Effective field theories: from Cosmology to Quark Gluon Plasma

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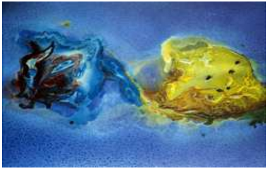
T30f - Technische Universität München

Young Scientist Workshop 2013
Ringberg, July 24^{th}

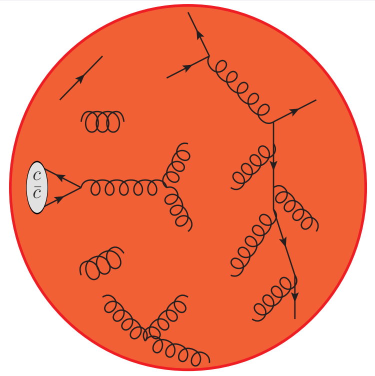


Outline

1. Motivation and introduction
2. EFT and Cosmology
3. Conclusions
4. Outlook: EFT and Quark Gluon Plasma

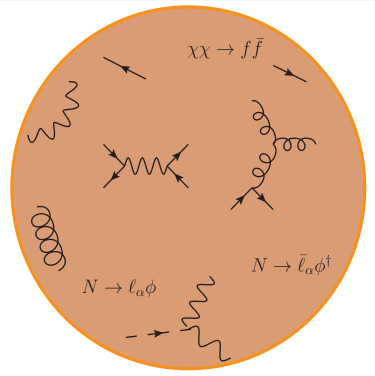
QCD and Cosmology

New phase of QCD matter



- study quark-gluon new phase
- jet quenching, quarkonia decays

Universe in its early stage



- dark matter
- baryon asymmetry

Energy scales and medium effect

Quantum field theory in hot medium:

- presence of a medium characterized with a temperature T

What are the medium induced modifications?

- particle masses or momenta bigger than T

$$M_{\chi,\mathrm{N}} \gg T\ , \quad M_Q, k \gg T$$

hierarchy of scales ⇒ Effective Field Theory (EFT)

- simplify the thermal field theory treatment
- get the thermal modification in medium
- systematic estimation of the temperature corrections

EFT in a nutshell I

Dealing with problems involving more than one energy scale

Effective Field Theory: $\mathcal{L}_{FT} \to \mathcal{L}_{EFT}$

1) Hierarchy of scale and the relevant low-energy d.o.f.

$$M \gg m\,, \quad \text{low-energy d.o.f with } E \sim m$$

2) Identify the symmetries to be preserved
3) Construct the most general EFT Lagrangian ($c_i \equiv$ Wilson coefficients)

$$\mathcal{L}_{EFT} = \sum_i c_i\left(\frac{\mu}{M}\right)\frac{\mathcal{O}_i}{M^{d_i-4}}$$

4) The EFT Lagrangian is organized as powers of

$$\left(\frac{m}{M}\right) \to \text{power counting}$$

EFT in a nutshell II

5) Choose the desired accuracy: choose the power N

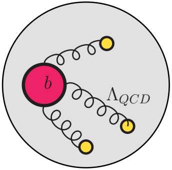
$$\left(\frac{m}{M}\right)^N \Rightarrow \text{accuracy of a physical observable}$$

6) Matching: determination of the Wilson coefficients at the scale m

$$\langle\Omega|\phi_1(x_1)\ldots\phi_n(x_n)|\Omega\rangle_{FT} \rightarrow \langle\Omega|\tilde{\phi}_1(x_1)\ldots\tilde{\phi}_n(x_n)|\Omega\rangle_{EFT}$$

The machinery really works:

- Heavy Quark Effective Theory,
  E. Eitchen and B. Hill (1990)
- Non-Relativistic QCD,
  G. T. Bodwin, E. Brateen, G. P. Lepage (1995)
- potential Non-Relativistic QCD,
  N. Brambilla, A. Pineda, J. Soto, A. Vairo (1999)
- Soft Collinear Effective Theory ...
  C. W. Bauer, S. Fleming, D. Pirjol, I. W. Stewart (2001)



$M_b \gg \Lambda_{QCD}$

[see talk by Vladyslav Shtabovenko]

Open problems in Cosmology (just two)

Dark Matter

- visible matter does not match its gravitational effects

$$\Omega_{CDM} h^2 = (0.122 \pm 0.006) \,, \quad \Omega_B h^2 = (0.022 \pm 0.001)$$

- WIMP models: heavy particle out of equilibrium $\chi\chi \to SM\, SM$

$$T < M_\chi$$

Baryon asymmetry in the Universe [see talk by Alexander Kartavtsev]

- universe strongly matter-antimatter asymmetric

$$\eta_B = \frac{n_{\mathrm{B}} - n_{\bar{\mathrm{B}}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

E. Komatsu et al. WMAP collaboration

- within SM *Jarlskog invariant* $\sim 10^{-20}$, too small!!
- Baryogenesis via Leptogenesis: $\Delta L \to \Delta B$
- Sakarov conditions $\to$ out of equilibrium process, $T < M_N$

EFT for Majorana fermions

- the condition $M > T$ calls for a non-relativistic treatment
- neutralinos, gravitinos, heavy neutrinos are Majorana fermions

$$\Downarrow$$

EFT for non-relativistic Majorana fermions

As a proof of concept...

- test the effective theory in the extension of the SM with one sterile neutrino

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\bar{\psi} i \partial\!\!\!/ \psi - \frac{M}{2}\bar{\psi}\psi - F_f \bar{L}_f \tilde{\phi} P_R \psi - F_f^* \bar{\psi} P_L \tilde{\phi}^\dagger L_f \, ,$$

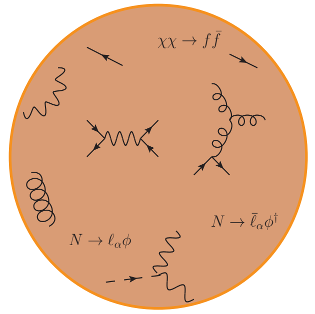
$$\psi = \nu_R + \nu_R^c$$

- thermal decay rate of one heavy neutrino in a plasma of SM particles

$$\Gamma_0 = \frac{|F|^2 M}{8\pi} \to \Gamma(T) = \Gamma_0 + (\text{thermal corrections})$$

EFT for Majorana fermions

Heavy neutrinos in SM plasma



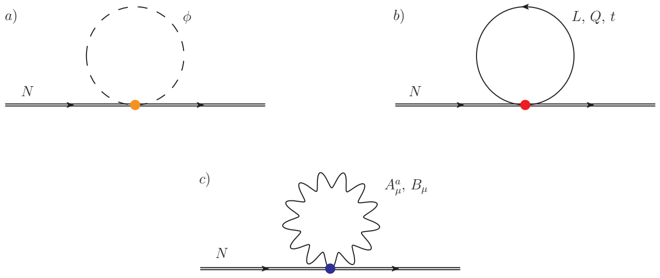
1) hierarchy: $M >> T$; the low-energy modes are: $E \sim T$
2) Poincaré and gauge symmetry
3) $\mathcal{L}_{\rm EFT} = \sum_i c_i \left(\frac{\mu}{M}\right) \frac{\mathcal{O}_i}{M^{d_i-4}}$
4) $\left(\frac{T}{M}\right) \to$ power counting
5) accuracy, relative order: $\left(\frac{T}{M}\right)^4$
6) matching (c_i): it happens integrating out $M >> T$

2-loops in relativistic thermal field theory $\to$ 1 (EFT) + 1 (T)

- matching at $T = 0$: one loop calculation at $T = 0$
- tadpole diagrams (one loop) that introduce the temperature T

EFT at work

- thermal contributions to Γ_0 from the plasma at $T \gg M_W$
- decay width connected with $\mathrm{Im}(\mathcal{D})$

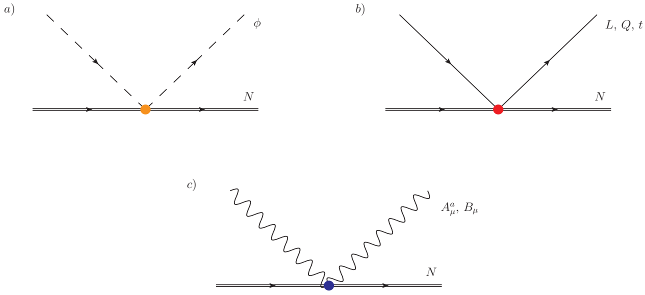


- thermal tadpoles do not carry an imaginary part
- the imaginary part can come only from the matching coefficients c_i

EFT for Majorana neutrinos

Low-energy Lagrangian at the T scale

$$\mathcal{L}_{\rm EFT} = \bar{N}\,(iv\cdot\partial)\,N + \frac{A}{M}\bar{N}N\phi^\dagger\phi + \frac{B}{M^3}\bar{N}N(\bar{f}\,v\cdot D\,f) + \frac{C}{M^3}\bar{N}N\mathcal{F}^2$$

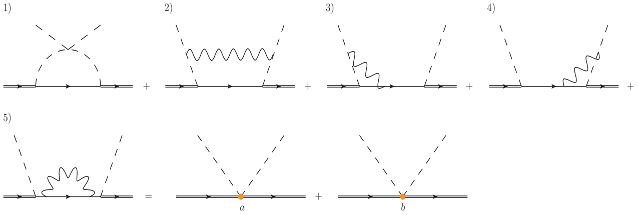


Power counting and thermal corrections

$$\delta\Gamma_\phi \propto \frac{T^2}{M}\,, \quad \delta\Gamma_f \propto \frac{T^4}{M^3}\,, \quad \delta\Gamma_F \propto \frac{T^4}{M^3}$$

Matching: integrating out the M scale

$$\mathcal{L}_{\mathrm{EFT},\phi} = \frac{a}{M} N^\dagger N \phi^\dagger \phi + \frac{b}{M^3} N^\dagger N D_0 \phi^\dagger D_0 \phi$$



Matching the amplitudes $M >> \Lambda >> T \to 0$:

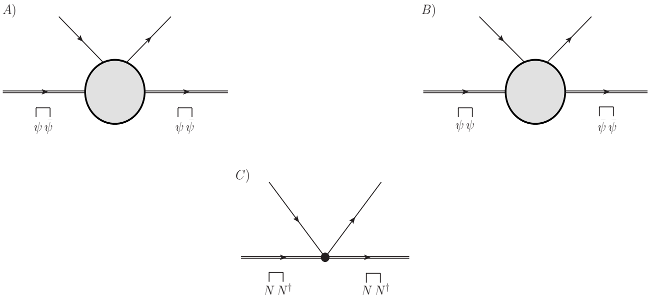
- $\sum_i \mathrm{Im}\,\mathcal{D}_i = -\frac{3}{8\pi}\frac{\lambda|F|^2}{M}\delta_{mn}\delta^{\mu\nu} - \frac{5}{32\pi}\frac{(3g^2+g'^2)|F|^2}{M^3}\delta_{mn}\delta^{\mu\nu}(q_0)^2$
- $\mathcal{D}_a + \mathcal{D}_b = \frac{a}{M}\delta_{mn}\delta^{\mu\nu} + \frac{b}{M^3}\delta_{mn}\delta^{\mu\nu}(q_0)^2$

$$\mathrm{Im}\, a = -\frac{3}{8\pi}|F|^2\lambda\,, \quad \mathrm{Im}\, b = -\frac{5}{32\pi}(3g^2+g'^2)|F|^2$$

What is different from HQET?

- Majorana fermions: $\psi = C\bar{\psi}^T = \psi^c$

$$\langle 0| T\left\{\psi(x)\psi(y)\right\}|0\rangle \neq 0\,, \quad \langle 0| T\left\{\bar{\psi}(x)\bar{\psi}(y)\right\}|0\rangle \neq 0$$

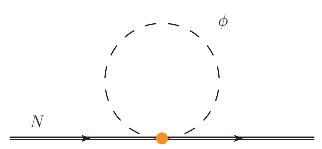


- HQET: describe non-relativistic Dirac fermions, there is no B) diagram
- In the EFT for Majorana fermions ⇒ some new operators

Thermal decay width

Last step: thermal tadpoles

- relativistic and thermal corrections factorize (EFT)



$$\Rightarrow \boxed{\Gamma_\phi = 2\frac{\mathrm{Im}\, a}{M}\langle \phi^\dagger(0)\phi(0)\rangle_T}$$

- compute the thermal loop

$$i\Delta_{11}(x-y) = \int \frac{d^4k}{(2\pi)^4}\left[\frac{i}{k^2+i\epsilon} + (2\pi)n_B(|k_0|)\delta(k^2)\right]e^{-ik\cdot(x-y)}$$

EFT for Majorana fermions works:

$$\Gamma = \frac{|F|^2M}{8\pi}\left\{1 - \lambda\left(\frac{T}{M}\right)^2 - \frac{\pi^2}{80}\left(\frac{T}{M}\right)^4(3g^2+g'^2) - \frac{7\pi^2}{60}\left(\frac{T}{M}\right)^4|\lambda_t|^2 + \mathcal{O}\left(\frac{T}{M}\right)^6\right\}$$

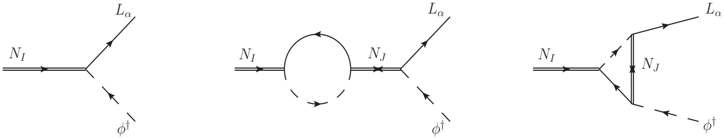
M. Laine and Y. Schröder (2012)

CP asymmetry from the vacuum to the medium

CP asymmetry in leptogenesis *M. Fukugita and T. Yanagida (1986)*

- the lepton asymmetry is produced by CP violating processes

$$\epsilon = \sum_{I,f} \frac{\Gamma(N_I \to \ell_f + X) - \Gamma(N_I \to \bar{\ell}_f + X)}{\Gamma(N_I \to \ell_f + X) + \Gamma(N_I \to \bar{\ell}_f + X)} \to \ \epsilon_{N_1} = 2\frac{\mathrm{Im}(F_1 F_2^*)^2 \mathrm{Im}(\mathcal{D})}{|F_1|^2}$$



$\epsilon \to \epsilon(T)$: *L. Covi, N. Rius, E. Roulet and F. Vissani (1998)*

- Decays happen in medium $\Rightarrow$ How to include thermal effects?
- Thermal propagators, interaction with particles in the medium
- How can we show clearly the size of the thermal corrections to ϵ ?

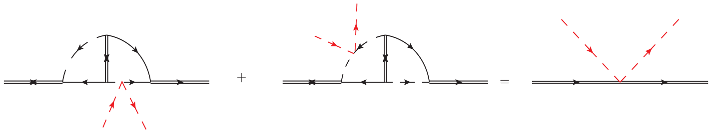
EFT and CP asymmetry

- What can EFT provide?
  1. power counting $\Rightarrow$ explicit structure in $\frac{T}{M}$
  2. systematic estimation of the medium induced corrections

Leading order thermal correction

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\bar{\psi}_I i\partial\!\!\!/ \psi_I - \frac{M}{2}\bar{\psi}_I\psi_I - F_{fI}\bar{L}_f\tilde{\phi}a_R\psi_I - F^*_{fI}\bar{\psi}_I\tilde{\phi}^\dagger a_L L_f$$

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \bar{N}(v\cdot\partial)N + \frac{a_{IJ}}{M}\bar{N}_I N_J\phi^\dagger\phi + \cdots$$



Preliminary result

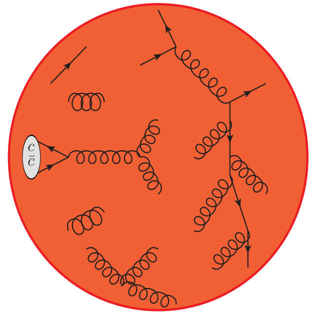
Leading order correction: $\epsilon(T) = \epsilon\left[1 + C\,\lambda\left(\frac{T}{M}\right)^2\right]$

Conclusions

- Majorana fermions enter in models for dark matter and leptogenesis
- The non-relativistic regime may be relevant
- Effective field theory for non-relativistic Majorana fermions
- Validation of the EFT approach in a particular model $\rightarrow$ sterile neutrinos
- Observable at finite temperature, $\epsilon \rightarrow \epsilon(T)$
- Suitable for other models with Majorana fermions

Quark Gluon Plasma and Hard probes

New QCD phase



- $T_c \simeq 150 - 300$ MeV (estimation),
- QGP time formation $\tau_0 \simeq 1$fm/c

Hard probes ⇒ experience the medium

- time formation smaller than QGP

  1) Example: highly energetic parton

$$\frac{1}{Q} \ll \tau_0 \,, \quad Q(\simeq 5\,\mathrm{GeV}) >> T$$

  2) Example: heavy quark bound state

$$\frac{1}{M_c} \ll \tau_0 \,, \quad M_c(\simeq 1.3\,\mathrm{GeV}) >> T$$

- EFT-Tools

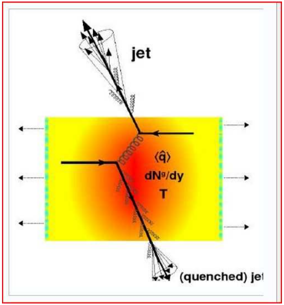
  a) Soft-Collinear Effective Theory

  b) pNRQCD and HTLpNRQCD

Jet broadening

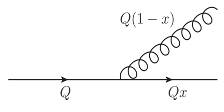
Soft-Collinear effective theory

- d.o.f. collinear quarks and gluons, soft gluons; $Q >> T$: $\lambda = \frac{T}{Q}$

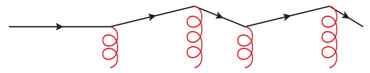


jet quenching process:

- parton energy loss: gluon radiation



- momentum broadening without radiation
  F. D'Eramo, H. Liu and K. Rajagopal (2010)

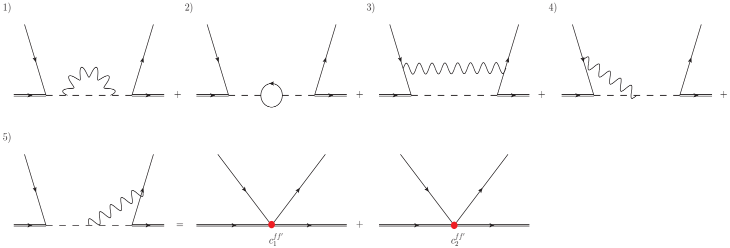


$\rightarrow$ absorb gluons from isotropic medium: $\hat{q}$

- Anisotropic medium? How changes $\hat{q}$?

Thank you for the attention

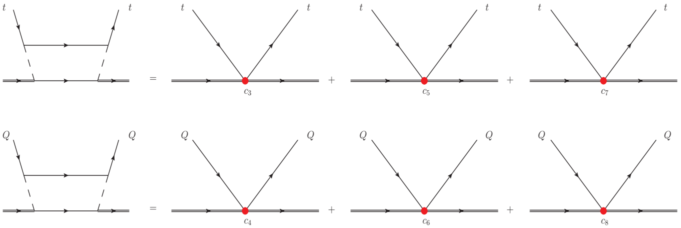
Lepton sector



$$\mathcal{L}_{lepton} = c_1^{ff'} \;\left[\left(\bar{N} P_L \, iv \cdot D L_f\right) \left(\bar{L}_{f'} P_R N +\right) - \left(\bar{N} P_R \, iv \cdot D L^c_{f'}\right) \left(\bar{L}^c_f P_L N\right)\right] +$$

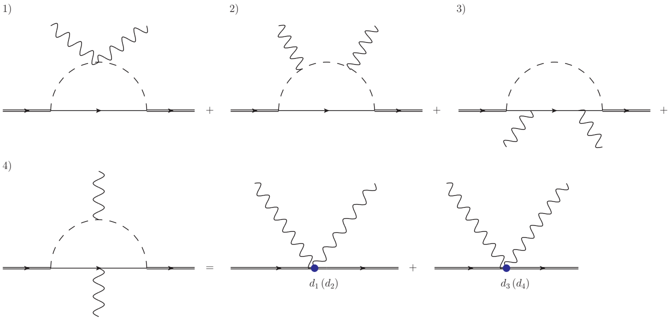
$$c_2^{ff'} \;\left[\left(\bar{N} P_L \, \gamma_\mu \gamma_\nu \, iv \cdot D L_f\right) \left(\bar{L}_{f'} \, \gamma^\nu \gamma^\mu \, P_R N\right) - \left(\bar{N} P_R \, \gamma_\mu \gamma_\nu \, iv \cdot D L^c_{f'}\right) \left(\bar{L}^c_f \, \gamma^\nu \gamma^\mu \, P_L N\right)\right]$$

Quark sector



$$\mathcal{L}_{quark} = c_3\ \bar{N}N\ (\bar{t}P_L\, v^\mu v^\nu \gamma_\mu\, iD_\nu t) + c_4\ \bar{N}N\ \left(\bar{Q}P_R\, v^\mu v^\nu \gamma_\mu\, iD_\nu Q\right) +$$
$$c_5\ \bar{N}\gamma^5\gamma^\mu\ N\ (\bar{t}P_L\, v\cdot\gamma\, iD_\mu t) + c_6\ \bar{N}\gamma^5\gamma^\mu\ N\ \left(\bar{Q}P_R\, v\cdot\gamma\, iD_\mu Q\right) +$$
$$c_7\ \bar{N}\gamma^5\gamma^\mu\ N\ (\bar{t}P_L\, \gamma_\mu\, iv\cdot Dt) + c_8\ \bar{N}\gamma^5\gamma^\mu\ N\ \left(\bar{Q}P_R\, \gamma_\mu\, iv\cdot DQ\right)$$

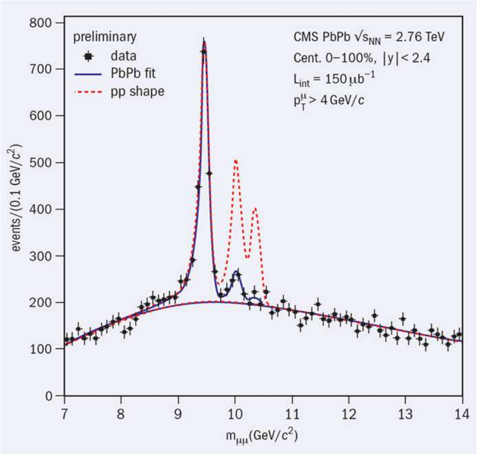
Bosonic sector



$$\mathcal{L}_{boson} = -d_1\ \bar{N}N\, v^{\mu} v_{\nu} W^{a}_{\alpha\mu} W^{a\,\alpha\nu} - d_2\ \bar{N}N\, v^{\mu} v_{\nu} F_{\alpha\mu} F^{\alpha\nu}$$

$$+d_3\ \bar{N}N\, W^{a}_{\mu\nu} W^{a\,\mu\nu} + d_4\ \bar{N}N\, F_{\mu\nu} F^{\mu\nu}$$

Quarkonia dissociation in medium



CMS-quark gluon plasma studies