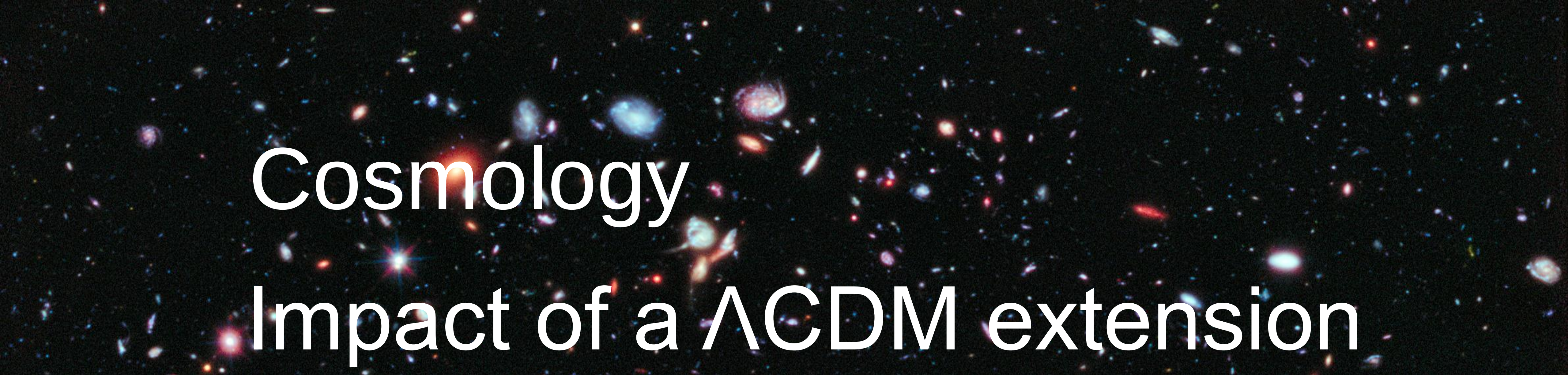
Impact of a ΛCDM extension on UHECR propagation

CRPropa Workshop 25th of September Janning Meinert meinert@uni-wuppertal.de



Cosmology

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UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
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SFB1491
PIERRE AUGER OBSERVATORY

Cosmology

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Astroparticlephysics

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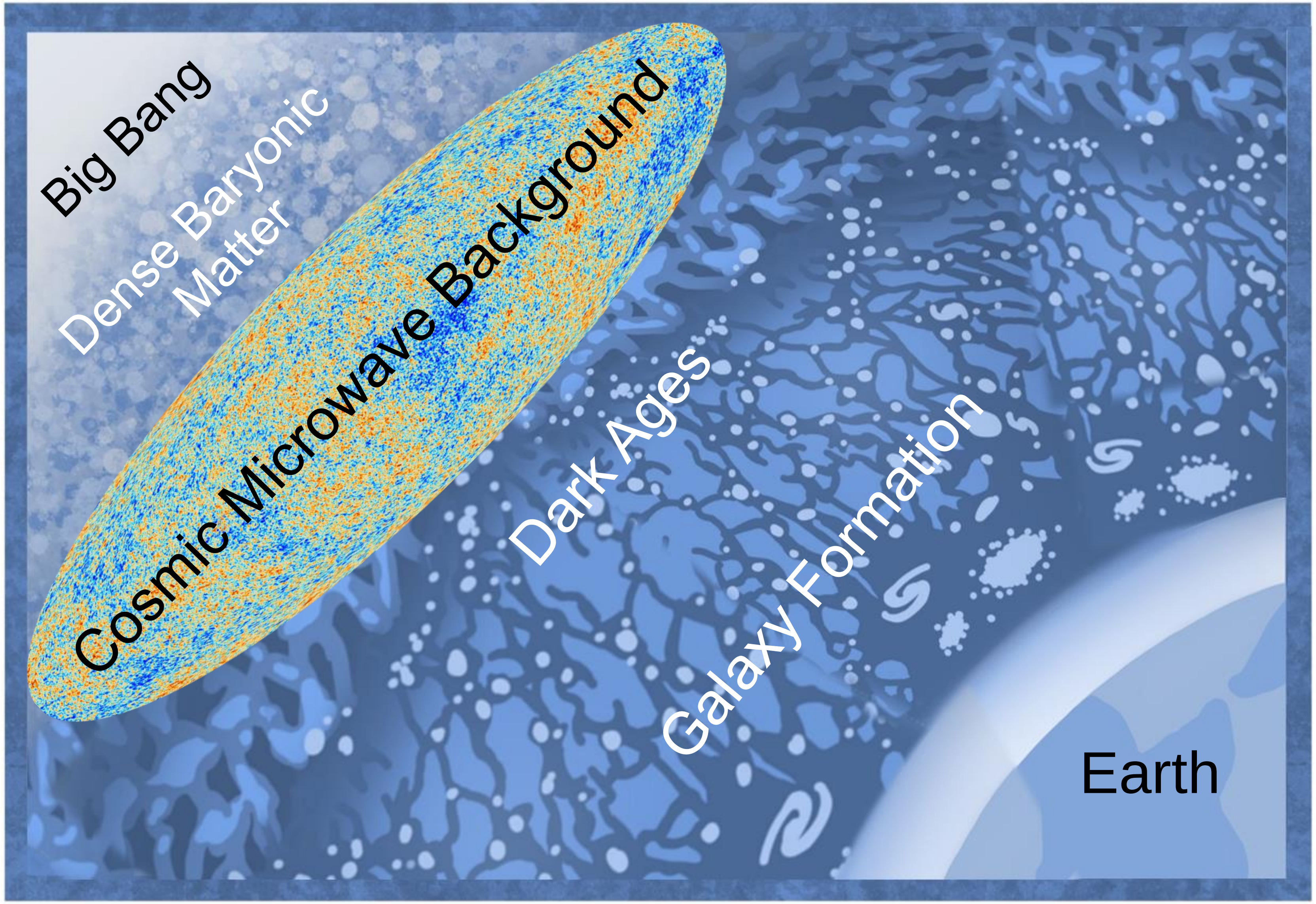
Epochs of the Universe



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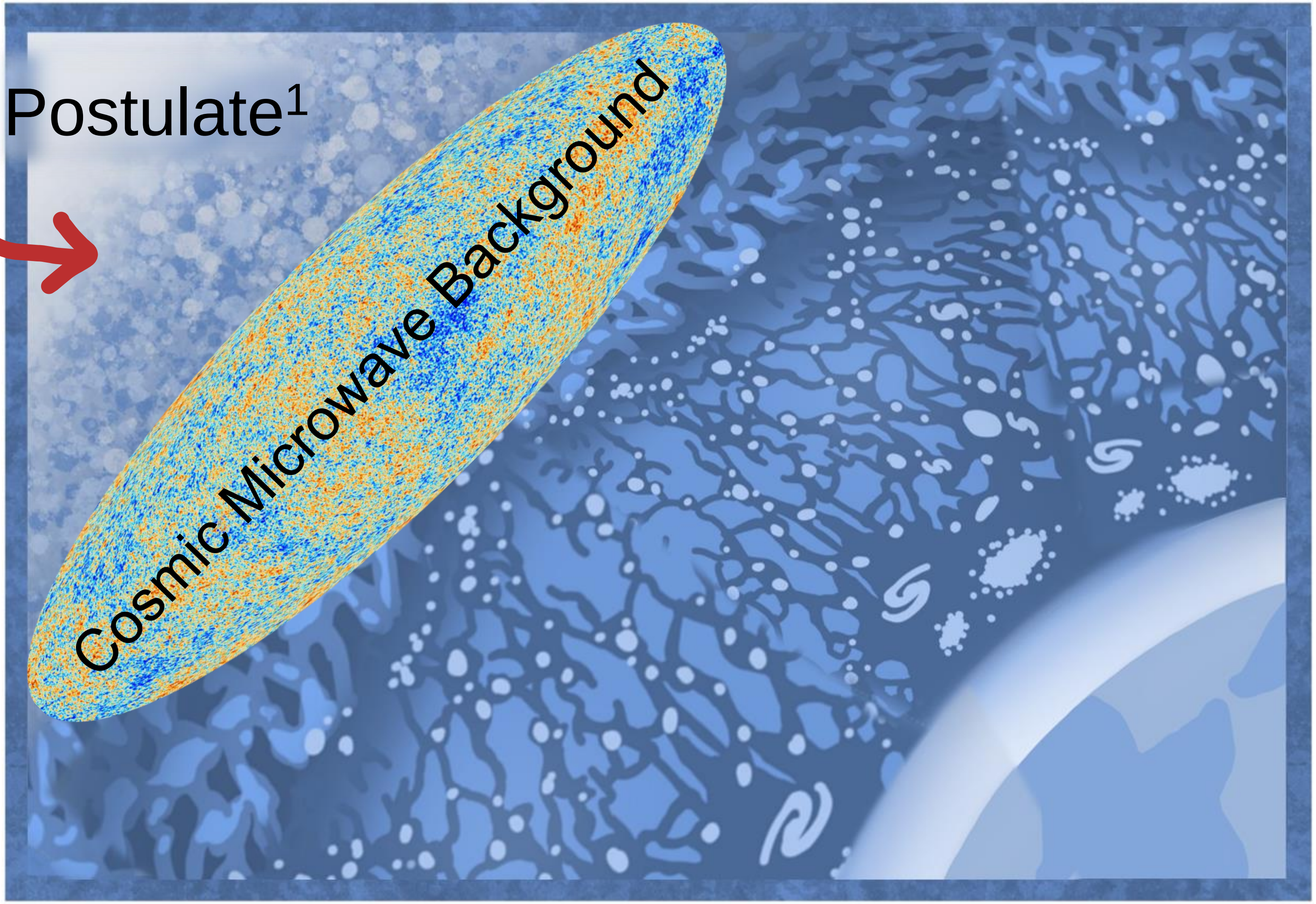
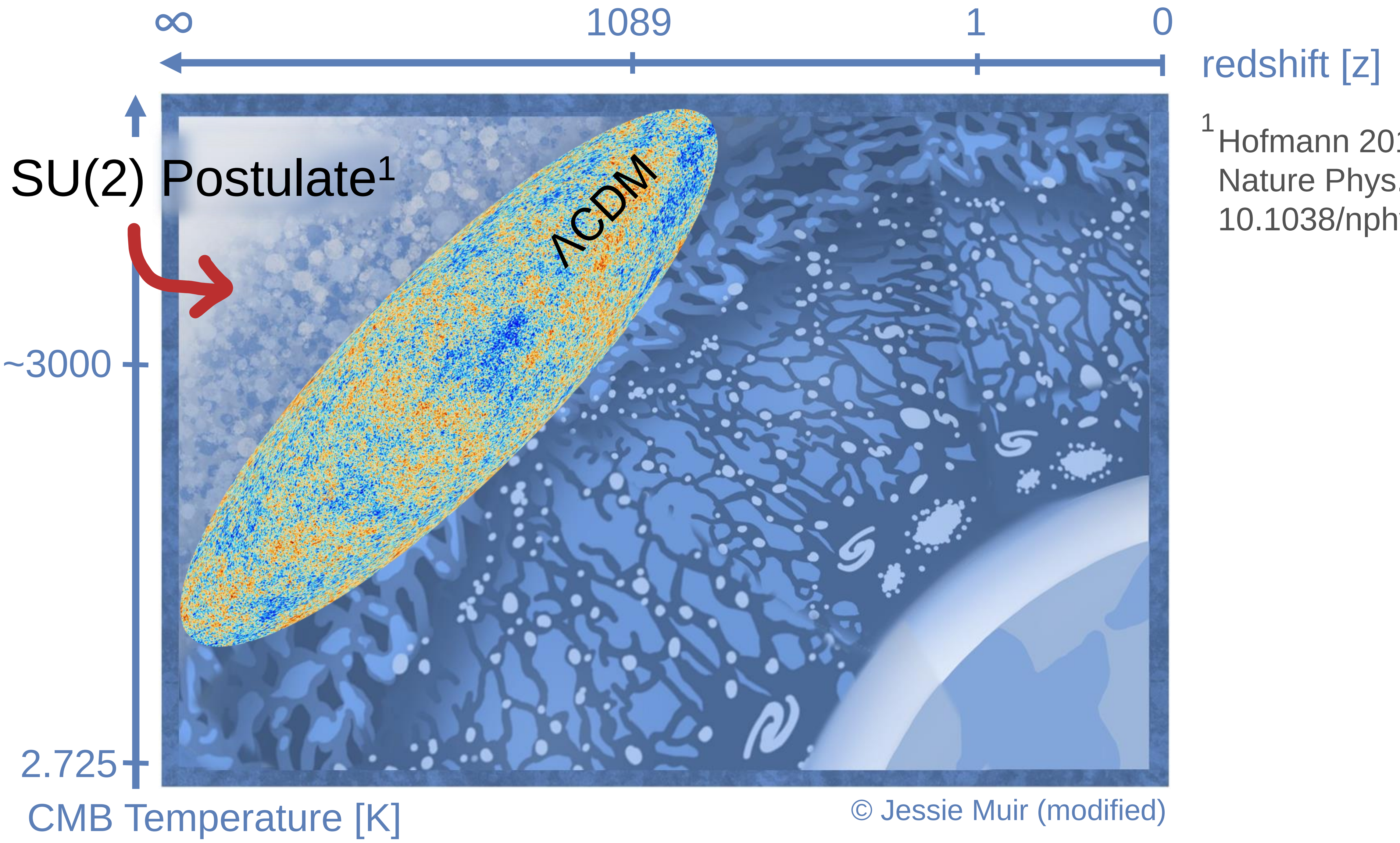
Epochs of the Universe

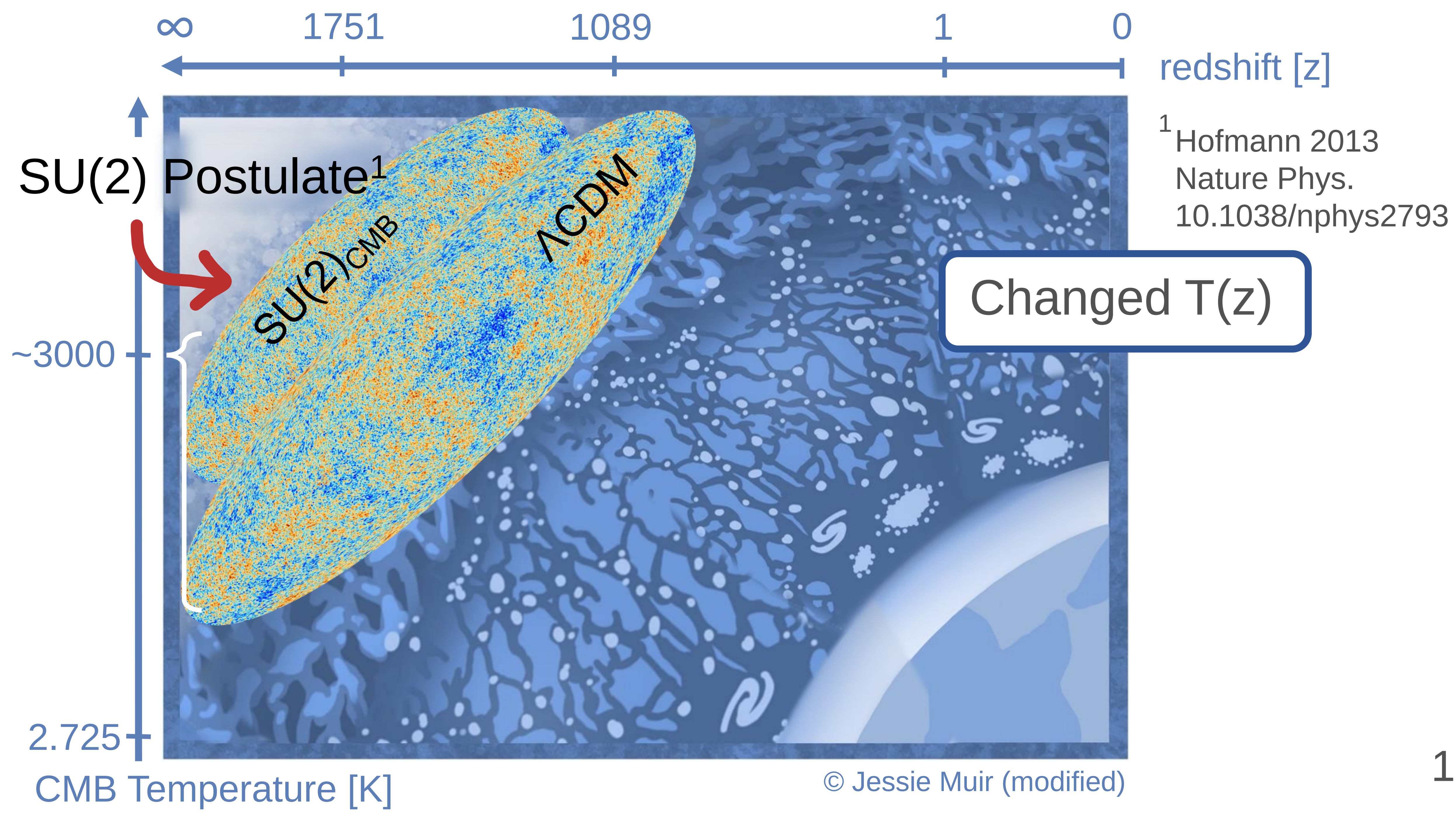
SU(2) Postulate[1]



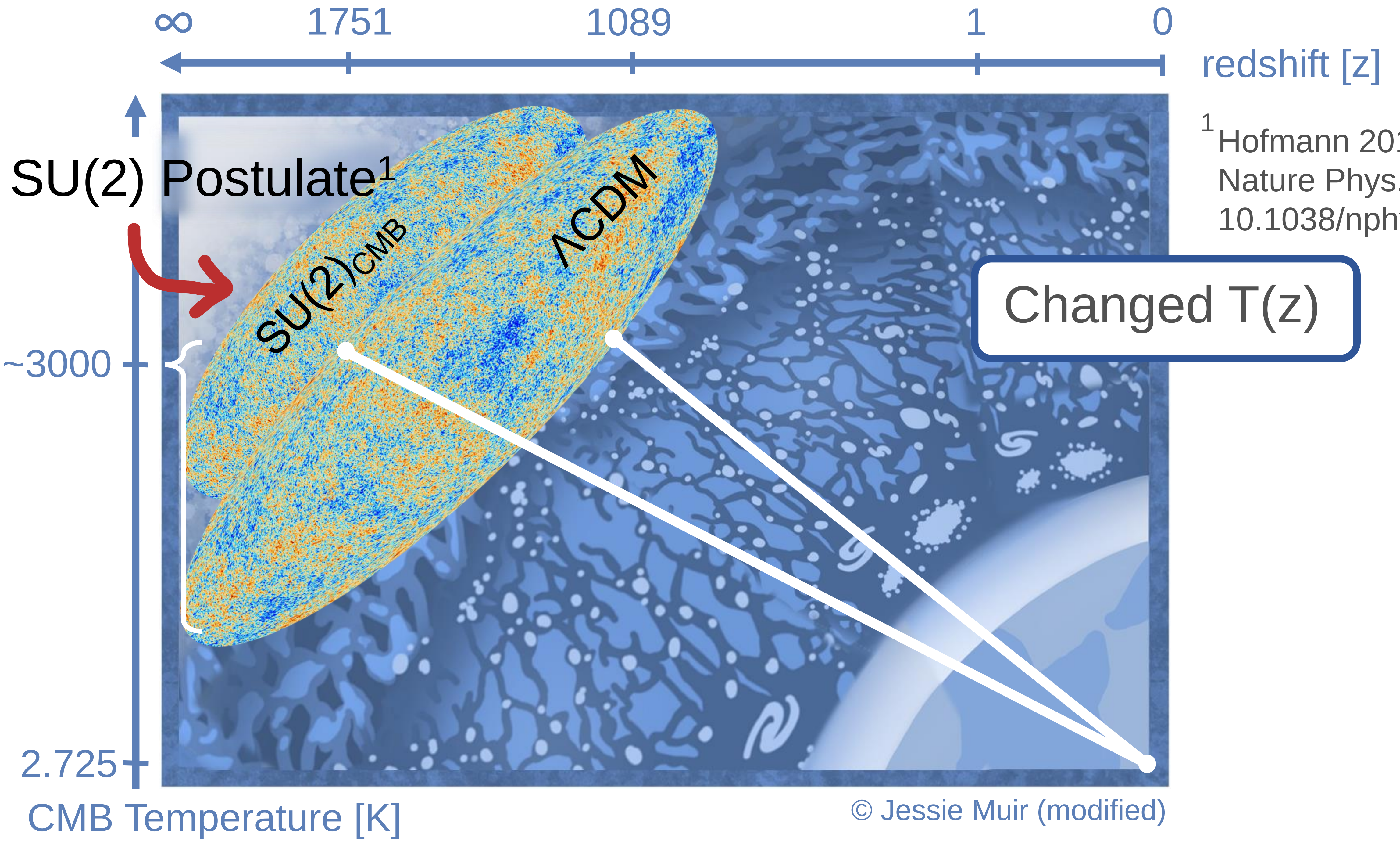
[1] Hofmann 2013 Nature Phys. 10.1038/nphys2793



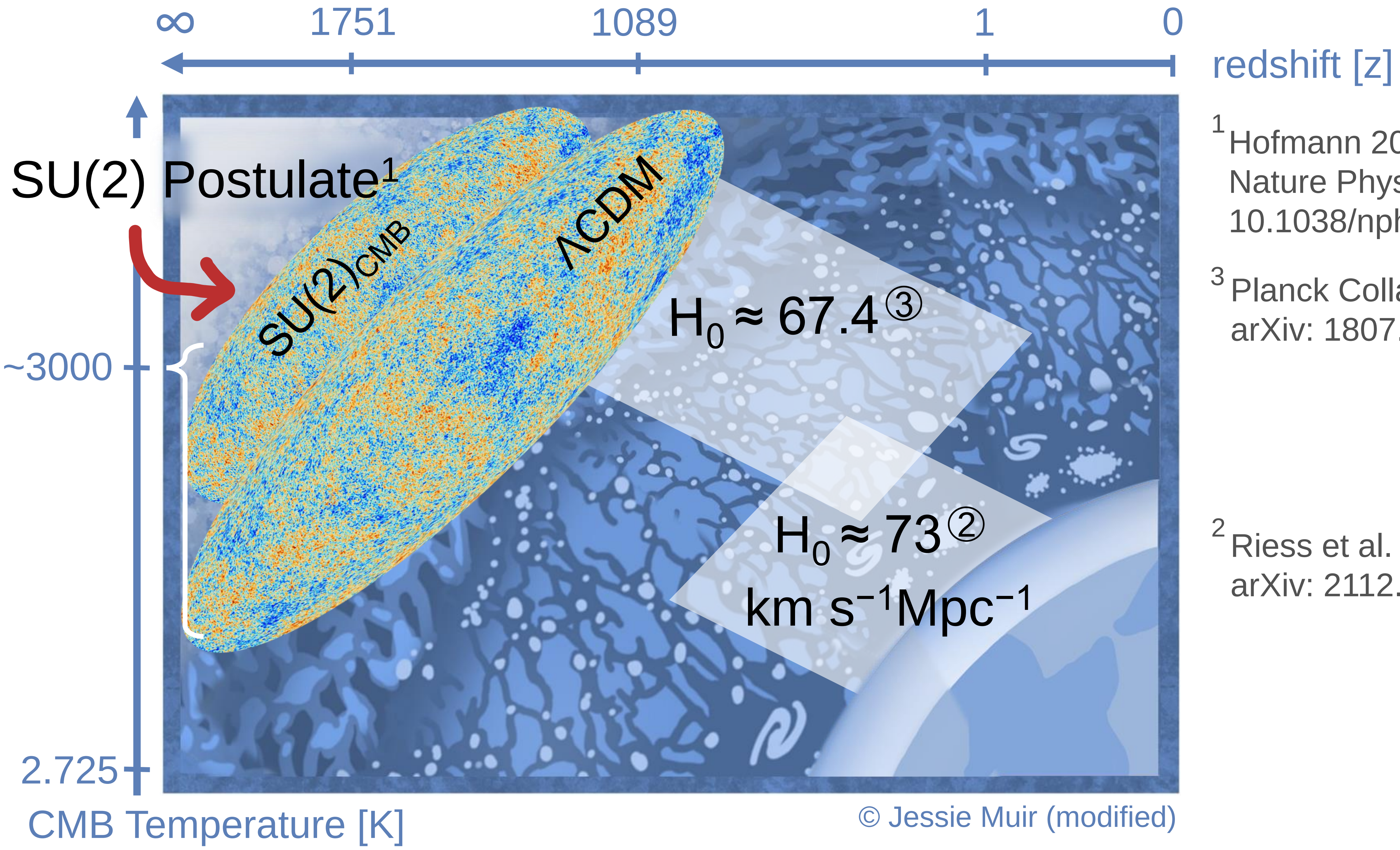
[1] Hofmann 2013 Nature Phys. 10.1038/nphys2793



∞
1751
1089
1
0
redshift [z]
[1] Hofmann 2013
Nature Phys.
10.1038/nphys2793
SU(2) Postulate[1]
SU(2)CMB
ΛCDM
Changed T(z)
~3000
2.725
CMB Temperature [K]
© Jessie Muir (modified)



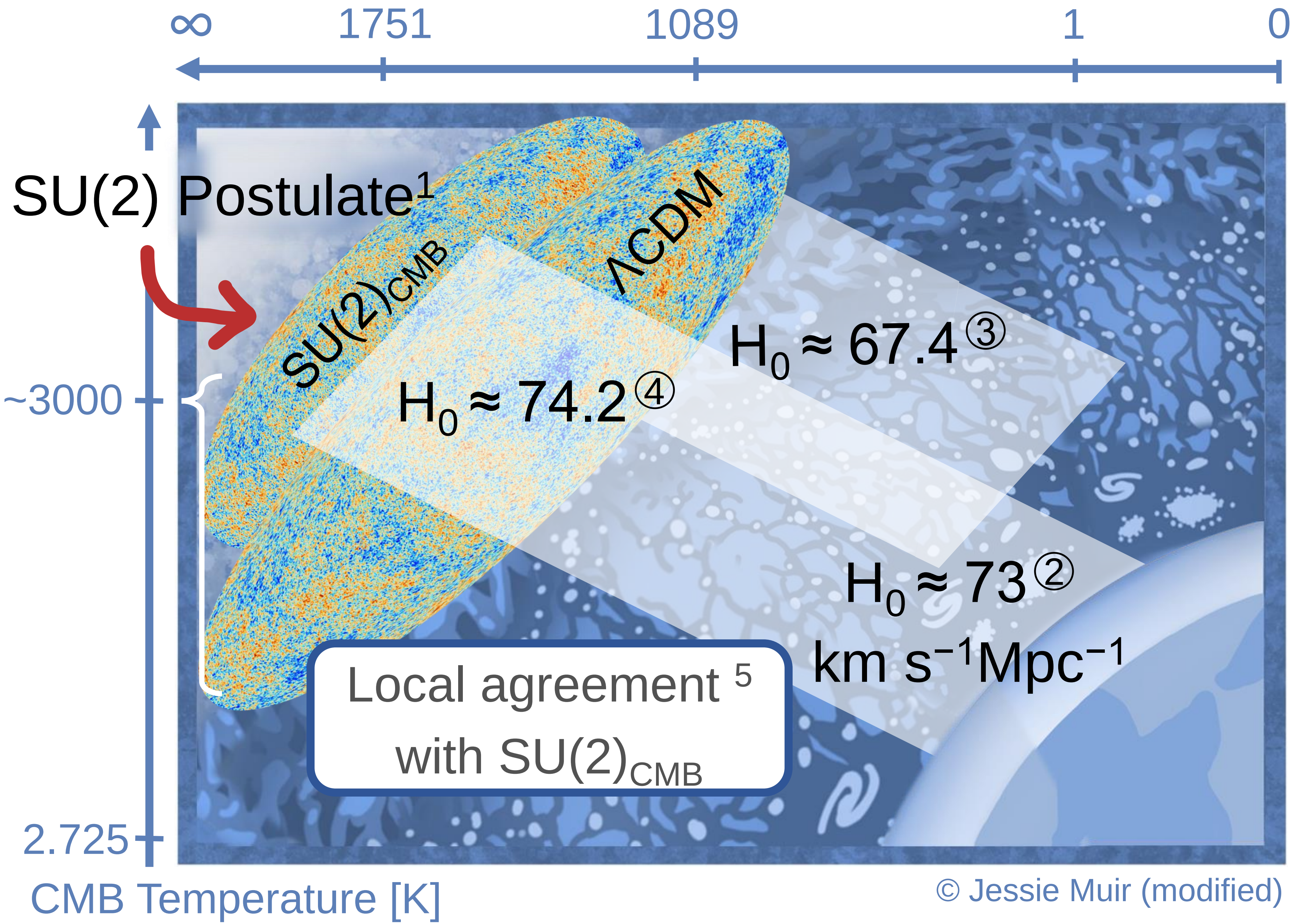
[1] Hofmann 2013 Nature Phys. 10.1038/nphys2793



[1] Hofmann 2013
Nature Phys.
10.1038/nphys2793

[3] Planck Collaboration
arXiv: 1807.06209

[2] Riess et al. 2021
arXiv: 2112.04510



[1] Hofmann 2013
Nature Phys.
10.1038/nphys2793

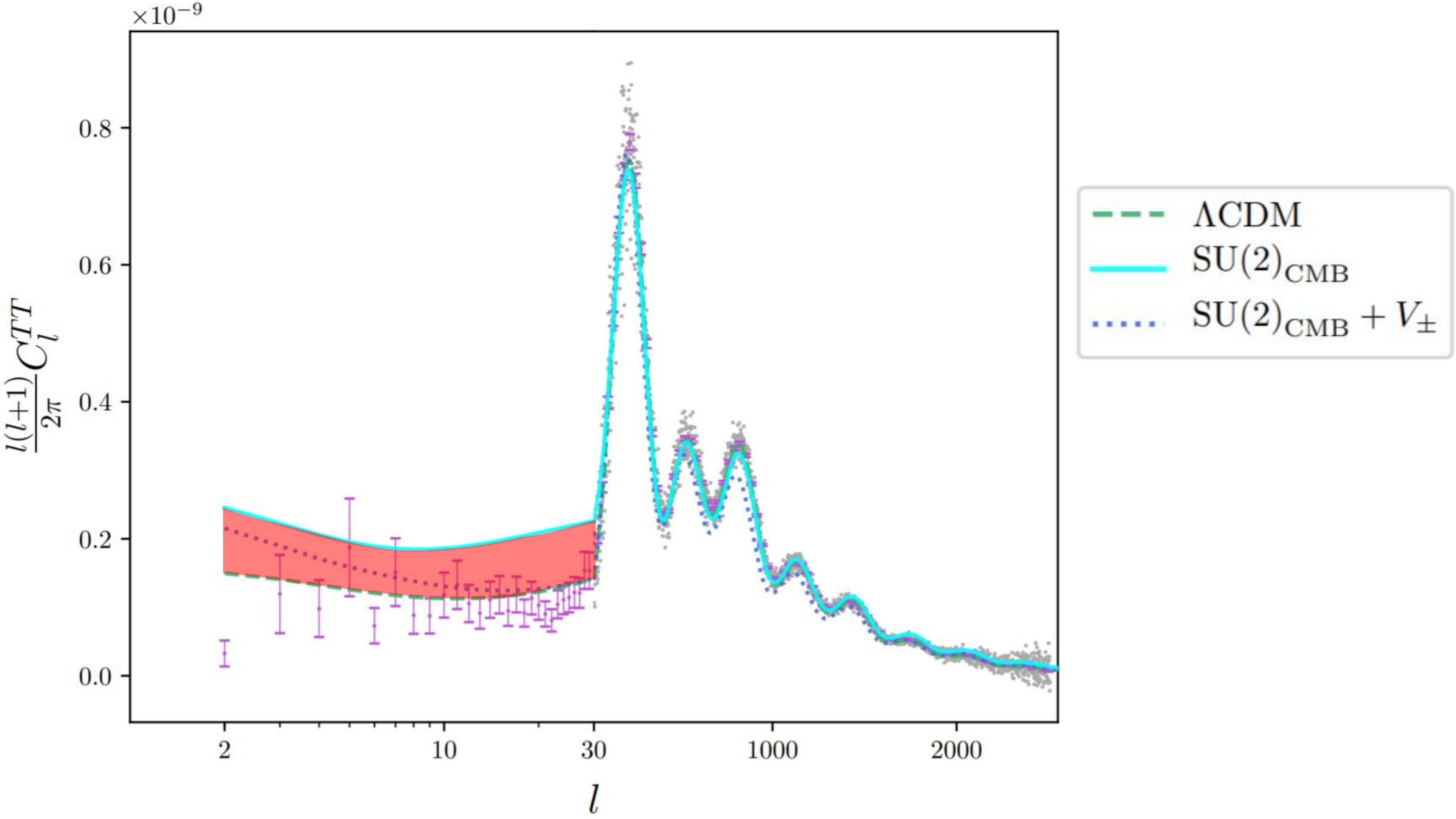
[3] Planck Collaboration
arXiv: 1807.06209

[4] Hahn et al. 2018
MNRAS
arXiv: 1810.01253

[2] Riess et al. 2021
arXiv: 2112.04510

[5] Hofmann+JM+Balaji
2023, AdP.
arXiv: 2205.11450

$SU(2)_{CMB}$ Fit



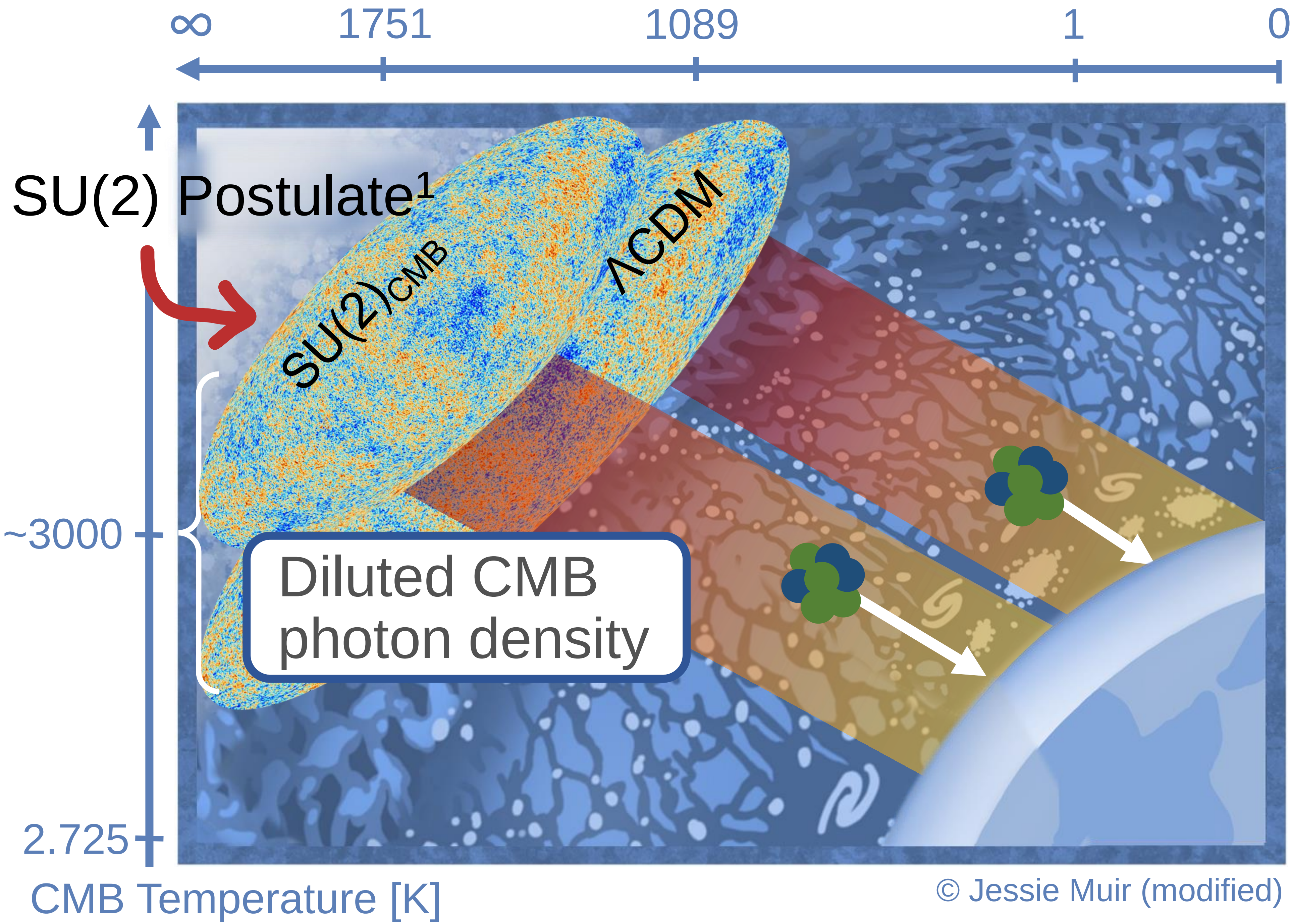
Hahn + Hofmann 2018, MNRAS, arxiv:1810.01253

Cosmological parameters

Parameter	ΛCDM (TT,TE,EE+lowE)	SU(2)
z_{re}	7.68 ± 0.79	6.23 ± 0.41
z^*	1089.95 ± 0.27	1715.9 ± 0.19
z_p	-	52.88 ± 4.06
H_0 [km s^{-1} Mpc^{-1}]	67.27 ± 0.60	74.24 ± 1.46
$\Omega_b h^2$	0.02236 ± 0.00015	0.0173 ± 0.0002
Ω_m	0.3166 ± 0.0084	0.384 ± 0.006
σ_8	0.8120 ± 0.0073	0.709 ± 0.020
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.834 ± 0.016	0.8021 ± 0.0227
Ω_{old}	-	0.113 ± 0.002
Ω_{new}	-	0.0771 ± 0.0012

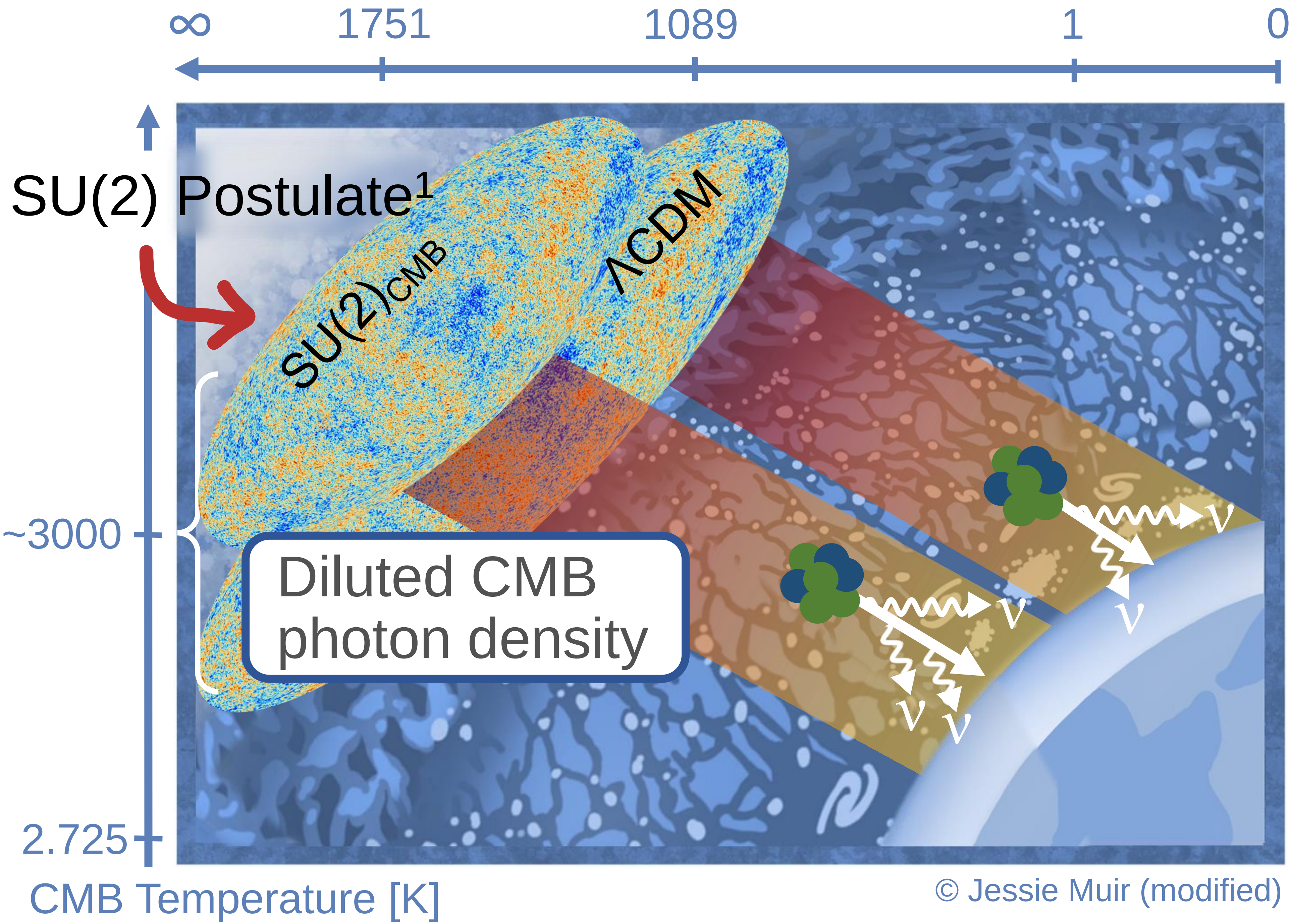
↯BBN?

Hahn + Hofmann 2018, MNRAS, arxiv:1810.01253



[1] Hofmann 2013 Nature Phys. 10.1038/nphys2793

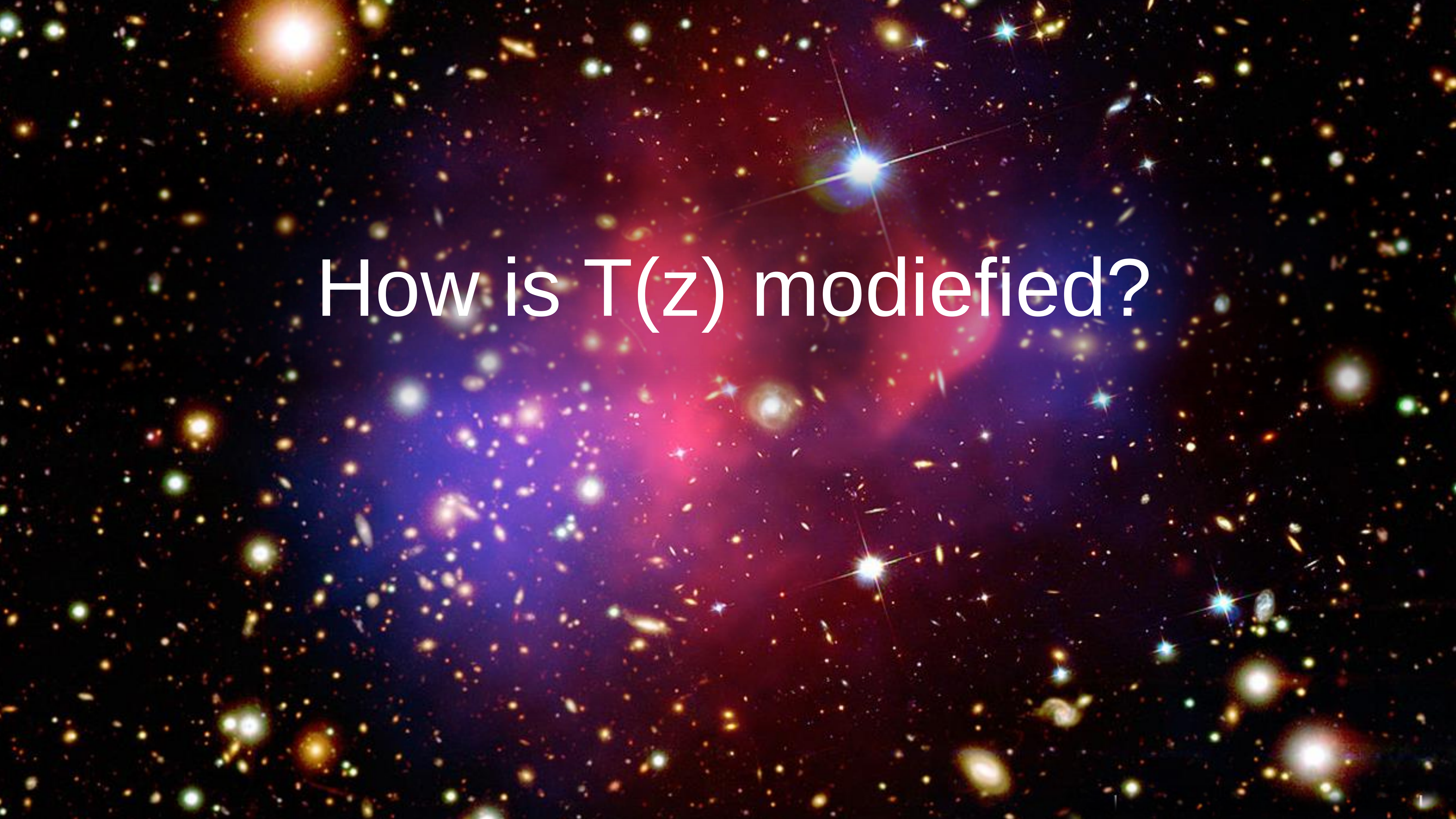
- Longer CR propagation length



[1] Hofmann 2013 Nature Phys. 10.1038/nphys2793

- Longer CR propagation length
- Slightly more cosmogenic neutrinos
- Shallower CR source evolution in comparison with ΛCDM

How is $T(z)$ modiefied?



Friedmann-Lemaître-Robertson-Walker Universe

energy density ↓ energy pressure ↓

continuity eq.:

$$\frac{\mathrm{d}\rho}{\mathrm{d}a} = -\frac{3}{a}(\rho + P) \,, \quad s = \frac{\rho + P}{T} \,.$$

$$a = \exp\left(-\frac{1}{3}\log\frac{s(T)}{s(T(z=0))}\right)$$

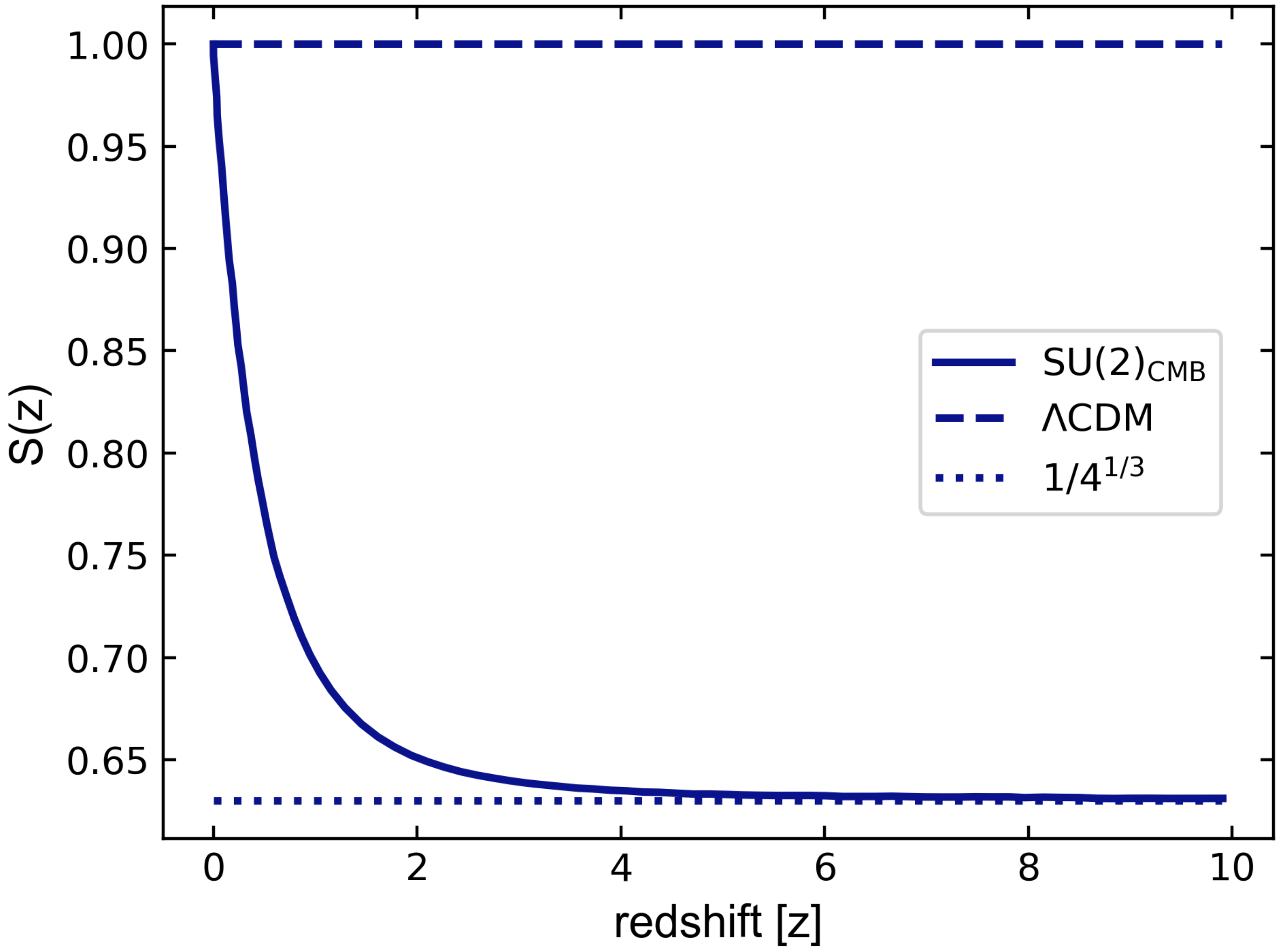
$$\frac{s(T)}{s(T(z=0))} = \frac{8}{2}\left(\frac{T}{T(z{=}0)}\right)^3 \,, \; (T \gg T(z=0))$$

$$a = \frac{1}{z+1} = \left(\frac{1}{4}\right)^{\frac{1}{3}} \frac{T_0}{T}$$

Changed T(z)

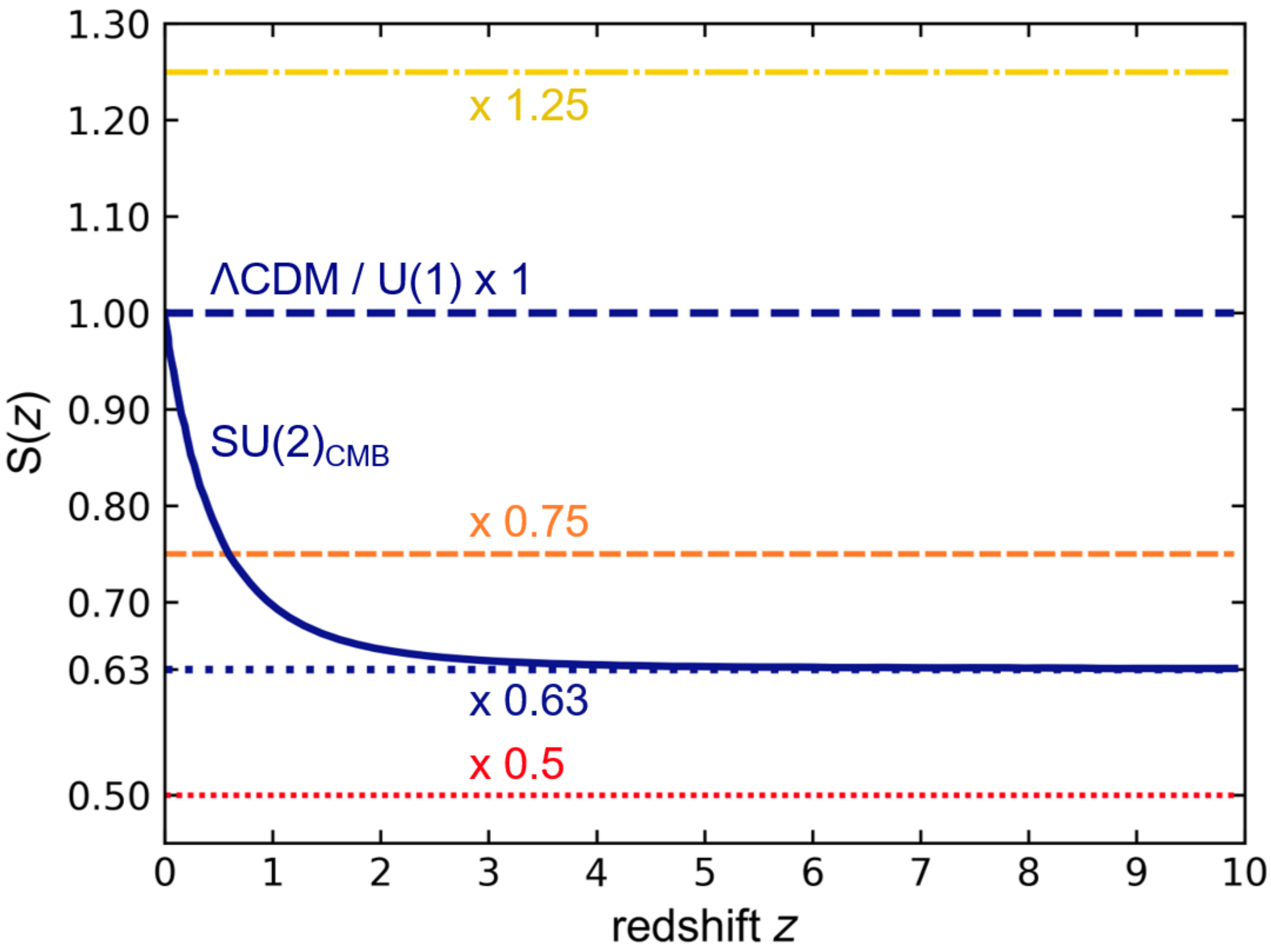
arxiv.org/pdf/1712.08561.pdf

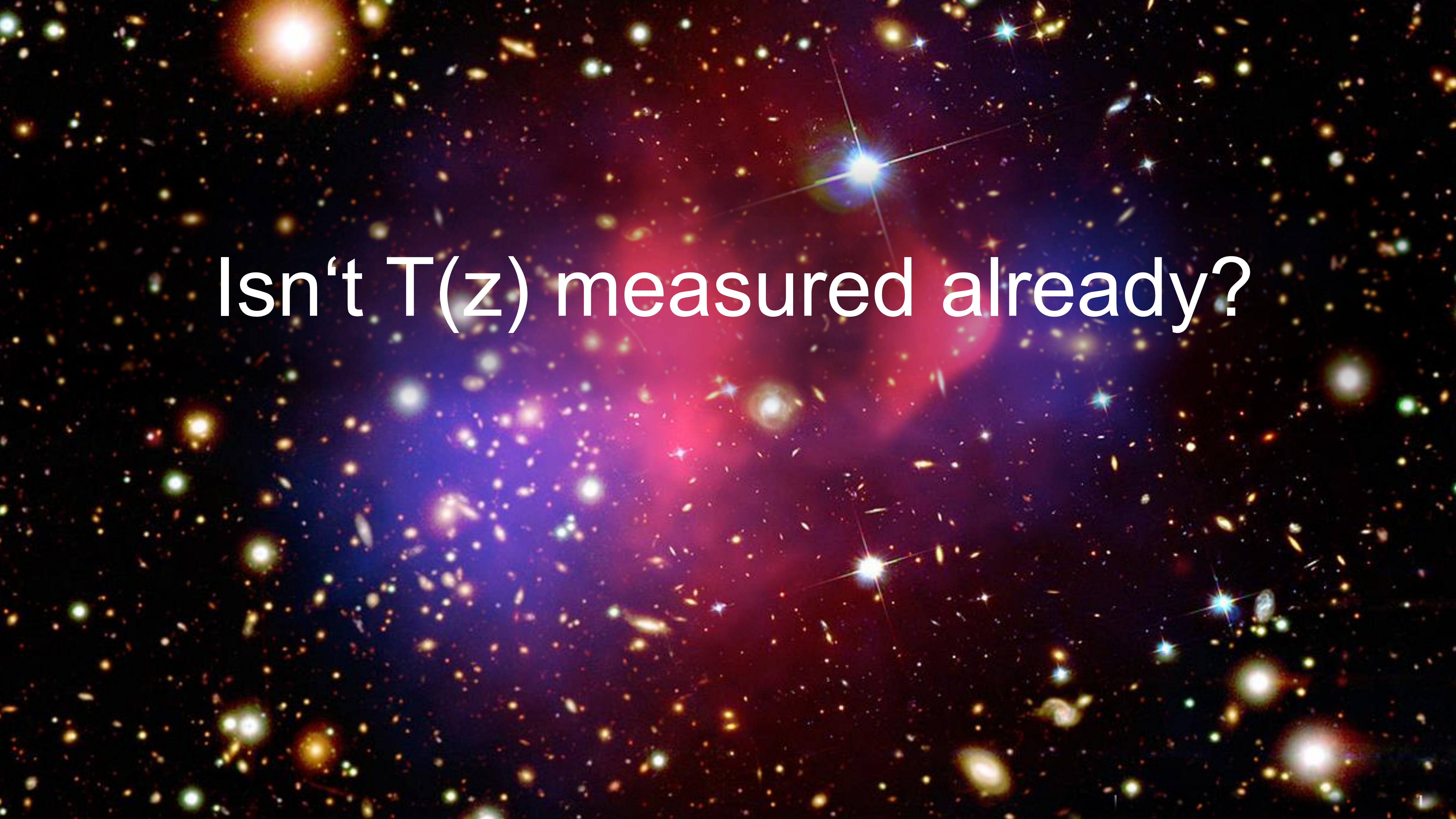
How do we change $T(z) = S(z)\,(1+z)\,T_0$



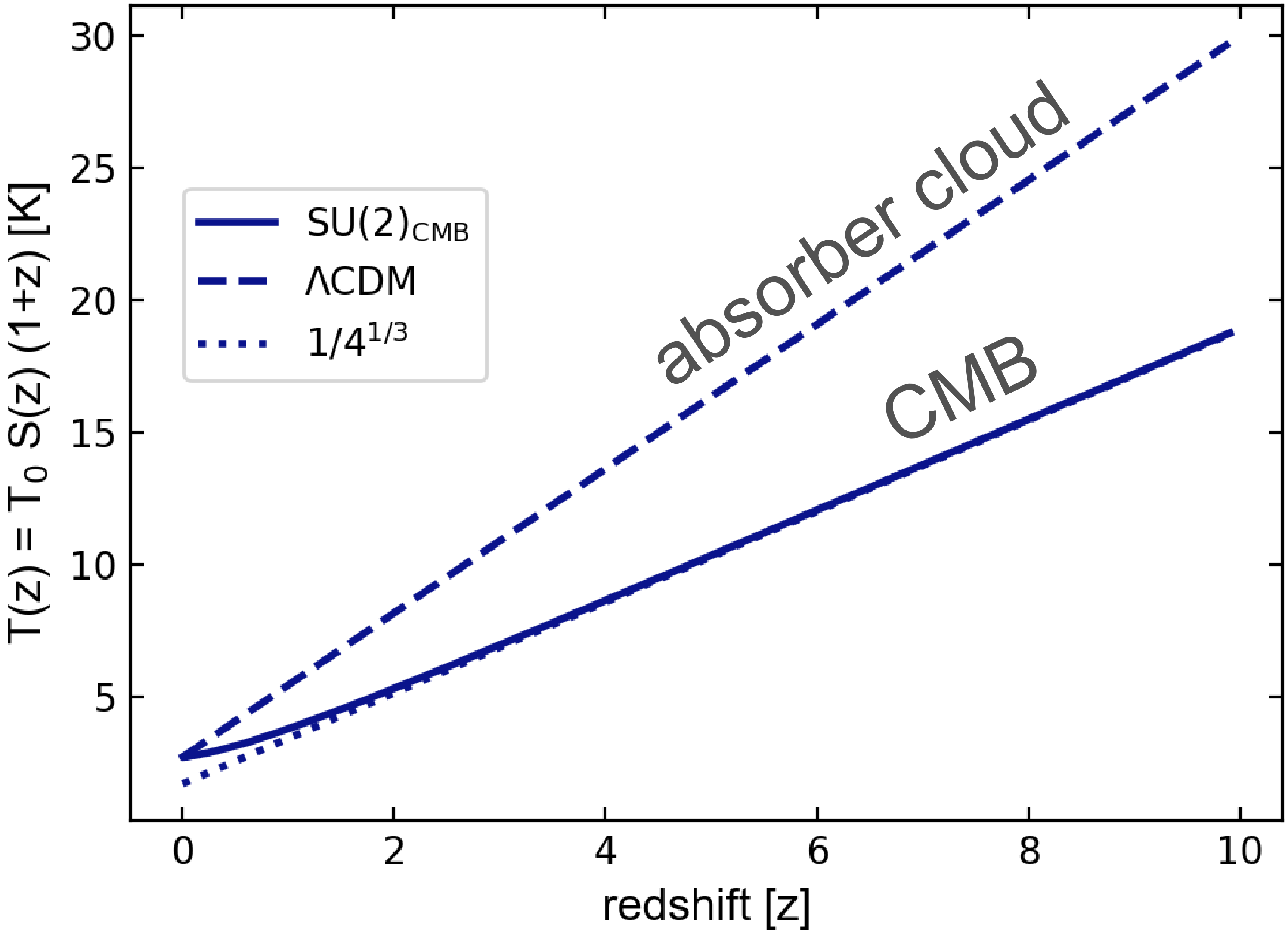
$$\approx \left(\frac{1}{4}\right)^{\frac{1}{3}}$$

How do we change $T(z) = S(z)\,(1+z)\,T_0$

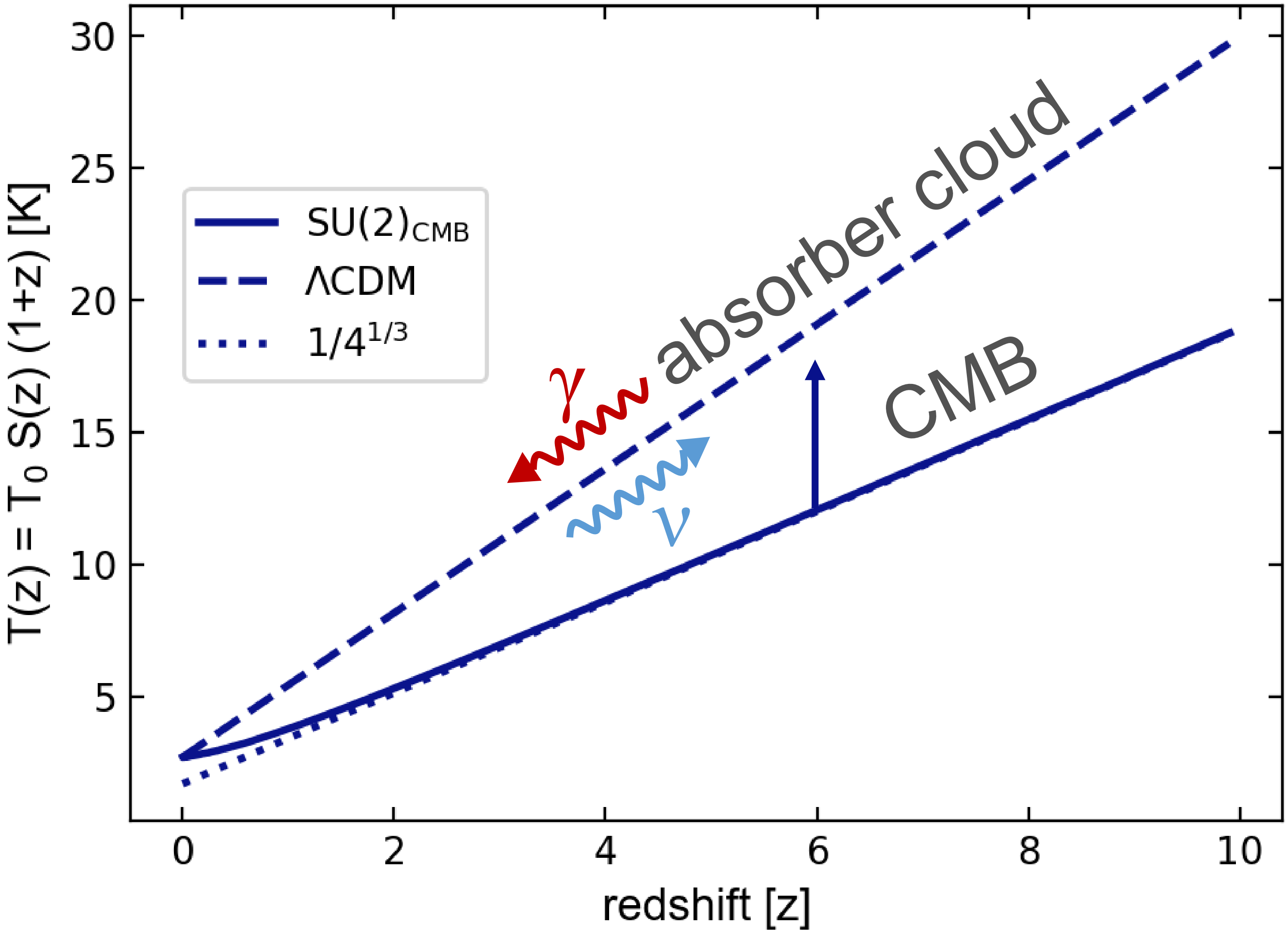



Isn‘t T(z) measured already?

How do we measure T(z)?



How do we measure T(z)?

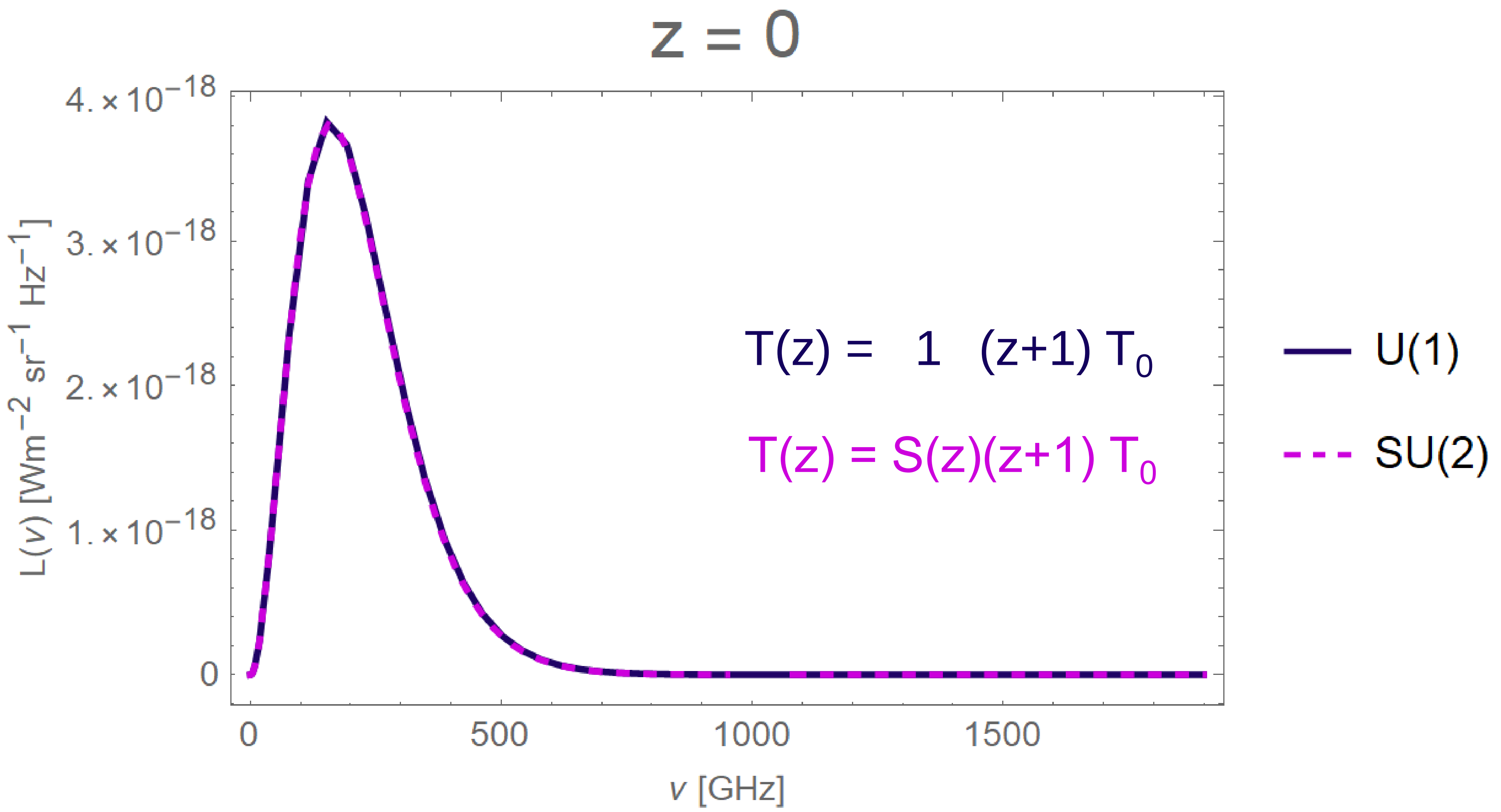


$$T(z) \underset{\text{b.b.}}{\overset{!}{=}} \nu(z)$$

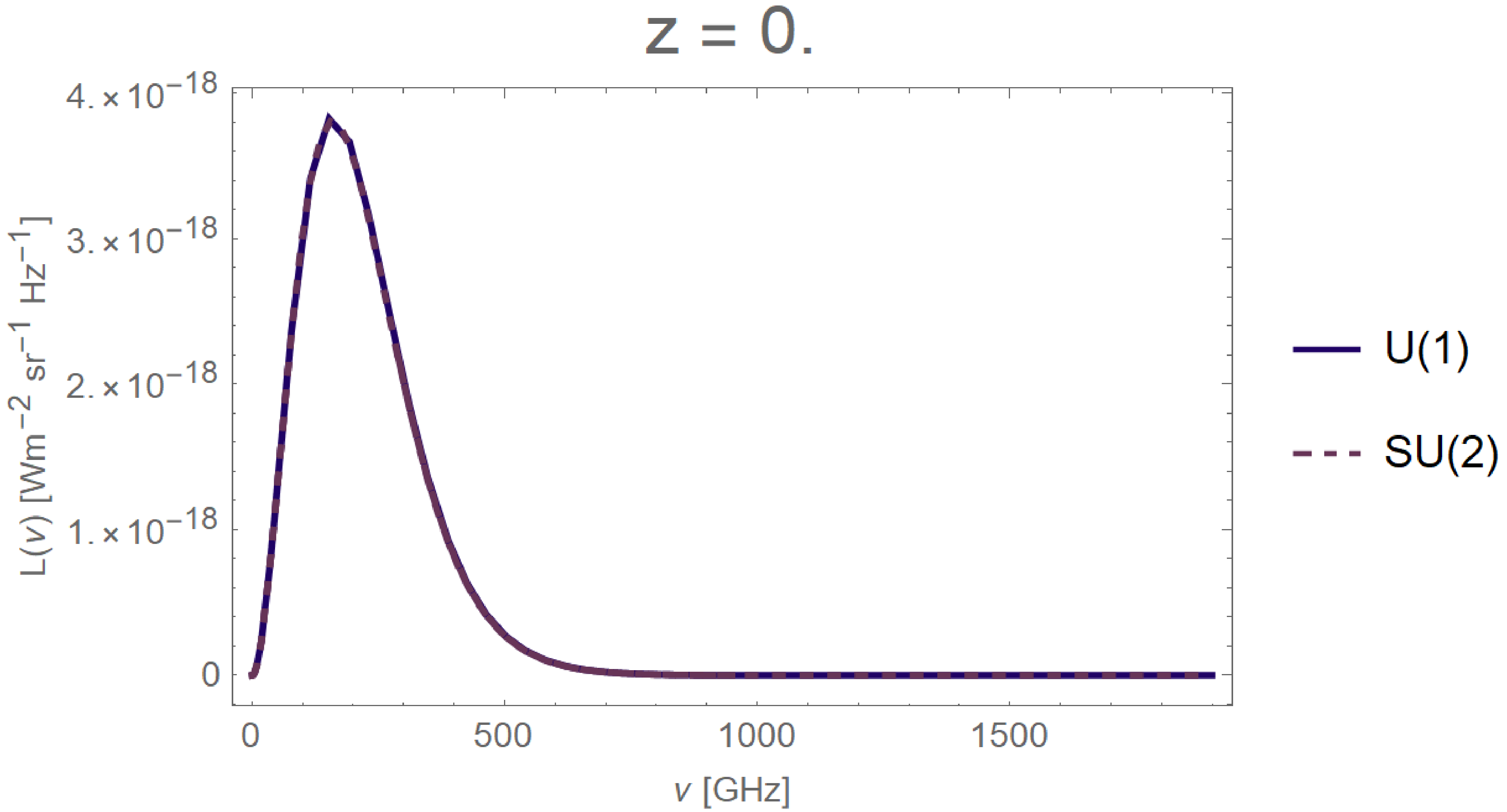
Hofmann + JM 2023
MDPI submitted
arXiv: 2303.16744

Summary of T(z) effect

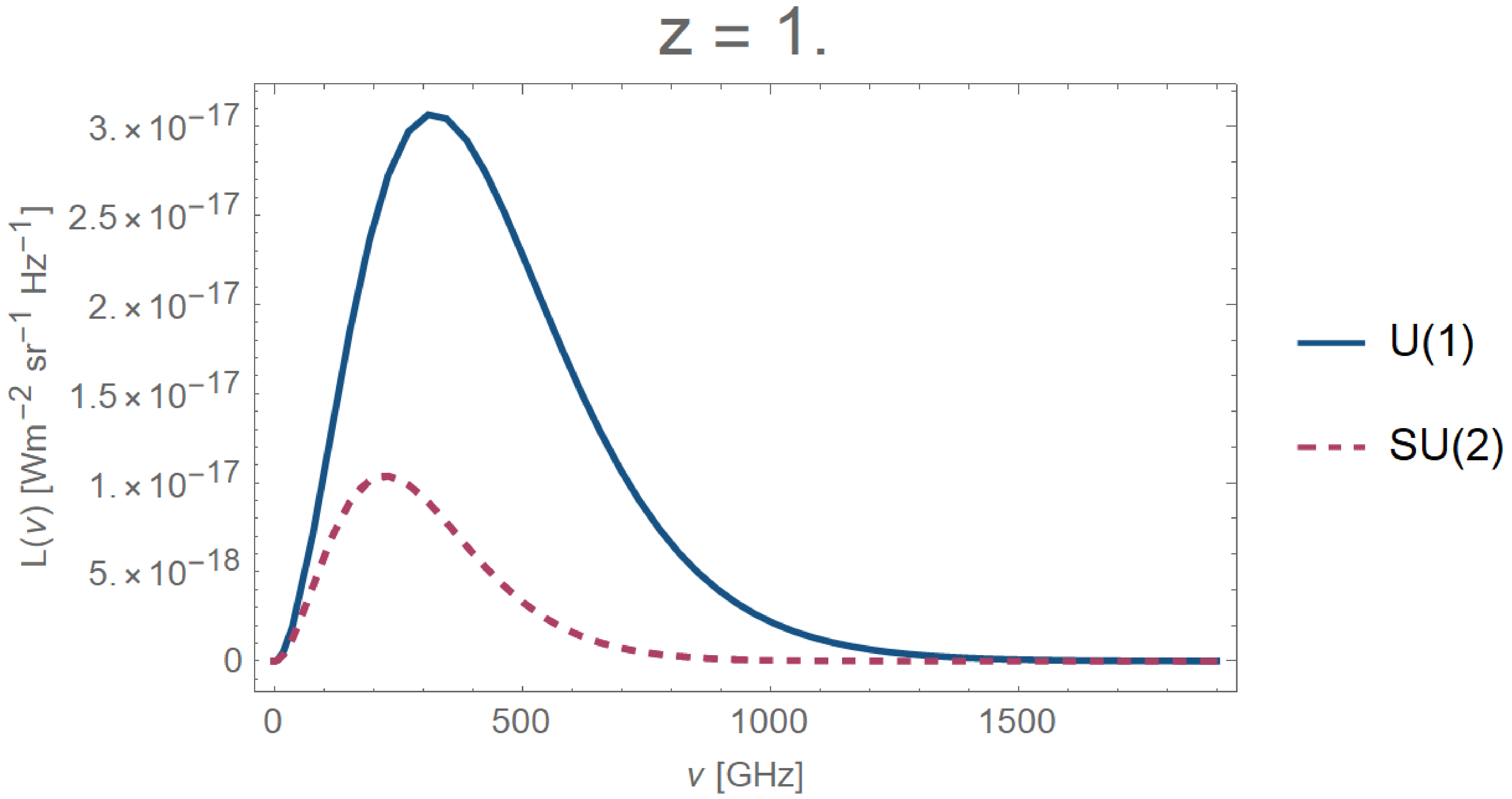
CMB Evolution



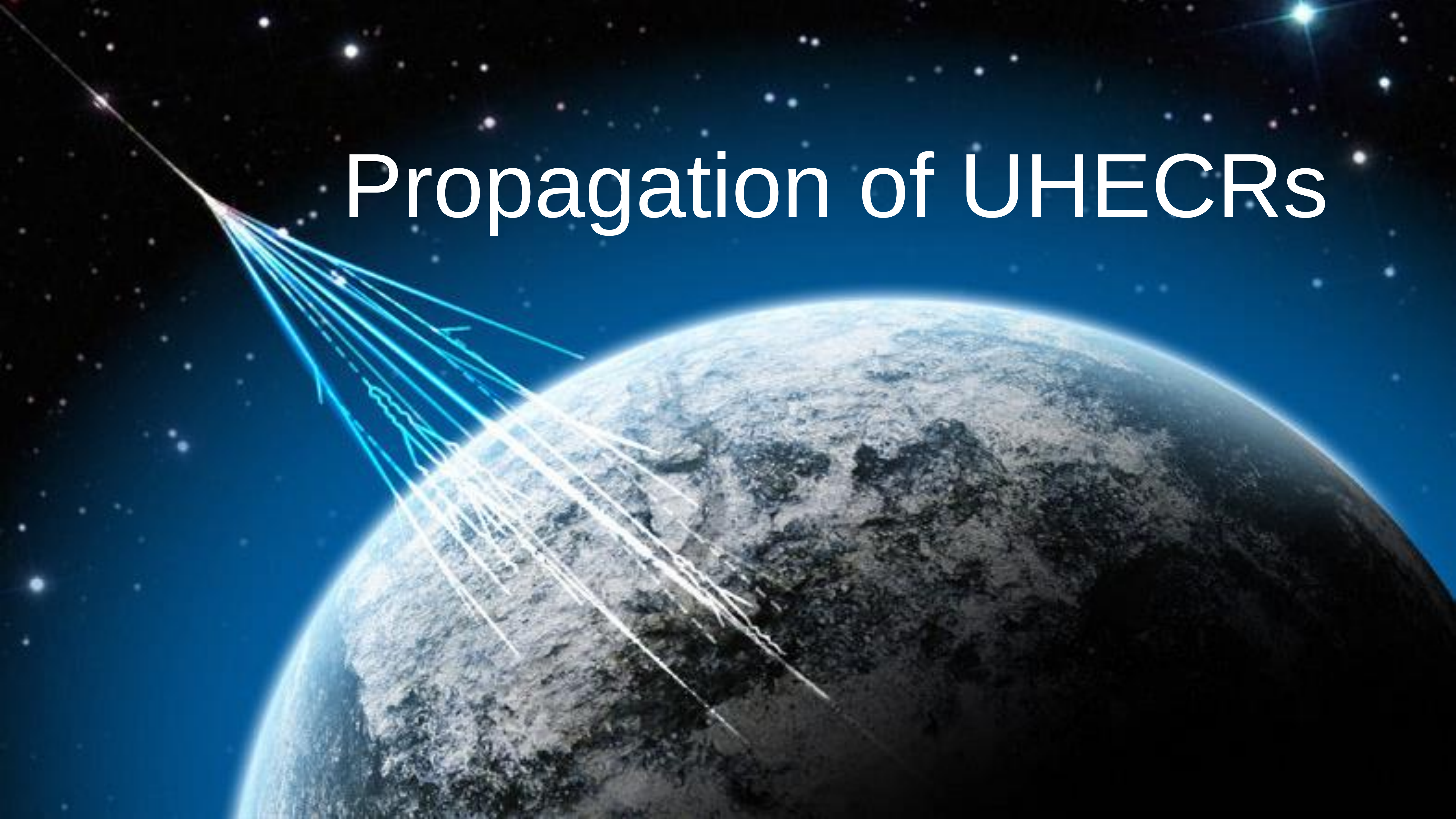
CMB Evolution

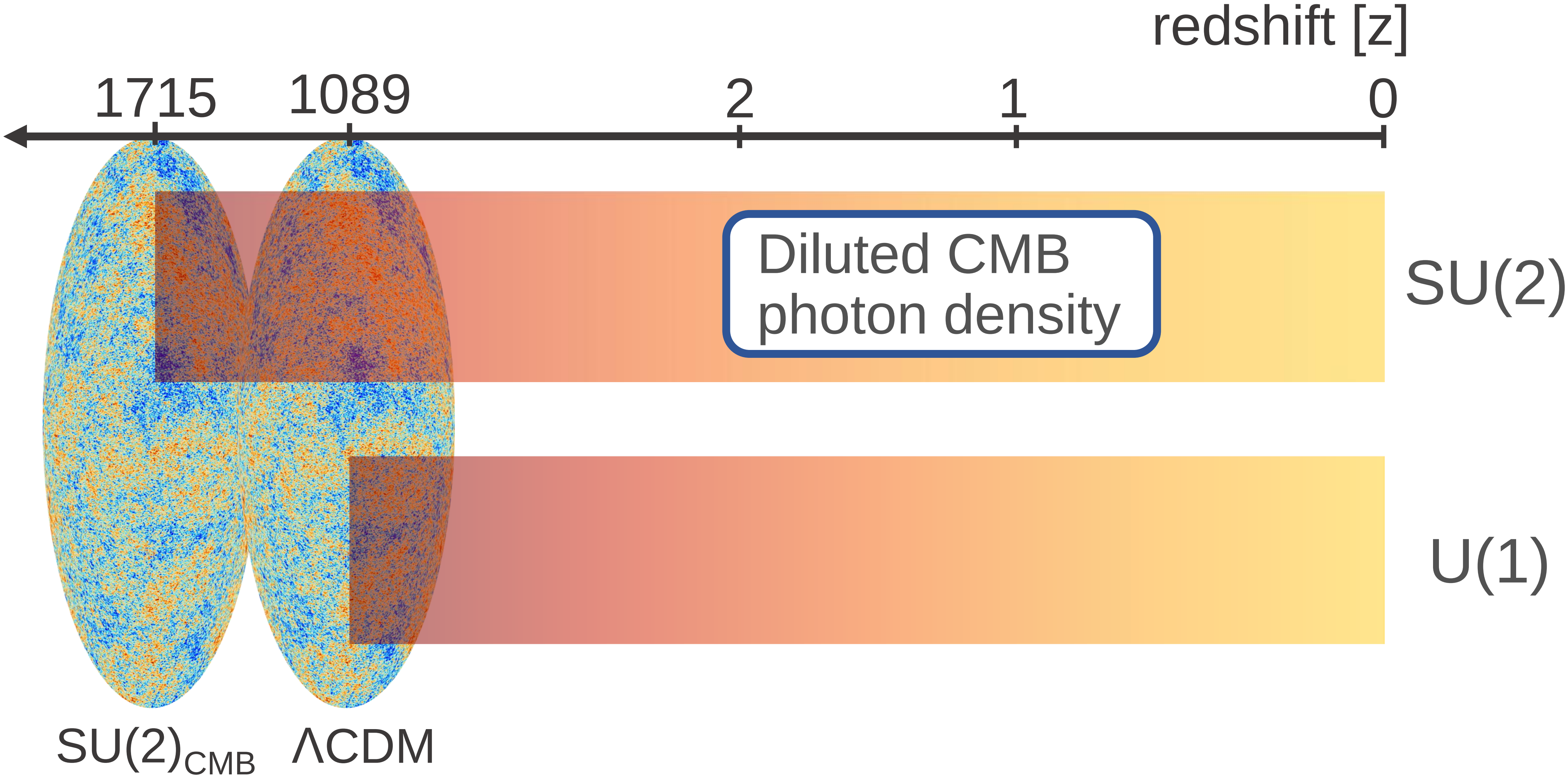


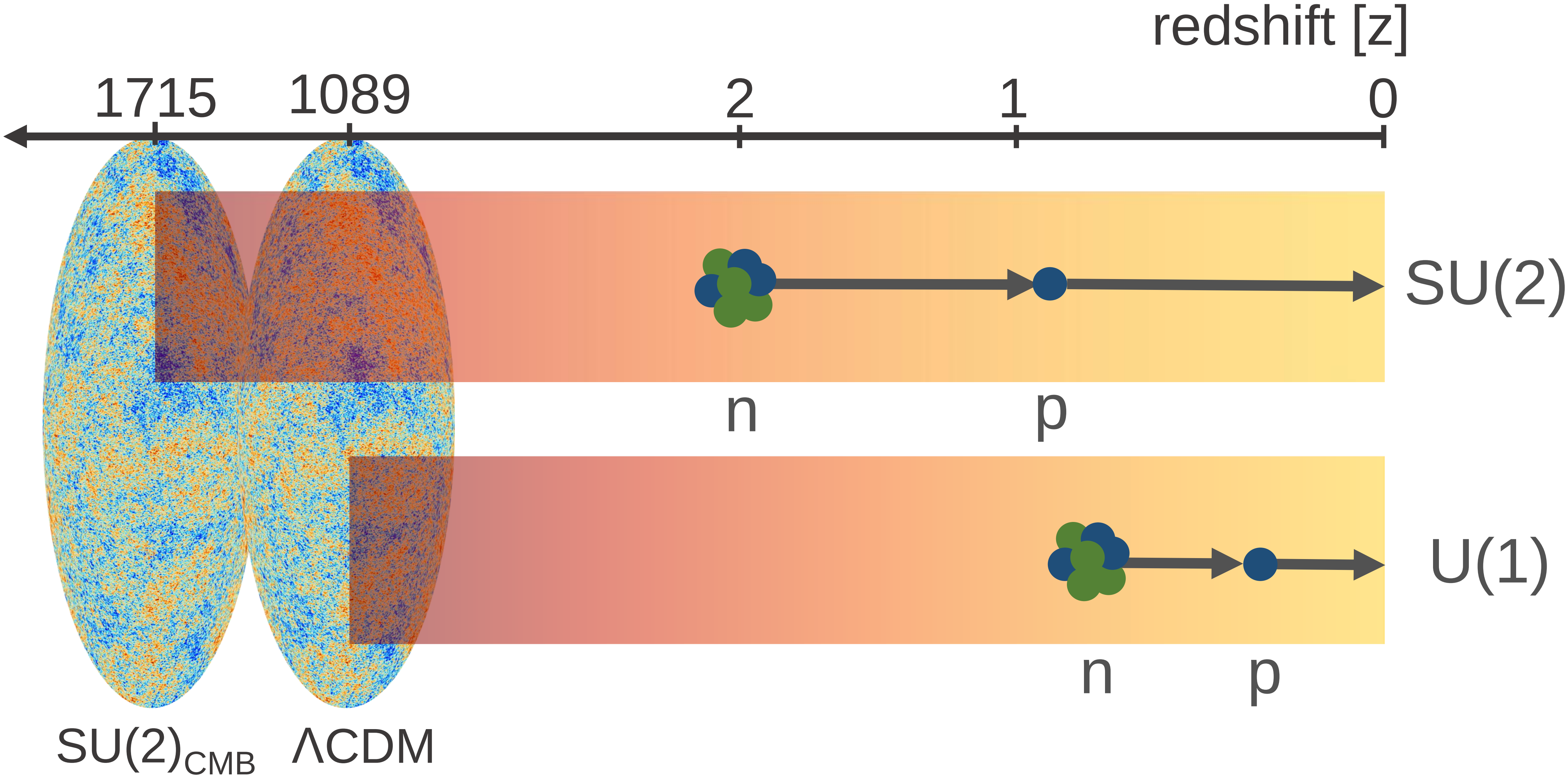
CMB Evolution

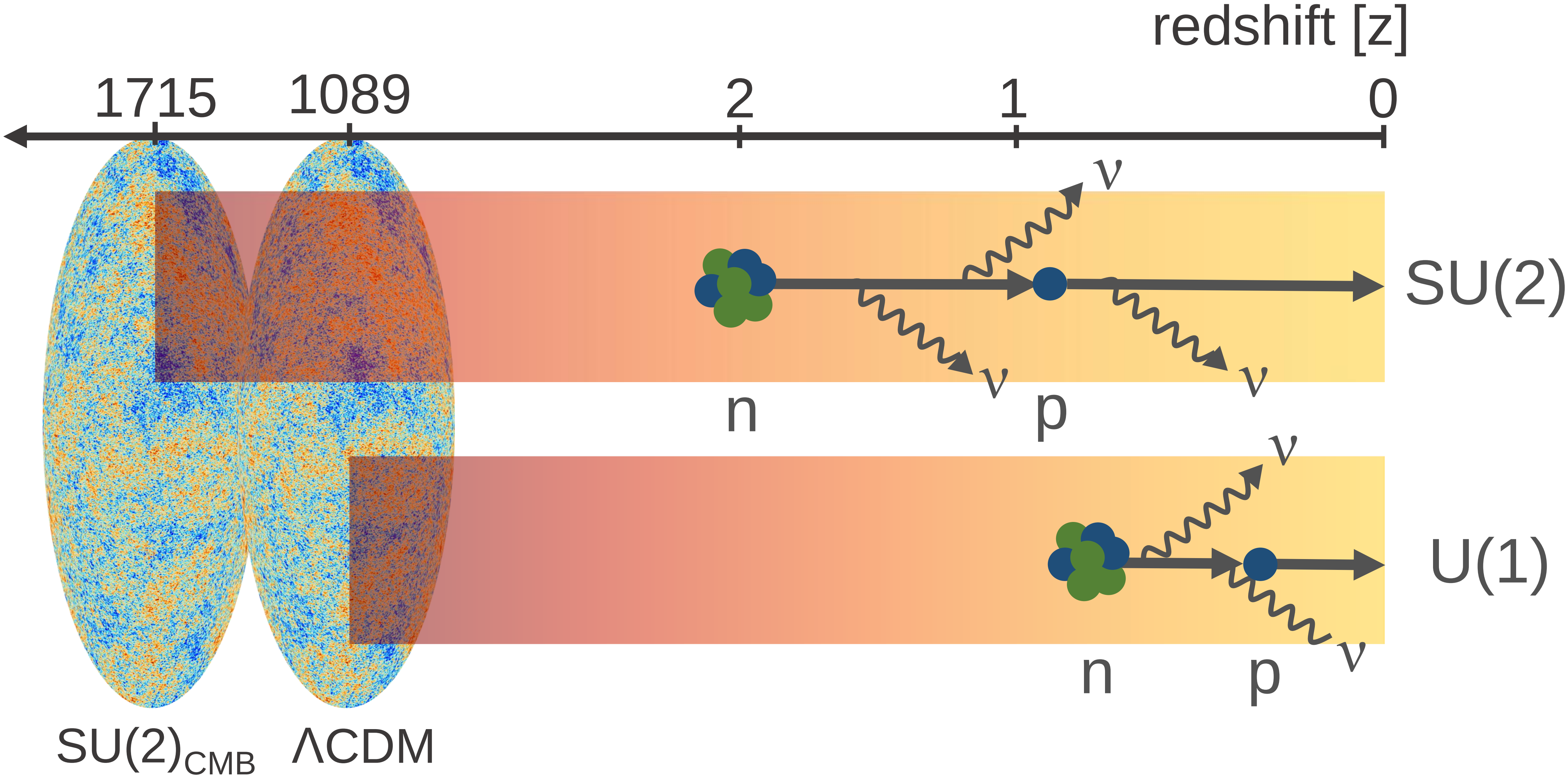


Propagation of UHECRs

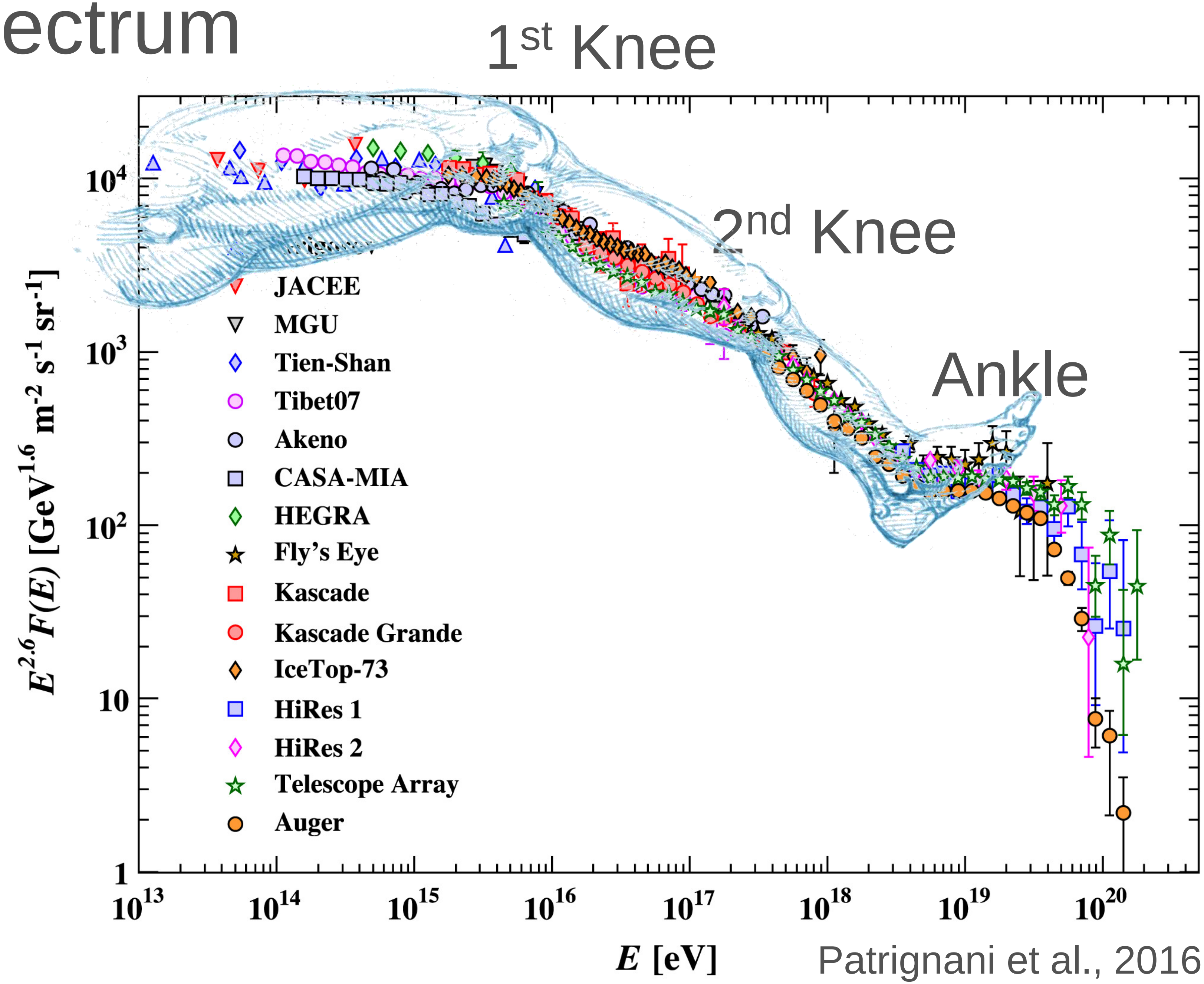



redshift [z]
1715
1089
2
1
0
Diluted CMB
photon density
SU(2)
U(1)
$SU(2)_{CMB}$
ΛCDM


redshift [z]
1715
1089
2
1
0
SU(2)
n
p
U(1)
n
p
SU(2)$_{CMB}$
ΛCDM

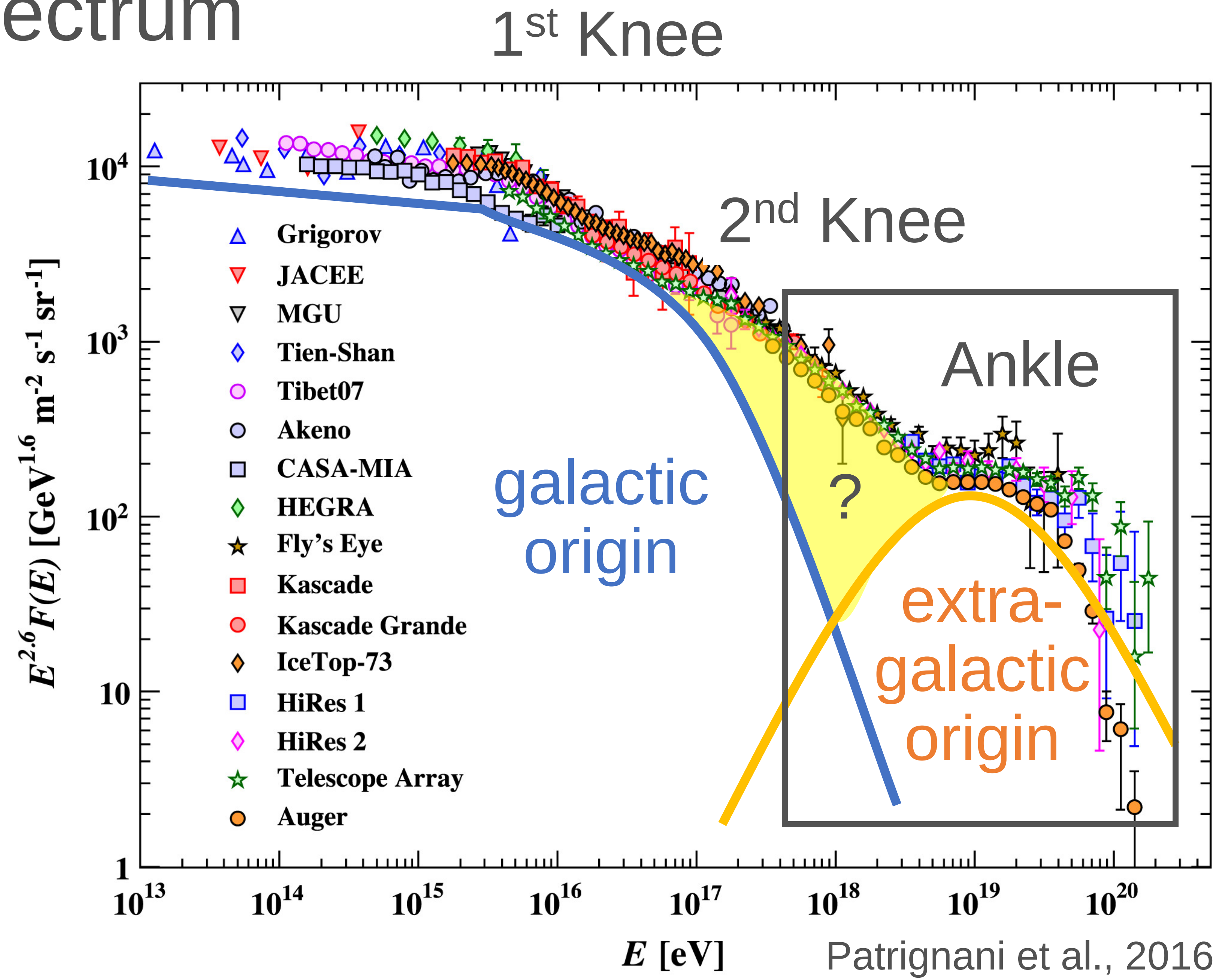

redshift [z]
1715
1089
2
1
0
ν
ν
ν
SU(2)
n
p
ν
ν
U(1)
n
p
SU(2)CMB
ΛCDM

CR spectrum



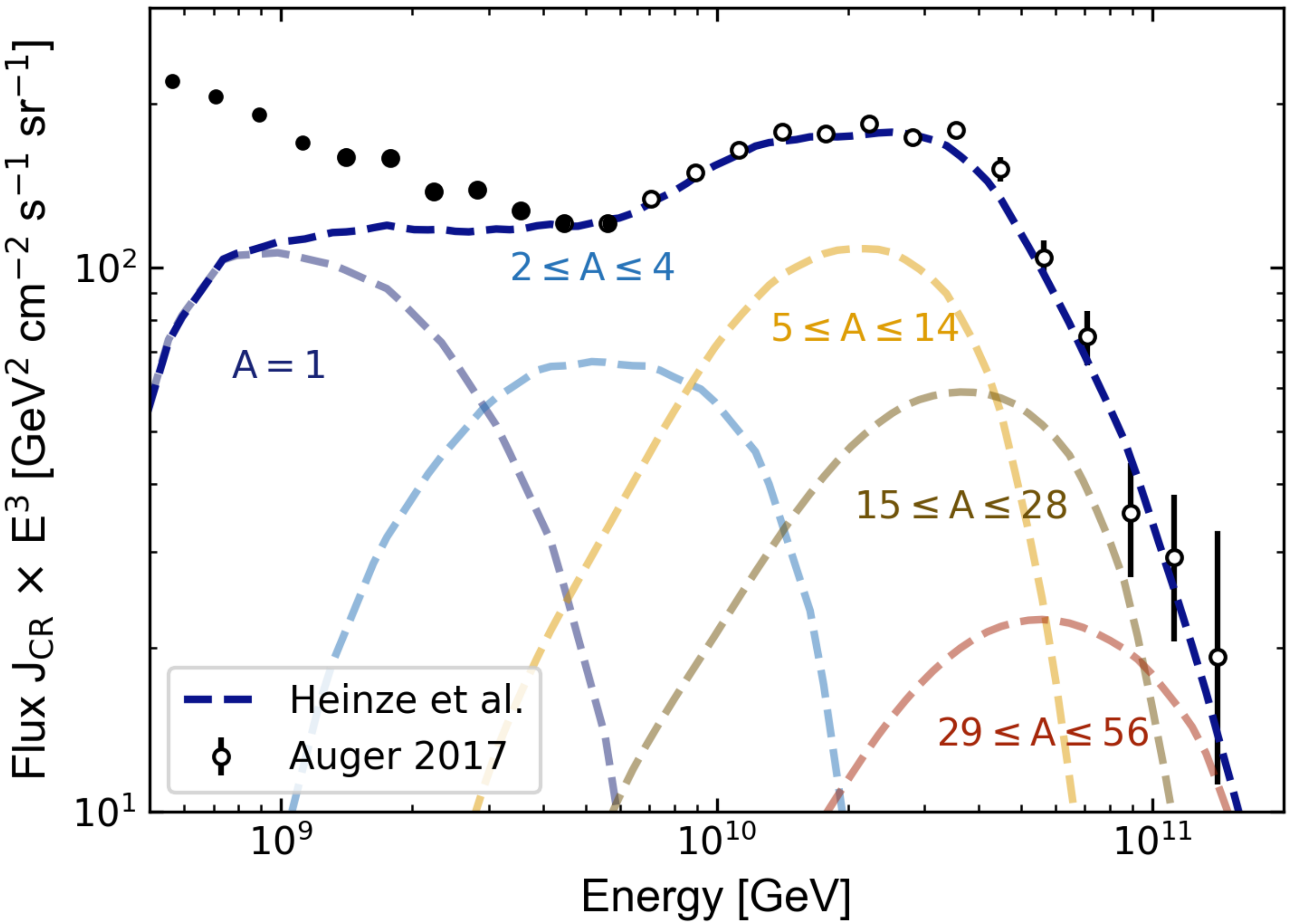
Patrignani et al., 2016

CR spectrum



Patrignani et al., 2016

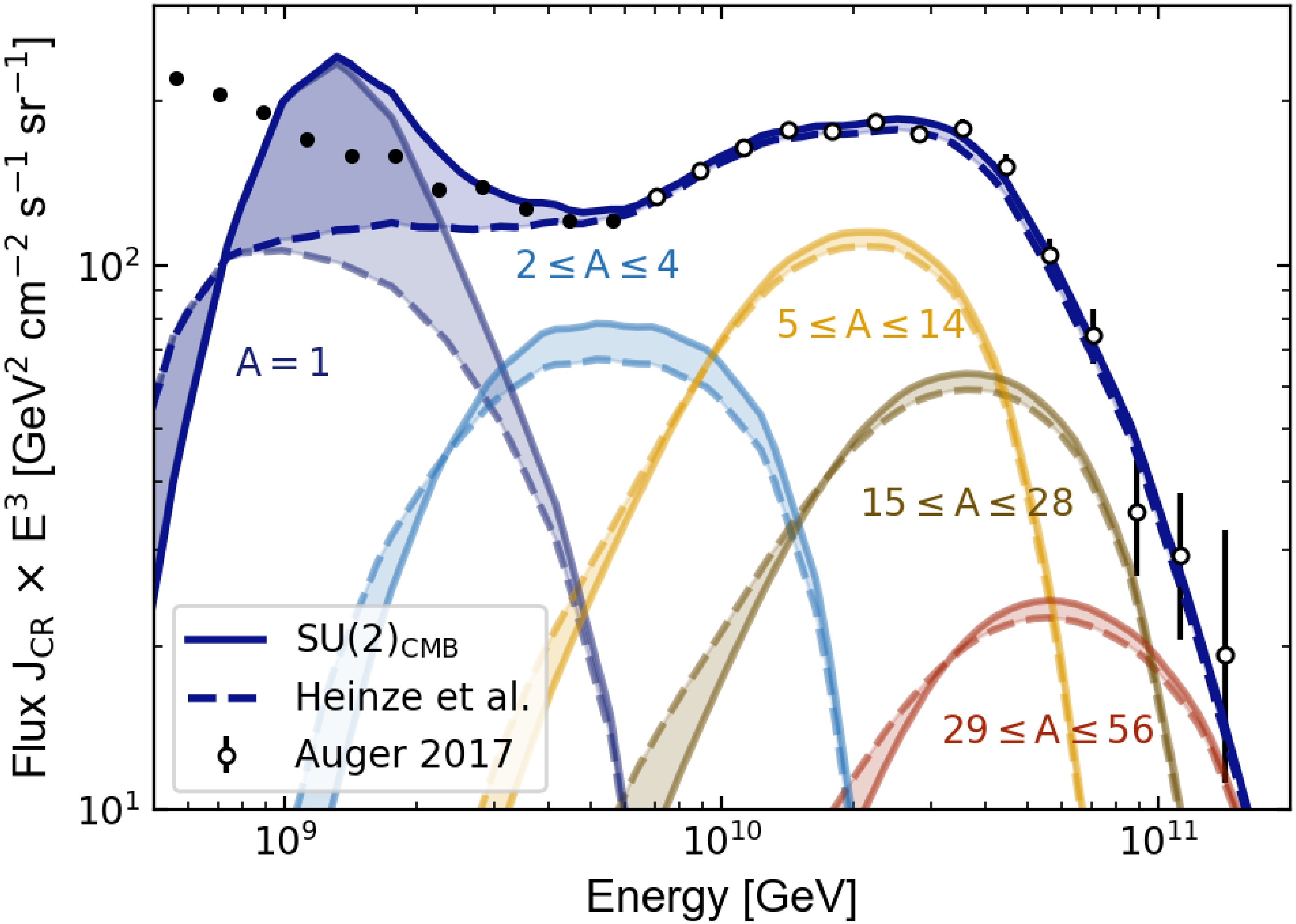
UHECR propagation with Prince-CR



- Use Prince-CR by Heinze et al.[1]
- 1D propagation simulation
- Reproduced compositional fit

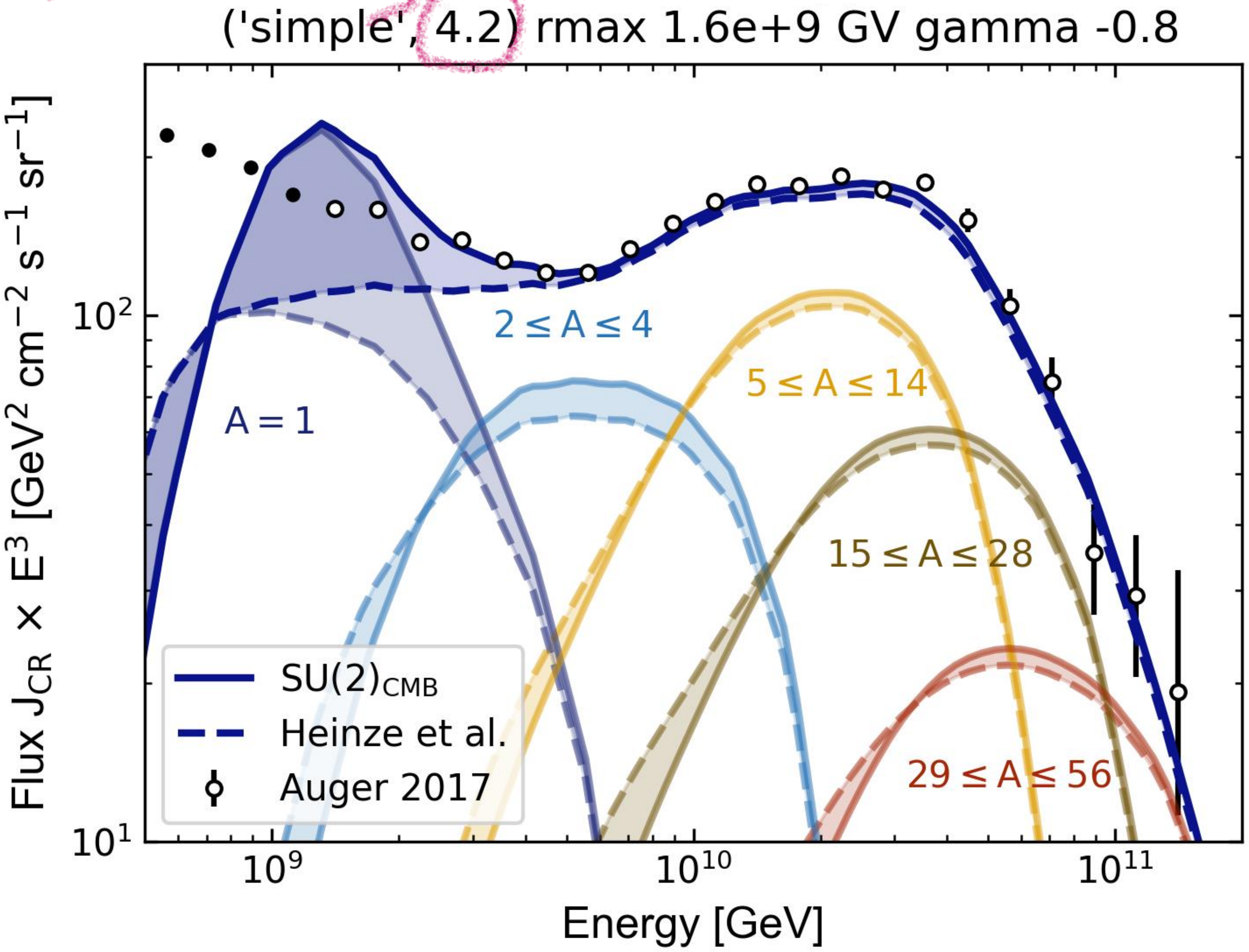
[1] Heinze et al 2019 Ap.J. 873 no.1, 88 arXiv: 1901.03338

UHECR propagation

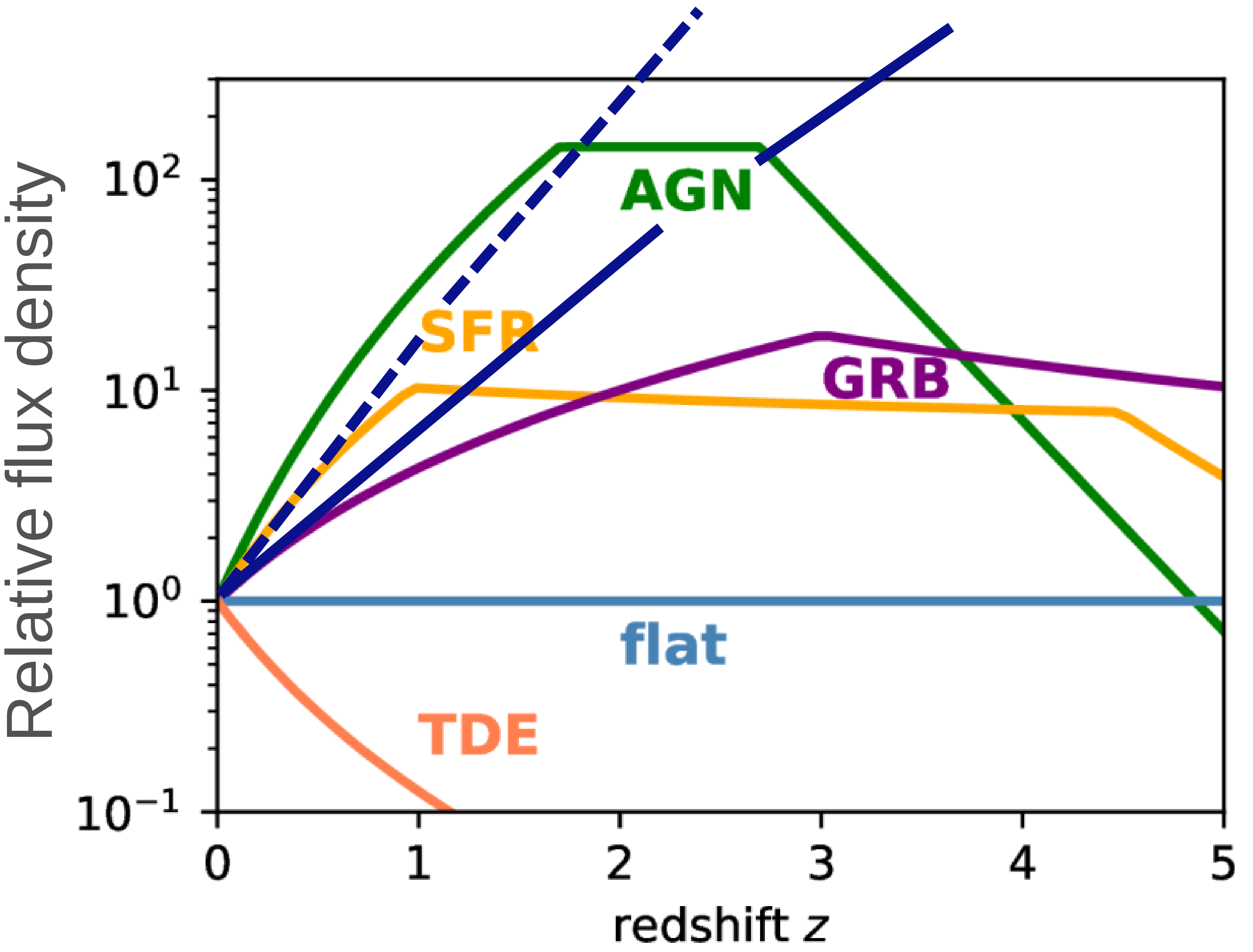


UHECR propagation

$(1+z)^m$



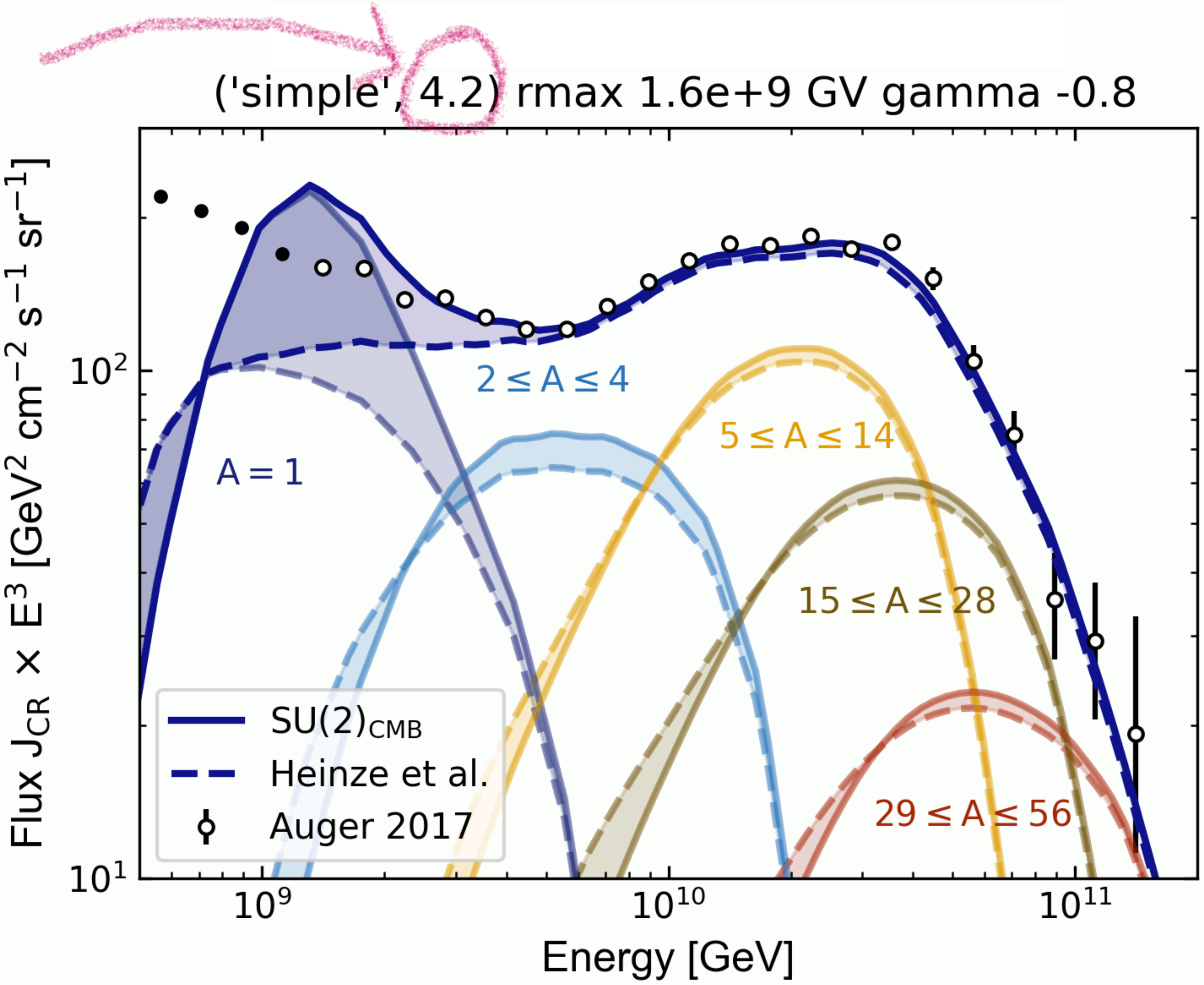
CR source distribution $(1+z)^{4.2}$ $(1+z)^{2.4}$



Heinze et al. (2019) 1901.03338

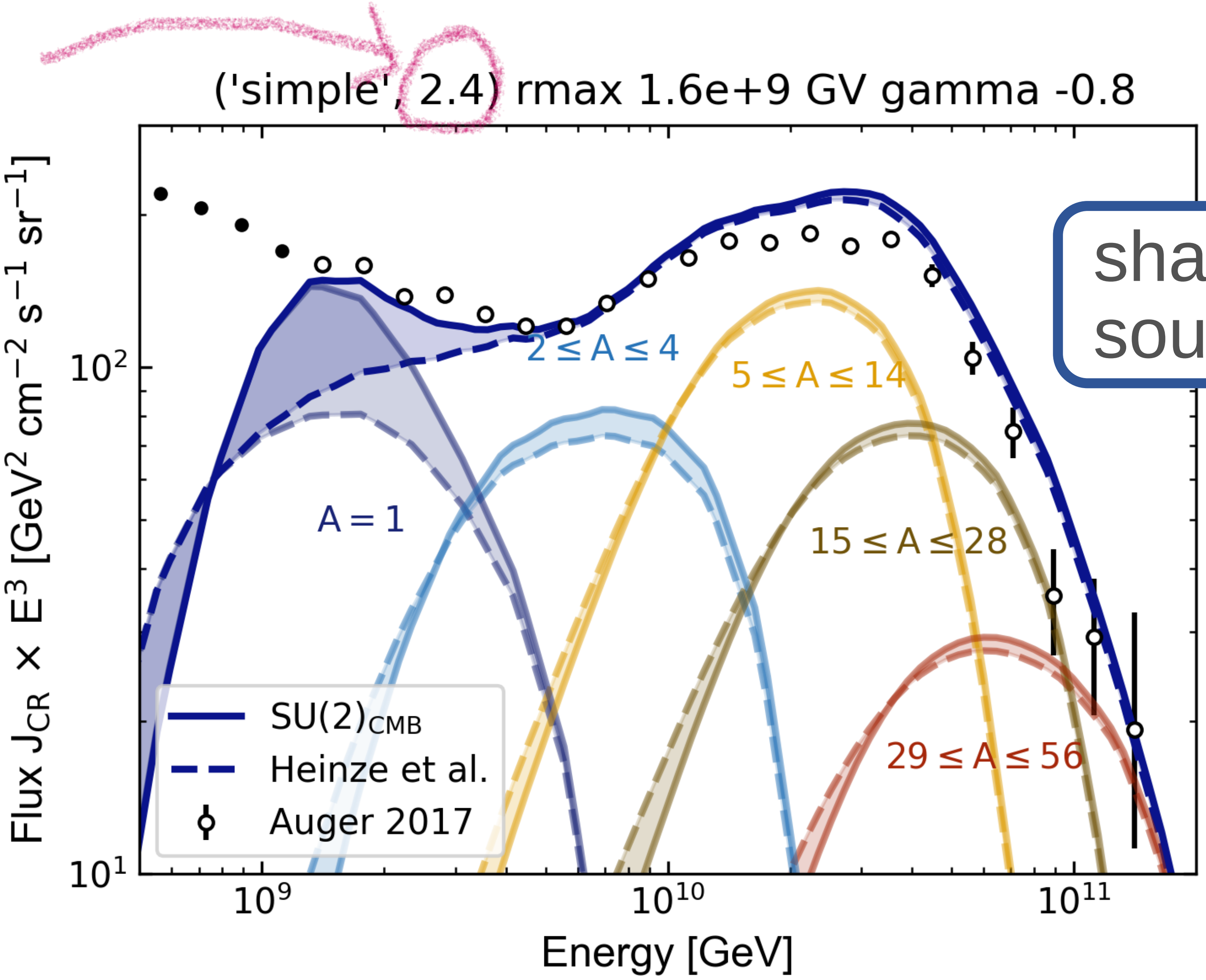
UHECR propagation

$(1+z)^m$



UHECR propagation

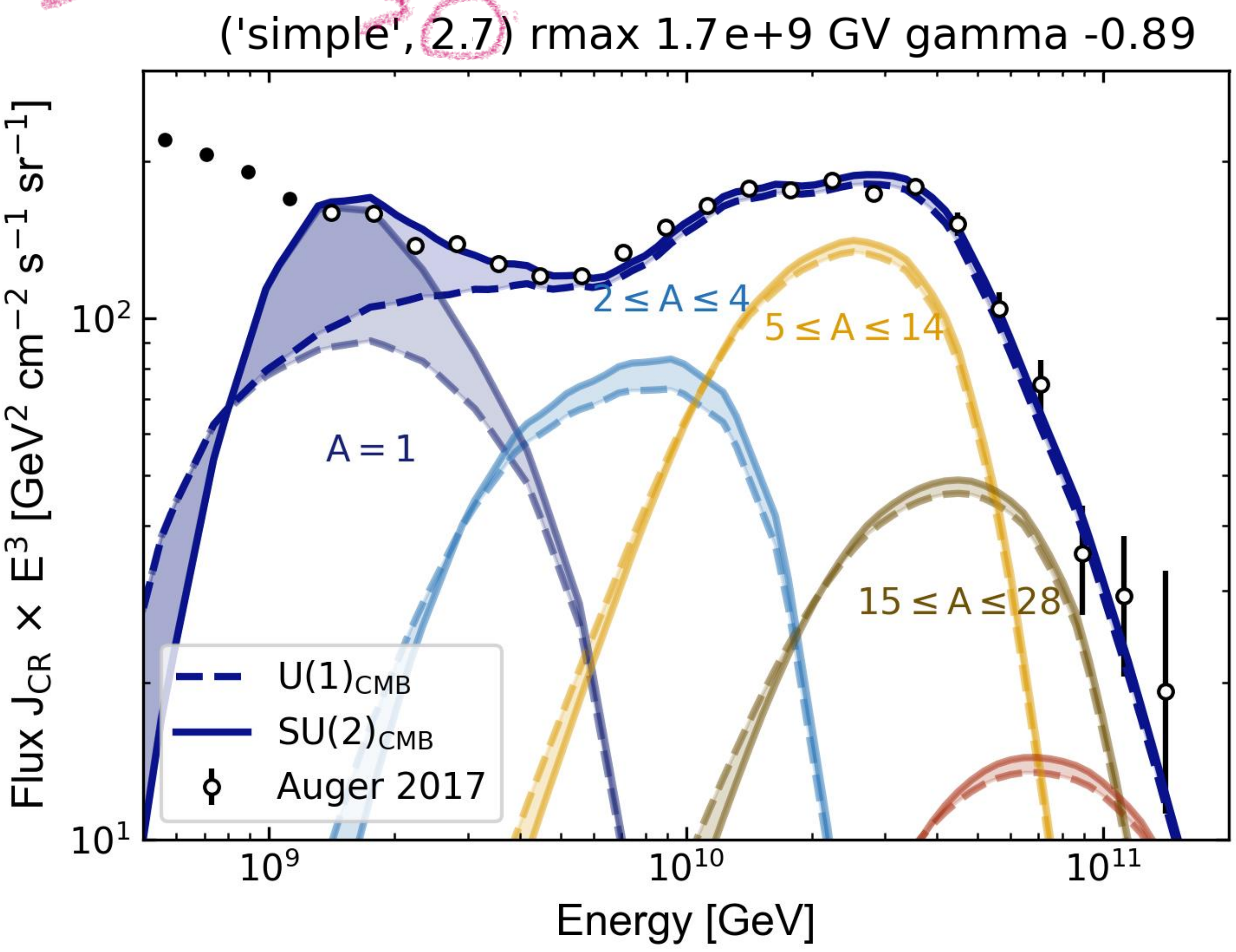
$(1+z)^m$



shallower CR source evolution

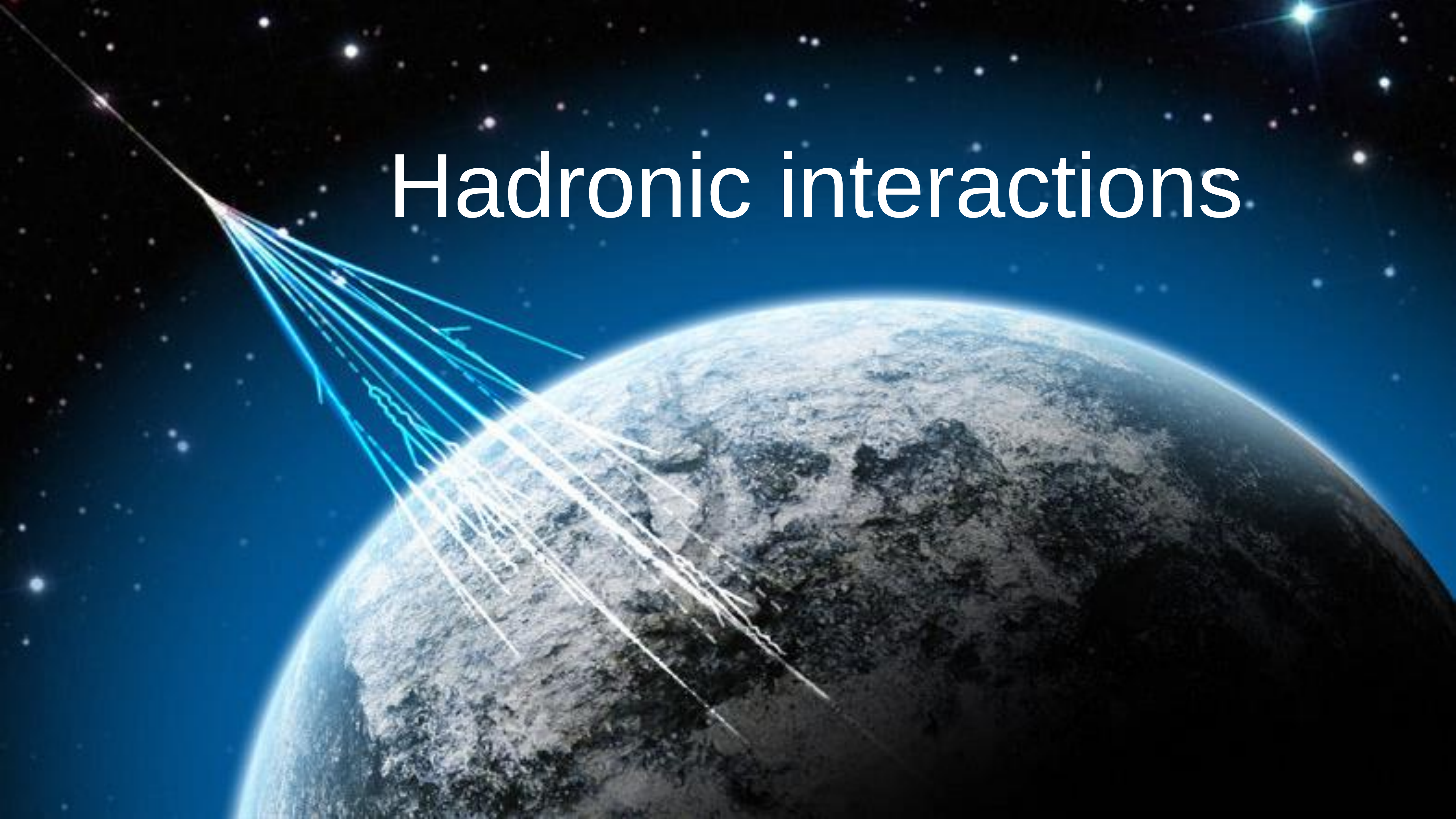
UHECR propagation

$(1+z)^m$

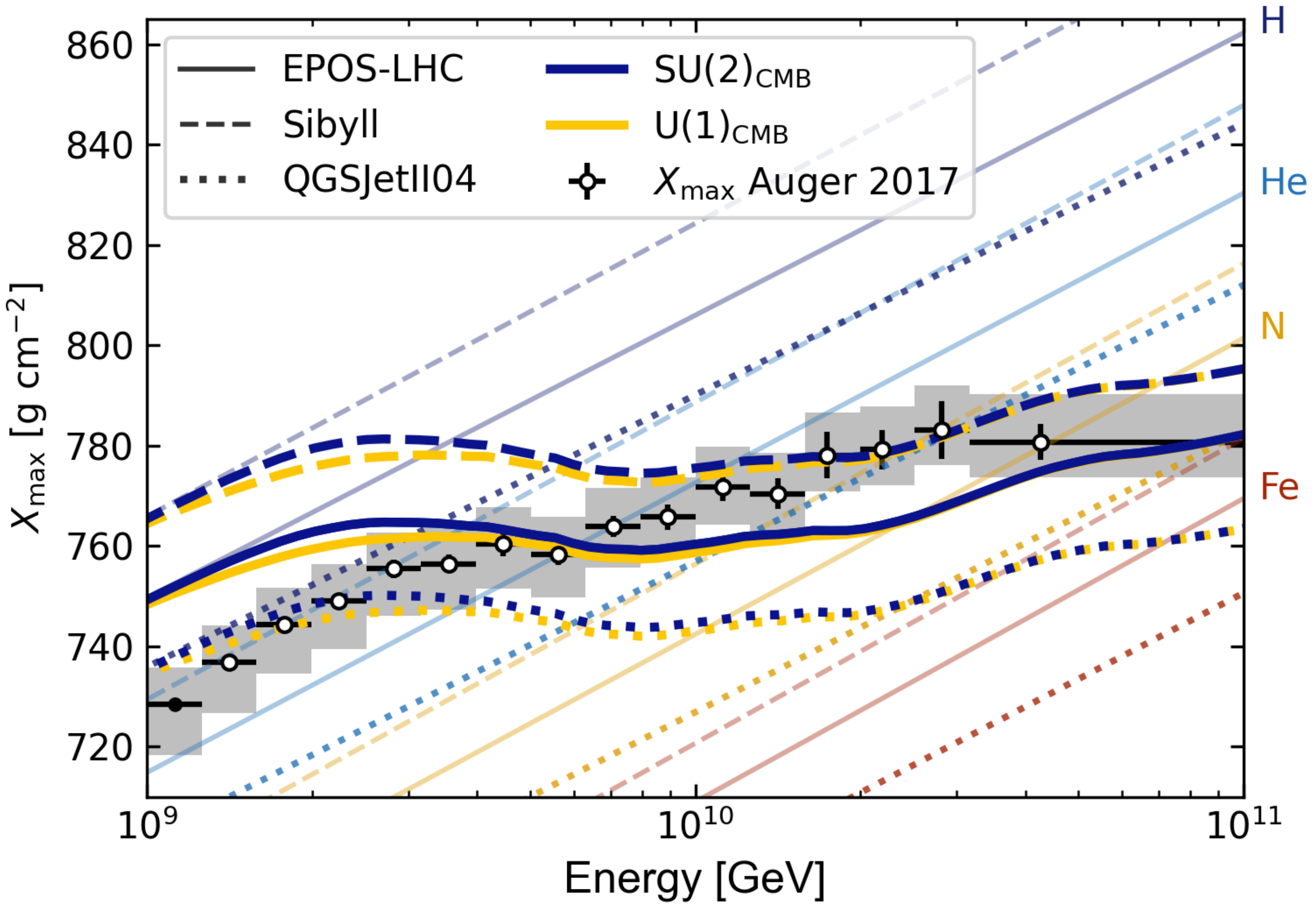


- Gradient descent

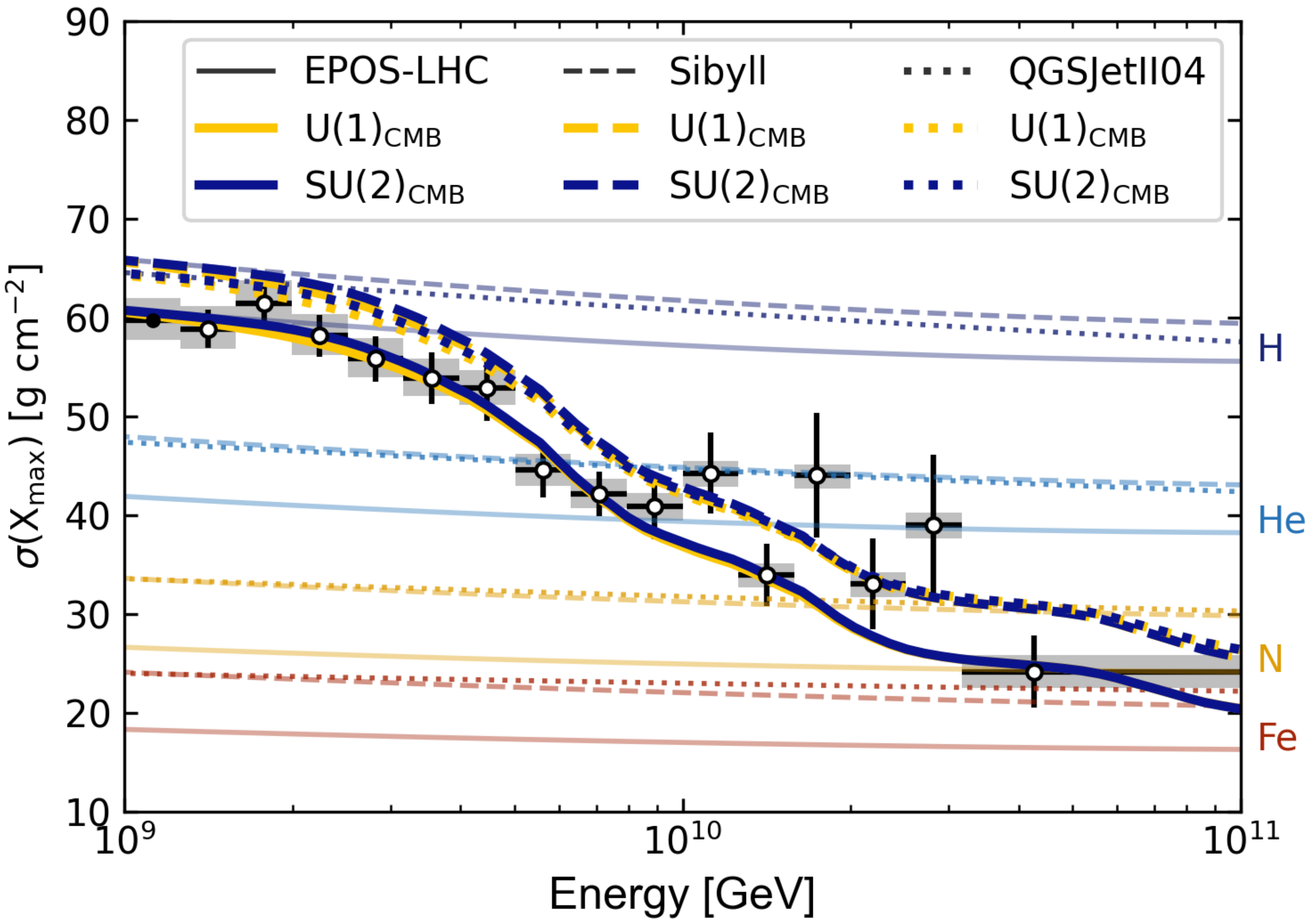
Hadronic interactions



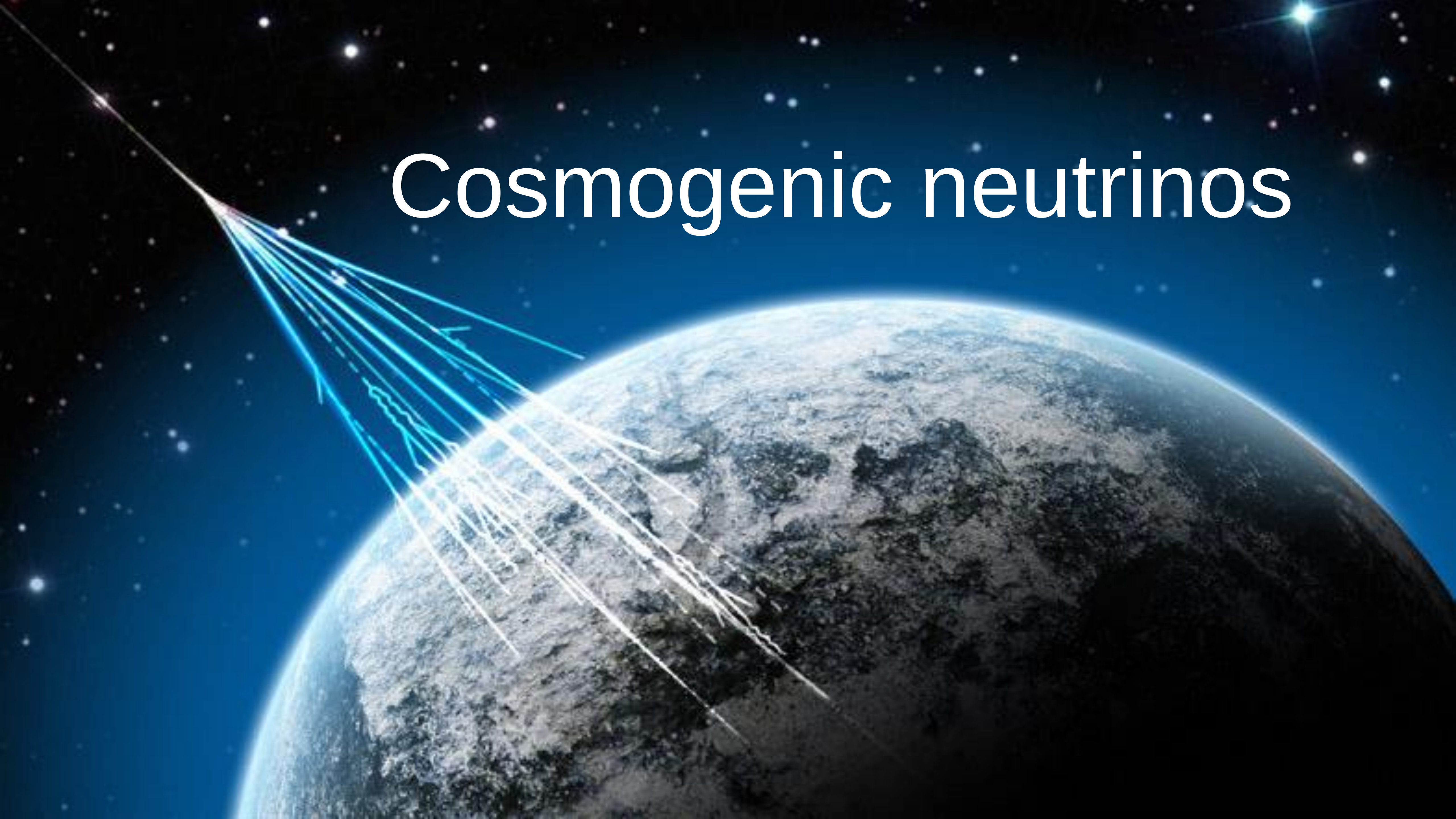
Hadronic Interaction models



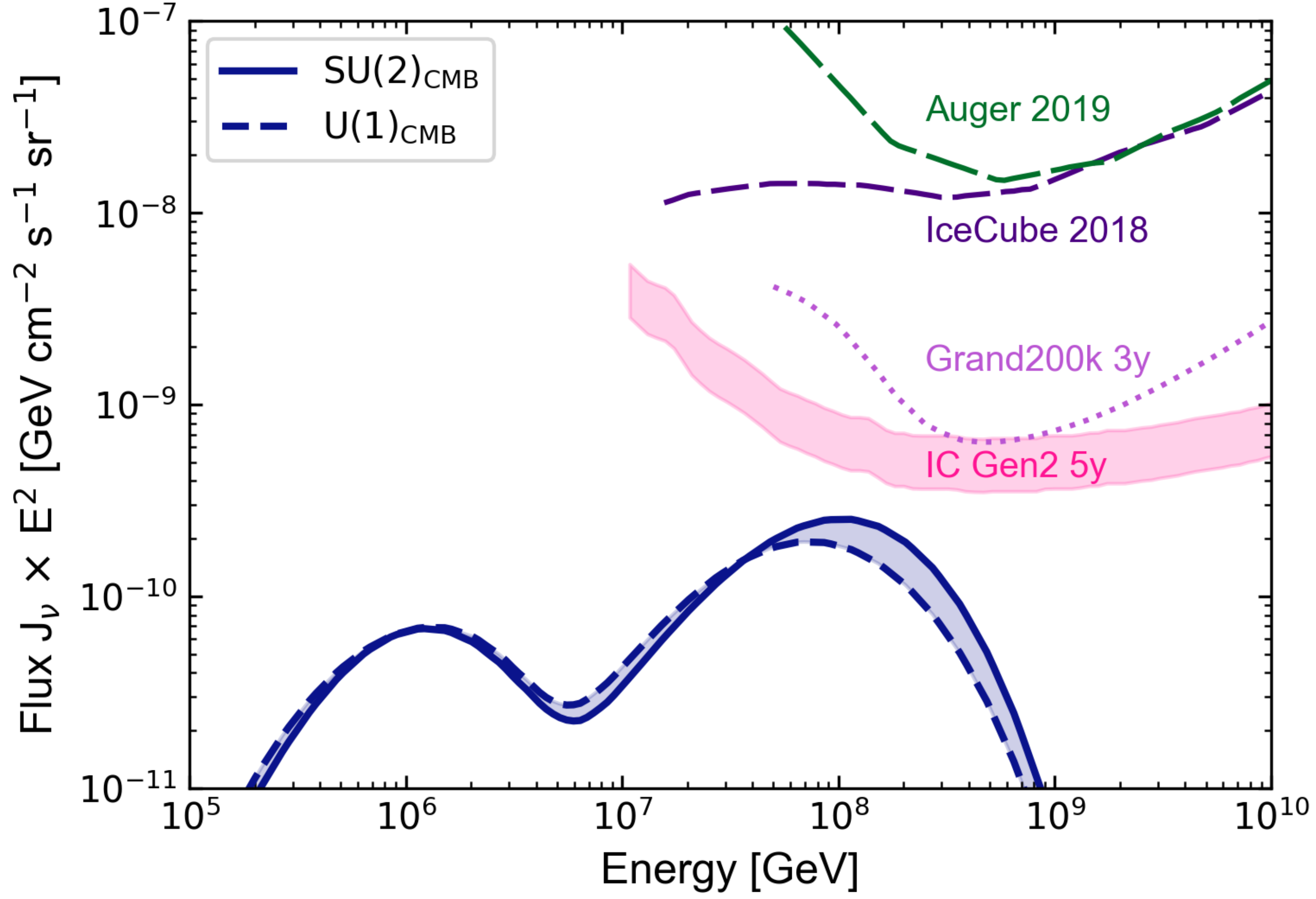
Hadronic Interaction models



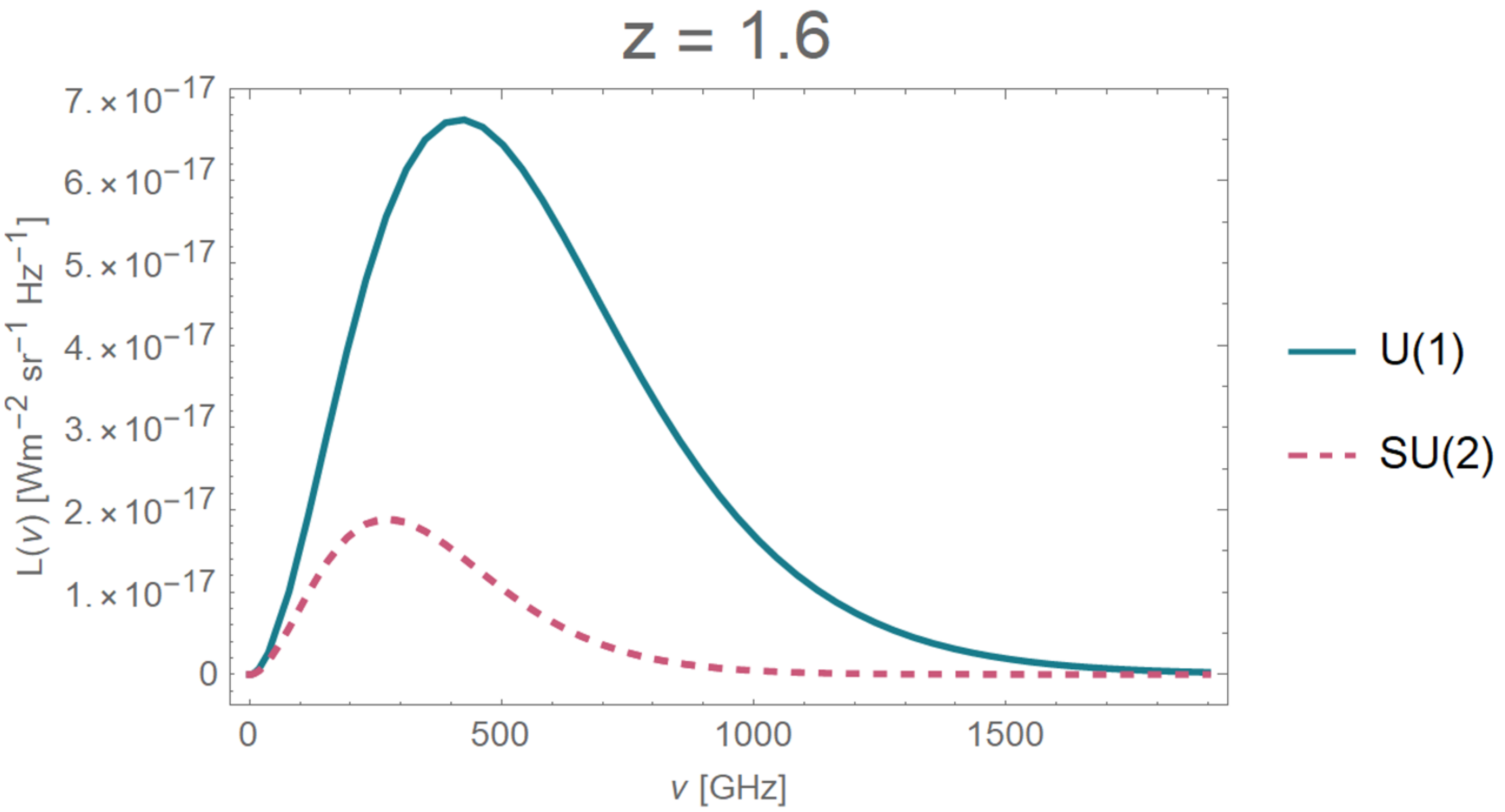
Cosmogenic neutrinos



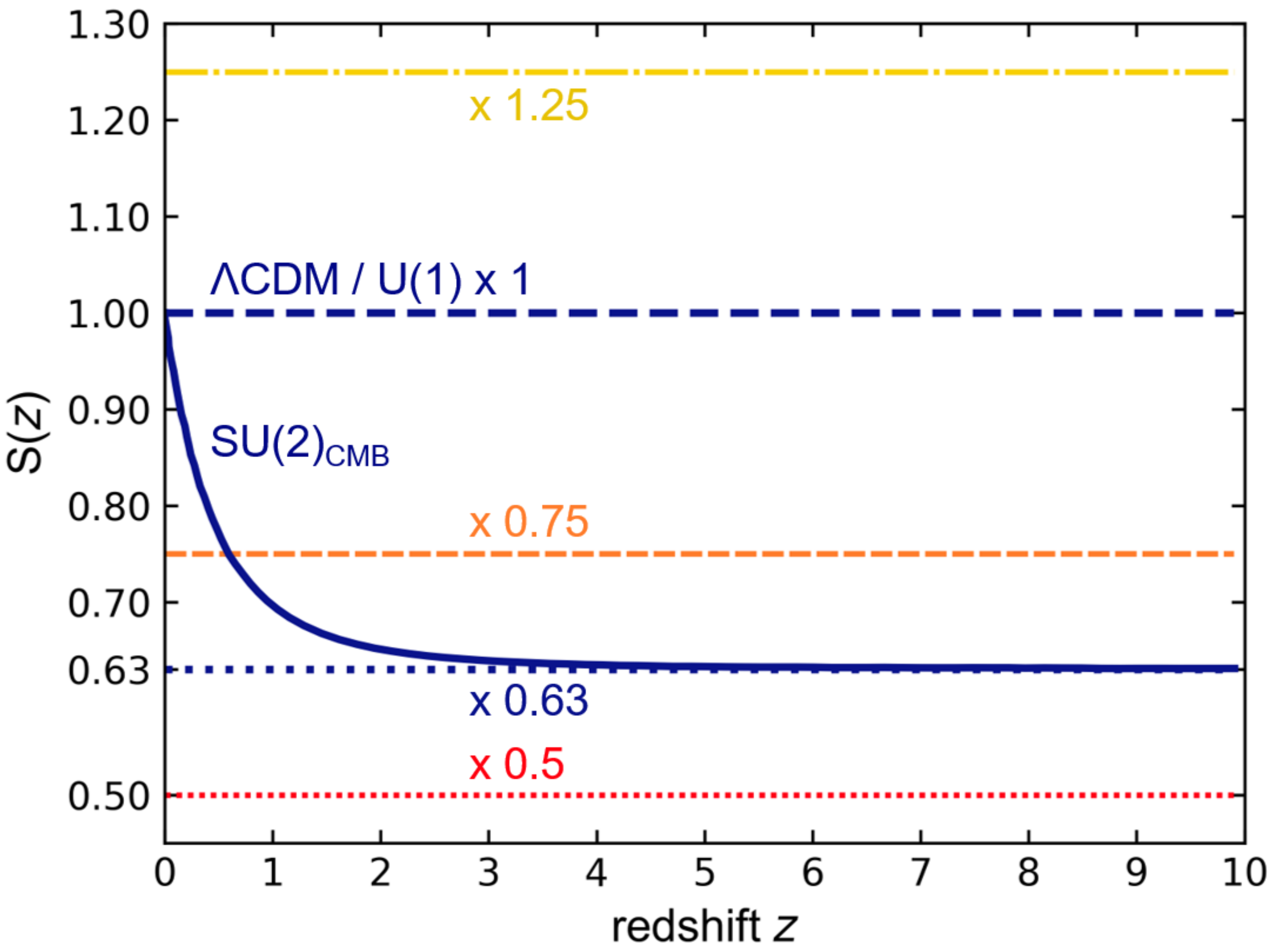
Cosmogenic Neutrinos



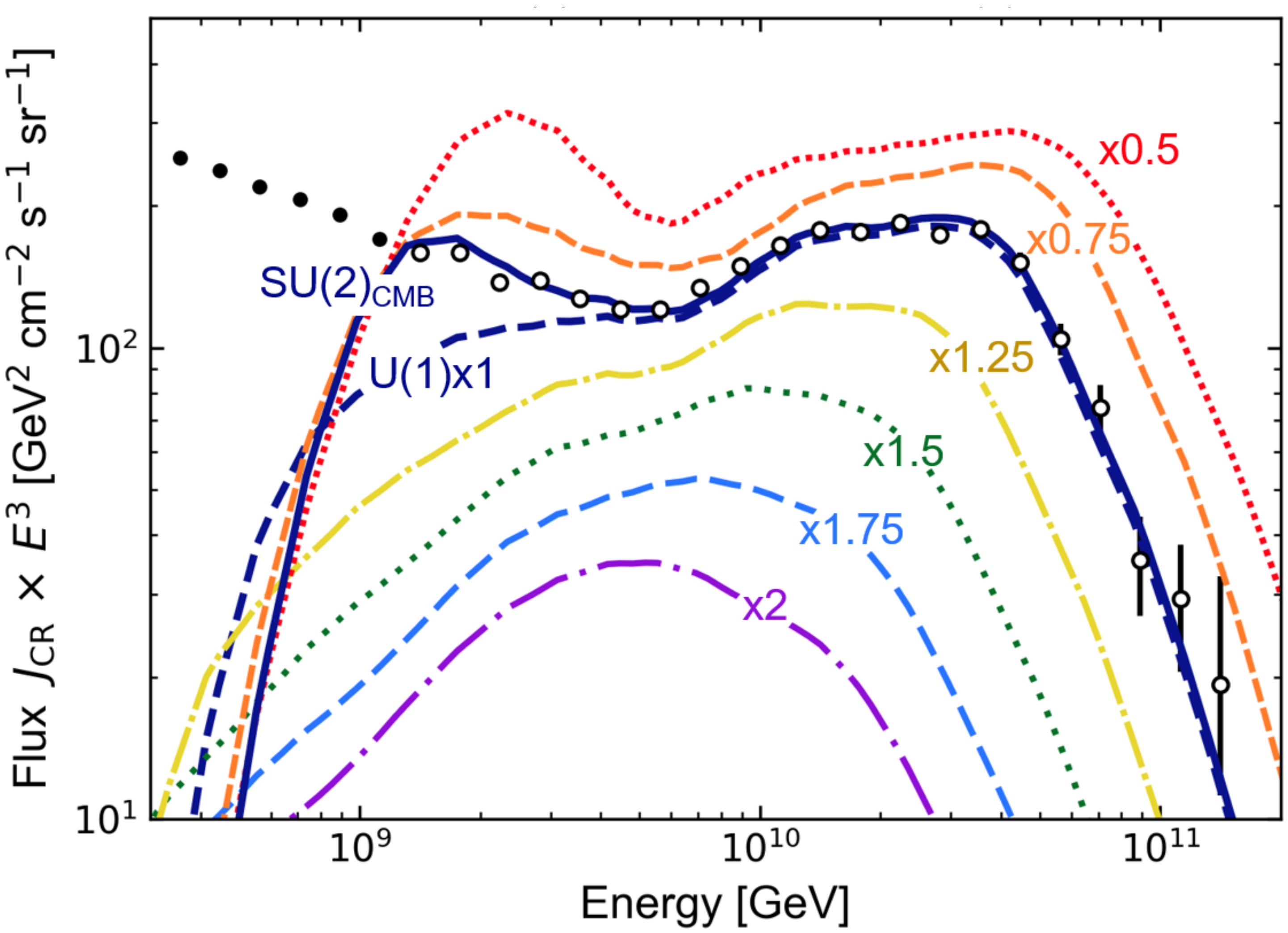
CMB Evolution



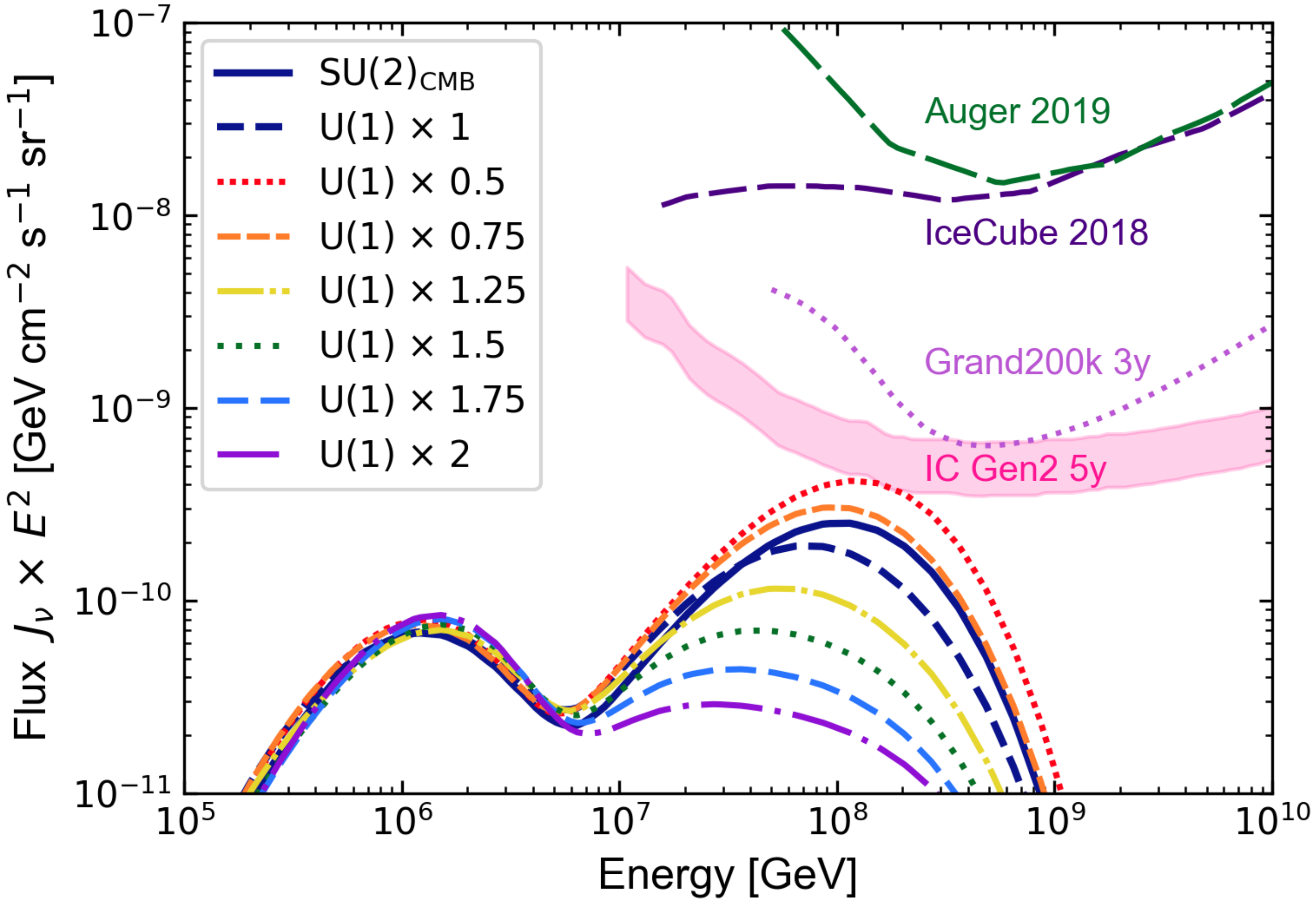
How do we change $T(z) = S(z)\,(1+z)\,T_0$



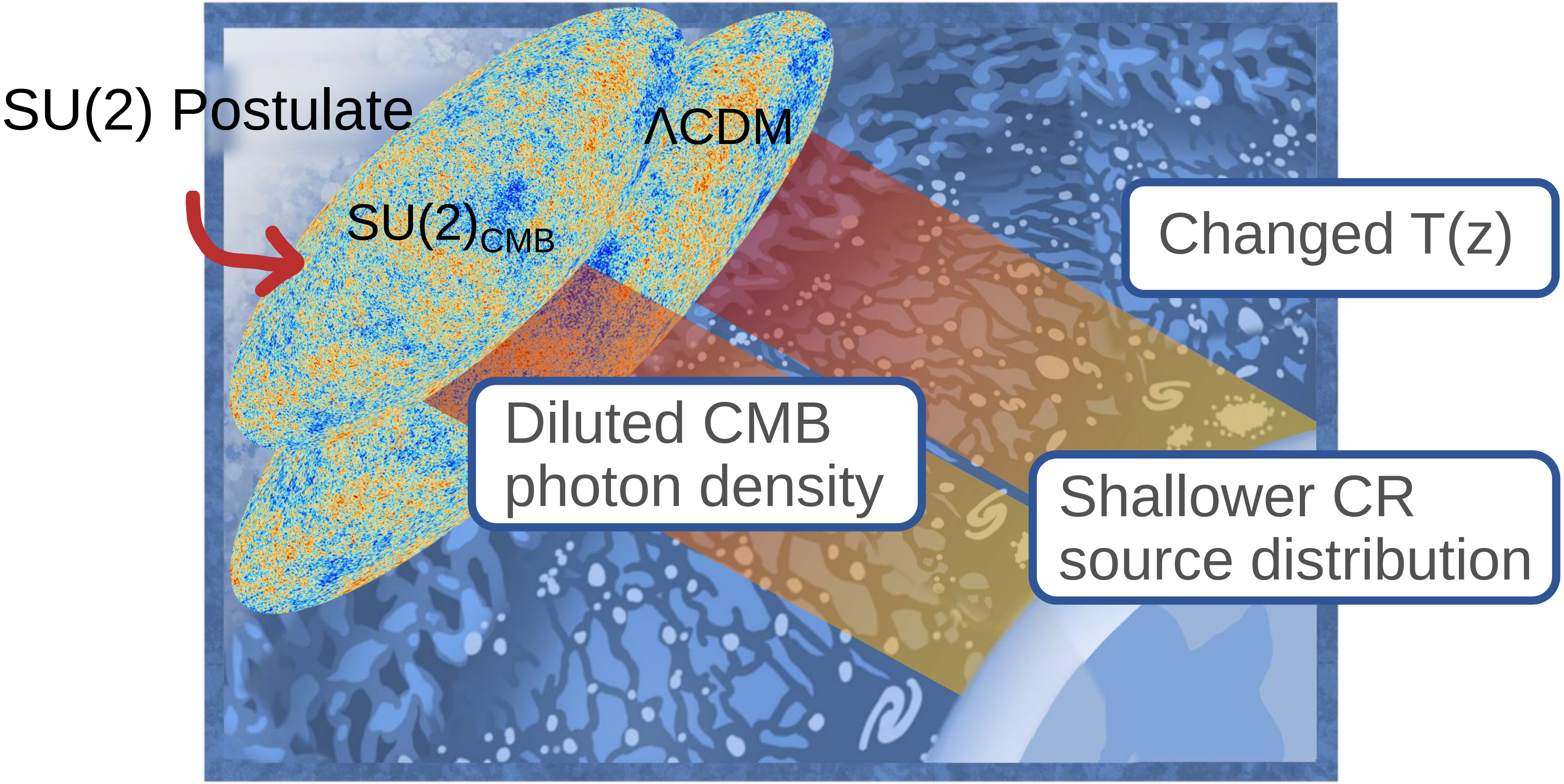
Overview of different T(z)



Overview of different T(z)



Summary



JM et al. (2023) 2309.08451

Thank you!

Dr. Leonel Morejón

Dr. Alexander Sandrock

Dr. Björn Eichmann

M.Sc. Jonas Kreidelmeyer

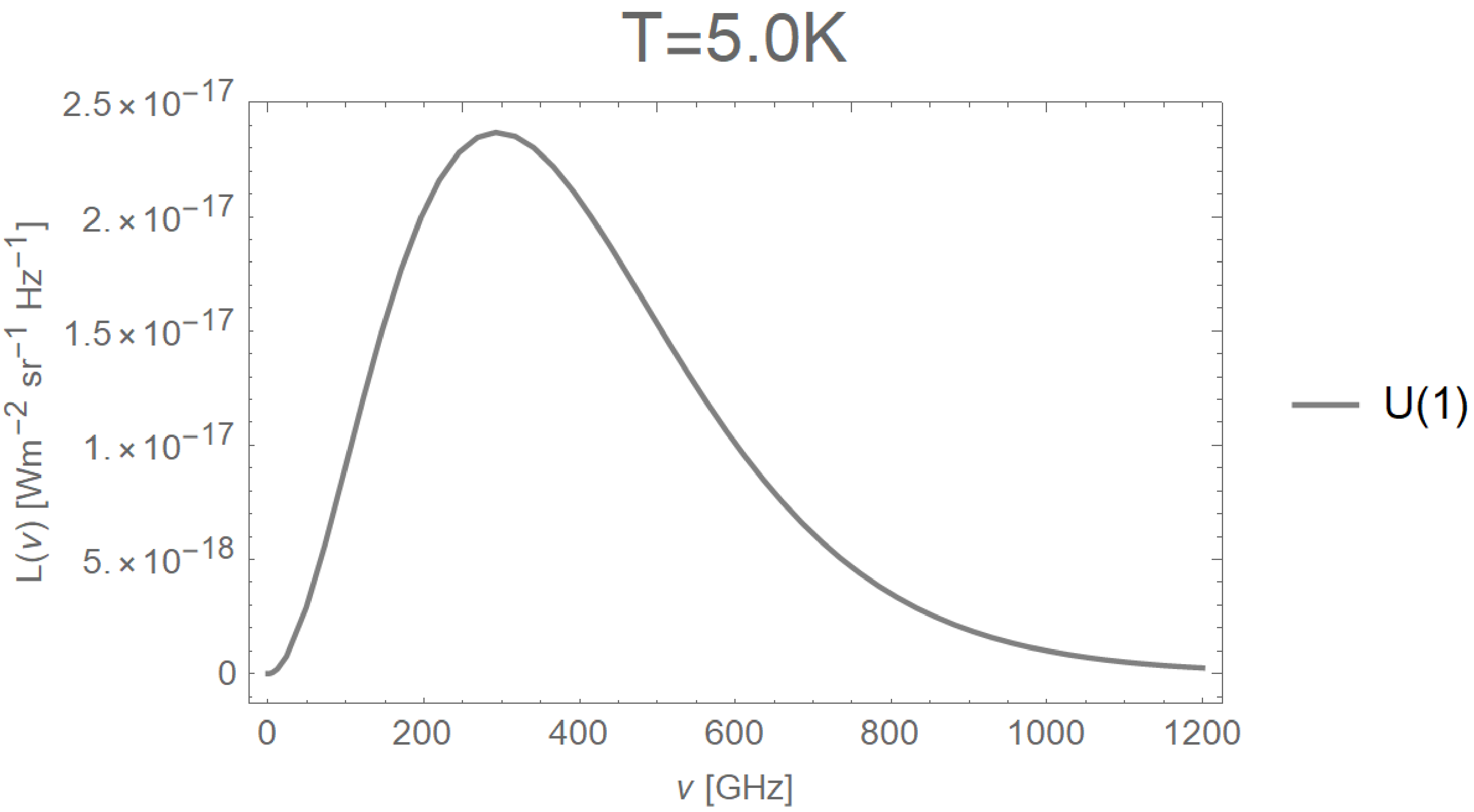
Prof. K.-H. Kampert

Supported by SFB 1491

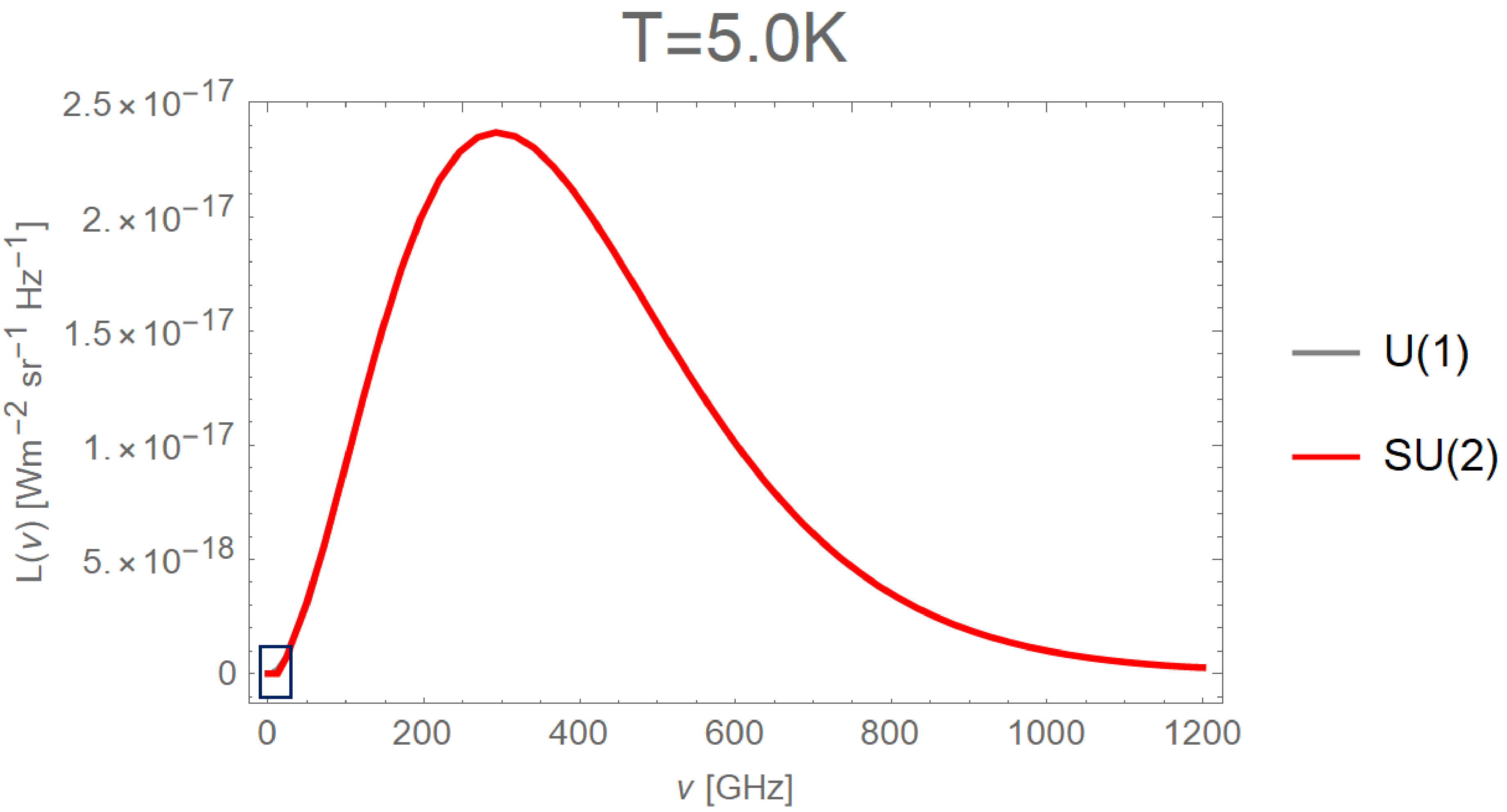
And the Vector Foundation under Grant number P2021-0102

Extra slides

Screening effects due to massive gauge modes

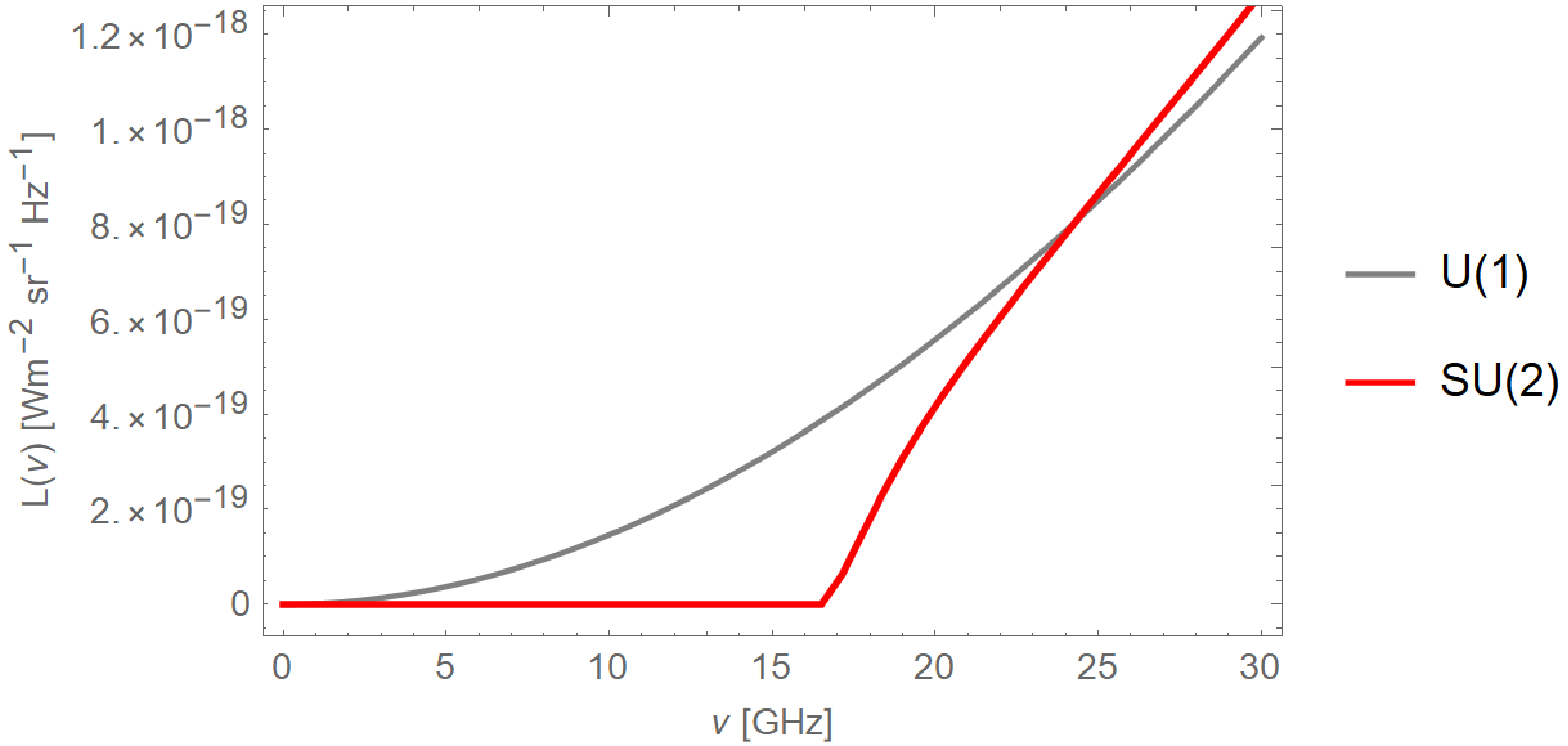


$$I_{\mathrm{U(1)}}(\nu) \equiv \frac{2h}{c^2} \frac{\nu^3}{\exp[\frac{h\,\nu}{k_B T}] - 1}$$

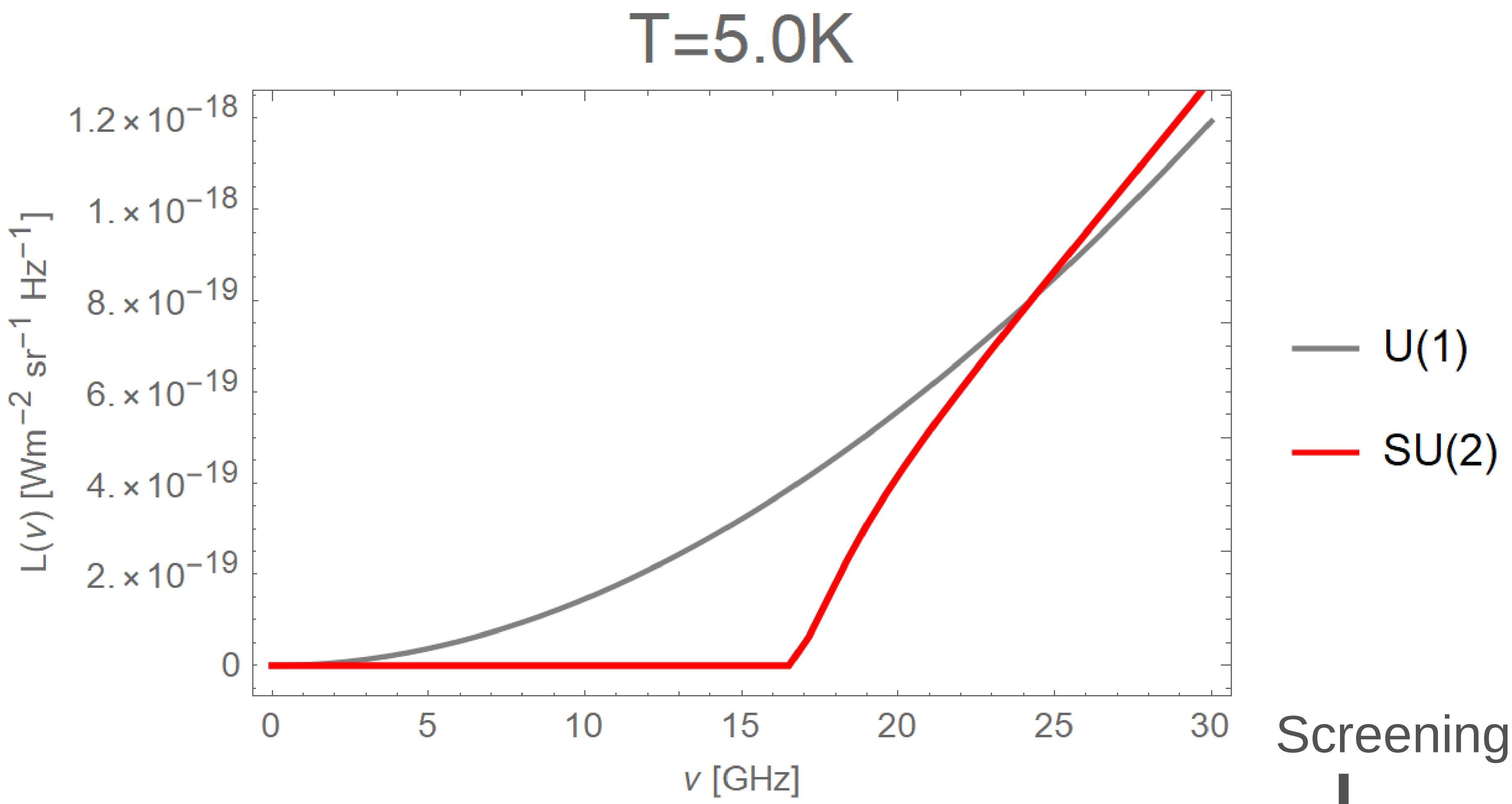


$$I_{\mathrm{U(1)}}(\nu) \equiv \frac{2h}{c^2}\,\frac{\nu^3}{\exp[\,\frac{h\,\nu}{k_B T}\,] - 1}$$

T=5.0K

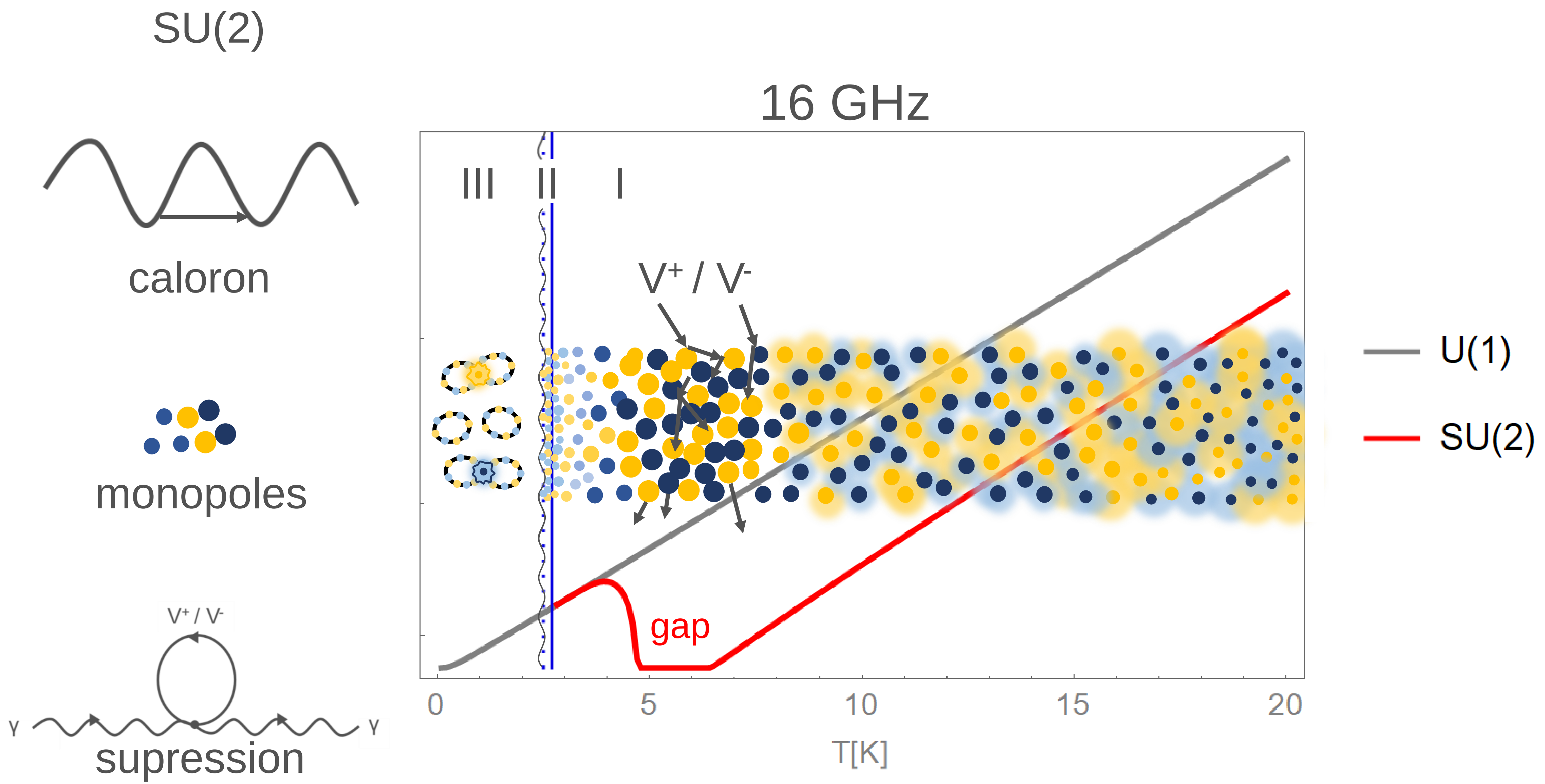


$$I_{\mathrm{U(1)}}(\nu) \equiv \frac{2h}{c^2} \frac{\nu^3}{\exp[\frac{h\,\nu}{k_B T}] - 1}$$

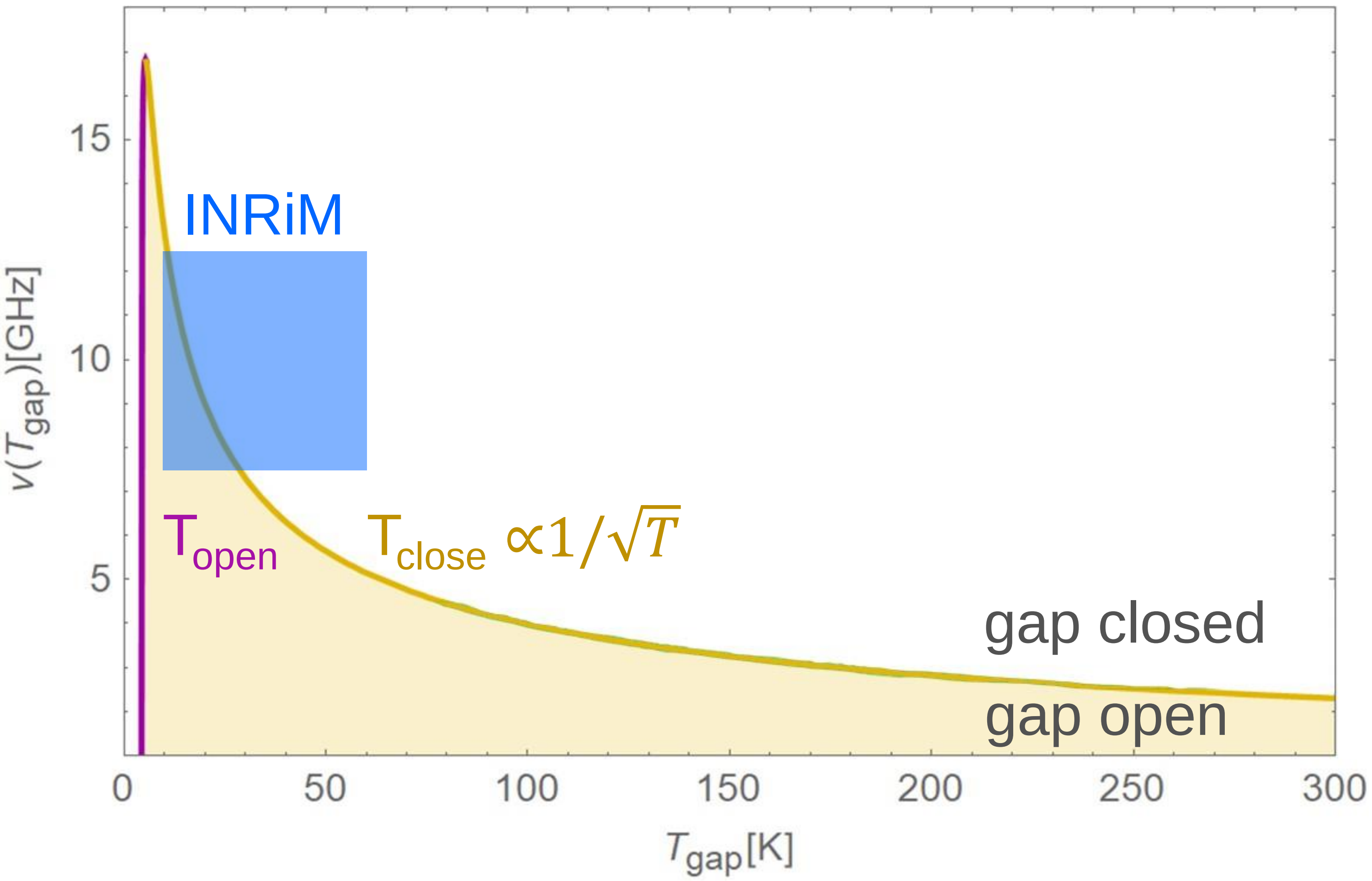


Screening function

$$I_{SU(2)}(\nu) = \frac{2h}{c^2} \frac{\nu^3}{\exp[\frac{h\nu}{k_B T}] - 1} \times \left(1 - \frac{G(\nu)}{\nu^2}\right)$$

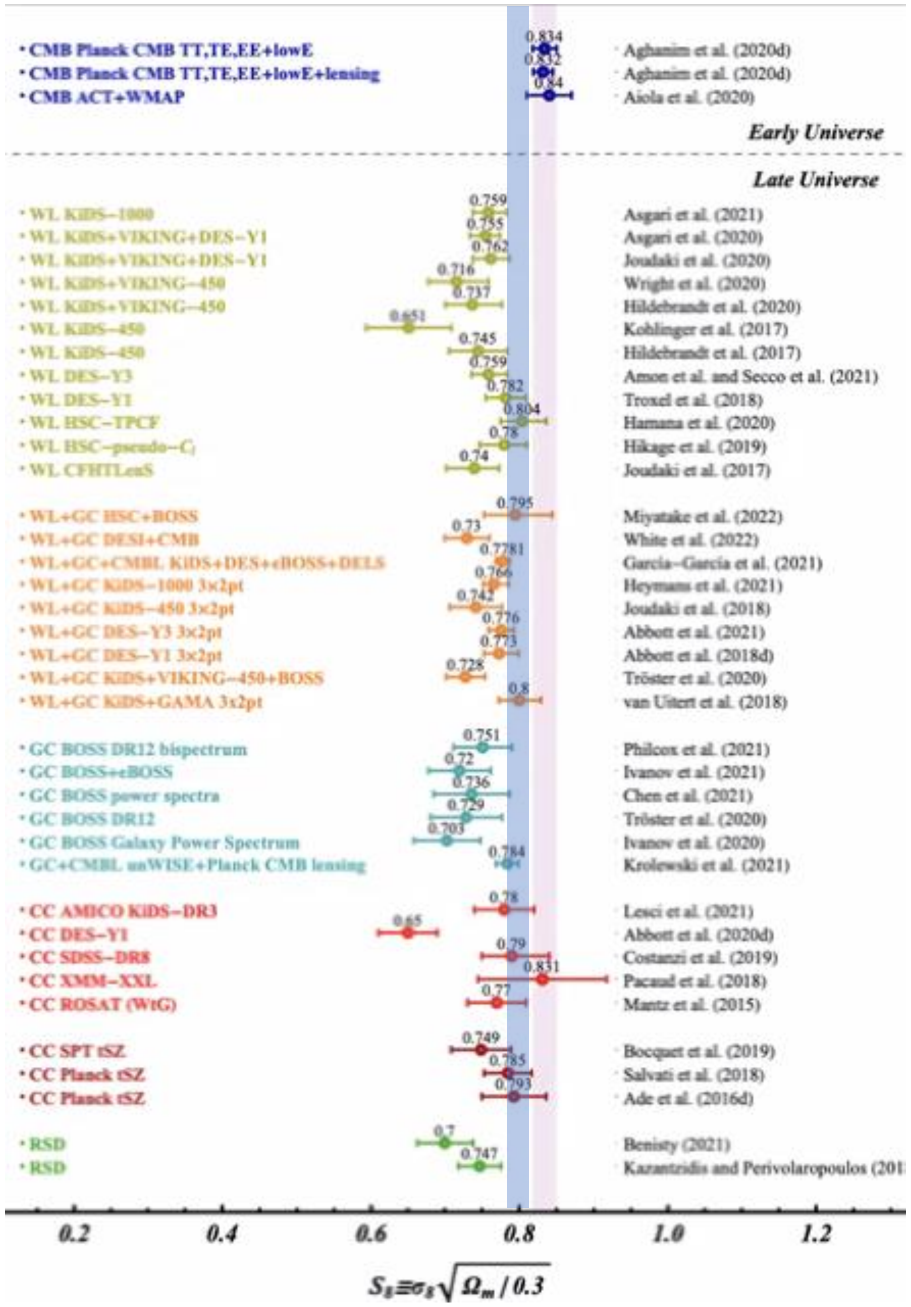


SU(2)
caloron
monopoles
V+ / V-
γ
γ
supression
16 GHz
III
II
I
V+ / V-
gap
0
5
10
15
20
T[K]
U(1)
SU(2)


INRiM
T_{open}
T_{close} $\propto 1/\sqrt{T}$
gap closed
gap open
$\nu(T_{gap})$[GHz]
T_{gap}[K]
0
50
100
150
200
250
300
5
10
15

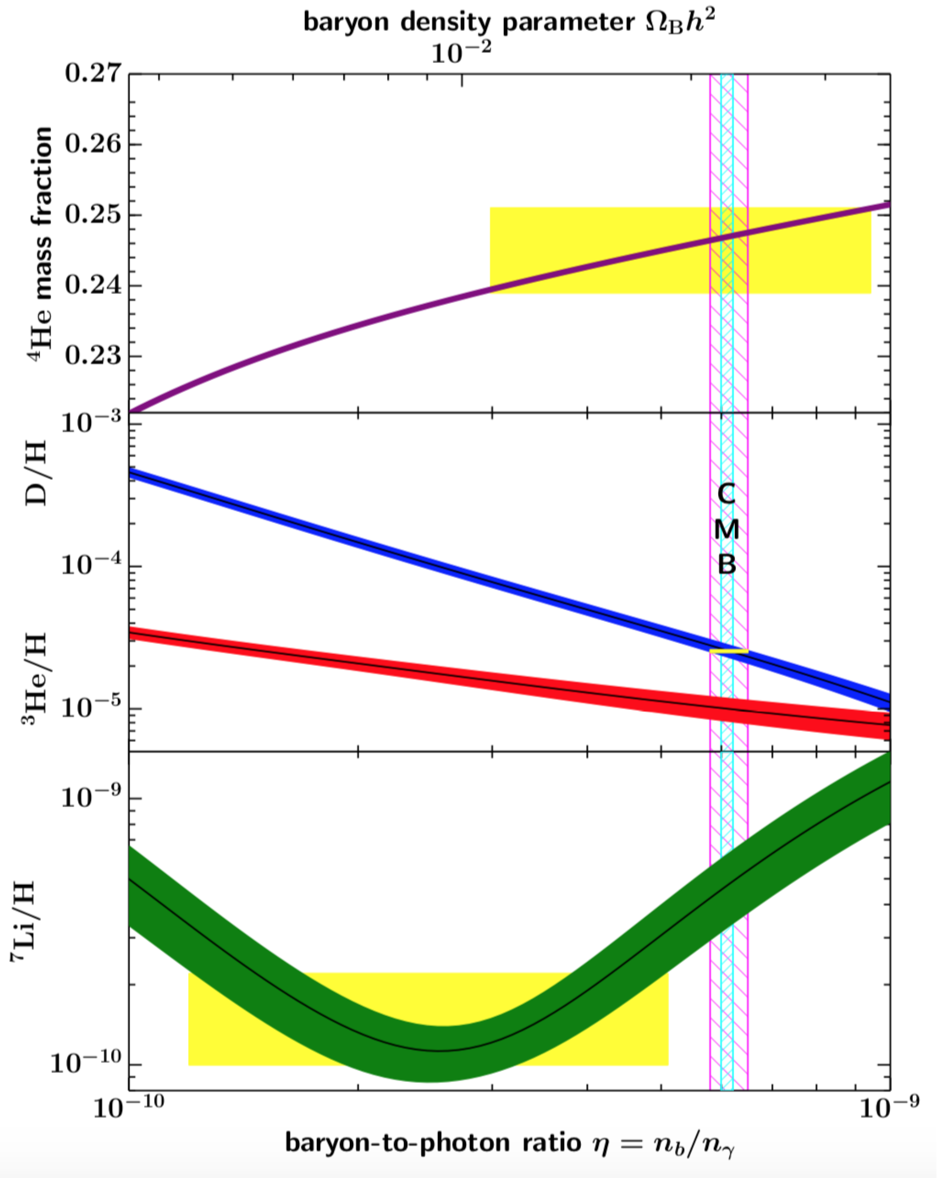
S8 tension

S8 Tension



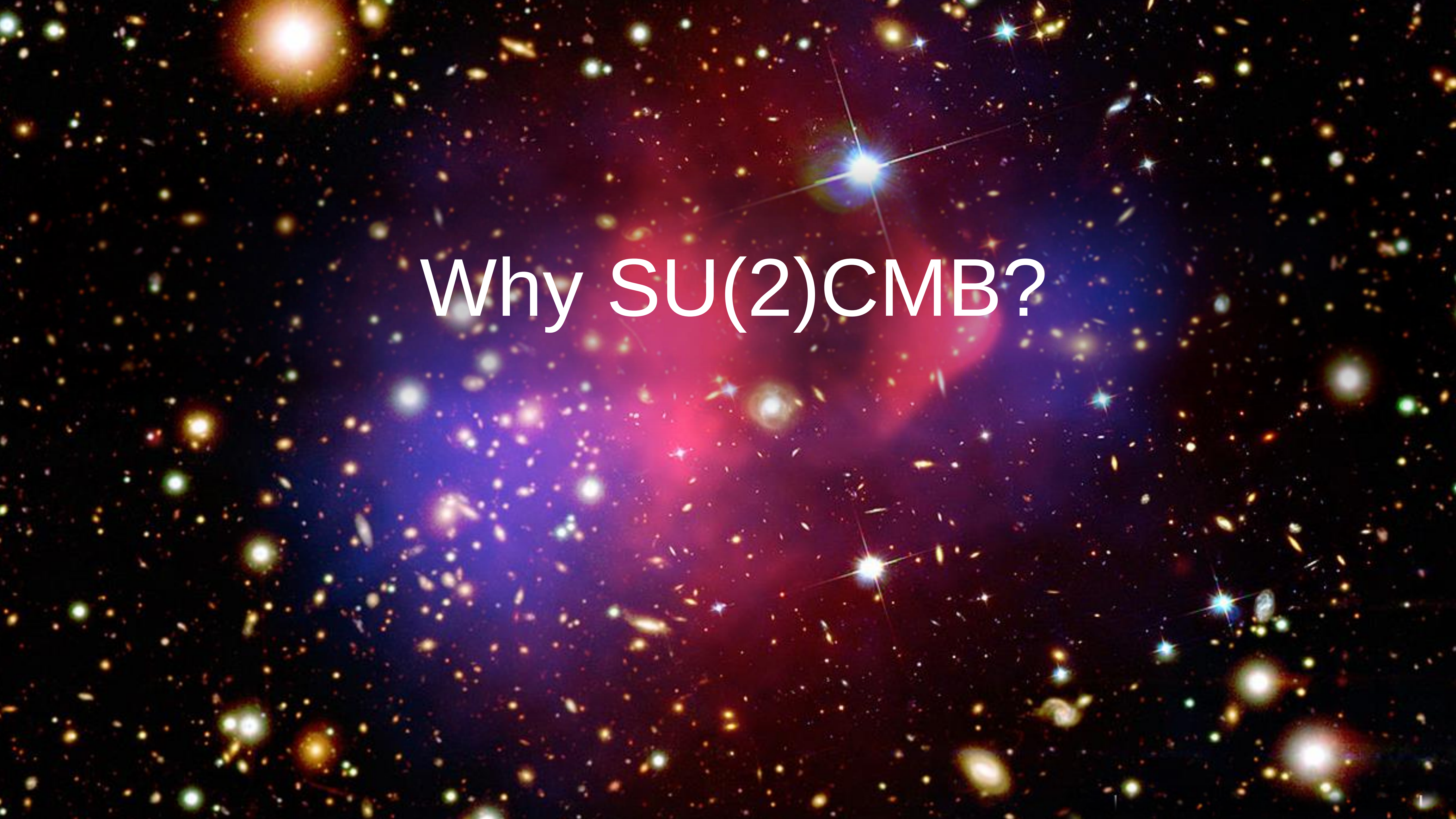
CMB Planck CMB TT,TE,EE+lowE
CMB Planck CMB TT,TE,EE+lowE+lensing
CMB ACT+WMAP
Early Universe
Late Universe
WL KiDS–1000
WL KiDS+VIKING+DES–Y1
WL KiDS+VIKING+DES–Y1
WL KiDS+VIKING–450
WL KiDS+VIKING–450
WL KiDS–450
WL KiDS–450
WL DES–Y3
WL DES–Y1
WL HSC–TPCF
WL HSC–pseudo–C_l
WL CFHTLenS
WL+GC HSC+BOSS
WL+GC DESI+CMB
WL+GC+CMBL KiDS+DES+eBOSS+DELS
WL+GC KiDS–1000 3x2pt
WL+GC KiDS–450 3x2pt
WL+GC DES–Y3 3x2pt
WL+GC DES–Y1 3x2pt
WL+GC KiDS+VIKING–450+BOSS
WL+GC KiDS+GAMA 3x2pt
GC BOSS DR12 bispectrum
GC BOSS+eBOSS
GC BOSS power spectra
GC BOSS DR12
GC BOSS Galaxy Power Spectrum
GC+CMBL unWISE+Planck CMB lensing
CC AMICO KiDS–DR3
CC DES–Y1
CC SDSS–DR8
CC XMM–XXL
CC ROSAT (WtG)
CC SPT tSZ
CC Planck tSZ
CC Planck tSZ
RSD
RSD
0.834
0.832
0.84
0.759
0.755
0.762
0.716
0.737
0.651
0.745
0.759
0.782
0.804
0.78
0.74
0.795
0.73
0.7781
0.766
0.742
0.776
0.773
0.728
0.8
0.751
0.72
0.736
0.729
0.703
0.784
0.78
0.65
0.79
0.831
0.77
0.749
0.785
0.793
0.7
0.747
Aghanim et al. (2020d)
Aghanim et al. (2020d)
Aiola et al. (2020)
Asgari et al. (2021)
Asgari et al. (2020)
Joudaki et al. (2020)
Wright et al. (2020)
Hildebrandt et al. (2020)
Kohlinger et al. (2017)
Hildebrandt et al. (2017)
Amon et al. and Secco et al. (2021)
Troxel et al. (2018)
Hamana et al. (2020)
Hikage et al. (2019)
Joudaki et al. (2017)
Miyatake et al. (2022)
White et al. (2022)
Garcia–Garcia et al. (2021)
Heymans et al. (2021)
Joudaki et al. (2018)
Abbott et al. (2021)
Abbott et al. (2018d)
Tröster et al. (2020)
van Uitert et al. (2018)
Philcox et al. (2021)
Ivanov et al. (2021)
Chen et al. (2021)
Tröster et al. (2020)
Ivanov et al. (2020)
Krolewski et al. (2021)
Lesci et al. (2021)
Abbott et al. (2020d)
Costanzi et al. (2019)
Pacaud et al. (2018)
Mantz et al. (2015)
Bocquet et al. (2019)
Salvati et al. (2018)
Ade et al. (2016d)
Benisty (2021)
Kazantzidis and Perivolaropoulos (201
0.2
0.4
0.6
0.8
1.0
1.2
$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$

BBN??

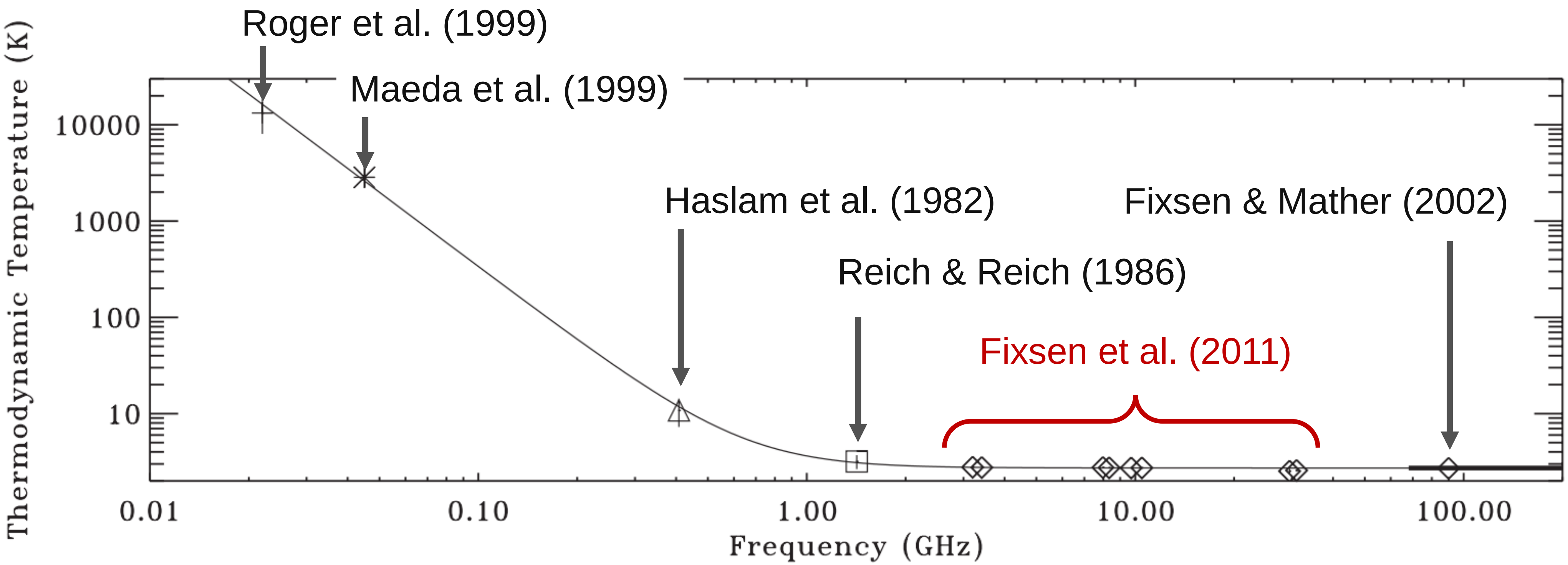


Tanabashi+ PRD 2018

Why SU(2)CMB?

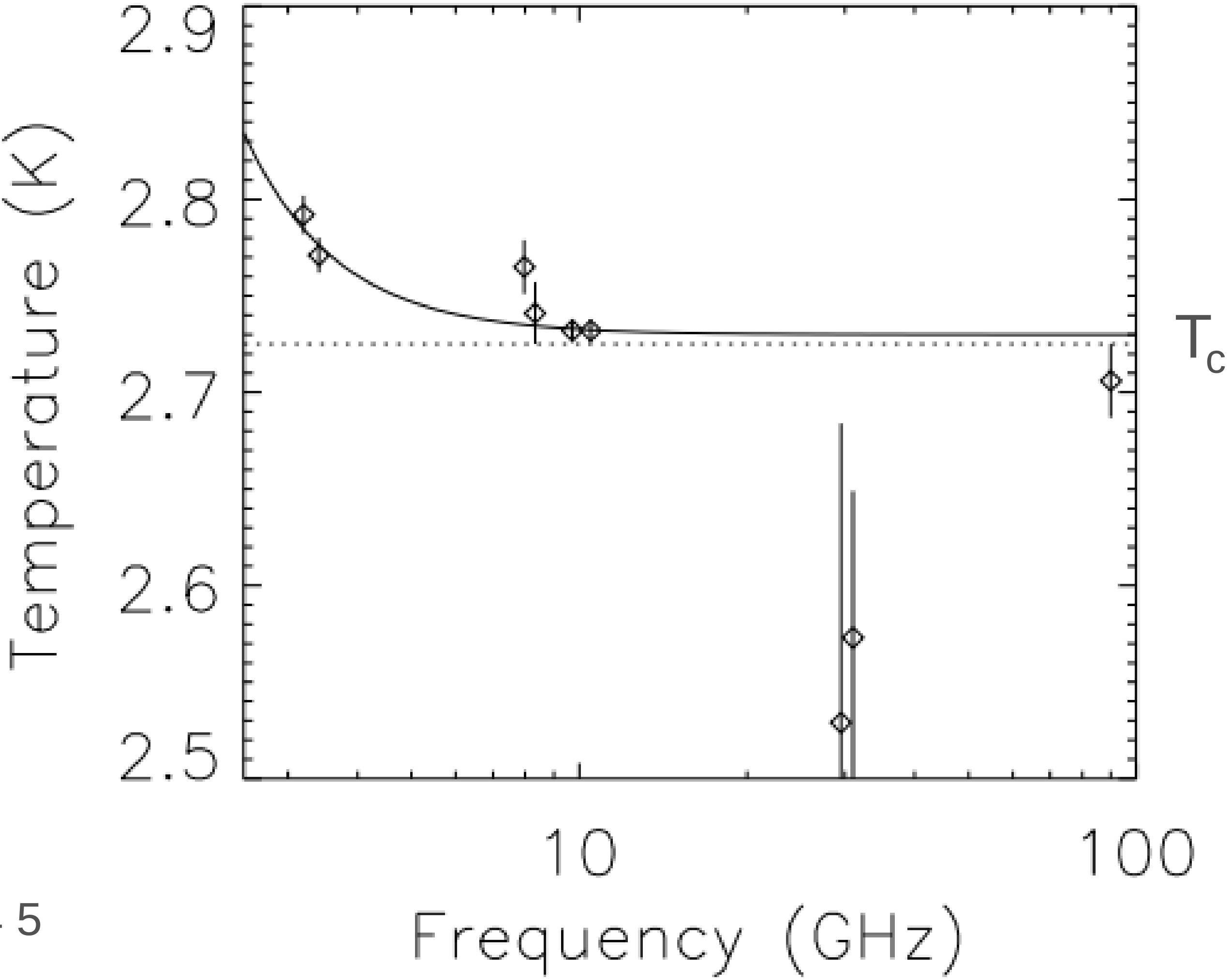


CMB radio excess

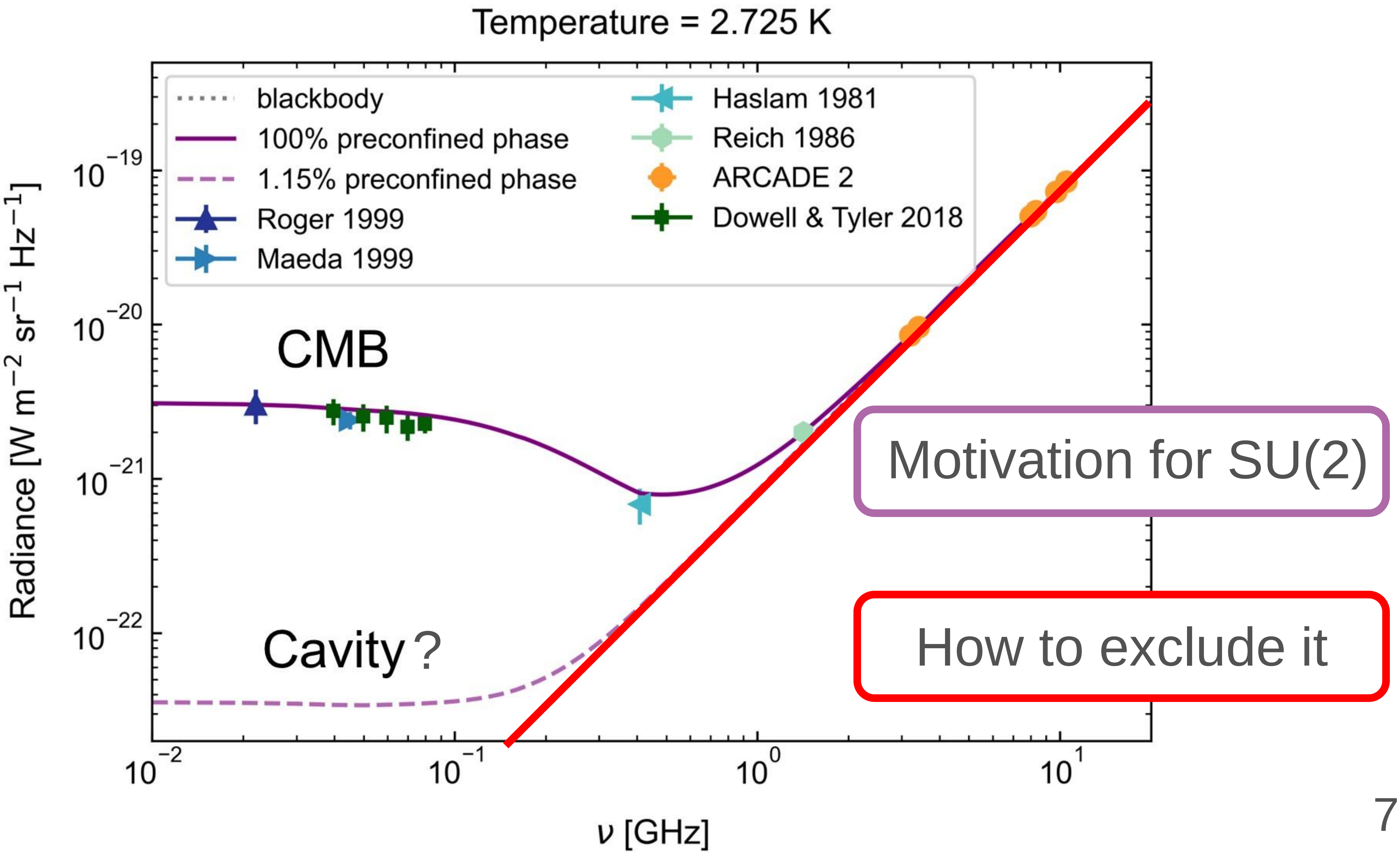


Seiffert et al. (2011)

ARCADE 2



D. J. Fixsen et al 2011 ApJ 734 5



Temperature = 2.725 K
blackbody
100% preconfined phase
1.15% preconfined phase
Roger 1999
Maeda 1999
Haslam 1981
Reich 1986
ARCADE 2
Dowell & Tyler 2018
CMB
Cavity?
Radiance [W m^{-2} sr^{-1} Hz^{-1}]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-2}
10^{-1}
10^{0}
10^{1}
ν [GHz]
Motivation for SU(2)
How to exclude it

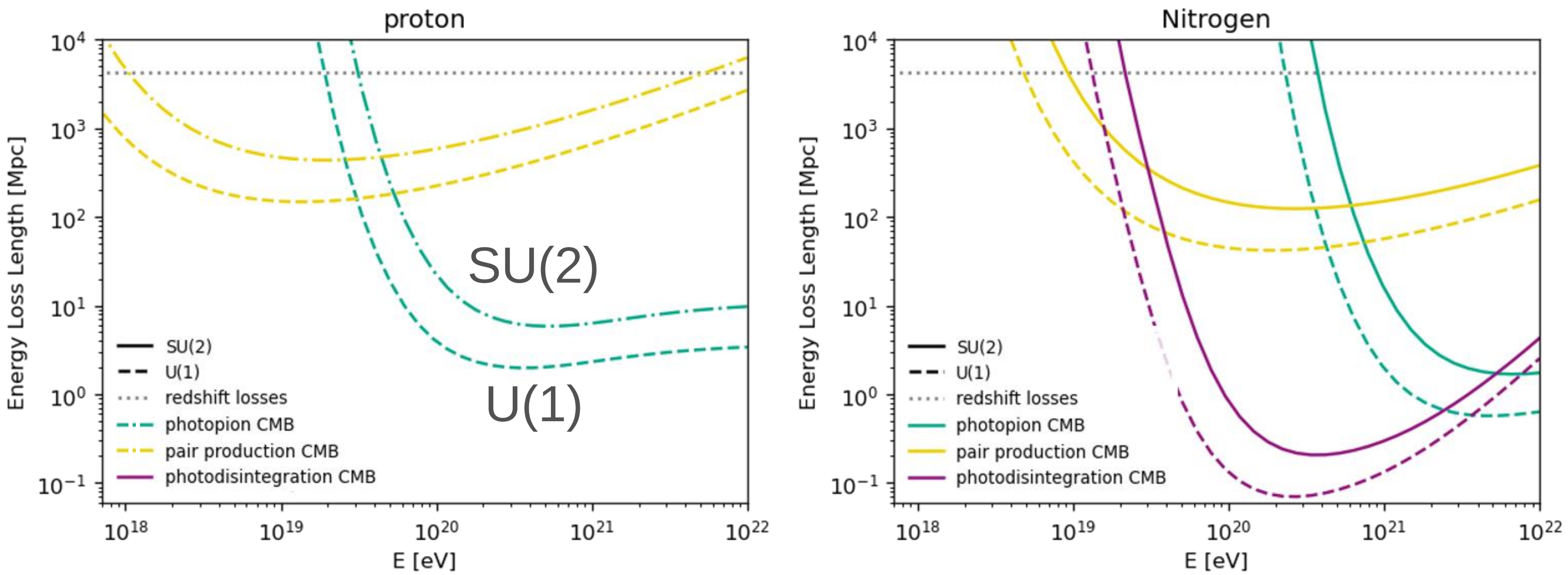
Isn‘t $T(z)$ measured already?

[2] To a very good approximation the spectral intensity $I(\nu)$ of today's CMB is given as $I_{z=0}(\nu)d\nu = 16\pi^2 \frac{\nu^3}{\exp\left(\frac{2\pi\nu}{T(z=0)}\right)-1} d\nu$ Mather et al. (1994). If we assume a T-z relation of $T(z=0) = \frac{1}{f(z)}T(z)$ and a ν-z relation of $\nu(z=0) \equiv \frac{1}{g(z)}\nu'$ with $f(z) \neq g(z)$, then the Stefan-Boltzmann law would still have redshifted according to the T-z relation: $\int d\nu I_{z=0}(\nu) = \frac{\pi^2}{15}T^4(z=0) = \frac{\pi^2}{15}\left(\frac{T(z)}{f(z)}\right)^4 = \left(\frac{1}{g(z)}\right)^4 \int d\nu' I_z(\nu')$. However, the maximum $\nu_{\max} = \frac{2.821}{2\pi}T(z=0)$ of the distribution $I_{z=0}(\nu)d\nu$ converts to a maximum $\nu'_{\max} = \frac{2.821}{2\pi}\frac{g(z)}{f(z)}T(z)$ of the distribution $I_z(\nu')d\nu' = 16\pi^2 \frac{(\nu')^3}{\exp\left(\frac{f(z)}{g(z)}\frac{2\pi\nu'}{T(z)}\right)-1} d\nu'$. Thus, $I_z(\nu')$ no longer would be a blackbody spectrum.

e-Print: 2303.16744 [hep-th]

Energy loss length

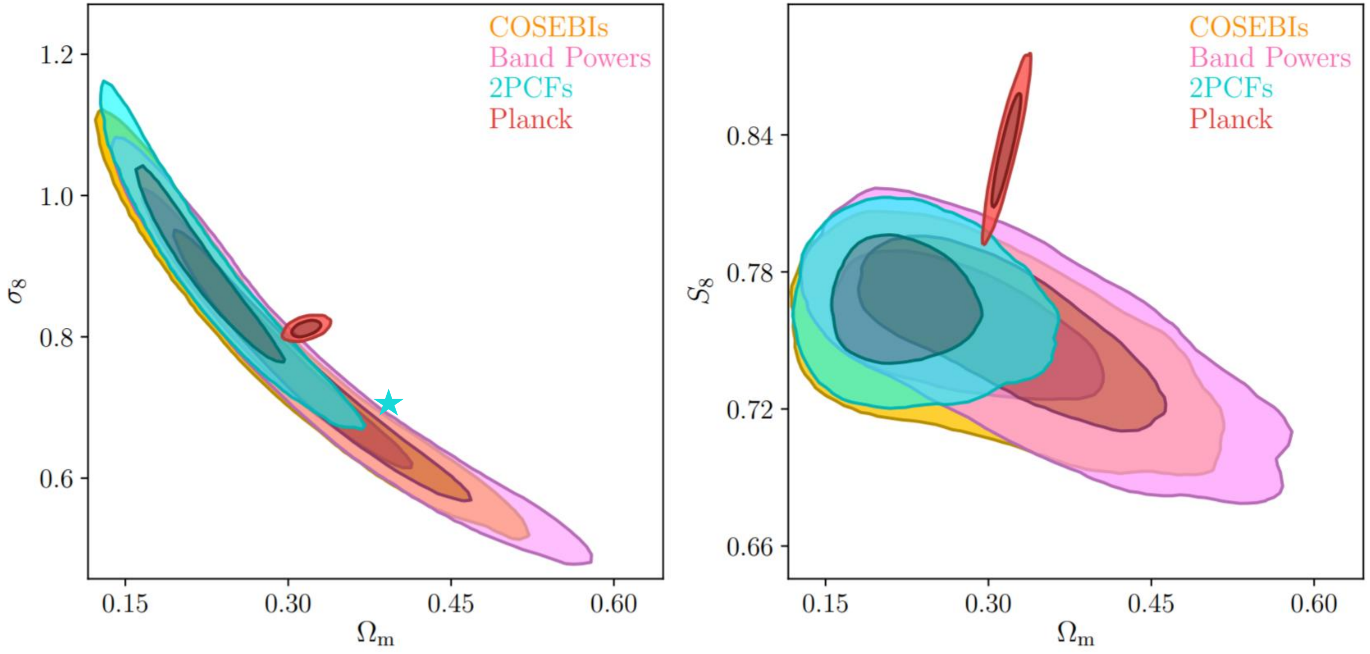
Changed Energy Loss Length



Lensing

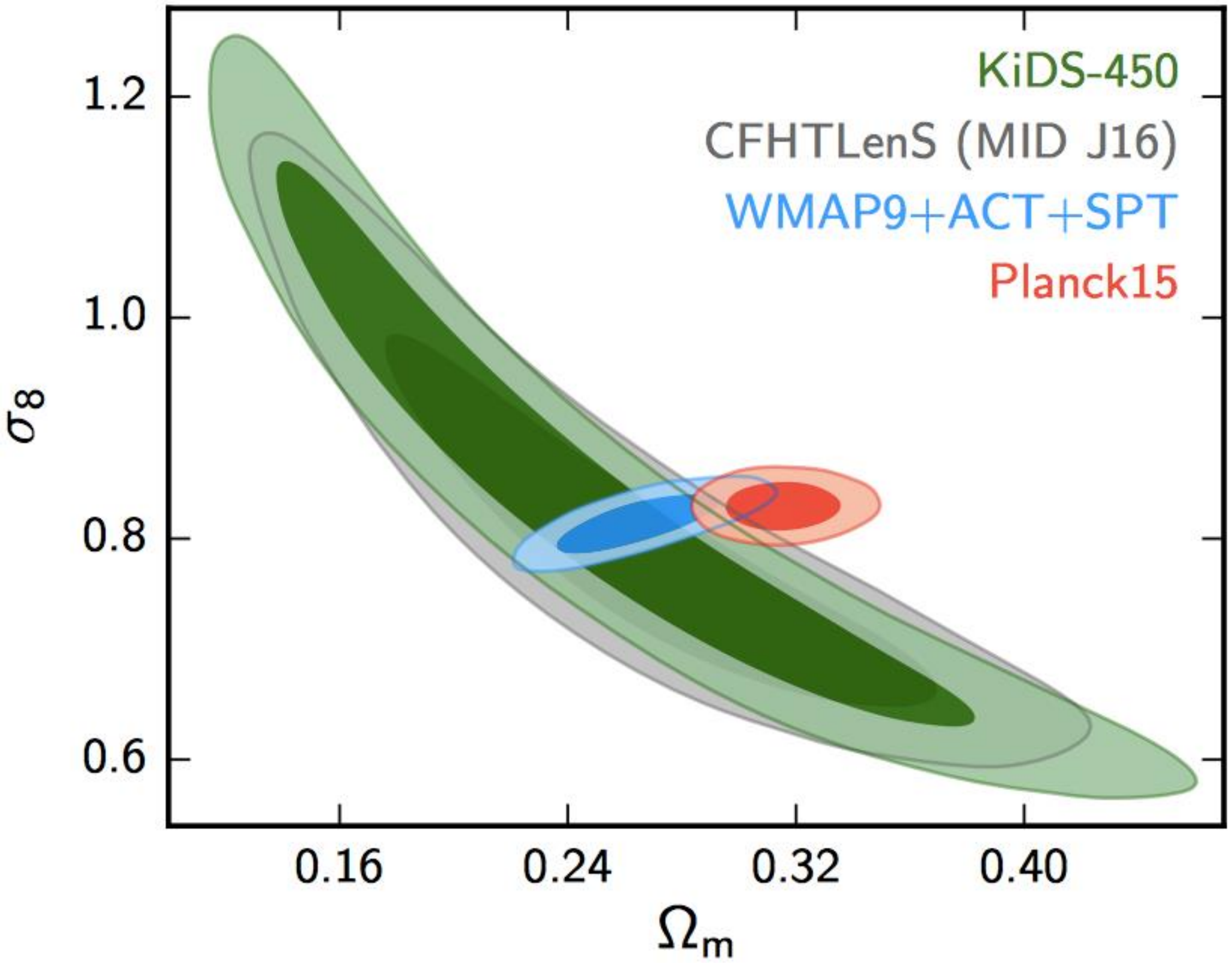
Cosmological parameters

Parameter	ΛCDM (TT,TE,EE+lowE)	SU(2)
z^*	1089.95 ± 0.27	1715.9 ± 0.19
Ω_m	0.3166 ± 0.0084	0.384 ± 0.006
σ_8	0.8120 ± 0.0073	0.709 ± 0.020



KiDS Collaboration arxiv.org/pdf/2007.15633

σ_8 tension



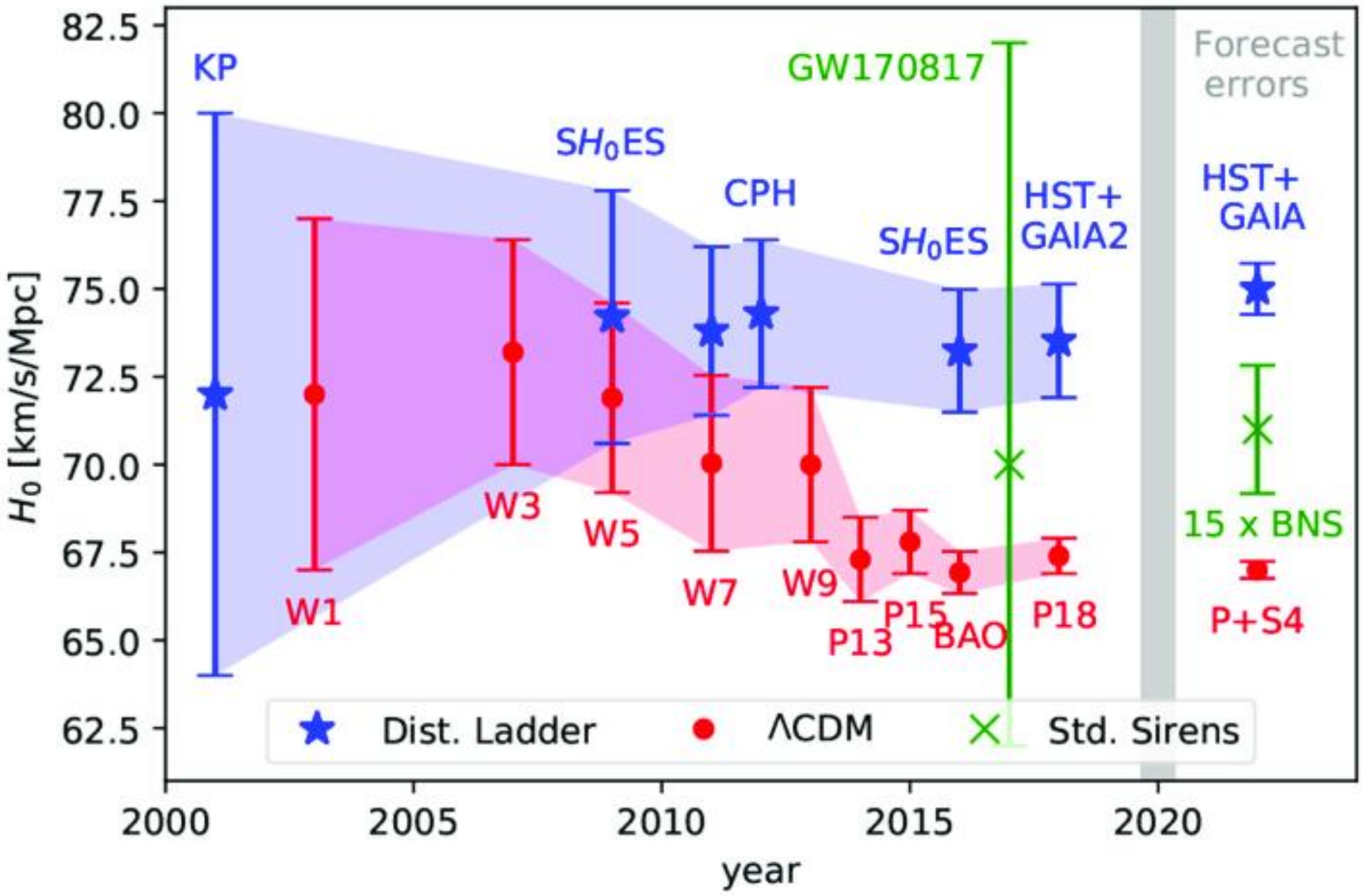
global

local

https://kids.strw.leidenuniv.nl/cosmicshear2016.php

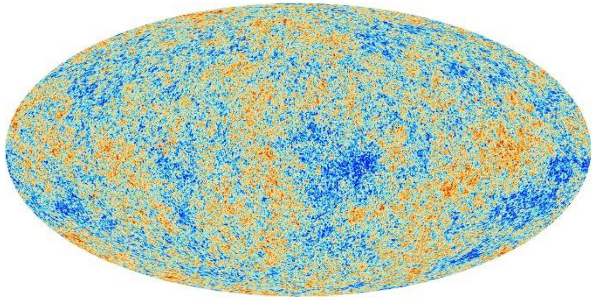
H_0 tension

Hubble Constant over time

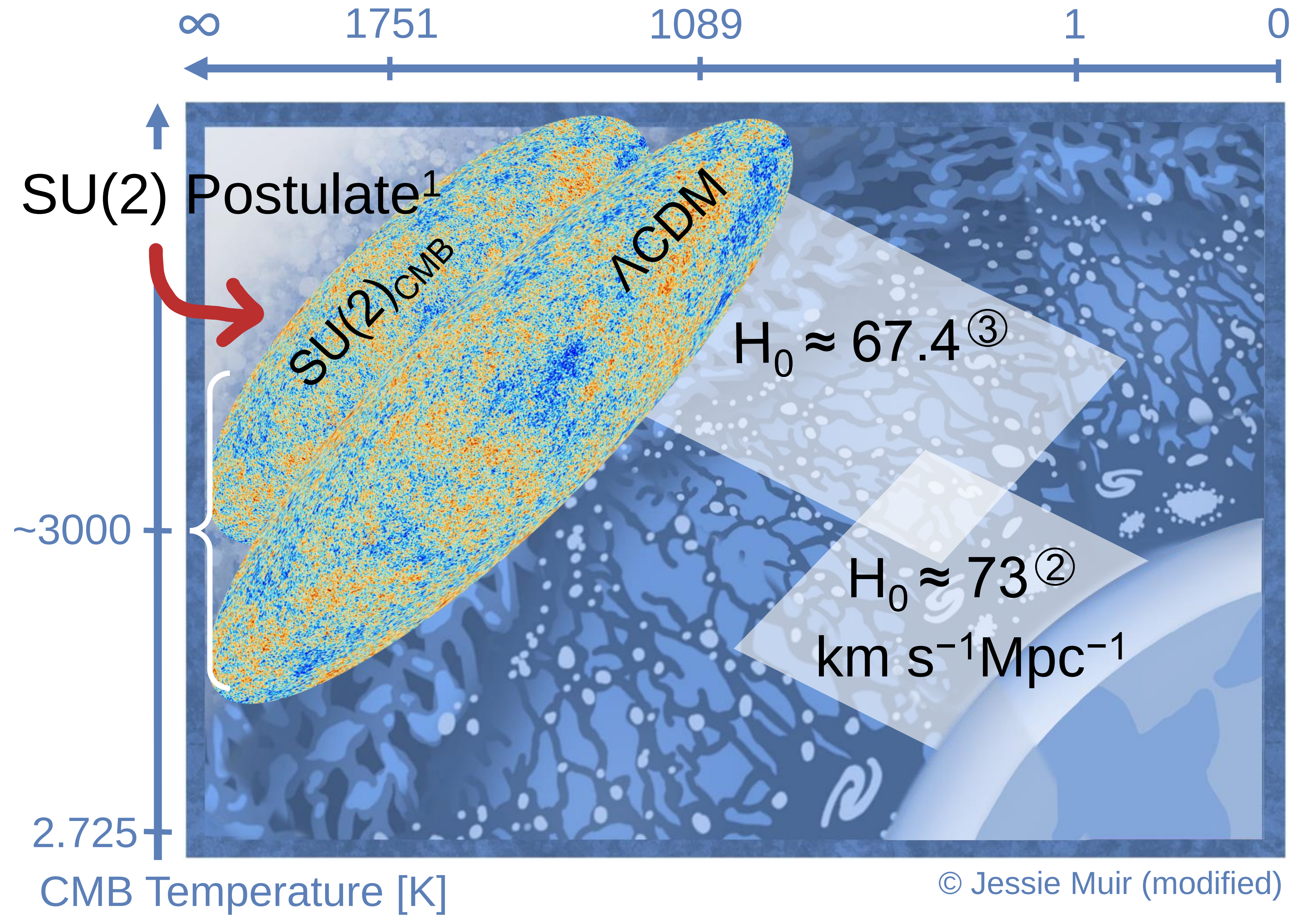


Freedman et al. / Astrophysical Journal

distance ladder



+ ΛCDM



[1] Hofmann 2013 Nature Phys. 10.1038/nphys2793

[3] Planck Collaboration arXiv: 1807.06209

[2] Riess et al. 2021 arXiv: 2112.04510