Low mass dark matter

GRAPPA
GRavitation AstroParticle Physics Amsterdam

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Effective Theories and Dark Matter, Mainz – 19th March 2015

1. General considerations

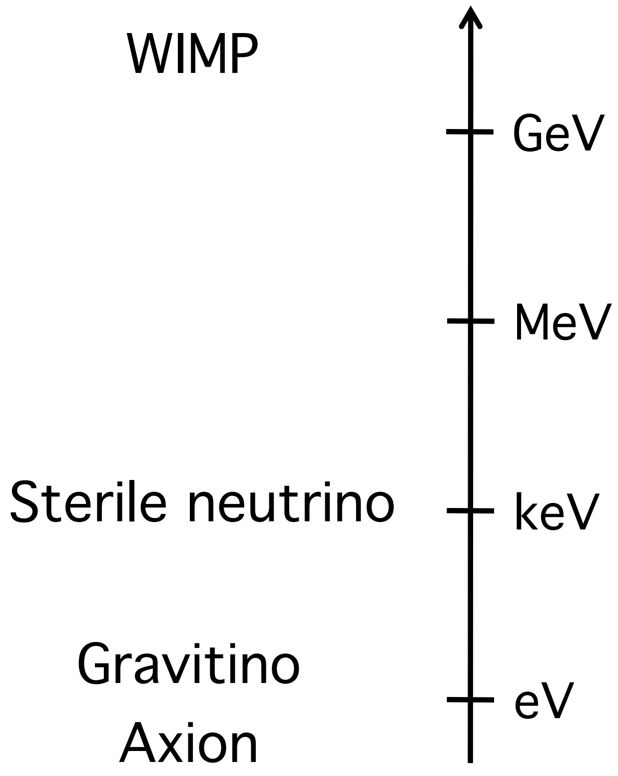
2. A peculiar neutralino model

Results from:
Boehm, Dolan, CM,
Increasing N_{eff} with particles in thermal equilibrium with neutrinos - arXiv:1207.0497
A lower bound on the mass of cold dark matter from Planck - arXiv:1303.6270

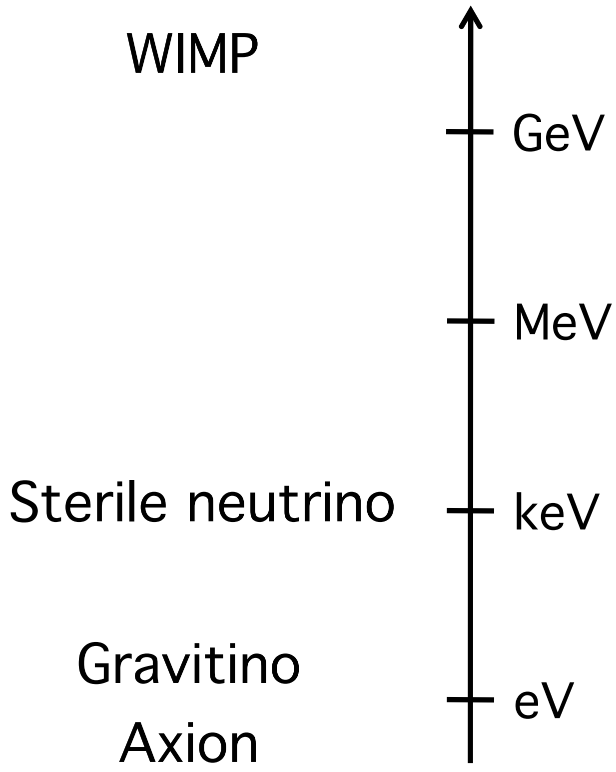
1. General considerations:

How low is low mass?

Low-mass dark matter candidates



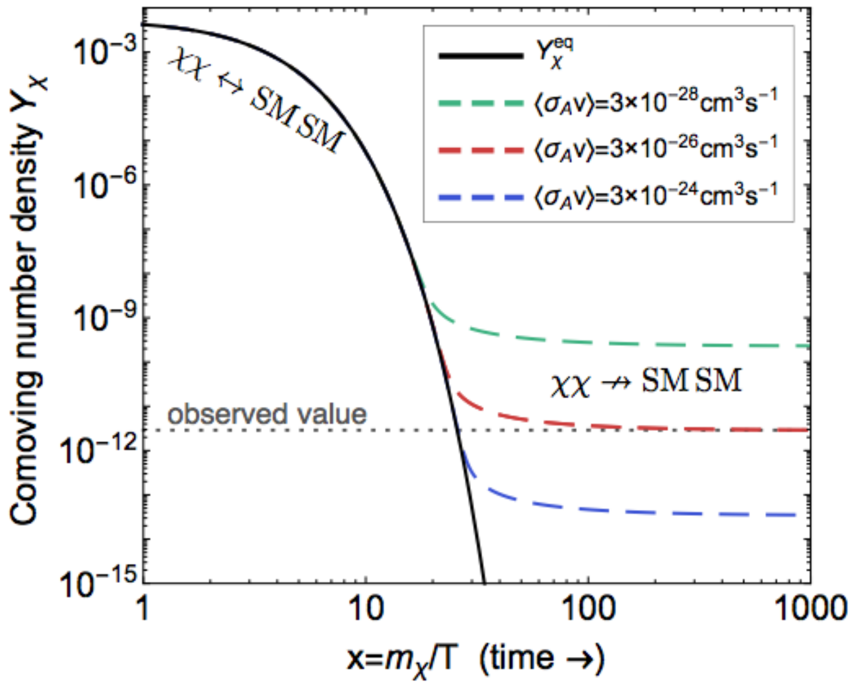
Low-mass dark matter candidates



How light can we make WIMPs?

What is a WIMP?

- Weak scale mass...
- Weak scale cross-section: ~0.1-10 pb
- Abundance from thermal freeze-out mechanism:



$$\Omega_{\rm DM}h^2 \simeq 0.1\,\frac{3\times10^{-26}\ \mathrm{cm^3 s^{-1}}}{\langle\sigma_A v\rangle}$$

WIMP mass?

- SM fermion get mass from the Higgs vev...
  ...yet most are below a GeV

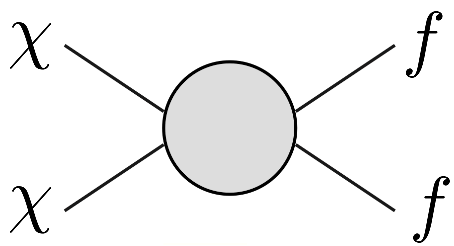
- Lee-Weinberg argument
  - On dimensional grounds: $\langle \sigma v \rangle = \dfrac{m_{\mathrm{DM}}^2}{m_{\mathrm{weak}}^4}$
  - If $m_{\mathrm{weak}} = 100\ \mathrm{GeV}$, for $\langle \sigma v \rangle \approx 1\ \mathrm{pb}$

$$\Rightarrow m_{\mathrm{DM}} \geq 1\ \mathrm{GeV}$$

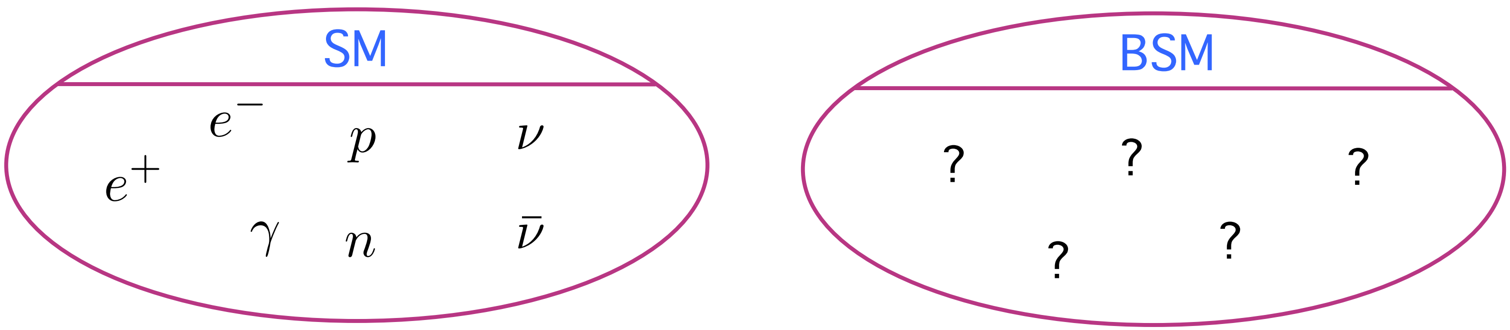
- Light WIMPs are sub-GeV
- Light WIMPs require a light mediator

The thermal bath

- ‘Freeze-out’ from what? Need a thermal bath of particles
- Kept in equilibrium with annihilations

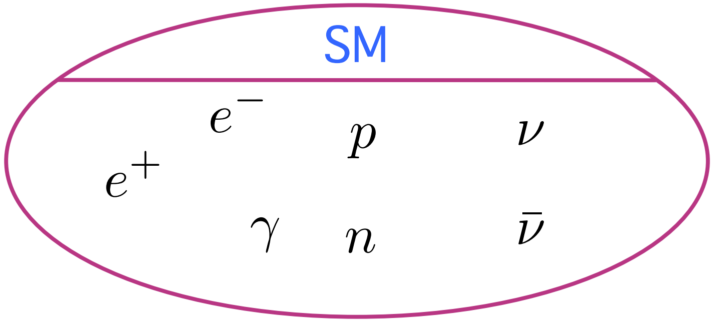


- f could be SM states or BSM states



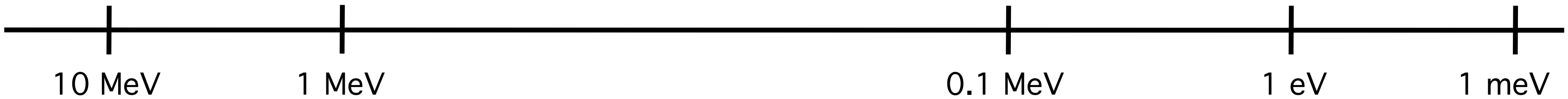
Two cases

- I'll consider when WIMP in equilibrium with SM particles

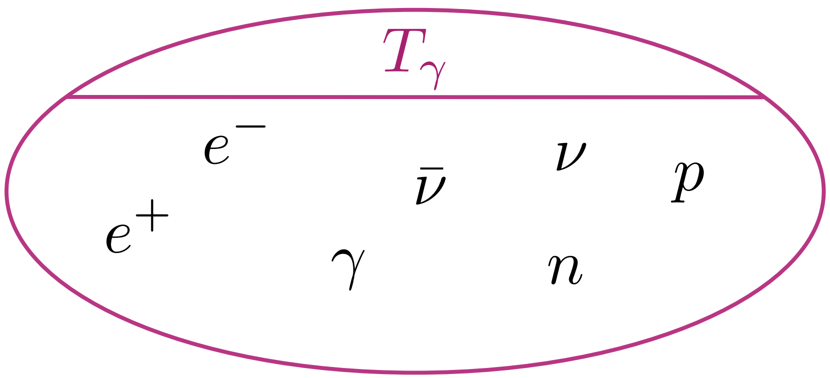


- Case 1: In equilibrium with neutrinos
- Case 2: In equilibrium with electrons/photons

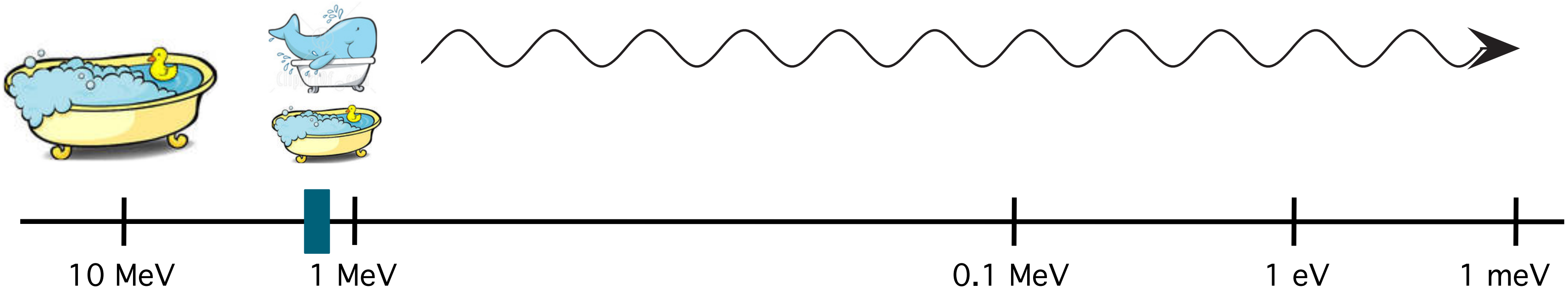
Reminder: The usual Timeline



- Plasma of particles in a thermal bath:

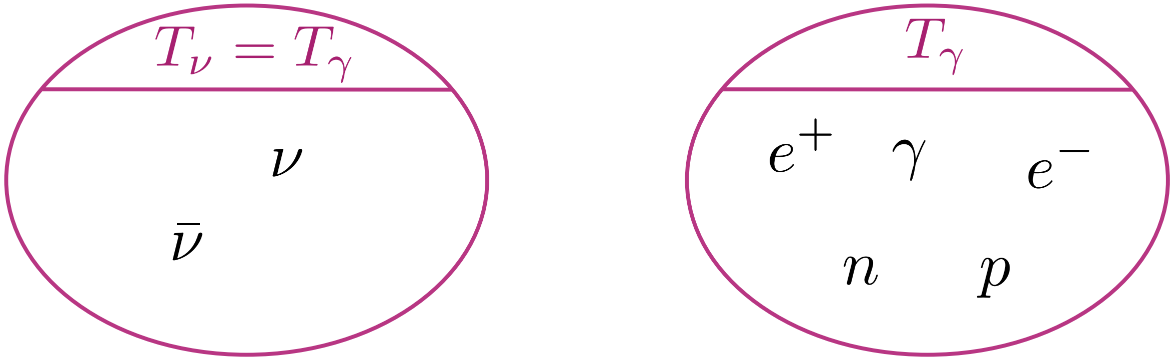


Timeline: Neutrino decoupling

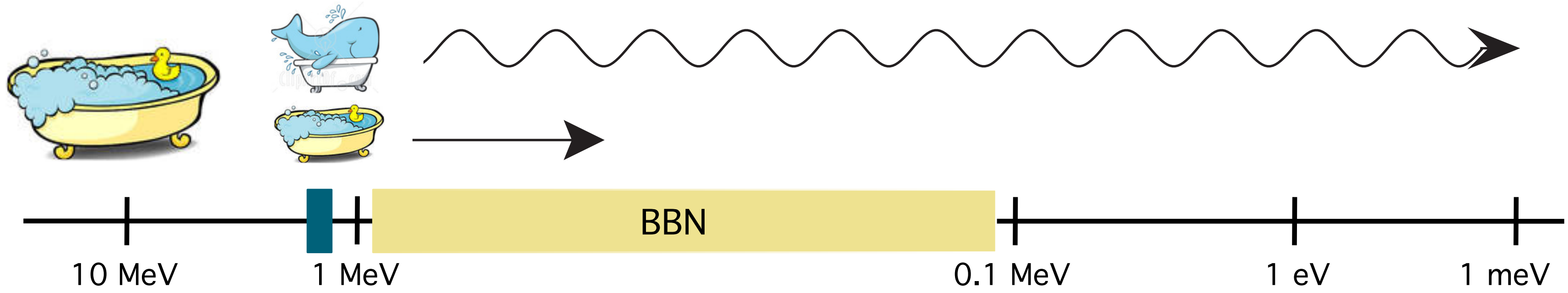


Events: ν decoupling

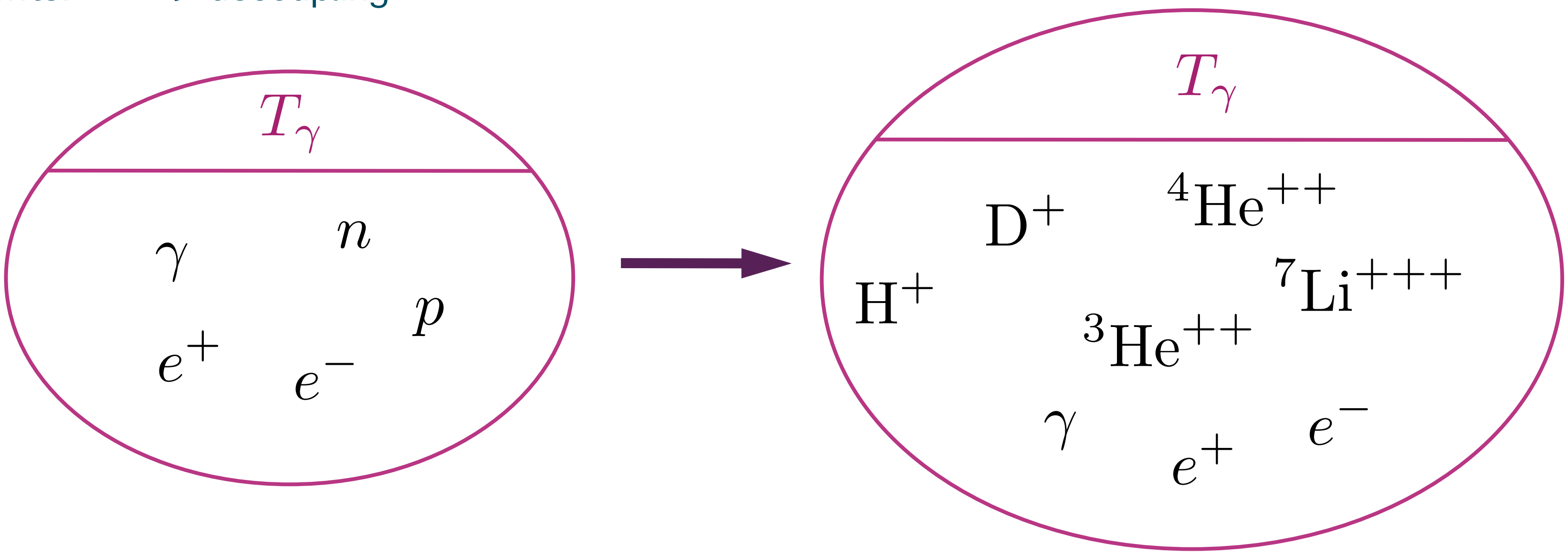
- Species remain in thermal equilibrium until $\Gamma = n\sigma v \sim H$
- Neutrinos decouple at ~2.3 MeV



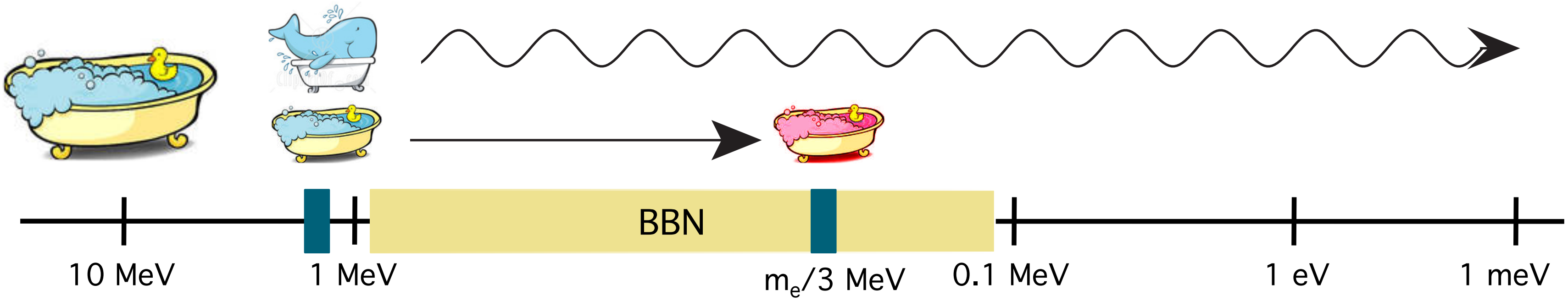
Timeline: Big Bang Nucleosynthesis



Events: ν decoupling



Timeline: Photon reheating

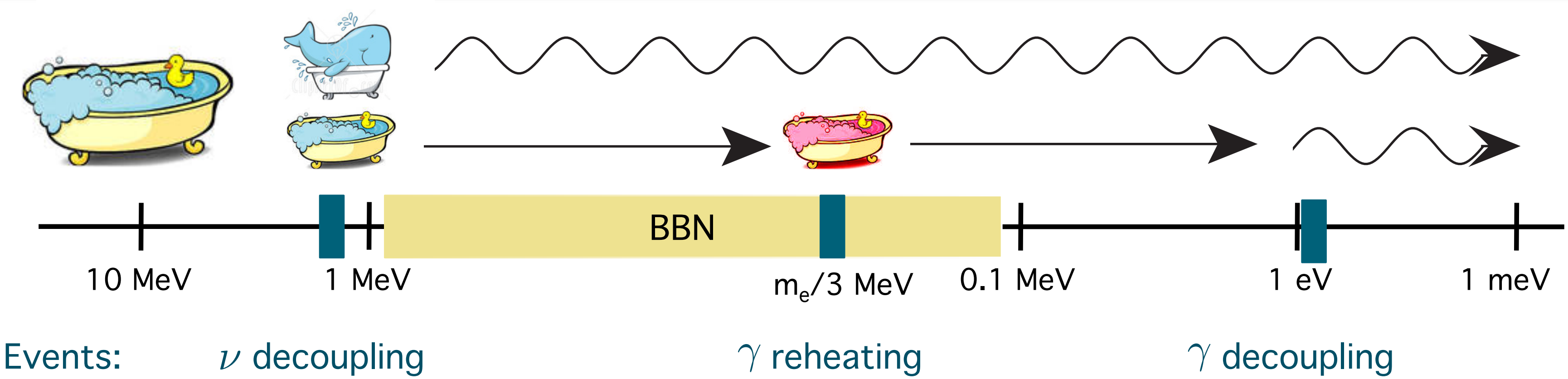


Events: ν decoupling γ reheating

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

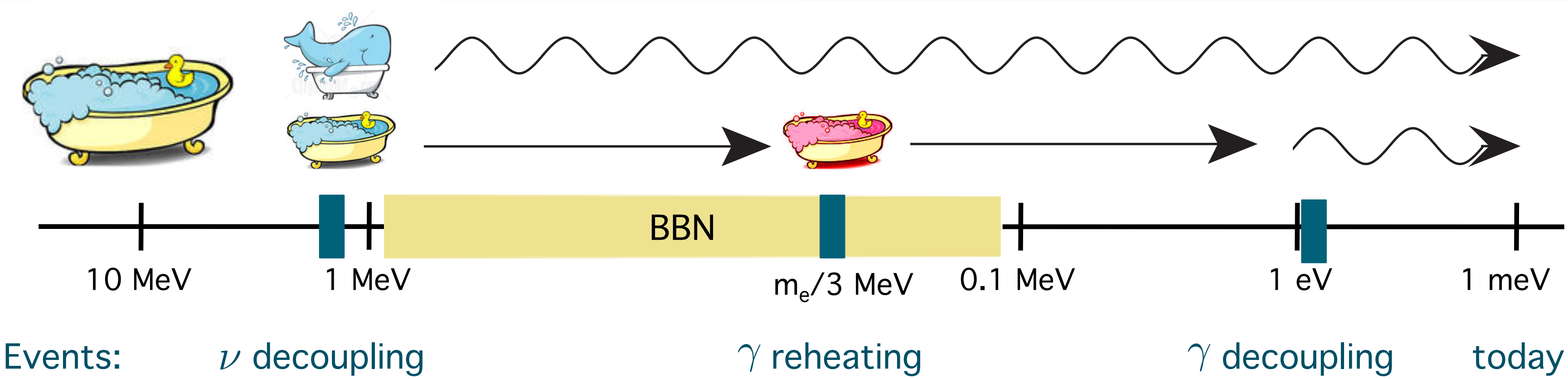
- Photon thermal bath heated relative to neutrino bath: $$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3}$$

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

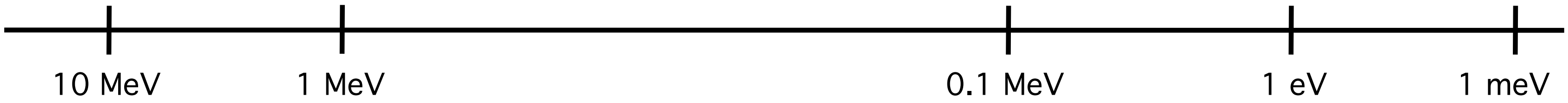


- Today we have (at least) two thermal relics:

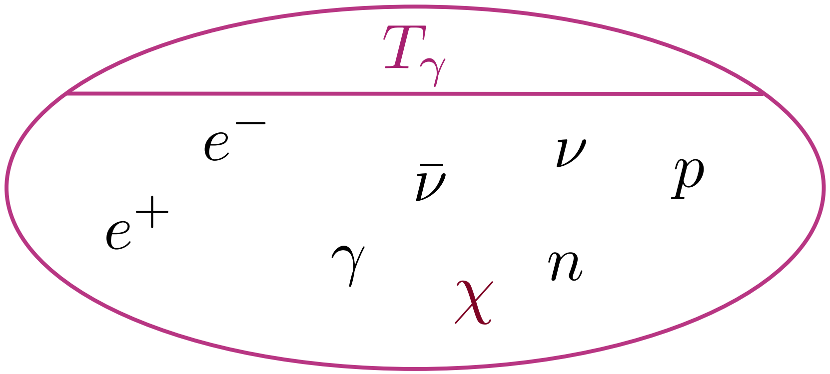
  1. CMB with $T_\gamma = 2.725\,\mathrm{K}$ (measured)

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

New timeline: With light dark matter



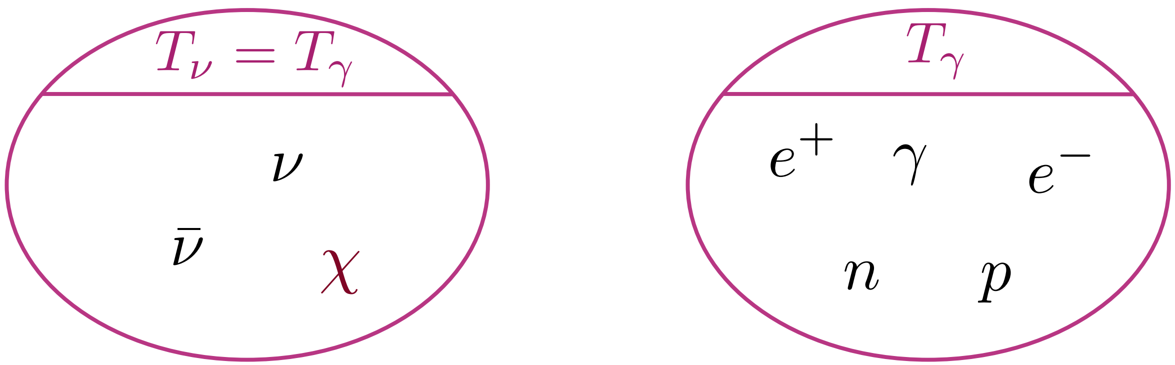
- Plasma of particles in a thermal bath, including χ , which is in equilibrium with the neutrinos



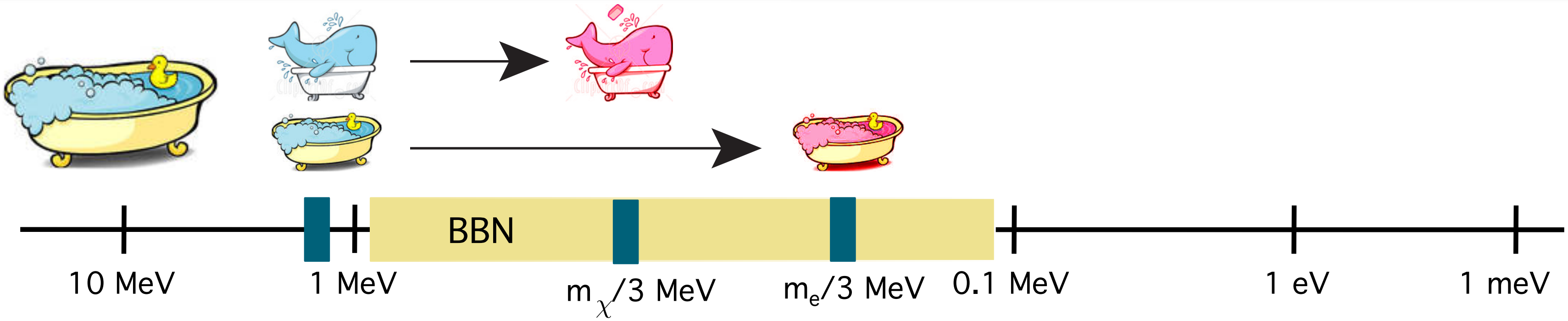
New timeline: Neutrino decoupling

Events: ν, χ decoupling

- Neutrinos and χ decouple at ~2.3 MeV



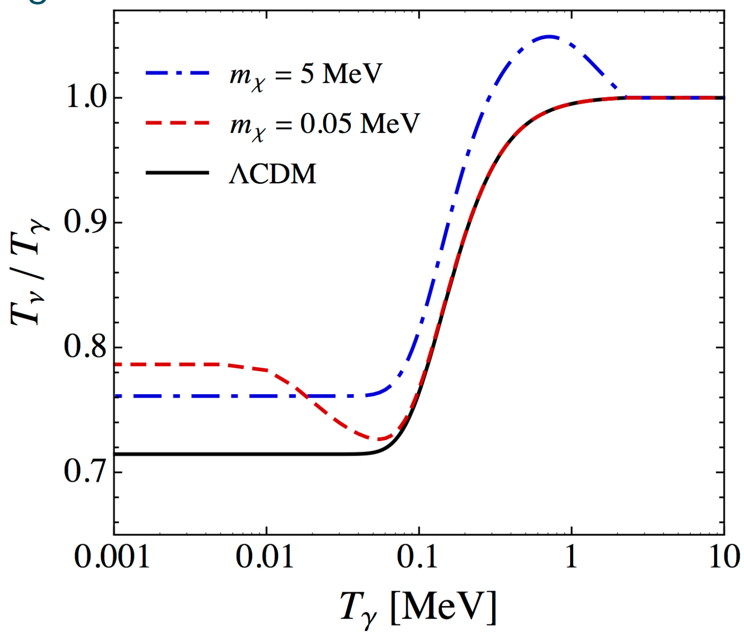
New timeline: Neutrino heating



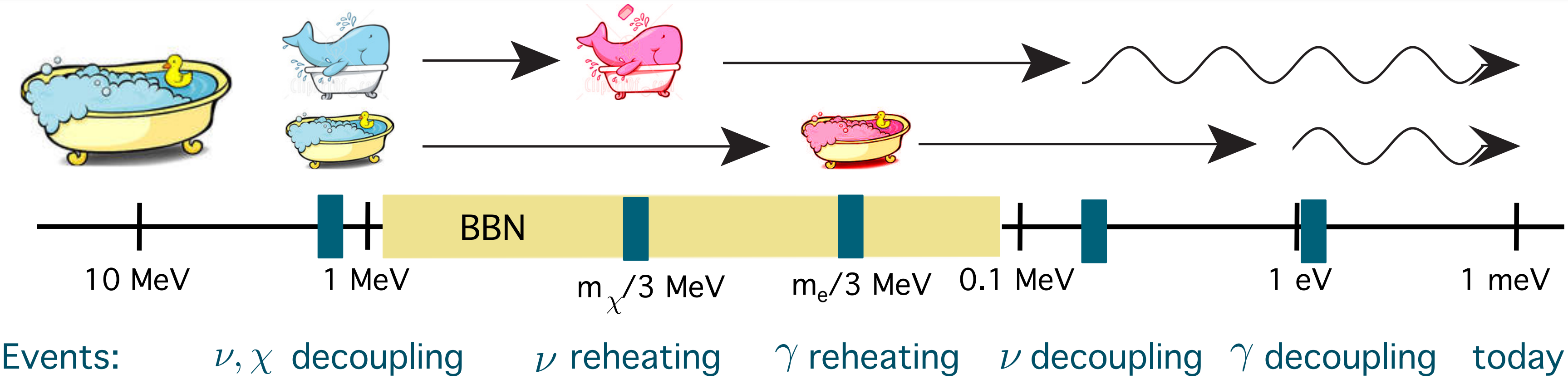
Events: ν, χ decoupling ν reheating γ reheating

- χ transfers entropy to neutrinos heating them
- Neutrinos hotter at end of BBN:

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



New timeline: Today



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

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

2. Cosmic neutrino background now warmer:

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

Changes to BBN?

Kolb, Turner, Phys.Rev. D34 (1986)
Raffelt, Serpico, Phys.Rev. D70 (2004)
Steigman, Nollett, arXiv:1312.5725

- A new light particle can contribute to the energy density (if it is still relativistic during BBN)

- A different neutrino-photon temperature ratio changes:

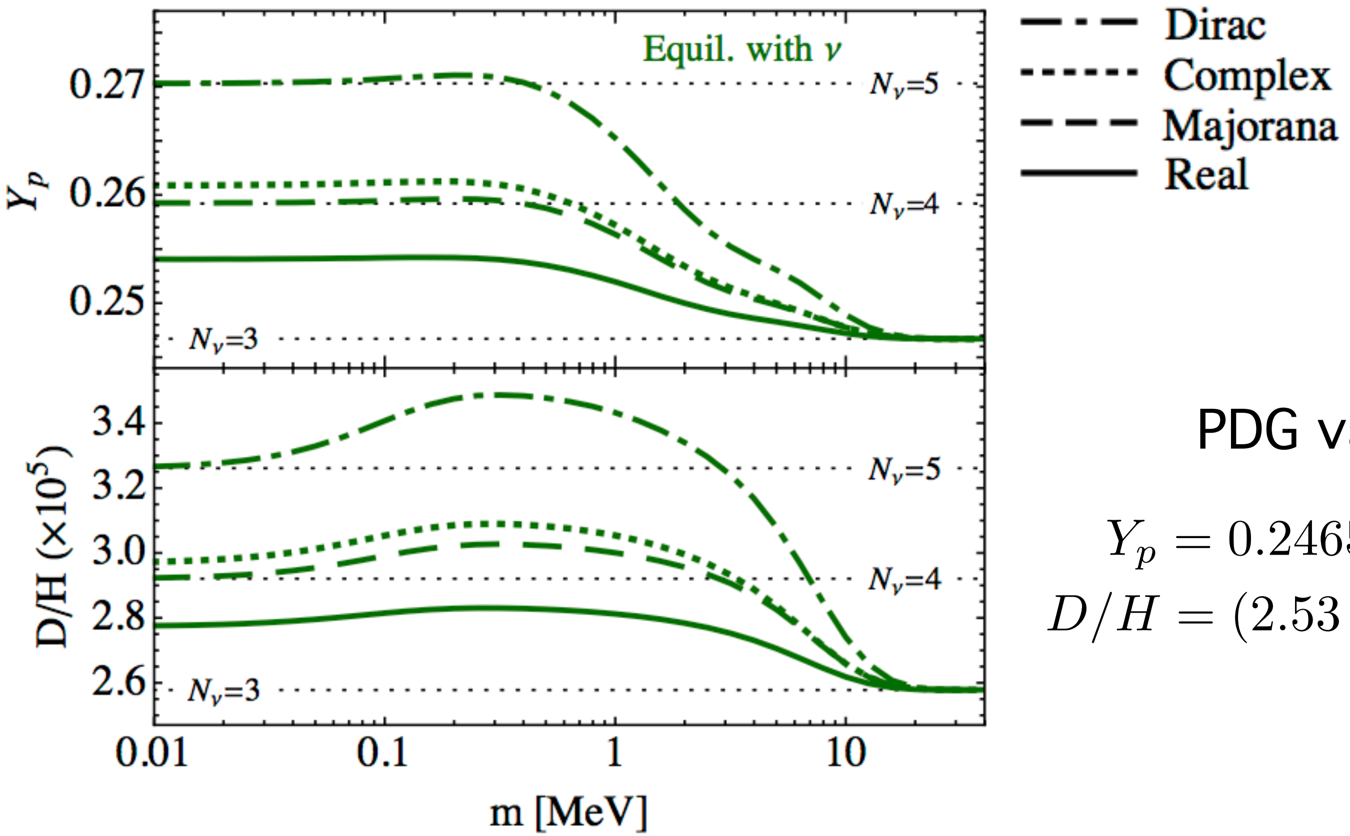
1. Neutrino energy density higher

2. Change to the weak interaction rates for proton <-> neutron conversion $(\nu_e + n \leftrightarrow p + e\ )$

Changes to abundances

- We implemented the changes into PArthENoPE BBN code

arXiv:0705.0290



PDG values

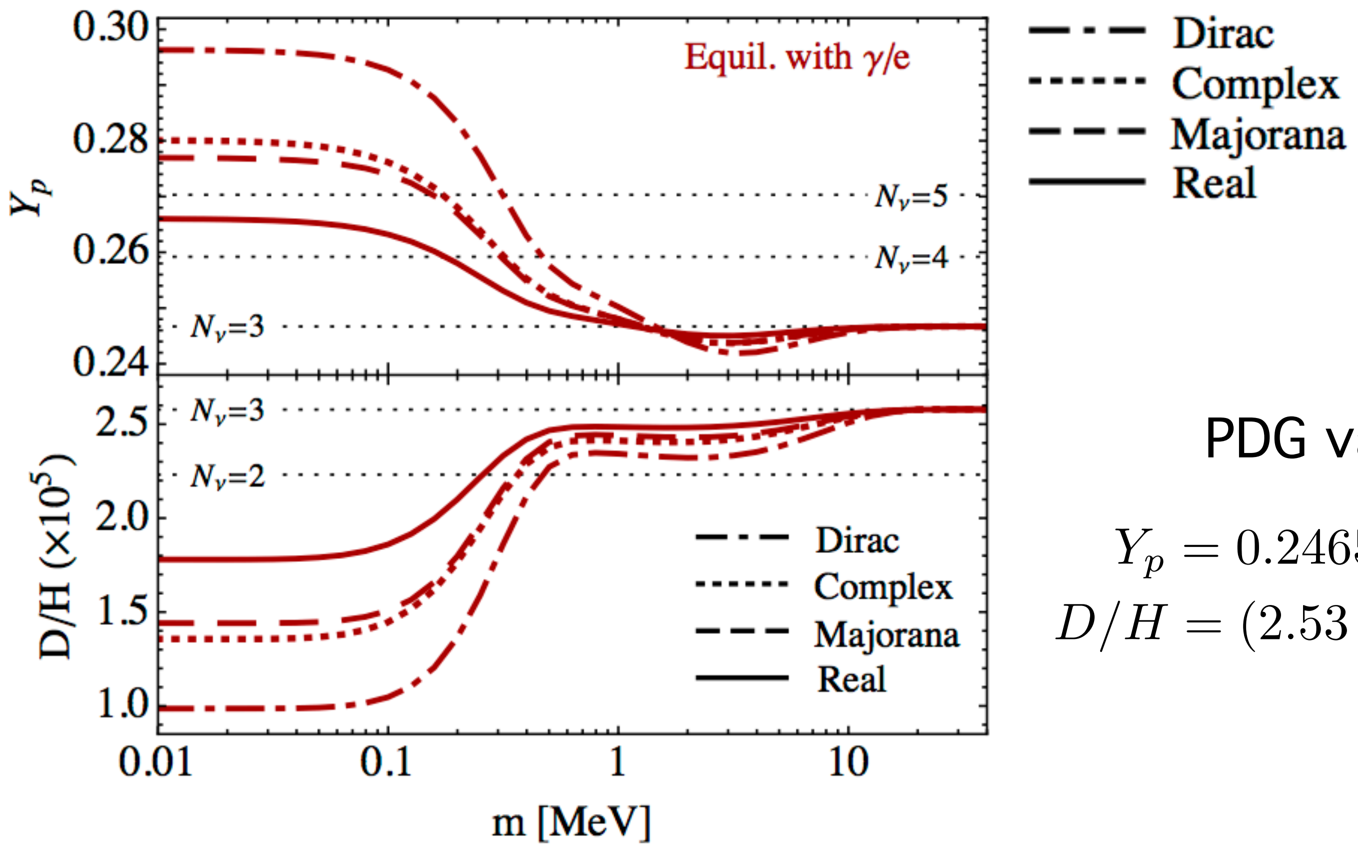
$$Y_p = 0.2465 \pm 0.0097$$

$$D/H = (2.53 \pm 0.04) \times 10^{-5}$$

In equilibrium with EM particles

- We implemented the changes into PArthENoPE BBN code

arXiv:0705.0290



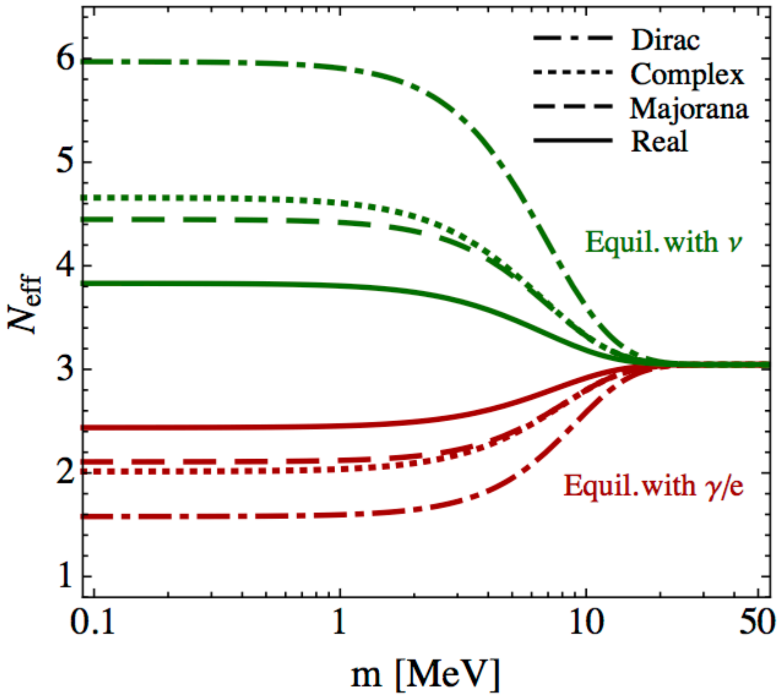
PDG values

$$Y_p = 0.2465 \pm 0.0097$$
$$D/H = (2.53 \pm 0.04) \times 10^{-5}$$

CMB: N_{eff} changes

- Higher neutrino temperature increases N_{eff}

$$N_{\text{eff}} = 3.046 \left[\frac{T_\nu}{T_\gamma} \Big/ \left(\frac{4}{11}\right)^{1/3} \right]^4$$



Planck TT,TE,EE
+lowP+BAO (2015)

$$N_{\text{eff}} = 3.04 \pm 0.18$$

Mini-conclusion

- Assumptions:
  - Light WIMPs are sub-GeV
  - If in equilibrium with SM particles…
- Then…MeV mass particles can show up through BBN and CMB through effects on the neutrino-photon temperature relation

2. A peculiar neutralino model

How light can we make the neutralino?

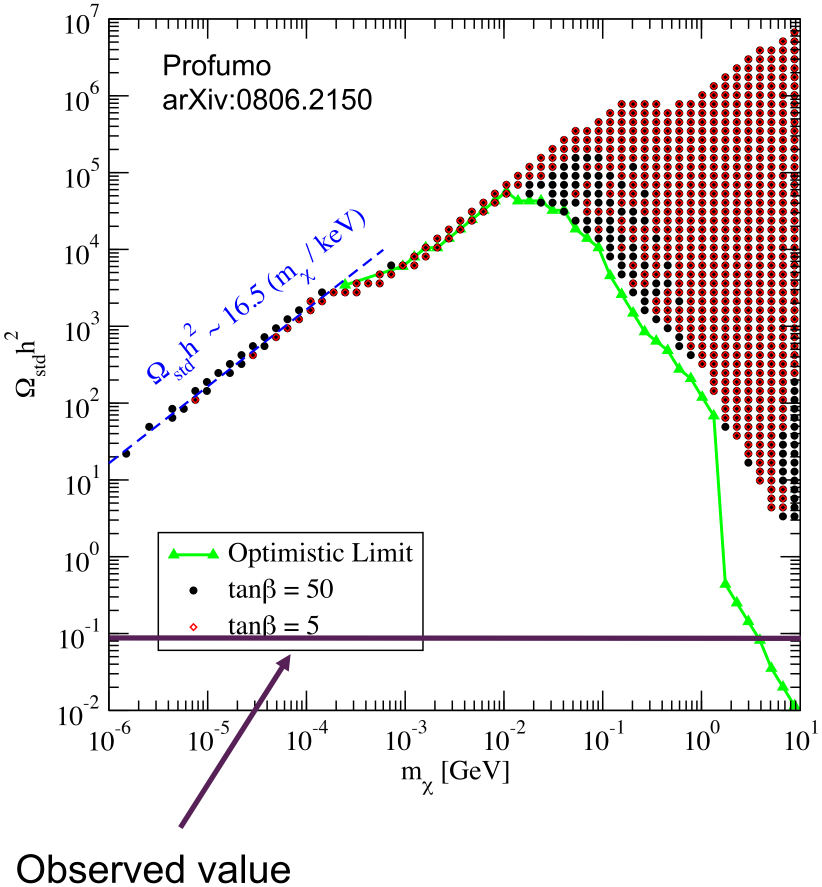
- The answer might be surprising:
  it can be as light as we like - even massless

Explored in a series of papers by Dreiner and others

- Certain conditions are required...
  - Bino-like
  - Selectrons and squarks are reasonably heavy
  - (some tuning of the parameters)

How light can we make neutralino dark matter?

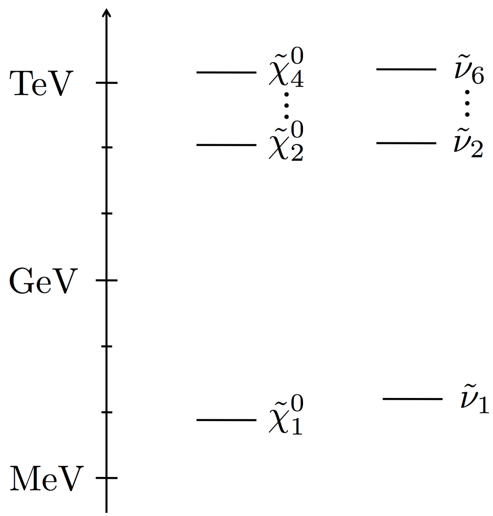
- In the MSSM, difficult to go below ~10 GeV:



Solution is clear: need another light superpartner

- Introduce sterile rhd sneutrino that mix with lhd sneutrino

$$V_{\text{soft}} \supset m^2_{\tilde{\nu}_L} |\tilde{\nu}_{Li}|^2 + m^2_{\tilde{n}} |\tilde{n}_i|^2 + A_{ij} h_u \cdot \tilde{L}_i \tilde{n}_j + \text{h.c.}$$

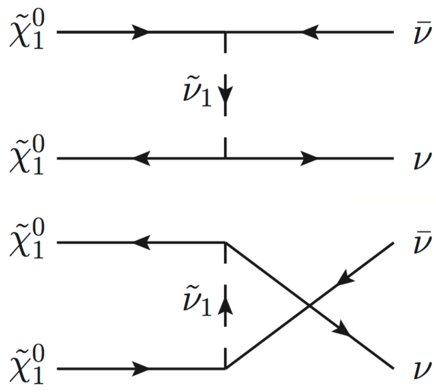


- Light mass eigenstates are mostly rhd

$\tilde{\nu}_1 = -\sin\theta_1 \; \tilde{\nu}^{\alpha}_L + \cos\theta_1 \; \tilde{n}^{\alpha\star}$ with $\tan 2\theta_i = \dfrac{2A_i v \sin\beta}{m^2_{\tilde{\nu}_L} - m^2_{\tilde{n}}} \sim 0.1\,.$

Solution is clear: need another light superpartner

- Neutralino remains in equilibrium with neutrinos:



- Freeze-out happens as usual with a weak scale cross-section:

$$\langle \sigma v \rangle \approx 7 \text{ pb} \left(\frac{\sin\theta}{0.1} \right)^4 \left(\frac{m_{\tilde{\chi}_1^0}}{5 \text{ MeV}} \right)^2 \left(\frac{35 \text{ MeV}}{m_{\tilde{\nu}_1}} \right)^4$$

How can we test this?

- No collider constraints
- Not visible in Z, h or meson decays
- No direct detection (from electron scattering):

$$\sigma_e \approx 3 \times 10^{-46}\ \mathrm{cm}^2 \left(\frac{195\ \mathrm{GeV}}{m_{\tilde{e}}}\right)^4$$

- No usual indirect detection signal:
  dominant annihilation is to low energy neutrinos

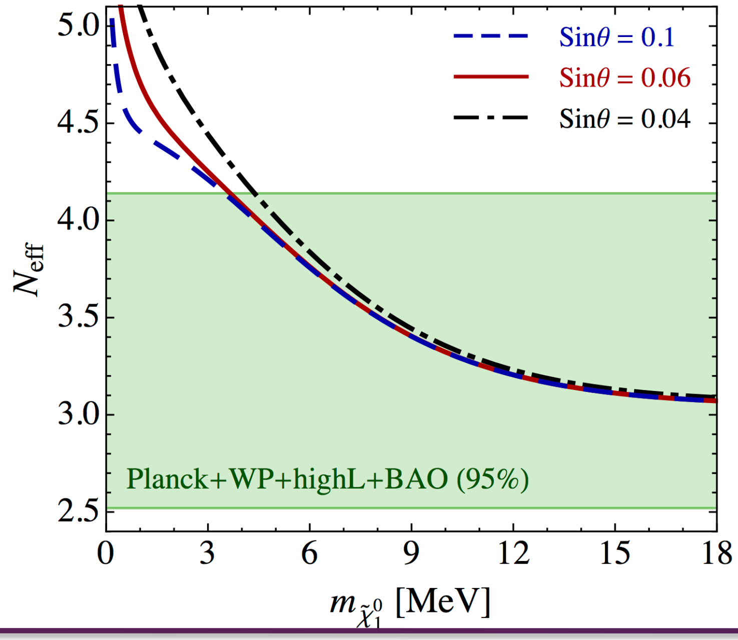
Is this WIMP invisible?

Consequence: N_{eff} is larger

- Recall: Higher neutrino temperature increases N_{eff}

$$N_{\text{eff}} = 3.046 \left[\frac{T_\nu}{T_\gamma} \bigg/ \left(\frac{4}{11} \right)^{1/3} \right]^4$$

- We now have a way to probe a light neutralino



Conclusions

- WIMPs can be light
  ...need a light mediator
- Usual detection strategies may fail
  ...direct/indirect/collider
- Can still have observable consequences
  ...BBN and CMB are sensitive probes of new physics