$N_{\rm eff}$ and the Search for Light Particles

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Motivation

New light particles are ubiquitous in BSM physics

- QCD axion (strong CP problem)
- Solutions 3, 9, 10 (& 1,2) to the hierarchy problem

  see N. Craig's talk
- Light (sub-MeV) dark matter
- Light mediators of new forces (perhaps DM-SM)

Often very weakly coupled / experimentally elusive

Toy Model

Axion-like couplings to gauge bosons:

$$\mathcal{L} \supset -\frac{1}{4}\frac{\phi}{\Lambda_\gamma}\tilde{F}_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\frac{\phi}{\Lambda_g}\tilde{G}_{\mu\nu}G^{\mu\nu}$$

Familon/Axion-like couplings to matter

$$\mathcal{L}_\psi = -\frac{\partial_\mu \phi}{\Lambda_\psi}\bar{\psi}_i\gamma^\mu(g_V^{ij} + g_A^{ij}\gamma^5)\psi_j$$

At low-energies

$$\mathcal{L}_\psi \approx \sqrt{2}\frac{(m_i \pm m_j)}{\Lambda_{ij}}\phi\bar{\psi}_i\psi_j$$

Astrophysical Constraints

Stellar Cooling

$$T \sim \mathcal{O}(1)\,\mathrm{keV}$$

$$t \sim \mathcal{O}(10^9)\,\mathrm{years}$$

$$\Lambda_\gamma > 10^{10}\,\mathrm{GeV}$$

e.g. Raffelt (hep-ph/0611350)

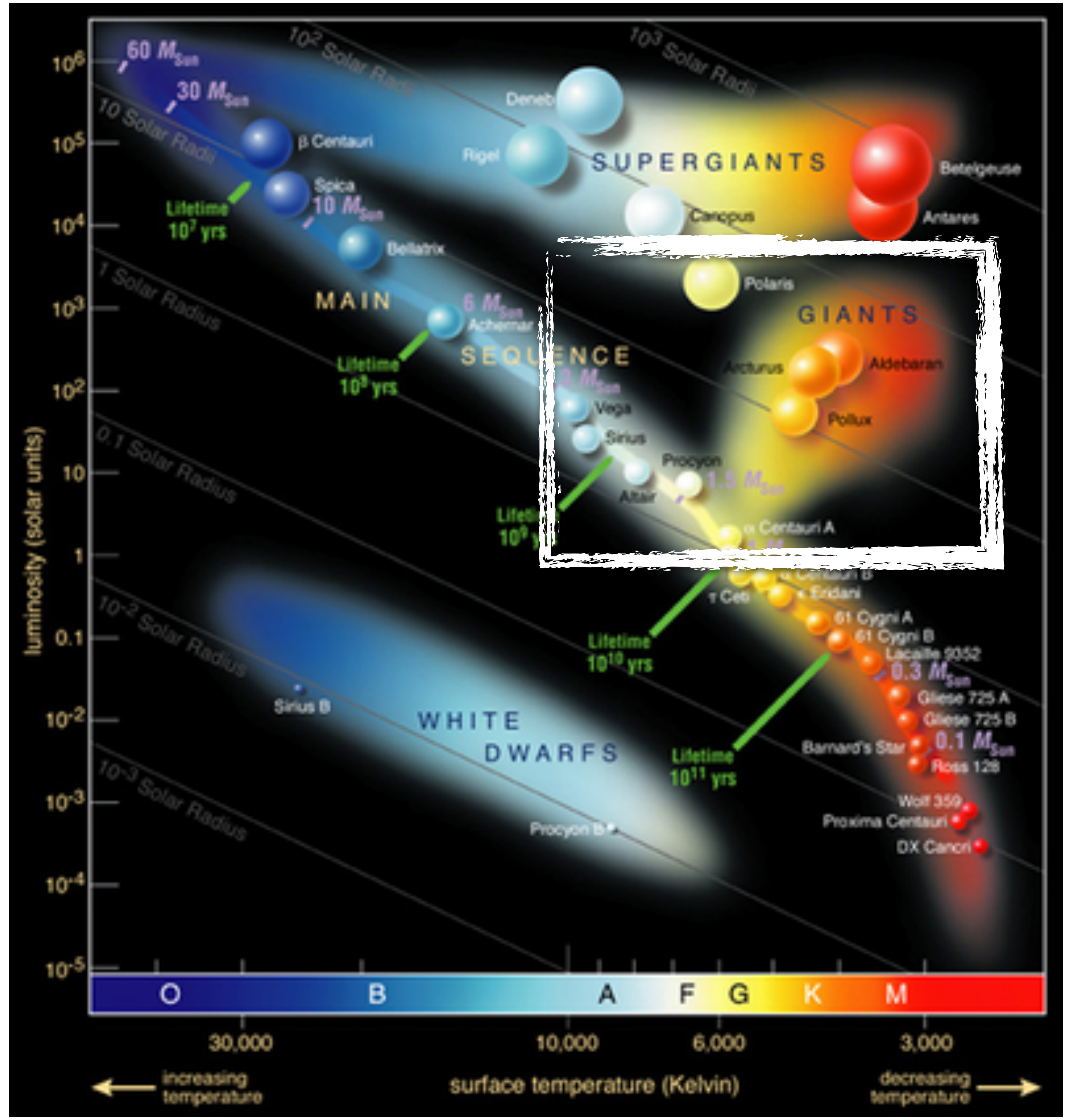


Image from ESO

Astrophysical Constraints

White Dwarf cooling

$$k_f \sim 400\,\mathrm{keV}$$

$$t \sim \mathcal{O}(10^9)\ \mathrm{years}$$

$$\Lambda_{ee} > 10^{10}\,\mathrm{GeV}$$

e.g. Hanson et al. (arXiv:1507.05665)

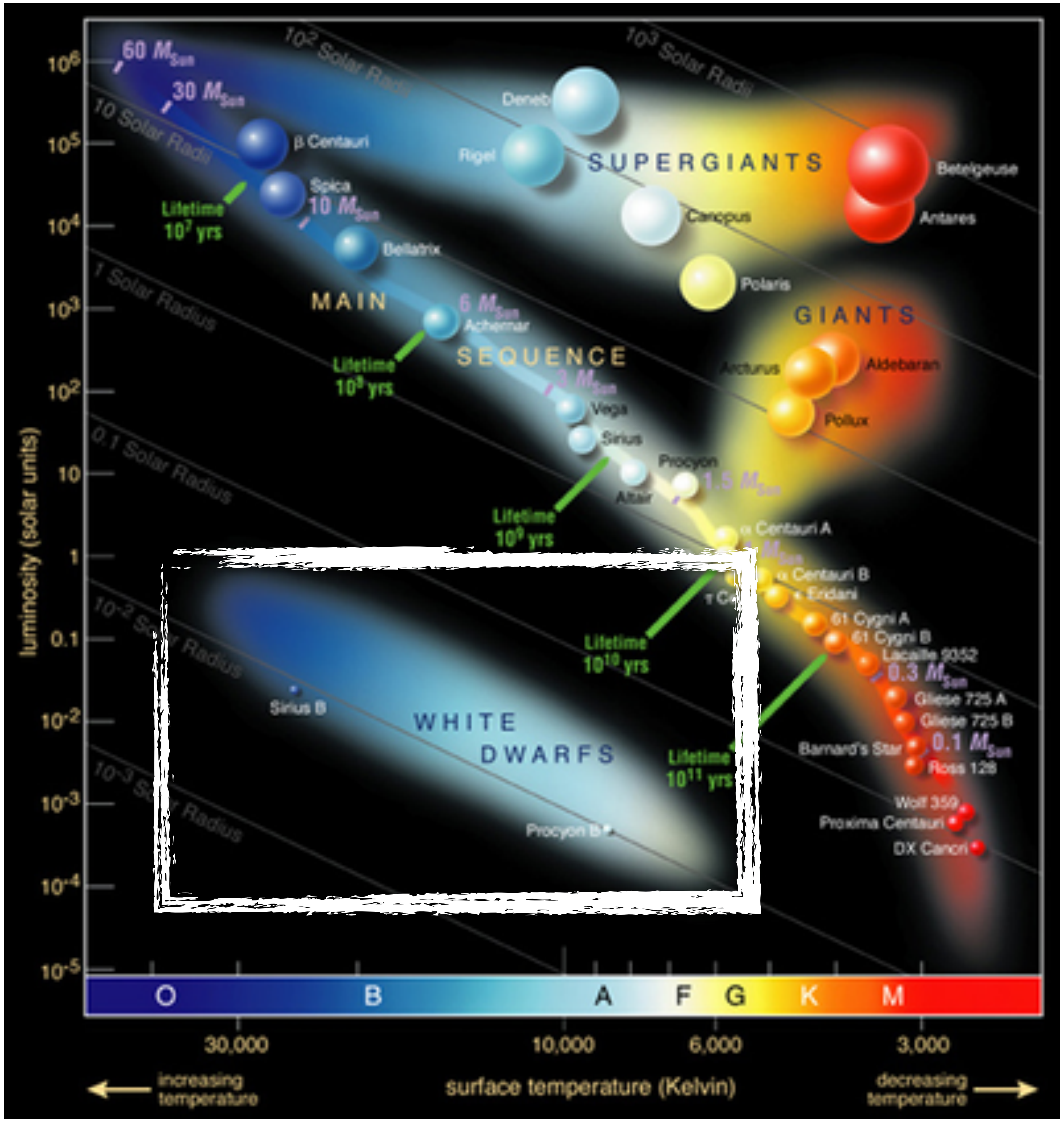


Image from ESO

Astrophysical Constraints

SN 1987a

$$T \sim 30\,\mathrm{MeV}$$

$$t \sim 10\,\mathrm{sec}$$

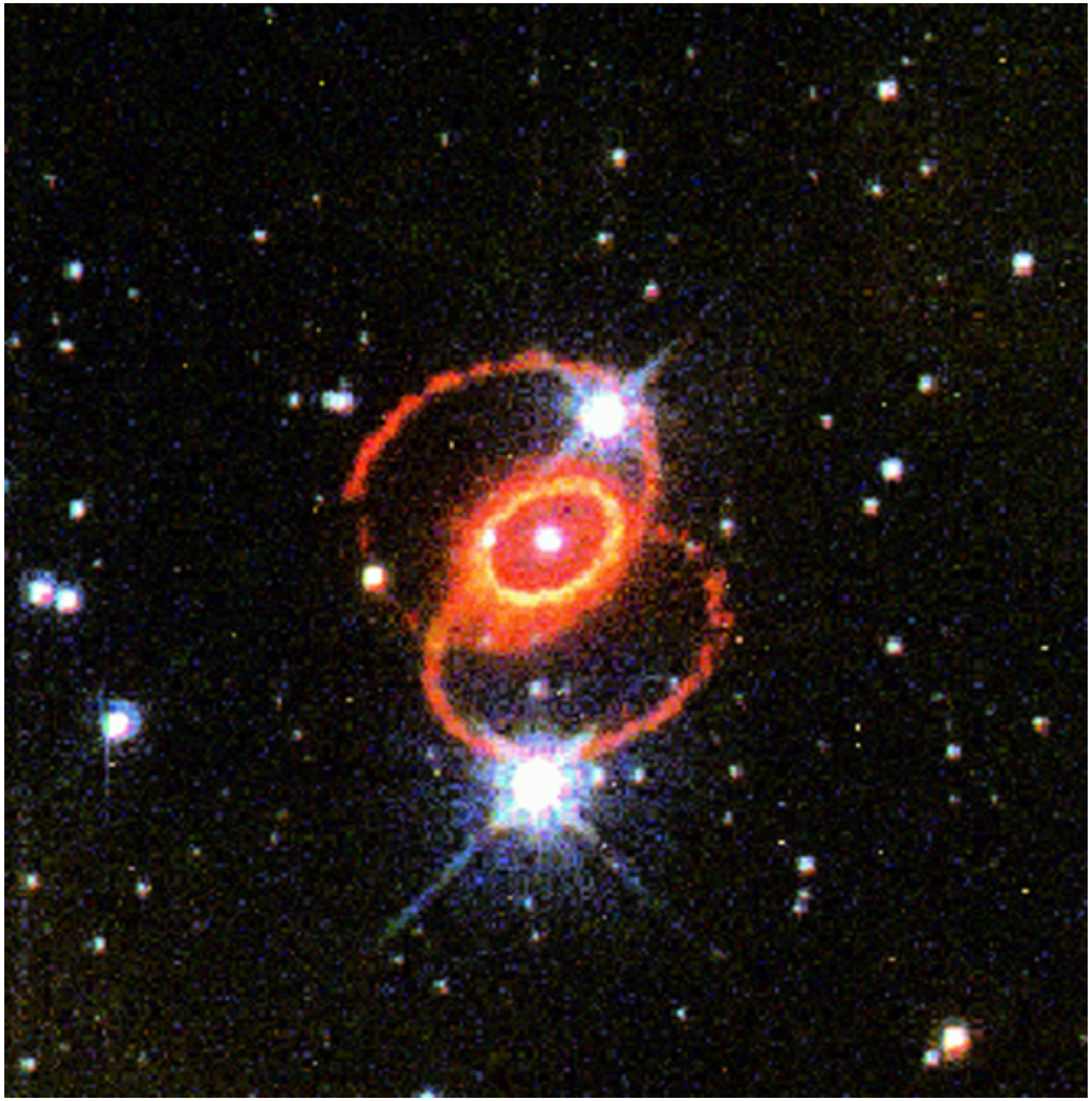


Image from HST

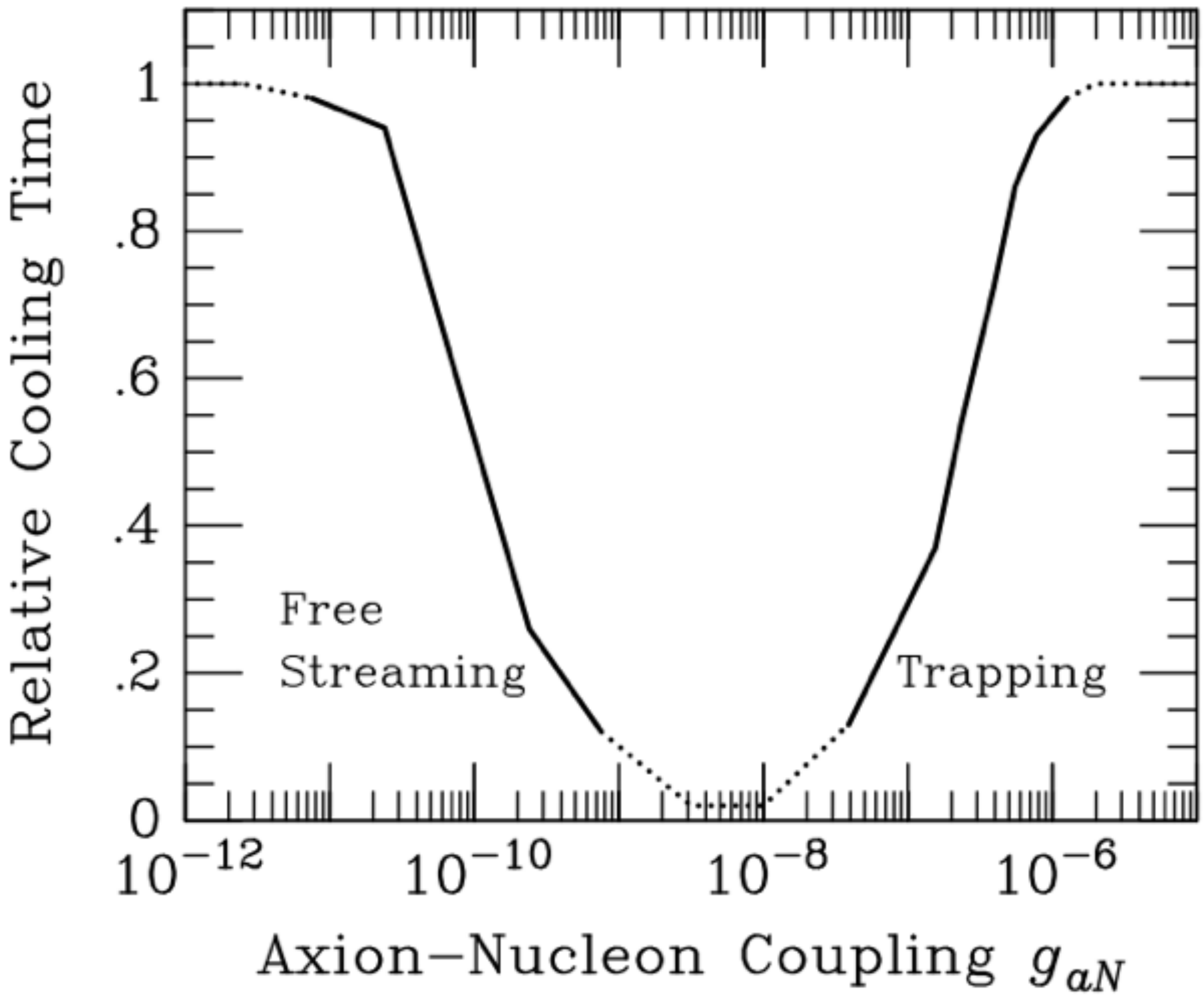
Astrophysical Constraints

SN 1987a

$$T \sim 30\,\mathrm{MeV}$$

$$t \sim 10\,\mathrm{sec}$$

$$g_{aN} \approx \frac{m_N}{\Lambda_N}$$



e.g. Raffelt (hep-ph/0611350)

Astrophysical Constraints

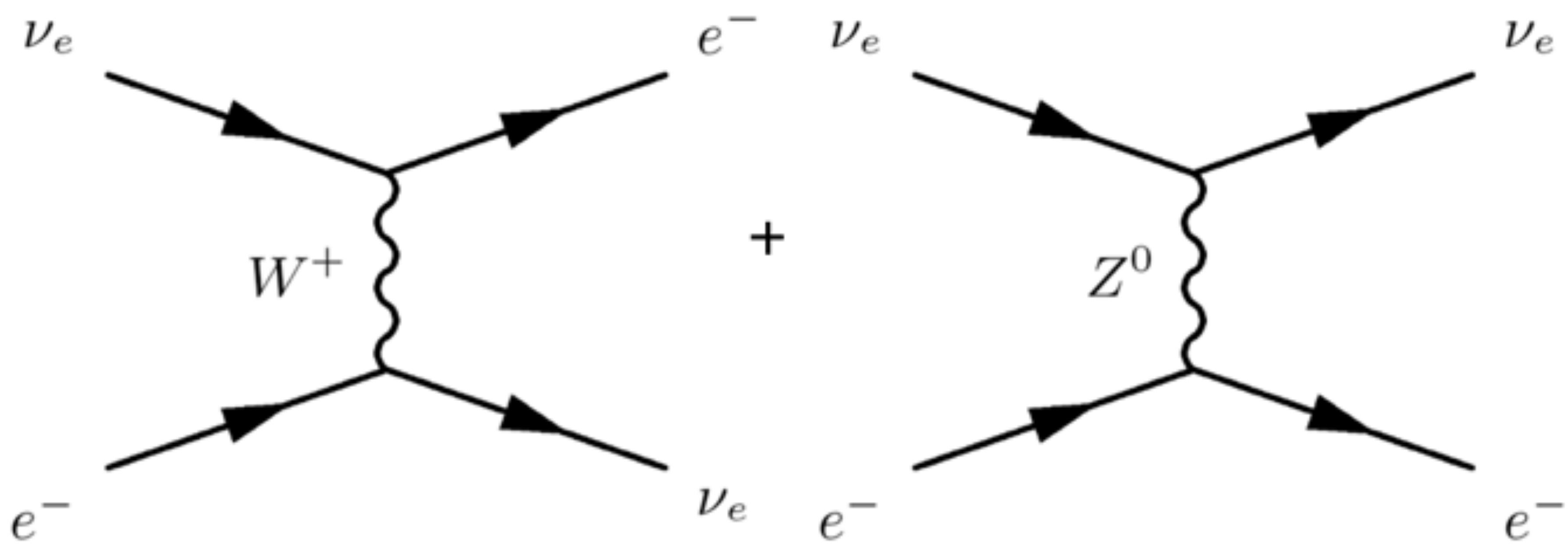
General lesson from astrophysics

- Free streaming particles have distinct effects
- Results are sensitive to neutrino cooling
- New light particles must be more weakly coupled
- Especially strong constraint for dim 4, 5 operators

Essentially the same is true of the early universe

Cosmic Neutrinos

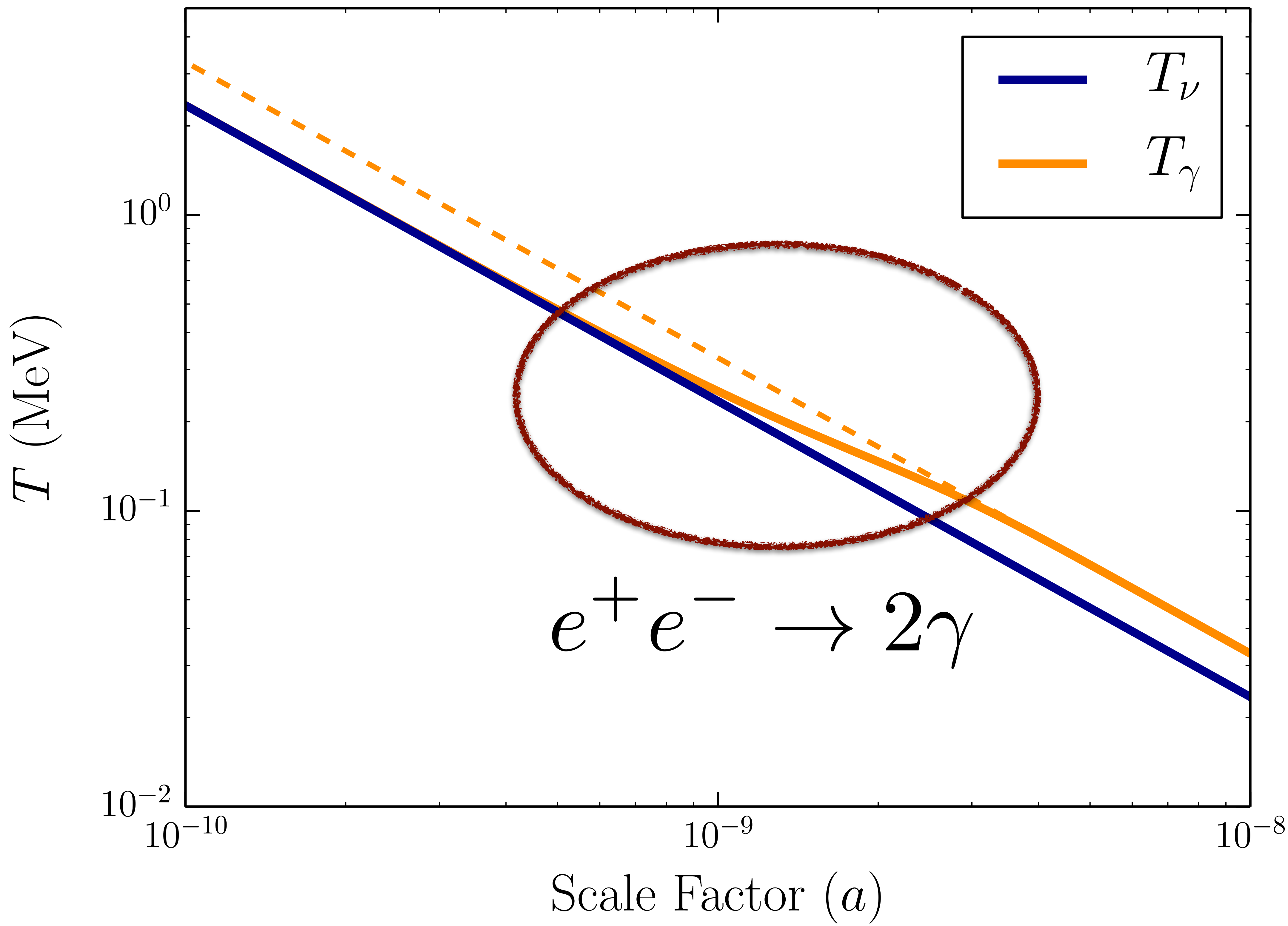
Freeze-out below $T \sim 10\,\mathrm{MeV}$



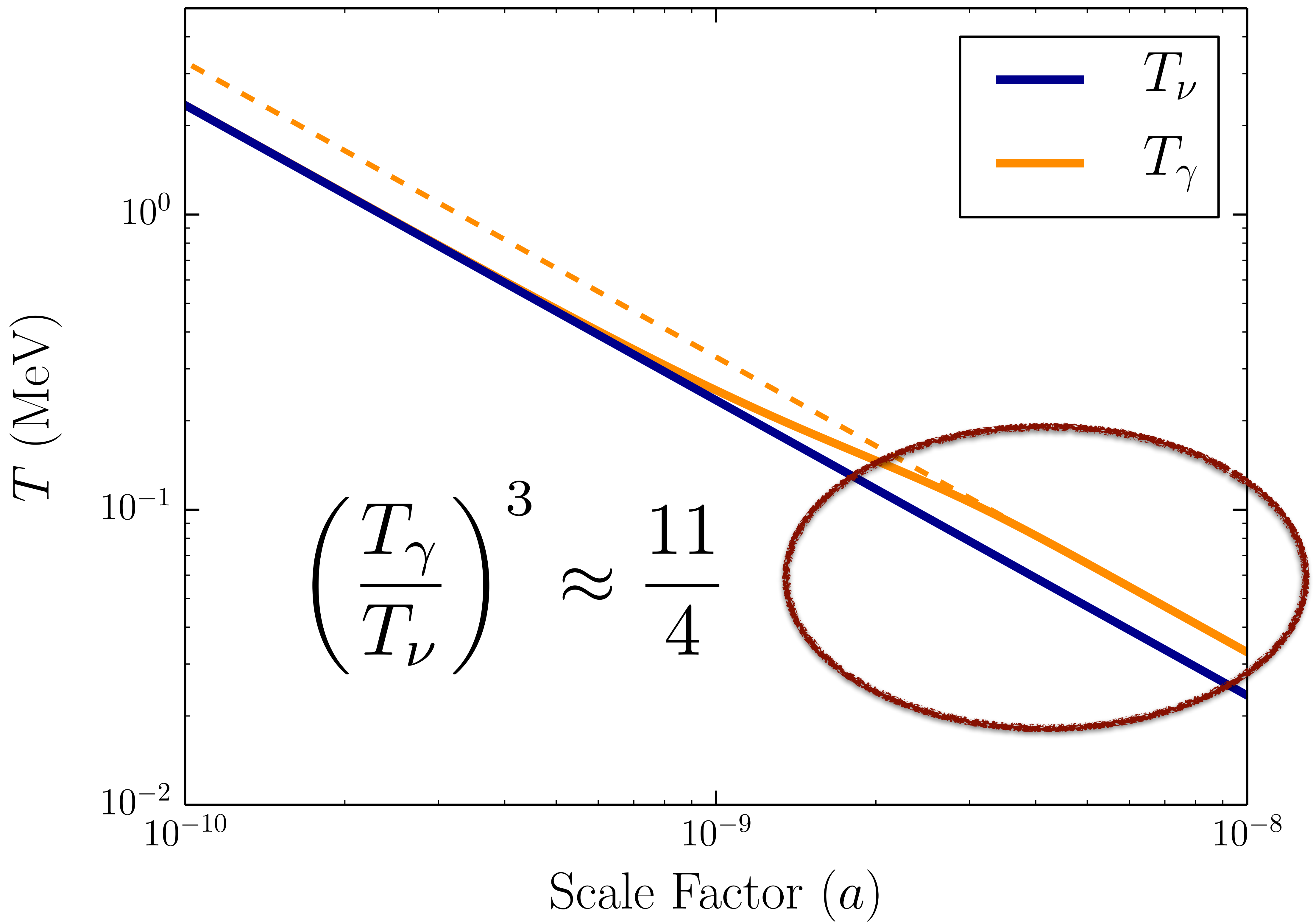
$$\Gamma_\nu \propto G_F^2 T^5 < H \propto \frac{T^2}{M_{\rm pl}}$$

Redshift alone would still leave $T_\nu = T_\gamma$

Cosmic Neutrinos



Cosmic Neutrinos



Cosmic Neutrinos

$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

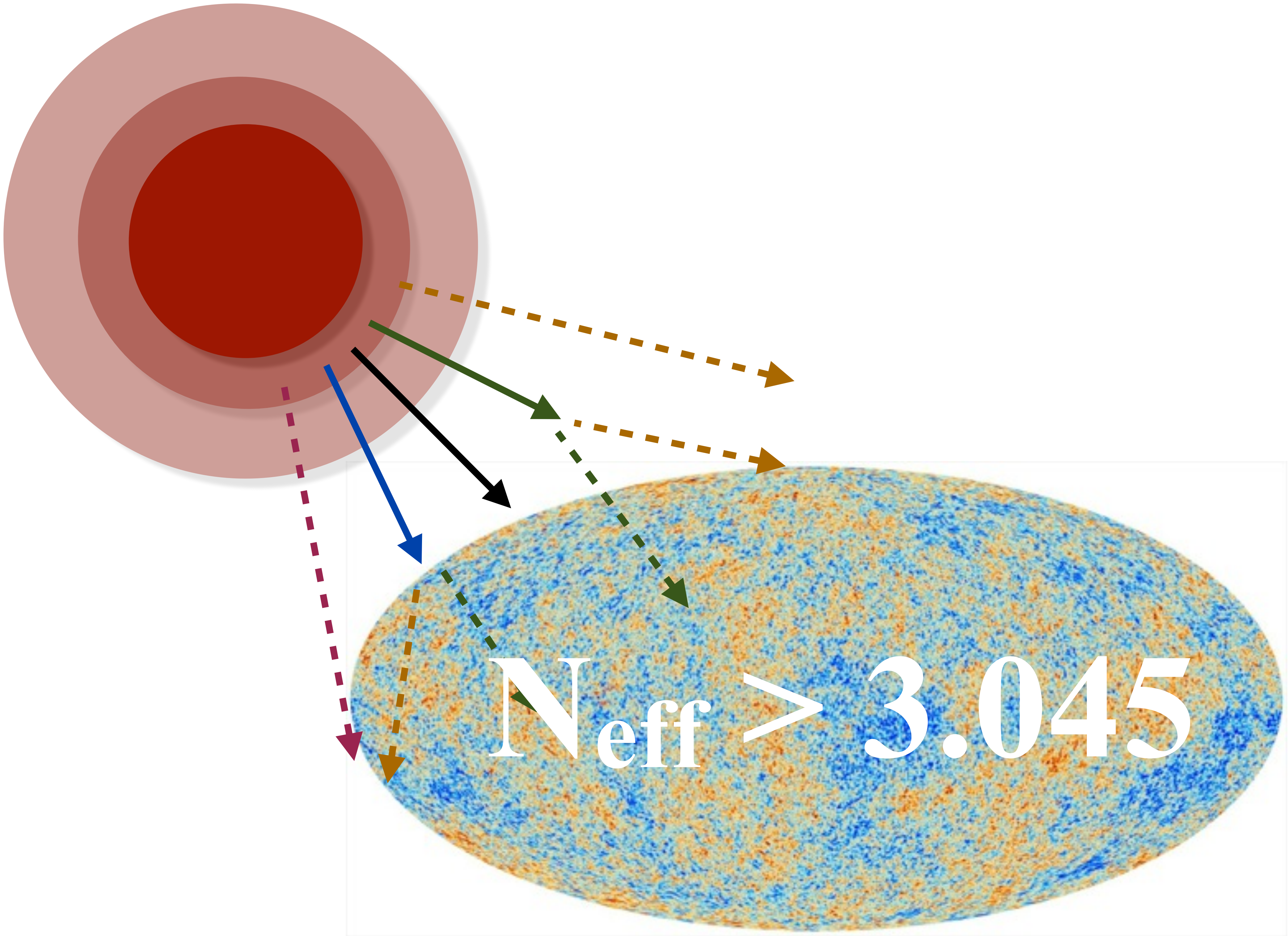
Perfect decoupling : $N_{\rm eff} = 3.$

Imperfect decoupling : $N_{\rm eff} = 3.035$

Imperfect decoupling + QED : $N_{\rm eff} = 3.045$

Salas & Pastor (2016);
Mangano et al. (2005)

Light Relics



Light Relics

Freeze-out is quite universal

$$\Gamma \propto \frac{1}{\Lambda^{2n}} T^{2n+1} \qquad\qquad H \propto T^2$$

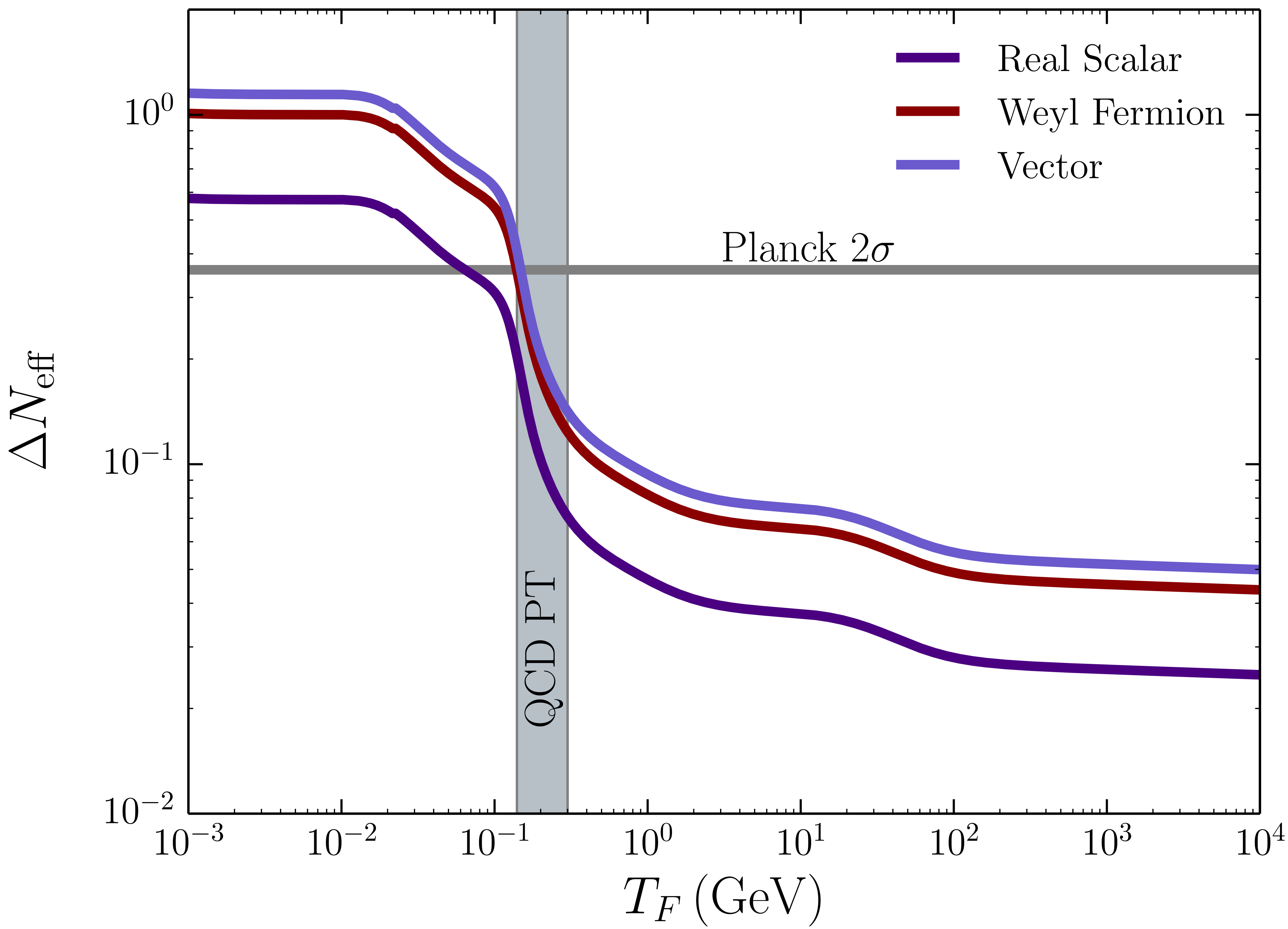
$$H \gg \Gamma \quad \text{for} \quad T < T_F$$

If $T_R > T_F$ then $\Delta N_{\rm eff} = f(T_F)$

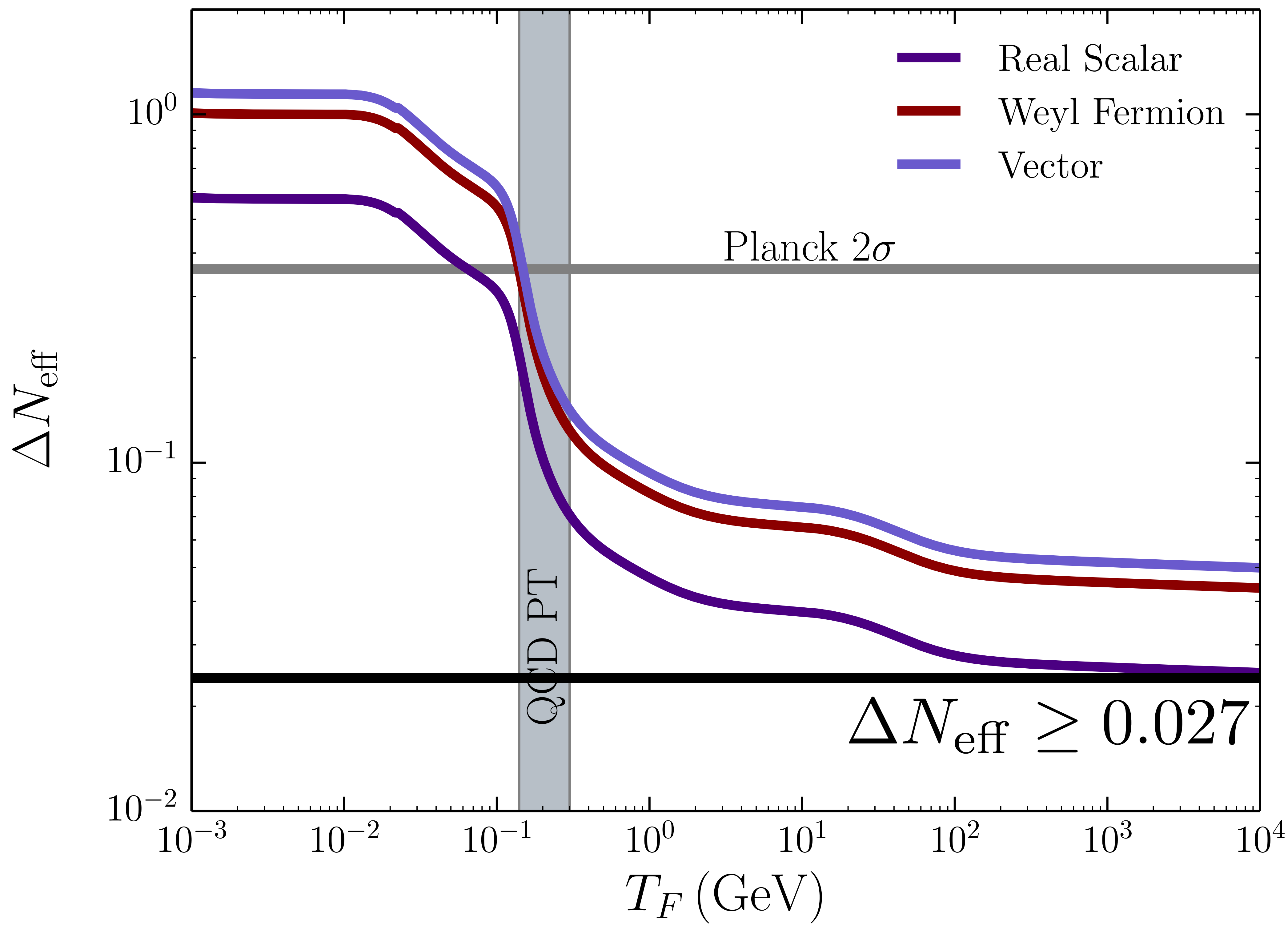
Observable predictions quite model-independent

Depends on spin and freeze-out temperature

Light Relics

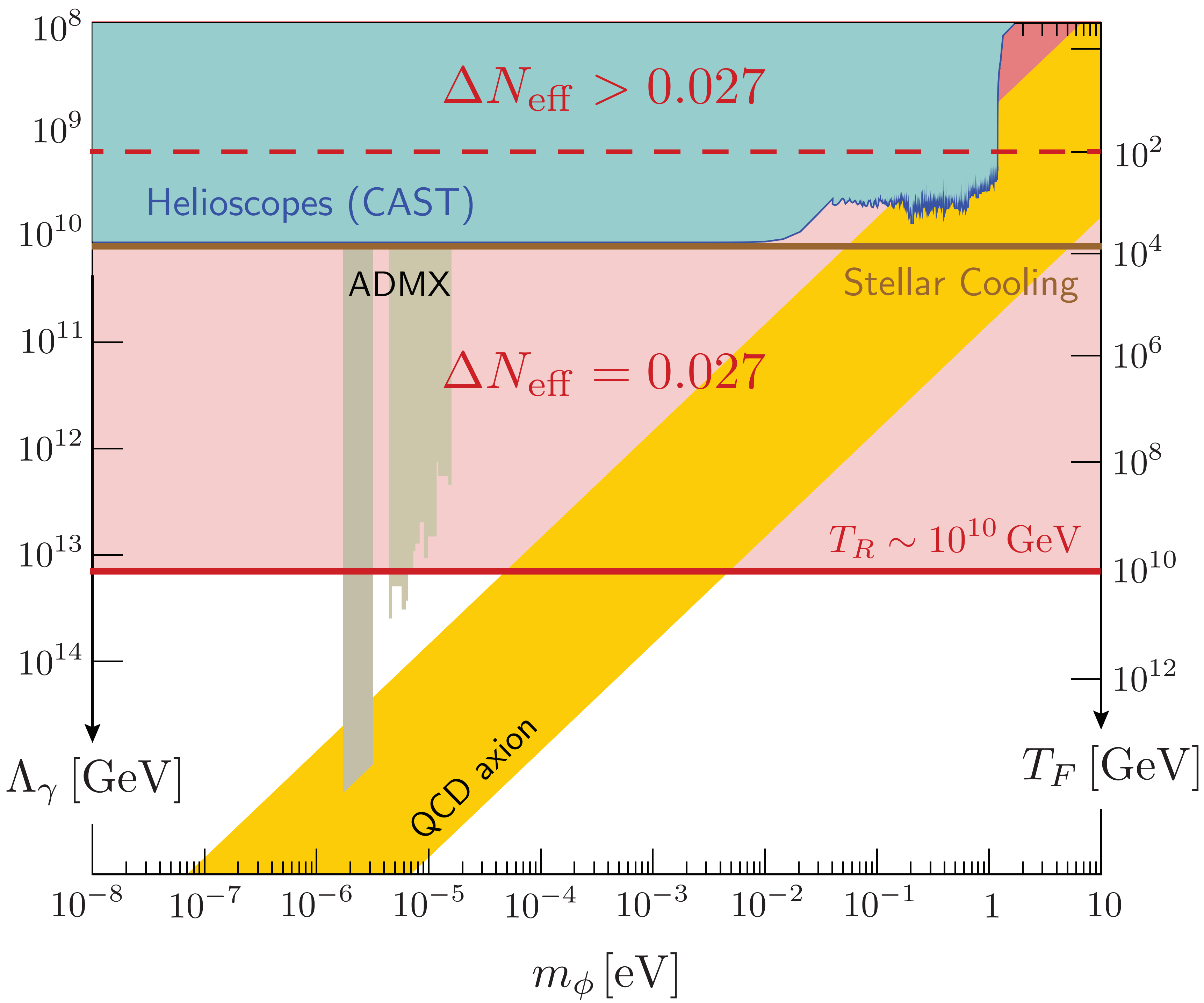


Light Relics



Axions

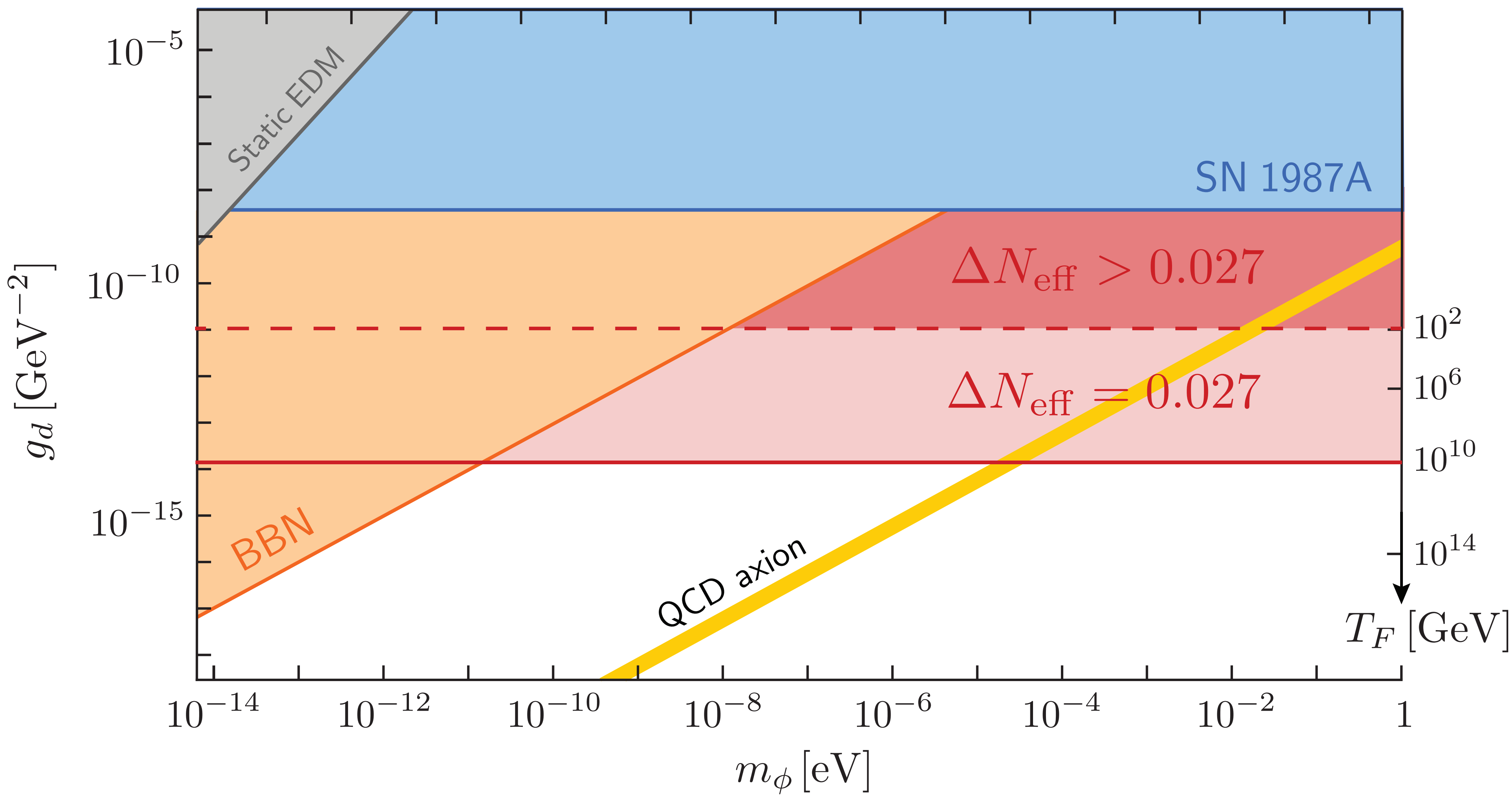
Λ_γ



Baumann, DG & Wallisch (2016)

Axions

$$g_d \sim \frac{10^{-4}}{\text{GeV}} \frac{1}{\Lambda_g}$$



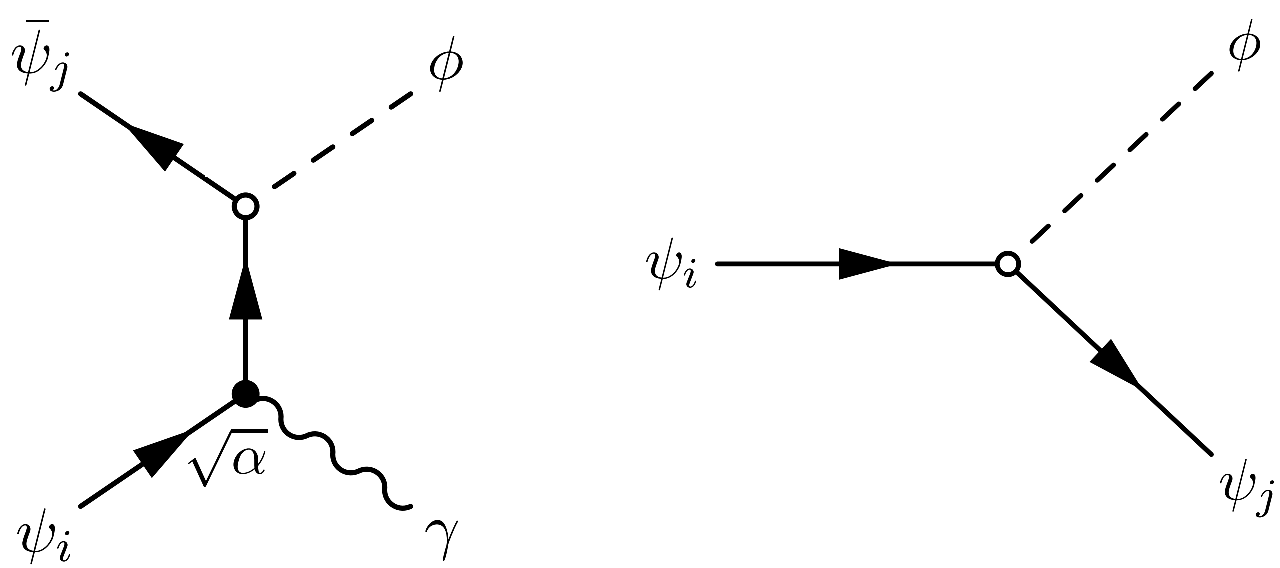
Baumann, DG & Wallisch (2016)

Freeze-in

Freeze-in possible below electro-weak scale

$$\mathcal{L}_\psi \approx \sqrt{2}\frac{(m_i \pm m_j)}{\Lambda_{ij}}\phi\bar{\psi}_i\psi_j$$

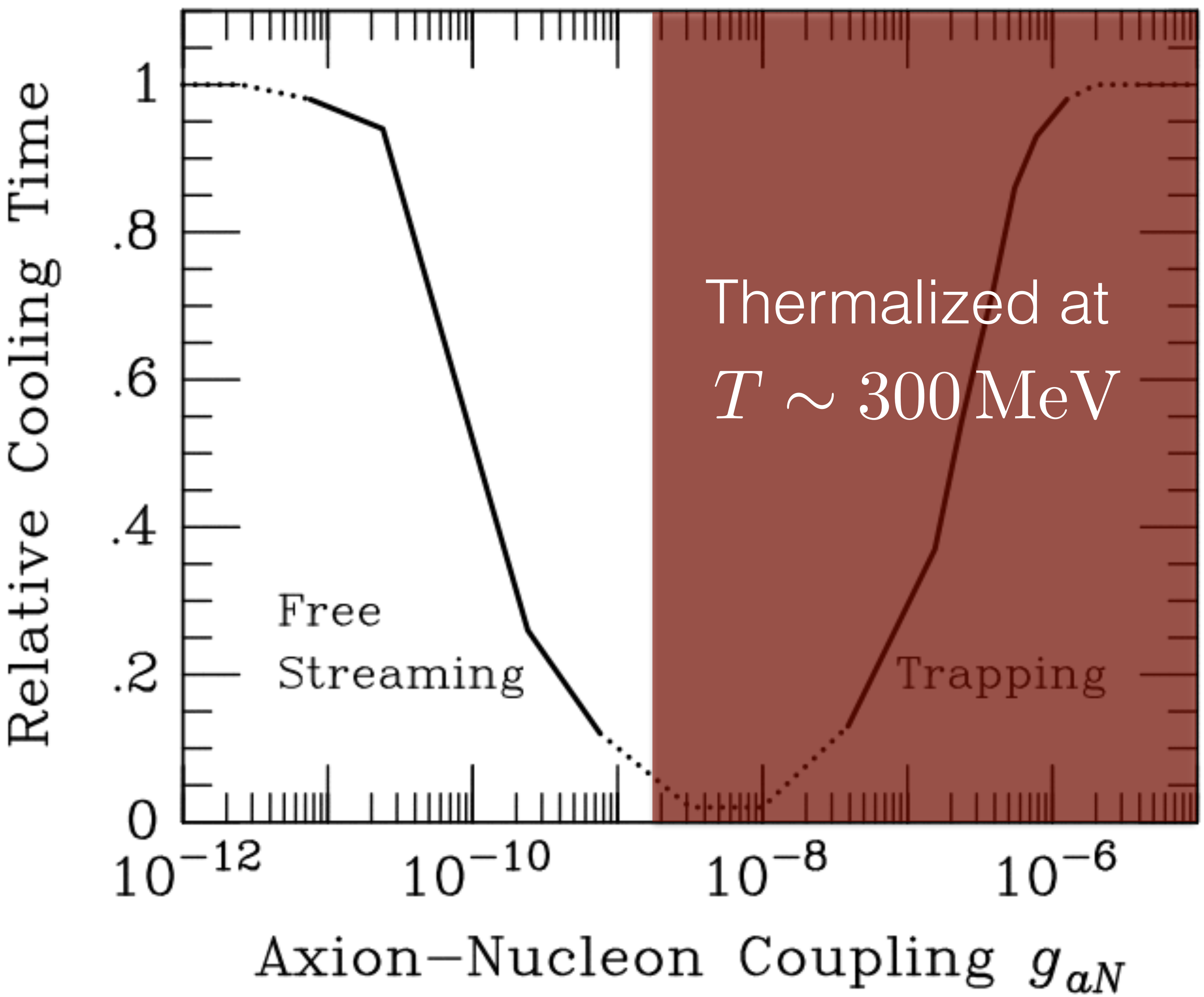
Efficient production at low-temperature



$$\Gamma \propto \frac{m^2}{\Lambda^2}T$$

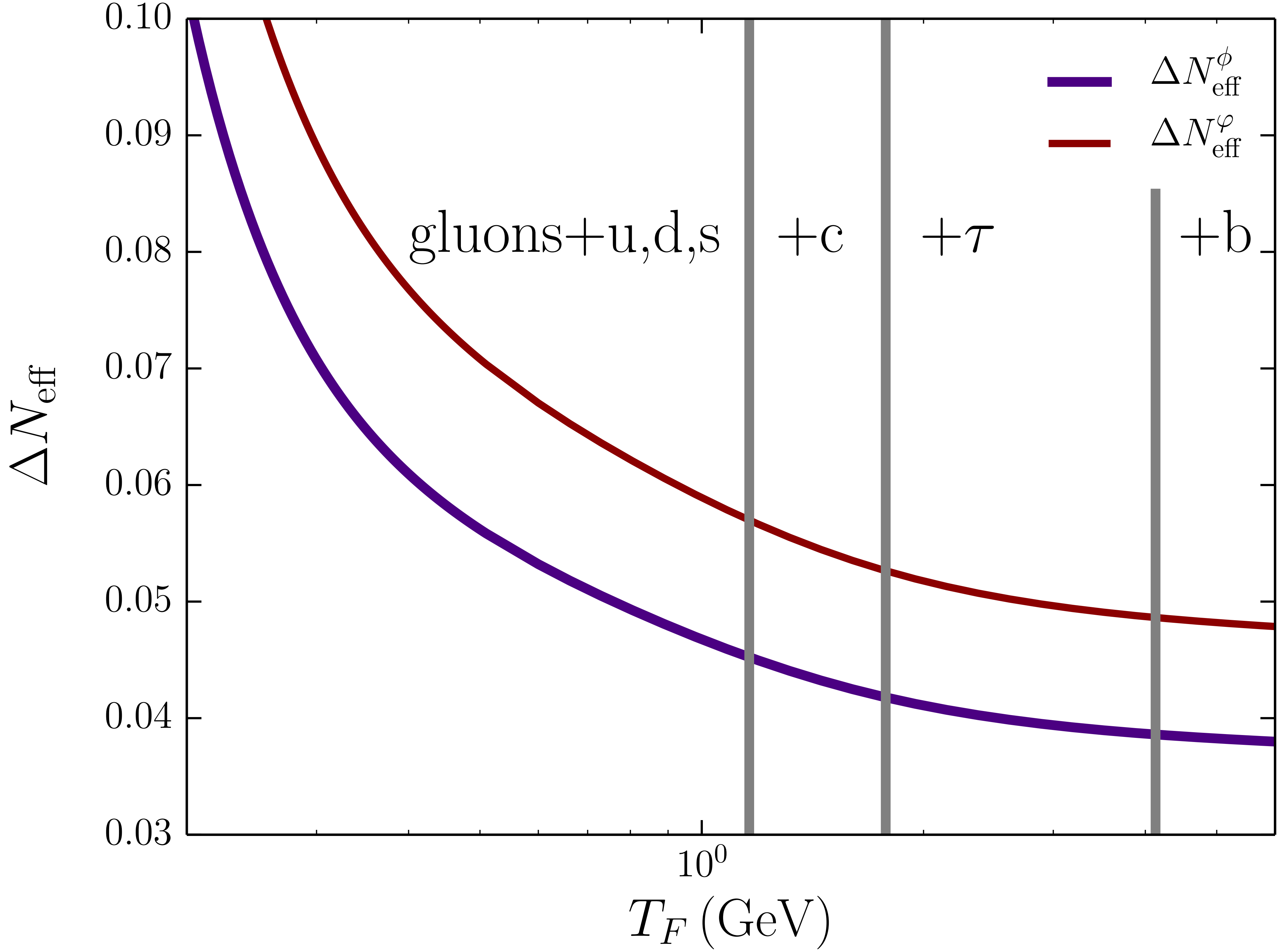
Equilibrium when $m_\psi < T < T_{\rm eq}$

Freeze-in



Relative Cooling Time
1
.8
.6
.4
.2
0
10^{-12}
10^{-10}
10^{-8}
10^{-6}
Axion–Nucleon Coupling g_{aN}
Free Streaming
Trapping
Thermalized at $T \sim 300\,\mathrm{MeV}$

Freeze-in



0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
$\Delta N_{\rm eff}$
$\Delta N_{\rm eff}^{\phi}$
$\Delta N_{\rm eff}^{\varphi}$
gluons+u,d,s
+c
$+\tau$
+b
10^0
T_F (GeV)

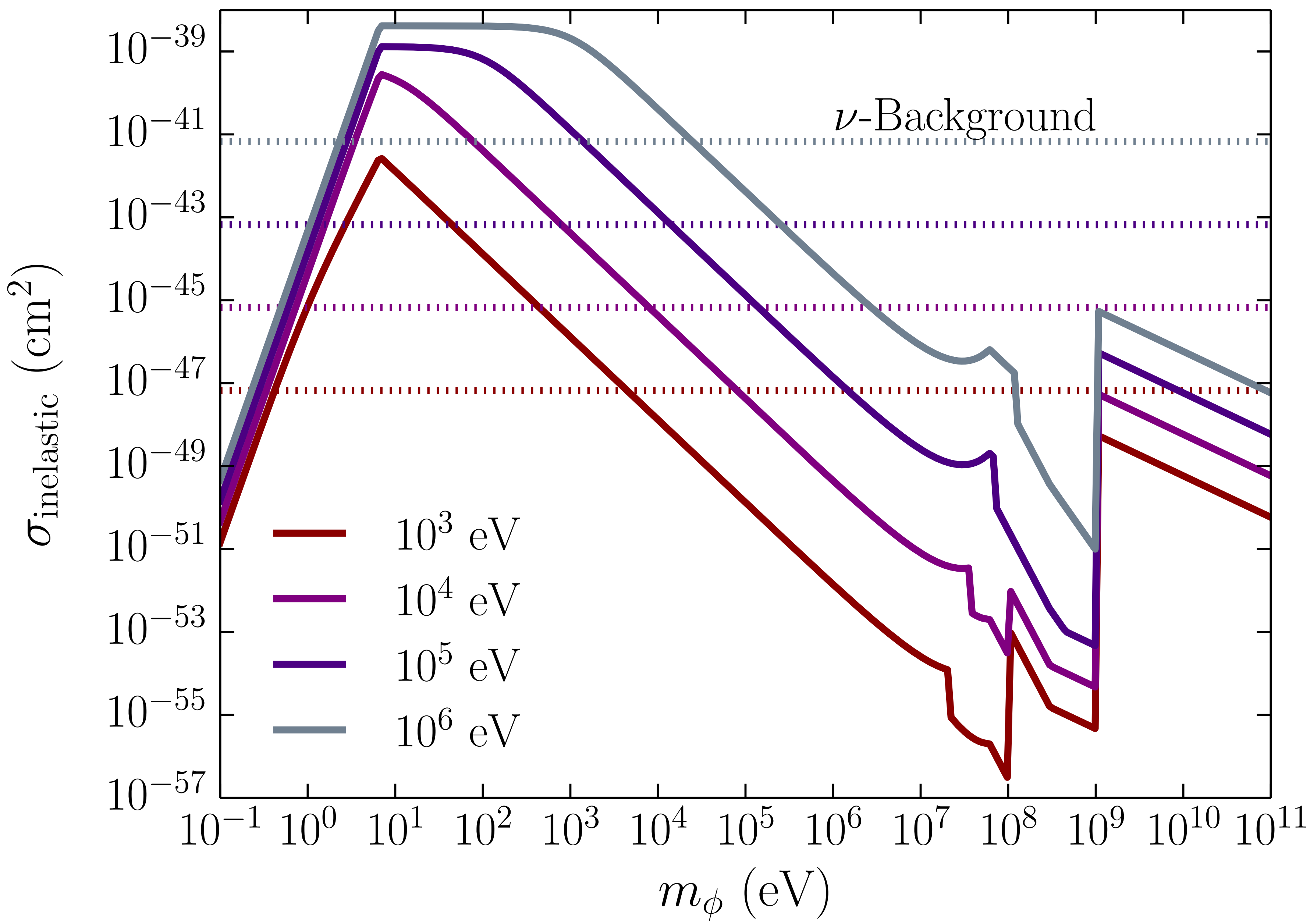
Freeze-in

	Current Constraints		Future CMB Constraints		
Coupling	Bound [GeV]	Origin	Freeze-Out [GeV]	Freeze-In [GeV]	$\Delta \tilde{N}_{\rm eff}$
Λ_{ee}	1.2×10^{10}	White dwarfs	6.0×10^{7}	2.7×10^{6}	1.3
$\Lambda_{\mu\mu}$	2.0×10^{6}	Stellar cooling	1.2×10^{10}	3.4×10^{7}	0.5
$\Lambda_{\tau\tau}$	2.5×10^{4}	Stellar cooling	2.1×10^{11}	9.5×10^{7}	0.05
Λ_{bb}	6.1×10^{5}	Stellar cooling	9.5×10^{11}	–	0.04
Λ_{tt}	1.2×10^{9}	Stellar cooling	3.5×10^{13}	–	0.03
$\Lambda_{\mu e}^{V}$	5.5×10^{9}	$\mu^+ \to e^+ \phi$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\mu e}$	3.1×10^{9}	$\mu^+ \to e^+ \phi \gamma$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\tau e}$	4.4×10^{6}	$\tau^- \to e^- \phi$	1.0×10^{11}	1.3×10^{8}	0.05
$\Lambda_{\tau\mu}$	3.2×10^{6}	$\tau^- \to \mu^- \phi$	1.0×10^{11}	1.3×10^{8}	0.05
Λ_{cu}^{A}	6.9×10^{5}	D^0-$\bar{D}^0$	1.3×10^{11}	2.0×10^{8}	0.05
Λ_{bd}^{A}	6.4×10^{5}	B^0-$\bar{B}^0$	4.8×10^{11}	3.7×10^{8}	0.04
Λ_{bs}	6.1×10^{7}	$b \to s\phi$	4.8×10^{11}	3.7×10^{8}	0.04
Λ_{tu}	6.6×10^{9}	Mixing	1.8×10^{13}	2.1×10^{9}	0.03
Λ_{tc}	2.2×10^{9}	Mixing	1.8×10^{13}	2.1×10^{9}	0.03

Baumann, DG & Wallisch (2016)

Freeze-in

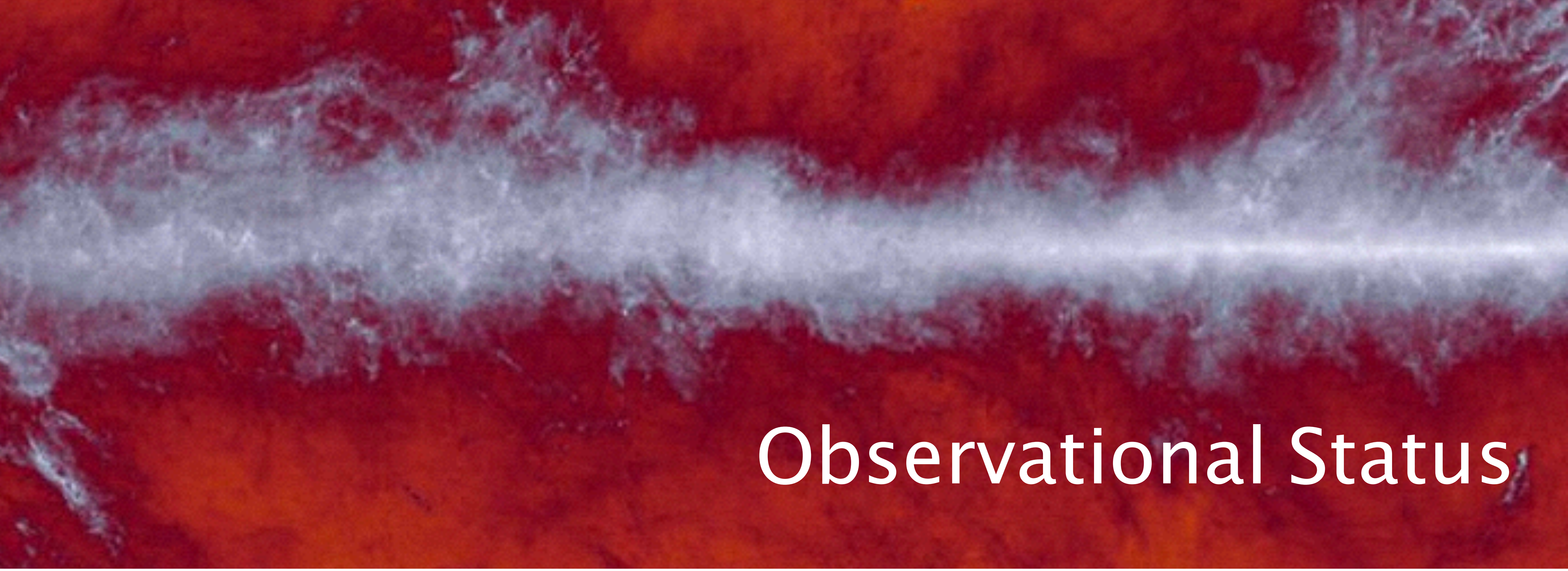
DM cross-section with nuclei



Upper limits assuming

$$\Delta N_{\text{eff}} < 0.09$$

DG & Rajendran (2016)



Observational Status

CMB

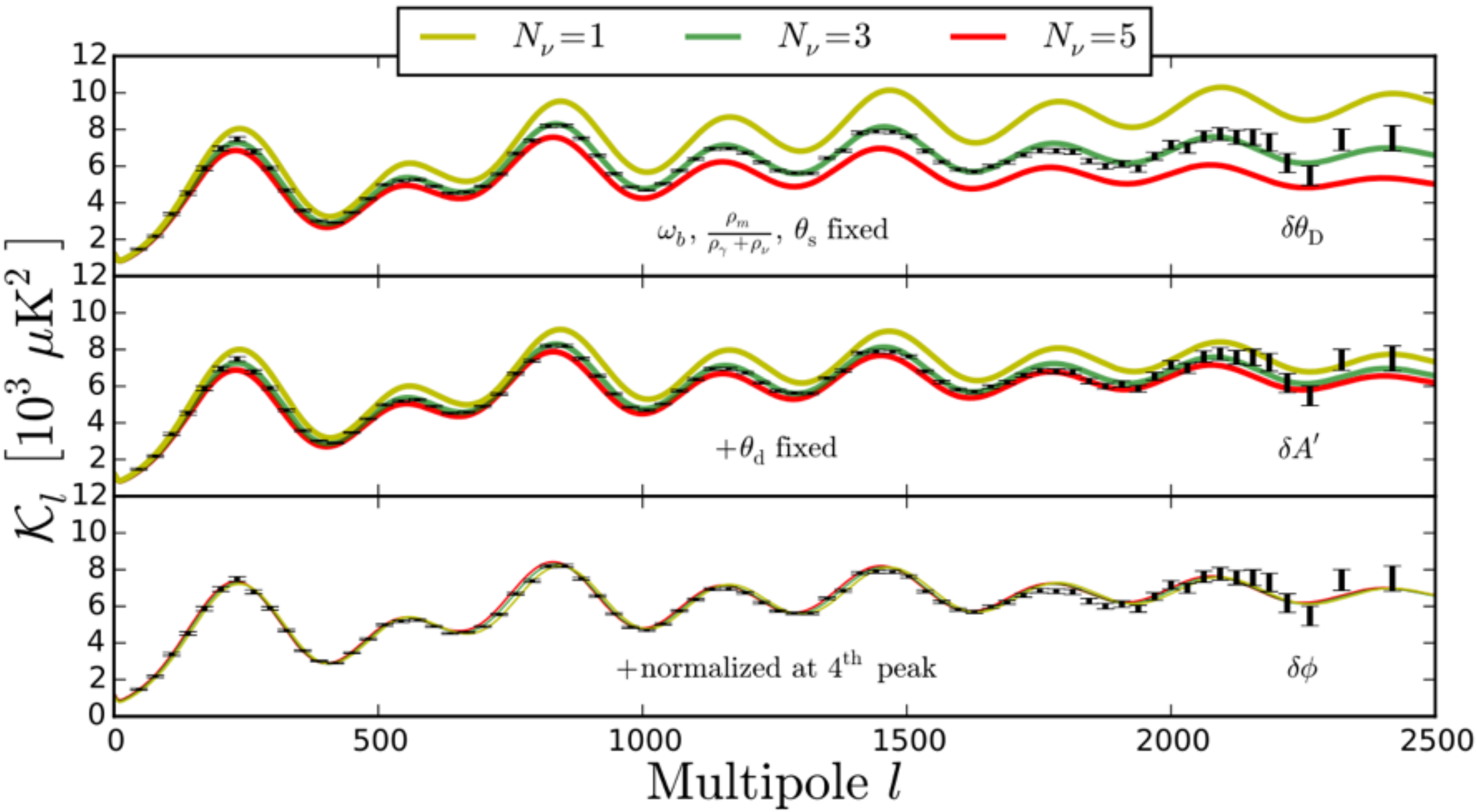
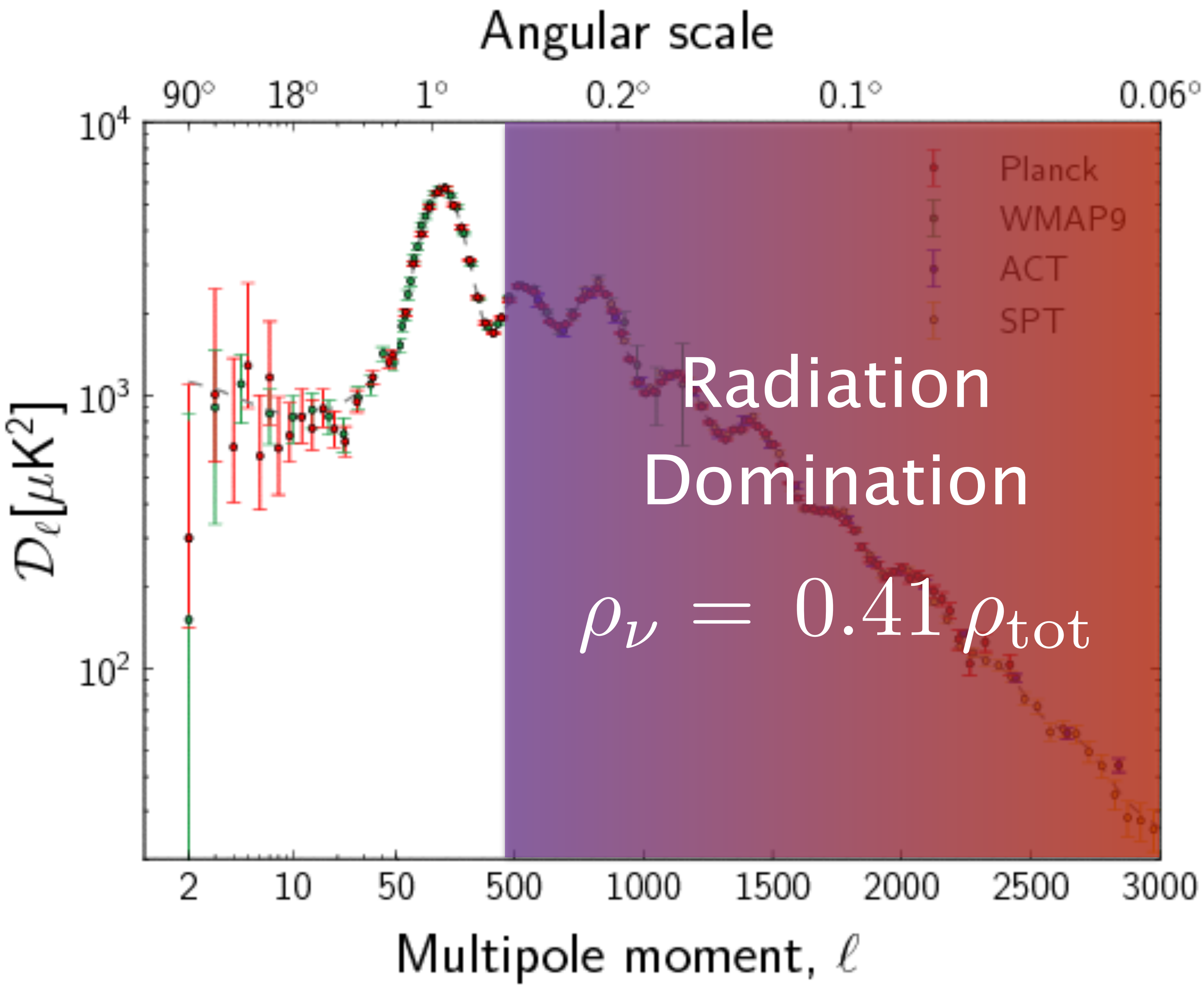


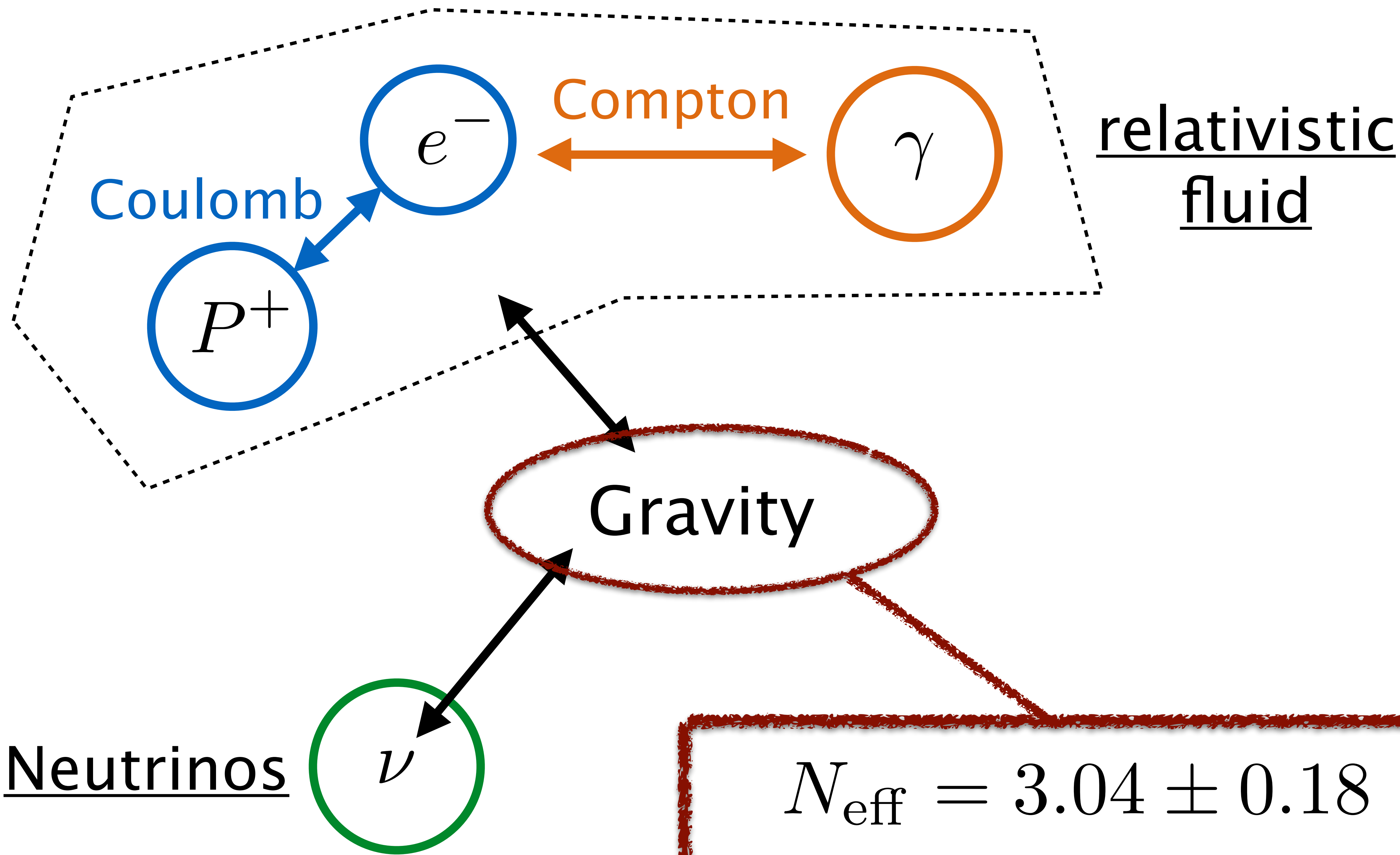
Image from Follin et al. (2015)

CMB



Angular scale
90°
18°
1°
0.2°
0.1°
0.06°
10^4
10^3
10^2
$\mathcal{D}_\ell[\mu K^2]$
Planck
WMAP9
ACT
SPT
Radiation
Domination
$\rho_\nu = 0.41\,\rho_{\rm tot}$
2
10
50
500
1000
1500
2000
2500
3000
Multipole moment, ℓ

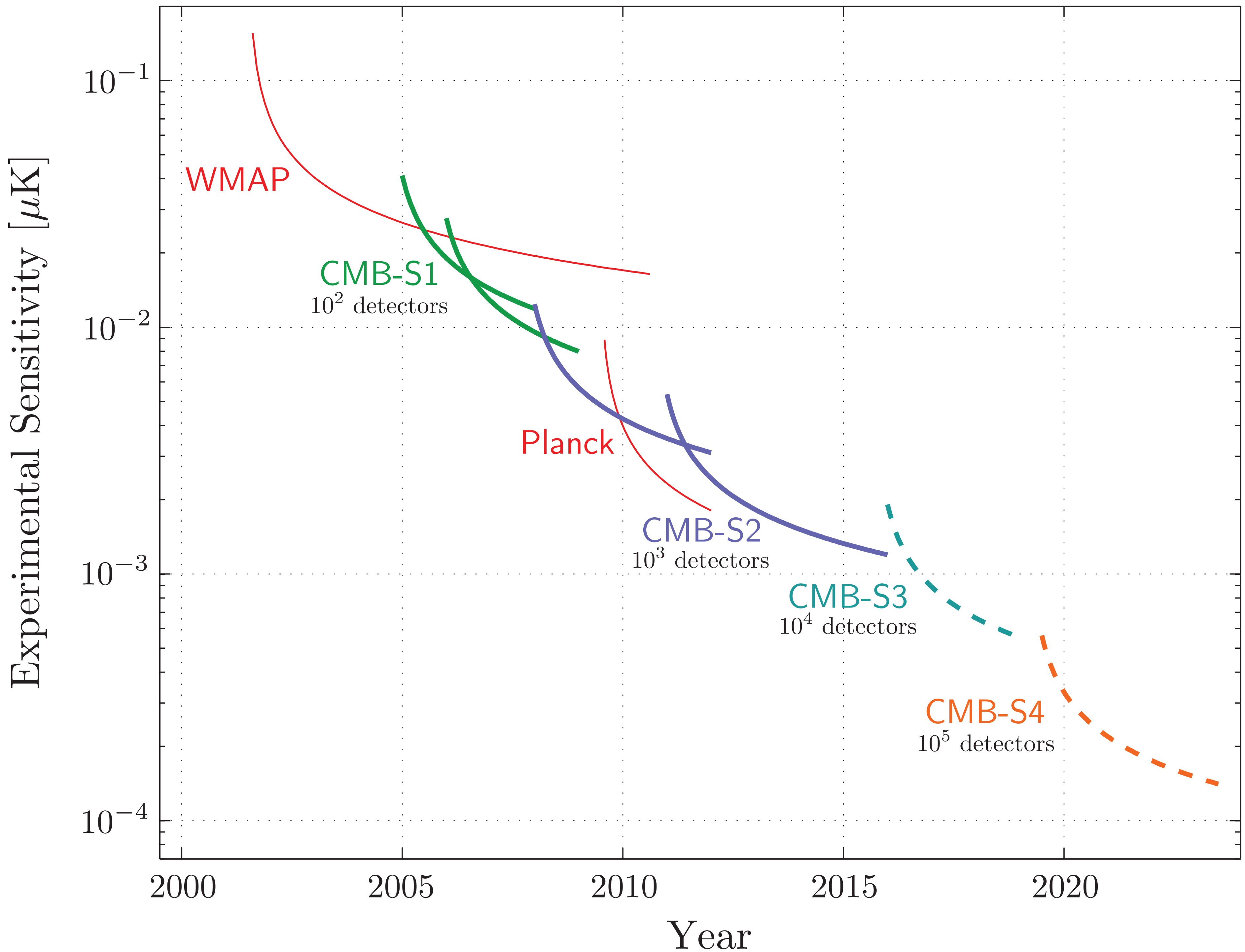
CMB



$$N_{\rm eff} = 3.04 \pm 0.18$$

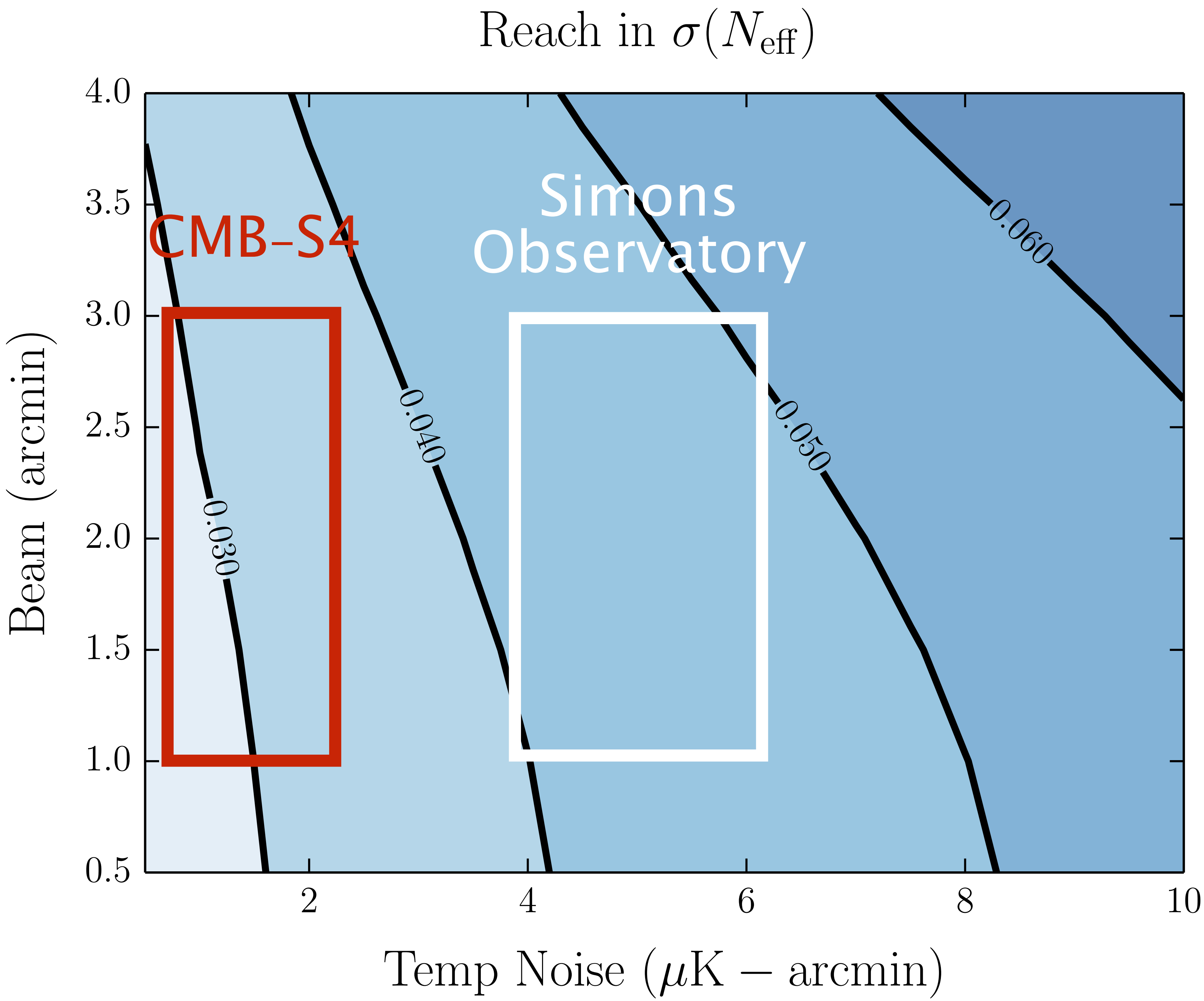
Planck collaboration (2015)

CMB



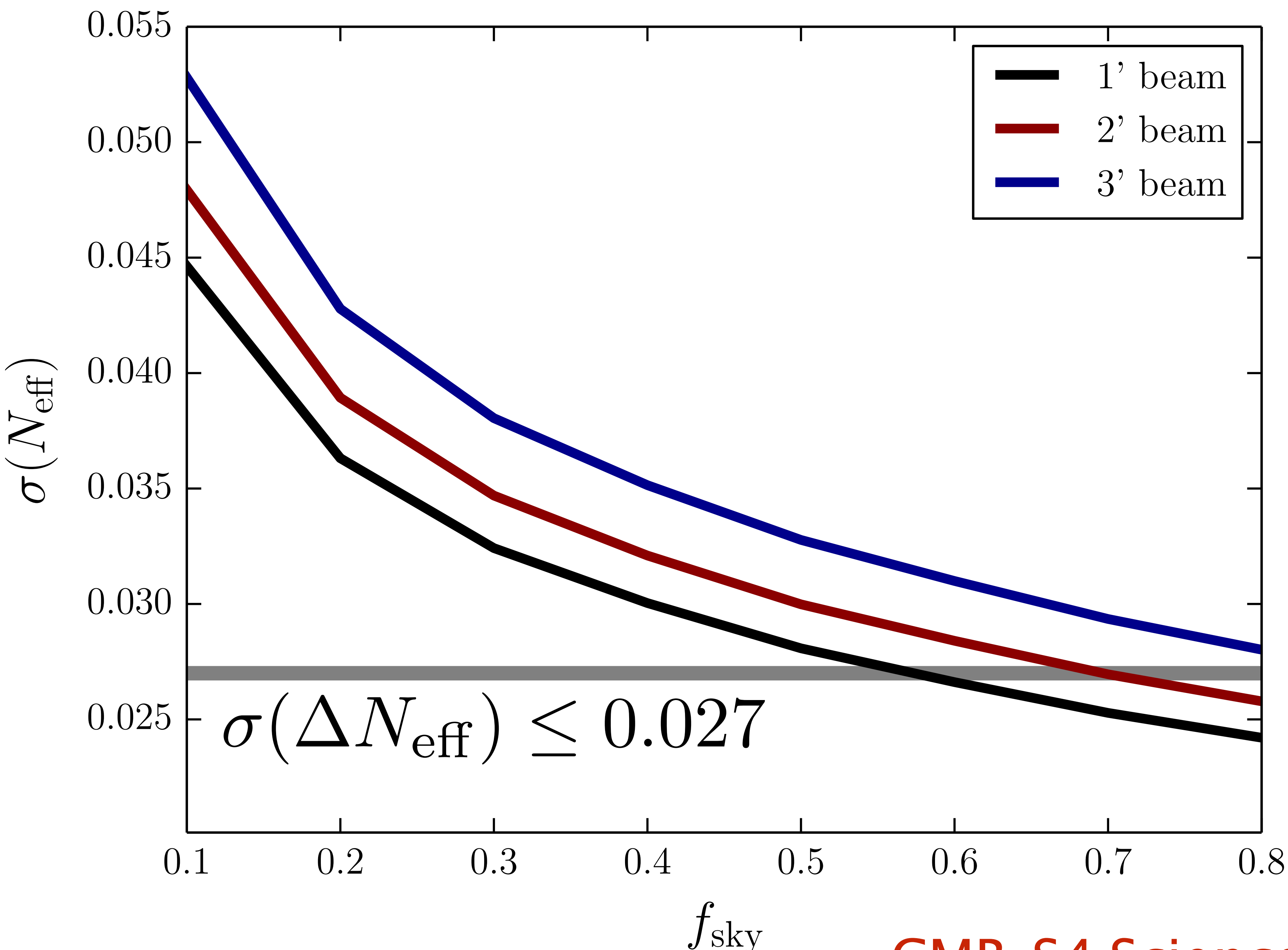
Experimental Sensitivity [μK]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
WMAP
CMB-S1
10^2 detectors
Planck
CMB-S2
10^3 detectors
CMB-S3
10^4 detectors
CMB-S4
10^5 detectors
2000
2005
2010
2015
2020
Year

CMB



Reach in $\sigma(N_{\rm eff})$
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
2
4
6
8
10
Beam (arcmin)
Temp Noise (μK − arcmin)
CMB-S4
Simons
Observatory
0.030
0.040
0.050
0.060

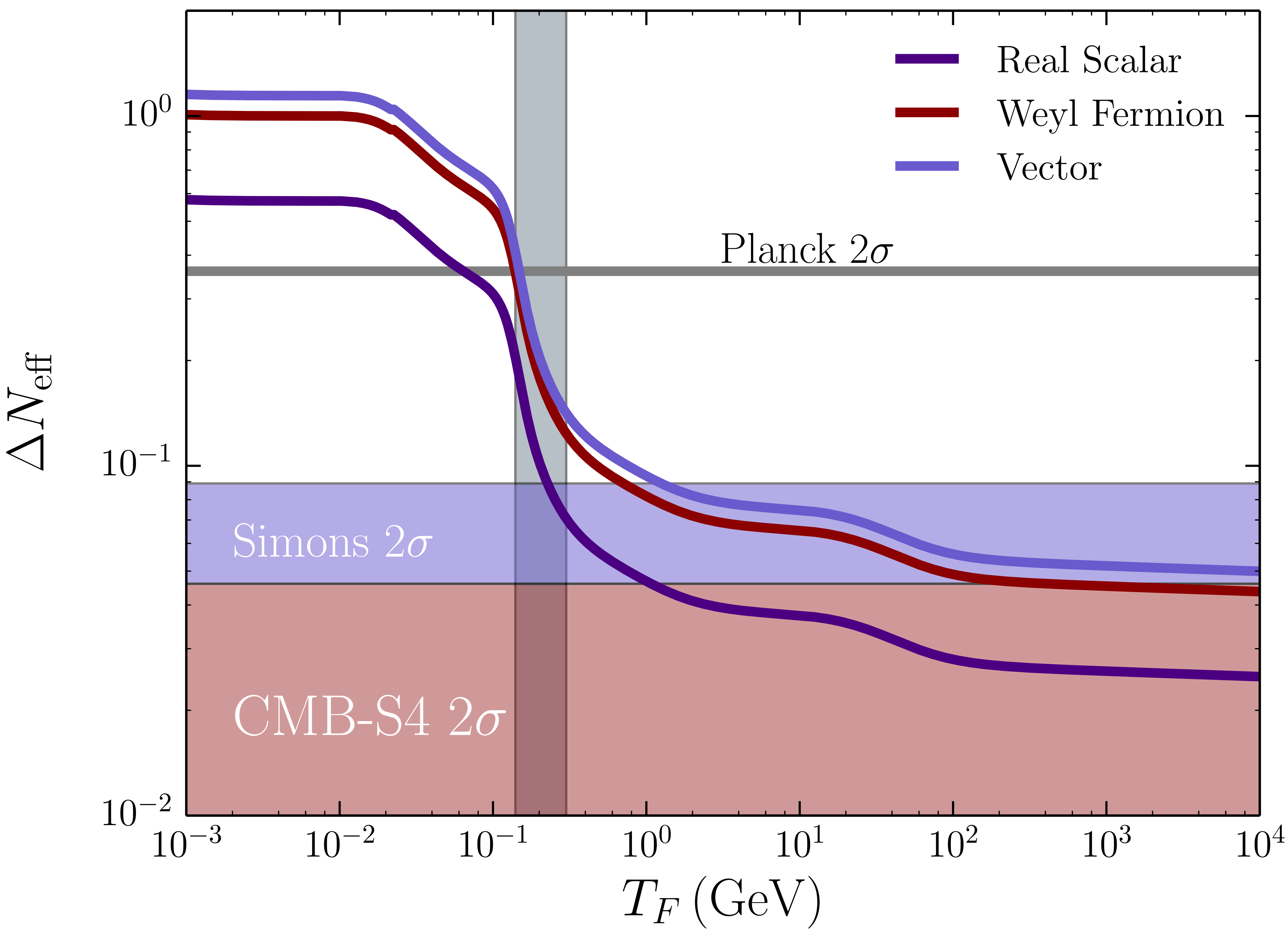
CMB



CMB-S4 Science Book

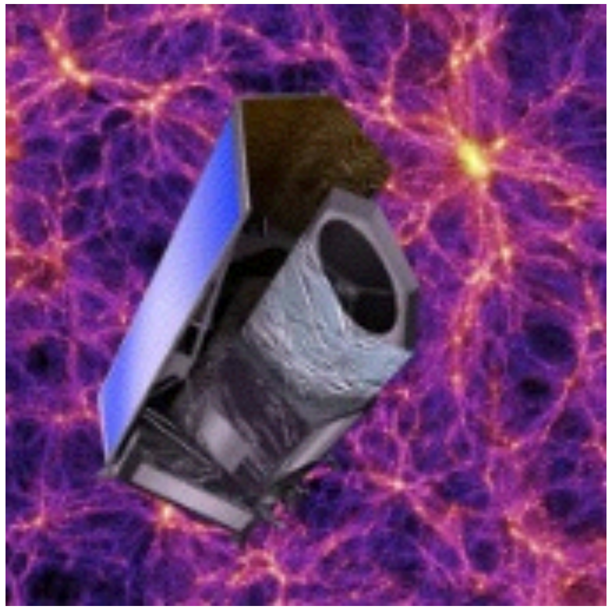
DG, Meyers & van Engelen (2016)

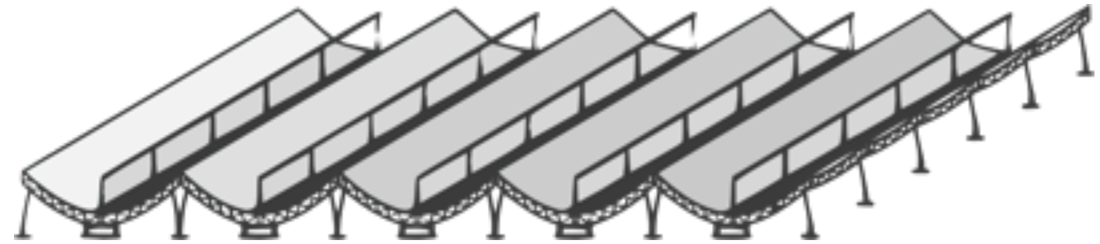
CMB

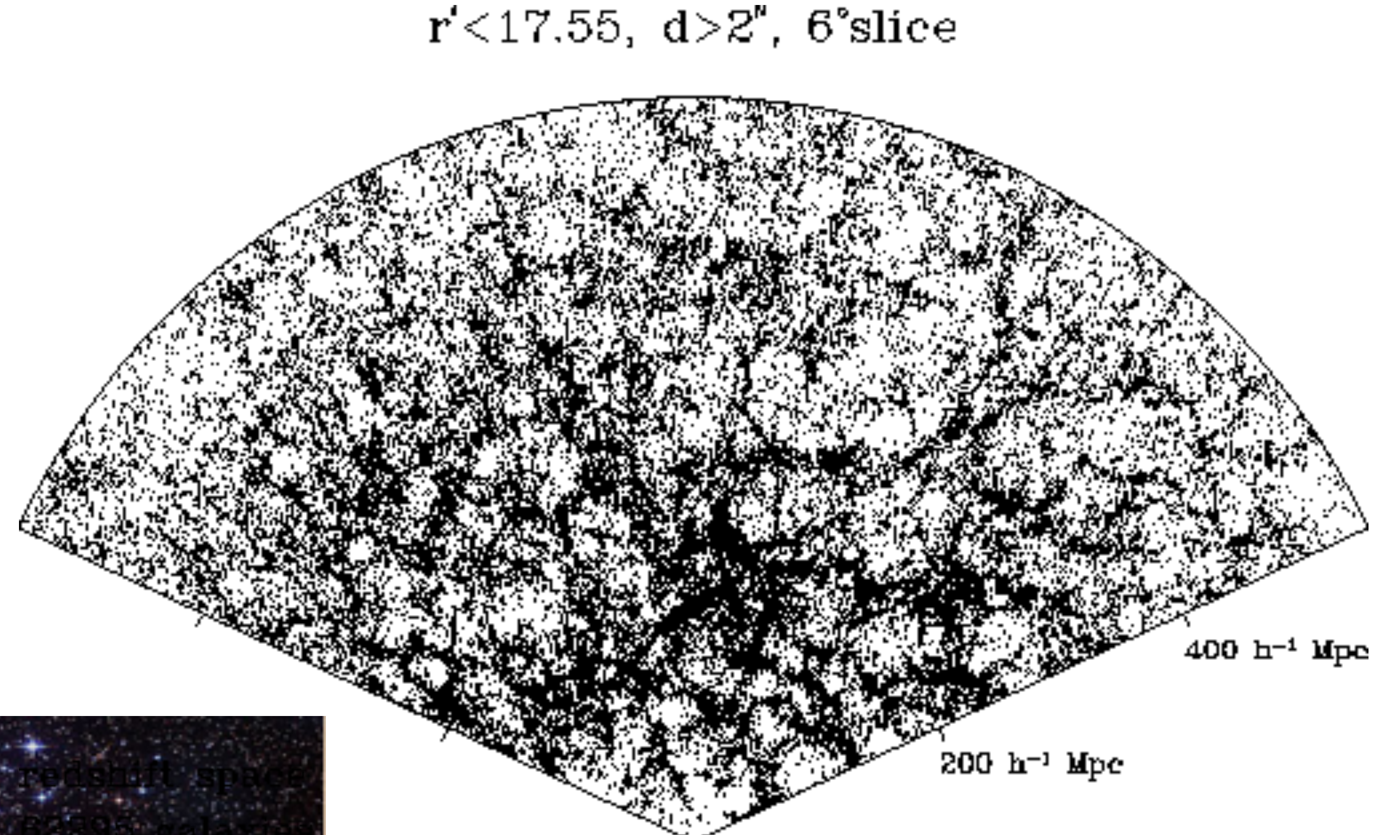


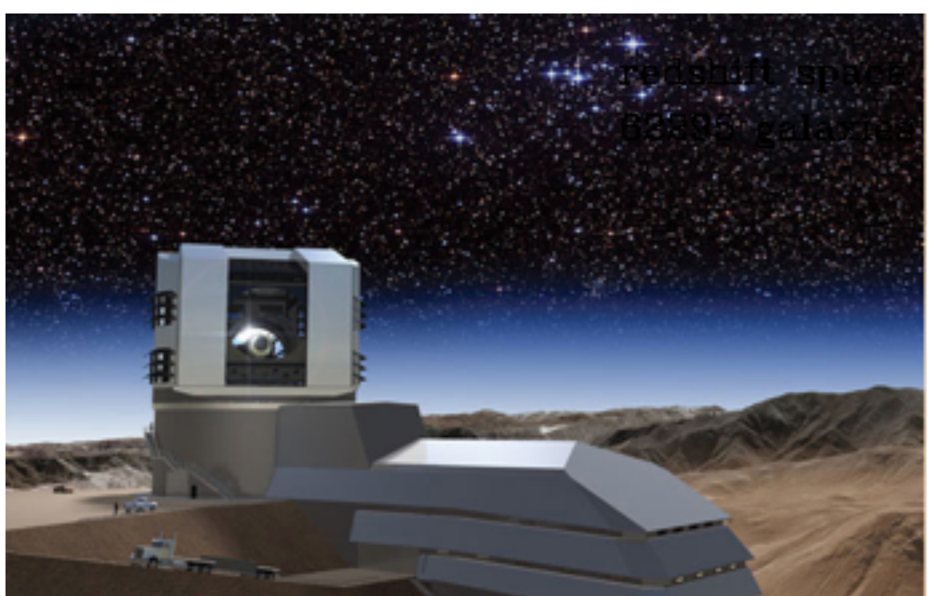
Real Scalar
Weyl Fermion
Vector
Planck 2σ
Simons 2σ
CMB-S4 2σ
$\Delta N_{\rm eff}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T_F (GeV)

Large Scale Structure (BAO)









BAO

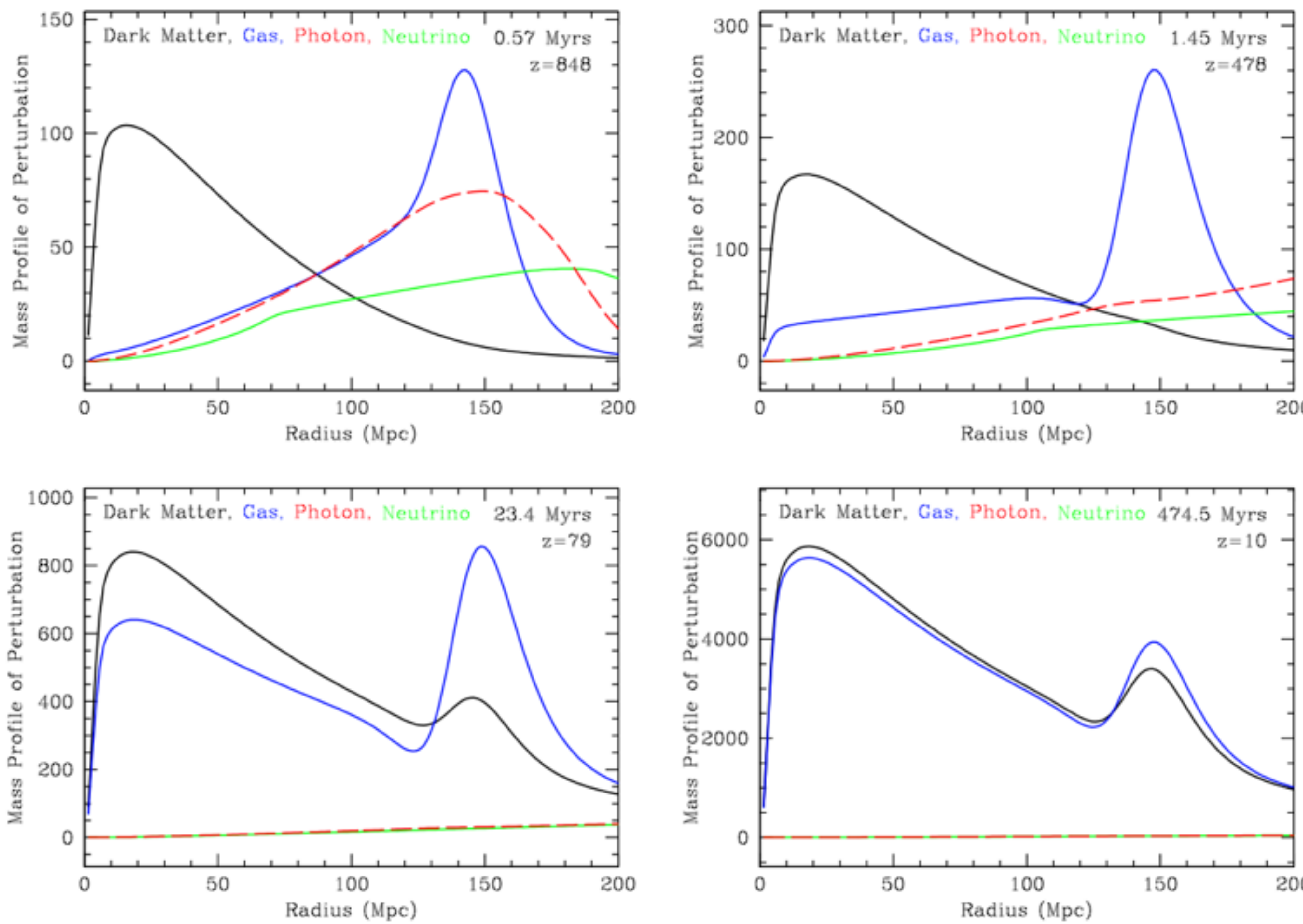
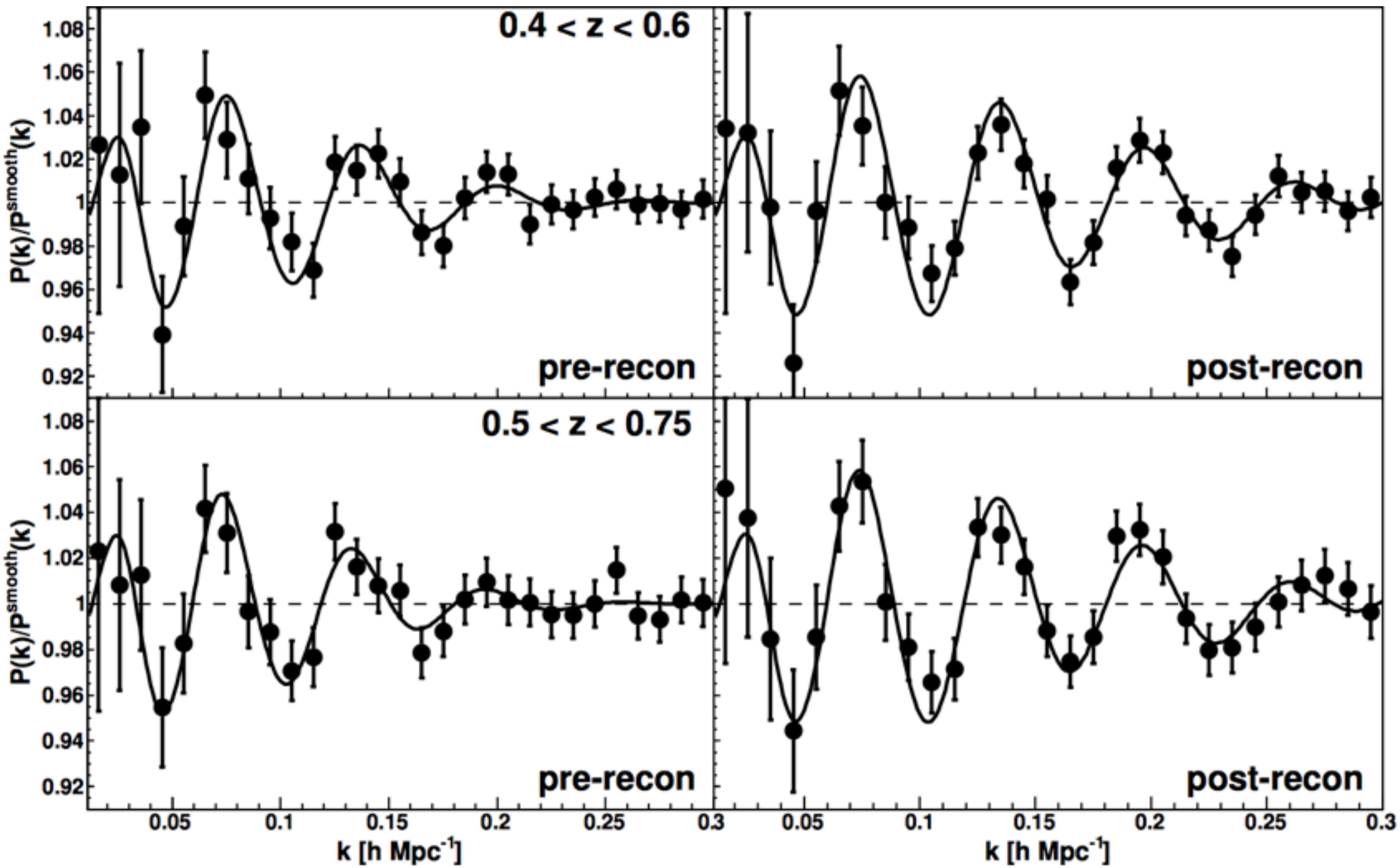


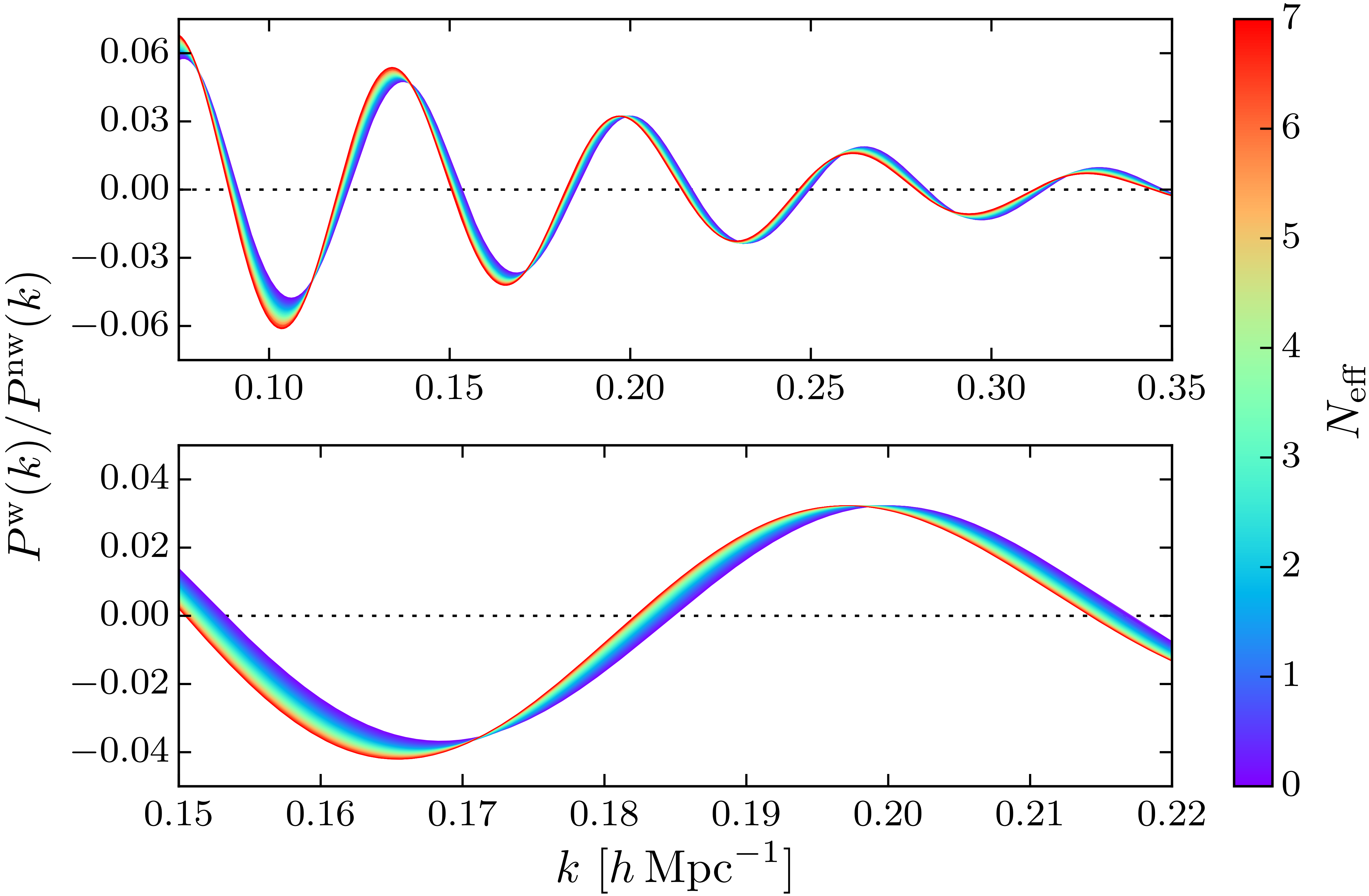
Image from Eisenstein et al. (2006)

BAO



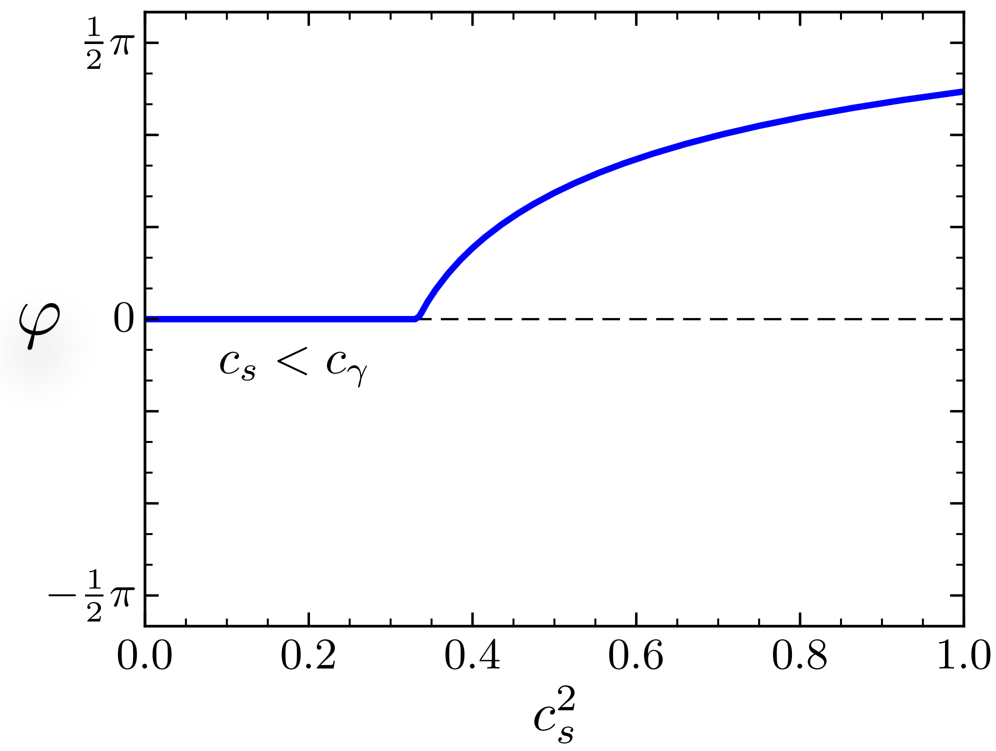
BOSS (Beutler et al.) (2016)

BAO



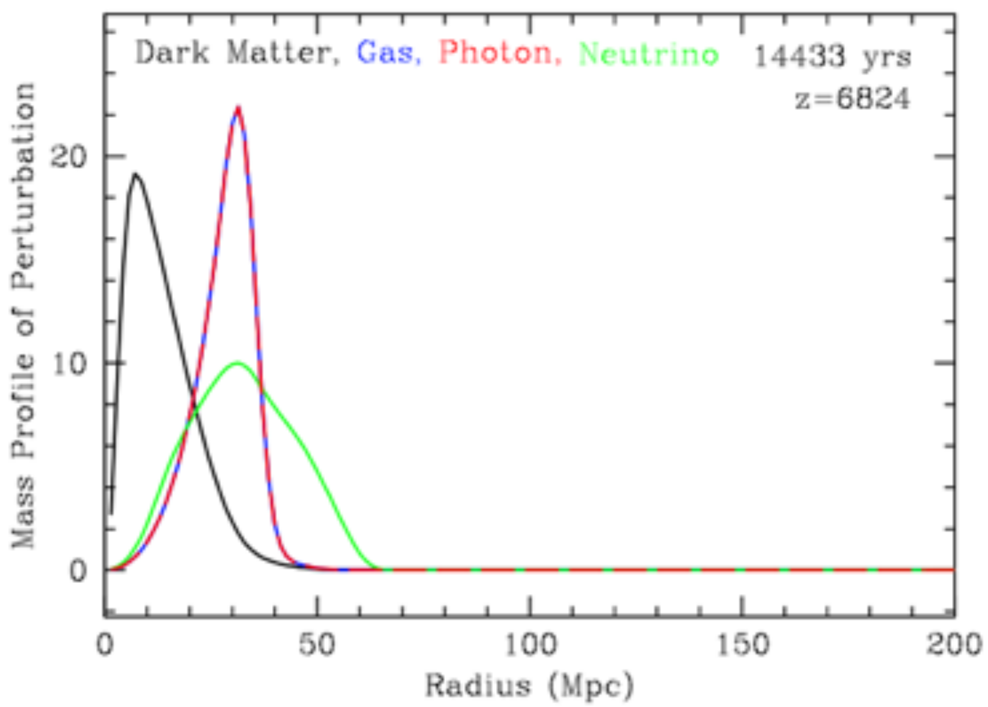
Baumann, DG & Zaldarriaga (2016)

BAO



$$\delta^w_{\vec{k}} \propto \zeta_{\vec{k}} \sin(k r_s + \varphi)$$

Bashinsky & Seljak (2003)
Baumann, DG, Meyers & Wallisch (2015)



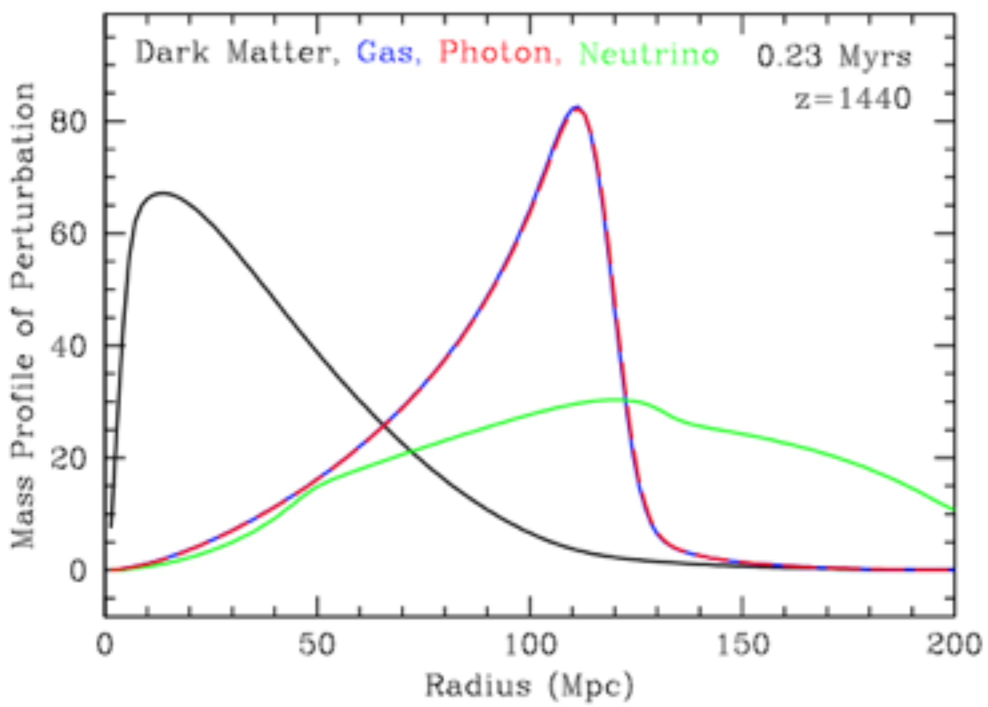


Image from Eisenstein et al. (2006)

BAO

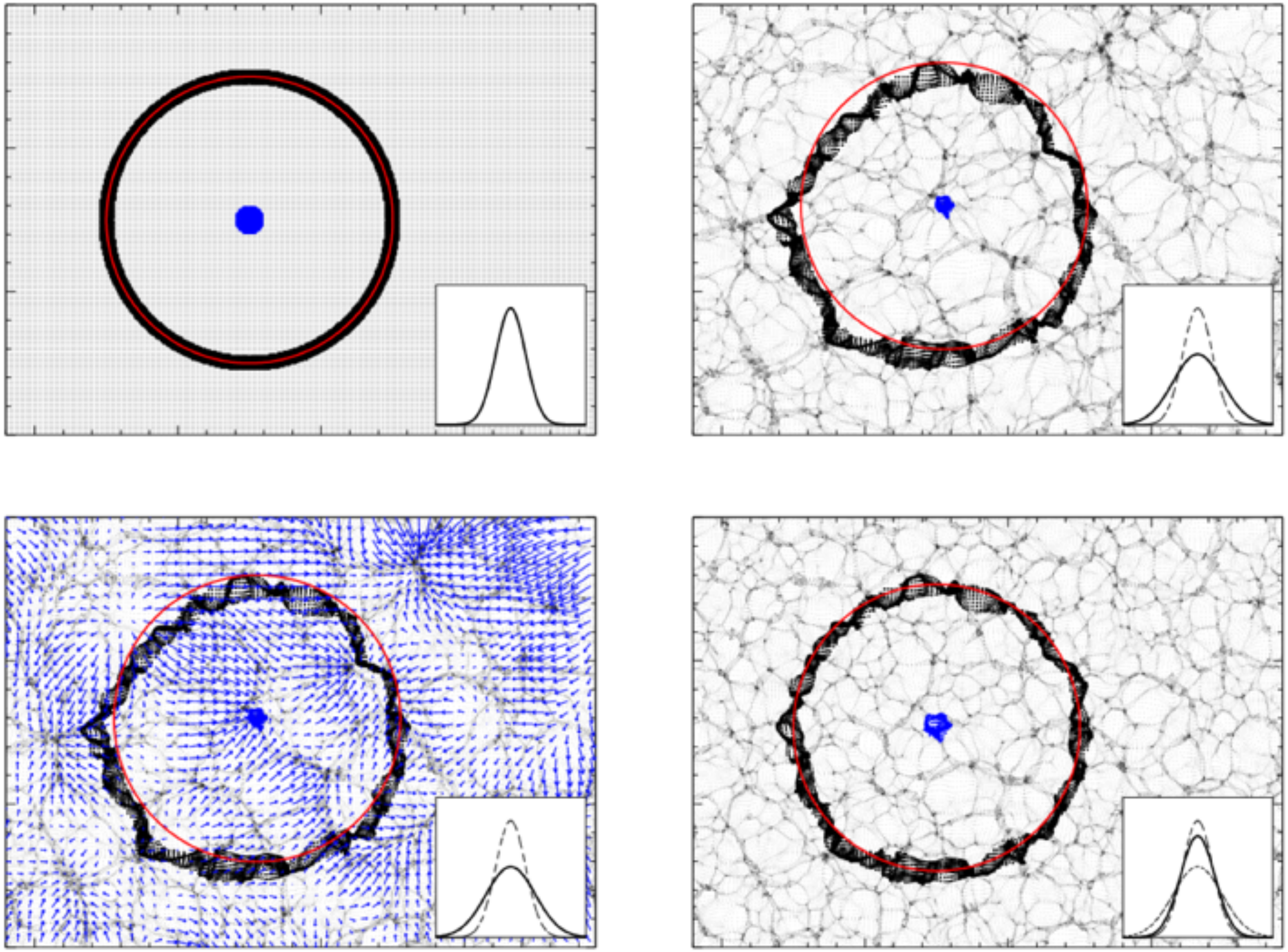
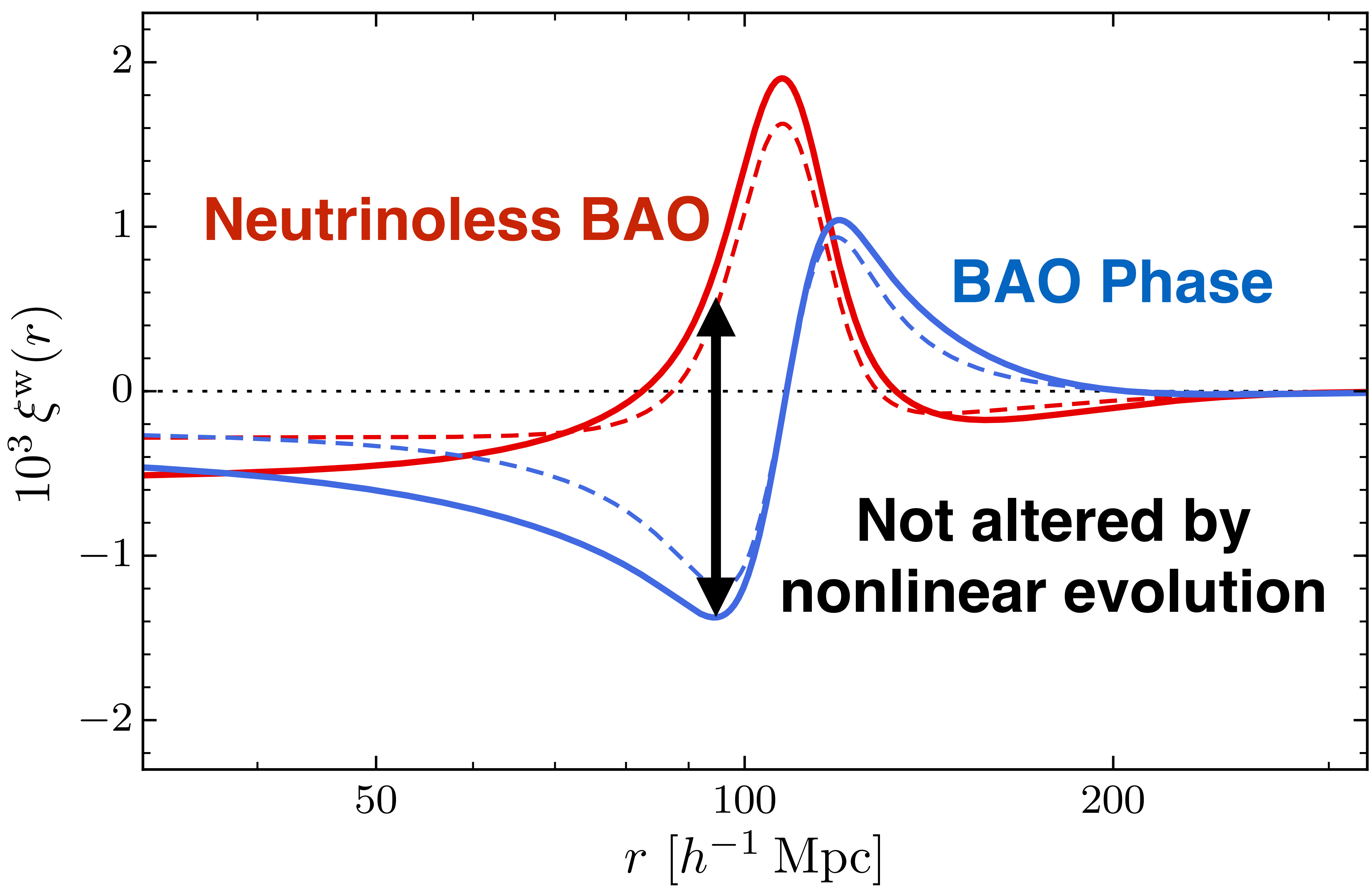


Image from Padmanabhan et al. (2012)

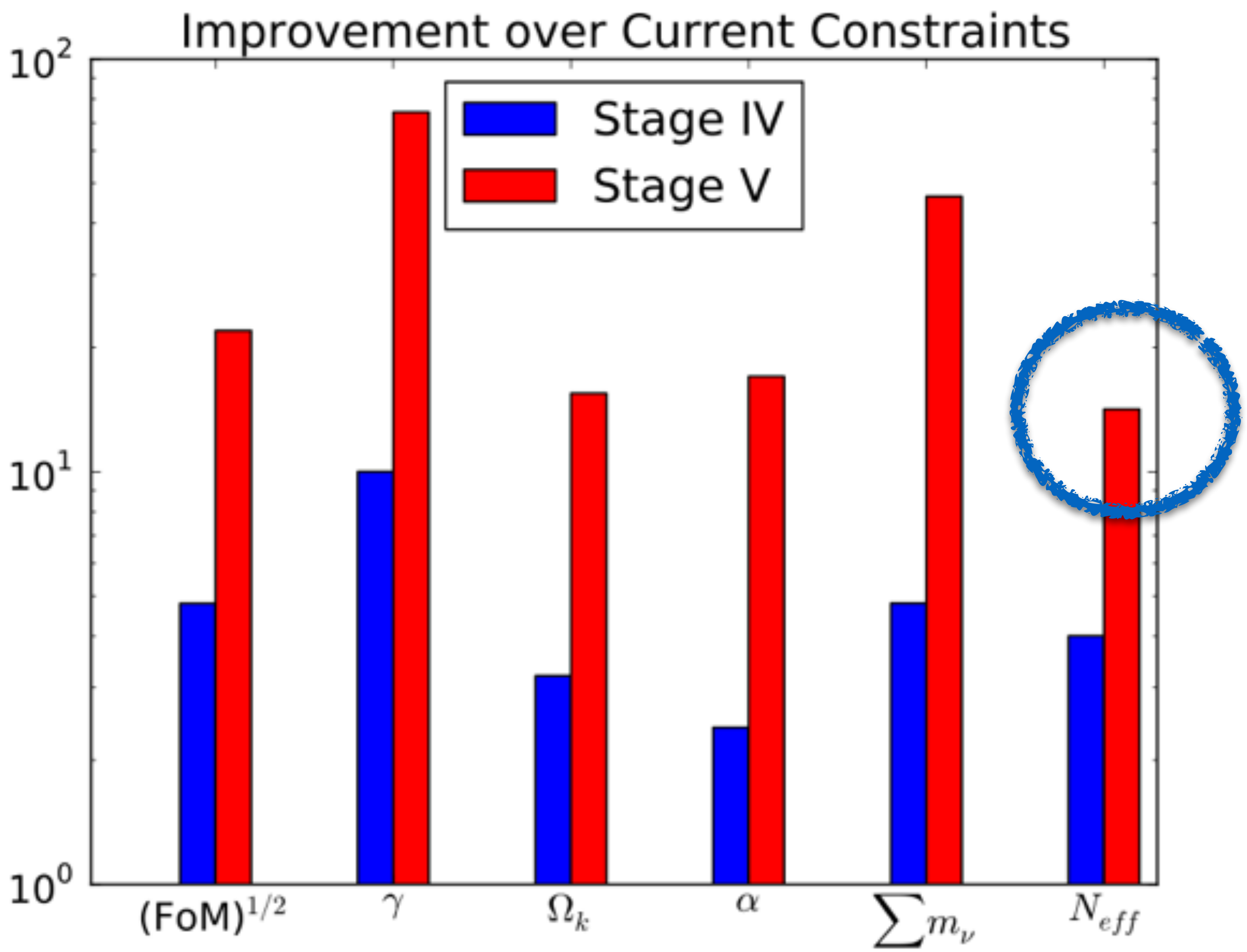
BAO



Baumann, DG & Zaldarriaga (2016)

BAO

Stage V / BOA — ‘Spectroscopic LSST’



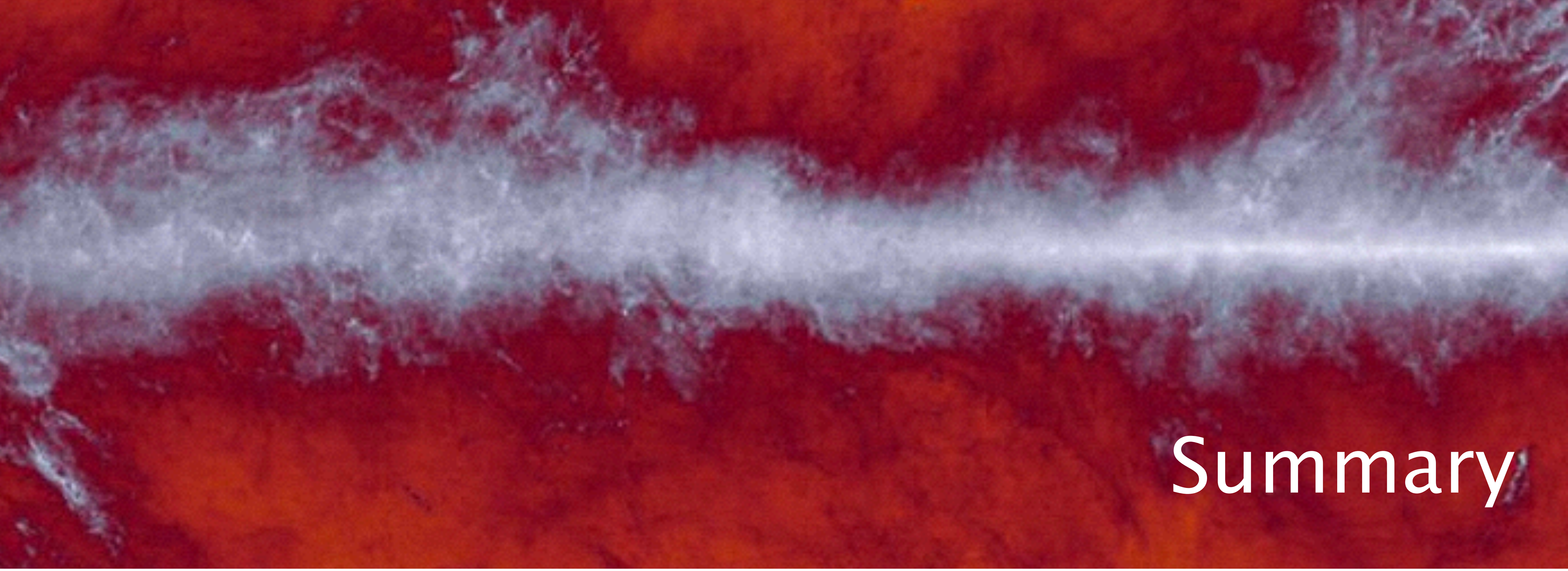
$$\sigma(N_{\rm eff}) = \mathcal{O}(10^{-2})$$

$$V \approx 100\,(h^{-1}\,\mathrm{Gpc}\,)^3$$

$$N_{\rm obj} \approx 10^9$$

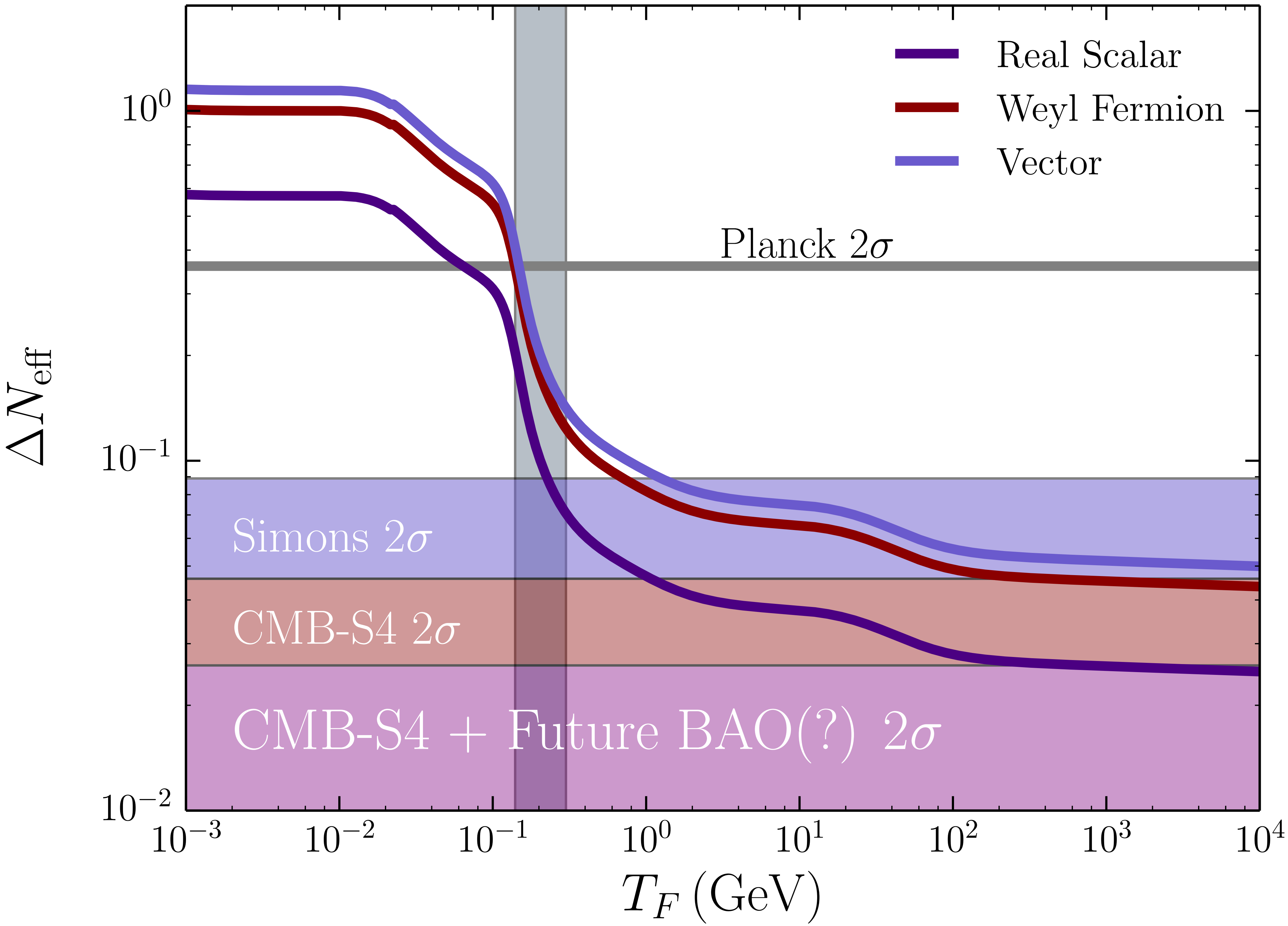
$$k_{\rm max} = 0.5\,h\,\mathrm{Mpc}^{-1}$$

Dodelson et al. (2016)



Summary

Summary



Real Scalar
Weyl Fermion
Vector
Planck 2σ
Simons 2σ
CMB-S4 2σ
CMB-S4 + Future BAO(?) 2σ
$\Delta N_{\rm eff}$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
T_F (GeV)