Freeze-in Dark Matter from Secret Neutrino Interaction

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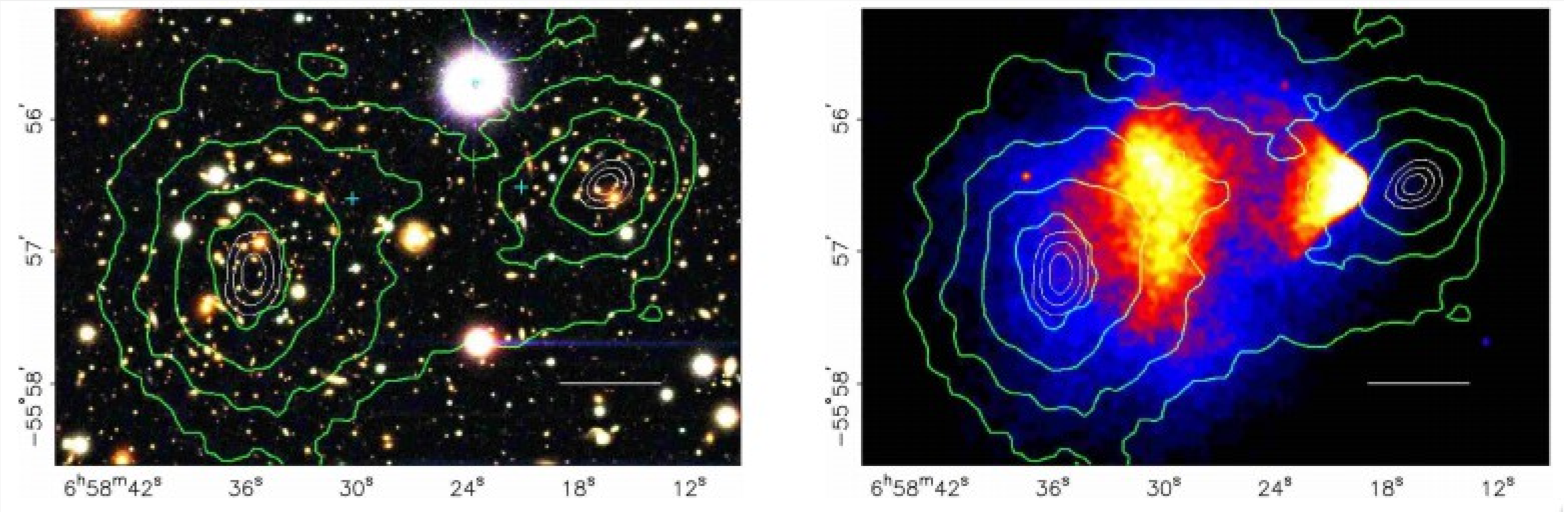
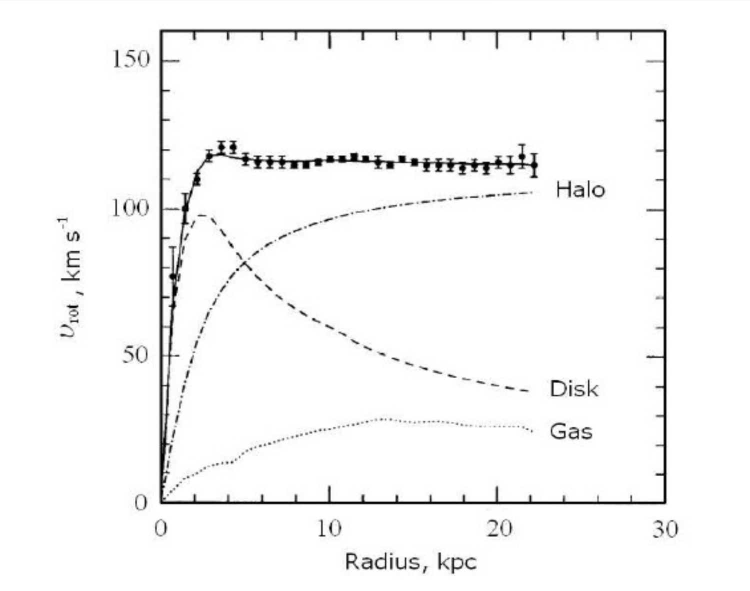
To be appeared 2005.xxxxxx

Evidence for Dark Matter

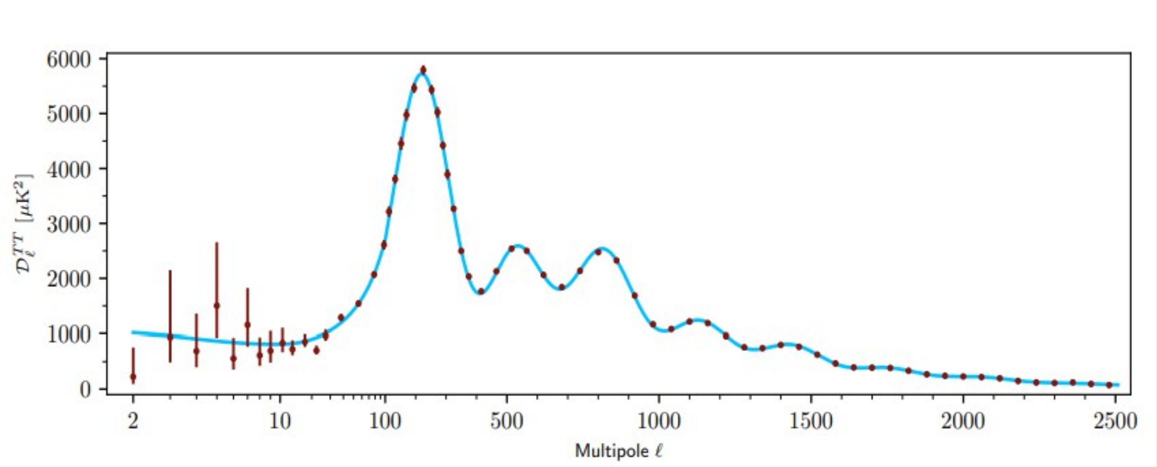


Bullet Cluster

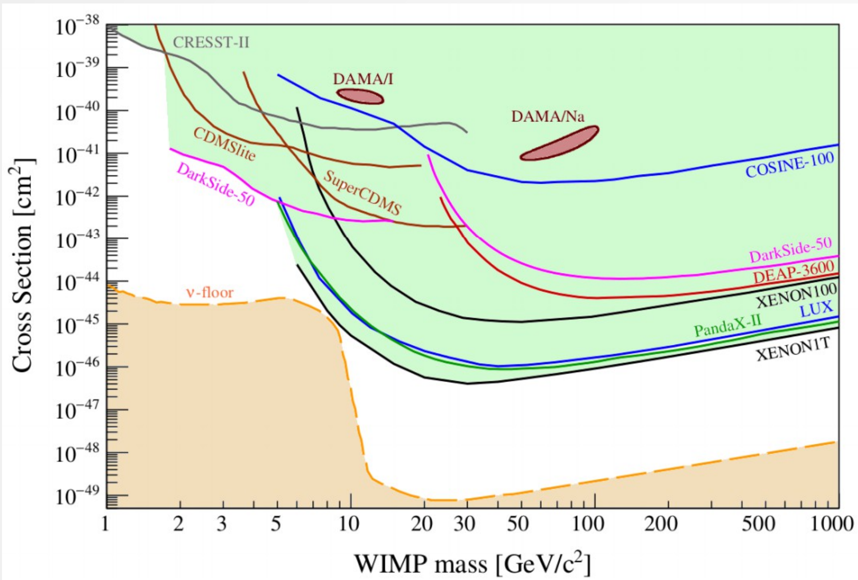
Rotation Curve

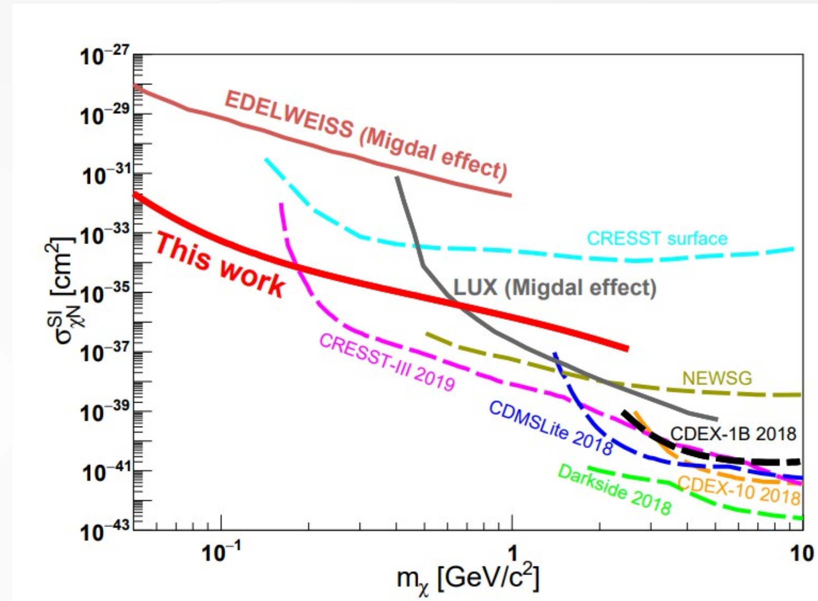


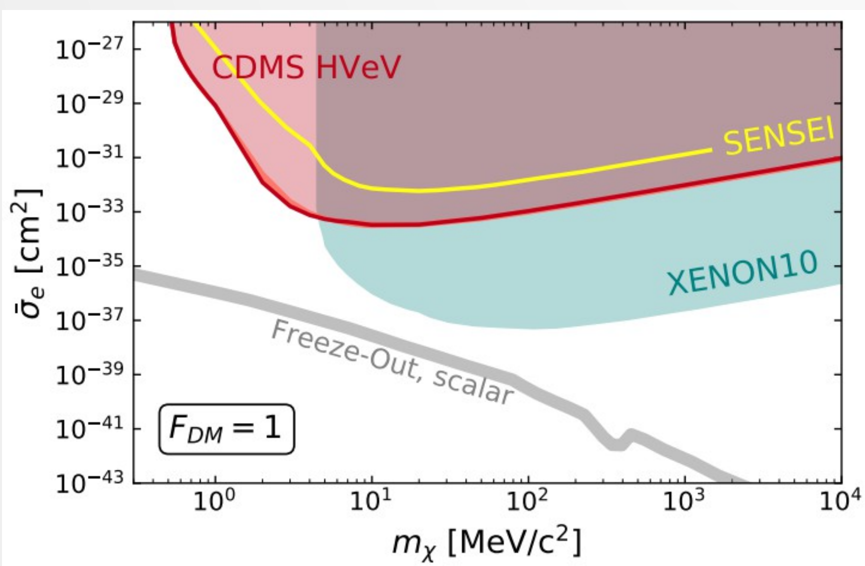
CMB Power Spectrum

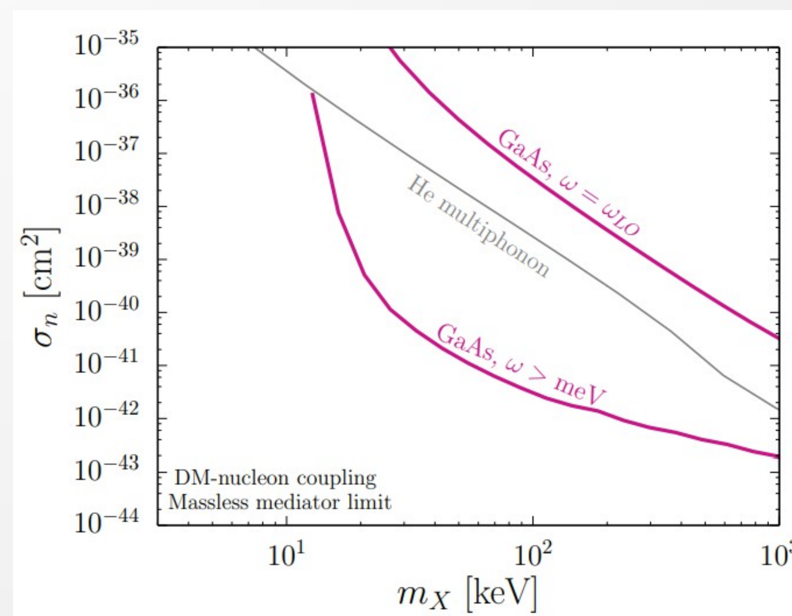


No Evidence From Direct Detections



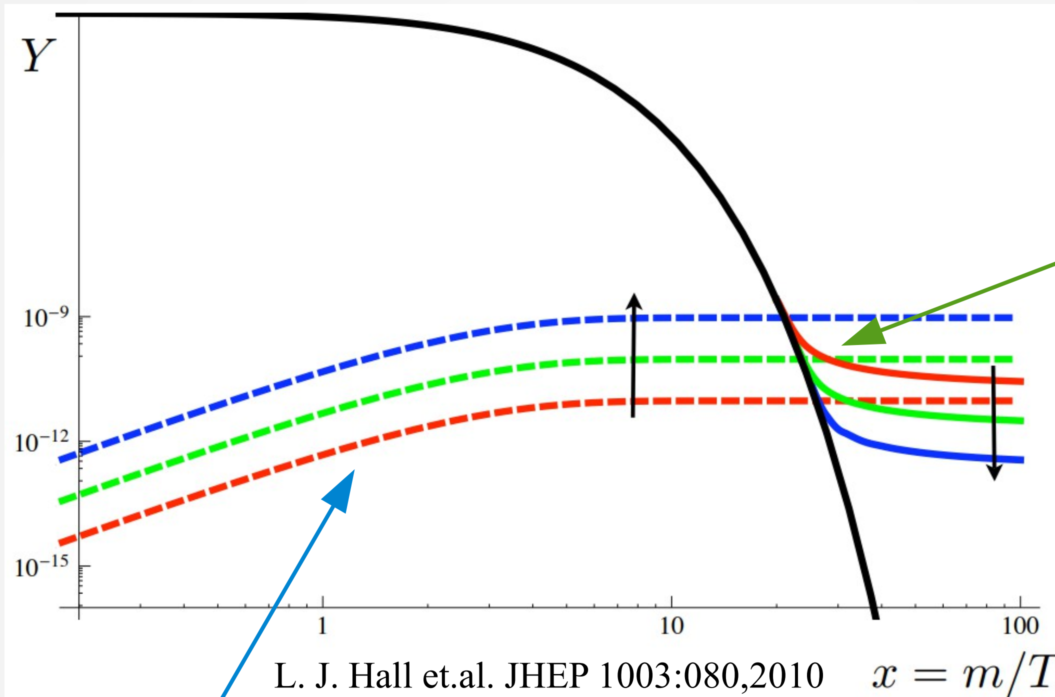






T.-Y. Lin arxiv:1904.07915, Phys. Rev. Lett. 123, 161301 (2019)

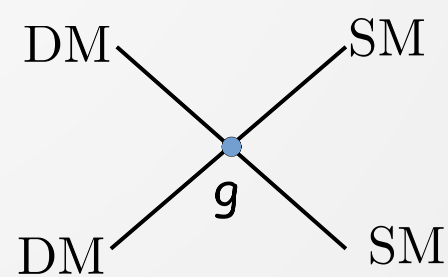
Freeze-In vs Freeze-Out



Freeze-Out:
Thermalize with SM sector
in early universe
With weak scale coupling

Freeze-In:
Never Thermalize with SM sector
With exceedingly small coupling

Small parameters in the SM: $m_\nu / \langle H \rangle$



Neutrino Portal dark matter

Our Simplified Model

Model contents

Dark matter: χ

Light Mediator: ϕ

Similar models are studied in
J.F.Cherry et.al. arxiv:1411.1071,
A. Berlin et.al. Phys. Rev. D99 (2019) 095030,
but with the freeze-out mechanism

$$\mathcal{L}_{\rm int} = \begin{cases} -g_\chi \phi \bar{\chi}\chi - g_\nu^i \phi \bar{\nu}_i \nu_i & \text{(Scenario I)}, \\ -i\bar{g}_\chi \phi \bar{\chi}\gamma^5 \chi - i\bar{g}_\nu^i \phi \bar{\nu}_i \gamma^5 \nu_i & \text{(Scenario II)}. \end{cases}$$

Two Possible UV completions that generate tiny $g_\nu, \ \bar{g}_\nu$

Type-I Seasaw + light scalar

$$\mathcal{L}_{\rm int} \supset g_{ji} \bar{L}_j \tilde{H} N_i + g_\phi \overline{N_i^c} N_i \phi + h.c.$$

$$\frac{1}{M_N^2} \phi (\bar{L}\tilde{H})(\tilde{H}^T L^c),$$

$$g_\nu \phi \bar{\nu} \nu \text{ with } g_\nu \sim \frac{v^2}{M_N^2},$$

Minimal Majoron Model

$$\mathcal{L}_{\rm int} \supset g_\Phi \overline{N^c} N \Phi - g_H \overline{L} \tilde{H} N + h.c.$$

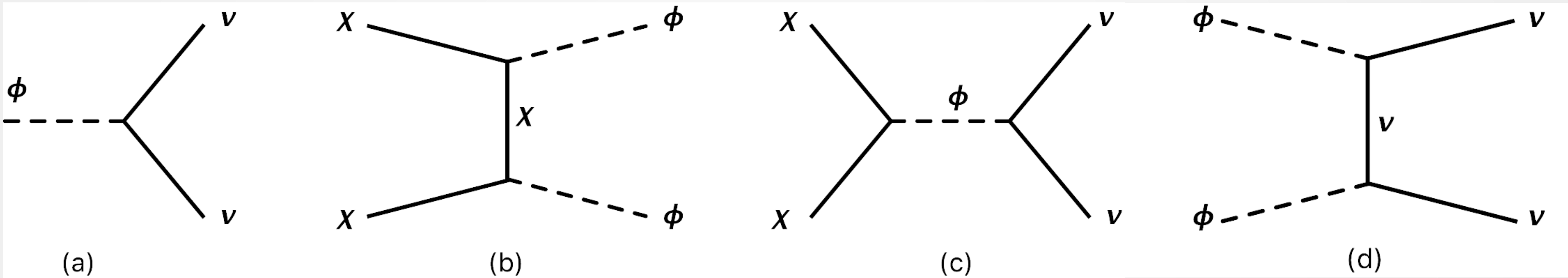
$$\Phi = \varphi + v_\Phi + i\phi$$

$$i \frac{g_\Phi g_H^2}{M_N^2} \phi (\overline{L}\tilde{H}) \gamma^5 (\tilde{H}^T L^c)$$

$$i\bar{g}_\nu \bar{\nu} \gamma^5 \nu \phi \text{ with } \bar{g}_\nu \sim \frac{v^2}{g_\phi^2 v_\Phi^2}$$

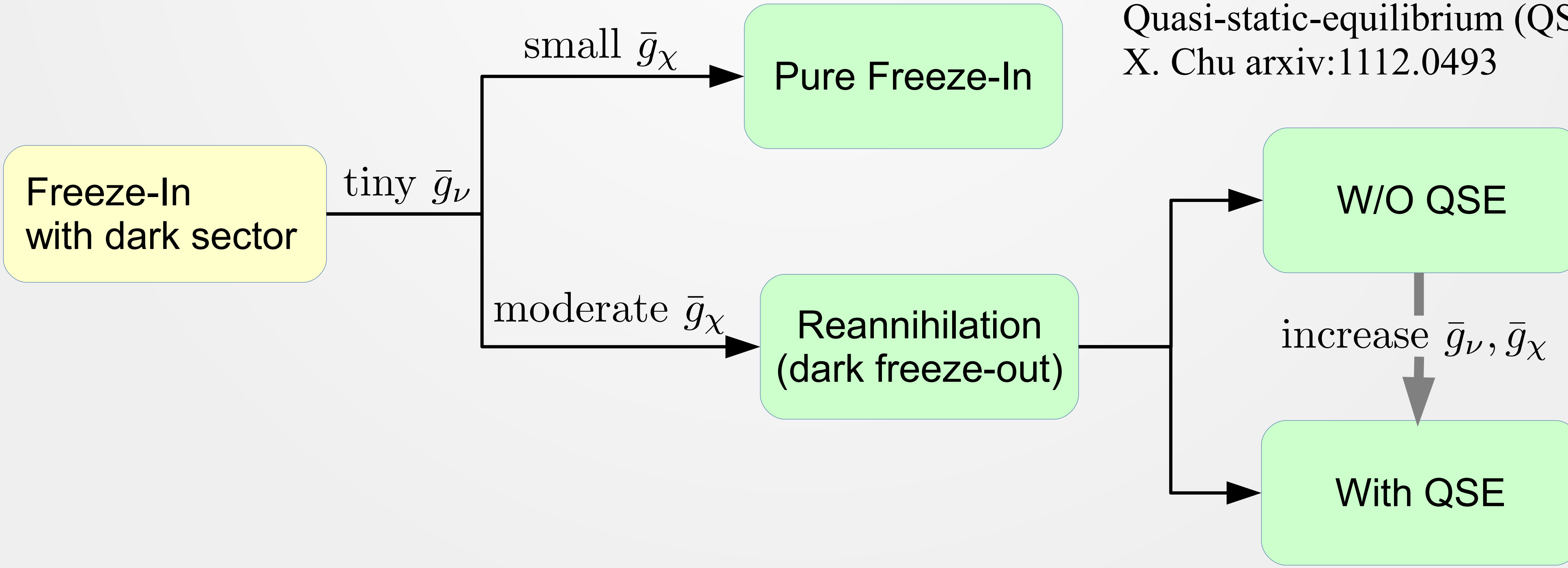
Relic Abundance

Quasi Static Equilibrium (QSE) X. Chu. et. al. JCAP 05 (2012) 034

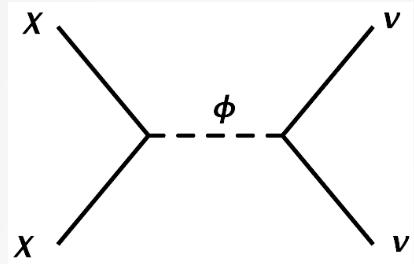


$$\frac{dn_\chi}{dt} = -3Hn_\chi - \left(n_\chi^2 - n_\chi^{\text{eq}}(T)^2\right)\langle\sigma_{\chi\chi\to\nu\nu}v\rangle_T - n_\chi^2\langle\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi} + n_\phi^2\langle\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi}$$

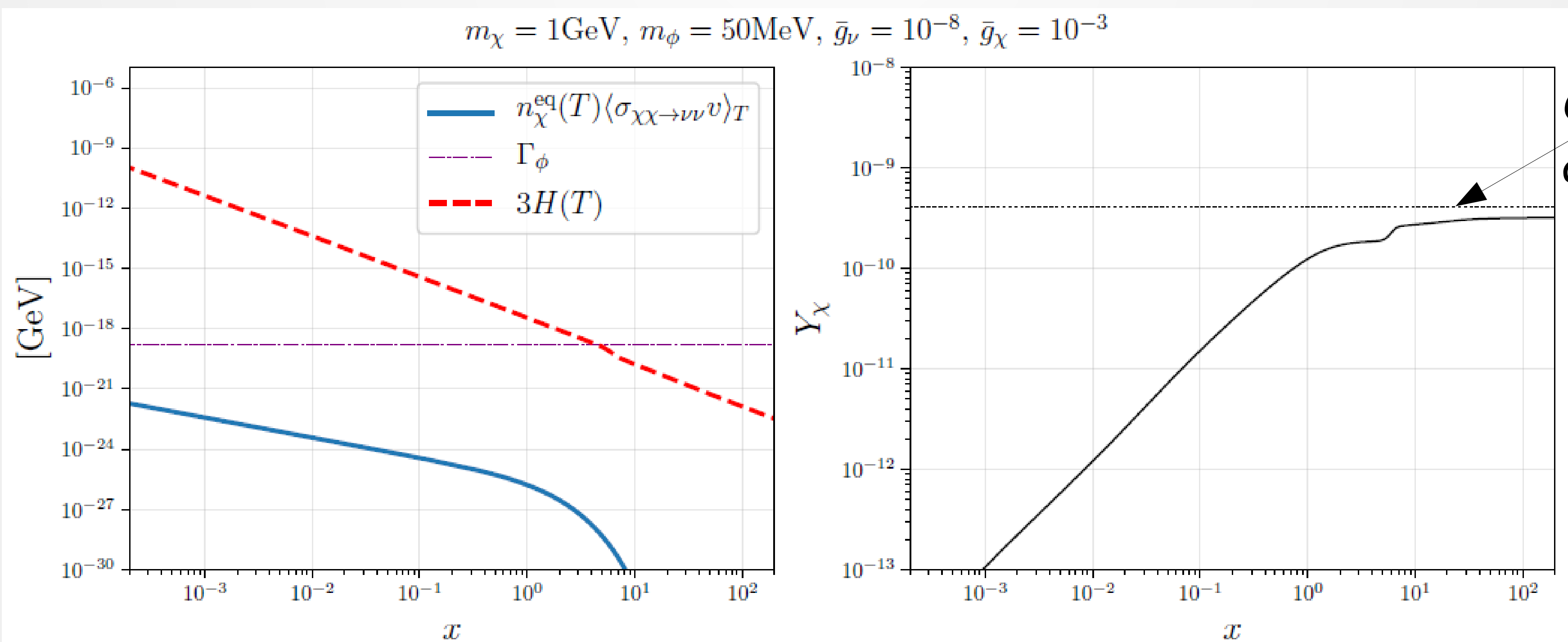
Quasi-static-equilibrium (QSE) X. Chu arxiv:1112.0493



Relic Abundance: Pure Freeze-In

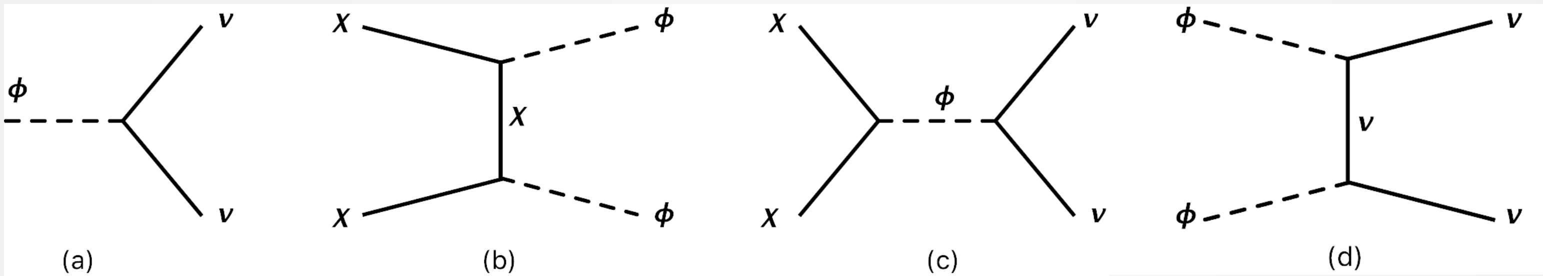


$$\frac{dn_\chi}{dt} = -3Hn_\chi + \left(n_\chi^{\text{eq}}(T)^2 - n_\chi^2\right)\langle\sigma_{\chi\chi\to\nu\nu}v\rangle_T - n_\chi^2\langle\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi} + n_\phi^2\langle\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi}$$



$$x = \frac{m_\chi}{T}$$

Relic Abundance: Reannihilation w/o QSE

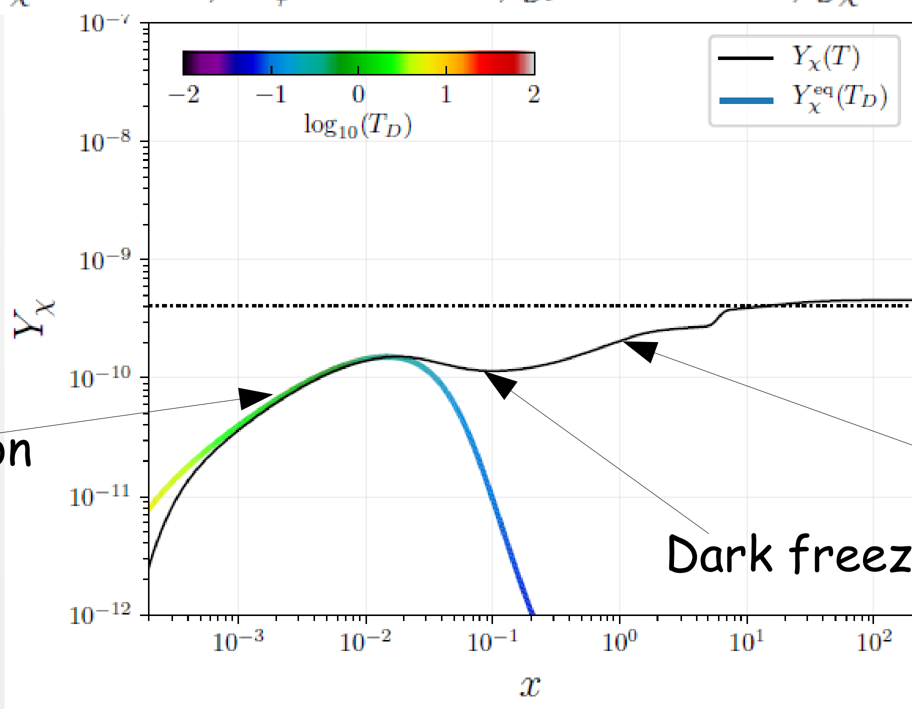


$$\frac{dn_\chi}{dt} \approx -3Hn_\chi + n_\chi^{\rm eq}(T)^2\langle\sigma_{\chi\chi\to\nu\nu}v\rangle_T - \left(n_\chi^2 - n_\chi^{\rm eq}(T_D)^2\right)\langle\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_D}$$

$$\frac{d\rho_D}{dt} = -3H(P_D+\rho_D) + 2n_\nu^{\rm eq}(T)^2\mathcal{P}_{\nu\nu\to\chi\chi}(T) + 2n_\nu^{\rm eq}(T)^2\mathcal{P}_{\nu\nu\to\phi\phi}(T) + n_\nu^{\rm eq}(T)^2\mathcal{P}_{\nu\nu\to\phi}(T) - n_\phi\mathcal{P}_{\phi\to\nu\nu}(T_D)$$

$$\rho_D(t) \to T_D(t)$$

$$m_\chi = 1\text{GeV},\ m_\phi = 50\text{MeV},\ \bar{g}_\nu = 8\times10^{-10},\ \bar{g}_\chi = 1.2\times10^{-2}$$



Dark Thermalization

Dark freeze out

Residual Freeze-In

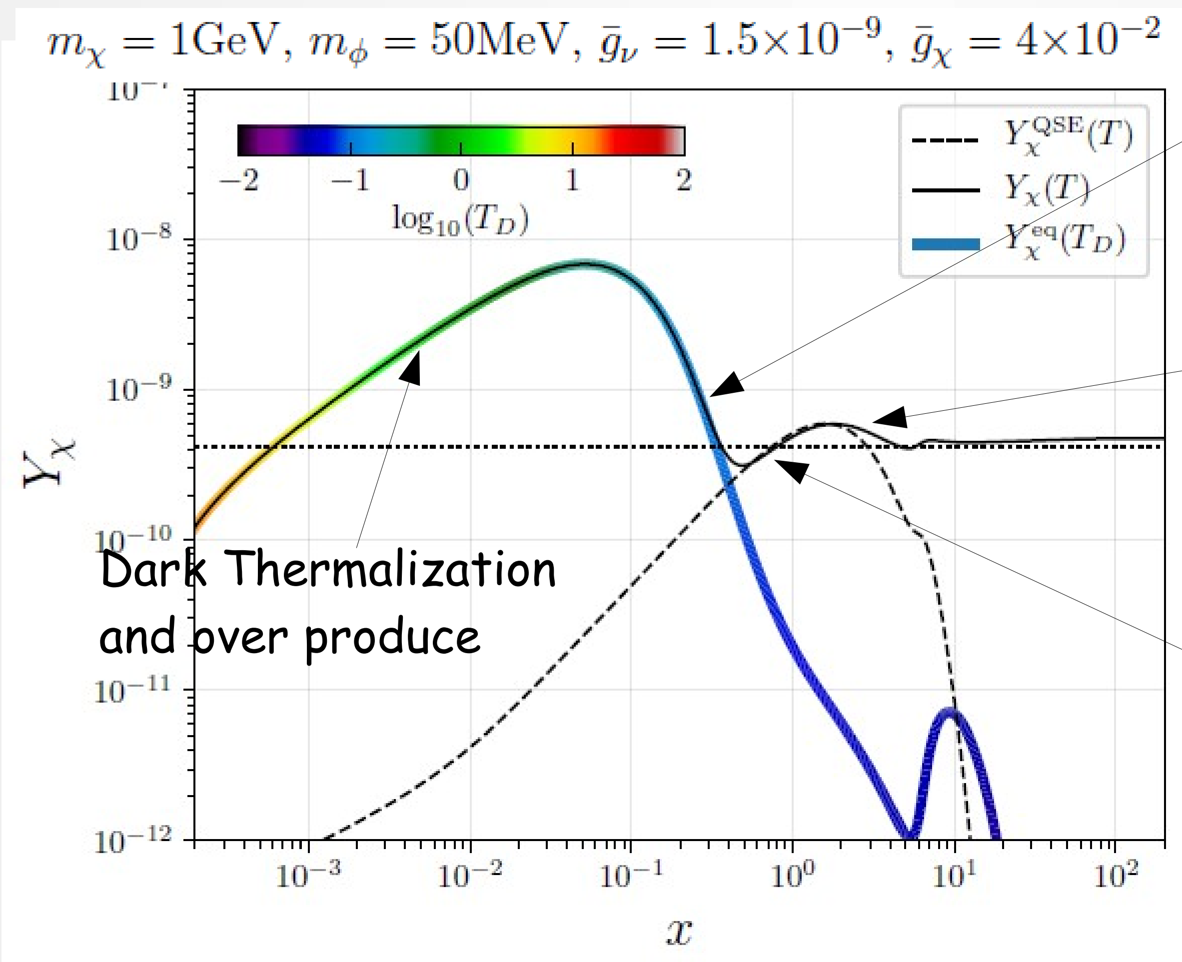
$$x = \frac{m_\chi}{T}$$

Relic Abundance: Reannihilation w QSE

$$\frac{dn_\chi}{dt} \approx -3Hn_\chi + n_\chi^{\rm eq}(T)^2\langle\sigma_{\chi\chi\to\nu\nu}v\rangle_T - \left(n_\chi^2 - n_\chi^{\rm eq}(T_D)^2\right)\langle\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_D}$$ ← QSE

$$\frac{dY_\chi}{dx} \approx \frac{s\langle\sigma_{\chi\chi\to\nu\nu}\rangle_T}{xH}Y_\chi^{eq2} - \frac{s\langle\sigma_{\chi\chi\to\phi\phi}\rangle}{xH}Y_\chi^2$$

$$Y_\chi(T) \approx Y_\chi^{\rm QSE}(T) \equiv Y_\chi^{\rm eq}(T)\sqrt{\frac{\langle\sigma_{\chi\chi\to\nu\nu}v\rangle_T}{\langle\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_D}}}$$



DM become non-relativistic

Dark freeze out from QSE

QSE

$$x = \frac{m_\chi}{T}$$

Decay of Mediator and Indirect detection bounds

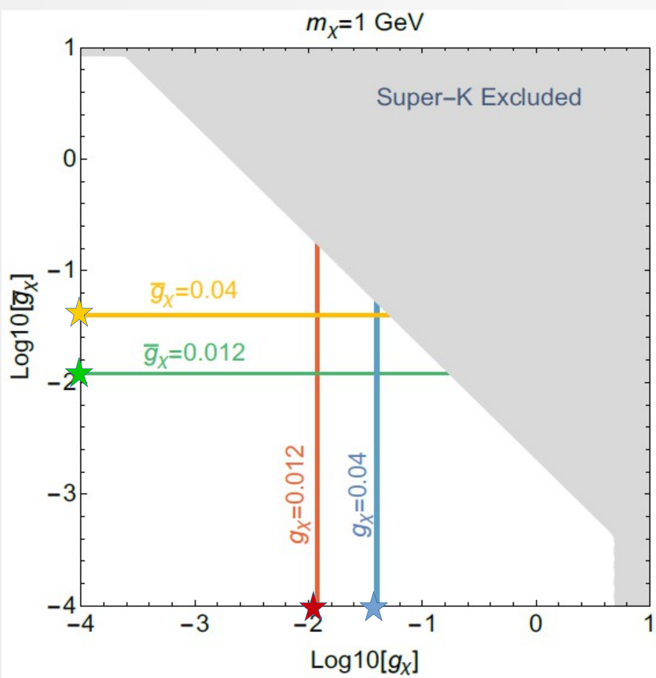
$$\Gamma_\phi \sim H(T_{\rm dec})$$

$$T_{\rm dec} \approx \frac{3\sqrt{\bar{g}_\nu^2 + g_\nu^2}}{4\sqrt{2}\pi}\left(\frac{10}{g_\star(T_{\rm dec})}\right)^{1/4}\left(\frac{m_\phi}{\rm MeV}\right)^{1/2}\left(\frac{M_P}{\rm MeV}\right)^{1/2}\,{\rm MeV}$$
$$\approx 10^{10}\times\sqrt{\bar{g}_\nu^2 + g_\nu^2}\left(\frac{10}{g_\star(T_{\rm dec})}\right)^{1/4}\left(\frac{m_\phi}{\rm MeV}\right)^{1/2}\,{\rm MeV}\ .$$

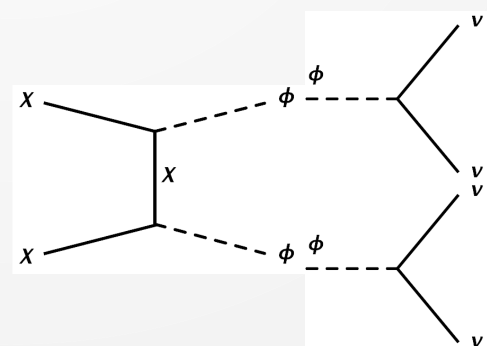
Avoid messing up with the BBN and CMB constraints,

we simply demand the $T_{\rm dec} > m_\phi > 10{\rm MeV}$

and we find $m_\chi = 1{\rm GeV},\ m_\phi = 50{\rm MeV}$ is enough.

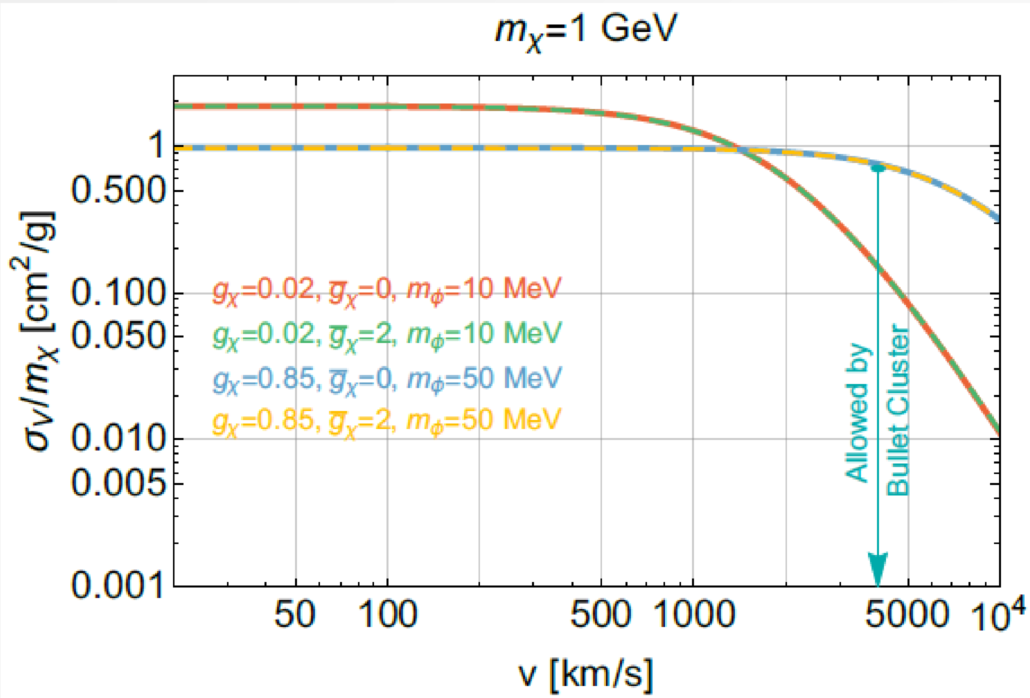


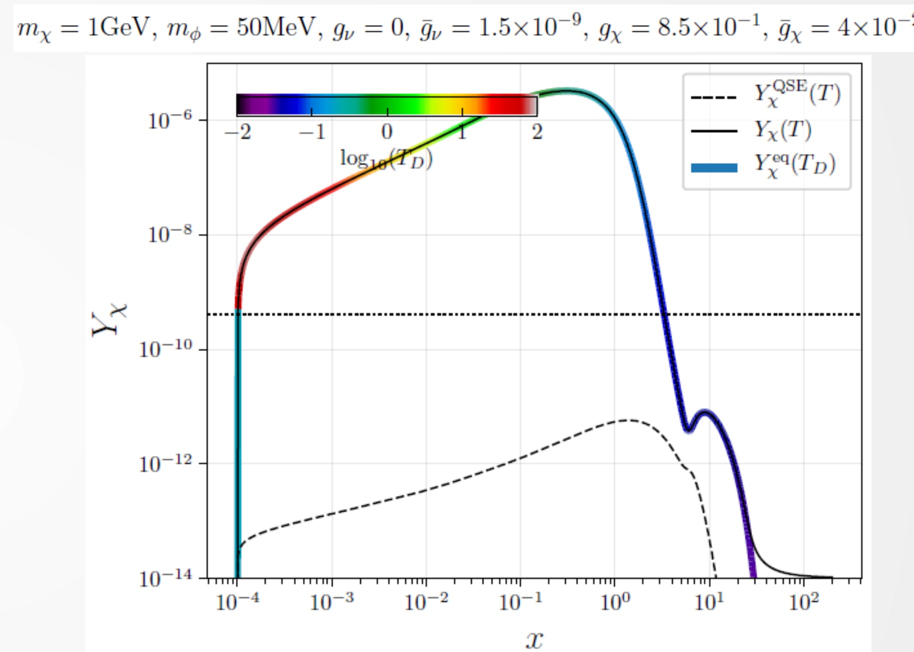
C. A. Argüelles, et.al. Arxiv:1912.09486



Most stringent bound comes from Super-K,
And our benchmarks all suvive from the constraint.

Possible Solution to Small Scale Structure Problems





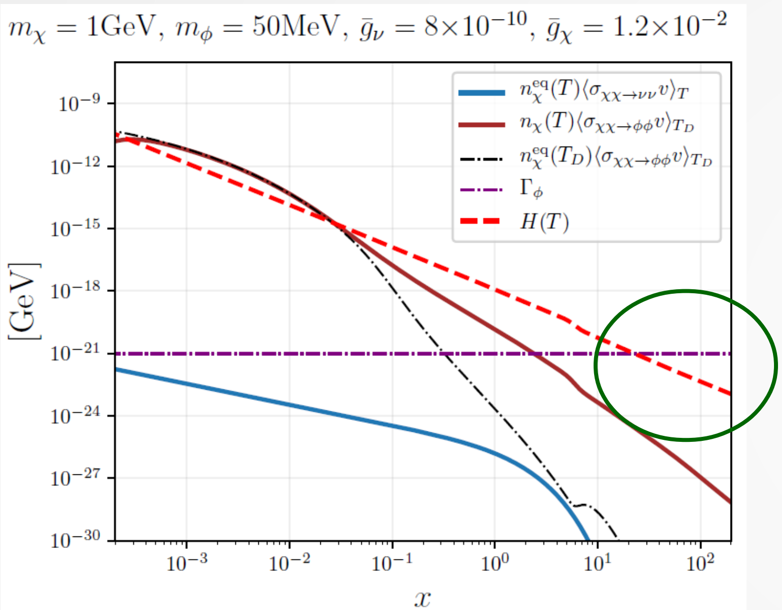
$$\sigma_V \equiv 2\pi \int_0^\pi \frac{d\sigma}{d\Omega}(1-\cos\theta^2)\sin\theta d\theta \qquad \sigma_V \sim \frac{g_\chi^4 m_\chi^2}{6\pi m_\phi^4}$$ in the expansion of small $\frac{m_\phi}{m_\chi}$

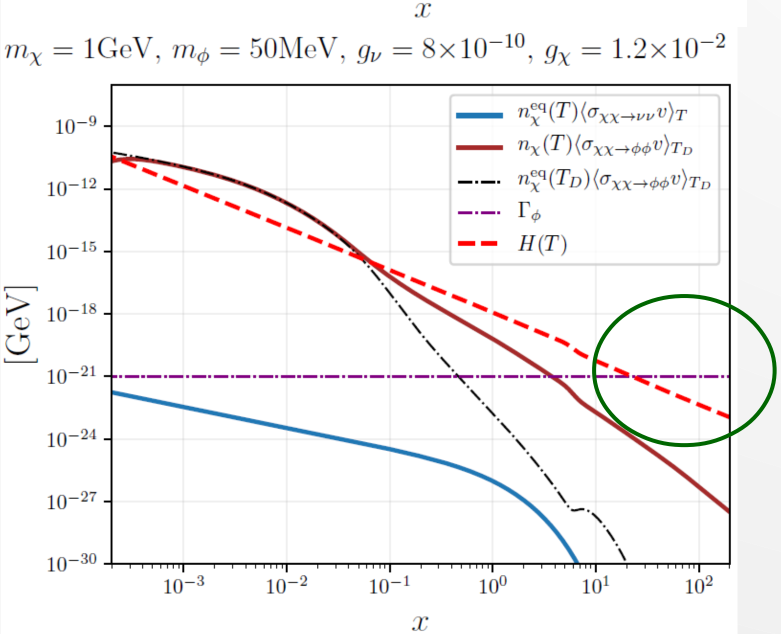
Positive observations	σ/m	v_{rel}
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1$ cm^2/g	30–200 km/s
Too-big-to-fail problem		
Milky Way	$\gtrsim 0.6$ cm^2/g	50 km/s
Local Group	$\gtrsim 0.5$ cm^2/g	50 km/s

H. -B. Yu and S. Tulin /
Physics Reports 730 (2018)

Tension between solving small scale structure problem and satisfing the cosmological constraints found within the Freeze-In scenario

Decay of Mediator and Indirect detection bounds





$$\Gamma_\phi \sim H(T_{\rm dec})$$

$$T_{\rm dec} \approx \frac{3\sqrt{\bar{g}_\nu^2 + g_\nu^2}}{4\sqrt{2}\pi}\left(\frac{10}{g_\star(T_{\rm dec})}\right)^{1/4}\left(\frac{m_\phi}{\rm MeV}\right)^{1/2}\left(\frac{M_P}{\rm MeV}\right)^{1/2}\ {\rm MeV}$$
$$\approx 10^{10}\times\sqrt{\bar{g}_\nu^2 + g_\nu^2}\left(\frac{10}{g_\star(T_{\rm dec})}\right)^{1/4}\left(\frac{m_\phi}{\rm MeV}\right)^{1/2}\ {\rm MeV}\ .$$

In-equilibrium decay:

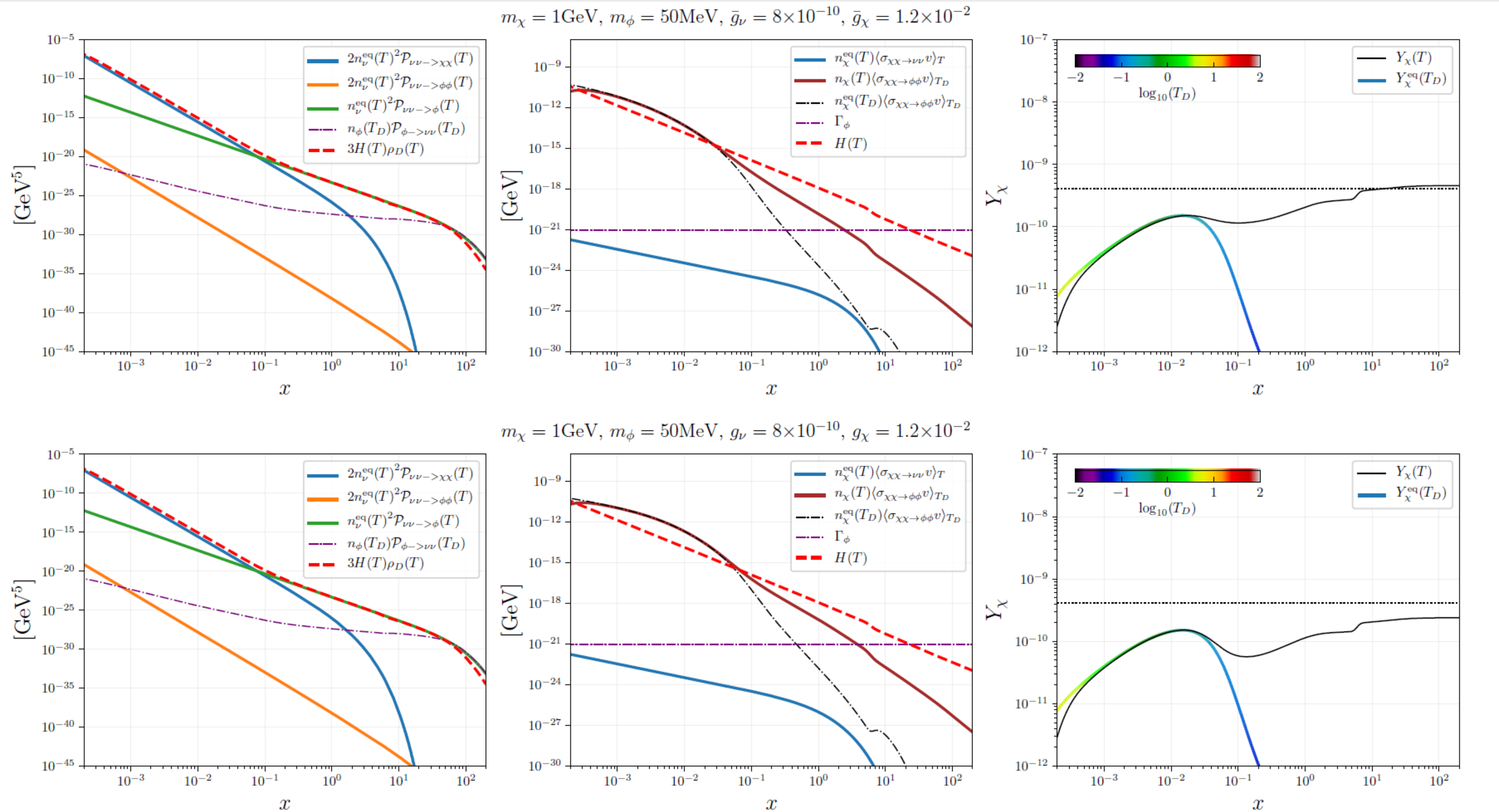
$$T_{\rm dec} > m_\phi > 10\text{MeV}$$

Out-silde-equilibrium decay:

Summary

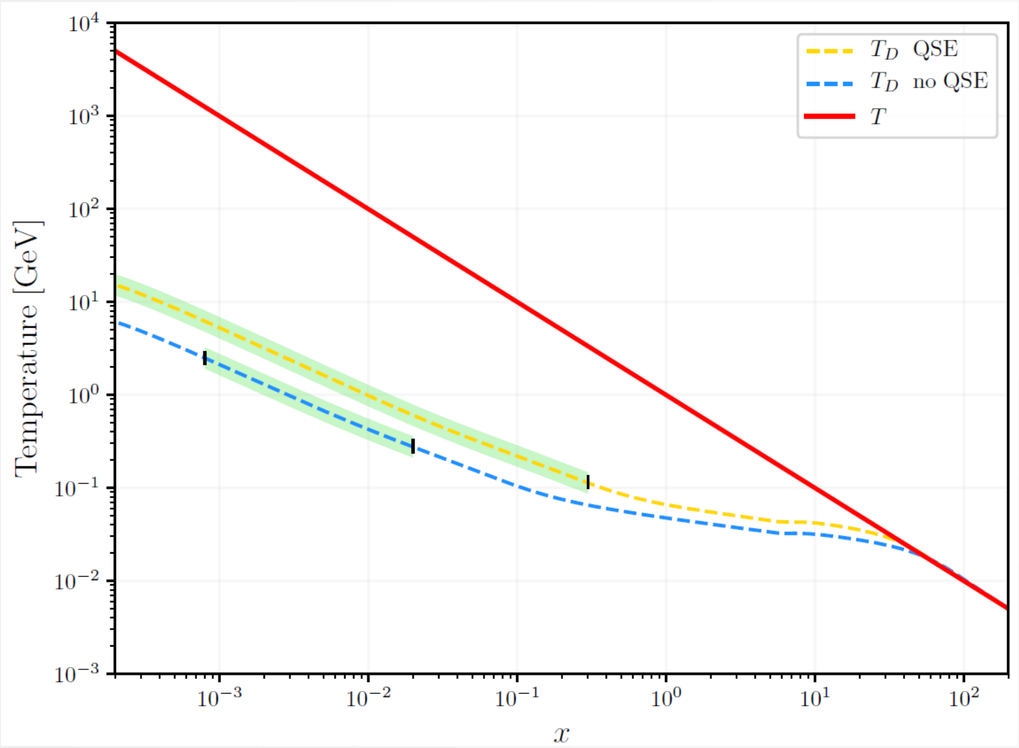
- We point out two UV origin of the samll coupling for neutrino mediator coupling
- We find the benchmark points satisfing the relic abundance with prue freeze-in scenario and reannihilation scenario with and w/o QSE
- We investigate the cosmological and indirect detection constraint
- We find tension for solving small scale structure prolem with staisfing the above constraint.

Backup



m_χ = 1GeV, m_ϕ = 50MeV, ḡ_ν = 8×10^−10, ḡ_χ = 1.2×10^−2
[GeV^5]
2n_ν^eq(T)^2 P_νν−>χχ(T)
2n_ν^eq(T)^2 P_νν−>ϕϕ(T)
n_ν^eq(T)^2 P_νν−>ϕ(T)
n_ϕ(T_D) P_ϕ−>νν(T_D)
3H(T) ρ_D(T)
[GeV]
n_χ^eq(T)⟨σ_χχ→νν v⟩_T
n_χ(T)⟨σ_χχ→ϕϕ v⟩_{T_D}
n_χ^eq(T_D)⟨σ_χχ→ϕϕ v⟩_{T_D}
Γ_ϕ
H(T)
Y_χ
log_10(T_D)
Y_χ(T)
Y_χ^eq(T_D)
x
m_χ = 1GeV, m_ϕ = 50MeV, g_ν = 8×10^−10, g_χ = 1.2×10^−2

Backup



T_D QSE
T_D no QSE
T
Temperature [GeV]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
x