

The photon as new physics mediator

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Next Frontiers in the Search for Dark Matter
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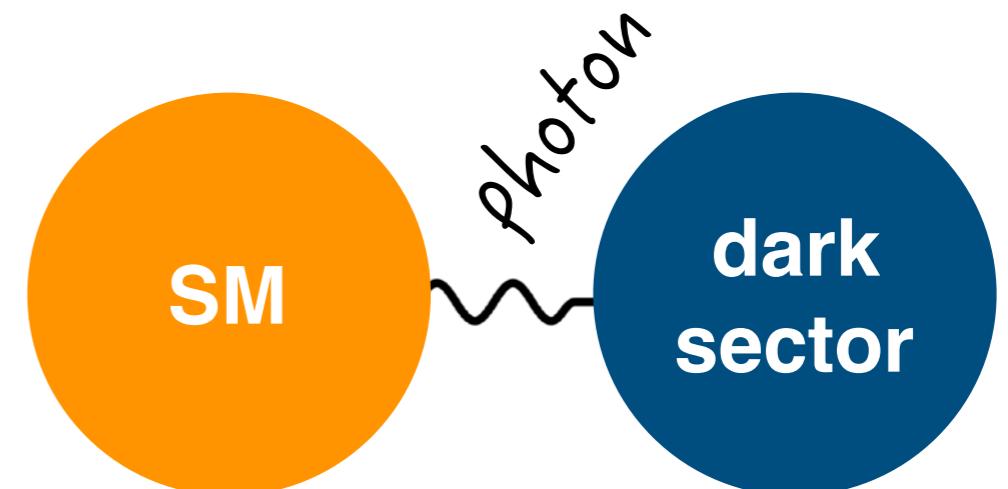
The photon as new physics mediator

In cosmology, most information has been brought to us through photons;
also true what regards the properties of the dark sector

=> in this talk photons will directly point back to sub-GeV dark sector
physics; consider direct effective photon coupling to dark states

“Photon-portal” to new physics

based on:



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

Xiaoyong Chu, Jui-Lin Kuo, JP, Lukas Semmelrock, arXiv:1908.00553

The photon as new physics mediator

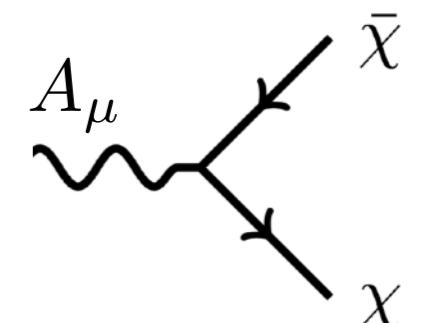
Tinkering with the photon may potentially affect many known phenomena

- 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



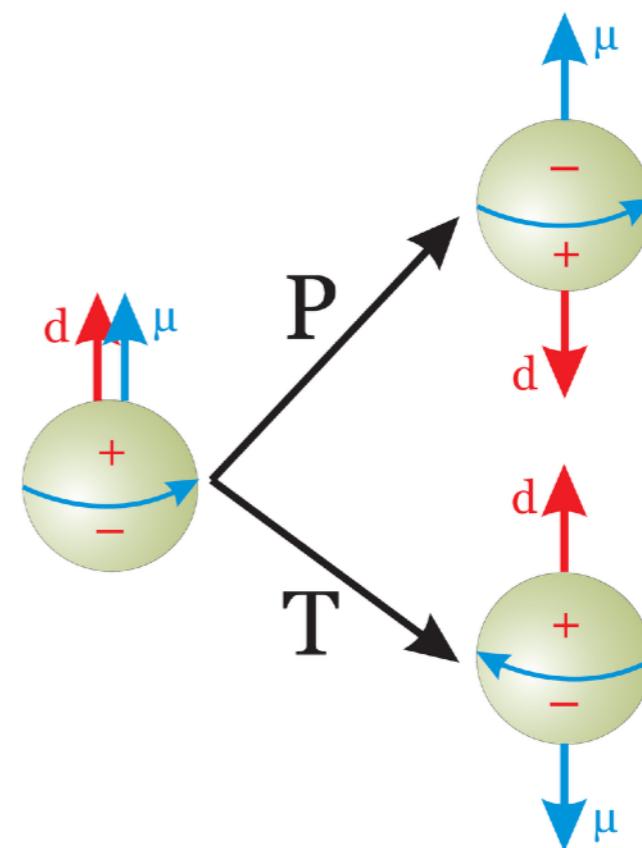
For a Dirac particle, best known are magnetic and electric dipole moments

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

P and T even

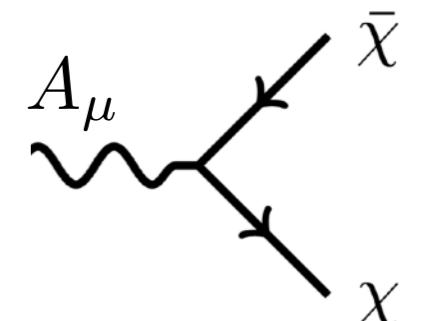
$$H_{\text{EDM}} = -d_\chi (\vec{E} \cdot \vec{\sigma}_\chi)$$

P and T odd \Rightarrow CP violating



Dark States with EM-interactions

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



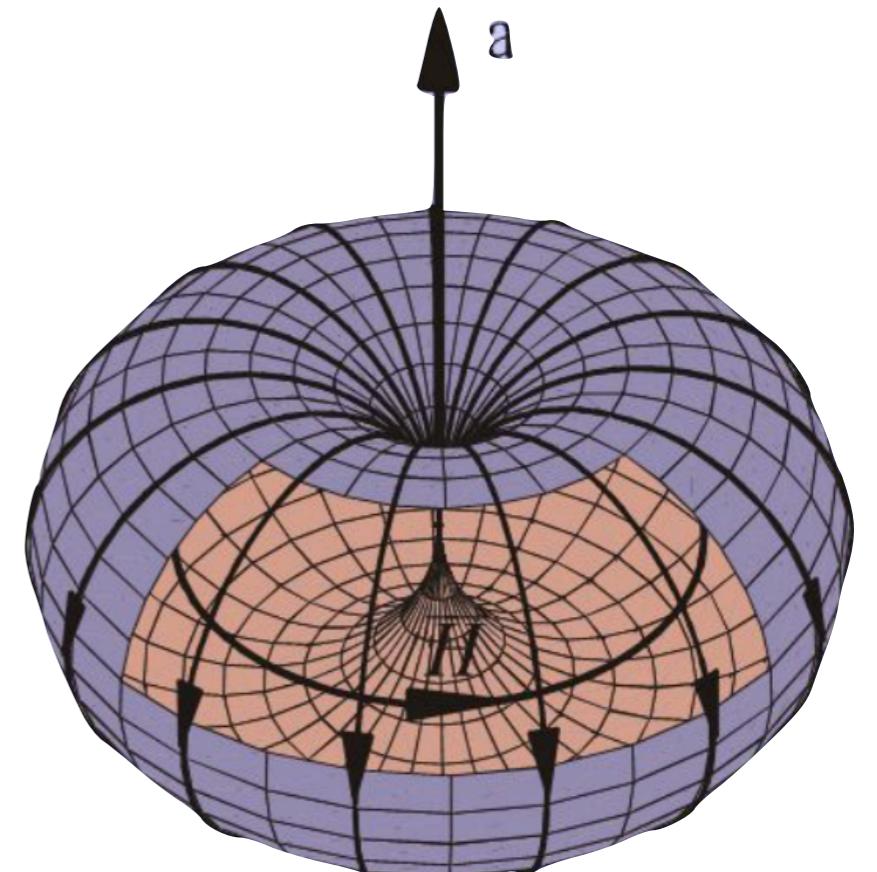
Charge radius interaction and anapole moments

$$H_{\text{AM}} = -a_\chi (\vec{J} \cdot \vec{\sigma}_\chi) \quad \text{Zel'dovich 1958}$$

P odd but CP even

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

P and T even



Dark States with EM-interactions

Interactions are assembled into matrix element of the EM current

$$\langle \chi(p_f) | J_\chi^\mu(0) | \chi(p_i) \rangle = \bar{u}(p_f) \Gamma^\mu(q) u(p_i)$$

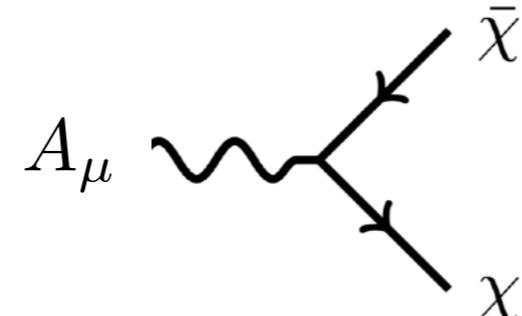
$$\Gamma^\mu(q) = i\sigma^{\mu\nu}q_\nu [M(q^2) + iD(q^2)\gamma^5] + (q^2\gamma^\mu - q^\mu q) [V(q^2) - A(q^2)\gamma^5]$$

$$\begin{array}{ccccc} \uparrow & \uparrow & & \uparrow & \uparrow \\ \text{magnetic} & \text{electric} & & \text{charge-radius} & \text{anapole moment} \\ & & \text{dipole} & & \end{array}$$

Assuming that the interactions are generated at a UV scale well above the typical CM energies of the high-intensity beams,

$$\mu_\chi = M(0), \quad d_\chi = D(0), \quad a_\chi = A(0), \quad b_\chi = V(0)$$

Dark States with EM-interactions



Effective operators

millicharge (ϵQ):

$$\epsilon e \bar{\chi} \gamma^\mu \chi A_\mu, \quad \text{dim 4}$$

magnetic dipole (MDM):

$$\frac{1}{2} \mu_\chi \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu}, \quad \dots \dots \dots$$

electric dipole (EDM):

$$\frac{i}{2} d_\chi \bar{\chi} \sigma^{\mu\nu} \gamma^5 \chi F_{\mu\nu}, \quad \text{dim5}$$

anapole moment (AM):

$$a_\chi \bar{\chi} \gamma^\mu \gamma^5 \chi \partial^\nu F_{\mu\nu}, \quad \dots \dots \dots$$

charge radius (CR):

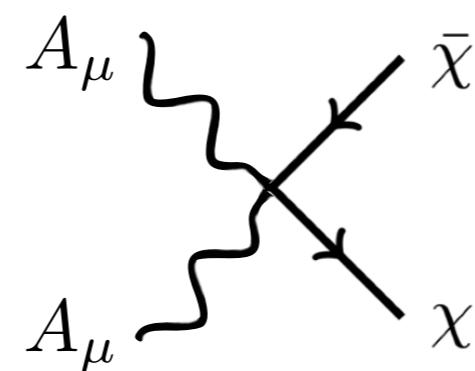
$$b_\chi \bar{\chi} \gamma^\mu \chi \partial^\nu F_{\mu\nu}. \quad \text{dim6}$$

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

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

dim 7

=> different (or loop-suppressed) phenomenology

Complex scalars: dim-6 Rayleigh and charge radius interaction

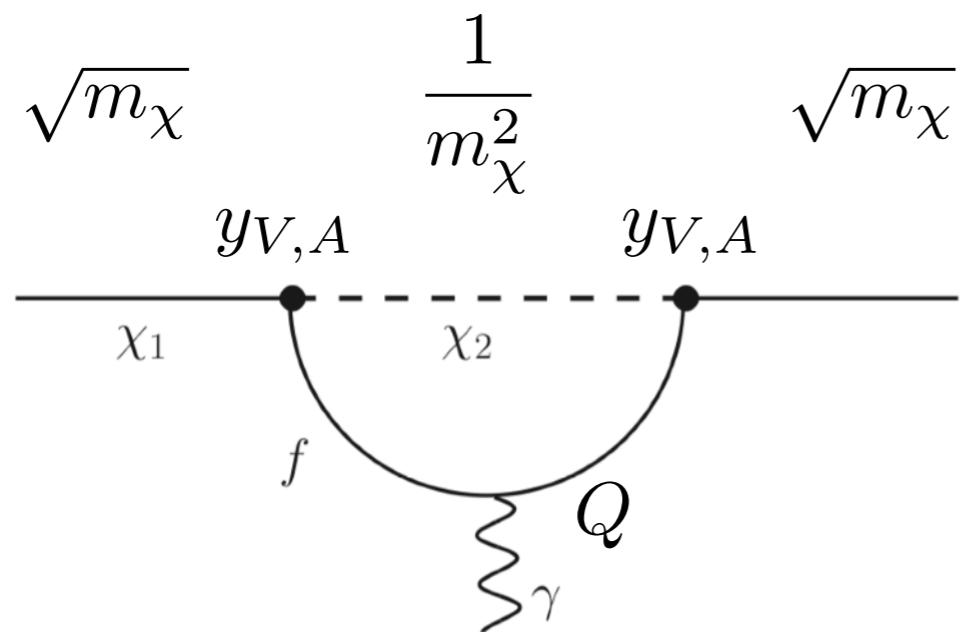
Vectors: also quadrupole moments exist

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)



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

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

or

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

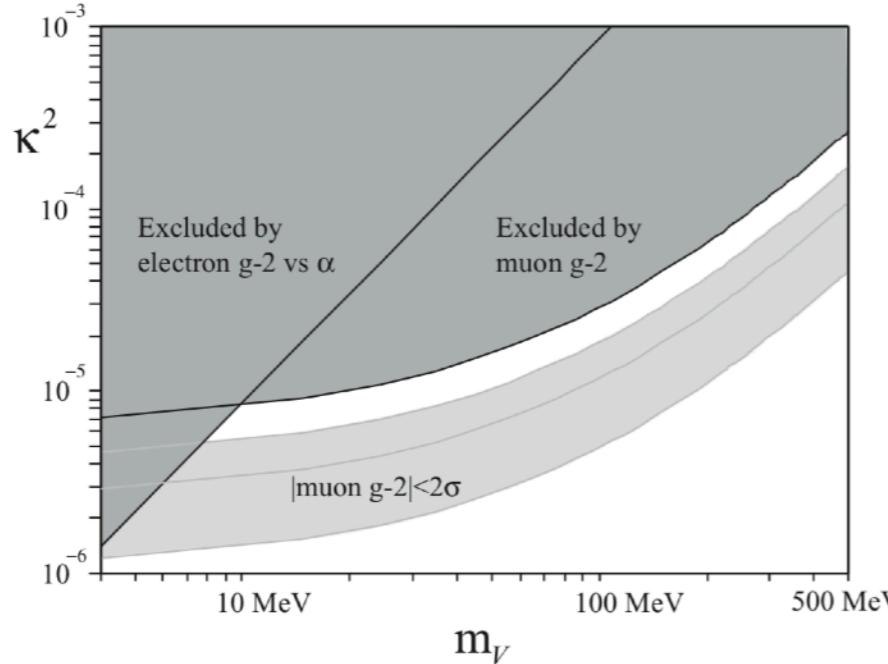
see also recent ref. Kavanagh, Panci, Ziegler 2018

Muon g-2

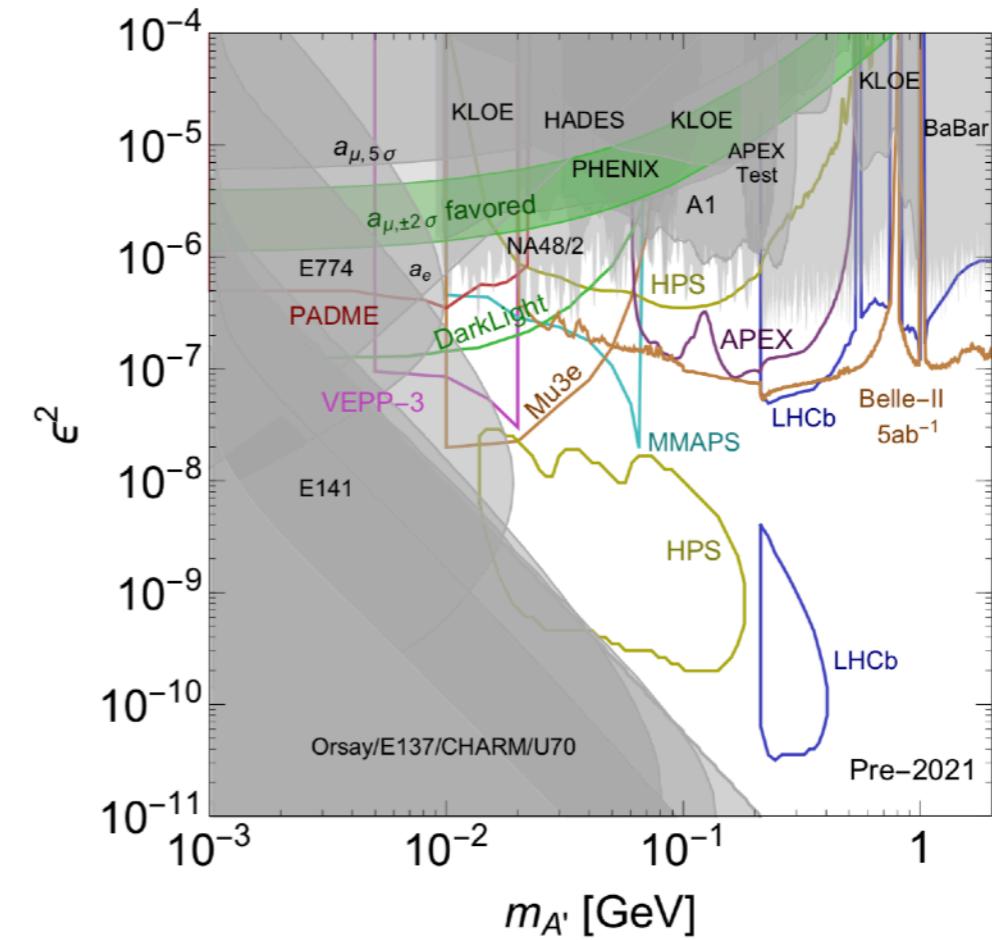
- Muon g-2 puzzle: $(3\text{-}4)\sigma$ tension between SM prediction and measurement

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

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



=>



Muon g-2

- Muon g-2 puzzle: $(3\text{-}4)\sigma$ tension between SM prediction and measurement

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

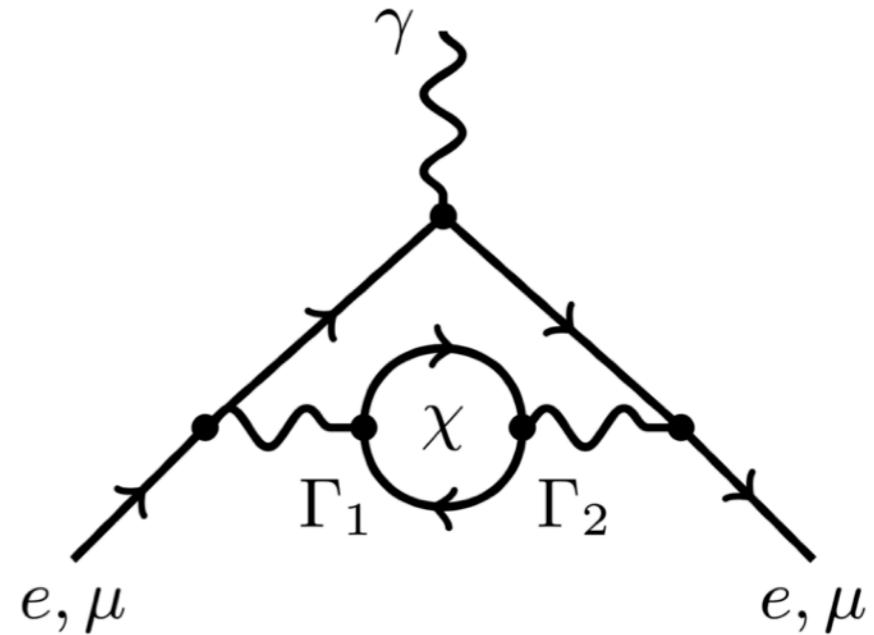
- For form-factor interactions, contributions enter through the vacuum polarization

e.g. use dispersion relation + unitarity

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

solution to g-2 for

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



Precision tests

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

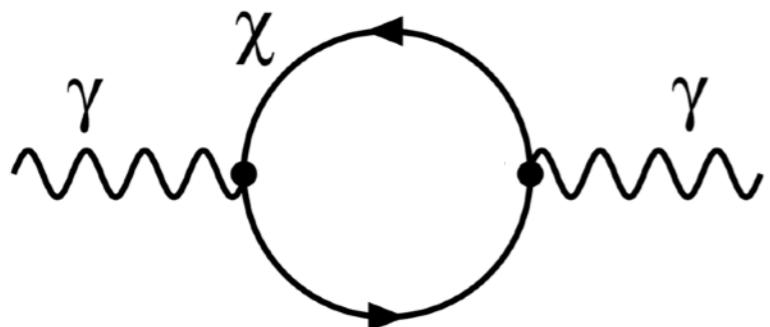
$$\Delta r_{\text{obs}} = 1 - \frac{A_0^2}{M_W^2 s_w^2} = 0.03492 \pm 0.00097$$

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

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

$$-0.0038 < \Delta r_{\text{new}} < 0.00018 \quad (\text{tighter upper limit from 1.8 tension})$$

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



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

(saturating upper limit)

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

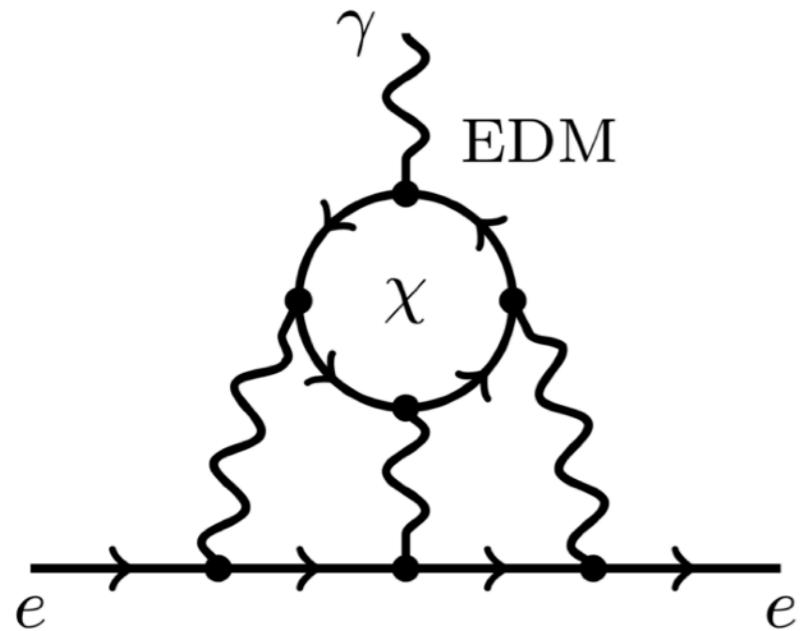
(saturating lower limit)

SM electric dipole moments?

- Recently, ACME collaboration improved bound on electron EDM

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

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



3 loop it is

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

$$\begin{aligned} (\text{mass})^{-1} &\sim \epsilon^3 e^3 / m_\chi, \mu_\chi^3 m_\chi^2, \\ &d_\chi^2 \mu_\chi m_\chi^2, b_\chi d_\chi^2 m_\chi^3 \dots \end{aligned}$$

e.g. dim-5 operators only:

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

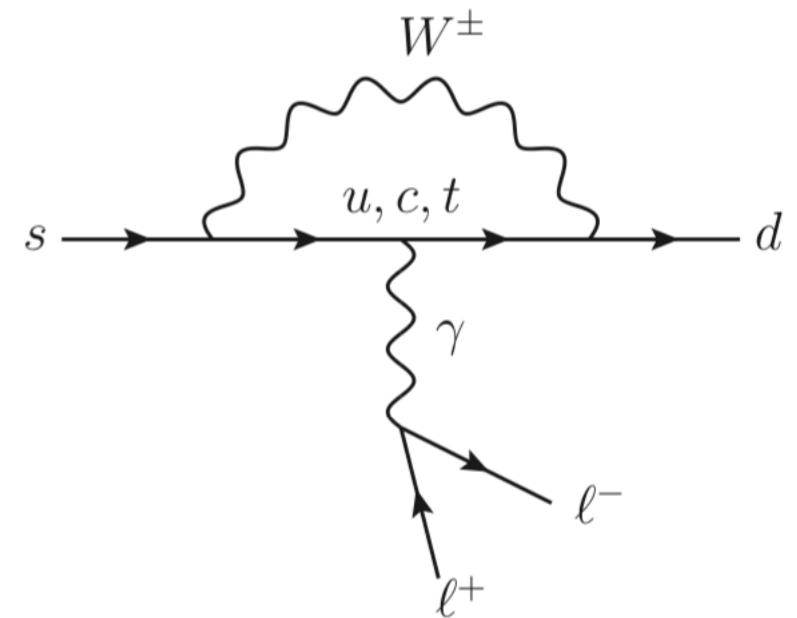
Rare Meson Decays

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

e.g. for Kaons

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

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



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

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

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

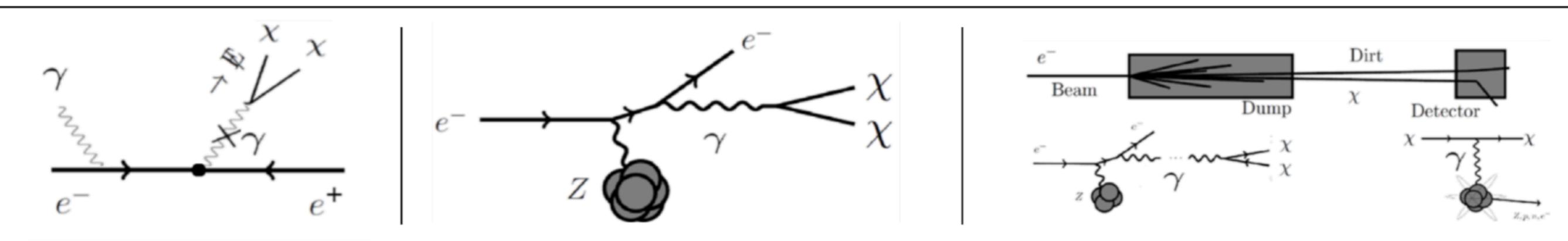
likewise for $\text{Br}(B^+ \rightarrow K^+ + \text{inv}) \lesssim 7 \times 10^{-5}$ BaBar 2003

A new target for the intensity frontier

missing momentum

missing energy

direct search



BaBar:

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

Belle II (projected):

- Luminosity: 50 ab^{-1}

Main Backgrounds:

- $e^+e^- \rightarrow \gamma\gamma$
- $e^+e^- \rightarrow \gamma\gamma\gamma$
- $e^+e^- \rightarrow \gamma e^+e^-$

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}

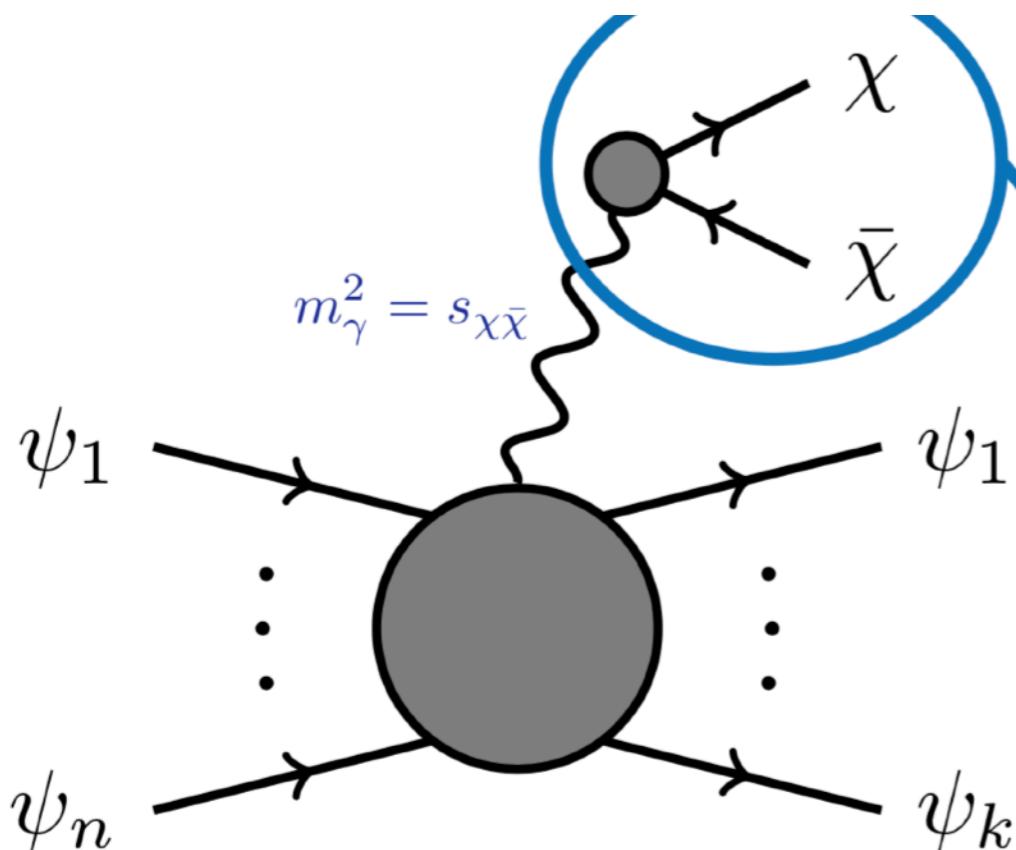
BDX (projected):

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

Main Backgrounds:

- High energy neutrinos

Unified description of various interactions



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

slide credit: Lukas Semmelrock

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

=> for example:

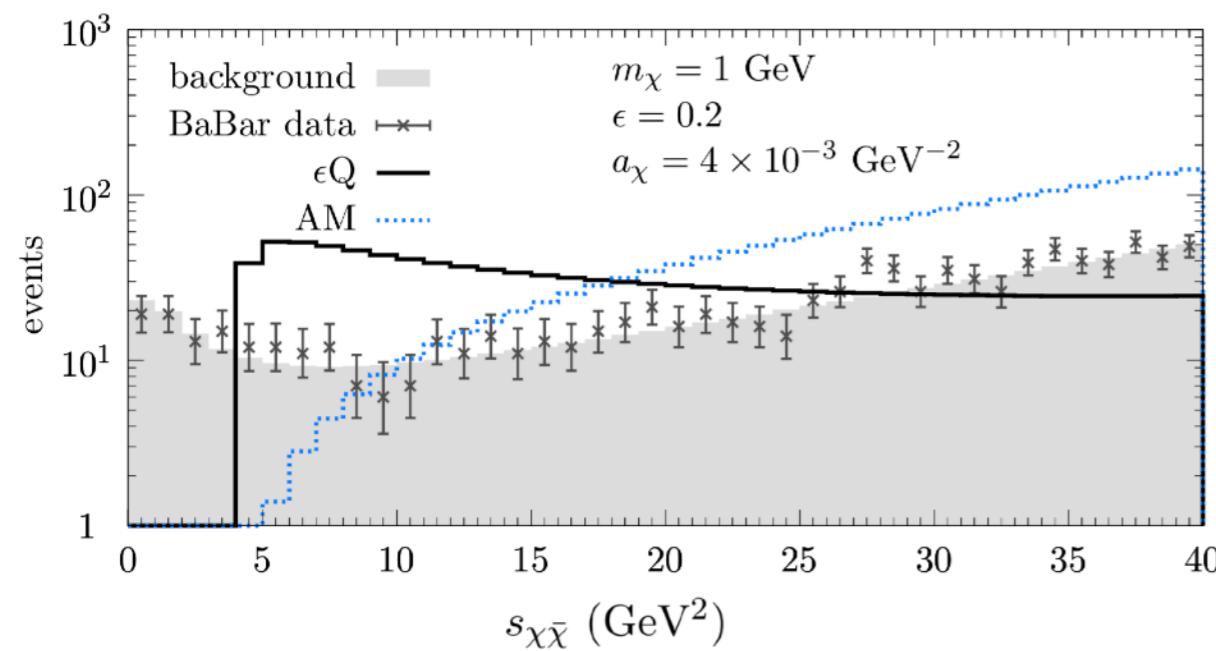
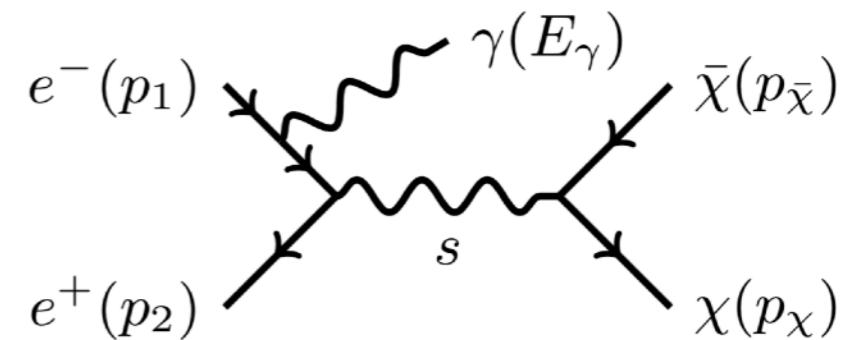
$$\frac{d\sigma_{2 \rightarrow 4}}{ds_{\chi\bar{\chi}}} = \sigma_{2 \rightarrow 3}(s_{\chi\bar{\chi}}) \frac{f(s_{\chi\bar{\chi}})}{16\pi^2 s_{\chi\bar{\chi}}^2} \sqrt{1 - \frac{4m_\chi^2}{s_{\chi\bar{\chi}}}}$$

Intensity frontier prospects

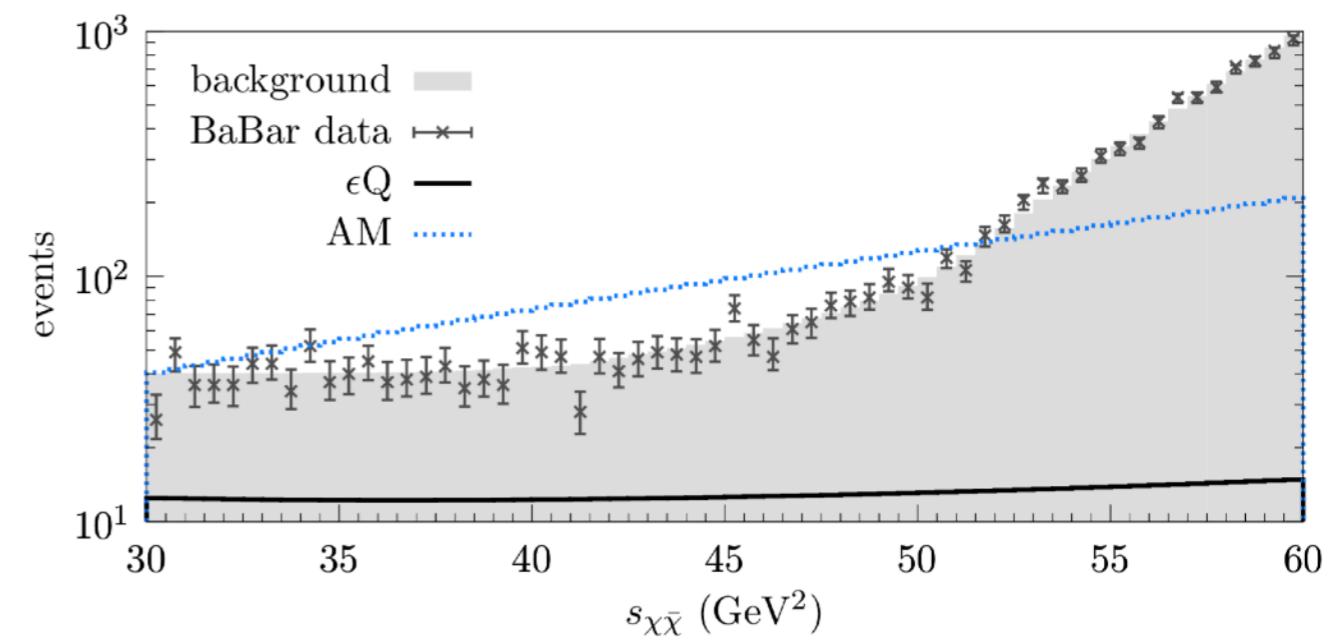
Production in $e^+ e^-$ annihilation, e.g. at BaBar, Belle-II

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



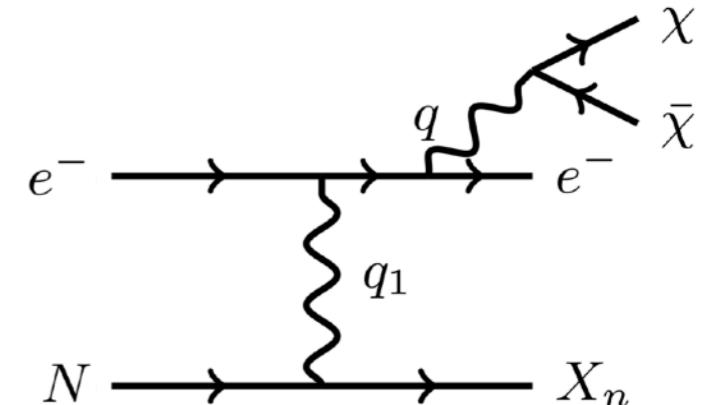
low-energy photon region

Intensity frontier prospects

Production in electron fixed target experiments

- Missing energy (NA64, LDMX)

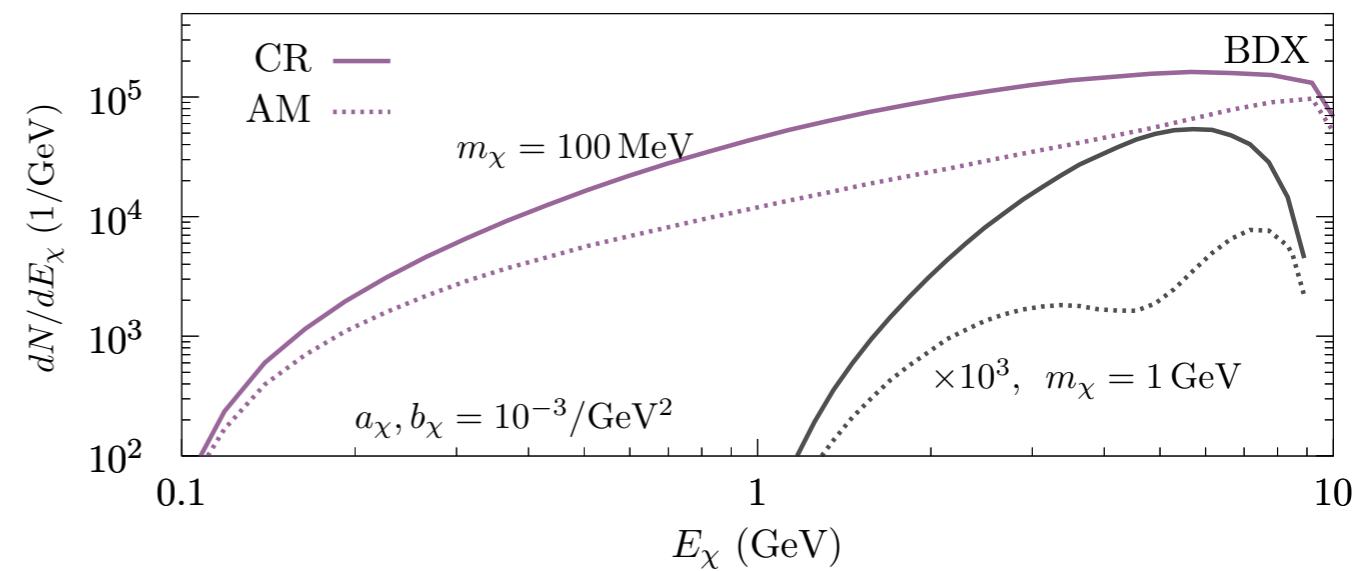
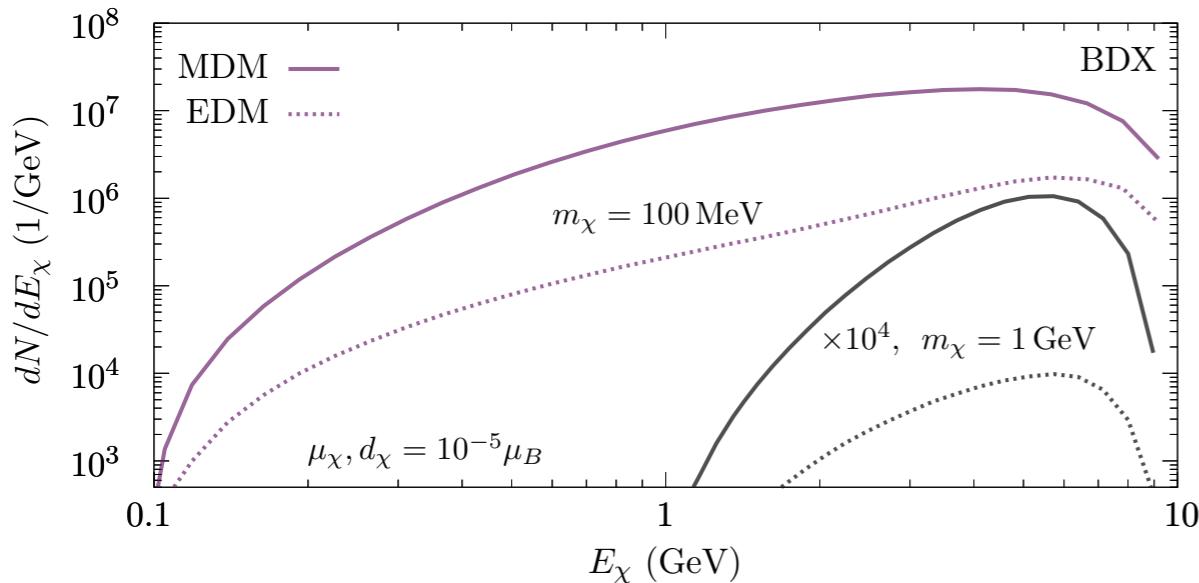
$$\frac{d\sigma_{2 \rightarrow 4}}{ds_{\chi\bar{\chi}}} = \sigma_{2 \rightarrow 3}(s_{\chi\bar{\chi}}) \frac{f(s_{\chi\bar{\chi}})}{8\pi} \sqrt{1 - \frac{4m_\chi^2}{s_{\chi\bar{\chi}}}}$$



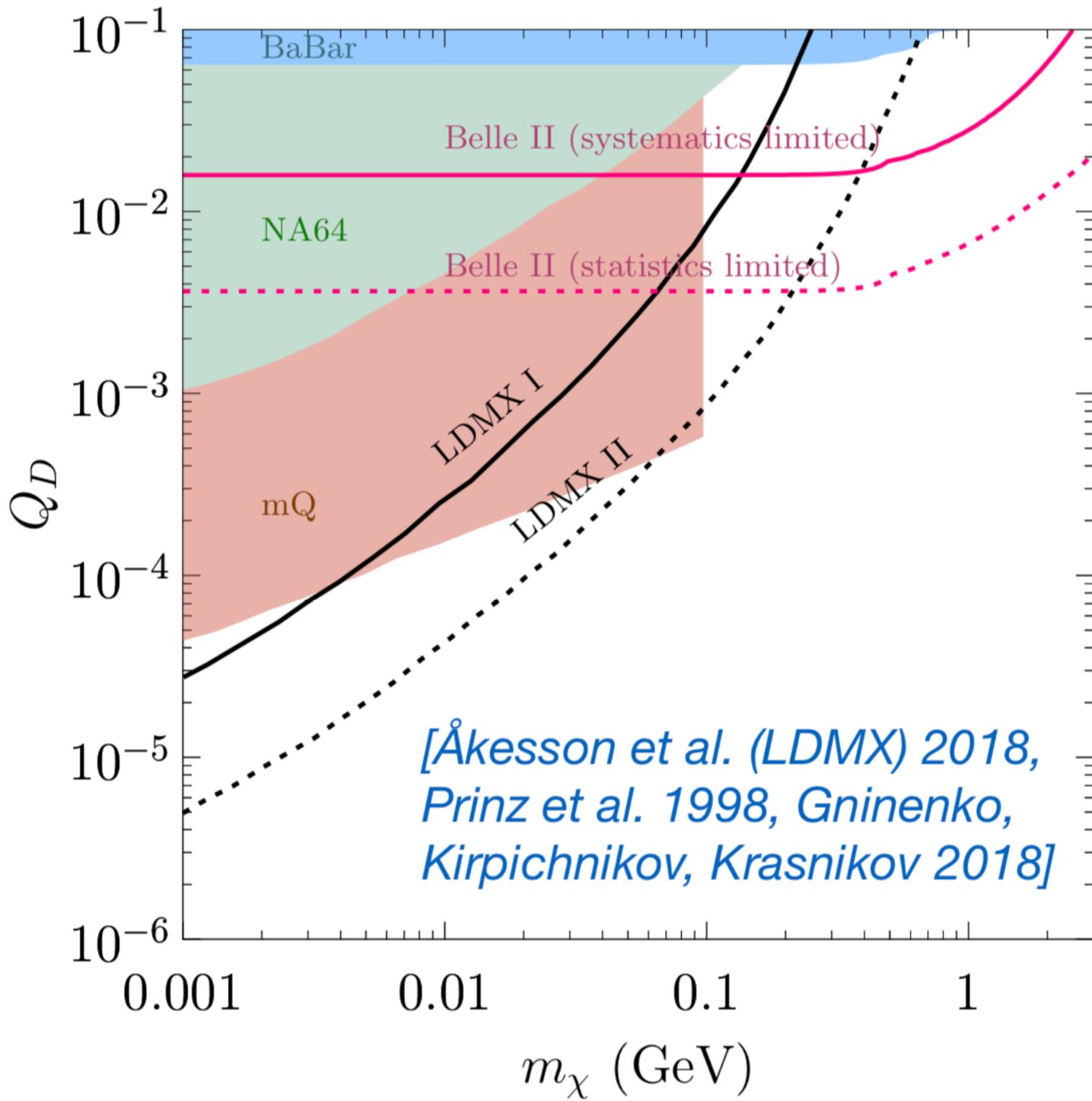
The f's carry the entire information of the new physics vertex

Cuts + veto system make searches largely background free

- Subsequent scattering (mQ, BDX)

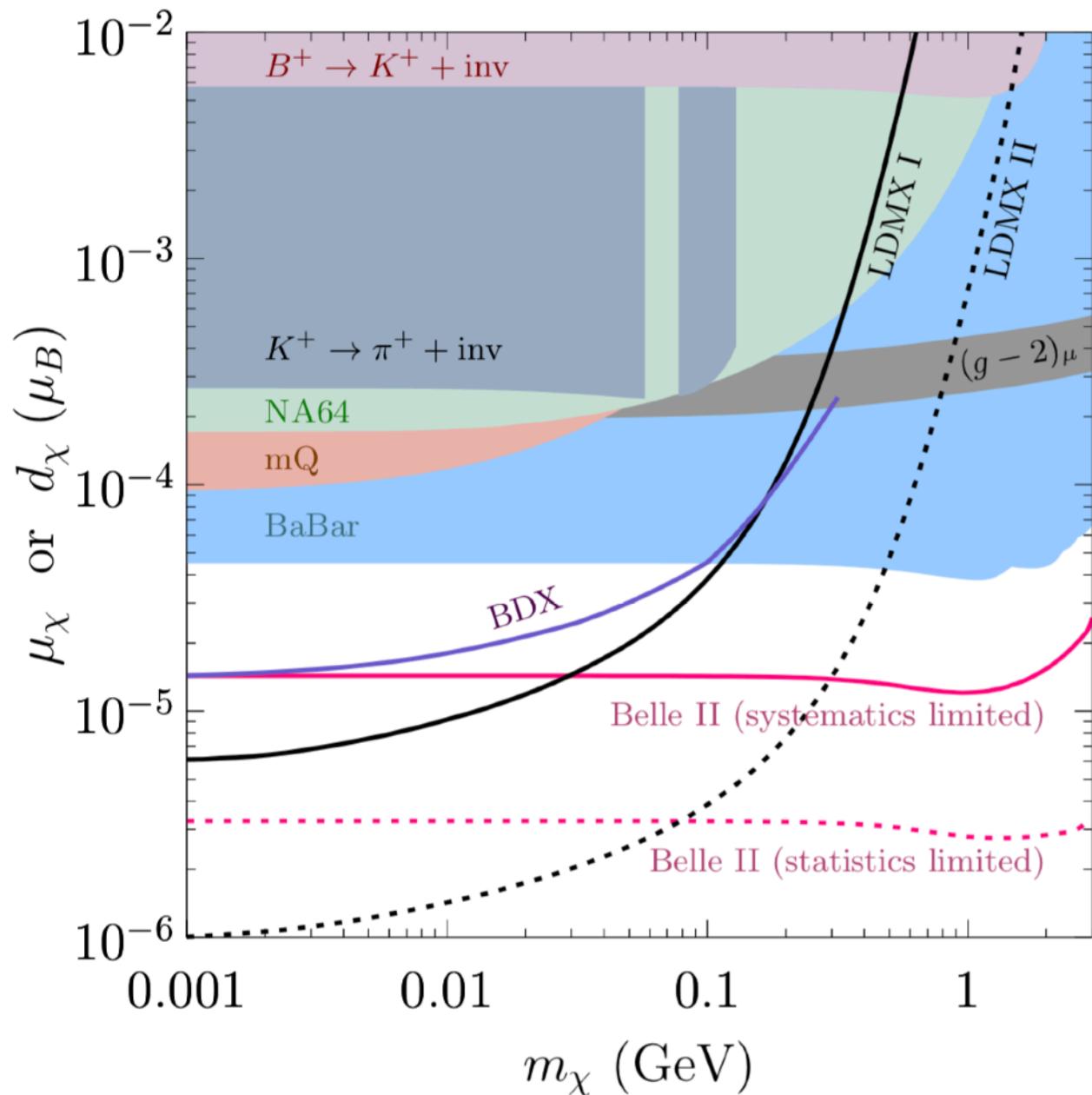


Milli-Charge



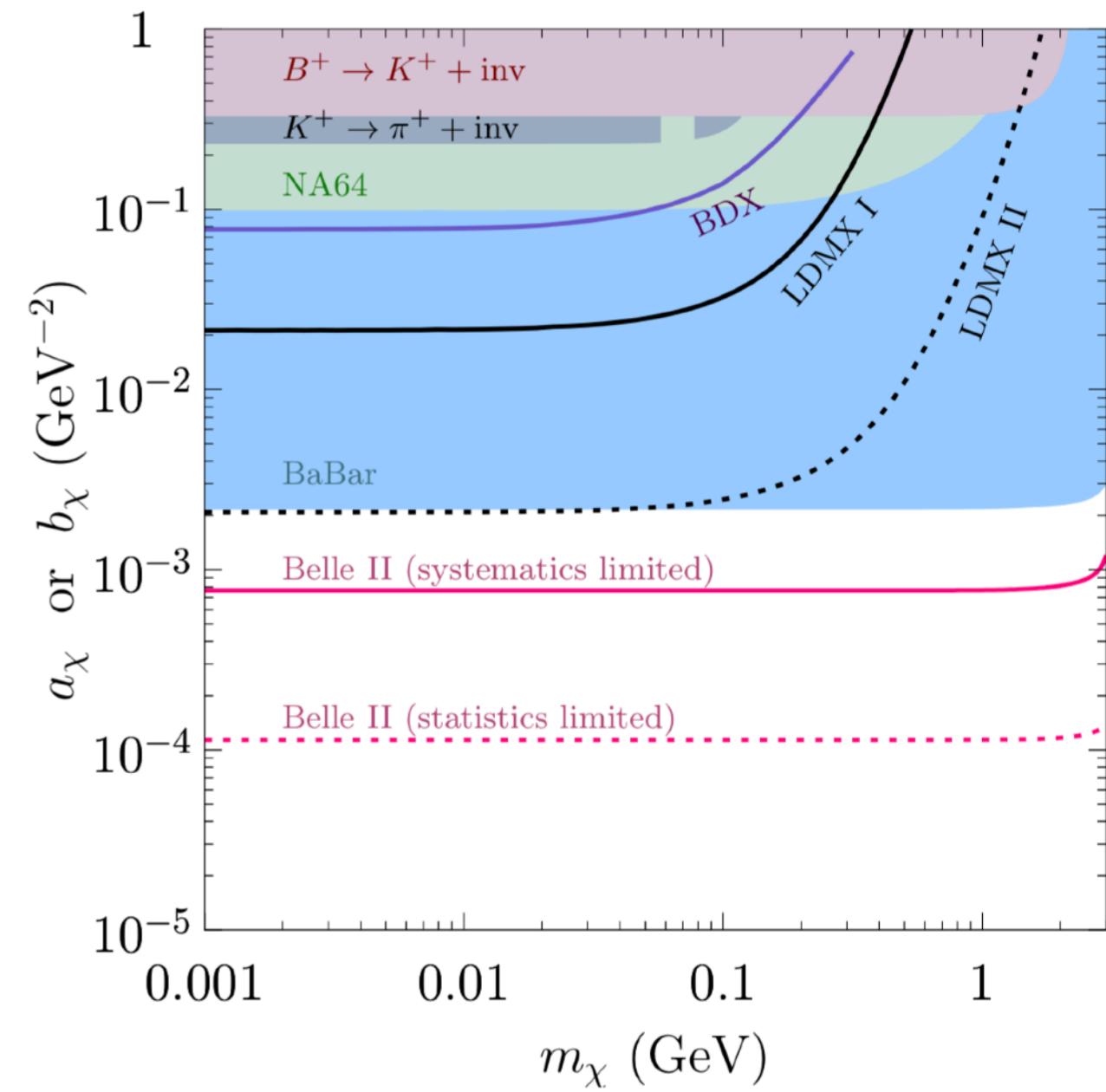
$$f(s_{\chi\bar{\chi}}) \propto s_{\chi\bar{\chi}}$$

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

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

Following this analysis, we get

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

Fortin, Tait 2011

- 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 colliders

Can it be dark matter?

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

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

$\langle \sigma_{\chi\bar{\chi} \rightarrow \gamma\gamma} v \rangle$ 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

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

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

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

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

<= 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

$$\begin{array}{lll} \mu_\chi, d_\chi \geq 10^{-9} \mu_B & \text{dim-5} & \Rightarrow m_\chi \gtrsim 7 - 10 \text{ MeV} \\ a_\chi, b_\chi \geq 5 \times 10^{-5} \text{ GeV}^{-2} & \text{dim-6} & \end{array}$$

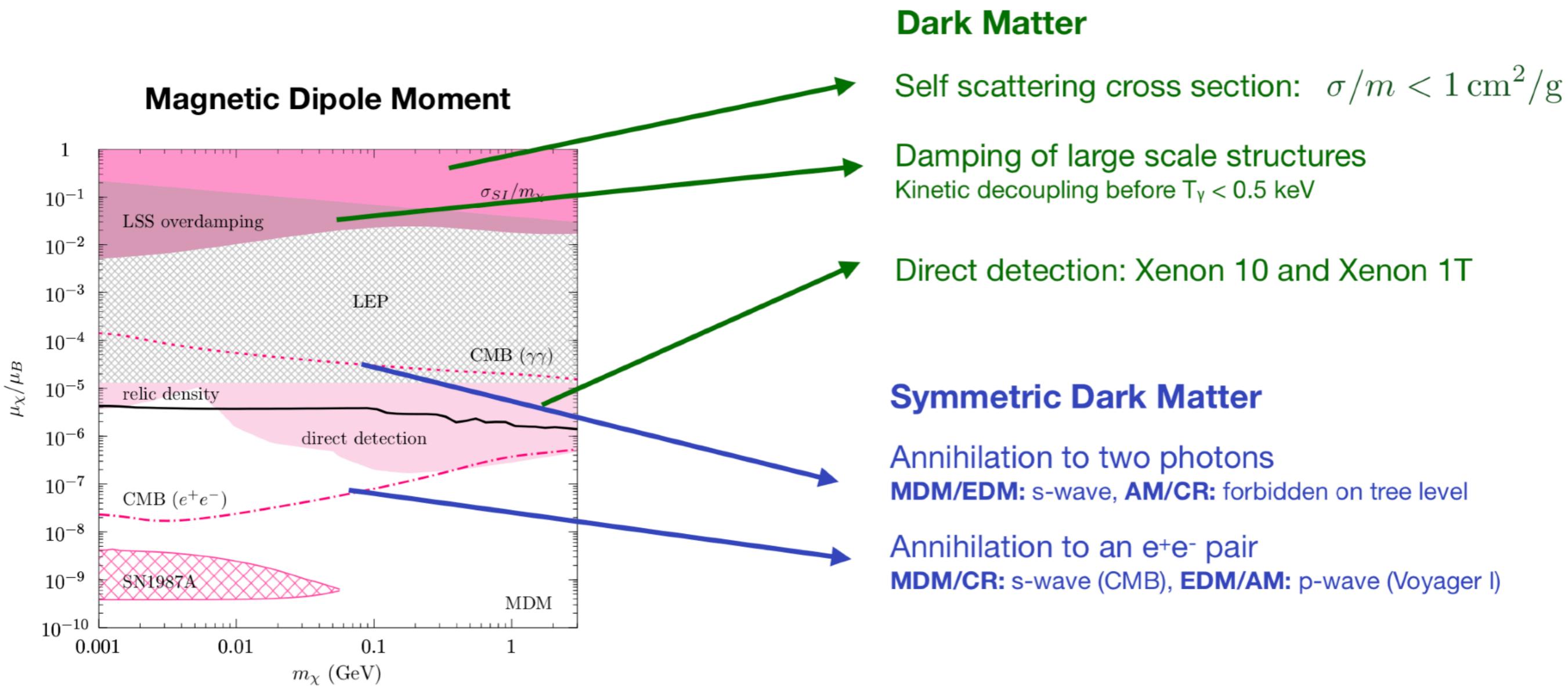
- DM self-interactions

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

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

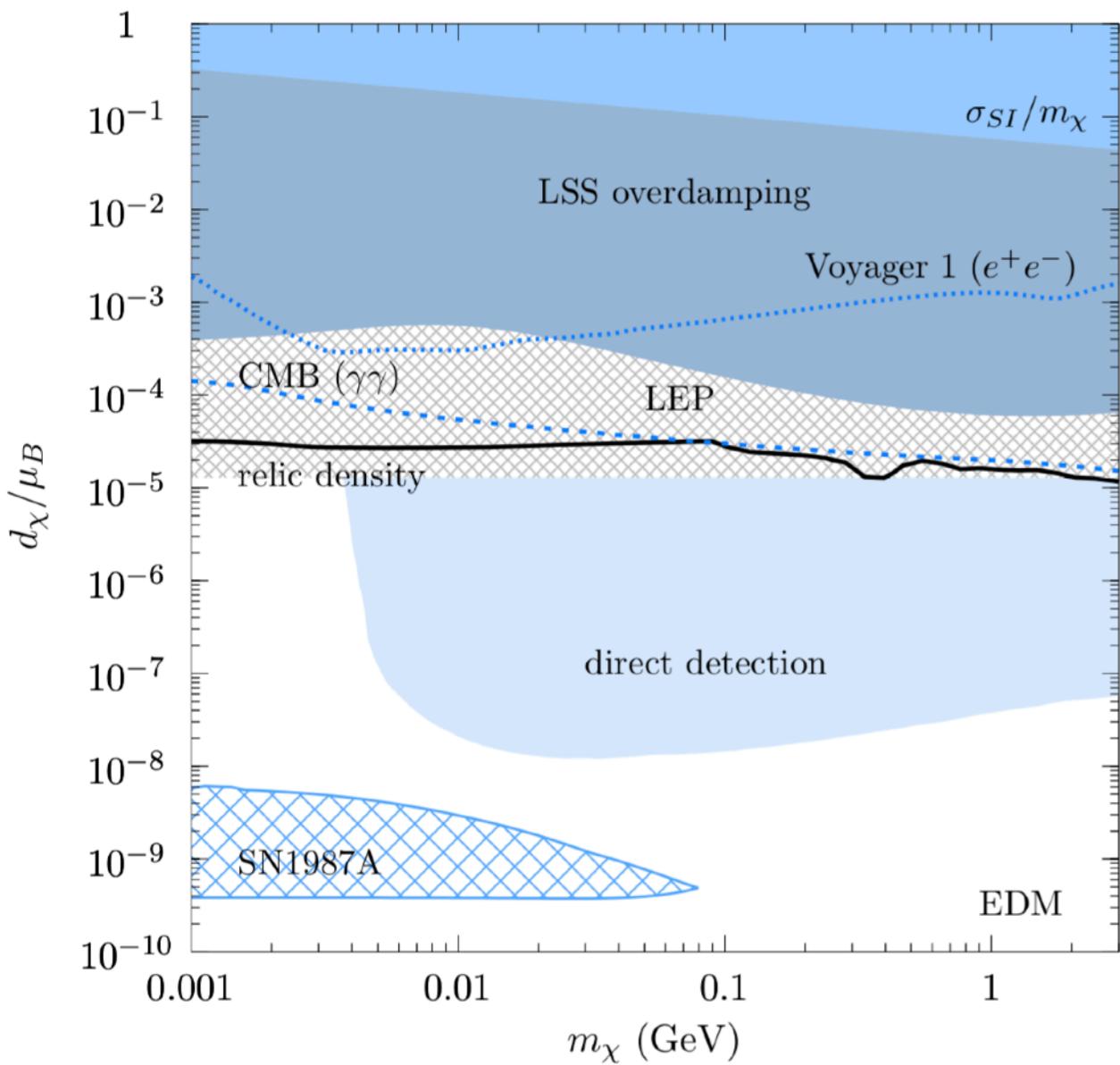
Robertson, Massey, Eke 2008

Summary of EMDM Dark Matter constraints

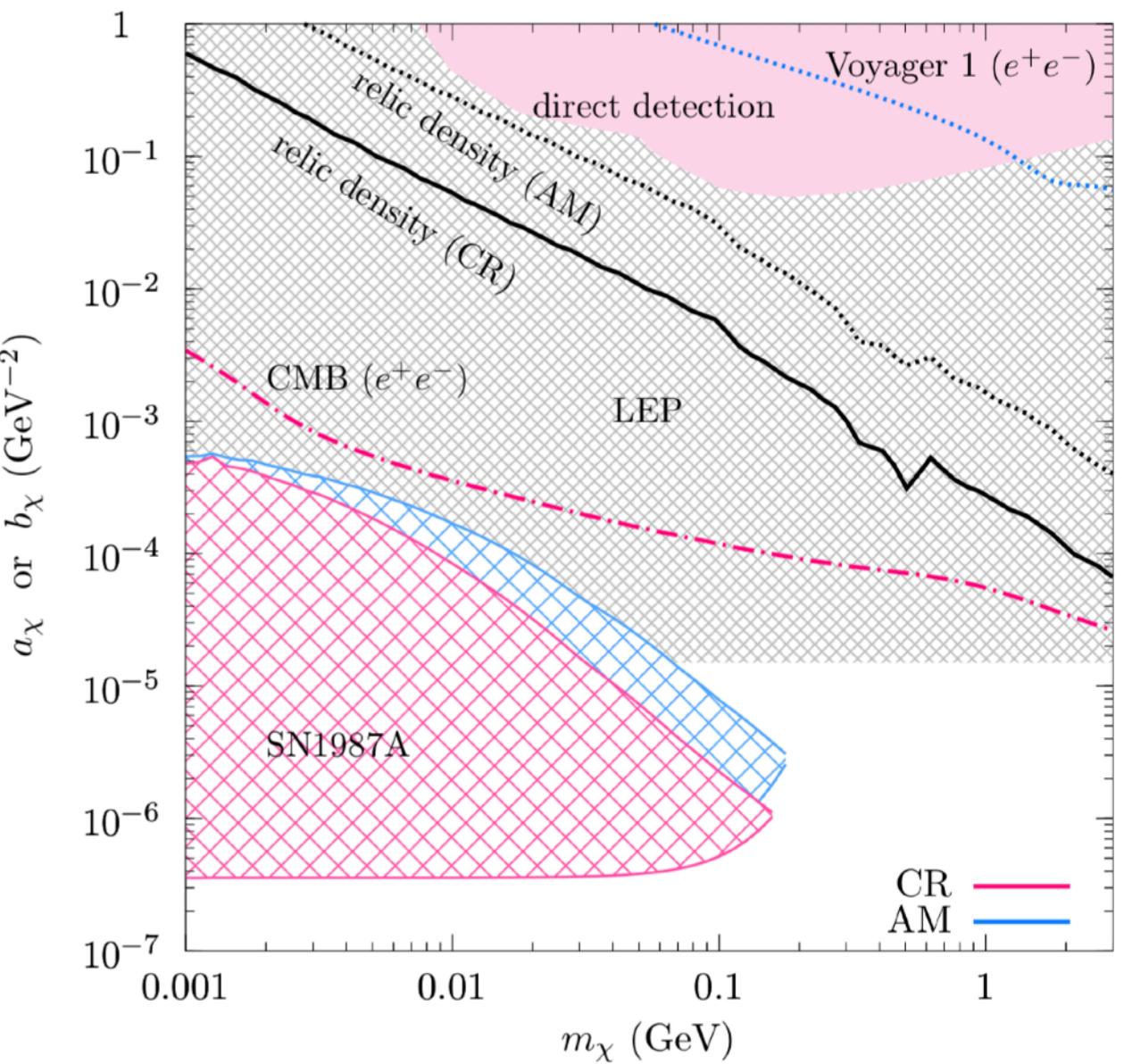


Summary of EMDM Dark Matter constraints

Electric Dipole Moment



Anapole Moment / Charge Radius



=> established a complete phenomenological picture
of dark states directly coupled to photon
from 1 MeV - few GeV

for sub-MeV mass:

- => strong astrophysical implications
- => stars as laboratories for dark-sector
photon interactions

Stars reacting to energy loss

$$\langle E_{\text{kin}} + E_{\text{grav}} \rangle \downarrow$$

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

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

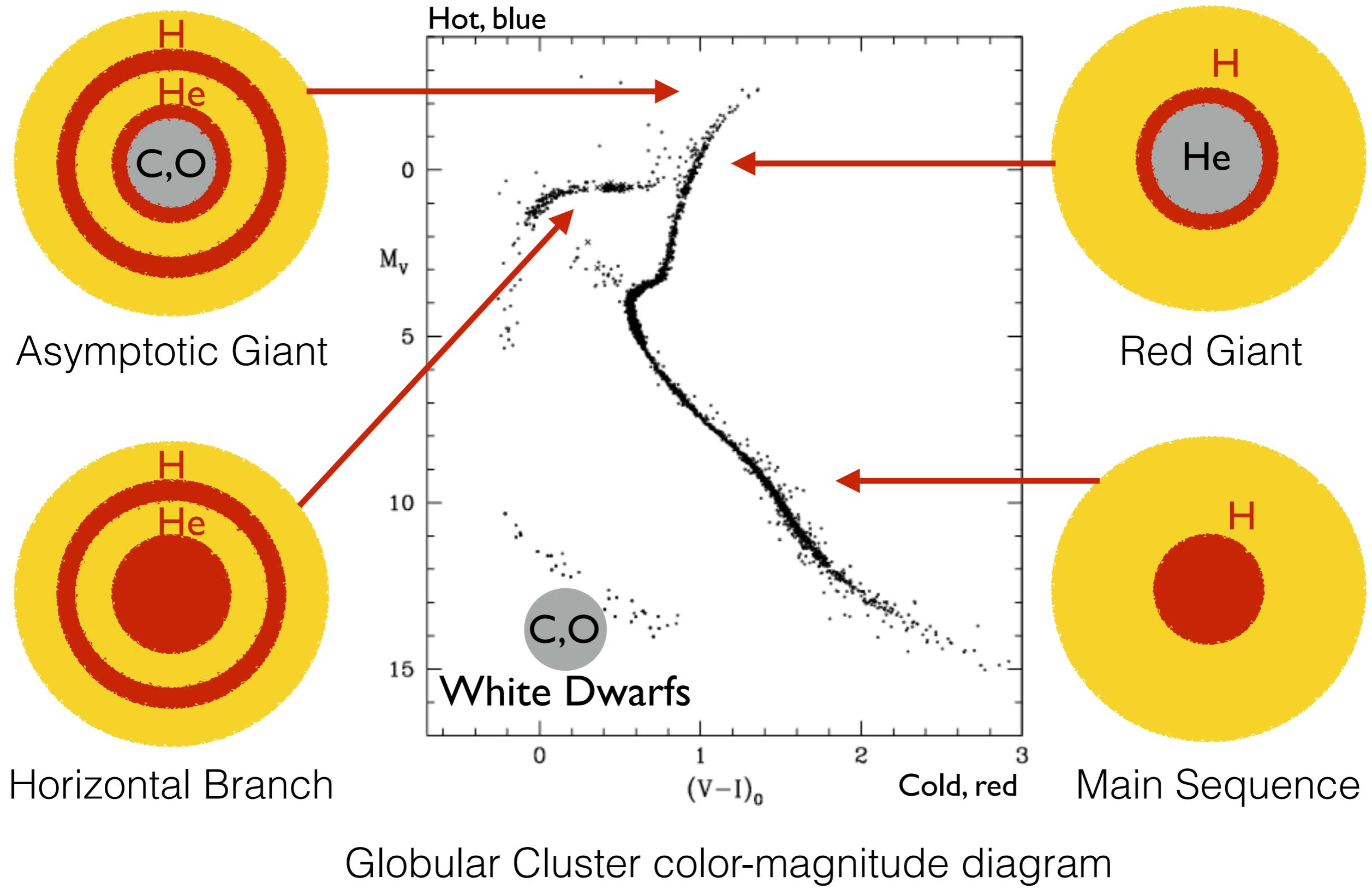
=> Gravitational potential energy becomes more negative (tighter bound)

=> 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

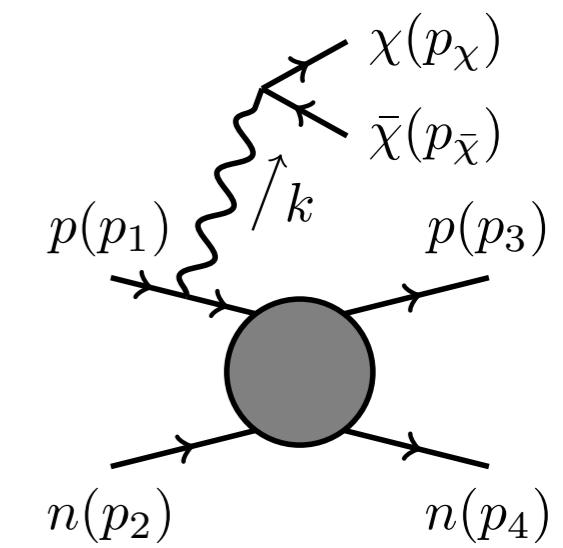
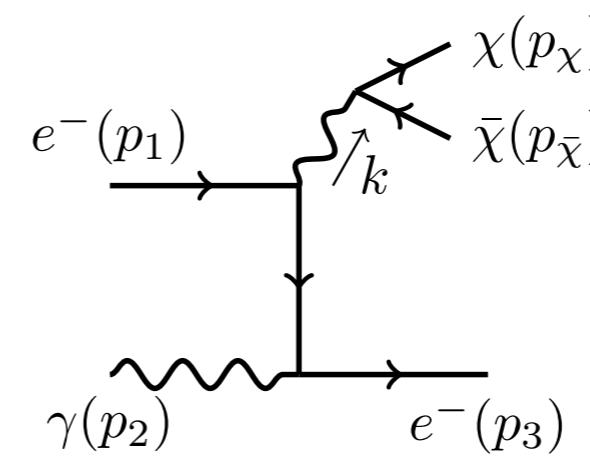
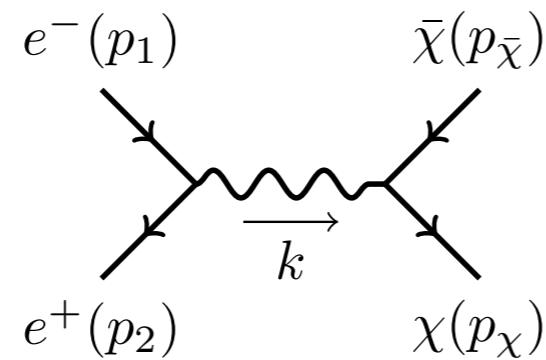
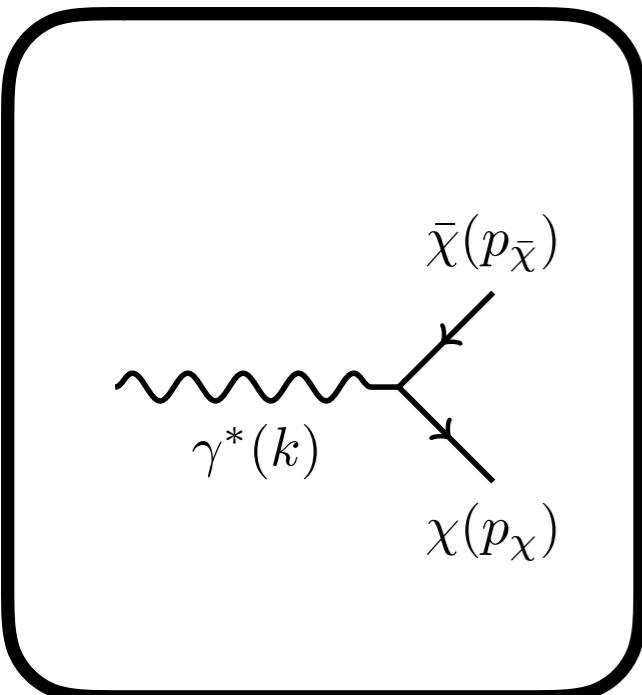
Stars as laboratories



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

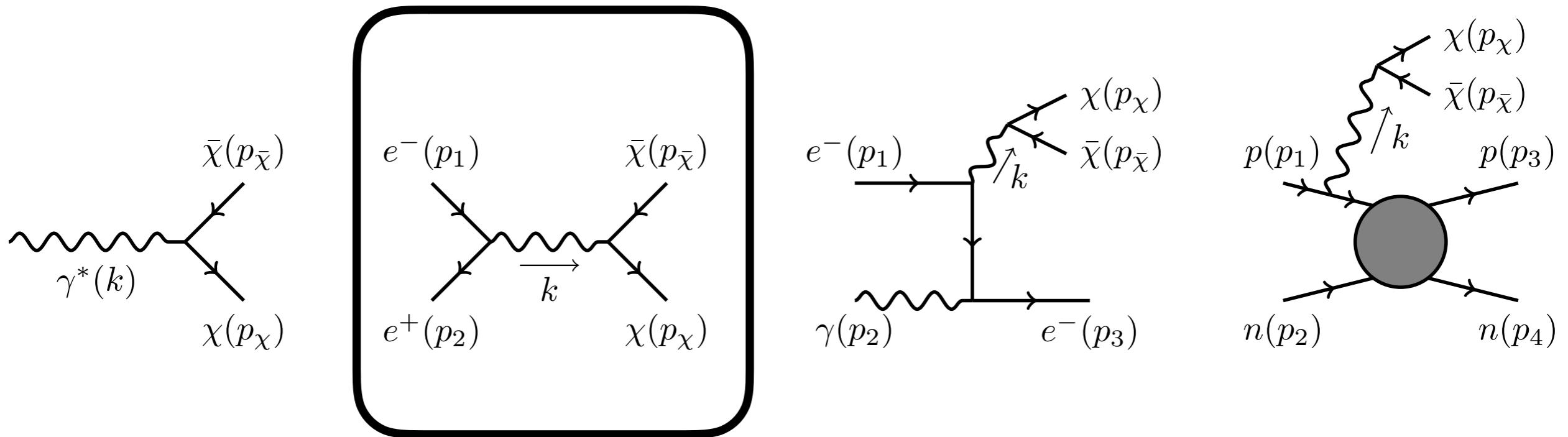


T/L “Plasmon” decay

(all)

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

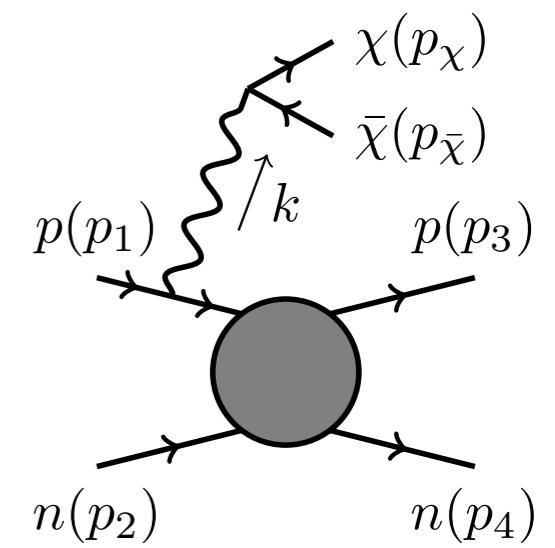
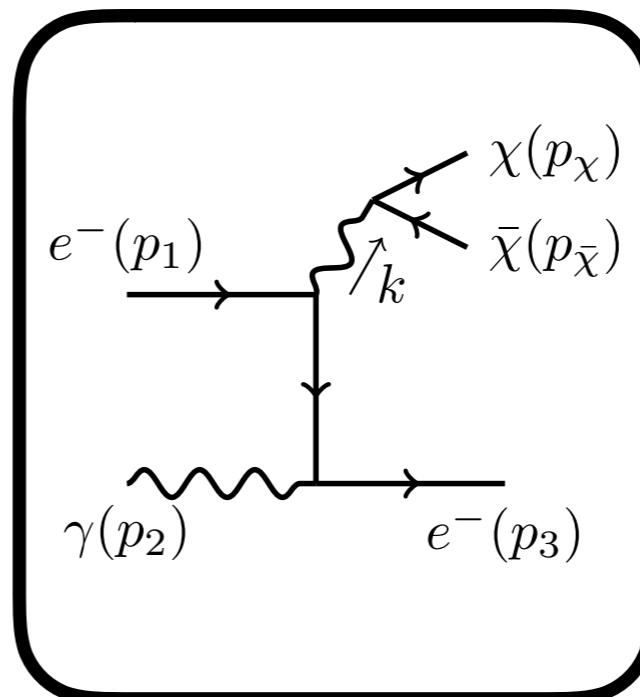
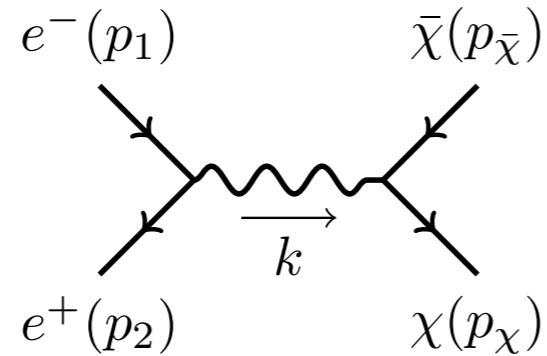
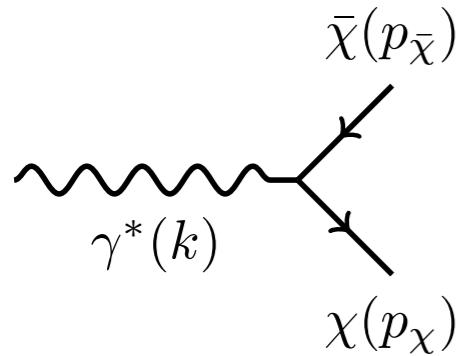
Stellar Probes of dark-sector photon interactions



e+e- annihilation
(SN)

NB: no overlap with plasmon decay

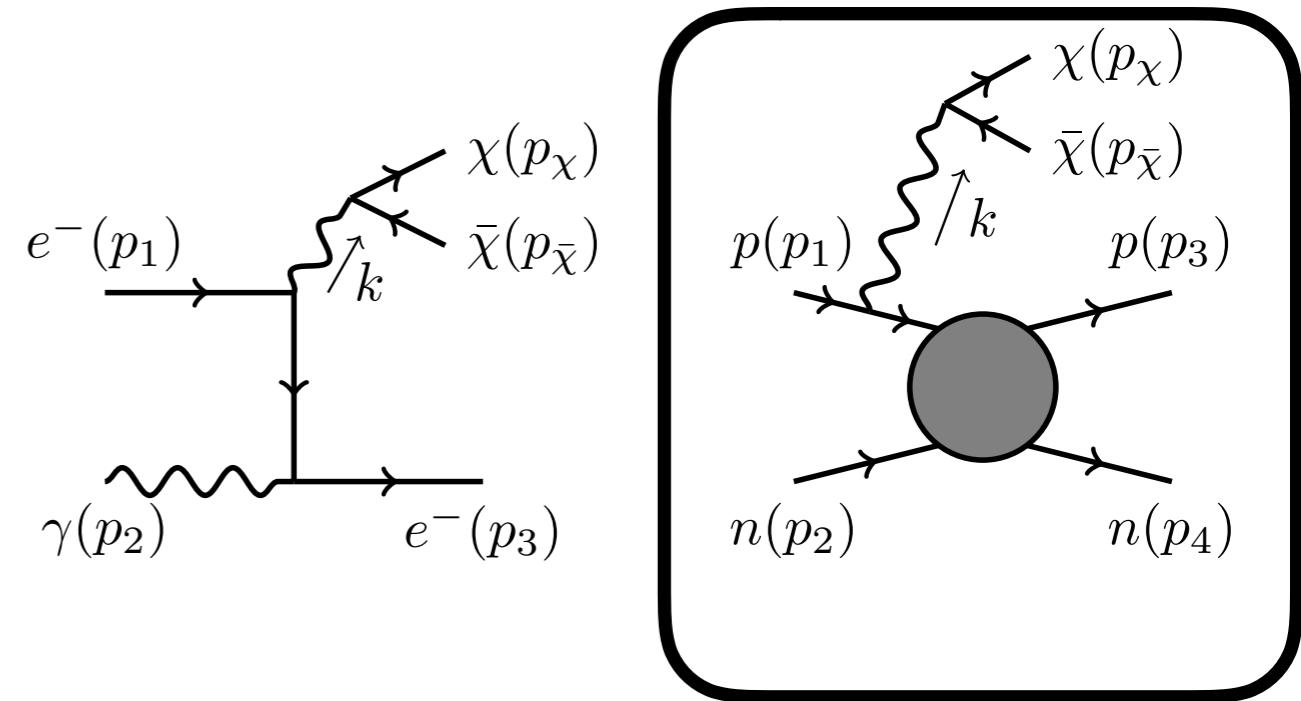
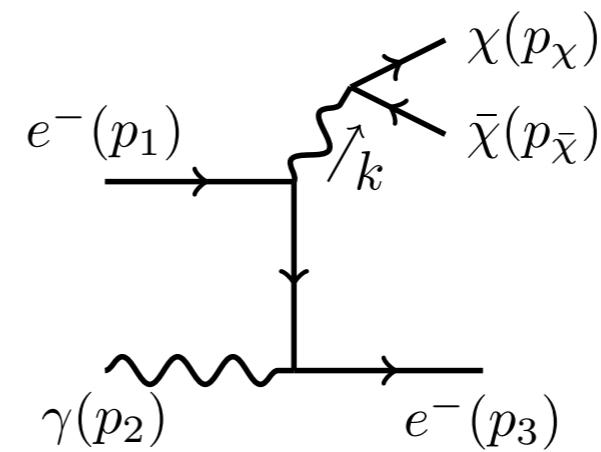
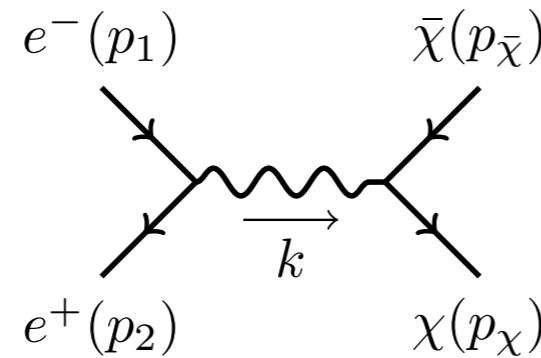
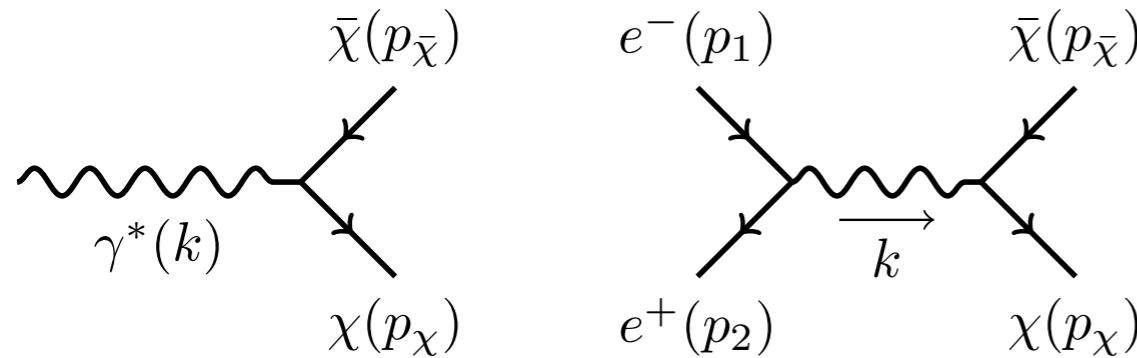
Stellar Probes of dark-sector photon interactions



Compton 2->3 production

(all)

Stellar Probes of dark-sector photon interactions



Electron-nucleus Bremsstrahlung

(RG, HB, Sun)

Neutron-proton Bremsstrahlung

(SN)

NB: soft-photon approximation
not applicable

NB: we use exp. data for np-brems
Rrapaj, Reddy 2016

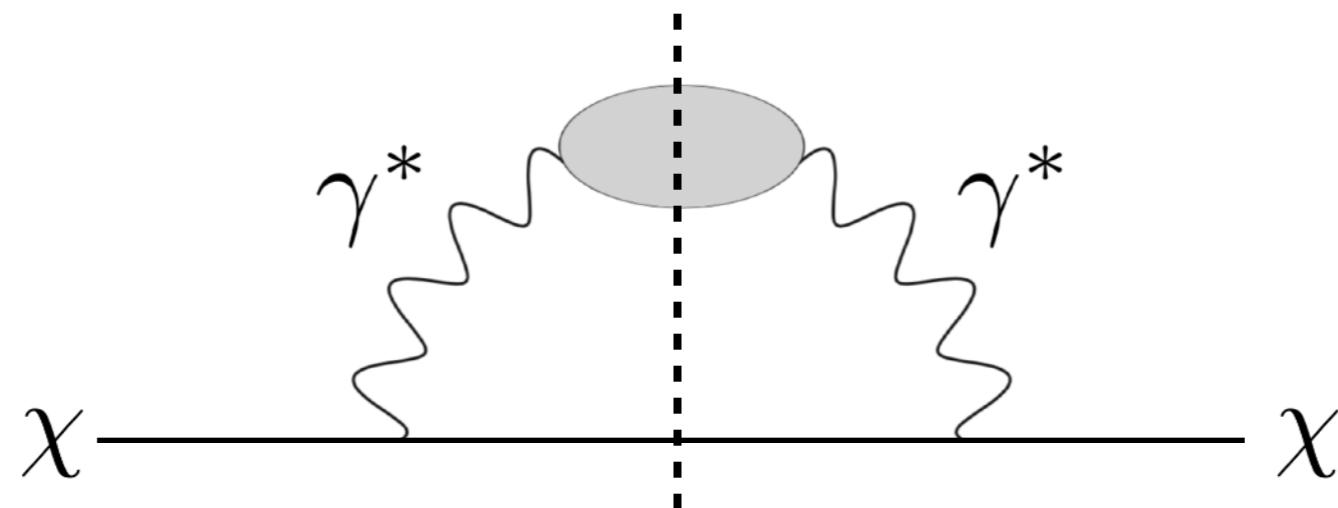
Exact Formula for pair-emission

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

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

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

Weldon 1983



Exact Formula for pair-emission

$$\begin{aligned} \frac{d\dot{N}_\chi}{ds_{\chi\bar{\chi}}} = & - \sum_{i=T,L} g_i \int \frac{d^3 \vec{k}}{(2\pi)^3} \frac{1}{(e^{\omega/T} - 1)} \frac{\text{Im } \Pi_i(\omega, \vec{k})}{\omega} \\ & \times \frac{f(s_{\chi\bar{\chi}})}{16\pi^2 |s_{\chi\bar{\chi}} - \Pi_i|^2} \sqrt{1 - \frac{4m_\chi^2}{s_{\chi\bar{\chi}}}} \end{aligned}$$

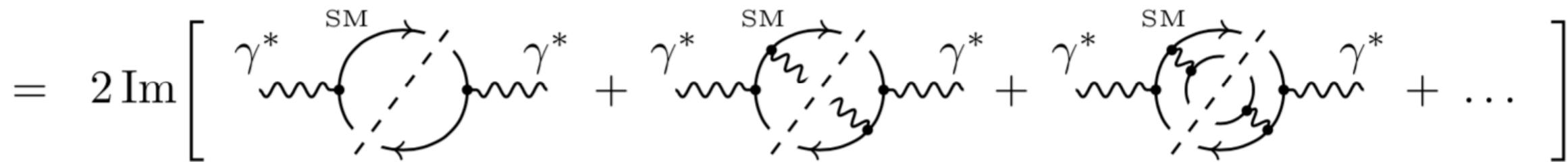
In this version (derived from works on dilepton-production in hot matter) the imaginary part of the *photon self-energy* enters

$$\Pi^{\mu\rho} = (\epsilon_{T,1}^\mu \epsilon_{T,1}^\rho + \epsilon_{T,2}^\mu \epsilon_{T,2}^\rho) \Pi_T + \epsilon_L^\mu \epsilon_L^\rho \Pi_L$$

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

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

Breakdown of other processes

$$2 \operatorname{Im} \left[\begin{array}{c} \gamma^* \\ \text{---} \\ \text{SM} \\ \text{---} \\ \gamma^* \end{array} \right] =$$
$$= 2 \operatorname{Im} \left[\begin{array}{c} \gamma^* \\ \text{---} \\ \text{SM} \\ \text{---} \\ \gamma^* \end{array} + \begin{array}{c} \gamma^* \\ \text{---} \\ \text{SM} \\ \text{---} \\ \gamma^* \end{array} + \begin{array}{c} \gamma^* \\ \text{---} \\ \text{SM} \\ \text{---} \\ \gamma^* \end{array} + \dots \right]$$


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

$$2 \operatorname{Im} \left[\begin{array}{c} \gamma^* \\ \text{---} \\ \text{SM} \\ \text{---} \\ \gamma^* \end{array} \right] =$$
$$= \int d\Pi_i \left[\left| \begin{array}{c} \text{SM} \\ \text{---} \\ \text{---} \\ \text{SM} \end{array} \right. \gamma^* \right|^2 + \left| \begin{array}{c} \text{SM} \\ \text{---} \\ \gamma \\ \text{---} \\ \text{SM} \end{array} \right. \gamma^* \right|^2 + \left| \begin{array}{c} \text{SM} \\ \text{---} \\ \text{SM} \\ \text{---} \\ \text{SM} \end{array} \right. \gamma^* \right|^2 + \dots \right]$$

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

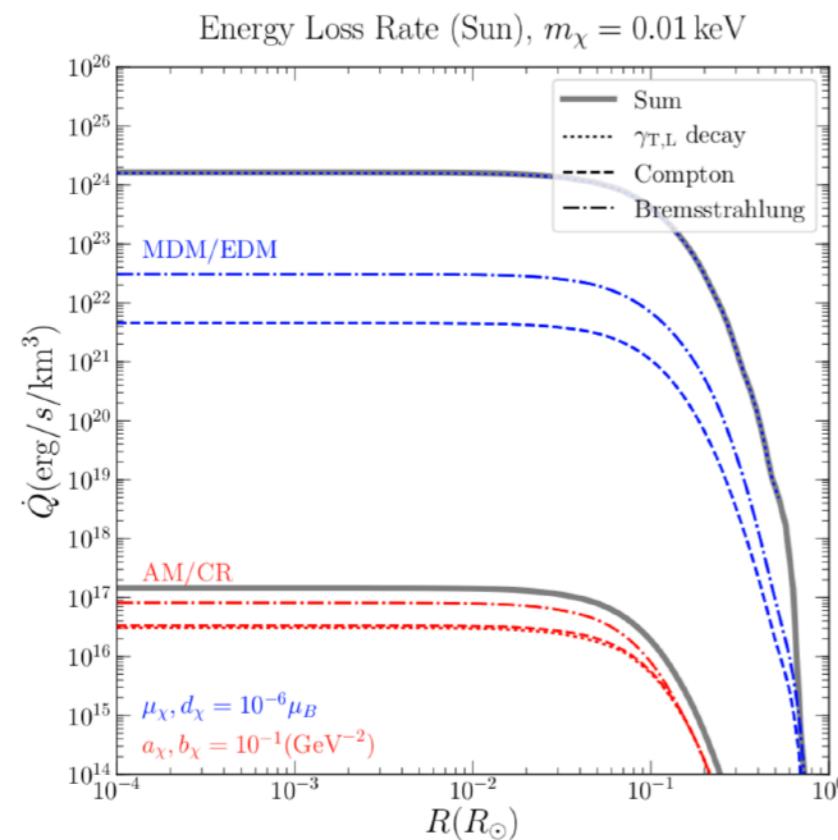
NB: in the paper we have a careful discussion on potential double-counting between the processes

Energy loss rates

Sun

dominant process:

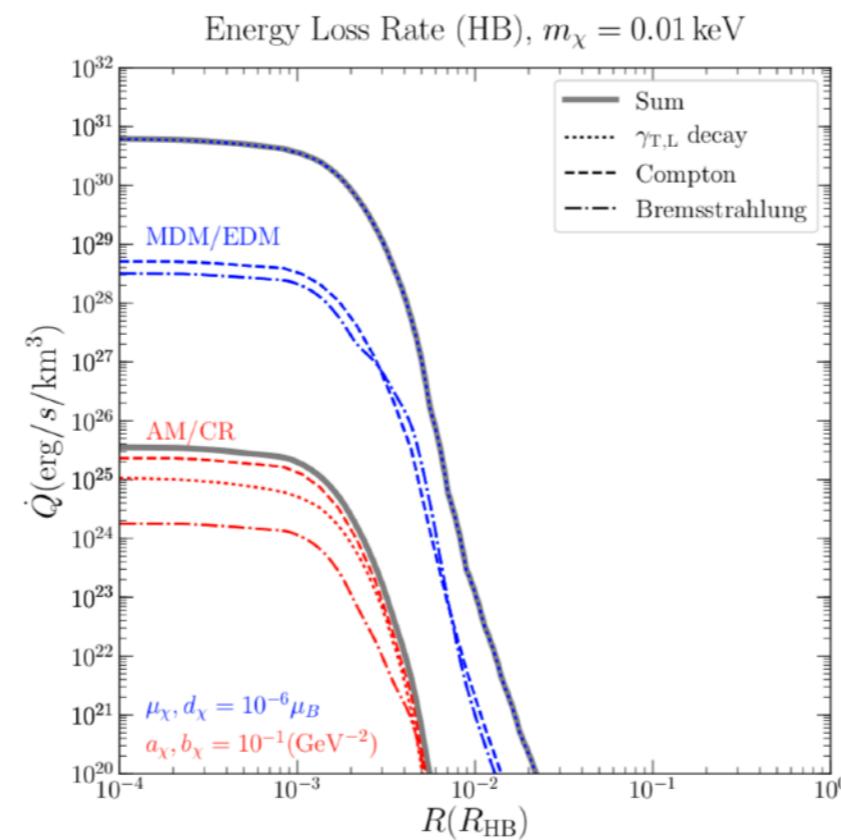
MDM/EDM: plasmon decay
AM/CR: all



Horizontal Brach Stars

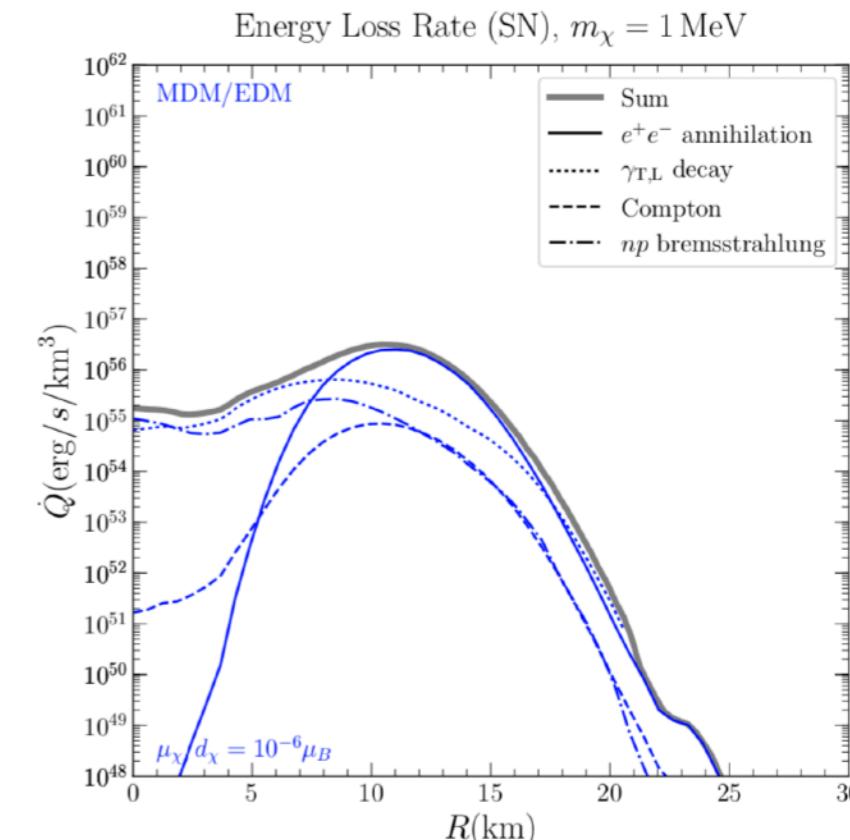
dominant process:

MDM/EDM: plasmon decay
AM/CR: plasmon decay, Compton scattering



Supernovae

dominant processes:
annihilation, bremsstrahlung,
plasmon decay





Supernova cooling

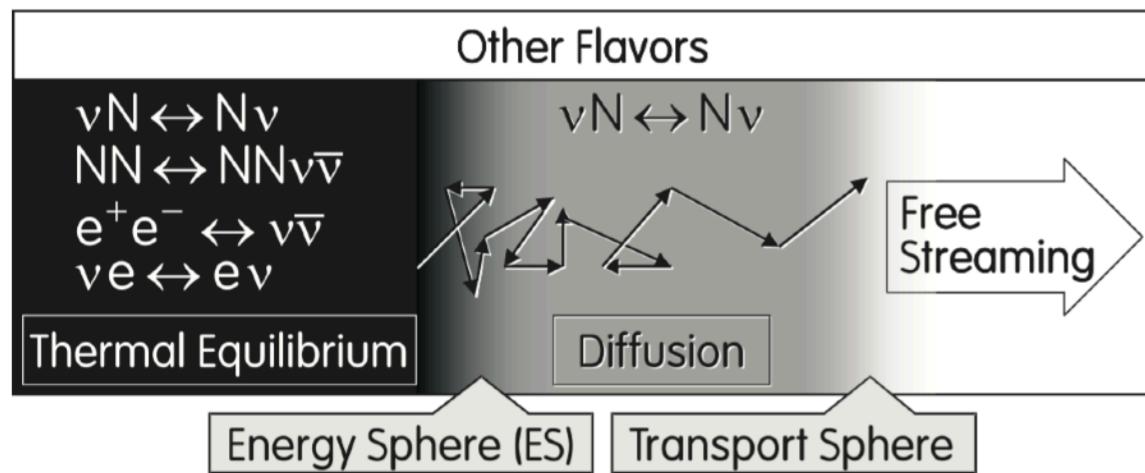
- Pair production of χ particles with $m_\chi \lesssim 400 \text{ MeV}$ in SN possible

Lower boundary: use “Raffelt-criterion”

$$\int_0^{r_{\text{core}}} d^3 r \dot{Q} \leq L_\nu$$

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

=> we do a detailed analysis accounting for diffusion zone

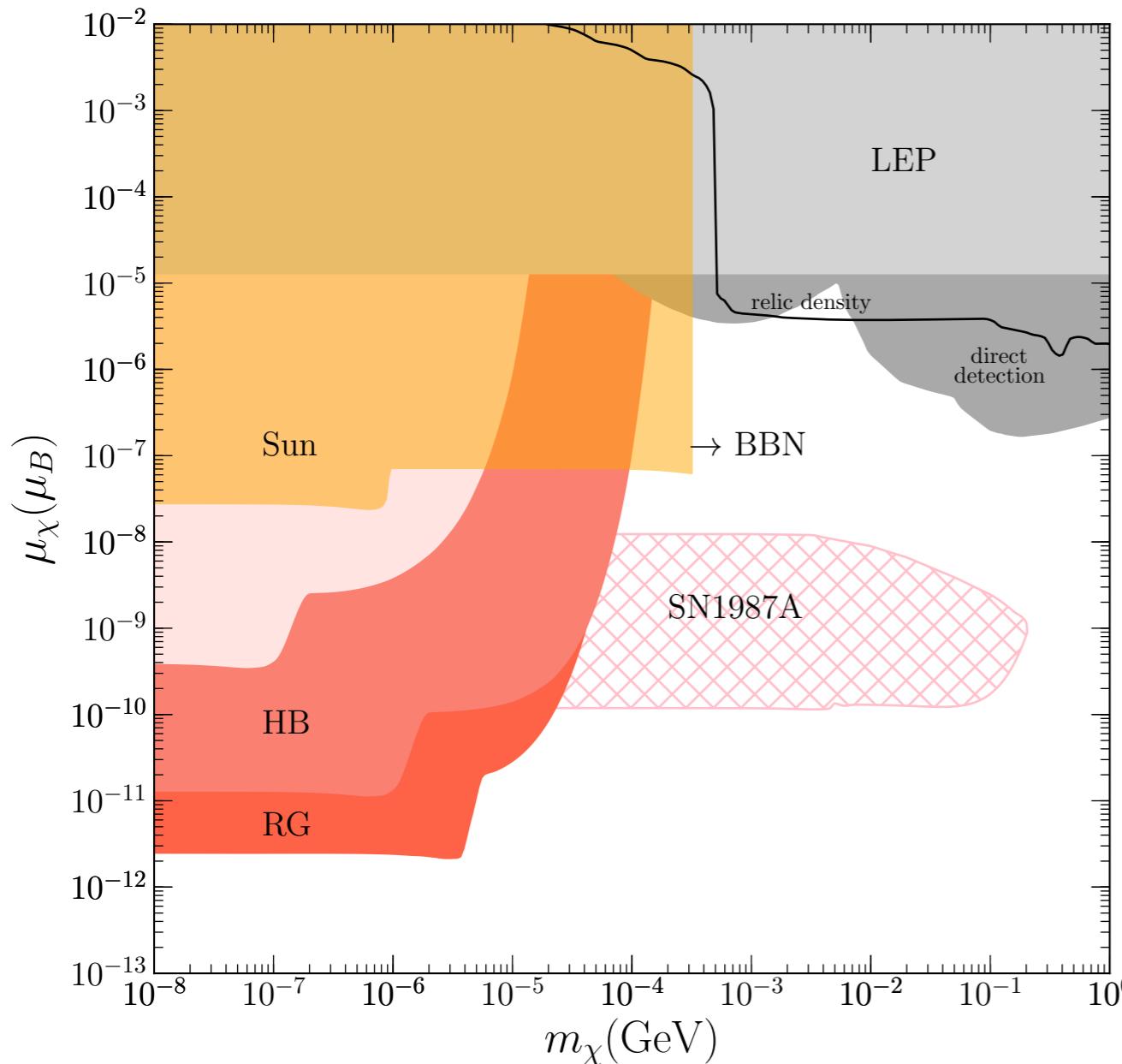


$$L_{\text{inf}} = L_\chi(r_{\text{ES}}) S_{\text{ES}}$$

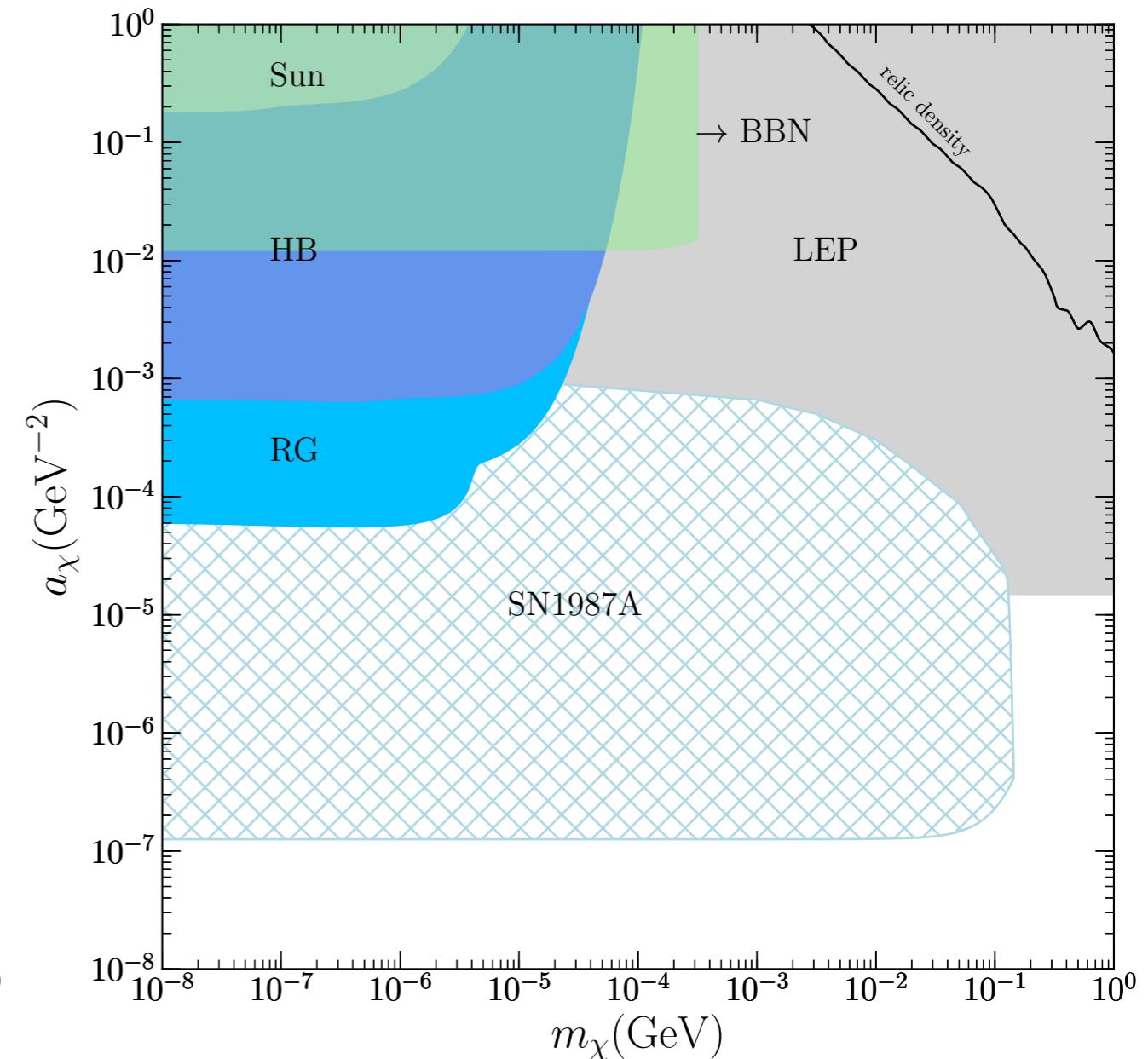
Raffelt 2001

Form-factor “landscape”

dim 5: magnetic dipole



dim 6: Anapole Moment



NB: for $m \rightarrow 0$ one recovers previous
limits on neutrino MDM interactions [Raffelt 1990++](#)

Photon as New Physics Mediator

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”.

An “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