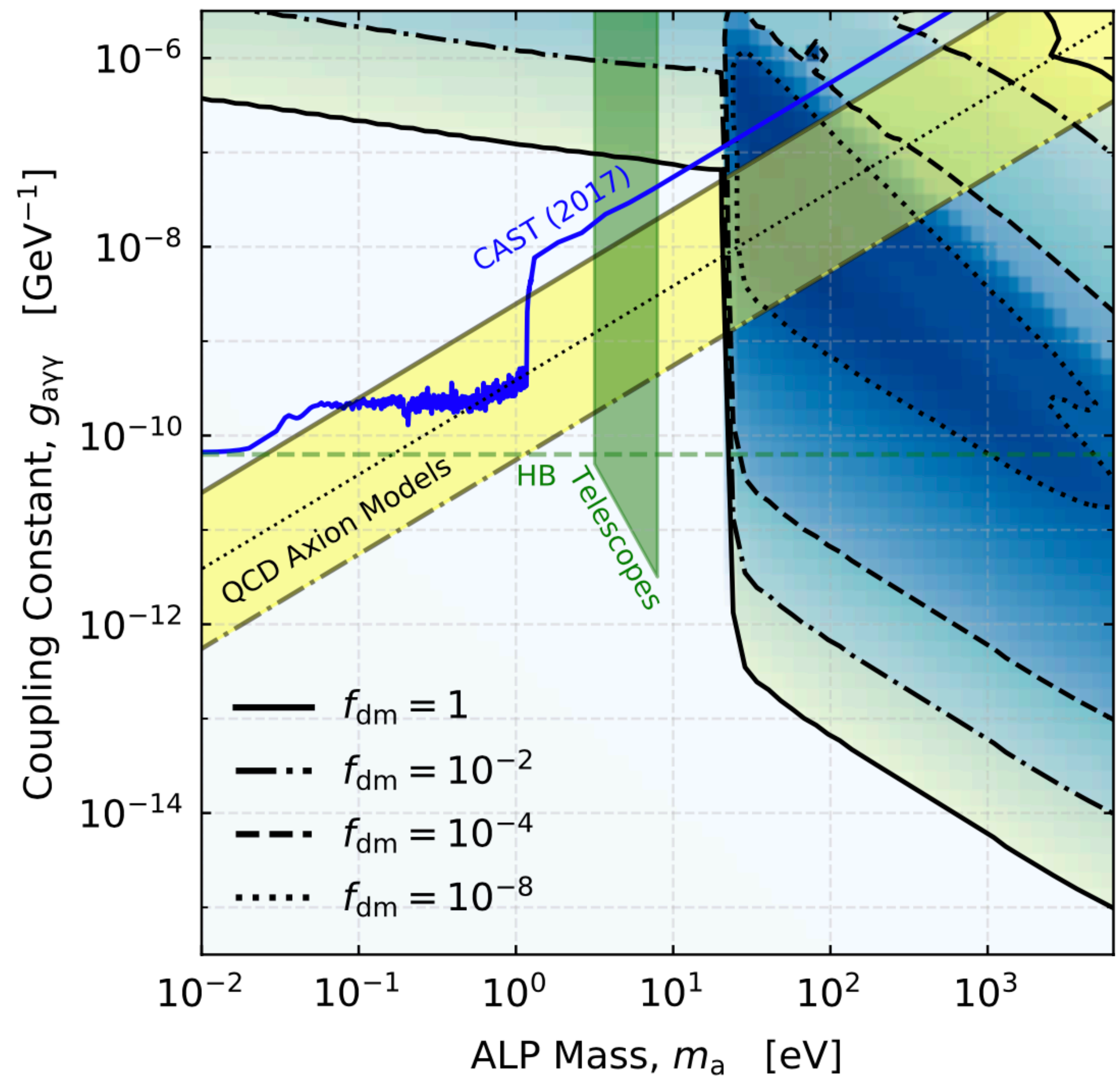
Spectral distortion constraints on photon injection from low-mass decaying particles

arxiv:2012.07292

accepted in MNRAS

Marcel Grossmann Meeting MG16 - July 2021



Boris Bolliet (Columbia)

With **Jens Chluba**, **Richard Battye** (JBCA Manchester)

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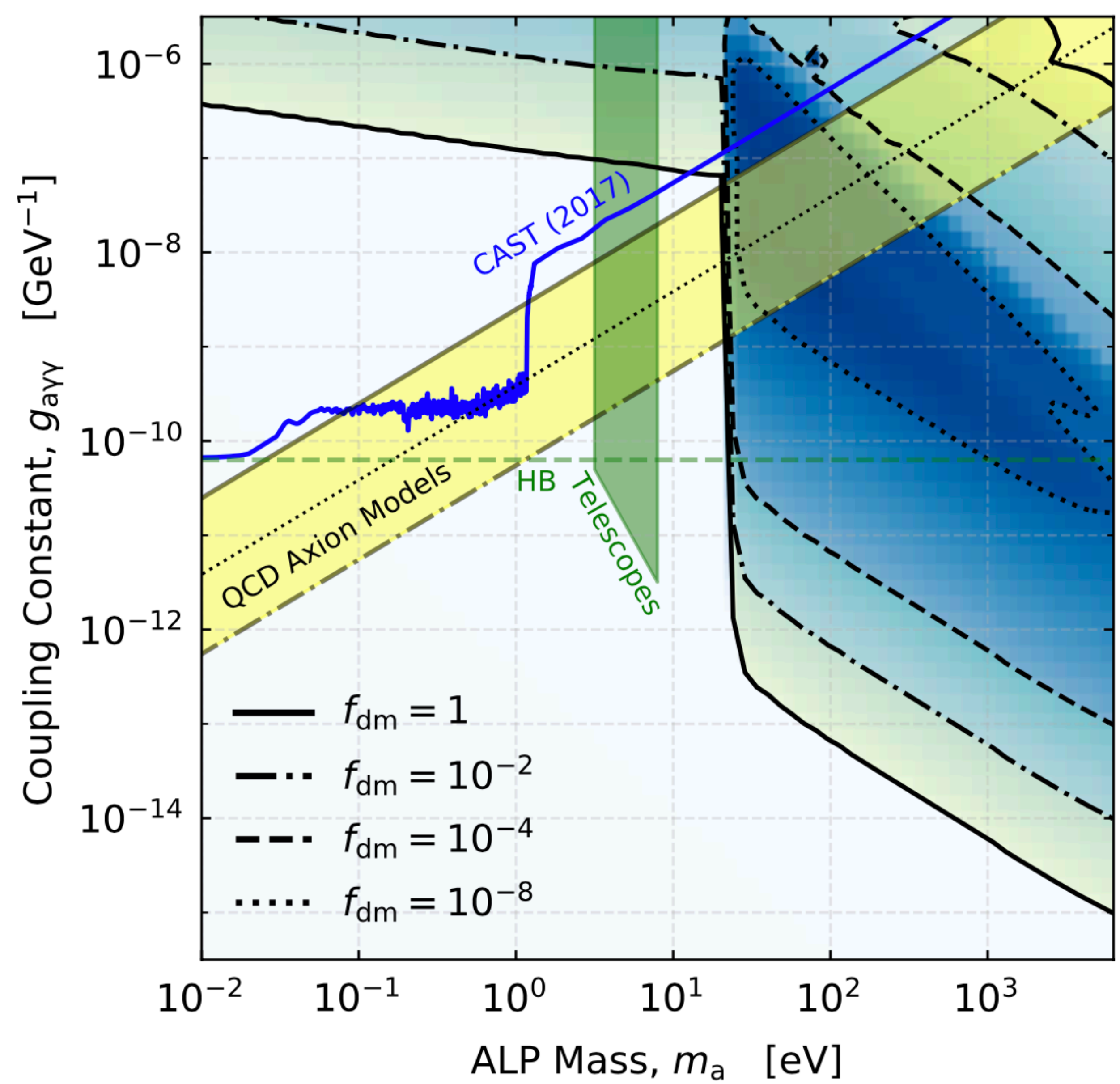

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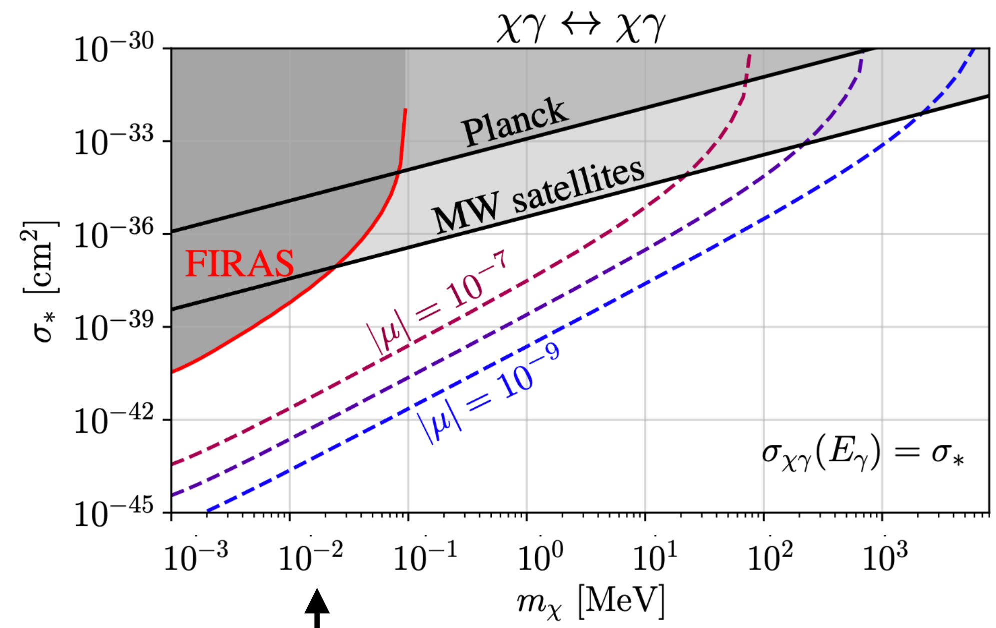
Spectral distortions are powerful probe of the thermal history

Decay/Annihilation of relic particles with coupling to photons/EM

Constraints on DM cross-section

$$\dot{\mathcal{Q}}_\chi = \frac{3}{2} n_\chi \Gamma_{\chi s}(T_s - T_\chi),$$

$$\Gamma_{\chi s} \equiv \frac{2}{3} \frac{m_\chi \rho_s}{(m_\chi + m_s)^2} \frac{\langle \sigma_{\chi s}(v) v^3 \rangle}{v_{\rm th}^2}$$



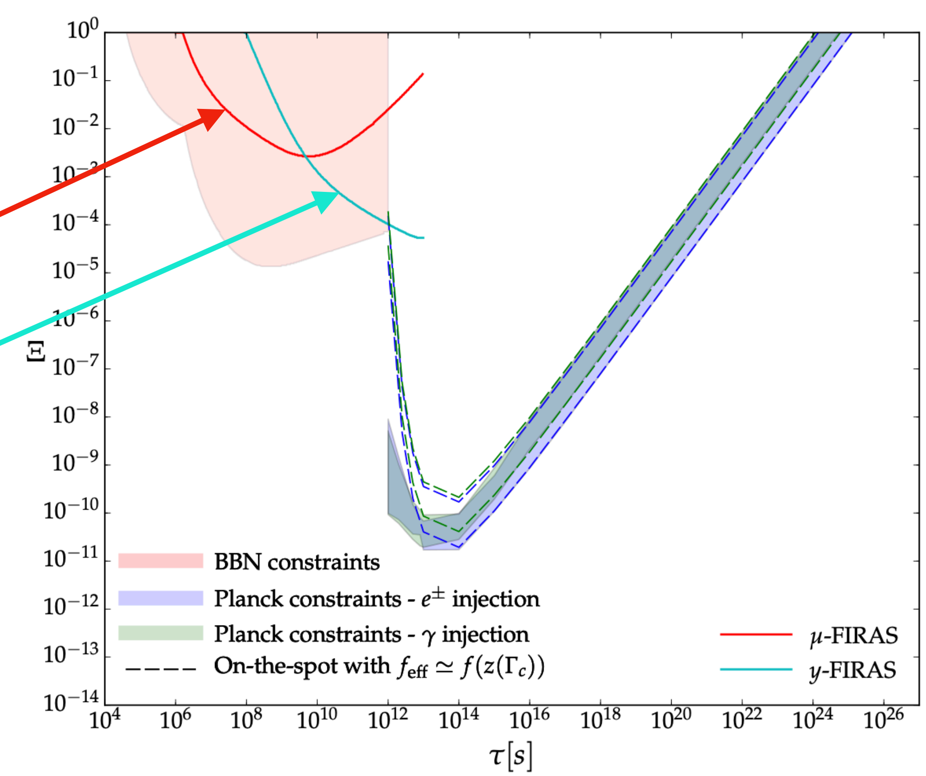
See e.g., Ali-Haïmoud, Chluba, Kamionkowski (1506.04745), **Ali-Haïmoud (2101.04070)**

Constraints on relic mass, lifetime and abundance

μ and y-distortions from energy injection

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

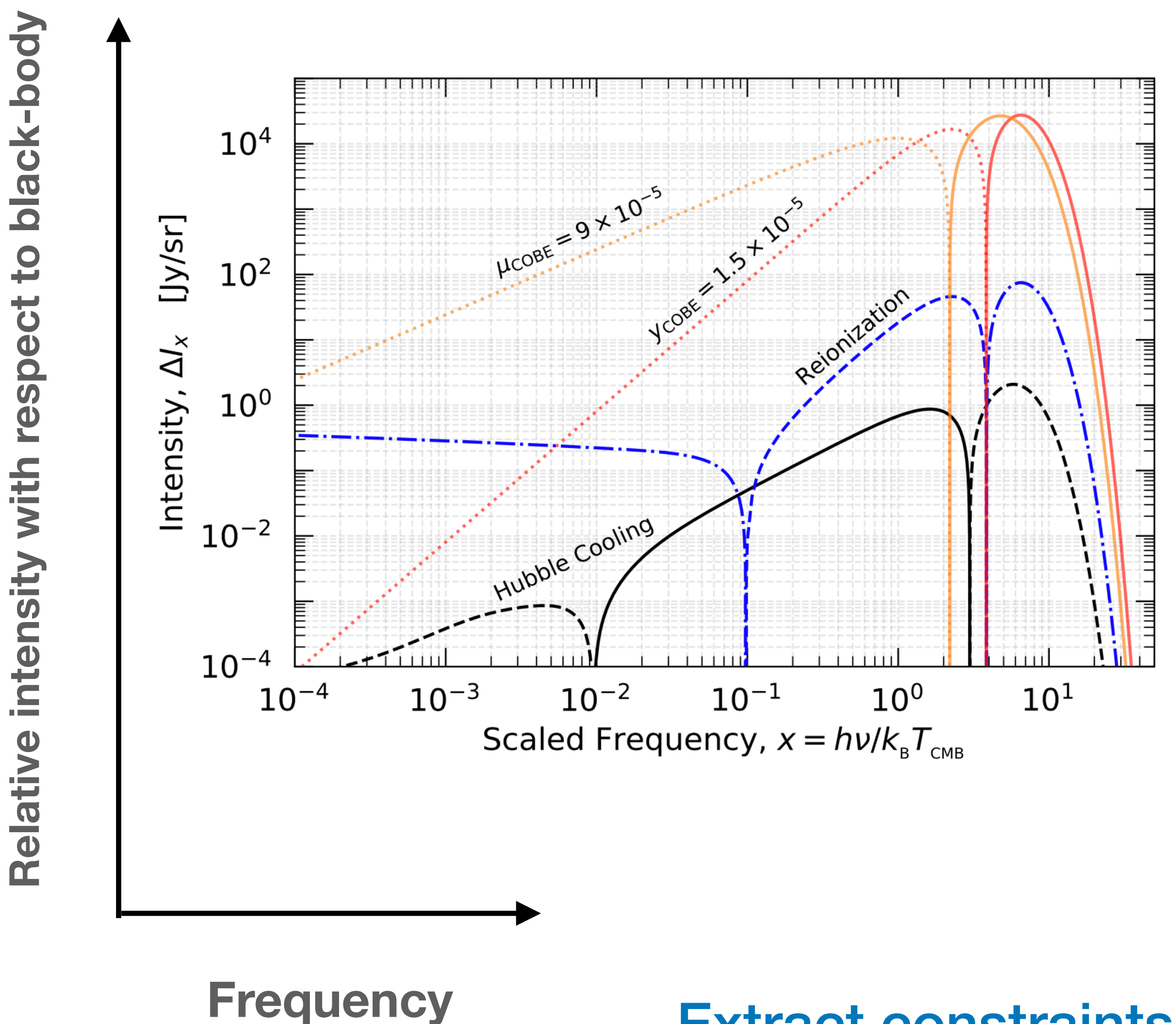
$$y \approx \frac{1}{4} \left. \frac{\Delta\rho_\gamma}{\rho_\gamma} \right|_y$$



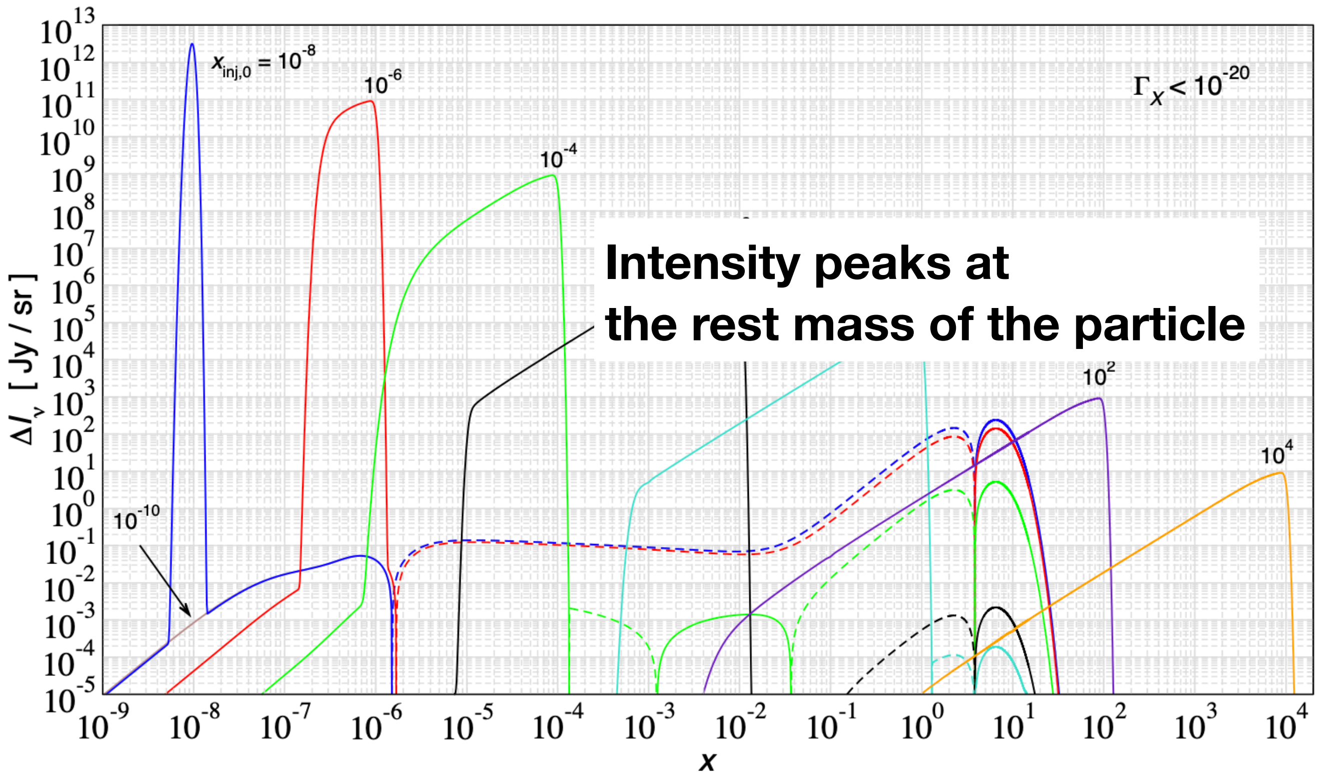
See e.g., Chluba (1506.06582), Poulin, Serpico, Lesgourgues (1610.10051)

- When injected photon don’t have time to scatter/comptonize, **simple μ and y-distortions are not sufficient** to characterize the CMB spectrum post-injection

Standard distortion shapes



Typical distortions from decaying particles into photons with long lifetime



Extract constraints that take into account the full distortion spectrum

Solving the thermalization problem with CosmoTherm

Chluba, Sunyaev 1109.6552

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

Compton scattering

Double-Compton and Bremsstrahlung

Compton energy exchange with **CSpack**
(Sarkar, Chluba, Lee 1905.00868)

BR emission with **BRpack**
(Chluba, Ravenni, Bolliet 1911.08861)

- Challenging numerical problem: photon and electron energy/temperature equations need to be solved simultaneously + ionization history
- Reionization (Poulin, Serpico, Lesgourgues 1508.01370)
- Refined treatment of HeI, HeII (Chluba, Ali-Haïmoud 1510.03877)
- Recombination with **Recfast** (Slatyer, Chluba,…)
  - All codes run from **Specdist**

specdist https://github.com/CMBSPEC/specdist

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

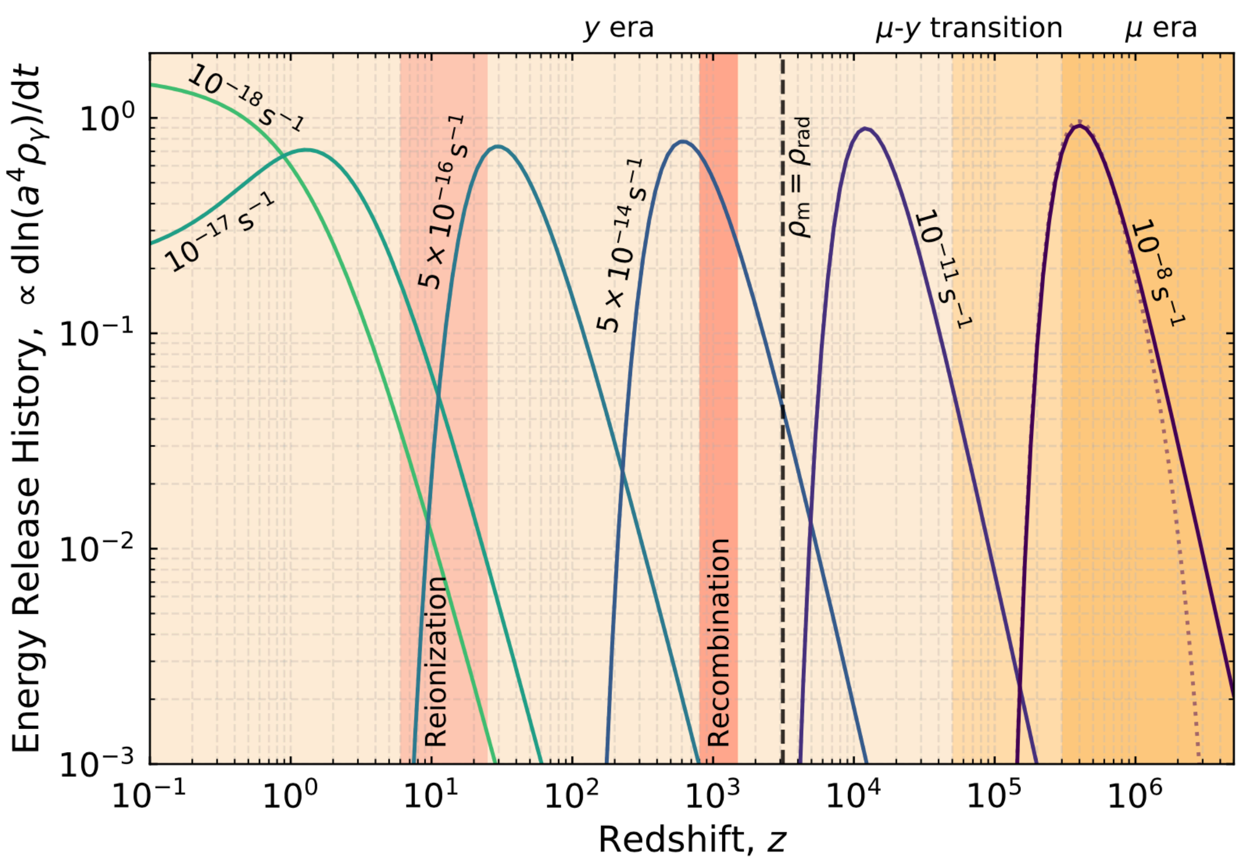
Python MIT 0 1 0 0 Updated on Mar 17

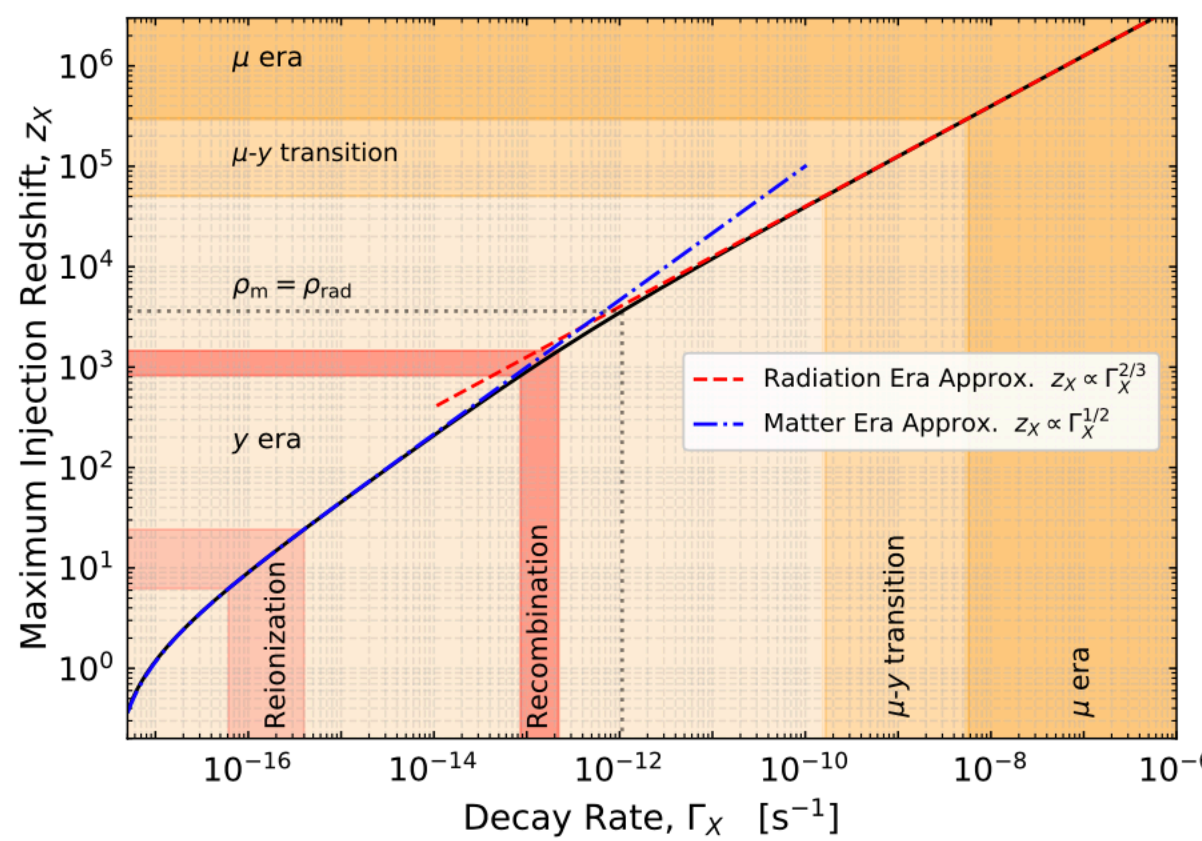
Two-photons decay $X \rightarrow \gamma + \gamma$ $E_{\text{inj}} = h\nu_{\text{inj}} = m_X c^2/2$

Excited states $X^* \rightarrow X + \gamma$ $E_{\text{inj}} = h\nu_{\text{inj}} = E_X^{\text{ex}}$

$$\frac{\mathrm{d}\ln a^3 N_X}{\mathrm{d}t} = -\Gamma_X$$

Decay rate dictates when the injection happens





→ *Determines the type of distortion and change in ionisation history*

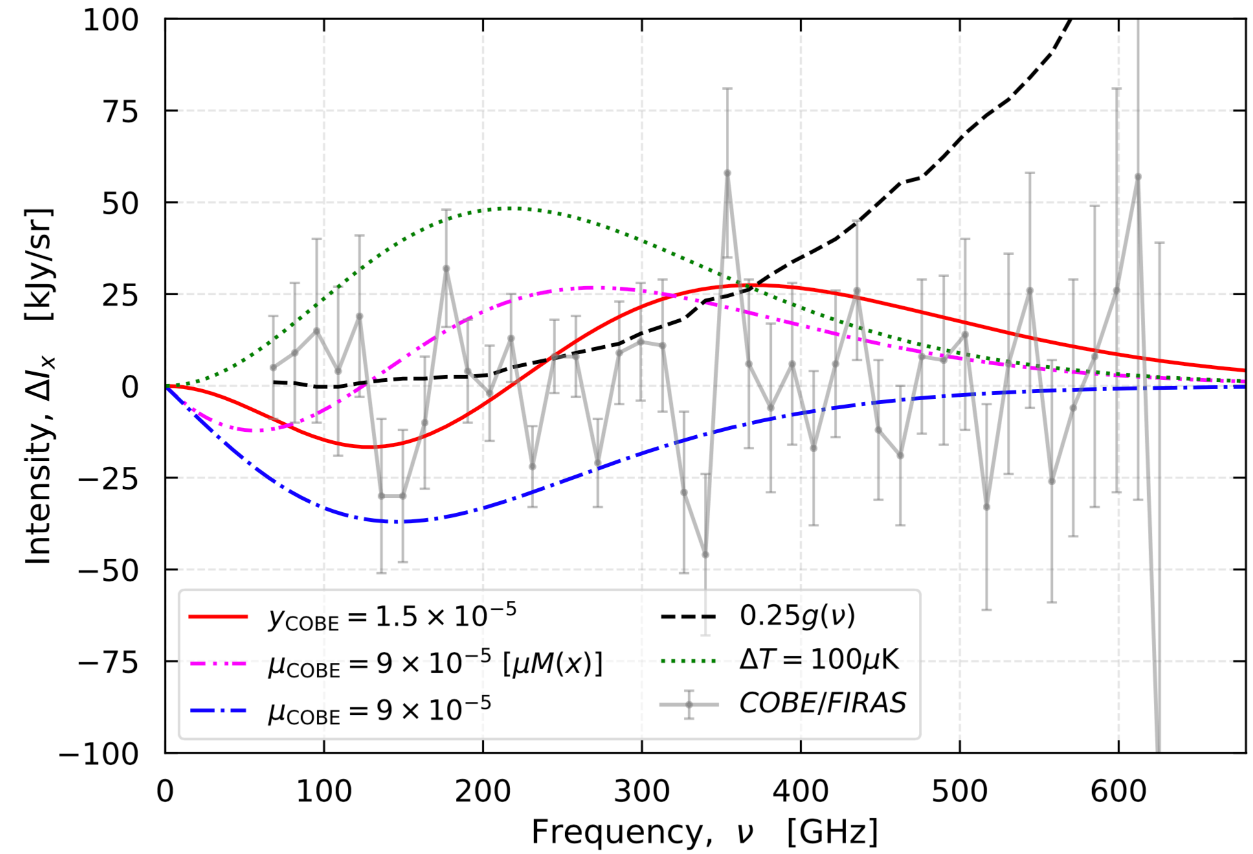
Spectrum of injected photons

- Line (narrow Gaussian) at the rest-mass energy of the particle

$$\left.\frac{\mathrm{d}n_x}{\mathrm{d}t}\right|_{\mathrm{inj}} = \mathcal{G}_2\, f_{\mathrm{inj}}\Gamma_X \exp\left(-\Gamma_X t\right) \times \frac{G\left(x, x_{\mathrm{inj}}, \sigma_x\right)}{x^2}$$

- Normalization of the spectrum proportional to abundance/DM fraction

$$f_{\mathrm{inj}} \approx 1.31 \times 10^4\ \frac{\epsilon f_{\mathrm{dm}}}{x_{\mathrm{inj},0}}\left[\frac{\Omega_{\mathrm{cdm}}h^2}{0.12}\right]$$

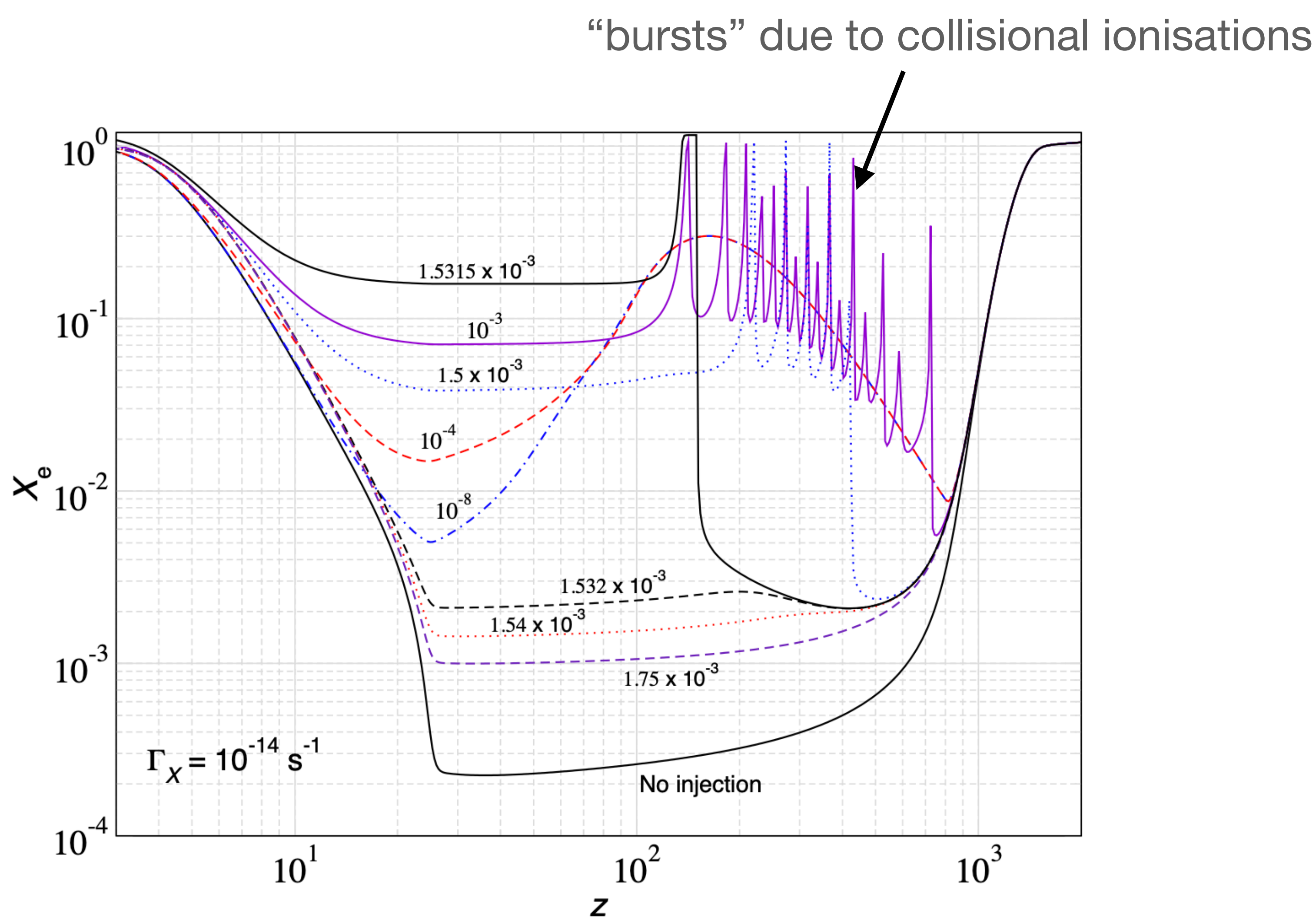


- Compare distortion versus measured CMB intensity to obtain constraints on mass, DM fraction and lifetime

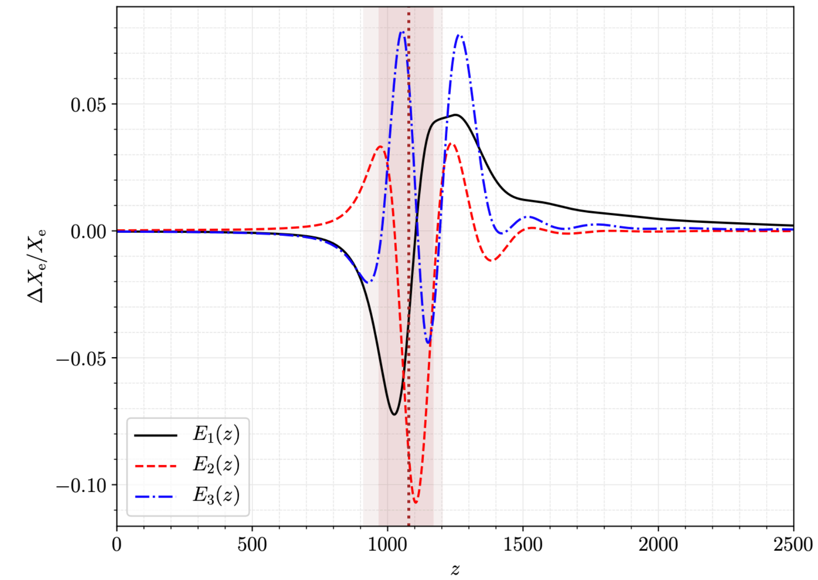
- CMB spectra data from COBE/FIRAS + EDGES brightness temperature at 78MHz

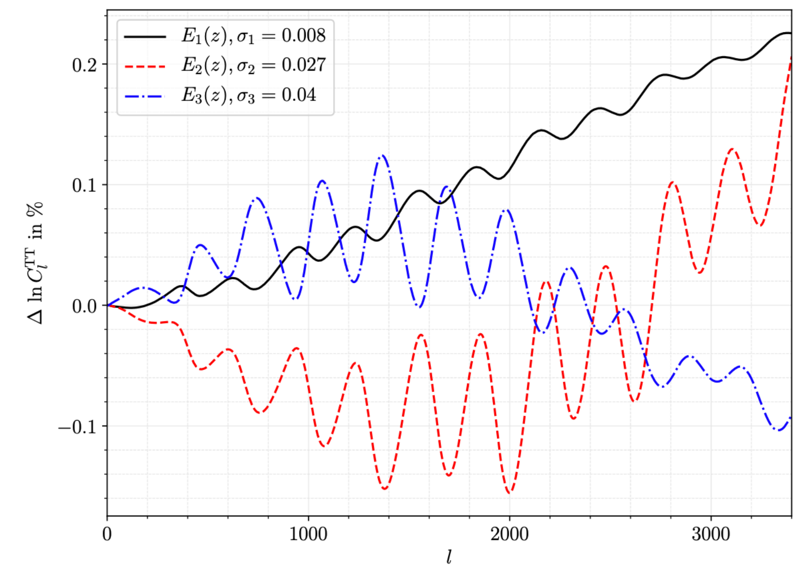
$$I(\nu) = B(T_0) + \Delta T\left.\frac{\partial B}{\partial T}\right|_{T_0} + \mu\left.\frac{\partial S_\mu}{\partial \mu}\right|_{T_0} + y\left.\frac{\partial S_y}{\partial y}\right|_{T_0} + G_0 g(\nu).$$

- Use perturbed recombination as complementary constraints from CMB anisotropy



Perturbed recombination for several injection energy

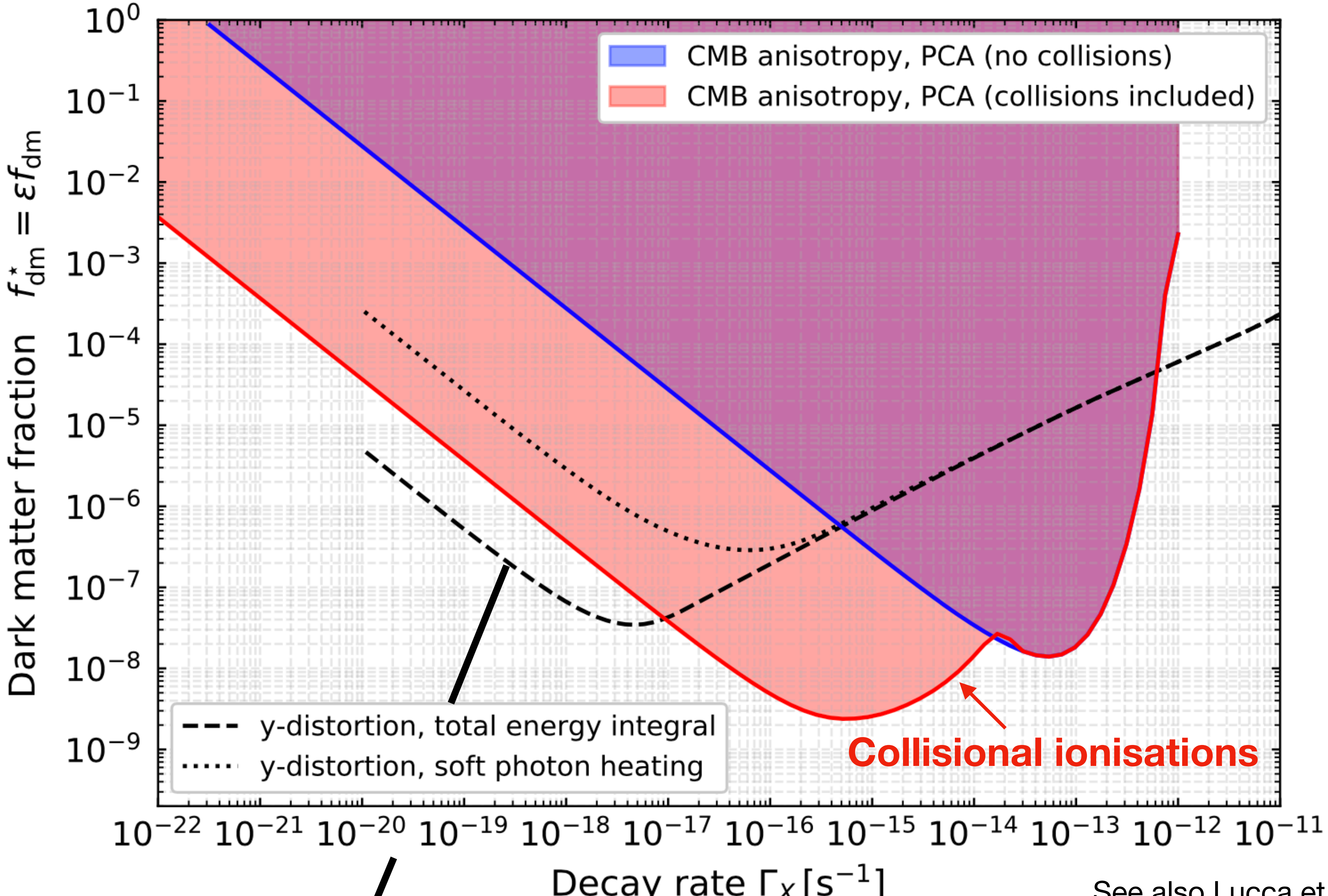




Perturbation of CMB TT spectra (bottom) from eigenmodes of recombination history (top)

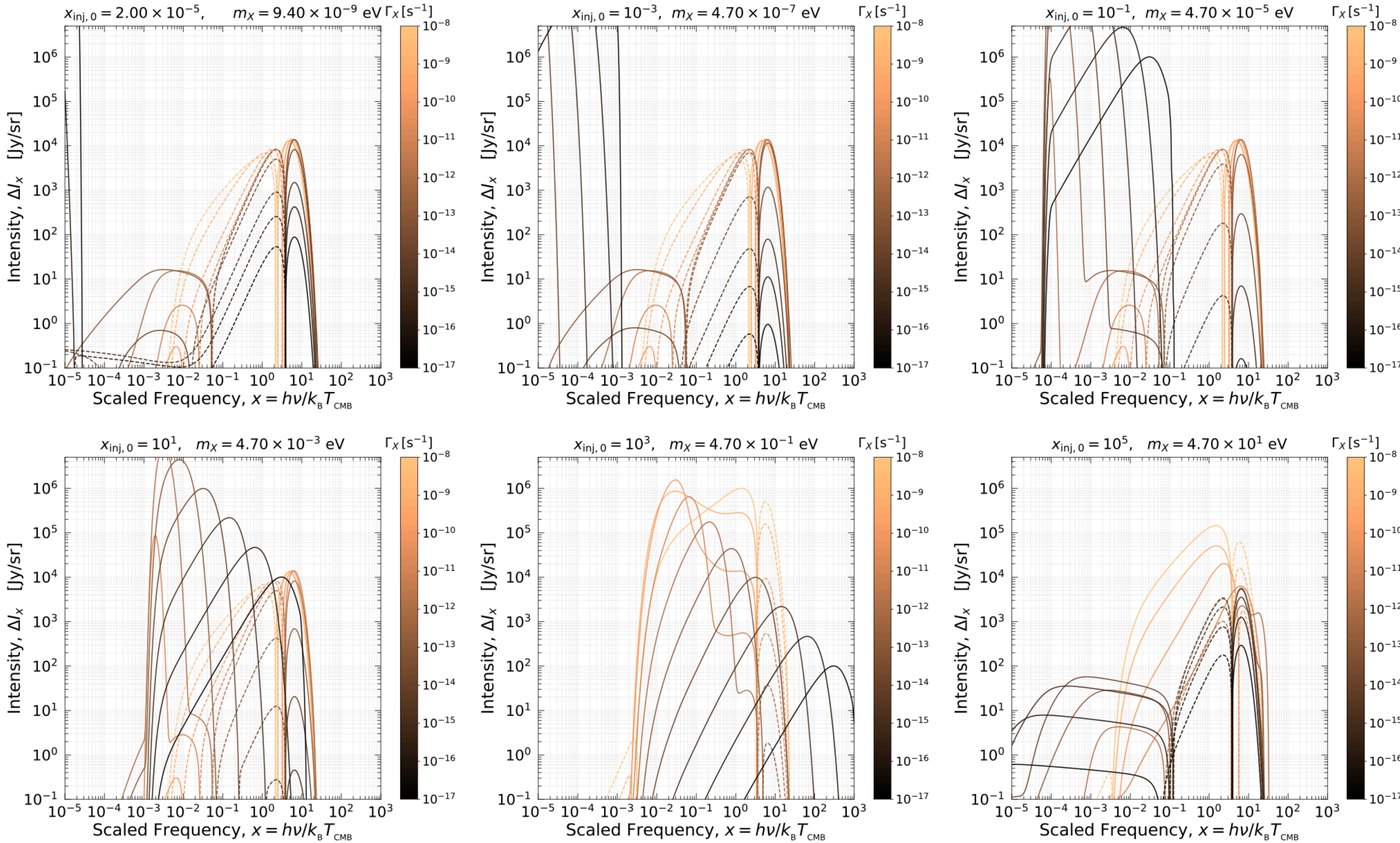
- Planck CMB TT.TE.EE data and projection method from Hart & Chluba (1912.04682)

Comparison of constraints from CMB anisotropy and y-distortion limits, for low-frequency injection

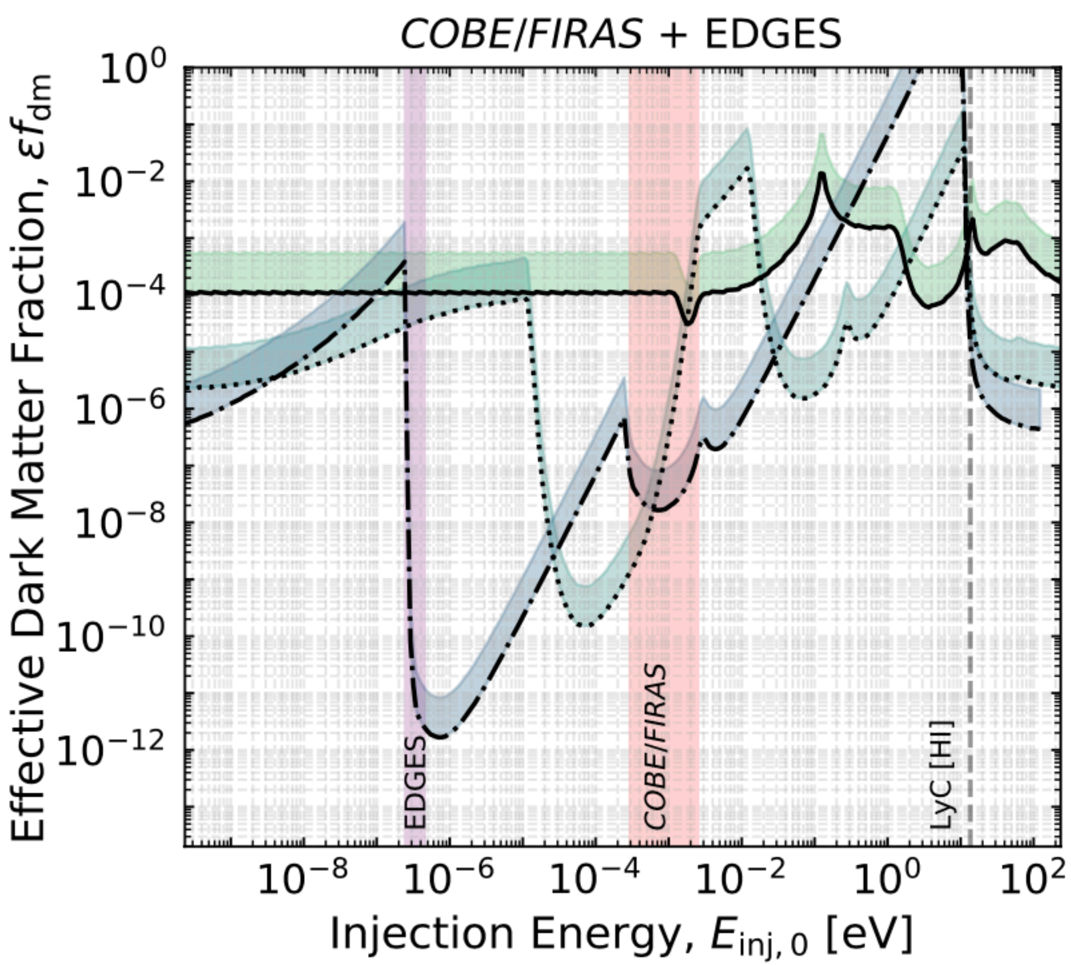


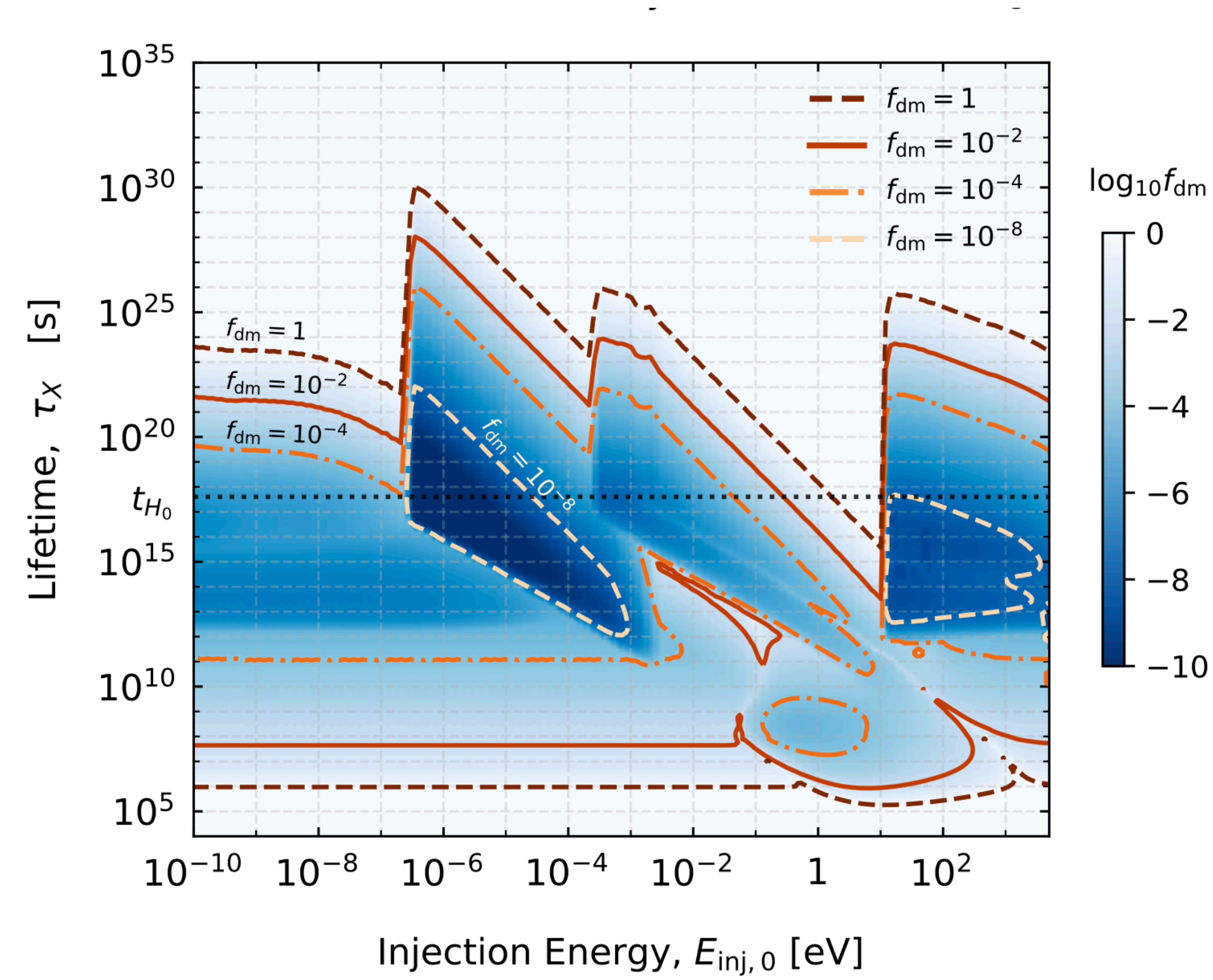
See also Lucca et al 1910.04619

*Spectrometer **beats** CMB anisotropy constraints !*



- Fast computation of spectra at any point in parameter space with interpolation
- Emulator for spectral distortions/ionisation histories (next step)





- $\Gamma_X = 10^{-11}\,\mathrm{s}^{-1}$ ~ end of μ-era
- $\Gamma_X = 10^{-14}\,\mathrm{s}^{-1}$ ~ recombination
- $\Gamma_X = 10^{-17}\,\mathrm{s}^{-1}$ ~ today

- μ and y constraints
- Negative μ

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

- LyC absorption
- Redshifted peaks

- Decay rate enhanced in ambient CMB photons bath

Caputo, Regis, Taoso, Witte 1811.08436

Frequency dependent term

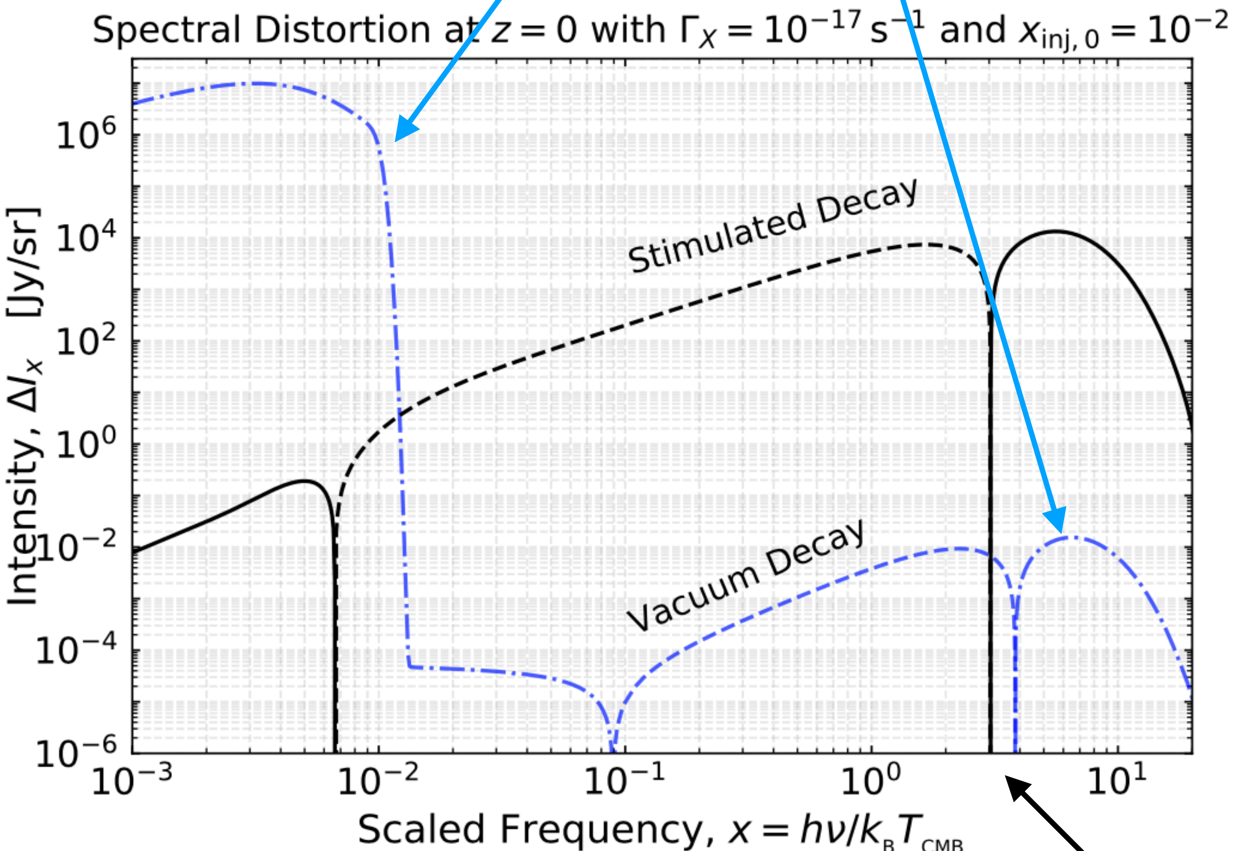
$n_\gamma(x_{\rm inj}) \approx (1+z)/x_{\rm inj,0}$

for $x_{\rm inj} \lesssim 1$

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

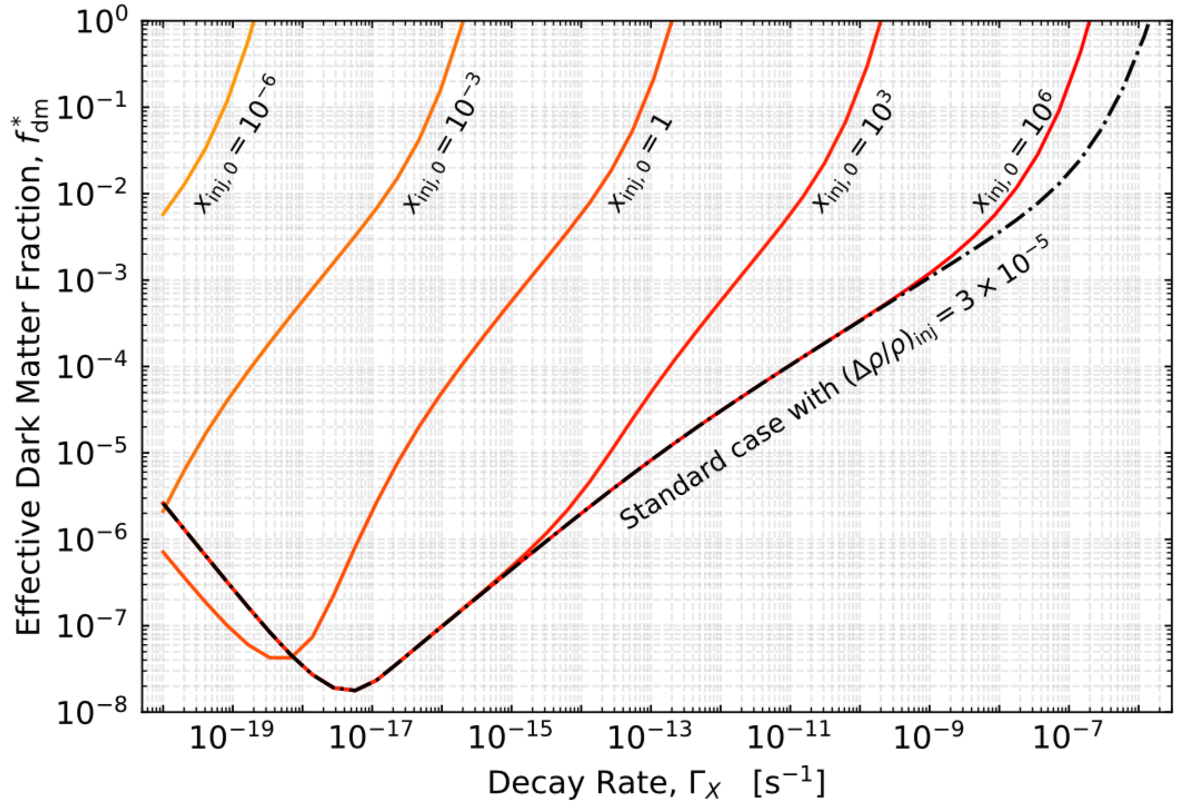
- Particles decay earlier than they would have in vacuum

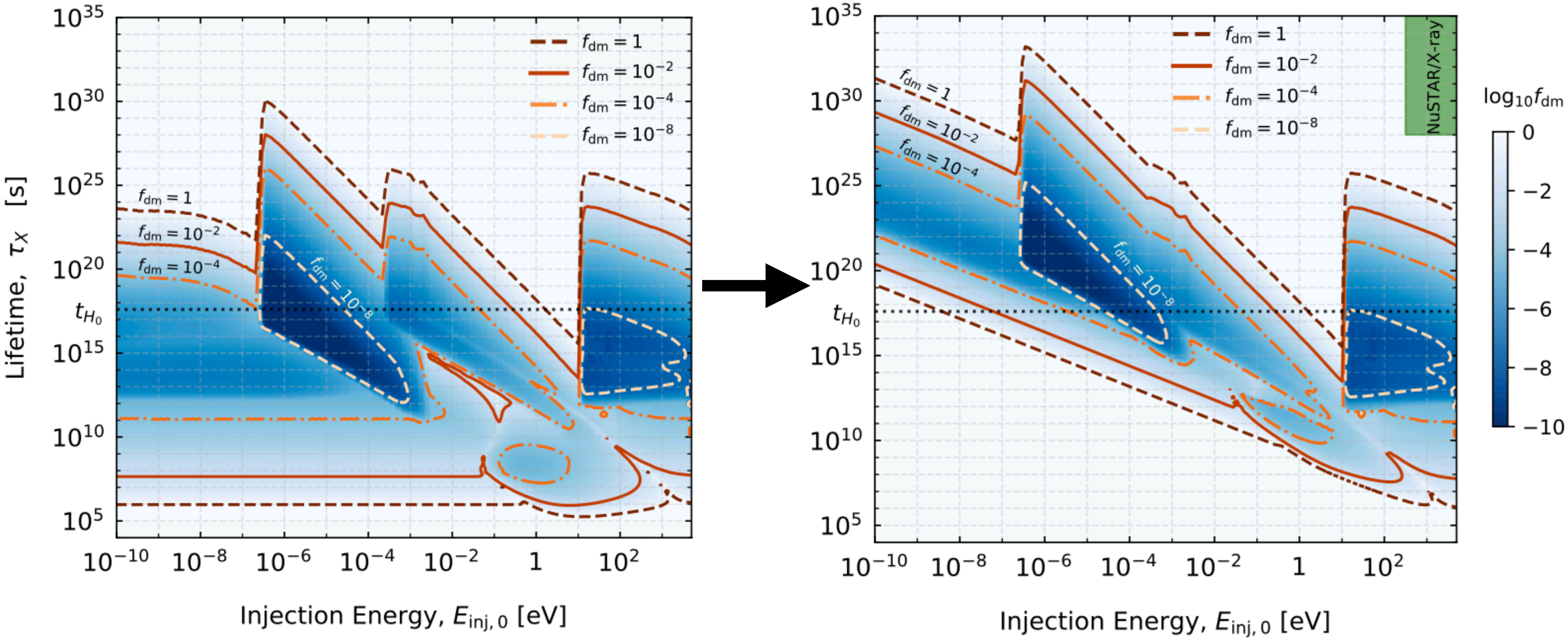
Peak + y-distortion



μ-distortion

DM fraction for fixed injected energy

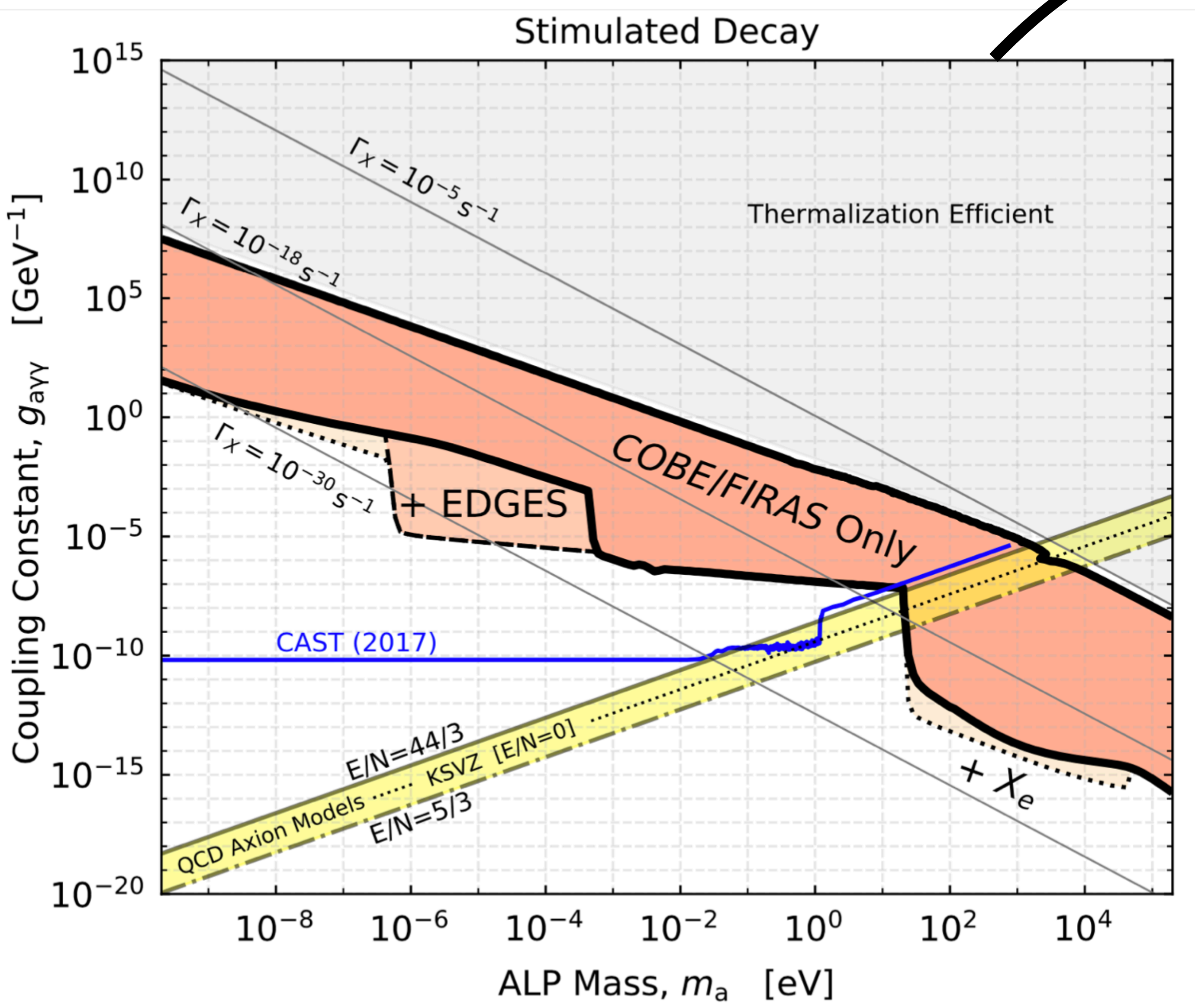




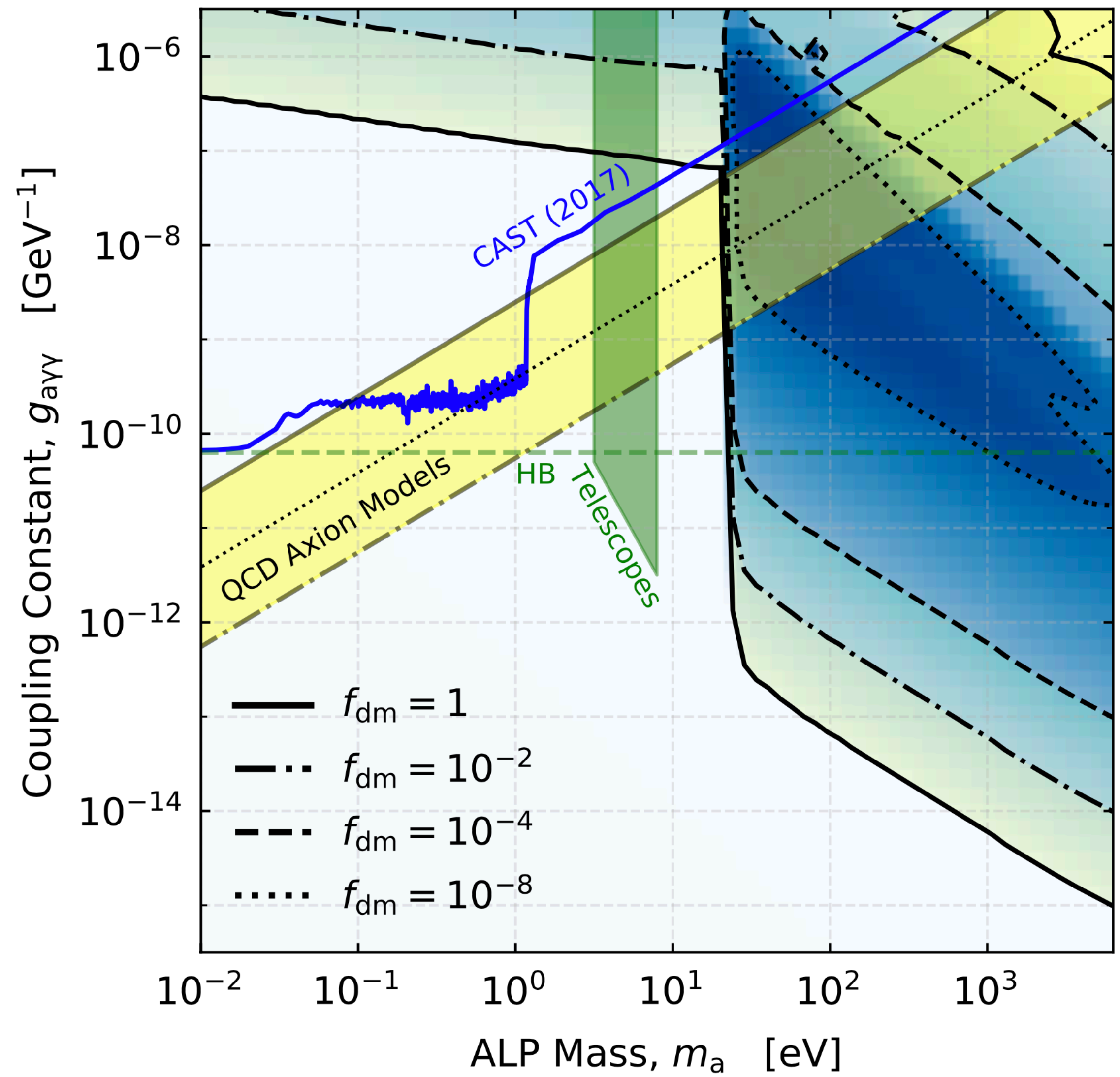
- ‘Tilted’ constraints regions towards long life-time compared to non-stimulated decay
- Complementarity with other constraints (e.g, Roach et al 1908.09037, sterile neutrino)
- Constraints can be translated to specific particle physics models

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

see, e.g., Raffelt 0611350



ZOOM IN



- First constraints from full distortion spectra calculations
- Still harvesting insights into dark matter from 30 years old COBE/FIRAS data

Next steps

- Machine learning to alleviate computationally expensive calculations
- Turning current work into forecast analysis