TRIUMF

X-rays from inelastic dark matter freeze-in

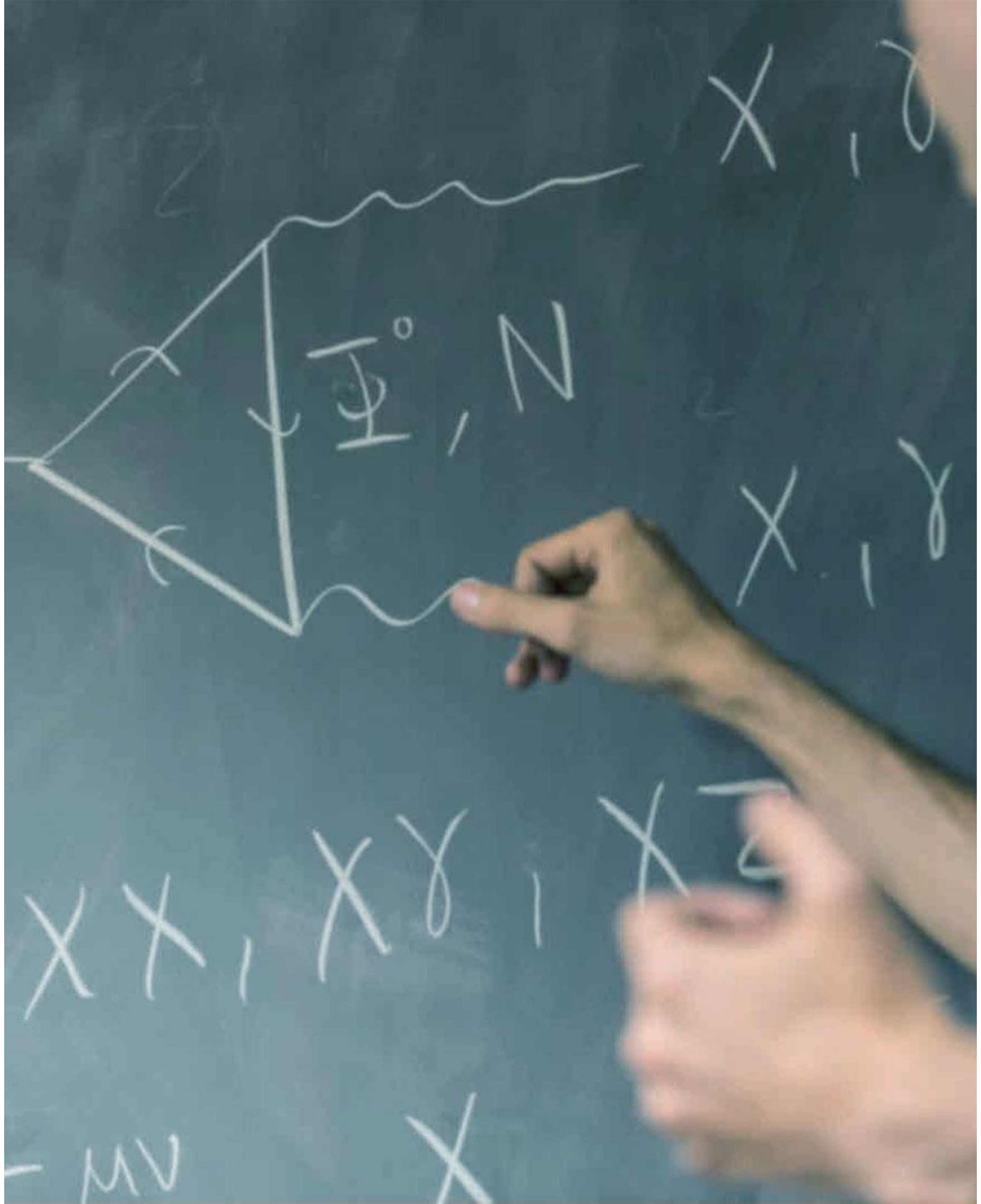
Riku Mizuta (he/him)

With G. Krnjaic, D. McKeen, D. Morrissey, G. Mohlabeng, D. Tuckler

arXiv: 2509.19428; Phys. Rev. D **112**, 115039

Phenomenology Symposium 2026

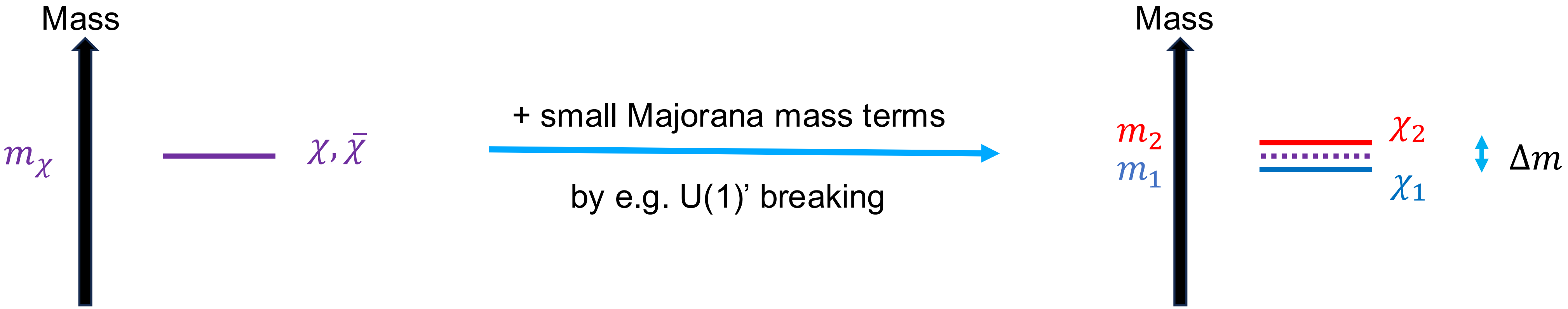
May 12, 2026



Discovery, accelerated

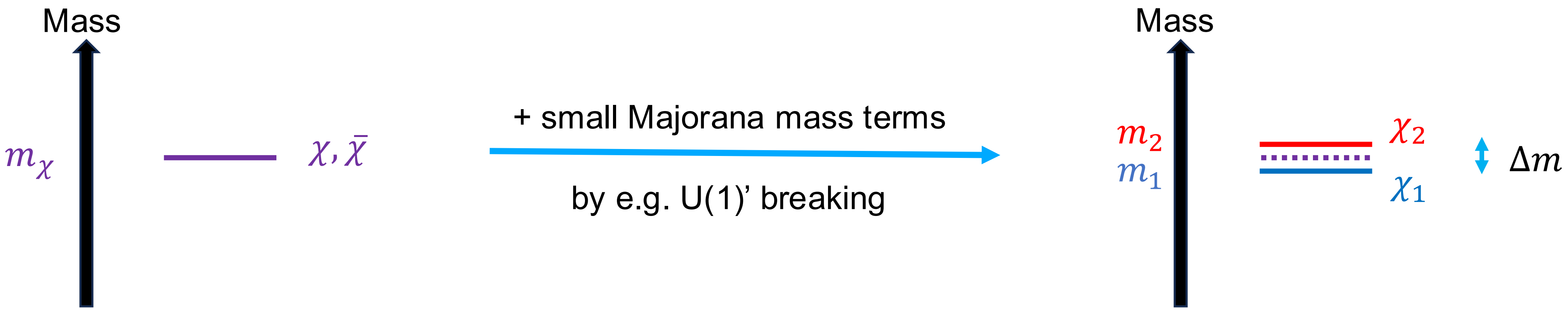
Model setup

Inelastic dark matter



Model setup

Inelastic dark matter



Two benchmark scenarios for a mediator that couples to χ_1, χ_2 and SM:

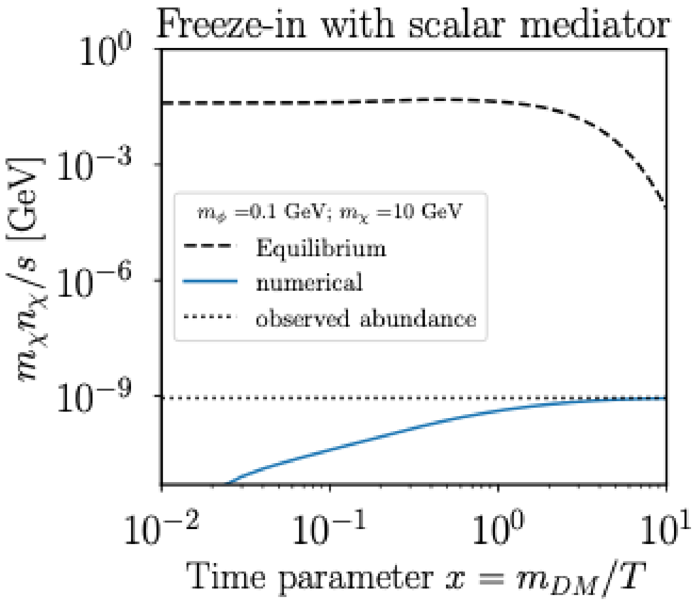
- Dark photon A': coupled to SM fermions universally
- Leptophilic scalar ϕ: couples to leptons mass-proportionally

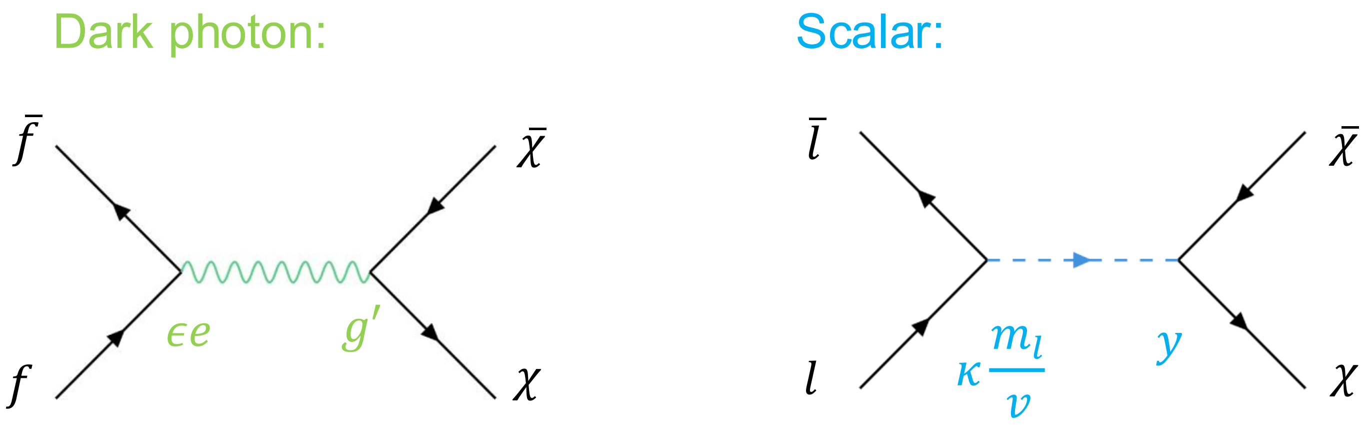
Freeze-in of inelastic dark matter

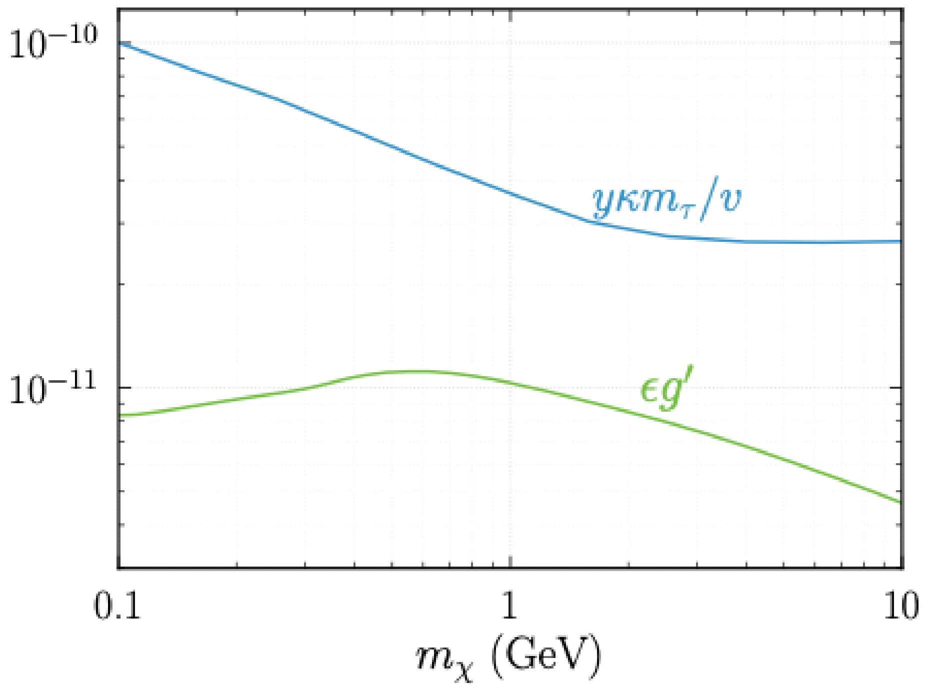
- We assume
  - no initial amount of DM
  - Feeble coupling between DM and SM
- DM is gradually populated by $f\,\bar{f} \to \bar{\chi}\chi$
- IR freeze-in: The production is dominated by $T \sim m_\chi$

➡ It does not depend on the initial conditions

- DM = ½ χ_1 + ½ χ_2!



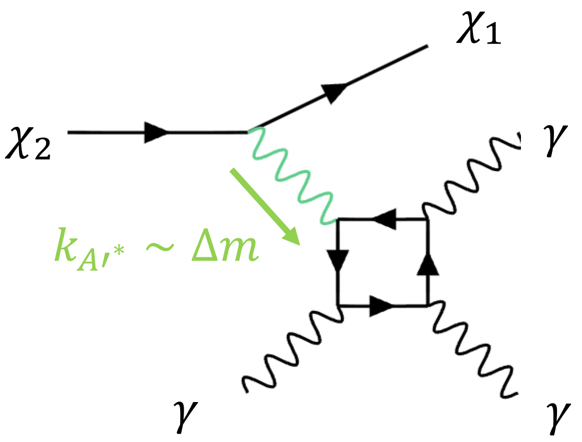




Decays of heavier state χ_2

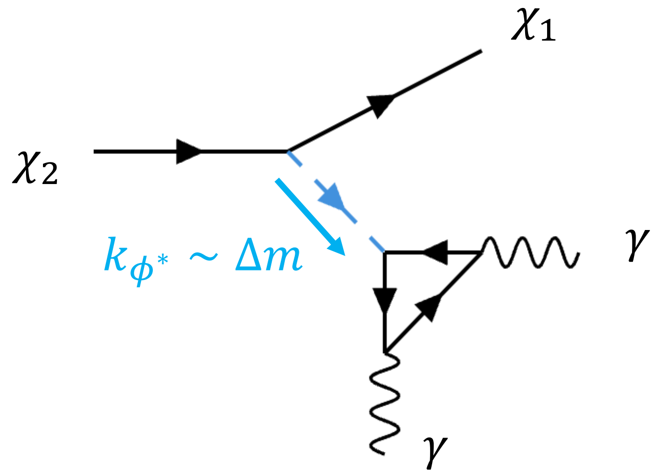
Below $\Delta m < 2m_e$, χ_2 is meta-stable and can decay into χ_1 and photons:

Dark photon:



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

Scalar mediator:



$$\frac{1}{\tau_{\chi_2 \to \chi_1 \gamma\gamma}} \sim \frac{1}{10^{23}\ \mathrm{s}} \left(\frac{\mathrm{coupling}}{10^{-9}}\right)^2 \left(\frac{\Delta m}{900\ \mathrm{keV}}\right)^{7} \left(\frac{30\ \mathrm{MeV}}{\mathrm{m}_{\phi}}\right)^4$$

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

X-ray signals from χ_2 decays

Expected photon flux from χ_2 decays is given by

Purple: astro/cosmo
Red: model param.

Fraction of χ_2 in DM

const.

$$\frac{d\Phi}{d\omega} = \frac{dN}{d\omega}\frac{1}{\tau_{\chi_2}}\frac{1}{m_2}\frac{1}{2}\int\frac{d\Omega}{4\pi}\int_{l.o.s.} ds\;\; s^2\,\rho_{DM} = \frac{dN}{d\omega}\frac{1}{\tau_{\chi_2}\, m_2}\frac{D}{8\pi}$$

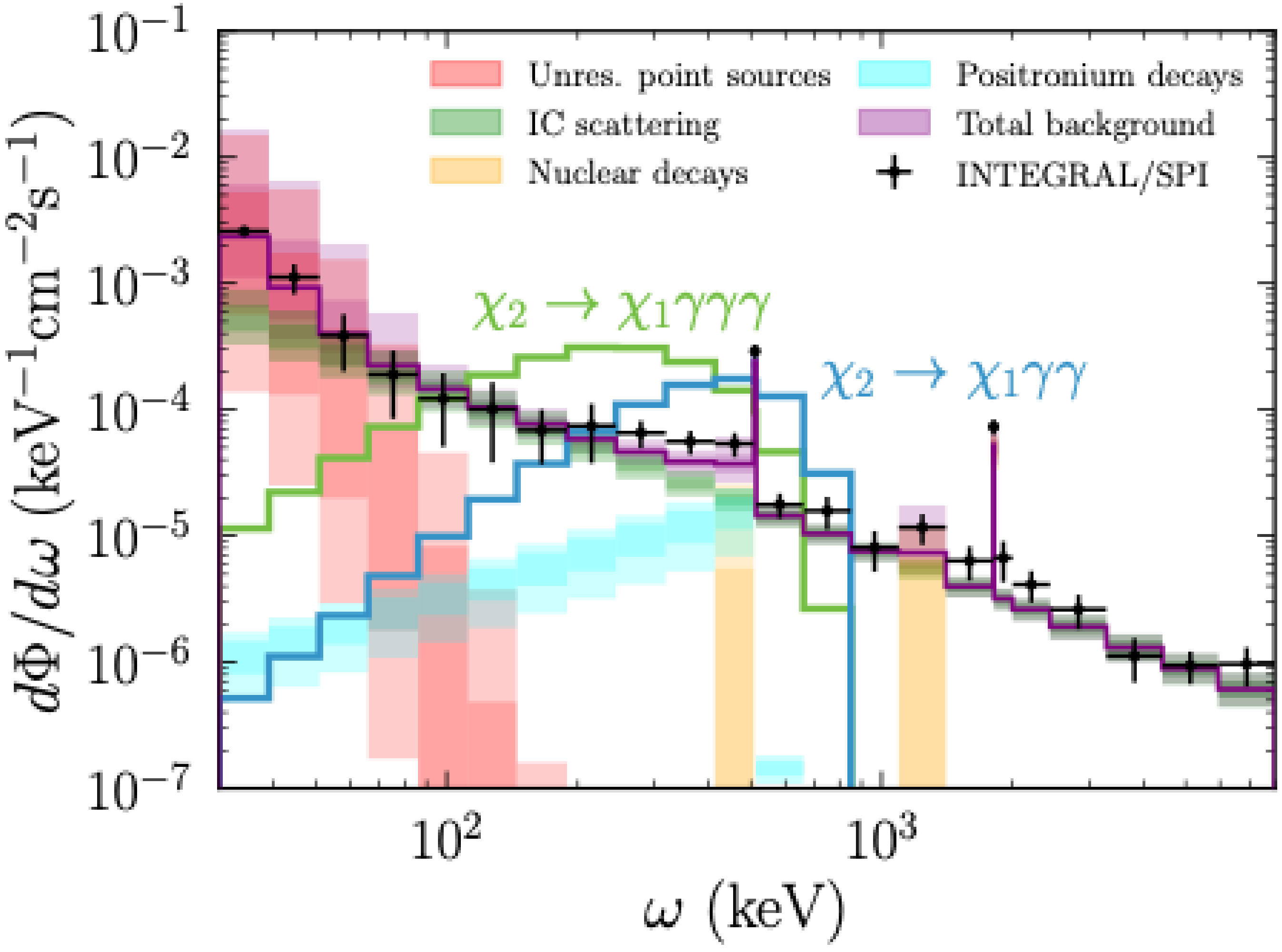
No. of χ_2 in line of sight

Photon's energy dist.

Decay rate

- Emitted photon's energy: $\omega \leq \Delta m < 2m_e \sim 1\ \mathrm{MeV}$ ⇨ 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



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

Berteaud + ‘22; Calore + ’23

Comparison to terrestrial experiments: dark photon

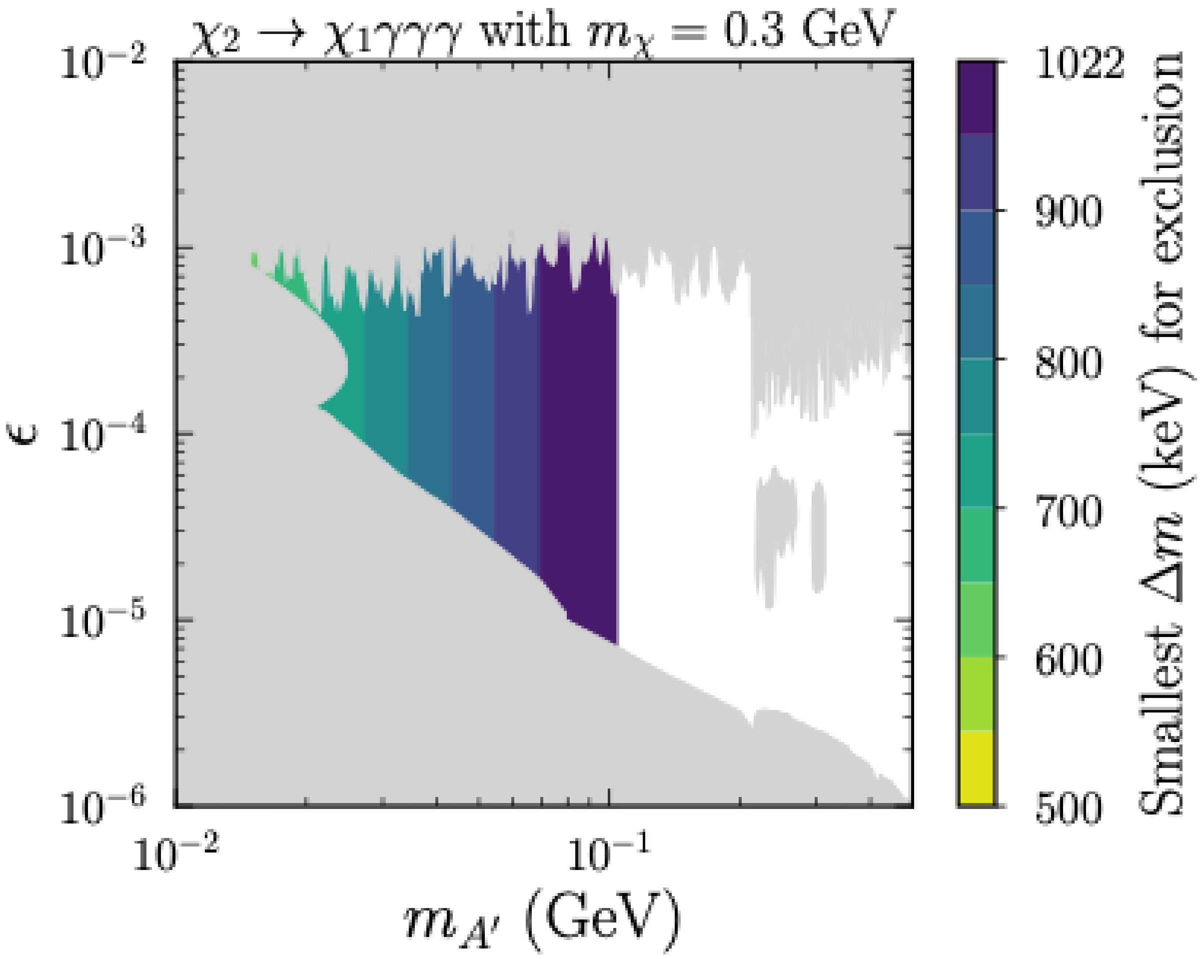
We translate our limits to mediator coupling to SM vs. mediator mass.

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!



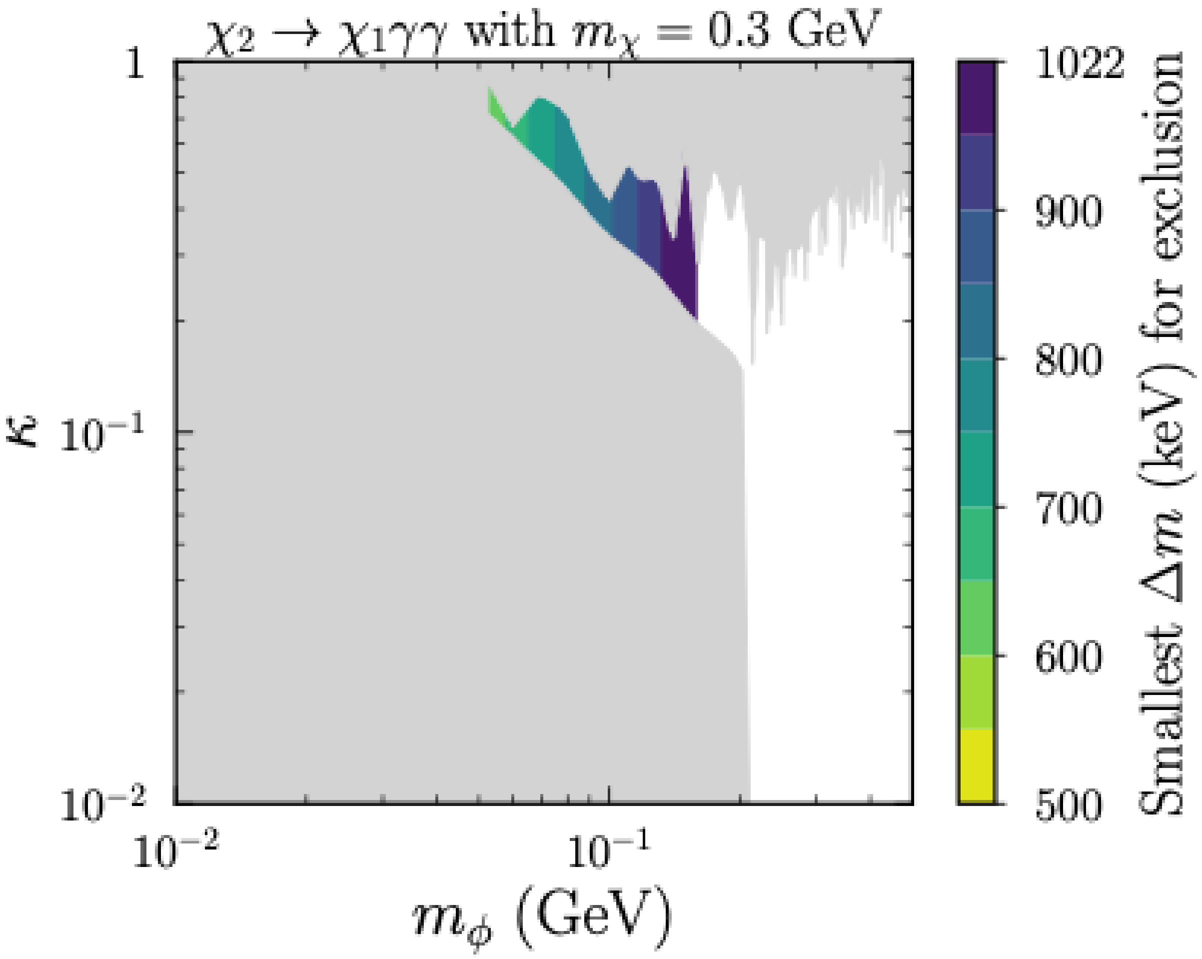
Comparison to terrestrial experiments: leptophilic scalar

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

Inelastic DM model

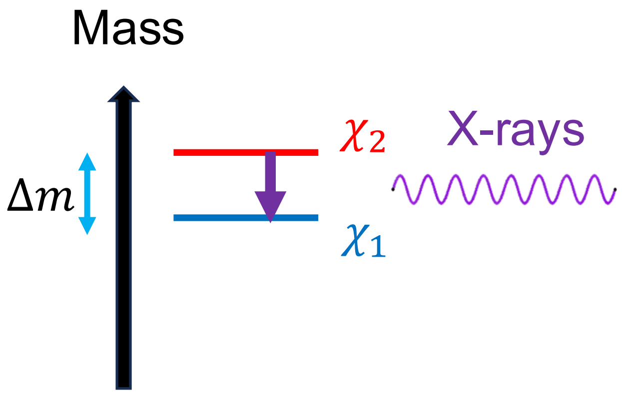
- Made of two almost degenerate states χ_1, χ_2 with $\Delta m \equiv m_2 - m_1$
- Two mediator scenarios: dark photon and lepton-specific scalar

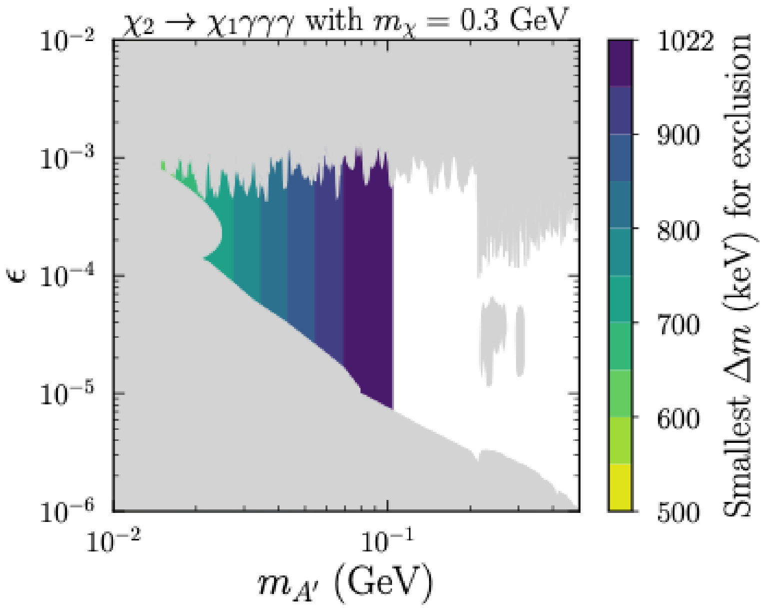
DM production: freeze-in

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

X-ray signals from χ_2 decays

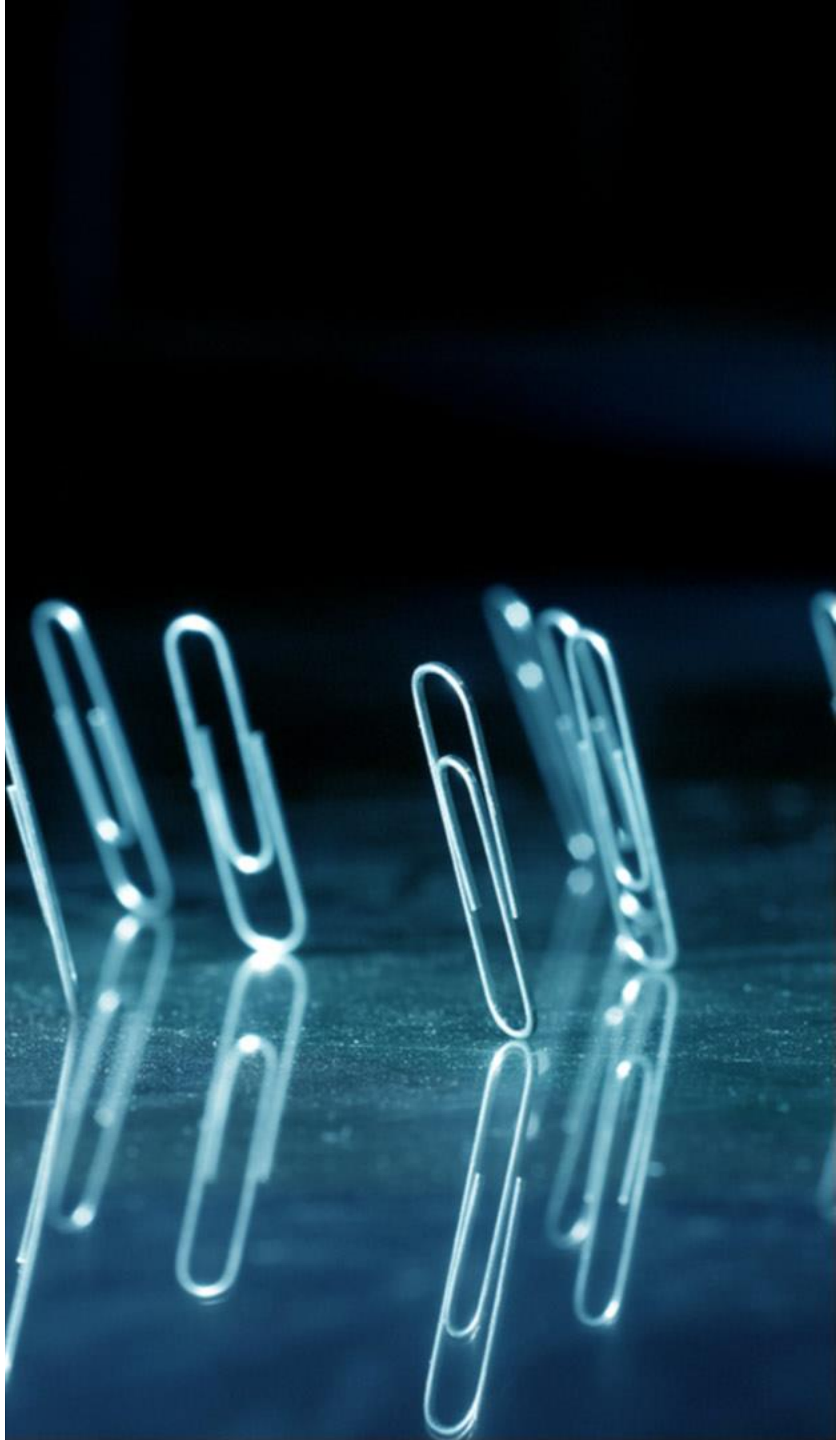
- For $\Delta m < 2m_e$, χ_2 can decay but is cosmologically long-lived
- $\chi_2 \to \chi_1\gamma\gamma\gamma$ / $\chi_2 \to \chi_1\gamma\gamma$ can be detected as X-ray signals
- Constraints on DM signal strength probe previously unexplored parameter space





Thank you!

BACKUP SLIDES



Inelastic dark matter

	$U(1)'$
η	1
ξ	-1

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

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

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

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

- Mass-diagonalizing,

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

And

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

Mediators' coupling to dark matter

Dark photon

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

- $|m_\eta - m_\xi| = \Delta m$
- 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.
- $y = \sqrt{|y_-|^2 + |y_+|^2} = 2 y_-$.

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

- 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

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

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

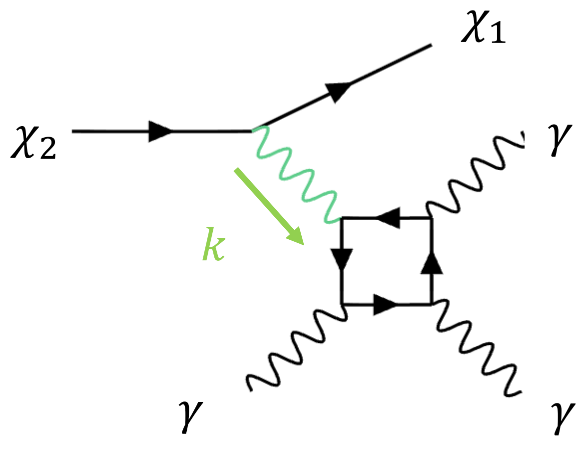
$$\Gamma_{A'}^0 = \frac{17\alpha_{EM}^4\left(\sqrt{k^2}\right)^9}{2^7 3^6 5^3 \pi^3 m_e^8} = \frac{1}{5.9\ \mathrm{s}}\left(\frac{\epsilon}{10^{-4}}\right)^2\left(\frac{\sqrt{k^2}}{900\ \mathrm{keV}}\right)^9,$$

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

- The leading order decay rate is

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

Dark photon:



Decays of χ_2 into photons: $\chi_2 \to \chi_1\gamma\gamma$ 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

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

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

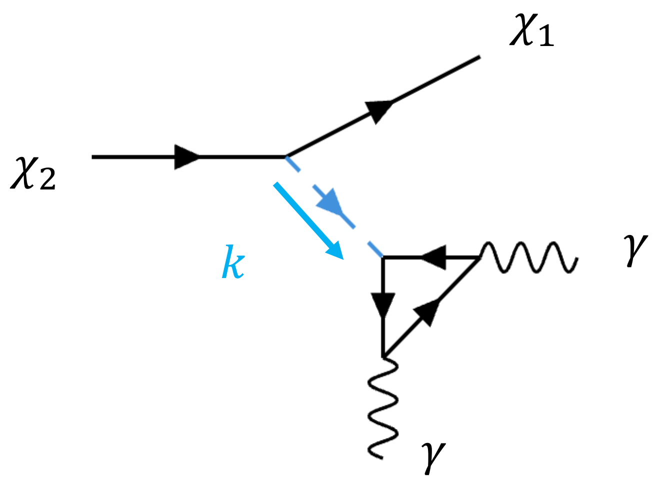
$$\Gamma_\phi^0 = \frac{\kappa^2 \alpha_{EM}^2 \left(\sqrt{k^2}\right)^3}{16\pi^3 v^2} = \frac{1}{0.15\ \mathrm{s}} \left(\frac{\kappa}{0.1}\right)^2 \left(\frac{\sqrt{k^2}}{900\ \mathrm{keV}}\right)^3,$$

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

- The leading order decay rate is

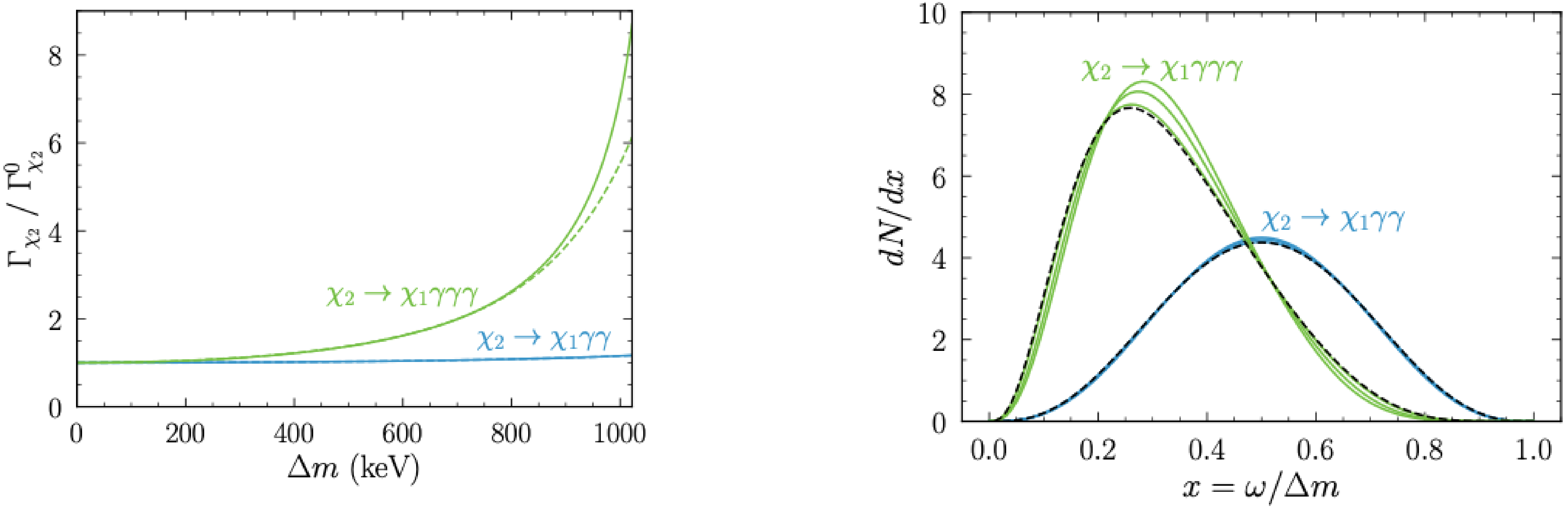
$$\Gamma_{\chi_2\to\chi_1\gamma\gamma}^0 = \frac{2^3}{3\times 5\times 7} \frac{(\mathrm{Im} y_-)^2}{4\pi^2} \frac{\Delta m^4}{m_\phi^4} \Gamma_\phi^0(\Delta m)$$

Scalar mediator:



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

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



Full one-loop $A'\gamma\gamma\gamma$ vertex: Dermott, Patel, Ramani: 1705.00619

Ingredients for X-ray flux: D factor

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

D-factor captures the astrophysical distribution of DM

- We assume NFW profile:

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

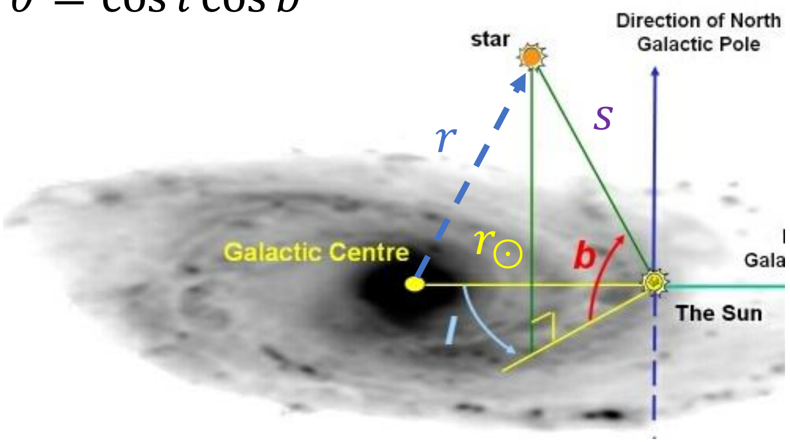
Assuming $r_s = 15$ kpc and $\rho_{\mathrm{DM},\odot} = 0.3\ \mathrm{GeV/cm^3}$ at $r_\odot = 8.5$ kpc (GAIA: Cautun +, ‘19)

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

- INTEGRAL/SPI observes longitude l and latitude b

$$-47.5^\circ < l, b < 47.5^\circ$$

- We get $D = 0.9 \times 10^{23}\ \mathrm{GeV/cm^3}$ and use it as the fiducial value.

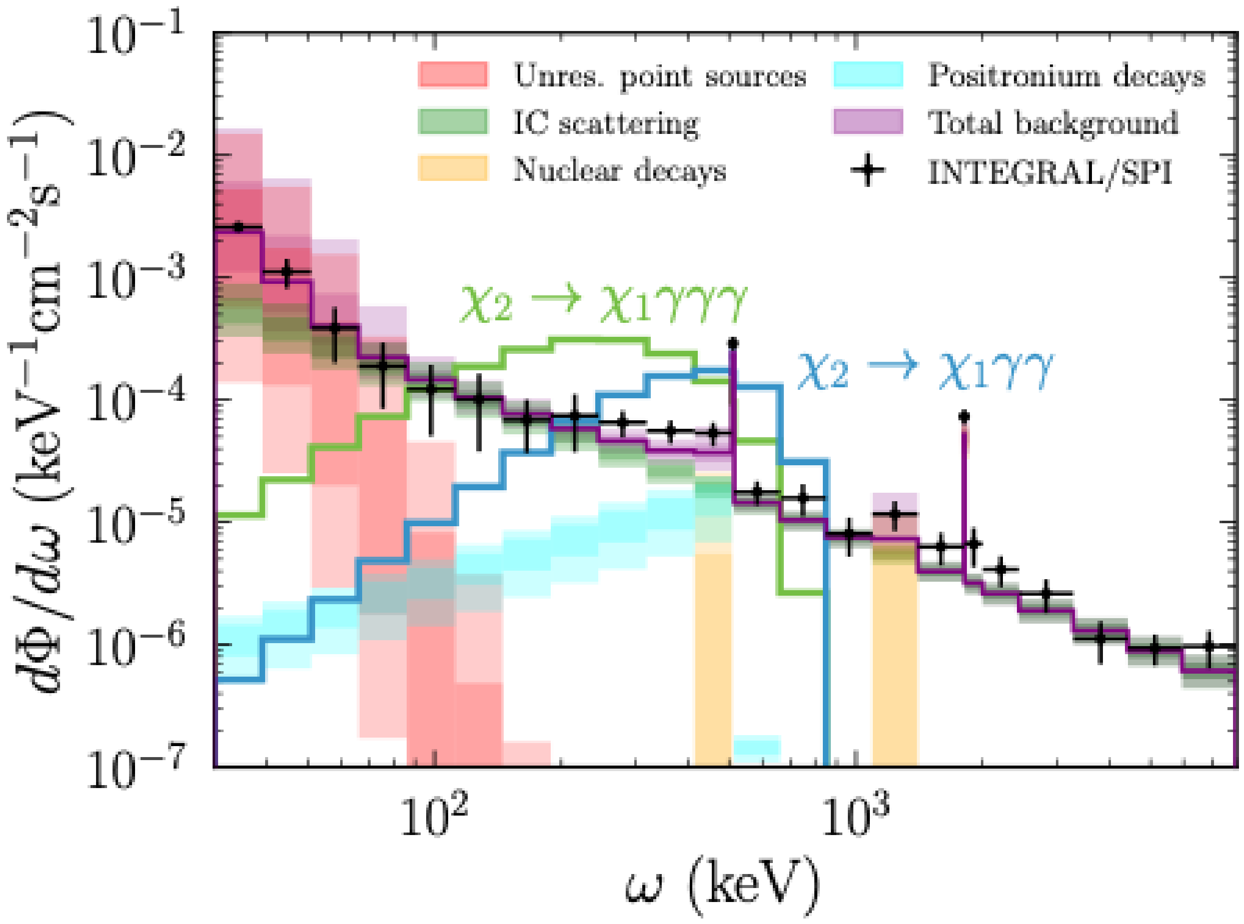


https://astronomy.swin.edu.au/cosmos/G/Galactic+Coordinate+System

Bayesian analysis

SPI Data:

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



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

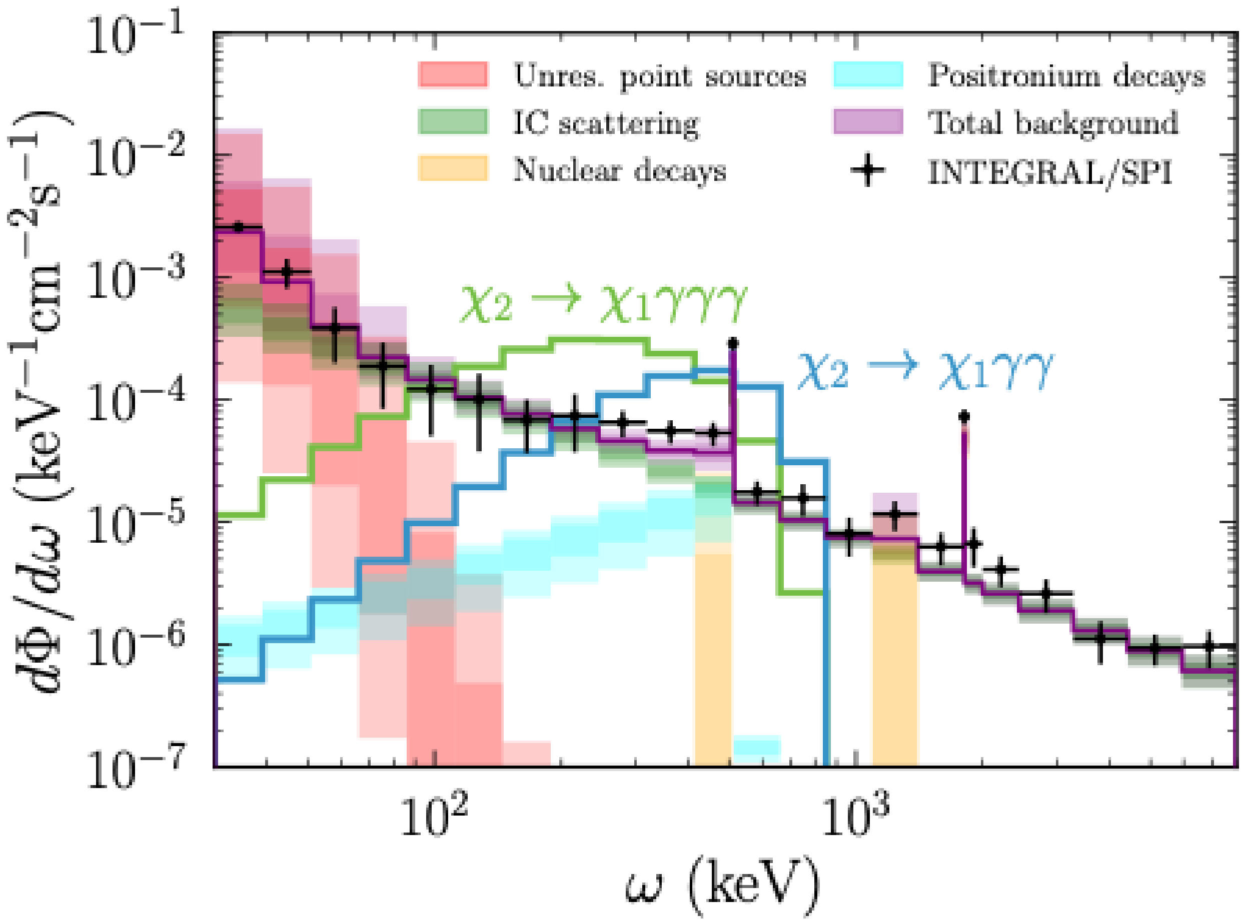
Bayesian analysis

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



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

Astrophysical backgrounds that compete with DM signals

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

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

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

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

Sources (Spectrum)	Parameter	Fix/Free	Value/Range	Unit	Prior distribution
Unresolved Sources	C_0	Free	10^{-5}–1.0	keV^{-1} s^{-1} 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	keV^{-1} s^{-1} 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	s^{-1} cm^{-2}	Log Uniform
	$f_{\rm Ps}$	Free	0.0–1.0	s^{-1} cm^{-2}	Truncated Gaussian $F=1,\ \mu=1,\ \sigma=0.2$
Nuclear line (^{7}Be)	$F_{\rm Be}$	Free	10^{-10}–1.0	s^{-1} cm^{-2}	Log Uniform
	$\sigma_{\rm Be}$	Fix	2.4	keV	-
	$\mu_{\rm Be}$	Fix	478	keV	-

Cf. Berteaud + '22; Calore + '23; Linden + '24

Nuclear line backgrounds

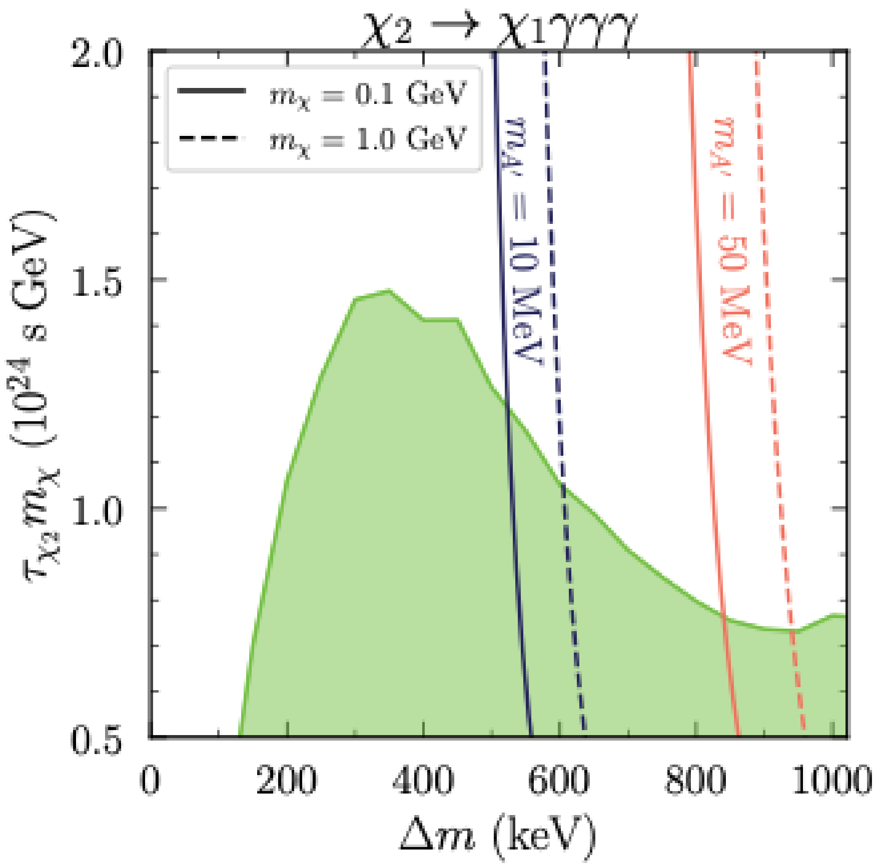
$$\Phi_{\mathrm{Be}} = \frac{F_{\mathrm{Be}}}{\sqrt{2\pi}\sigma_{\mathrm{Be}}} \exp\left(-\frac{(E-\mu_{\mathrm{Be}})^2}{2\sigma_{\mathrm{Be}}^2}\right)$$

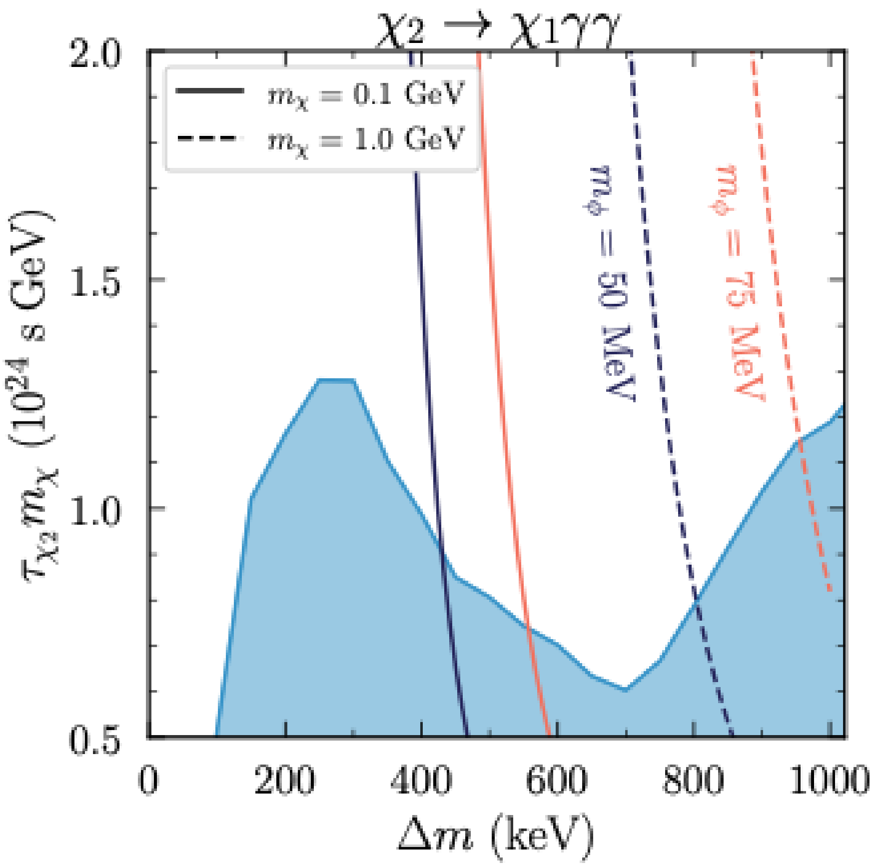
Sources	Parameter	Fix/Free	Value/Range	Units	Priors
$^{7}\mathrm{Be}$	F_{Be}	Free	10^{-10}–1.0	$\mathrm{s}^{-1}\ \mathrm{cm}^{-2}$	Truncated Gaussian F=1, $\mu =$, **FWHM**$= 2.0 \times 10^{-4}$
	σ_{Be}	Fix	2.4	keV	-
	μ_{Be}	Fix	478	keV	-
$^{26}\mathrm{Al}$	F_{Al}	Free	10^{-10}–1.0	$\mathrm{s}^{-1}\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

Translating results to lower limits on τm_2

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

- 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

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