Cosmological Probes of Dark Sectors

Bryce Cyr

Dark Interactions, Oct 18th, 2024

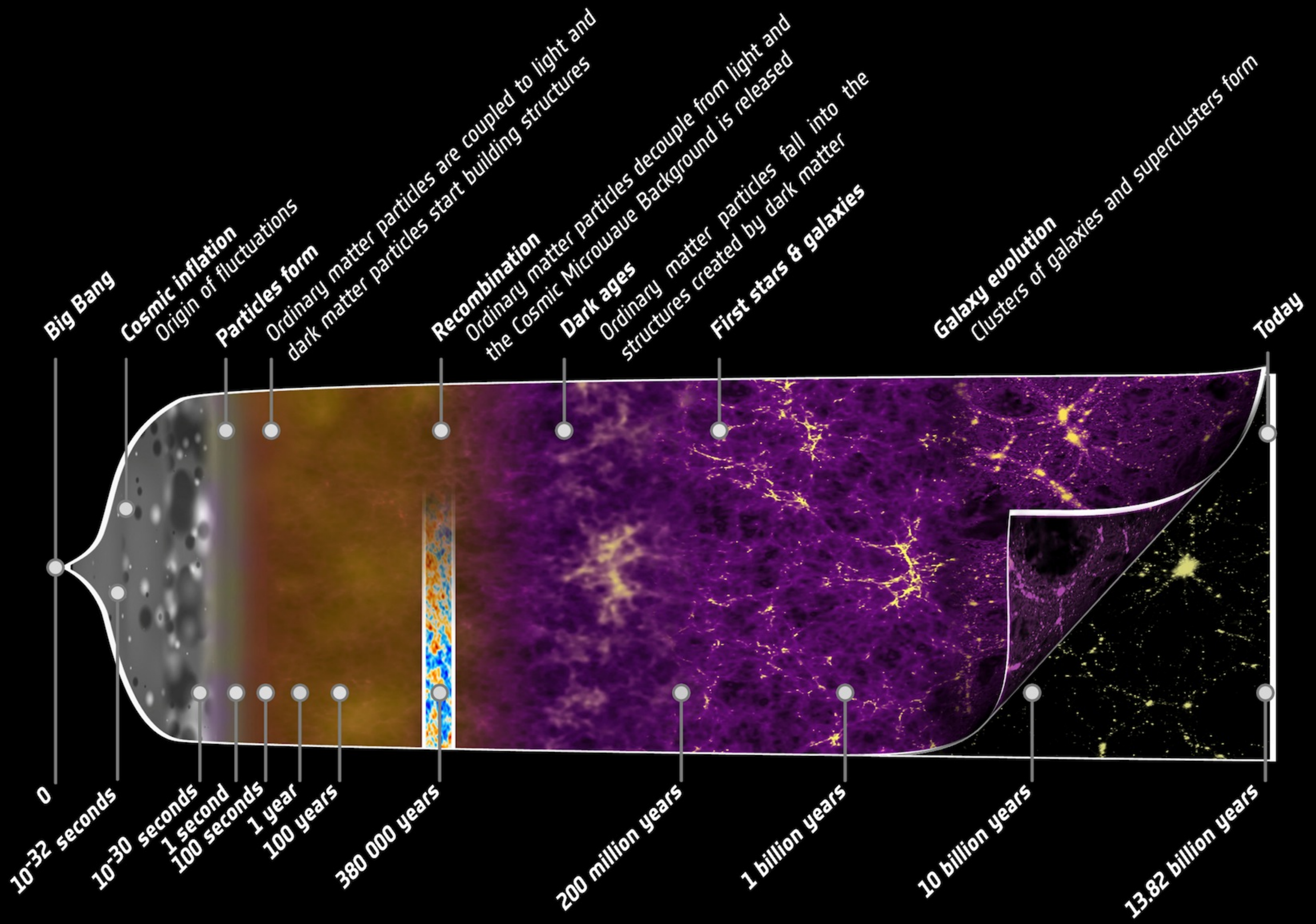
Outline

- Large Scale Structure (LSS).
  - E.g. Warm dark matter.

- 21cm Cosmology and Soft Photon Heating.
  - E.g. Anomalous radio backgrounds and decaying/annihilating DM.

- Cosmic Microwave Background (CMB) Anisotropies.
  - E.g. PBHs.

- CMB Spectral Distortions.
  - E.g. Dark photons.



Big Bang
Cosmic inflation
Origin of fluctuations
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
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10^{-32} seconds
10^{-30} seconds
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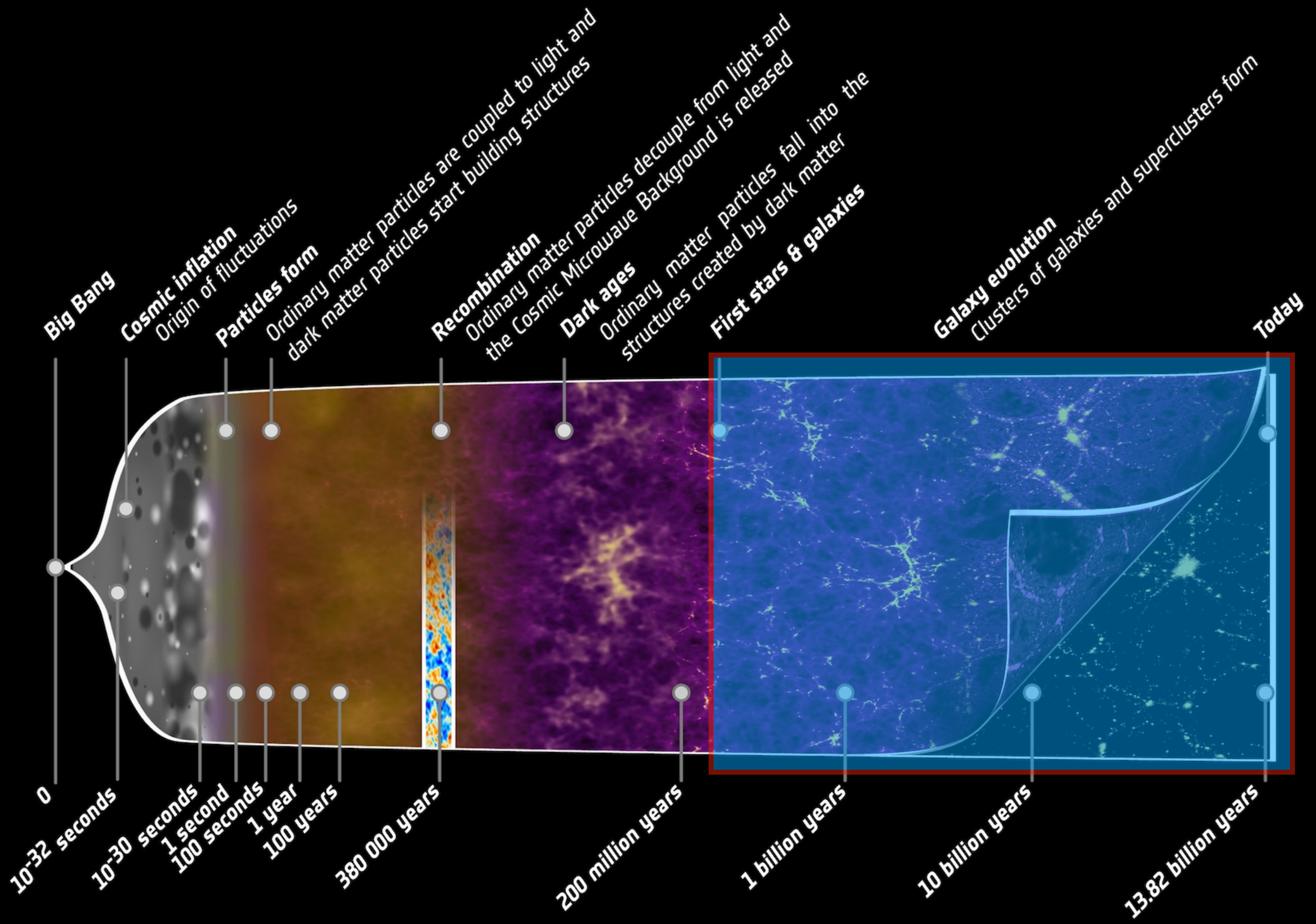
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years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LSS

Large scale structure

Goal: Create (and understand) maps of distribution of luminous/dark matter throughout cosmic time.

Constraints on dark sectors come from combinations of:

- Observations (Galaxy surveys, Ly-α, Weak lensing).
- Large volume simulations (Hydro/N-body). Review: Angulo and Hahn (2021)
- (Semi-)Analytics (EFTofLSS). Seminal Work: Senatore++ ($\gtrsim$2012) Les Houches Lectures: Baldauf (2020)

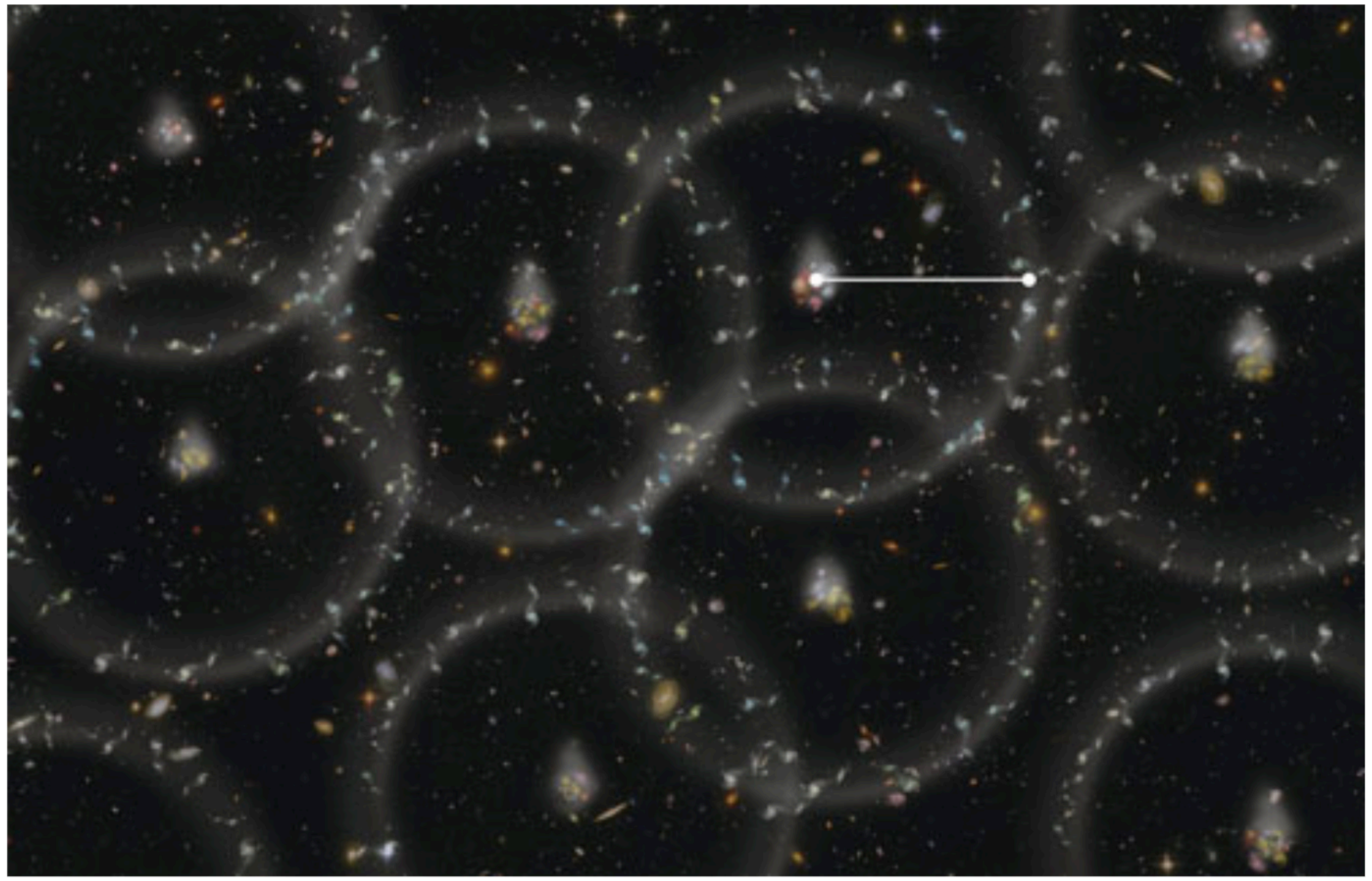
Key observable: Baryon Acoustic Oscillations (BAO)

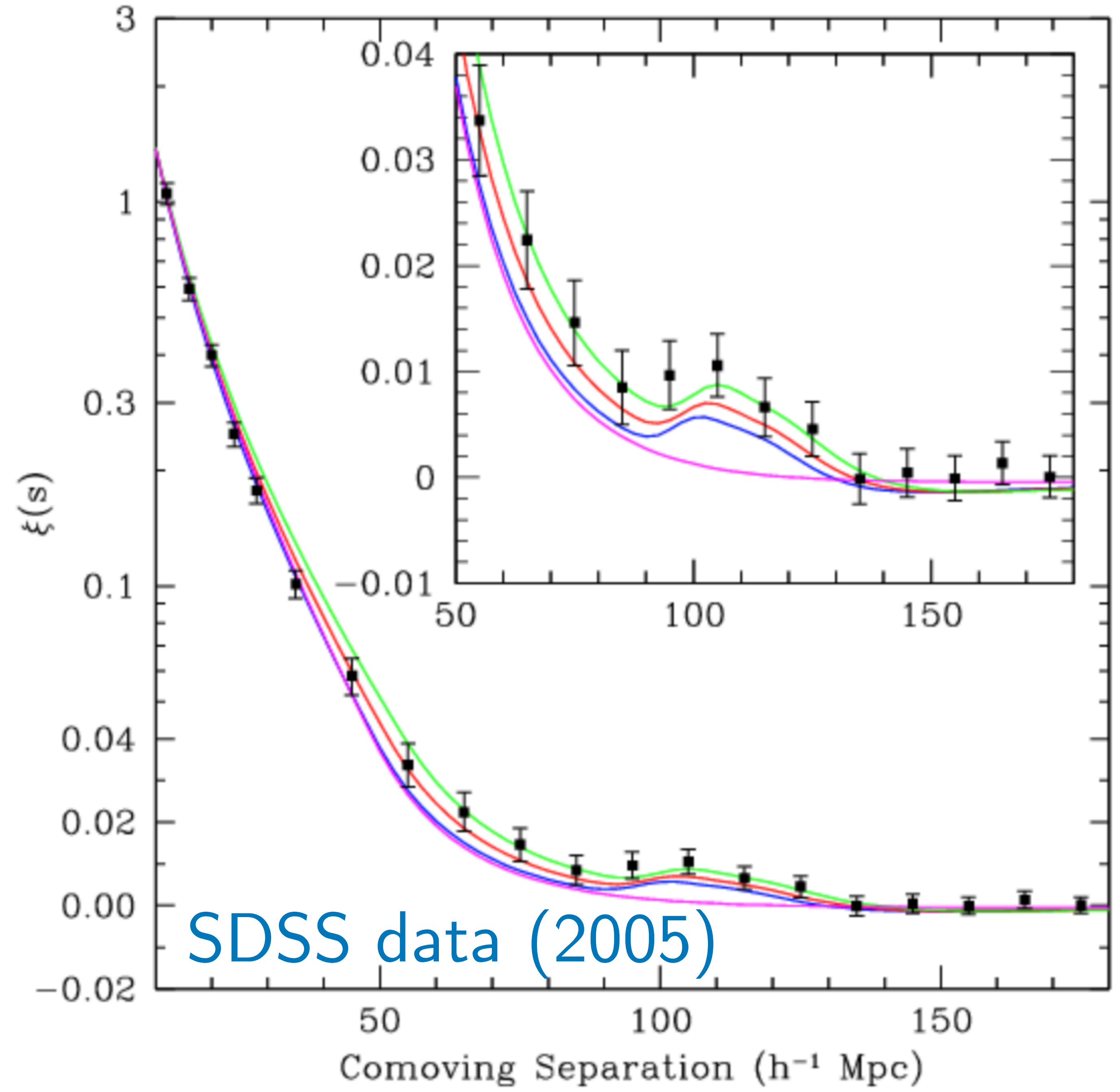
- Spike in the galaxy correlation function at $r \simeq 150$ Mpc (comoving).
- Measuring BAO along line of sight can determine $H(z)$, transverse gives angular diameter distance.

Large scale structure: DESI observations

Dark Energy Spectroscopic Instrument (DESI): Uses multiple tracers to reconstruct the BAO feature.

- Spectra from 6M objects, $0.1 < z < 4.2$.
- Galaxies $0.1 < z < 1.6$, Quasar/Lyman-α forest $0.8 < z < 4.16$.
- Roughly 5% (10%) sky coverage in Y1 (Y5).

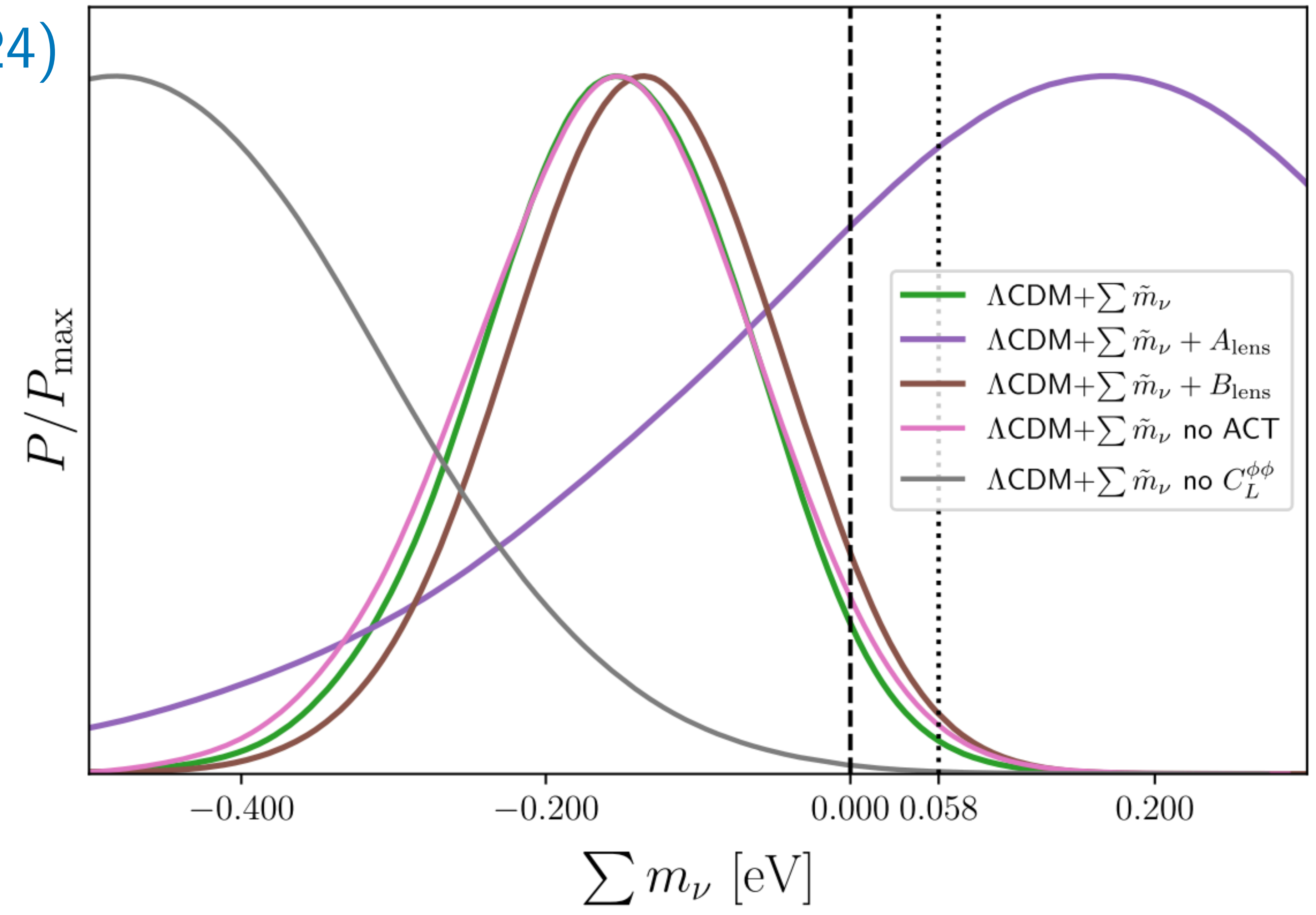




DESI Mysteries?

*Physical interpretation = excess clustering on small scales
(Flavour oscillations imply $\sum m_\nu \geq 0.058$)

Green and Meyers (2024)



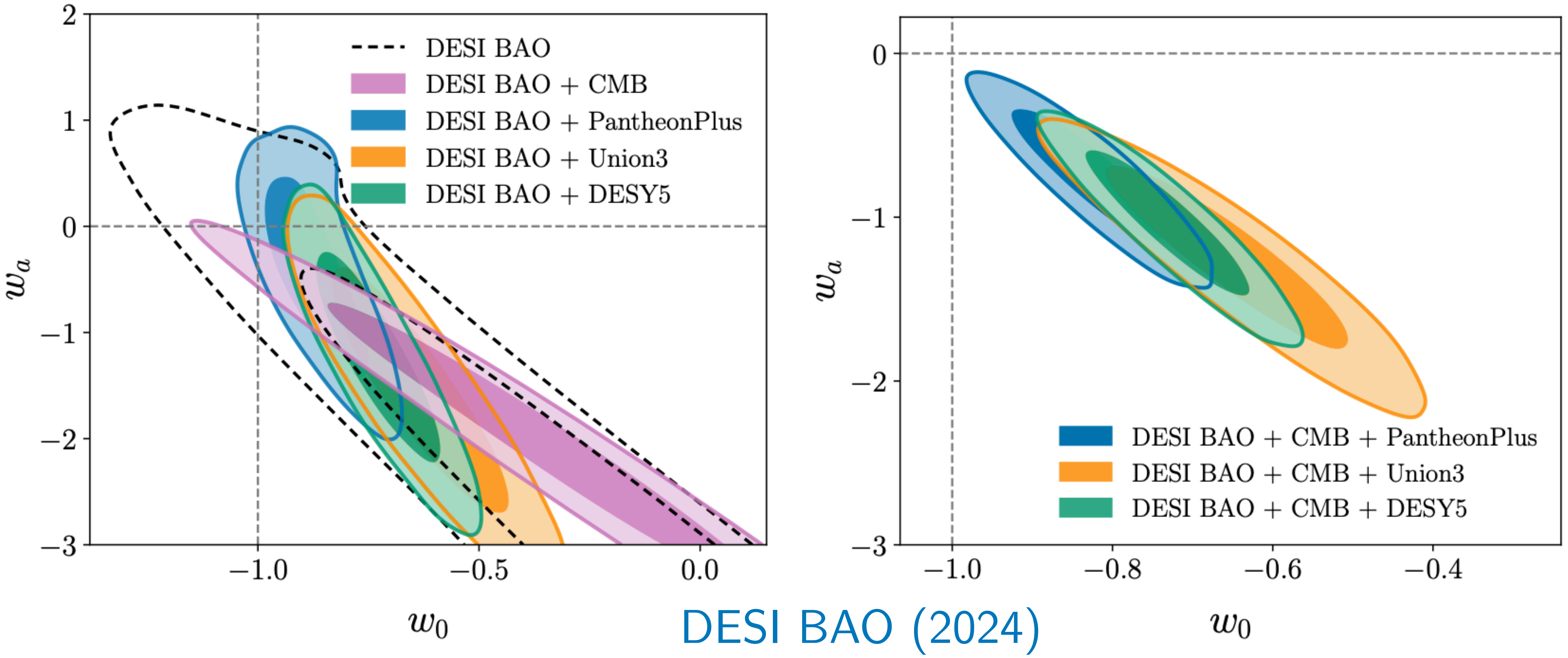
Negative* $\sum m_\nu$?

- Preference for this is insensitive to other 2-pt lensing anomalies, constraints instead driven by information in the 4-pt statistics.

Time varying equation of state?

- Up to a 3.9σ tension with usual CC.

$$w(a) = w_0 + w_a(1 - a)$$



DESI BAO (2024)

Large scale structure: warm dark matter

Iršič et al. (2024)

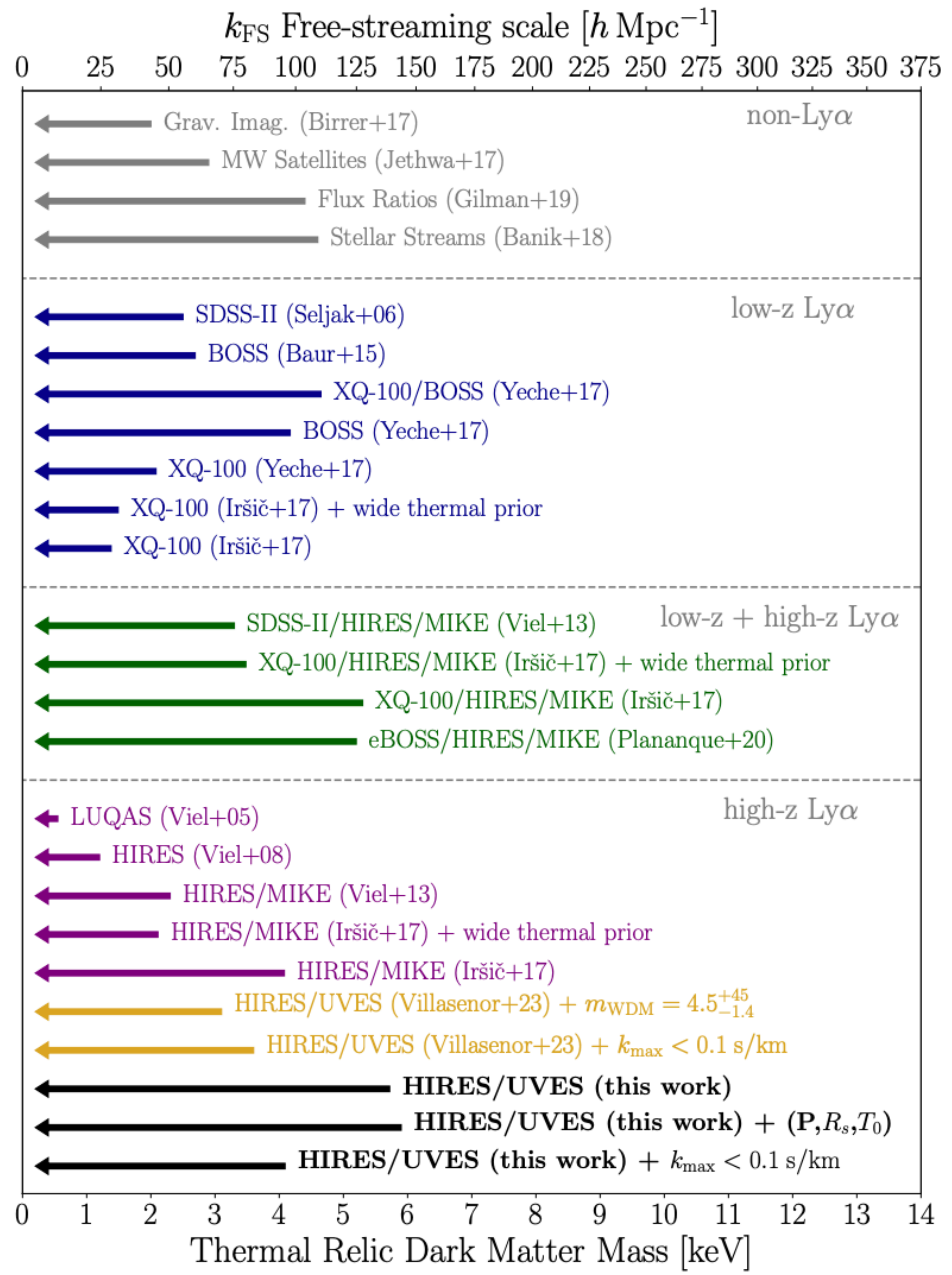
Warm dark matter - a thermal sector with $m_{\rm dm}/T_{\rm dm} \simeq 1$.

High kinetic energy allows dark matter to free-stream out of overdensities, suppressing growth of small-scale structures.

Simulation-based Bayesian inference yields constraints from Ly-α forest observations of high redshift quasars from the VLT and Keck.

Karaçaylı et al. (2024)

Data from DESI promises further improvements.



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New fractional WDM constraints coming soon!
(Vera Gluscevic's talk)

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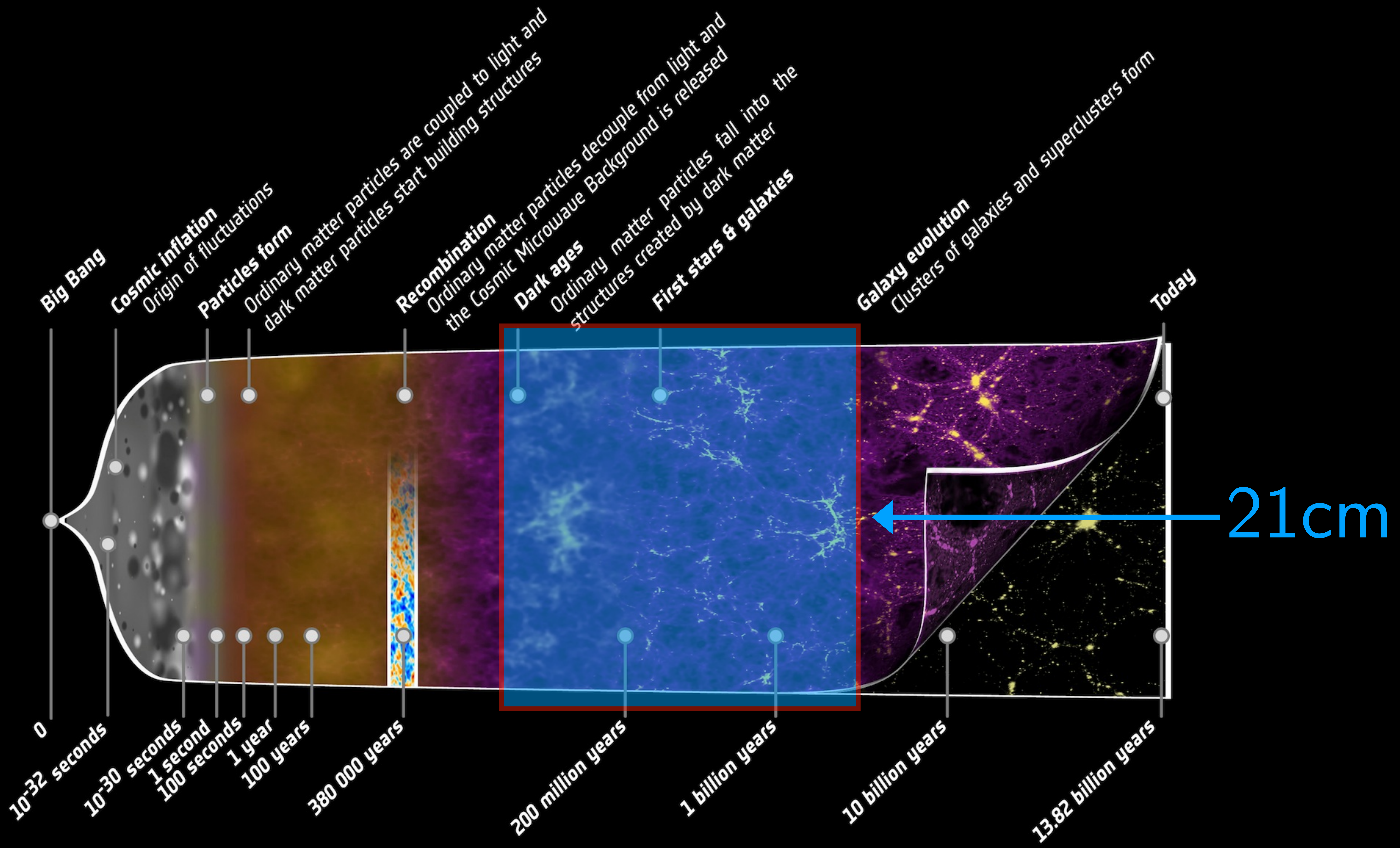

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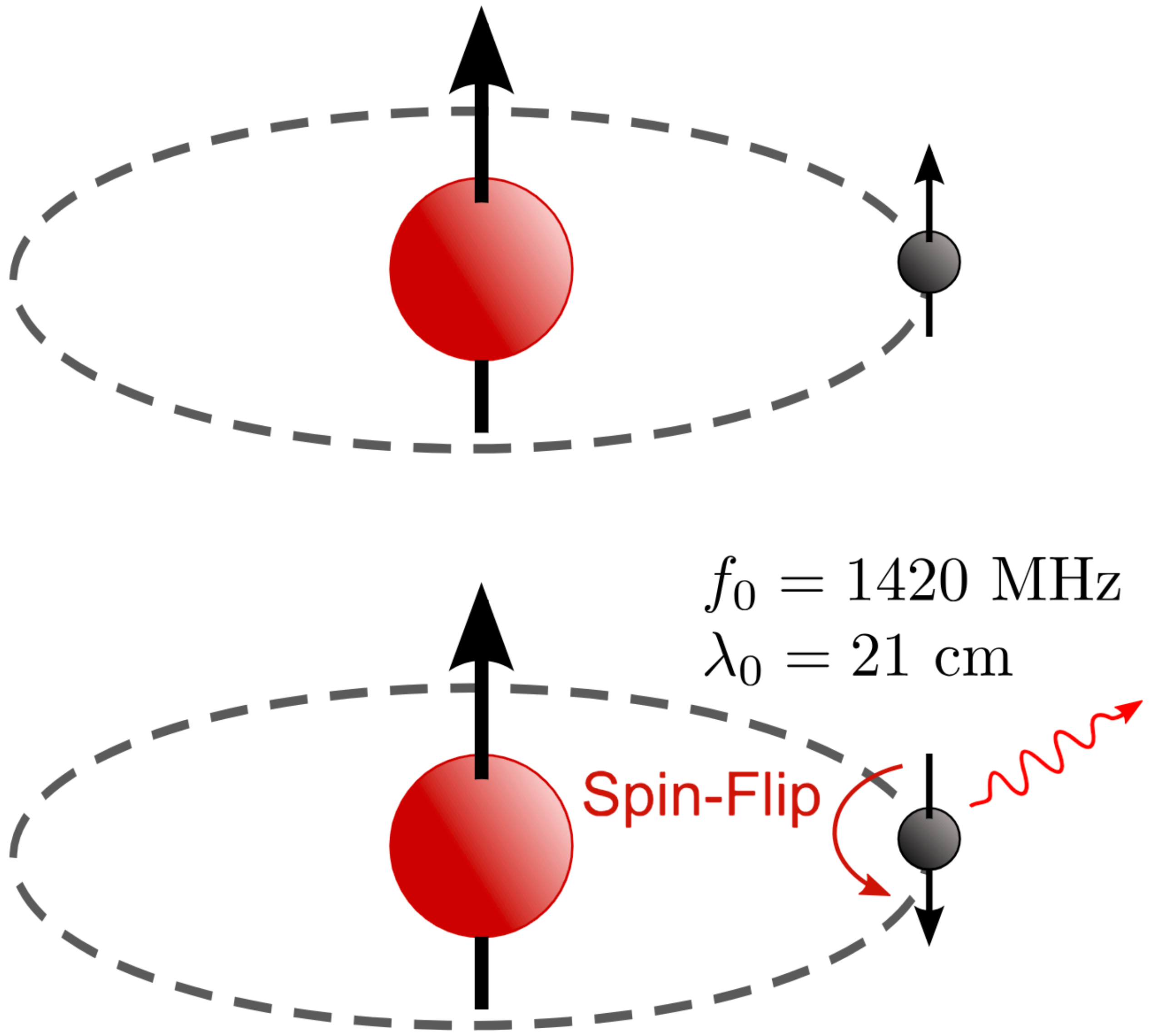
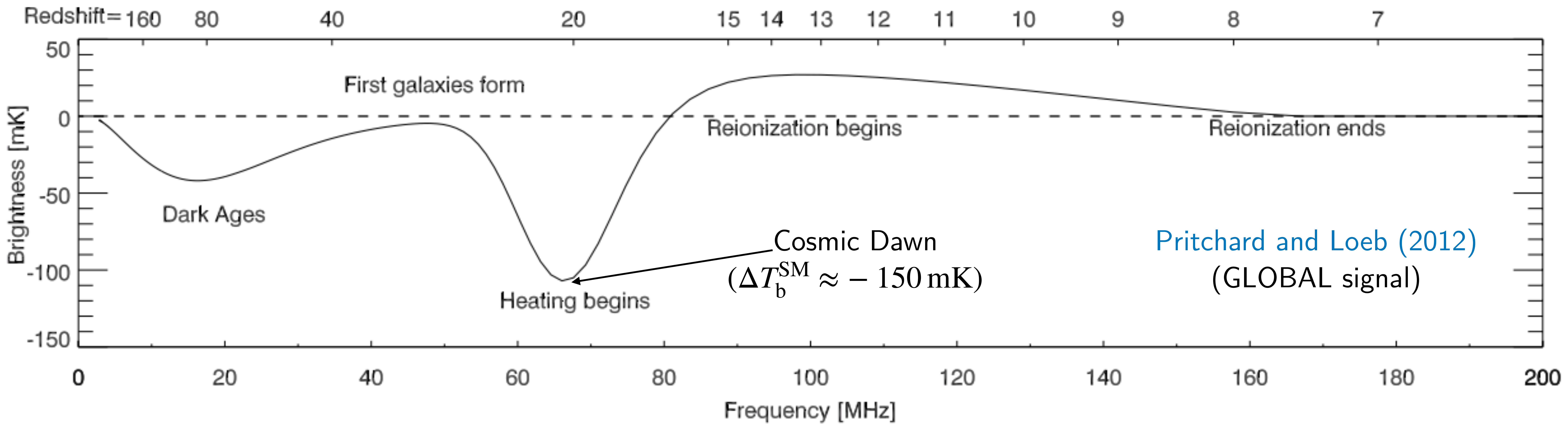
21-cm cosmology



Goal: Map out the distribution of neutral hydrogen by searching for redshifted 21cm line emission from spin-flip transition ($\tau \simeq 11$ Myr).



$$\Delta T_b = 27 x_{HI}(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2}\left(\frac{\partial_r v_r}{(1+z)H(z)}\right)\left(1-\frac{T_R}{T_{spin}}\right)\text{mK}$$

21-cm co

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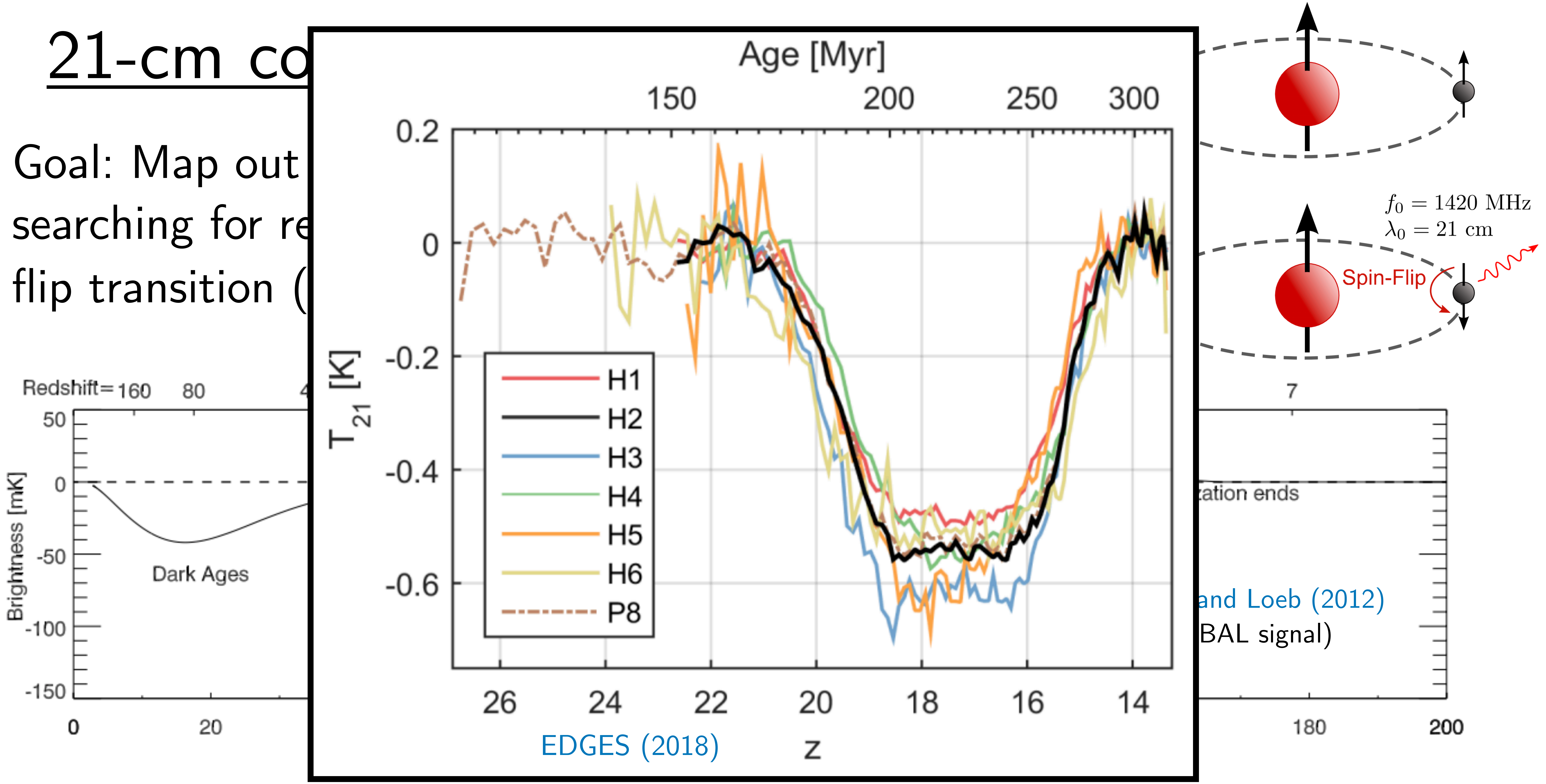

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The spin temperature

$\Delta T_b \propto x_{HI}(1 - T_R/T_{spin})$

The ST counts relative occupation between triplet and singlet states, determined by three main (redshift dependent) effects:

- Interactions between radiation bath at 21-cm.
- Heating via collisions with particles in-media.
- Resonant Ly-α scattering.

Exotic phenomena modify spin temperature through variations of T_R (extra radio backgrounds) and/or T_{spin} (e.g. milli-charged dark matter).

Venumadhav et al. (2018), Fialkov and Barkana (2019)
Brandenberger, BC, Shi (2019)

Kovetz et al. (2018), ++

Dark sectors must not increase brightness temperature more than current limits $\Delta T_b \gtrsim -500$ mK.

~EDGES (2018)
SARAS-3 (2022)

Extra radio backgrounds: soft photon heating

Hard photons: Defined by $E_\gamma \gtrsim 10\,\mathrm{eV}$, can cause direct excitations and ionizations of the background, highly constrained by CMB anisotropy measurements.

Acharya, BC, Chluba (2023)
BC et al. (2024)

Soft photons: Lower energies ($E_{\rm ff,abs}(z) \lesssim E_\gamma \lesssim 10\,\mathrm{eV}$) will mostly free-stream. Photons with $E_\gamma \lesssim E_{\rm ff,abs}(z)$ will be absorbed (inverse-Brem), in some cases heating the gas significantly.

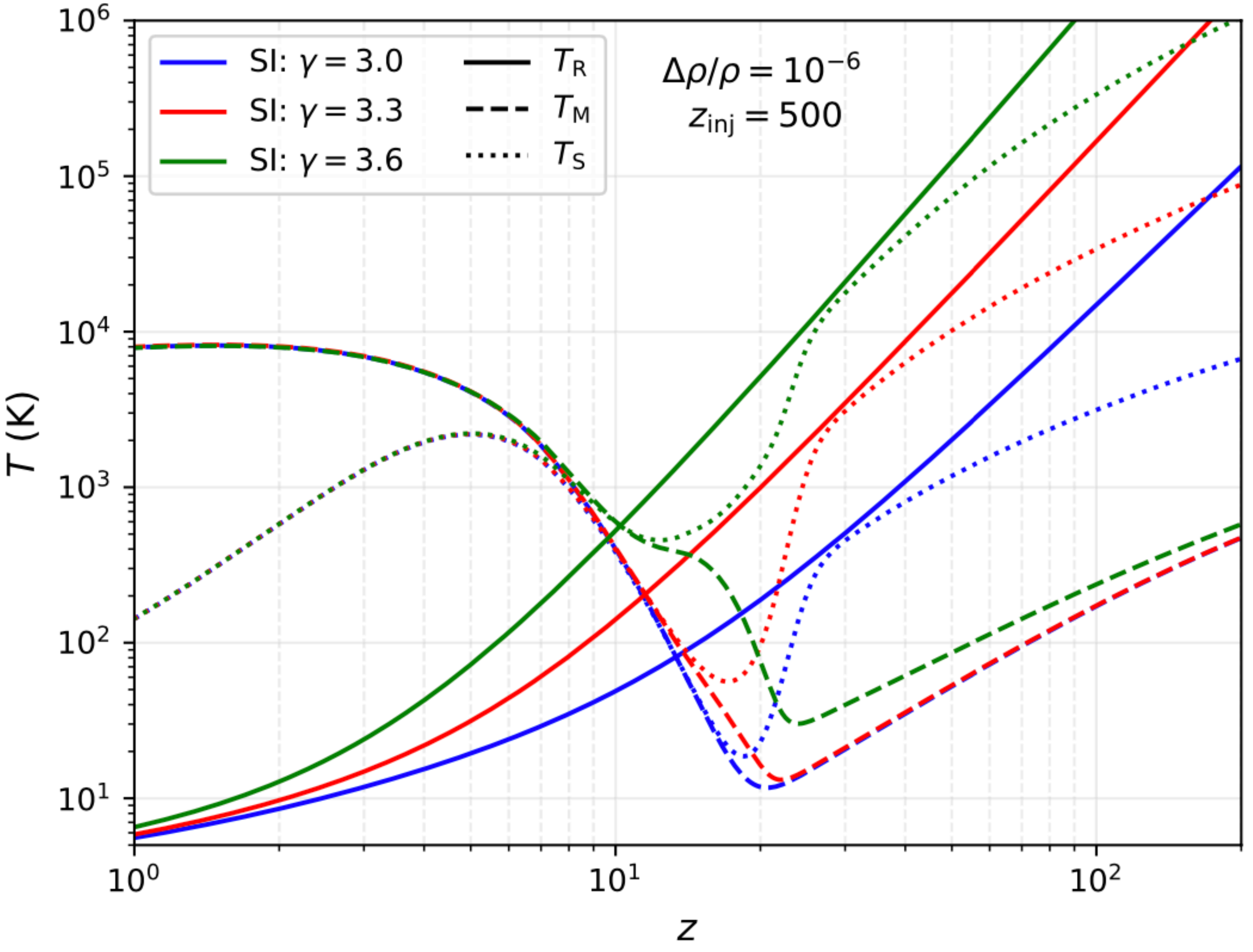
This implies that when $T_{\rm R} \uparrow$, one can also have $T_{\rm spin} \uparrow (\uparrow\uparrow)$

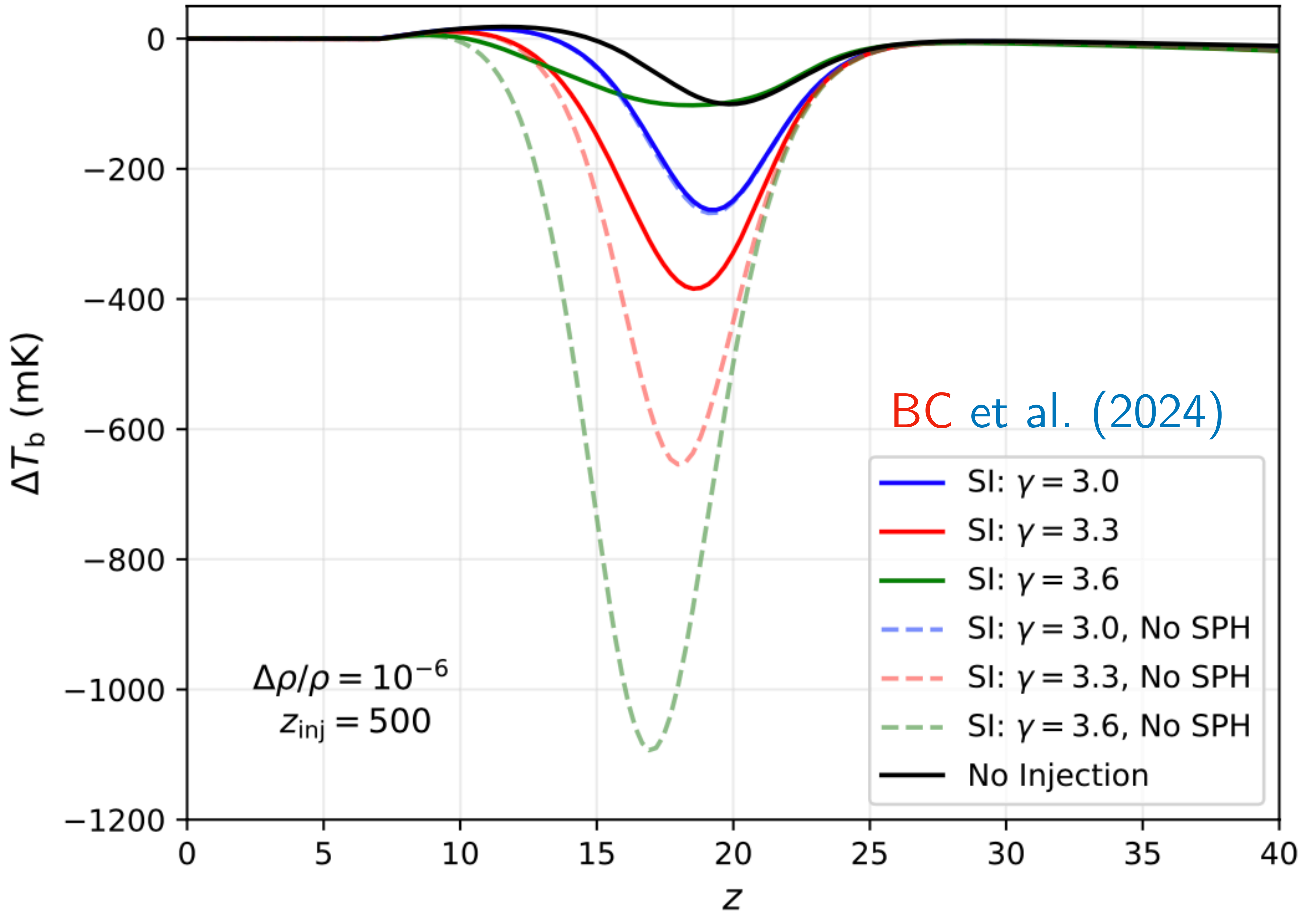
(Note: Definitions apply for post-recombination injections.)

$$\Delta T_{\rm b} \propto x_{\rm HI}(1 - T_{\rm R}/T_{\rm spin})$$

Anomalous radio backgrounds

$$T_{\rm bg} = T_{\rm bg,0}\left(\frac{\nu}{\nu_0}\right)^{1-\gamma}$$





21cm constraints on dark sectors which produce significant soft photons are greatly relaxed (e.g. cosmic strings, axion-dark photon-photon systems).

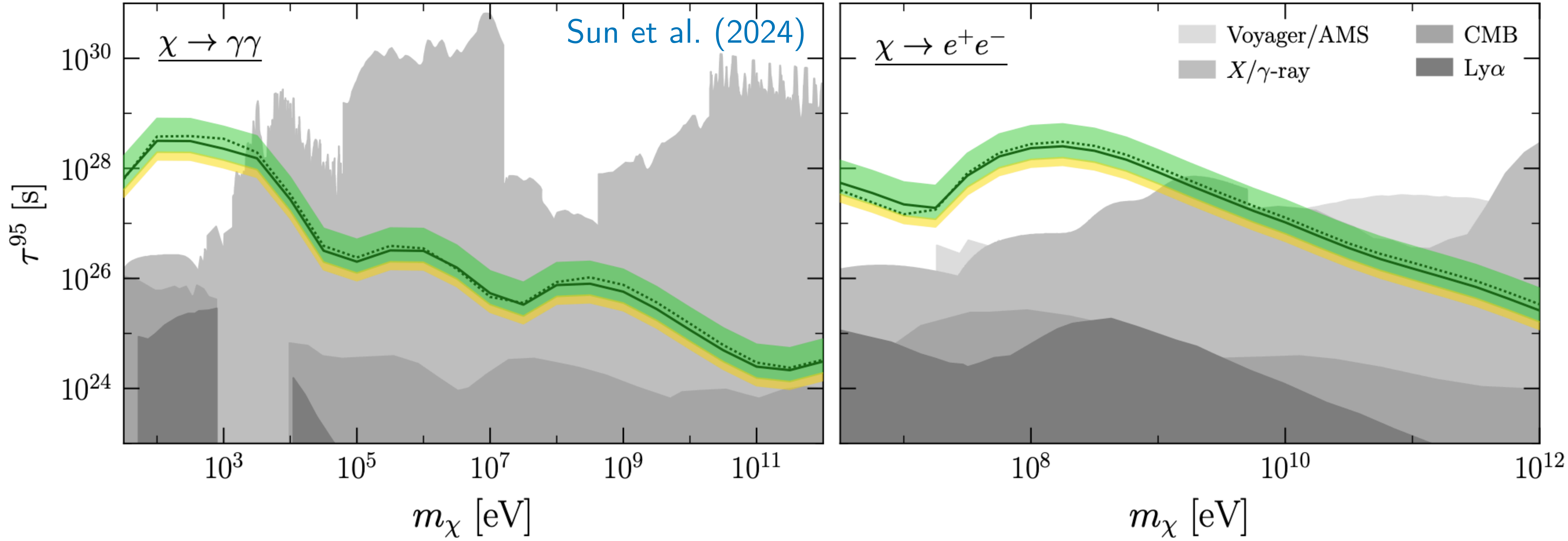
BC et al. (2023) Caputo et al. (2022)

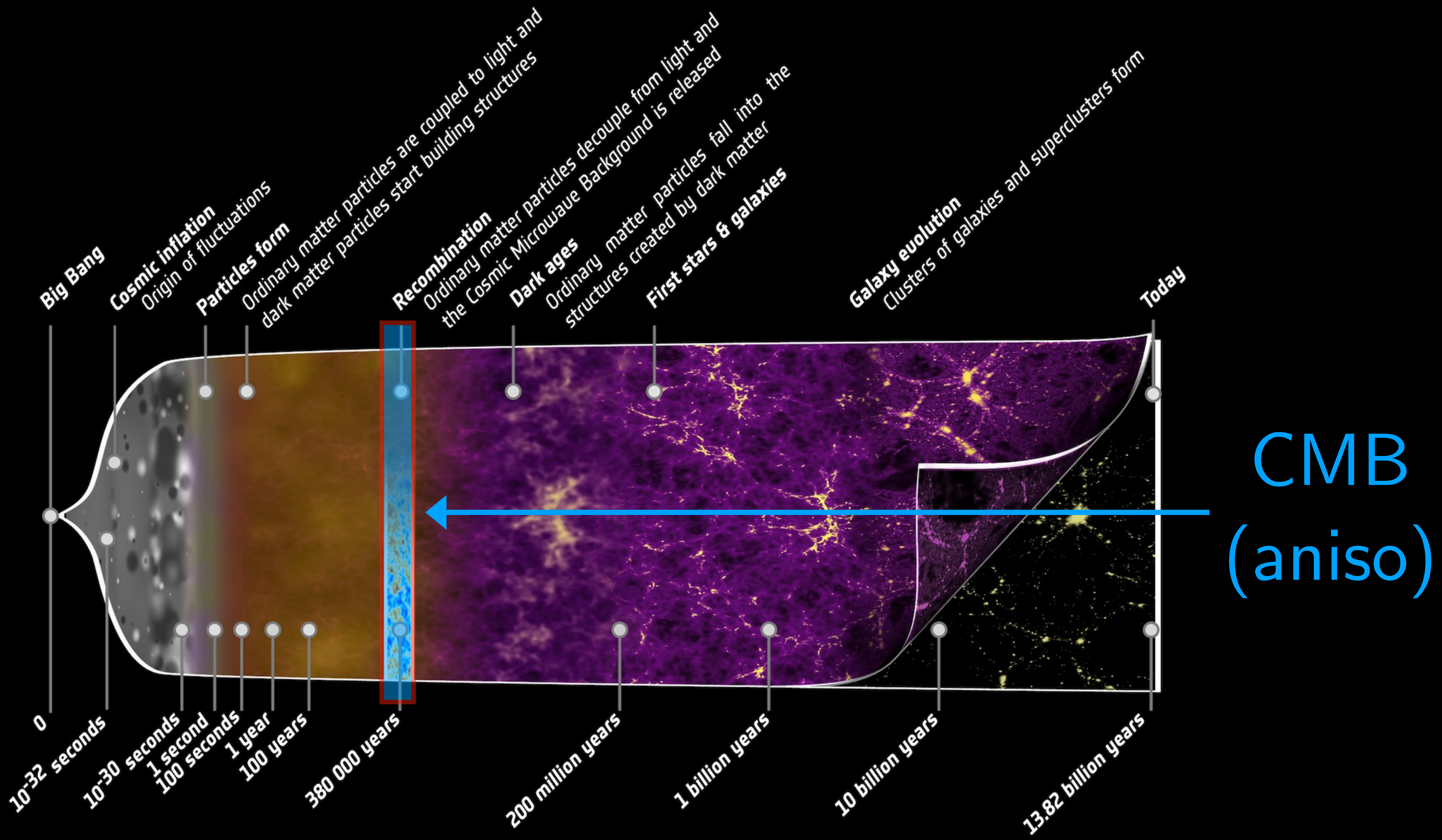
Decaying/annihilating dark matter

Dark matter decays and annihilations can be probed through their impacts on 21cm power spectrum (typically hard heating). Sun et al. (2024), ++

Formation of first stars in such environments also active area of study. Qin et al. (2023)

HERA forecasts





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CMB
(aniso)

Cosmic microwave background (anisotropies)

Goal: Utilize the statistics of CMB temperature and polarization maps to gain insights on the thermal history of the Universe.

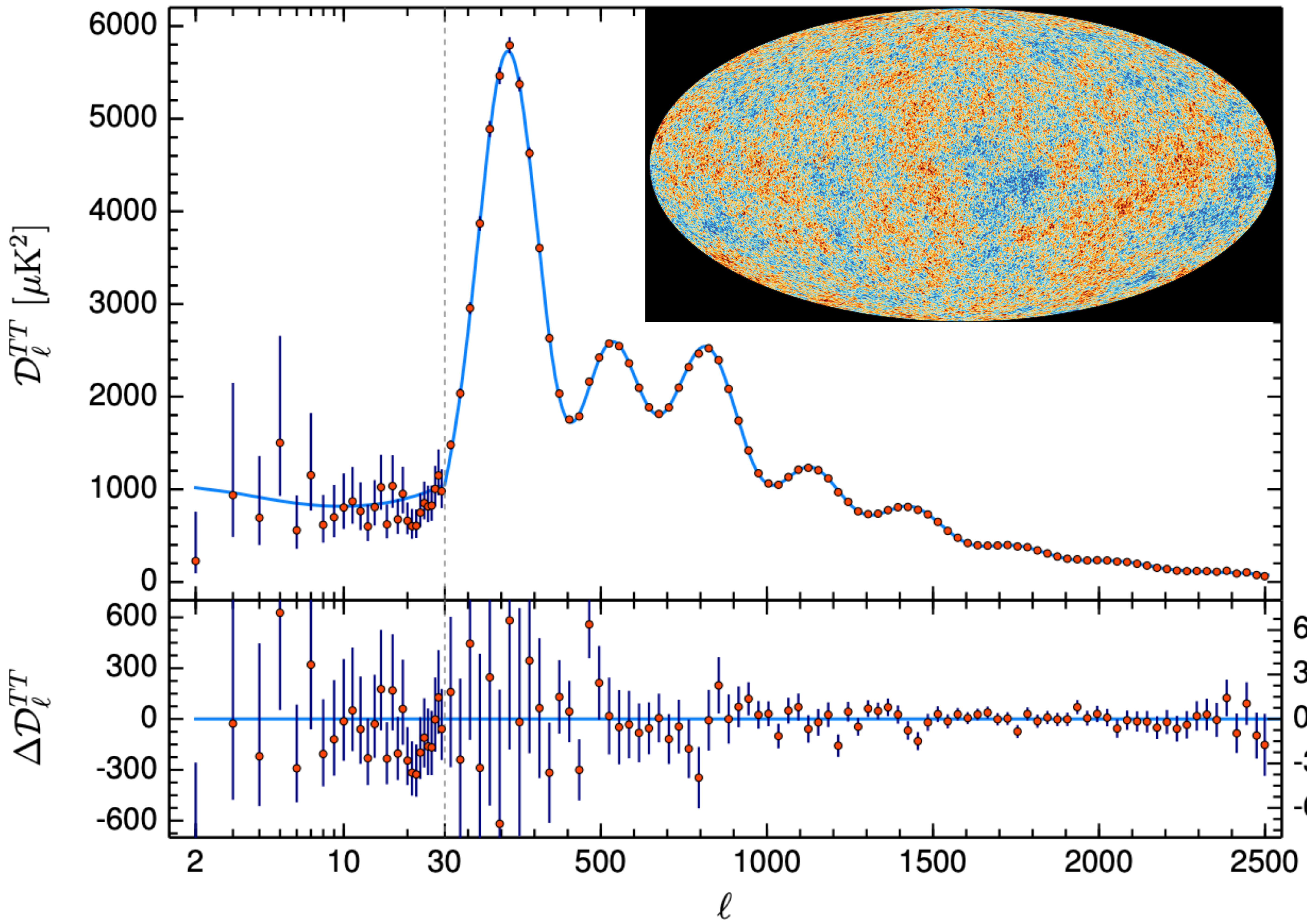
Primary anisotropies:

- Sachs-Wolfe
- Acoustic waves
- Doppler shifts

Secondary anisotropies:

- ISW effect
- Gravitational lensing
- Sunyaev-Zel'dovich effect

Planck (2018)



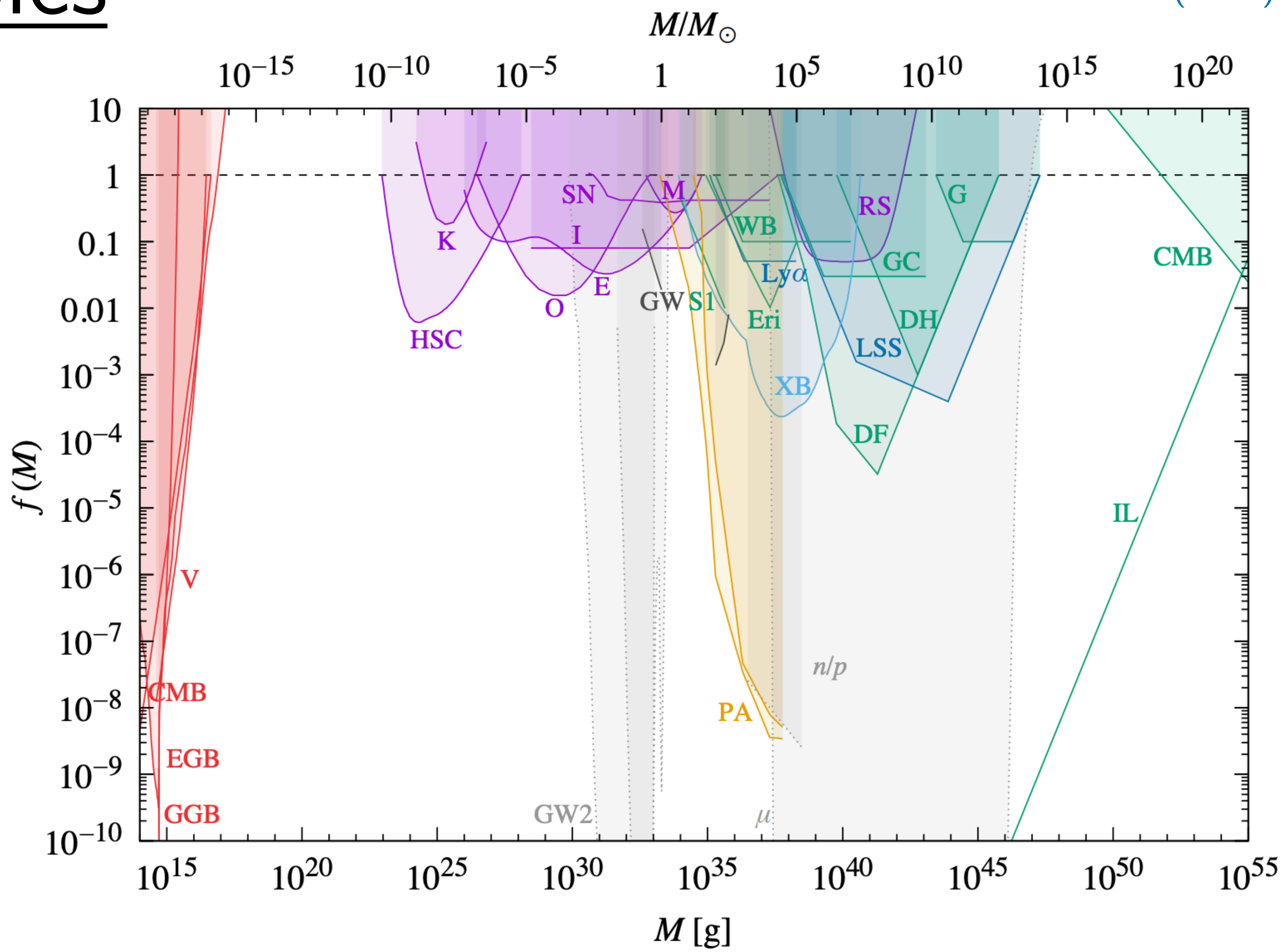
Primordial black holes

Carr and Kuhnel (2021)

Main idea: Density fluctuations exceeding a critical threshold can collapse upon horizon re-entry.

Usually characterized by a deviations away from near-scale invariance on small scale power spectrum.

Rather generic prediction of e.g. ultra slow roll inflation.



Nb: These constraints assume Gaussian density perturbations on all scales

Primordial black holes

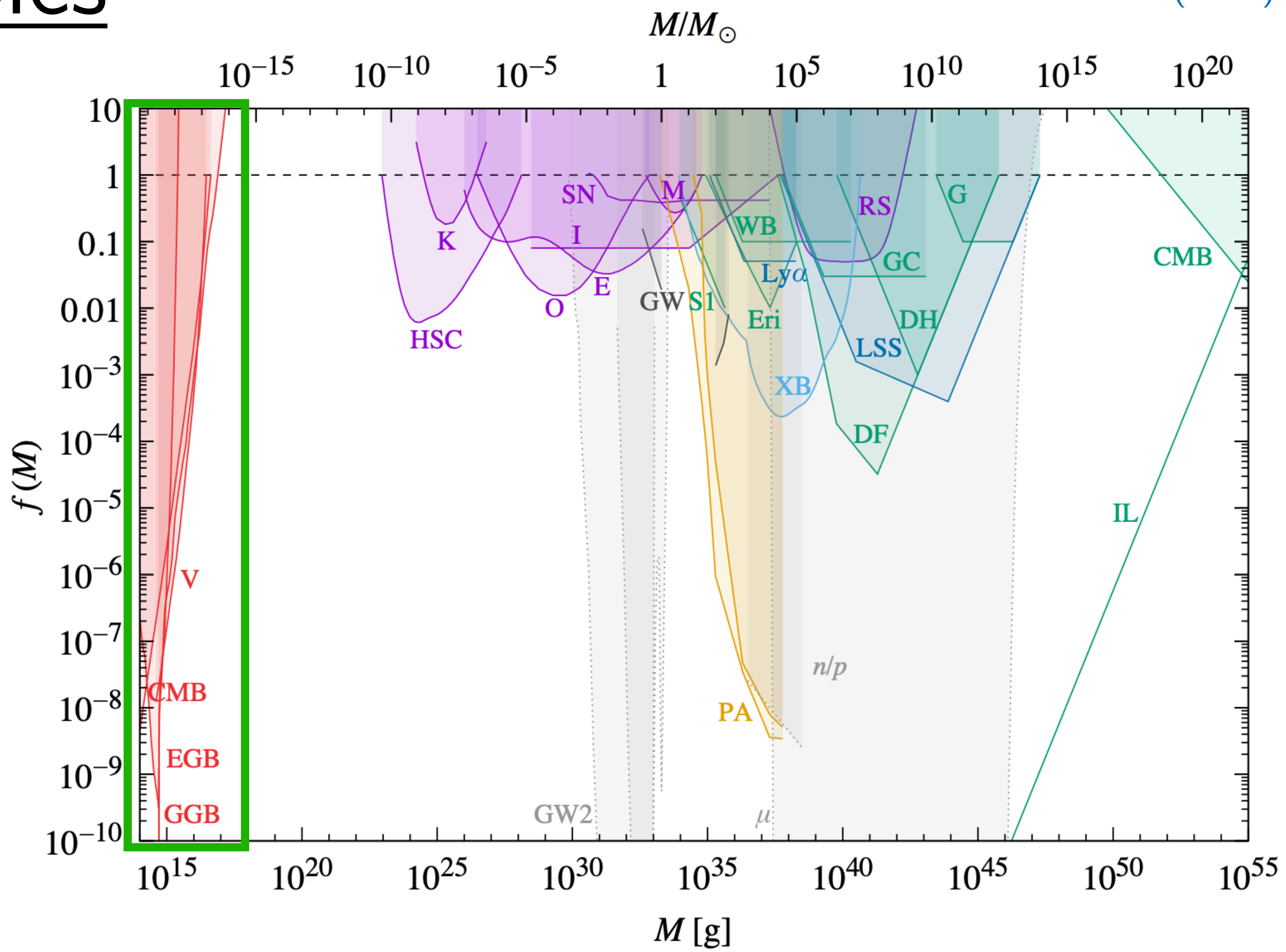
Carr and Kuhnel (2021)

Low mass end: Evaporation.

$$T_{\rm hawk} = \frac{1}{8\pi M}$$

Spectrum of particles produced is grey-body for all species $m_i < T_{\rm hawk}$.

Evaporation around recombination causes all sorts of problems.



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Primordial black holes

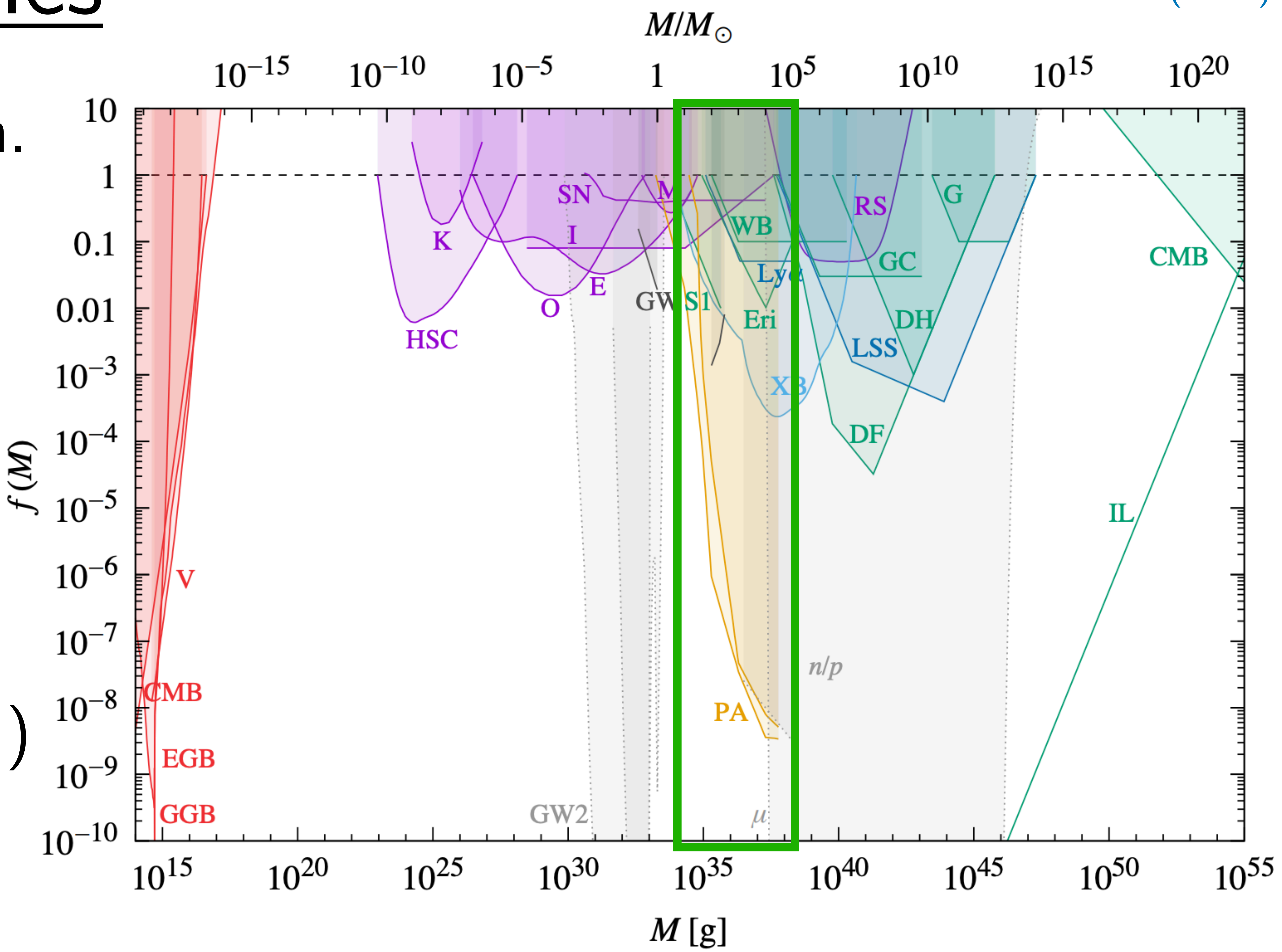
Carr and Kuhnel (2021)

Intermediate masses: accretion.

Accretion of matter and subsequent halo formation possible after $z_{\rm eq}$.

This comes with inevitable luminosity $L = \epsilon \dot{M}_{\rm pbh}$ $(\epsilon \approx 0.1)$

This heats surrounding medium, induces photoionization, etc.



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Primordial black holes

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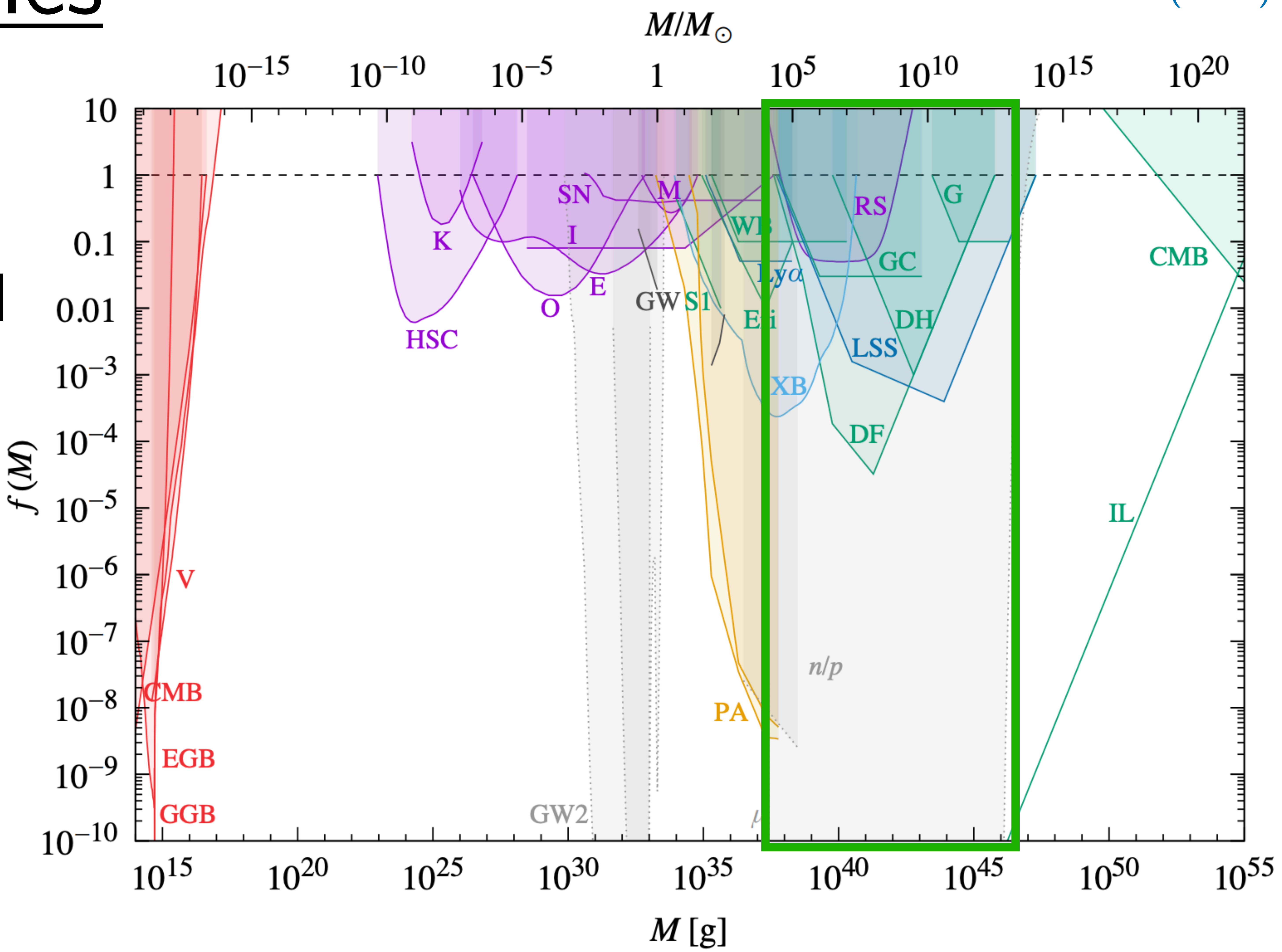
Background constraint:

CMB spectral distortions - will touch on this later.

Possible to evade with significant non-Gaussianity in primordial curvature fluctuations.



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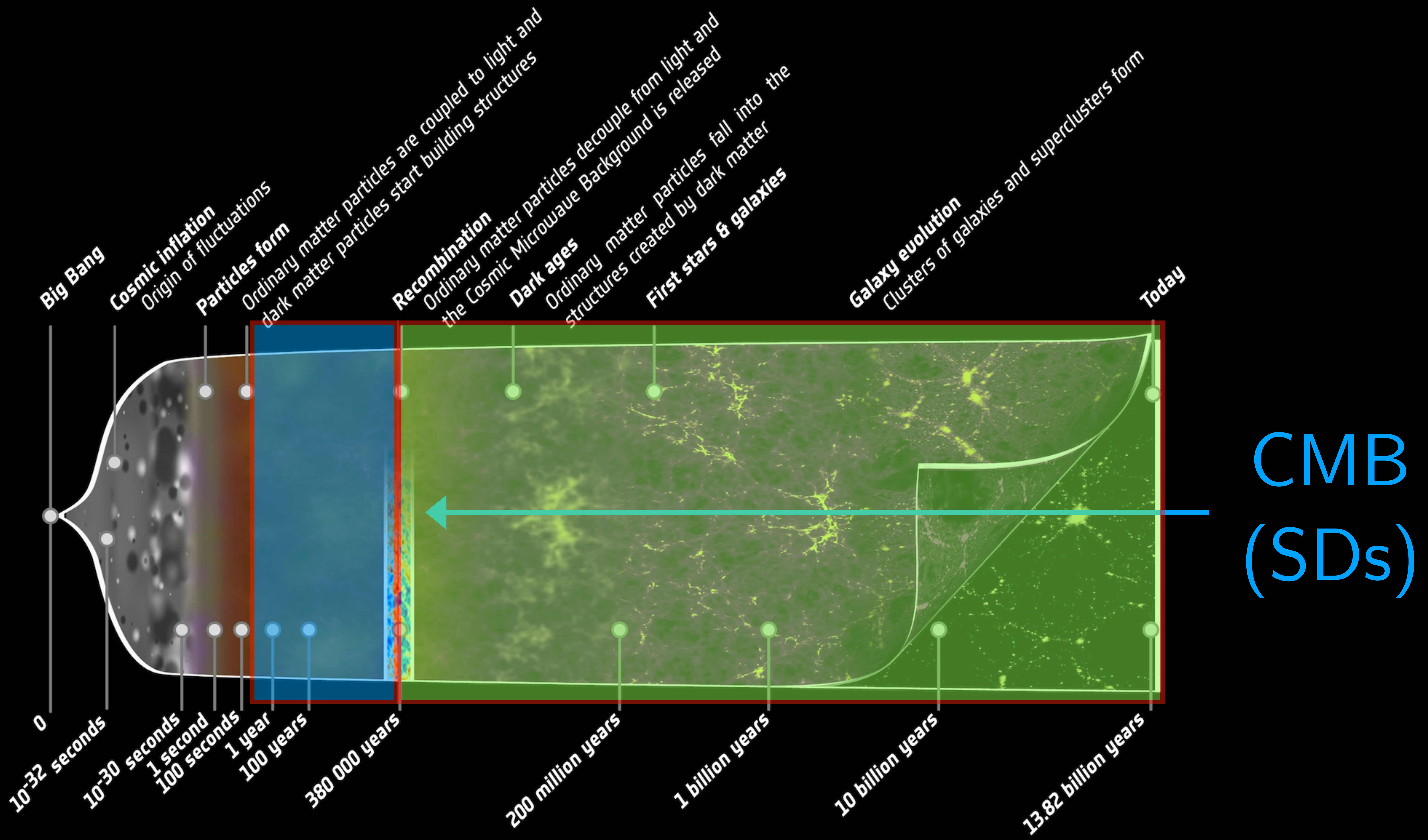
A non-exhaustive list of other fun bounds

- Self-interacting dark matter.
- Heavier ($m \gtrsim \mathrm{eV}$) dark matter decays and annihilations.
- Early dark energy, H_0 vs σ_8.
- Cosmic strings and other topological defects.
- ΔN_{eff} bounds on resonant photon->dark photon/axion conversions.
- Sterile neutrinos.
- Primordial gravitational waves (B-mode generation).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CMB
(SDs)

What is a CMB spectral distortion?

COBE/FIRAS measured nearly perfect blackbody of the CMB.

$$\frac{\Delta I_\nu}{I_\nu} \lesssim 10^{-5} \qquad I_\nu = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1}$$

COBE/FIRAS

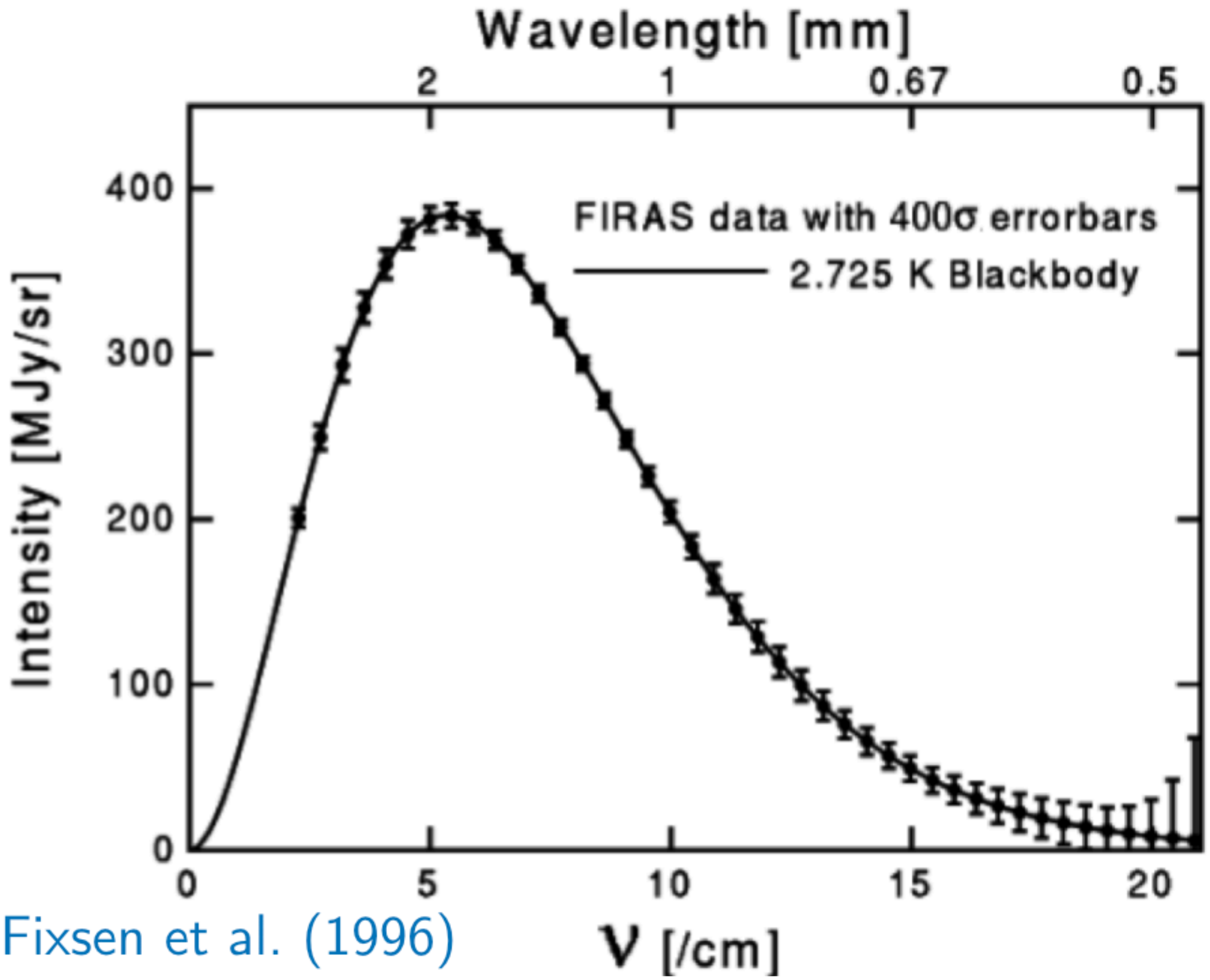
$|\mu| \lesssim 10^{-4}$

$|y| \lesssim 10^{-5}$

PIXIE

$|\mu| \lesssim 10^{-8}$

$|y| \lesssim 2 \times 10^{-8}$



Fixsen et al. (1996)

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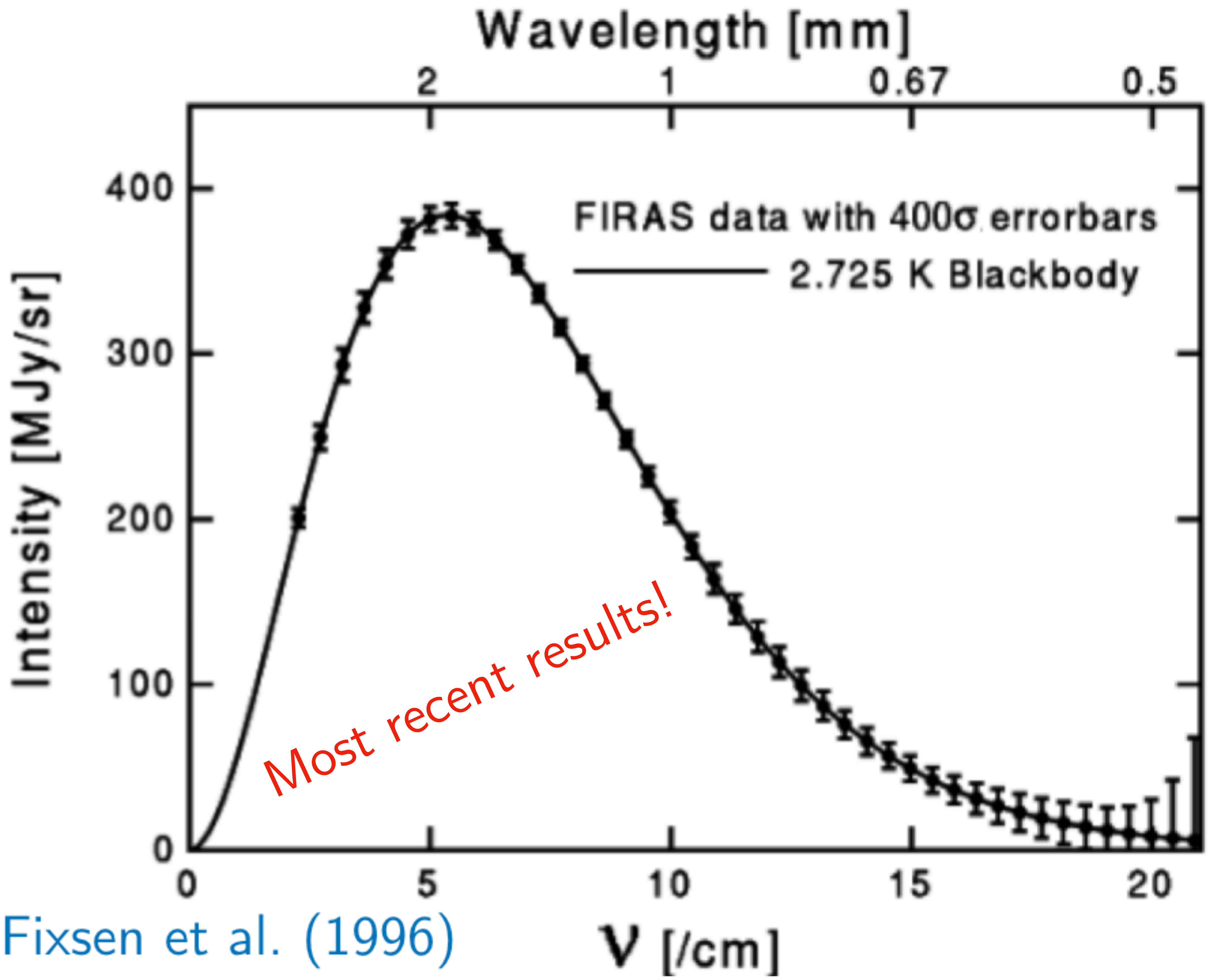

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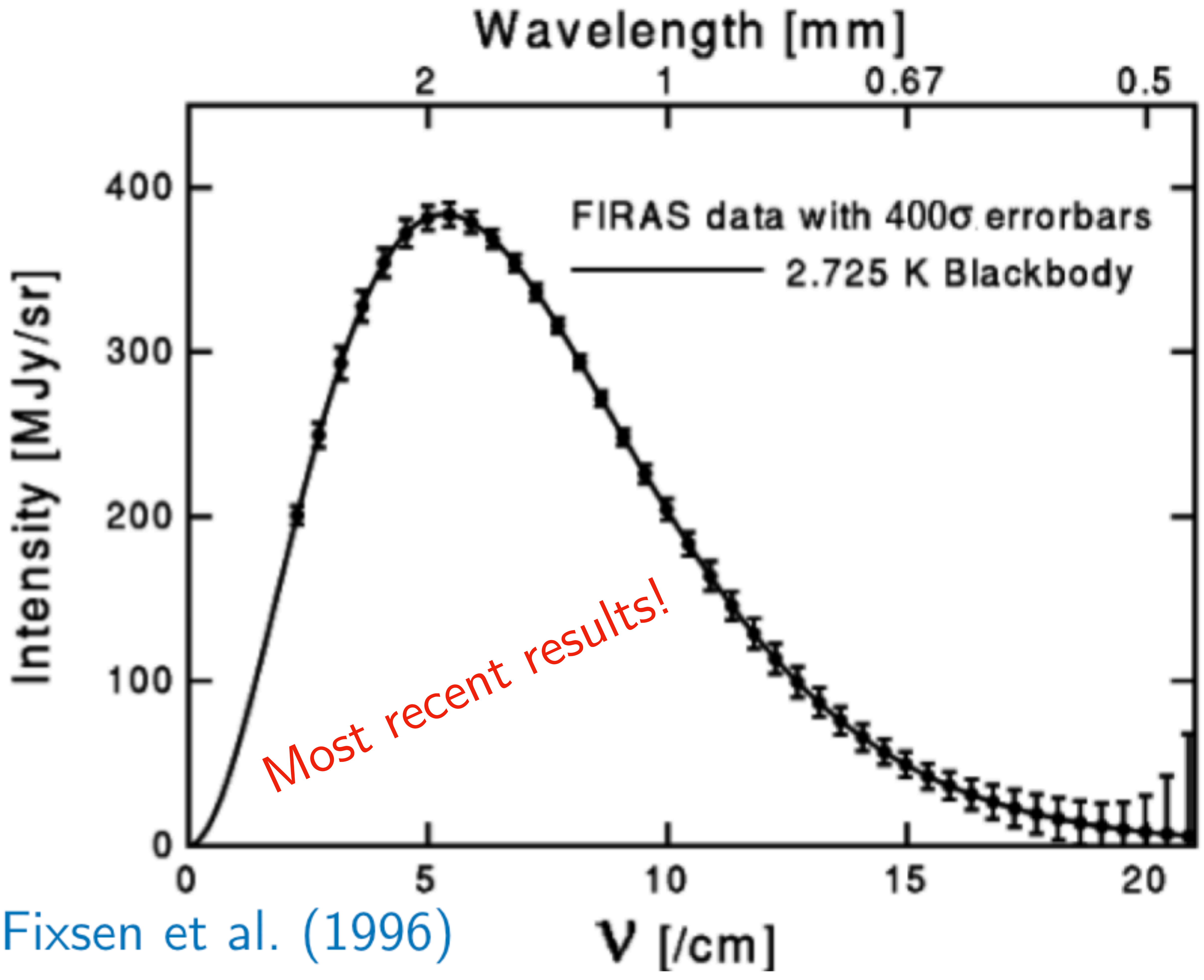
Nonthermal injections of energy and entropy into the plasma can distort the spectrum!



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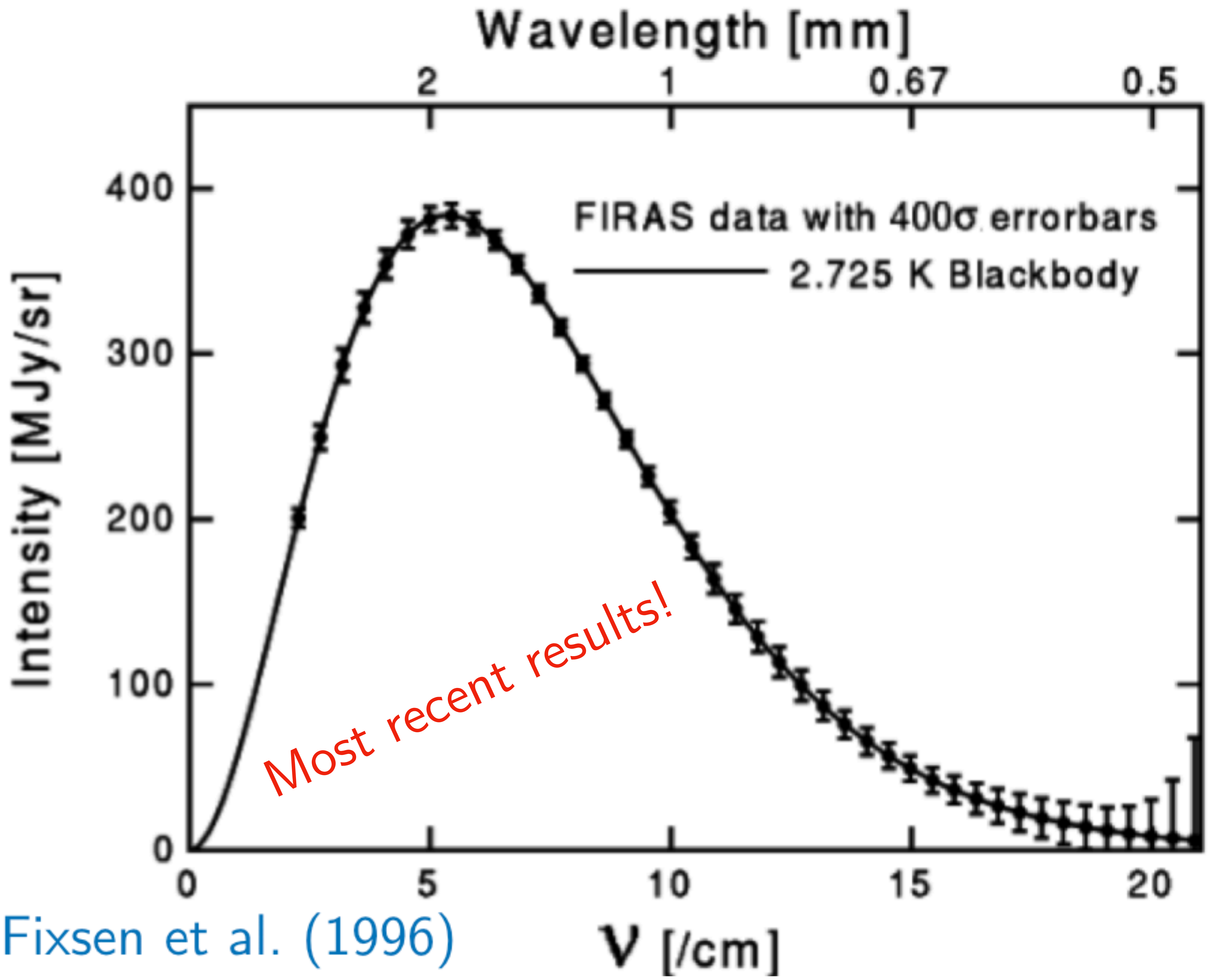

Fixsen et al. (1996)

SM signals at $\Delta I_\nu / I_\nu \simeq 10^{-8}$

Exotic signals?

Thermalization 101

How does one thermalize a distorted spectrum?

- Energy redistribution
- Photon creation/destruction

Freeze out redshift important! $\Gamma \simeq H$ $\Gamma = n\sigma v$

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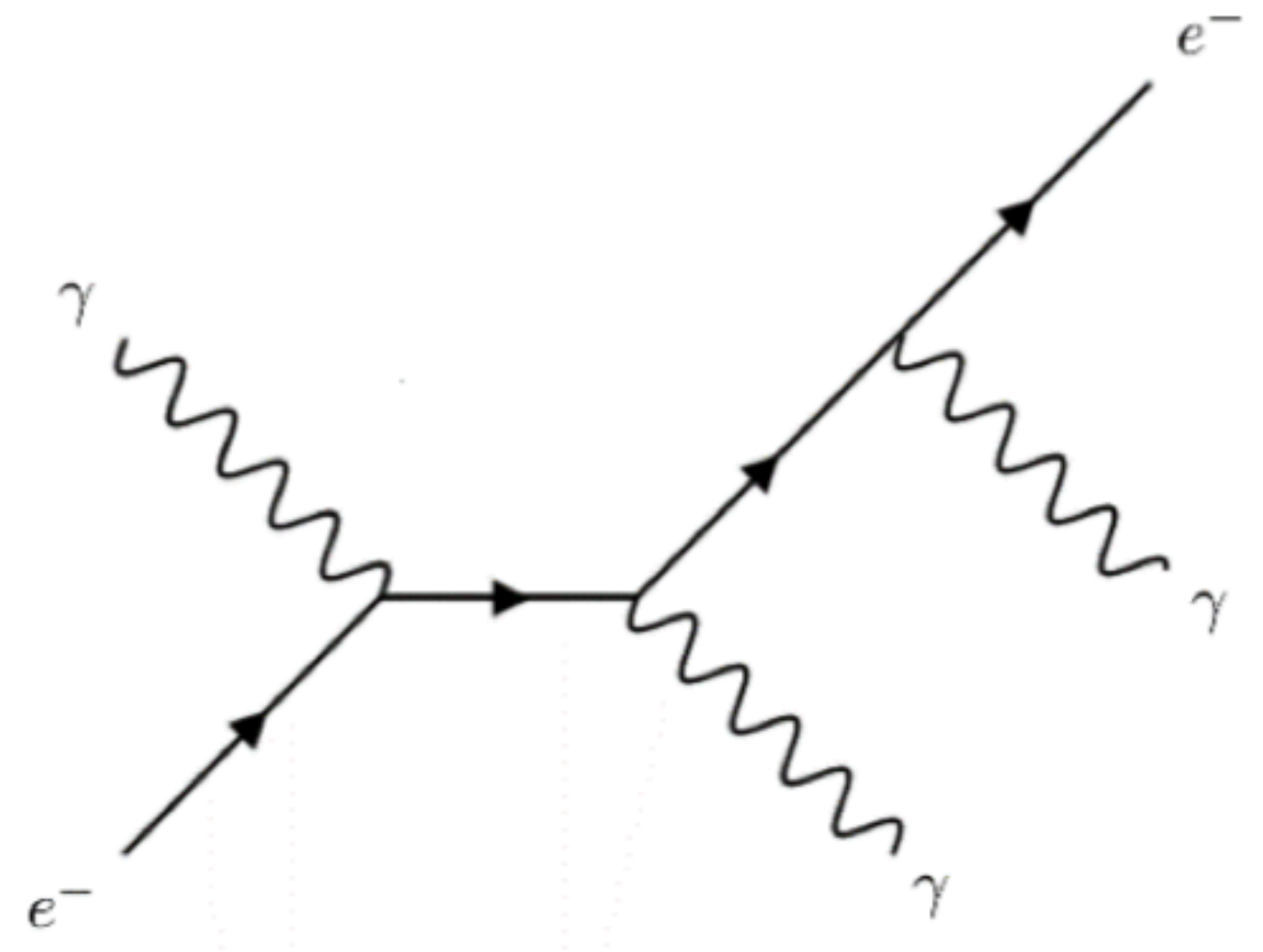
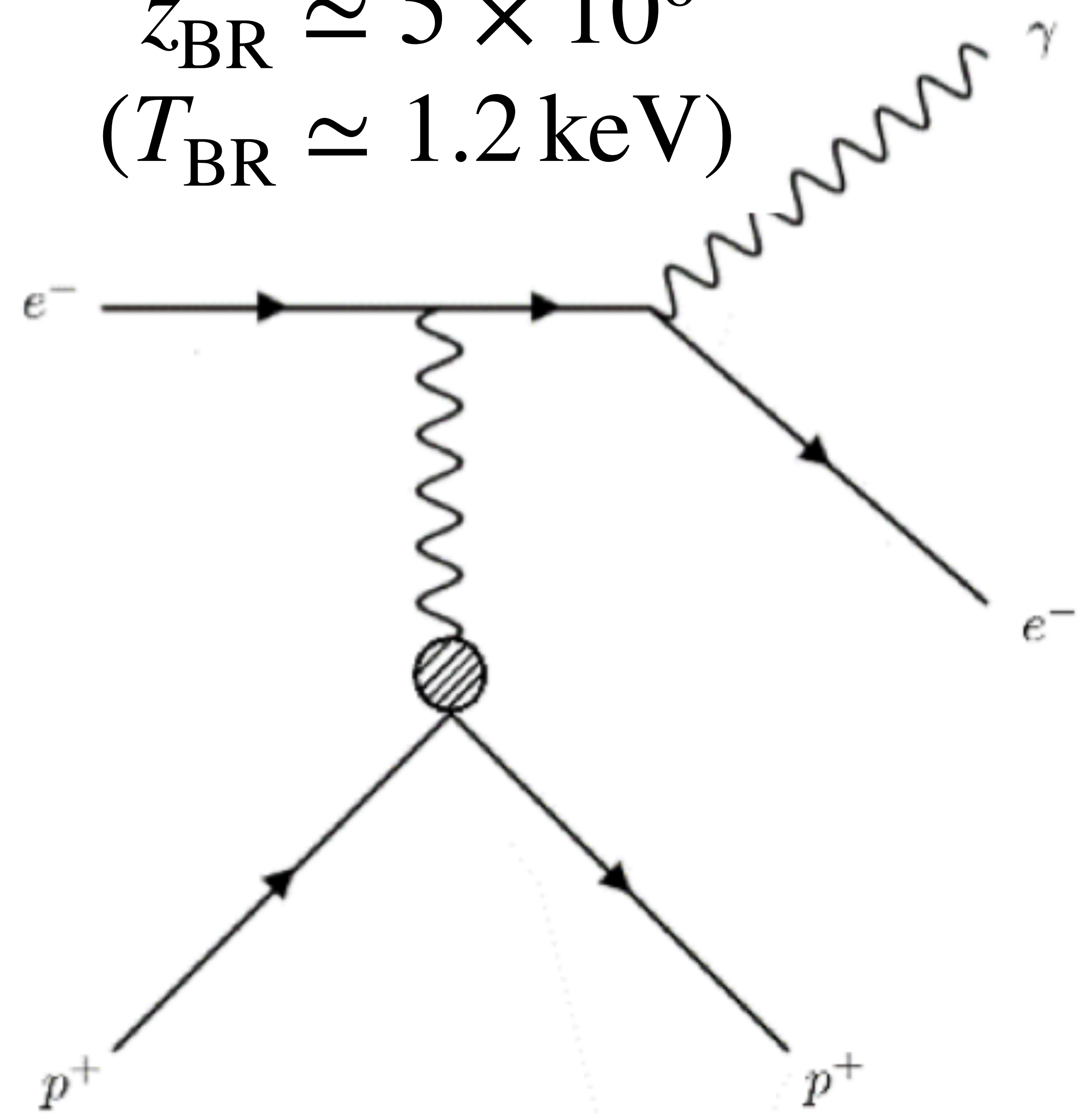
Double Compton
(number changing)

$z_{\rm DC} \simeq 2 \times 10^6$
$(T_{\rm DC} \simeq 470\,{\rm eV})$



Bremsstrahlung
(number changing)

$z_{\rm BR} \simeq 5 \times 10^6$
$(T_{\rm BR} \simeq 1.2\,{\rm keV})$



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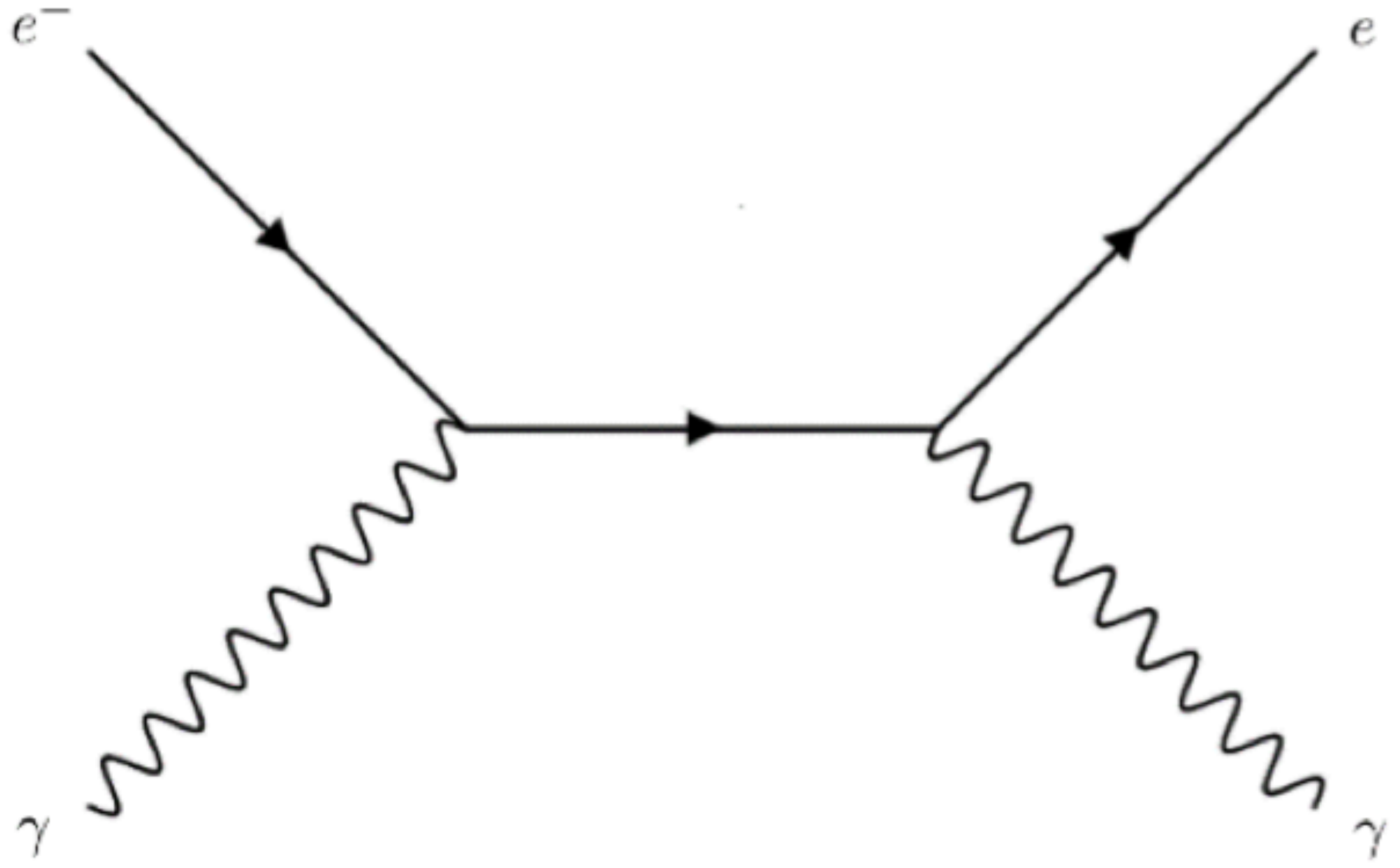
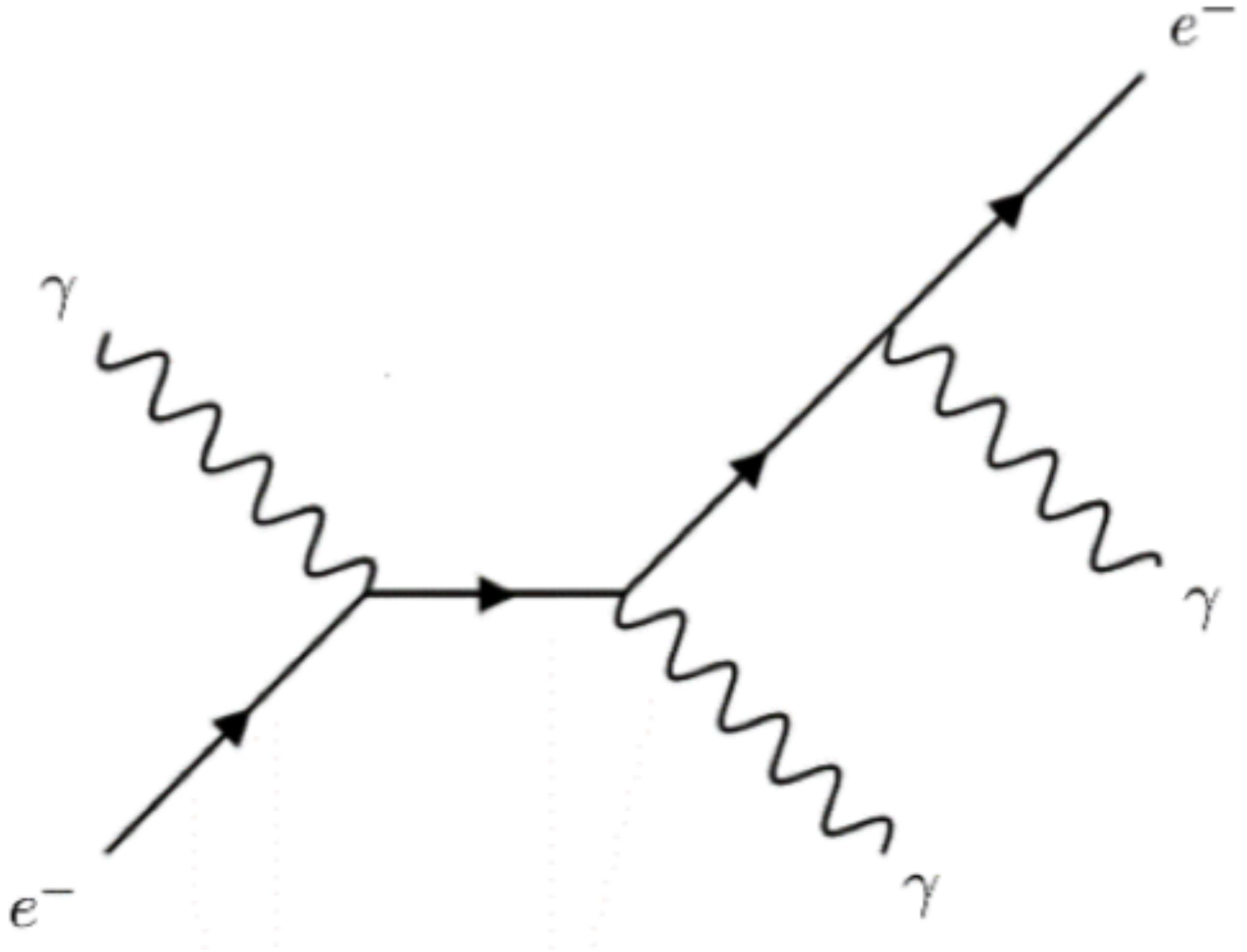
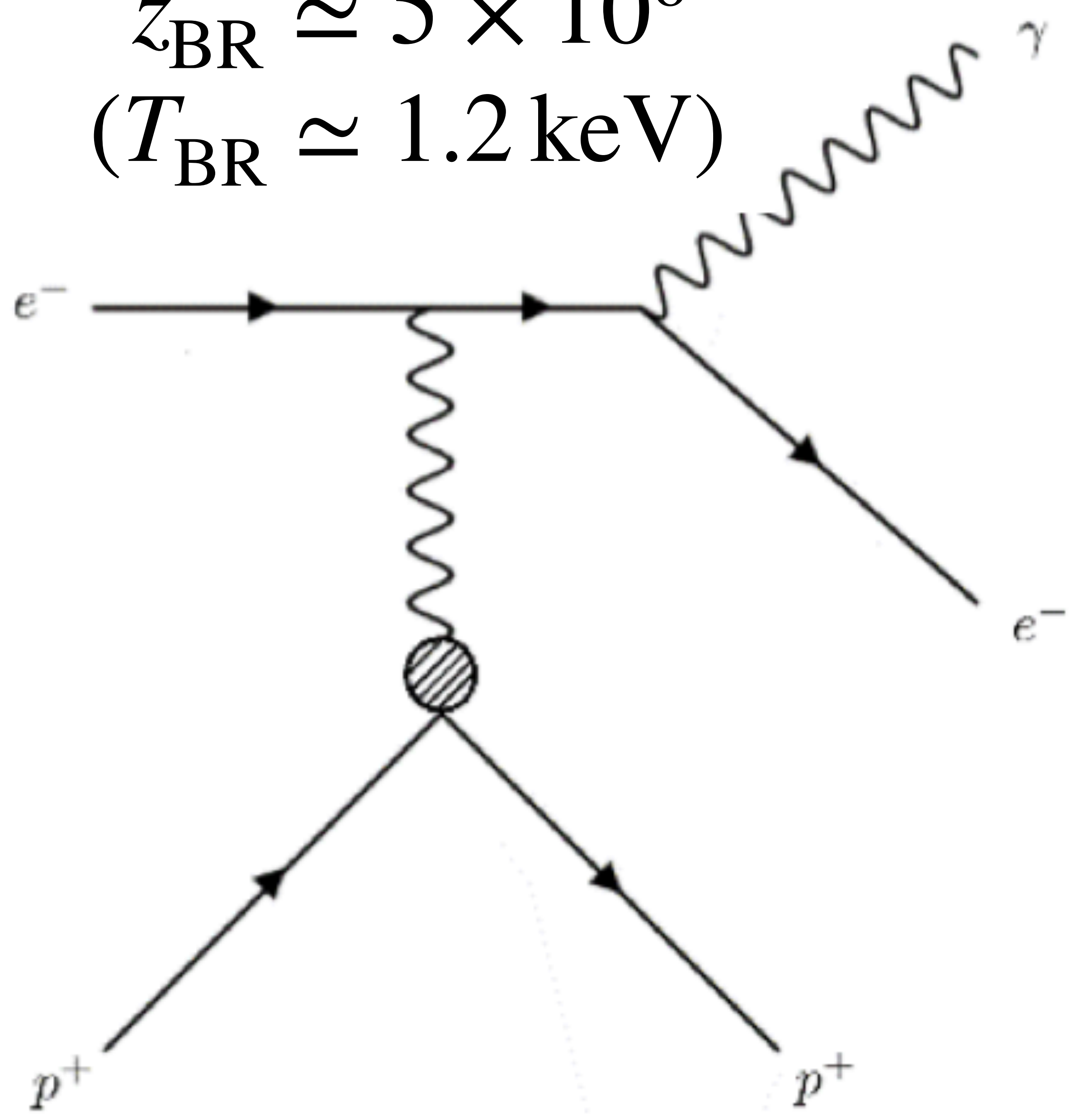
Compton	Double Compton	Bremsstrahlung
(energy changing)	(number changing)	(number changing)
$z_{\rm C} \simeq 5 \times 10^4$	$z_{\rm DC} \simeq 2 \times 10^6$	$z_{\rm BR} \simeq 5 \times 10^6$
$(T_{\rm C} \simeq 12\,{\rm eV})$	$(T_{\rm DC} \simeq 470\,{\rm eV})$	$(T_{\rm BR} \simeq 1.2\,{\rm keV})$







Thermalization 101

How does one thermalize a distorted spectrum?

- Energy redistribution
- Photon creation/destruction

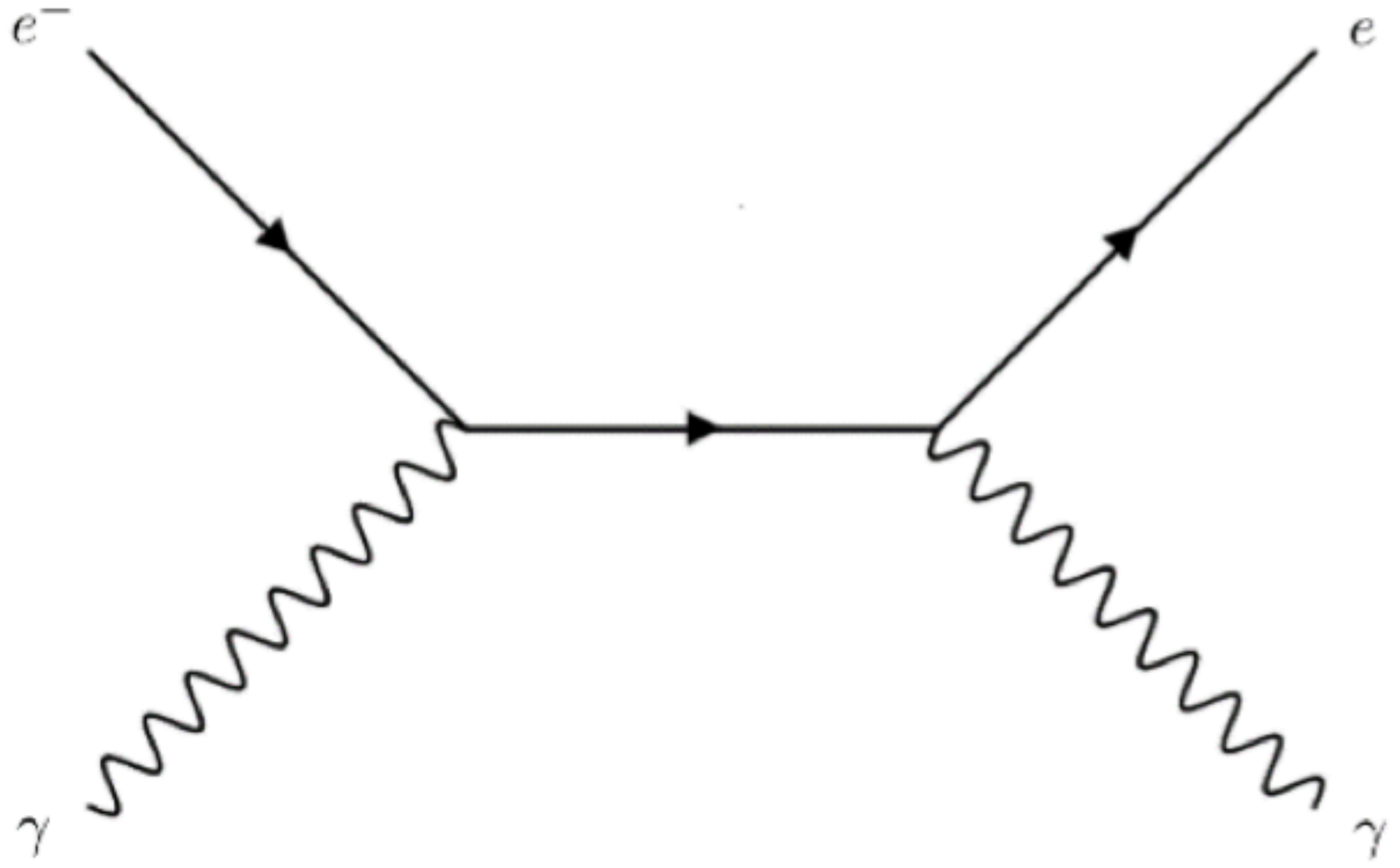
Freeze out redshift important! $\Gamma \simeq H \qquad \Gamma = n\sigma v$

μ-window: $5 \times 10^4 \lesssim z \lesssim 2 \times 10^6$

y-window: $z \lesssim 5 \times 10^4$

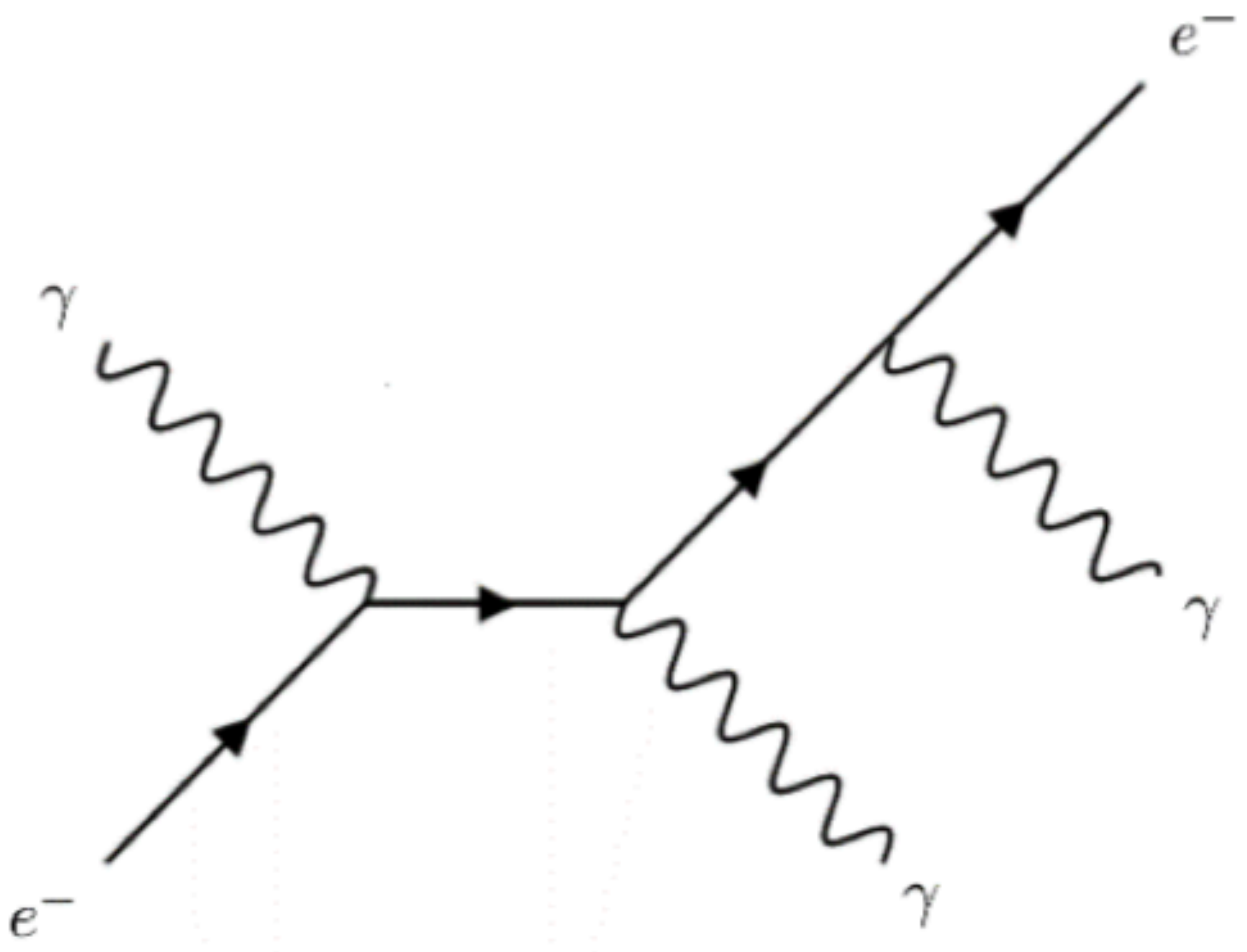
Compton
(energy changing)

$z_{\rm C} \simeq 5 \times 10^4$
$(T_{\rm C} \simeq 12\,{\rm eV})$



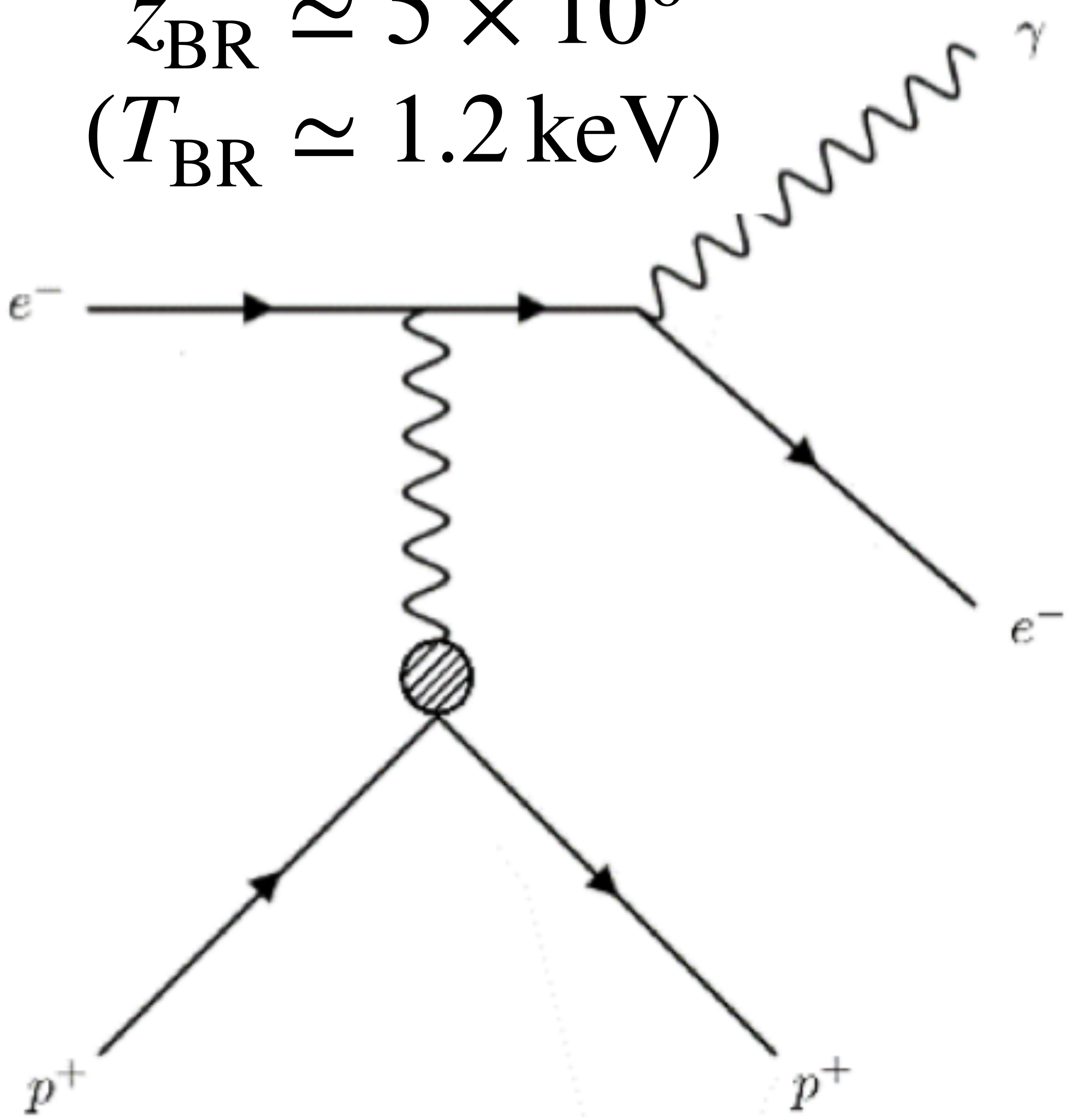
Double Compton
(number changing)

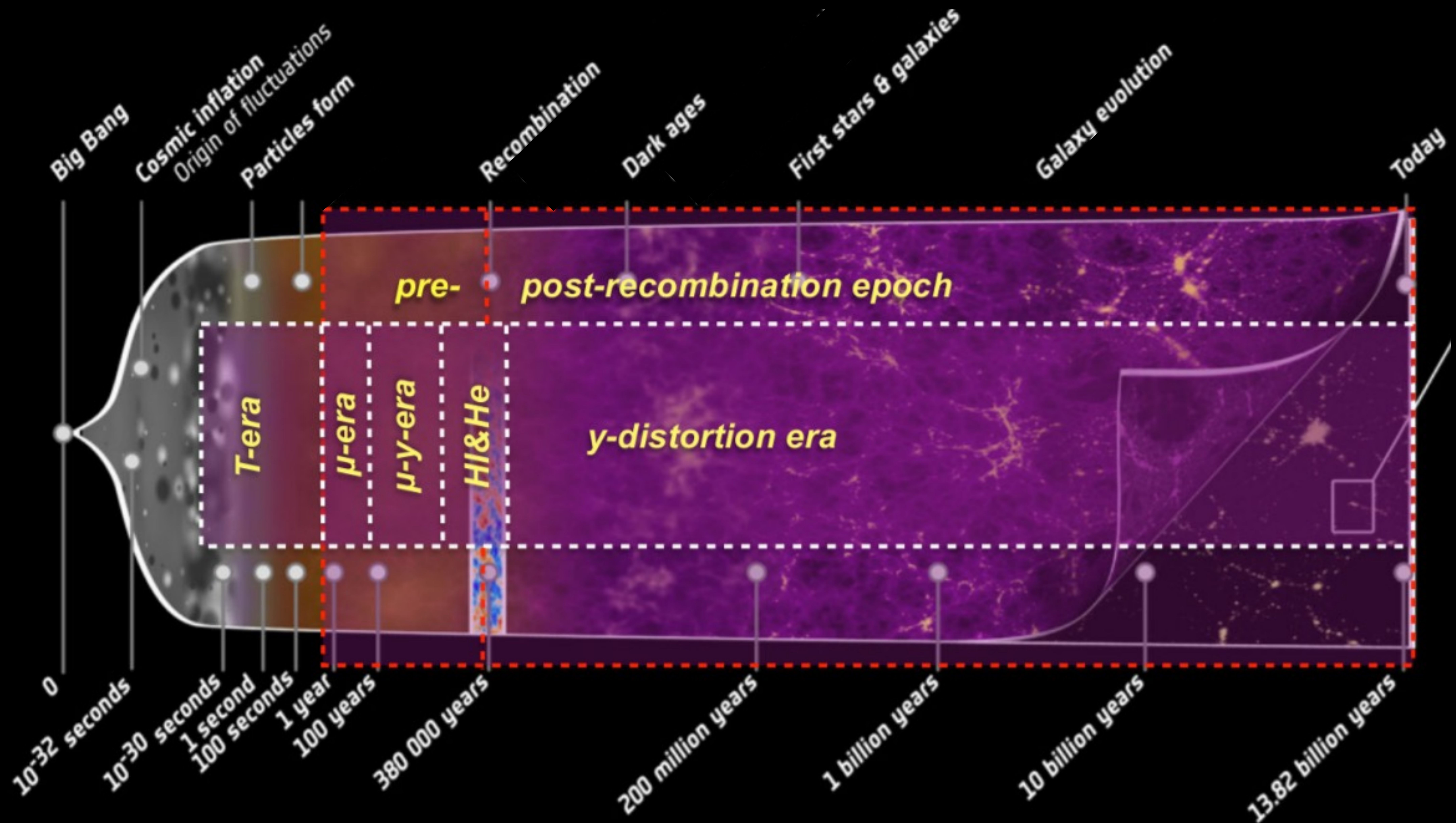
$z_{\rm DC} \simeq 2 \times 10^6$
$(T_{\rm DC} \simeq 470\,{\rm eV})$



Bremsstrahlung
(number changing)

$z_{\rm BR} \simeq 5 \times 10^6$
$(T_{\rm BR} \simeq 1.2\,{\rm keV})$





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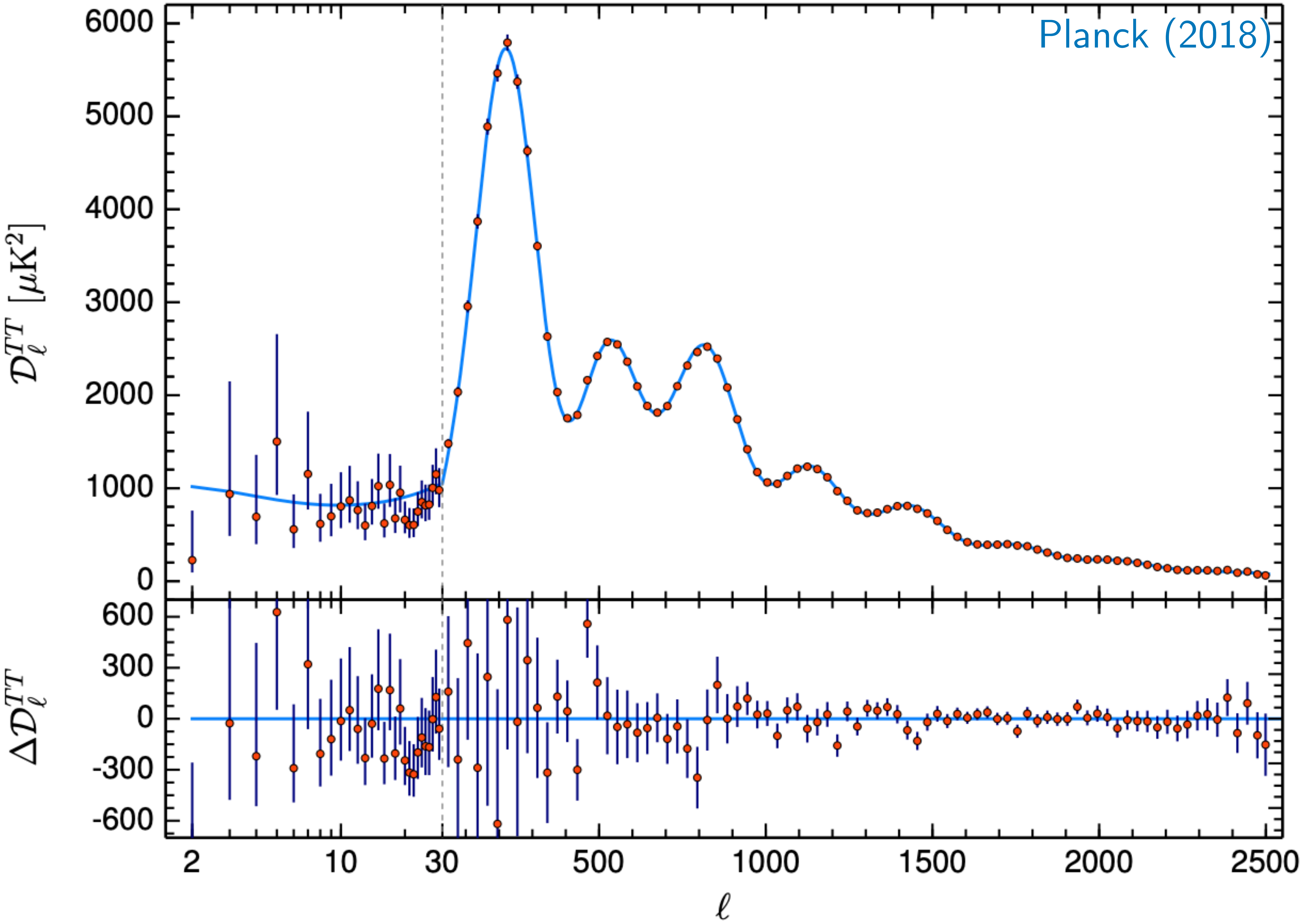
Silk damping: A standard model signal

Modes enter the horizon, begin to oscillate, and suffer diffusion (Silk) damping as electrons and photons of different temperatures mix.

Measured amplitude of small scale modes are greatly suppressed.

Where does that initial energy go? Into the plasma!



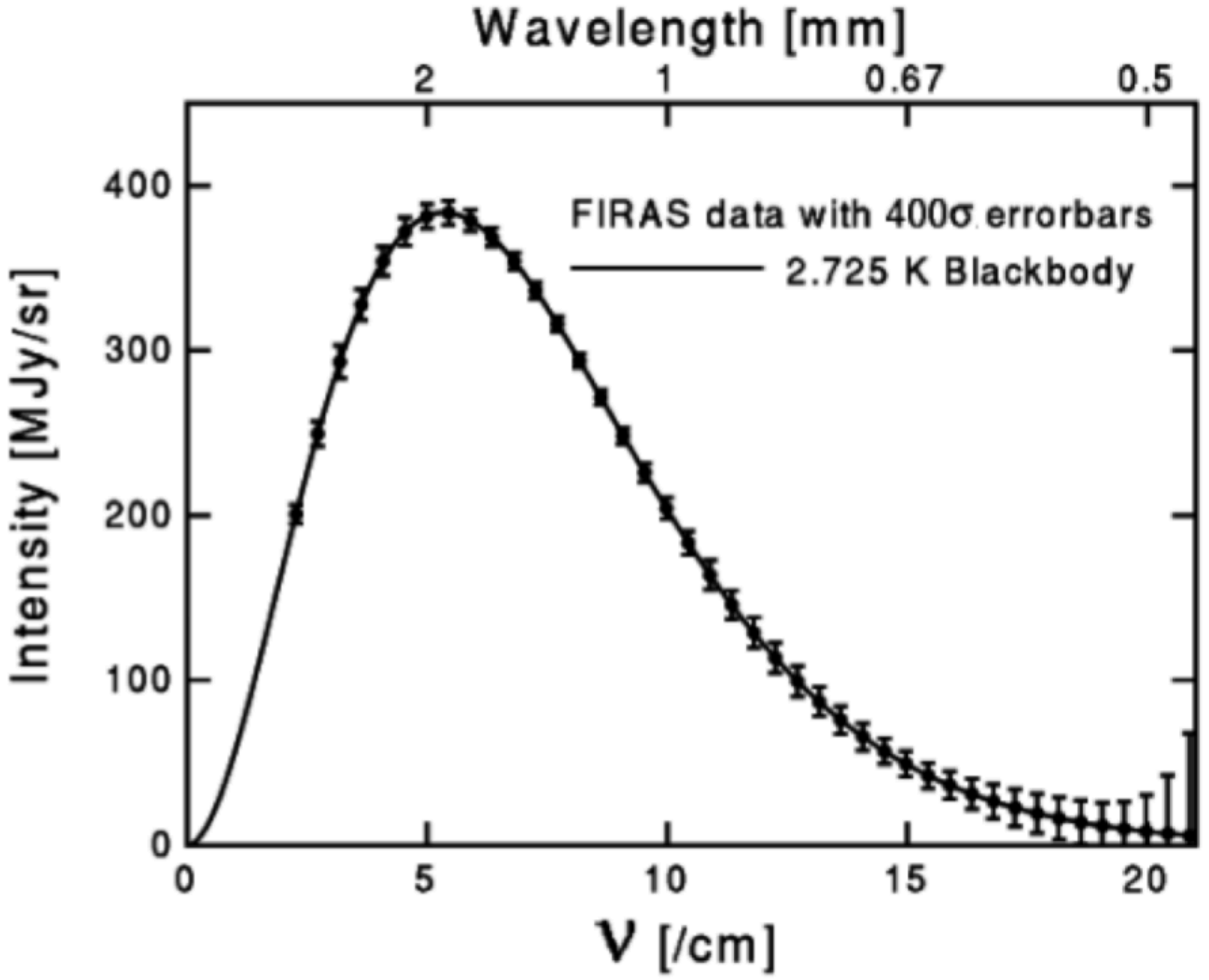
Mixing of blackbodies

Hu and Sugiyama (1995)
Chluba, Khatri, Sunyaev (2012)
BC et al. (2023b)

The sum of unequal temperature BBs will not produce a thermal spectrum.

$$T - \delta T \qquad\qquad T + \delta T \qquad\qquad \rho_{\rm av} \propto T^4[1 + 6(\delta T/T)^2]$$

$$\mu, y = 0 \qquad\qquad \mu, y = 0 \qquad\qquad \mu = 2.8\left(\frac{\delta T}{T}\right)^2, \quad y = \frac{1}{2}\left(\frac{\delta T}{T}\right)^2$$



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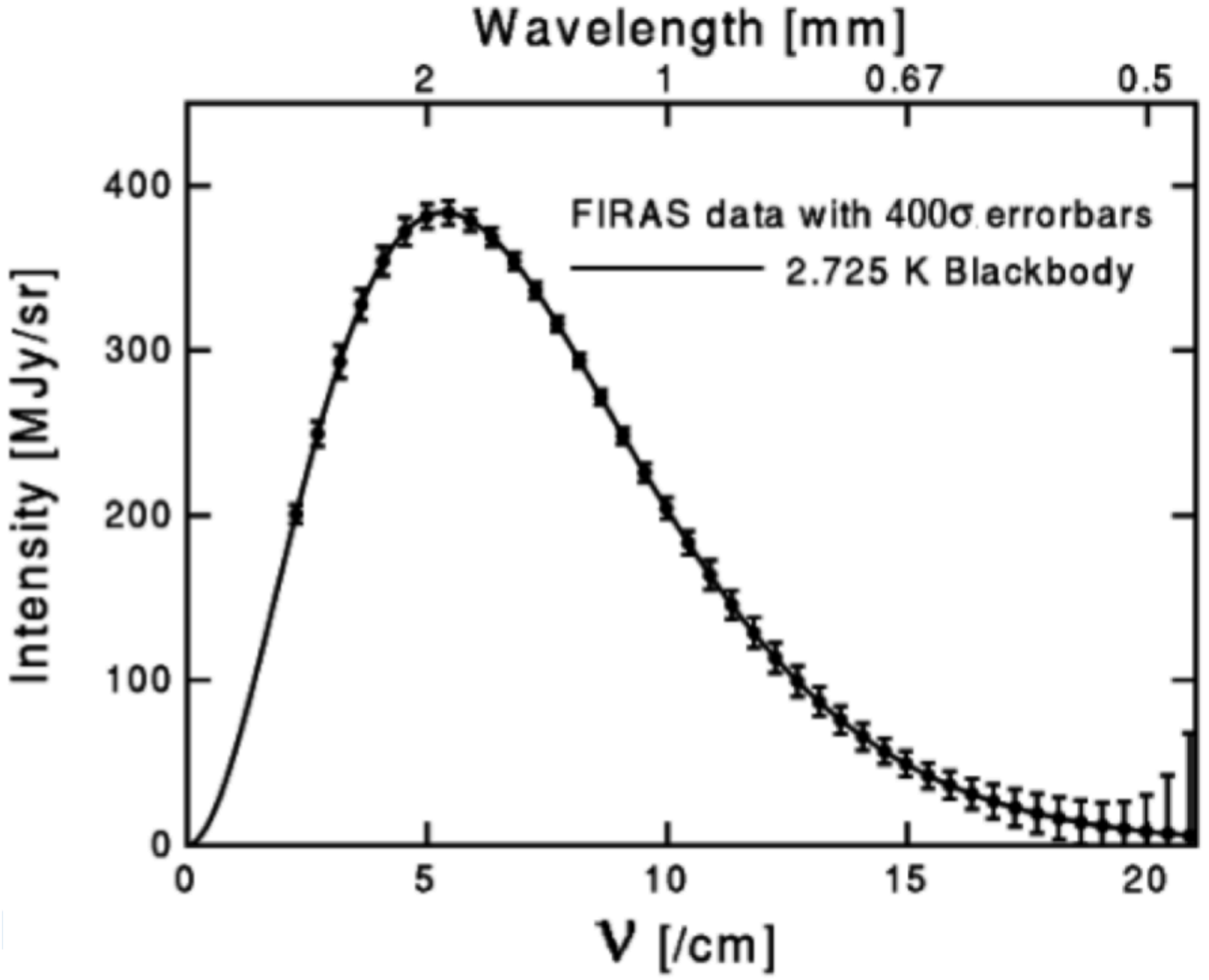

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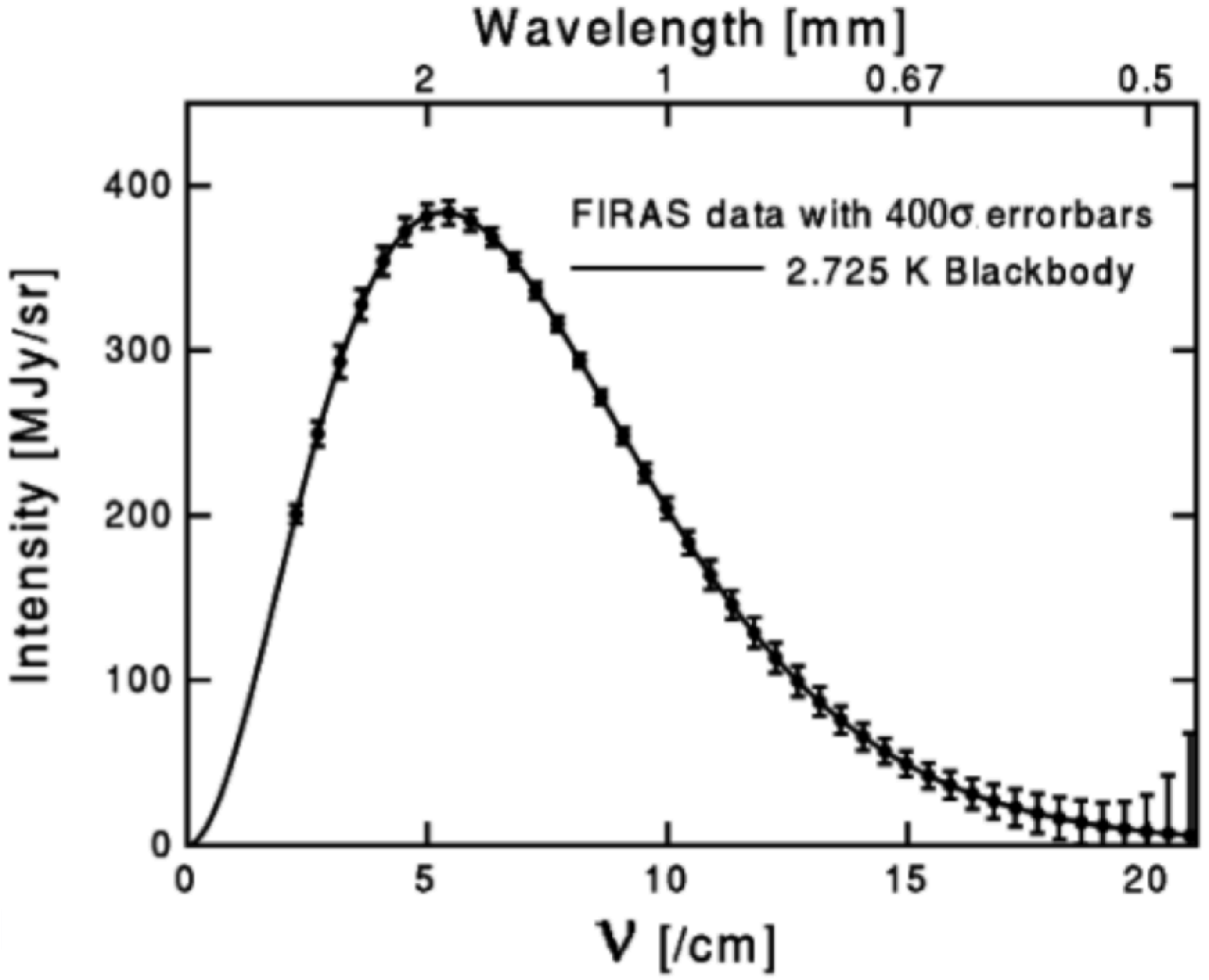

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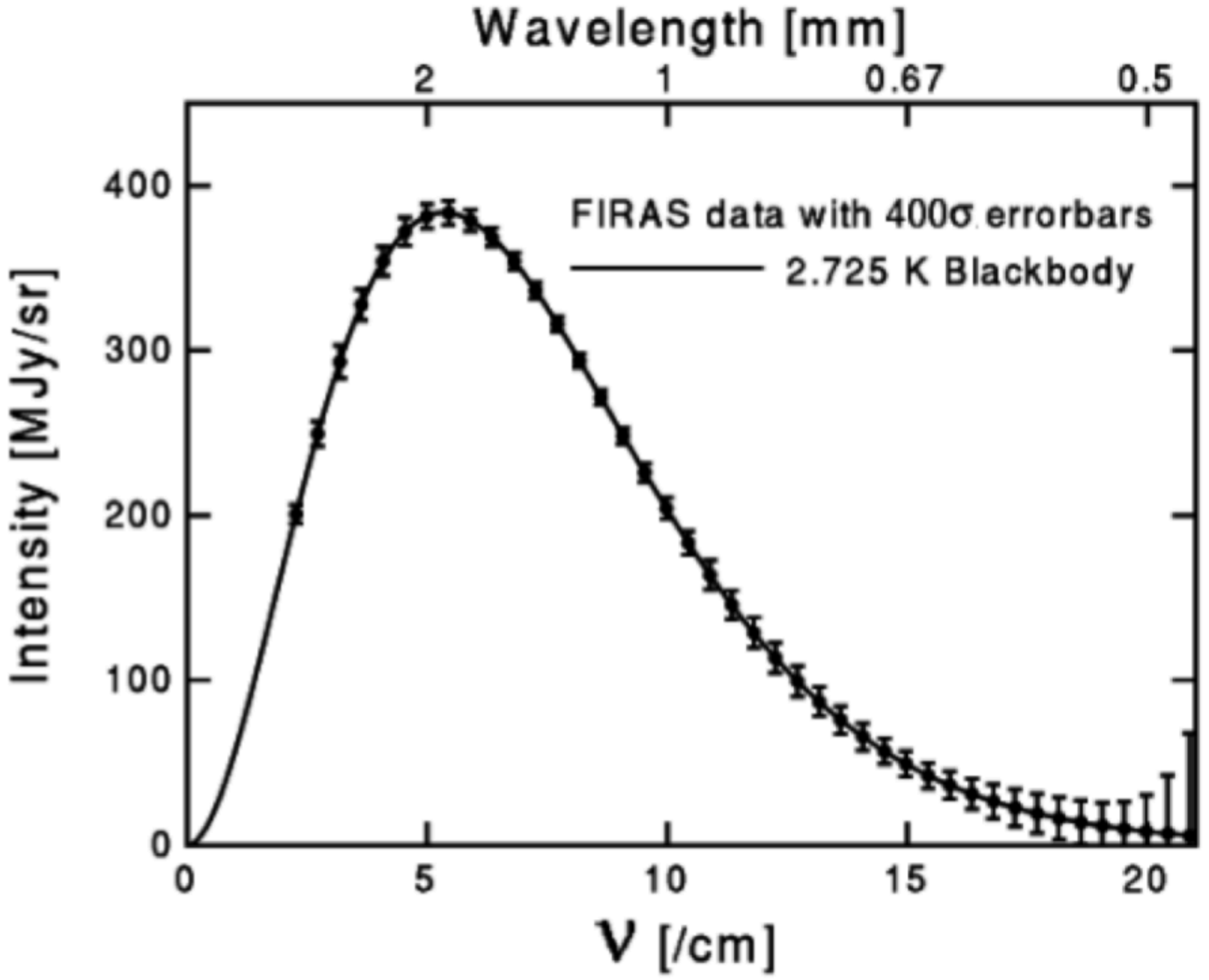

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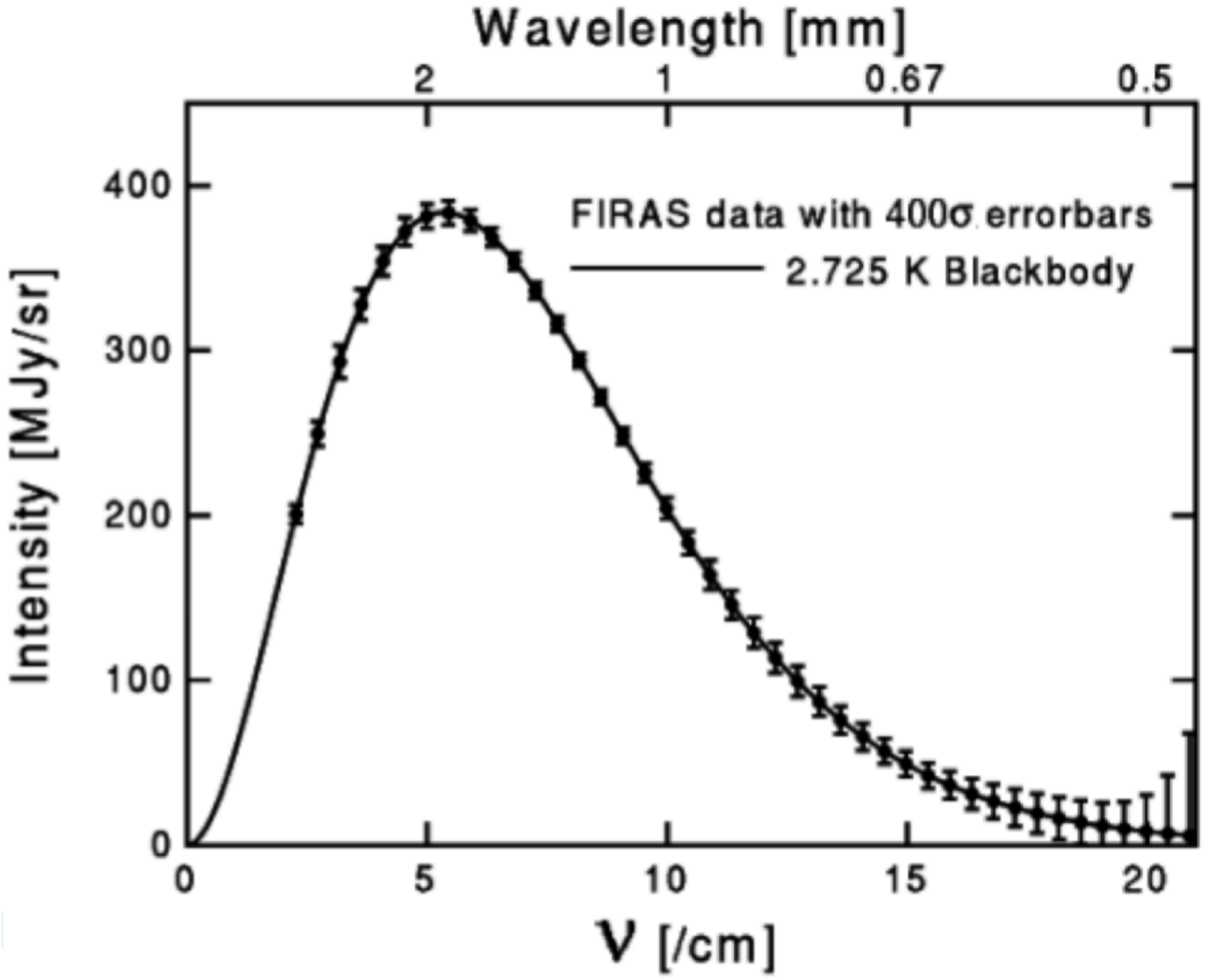

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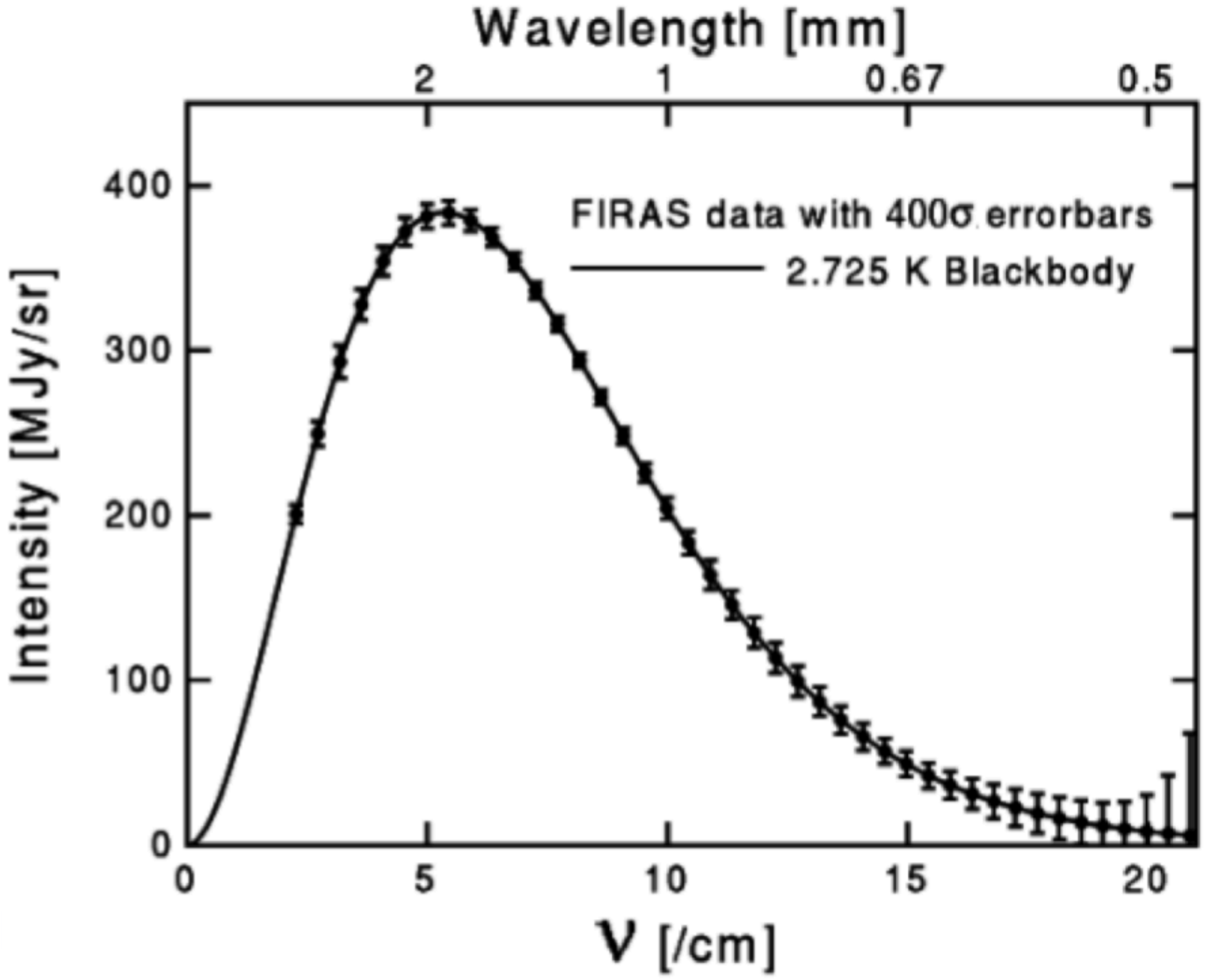
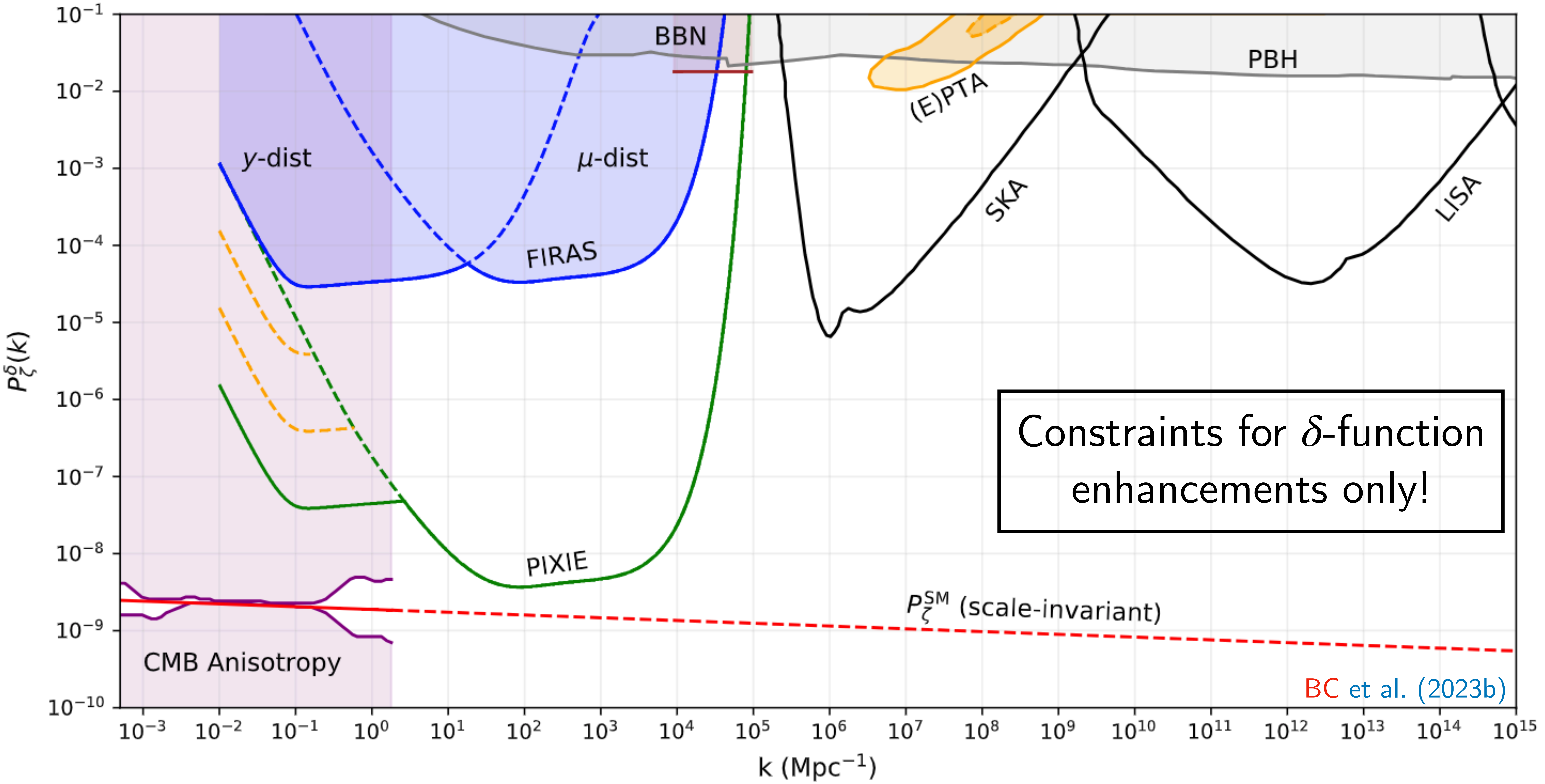


SDs sensitive to $A_{\rm s}$ at $50\,{\rm Mpc}^{-1} \lesssim k \lesssim 10^4\,{\rm Mpc}^{-1}$
Silk damping prediction: $\mu \simeq 2 \times 10^{-8}$

The scalar primordial power spectrum (PPS)

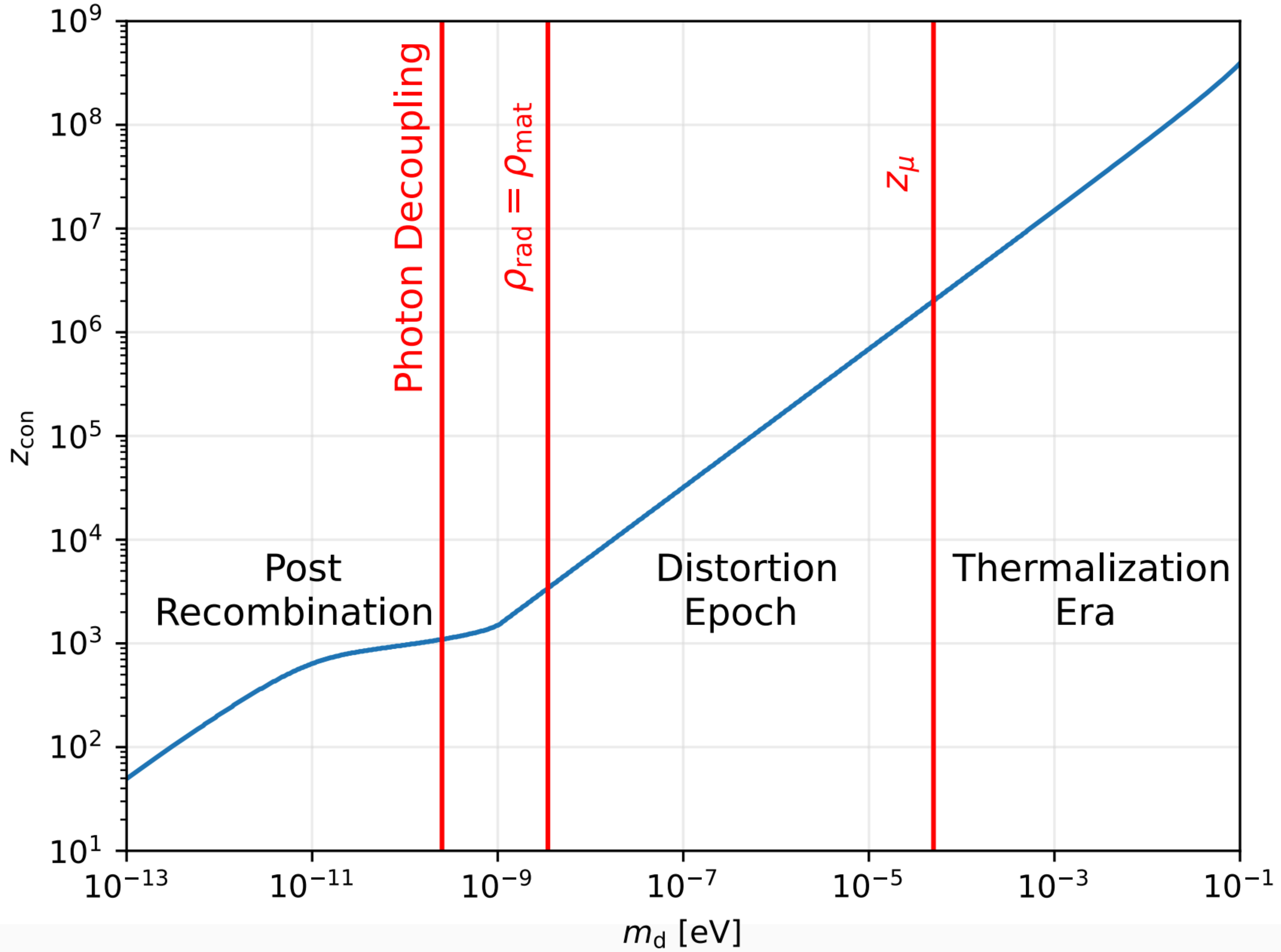


Dark photon spectral distortions

DM model with additional $U(1)$ gauge boson of mass $m_{\rm d}$, kinetically coupled to SM photon with interaction strength ϵ.

Two-level system: Resonant conversions can take place when $m_\gamma \simeq m_{\rm d}$.

Chluba, BC, Johnson (2024)



$$P_{\gamma \leftrightarrow \gamma_{\rm d}}(\gamma_{\rm con}, \omega) \simeq 1 - \exp\left(-\frac{\gamma_{\rm con}}{\omega}\right)$$

$$\gamma_{\rm con} = \gamma_{\rm con}(m_{\rm d}, \epsilon, z)$$

Conversion dominated by low frequencies!

[See also Arsenadze et al. (2024)]

Dark photon spectral distortions

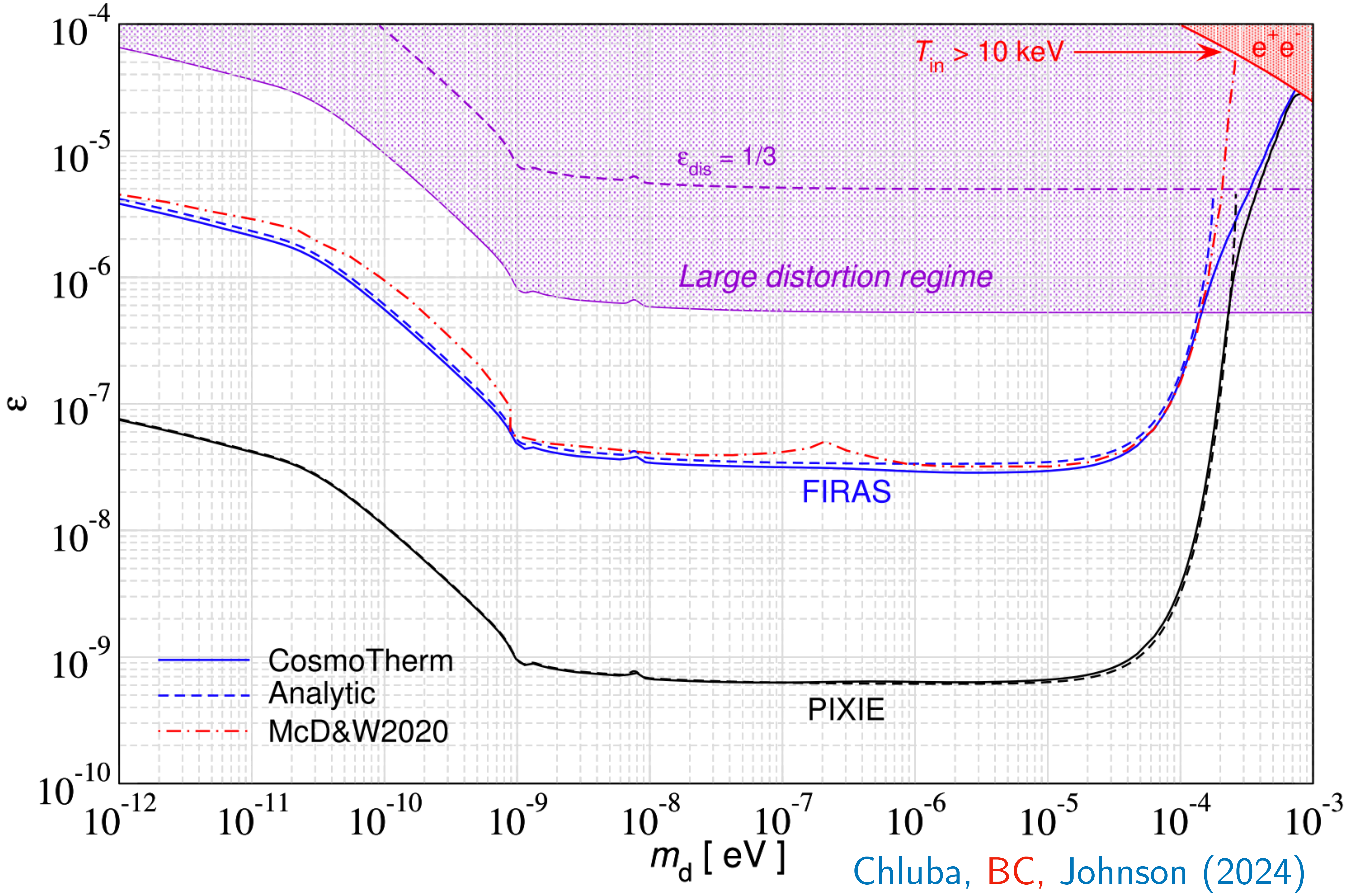
$(\rho_{\rm dp} \ll \rho_{\rm cdm})$

Pre-recombination, amplitude of distortion can be estimated with Green's function approach:

$$\mu \simeq 1.401 \left[\frac{\Delta\rho}{\rho} - \frac{4}{3}\frac{\Delta N}{N}\right]_{\rm dist}$$

Post-recombination, utilize full residuals from COBE/FIRAS.

Inclusion of entropy term increasing constraining power by $\simeq 1.5$ and flips sign of distortion!



Chluba, BC, Johnson (2024)

A powerful probe of exotic physics

Decaying/annihilating dark matter

Primordial magnetic fields

SM signals

Axion-photon couplings

Reionization probe

Phase transition dynamics

Silk damping

Topological defects

Recombination lines

Primordial GW backgrounds

Primordial black holes

Enhancement of small-scale power spectrum

BSM constraint space

+100s additional models

Experimental prospects

Ground-based:

- TMS - Targeting 10-20 GHz region, ARCADE-2 coverage.
- COSMO - Measuring from Antarctica, target is global SZ signal.

Balloon-based:

- BISOU - Balloon targeting global SZ distortion $(y \simeq 10^{-6})$.
  Recently entered phase A, measurement late 2020s (!!!)

Space-based:

- COBE/FIRAS - Early 90s mission, measured $\Delta I_\nu / I_\nu \lesssim 10^{-5}$.
- PIXIE - Proposed and rejected multiple times, target $\Delta I_\nu / I_\nu \lesssim 10^{-8}$.
- ESA Voyage2050 - Stay tuned...

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Conclusions

Cosmology offers a myriad of unique ways to probe nature on the largest (and smallest!) scales.

Many of the models discussed offer signatures in multiple different probes, which is great for this new age of multi-messenger astrophysics and cosmology.

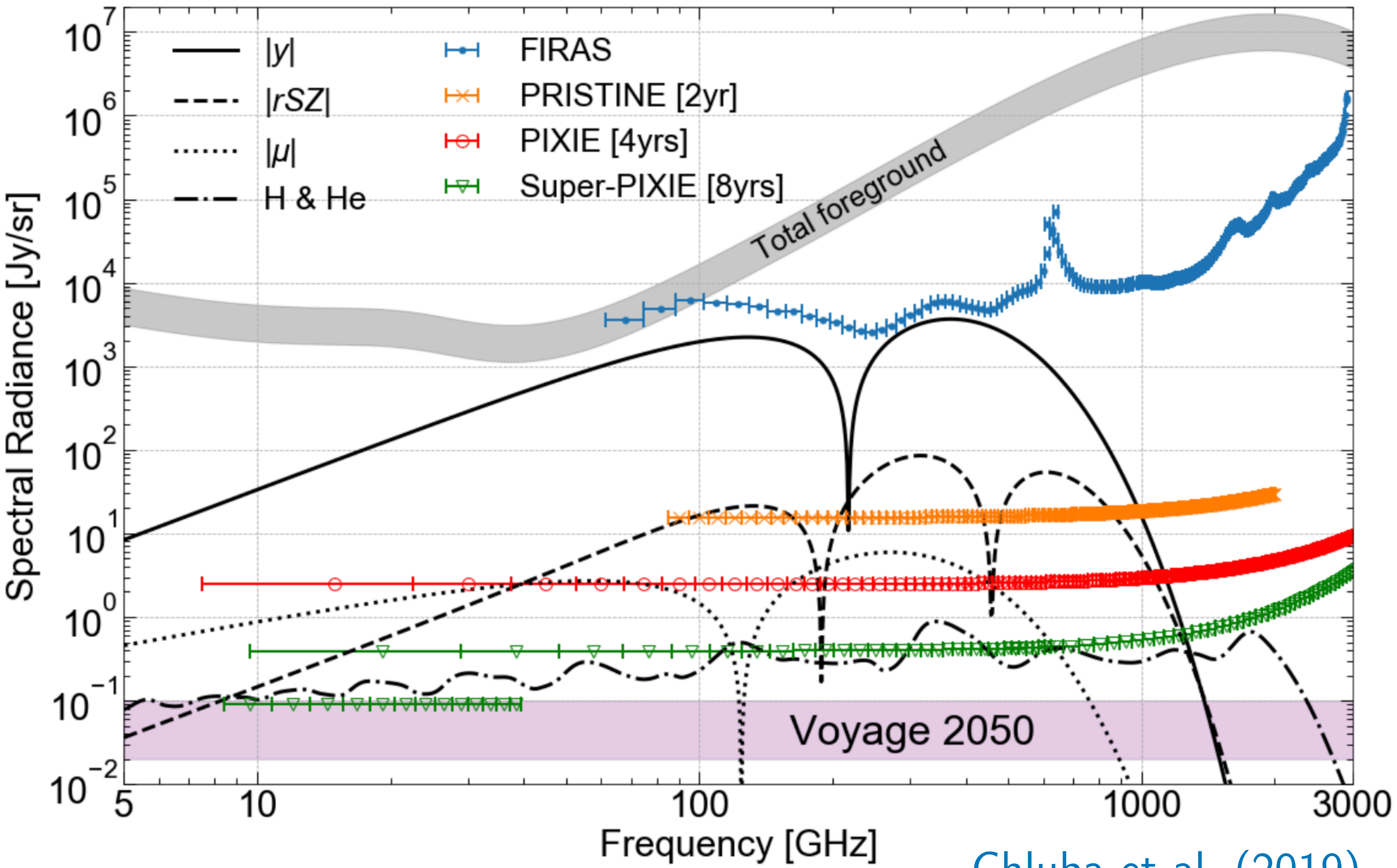
Lots of work to do on observational, numerical, and theoretical fronts if we are to take advantage of all new data coming from LSS, 21cm, gravitational waves, and soon the CMB spectrum.

Thank you!

Backup

What distortions do we expect?

- Global SZ distortion
$$y \simeq 10^{-6}$$
- Relativistic SZ and reionization heating
$$y \simeq 10^{-8} - 10^{-7}$$
- Dissipation of small scale modes (Silk damping)
$$|\mu| \simeq 2 \times 10^{-8}$$
- Recombination lines
$$\left|\frac{\Delta I}{I}\right| \simeq 10^{-9}$$



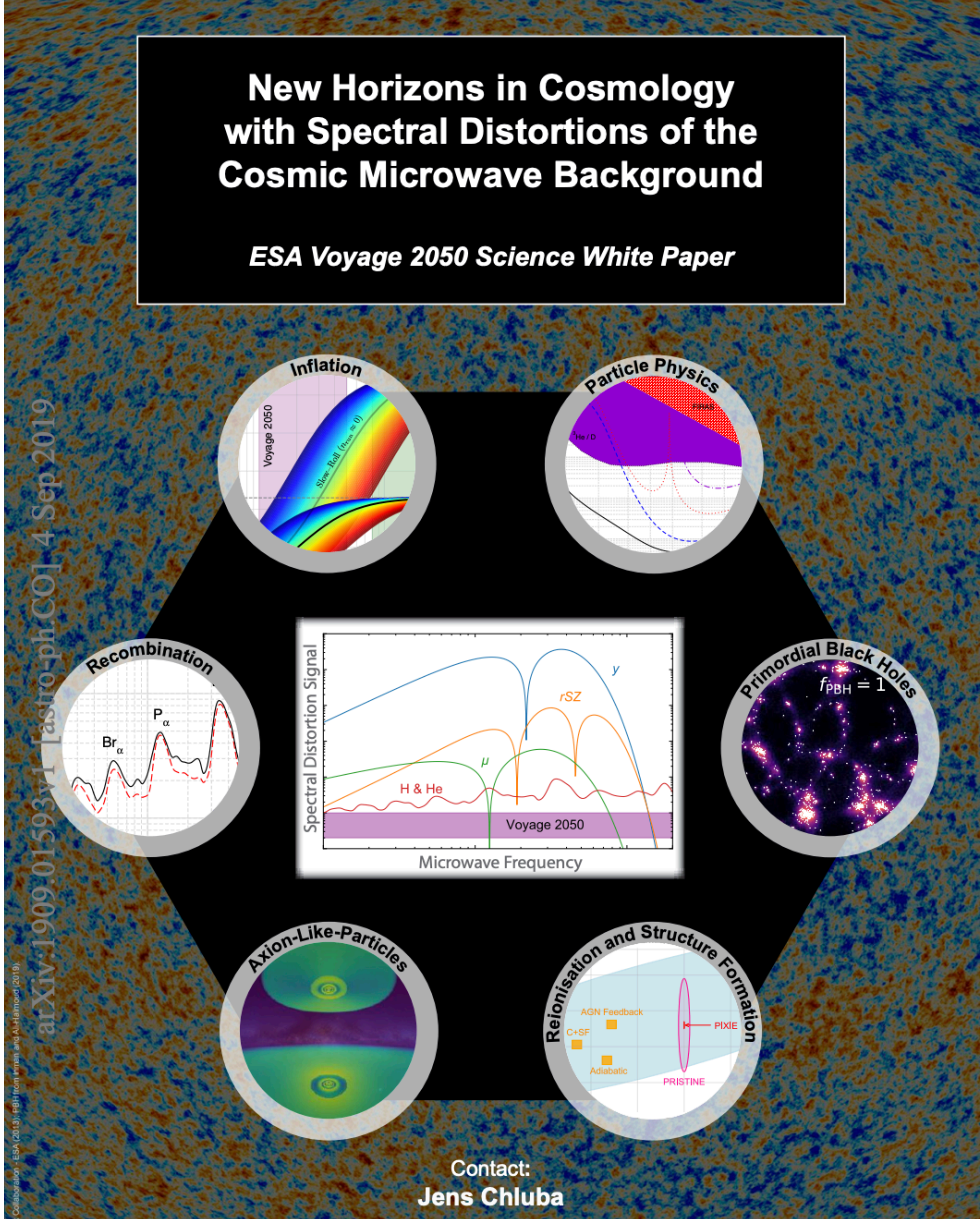
Chluba et al. (2019)

The Voyage2050 program

- Spectral distortions have been recognized by ESA as a high priority target for one of the three Voyage2050 L-class missions.

- Preparation has started for eventual call for proposals.

- Opportunities available for those interested in foreground science, synergies, experimental design, distortion theory.



Distortion calculations: analytics

Chluba (2012. 2015)

Green's function method allows for simple estimates when non-thermal source terms can be computed (eg. $\mathrm{d}Q/\mathrm{d}z,\ \mathrm{d}N/\mathrm{d}z$).

μ-era:

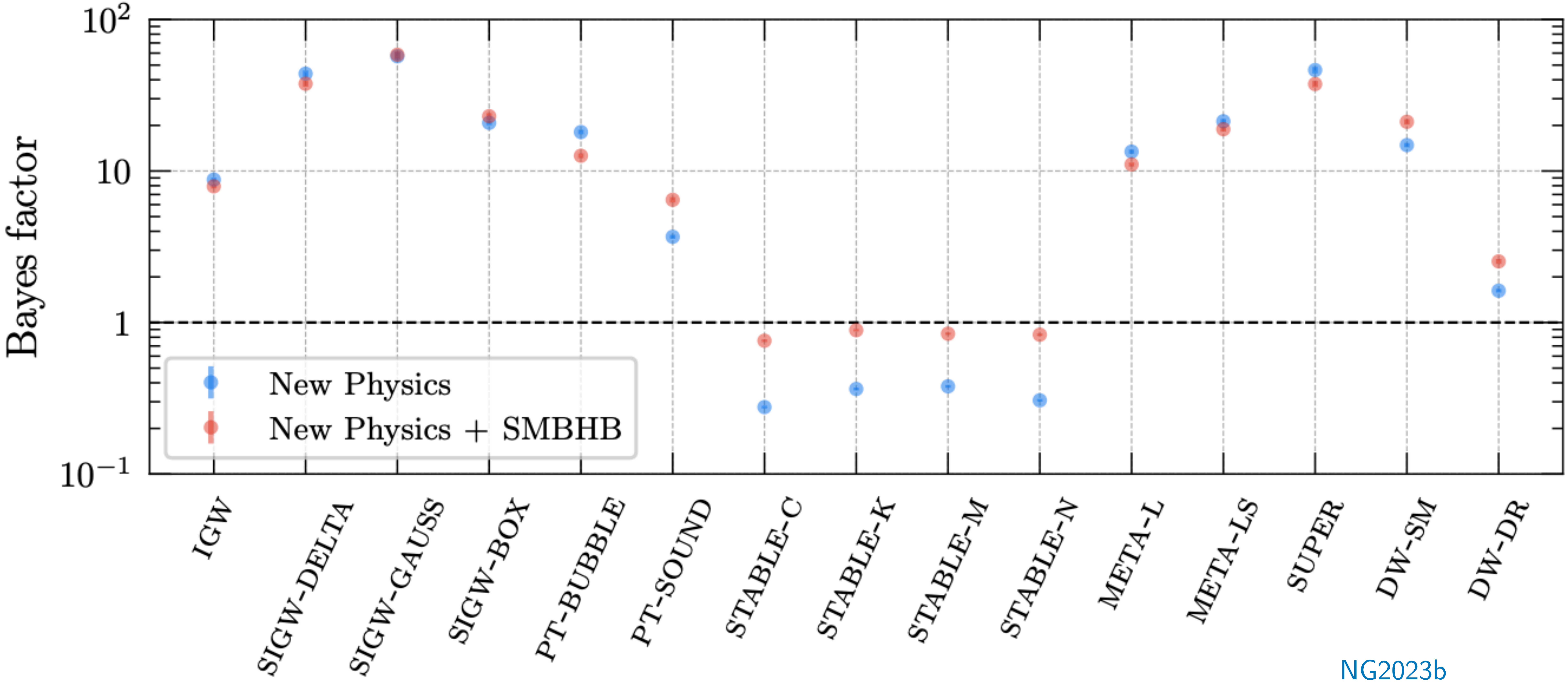
$$\mu \simeq 1.401 \int_{z_{\mu/y}}^{\infty} \mathrm{d}z \left(\frac{1}{\rho_\gamma} \frac{\mathrm{d}Q}{\mathrm{d}z} - \frac{4}{3} \frac{1}{N_\gamma} \frac{\mathrm{d}N}{\mathrm{d}z} \right) \mathrm{e}^{-\left(\frac{z}{2\times 10^6}\right)^{5/2}} \qquad z_{\mu/y} \simeq 5 \times 10^4$$

y-era:

$$y \simeq \frac{1}{4} \int_{z_{\mathrm{rec}}}^{z_{\mu/y}} \mathrm{d}z \, \frac{1}{\rho_\gamma} \frac{\mathrm{d}Q}{\mathrm{d}z} \qquad (\mathrm{d}N/\mathrm{d}z \ll 1)$$

Formalism breaks down for large entropy injection in y-era, and if dominant non-thermal injection happens near $z_{\mu/y}$.

NANOGrav analysis



NG2023b

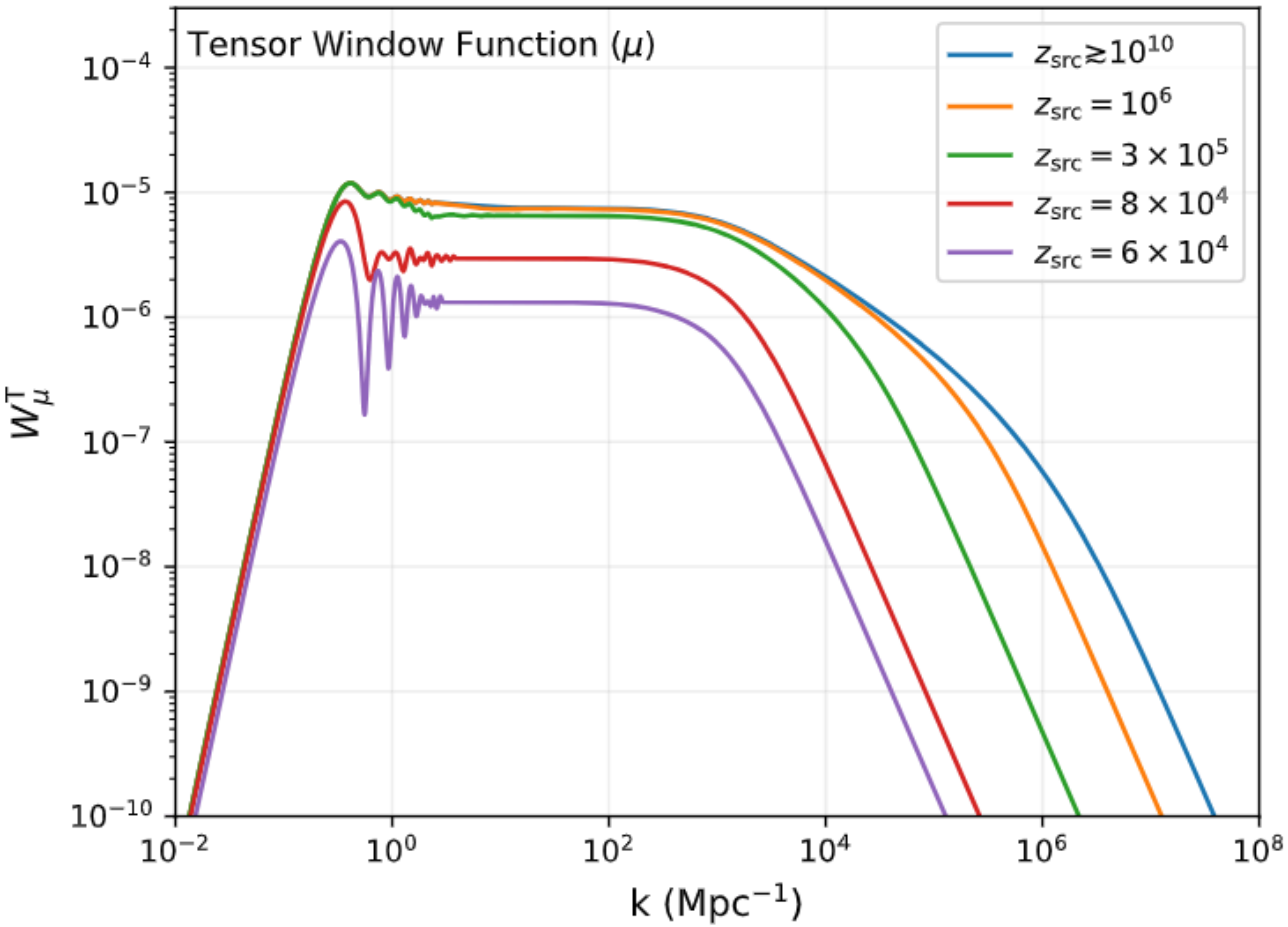
Direct tensor dissipation

Kite et al. (2021)
BC et al. (2023a)

Tensors sourced at arbitrarily high redshifts ($z_{\rm src} \gtrsim 10^8$):

$$\langle \mu_{\rm GW} \rangle = \int_0^\infty \mathrm{d}k \frac{k^2}{2\pi^2} P_{\rm T}(k) W_\mu^T$$

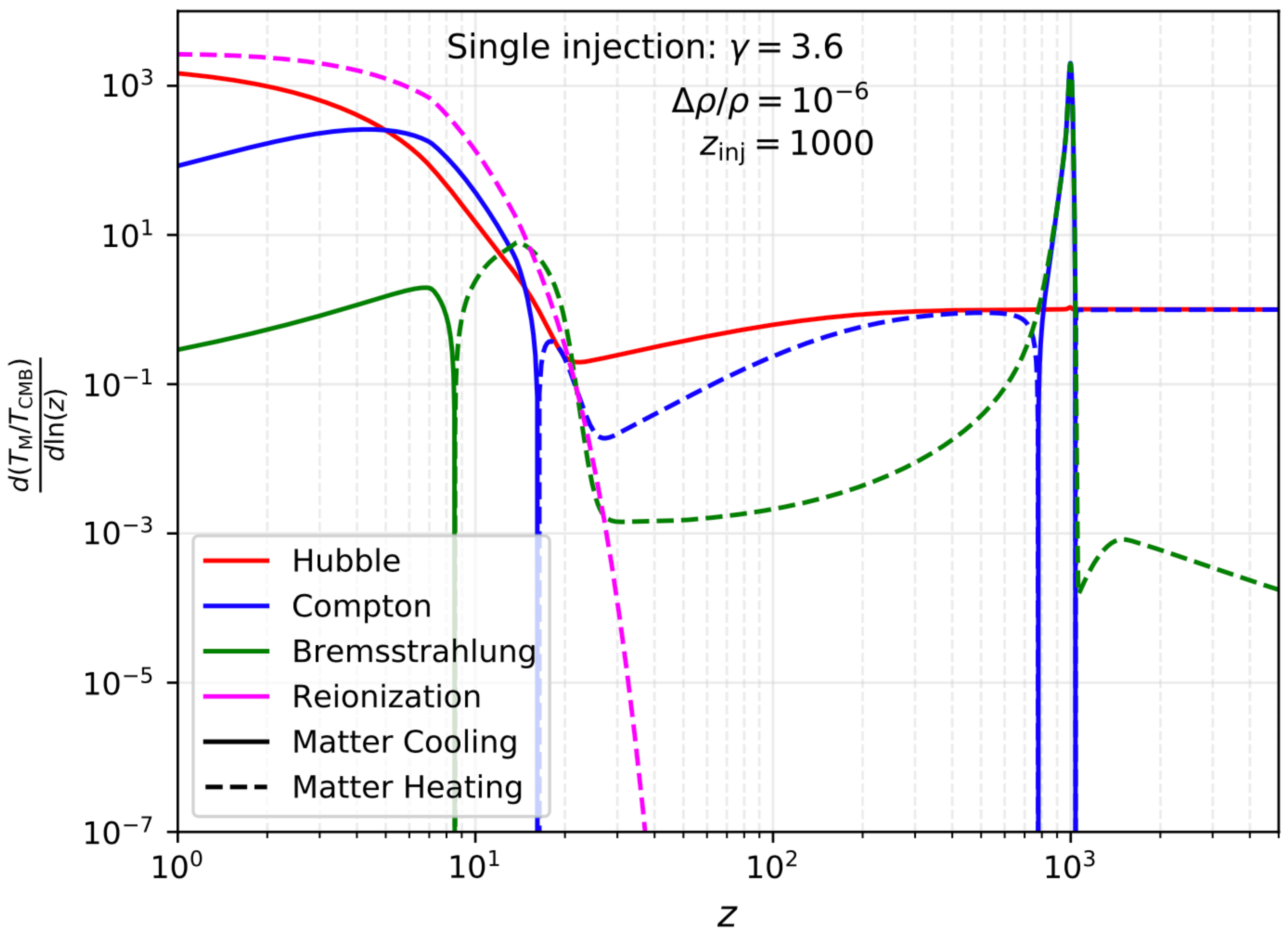
If generated closer to the distortion window, generalization using "Window Primitive" ($\mathscr{W}_\mu^{\rm T}$)

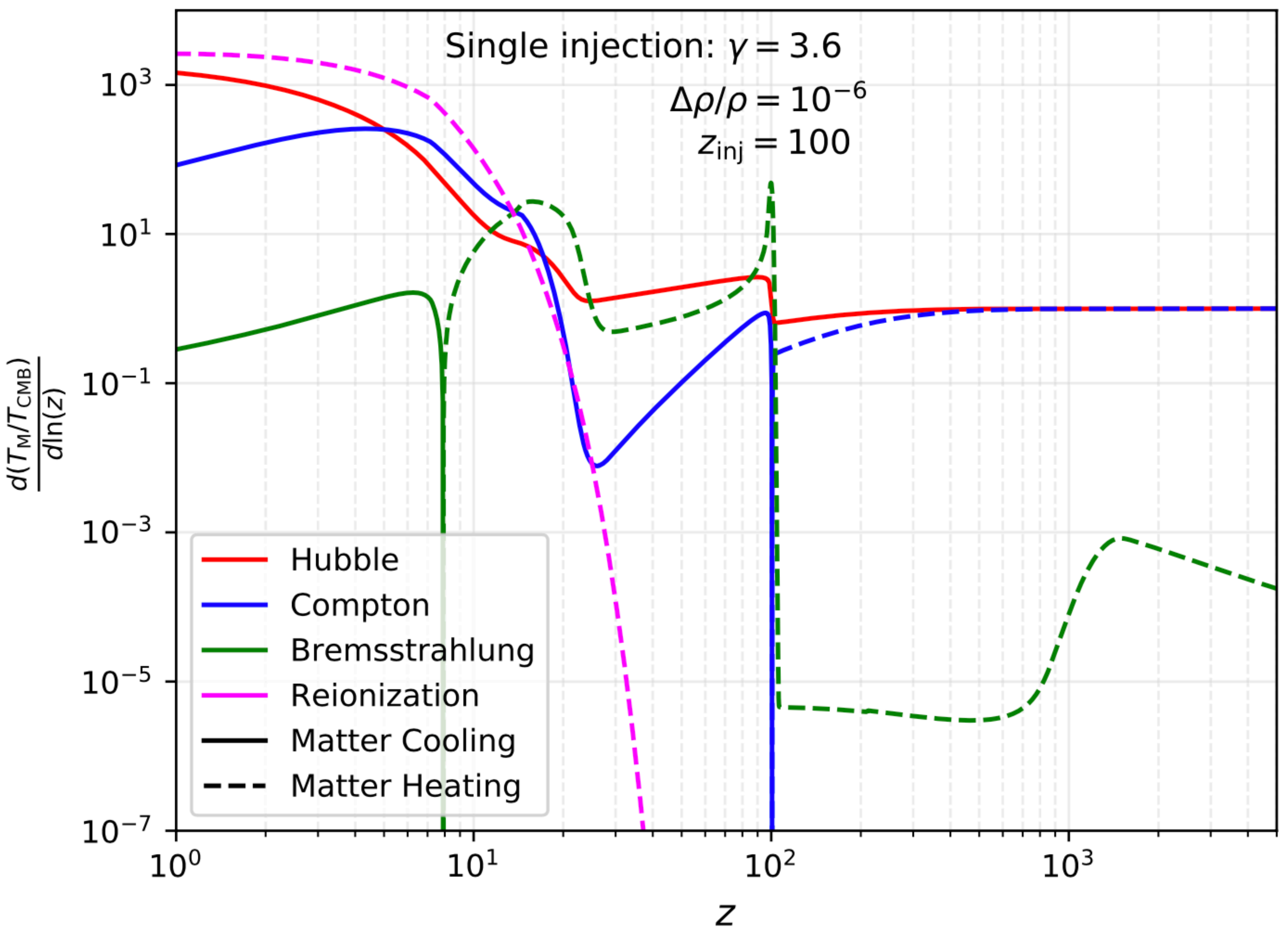


$$W_\mu^{\rm T} = \int_0^\infty \mathrm{d}z\, \mathscr{W}_\mu^{\rm T}$$

$$\langle \mu_{\rm GW} \rangle \Big|_{z=0} = \int_0^\infty \mathrm{d}k \frac{k^2}{2\pi^2} \int_0^\infty \mathrm{d}z\, P_{\rm T}(k, z) \mathscr{W}_\mu^{\rm T}(k, z)$$

High-z Synchrotron Injections





$$\frac{\mathrm{d}T_{\rm M}}{\mathrm{d}z} = \frac{2T_{\rm M}}{1+z} + \frac{X_{\rm e}}{1+X_{\rm e}+f_{\rm He}} \frac{8\sigma_{\rm T}\rho_{\rm CMB}}{3m_{\rm e}c} \frac{T_{\rm M}-T_{\rm CMB}}{H(z)(1+z)} + \frac{\mathrm{d}T_{\rm ff}}{\mathrm{d}z}$$

Energy injection rate

Physical picture: A given k-mode enters the horizon, oscillates, and dumps energy into the background when crossing the damping scale ($k_\mathrm{D}[z]$)

Hu and Sugiyama (1995)
Chluba, Khatri, Sunyaev (2012)
BC et al. (2023a)

$$\frac{\mathrm{d}(Q_\mathrm{ac}/\rho_\gamma)}{\mathrm{d}z} \approx \frac{A^2}{Ha}\frac{32c^2}{45\dot{\tau}(z)}\int \mathrm{d}k \frac{k^4}{2\pi^2}P_\zeta(k)\mathrm{e}^{-k^2/k_\mathrm{D}^2(z)}$$

Chluba and Grin (2013)

- $A \approx 0.9$ for adiabatic fluctuations, suppressed for isocurvature.
- $\dot{\tau} = \sigma_\mathrm{T} N_\mathrm{e} c$ is rate of Thomson scattering.
- $\partial_t k_\mathrm{D}^{-2} \approx 8c^2/45a^2\dot{\tau}$ determines damping scale. Kosowsky and Turner (1995)

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SM prediction: $\mu \simeq 2\times 10^{-8}$