Inflationary particle production

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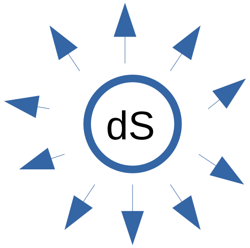
Parker, Grib, Zeldovich, Starobinsky,... 60-70's

– **inflation produces all particles:**



non-thermal dark matter

SM fields

etc.

– **background for any model bulding:**

$Y(0) \gg 0$

initial conditions for freeze-in

SM radiation

– **yet many questions:**

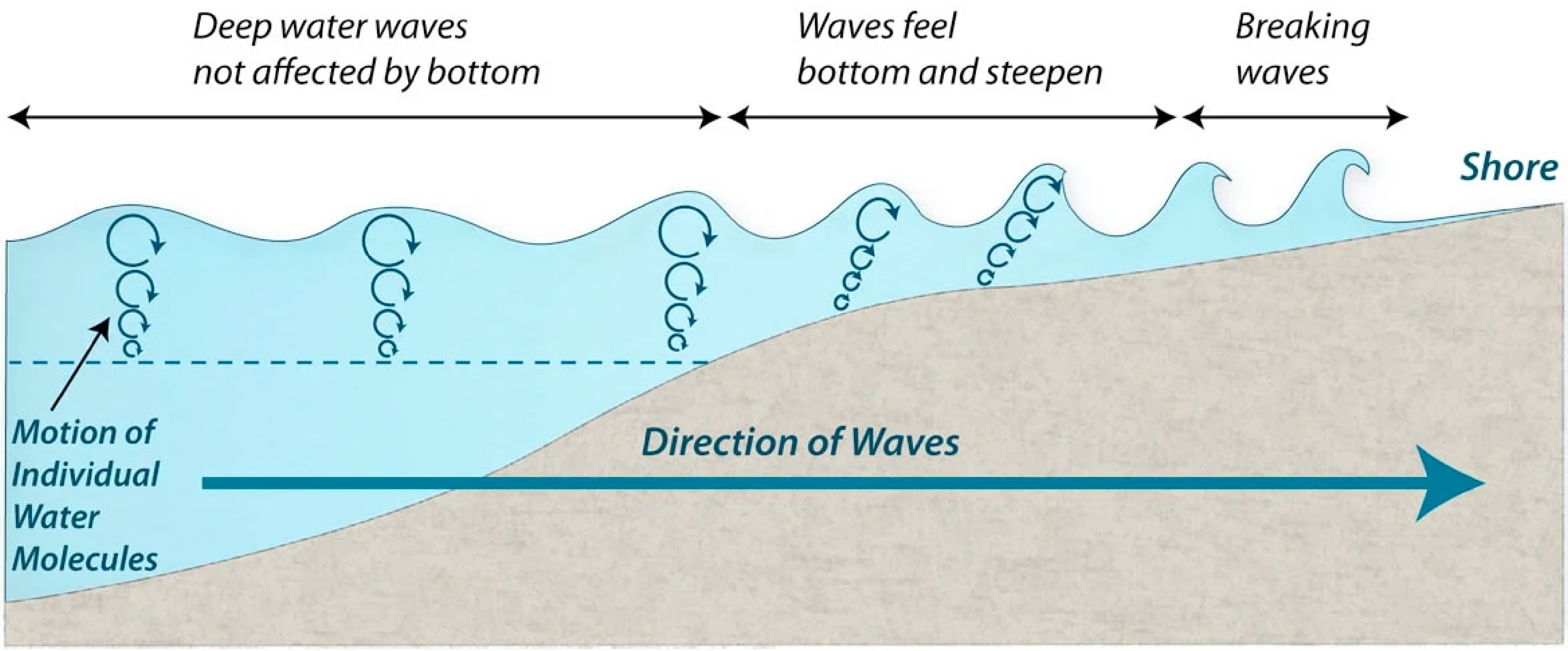
How efficient? How reliable?

Do different approaches agree?

How many quarks has inflation produced???

Inflationary particle production:

fluctuations → *particles*



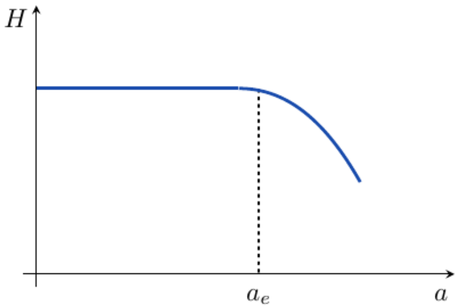
Bogolyubov

Wavefunction evolution with in- and out-boundary conditions

$$\chi_k'' + \omega_k^2 \chi_k = 0$$

Past:

| **in** >



Future:

| **out** >

Particle number:

$$\langle 0^{\rm in}|N^{\rm out}|0^{\rm in}\rangle = V \int \frac{d^3\mathbf{k}}{(2\pi)^3}\, |\beta_k|^2$$

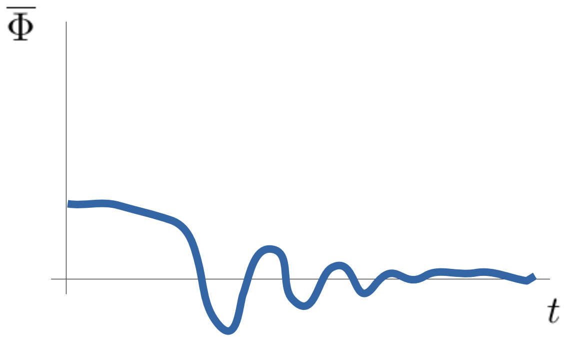
$$\beta_k = i(\chi_k^{\rm out\,\prime}\chi_k^{\rm in} - \chi_k^{\rm out}\chi_k^{\rm in\,\prime})$$

Starobinsky

Evolution of the “condensate” with quantum noise

$$\frac{d}{dt}\langle\overline{\Phi}^2\rangle = -\frac{2}{3}\frac{m^2}{H}\langle\overline{\Phi}^2\rangle + \frac{H^3}{4\pi^2}$$

After inflation:
condensate → *particles*



Particle number:

$$n = \frac{\rho}{m} = \frac{1}{2} m \overline{\Phi}^2$$

Bogolyubov approach :

$$\phi(\eta, \mathbf{x}) = \int \frac{d^3\mathbf{k}}{(2\pi)^3} \left[a_\mathbf{k}\, \chi_k(\eta)\, e^{i\mathbf{k}\cdot\mathbf{x}} + a_\mathbf{k}^\dagger\, \chi_k^*(\eta)\, e^{-i\mathbf{k}\cdot\mathbf{x}} \right]$$

free light scalar

$$\chi_k'' + \omega_k^2\, \chi_k = 0\ ,$$

$$\omega_k^2(\eta) = k^2 + a^2(\eta)\, m^2 + \left(\frac{1}{6} - \xi\right)\, a^2(\eta)\, R(\eta)$$

Asymptotic solutions :
("Minkowski-like")

$$\chi_k^{\rm in}(\eta \to -\infty) \to \frac{e^{-i\int^\eta d\eta' \omega_k(\eta')}}{\sqrt{2\omega_k(\eta)}}\ ,$$

$$\chi_k^{\rm out}(\eta \to +\infty) \to \frac{e^{-i\int^\eta d\eta' \omega_k(\eta')}}{\sqrt{2\omega_k(\eta)}}\ .$$

Bogolyubov transform :

$$\begin{cases} \chi_k^{\rm in}(\eta) = \alpha_k\, \chi_k^{\rm out}(\eta) + \beta_k\, \chi_k^{\rm out\,*}(\eta) \\[2ex] a_\mathbf{k}^{\rm in} = \alpha_k^*\, a_\mathbf{k}^{\rm out} - \beta_k^*\, a_{-\mathbf{k}}^{\rm out\,\dagger} \end{cases}$$

Bunch-Davies vacuum :
(no particles initially)

$$a_{\mathbf{k}}^{\rm in}\,|0^{\rm in}\rangle = 0$$

Particle number at late times:

$$\langle 0^{\rm in}|N^{\rm out}|0^{\rm in}\rangle = V\int \frac{d^3\mathbf{k}}{(2\pi)^3}\,|\beta_k|^2$$

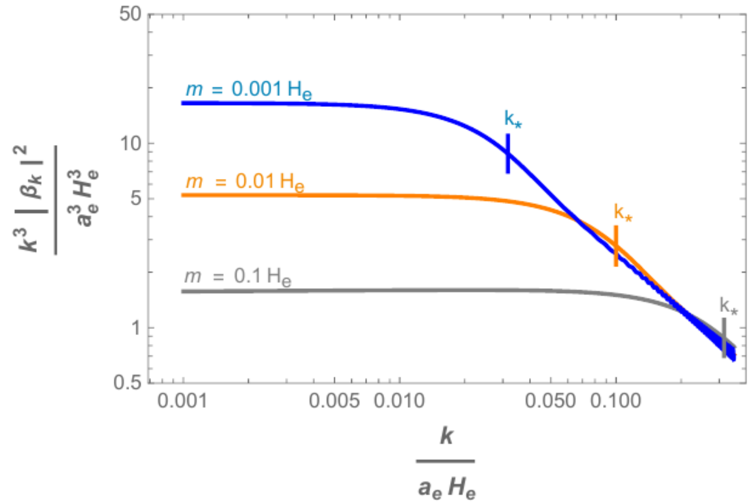
$$\beta_k = i(\chi_k^{\rm out\,\prime}\chi_k^{\rm in} - \chi_k^{\rm out}\chi_k^{\rm in\,\prime})$$

Example: inflation followed by radiation-domination

Feiteira, OL' 25

Integral converges, dominated by momenta $k < k_*$

$$k_* = \sqrt{m a_e^2 H_e}$$



$$a^3 n = \frac{3\kappa^2\,a_e^3}{4\pi^2}\frac{H_e^{11/2}}{m^{5/2}}$$

finite, but huge for light m

$$\langle\Phi^2\rangle_{\rm IR} = \frac{1}{a^2(\eta)}\int^{\epsilon a H}\frac{d^3\mathbf{k}}{(2\pi)^3}\,\left|\chi_k^{\rm in}(\eta)\right|^2 = \frac{3}{8\pi^2}\,\frac{H^4}{m^2}$$

anomalously large average field at the end of inflation (correlator / condensate)

Starobinsky

$$\Phi = \overline{\Phi}(t,\mathbf{r}) + \int \frac{d^3\mathbf{k}}{(2\pi)^3}\,\theta(k-\epsilon a(t)H)\,\left(a_{\mathbf{k}}\chi_k(t)\,e^{i\mathbf{k}\cdot\mathbf{r}} + a^\dagger_{\mathbf{k}}\chi^*_k(t)\,e^{-i\mathbf{k}\cdot\mathbf{r}}\right)$$

long wavelength *short wavelength*

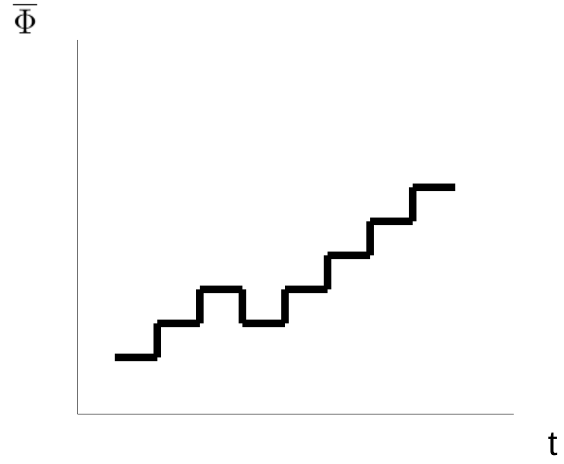
Random walk:

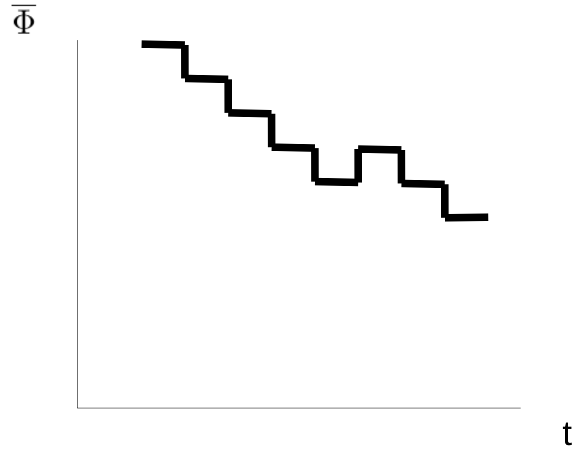
$$\frac{d}{dt}\langle\overline{\Phi}^2\rangle = -\frac{2}{3}\,\frac{m^2}{H}\,\langle\overline{\Phi}^2\rangle + \frac{H^3}{4\pi^2}$$

$$\langle\overline{\Phi}^2\rangle = \frac{3H^4}{8\pi^2m^2} + \left(\langle\overline{\Phi}^2\rangle_0 - \frac{3H^4}{8\pi^2m^2}\right)\,e^{-\frac{2m^2}{3H}\,(t-t_0)} \to \frac{3}{8\pi^2}\,\frac{H^4}{m^2}$$

Timescale:

$$\#\text{ of e}-\text{folds} > \mathcal{O}\left(\frac{H^2}{m^2}\right)$$ >>> 1 (e.g. 10^{26})





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Bogolyubov

infinitely long inflation

$$a_{\mathbf{k}}^{\rm in}\,|0^{\rm in}\rangle = 0$$

$$\eta \to -\infty$$

Starobinsky

finite inflation

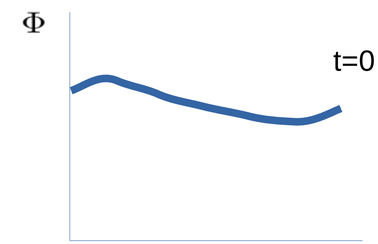
non-trivial initial conditions

$$\langle \overline{\Phi}^2 \rangle_0$$

Agree if inflation is super-long !

$$\langle \overline{\Phi}^2 \rangle \to \frac{3}{8\pi^2}\frac{H^4}{m^2}$$

Inflaton is not in the Bunch-Davies vacuum, why should any other scalar be ?



parametrize particle abundance in terms of unknown "condensate" value at the end of inflation $\overline{\Phi}$

$$Y \simeq 0.07 \times \frac{\overline{\Phi}^2}{m^{1/2} M_{\rm Pl}^{3/2}}$$

$$\overline{\Phi} > H_e \quad \Rightarrow \quad m \ll \;{\rm eV}$$

General result for *inflationary* scalar production:

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$$Y \propto \frac{\overline{\Phi}^2}{m_{\text{eff}}^{1/2}} \times \left(\frac{H_R}{m_{\text{eff}}}\right)^{\gamma}$$

γ = 0 (radiation dom.) or ½ (matter dom.)

Includes

- weak self-coupling λ
- small non-minimal coupling to gravity ξ
- general initial conditions

Intermediate conclusion:

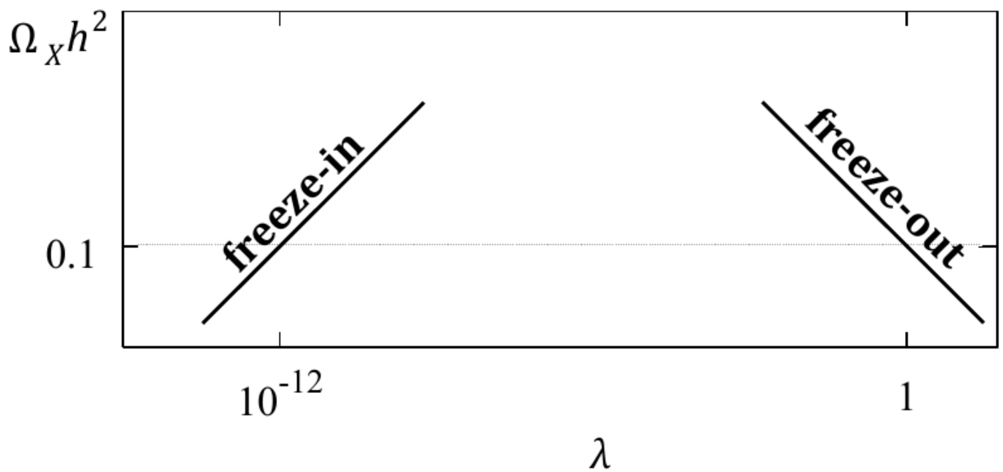
– ***scalar abundance cannot be predicted even within classical gravity !***

– ***very strong lower bounds exist (m << eV or T_R < GeV)***

– ***even worse in quantum gravity*** $\frac{\varphi^4\Phi^2}{M_{\rm Pl}^2}, \frac{\varphi^6\Phi^2}{M_{\rm Pl}^4}, \frac{\varphi^8\Phi^2}{M_{\rm Pl}^6}$

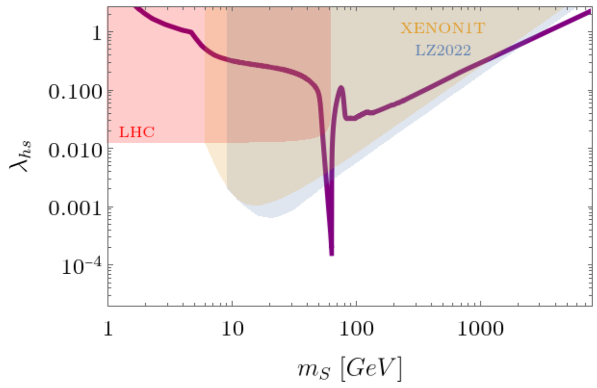
Dark Matter freeze-in problematic unless T_R is low

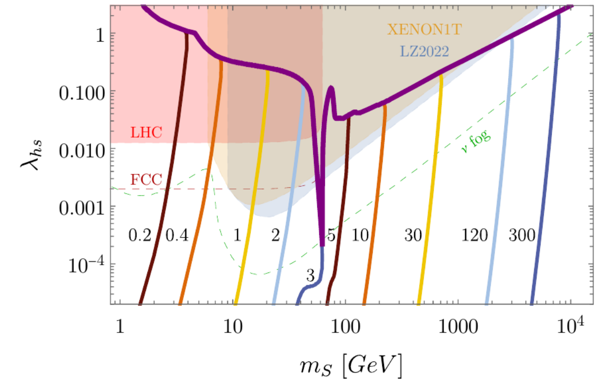
Cosme,Costa,OL ‘23



freeze-in at stronger coupling

Arcadi,Costa,Goudelis,OL ‘24





Feiteira, Koutroulis, OL, Pokorski ‘25

Quark / Lepton inflationary production

By conformal transformation:

$$(i\gamma^\mu \partial_\mu - a(\eta) M)\, \Psi = 0$$

$$Y \propto \left(\frac{M}{M_{\rm Pl}}\right)^{3/2}$$

Parker ‘ 71
Chung, Everett, Yoo, Zhou ‘11

tiny for standard fermion masses!

Starobinsky, Yokoyama ‘94

But for the minimally coupled Higgs:

$$\langle h^2 \rangle \to 0.1 \frac{H^2}{\sqrt{\lambda_h}}$$

$$M_f = \frac{1}{\sqrt{2}} Y_f \langle h \rangle$$

→ SM fermions super-heavy

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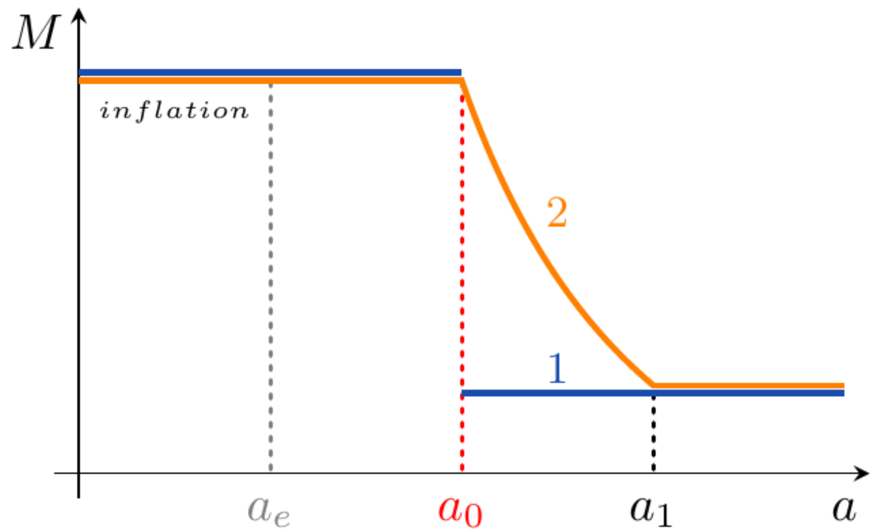
solve the Dirac equation in a time-dependent background
with a time-dependent mass

Mass Profiles**:**



Results:

$$Y^{\rm SM} \sim 10^{-3} \times \frac{Y_f^{7/2}}{\lambda_h} \left(\frac{H_e}{M_{\rm Pl}}\right)^{3/2}$$

up to 10^{20} above naive estimate

Very efficient for sterile neutrinos if $\Delta\mathcal{L} = \frac{1}{2}\mathcal{Y}^s\, s\, \nu_R \nu_R + \text{h.c.}$ → DM (?)

CONCLUSION

- *inflation is efficient in particle production (uncertainty!)*
- *dark relics are (over)produced during/after inflation*
- *traditional freeze-in models problematic*
- *SM fermions produced by inflation*
- *Bogolyubov*  *Starobinsky*