Neutrino decoupling in the early Universe: Constraints on light Z′ bosons and the ATOMKI X17

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Work with

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Early Universe

In the very early Universe after reheating all particle species were relativistic and in thermal equilibrium

When interaction rates fell below expansion rate, some particle species decoupled from equilibrium and evolved separately in their own equilibrium

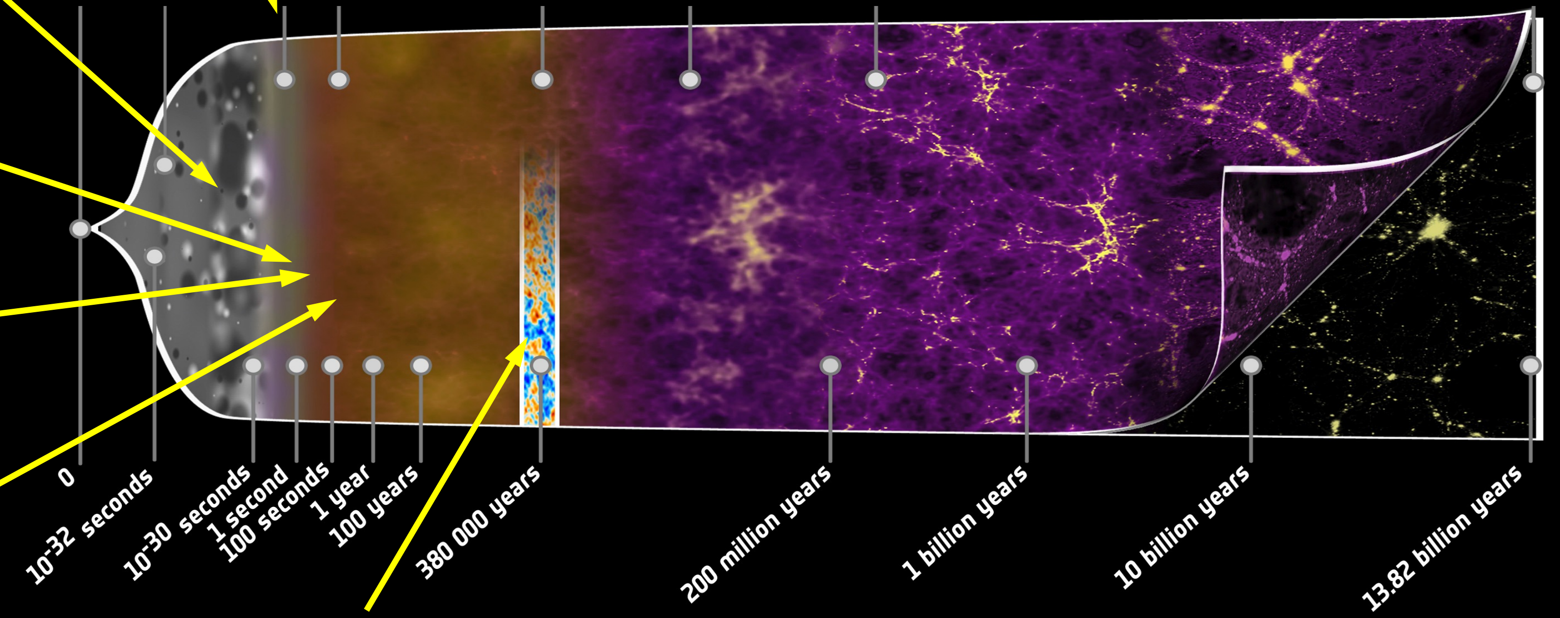
Dark matter

Electroweak phase transition
(t ~ picoseconds)

Neutrino decoupling from plasma
(t ~ 1 second)

Electron-positron annihilation
(t ~ 5 seconds)

Big Bang Nucleosynthesis
(t ~ 3 minutes)



Recombination, CMB
(t = 380 000 years)

Image from Planck collaboration http://www.cosmos.esa.int

Timeline for the neutrinos

- Neutrinos decouple from photons and electrons:

  T ~ 1 MeV or at time **t ~ 1 s** (redshift $z \sim 6\times10^9$)
- e^+e^- annihilation:

  T ~ 0.5 MeV or at time **t ~ 6 s** (redshift $z \sim 4\times10^9$)

How do we know?

- Interaction rate for $e^+e^- \leftrightarrow \nu\nu$ = Hubble rate gives T=1 MeV
- e^+e^- annihilate when $T < m_e$

After decoupling, neutrinos form a separate neutrino background with its own temperature – no interaction with photons and electrons

Note that neutrino decoupling and e^+e^- annihilation are close in time!

Processes:

$$e^+e^- \leftrightarrow \bar{\nu}_i\nu_i$$
$$e^\pm\nu_i \leftrightarrow e^\pm\nu_i$$
$$e^\pm\bar{\nu}_i \leftrightarrow e^\pm\bar{\nu}_i$$
$$\nu_i\nu_j \leftrightarrow \nu_i\nu_j$$
$$\nu_i\bar{\nu}_j \leftrightarrow \nu_i\bar{\nu}_j$$
$$\bar{\nu}_i\nu_i \leftrightarrow \bar{\nu}_j\nu_j$$

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Neutrino decoupling

Entropy conservation and no. of d.o.f. before and after decoupling gives:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

This assumes *instantaneous* decoupling.

Today:
T_γ=2.73 K
T_ν=1.95 K

More realistic: Neutrino decoupling is not instantaneous, overlaps with e^+e^- annihilation, affected by SM interactions ***and potentially by BSM interactions***

➢ Define **N_{eff} = effective no. of neutrinos**

$$\boxed{N_\mathrm{eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_\mathrm{rad} - \rho_\gamma}{\rho_\gamma}}$$

If only γ and ν are present, then N_{eff} is related to ratio of temperatures:

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

N_{eff}=3 for instantaneous decoupling

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Neutrino decoupling as probe of new physics

N_{eff} is determined from the **cosmic microwave background** (95% CL):

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$$

[Planck Collaboration, 1807.06209]

SM prediction:
Take into account interactions and that neutrinos are not completely decoupled at e^+e^- annihilation. State-of-the-art calculation:

$$N_{\rm eff} = 3.045$$

[Work by several groups:
Mangano et al hep-ph/0506164; de Salas & Pastor, 1606.06986;
Bennett et al, 1911.04505; Froustey & Pitrou, 1912.09378]

There is room for BSM contributions to Neff, and BSM can be constrained!

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Calculation of neutrino decoupling

→Calculations of Neff are computationally expensive,
– not feasible for BSM models with parameter scans

→Many earlier BSM studies: instantaneous decoupling
– does not give correct N_{eff}

This situation was addressed by Miguel Escudero in a series of papers [arXiv:1812.05606, 2001.04466,1901.02010]

→ We implement Z' in his code **NUDEC_BSM**

NUDEC_BSM uses integrated Boltzmann equation obtained from the Liouville equation for the distribution functions
– calculation turns into a much simpler set of ODEs
– assumes FD, BE, MB distributions away from the decoupling

Liouville equation

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_i = \mathcal{C}[f_i]$$

$$H^2 = \frac{8\pi G}{3}\rho$$

Collision term, describes interactions

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In the end: evolution equations for T_γ and T_ν

Evolution for **SM only**:

$$\frac{dT_\gamma}{dt} = -\frac{4H\rho_\gamma + 3H\left(\rho_e + p_e\right) + \frac{\delta\rho_{\nu_e}}{\delta t} + 2\frac{\delta\rho_{\nu_\mu}}{\delta t}}{\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma}}$$

$$\frac{dT_{\nu_\alpha}}{dt} = -HT_{\nu_\alpha} + \frac{\delta\rho_{\nu_\alpha}}{\delta t} \Big/ \frac{\partial\rho_{\nu_\alpha}}{\partial T_{\nu_\alpha}}$$

Energy transfer rates, obtained by integrating collision terms

QED corrections not shown here, included in the calculation

The particle physics is in the **energy transfer rates** – contain decay rates and cross sections for all included processes

N_{eff} is then related to the ratio of T_ν and T_γ

BSM: For Z′ there will be another equation for the Z′ temperature
– the most important contribution is from Z′ ↔ e^+e^-

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Why we are doing this: The ATOMKI/X17 anomaly

- An experiment at ATOMKI in Hungary saw a resonance in an excess of e^+e^- in nuclear transitions from excited states [Krasznahorkay et al]

  2016: 6.8σ in ^{8}Be* transition ($^8\mathrm{Be}^* \rightarrow {}^8\mathrm{Be} + e^+e^-$)

  2019: 7.2σ in ^{4}He* transition

  2023: 4.2σ in ^{12}C* transition
- Can be interpreted as a bosonic X17 particle: Scalars/pseudoscalars disfavored from parity, Z′ possible
- The PADME experiment searched for it: Small excess at 16.9 MeV – 2.5σ (local), 1.8σ (global)
- No independent confirmation of ATOMKI yet, but PADME has taken more data

Slide adapted from a talk by Johan Rathsman in Uppsala last week

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Constraints on X17

There are many, many experimental constraints on X17 and proposed ways to search for it. Two examples:

- Light Z′ generate non-standard neutrino interactions (NSI) affecting propagation. We put constraints using IceCube data.
  [RE, Hiçyılmaz, Moretti, Pérez de los Heros, Waltari, arXiv:2404.04717]
- X17 can contribute to coherent elastic neutrino-nucleus scattering (CEvNS). Existing experiments as well as proposed experiments (at ESS).
  [Cederkäll, Hiçyılmaz, Lytken, Moretti, Rathsman, 2509.15128, 2603.15246, 2605.10689]

Also constraints from NA64, KLOE, NA48, TEXONO

Here we'll introduce another constraint from cosmology

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General Z′ and ATOMKI anomaly

- Start here with a generic Z′ simplified model:

$$\mathcal{L}^{Z'} = C_L^{ll'}\, \bar{\nu}_l\, \gamma^\mu P_L \nu_{l'} Z'_\mu + \bar{l}\, \gamma^\mu \left(C_L^{ll'} P_L + C_R^{ll'} P_R \right) l' Z'_\mu$$

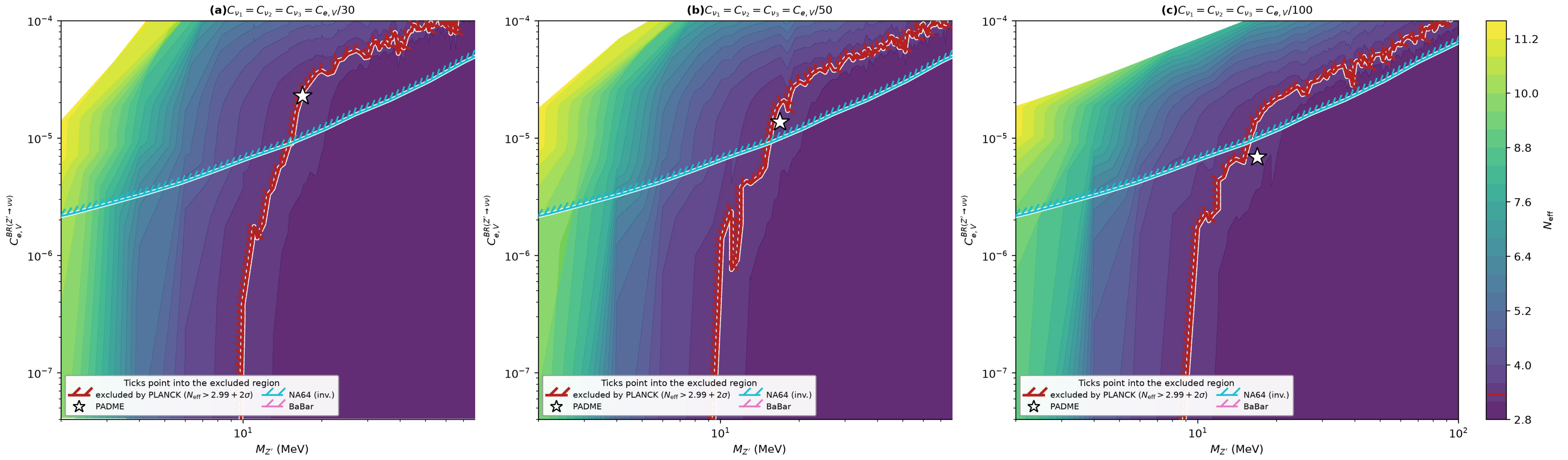
- Use also explicit model for the X17 used in our previous paper on IceCube constraints [model by Hiçyılmaz, Khalil, Moretti and others]
- For generic Z′ model: arbitrary mass in 1–100 MeV region
- This model is not supposed to be realistic but you can read off allowed couplings (e.g. it is not anomaly free)

Model independent examples

Star = PADME fit   Lines show NA64 bound and N_{eff} bound

$C_{e,V} \times BR(Z' \to \nu\nu)^{1/2}$

Preliminary!



$M_{Z'}$

Generally, lighter Z′ are excluded by N_{eff}

Conclusions

- Light particles that interact with neutrinos and electrons may affect neutrino decoupling one second after the Big Bang
- This provides experimental bounds on such particles
- We have computed bounds on Z′ with masses around MeV scale
- Some of these Z′ might explain the ATOMKI anomaly

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Backup slides

Details on calculation

The collision term is complicated, which gives a large number of coupled integro-differential equations. For example for ψ+X→Y

$$\mathcal{C}[f_\psi] = -\frac{1}{2E_\psi}\sum_{X,Y}\int\prod_i d\Pi_{X_i}\prod_j d\Pi_{Y_j}\,(2\pi)^4\delta^4(p_\psi + p_X - p_Y)\times$$

$$\left[|\mathcal{M}|^2_{\psi+X\to Y}\, f_\psi \prod_i f_{X_i}\prod_j\left(1\pm f_{Y_j}\right) - |\mathcal{M}|^2_{Y\to\psi+X}\prod_j f_{Y_j}\left(1\pm f_\psi\right)\prod_i\left(1\pm f_{X_i}\right)\right]$$

Integrate Liouville equation over phase spaces of particles. This gives ODEs:

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_i = \mathcal{C}[f_i] \quad\Rightarrow\quad \begin{aligned} &\frac{dn}{dt} + 3Hn = \frac{\delta n}{\delta t} \\ &\frac{d\rho}{dt} + 3H\left(\rho + p\right) = \frac{\delta \rho}{\delta t} \end{aligned}$$

Energy transfer rates

Energy transfer rates

Obtained by integrating the collision term and averaging over momenta. For SM only, they are (for densities)

$$\frac{\delta\rho_{\nu_e}}{\delta t} = \frac{G_F^2}{\pi^5}\left[\left(1+4s_W^2+8s_W^4\right)F\left(T_\gamma, T_{\nu_e}\right) + 2F\left(T_{\nu_\mu}, T_{\nu_e}\right)\right]$$

$$\frac{\delta\rho_{\nu_\mu}}{\delta t} = \frac{G_F^2}{\pi^5}\left[\left(1-4s_W^2+8s_W^4\right)F\left(T_\gamma, T_{\nu_\mu}\right) - F\left(T_{\nu_\mu}, T_{\nu_e}\right)\right]$$

$$F\left(T_1, T_2\right) = 32\left(T_1^9 - T_2^9\right) + 56 T_1^4 T_2^4 \left(T_1 - T_2\right)$$

for Maxwell-Boltzmann statistics. In the code there are corrections for FD and BE statistics.

Processes:

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