Spectral Signatures of Superconducting Cosmic Strings

Based on arxiv:2305.09816

w/ Jens Chluba and Sandeep Acharya

Jodrell Bank Centre for Astrophysics

Bryce Cyr

MANCHESTER 1824 The University of Manchester

Blois, May 18th 2023

NSERC CRSNG

Frequency Spectrum of the CMB

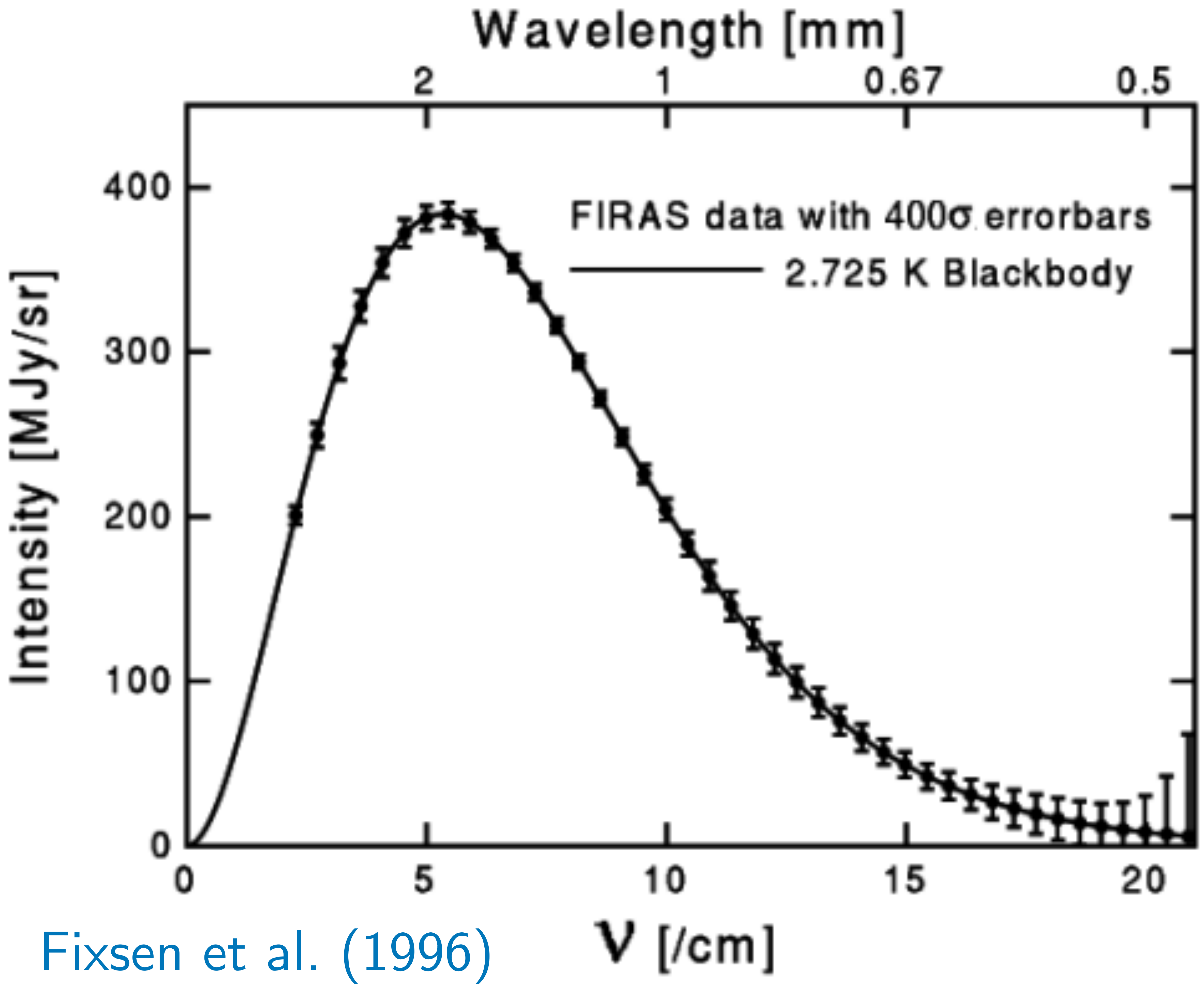
COBE/FIRAS measured nearly perfect blackbody of the CMB

$$\frac{\Delta I_\nu}{I_\nu} \leq 10^{-5}$$

Nonthermal injections of energy and entropy distort the spectrum!

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

Exotic signals?



Fixsen et al. (1996)

$$I_\nu = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/kT} - 1}$$

Thermalization Problem

How does one thermalize a distorted spectrum?

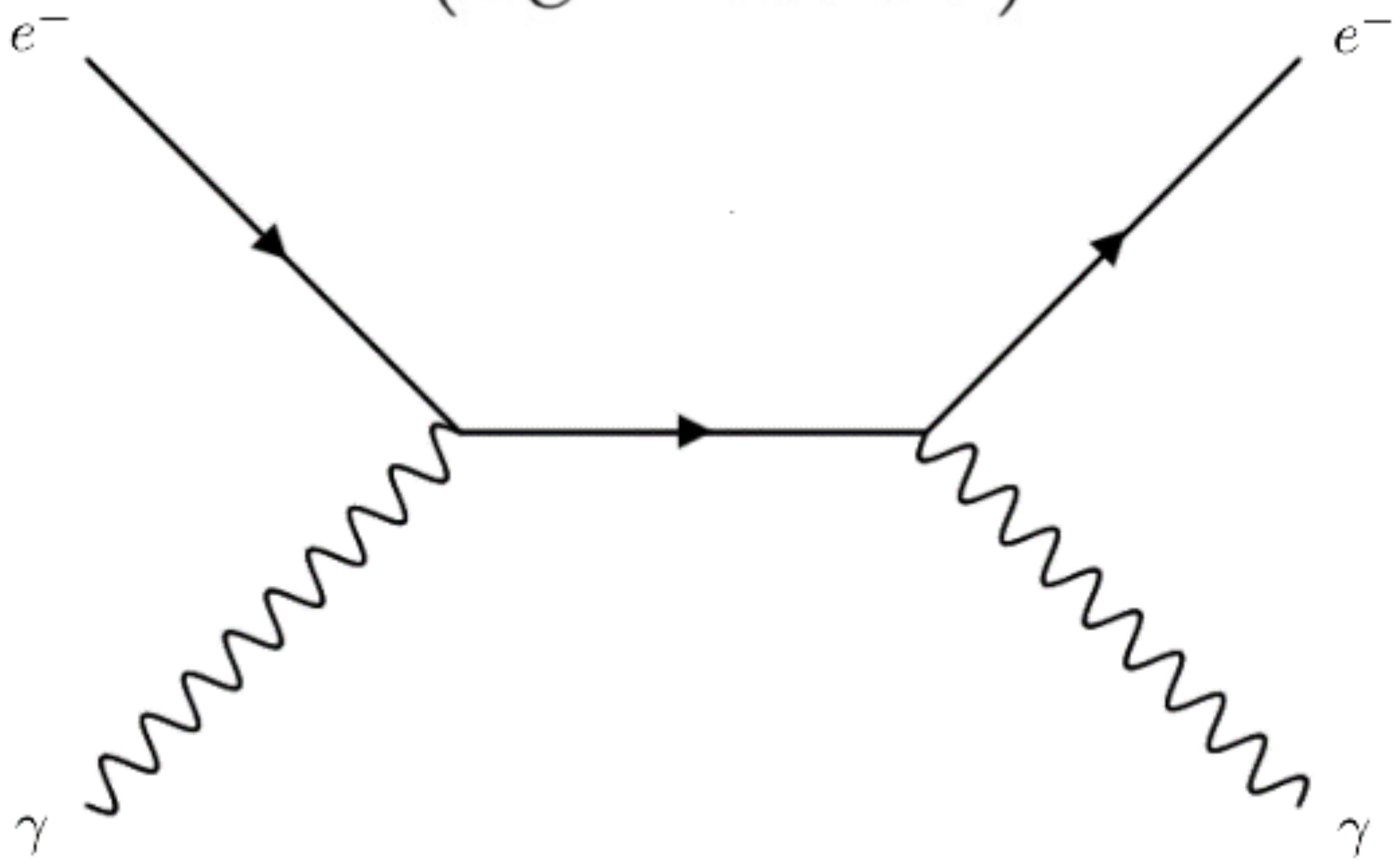
- Energy redistribution
- Photon creation/destruction

Freeze out redshift important! $\Gamma \approx H$ $\Gamma \equiv n\sigma v$

Compton (energy changing)

$z_C \approx 5 \cdot 10^4$

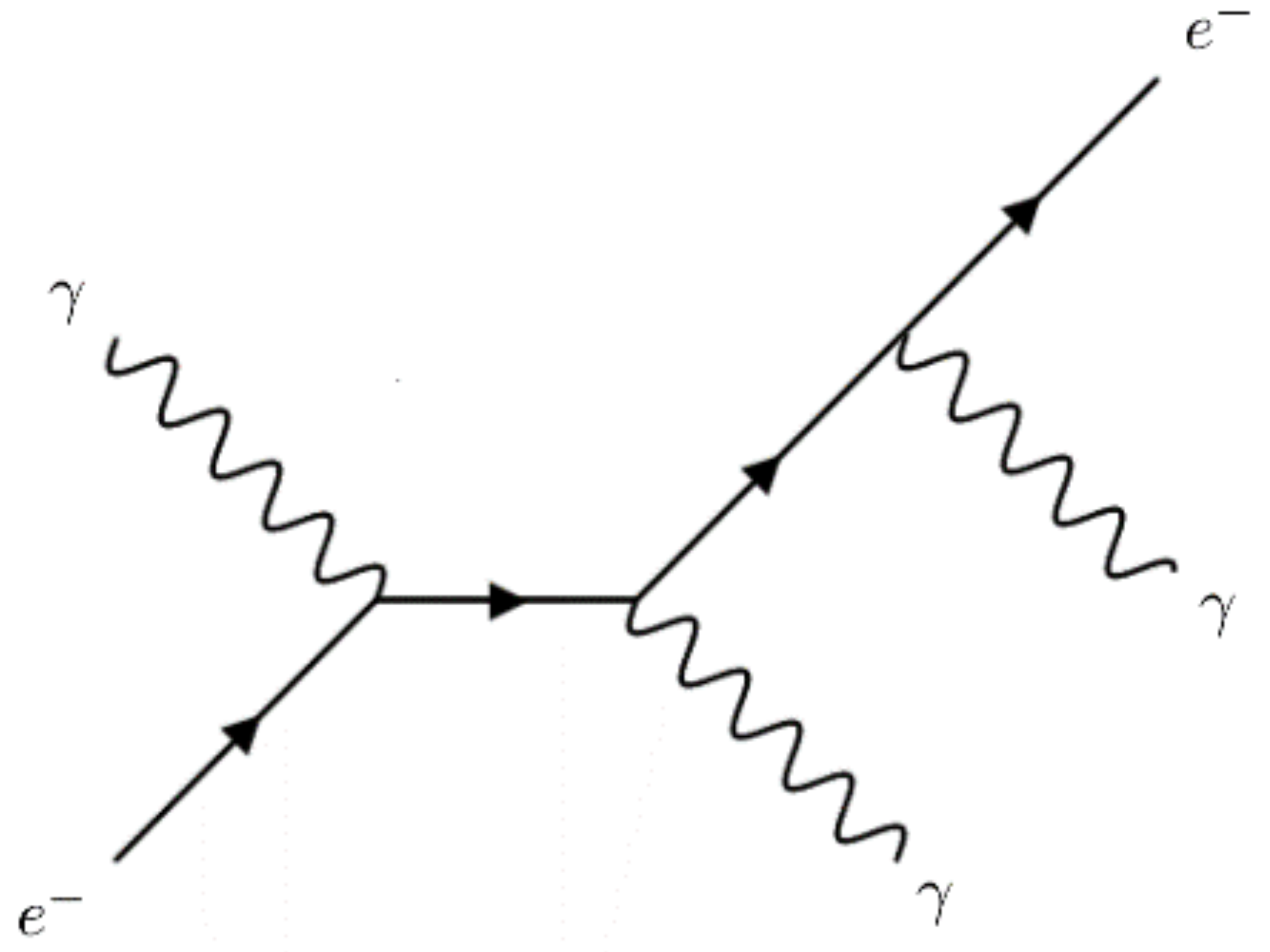
$(T_C \approx 12 \text{ eV})$



Double Compton (number changing)

$z_{DC} \approx 2 \cdot 10^6$

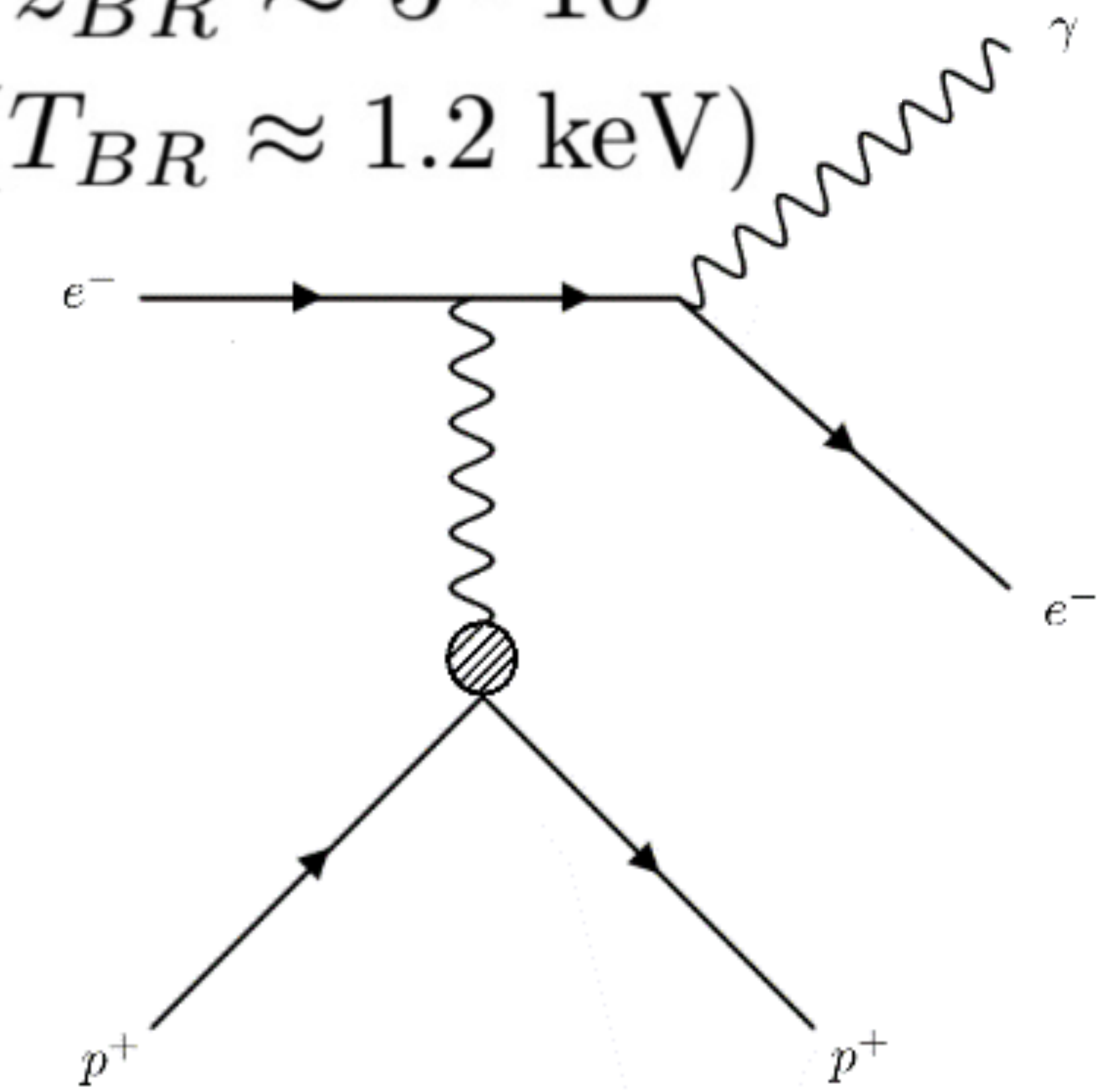
$(T_{DC} \approx 470 \text{ eV})$



Bremsstrahlung (number changing)

$z_{BR} \approx 5 \cdot 10^6$

$(T_{BR} \approx 1.2 \text{ keV})$



Constraints on Distortion Parameters

Distortion parameters:

$$\mu \approx 1.401 \int_{z_C}^{z_{DC}} dz \frac{1}{\rho_\gamma} \frac{dQ}{dz}$$

$$y \approx \frac{1}{4} \int_{z_{rec}}^{z_C} dz \frac{1}{\rho_\gamma} \frac{dQ}{dz}$$

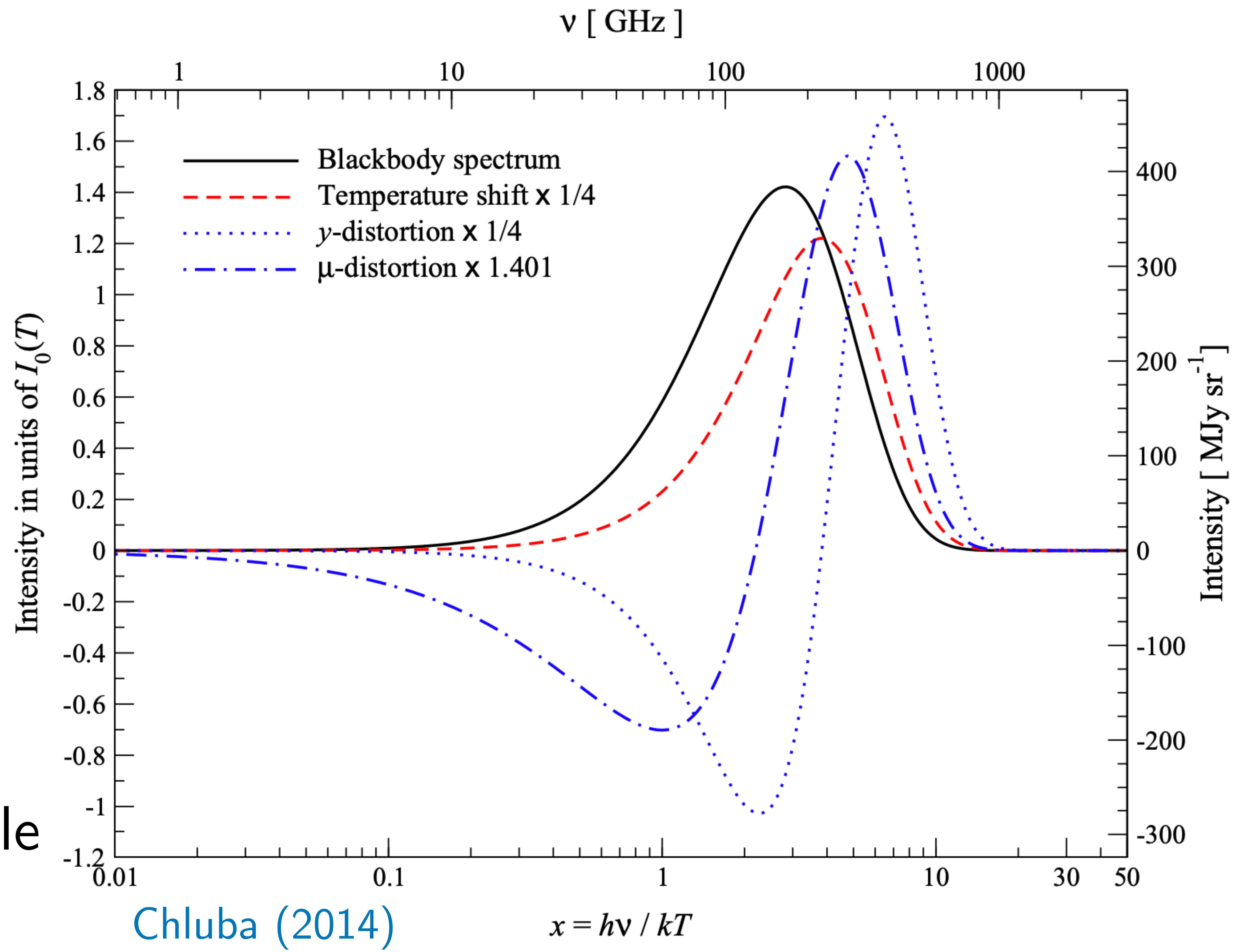
COBE/FIRAS:

$$|\mu| \leq 10^{-4} \quad |y| \leq 10^{-5}$$

PIXIE:

$$|\mu| \leq 10^{-8} \quad |y| \leq 2 \times 10^{-9}$$

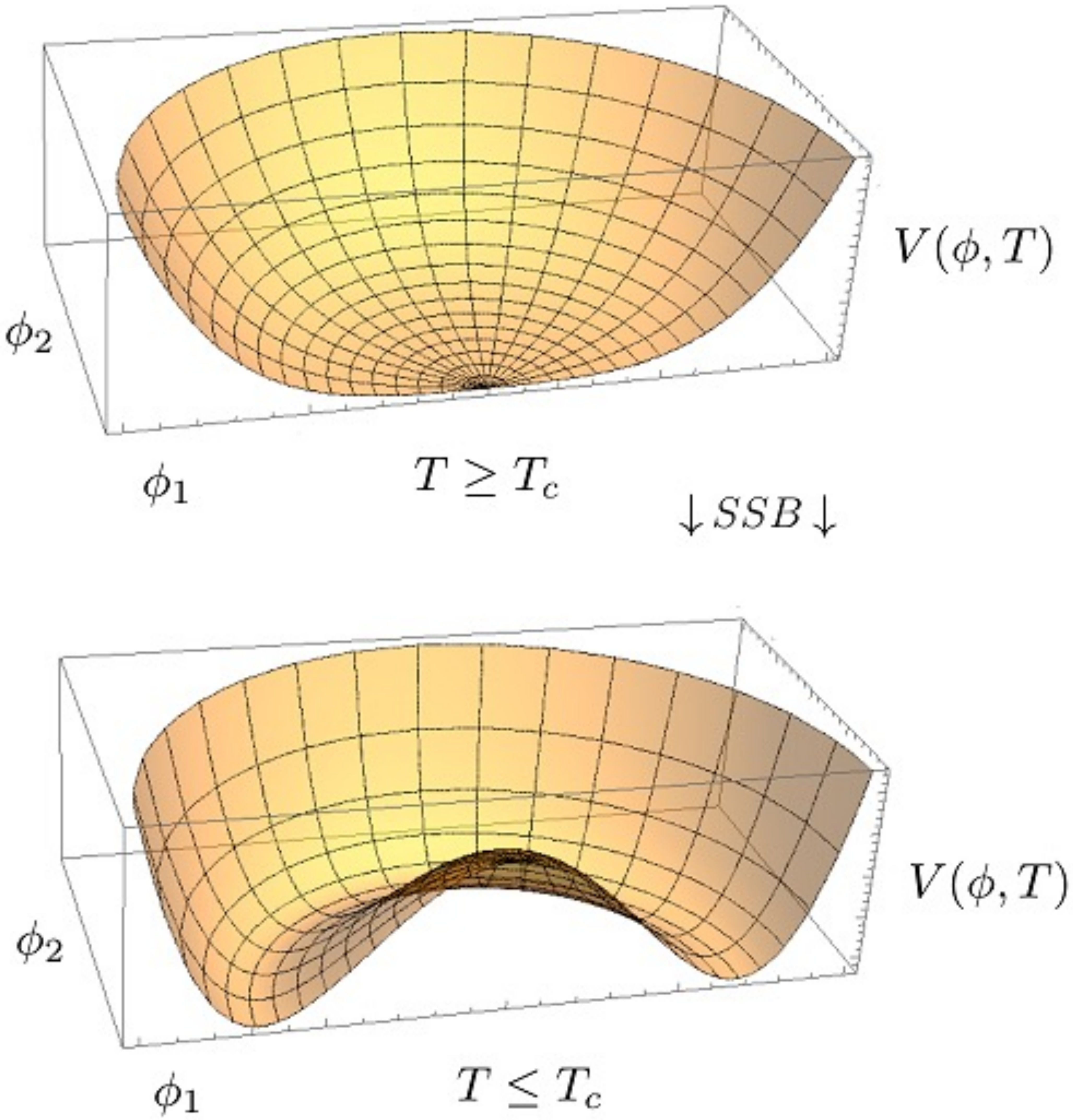
Full spectral analysis possible with COSMOTHERM

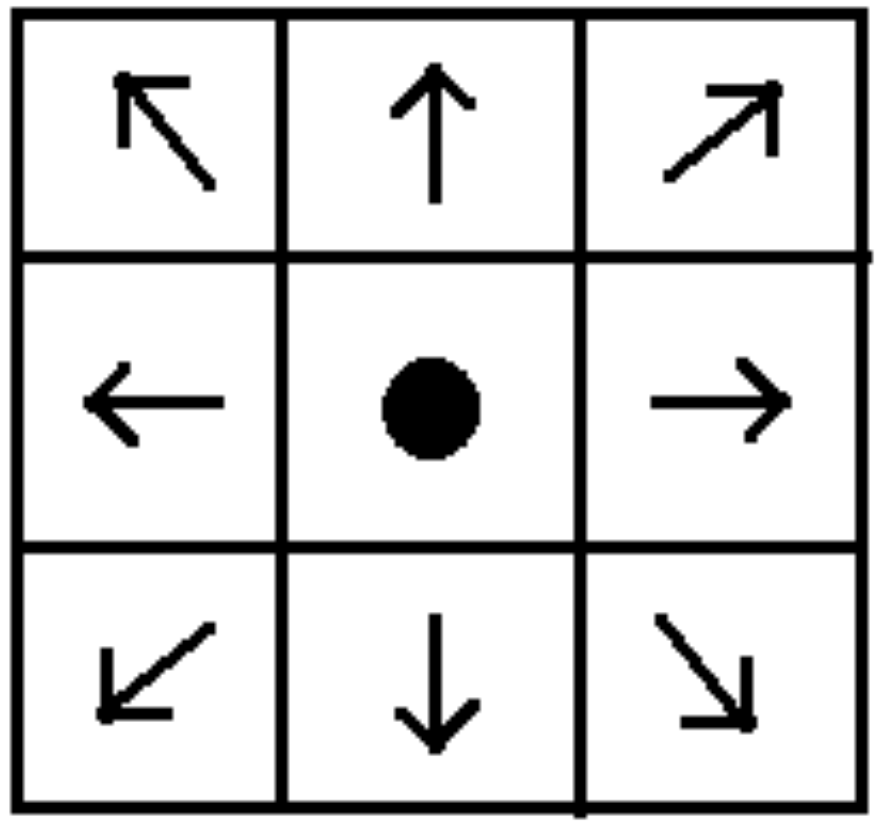


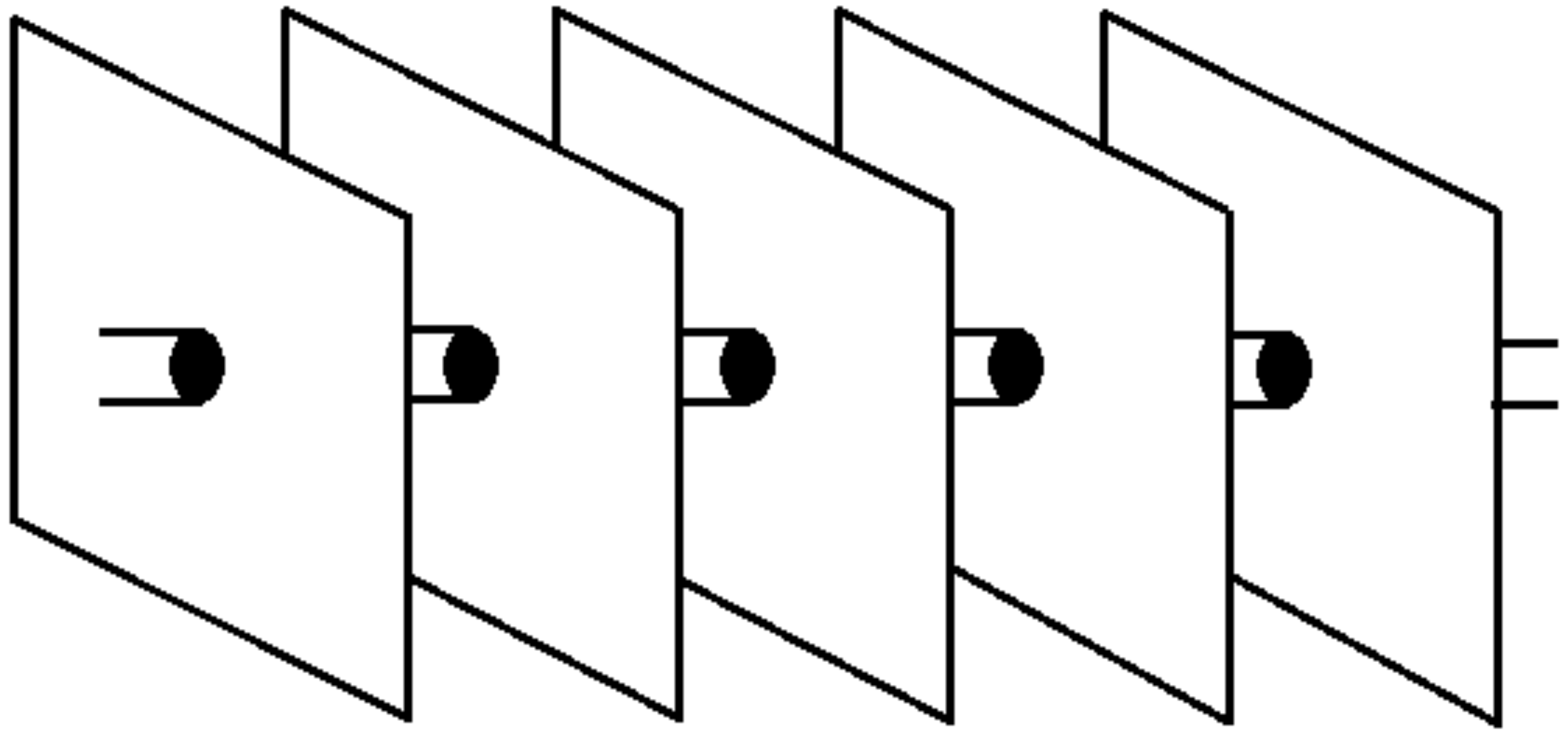
Chluba (2014)

(Superconducting) cosmic strings

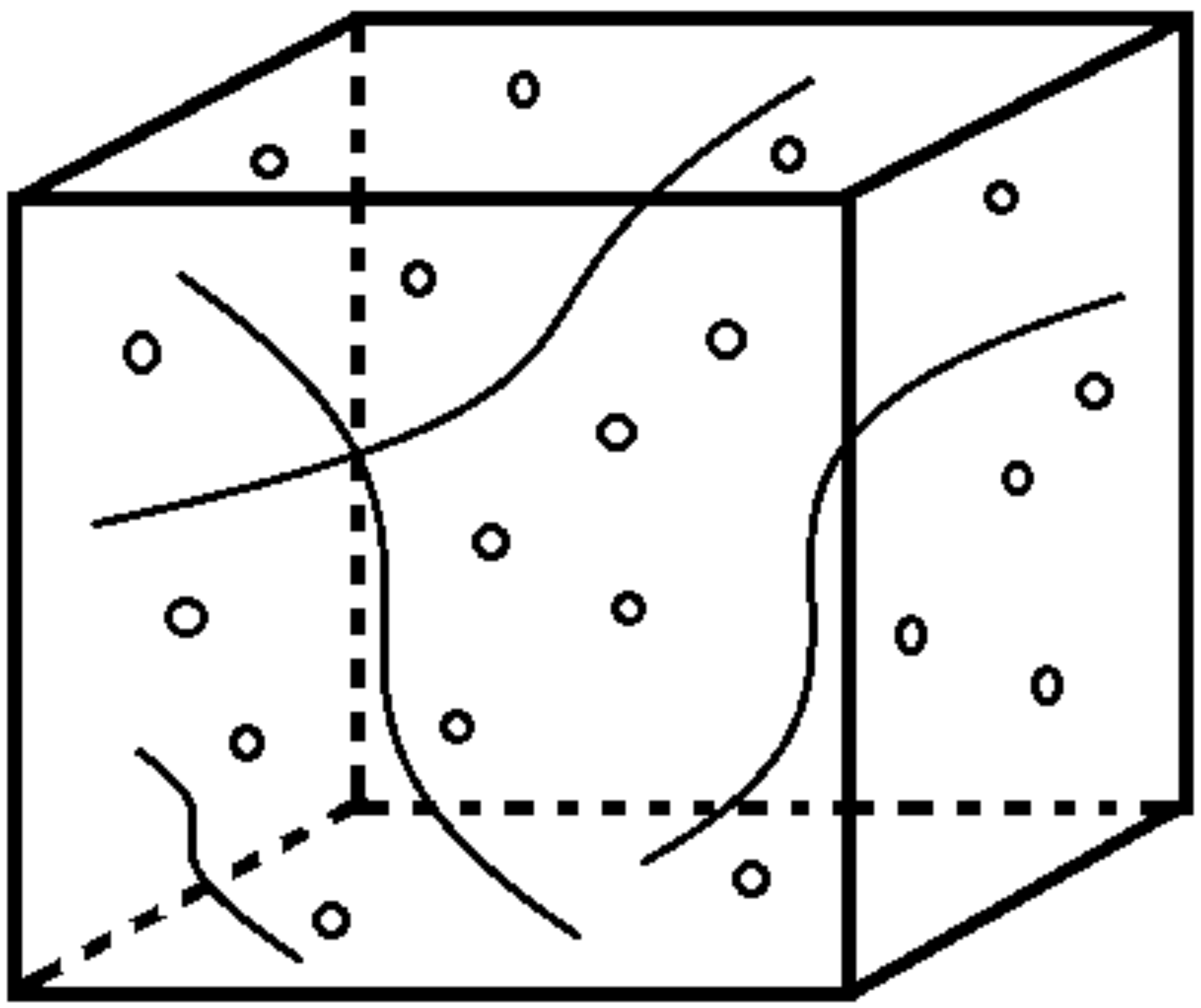
- Cosmological phase transitions may source distribution of topological defects
- Defect network generically long-lived, with possible direct EM couplings
- Parameter space for strings effectively described by $G\mu \sim (\eta/M_{\rm pl})^2$ and $\mathcal{I}$
- Top-down probe of particle physics







String networks



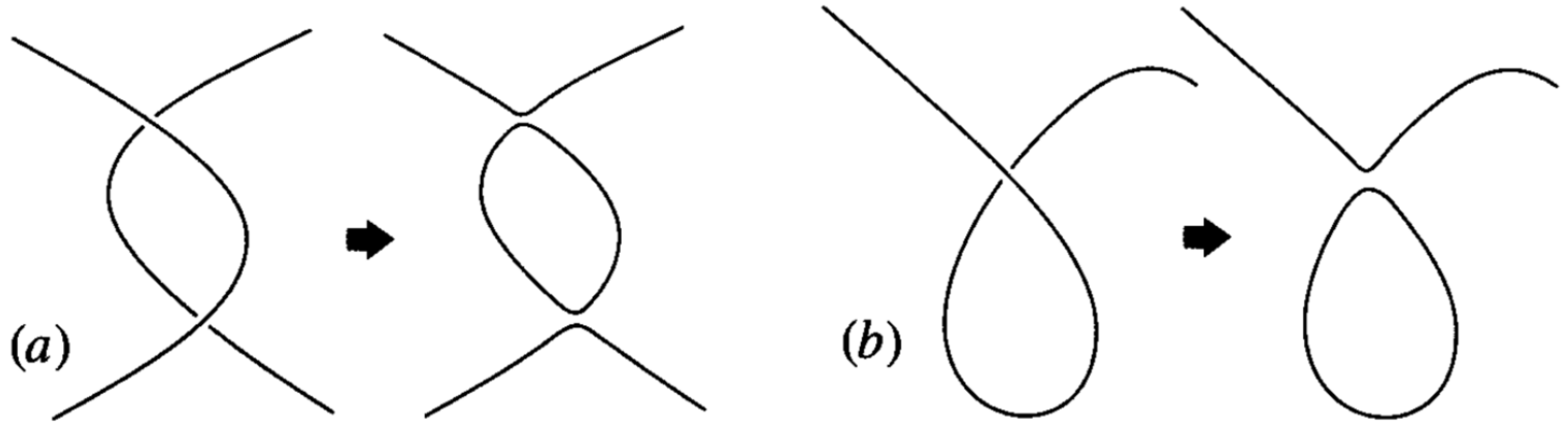
A few long strings expected per Hubble volume, following a scaling distribution.

Collisions and self-intersections of long strings seed a loop distribution with radii

$$L_c^{\mathrm{EM/GW}}(t) \leq L \leq \beta t \qquad (\beta \sim 0.1)$$

Energy leaves string network through small loops decaying via gravitational waves/cusp annihilations.

$$G\mu \leq 10^{-7} \qquad \text{(CMB)}$$
$$G\mu \leq 10^{-10} \qquad \text{(PTA)}$$



Vilenkin and Shellard (2001)

Loop decay mechanisms

Substructure on loops decay into GW ($P_g \simeq \Gamma_g G\mu^2$) and EM radiation ($P_\gamma \simeq \Gamma_\gamma \mathcal{I}\mu^{1/2}$)

Equate power to define

$$\mathcal{I}_* = \frac{\Gamma_g}{\Gamma_\gamma}\frac{(G\mu)^{3/2}}{G^{1/2}}$$

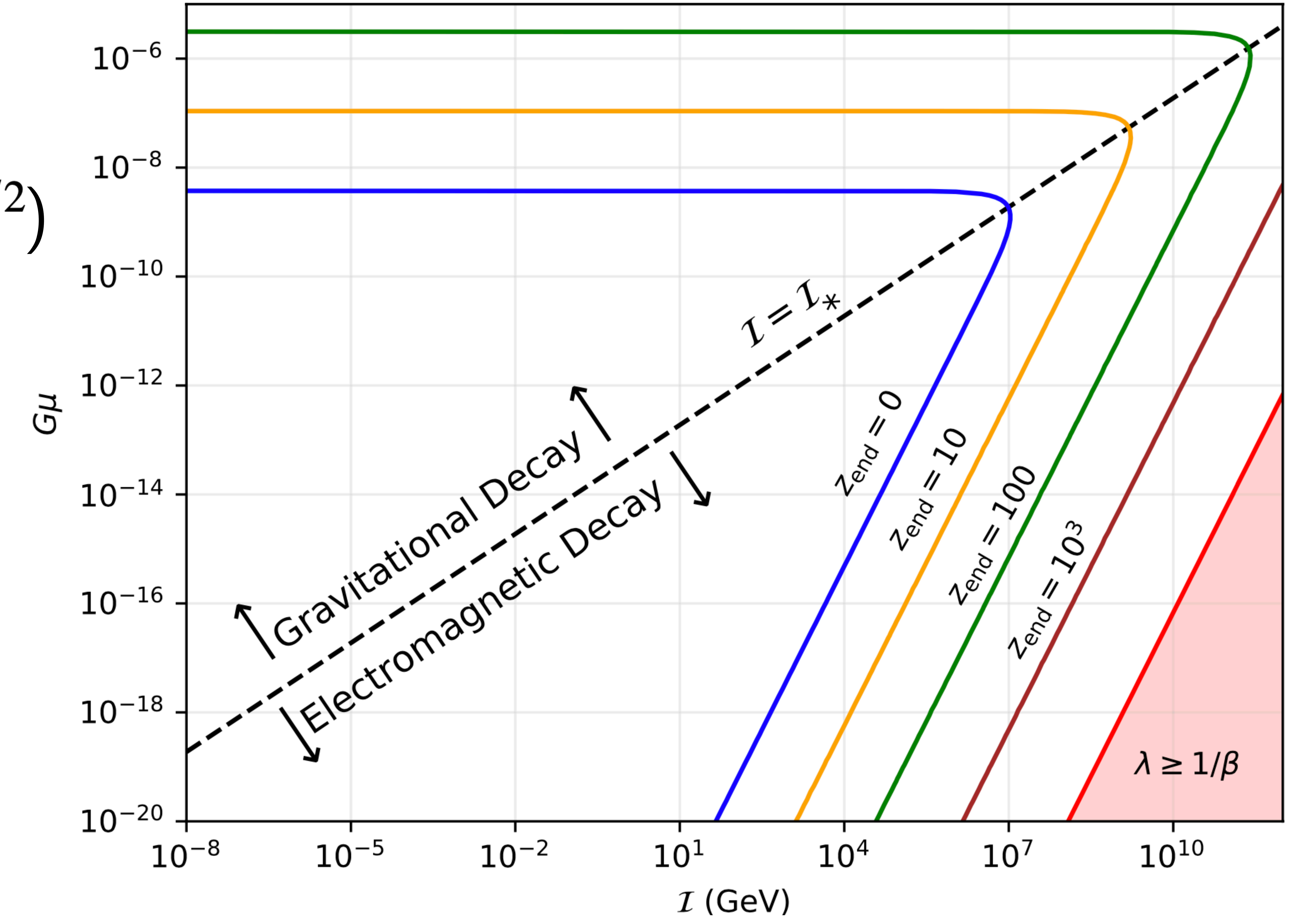
Smallest 'stable' loop length

$$L_c(t) \approx \Gamma G\mu t = \frac{(P_g + P_\gamma)}{\mu}t$$

Vilenkin and Vachaspati (1987)

Cai et al (2012)

$(\Gamma_g \sim 100, \quad \Gamma_\gamma \sim 10)$

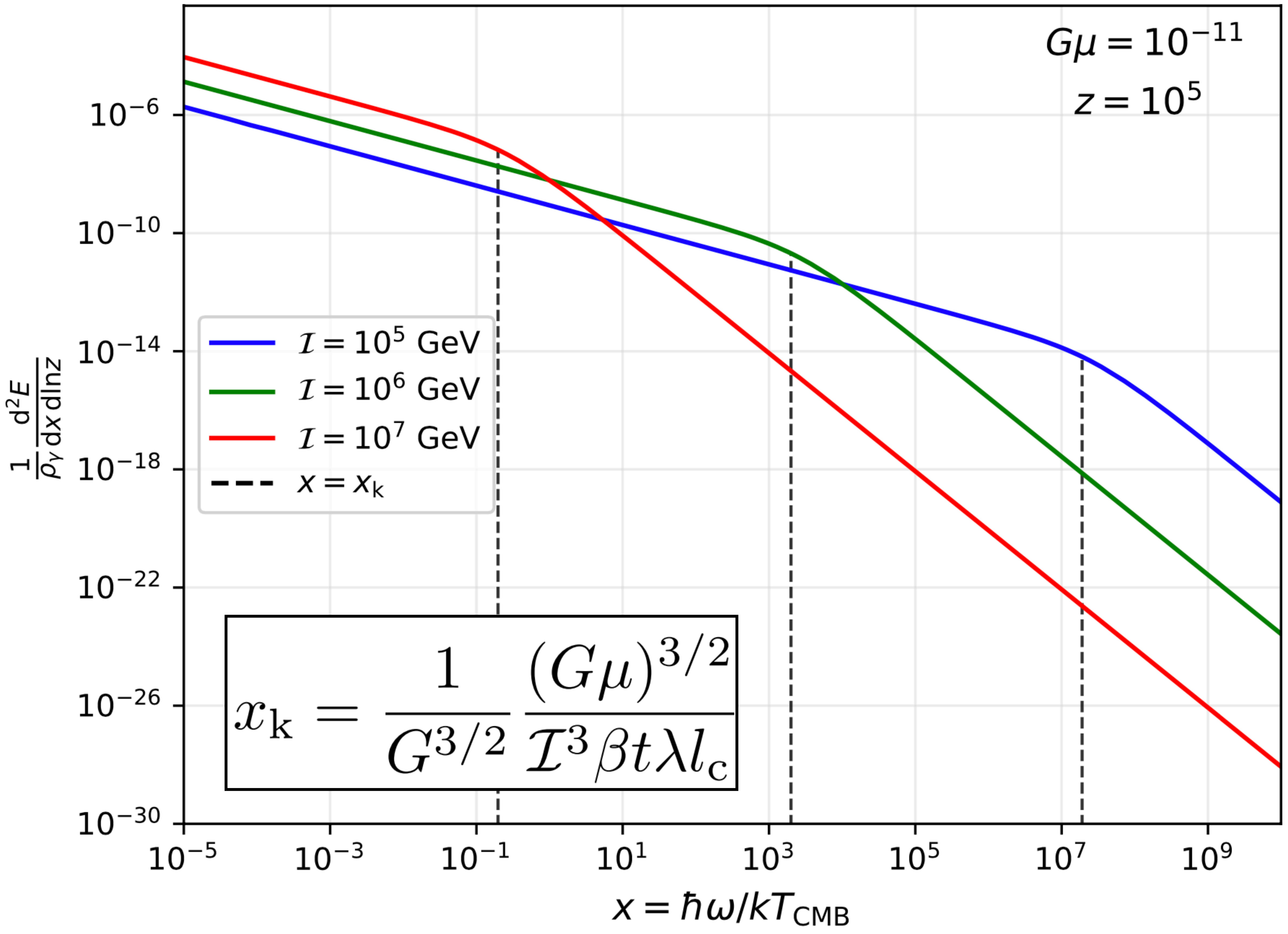


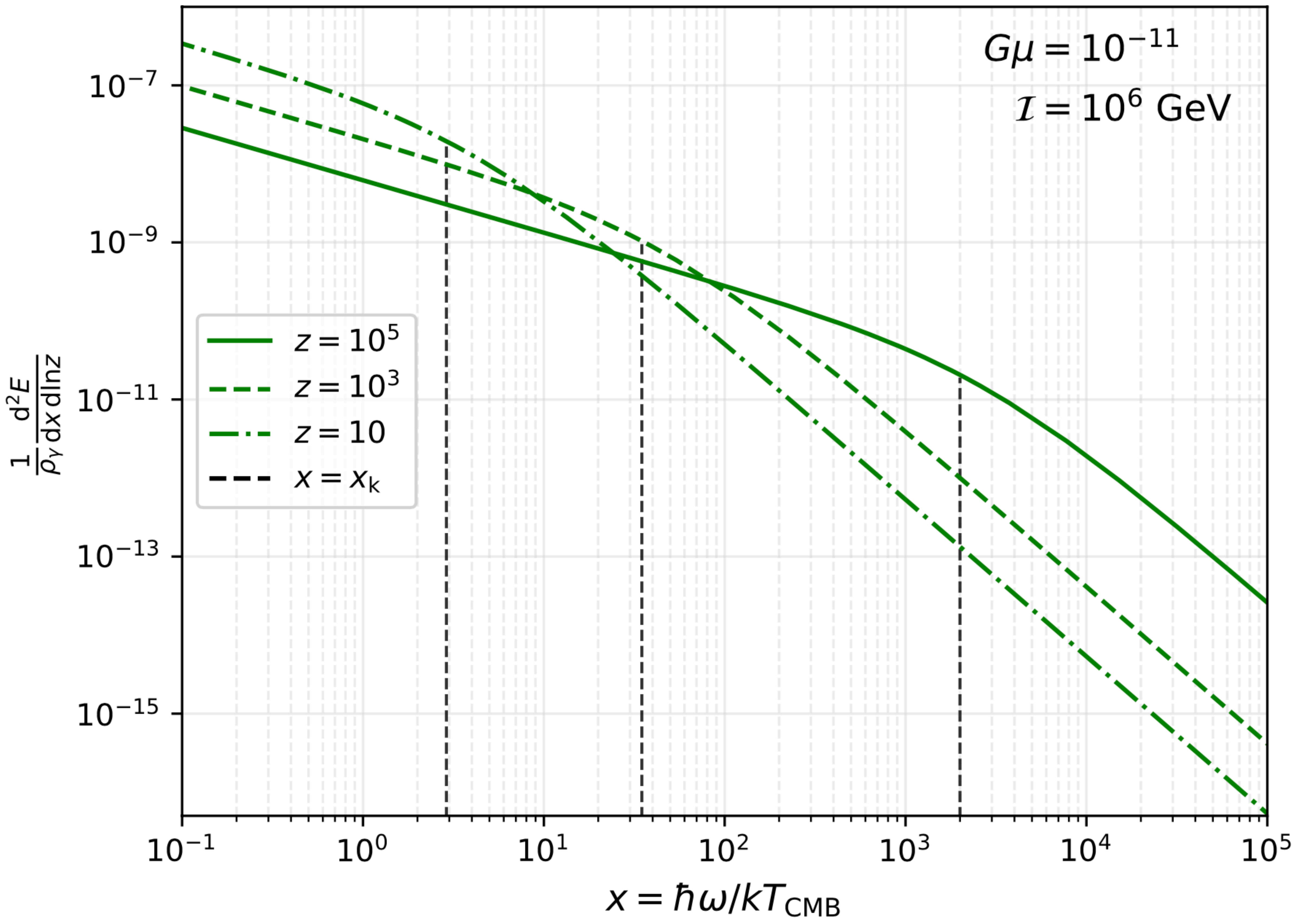
$$\lambda = \Gamma G\mu/\beta$$

$$t_{decay} = \left(\frac{1+\lambda}{\lambda}\right) t_{form}$$

Instantaneous emission spectra

Oscillation averaged injection from a single loop: $$\frac{d^2 N_\gamma^c}{dt d\omega} = \left(\frac{\Gamma_\gamma}{3}\right)\frac{\mathcal{I}^2 L^{1/3}}{\omega^{5/3}}$$





Spectral injection from radiation loops: $$\left.\frac{d^2 E}{d\omega dt}\right|_\mathrm{r} \approx \left(\frac{\alpha\Gamma_\gamma}{3}\right)\frac{\mathcal{I}^2(1+\lambda)^{3/2}}{\omega^{2/3}(\Gamma G\mu)^{7/6} t^{8/3}}\frac{\mathcal{F}_\infty}{1+(\omega/\omega_\mathrm{k})^{7/6}}$$

Analytics - energy injection

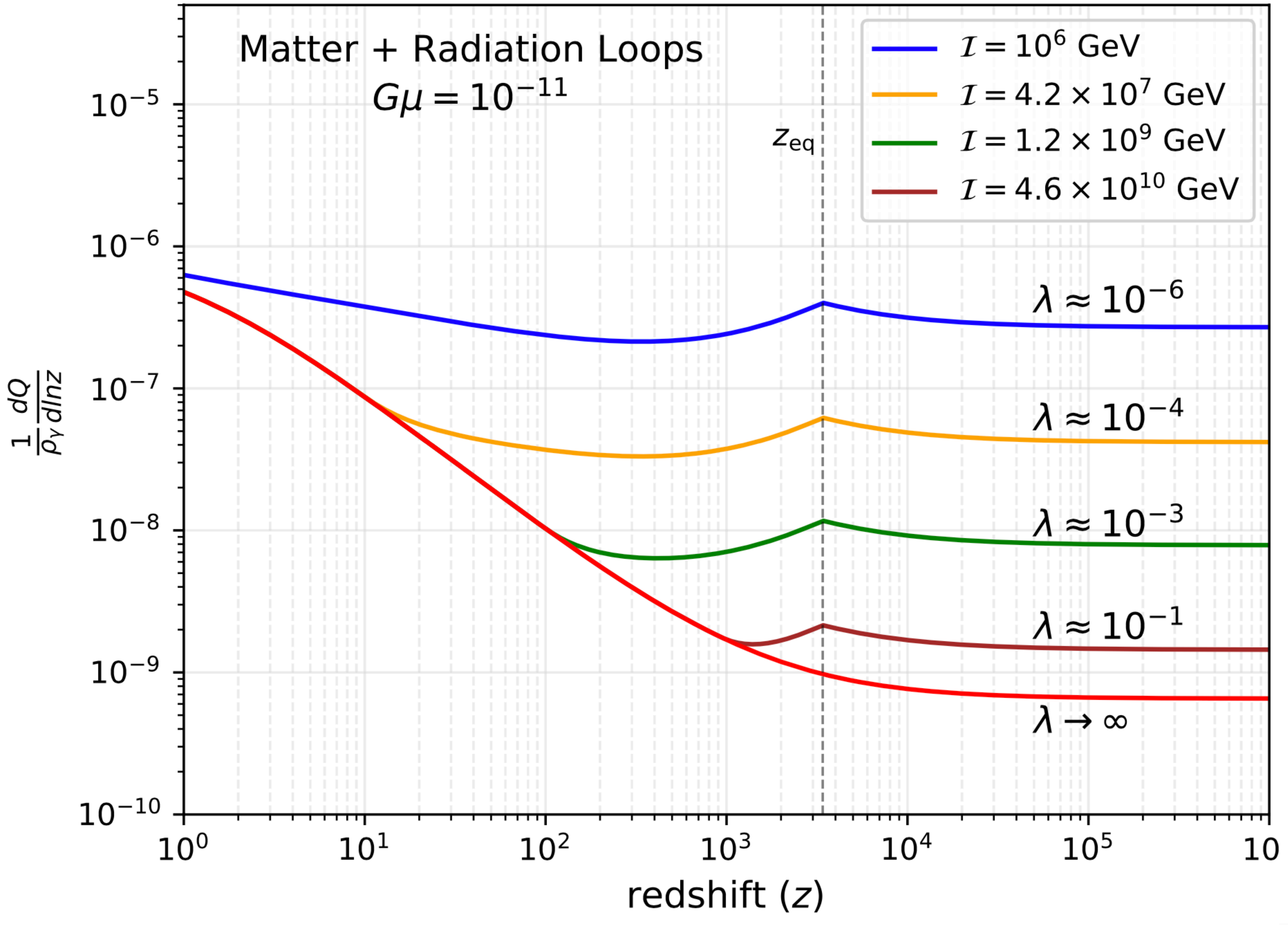
Tashiro et al. (2012)
Miyamoto and Nakayama (2013)
BC et al. (2023)

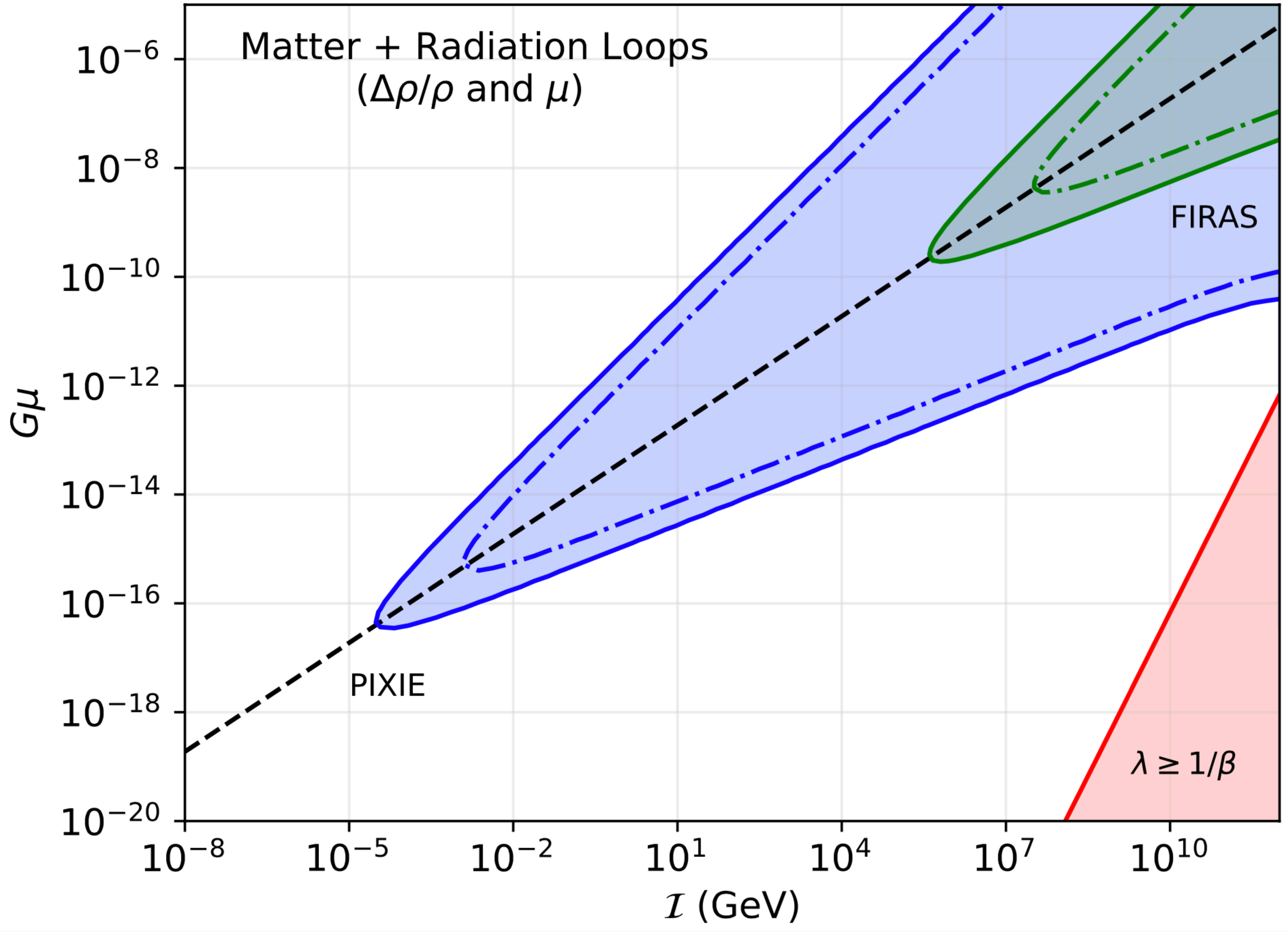
Energy injection is roughly constant in distortion window.

$$\frac{dQ}{dt} = \int_0^{L_{\max}(t)} dL \frac{dN_{\mathrm{loops}}}{dL} P_\gamma(L)$$

$$\mu \approx 1.401 \int_{z_\mathrm{C}}^{z_\mathrm{DC}} dz \frac{1}{\rho_\gamma} \frac{dQ}{dz}$$

$$y \approx \frac{1}{4} \int_{z_\mathrm{rec}}^{z_\mathrm{C}} dz \frac{1}{\rho_\gamma} \frac{dQ}{dz}$$



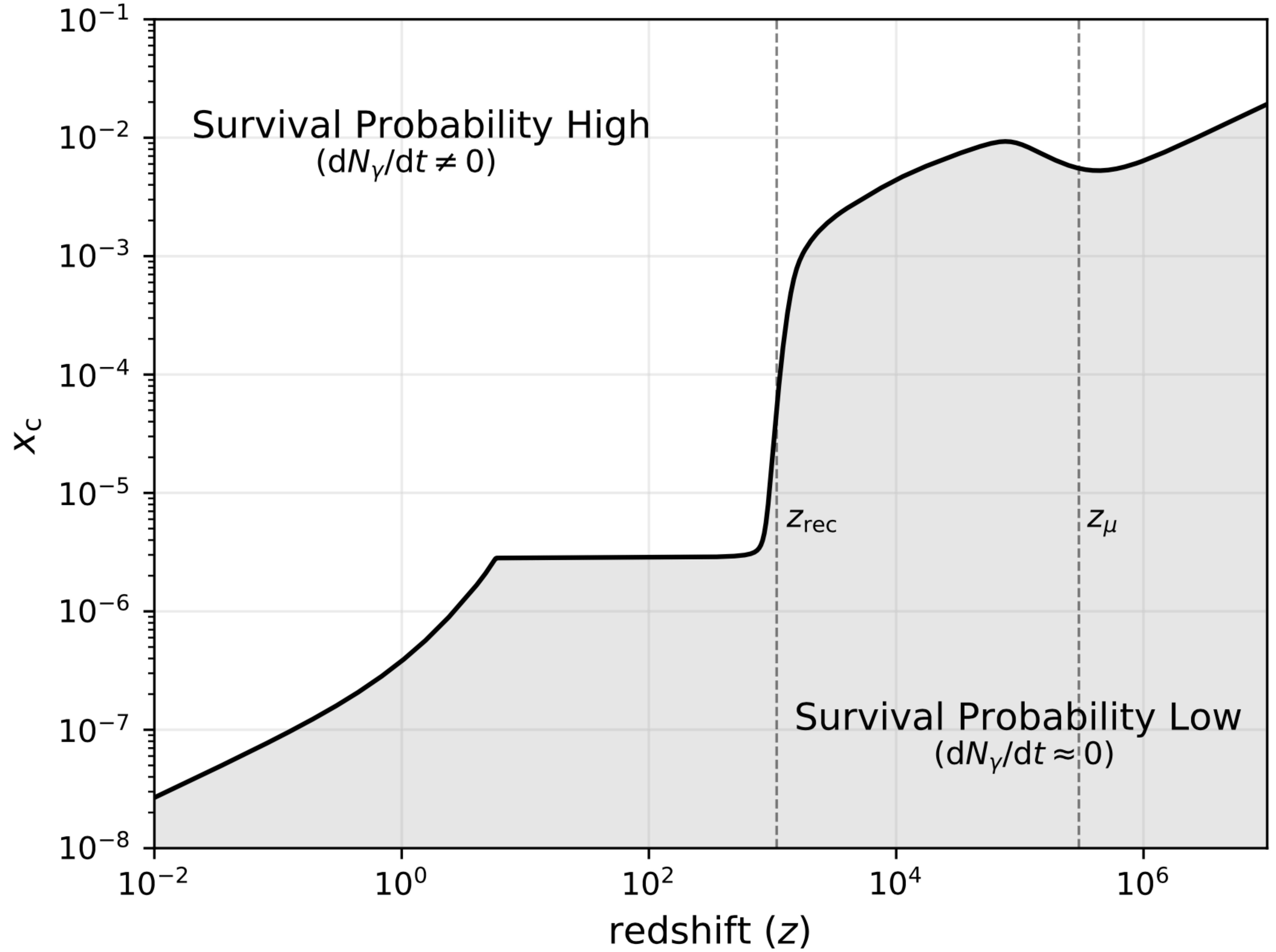


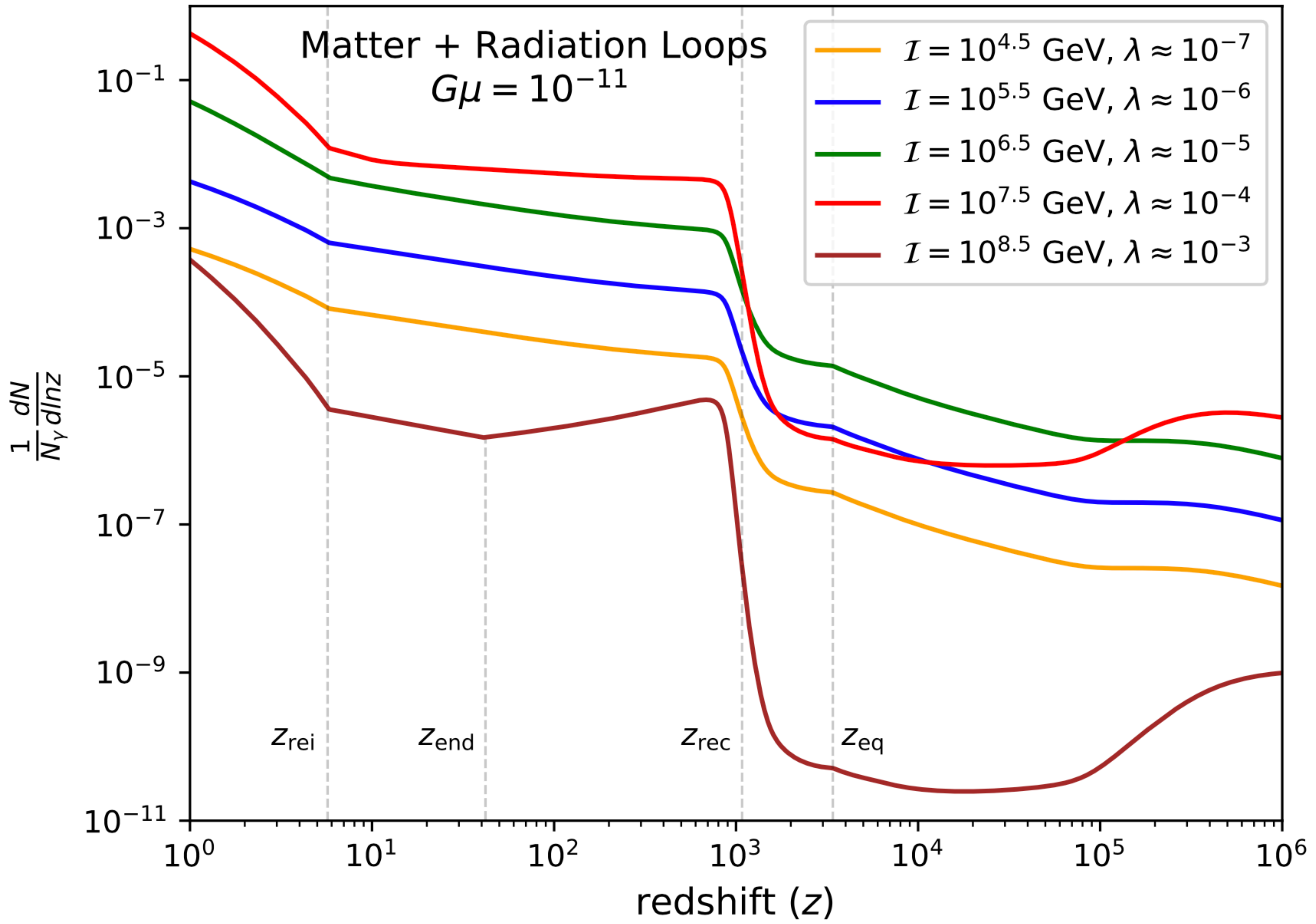
Analytics - energy+entropy injection

Photon injection sources negative distortion (in μ era): $\mu \approx 1.401 \left(\frac{\Delta \rho_\gamma}{\rho_\gamma} - \frac{4}{3} \frac{\Delta N_\gamma}{N_\gamma} \right)$

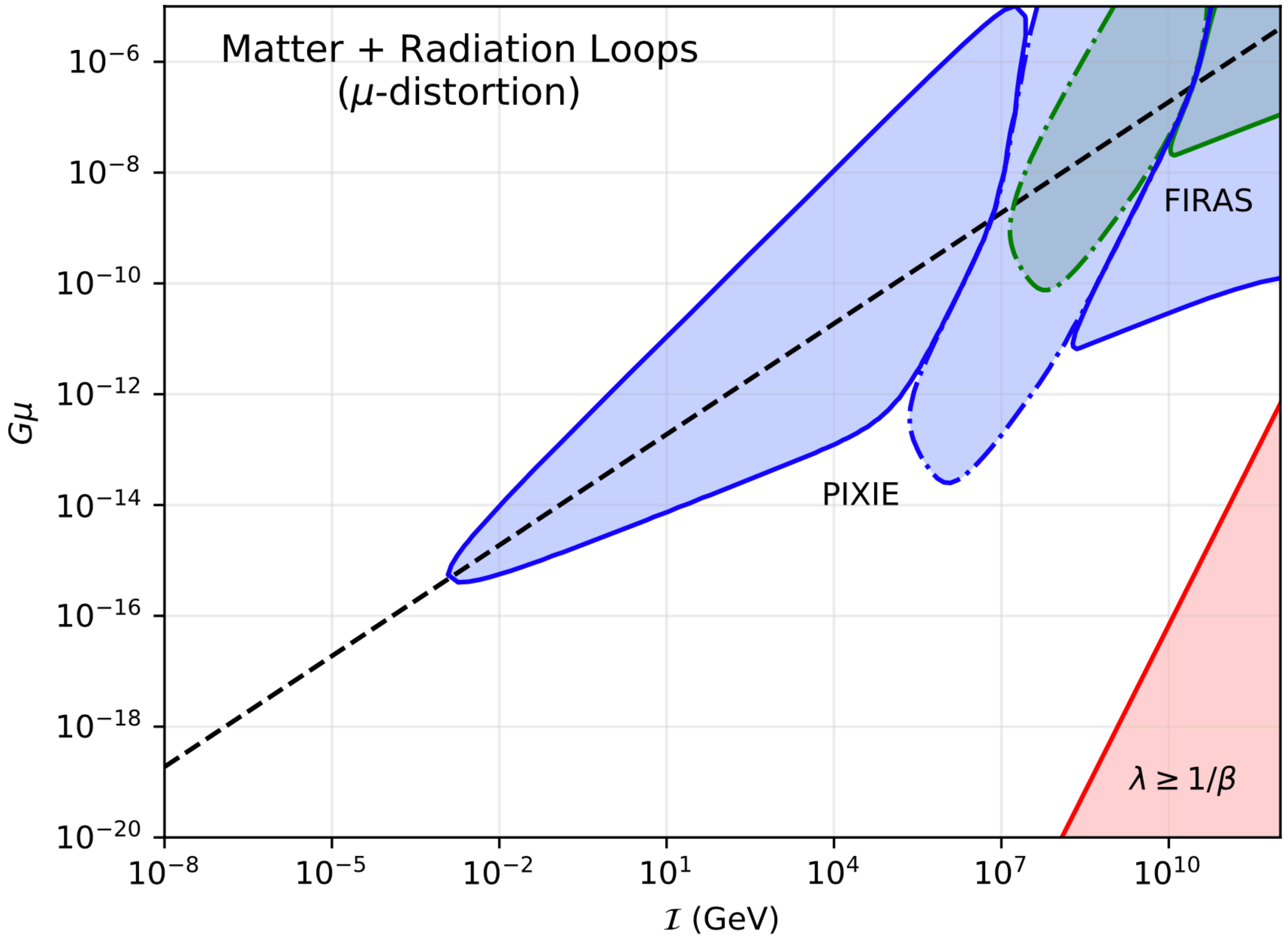
Chluba (2015)

However, not all produced photons provide entropy to background.

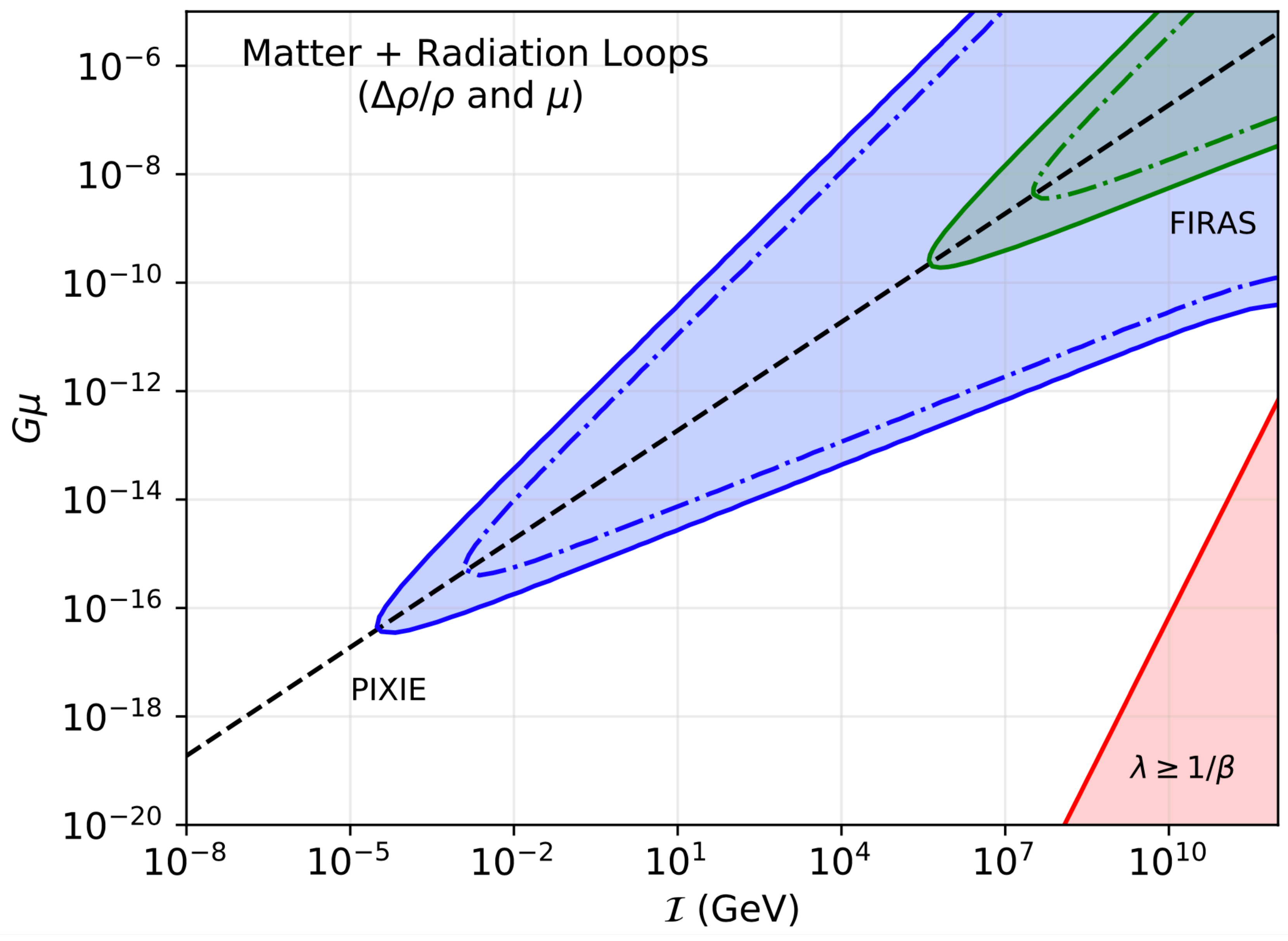




Analytics - energy+entropy injection



Entropy injection causes significant negative distortions. New regions of parameter space covered.



COSMOTHERM Chluba and Sunyaev (2012)

A fully numeric approach to solve for the evolution of the photon phase space distribution

$$\frac{df}{dt} = C[f] \qquad C[f] = C[f]_{CS} + C[f]_{BR} + C[f]_{DC} + C[f]_S$$

Input: A photon source term, heating term, or other general quantities

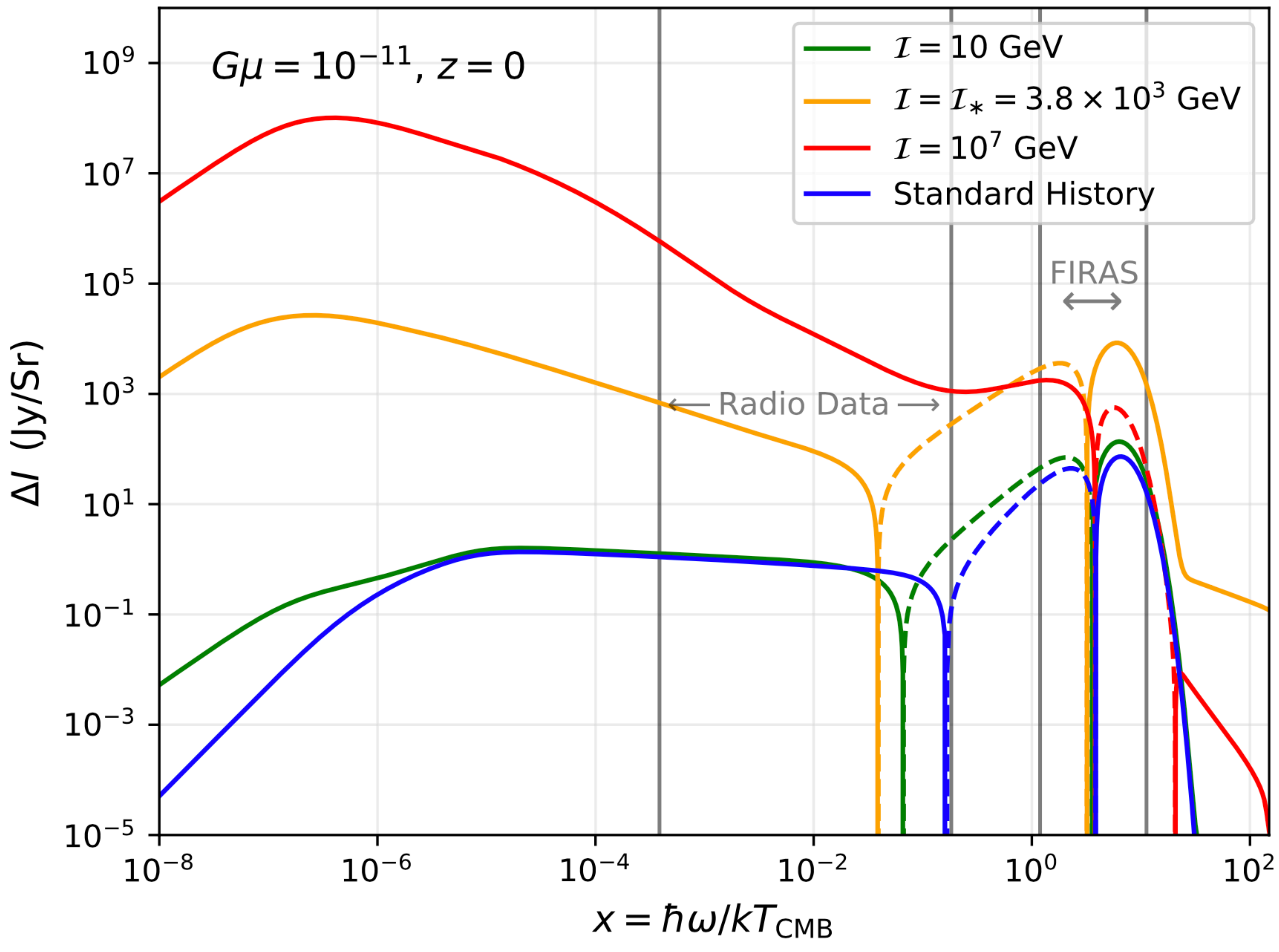
$$\frac{d^2 N_\gamma}{d\omega dt} \qquad \frac{d^2 \rho_\gamma}{d\omega dt} \qquad A_s,\ n_s,\ \text{etc.}$$

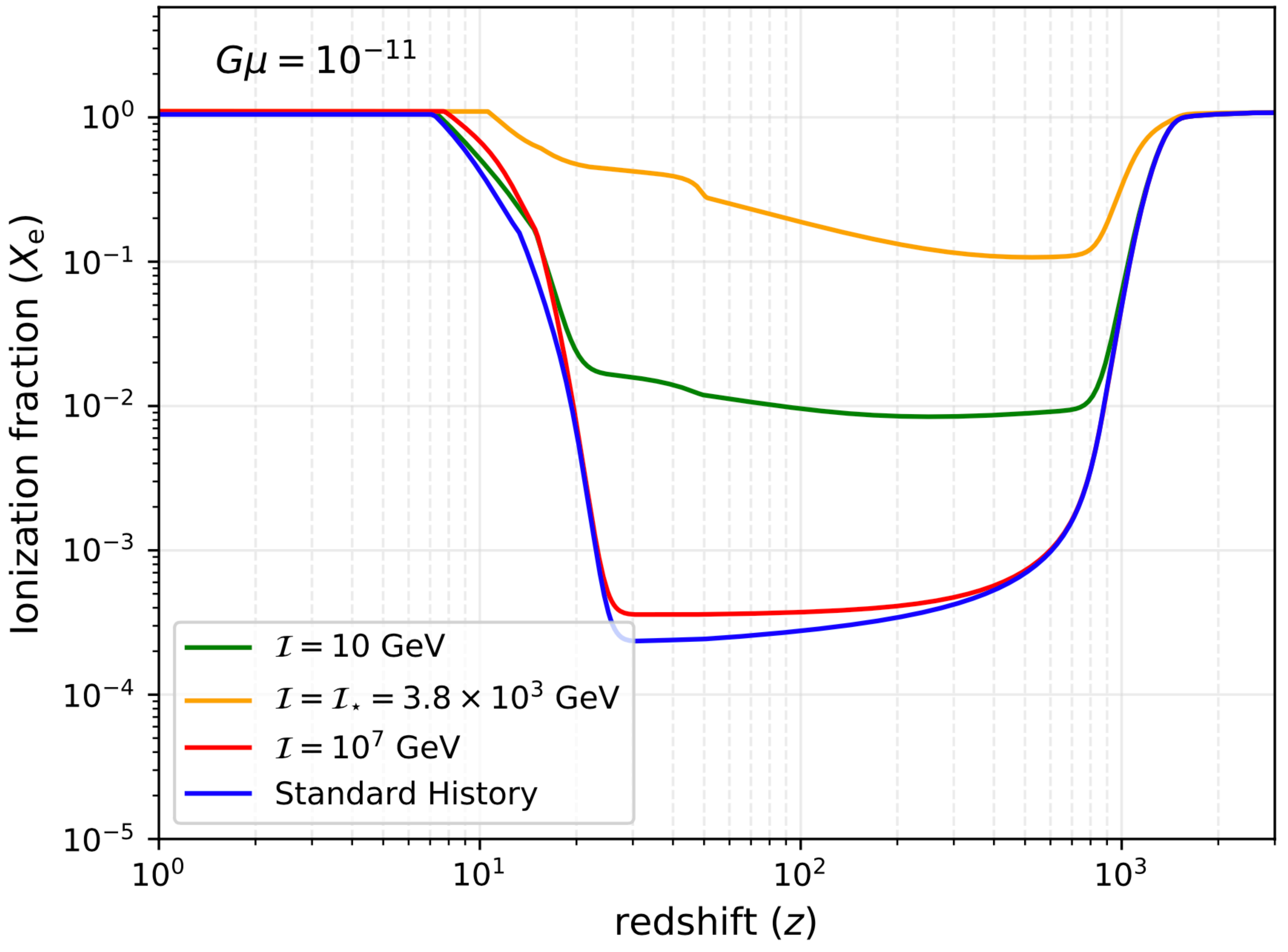
Output:

- Exact computation of the photon spectrum on finely spaced redshift grid
- Complete evolution history of ionization fraction ($X_{\rm e}$)
- Rudimentary likelihood analysis to COBE/FIRAS, ARCADE datasets
- Forecasting capabilities to future spectral distortion experiments
- and more...

COSMOTHERM output

Rich spectral data can be observed not just in the CMB band, but also in the radio and intermediary regimes.

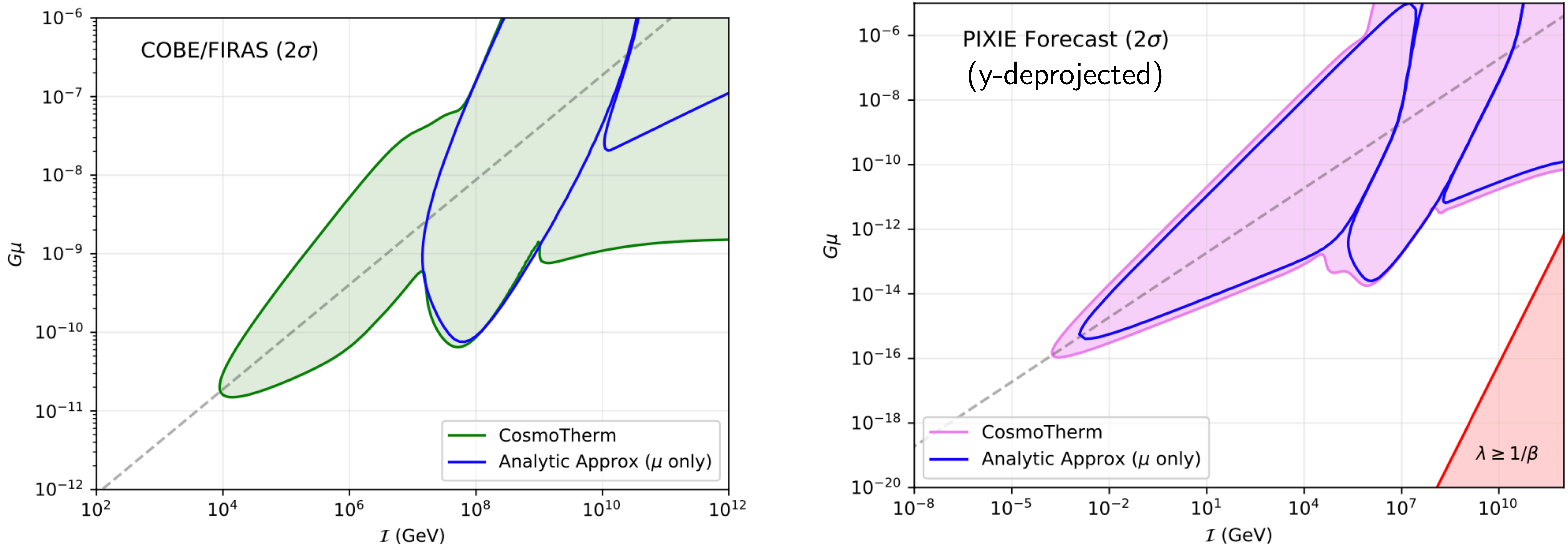




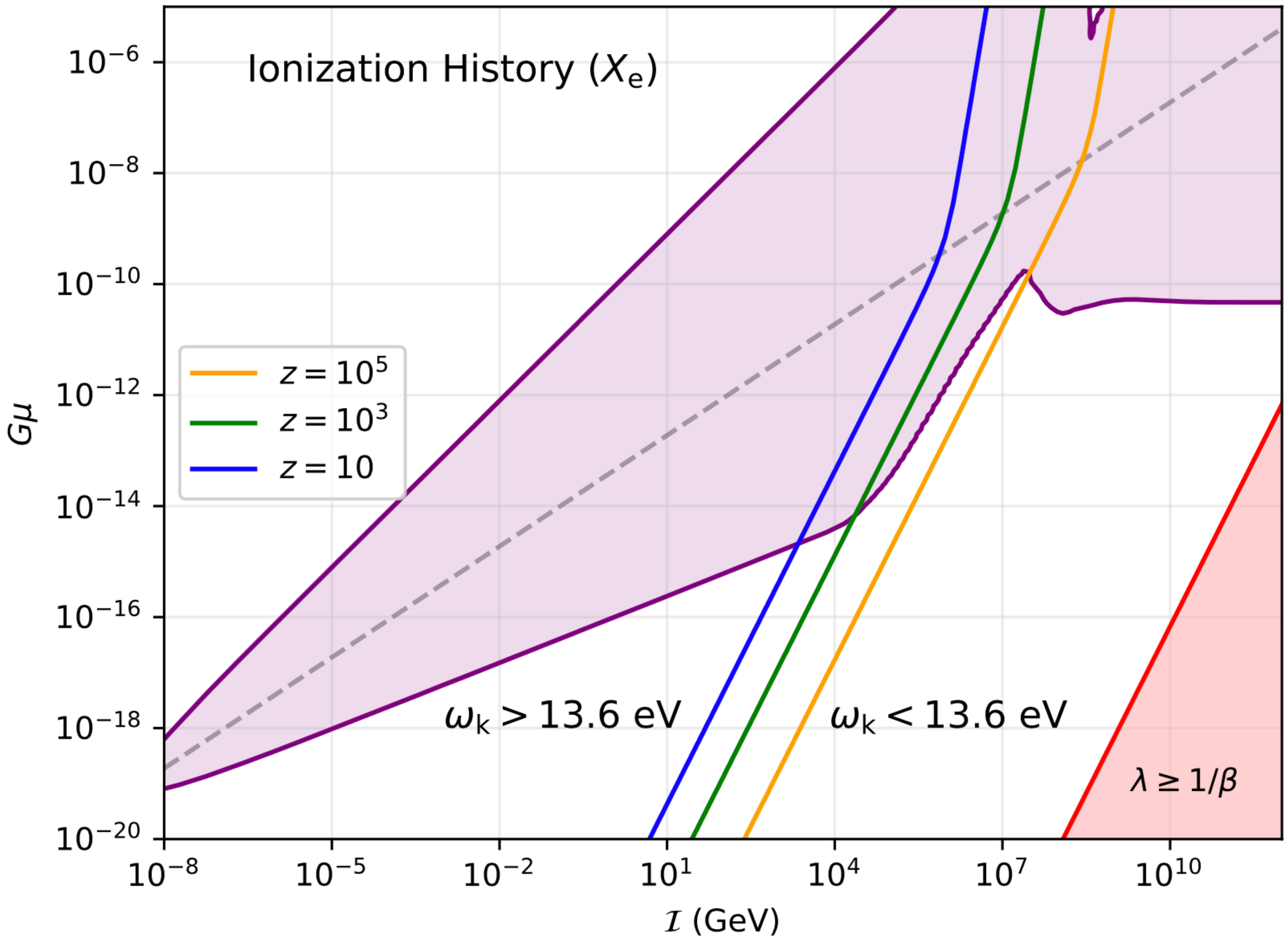
How good are the analytics?

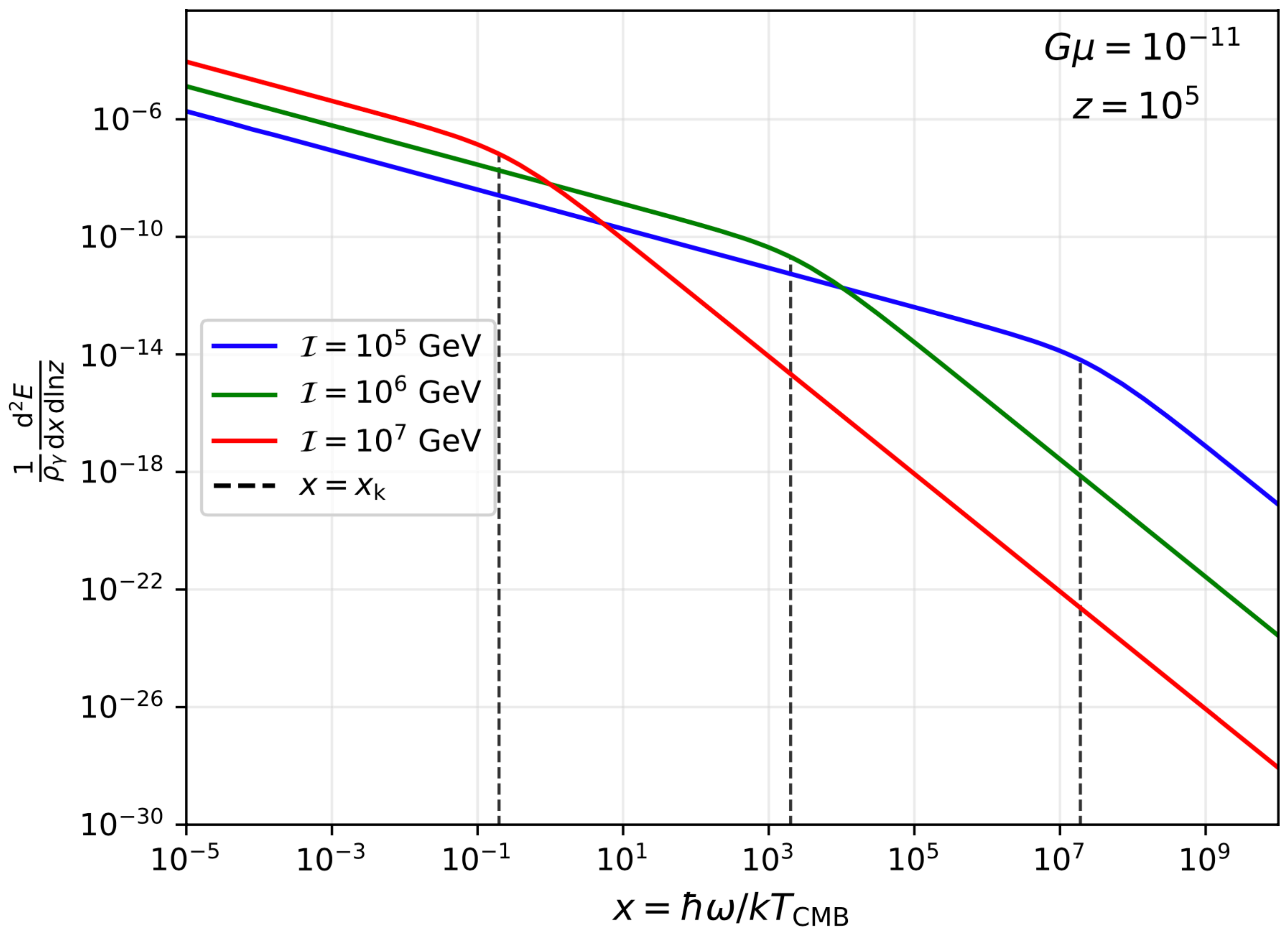
Negative (entropy injection) distortion well approximated by analytics.

Extra constraining power from non-μ, non-y type distortions.



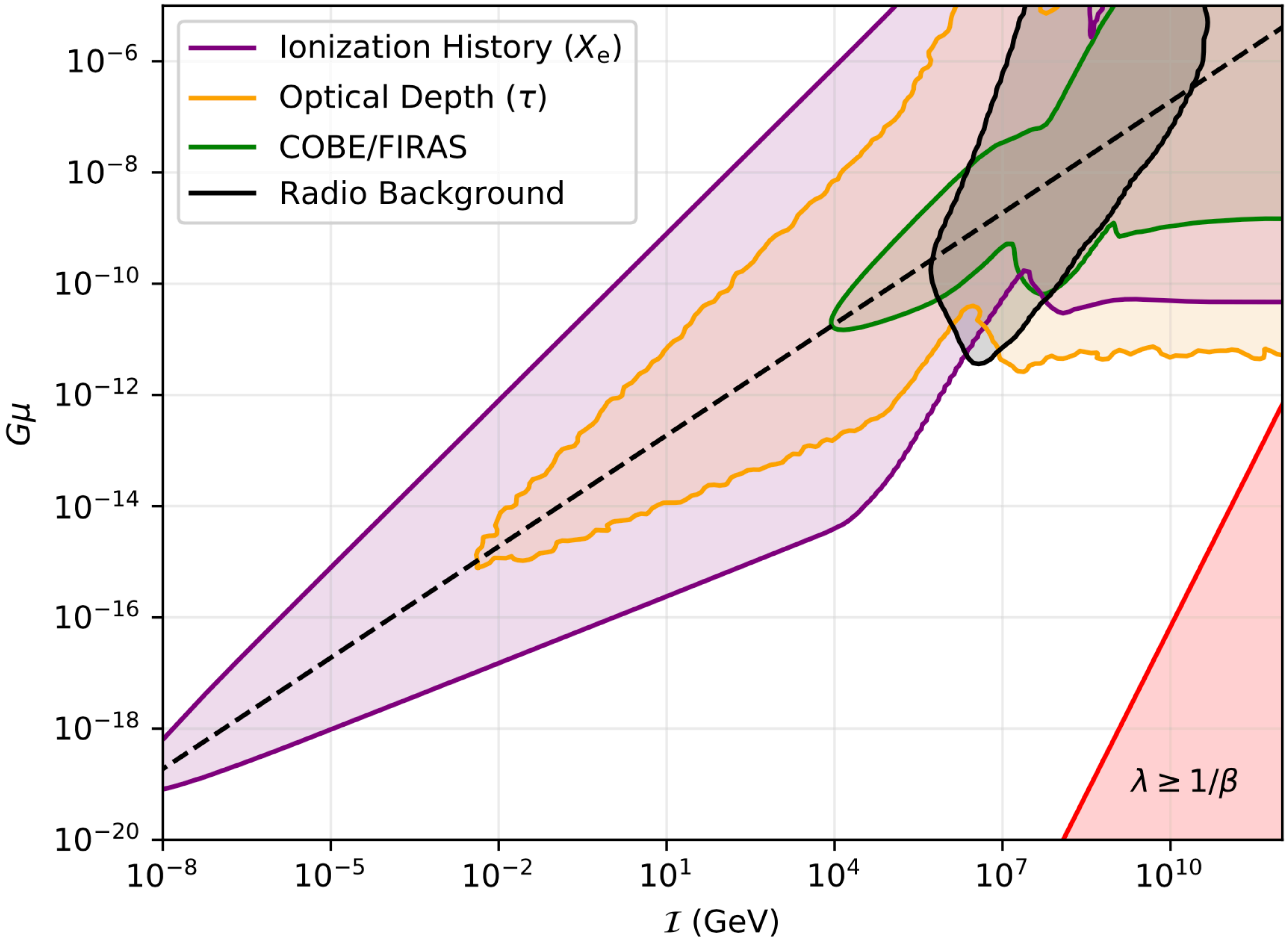
Ionization history constraints



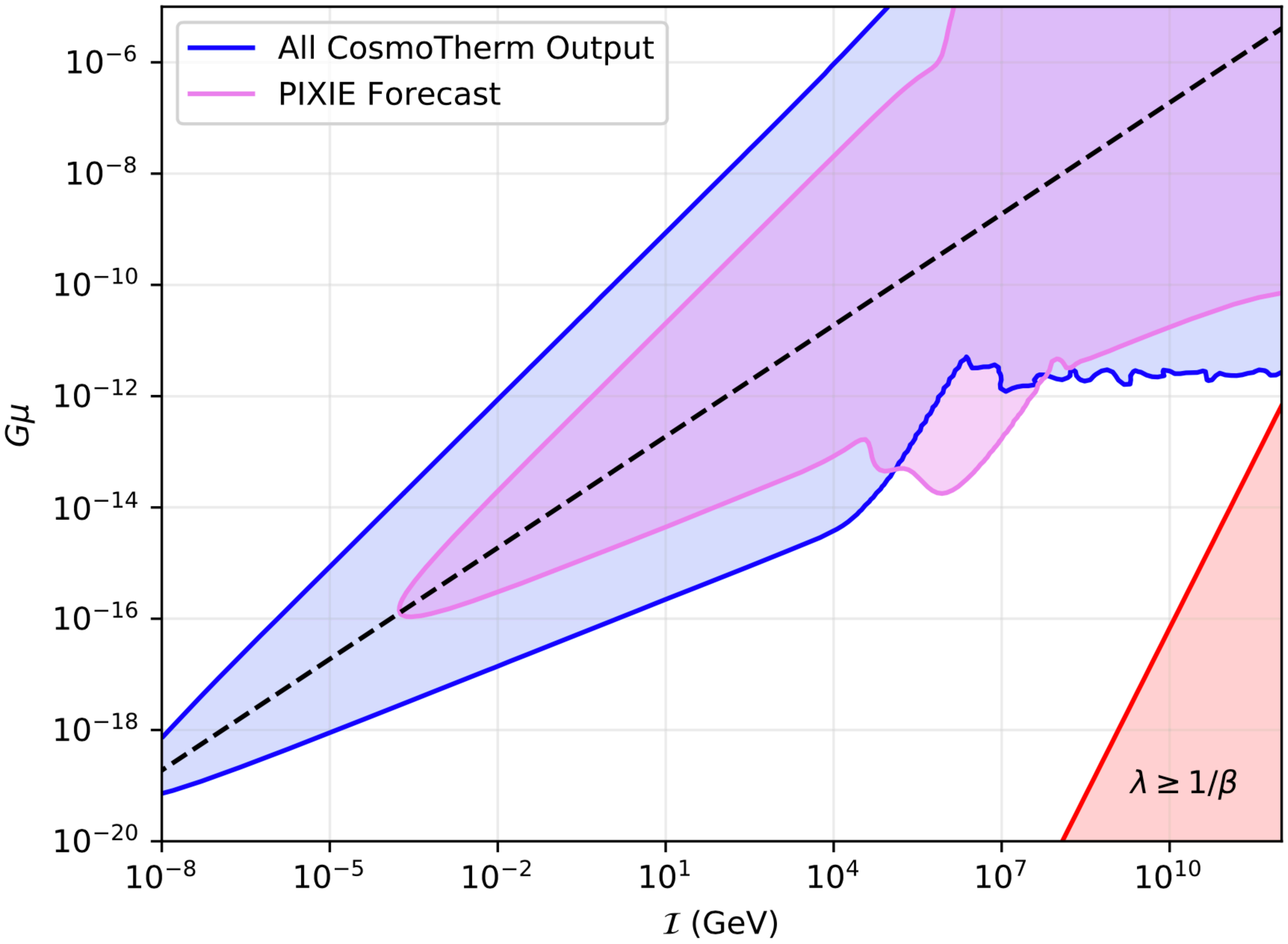


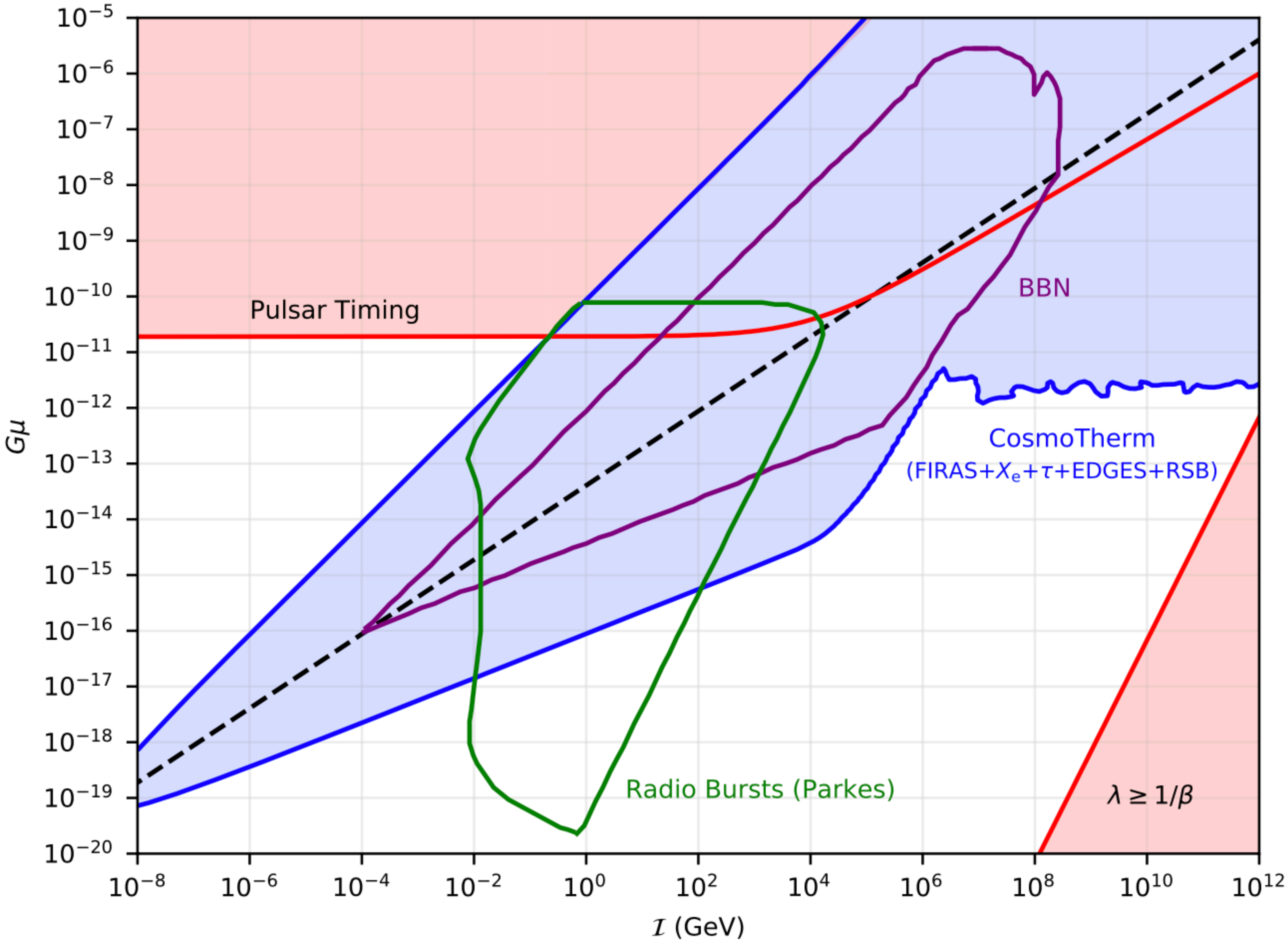
$$\omega_k = \frac{1}{G^{3/2}} \frac{(G\mu)^{3/2}}{\mathcal{I}^3 \beta t \lambda l_c} \frac{1}{T}$$

Summary of constraints



PIXIE - Forecasting





Pulsar Timing
BBN
CosmoTherm
(FIRAS+X_e+τ+EDGES+RSB)
Radio Bursts (Parkes)
$\lambda \geq 1/\beta$
$G\mu$
$\mathcal{I}$ (GeV)

Conclusions

- Cosmic strings are a well-motivated top down probe of particle physics capable of emitting strong bursts of GWs and EM radiation.

- We have made improvements to the analytic and numeric understandings of the spectral distortion signature from these loops.

- New and updated constraints derived from SDs, CMB anisotropies, 21-cm signals, and the radio synchrotron background.

- COSMOTHERM analysis easily extended to other models (PBHs, enhanced small scale perturbations, axions, etc.).

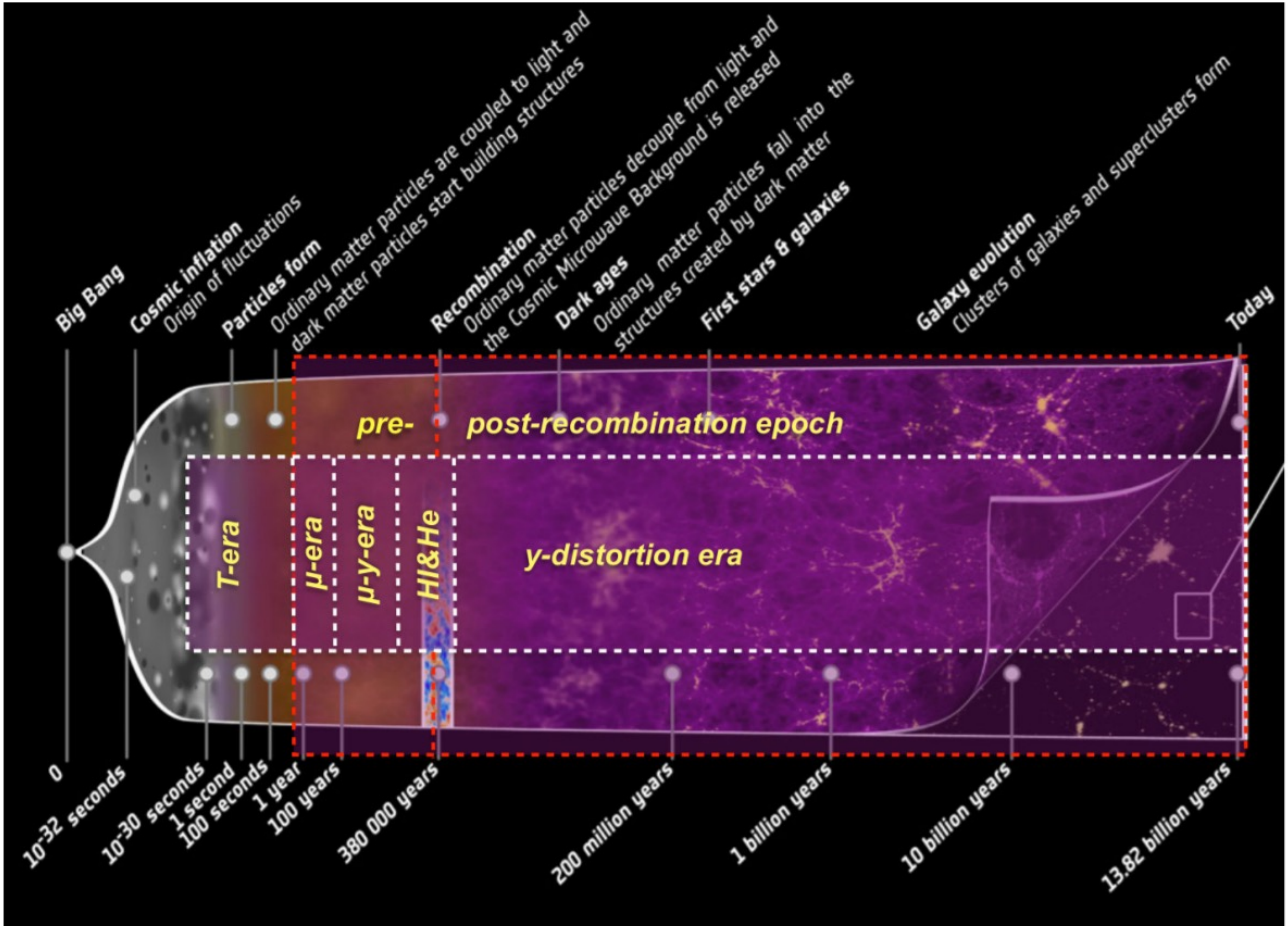
- Stay tuned: possible explanation of RSB from strings on the horizon...

Thank you!

Extra slides

Particle Physics to Astrophysics Dictionary

	Particle Physics	SI	Astrophysics
μ	1.5×10^{27} GeV^2	1.4×10^{16} kg/m	208 $M_\odot$/pc
$\mathcal{I}$	10^4 GeV	8.0×10^9 Amps	—————-
$P_\mathrm{g} \simeq P_\gamma$	3.0×10^{18} GeV^2	7.3×10^{32} Watts	7.3×10^{39} erg/s
L_c	2.4×10^{33} GeV^{-1}	4.7×10^{17} m	15.4 pc



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
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Photon production from strings

String loops can produce photons in a number of ways

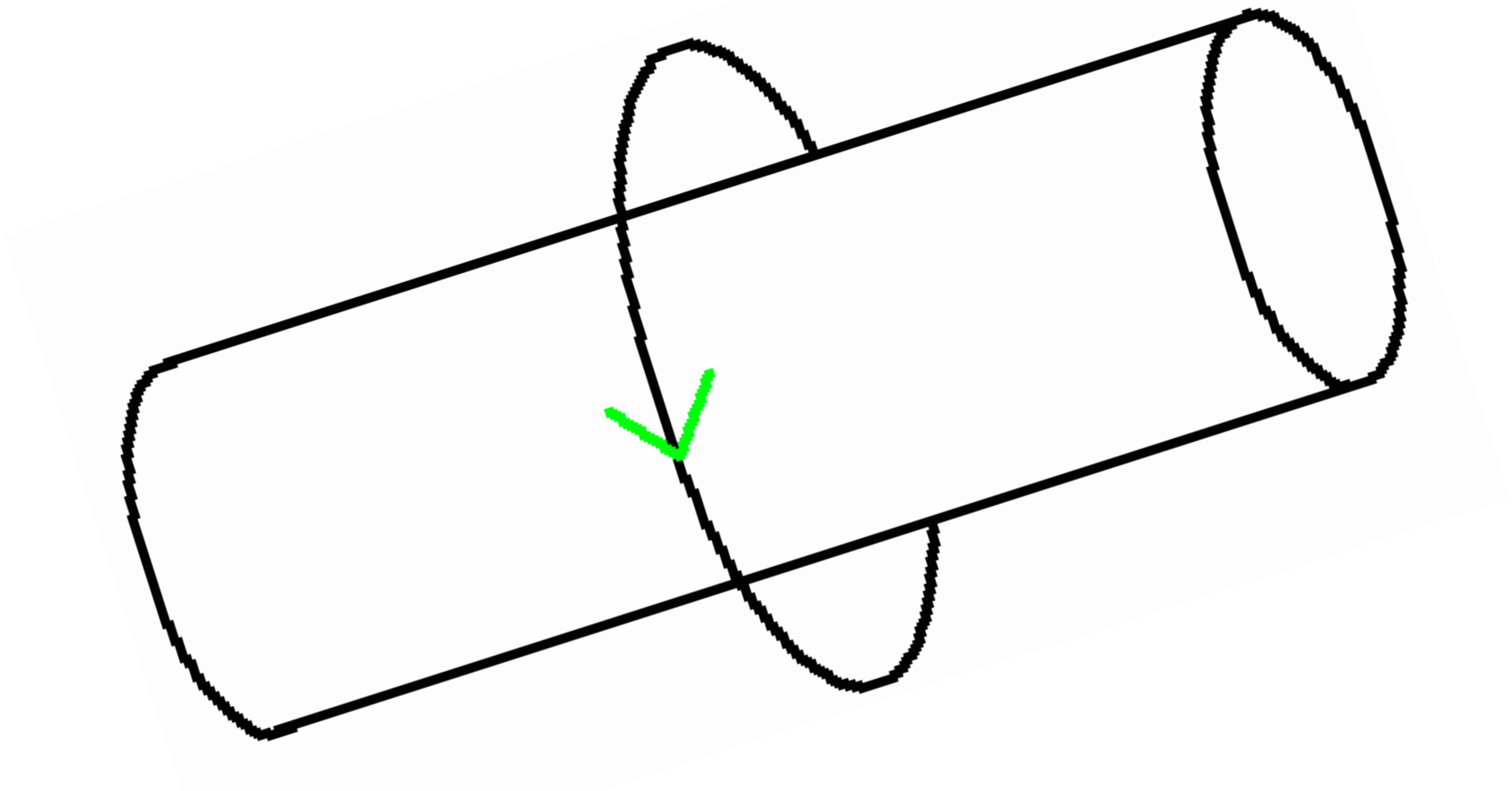
- Cusp annihilations
- Kinks
- Kink-Kink collisions

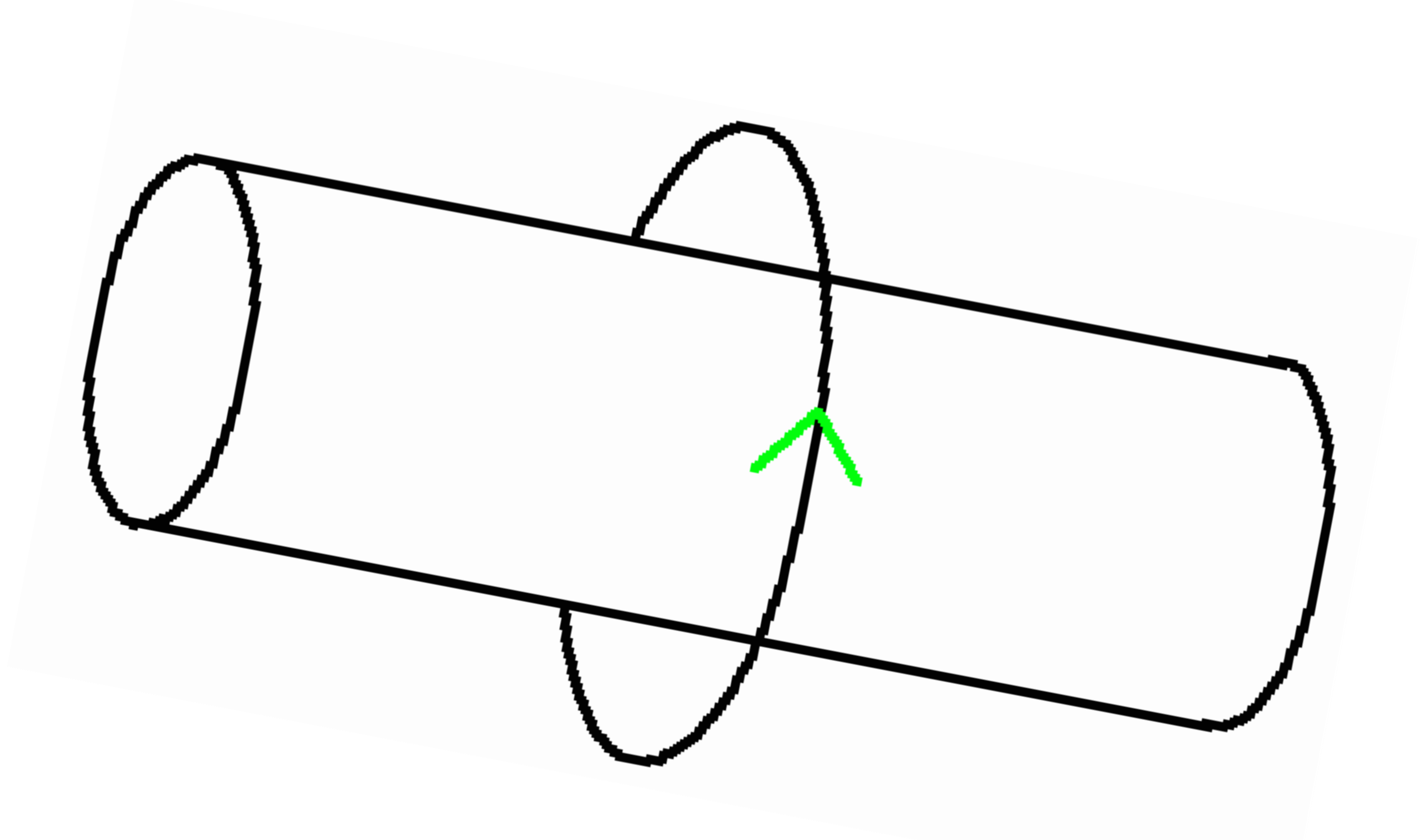
Vilenkin and Vachaspati: PRL (1987)

Cai et al. 1205.3170

Cusp annihilations are strongest... what are they?

- Strings have intrinsic winding
- Antistrings are strings with opposite winding





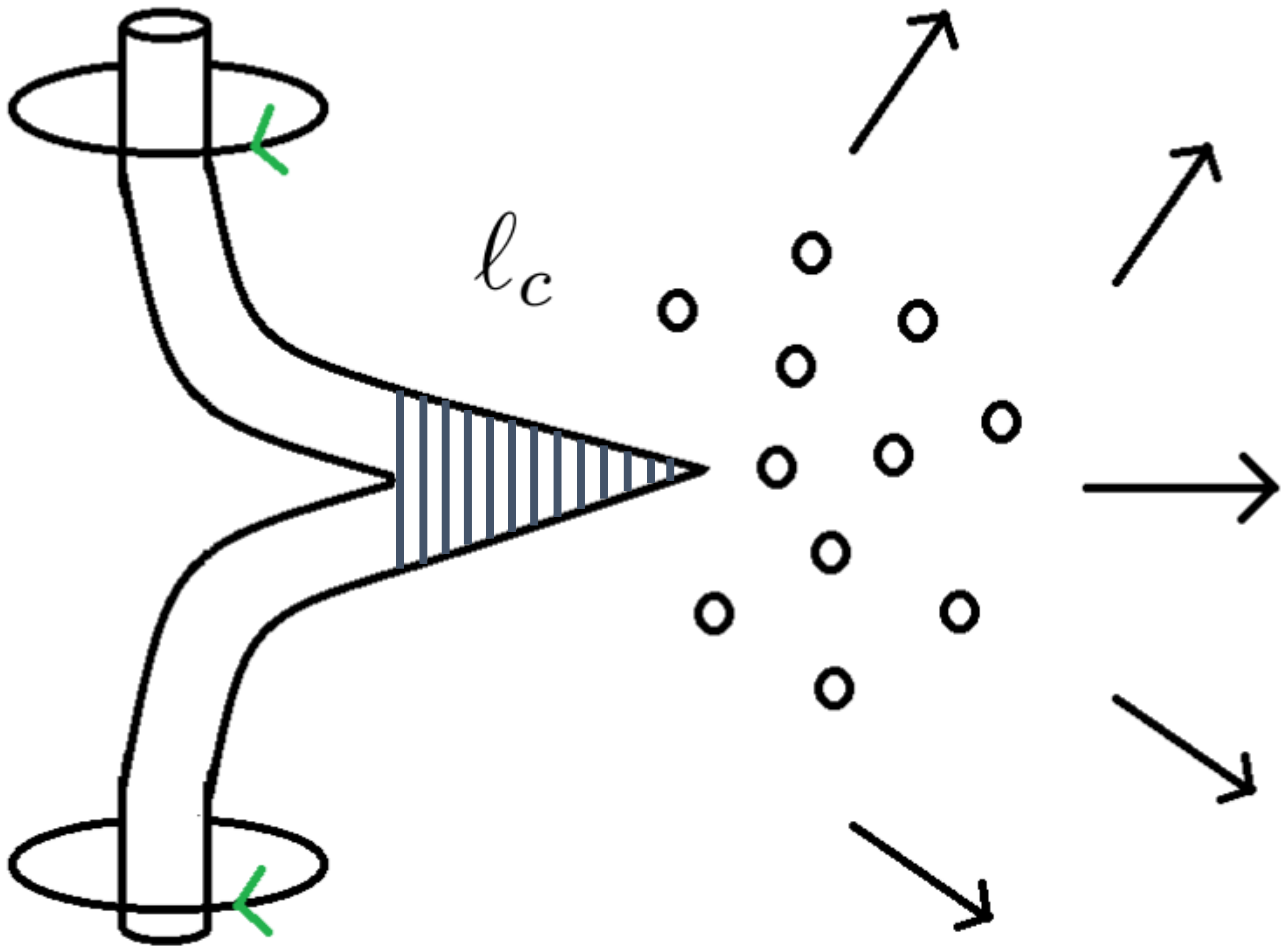
Cusp annihilations

Once per loop oscillation time ($T \approx L$), string develops luminal points and doubles back on itself.

Explosive energy production in tight beam $\Omega \approx (\omega L)^{-2/3}$

- Gravitational: $P_{\rm g} = \Gamma_{\rm g}(G\mu)^2/G$
- Electromagnetic: $P_\gamma = \Gamma_\gamma \mathcal{I}(G\mu)^{1/2}/G^{1/2}$

$(\Gamma_{\rm g} \sim 100, \quad \Gamma_\gamma \sim 10)$



Equating power yields critical current

$$\mathcal{I}_* = \frac{\Gamma_{\rm g}}{\Gamma_\gamma}\frac{(G\mu)^{3/2}}{G^{1/2}}$$

Analytics – Energy Injection

Case study – Radiation loops

$$\frac{dN_{\rm loops}}{dL} = \frac{\alpha(1+\lambda)^{3/2}}{t^{3/2}(L+\Gamma G\mu t)^{5/2}} \times \begin{cases} 1 & (t \leq t_{\rm eq}) \\ \left(\frac{t_{\rm eq}}{t}\right)^{1/2} & (t > t_{\rm eq}) \end{cases}$$

Injection rate of strings:

$$\frac{dQ}{dt} = \int_0^{L_{\rm max}(t)} dL \frac{dN_{\rm loops}}{dL} P_\gamma(L)$$

Distortions sourced through

$$\mu \approx 1.401 \int_{z_{\rm C}}^{z_{\rm DC}} dz \frac{1}{\rho_\gamma} \frac{dQ}{dz} \qquad y \approx \frac{1}{4} \int_{z_{\rm rec}}^{z_{\rm C}} dz \frac{1}{\rho_\gamma} \frac{dQ}{dz}$$

Analytics – Energy+Entropy

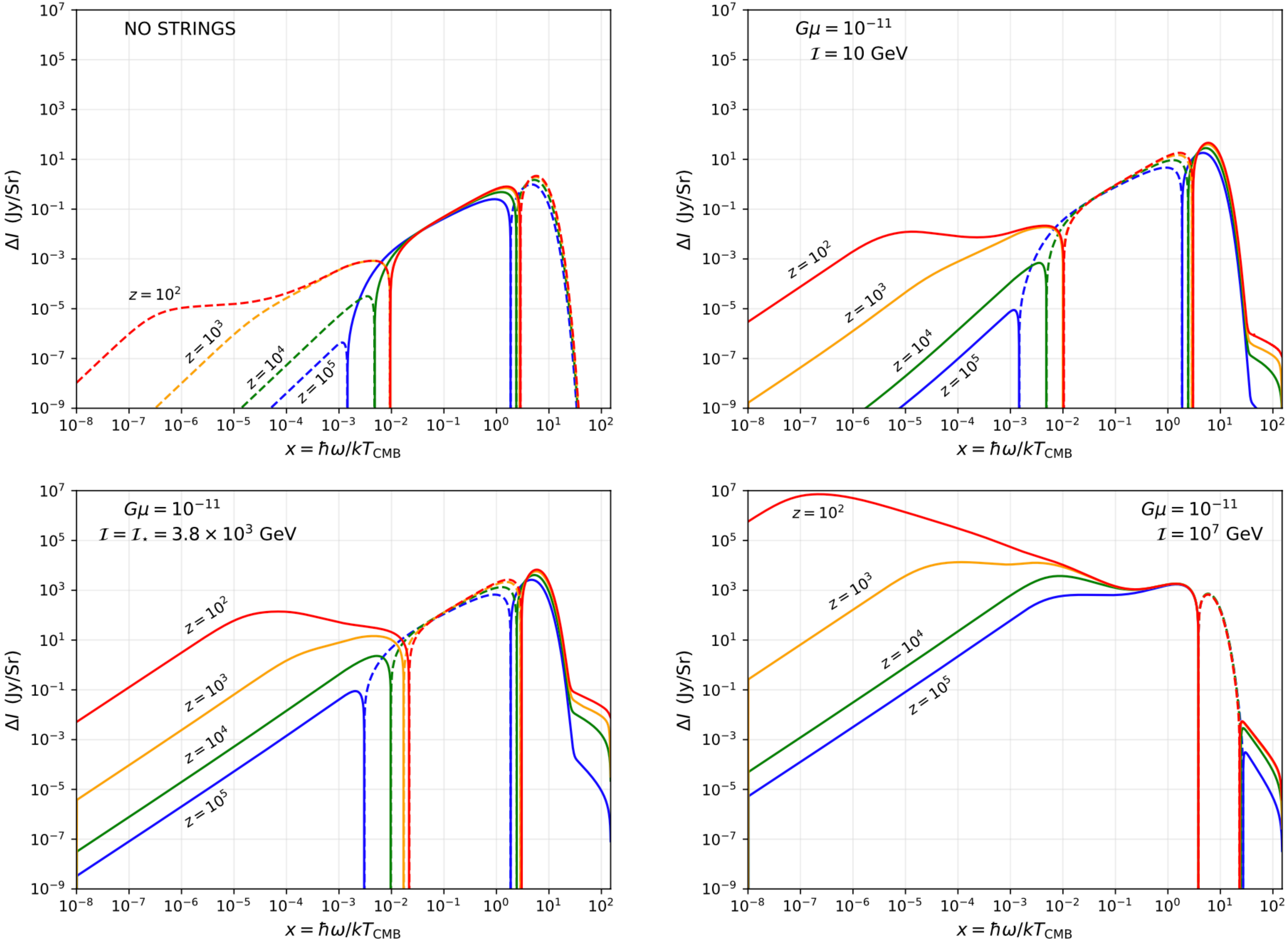
Effective μ distortion given by

$$\mu \approx 1.401 \left(\frac{\Delta\rho_\gamma}{\rho_\gamma} - \frac{4}{3}\frac{\Delta N_\gamma}{N_\gamma} \right)$$

Analytic description breaks down in y-era, due to inefficient energy redistribution. Numerical approach is necessary!

Each loop emits a spectrum of photons (averaged over oscillation time)

$$\frac{d^2 N_\gamma^c}{dt d\omega} = \left(\frac{\Gamma_\gamma}{3} \right) \frac{\mathcal{I}^2 L^{1/3}}{\omega^{5/3}} \qquad \omega_{\rm max} = \frac{1}{G^{3/2}} \frac{(G\mu)^{3/2}}{\mathcal{I}^3 L}$$



NO STRINGS
$G\mu = 10^{-11}$
$\mathcal{I} = 10$ GeV
$G\mu = 10^{-11}$
$\mathcal{I} = \mathcal{I}_\star = 3.8 \times 10^3$ GeV
$G\mu = 10^{-11}$
$\mathcal{I} = 10^7$ GeV
$z = 10^2$
$z = 10^3$
$z = 10^4$
$z = 10^5$
ΔI (Jy/Sr)
$x = \hbar\omega/kT_{\rm CMB}$

Soft photon heating and RSB