Particle Avenues in the Dark Universe Arena (PADUA): Light Dark Sectors

Connect the visible and dark Universe via one photon

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ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

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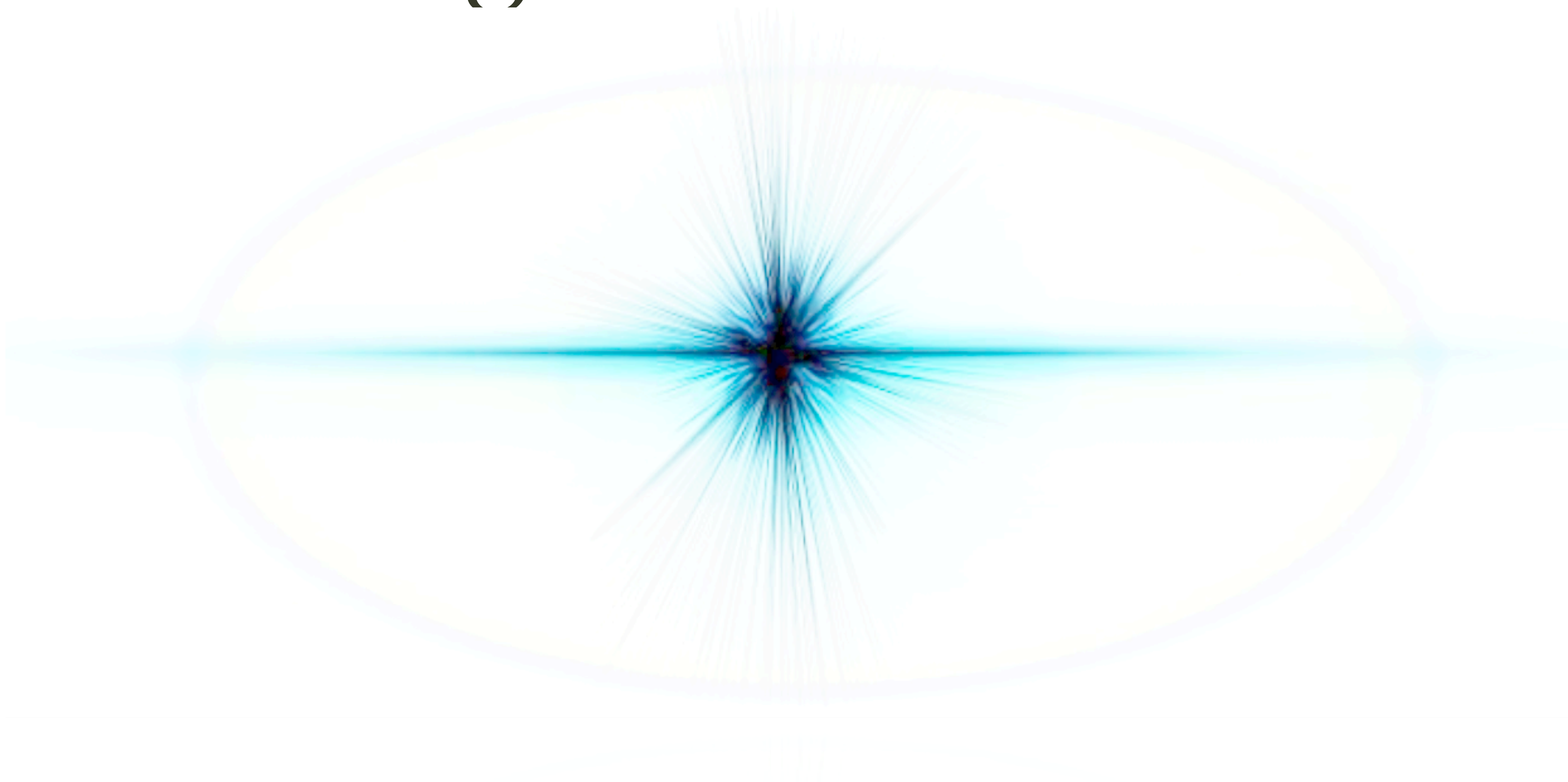
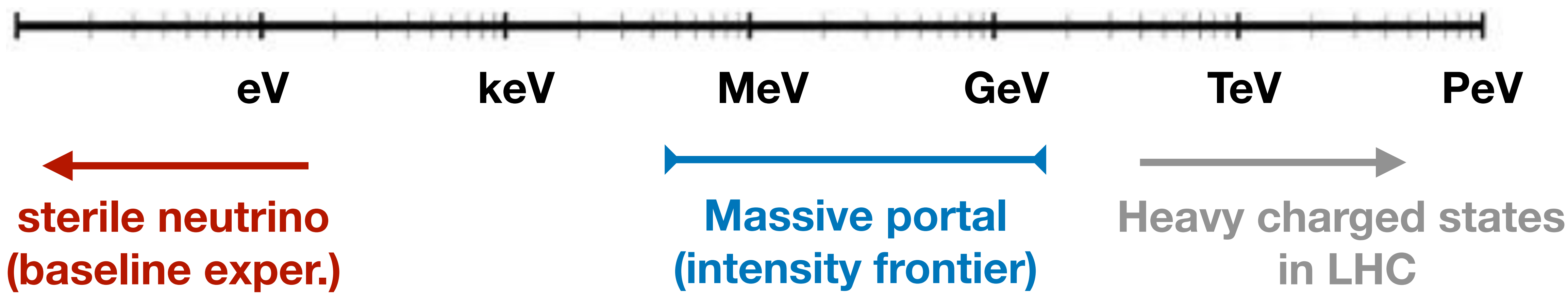
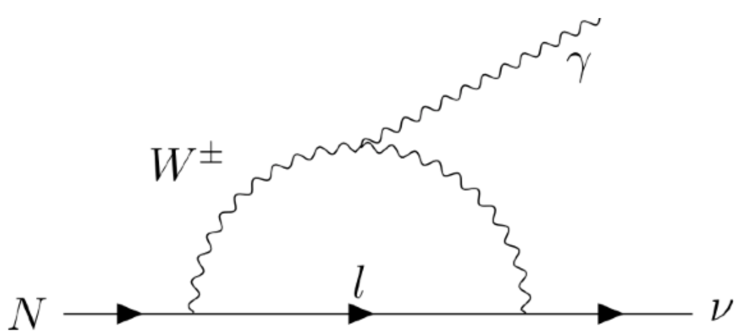
I. a light dark sector

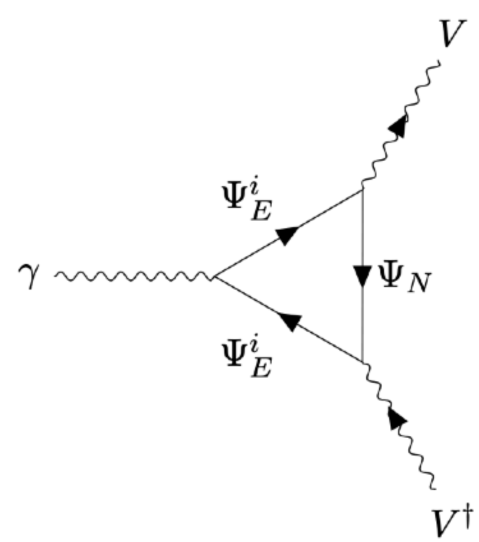


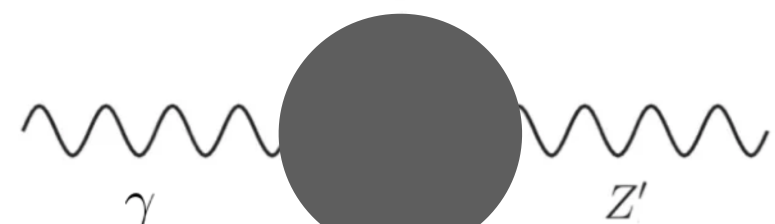
Search for new dark particles:



Each can easily couple to a photon:







SM/BSM charged particles

general kinetic mixing

No hint of new light d.o.f. from cosmology?

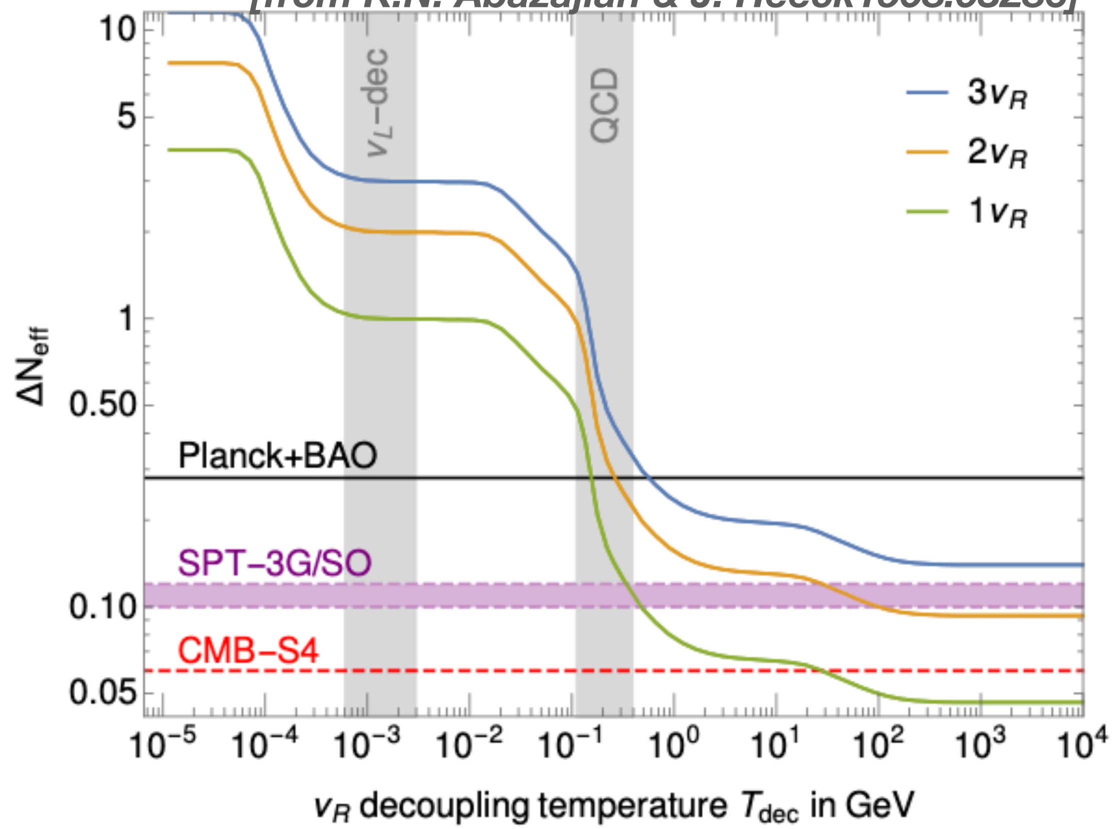
Planck 2018 *[1807.06209]*

$$N_{\rm eff} = 2.96^{+0.34}_{-0.33},$$ 95 %, *Planck* TT,TE,EE+lowE +lensing+BAO.

$$N_{\rm eff} = 2.95^{+0.56}_{-0.52}$$ BBN + BAO

That is, new light mediator can only be feeble.

[from K.N. Abazajian & J. Heeck1908.03286]

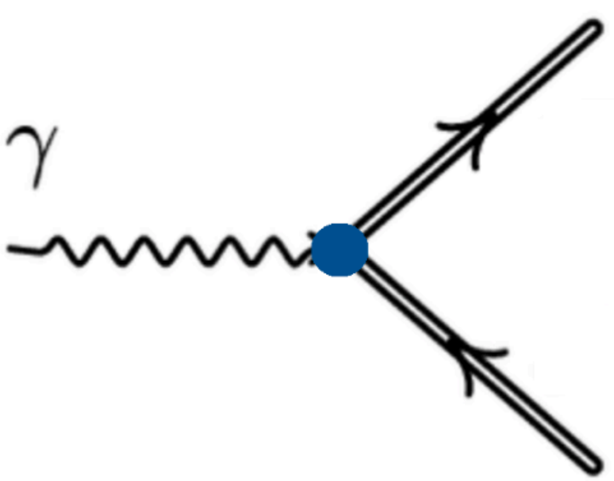


In order to take advantage of a (nearly) massless mediator:

SM photon portal

via dark loop/mixing/confinement

[e.g. Holdom 1986, Raby, West 1987, Bagnasco, Dine, Thomas 1993, Foadi, Frandsen, Sannino 2008, …]



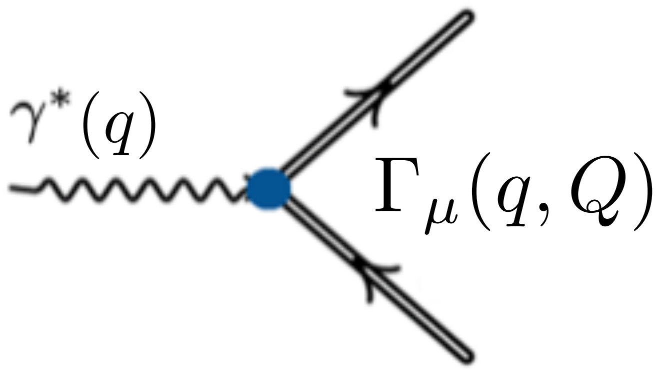
What can a photon portal be?

Explore the possible **EM form factors** of **light dark particles**:

the most general Lagrangian

$$L_{\text{int}} = -iA^{\mu}(q)J_{\mu}(q,Q)$$

taking non-relativistic limit



1. milli-charge of a new particle: electric monopole

$$q = \int d^3x \rho_{\text{EM}}(\vec{x}) \propto J_0(q=0, Q=0)$$

Non-vanishing terms

→ the interaction operator

Complex scalar	$\phi^*(\partial_\mu \phi) - (\partial_\mu \phi^*)\phi$
Dirac fermion	$\bar{\psi}\gamma_\mu \psi$
Complex vector	$V_\alpha^+(\partial_\mu V^\alpha) - (\partial_\mu V_\alpha^+)V^\alpha$ imposing Lorentz gauge

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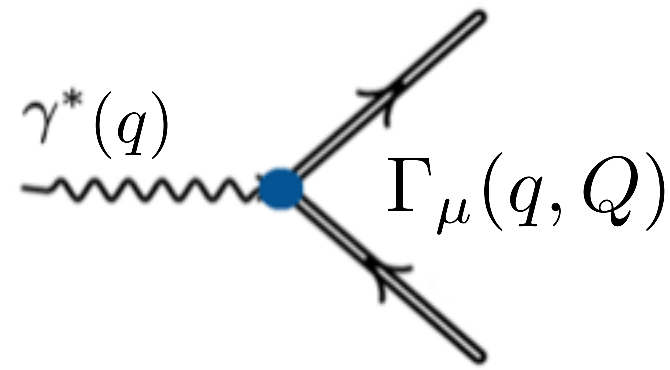

2. in case that dark particle is QED neutral: dipoles, quadrupoles, …

$$\vec{d}_{\text{E}} = \int d^3x \vec{x} \rho_{\text{EM}}(\vec{x}) \propto \frac{\partial J_0}{\partial \vec{q}}|_{\vec{q}=0}$$

- electric dipole

$$\vec{\mu}_{\text{M}} = \frac{1}{2} \int d^3x \vec{x} \times \vec{J}_{\text{EM}}(\vec{x}) \propto (\nabla_{\vec{q}} \times \vec{J})|_{\vec{q}=0}$$

- magnetic dipole

$$\int d^3x x_i x_j \rho_{\text{EM}}(\vec{x}) \propto \frac{\partial^2 J_0}{\partial q^i \partial q^j}|_{\vec{q}=0}$$

- (trace) charge radius
- (traceless) electric quadrupole

$$\nabla_{q^i} (\nabla_{\vec{q}} \times \vec{J})_j + (i \leftrightarrow j)|_{\vec{q}=0}$$

- magnetic quadrupole, … …

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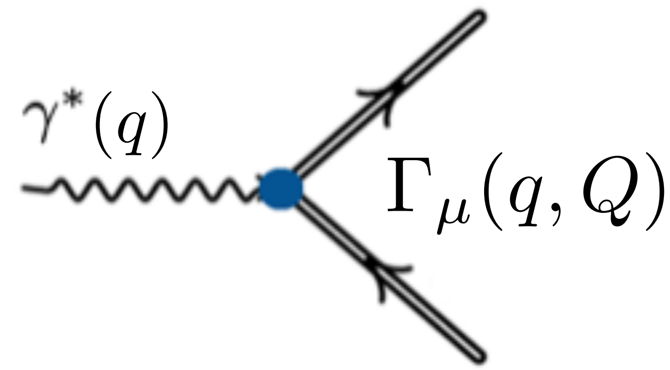

2. in case that dark particle is QED neutral: dipoles, quadrupoles, …

interaction type	coupling	C	P	CP
magn. dipole	μ	$+1$	$+1$	$+1$
elec. dipole	d	$+1$	-1	-1
elec. quadrupole	Q	$+1$	$+1$	$+1$
magn. quadrupole	$\tilde{Q}$	$+1$	-1	-1
charge radius	g_1^A/m^2	$+1$	$+1$	$+1$
toroidal moment	g_4^A/m^2	-1	$+1$	-1
anapole moment	g_5^A/m^2	-1	-1	$+1$

Scalars have no-spin, thus only can have

- (trace) charge radius

$$(\phi^* \overleftrightarrow{\partial}_\mu \phi)\partial_\nu F^{\mu\nu}$$

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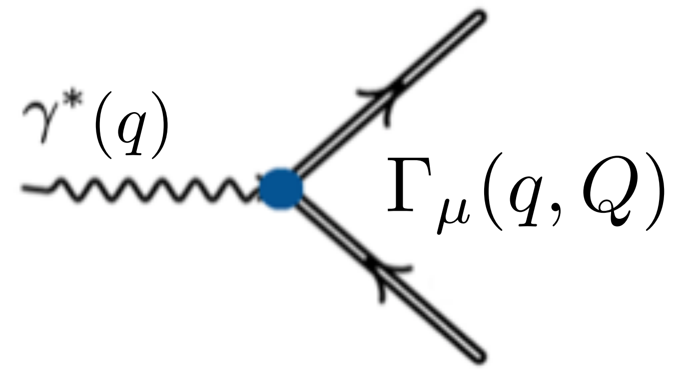

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independent indices for **Dirac fermion**

- $\sigma^{\mu\nu} q_\nu$ — $\bar\chi \sigma^{\mu\nu} \chi F_{\mu\nu}$
- $\sigma^{\mu\nu} q_\nu \gamma^5$ — $\bar\chi \sigma^{\mu\nu} \gamma^5 \chi F_{\mu\nu}$
- $[q^2\gamma^\mu - q^\mu \not{q}]$ — $\bar\chi \gamma^\mu \chi \partial^\nu F_{\mu\nu}$ (← charge radius)
- $[q^2\gamma^\mu - q^\mu \not{q}]\, \gamma^5$ — $\bar\chi \gamma^\mu \gamma^5 \chi \partial^\nu F_{\mu\nu}$ (← anapole moment)

[e.g. Pospelov, Veldhuis 2000, Sigurdson, Doran, Kurylov, Caldwell, Kamionkowski 2004, Ho, Scherrer 2012, Kadota, Silk 2014, Mohanty, Rao 2015, …]

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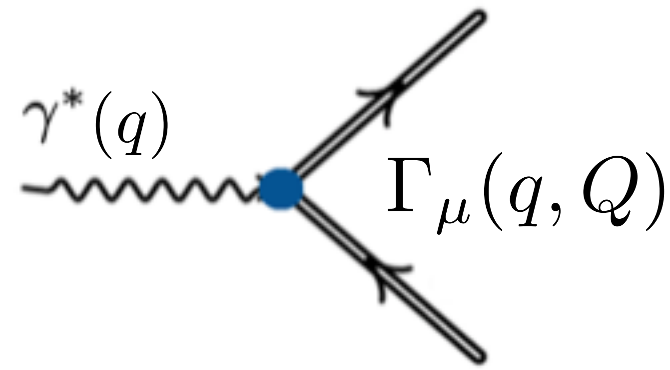

2. in case that dark particle is QED neutral: dipoles, quadrupoles, …

interaction type	coupling	C	P	CP
magn. dipole	μ	+1	+1	+1
elec. dipole	d	+1	−1	−1
elec. quadrupole	Q	+1	+1	+1
magn. quadrupole	$\tilde{Q}$	+1	−1	−1
charge radius	g_1^A/m^2	+1	+1	+1
toroidal moment	g_4^A/m^2	−1	+1	−1
anapole moment	g_5^A/m^2	−1	−1	+1

independent indices for **vector boson**

imposing Lorentz gauge

$$-2im_V\mu_V\left[k^\alpha g^{\mu\beta}-k^\beta g^{\mu\alpha}+\frac{1}{4m_V^2}\left(k^2g^{\alpha\beta}p^\mu-2k^\alpha k^\beta p^\mu\right)\right]$$
$$-\frac{iQ_V}{4}\left(k^2g^{\alpha\beta}p^\mu-2k^\alpha k^\beta p^\mu\right)$$
$$-\frac{id_V}{2m_V}p^\mu\,[kp]^{\alpha\beta}-\frac{i\tilde{Q}_V}{4}\left(p^\mu\,[kp]^{\alpha\beta}+4m_V^2\epsilon^{\mu\alpha\beta\rho}k_\rho\right)$$
$$-\frac{ieg_1^A}{2m_V^2}k^2p^\mu g^{\alpha\beta}-\frac{eg_4^A}{m_V^2}k^2(k^\alpha g^{\mu\beta}+k^\beta g^{\mu\alpha})-\frac{eg_5^A}{m_V^2}k^2\epsilon^{\mu\alpha\beta\rho}p_\rho$$

What can a photon portal be?

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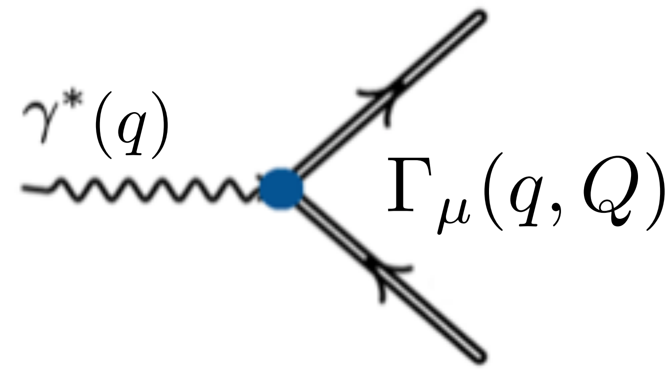

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anapole moment	g_5^A/m^2	-1	-1	$+1$

If self-conjugate particles, only C-violating factors survive

[F. Boudjema, C. Hamzaoui, V. Rahal, and H. C. Ren, Phys. Rev. Lett. 62, 852, 1989]

What can a photon portal be?

Explore the possible **EM form factors** of **light dark particles**:

1. milli-charge of a new particle: electric monopole

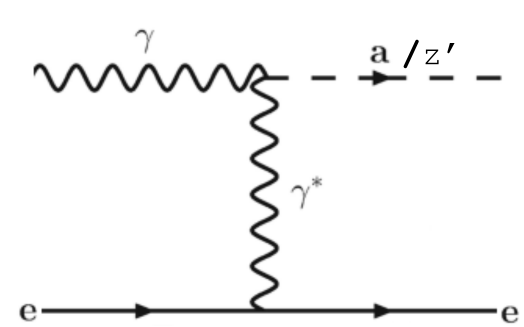
Relevant for EDGES anomaly, and well constrained recently, see e.g. E. Gabrielli, L. Marzola, M. Raidal & H. Veermäe 1507.00571, A. Berlin, D. Hooper, G. Krnjaic, S. D. McDermott 1803.02804, E. D. Kovetz, V. Poulin, V. Gluscevic, K. K. Boddy, R. Barkana, M. Kamionkowski 1807.11482, T. Emken, R. Essig, C. Kouvaris & M. Sholapurkar, 1905.06348, S. Foroughi-Abari, F. Kling & Y. Tsai 2010.07941, M. A. Buen-Abad, R. Essig, D. McKeen, Y. Zhong 2107.12377, M. Montigny, P. A. Ouimet, J. Pinfold, A. Shaa & M. Staelens 2307.07855, …

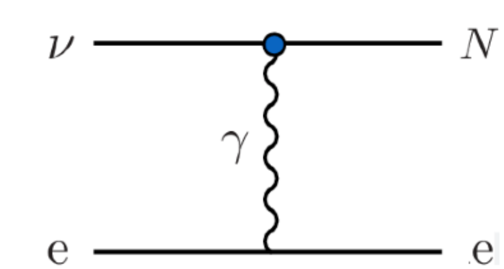
2. in case that dark particle is QED neutral: dipoles, quadrupoles, …

For technical details on multipole expansions, see e.g. K. Gaemers & G. Gounaris, 1979, K. Hagiwara, R. D. Peccei, D. Zeppenfeld & K. Hikasa, 1987, J. F. Nieves & P. B. Pal 1996, …

3. Inelastic cases:

typically easier to produce and detect;
but will not discussed.

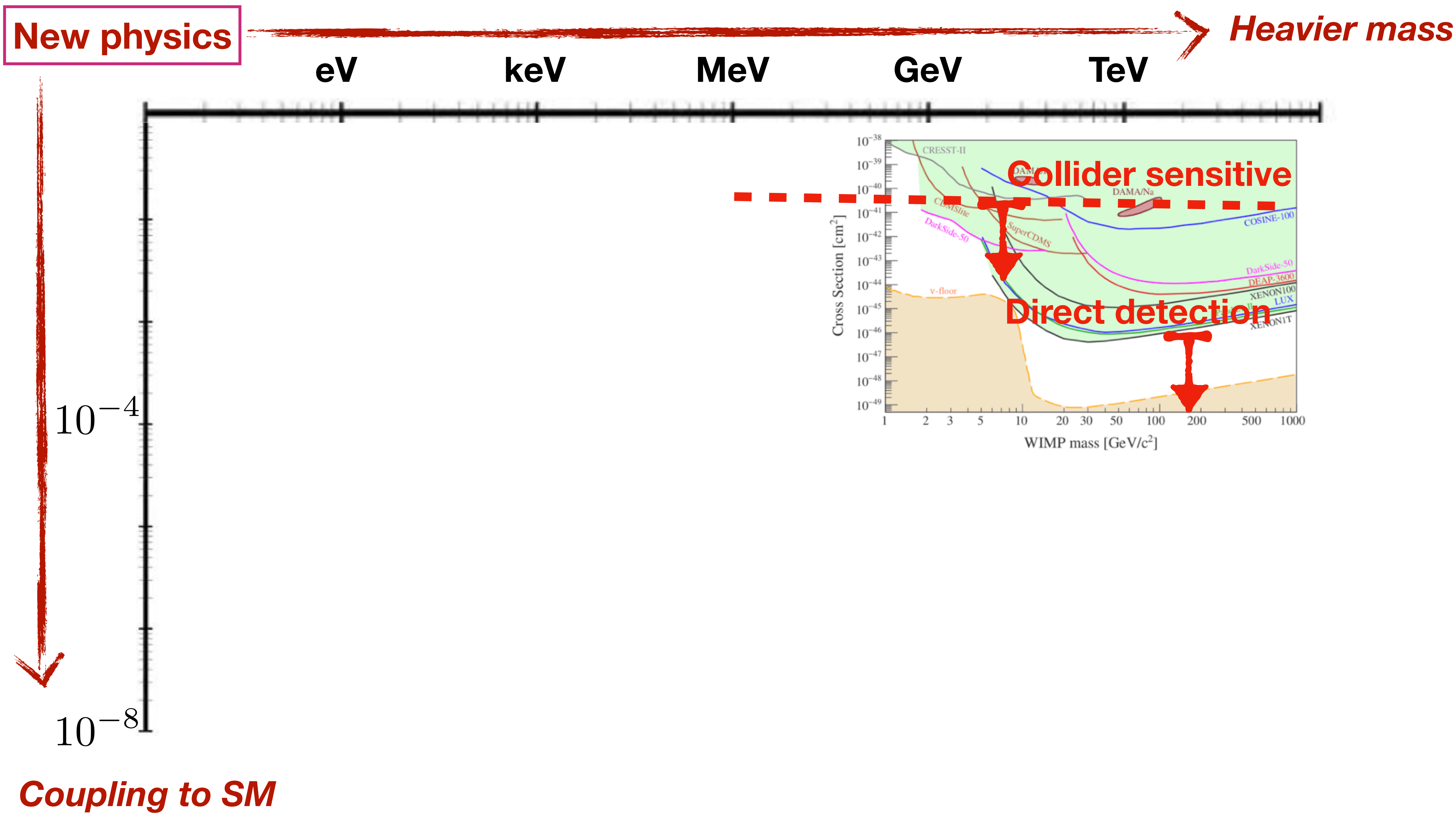




II. probe a **neutral** dark sector:

spin-1/2 v.s. spin-1

A typical constrain plot for a light dark particle



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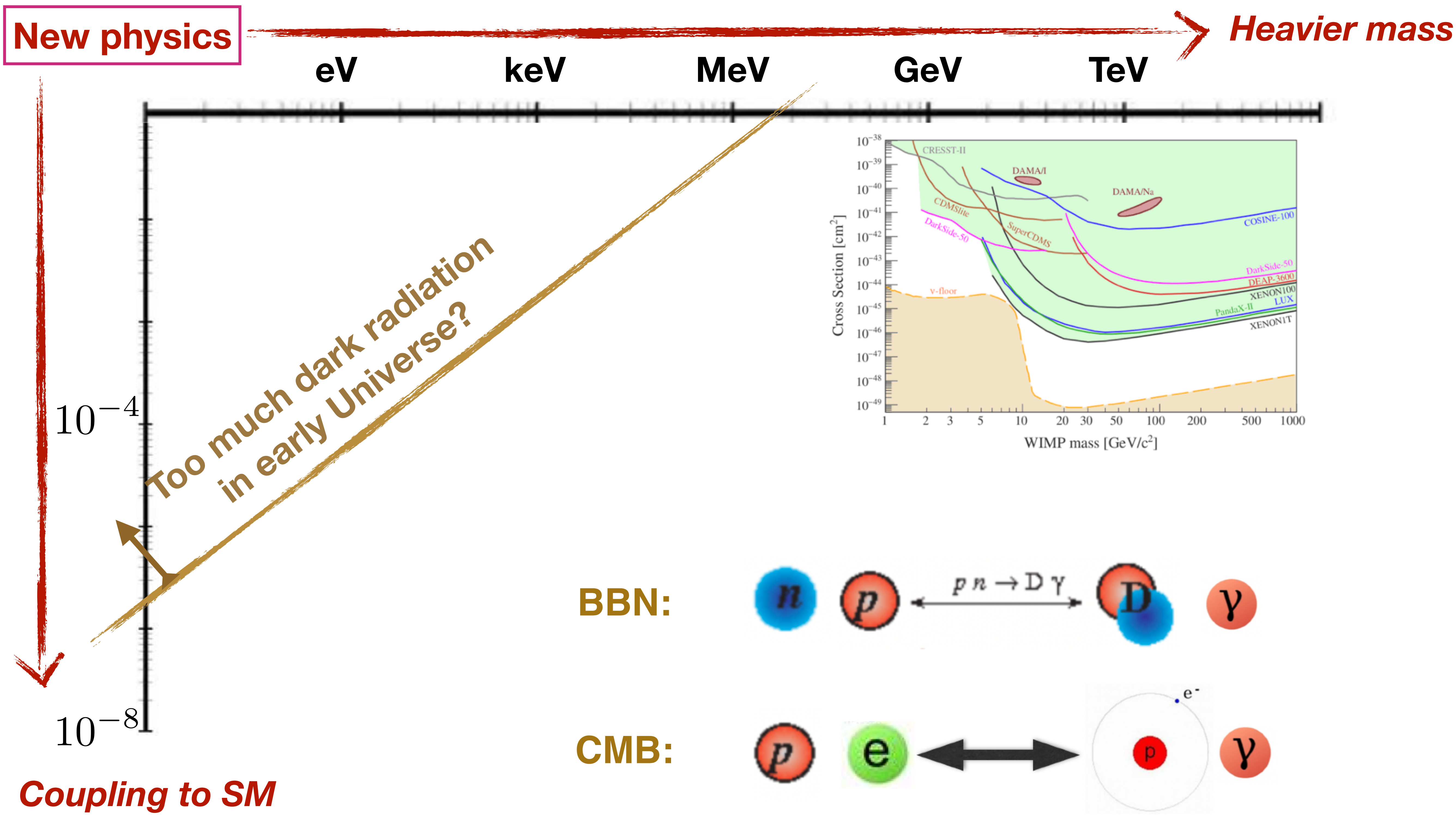

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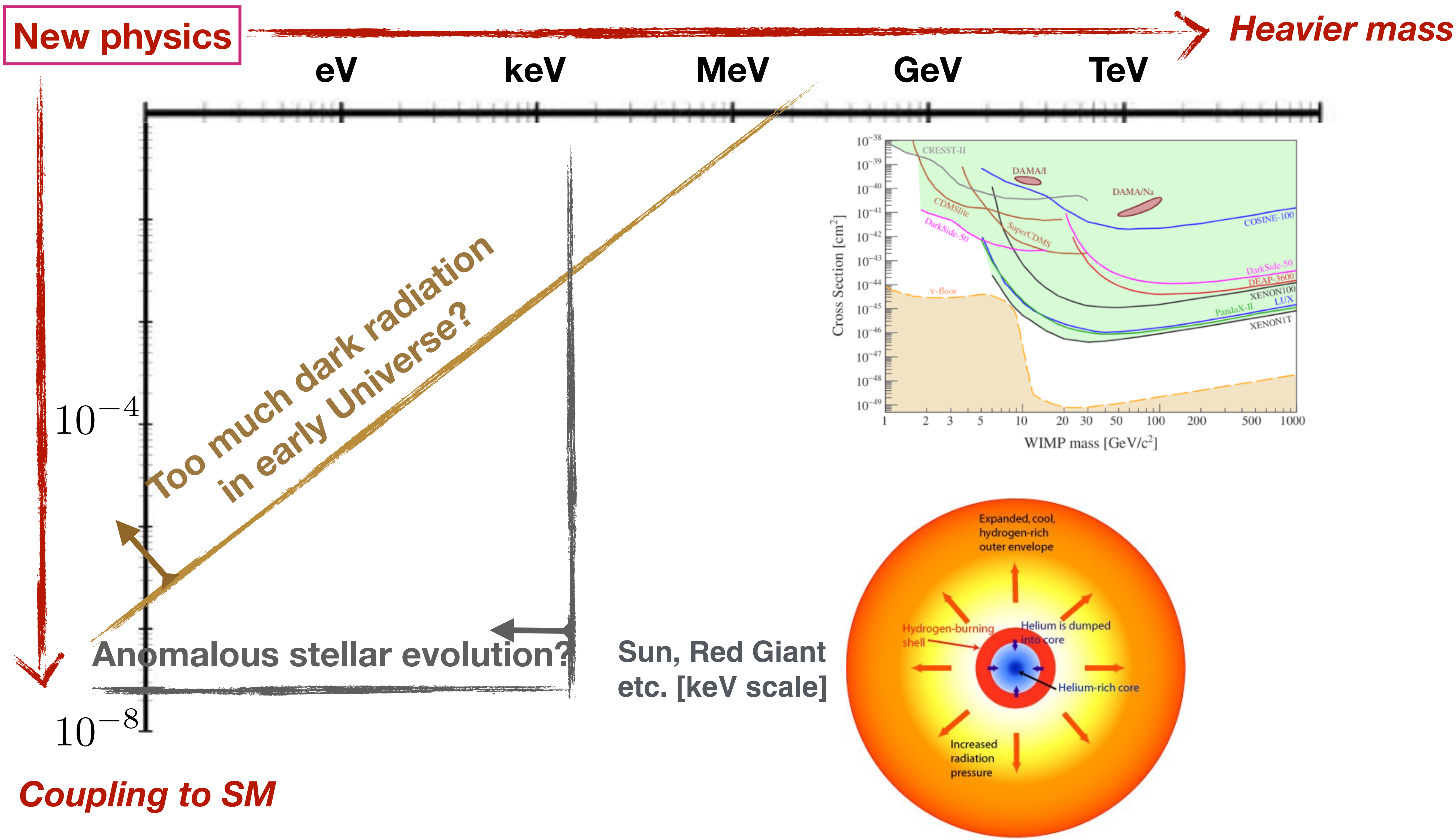

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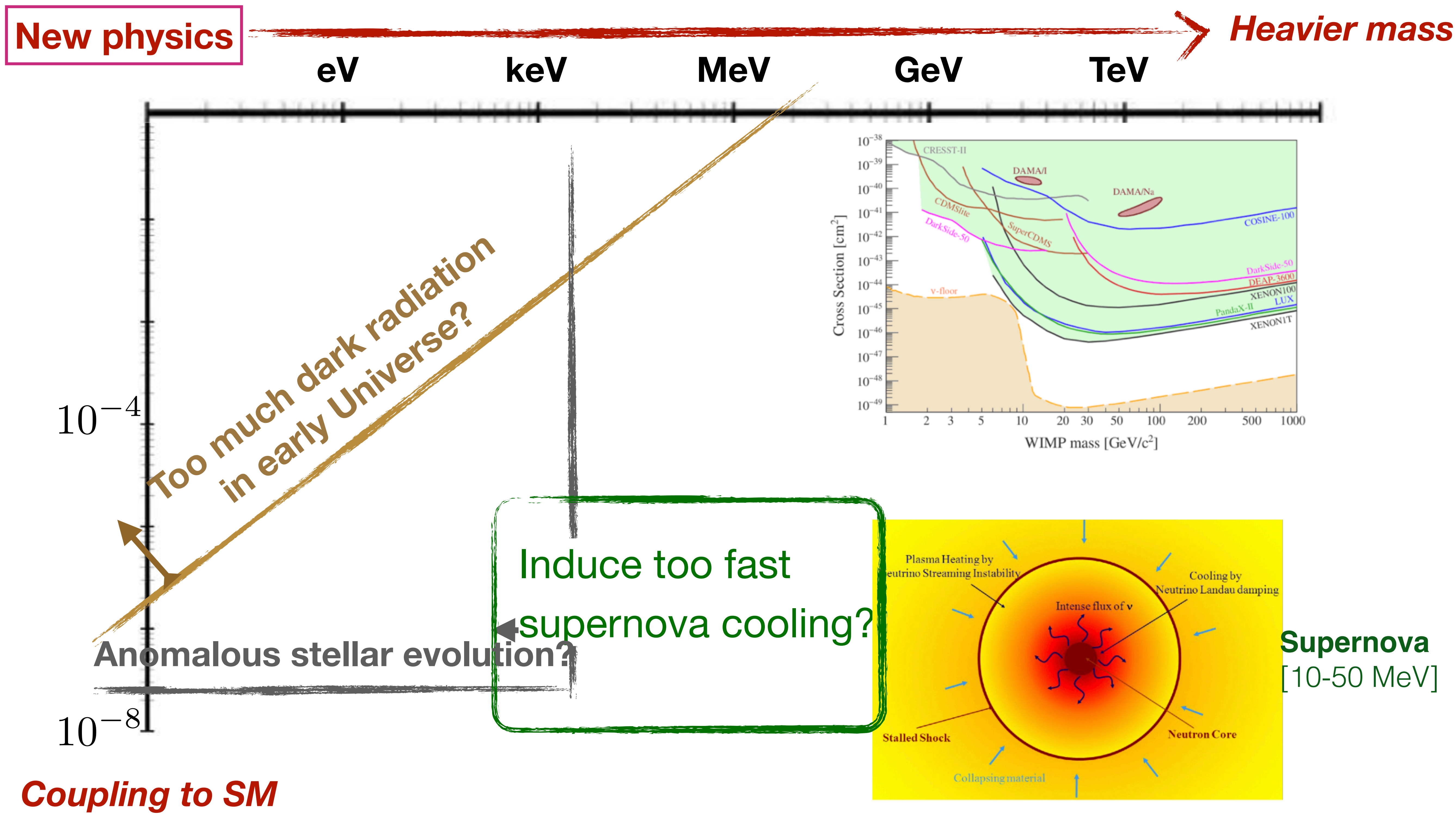

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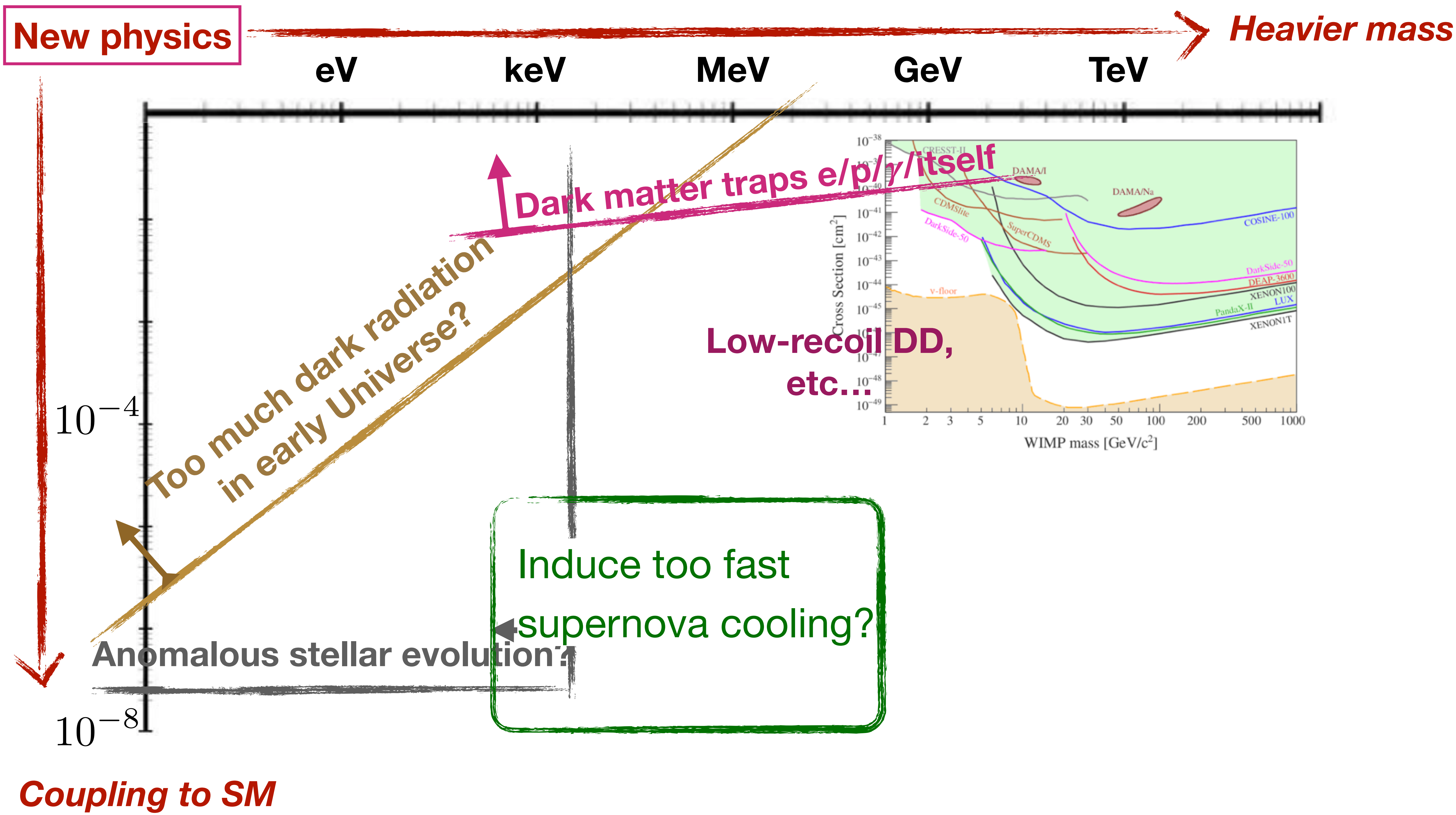
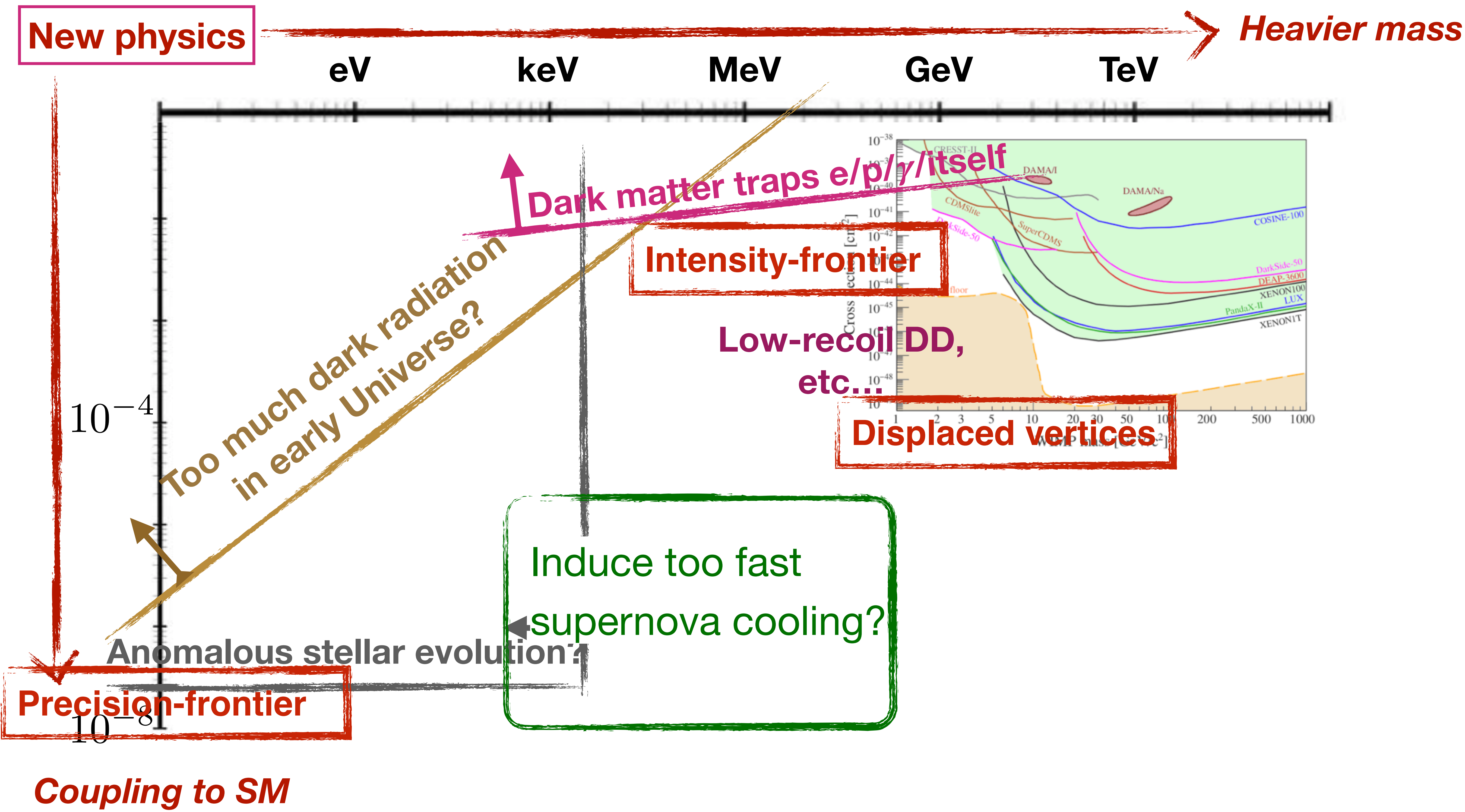
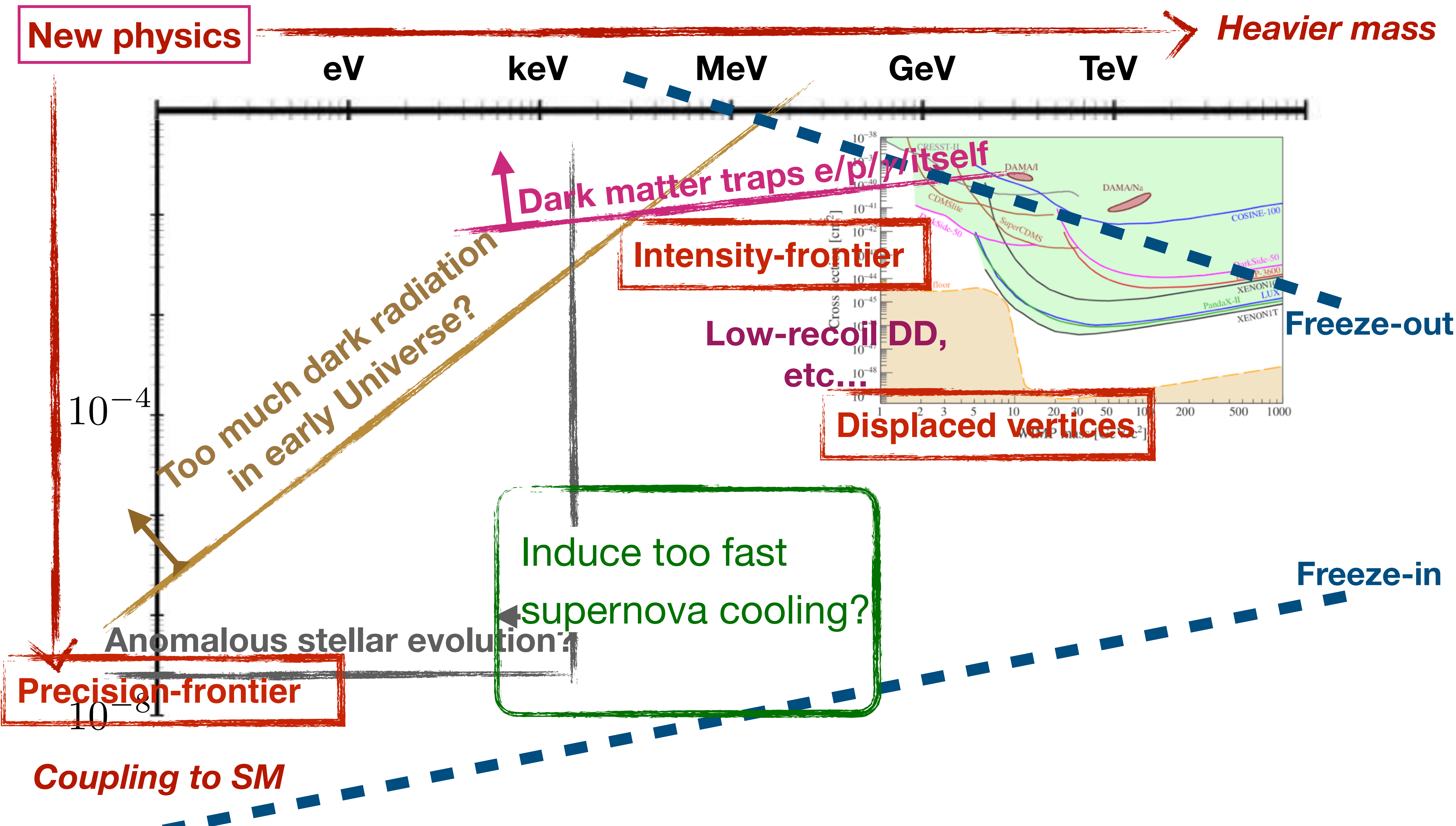


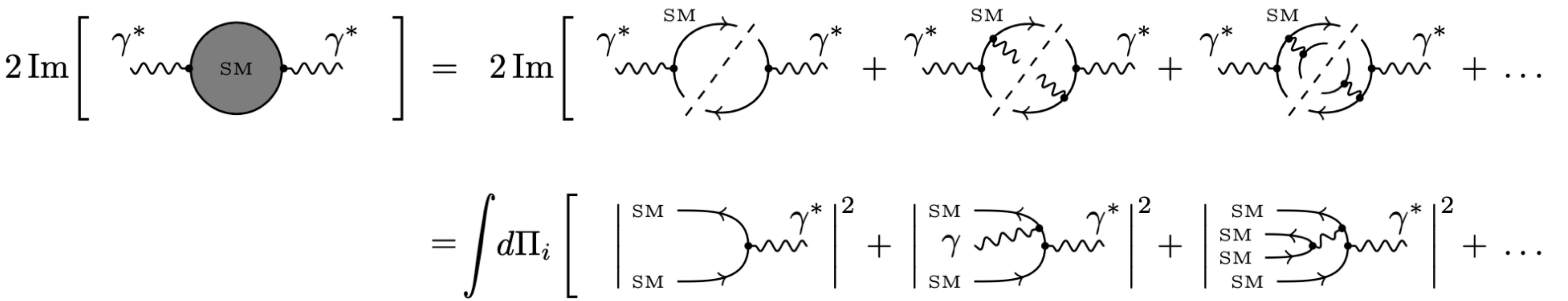
A typical constrain plot for a light dark particle



A typical constrain plot, adding production



First half: **total production rate of (off-shell) photons in medium**



SM particle pair annihilation

Compton scattering

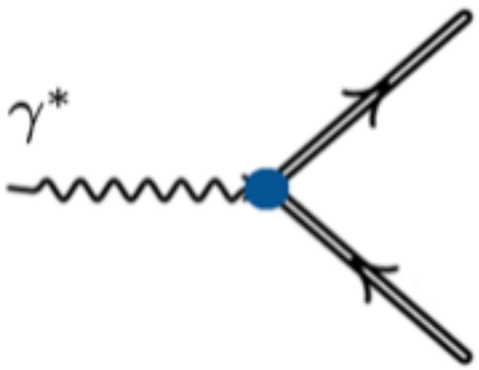
SM particle Bremsstrahlung

Preciser to separate the **resonant (plasmon)** and **non-resonant** contributions

$$-\frac{\mathrm{Im}\Pi_{L,T}}{\pi|s_{\gamma^*} - \Pi_{L,T}|^2} = \delta(s_{\gamma^*} - \Pi_{L,T}) + \text{non-reson.}$$

Cosmos/Stellar: **dark state production**

Second half: **plasmon/photon decays** into a pair of **dark particles (1,2)** via



$$I^{\mu\nu}_{\text{invis.}} = \int d\Pi_{p_1,p_2}(2\pi)^4\delta^4(q-p_1-p_2)M^{\mu}_{\gamma^*\to 12}M^{\nu *}_{\gamma^*\to 12}$$

$$= \frac{1}{8\pi}\sqrt{1-\frac{4m_{12}^2}{s_{\gamma^*}}}\,f(s_{\gamma^*})\left(-g^{\mu\nu}+\frac{q^\mu q^\nu}{s_{\gamma^*}}\right)$$

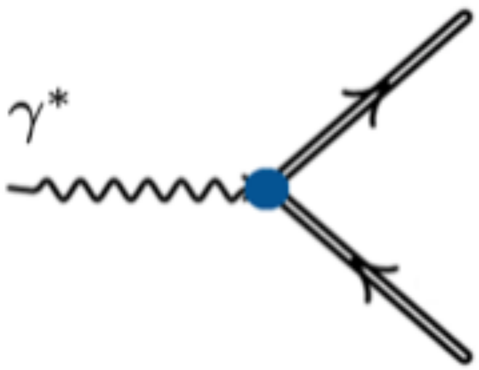
E.g. plasmon decay $\Gamma_{\mathrm{T,L}} = \frac{1}{16\pi} Z_{\mathrm{T,L}} \sqrt{1-\frac{4m_\chi^2}{\omega_{\mathrm{T,L}}^2-|\vec{k}|^2}}\,\frac{f(\omega_{\mathrm{T,L}}^2-|\vec{k}|^2)}{\omega_{\mathrm{T,L}}}$

Stellar cooling bounds are thus derived from dark pair production:

- For T << m, **plasmon decay** usually dominates the dark production;
- For T ~ m, **electron annihilation** (in SN) or **np Bremsstrahlung** (in RG/HB).

Cosmos/Stellar: **dark state production**

Second half: **plasmon/photon decays** into a pair of **dark particles (1,2)** via



$$I^{\mu\nu}_{\text{invis.}} = \int d\Pi_{p_1,p_2}(2\pi)^4\delta^4(q-p_1-p_2)M^{\mu}_{\gamma^*\to 12}M^{\nu *}_{\gamma^*\to 12}$$

$$= \frac{1}{8\pi}\sqrt{1-\frac{4m_{12}^2}{s_{\gamma^*}}}f(s_{\gamma^*})(-g^{\mu\nu}+\frac{q^\mu q^\nu}{s_{\gamma^*}})$$

Before showing the constraints:

– **compare f(s)** for milli-charged scalar(S) / fermion(F) / vector(V)

$$f_S(s) = \frac{(\epsilon e)^2 s(1+4m_\phi^2/s)}{3}$$

$$f_F(s) = \frac{4(\epsilon e)^2 s(1+2m_\chi^2/s)}{3}$$

$$f_V(s) = \frac{(\epsilon e)^2(s-4m_V^2)(s^2-4m_V^2 s+12m_V^4)}{12m_V^4}$$

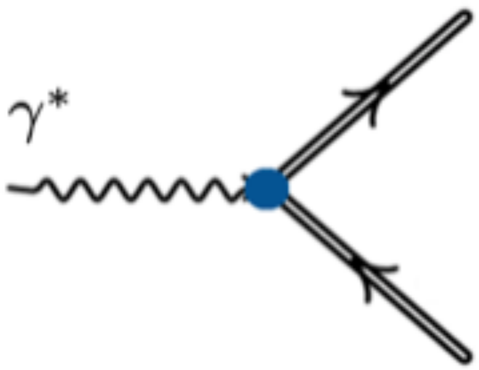
More factor

$$s/m_V^2$$

for dark vector.

Cosmos/Stellar: **dark state production**

Second half: **plasmon/photon decays** into a pair of **dark particles (1,2)** via



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$$= \frac{1}{8\pi}\sqrt{1-\frac{4m_{12}^2}{s_{\gamma^*}}}\,f(s_{\gamma^*})(-g^{\mu\nu}+\frac{q^\mu q^\nu}{s_{\gamma^*}})$$

interaction type	fermion $f(s)$	vector $f(s)$
magnetic dipole	$\frac{2}{3}\mu_\chi^2 s^2(1+\frac{8m_\chi^2}{s})$	$\frac{\mu_V^2 s(s-4m_V^2)(16m_V^2+3s)}{12m_V^2}$
electric dipole	$\frac{2}{3}d_\chi^2 s^2(1-\frac{4m_\chi^2}{s})$	$\frac{d_V^2 s(s-4m_V^2)^2}{6m_V^2}$
electric quadrupole		$\frac{Q_V^2 s^2(s-4m_V^2)}{16}$
magnetic quadrupole		$\frac{\tilde{Q}_V^2 s^2(s+8m_V^2)}{24}$
charge radius	$\frac{4}{3}\frac{e^2(g_1^\chi)^2 s^3}{m_\chi^4}(1+\frac{2m_\chi^2}{s})$	$\frac{e^2(g_1^A)^2 s^2(s-4m_V^2)(12m_V^4-4m_V^2 s+s^2)}{48m_V^8}$
toroidal moment		$\frac{e^2(g_4^A)^2 s^3(s-4m_V^2)}{3m_V^6}$
anapole moment	$\frac{4}{3}\frac{e^2(g_5^\chi)^2 s^3}{m_\chi^4}(1-\frac{4m_\chi^2}{s})$	$\frac{e^2(g_5^A)^2 s^2(s-4m_V^2)^2}{3m_V^6}$

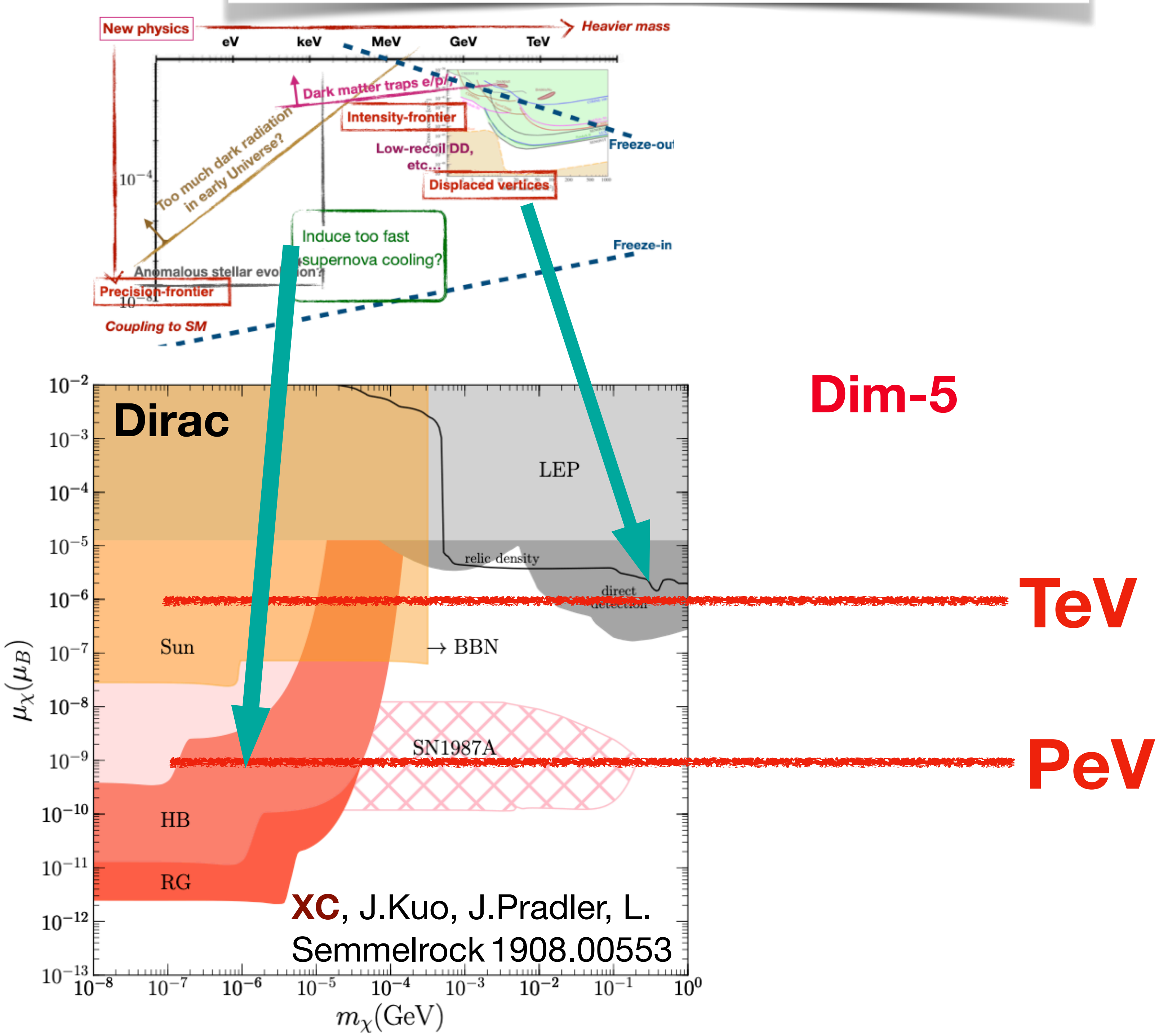
More factor

$$s/m_V^2$$

for dark vector.

Summarize the **constraints** derived

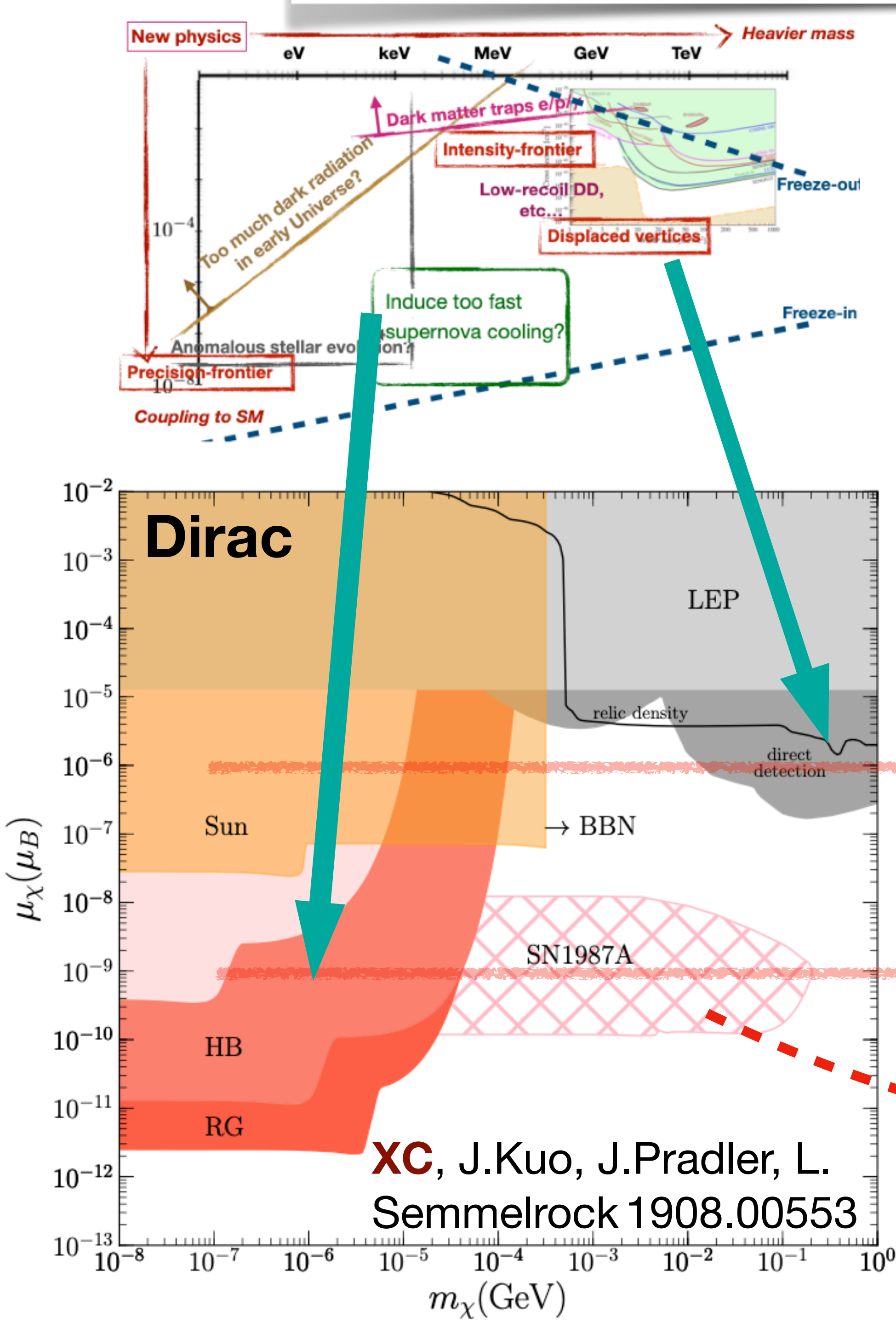
interaction type	fermion $f(s)$
magnetic dipole	$\frac{2}{3}\mu_\chi^2 s^2(1+\frac{8m_\chi^2}{s})$



Thermal freeze-out via **EM factors** is unlikely, while small regions left for **p/d-wave annihilation**.

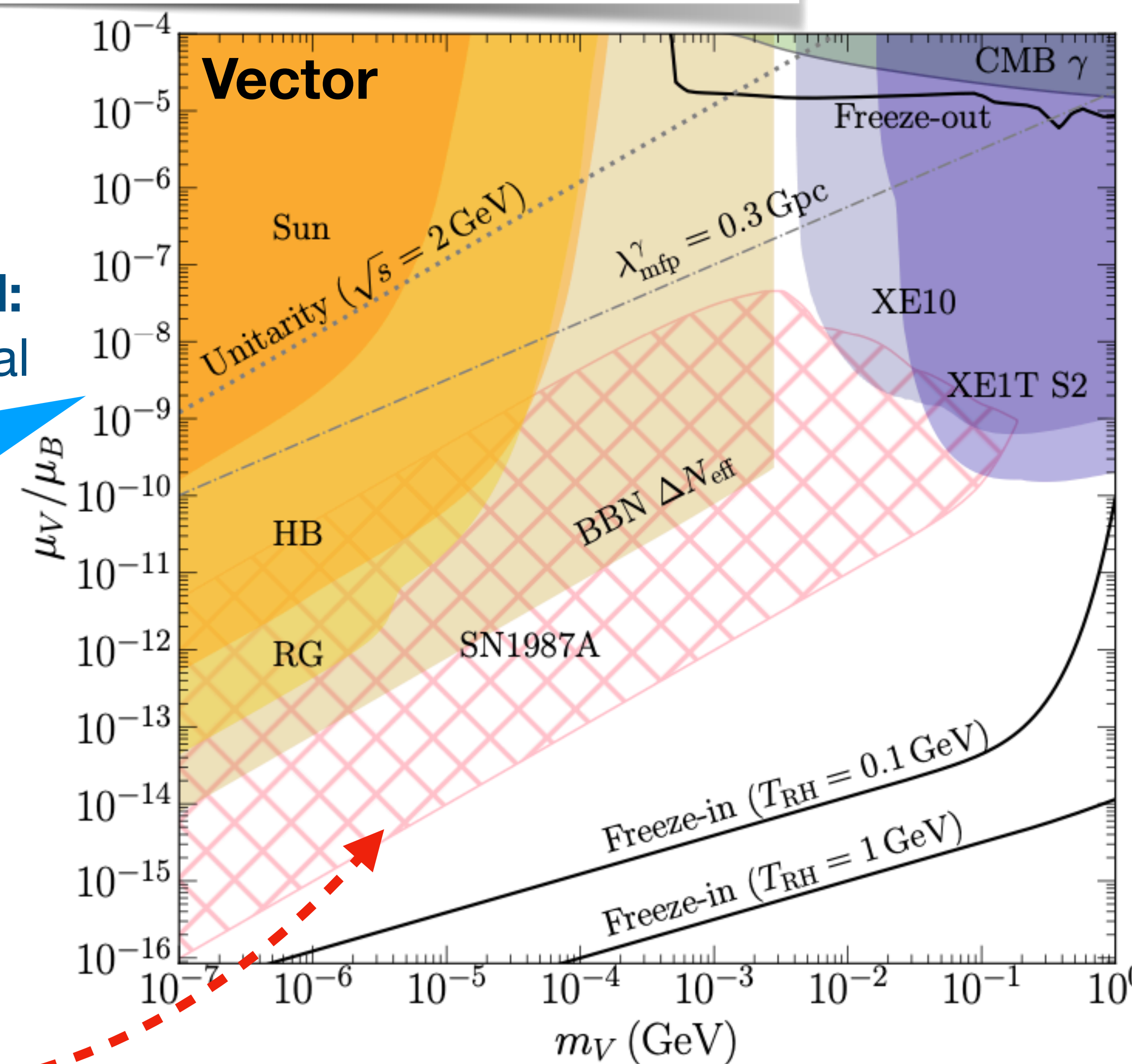
Lesson-1. vector is different

interaction type	fermion $f(s)$	vector $f(s)$
magnetic dipole	$\frac{2}{3}\mu_\chi^2 s^2 (1+\frac{8m_\chi^2}{s})$	$\frac{\mu_V^2 s(s-4m_V^2)(16m_V^2+3s)}{12m_V^2}$



XC, J.Kuo, J.Pradler, L. Semmelrock 1908.00553

1/m-enhanced: from longitudinal mode



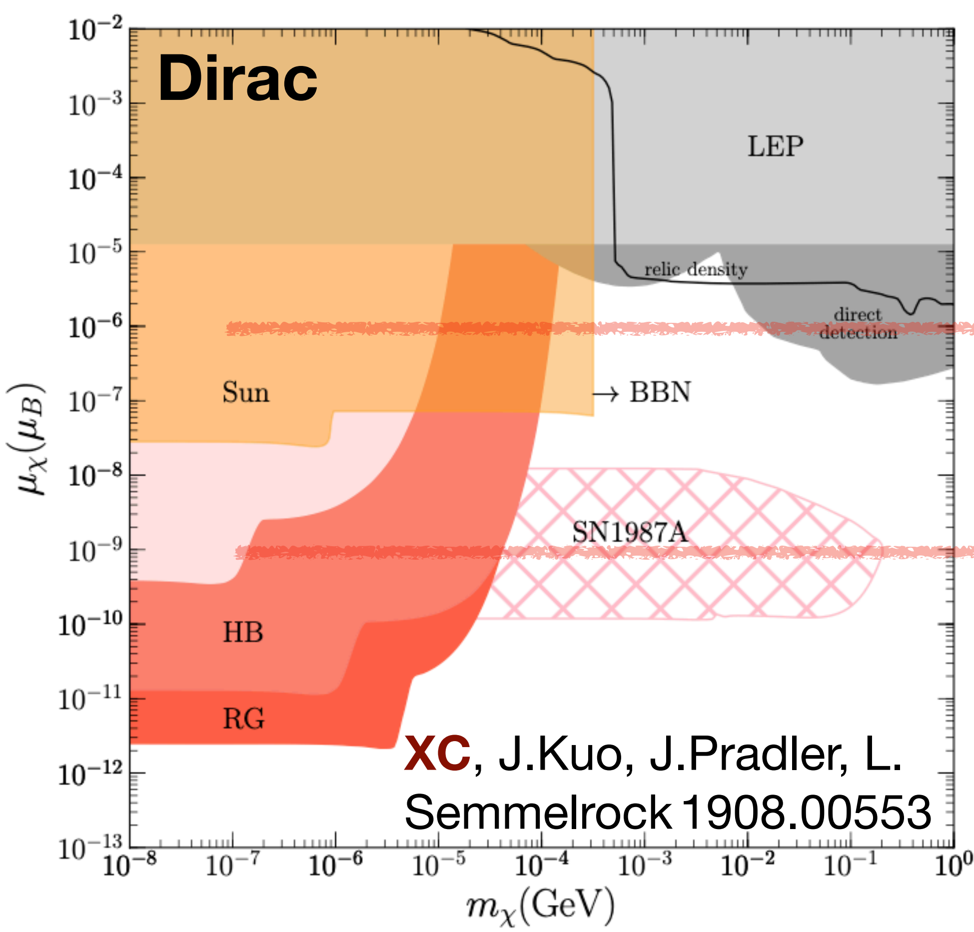
XC, J. Hisano, A.Ibarra, J.Kuo, J.Pradler, 2303.13643

Lesson-2. cosmos/stellar: CP affects mildly

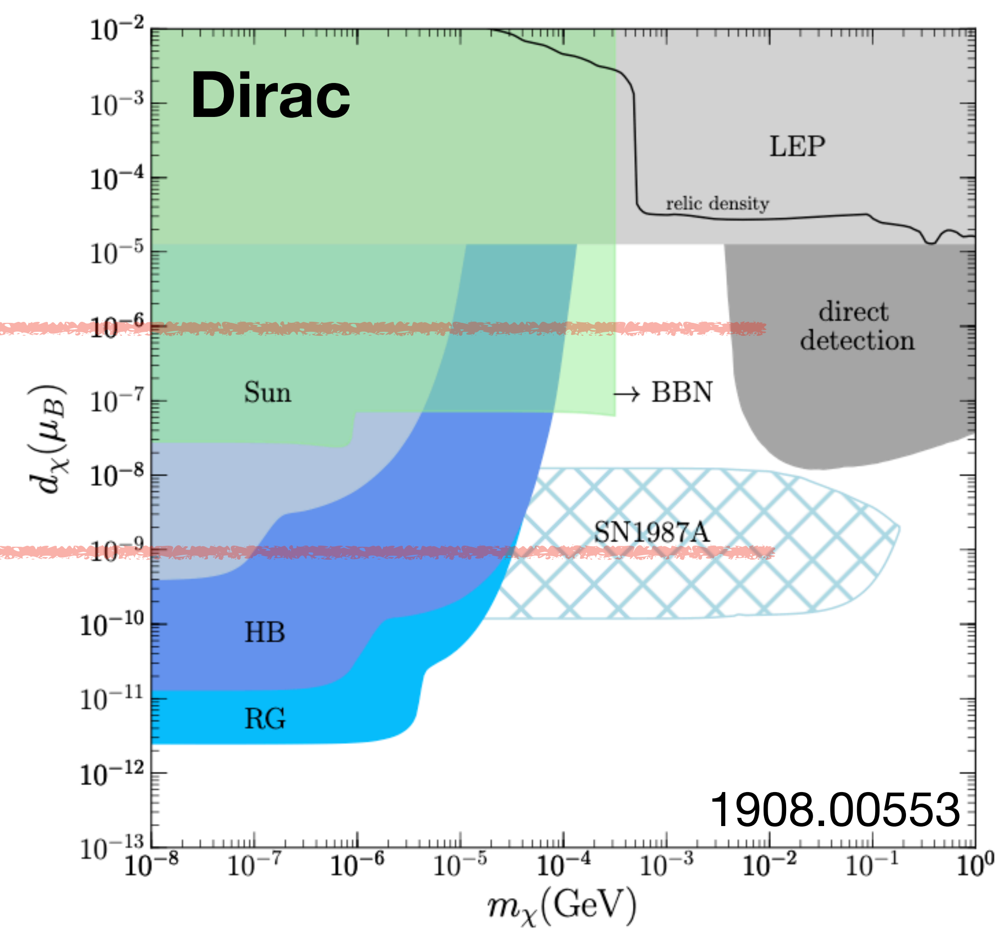
interaction type	coupling	C	P	CP
magn. dipole	μ	$+1$	$+1$	$+1$
elec. dipole	d	$+1$	-1	-1

up to velocity suppressions
in non-relativistic regime

MDM



EDM



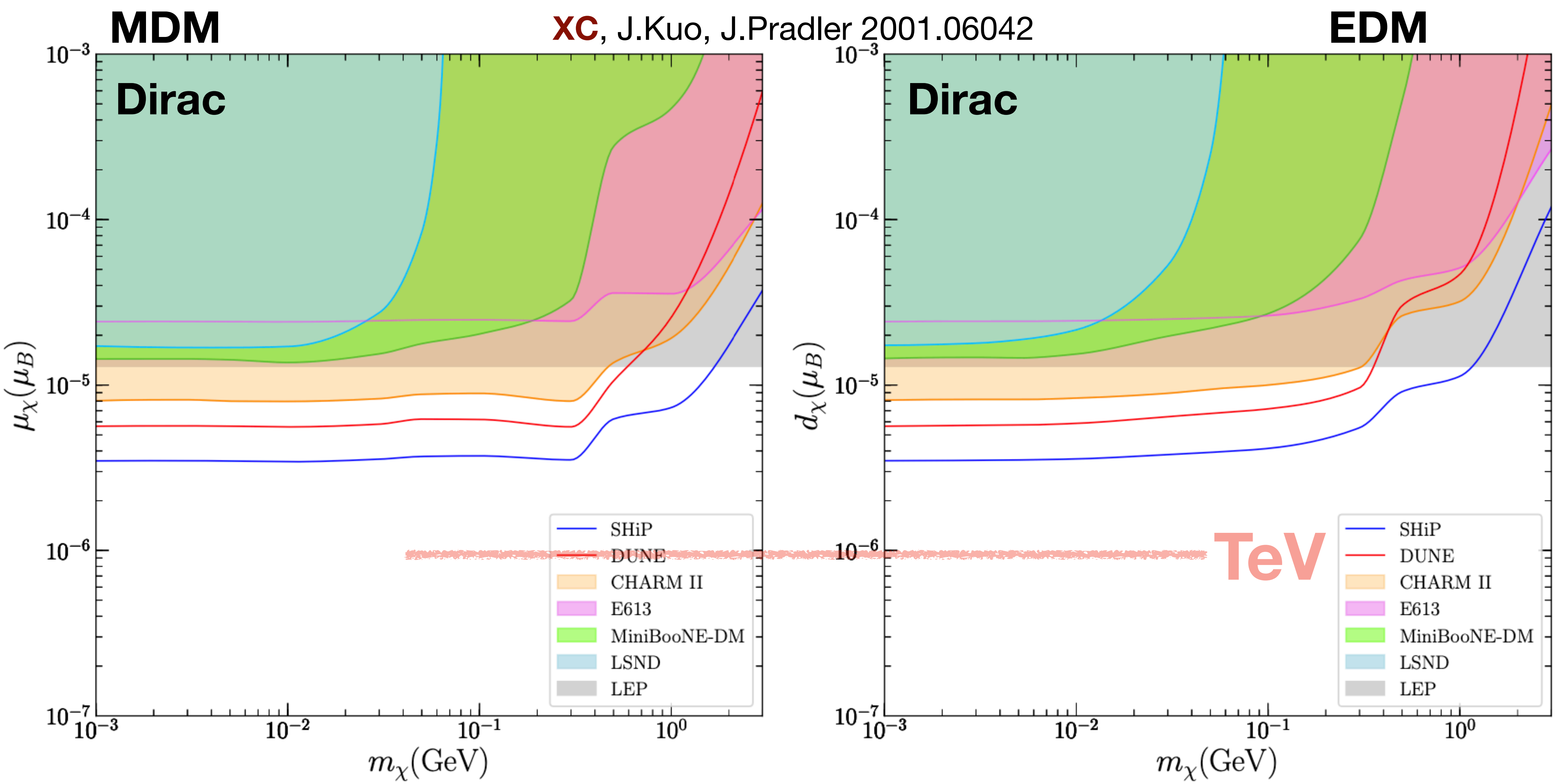
Lesson-3. intensity-frontier: same but weaker bounds

interaction type	coupling	C	P	CP
magn. dipole	μ	$+1$	$+1$	$+1$
elec. dipole	d	$+1$	-1	-1

Difficult to constrain

effective operators

at **low-energy** experiments.



III. Validity of the constraints

Caveats and theoretical validity

On the observational side:

Caveats do exist in extensions, such as:

- dark state **trapping** by additional dark states *[e.g. Y. Zhang 1404.7172]*;
- **Production suppression** from large thermal mass of dark states *[e.g. W. DeRocco, P. W. Graham, S. Rajendran 2006.15112].*
- if **SN1987A** was not neutrino-driven explosion *[e.g. N. Bar, K. Blum & Guido D'Amico 1907.05020, and earlier 1601.03422].*

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On the theoretical side:

EM form factors are defined at extremely IR-end:

- *For all spins, the C.o.M energy has to be below UV-theory scale ∧.*

  we do not exclude regions where dimensionless coeff. × (C.o.M)^n ≥ 1

- *Spin-1 case needs to be treated with additional caution:*

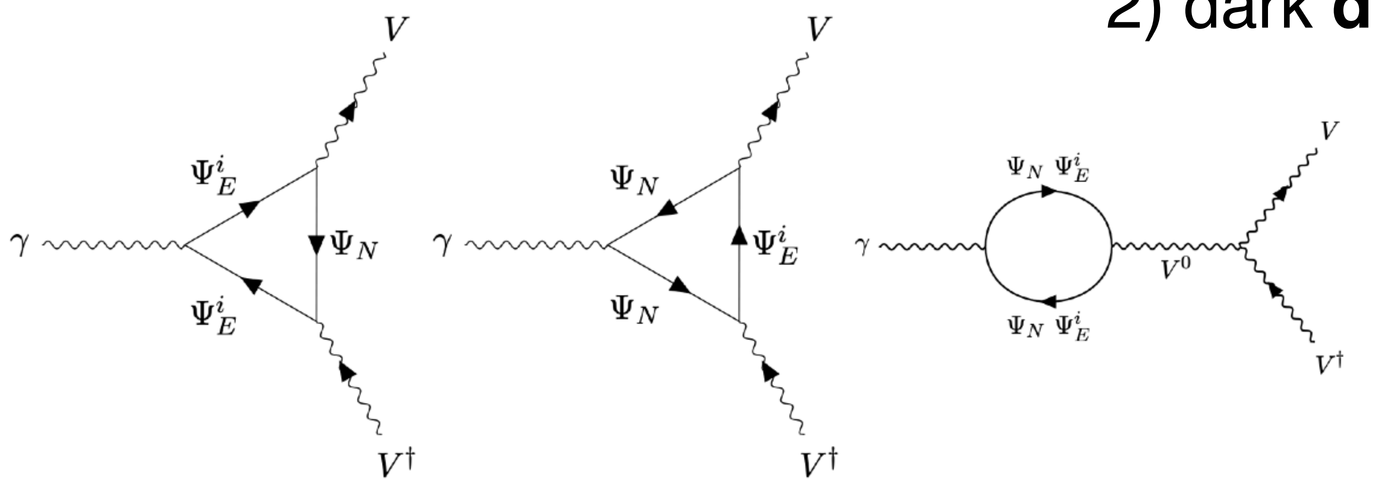
  we indicate unitarity bound as: $\sigma_{V+V\to V+V}(s) \lesssim \frac{4\pi}{s}\sum_l (2l+1)$

Similar to WW-scattering, may not be enough, and **should turn to UV-completion**.

J. Hisano, A.Ibarra, and R. Nagai, 2007.03216

Dark SU(2) gauge bosons with: 1) dark **doublet leptons** that couple to photon;

2) dark **doublet Higgs** that generates masses.



In the limit of heavy dark fermions/scalars

one can write down **all the EM form factors** **in terms of UV parameters**

Realization of **UV-completion**

XC, J. Hisano, A.Ibarra, J.Kuo, J.Pradler, 2303.13643

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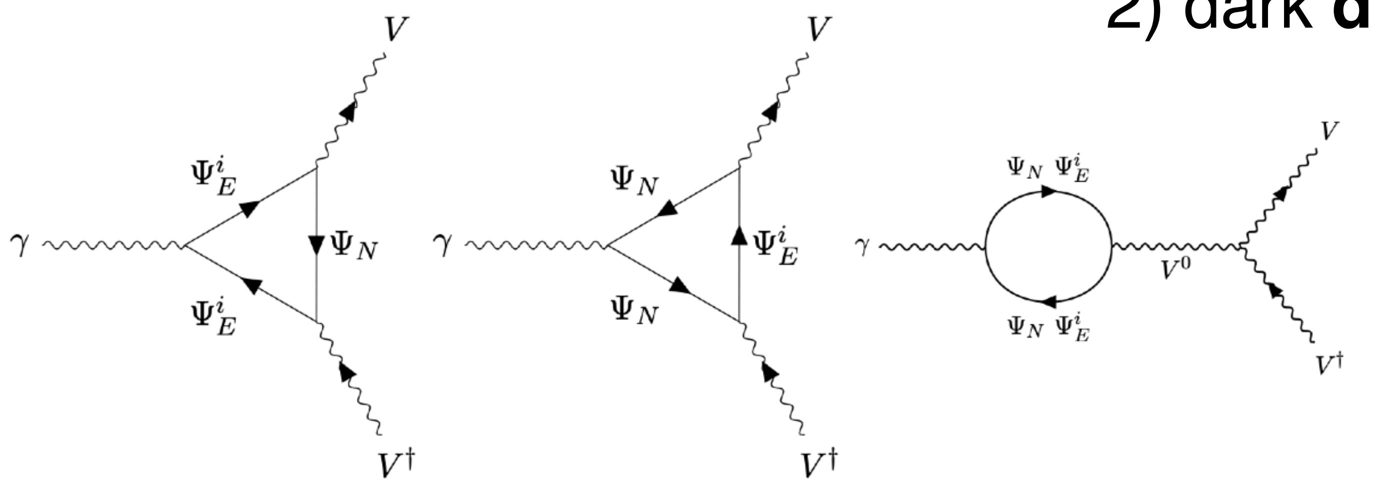

A) consider terms with CP (**+ -**):

interaction type	coupling	C	P	CP
elec. dipole	d	$+1$	-1	-1
magn. quadrupole	$\tilde{Q}$	$+1$	-1	-1

where each amplitude diverges even for transverse V-boson production.

In this UV, there is, at first-order,

$$d_V = -\tilde{Q}_V m_V/2$$

the divergences in transverse modes cancel with each other.

- Maybe unphysical to **separate the two operators** for vector states;
- Nevertheless, bounds are mostly sensitive to **the scaling of f(s)**, and thus easy to generalize.

Realization of **UV-completion**

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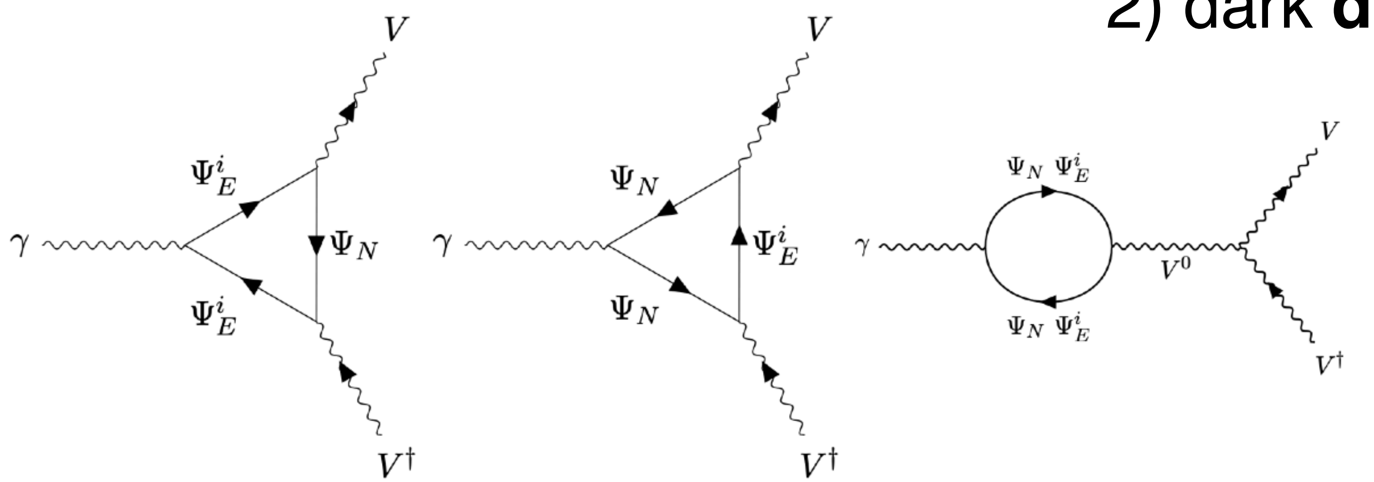


B) dim-6 terms:

interaction type	coupling	C	P	CP
charge radius	g_1^A/m^2	+1	+1	+1
toroidal moment	g_4^A/m^2	−1	+1	−1
anapole moment	g_5^A/m^2	−1	−1	+1

This UV model gives at first-order:

$$g_1^A \propto g_5^A \propto m_V^2/m_F^2 \quad \text{and} \quad g_4^A = 0$$

so the full couplings are **independent of m_V.**

For such terms, a UV-completion gives the correct scaling of production rates,

$$\dot{Q}_{\lambda\lambda'} \propto \begin{cases} g_D^4/m_V^4 & \lambda\lambda' = \mathrm{LL}, \\ g_D^4/m_V^2 & \lambda\lambda' = \mathrm{LT}, \\ g_D^4 & \lambda\lambda' = \mathrm{TT}. \end{cases}$$

seen from $\epsilon_{\rm L} = \left(\frac{p}{m_V}, 0, 0, \frac{E}{m_V}\right)$, $\epsilon_{\rm T}^{\pm} = \left(0, \frac{1}{\sqrt{2}}, \pm\frac{i}{\sqrt{2}}, 0\right)$

which can stay valid until the SSB scale, which **heavy dark higgs** enters.

V. Conclusions

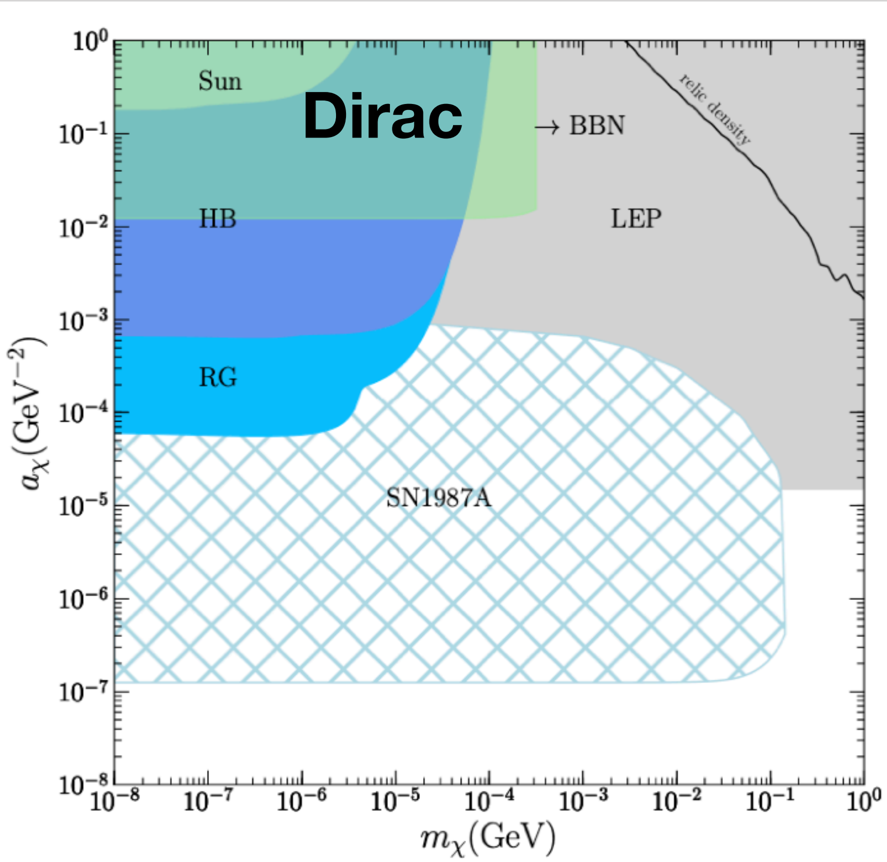
Conclusions

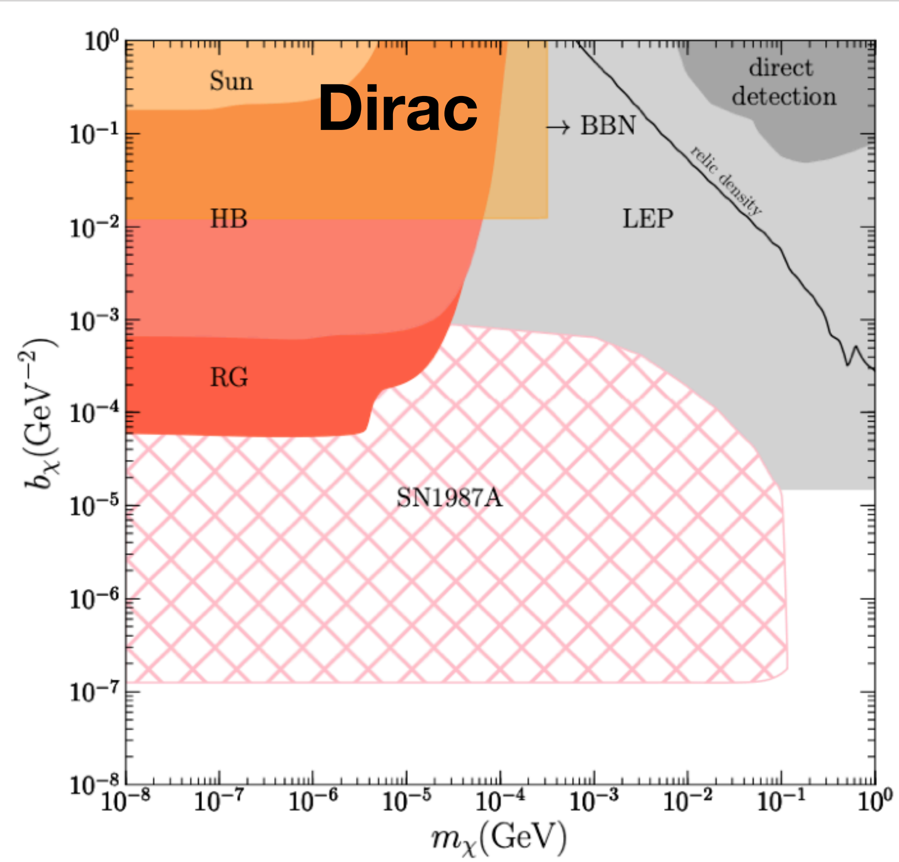
- So far no heavy new particles, try **something (with) light**?
- **Multi-messenger** constraints/observations will be important to identify dark states;
- **Intensity/neutrino** experiments play an important role.
- **Astrophysics** can be extremely useful in probing light dark states.
- **Parameters/values of EM factors** not always justified by UV models.

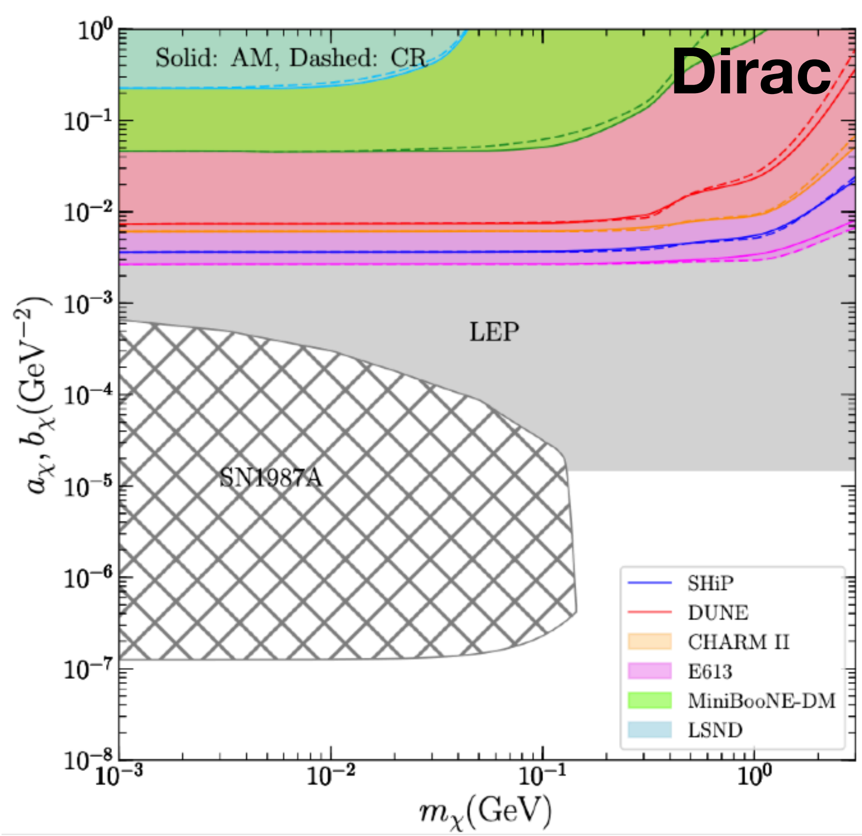
Backup

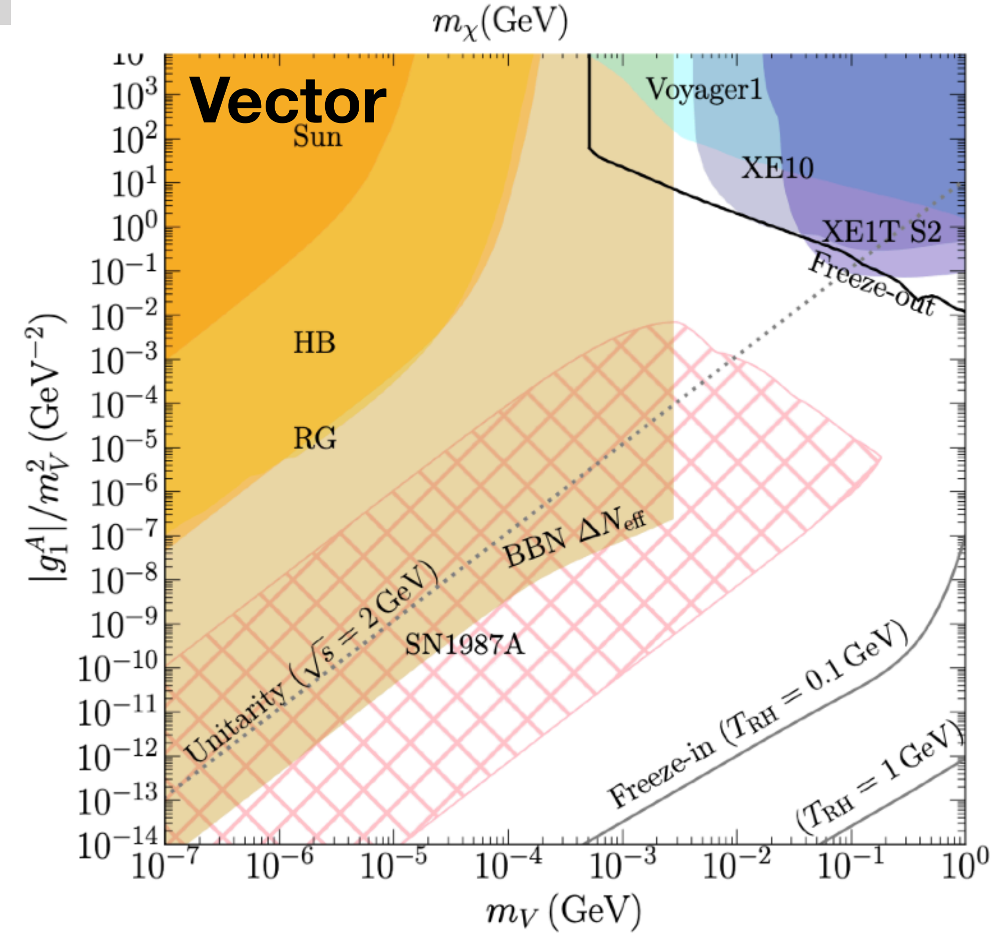
Anapole Moment and **Charge Radius**

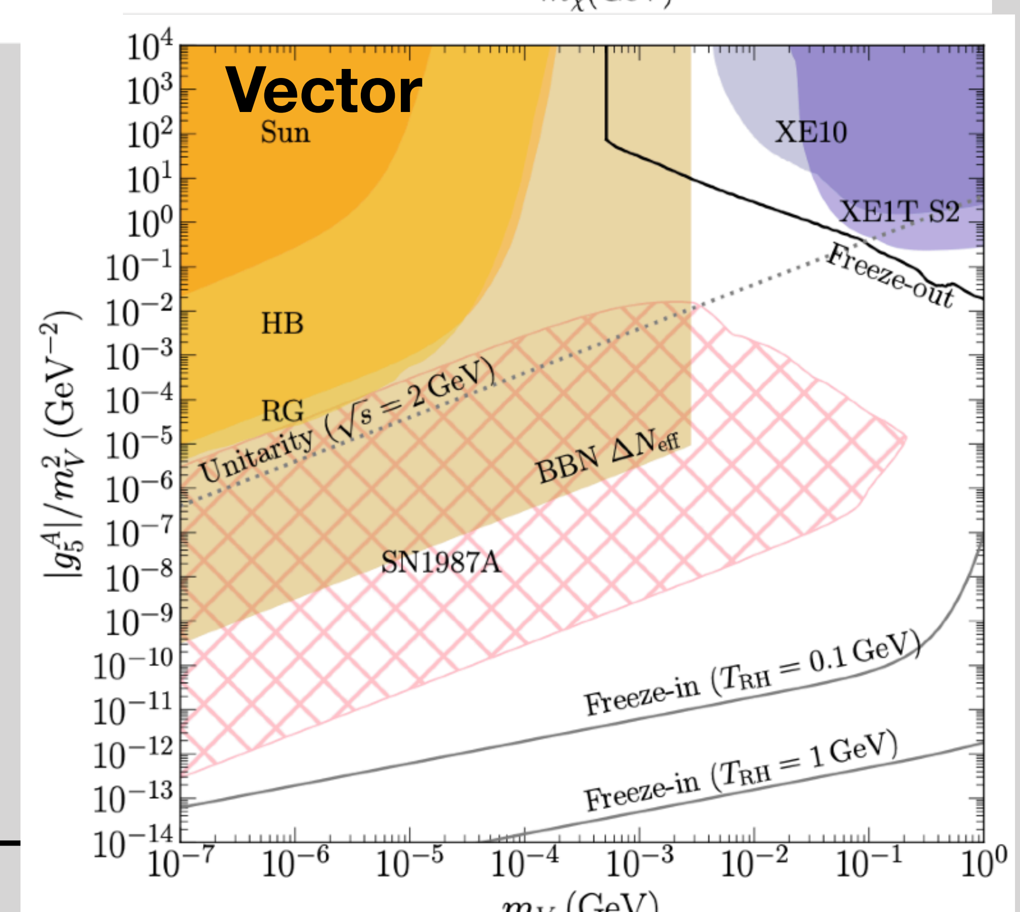
$(\boldsymbol{E}\cdot\boldsymbol{\sigma}_\chi)$ → electric dipole (EDM)
$(\boldsymbol{B}\cdot\boldsymbol{\sigma}_\chi)$ → magnetic dipole (MDM)
$(\boldsymbol{J}\cdot\boldsymbol{\sigma}_\chi)$ → anapole moment (AM)
$(\boldsymbol{\nabla}\cdot\boldsymbol{E})$ → charge radius (CR)











Milli-charged fermions, mostly **in the literature**