

X-rays from inelastic dark matter freeze-in

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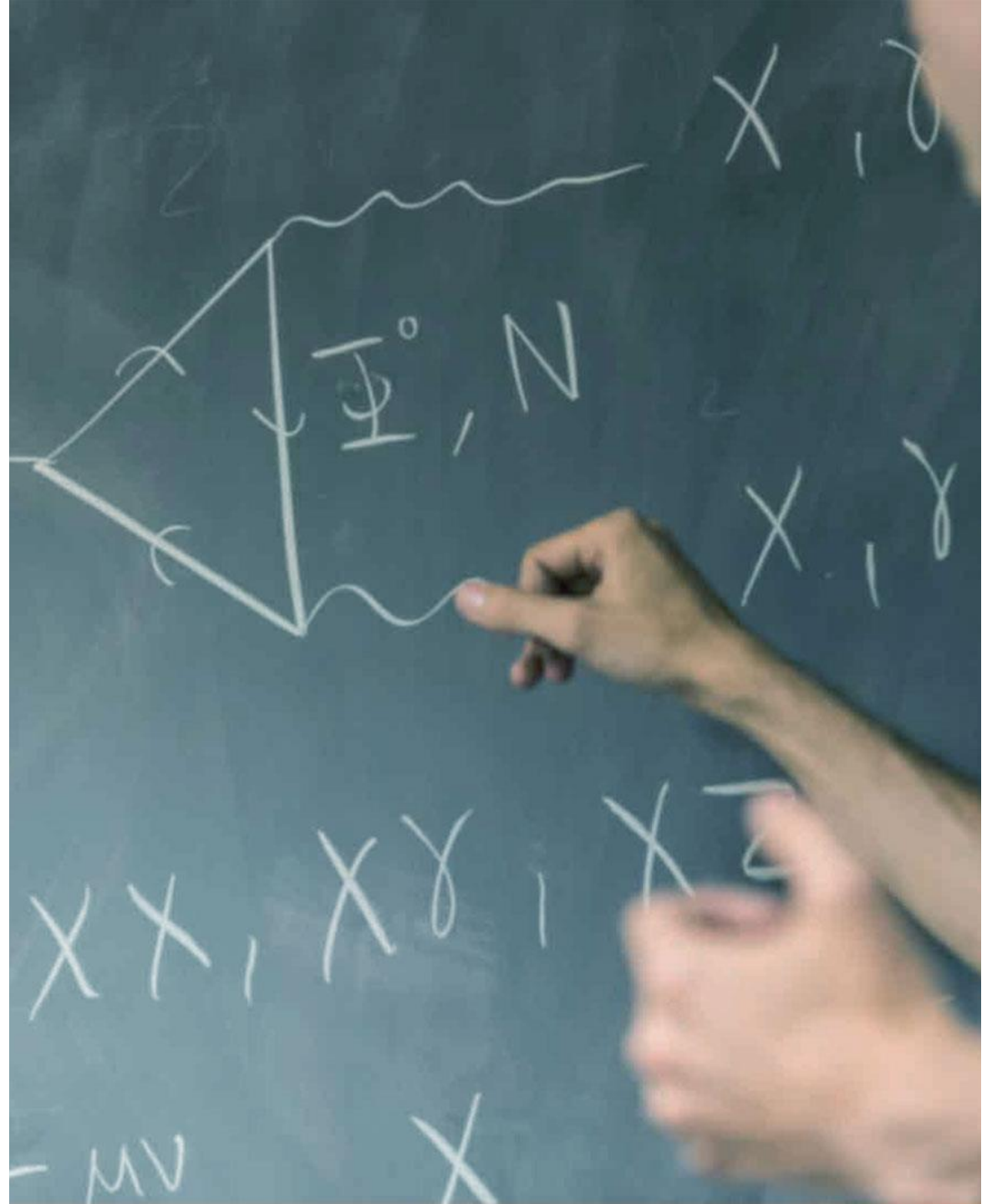
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Mohlabeng, D. Tuckler

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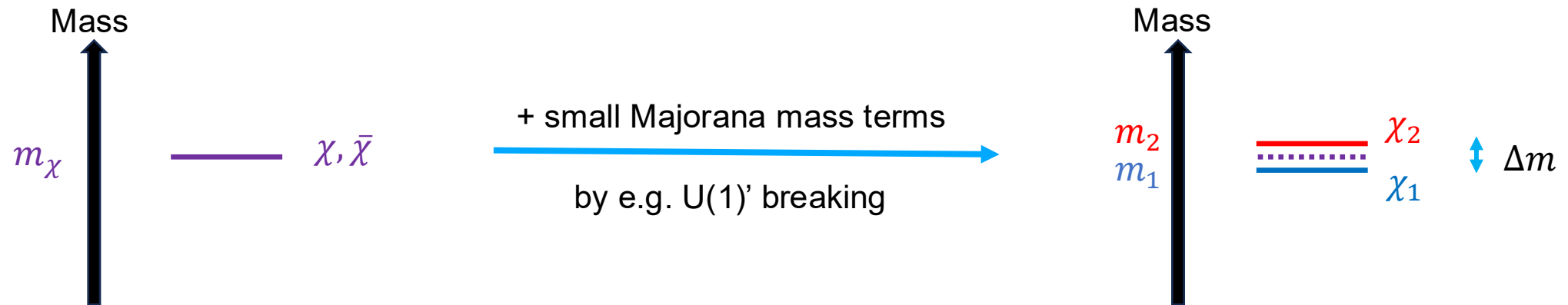
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2026-07-28



Model setup

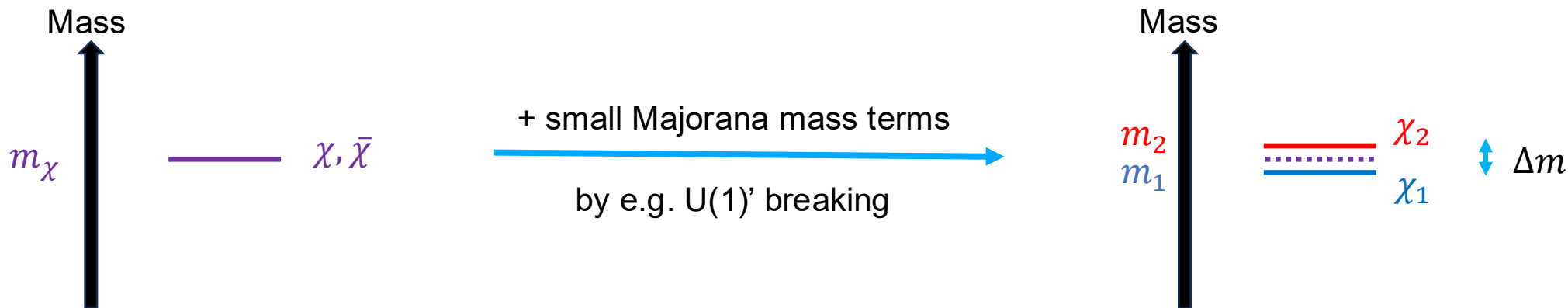
Inelastic dark matter



Model setup

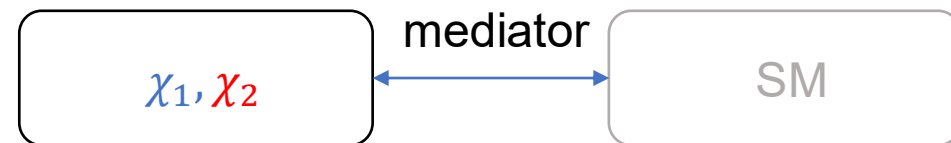
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Inelastic dark matter



2 benchmark mediators that couples to χ_1, χ_2 and SM:

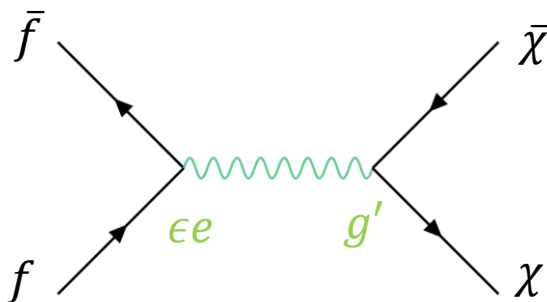
- Dark photon A' : coupled to SM fermions universally
- Leptophilic scalar ϕ : couples to leptons mass-proportionally



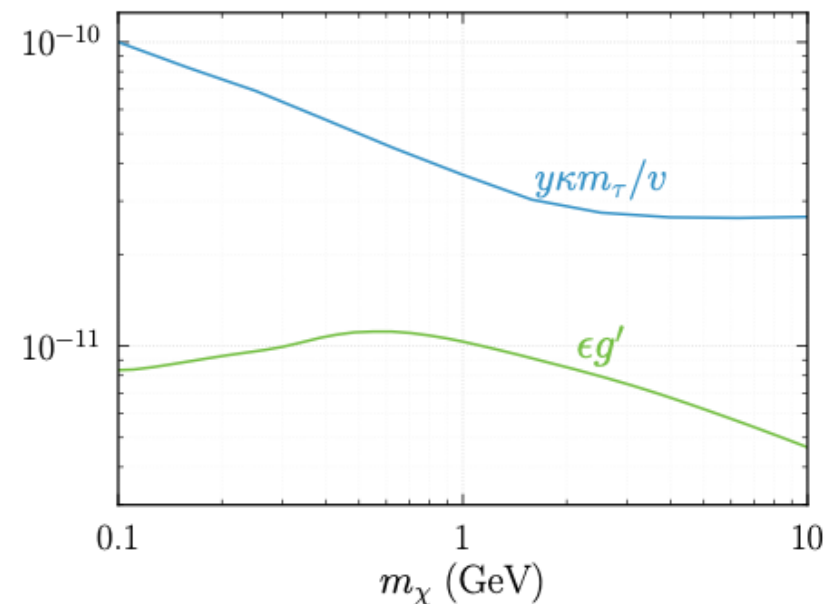
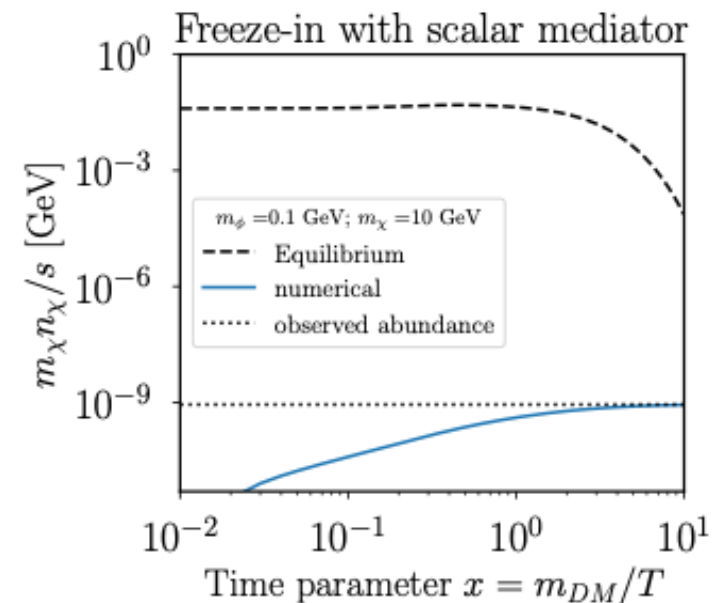
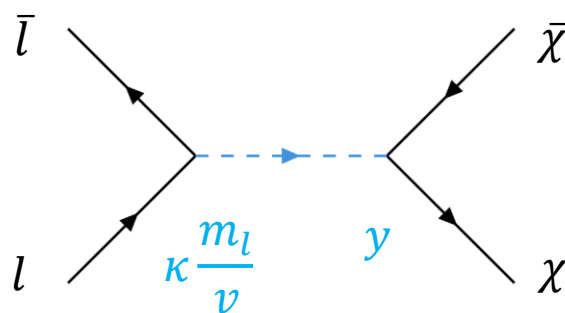
Freeze-in of inelastic dark matter

- We assume
 - no initial amount of DM
 - Feeble coupling between DM and SM
- DM is gradually populated by $f \bar{f} \rightarrow \bar{\chi} \chi$
 - $m_{med} < 2m_\chi$, $g_{SM} \gtrsim g_{DM}$
- IR freeze-in: The production is dominated by $T \sim m_\chi$
 - Relatively insensitive to the initial conditions
- DM = $\frac{1}{2} \chi_1 + \frac{1}{2} \chi_2$!

Dark photon:



Scalar:

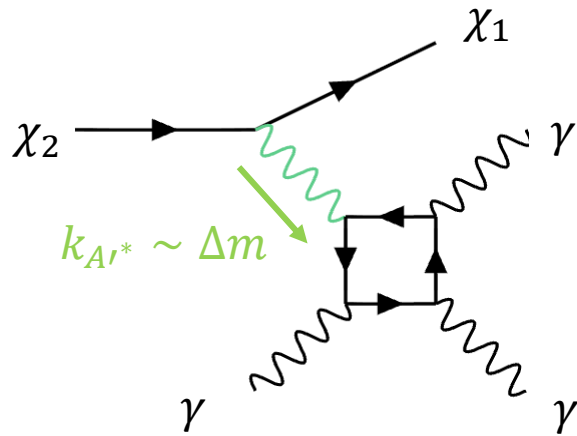


Decays of heavier state χ_2

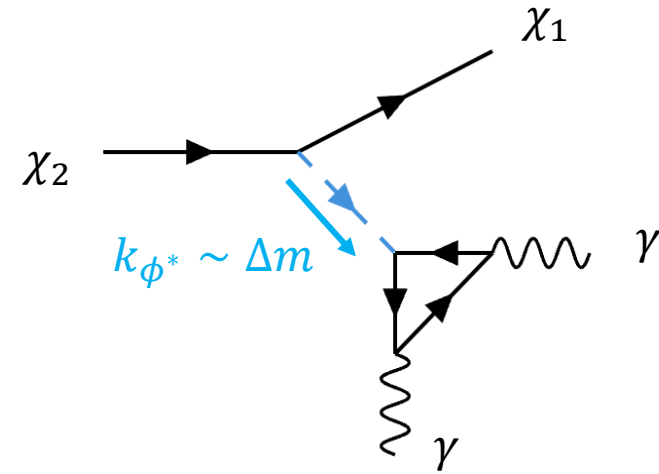
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Below $\Delta m < 2m_e$, χ_2 is meta-stable and can decay into χ_1 and photons:

Dark photon:



Scalar mediator:



$$\frac{1}{\tau_{\chi_2 \rightarrow \chi_1 \gamma \gamma \gamma}} \sim \frac{1}{10^{24} \text{ s}} \left(\frac{\text{coupling}}{10^{-11}} \right)^2 \left(\frac{\Delta m}{900 \text{ keV}} \right)^{13} \left(\frac{30 \text{ MeV}}{m_{A'}} \right)^4$$

$$\frac{1}{\tau_{\chi_2 \rightarrow \chi_1 \gamma \gamma}} \sim \frac{1}{10^{23} \text{ s}} \left(\frac{\text{coupling}}{10^{-11}} \right)^2 \left(\frac{\Delta m}{900 \text{ keV}} \right)^7 \left(\frac{30 \text{ MeV}}{m_\phi} \right)^4$$

- More than million times longer than the age of the Universe: $\sim 10^{17} \text{ s}$
- Nearly all χ_2 has survived up to today, making up a half of dark matter!

X-ray signals from χ_2 decays

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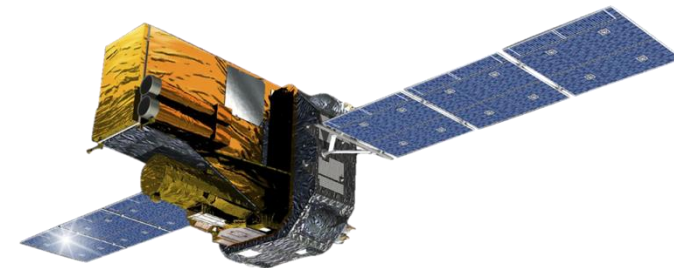
Expected photon flux from χ_2 decays is given by

$$\frac{d\Phi}{d\omega} = \underbrace{\frac{dN}{d\omega} \frac{1}{\tau_{\chi_2}} \frac{1}{m_2} \frac{1}{2} \int \frac{d\Omega}{4\pi} \int_{l.o.s.} ds s^2 \rho_{DM}}_{\text{No. of } \chi_2 \text{ in line of sight}} = \underbrace{\frac{dN}{d\omega} \frac{1}{\tau_{\chi_2}} \frac{1}{m_2}}_{\text{Flux shape}} \underbrace{\frac{D}{8\pi}}_{\text{Overall strength}}$$

Fraction of χ_2 in DM
 const. $\downarrow$
 Purple: astro/cosmo
 Red: model param.

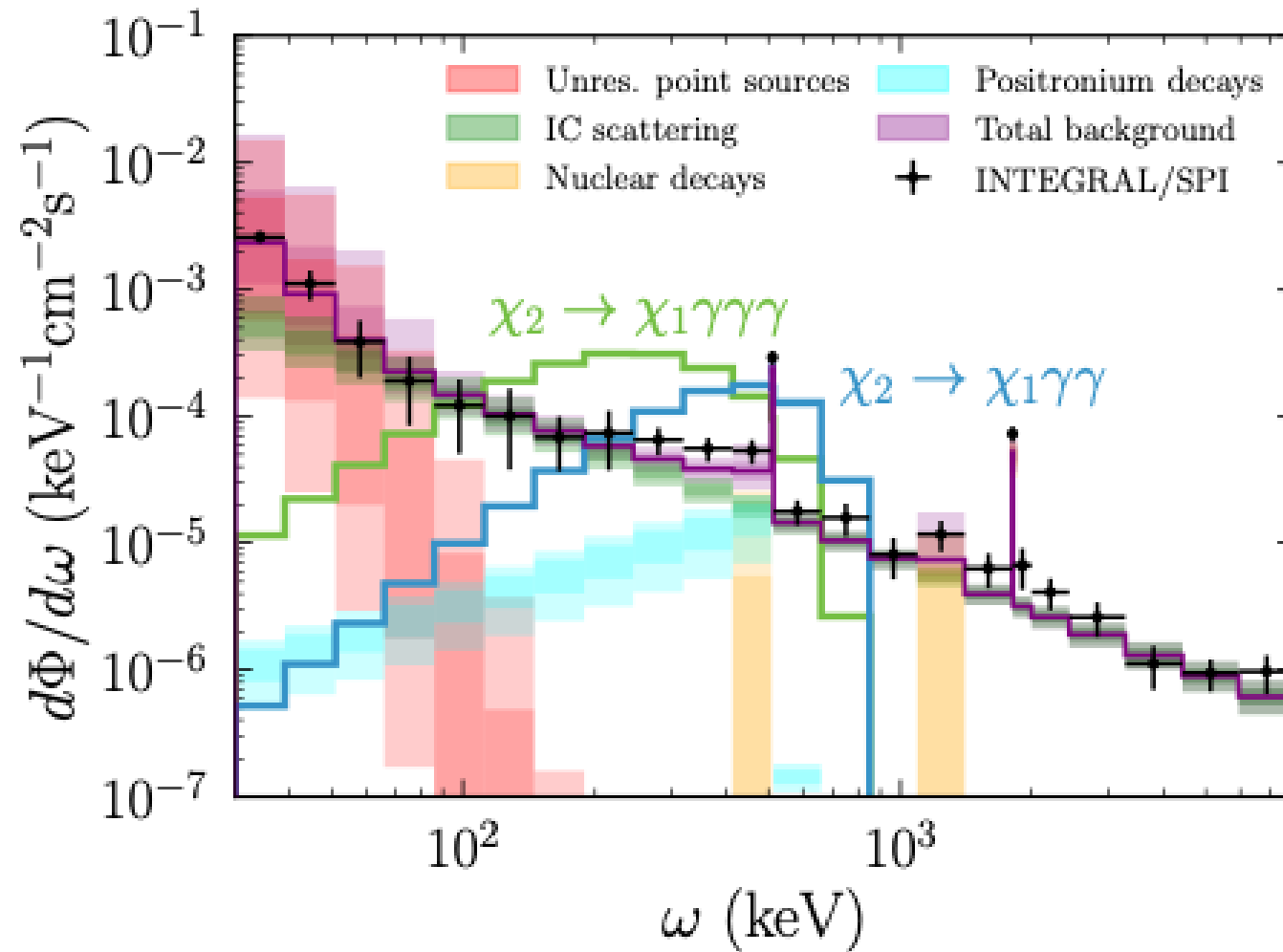
Photon's energy dist.
 Decay rate

- Emitted photon's energy: $\omega \leq \Delta m < 2m_e \sim 1 \text{ MeV} \Rightarrow$ hard X-ray region
- Despite χ_2 's long decay time, the expected signal from χ_2 decaying today in Milky Way galaxy matches the sensitivity of the INTEGRAL telescope



X-ray spectrum and background

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DM flux example: $\Delta m = 900$ keV, $\tau_{\chi_2} m_2 = 10^{23}$ s

Comparison to terrestrial experiments: dark photon

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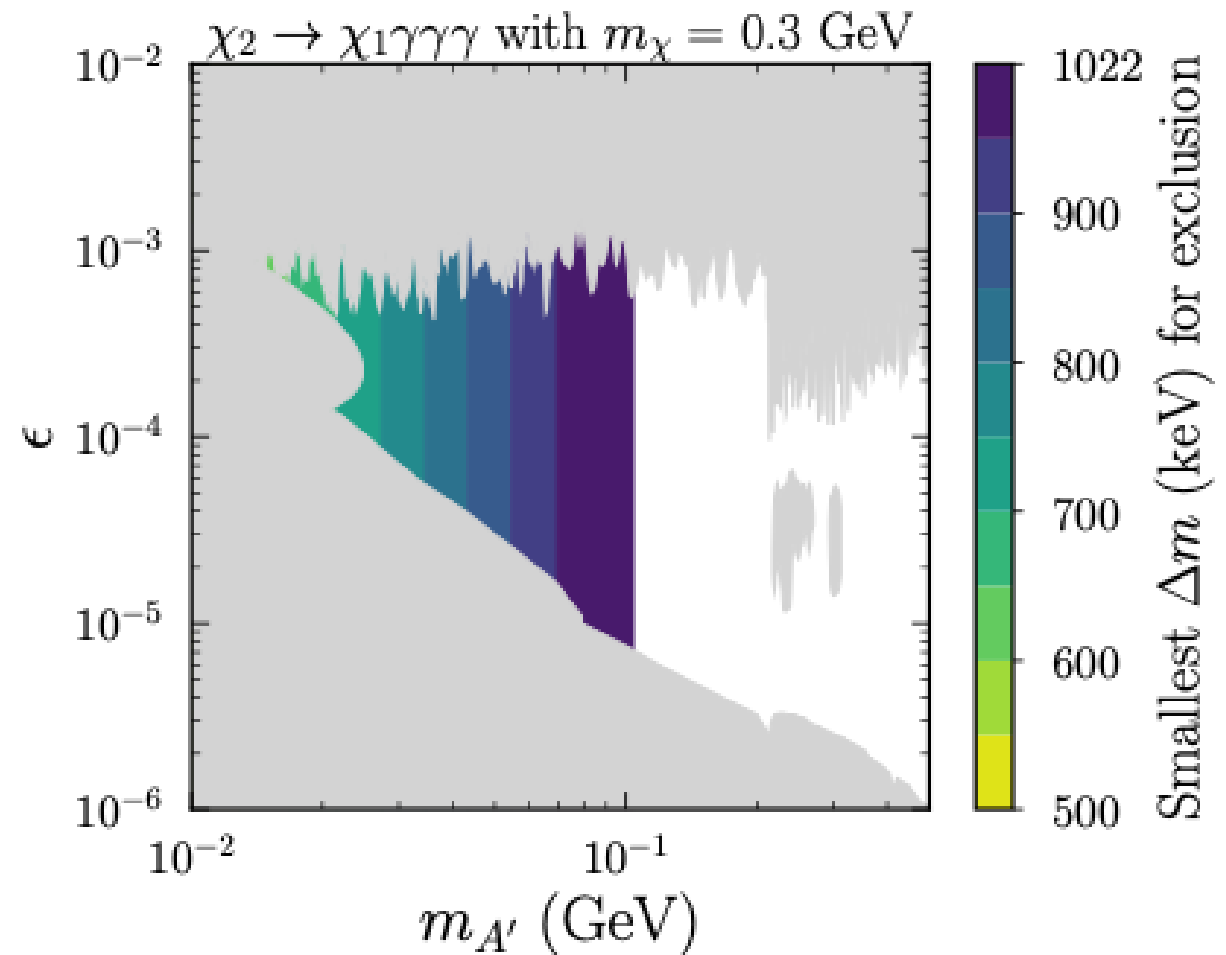
We translate our limits to mediator coupling to SM vs. mediator mass.

Gray regions: visible decays of A' from beam dump/ fixed targets (bottom) and colliders (top).

- On this plot, we fix m_2

$$\frac{d\Phi}{d\omega} \propto \frac{1}{\tau_{\chi_2} m_2} \propto \frac{(\epsilon g')^2 \Delta m^{13}}{m_{A'}^4} \frac{1}{m_2}$$

- $\epsilon g'$ is fixed for DM production, given m_2
- At each Δm , we set a lower limit for $m_{A'}$
- Larger Δm can probe larger $m_{A'}$
- In this inelastic DM scenario, we get to constrain the previously unexplored parameter space!



Comparison to terrestrial experiments: leptophilic scalar

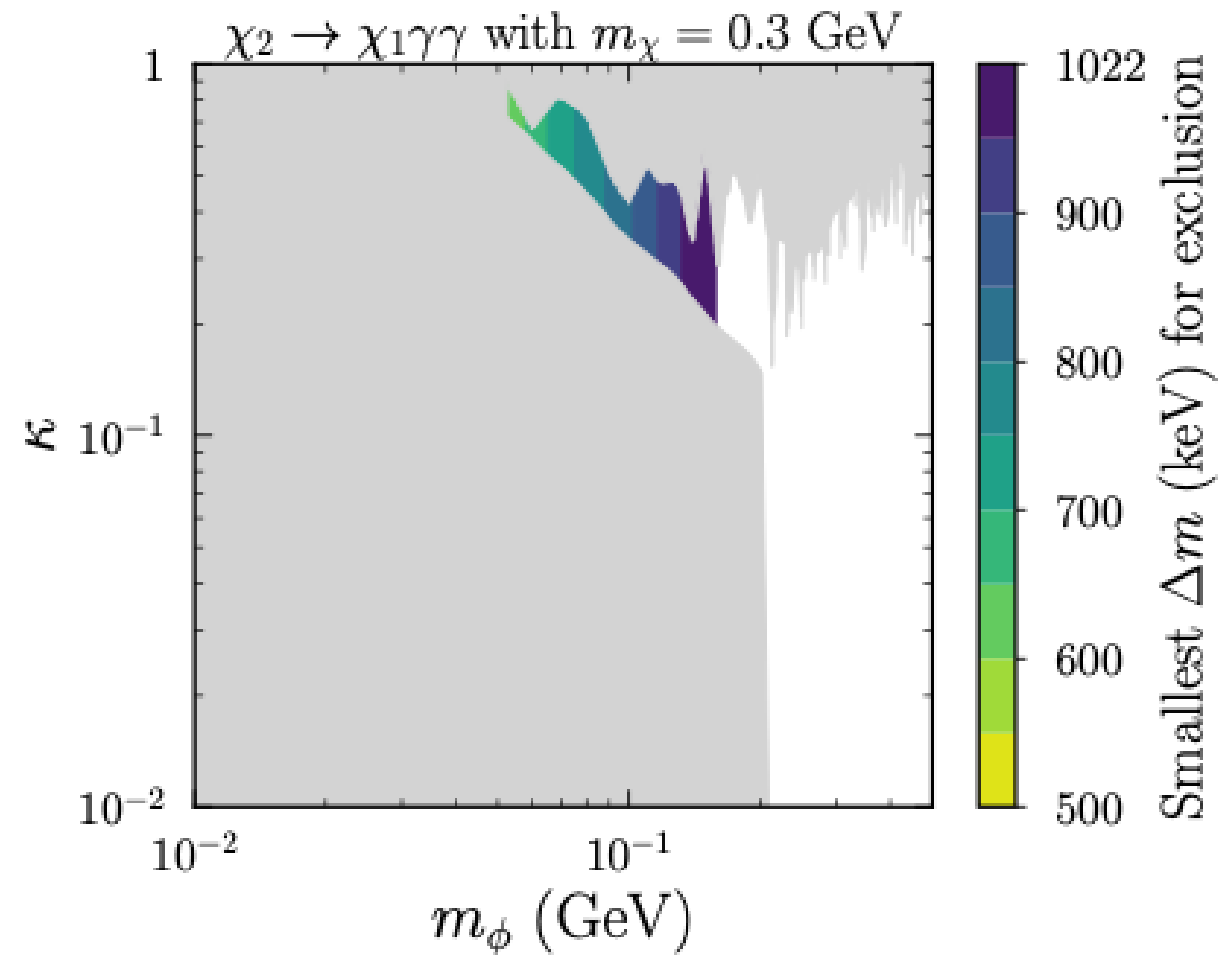
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We process the limits similarly for leptophilic scalar.

- Gray regions: visible decays of ϕ from beam dump/ fixed targets (bottom) and colliders (top).
- On this plot, we fix m_2

$$\frac{d\Phi}{d\omega} \propto \frac{1}{\tau_{\chi_2} m_2} \propto \frac{(\kappa y m_l / v)^2 \Delta m^7}{m_\phi^4} \frac{1}{m_2}$$

- $\kappa y m_l / v$ is fixed for DM production, given m_2
- At each Δm , we set a lower limit for m_ϕ
- Larger Δm can probe larger m_ϕ
- In this inelastic DM scenario, we get to constrain the previously unexplored parameter space!



Conclusion

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Inelastic DM model

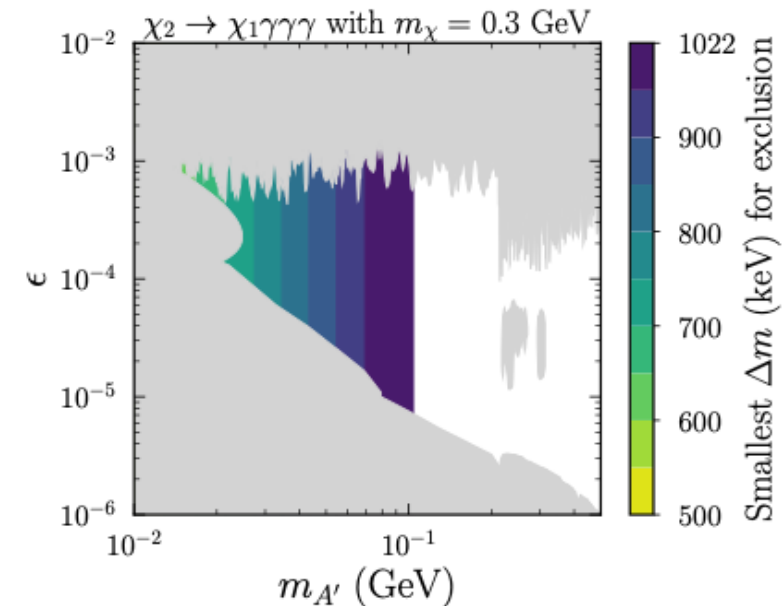
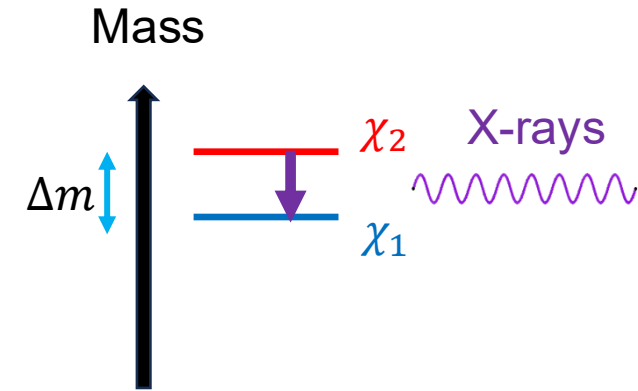
- Made of two almost degenerate states χ_1, χ_2 with $\Delta m \equiv m_2 - m_1$
- Two mediator scenarios: **dark photon** and **lepton-specific scalar**

DM production: freeze-in

- DM is feebly coupled to SM and gradually produced via $\bar{f}f \rightarrow \bar{\chi}\chi$
- χ_1, χ_2 make up half of DM each

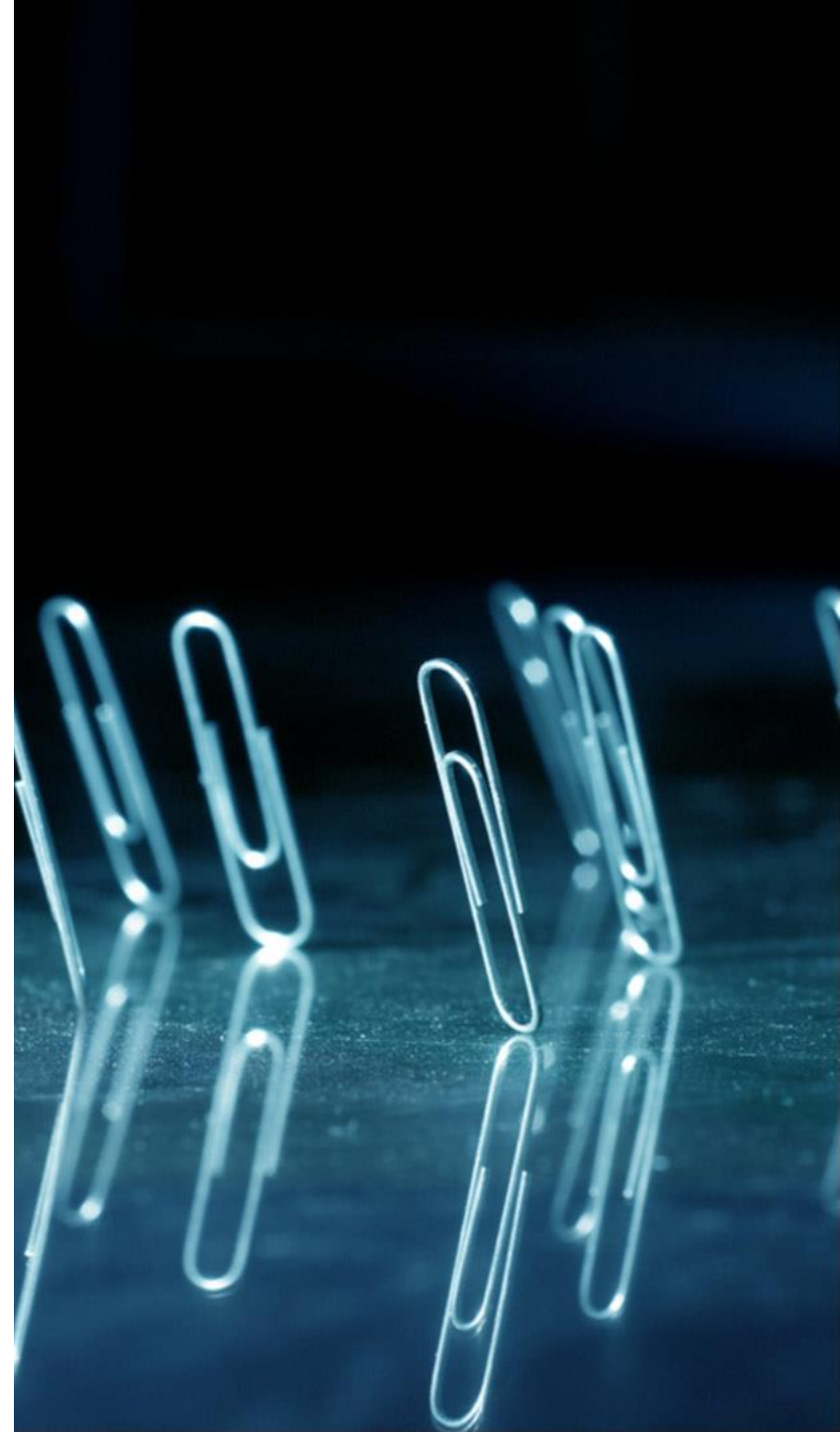
X-ray signals from χ_2 decays

- For $\Delta m < 2m_e$, χ_2 can decay but is cosmologically long-lived
- $\chi_2 \rightarrow \chi_1 \gamma \gamma \gamma$ / $\chi_2 \rightarrow \chi_1 \gamma \gamma$ can be detected as X-ray signals
- Constraints on DM signal strength probe previously unexplored parameter space



Thank you!

BACKUP SLIDES



Inelastic dark matter

	$U(1)'$
η	1
ξ	-1

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- Write down 4-component spinor in terms of 2-component spinors charged under $U(1)'$:

$$\chi = \begin{pmatrix} \eta \\ \xi^\dagger \end{pmatrix}; \quad \mathcal{L} \supset \eta^\dagger i \bar{\sigma}^\mu \partial_\mu \eta + \xi^\dagger i \bar{\sigma}^\mu \partial_\mu \xi - (m_\chi \eta \xi + \frac{m_\eta}{2} \eta \eta + \frac{m_\xi}{2} \xi \xi + h.c.)$$

- $U(1)'$ SSB w/ $\rightarrow$ small Majorana mass terms + symmetry-preserving Dirac mass terms

$$\mathcal{L} \supset \eta^\dagger i \bar{\sigma}^\mu \partial_\mu \eta + \xi^\dagger i \bar{\sigma}^\mu \partial_\mu \xi - (m_\chi \eta \xi + \frac{m_\eta}{2} \eta \eta + \frac{m_\xi}{2} \xi \xi + h.c.)$$

- Mass-diagonalizing,

$$\begin{aligned} \chi_1 &= \frac{i}{\sqrt{2}} \left[- \left(1 - \frac{m_\eta - m_\xi}{4m_\chi} \right) \eta + \left(1 + \frac{m_\eta - m_\xi}{4m_\chi} \right) \xi \right], \\ \chi_2 &= \frac{1}{\sqrt{2}} \left[\left(1 + \frac{m_\eta - m_\xi}{4m_\chi} \right) \eta + \left(1 - \frac{m_\eta - m_\xi}{4m_\chi} \right) \xi \right] \end{aligned}$$

And

$$m_{1,2} = m_\chi \mp \frac{\Delta m}{2}, \Delta m = |m_\eta - m_\xi|$$

Mediators' coupling to dark matter

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Dark photon

$$\mathcal{L} \supset ig' A'_\mu \left[(\chi_2^\dagger \bar{\sigma}^\mu \chi_1 - \chi_1^\dagger \bar{\sigma}^\mu \chi_2) + \frac{m_\eta - m_\xi}{2m_\chi} (\chi_2^\dagger \bar{\sigma}^\mu \chi_2 - \chi_1^\dagger \bar{\sigma}^\mu \chi_1) \right]$$

- $|m_\eta - m_\xi| = \Delta m$
- The off-diagonal coupling is small because $(m_\eta - m_\xi) / m_\chi \ll 1$

Lepton-specific scalar

$$\mathcal{L} \supset -\frac{\phi}{2} \left[\frac{y_+}{2} (-\chi_1 \chi_1 + \chi_2 \chi_2) + i y_- \chi_1 \chi_2 \right] + h.c.$$

- $y_\pm = y_\eta \pm y_\xi$ can be comparable in size.
- Here we assume that $y_- = y_+$ with both real and components equal.
- $y = \sqrt{|y_-|^2 + |y_+|^2} = 2y_-$.

Decays of χ_2 into photons: $\chi_2 \rightarrow \chi_1 \gamma \gamma \gamma$ with A^*

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- The leading-order, Heisenberg-Euler Lagrangian is given by

$$\mathcal{L}_{A'\gamma\gamma\gamma} = \frac{\epsilon\alpha_{EM}^2}{45m_e^4} F'_{\mu\nu} (14F^{\nu\rho}F_{\rho\sigma}F^{\sigma\mu} - 5F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma})$$

- The decay rate of χ_2 is

$$\Gamma_{\chi_2 \rightarrow \chi_1 3\gamma} = \frac{g'^2}{2\pi^2 m_{A'}^4} \int_0^{\Delta m^2} \frac{dk^2}{\sqrt{k^2}} d(\Delta m^2 - k^2)^{3/2} \Gamma_{A'}(\sqrt{k^2})$$

- $\Gamma_{A'}(\sqrt{k^2})$ is the decay rate of $A' \rightarrow \gamma\gamma\gamma$ at its effective mass $\sqrt{k^2}$:

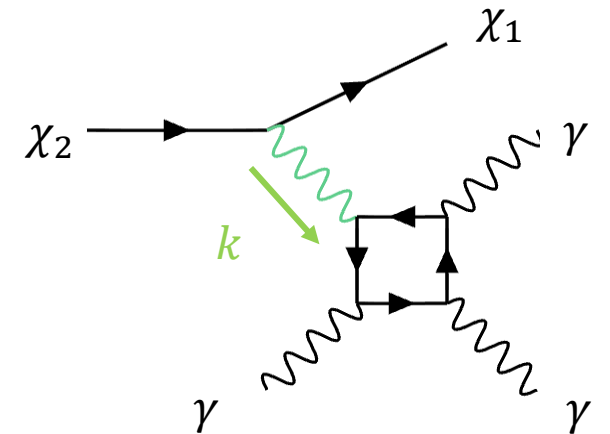
$$\Gamma_{A'}^0 = \frac{17\alpha_{EM}^4 (\sqrt{k^2})^9}{2^7 3^6 5^3 \pi^3 m_e^8} = \frac{1}{5.9 \text{ s}} \left(\frac{\epsilon}{10^{-4}} \right)^2 \left(\frac{\sqrt{k^2}}{900 \text{ keV}} \right)^9,$$

which ensures that A' decays away before BBN for $m_{A'} > 10 \text{ MeV}$.

- The leading order decay rate is

$$\Gamma_{\chi_2 \rightarrow \chi_1 \gamma \gamma}^0 = \frac{2^9}{3 \times 5 \times 7 \times 11 \times 13} \frac{g'^2}{4\pi^2} \frac{\Delta m^4}{m_{A'}^4} \Gamma_{A'}^0(\Delta m)$$

Dark photon:



Decays of χ_2 into photons: $\chi_2 \rightarrow \chi_1 \gamma \gamma$ with ϕ^*

- The leading-order Lagrangian is given by

$$\mathcal{L}_{\phi\gamma\gamma} = \sum_{l=e,\mu,\tau} \frac{\kappa m_l}{v} \times \frac{\alpha_{EM}}{6\pi m_l} \phi F^{\mu\nu} F_{\mu\nu} \sim \frac{\alpha_{EM} \kappa}{2\pi v} \phi F^{\mu\nu} F_{\mu\nu}$$

- The decay rate of χ_2 is

$$\Gamma_{\chi_2 \rightarrow \chi_1 2\gamma} = \frac{(\text{Im} y_-)^2}{8\pi m_\phi^4} \int_0^{\Delta m^2} dk^2 d\sqrt{\Delta m^2 - k^2} \Gamma_\phi(\sqrt{k^2})$$

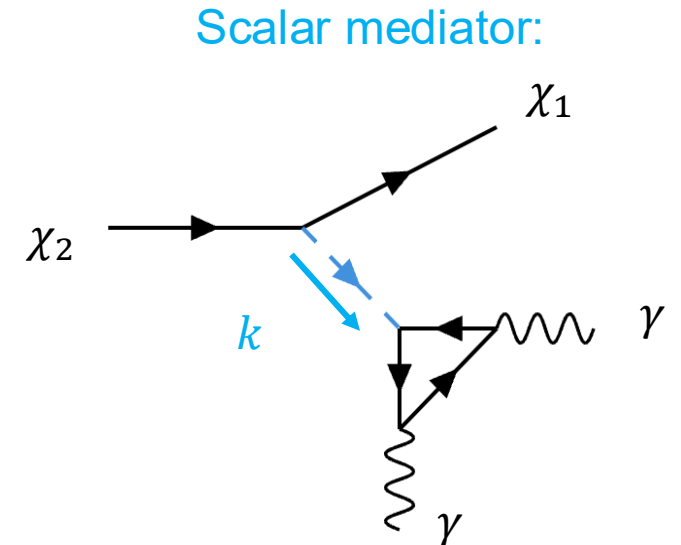
- $\Gamma_\phi(\sqrt{k^2})$ is the decay rate of $\phi \rightarrow \gamma\gamma$ at invariant mass $\sqrt{k^2}$:

$$\Gamma_\phi^0 = \frac{\kappa^2 \alpha_{EM}^2 (\sqrt{k^2})^3}{16\pi^3 v^2} = \frac{1}{0.15 \text{ s}} \left(\frac{\kappa}{0.1} \right)^2 \left(\frac{\sqrt{k^2}}{900 \text{ keV}} \right)^3,$$

which ensures that ϕ decays away before BBN for $m_\phi > 10 \text{ MeV}$.

- The leading order decay rate is

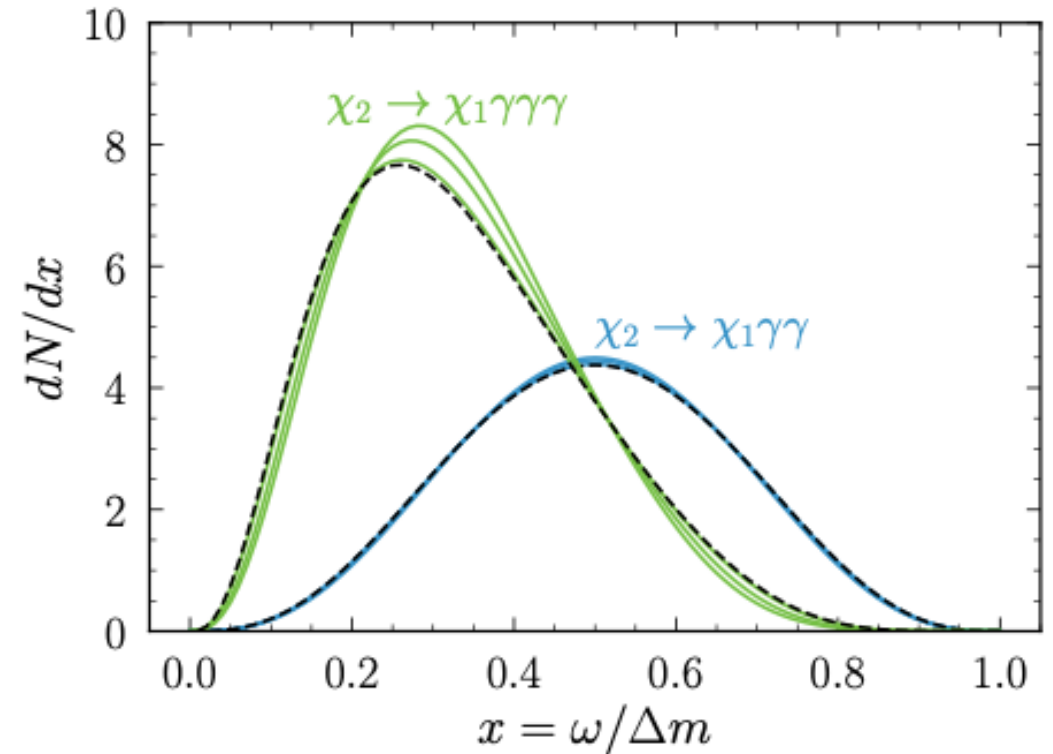
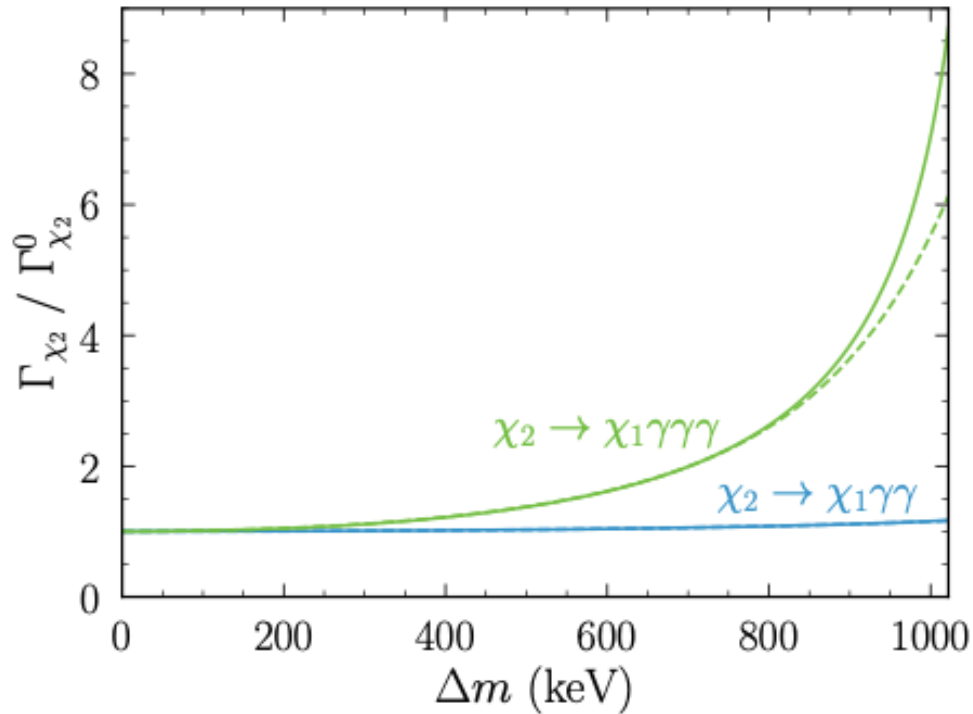
$$\Gamma_{\chi_2 \rightarrow \chi_1 \gamma \gamma}^0 = \frac{2^3}{3 \times 5 \times 7} \frac{(\text{Im} y_-)^2}{4\pi^2} \frac{\Delta m^4}{m_\phi^4} \Gamma_\phi^0(\Delta m)$$



EFT expansion for $\Delta m \rightarrow 2m_e$

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As Δm approaches the $2m_e$ threshold, higher-order terms need to be included in both decay rate and photon energy distributions, $dN/d\omega$.



Ingredients for X-ray flux: D factor

$$\frac{d\Phi}{d\omega} \propto \int \frac{d\Omega}{4\pi} \int_{l.o.s.} ds \, s^2 \rho_{DM} = \frac{D}{4\pi}$$

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D-factor captures the astrophysical distribution of DM

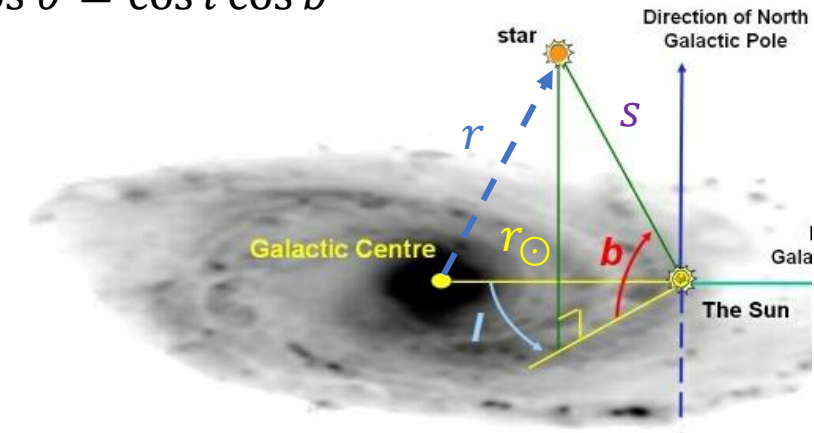
- We assume NFW profile:

$$\rho_{NFW}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}; \quad \rho_s = \rho_{DM,\odot} \left(\frac{r_\odot}{r_s}\right) \left(1 + \frac{r_\odot}{r_s}\right)^2$$

Assuming $r_s = 15$ kpc and $\rho_{DM,\odot} = 0.3$ GeV/cm³ at $r_\odot = 8.5$ kpc (GAIA: Cautun +, '19)

$$D = r_\odot \rho_\odot \int dl \, db \, \cos b \int \frac{ds}{r_\odot} \frac{\rho(r, \cos \theta)}{\rho_\odot}; \quad r = \sqrt{s^2 + r_\odot^2 - 2sr_\odot \cos \theta}; \quad \cos \theta = \cos l \cos b$$

- INTEGRAL/SPI observes longitude l and latitude b
 $-47.5^\circ < l, b < 47.5^\circ$
- We get $D = 0.9 \times 10^{23}$ GeV/cm³ and use it as the fiducial value.

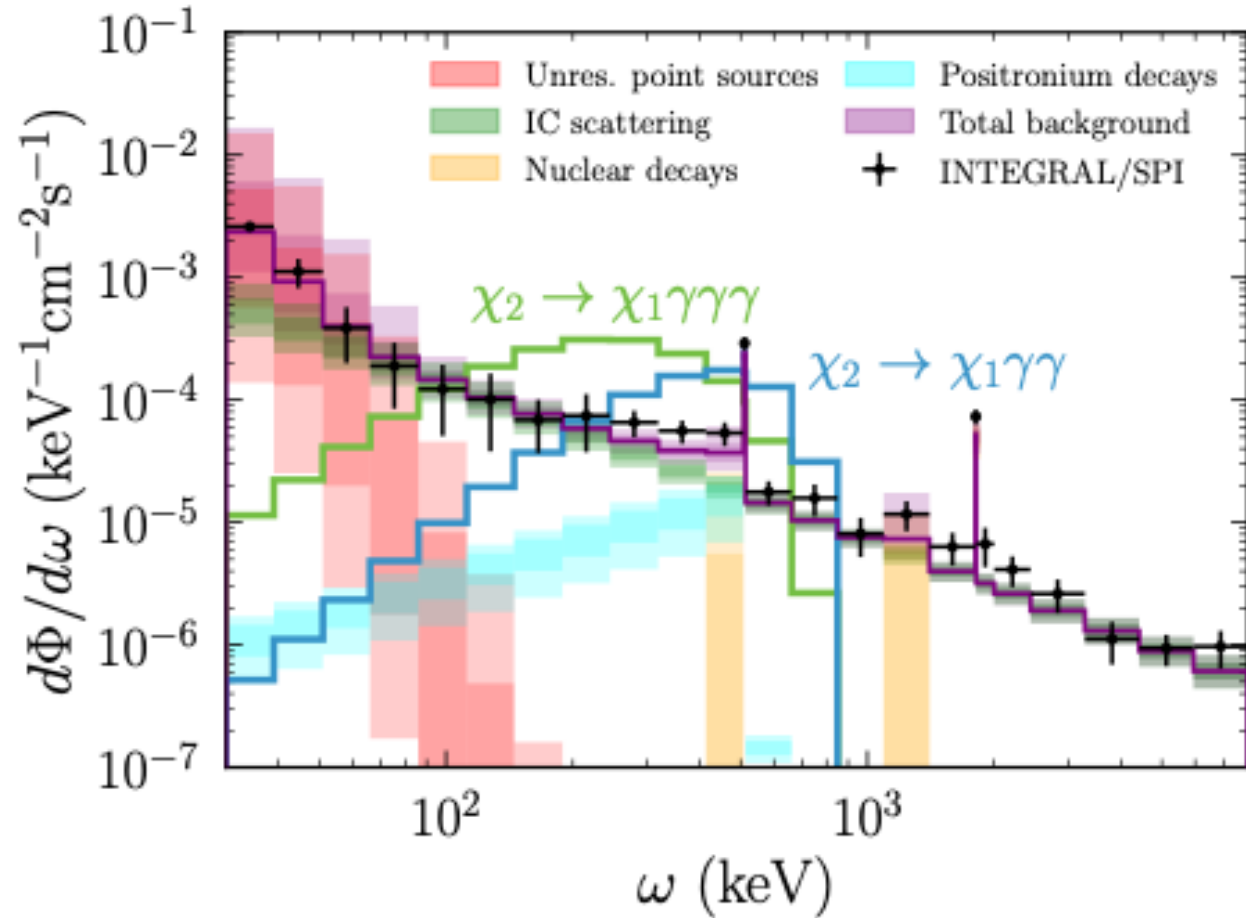


Bayesian analysis

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SPI Data:

- Adapted from Berteaud + '22; Calore +, '23
- Data: 30 keV – 8000 keV
- Observation time: 16 years
- Observation range: $-47.5^\circ < l, b < 47.5^\circ$



DM flux example: $\Delta m = 900 \text{ keV}, \tau = 10^{24} \text{ s}$

Bayesian analysis

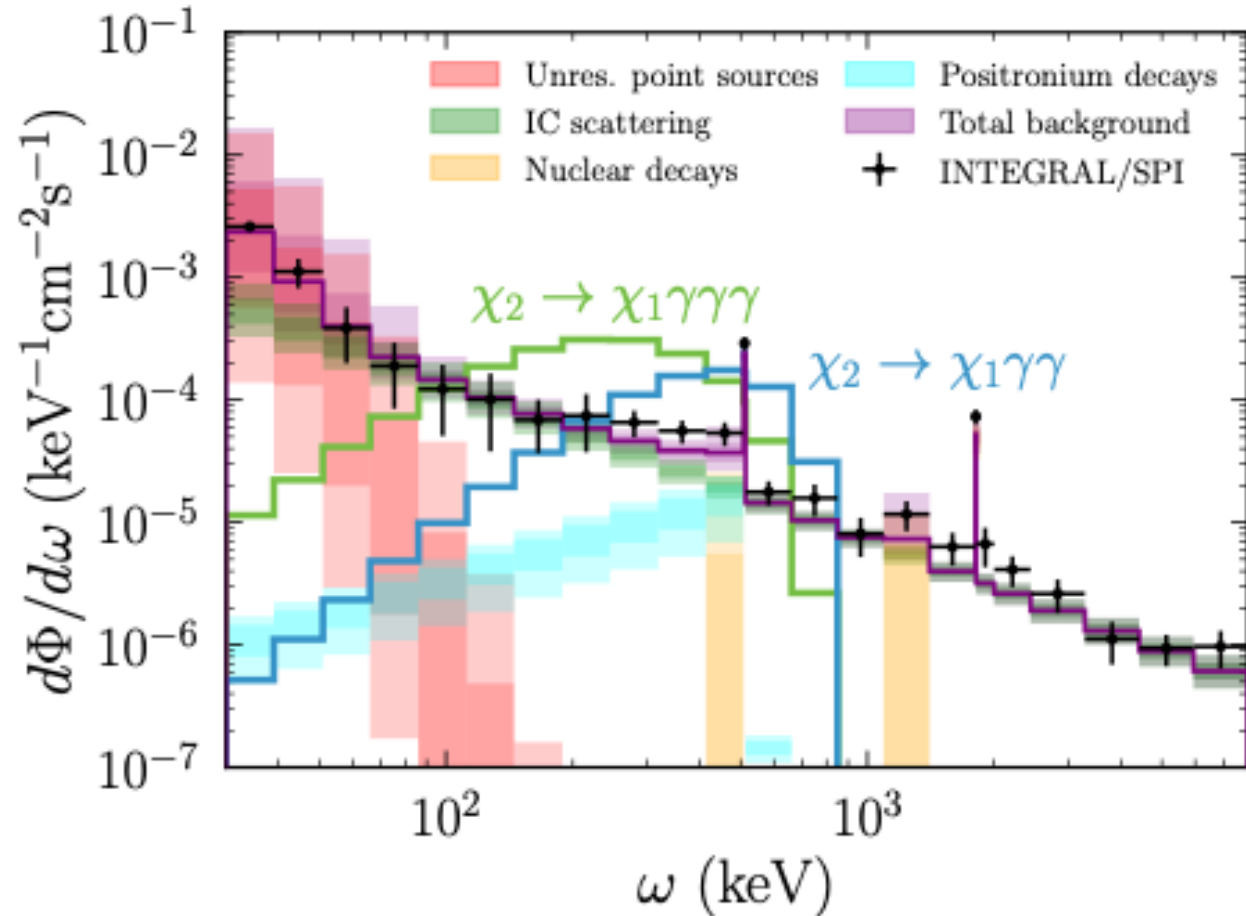
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Data analysis:

- Performed Bayesian analysis on python platform “3ML” with MCMC sampler “emcee”
- We float overall DM signal strength and scan over $\Delta m \in (0, 2m_e)$, which determines $\frac{dN}{d\omega}$

$$\frac{d\Phi}{d\omega} = \text{signal strength} \times \frac{dN}{d\omega}(\Delta m)$$

- Signal strength: $0 - 1 \text{ keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$, Uniform Prior
- Given null evidence for DM signals + background, set 95% credible upper limit for signal strength



DM flux example: $\Delta m = 900 \text{ keV}, \tau = 10^{24} \text{ s}$

Astrophysical backgrounds that compete with DM signals

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$$\Phi_{\text{unres}} = C_0 \left(\frac{E}{E_0} \right)^{\alpha_0} \exp \left(- \frac{E}{E_C} \right)$$

$$\Phi_{\text{IC}} = C_1 \left(\frac{E}{E_1} \right)^{\alpha_1}$$

$$\Phi_{\text{Ps}} = F_{\text{Ps}} \left[L_{\text{pPs}}(E) + \frac{9f_{\text{Ps}}}{8 - 6f_{\text{Ps}}} C_{\text{oPs}}(E) \right]$$

$$\Phi_{\text{Be}} = \frac{F_{\text{Be}}}{\sqrt{2\pi}\sigma_{\text{Be}}} \exp \left(- \frac{(E - \mu_{\text{Be}})^2}{2\sigma_{\text{Be}}^2} \right)$$

Sources (Spectrum)	Parameter	Fix/Free	Value/Range	Unit	Prior distribution
Unresolved Sources	C_0	Free	10^{-5} –1.0	$\text{keV}^{-1} \text{ s}^{-1} \text{ cm}^{-2}$	Log Uniform
	E_0	Fix	50	keV	-
	α_0	Fix	0.0	-	-
	E_C	Free	1–100	keV	Truncated Gaussian $F = 1, \mu = 7, \sigma = 3$
Inverse Compton	C_1	Free	10^{-10} –1.0	$\text{keV}^{-1} \text{ s}^{-1} \text{ cm}^{-2}$	Log Uniform
	E_1	Fix	1000	keV	-
	α_1	Free	-3.0–0.0	-	Uniform
Positronium	F_{511}	Free	10^{-6} –0.1	$\text{s}^{-1} \text{ cm}^{-2}$	Log Uniform
	f_{Ps}	Free	0.0–1.0	$\text{s}^{-1} \text{ cm}^{-2}$	Truncated Gaussian $F = 1, \mu = 1, \sigma = 0.2$
Nuclear line (${}^7\text{Be}$)	F_{Be}	Free	10^{-10} –1.0	$\text{s}^{-1} \text{ cm}^{-2}$	Log Uniform
	σ_{Be}	Fix	2.4	keV	-
	μ_{Be}	Fix	478	keV	-

Nuclear line backgrounds

$$\Phi_{\text{Be}} = \frac{F_{\text{Be}}}{\sqrt{2\pi}\sigma_{\text{Be}}} \exp\left(-\frac{(E - \mu_{\text{Be}})^2}{2\sigma_{\text{Be}}^2}\right)$$

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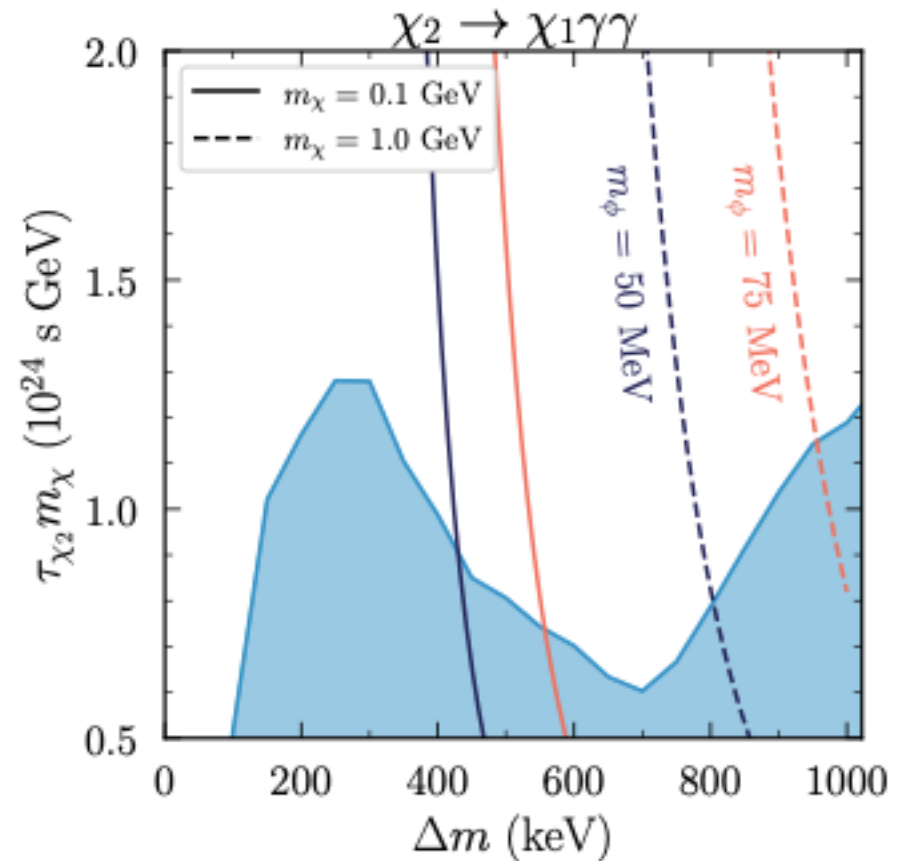
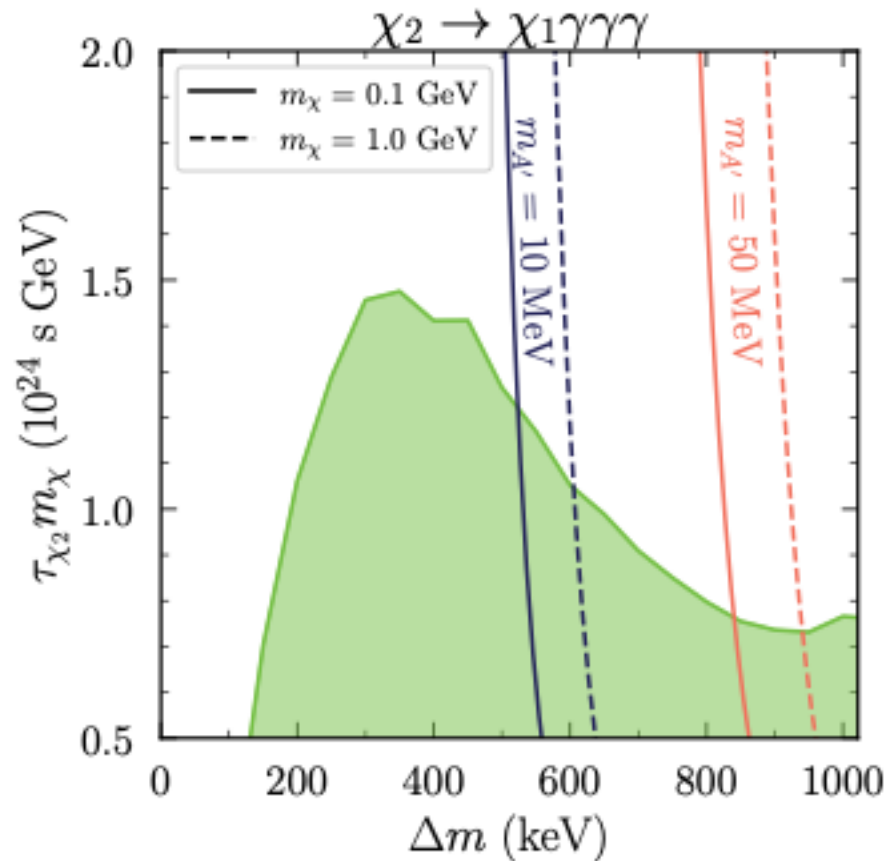
Sources	Parameter	Fix/Free	Value/Range	Units	Priors
⁷ Be	F_{Be}	Free	10^{-10} –1.0	$\text{s}^{-1} \text{ cm}^{-2}$	Truncated Gaussian F=1, $\mu =$, FWHM = 2.0×10^{-4}
	σ_{Be}	Fix	2.4	keV	-
	μ_{Be}	Fix	478	keV	-
²⁶ Al	F_{Al}	Free	10^{-10} –1.0	$\text{s}^{-1} \text{ cm}^{-2}$	Log Uniform ($F_{\text{Al}} = aF_{\text{Fe}}$)
	a	Free	0–1	-	Gaussian 0.18 ± 0.08
	σ_{Al}	Fix	1.7	keV	-
	μ_{Al}	Fix	1809	keV	-
⁶⁰ Fe ₁	F_{Fe_1}	Free	10^{-10} –1.0	$\text{s}^{-1} \text{ cm}^{-2}$	Log Uniform ($F_{\text{Fe}_1} = F_{\text{Fe}_2}$)
	σ_{Fe_1}	Fix	1.5	keV	-
	μ_{Fe_1}	Fix	1173	keV	-
⁶⁰ Fe ₂	F_{Fe_2}	Free	10^{-10} –1.0	$\text{s}^{-1} \text{ cm}^{-2}$	Log Uniform ($F_{\text{Fe}_1} = F_{\text{Fe}_2}$)
	σ_{Fe_2}	Fix	1.5	keV	-
	μ_{Fe_2}	Fix	1332	keV	-
²² Na	F_{Na}	Free	10^{-10} –1.0	$\text{s}^{-1} \text{ cm}^{-2}$	Truncated Gaussian F=1, $\mu =$, FWHM = 1.3×10^{-4}
	σ_{Na}	Fix	8.5	keV	-
	μ_{Na}	Fix	1275	keV	-

Translating results to lower limits on τm_2

$$\frac{d\Phi}{d\omega dt} = \frac{dN}{d\omega} \frac{1}{\tau_{\chi_2}} \frac{1}{m_2} \frac{D}{8\pi}$$

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- We derive the limits for the maximum signal strength allowed at each Δm
- We translate the limits to $\tau_{\chi_2} m_2$



Mediator plots with Δm fixed

$$\frac{d\Phi}{d\omega dt} = \frac{dN}{d\omega} \frac{1}{\tau_{\chi_2}} \frac{1}{m_2} \frac{D}{8\pi} \propto \frac{\text{coupling}^2 \Delta m^c}{m_{med}^4} \frac{1}{m_2}$$

