Title: Asymmetric reheating and chilly dark sectors

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Abstract: In a broad class of theories, the relic abundance of dark matter is determined by interactions internal to a thermalized dark sector, with no direct involvement of the Standard Model. These theories raise an immediate cosmological question: how was the dark sector initially populated in the early universe? I will discuss one possibility, asymmetric reheating, which can populate a thermal dark sector that never reaches thermal equilibrium with the SM.

Asymmetric reheating and chilly dark sectors

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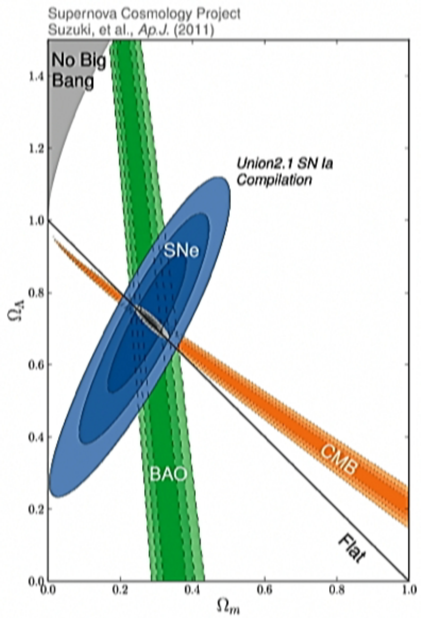
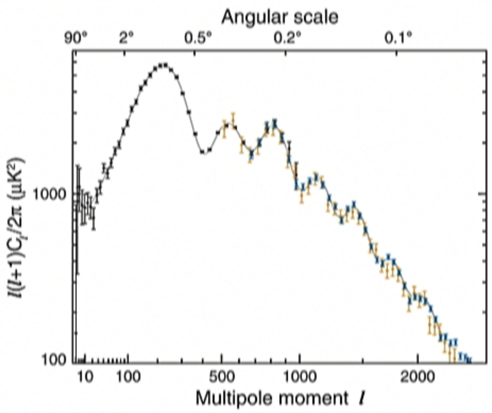
-JHEP 1606 (2016) 016 (arXiv:1604.02548)

Motivation

- Dark matter is one of the biggest unexplained mysteries in physics
  - abundant *gravitational* evidence for dark matter

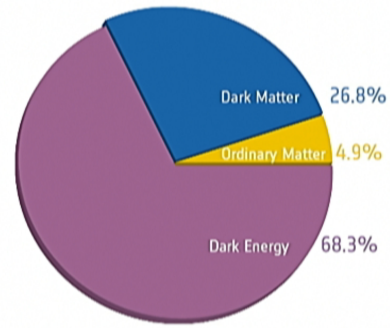




- We know its present day abundance
- It must be cold
- With limited self-interactions

Particle dark matter

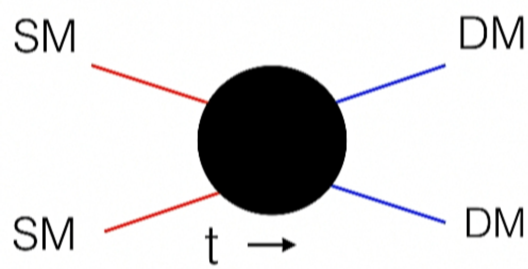
"We don't know what all the stuff is"

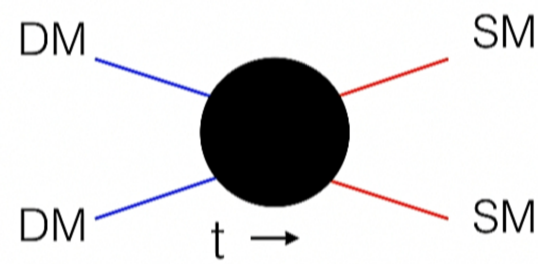


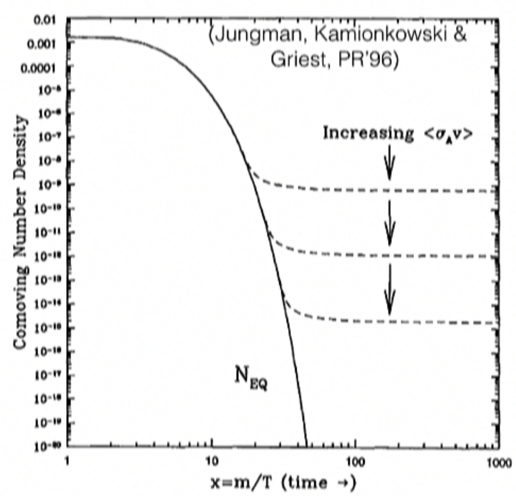
- Particle dark matter is the dominant paradigm
- It is *strictly* physics beyond the standard model (SM) of particle physics
  - Requires at least one new degree of freedom
  - Must be have very long lifetime
- But no phenomenology in particle physics requires dark matter
  - "Tyranny" of the WIMP miracle

WIMP Miracle

- WIMP miracle: $\dot{n} + 3Hn = \langle \sigma_{\rm ann} v \rangle (n^2 - n_{\rm eq}^2)$







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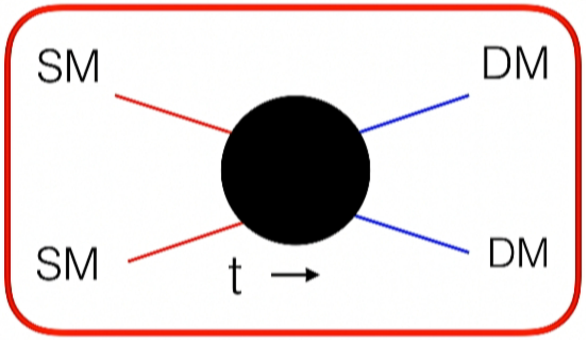

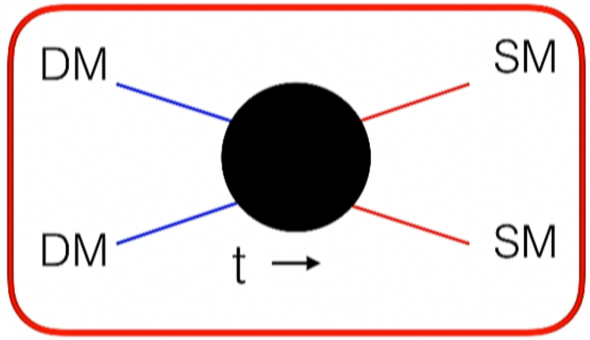

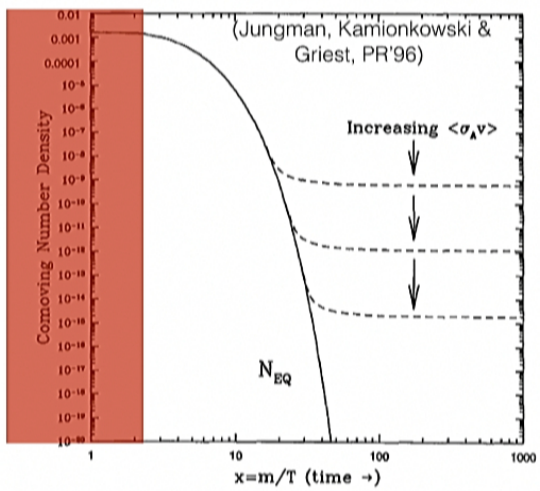

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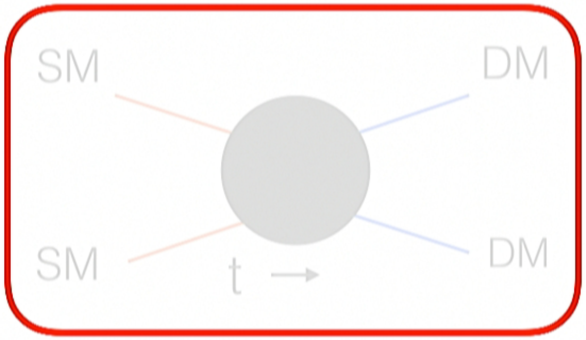

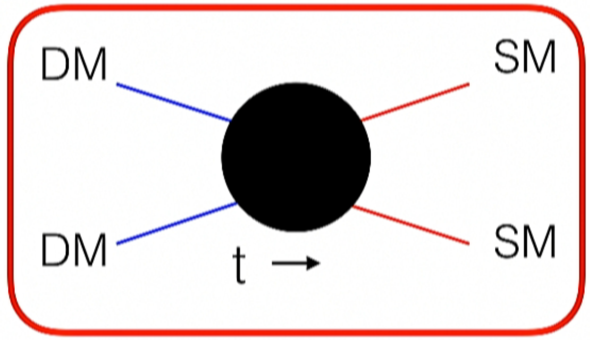

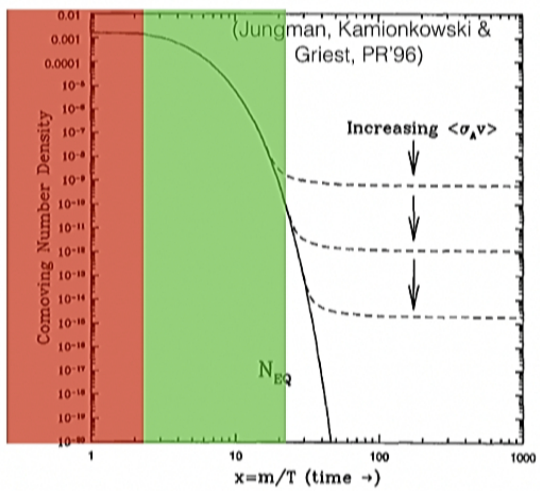

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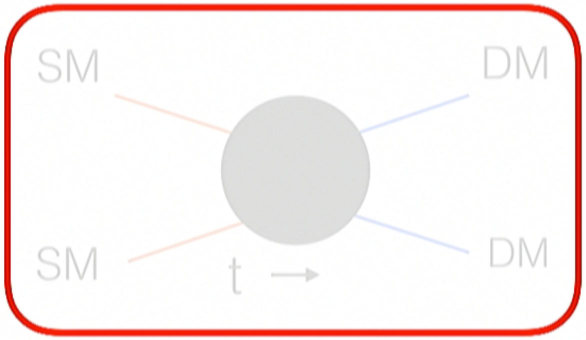
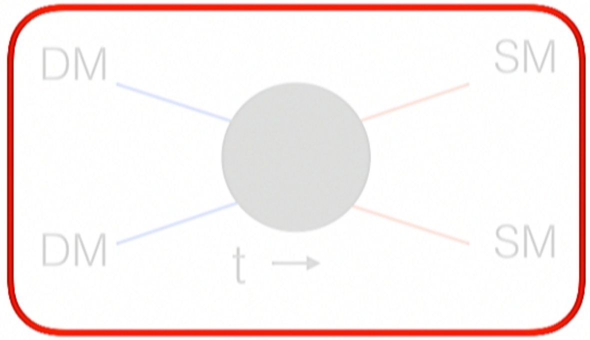
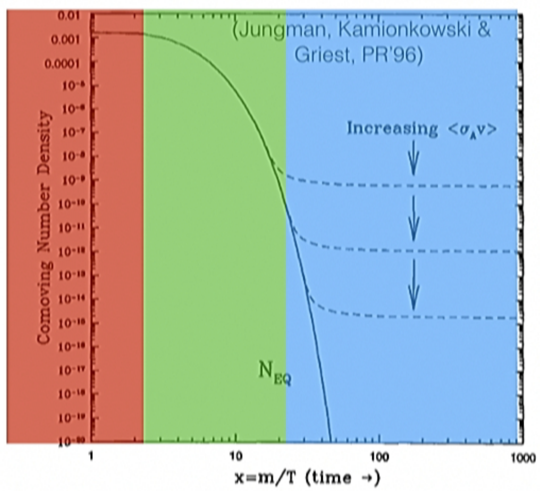






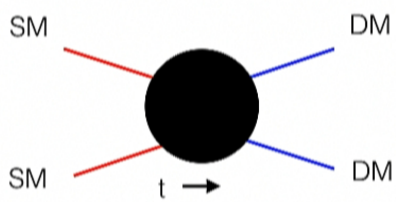
$$\Omega_{\rm DM} \propto \langle \sigma v \rangle^{-1}$$
$$\sim 0.1 \left(\frac{G_{\rm Fermi}}{G_\chi}\right)^2 \left(\frac{M_{\rm weak}}{m_\chi}\right)^2$$

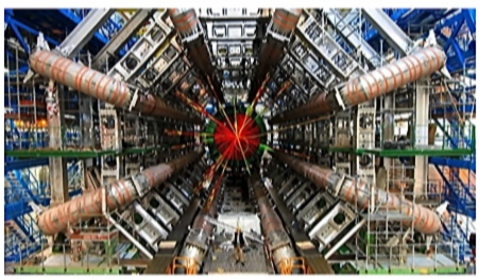
- Natural consequence of the weak scale(?)

WIMP Searches: "Gardening"

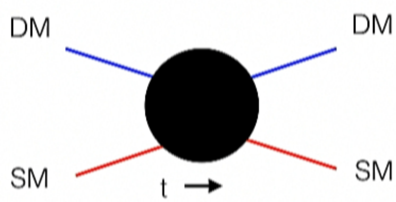
- WIMP miracle is testable:
  - Because it couples to the SM we can search for it

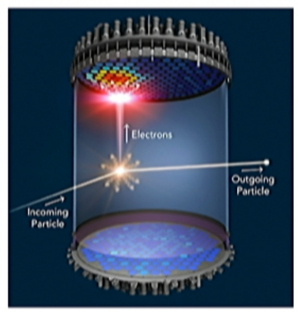
Direct production



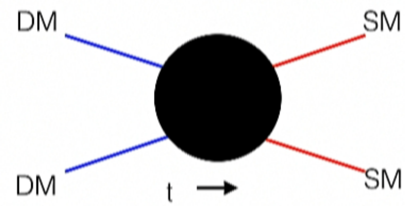


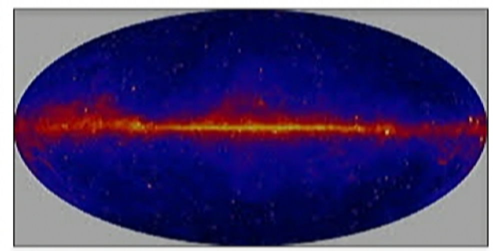
Direct Detection





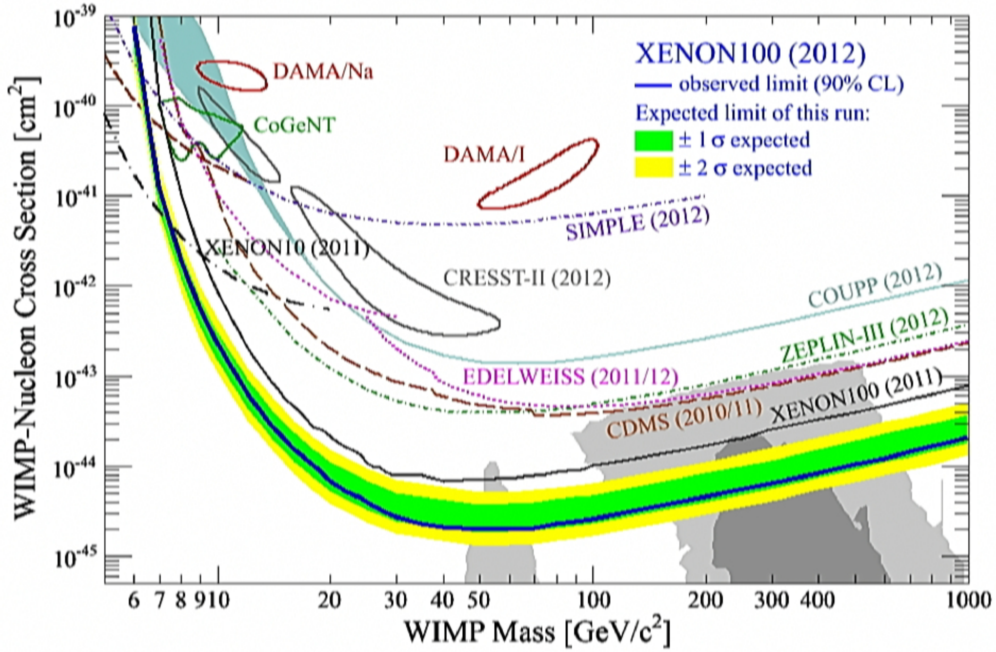
Indirect detection





But we haven't seen anything, yet.

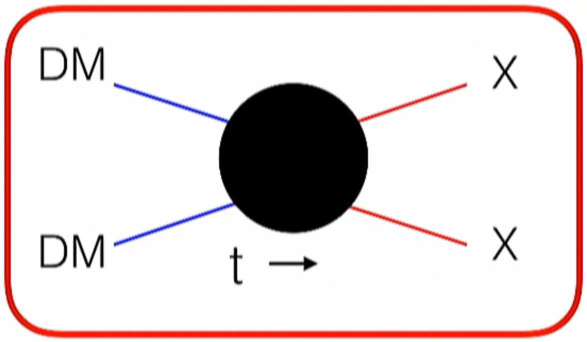
- Xenon 100 — many weeds pulled!

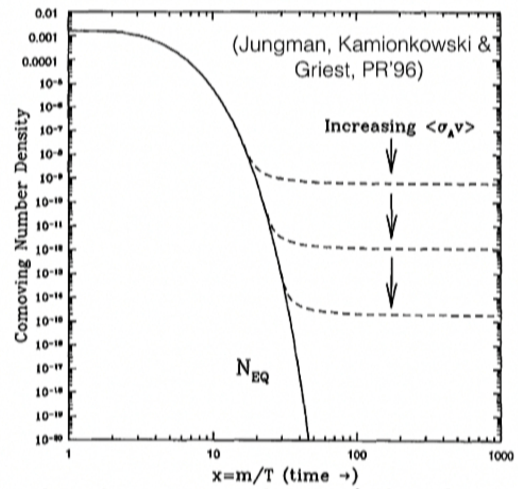


- Much of the 'nice' parameter space already gone!
- Is the WIMP miracle dead?

Dark sectors

- Nothing about WIMP miracle required SM couplings





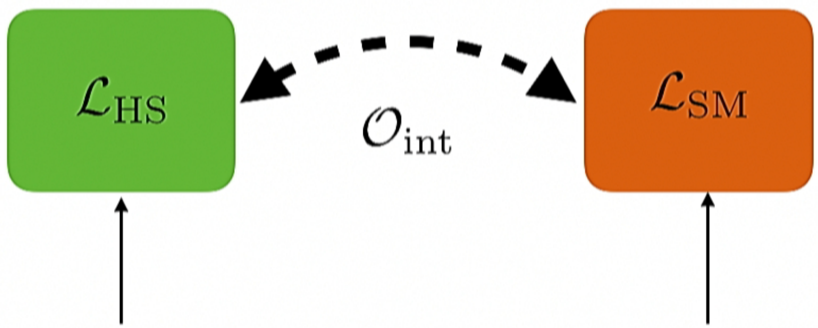
$$\Omega_{\rm DM} \propto \langle \sigma v \rangle^{-1}$$

- X is some stable light dark species (dark radiation)
  - general way to invisibly sequester HS entropy
  - can mediate long-range forces
  - accommodate relics required by symmetries, e.g. mirror matter

Dark sectors

— Tilling some new ground!

- Disconnect dark matter production from SM couplings



Dark sector: dark matter lives here

Visible sector: standard model lives here

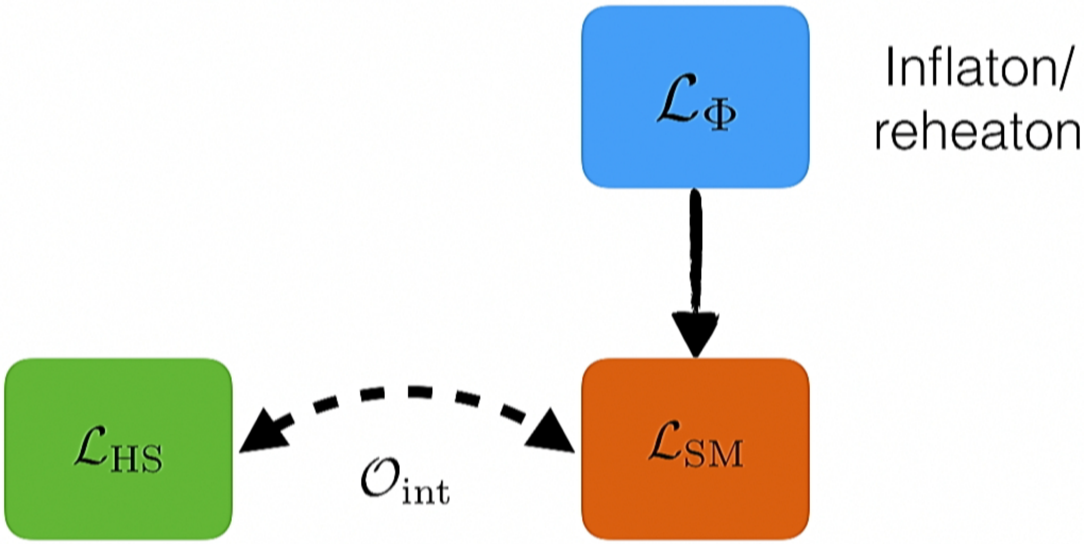
- Interaction between sectors doesn't determine Dark matter abundance

Dark sectors

- Why consider dark sectors?
  - WIMP paradigm under increasing pressure
    -Decouple DM production from SM-DM couplings
  - New solutions to cosmic problems: baryogenesis, hierarchy, galaxy structure
  - Qualitatively new/novel signals
  - Important to map out what can live in the sector that comprises 26% of the energy budget

Cosmology of dark sectors

- Dark sectors immediately raise the question: how was it populated?



- Through interactions with the SM?

Cosmology of dark sectors

- But we want cold dark sectors to accommodate dark radiation
- CMB, BBN sensitive to extra relativistic degrees of freedom: N_{eff}
  - expansion rate of universe: e.g. high-l peaks in CMB

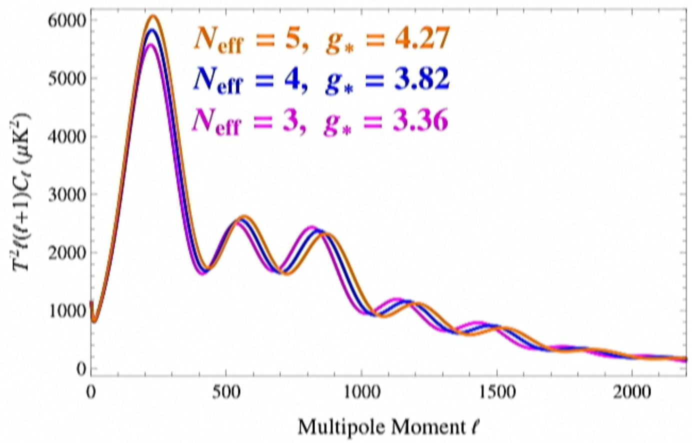


Fig from:
(Broust, Kaplan, and Walters 1303.5379)

Cosmology of dark sectors

- Current CMB constraints on N_{eff} already limit size of any such HS once in thermal equilibrium with SM:

$$\Delta N_{\rm eff} < 0.564$$ (Planck Collaboration, 1502.01589)

- This translates to

$$\begin{aligned}\Delta N_{\rm eff} =& 2.2 (g_*)^{\rm IR}_{\rm HS} \left(\frac{T^{IR}_{\rm HS}}{T^{IR}_{SM}}\right)^4 \\ =& 2.2 (g_*)^{\rm IR}_{\rm HS} \left(\frac{(g_{*S})^{\rm UV}_{\rm HS}}{(g_{*S})^{\rm IR}_{\rm HS}}\right)^{4/3} \left(\frac{(g_{*S})^{\rm IR}_{\rm HS}}{(g_{*S})^{\rm UV}_{\rm HS}}\right)^{4/3}\end{aligned}$$

- In the UV, this restricts
  - scalar radiation: $(g_{*S})^{UV}_{HS} < 9.8$
  - vector radiation: $(g_{*S})^{UV}_{HS} < 11.7$
  - already too small for e.g. octet of SU(3)!

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Cosmology of dark sectors

- Future CMB experiments (e.g. S4) will constrain

$$\sigma(N_{\rm eff}) \lesssim 0.015 - 0.03$$

  - A minimal candidate hidden sector contains 1 scalar dark matter species, one scalar radiation species: g_S=2

$$\Rightarrow \Delta N_{\rm eff} > 0.067$$

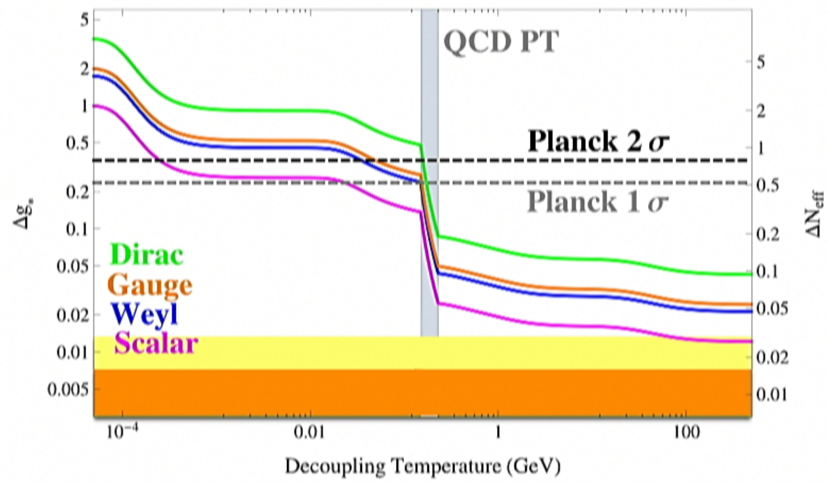

Fig from:
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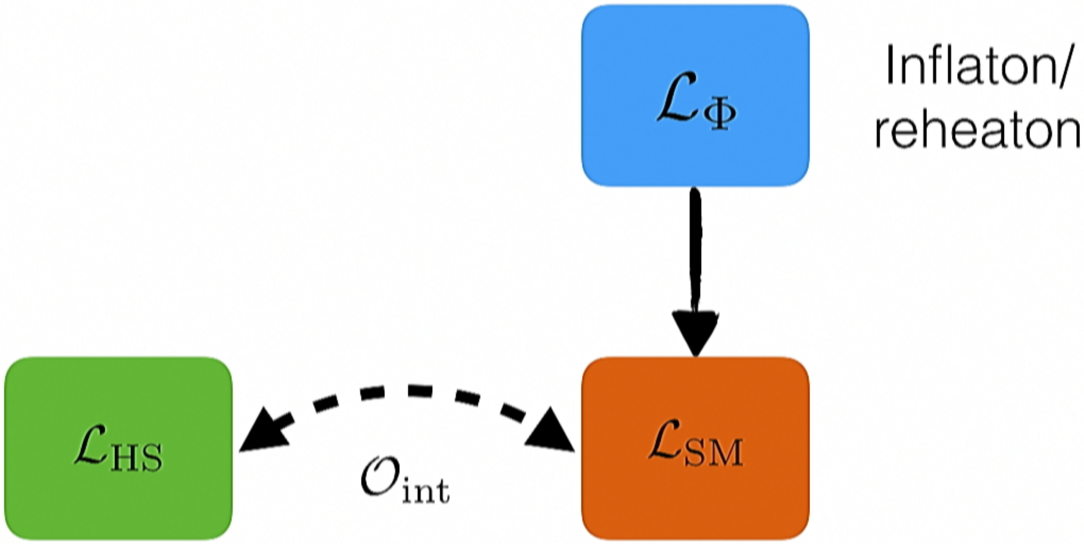
  - No new light states (m << eV) allowed to be in thermal equilibrium with SM!

(Broust, Kaplan, and Walters '13, Abazajian et al '13; Wu et al '14; Errard et al '15)

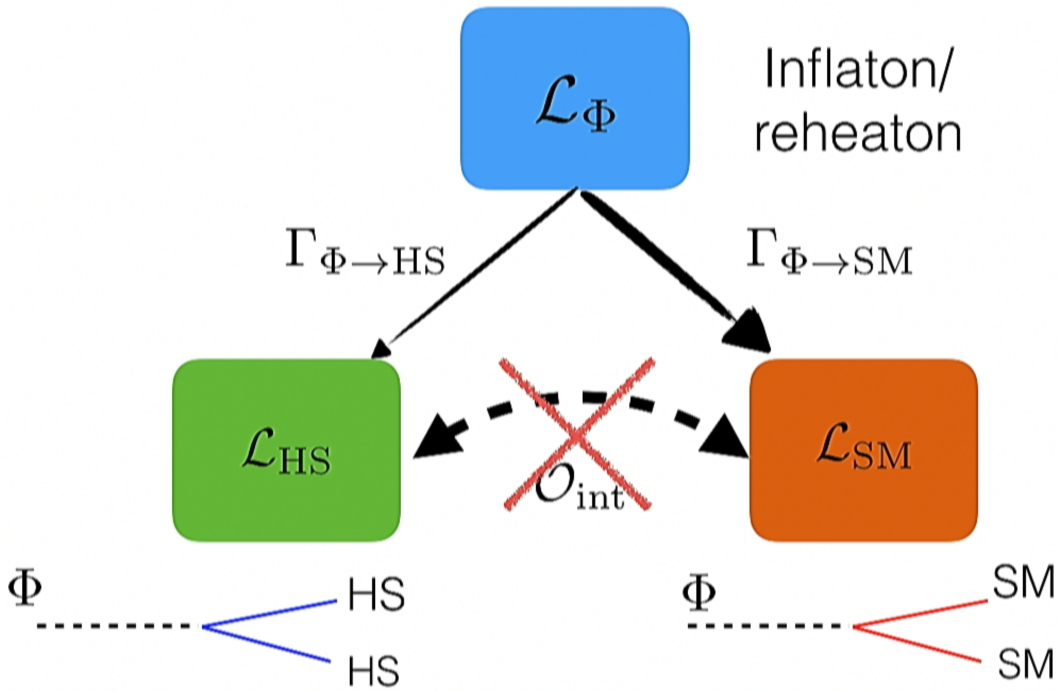
A colder dark sector?

- How might we obtain a colder dark sector?
  - Through interactions with the SM that never reach thermal eq?



A colder dark sector?

- How might we obtain a colder dark sector?
  - Asymmetric reheating?



$$\Gamma_{\Phi\to\mathrm{HS}} \ll \Gamma_{\Phi\to\mathrm{SM}} \Rightarrow T_{\mathrm{HS}} \ll T_{\mathrm{SM}}$$

(Kolb, Turner ’85; Berezhiani, Dolgov, Mohapatra ’95)

A colder dark sector?

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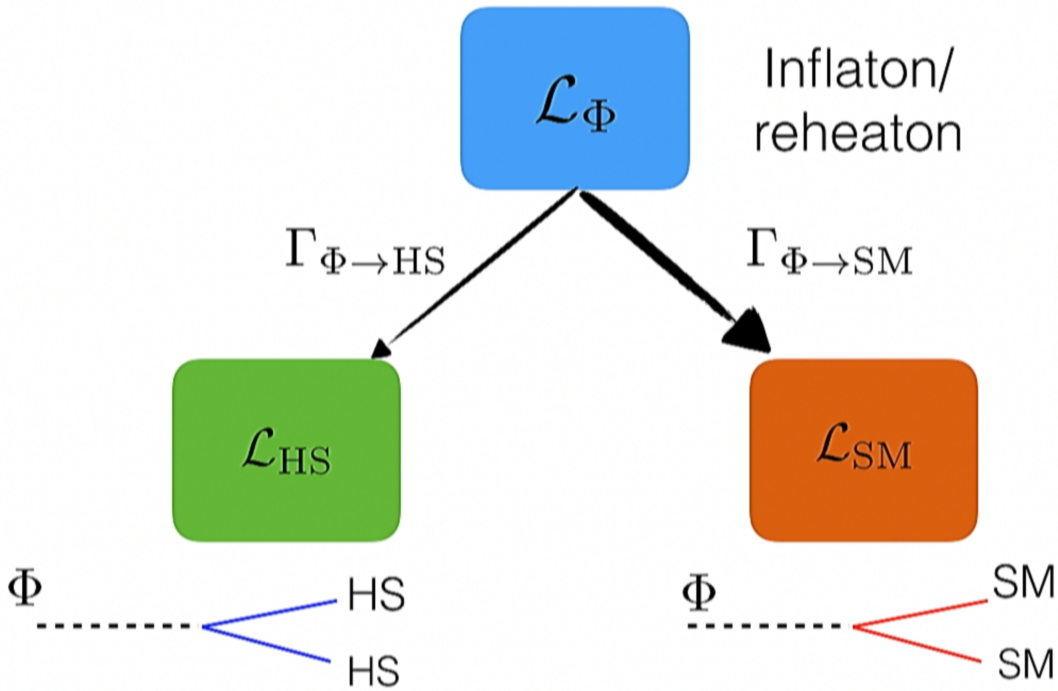

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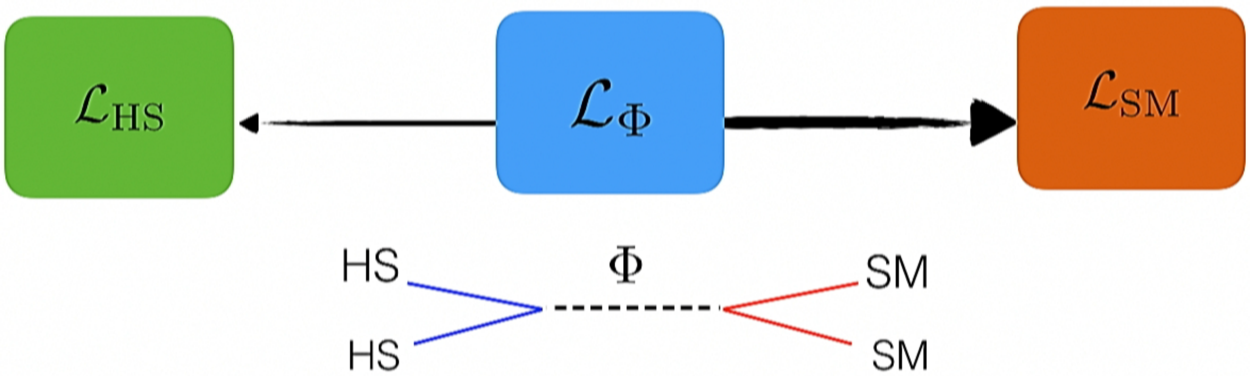
A colder dark sector?

- Not so fast…
  - the sectors are *necessarily* coupled in the UV

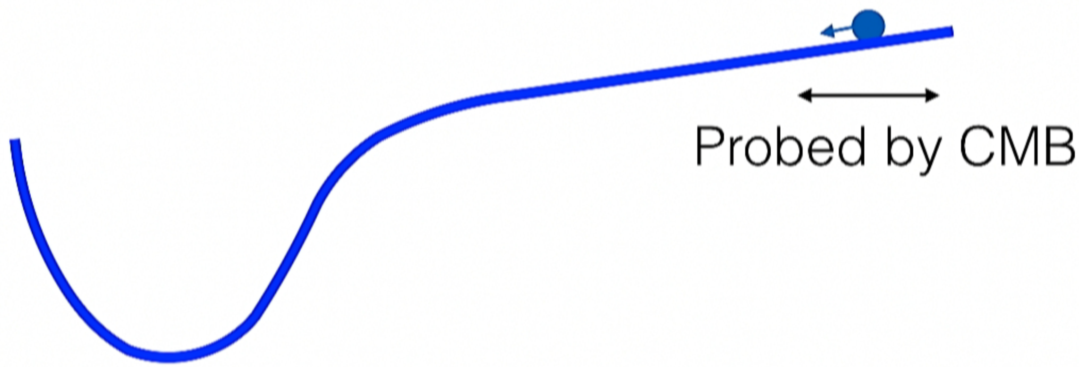


- Inflaton scattering can mediate energy transfer between the sectors
- Can this erase a nascent temperature asymmetry?
- What can we learn from requirement of non-thermalization?

The end of inflation: reheating

- Inflation: $\ddot{a} > 0 \Leftrightarrow \epsilon_H = \frac{\dot{\phi}^2}{2H^2 M_{\rm Pl}^2} < 1 \sim \epsilon_V = \frac{M_{\rm Pl}^2}{2} \frac{V'^2}{V^2} < 1$

- Slow roll: $\epsilon_H, \epsilon_V \ll 1$



The end of inflation: reheating

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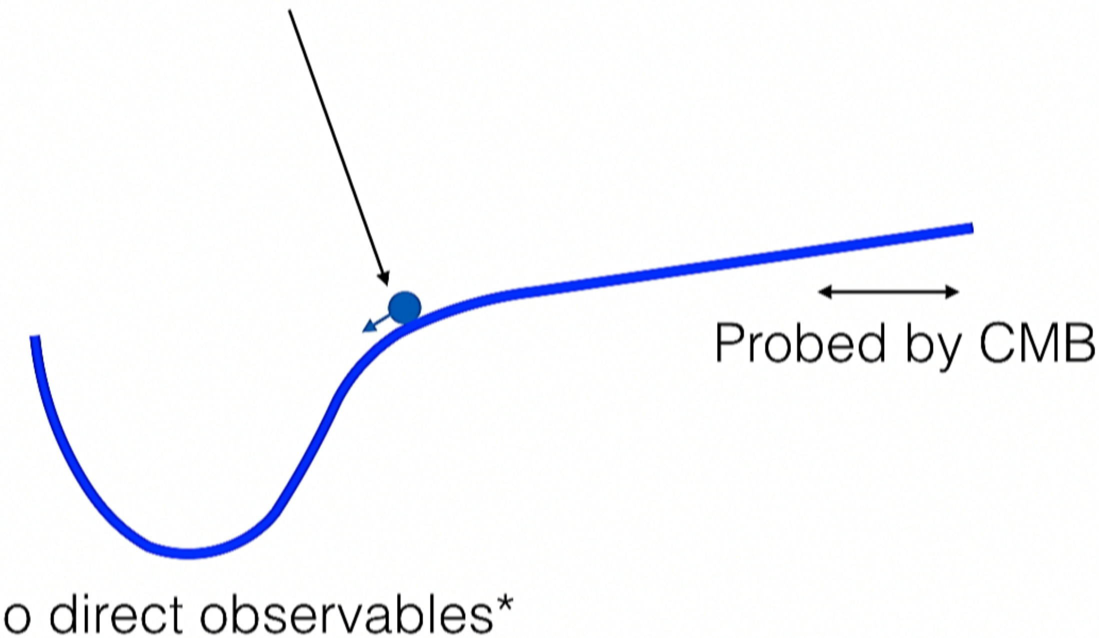
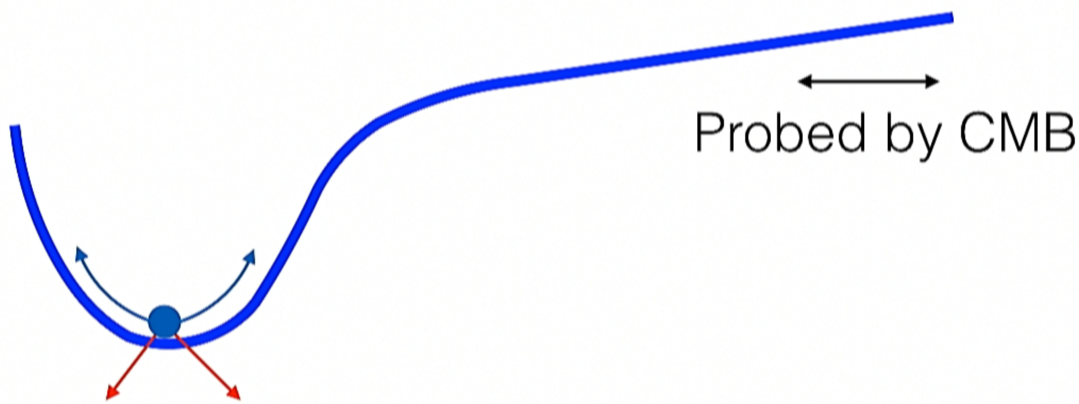
- Inflation terminates: $\epsilon_H = 1, \epsilon_V \sim 1$



The end of inflation: reheating

- Inflaton decay:

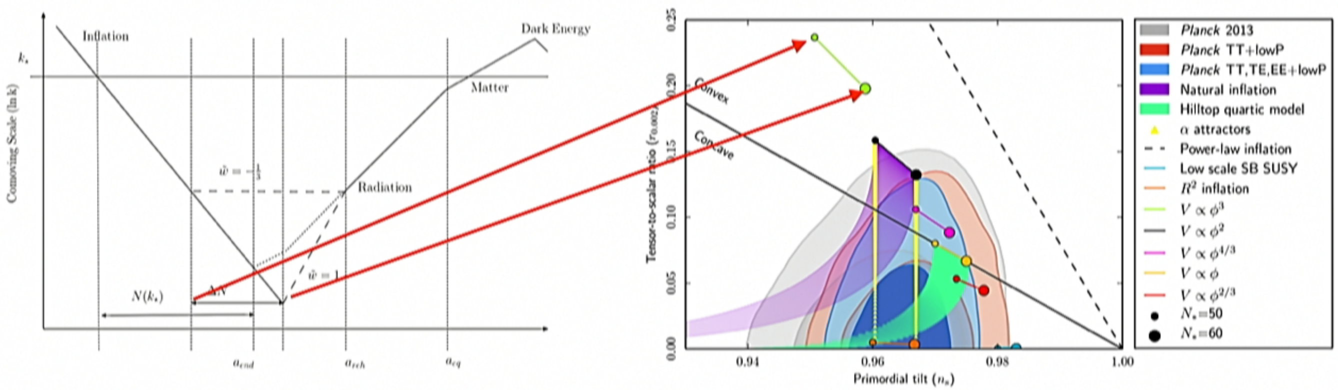
- Very little is known about reheating!



Reheating?

- Super-horizon adiabatic modes are *insensitive* to processes happening on sub-horizon scales

-S. Weinberg



- Only impact is on the unknown expansion history
  - We don't know exactly where on the potential the fluctuations are generated
- Reheating could provide clues for unification of inflation and SM

The end of inflation: reheating

(Abbot, Farhi, Wise '82; Albrecht, Steinhardt, Turner, Wilczek '82…)

- Inflaton decay:

- Duration of reheating controlled by: $\Gamma_{\Phi \to XX}$
  - Reheating completes when $\Gamma_{\Phi \to XX} \sim H$
  - Reheat temp $T_{\rm RH} \sim \sqrt{\Gamma M_{\rm Pl}}$

The end of inflation: reheating

(Abbot, Farhi, Wise '82; Albrecht, Steinhardt, Turner, Wilczek '82…)

- Inflaton decay:

- Duration of reheating controlled by: $\Gamma_{\Phi \to XX}$
  - Reheating completes when $\Gamma_{\Phi \to XX} \sim H$
  - Reheat temp $T_{\rm RH} \sim \sqrt{\Gamma M_{\rm Pl}}$

- Final reheating temp independent of:
  - Inflaton/reheaton mass M_Φ
  - Energy scale of end of inflation $V(\Phi_{\rm end})$

- Reheating weakly constrained by expansion history, BBN…

Boltzmann equations for reheating

- Classic Boltzmann equations for reheating:
  - Neglect parametric resonances

Quadratic oscillations: look like matter

Perturbative particle creation

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma\rho_\phi$$

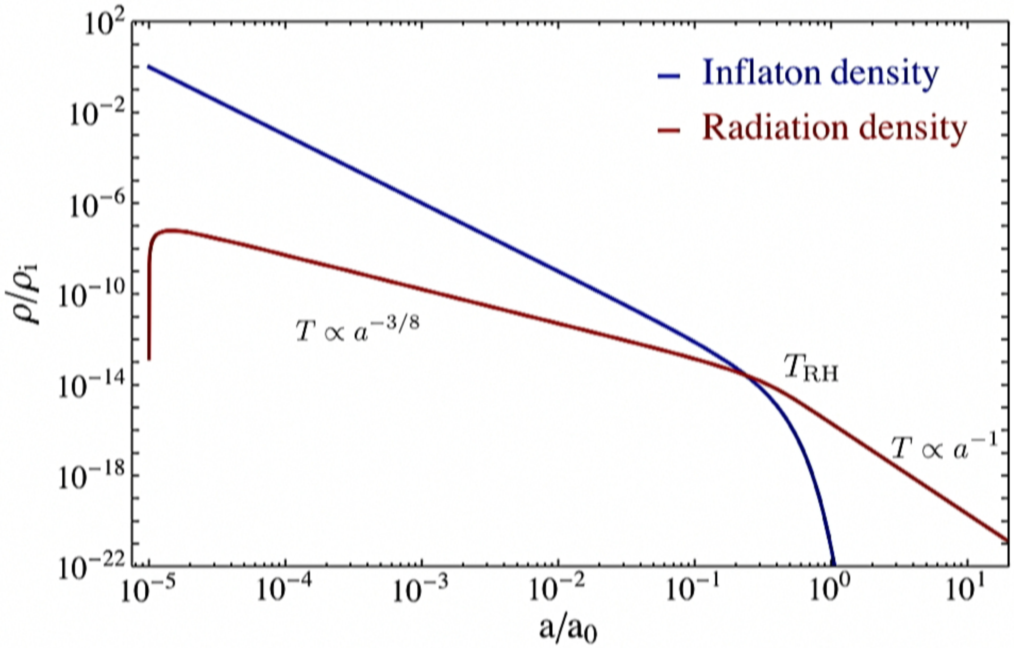
$$\dot{\rho}_{\mathrm{R}} + 4H\rho_{\mathrm{R}} = \Gamma\rho_\phi$$

Relativistic daughter particles

Constant production rate: neglect thermal effects

Boltzmann equations for reheating

- Solution



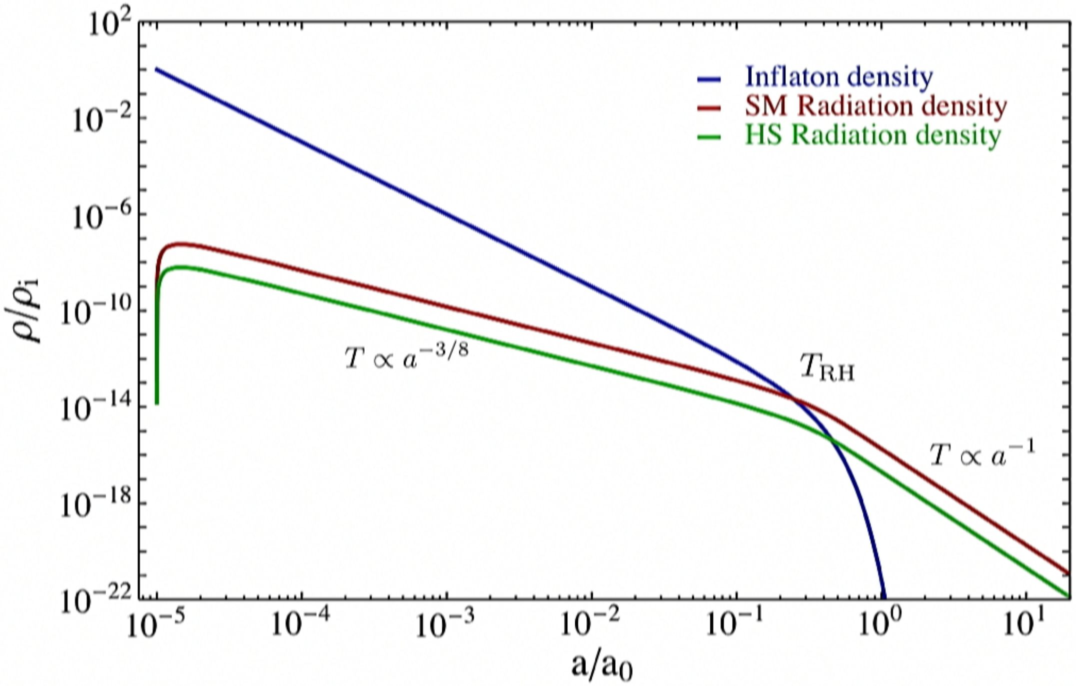
Two-sector reheating

- Boltzmann eqn for 2-sector reheating

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma\rho_\phi$$
$$\dot{\rho}_{\mathrm{SM}} + 4H\rho_{\mathrm{SM}} = \Gamma_{\mathrm{SM}}\rho_\phi$$
$$\dot{\rho}_{\mathrm{HS}} + 4H\rho_{\mathrm{HS}} = \Gamma_{\mathrm{HS}}\rho_\phi$$

Two-sector reheating

- Solution



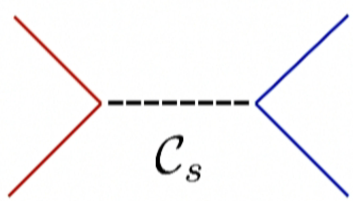
- Temps differ by: $$\frac{T_{\rm HS}}{T_{\rm SM}} = \sqrt{\frac{\Gamma_{\Phi\to\rm HS}}{\Gamma_{\Phi\to\rm SM}}}$$

Two-sector reheating

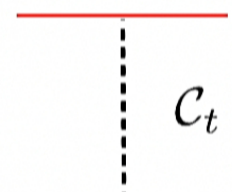
- Boltzmann eqn for 2-sector reheating

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma(f_{\rm SM}, f_{\rm HS})\rho_\phi$$
$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = \Gamma_{\rm SM}(f_{\rm SM})\rho_\phi + \mathcal{C}[f_{\rm SM}, f_{\rm HS}]$$
$$\dot{\rho}_{\rm HS} + 4H\rho_{\rm HS} = \Gamma_{\rm HS}(f_{\rm HS})\rho_\phi - \mathcal{C}[f_{\rm SM}, f_{\rm HS}]$$

- Decay rate: $\Gamma = \Gamma_{\rm HS} + \Gamma_{\rm SM}$
- Energy transfer rate: $\mathcal{C} = \mathcal{C}_t + \mathcal{C}_s$



$\Delta E_s = E_1 + E_2$



$\Delta E_t = E_1 - E_2$

Two-sector reheating

- Boltzmann eqn for 2-sector reheating

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma(f_{\rm SM}, f_{\rm HS})\rho_\phi$$
$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = \Gamma_{\rm SM}(f_{\rm SM})\rho_\phi + \mathcal{C}[f_{\rm SM}, f_{\rm HS}]$$
$$\dot{\rho}_{\rm HS} + 4H\rho_{\rm HS} = \Gamma_{\rm HS}(f_{\rm HS})\rho_\phi - \mathcal{C}[f_{\rm SM}, f_{\rm HS}]$$

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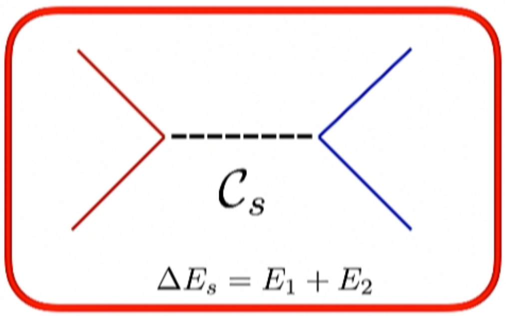
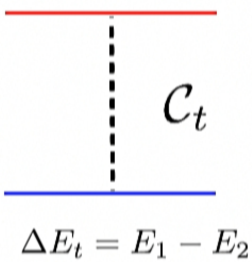




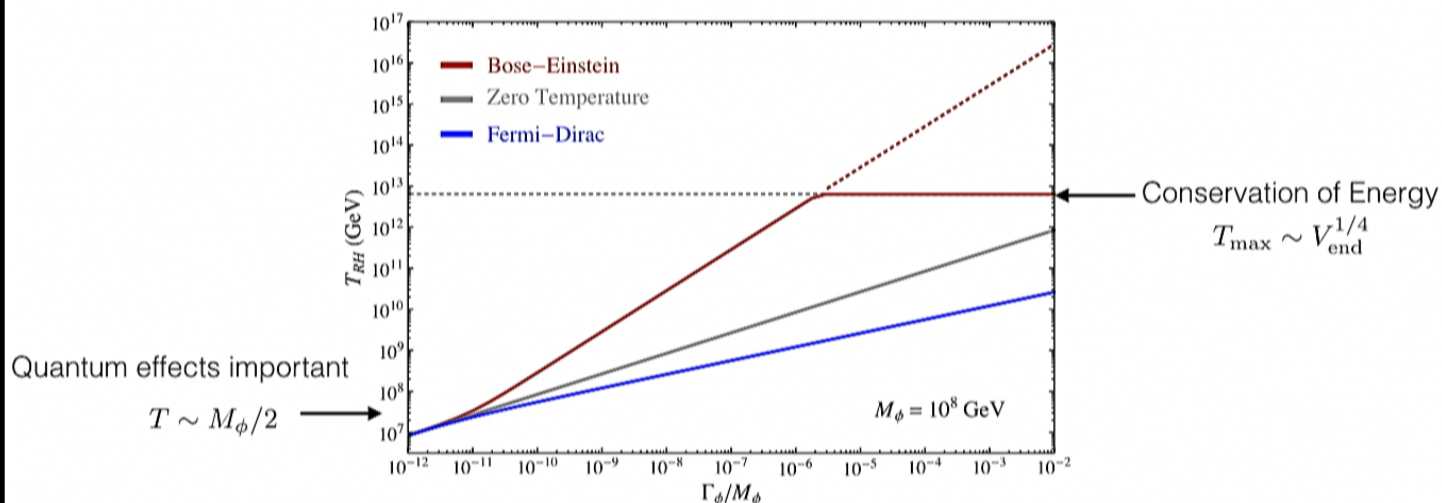
The importance of quantum statistics I

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma(f_{\rm SM}, f_{\rm HS})\rho_\phi$$

- There is no reason to expect Maxwell-Boltzmann statistics to be a good approximation. It isn't.
  - Bose enhancement or Pauli blocking alters the 2-body phase space

$$\Gamma(T) = \Gamma_0\left(1 \pm \frac{2}{e^{\beta M_\phi/2} \mp 1}\right)$$

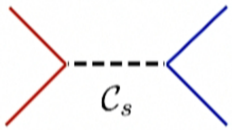
  - Bosons reheat to higher temps:



The importance of quantum statistics II

$$\dot{\rho}_{\rm HS} + 4H\rho_{\rm HS} = \Gamma_{\rm HS}(f_{\rm HS})\rho_\phi + \mathcal{C}[f_{\rm SM}, f_{\rm HS}]$$

- The rate at which energy is transferred between the sectors is



$$n^2\langle\sigma v \Delta E\rangle \equiv \int d\Pi_i |\mathcal{M}(12\to 34)|^2 (E_1+E_2) f_1 f_2 (1\pm f_3)(1\pm f_4)$$

- For Boltzmann stats, integrals analytic

$$n_1 n_2 \langle\sigma v \Delta E\rangle = \frac{2\pi^2}{(2\pi)^6}\frac{T}{16\pi}\int_{4m^2}^{\infty} \mathrm{d}s\,(s-4m^2)\,\hat{S}|\mathcal{M}(s)|^2 K_2\left(\frac{\sqrt{s}}{T}\right).$$

- Can get excellent analytic results by approximating the scalar propagator[2]

$$\frac{1}{(s-M_\Phi^2)^2 + M_\Phi^2\Gamma^2} \approx \frac{1}{M_\Phi^4} + \frac{\pi}{M_\Phi^3\Gamma}\delta(s-M_\phi^2) + \frac{1}{s^2}$$

Thermalization of hidden sectors

- After reheating is complete

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma(f_{\rm SM}, f_{\rm HS})\rho_\phi$$
$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = \Gamma_{\rm SM}(f_{\rm SM})\rho_\phi + \mathcal{C}[f_{\rm SM}, f_{\rm HS}]$$
$$\dot{\rho}_{\rm HS} + 4H\rho_{\rm HS} = \Gamma_{\rm HS}(f_{\rm HS})\rho_\phi - \mathcal{C}[f_{\rm SM}, f_{\rm HS}]$$

Thermalization of hidden sectors

- After reheating is complete

$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = +\,\mathcal{C}[f_{\rm SM}, f_{\rm HS}]$$
$$\dot{\rho}_{\rm HS} + 4H\rho_{\rm HS} = -\,\mathcal{C}[f_{\rm SM}, f_{\rm HS}]$$

- We use the simple criteria, consider $T < T_{\rm RH}$
  - Assuming internal thermal equilibrium
  - Does the energy transfer rate come into equilibrium?

$$\Gamma^E = \frac{n^2\langle\sigma v\Delta E\rangle}{\rho} > H(T)$$

Representative EFT approach

- Consider representative reheating models
  - Scalar-scalar

$$\mathcal{L} \supset -\frac{\mu_a}{2}\Phi S_a^2 - \frac{\mu_b}{2}\Phi S_b^2$$

  - Fermion-fermion

$$\mathcal{L} \supset -y_a \Phi \bar{\psi}_a \psi_a - y_b \Phi \bar{\psi}_b \psi_b$$

  - Gauge-gauge

$$\mathcal{L} \supset -\frac{\Phi}{4\Lambda_a}\tilde{F}_a^{\mu\nu} F_{a\mu\nu} - \frac{\Phi}{4\Lambda_b}\tilde{F}_b^{\mu\nu} F_{b\mu\nu}$$

  - Gauge-fermion

$$\mathcal{L} \supset -\frac{\Phi}{4\Lambda_a}\tilde{F}^{\mu\nu} F_{\mu\nu} - \frac{\Phi}{\Lambda_b} m_\psi \bar{\psi}\gamma_5 \psi$$

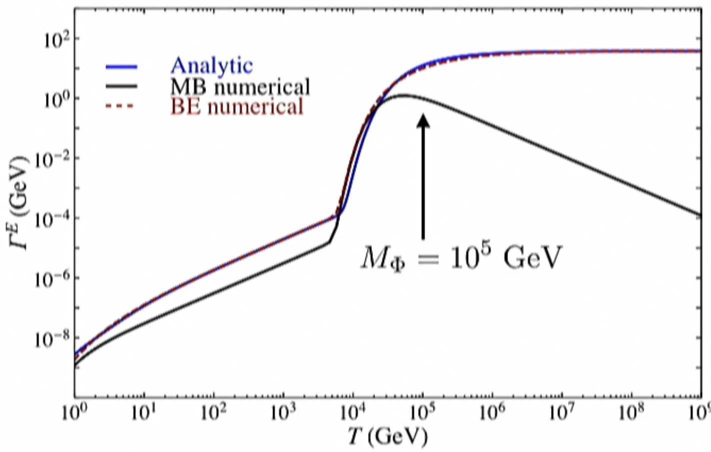
  - Scalar-fermion

$$\mathcal{L} \supset -\frac{\mu_a}{2}\Phi S_a^2 - y_2 \Phi \bar{\psi}_b \psi_b$$

Everyone's a scalar

$$\mathcal{L} \supset -\frac{\mu_a}{2}\Phi S_a^2 - \frac{\mu_b}{2}\Phi S_b^2$$

- Resonance and quantum stats are important
- Significant enhancement due to resonant inflaton exchange

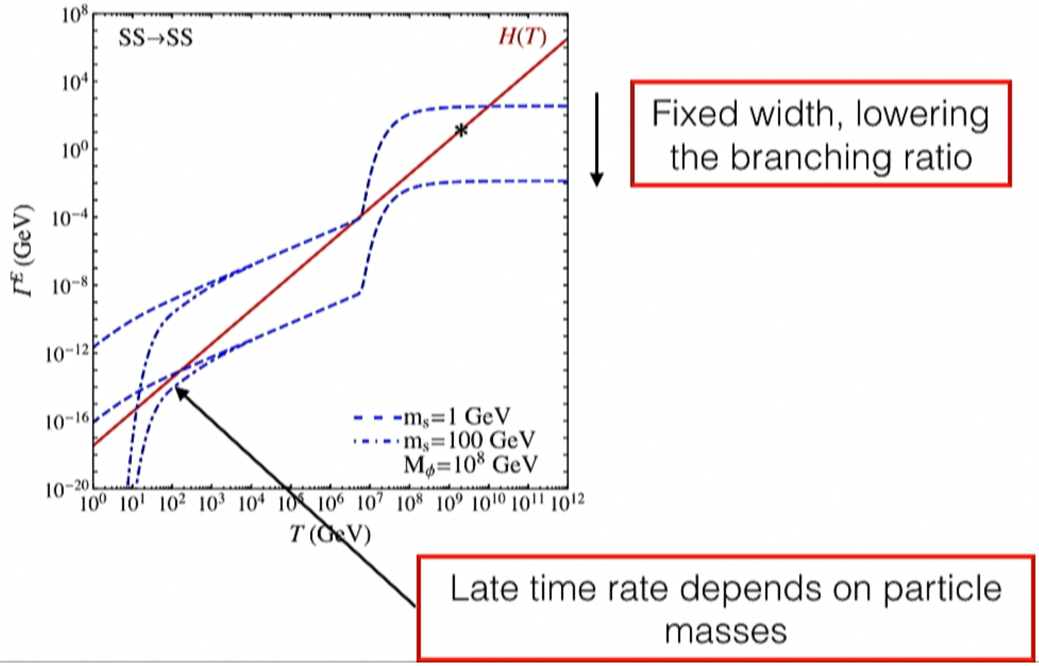


Flat rate at large T from overlap of low-p modes with resonance (Bose-Einstein stats)

Everyone's a scalar

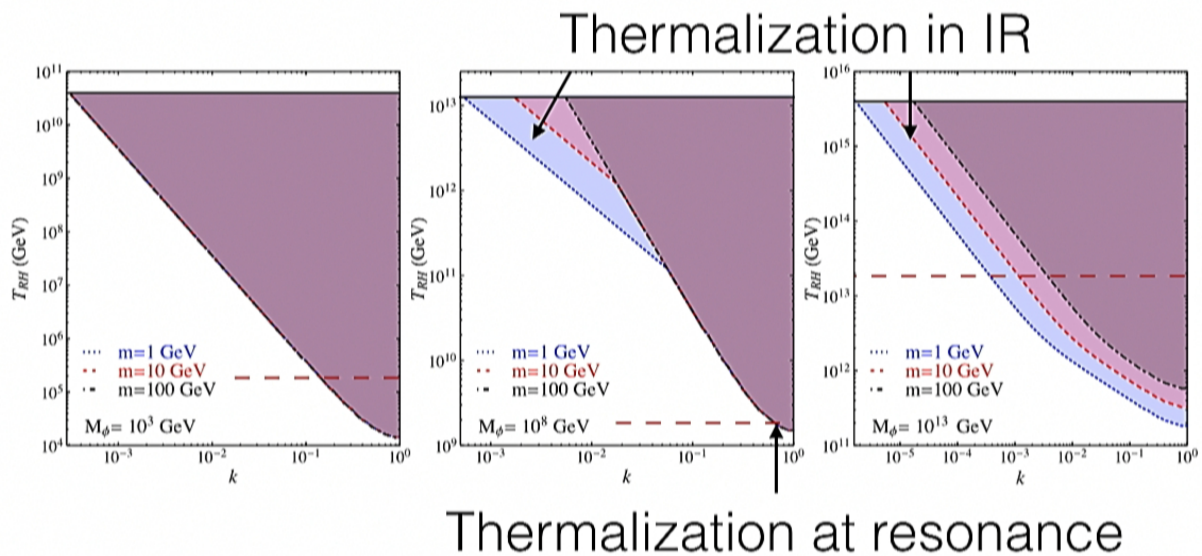
$$\mathcal{L} \supset -\frac{\mu_a}{2}\Phi S_a^2 - \frac{\mu_b}{2}\Phi S_b^2$$

- Resonance and quantum stats are important
- Significant enhancement due to resonant inflaton exchange
- E transfer decreases slower than H at late time, thermalization becomes IR dep.



Everyone's a scalar

- Shaded regions indicate thermalizable: $\Gamma^E > H$
- Scan parameters: $k = \Gamma_a^0/\Gamma_b^0 \sim (T_a^0/T_b^0)^2$



- Upper bound from energy conservation: $T_{\rm RH} \sim \sqrt{M_\Phi \Phi}$

- Caveat: red line indicates where *preheating* important

Preheating/parametric resonance

(Traschen, Brandenburger '92; Kofman, Linde, Starobinsky '94-97;…)

- At large enough coupling, time dependence of the background cannot be ignored, particle production becomes non-perturbative
  - Ignoring Hubble, mode equation for daughter S fields:

$$\ddot{S}_k + (k^2 + \mu\Phi_0 \sin(M_\phi t))S_k = 0$$

  - Mathieu eqn: exact solutions known, have stable and unstable bands

$$S_k \sim e^{\mu_k t} P(k,t)$$

  - Can show that (at low coupling) this is equivalent to the Bose effect we compute for the decay rate
  - Likely that this simply raises the reheat temp, making thermalization *more* likely

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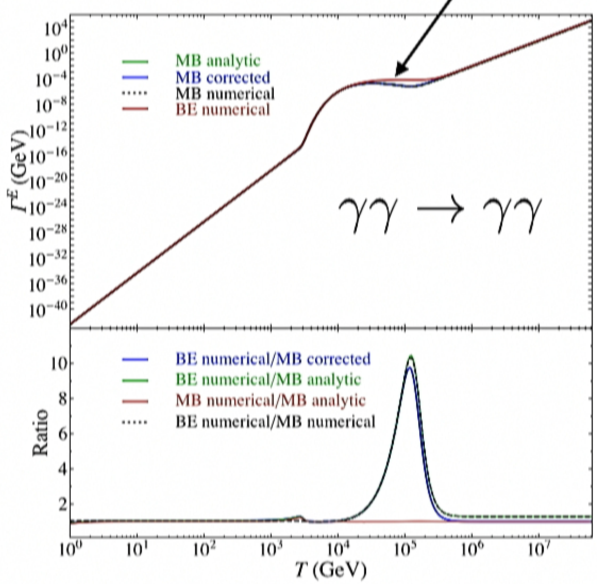
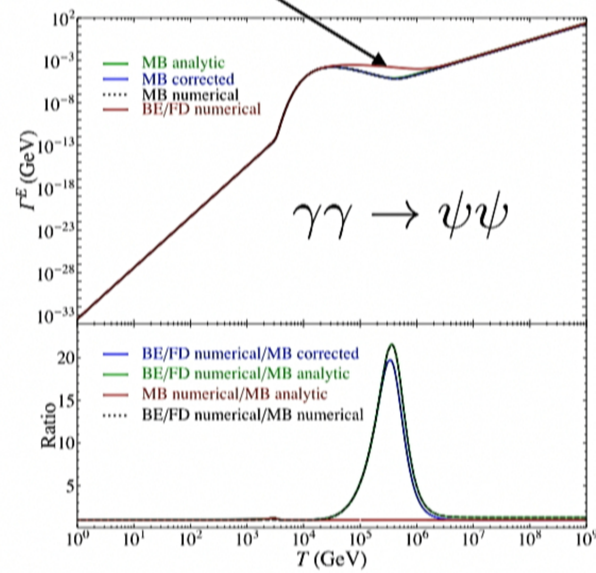
Pseudo-scalar scattering

- Higher dimension coupling cuts off low energy phase space

MB excellent everywhere, except near resonance





Reheating after pseudo-scalar inflation

- Pseudo-scalars are very attractive candidates for the inflaton

- Shift symmetries protect the form of the potential

$$\Phi \to \Phi + c$$

- Severely restrict couplings to matter

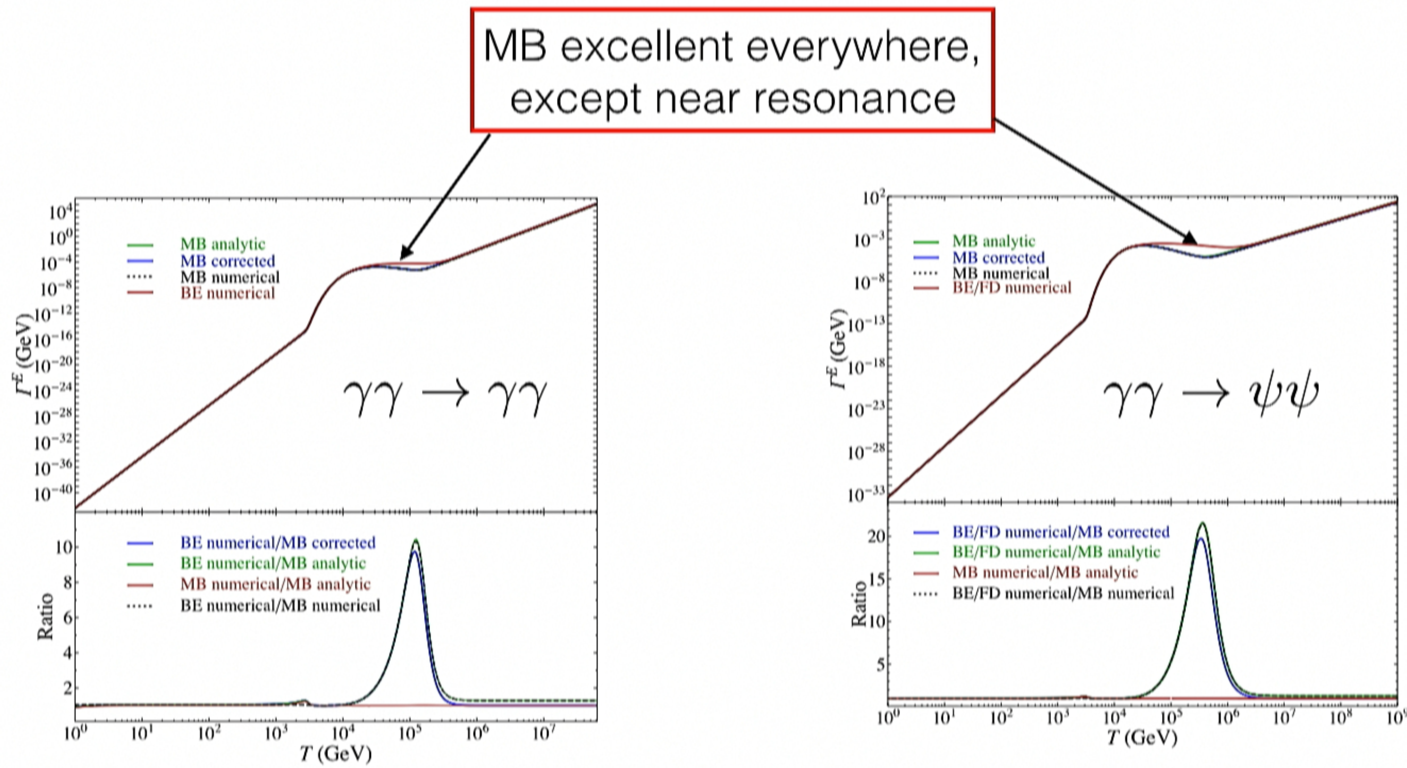
$$\mathcal{L} \supset \frac{\Phi}{\Lambda_a} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{\partial_\mu \Phi}{\Lambda_b} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

$$\frac{m_\psi \Phi}{\Lambda_b} \bar{\psi} \gamma_5 \psi$$

- Fermion production suppressed relative to gauge boson

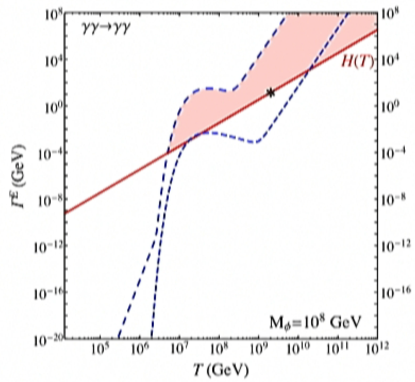
Pseudo-scalar scattering

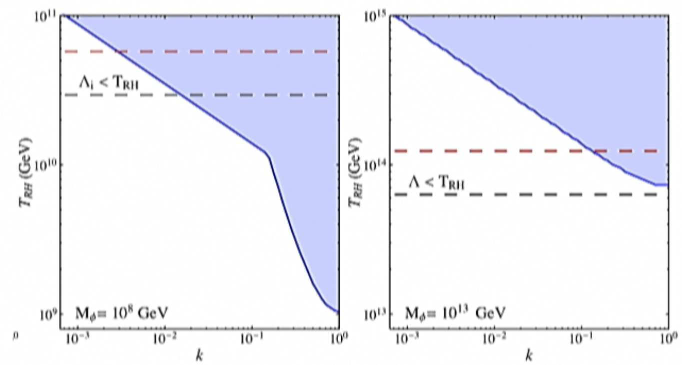
- Higher dimension coupling cuts off low energy phase space



Gauge-gauge scattering

- Suppressed couplings make thermalization challenging

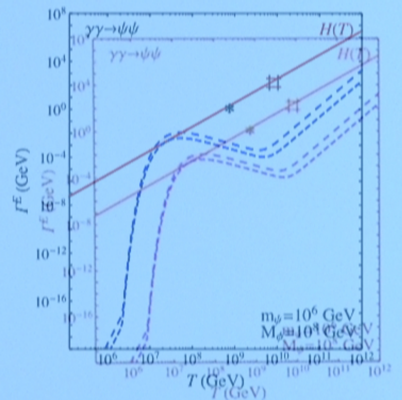


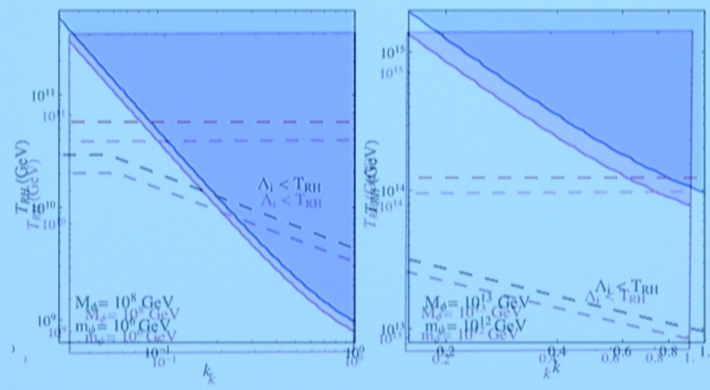


- Thermalization possible at resonance, or above resonance at high temp.
- Caveats:
  - EFT description breaks $T_{\mathrm{RH}} > \Lambda_i$
  - Preheating very strong

Gauge-fermion scattering

- Suppressed couplings make thermalization challenging

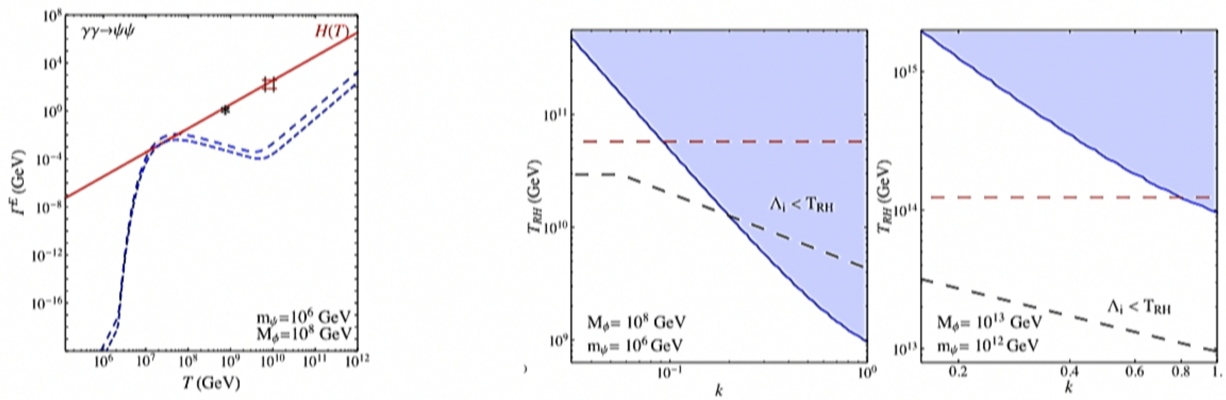




- Small fermion mass + irrelevant op. makes for easy asymmetric reheating
- Thermalization possible only at resonance

Gauge-fermion scattering

- Suppressed couplings make thermalization challenging



- Small fermion mass + irrelevant op. makes for easy asymmetric reheating
- Thermalization possible only at resonance

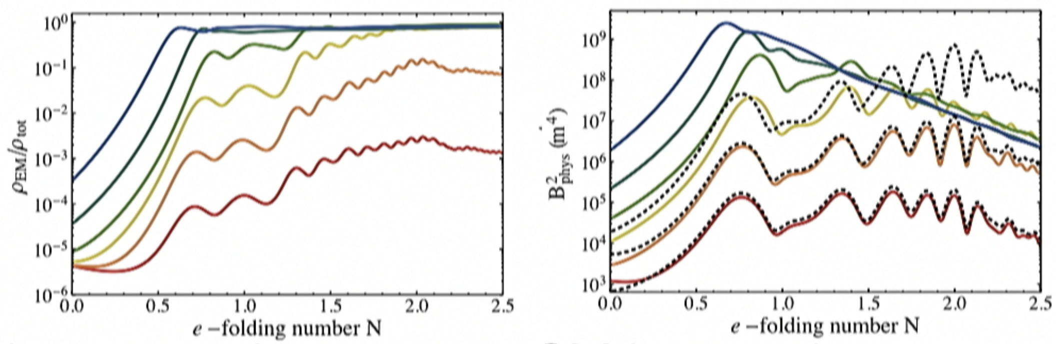
Conclusions

- Future CMB missions will put exquisite constraints on N_{eff}
- Asymmetric reheating is a minimal scenario for the origin of a cold dark sector
- Requirement of a never-equilibrated dark sector has consequences for possible cosmological histories:
  - restricts range of masses, reheating temperatures, dominant coupling structure of inflaton/reheaton
  - or requires non-minimal (multifield) reheating
  - or a non-minimal cosmological history for one or both sectors
- Low scale inflation may have issues getting asymmetric reheating
- Reheating regimes with rich thermal &/or non equilibrium dynamics: inflaton exchange more important

Gauge-boson preheating

(PA, J. Giblin, T Scully, E Sfakianakis)

- In the non-perturbative limit, reheating is near instantaneous



- If the gauge bosons are SM hyper-charge, strong (helical) B-fields are produced

$$B_{\rm Max} \sim 0.2 \left(\frac{M_{\rm Pl}^2}{M_\phi^2}\right) \sim 10^{10}{\rm G}$$

→ MHD "Black Box" →

$$B_{\rm phys}(t_0) \sim 10^{-8}\left(\frac{\lambda_{\rm phys}}{1{\rm Mpc}}\right) G$$