Towards the SM N_{eff}

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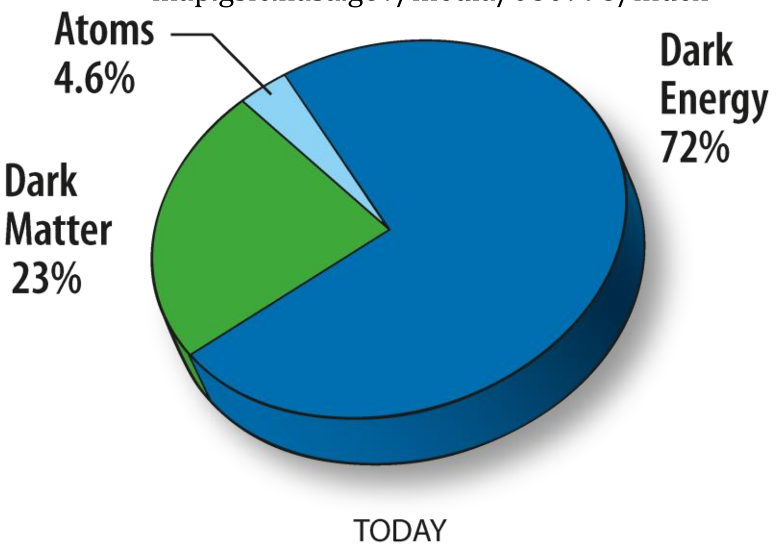
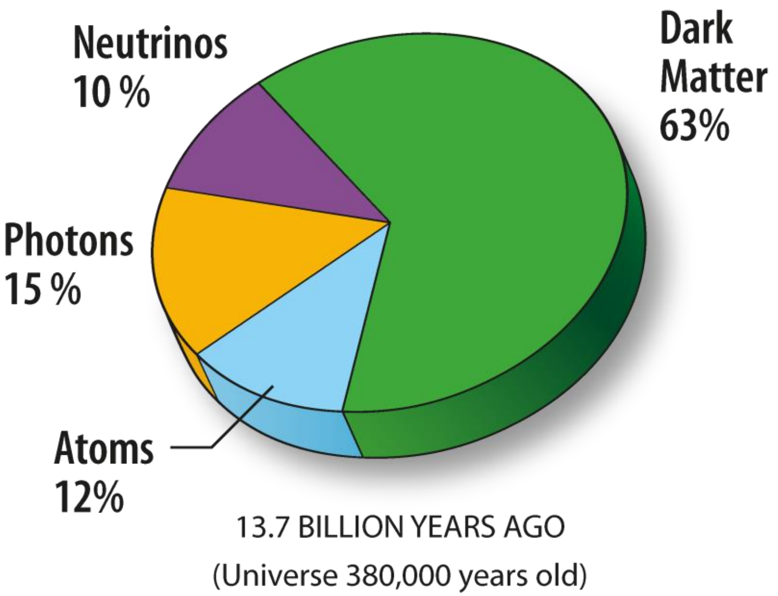
Effective number of neutrinos

- How is the **total energy density** is divided up?
- $\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right]\rho_\gamma$
- Current value $\boldsymbol{N_{\text{eff}} = 3.044}$ (Gariazzo, de Salas, Pastor, 2019), but before, discrepant result
- $N_{\text{eff}} = 3.052$ (Grohs et al. 2015)
- Limits precision of cosmological observables

map.gsfc.nasa.gov/media/080998/index

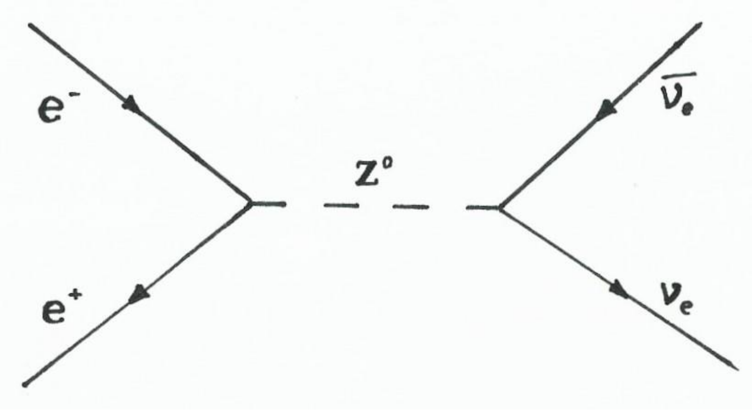




Outline

- Theory;
  - Neutrino and $e^{\pm}$ decoupling
  - **Finite temperature QED**

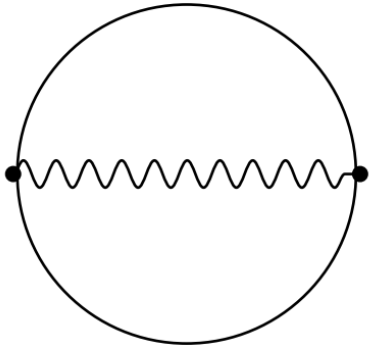
- Our work:
  - Partition function
  - Solve ODE, add next order
  - Optical Theorem → decoupling temperature



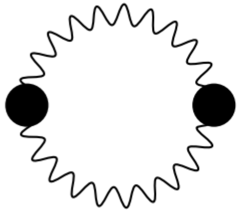
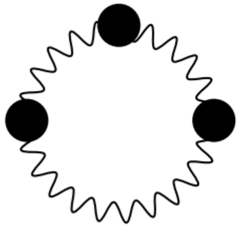
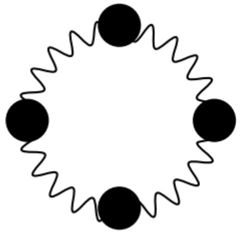
Finite T QED

- Calculate **partition function** using **FT statistical field theory**

$$\ln Z = \underbrace{\ln Z^0}_{\text{ideal gas}} + \underbrace{\ln Z^{(2)}}_{\mathcal{O}(e^2)} + \underbrace{\ln Z^{(3)}}_{\mathcal{O}(e^3)} + \cdots$$

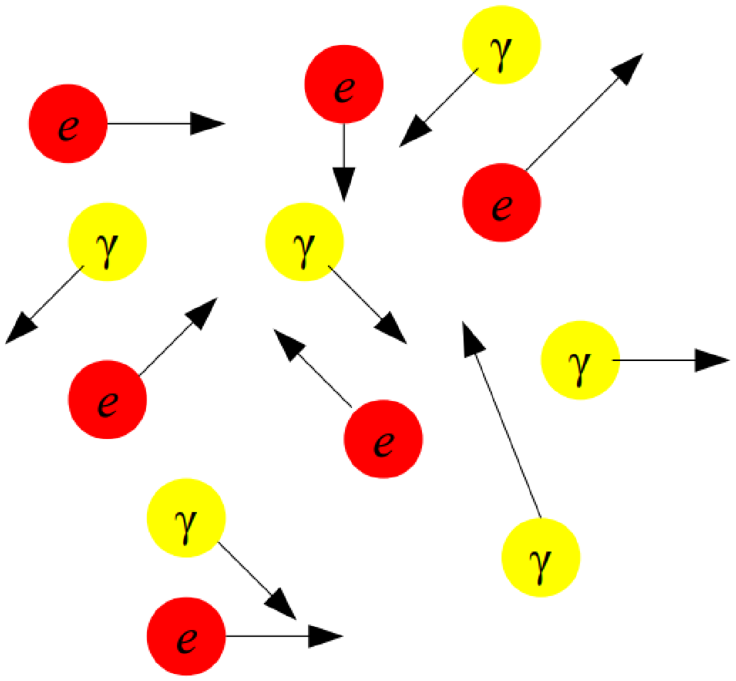
$\ln Z^{(2)} = -\frac{1}{2}$ 

Use these guys

$\ln Z^{(3)} = \frac{1}{2}\Big[\ \frac{1}{2}$  $-\ \frac{1}{3}$  $+\ \frac{1}{4}$  $+\ \cdots\ \Big]$

Ideal gas vs interactions Image

Ideal gas



Energy = kinetic energy + rest mass

Pressure = from kinetic energy

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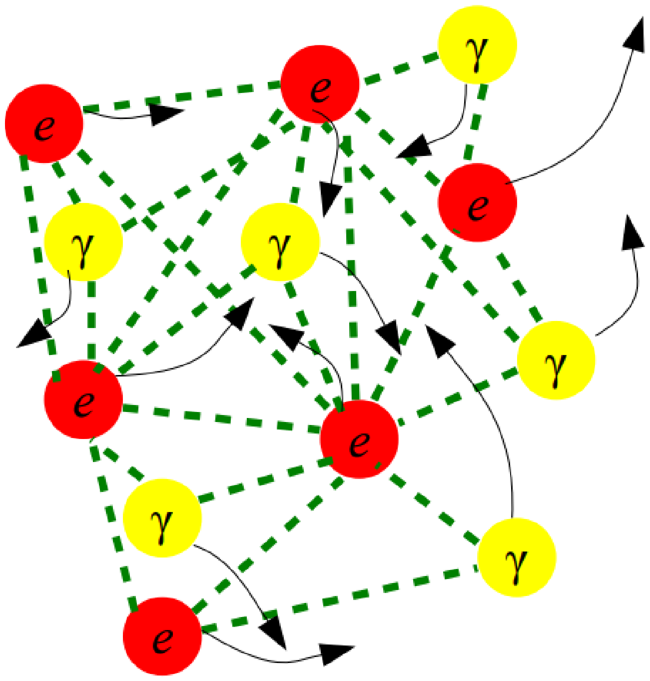
+ EM interactions



Temperature -dependent dispersion relation + Forces

Energy = **modified** kinetic energy + **T-dependent masses** + **interaction potential** energy

Pressure = from **modified** kinetic energy + **EM forces**

Modified QED equation of state

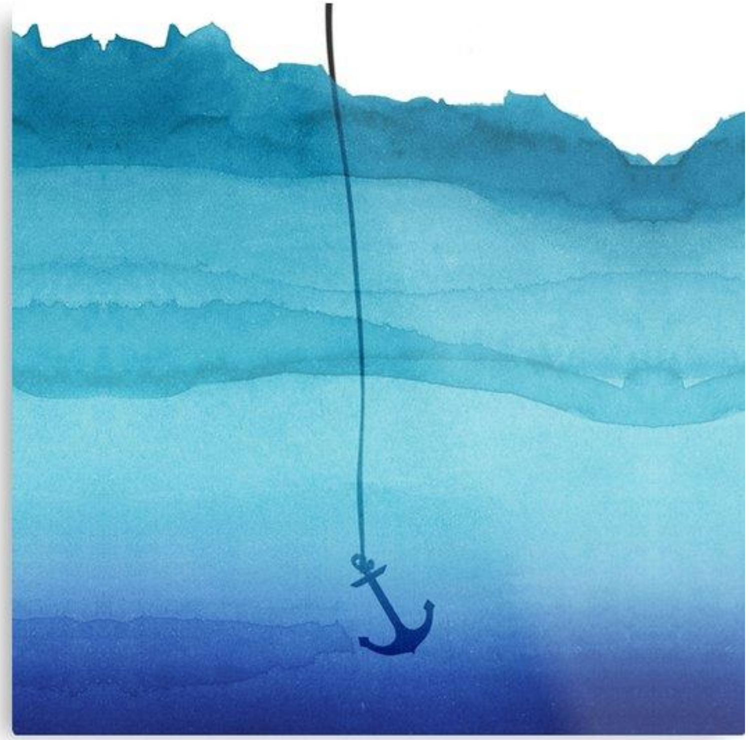
Continuity equation

Need three equations:

Continuity $$\frac{\mathrm{d}}{\mathrm{d}t}\rho = -3H(\rho + P)$$

Pressure $$P^{(n)} = T\frac{\partial \ln Z^{(n)}}{\partial V}$$

Energy density $$\rho^{(n)} = -P^{(n)} + T\frac{\partial P^{(n)}}{\partial T}$$

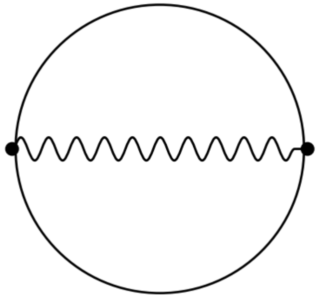


Solution leads to N_{eff}

Results part one: which method is correct?

Correct partition function gives
$N_{\text{eff}} = 3.044$

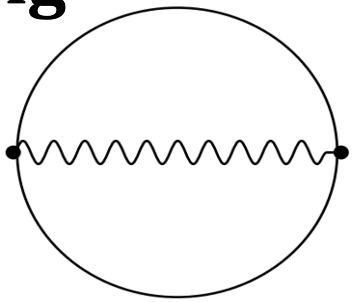
Thermal part **correct** size

$\ln Z^{(2)} = -\frac{1}{2}$ 

Miss out the factor 1/2 gives
$N_{\text{eff}} = 3.052$

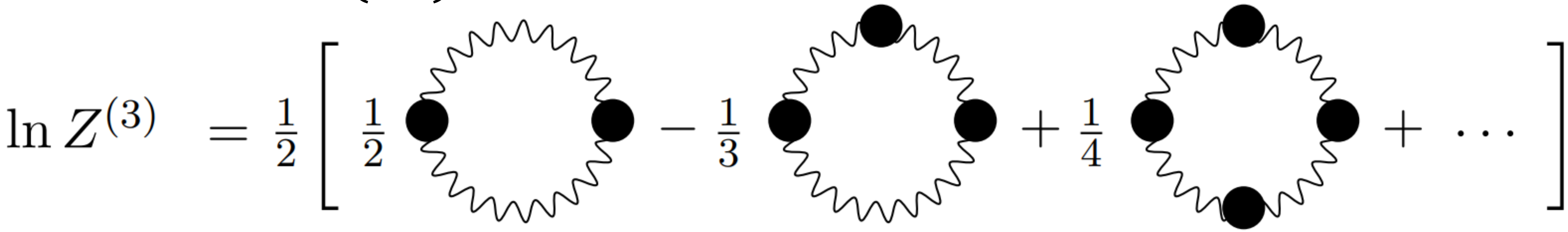
Equivalent to changing mass in **dispersion relation**.

Thermal part **too big**

$\ln Z^{(2)} = -\cancel{\frac{1}{2}}$ 

Higher Orders

- Then include $\mathcal{O}(e^3)$



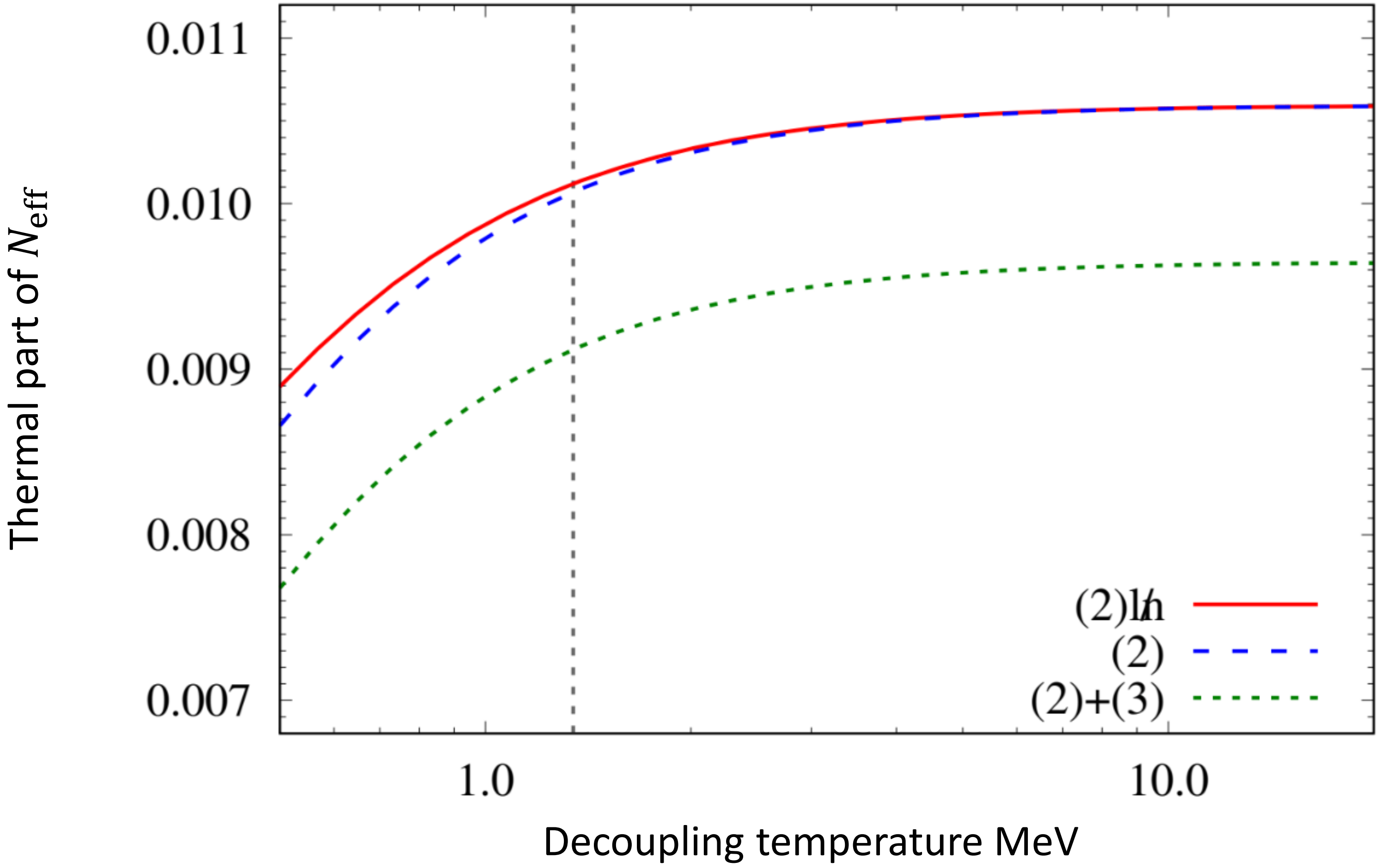
- Find a change $\Delta N_{\text{eff}}^{(3)} \simeq -0.001$

- This order is caused by **charge screening** (think Debye screening)

- What about **higher orders**? $\mathcal{O}(e^4)$ gives $\Delta N_{\text{eff}} \simeq -4 \times 10^{-6}$. **Tiny!**

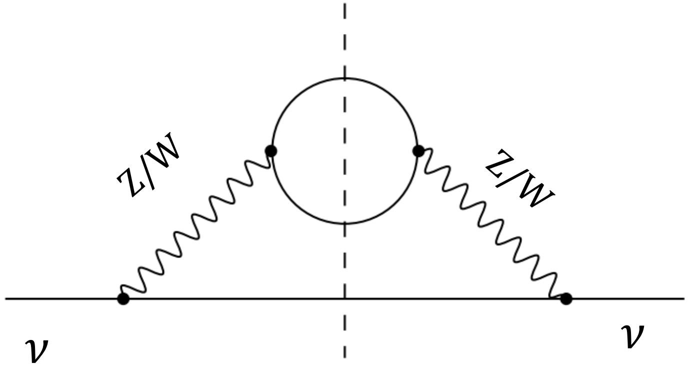
Results Part One: including $\mathcal{O}(e^3)$

- Regardless of decoupling temperature T_d, N_{eff} decreases.
- $\mathcal{O}(e^3)$ effect same size as **neutrino oscillations**
- $\therefore\ \mathcal{O}(e^3)$ should be included in full calculation



Decoupling Temperature

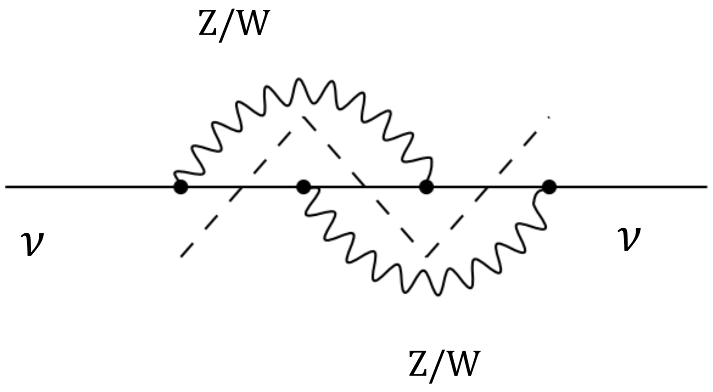
- Use **Optical theorem** to calculate Im part of self energy.
  - $\text{Im}\,(\Pi) \sim |\mathcal{M}|^2$



- Why?
  - **Thermal propagators**
  - Future work

Results:

$T_d = 1.35$ MeV



- Recover **collision integrals** from literature

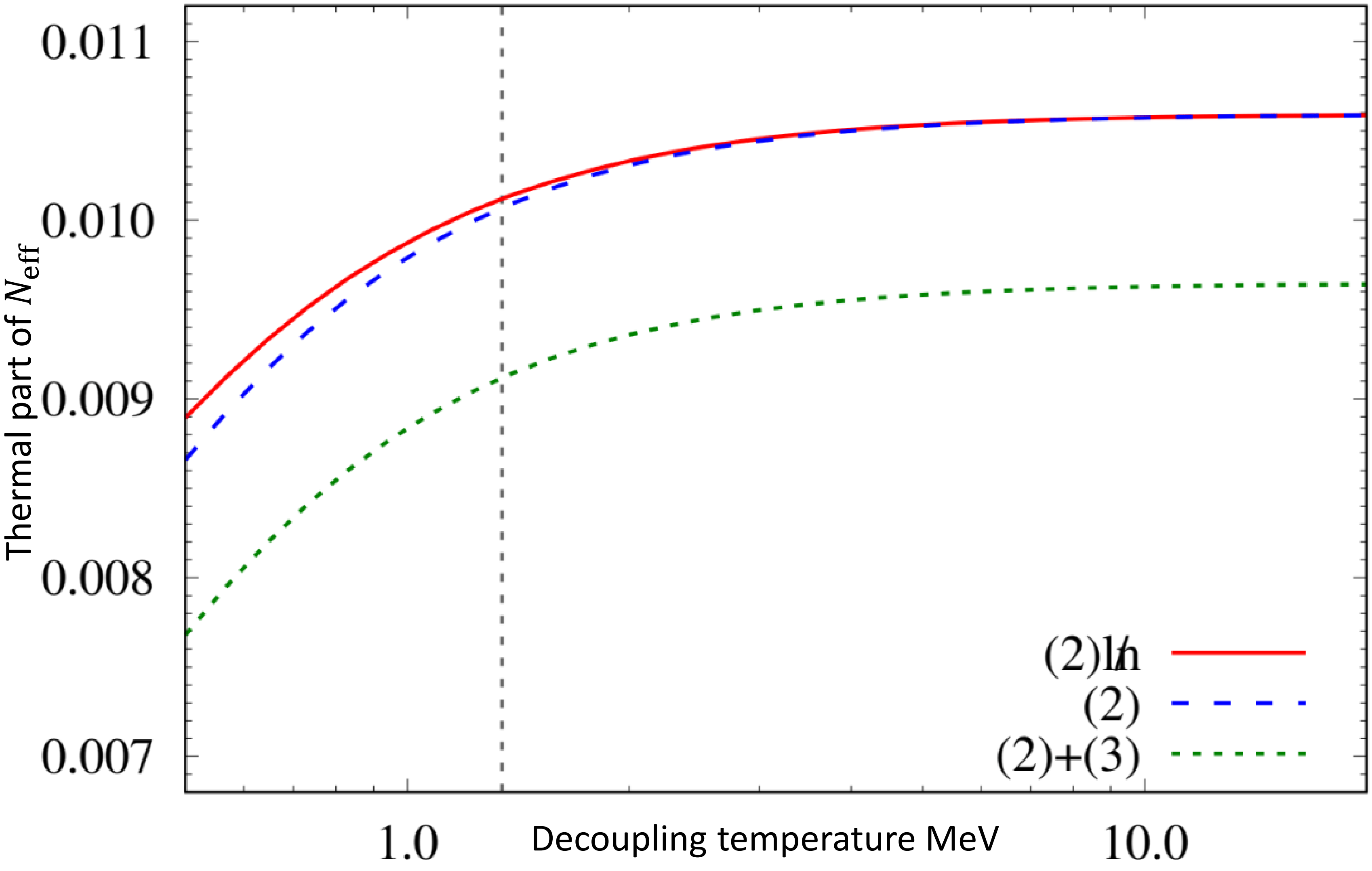
Very close to lit.

$T_d = 1.41$ MeV

(Fornengo, Kim, Song. 1997)

Results Part two

- Grey line at $T_d = 1.35$ MeV
- y-axis is part of N_{eff} not due to transport
- Becomes sensitive to how strong **weak interactions** are



Future and Conclusions

Conclusions

- Method giving $N_{\text{eff}} = 3.044$ right: remembers the ½.
- $\mathcal{O}(e^3)$ not negligible $\delta N_{\text{eff}} \simeq -0.001$
- Optical theorem can give literature results, useful going forward

Future (in progress)

- Need to include neutrino decoupling effects.
  - Preliminary results
- Add higher order effects to neutrino decoupling via optical theory

Thank you for listening!