High-ℓ Science with PICO

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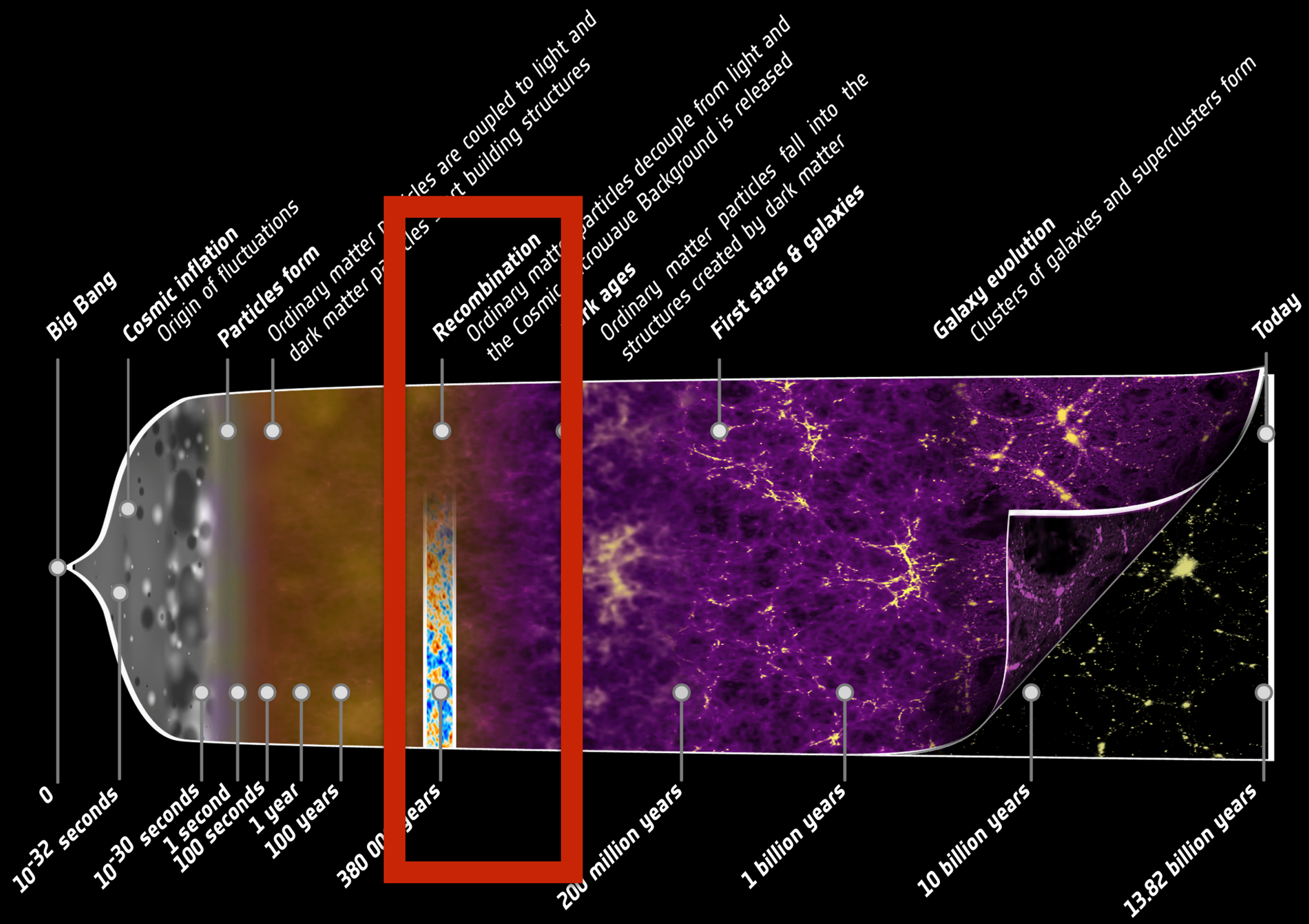
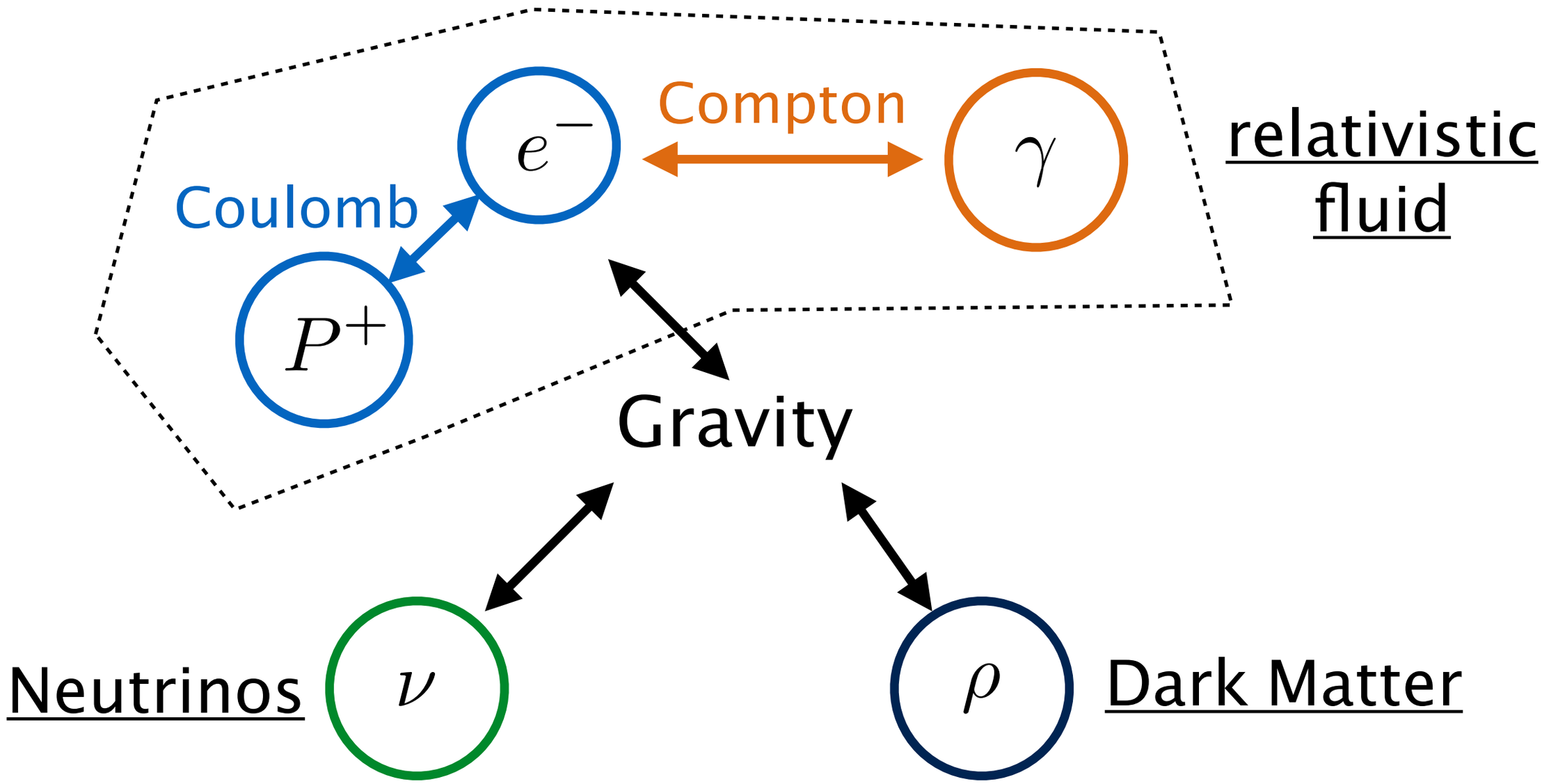

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter
dark matter
Recombination
Ordinary matt
the Cosmic
rk ages
Ordinary matter particles fall into the
structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 00 years
200 million years
1 billion years
10 billion years
13.82 billion years


e^-
Compton
γ
relativistic fluid
Coulomb
P^+
Gravity
Neutrinos
ν
ρ
Dark Matter

High-ℓ Targets

Inflation: $n_s, \alpha_s, \zeta_{\vec{k}}, f_{\rm NL}^{\rm eq.}, \ldots$

Early universe: Y_p/BBN, isocurvature, CνB/$N_{\rm eff}$

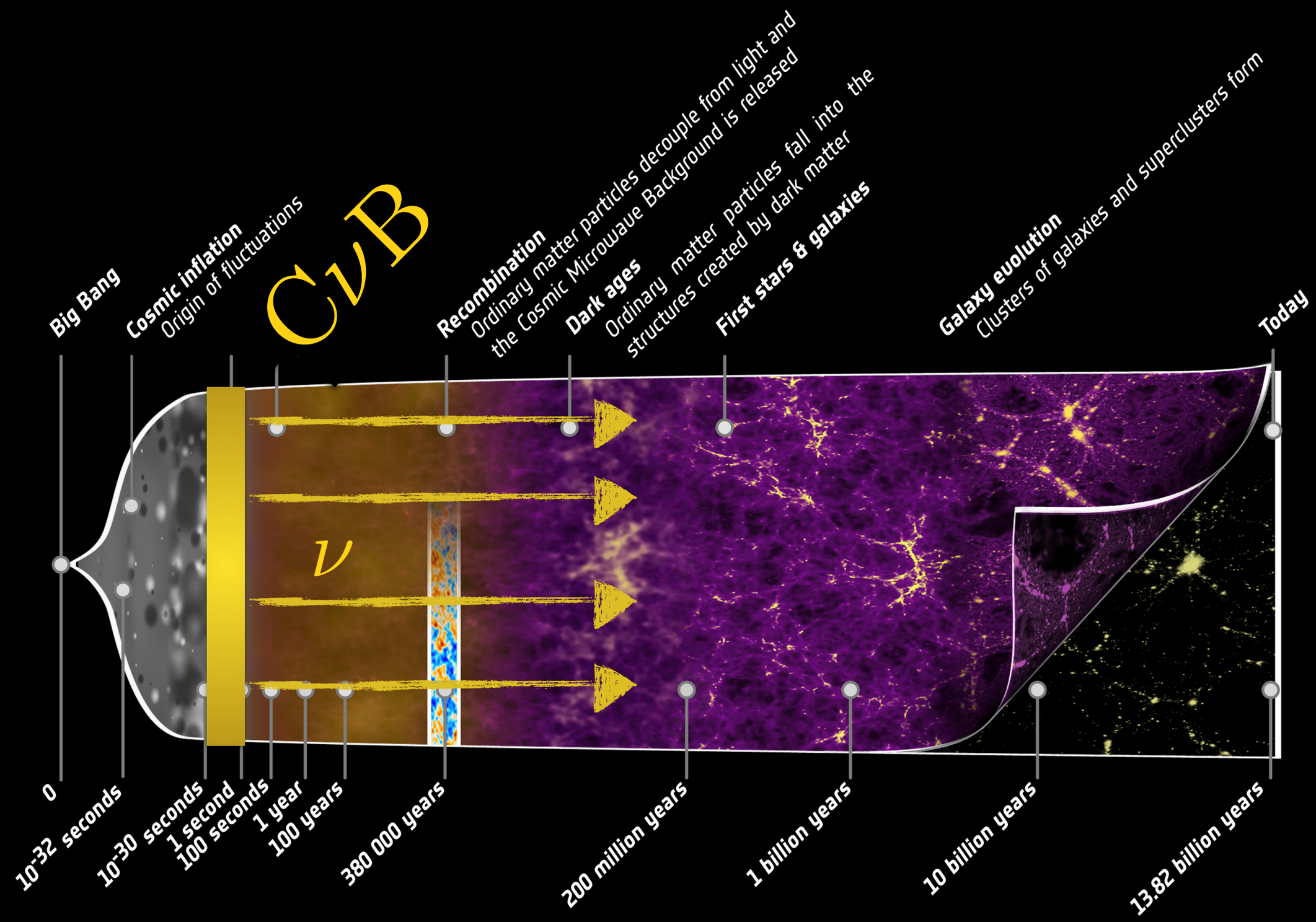
Dark sectors: forces between SM, DM and/or DR

Other: recombination history, neutron lifetime

High-ℓ Target

$N_{\rm eff}$ is a good reference for high-ℓ science

- Affects damping tail & acoustic structure
- Has well defined theoretical targets
- Forecasts do not depend sensitively on low-ℓ
- Relative improvement similar for other parameters
- Can be a useful metric for optimizing design

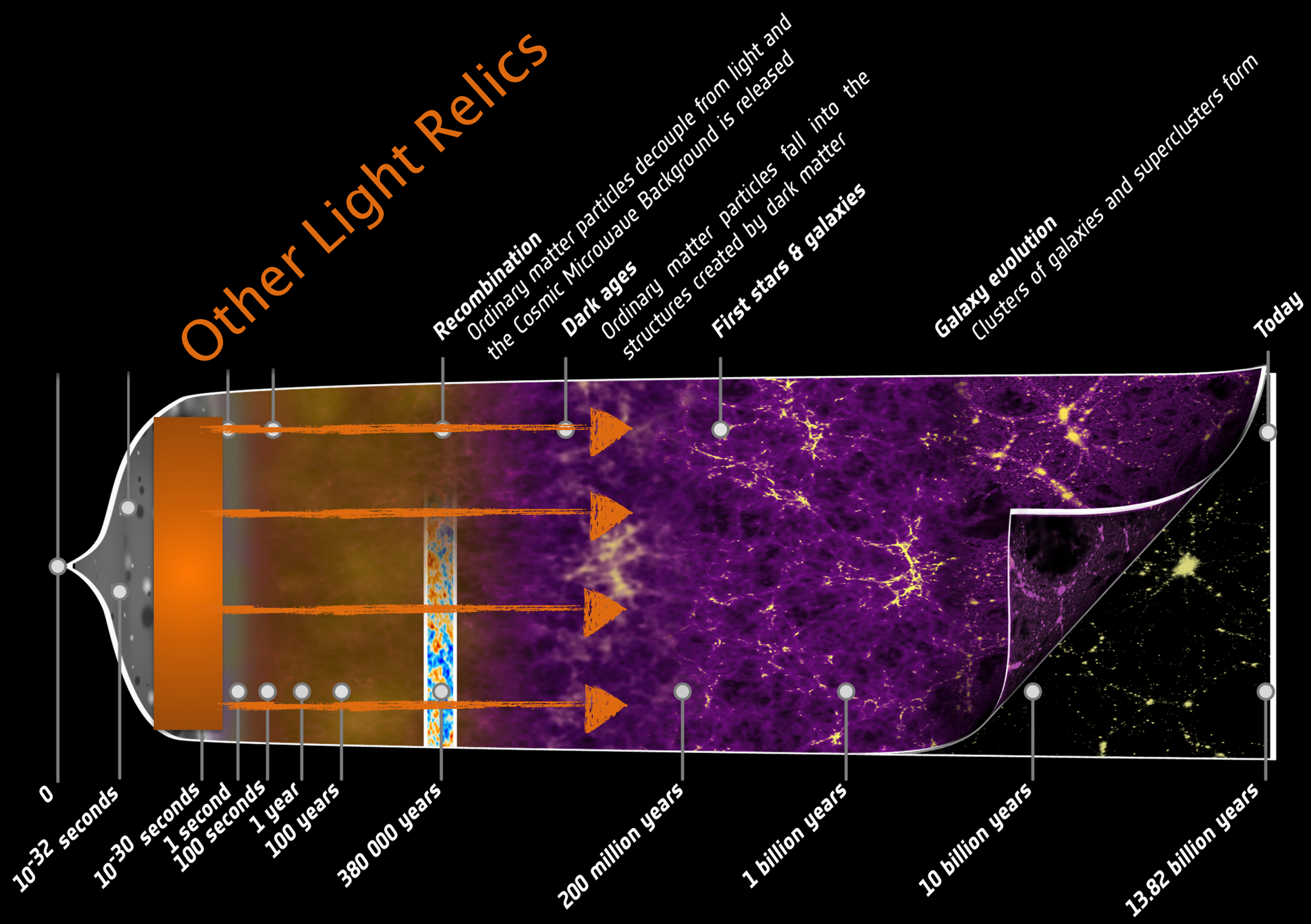

CνB
ν
Big Bang
Cosmic inflation
Origin of fluctuations
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
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

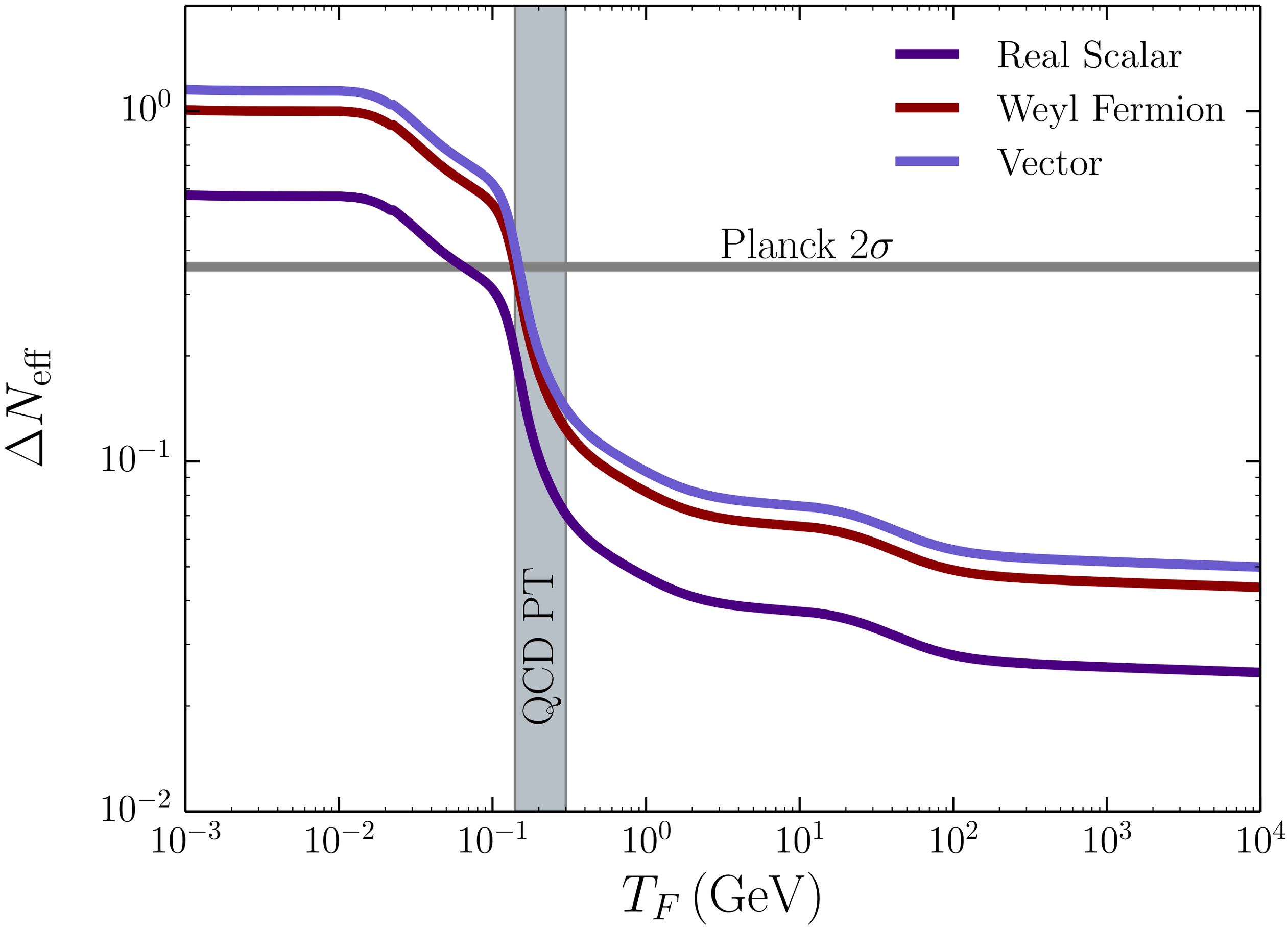
$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

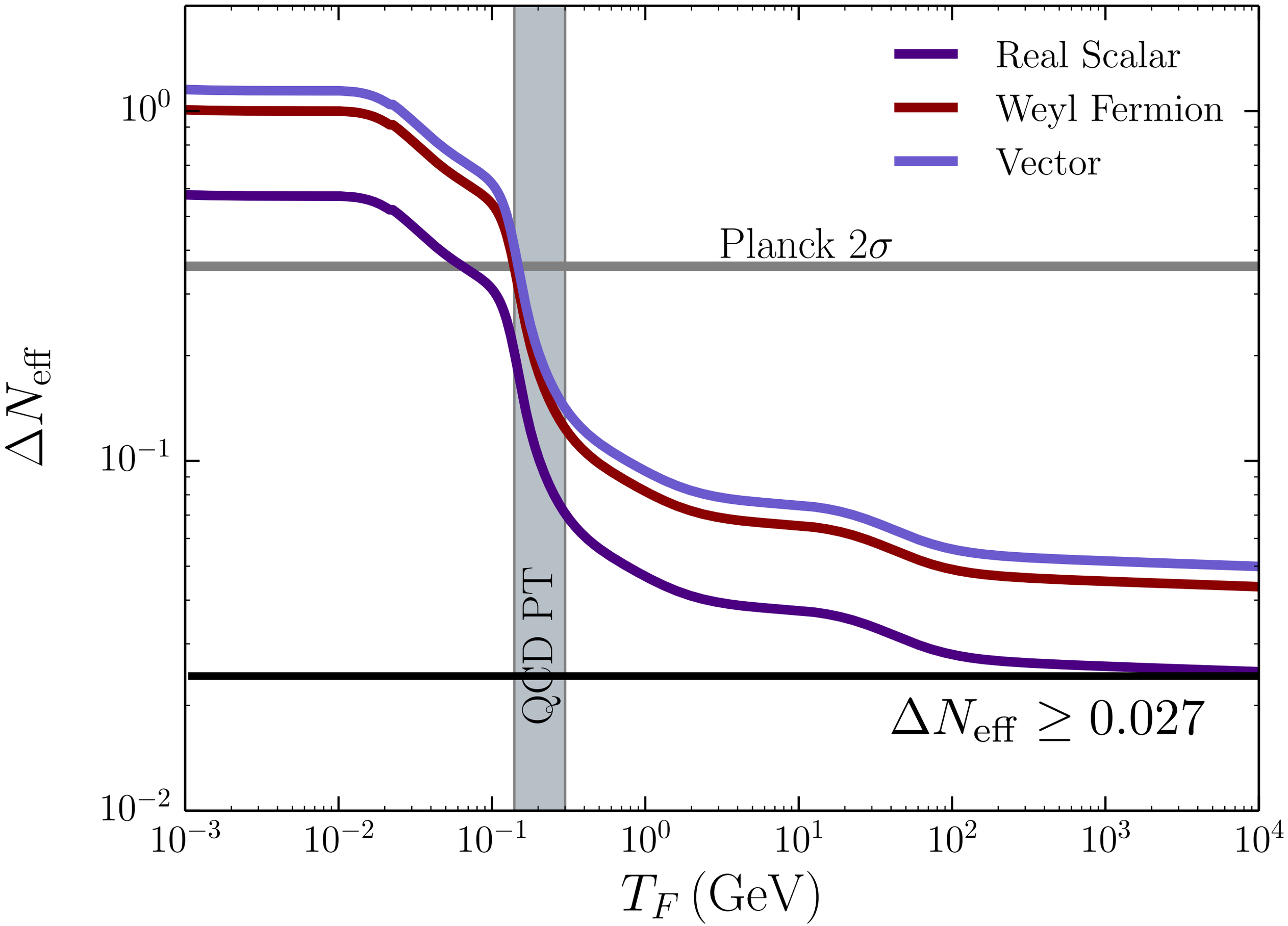
Perfect decoupling : $N_{\rm eff} = 3.$

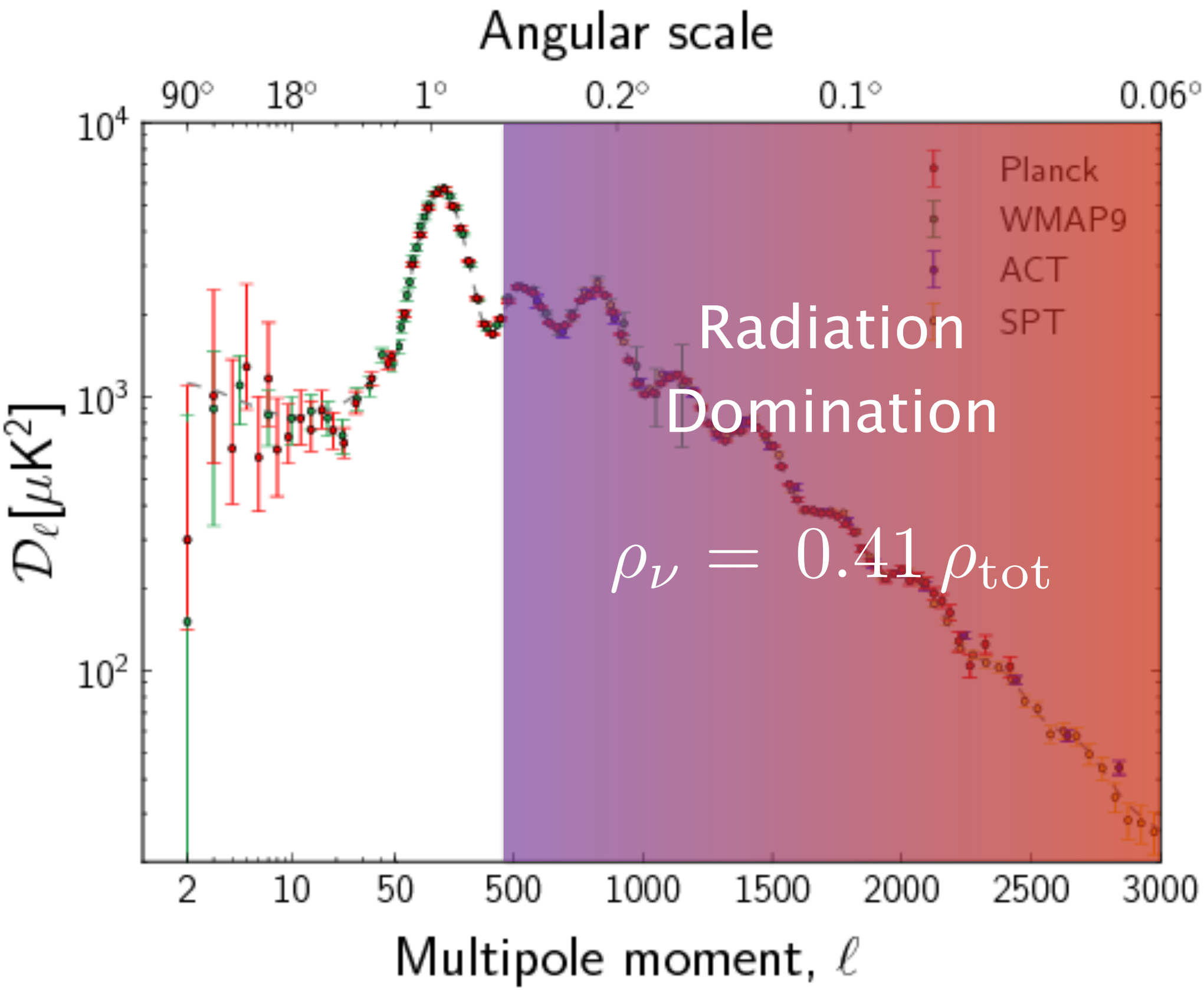
Imperfect decoupling + QED : $N_{\rm eff} = 3.045$

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

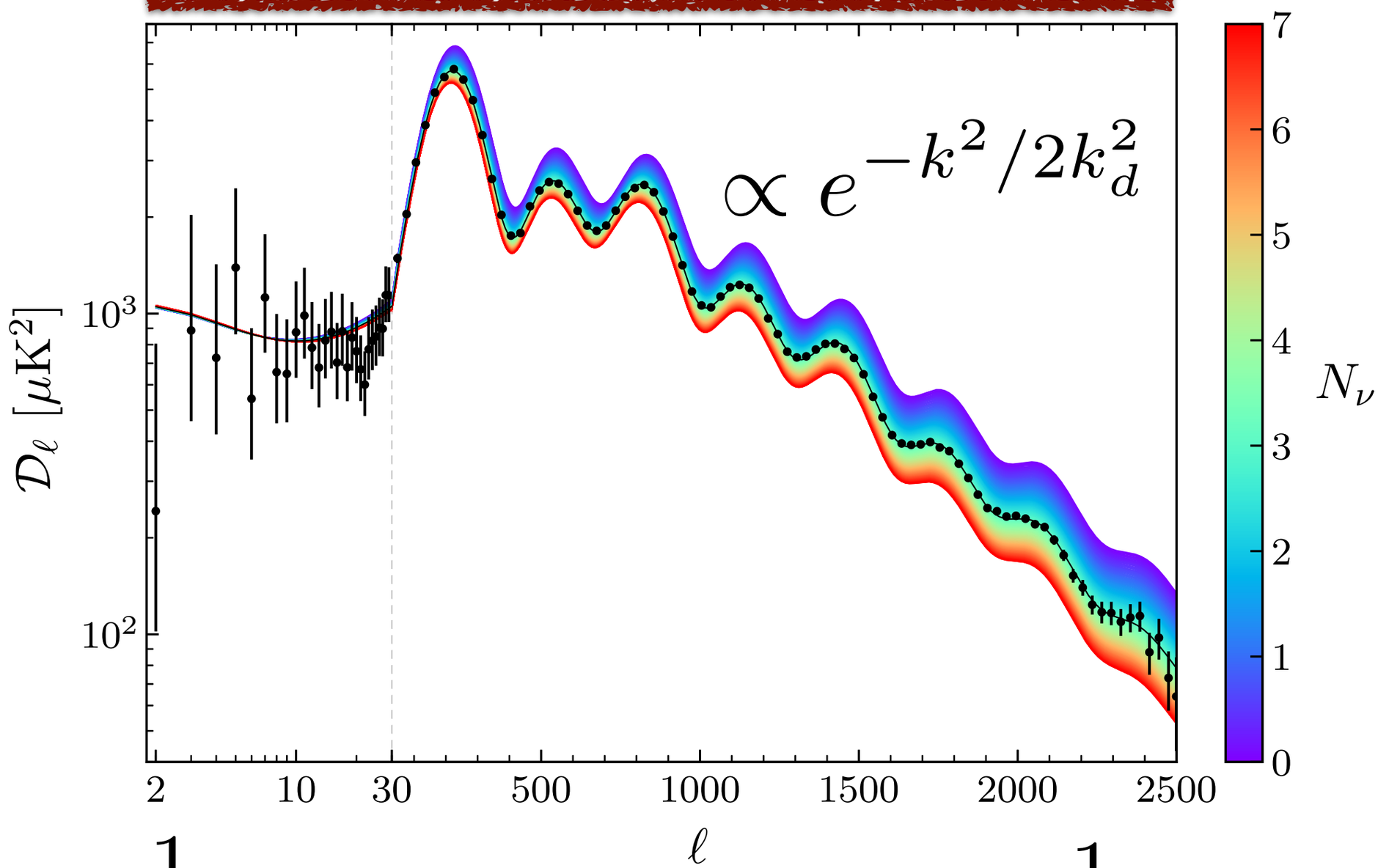

Other Light Relics
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
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


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


Real Scalar
Weyl Fermion
Vector
Planck 2σ
QCD PT
$\Delta N_{\rm eff} \geq 0.027$
$\Delta N_{\rm eff}$
T_F (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4

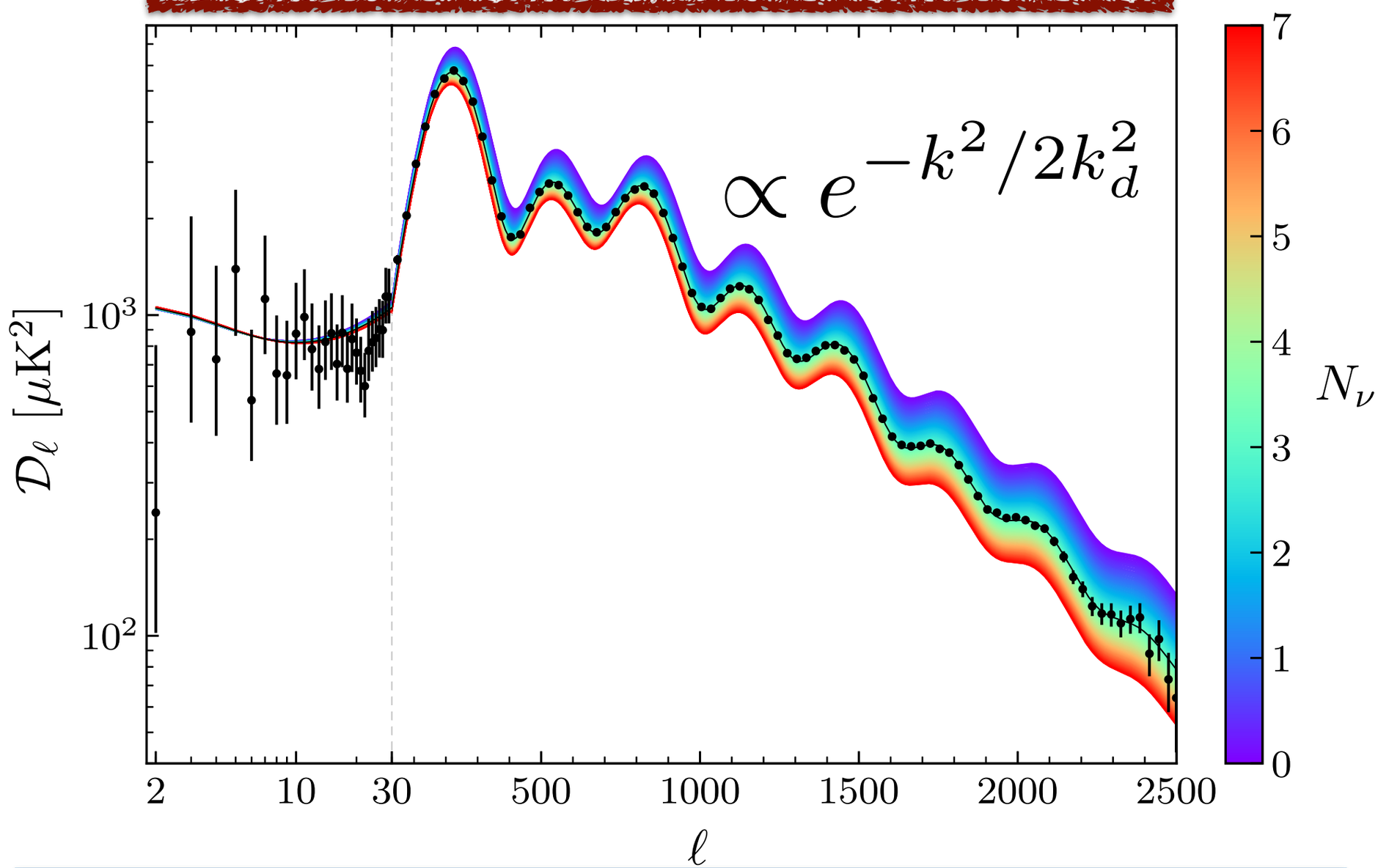

Angular scale
90°
18°
1°
0.2°
0.1°
0.06°
10^4
10^3
10^2
$\mathcal{D}_\ell [\mu K^2]$
Planck
WMAP9
ACT
SPT
Radiation
Domination
$\rho_\nu = 0.41\,\rho_{\rm tot}$
2
10
50
500
1000
1500
2000
2500
3000
Multipole moment, ℓ

$$3M_{\rm pl}^2 H^2 = \rho_\gamma + \rho_\nu$$

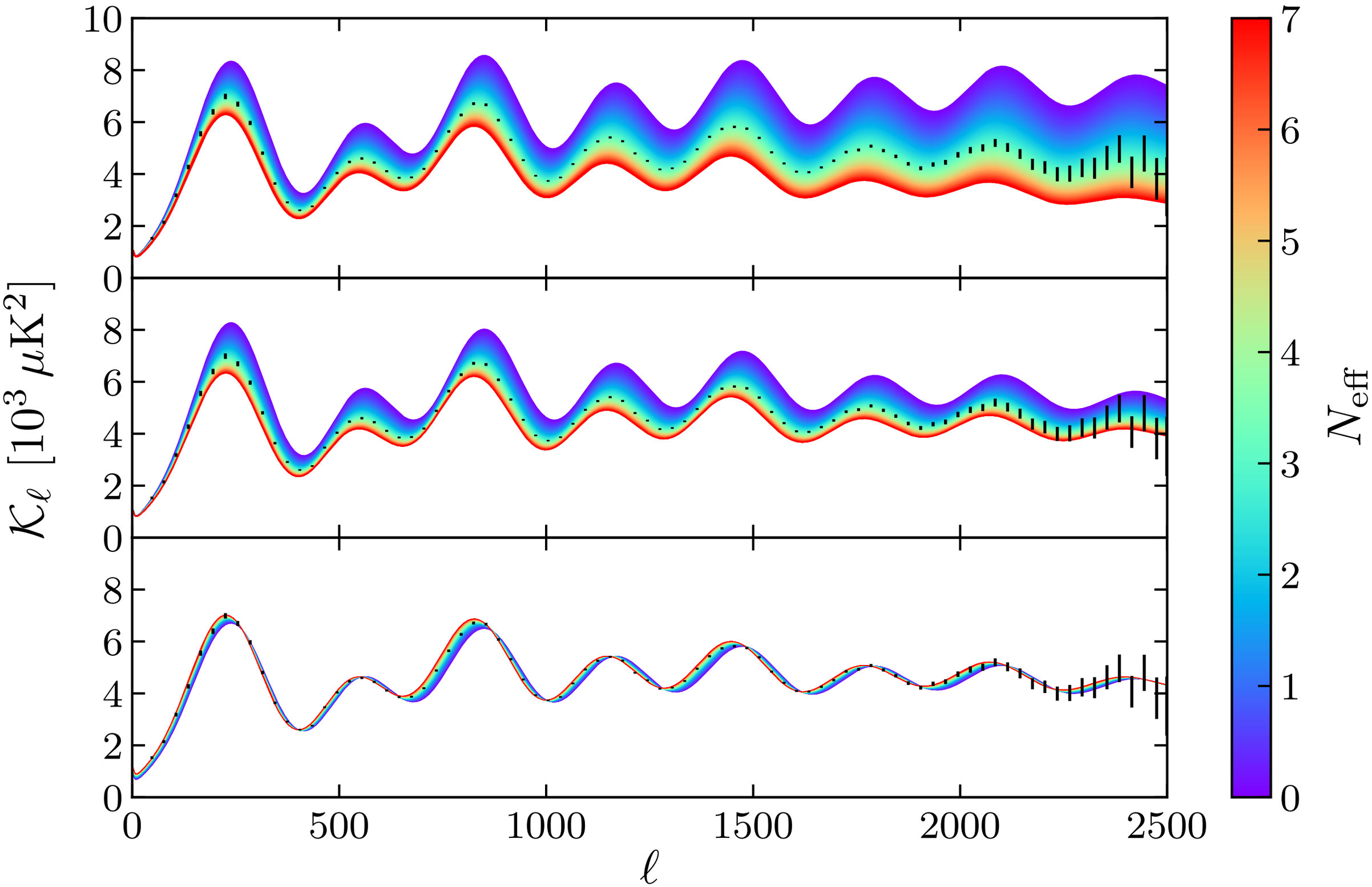


$$\frac{1}{k_d^2} \sim \langle \Delta x^2 \rangle \propto t \qquad t \propto \frac{1}{H}$$

$$3M_{\rm pl}^2 H^2 = \rho_\gamma + \rho_\nu$$

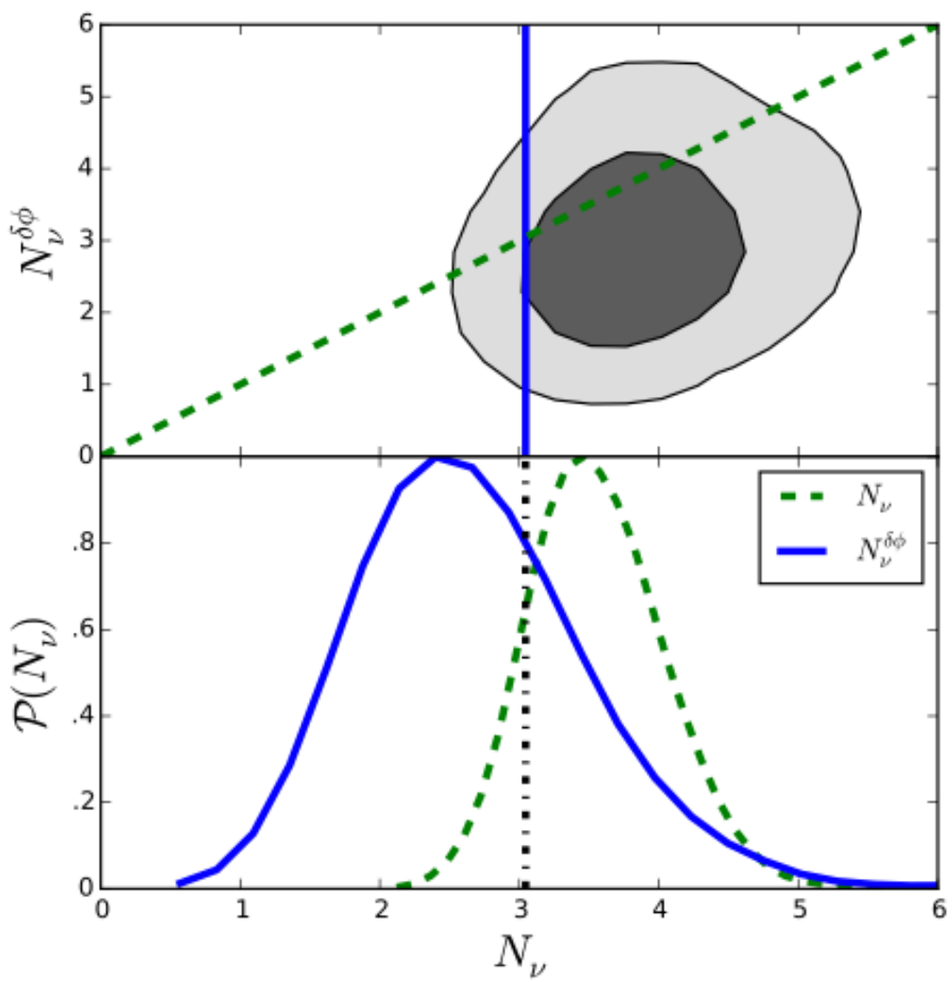


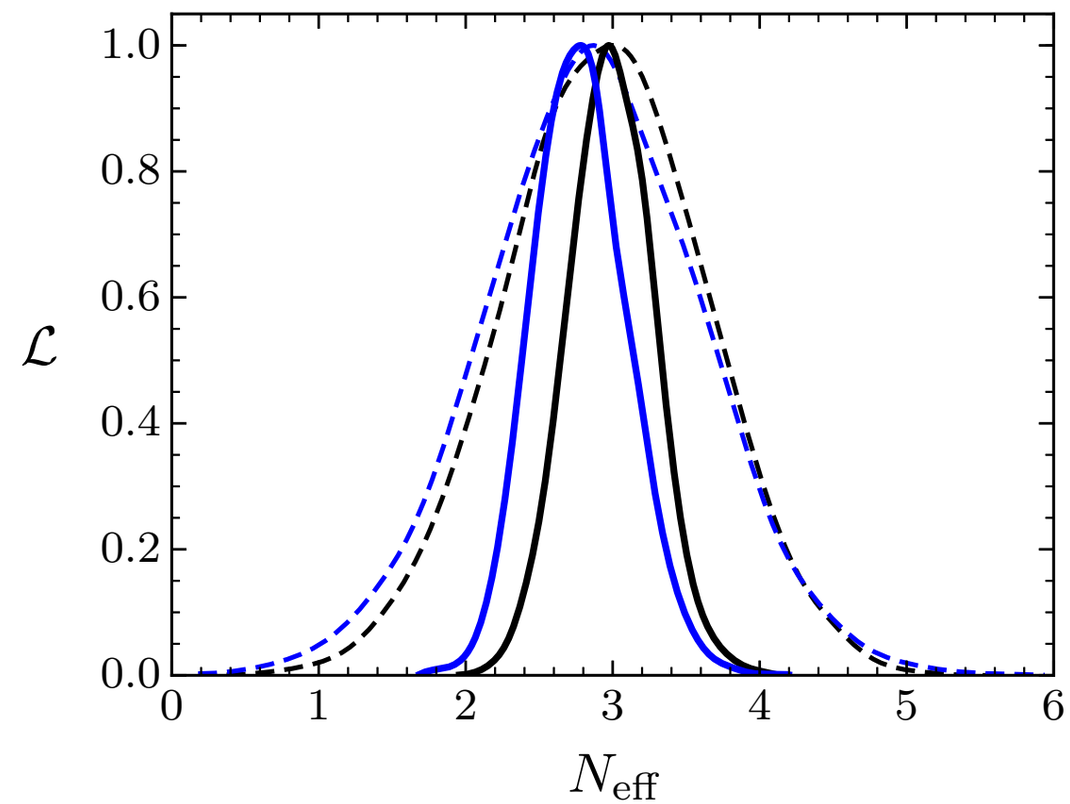
$$N_{\rm eff} = 3.04 \pm 0.18$$ Planck (2015)


$\mathcal{K}_\ell$ [10^3 μK^2]
ℓ
$N_{\rm eff}$
0
500
1000
1500
2000
2500
0
2
4
6
8
10
0
1
2
3
4
5
6
7

Phase shift = Free streaming

Bashinsky & Seljak (2003)





$$N_{\rm eff}^{\rm phase} = 2.3^{+1.1}_{-0.4}$$

Follin et al. (2015)

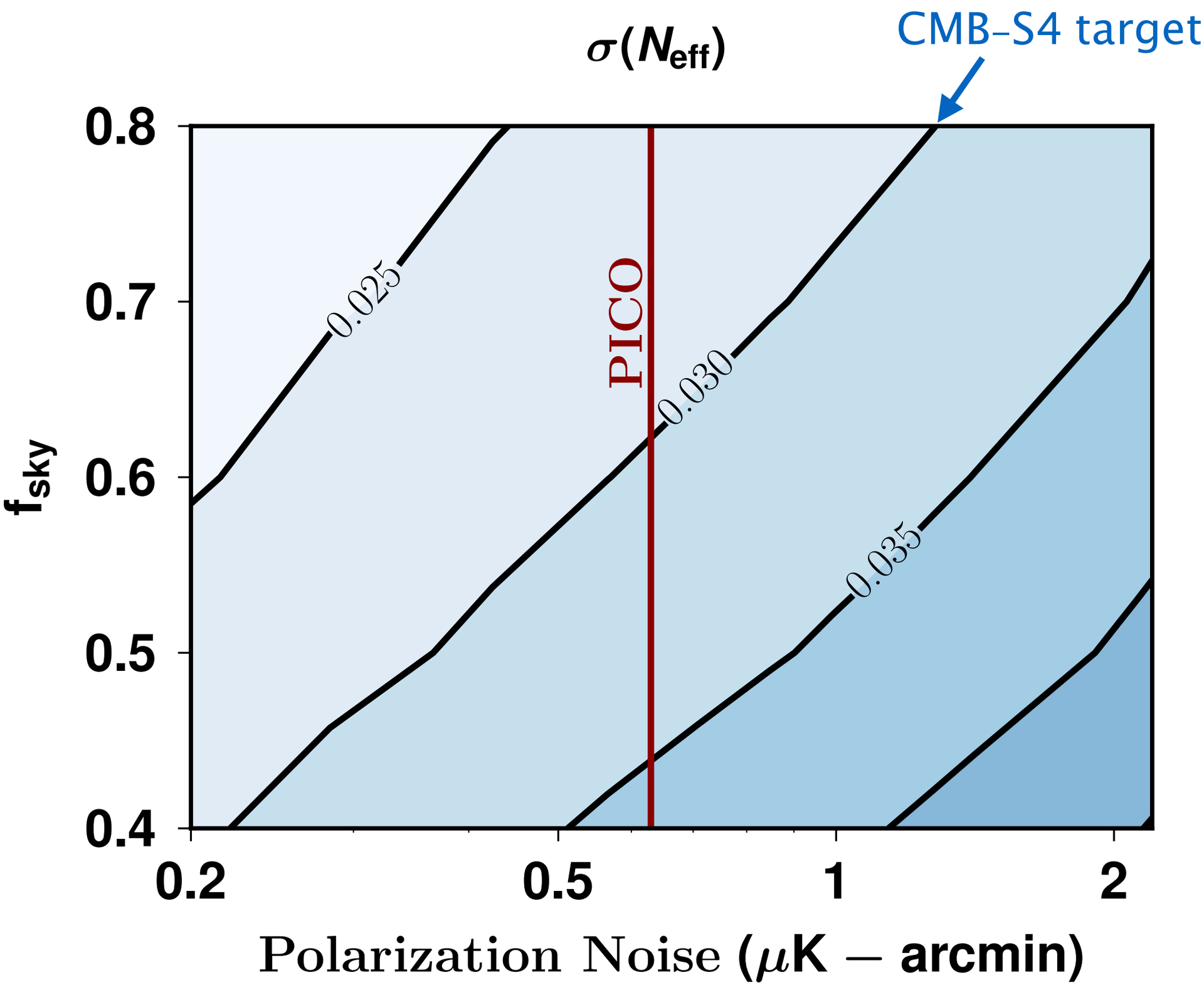
$$N_{\rm eff}^{\rm phase} = 2.80^{+0.24}_{-0.23}$$

Baumann, DG, Meyers, Wallisch (2015)

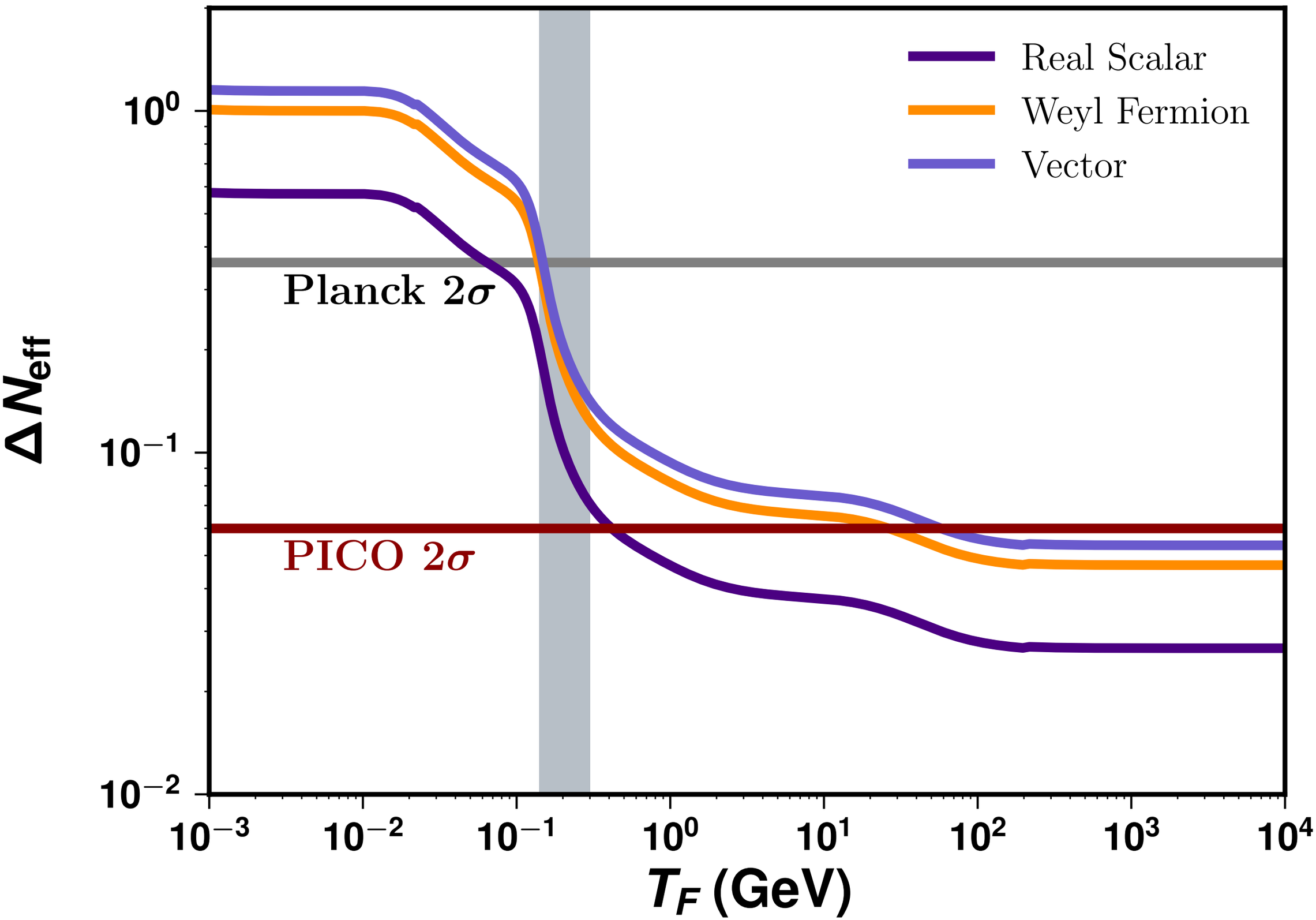
PICO Forecasts

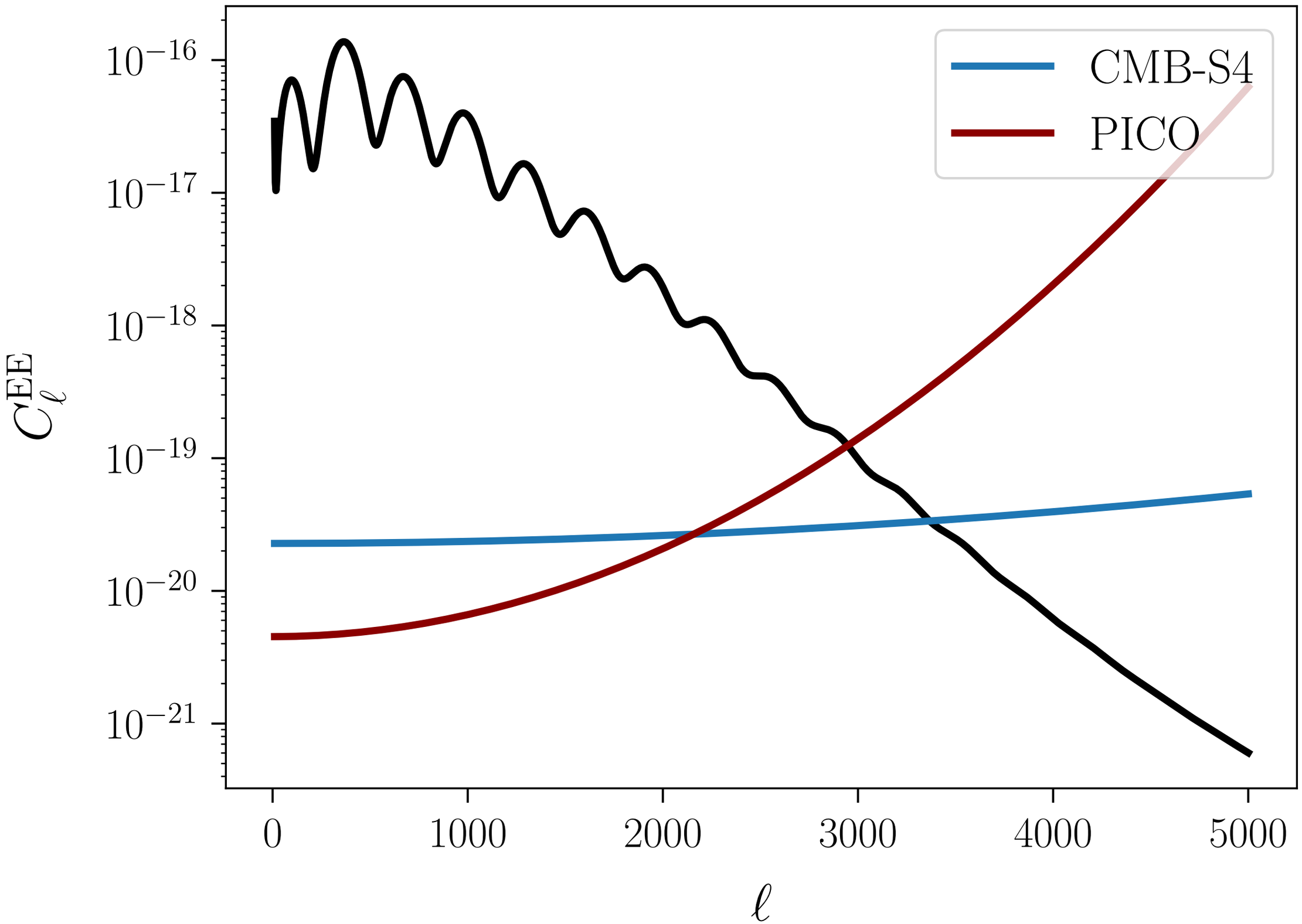
Central questions for PICO

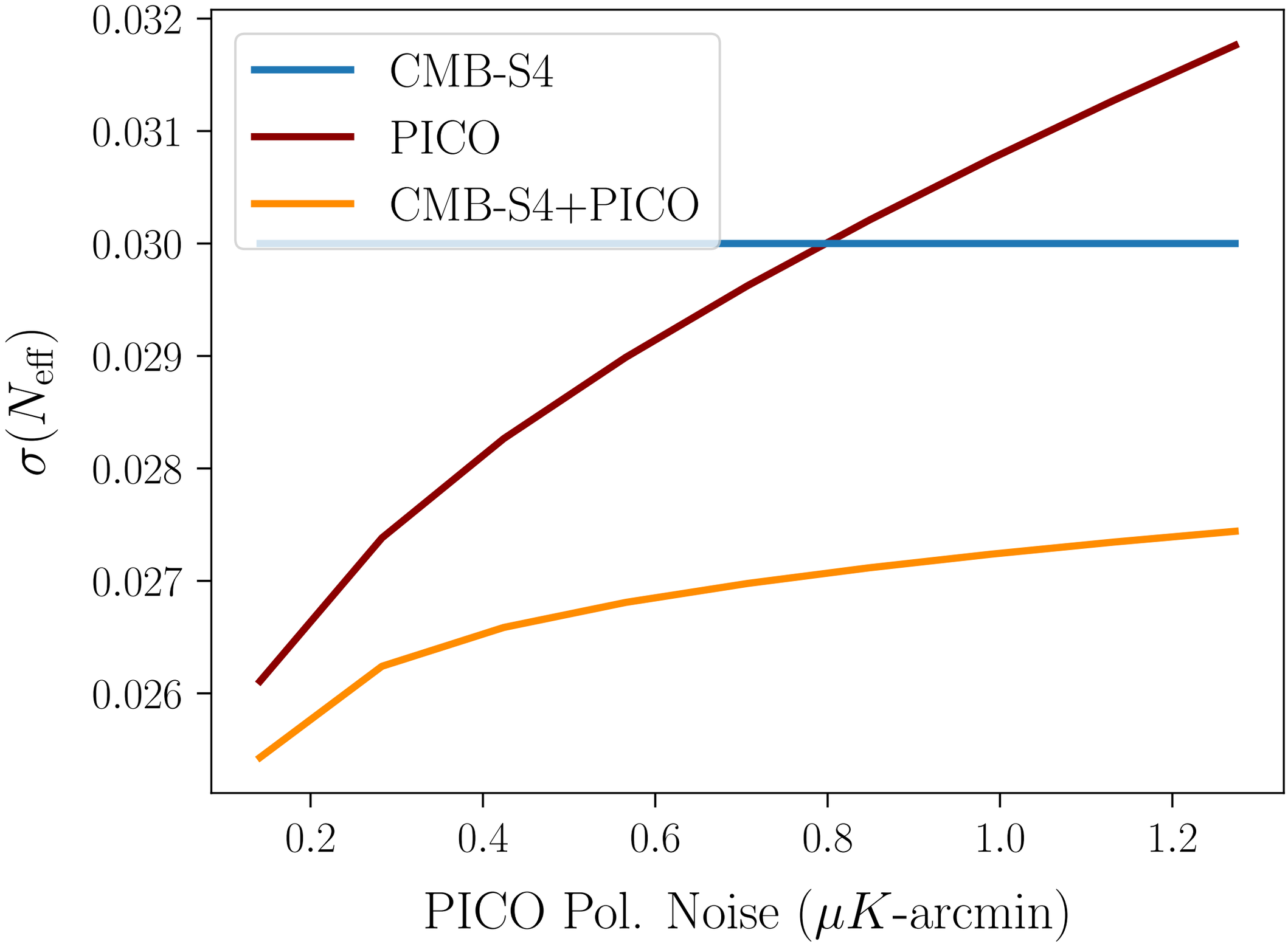
- Can PICO reach well-motivated targets?
- Are there unique advantages to space?
- Opportunities when combined with ground-based?
- Does this suggest other interesting observables?



w. Meyers, includes delensing from DG, Meyers, van Engelen


Real Scalar
Weyl Fermion
Vector
Planck 2σ
PICO 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)


CMB-S4
PICO
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
C_ℓ^{EE}
0
1000
2000
3000
4000
5000
ℓ



DG forecasts, do not include delensing

Take-away

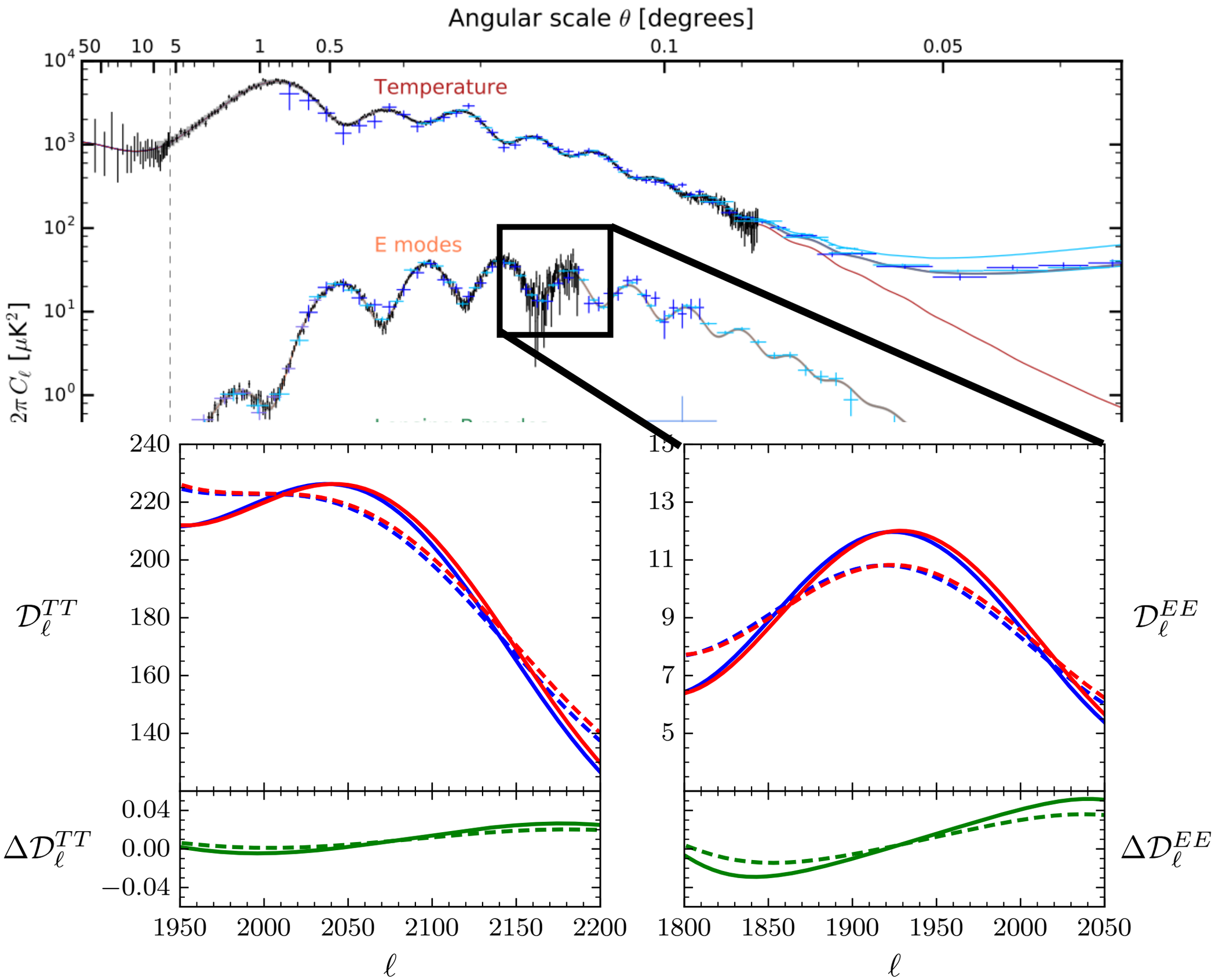
PICO would have comparable sensitivity to CMB-S4:

- CMB-S4 beam reaches higher ℓ
- PICO has larger f_{sky}
- These two roughly offset
- Lower PICO noise limited because of CV

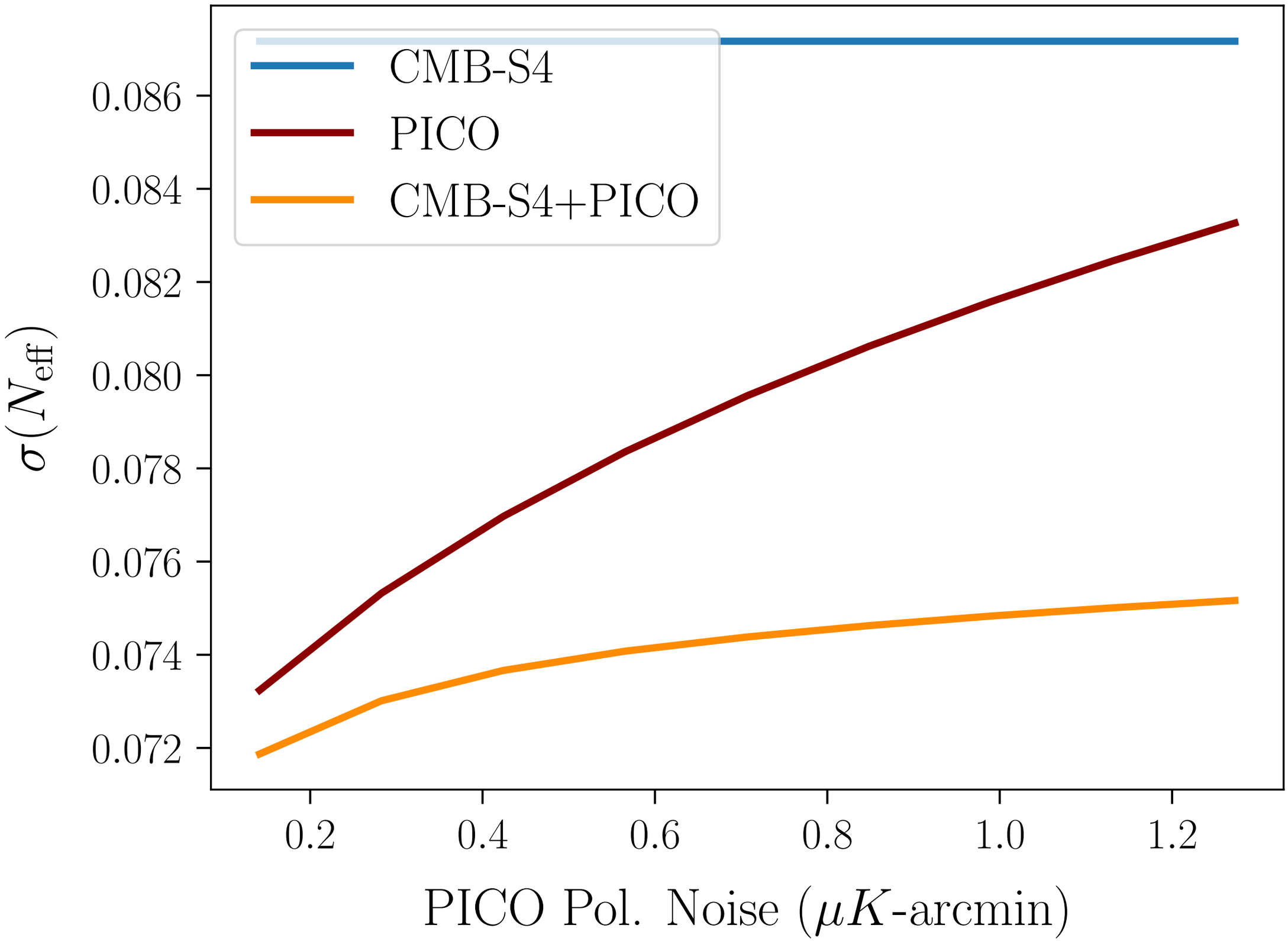
Y_p marginalization

PICO measures more E-modes with $\ell \lesssim 2000$

- Acoustic peaks are sharper in E-modes
- Can lead to better constraints
- The neutrino phase shift is one such observable
- Capture this effect by marginalizing over Y_p



Baumann, DG, Meyers, Wallisch (2015)

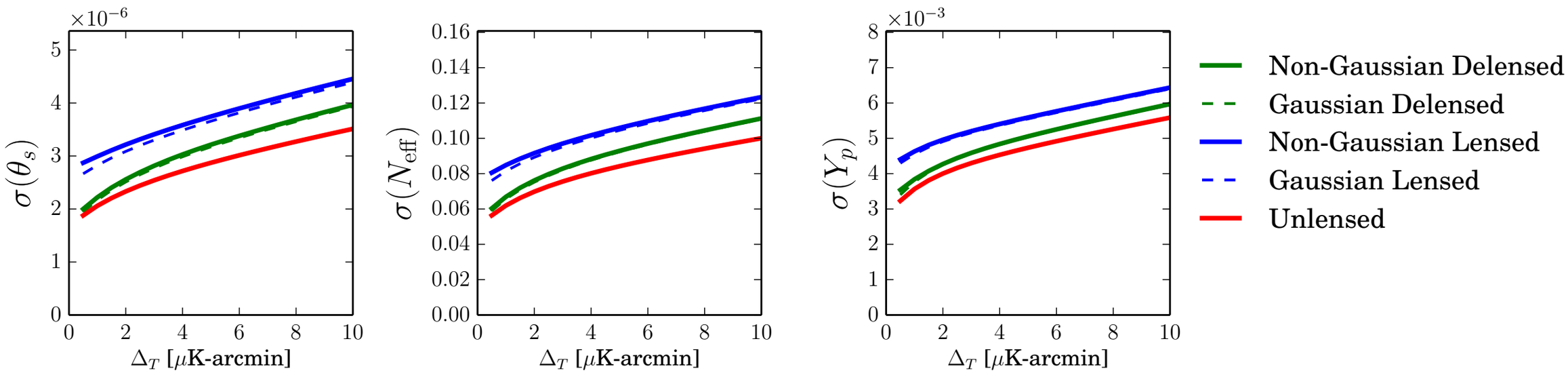


DG forecasts, do not include delensing

Lensing & Delensing (T/E)

Improvements from CMB (de)lensing will help more:

- EB estimator can benefit from lower noise of PICO
- Delensing can improve parameter constraints



DG, Meyers & van Engelen (2016)

Summary

High-ℓ science with PICO driven by f_{sky}

- More CVL modes, especially E-modes
- Ground benefits most from high-ℓ TE
- Combining PICO and CMB-S4 is useful

Thank you