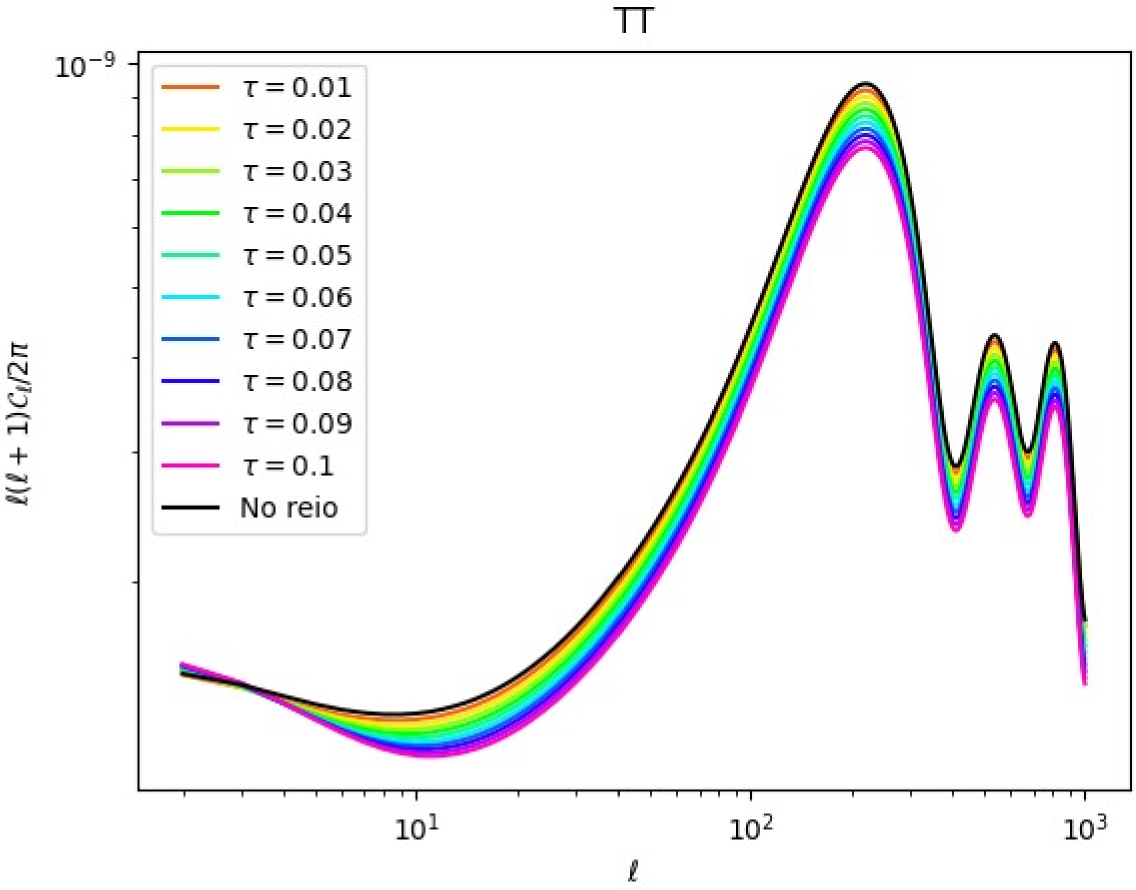

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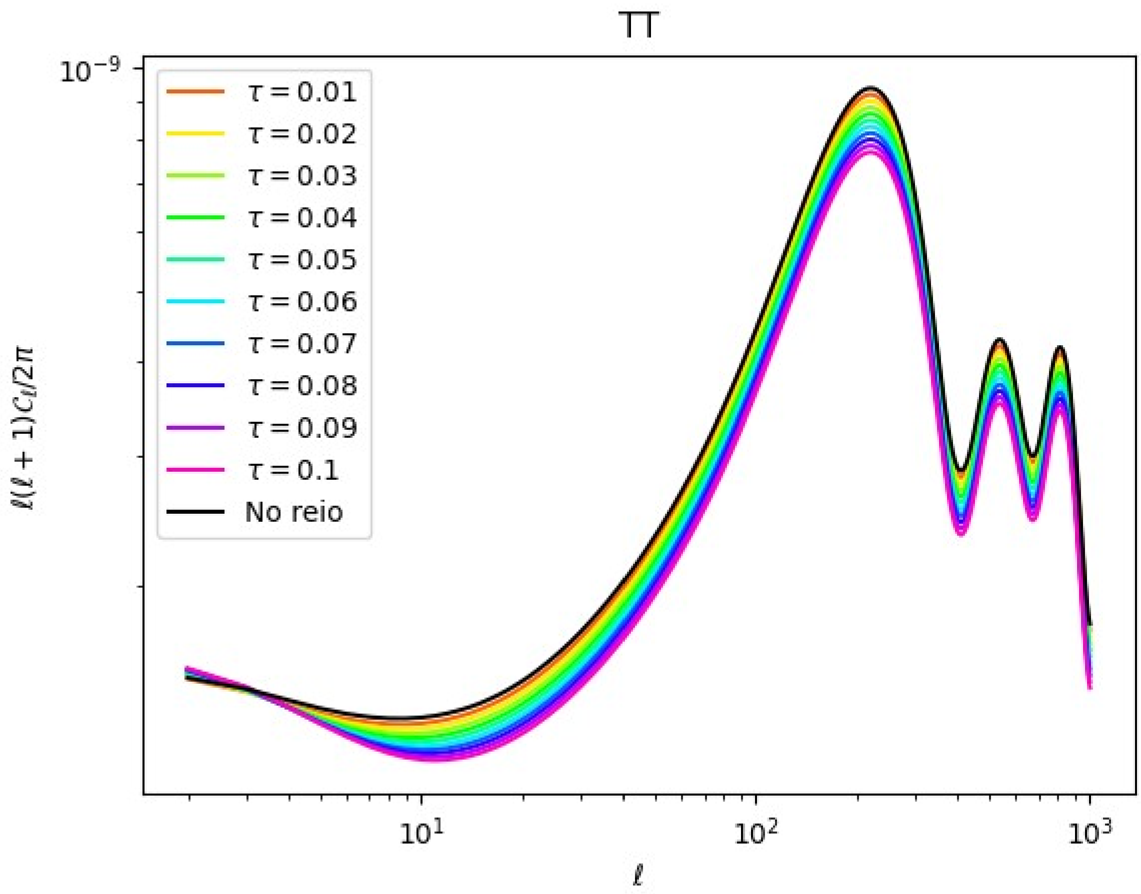

Rescaling A_s by exp(-2τ)

II) Reionisation & the CMB

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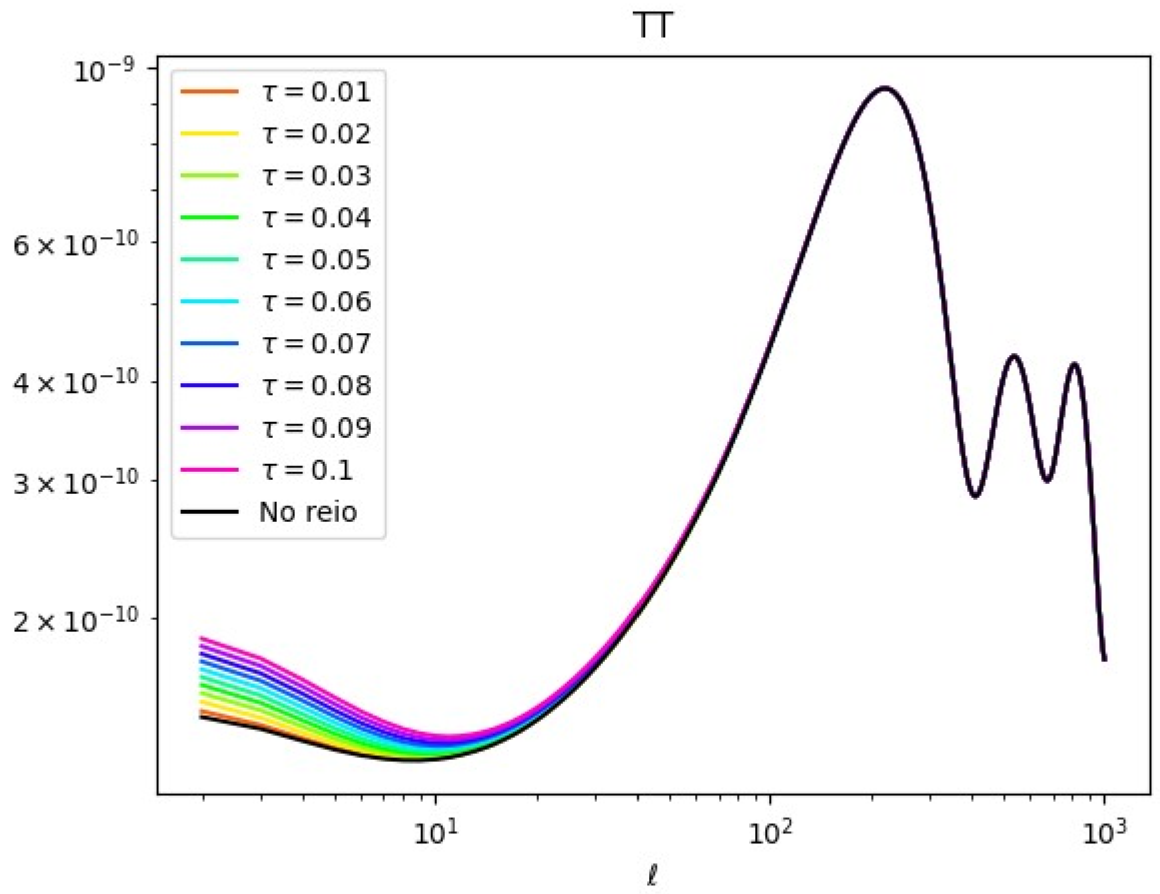

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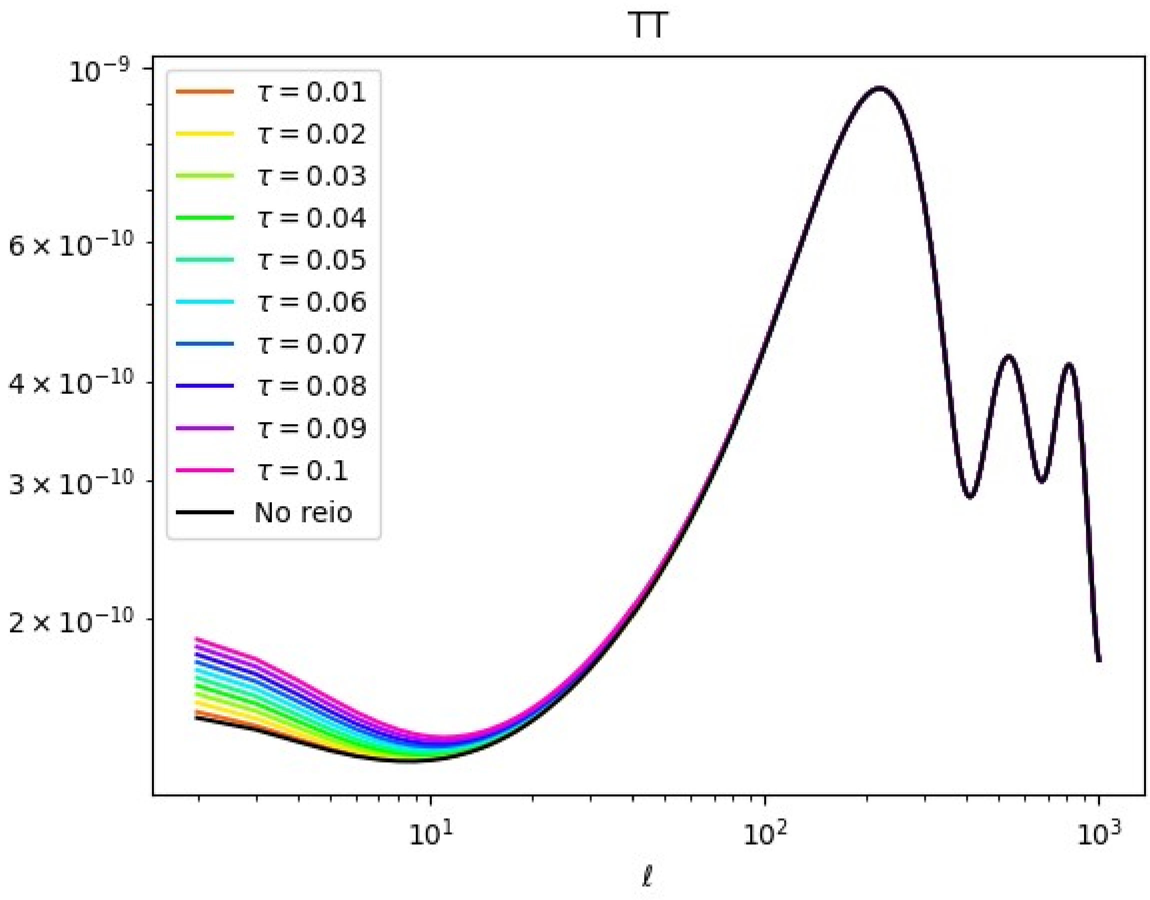

Adds power around scales ~ horizon at scattering time

Rescaling A_s by $\exp(-2\tau)$

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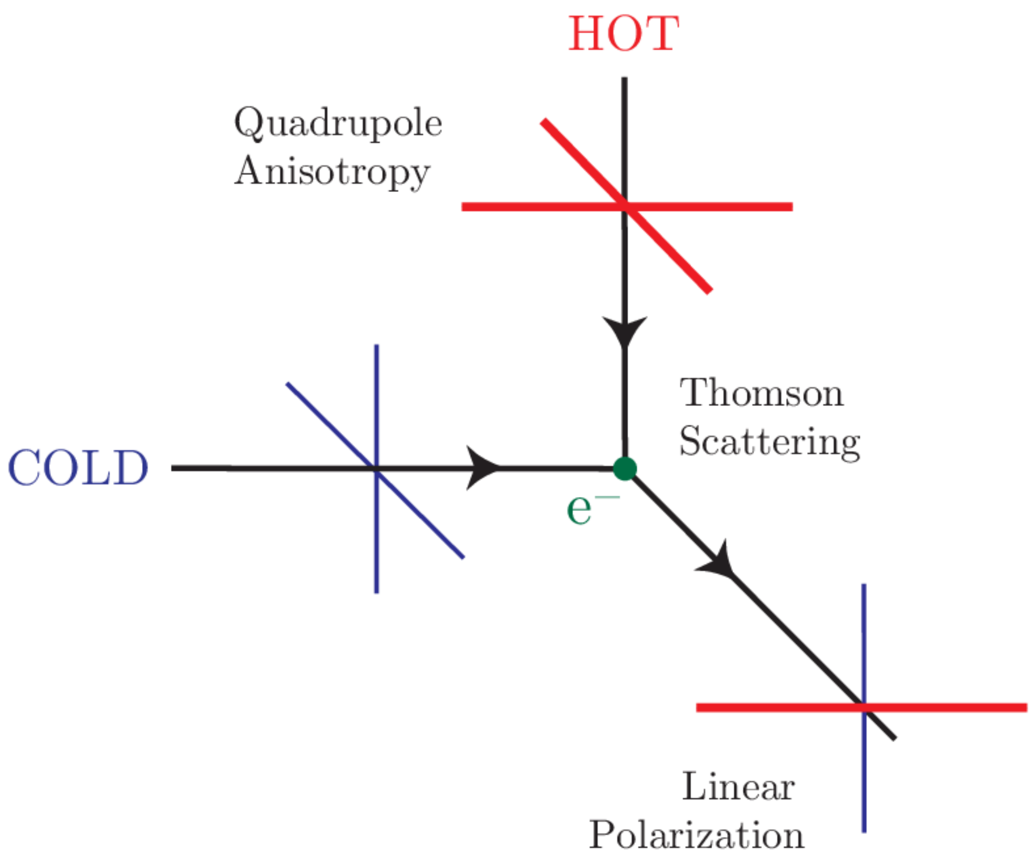

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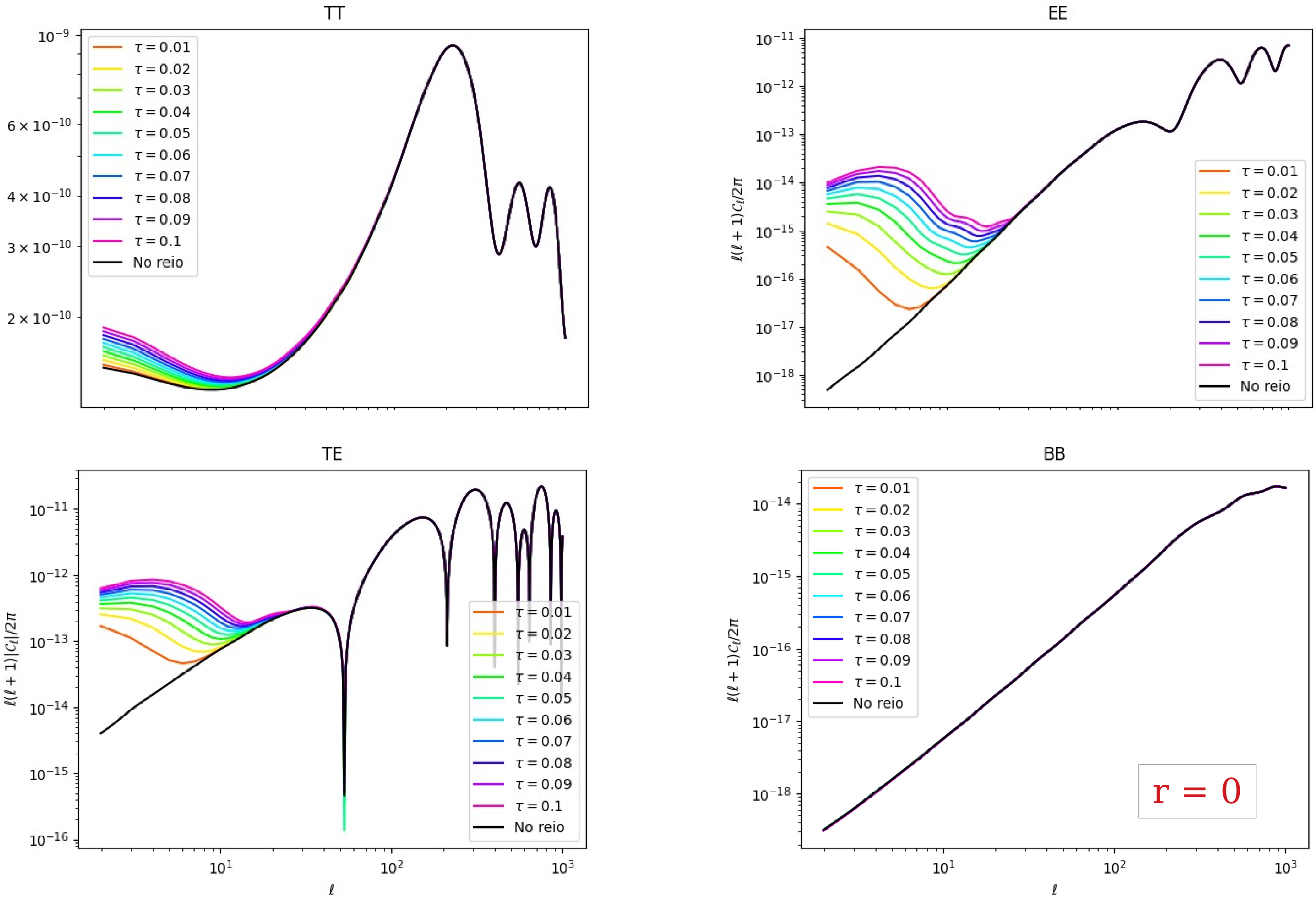

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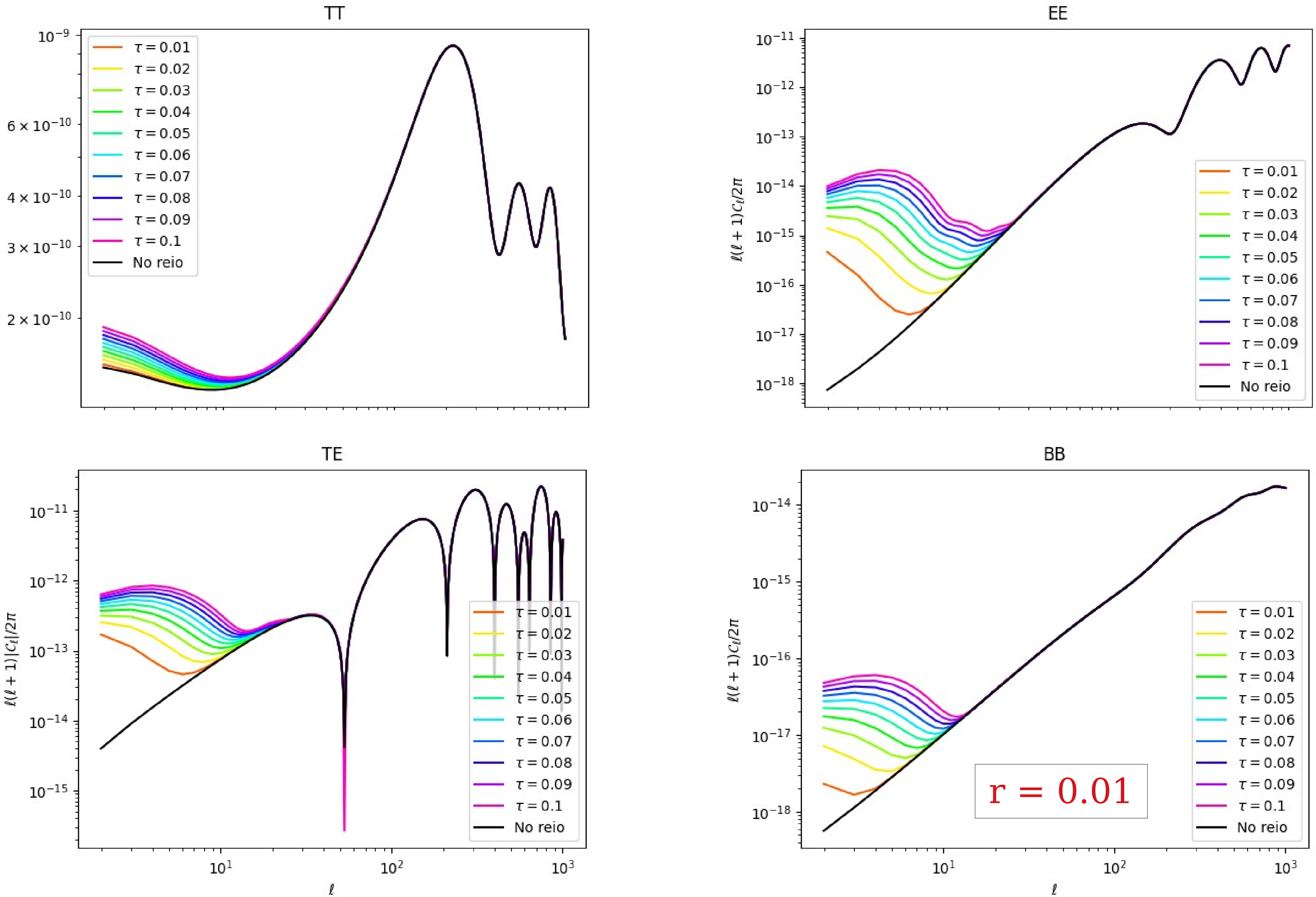


II) Reionisation & the CMB

Phys. Rev. D. 2009

CMB polarization features from inflation versus reionization

Michael J. Mortonson,[1,2,*] Cora Dvorkin,[1,2,†] Hiranya V. Peiris,[3,‡] and Wayne Hu[4,2,§]

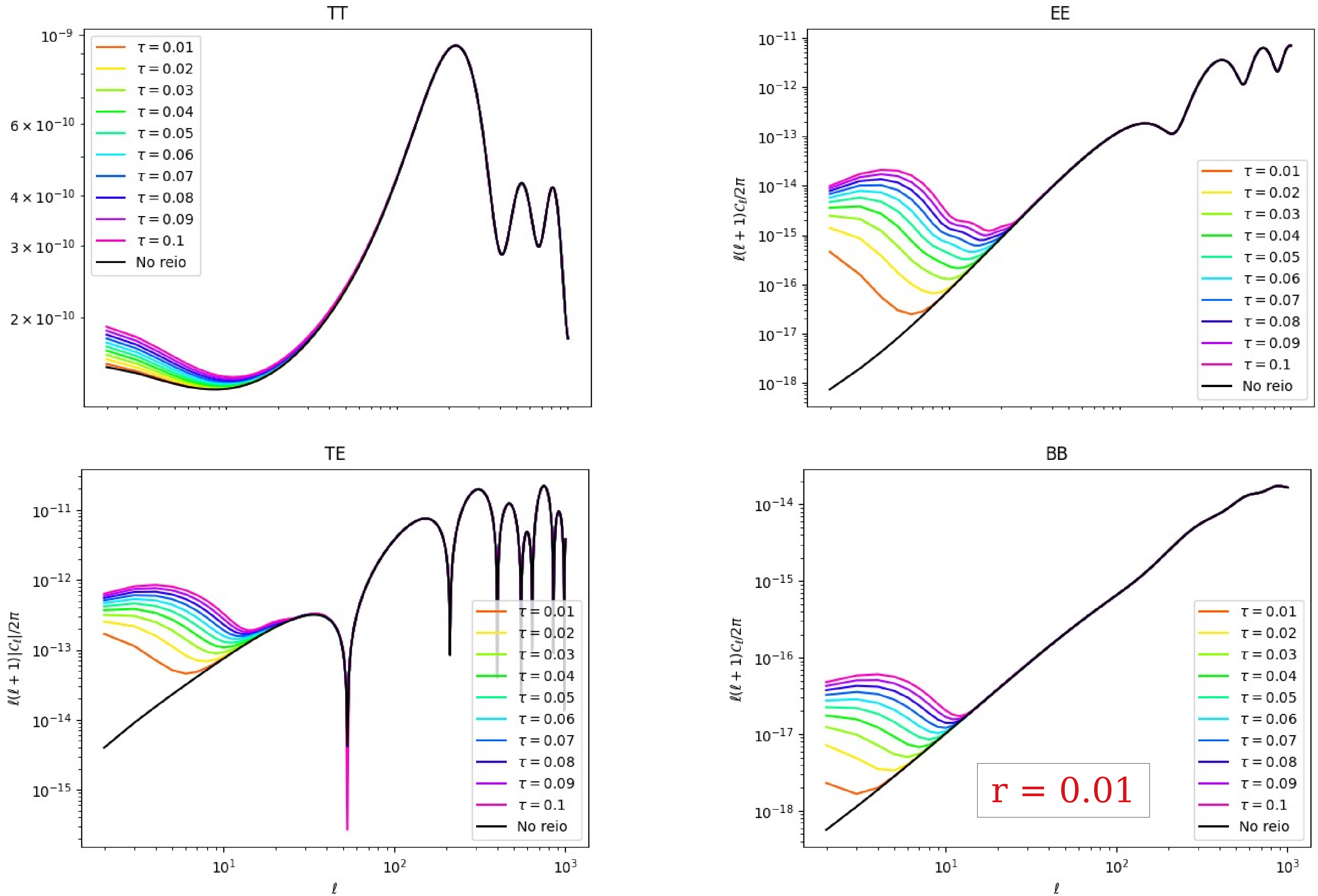
[1]*Department of Physics, University of Chicago, Chicago IL 60637*
[2]*Kavli Institute for Cosmological Physics and Enrico Fermi Institute, University of Chicago, Chicago IL 60637, U.S.A.*
[3]*Institute of Astronomy, University of Cambridge, Cambridge CB3 0HA, U.K.*
[4]*Department of Astronomy & Astrophysics, University of Chicago, Chicago IL 60637*

(Dated: November 5, 2018)

The angular power spectrum of the cosmic microwave background temperature anisotropy observed by WMAP has an anomalous dip at $\ell \sim 20$ and bump at $\ell \sim 40$. One explanation for this structure is the presence of features in the primordial curvature power spectrum, possibly caused by a step in the inflationary potential. The detection of these features is only marginally significant from temperature data alone. However, the inflationary feature hypothesis predicts a specific shape for the E-mode polarization power spectrum with a structure similar to that observed in temperature at $\ell \sim 20-40$. Measurement of the CMB polarization on few-degree scales can therefore be used as a consistency check of the hypothesis. The Planck satellite has the statistical sensitivity to confirm or rule out the model that best fits the temperature features with 3 σ significance, assuming all other parameters are known. With a cosmic variance limited experiment, this significance improves to 8 σ. For tests of inflationary models that can explain both the dip and bump in temperature, the primary source of uncertainty is confusion with polarization features created by a complex reionization history, which at most reduces the significance to 2.5 σ for Planck and $5-6$ σ for an ideal experiment. Smoothing of the polarization spectrum by a large tensor component only slightly reduces the ability of polarization to test for inflationary features, as does requiring that polarization is consistent with the observed temperature spectrum given the expected low level of TE correlation on few-degree scales. If polarized foregrounds can be adequately subtracted, Planck will supply valuable evidence for or against features in the primordial power spectrum. A future high-sensitivity polarization satellite would enable a decisive test of the feature hypothesis and provide complementary information about the shape of a possible step in the inflationary potential.

II) Reionisation & the CMB

Impact on CMB angular power spectra:



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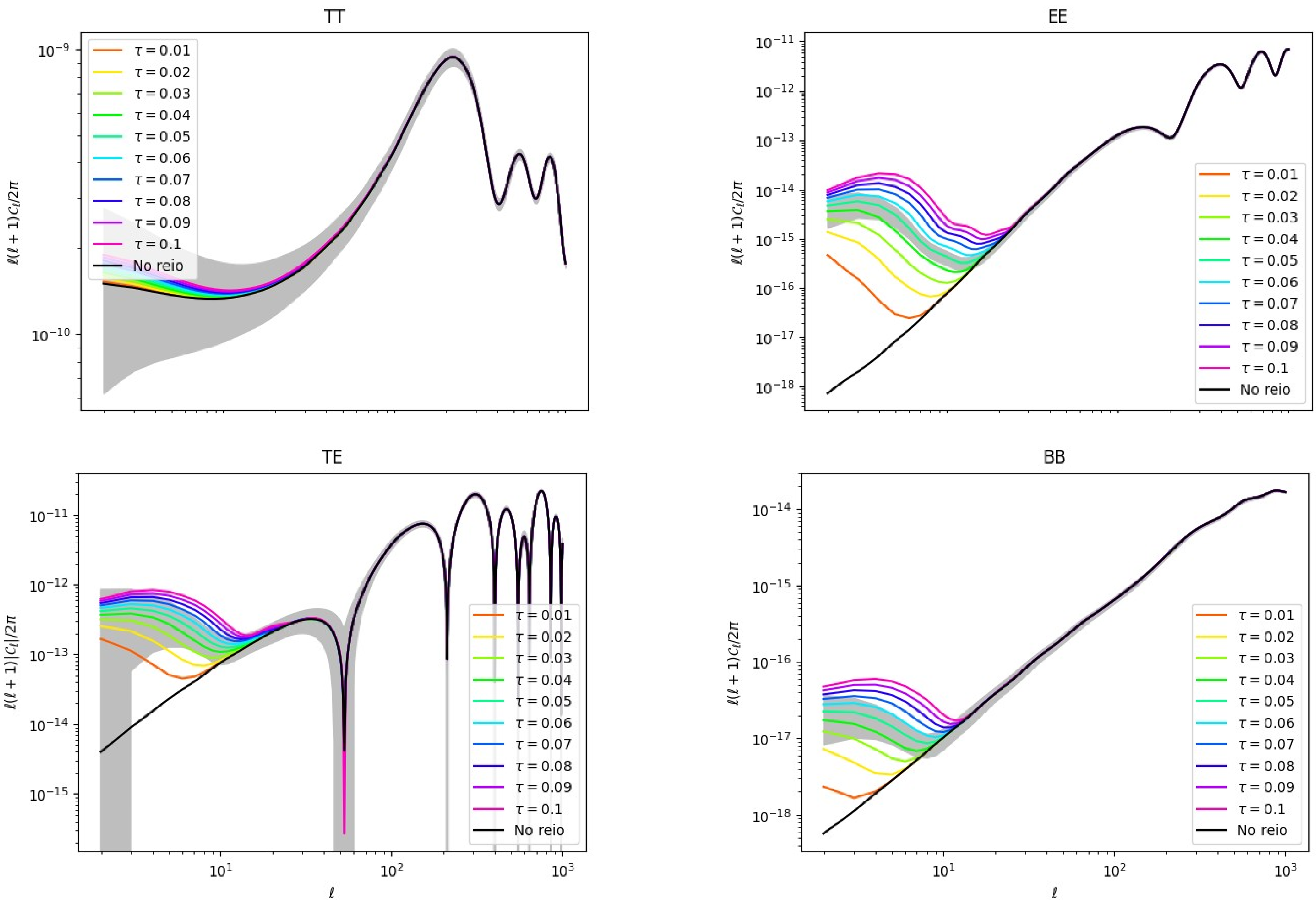

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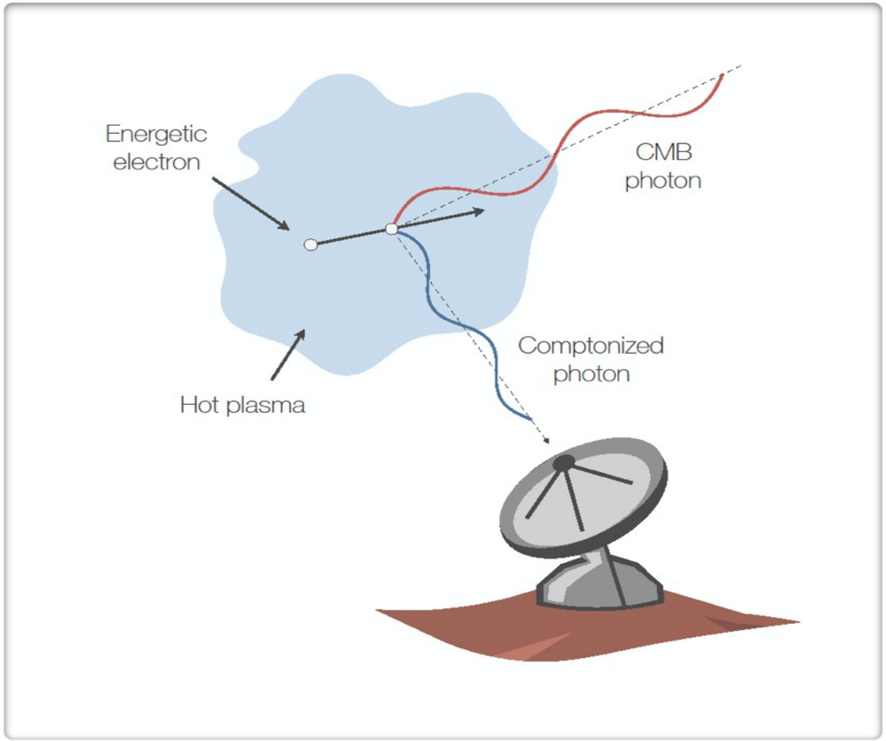
Impact on CMB:

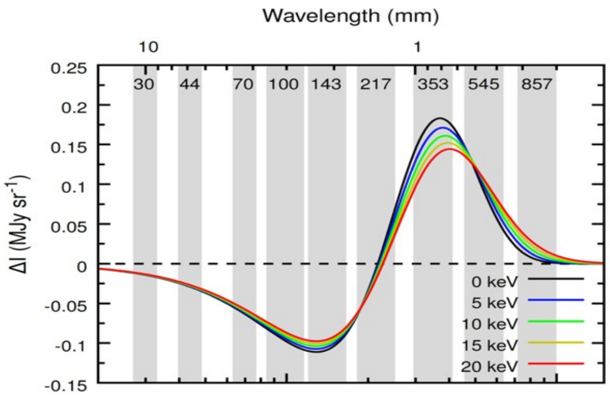
- suppression of power at high multipoles
  (degeneracy with other cosmological parameters – and foregrounds)

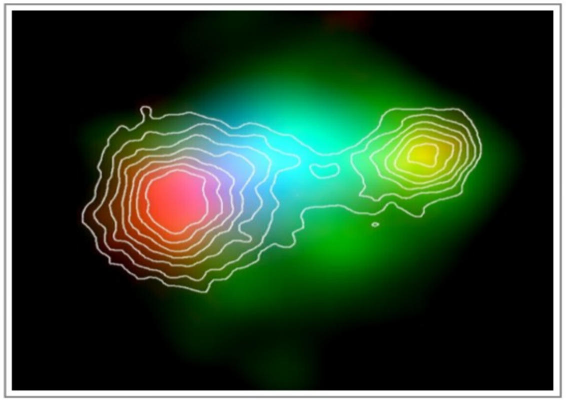
- new anisotropies at large angular scale
  (horizon has grown to a much larger size)

II) Reionisation & the CMB

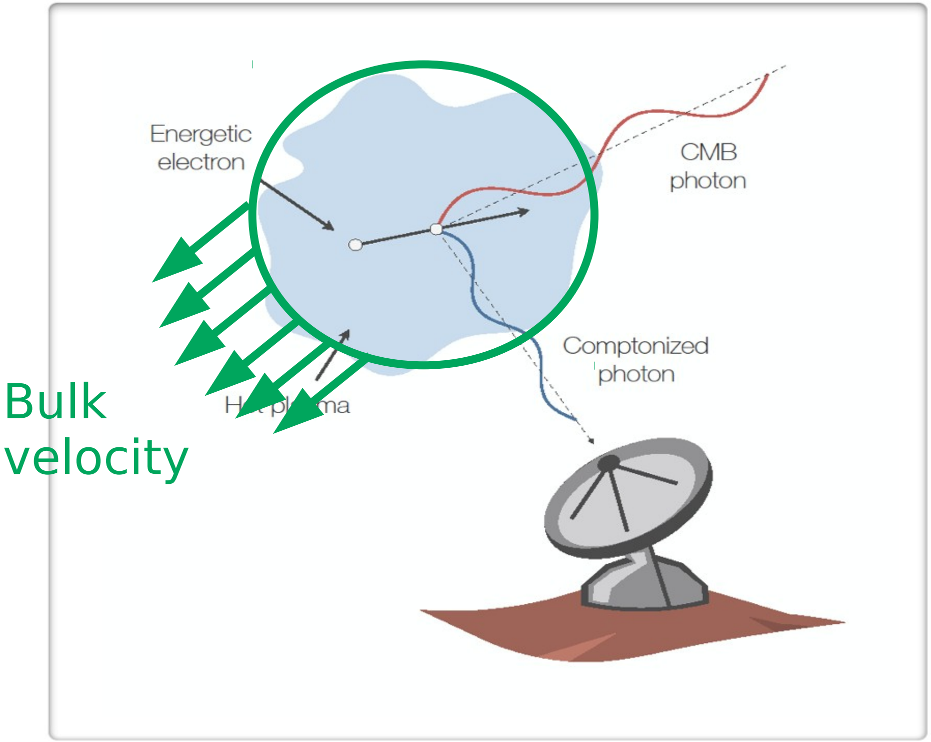
(Thermal) Sunyaev-Zel'dovich effect







Kinetic Sunyaev-Zel’dovich (kSZ) effect



Bulk velocity of free electrons relative to the CMB introduces a Doppler shift to the scattered photons

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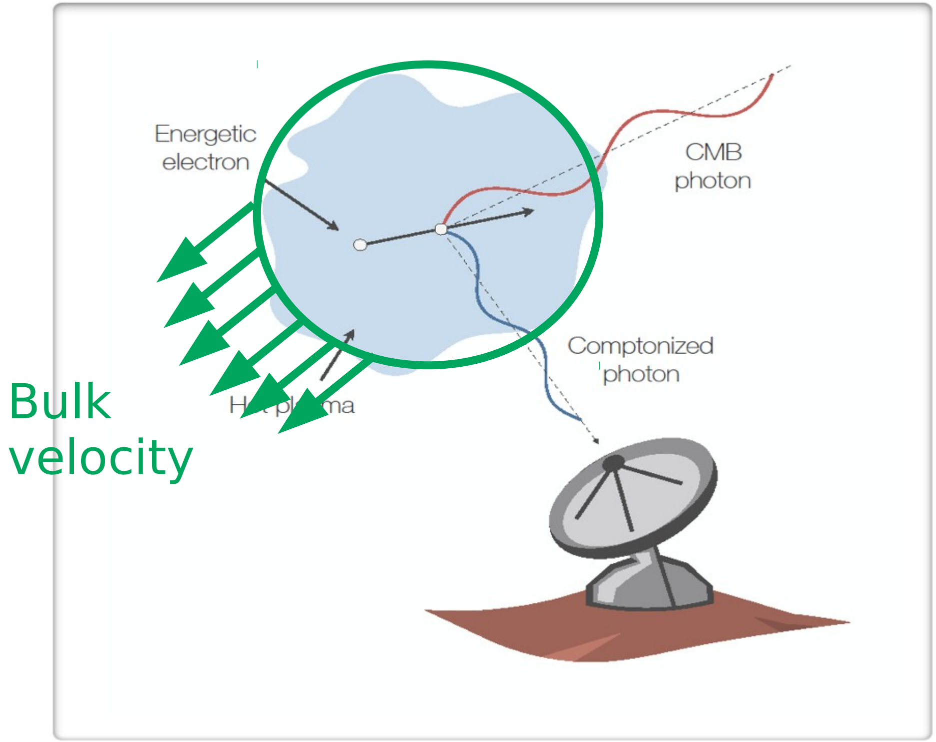

Bulk velocity of free electrons relative to the CMB introduces a Doppler shift to the scattered photons

Commonly divided into two components:

- homogeneous kSZ, sourced by density perturbations of the late, fully ionised Universe
- patchy kSZ, sourced by ionization perturbations during reionisation

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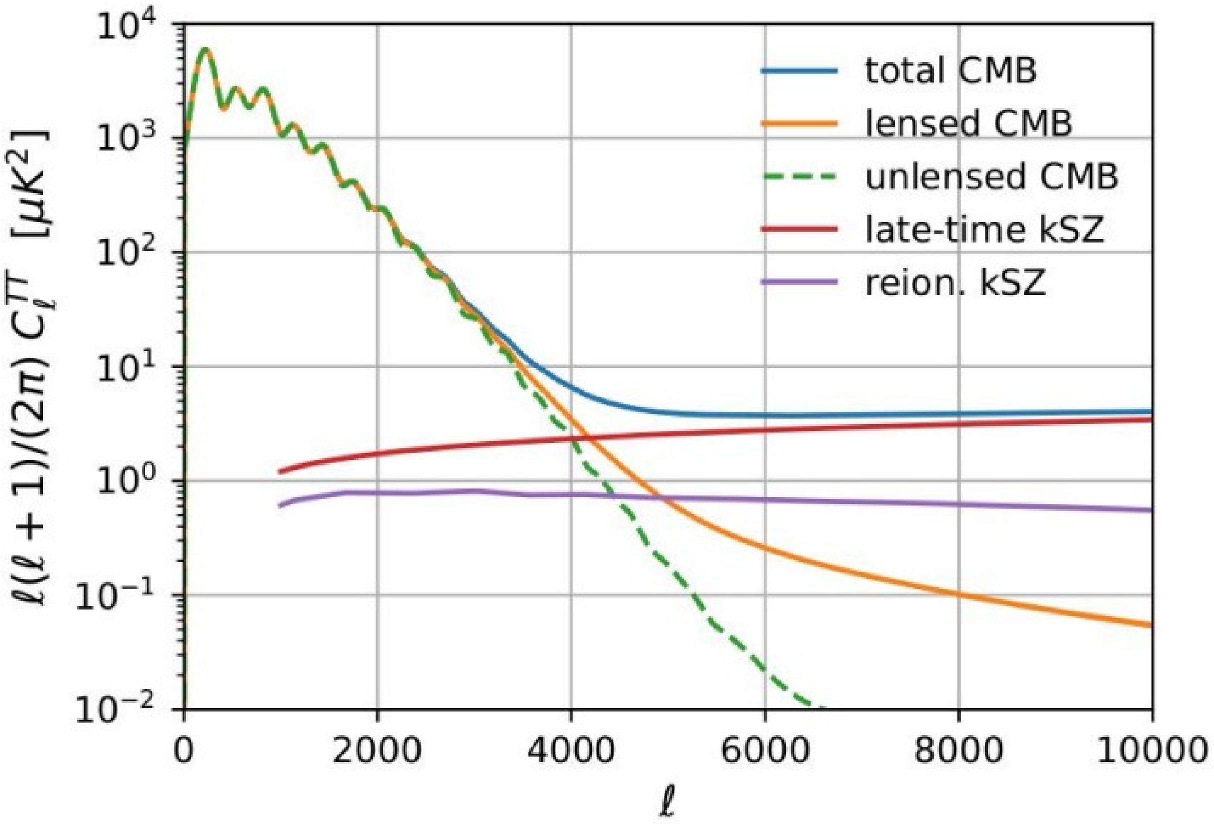

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  (horizon has grown to a much larger size)

- kinetic Sunyaev-Zel'dovich effect
  (small scale re-scattering of photons off newly liberated electrons)

III) How to model the EoR

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$$\tau = \int_0^{\eta_0} a n_e \sigma_T d\eta$$

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Free electron density

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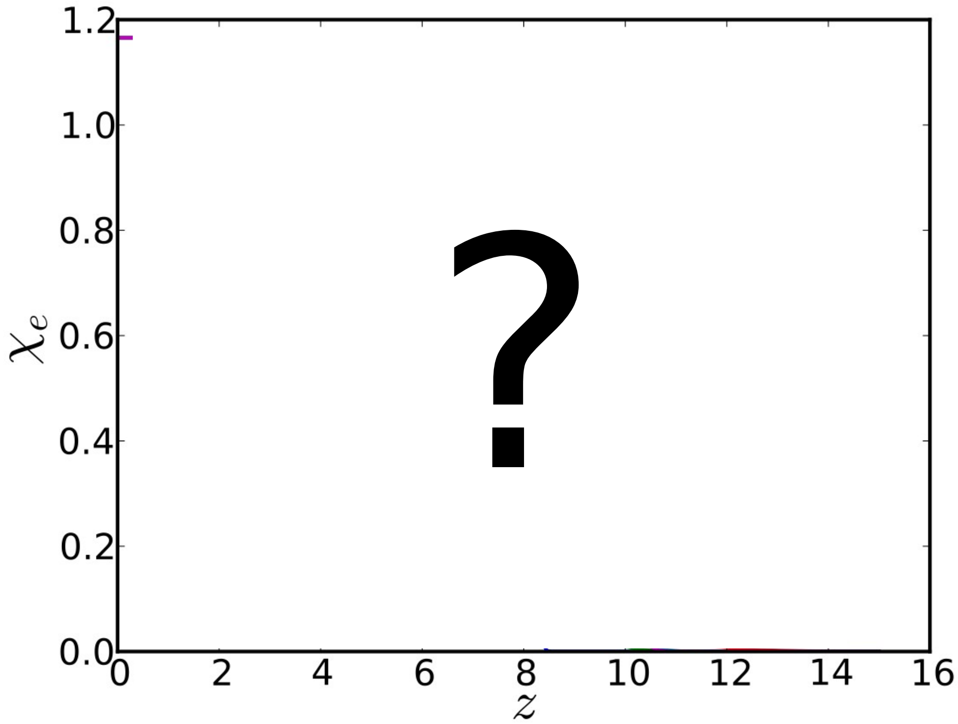

χ_e = ionization fraction as a function of the redshift

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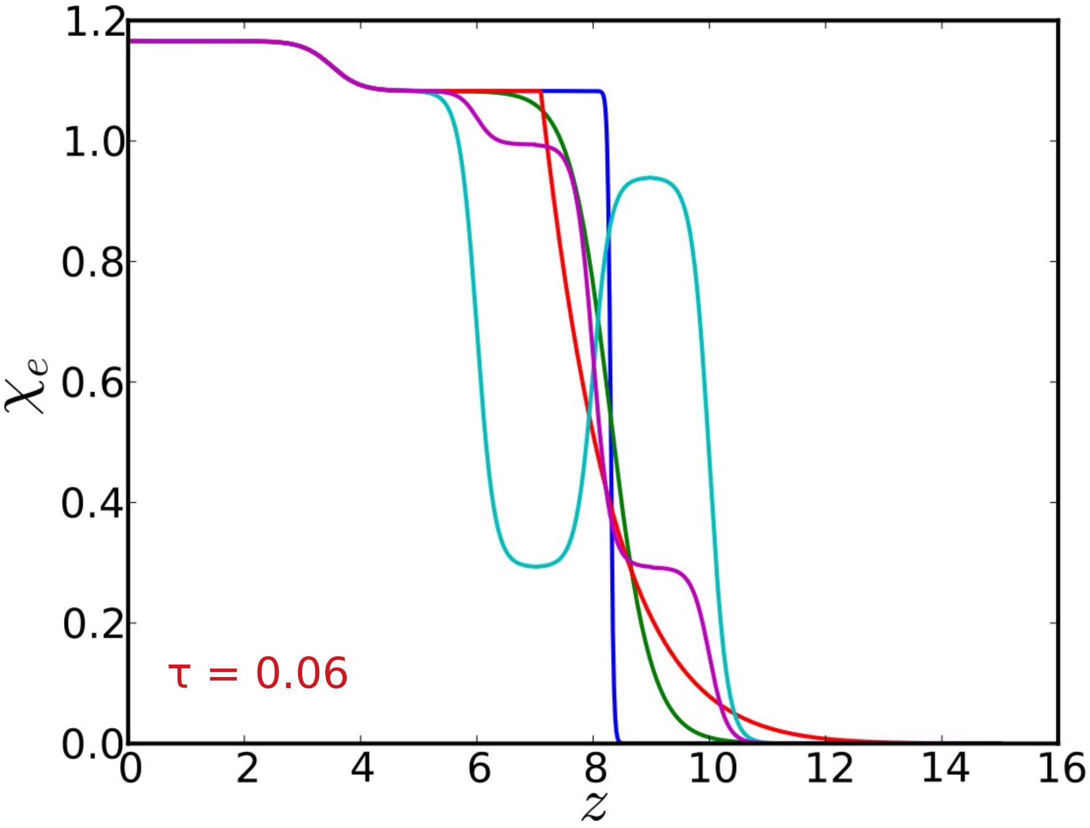

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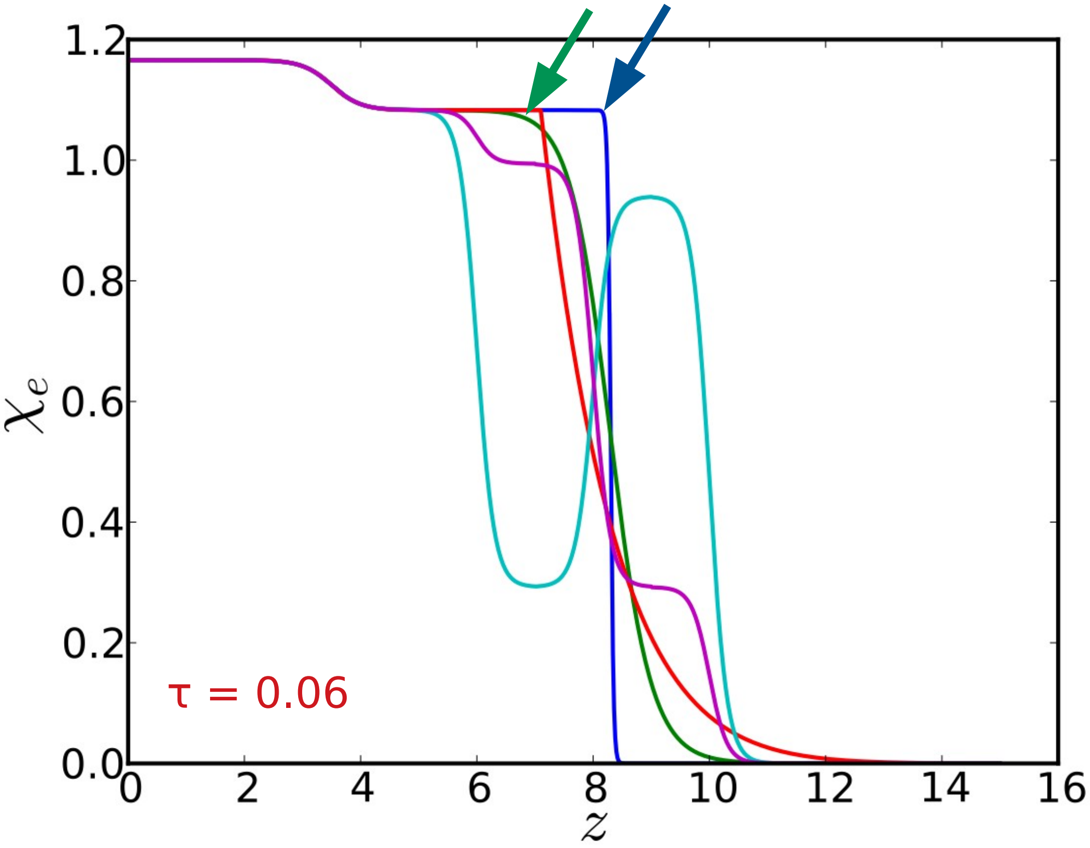

- symmetric (standard tanh)
  - 1 or 2 parameter(s): z_{re}, Δz, τ (pick 2 at most)

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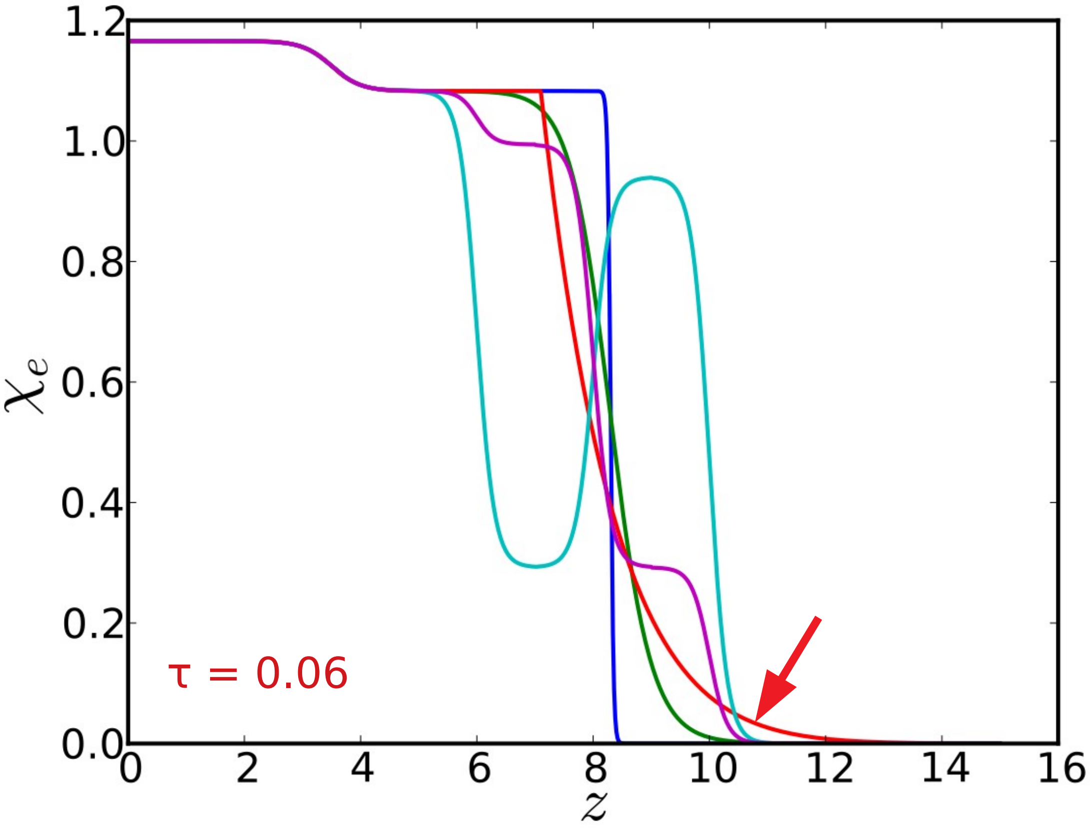

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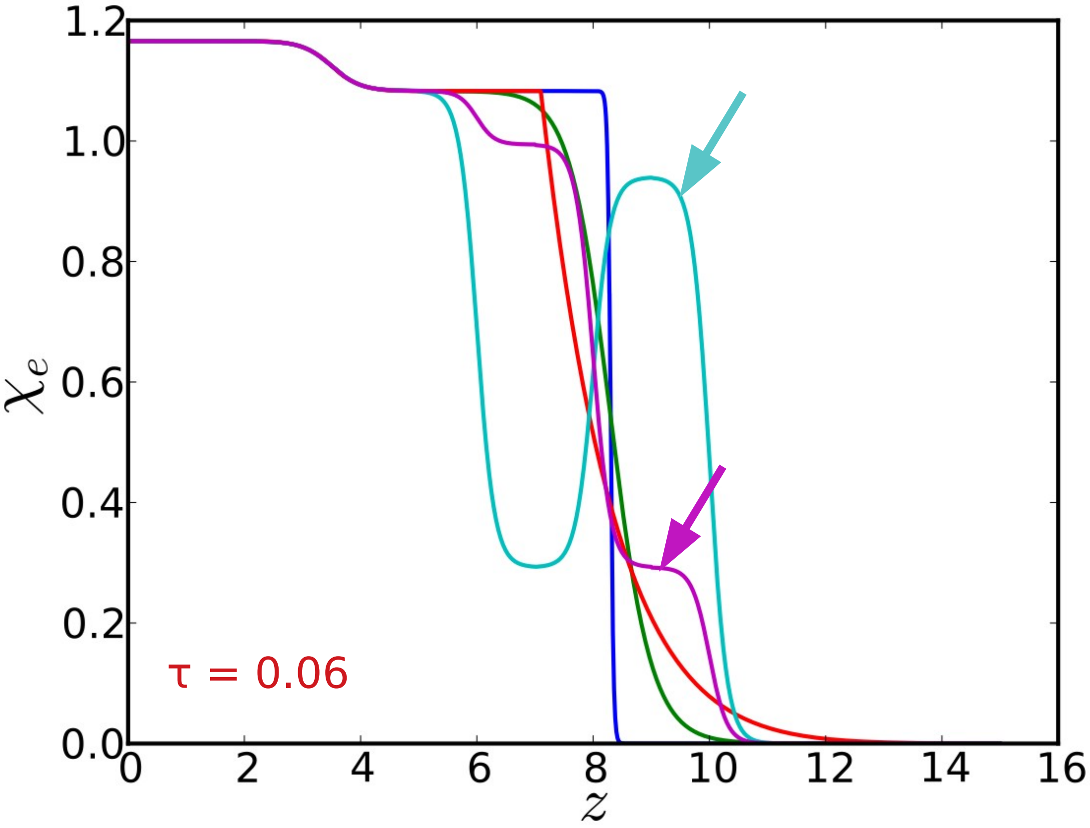
- asymmetric
  - emulates 2 populations of sources :
    1. "gentle" : stars & DGs
    2. "abrupt" : QSOs finish
  - phenomenological description :
    z_{start}, z_{end}, z_{trans} ↔ z_{re}, Δz_{begin}, Δz_{end}

III) How to model the EoR



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- model-independent
  - $x_e(z)$ in redshift bins
  - Principal Component Analysis
  - Piecewise Cubic Hermite Interpolating Polynomials (PCHIP)
  - FlexKnot (Milea & Bouchet 2018)
  - ...

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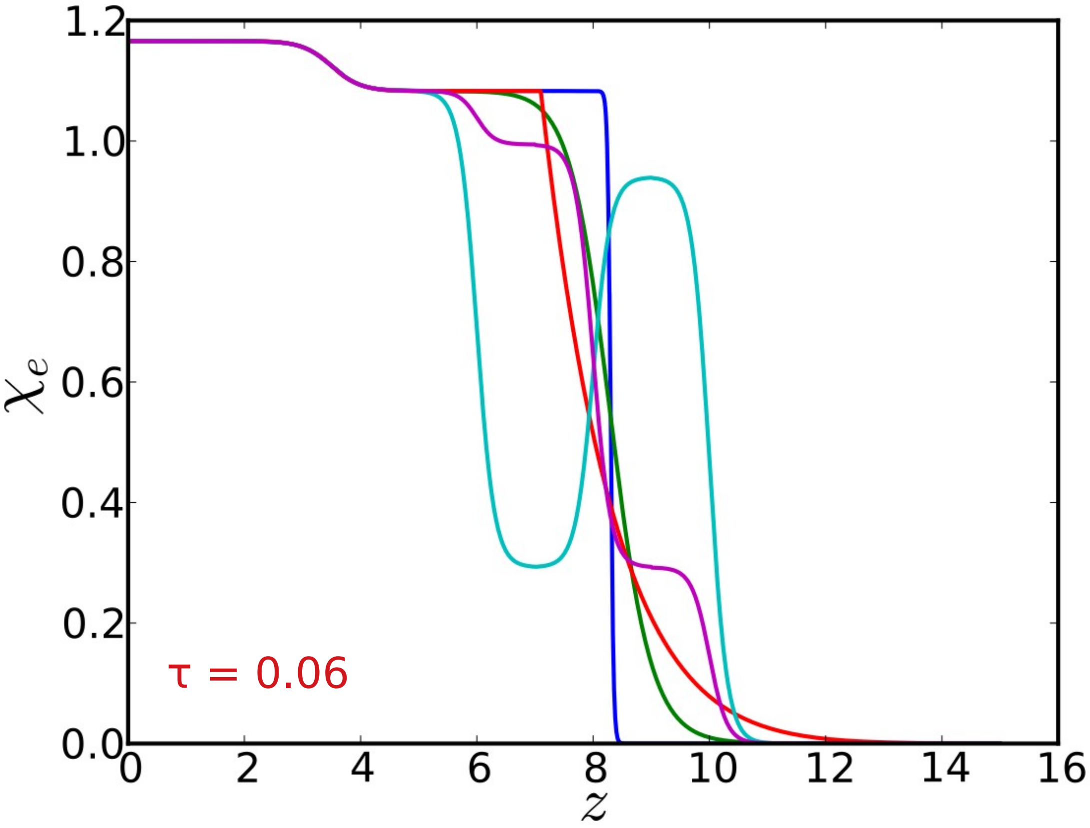

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+ physical models: see Daniela Paoletti poster (combination with other astro data)

III) How to model the EoR

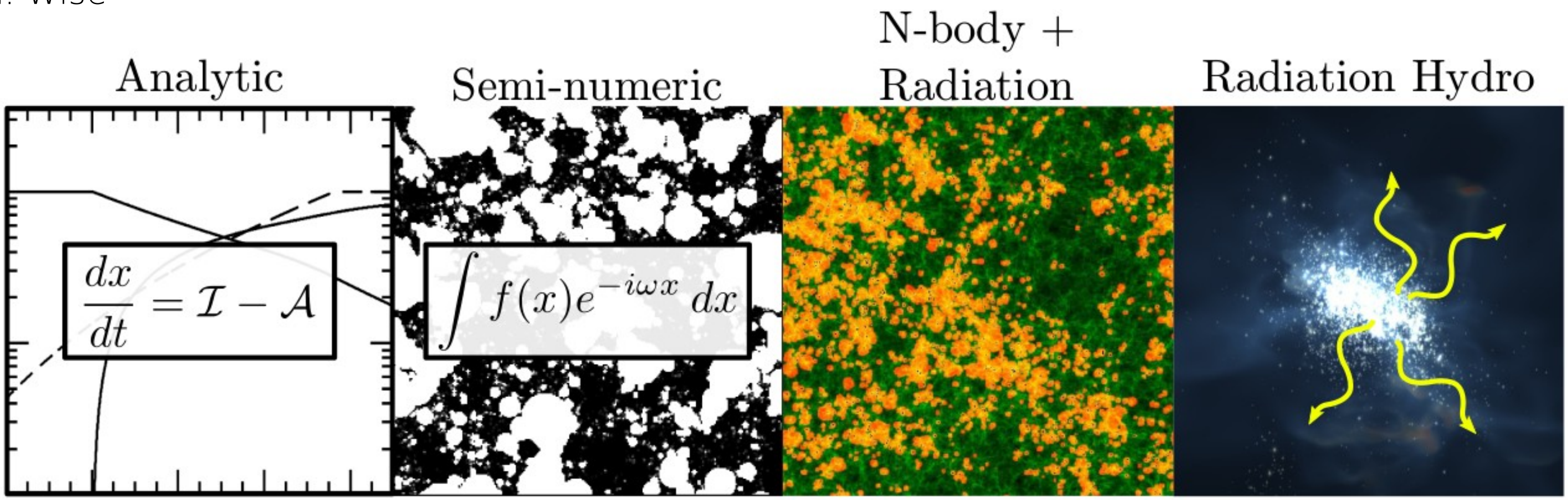
Modelling the kSZ effect

- homogeneous kSZ → density perturbations → δ_b
  → need to know about small-scale matter distribution

- patchy kSZ → ionization perturbations → δ_χ
  → depends on duration of reionisation and distribution of ionised bubble sizes

Modelling the kSZ effect

J. H. Wise



- volume-averaged analytic models
- spatially-dependent semi-numeric models
- radiative transfer calculations using matter distributions from N-body sims
- full radiation hydrodynamic galaxy formation simulations

Modelling the kSZ effect

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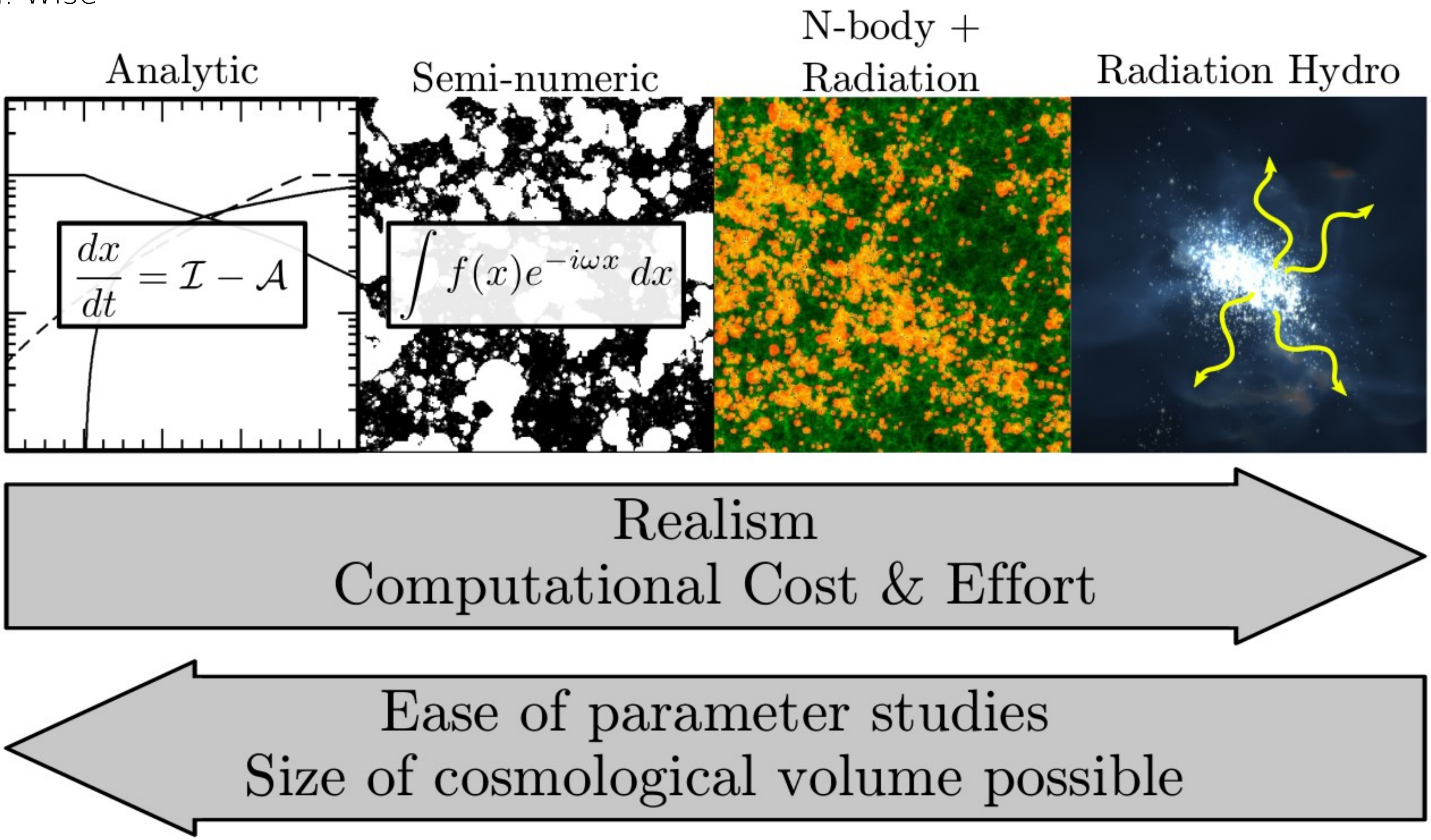

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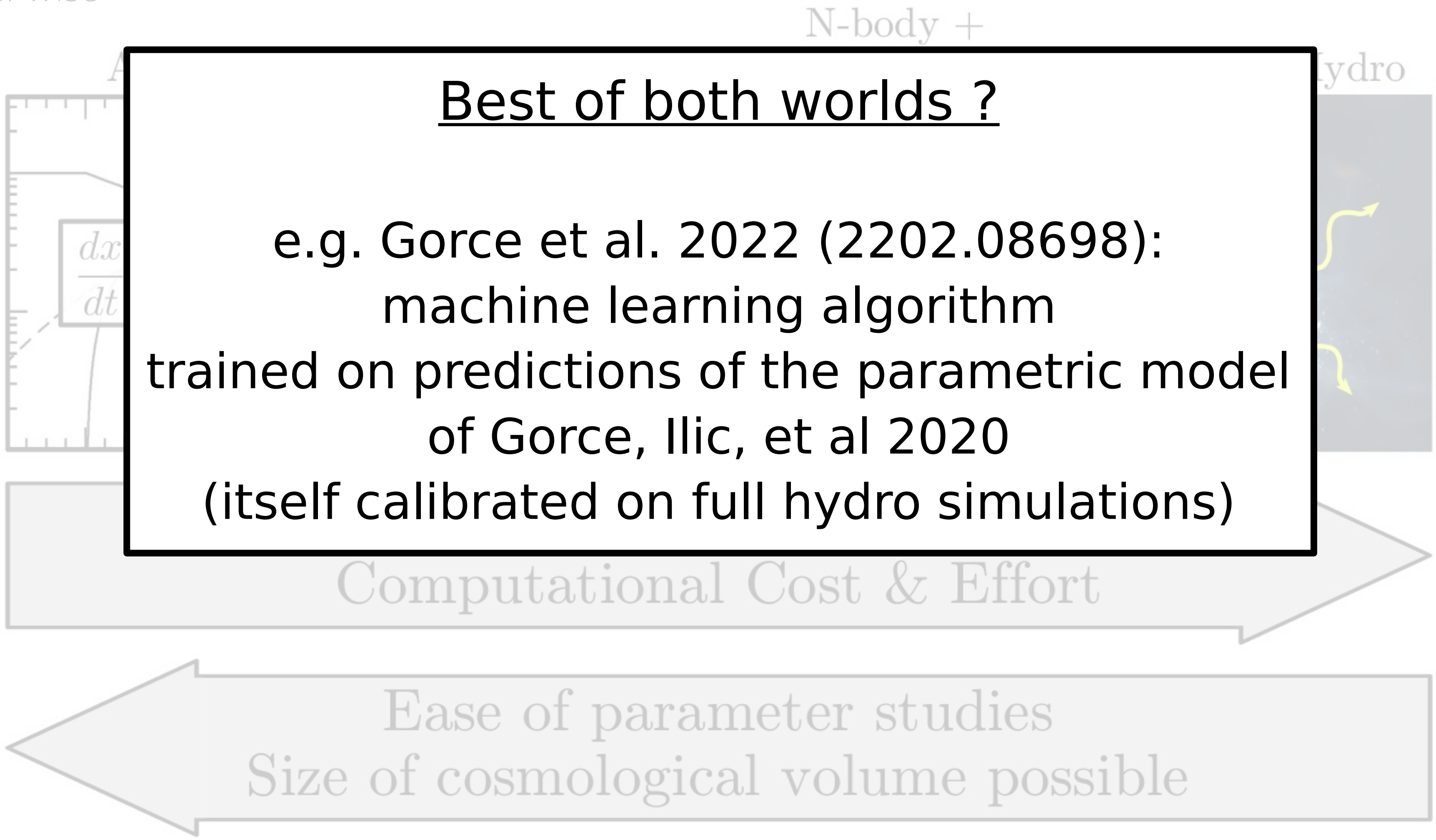


Best of both worlds ?

e.g. Gorce et al. 2022 (2202.08698):
machine learning algorithm
trained on predictions of the parametric model
of Gorce, Ilic, et al 2020
(itself calibrated on full hydro simulations)

III) How to model the EoR

In CMB studies like Planck: templates with rescaling

- homogeneous kSZ

$$D_\ell^{h-kSZ} \propto \left(\frac{\tau}{0.076}\right)^{0.44}$$

[Shaw et al., 2012]

- patchy kSZ

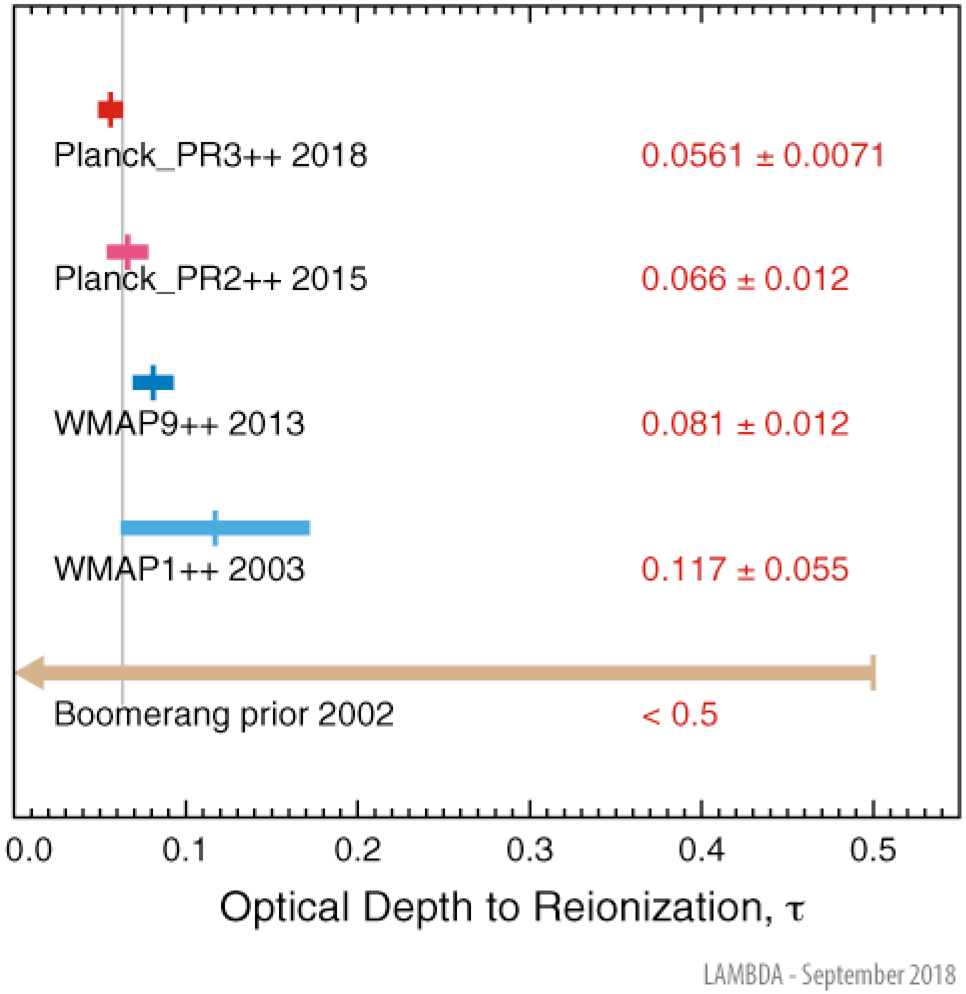
$$D_\ell^{p-kSZ} \propto \left[\left(\frac{1+z_{reio}}{11}\right) - 0.12\right]\left(\frac{\Delta_z}{1.05}\right)^{0.51}$$

[Battaglia et al., 2013]

IV) Current constraints on reionisation

IV) Current constraints on reionisation

<u>Symmetric reionisation:</u>



<u>Significant progress in the past two decades</u>

IV) Current constraints on reionisation

Symmetric reionisation:

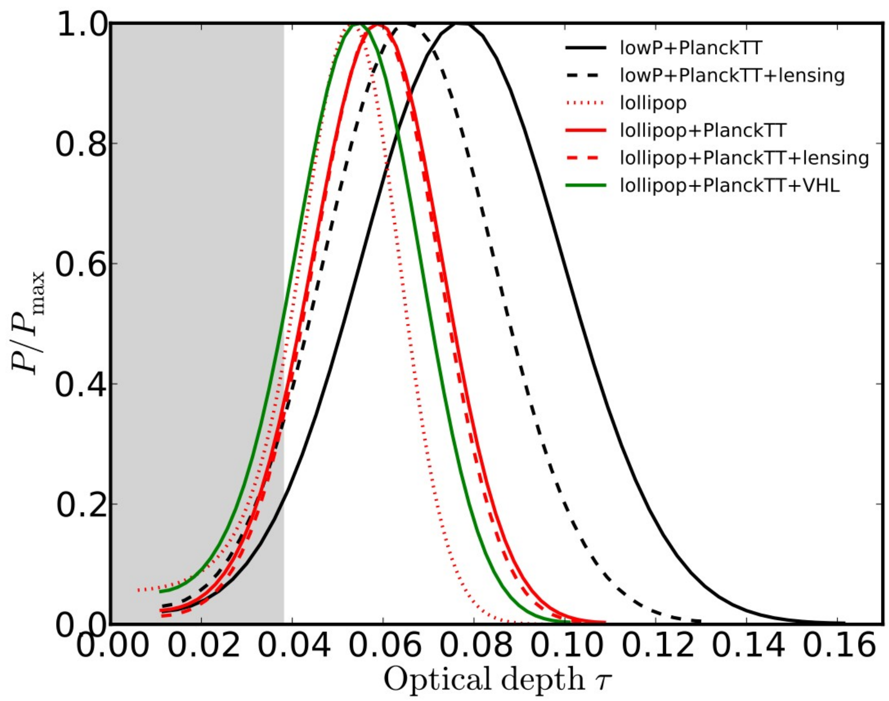
Parameter	TT,TE,EE+lowE 68% limits	
$\Omega_b h^2$	0.02236 ± 0.00015	0.67%
$\Omega_c h^2$	0.1202 ± 0.0014	1.16%
$100\theta_{MC}$	1.04090 ± 0.00031	0.03%
τ	$0.0544^{+0.0070}_{-0.0081}$	13.9%
$\ln(10^{10} A_s)$	3.045 ± 0.016	0.53%
n_s	0.9649 ± 0.0044	0.46%

But remains one of the most poorly known aspects of our cosmological model

IV) Current constraints on reionisation

Symmetric reionisation:

"Planck constraints on reionization history"
[Planck intermediate results. XLVII (2016)]



$\tau = 0.053^{+0.014}_{-0.016}$, lollipop[5] ;

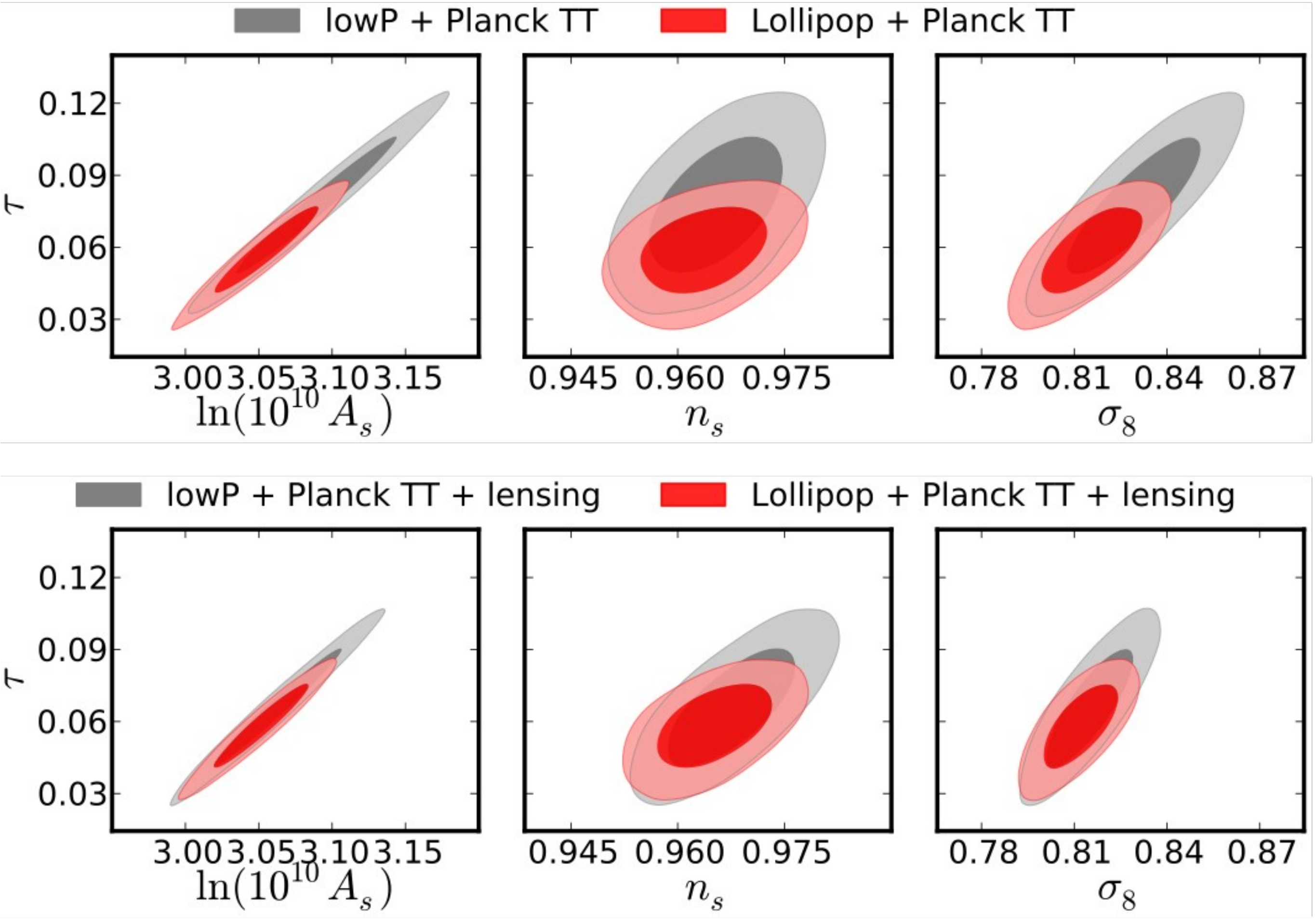
$\tau = 0.058^{+0.012}_{-0.012}$, lollipop+PlanckTT ;

$\tau = 0.058^{+0.011}_{-0.012}$, lollipop+PlanckTT+lensing ;

$$\boldsymbol{\tau} = 0.058 \pm 0.012 \left(\begin{array}{l} \pm\, 0.009\ \text{(stat)} \\ \pm\, 0.008\ \text{(sys)} \end{array} \right)$$

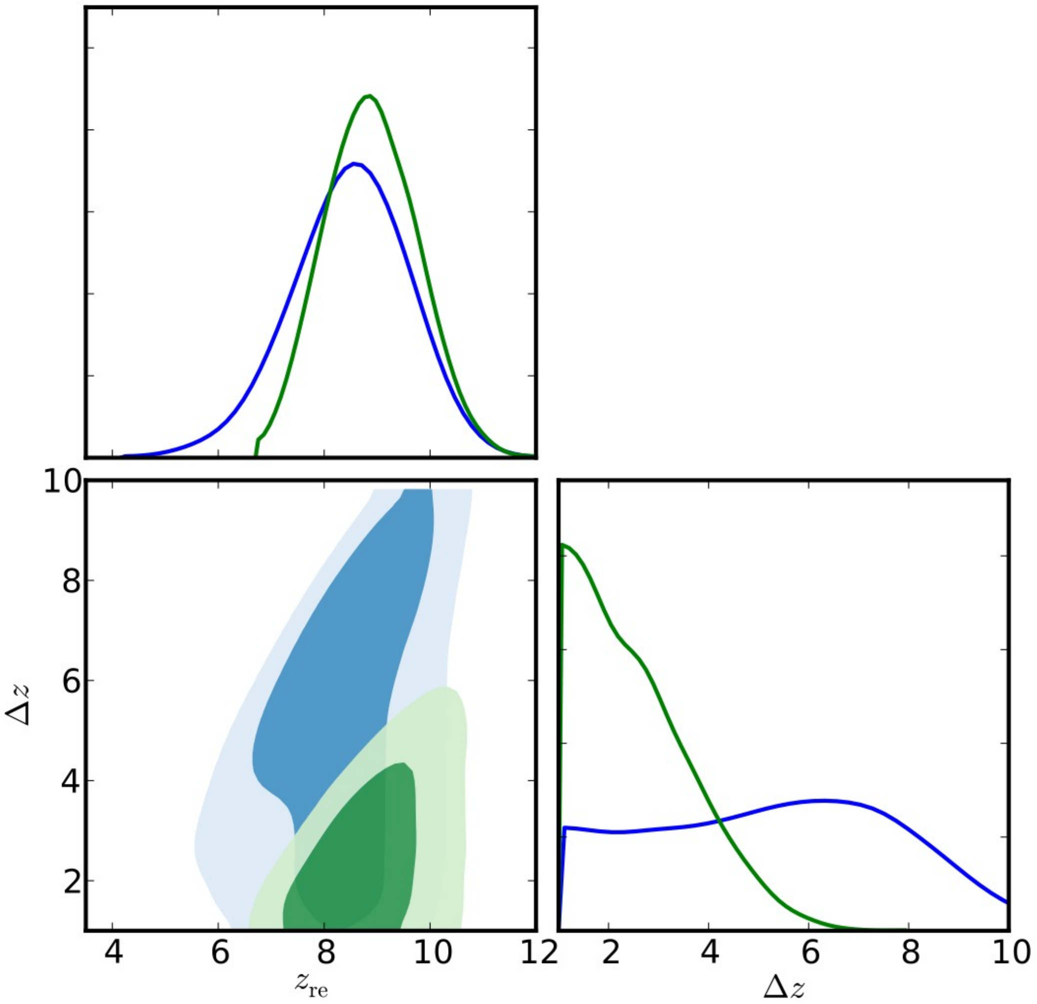
IV) Current constraints on reionisation

Symmetric reionisation:

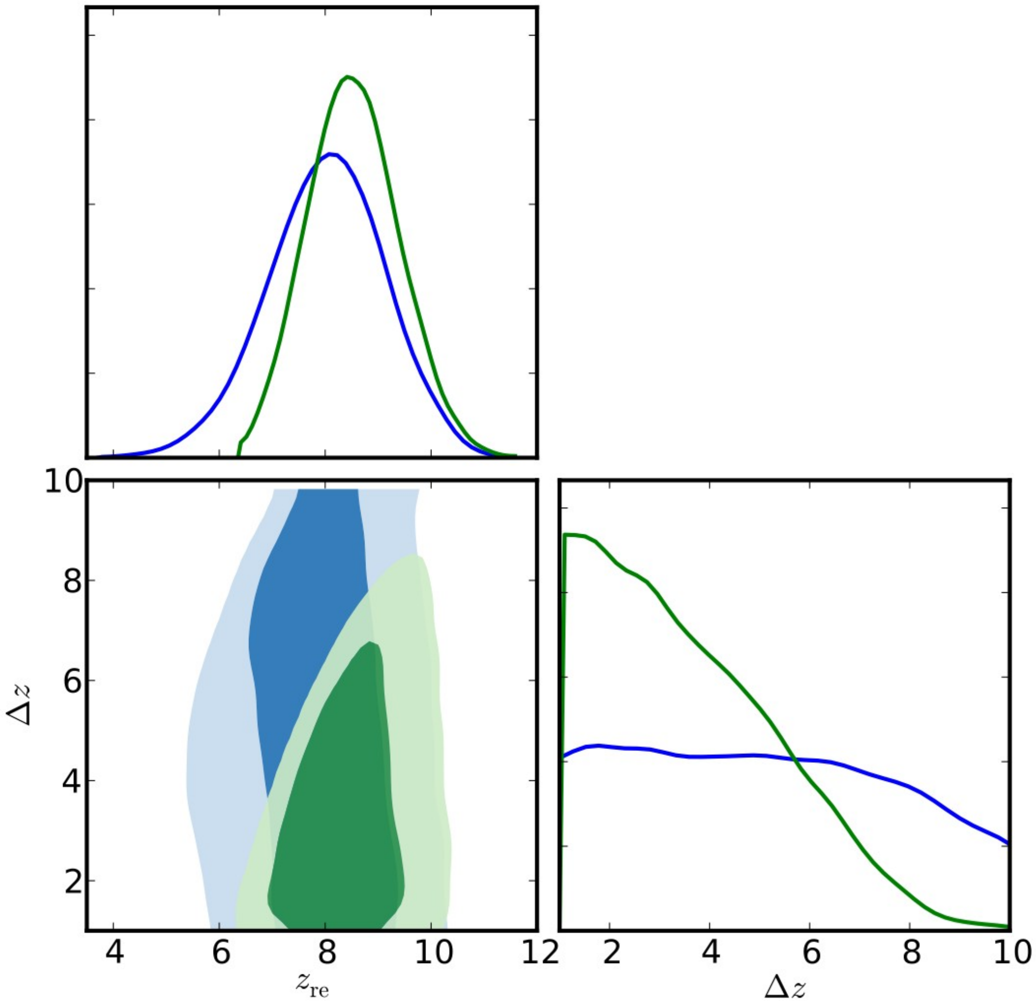


IV) Current constraints on reionisation

Symmetric reionisation:

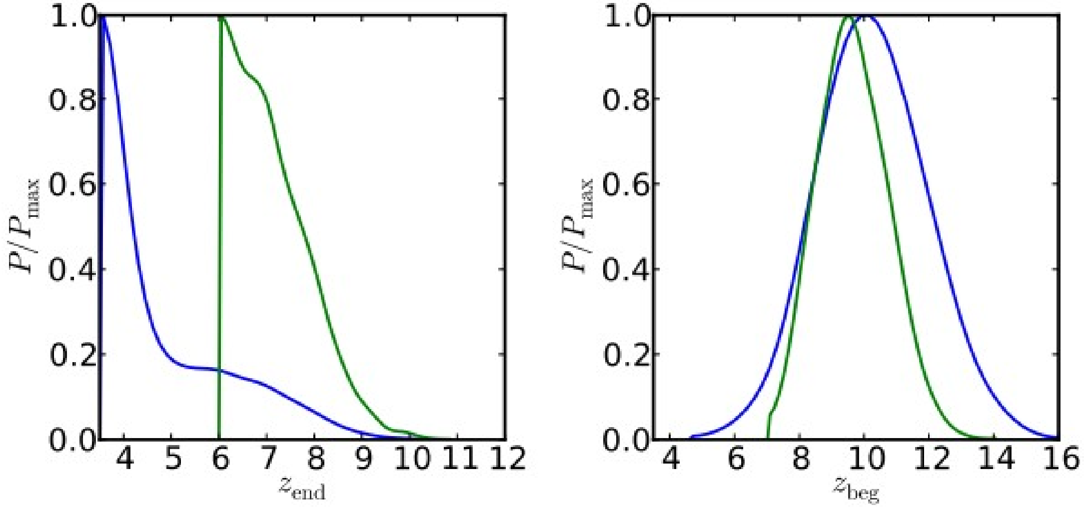


Asymmetric reionisation:

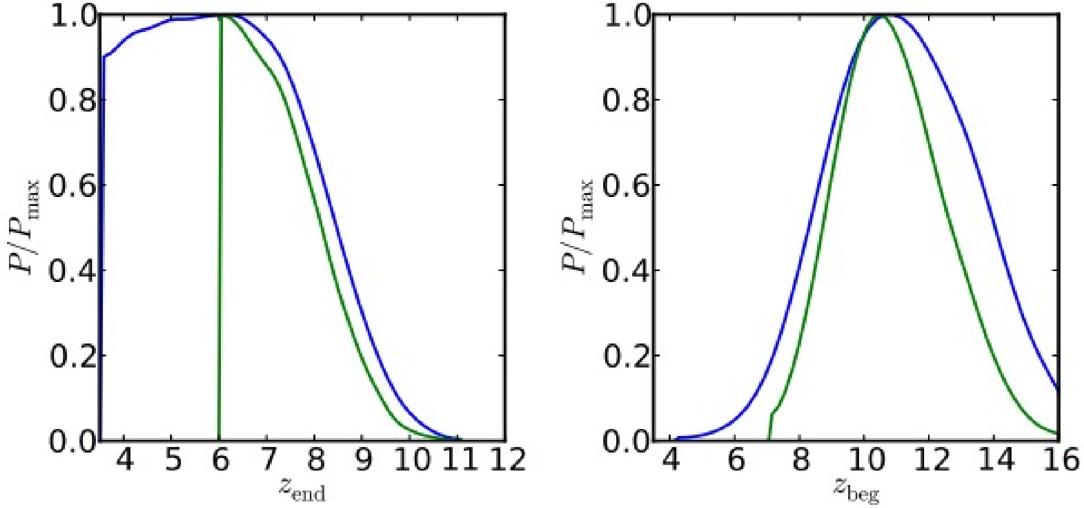


IV) Current constraints on reionisation

<u>Symmetric reionisation</u>



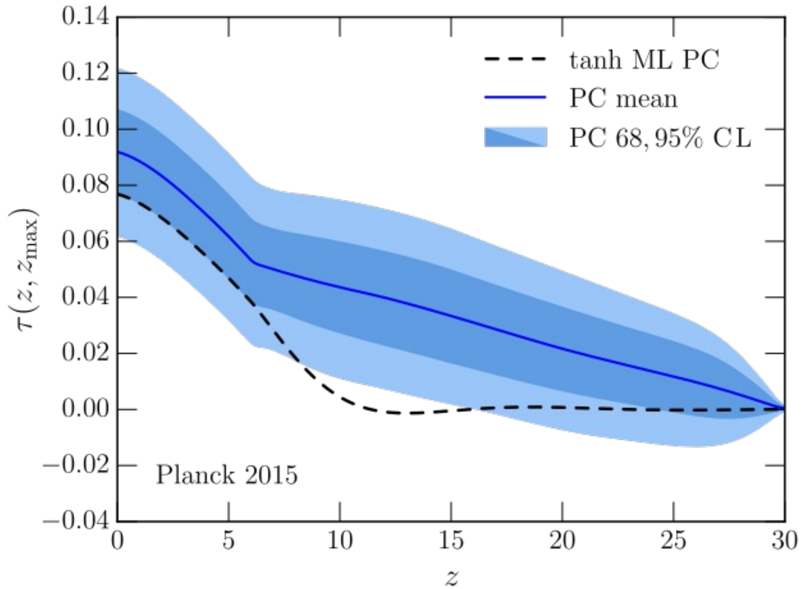
<u>Asymmetric reionisation</u>



IV) Current constraints on reionisation

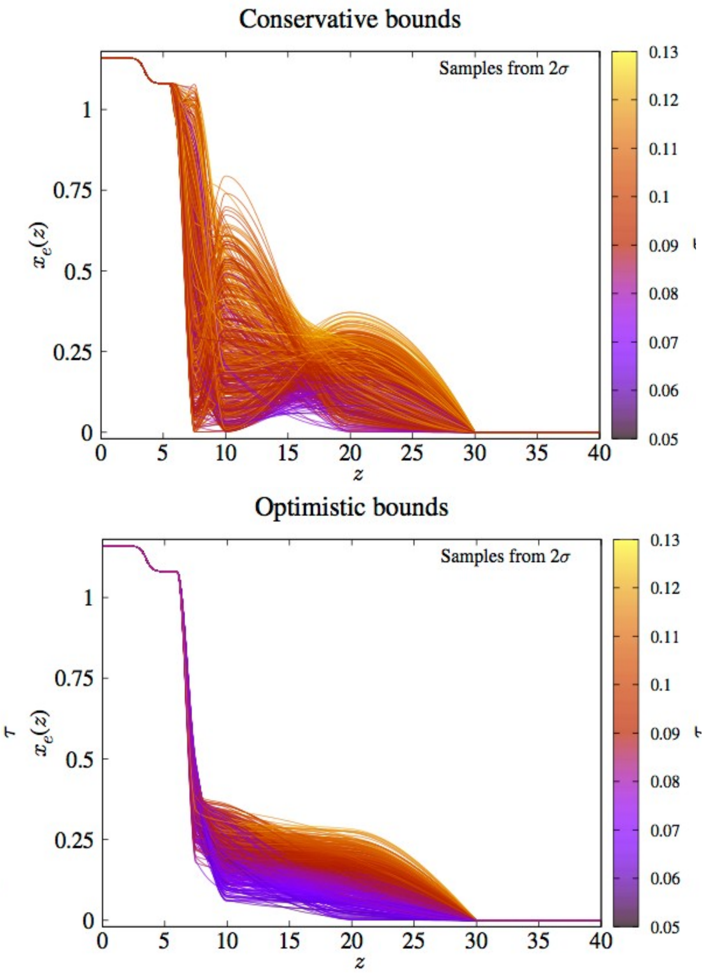
Model-independent approaches

PCA reconstruction



[Heinrich, Miranda & Hu PRD 95, 023513 (2017)]
[Heinrich & Hu, arXiv:1802.00791 (2018)]

Piecewise Cubic Hermite Interpolating Polynomials (PCHIP)

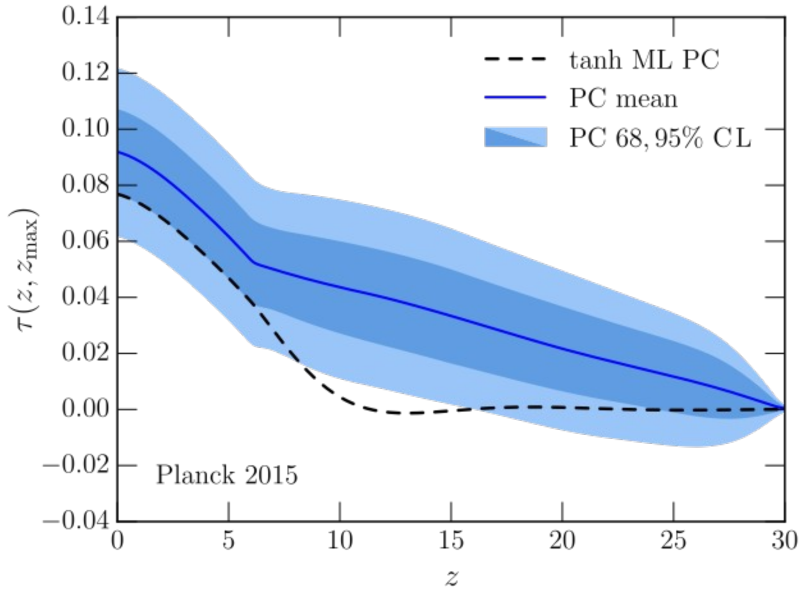


[Hazra & Smoot, JCAP, 11, 028 (2017)]

IV) Current constraints on reionisation

Model-independent approaches

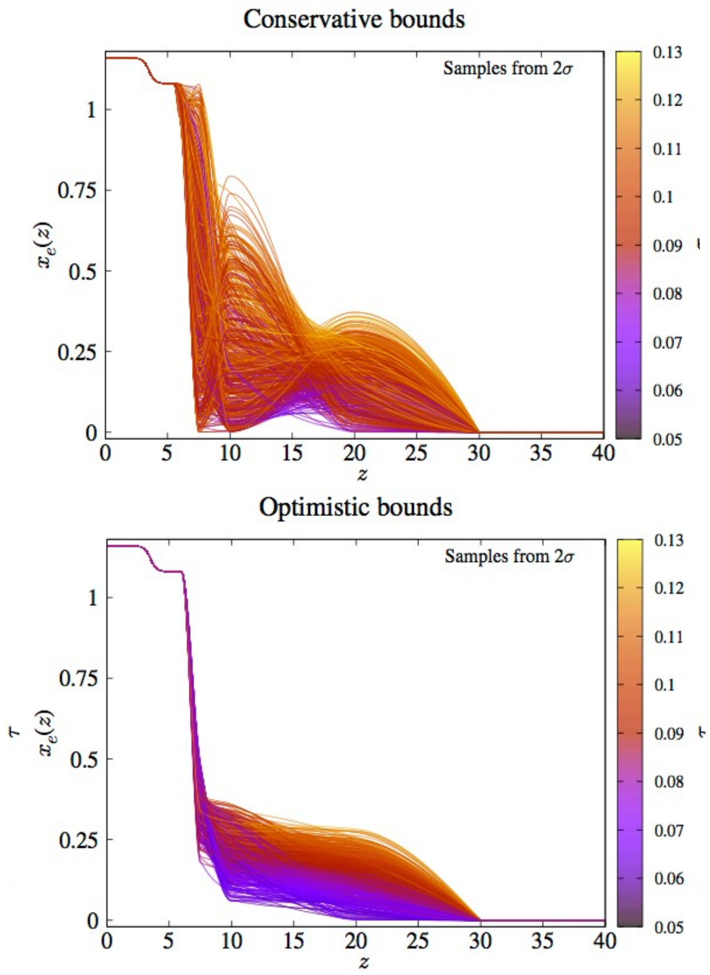
PCA reconstruction



[Heinrich, Miranda & Hu PRD 95, 023513 (2017)]
[Heinrich & Hu, arXiv:1802.00791 (2018)]

Some care required concerning non-explicit priors

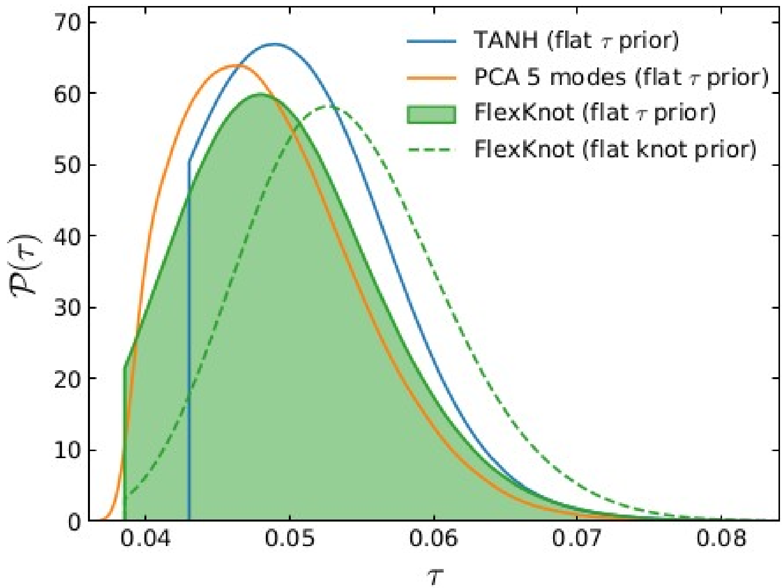
Piecewise Cubic Hermite Interpolating Polynomials (PCHIP)

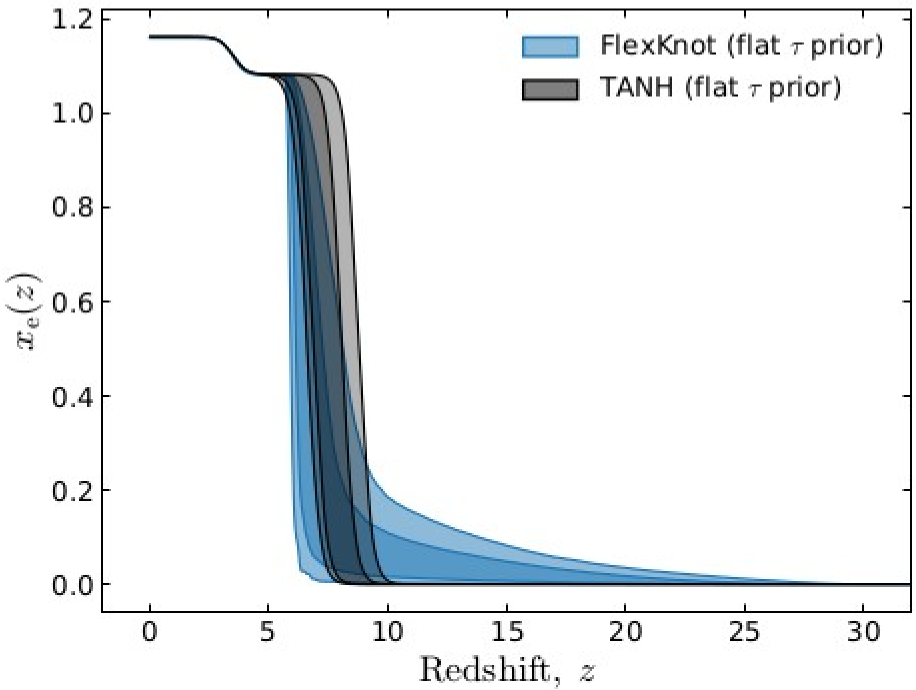


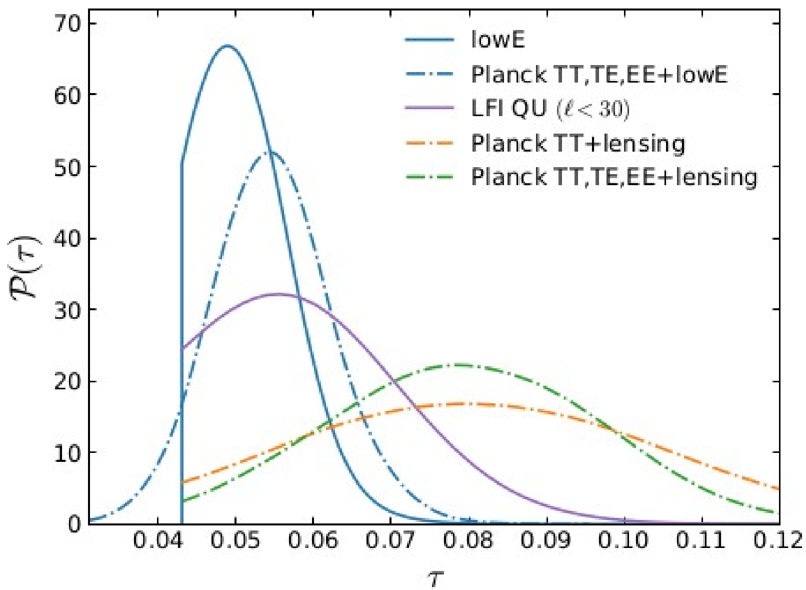
[Hazra & Smoot, JCAP, 11, 028 (2017)]

IV) Current constraints on reionisation

[Planck 2018 results. VI (2019)]







$$\tau = 0.0519^{+0.0030}_{-0.0079} \quad \text{(lowE; flat } \tau \text{ prior; TANH);}$$

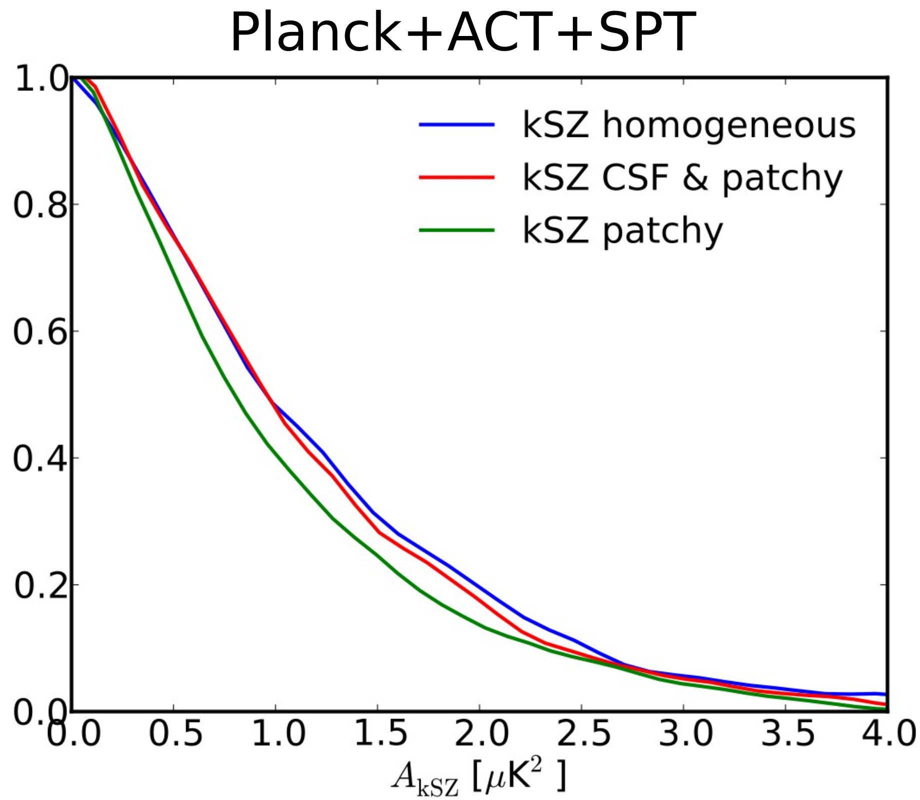
$$\tau = 0.0504^{+0.0050}_{-0.0079} \quad \text{(lowE; flat } \tau \text{ prior; FlexKnot);}$$

$$\tau = 0.0487^{+0.0038}_{-0.0081} \quad \text{(lowE; flat } \tau \text{ prior; PCA).}$$

IV) Current constraints on reionisation

Planck is not able to measure kSZ independently

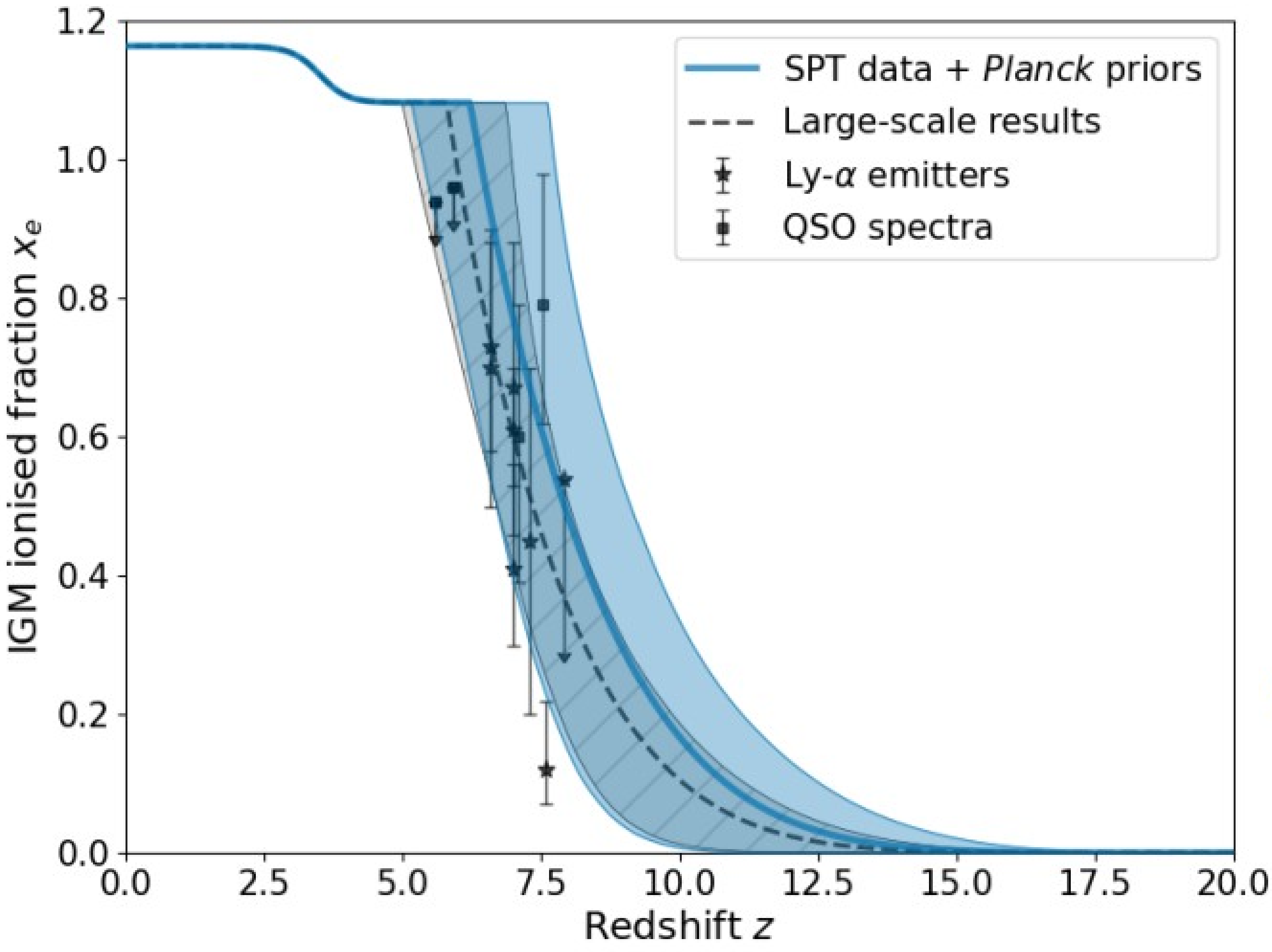
→ need high resolution CMB data (ACT,0 SPT)



Current constraints from CMB on kSZ amplitude are very weak and model dependent
→ need high-sensitivity, small-scale measurements

IV) Current constraints on reionisation

Gorce et al. 2022 (2202.08698)



$$z_{\rm re} = 7.9^{+1.1}_{-1.3}\ (68\%\ \text{C.L.})$$

$$\tau = 0.062^{+0.012}_{-0.014}\ (68\%\ \text{C.L.})$$

$$\mathcal{D}^{\rm kSZ}_{3000} = 3.3^{+0.5}_{-0.3}\ \mu\text{K}^2\ (68\%\ \text{C.L.})$$

$$\mathcal{D}^{\rm pkSZ}_{3000} < 1.58\ \mu\text{K}^2\ (95\%\ \text{C.L.})$$

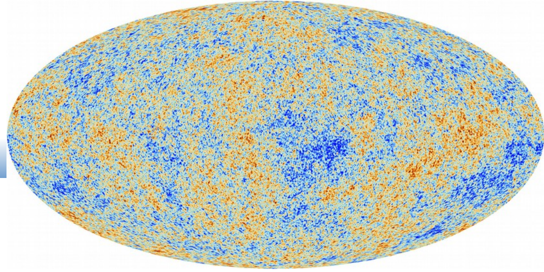
IV) Current constraints on reionisation

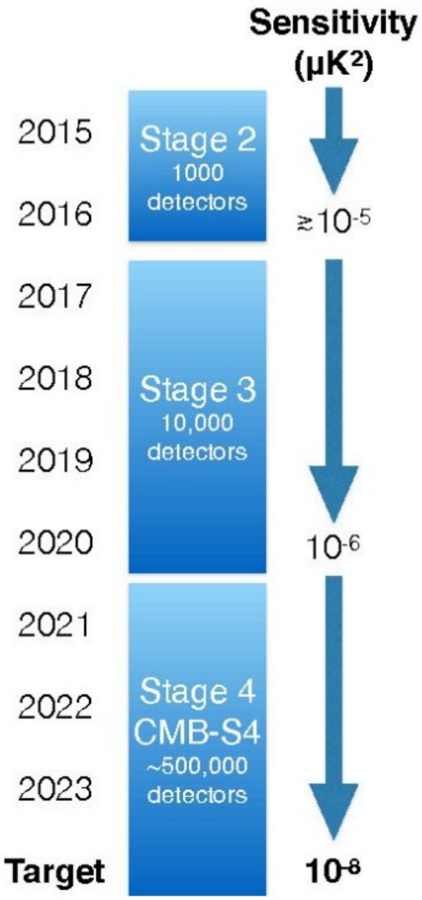
- CMB results consistent with a fully reionised Universe at z ~ 6
- Good agreement with recent constraints from particular objects (QSOs, GRB, Ly-α)
- Disfavors large abundances of star-forming galaxies beyond z = 15
- Sufficient to comply with all the observational constraints without the need for high-redshift (z = 10 to 15) galaxies.

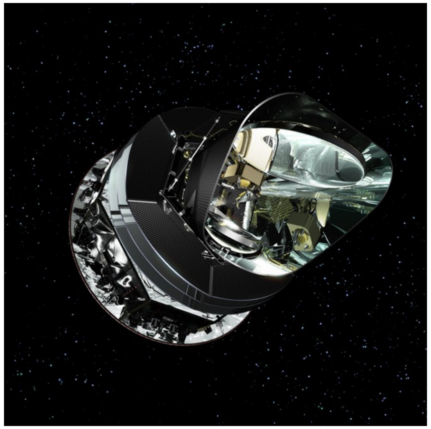
- CMB results on reionisation history is model dependent
- Need to be careful about “model-independent” approaches
- Emphasis on the need for complementary probes of reionisation (especially given the small tau value)

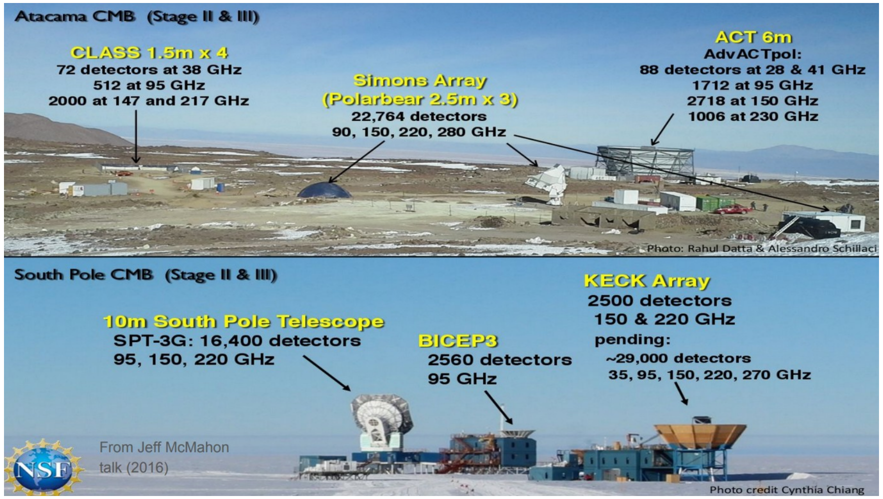
V) Perspectives & future constraints

V) Upcoming CMB surveys







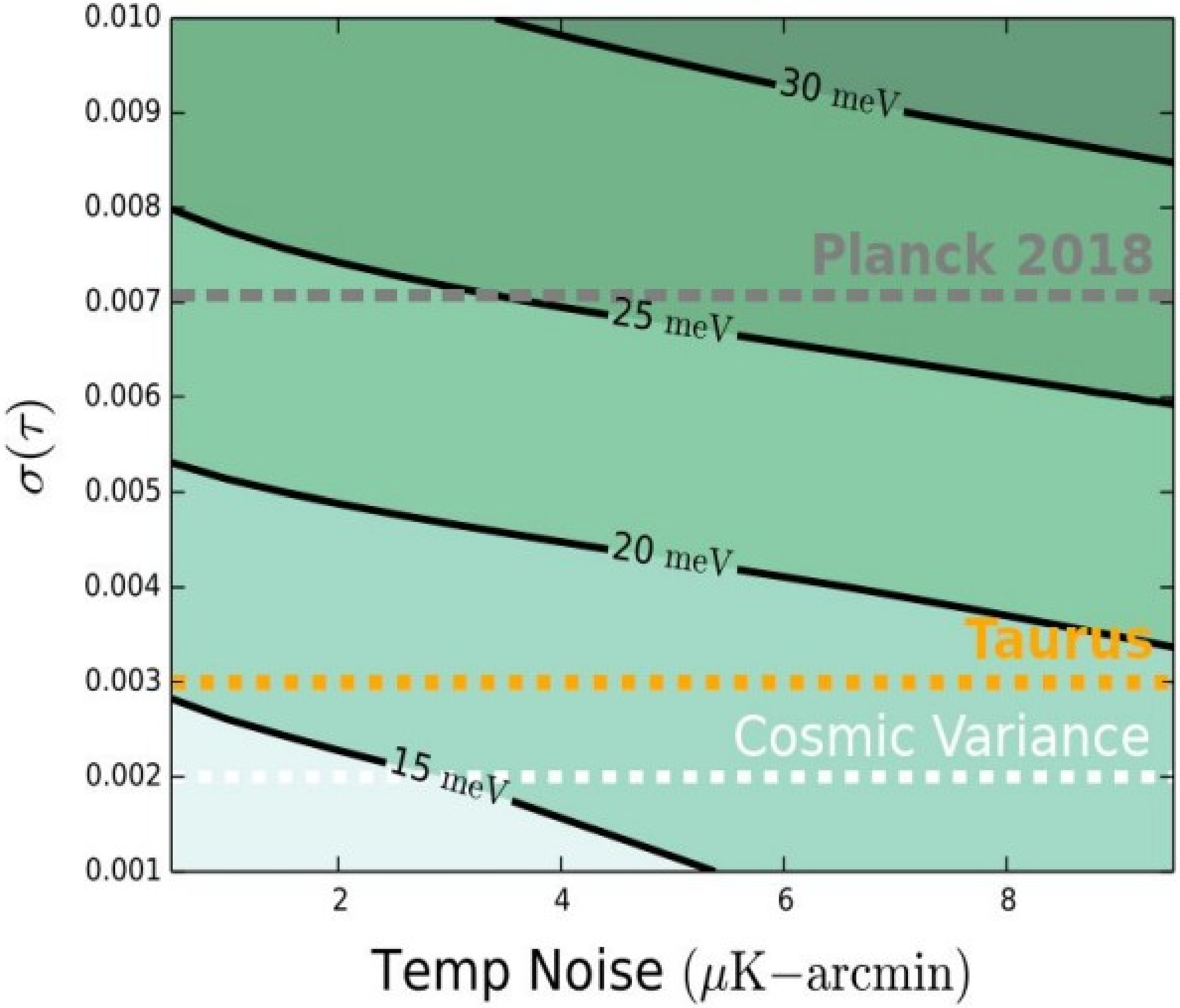


<u>Future:</u>

- Simons Observatory
- LiteBIRD
- CMB Stage-4
- Balloons
- ...

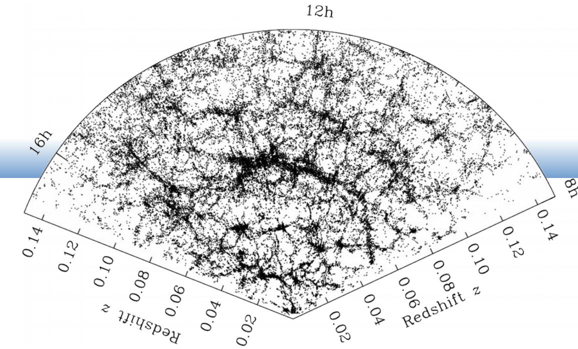
V) Upcoming CMB surveys

Credit: Taurus



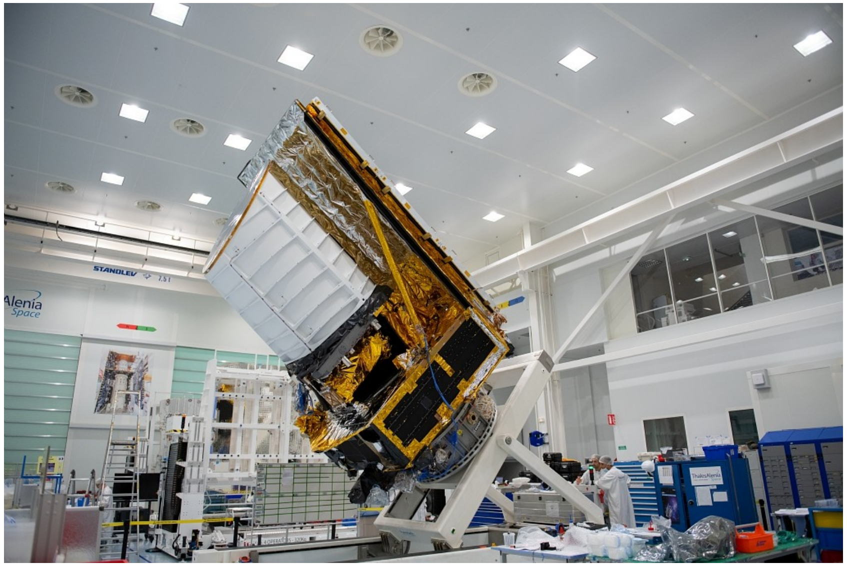
+ improvements on analysis pipeline (foregrounds cleaning, etc.)

V) Upcoming LSS surveys



<u>DETF classification:</u>

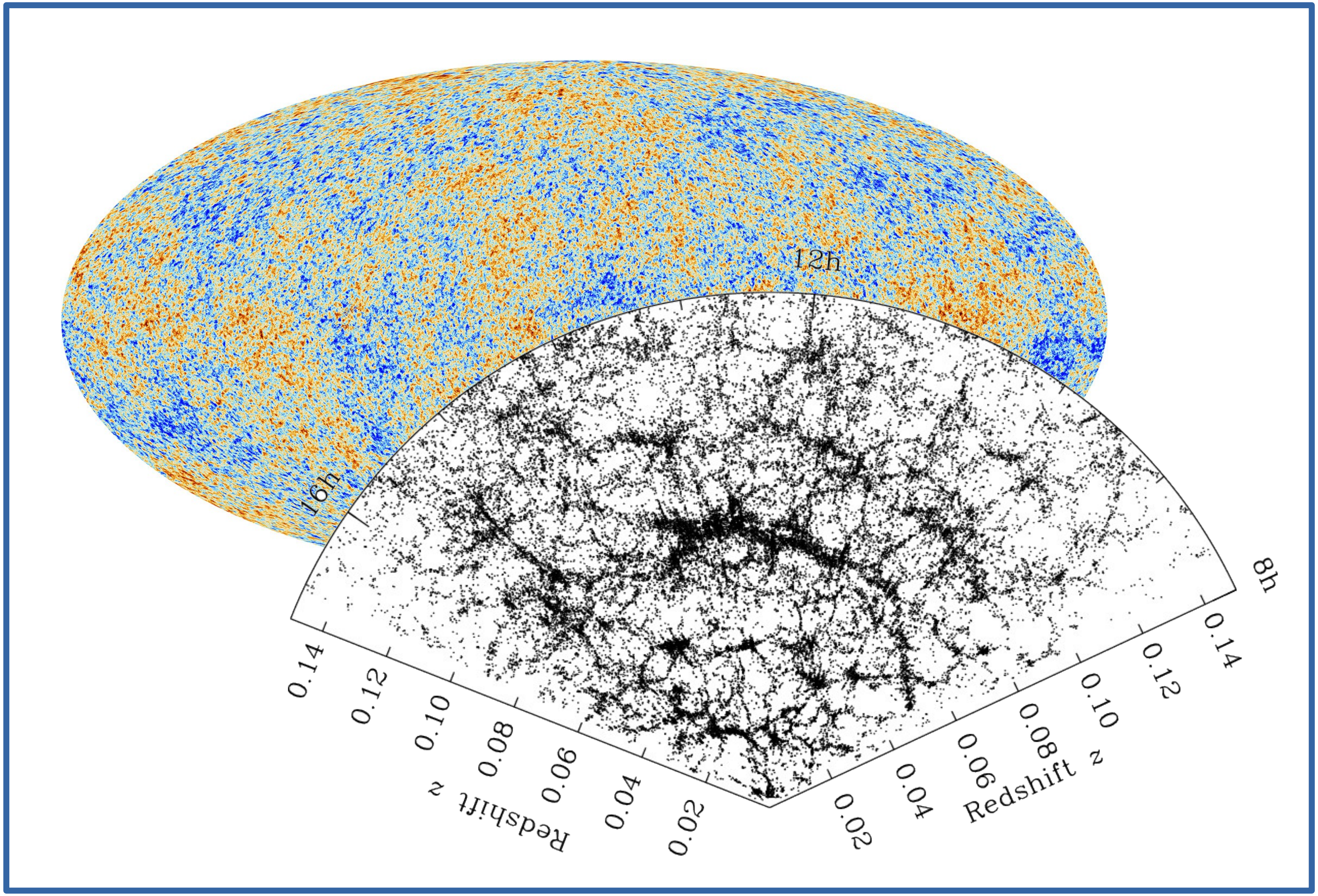
- Stage II: SDSS, KiDS, …
- Stage III: DES, …
- Stage IV: DESI, LSST, <u>Euclid</u>



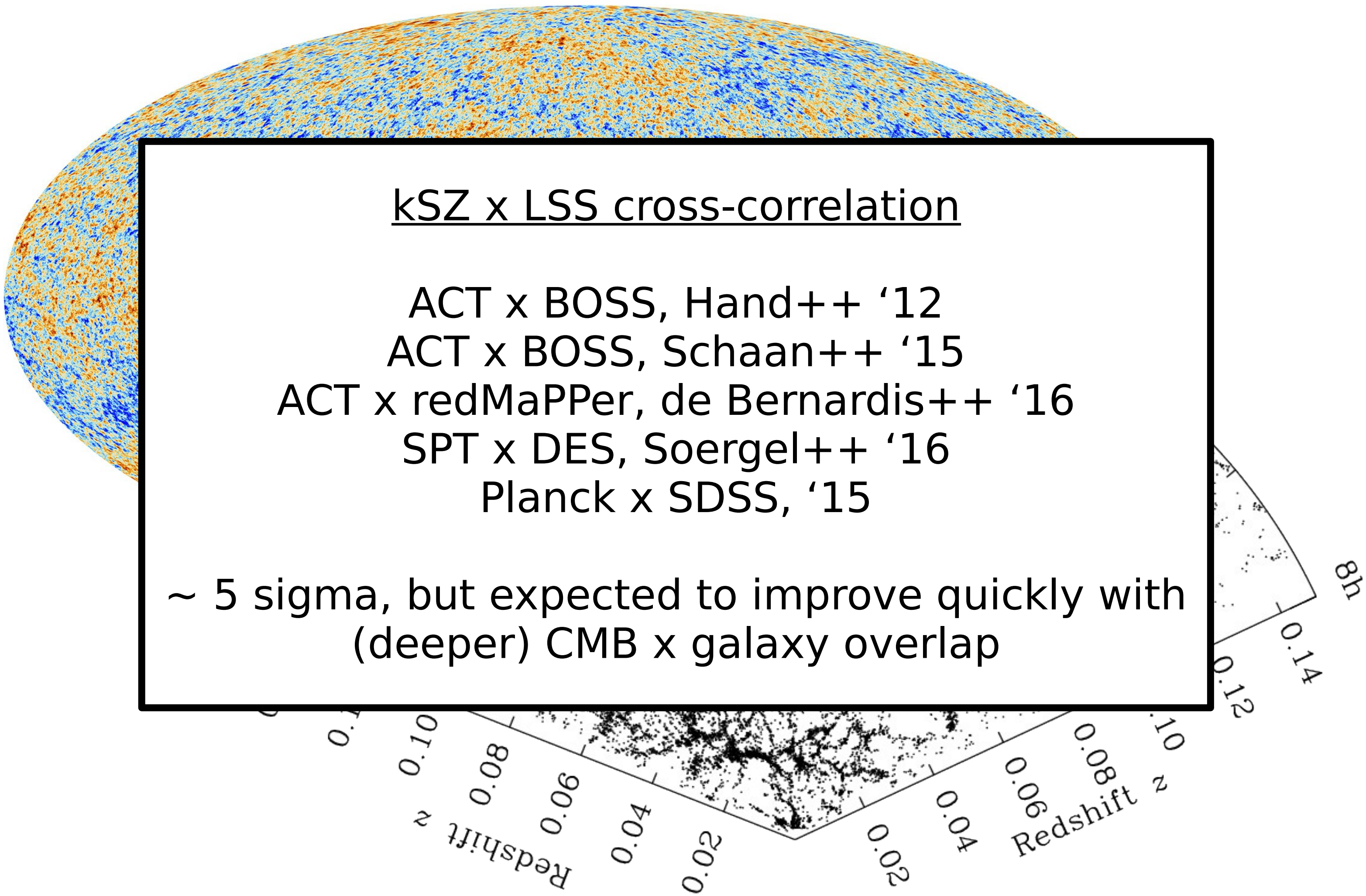
<u>Fact sheet:</u>

- Orbit around L2
- ~6 years of mission
- Launch date (!): Feb. 5^{th} 2023
- Q1 after 17 months, DR1 at 29
- VIS & NISP instruments
- ~15,000 sq. deg.
- Spectro + photo survey
- Gal. Clustering & Weak Lensing

V) CMB-LSS joint analysis



V) CMB-LSS joint analysis



<u>kSZ x LSS cross-correlation</u>

ACT x BOSS, Hand++ ‘12
ACT x BOSS, Schaan++ ‘15
ACT x redMaPPer, de Bernardis++ ‘16
SPT x DES, Soergel++ ‘16
Planck x SDSS, ‘15

~ 5 sigma, but expected to improve quickly with (deeper) CMB x galaxy overlap

V) Euclid CMBX forecasts paper

Ilic et al. 2021, A&A, arXiv:2106.08346

Astronomy & Astrophysics manuscript no. main
September 13, 2021

Euclid preparation: XV. Forecasting cosmological constraints for the *Euclid* and CMB joint analysis

Euclid Collaboration: S. Ilić[1,2,3]⋆, N. Aghanim[4], C. Baccigalupi[5,6,7,8], J.R. Bermejo-Climent[9,10,11], G. Fabbian[12,114], L. Legrand[4,13], D. Paoletti[10,14], M. Ballardini[10,11,15], M. Archidiacono[16,17], M. Douspis[4], F. Finelli[10,11], K. Ganga[18], C. Hernández-Monteagudo[9,19,20], M. Lattanzi[21], D. Marinucci[22], M. Migliaccio[22,23], C. Carbone[24], S. Casas[25], M. Martinelli[26], I. Tutusaus[3,27,28], P. Natoli[21,29], P. Ntelis[30], L. Pagano[29], L. Wenzl[31], A. Gruppuso[10,14], T. Kitching[32], M. Langer[4], N. Mauri[14,33], L. Patrizii[14], A. Renzi[34,35], G. Sirri[14], L. Stanco[34], M. Tenti[14], P. Vielzeuf[5,6], F. Lacasa[4], G. Polenta[36], V. Yankelevich[37], A. Blanchard[3], Z. Sakr[3,38], A. Pourtsidou[39], S. Camera[40,41], V.F. Cardone[42,43], M. Kilbinger[25], M. Kunz[13], K. Markovic[44], V. Pettorino[25], A.G. Sánchez[45], D. Sapone[46], A. Amara[47], N. Auricchio[10], R. Bender[45,48], C. Bodendorf[45], D. Bonino[49], E. Branchini[43,50,51], M. Brescia[52], J. Brinchmann[53,54], V. Capobianco[49], J. Carretero[55], F.J. Castander[27,28], M. Castellano[43], S. Cavuoti[52,56,57], A. Cimatti[58,59], R. Cledassou[60,61], G. Congedo[62], C.J. Conselice[63], L. Conversi[64,65], Y. Copin[66], L. Corcione[49], A. Costille[67], M. Cropper[32], A. Da Silva[68,69], H. Degaudenzi[70], F. Dubath[70], C.A.J. Duncan[71], X. Dupac[65], S. Dusini[34], A. Ealet[66], S. Farrens[25], P. Fosalba[27,28], M. Frailis[8], E. Franceschi[10], P. Franzetti[24], M. Fumana[24], B. Garilli[24], W. Gillard[30], B. Gillis[62], C. Giocoli[72,73], A. Grazian[74], F. Grupp[45,48], L. Guzzo[16,17,75], S.V.H. Haugan[76], H. Hoekstra[77], W. Holmes[44], F. Hormuth[78,79], P. Hudelot[80], K. Jahnke[79], S. Kermiche[30], A. Kiessling[44], R. Kohley[65], B. Kubik[66], M. Kümmel[48], H. Kurki-Suonio[81], R. Laureijs[82], S. Ligori[49], P. B. Lilje[76], I. Lloro[83], O. Mansutti[8], O. Marggraf[84], F. Marulli[10,14,58], R. Massey[85], S. Maurogordato[86], M. Meneghetti[10,14,87], E. Merlin[43], G. Meylan[88], M. Moresco[10,58], B. Morin[25], L. Moscardini[10,11,58], E. Munari[8], S.M. Niemi[82], C. Padilla[55], S. Paltani[70], F. Pasian[8], K. Pedersen[89], W. Percival[90,91,92], S. Pires[25], M. Poncet[61], L. Popa[93], L. Pozzetti[10], F. Raison[45], R. Rebolo[9,19], J. Rhodes[44], M. Roncarelli[10,58], E. Rossetti[58], R. Saglia[45,48], R. Scaramella[42,43], P. Schneider[84], A. Secroun[30], G. Seidel[79], S. Serrano[27,28], C. Sirignano[34,35], J.L. Starck[25], P. Tallada-Crespí[94], A.N. Taylor[62], I. Tereno[68,95], R. Toledo-Moreo[96], F. Torradeflot[55,94], E.A. Valentijn[97], L. Valenziano[10,14], G.A. Verdoes Kleijn[97], Y. Wang[98], N. Welikala[62], J. Weller[45,48], G. Zamorani[10], J. Zoubian[30], E. Medinaceli[72], S. Mei[18], C. Rosset[18], F. Sureau[25], T. Vassallo[48], A. Zacchei[8], S. Andreon[75], A. Balaguera-Antolínez[9,19], M. Baldi[10,14,15], S. Bardelli[10], A. Biviano[5,8], S. Borgani[5,7,8,99], E. Bozzo[70], C. Burigana[11,29,100], R. Cabanac[3], A. Cappi[10,86], C.S. Carvalho[95], G. Castignani[58], C. Colodro-Conde[19], J. Coupon[70], H.M. Courtois[101], J. Cuby[67], S. de la Torre[67], D. Di Ferdinando[14], H. Dole[4], M. Farina[102], P.G. Ferreira[71], P. Flose-Reimberg[80], S. Galeotta[8], G. Gozaliasl[103,104], J. Graciá-Carpio[45], E. Keihanen[104], C.C. Kirkpatrick[81], V. Lindholm[104,105], G. Mainetti[106], D. Maino[16,17,24], N. Martinet[67], M. Maturi[107,108], R.B. Metcalf[10,15], G. Morgante[10], C. Neissner[55], J. Nightingale[85], A.A. Nucita[109,110], D. Potter[111], G. Riccio[52], E. Romelli[8], M. Schirmer[79], M. Schultheis[86], V. Scottez[80], R. Teyssier[111], A. Tramacere[70], J. Valiviita[105,112], M. Viel[5,6,7,8], L. Whittaker[63,113], E. Zucca[10]

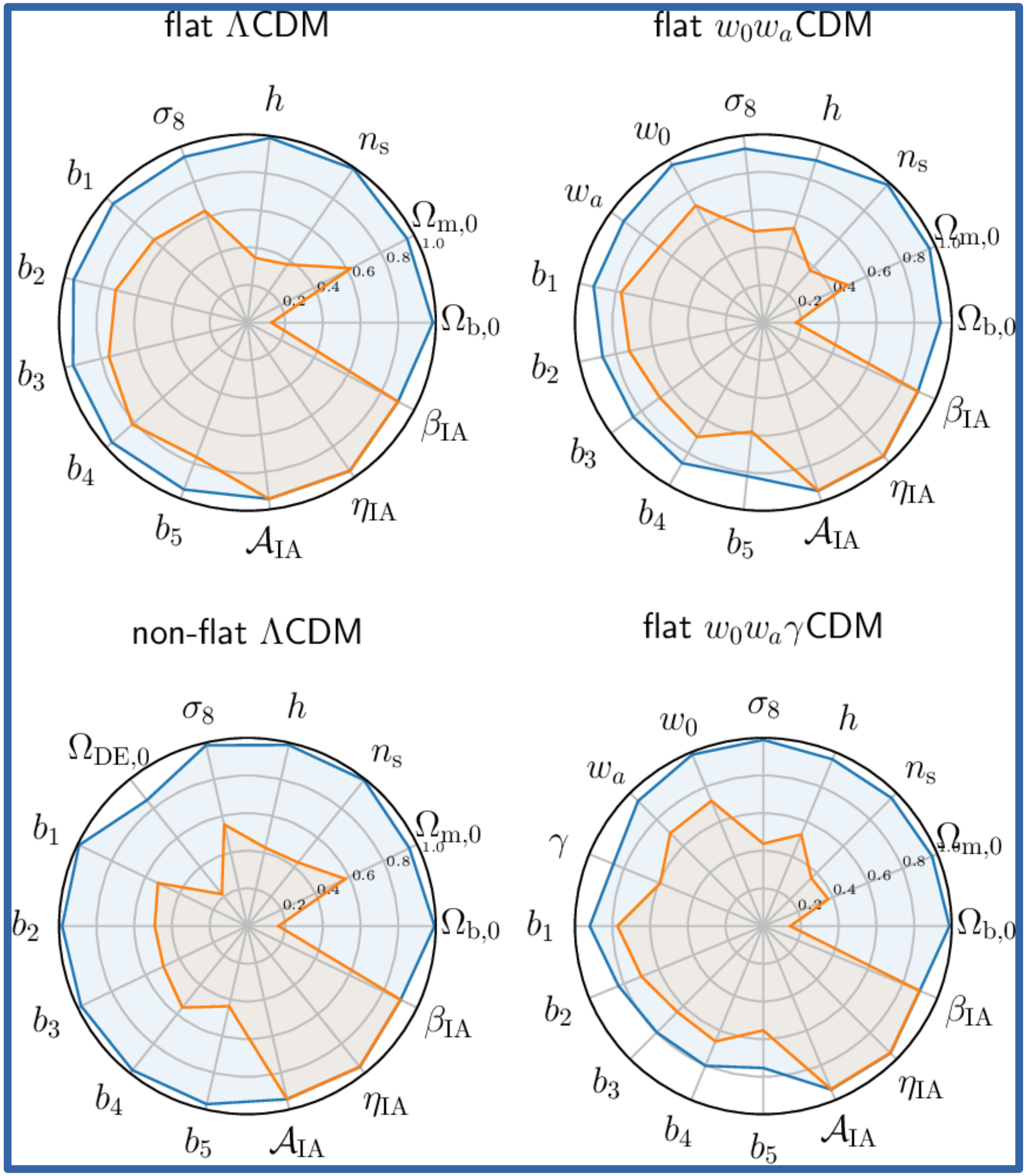
(Affiliations can be found after the references)

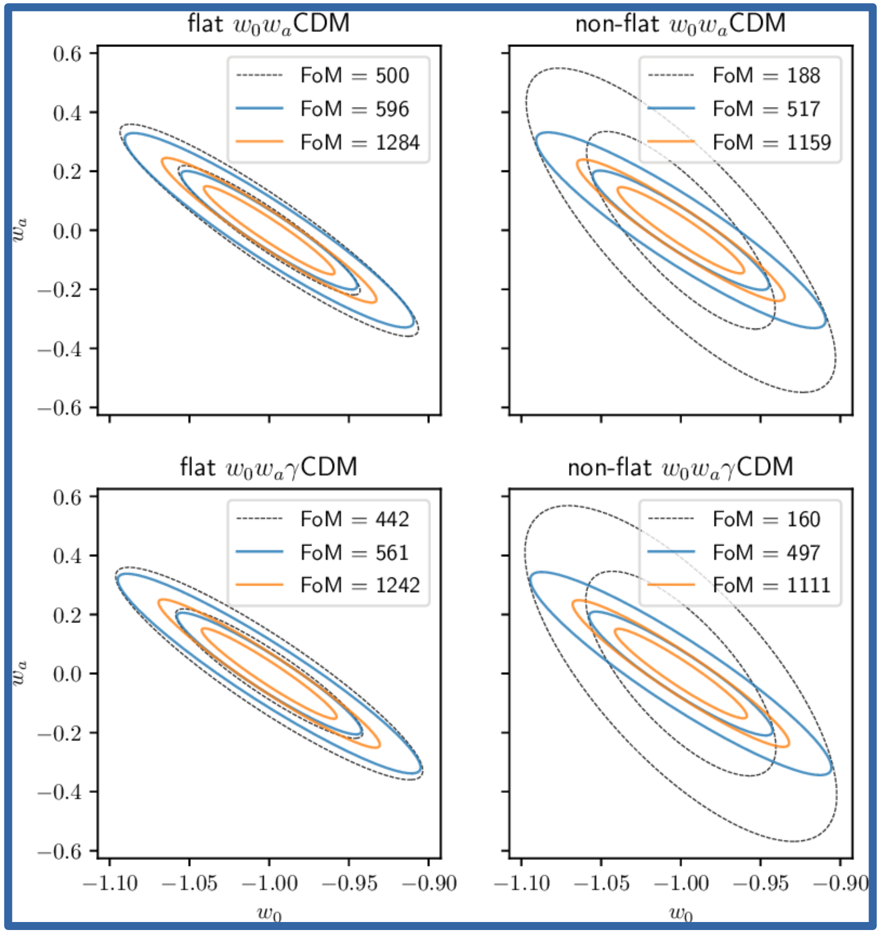
ABSTRACT

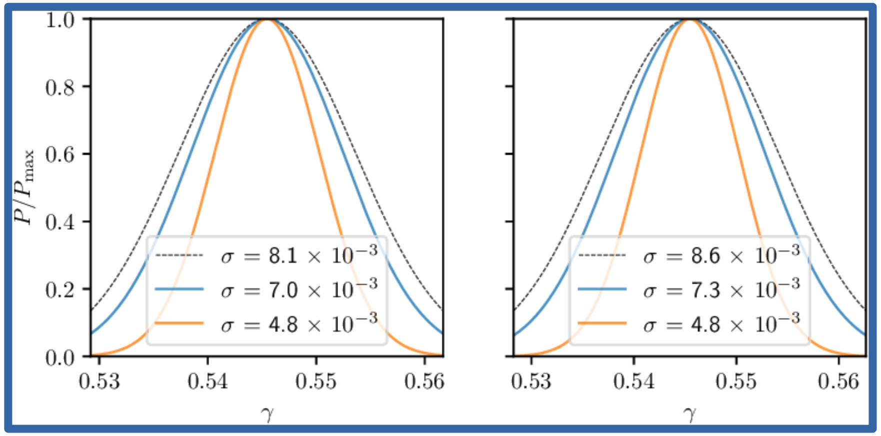
The combination and cross-correlation of the upcoming *Euclid* data with cosmic microwave background (CMB) measurements is a source of great expectation since it will provide the largest lever arm of epochs, ranging from recombination to structure formation across the entire past light cone. In this work, we present forecasts for the joint analysis of *Euclid* and CMB data on the cosmological parameters of the standard cosmological model and some of its extensions. This work expands and complements the recently published forecasts based on *Euclid*-specific probes, namely galaxy clustering, weak lensing, and their cross-correlation. With some assumptions on the specifications of current and future CMB experiments, the predicted constraints are obtained from both a standard Fisher formalism and a posterior-fitting approach based on actual CMB data. Compared to a *Euclid*-only analysis, the addition of CMB data leads to a substantial impact on constraints for all cosmological parameters of the standard Λ-cold-dark-matter model, with improvements reaching up to a factor of ten. For the parameters of extended models, which include a redshift-dependent dark energy equation of state, non-zero curvature, and a phenomenological modification of gravity, improvements can be of the order of two to three, reaching higher than ten in some cases. The results highlight the crucial importance for cosmological constraints of the combination and cross-correlation of *Euclid* probes with CMB data.

Key words. Cosmology:large-scale structure of Universe, cosmic background radiation, Surveys, Methods: statistical

V) Focus: Pessimistic Euclid+CMB from SO





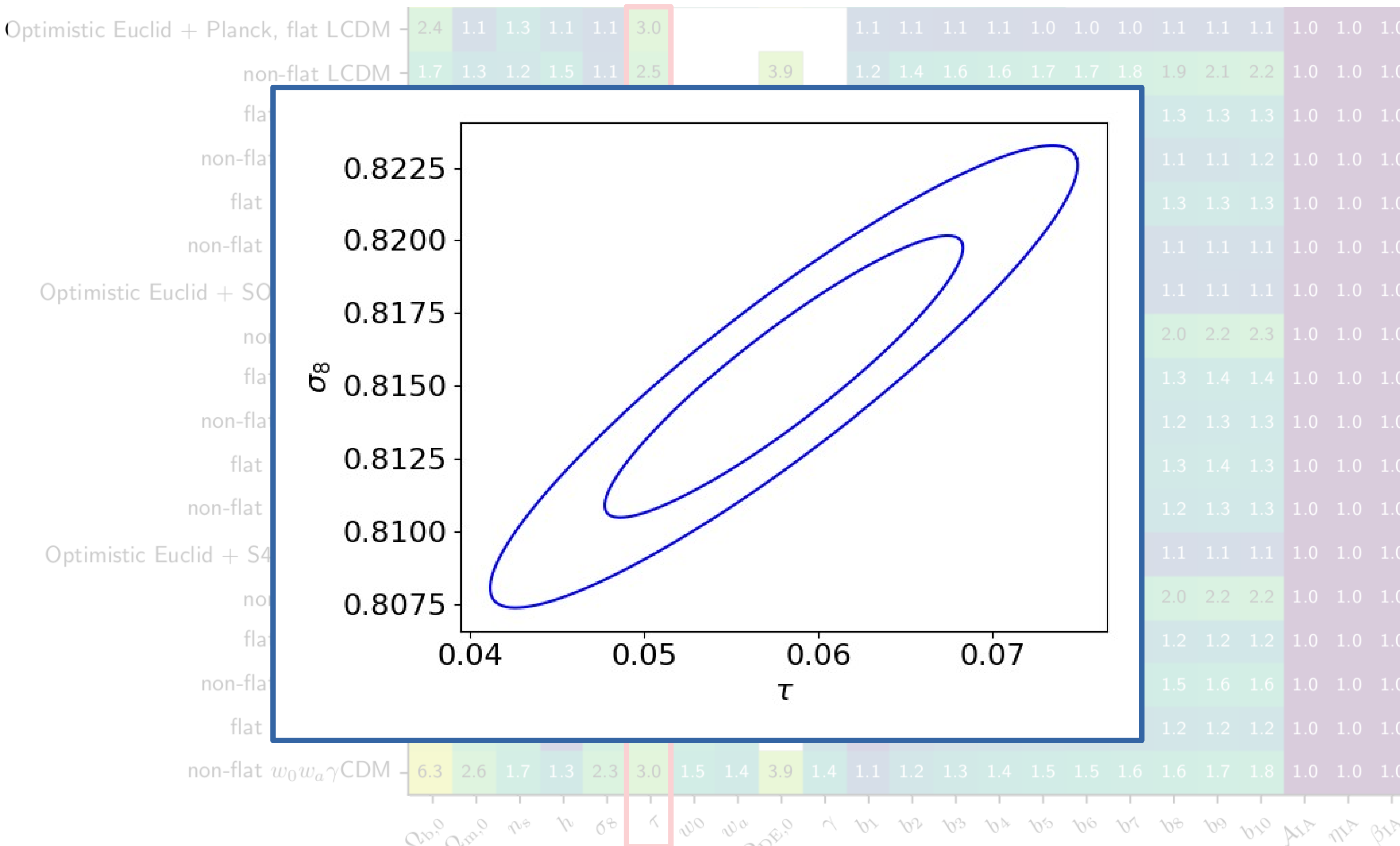


V) Focus on tau

	$\Omega_{b,0}$	$\Omega_{m,0}$	n_s	h	σ_8	τ	w_0	w_a	$\Omega_{DE,0}$	γ	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	A_{IA}	η_{IA}	β_{IA}
Optimistic Euclid + Planck, flat LCDM	2.4	1.1	1.3	1.1	1.1	3.0					1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.1	1.1	1.1	1.0	1.0	1.0
non-flat LCDM	1.7	1.3	1.2	1.5	1.1	2.5			3.9		1.2	1.4	1.6	1.6	1.7	1.7	1.8	1.9	2.1	2.2	1.0	1.0	1.0
flat w_0w_aCDM	2.2	1.7	1.6	1.1	1.5	1.9	1.6	1.4			1.0	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.0	1.0	1.0
non-flat w_0w_aCDM	2.1	1.3	1.1	1.2	1.4	1.8	1.4	1.6	3.6		1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.0	1.0	1.0
flat $w_0w_a\gamma$CDM	2.4	1.9	1.7	1.1	1.7	1.9	1.5	1.3		1.2	1.0	1.1	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.0	1.0	1.0
non-flat $w_0w_a\gamma$CDM	2.5	1.5	1.1	1.1	1.7	1.8	1.3	1.5	3.1	1.3	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.0	1.0	1.0
Optimistic Euclid + SO, flat LCDM	5.3	1.1	1.5	1.5	1.1	3.9					1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.0	1.0	1.0
non-flat LCDM	4.0	1.3	1.4	1.5	1.2	1.9			4.1		1.2	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.2	2.3	1.0	1.0	1.0
flat w_0w_aCDM	4.3	2.1	1.8	1.2	1.7	2.4	1.8	1.5			1.0	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.4	1.4	1.0	1.0	1.0
non-flat w_0w_aCDM	4.4	1.6	1.3	1.2	1.7	2.4	1.6	1.5	3.0		1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.0	1.0	1.0
flat $w_0w_a\gamma$CDM	4.6	2.2	1.9	1.1	2.0	2.4	1.6	1.3		1.2	1.0	1.1	1.2	1.3	1.3	1.3	1.3	1.3	1.4	1.3	1.0	1.0	1.0
non-flat $w_0w_a\gamma$CDM	4.9	1.9	1.4	1.2	1.9	2.5	1.4	1.3	3.0	1.2	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.0	1.0	1.0
Optimistic Euclid + S4, flat LCDM	6.5	1.1	1.6	1.6	1.1	3.9					1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.0	1.0	1.0
non-flat LCDM	4.9	1.3	1.5	1.3	1.3	1.4			3.7		1.4	1.6	1.7	1.7	1.8	1.8	1.9	2.0	2.2	2.2	1.0	1.0	1.0
flat w_0w_aCDM	5.2	2.1	1.8	1.1	1.9	2.8	1.9	1.5			1.0	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.0	1.0	1.0
non-flat w_0w_aCDM	5.5	2.1	1.6	1.3	2.1	2.9	1.8	1.5	3.0		1.2	1.3	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.0	1.0	1.0
flat $w_0w_a\gamma$CDM	5.6	2.1	1.7	1.0	2.0	2.8	1.7	1.4		1.2	1.0	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.0	1.0	1.0
non-flat $w_0w_a\gamma$CDM	6.3	2.6	1.7	1.3	2.3	3.0	1.5	1.4	3.9	1.4	1.1	1.2	1.3	1.4	1.5	1.5	1.6	1.6	1.7	1.8	1.0	1.0	1.0

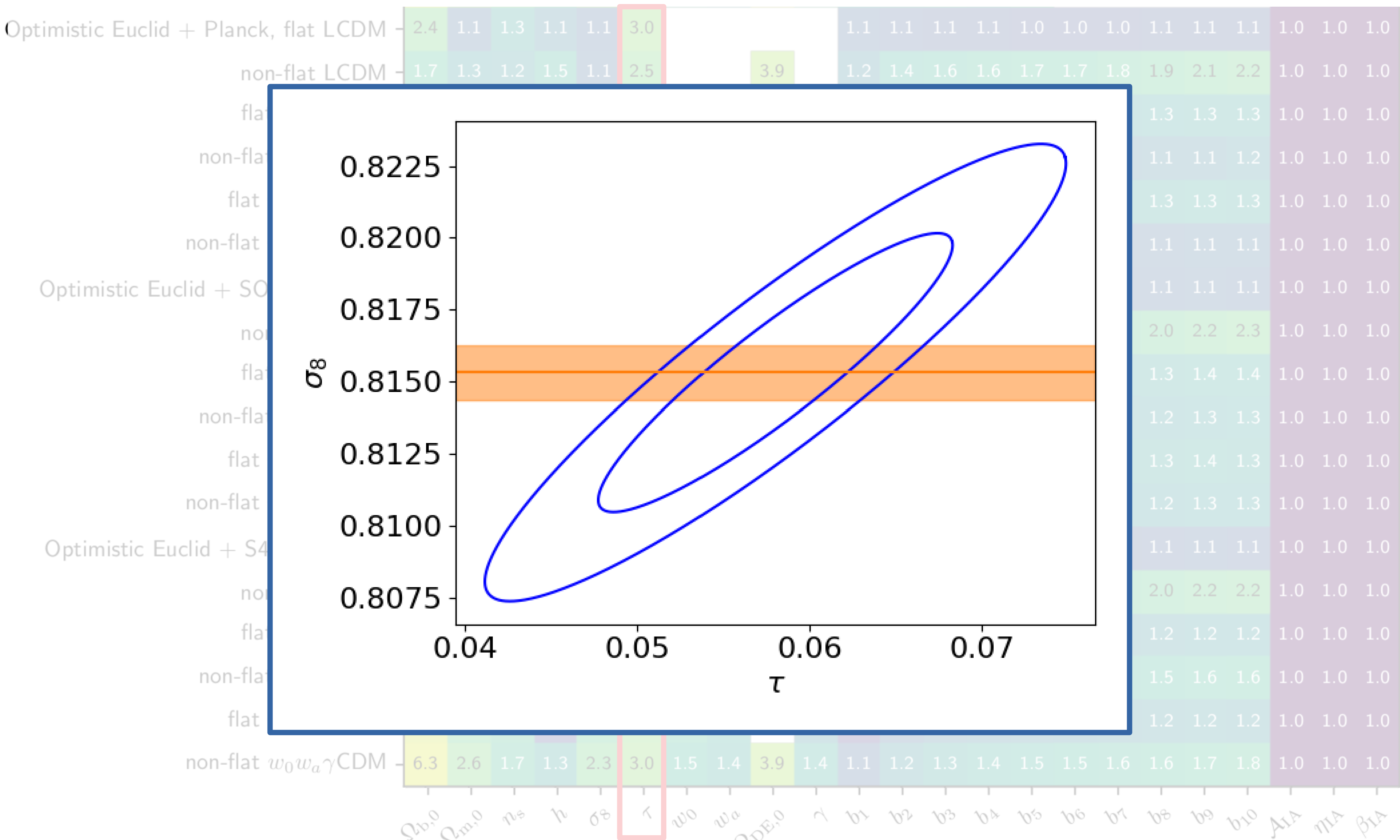
Improvement factors = $\sigma_{before} / \sigma_{after}$

V) Focus on tau



Improvement factors = $\sigma_{before} / \sigma_{after}$

V) Focus on tau



Improvement factors = σ_{before} / σ_{after}

V) Further observations

- QSO spectra
- Lyman-alpha forests
- IGM temperature measurements
- ...

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- QSO spectra
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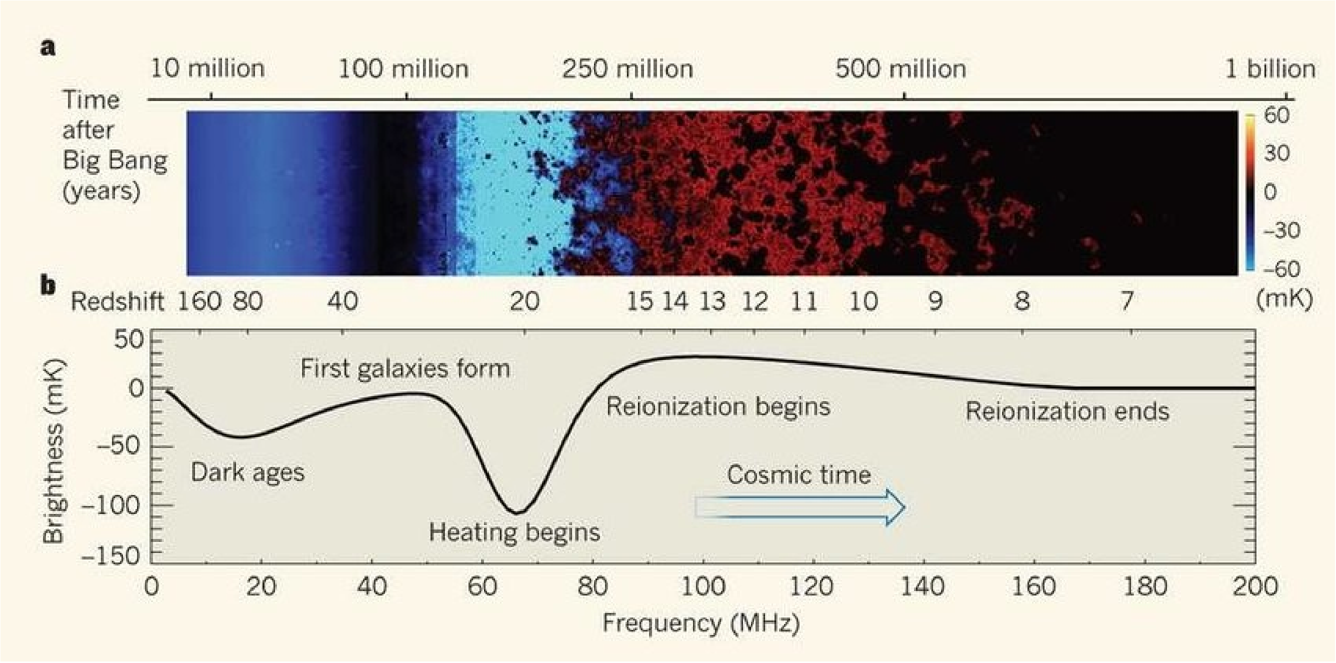
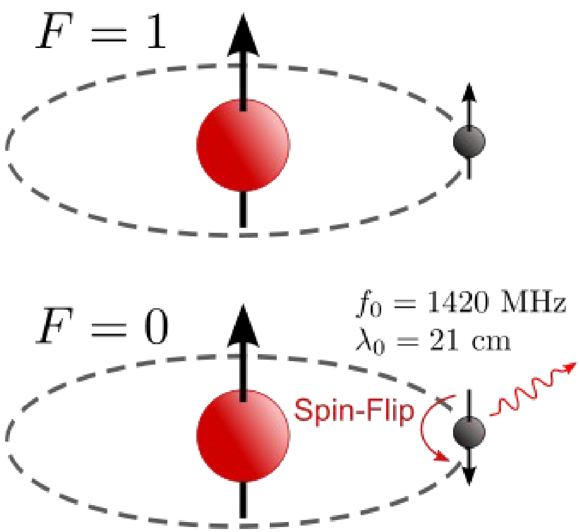
- <u>Neutral hydrogen (21cm) absorption/emission</u>





The end

Thank you very much
for your attention !