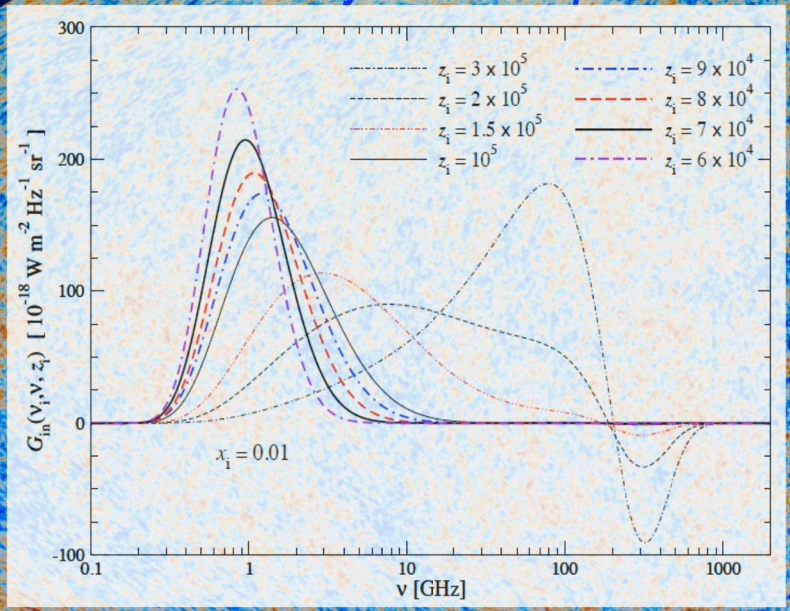
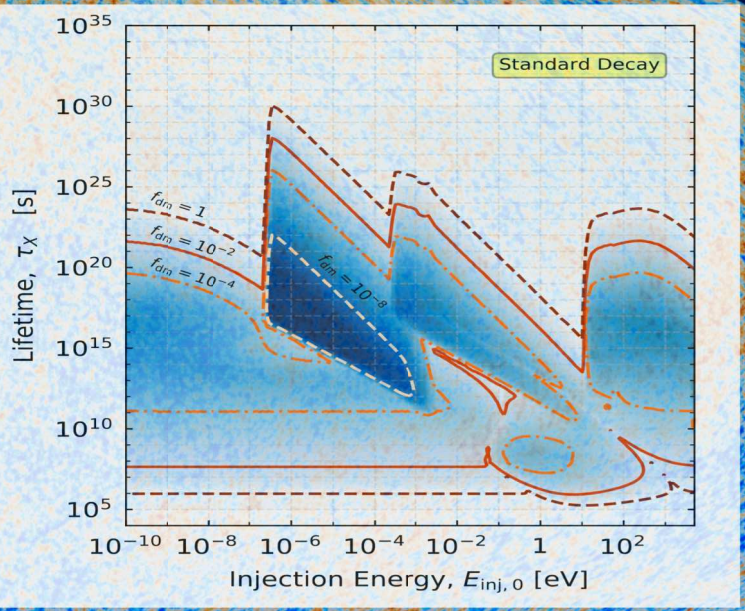
Low-frequency spectral distortions of the CMB

Photon injection example



Constraints from FIRAS



Jens Chluba

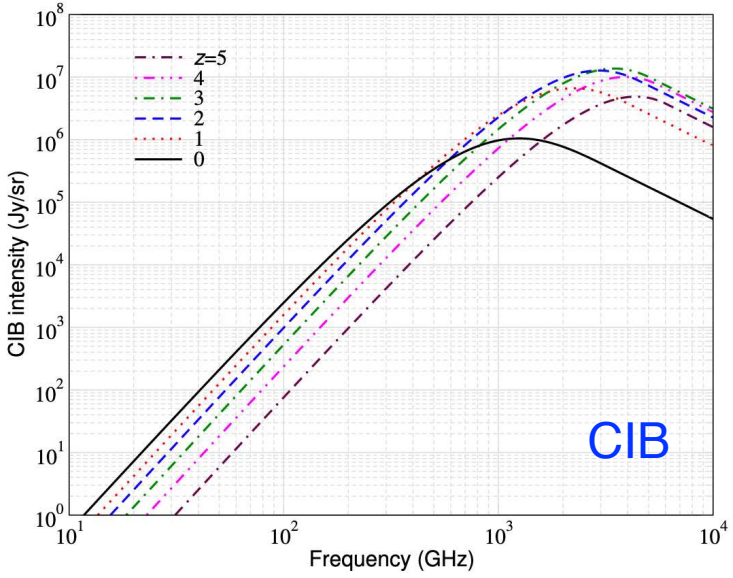
The University of Manchester

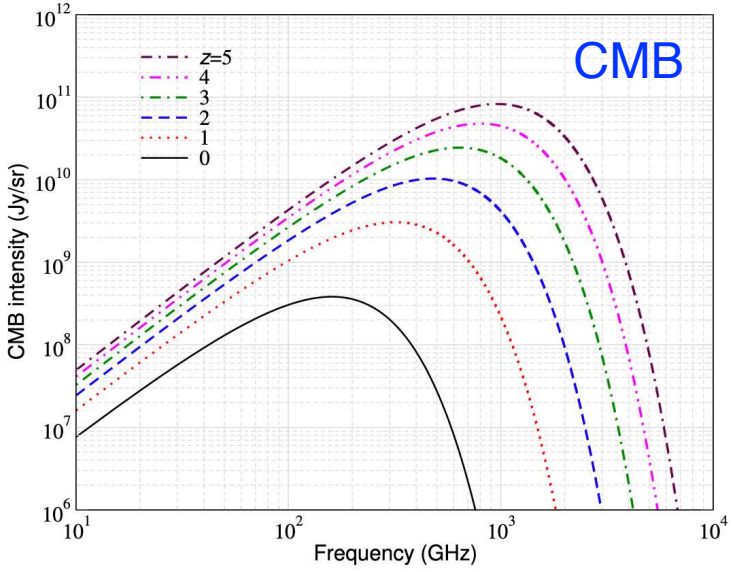
BAM on Radio Synchrotron Backgrounds

June 16th 2022

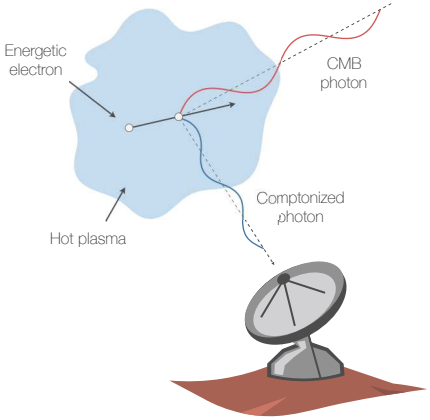
Before we get started…

Like for the radio there is a CIB-SZ effect!

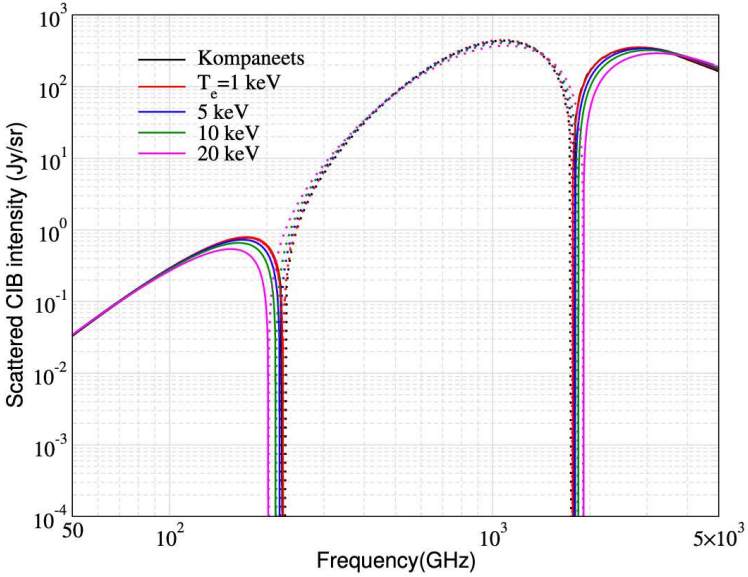


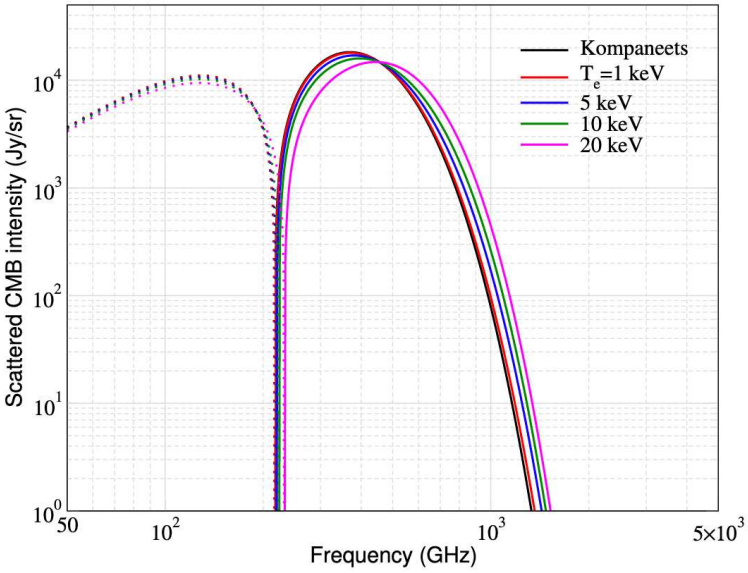


Hot electrons



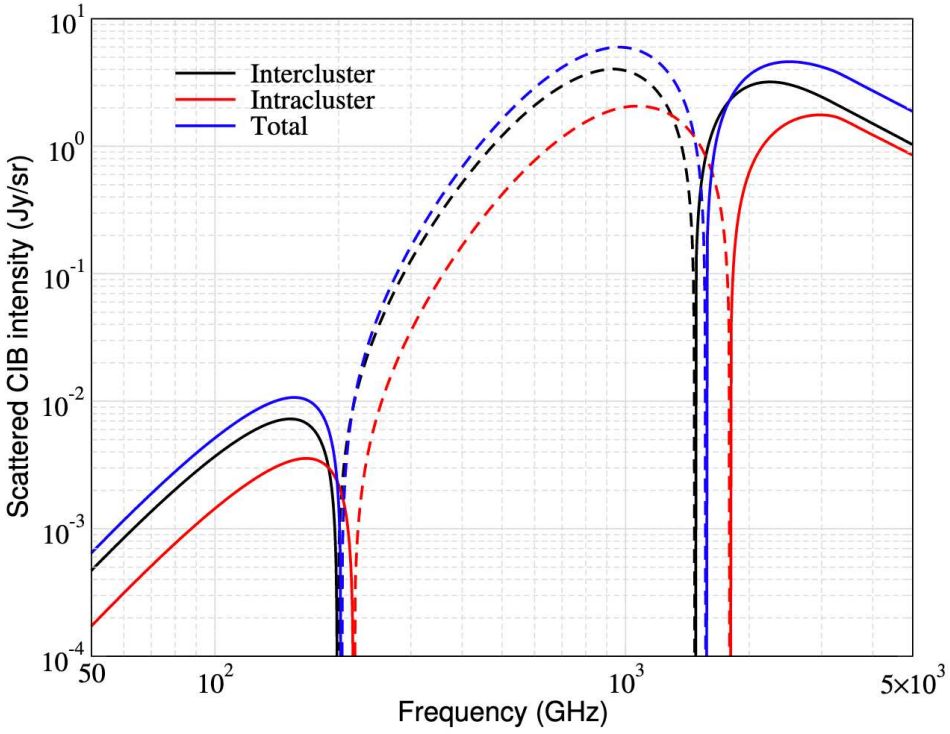
Sandeep Acharya

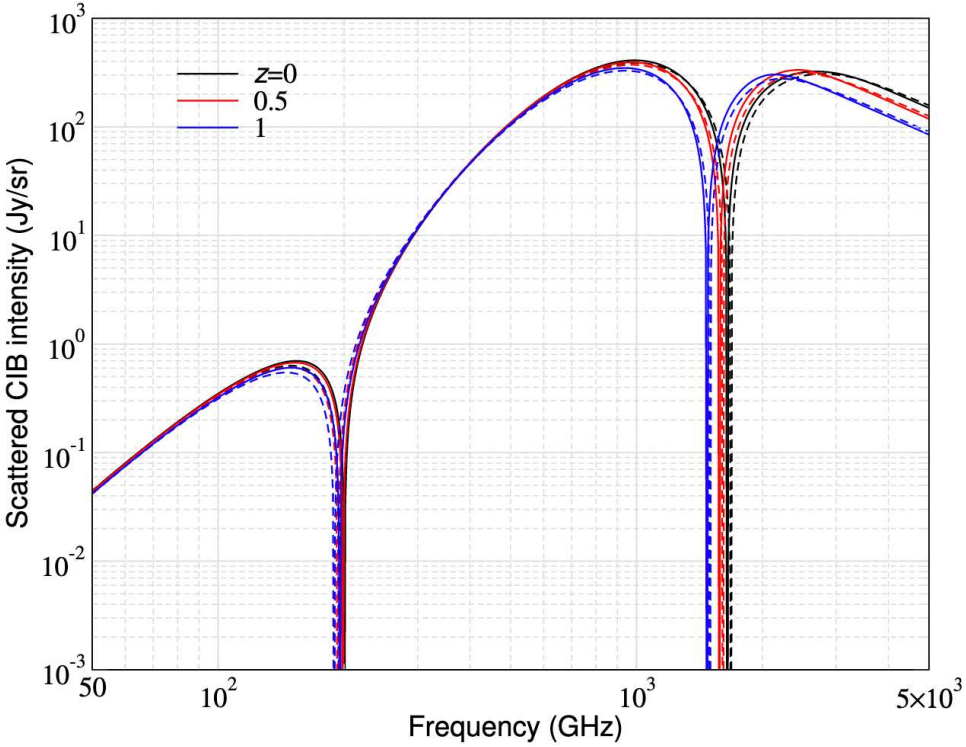




Holder & JC, ArXiv:2110.08373
Sabyr, 2022, ArXiv:2202.02275
Acharya & JC, ArXiv:2205.00857

Intra-cluster scattering and redshift dependence





- *Intra-cluster* contribution as important as *inter-cluster* signal
- Changes shape of the signal (no redshifting)
- Intra-cluster scattering form factor

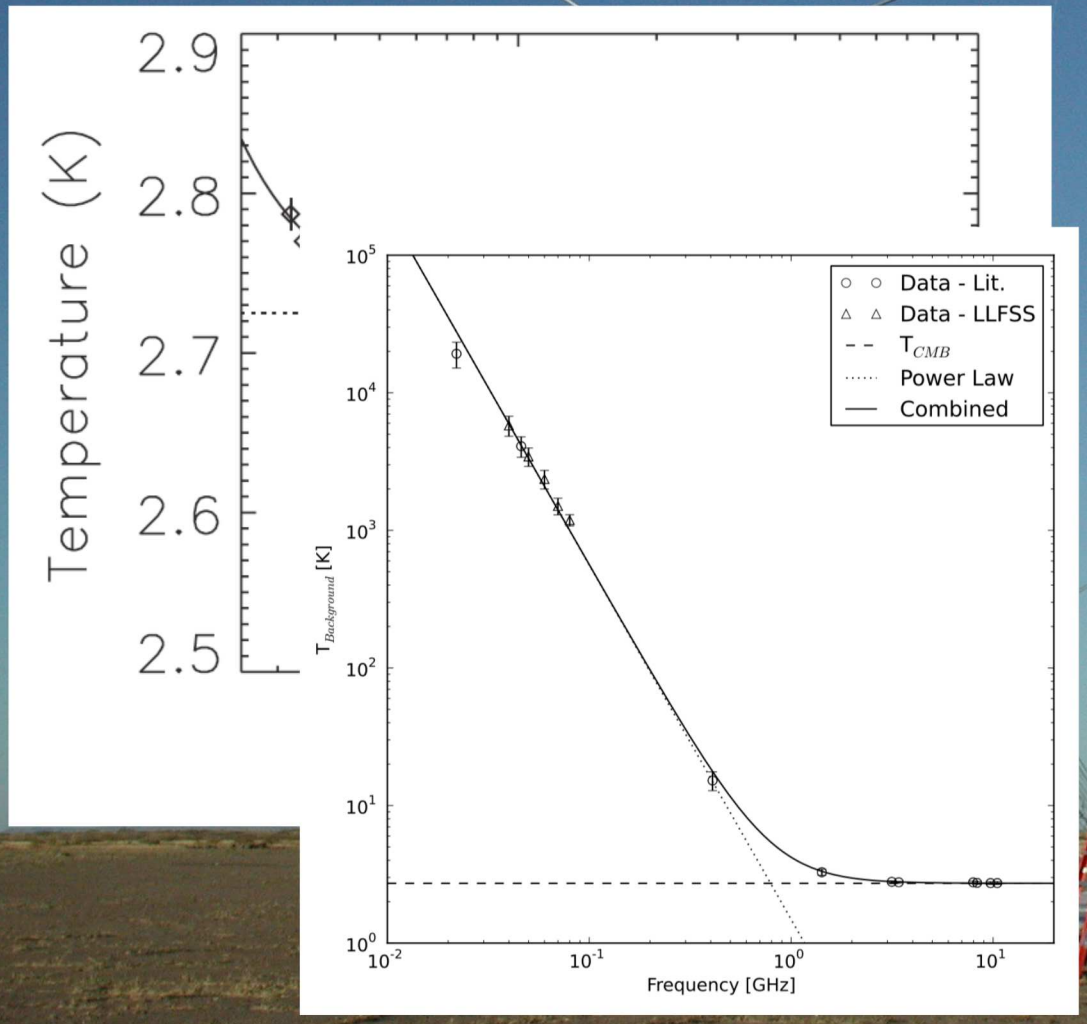
- CIB scattering signal is redshift dependent
- Combination of tCIB and tSZ allows to do tomography
- High frequencies needed!

Acharya & JC, ArXiv:2205.00857

What could low-frequency distortions have to do with the ARCADE excess and EDGES?

ARCADE

(Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission)



- Found low-frequency excess
- Spectrum:

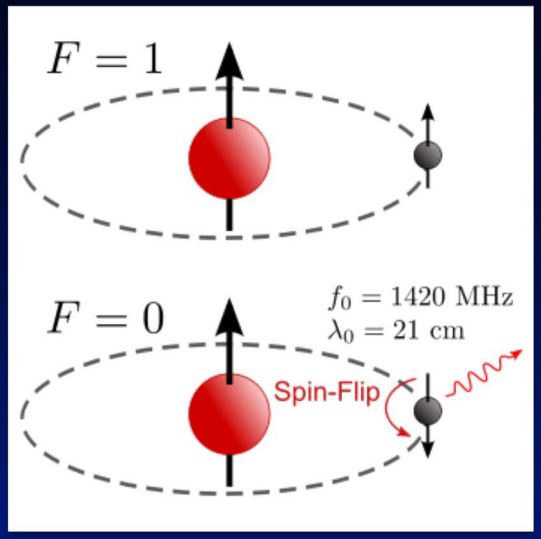
$$T(\nu) = (24.1 \pm 2.1)\mathrm{K}(\nu/\nu_0)^{-2.599\pm0.036}$$

$$\nu_0 = 310\,\mathrm{MHz}$$

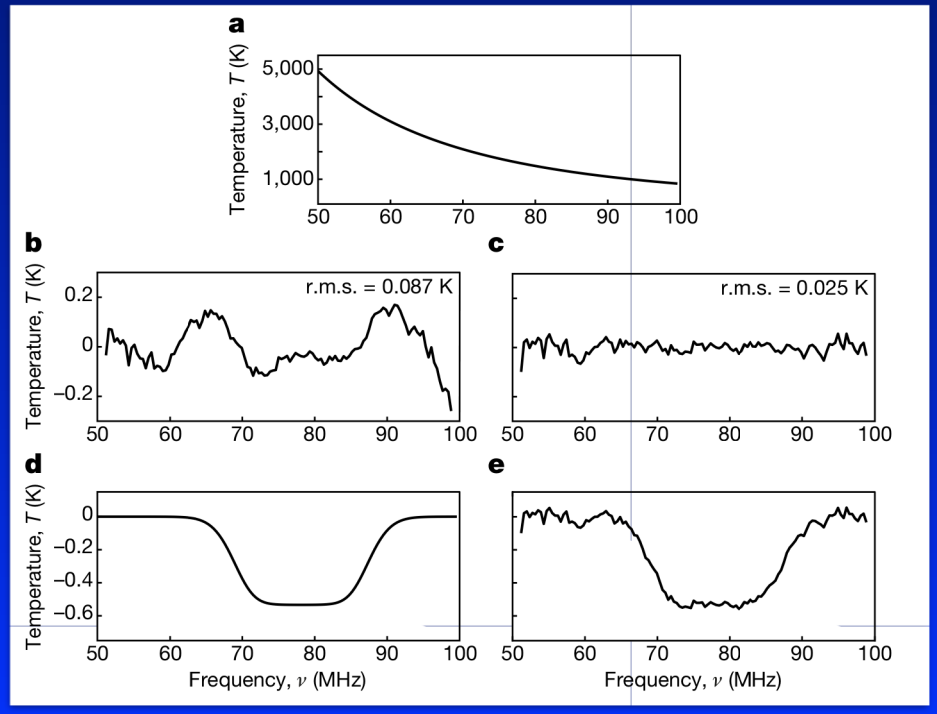
- Origin of excess *unclear*
- New population of radio sources?
- Systematic effect?
- In tension with TRIS results?
- Confirmed by Dowell & Taylor 2018?

Kogut et al. 2006, New Astronomy Rev., 50, 925
Kogut et al., 2011, ApJ, 734, 9
Fixsen et al., 2011, ApJ, 734, 11
Seiffert et al., 2011, ApJ, 734, 8

EDGES detection of cosmological 21cm absorption?

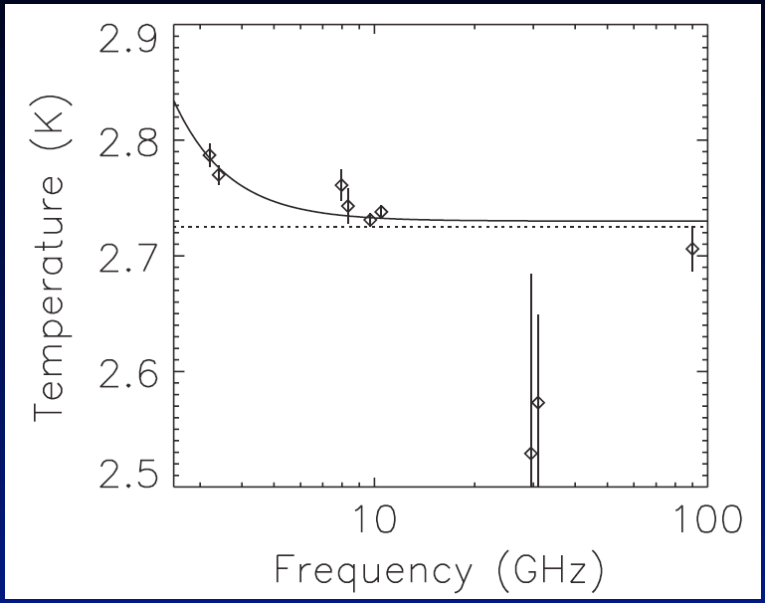


- Stimulated lots of discussion
- Signal much larger than expected in standard scenario
- Shape very unusual
- Possible connection to DM physics / interactions?



Bowman et al., Nature, 2018

Can primordial distortions at low frequencies help?

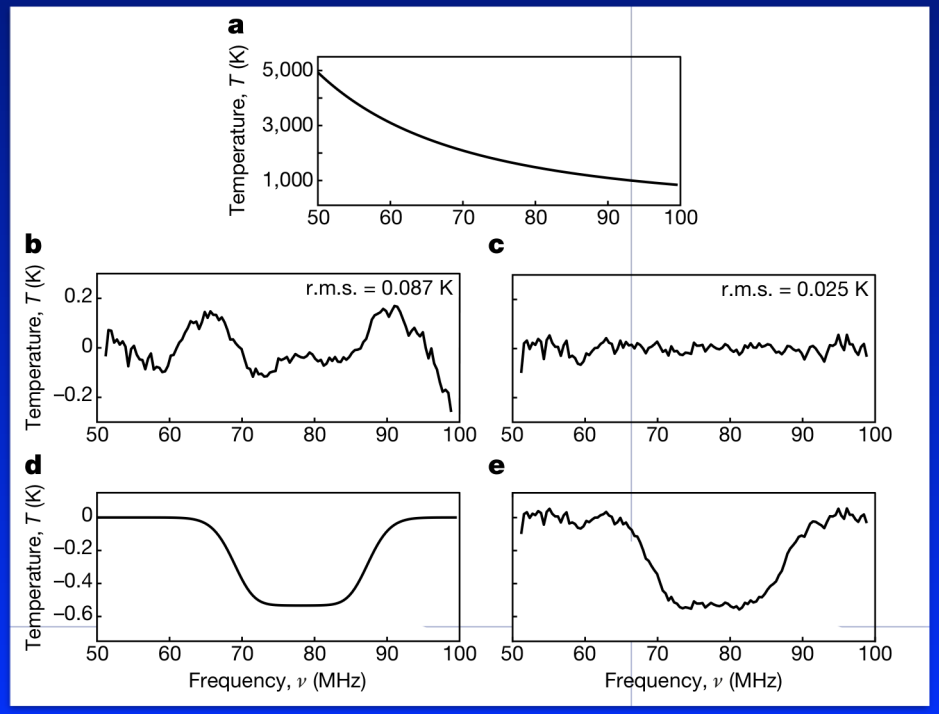


Is there a link to soft-photon injection?
(e.g., JC 2015, ArXiv:1506.06582)

- Which mechanism?
- Late injection?
- early injection?
- unpolarized?

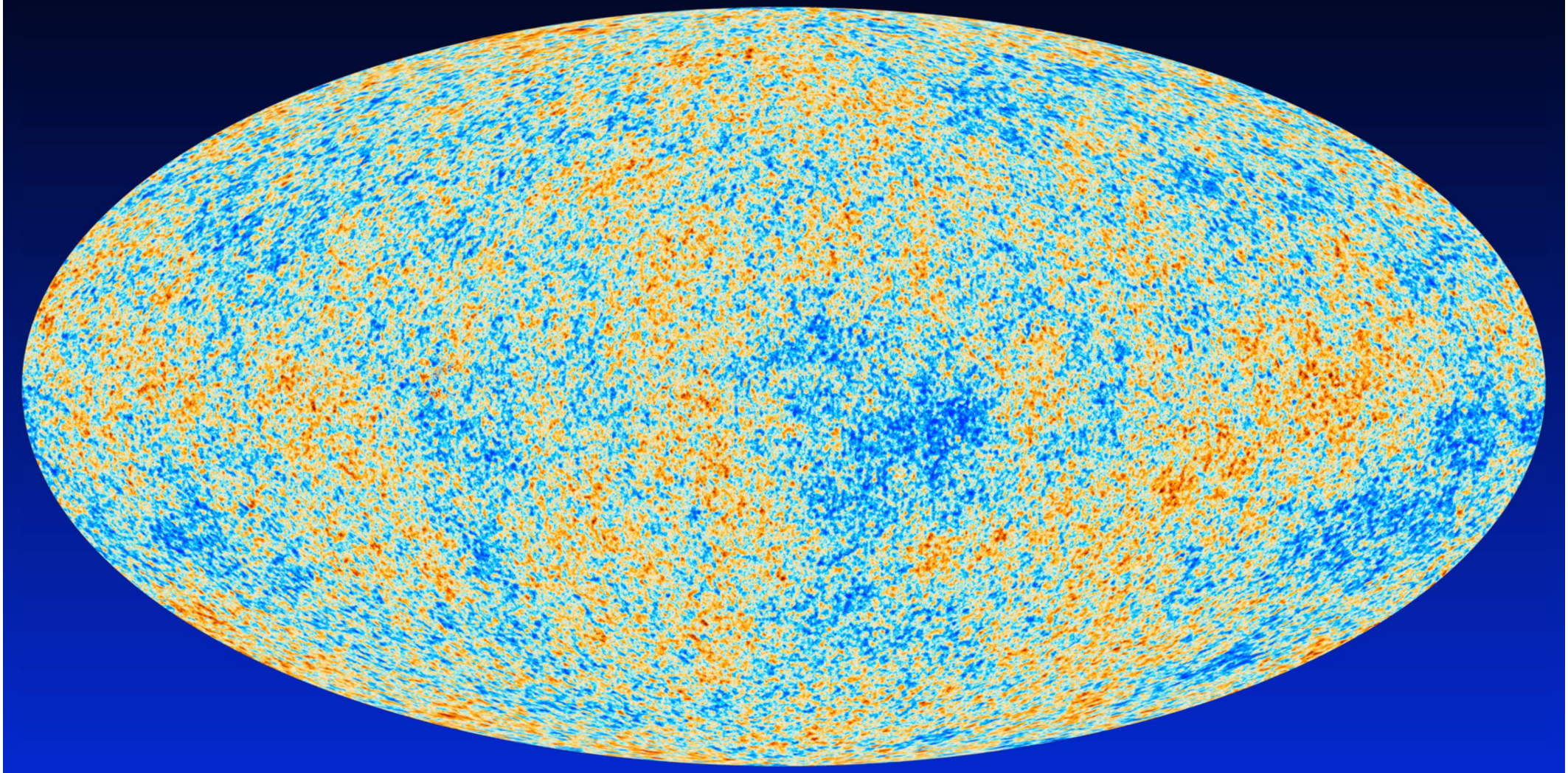
Could a low-frequency distortion explain EDGES?
(e.g., Feng & Holder 2018, ArXiv:1802.07432)

- Distortion needed @ z~20
- Is this connected to ARCADE?
- Shape and amplitude?



Some CMB spectral distortion Physics

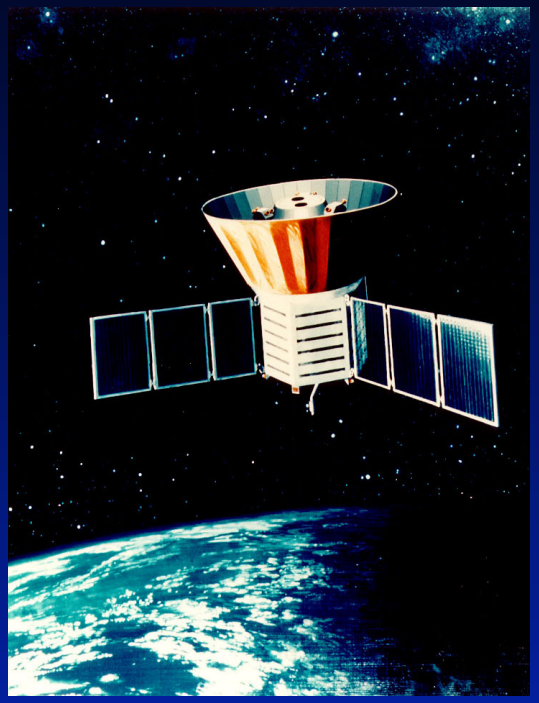
Cosmic Microwave Background Anisotropies



Planck all-sky temperature map

- CMB has a blackbody spectrum in every direction
- tiny variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

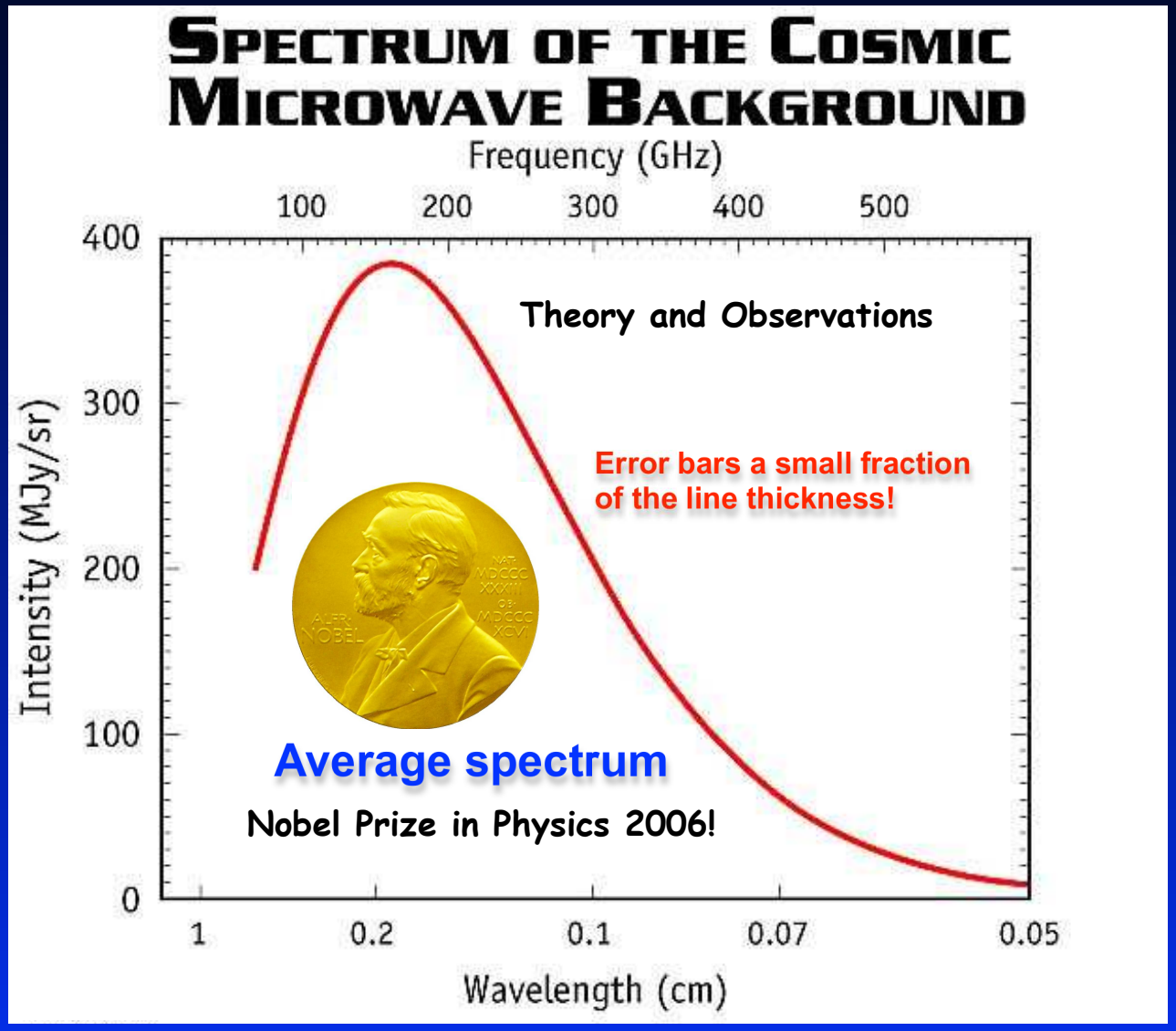
COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

$$|y| \leq 1.5\times10^{-5}$$

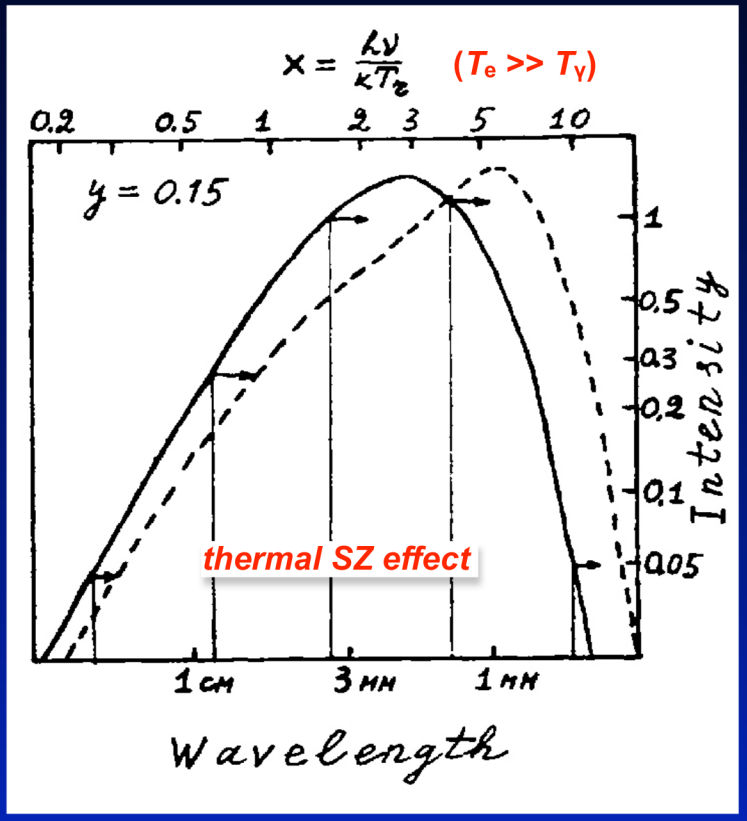
$$|\mu| \leq 9\times10^{-5}$$



Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen et al., 2003, ApJ, 594, 67

Standard types of primordial CMB distortions

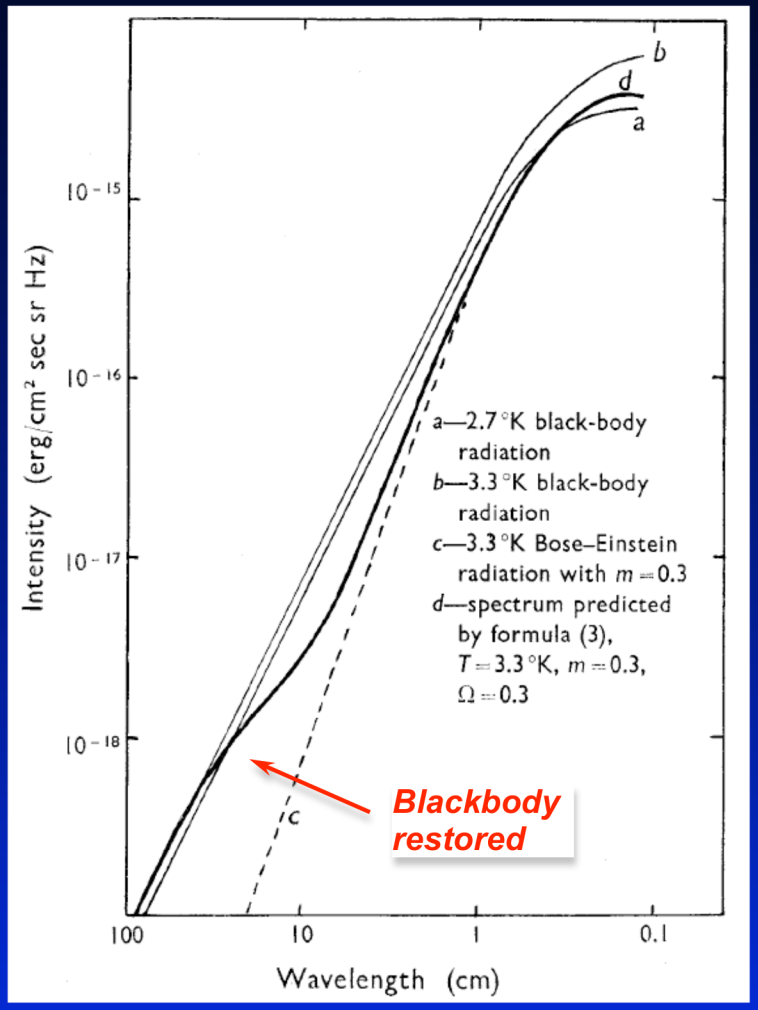
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

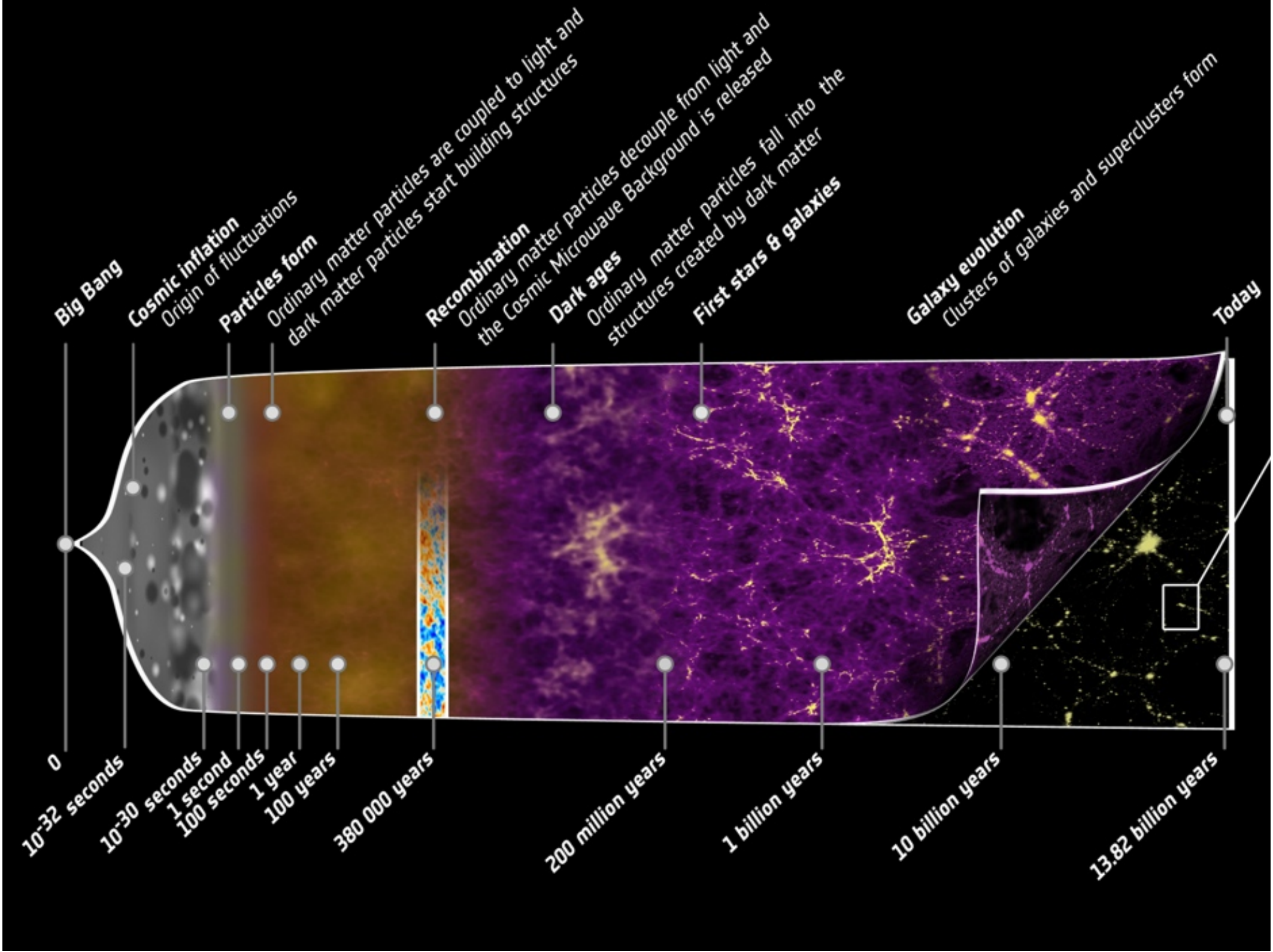
- also known from thSZ effect
- up-scattering of CMB photon
- important at late times (z<50000)
- scattering `inefficient'

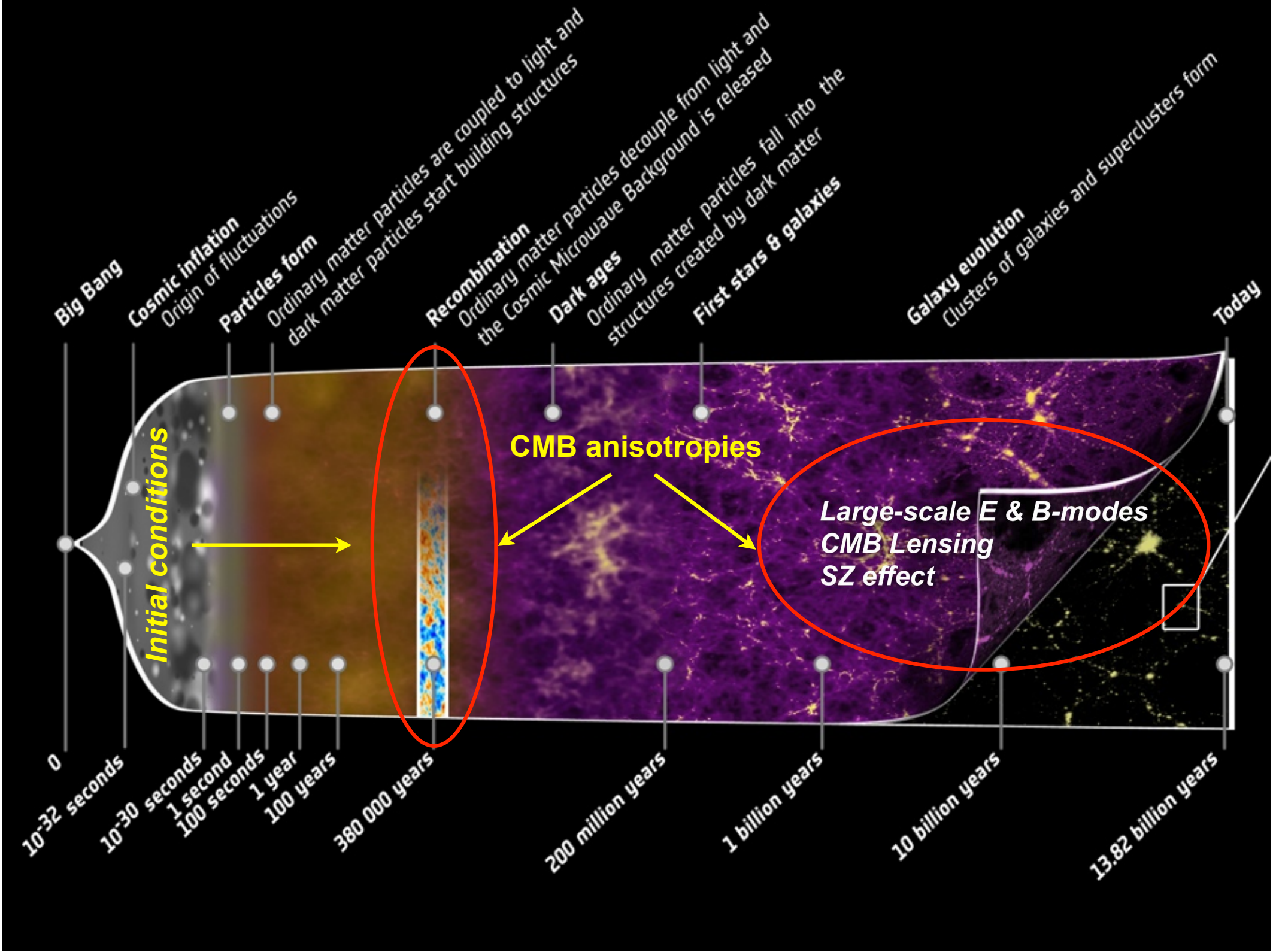
Chemical potential μ-distortion



Sunyaev & Zeldovich, 1970, ApSS, 2, 66

- important at very times (z>50000)
- scattering `very efficient'


Big Bang
0
Cosmic inflation
Origin of fluctuations
10-32 seconds
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
10-30 seconds
1 second
100 seconds
1 year
100 years
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
380 000 years
Dark ages
Ordinary matter particles fall into the structures created by dark matter
200 million years
First stars & galaxies
1 billion years
Galaxy evolution
Clusters of galaxies and superclusters form
10 billion years
Today
13.82 billion years


Big Bang
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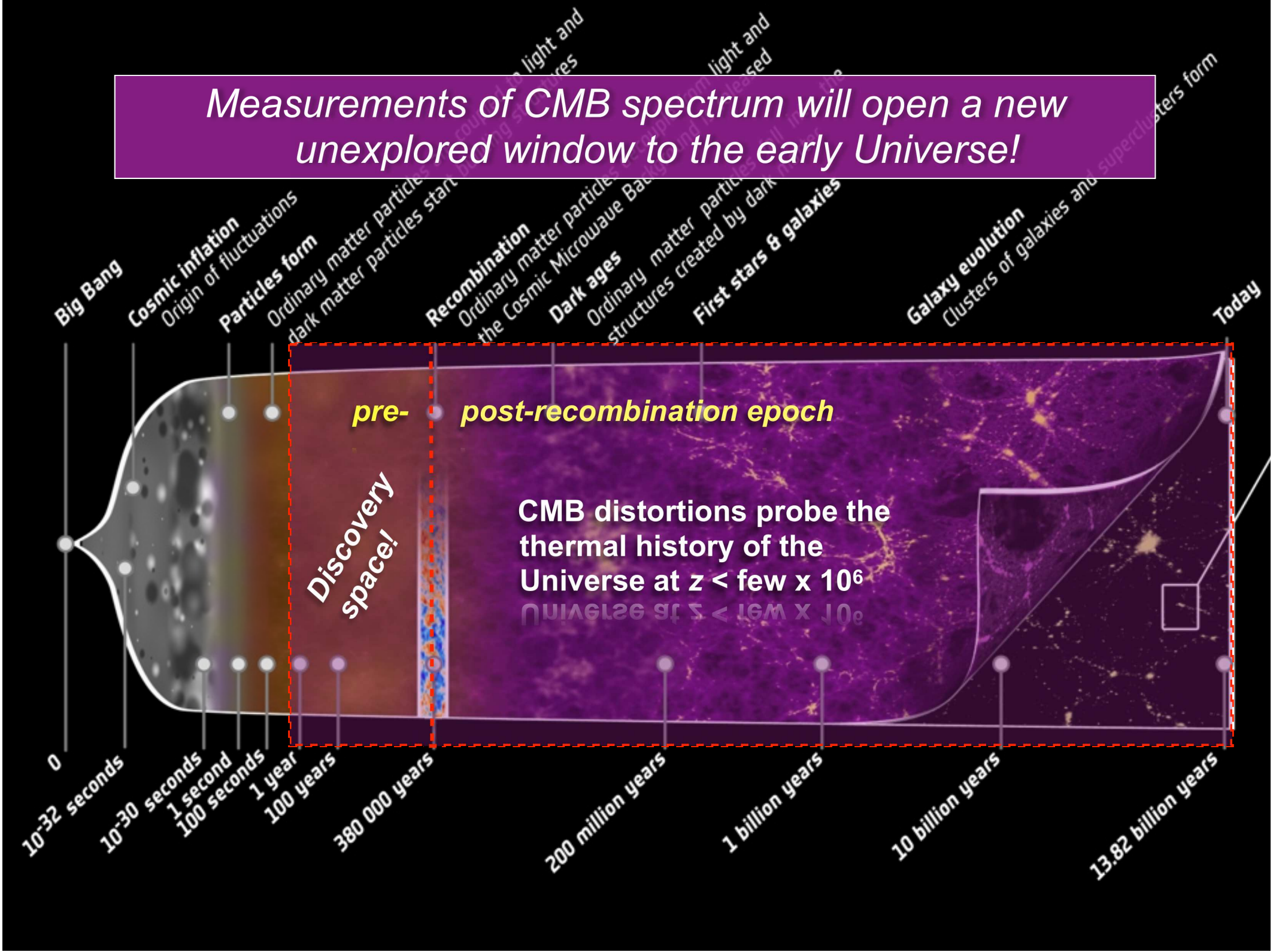
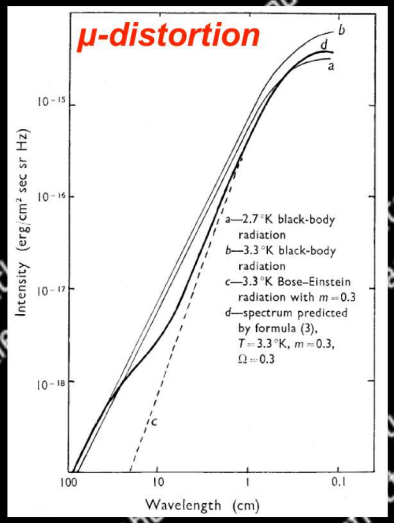
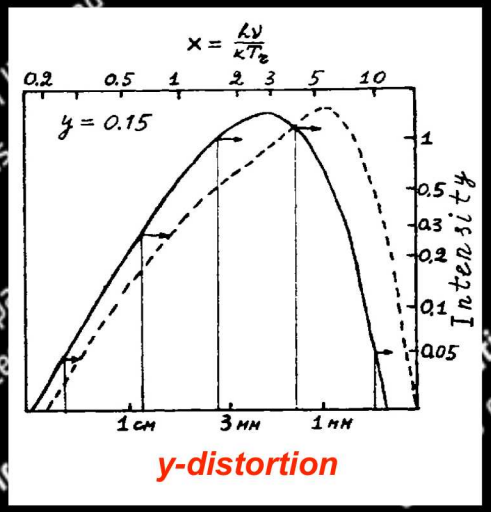
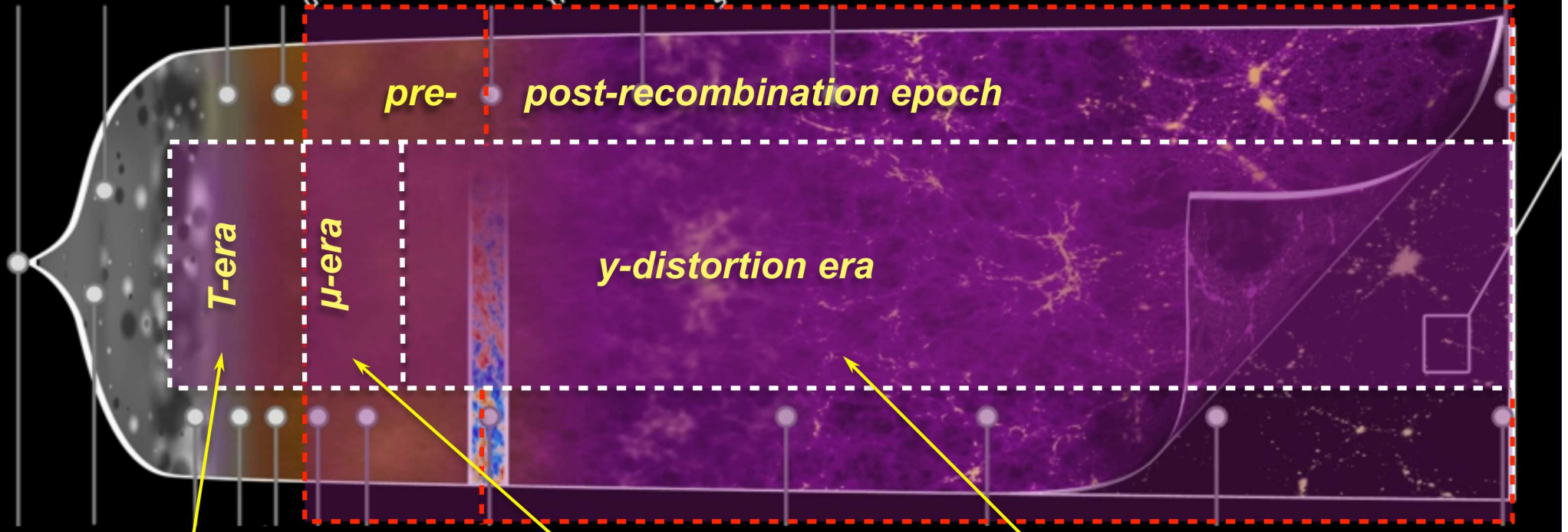
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
Initial conditions
CMB anisotropies
Large-scale E & B-modes
CMB Lensing
SZ effect
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Measurements of CMB spectrum will open a new unexplored window to the early Universe!

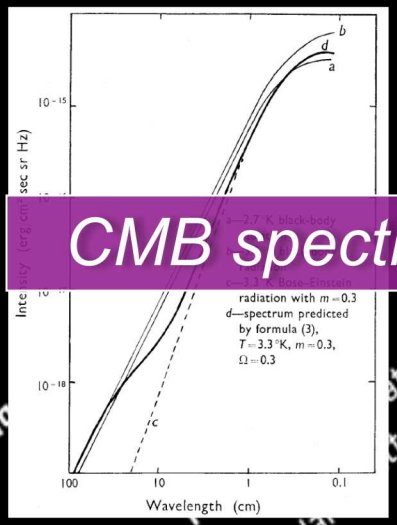


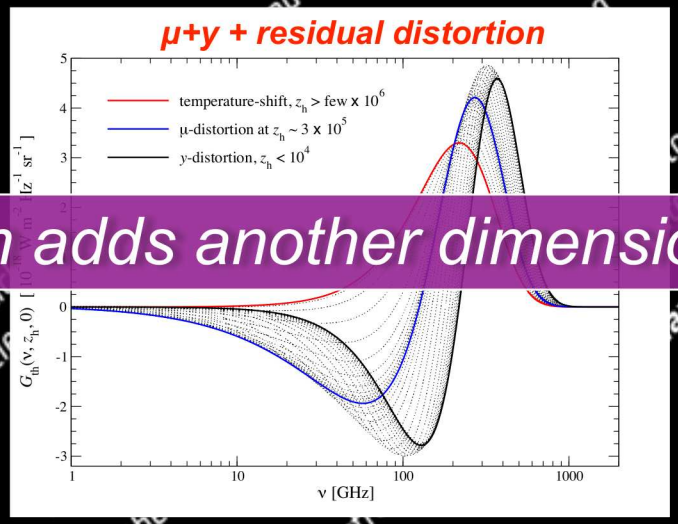


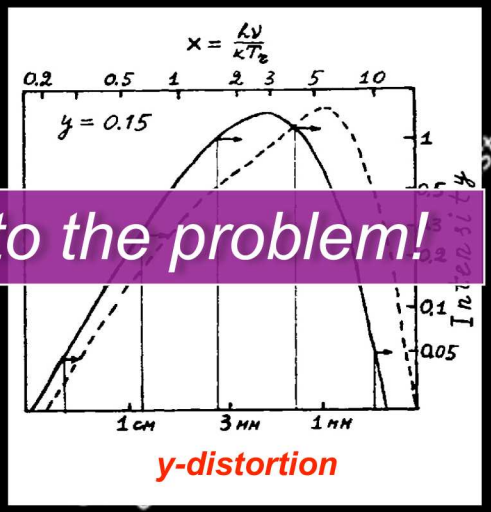




$$\frac{\Delta T}{T} \simeq \frac{1}{4}\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_T \qquad \mu \simeq 1.4\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu \qquad y \simeq \frac{1}{4}\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$$







CMB spectrum adds another dimension to the problem!

pre- post-recombination epoch

T-era

μ-era

μ-y-era

HI&He

y-distortion era

extra time-slicing at recombination

New hybrid era

Big Bang

Today

0

10^{-32} seconds

10^{-30} seconds

1 second

100 seconds

1 year

100 years

380 000 years

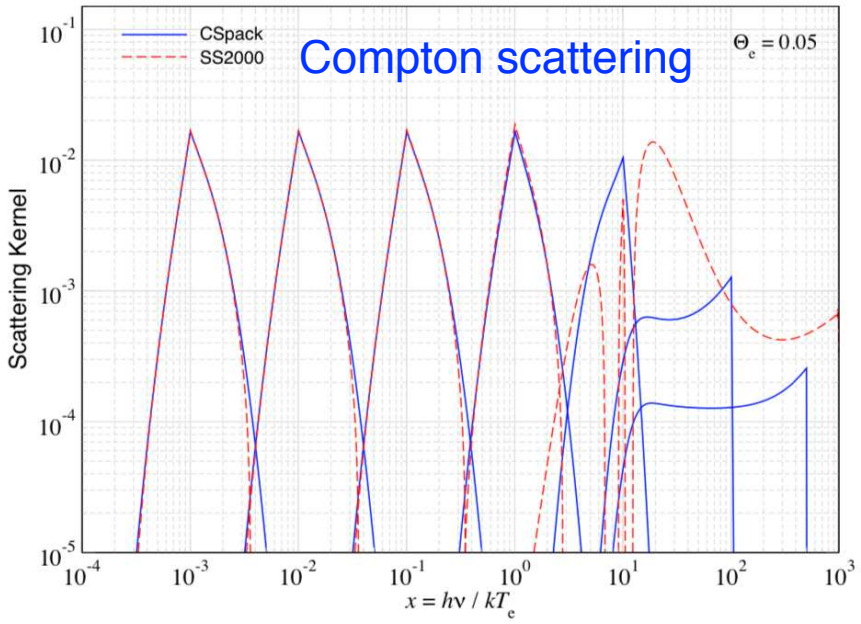
200 million years

1 billion years

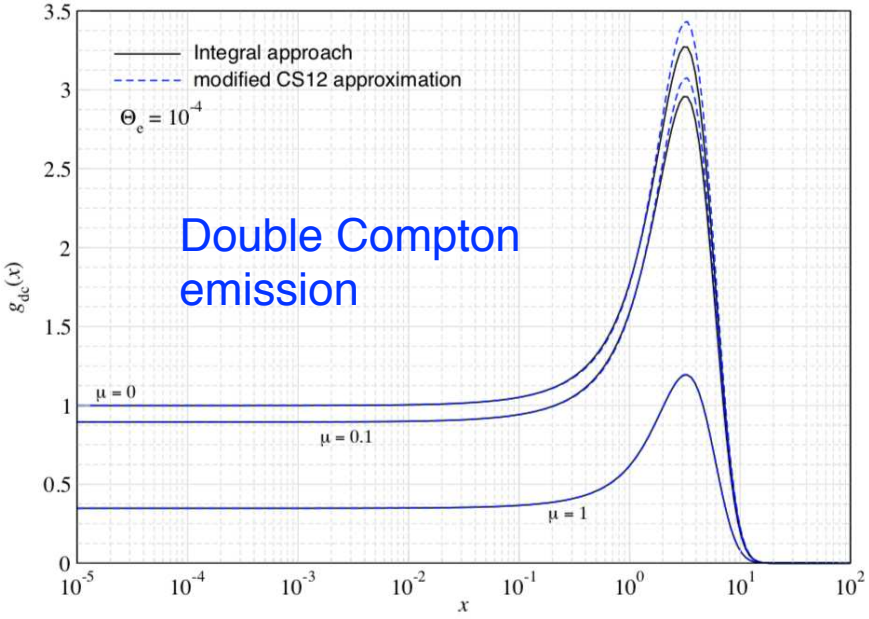
10 billion years

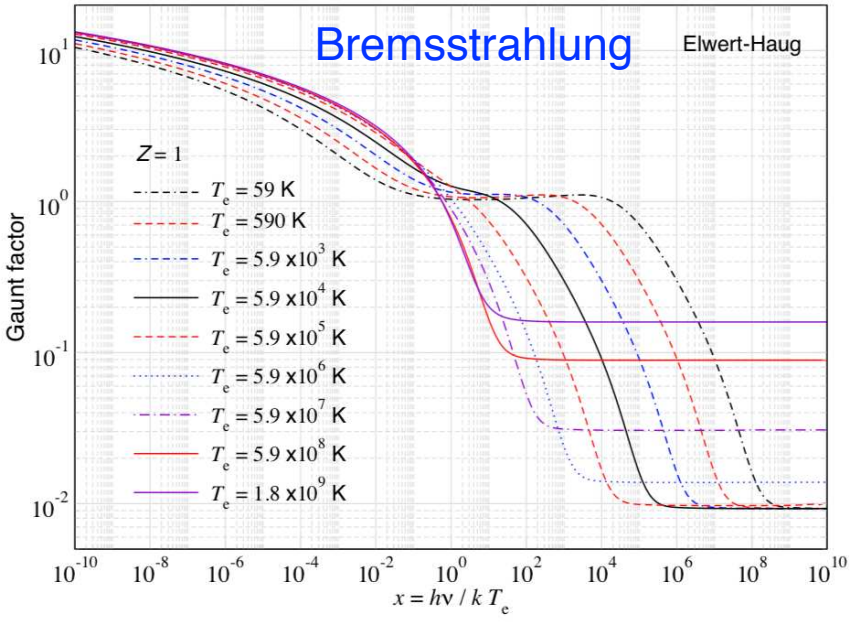
13.82 billion years

Modeling of main physical processes now very accurate!



- Compton scattering for redistribution of photons
- Double Compton and Bremsstrahlung for production of photons
- All accurately modeled using *CosmoTherm*





JC, Ravenni & Bolliet, ArXiv:1911.08861; Ravenni &JC, ArXiv:2005.06941 and JC, Ravenni & Acharya, ArXiv:2005.11325

Physical mechanisms that lead to spectral distortions

- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
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  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation*
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

pre-recombination epoch

„high“ redshifts

„low“ redshifts

- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- Additional exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

post-recombination

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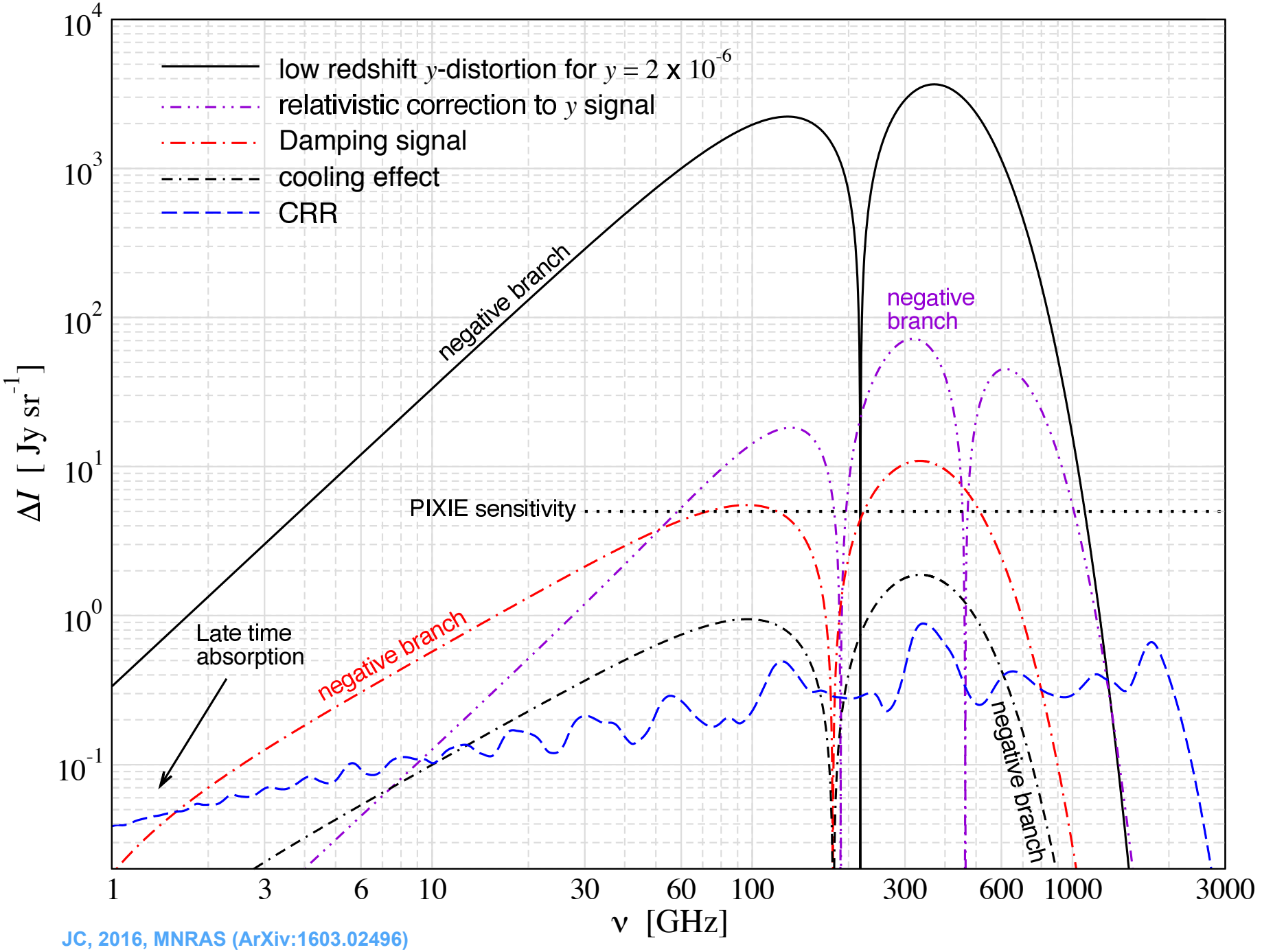
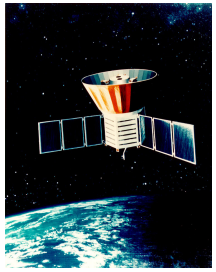
post-recombination

Average CMB spectral distortions



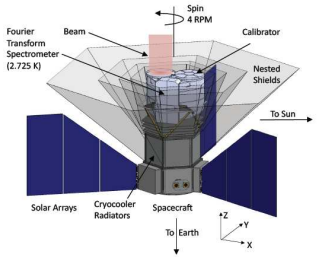
JC, 2016, MNRAS (ArXiv:1603.02496)

History of distortion experiments and proposals



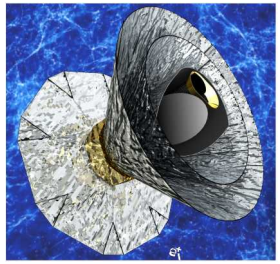
COBE/FIRAS

Mather & Fixsen



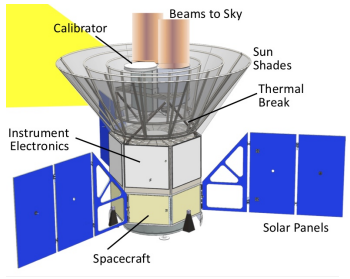
PIXIE

Kogut & Fixsen



PRISM

De Bernardis



PIXIE

Kogut & Fixsen

(PIXIE)

Super-PIXIE

PRISTINE

Aghanim

FOSSIL

Aghanim

ARCADE 2

Kogut & Fixsen

Maffei

TRIS

Gervasi, Zannoni & Tartari

APSERa

Subrahmanyan & Rao

COSMO

De Bernardis, Masi & Battistelli

TMS

Rubiño-Martin

1989 2008 2011 2013 2015 2016 2018 2022

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post-recombination

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- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation*
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

pre-recombination epoch

„high“ redshifts

„low“ redshifts

- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- Additional exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

post-recombination

Axion interactions can lead to photon injection

Early-Universe solutions are *not* as simple….

Radio sky reveals primordial electron-proton interactions

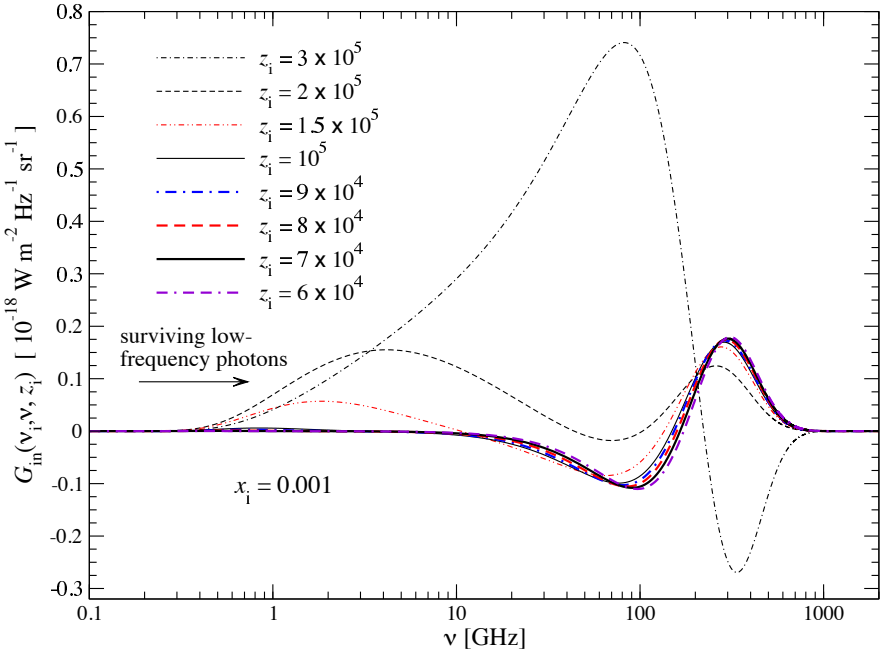
Shyam Balaji,[1] Maura E. Ramírez-Quezada,[2] Céline Bœhm[3]

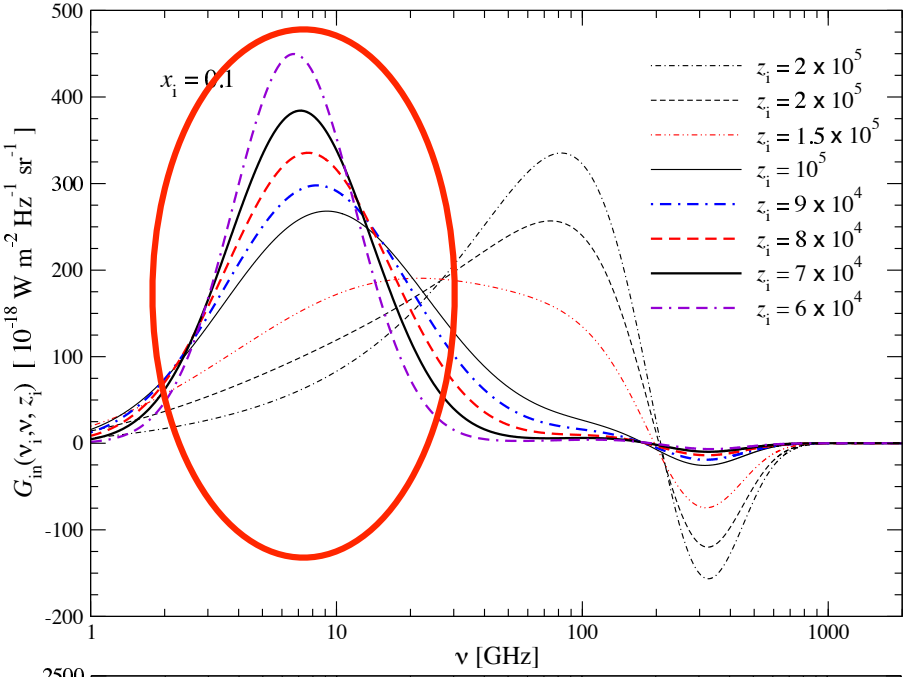
For several decades, astronomers have measured the electromagnetic emission in the universe from the lowest to the highest energies with incredible precision. The lowest end of the spectrum, corresponding to radio waves, is fairly well studied and understood. Yet there is a long standing discrepancy between measurements and predictions, which has prompted the construction of many new models of radio emitters. Here we show that remnant electron-proton interactions, leading to photon production in the early universe, also referred to as cosmic free-free emission, solves the discrepancy between theory and observations. While the possibility of cosmic free-free emission has been postulated for several decades, this is the first time that the amplitude and shape of the signal has been computed and its existence demonstrated. Using current measurements we estimate this emission to become important from around a redshift of $z \simeq 2150$. This contribution from fundamental particles and interactions represents the lowest energy test from the early universe of one of the pillars of modern physics, Quantum Electrodynamics. The next generation of deep radio surveys will be able to measure primordial signals from this cosmic era with greater precision and further solidify our understanding of the radio sky.

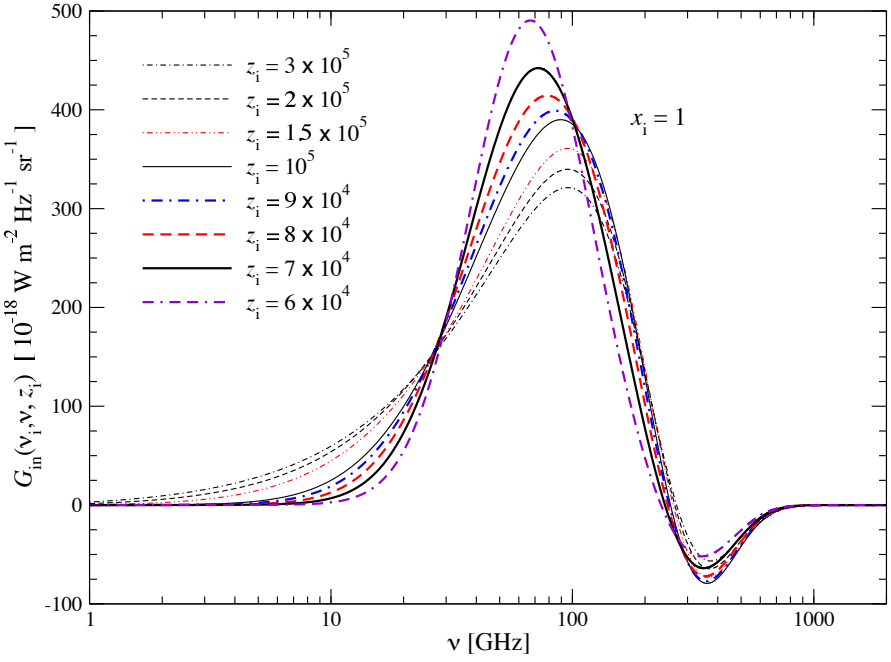
- Photon absorption at low frequencies is very efficient
- Distortions erased very quickly by thermal Bremsstrahlung
- Detailed balance should be properly taken into account….

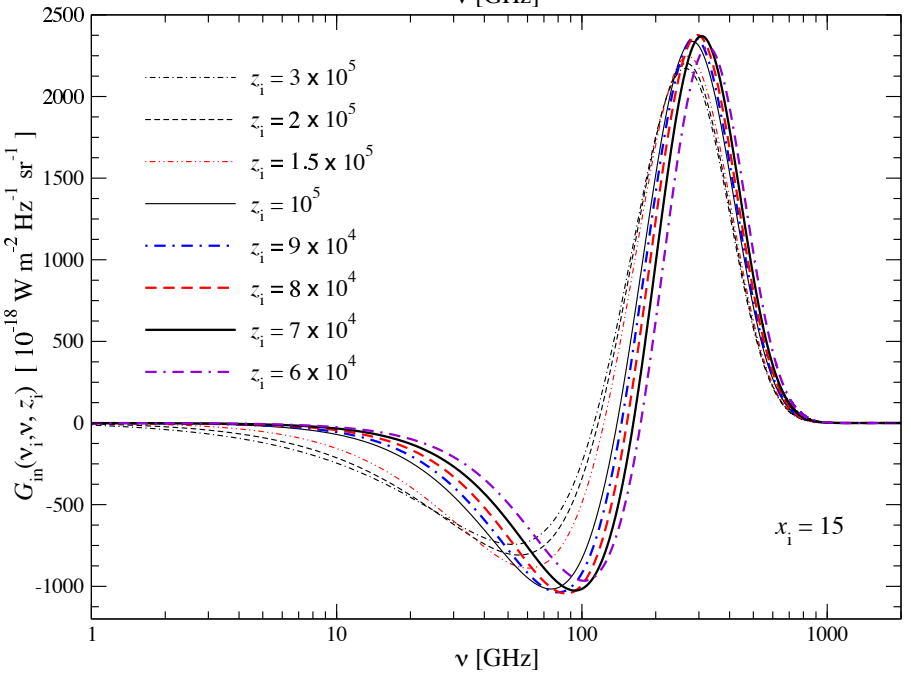
Balaji et al., ArXiv:2204.13711

Rich phenomenology of photon injection distortions



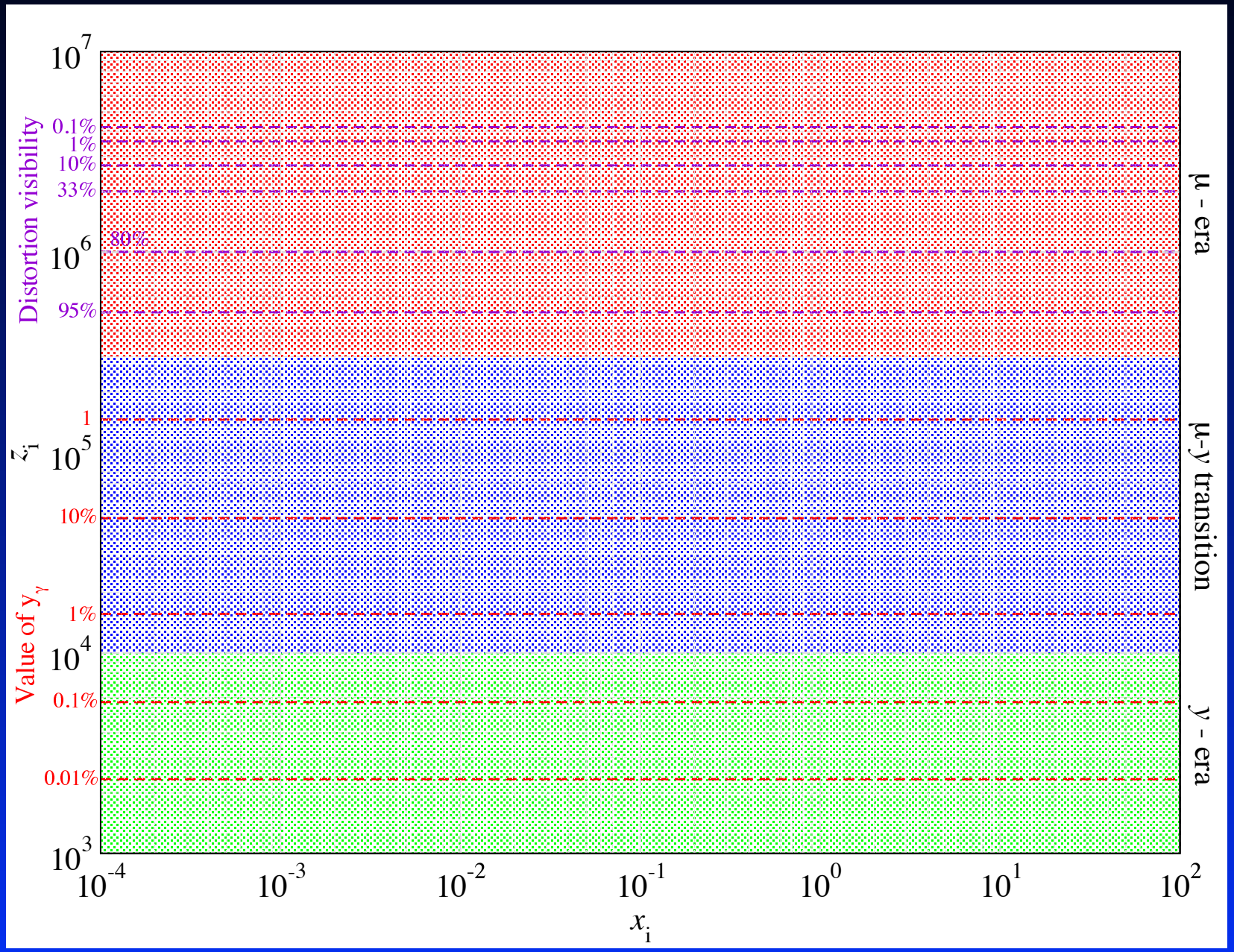






JC 2015, ArXiv:1506.06582

Different regimes for photon injection



JC 2015, ArXiv:1506.06582

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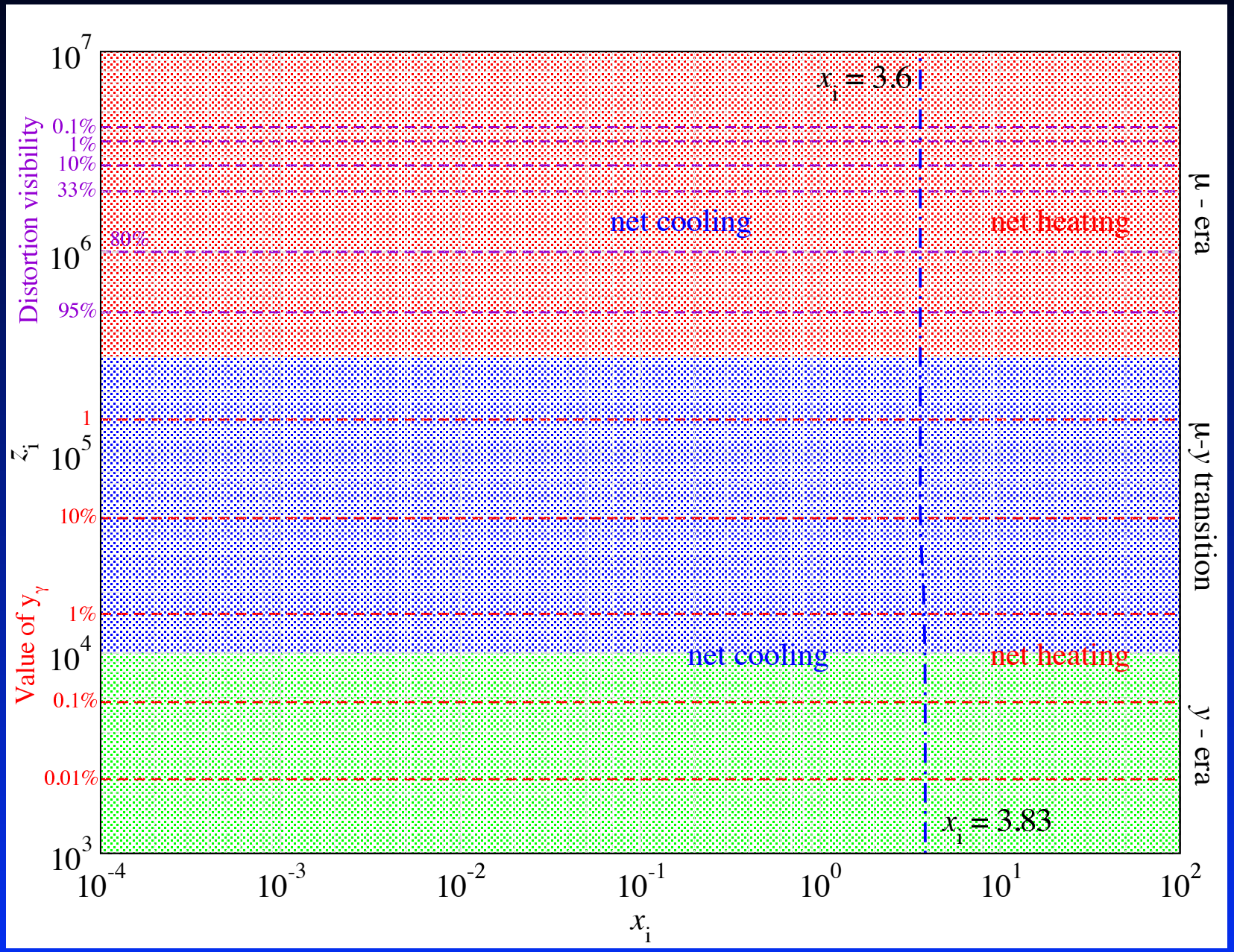

JC 2015, ArXiv:1506.06582

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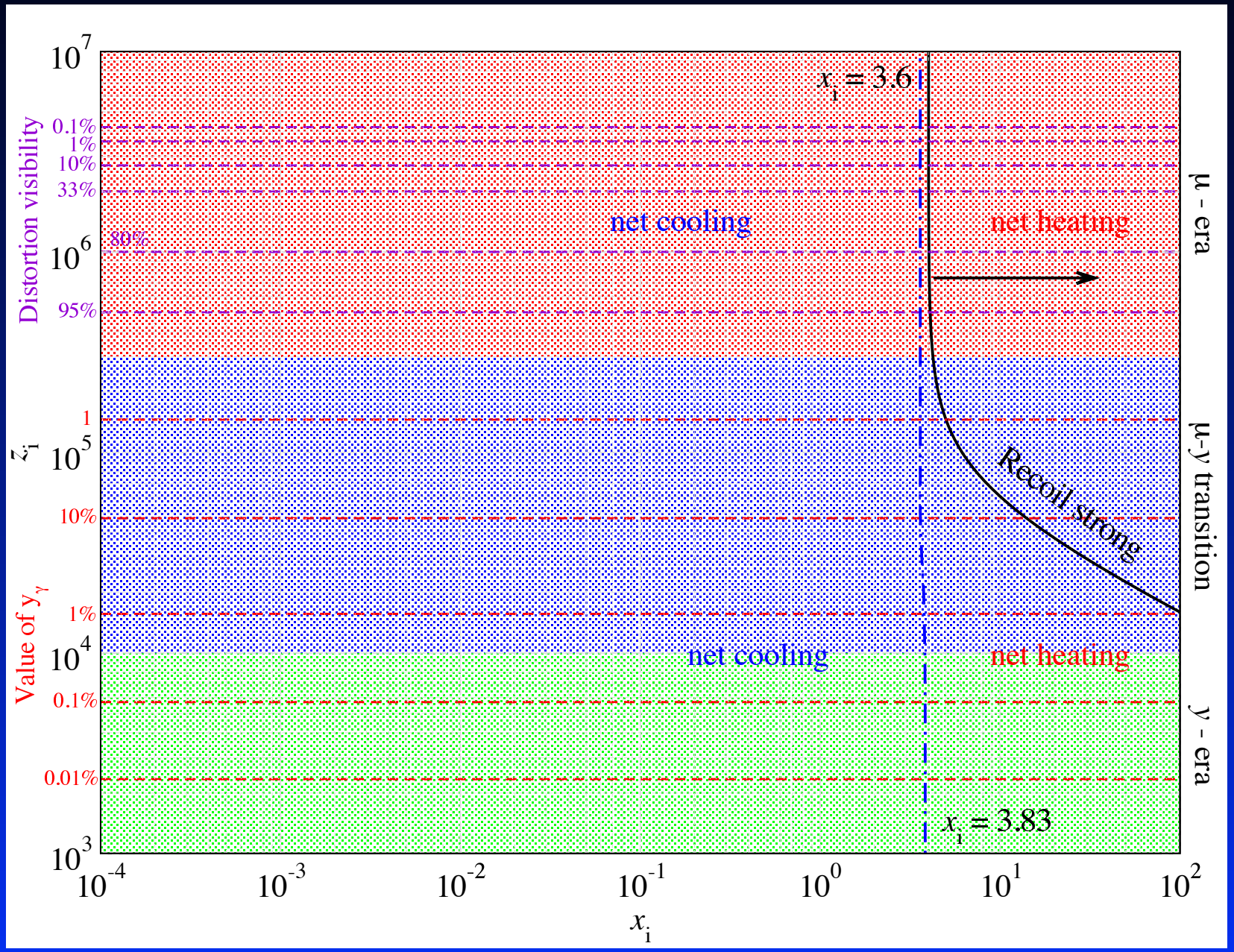

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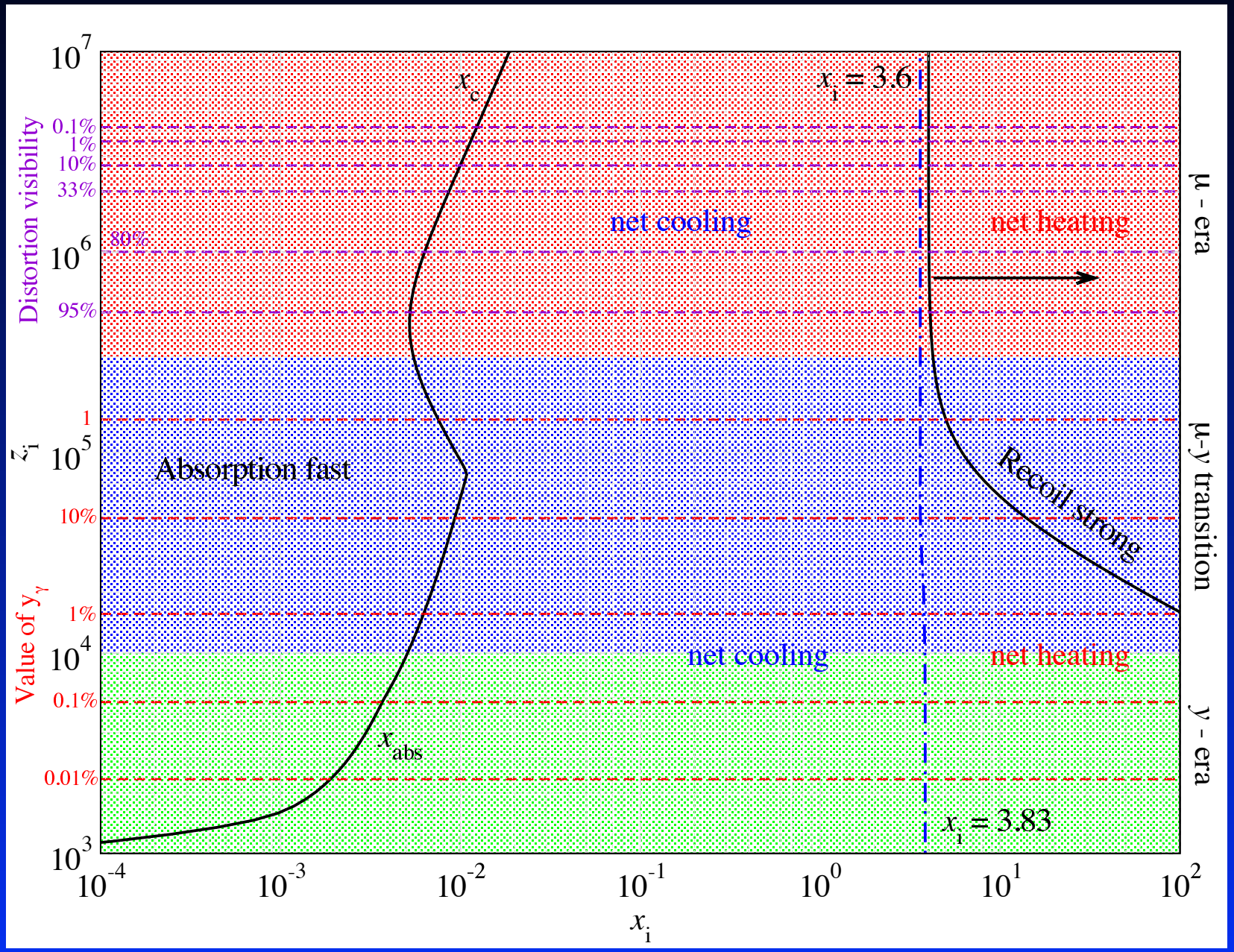

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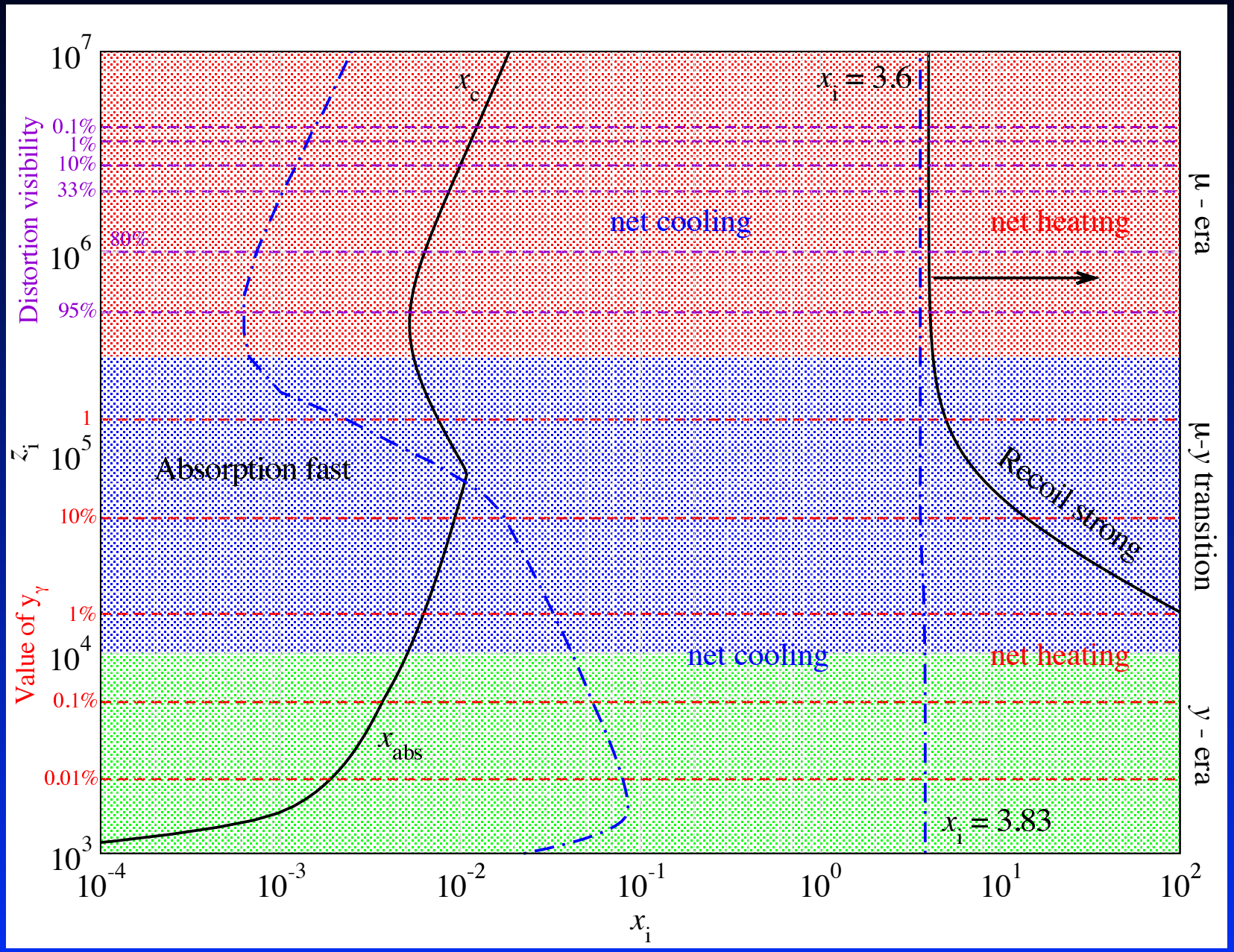
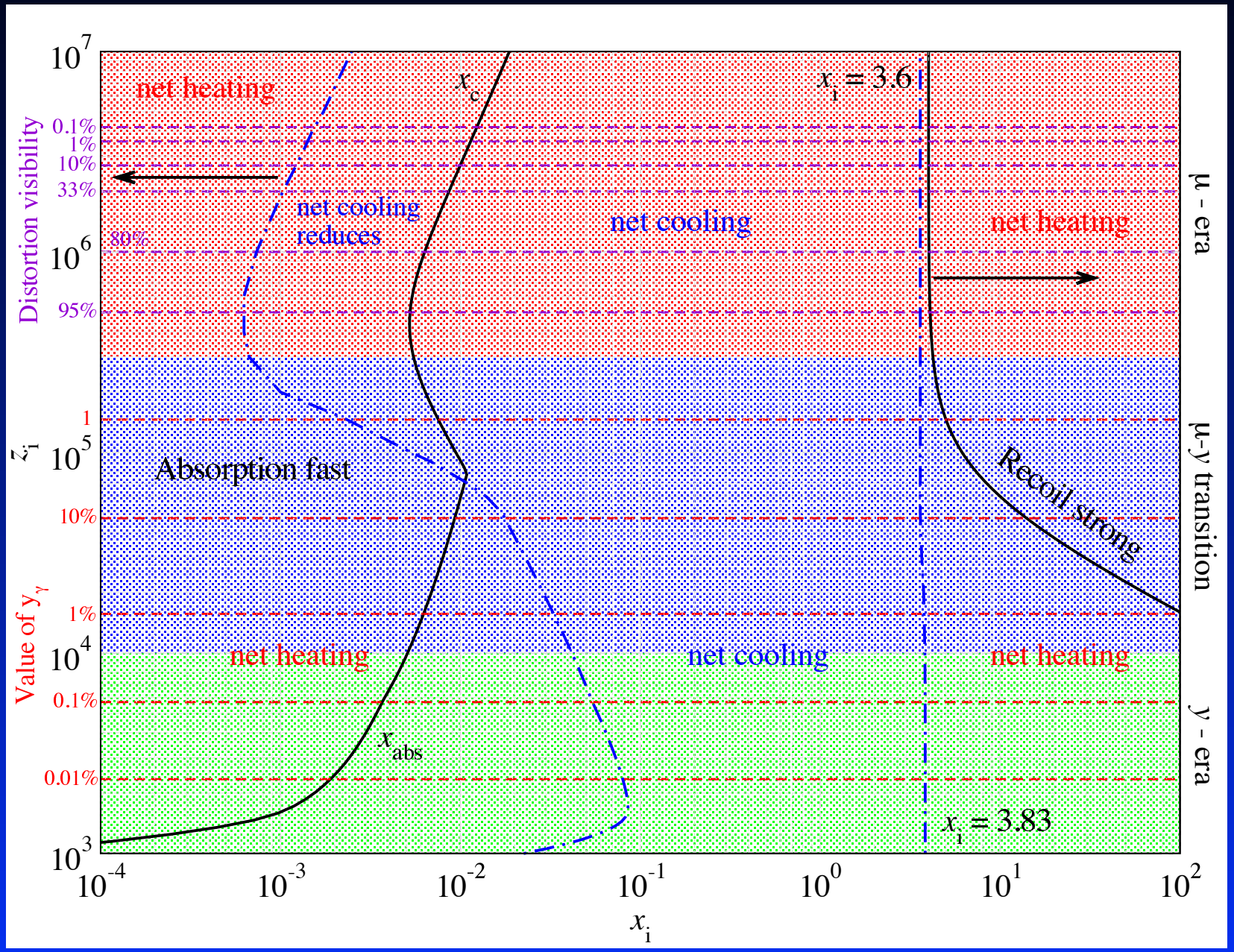
Different regimes for photon injection



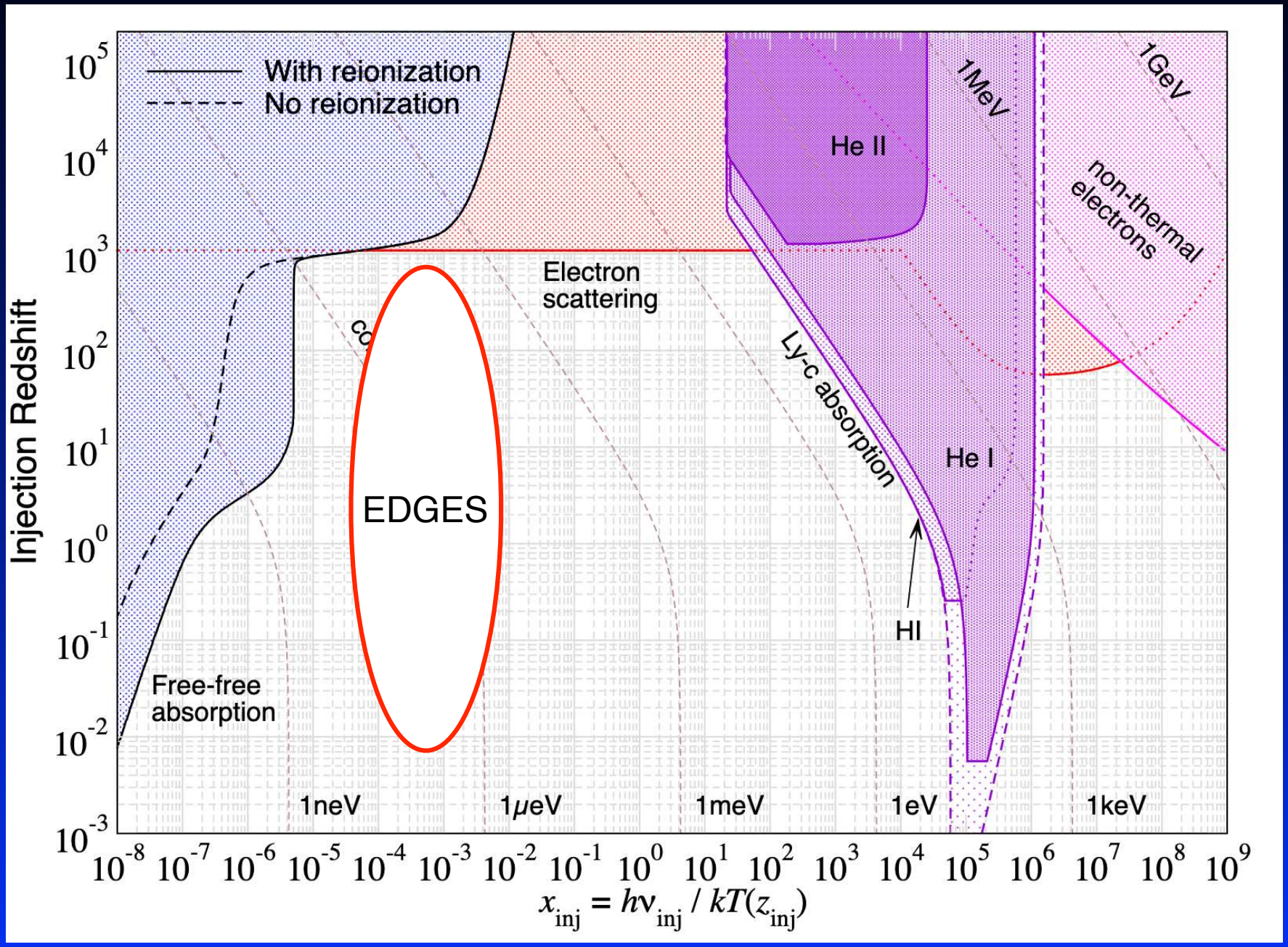
JC 2015, ArXiv:1506.06582

Different regimes for photon injection



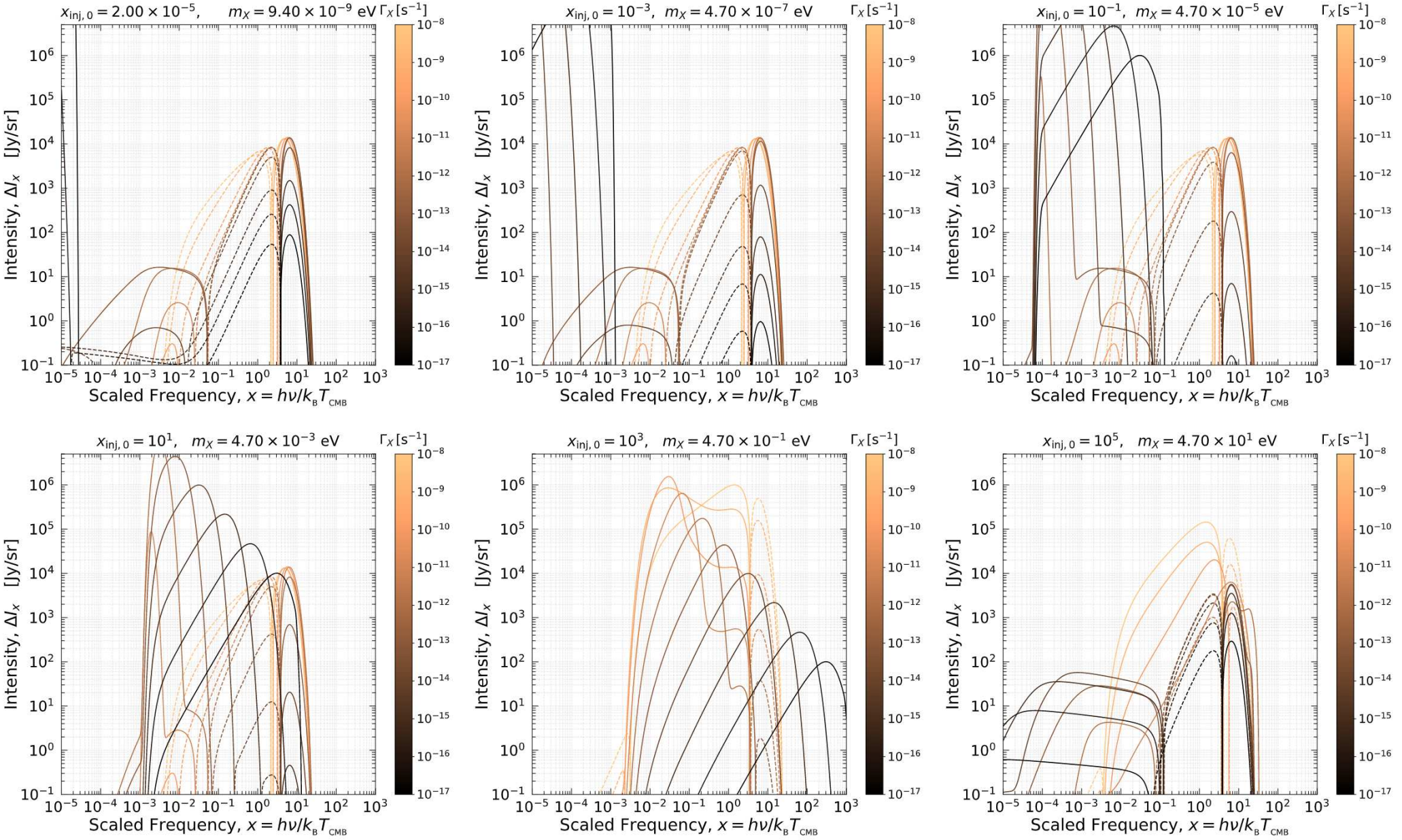
JC 2015, ArXiv:1506.06582

Extension to late times



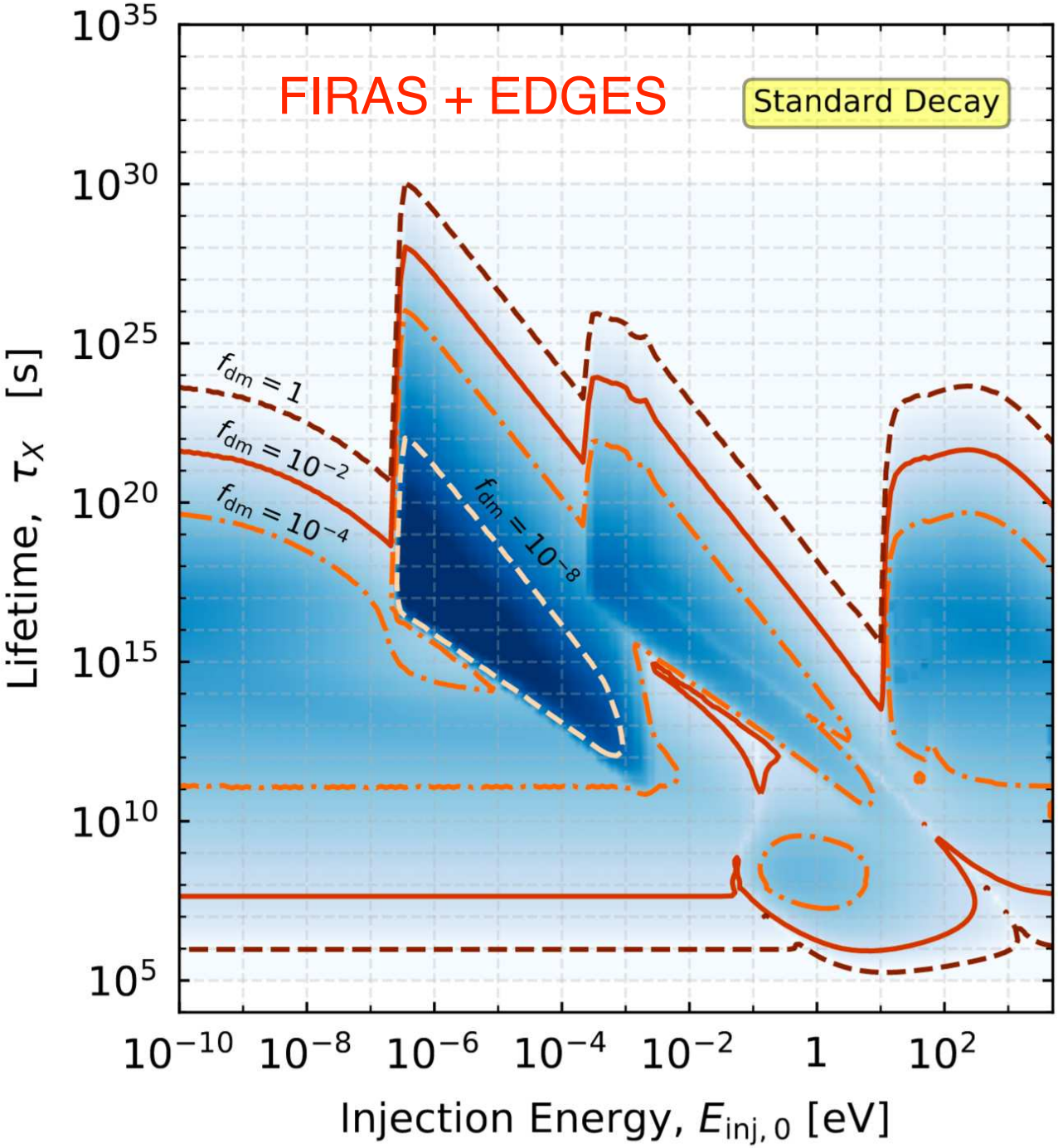
Bolliet, JC & Battye, 2020, ArXiv:2012.07292

Photon injection distortions from particle decays



Bolliet, JC & Battye, 2020, ArXiv:2012.07292

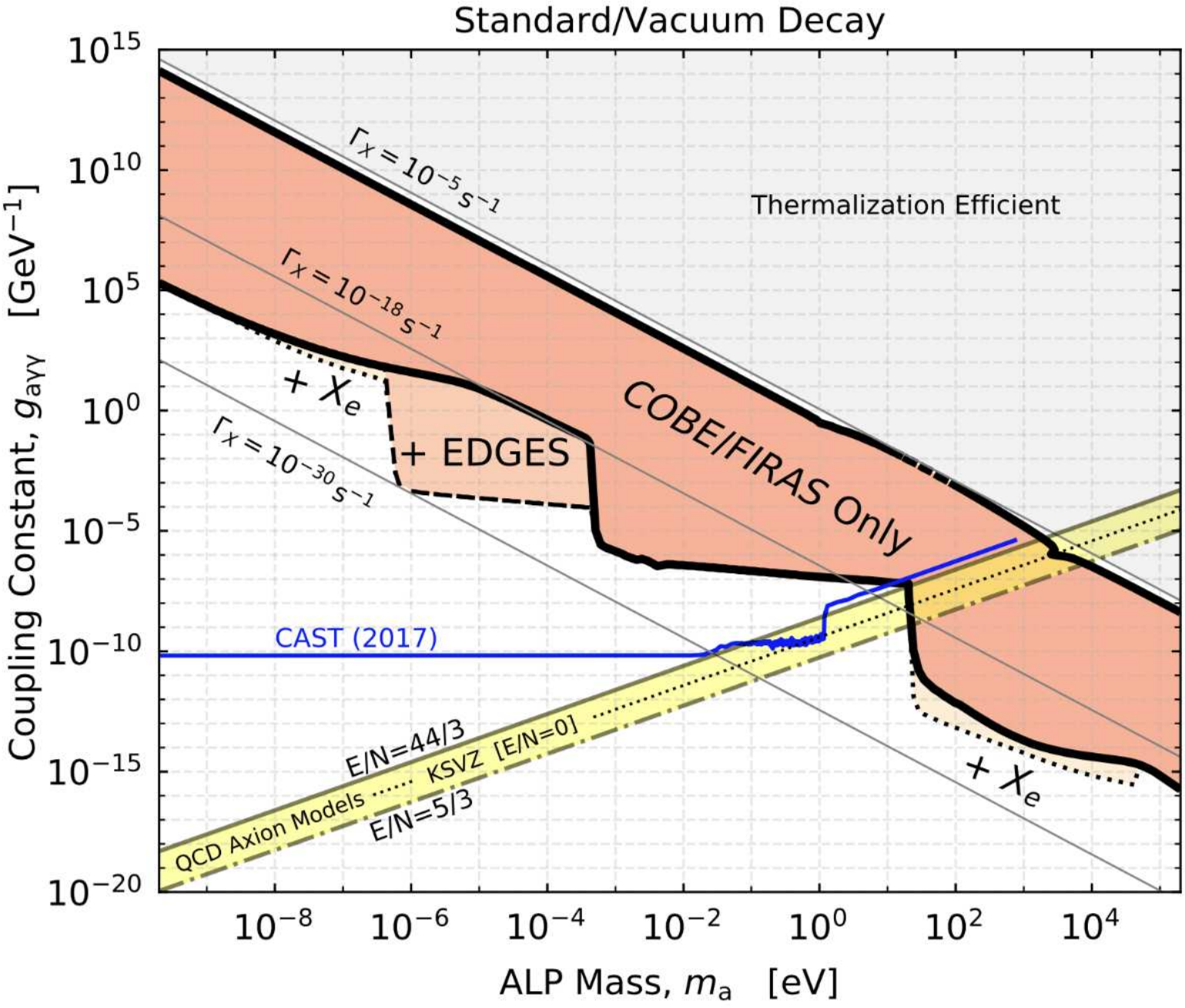
Photon injection distortions from particle decays



- New way to constrain particle decays/ excited states of DM
- Application to axions
- Possible link to ARCADE e*xcess* and EDGES?

Bolliet, JC & Battye, 2020, ArXiv:2012.07292

Interpretation in terms of Axions



Bolliet, JC & Battye, 2020, ArXiv:2012.07292

Extension with soft photon emission process

- Decay processes or PBH accretion/evaporation can be high-energy process that still leads to many soft photon

- What happens if one adds a soft photon tail to the high energy particles?

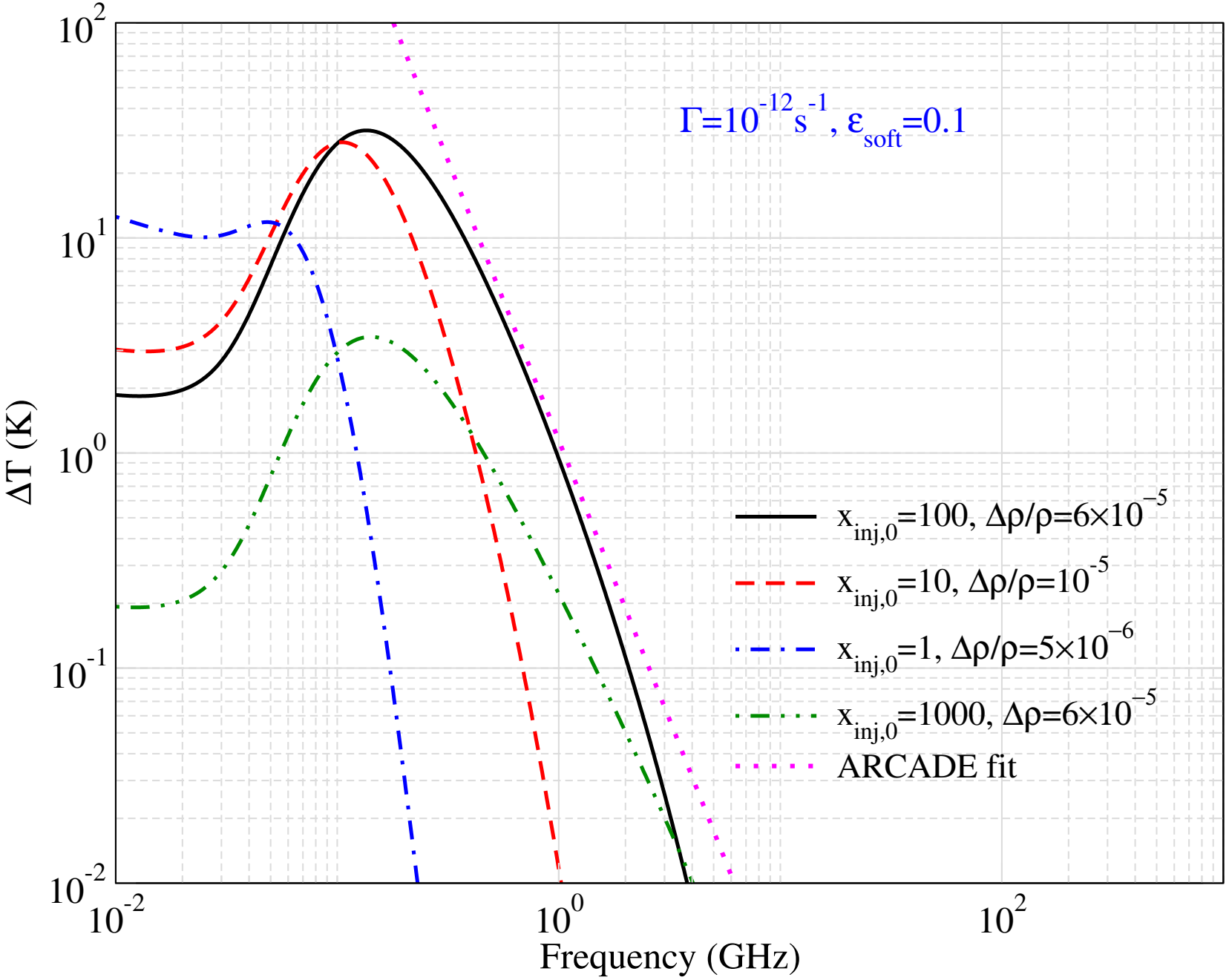
Sandeep Acharya

Jiten Dhandha

- Add free-free like injection to `CosmoTherm`
- Energy fraction can be adjusted
- Computation of 21 cm signal

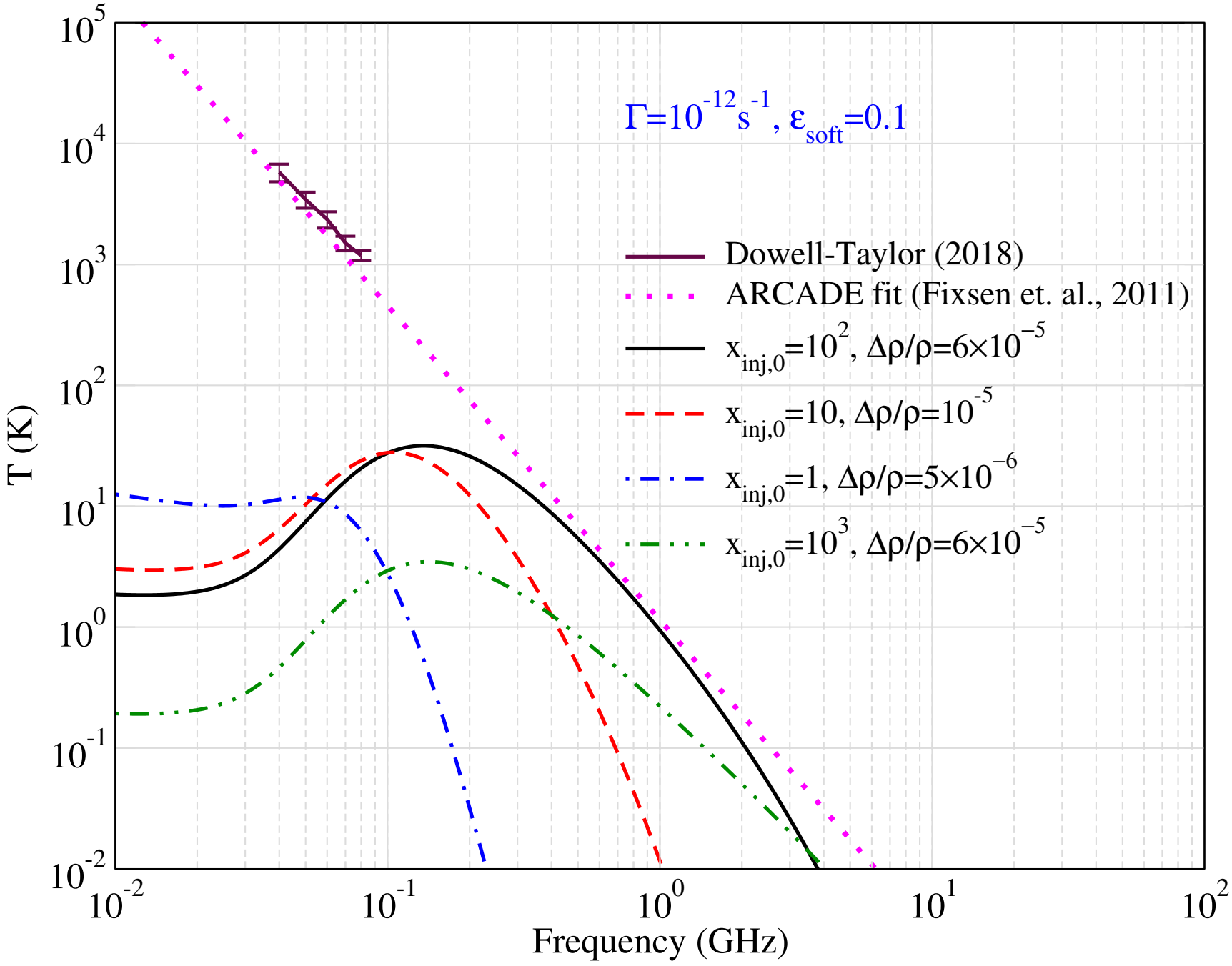
Acharya, Dhandha & JC in preparation

Preliminary results (from last night)



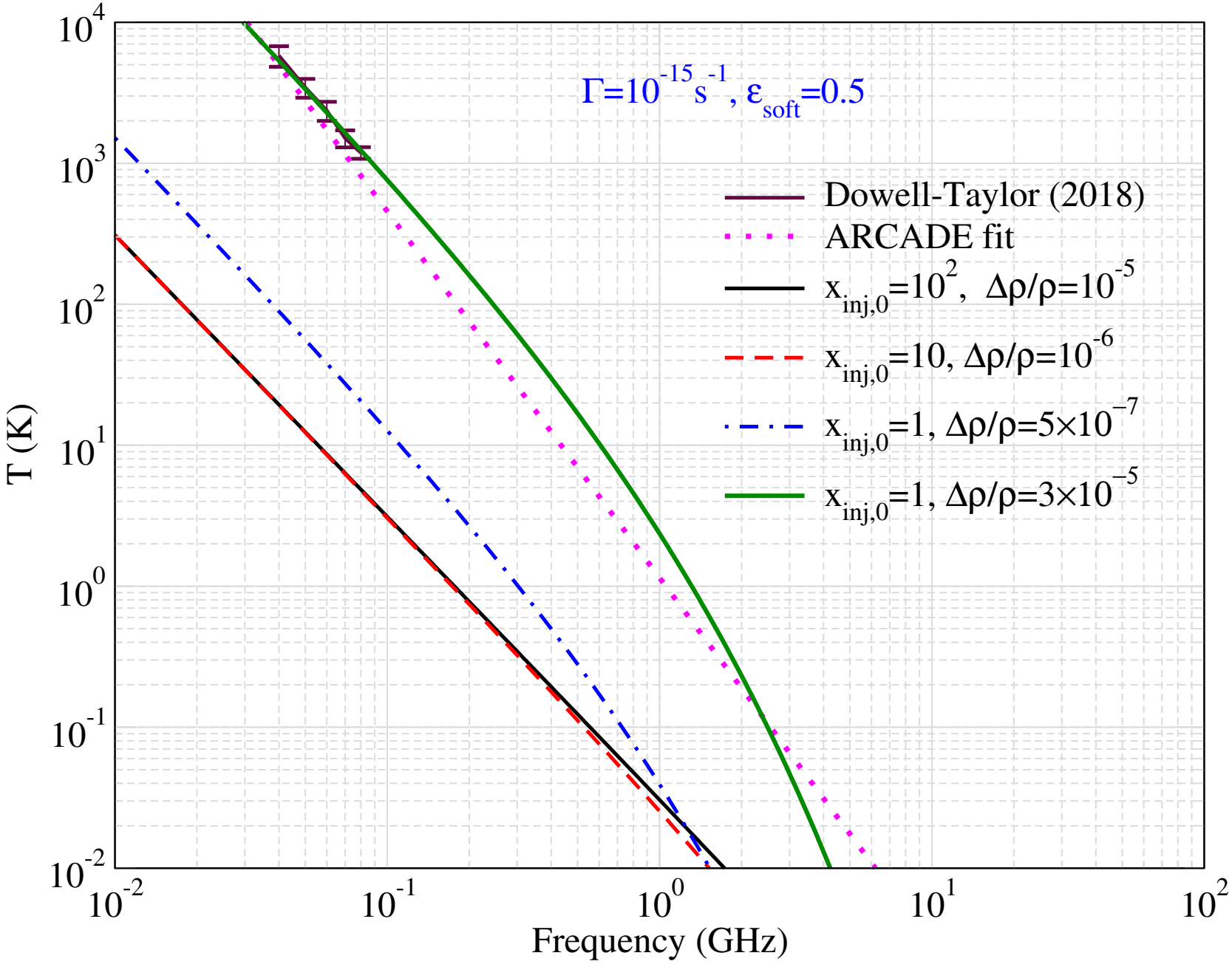
Acharya, Dhandha & JC in preparation

Preliminary results (from last night)



Acharya, Dhandha & JC in preparation

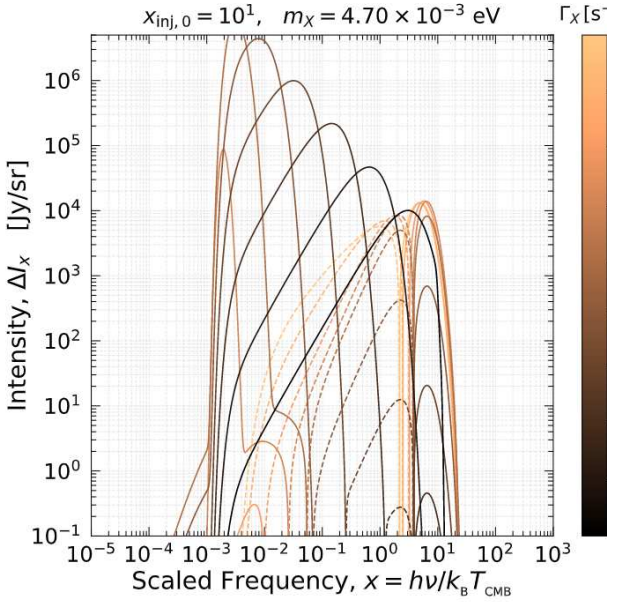
Preliminary results (from last night)

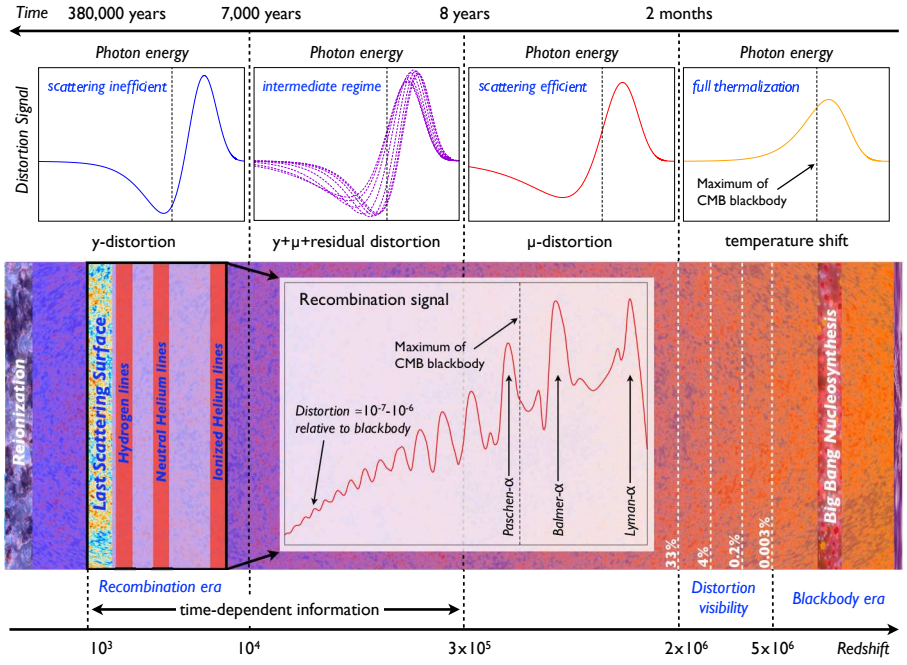


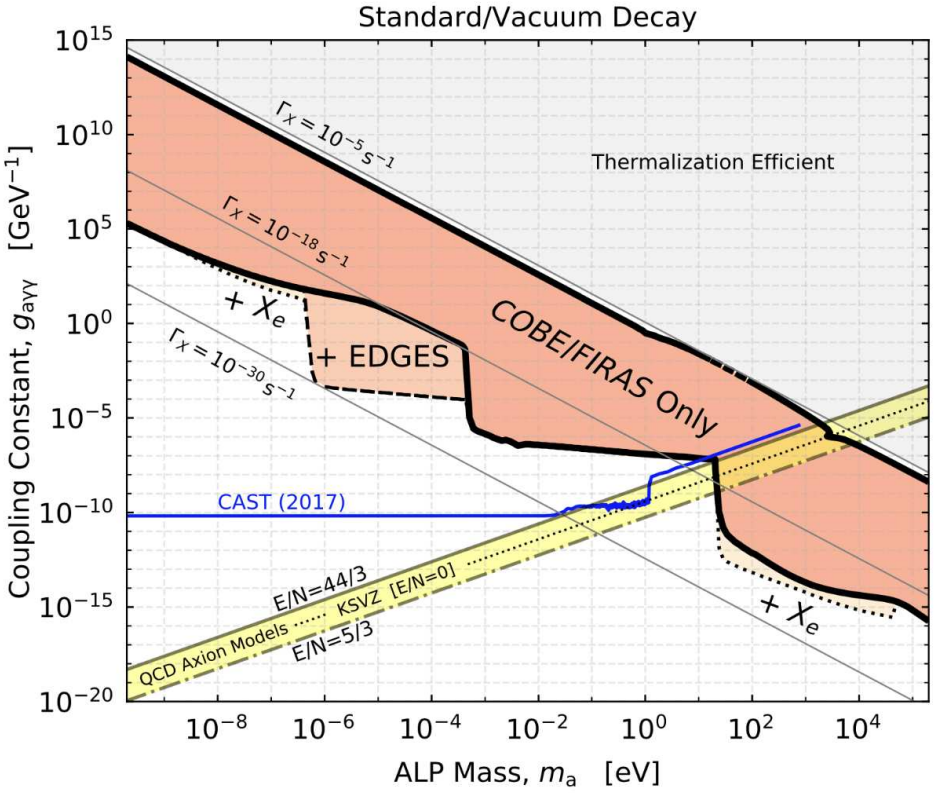
Acharya, Dhandha & JC in preparation

Conclusions

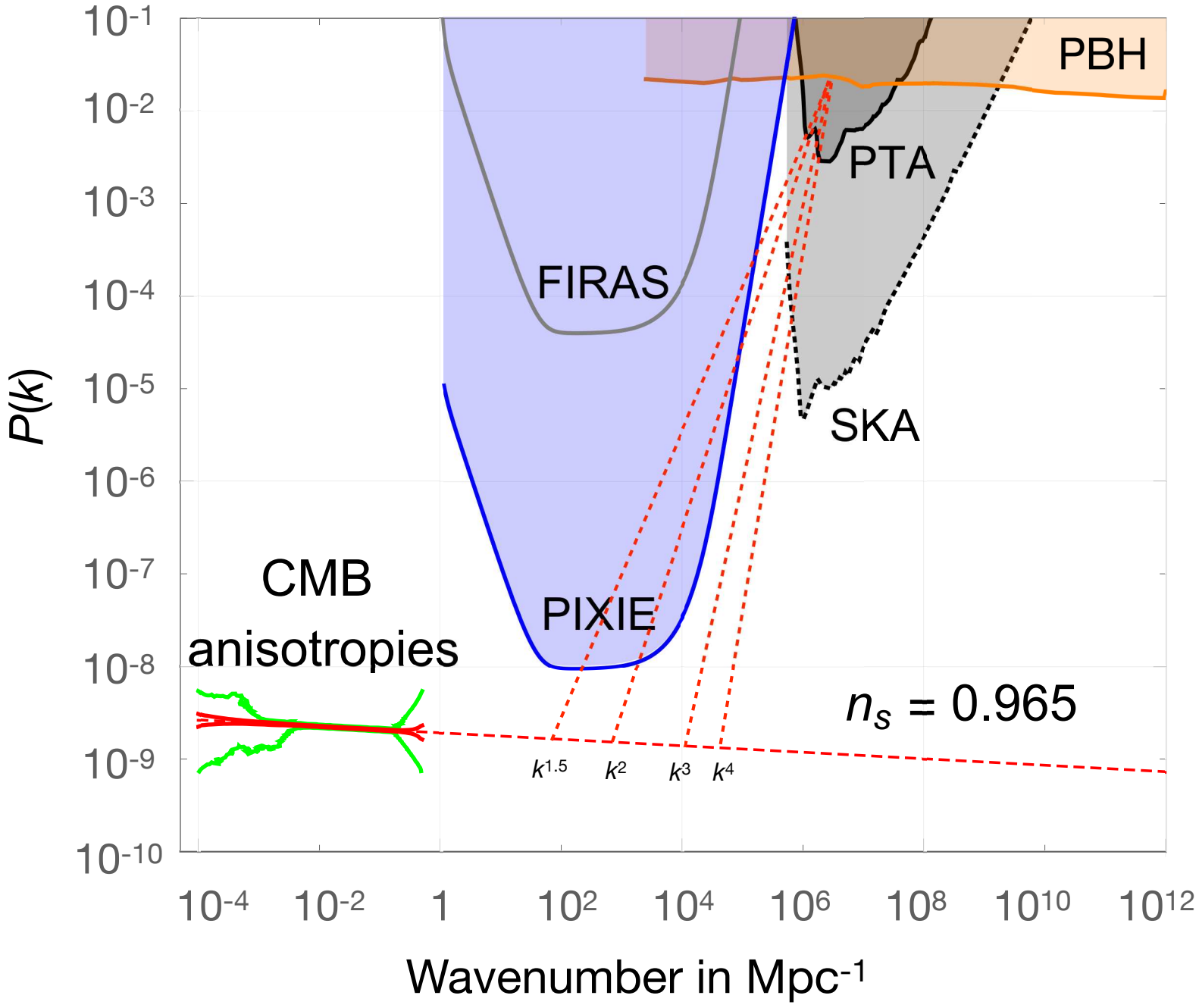
- CMB spectral distortions are great!
- Soft photon injection could play an interesting role for ARCADE and EDGES
- Detailed calculations are needed
- Possibly two sides of the same coin?



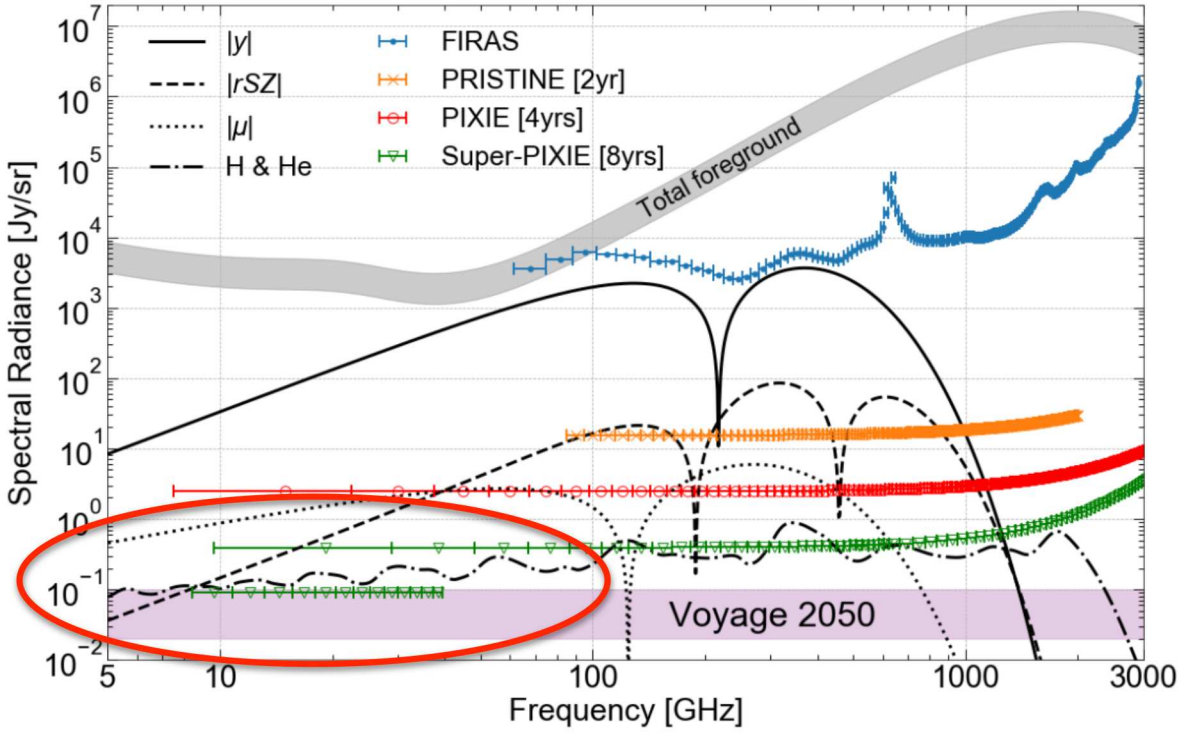


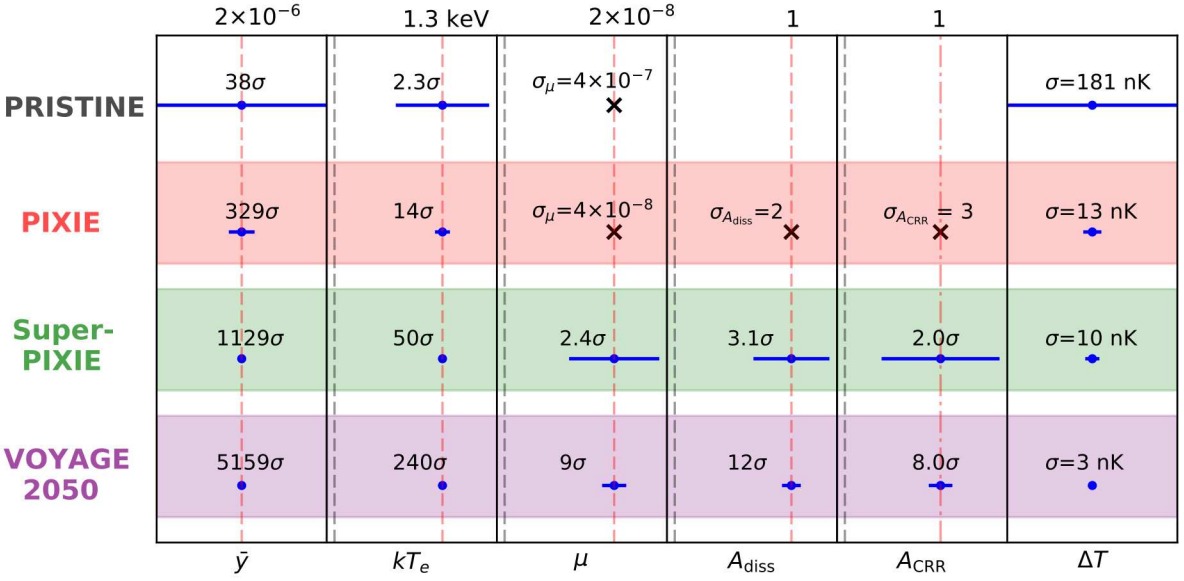


Small-scale power and PBH link



Importance of low frequency coverage





- Low frequency coverage is crucial for μ
  (Abitbol et al. 2017)
- Is a low frequency FTS really the best solution?
  - Few channels
  - Runs out of steam w.r.t. sensitivity
- Possible alternatives
  - radiometers?
  - Spectrometers on a chip?
  - FTS on chips
    (priv. conv. Kirit Karkare)?

The distortion gang is getting organized!

Distortion Workshop coming in October 2022!

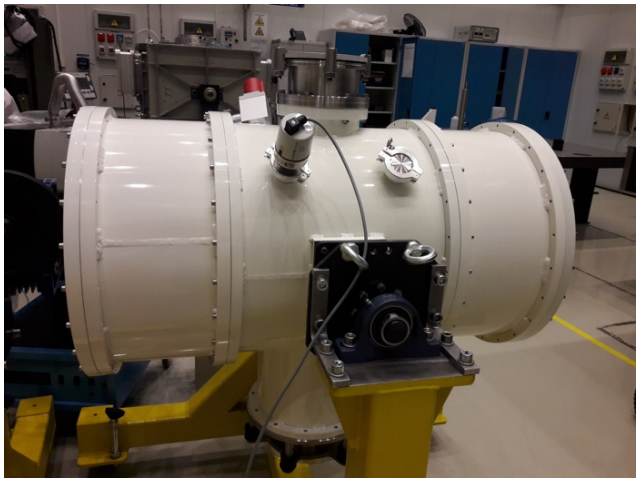
Organizers: Subodh Patil, Ema Dimastrogiovanni, Daan Meerburg, Jacques Delabrouille and JC

- ***Main goals***:
  - start building a bigger community
  - bring experimentalists on board
- ***Guiding questions***:
  - What theory developments are still needed?
  - New component separation methods?
  - New technology ideas for low-frequency coverage

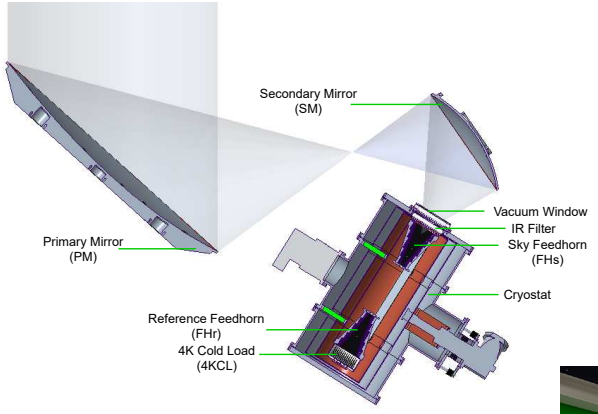
Tenerife Microwave Spectrometer (TMS), 10-20GHz

UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"
Ref. de la ayuda: ICTS-2019-03-IAC-12

- **IAC project. Instrumental participation:** INAF OAS BOLOGNA, Universidad Politécnica de Cartagena, UNIVERSITÀ DEGLI STUDI DI MILANO, idom



- **Science driver**: Ground-based low resolution spectroscopy observations in the 10-20GHz range to characterize foregrounds (monopole signals; spectral dependence of monopole signals; ARCADE results) and CMB spectral distortions. Provides frequency intercalibration for QUIJOTE. (Rubino-Martin et al. 2020).
- **Location**: Teide Observatory (former VSA enclosure). Full sky dome.
- **Prototype for future instruments**. Also important **legacy value,** complementing future space missions.
- **Proposed instrument concept**:
  - FEM cooled to 4-10K (HEMTs).
  - Reference 4K load.
  - DAS based on FPGAs.
  - ~3deg beam, 0.25 GHz spectral resolution (40 bands).



- **Project Status**:
  - Enclosure and dome at the Teide Observatory. ✓
  - Platform fabricated. Installation summer 2022. ✓
  - Mirrors designed (Alonso-Arias et al 2022). To be fabricated (→ Fall 2022).
  - Cryostat at the IAC since July 2019. ✓
  - Optomechanics in final fabrication phase.
  - Reference load fabricated (Nov 2021). ✓
  - DAS based on FPGAs (→ end 2022).
  - Commissioning in 2023.

Courtesy: J.A. Rubiño-Martin