MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

The electromagnetic properties of a light dark sector

Xiaoyong Chu (HEPHY, Vienna)

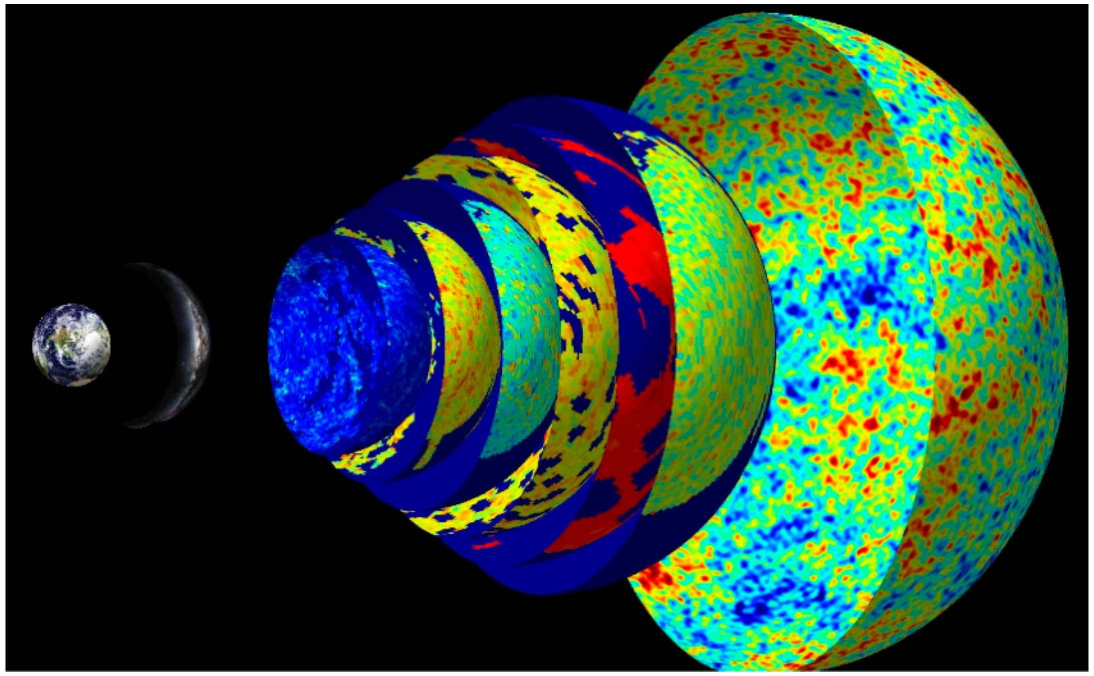
In collaboration with Junji Hisano, Alejandro Ibarra, Jui-Lin Kuo, Josef Pradler and Lukas Semmelrock

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

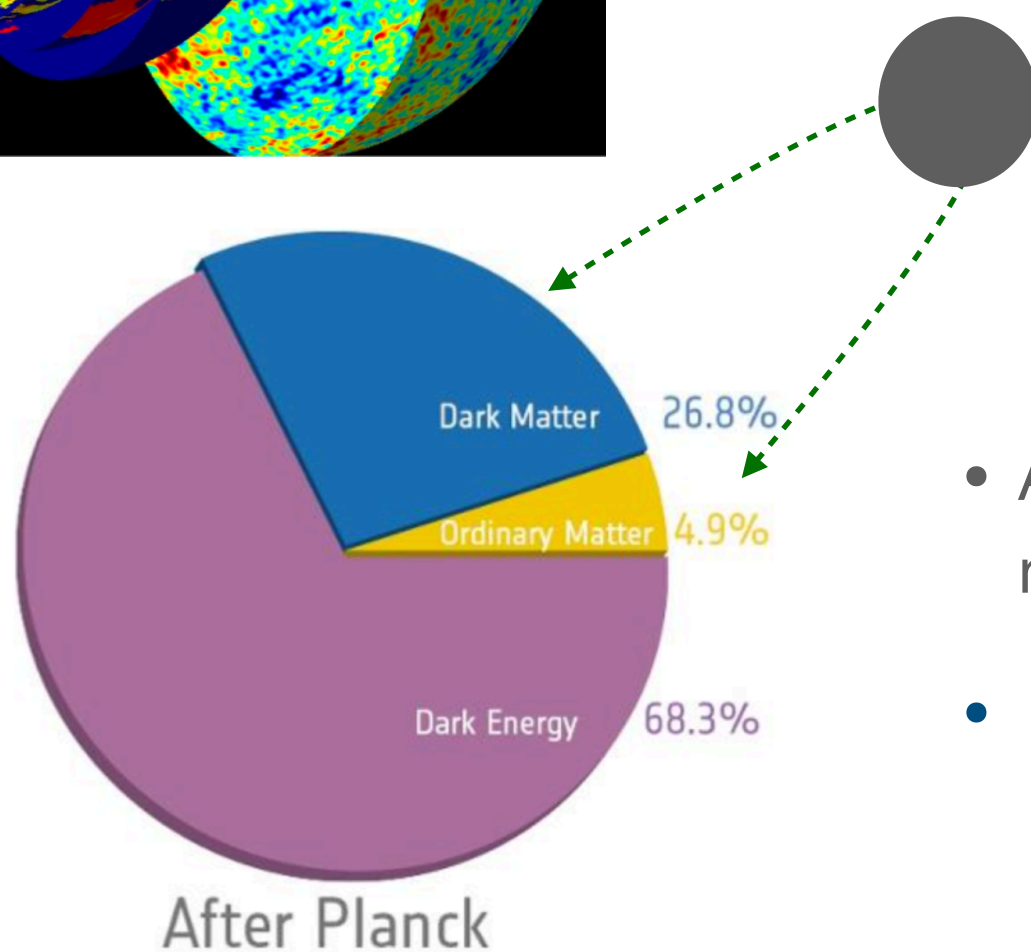
HEPHY Institut für Hochenergiephysik

I. Brief motivations

Standard cosmology requires a dark sector



If both sectors are connected via a **portal** that involves **integer-charged particles:**



- A **new integer-charged particle** is necessarily heavy;
- But the **dark particle** can be light.

From the aspect of **particle physics:**

eV **keV** **MeV** **GeV** **TeV** **PeV**

sterile neutrino (baseline exper.)

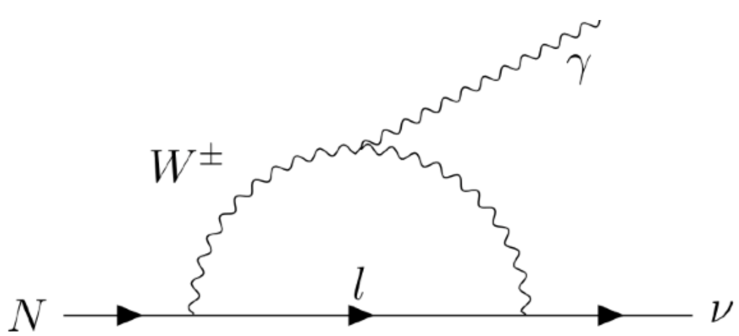
Massive portal (intensity frontier)

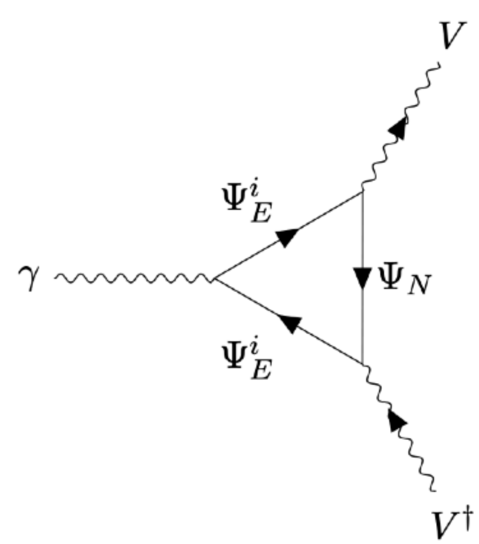
Heavy charged states in LHC

Typically, above EW-scale

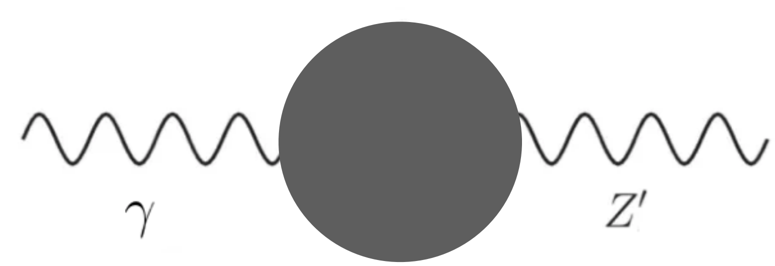
[e.g. D.Egana-Ugrinovic, M.Low&J.T.Ruderman 1801.05432, CMS 2012.08600 …]

Light particle can easily couple to a photon:





SM/BSM charged particles



general kinetic mixing

Moreover, **no new light d.o.f.** from cosmology yet

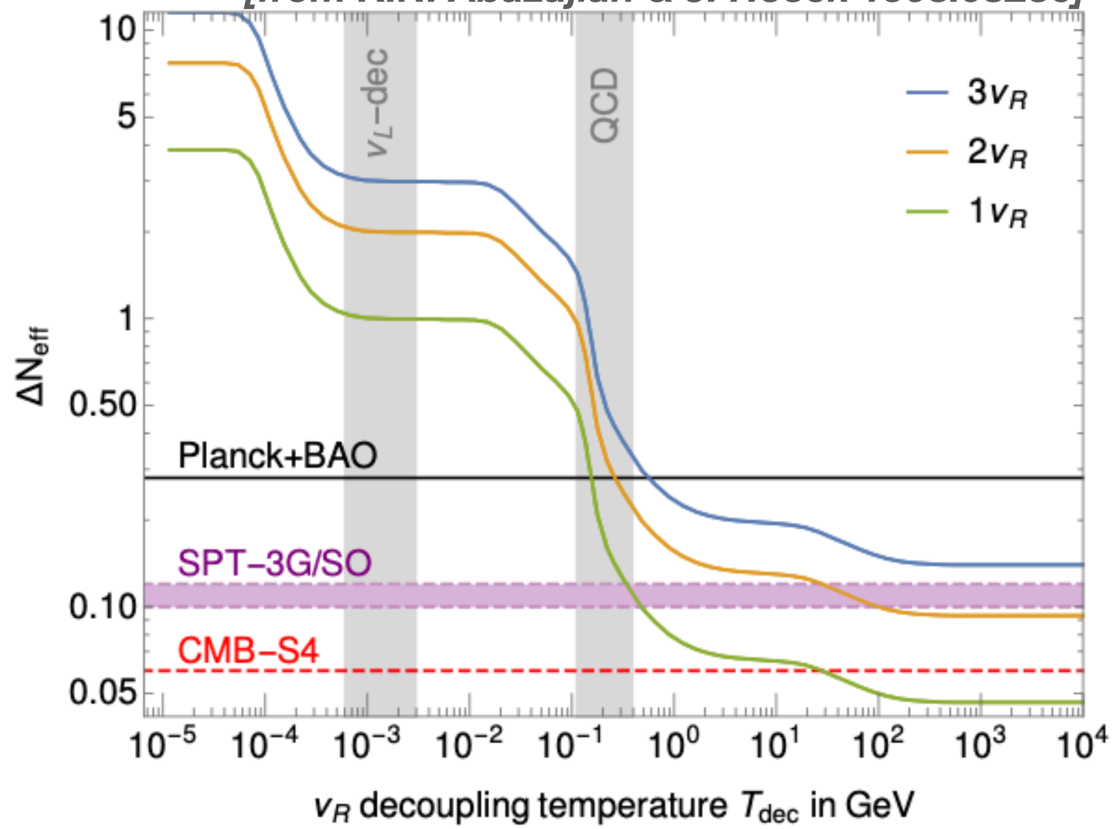
Planck 2018 *[1807.06209]*

$$N_{\rm eff} = 2.96^{+0.34}_{-0.33},$$ 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. Heeck 1908.03286]

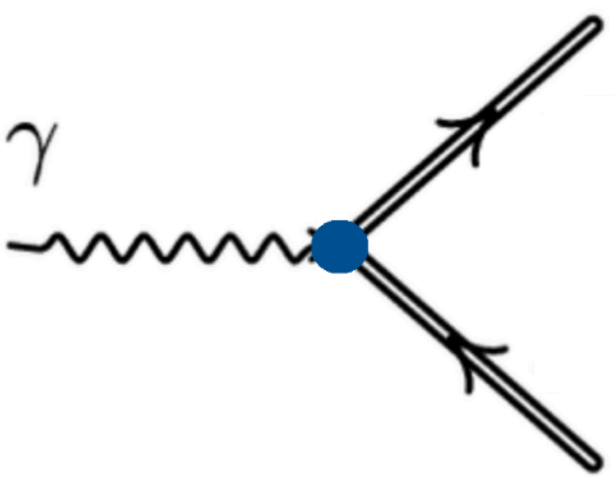


A simple and rich example of a light mediator:

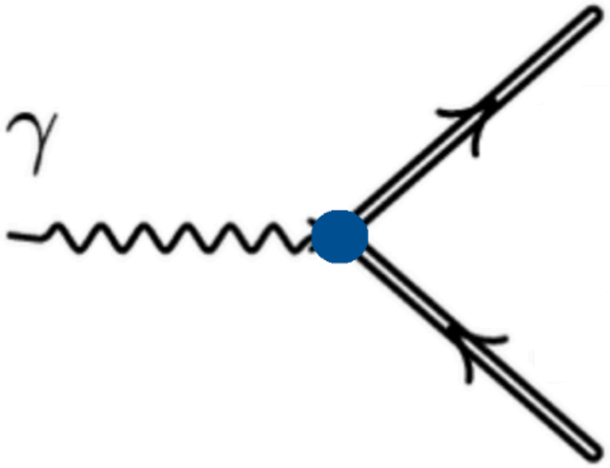
SM photon portal

via dark loop/mixing/confinement

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



II. Electric-magnetic (EM) form factors, effectively



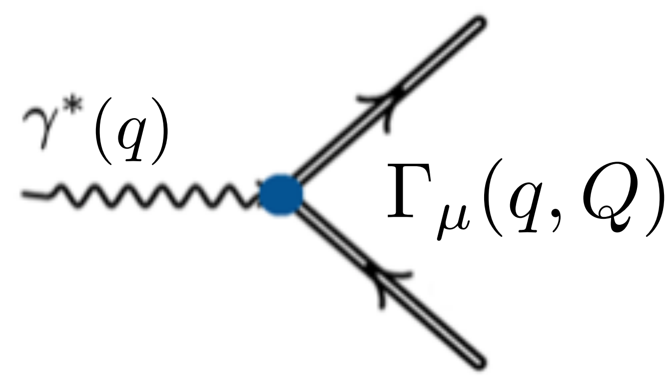
What can a photon portal be?

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

the most general Lagrangian

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

taking non-relativistic limit



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

Non-rel. definition → momentum-space

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

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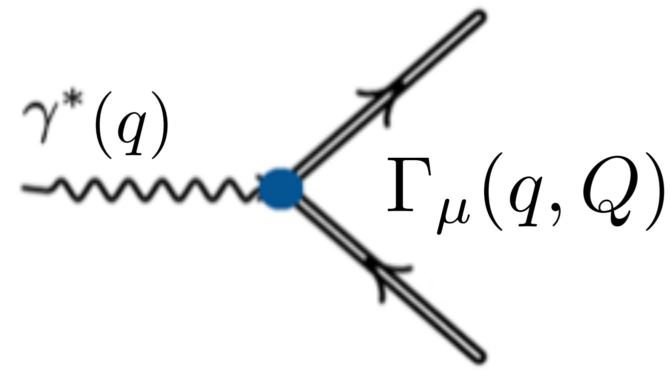

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Non-rel. definition → momentum-space

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

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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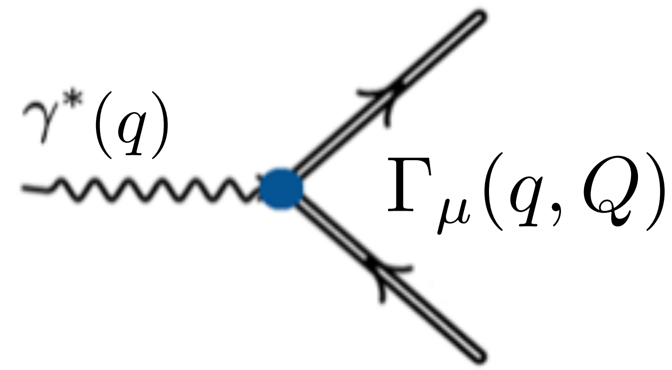

2. At higher-order (or a EM-neutral particle): dipoles, quadrupoles, …

Non-rel. definition → momentum-space

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

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

$$\int d^3x x_i x_j \rho_{\rm EM}(\vec{x}) \propto \frac{\partial^2 J_0}{\partial q^i \partial q^j}|_{\vec{q}=0}$$
- (trace) charge radius
- (traceless) electric quadrupole

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

$$(\vec{r}\cdot\vec{J})\vec{r} - 2r^2\vec{J}$$ - anapole moment, … …

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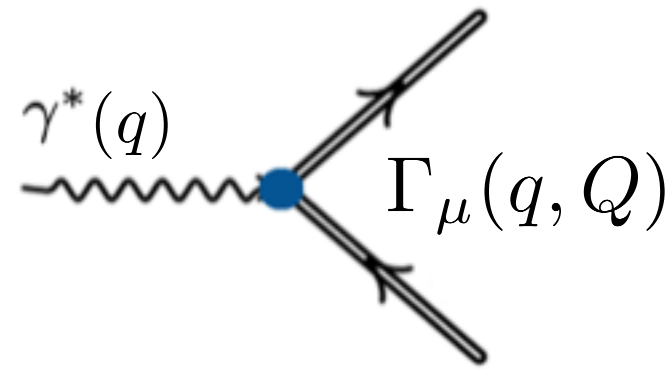

2. At higher-order (or a EM-neutral particle): dipoles, quadrupoles, …

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	$+1$

1. **Scalars** have no-spin, thus, at higher-order, only can have

- (trace) charge radius

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

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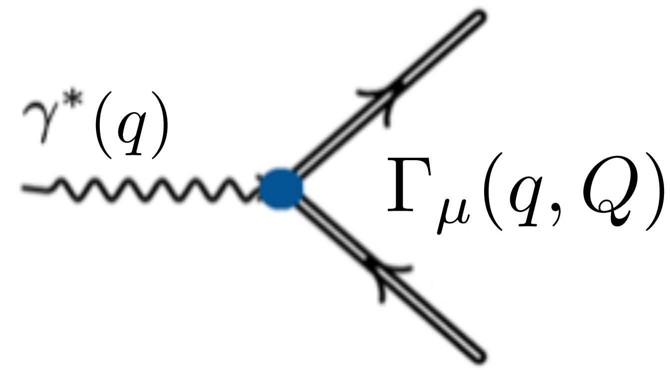

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2. independent indices for **Dirac fermion**

- magn. dipole → $\sigma^{\mu\nu}q_\nu$ $\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$
- elec. dipole → $\sigma^{\mu\nu}q_\nu\gamma^5$ $\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$
- charge radius → $[q^2\gamma^\mu - q^\mu \not{q}]$ $\bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}$
- anapole moment → $[q^2\gamma^\mu - q^\mu \not{q}]\,\gamma^5$ $\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu}$

[e.g. Pospelov, Veldhuis 2000, Sigurdson, Doran, Kurylov, Caldwell, Kamionkowski 2004, M. Nowakowski, E. A. Paschos J. M. Rodriguez 2004, Ho, Scherrer 2012, Kadota, Silk 2014, Mohanty, Rao 2015, …]

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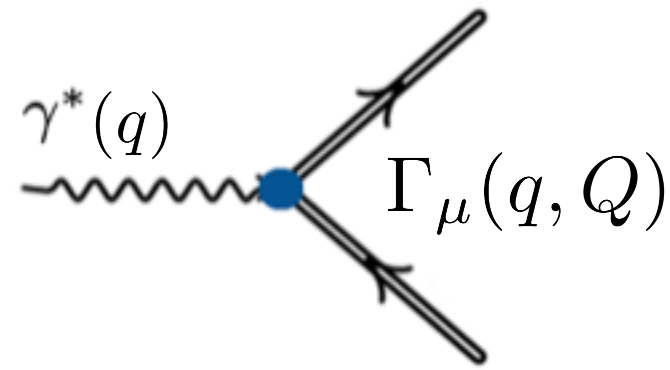

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3. independent indices for **vector boson**

Lorentz gauge

$$-2im_V\mu_V\left[k^\alpha g^{\mu\beta} - k^\beta g^{\mu\alpha} + \frac{1}{4m_V^2}\left(k^2 g^{\alpha\beta}p^\mu - 2k^\alpha k^\beta p^\mu\right)\right]$$

$$-\frac{iQ_V}{4}\left(k^2 g^{\alpha\beta}p^\mu - 2k^\alpha k^\beta p^\mu\right)$$

$$-\frac{id_V}{2m_V}p^\mu\,[kp]^{\alpha\beta} - \frac{i\tilde{Q}_V}{4}\left(p^\mu\,[kp]^{\alpha\beta} + 4m_V^2\epsilon^{\mu\alpha\beta\rho}k_\rho\right)$$

$$-\frac{ieg_1^A}{2m_V^2}k^2p^\mu g^{\alpha\beta} - \frac{eg_4^A}{m_V^2}k^2\left(k^\alpha g^{\mu\beta} + k^\beta g^{\mu\alpha}\right) - \frac{eg_5^A}{m_V^2}k^2\epsilon^{\mu\alpha\beta\rho}p_\rho$$

[e.g. K.Hagiwara, R.Peccei, D.Zeppenfeld&K.Hikasa 1987, J.Nieves & P. B.Pal 1996]

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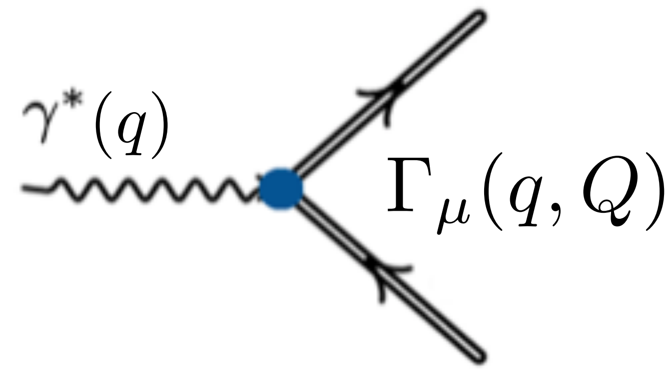

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For Self-Conjugate particles,

only C-violating factors survive:

$$\mathrm{C}: \quad \Gamma_\mu(q, Q) \to -\Gamma_\mu(-q, -Q)$$

$$\mathrm{SC}: \quad \Gamma_\mu(q, Q) \to \Gamma_\mu(-q, -Q)$$

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

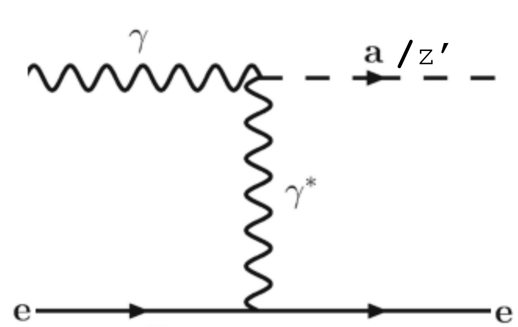
Relevant for EDGES anomaly, and well constrained recently, see e.g. E. Gabrielli, L. Marzola, M. Raidal & H. Veermäe 1507.00571, A. Berlin, D. Hooper, G. Krnjaic, S. D. McDermott 1803.02804, E. D. Kovetz, V. Poulin, V. Gluscevic, K. K. Boddy, R. Barkana, M. Kamionkowski 1807.11482, T. Emken, R. Essig, 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, …

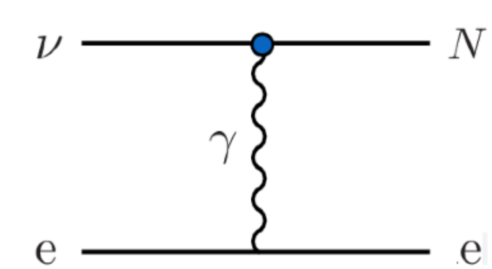
2. At higher-order (or a EM-neutral particle): dipoles, quadrupoles, …

For technical details on multipole expansions, see e.g. V. M. Dubovik and A. A. Cheshkov. 1974, K. Gaemers & G. Gounaris, 1979, J. F. Nieves & P. B. Pal 1996, …

3. Inelastic cases *(and two-photon cases):*

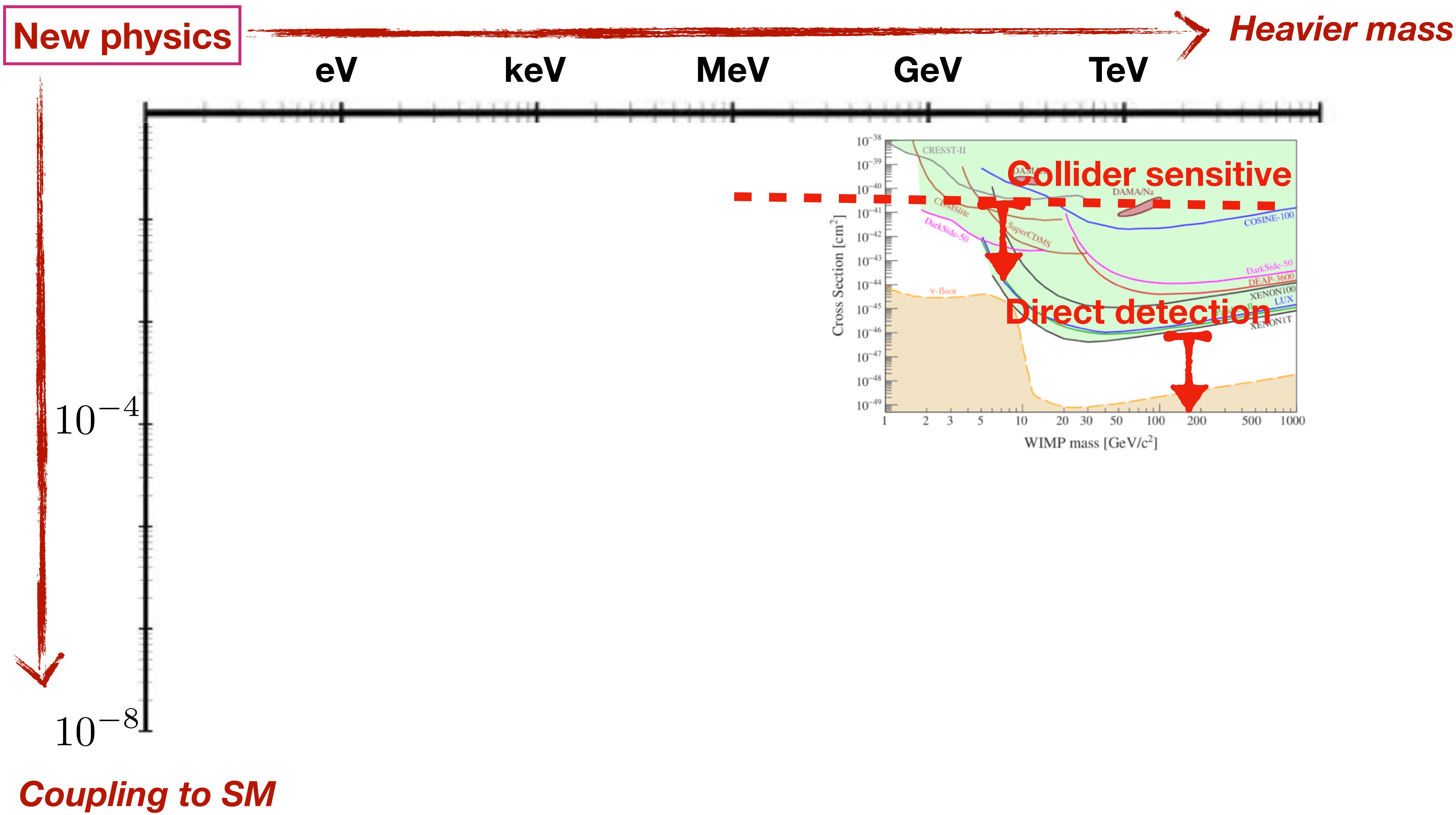
typically easier to produce and detect;
but will not discussed.





III. Sketch of constraints

A typical exclusion plot for a light dark particle



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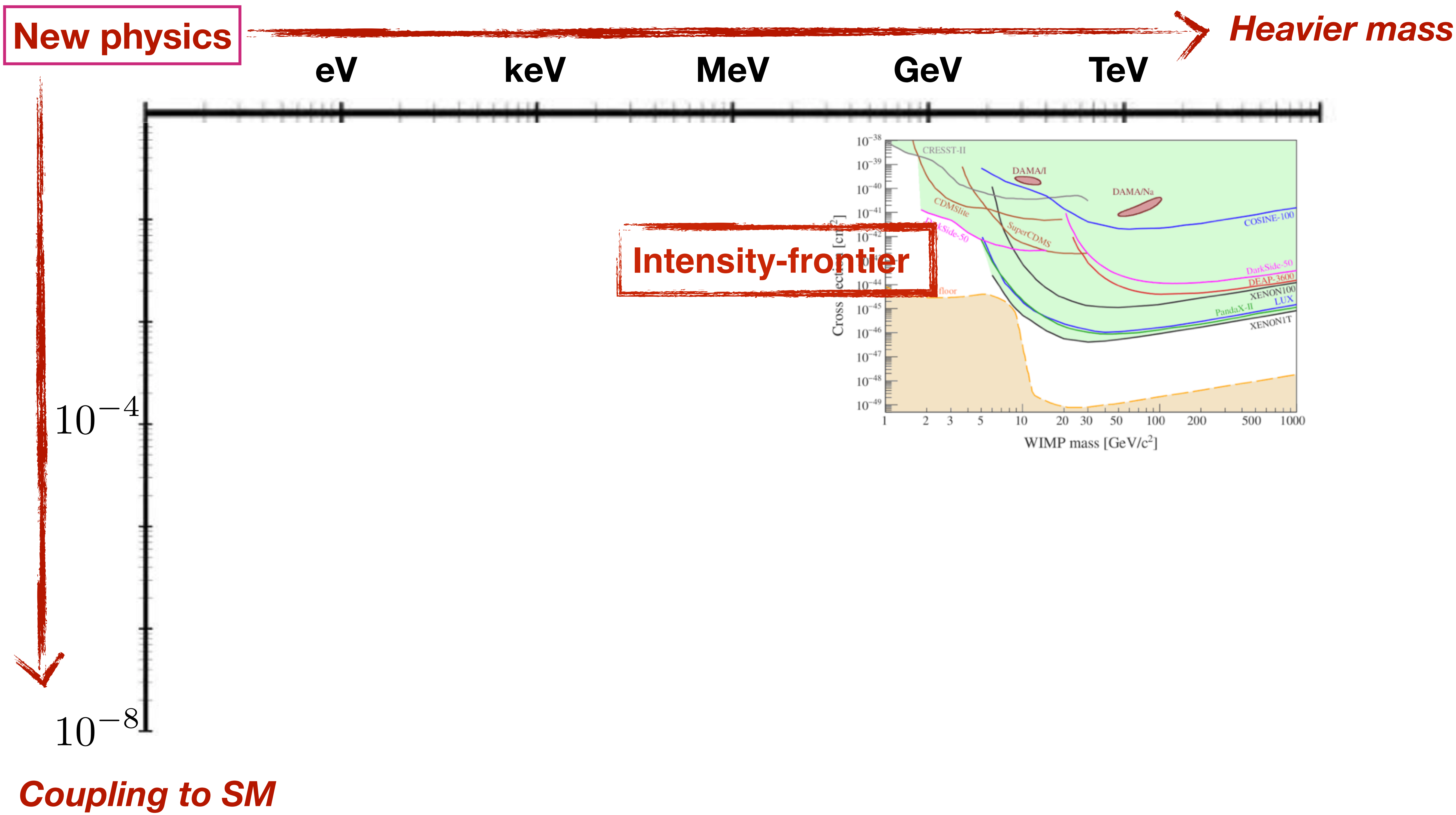
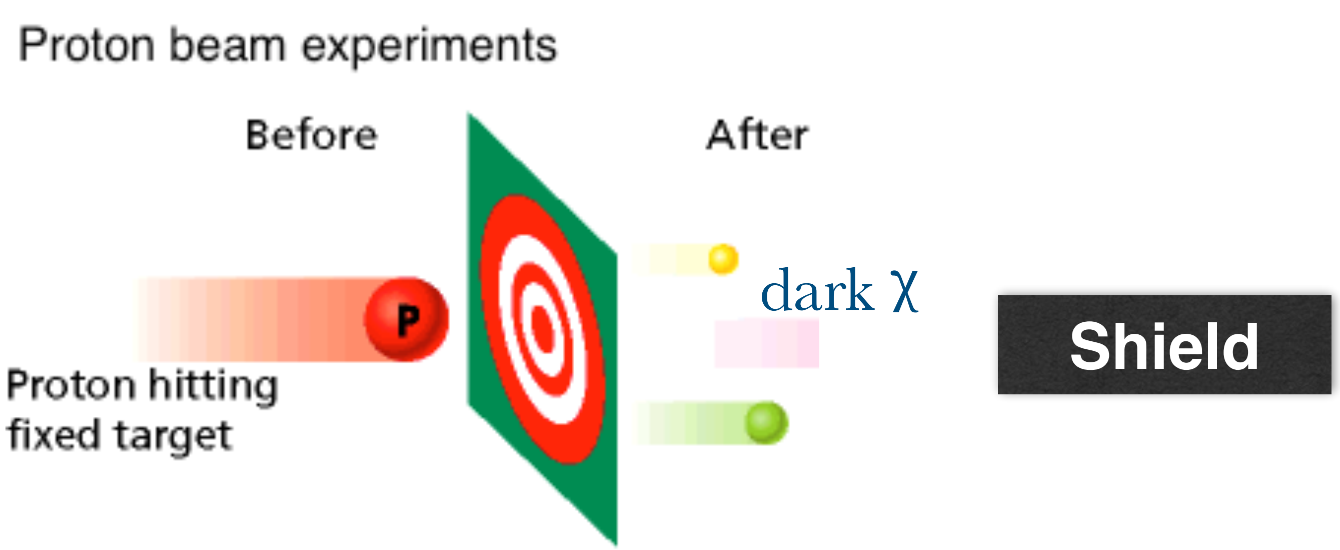
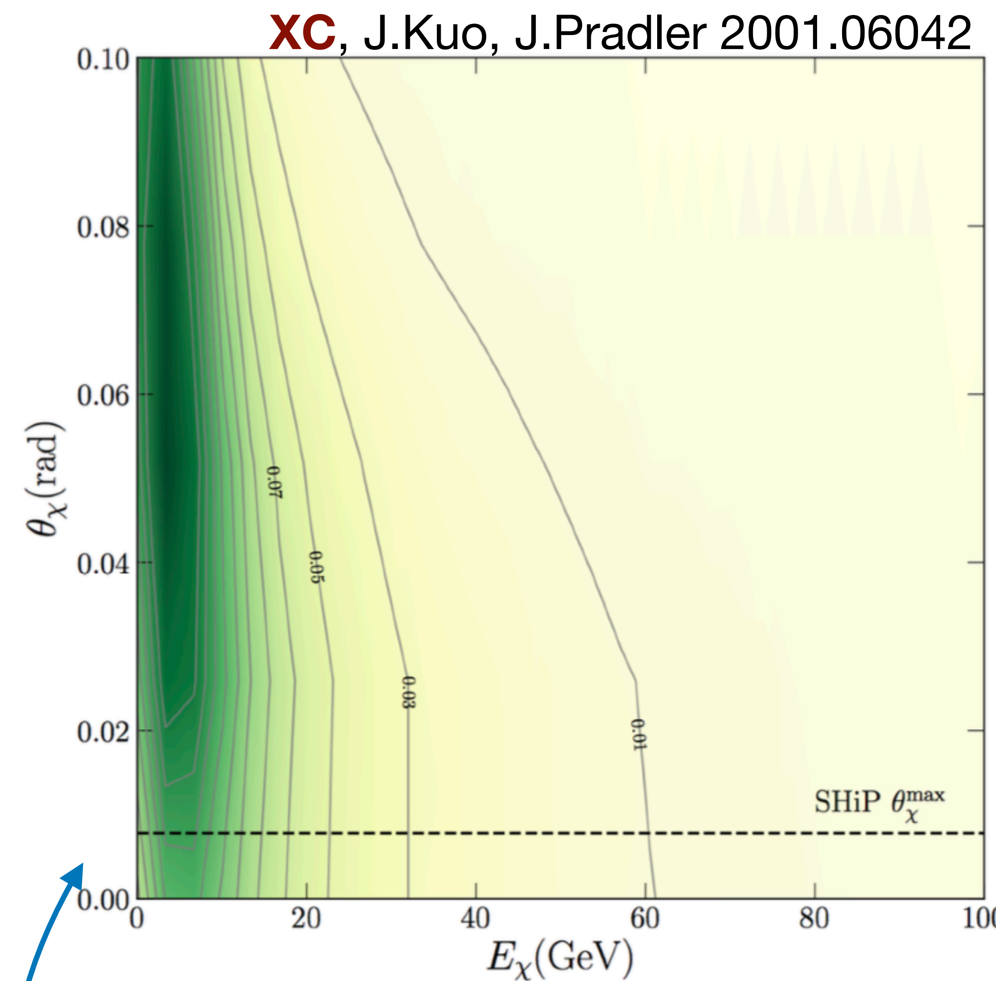


dark χ around GeV: intensity-frontier

Proton-beam experiments:

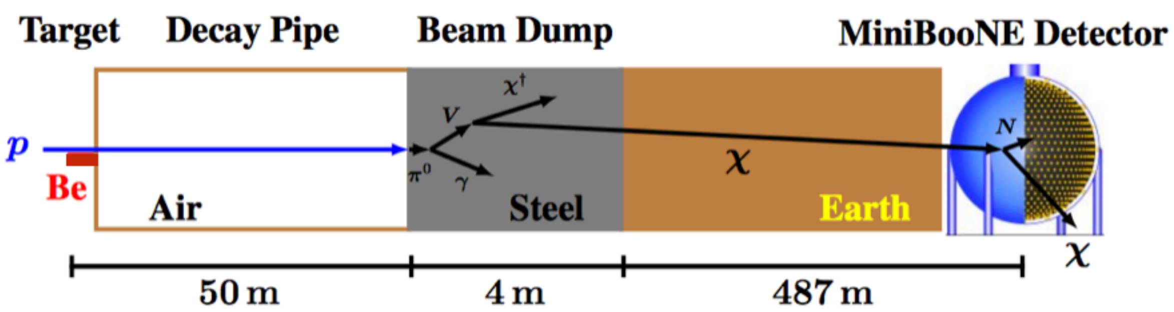


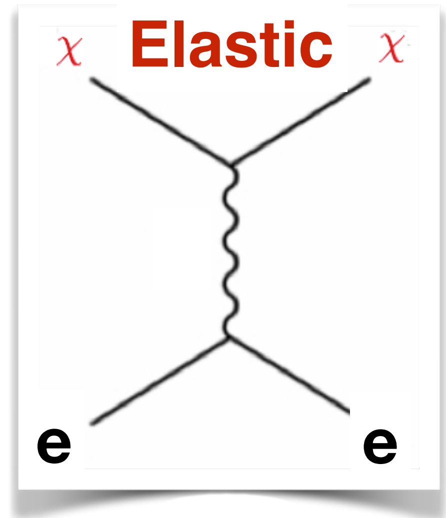


- Parton collisions via **pp→DS pair (DY)**;
- Proton Bremsstrahlung via **pp→pp'+DS pair**;
- Secondary production via **meson decay** *(potentially double-counting e.g. conversion of vector meson to off-shell photon)*;
- Secondary collisions ….

Only a tiny fraction
of dark particles
enter the detector

dark χ around GeV: intensity-frontier



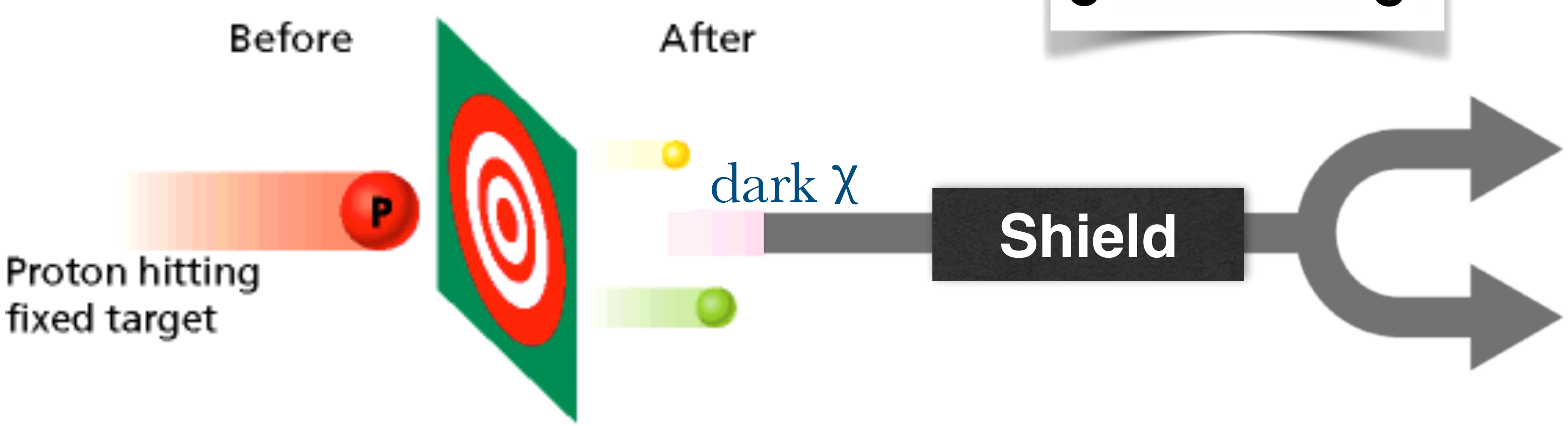


sub-GeV recoil, hard scattering:

e-recoil $(E_R \in [75, 850]\,\mathrm{MeV},\ \theta_R \leq 140\,\mathrm{mrad})$

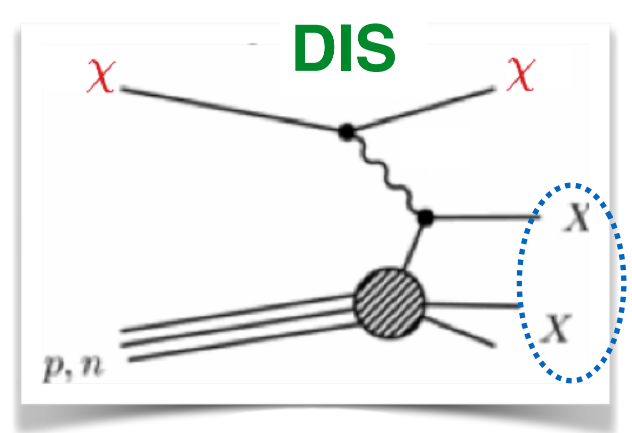
10^{20} POT **produced no single-e events** (after cut)!

Proton beam experiments



elastic scattering off electron

deep inelastic scattering



$E_{\mathrm{beam}} \setminus$ meson
8.9 GeV (MiniBooNE-DM)
120 GeV (DUNE)
400/450 GeV (SHiP, E613/CHARM II)

above-GeV hadronic shower:

(take E613 at FermiLab)

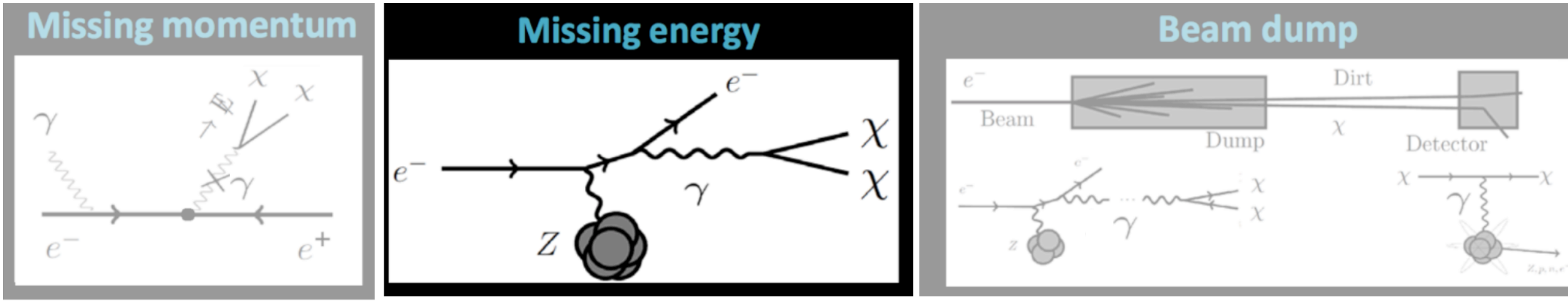
$$E_N^{\mathrm{dep}} \geq 20\,\mathrm{GeV}\ \text{per event}$$

bkg N: below 180

dark χ around GeV: intensity-frontier

With electron-beam: additional search for missing momentum/energy

credit: B. Eachenard



I) **Babar**, projected Belle

II) **NA64**, projected LDMX

III) **mQ**, projected BDX

Signature: mono-γ + missing momentum (low-energy colliders).

Signature: forwardly-scattered **electron**, with **significant energy loss.**

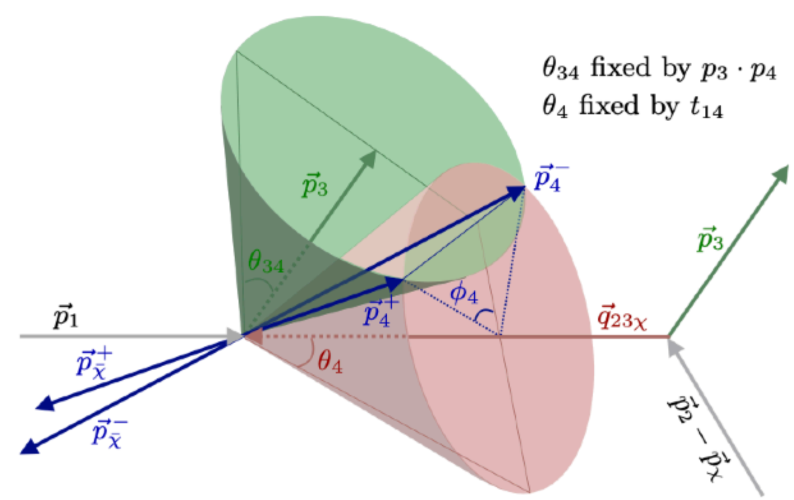
Signature: similar to proton-beam above.

Analytically solve

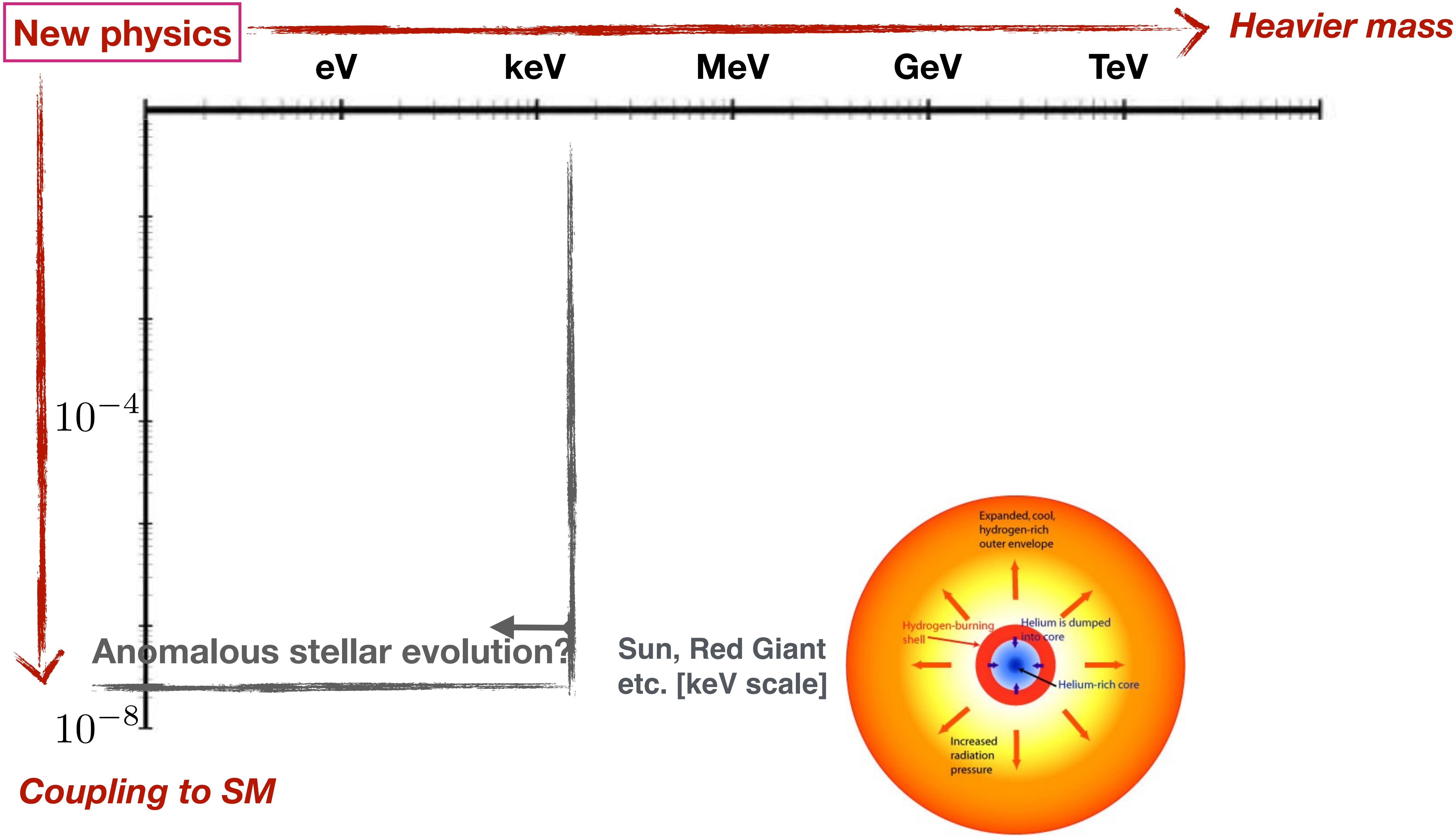
$$\frac{d^2\sigma_{eN\to eN\chi\chi}}{dE_e\, d\cos\theta_e}$$

missing energy larger than $0.5E_0$

polar angular coverage of $\theta_4 < 0.23\,\mathrm{rad}$



A typical exclusion plot for a light dark particle



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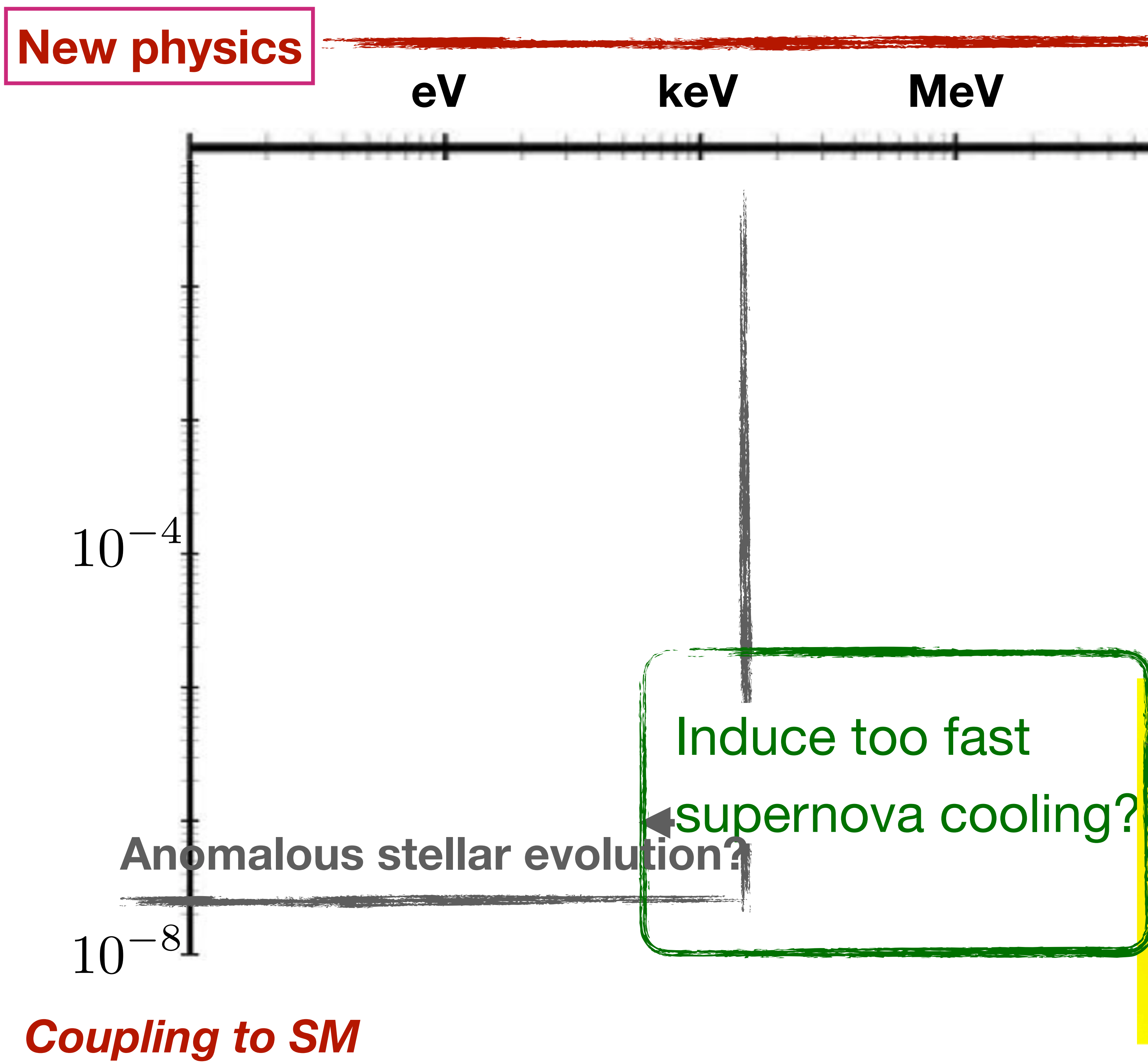
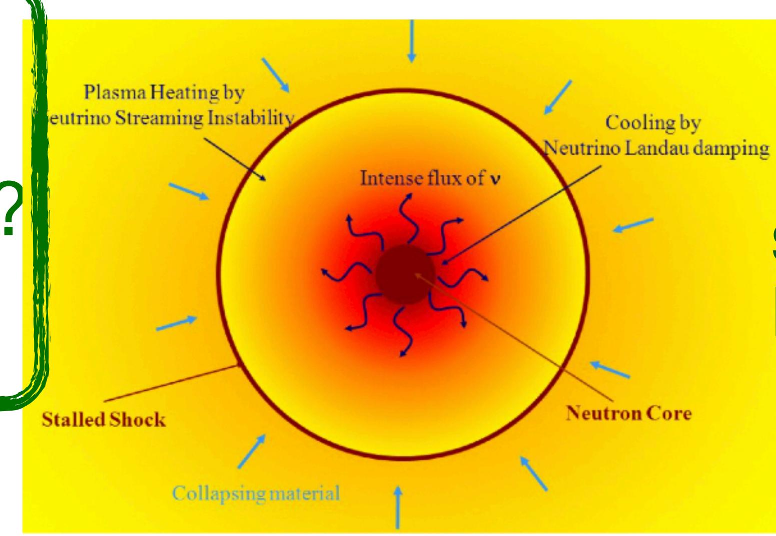
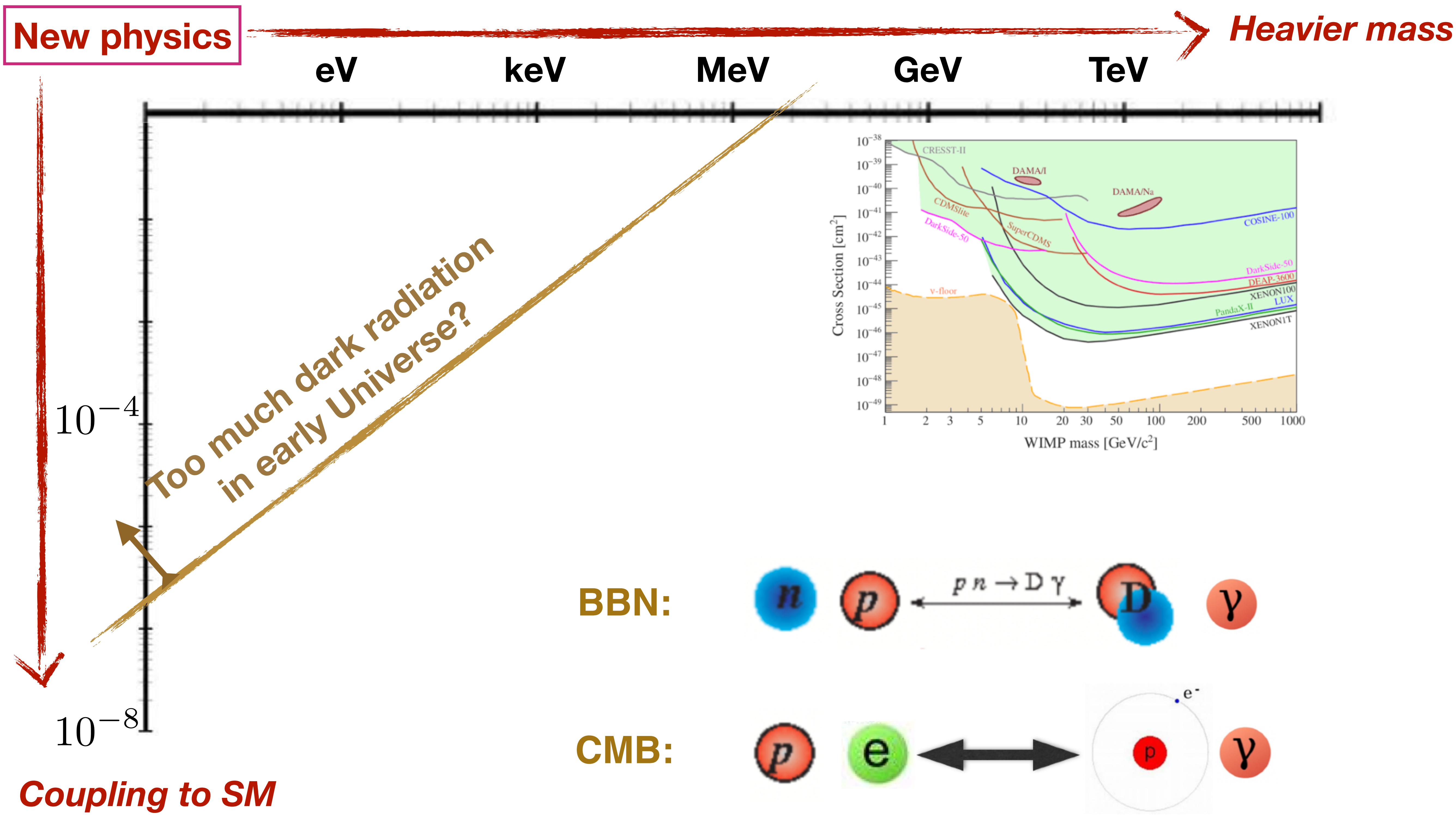




Supernova
[10-50 MeV]

A typical exclusion plot for a light dark particle



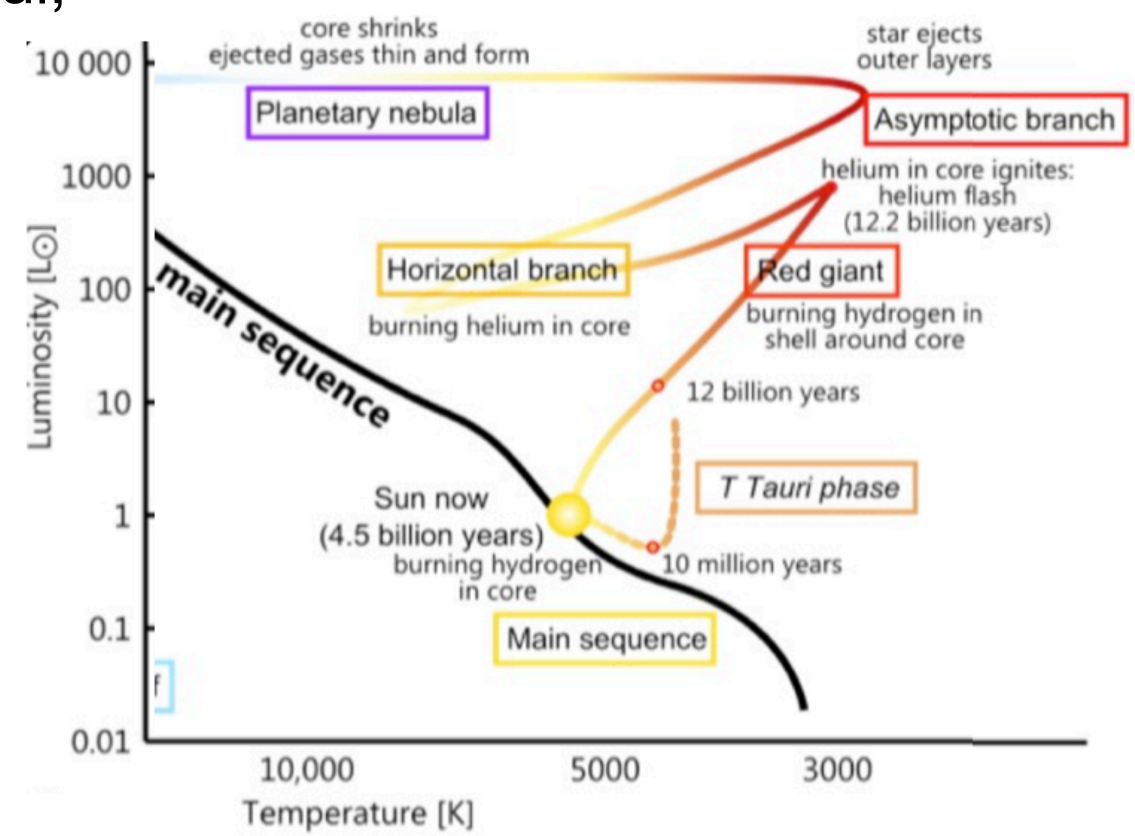
dark χ around keV-MeV: cosmos/stellar

They all are based on the argument that:

(Meta-)stable dark particle should not be **overproduced** in dense medium.

1. Standard Solar Model has been quite successful, constraining anomalous energy loss *[J. A. Frieman, S. Dimopoulos&M. S. Turner 1987, G. G. Raffelt and G. D. Starkman 1989]*:

$$\int_{\rm Sun} dV\,\dot{Q} < 10\% \times L_\odot \quad ({\rm Sun}).$$



2. **Maximal core mass NOT to ignite Helium burning** (red giant) *[G. G. Raffelt 1995]*:

$$\dot{Q} < 10\,{\rm erg/g/s} \times \rho \quad ({\rm RG}).$$

3. Anomalous cooling speeds up stable Helium burning in Horizontal branch, reducing its typical ratio in Globular Cluster observations *[G. G. Raffelt 1995]*:

$$\int_{\rm core} dV\,\dot{Q} < 10\% \times L_{\rm HB} \quad ({\rm HB})\,.$$

dark χ around keV-MeV: cosmos/stellar

They all are based on the argument that:

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4. To have successful **neutrino-driven SN explosion:**

$$\int_{\rm core} dV\,\dot{Q} < L_\nu = 3\times 10^{52}\,{\rm erg}/s \quad ({\rm SN}).$$

*To make χ escape, its **mean-free-path in SN** should be longer than~40 km (or than ν).*

5. At early Universe (BBN time), medium is at most mild for dark above electron mass, so zero-temperature QFT is adopted here.

	ω_p	T
Sun's core	0.3 keV	1.4 keV
HB's core	2.6 keV	10.6 keV
RG's core	8.6 keV	8.6 keV
SN's core	17.6 MeV	12.1 MeV

BBN: T ~ MeV

Anomalous cooling relies on its production in medium

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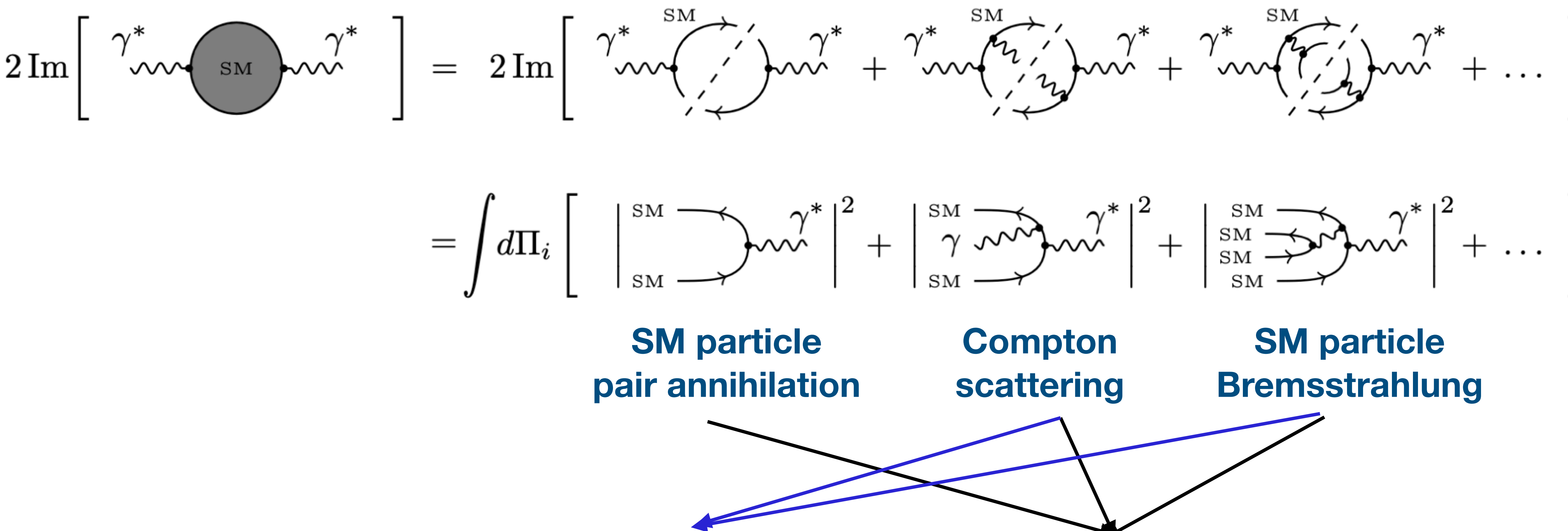
Caveats do exist in the argument, such as:

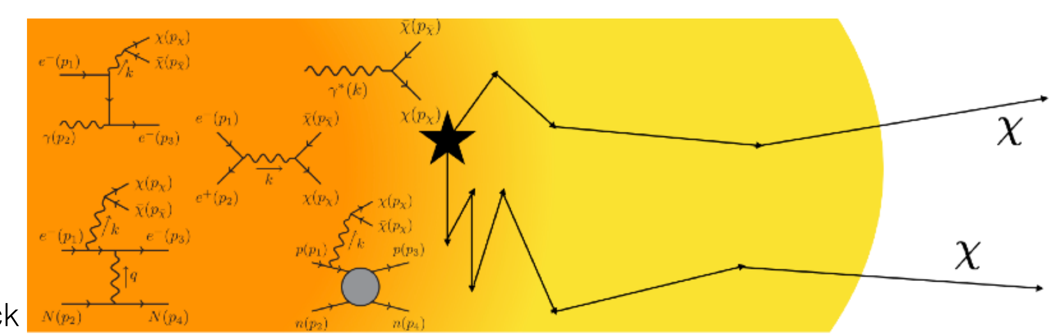
- dark state **trapping** by additional dark states *[e.g. Y. Zhang 1404.7172]*;
- **Production suppression** from large **thermal** mass/small **thermal** coupling of dark states *[e.g. W. DeRocco, P. W. Graham, S. Rajendran 2006.15112]*.
- if **SN1987A** was not neutrino-driven explosion *[e.g. N.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

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



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

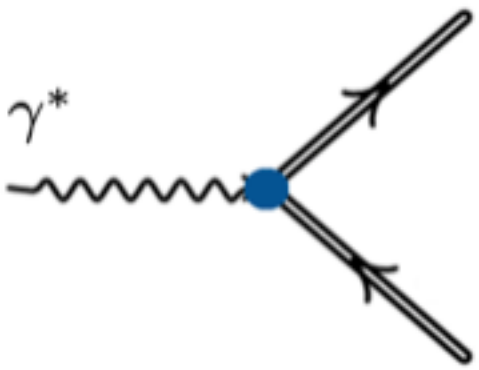
$$-\frac{\mathrm{Im}\Pi_{L,T}}{\pi|s_{\gamma^*}-\Pi_{L,T}|^2} = \delta(s_{\gamma^*}-\Pi_{L,T}) + \text{non-reson.}$$



credit: L.Semmelrock

Anomalous cooling relies on its production in medium

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



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

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

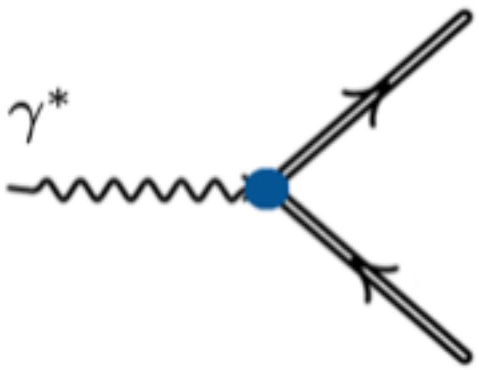
E.g. plasmon decay
$$\Gamma_{\rm T,L} = \frac{1}{16\pi}Z_{\rm T,L}\sqrt{1-\frac{4m_\chi^2}{\omega_{\rm T,L}^2-|\vec{k}|^2}}\frac{f(\omega_{\rm T,L}^2-|\vec{k}|^2)}{\omega_{\rm T,L}}$$

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).

Anomalous cooling relies on its production in medium

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



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

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

Need to be aware of: **vector particle is different**

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

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

similar up to a pre-factor

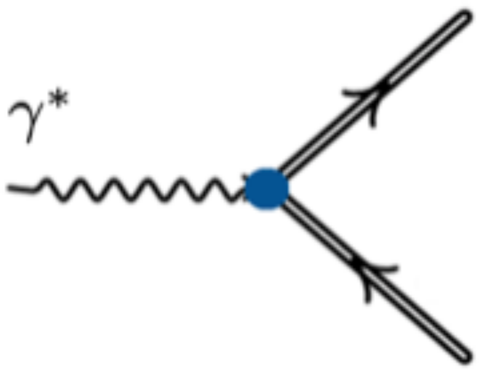
$$f_F(s) = \frac{4(\epsilon e)^2 s (1 + 2m_\chi^2/s)}{3}$$

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

diverge at $m_V \to 0$?

Anomalous cooling relies on its production in medium

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



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

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

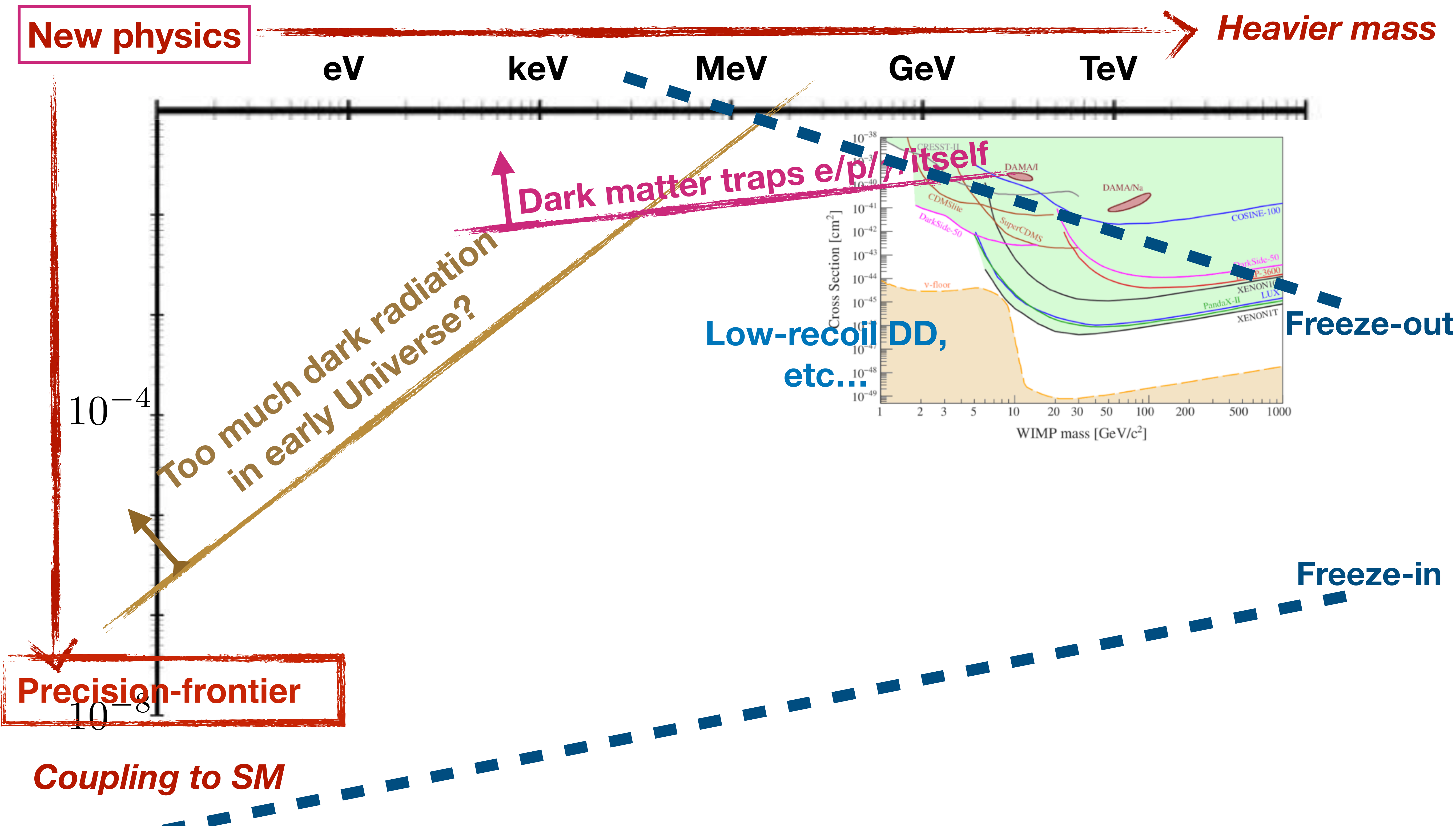
interaction type	fermion $f(s)$	vector $f(s)$
magnetic dipole	$\frac{2}{3}\mu_\chi^2 s^2(1+\frac{8m_\chi^2}{s})$	$\frac{\mu_V^2 s(s-4m_V^2)(16m_V^2+3s)}{12m_V^2}$
electric dipole	$\frac{2}{3}d_\chi^2 s^2(1-\frac{4m_\chi^2}{s})$	$\frac{d_V^2 s(s-4m_V^2)^2}{6m_V^2}$
electric quadrupole		$\frac{Q_V^2 s^2(s-4m_V^2)}{16}$
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

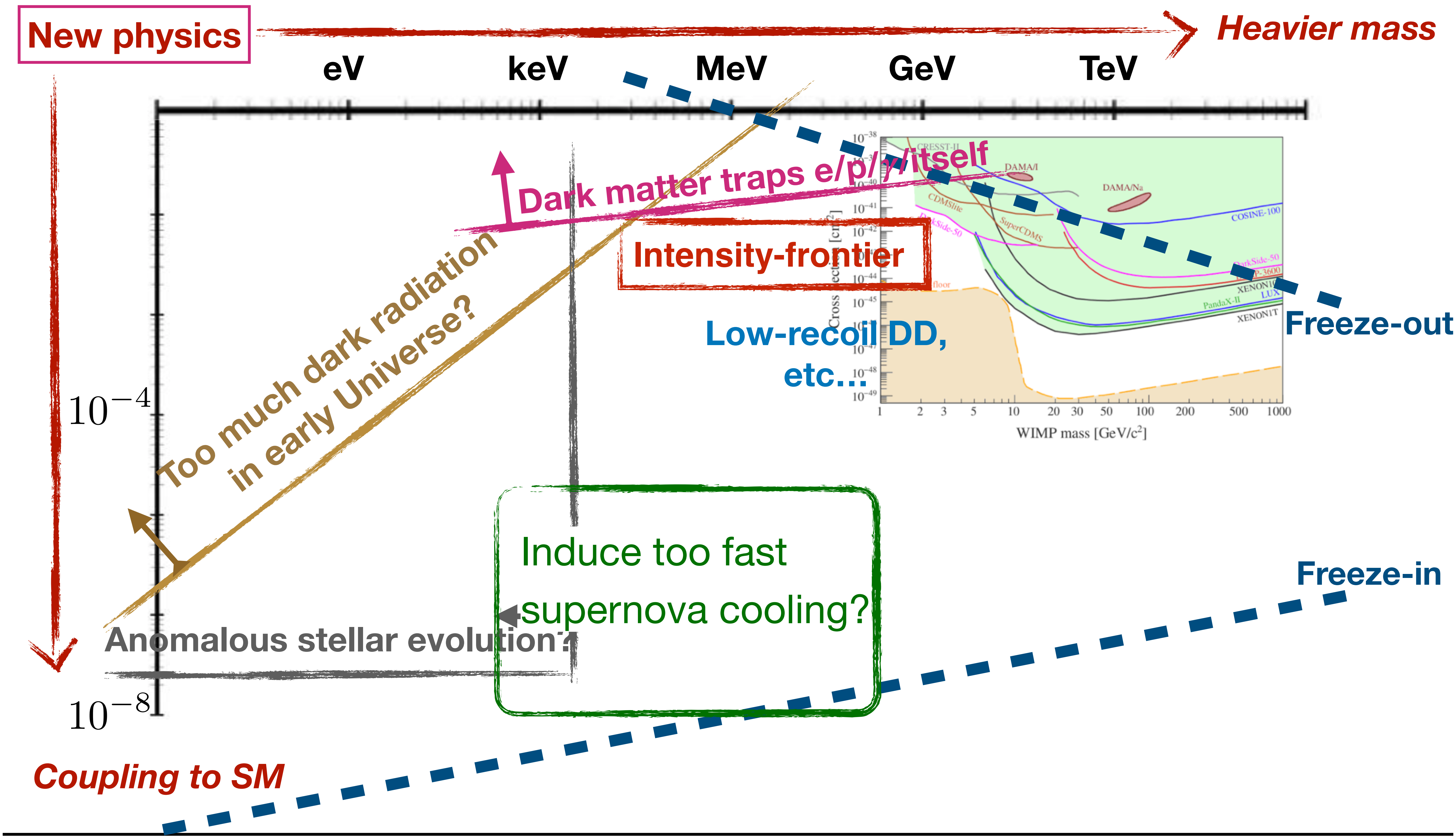
$$s/m_V^2$$

for dark vector.

A typical exclusion plot for a light dark particle



To sum up, also with dark matter production



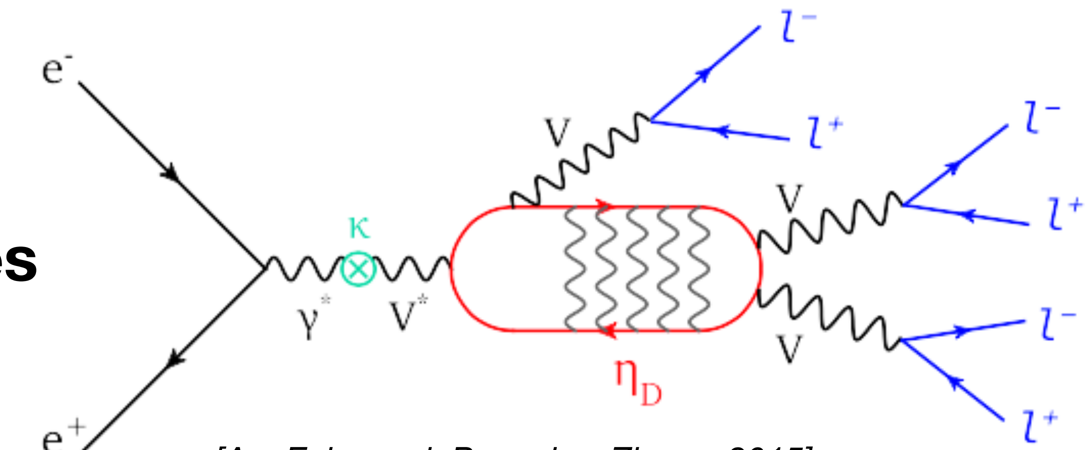
More dark structure, more signatures:

Higher-derivatives, more photons, non-conserved current, ….

Displaced vertex in detectors:

e.g. mixing with long-lived A’, dark bound states

Displaced vertex

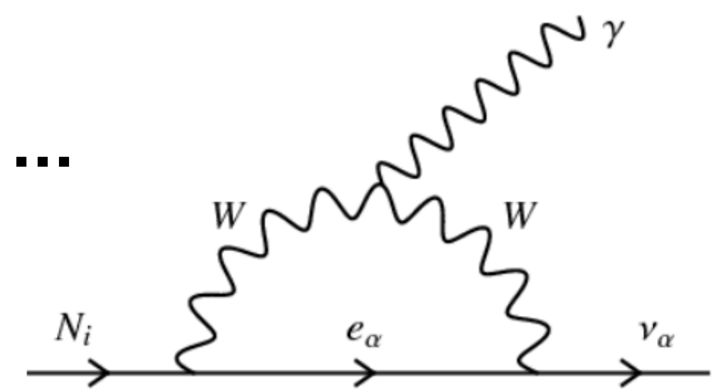


[An, Echenard, Pospelov, Zhang, 2015]

Low-energy cosmic photon beyond background:

excited state *[Tucker-Smith &Weiner, 2001],* **sterile neutrino** *[Dodelson& Widrow 1993],* **…**

Detailed cosmos/astro.

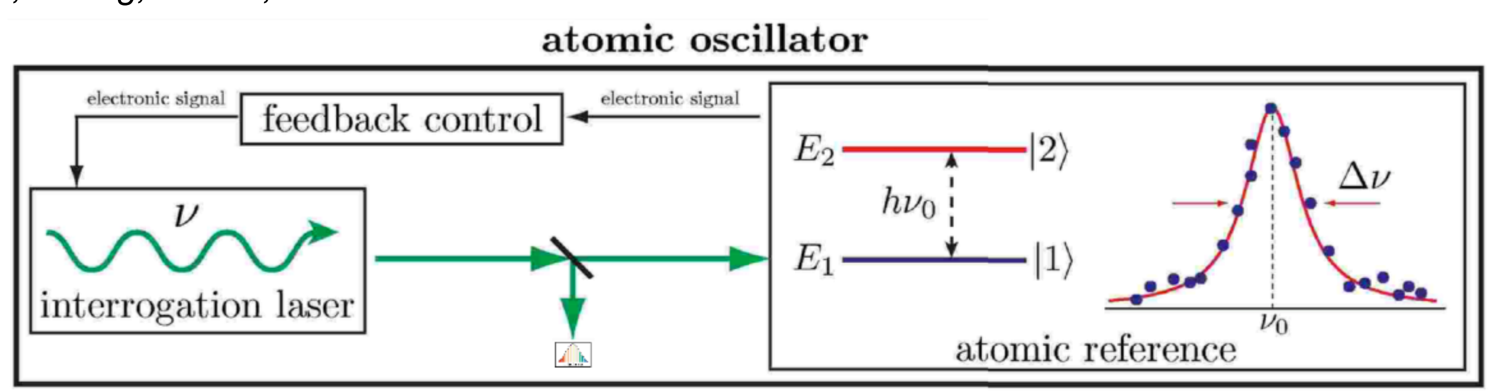


Oscillating fine-structure constant:

e.g. a light scalar *[Arvanitaki, Huang, Tilburg, 2014, Tilburg, Leefer , Bougas, Budker, 2015, Stadnik and V. V. Flambaum 2015, …]*

$$sF^{\mu\nu}F_{\mu\nu}$$

Precision-frontier

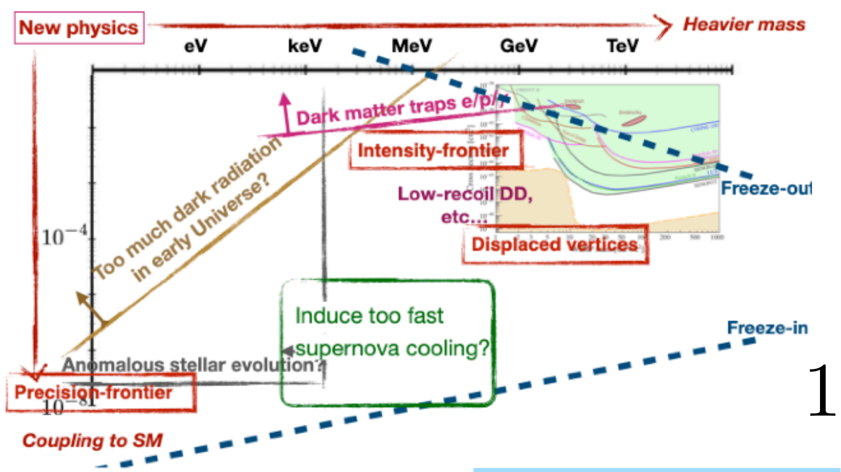


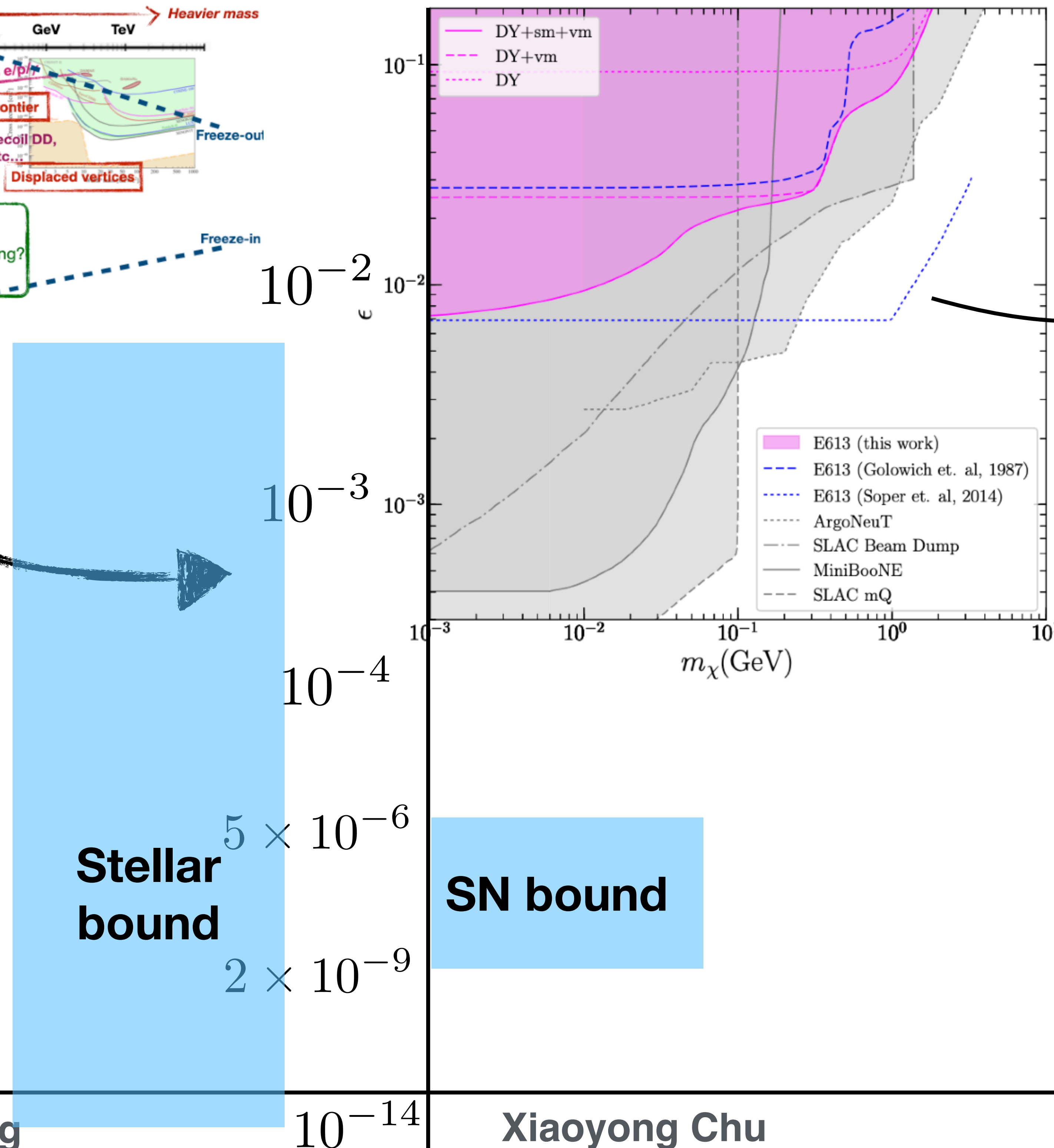
III. discuss exclusions

Summarise **dim-4 constraints:**

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, ...

milli-charged, well known in the literature





XC, J.Kuo, J.Pradler 2001.06042

We corrected a previous result by including the **attenuation of protons.**

Summarise **dim-4 constraints:**

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, ...

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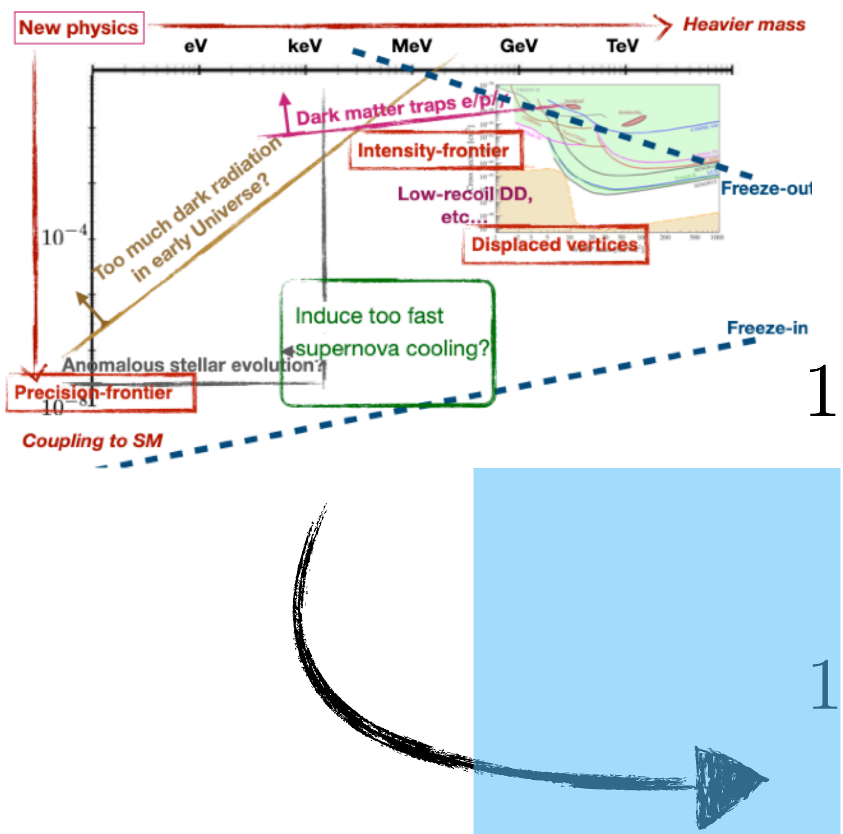
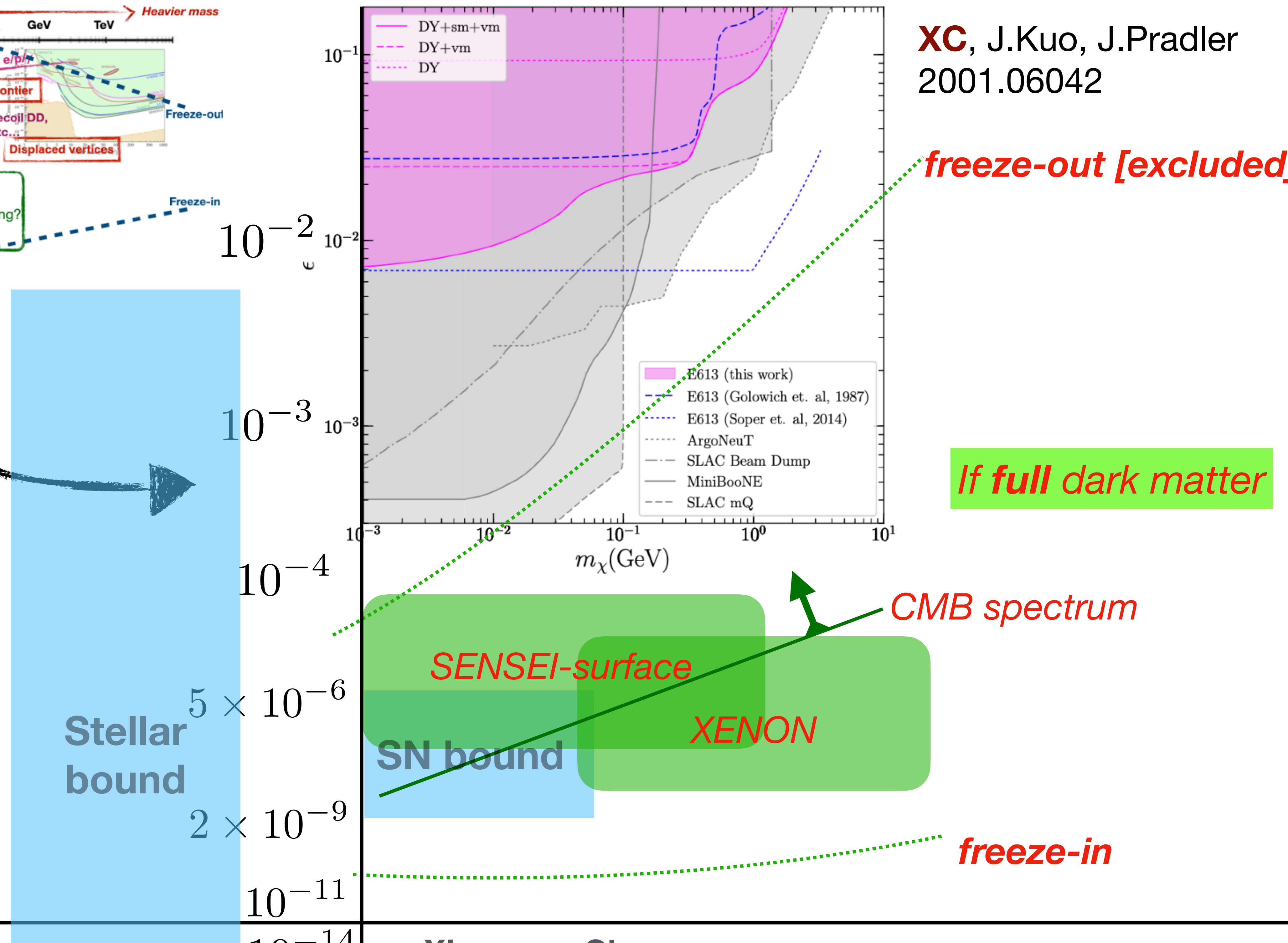


XC, J.Kuo, J.Pradler 2001.06042



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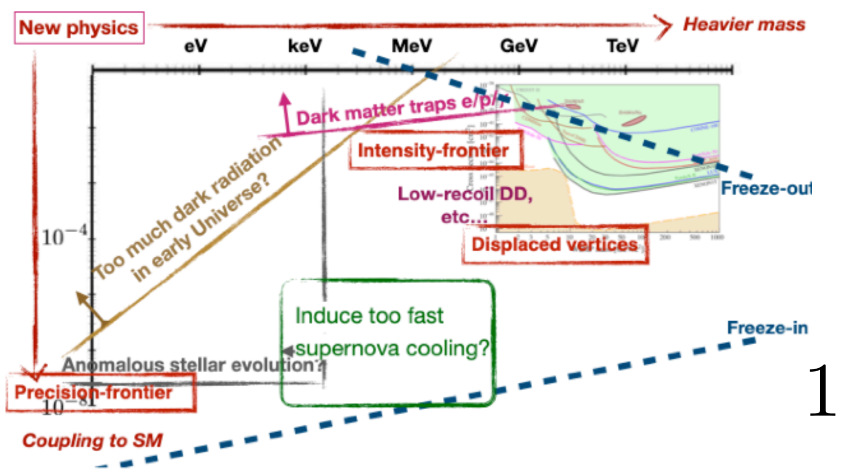
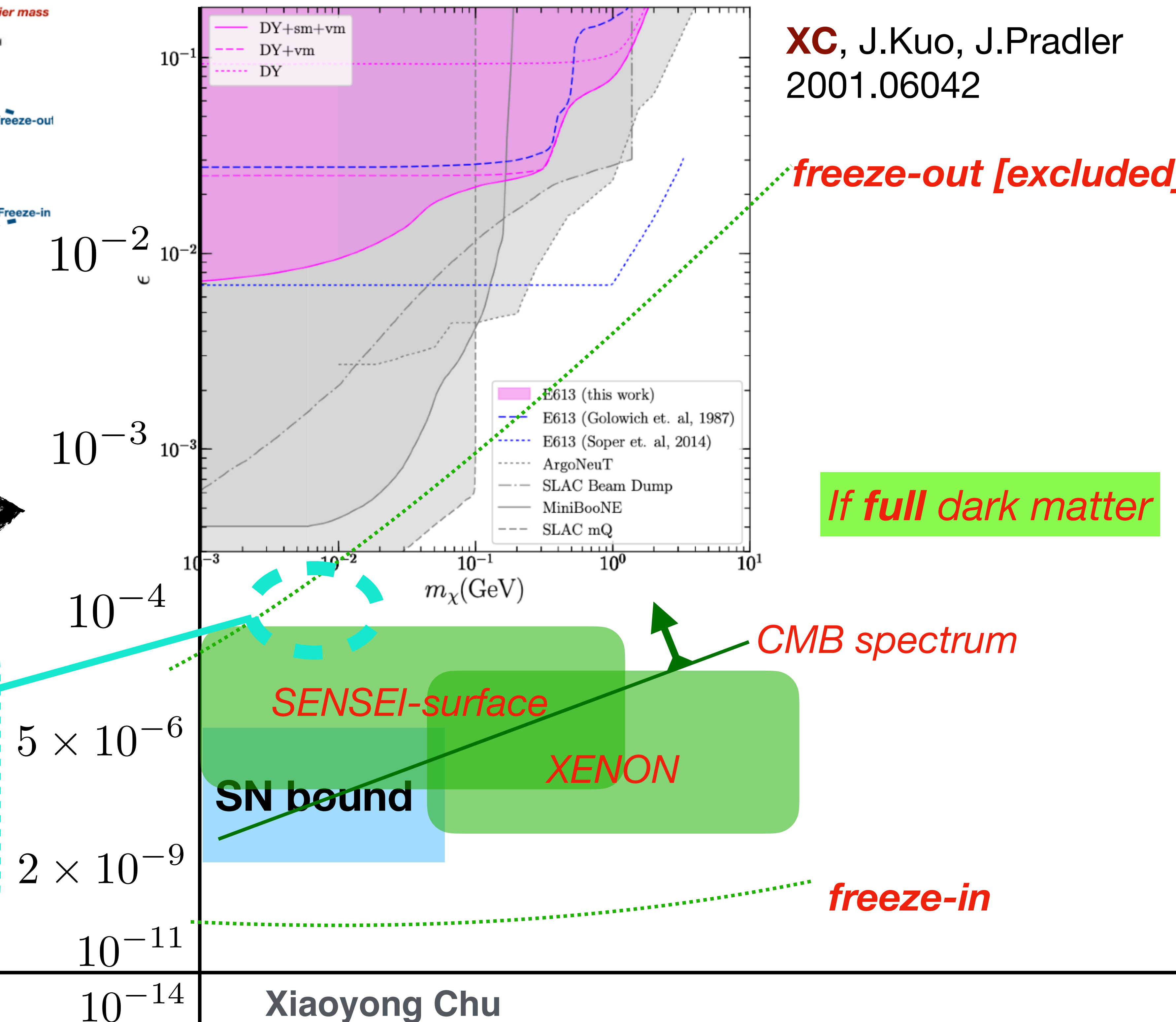
Summarise dim-4 constraints:

milli-charged, well known in the literature



Dim-4



XC, J.Kuo, J.Pradler 2001.06042

adding neutrino annihilation

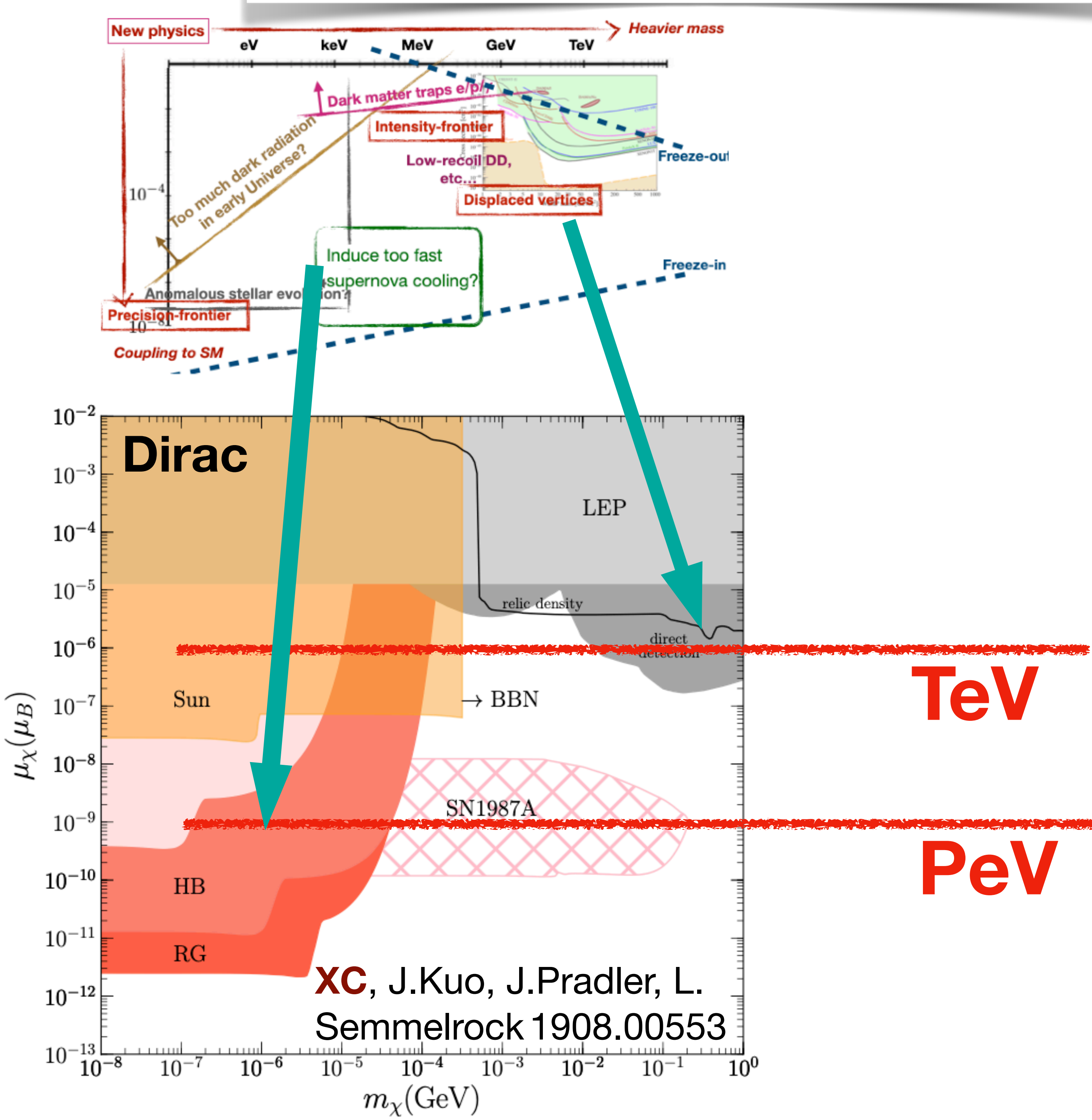
$$\sigma v_\nu \sim 10^2 \sigma v_\gamma$$

→ 0.2% DM relic, explaining EDGES

[XC & J.Pradler 2310.06611]

Summarise **dim-5 constraints** on fermions:

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 (**p/d**-wave annihilation) left for detailed investigation.
- **High-order operators** are **not** enough to **cool down baryons** for 21cm observables (EDGES).

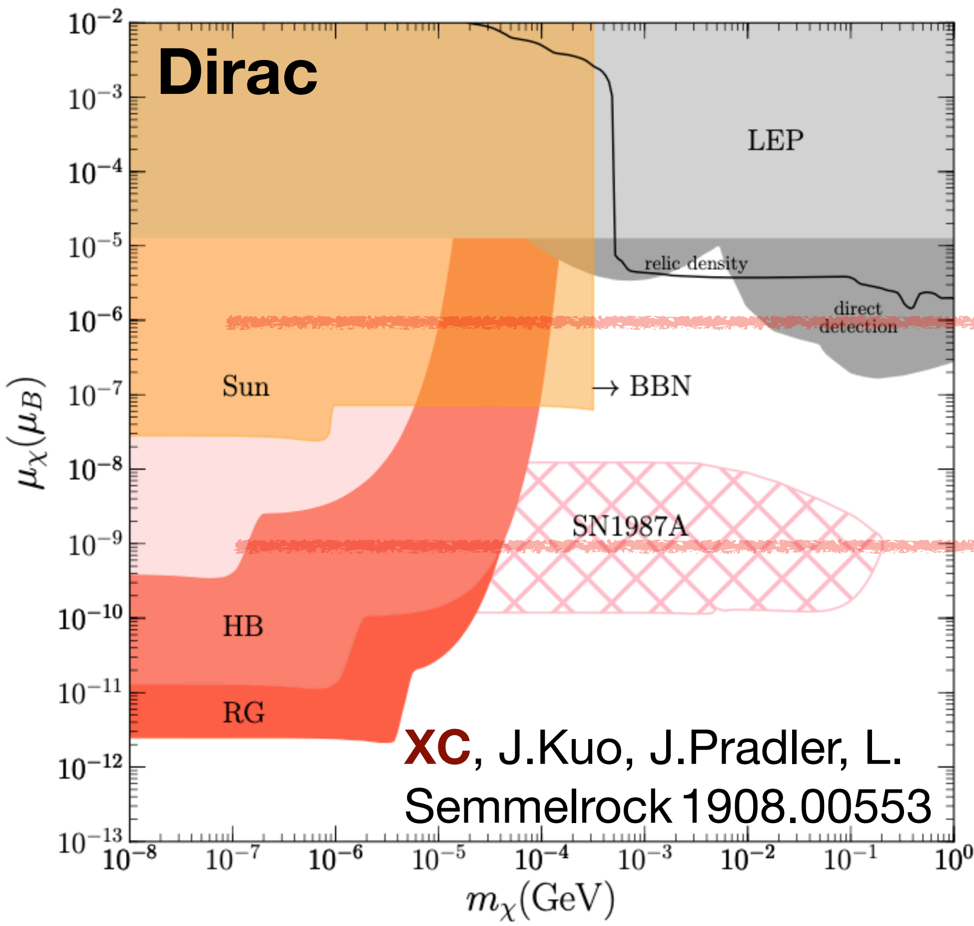
Summarise dim-5 constraints on fermions:

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

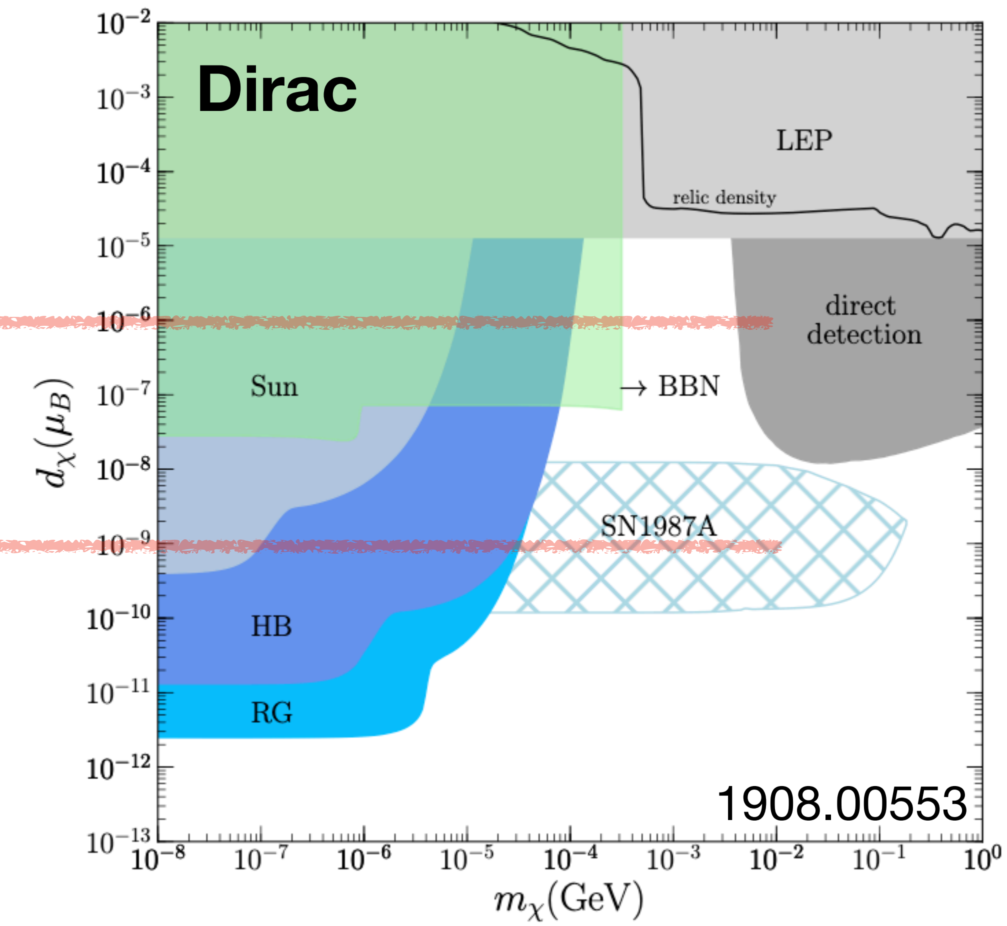
CP affects mildly

up to velocity suppressions in non-relativistic regime

MDM



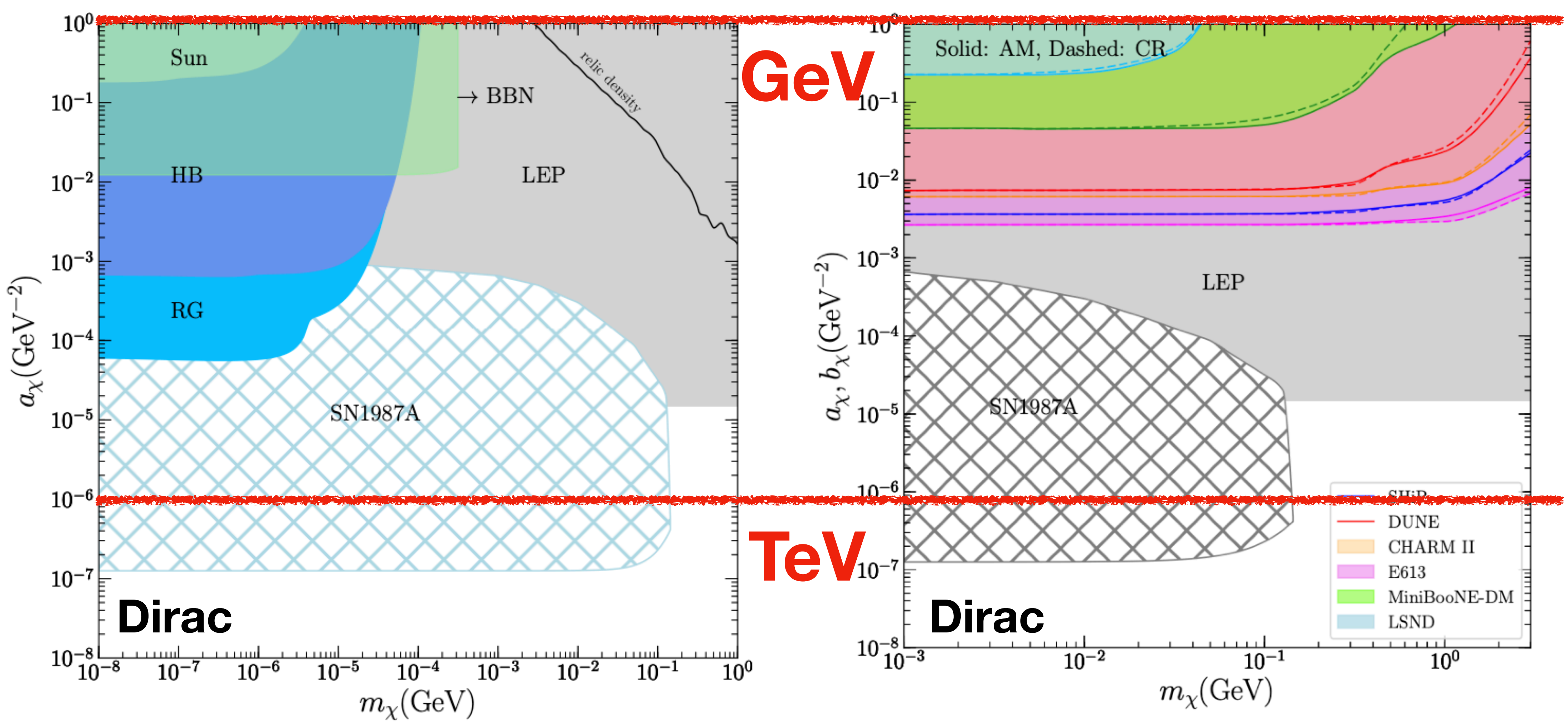
EDM



Summarise **dim-6 constraints** on fermions:

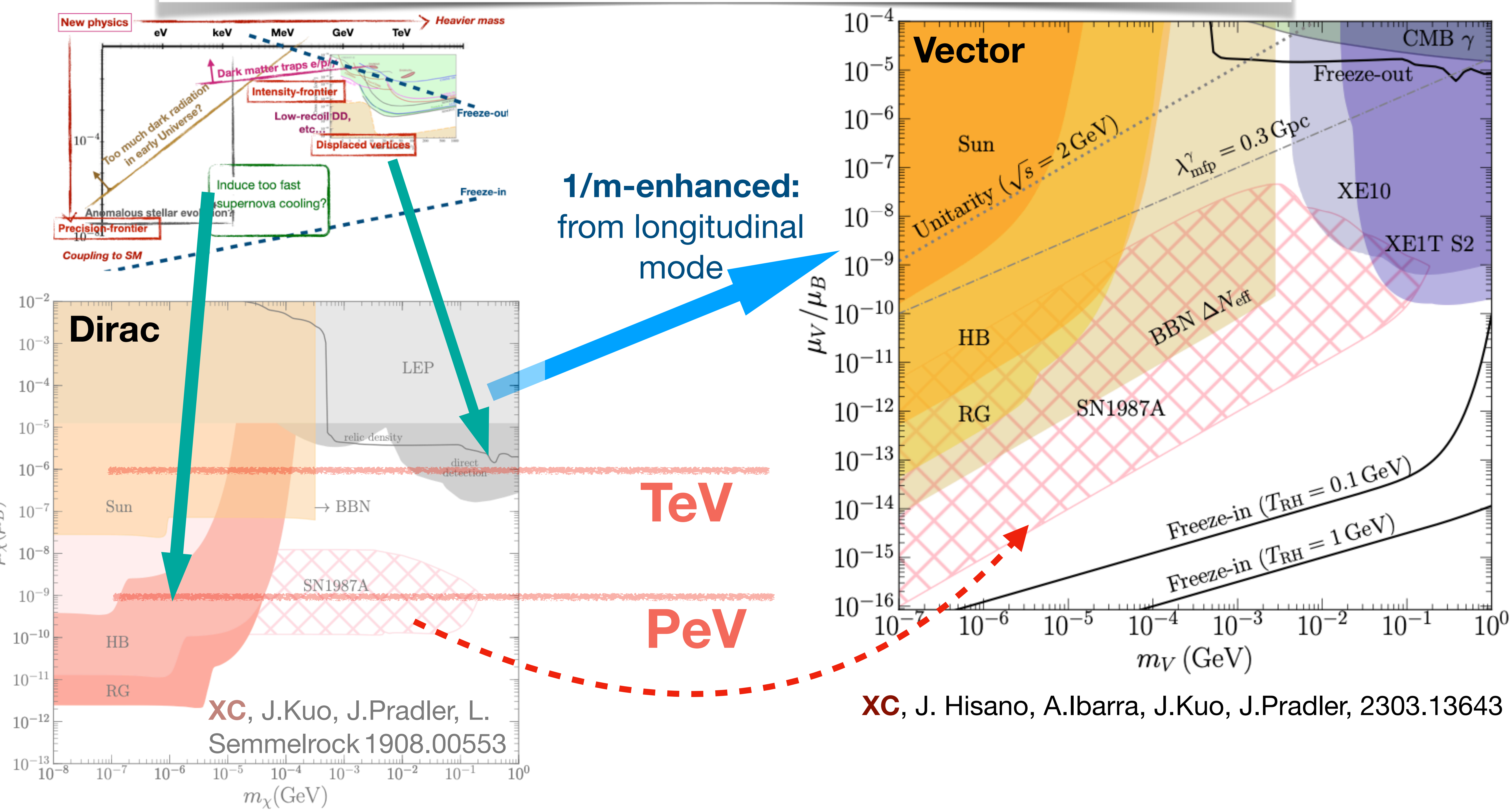
interaction type	fermion $f(s)$
charge radius	$\frac{4}{3}\frac{e^2(g_1^\chi)^2 s^3}{m_\chi^4}(1+\frac{2m_\chi^2}{s})$
anapole moment	$\frac{4}{3}\frac{e^2(g_5^\chi)^2 s^3}{m_\chi^4}(1-\frac{4m_\chi^2}{s})$

- Thermal **freeze-out fully excluded**.
- **LEP** easily beats **intensity-frontier for dim-6 operators**, while both hardly apply to GeV UV-scales.



Turn to spin-1 case: vector is different

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



V. Validity of the constraints

Theoretical validity

EM form factors are defined at extremely IR-end:

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

  we can not exclude regions where dimensionless coeff. $\times$ (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 (with a dark higgs mass above the energy-scale).

This is still not enough, which can be seen in a **UV-completion**.

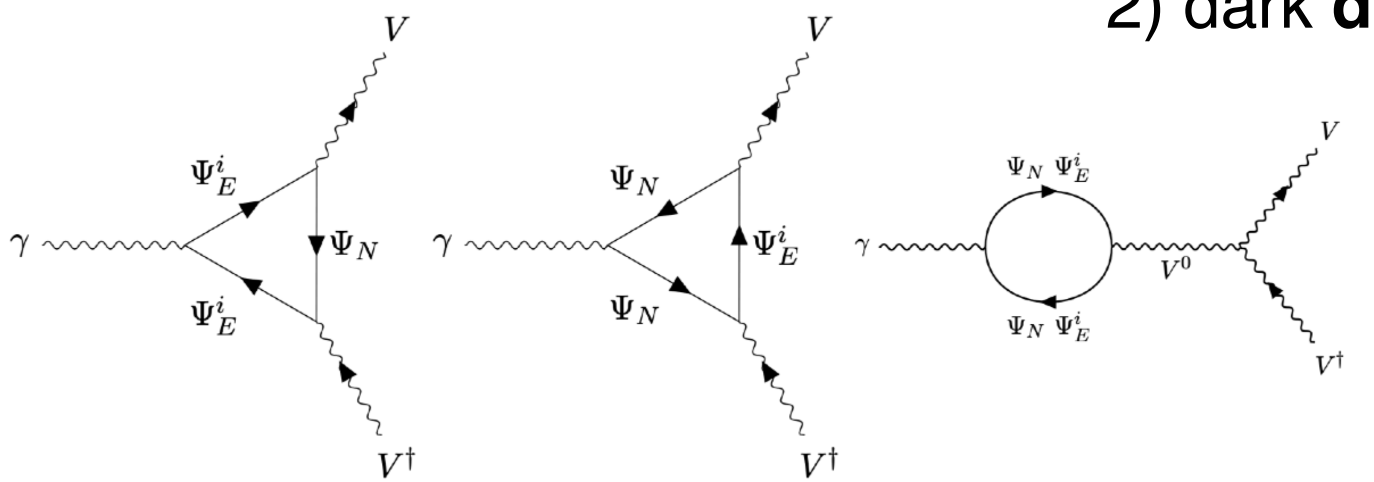
- EM form factors are not necessarily independent.

Realization of **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

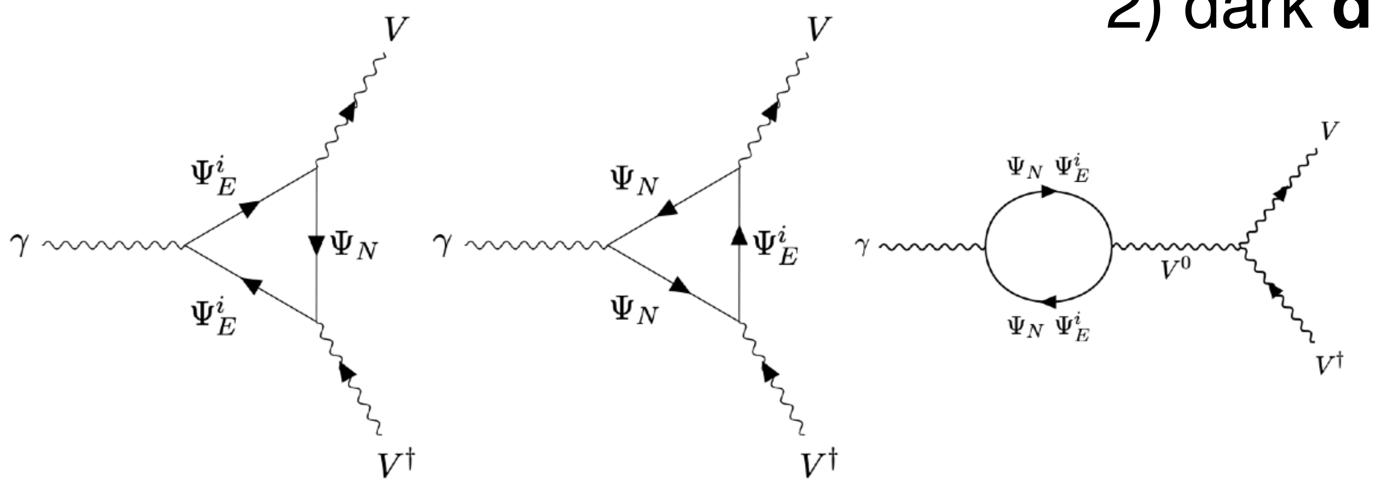
one can write down **all the EM form factors** **in terms of UV parameters**

Realization of **UV-completion**

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

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

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



A) 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,

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

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

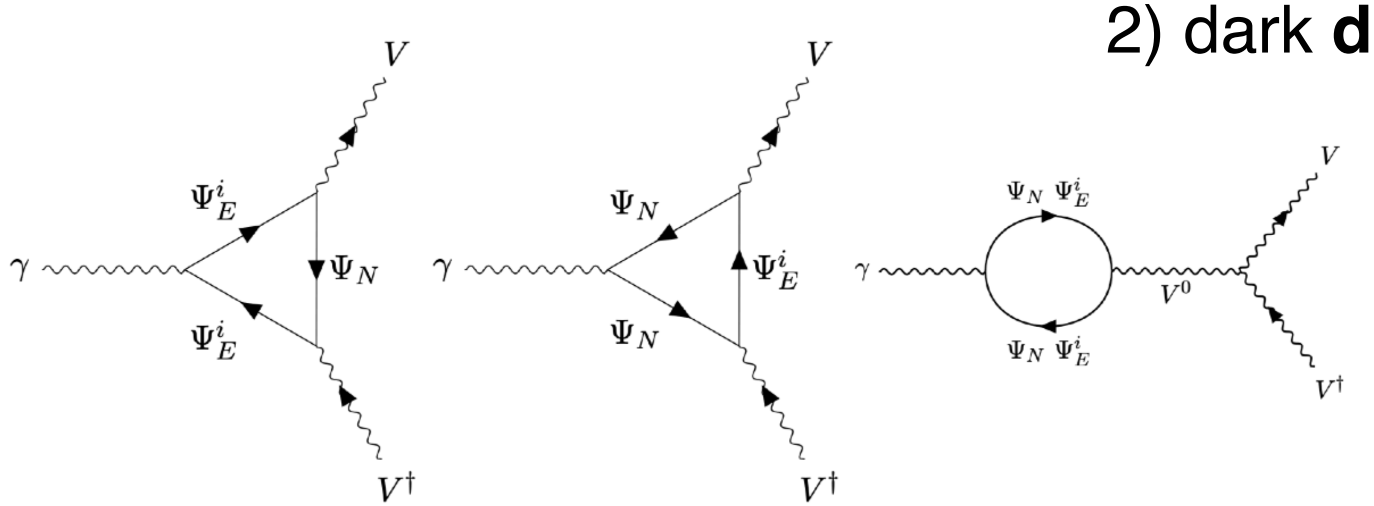
which can stay valid until the SSB scale, which **heavy dark higgs** enters.

Realization of **UV-completion**

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

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

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



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

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

each amplitude diverges at mV→0, even for transverse V-boson production.

In the UV model, there is, at first-order,

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

the divergences in transverse modes cancel with each other.

- Seems unphysical to **separate the two operators** for vector states *-under investigation*;
- Operators with the same CP can be seen as belonging to the same group.
- Our bounds are mostly sensitive to **the scaling of f(s)**, and thus easy to generalize.

VI. Conclusions

Conclusions

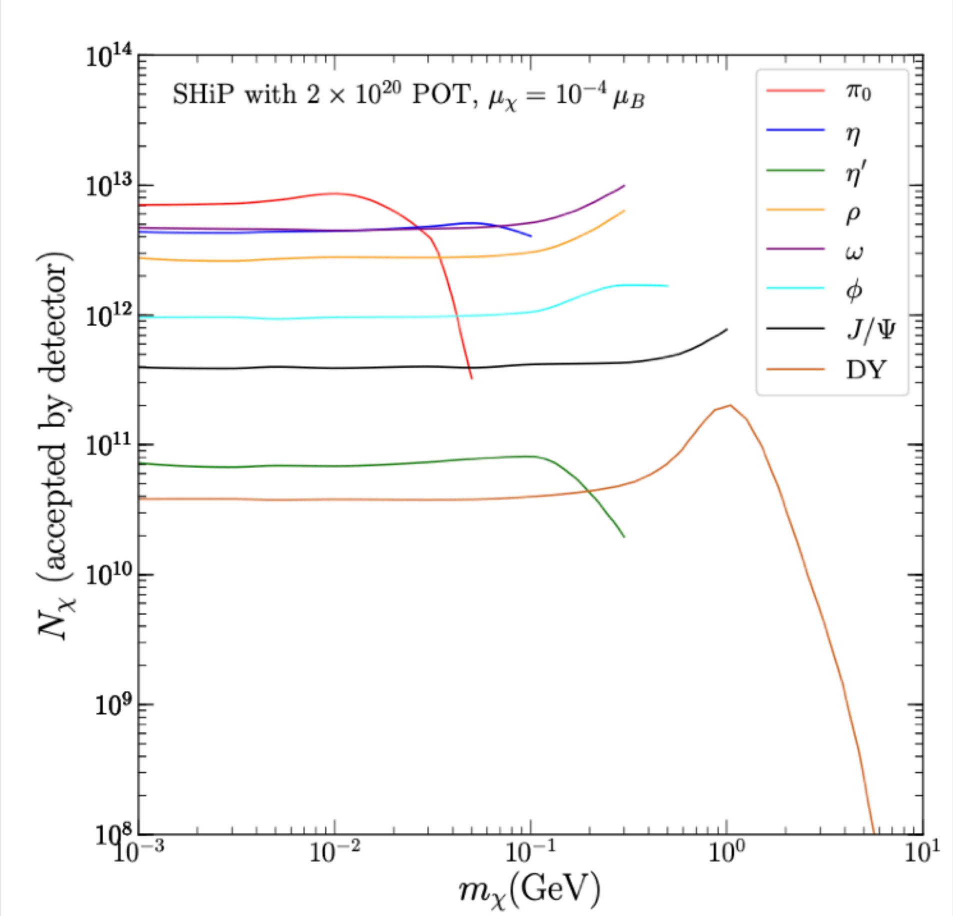
- So far no heavy new particles, try **something (with) light**?
- Most appealing light portal: **multi-messenger** constraints/observations will be important to identify dark states;
- **Intensity/neutrino** experiments play an important role.
- **Astrophysics** can be extremely useful in probing feeble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

Backup

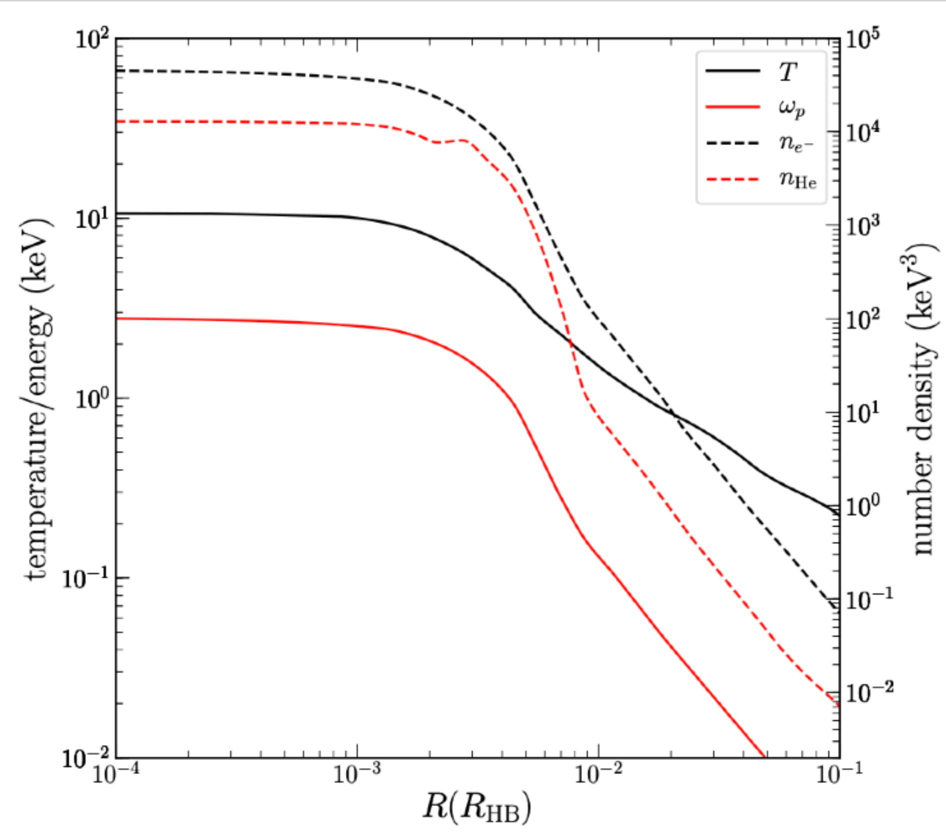
Experimental parameters

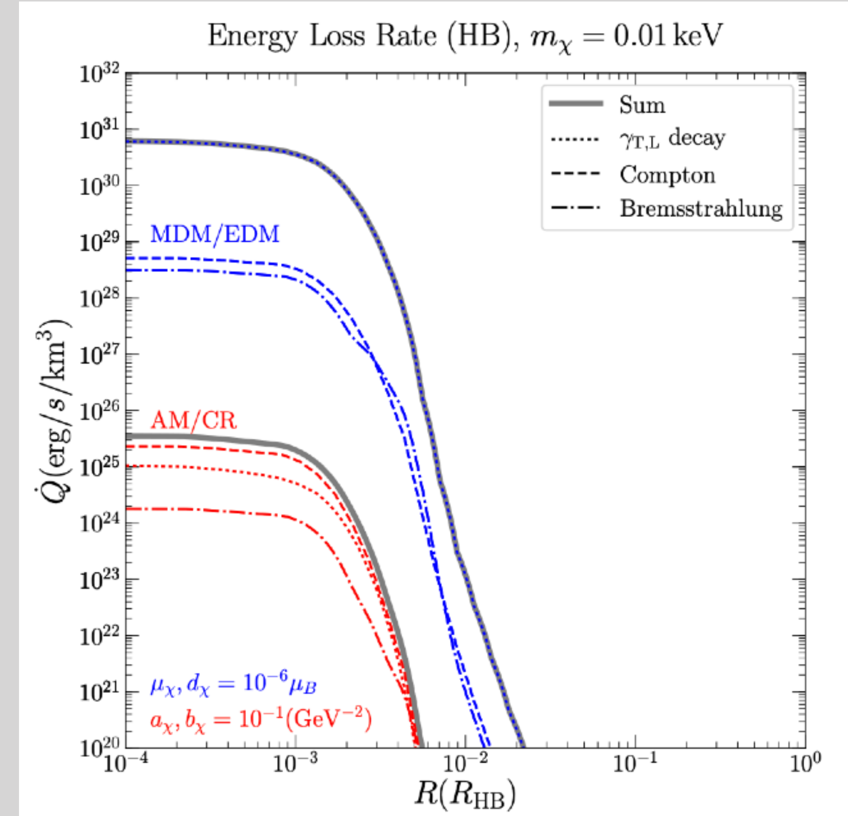
E_{beam} \ meson	π^0	η	η'	ρ	ω	ϕ	J/Ψ
8.9 GeV (MiniBooNE-DM)	8.6×10^{-1}	8.2×10^{-2}	4.9×10^{-3}	6.9×10^{-2}	7.4×10^{-2}	1.1×10^{-4}	0
120 GeV (DUNE)	2.9	3.2×10^{-1}	3.4×10^{-2}	3.7×10^{-1}	3.7×10^{-1}	1.1×10^{-2}	5.0×10^{-7}
400/450 GeV (SHiP, E613/CHARM II)	4.1	4.6×10^{-1}	5.1×10^{-2}	5.4×10^{-1}	5.4×10^{-1}	1.9×10^{-2}	8.0×10^{-6}

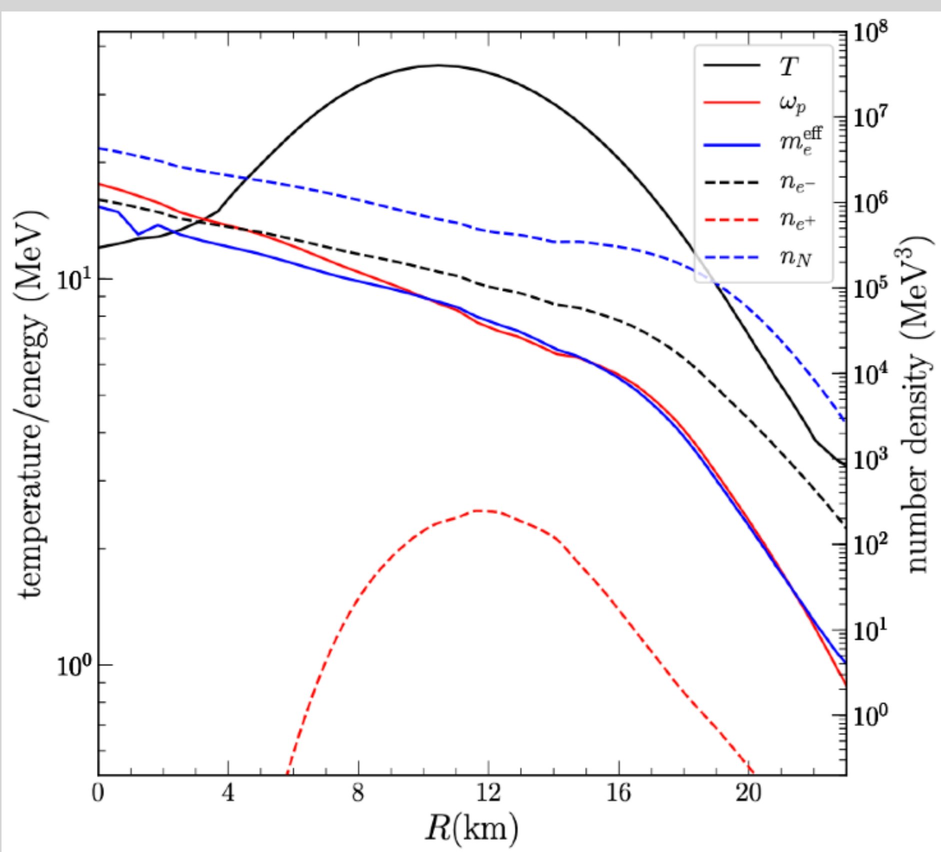
Experiments	POT (10^{20})	$\lvert\theta_\chi^{max}\rvert$	Signal process and cuts	N_{bkg}	ϵ_{eff}	on/off axis
LSND	1800	-	e-recoil ($E_R \in [18, 52]$ MeV, $\theta_R \leq \pi/2$)	$N_{sig} \leq 110$	0.16	31°
MiniBooNE-DM	1.86	12.4 mrad	e-recoil ($E_R \in [75, 850]$ MeV, $\theta_R \leq 140$ mrad)	0	0.2	0°
CHARM II	0.25	2.1 mrad	e-recoil ($E_R \in [3, 24]$ GeV, $E_R\theta_R^2 \leq 3$ MeV)	5429	~ 1	0°
DUNE (10 yr)	11/yr	3.4 mrad	e-recoil ($E_R \in [0.6, 15]$ GeV, $E_R\theta_R^2 \leq 1$ MeV)	8930/yr	0.5	0°
SHiP	2	7.8 mrad	e-recoil ($E_R \in [1, 20]$ GeV, $\theta_R \in [10, 20]$ mrad)	846	~ 1	0°
E613	0.0018	12.8 mrad	had. shower ($E_N^{dep} \geq 20$ GeV per event)	$N_{sig} \leq 180$	~ 1	0°

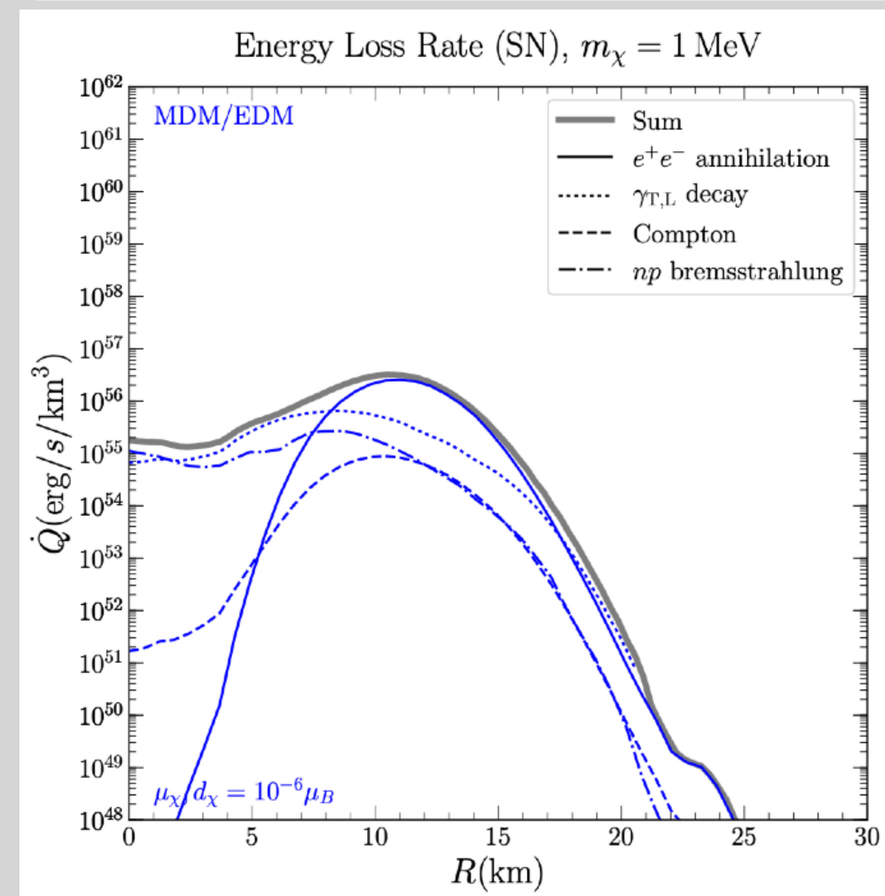


Stellar parameters









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

$$-\mu(\vec{B}\cdot\vec{\sigma}) - d(\vec{E}\cdot\vec{\sigma}) - a(\vec{j}\cdot\vec{\sigma})$$

$$-b(\nabla\cdot\vec{E}) - Q_{ij,\,\mathrm{traceless}}\nabla_i \vec{E}_j - \tilde{Q}_{ij}\nabla_i B_j - \ldots$$