Late Reheating scenarios

How low can we really go?

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Winter Meeting

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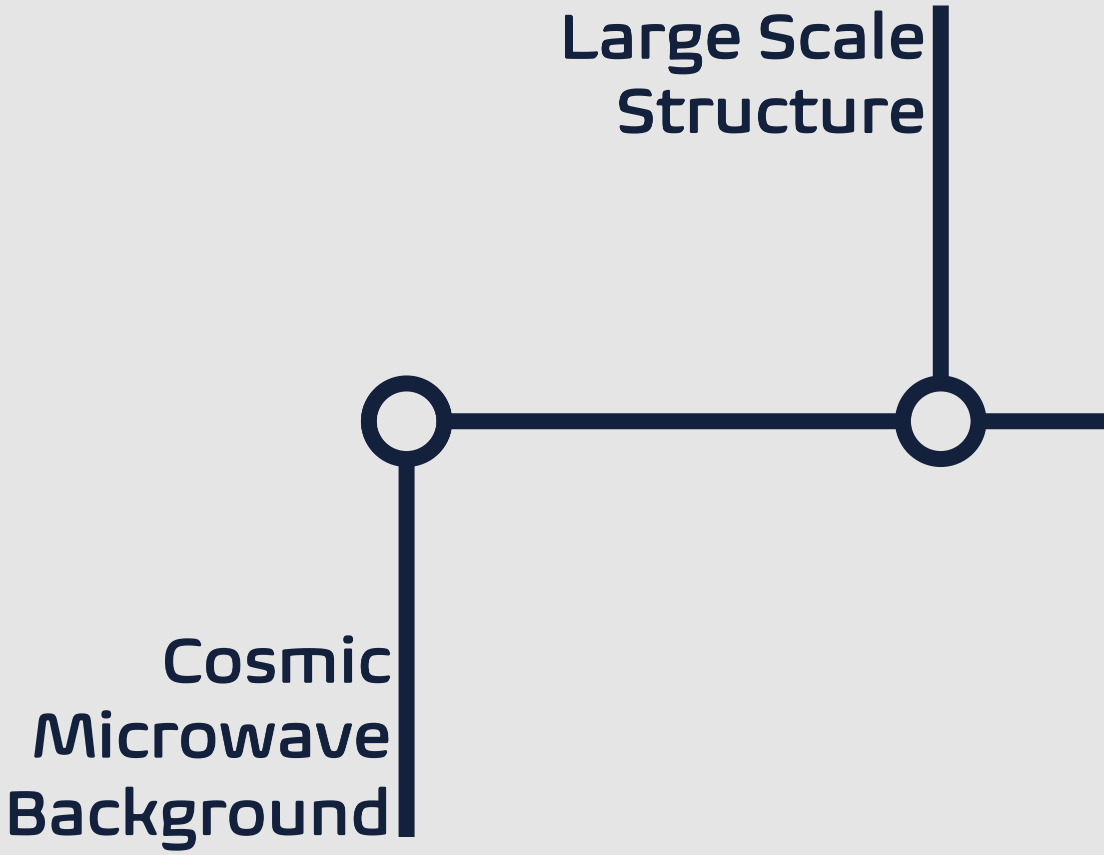
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA
EXCELENCIA MARÍA DE MAEZTU 04/2025-03/2031
UNIVERSITAT DE BARCELONA
Facultat de Física

Motivation

Large Scale Structure

Motivation



Motivation

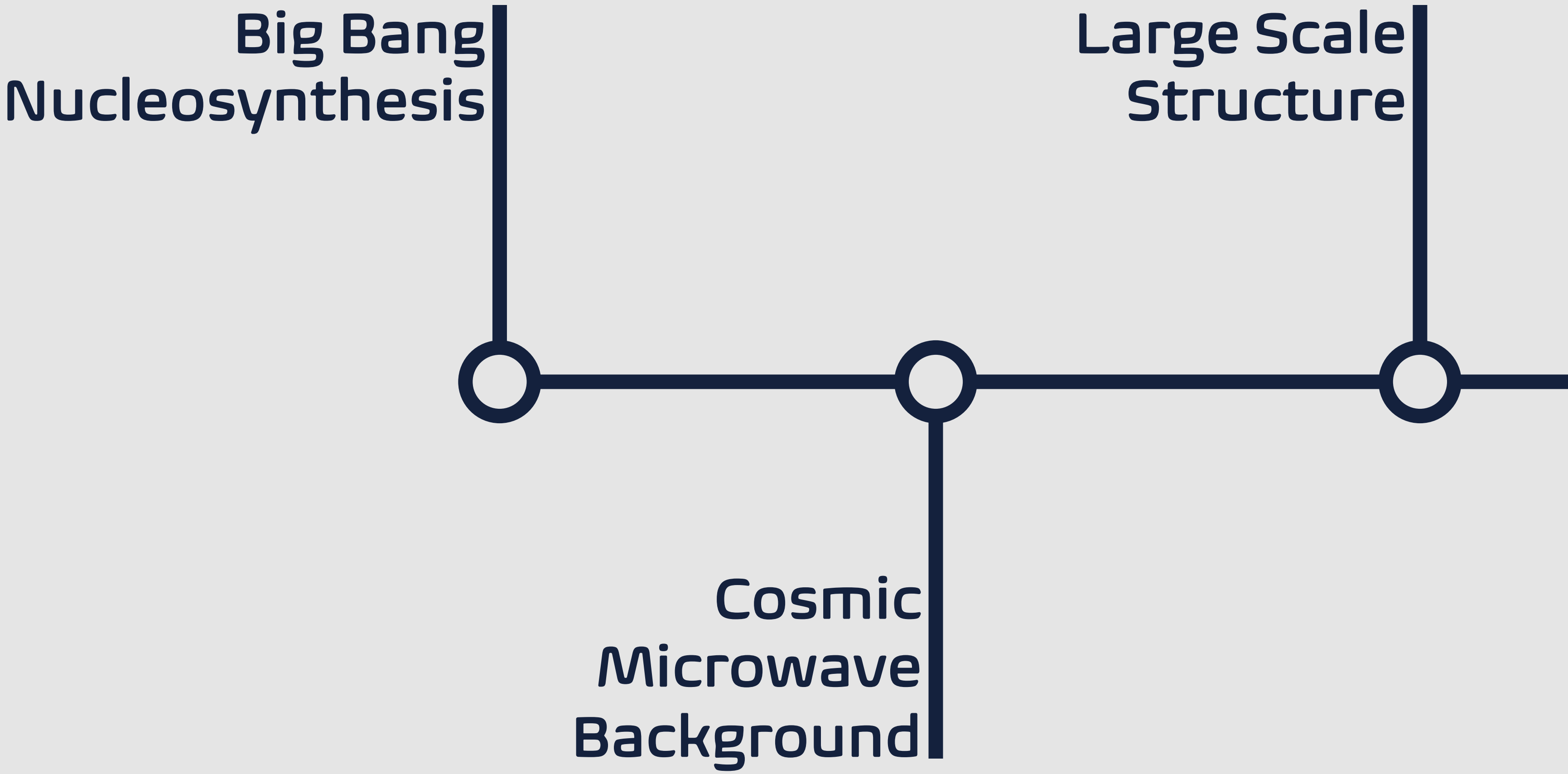
Big Bang Nucleosynthesis

Cosmic Microwave Background

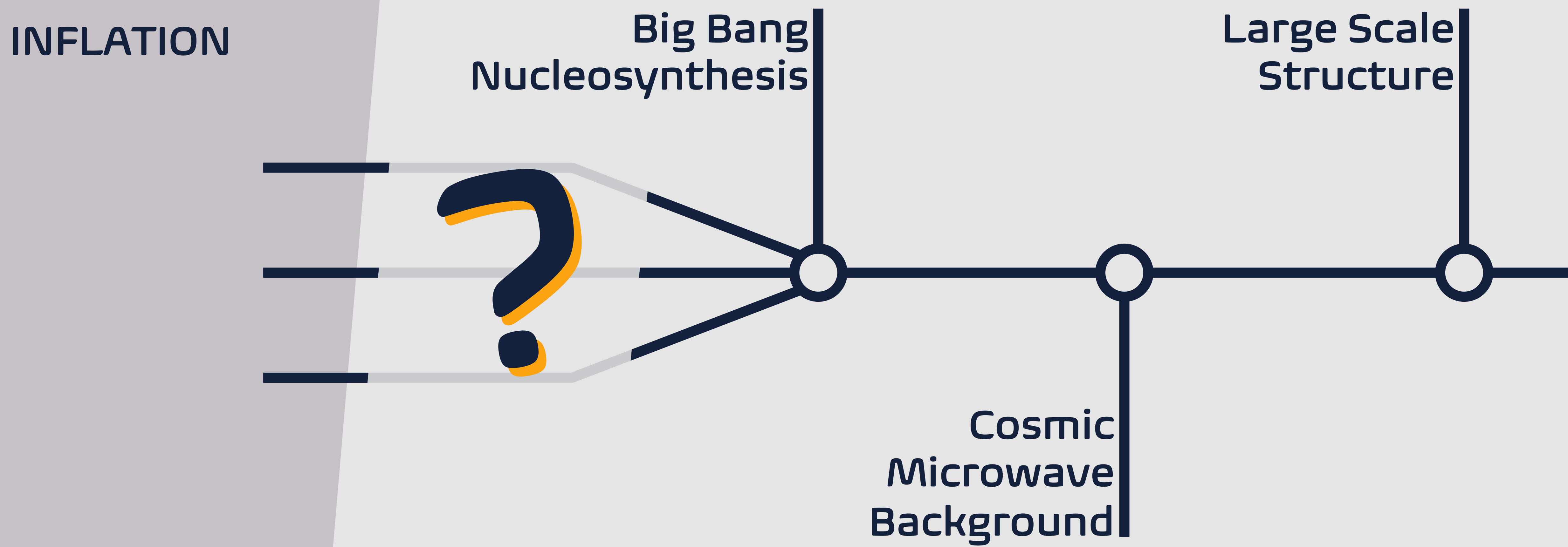
Large Scale Structure

Motivation

INFLATION



Motivation


INFLATION
Big Bang
Nucleosynthesis
Large Scale
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?
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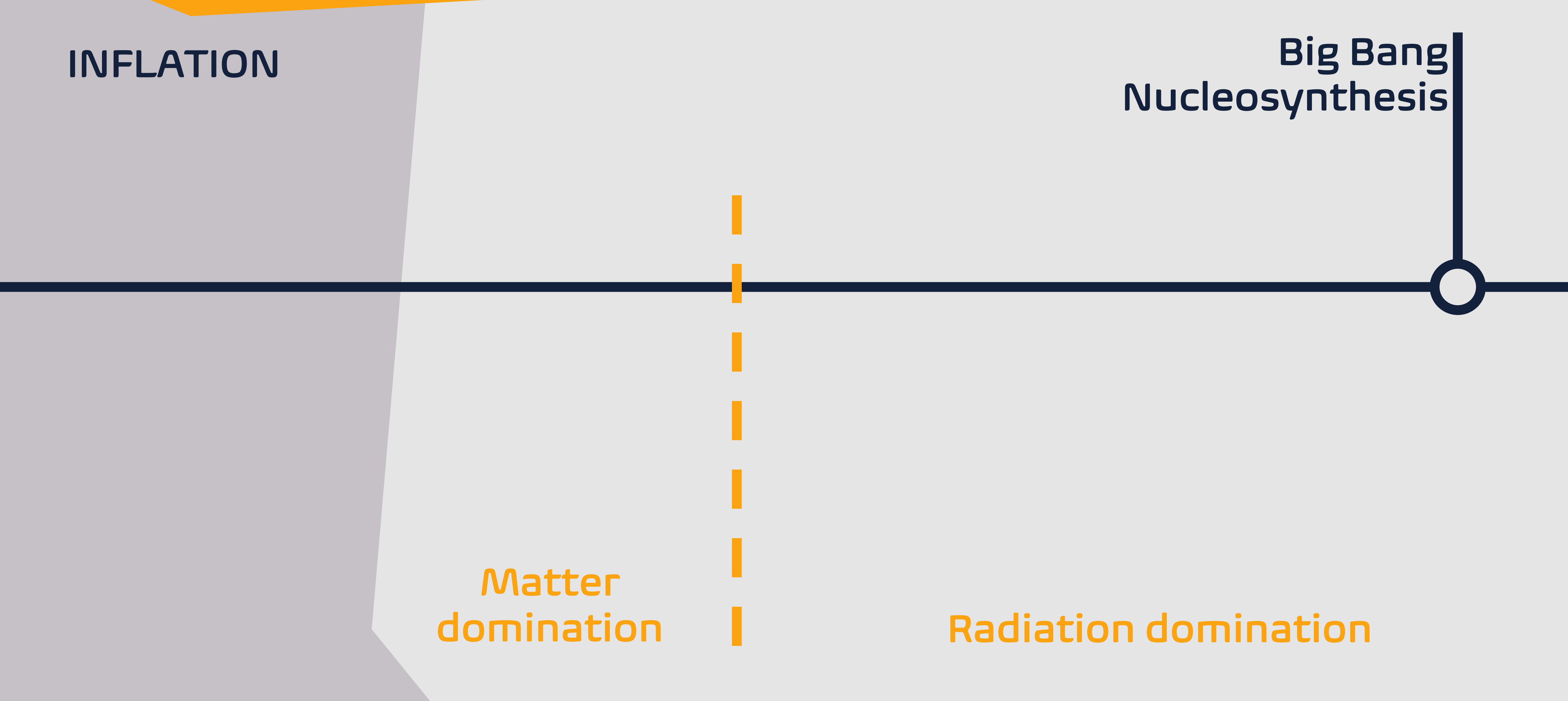
INFLATION
Big Bang
Nucleosynthesis
Matter
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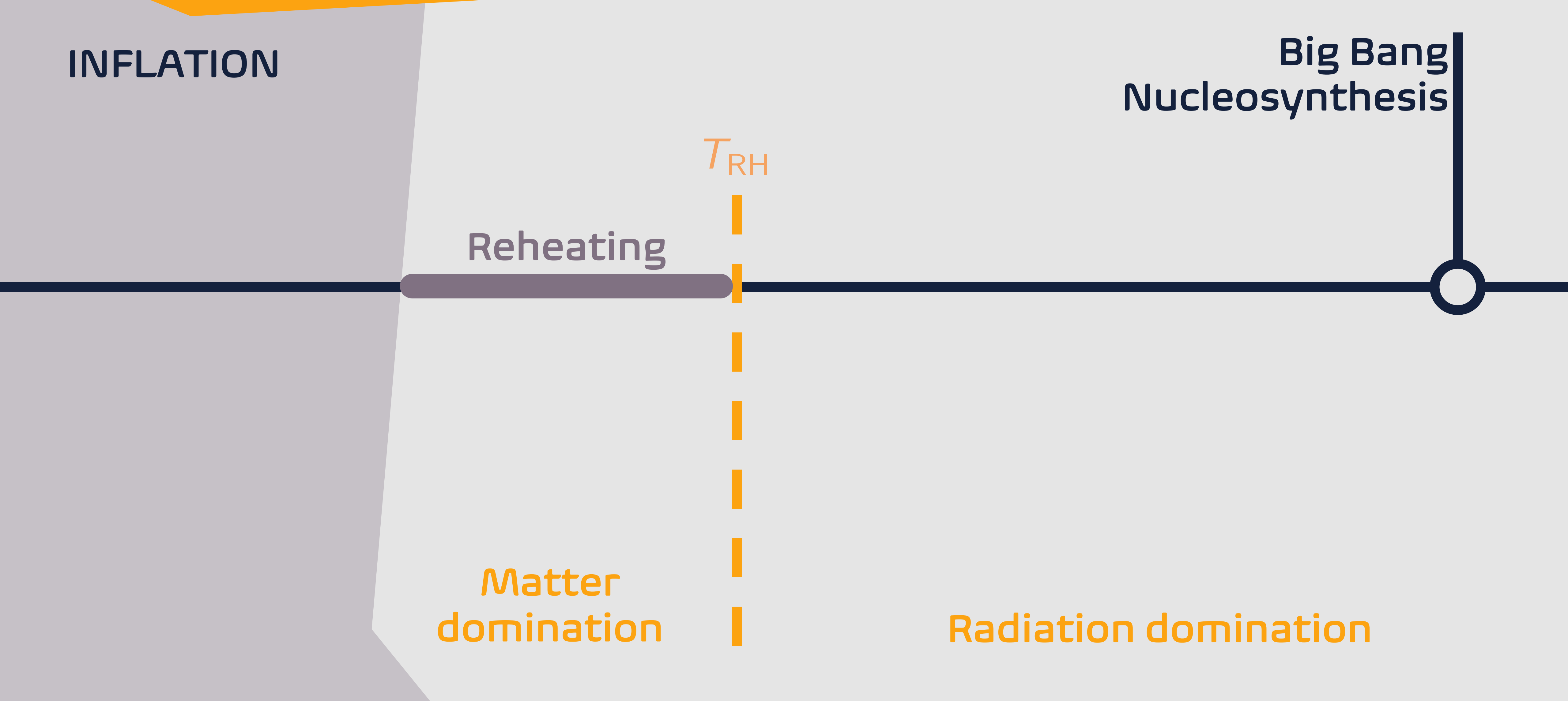
Motivation


INFLATION
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Motivation


INFLATION
Big Bang
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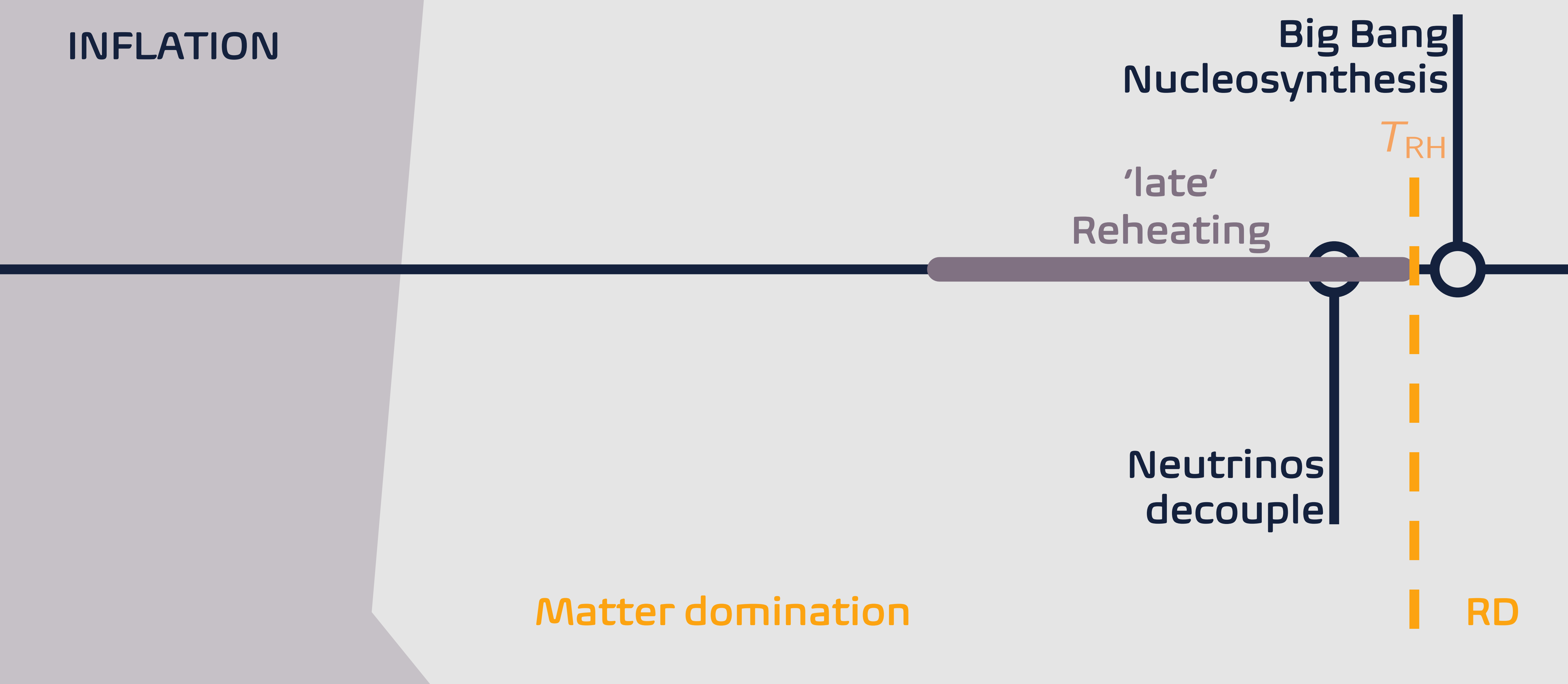
RD

Motivation


INFLATION
Big Bang
Nucleosynthesis
T_{RH}
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Neutrinos
decouple
Matter domination
RD

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2. Theory
3. Results
4. Conclusions
5. Future work

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1. Motivation
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Theory:

χ evolution

χ

Theory:
X evolution

Non-relativistic
(around BBN)

X

Out of Equilibrium X Thermal bath

Theory:

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Stores some energy
($\rho_{X,0}$) before BBN

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Decays around BBN

$$\Gamma_X = 10^0 - 10^3\ \mathrm{s}^{-1}$$

Out of Equilibrium X Thermal bath

Theory:

X evolution

Non-relativistic
(around BBN)

$$\frac{d\rho_X}{dt} = -(\Gamma_X + 3H)\rho_X$$

Hubble rate

X

Stores some energy ($\rho_{X,0}$) before BBN

Decays around BBN

$$\Gamma_X = 10^0 - 10^3 \text{ s}^{-1}$$

Theory:

Photon and electron evolution

γ

$e^{\pm}$

Out of Equilibrium X

$e^{\pm}$ γ Thermal bath

Theory:

Photon and electron evolution

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$e^{\pm}$

Massless vector

$$\rho_\gamma = \frac{\pi^2}{15} T_\gamma^4$$

$$P_\gamma = \frac{\rho_\gamma}{3}$$

Temperature
of the bath

Theory:

Photon and electron evolution

γ → Massless vector

$$\rho_\gamma = \frac{\pi^2}{15} T_\gamma^4 \qquad P_\gamma = \frac{\rho_\gamma}{3}$$

$e^\pm$ → Massive fermion

$$\rho_e = \rho_e(T_\gamma) \qquad P_e = P_e(T_\gamma)$$

Temperature of the bath

Theory:

Neutrino evolution

- Neutrinos decouple at $\mathcal{O}(1)$ MeV
  - → Important neutrino dynamics

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Out of Equilibrium X ν_α $e^\pm$ γ Thermal bath

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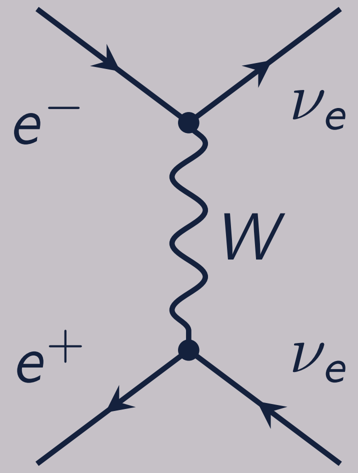

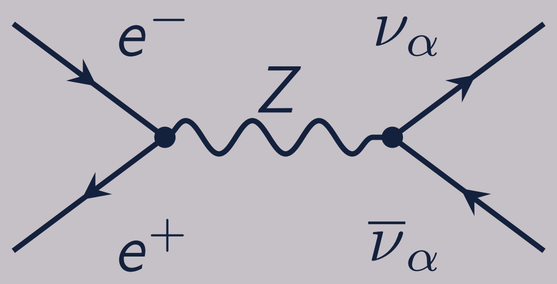

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- All charged leptons but electrons are suppressed
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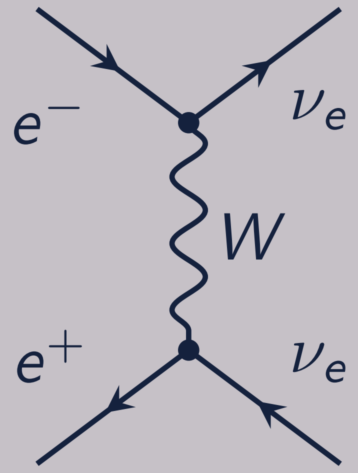
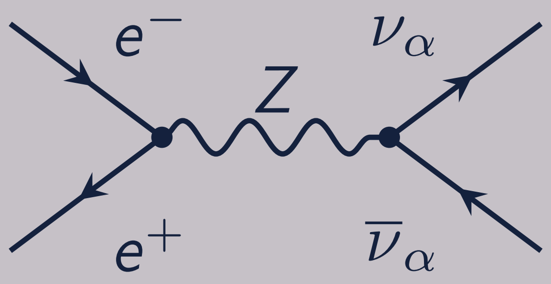
- Negligible 3rd gen effects[1]

Effective two-flavor mixing





[1] Hasegawa et al. (arXiV:1908.10189)

Out of Equilibrium X ← ν_α $e^\pm$ γ Thermal bath

Theory:

Effective two-flavor mixing

Spectator flavor ν_{sp}

$\nu_e \rightleftarrows \nu_x$ Active flavors

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Boltzmann equation

$$\frac{df_{\nu_{\text{sp}}}}{dt} = C(f_{\nu_{\text{sp}}})$$

Collision term

Out of Equilibrium X

ν_α $e^\pm$ γ Thermal bath

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Effective two-flavor mixing

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Quantum Kinetic Equation

$$\frac{d \varrho_p}{dt} = -i \left[\mathcal{H}_p, \varrho_p\right] + C(\varrho_p)$$

Hamiltonian

$$\varrho_p = \begin{pmatrix} f_{\nu_e} & \rho_{ex} \\ \rho^*_{ex} & f_{\nu_x} \end{pmatrix}$$

Out of Equilibrium X ν_α $e^\pm$ γ **Thermal bath**

QKE $\frac{d\varrho_p}{dt} = -i\,[\mathcal{H}_p\,,\varrho_p] + C(\varrho_p)$

Theory:

Neutrino Hamiltonian

$$\mathcal{H}_p = \frac{\mathrm{M}^2}{2p} - \frac{8\sqrt{2}}{3} G_F\, p \left[\frac{\mathbf{E}_l}{m_W^2} + \frac{\mathbf{E}_\nu}{m_Z^2}\right] + \sqrt{2} G_F \int \frac{d^3\mathbf{p}'}{(2\pi)^3} (\varrho_{\mathbf{p}'} - \overline{\varrho}_{\mathbf{p}'})$$

Theory:

Neutrino Hamiltonian

Mass matrix

$$\mathcal{H}_p = \underbrace{\frac{\mathsf{M}^2}{2p}}_{\mathcal{H}_{p,\mathrm{vac}}} - \frac{8\sqrt{2}}{3} G_F\, p \left[\frac{\mathbf{E}_l}{m_W^2} + \frac{\mathbf{E}_\nu}{m_Z^2}\right] + \sqrt{2} G_F \int \frac{d^3\mathbf{p}'}{(2\pi)^3} (\varrho_{\mathbf{p}'} - \bar{\varrho}_{\mathbf{p}'})$$

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Flavor oscillations

Matter effects

QKE $\frac{d\varrho_p}{dt} = -i\left[\mathcal{H}_p, \varrho_p\right] + C(\varrho_p)$

Theory:

Polarization basis

- Polarization basis = Pauli matrix decomposition

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2x2 complex matrix

4 real values

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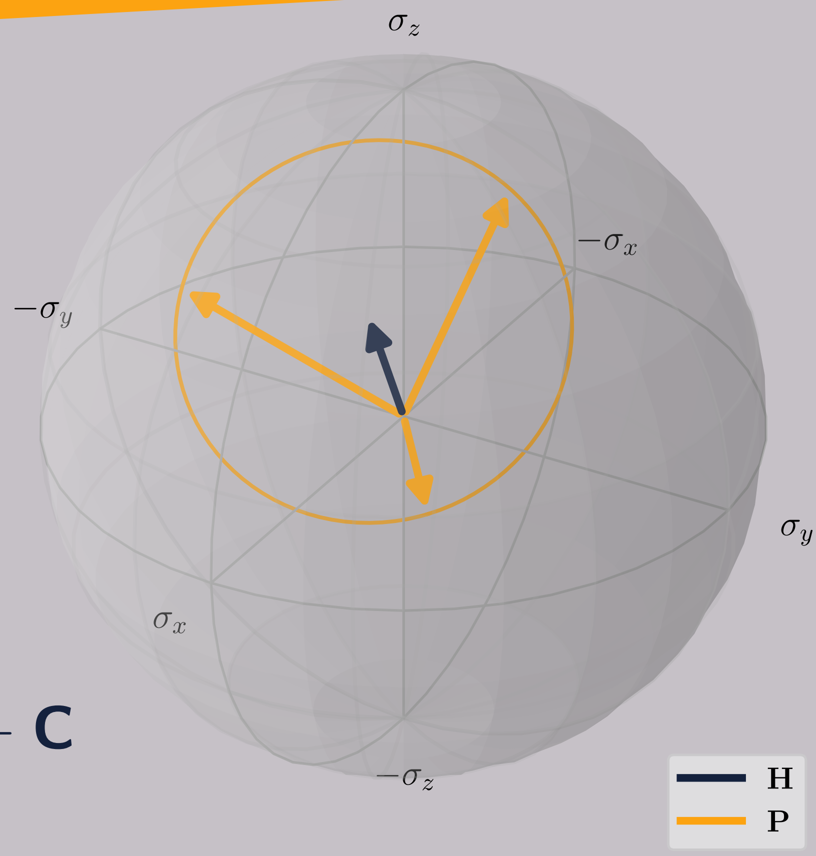

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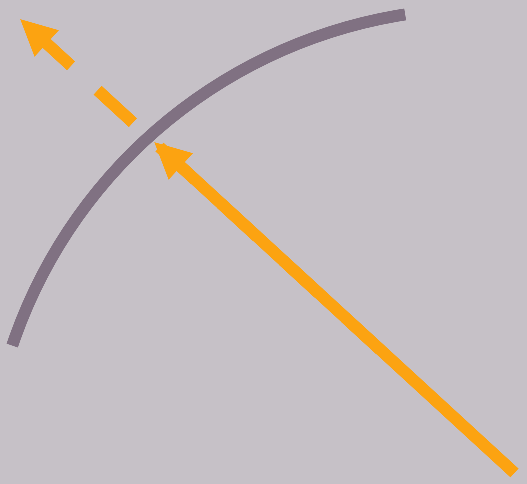

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Out of Equilibrium X ν_α $e^\pm$ γ Thermal bath

Theory:
Temperature evolution

$$\frac{d\rho}{dt} = -3H(\rho + P)$$

Total energy conservation

Out of Equilibrium X ν_α $e^\pm$ γ Thermal bath

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Temperature evolution

$$\frac{d\rho}{dt} = -3H(\rho + P)$$

Total energy conservation

$$\frac{dT_\gamma}{dt} = \frac{\Gamma_X \rho_X - 4H\left(\rho_\gamma + \rho_\nu\right) - 3H\left(\rho_e + P_e\right) - \dfrac{d\rho_\nu}{dt}}{\left.\dfrac{\partial \rho_e}{\partial T_\gamma}\right|_{a(t)} + \left.\dfrac{\partial \rho_\gamma}{\partial T_\gamma}\right|_{a(t)}}$$

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Temperature evolution

$$\frac{d\rho}{dt} = -3H(\rho + P)$$

Total energy conservation

Decay

$$\frac{dT_\gamma}{dt} = \frac{\Gamma_X \rho_X - 4H\left(\rho_\gamma + \rho_\nu\right) - 3H\left(\rho_e + P_e\right) - \frac{d\rho_\nu}{dt}}{\left.\frac{\partial \rho_e}{\partial T_\gamma}\right|_{a(t)} + \left.\frac{\partial \rho_\gamma}{\partial T_\gamma}\right|_{a(t)}}$$

Theory:

Temperature evolution

$$\frac{d\rho}{dt} = -3H(\rho + P)$$

Total energy conservation

Decay — Universe expansion

$$\frac{dT_\gamma}{dt} = \frac{\underbrace{\Gamma_X \rho_X}_{\text{Decay}} \underbrace{- 4H(\rho_\gamma + \rho_\nu) - 3H(\rho_e + P_e)}_{\text{Universe expansion}} - \frac{d\rho_\nu}{dt}}{\left.\frac{\partial \rho_e}{\partial T_\gamma}\right|_{a(t)} + \left.\frac{\partial \rho_\gamma}{\partial T_\gamma}\right|_{a(t)}}$$

Out of Equilibrium — X — ν_α — $e^\pm$ — γ — Thermal bath

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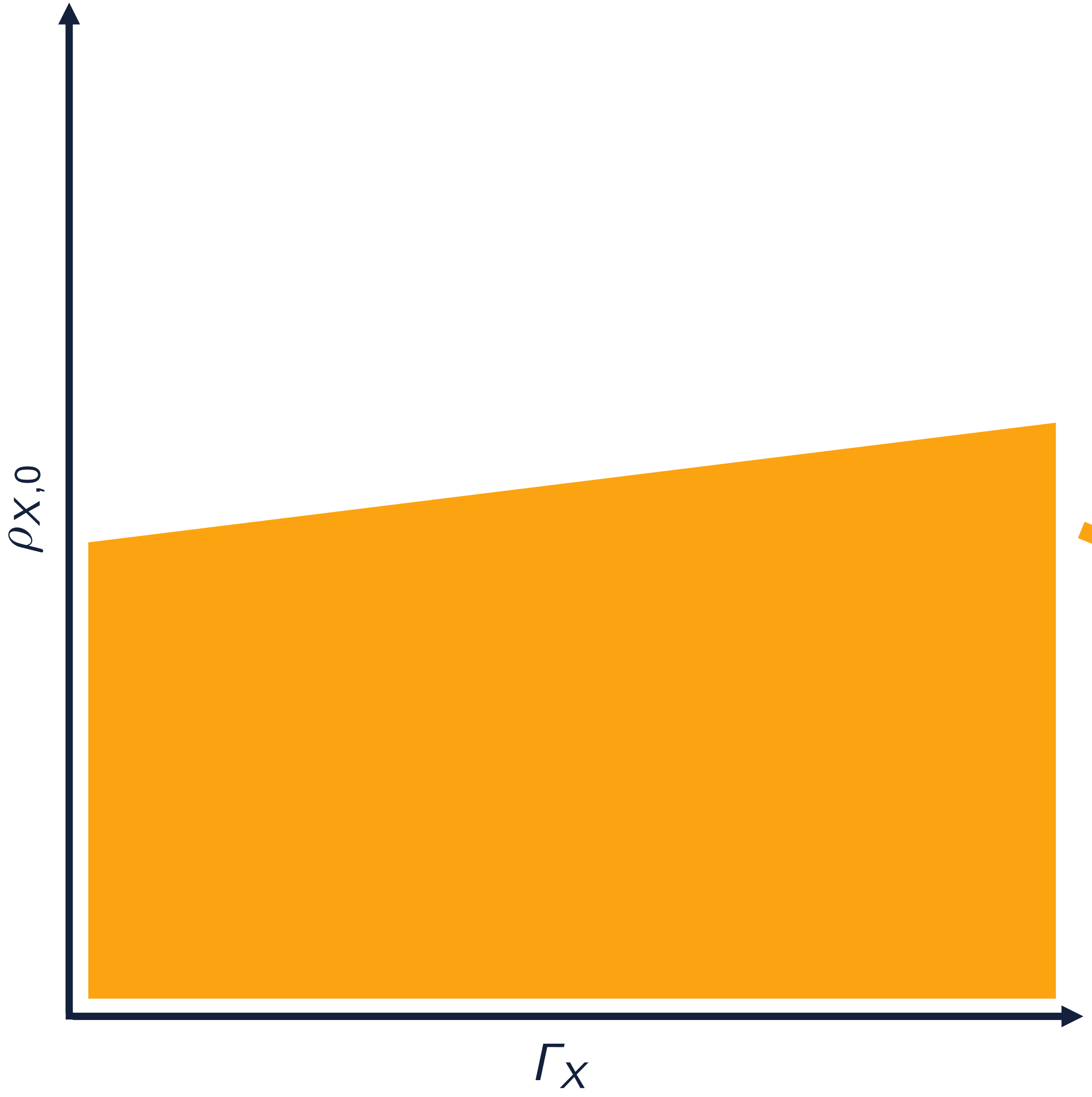
Results:

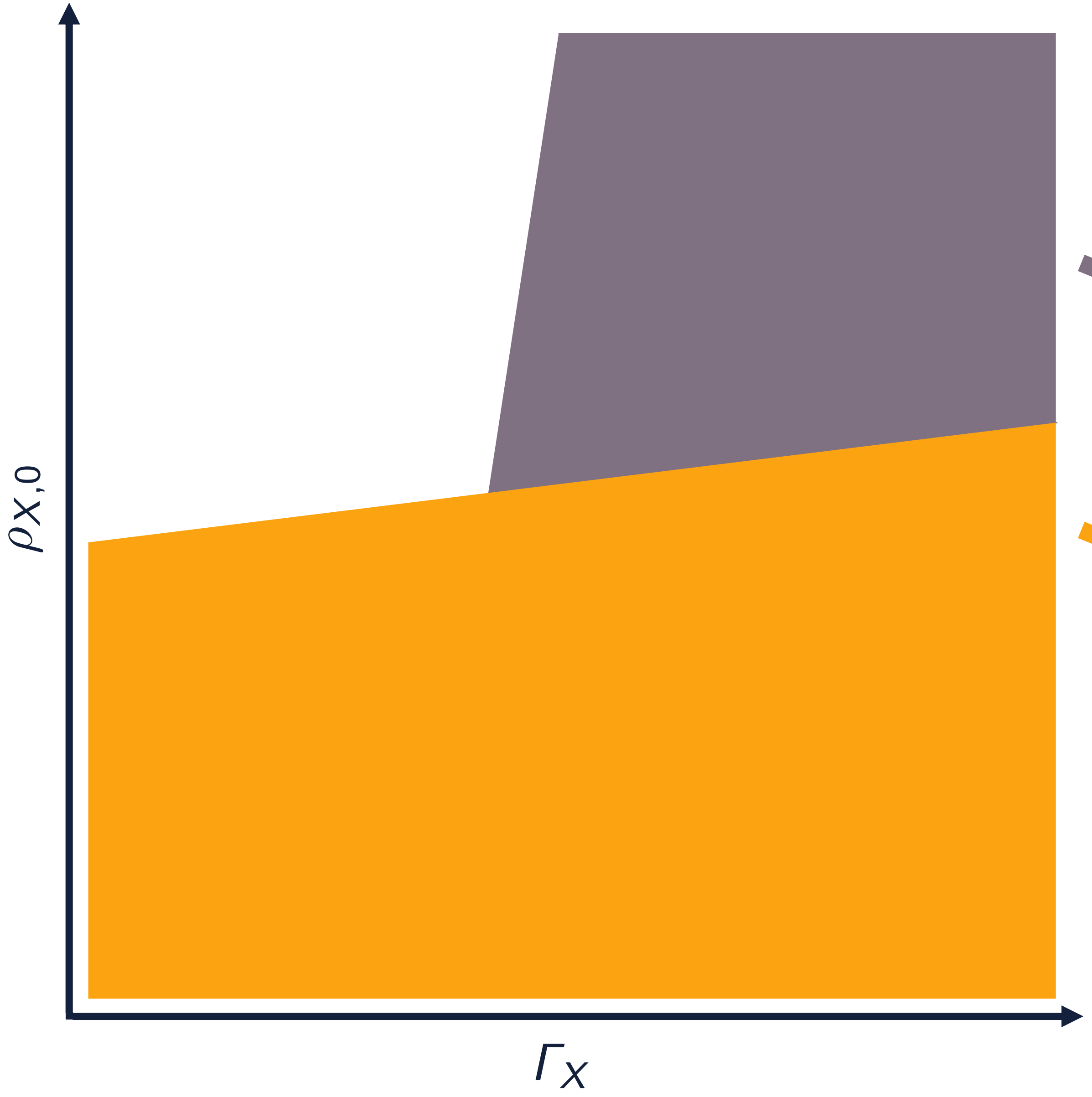
Expectation



Recover Standard cosmology

Results:

Expectation



Small deviation from Standard Cosmology

Recover Standard cosmology

Results:

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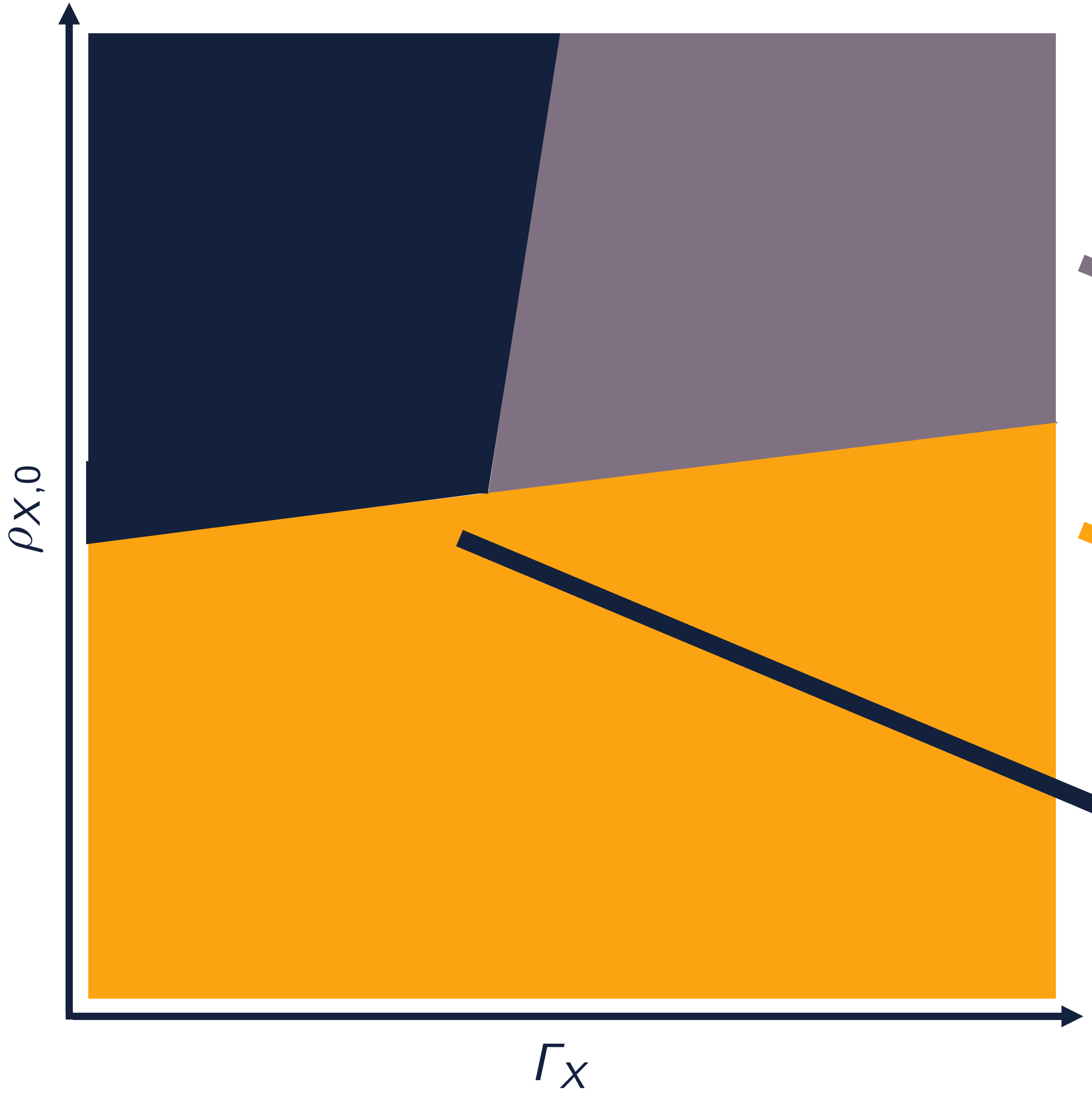


Small deviation from Standard Cosmology

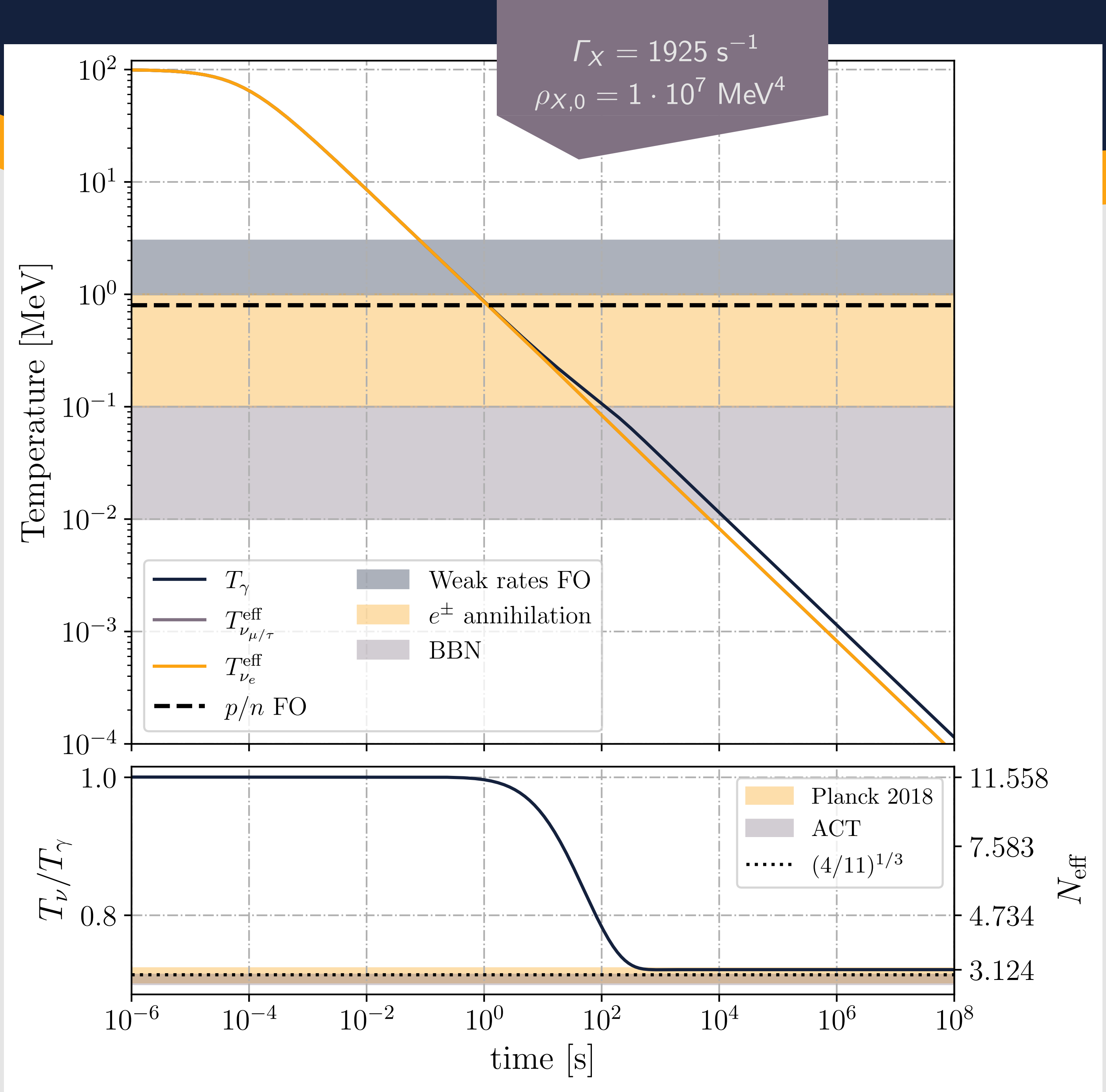
Recover Standard cosmology

Big deviation from Standard cosmology

Results:

Temperature evolution

(Standard-ish case)



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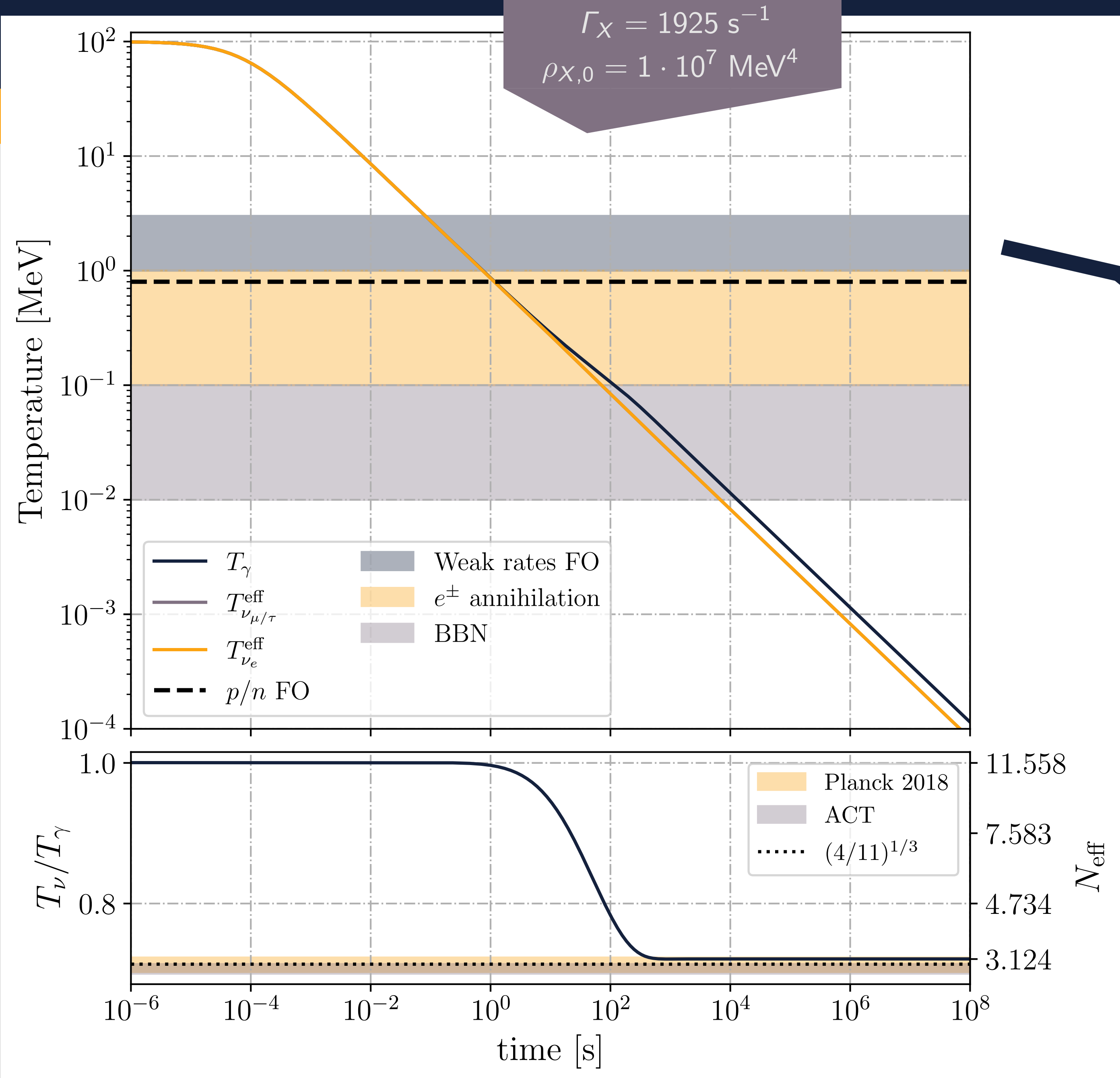


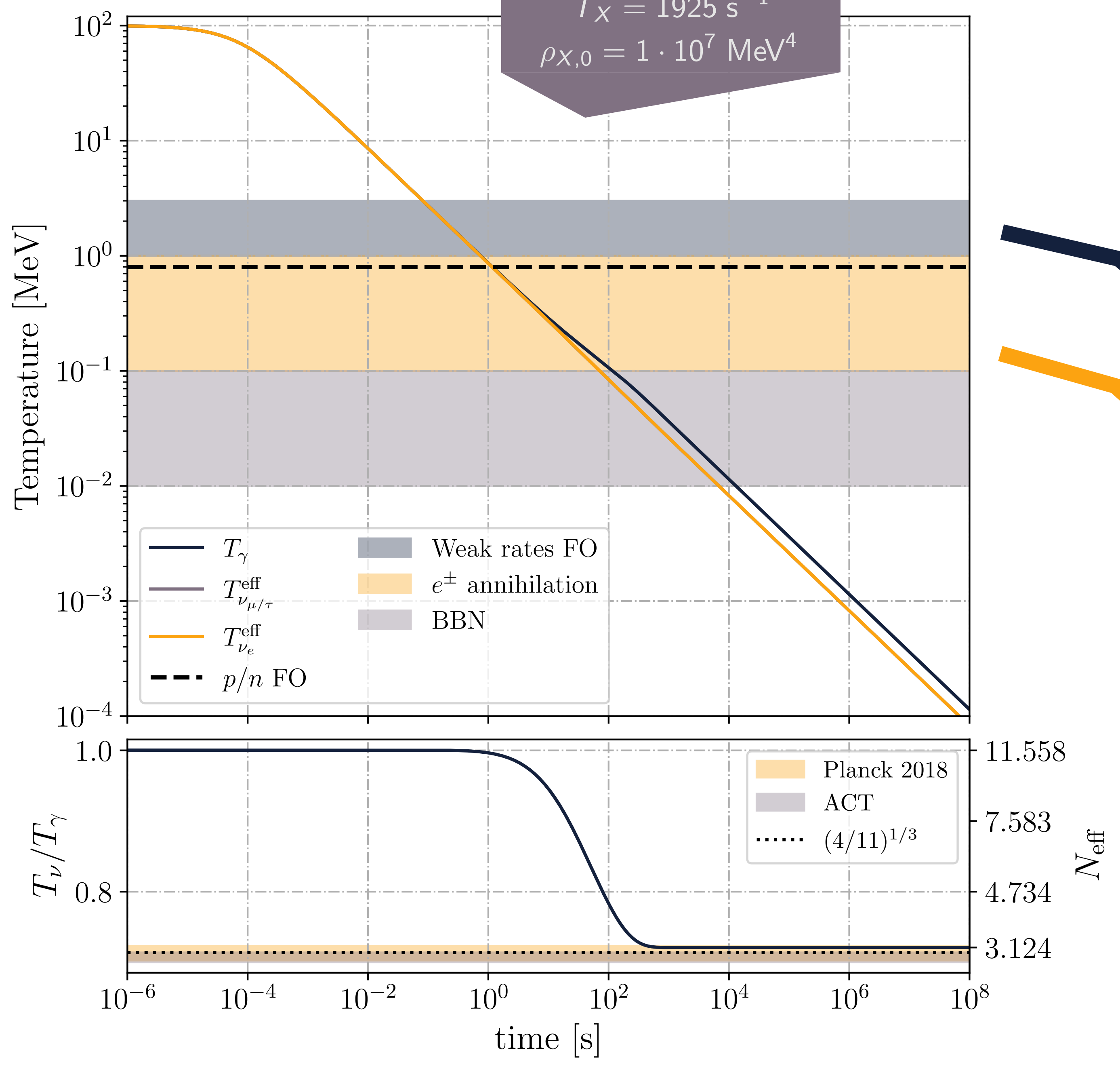
Neutrinos decouple

Results:

Temperature evolution

(Standard-ish case)

$\Gamma_X = 1925\ \mathrm{s}^{-1}$
$\rho_{X,0} = 1 \cdot 10^7\ \mathrm{MeV}^4$

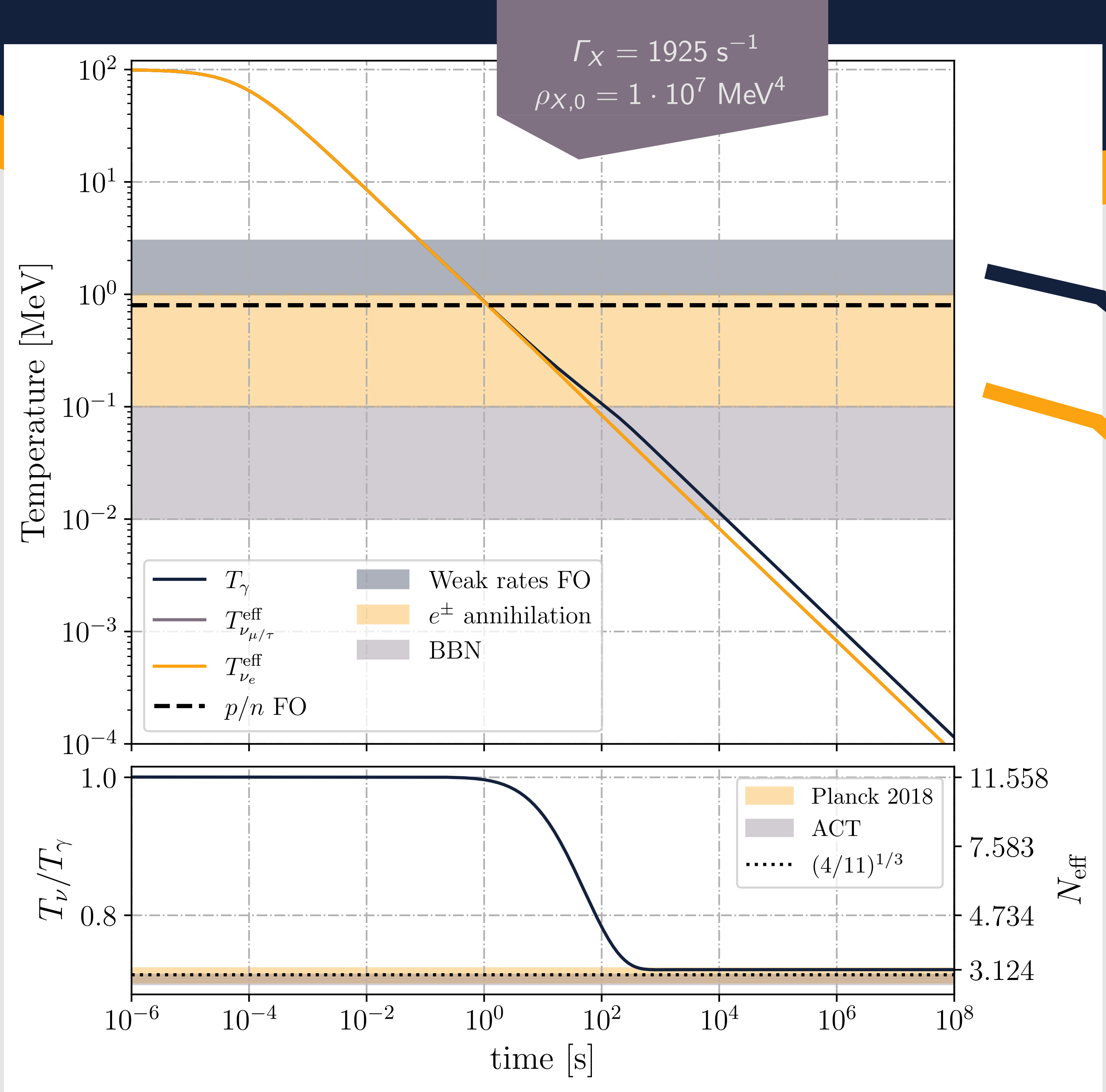


Neutrinos decouple

Energy from annihilation goes mostly to the bath

Results:

Temperature evolution
(Standard-ish case)



Neutrinos decouple

Energy from annihilation goes mostly to the bath

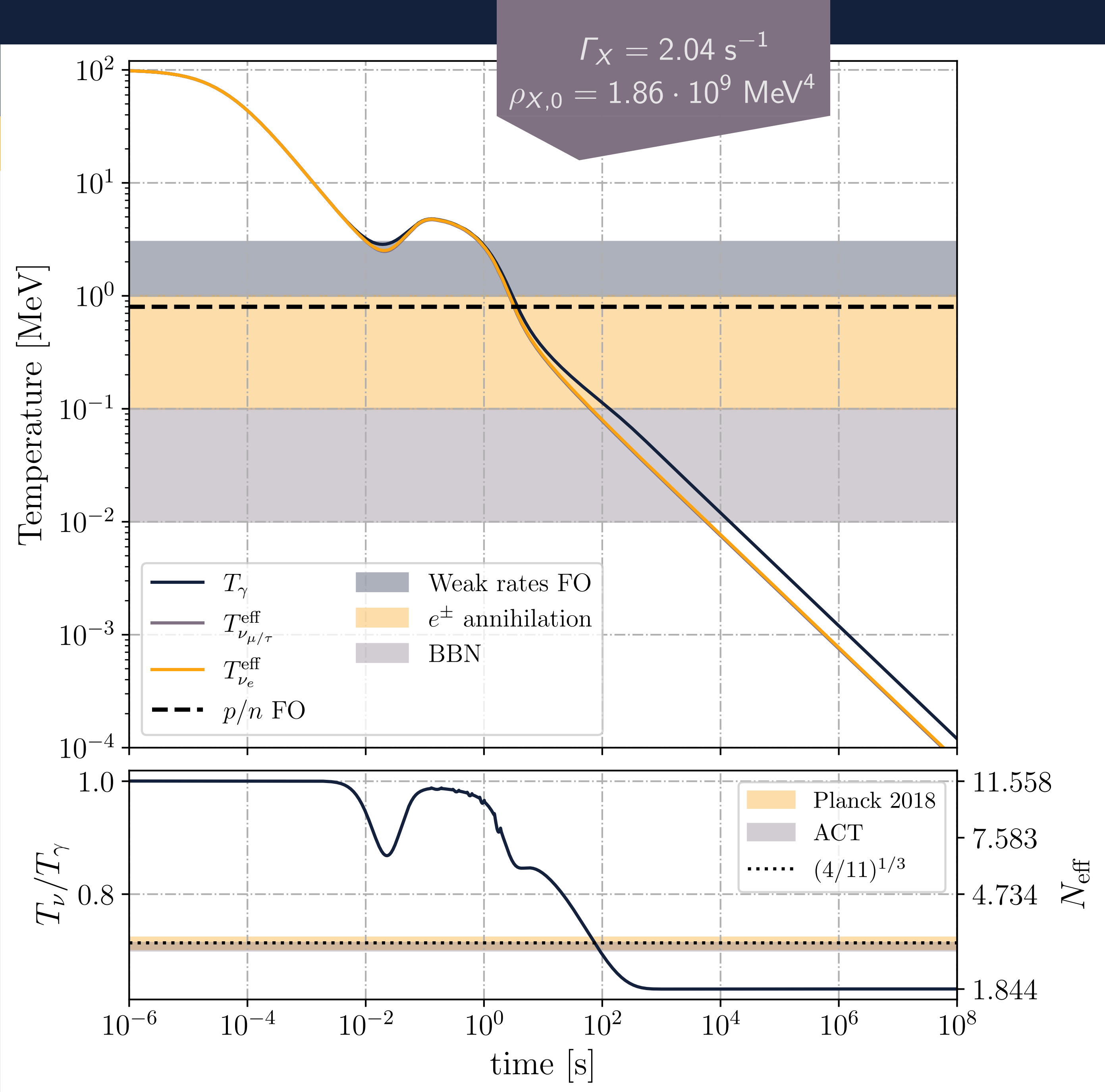
$$N_{\mathrm{eff}} = 3\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4$$

Relativistic degrees of freedom

Results:

Temperature evolution

(Extreme case)



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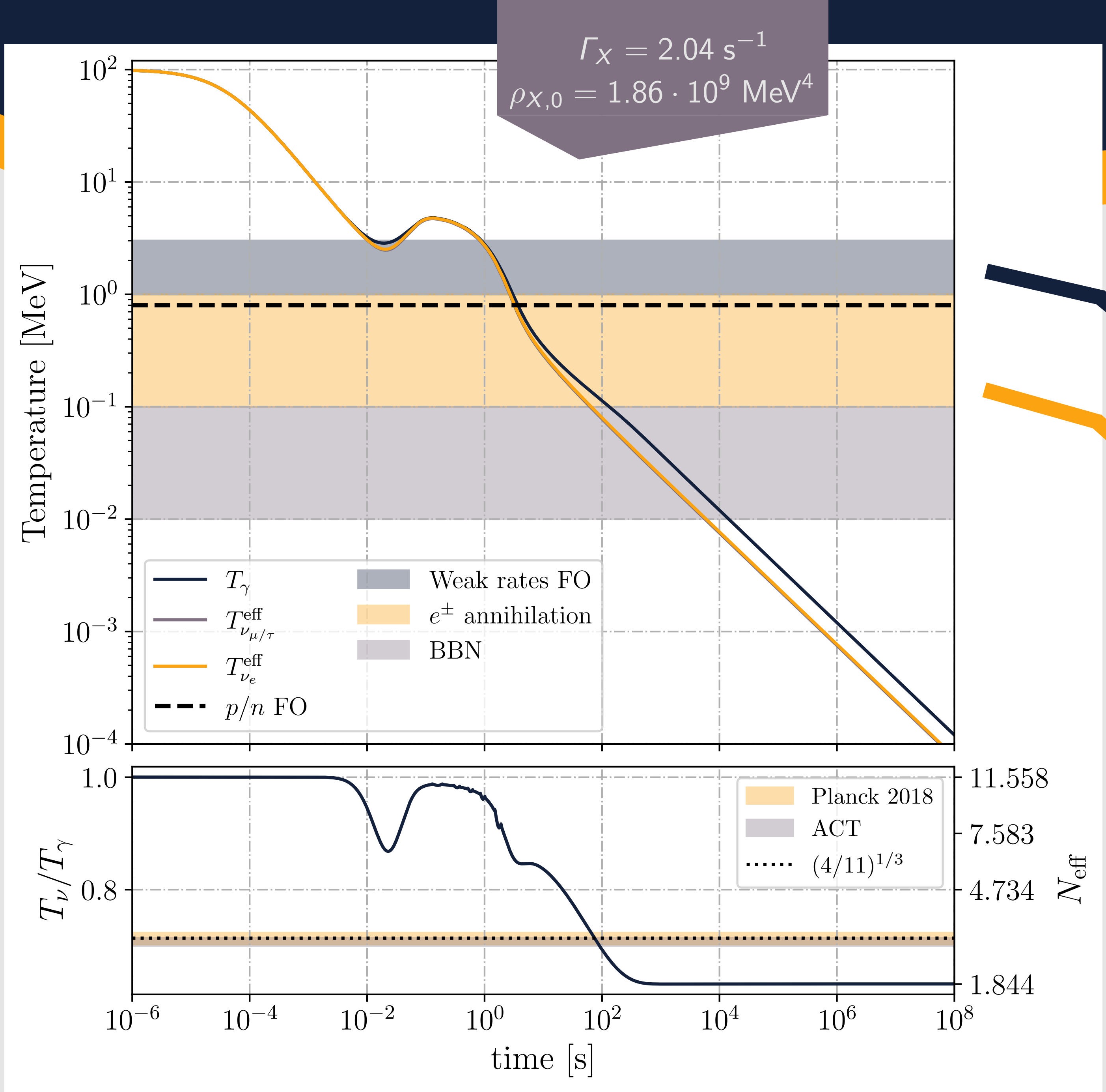

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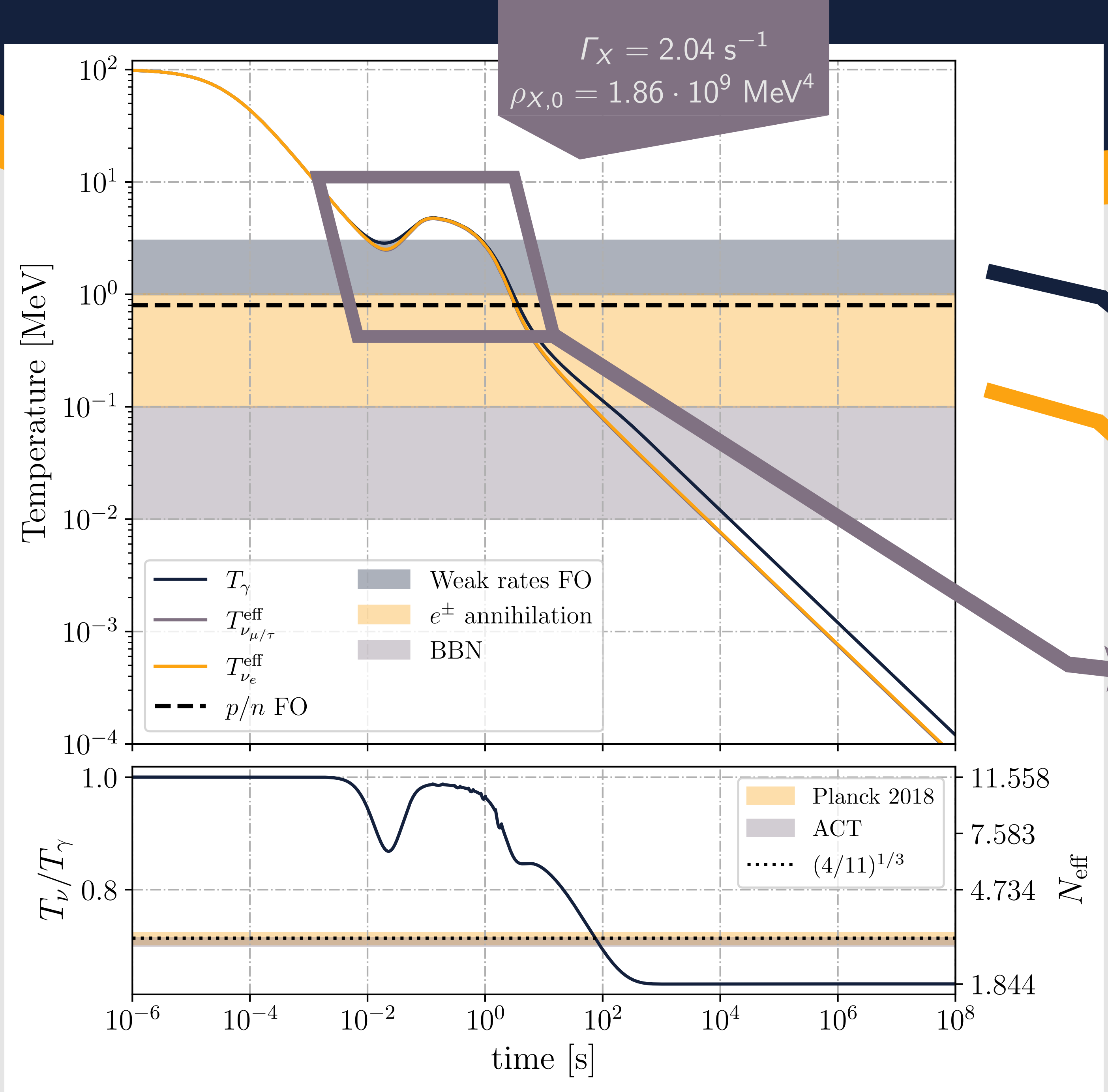

Neutrinos decouple

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Incomplete thermalization

Results:

Temperature evolution
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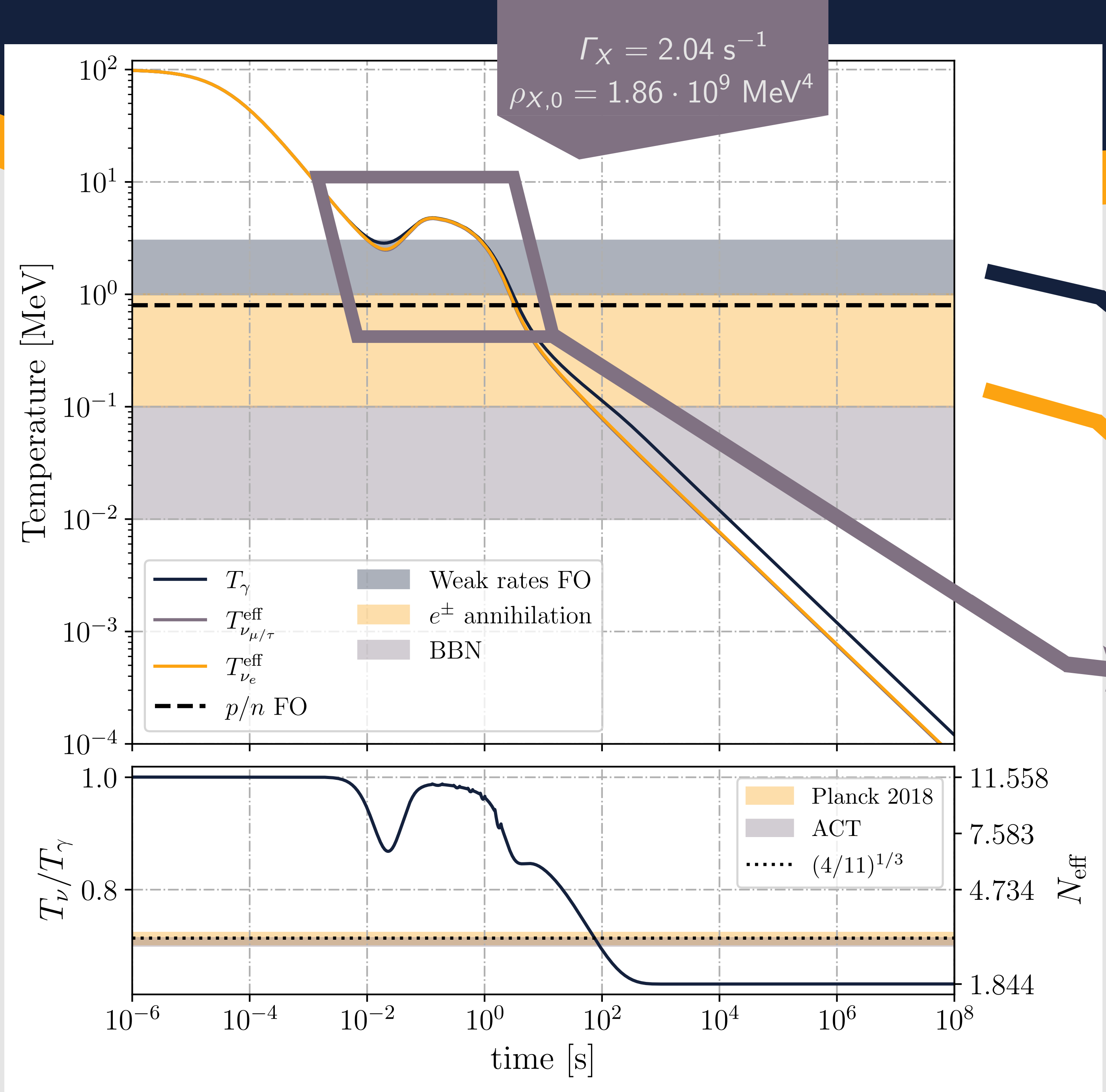

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Relativistic degrees of freedom

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Conclusions

1

Reheating close to BBN can have an impact on observables

Conclusions

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Reheating close to BBN can have an impact on observables

We are able to solve the whole neutrino distribution, w/o assuming Fermi-Dirac

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Conclusions

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Reheating close to BBN can have an impact on observables

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We are able to solve the whole neutrino distribution, w/o assuming Fermi-Dirac

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To find real constraints, it is important to consider all decay channels

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Future work

1

Adding hadronic decays of the X particle

Future work

1

Adding hadronic decays of the X particle

2

Adding neutrino decays of the X particle

Future work

1

Adding hadronic decays of the X particle

2

Adding neutrino decays of the X particle

3

Merge the code with CLASS to obtain CMB observables

Thank you for your attention

Happy to answer any questions