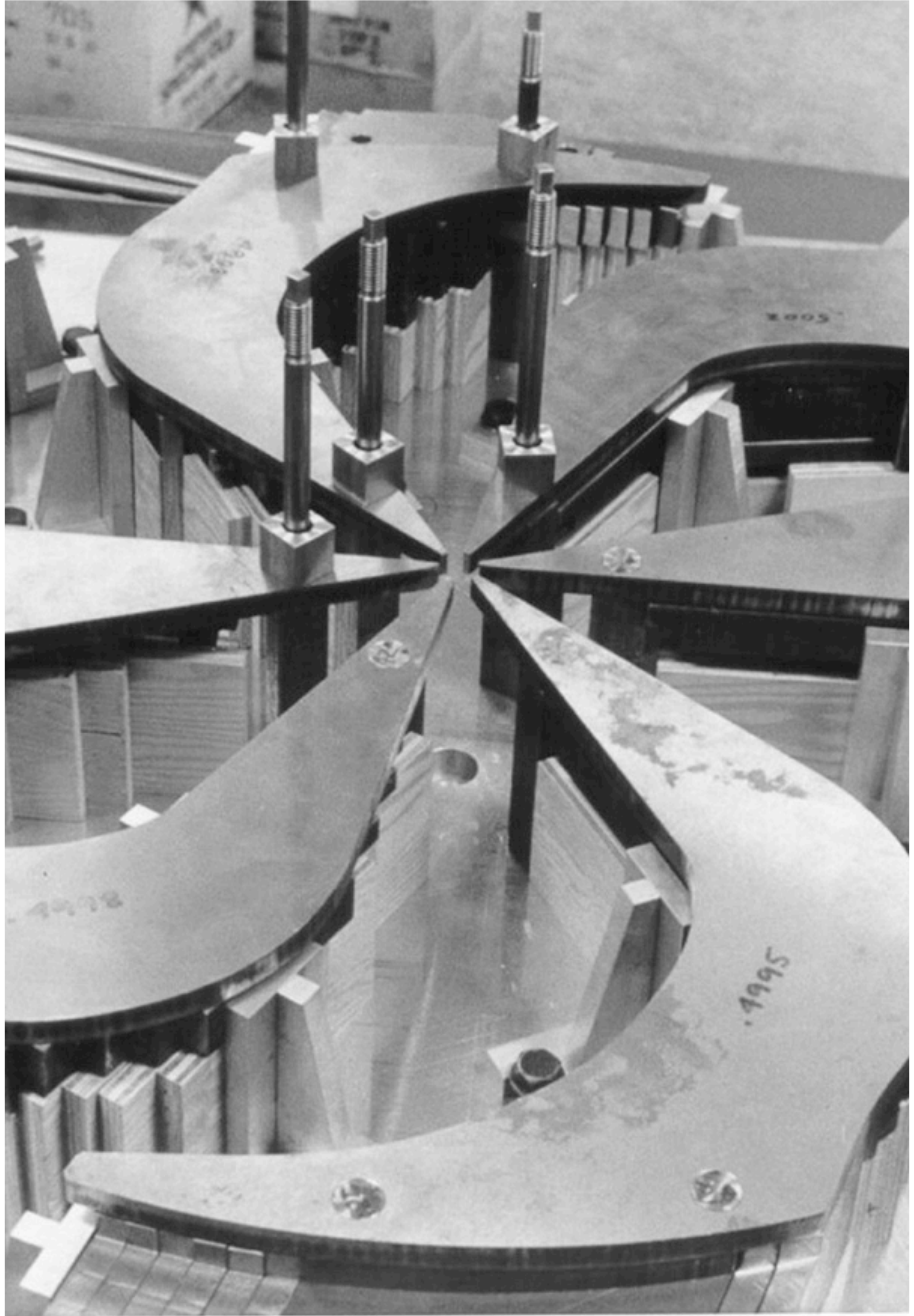
TRIUMF

BBN and CMB bounds on hidden sector vectors

Graham White, TRIUMF

JHEP 1901 (2019) 074 and arxiv 2002.xxxx
with John Coffey, Lindsey Forestell and David Morrissey



Discovery, accelerated

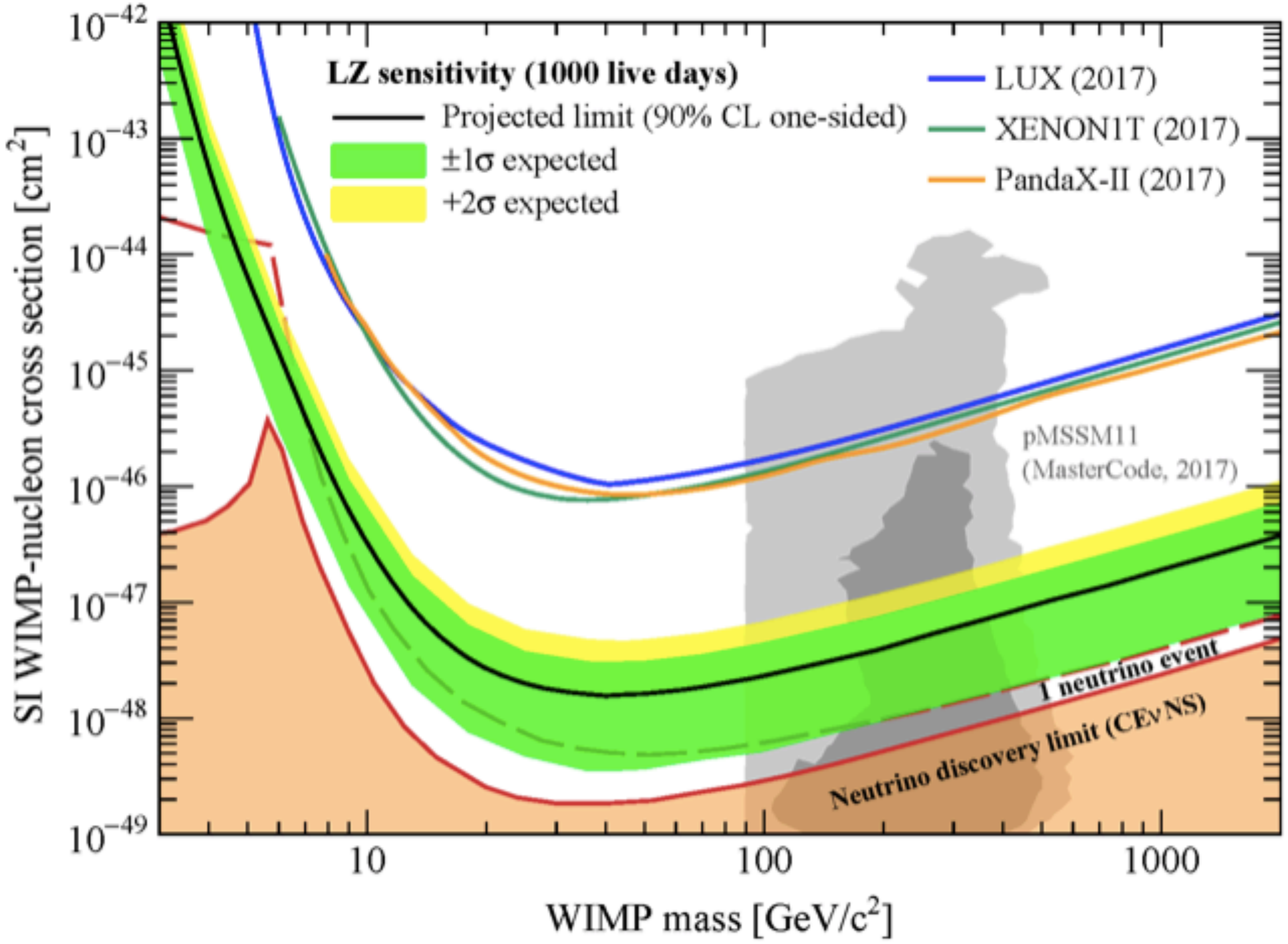
Where to look for hidden sectors

Collider builders

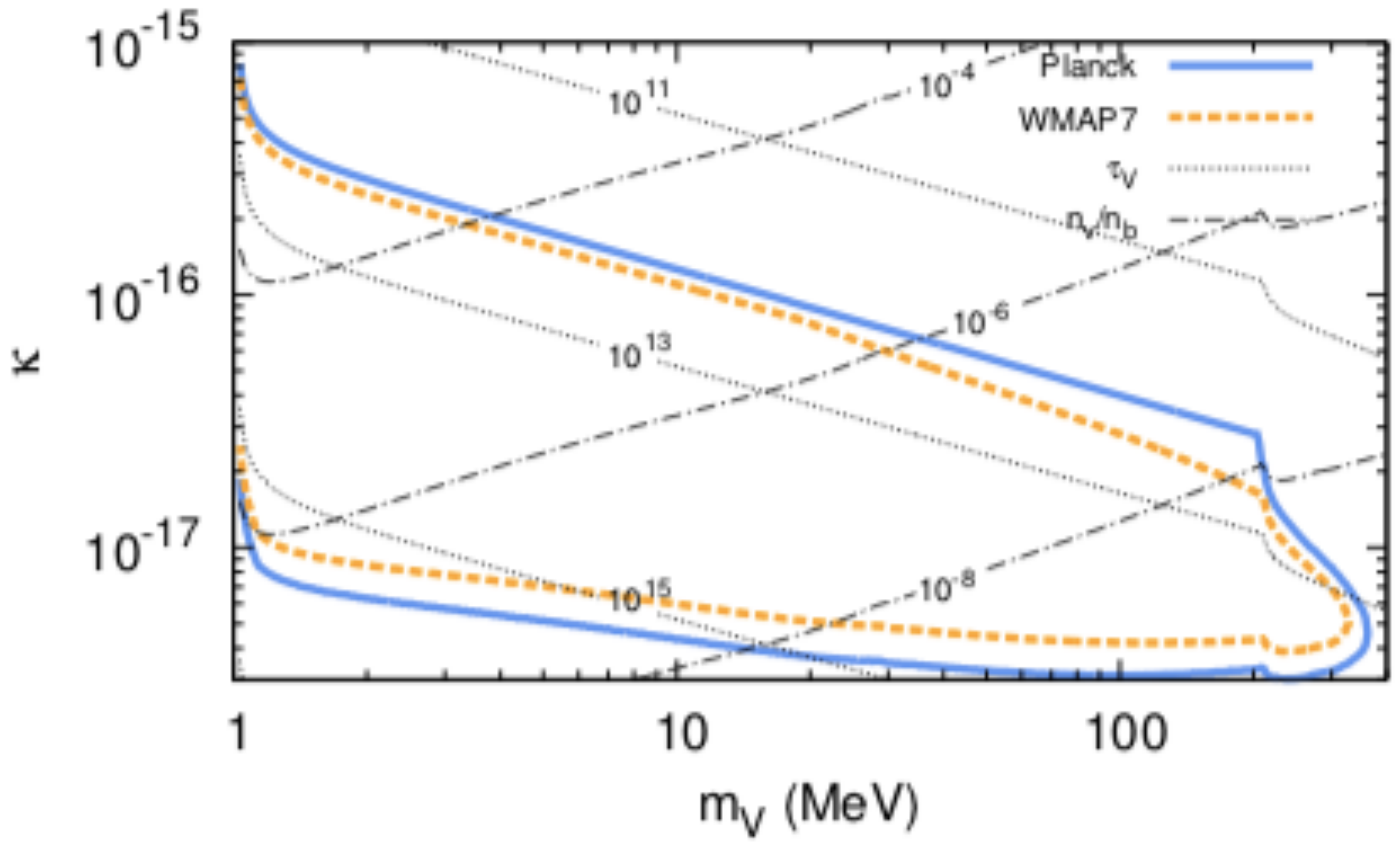
New physics

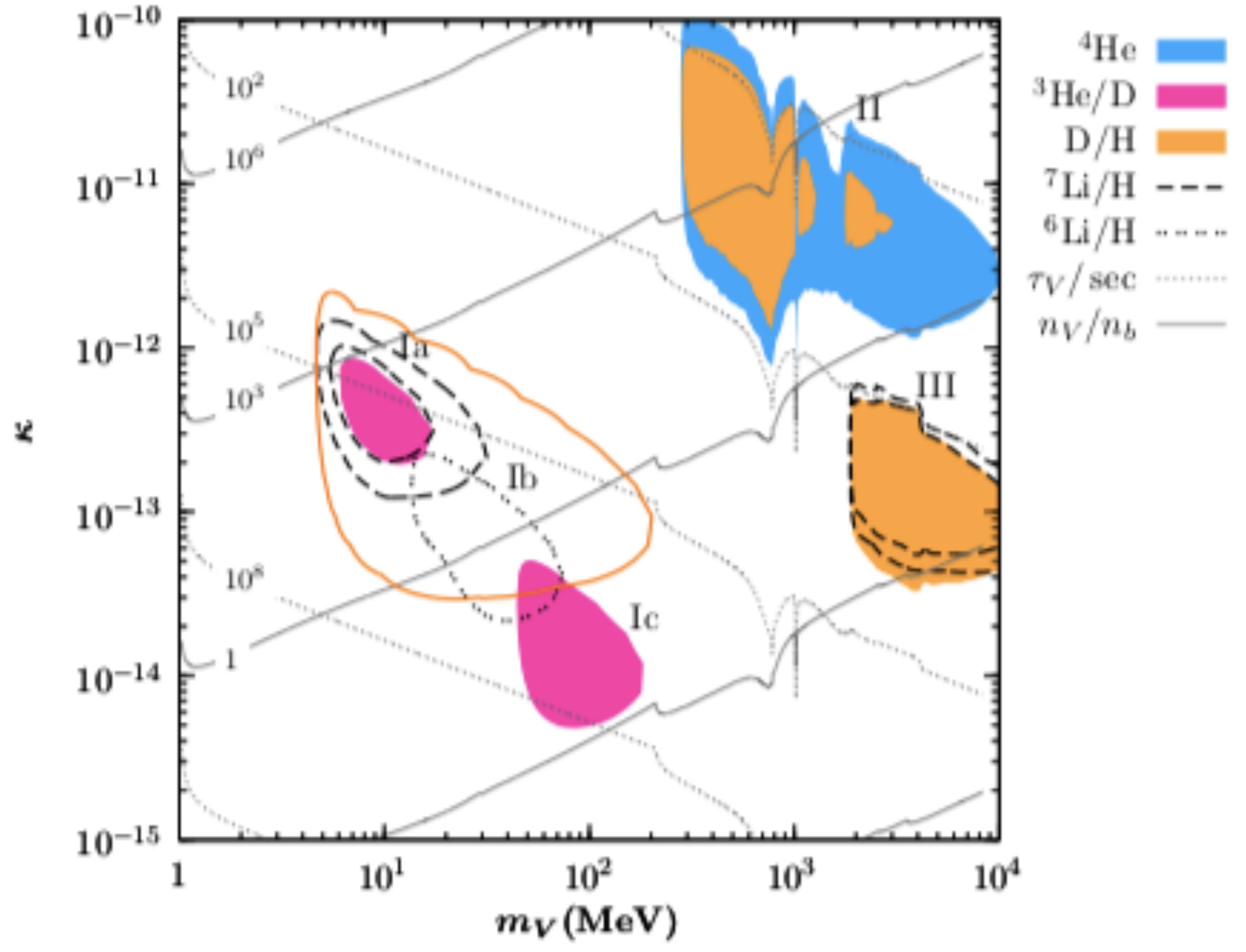
Mass

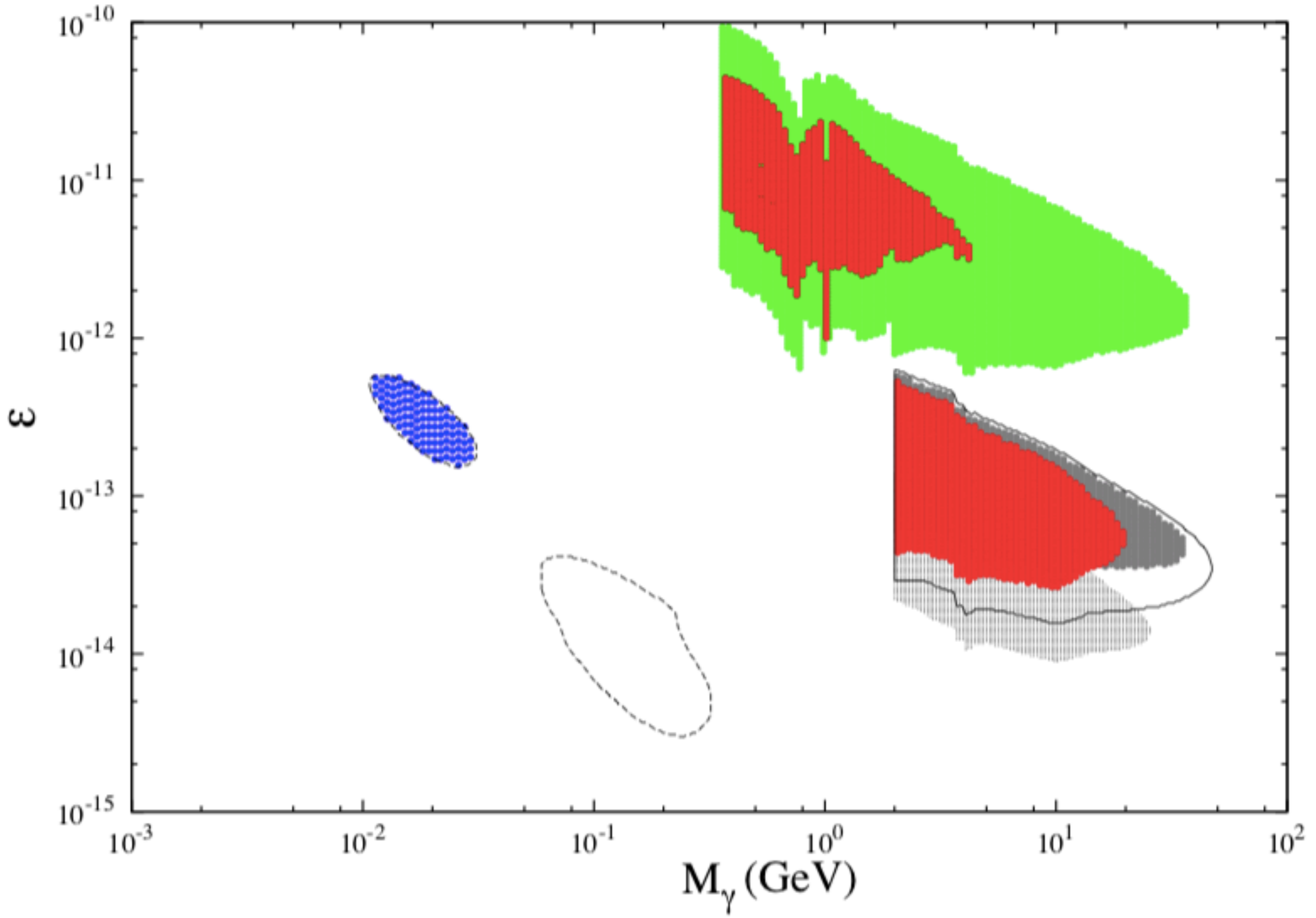
Where to look for hidden sectors

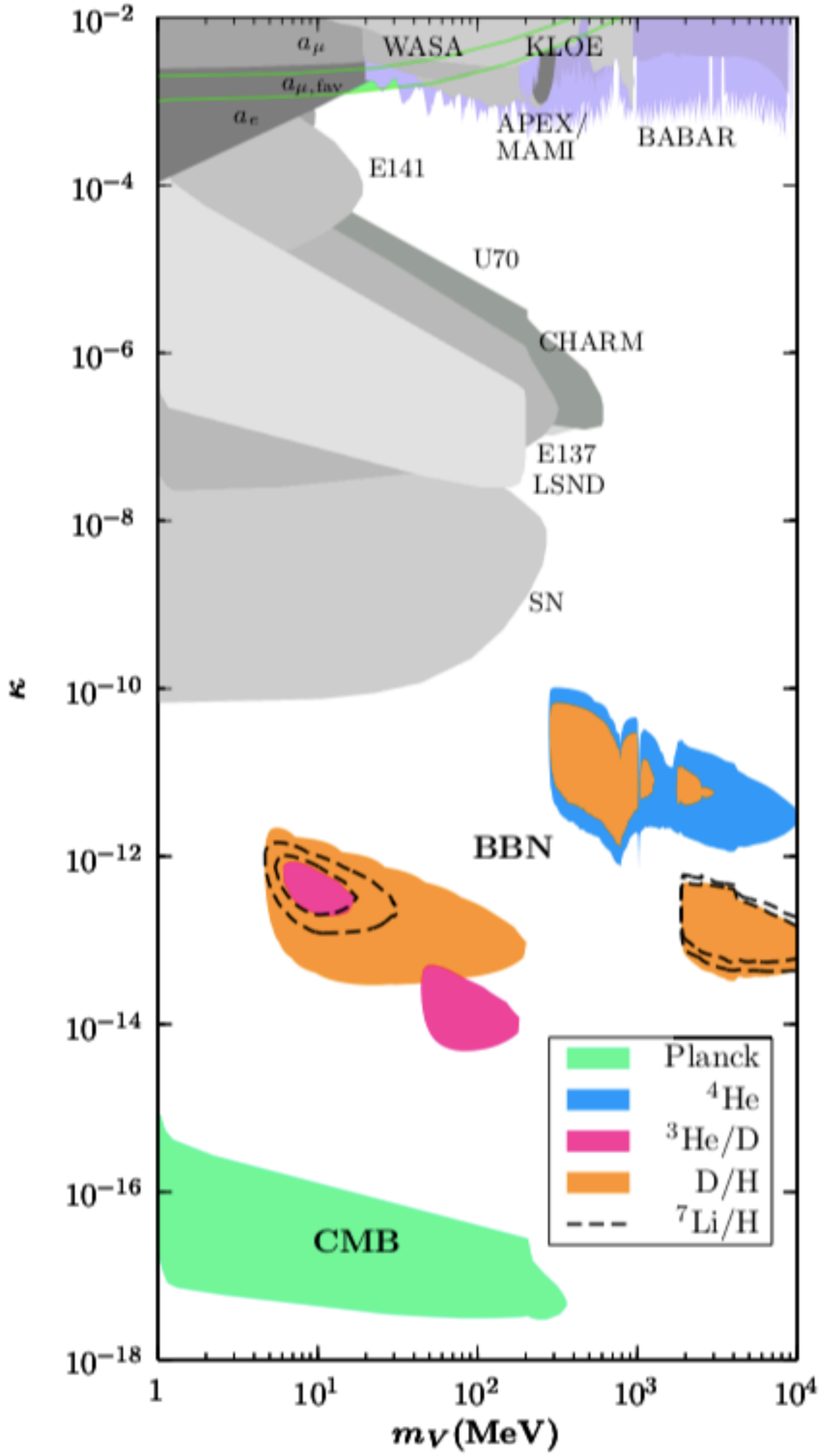


Why bother with cosmo?









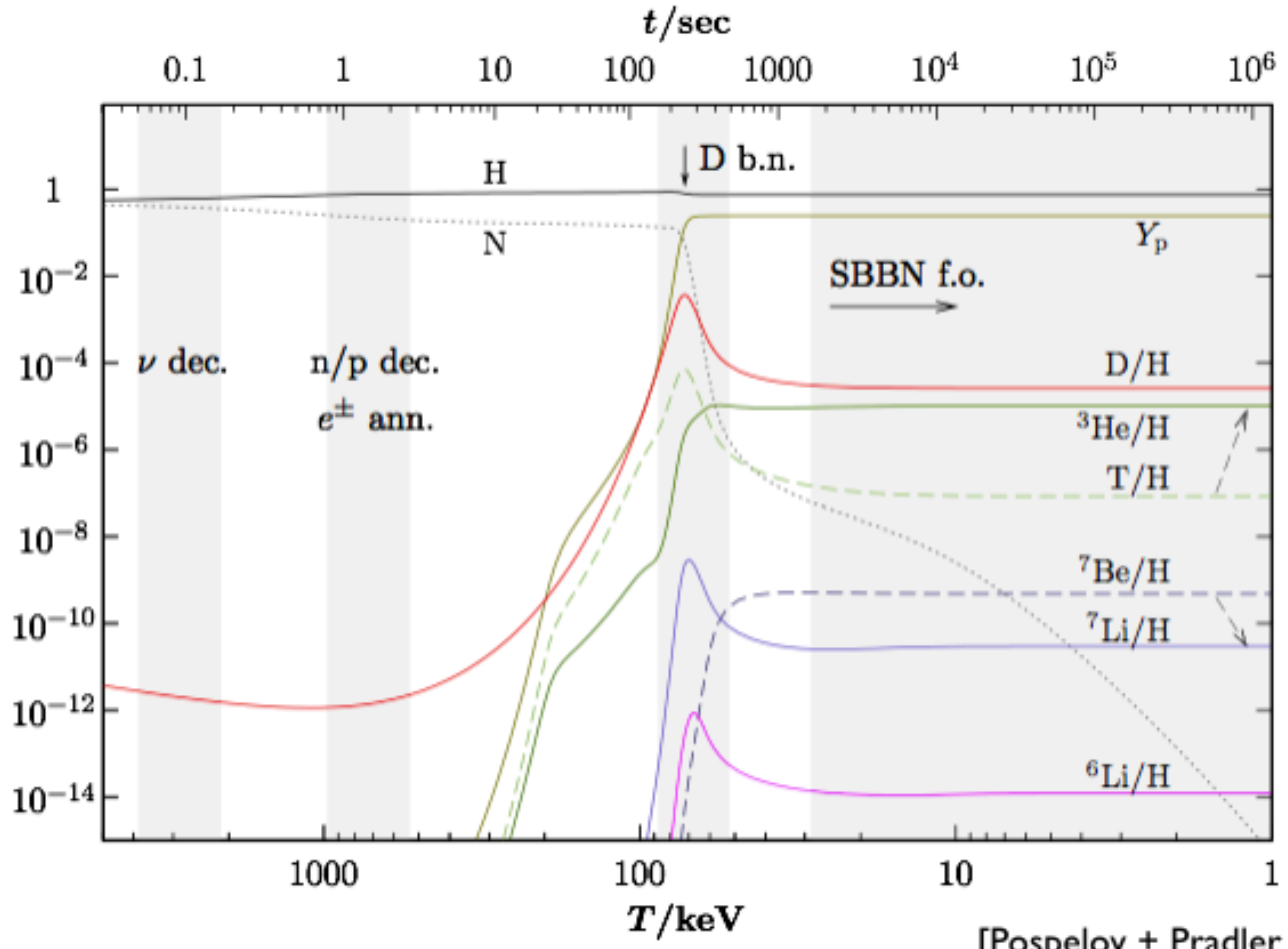
arXiv:1407.0993 Fradette et al
arXiv1605.07195 Berger et al

Outline

1. Big Bang nucleosynthesis
2. Model independent BBN constraints
3. Ionization of the intergalactic medium during recombination
4. Spectral distortions to the cosmic microwave background
5. Model Dependent constraints

Big Bang nucleosynthesis

- Inverse beta decay $p + e \rightarrow n + \nu_e$
- n/p~ frozen out at ~0.8 MeV
- Deuterium bottleneck $D + \gamma \rightarrow p + n$
- At T ~ 150 keV bottleneck is broken and abundances are frozen in
- Most in Hydrogen and ^{4}He



[Pospelov + Pradler 2010]

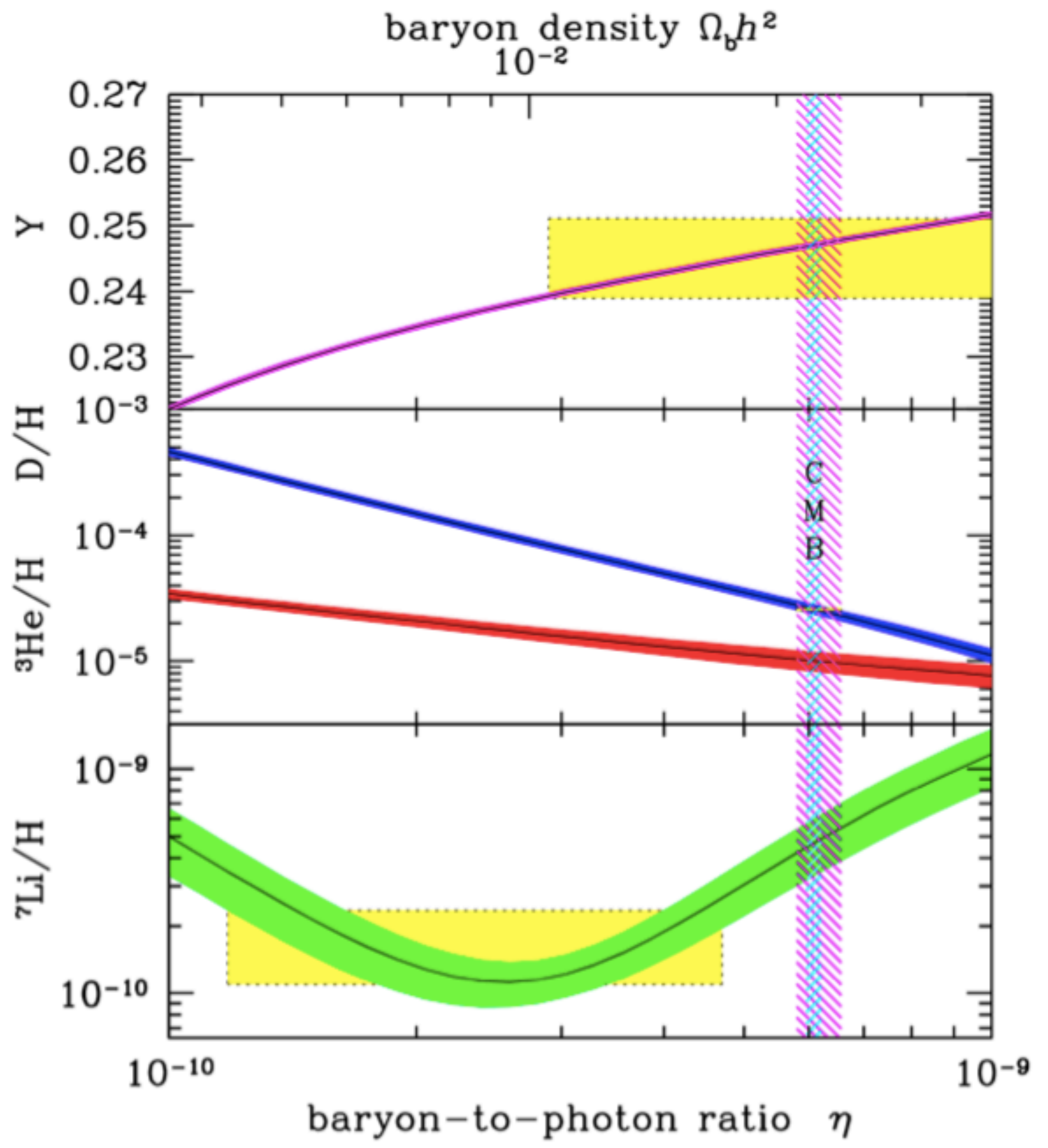
Big Bang nucleosynthesis

Takes only BAU as input

BAU from cmb
Predicts observed light element abundances

Constrains energy injection from new long lived particles

Most focus has been on the injections >> GeV



Particle data group

Big Bang nucleosynthesis

Focus on EM injection < 1 GeV

Initial injection of photons, electrons, muons, pions or neutrinos

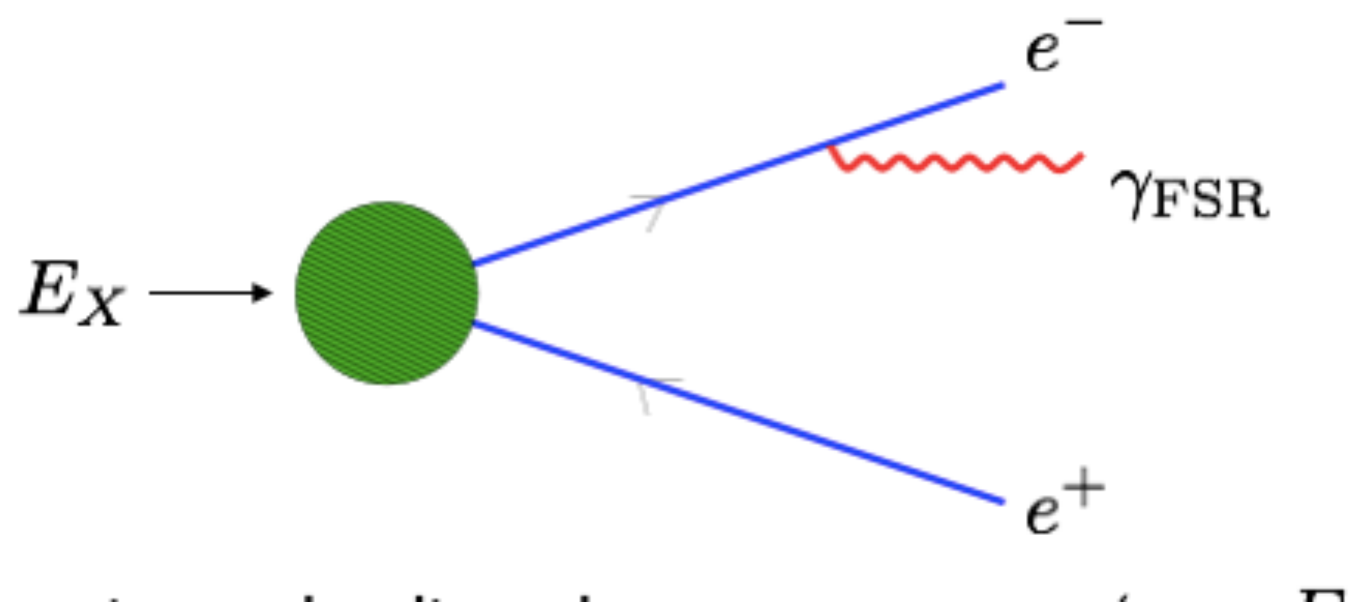
Neutrinos decouple, muons and pions decay

Electrons and photons interact with the background resulting in an EM cascade

EM cascade breaks up nuclei

Electromagnetic Cascade

Photon-photon pair production	$\gamma + \gamma_{\rm BG} \to e^+ + e^-$
Photon photon scattering	$\gamma + \gamma_{\rm BG} \to \gamma + \gamma$
Pair creation on nuclei	$\gamma + N_{\rm BG} \to N_{\rm BG} + e^+ + e^-$
Compton scattering	$\gamma + e^-_{\rm BG} \to \gamma + e^-$
Inverse Compton	$e^{\mp} + \gamma_{\rm BG} \to e^{\mp} + \gamma$
Final state radiation	$X \to e^+ + e^- + \gamma$



New

Photon spectrum

- Spectrum $N^i_\gamma \equiv \frac{dn^i_\gamma}{dE} \to N^f_\gamma$
- Rate of injection $R = n_X(t)/\tau_x$
- Distribution: $\bar{f}(E) = \frac{1}{R} N_\gamma(E) - \frac{\xi_\gamma}{\Gamma_\gamma(E_X)} \delta(E - E_X)$
- Conventional wisdom: Universal spectrum

$$\frac{dn_\gamma}{dE} \approx R \frac{p_\gamma(E_\gamma)}{\Gamma_\gamma(E_\gamma)}$$

Effective threshold for pair production

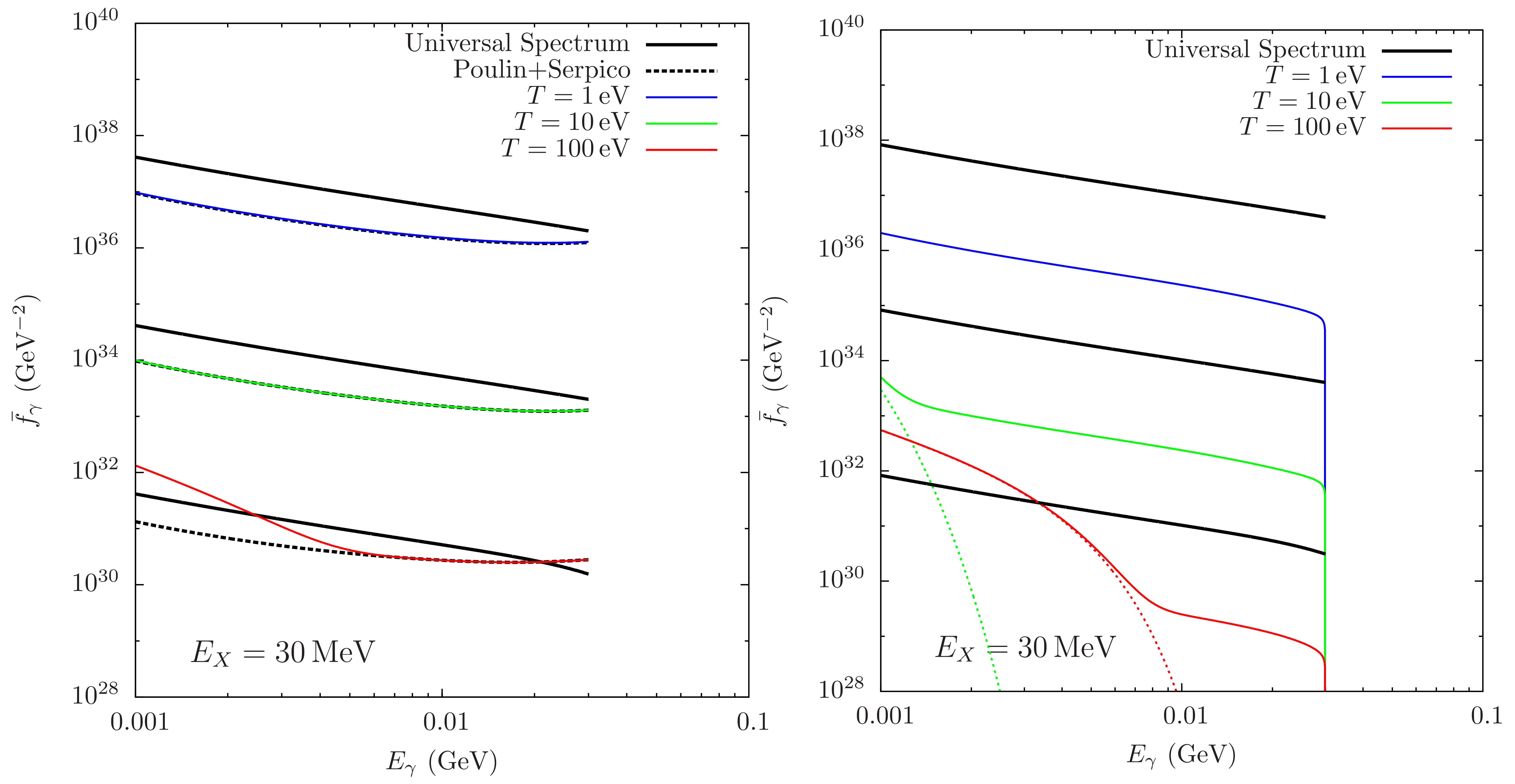
$$p_\gamma(E_\gamma) \simeq \begin{cases} 0 & ; \quad E_\gamma > E_c \\ K_0 \left(\frac{E_\gamma}{E_m}\right)^{-2.0} & ; \quad E_m < E_\gamma < E_c \\ K_0 \left(\frac{E_\gamma}{E_m}\right)^{-1.5} & ; \quad E_\gamma < E_m \end{cases},$$

Photon spectrum

- Problems with Universal spectrum for low E injections:
  - $E_X < (E_C, E_m)$
  - Nuclear thresholds

$$p_\gamma(E_\gamma) \simeq \begin{cases} 0 & ; \quad E_\gamma > E_c \\ K_0 \left(\frac{E_\gamma}{E_m}\right)^{-2.0} & ; \quad E_m < E_\gamma < E_c \\ K_0 \left(\frac{E_\gamma}{E_m}\right)^{-1.5} & ; \quad E_\gamma < E_m \end{cases},$$

Electromagnetic Cascade



Light element abundances

$$Y_p = 0.245 \pm 0.004$$ **(Helium mass fraction)**

$$\frac{n_D}{n_H} = (2.53 \pm 0.05) \times 10^{-5}$$

$$\frac{n_{^3\mathrm{He}}}{n_H} = (1 \pm 0.5) \times 10^{-5}$$

Light element abundances

$$Y_p = 0.245 \pm 0.004$$

Emission lines from
Metal poor extragalactic regions
1503.08146

$$\frac{n_D}{n_H} = (2.53 \pm 0.05) \times 10^{-5}$$

Theory uncertainty
(photon capture)

$$\frac{n_{^3\mathrm{He}}}{n_H} = (1 \pm 0.5) \times 10^{-5}$$

Observations of solar winds etc
To determine composition of proto-solar cloud

Boltzmann equations

- Take BBN products as initial conditions

$$\frac{dY_A}{dt} = \sum_i Y_i \int_0^\infty N_\gamma(E_\gamma)\sigma_{y+i\to A}(E_\gamma) - Y_A \sum_f \int_0^\infty N_\gamma(E_\gamma)\sigma_{y+A\to f}(E_\gamma)$$

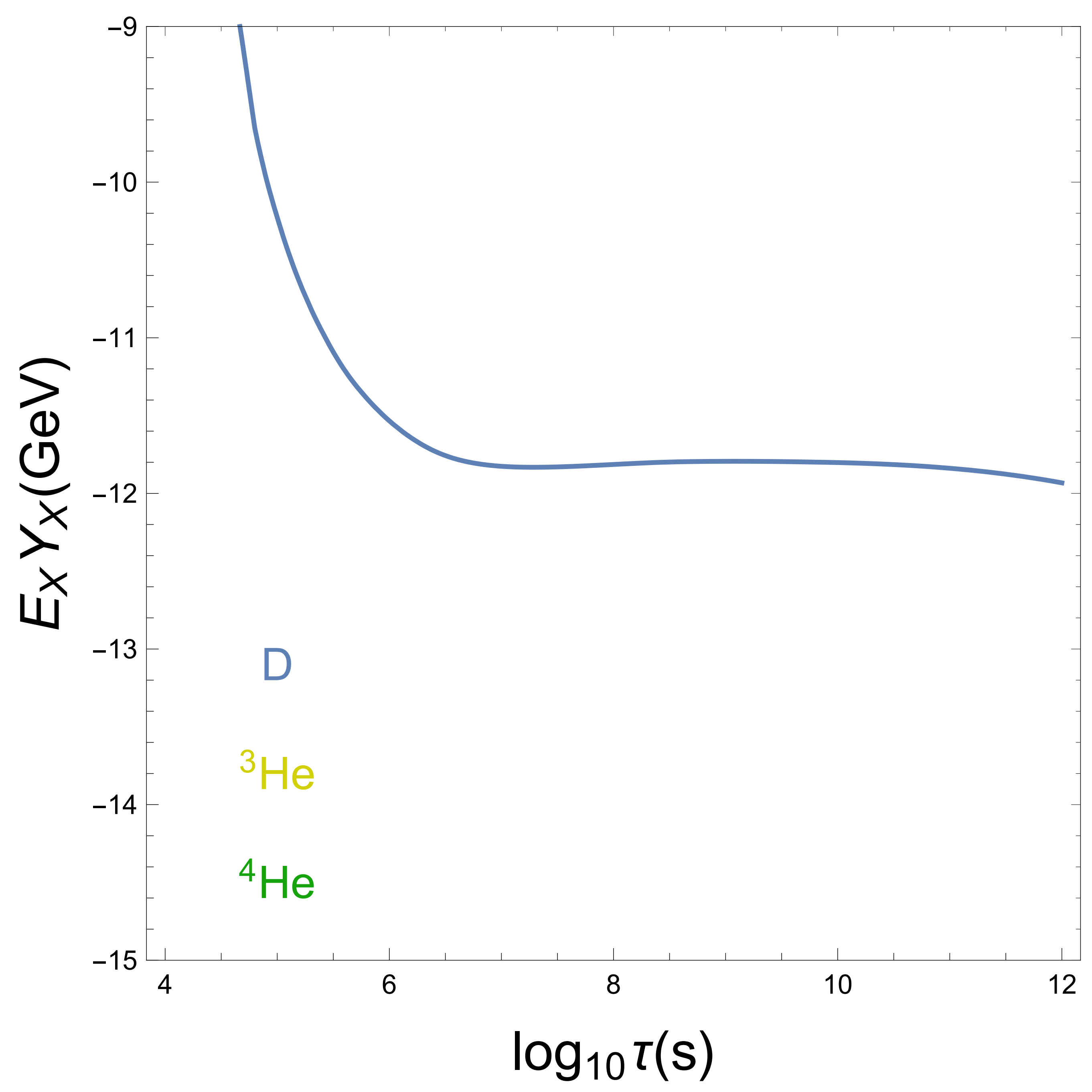
Nucleon-destruction

First Deuteron destruction (2.2 MeV) $D + \gamma \rightarrow p + n$

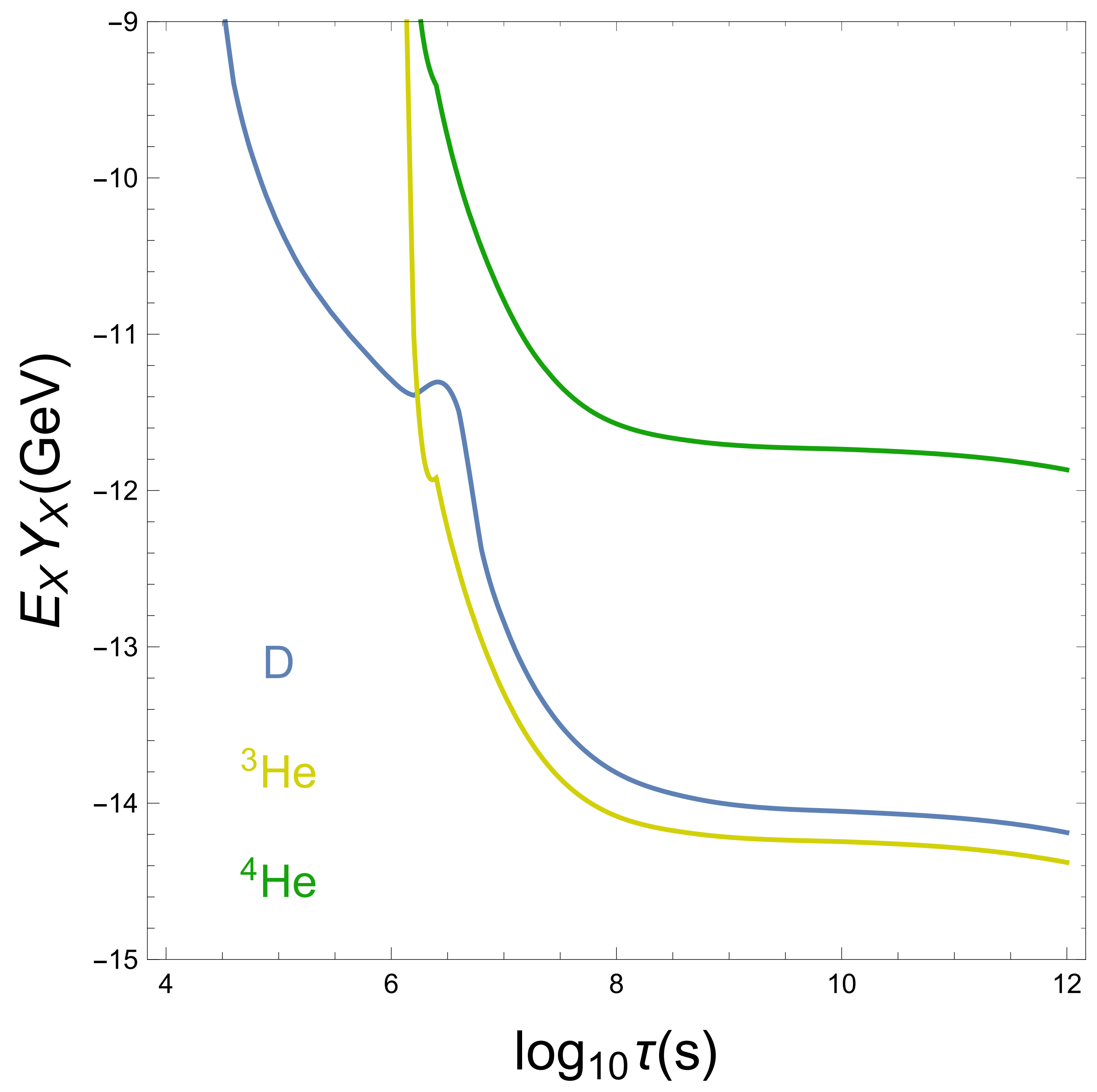
First Deuteron creation (5.5 MeV) $^3\mathrm{He} + \gamma \rightarrow D + p$

First (important) Helium destruction (20.6 MeV) $^4\mathrm{He} + \gamma \rightarrow {}^3\mathrm{He} + n$

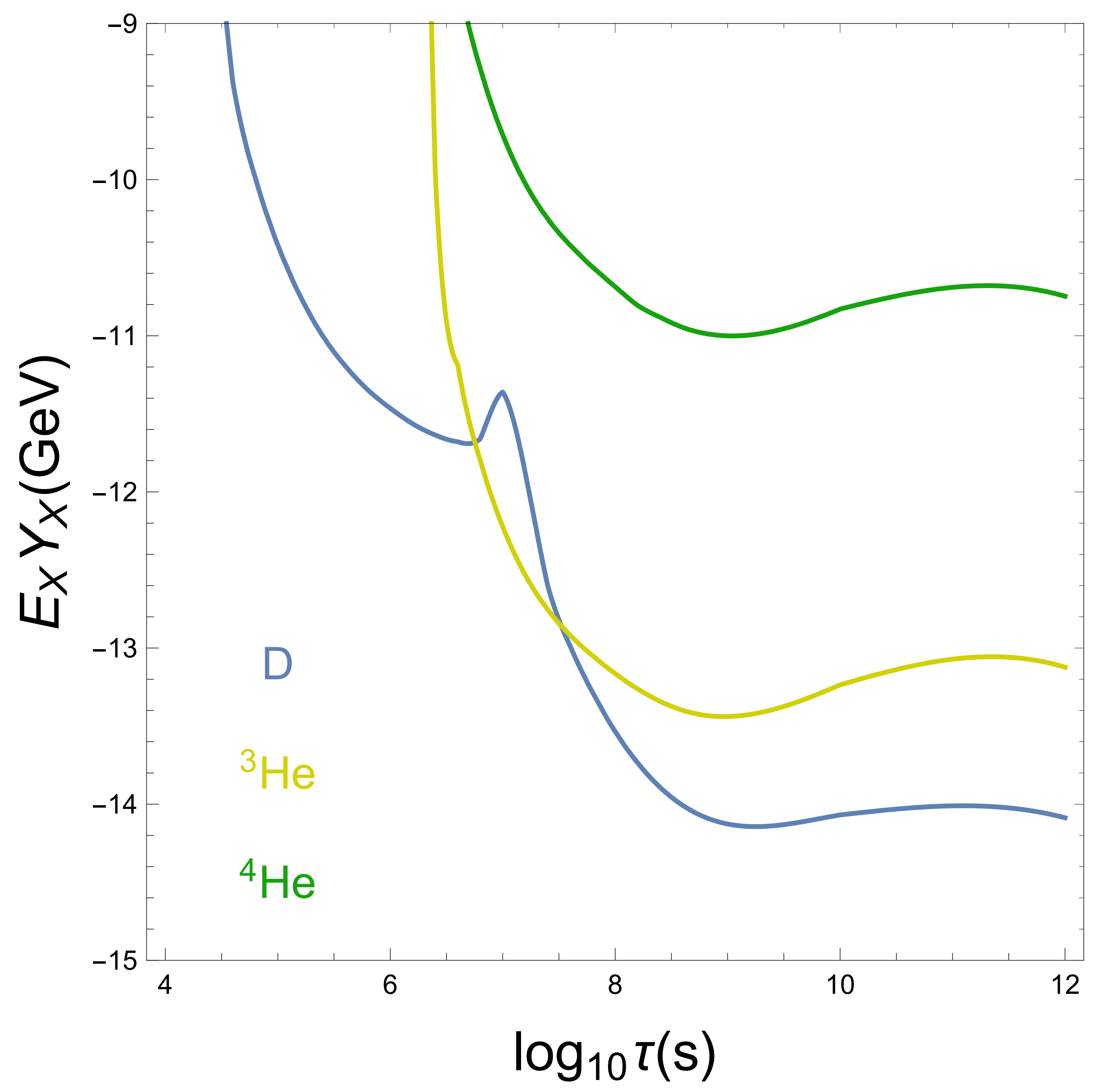
Benchmarks for photon injection



10 MeV

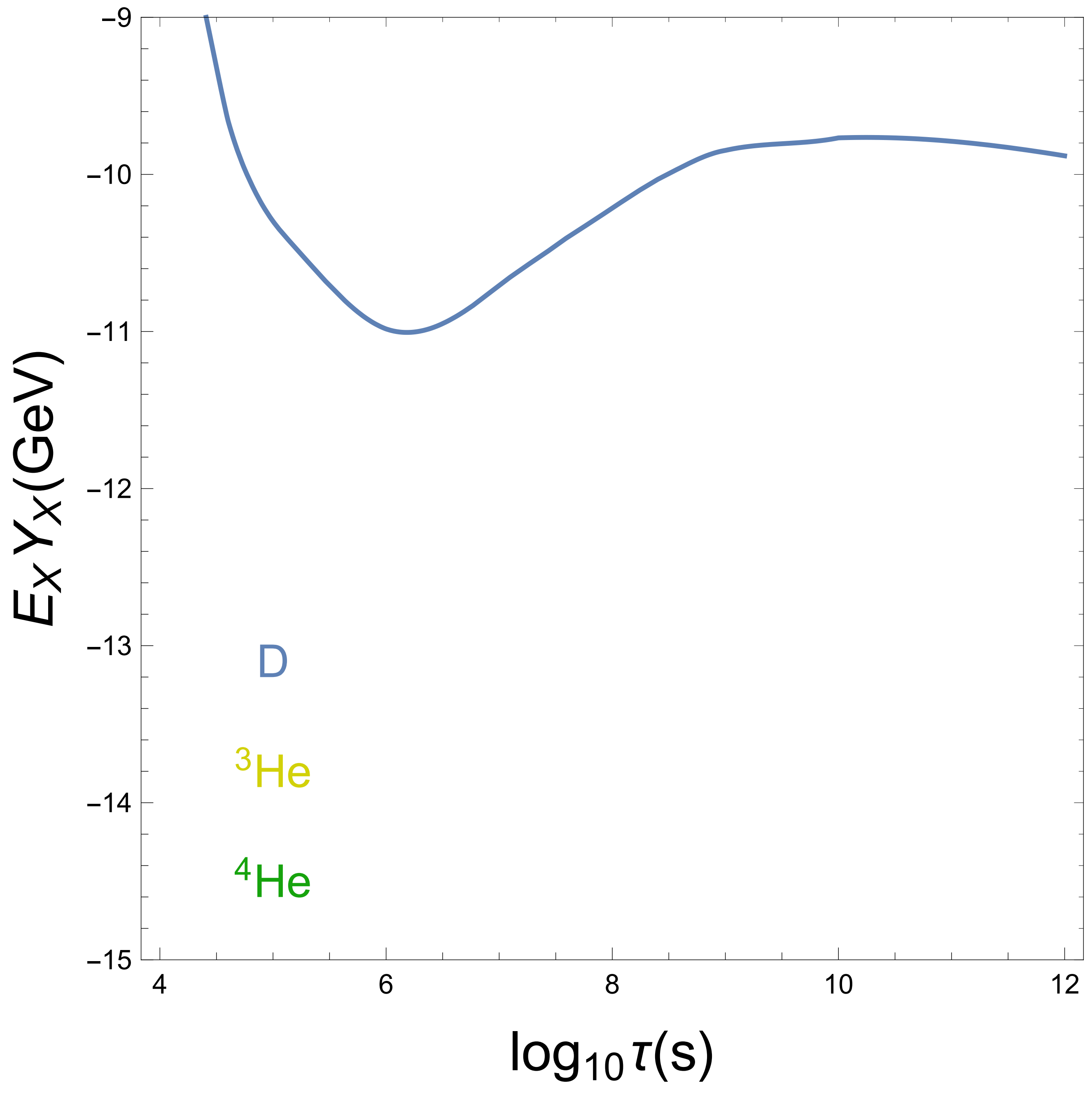


30 MeV

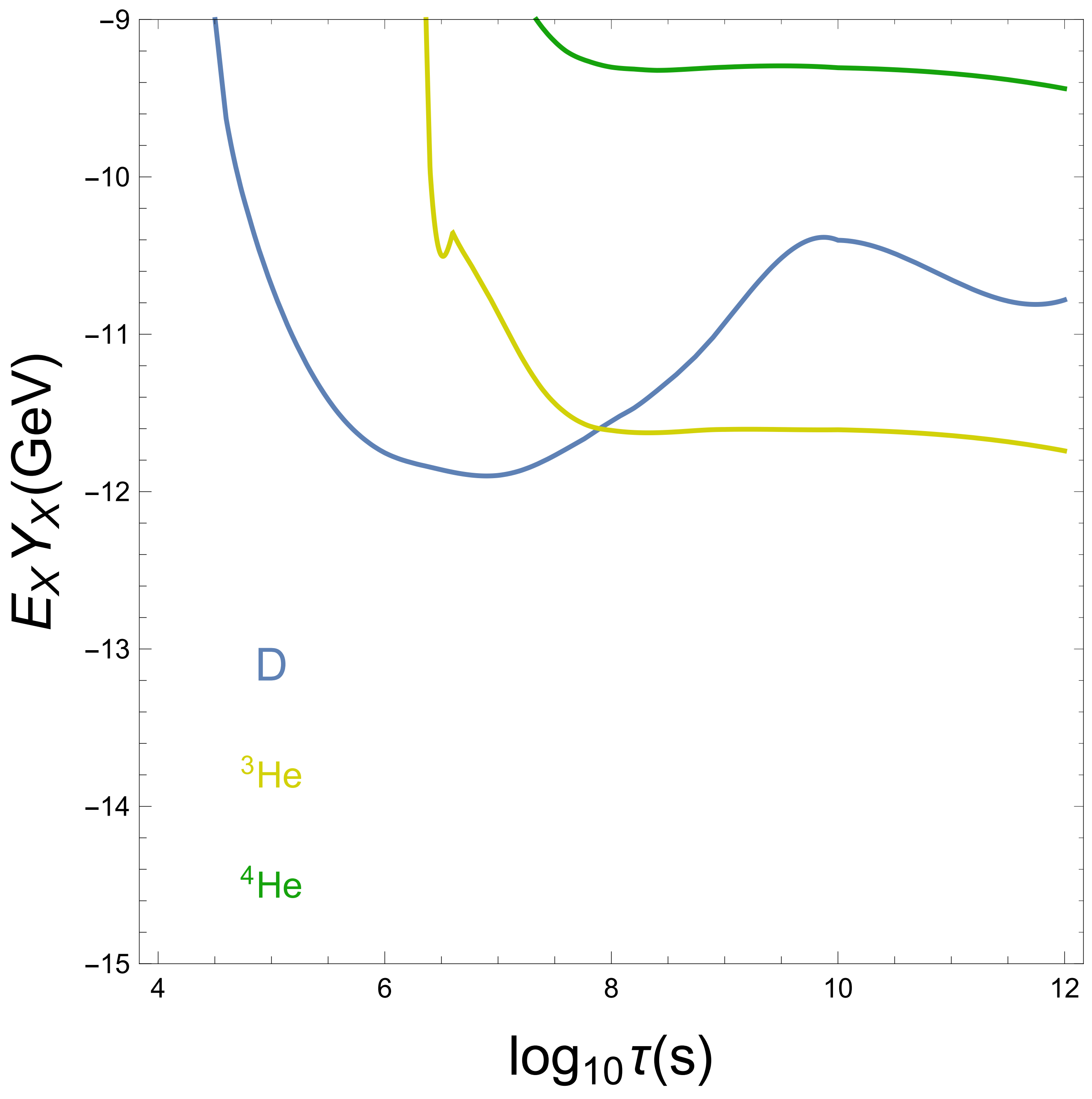


100 MeV

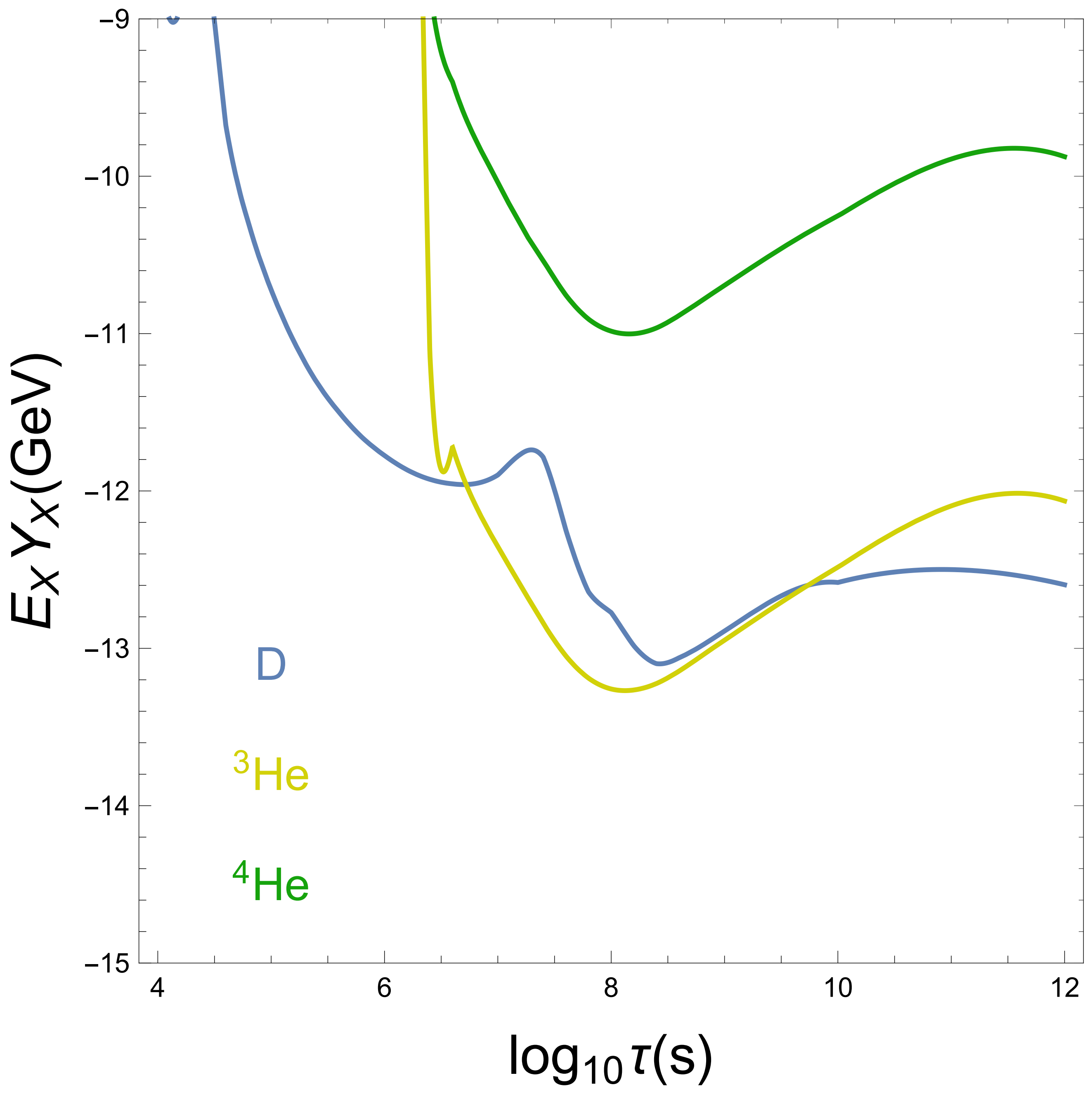
Benchmarks for electron injection



10 MeV

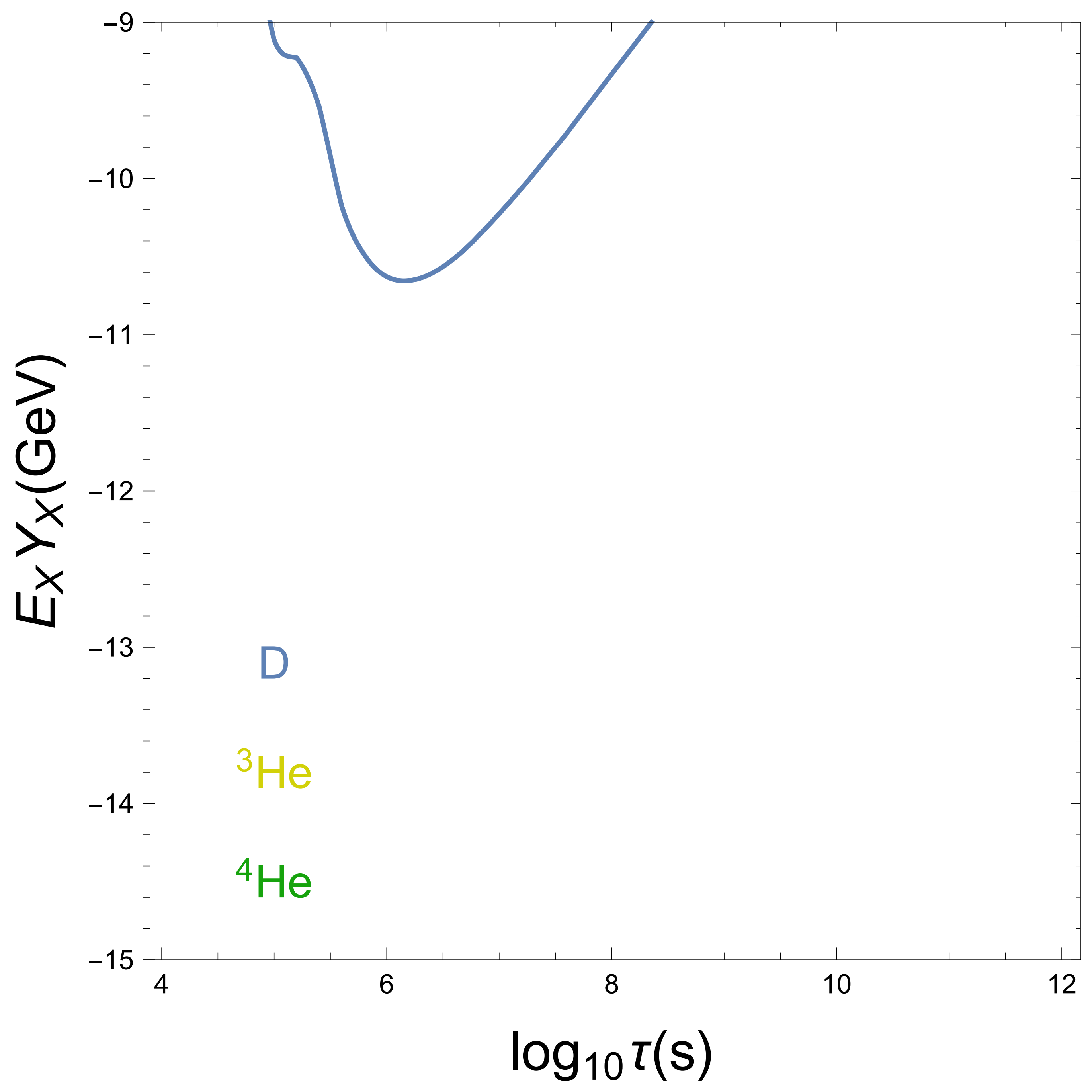


30 MeV

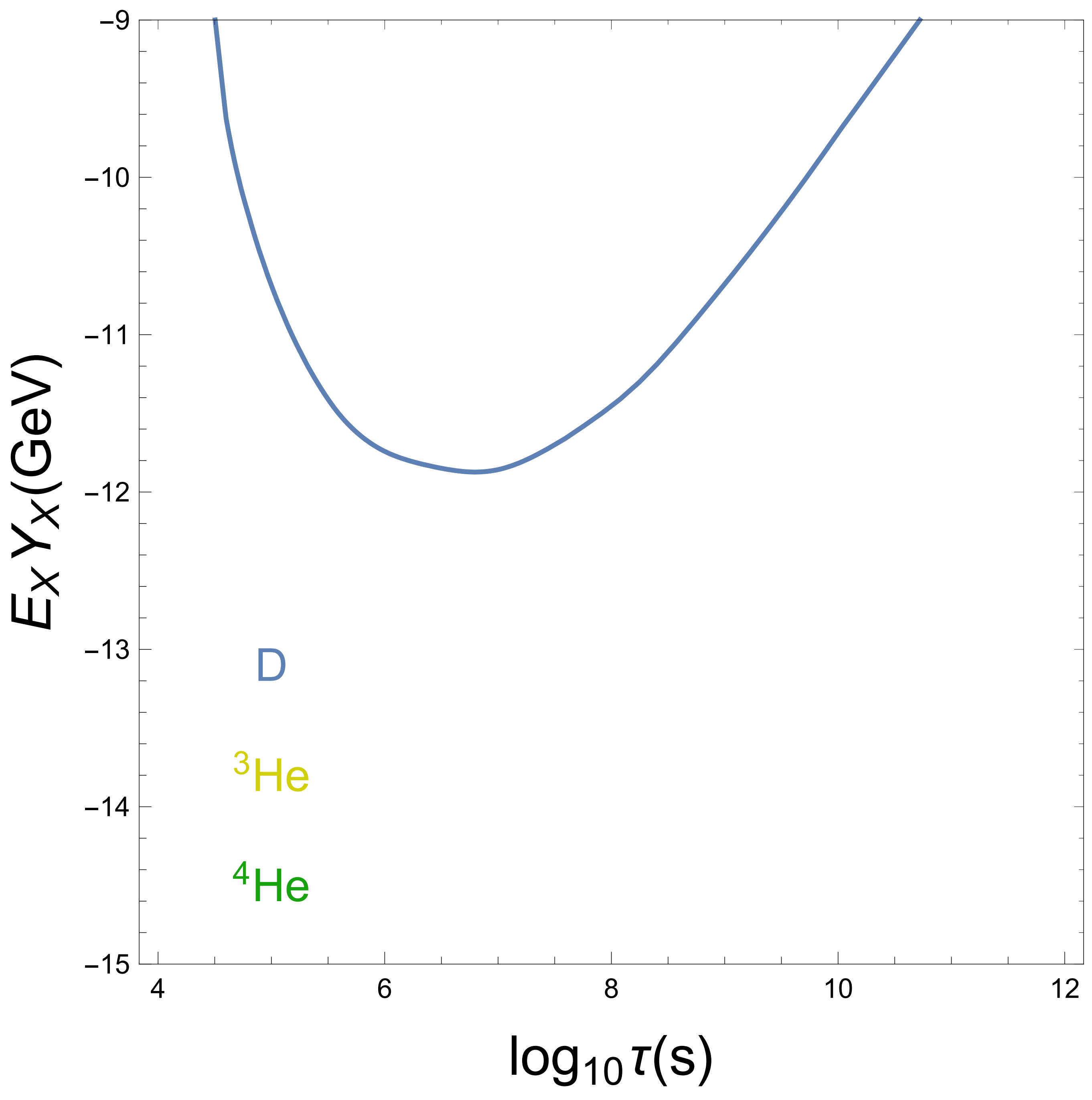


100 MeV

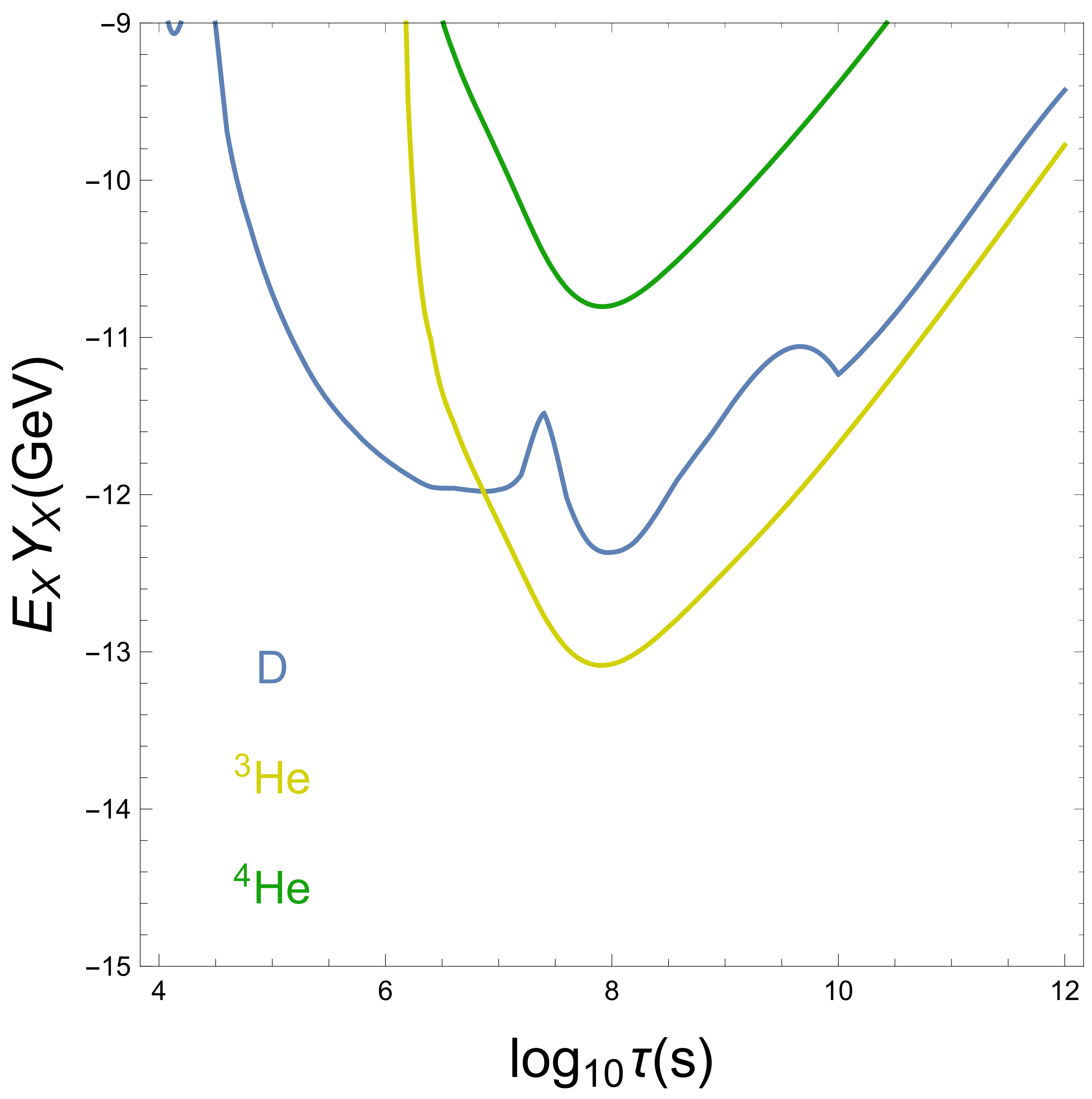
Benchmarks for electron injection



10 MeV

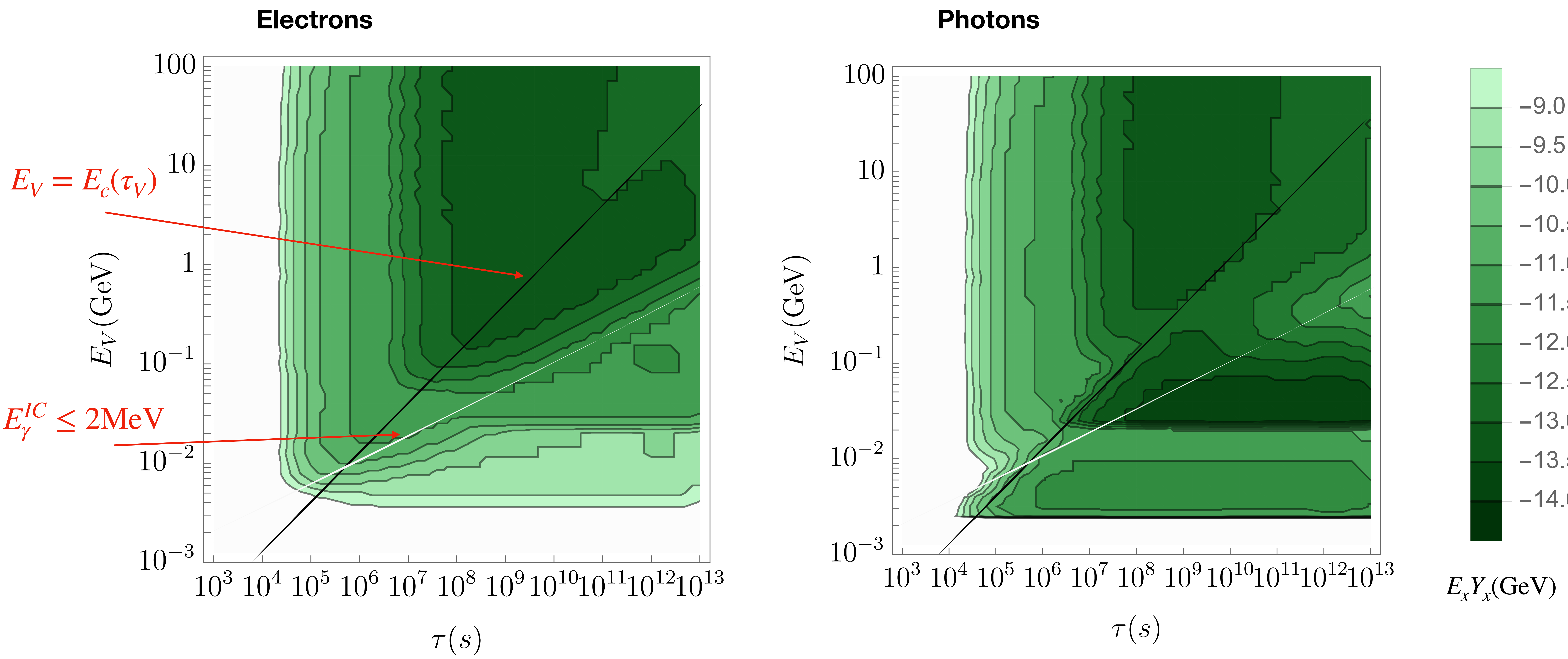


30 MeV



100 MeV

Monochromatic injection



Other model independent constraints

Monochromatic Injection into

1. **Muons**
2. $\pi^+\pi^-$
3. $\pi^0\gamma$
4. $\pi^+\pi^-\pi^0$

Other model independent constraints

Monochromatic Injection into

1. **Muons**
2. $\pi^+\pi^-$
3. $\pi^0\gamma$
4. $\pi^+\pi^-\pi^0$

All unstable — calculate the final photon and electron spectrum .

$$\frac{dN}{dE_\gamma} = \left.\frac{dN}{dE_\gamma}\right|_{\rm rad} + \left.\frac{dN}{dE_\gamma}\right|_{\rm FSR} + \left.\frac{dN}{dE_\gamma}\right|_{\rm dir}$$

Some energy lost into neutrinos

$$\frac{dN}{dE_e} = \left.\frac{dN}{dE_e}\right|_{\rm rad} + \left.\frac{dN}{dE_\gamma}\right|_{\rm dir}$$

Other model independent constraints

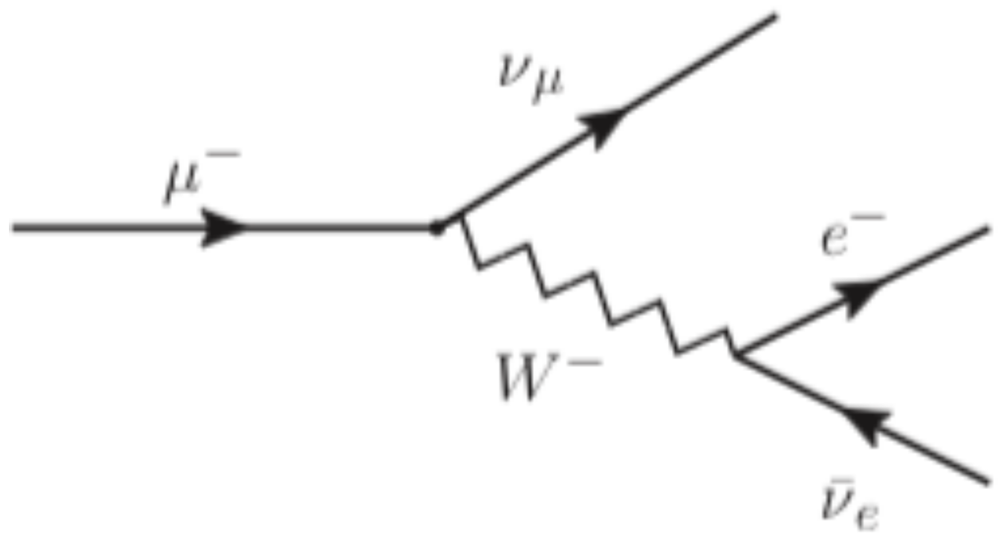
Can calculate spectrum from decays of SM particles in the rest frame and boosting

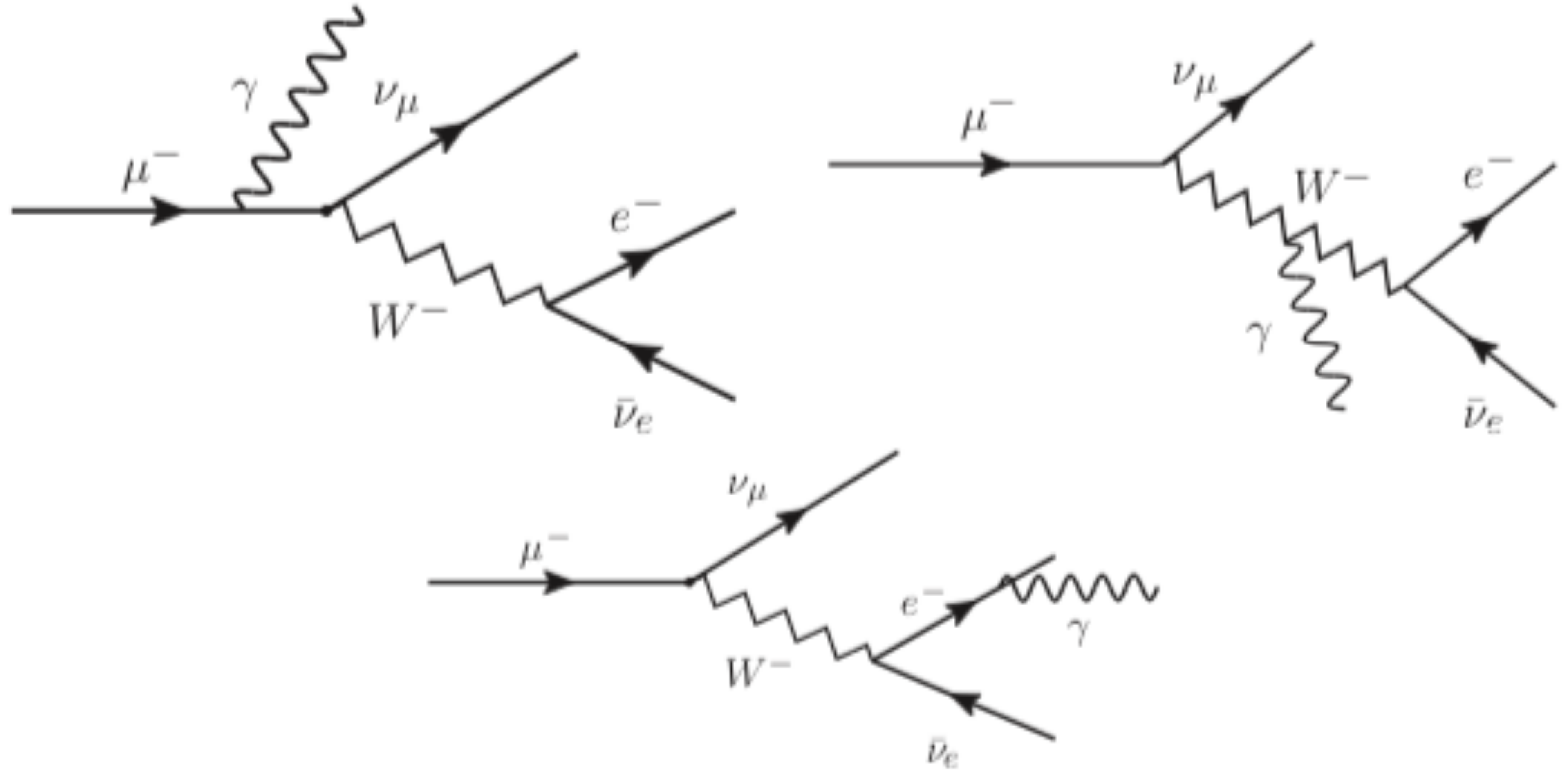
$$\gamma = m_V/2m_{\rm SM} = 1/\sqrt{1-\beta^2}$$

$$\frac{dN_x}{dE} = \frac{2}{4\pi}\int d\Omega' \frac{1}{\gamma(1+\beta\cos\theta' E'/p')}\frac{dN_x}{dE'}$$

Other model independent constraints

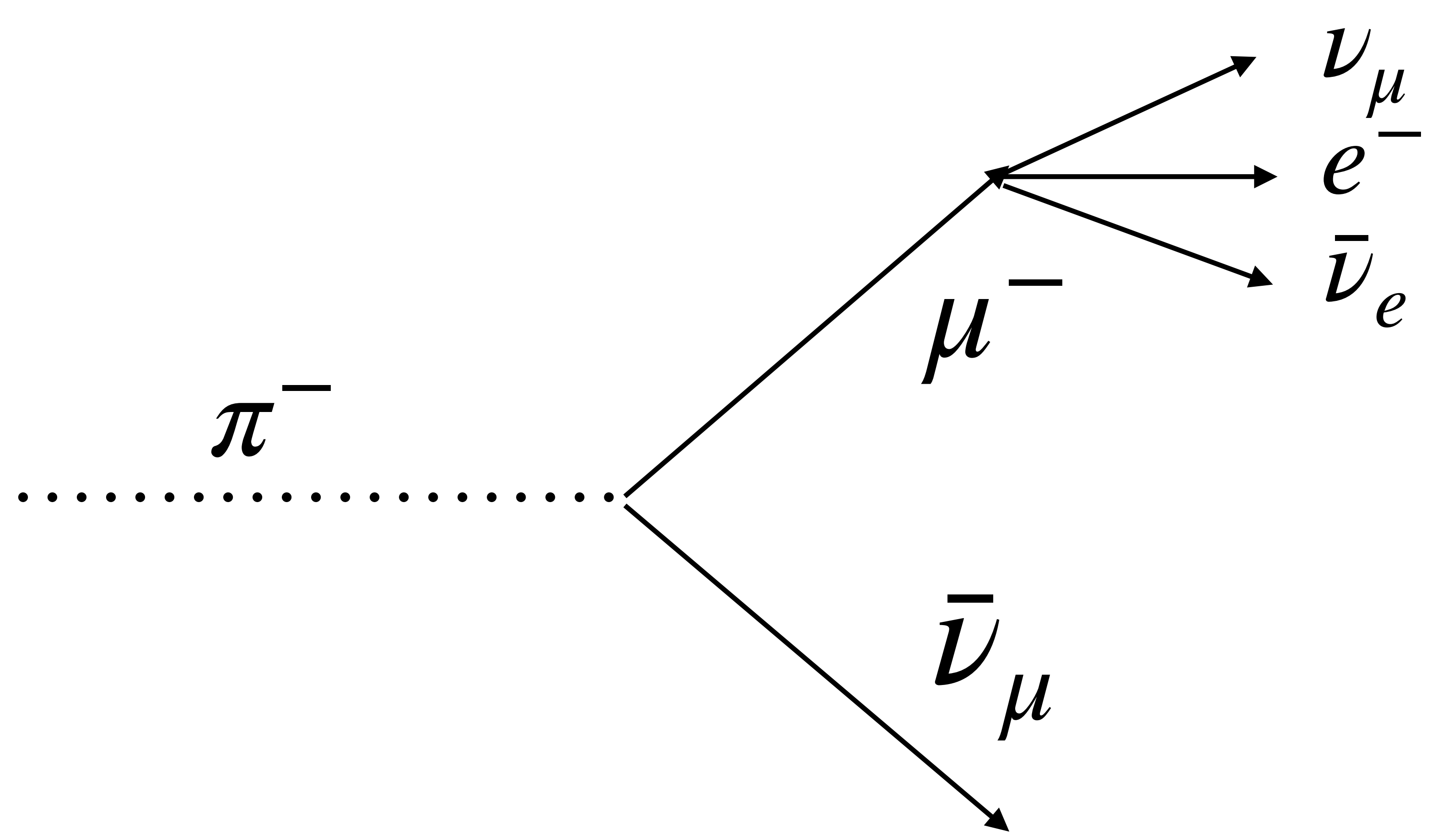
Radiative contributions for muons





Other model independent constraints

Radiative contributions for charged pions



Note: take polarization into account

Other model independent constraints

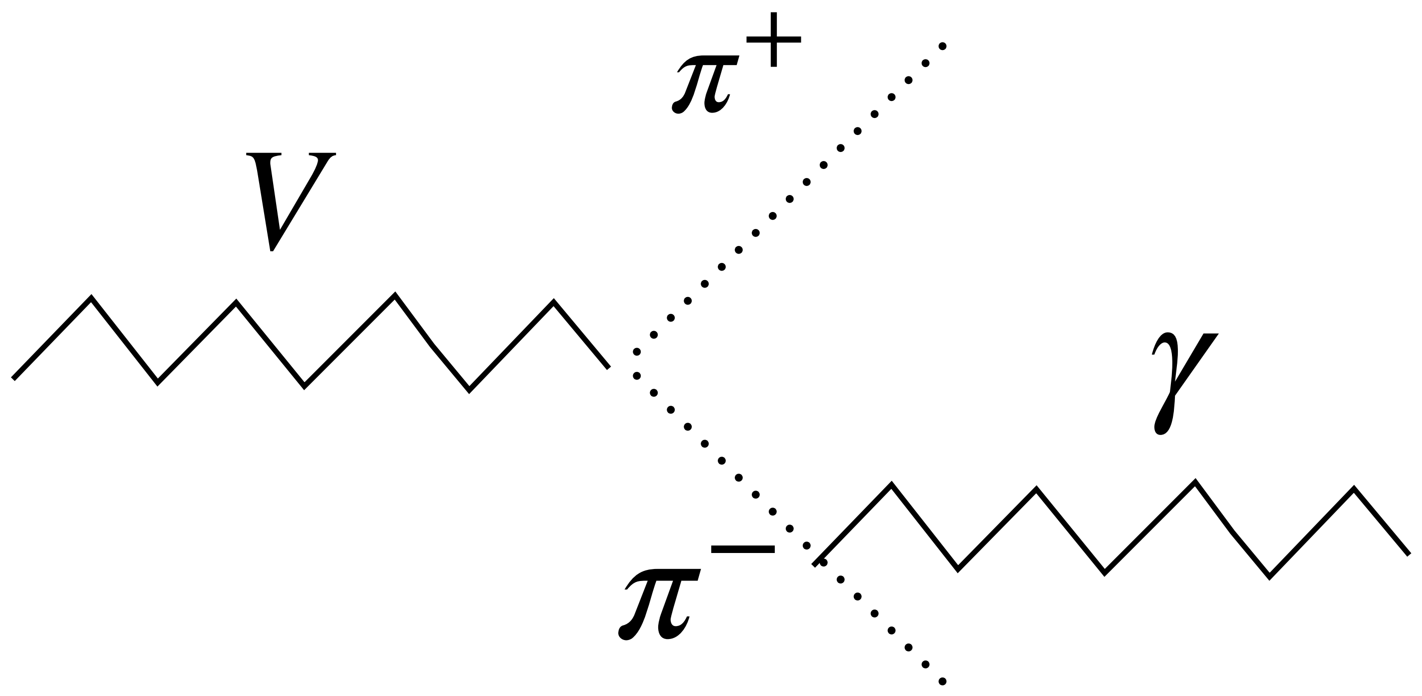
Radiative contributions for charged pions

$$\frac{dN}{dE_\gamma} = \sum_{l \in e,\mu} \mathrm{BR}(\pi^+ \to l,\mu) \frac{dN}{dE_\gamma}\bigg|_{\pi^+ \to l^+ \nu_l} + \mathrm{BR}(\pi^+ \to \mu^+ \nu_\mu) \frac{dN}{dE_\gamma}\bigg|_{\mu}$$

See also 1) HAZMA 2) Plehn et al 1911.11147

Other model independent constraints

FSR contributions for charged pions

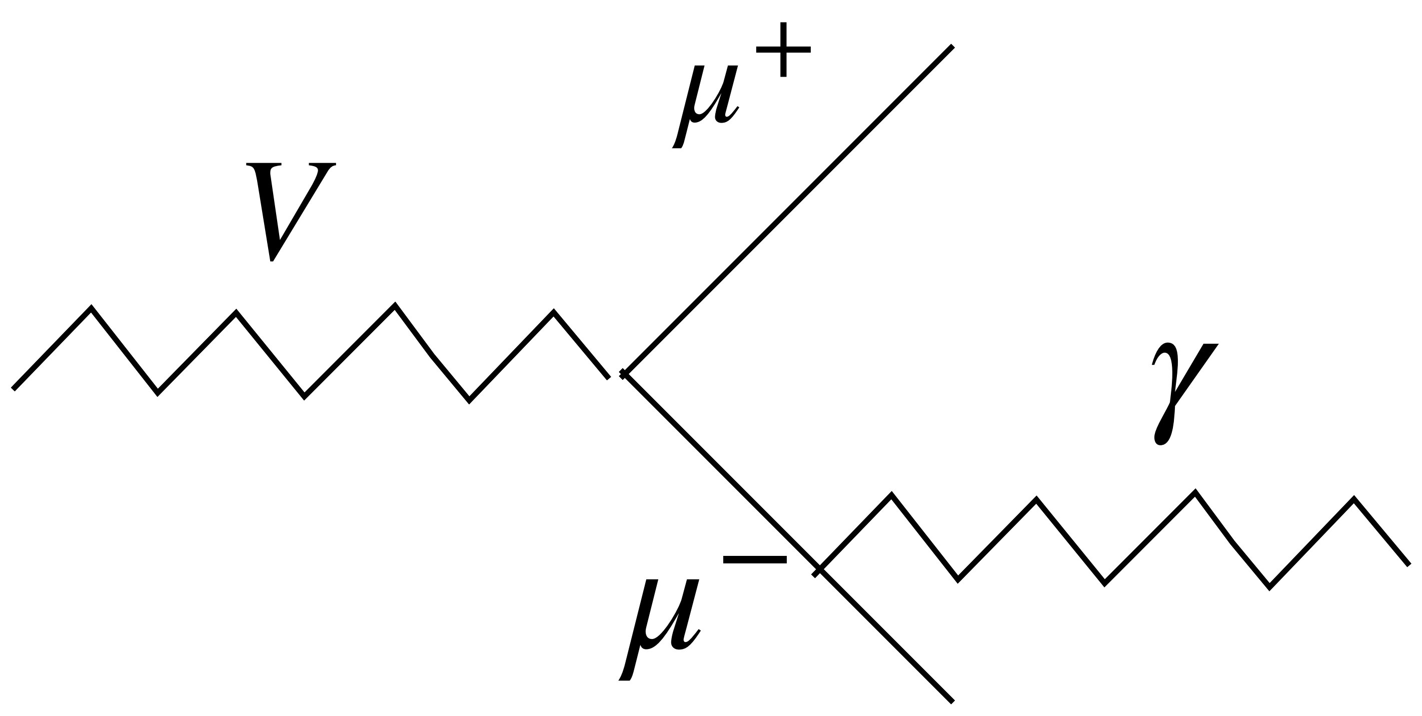


$$\frac{dN}{dE} \sim \frac{\alpha m_{\pi^+}}{\pi} \frac{2(1-x)}{x} \log\left(\frac{m_V^2(1-x)}{m_{\pi^+}^2}\right)$$

Typically subdominant!

Other model independent constraints

FSR contributions for muons

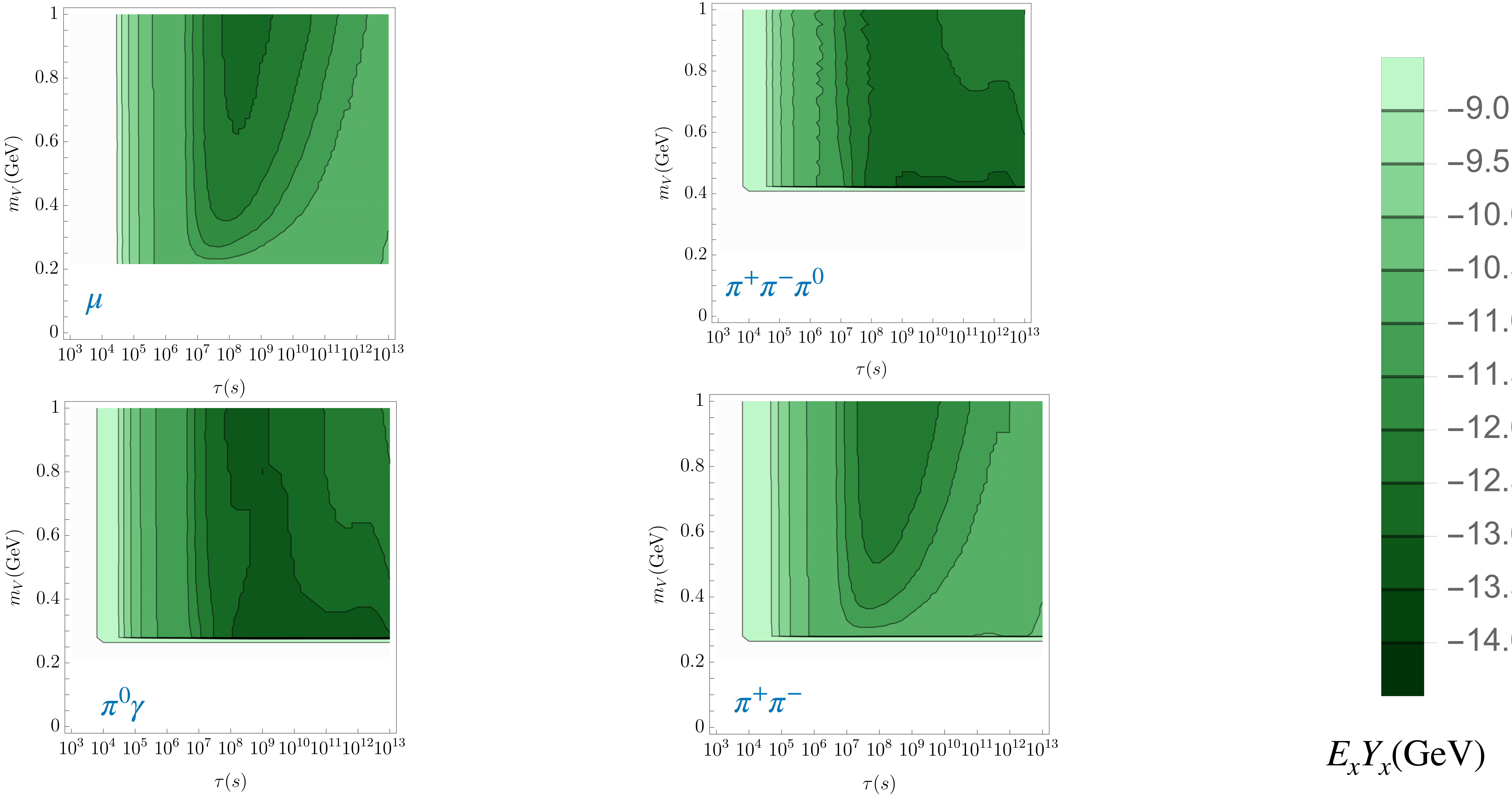


$$\frac{dN}{dE} \sim \frac{\alpha m_{\pi^+}}{\pi} \frac{1+(1-x)^2}{x} \log\left(\frac{m_V^2(1-x)}{m_\mu^2}\right)$$

Typically dominant!

Note: Leading log becomes a poor approximation for light dark matter! We use the full FSR spectrum

Other model independent constraints



Model dependent constraints

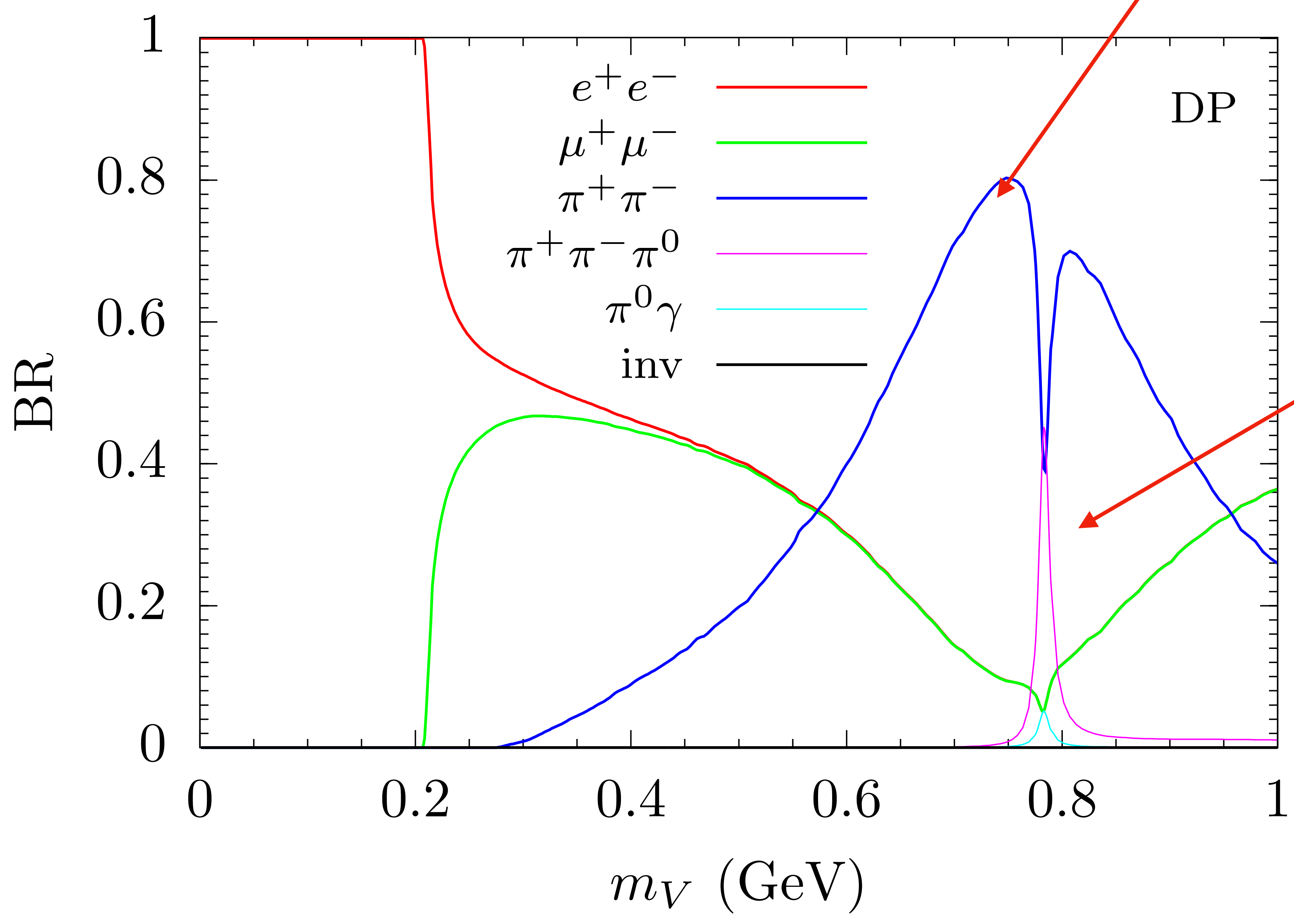
Vector mediators:
Dark Photons
Gauged lepton family numbers
$\mathrm{U}(1)_{B-L}$

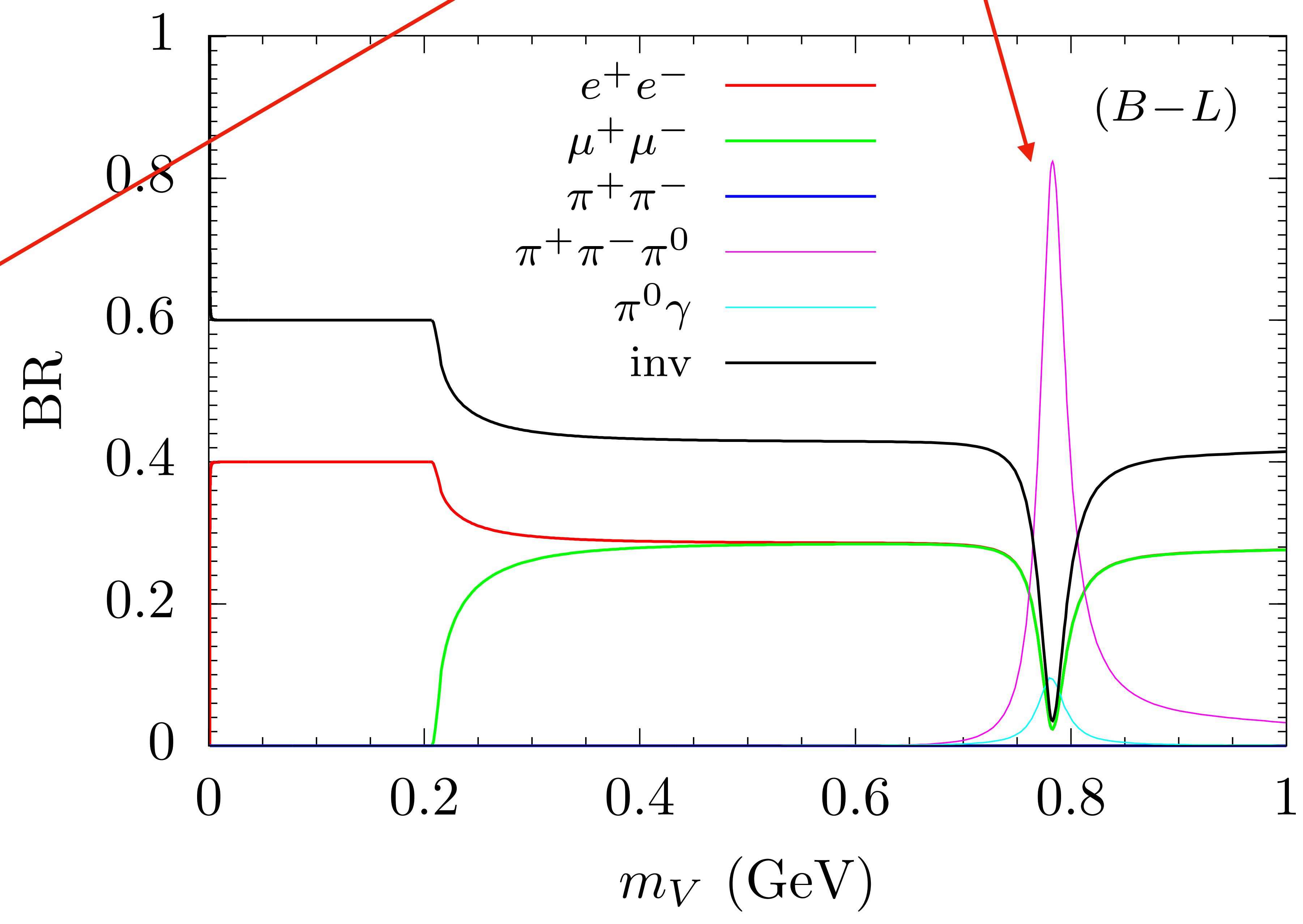
Model dependent constraints

Vector mediators:
Dark Photons
Gauged lepton family numbers
$U(1)_{B-L}$

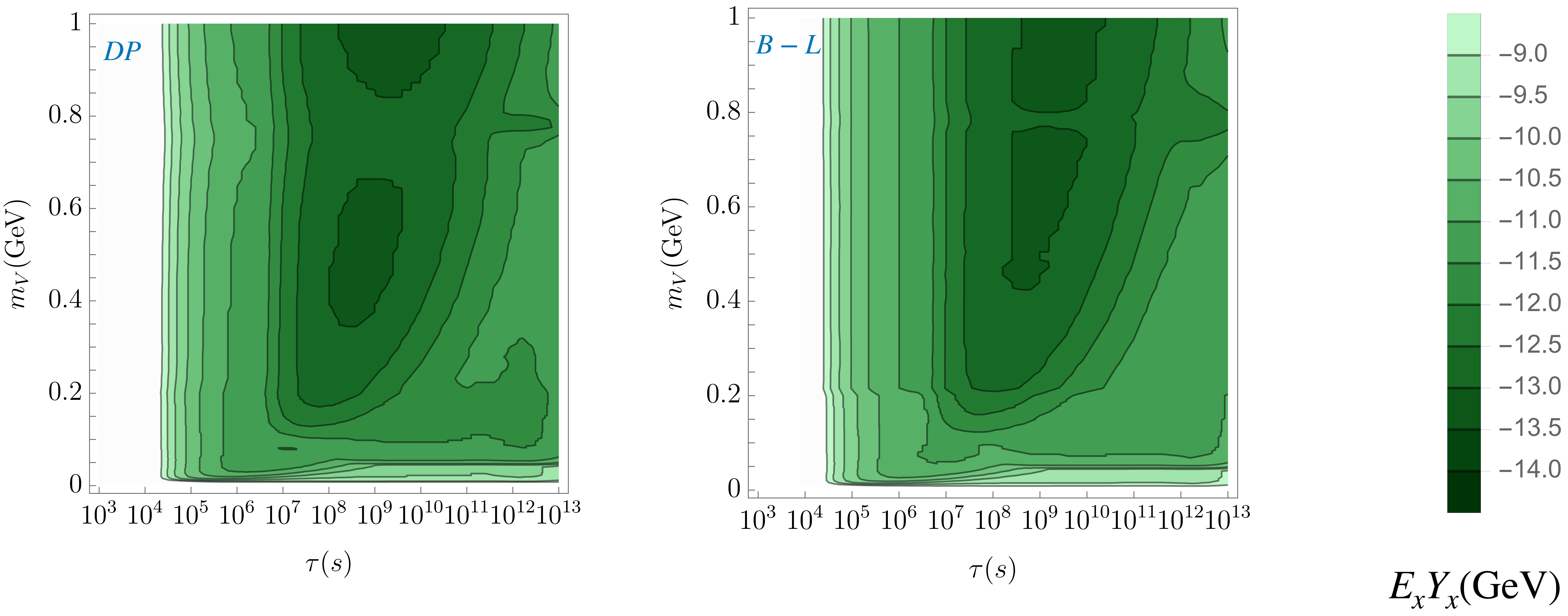
Data driven calculation of ρ meson decays

VMD to estimate ω decays

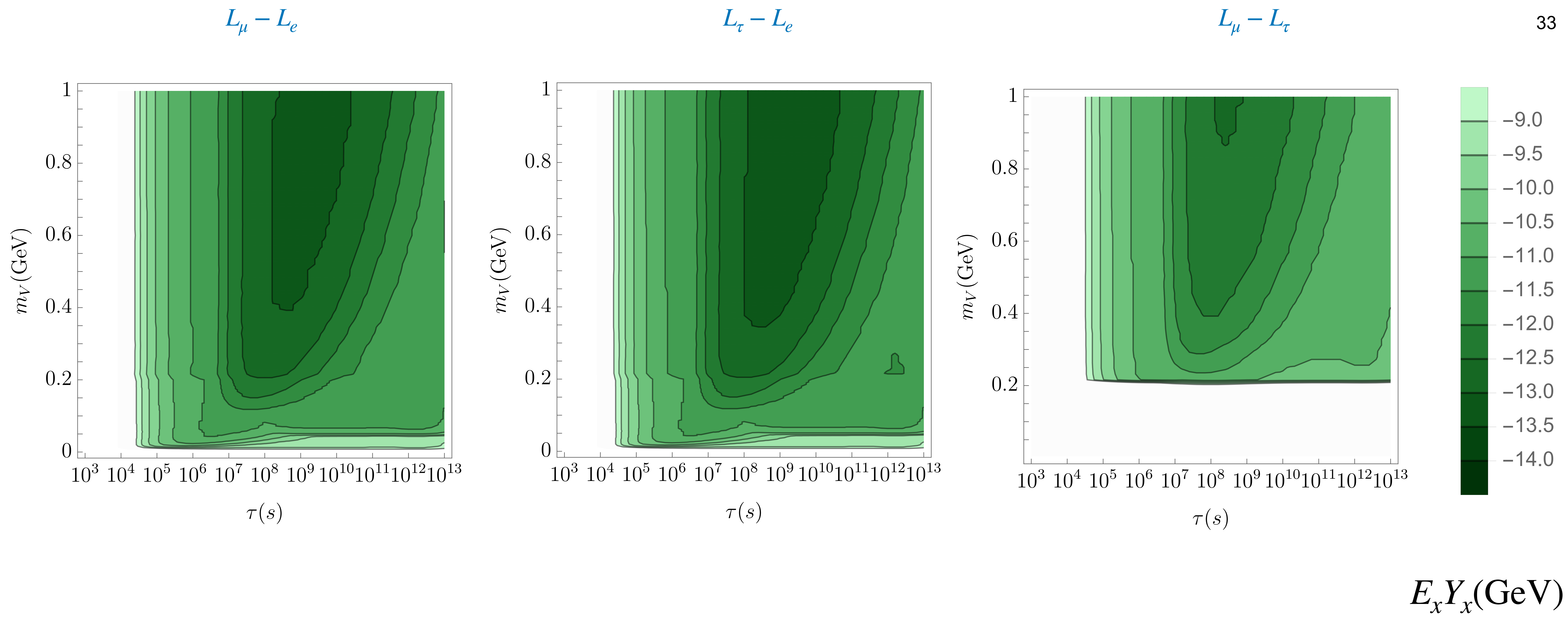




Model dependent constraints



Model dependent constraints



CMB ionization constraints

Energy injected at very late times can affect the ionization history of the Universe, modifying the CMB

Constraints on the dark matter fraction from $10^{12}s \lesssim \tau \lesssim 10^{25}s$

CMB ionization constraints

Not all energy injected is deposited into the intergalactic medium

$$\left(\frac{d\rho}{dt}\right)\bigg|_{\text{dep}} = f(z)\left(\frac{d\rho}{dt}\right)\bigg|_{\text{inj}}$$

Depletion of initial abundance

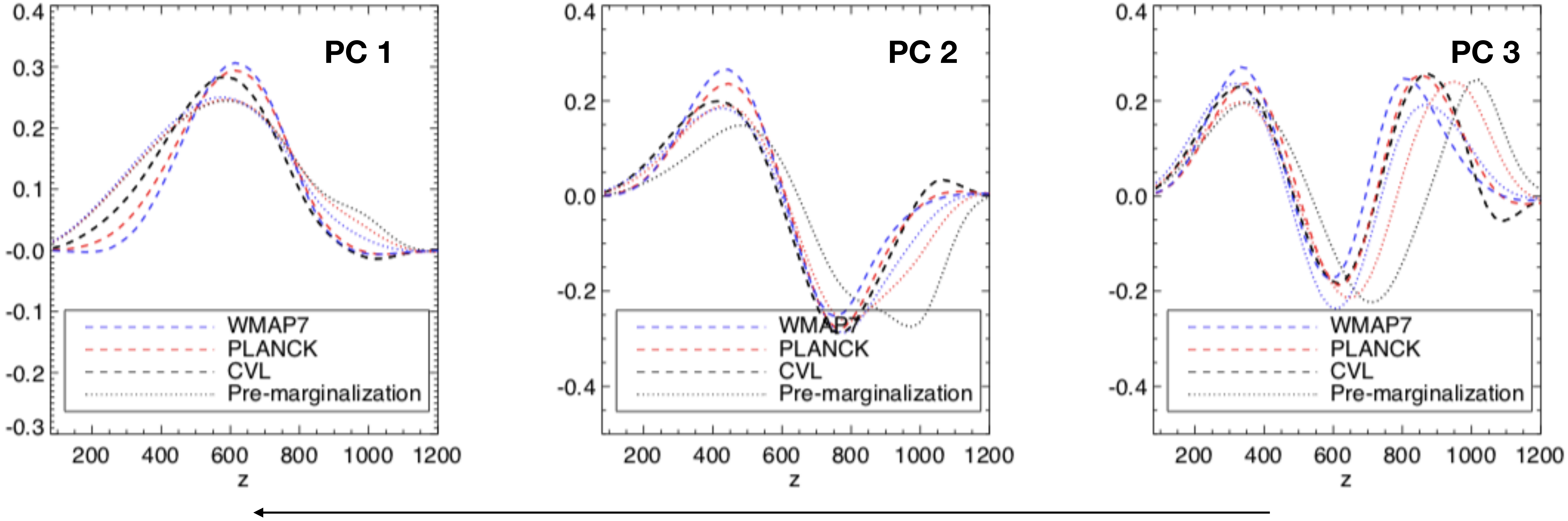
$$f_{\text{ion}}(z) = \frac{H(z)\sum_{\text{species}}\int_z^{\infty}\frac{d\log(1+z_{\text{in}})}{H(z_{\text{in}})}\int T(z_{\text{in}}, z, E)E\frac{dN}{dE}dE e^{-t(z)/\tau_\chi}}{\sum_{\text{species}}\int E\frac{dN}{dE}dE}$$

Energy is not deposited immediately

Only care about energy deposited into ionization

CMB ionization constraints

Principal components

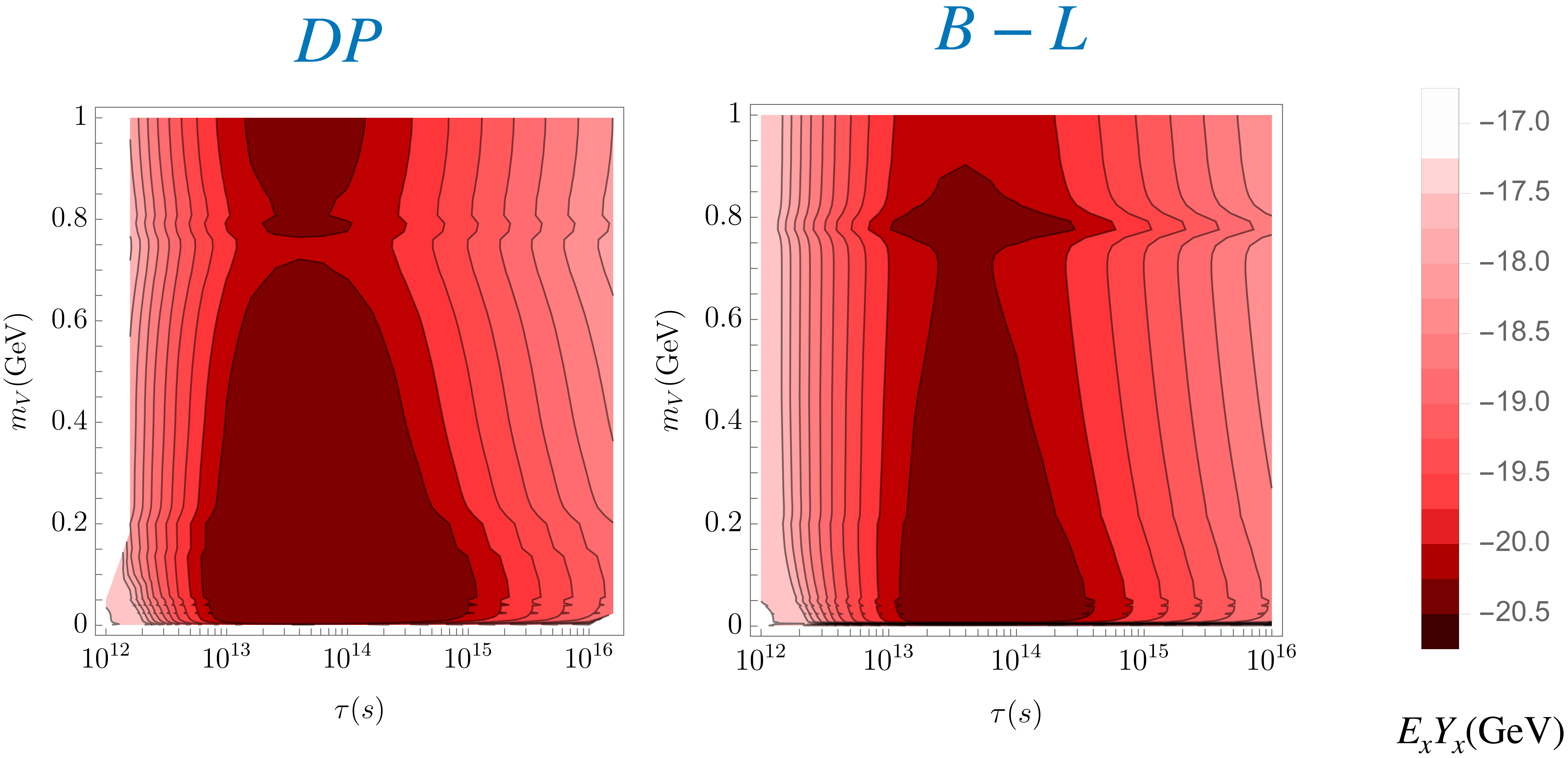


Most important

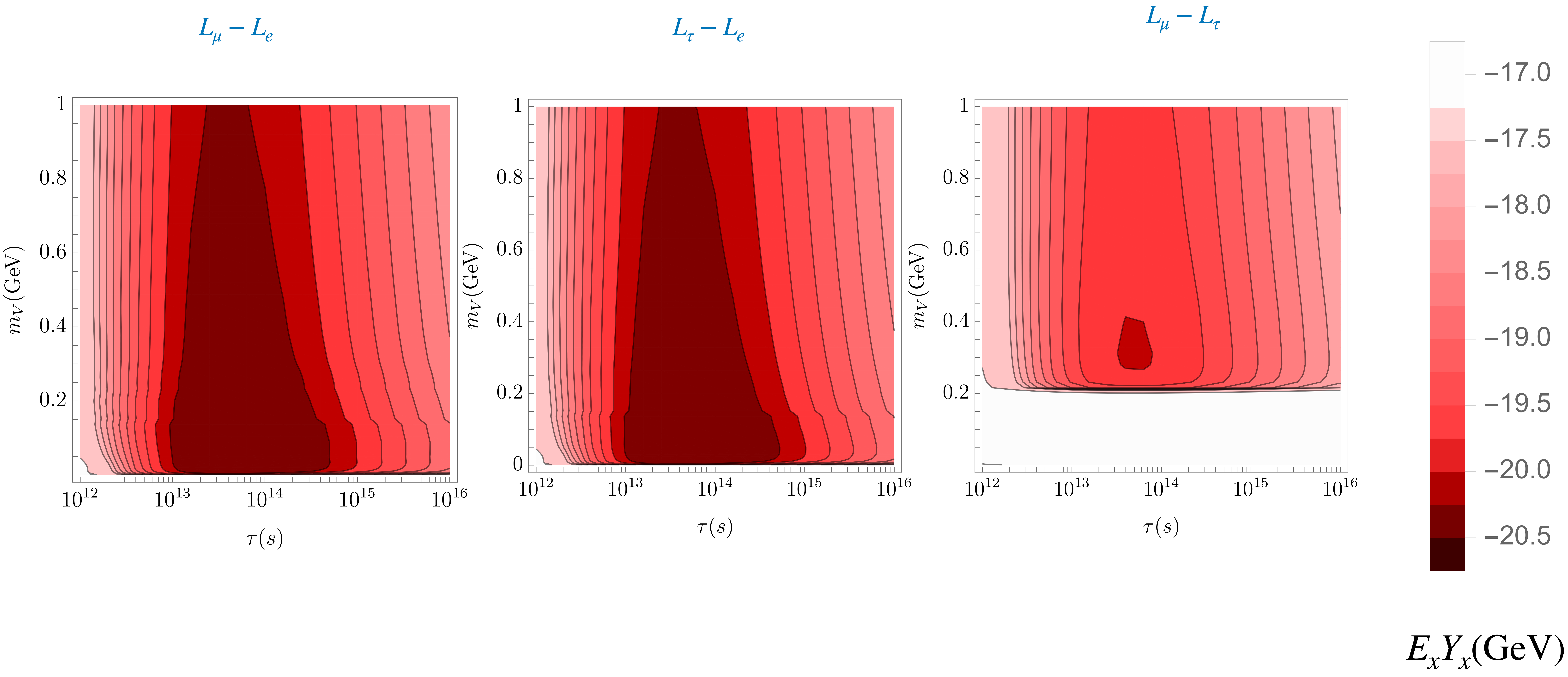
Constraints $\sim e_i(z) \int \frac{dz}{z} \sum_i PC_i(z) f(z)$

Tracy Slatyer 1109.6322
See also her work in 2015/2016 (project epsilon)

CMB ionization constraints



CMB ionization constraints



CMB spectral distortion constraints

Cobe/FIRAS and PIXIE can detect departures from a black body spectrum

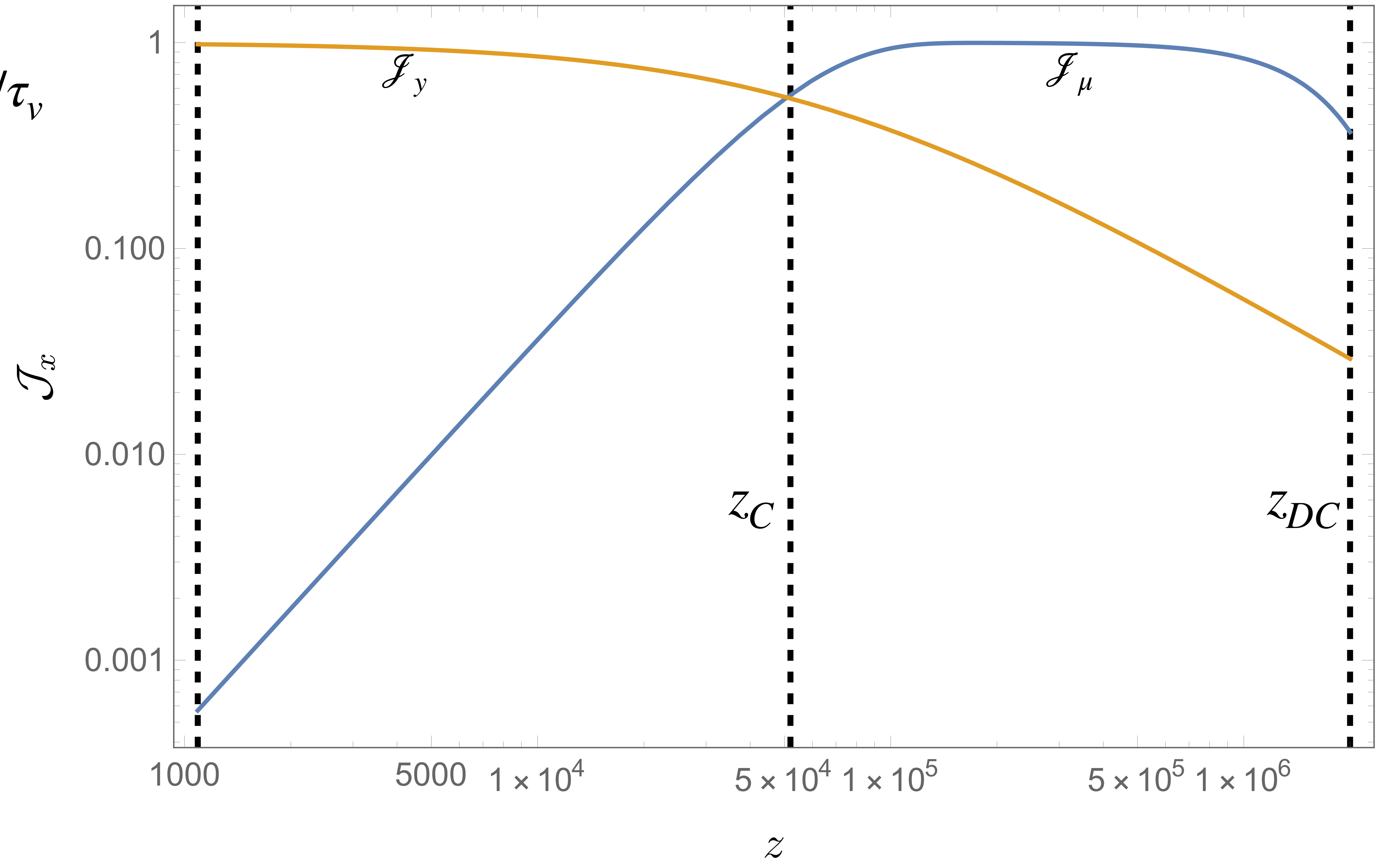
Decays occurring between the decoupling of double Compton scattering and Compton scattering $2 \times 10^6 \gtrsim z \gtrsim 5.2 \times 10^4$ **change the photon chemical potential**

Decays after decoupling of Compton scattering and recombination $(5.2 \times 10^4 \gtrsim z \gtrsim 1090)$ **change the Compton y parameter**

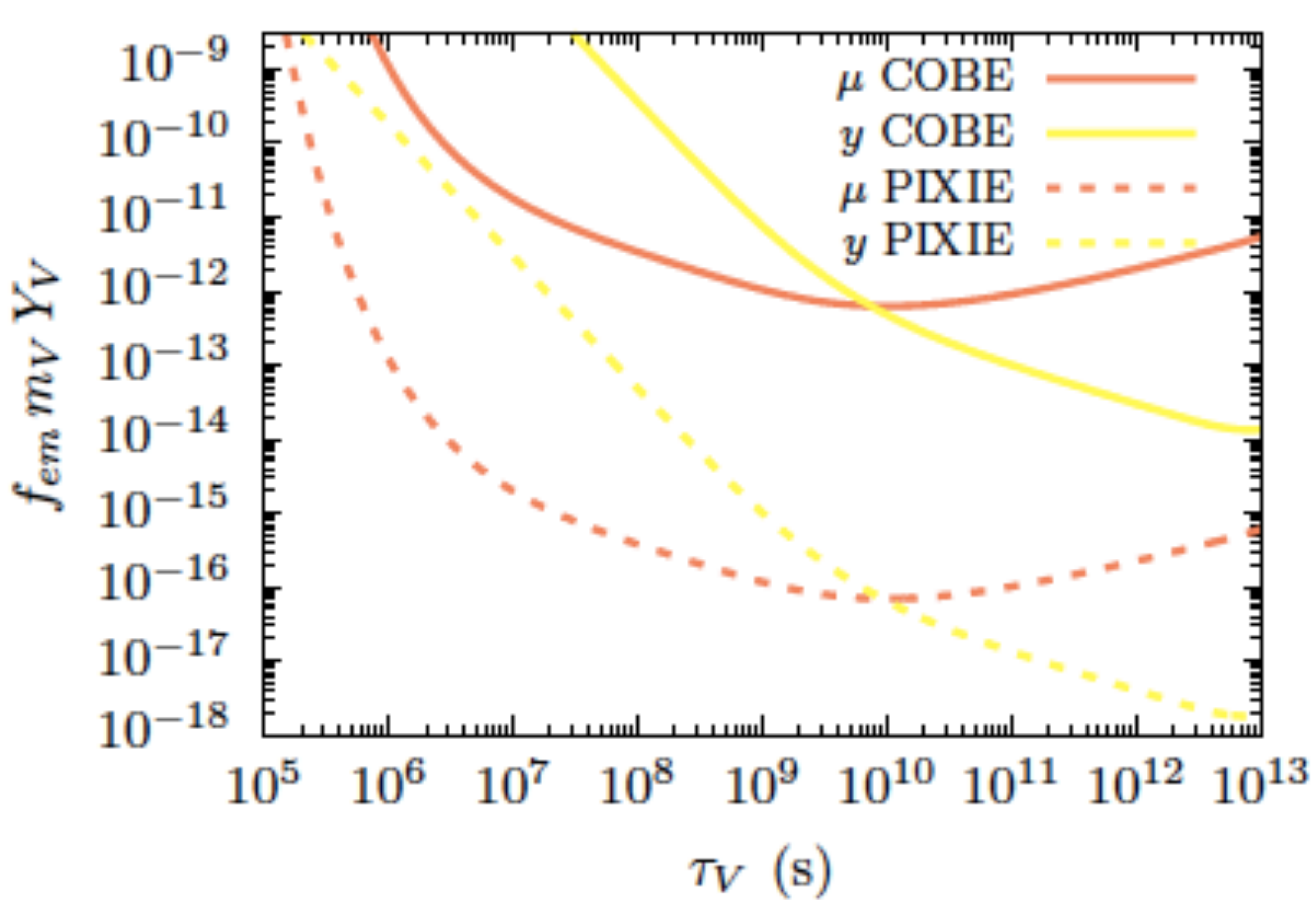
CMB spectral distortion constraints

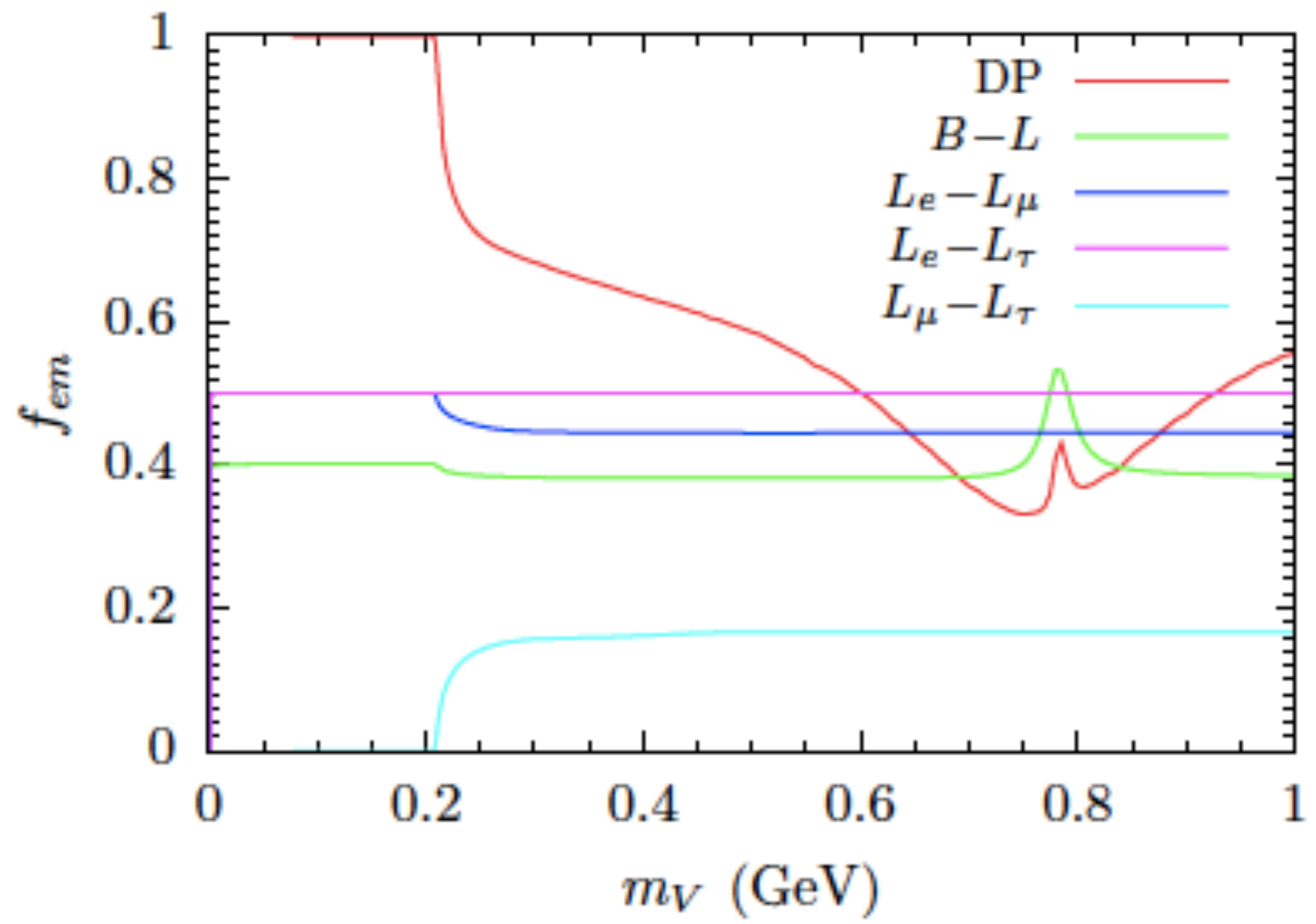
$$\mu_\gamma \sim 1.4 \int dt \mathcal{J}_\mu(t) \left(\frac{\Delta \dot{\rho}_\gamma}{\rho_\gamma} \right) \qquad y \sim 4 \int dt \mathcal{J}_y(t) \left(\frac{\Delta \dot{\rho}_\gamma}{\rho_\gamma} \right)$$

$$\Delta \dot{\rho}_\gamma = f_{\rm em} m_V \frac{n_V^0}{\tau_V} e^{-t/\tau_v}$$



Cobe and Pixie Limits





$$\text{COBE}: \mu < 9\times10^{-5}\ , \quad |y| < 1.5\times10^{-5}$$

$$\text{PIXIE}: \mu < 1\times10^{-8}\ , \quad |y| < 2\times10^{-9}$$

Freeze in abundances

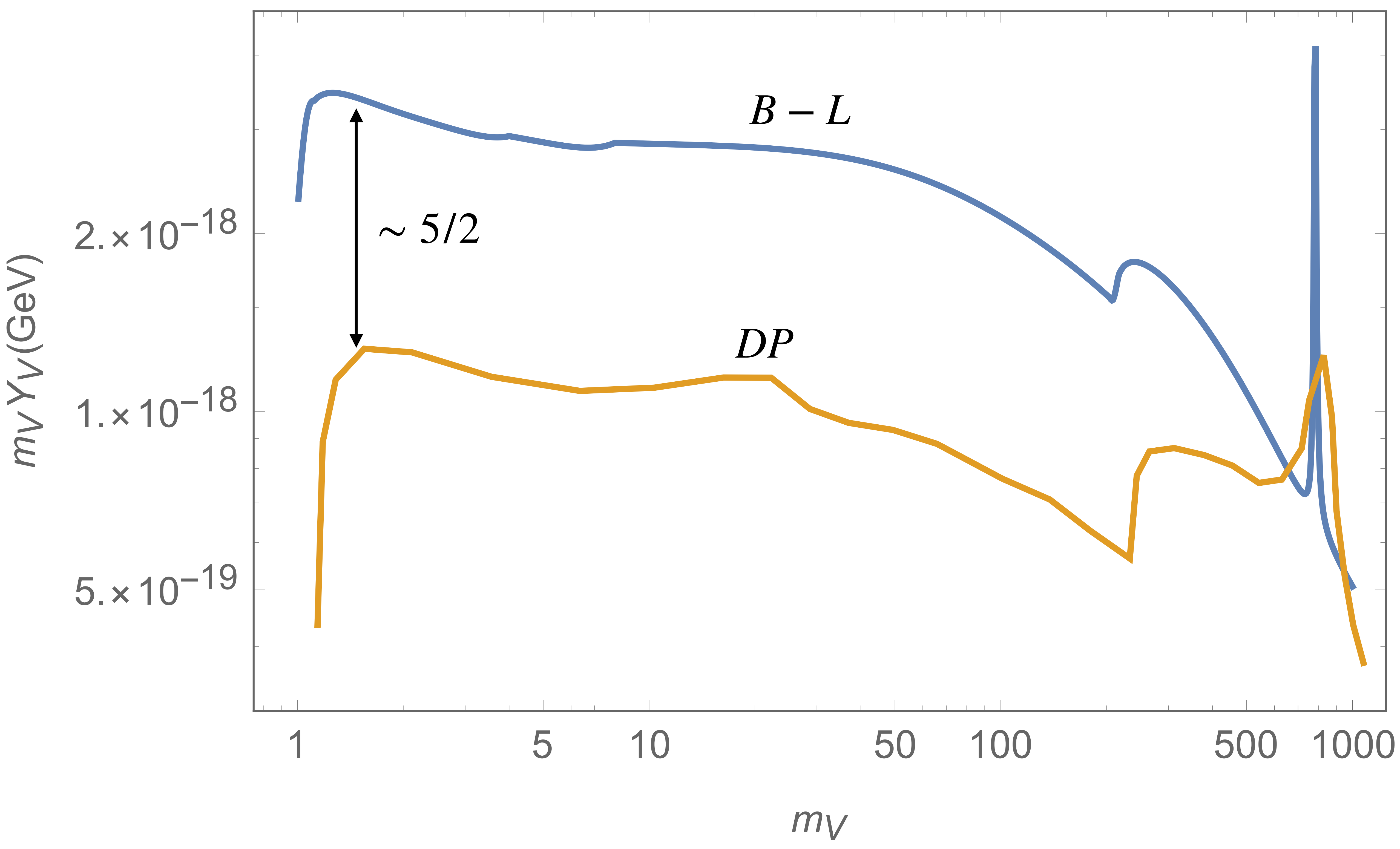
$$s\frac{dY_V}{dt} = \langle\frac{1}{\gamma}\rangle n_V^{\text{eq}}\Gamma_V$$

$$Y_V = \left(Y_V\right)_I + \left(Y_V\right)_{II}$$

$$\left(Y_V\right)_I = \frac{3}{2\pi^2} m_V^3 \tilde{\Gamma}_V \int_0^{x_{\text{QCD}}} dx \frac{K_1(x)}{x^2 s H}$$

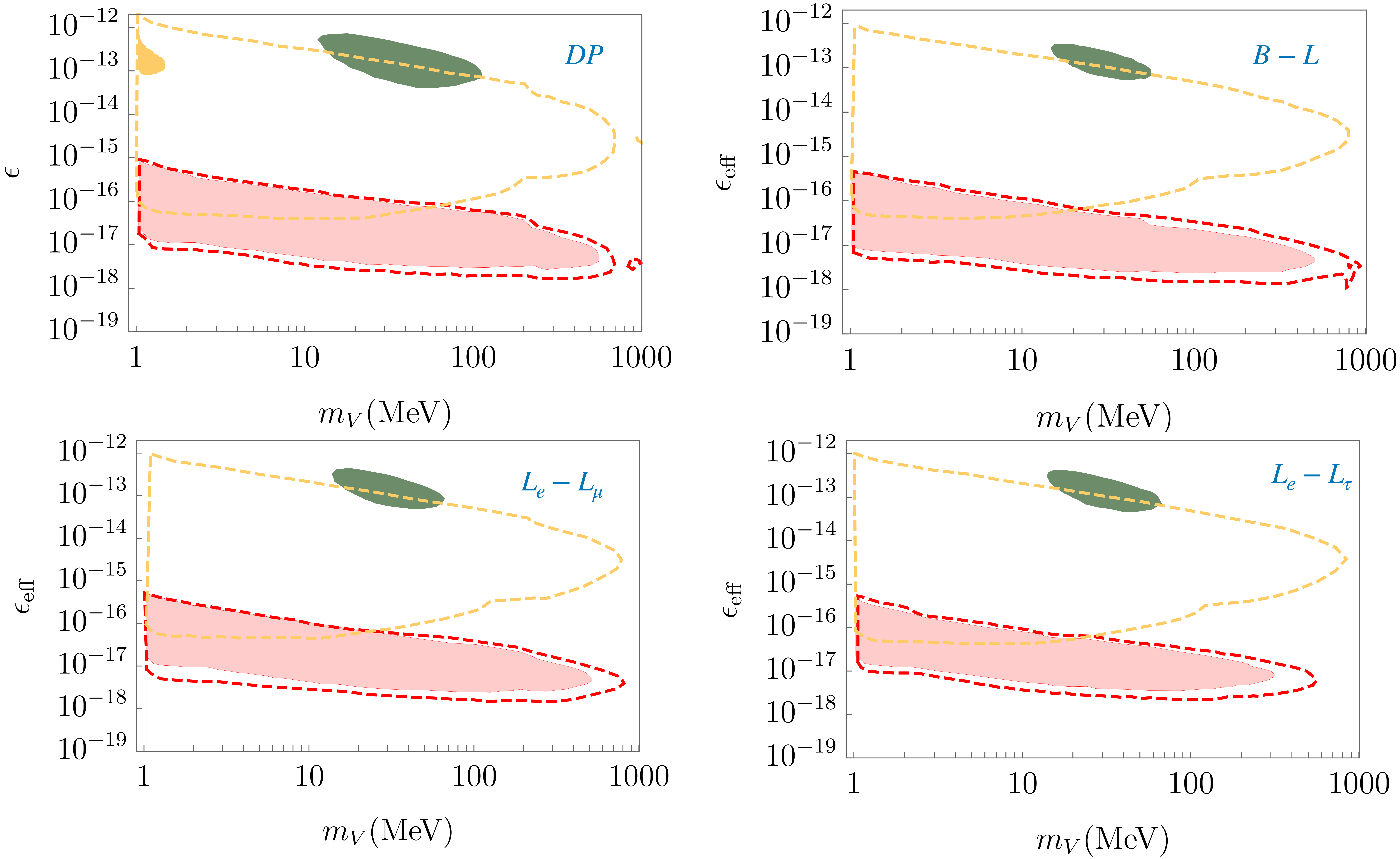
$$\left(Y_V\right)_{II} = \frac{3}{2\pi^2} m_V^3 \Gamma_V \int_{x_{\text{QCD}}}^{\infty} dx \frac{K_1(x)}{x^2 s H}$$

Freeze in abundances



Parameter constraints

$\epsilon_{\text{eff}} = g\sqrt{1/4\pi\alpha_{em}}$



Conclusions

We are motivated to look for light hidden sectors
Cosmological constraints become very interesting in this region
Between Spectral distortion, ionization history and BBN, an enormous parameter space can be probed!
We demonstrated this for several well motivated hidden sector vector mediators

Back up slides

Extra details on Tracy's code

Used functions from 2015 code to get f_ion

Used functions from 2012 code to do the PCA, rescaling f by the assumed ionization fraction and using f_ion generated by the 2015 code