Workshop on Multi-front Exotic phenomena in Particle and Astrophysics

Electromagnetic properties of sub-GeV dark states

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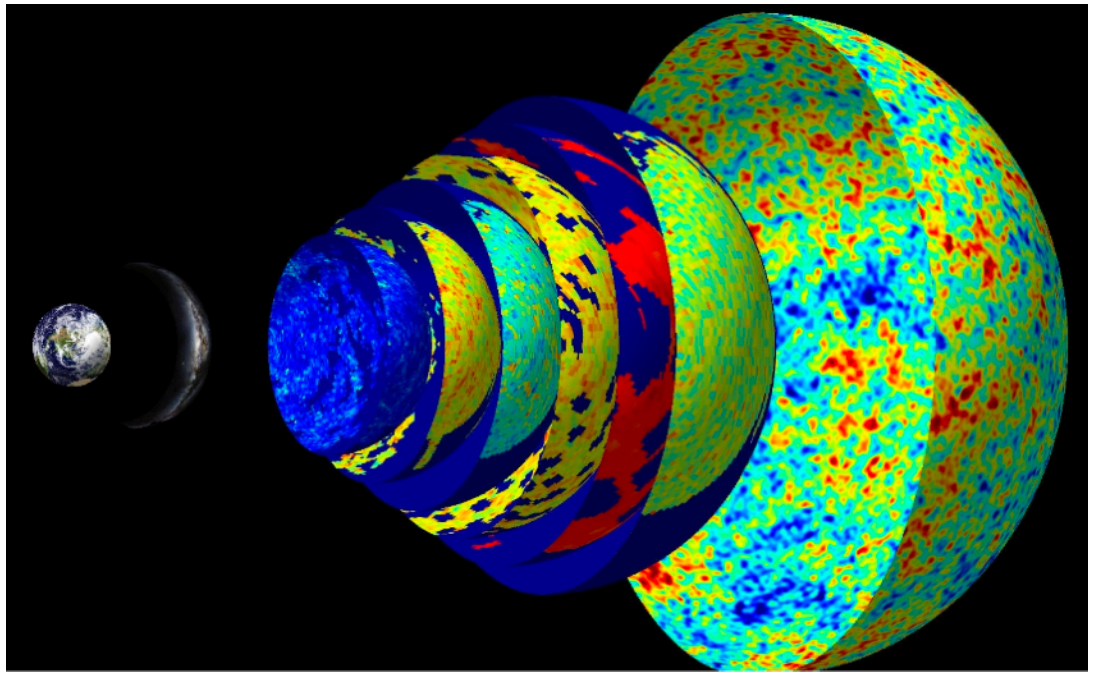
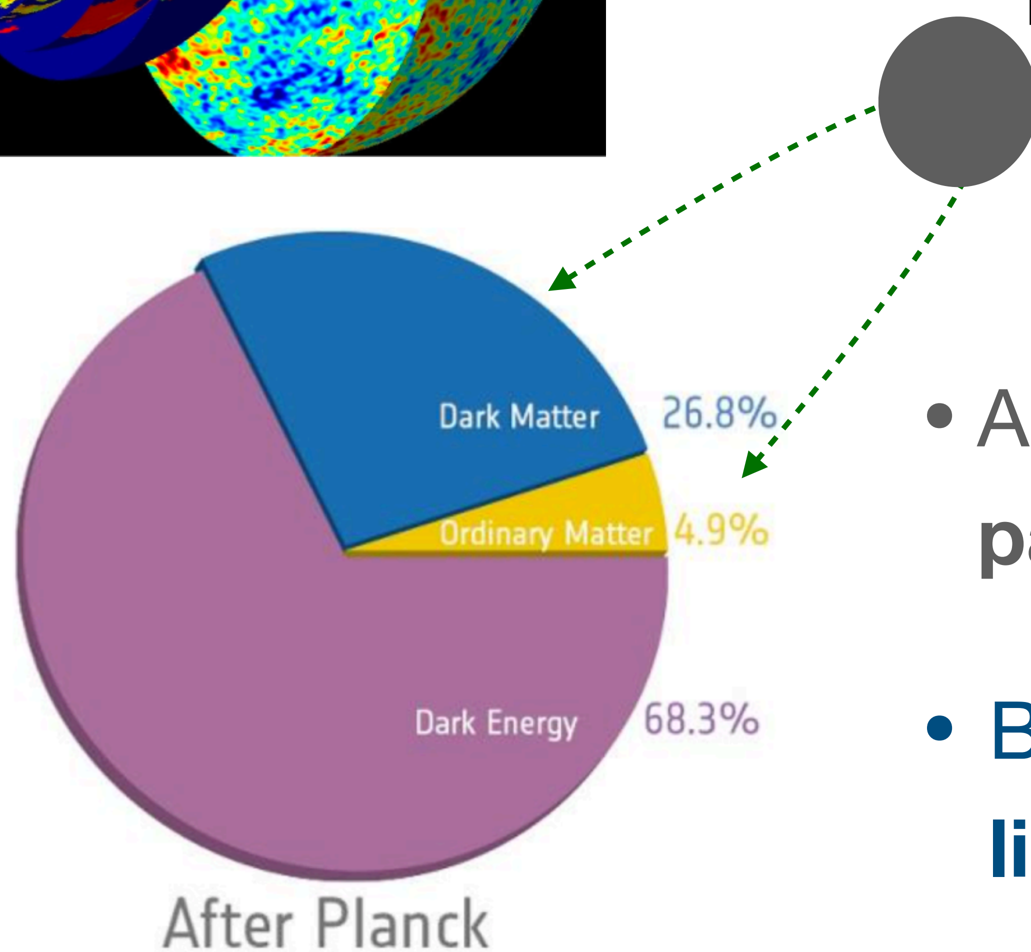
In collaboration with Junji Hisano, Alejandro Ibarra, Jui-Lin Kuo, Josef Pradler and Lukas Semmelrock

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 some **dark particle** can be **light**, and connect to **light**.

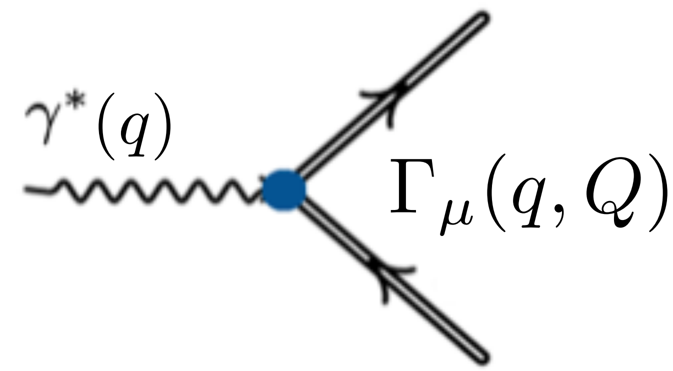
What can a photon portal be?

Explore the **electromagnetic (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

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

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

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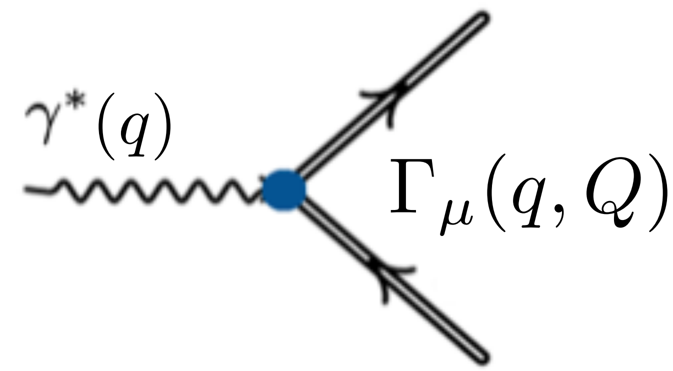

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$$q = \int d^3x \rho_{\text{EM}}(\vec{x}) \propto J_0(q=0, Q=0)$$

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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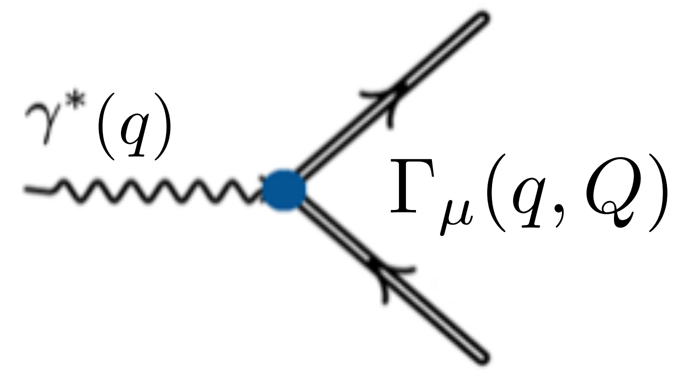

2. At higher-order (or a EM-neutral particle): dipoles, quadrupoles, …

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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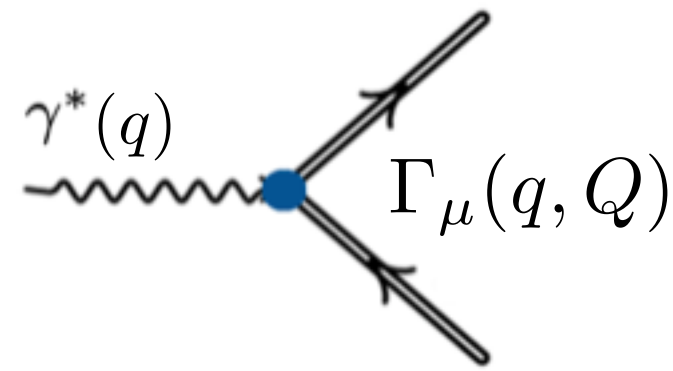

2. At higher-order (or a EM-neutral particle): dipoles, quadrupoles, …

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	$+1$

a. **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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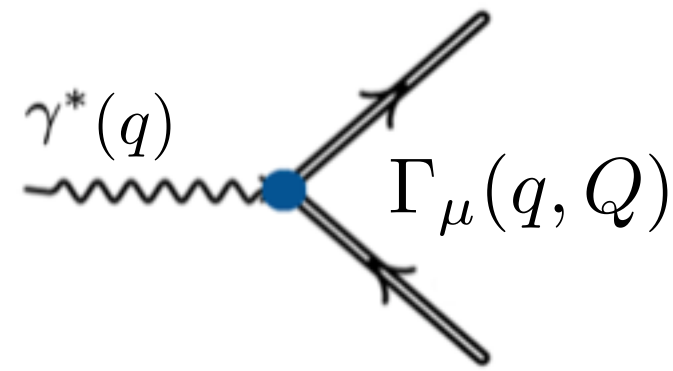

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b. independent indices for **Dirac fermion**

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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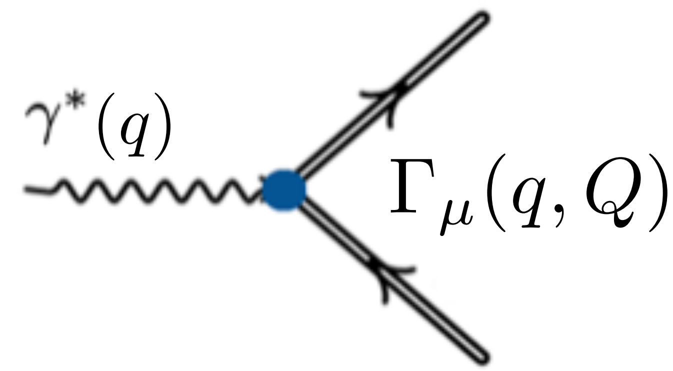

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c. independent indices for **vector boson**

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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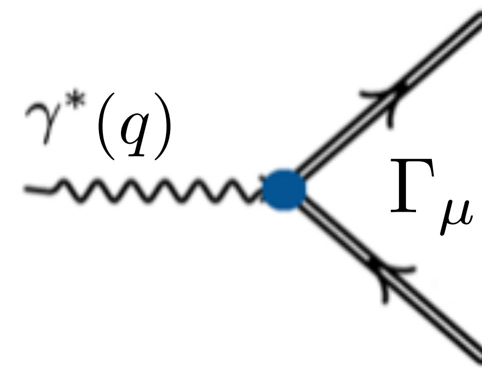

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For Self-Conjugate particles,

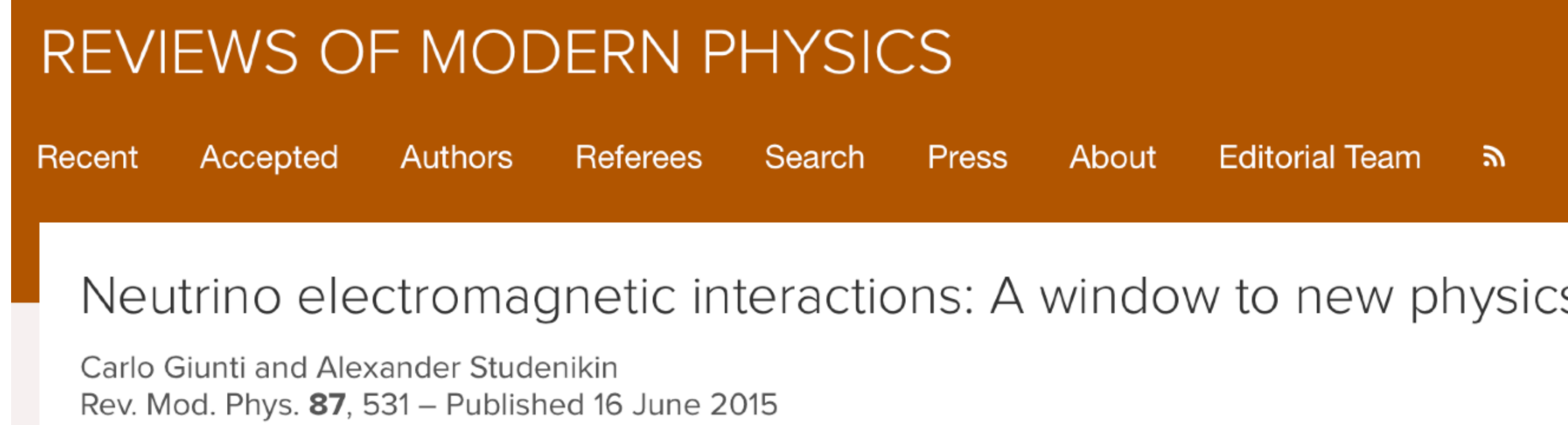
only C-odd factors survive:

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

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

Most have been done for

massless SM neutrinos.



Incomplete references

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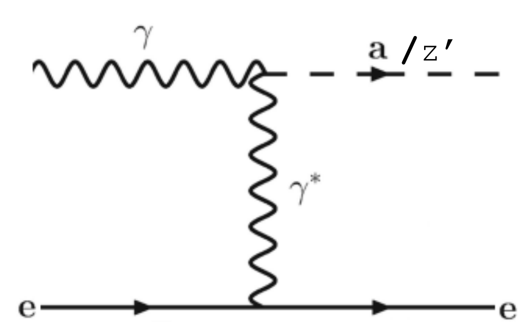
2. At higher-order (or a EM-neutral particle): dipoles, quadrupoles, …

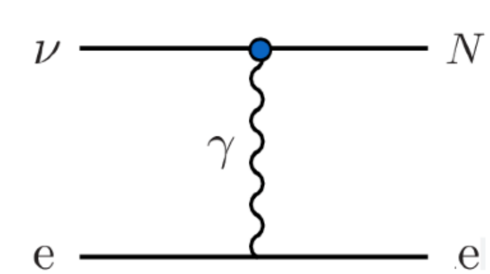
For technical details on multipole expansions, see e.g. V. M. Dubovik and A. A. Cheshkov. 1974, K. Gaemers & G. Gounaris, 1979, J. F. Nieves & P. B. Pal 1996, …

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

typically easier to produce and detect;

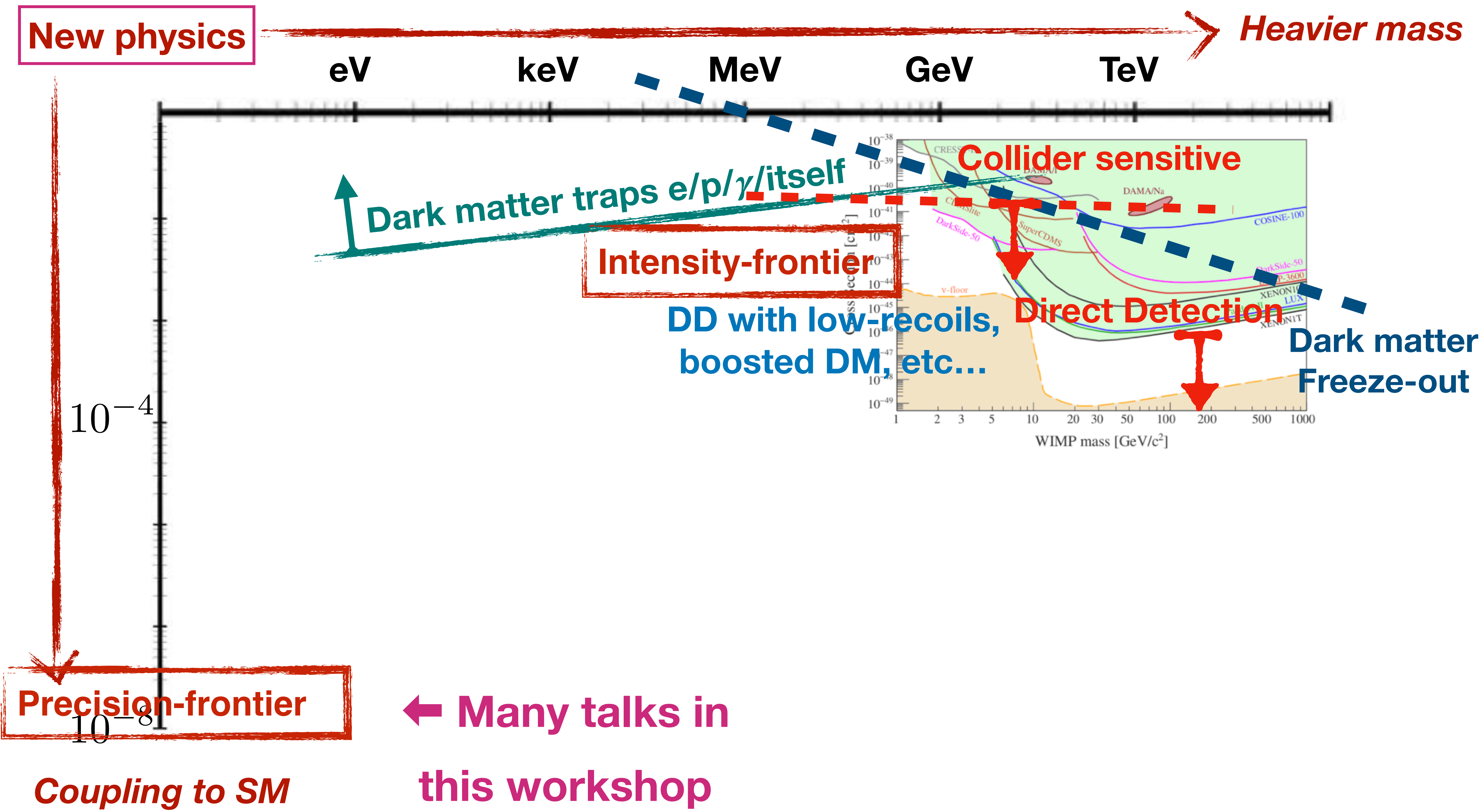
but **will not discussed here.**





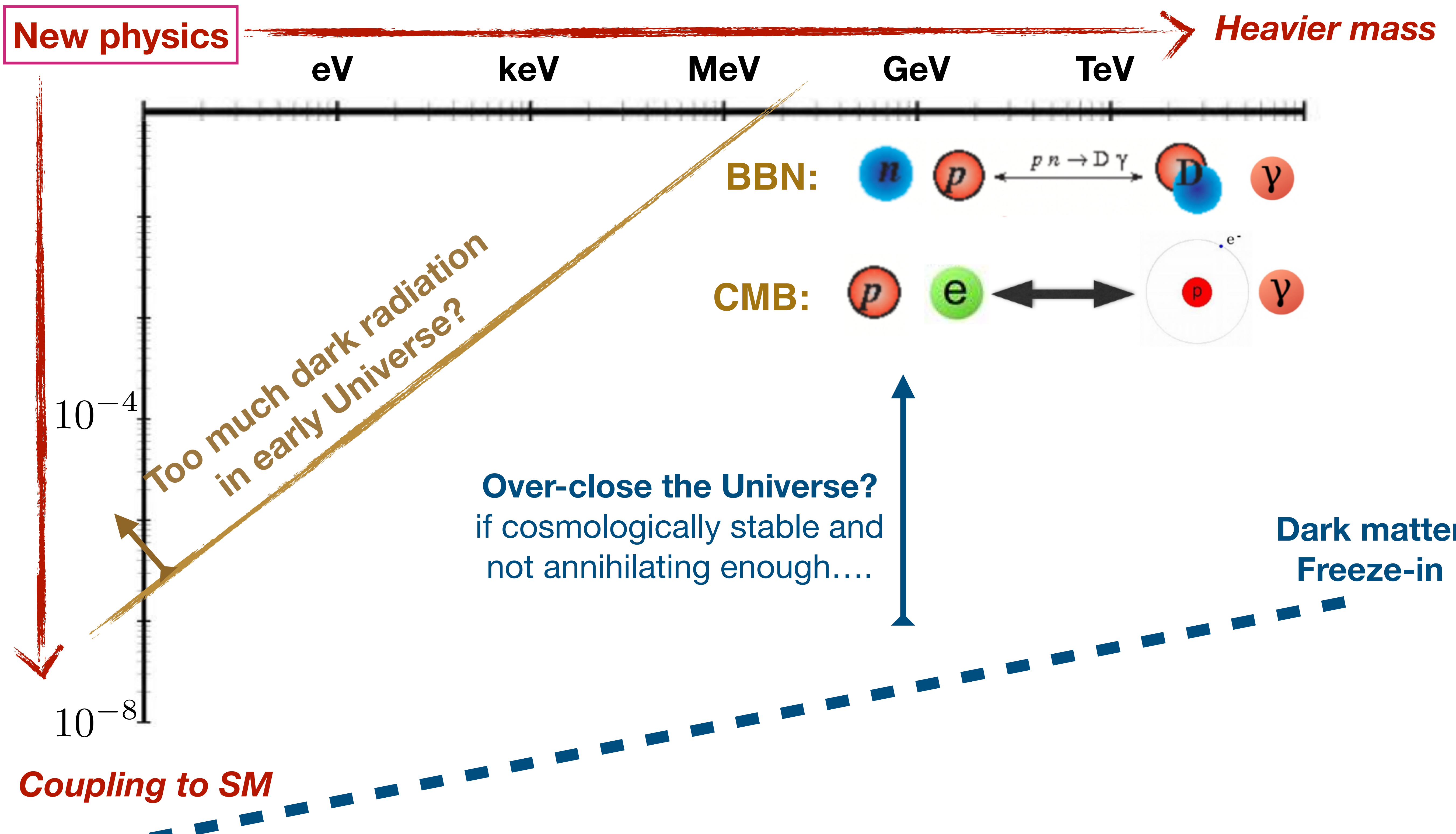
II. Sketch of constraints

A typical exclusion plot for a light dark particle



⬅ Many talks in this workshop

Many involves dark **pair production in medium**



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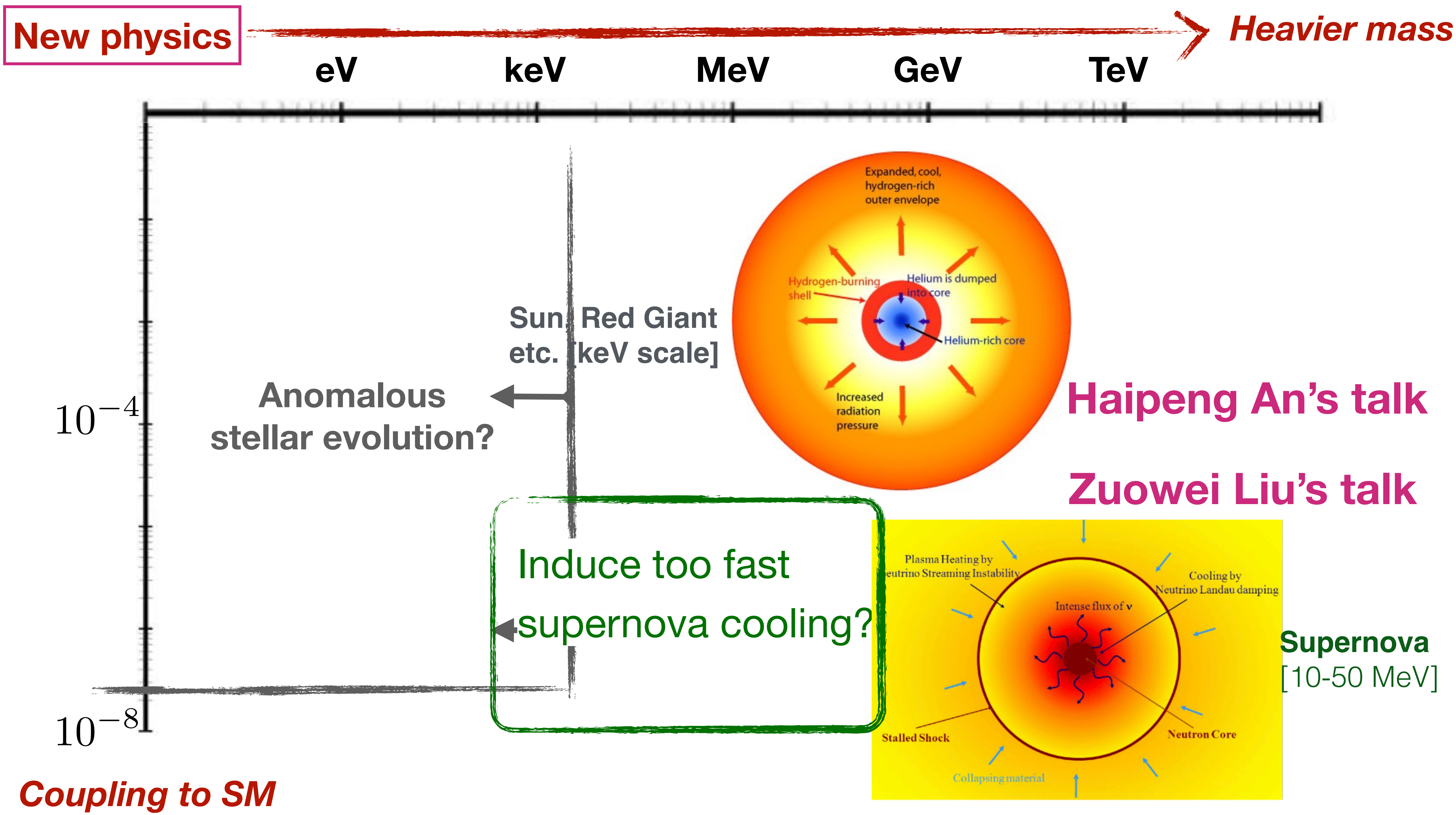
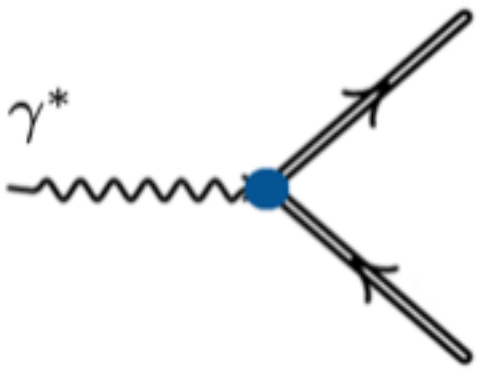


All rely on pair production through a (thermal) photon

Plasmon/photon decays into a pair of **dark particles (1,2)** via



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

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

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

For milli-charged scalar (S) and charge radius of scalar

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

$$f_S^{CR}(s) = \frac{g_1^2 s^3(1+4m_\phi^2/s)}{3m_\phi^4}$$

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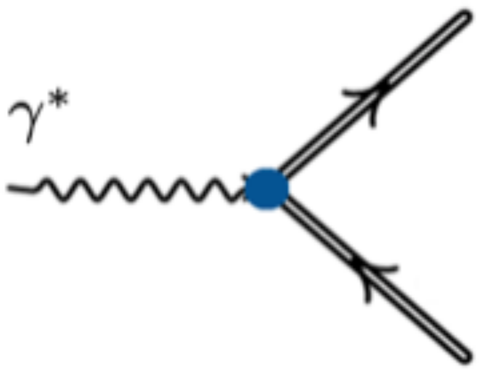

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For milli-charged scalar, fermion, and vector: **spin matters !**

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

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

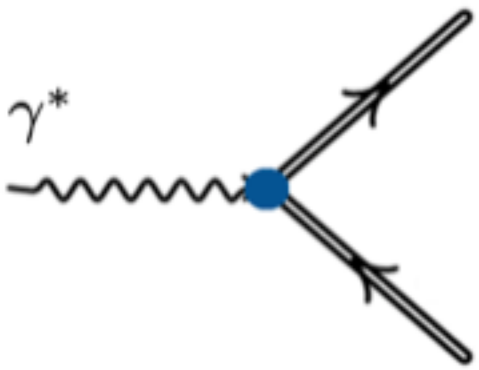
similar up to a pre-factor

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

apparent divergence at $m_V \to 0$.

All rely on pair production through a (thermal) photon

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.**

III. Energy scales excluded

Summarise **dim-4** constraints:

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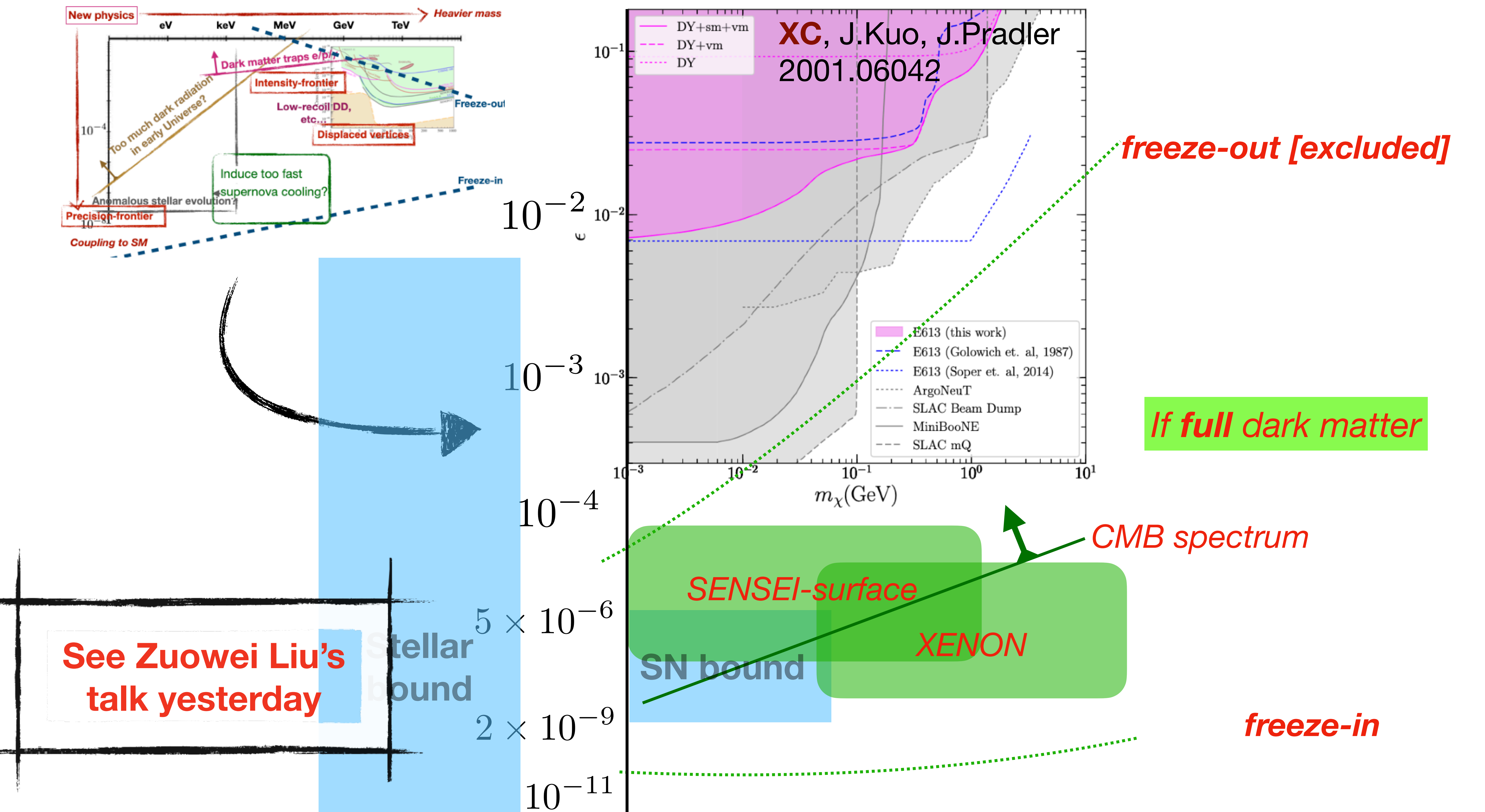
milli-charged, many known in the literature



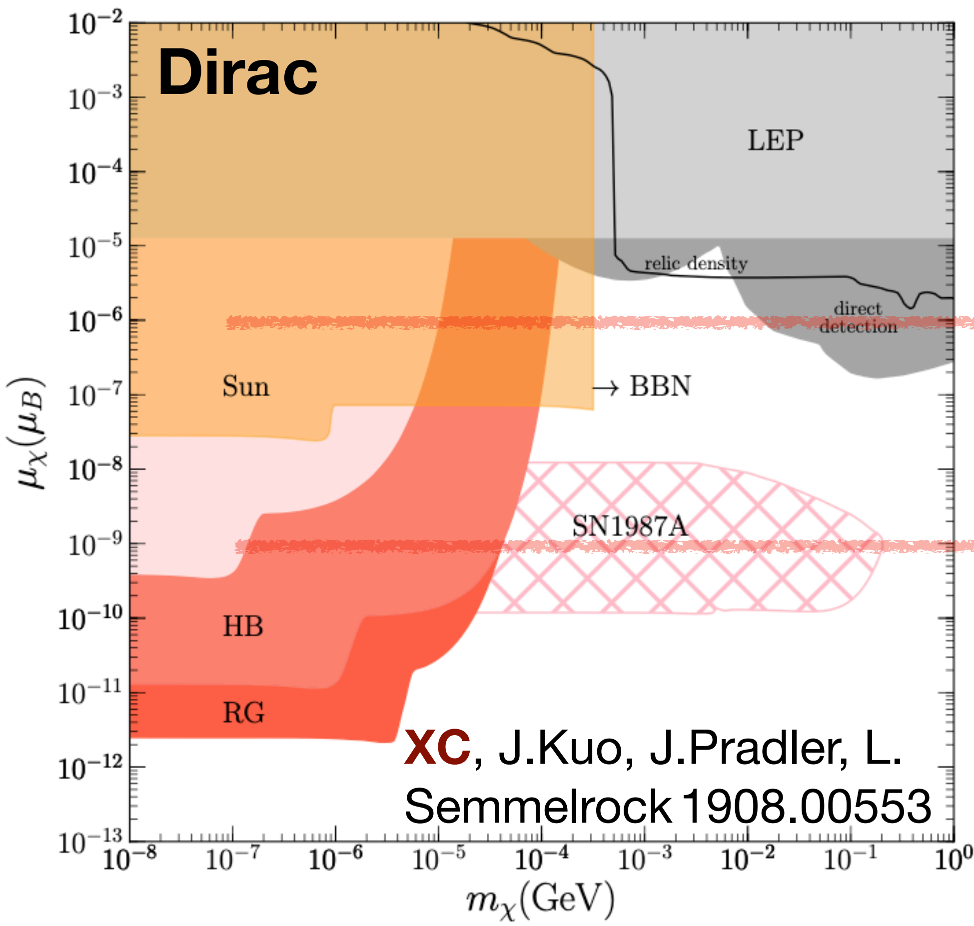
Summarise **dim-5 constraints** on fermions:

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

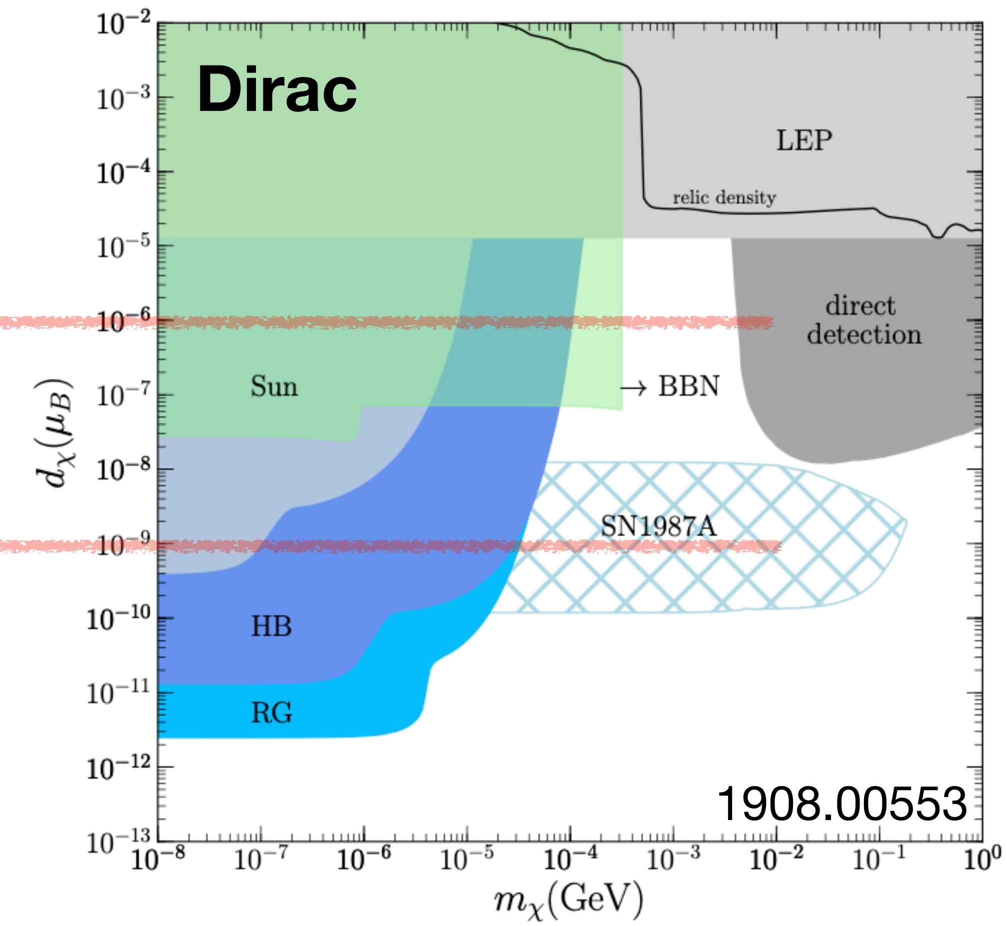


Intensity-frontier (see backup)

TeV

PeV

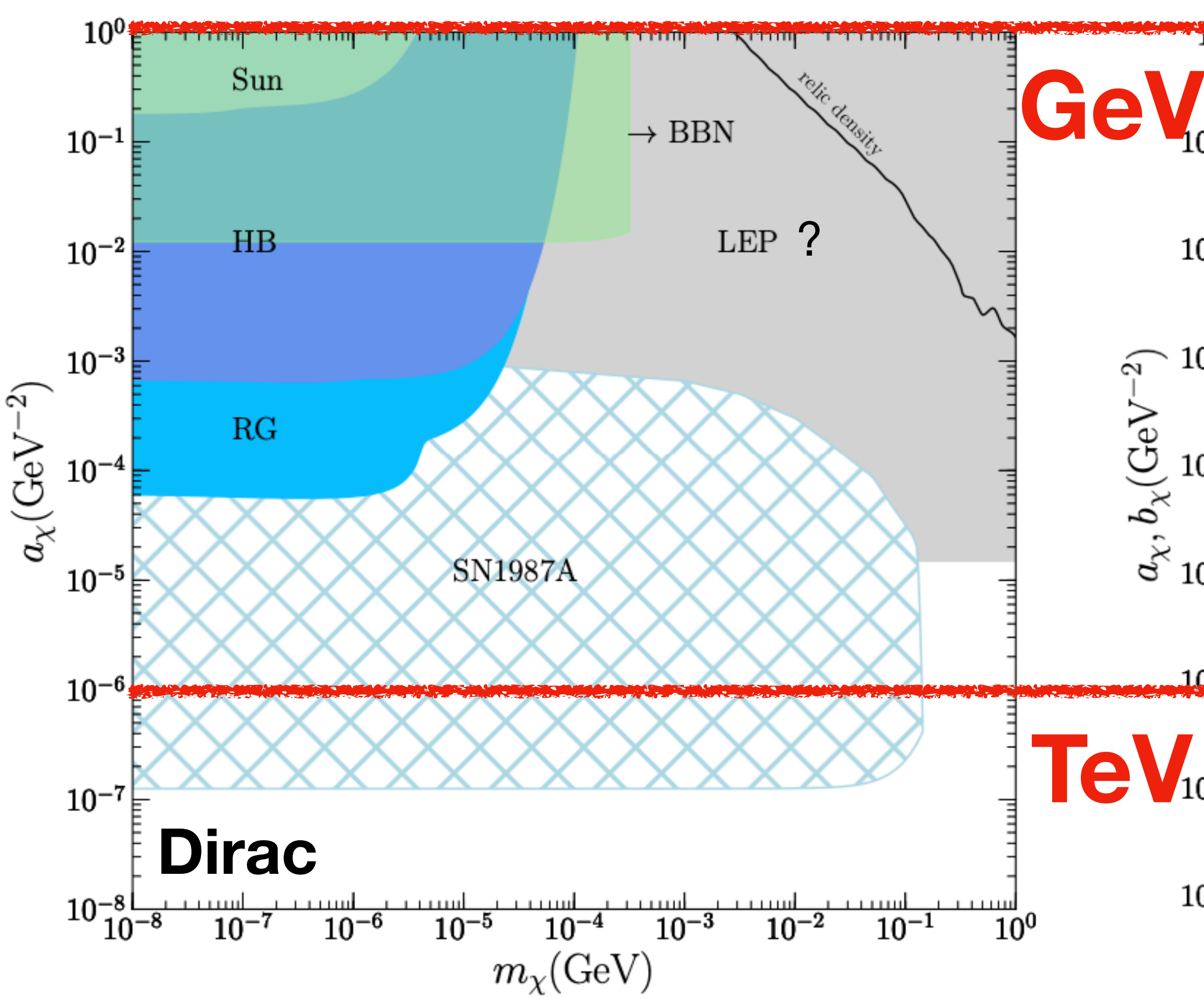
EDM

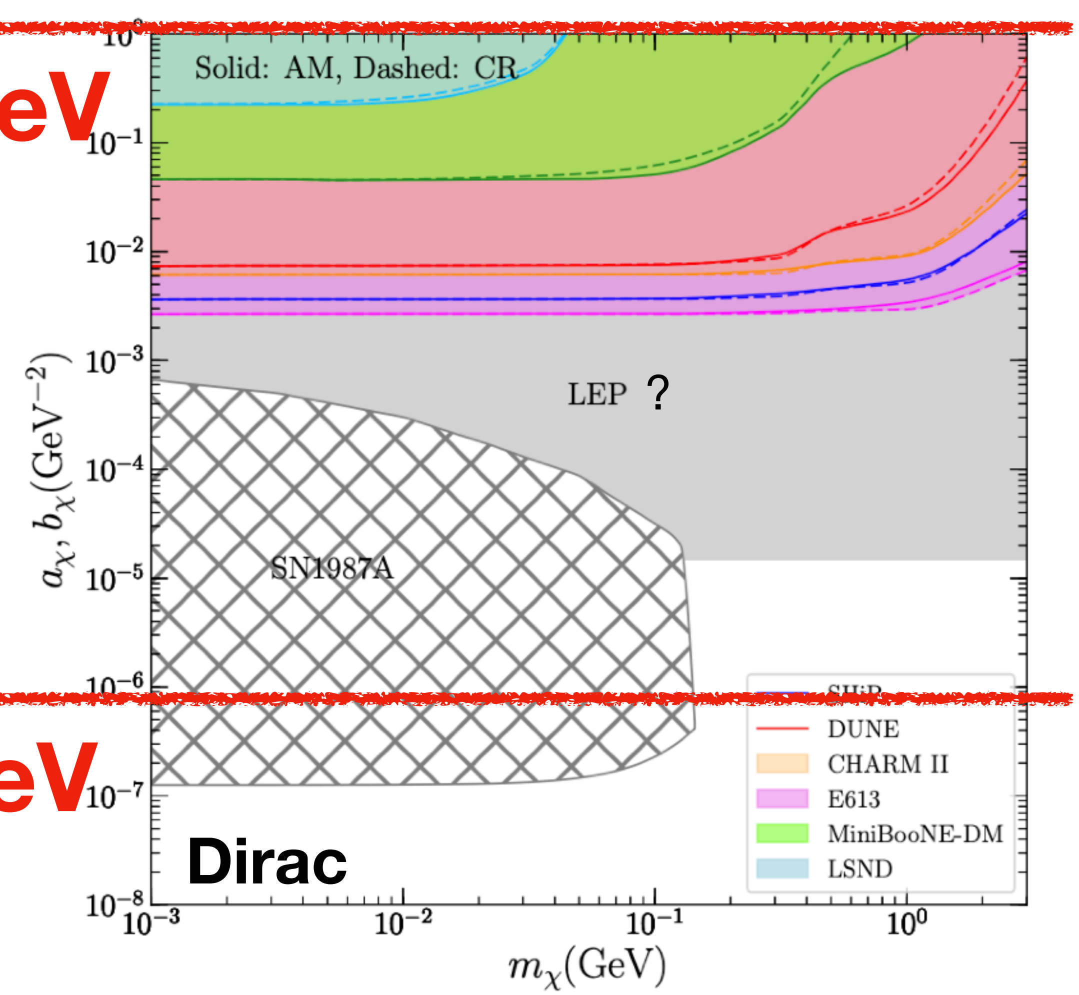


Summarise **dim-6 constraints** on fermions:

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	$\frac{4}{3}\frac{e^2(g_5^\chi)^2 s^3}{m_\chi^4}(1-\frac{4m_\chi^2}{s})$

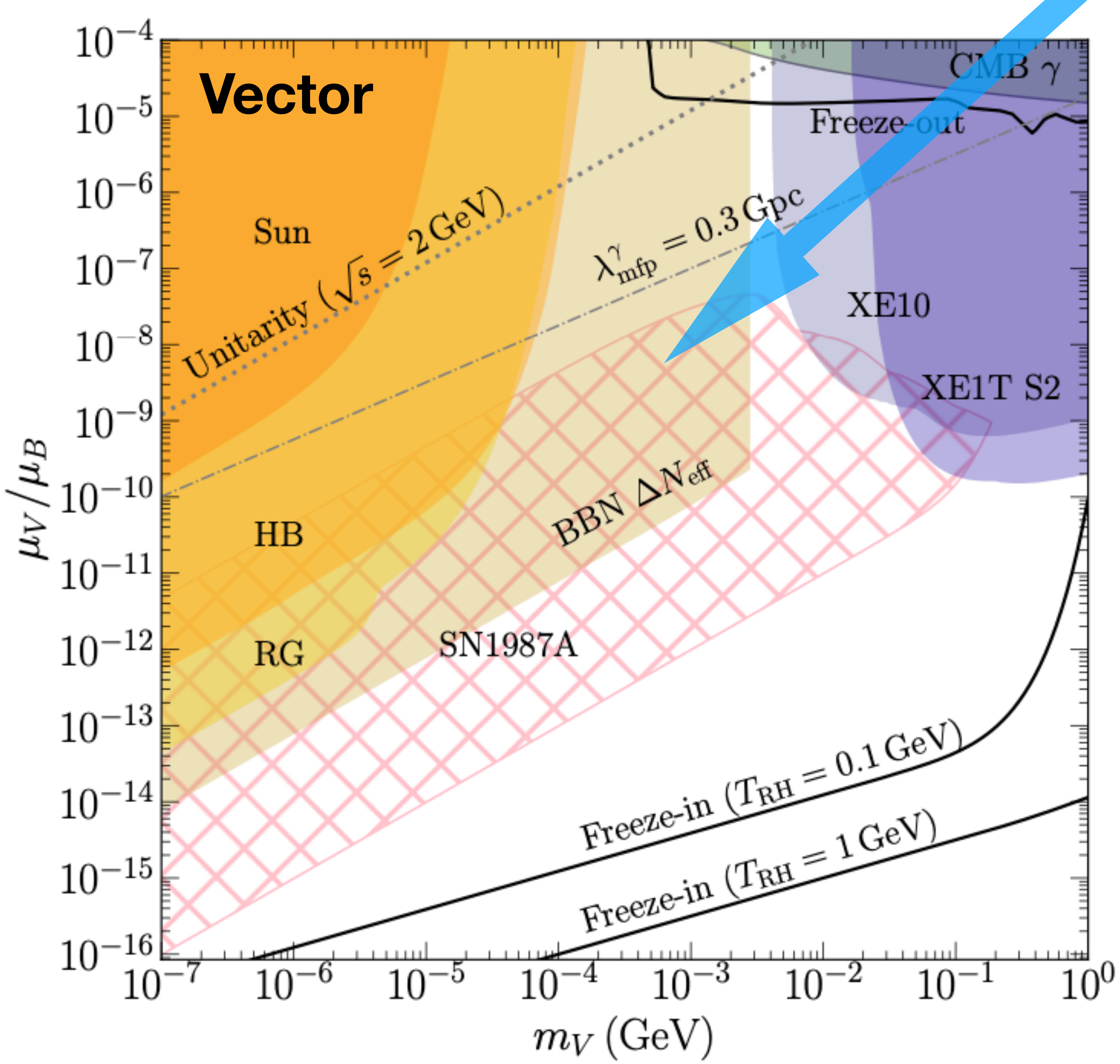
- **Colliders** easily beats **intensity-frontier for dim-6 operators**, while both **hardly apply to GeV** UV-scales.





Turn to spin-1 case: vector is different

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



1/m-enhanced:
mostly from
longitudinal modes

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

IV. Validity of vector constraints

Theoretical validity

EM form factors are defined at extreme 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. × (C.o.M)^{n} ≥ 1

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

  we impose 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 **UV-completions:**

- EM form factors are not necessarily independent.

Realization of **UV-completion**

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

E.g. consider terms with CP (**+ -**):

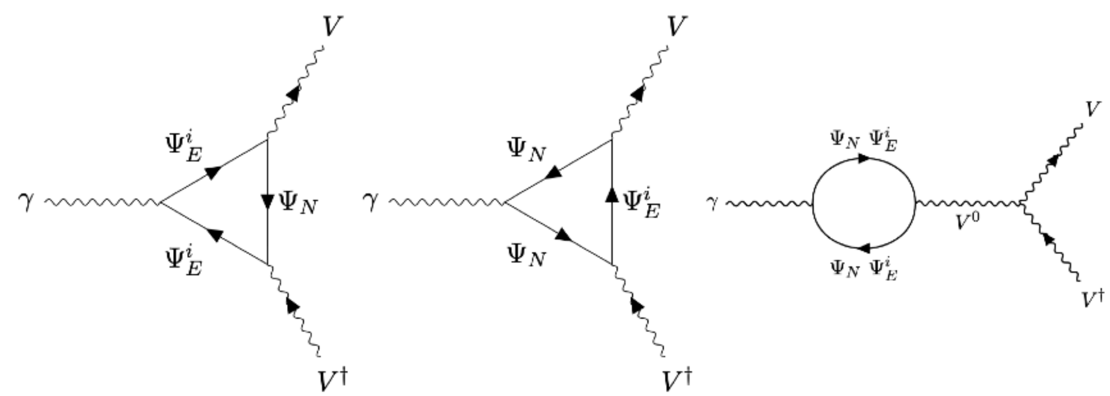
interaction type	coupling	C	P	CP
elec. dipole	d	$+1$	-1	-1
magn. quadrupole	$\tilde{Q}$	$+1$	-1	-1

each amplitude **diverges** at mV→0, even for transverse mode of V-production.

Dark SU(2) gauge bosons

with: 1) dark **doublet fermions** coupled to photon;

2) dark **doublet Higgs** generating masses.



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

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

the **divergences** in transverse modes **cancel** with each other.

CAUTION EM properties of a particle may not be independent from each other (if they have the **same CP**).

V. Conclusions

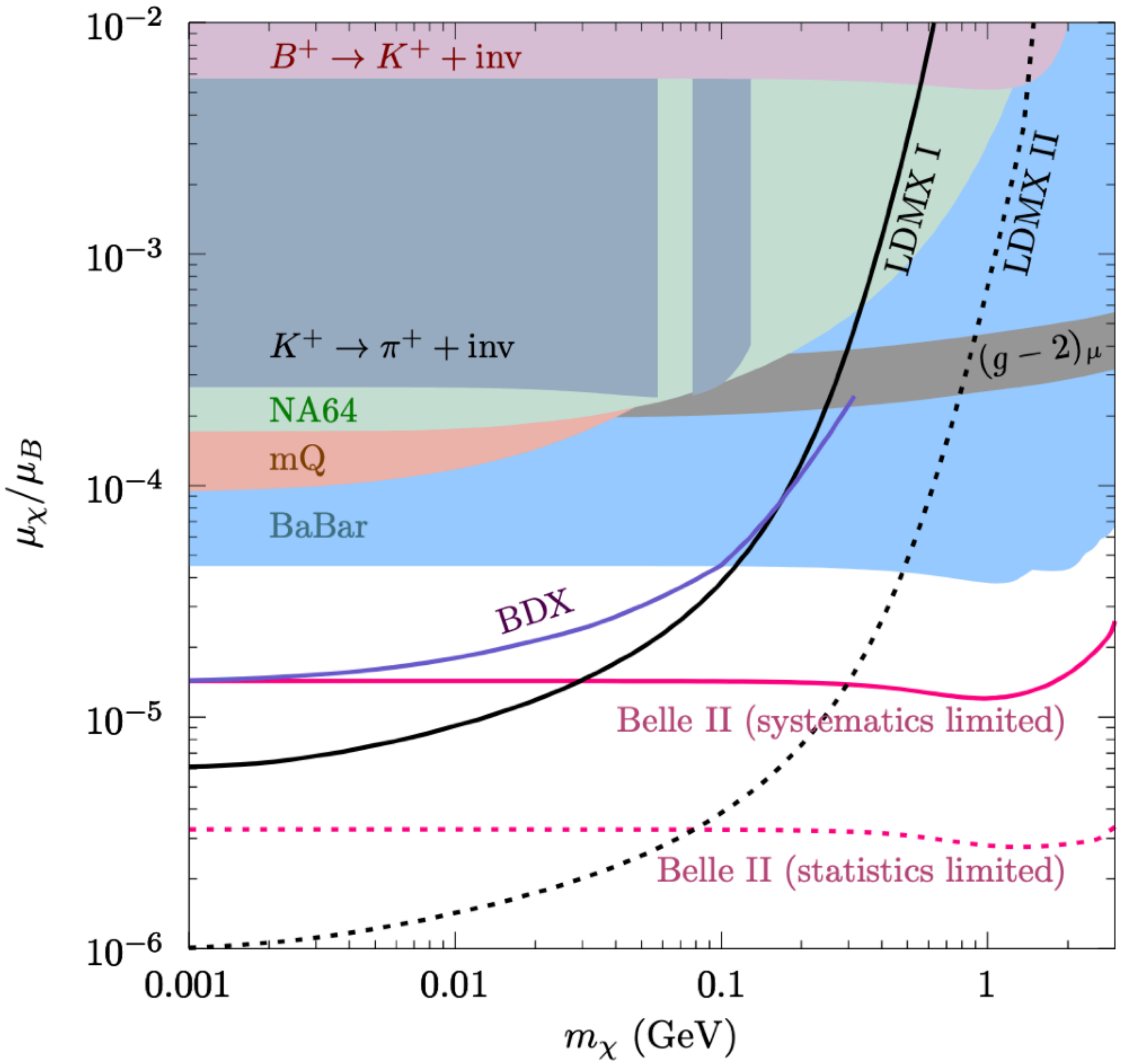
Conclusions

- So far no heavy new particles, try **something (with) light**?
- Appealing **light portal**: **multi-messenger** constraints/observations will be important to identify dark states;
- **Astrophysics** can be extremely useful in probing feeble dark states.
- Bounds on **EFT parameters/EM factors** are not always justified by UV models.

Backup

dark χ around keV-MeV: intensity-frontier

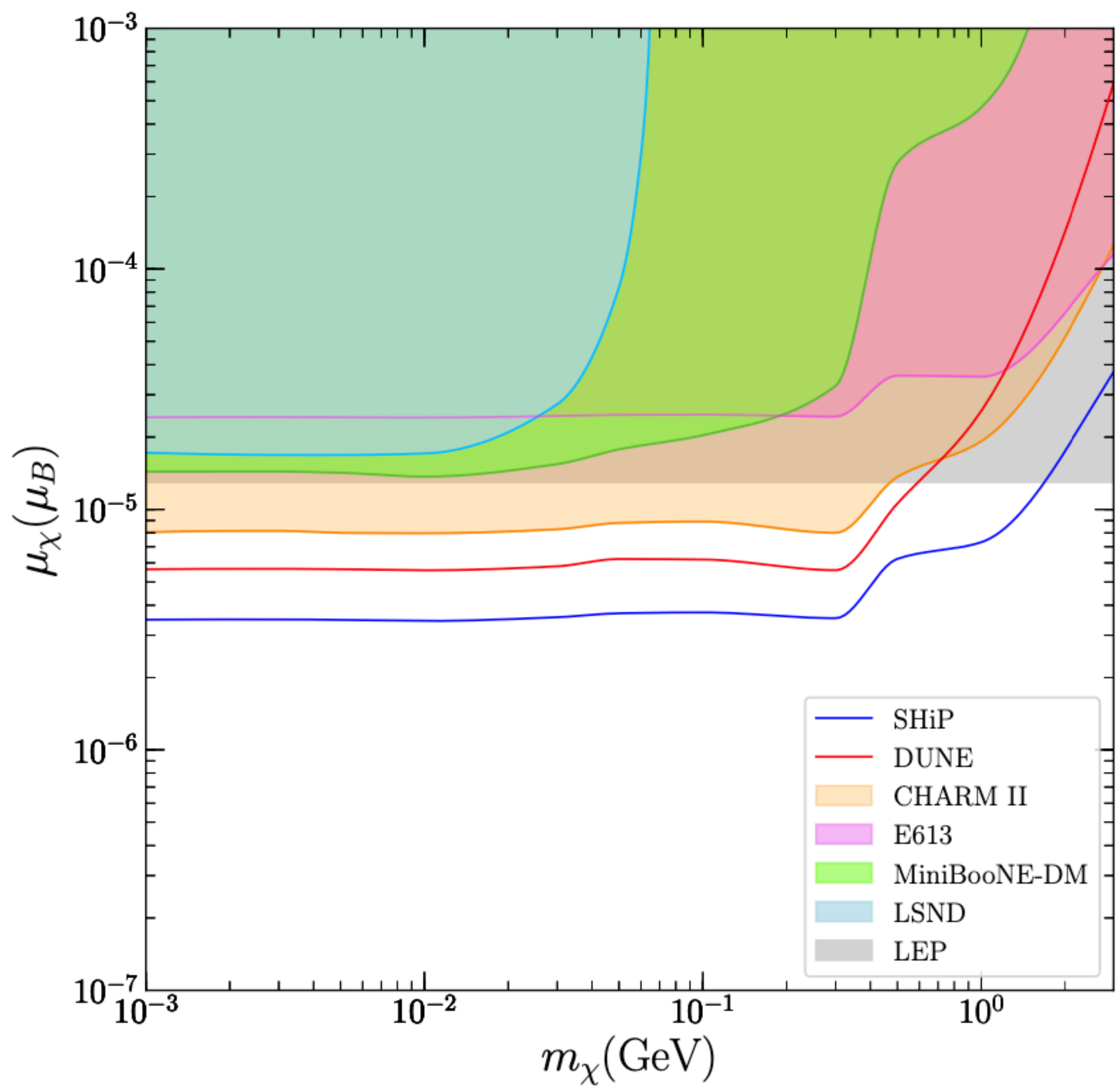
Electron-beam



XC, J.Pradler, L. Semmelrock 1811.04095

Proton-beam

XC, J.Kuo, J.Pradler 2001.06042



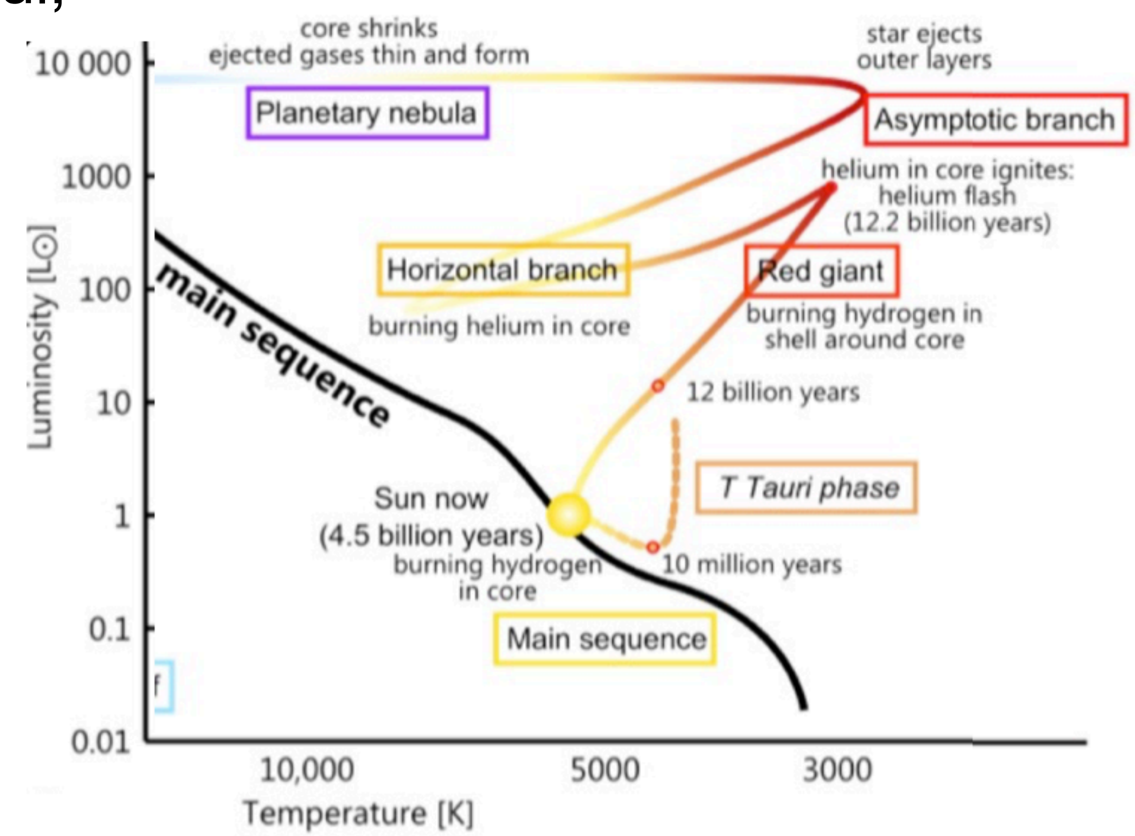
dark χ around keV-MeV: cosmos/stellar

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:

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

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

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.

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

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

Caveats do exist in the argument, such as:

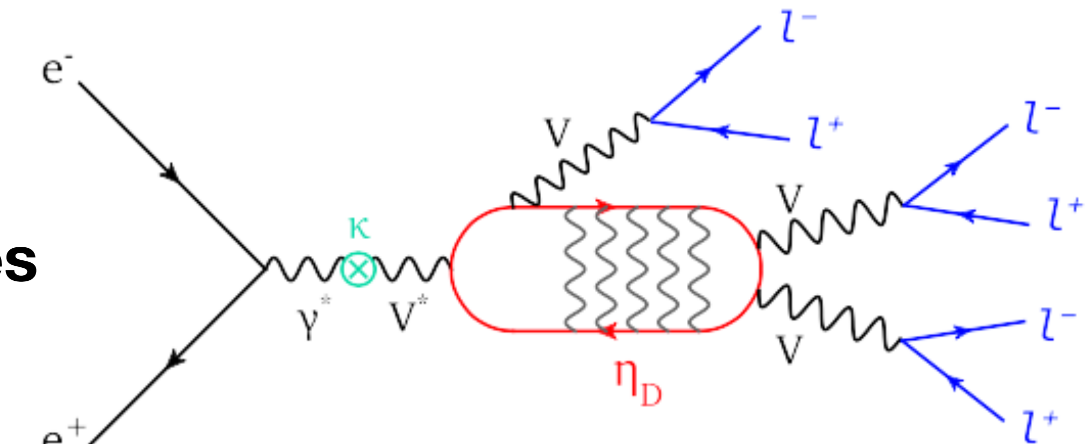
- dark state **trapping** by additional dark states *[e.g. Y. Zhang 1404.7172]*;
- **Production suppression** from large **thermal** mass/small **thermal** coupling of dark states *[e.g. W. DeRocco, P. W. Graham, S. Rajendran 2006.15112]*.
- if **SN1987A** was not neutrino-driven explosion *[e.g. N.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

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

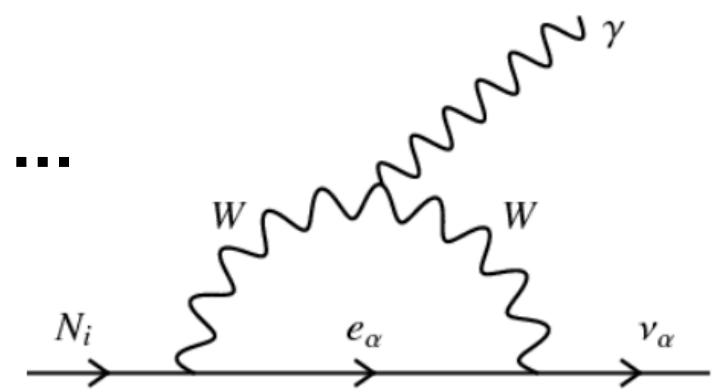


[An, Echenard, Pospelov, Zhang, 2015]

Displaced vertex

Low-energy cosmic photon beyond background:

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

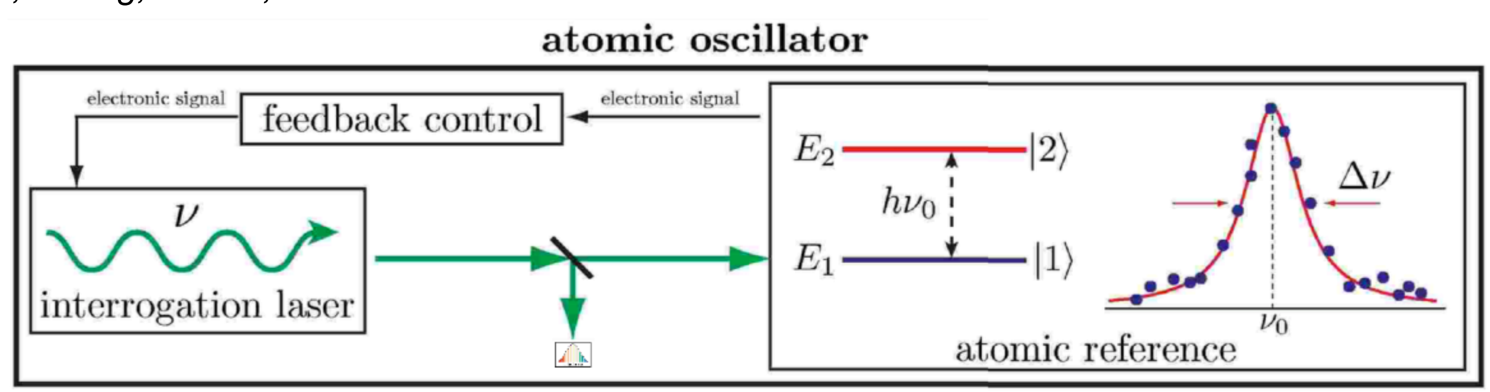


Detailed cosmos/astro.

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