Hints of new physics from the early Universe

Durham University

IP3

www.ippp.dur.ac.uk

Christopher McCabe

in collaboration with

Matt and Celine

To appear soon…

Durham - 15th June 2012

Outline

1. The history of the Universe: the usual picture
2. Hints for extra energy density from BBN/CMB
3. A new particle in equilibrium with neutrinos?
4. For fun: MeV neutralino
5. Conclusion

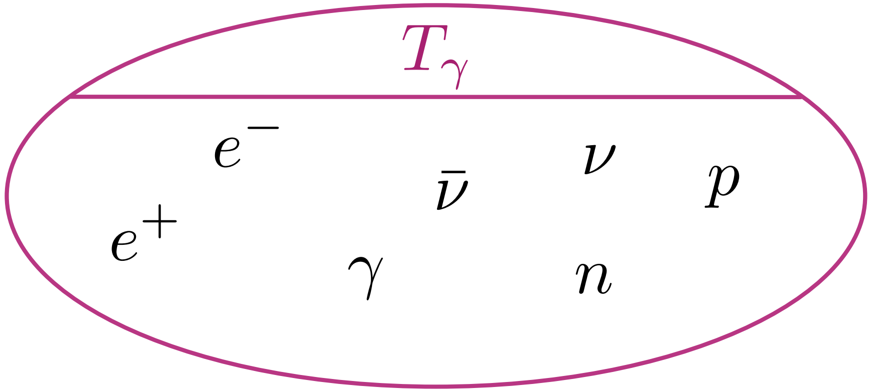
Timeline: Very early Universe

- Inflation
- Leptogenesis/Baryogenesis
- Electroweak phase transition
- Quark-hadron phase transition
- ...
- No direct window of the early Universe at these temperatures...

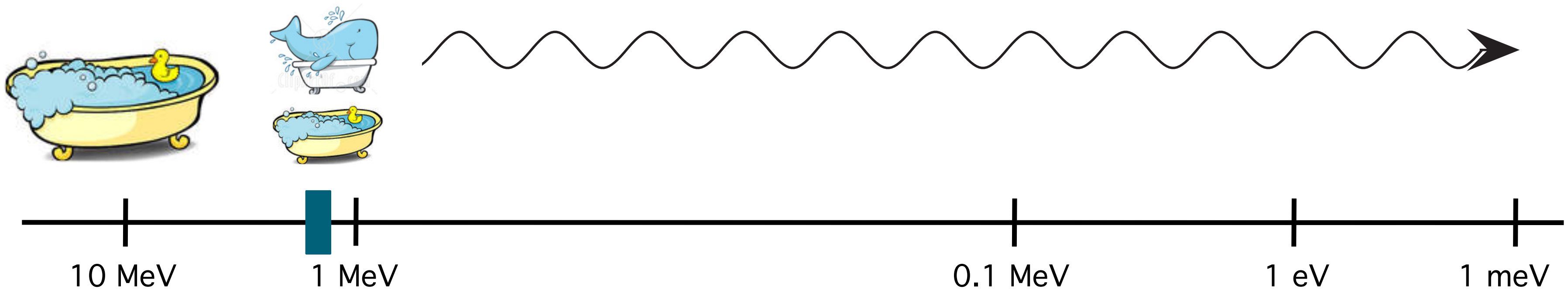
  ...Focus on lower temperatures

Timeline: Thermal bath

- Plasma of particles in a thermal bath:

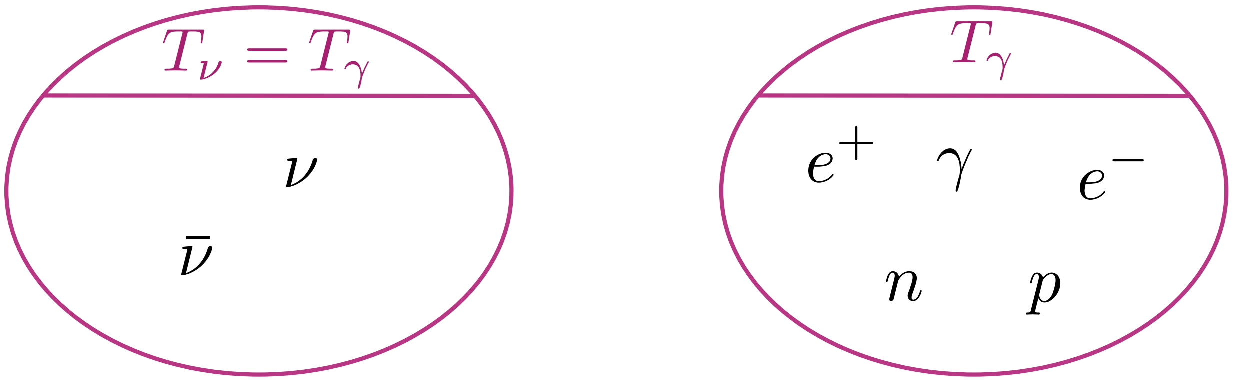


Timeline: Neutrino decoupling

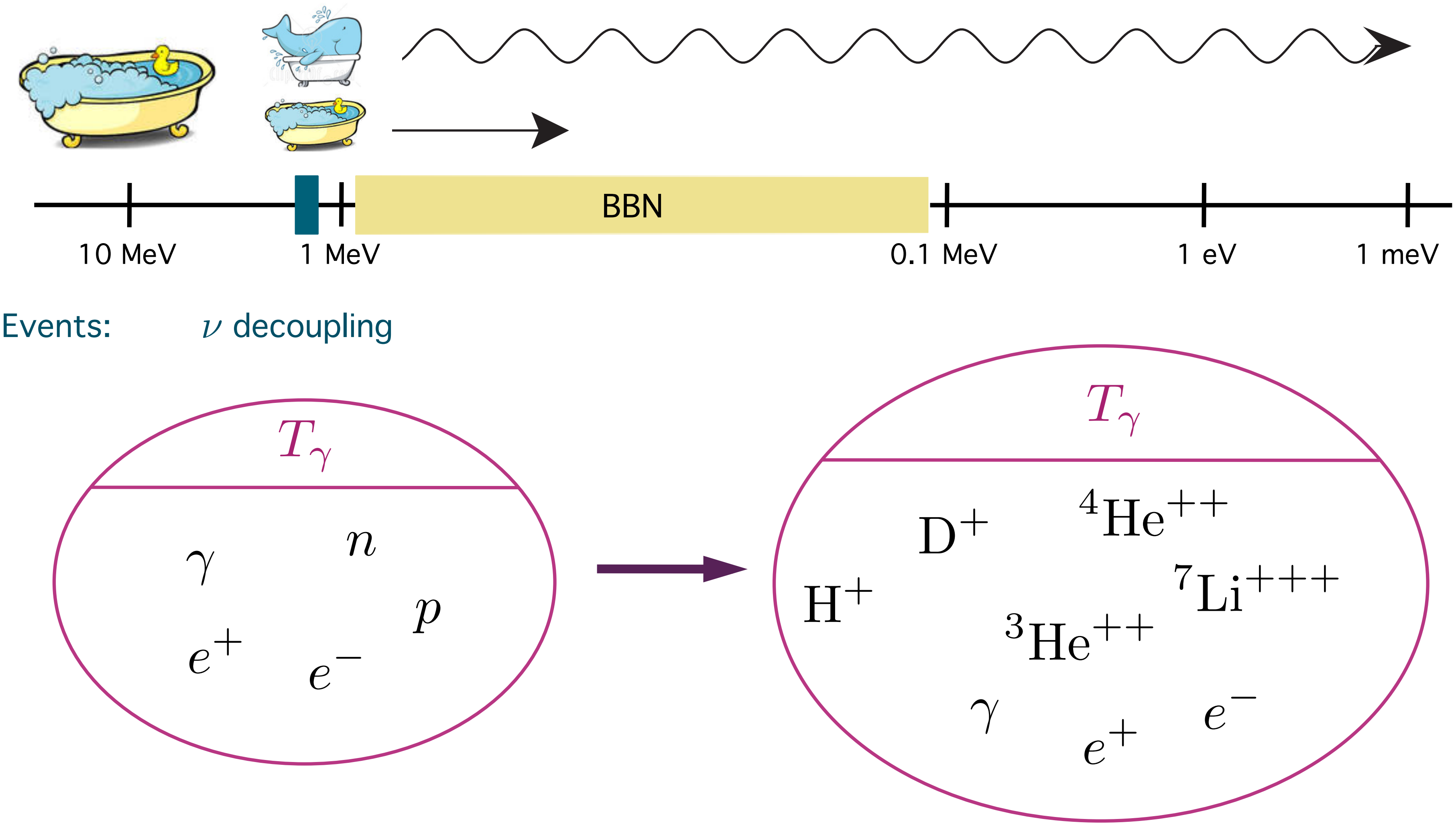


Events: ν decoupling

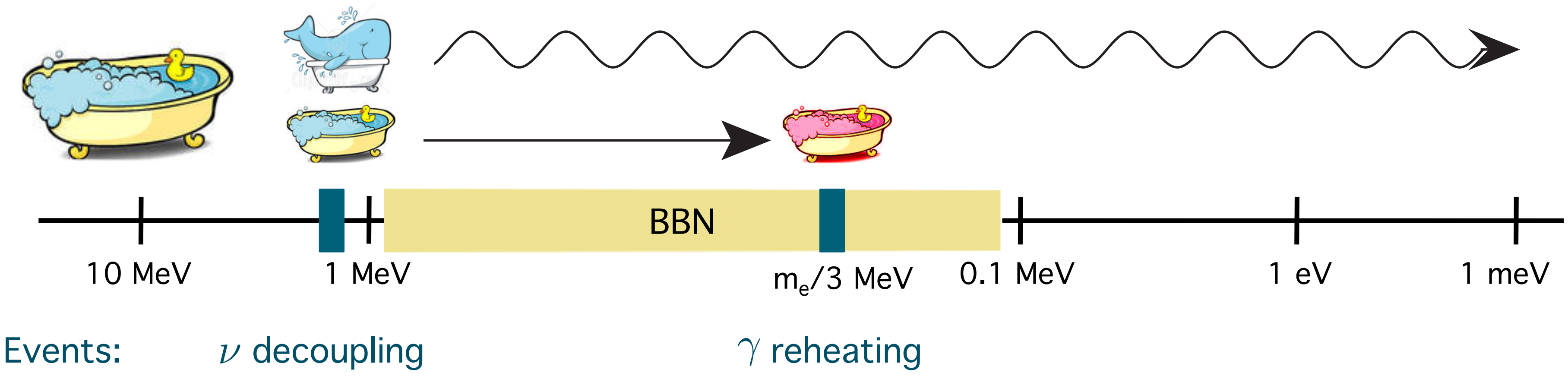
- Species remain in thermal equilibrium until $\Gamma = n\sigma v \sim H$
- Neutrinos decouple at ~2.3 MeV



Timeline: Big Bang Nucleosynthesis



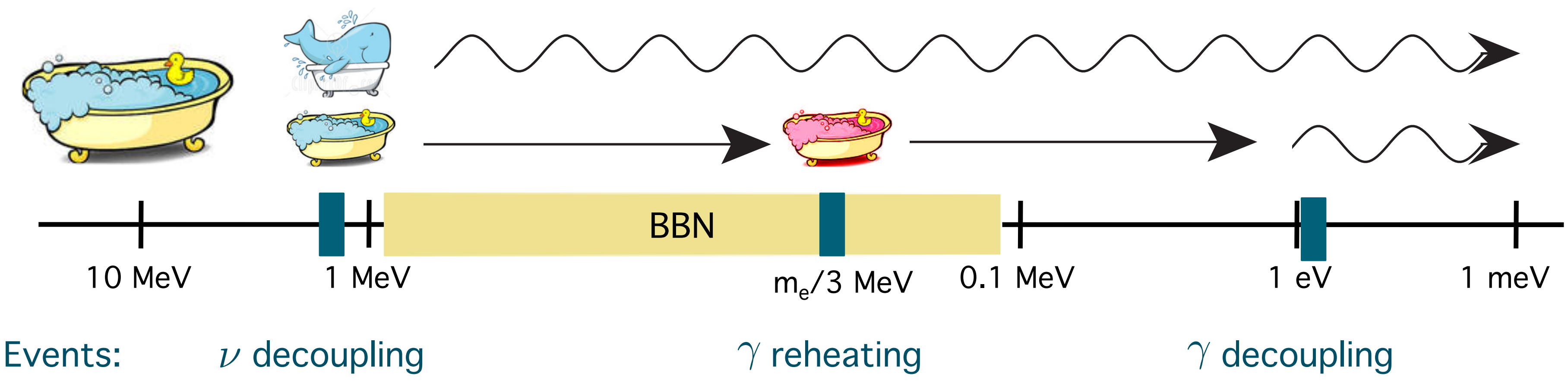
Timeline: Photon reheating



- When electrons and positrons become non-relativistic, they transfer their entropy to photons

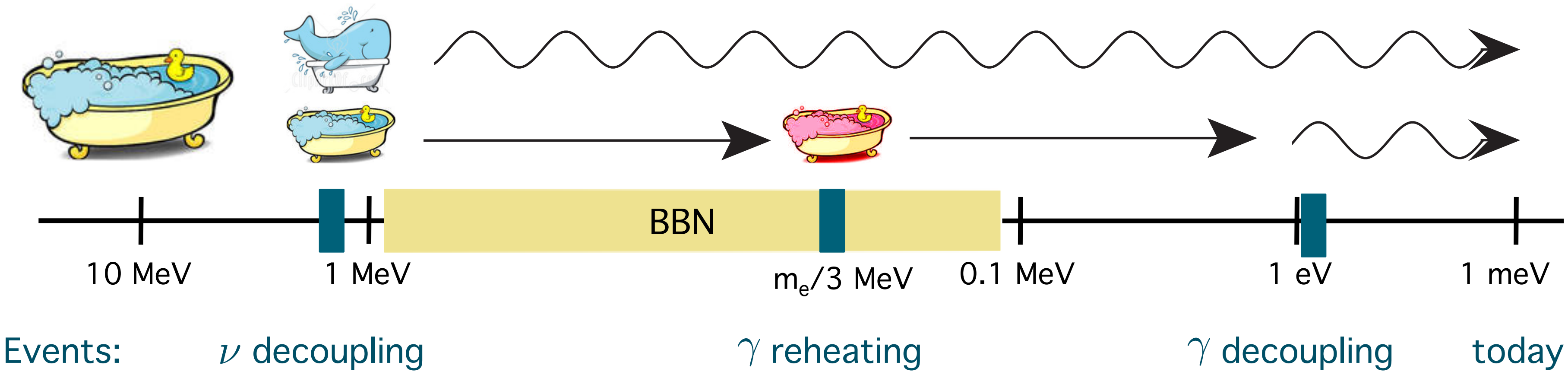
- Photon thermal bath heated relative to neutrino bath: $$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3}$$

Timeline: CMB formation



- Electrons recombine with protons: $\mathrm{H}^+ + \mathrm{e}^- \rightarrow \mathrm{H} + \gamma$
- Photons decouple from matter: cosmic microwave background is formed

Timeline: Today



- Today we have (at least) two thermal relics:

  1. CMB with $T_\gamma = 2.725\,\mathrm{K}$ (measured)

  2. Cosmic neutrino background
     with $T_\nu = 1.945\,\mathrm{K}$ (not measured)

Hints for new physics?

- We can measure primordial nuclei created during BBN and the relic photons of CMB
- Data currently favours extra energy density present during BBN and CMB

- Energy density parameterized in terms of $N_{\rm eff}$
- $N_{\rm eff}$ is the number of Majorana fermions at temperature

$$T = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

- In the standard picture of the Universe with three neutrinos $N_{\rm eff} = 3.046$

Questions...

- Why is BBN sensitive to N_{eff}?
- What are the current experimental constraints?

- Why is the CMB sensitive to N_{eff}?
- What are the current experimental constraints?

- What will future experimental results tell us?

BBN: the helium abundance

- n and p kept in equilibrium through weak interactions:

$$\nu_e + n \leftrightarrow e^- + p$$
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$
$$n \leftrightarrow \bar{\nu}_e + e^- + p$$

- Equilibrium number densities follow $\left(\frac{n_n}{n_p}\right)_{\rm eq} = \exp\left(-\frac{m_n - m_p}{T}\right)$

- Reactions freeze out when $T \sim 0.7\,\mathrm{MeV}$, so that $\left(\frac{n_n}{n_p}\right)_{\rm fo} \sim \frac{1}{7}$

- Essentially all of the neutrons end up as $^4\mathrm{He}$, so $n_{\rm He} \simeq \frac{n_n}{2}$

- Abundance parameterised in terms of the mass fraction:

$$Y_p \simeq \frac{4 n_{\rm He}}{n_n + n_p} \simeq \frac{2(n_n/n_p)_{\rm fo}}{1 + (n_n/n_p)_{\rm fo}} \approx 0.25$$

Helium: measure of $N_{\rm eff}$

Wagoner, Fowler, Hoyle (1967)

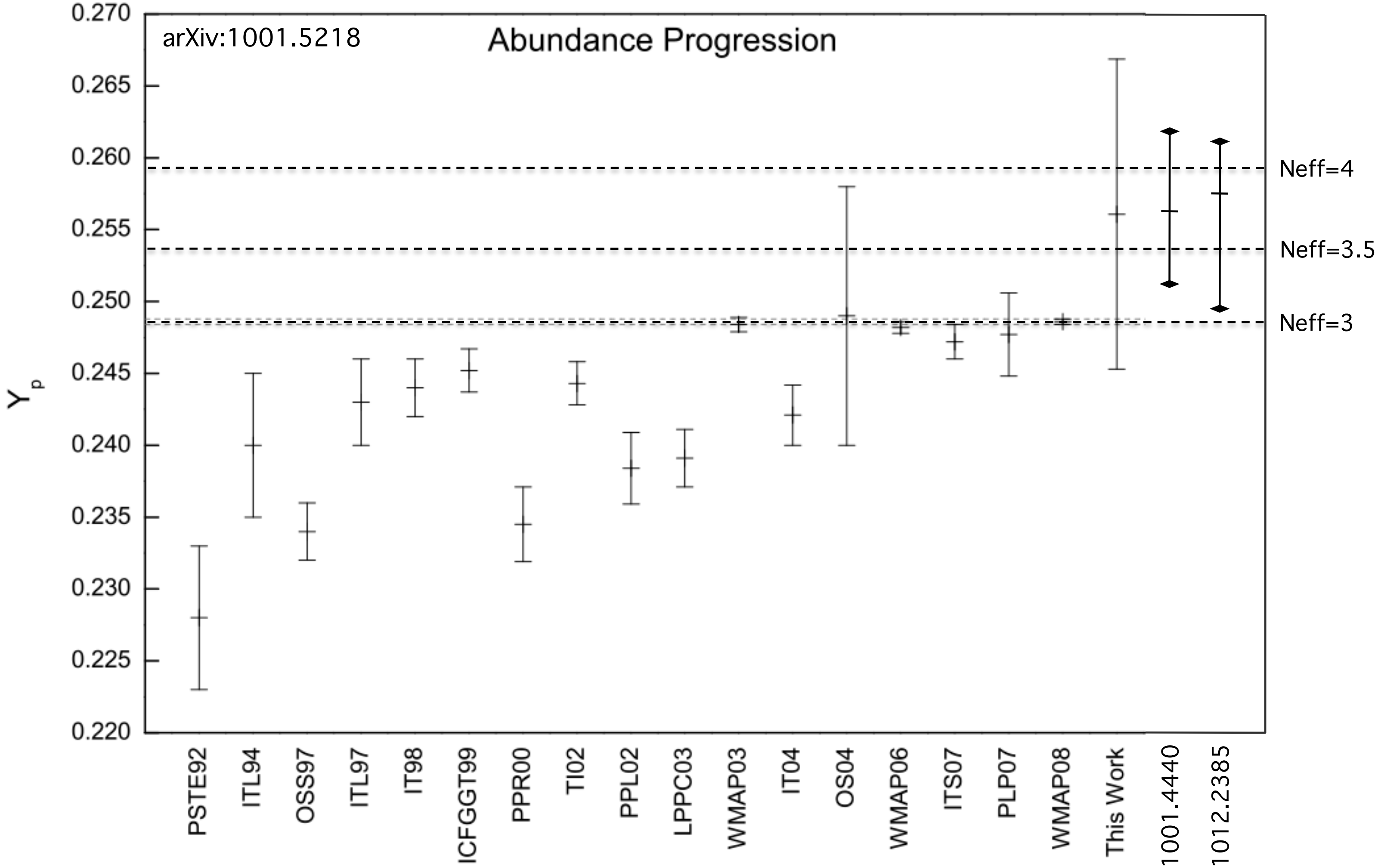
- In more detail, the weak interactions freeze out when $\Gamma \simeq H$

- But $H \sim N_{\rm eff}$, so increasing $N_{\rm eff}$ increases the expansion rate

$\Longrightarrow$ leads to a larger value for $\left(\frac{n_n}{n_p}\right)_{\rm fo}$

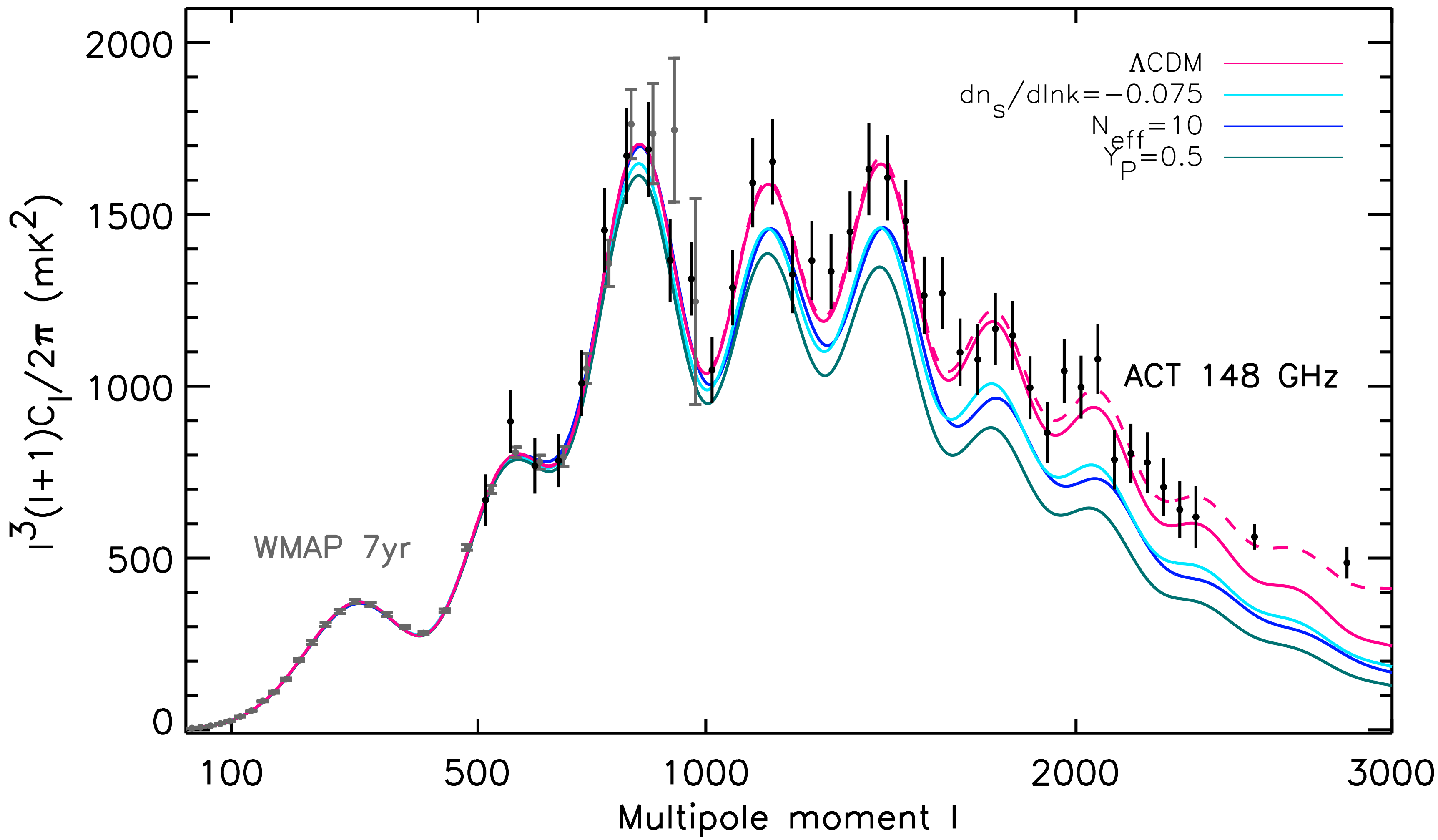
$\Longrightarrow$ leads to a larger value for Y_p

Helium abundance over time



CMB: temperature anisotropies

ACT arXiv:1009.0866



CMB: Silk damping

- 'Silk damping' or 'diffusion damping': photons diffuse from hot to cold regions damping temperature anisotropies

- Amount of damping depends on expansion rate: $H \sim N_{\rm eff}$, so damping sensitive to $N_{\rm eff}$

- Degenerate with Y_p . Helium recombines with free electrons. More helium $\Longrightarrow$ fewer free electrons $\Longrightarrow$ photons diffuse further $\Longrightarrow$ more damping

CMB: temperature anisotropies

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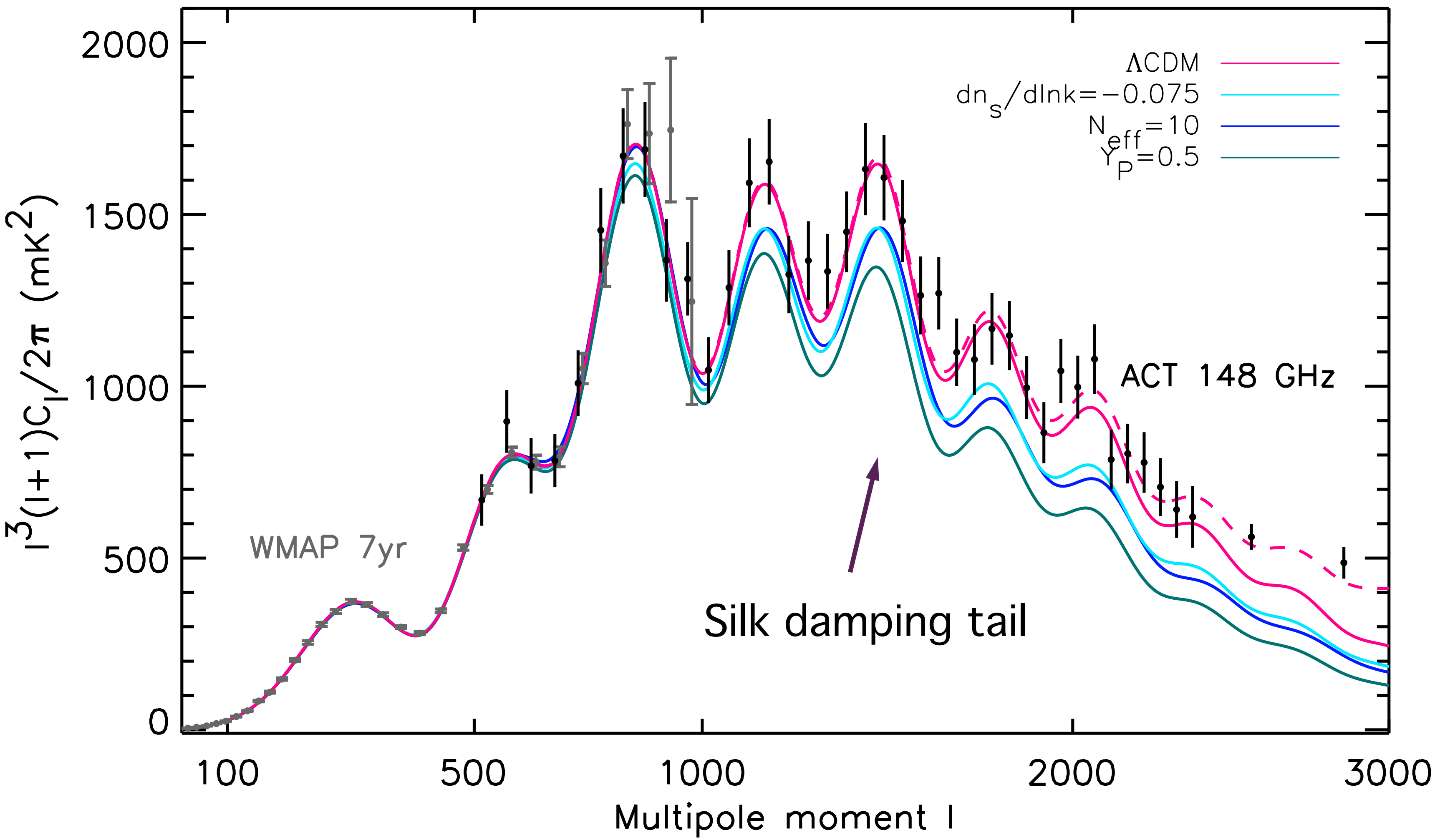
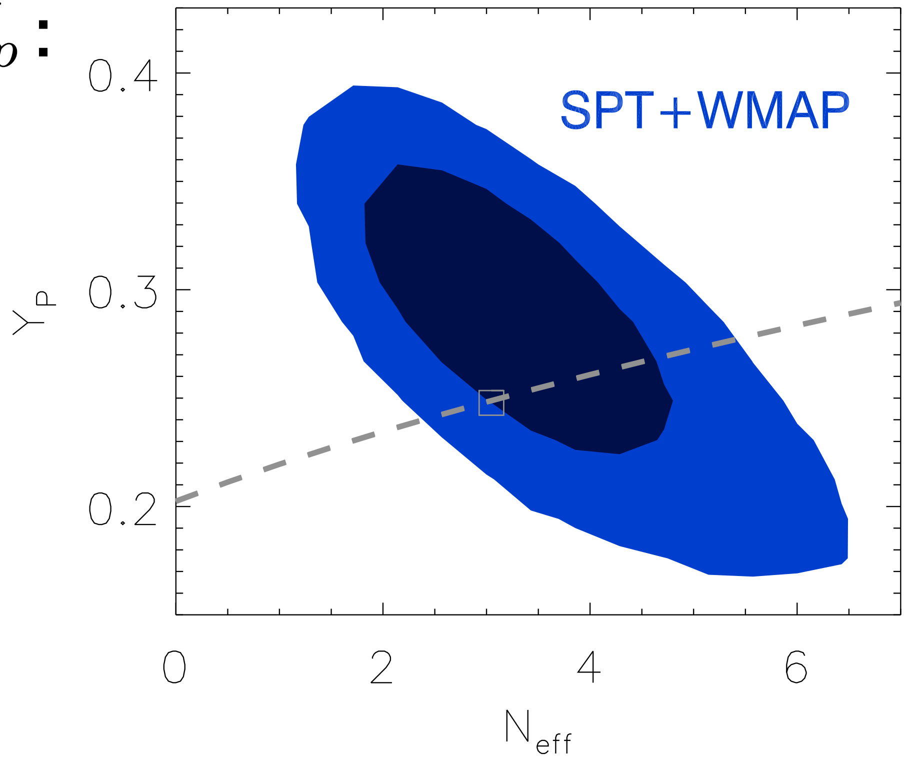


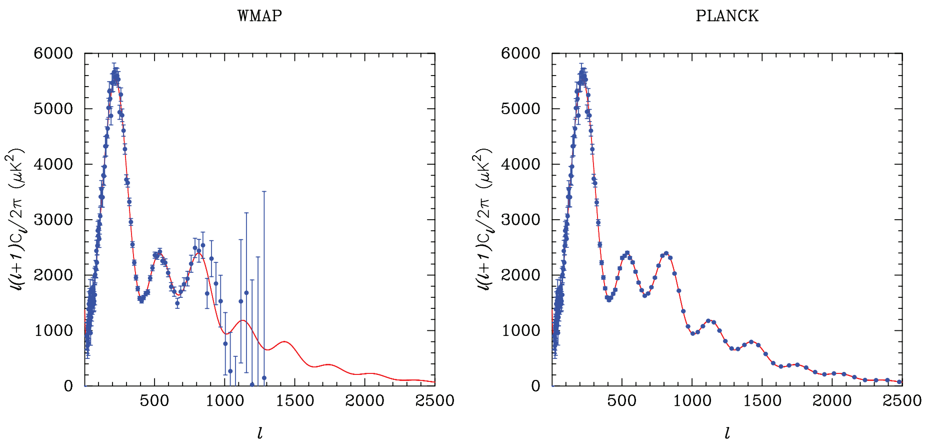
CMB: measuring N_{eff}

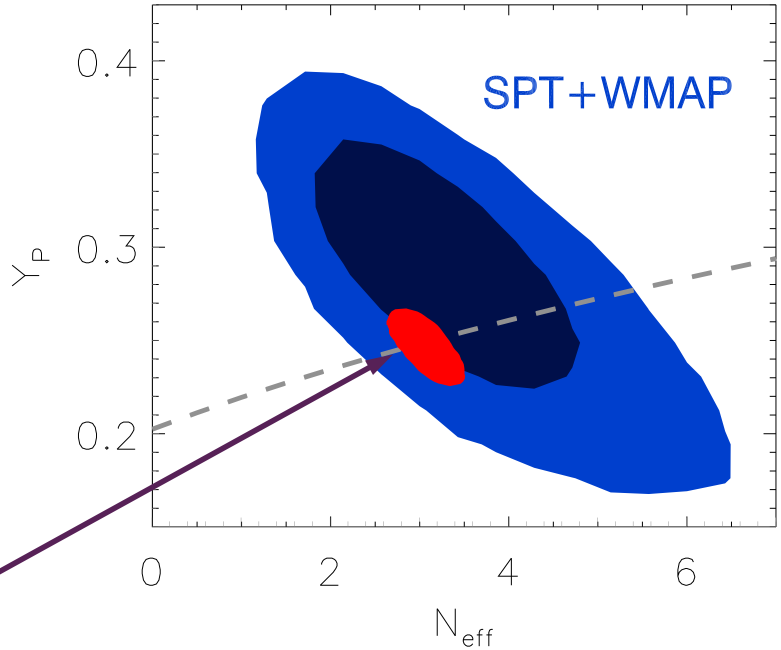
- With Y_p fixed:
    - ACT find $N_{\text{eff}} = 4.6 \pm 0.8\,(1\sigma)$
    - SPT find $N_{\text{eff}} = 3.9 \pm 0.4\,(1\sigma)$
- With free Y_p :



Status of results

- BBN : 1-2σ evidence for increased Neff
- CMB: 1-2.5σ evidence for increased Neff
- But…impending results from Planck will lead to significant improvements:





Forecast of Planck
1σ region

Ways of increasing N_{eff}

- Recall the definition of N_{eff} : number of Majorana fermions with usual $\nu - \gamma$ temperature relation

$$N_{\text{eff}} = N_\nu \cdot \left[\frac{T_\nu}{T_\gamma} \Big/ \left(\frac{4}{11} \right)^{1/3} \right]^4 + N_x \cdot \left[\frac{T_x}{T_\gamma} \Big/ \left(\frac{4}{11} \right)^{1/3} \right]^4$$

- Two obvious ways to increase N_{eff} :

1. The popular option: Introduce extra massless or very light particles eg sterile neutrino, hidden photon...
2. The underexplored option: Increase the $\nu - \gamma$ temperature ratio

We have been exploring option 2

Heating the neutrinos

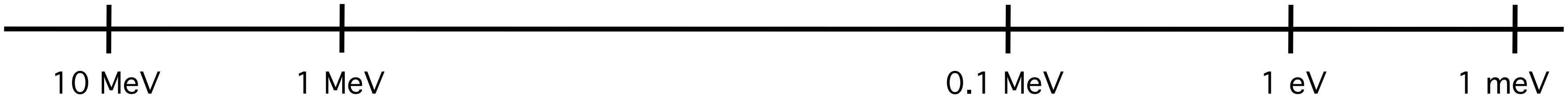
- Recall, in the standard picture, photons reheated when electrons and positrons become non-relativistic
- Conditions the electrons must satisfy:

1. Decouple from neutrinos at ~2.3 MeV while still relativistic
2. Remain in thermal equilibrium with photons until non-relativistic

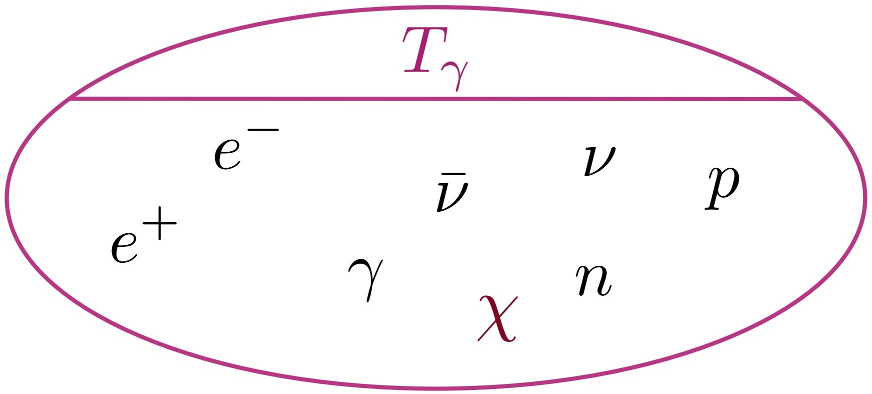
- Now, introduce particle χ that couples dominantly with neutrinos. It must:

1. Decouple *with* neutrinos at ~2.3 MeV while still relativistic $\implies m_\chi \sim 1\,\mathrm{MeV}$
2. Remain in thermal equilibrium with *neutrinos* until non-relativistic

New timeline: Thermal bath



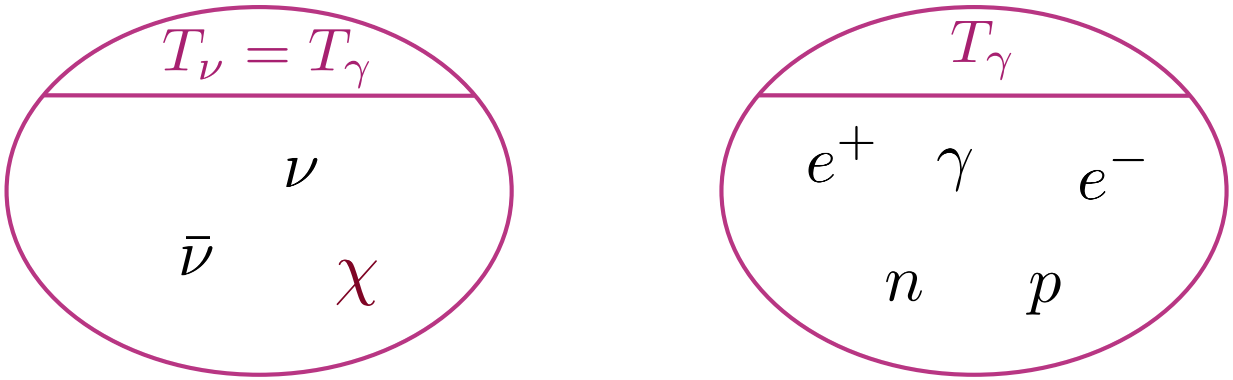
- Plasma of particles in a thermal bath. Now includes χ



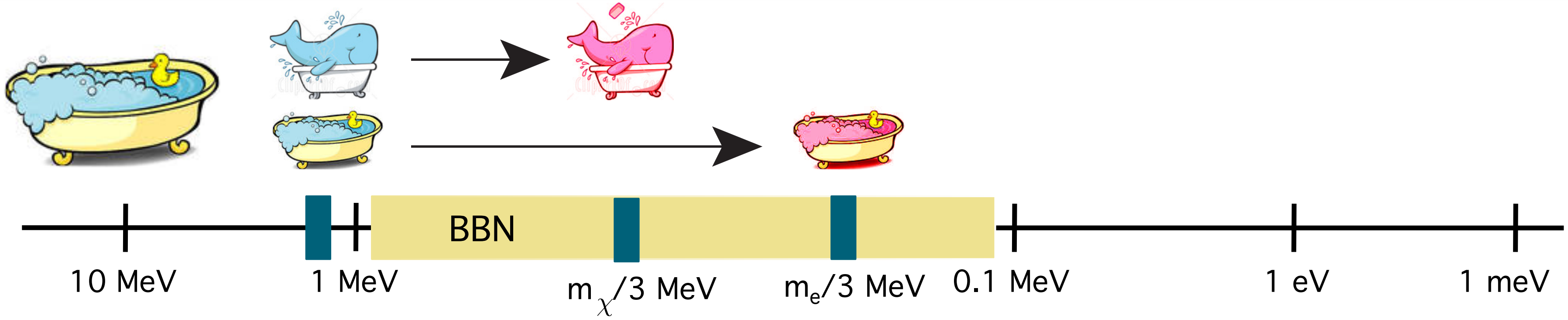
New timeline: Neutrino decoupling

Events: ν, χ decoupling

- Neutrinos and χ decouple at ~2.3 MeV



New timeline: Reheating



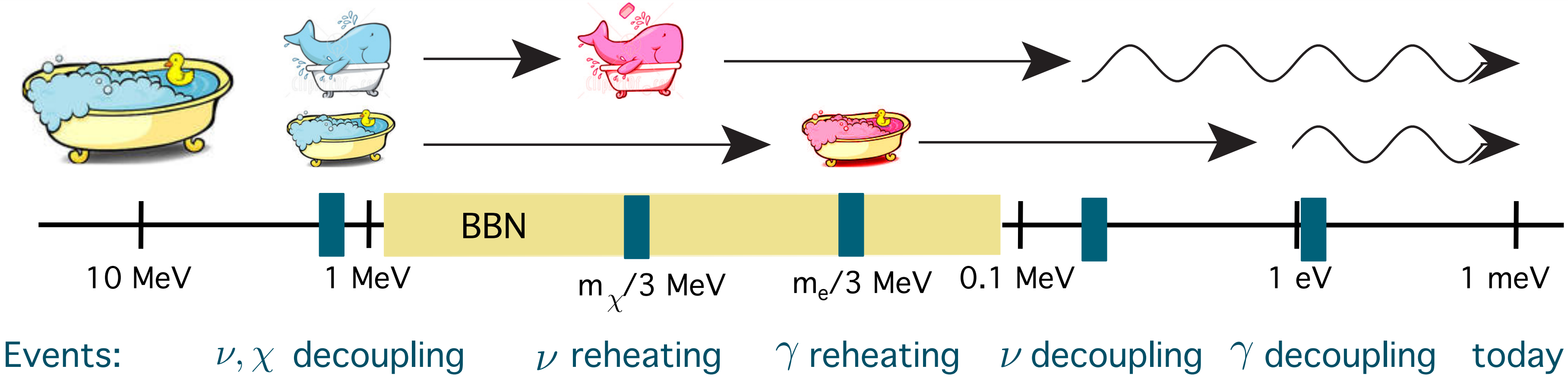
Events: ν, χ decoupling ν reheating γ reheating

- New temperature relation at end of BBN

$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3} \left[\frac{3 + F(m_\chi/2.3\,\mathrm{MeV})}{3 + F(m_\chi/T_\gamma)}\right]^{1/3}$$

- $F(m_\chi/T)$ smoothly varies between 0 ($m_\chi \to \infty$) and 1 ($m_\chi \to 0$)

New timeline: Today



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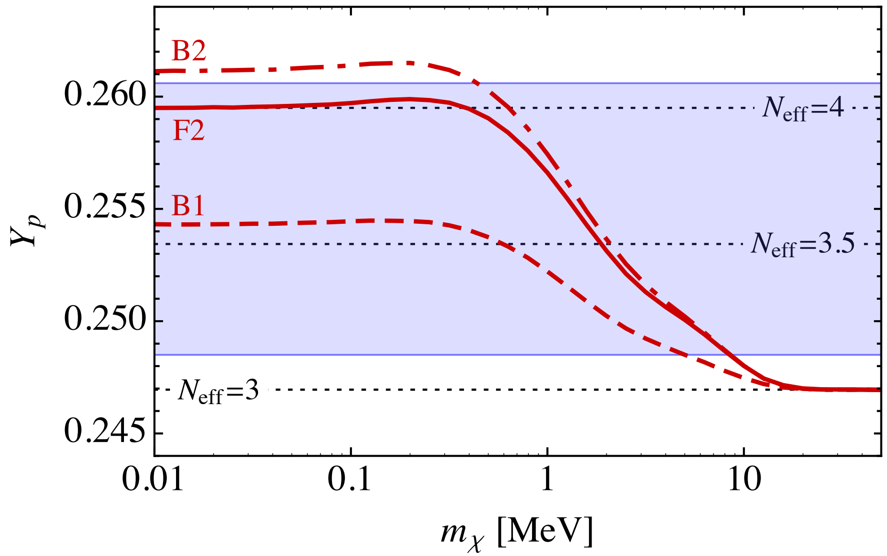
2. Cosmic neutrino background with

$$T_\nu = 1.945\,\mathrm{K} \cdot \left[1 + \frac{F(m_\chi/2.3\,\mathrm{MeV})}{3}\right]^{1/3}$$ (not measured)

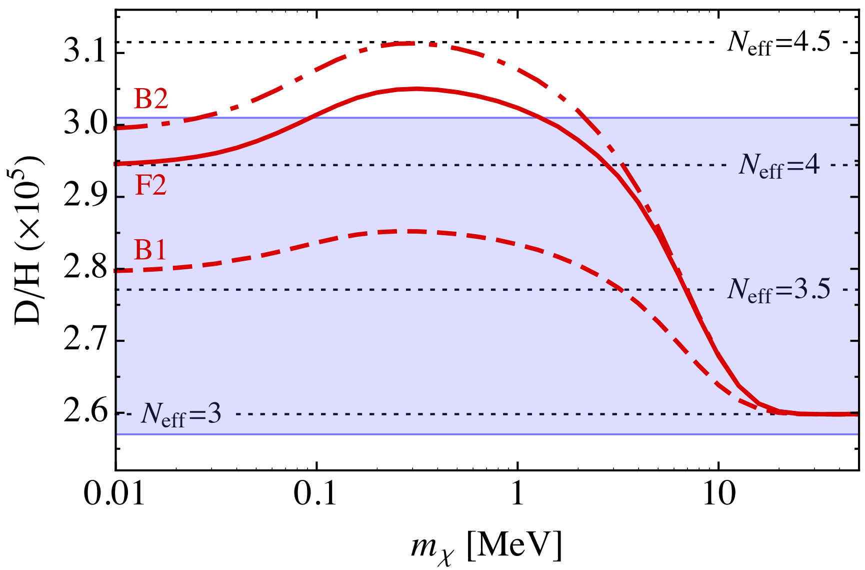
Change at BBN

Kolb, Turner, Walker 1986
Serpico Raffelt 2004

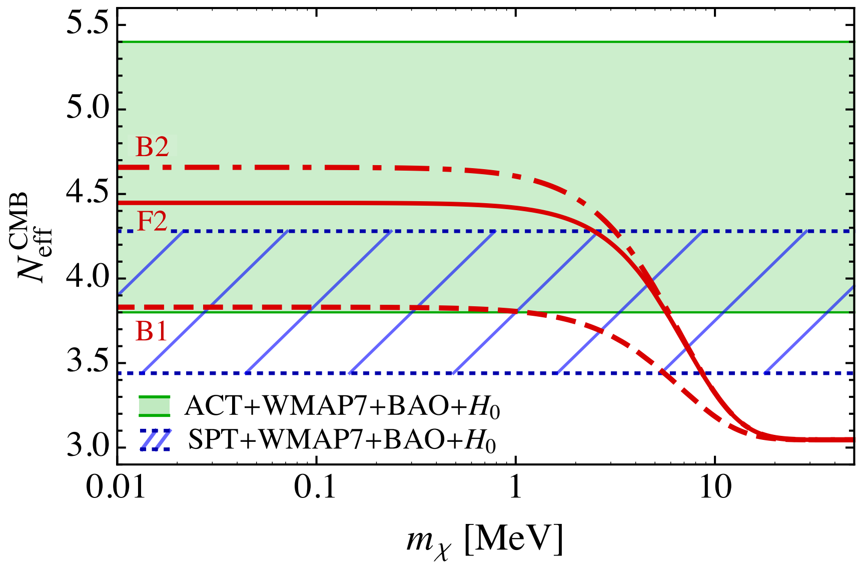


B1: real scalar
B2: complex scalar
F2: Majorana fermion

Blue bands show
1σ measurements



Change at recombination (CMB)



B1: real scalar
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Bands show
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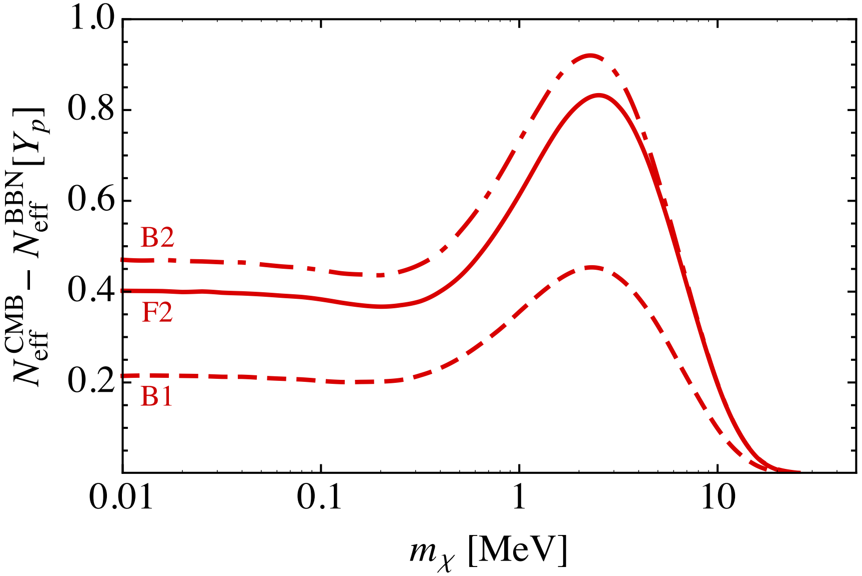


The future?

- All values of m_χ are consistent with the data at just over 1σ

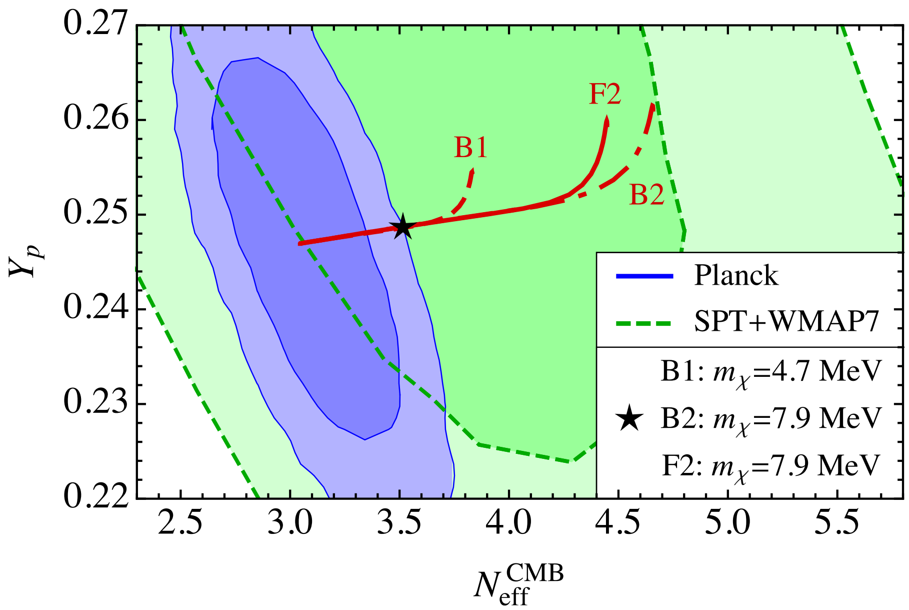
- How well will Planck do?
- Generate mock data with the following parameters

Standard values

Values for Majorana fermion at 1 MeV

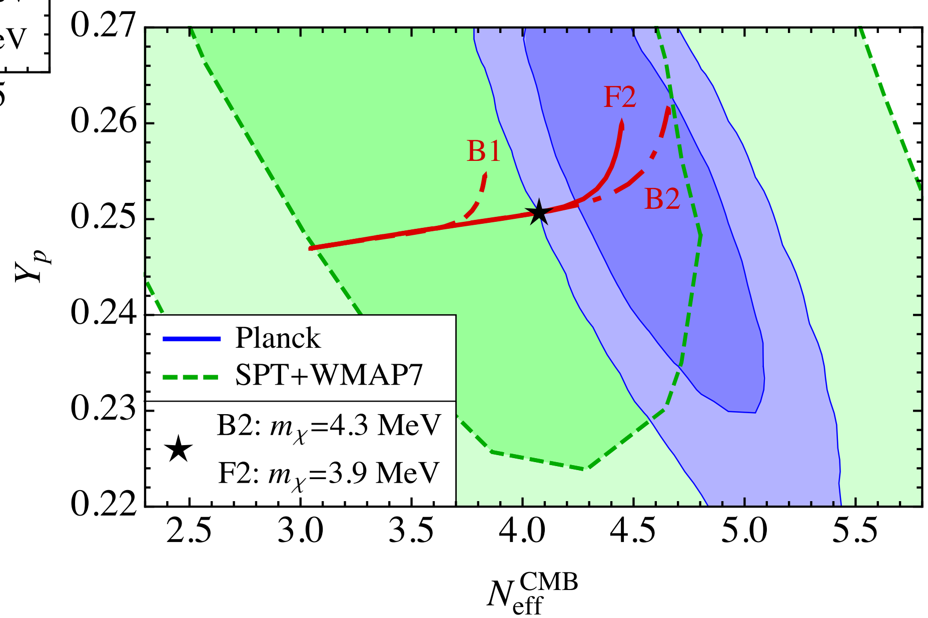
Parameter	Fiducial values ΛCDM	Fiducial values ΛCDM+χ	Prior range
$\Omega_b h^2$	0.0223	0.0223	$0.005 \to 0.1$
$\Omega_{DM} h^2$	0.110	0.135	$0.01 \to 0.99$
h	0.71	0.76	$0.4 \to 1.0$
$100\,\theta_S$	1.041	1.039	$0.5 \to 10$
τ	0.09	0.09	$0.01 \to 0.8$
$\ln[10^{10} A_S]$	3.05	3.05	$2.7 \to 4$
n_S	0.96	0.96	$0.5 \to 1.5$
f_ν	0.008	0.015	$0 \to 1$
N_{eff}	3.046	4.418	$0 \to 7$
Y_p	0.247	0.257	$0.22 \to 0.27$

Planck forecast: Results



Contours shown at 1σ and 95%

Planck will give significant constraints on the mass



Model: MeV neutralino dark matter

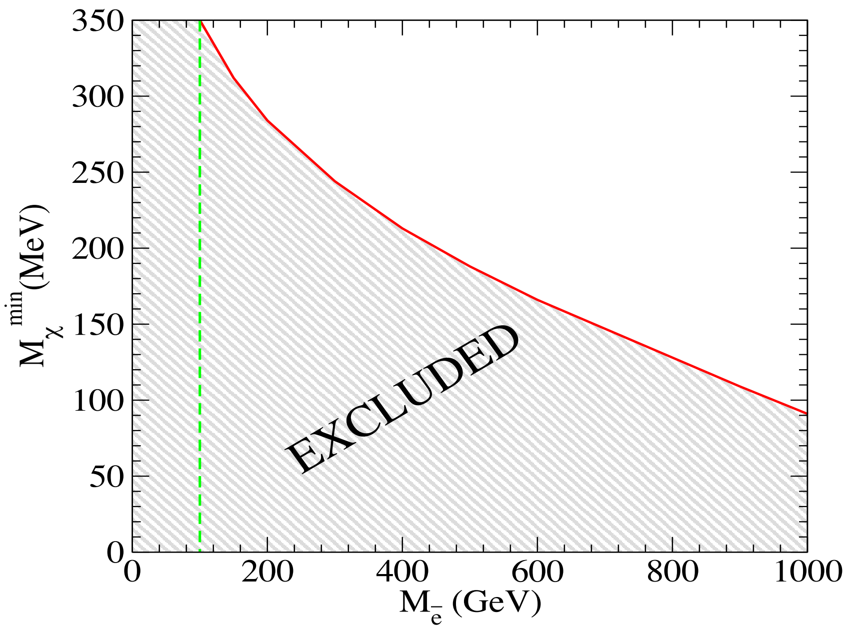
- Somewhat surprisingly, Dreiner et al have shown that a bino-like neutralino can be massless

- Satisfies constraints from
  - Collider bounds
  - Precision electroweak
  - Rare meson decays
  - Cosmological bounds
  - Astrophysical bounds

Supernovae constraints

- Supernovae core temperature ~ 40 MeV
- SN1987a sets limits on how rapidly supernova loses energy
- Light neutralino opens new channel for energy loss through

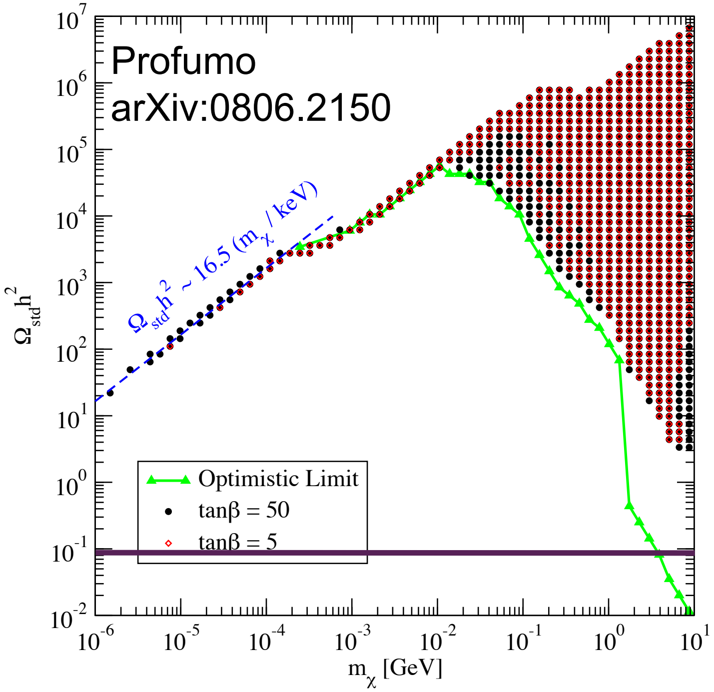
$$e^+ + e^- \longrightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0\,,$$
$$N + N \longrightarrow N + N + \tilde{\chi}_1^0 + \tilde{\chi}_1^0$$



Need to couple weakly to quarks and electrons:
Squark mass > 300 GeV
Selectron mass > 1.2 TeV

MeV neutralino dark matter

- In general, the relic density is too large



- Need a light mediator to keep in thermal equilibrium for longer

Model: MSSM+RHD sneutrinos

- Introduce sterile rhd sneutrino that mixes with lhd sneutrino
- Light states will be mostly rhd

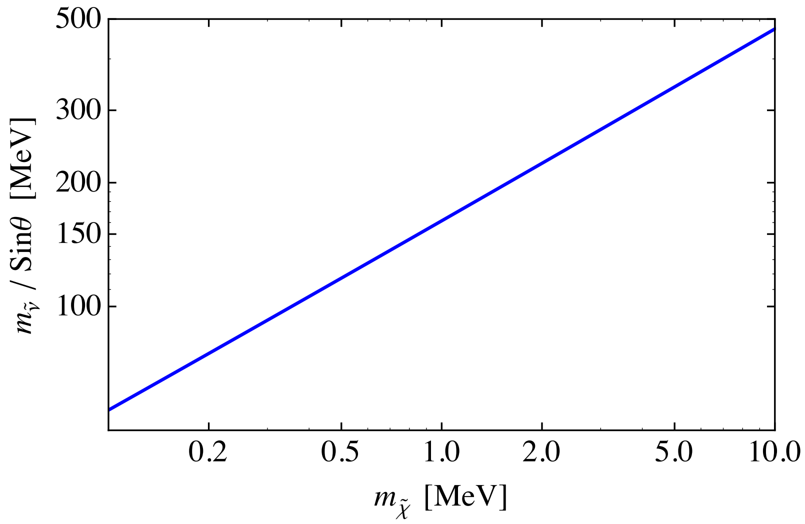
$$\Delta\mathcal{L} = -m^2_{\tilde{n}_i}|\tilde{n}_i|^2 - A_i h_u \tilde{L}_i \tilde{n}_i$$

$$\tilde{\nu}_i = -\sin\theta_i\ \tilde{\nu}_{Li} + \cos\theta_i\ \tilde{n}_i^\star \qquad \tan 2\theta_i = \frac{2A_i v \sin\beta}{M^2_{Li} - M^2_{Ri}}$$

- Constraints on mixing angle from Z-width, Higgs-width, supernova. All OK if $\sin\theta \lesssim 0.1$

Model: relic density

- Sneutrino keeps neutralino in equilibrium with neutrinos
- Can get the right relic density



- Neutralino remains in equilibrium until $T \sim \frac{m_\chi}{15}$

Recall: Heating the neutrinos

- Recall, conditions to reheat neutrinos:

1. Decouple *with* neutrinos at ~2.3 MeV while still relativistic
2. Remain in thermal equilibrium with *neutrinos* until non-relativistic

- MeV neutralino satisfy both conditions:

1. Supernova constraint implies coupling to electron must be very small
2. Typically MeV neutralino gives a relic abundance that is too large – requirement to get correct relic abundance ensures the neutralino must be in equilibrium with neutrinos
3. Decouples from neutrinos at $T \sim \frac{m_\chi}{15}$, ie, while non-relativistic

Conclusions

- Hints for additional energy density in the early Universe from

1. increased helium abundance from BBN
2. Additional damping in the CMB power spectrum

- Planck will soon accurately measure damping leading to dramatically improved constraints

- Motivated MeV-mass particle in thermal equilibrium with neutrinos and looked at current and future constraints

- Suggested MeV neutralino to highlight how this MeV particle will arise