Freeze-in in micrOMEGAs

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Outline

- Freeze-in: general framework (reminder?)
- Implementation in micrOMEGAs 5
- A few examples
- Summary and outlook

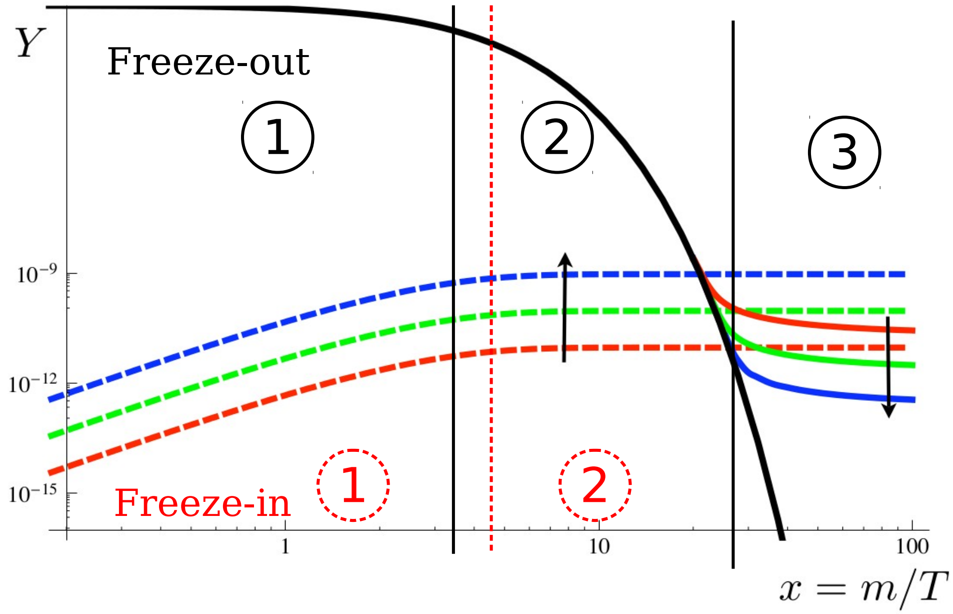
Based on:

- G. Bélanger, F. Boudjema, A.G., A. Pukhov, B. Zaldivar, arXiv:1801.03509
- A. G. *et al*, contribution in arXiv:1803.10379
- A.G. *et al*, arXiv:1811.05478
- A. G., K. A. Mohan, D. Sengupta, arXiv:1807.06642

Freeze-in: general idea

arXiv:hep-ph/0106249
arXiv:0911.1120
arXiv:1706.07442...

Tweaked from arXiv:0911.1120



Two basic premises :

- DM interacts *very* weakly with the SM.
- DM has a negligible initial density.

Assume that in reaction $A \to B$, ξ_A/ξ_B particles of type χ are destroyed/created.
Integrated Boltzmann equation :

$$\dot{n}_\chi + 3Hn_\chi = \sum_{A,B} (\xi_B - \xi_A)\mathcal{N}(A \to B)$$

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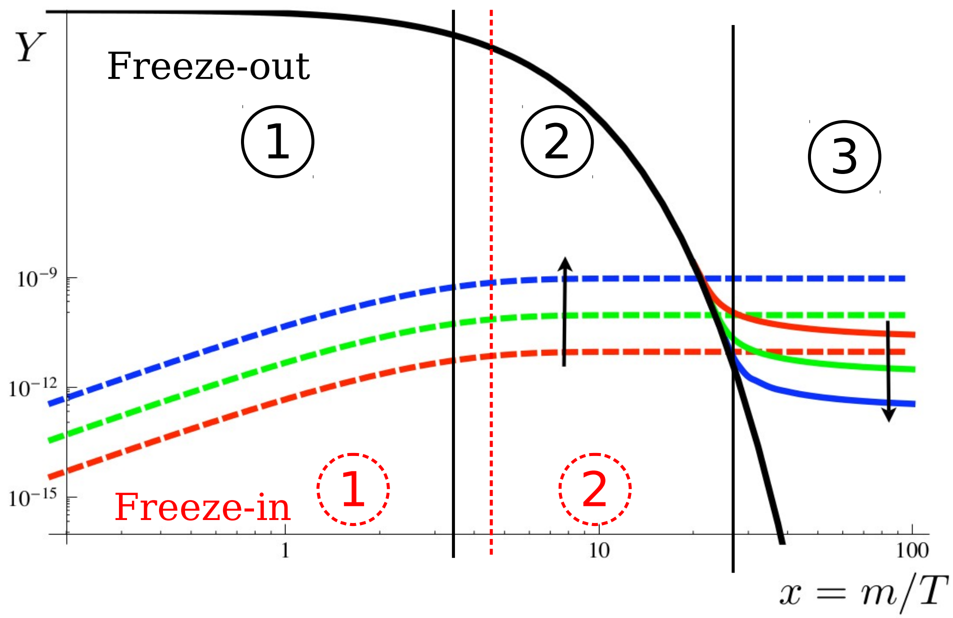

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$$\mathcal{N}(in \to out) = \int \prod_{i=in} \left(\frac{d^3 p_i}{(2\pi)^3 2E_i} f_i \right) \prod_{j=out} \left(\frac{d^3 p_j}{(2\pi)^3 2E_j} (1 \mp f_j) \right) \times (2\pi)^4 \delta^4 (\sum_{i=in} P_i - \sum_{j=out} P_j) C_{in} |\mathcal{M}|^2$$

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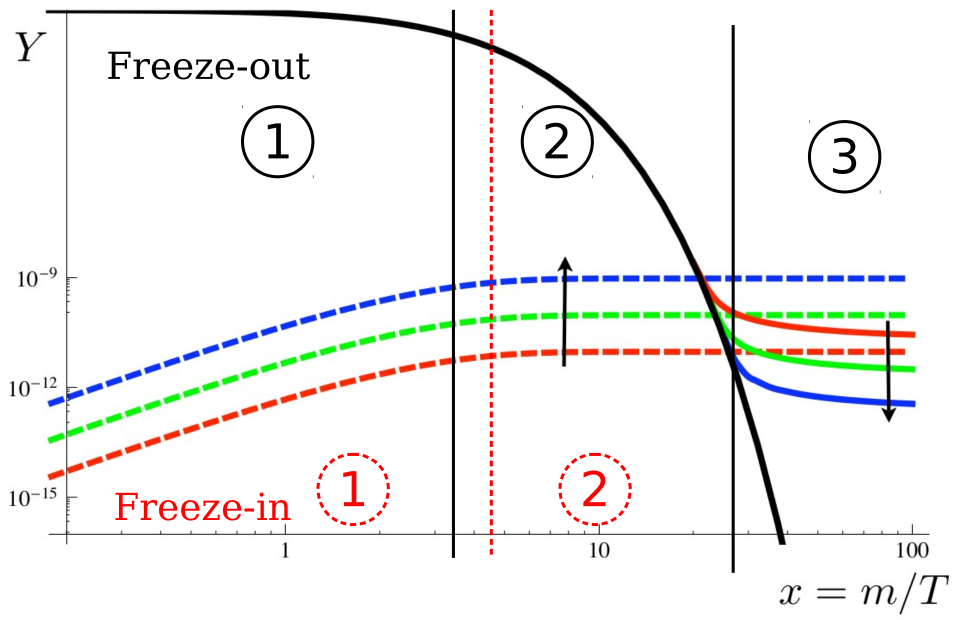

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1. DM produced from decays/annihilations of other particles.
2. DM production disfavoured → Abundance *freezes-in*

Freeze-in vs freeze-out

Naively, the freeze-in BE is simpler than the freeze-out one. However :

Initial conditions:

· FO: equilibrium erases all memory.

· FI: Ωh^2 depends on the initial conditions.

Heavier particles:

· FO: pretty irrelevant (exc. coannihilations/late decays).

· FI: their decays can dominate DM production.

Need to track the evolution of heavier states

In equilibrium? Relics? FIMPs?

Need dedicated Boltzmann eqs

Relevant temperature:

· FO: around $m_\chi/20$.

· FI: several possibilities ($m_\chi/3$, $m_{\text{parent}}/3$, T_R or higher), depending on nature of underlying theory.

- Statistics/early Universe physics can become important.

Automatising freeze-in calculations

Given the previous subtleties and the potentially large number of contributing processes, freeze-in calculations can get tricky.

micrOMEGAs5.0 : freeze-in

G. Bélanger[1†], F. Boudjema[1‡], A. Goudelis[2§], A. Pukhov[3¶], B. Zaldivar[1††]

arXiv:1801.03509

Can compute the freeze-in DM abundance in fairly generic BSM scenarios:

- Scattering of bath particles
- Decays of bath particles/FIMPs
- Decays of thermal relics — "super-WIMP" scenario

Boost activity in

- · Model-building: what types of ("well-motivated") models can accommodate freeze-in?
- · Phenomenology: what are the "standard" signatures of freeze-in scenarios?

Example: freeze-in with a charged parent

Consider SM extension by a Z_2-odd real singlet scalar *s* (DM) along with a Z_2-odd vector-like SU(2)-singlet fermion *F* (parent).

contribution in arXiv:1803.10379
and arXiv:1811.05478

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\; \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right)$$
$$+ \bar{F}\left(iD\right) F - m_F \bar{F} F - \sum_f y_s^f \left(s\bar{F}\left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right)$$

Focus here on scenario $f = \{e,\mu,\tau\}$, *i.e.* *F* is a "Heavy Lepton".

For quark case *cf* arXiv:1811.05478
For neutral parent *cf* *e.g.* arXiv:1805.04423

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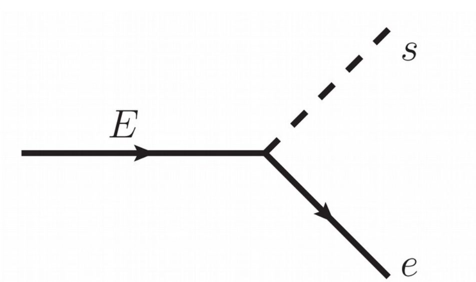
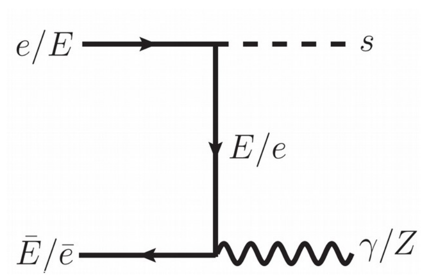
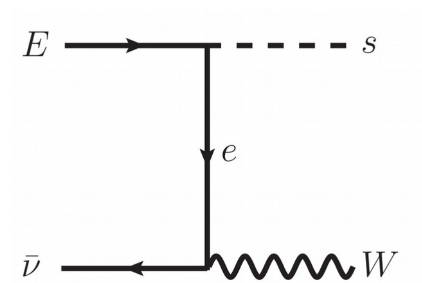
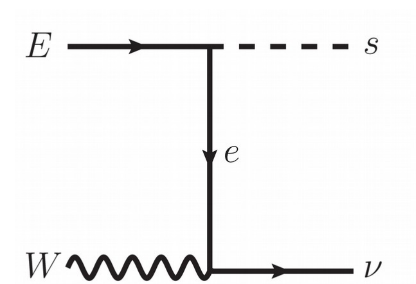
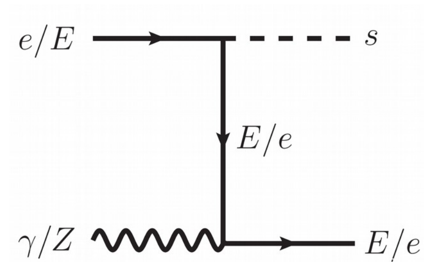
In this model DM is generated through processes of the type:











In practice

To compute the freeze-in abundance of s in this model you need to:

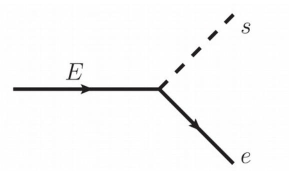
· Implement the model in CalcHEP, *e.g.* using FeynRules, SARAH, LanHEP etc.

· Sort odd particles by mass and declare which particles are feebly coupled :

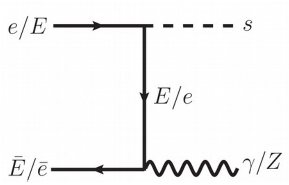
```
err=sortOddParticles(cdmName);
toFeebleList(CDM1);
```

· Compute the abundance from each process and sum all contributions, *e.g.* :

```
darkOmegaFiDecay(TR, "~he", KE, plot);
```




```
darkOmegaFi22(TR, "e-, ~HE → Z, ~s0", vegas, plot, &err);
```

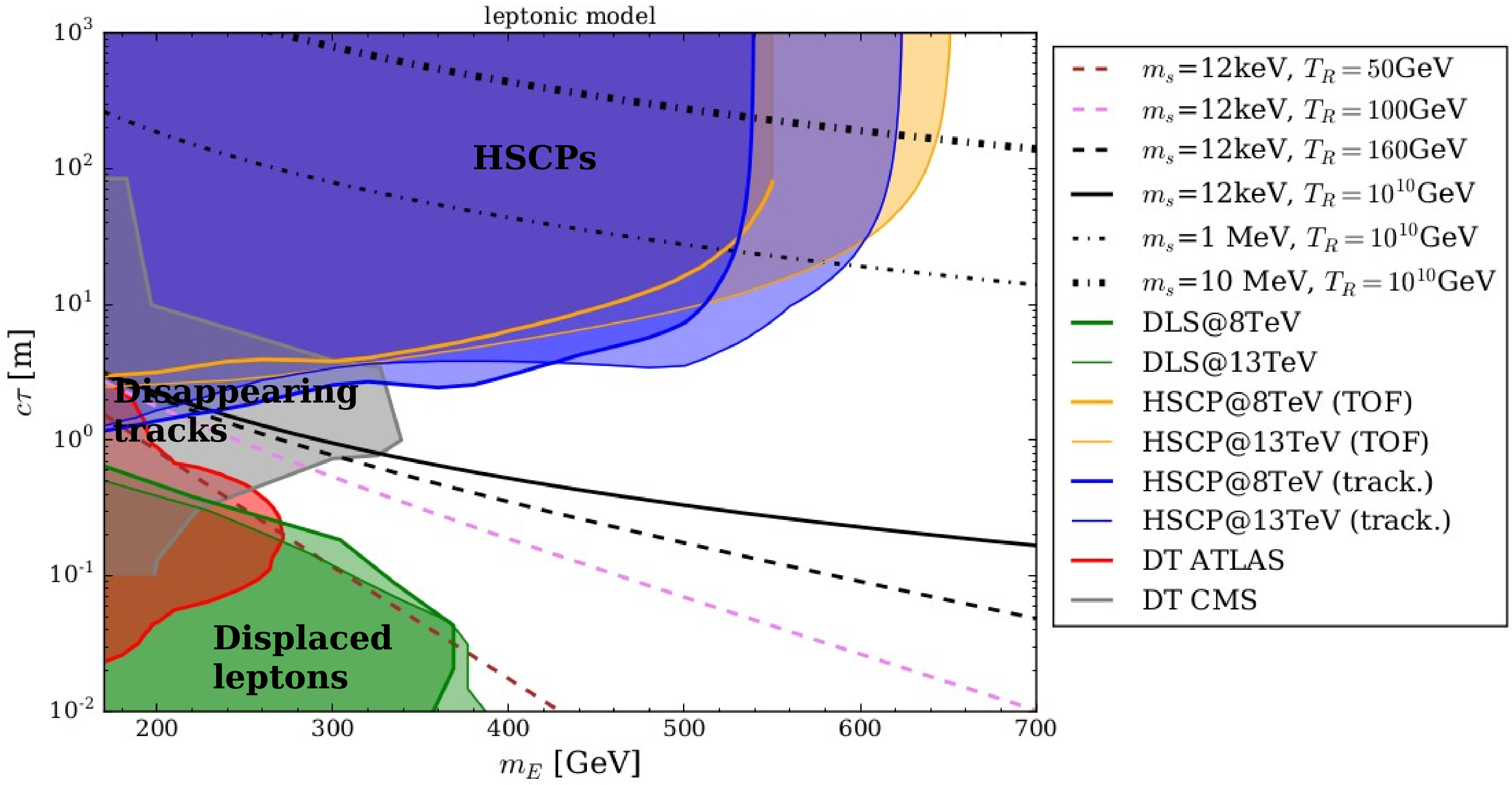


· Or let micrOMEGAs do the job for you:

```
darkOmegaFi(TR, &err);
```

FI with a charged parent: results

Freeze-in DM abundance as computed with micrOMEGAs 5, combined with various constraints from LHC searches for long-lived particles:

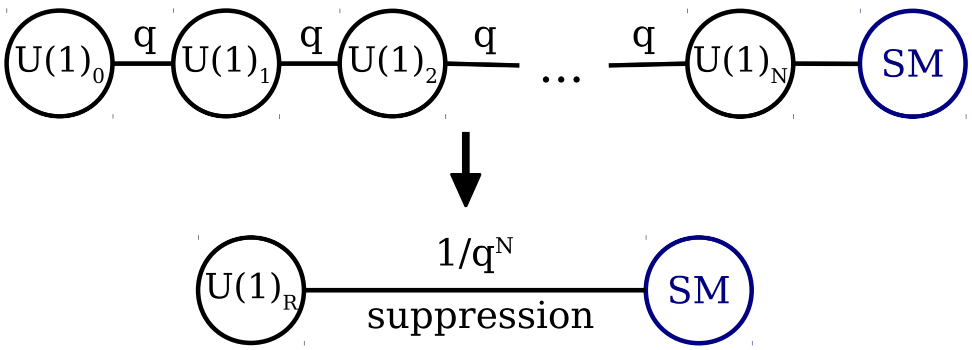


In this region of parameter space DM abundance dominated by heavy lepton decays, scattering can dominate in others.

Another example: scalar Clockwork FIMP

arXiv:1709.04105, arXiv:1807.06642

- Start from the original Clockwork Lagrangian and couple the N-th site to the SM through the Higgs portal interaction.



- Add an additional mass term for all sites → Now can control the zero mode mass.

- Huge number of processes from zero mode/gear quartic interactions.

Computationally untractable

- Deform quartic piece of the scalar potential to eliminate them.

$$\mathcal{L}_{sFIMP} = \mathcal{L}_{kin} - \frac{1}{2}\sum_{i,j=0}^{N} \phi_i M_{ij}^2 \phi^j - \frac{m^2}{24 f^2}\sum_{i,j=0}^{N} (\phi_i \tilde{M}_{ij}^2 \phi^j)^2 - \kappa |H^\dagger H| \phi_n^2 + \sum_{i=0}^{n} \frac{t^2}{2}\phi_i^2$$

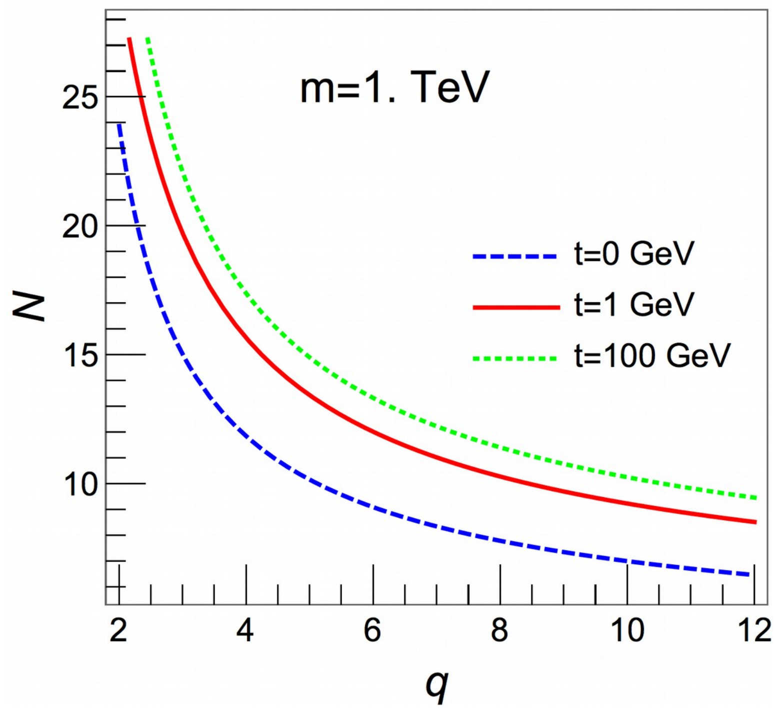
NB: Now includes t-terms

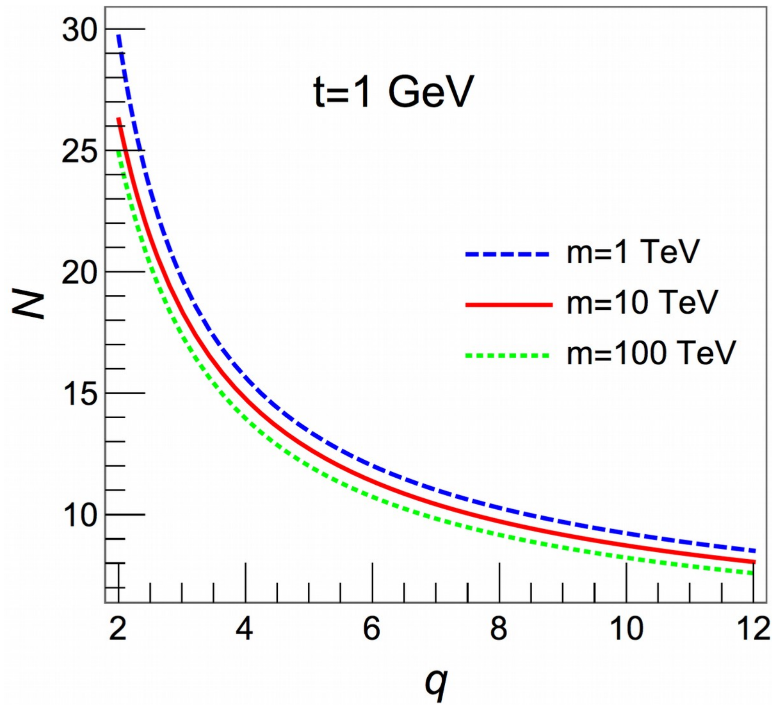
$$\left(\tilde{M}_{ij} \equiv M_{ij} + \kappa v^2 \delta_{iN}\delta_{jN}\right)$$

A scalar Clockwork FIMP - Results

arXiv:1807.06642

Combinations of (q,N) for which we can obtain correct freeze-in:





· Higgs portal set to 1

· For these parameter choices, DM abundance dominated by gear decays $a_i \rightarrow a_0 + h$

Summary and outlook

· The freeze-in mechanism is an attractive alternative to thermal freeze-out, predicting new and exciting DM phenomenological signatures, notably related to LHC (and other) searches for long-lived particles.

· Freeze-in is now implemented in micrOMEGAs. Have fun with it!

· Many different cases can be handled and/or combined and if your favourite functionality is not included in the code we're happy to receive feedback.

· Many ideas for the future: Conversion-driven freeze-out, finite temperature effects, beyond instantaneous reheating approximation...