Constraints on Photon Injection Processes with CMB Spectral Distortions

Boris Bolliet
Columbia University

In collaboration with
Jens Chluba and **Richard Battye**
The University of Manchester

3rd Global 21-cm Workshop, Cambridge (online), 19th-22nd October 2020

CMB Spectral Distortions

- CMB origin: photons and electrons in thermal equilibrium —> Black Body spectrum
- If photons and electrons not in thermal equilibrium —> Spectral Distortions = departure from the Black Body law
- Examples:
  - ✤ Silk damping μ-distortion

$$\mu \approx 1.4 \int_0^{t(z_y)} dt \frac{Q(t)}{\rho_\gamma} \exp[-(z/z_\mu)^{5/2}]$$

(see, e.g., Chluba, Khatri & Sunyaev 2012)

  - ✤ Galaxy clusters y-distortion

$$y \approx \int \frac{k[T_e - T_\gamma]}{m_e c^2} N_e \sigma_T c \, dt$$

(Sunyaev and Zeldovich 70)

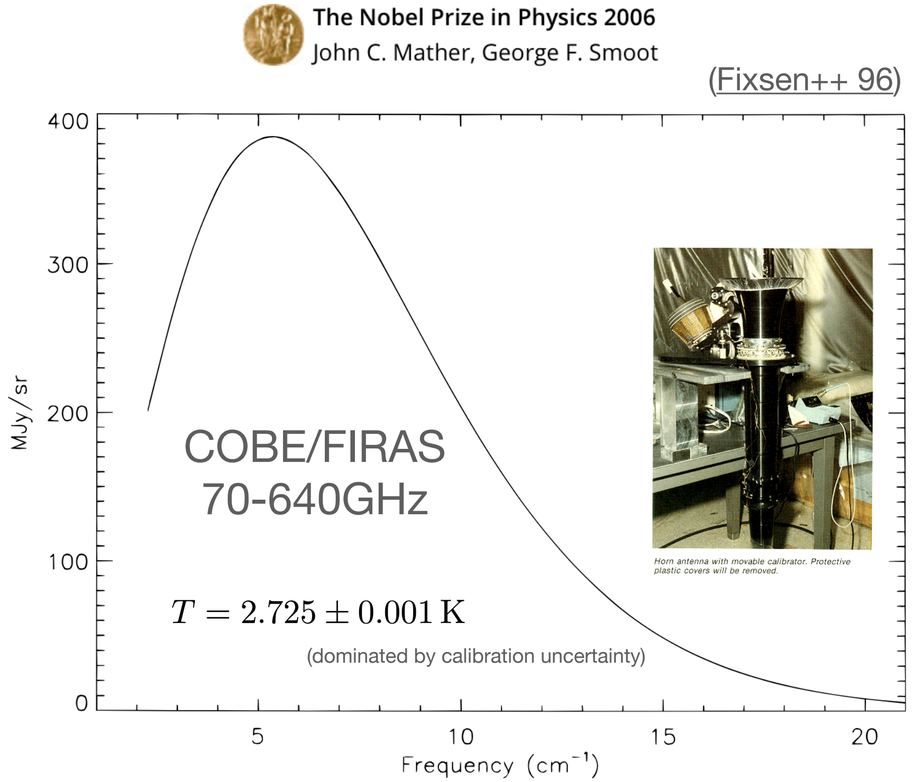


FIG. 4.—Uniform spectrum and fit to Planck blackbody (T). Uncertainties are a small fraction of the line thickness.

Motivations for CMB Spectral Distortions

"Spectral distortions are the earliest direct observational probe of cosmology"

(see e.g. Wayne Hu's PhD Thesis (1995)

and CUSO lectures by Jens Chluba)

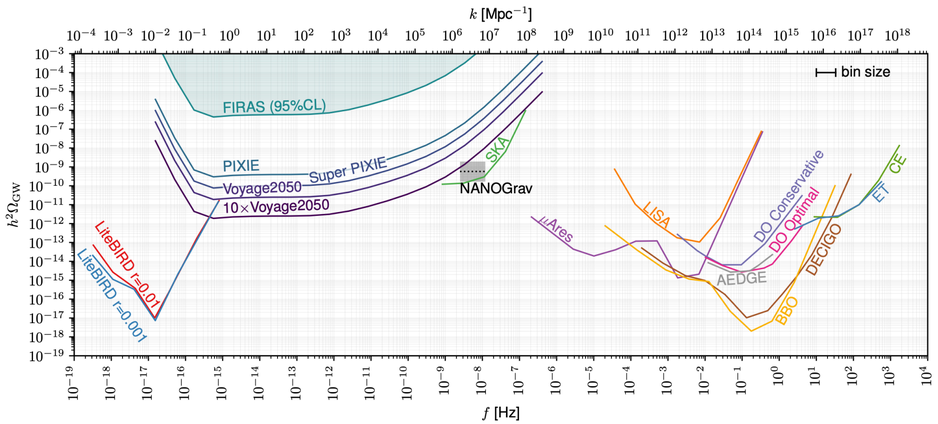
- Global μ and y predicted but never measured*
- Powerful probe: 1995 COBE/FIRAS bounds still used to set new constraints

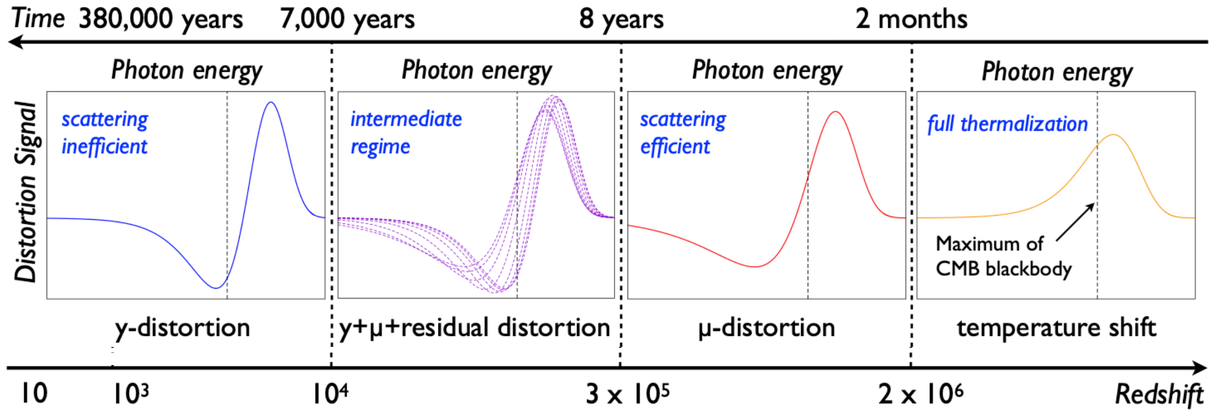
$$|y| \leq 1.5 \times 10^{-5} \ (95\%\mathrm{CL})$$

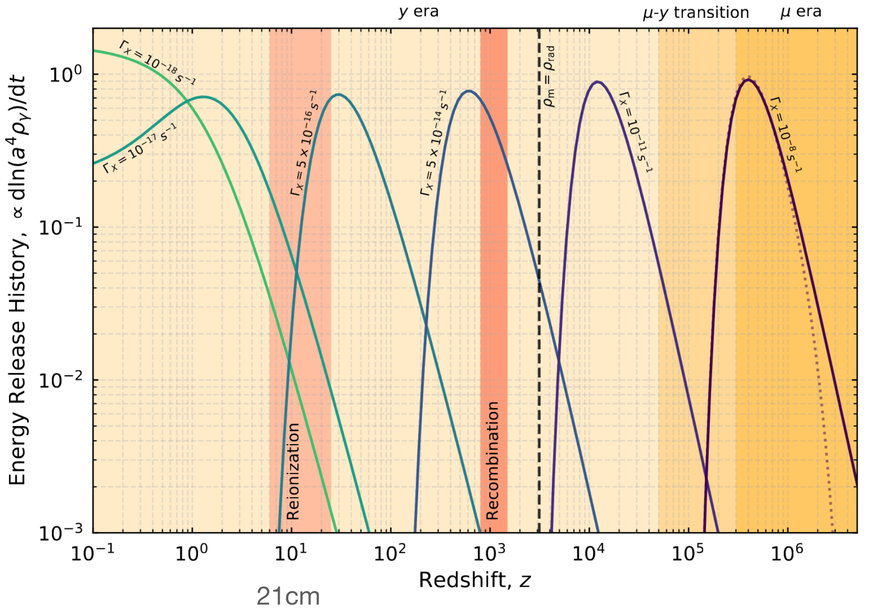
$$|\mu| \leq 9 \times 10^{-5} \ (95\%\mathrm{CL})$$

(Fixsen++ 96)

Example: new constraints on GW (Kite++ 2020)







Double Compton
+
Bremsstrahlung
=
Thermalisation

Motivations for CMB Spectral Distortions

- Case for a future mission:

✤ Inflation

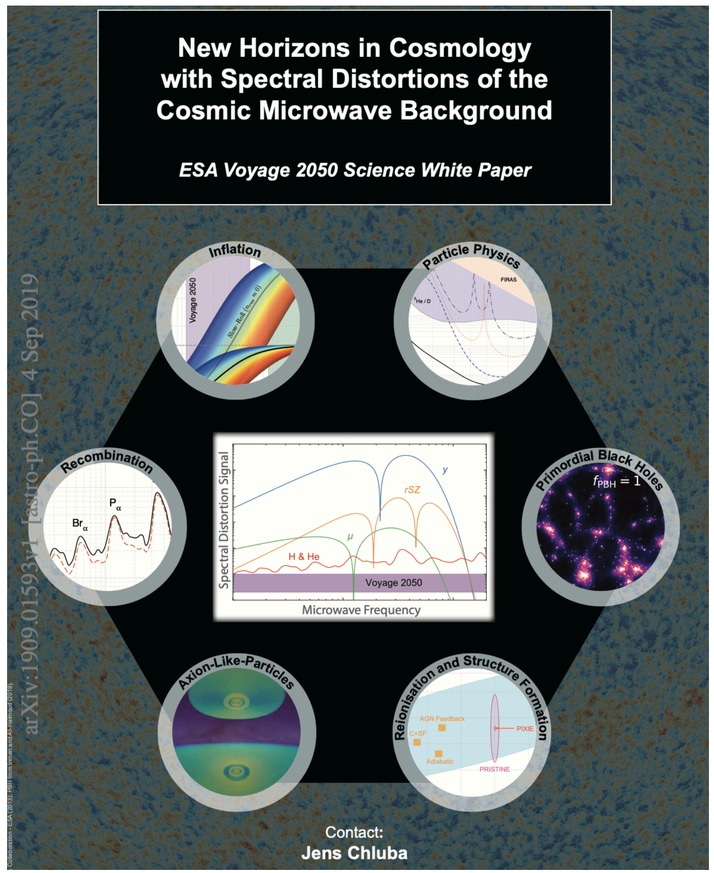
✤ Primordial non-Gaussianity

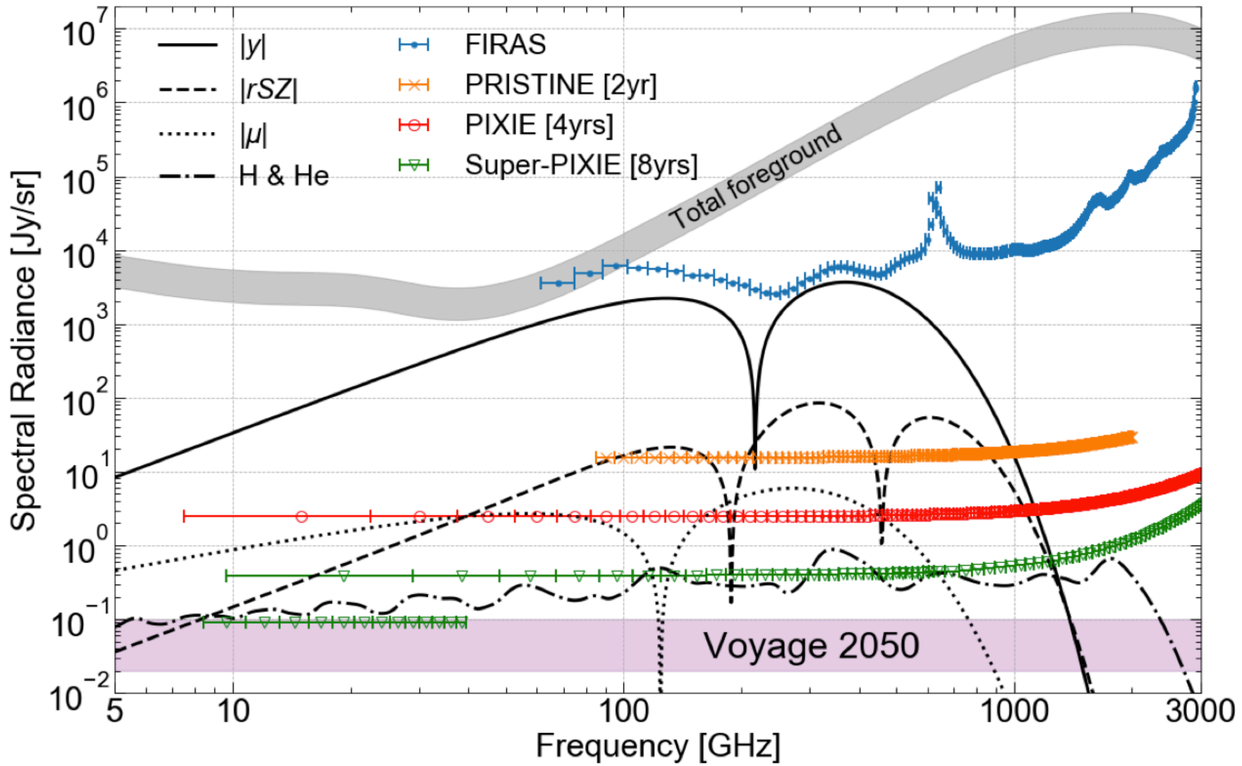
✤ Recombination

✤ Dark Matter, Primordial Black Holes

✤ Thermal dust

✤ Resonant Scattering by O,N,C lines



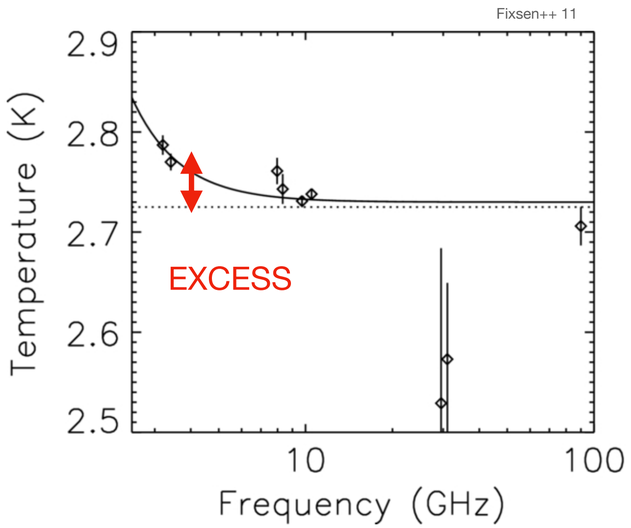


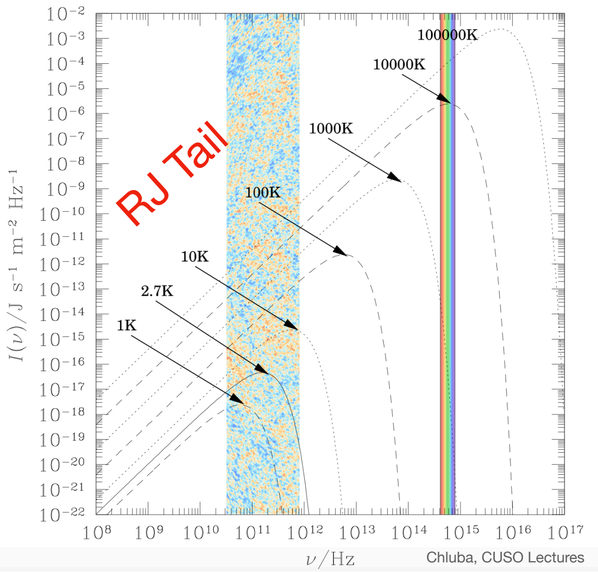
The CMB spectrum at low frequency I

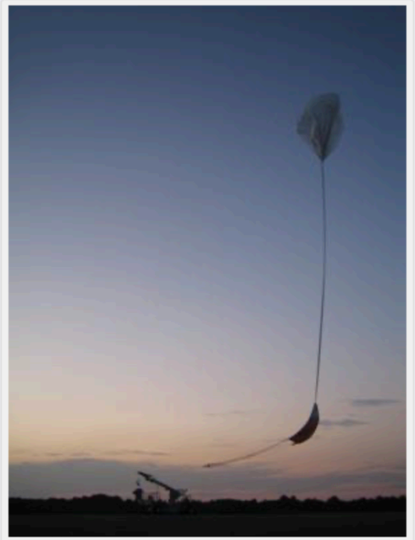
- Rayleigh-Jeans Law —> Intensity ~ Temperature $I_\nu \propto \nu^2 T$

$$x = \frac{h\nu}{kT} \ll 1 \qquad \text{For T=2.725K:} \quad x = 10^{-2} \Leftrightarrow \nu \simeq 570\,\mathrm{MHz}$$

- ARCADE2 (Fixsen et al 2011)
  - ✤ Absolute Radiometer for Cosmology, Astrophys. and Diffuse Emission
  - ✤ Balloon-born instrument
  - ✤ Excess of 54 ± 6 mK at 3.3 GHz
  - ✤ Extra radio component? (Seiffert et al 2011)
  - ✤ Decaying/annihilating particle? (Chluba 15)
  - ✤ Link with EDGES? *(Feng and Holder 2018; Caputo et al 2020)*







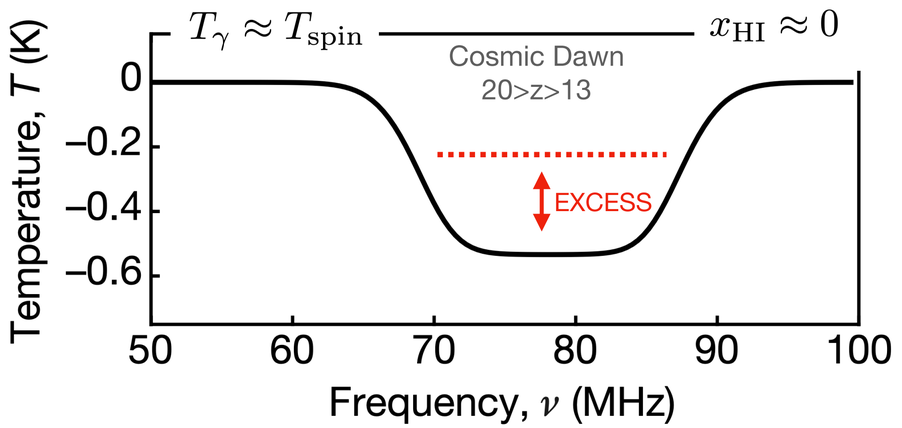
Photograph of 2005 ARCADE 2 launch, from NASA's Columbia Scientific Balloon Facility in Palestine, TX. The balloon and flight train dominate the image, and the instrument hangs from the crane-like launch vehicle.

The CMB spectrum at low frequency II

- EDGES (Bowman++ 18)

collisional coupling inefficient for z<40

Universe ionized z<7



$$T_{21} \propto x_{\rm HI}\left(1-\frac{T_\gamma}{T_{\rm spin}}\right)$$

- ✤ Excess absorption profile of the global 21cm signal
- ✤ Twice as large as standard expectation
- ✤ Potential Implications:

1. Baryons cooler than expected (low spin T)
   - ✓ DM-baryons scattering
     (e.g., Barkana 2018, Muñoz and Loeb 2018,
     see talk by Gluscevic, Muñoz, also Kovetz, Poulin)
2. Background radiation hotter than expected, high radiation T
   (Feng and Holder 2018)
   - ✓ Already at z~20
   - ✓ Achieved by photon injection
   - ✓ DM-EM coupling
     (e.g., Pospelov++18, Fraser++18, Hektor++18, Caputo++20)
   - ✓ This talk: non-relativistic, cold decaying dark matter particle (or excited states)

Spectral Distortions from a simple photon injection process

(based on Chluba & Sunyaev 08, Chluba 15, see also Brahma++ 20 for EDGES)

- Decaying particle: $X \rightarrow \gamma + \gamma$ $\quad m = 2E_{\rm inj}$

Non relativistic particle

Energy of each injected photon

$$E_{\rm inj} = h\nu$$

- Excited states: $X^* \rightarrow X + \gamma$ $\quad \Delta m = E_{\rm inj}$

- No specific condition for the abundance

- Exponential decay $\left.\dfrac{{\rm d}\ln a^3 N_\gamma}{{\rm d}t}\right|_{\rm inj} \propto \exp\left(-\Gamma_X t\right)$

- Injection spectrum modelled by a narrow Gaussian $\left.\dfrac{{\rm d}n_\gamma}{{\rm d}t}\right|_{\rm inj} \propto {\rm G}\left(\nu, \nu_{\rm inj}, \sigma_\nu\right)$

Spectral Distortions from a simple photon injection process

(based on Chluba & Sunyaev 08, Chluba 15, see also Brahma++ 20 for EDGES)

- Decaying particle: $X \to \gamma + \gamma$ $\quad m = 2E_{\rm inj}$

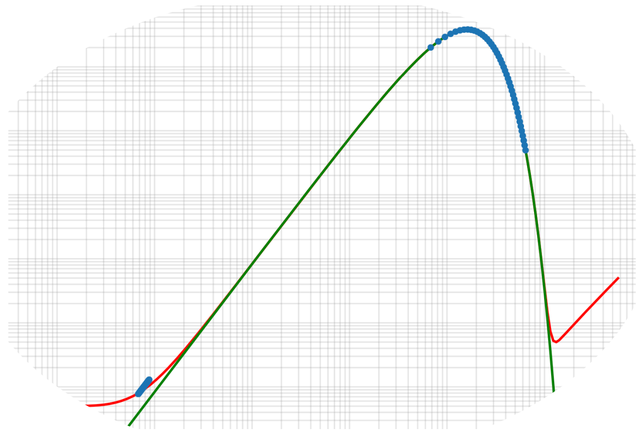
Non relativistic particle

Energy of each injected photon

$$E_{\rm inj} = h\nu$$

- Excited states: $X^* \to X + \gamma$ $\quad \Delta m = E_{\rm inj}$

- No specific condition for the abundance



- Exponential decay $\left.\dfrac{{\rm d}\ln a^3 N_\gamma}{{\rm d}t}\right|_{\rm inj} \propto \exp\left(-\Gamma_X t\right)$

- Injection spectrum modelled by a narrow Gaussian $\left.\dfrac{{\rm d}n_\gamma}{{\rm d}t}\right|_{\rm inj} \propto {\rm G}\left(\nu, \nu_{\rm inj}, \sigma_\nu\right)$

- Remark: Not just low energy but also study the frequency range relevant to COBE/FIRAS at higher frequency

Spectral Distortions from a simple photon injection process

Three parameters

$$x_{\rm inj,0} = \frac{E_{\rm inj}}{kT_{\rm CMB}}$$

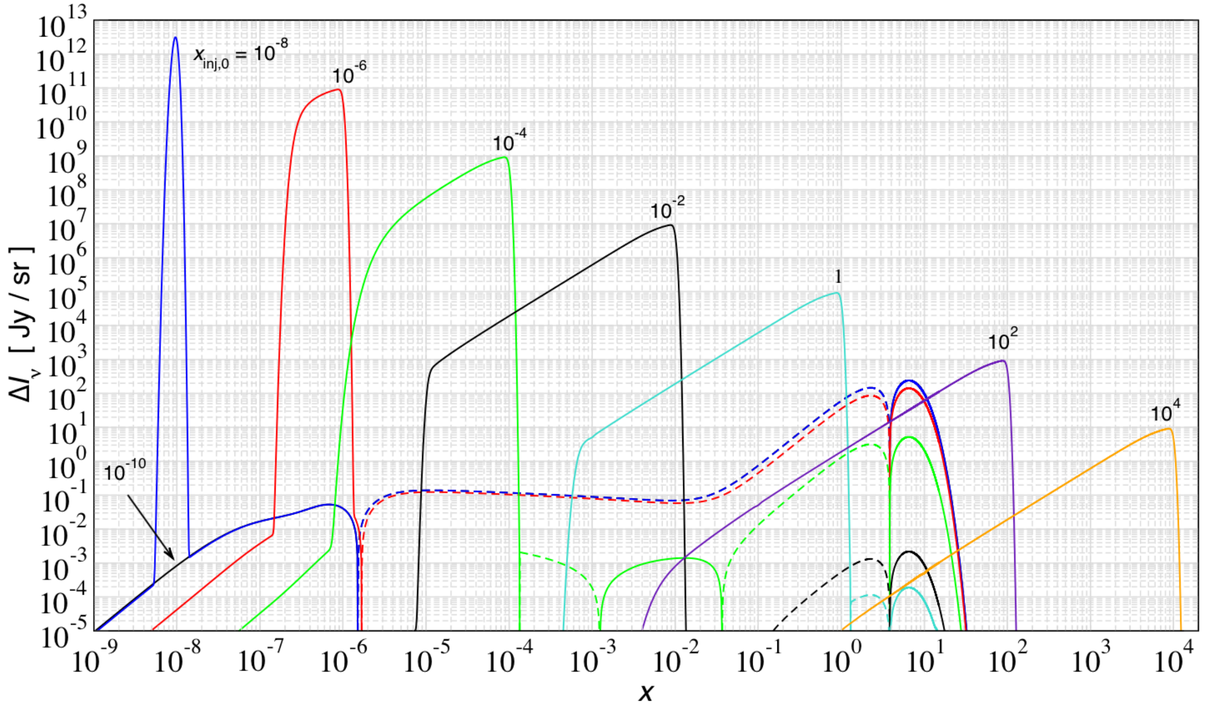
Which frequency?

$$\Gamma_X$$

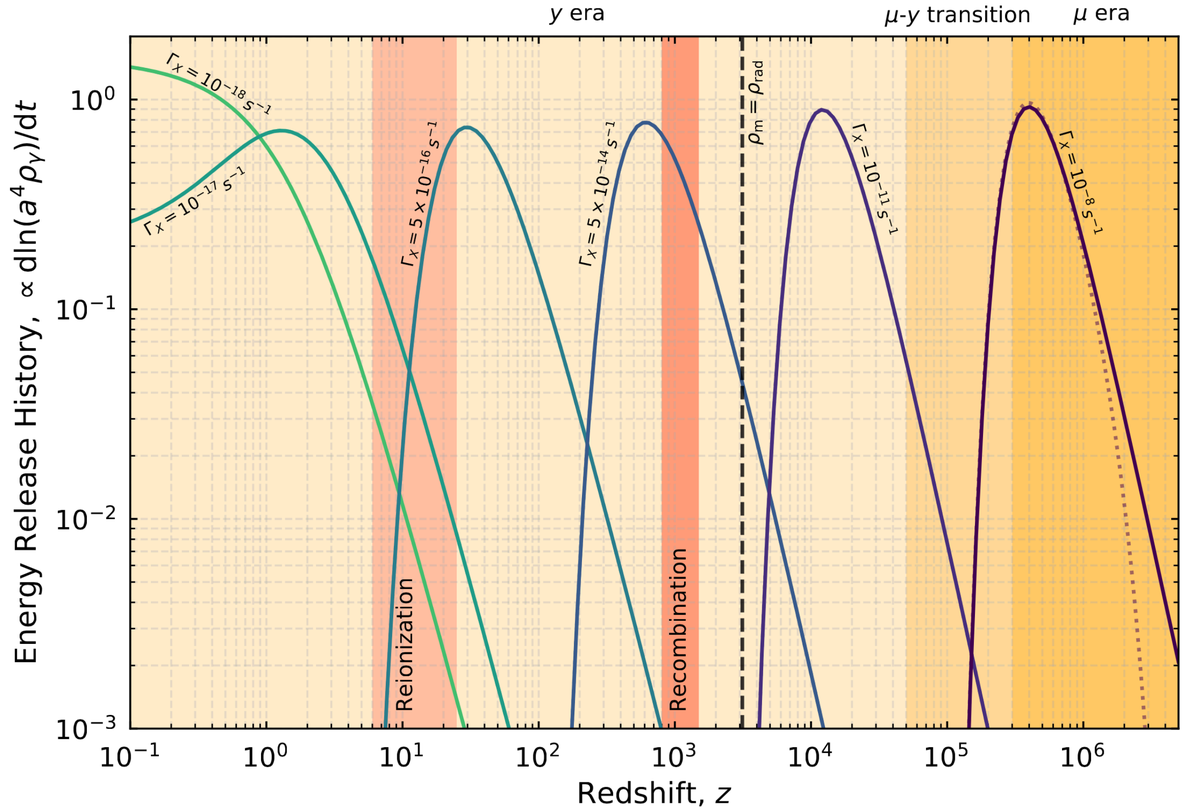
When?

$$f_{\rm dm}$$

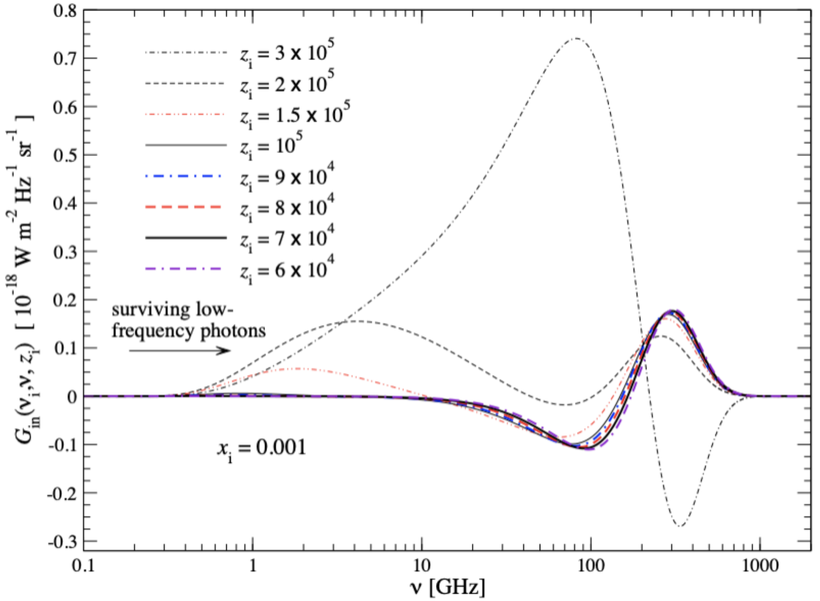
How much?

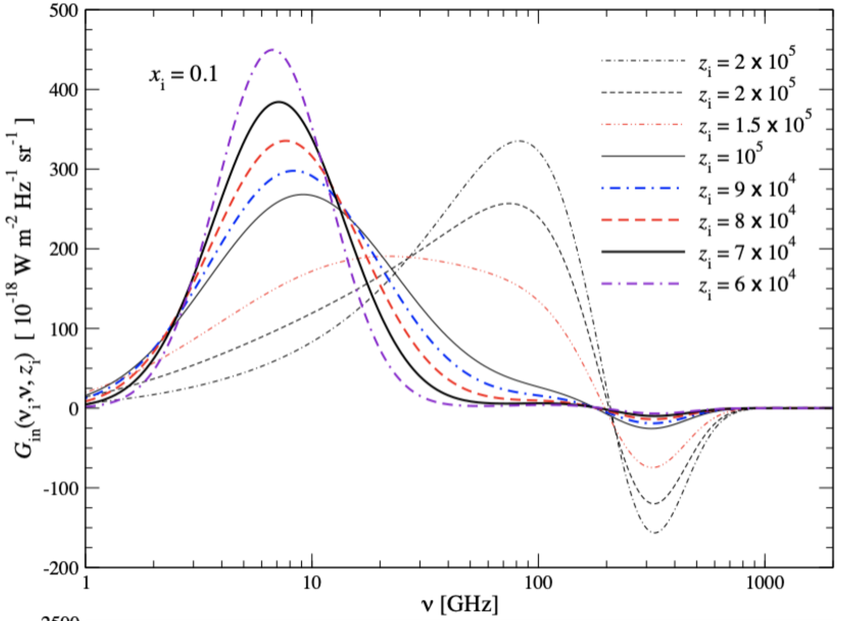


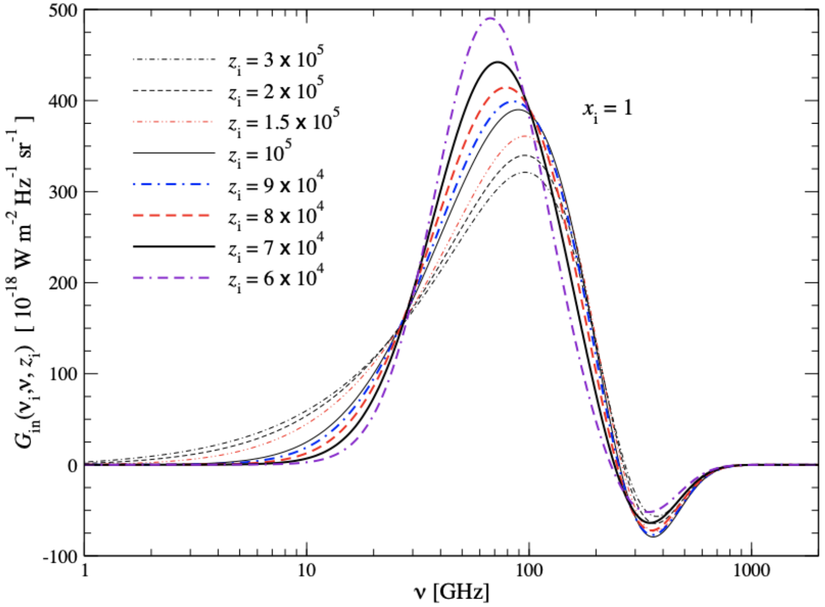
Frequency

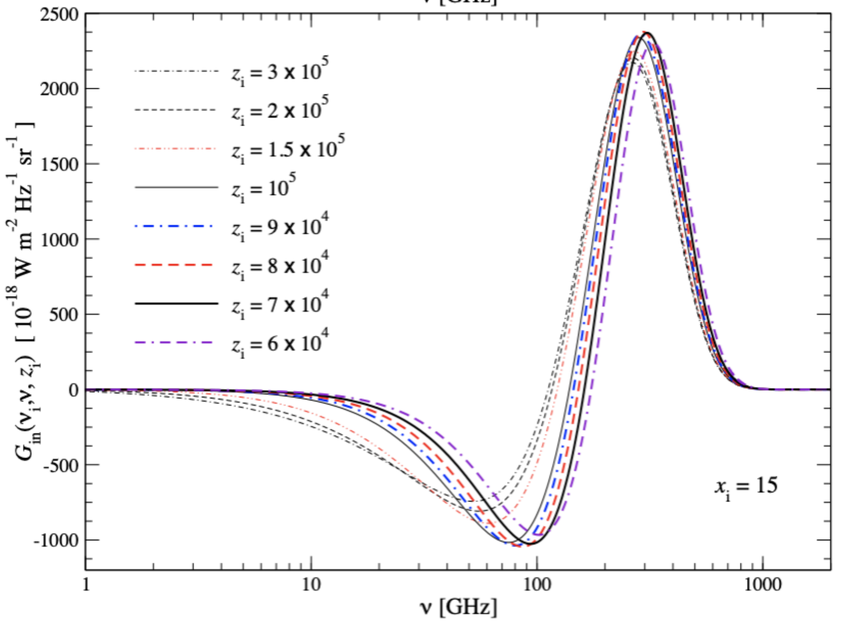


Rich phenomenology of photon injection distortions









JC 2015, ArXiv:1506.06582

Spectral Distortions in Manchester

CosmoTherm.rel_corr

Bremsstrahlung

Recfast++.vX

class_sz
Forked from lesgourg/class_public

Cosmic Linear Anisotropy Solving System With Thermal Sunyaev Zeldovich Power Spectrum Computation

C 1 2

specdist

Python package to study spectral distortions of the cosmic microwave background radiation.

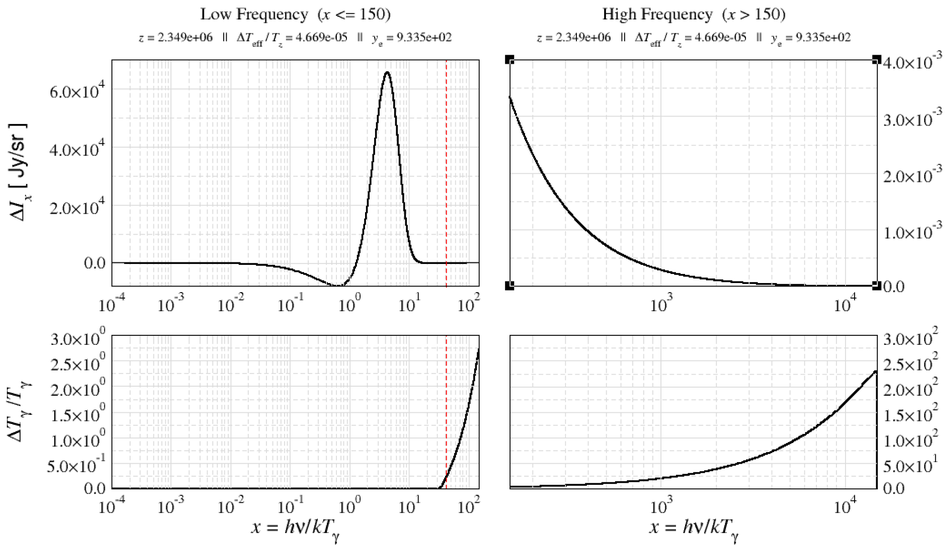
Python

GW2SD

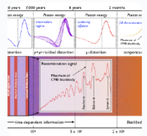
A simple tool for getting accurate window functions to calculate SD signals from GW.

Python 0 0 0 0 Updated 12 days ago

Snapshot of CosmoTherm output



All codes will become public at



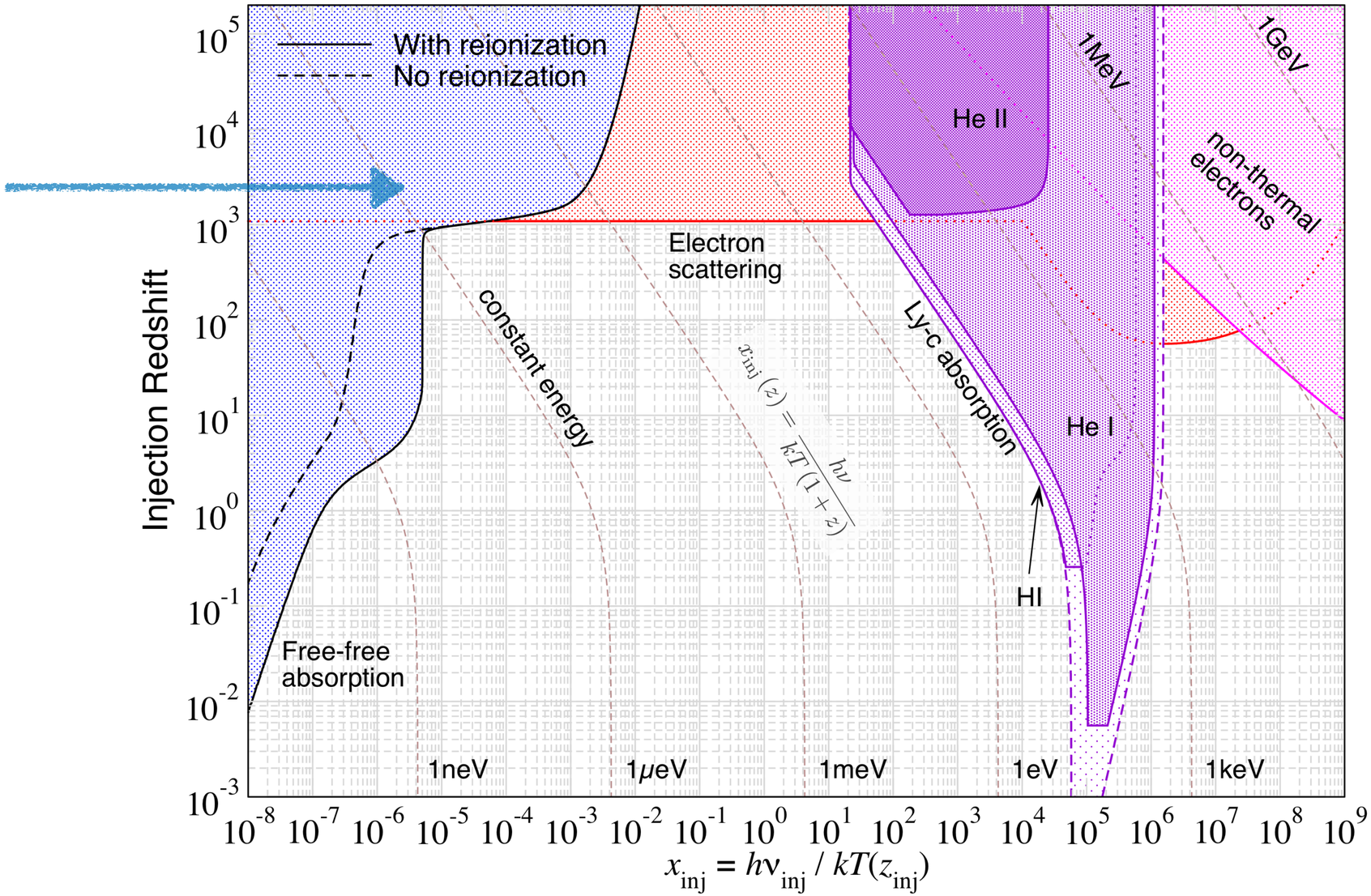
CMBSPEC

Jens Chluba's group ~ 2 months BCE

Phenomenology of Photon Injection Distortions

- Relevant process for a photon injected at z?

- Photons are absorbed by free-free
  - ✤ Heating of electrons
  - ✤ Positive μ or y distortion (and free-free distortion)

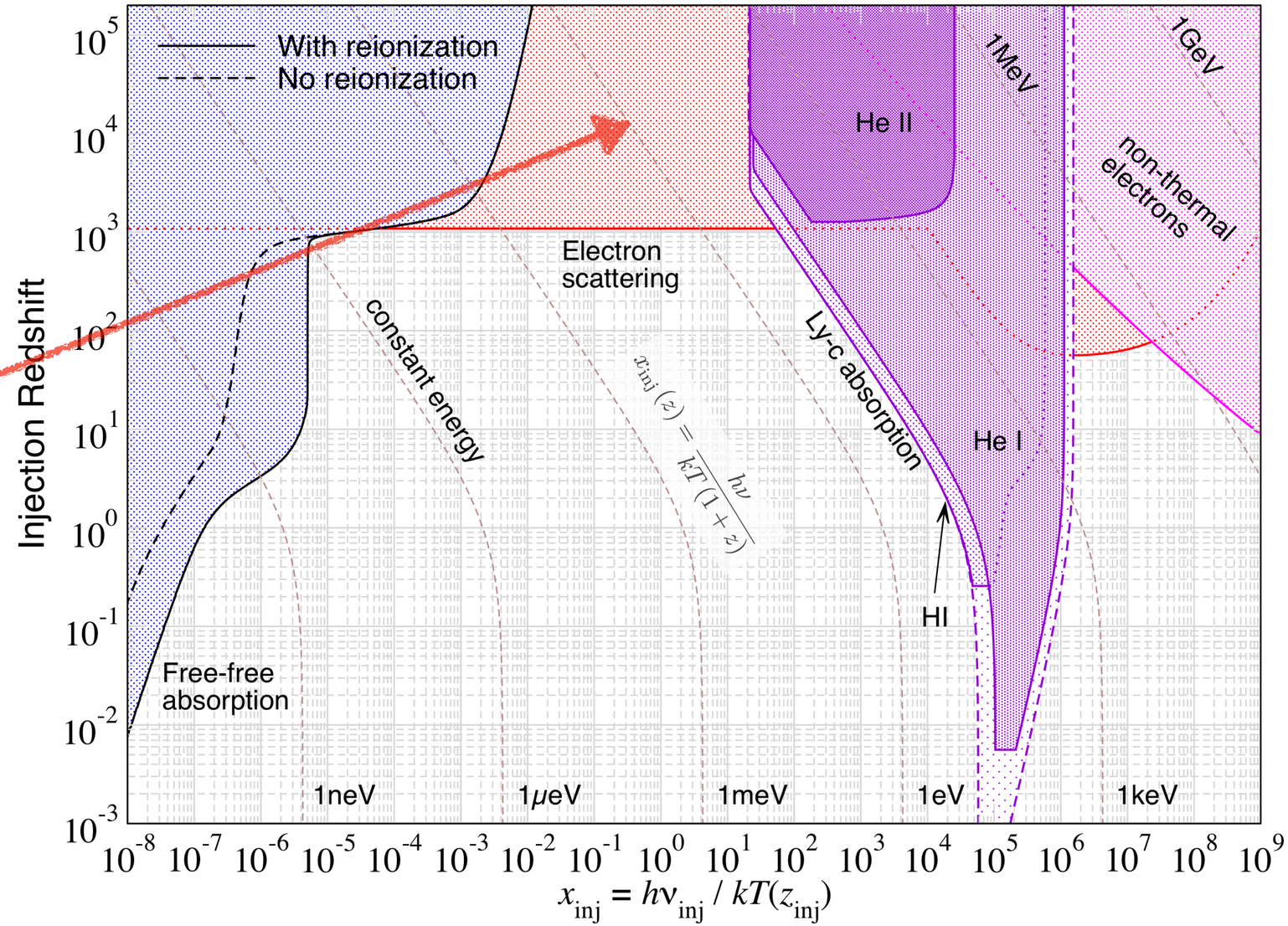


Phenomenology of Photon Injection Distortions

- Relevant process for a photon injected at z?

- Photons are absorbed by free-free
  - ✤ Heating of electrons
  - ✤ Positive μ or y distortion (and free-free distortion)

- Photons are Compton Scattered
  - ✤ Energy exchange
  - ✤ Small (positive or negative) y distortion and peak



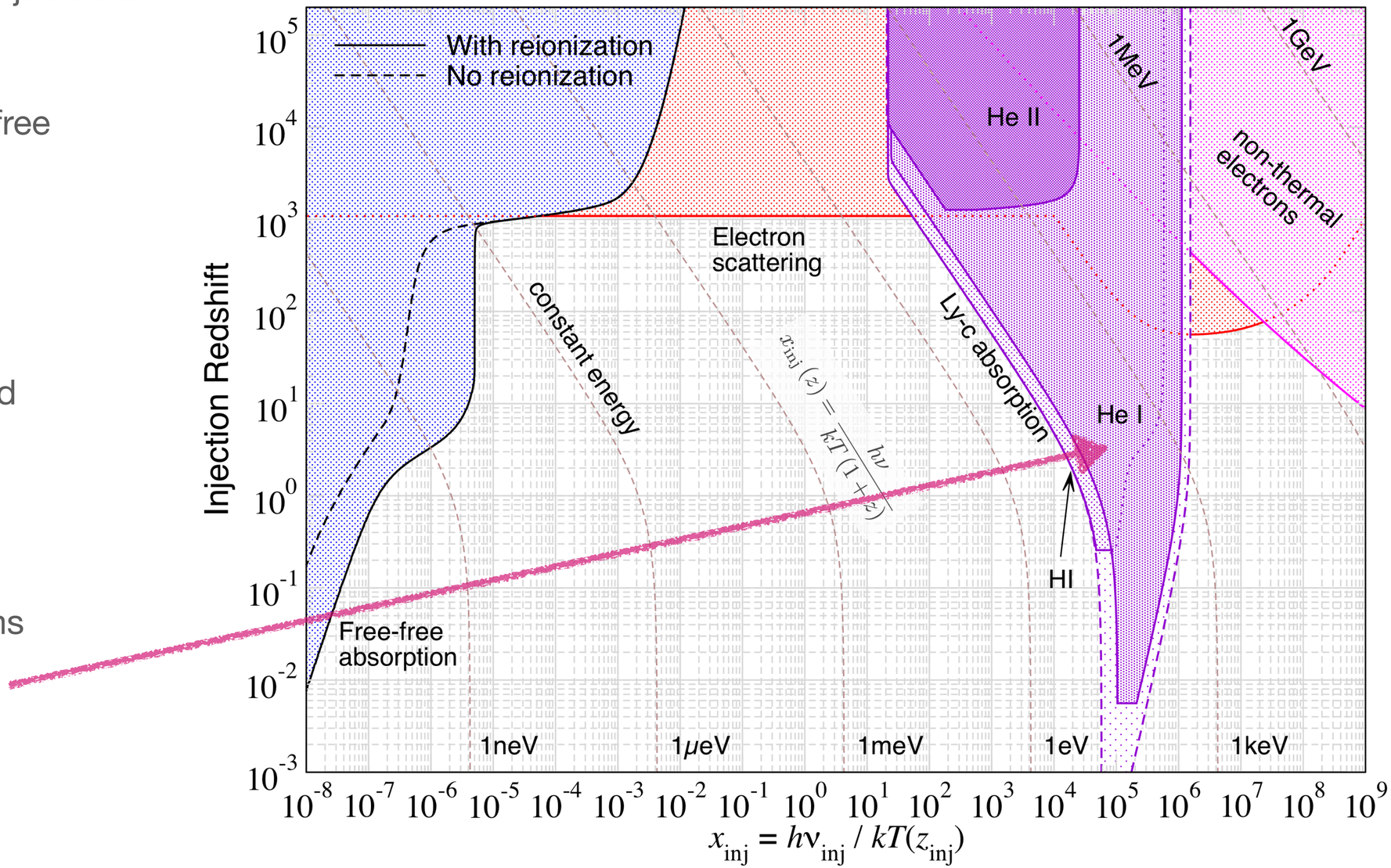
Phenomenology of Photon Injection Distortions

- Relevant process for a photon injected at z?

- Photons are absorbed by free-free
  - ✤ Heating of electrons
  - ✤ Positive μ or y distortion (and free-free distortion)

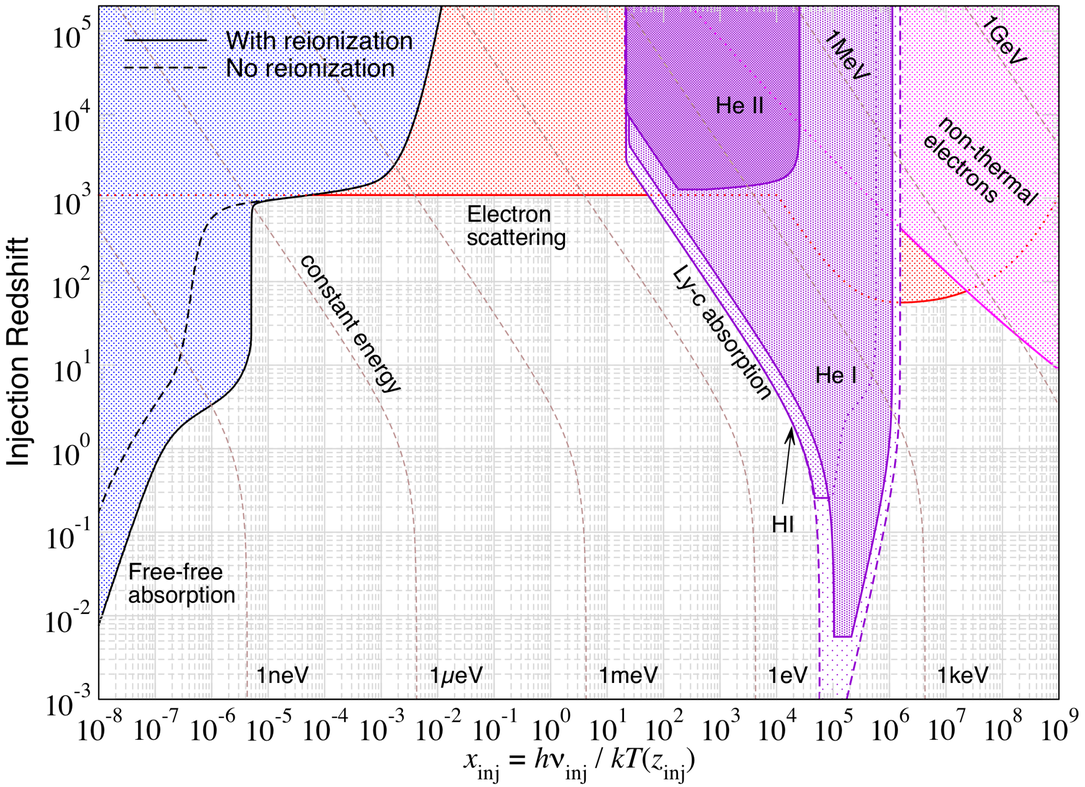
- Photons are Compton Scattered
  - ✤ Energy exchange
  - ✤ Small (positive or negative) y distortion and peak

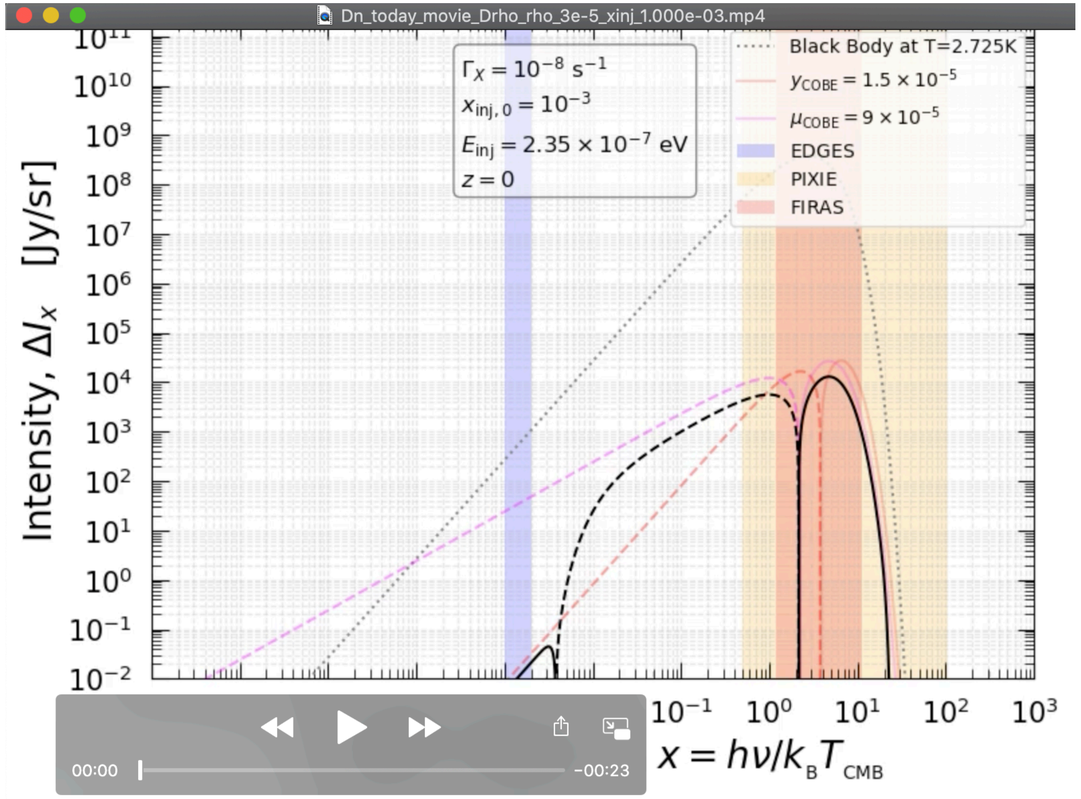
- Photons are absorbed by atoms
  - ✤ Heating of matter
  - ✤ Positive y distortion and peak



Phenomenology of Photon Injection Distortions

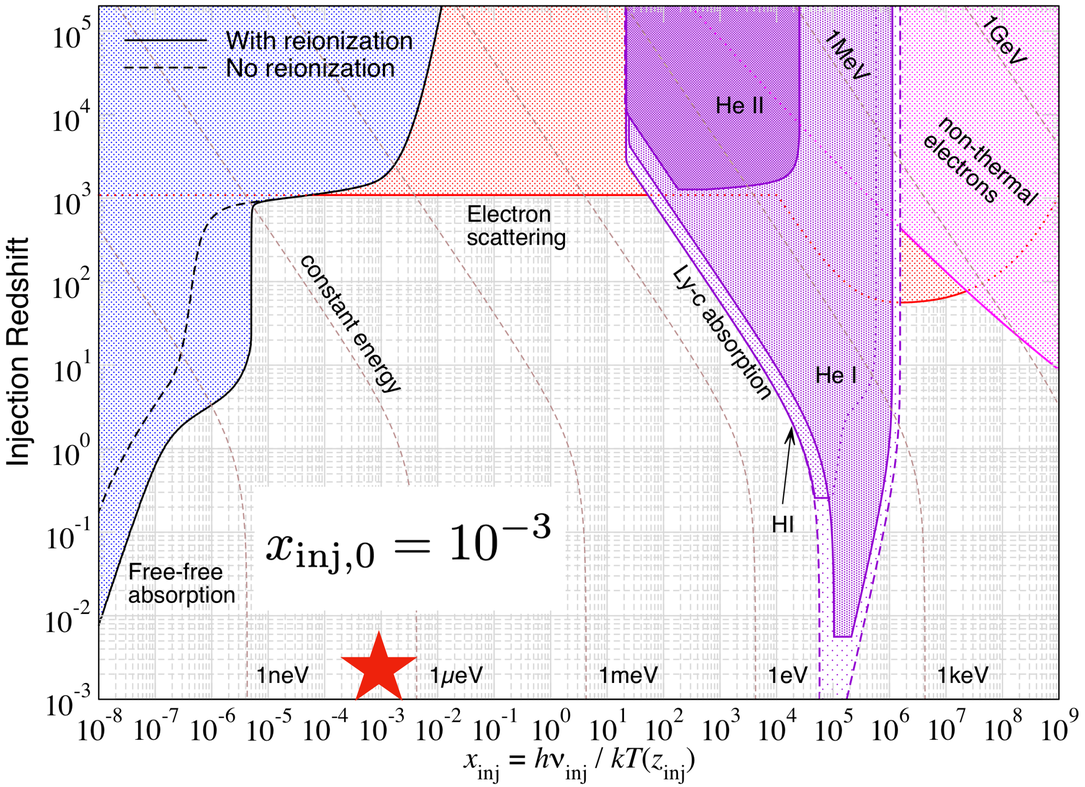
- Examples of Photon Injection spectra today for different lifetimes
- Evolution starts at very high z

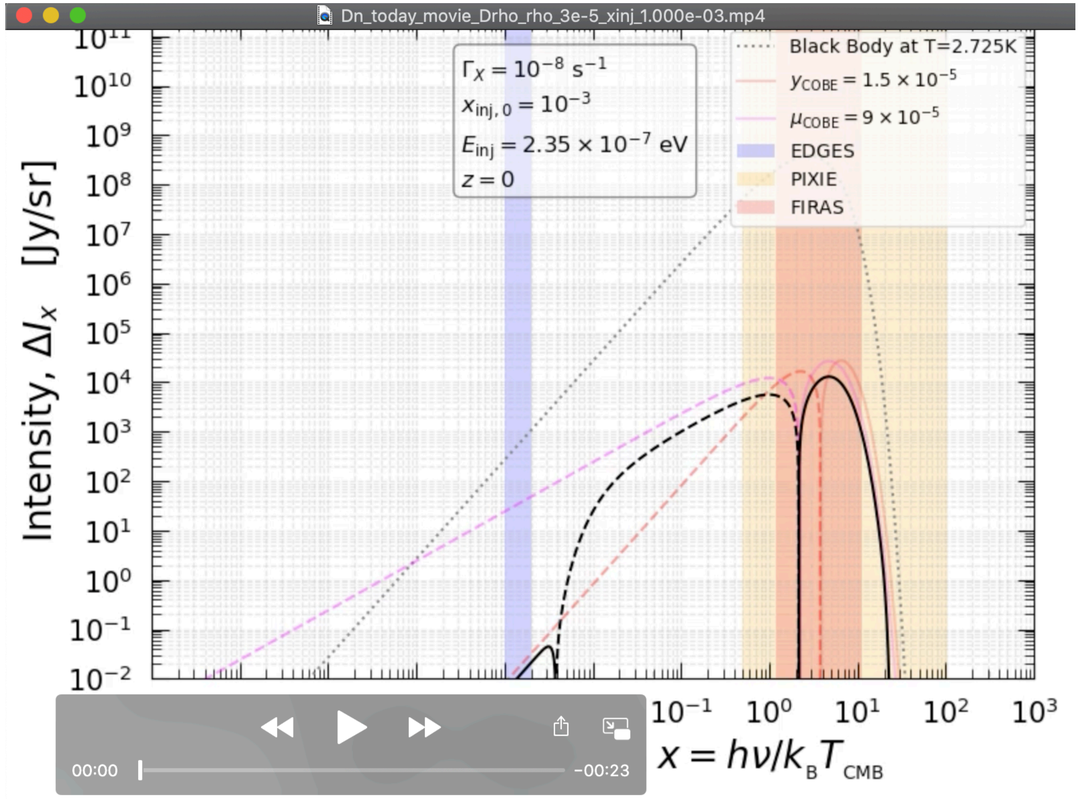




Phenomenology of Photon Injection Distortions

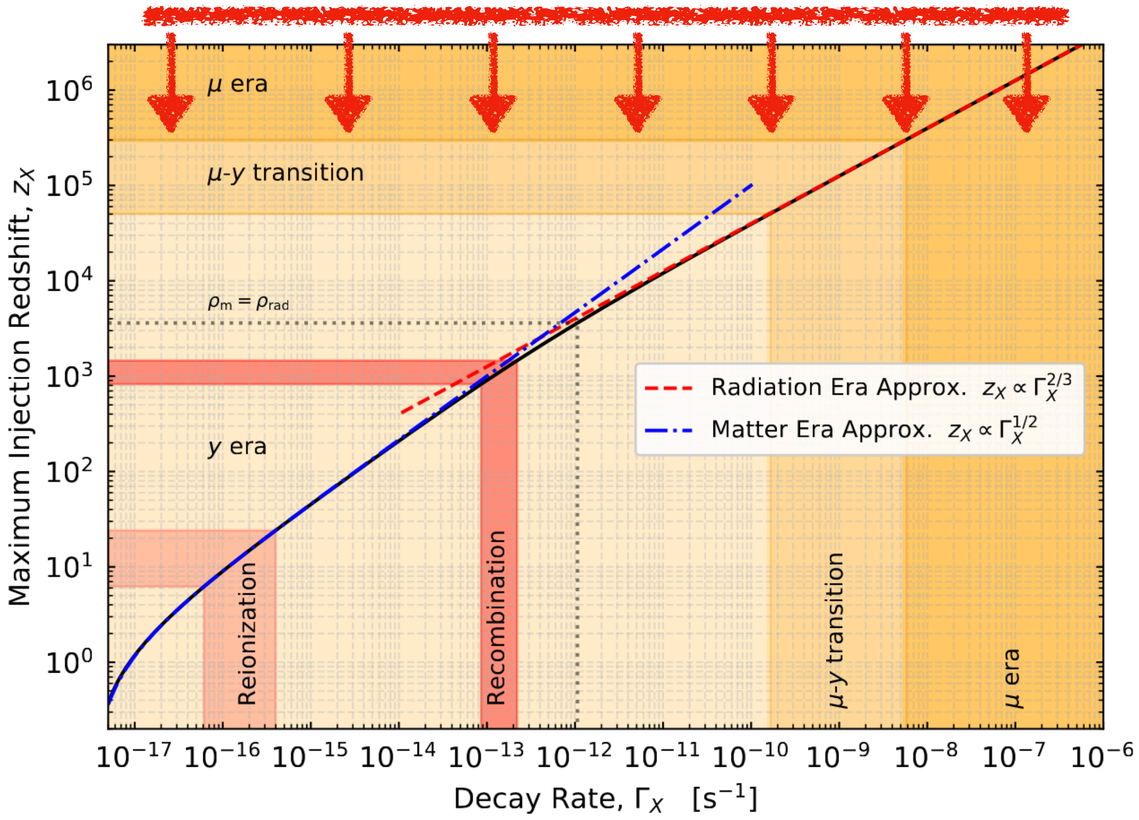
- Examples of Photon Injection spectra today for different lifetimes
- Evolution starts at very high z

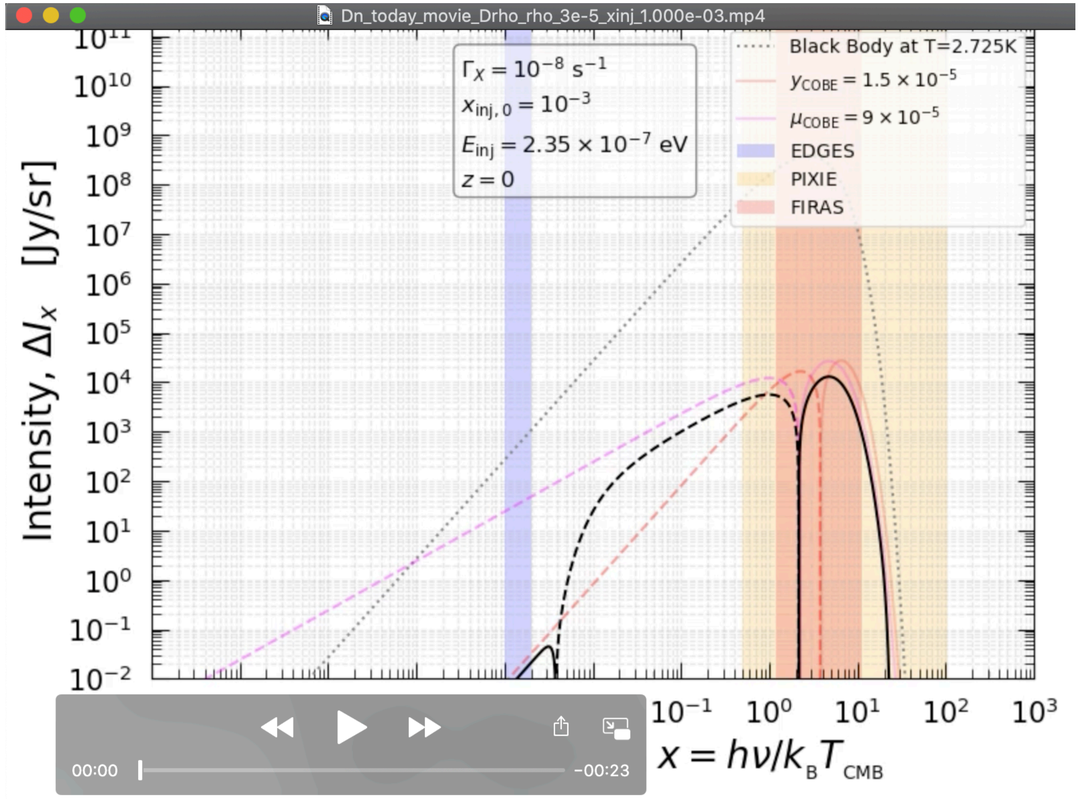




Phenomenology of Photon Injection Distortions

- Examples of Photon Injection spectra today for different lifetimes
- Evolution starts at very high z





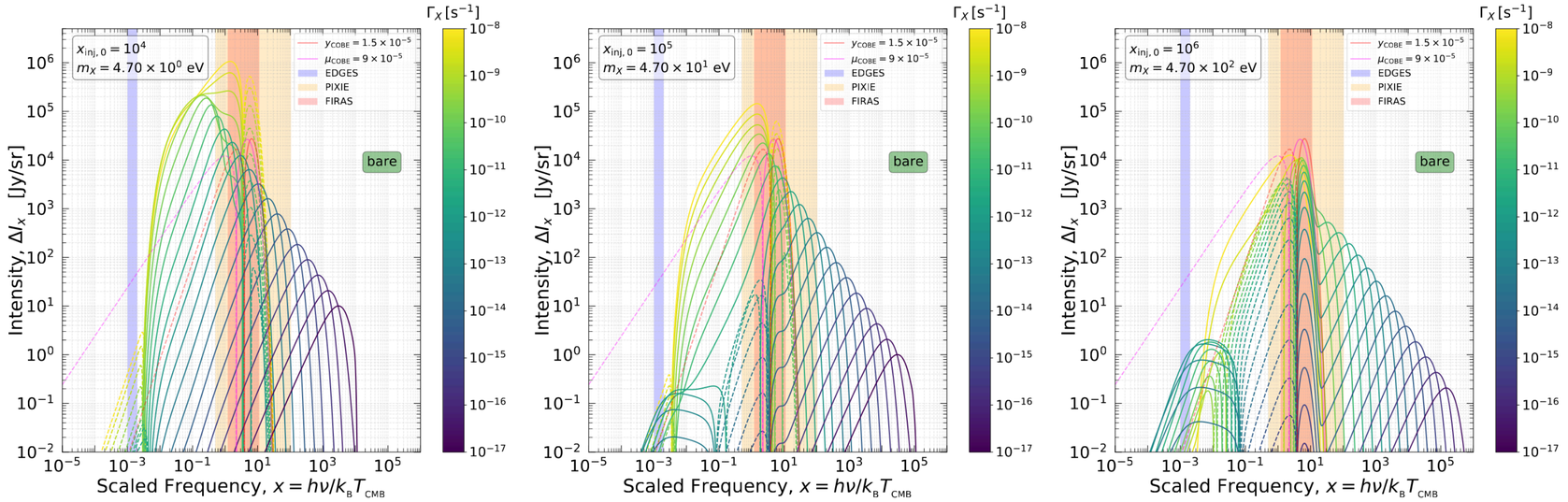
Lyman continuum absorption

- Injection near photo-ionisation threshold of Hydrogen (and Helium)

➡ Photons are absorbed

➡ Heating of matter
positive y distortion

➡ Free-free emission
at low frequency



- Important near recombination

(See, e.g., Zeldovich++ 68, Seager++ 00, Chluba & Sunyaev 07)

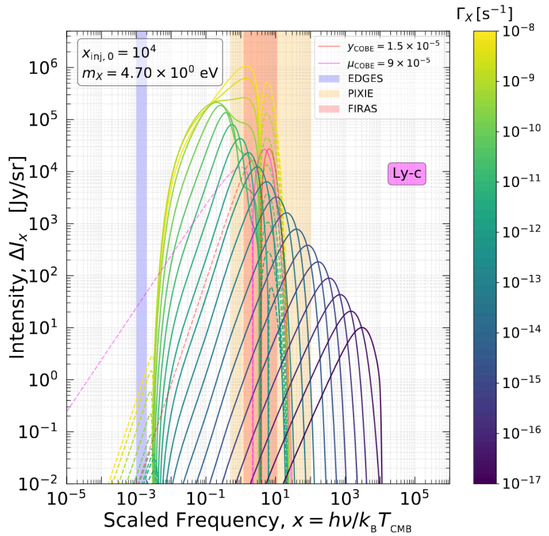
Lyman continuum absorption

- Injection near photo-ionisation threshold of Hydrogen (and Helium)

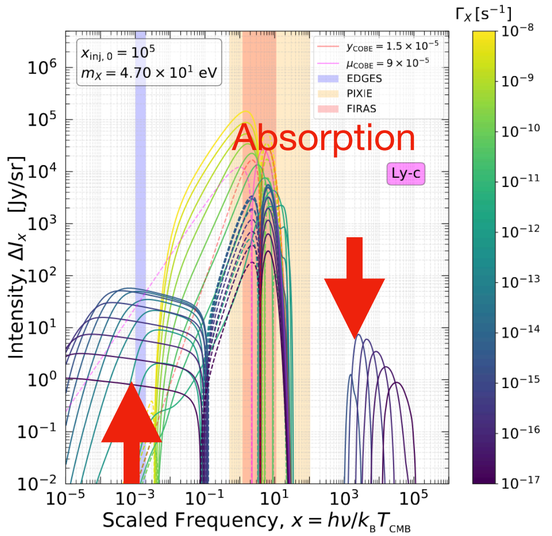
➡ Photons are absorbed

➡ Heating of matter
positive y distortion

➡ Free-free emission
at low frequency

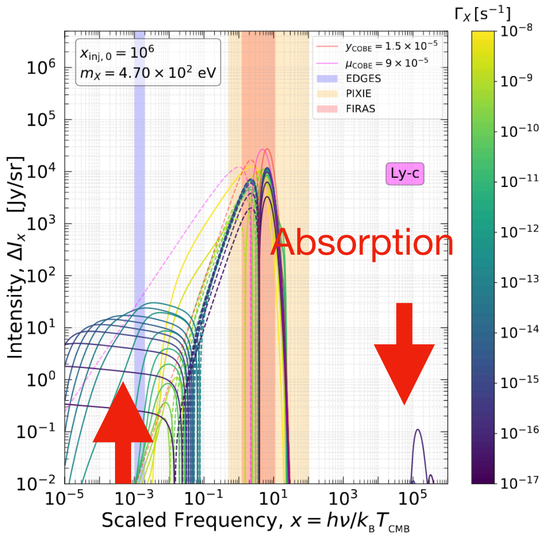


No difference



free-free

Heating



free-free

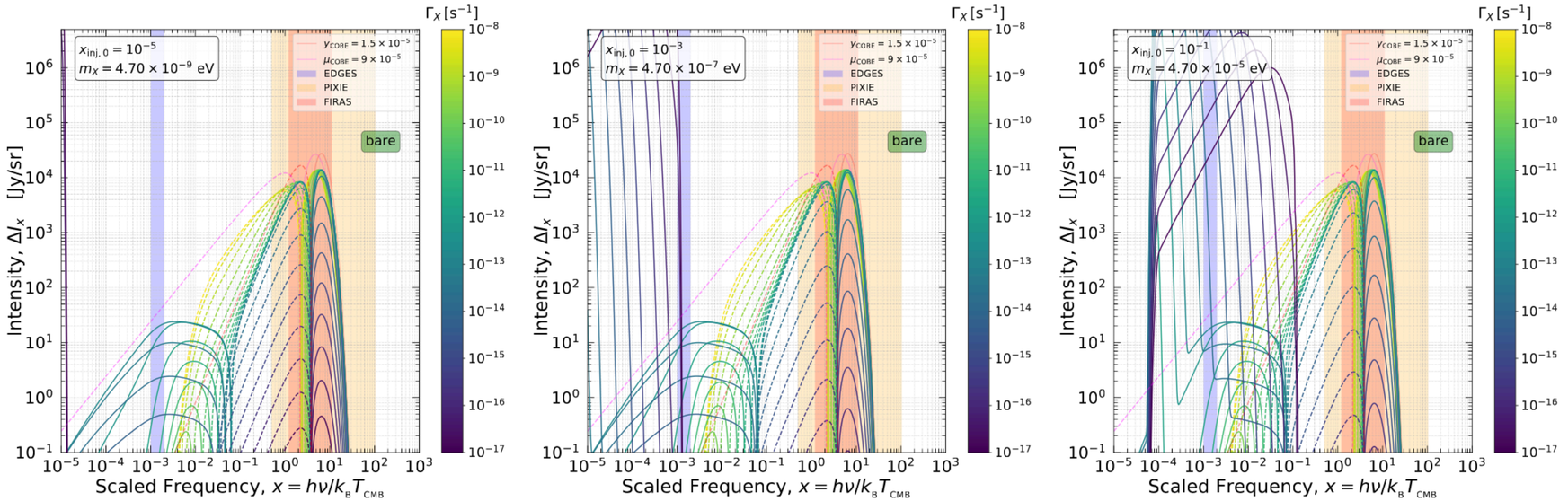
Heating

- Important near recombination

(See, e.g., Zeldovich++ 68, Seager++ 00, Chluba & Sunyaev 07)

With reionization

- Enhance free-free absorption $\propto N_e N_p$
- Heating
- More y-distortion



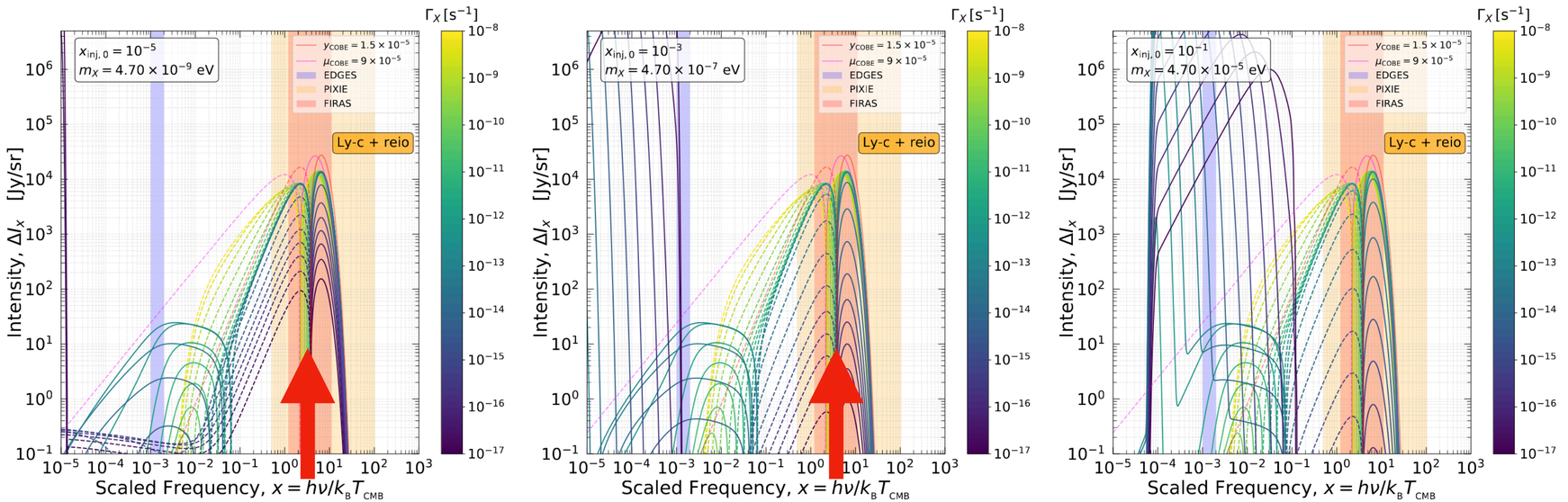
- Important to include for:
  - ✤ Late injection
  - ✤ Low frequency injection
    (higher frequency injection not absorbed by free-free at late time…)

With reionization

- Enhance free-free absorption $\propto N_e N_p$

- Heating

- More y-distortion



Heating

Heating

- Important to include for:

  - ✤ Late injection

  - ✤ Low frequency injection
    (higher frequency injection not absorbed by free-free at late time…)

Important Points

- Photons injection distortions are not simple μ and y, they have a rich phenomenology

- Lyman continuum absorption (Hydrogen and Helium) important to take into account for injection happening near or after recombination and at injection frequencies higher than or near the photo-ionisation thresholds

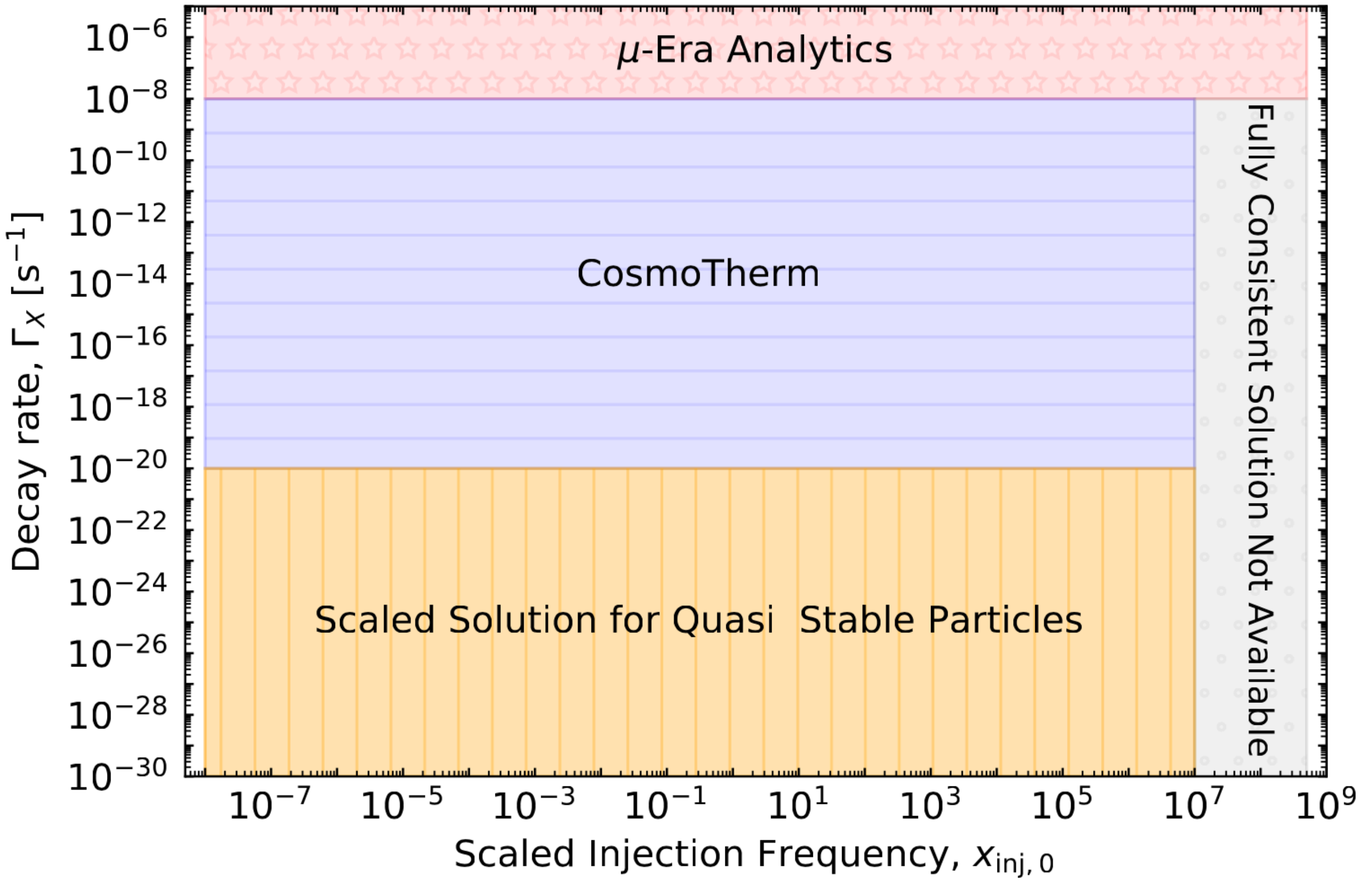
- Reionization is important to take into account for low frequency injection at late time

  ➡ Without these included, we would be underestimating the y-distortion in the COBE/FIRAS range and misestimating the free-free distortion in the low frequency (RJ) range of the CMB spectrum

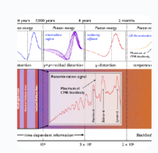
  ➡ Important for constraints

Photon Injection Database

- We computed a grid of spectra covering the whole parameter space: "Library of spectra"
- Obtain spectra for any lifetime, injection frequency, DM fraction, by interpolating the library



(The database will be available online)

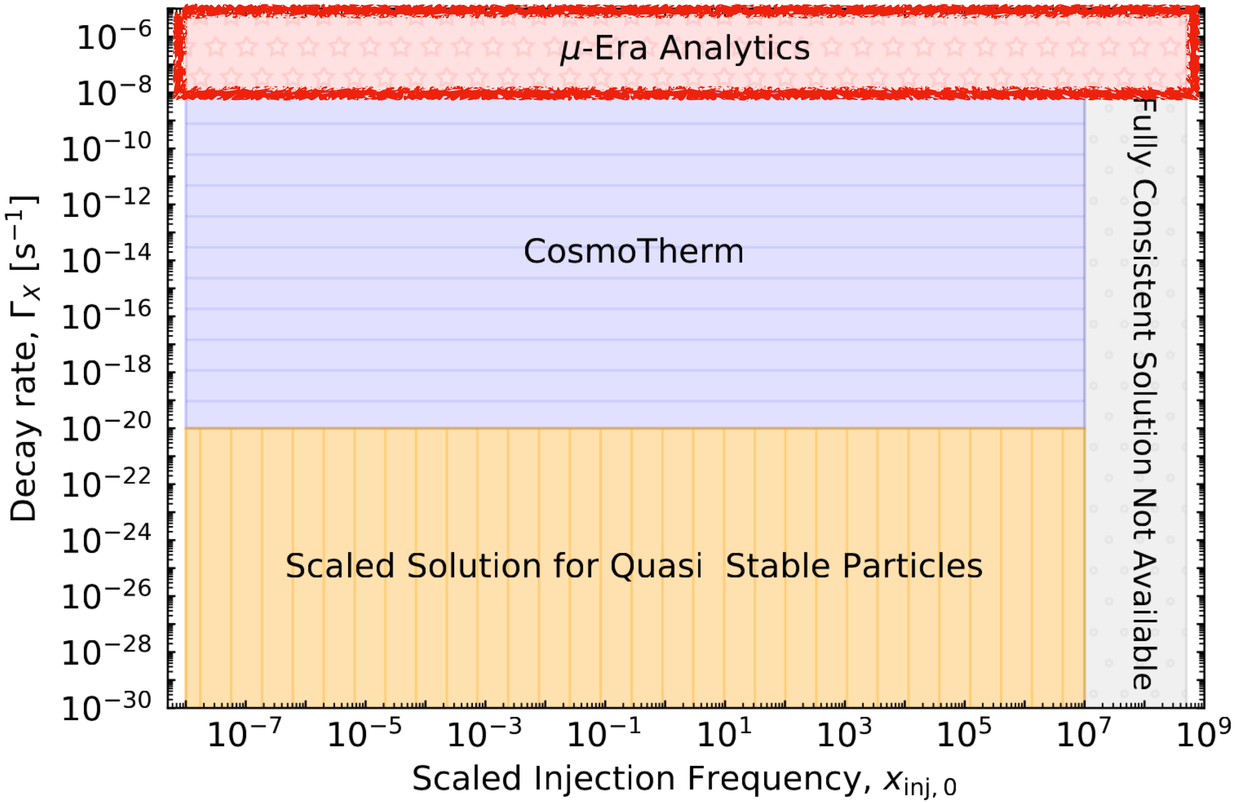


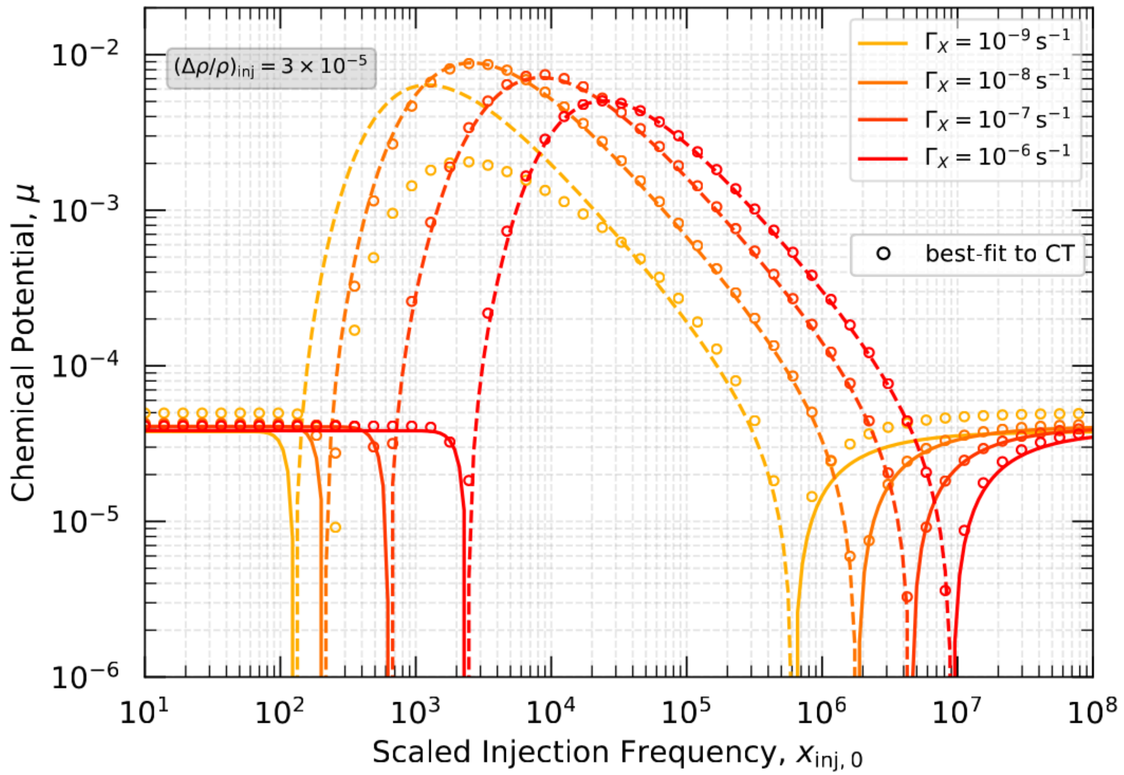
CMBSPEC

Early injection case

- For μ-era injection, analytic treatment available
- Green's function method (Chluba 15):

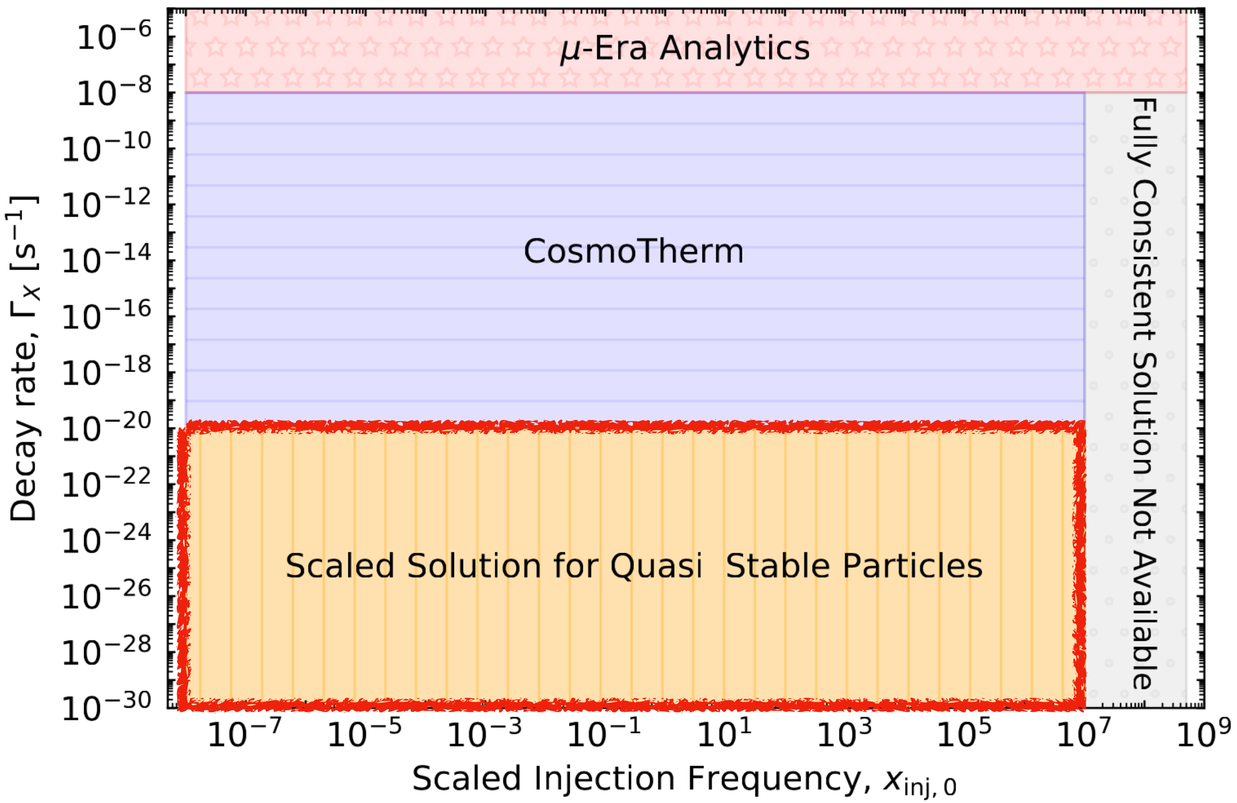
$$\mu_{\rm inj} \approx 1.401 \int \left[x_{\rm inj} - x_{\rm null}\, \mathcal{P}_s(x_{\rm inj}, z)\right] \alpha_\rho \frac{{\rm d}\ln N_\gamma}{{\rm d}z}\, \mathcal{J}^*_{\rm bb}(z)\, {\rm d}z$$

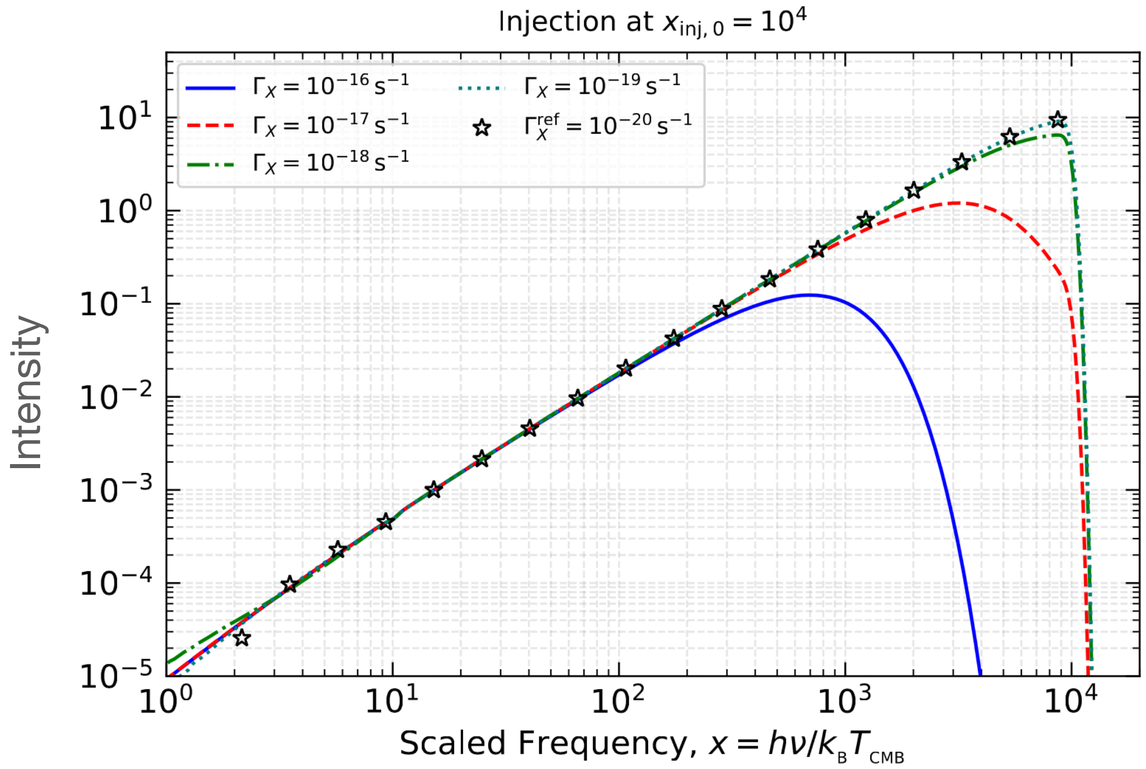




Late injection case

- For late injection (“Quasi-Stable particles”), all spectra converge to the same shape
- Method: rescale a reference spectrum





Constraints on Photon Injection using COBE/FIRAS

- For μ-era injection:

  ➡ Compute μ given lifetime and injection frequency

$$\mu_{\rm inj} \approx 1.401 \int \left[x_{\rm inj} - x_{\rm null}\, \mathcal{P}_s(x_{\rm inj}, z)\right] \alpha_\rho \frac{{\rm d}\ln N_\gamma}{{\rm d}z}\, \mathcal{J}^*_{\rm bb}(z)\, {\rm d}z$$

(Chluba 15)

Constraints on Photon Injection using COBE/FIRAS

- For μ-era injection:

  ➡ Compute μ given lifetime and injection frequency $\mu_{\rm inj} \approx 1.401 \int \left[x_{\rm inj} - x_{\rm null}\, \mathcal{P}_s(x_{\rm inj}, z)\right] \alpha_\rho \dfrac{{\rm d}\ln N_\gamma}{{\rm d}z}\, \mathcal{J}^*_{\rm bb}(z)\, {\rm d}z$ (Chluba 15)

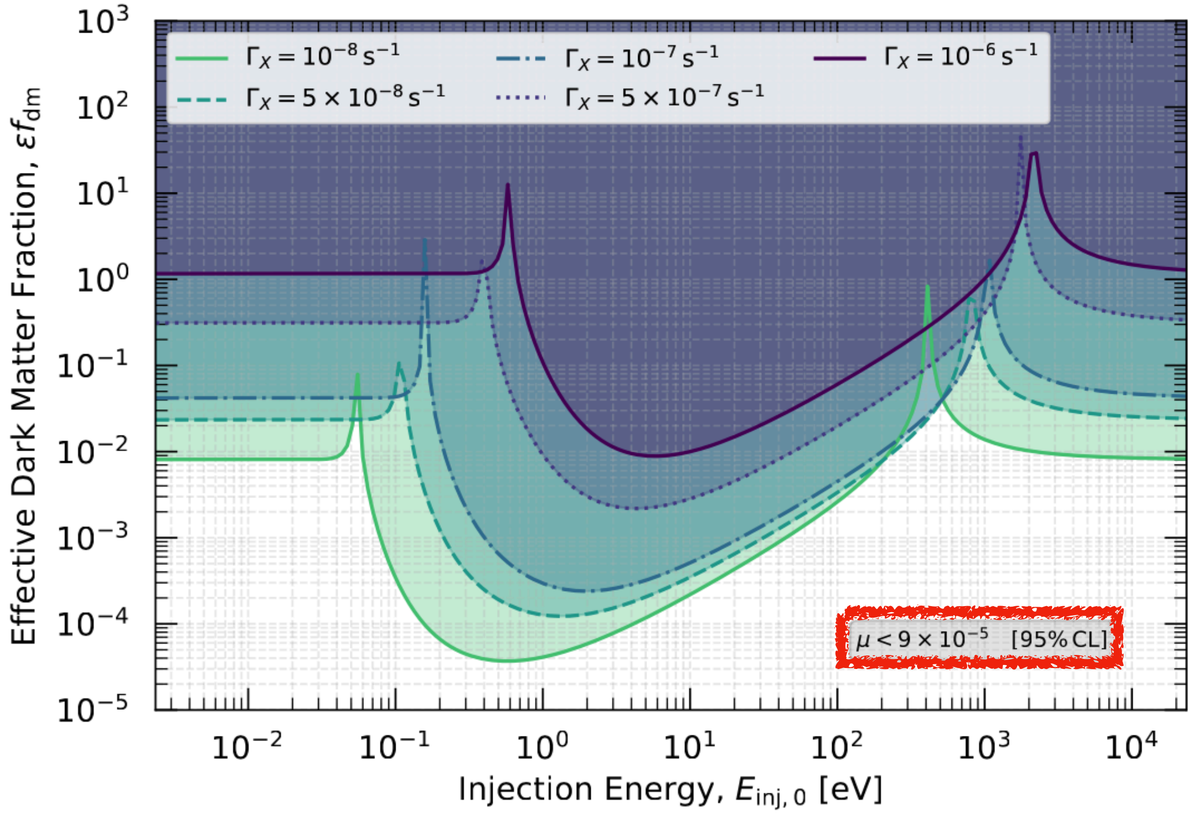
  ➡ Determine maximum allowed DM fraction given COBE/FIRAS bound

Constraints on Photon Injection using COBE/FIRAS

- For μ-era injection:

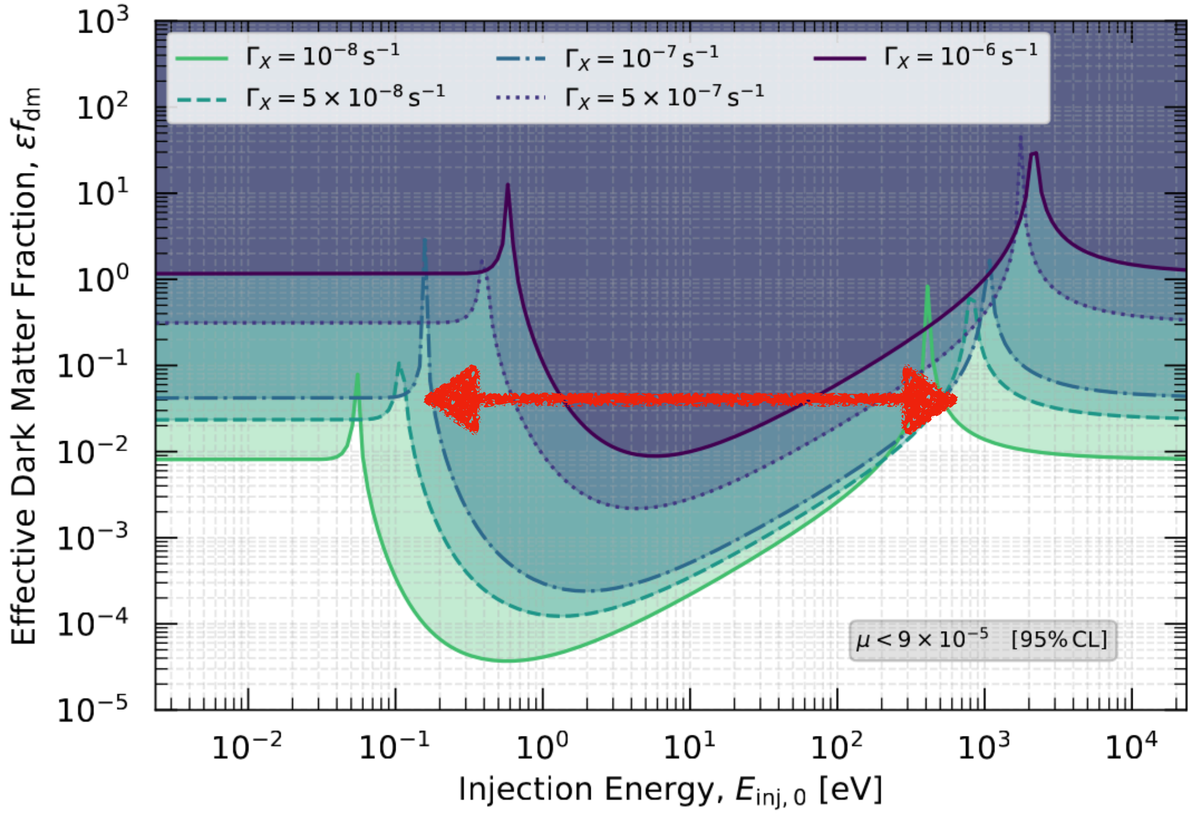
  ➡ Compute μ given lifetime and injection frequency $$\mu_{\rm inj} \approx 1.401 \int \left[x_{\rm inj} - x_{\rm null}\,\mathcal{P}_s(x_{\rm inj}, z)\right] \alpha_\rho \frac{{\rm d}\ln N_\gamma}{{\rm d}z}\,\mathcal{J}^*_{\rm bb}(z)\,{\rm d}z$$ (Chluba 15)

  ➡ Determine maximum allowed DM fraction given COBE/FIRAS bound



Constraints on Photon Injection using COBE/FIRAS

- For μ-era injection:
  - ➡ Compute μ given lifetime and injection frequency $\mu_{\rm inj} \approx 1.401 \int \left[x_{\rm inj} - x_{\rm null}\,\mathcal{P}_s(x_{\rm inj}, z)\right] \alpha_\rho \dfrac{\mathrm{d}\ln N_\gamma}{\mathrm{d}z}\,\mathcal{J}^*_{\rm bb}(z)\,\mathrm{d}z$ (Chluba 15)
  - ➡ Determine maximum allowed DM fraction given COBE/FIRAS bound



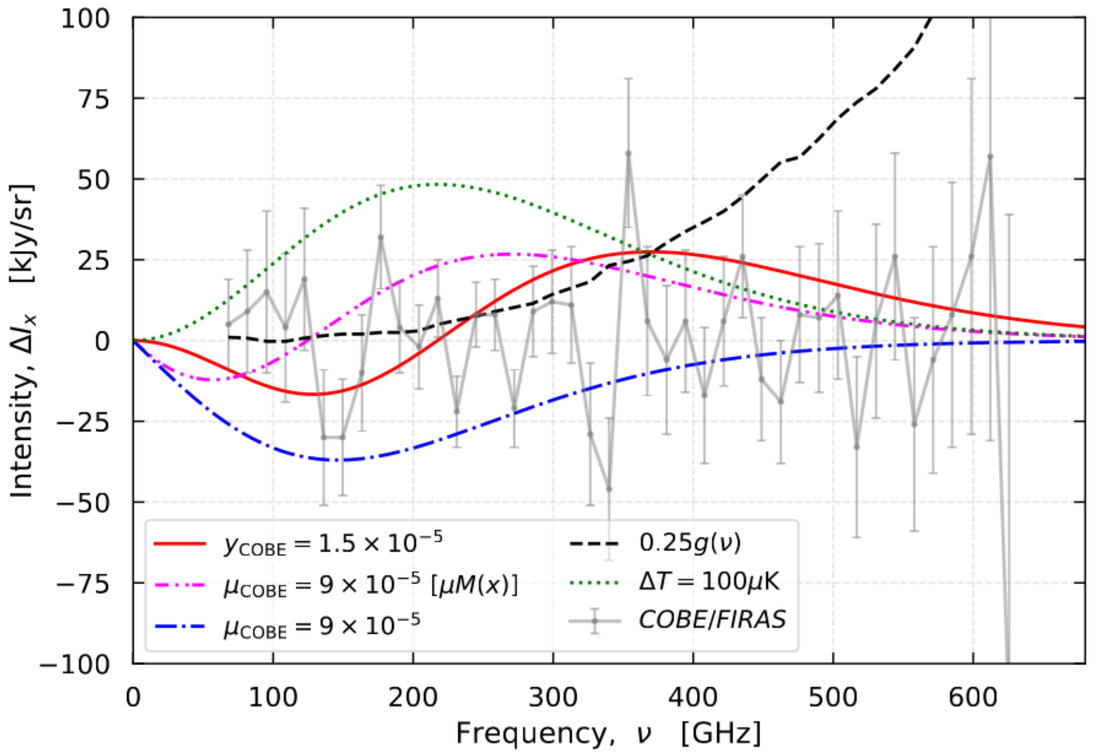
Negative μ-distortion:

Redistribution of added photons requires more energy than was added

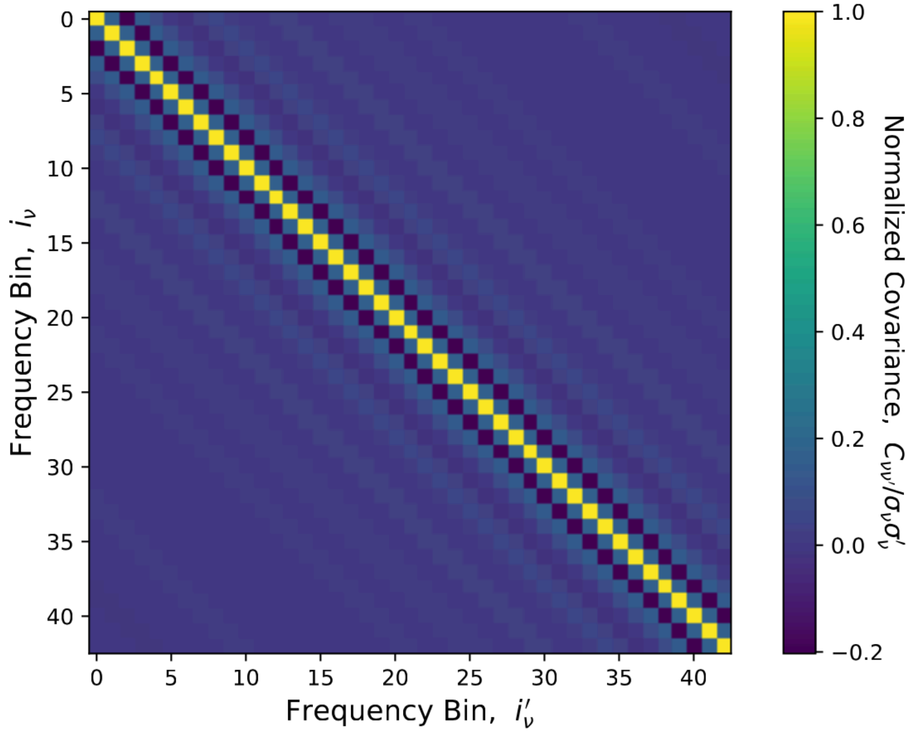
Constraints on Photon Injection using COBE/FIRAS

- For later injection:

➡ Fisher analysis on COBE/FIRAS data (Fixsen++ 96)

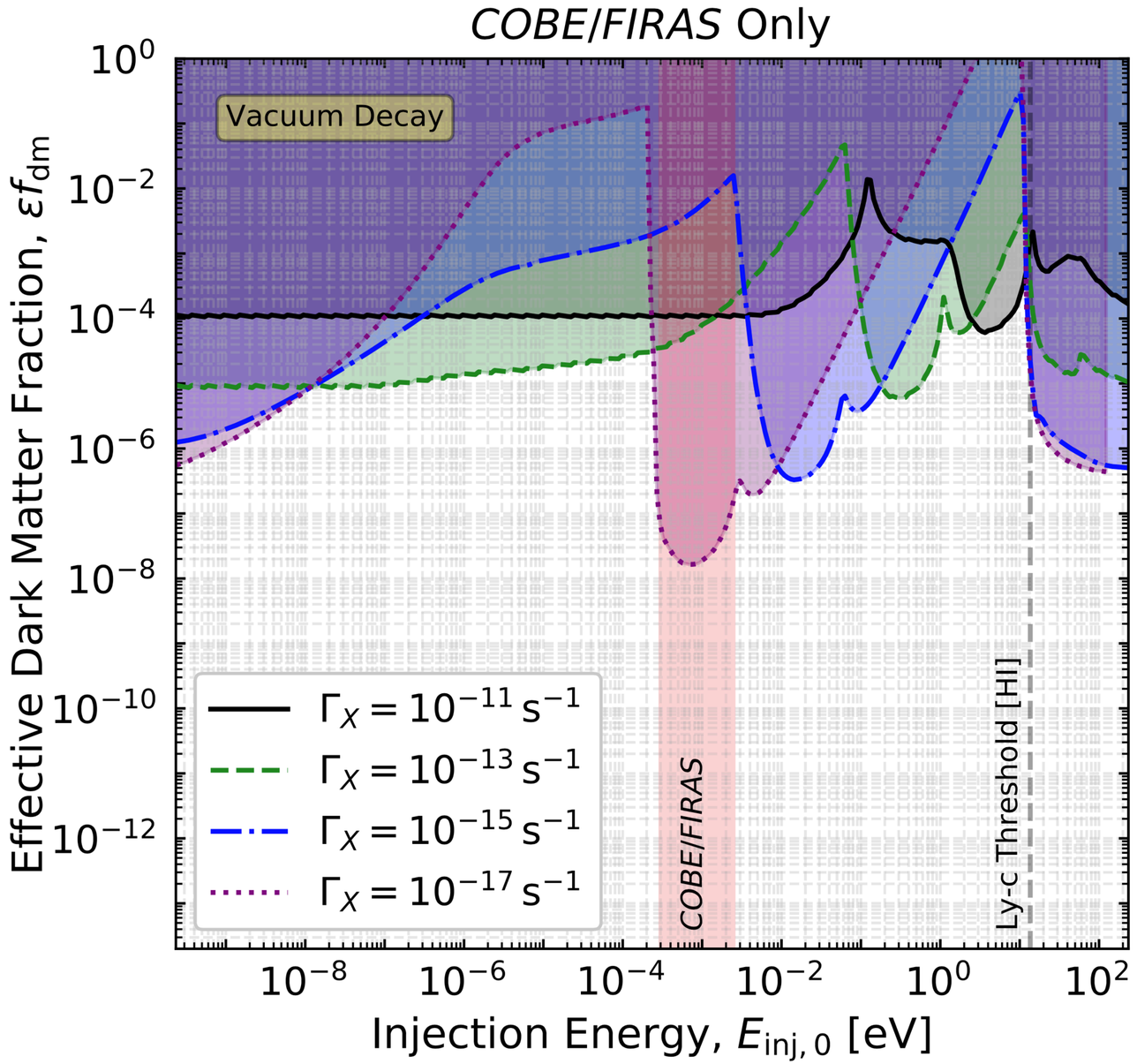


COBE/FIRAS data covariance matrix



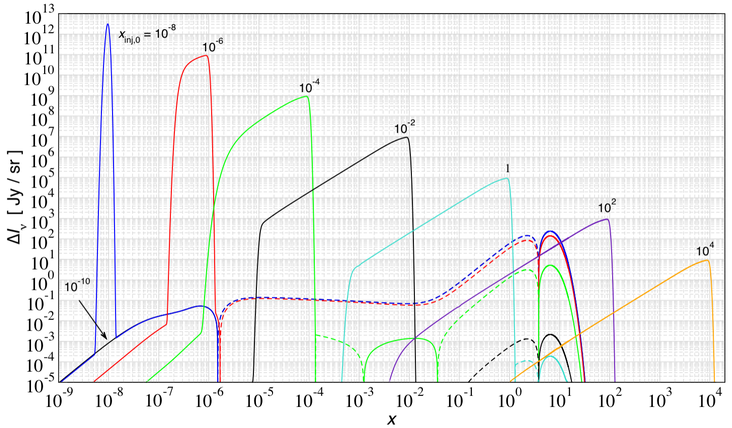
➡ Deduce 95%CL limit on DM fraction for each lifetime and injection frequency

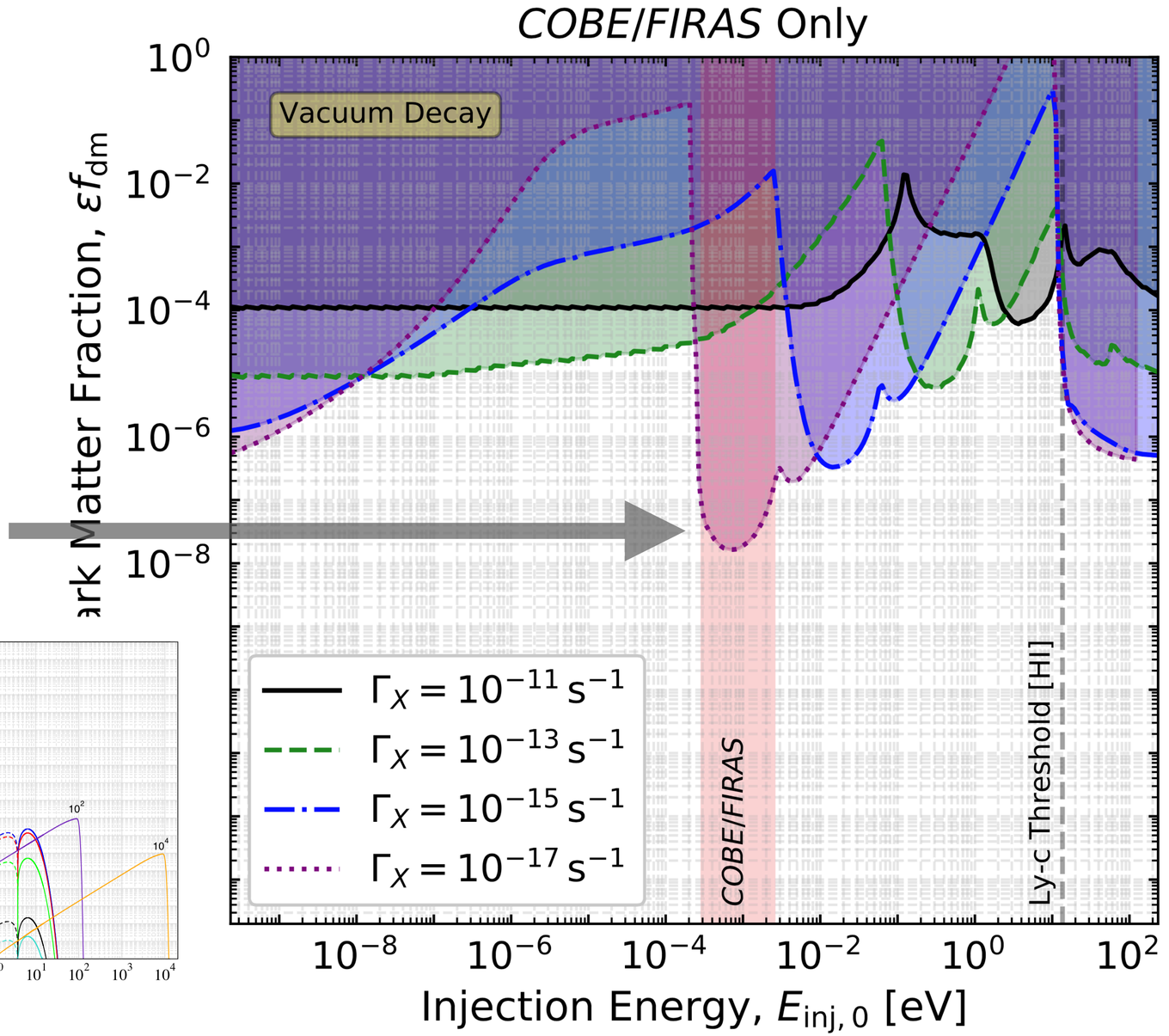
Constraints on Photon Injection using COBE/FIRAS



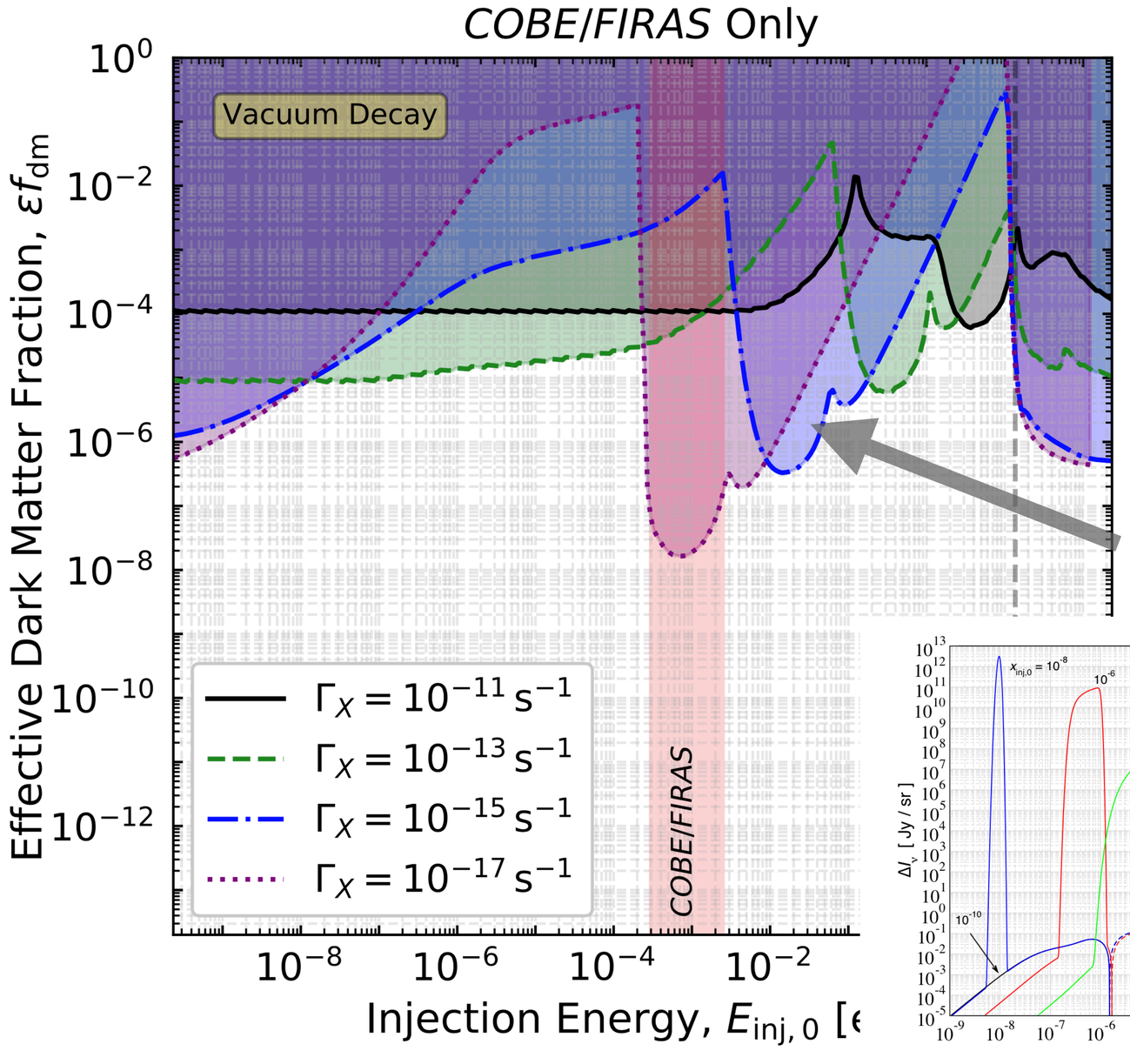
Constraints on Photon Injection using COBE/FIRAS

Constraint driven by
'peak' of the distortion

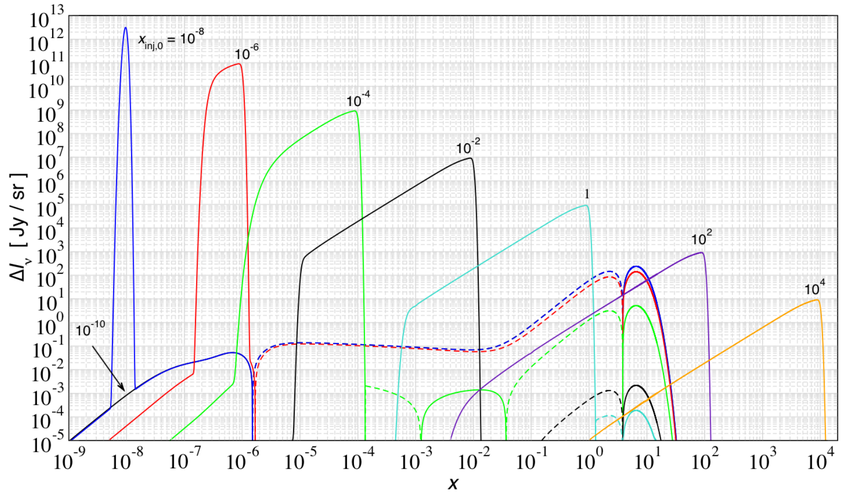




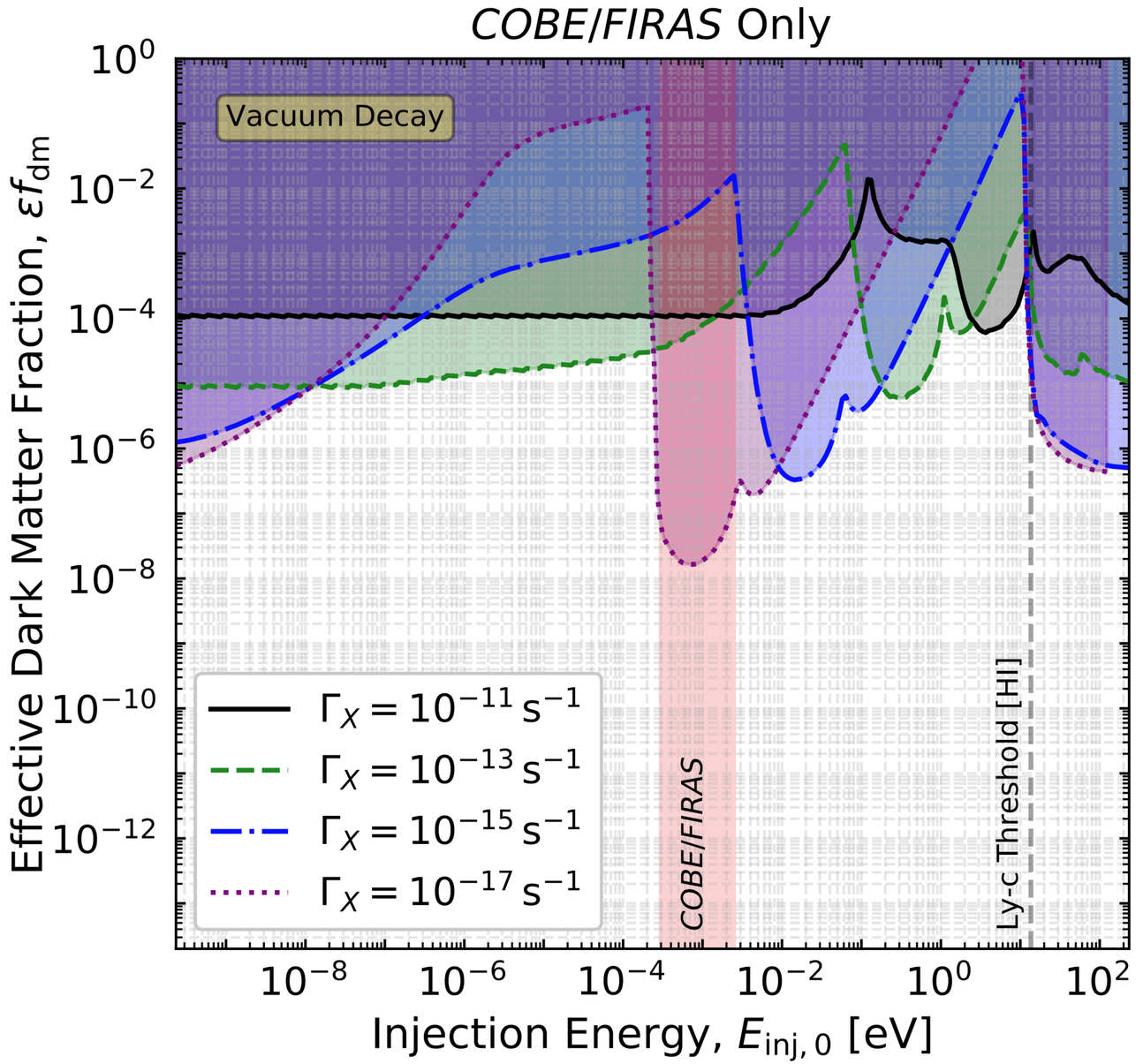
Constraints on Photon Injection using COBE/FIRAS



Constraint driven by
'slope' of the distortion



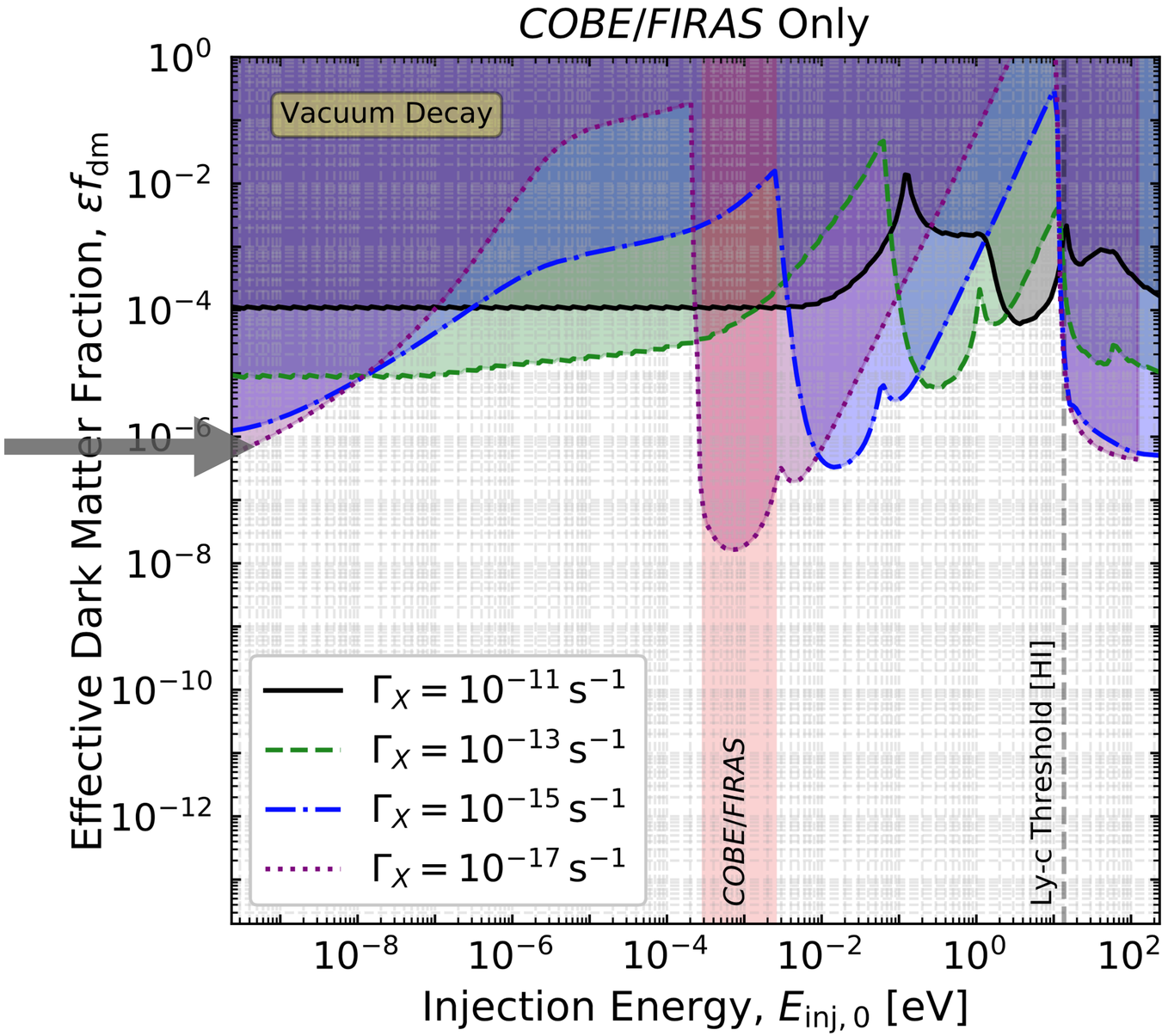
Constraints on Photon Injection using COBE/FIRAS



Constraint driven by
y-distortion
due to heating
from Ly-c absorption

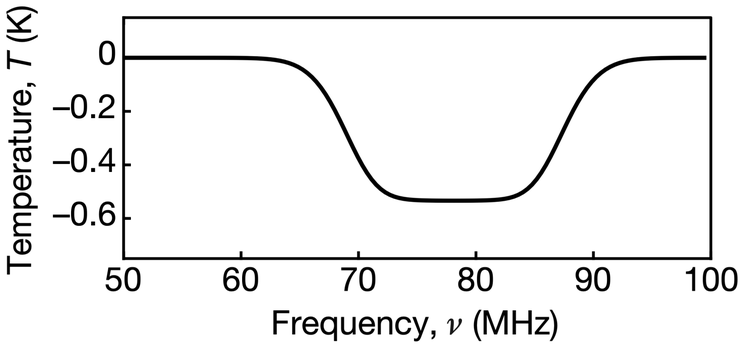
Constraints on Photon Injection using COBE/FIRAS

Constraint driven by
y distortion from heating
due to low frequency
free-free absorption

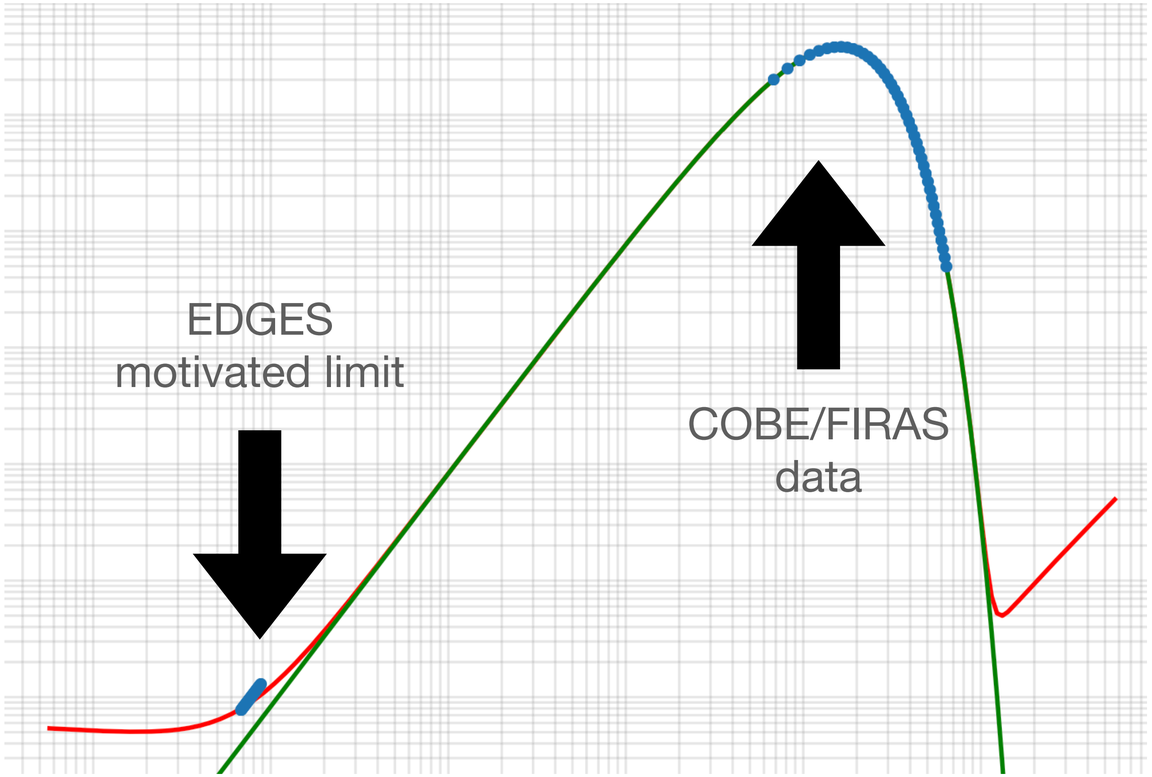


Adding Edges

- EDGES measurements set an upper limit on the CMB temperature at ~78MHz



- Upper limit on the CMB intensity

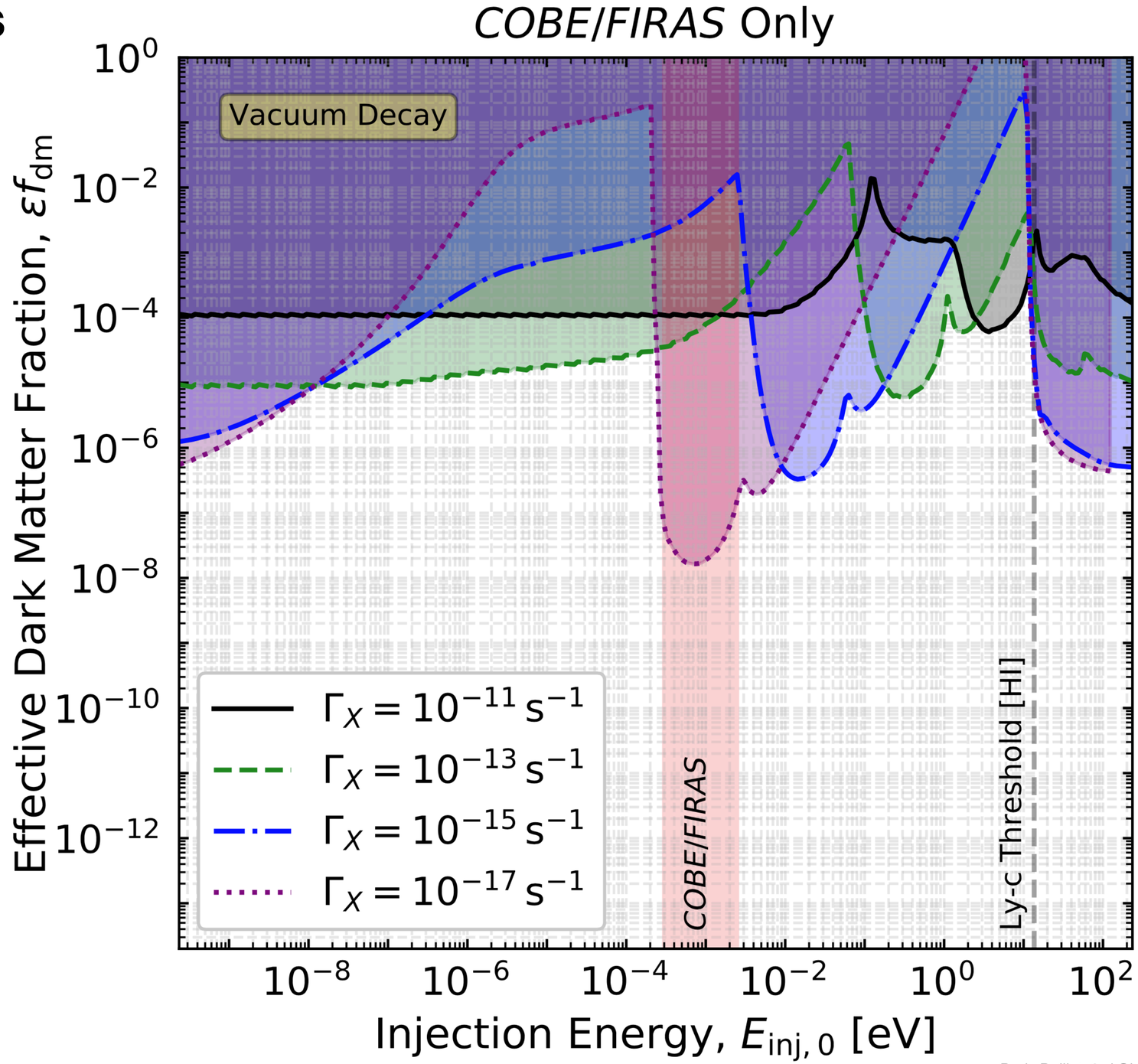


$$T_{21} \propto x_{\rm HI}\left(1-\frac{T_\gamma}{T_{\rm spin}}\right)$$

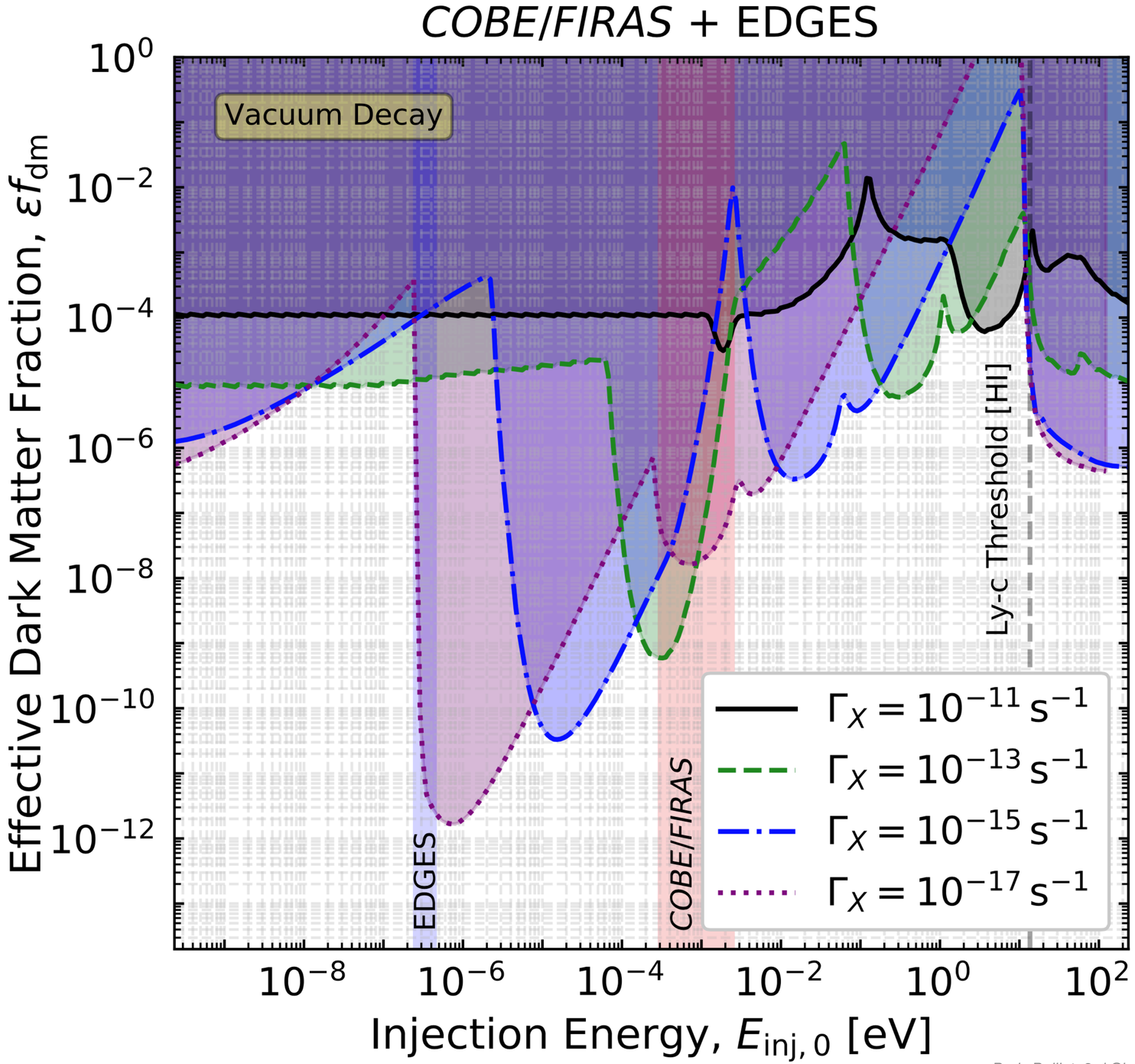
- Demand that distortion is compatible with EDGES at ~78MHz

- Re-run the Fisher analysis

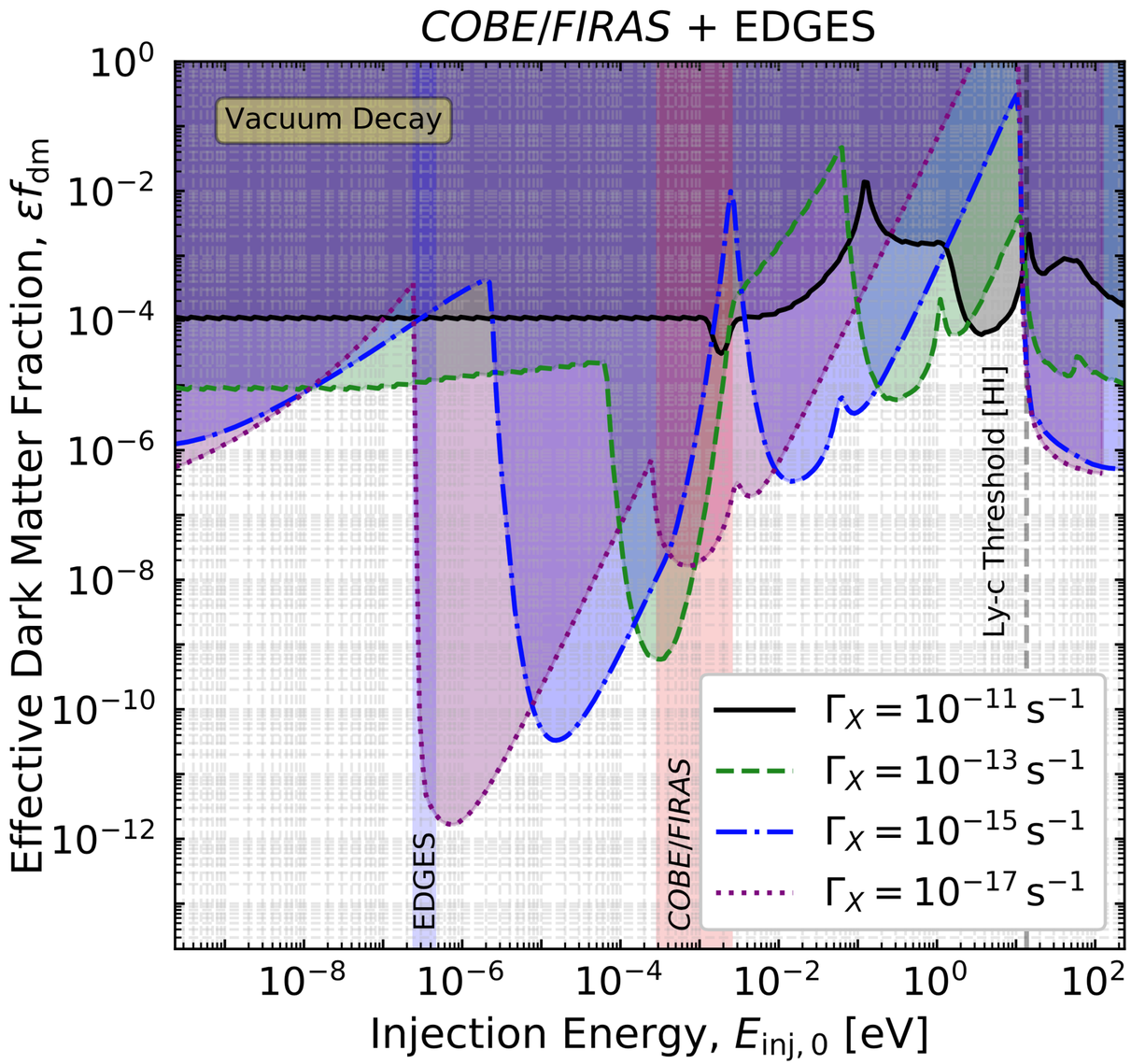
Adding Edges



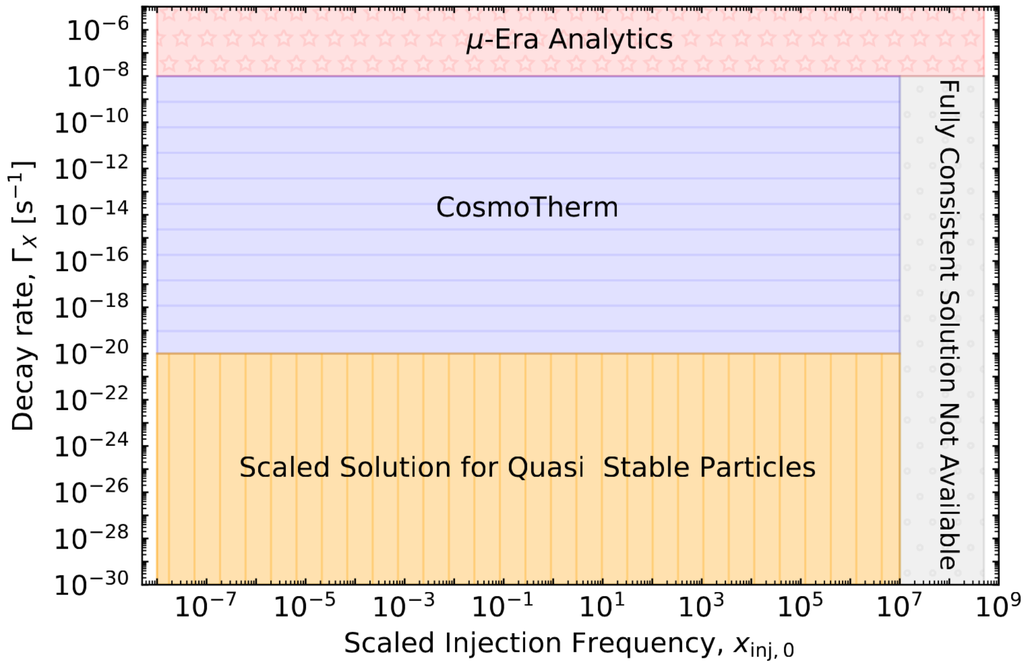
Adding Edges



Adding Edges

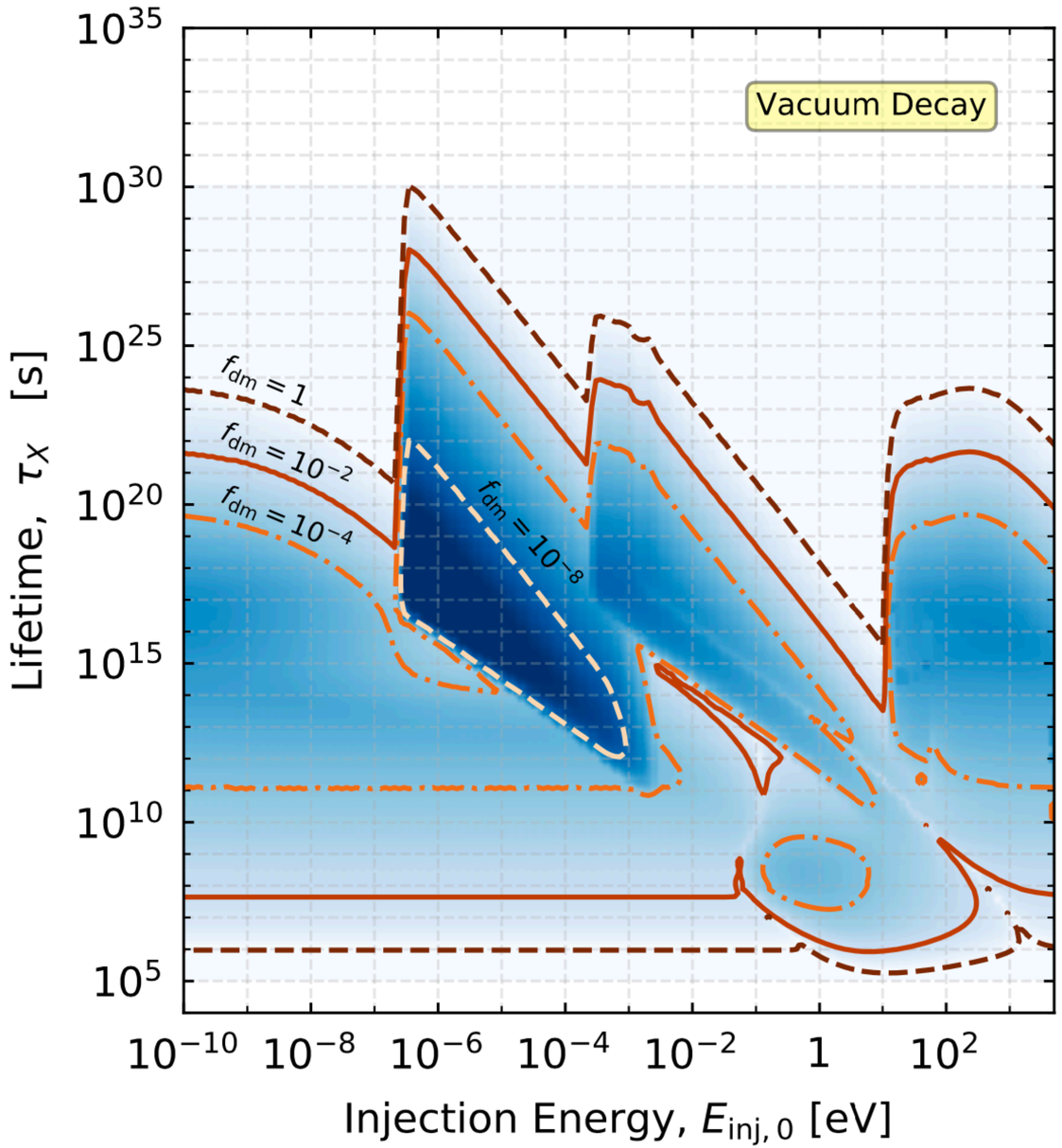


- Find the maximum allowed Dark Matter fraction for all lifetime and injection frequency



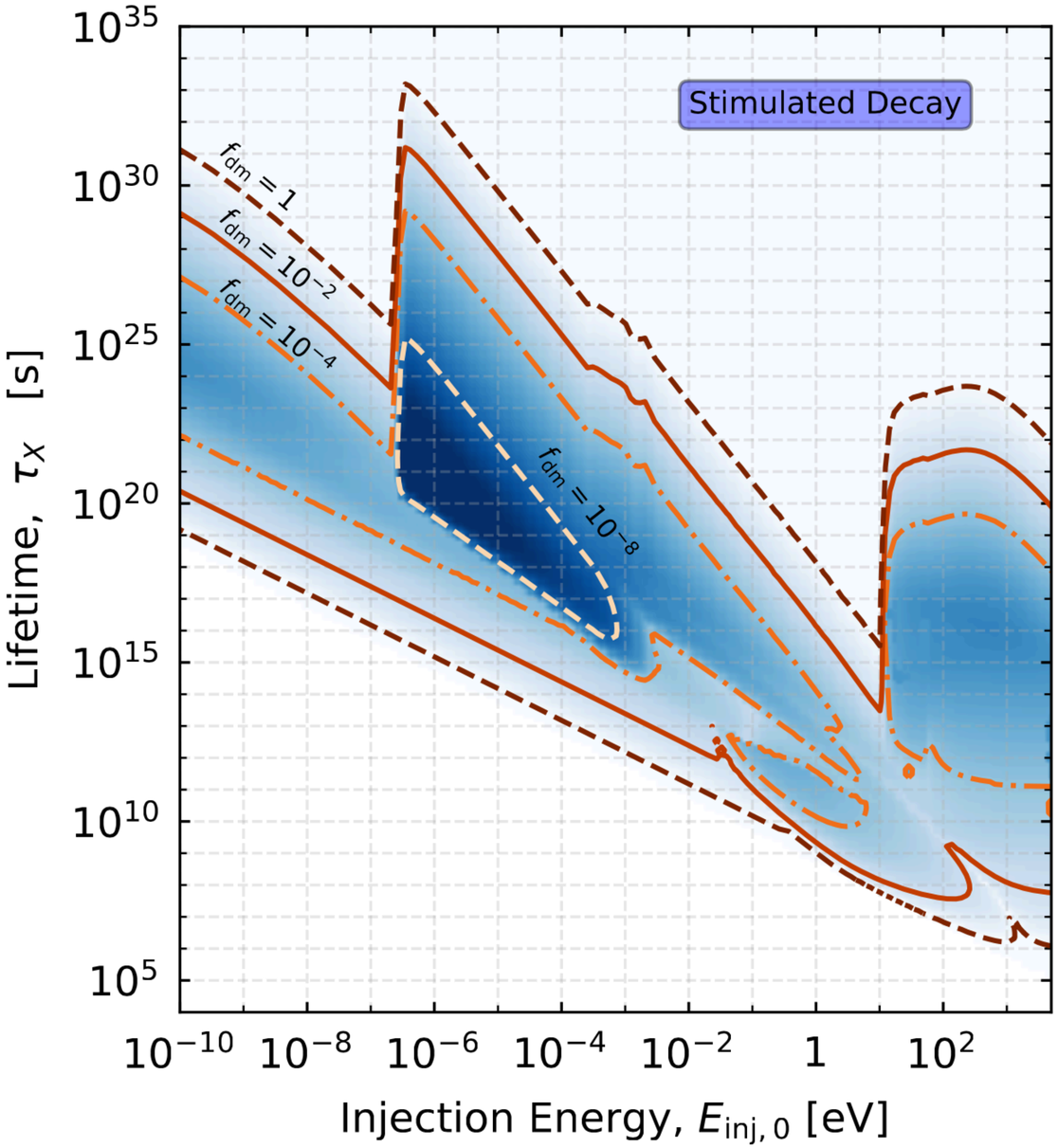
- 2d plot with contour levels for DM fraction

Vacuum Decay



- White area allowed
  - ✤ Thermalisation efficient (very short lifetime)
  - ✤ Or no significant injection (very long lifetime)
- Shaded area excluded by EDGES and COBE/FIRAS
- Can be complemented with constraints from CMB anisotropy based on ionisation history (see backup)
- Vacuum decay

Stimulated Decay



- Resonant emission (see, e.g., Caputo++ 18)

- Decay law becomes frequency dependent

$$\Gamma_X^{\rm stim} = [1 + 2n_\gamma(x_{\rm inj})]\Gamma_X$$

- Low frequency injection: faster decay (see backup)

- High frequency injection: no difference

➡ Low injection energy constraints map to longer lifetimes

Mapping to ALP models

- Axion Like Particles, initially motivated by solutions to the strong CP problem (see, e.g., Marsh 16)

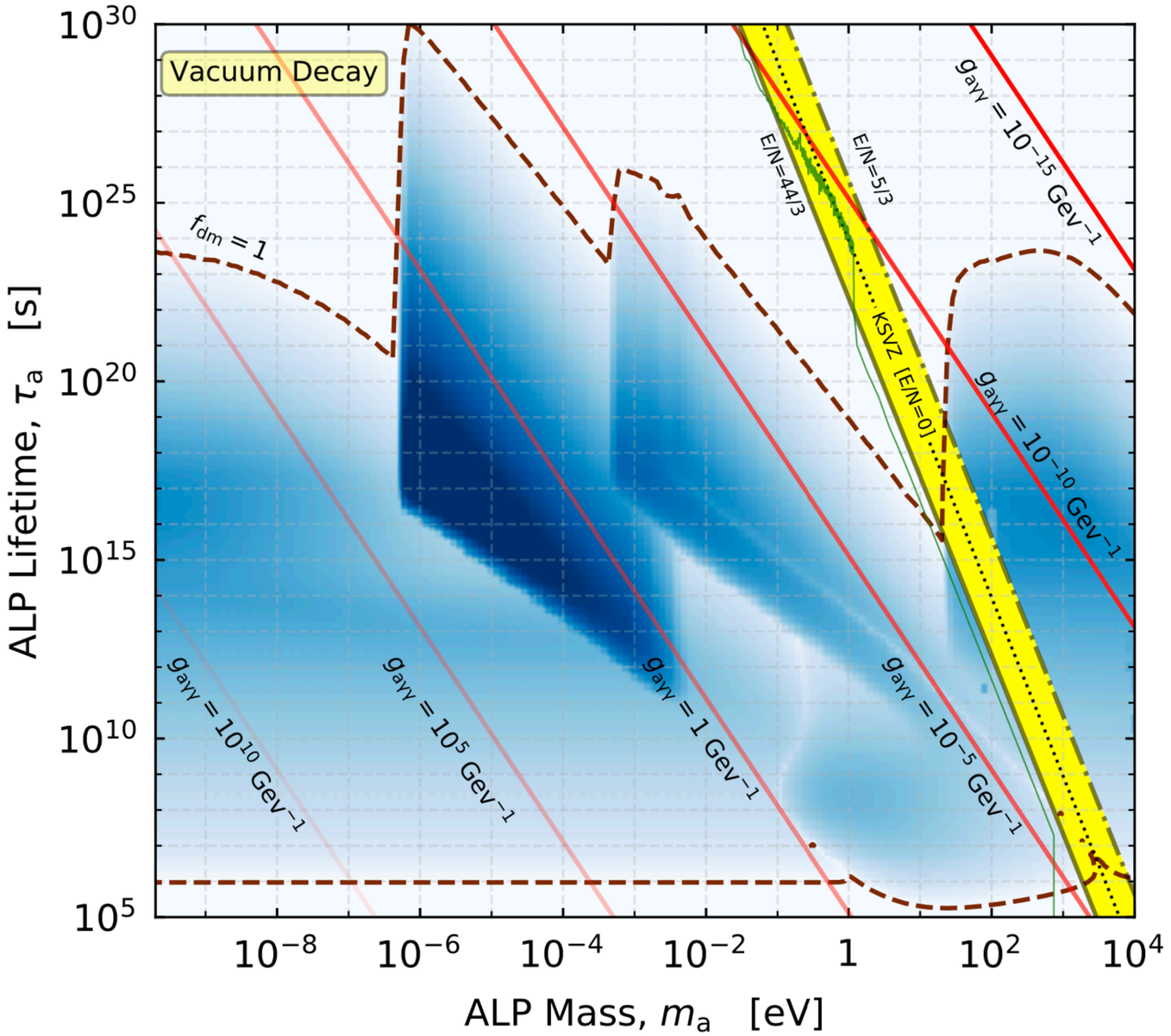
- Coupling to EM via several channels, including two-photons decay

- Coupling constant for two-photons decay —> relation between ALP mass and lifetime

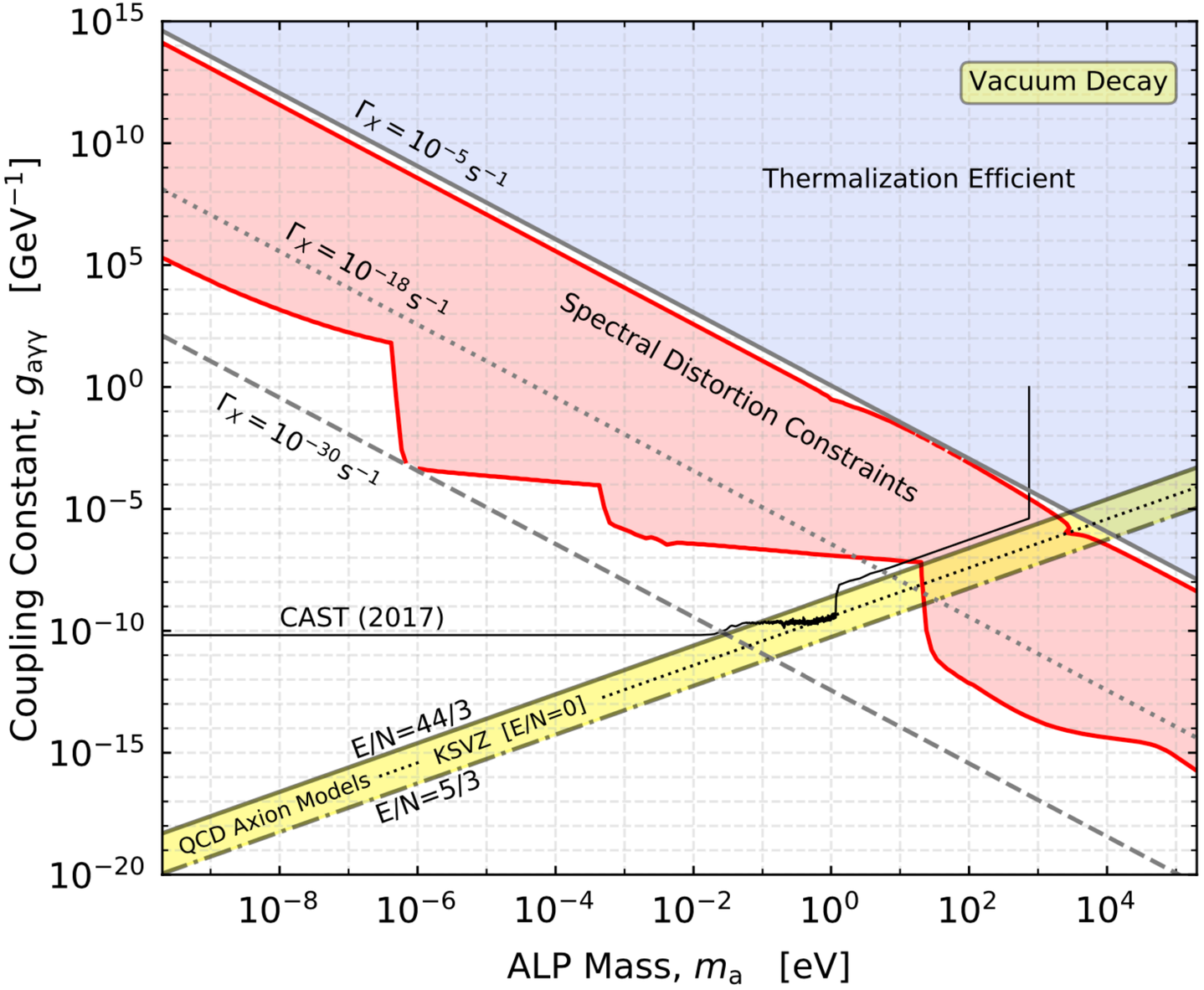
$$g_{a\gamma\gamma} = \left(\frac{64\pi\Gamma_a}{m_a^3}\right)^{1/2} \approx \frac{3.63\times10^{-2}}{\mathrm{GeV}}\left[\frac{\Gamma_a}{10^{-17}\mathrm{s}^{-1}}\right]^{1/2}\left[\frac{m_a c^2}{\mathrm{meV}}\right]^{-3/2}$$

- Fix a value of DM fraction and set constraint on coupling constant

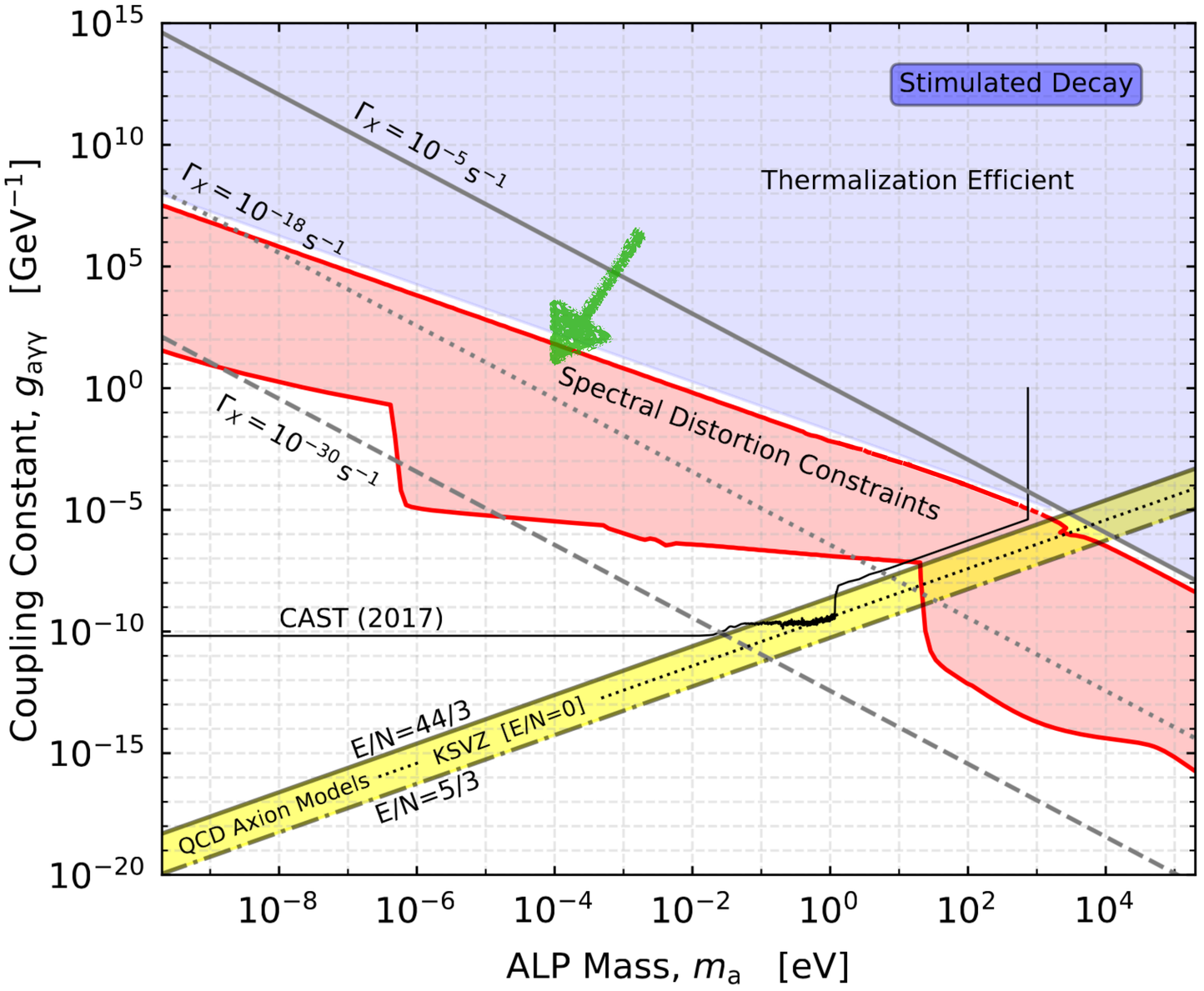
Mapping to ALP models



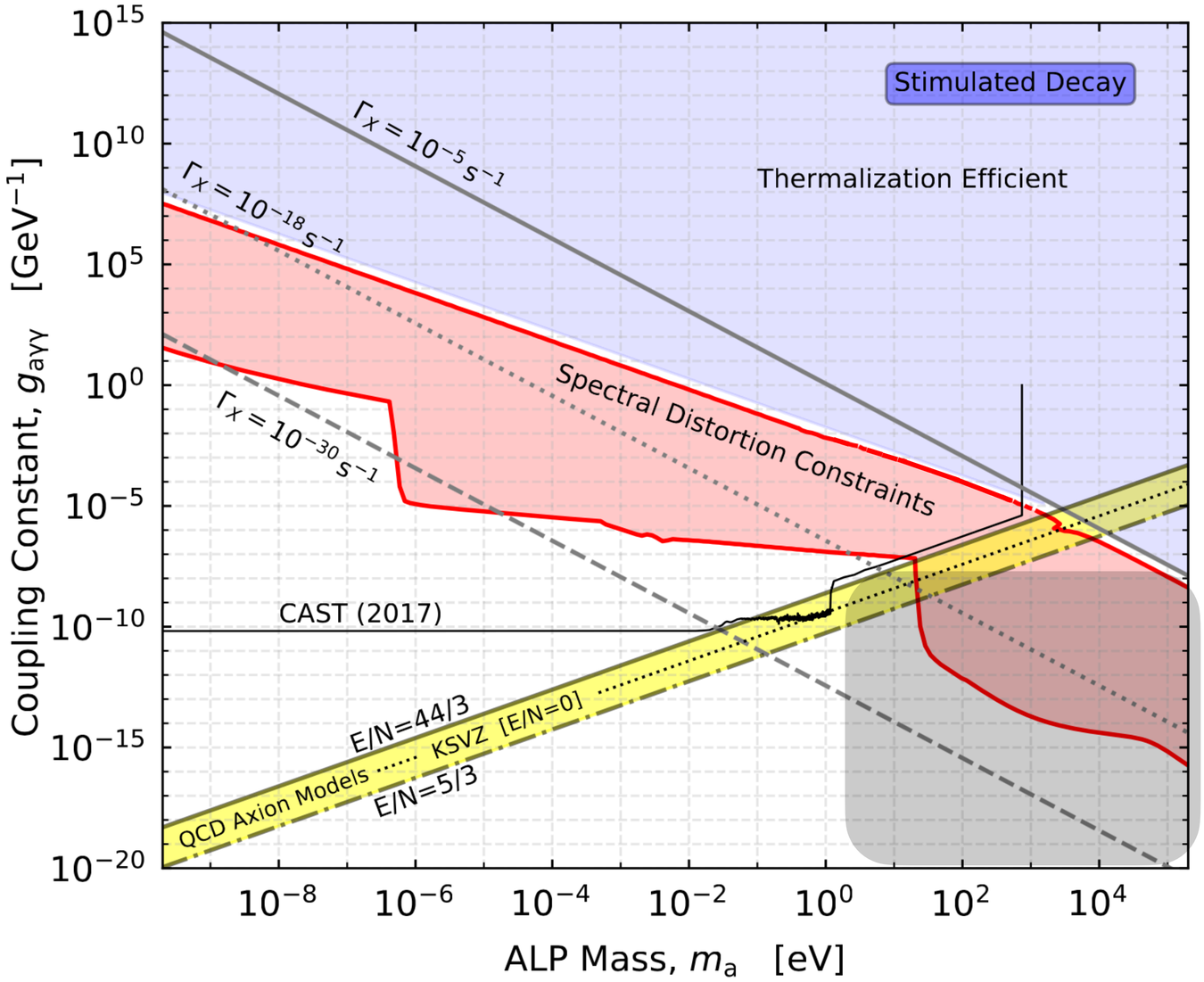
Mapping to ALP models - Vacuum Decay



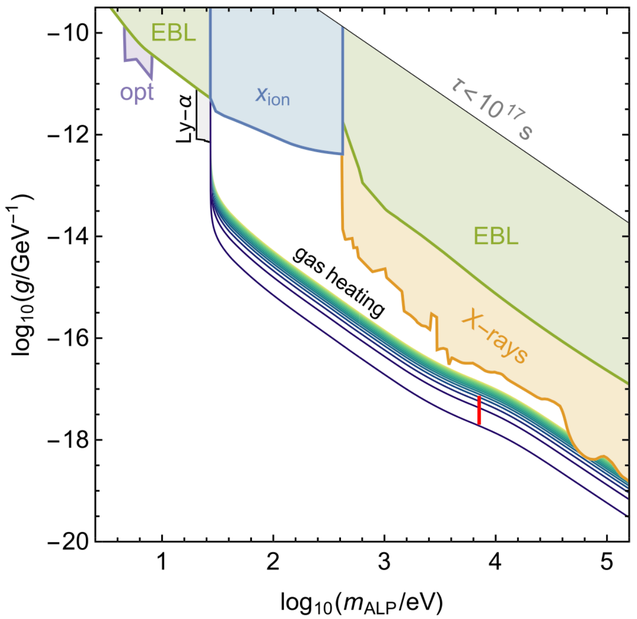
Mapping to ALP models - Stimulated Decay



Mapping to ALP models

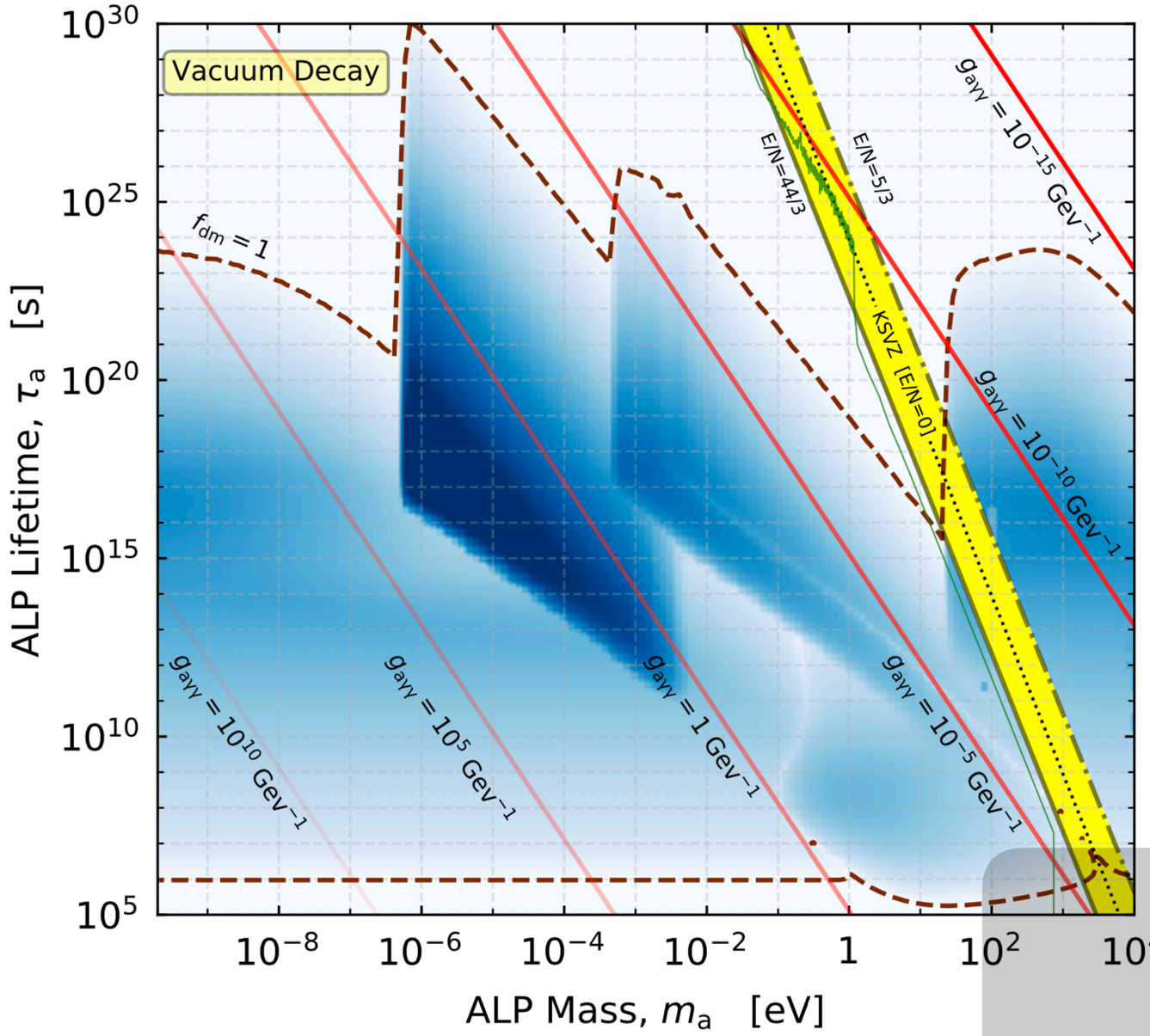


Hektor++ 18

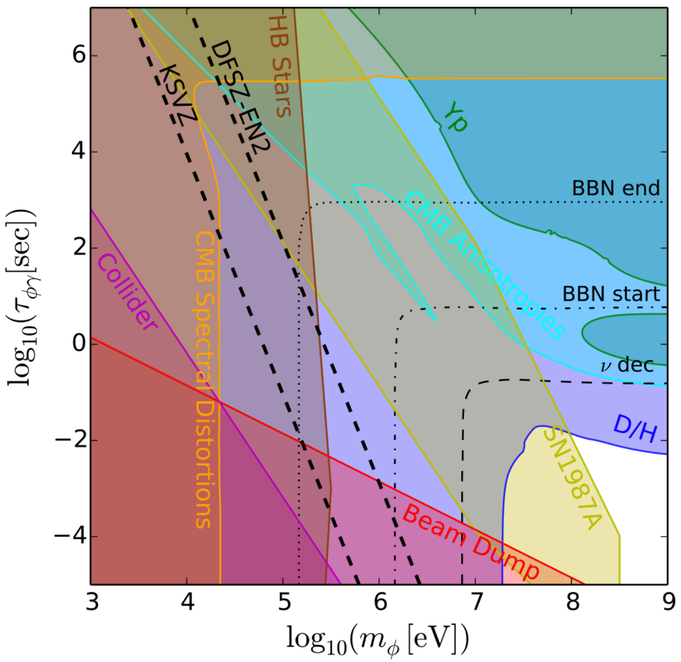


EDGES based constraints

Mapping to ALP models

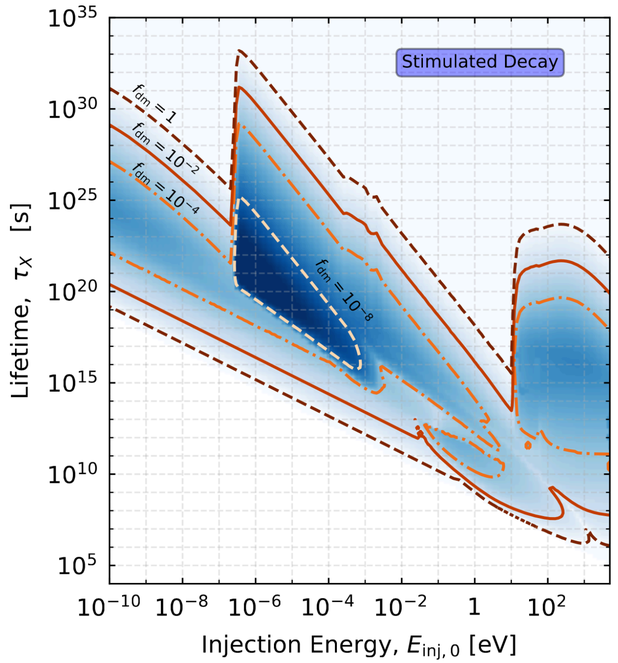


Millea, Knox and Fields 15

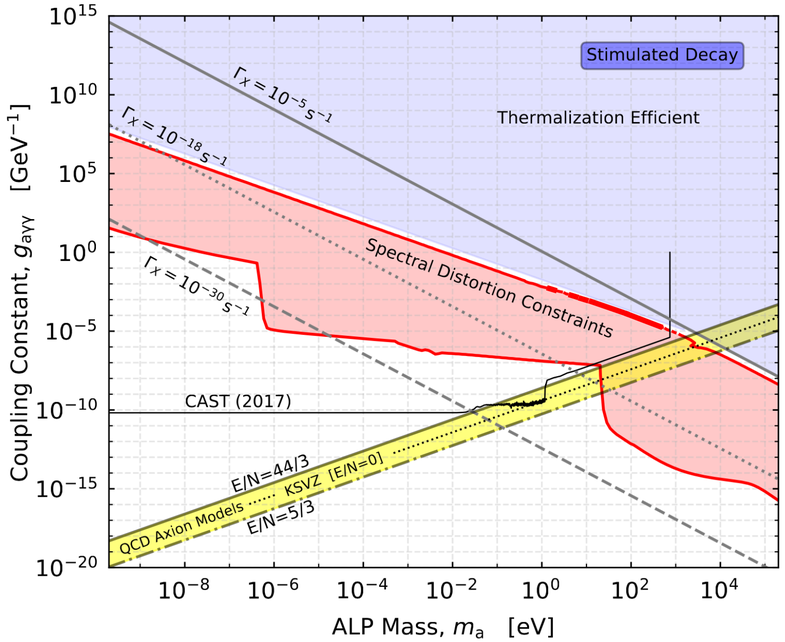


COBE/FIRAS based constraints
(See also Cadamuro and Redondo 12)

Important Points



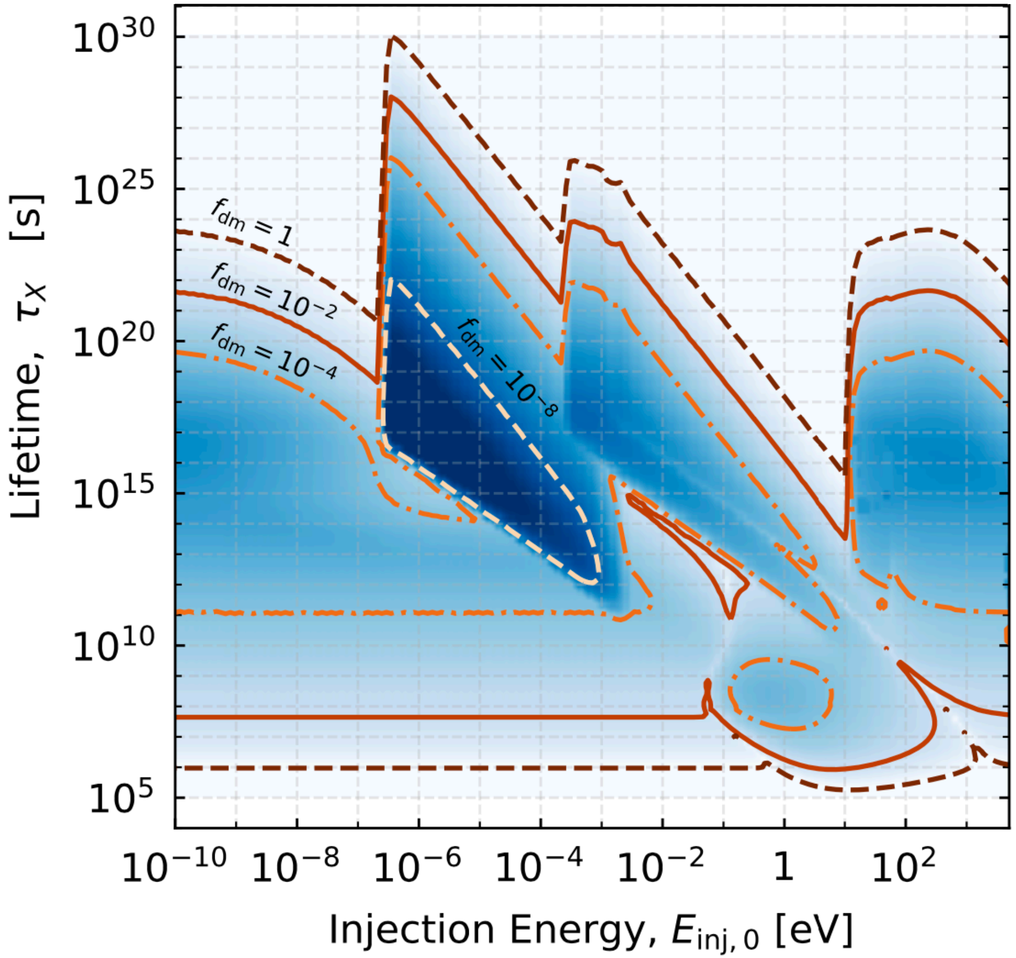
- New constraints on photon injection derived from COBE/FIRAS
- First constraints from the actual frequency dependent spectra
- EDGES useful to constrain photon injection at ~μeV energies

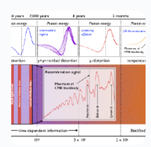


- Model independent constraints can be mapped to specific models
- Example: ALPs two-photons decay
- Spectral distortion constraints on ALPs are competitive at high mass

Conclusions

- State-of-the-art thermalisation solutions for photon injection
- Library of photon injection spectra
- New Model independent constraints using COBE/FIRAS and EDGES
- Mapping to models relatively straightforward
- Library can be used to search for injections with specific features
- Bolliet, Chluba, Battye — to appear

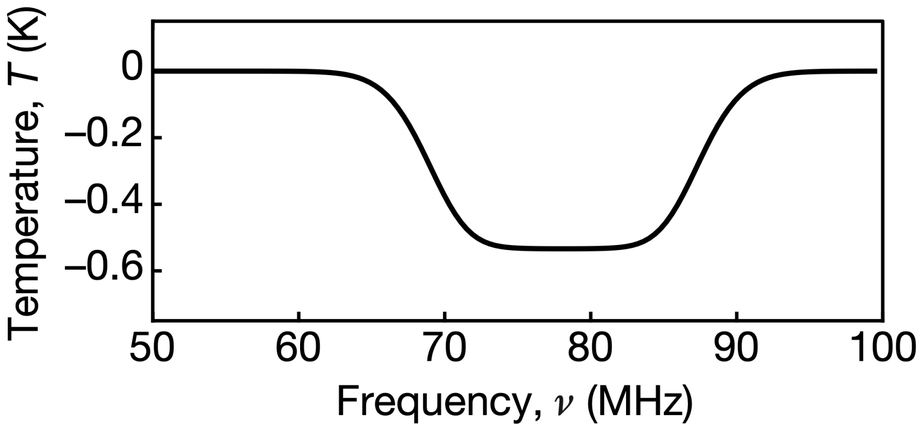




CMBSPEC

Can we place more stringent constraints using EDGES data?

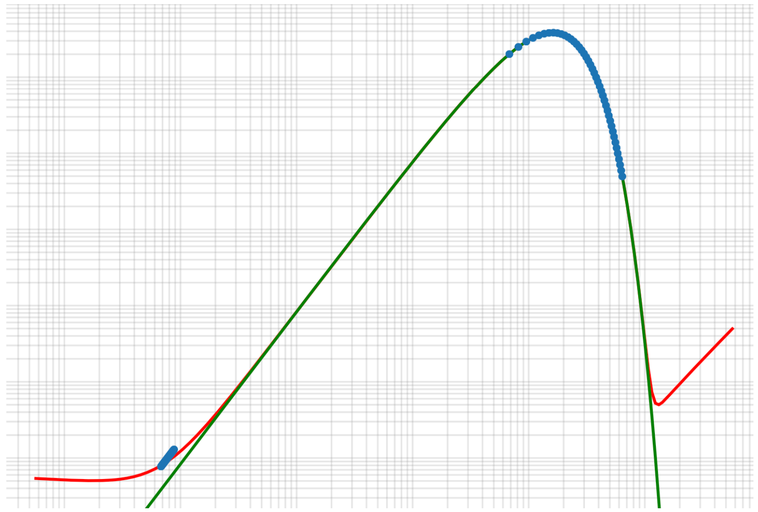
- Yes, in principle EDGES requires the CMB temperature to be twice larger than expected between ~65-90MHz

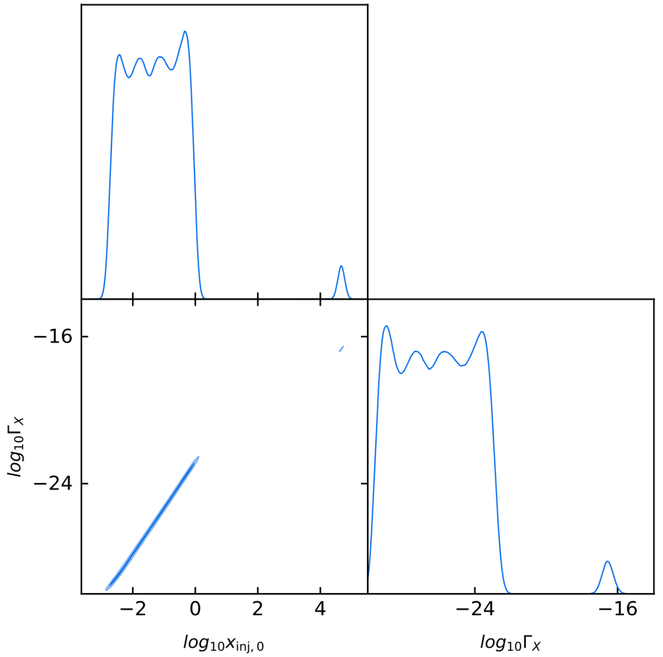


- We can look for models that do exactly this, while being consistent with COBE/FIRAS

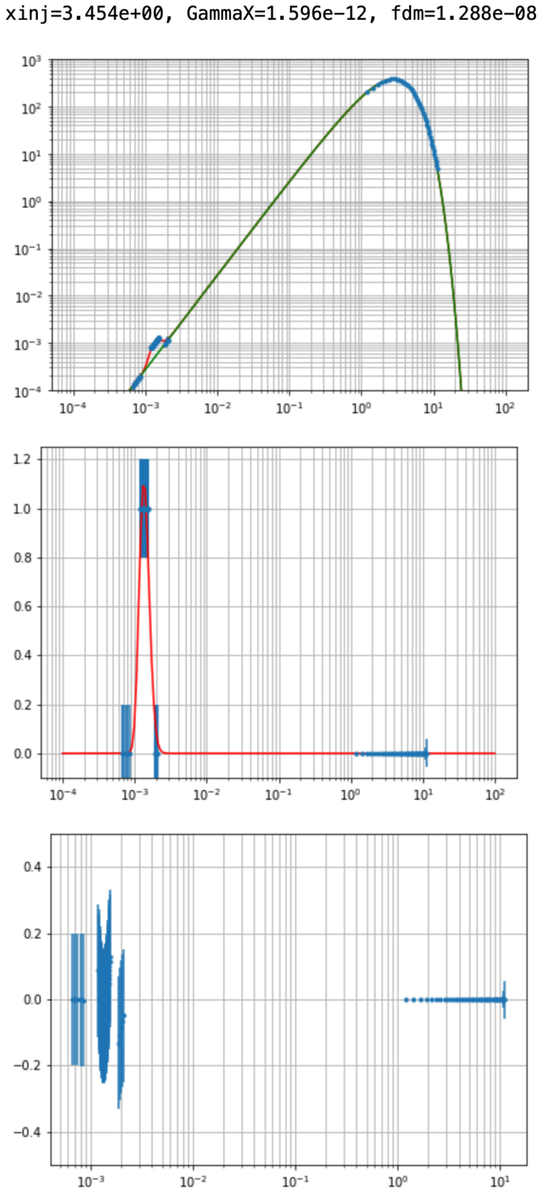
- EDGES-like data points and MCMC analysis using our distortion database

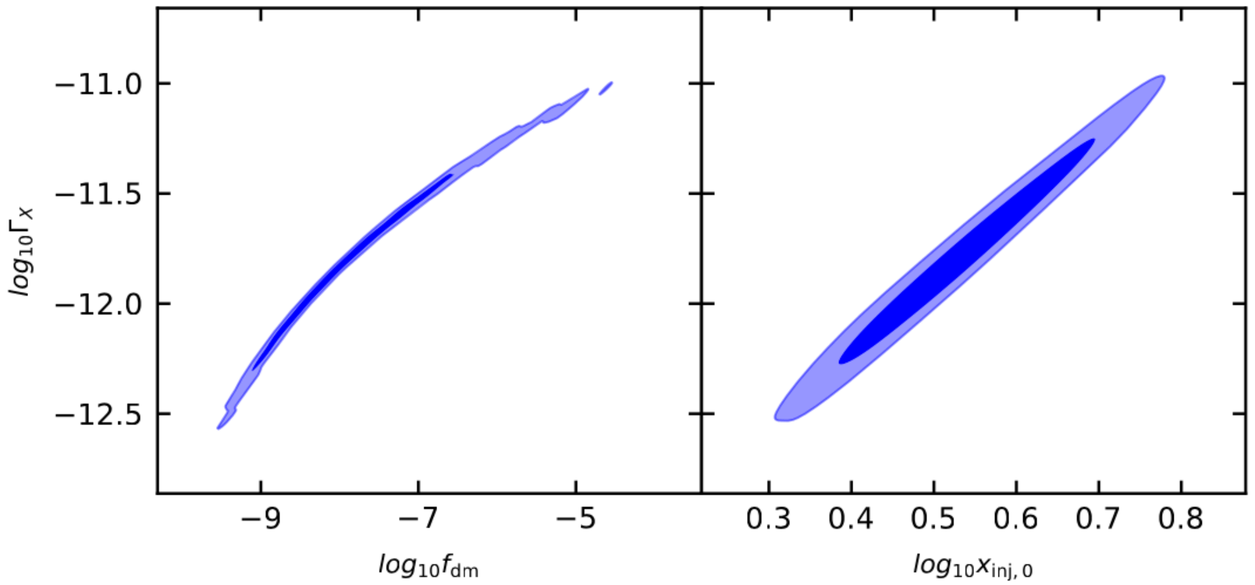
- Example:





More tuning….





Characterising the set of models that have a very specific feature at 80MHz:

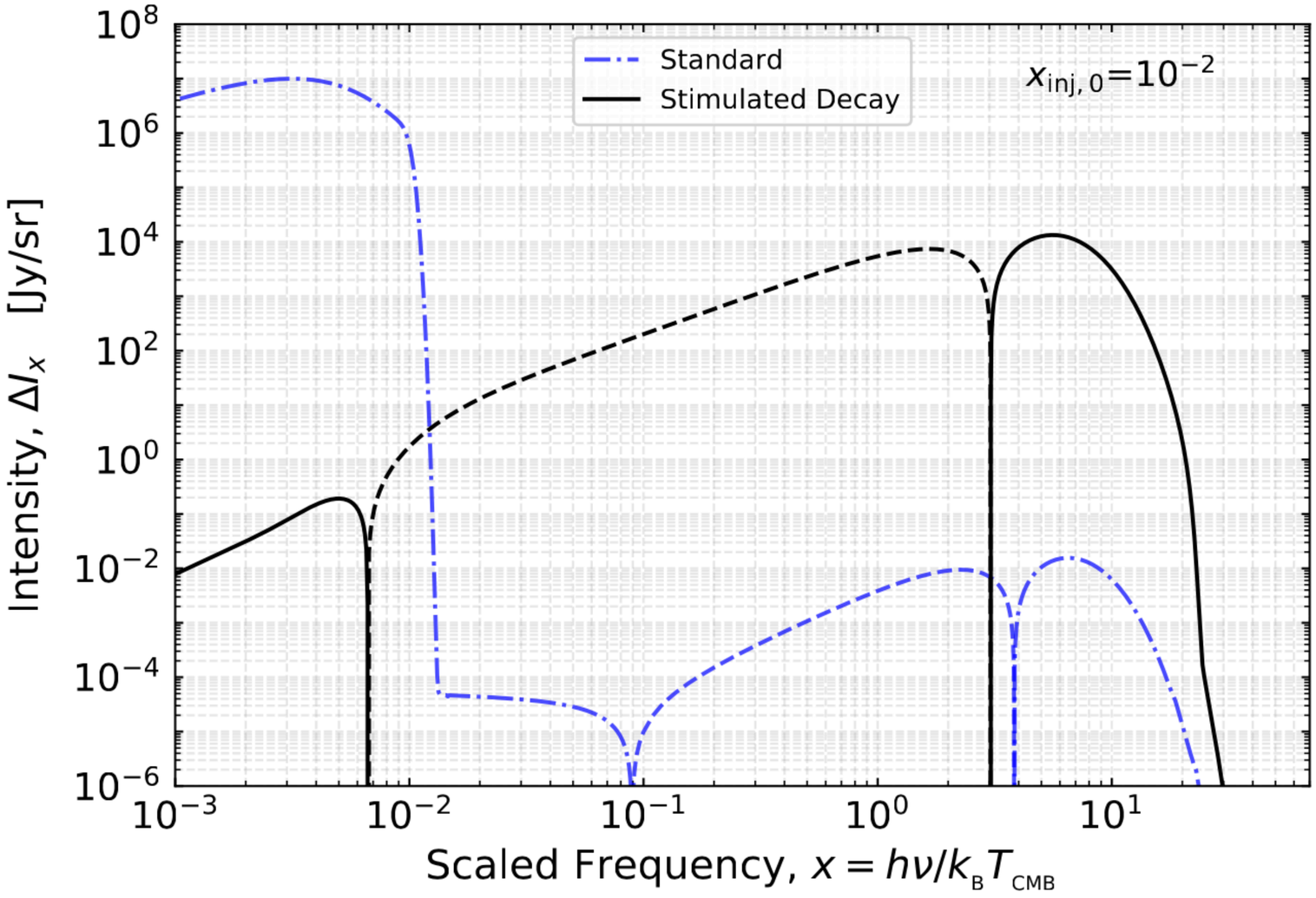
Γ_X such that $5 \times 10^{-13}\mathrm{s}^{-1} \leqslant \Gamma_X \leqslant 5 \times 10^{-12}\mathrm{s}^{-1}$

$x_{\rm inj,0} = (\Gamma/2 \times 10^{-14}\mathrm{s}^{-1})^{0.28}$ $\qquad f_{\rm dm} = 10^{y}$ $\qquad y = ax^2 + bx + c$

$(a, b, c) = (1.11, 29.23, 182.4)$

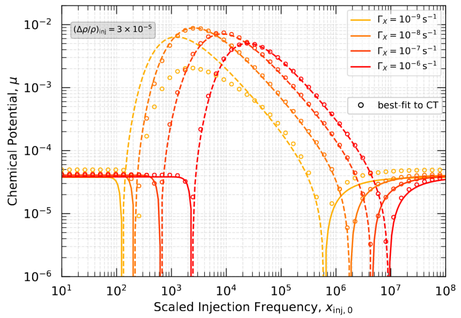
Stimulated Decay

here: lifetime = age of the universe



Photon Injection Spectra Today

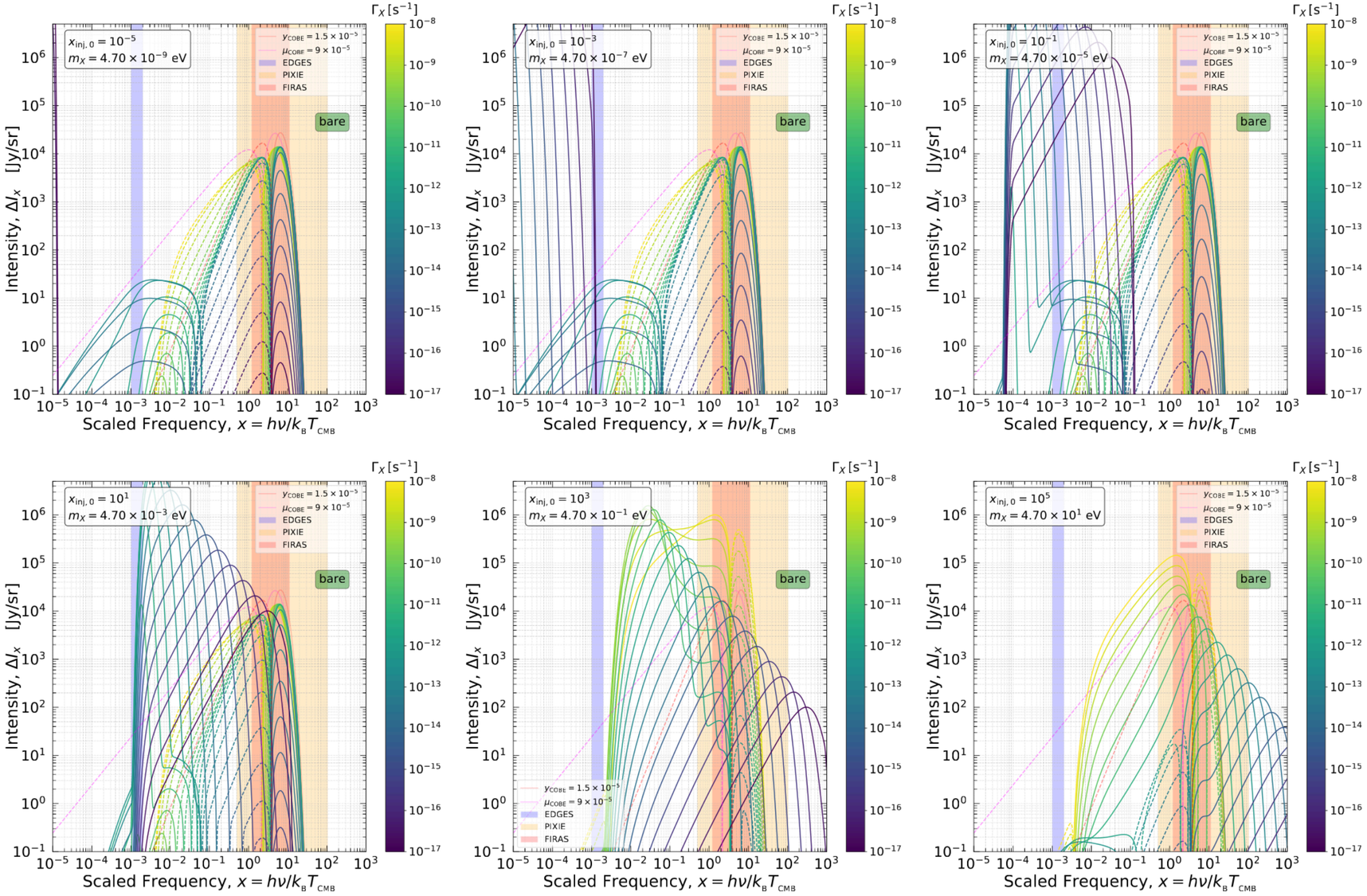
- Very early injection
  - ➡ positive mu distortion
  - ➡ except at some high frequency: negative μ



- Intermediate injection
  - ➡ positive y distortion
  - ➡ except at some high frequency: negative y

(Chluba 15, BCB20)

- Late injection
  - ➡ peak, ‘typewriter’
  - ➡ small y



These distortions are generally not the common mu and y distortions

Solving the Thermalisation problem with CosmoTherm

- PDE Solver

$$\frac{\partial n_\nu}{\partial \tau} - \frac{t_{\rm C}}{t_{\rm H}} \nu \frac{\partial n_\nu}{\partial \nu} = \left.\frac{{\rm d}n_\nu}{{\rm d}\tau}\right|_{\rm C} + \left.\frac{{\rm d}n_\nu}{{\rm d}\tau}\right|_{\rm DC} + \left.\frac{{\rm d}n_\nu}{{\rm d}\tau}\right|_{\rm BR} + \left.\frac{{\rm d}n_\nu}{{\rm d}\tau}\right|_{\rm PI}$$

(Chluba & Sunyaev 12)

- Initial condition before the distortion era

- Normalisation fixed by condition on total injected energy injected during distortion era:

$$\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_{\rm inj} = \int \frac{{\rm d}\ln\rho_\gamma}{{\rm d}z}\,\mathcal{J}_{\rm bb}(z)\,{\rm d}z \quad \text{such that} \quad \Delta\rho/\rho|_{\rm inj} = 3\times10^{-5}$$

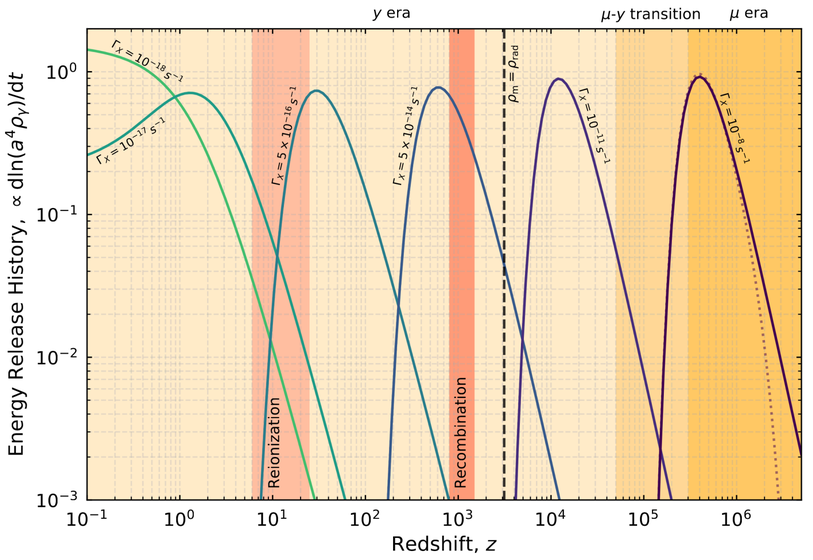
corresponding to 68%CL (stat.) COBE/FIRAS limit on mu/y

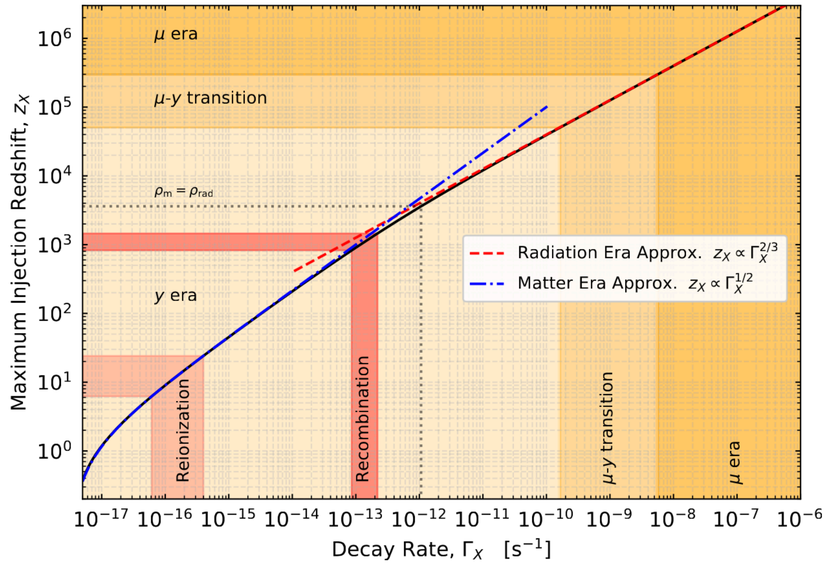
Recall:

$$y \approx \frac{1}{4}\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$$

$$\mu_0 \approx 1.401\left[\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu - \frac{4}{3}\left.\frac{\Delta N_\gamma}{N_\gamma}\right|_\mu\right]$$

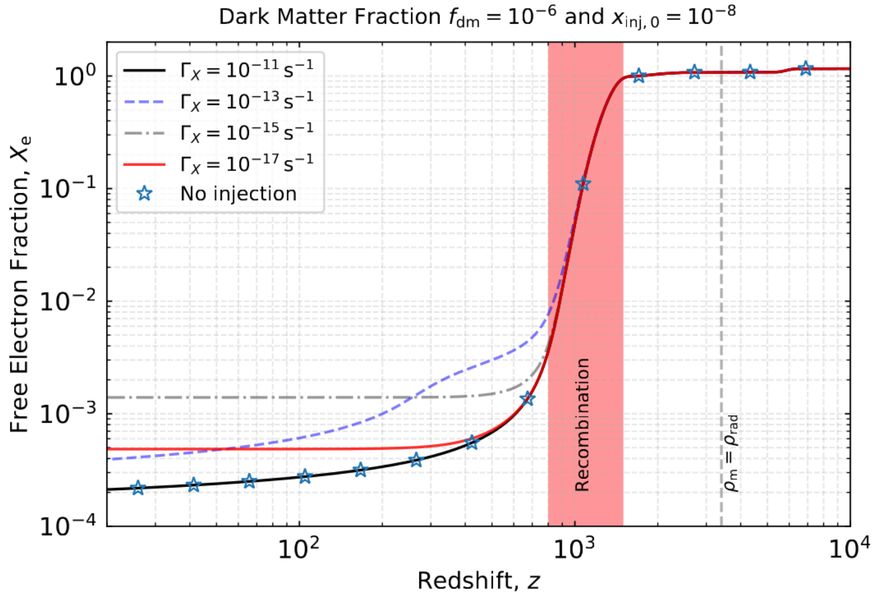
(see, e.g., Jens's CUSO lecture)



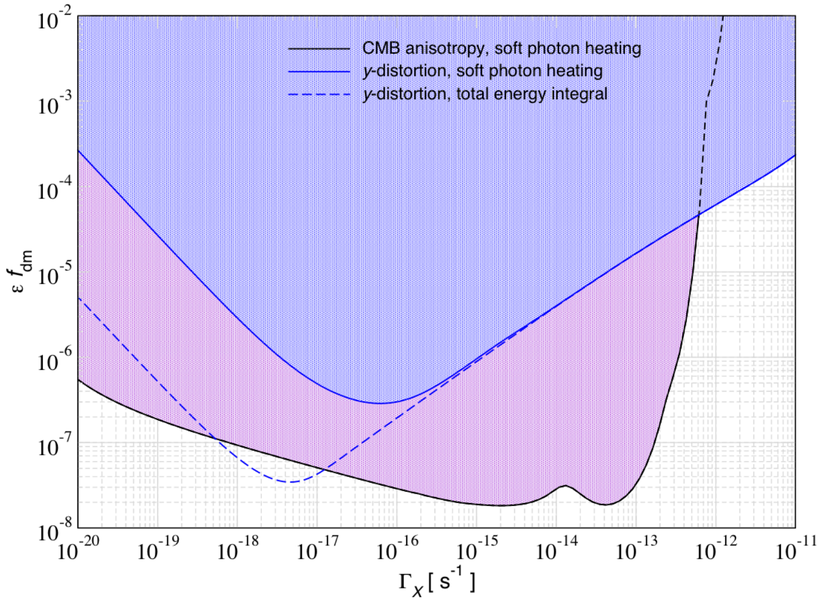


Adding CMB anisotropy constraints on ionisation history

- Simple for low frequency injection: y-distortion



$$y \approx \int \frac{k[T_e - T_\gamma]}{m_e c^2} N_e \sigma_T c \, dt$$

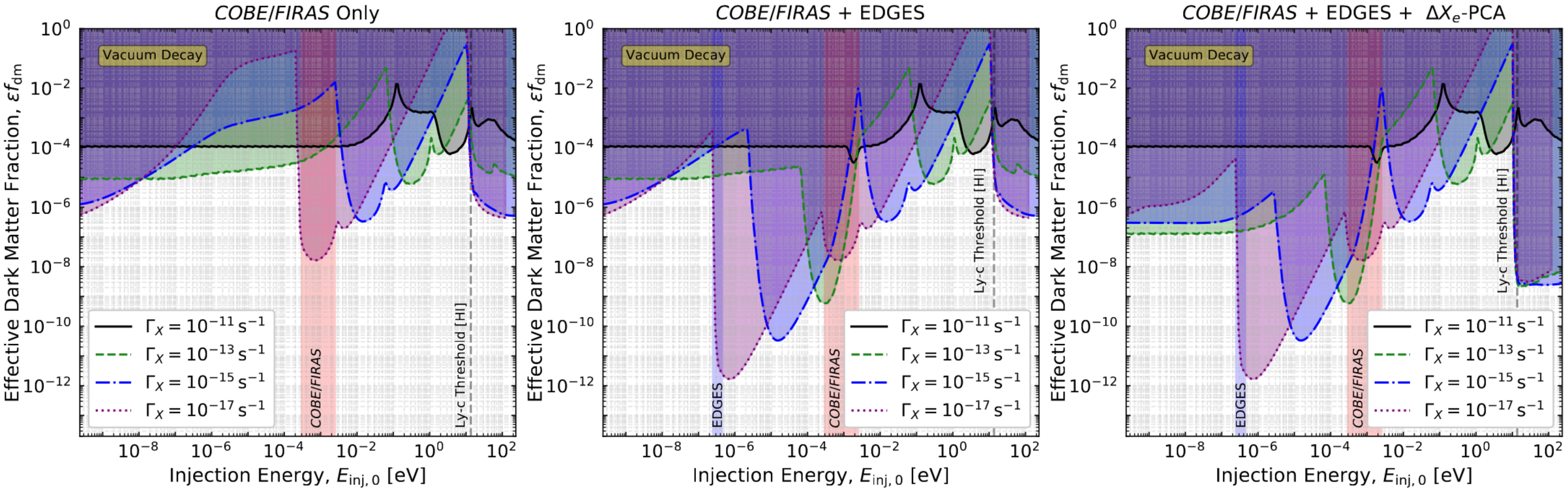


- PCA method for other frequencies

$$\rho_i^{inj} = \int \zeta_{inj}(z)\, E_i(z)\, dz$$

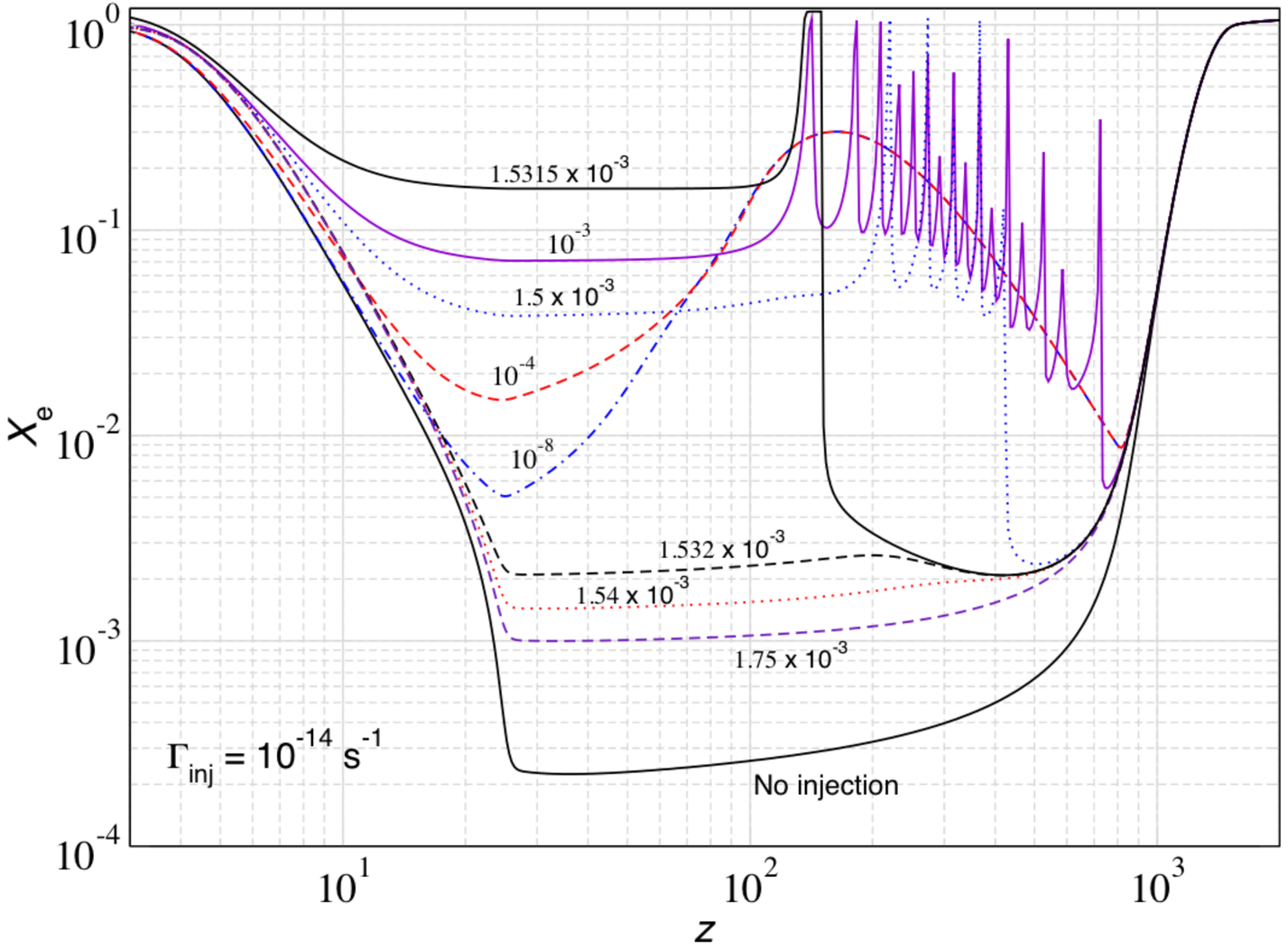
$$\epsilon f_{dm} \lesssim 2 \left[\sum_i \frac{(\hat{\rho}_i^{inj})^2}{\sigma(\mu_i)^2} \right]^{-1/2}$$

Adding CMB anisotropy constraints on ionisation history



Adding CMB anisotropy constraints on ionisation history

- Singular behaviour when collisions are included



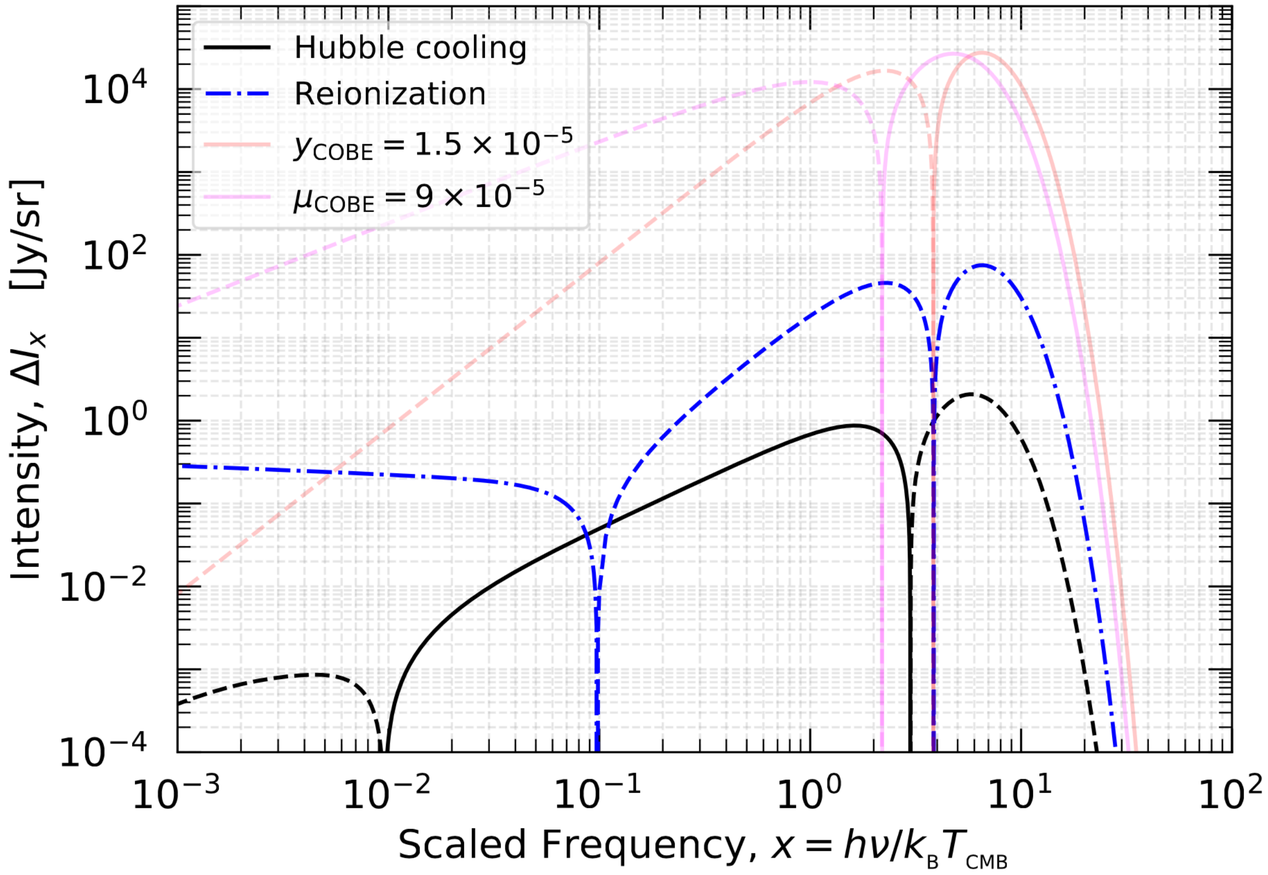
Spectral Distortions in Lambda CDM

- Standard mu and y distortions

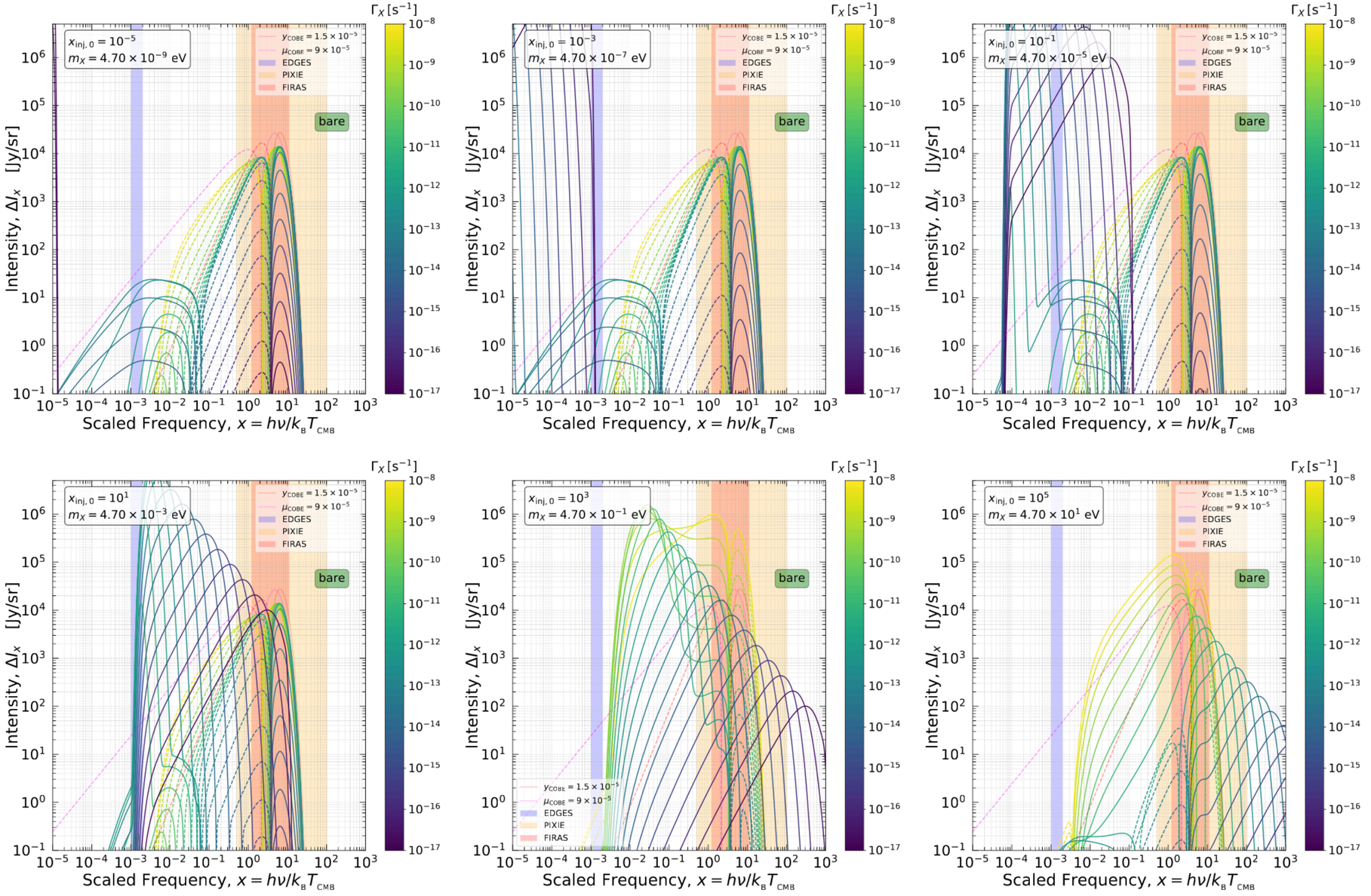
- Distortion from reionisation
  - ✤ positive y distortion from heating
  - ✤ free-free distortion

- Hubble cooling distortion
  - ✤ At z>200 electrons extract energy from CMB to maintain $T_e \approx T_\gamma$
  - ✤ Combination of small negative μ and y:

$$\mu \simeq -3 \times 10^{-9} \qquad y \simeq -5 \times 10^{-10}$$



Photon Injection Spectra Today



Spectral Distortions from a simple photon injection process

- Photon injection term in the PDE for photon occupation number

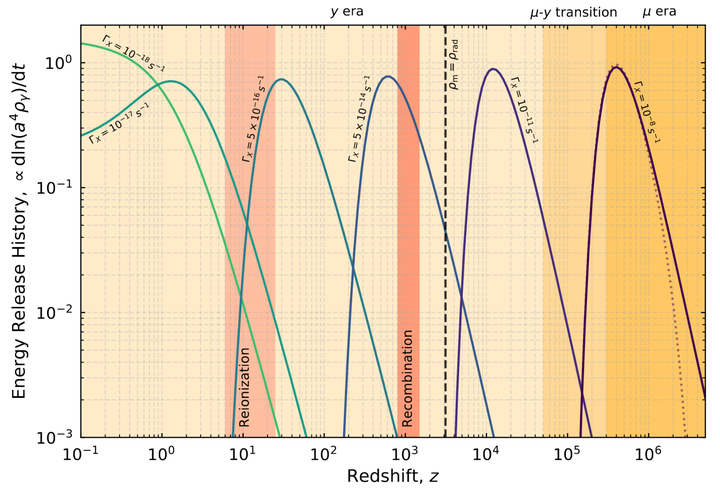
$$\left.\frac{\mathrm{d}n_x}{\mathrm{d}t}\right|_{\mathrm{inj}} = \mathcal{G}_2\, f_{\mathrm{inj}} \Gamma_X \exp\left(-\Gamma_X t\right) \times \frac{G\left(x, x_{\mathrm{inj}}, \sigma_x\right)}{x^2} \qquad \text{with} \qquad x = \frac{h\nu}{kT_\gamma} \qquad \text{and} \qquad T_\gamma = T_{\mathrm{CMB}}\left(1+z\right)$$

- Normalisation can be written in terms of dark matter fraction in particle X (before decay): f_{dm}

- Three parameters:

$$x_{\mathrm{inj},0} = \frac{E_{\mathrm{inj}}}{kT_{\mathrm{CMB}}} \qquad \Gamma_X \qquad f_{\mathrm{dm}}$$

Which frequency? When? How much?

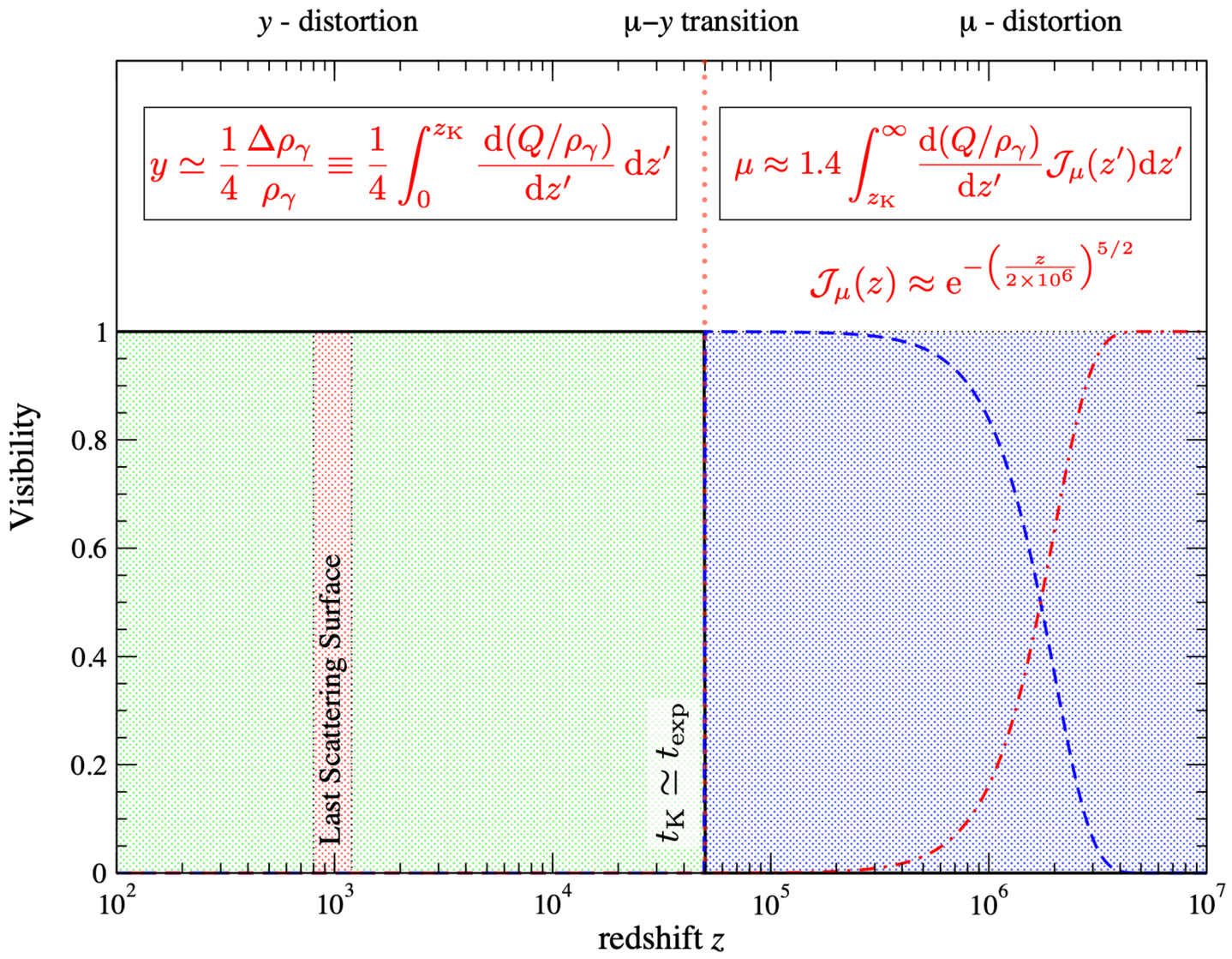


- Amount of energy injected in the distortion era:

$$\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_{\mathrm{inj}} = \int \frac{\mathrm{d}\ln\rho_\gamma}{\mathrm{d}z}\, \mathcal{J}_{\mathrm{bb}}(z)\, \mathrm{d}z \qquad \text{with} \qquad \frac{\mathrm{d}\ln a^4\rho_\gamma}{\mathrm{d}t} = \epsilon f_{\mathrm{dm}} \frac{\rho_{\mathrm{cdm},0}}{\rho_{\gamma,0}} \frac{\Gamma_X \exp\left(-\Gamma_X t\right)}{1+z} \qquad \text{and} \qquad \mathcal{J}_{\mathrm{bb}}(z) \approx \mathrm{e}^{-(z/z_\mu)^{5/2}} \text{ with } z_\mu = 1.98 \times 10^6$$

does not depend on E_{inj}

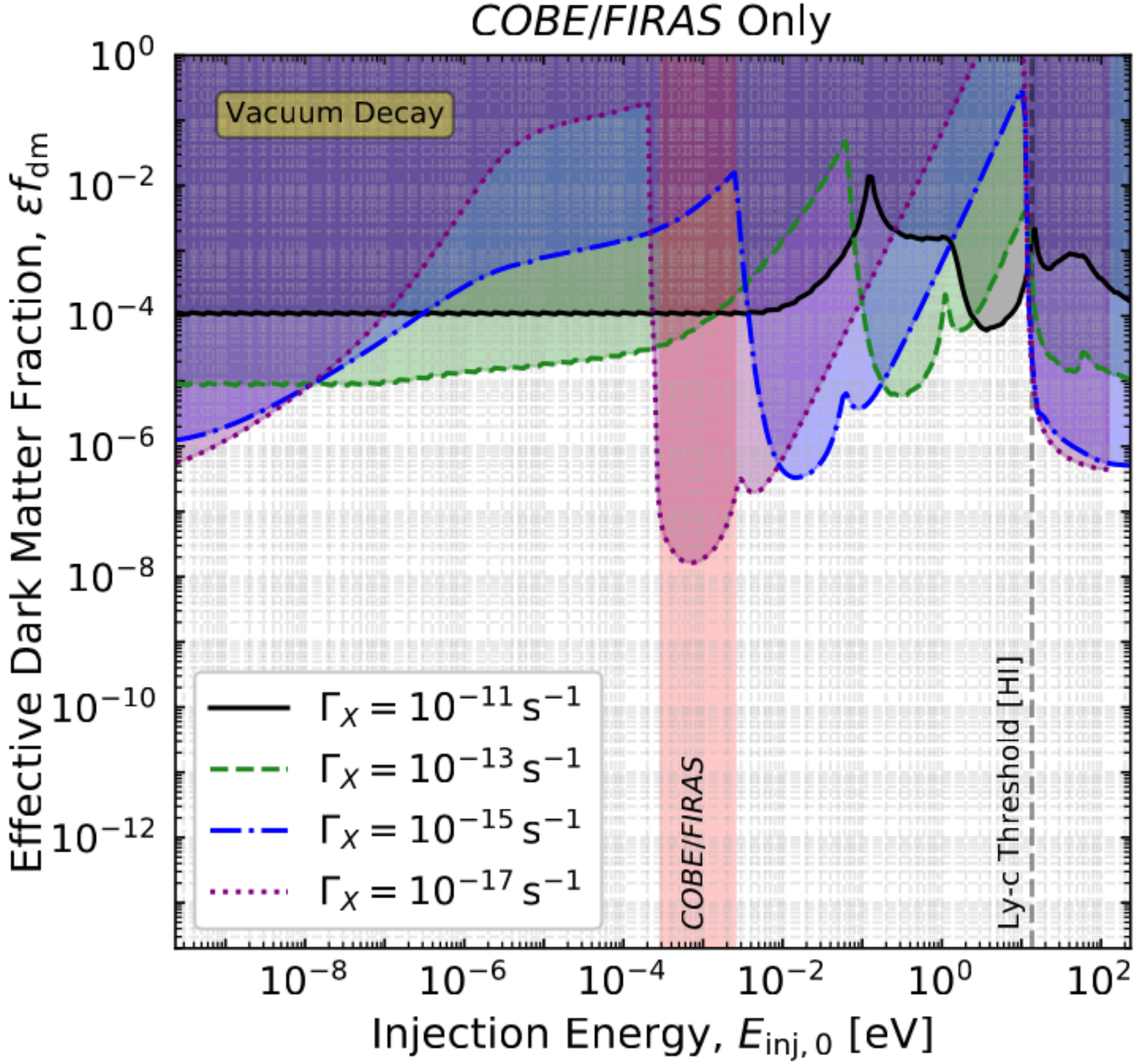
Distortion visibility function $\mathcal{J}_{\rm bb}(z) \approx {\rm e}^{-(z/z_\mu)^{5/2}}$ with $z_\mu = 1.98 \times 10^6$



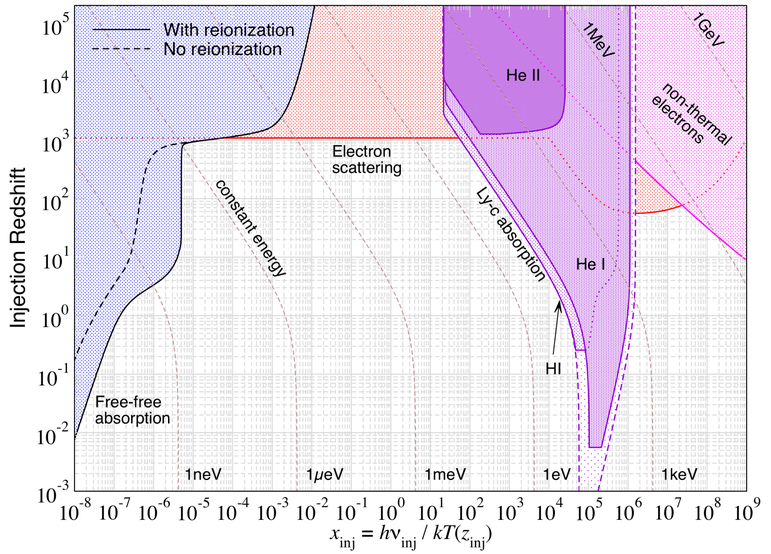
(Figure from Jens's lectures and notes)

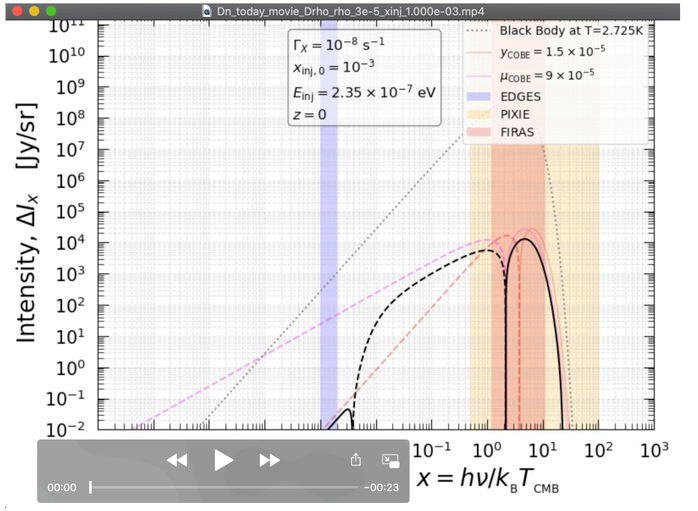
- High redshift: injected energy thermalised, No distortion
- Lower redshift: DC+BR not efficient, but still efficient Compton Scattering, Compton Equilibrium mu-distortion
- Even lower redshift: DC+BR and CS not efficient y-distortion

Constraints on Photon Injection using COBE/FIRAS



Why is the feature moving to the right?





Constraints on Excited States