Superheavy Decaying Dark Matter

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Mitchell Conference on
Collider, Dark Matter, and Neutrino Physics 2024

MIFPA, Texas A&M University

May 23-26, 2024

Outline:

- Introduction
- A setup
- An explicit model (high-scale SUSY with RPV):

  - DM relic density

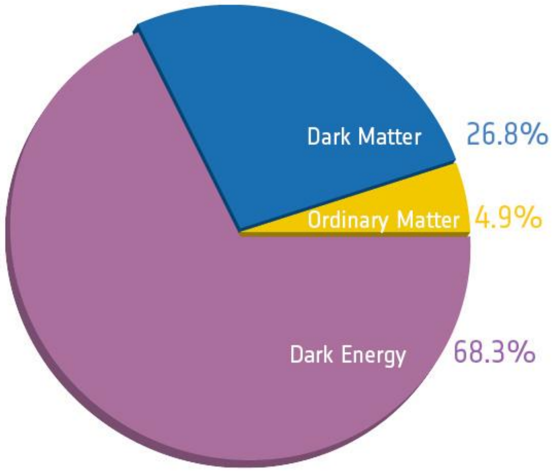
  - Indirect detection signals
- Conclusion & Outlook

Based on recent work:

RA, Arina, Chianese, Cicoli, Massaro, Maltoni, Osinski JHEP 02, 192 (2024)
RA, Broeckel, Cicoli, Osinski JHEP 02, 026 (2021)

Introduction:

The present universe according to observations:



Important question abut DM:

(1) Its identity (particle physics).

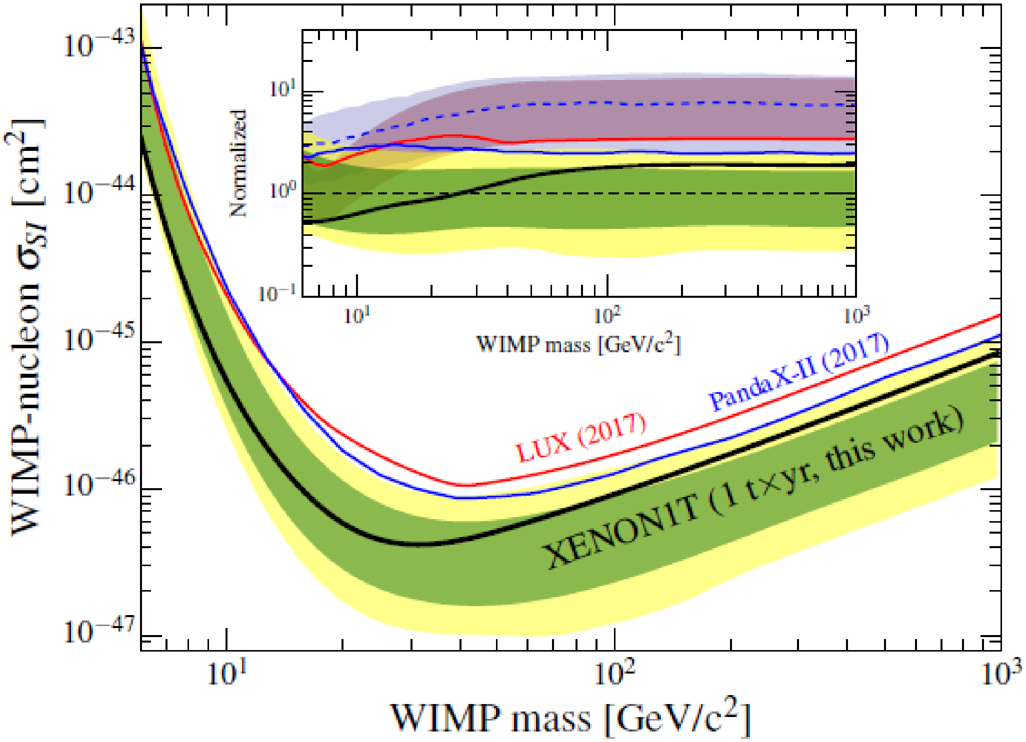
(2) Its relic abundance (particle physics + thermal

WIMPs have been the frontrunners until recently:

Well-motivated in BSM + WIMP miracle

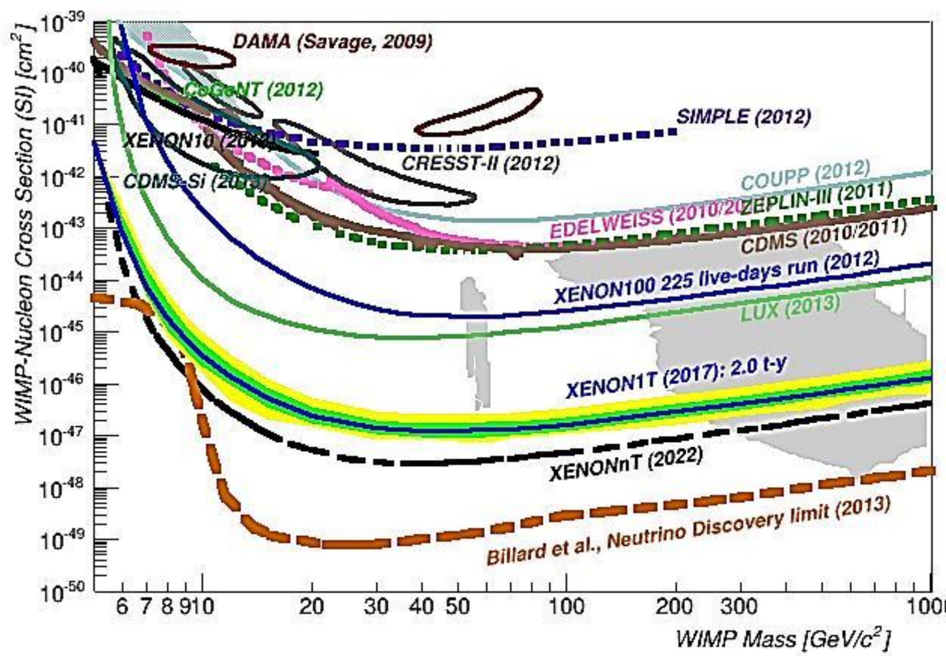
Searches within the canonical WIMP mass range (few-1000 GeV) have only resulted in limits.

Outside the box: light (sub-GeV) DM, **superheavy DM**.



PRL 121, 111302 (2018)

XENON Collaboration



Superheavy DM is motivated (for example, high-scale SUSY).

Issues:

(1) Thermal overproduction.
Griest, Kamionkowski PRL 64, 615 (1990)

(2) Highly suppressed signals.
- Collider (energy).
- Direct ($\propto n$).
- Indirect (annihilation signal $\propto n^2$).

Prospects for indirect detection improve for decaying DM ($\propto n$).

Current limits require lifetimes well above the age of the universe
→ Superheavy and extremely long lifetimes?

A Setup:

Type IIB flux compactifications.

Typical prediction: $H_{inf} \lesssim m_{3/2}$

Obtaining the correct amplitude for density perturbations:

$$H_{inf} \sim 10^{10} - 10^{11}\ GeV$$

How to get low-scale SUSY in this context?

$$H_{inf} \gg m_{3/2} \qquad m_{soft} \sim O(TeV)$$

KKLT with two exponents (as in the racetrack model) → tuned situation

Kallosh, Linde JHEP 12, 004 (2004)

$$H_{inf} \lesssim m_{3/2} \gg m_{soft} \sim O(TeV)$$

Sequestered LVS → very specific brane configurations and Kahler metric

Blumenhagen, Conlon, Krippendorf, Moster, Quevedo JHEP 09, 007 (2009)

High-scale SUSY is the more natural case:

$$H_{inf} \lesssim m_{3/2} \qquad m_{soft} \gg O(TeV)$$

DM is the lightest neutralino (a superheavy WIMP).

How to solve thermal overproduction?

To exploit early matter domination (EMD) driven by string moduli.

The entire DM abundance produced from decay of a modulus ϕ :

$$\frac{n_\chi}{s} = \frac{3T_{\rm R}}{4m_\varphi}\,{\rm Br}_\chi \qquad\qquad T_R \sim \left(\frac{m_\phi^3}{M_P}\right)^{1/2}$$

How to get very long lifetimes?

Tiny RPV couplings from stringy instantons:

$$\lambda \sim e^{-S_{inst}} \qquad S_{inst} \sim 2\pi g_s^{-1}$$

Task: Realization within explicit models.

An Explicit Model:

Type IIB model with three Kahler moduli:

$$\mathcal{V} = \tau_{\rm big}^{3/2} - \tau_{\rm vis}^{3/2} - \tau_{\rm inf}^{3/2}$$

RA, Broeckel, Cicoli, Osinski JHEP 02, 026 (2021)

$$K = -2\ln\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right)$$

$$W = W_0 + A_{\rm vis}\, e^{-a_{\rm vis}T_{\rm vis}} + A_{\rm inf}\, e^{-a_{\rm inf}T_{\rm inf}}$$

$$\epsilon \equiv \frac{W_0}{\mathcal{V}} \ll 1 \qquad\qquad \kappa \equiv \frac{g_s}{8\pi} \ll 1$$

σ: inflaton $\qquad$ ϕ: modulus

$$m_\sigma^2 \simeq \kappa\, \epsilon^2\, (\ln\epsilon)^2\, M_{\rm P}^2 \qquad\qquad m_\phi^2 \simeq \frac{\epsilon\, m_\sigma^2}{g_s^{3/2} W_0\, |\, (\ln\epsilon)^3\, |} \ll m_\sigma^2$$

$$m_{3/2} = \sqrt{\kappa}\, \epsilon\, M_{\rm P} \qquad\qquad m_0 \simeq M_{1/2} \simeq \frac{m_{3/2}}{|\ln \epsilon|}$$

$$m_\chi \simeq m_0 \simeq M_{1/2}$$

$\uparrow$

DM is the LSP

$$m_\phi^2 \simeq \frac{\epsilon\, |\ln \epsilon|}{g_s^{3/2} W_0}\, m_\chi^2 \ll m_\chi^2 \quad \text{for} \quad \epsilon \ll 1$$

$$\boxed{m_\sigma > m_\chi > m_\phi}$$

MSSM-like hidden sector:

(1) $\Lambda_{QCD}^{hid} \gg \Lambda_{QCD}$.

(2) R-parity violation.

(3) Very light hidden electrons (similar to visible sector neutrinos → DR).

Post-inflationary thermal history:

(1) $\Gamma_\sigma \lesssim H < H_{inf}$

EMD from inflaton oscillations.

Inflaton mainly decays to the hidden sector (DR) + DM.

(2) $H_D \lesssim H < \Gamma_\sigma$

Inflationary reheating completes, transition to RD.

(3) $\Gamma_\phi \lesssim H < H_D$

EMD driven by modulus oscillations.

Entropy released in the visible sector, dilutes DR & DM abundance.

(4) $\Gamma_\phi \lesssim H < H_D$

Modulus decay completes. Transition to RD prior to BBN.

Couplings:

$$\mathcal{L} \supset -\frac{1}{4}\frac{c_{\rm hid}}{M_{\rm P}}\,\sigma\,F^{\rm hid}_{\mu\nu}F^{\mu\nu}_{\rm hid} - \frac{1}{4}\frac{c_{\rm vis}}{M_{\rm P}}\,\sigma\,F^{\rm vis}_{\mu\nu}F^{\mu\nu}_{\rm vis}$$

$$c_{\rm hid} \simeq g_s^{3/4}\sqrt{\mathcal{V}} \gg 1 \qquad \text{and} \qquad c_{\rm vis} \simeq c_{\rm hid}^{-1}$$

$$\boxed{\Gamma_\sigma = N_g^{\rm hid}\,\frac{c_{\rm hid}^2}{64\pi}\left(1+\frac{N_g}{N_g^{\rm hid}}\frac{1}{c_{\rm hid}^4}\right)\frac{m_\sigma^3}{M_{\rm P}^2} \simeq N_g^{\rm hid}\,\frac{c_{\rm hid}^2}{64\pi}\,\frac{m_\sigma^3}{M_{\rm P}^2}}$$

$$N_g^{hid} = 12$$

$$\mathcal{L} \supset -\frac{1}{4}\frac{\lambda_{\rm hid}}{M_{\rm P}}\,\phi\,F^{\rm hid}_{\mu\nu}F^{\mu\nu}_{\rm hid}\,, \qquad \lambda_{\rm hid} \simeq \frac{1}{|\ln\epsilon|}$$

$$\mathcal{L} \supset -\frac{1}{4}\frac{\lambda_{\rm vis}}{M_{\rm P}}\,\phi\,F^{\rm vis}_{\mu\nu}F^{\mu\nu}_{\rm vis}\,, \qquad \lambda_{\rm vis} \simeq \frac{1}{|\ln\epsilon|}$$

$$\mathcal{L} \supset \lambda_{\rm DR}\,\frac{m_\phi^2}{M_{\rm P}}\,\phi\,a_{\rm DR}\,a_{\rm DR}\,, \qquad \lambda_{\rm DR} \simeq \frac{1}{\sqrt{6}}$$

Plus the Giudice-Masiero term (decay to the Higgs).

$$\boxed{\Gamma_\phi = \frac{1+Z^2}{48\pi}\,\frac{m_\phi^3}{M_{\rm P}^2}}$$

System of Boltzmann equations governing various species:

$$\frac{d\rho_\sigma}{dt} + 3H\rho_\sigma = -\Gamma_\sigma\,\rho_\sigma\,,$$

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi\,\rho_\phi\,,$$

$$\frac{d\rho_{\rm DR}}{dt} + 4H\rho_{\rm DR} = \Gamma_{\sigma\to{\rm DR}}\rho_\sigma + \Gamma_{\phi\to{\rm DR}}\rho_\phi\,,$$

$$\frac{d\rho_{\rm R}}{dt} + 4H\rho_{\rm R} = \Gamma_{\sigma\to{\rm vis}}\rho_\sigma + \Gamma_{\phi\to{\rm vis}}\rho_\phi\,,$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = {\rm Br}_\chi\Gamma_\sigma\left(\frac{\rho_\sigma}{m_\sigma}\right) + \langle\sigma_{\rm ann}v\rangle\left(n_{\chi,{\rm eq}}^2 - n_\chi^2\right),$$

The expected range of parameters:

$W_0 \in [1, 10^3]$ $g_s \in [10^{-3}, 0.1]$ $\lambda \in [10, 10^4]$ $Y_\phi \in [0.01, 1]$

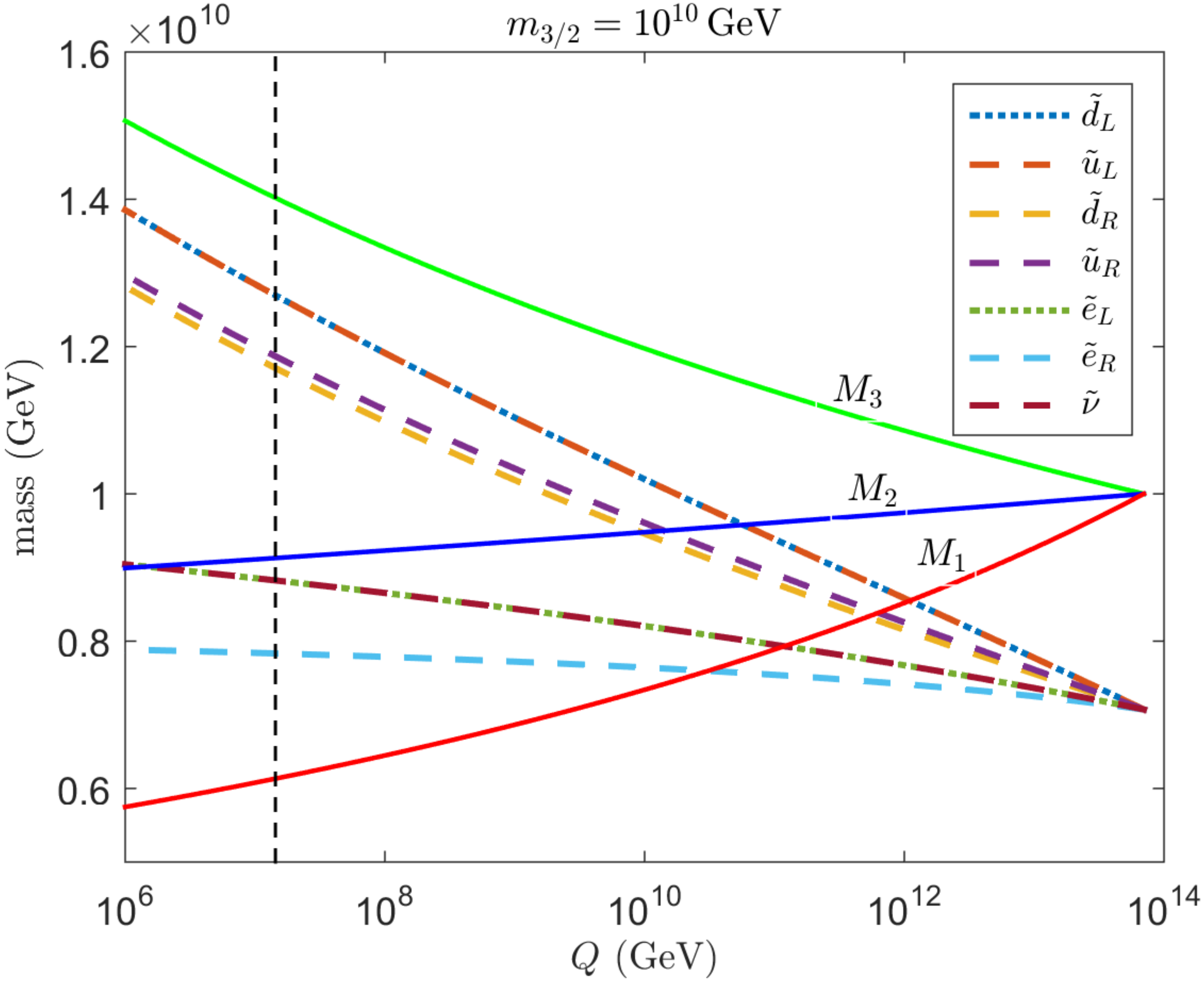
EMD also affects inflationary observables.

A consistent picture with the correct relic density is found for:

$$\boxed{m_\chi \sim 10^{10} - 10^{11}\ GeV}$$

RA, Broeckel, Cicoli, Osinski JHEP 02, 026 (2021)

The visible sector mass spectrum:



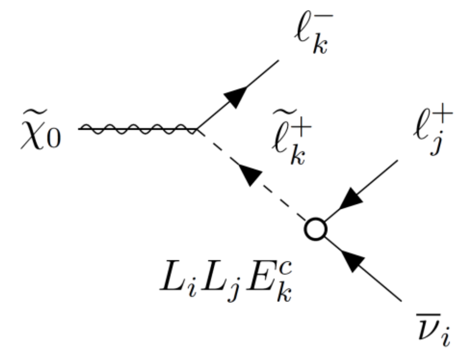
RA, Arina, Chianese, Cicoli, Massaro, Maltoni, Osinski JHEP 02, 192 (2024)

The LSP is Bino-like.

RPV couplings:

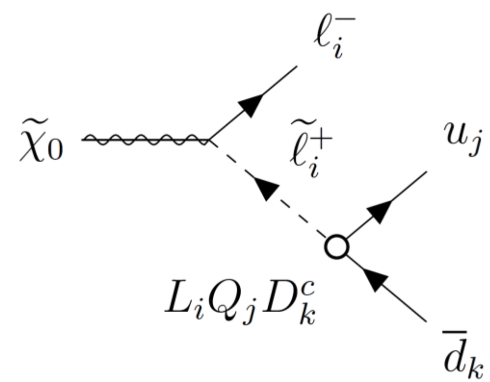
$$W_{\rm LLE} = \epsilon^{\sigma\rho}\left(\lambda_{ijk} L_{i\sigma} L_{j\rho} E^c_k\right)$$

$$\Gamma^{\rm LLE}_{\widetilde{\chi}_0} = \lambda^2_{ijk} \frac{\alpha(m^2_{\widetilde{\chi}_0})}{128\pi^2} \frac{m^5_{\widetilde{\chi}_0}}{m^4_{\widetilde{f}}}$$



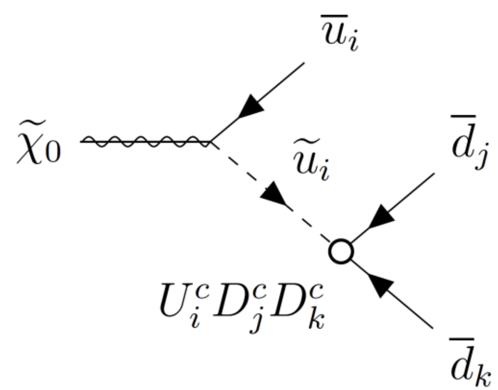
$$W_{\rm LQD} = \epsilon^{\sigma\rho}\left(\lambda'_{ijk} L_{i\sigma} Q_{j\rho\alpha} D^c_{k\alpha}\right)$$

$$\Gamma^{\rm LQD}_{\widetilde{\chi}_0} = \lambda'^2_{ijk} \frac{3\alpha(m^2_{\widetilde{\chi}_0})}{128\pi^2} \frac{m^5_{\widetilde{\chi}_0}}{m^4_{\widetilde{f}}}$$



$$W_{\rm UDD} = 2\epsilon^{\alpha\beta\gamma} \lambda''_{ijk} U^c_{i\alpha} D^c_{j\beta} D^c_{k\gamma}$$

$$\Gamma^{\rm UDD}_{\widetilde{\chi}_0} = \lambda''^2_{ijk} \frac{3\alpha(m^2_{\widetilde{\chi}_0})}{64\pi^2} \frac{m^5_{\widetilde{\chi}_0}}{m^4_{\widetilde{f}}}$$



Photon flux from DM decay:

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma \mathrm{d}\Omega} = \frac{1}{4\pi m_\chi \tau_\chi} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \int_0^{+\infty} \mathrm{d}s\, \rho_\chi[r(s,\ell,b)] \exp[-\tau_{\gamma\gamma}(E_\gamma, s, b, \ell)]\,;$$

$$\Phi_\gamma^\chi(E_\gamma) = \frac{1}{\Omega_{\rm exp}} \int_{E_\gamma}^{\infty} \mathrm{d}E'_\gamma \int_{\Omega_{\rm exp}} \mathrm{d}\Omega \frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E'_\gamma \mathrm{d}\Omega}$$

Neutrino flux from DM decay:

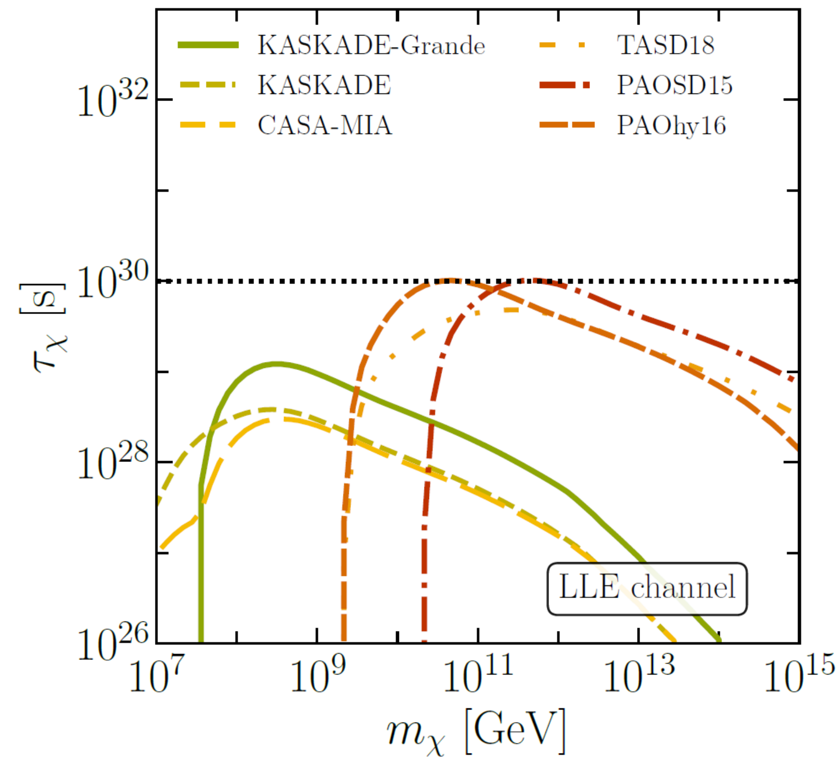
$$\frac{\mathrm{d}\Phi^{\rm gal}_{\nu_\alpha+\overline{\nu}_\alpha}}{\mathrm{d}E_\nu \mathrm{d}\Omega} = \frac{1}{4\pi m_\chi \tau_\chi} \frac{\mathrm{d}N_\alpha}{\mathrm{d}E_\nu} \int_0^{+\infty} \mathrm{d}s\, \rho_\chi[r(s,\ell,b)]$$

$$\frac{\mathrm{d}\Phi^{\rm ex\text{-}gal}_{\nu_\alpha+\overline{\nu}_\alpha}}{\mathrm{d}E_\nu \mathrm{d}\Omega} = \frac{\Omega_\chi\, \rho_{\rm c}}{4\pi m_\chi \tau_\chi} \int_0^{+\infty} \frac{\mathrm{d}z}{H(z)} \frac{\mathrm{d}N_\alpha}{\mathrm{d}E'_\nu}\bigg|_{E'_\nu = E_\nu(1+z)}$$

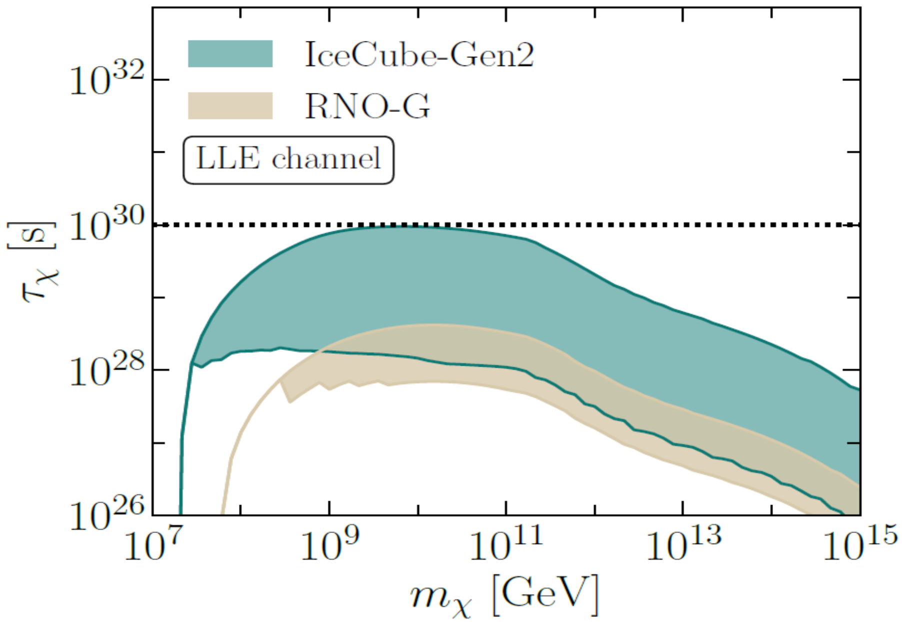
$$\frac{\mathrm{d}\Phi^\chi_{3\nu}}{\mathrm{d}E_\nu} = \sum_\alpha \int_{4\pi} \mathrm{d}\Omega \left[\frac{\mathrm{d}\Phi^{\rm gal}_{\nu_\alpha+\overline{\nu}_\alpha}}{\mathrm{d}E_\nu \mathrm{d}\Omega} + \frac{\mathrm{d}\Phi^{\rm ex\text{-}gal}_{\nu_\alpha+\overline{\nu}_\alpha}}{\mathrm{d}E_\nu \mathrm{d}\Omega} \right]$$

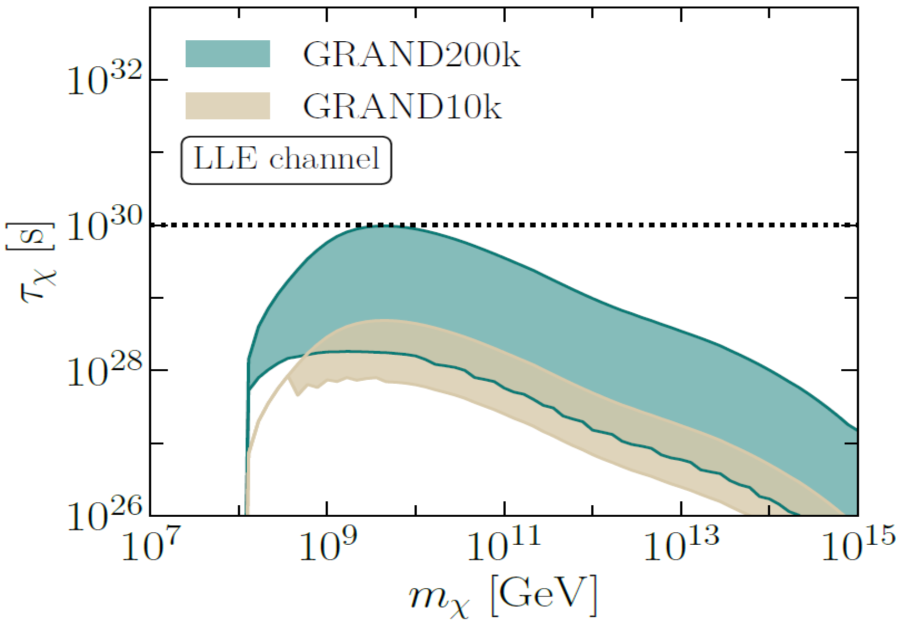
LLE:

Limits from current gamma-ray data:



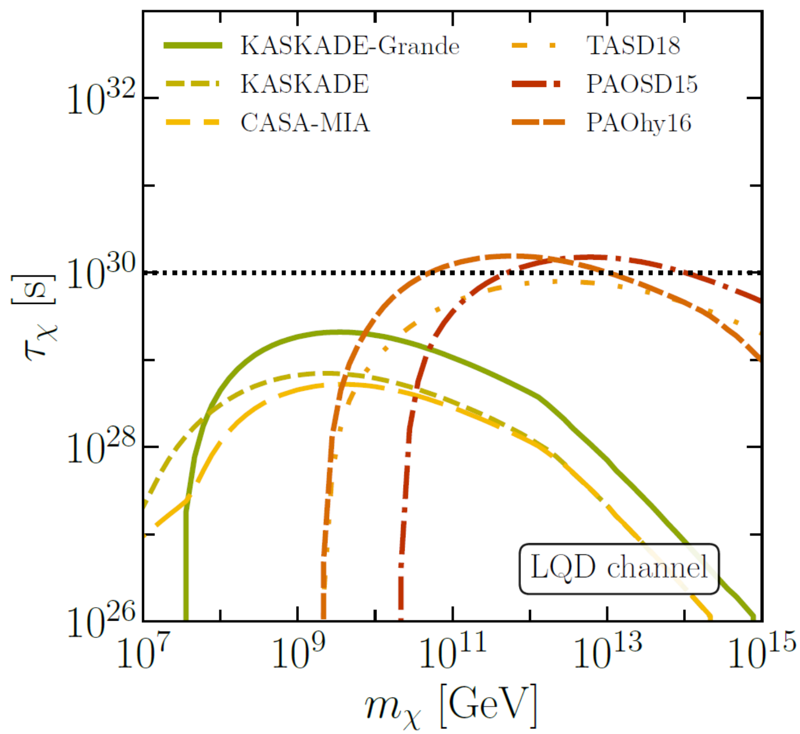
Forecast from future neutrino data:



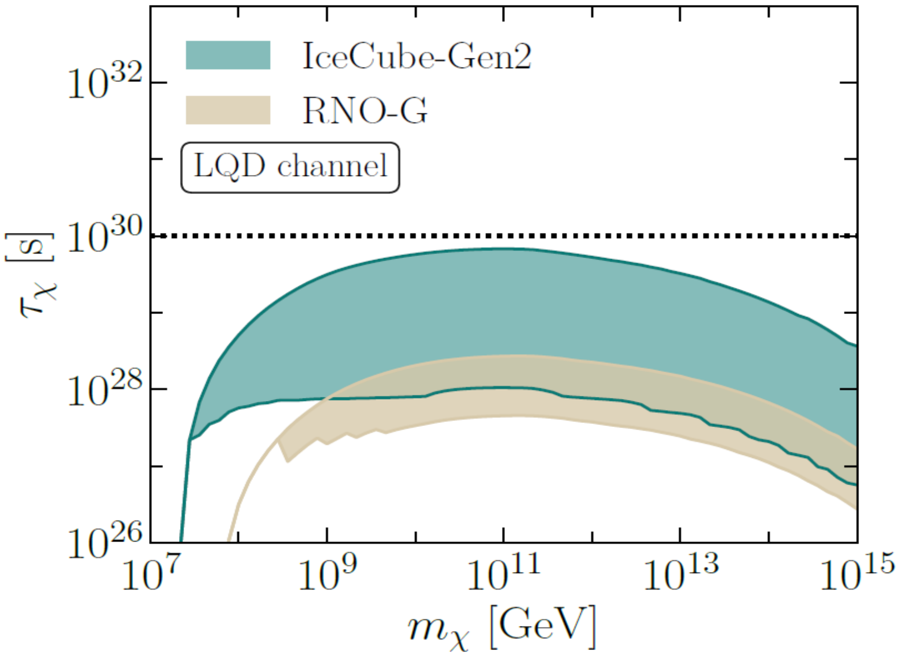


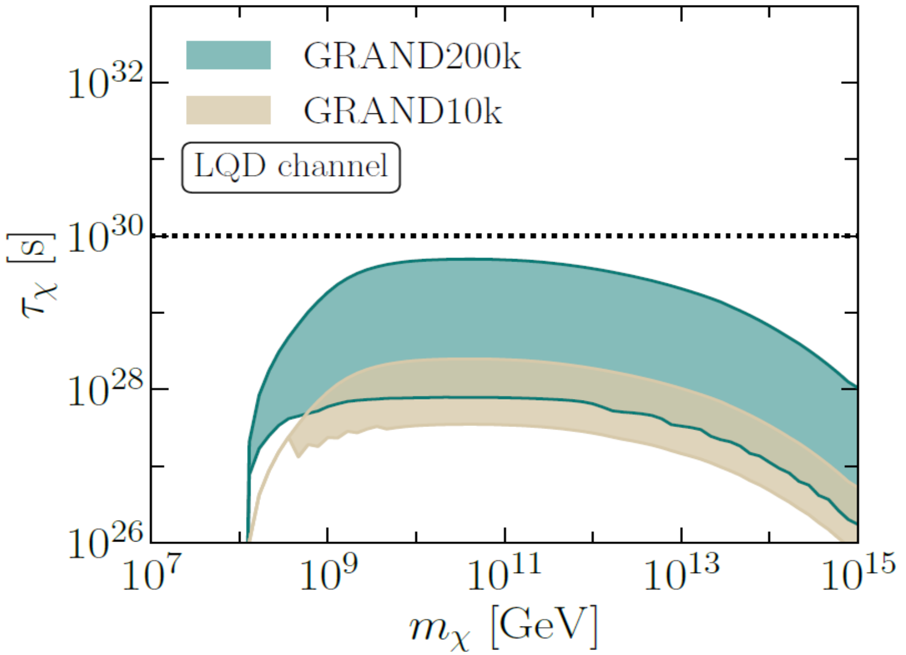
LQD:

Limits from current gamma-ray data:



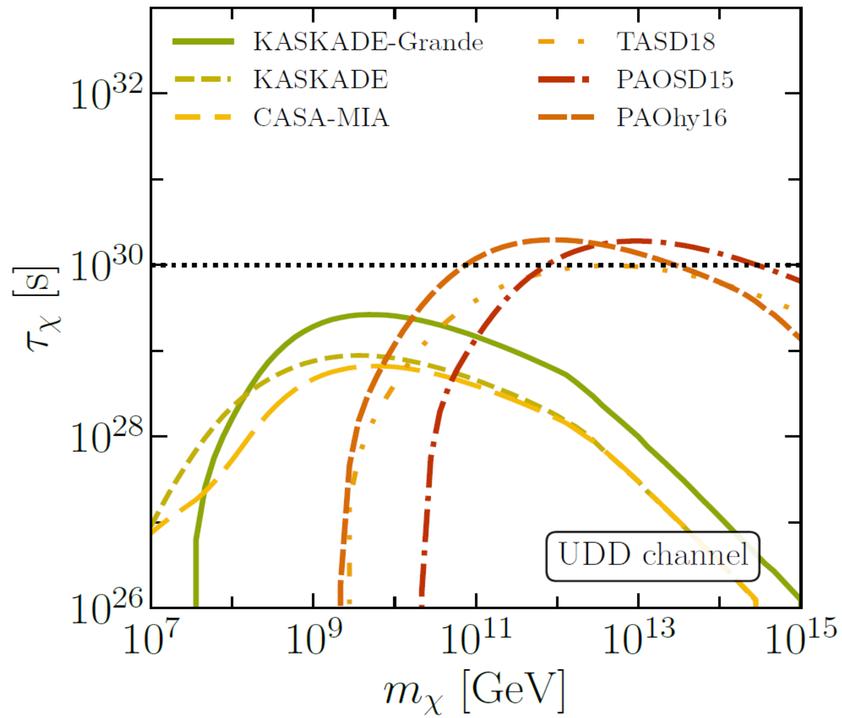
Forecast from future neutrino data:



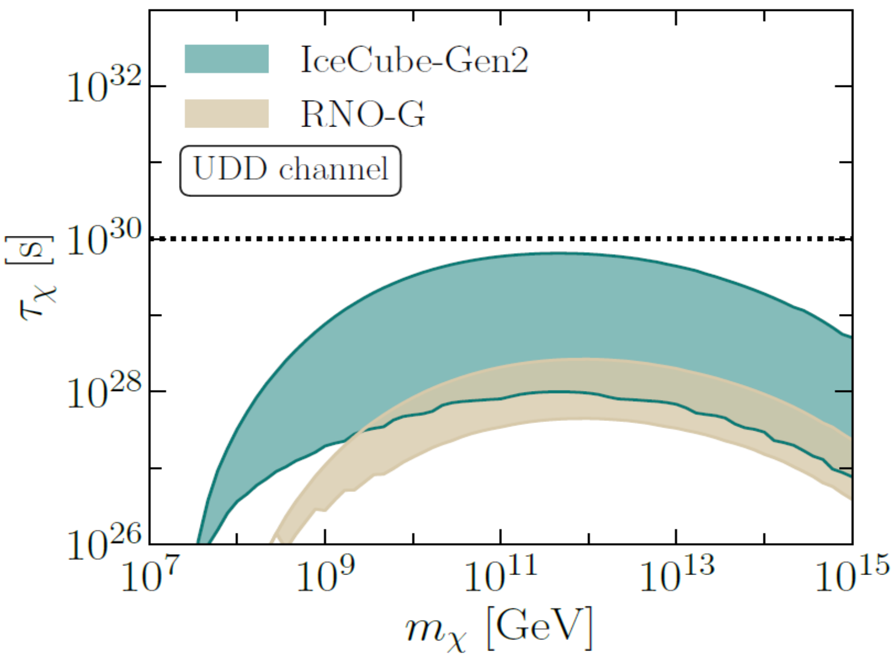


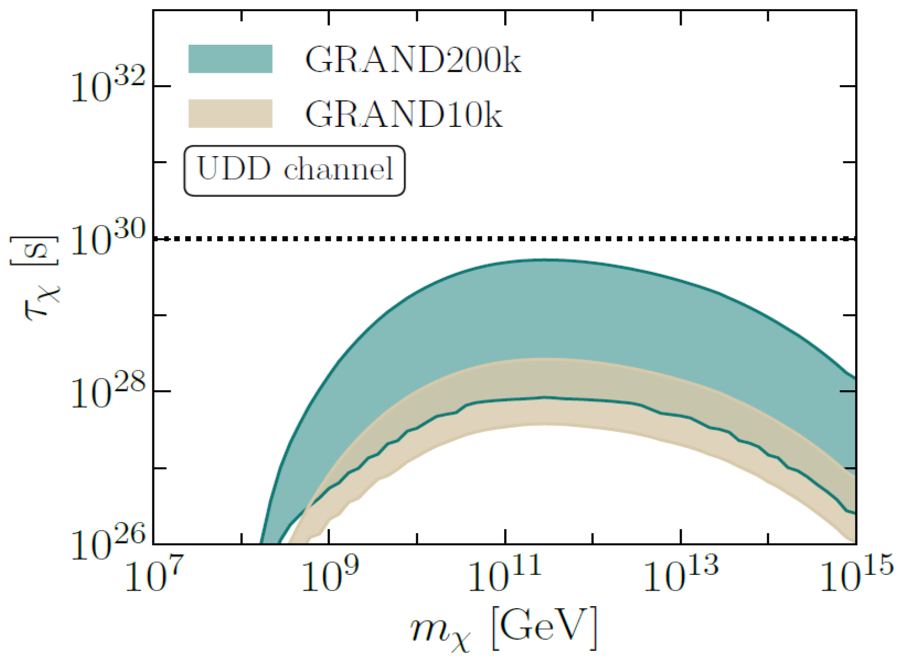
UDD:

Limits from current gamma-ray data:

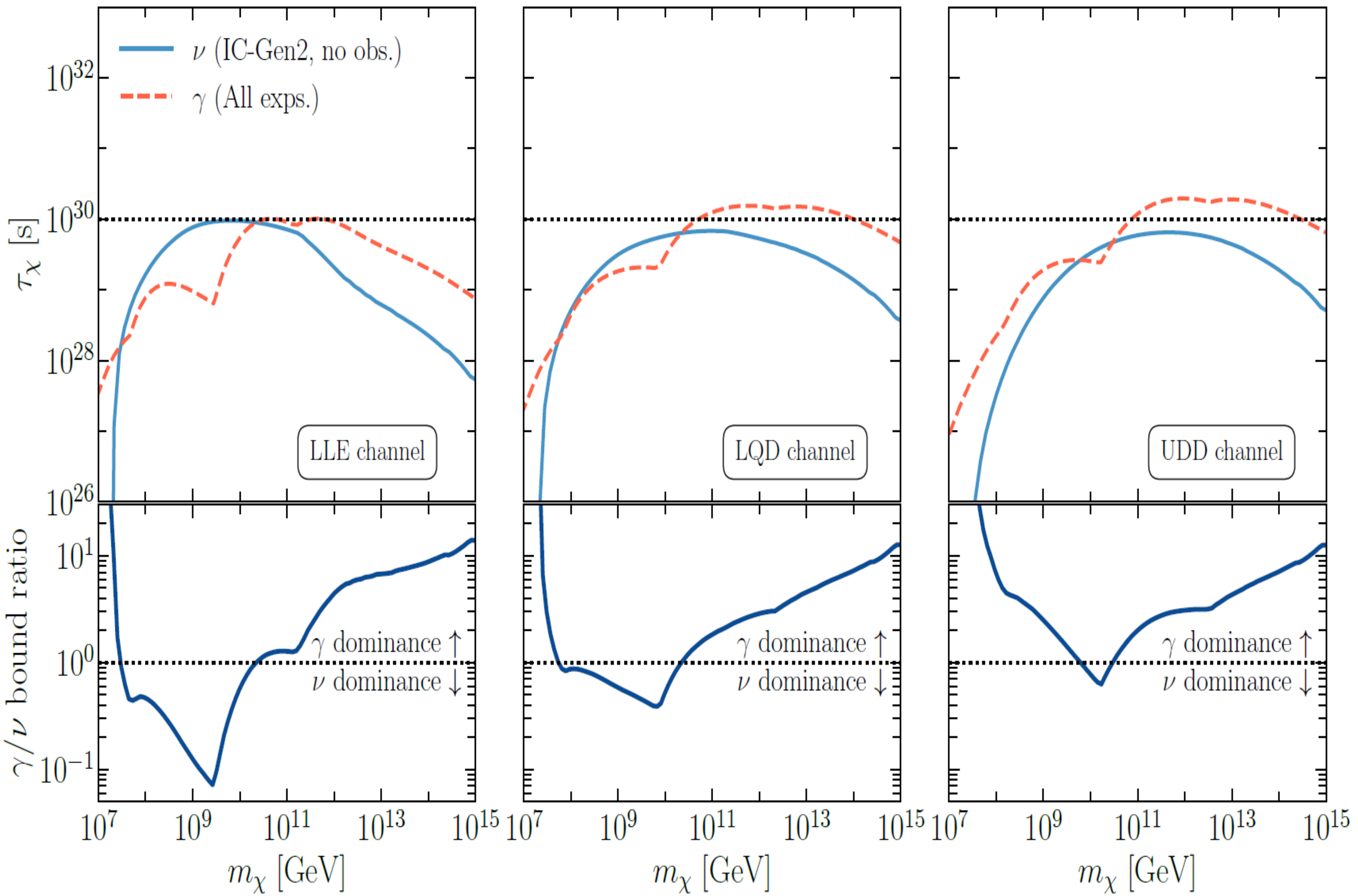


Forecast from future neutrino data:

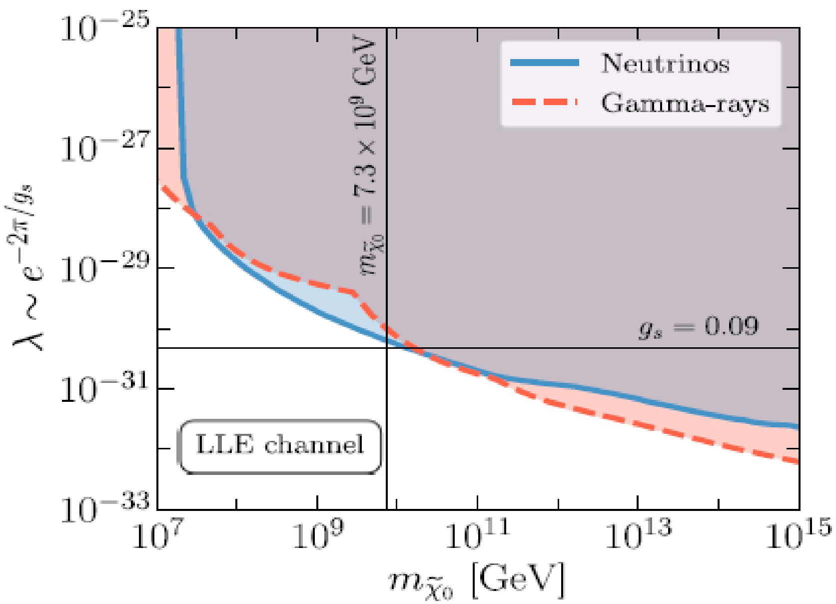


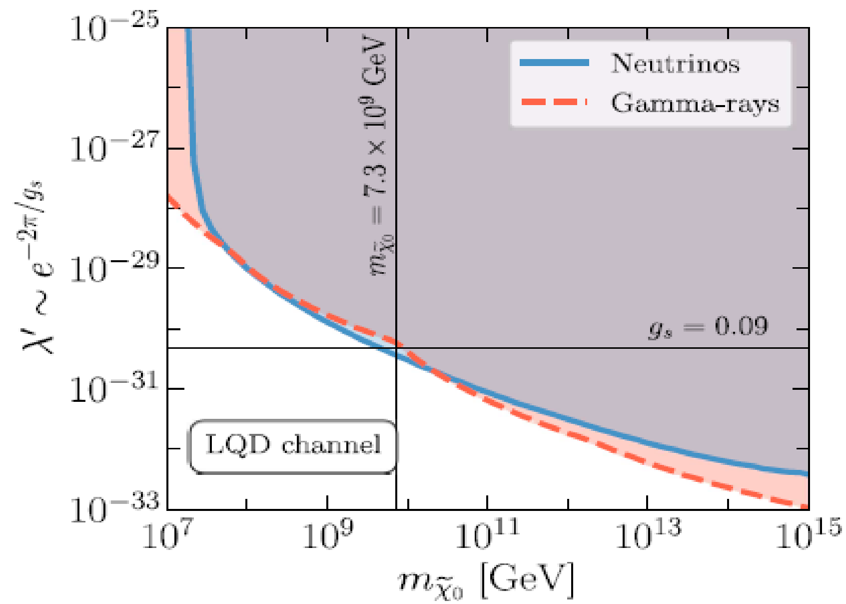


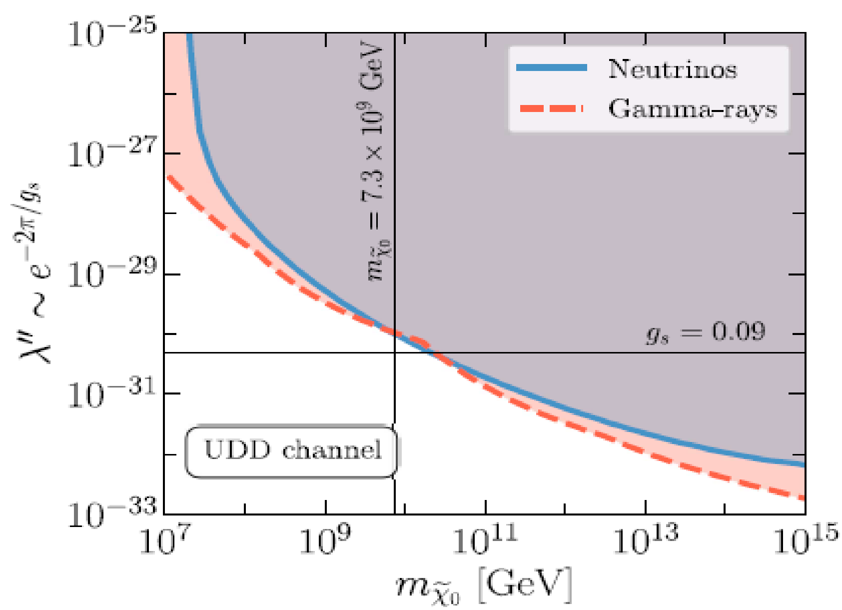
Complementarity between gamma-ray and neutrino bounds:



Resulting bounds on the string coupling constant:







Conclusion & Outlook:

- Superheavy DM can naturally arise within string constructions.
- An explicit LVS model with Bino-like DM presented.
- Epoch(s) of EMD from moduli can solve the overabundance problem.
- Successful cosmology obtained for DM mass $\sim 10^{10} - 10^{11}\ GeV$.
- Tiny RPV couplings from stringy instantons give rise to decaying DM.
- 3-body DM decays produce very high energy photons & neutrinos.
- Very tight limits on DM lifetime for DM mass above $\sim 10^{9}\ GeV$.
- Interesting to consider 2-body decays of LH/RH sneutrino DM

Backup Slides

Final DM abundance:

$$\frac{n_\chi}{s} \simeq \frac{3}{4} \times 10^{-3} \frac{1}{Y_\phi^2} \frac{\Gamma_{\sigma\to\text{vis}}}{\Gamma_\sigma} \frac{\Gamma_\phi}{\Gamma_{\phi\to\text{vis}}} \frac{T_\text{R}}{m_\sigma}$$

$$T_\text{R} = \left(\frac{90}{\pi^2 g_{*,\text{R}}} \frac{\Gamma_{\phi\to\text{vis}}}{\Gamma_\phi}\right)^{1/4} \sqrt{\Gamma_\phi M_\text{P}}$$: final reheating temperature

$$Y_\phi \equiv \phi_0 / M_\text{P}$$

$$\frac{\rho_\text{DR}}{\rho_\text{R}} \simeq \frac{1}{Y_\phi^{8/3}} \left(\frac{\Gamma_\phi}{\Gamma_\sigma}\right)^{2/3} \frac{\Gamma_{\sigma\to\text{DR}}}{\Gamma_\sigma} \frac{\Gamma_\phi}{\Gamma_{\phi\to\text{vis}}} + \frac{\Gamma_{\phi\to\text{DR}}}{\Gamma_{\phi\to\text{vis}}}$$

Note that:

$$Y_\phi \uparrow \Rightarrow \frac{n_\chi}{s} \downarrow, \frac{\rho_{DR}}{\rho_R} \downarrow$$

Expected → a longer EMD epoch results in a larger dilution factor.

EMD also affects inflationary observables:

$$N_{\rm e} \simeq 57 + \frac{1}{4}\ln r - \frac{1}{4}N_{\rm reh} - \frac{1}{4}N_{\phi}$$

r: tensor-to-scalar ratio

$$N_{\rm reh} \simeq \frac{2}{3}\ln\left(\frac{H_{\rm inf}}{\Gamma_\sigma}\right)$$

$$N_\phi \simeq \frac{2}{3}\ln\left(\frac{H_{\rm D}}{\Gamma_\phi}\right) \simeq \frac{2}{3}\ln\left(Y_\phi^4\frac{\Gamma_\sigma}{\Gamma_\phi}\right)$$

$$N_{\rm e} \simeq 57 + \frac{1}{4}\ln r - \frac{1}{6}\ln\left(Y_\phi^4\frac{H_{\rm inf}}{\Gamma_\phi}\right)$$

The scalar spectral index follows:

$$n_{\rm s} = 1 - \frac{a}{N_{\rm e}}$$

In our model $a = 2$ (similar to Starobinsky model & Higgs inflation):

$$N_{\rm e} \gtrsim \frac{2}{1 - n_{\rm s,min}}$$

$$Y_\phi \uparrow \Rightarrow N_e \downarrow, n_{s,min} \downarrow$$

Opposite constraints from $\frac{n_\chi}{s}$ and n_s on the duration of EMD.

Inflationary observables:

$$N_{\rm reh} \simeq \frac{2}{3}\ln\left(\sqrt{\frac{3}{2}\frac{512^2\pi^4}{(2\pi)^{3/2}}}\frac{\mathcal{V}^{1/2}}{N_g^{\rm hid}W_0^2 g_s^{5/2}\,|\ln\epsilon|^{9/4}}\right)$$

$$N_\phi \simeq \frac{2}{3}\ln\left(Y_\phi^4\frac{\Gamma_\sigma}{\Gamma_\phi}\right) \simeq \frac{2}{3}\ln\left(\frac{3}{4}\frac{N_g^{\rm hid}}{1+Z^2}Y_\phi^4\,g_s^{15/4}\,\mathcal{V}^{5/2}\,|\ln\epsilon|^{9/2}\right)$$

$$r \simeq 16\times 3.7\times 10^6\left(\frac{3}{2}\frac{|\ln\epsilon|^{3/2}}{(2\pi)^{3/2}}\right)\frac{g_s}{16\pi}\frac{W_0^2}{\mathcal{V}^3}$$

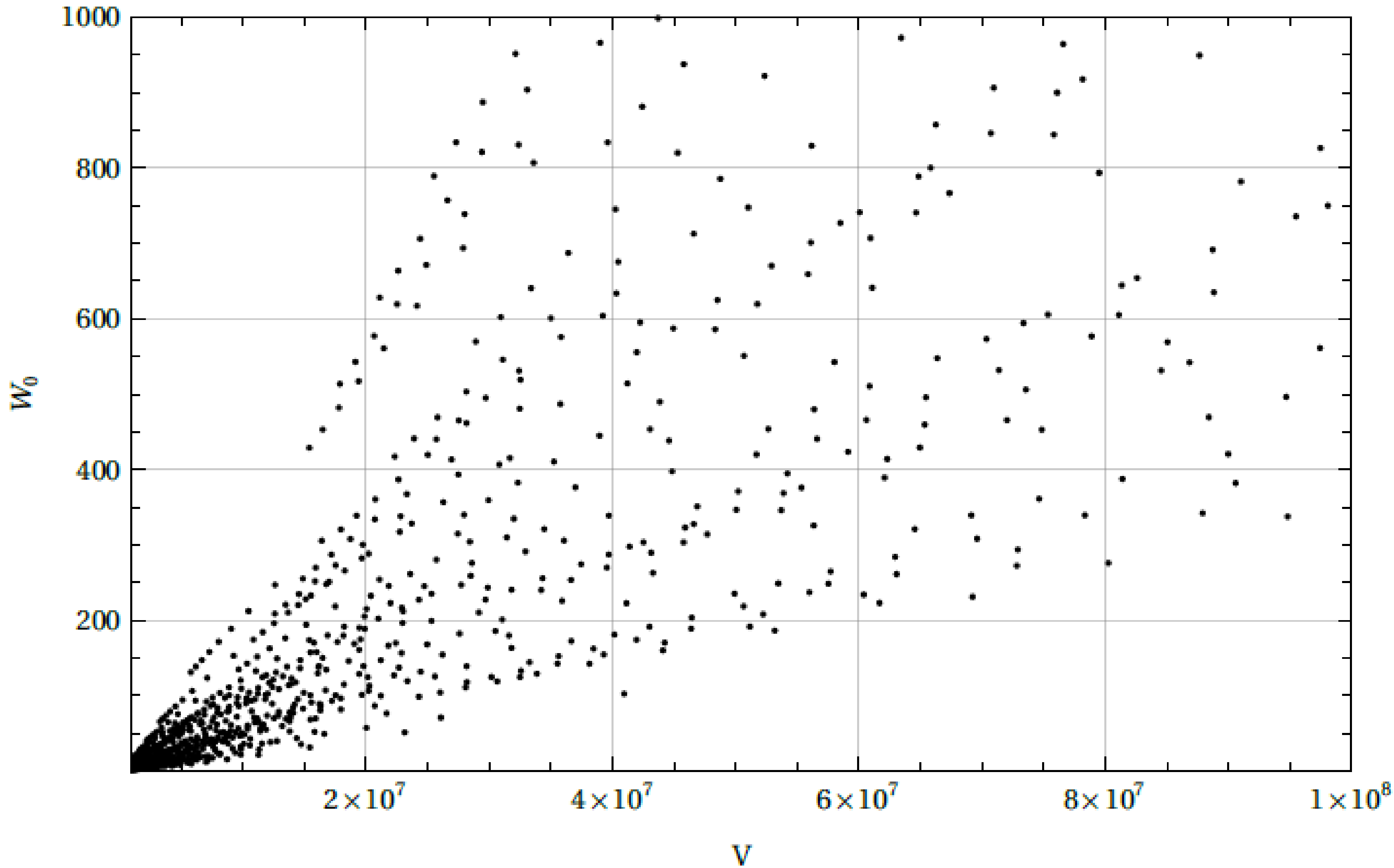
$$N_{\rm e} \simeq 60.1 - \frac{1}{6}\ln\left(\frac{Y_\phi^4\,\mathcal{V}^{15/2}}{5g_s^{1/4}W_0^5\,|\ln\epsilon|^{9/4}}\right)$$

Obtaining the right density perturbations gives the following relation:

$$\mathcal{V}^{2/3} \simeq \lambda\left(\frac{\alpha^{1/4}\mathcal{V}}{g_s^{1/2}W_0\,|\ln\epsilon|^{3/4}\,N_{\rm e}}\right)^4$$

$$\mathcal{V}^{2/3} \simeq \lambda\,\tau_{\rm inf} \qquad \lambda \gg 1$$

Points that yield the correct density perturbations and DM abundance:

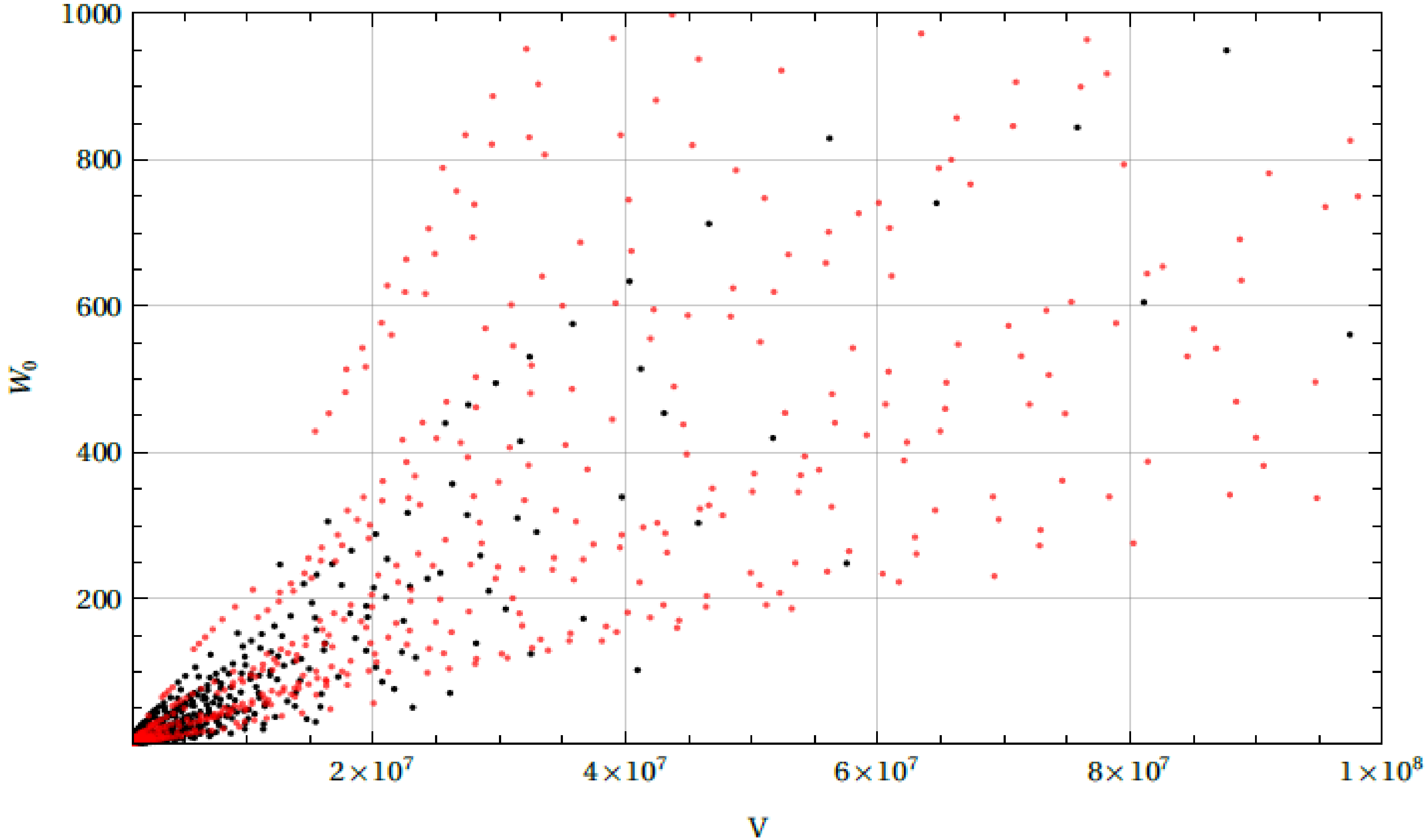


$$\frac{n_\chi}{s} \propto Y_\phi^{-2} V^{-13/4}$$

Black: n_s *in the* 2σ *range* $0.9565 < n_s < 0.9733$

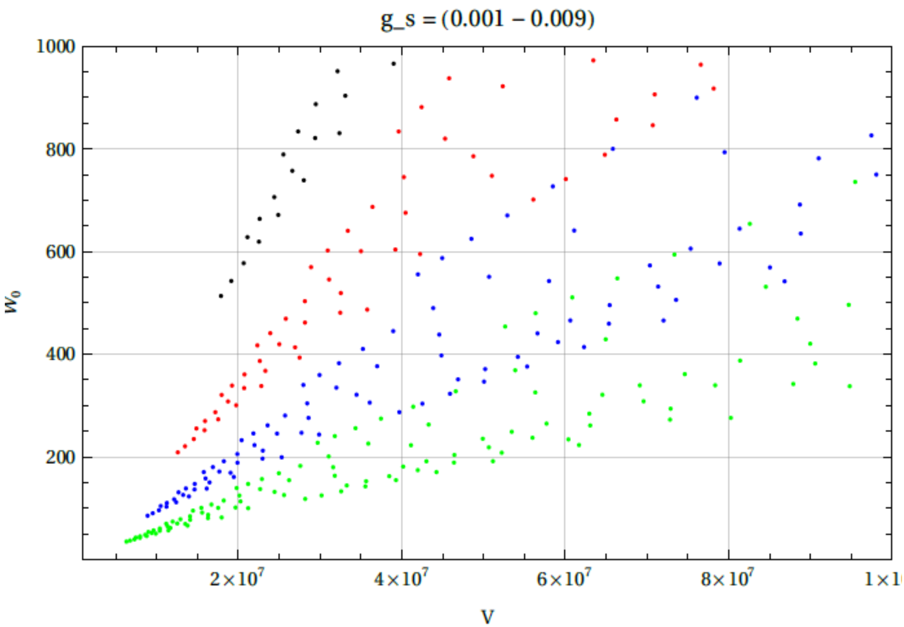
Red: n_s *in the* 3σ *range (but outside* 2σ*)* $0.9523 < n_s < 0.9775$

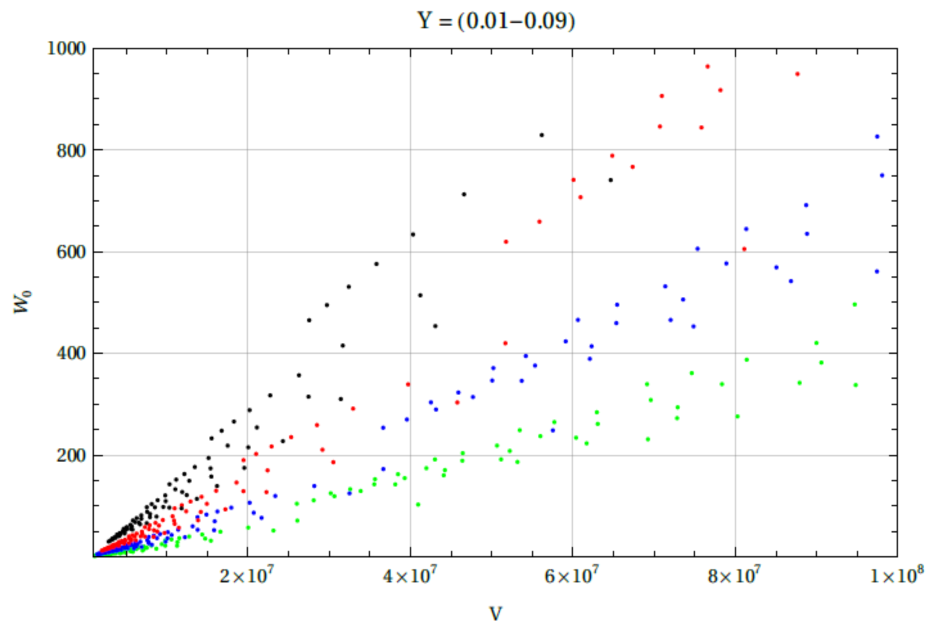
Planck 2018 Astron. Astrophys. 641, A10 (2020)

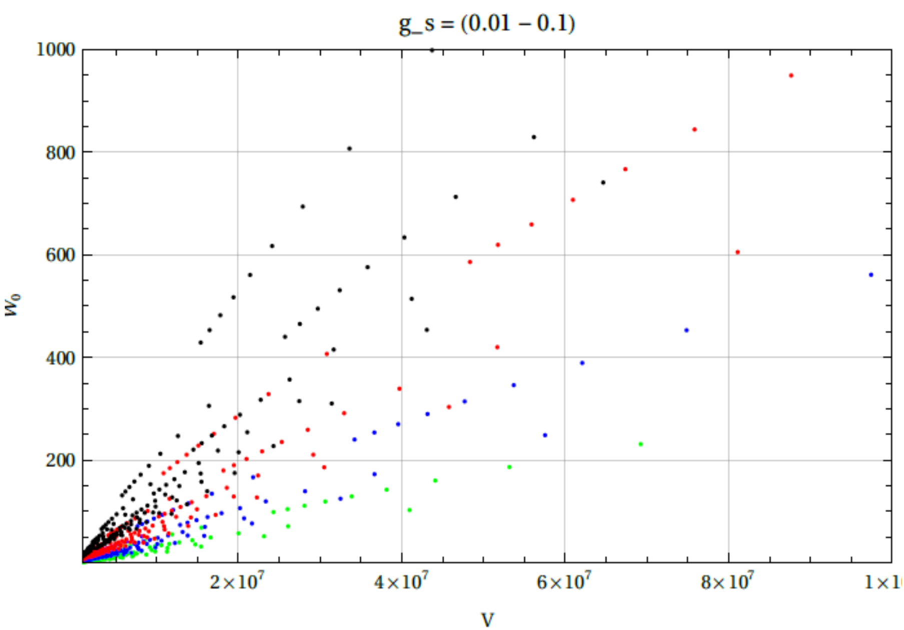


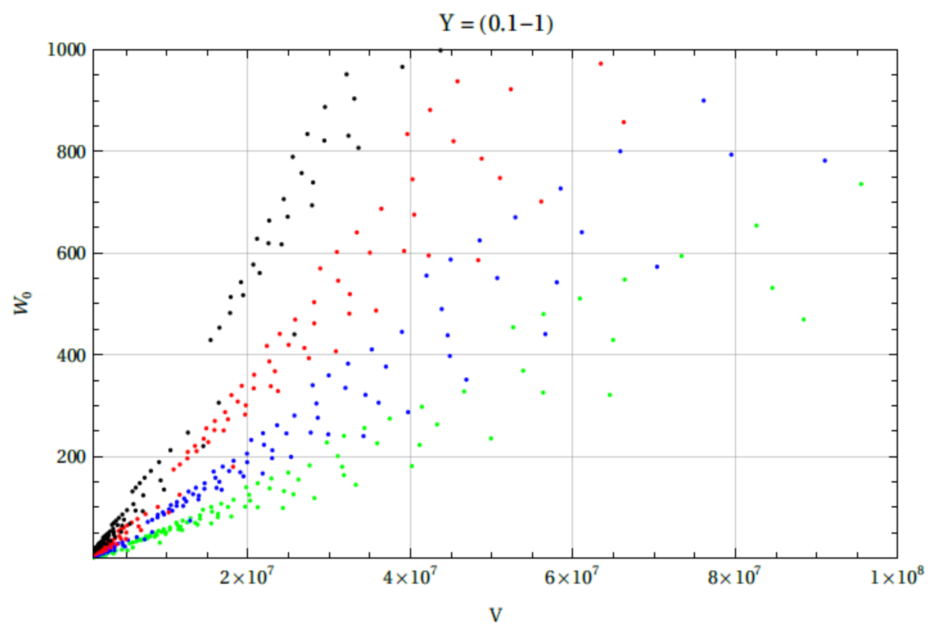
Subsets varying g_s :

Subsets varying Y_ϕ:





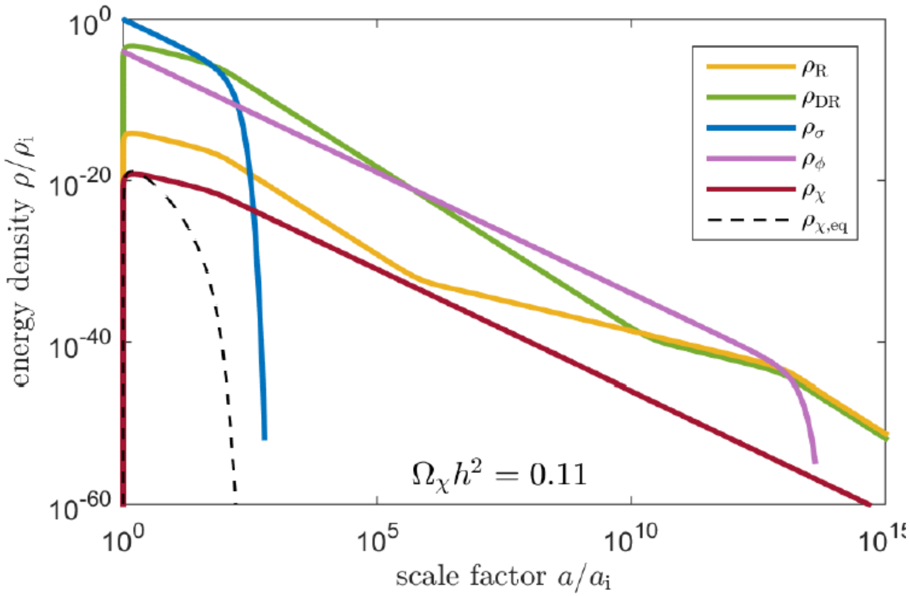




A chosen benchmark point:

W_0	39.1
$\mathcal{V}$	8.4×10^6
N_e	47.4
$N_{\rm reh}$	3.7
N_ϕ	16.4
n_s	0.9578
m_σ	8.7×10^{12}GeV
m_ϕ	3.9×10^8GeV
$m_{3/2}$	7.1×10^{11}GeV
m_χ	5.8×10^{10}GeV
$c_{\rm hid}$	514.7

Various energy densities:



Visible sector temperature: