Particle production and equilibration rates: the case of right-handed neutrinos in the broken phase

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tBBatLB-NEPiCaiHIC, CERN, July 13 2016

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An excellent password!

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Introduction

- There is a host of problems in bangs of all sizes where some fields/particles are weakly coupled to a thermal bath and hence out of equilibrium with it
- One can then study their thermal production and equilibration rates
- Classic examples
	- Photons/dileptons in heavy ion collision
	- Thermal relics (DM, right-handed neutrinos...) in the EU
- A well-defined Thermal Field Theory problem

Thermal production

Assume an equilibrated hot bath (QGP, early universe) with its internal coupling *g* and a particle *φ*, weakly coupled (coupling *h*) to other d.o.f.s, so that ϕ is not in equilibrium

$$
\mathcal{L} = \mathcal{L}_{\phi} + h\phi^* J + h^* J^* \phi + \mathcal{L}_{\text{bath}}
$$

J built of bath operators

• With a simple derivation one obtains that the rate (per unit volume) is proportional to a thermal average of a *JJ* correlator

$$
\frac{d\Gamma_{\phi}}{d^{3}k} = \frac{|h|^{2}}{2E_{k}}\Pi^{<}(k) = \frac{|h|^{2}}{2E_{k}}\int d^{4}X e^{iK\cdot X}\text{Tr}\,\rho_{\text{bath}}J(0)J(x)
$$

• The expression is LO in *h* but to all orders in *g*

Example: photon production

- In the case of photon/dilepton production then $J=J^{\mu}$ EM, $h=e$ and $g=g_s$
- At leading order in QED and to all orders in QCD the photon and dilepton rates are given by

$$
\frac{d\Gamma_{\gamma}(k)}{d^{3}k} = -\frac{\alpha}{4\pi^{2}k} \int d^{4}X e^{iK \cdot X} \text{Tr}\rho J^{\mu}(0) J_{\mu}(X)
$$

$$
\frac{d\Gamma_{l^{+}l^{-}}(k)}{dk^{0}d^{3}k} = -\frac{\alpha^{2}}{6\pi^{3}K^{2}} \int d^{4}X e^{iK \cdot X} \text{Tr}\rho J^{\mu}(0) J_{\mu}(X)
$$

The ingredients

$$
\Pi^{\lt}(K) \equiv \int d^4X e^{iK \cdot X} \text{Tr} \rho J^{\mu}(0) J_{\mu}(X)
$$

- electromagnetic current *J*: how the d.o.f.s couple to photons
- density operator ρ . In the equilibrium (possibly just local) approximation it becomes the thermal density $\rho \propto e^{-\beta H}$ and the whole thing a thermal average
- The action *S*: how the d.o.f.s propagate and interact

- Sterile right-handed neutrinos with *O*(GeV) masses could play a big role in cosmology
- They can generate a lepton asymmetry through oscillations, which can then be converted to a baryon asymmetry (sphalerons): **leptogenesis** Akhmedov Rubakov Smirnov **PRL81** (1998), Asaka Shaposhnikov **PLB620** (2005)
- If a large lepton asymmetry $(n_l \gg n_B)$ persists to $T \sim 1$ GeV it can be resonantly converted to keV scale sterile, dark matter neutrinos Shi Fuller **PRL82** (1999)

Motivation

- Computing reliably the lepton asymmetry in a specific scenario is usually challenging (CP violation, oscillations, plasma physics)
- On the other hand, establishing whether an existing asymmetry gets *washed out* allows to put constraints (or rule out) scenarios
- In this talk: three related quantities that govern the dynamics of GeV scale sterile neutrinos and of the lepton asymmetry in the broken phase

In this talk

- Three related quantities
	- Production rate of RHNs
	- Equilibration rate of RHNs
	- Washout rate of the lepton asymmetry
- In the broken phase 5 GeV<*T*<160 GeV
- GeV scale RHNs (*M*≪*T*). Relevance for the SHiP experiment at CERN

JG Laine **JCAP07** (2016)

In this talk

- The considered range fills a gap in the literature where, as I will show, these rates peak
- Previous calculations in the symmetric phase for all kinematic ranges, and deep in the broken phase *T*<5 GeV

Salvio Lodone Strumia (2011), Laine Schröder (2012), Biondini Brambilla Escobedo Vairo (2012), Garbrecht Glowna Herranen (2013), Laine (2013), Anisimov Besak Bödeker (2010-12), Ghisoiu Laine (2014) Asaka Laine Shaposhnikov (2006), JG Laine (2015), Venumadhav Cyr-Racine Abazajian Hirata (2015)

Overview

- Add 3 sterile, Majorana neutrinos coupling to the three active lepton flavours and the Higgs field $\mathcal{L} = \mathcal{L}_{\rm SM} +$ 1 2 \sum *I* $\bar{N}_I \big(i \gamma^\mu \partial_\mu - M_I \big) N_I - \sum \limits$ *I,a* $(\bar{N}_I h_{Ia} \tilde{\phi}^\dagger a_L l_a + \bar{l}_a a_R \tilde{\phi} h_{Ia}^* N_I)$
- At *T*>5 GeV all SM leptons are effectively massless and the information we need is encoded in the spectral function of this SM two-point function

$$
\Pi_{\mathcal{E}}(K) \equiv \text{Tr}\Big\{i\cancel{K}\int_{0}^{1/T} d\tau \int_{\mathbf{x}} e^{iK\cdot X} \left\langle (\tilde{\phi}^{\dagger} a_{L} \, l)(X) \, (\bar{l} \, a_{R} \, \tilde{\phi})(0) \right\rangle_{T} \Big\}
$$

$$
\rho(K) \equiv \text{Im} \, \Pi_{\mathcal{E}}(K)|_{k_{n}\to -i(k_{0}+i\epsilon)}
$$

Thermal average of SM operators coupling to RHNs

$$
\Pi_{\mathcal{E}}(K) \equiv \text{Tr}\Big\{iK \int_0^{1/T} d\tau \int_{\mathbf{x}} e^{iK \cdot X} \Big\langle (\tilde{\phi}^\dagger a_L l)(X) (\bar{l} a_R \tilde{\phi})(0) \Big\rangle_T \Big\}
$$

$$
\rho(K) \equiv \text{Im} \Pi_{\mathcal{E}}(K)|_{k_n \to -i(k_0 + i\epsilon)}
$$

RHN equilibration rate

$$
\dot{f}_{I\mathbf{k}} = \gamma_{I\mathbf{k}} \left(n_{\text{F}}(E_{I}) - f_{I\mathbf{k}} \right) + \mathcal{O}\left[\left(n_{\text{F}} - f_{I\mathbf{k}} \right)^{2}, n_{a}^{2} \right]
$$

$$
\gamma_{I\mathbf{k}} = \sum_{a} \frac{|h_{Ia}|^{2} \rho(K)}{E_{I}} + \mathcal{O}(h^{4})
$$

Approach to equilibrium of the RHN phase space distribution (on-shell RHNs, *EI*=(**k**2+*M*2)1/2) Bödeker Sangel Wörmann **PRD93** (2015)

$$
\Pi_{\mathcal{E}}(K) \equiv \text{Tr}\Big\{iK \int_0^{1/T} d\tau \int_{\mathbf{x}} e^{iK \cdot X} \left\langle (\tilde{\phi}^\dagger a_L l)(X) (\bar{l} a_R \tilde{\phi})(0) \right\rangle_T \Big\}
$$

$$
\rho(K) \equiv \text{Im} \Pi_{\mathcal{E}}(K)|_{k_n \to -i(k_0 + i\epsilon)}
$$

RHN production rate when $f_{I\mathbf{k}}$ $\ll n_F$

$$
\begin{aligned} \dot{n}_I &= \sum_a \int \frac{d^3k}{(2\pi)^3} \frac{2n_{\rm F}(E_I) |h_{Ia}|^2 \rho(K)}{E_I} + \mathcal{O}(h^4, n_I) \\ n_I &= 2 \int \frac{d^3k}{(2\pi)^3} f_{I\mathbf{k}} \end{aligned}
$$

Growth of the RHN number density far from equilibrium

 \mathbb{R}^n

$$
\Pi_{\mathcal{E}}(K) \equiv \text{Tr}\Big\{i\cancel{K}\int_{0}^{1/T} d\tau \int_{\mathbf{x}} e^{iK\cdot X} \left\langle (\tilde{\phi}^{\dagger} a_{L} \, l)(X) \, (\bar{l} \, a_{R} \, \tilde{\phi})(0) \right\rangle_{T} \Big\}
$$
\n
$$
\rho(K) \equiv \text{Im} \, \Pi_{\mathcal{E}}(K)|_{k_{n}\to -i(k_{0}+i\epsilon)}
$$

• Washout rate for the lepton number for flavour *a*

$$
\dot{n}_a = -\gamma_{ab} n_b + \mathcal{O}[n_a (n_F - f_{I\mathbf{k}}), n_a^3]
$$

$$
\gamma_{ab} = -\sum_I \int \frac{d^3k}{(2\pi)^3} \frac{2n'_{\rm F}(E_I)|h_{Ia}|^2 \rho(K)}{E_I} \Xi_{ab}^{-1} + \mathcal{O}(h^4)
$$

Depends on the susceptibility $\Xi_{ab} = \partial n_a/\partial \mu_b|_{\mu_b=0}$ not diagonal because of charge neutrality constraints Bödeker Laine **JCAP05** (2014)

Suppose that Computing ρ magnitude, and "small" in the sense that g2 ≪ π2.
"small" in the sense that g2 ≪ π2. The
"small" in the sense that g2 ≪ π2. The sense that g2 ≪ π2. Th the neutral component of the Higgs field has an expectation value. The expectation value \sim $v_{\rm eff}$ at T $v_{\rm eff}$ at T $v_{\rm eff}$ at T $v_{\rm eff}$ and $v_{\rm eff}$ and $v_{\rm eff}$ are gime in which v $v_{\rm eff}$ and $v_{\rm eff}$

- In the broken phase the Higgs e.v. *v*>0. We consider the parametric range *T*≳*v*, so that thermal masses $(O(gT))$ and Higgs mechanism masses $(O(gv))$ are of the same order. In practice where $g=(g_1,g_2,h_t,\lambda^{1/2})$ (parametrically equivalent) • In the broken phase the Higgs e.v. *v*>0. We consider $T = 200$ $k = \frac{1}{\sqrt{2}} \int \frac{1}{\sqrt{2}} \arctan \left(\frac$ $30 \,\text{GeV} \lesssim T \lesssim 160 \,\text{GeV}$
	- In this region *MI*≲*gT*
	- We also consider $m_W \ge \pi T$ to cover the low-temperature region down to 5 GeV

• The Higgs doublet can be a propagating d.o.f. (Higgs $\Pi_{\text{E}}(K) \equiv \text{Tr}\Big\{$ $i \not \!\! K$ $\int 1/T$ $0 \t Jx$ $d\tau$ Z $e^{iK \cdot X} \left\langle (\tilde{\phi}^\dagger a_L l)(X) (\bar{l} a_R \tilde{\phi})(0) \right\rangle$ *T* $\overline{\mathcal{L}}$

Distinction into direct and indirect processes or Goldstone) or an expectation value insertion. $\frac{1}{6}$ In *K*₂ In *K*² In *K*² In *K*²

Direct and Direct Indirect $1 \leftrightarrow 2$ $2 \leftrightarrow 2$ $F_{\text{in} \text{direct}}$ from a Yukawa interaction. (b) Examples of 1 + n ↔ 2 + n processes for the generation of lefthanded neutrinos which subsequently oscillate into right-handed ones. Arrowed, and wight-handed ones. Arrowed, and wight-handed ones. Arrowed, and wight-handed ones. Arrowed, and wight-handed ones. Arrowed, and wight-hand lines correspond to Standard Model fermions, respectively, respectively, respectively, respectively, respective $\frac{1}{2}$ does are denoted by a double denotes a $\frac{1}{2}$ thers, and crossings and others, and Figure 1: (a) Examples of 1+1 $\frac{1}{n}$ and $\frac{1}{n}$ $\frac{1}{\sqrt{1 + \frac{1}{\sqrt{1 +$ handed neutrinos which subsequently oscillate into right-handed ones. Arrowed, dashed, and wiggly $\mathcal{H}_{\mathcal{H}_{\mathcal{A}}}$ does are denoted by a double denotes a Higgs expectation value. and others, and crossings and others, and crossings and others, and crossings $\begin{array}{ccc} \begin{array}{ccc} \text{1} & \text$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ and $\frac{1}{2}$ $\frac{1}{2$ | and others, and crossings | and others, and crossings | \sim 1 \cdot 1 \cdot \cdot \cdot \cdot \cdot \cdot τ and others, and crossings F_{max} is the direct generation of F_{max} $f(z) = \begin{vmatrix} 1 & 1 & 1 & 1 \ 0 & 1 & 1 & 1 \end{vmatrix}$ and $f(z) = \begin{vmatrix} 1 & 1 & 1 \ 0 & 1 & 1 \end{vmatrix}$ \sim correspond to Standard Model fermions, scalars, respectively, respectively, respectively, \sim right-section \sim

- C Crify the sunt is gauge flivatiant. Feyinitan Λ_ζ gauge simplest which subsequently oscillate into right-handed ones. The notation is as in fig. 1. The complete set for $\mathbf{I}_{\mathbf{L}}$ which subsequently oscillate into right-handed ones. The notation is as in fig. 1. The complete set for \mathcal{L} Ohly the sulli is gauge lination. Teyllinali κ_ξ gauge • Only the sum is gauge invariant. Feynman *R_ξ* gauge
	- Direct processes give $\rho \sim g^2 T^2$. Indirect processes can Have a Heal-resonalit enhancement (Hold OII) (a) (b) (a) (b) have a near-resonant enhancement (hold on)

The computation

- Since all masses are *O*(*gT*), tree level processes (if possible) are $\sim m^2 \sim g^2 T^2$ and collinear F_{F} and F_{F} is the direct generation of F_{F} handed neutrinos which subsequently oscillate into right-handed ones. Arrowed, dashed, and wiggly
- Long formation times $O(1/g^2T)$ imply that soft scatterings, at rate g^2T , need to be resummed to all orders ⇒ Landau-Pomeranchuk-Migdal (LPM) effect Long QCD history (BDMPS, AMY). Introduced for RHNs in the *symmetric phase* in Anisimov Besak Bödeker **JCAP03** (2011), Besak Bödeker **JCAP03** (2012), Ghisoiu Laine **JCAP12** (2014) handed neutrinos are denoted by a double line. The closed blob denotes a Higgs expectation value. (20011260)

Symmetric phase LPM where mH ≈ 125 GeV is the physical Higgs mass. Soft gauge scattering are represented by the physical Higgs mass
The physical Higgs mass. Soft gauge scattering are represented by the physical Higgs mass. Soft gauge scatter a thermal width $\mathcal{L}(\mathcal{L}) = \mathcal{L}(\mathcal{L})$ # 2 die eerste van die gewone van die g
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• In the **symmetric phase** etr E i
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¹⁶ , m²

$$
\rho(K)^{\text{LPM}} = \frac{1}{16\pi} \int_{-\infty}^{\infty} d\omega \left[1 - n_{\text{F}}(\omega) + n_{\text{B}}(k_0 - \omega) \right] \frac{k_0}{k_0 - \omega}
$$

$$
\times \lim_{\mathbf{y} \to 0} 4 \left\{ \frac{M^2}{k_0^2} \text{Im} \left[g \left(\mathbf{y} \right) \right] + \frac{1}{\omega^2} \text{Im} \left[\nabla_{\perp} \cdot \mathbf{f} \left(\mathbf{y} \right) \right] \right\}
$$

• The functions **f** and *g* encode the resummed soft interactions through \overline{a} \tanh $\frac{6}{11^2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\hat{H} = \frac{M^2}{\hat{H}} + \frac{m_{\tilde{l}}^2 - V_{\perp}^2}{\hat{H}} + \frac{m_{\phi}^2 - V_{\perp}}{2\hat{H}} = i \Gamma(i)$ and in the intervals of $2k_0$ $(\hat{H} + i0^{+}) g({\bf y}) = \delta^{(2)}({\bf y}) \; , \quad (\hat{H} + i0^{+}) \, {\bf f}({\bf y}) = - \nabla_{\perp} \delta^{(2)}({\bf y})$ \hat{H} \equiv M^2 2*k*⁰ $+$ $m_l^2 - \nabla_\perp^2$ 2ω $+$ $\frac{m_\phi^2-\nabla_\perp^2}{2(k_0-\omega)}-i\,\Gamma(y)$ $\mathcal{L}1v_0$ and $\mathcal{L}\left(\frac{1}{v_0}, \ldots, \frac{1}{v_n}\right)$ $\sqrt{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $rac{1}{\sqrt{1-\frac{1}{2}}}\frac{1}{\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}$ \overline{a}

where m_l and m_ϕ are the thermal masses of leptons and scalars and the soft interactions are ($m_{\rm E\it i}$ screening masses) Im Scalars and ne soft \overline{a} erac $\overline{ }$ \overline{a} u and m_{ϕ} are the f nal masses of leptons and $\frac{1}{2}$ scalars and the soft interactions are $(m_E; \text{screen}$ masses) a thermal width which we

$$
\Gamma(y) = \frac{T}{8\pi} \sum_{i=1}^{2} d_i g_i^2 \left[\ln\left(\frac{m_{\mathrm{E}i}y}{2}\right) + \gamma_{\mathrm{E}} + K_0(m_{\mathrm{E}i}y) \right]
$$

where mH ≈ 125 GeV is the physical Higgs mass. Soft gauge scattering are represented by the physical Higgs mass
The physical Higgs mass. Soft gauge scattering are represented by the physical Higgs mass. Soft gauge scatter a thermal width \overline{a} \overline{b} \overline{c} \overline{d} $\overline{$ # 2 il_{om} and a state of the state of the
) and () and ' (Symmetric phase LPM

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• In **QCD** (photon/dilepton production) toi $\frac{1}{2}$ \overline{O} $\frac{1}{2}$ + $\frac{1}{2}$

¹⁶ , m²

$$
\rho(K)^{\text{LPM}} = \frac{N_c}{\pi} \int_{-\infty}^{\infty} d\omega \left[1 - n_{\text{F}}(\omega) - n_{\text{F}}(k_0 - \omega) \right]
$$

$$
\times \lim_{\mathbf{y} \to \mathbf{0}} \left\{ \frac{M^2}{k_0^2} \text{Im} \left[g(\mathbf{y}) \right] + \left(\frac{1}{2\omega^2} + \frac{1}{2(k_0 - \omega)^2} \right) \text{Im} \left[\nabla_{\perp} \cdot \mathbf{f}(\mathbf{y}) \right] \right\}
$$

 \hat{H} \equiv M^2 $2k_0$ $+$ $m_q^2 - \nabla_\perp^2$ 2ω $+$ $\frac{m_q^2-\nabla_\perp^2}{2(k_0-\omega)}-i\,\Gamma(y)$ • The functions **f** and *g* encode the resummed soft interactions through where m_q is the thermal mass of quarks and the soft interactions are ($m_{\rm D}$ SU(3) screening mass) $\frac{1}{2}$ $\frac{20}{3}$ mmad soft $\frac{1}{2}$ through $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\hat{H} = \frac{M^2}{4} + \frac{m_q - v_{\perp}}{4} + \frac{m_q - v_{\perp}}{4} - i \Gamma(q)$ and $2k_0$ $(\hat{H} + i0^{+}) g(\mathbf{y}) = \delta^{(2)}(\mathbf{y}), \quad (\hat{H} + i0^{+}) \mathbf{f}(\mathbf{y}) = -\nabla_{\perp} \delta^{(2)}(\mathbf{y})$ Included are $(m_D \ SU(3))$

$$
\Gamma(y) = \frac{g^2 C_F T}{2\pi} \left[\ln \left(\frac{m_D y}{2} \right) + \gamma_E + K_0 (m_D y) \right]
$$

The soft interactions x− ∞ x− (1/T ≪ 1/T ≪ 1/
The contract of the contrac COST INTAIN

Collinear ⇒ almost on-shell ⇒ almost on-shell ⇒ large x separation ⇒ large x separation ⇒ large x separation ⇒
Description → large x separation → large x separation → large x separation → large x separation → large x sepa

 $\propto e^{-\Gamma(y)L}$

BDMPS-Z, Wiedemann, Casalderrey-Solana Salgado, D'Eramo Liu (*T^W /*2*,* r*/*2) and *x*² = (*T^W /*2*,* r*/*2). Time direction is from left to right, thus the Rajagopal, Benzke Brambilla Escobedo Vairo SPACALIKA OL LIONTLIKA SANAR

- All points at spacelike or lightlike separation, only preexisting correlations it spacelike or ligntlike separation, of $\mathbf 1$ and $\mathbf 2$ and $\mathbf 1$ and $\mathbf 1$ and $\mathbf 1$ and $\mathbf 2$ path integral as a p *D***n**S 15
- Soft contribution becomes Euclidean! Caron-Huot PRD79 (2008) ation de comes multipolitic Caroli-Fre
	- Can be "easily" computed in perturbation theory easily computed if
	- Possible lattice QCD measurements Laine Rothkopf **JHEP1307** (2013) Panero Rummukainen Schäfer **PRL112** (2014) *T^W T^W T*2 *W* lattice QUD measurements Laine Rot pressed. We have also dropped terms that do not depend on *r*, such as self energies. not relevant for the potential. The matching condition *G*NRQCD = *G*pNRQCD at the

Euclideanization of light-cone soft physics

• For *t/x_z* = 0: equal time Euclidean correlators.

$$
G_{rr}(t=0, \mathbf{x}) = \sum_{p}^{r} G_E(\omega_n, p) e^{i \mathbf{p} \cdot \mathbf{x}}
$$

SW Euclideanization of light-cone soft physics

- For *t/xz =*0: equal time Euclidean correlators. $G_{rr}(t=0,\mathbf{x})=\sum_{r}^{r} \mathbf{y}(r_{rr}^2)$ $\frac{1}{\sqrt{2}}$ $G_E(\omega_n, p) e^{i \mathbf{p} \cdot \mathbf{x}}$
- Consider the more general case *p* $|t/x^{z}| < 1$ $G_{rr}(t, \mathbf{x}) = \int dp^0 dp^z d^2p_{\perp} e^{i(p^z x^z + \mathbf{p}_{\perp} \cdot \mathbf{x}_{\perp} - p^0 x^0)}$ (1) $\frac{1}{2} + n_{\text{B}}(p^0)$ ◆ $(G_R(P) - G_A(P))$

SW Euclideanization of light-cone soft physics

• For *t/x_z* = 0: equal time Euclidean correlators. $\frac{1}{\sqrt{2}}$

$$
G_{rr}(t=0,\mathbf{x}) = \sum F G_E(\omega_n, p) e^{i\mathbf{p}\cdot\mathbf{x}}
$$

• Consider the more general case • Change variables to $\tilde{p}^z = p^z - p^0(t/x^z)$ *p* $|t/x^{z}| < 1$ $G_{rr}(t, \mathbf{x}) = \int dp^0 dp^z d^2p_{\perp} e^{i(p^z x^z + \mathbf{p}_{\perp} \cdot \mathbf{x}_{\perp} - p^0 x^0)}$ (1) $\frac{1}{2} + n_{\text{B}}(p^0)$ ◆ $(G_R(P) - G_A(P))$ $G_{rr}(t,\mathbf{x}) = \int dp^0 d\tilde{p}^z d^2p_\perp e^{i(\tilde{p}^z x^z + \mathbf{p}_\perp \cdot \mathbf{x}_\perp)}$ (1) $\frac{1}{2} + n_{\text{B}}(p^0)$ ◆ $(G_R(p^0, \mathbf{p}_{\perp}, \tilde{p}^z + (t/x^z)p^0) - G_A)$

SW Euclideanization of light-cone soft physics

• For *t/x_z* = 0: equal time Euclidean correlators.

$$
G_{rr}(t=0, \mathbf{x}) = \sum_{\mathbf{F}} G_E(\omega_n, p) e^{i \mathbf{p} \cdot \mathbf{x}}
$$

• Consider the more general case • Change variables to $\tilde{p}^z = p^z - p^0(t/x^z)$ *p* $|t/x^{z}| < 1$ $G_{rr}(t, \mathbf{x}) = \int dp^0 dp^z d^2p_{\perp} e^{i(p^z x^z + \mathbf{p}_{\perp} \cdot \mathbf{x}_{\perp} - p^0 x^0)}$ (1) $\frac{1}{2} + n_{\text{B}}(p^0)$ ◆ $(G_R(P) - G_A(P))$

$$
G_{rr}(t,\mathbf{x}) = \int dp^0 d\tilde{p}^z d^2p_{\perp} e^{i(\tilde{p}^z x^z + \mathbf{p}_{\perp} \cdot \mathbf{x}_{\perp})} \left(\frac{1}{2} + n_{\text{B}}(p^0)\right) \left(G_R(p^0, \mathbf{p}_{\perp}, \tilde{p}^z + (t/x^z)p^0) - G_A\right)
$$

• Retarded functions are analytical in the upper plane in any timelike or lightlike variable \Rightarrow *G_R* analytical in p^0

Euclideanization of light-cone soft physics

• For *t/x_z* = 0: equal time Euclidean correlators.

$$
G_{rr}(t=0, \mathbf{x}) = \sum_{\mu} G_E(\omega_n, p) e^{i \mathbf{p} \cdot \mathbf{x}}
$$

• Consider the more general case *p* $|t/x^{z}| < 1$ $G_{rr}(t, \mathbf{x}) = \int dp^0 dp^z d^2p_{\perp} e^{i(p^z x^z + \mathbf{p}_{\perp} \cdot \mathbf{x}_{\perp} - p^0 x^0)}$ (1) $\frac{1}{2} + n_{\text{B}}(p^0)$ ◆ $(G_R(P) - G_A(P))$

• Change variables to
$$
\tilde{p}^z = p^z - p^0(t/x^z)
$$

$$
G_{rr}(t, \mathbf{x}) = \int dp^0 d\tilde{p}^z d^2 p_\perp e^{i(\tilde{p}^z x^z + \mathbf{p}_\perp \cdot \mathbf{x}_\perp)} \left(\frac{1}{2} + n_\text{B}(p^0)\right) (G_R(p^0, \mathbf{p}_\perp, \tilde{p}^z + (t/x^z)p^0) - G_A)
$$

• Retarded functions are analytical in the upper plane in any timelike or lightlike variable \Rightarrow G_R analytical in p^0 \sum z
Z

$$
G_{rr}(t, \mathbf{x}) = T \sum_{n} \int dp^{z} d^{2}p_{\perp} e^{i(p^{z}x^{z} + \mathbf{p}_{\perp} \cdot \mathbf{x}_{\perp})} G_{E}(\omega_{n}, p_{\perp}, p^{z} + i\omega_{n}t/x^{z})
$$

Euclideanization of light-cone soft physics

• For *t/x_z* = 0: equal time Euclidean correlators.

$$
G_{rr}(t=0, \mathbf{x}) = \sum G_E(\omega_n, p) e^{i \mathbf{p} \cdot \mathbf{x}}
$$

- Consider the more general case *p* $|t/x^{z}| < 1$ $G_{rr}(t, \mathbf{x}) = \int dp^0 dp^z d^2p_{\perp} e^{i(p^z x^z + \mathbf{p}_{\perp} \cdot \mathbf{x}_{\perp} - p^0 x^0)}$ (1) $\frac{1}{2} + n_{\text{B}}(p^0)$ ◆ $(G_R(P) - G_A(P))$
- Change variables to $\tilde{p}^z = p^z p^0(t/x^z)$ $G_{rr}(t,\mathbf{x}) = \int dp^0 d\tilde{p}^z d^2p_\perp e^{i(\tilde{p}^z x^z + \mathbf{p}_\perp \cdot \mathbf{x}_\perp)}$ (1) $\frac{1}{2} + n_{\text{B}}(p^0)$ ◆ $(G_R(p^0, \mathbf{p}_{\perp}, \tilde{p}^z + (t/x^z)p^0) - G_A)$
- Retarded functions are analytical in the upper plane in any timelike or lightlike variable \Rightarrow G_R analytical in p^0 • Soft physics dominated by *n=0* (and *t*-independent) $=\angle$ EQCD! Caron-Huot **PRD79** (2009) $G_{rr}(t,\mathbf{x})=T$ \sum *n* z
Z $dp^z d^2p_\perp e^{i(p^zx^z+\mathbf{p}_\perp\cdot\mathbf{x}_\perp)}G_E(\omega_n,p_\perp,p^z+i\omega_nt/x^z)$

Euclideanization of light-cone soft physics

• For *t/x_z* = 0: equal time Euclidean correlators.

$$
G_{rr}(t=0, \mathbf{x}) = \sum_{\mu} G_E(\omega_n, p) e^{i \mathbf{p} \cdot \mathbf{x}}
$$

• Consider the more general case • Change variables to $\tilde{p}^z = p^z - p^0(t/x^z)$ *p* $|t/x^{z}| < 1$ $G_{rr}(t, \mathbf{x}) = \int dp^0 dp^z d^2p_{\perp} e^{i(p^z x^z + \mathbf{p}_{\perp} \cdot \mathbf{x}_{\perp} - p^0 x^0)}$ (1) $\frac{1}{2} + n_{\text{B}}(p^0)$ ◆ $(G_R(P) - G_A(P))$

$$
G_{rr}(t, \mathbf{x}) = \int dp^0 d\tilde{p}^z d^2 p_\perp e^{i(\tilde{p}^z x^z + \mathbf{p}_\perp \cdot \mathbf{x}_\perp)} \left(\frac{1}{2} + n_\text{B}(p^0)\right) (G_R(p^0, \mathbf{p}_\perp, \tilde{p}^z + (t/x^z)p^0) - G_A)
$$

- Retarded functions are analytical in the upper plane in any timelike or lightlike variable \Rightarrow *G_R* analytical in p^0 $G_{rr}(t,\mathbf{x})_{\text{soft}} = T$ $\overline{}$ $d^3p\,e^{i{\bf p}\cdot{\bf x}}\,G_E(\omega_n=0,{\bf p})$
- Soft physics dominated by *n=0* (and *t*-independent) =>EQCD! Caron-Huot **PRD79** (2009)

Euclideanization of light-cone soft physics Collinear ⇒ almost on-shell ⇒ large x separation anızatıon of lig Consider spacetime trajectory of q, q¯: Trajectory in

$$
\propto e^{-\Gamma(y)L}
$$

• At leading order (*T^W /*2*,* r*/*2) and *x*² = (*T^W /*2*,* r*/*2). Time direction is from left to right, thus the

$$
\Gamma(y) \propto T \int \frac{d^2 q_{\perp}}{(2\pi)^2} \left(1 - e^{i\mathbf{x}_{\perp} \cdot \mathbf{q}_{\perp}}\right) G_E^{++}(\omega_n = 0, q_z = 0, q_{\perp}) = T \int \frac{d^2 q_{\perp}}{(2\pi)^2} \left(1 - e^{i\mathbf{x}_{\perp} \cdot \mathbf{q}_{\perp}}\right) \left(\frac{1}{q_{\perp}^2} - \frac{1}{q_{\perp}^2 + m_D^2}\right)
$$

• Agrees with the earlier sum rule in Aurenche Gelis Zaraket **JHEP0205** (2002) **where** $q = 0.001$ **is the Value of Value 10 is the Value of Value 10 is the Value of Value 10 is the Value of Value of Value 10 is the Value of Value o** *ler sum rule in Aurer* $\overline{}$ r sum ruie in Aurenche Gel of Little and Soft gluons in volved as and Bose factor $\left($ ∠ **•** Agrees with the earlier sum rule in Aurench

where mH ≈ 125 GeV is the physical Higgs mass. Soft gauge scattering are represented by the physical Higgs mass
The physical Higgs mass. Soft gauge scattering are represented by the physical Higgs mass. Soft gauge scatter a thermal width $\mathcal{L}(\mathcal{L}) = \mathcal{L}(\mathcal{L})$ # 2 die eerste van die gewone van die g
Die gewone van die g
 (Symmetric phase LPM

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, (3.3) and (3.3) and (3.3) \sim

• In the **symmetric phase** etr E i
in a a a

¹⁶ , m²

$$
\rho(K)^{\text{LPM}} = \frac{1}{16\pi} \int_{-\infty}^{\infty} d\omega \left[1 - n_{\text{F}}(\omega) + n_{\text{B}}(k_0 - \omega) \right] \frac{k_0}{k_0 - \omega}
$$

$$
\times \lim_{\mathbf{y} \to 0} 4 \left\{ \frac{M^2}{k_0^2} \text{Im} \left[g \left(\mathbf{y} \right) \right] + \frac{1}{\omega^2} \text{Im} \left[\nabla_{\perp} \cdot \mathbf{f} \left(\mathbf{y} \right) \right] \right\}
$$

• The functions **f** and *g* encode the resummed soft interactions through \overline{a} \tanh $\frac{6}{11^2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\hat{H} = \frac{M^2}{\hat{H}} + \frac{m_{\tilde{l}}^2 - V_{\perp}^2}{\hat{H}} + \frac{m_{\phi}^2 - V_{\perp}}{2\hat{H}} = i \Gamma(i)$ and in the intervals of $2k_0$ $(\hat{H} + i0^{+}) g({\bf y}) = \delta^{(2)}({\bf y}) \; , \quad (\hat{H} + i0^{+}) \, {\bf f}({\bf y}) = - \nabla_{\perp} \delta^{(2)}({\bf y})$ \hat{H} \equiv M^2 2*k*⁰ $+$ $m_l^2 - \nabla_\perp^2$ 2ω $+$ $\frac{m_\phi^2-\nabla_\perp^2}{2(k_0-\omega)}-i\,\Gamma(y)$ $\mathcal{L}1v_0$ and $\mathcal{L}\left(\frac{1}{v_0}, \ldots, \frac{1}{v_n}\right)$ $\sqrt{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $rac{1}{\sqrt{1-\frac{1}{2}}}\frac{1}{\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}$ \overline{a}

where m_l and m_ϕ are the thermal masses of leptons and scalars and the soft interactions are ($m_{\rm E\it i}$ screening masses) Im Scalars and ne soft \overline{a} erac $\overline{ }$ \overline{a} u and m_{ϕ} are the f nal masses of leptons and $\frac{1}{2}$ scalars and the soft interactions are $(m_E; \text{screen}$ masses) a thermal width which we

$$
\Gamma(y) = \frac{T}{8\pi} \sum_{i=1}^{2} d_i g_i^2 \left[\ln\left(\frac{m_{\mathrm{E}i}y}{2}\right) + \gamma_{\mathrm{E}} + K_0(m_{\mathrm{E}i}y) \right]
$$

Broken phase LPM Γ (y) Γ **2** 4 ! q⊥ eiq⊥·^y " 1 \blacksquare ha: # , (3.17) ΓZ (γ) ≡ (γ) ∈ (γ) ∈ (γ) ∈ (γ) ∈ (γ) ∈ (γ) ∈
2)T (γ) ∈ (γ eiq⊥·^y

of temporal components can be expressed as in eqs. (3.15). We define the widths α in eqs. (3.16). We define the widths α

$$
\rho(K)^{\text{LPM}} = \frac{1}{16\pi} \int_{-\infty}^{\infty} d\omega \left[1 - n_{\text{F}}(\omega) + n_{\text{B}}(k_0 - \omega) \right] \frac{k_0}{k_0 - \omega}
$$

$$
\times \lim_{\mathbf{y} \to \mathbf{0}} 4 \left\{ \frac{M^2}{k_0^2} \text{Im} \left[g \left(\mathbf{y} \right) \right] + \frac{1}{\omega^2} \text{Im} \left[\nabla_{\perp} \cdot \mathbf{f} \left(\mathbf{y} \right) \right] \right\}
$$

- Broken electroweak symmetry implies \mathbf{F} the width determined, let us generalize the Hamiltonian of eq. (3.1) to contain a set of eq. production can by miniciry miquied
- Broken degeneracy of scalar masses $m_\phi^2 \rightarrow \text{diag}(m_{\phi_0}^2, m_{\phi_3}^2, m_\phi^2)$ $\frac{2}{\phi_1}$ $m_{\phi_1}^2$ ⎛ 2Γ^W (0) + Γ^Z (0) −Γ^Z (y) −Γ^W (y) −Γ^W (y) −Γ^Z (y) 2Γ^W (0) + Γ^Z (0) −Γ^W (y) −Γ^W (y)
	- Soft interactions become sensitive to "vacuum" masses and to the electromagnetic charges $T_{\rm eff}$ and functions g and functions g and f are generalized to 3-component vectors. With the 3 width the 3 wid The sensitive to "vacuum" A crosscheck, we note that in the symmetric phase, the parameters appearing in \overline{O} , we can allow \overline{O} ll
 $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ ΠOIIS DECOINE SENSITIVE TO VAC $^{\rm 11}$ 1 T (0) T (1) T (1) T (0) corresponds to the active T

⇒ Matrix structure between the *νφ*0 , *νφ*3 and *eφ*± states

reduce the 3 × 3 matrix into a single function,

Broken phase LPM Γ (y) Γ **2** 4 ! q⊥ eiq⊥·^y " 1 \blacksquare ha: # , (3.17) ΓZ (γ) ≡ (γ) ∈ (γ) ∈ (γ) ∈ (γ) ∈ (γ) ∈ (γ) ∈
2)T (γ) ∈ (γ eiq⊥·^y

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$$
\rho(K)^{\text{LPM}} = \frac{1}{16\pi} \int_{-\infty}^{\infty} d\omega \left[1 - n_{\text{F}}(\omega) + n_{\text{B}}(k_0 - \omega) \right] \frac{k_0}{k_0 - \omega}
$$

$$
\times \lim_{\mathbf{y} \to \mathbf{0}} \sum_{\mu=0}^{3} \left\{ \frac{M^2}{k_0^2} \text{Im} \left[g_{\mu}(\mathbf{y}) \right] + \frac{1}{\omega^2} \text{Im} \left[\nabla_{\perp} \cdot \mathbf{f}_{\mu}(\mathbf{y}) \right] \right\}
$$

- Broken electroweak symmetry implies \mathbf{F} the width determined, let us generalize the Hamiltonian of eq. (3.1) to contain a set of eq. production can by miniciry miquied
- Broken degeneracy of scalar masses $m_\phi^2 \rightarrow \text{diag}(m_{\phi_0}^2, m_{\phi_3}^2, m_\phi^2)$ $\frac{2}{\phi_1}$ $m_{\phi_1}^2)$) ⎛ 2Γ^W (0) + Γ^Z (0) −Γ^Z (y) −Γ^W (y) −Γ^W (y) −Γ^Z (y) 2Γ^W (0) + Γ^Z (0) −Γ^W (y) −Γ^W (y)
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 $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ ΠOIIS DECOINE SENSITIVE TO VAC $^{\rm 11}$ 1 T (0) T (1) T (1) T (0) corresponds to the active T

⇒ Matrix structure between the *νφ*0 , *νφ*3 and *eφ*± states $\mathbf{1}$ $\mathbf{1}$ $\mathbf{1}$ $\mathbf{1}$ $\mathbf{1}$ Γ_{1×1} = lim % & ΓW (10) − ΓW (γ) − ΓW (γ) B tructure between the ν *b*^{α} and e*b*, sta x betative between the $\nu \psi_0$, $\nu \psi_3$ and x

$$
\Gamma_{3\times 3} = \begin{pmatrix} 2\Gamma_W(0) + \Gamma_Z(0) & -\Gamma_Z(y) & -2\Gamma_W(y) \\ -\Gamma_Z(y) & 2\Gamma_W(0) + \Gamma_Z(0) & -2\Gamma_W(y) \\ -\Gamma_W(y) & -\Gamma_W(y) & 2\Gamma_W(0) + \Gamma_{Z'}(0) - \Gamma_{Z'}(y) \end{pmatrix}
$$

Direct 1←>2 processes

- Red: tree level processes with collinear $(m \ll T)$ approx. Unphysical growth at low T \mathbf{v} 1
- Blue: full tree level with *ml*=0, proper *mφ*, accurate at low *T*
	- Black: full solution of the LPM equations at high *T*, manually switched to blue at low *T*. **Final 1**↔**2 result** $\overline{\mathbf{r}}$

 $\mathbf{F}_{\mathbf{r}}$ is (a) Examples of 1+n processes for the direct generation of right-handed neutrinos for $\mathbf{r}_{\mathbf{r}}$

• As long as all external state masses are $O(gT)$ or $O(gv)$ they can be neglected at leading order (*O*(*g*²*T*2)). Hence, no change with respect to the symmetric phase evaluation in Besak Bödeker **JCAP03** (2012) real at leading order $(\cup (\mathcal{G}^2L^2))$. Hence, no \mathcal{L} and \mathcal{L} ones. The notation is as in fig. 1. The complete set for \mathcal{L} $\frac{1}{2}$ is shown in fig. 1 of $\frac{1}{2}$

 $f(p)f(p')(1 \pm f(k'))|\mathcal{M}|^2\delta^4(P+P'-K-K')$ messive. We say the rate at low $\frac{1}{\sqrt{2}}$ **by multiplying it for** $\frac{1}{\sqrt{2}}$ z
Z ph*.* space $f(p)f(p')(1 \pm f(k'))|\mathcal{M}|^2\delta^4(P+P'-K-K')$

Phase space convolution exchange. Analiticity arguments lead to a simple form for the soft part of the result Besak Bödeker JCAP03 (2012) JG Hong negligible in Kurkela Moore Teaney JHEP05 (2013) coupled from the computation of the top quark becomes non-relativistic at a somewhat COIL VOIGCIOIL OI elements. HTL resummation needed for soft fermion $\frac{\text{total}}{\text{total}}$ is $\frac{\text{total}}{\text{total}}$ by $\left(2010\right)$ • Phase space convolution of statistical functions and matrix Lu Kurkela Moore Teaney **JHEP05** (2013)

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- At low *T<mw* initial state bosons (scalar or gauge) are very massive. We switch off the rate at low *T* by multiplying it for the *W* boson susceptibility $\frac{1}{2}$ ϵ contraction (the trace at to α is ϵ) and ϵ non-relativistic algebra ϵ
- The formally leading-order contribution at low *T* is scalarmediated scatterings off *b* quarks. We find it is however negligible In the regime of eq. (2.10), there are two types of contributions to Im ΠR. First, the Higgs field in eq. (2.2) leading-order contribution at low T is scalar-

Direct 2↔2 processes from a Yukawa interaction. (b) Examples of 1 + n processes for 1 + n processes for the generation of left-base
The generation of left-base for the generation of left-base for the generation of left-base for left-base for $h_n = \frac{1}{n}$ hande $\frac{1}{n}$ which subsequently oscillate into right-handed ones. Arrowed, and wiggly $\frac{1}{n}$ lines correspond to Standard Model fermions, scalars, and gauge bosons, respectively, whereas righthanded neutrinos are denoted by a double line. The closed by a double line. The closed by a Higgs expectation v
Higgs expectation value. The closed by a Higgs expectation value. The closed by a Higgs expectation value. The

 $\mathbf{F}_{\mathbf{r}}$ is (a) Examples of 1+n $\mathbf{F}_{\mathbf{r}}$ and direct generation of right-handed neutrinos for the direct generation of $\mathbf{F}_{\mathbf{r}}$

• Besak-Bödeker rate susceptibility case (a) is shown in fig. 1 of ref. [29] and for case (b) in fig. 7 below.

k = 3T

scatterings off *b* quarks higher temperature). Fermi limi

from a Yukawa interaction. (b) Examples of 1 + n ↔ 2 + n processes for the generation of left-**Indirect processes** lines correspond to Standard Model fermions, scalars, and gauge bosons, respectively, whereas righthanded neutrinos are denoted by a double line. The closed by a double line. The closed by a Higgs expectation mm man mund routing money the

Figure 1: (a) Examples of 1+n ↔ 2+n processes for the direct generation of right-handed neutrinos

• In the indirect case ρ is directly proportional to the spf of active neutrinos, i.e.

$$
\rho(K)^{\text{indir.}} = \frac{v^2}{2} \frac{M^2 \, 2K \cdot \text{Im} \, \Sigma}{(M^2 + 2K \cdot \text{Re} \, \Sigma)^2 + 4(K \cdot \text{Im} \, \Sigma)^2}
$$

- Real part of the active neutrino self- energy At lower temperature the definition of the control by
- At high *T* coupled from the computation $(1 + 1 \text{ m})$ or $(1 + 1 \text{ m})$ • At high T $2K \cdot \text{Re } \Sigma = -m_l^2 \sim g^2 T^2$
- At low *T* (positive) matter potential $I₁$ Λ μ Λ _r σ μ ¹ σ σ ¹ Field we are positive) indical potential
- (Broad) resonance $\left(D_{\text{max}}\right)$ because as $\left(2, 2\right)$ of 1 + n ↔ 2 + n processes are shown in fig. 1(a) and of 2 ↔ 2 processes in fig. 2(a). Second, • (Broad) resonance

Indirect processes from a Yukawa interaction. (b) Examples of 1 + n ↔ 2 + n processes for the generation of leftlines correspond to Standard Model fermions, scalars, and gauge bosons, respectively, whereas righthanded neutrinos are denoted by a double line. The closed by a double line. The closed by a Higgs expectation

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$$

Indirect processes from a Yukawa interaction. (b) Examples of 1 + n ↔ 2 + n processes for the generation of leftlines correspond to Standard Model fermions, scalars, and gauge bosons, respectively, whereas righthanded neutrinos are denoted by a double line. The closed by a double line. The closed by a Higgs expectation

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Figure 1: (a) Examples of 1+n ↔ 2+n processes for the direct generation of right-handed neutrinos

mm man mund

$$
\rho(K)^{\text{indir.}} = \frac{v^2}{2} \frac{M^2 \, 2K \cdot \text{Im} \, \Sigma}{(M^2 + 2K \cdot \text{Re} \, \Sigma)^2 + 4(K \cdot \text{Im} \, \Sigma)^2}
$$

- Imaginay part of the active neutrino self- energy: active neutrino width $2K \cdot \text{Im } \Sigma = k_0 \Gamma$ At languay part of the active neutrino sen-energy. active $2K \cdot \text{Im } \Sigma = k_0 \Gamma$
- At high *T* dominated by soft 2 \leftrightarrow 2 scatterings. $\Gamma \sim g^2T$ and thus (for $M \sim gT$) $\rho \sim v^2$
- At low *T* dominated by $1 \leftrightarrow 2$ decays of gauge bosons $\frac{1}{\sqrt{2}}$ σ ^{2. The} At low T dominated by $1 \leftrightarrow 2$ $\frac{1}{2}$ interaction. The generation of $\frac{1}{2}$ + 2

Figure 1: (a) Examples of 1+n ↔ 2+n processes for the direct generation of right-handed neutrinos

• In the indirect case ρ is directly proportional to the spf of active neutrinos, i.e.

$$
\rho(K)^{\text{indir.}} = \frac{v^2}{2} \frac{M^2 \, 2K \cdot \text{Im} \, \Sigma}{(M^2 + 2K \cdot \text{Re} \, \Sigma)^2 + 4(K \cdot \text{Im} \, \Sigma)^2}
$$

- Real part of the active neutrino self- energy At lower temperature the definition of the control by
- Imaginary part of the active self energy $\mathbf r$ computation (the top quark becomes non-relativistic algebra $\mathbf r$ at a somewhat $\mathbf r$ higher temperature).
- Medium-modified mixing angle squared I_n In the regime of equipment of contributions I_n Fig. 1994 of the equal represent a property and the property of the property of the set of the set of the total state of the set of th δ as a have previously been considered in the symmetric phase M^2 $\sigma_{\text{med}} = \frac{1}{2} \sqrt{(M^2 + 2K \cdot \text{Re}\Sigma)^2 + 4(K \cdot \text{Im}\Sigma)^2}$ $\angle (M^2 + \angle K \cdot \text{Re } \angle) = + 4(N \cdot \text{Im } \angle) =$ $\theta_{\text{med}}^2 = \frac{1}{2} \frac{1}{(11)^2 + 91}$ $2 (M^2 + 2K \cdot K)$ $\theta^2_{\rm med} =$ v^2 2 M^2 $(M^2 + 2K \cdot \text{Re }\Sigma)^2 + 4(K \cdot \text{Im }\Sigma)^2$

Indirect 2↔2 processes handed neutrinos which subsequently oscillate into right-handed ones. Arrowed, and wiggly ones. Arrowed, and w
Arrowed, and wiggly ones. Arrowed, and wiggly ones. Arrowed, and wiggly ones. Arrowed, and wiggly ones. Arrowe lines correspond to Standard Model fermions, scalars, and gauge bosons, respectively, whereas righthanded neutrinos are denoted by a double line. The closed blob denotes a Higgs expectation value.

from a Yukawa interaction. (b) Examples of 1 \sim 1 \sim

- Naively $\Gamma \sim g^4 T$, but soft $(Q \sim gT)$ *t*-channel gauge boson scatterings have a large enhancement. Need to resum the "vacuum" masses and Hard Thermal Loops C ander 2: C C C and C C α Yacuum α masses and Hard Thermal Loop α
- Euclideanization (Caron-Huot **PRD82** (2008)) still applicable. In the *W* exchange case transverse Euclidean propagator (vacuum mass only) longitudinal propagator (vacuum and SU(2) screening mass) a^2T \int_0^∞ \int_0^∞ 1 $\Gamma_W^{\text{soft}} = \frac{92L}{4\pi} \int dq_\perp q_\perp \left(\frac{1}{a^2 + m^2} - \frac{1}{a^2}\right)$ for indinal propagator (yacuum and SUI) same processes as have previously been considered in the symmetric phase [27, 28]; examples g_2^2T 4π \int^{∞} 0 $dq_{\perp} q_{\perp}$ $\begin{bmatrix} 1 \end{bmatrix}$ $q_\perp^2 + m_W^2$ $-\frac{1}{a^2 + m^2}$ $q_\perp^2 + m_W^2 + m_{E2}^2$ $\overline{}$
- *Z* exchange more complicated (mixing of $SU(2)_L$ and $U(1)_Y$) but conceptually the same the same could be replaced by the same $\frac{1}{2}$ z and consider peaking and behind

handed neutrinos which subsequently oscillate into right-handed ones. Arrowed, and wiggly ones. Arrowed, and w
Arrowed, and wiggly ones. Arrowed, and wiggly ones. Arrowed, and wiggly ones. Arrowed, and wiggly ones. Arrowe Indirect 2↔2 processes lines correspond to Standard Model fermions, scalars, and gauge bosons, respectively, whereas righthanded neutrinos are denoted by a double line. The closed blob denotes a Higgs expectation value. $\frac{1}{2}$ $\begin{array}{ccc} & & & \text{if} & \mathbf{c} \\ \mathbf{c} & & & \text{if} & \mathbf{c} \end{array}$ 1 $\overline{}$ g_2^2T \int_0^∞ $-\frac{1}{a^2 + m^2}$ $\Gamma_W^{\rm soft}=$ $dq_{\perp} q_{\perp}$ $\Gamma_W^{\text{sort}} = \frac{\sigma_Z}{4\pi}$ direct dq_{\perp} and q_{\perp} and $\frac{1}{\sigma_Z^2}$ and $\frac{1}{\sigma_Z^2}$ and $\frac{1}{\sigma_Z^2}$ $q_\perp^2 + m_W^2$ $q_\perp^2 + m_W^2 + m_{E2}^2$ 4π $4\pi J_0$ examples $Q_{\perp} + m_W$ and $Q_{\perp} + m_W$ 0

from a Yukawa interaction. (b) Examples of 1 \sim 1 \sim

- At low *T* these approximations are inaccurate, they don't go into the Fermi limit which subsequently oscillate into right-handed ones. The notation is as in fig. 1. The complete set for α
- We replace them with the Fermi limit results from Asaka Laine Shaposhnikov **JHEP01** (2007) (in a more compact form, as the masses of all scatterers are negligible for *T*>5 GeV) I_{α} form so the masses of all scatterers are neal form, as the masses of an seathers are neg. \mathbf{S}

Indirect 1↔2 processes

- At high *T* they are very similar to the direct $1 \leftrightarrow 2$ processes, with the scalar replaced by a gauge boson and the coupling *h*→*g*. Hence *k*0Γ~*g*²*m*2~*g*⁴*T*2 and thus **negligible** w.r.t. the indirect 2⇔2 processes handed neutrinos which subsequently or $\frac{1}{1}$ and wiggly $\frac{1}{1}$ and $n\rightarrow g$. There $\kappa_{01}\sim g$ - $m\sim g$ -T and dius negligibit
	- At **low** *T* the LPM effect becomes negligible. The Born-level decays of gauge bosons into leptons *k*0Γ~*g*²*m*2 become the **leading contribution**, also w.r.t the indirect $2 \leftrightarrow 2$ processes (a) (b)

Indirect processes

- Soft $2 \leftrightarrow 2$ scatterings, leading at high *T*
- $2 \leftrightarrow 2$ scatterings in the Fermi limit, accurate but subleading at low *T*
- Born $1 \leftrightarrow 2$ rate, leading at low *T*, inaccurate but negligible at high *T*
- **Total:** $1 \leftrightarrow 2 +$ the appropriate (smallest) $2 \leftrightarrow 2$

Results

• Indirect processes rapidly dominate and peak at low *T* (in our 1-loop parameter fixing *T*EW≈150 GeV)

30 60 90 120 150 180 30 60 \pm 00 \pm 10-2 Results

k = 1 T

 \blacksquare Figure 8. Indirect processes rapidly dominate and neak at low T section 3 (decreed the direct 2 section 3 \pm 2 section 3 \pm 3 section 4 (dotted lines); as well as the second lines); as well as the direct 2 \pm 3 section 4 (dotted lines); as the direct 2 second lines); as well as t (in our 1-loop parameter fixing $T_{\text{EW}} \approx 150 \text{ GeV}$) ${1, 1, \ldots, T, 1, \ldots, T, T}$ • Indirect processes rapidly dominate and peak at low *T* (in our 1-loop parameter fixing *T*EW≈150 GeV)

M = 1 GeV

M = 0.5 GeV

Cosmological implications

• Compare the equilibration and washout rates to the Hubble rate ˙*fI*^k ⁼ *I*^k

$$
\gamma_{I\mathbf{k}} = \sum_{a} \frac{|h_{Ia}|^2 \rho(K)}{E_I}
$$

$$
\gamma_{ab} = -\sum_{I} \int \frac{d^3k}{(2\pi)^3} \frac{2n'_{\rm F}(E_I)|h_{Ia}|^2 \rho(K)}{E_I} \Xi_{ab}^{-1}
$$

$$
H = \sqrt{\frac{8\pi e}{3m_{\rm Pl}^2}}
$$

• Fix the RHNs Yukawa couplings in a seesaw scenario with hierarchical neutrinos, with only one Yukawa coupling contributing to a given mass difference $|\Delta m| = |h_{Ia}|^2 v^2/(2M)$ $\overline{ }$ akawa couplings in a seesaw scenario with $\frac{1}{\sqrt{1-\frac{1$ at heutrinos, with only one Tukawa coupling ² from γI^k to get

0 5 10 15 k / T 0 5 10 15 k / T Figure 10. The dependence of Im ^ΠR/T² on ^k for ^M = 0.5 GeV (left) and ^M = 2 GeV (right). The spectra at these and other temperatures can be downloaded as explained in footnote 11. 100 1111 P 10-2 80 10 11 21 12 10-2

10-2

10-2

• Leptogenesis possible because no equilibrium at T≥130 GeV explose homo possible because no equinditain at 1≈100

• Resonant generation of keV scale RHNs hindered by washout at T≲30 GeV. Fine-tuned windows still possible $\mathcal{L} = \mathcal{L} = \mathcal$ Resonant generation of keV scale RHNs hinder WE HOUGH SO COMME THE THINGS WHILE THE DUIT PODDINIC

Summary

- We have studied the dynamics of **GeV scale right-handed neutrinos** with Yukawa couplings to SM leptons and scalars in the **broken phase in the early universe**
- We have determined the **equilibration, production and washout rates at leading order** for 5 GeV<*T*<160 GeV
- In the broken phase **these rates peak at** *T***~10-30 GeV**, due to the **efficient, resonance-like indirect processes**, with consequences for leptogenesis and keV scale dark matter

• Advancements in the understanding of HTLs and LPM in the broken phase Spectra available for download at <http://www.laine.itp.unibe.ch/production-midT/>

Backup

Resonant sterile neutrino production

• Resonant production of right-handed neutrinos: a non-zero lepton asymmetry (left) creates a resonance that efficiently converts it into right-handed neutrino (DM) abundance (right) JG Laine **JHEP1511** (2015)

 $^{\prime}$

Broken phase LPM Krayan nhace UM (0) rate, re-derived in some more detail in section 5.5 (cf. eq. (5.33)). Here that the pairs equal, we can choose one of the contributions from \mathcal{A} φ1 and φ2 are degenerate. The task now is to determine the Hamiltonian Home is to determine the Hamiltonian Ho
This situation is to determine the Hamiltonian H↑ for this situation. He had to determine the Hamiltonian Home description [34, 35], the static self-energies are momentum independent. Therefore mixing conduction by constant angles, separate for spatial angles, separate for spatial and temporal gauge fields. A The standard weak mixing and standard weak mixing and as

g2

in ref. [32], the quantities of our interest (see below) can be reduced to (static) Matsubara

⎟⎟⎟⎟⎟⎠

$$
\Gamma_{3\times 3} = \begin{pmatrix}\n2\Gamma_W(0) + \Gamma_Z(0) & -\Gamma_Z(y) & -2\Gamma_W(y) \\
-\Gamma_Z(y) & 2\Gamma_W(0) + \Gamma_Z(0) & -2\Gamma_W(y) \\
-\Gamma_W(y) & -\Gamma_W(y) & 2\Gamma_W(0) + \Gamma_{Z'}(0) - \Gamma_{Z'}(y)\n\end{pmatrix}
$$

representative. Then, then
Into a 3 × 3 × 3 form, then, the

sin
Esimene

• In the *Z* and photon exchanges (*Z'* ≡ combination that couples to charged left-handed leptons) the mixing of $SU(2)_L$ and $U(1)_Y$ components is different in the longitudinal and transverse gauge bosons exchanges proofs \overline{C} \overline{A} and is the consequence of this reduction is the infrared divergence reduction is the photon is that infrared to photon is the consequence of the photon exchange of the infrared divergences related to photon excha $\mathcal L$ and photon exchanges ($\mathcal L$ $=$ com σ , σ , σ , σ , σ , σ nts is differe
່າ , (3.23) In the Z and photon exchange $(Z'$ combination that couples to μ and μ and μ and μ components can be expressed as μ charged left-handed leptons) the mixing of $SU(2)_L$ and $U(1)_Y$ $\frac{1}{2}$ ang ·······
· onents is different in the longitud
ps exchanges \sim provide a proof of p $\frac{1}{2}$, $\frac{1}{2}$ μ and photon exchanges (μ = compliation that couples σ can be described by constant and the spatial and temporal gauge for σ sin
Esimene proofs JCAP_003P_0616 oton exchanges $(Z' \equiv$ combination that couple arged left-handed leptons) the mixing of $SU(2)$ and $U(1)_Y$. the static temporal components is denoted by $\frac{1}{\sqrt{2}}$ ges $\mathcal{L} = \mathcal{L} \times \mathcal{L}$ \sim

$$
\Gamma_{Z}(y) \equiv \frac{(g_1^2 + g_2^2)T}{4} \int_{\mathbf{q}_{\perp}} e^{i\mathbf{q}_{\perp} \cdot \mathbf{y}} \left[\frac{1}{q_{\perp}^2 + m_Z^2} - \frac{\cos^2(\theta - \tilde{\theta})}{q_{\perp}^2 + m_Z^2} - \frac{\sin^2(\theta - \tilde{\theta})}{q_{\perp}^2 + m_{\tilde{Q}}^2} \right],
$$

\n
$$
\Gamma_{Z'}(y) \equiv \frac{(g_1^2 + g_2^2)T}{4} \int_{\mathbf{q}_{\perp}} e^{i\mathbf{q}_{\perp} \cdot \mathbf{y}} \left[\frac{\cos^2(2\theta)}{q_{\perp}^2 + m_Z^2} + \frac{\sin^2(2\theta)}{q_{\perp}^2} - \frac{\cos^2(\theta + \tilde{\theta})}{q_{\perp}^2 + m_{\tilde{Z}}^2} - \frac{\sin^2(\theta + \tilde{\theta})}{q_{\perp}^2 + m_{\tilde{Q}}^2} \right]
$$

\n
$$
m_{\tilde{w}}^2 \equiv m_w^2 + m_{\text{E}2}^2, \quad m_{\tilde{z}}^2 \equiv m_+^2, \quad m_{\tilde{Q}}^2 \equiv m_-^2,
$$

\n
$$
m_{\pm}^2 \equiv \frac{1}{2} \left\{ m_z^2 + m_{\text{E}1}^2 + m_{\text{E}2}^2 \pm \sqrt{\sin^2(2\theta)m_z^4 + [\cos(2\theta)m_Z^2 + m_{\text{E}2}^2 - m_{\text{E}1}^2]^2} \right\}
$$

\n
$$
\sin(2\tilde{\theta}) \equiv \frac{\sin(2\theta)m_Z^2}{\sqrt{\sin^2(2\theta)m_Z^4 + [\cos(2\theta)m_Z^2 + m_{\text{E}2}^2 - m_{\text{E}1}^2]^2}}
$$