Light dark states: phenomenology and detection

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1

Detection

Increasing sensitivity reach of *direct detection*

Essig, JP, Sholapurkar, Yu PRL 2020

2

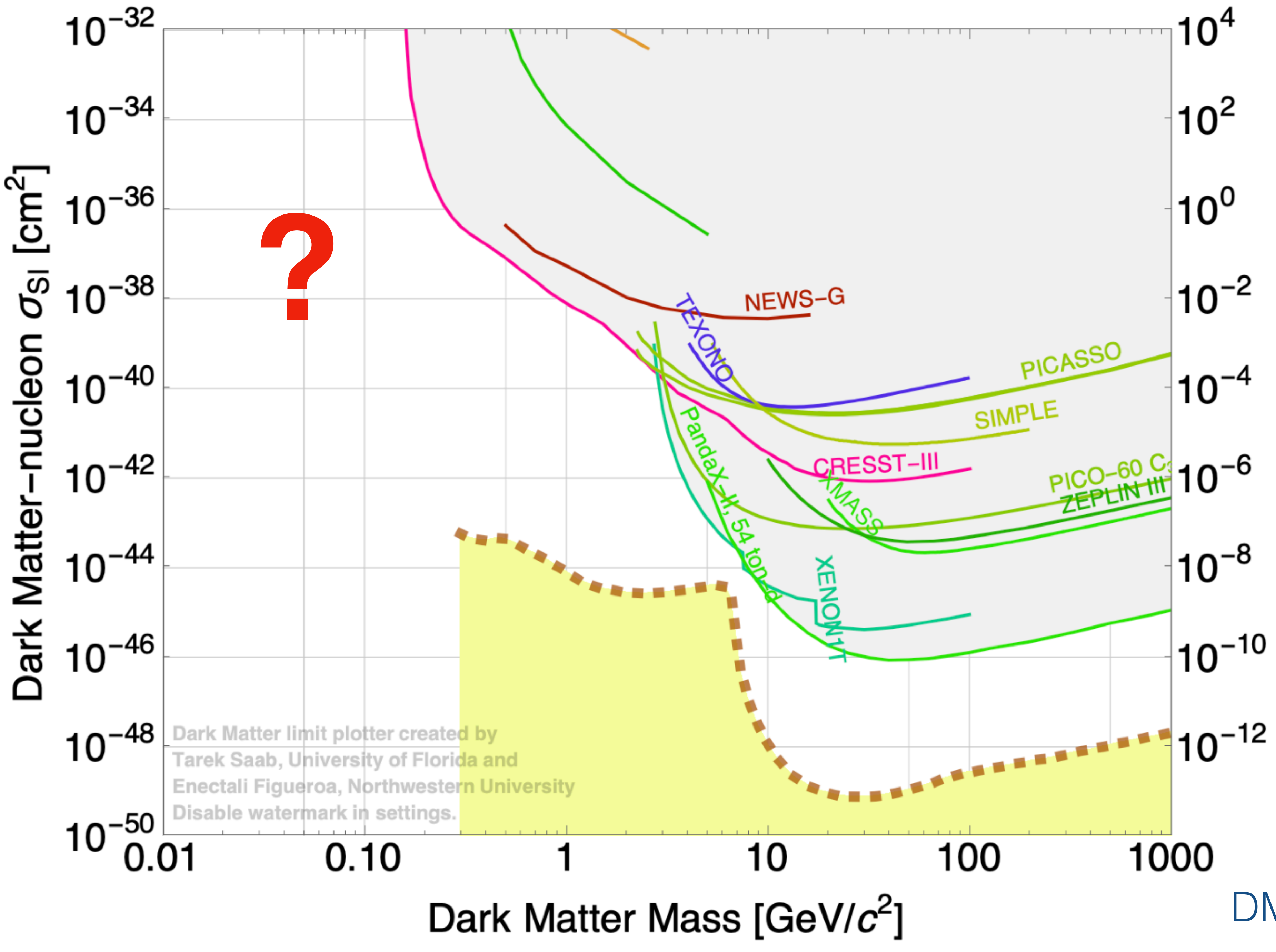
Phenomenology

Light dark states through the *photon portal*

Chu, JP, Semmelrock, PRD 2019, arXiv:1811.04095
Chu, Kuo, JP, Semmelrock, PRD 2019, arXiv:1908.00553
Chu, Kuo, JP, arXiv:2001.06042

1 Detection

Increasing sensitivity reach of *direct detection*

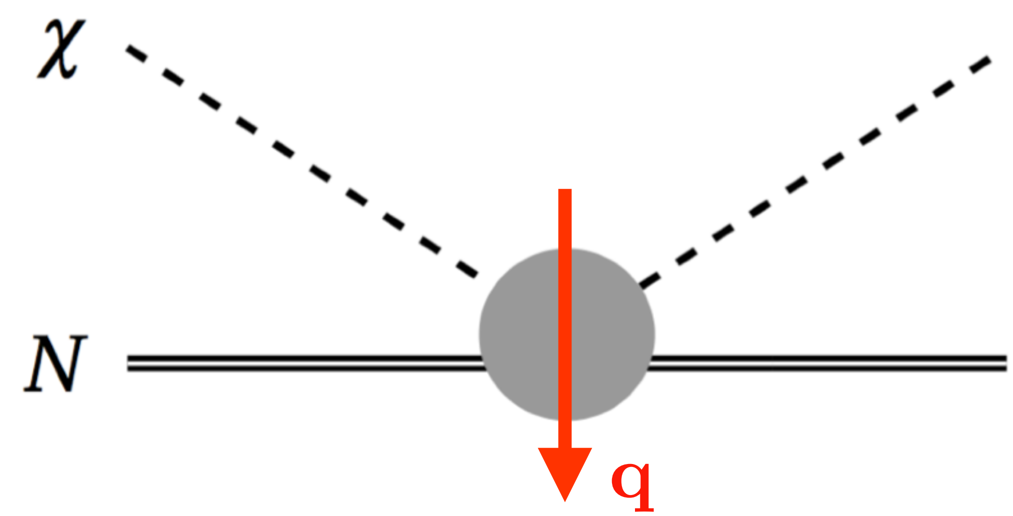


DM Limit Plotter

Direct Detection

Nuclear kinetic recoil energy

$$E_R = \frac{\mathbf{q}^2}{2m_N} = \frac{\mu_N^2 v^2}{m_N}(1 - \cos\theta_*)$$



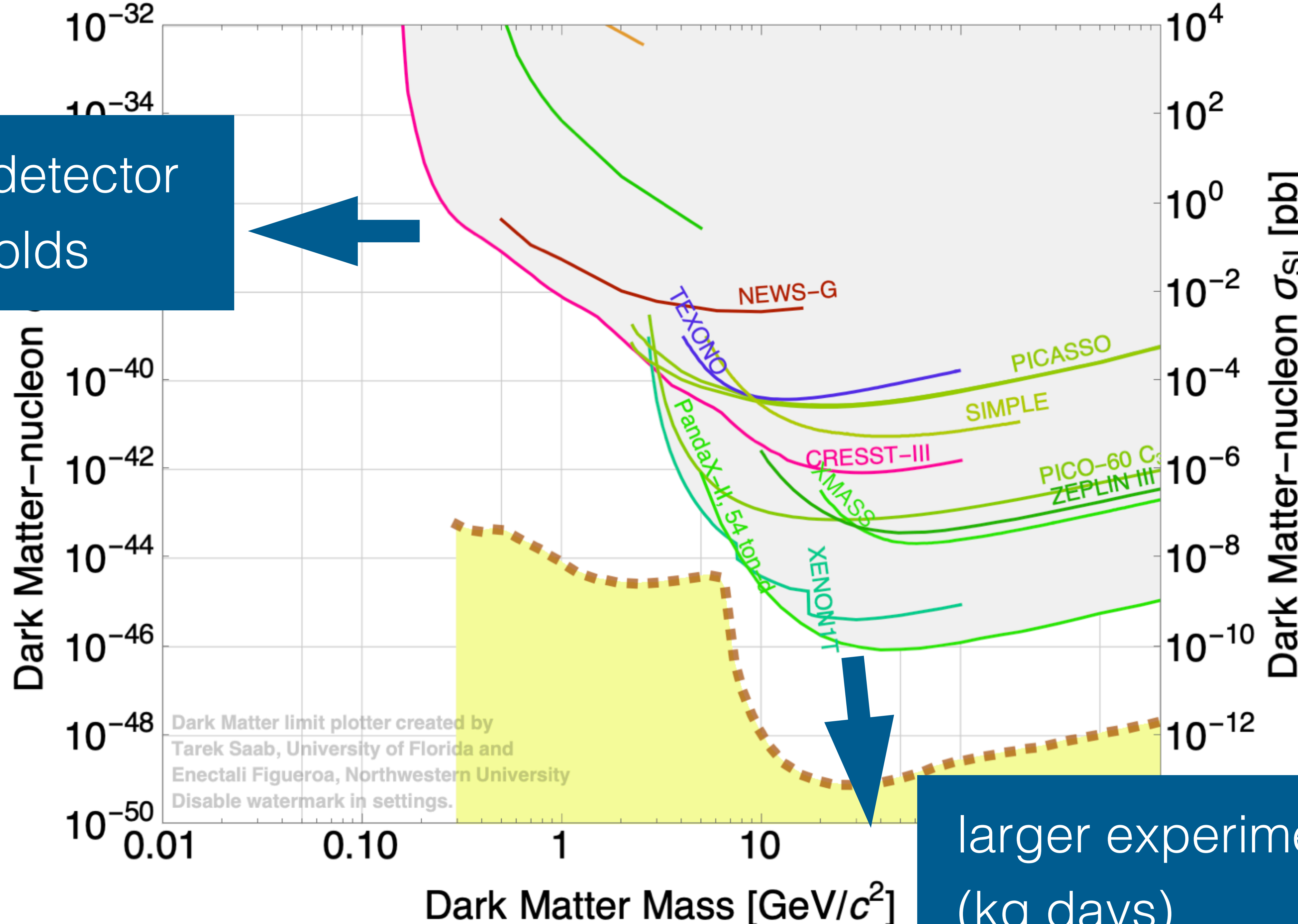
=> A given recoil, demands a *minimum* relative velocity

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} \simeq \left(\frac{E_R}{0.5\,\mathrm{keV}}\right)^{1/2} \frac{1\,\mathrm{GeV}}{m_\chi} \times \begin{cases} 1700\,\mathrm{km/s} & \mathrm{Xenon} \\ 600\,\mathrm{km/s} & \mathrm{Oxygen} \end{cases}$$

=> if m < 1 GeV, then there are no particles bound to the Galaxy that could induce a 0.5 keV nuclear recoil on a Xenon atom!

"kinematical no-go theorem"

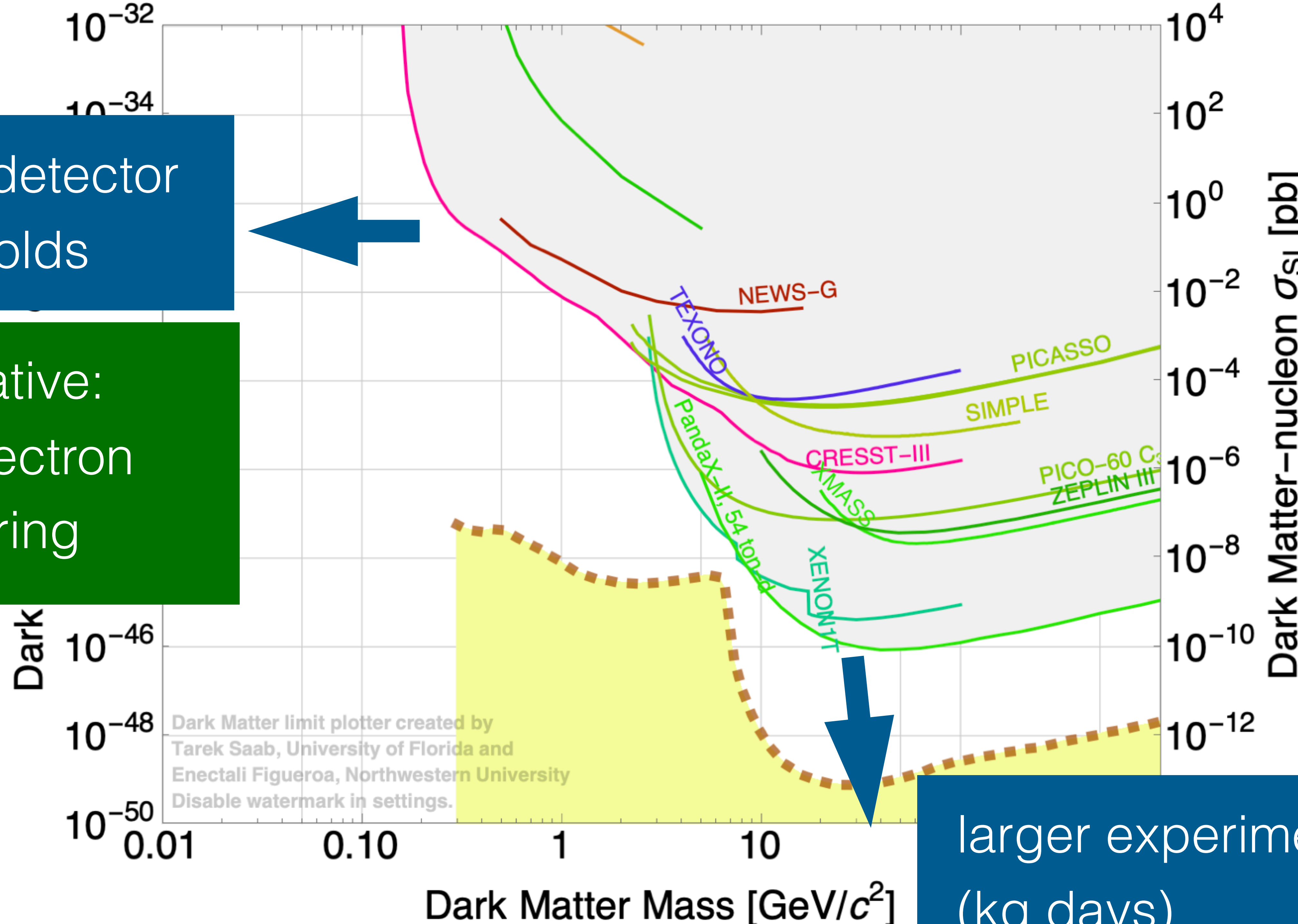
Direct detection low-mass frontier



lower detector thresholds

larger experiments (kg days)

Direct detection low-mass frontier

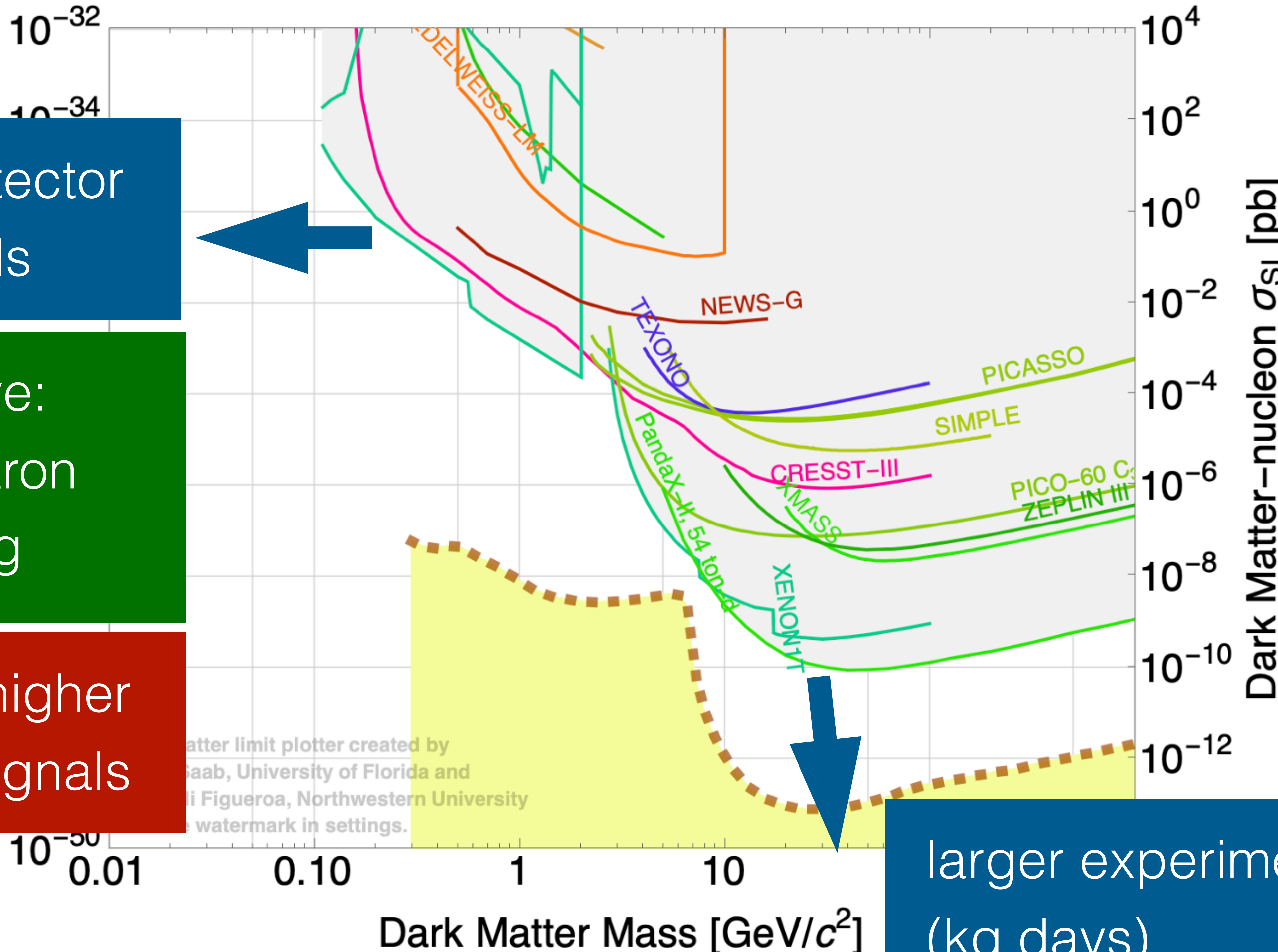


lower detector thresholds

alternative: DM-electron scattering

larger experiments (kg days)

Direct detection low-mass frontier



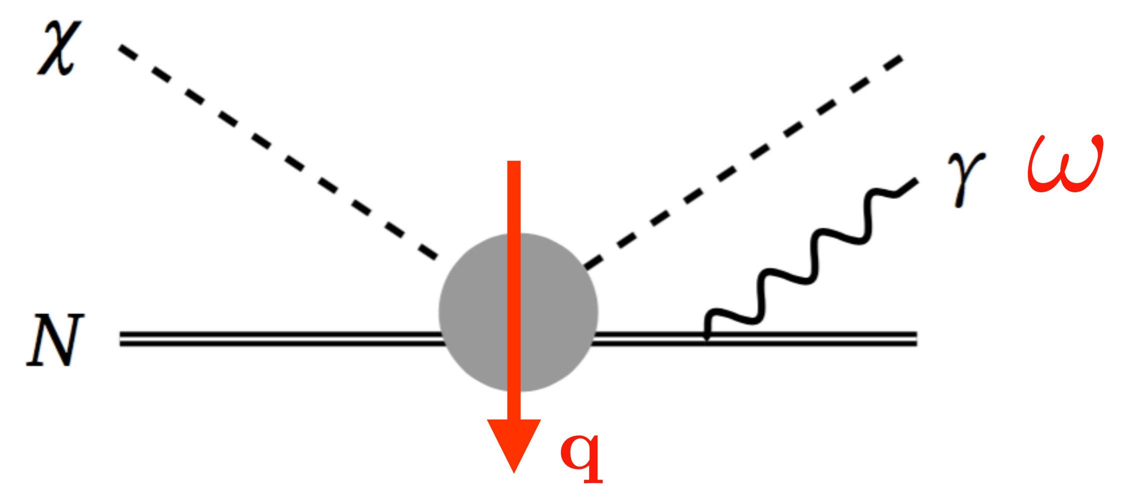
lower detector thresholds

alternative: DM-electron scattering

intrinsic higher energy signals

larger experiments (kg days)

Gaining access to sub-GeV Dark Matter *through nuclear recoils*



Inelastic channel of photon emission from the nucleus

Maximum photon energy

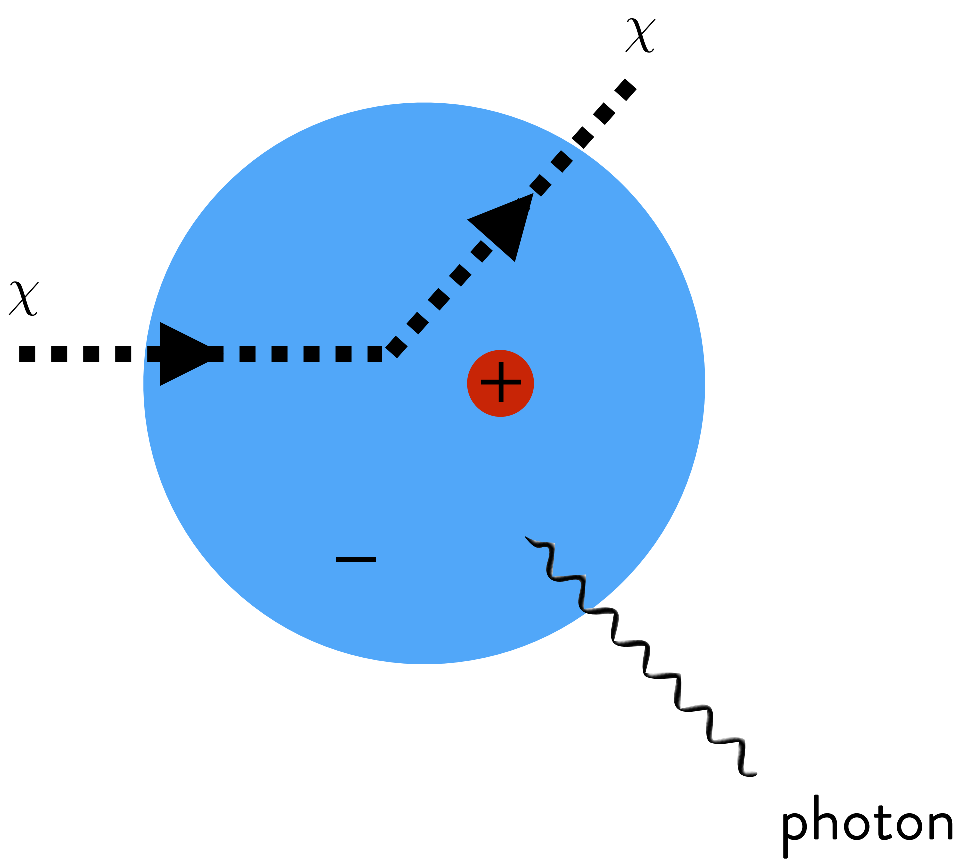
$$\omega_{\max} \simeq \mu_N v^2/2 \simeq m_\chi v^2/2$$
$$\simeq 0.5\,\mathrm{keV}\,\frac{m_\chi}{100\,\mathrm{MeV}}$$

Key I: $E_{R,\max} = 4(m_\chi/m_N)\omega_{\max} \ll \omega_{\max} \quad (m_\chi \ll m_N)$

Key II: 0.5 keV nuclear recoil is easily missed,
0.5 keV photon is never missed!

Irreducible signal components

prompt atomic response following nuclear recoil

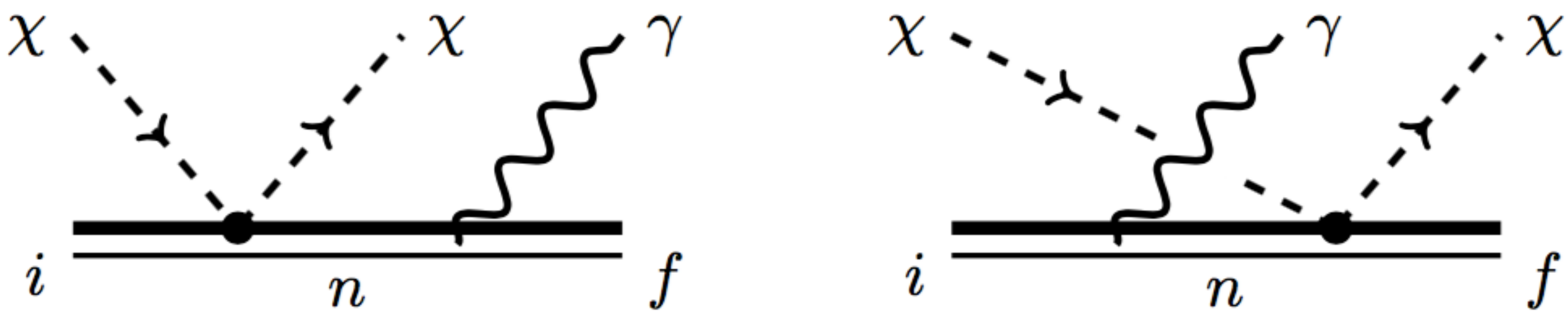


momentary polarization of
the atom creates a dipole
on which photon can be radiated

Bremsstrahlung

Kouvaris, JP PRL 2016

Bremsstrahlung in DM-nucleus collision

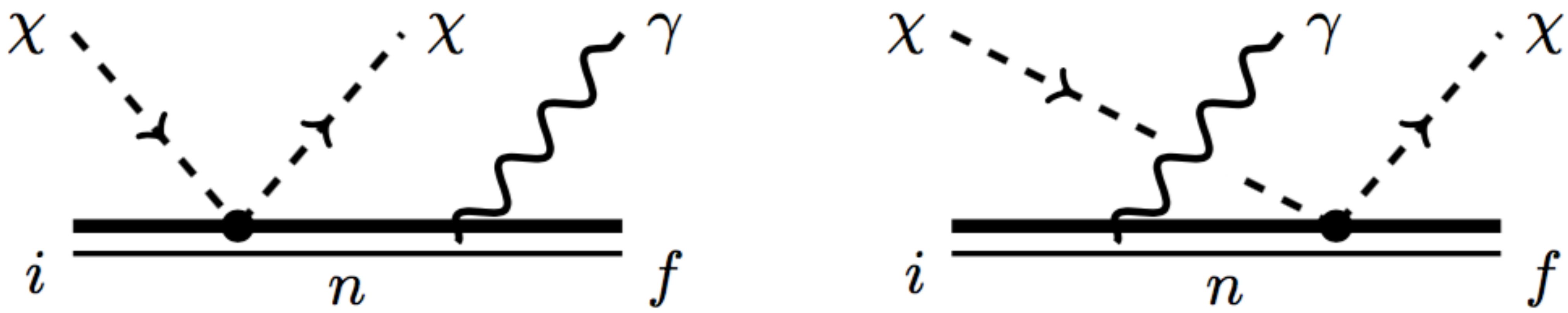


$$|V_{fi}|^2 = 2\pi\omega |M_{\rm el}|^2 \left| \sum_{n\neq i,f} \left[\frac{(\mathbf{d}_{fn}\cdot\hat{\mathbf{e}}^*)\langle n|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|i\rangle}{\omega_{ni}-\omega} + \frac{(\mathbf{d}_{ni}\cdot\hat{\mathbf{e}}^*)\langle f|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|n\rangle}{\omega_{ni}+\omega} \right] \right|^2$$

dipole matrix element for emission of photon

boost of the electron cloud

Bremsstrahlung in DM-nucleus collision



dipole emission — polarizability of the atom

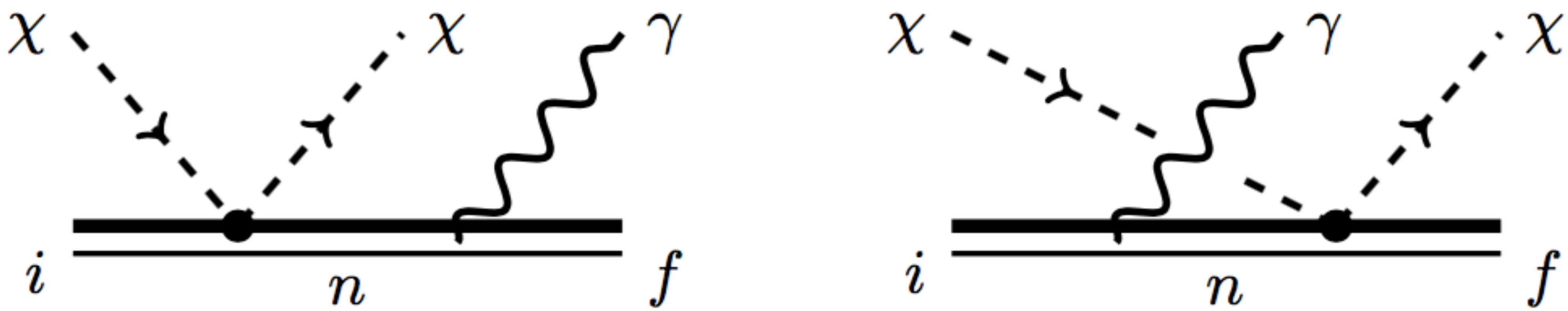
For f=i:

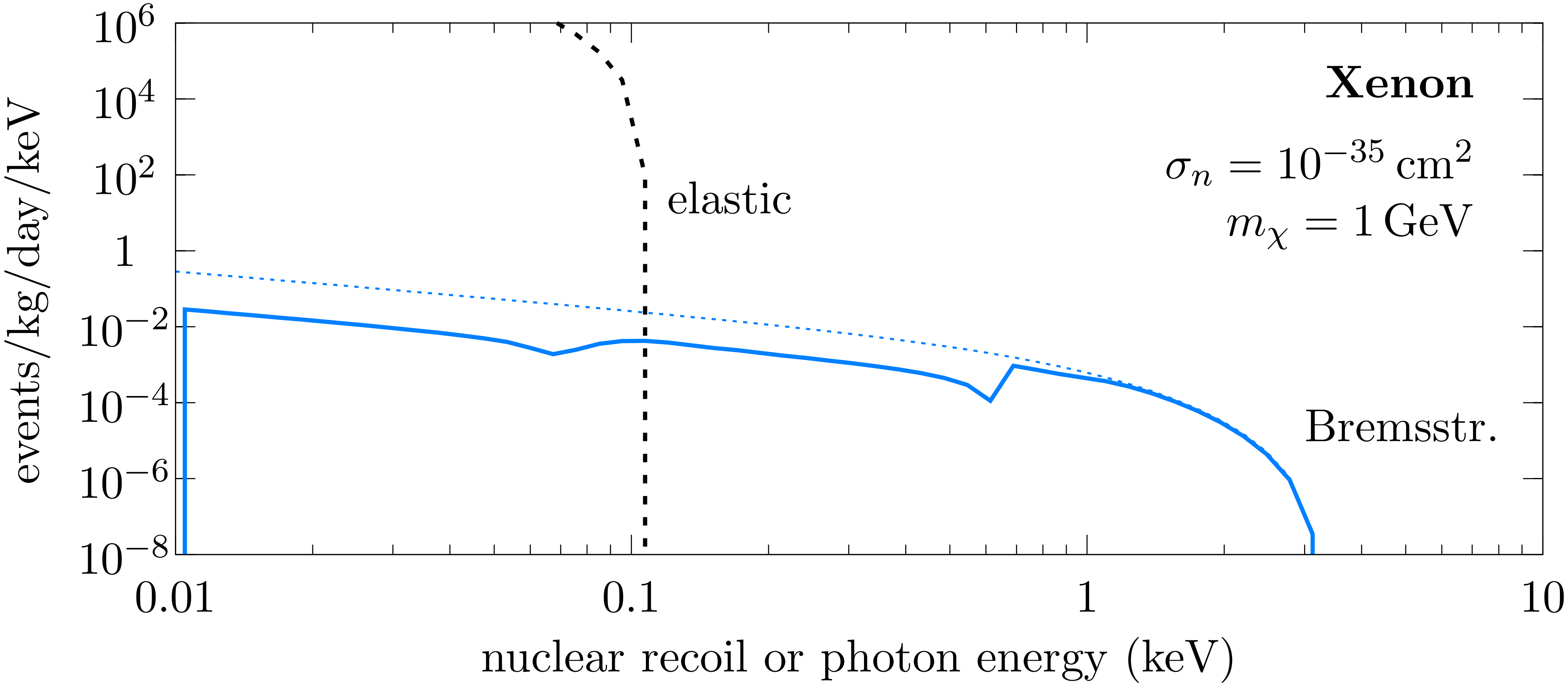
$$\frac{d\sigma}{d\omega dE_R} \propto \omega^3 \times |\alpha(\omega)|^2 \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

$$\rightarrow \frac{Z^2\alpha}{\omega} \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

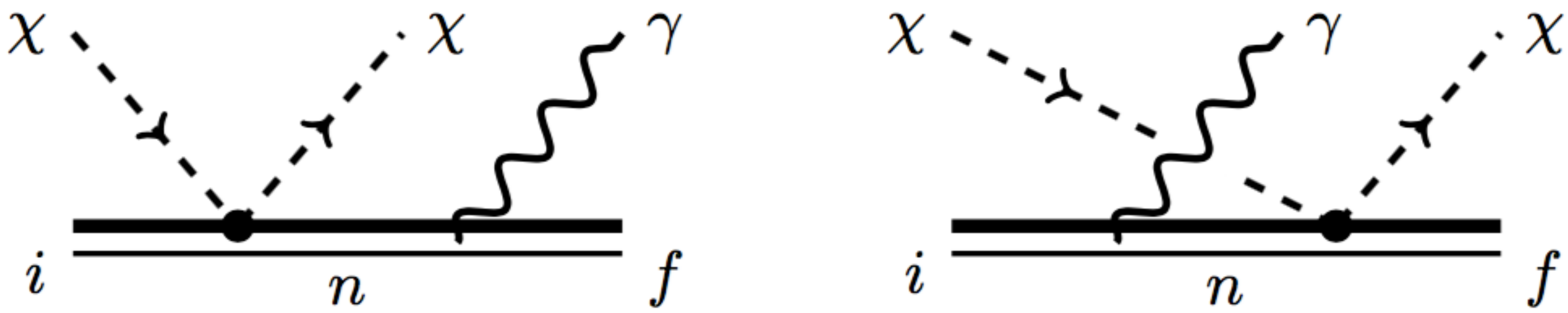
for large ω naive result is recovered ✓

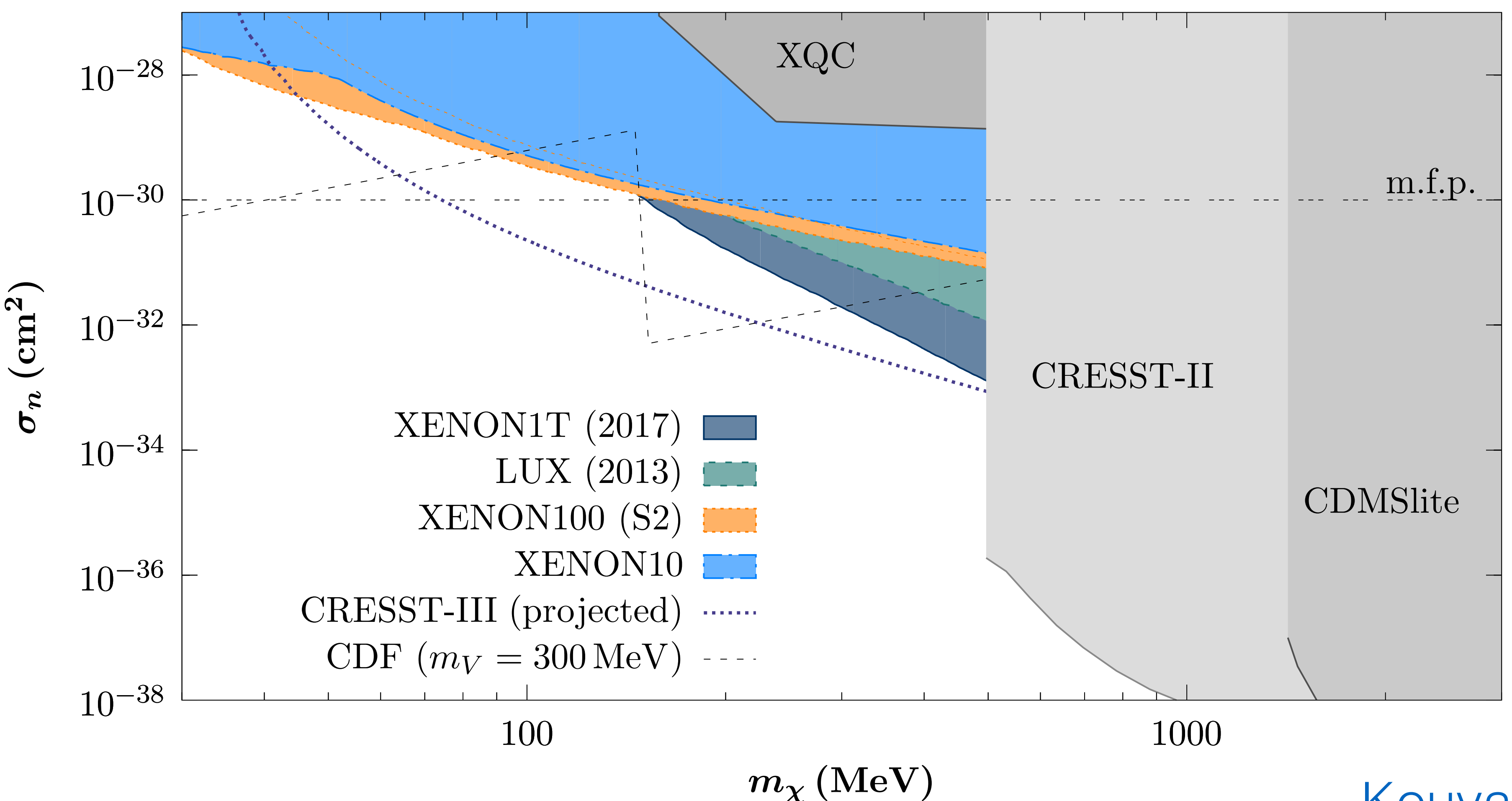
Bremsstrahlung in DM-nucleus collision





Bremsstrahlung in DM-nucleus collision





Kouvaris, JP PRL 2016

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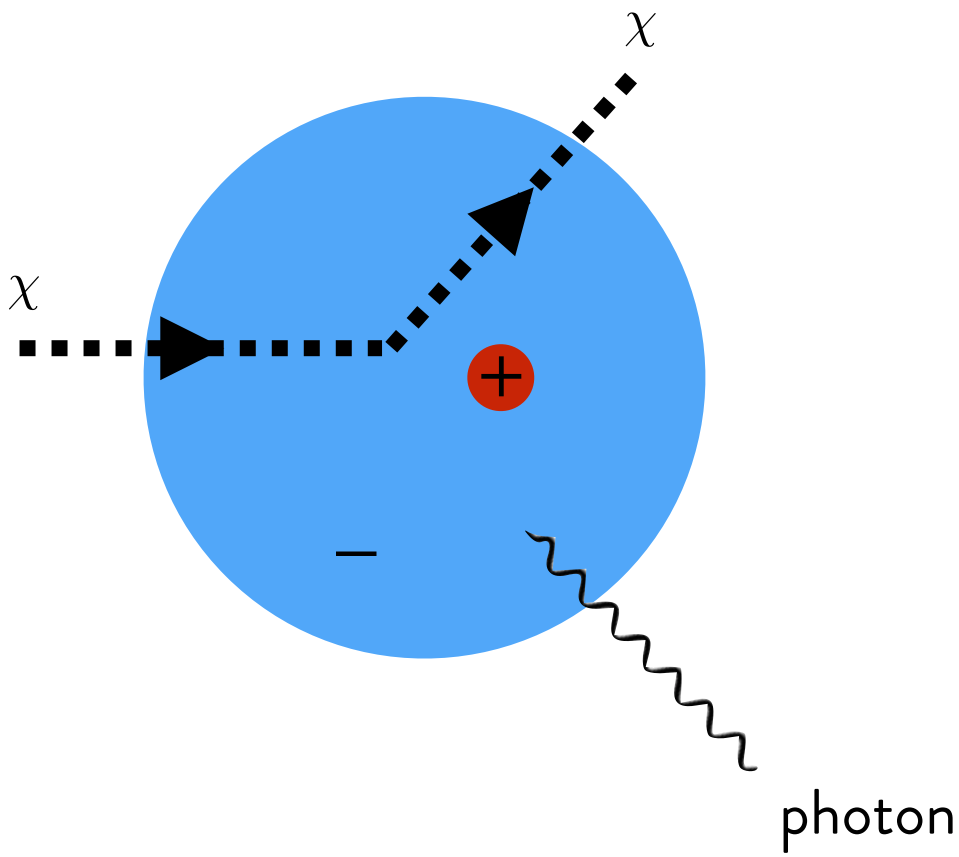

Bremsstrahlung

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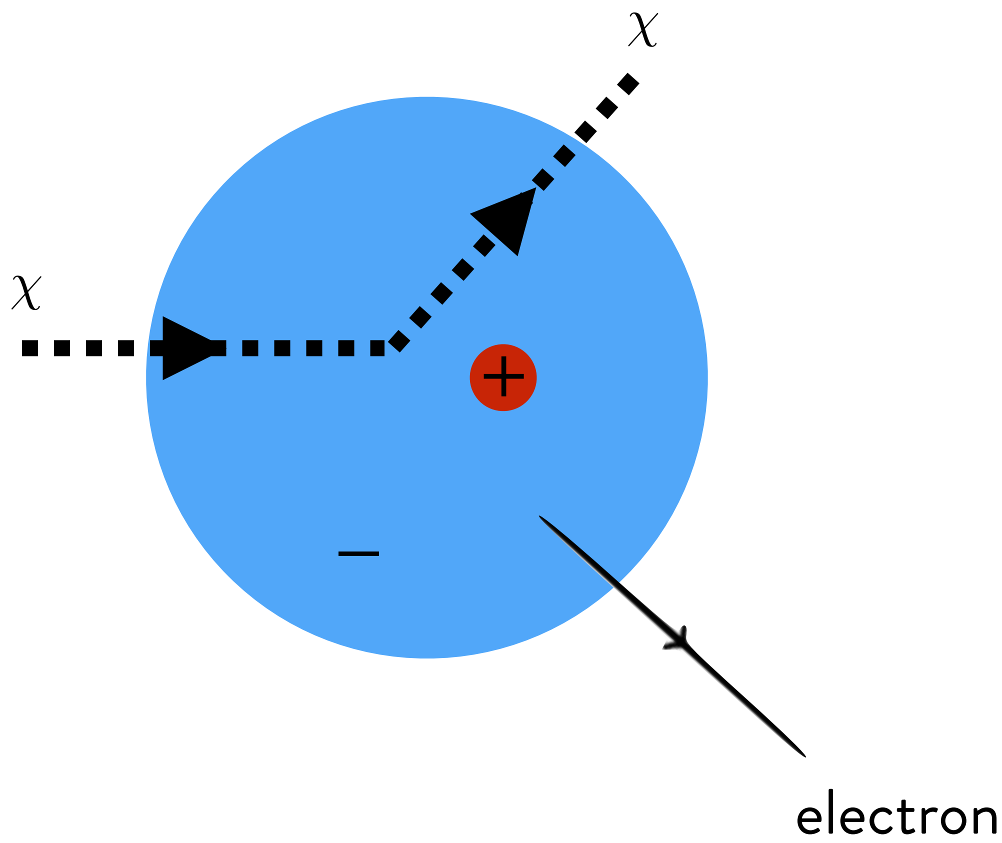

Migdal-effect

Ibe et al JCAP 2017

Migdal effect

Midgal effect: boost of electronic cloud relative to nucleus

$$\langle f | e^{i \frac{m_e}{m_N} \boldsymbol{q} \cdot \sum_\alpha \boldsymbol{x}^{(\alpha)}} | i \rangle \simeq \frac{i}{e} \frac{m_e}{m_N} \boldsymbol{q} \cdot \boldsymbol{d}_{fi} \quad (i \neq f) \qquad \boldsymbol{v}'_N = \boldsymbol{q}/m_N$$

atom dipole transition element $\boldsymbol{d}_{fi} = \langle f | e \sum_\alpha \boldsymbol{x}^{(\alpha)} | i \rangle$

=> in single electron transitions $\boldsymbol{d}_{fi} \to \boldsymbol{d}_{fi}^{(\beta)} = \langle f | e \boldsymbol{x}^{(\beta)} | i \rangle$

Migdal effect

Midgal effect: boost of electronic cloud relative to nucleus

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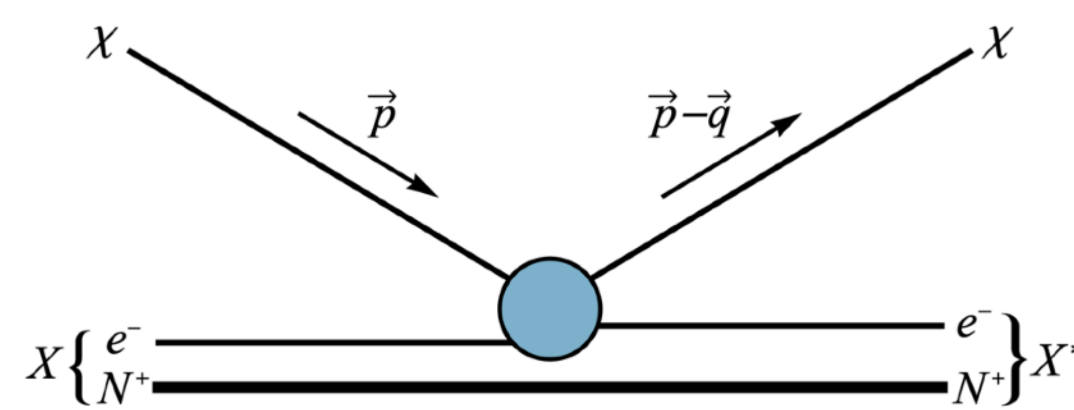
DM-electron scattering

$$\langle f|e^{i\boldsymbol{q}\cdot\boldsymbol{x}^{(\beta)}}|i\rangle \simeq \frac{i}{e}\boldsymbol{q}\cdot\boldsymbol{d}_{fi}^{(\beta)} \quad (i \neq f)$$



Relation between Migdal and DM-e

Essig, JP, Sholapurkar, Yu PRL 2020

Migdal ionization probability $\left|\langle p_e, l'| e^{i\frac{m_e}{m_N}\boldsymbol{q}\cdot\sum_\alpha \boldsymbol{x}^{(\alpha)}}|n, l\rangle\right|^2 = \frac{1}{2\pi}\frac{dp_{nl\to E_e}(q)}{dE_e}$

Related to atomic form factor in DM-electron scattering

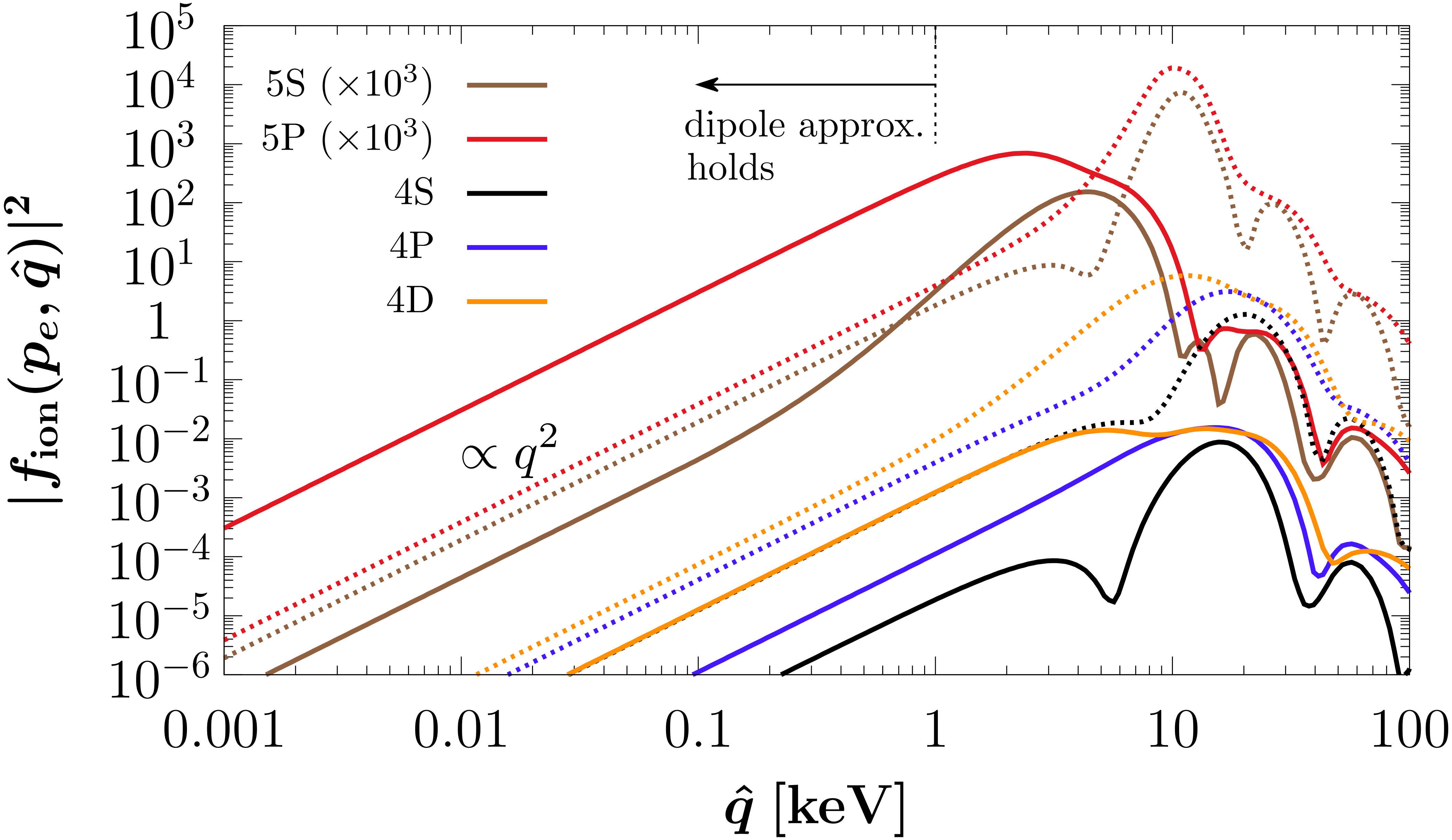
$$\frac{dp_{nl\to E_e}}{d\ln E_e} = \frac{\pi}{2}|f_{nl}^{\text{ion}}(p_e, q_e)|^2 \qquad q_e \simeq \frac{m_e}{m_N} q$$

Midgal **"DM-e"**

=> *same underlying atomic form factor, evaluated at very different momentum scales*

$|f_{nl}^{\text{ion}}(p_e, q_e)|^2 =$ (selection rules) x (overlap integral)

Relation between Migdal and DM-e



Migdal

DM-e

Relation between Migdal and DM-e

comparison of cross sections

Velocity average of ionization cross section

$$\frac{d\langle\sigma_{n,l}v\rangle}{dE_e} = \int_{|\vec{v}|>v_{\rm min}} d^3\vec{v}\, g_{\rm det}(\vec{v}) \frac{d\sigma_{n,l}v}{dE_e}$$

Migdal effect ($F_N = 1$)

$$\frac{d\langle\sigma_{n,l}v\rangle}{d\ln E_e} = A^2 \frac{\bar{\sigma}_n}{8\mu_n^2} \int dq\ \left\{q|F_{\rm DM}(q)|^2 |f_{nl}^{\rm ion}(p_e, q_e)|^2 \eta[v_{\rm min}(q, \Delta E_{n,l})]\right\}$$

$$q_e = \frac{m_e}{m_N} q \sim \frac{10^{-3}}{A} q$$

DM-electron scattering

$$\frac{d\langle\sigma_{n,l}^{\rm DM-e}v\rangle}{d\ln E_e} = \frac{\bar{\sigma}_e}{8\mu_e^2} \int dq\ \left\{q|F_{\rm DM}(q)|^2 |f_{nl}^{\rm ion}(p_e, q)|^2 \eta[v_{\rm min}(q, \Delta E_{n,l})]\right\}$$

Relation between Migdal and DM-e

comparison of event rates

In any concrete model of DM, there is a relation between DM-nuclear and DM-electron scattering

Example: dark photon mediator

$$\bar{\sigma}_e = \frac{16\pi\varepsilon^2\alpha\alpha_D\mu_e^2}{(q_0^2 + m_V^2)^2}, \quad \bar{\sigma}_p = \frac{\mu_p^2}{\mu_e^2}\bar{\sigma}_e$$

=> ratio of differential event rates

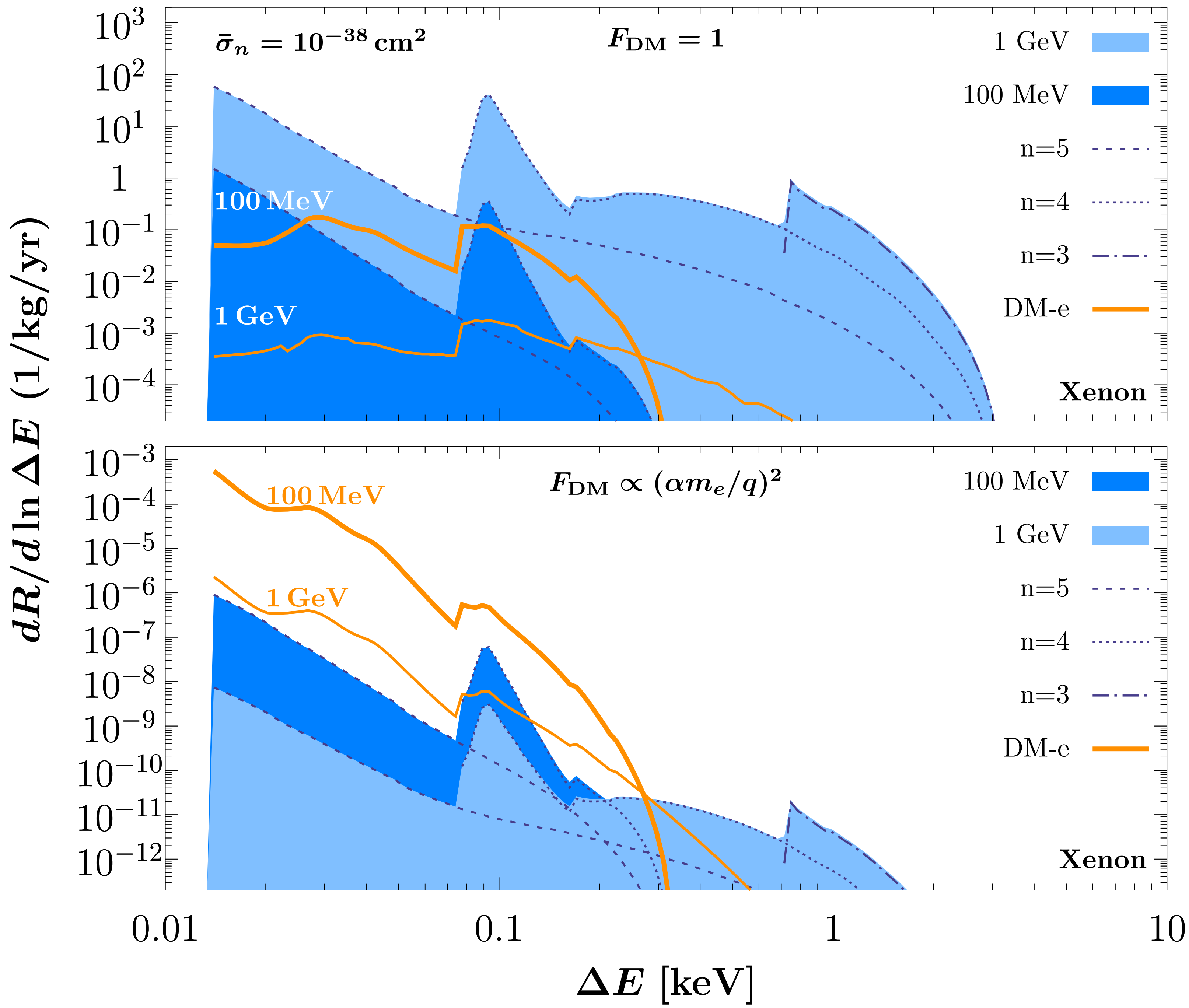
$$\frac{d\langle\sigma_{n,l}^{\mathrm{Migdal}} v\rangle/(d\ln E_e dq)}{d\langle\sigma_{n,l}^{\mathrm{DM-e}} v\rangle/(d\ln E_e dq)} = Z^2 \times \frac{|f_{nl}^{\mathrm{ion}}(p_e, q_e)|^2}{|f_{nl}^{\mathrm{ion}}(p_e, q)|^2}$$

=> naive Dipole scaling of form factors would suggest DM-e always dominant

=> because of form-factor suppression once q > r_{Electron} Migdal effect dominates over DM- electron scattering for higher (GeV) mass DM

Relation between Migdal and DM-e

comparison of event rates



Migdal in semiconductors

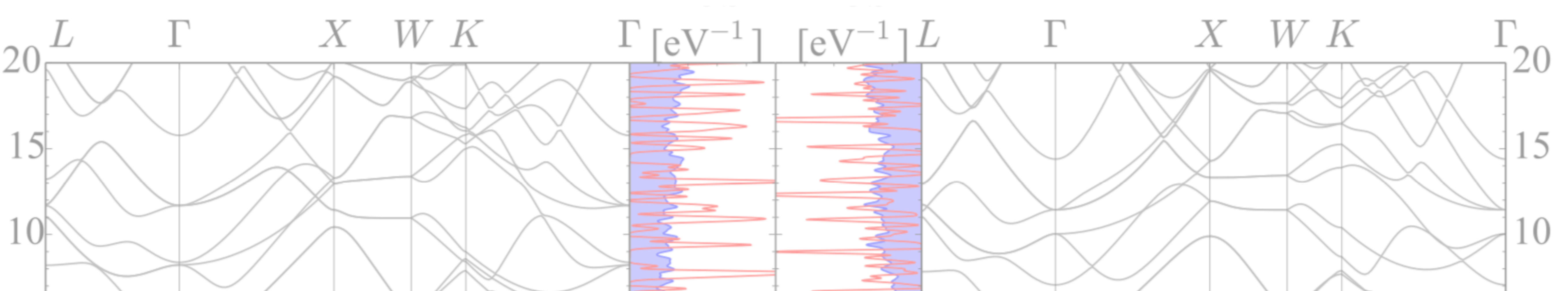
With the relation between Migdal effect and DM-electron scattering, we may latch on to previous calculations of DM-electron scattering in **semiconductors**

Entirely different electron structure => previous experimental Migdal papers only used inner shell ionization probabilities (e.g. Edelweiss)

$$|f_{n,l}^{\mathrm{ion}}(q_e, E_e)|^2 \to \frac{8\alpha m_e^2 E_e}{q_e^3} \times |f_{\mathrm{crystal}}(q_e, E_e)|^2$$

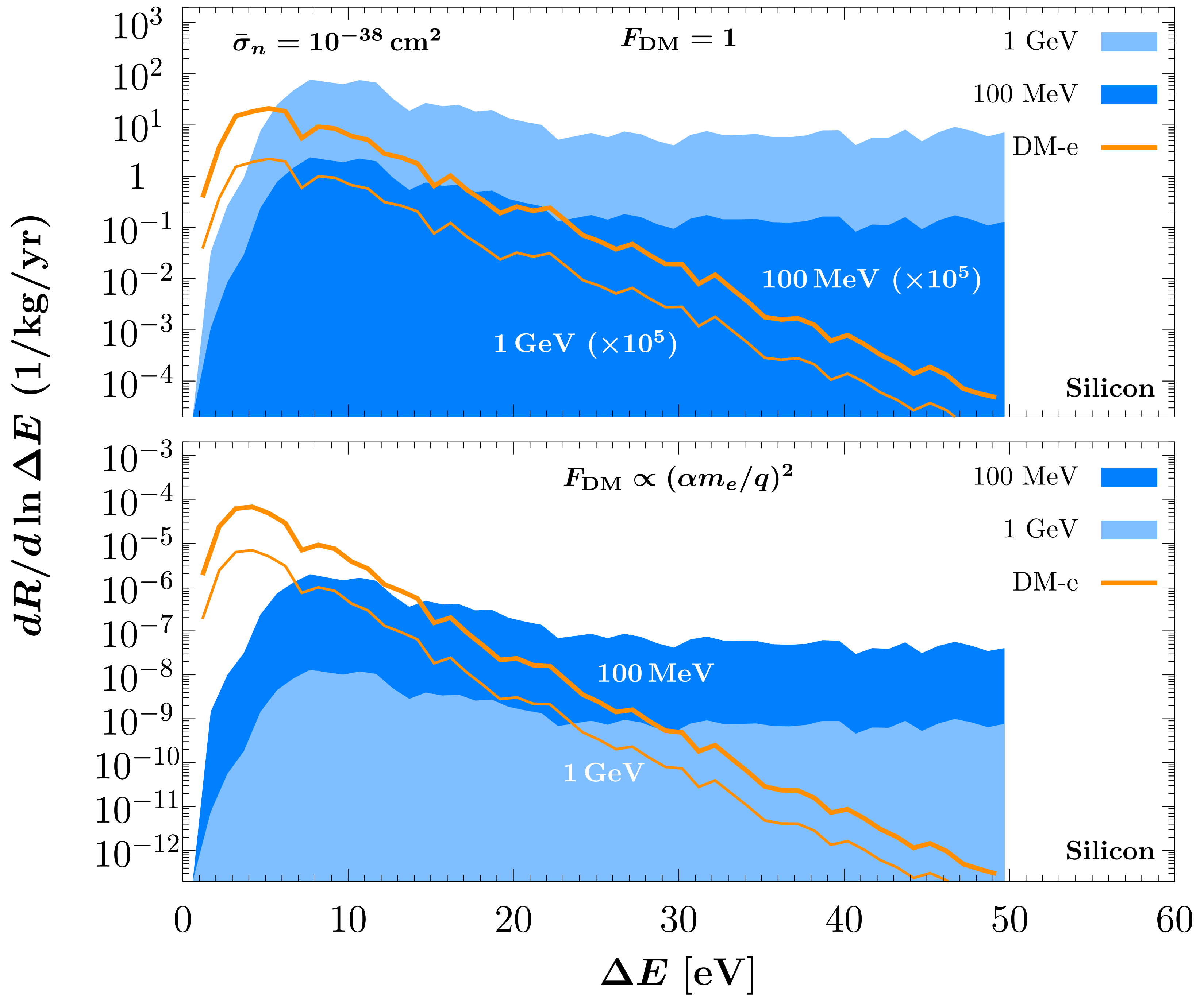
"crystal" form factor was computed using solid state tool "QuantumESPRESSO" [QEDark]

Essig et al JEHP 2016;

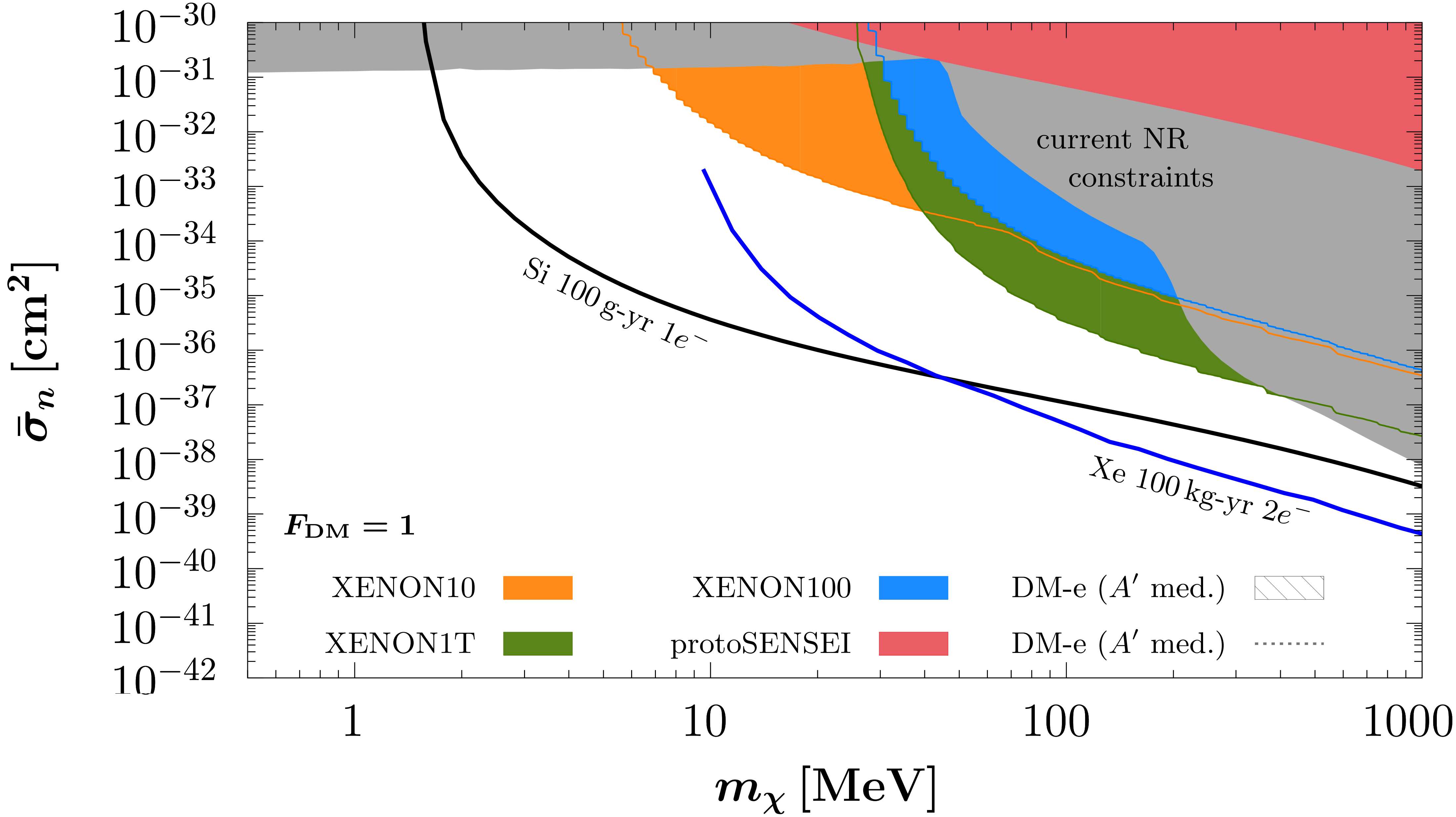


Migdal in semiconductors

=> first proof-of-principle calculation of Migdal scattering in SC

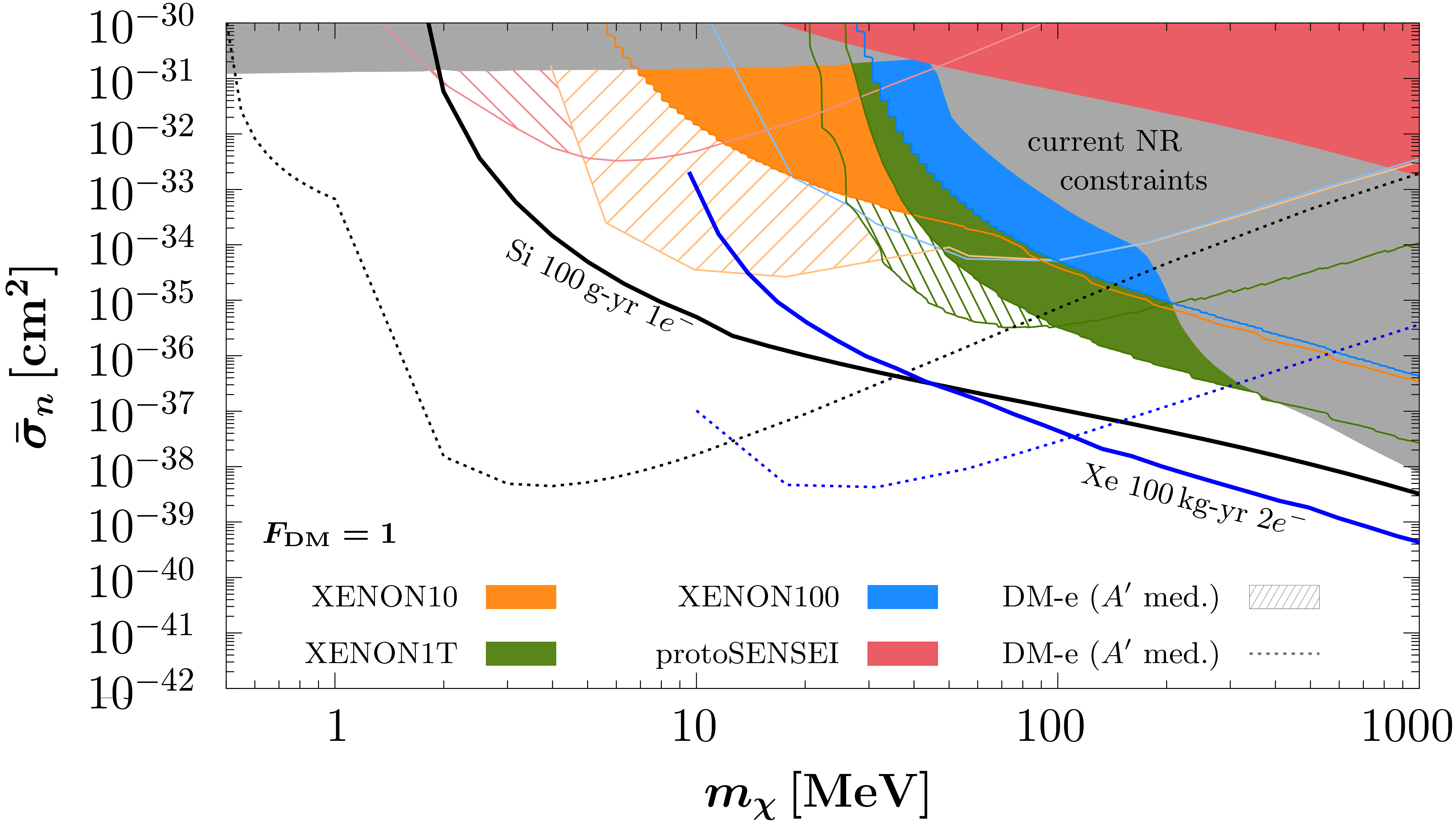


New limits and projections



=> First direct limit on DM-nuclear scattering down to 10 MeV DM mass

New limits and projections



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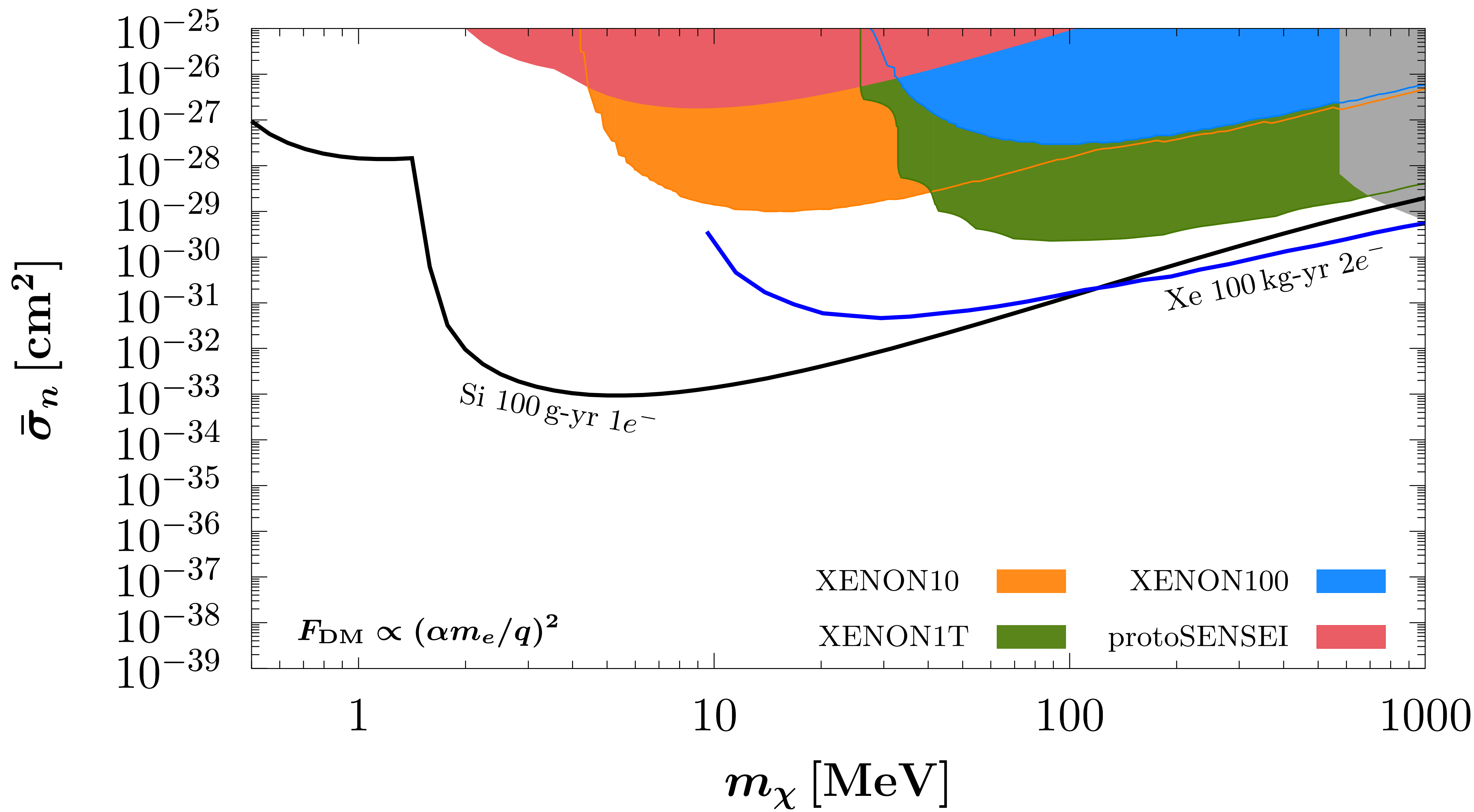

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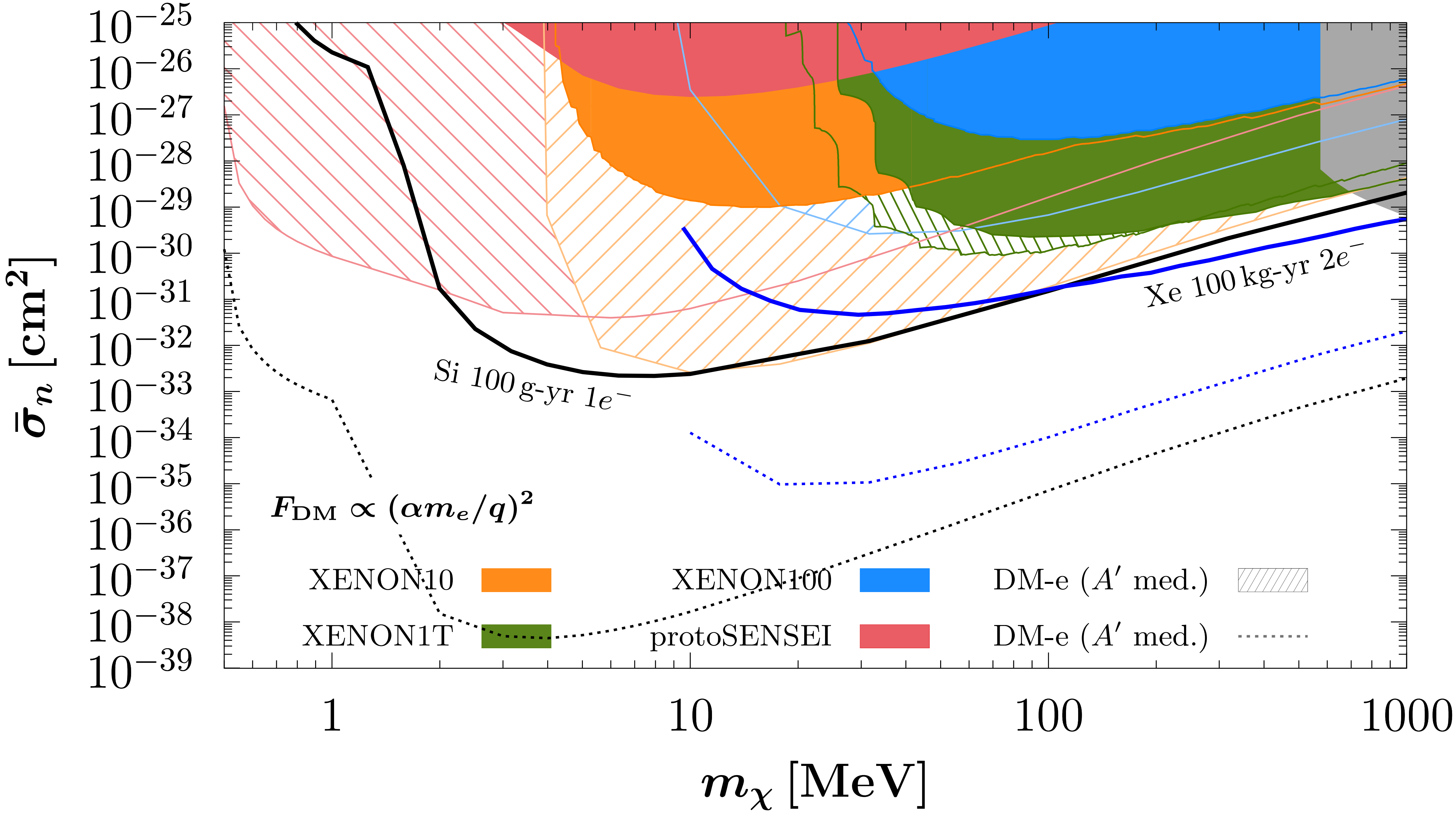
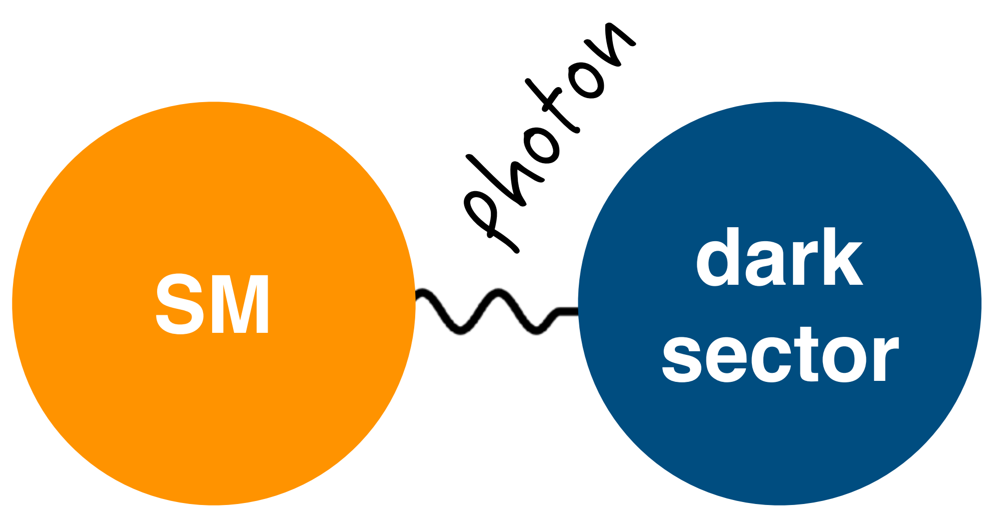


=> First direct limit on DM-nuclear scattering down to 10 MeV DM mass

2 Phenomenology

Light dark states through the *photon portal*

Consider a sub-GeV dark sector that talks to SM through direct effective couplings to the photon



Based on

Chu, JP, Semmelrock, PRD 2019, arXiv:1811.04095

Chu, Kuo, JP, Semmelrock, PRD 2019, arXiv:1908.00553

Chu, Kuo, JP, arXiv:2001.06042 (today)

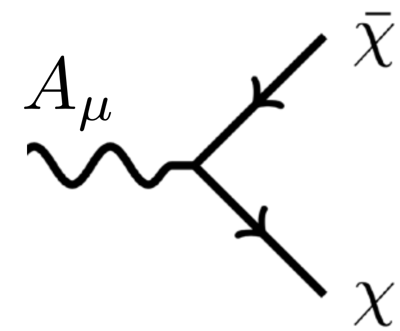
The photon as new physics mediator

Tinkering with the photon may potentially affect many known phenomena

- change the strength of the EM interaction at various energy scales
- other SM precision observables may be affected, e.g. g-2
- new photon-mediated decay channels in flavor physics may open
- cosmological viability of dark states coupled with the photon
- can we make dark matter through the photon coupling?
- astrophysical implications - stellar cooling

Dark States with EM-interactions

Immediate possibility is (milli)charge of dark states



Electromagnetic neutral particles χ can still interact with the photon through higher-dimensional operators

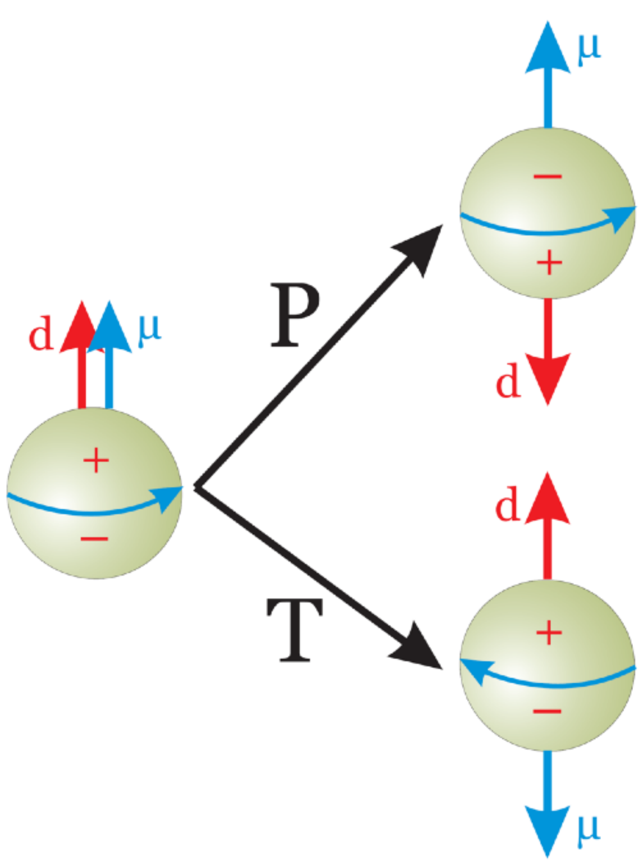
For a Dirac particle, best known are magnetic and electric dipole moments

$$H_{\rm MDM} = -\mu_\chi(\vec{B}\cdot\vec{\sigma}_\chi)$$

P and T even

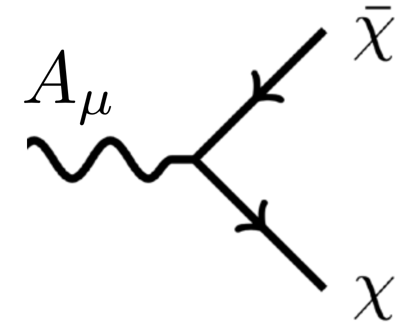
$$H_{\rm EDM} = -d_\chi(\vec{E}\cdot\vec{\sigma}_\chi)$$

P and T odd => CP violating



Dark States with EM-interactions

Electromagnetic neutral particles χ can interact with the photon through higher-dimensional operators



Charge radius interaction and anapole moments

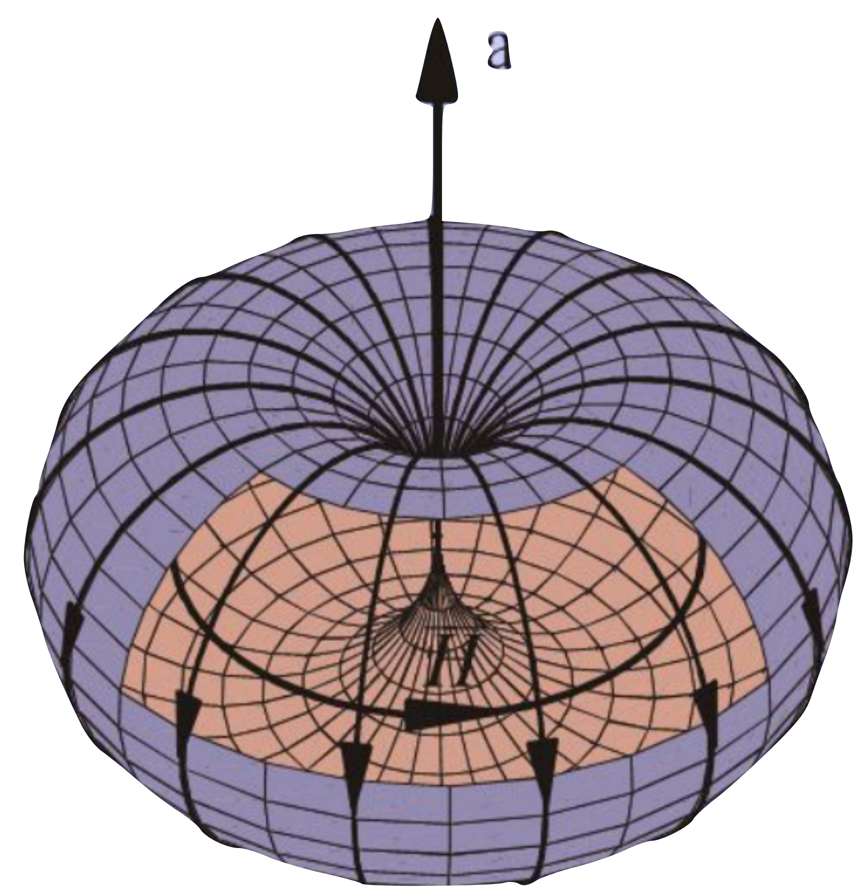
$$H_{\rm AM} = -a_\chi (\vec{J} \cdot \vec{\sigma}_\chi)$$

Zel'dovich 1958

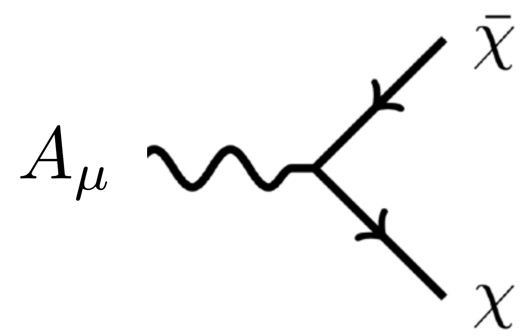
P odd but CP even

$$H_{\rm CR} = -b_\chi (\vec{\nabla} \cdot \vec{E})$$

P and T even



Dark States with EM-interactions



Effective operators

millicharge (ϵQ):	$\epsilon e\,\bar{\chi}\gamma^\mu\chi A_\mu,$	dim 4
magnetic dipole (MDM):	$\frac{1}{2}\mu_\chi\,\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu},$	dim5
electric dipole (EDM):	$\frac{i}{2}d_\chi\,\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu},$	
anapole moment (AM):	$a_\chi\,\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu},$	dim6
charge radius (CR):	$b_\chi\,\bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}.$	

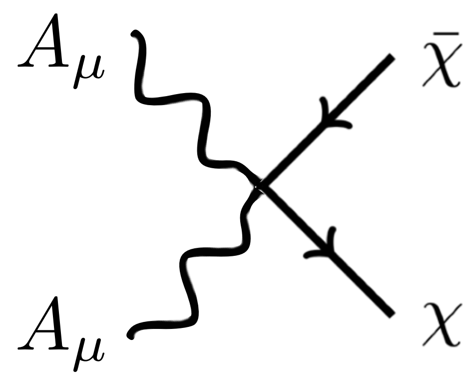
NB: Millicharged states have been studied previously

Prinz et 1998; recent refs Magill et al 2018; Berlin et al 2018,

Dark States with EM-interactions

Rayleigh/Susceptibility ops

$$\begin{matrix} \bar{\chi}\chi \\ \bar{\chi}\gamma^5\chi \end{matrix} \otimes \begin{matrix} F_{\mu\nu}F^{\mu\nu} \\ F_{\mu\nu}\tilde{F}^{\mu\nu} \end{matrix}$$



....

dim 7

....

=> different (or loop-suppressed) phenomenology

Complex scalars: dim-6 Rayleigh and charge radius interaction

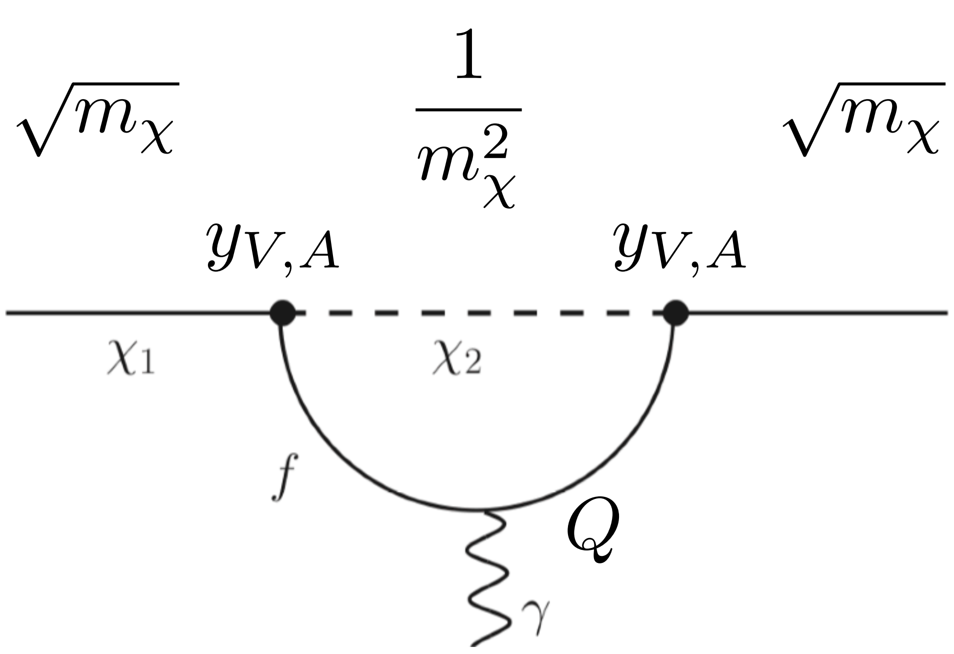
Vectors: also quadrupole moments exist

Origin of form factor interactions

a) compositeness

e.g. Bagnasco, Dine, Thomas 1994; Foadi, Frandsen, Sannino 2009; Antipin, Redi, Strumia, and Vigiani 2015

b) radiatively (possibly enhanced by mass degeneracies)



$$\mu_\chi \sim \frac{Q|y_{A,V}|^2}{m_\chi} \qquad d_\chi \sim \frac{Q\,\mathrm{Im}[\mathrm{y_V y_A^*}]}{m_\chi}$$

$$a_\chi,\, b_\chi \sim \frac{Q|y_{A,V}|^2}{M^2}$$

or $$a_\chi,\, b_\chi \sim \frac{Q|y_{A,V}|^2}{m_\chi} \times \frac{1}{\Delta m}$$

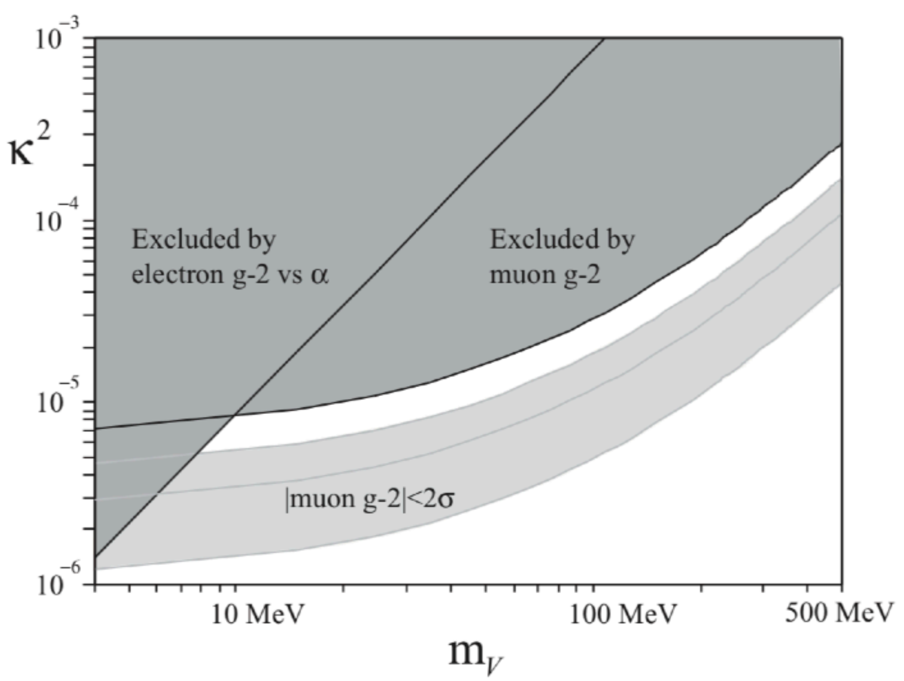
see also Kavanagh, Panci, Ziegler 2018

Muon g-2

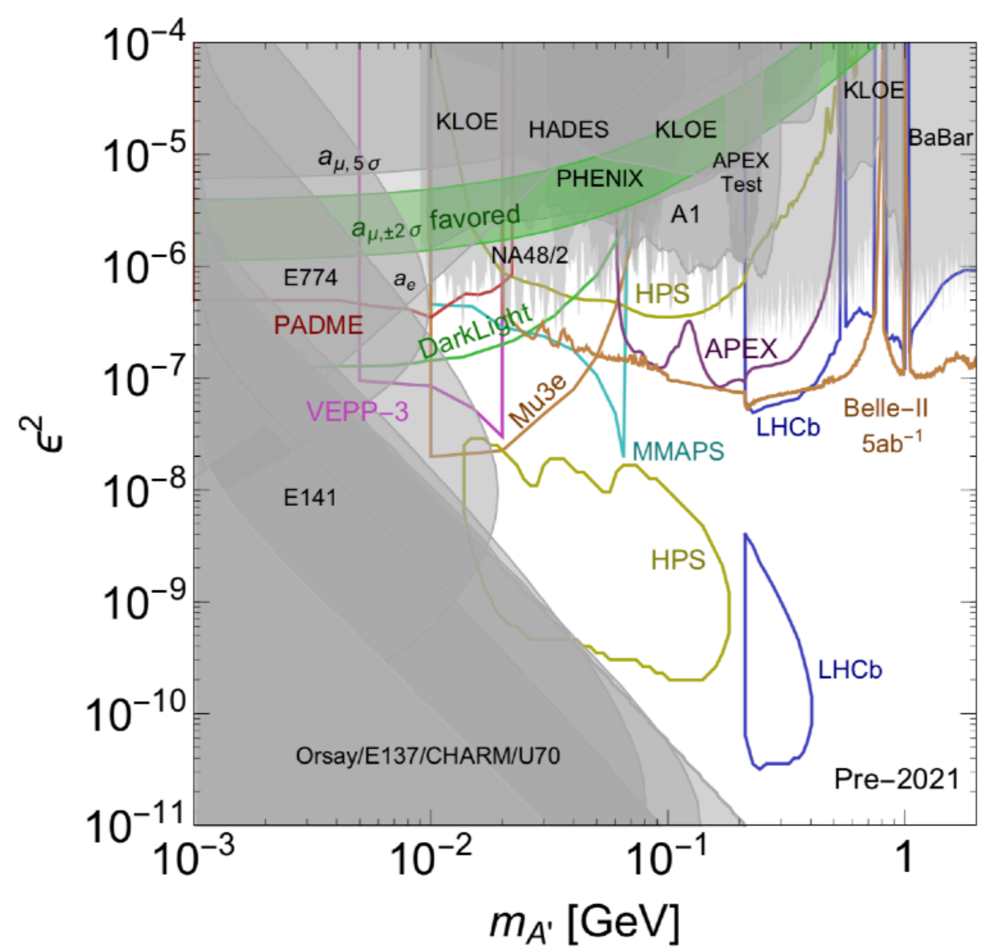
- Muon g-2 puzzle: (3-4)σ tension between SM prediction and measurement

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (290 \pm 90) \times 10^{-11}$$

- Prospective solutions became a driver for intensity frontier efforts, think: dark photon.



=>



Pospelov 2009

2016 Dark Sectors **Community Report**

Muon g-2

- Muon g-2 puzzle: (3-4)σ tension between SM prediction and measurement

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (290 \pm 90) \times 10^{-11}$$

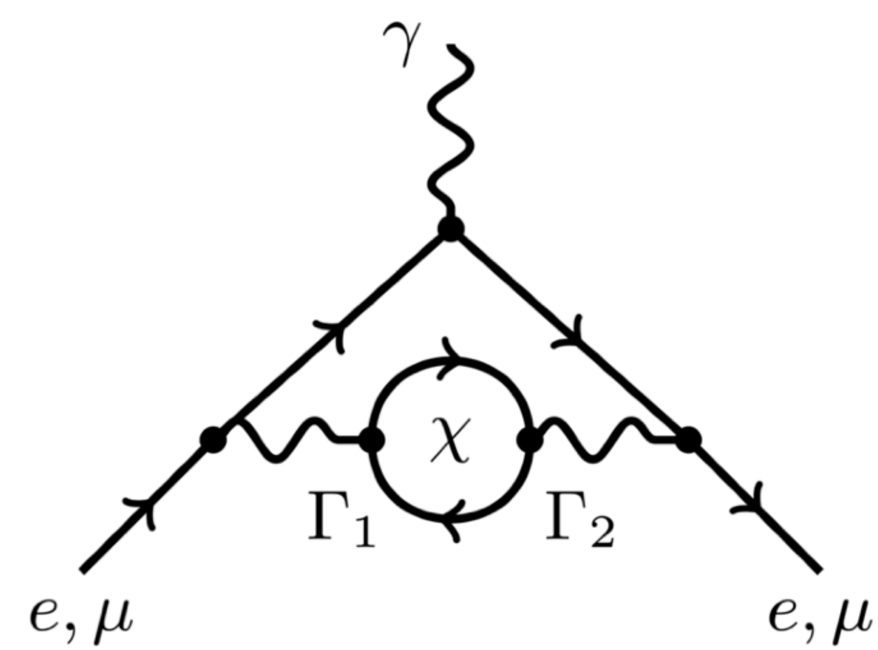
- For form-factor interactions, contributions enter through the vacuum polarization

e.g. use dispersion relation + unitarity

$$\Delta a_\mu = \frac{1}{4\pi^3}\int_{4m_\chi^2} ds\, \sigma_{e^+e^-\to\chi\bar{\chi}}(s)K(s)$$

solution to g-2 for

$$|\mu_\chi|,\ |d_\chi| \sim \text{few} \times 10^{-3}\mu_{\rm B}$$



Precision tests

- In EW theory, G_F, m_W and m_Z are related and receive calculable quantum corrections, summarized in the Δr parameter

$$\Delta r_{\rm obs} = 1 - \frac{A_0^2}{M_W^2 s_w^2} = 0.03492 \pm 0.00097$$

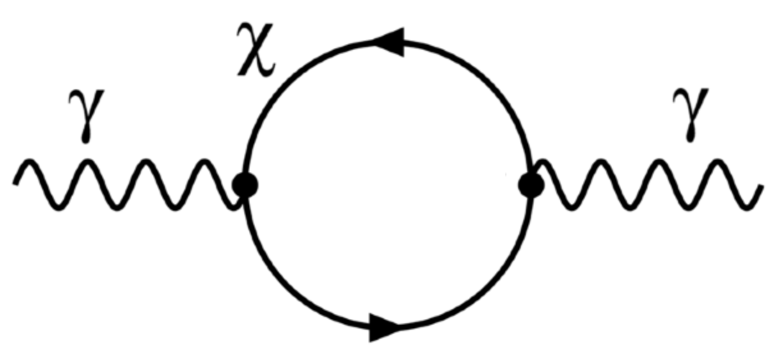
$$A_0 = (\pi\alpha/\sqrt{2}G_F)^{1/2}$$

$$s_w^2 = 1 - M_W^2/M_Z^2$$

$$-0.0038 < \Delta r_{\rm new} < 0.00018$$

(tighter upper limit from 1.8 tension)

Running of α contributes $\Delta r_{\rm new} \simeq \Pi(-M_Z^2) - \Pi(0)$



$$|\mu_\chi| \text{ or } |d_\chi| \; < 3.2\times 10^{-6}\mu_B$$

(saturating upper limit)

$$|a_\chi| \text{ or } |b_\chi| \; < 3.2\times 10^{-5}/{\rm GeV}^2$$

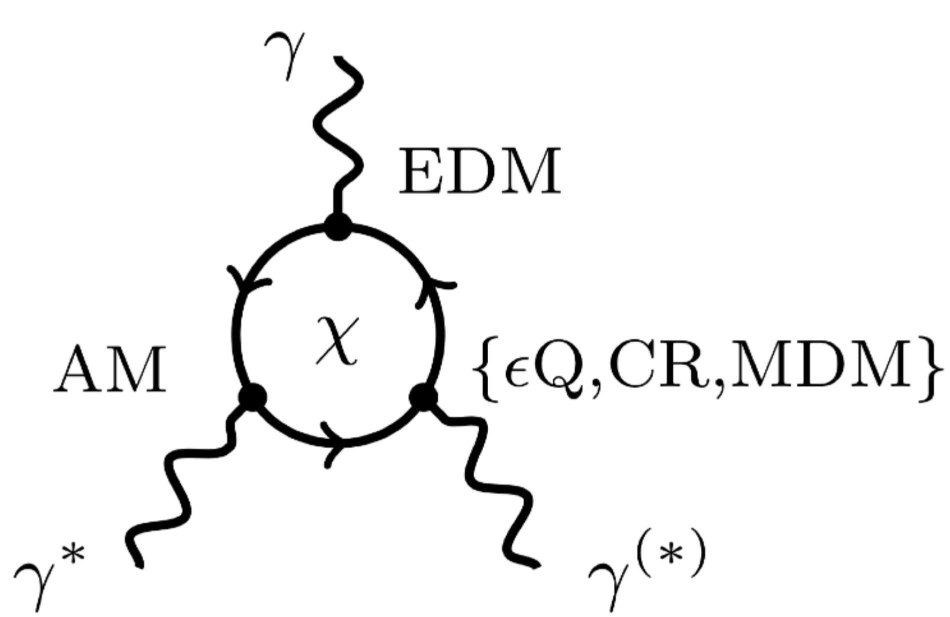
(saturating lower limit)

SM electric dipole moments?

- Recently, ACME collaboration improved bound on electron EDM

$$|d_e| < 1.1 \times 10^{-29}\, e\,\mathrm{cm}\ = 6 \times 10^{-19} \mu_B$$

- Dark states may induce an EDM operator via insertion of dark d_χ



2 loop?

NB: the left loop does not vanish, AM is C-odd operator, so Furry theorem does not hold (in the usual way)

SM electric dipole moments?

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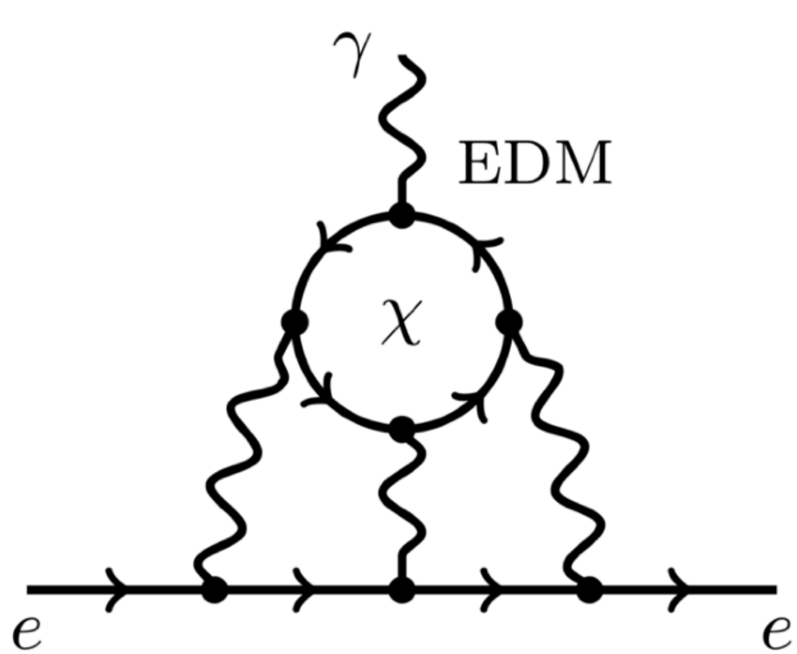
- Dark states may induce an EDM operator via insertion of dark d_χ



3 loop it is

$$d_e \sim e^3 m_e d_\chi \times (\mathrm{mass})^{-1}$$

$$(\mathrm{mass})^{-1} \sim \epsilon^3 e^3 / m_\chi, \mu_\chi^3 m_\chi^2, \\ d_\chi^2 \mu_\chi m_\chi^2,\; b_\chi d_\chi^2 m_\chi^3 \ldots$$

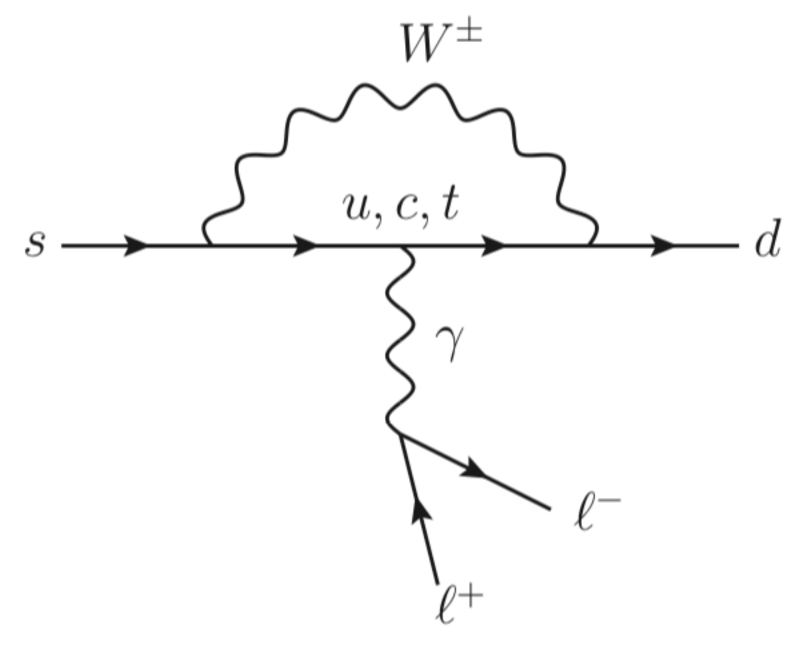
e.g. dim-5 operators only:

$$(10^{-5} - 10^{-6})\, \mu_B \sqrt{\mathrm{GeV}/m_\chi}$$

Rare Meson Decays

- χ pair-production through γ^* in flavor changing s->d and b->s transition closely related to $K^+ \to \pi^+ l^+ l^-$ and $B^+ \to K^+ l^+ l^-$

e.g. for Kaons



$$\frac{\Gamma(K^+ \to \pi^+ \bar{\chi}\chi)}{\Gamma(K \to \pi e^+ e^-)} \simeq 1.9 \times 10^4 \left(\frac{\mu_\chi \text{ or } d_\chi}{\mu_B}\right)^2$$

$$\frac{\Gamma(K^+ \to \pi^+ \bar{\chi}\chi)}{\Gamma(K \to \pi e^+ e^-)} \simeq 2.6 \times 10^4 \left(\frac{a_\chi \text{ or } b_\chi}{\text{TeV}^2}\right)^2$$

constrained from $\text{Br}(K^+ \to \pi^+ + \text{inv}) \lesssim 4 \times 10^{-10}$ E949; see also NA62

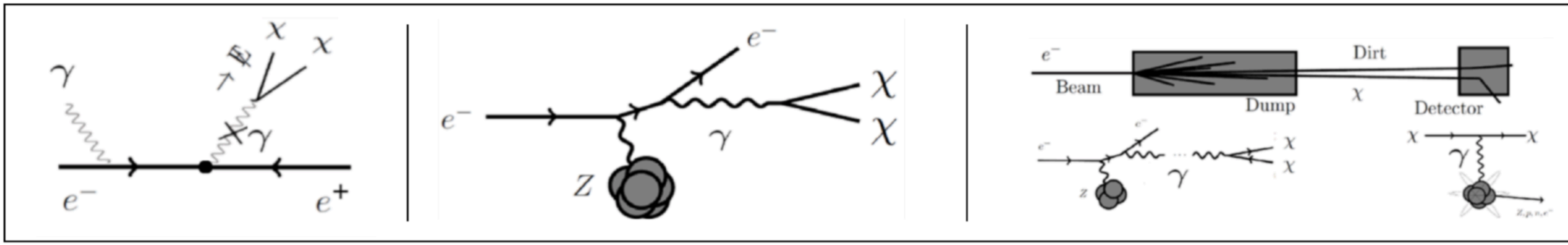
$$|\mu_\chi| \text{ or } |d_\chi| \lesssim 3 \times 10^{-4} \mu_B$$

$$|a_\chi| \text{ or } |b_\chi| \lesssim 0.2\,\text{GeV}^{-2}$$

likewise for $\text{Br}(B^+ \to K^+ + \text{inv}) \lesssim 7 \times 10^{-5}$ BaBar 2003

A new target for the intensity frontier

missing momentum | missing energy | direct search



BaBar:

- CM energy: 10 GeV
- Luminosity: 28/19 fb^{-1}

Belle II (projected)**:**

- Luminosity: 50 ab^{-1}

Main Backgrounds:

- $e^+e^- \to \gamma\gamma$
- $e^+e^- \to \gamma\gamma\gamma$
- $e^+e^- \to \gamma\, e^+e^-$

NA64:

- Beam energy: 100 GeV
- Lead Target
- EOT: 10^{10}

LDMX (projected)**:**

- Beam energy: 4/8 GeV
- Tungsten/Aluminum Target
- EOT: 10^{14} / 10^{15}

Almost no Backgrounds:

- Active veto system
- Cuts on search region

mQ:

- Beam energy: 30 GeV
- Tungsten Target
- EOT: 10^{19}

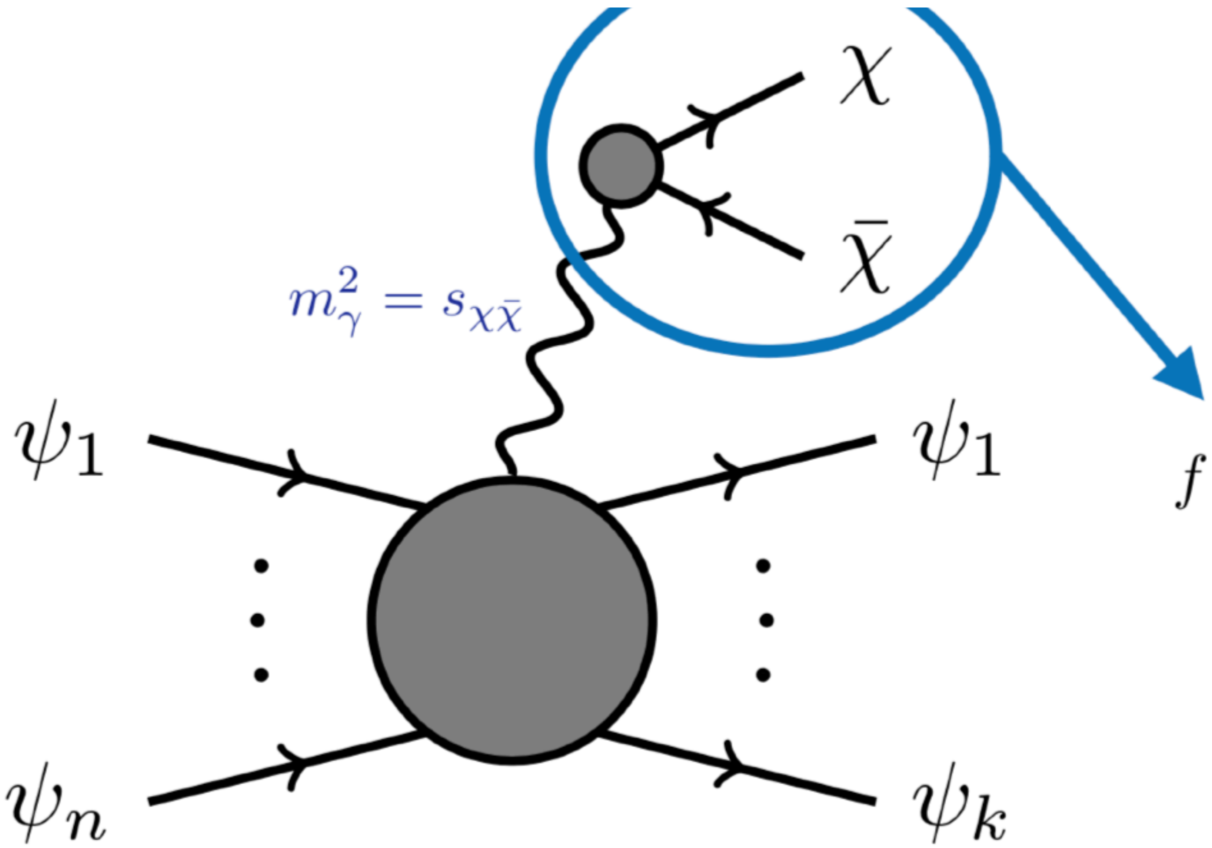
BDX (projected)**:**

- Beam energy: 11 GeV
- Aluminum Target
- EOT: 10^{22}

Main Backgrounds:

- High energy neutrinos

Unified description of various interactions



$$f(s_{\chi\bar{\chi}}) = \begin{cases} \frac{4}{3}\epsilon^2 e^2 \, s_{\chi\bar{\chi}} \left(1 + \frac{2m_\chi^2}{s_{\chi\bar{\chi}}}\right) & \text{millicharge} \\ \frac{2}{3}\mu_\chi^2 \, s_{\chi\bar{\chi}}^2 \left(1 + \frac{8m_\chi^2}{s_{\chi\bar{\chi}}}\right) & \text{magnetic dipole} \\ \frac{2}{3}d_\chi^2 \, s_{\chi\bar{\chi}}^2 \left(1 - \frac{4m_\chi^2}{s_{\chi\bar{\chi}}}\right) & \text{electric dipole} \\ \frac{4}{3}a_\chi^2 \, s_{\chi\bar{\chi}}^3 \left(1 - \frac{4m_\chi^2}{s_{\chi\bar{\chi}}}\right) & \text{anapole} \\ \frac{4}{3}b_\chi^2 \, s_{\chi\bar{\chi}}^3 \left(1 + \frac{2m_\chi^2}{s_{\chi\bar{\chi}}}\right) & \text{charge radius} \end{cases}$$

$$\int \frac{d\Omega_\chi^{R\chi\bar{\chi}}}{4\pi} \mathrm{Tr}\left[(\not{p}_\chi + m_\chi)\Gamma_\mu(q)(\not{p}_{\bar{\chi}} - m_\chi)\bar{\Gamma}_\nu(q)\right] = f(s_{\chi\bar{\chi}}) \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{s_{\chi\bar{\chi}}}\right)$$

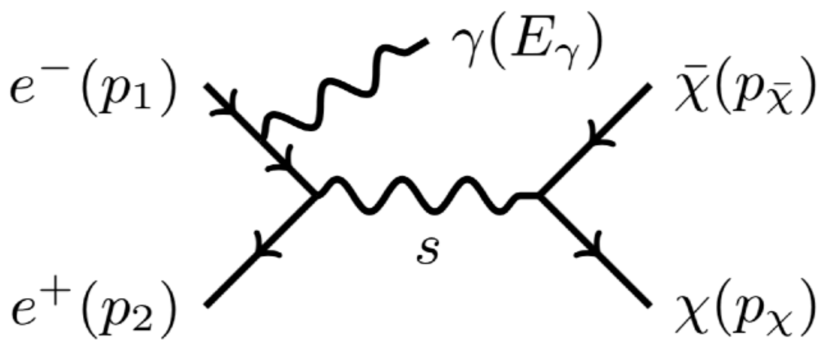
=> for example: $$\frac{d\sigma_{2\to4}}{ds_{\chi\bar{\chi}}} = \sigma_{2\to3}\left(s_{\chi\bar{\chi}}\right) \frac{f\left(s_{\chi\bar{\chi}}\right)}{16\pi^2 s_{\chi\bar{\chi}}^2} \sqrt{1 - \frac{4m_\chi^2}{s_{\chi\bar{\chi}}}}$$

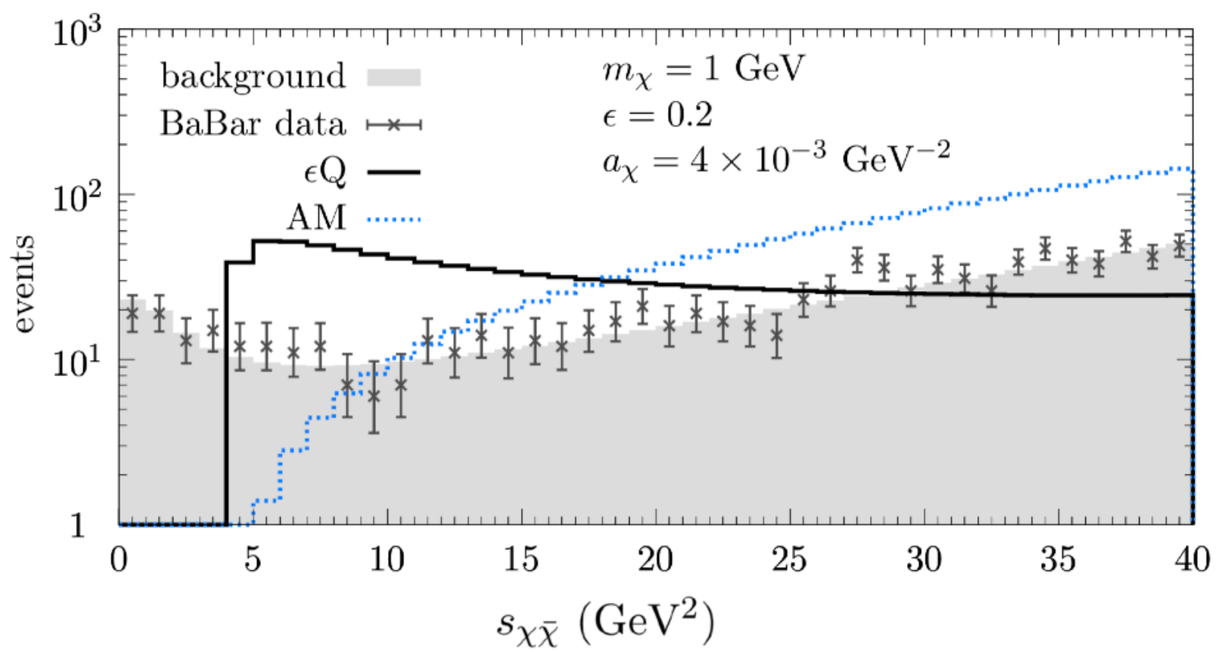
Intensity frontier prospects

Production in e+ e- annihilation, e.g. at BaBar, Belle-II

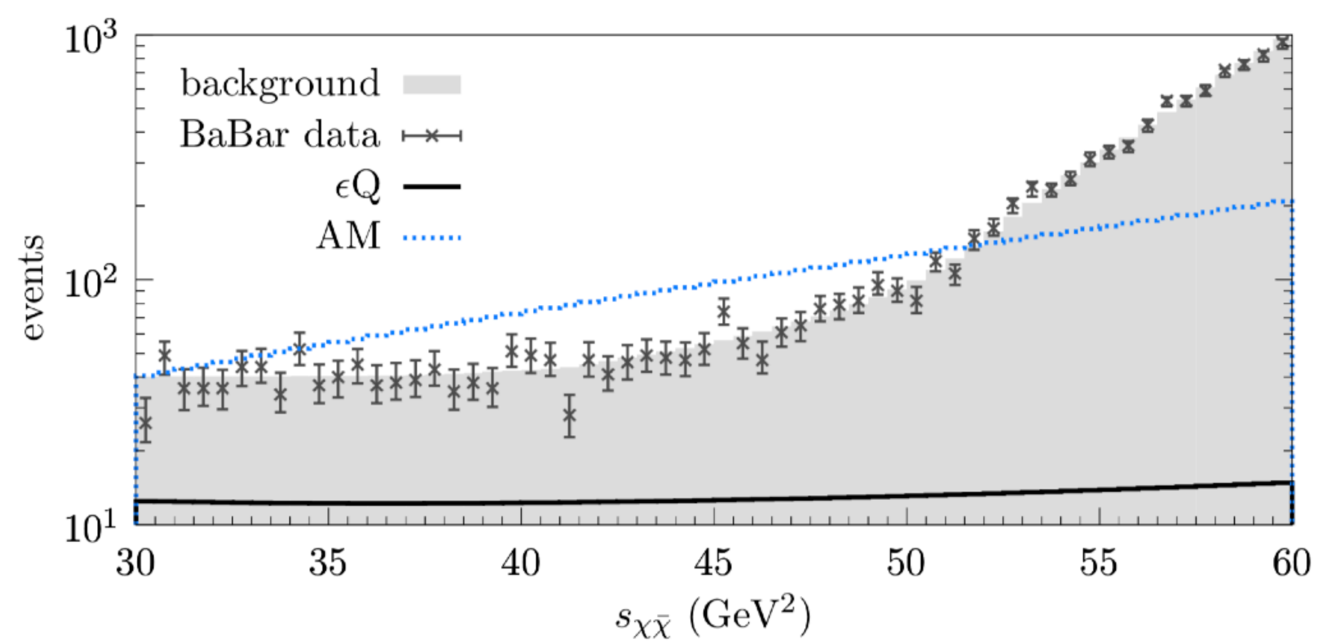
Mono-photon search $x_\gamma = E_\gamma/\sqrt{s}$

$$\frac{d\sigma_{e^+e^-}}{dx_\gamma d\cos\theta_\gamma} = \sigma_{e^+e^-}(s, s_{\chi\bar{\chi}})\,\mathcal{R}^{(\alpha)}(x_\gamma, \theta_\gamma, s)$$





high-energy photon region



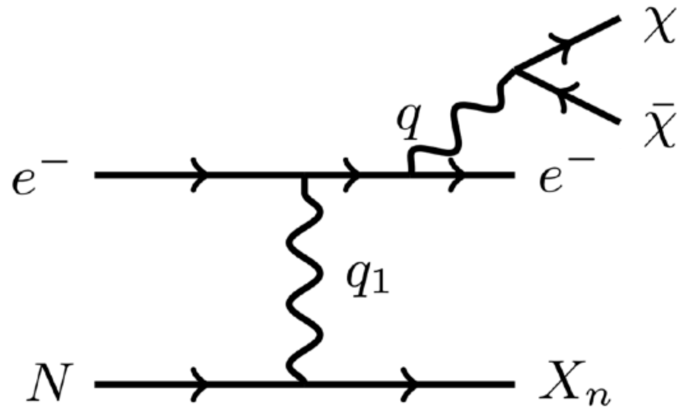
low-energy photon region

Intensity frontier prospects

Production in electron fixed target experiments

- Missing energy (NA64, LDMX)

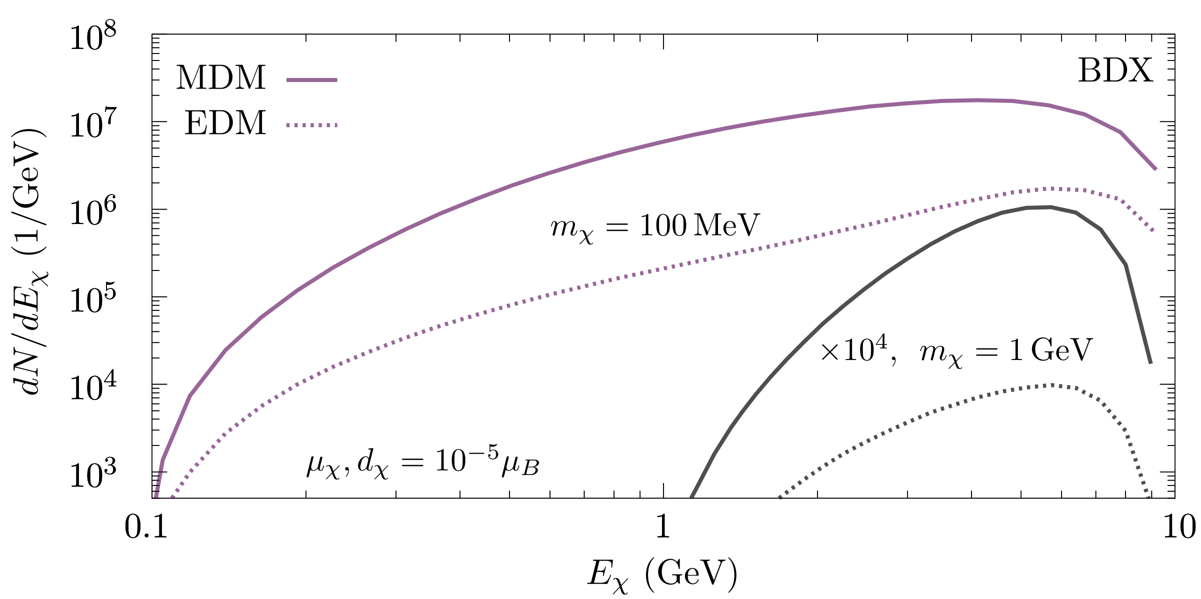
$$\frac{d\sigma_{2\to4}}{ds_{\chi\bar{\chi}}} = \sigma_{2\to3}\left(s_{\chi\bar{\chi}}\right)\frac{f\left(s_{\chi\bar{\chi}}\right)}{8\pi}\sqrt{1-\frac{4m_\chi^2}{s_{\chi\bar{\chi}}}}$$

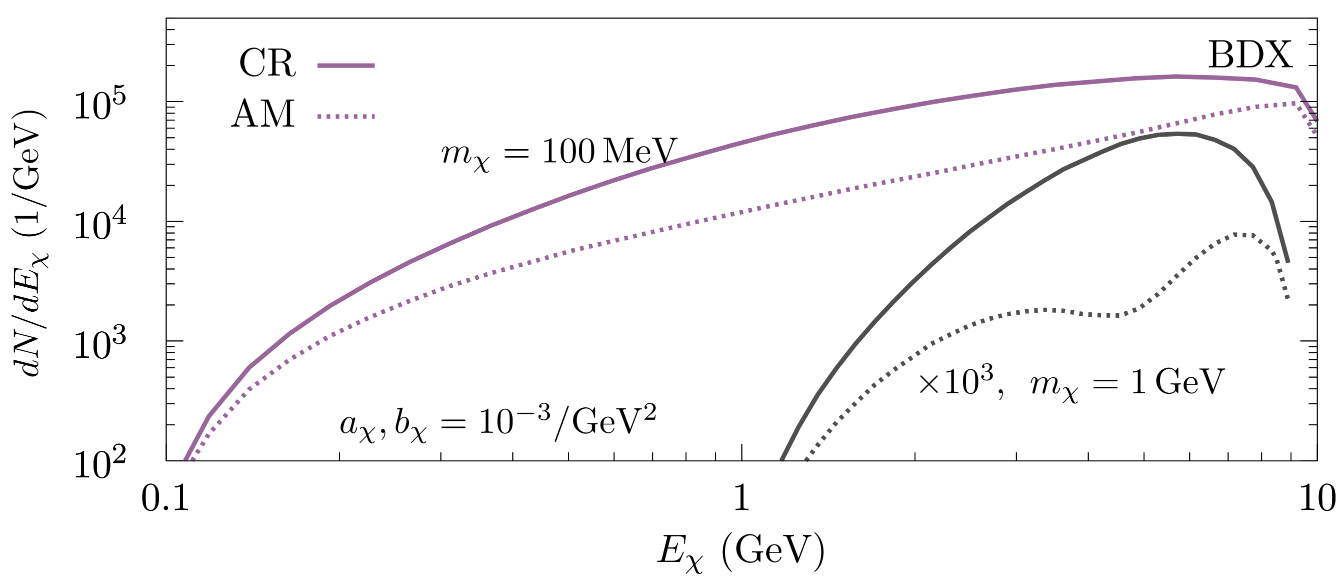


The f's carry the entire information of the new physics vertex

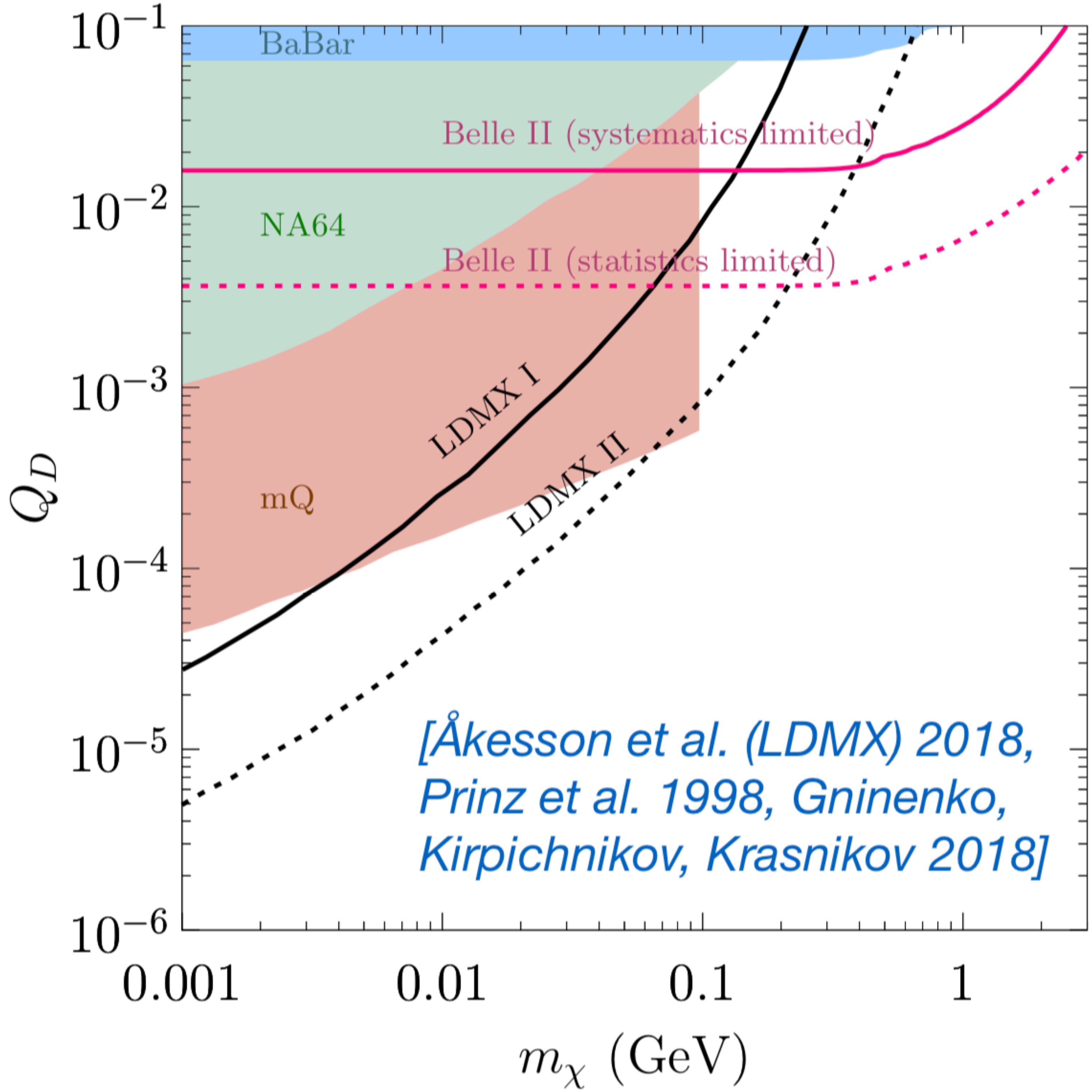
Cuts + veto system make searches largely background free

- Subsequent scattering (mQ, BDX)



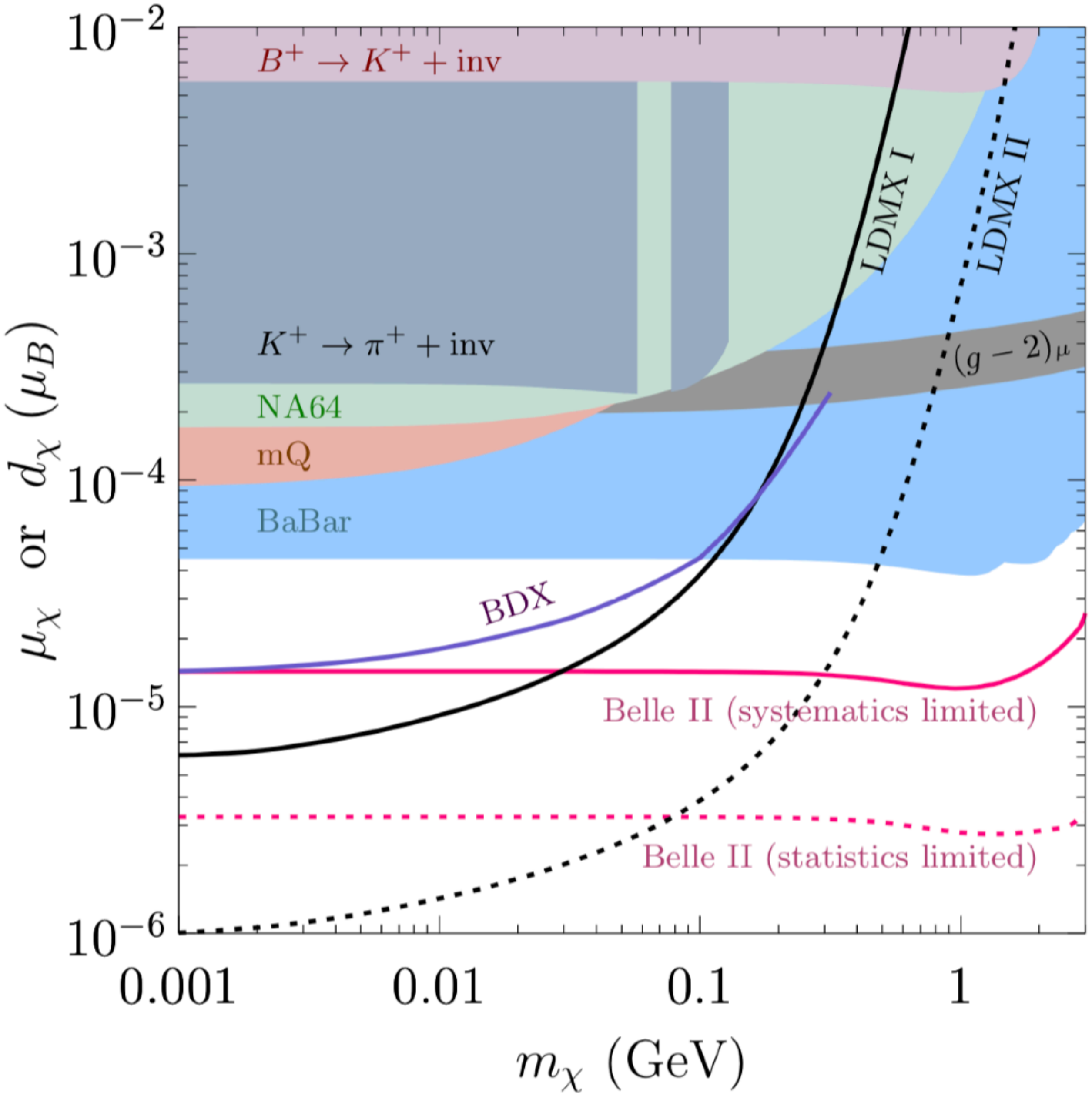


Milli-Charge



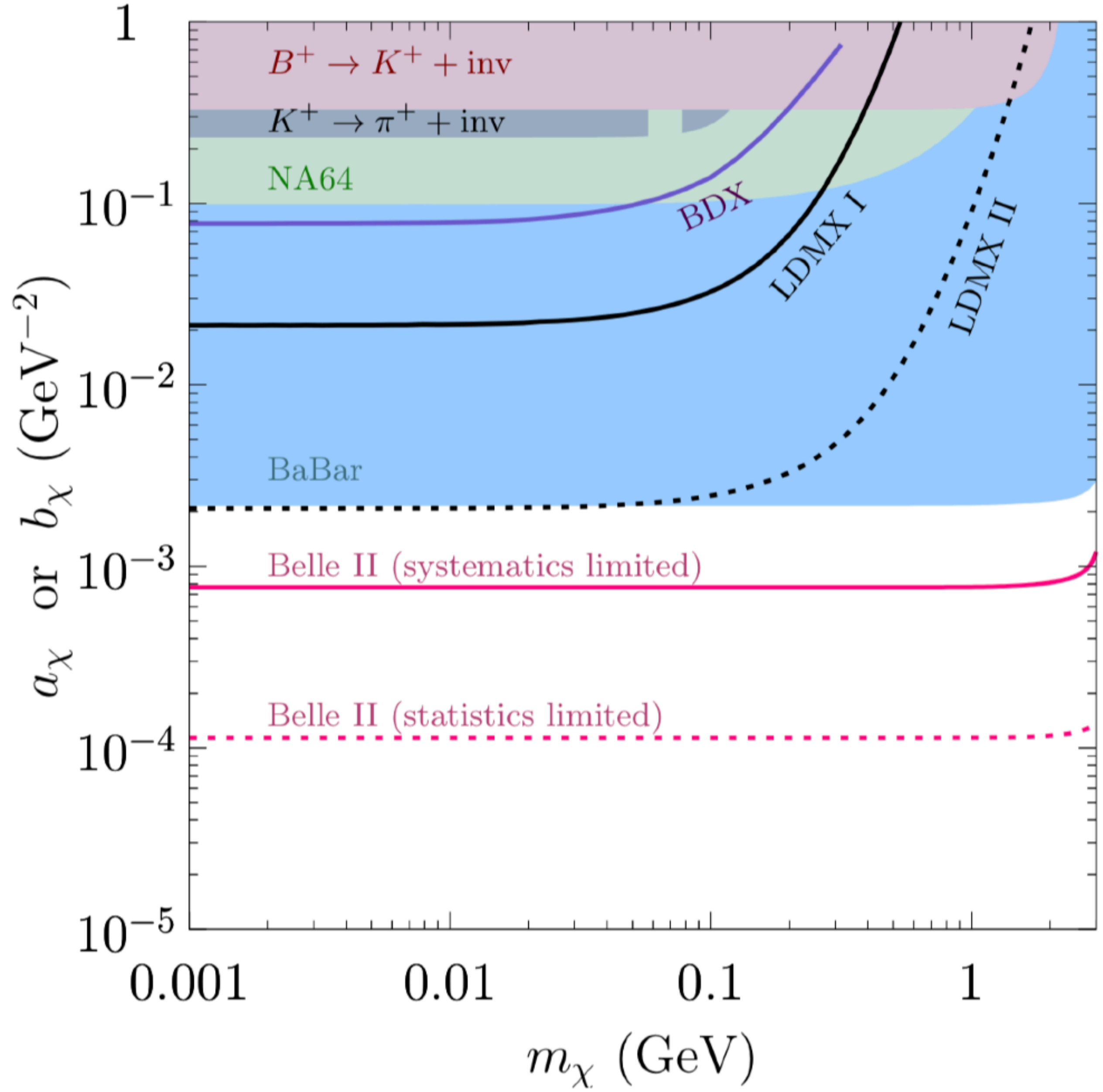
$$f(s_{\chi\bar{\chi}}) \propto s_{\chi\bar{\chi}}$$

Dipole Moment



$$f(s_{\chi\bar{\chi}}) \propto s_{\chi\bar{\chi}}^2$$

Charge Radius



$$f(s_{\chi\bar{\chi}}) \propto s_{\chi\bar{\chi}}^3$$

LEP & LHC

- LEP Mono-photon constraint

$$|\mu_\chi| \text{ or } |d_\chi| \; < \; 1.3 \times 10^{-5} \mu_B .$$

Fortin, Tait 2011

Following this analysis, we get

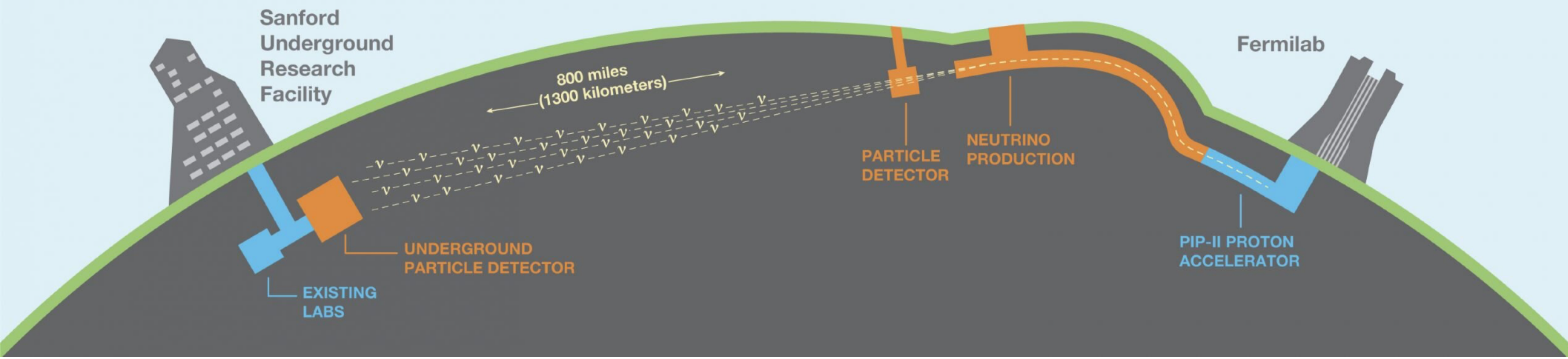
$$|a_\chi| \text{ or } |b_\chi| \; < \; 1.5 \times 10^{-5} \, \text{GeV}^{-2}$$

- LHC constraints based on mono-photon and monojets comparable

see Barger et al 2012; Gao, Ho, Scherrer 2014

=> Lesson is that high-energy colliders do comparable at dim-5 and are superior for dim-6 operators compared to low-energy, high-intensity e-beams

Proton-beams



based on X. Chu, J.-L. Kuo, JP (arXiv last week)

- proton beams are the workhorses of the short- and long-baseline neutrino program
- new light physics cases explored at near detectors, e.g. at LSND, MiniBooNE, COHERENT, DUNE etc.
- plus dedicated experiments that aim to probe dark sector states such as SHiP

Proton-beams

- primary production channels

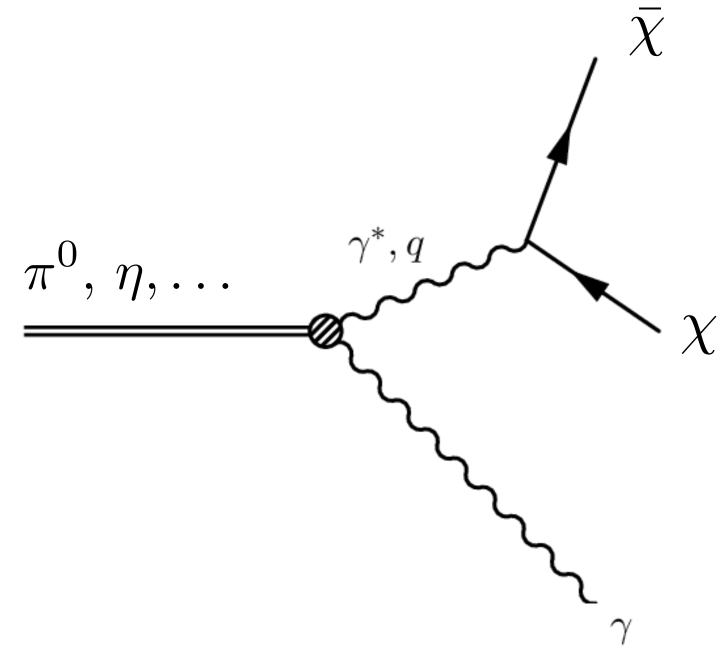
  scalar meson Dalitz decay

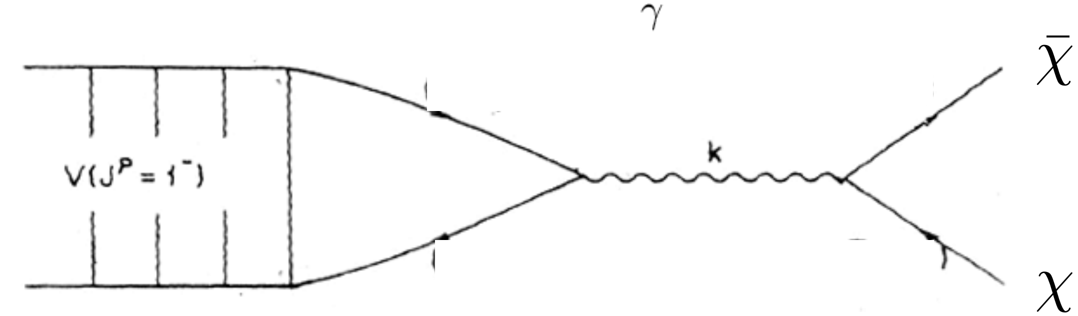
  vector meson 2-body decay

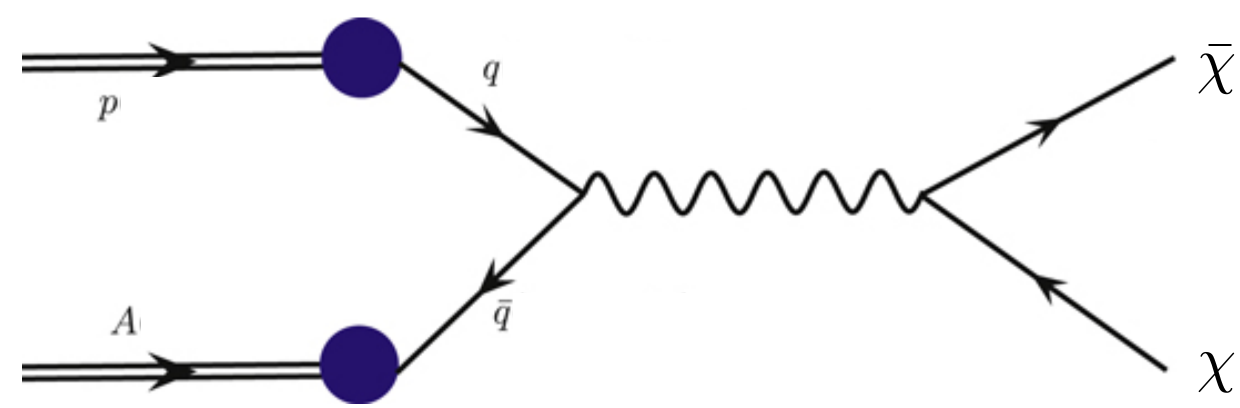
  Drell-Yan production

  Bremsstrahlung

  pion capture on nuclei



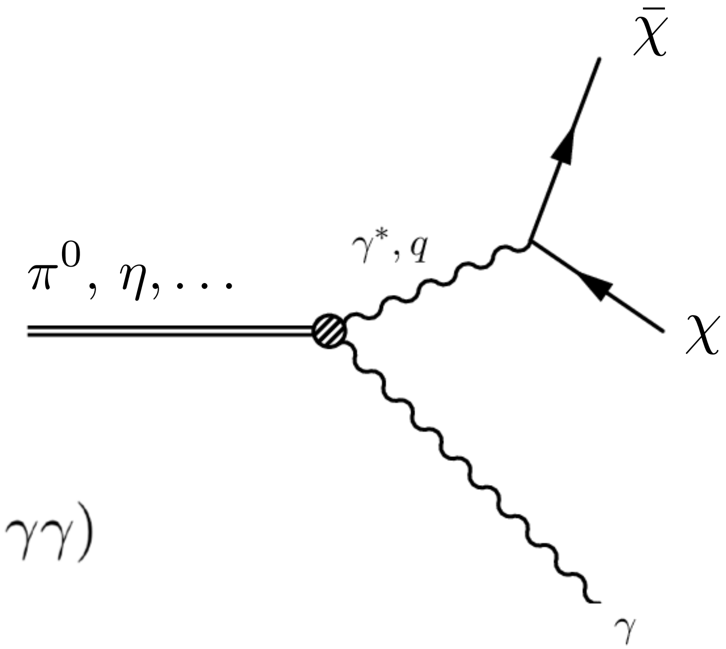




Proton-beams

- primary production channels

e.g. scalar meson Dalitz decay



$$\mathrm{Br}(\mathrm{sm} \to \gamma\chi\bar{\chi}) = \frac{\Gamma_{\mathrm{sm}\to\gamma\chi\bar{\chi}}}{\Gamma_{\mathrm{sm}\to\gamma\gamma}} \times \mathrm{Br}(\mathrm{sm} \to \gamma\gamma)$$

observations:

extra energy scale E needed to compensate for the presence of the dimensionful coupling (E for dim-5 and E^2 for dim-6)

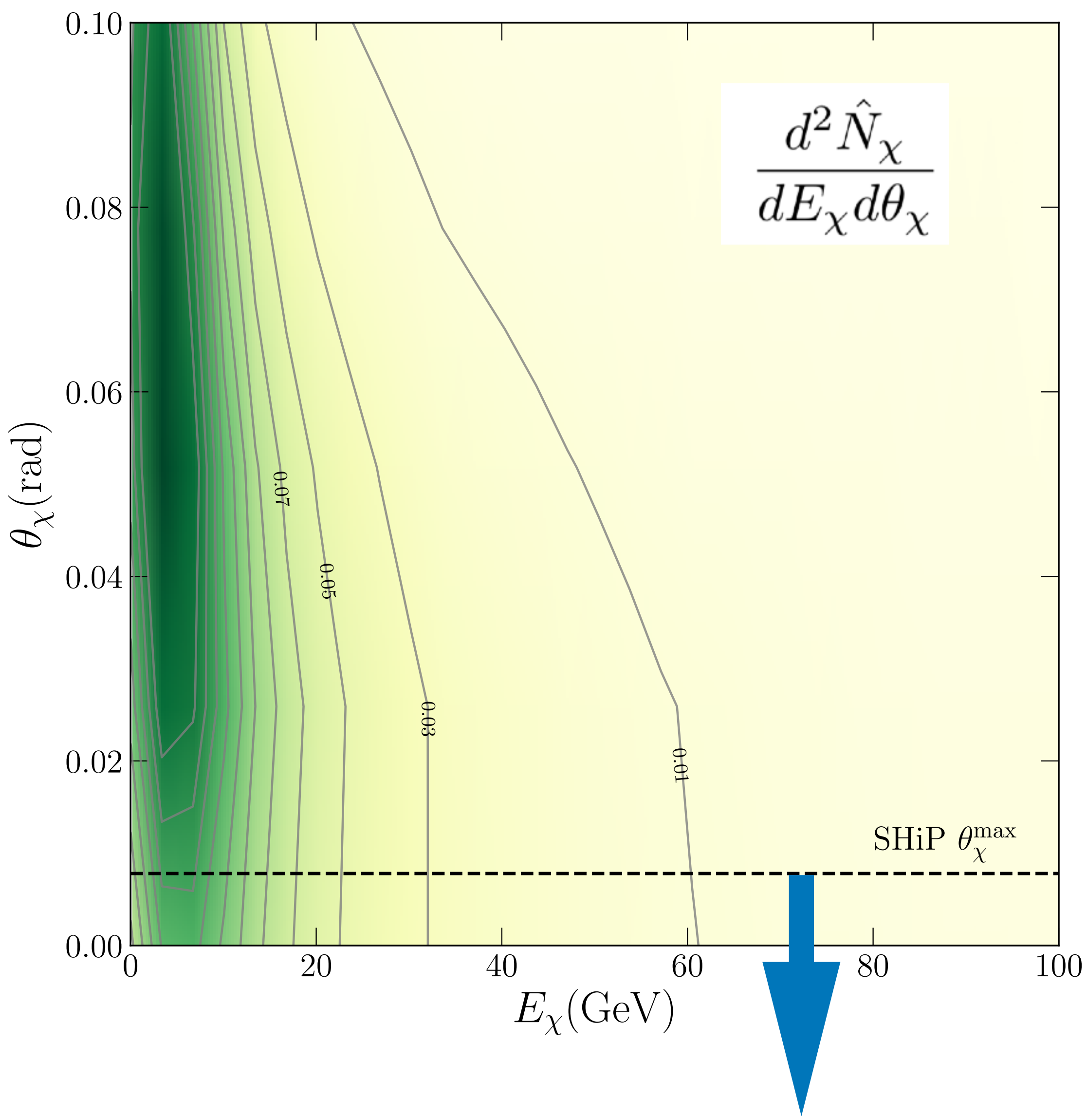
=> Drell-Yan gains importance as E ~ $\sqrt{s}$ compared to E ~ m_{meson}

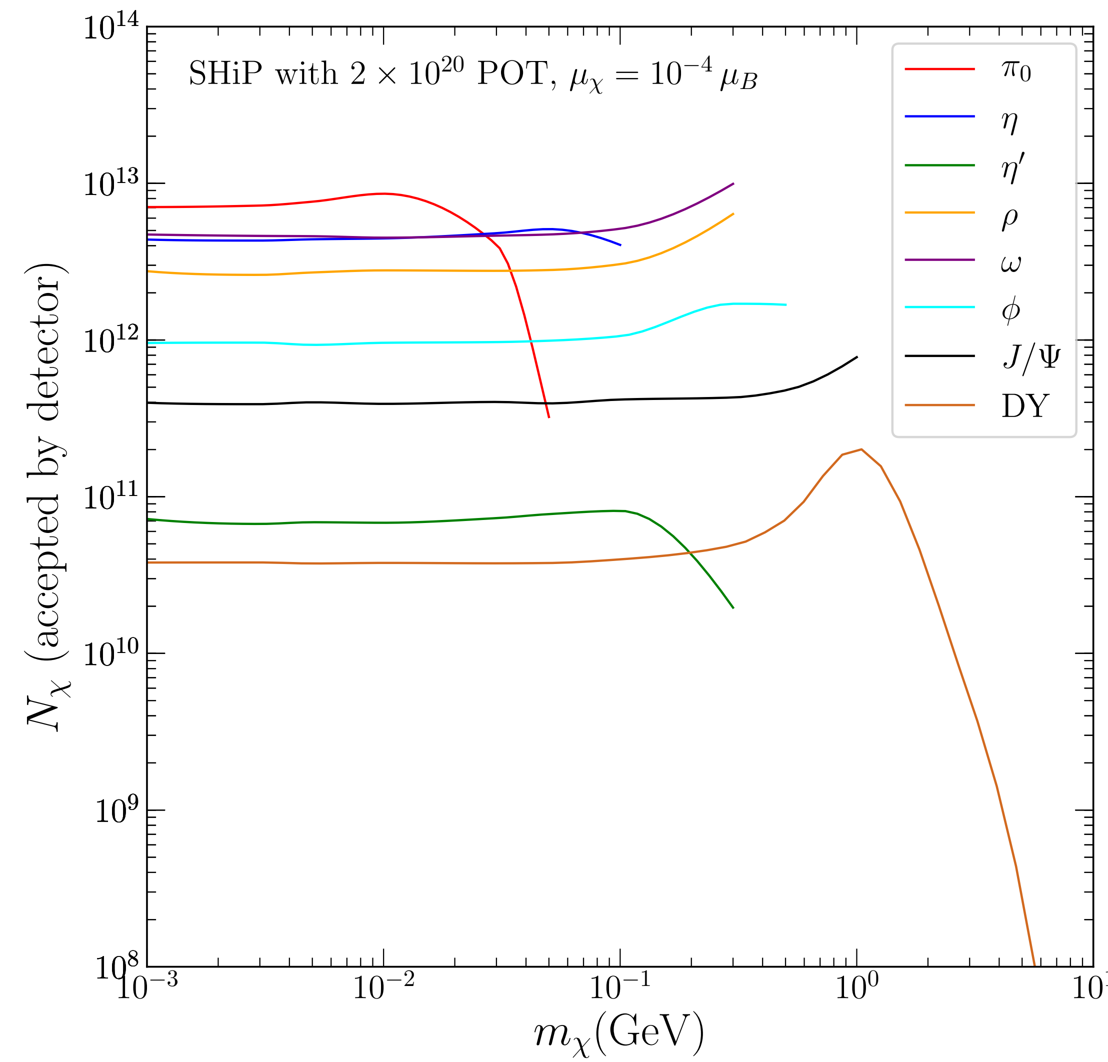
=> higher mass meson decays become important

Proton-beams

- primary production channels

e.g. for SHiP

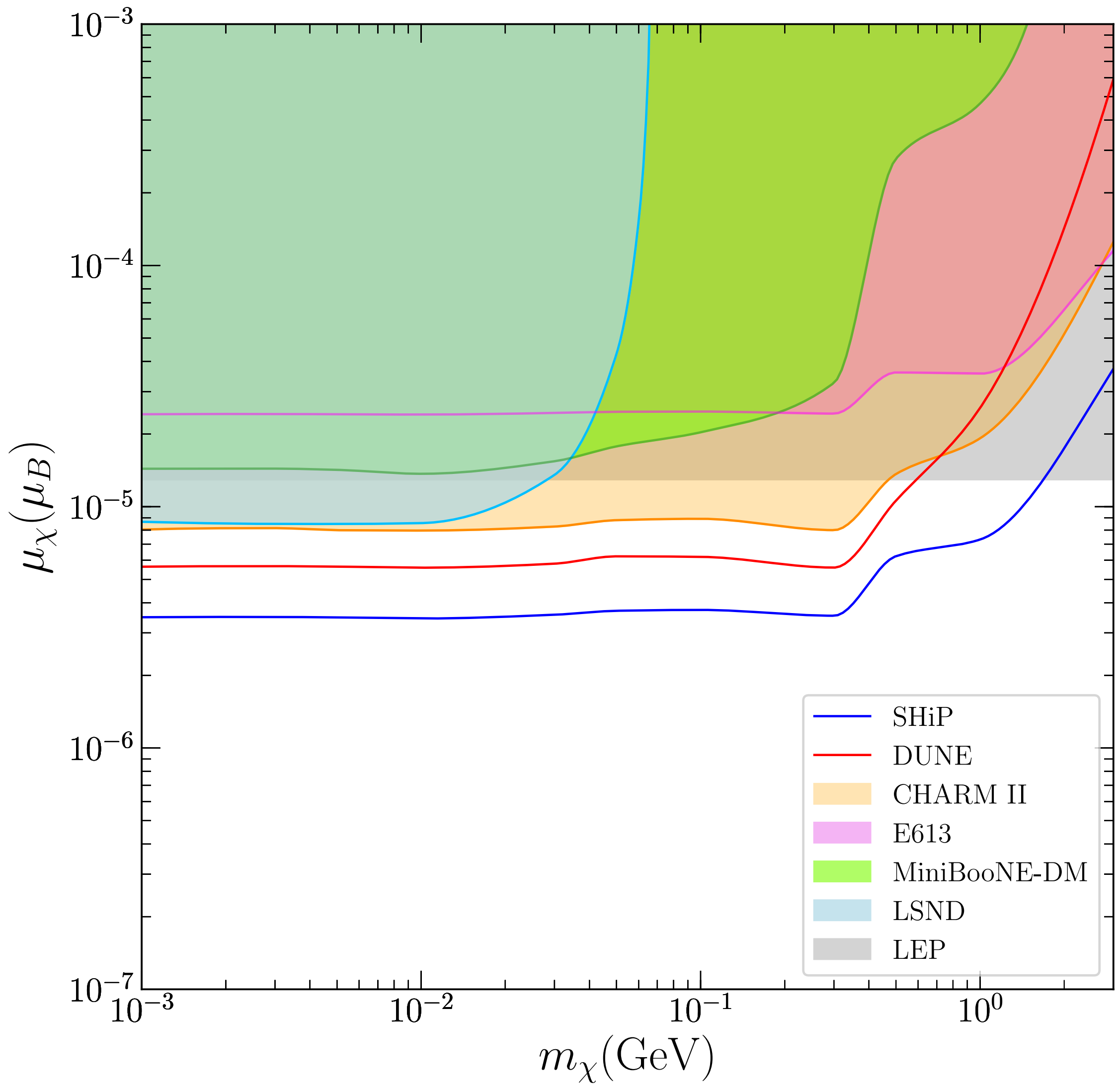


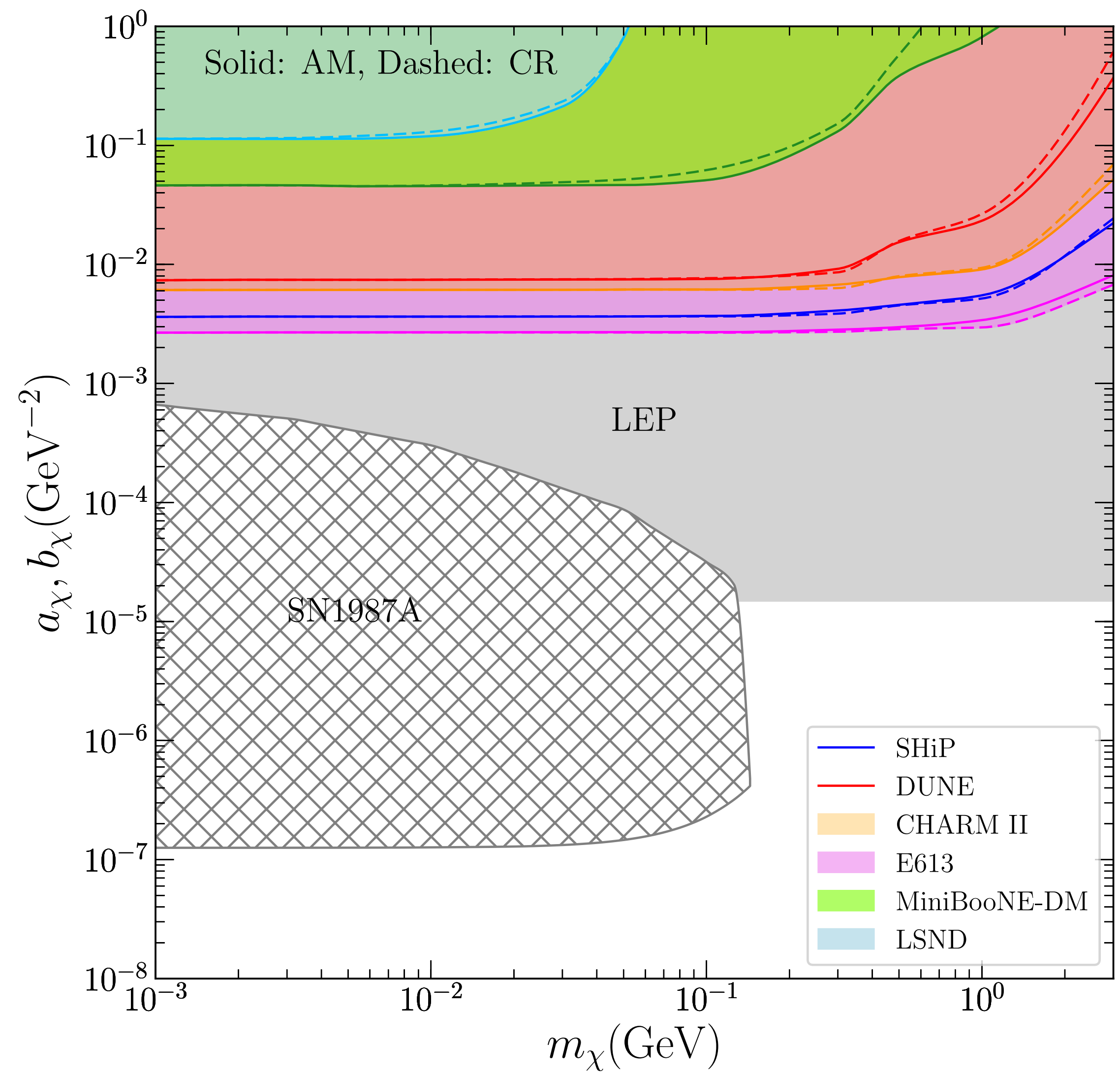


only a small fraction reach the detector

Proton-beams

- detection through electron-recoils and hadronic showers via DIS





=> not much improvement beyond that to be expected at intensity frontier;
=> high(er) energy colliders with efforts to detect milli-charged states beneficial

Can it be dark matter?

- Non-relativistic operators behave very differently, e.g. in annihilation

$\langle \sigma_{\chi\bar{\chi}\to l^+l^-} v \rangle$ s-wave for εQ, MDM, CR; p-wave for EDM, AM

$\langle \sigma_{\chi\bar{\chi}\to \gamma\gamma} v \rangle$ s-wave for εQ, MDM, EDM; 0 for AM, CR

=> also govern the indirect CMB and, for p-wave, Voyager limits

- Direct detection: sub-GeV region better probed by DM-electron scattering

$$\text{MDM:} \quad \overline{|M_{\chi e}(q)|^2} = 16\pi \mu_\chi^2 \alpha m_\chi^2,$$

$$\text{EDM:} \quad \overline{|M_{\chi e}(q)|^2} = \frac{64\pi d_\chi^2 \alpha m_e^2 m_\chi^2}{q^2},$$

$$\text{AM:} \quad \overline{|M_{\chi e}(q)|^2} = 16\pi a_\chi^2 \alpha m_\chi^2\, q^2,$$

$$\text{CR:} \quad \overline{|M_{\chi e}(q)|^2} = 64\pi b_\chi^2 \alpha m_e^2 m_\chi^2.$$

<= various q-dependencies that are moved into an atomic form factor

Cosmo- and astro-constraints

- Dark radiation / N_{eff}

(sub-)MeV mass χ particles reach thermal equilibrium for T>m once

$$\mu_\chi, d_\chi \geq 10^{-9}\mu_B \quad \text{dim-5}$$

$$a_\chi, b_\chi \geq 5\times 10^{-5}\,\mathrm{GeV}^{-2} \quad \text{dim-6}$$

=> $m_\chi \gtrsim 7 - 10\,\mathrm{MeV}$

- DM self-interactions

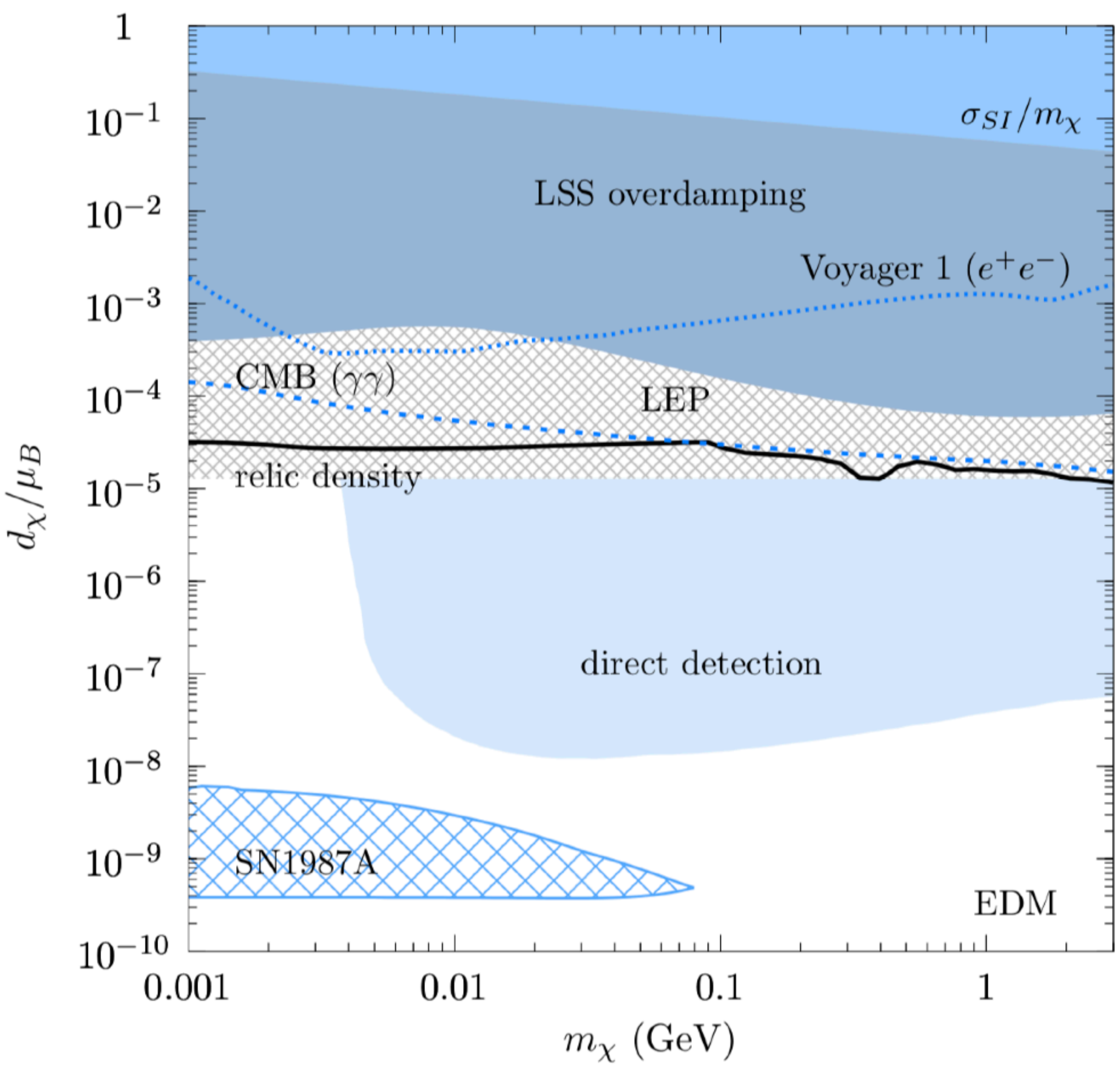
In contrast to Millicharged DM, EM-moments have no enhancement at low relative velocities

=> Bullet-cluster limit applies $\sigma_{\mathrm{SI}}/m_\chi \lesssim 1.25\,\mathrm{cm}^2/\mathrm{g}$

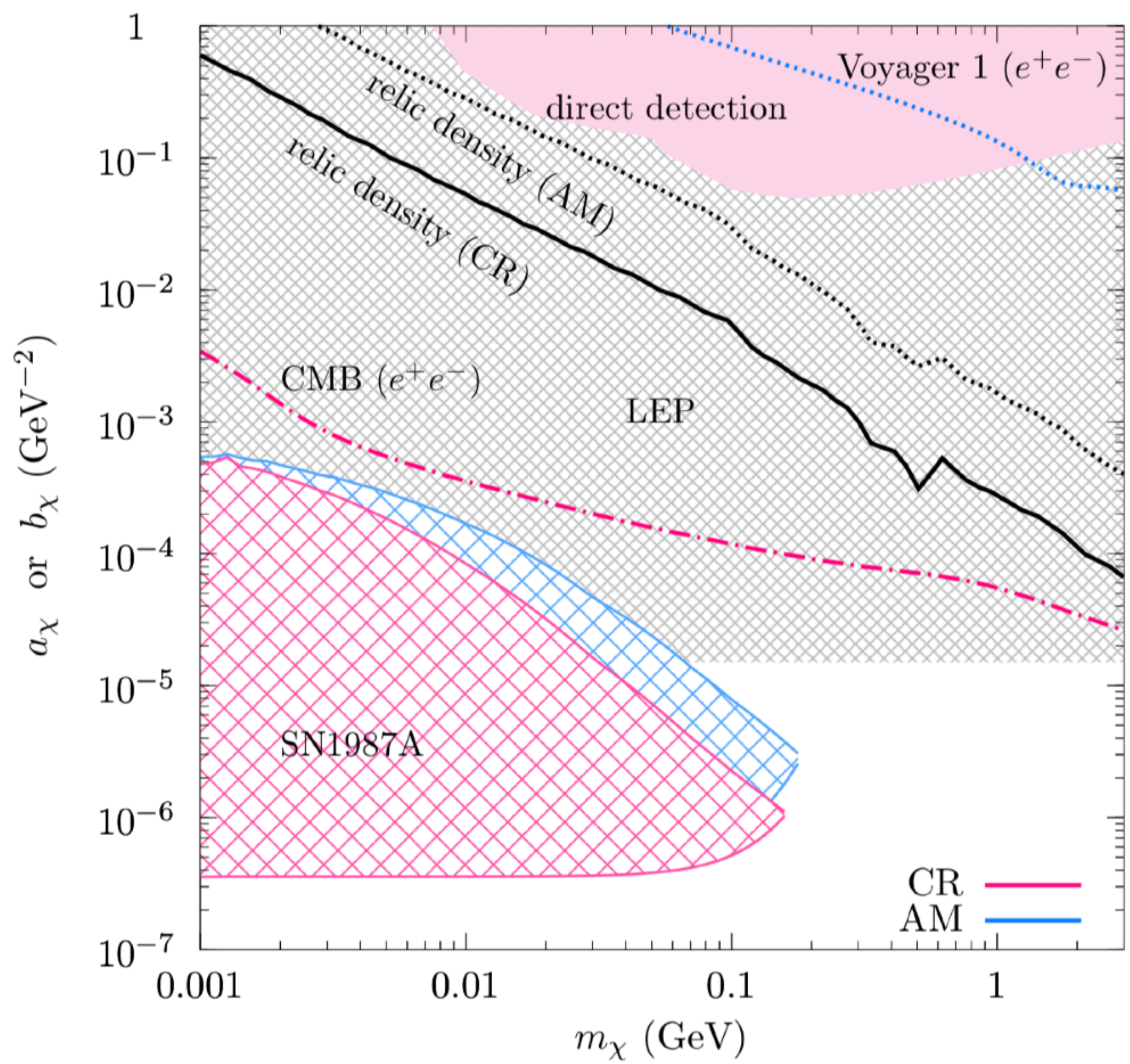
Robertson, Massey, Eke 2008

Summary of EMDM Dark Matter constraints

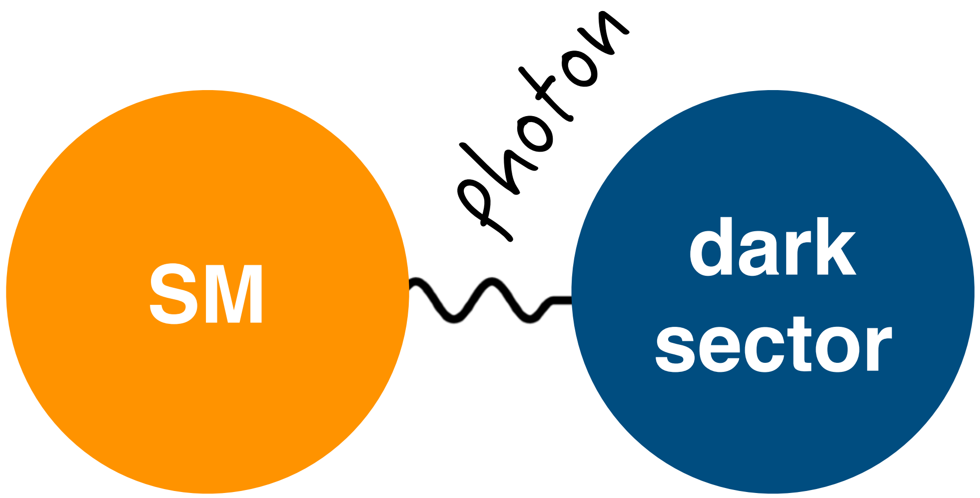
Electric Dipole Moment



Anapole Moment / Charge Radius



Light dark states through the *photon portal*



MeV - GeV mass-bracket:

=> established a complete phenomenological picture

sub-MeV masses:

=> strong astrophysical implications

=> stars as laboratories for dark-sector photon interactions

Stars reacting to energy loss

$$\langle E_{\mathrm{kin}} + E_{\mathrm{grav}} \rangle \searrow$$

1. Stars supported by radiation pressure (active stars):

Virial theorem: $\langle E_{\mathrm{kin}} \rangle = -\frac{1}{2} \langle E_{\mathrm{grav}} \rangle$

=> Gravitational potential energy becomes more negative (tighter bound)

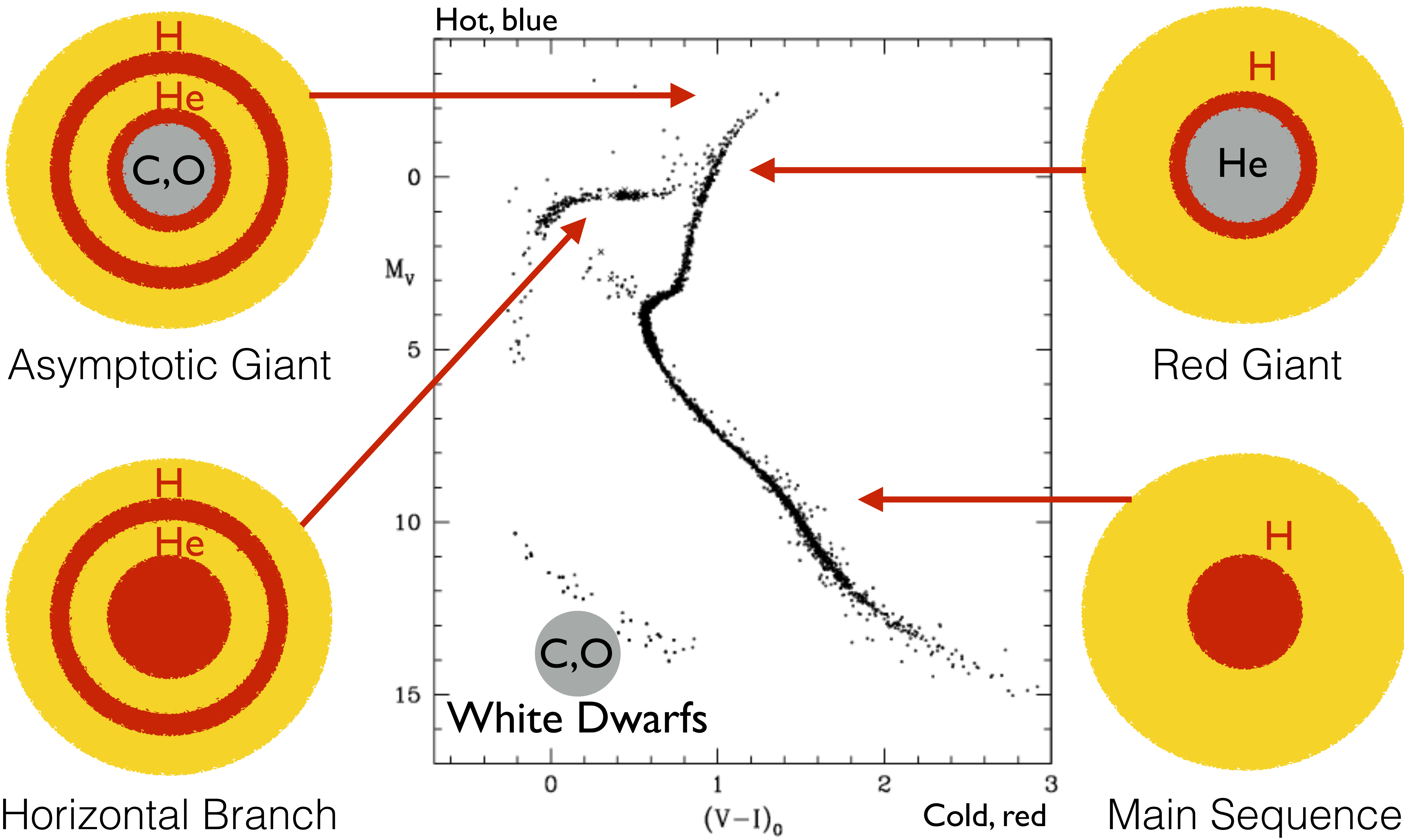
=> average kinetic energy increases, star becomes hotter,

negative heat capacity

2. Stars supported by degeneracy pressure (white dwarfs, neutron stars):

possess positive heat capacity, the star actually cools by the energy loss

Stars as laboratories



Globular Cluster color-magnitude diagram

Inferred limits on anomalous energy loss

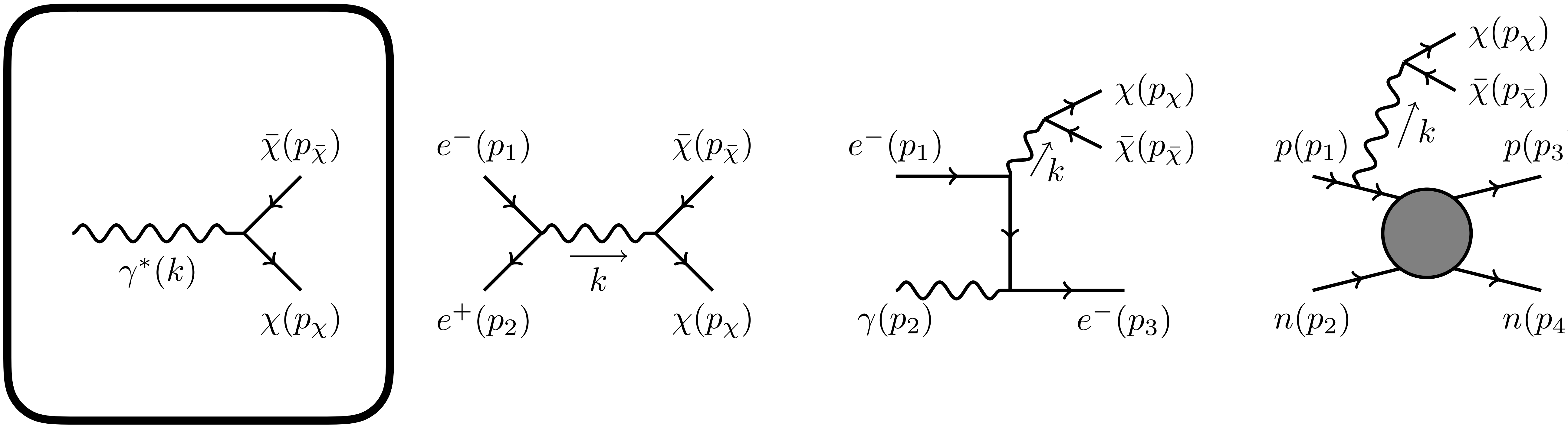
Sun $\int_{\text{sun}} dV\,\dot{Q} < 10\% \times L_\odot$ Inferred from observed boron neutrino flux

HB $\int_{\text{core}} dV\,\dot{Q} < 10\% \times L_{\text{HB}}$ Inferred from He-burning lifetime

RG $\dot{Q} < 10\,\text{erg/g/s} \times \rho_{\text{RG}}$ Inferred from maximum RG core mass

SN $\int_{\text{core}} dV\,\dot{Q} < L_\nu$ Inferred from cooling curve of SN1987A

Stellar Probes of dark-sector photon interactions

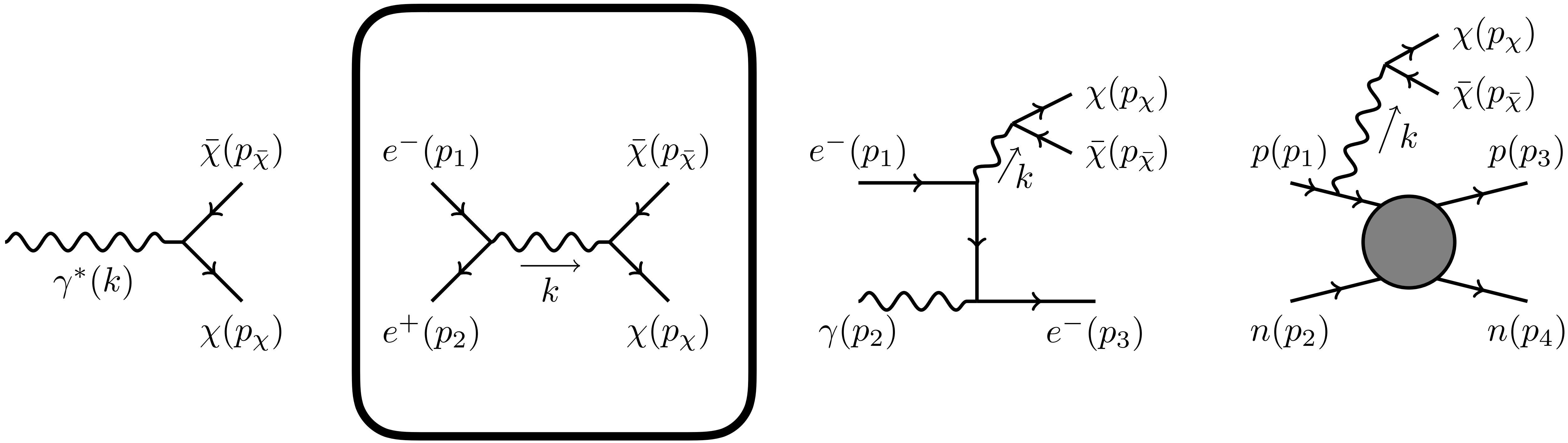


T/L "Plasmon" decay

(all)

$$\omega_p \sim \begin{cases} 0.3\,\mathrm{keV} & \text{Sun's core} \\ 2.6\,\mathrm{keV} & \text{HB's core} \\ 8.6\,\mathrm{keV} & \text{RG's core} \\ 17.6\,\mathrm{MeV} & \text{SN's core} \end{cases}$$

Stellar Probes of dark-sector photon interactions

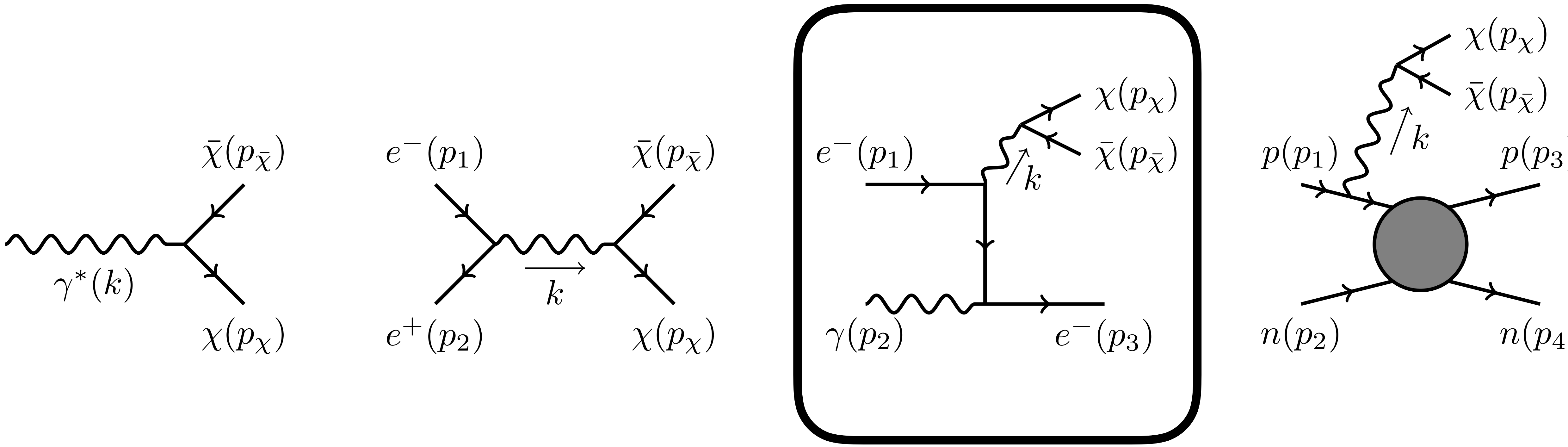


e+e- annihilation

NB: no overlap with plasmon decay

(SN)

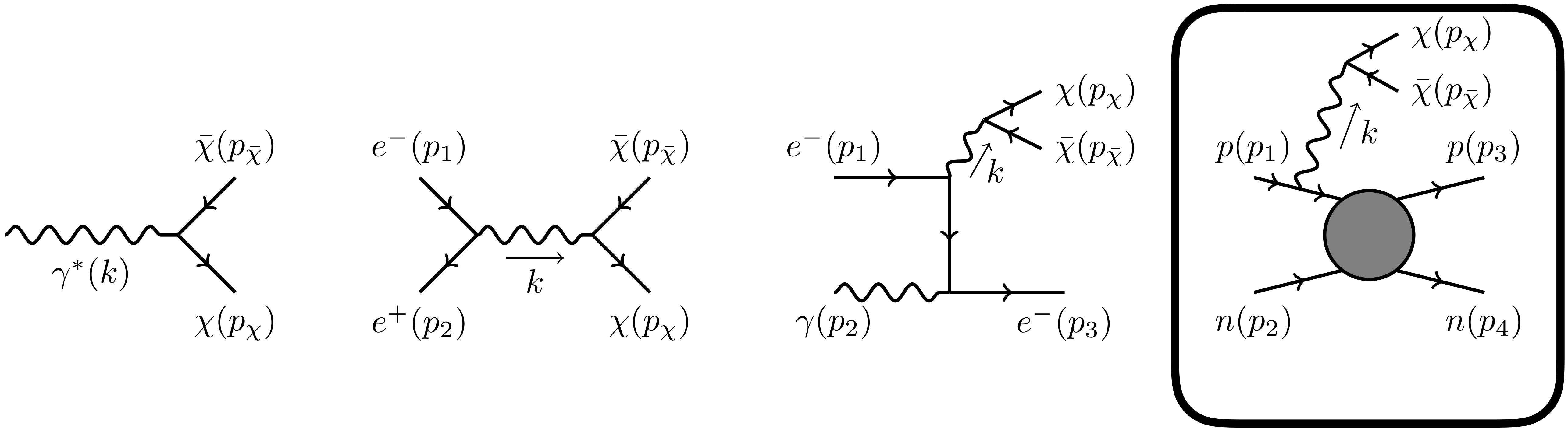
Stellar Probes of dark-sector photon interactions



Compton 2->3 production

(all)

Stellar Probes of dark-sector photon interactions



Electron-nucleus Bremsstrahlung

(RG, HB, Sun)

NB: soft-photon approximation not applicable

Neutron-proton Bremsstrahlung

(SN)

NB: we use exp. data for np-brems

Rrapaj, Reddy 2016

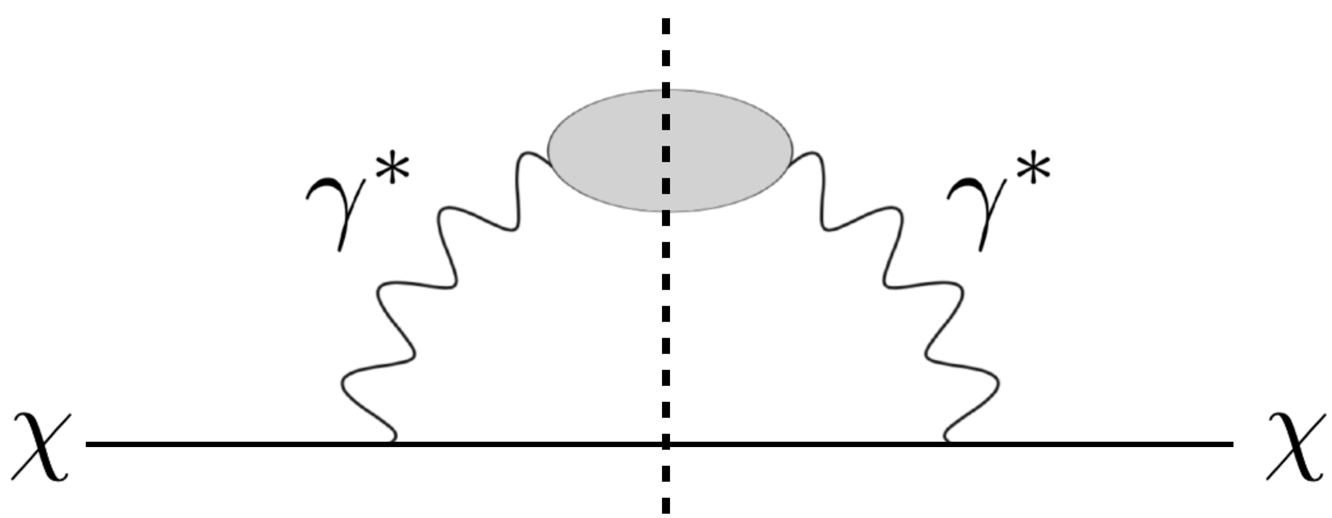
Exact Formula for pair-emission

$$\dot{N}_\chi = -\int \frac{d^3\vec{p}_\chi}{(2\pi)^3} \frac{1}{(e^{E_\chi/T}+1)} \frac{\mathrm{Im}\,\Pi_\chi(E_\chi,\vec{p}_\chi)}{E_\chi}$$

Finite-T optical theorem: rate with which a particle comes into thermal equilibrium is given by the discontinuity of the self energy

Weldon 1983

$$\mathrm{Im}\,\Pi_\chi(E_\chi,\vec{p}_\chi) = \bar{u}(p_\chi)\Sigma(E_\chi,\vec{p}_\chi)u(p_\chi)$$



Exact Formula for pair-emission

$$\frac{d\dot{N}_\chi}{ds_{\chi\bar{\chi}}} = -\sum_{i=\mathrm{T,L}} g_i \int \frac{d^3\vec{k}}{(2\pi)^3} \frac{1}{(e^{\omega/T}-1)} \frac{\mathrm{Im}\,\Pi_i(\omega,\vec{k})}{\omega}$$

$$\times \frac{f(s_{\chi\bar{\chi}})}{16\pi^2|s_{\chi\bar{\chi}} - \Pi_i|^2}\sqrt{1-\frac{4m_\chi^2}{s_{\chi\bar{\chi}}}}$$

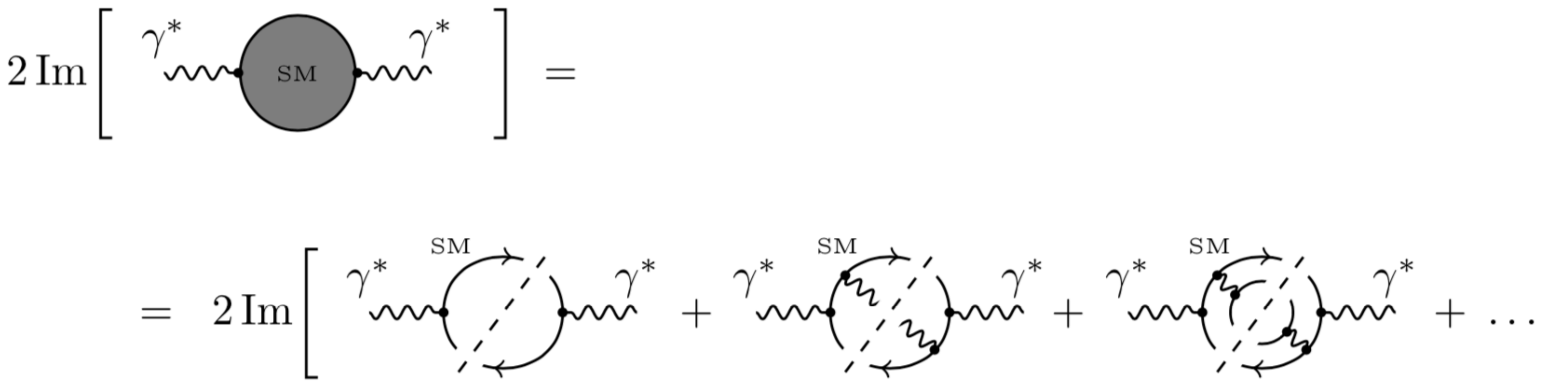
In this version (derived from works on dilepton-production in hot matter) the imaginary part of the *photon self-energy* enters

$$\Pi^{\mu\rho} = (\epsilon^\mu_{\mathrm{T},1}\epsilon^\rho_{\mathrm{T},1} + \epsilon^\mu_{\mathrm{T},2}\epsilon^\rho_{\mathrm{T},2})\,\Pi_\mathrm{T} + \epsilon^\mu_\mathrm{L}\epsilon^\rho_\mathrm{L}\,\Pi_\mathrm{L}$$

=> leading contribution from the pole $s_{\chi\bar{\chi}} = \mathrm{Re}\,\Pi_{\mathrm{L,T}}$
recover plasmon-decay rate

=> further contributions to chi-pair production found from identifying the contributions to the photon self-energy

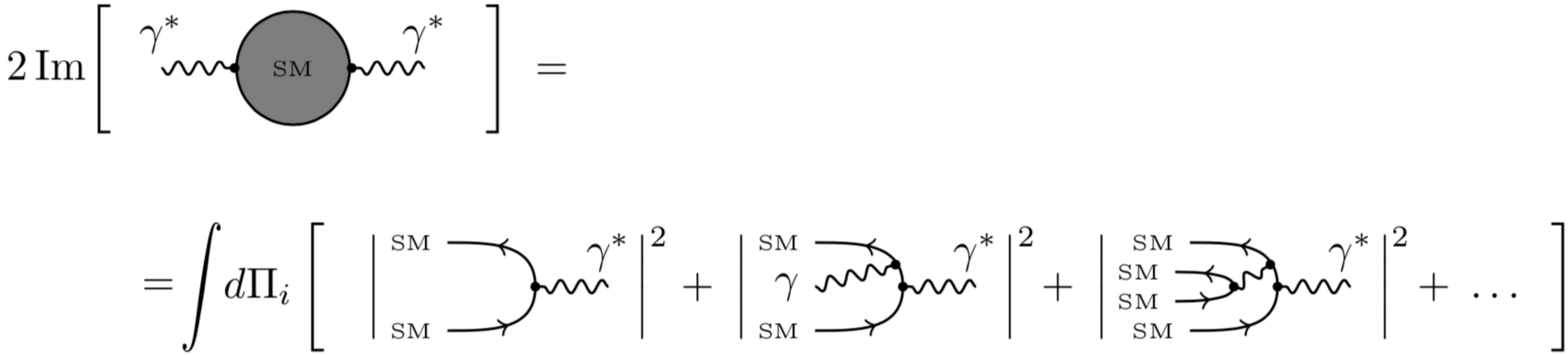
Breakdown of other processes



One identifies all other important processes:
annihilation, Compton-production, Bremsstrahlung, …

NB: in the paper we have a careful discussion on potential double-counting between the processes

Breakdown of other processes



One identifies all other important processes:
annihilation, Compton-production, Bremsstrahlung, …

NB: in the paper we have a careful discussion on potential double-counting between the processes

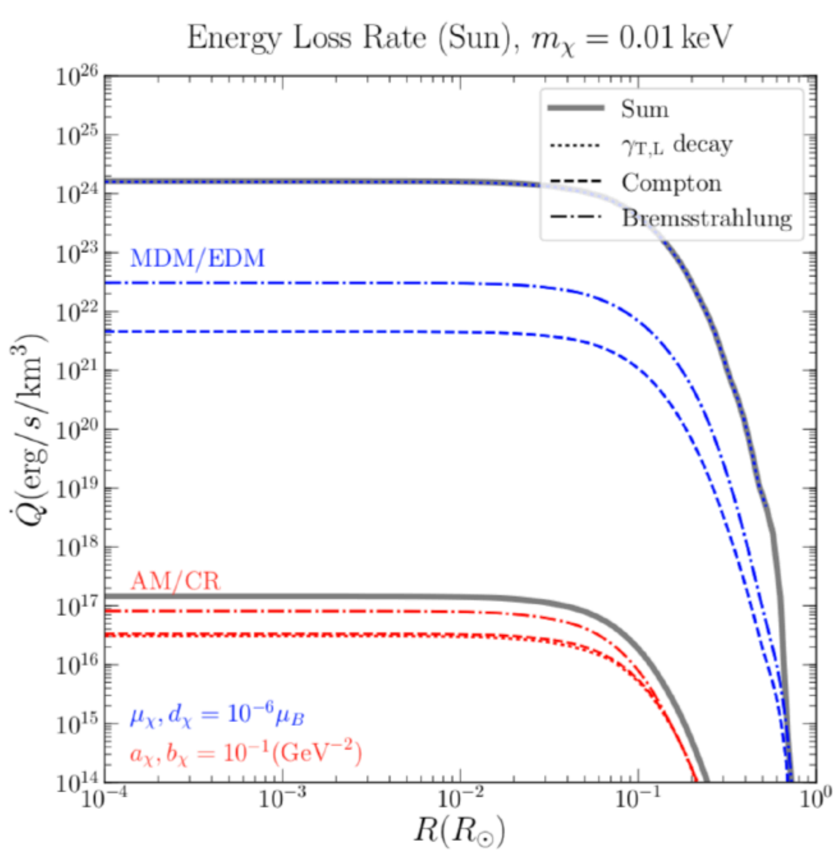
Energy loss rates

Sun

dominant process:

MDM/EDM: plasmon decay

AM/CR: all

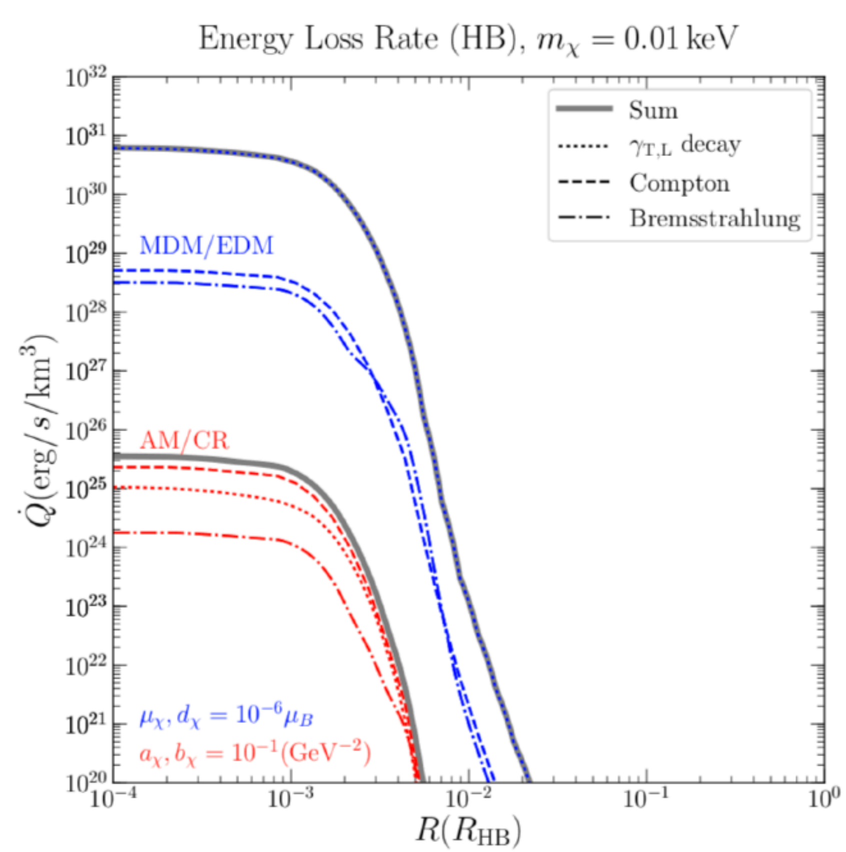


Horizontal Brach Stars

dominant process:

MDM/EDM: plasmon decay

AM/CR: plasmon decay, Compton scattering

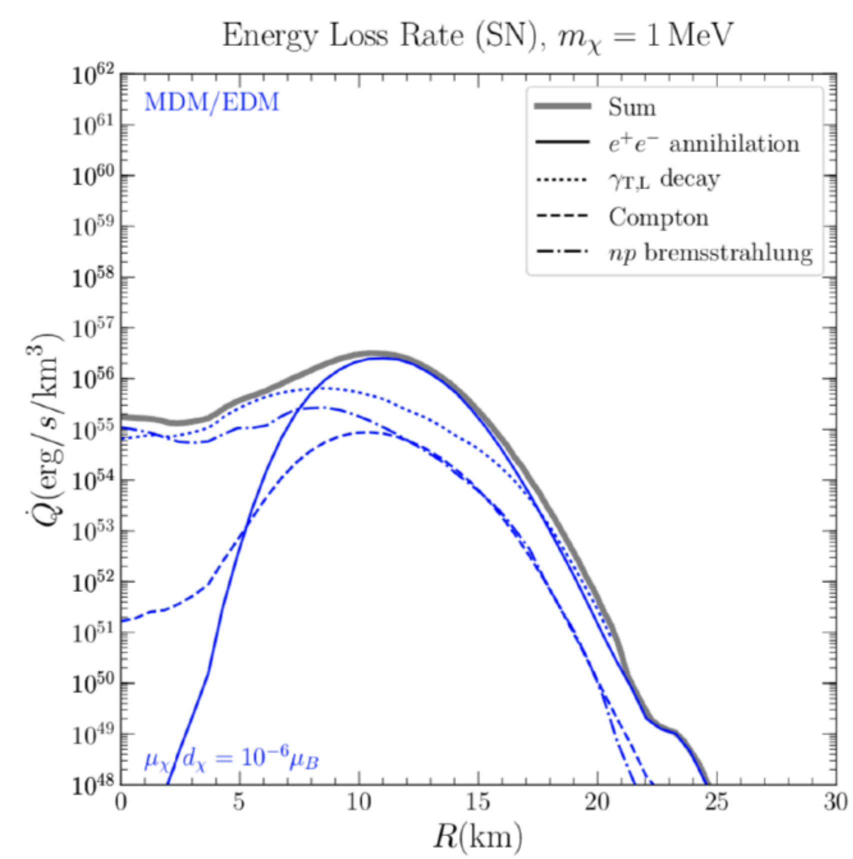


Supernovae

dominant processes:

annihilation, bremsstrahlung,

plasmon decay



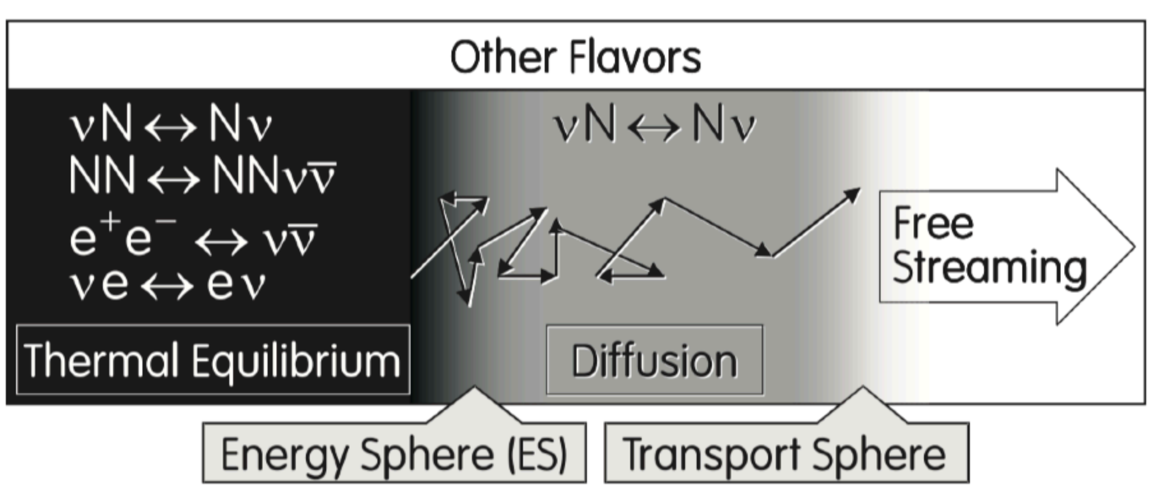
Supernova cooling

- Pair production of χ particles with $m_\chi \lesssim 400\,\mathrm{MeV}$ in SN possible

Lower boundary: use “Raffelt-criterion” $$\int_0^{r_{\rm core}} d^3r\,\dot{Q} \leq L_\nu$$

Upper boundary: energy-loss fails to be efficient because of trapping, rough criterion

=> we do a detailed analysis accounting for diffusion zone

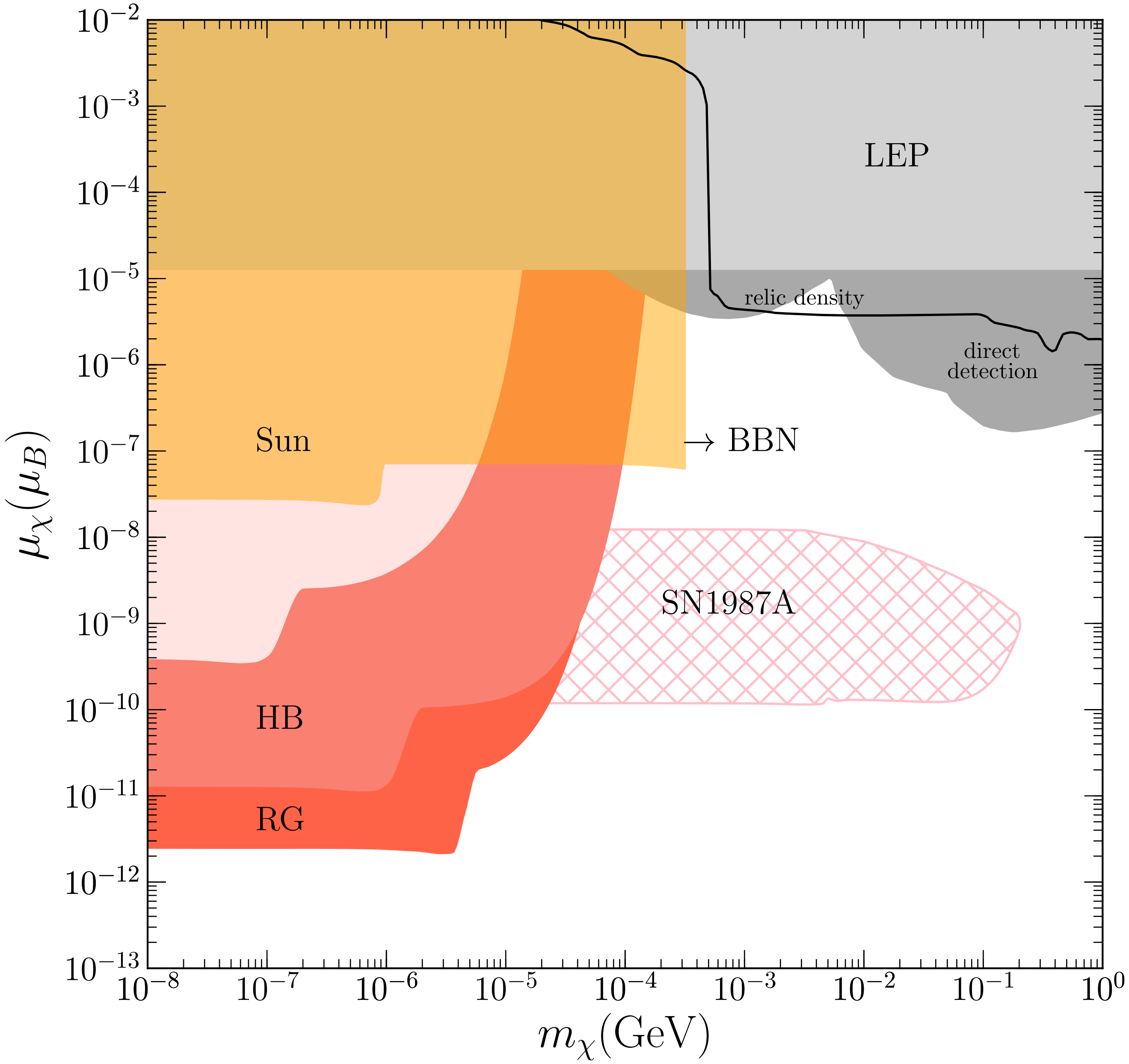


$$L_{\rm inf} = L_\chi(r_{\rm ES})\,S_{\rm ES}$$

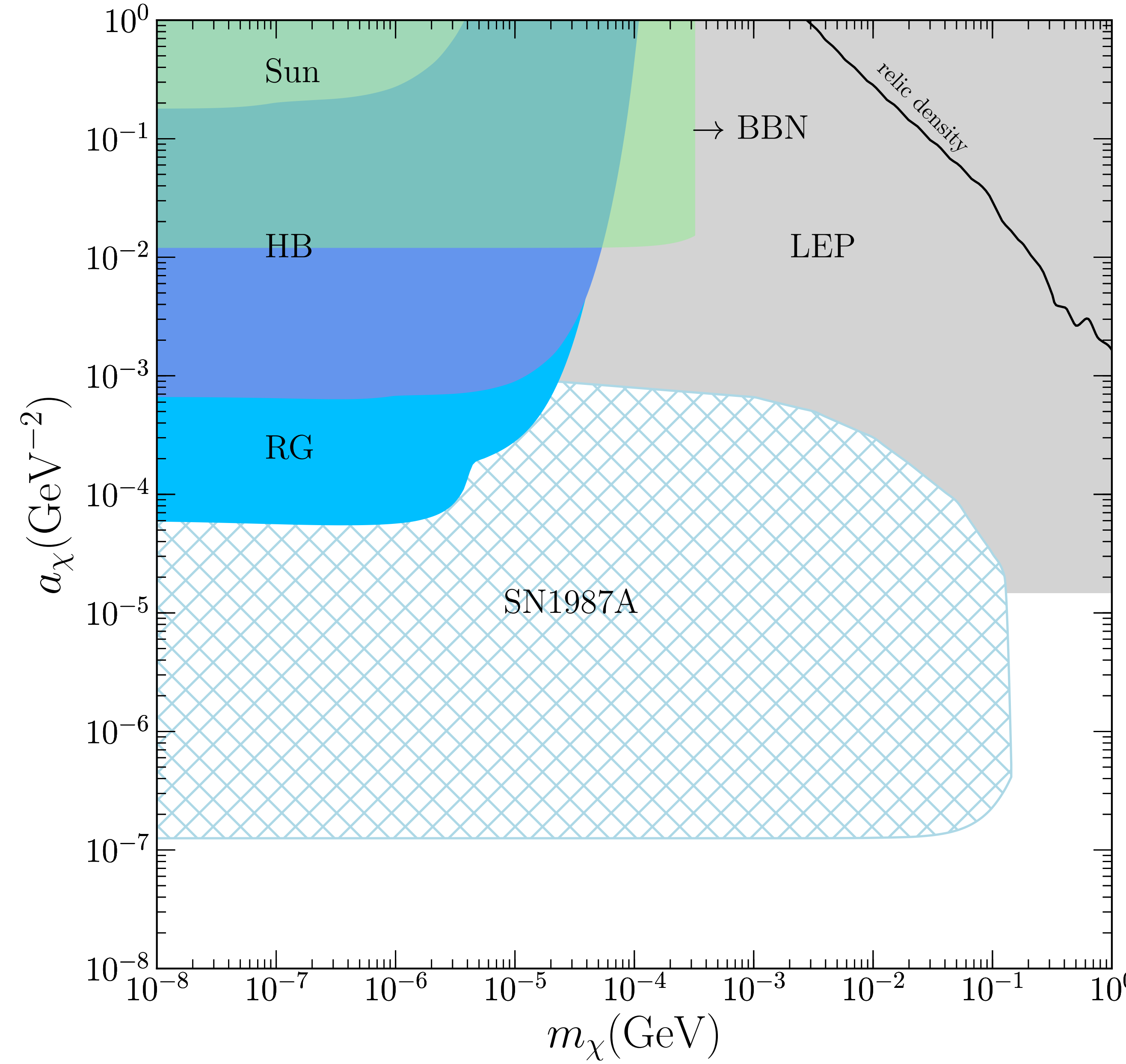
Raffelt 2001

Form-factor “landscape"

dim 5: magnetic dipole



dim 6: Anapole Moment



NB: for m->0 one recovers previous limits on neutrino MDM interactions Raffelt 1990++

2 Phenomenology of photon portal

Neutral sub-GeV dark sector particles may directly talk to the photon through electromagnetic interactions, such as magnetic and electric dipole moments, anapole moment or charge radius interactions.

We filled the associated sub-GeV dark sector "landscape".

New "intensity frontier" science case, although high energy colliders tend to do better for higher-dimensional interactions => additional constraints from UV completion expected.

Thermal DM is excluded. Freeze-in DM is possible (UV-dependence).

Stellar physics is by far the best probe below the MeV (keV) mass scale, pointing to a UV scale of 10^9 GeV (10^7 GeV) for mass-dimension five, and 100 GeV (2.5 TeV) for mass-dimension six operators

1 On the direct detection of light DM

Prompt electron ionization signal that may accompany DM-nuclear scattering, "Migdal effect", allows to extend the sensitivity of noble liquid and semiconductor DM detectors into the MeV mass region.

Theoretical description of Migdal effect closely related to DM-electron scattering. Same underlying atomic form factor, but evaluated at very different momentum scale $(m_e/m_N)\ q \sim 10^{-3} / A$

In a concrete model of DM, direct comparison is possible; for (heavy) dark photon mediator, Migdal dominates for GeV-scale masses and DM-e for MeV-scale masses.

Set the lowest DM-mass constraints on DM-nuclear scattering using XENON10 and XENON100 data.

First step towards a concise formulation of the Migdal effect in semiconductors.