WIMP less Dark Matter

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Outline

- The WIMPless “Miracle” and AMSB
- A simple Abelian model: SQED
- Cosmological implications and observables

The WIMP miracle

$$\Omega_X \propto \frac{1}{\langle \sigma_{\rm an} v \rangle} \sim \frac{m_X^2}{g_X^4}$$

$$g_X \sim g_{\rm weak} \sim 0.6$$

$$m_X \sim m_{\rm weak} \sim 100 \text{ GeV} - 1 \text{ TeV}$$

$$\Omega_X \sim 0.1$$

T WIMPLESS iracle

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$$m_X \sim m_{\rm weak} \sim 100 \text{ GeV} - 1 \text{ TeV}$$

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WIMPless Dark Matter with AMSB

- In AMSB, SUSY breaking gaugino masses scale like

$$m_\chi \sim \frac{bg^2}{16\pi^2} M_{3/2} \qquad \beta(g) = \frac{b}{16\pi^2} g^3$$

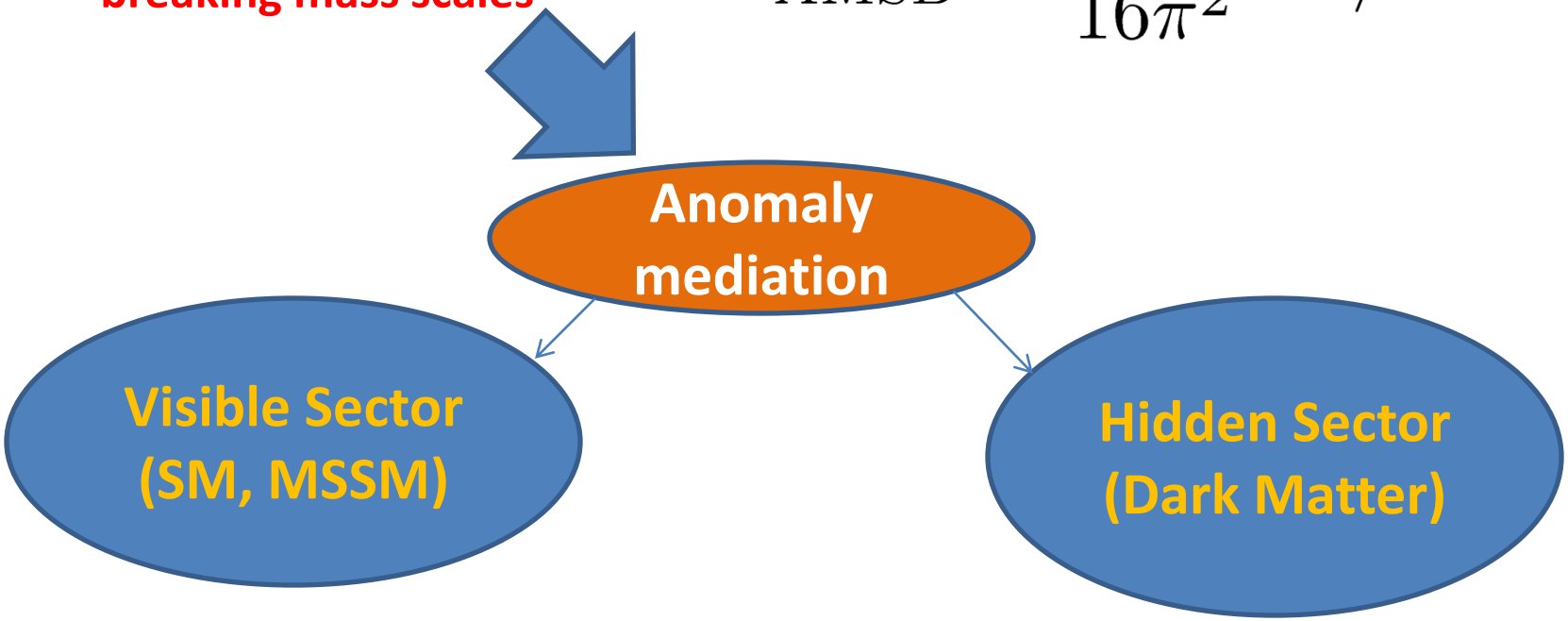
- Scalar masses scale like

$$m_\phi^2 = \frac{bg^4}{16\pi^2} M_{3/2}^2$$

Hidden Sectors

Dictates size of SUSY breaking mass scales

$$m_{\rm AMSB}^{\rm soft} \sim \frac{g^2}{16\pi^2} M_{3/2}$$



$$M_{3/2} \sim 100 \text{ TeV}$$

Hidden Sector and Visible Sector AMSB masses

$$m_{\rm AMSB}^{\rm soft} \sim \frac{g^2}{16\pi^2} M_{3/2} \qquad M_{3/2} \sim 100 \text{ TeV}$$

$$\Omega_X \propto \frac{1}{\langle \sigma_{\rm an} v \rangle} \sim \frac{m_X^2}{g_X^4}$$

Hidden Sector

Visible Sector

$$\frac{m_X}{g_X^2} \sim \frac{1}{16\pi^2} M_{3/2} \sim \frac{m_{\rm weak}}{g_{\rm weak}^2}$$

Is the Dark Matter mass set just by the AMSB mass?

What if you have a μ -term?

$$\tilde{m}_{\rm phys} \sim \frac{g^2}{16\pi^2} M_{3/2} + \mu$$

We hope that… $$\mu \sim \frac{g'^2}{16\pi^2} M_{3/2}$$

$$\tilde{m}_{\rm phys} \sim \frac{g^2}{16\pi^2} f(R) M_{3/2} \qquad R = \frac{g'^2}{g^2} = \frac{\mu}{m_{\rm AMSB}}$$

$$R \sim \mathcal{O}(1)$$

$$\Omega_X \propto \frac{1}{\langle \sigma_{\rm an} v \rangle} \sim \frac{m_X^2}{g_X^4} \sim f(R) M_{3/2}$$

- In addition to the right ratio of mass to couplings, the Hidden Sector needs a thermal bath to get freeze-out of the thermal relic
- This thermal bath contributes to the light degrees of freedom g* which is constrained at CMB and BBN
- Usually parameterized as effective number of neutrinos

$$\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM}$$

$$\Delta N_{\rm eff} = 0.19 \pm 1.2 \ (95\% \ {\rm CL}) \ {\rm BBN}$$

$$\Delta N_{\rm eff} = 1.29^{+0.86}_{-0.88} \ (68\% \ {\rm CL}) \ {\rm CMB}$$

Model: SQED with N_f flavors

$U(1)$ gauge symmetry, photon γ, photino $\tilde{\gamma}$

N_f chiral electron superfields $\hat{e}^+$

N_f chiral electron superfields $\hat{e}^-$

$$b = 2N_f$$

$$W = \mu \hat{e}_i^+ \hat{e}_i^-$$

$$m_{\tilde{\gamma}} = b \frac{g^2}{16\pi^2} M_{3/2}$$

$$m_{e_i} = |\mu|$$

$$m^2_{\tilde{e}_{i\,1,2}} = \left[|\mu|^2 - 2b \left(\frac{g^2}{16\pi^2} M_{3/2} \right)^2 \right]^{1/2}$$

$$N_f, \mu/m_{\tilde{\gamma}}$$

Spectrum

$$N_f, \mu/m_{\tilde{\gamma}}$$

$$M_{3/2}$$

$$b = 2N_f$$

Visible sector **Hidden Sector**

MSSM Superpartners

$$m_{\tilde{\gamma}} = b\frac{g^2}{16\pi^2}M_{3/2}$$

SM particles

$$m_{e_i} = |\mu|$$

$$m^2_{\tilde{e}_{i\,1,2}} = \left[|\mu|^2 - 2b\left(\frac{g^2}{16\pi^2}M_{3/2}\right)^2\right]^{1/2}$$

SM Photon

$$m_\gamma = 0$$

Dark Photon

Spectrum

$$N_f, \mu/m_{\tilde{\gamma}}$$

$$M_{3/2}$$

$$b = 2N_f$$

Visible sector | **Hidden Sector**

MSSM Superpartners

$$m_{\tilde{\gamma}} = b\frac{g^2}{16\pi^2}M_{3/2}$$

Charged!

SM particles

$$m_{e_i} = |\mu|$$

$$m^2_{\tilde{e}_{i\,1,2}} = \left[|\mu|^2 - 2b\left(\frac{g^2}{16\pi^2}M_{3/2}\right)^2\right]^{1/2}$$

SM Photon

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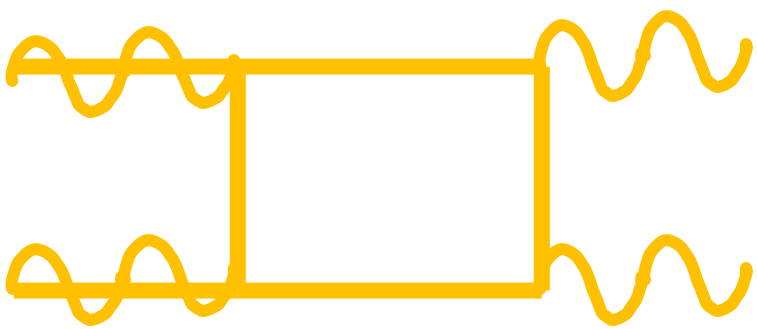
Dark Photon

Annihilation Processes

$$e_i^+ e_i^- \to \gamma\gamma$$

$$\tilde{e}_i^+ \tilde{e}_i^- \to \gamma\gamma$$

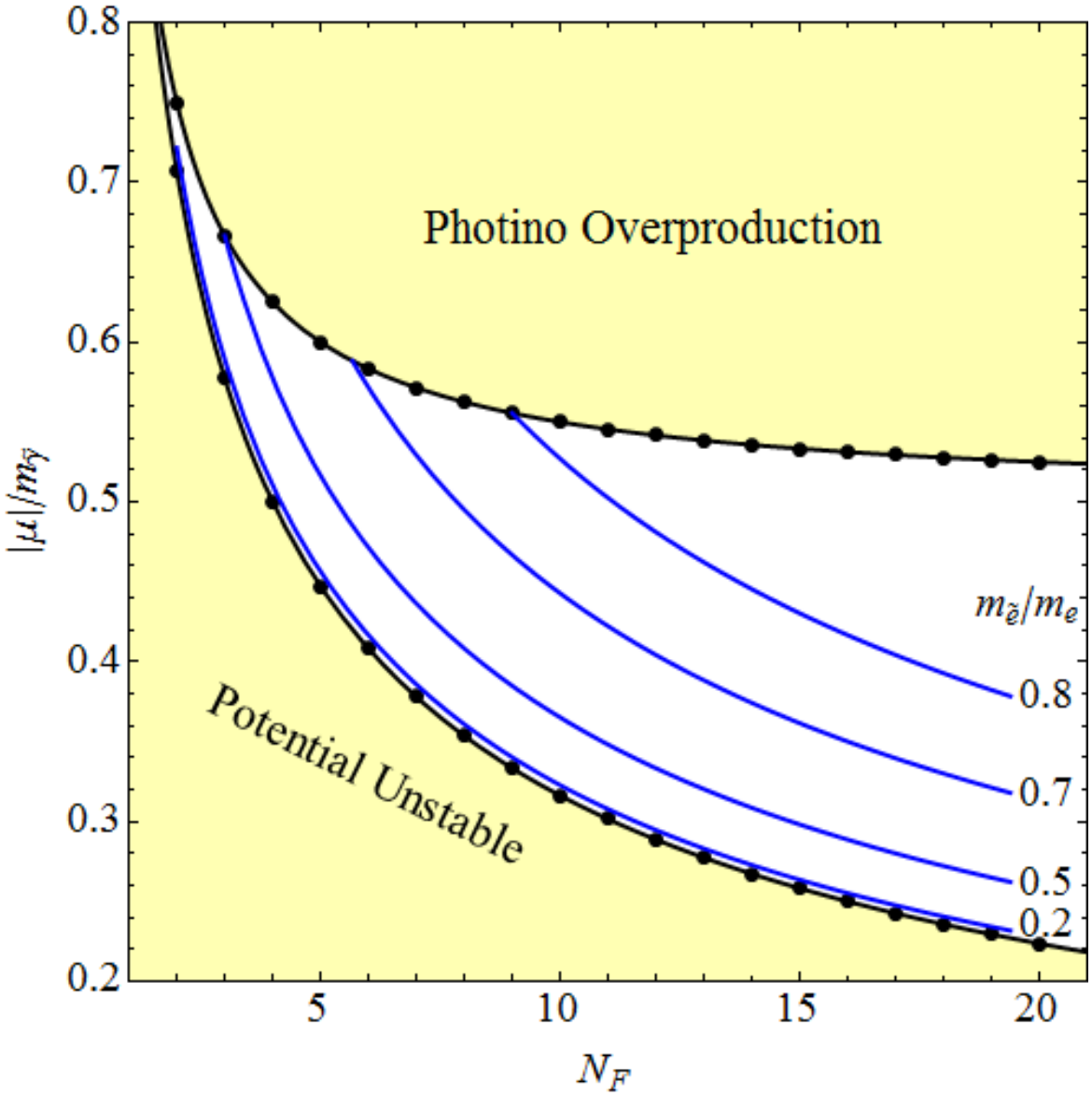
$$\tilde{\gamma}\tilde{\gamma} \to \gamma\gamma$$



Photino not a good WIMPless relic!

$$\sigma \propto \left(\frac{g^2}{16\pi^2}\right)^2 \frac{g^4}{m^2}$$

Ratio of selectron and electron masses



- Dark matter is made up of both electrons and selectrons protected by charge, flavor symmetry
- Halos are like a plasma, so the long range force is actually screened (Debye screening length)
- Dark force! Constraints from self interacting dark matter
- Dark photon contributes to the light degrees of freedom (g* or $\Delta N_{\rm eff}$) at CMB and BBN
- Relic Density fixed by $M_{3/2}$ at each point in the parameter space

Relic Density

$$\sigma_{\rm an} v \approx \sigma_0 \equiv k_X \frac{\pi \alpha_X^2}{m_X^2}$$

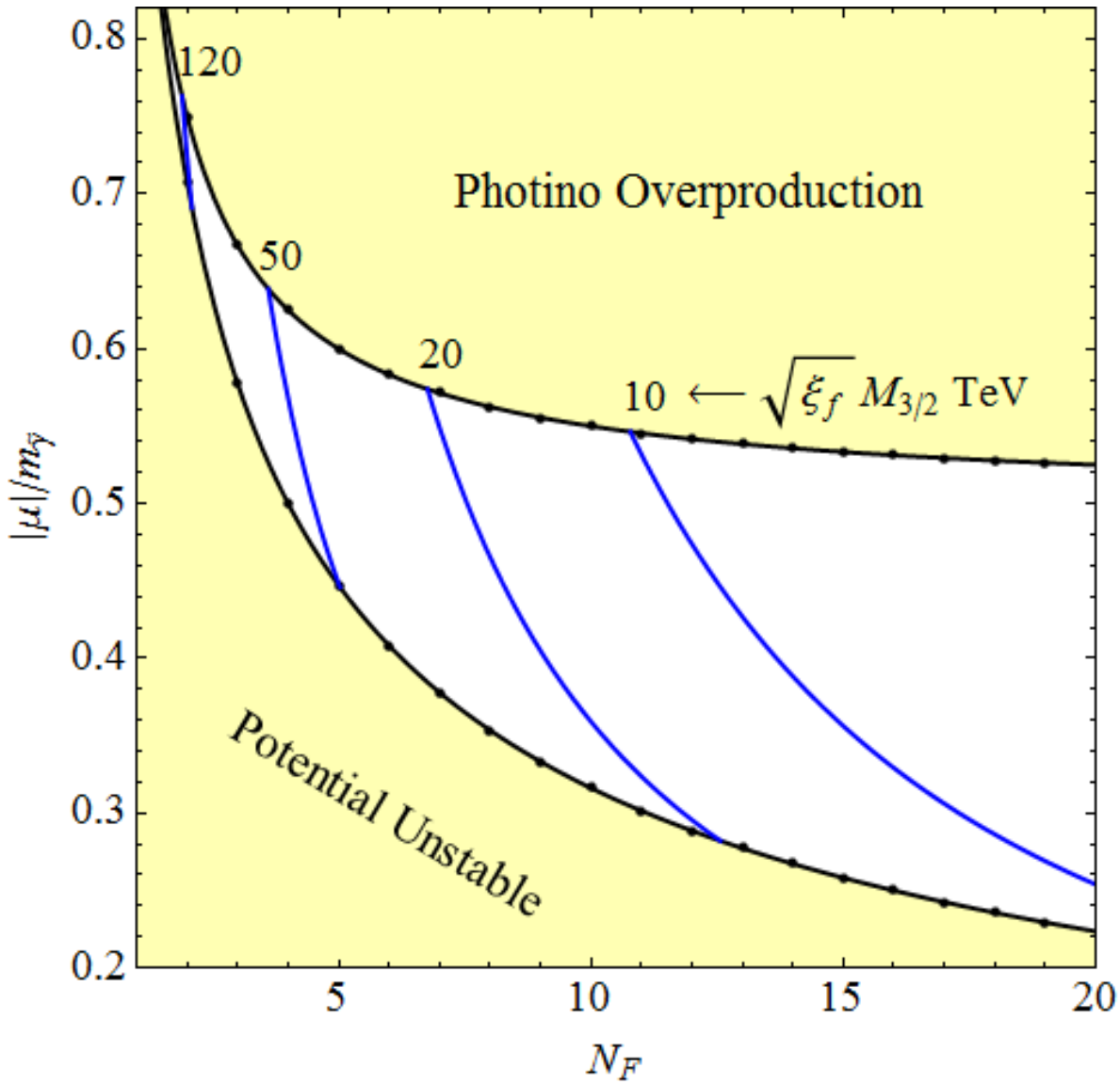
$$\Omega_X \approx \xi_f \frac{0.17 \text{ pb}}{\sigma_0} \simeq 0.23\, \xi_f \frac{1}{k_X} \left[\frac{0.025}{\alpha_X} \frac{m_X}{\text{TeV}} \right]^2$$

(Assuming s-wave annihilation)

$$\xi_f = \frac{T_f^h}{T_f^{\rm vis}}$$

$$\Omega_X = 0.23 \mathcal{F} \left(N_F, \frac{|\mu|^2}{m_{\tilde{\gamma}}^2} \right) \left(\frac{\sqrt{\xi_f}\, M_{3/2}}{100 \text{ TeV}} \right)^2$$

Gravitino Mass… ?



What determines $\xi_f = \frac{T_f^h}{T_f^{\rm vis}}$?

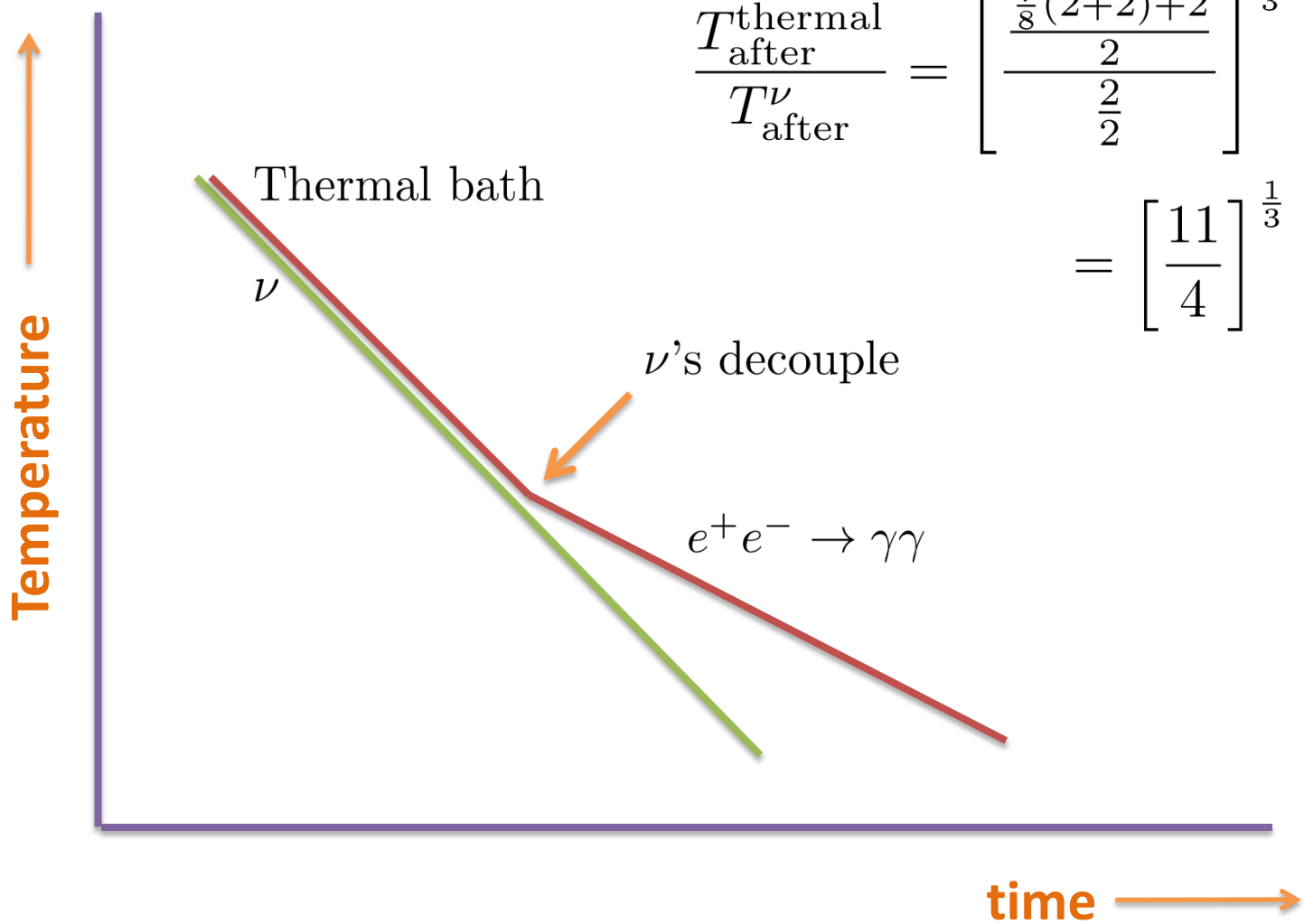
- Reheating might heat both sectors differently
- Or we could assume both sectors were in thermal contact in the early universe

$$\frac{T_f^h}{T_f^{\rm vis}} = \left[\frac{\frac{g_*^{\rm h}(T_\infty^{\rm h})}{g_*^{\rm h}(T_f^{\rm h})}}{\frac{g_*^{\rm h}(T_\infty^{\rm v})}{g_*^{\rm h}(T_f^{\rm v})}} \right]^{\frac{1}{3}} \frac{T_\infty^h}{T_\infty^{\rm vis}}$$

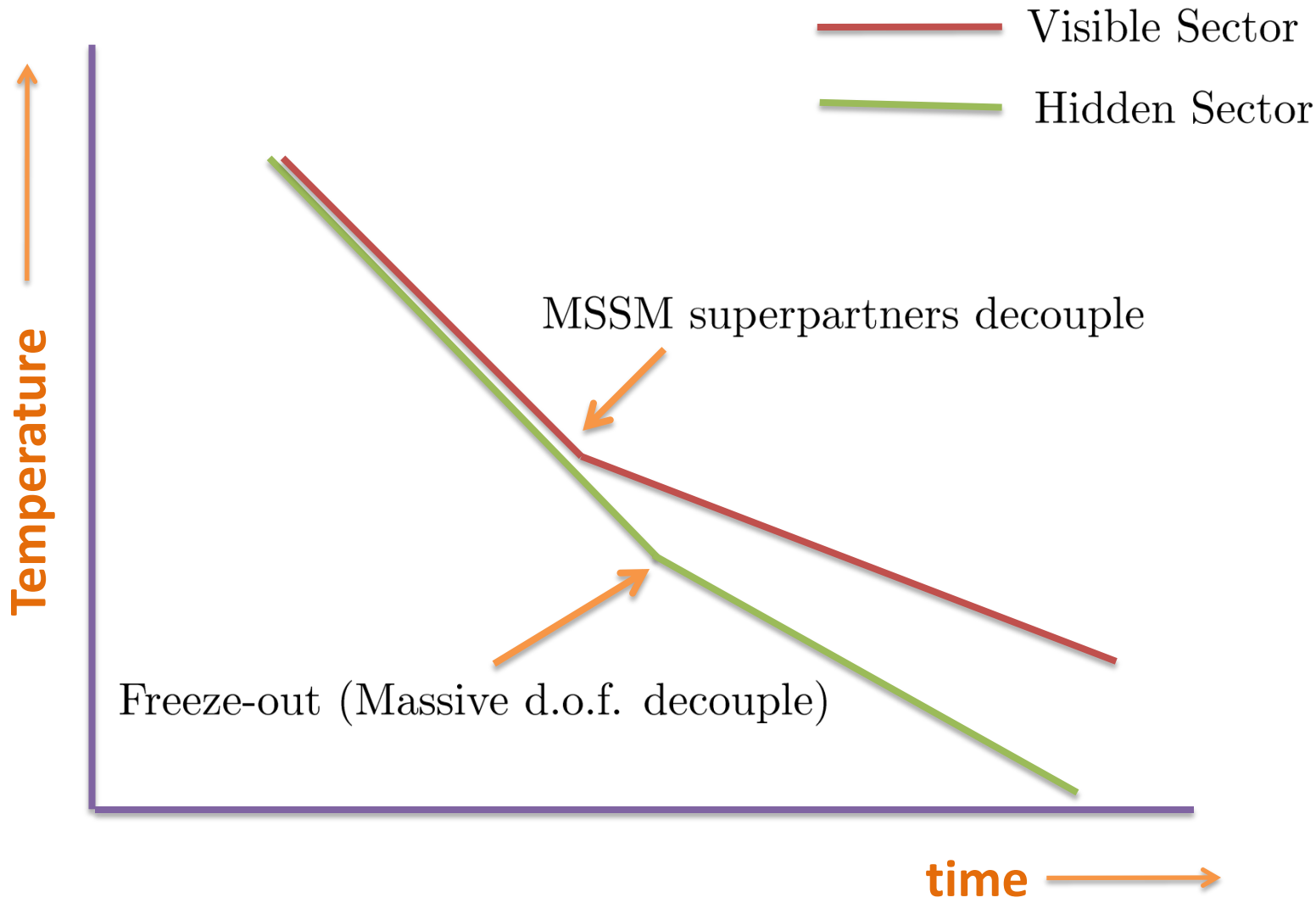
Energy dumping in the SM

$$\frac{T^{\text{thermal}}_{\text{after}}}{T^{\nu}_{\text{after}}} = \left[\frac{\frac{\frac{7}{8}(2+2)+2}{2}}{\frac{2}{2}}\right]^{\frac{1}{3}} \frac{T^{\text{thermal}}_{\text{before}}}{T^{\nu}_{\text{before}}}$$

$$= \left[\frac{11}{4}\right]^{\frac{1}{3}} \frac{T^{\text{thermal}}_{\text{before}}}{T^{\nu}_{\text{before}}}$$



Energy dumping



Spectrum

$$N_f, \mu/m_{\tilde{\gamma}}$$

$$M_{3/2}$$

$$b = 2N_f$$

Visible sector **Hidden Sector**

MSSM Superpartners

$$m_{\tilde{\gamma}} = b\frac{g^2}{16\pi^2}M_{3/2}$$

SM particles

$$m_{e_i} = |\mu|$$

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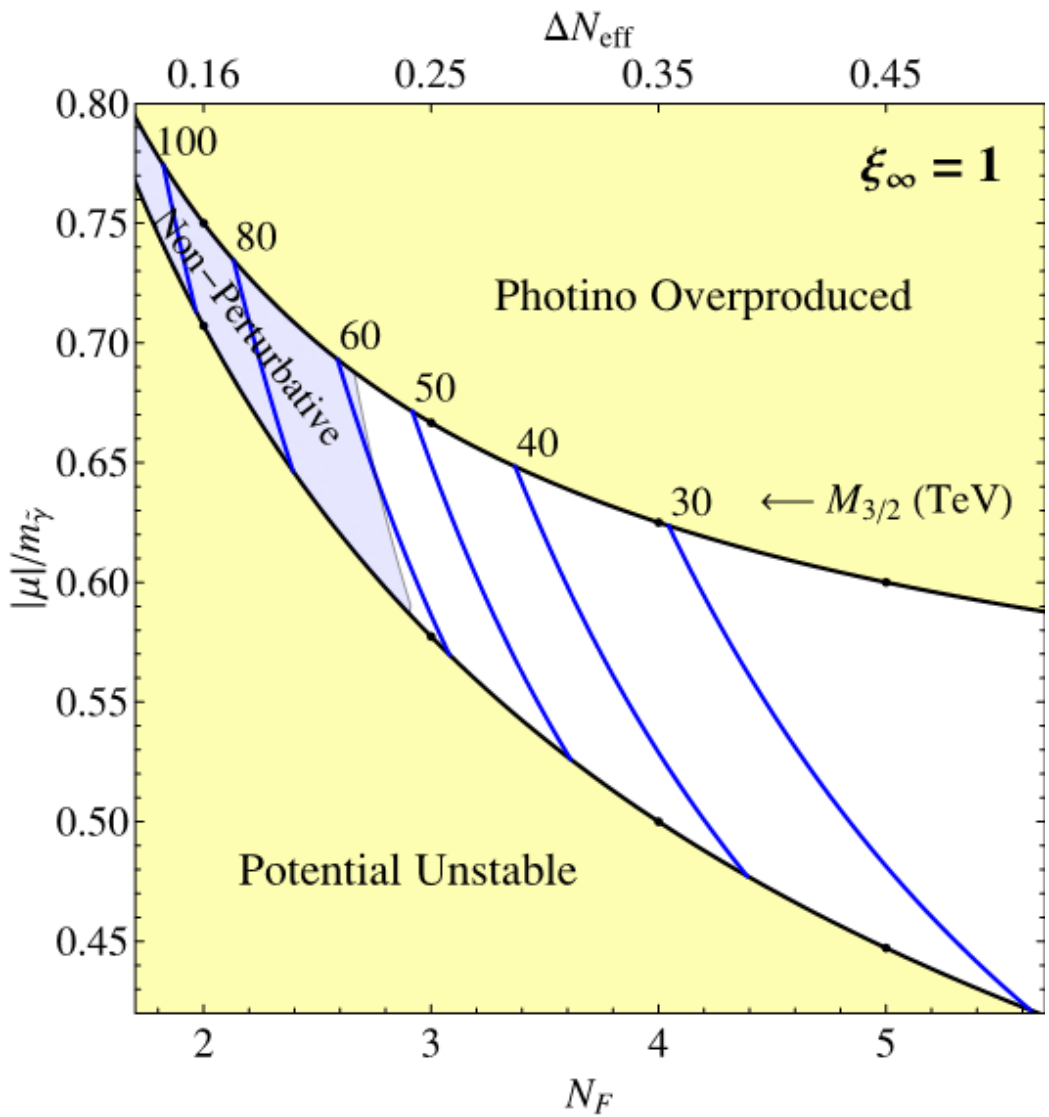
SM Photon

$$m_\gamma = 0$$

Dark Photon

Gravitino mass*



* With assumptions of a desert

Effective number of neutrinos

$$\Omega_{\rm DR} \propto g_*^{\rm h}(T_{\rm CMB}^{\rm h}){T_{\rm CMB}^{h}}^4$$

$$\Omega_\nu \propto g_*^\nu(T_{\rm CMB}^\nu){T_{\rm CMB}^{\nu}}^4$$

$$\propto \frac{7}{8}2N_\nu\left[\frac{4}{11}\right]^{\frac{4}{3}}{T_{\rm CMB}^{\rm vis}}^4$$

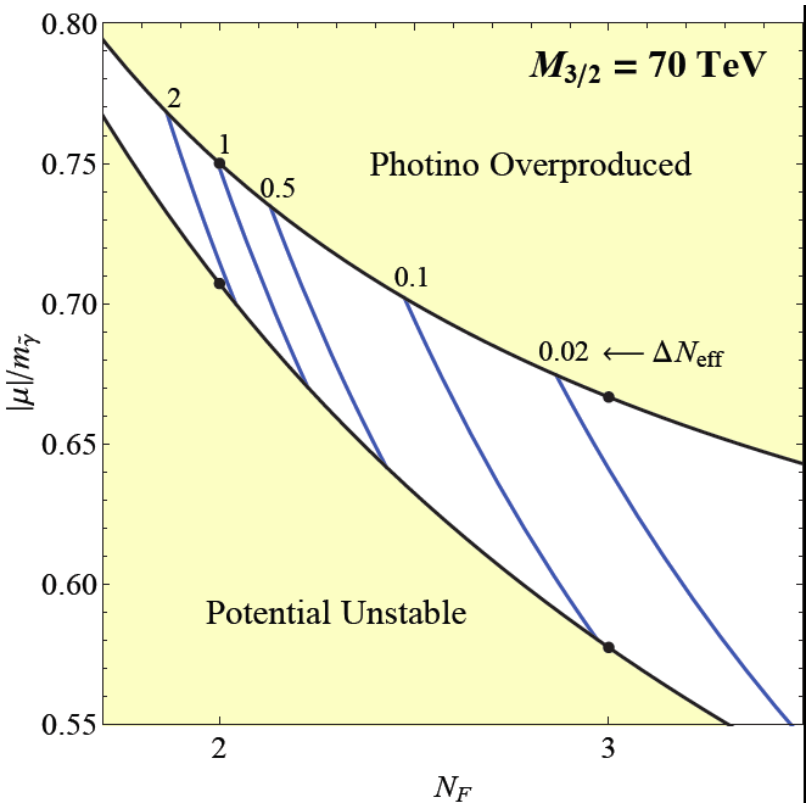
$$\boxed{\Delta N_{\rm eff} = \left(\frac{\xi_f}{2.60}\right)^4\left[\frac{106.75}{g_*^{\rm v}(T_f^{\rm v})}\right]^{\frac{4}{3}}}$$

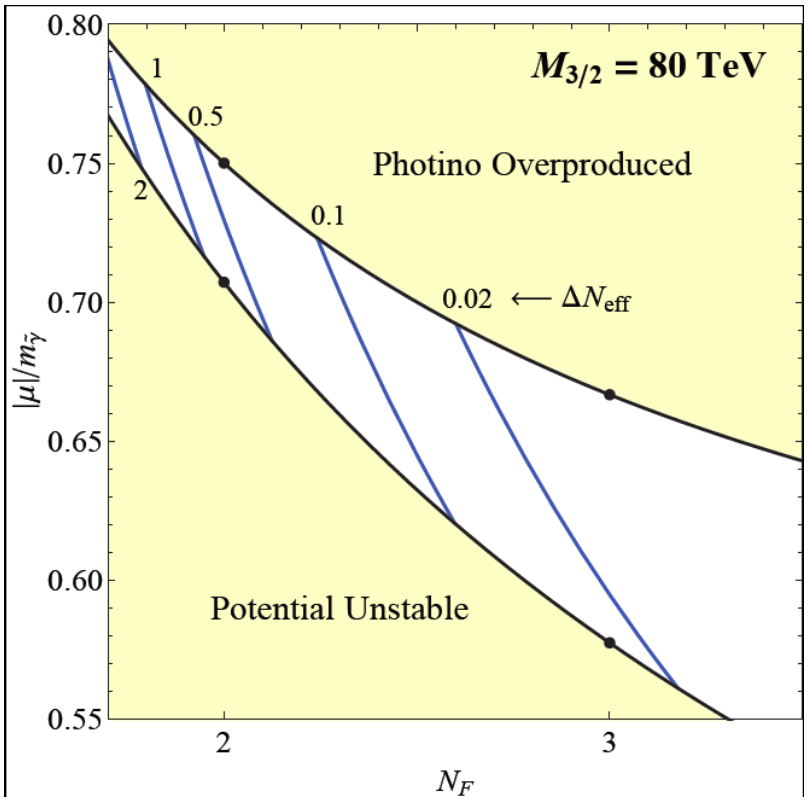
(in general)

$$\Delta N_{\rm eff} = 0.20\left(\frac{N_F + \frac{8}{15}}{3}\right)^{\frac{4}{3}}\xi_\infty^4$$

(With the assumption of a desert)

Effective number of neutrinos





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Self interaction constraints

- Dark matter in halos is an ionic plasma of positively and negatively charged electrons and selectrons
- Strongest self interaction constraint is from halo shapes of dwarf galaxies
- Elliptical halos would become spherical if the dark matter particles could exchange an O(1) fraction of their energy

Self interaction constraint

$$\tau_{\rm r} \simeq \frac{m_X^3 v_0^3}{4\sqrt{\pi}\alpha_X^2 \rho_X C}$$

Relaxation time for halos

$$\tau_{\rm r} \simeq 9.0 \times 10^9 \ {\rm yr} \left(\frac{m_X}{\rm TeV}\right)^3 \left(\frac{0.01}{\alpha_X}\right)^2 \frac{90}{C}$$

Requiring this to be greater than the age of the universe:

$$\tau_{\rm r} > 10^{10} \ {\rm yr}$$

$$m_{e_i} > m_{\rm DM}^{\rm min} \equiv \left[\frac{6.6}{N_F\,(\mu/m_{\tilde{\gamma}})}\right]^2 \left(\frac{100 \ {\rm TeV}}{M_{3/2}}\right)^2 {\rm TeV}$$

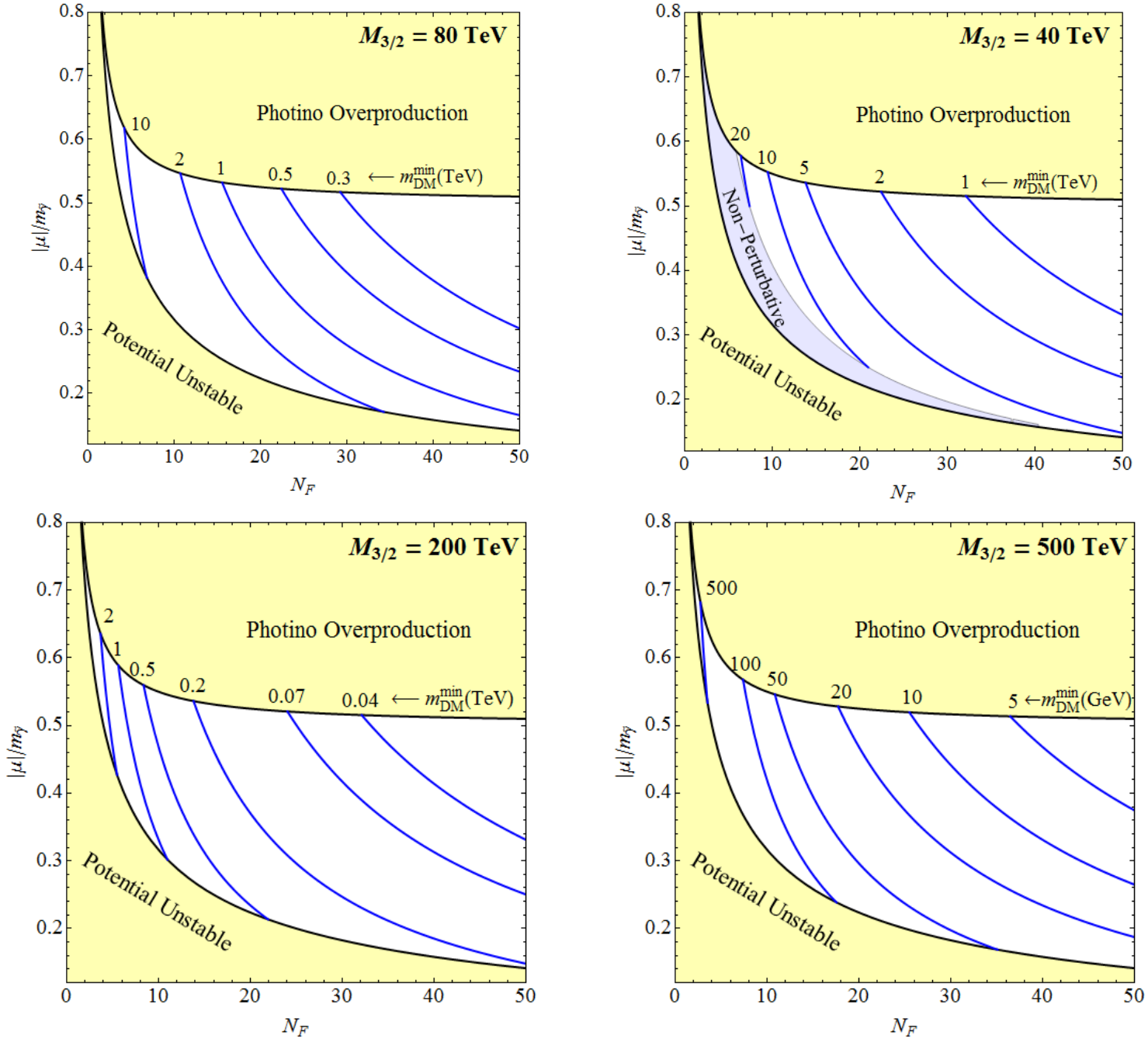
or $\alpha > \alpha_{\rm min}$

Perturbativity constraint

$$m_{\tilde{\gamma}} < M_{3/2}$$

$$2N_F\alpha_X/(4\pi) < 1$$

- **Perturbativity sets an upper bound on the coupling at each point in the parameter space**
- **Halo shapes sets a lower bound on the coupling at each point in the parameter space**
- **If they are in conflict that region of parameter space is excluded**


$M_{3/2}$ = 80 TeV
Photino Overproduction
Potential Unstable
10
2
1
0.5
0.3
$\longleftarrow m_{DM}^{min}$(TeV)
$M_{3/2}$ = 40 TeV
Photino Overproduction
Non−Perturbative
Potential Unstable
20
10
5
2
1
$\longleftarrow m_{DM}^{min}$(TeV)
$M_{3/2}$ = 200 TeV
Photino Overproduction
Potential Unstable
2
1
0.5
0.2
0.07
0.04
$\longleftarrow m_{DM}^{min}$(TeV)
$M_{3/2}$ = 500 TeV
Photino Overproduction
Potential Unstable
500
100
50
20
10
5
$\leftarrow m_{DM}^{min}$(GeV)
$|\mu|/m_{\tilde{\gamma}}$
N_F

Summary and conclusions

- WIMPless dark matter suggests a larger range of dark matter masses and couplings than previously assumed
- Simple model shows that AMSB WIMPless models are predictive and have a rich phenomenology
- Requirement of freeze out in the Hidden sector requires a long range force
- Leads to a prediction for the effective number of neutrinos
- Constrained/could be further tested by signals of dark matter self interactions

QUESTIONS, COMMENTS, SUGGESTIONS?