

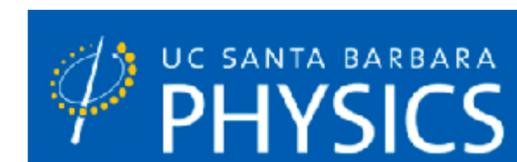


Effective Field Theories for Dark Matter Phenomenology

Zhengkang “Kevin” Zhang (UCSB)

Snowmass CSS, July 2022

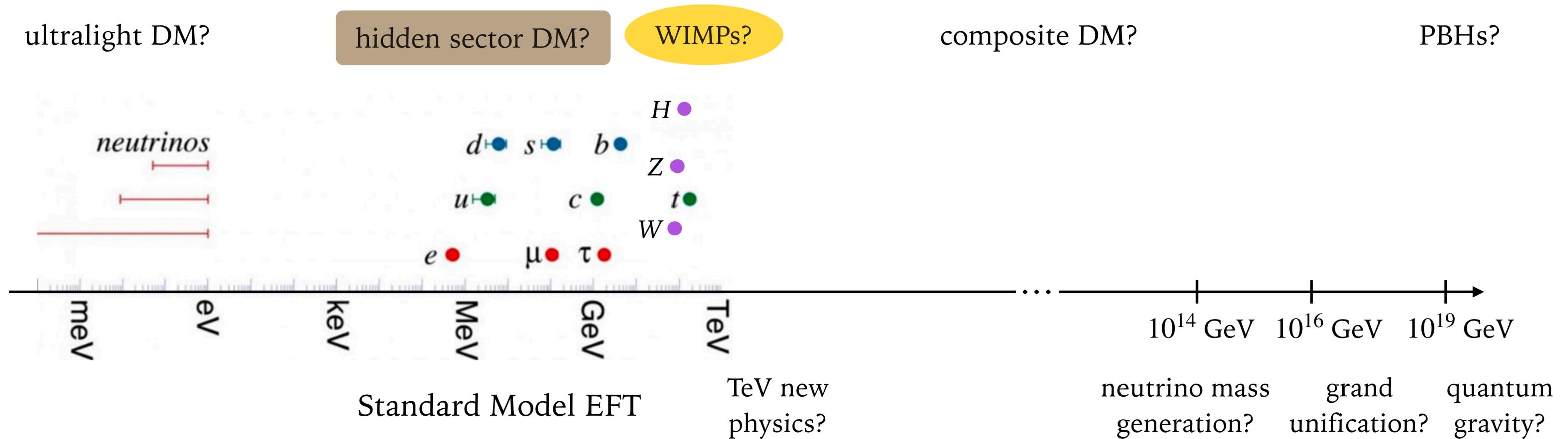
M. Baumgart, F. Bishara, J. Brod, T. Cohen, A. L. Fitzpatrick, M. Gorbahn, U. Moldanazarova, M. Reece, N. L. Rodd, M. P. Solon, R. Szafron, ZZ, J. Zupan [arXiv:2203.08204].



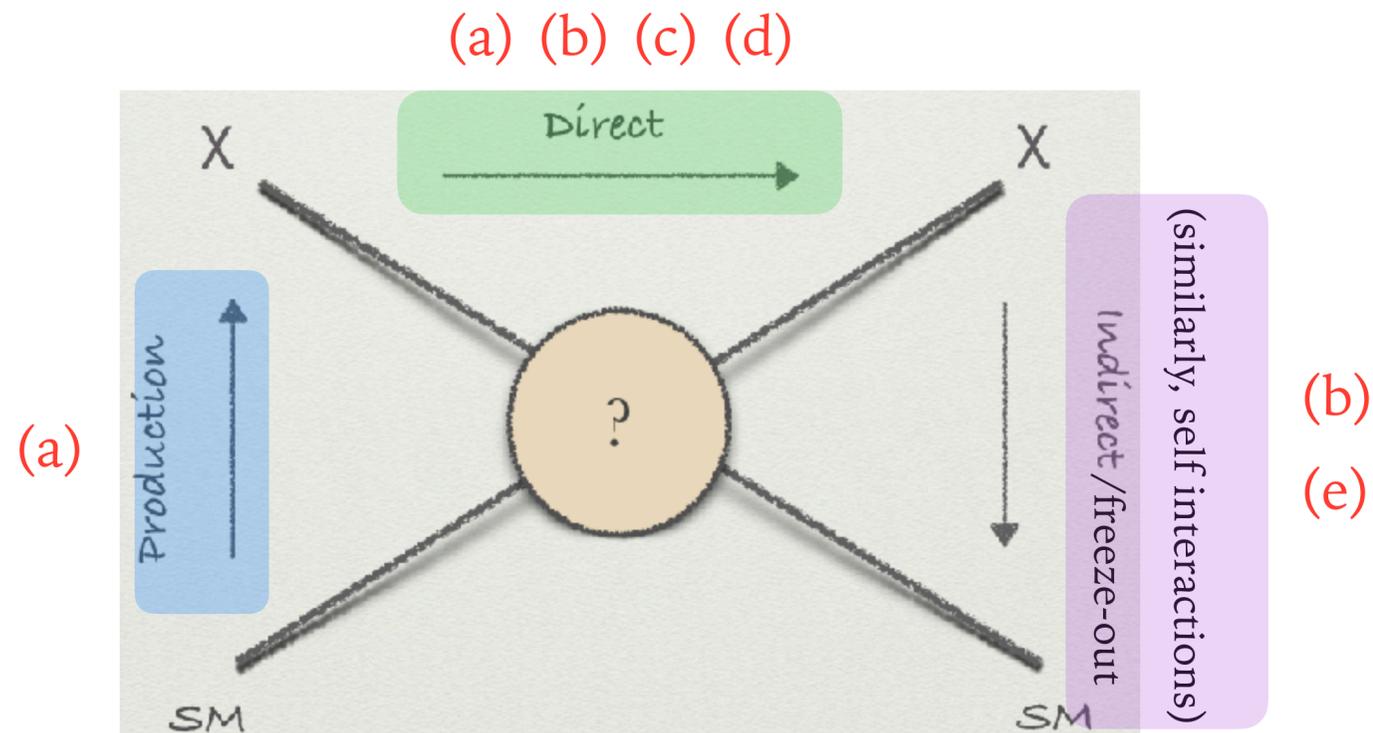
A tale of scales

Effective field theory (EFT): organizing framework when there's **scale separation**.

Unknown nature of dark matter (DM) \Rightarrow playground for a variety of EFT techniques.



Landscape of EFTs for DM phenomenology



- (a) SMEFT+DM (+mediator)
- (b) heavy particle/nonrelativistic EFT
- (c) ChPT, nuclear EFT
- (d) atomic/condensed matter EFT
- (e) soft collinear effective theory

Snowmass White Paper: Effective Field Theories for Dark Matter Phenomenology

Matthew Baumgart,^a Fady Bishara,^b Joachim Brod,^c Timothy Cohen,^d A. Liam Fitzpatrick,^e Martin Gorbahn,^f Ulserik Moldanazarova,^g Matthew Reece,^h Nicholas L. Rodd,ⁱ Mikhail P. Solon,^j Robert Szafron,^k Zhengkang Zhang,^l Jure Zupan^c

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Rich and exciting subject. (Apologies for not being comprehensive.)

[arXiv:2203.08204]

Recurring themes

Things become **simple** when scales are separated.

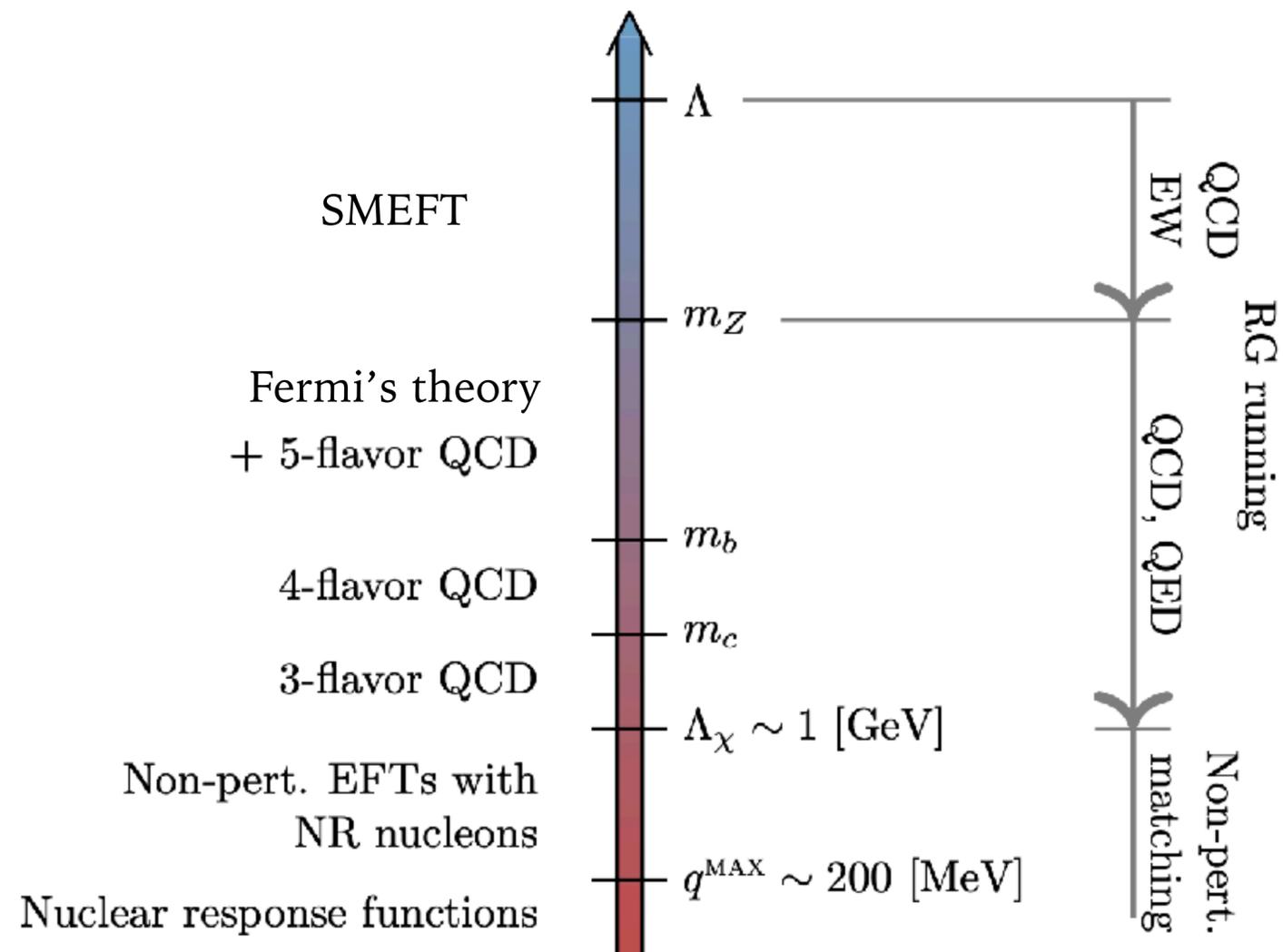
Small set of parameters at leading order; systematically improvable by EFT power counting.

Things become **complicated** when scales are separated.

Perturbation theory is plagued by large logs and may break down; resummation is required.

EFTs are both convenient and indispensable.

Direct detection: an EFT pipeline



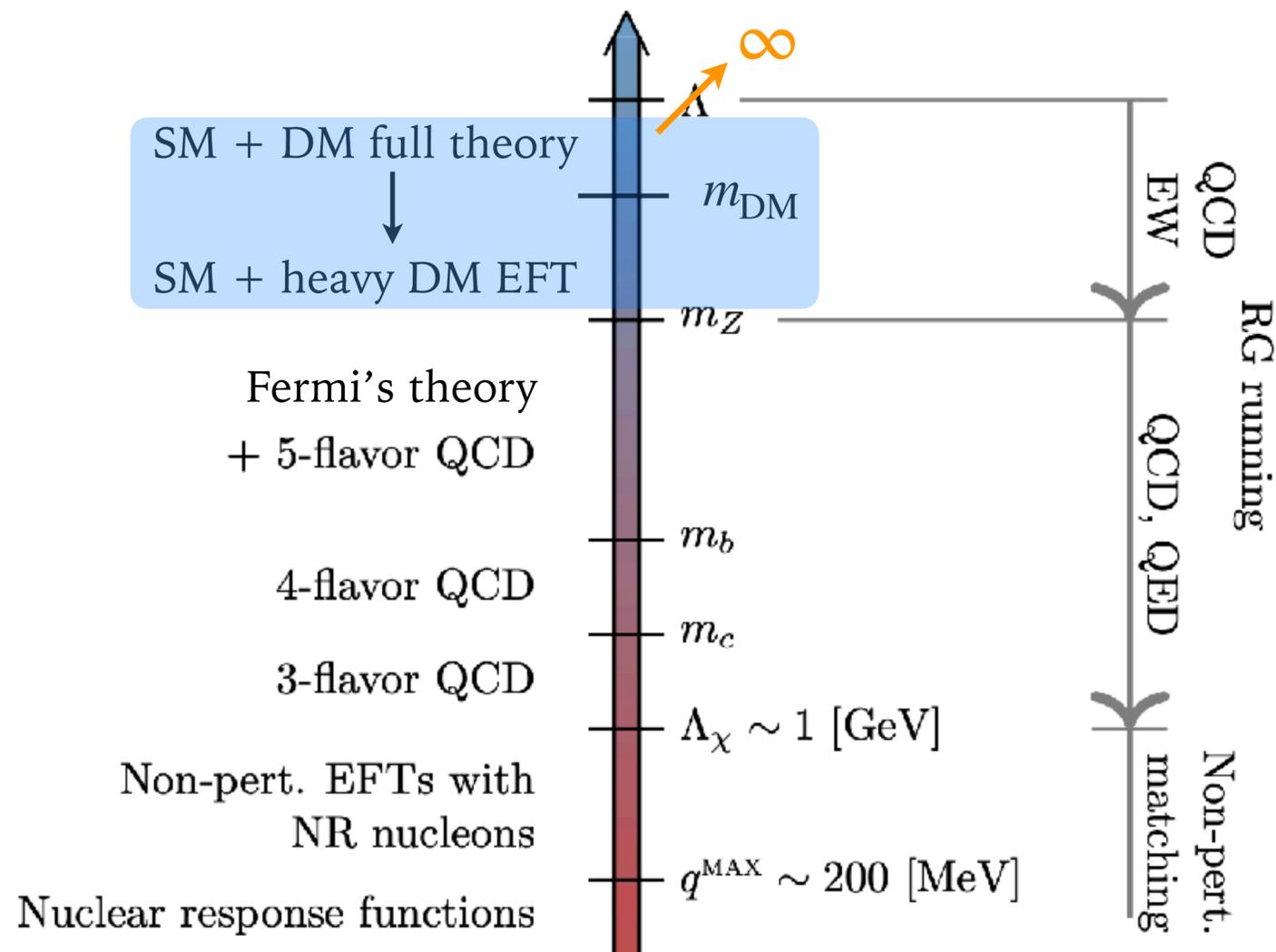
m_{DM} introduces another scale to integrate out* somewhere along the flow.

* integrate out the mass but not the particle; match onto heavy particle/nonrelativistic EFT

Figure adapted from F.Bishara, J.Brod, B.Grinstein, J.Zupan, 1809.03506.

Direct detection: an EFT pipeline

Example: electroweak-charged WIMPs (e.g. 3TeV thermal wino benchmark).



Heavy particle ($1/M$) expansion \Rightarrow

$$\mathcal{L} = \bar{h}_v \left\{ i v \cdot D - \delta m - \frac{D_\perp^2}{2M} + c_H \frac{H^\dagger H}{M} + c_{W1} \frac{\sigma^{\mu\nu} W_{\mu\nu}}{M} + c_{W2} \frac{\epsilon^{\mu\nu\rho\sigma} \sigma_{\mu\nu} W_{\rho\sigma}}{M} + \dots \right\} h_v$$

LO: **universal** heavy DM limit.

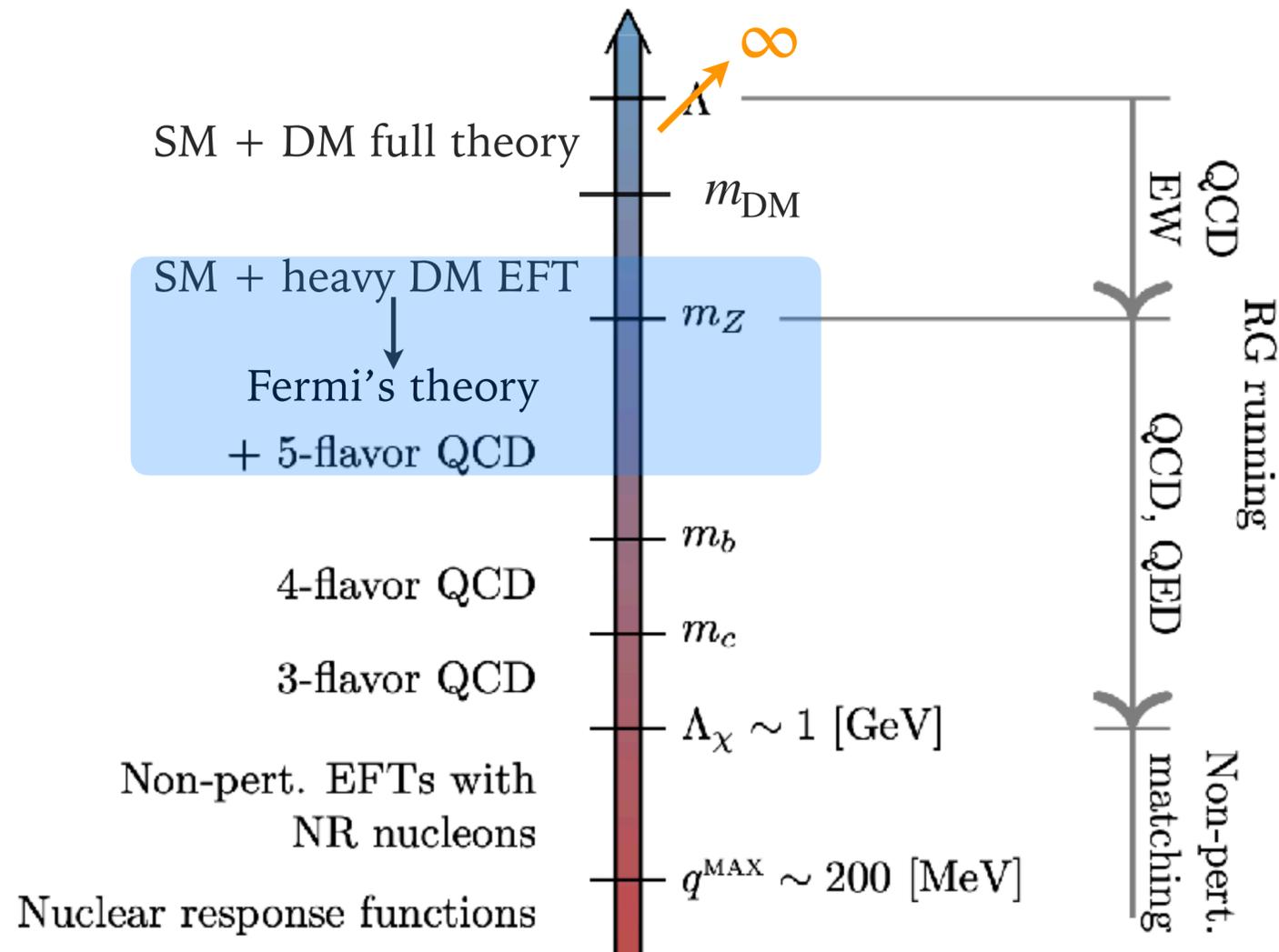
NLO: $1/M$ power correction; for SI scattering, model dependence encoded in a **single parameter c_H** .

Hill, Solon, 1111.0016.

Chen, Hill, Solon, Wijangco, 1801.08551.

Direct detection: an EFT pipeline

Example: electroweak-charged WIMPs (e.g. 3TeV thermal wino benchmark).



Weak scale matching \Rightarrow

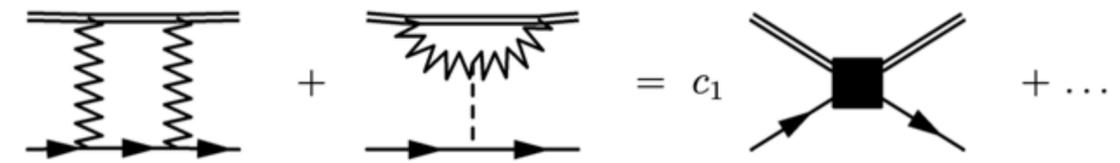
$$\mathcal{L}_{\phi_0, \text{SM}} = \frac{1}{m_W^3} \phi_v^* \phi_v \left\{ \sum_q \left[c_{1q}^{(0)} O_{1q}^{(0)} + c_{1q}^{(2)} v_\mu v_\nu O_{1q}^{(2)\mu\nu} \right] + c_2^{(0)} O_2^{(0)} + c_2^{(2)} v_\mu v_\nu O_2^{(2)\mu\nu} \right\} + \dots$$

$$O_{1q}^{(0)} = m_q \bar{q} q,$$

$$O_2^{(0)} = (G_{\mu\nu}^A)^2,$$

$$O_{1q}^{(2)\mu\nu} = \bar{q} \left(\gamma^{\{\mu} i D^{\nu\}} - \frac{1}{d} g^{\mu\nu} i \not{D} \right) q,$$

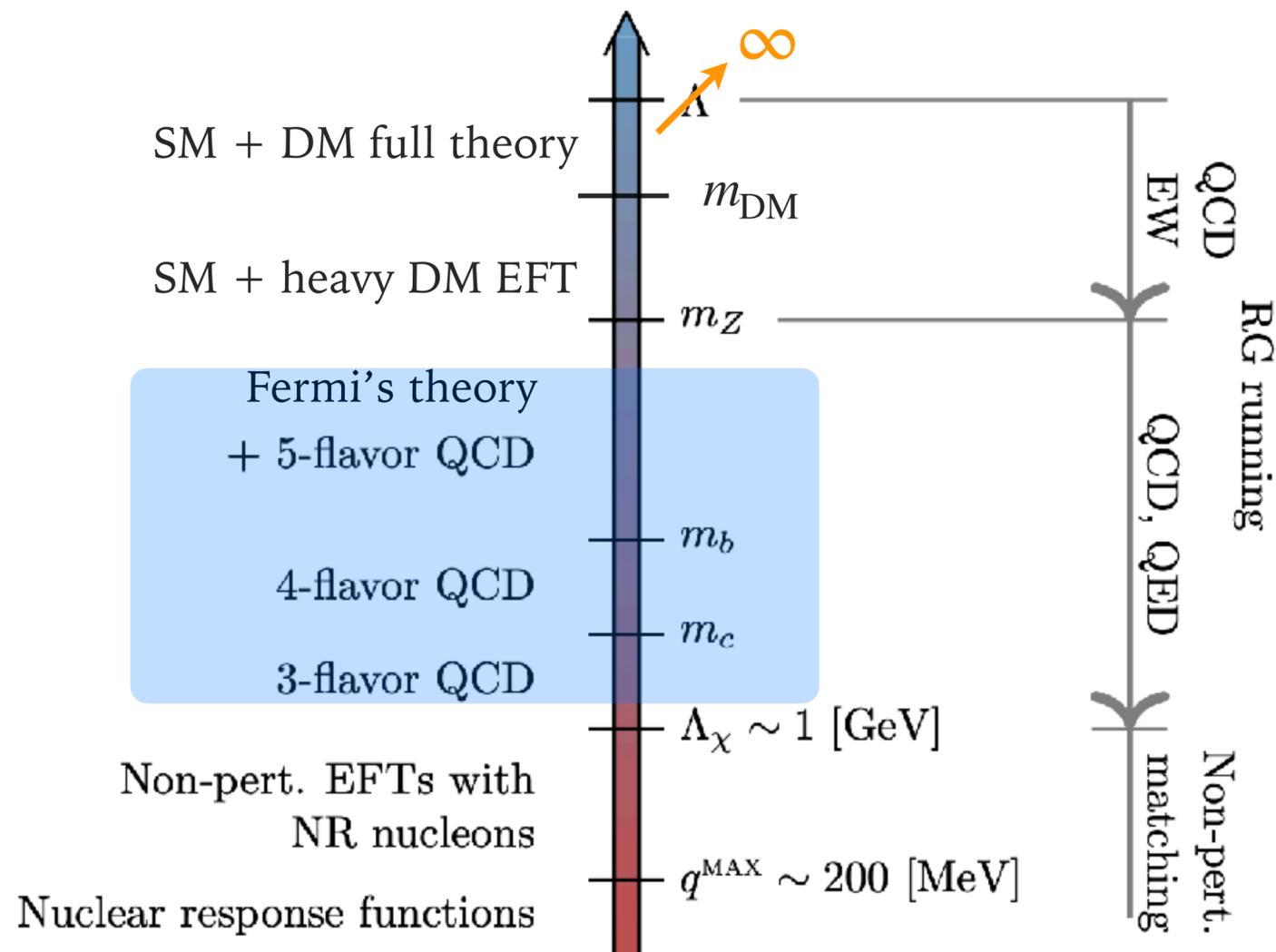
$$O_2^{(2)\mu\nu} = -G^{A\mu\lambda} G_{\lambda\nu}^A + \frac{1}{d} g^{\mu\nu} (G_{\alpha\beta}^A)^2.$$



Hill, Solon, 1401.3339.

Direct detection: an EFT pipeline

Example: electroweak-charged WIMPs (e.g. 3TeV thermal wino benchmark).



$$\mathcal{L}_{\phi_0, \text{SM}} = \frac{1}{m_W^3} \phi_v^* \phi_v \left\{ \sum_q \left[c_{1q}^{(0)} O_{1q}^{(0)} + c_{1q}^{(2)} v_\mu v_\nu O_{1q}^{(2)\mu\nu} \right] + c_2^{(0)} O_2^{(0)} + c_2^{(2)} v_\mu v_\nu O_2^{(2)\mu\nu} \right\} + \dots$$

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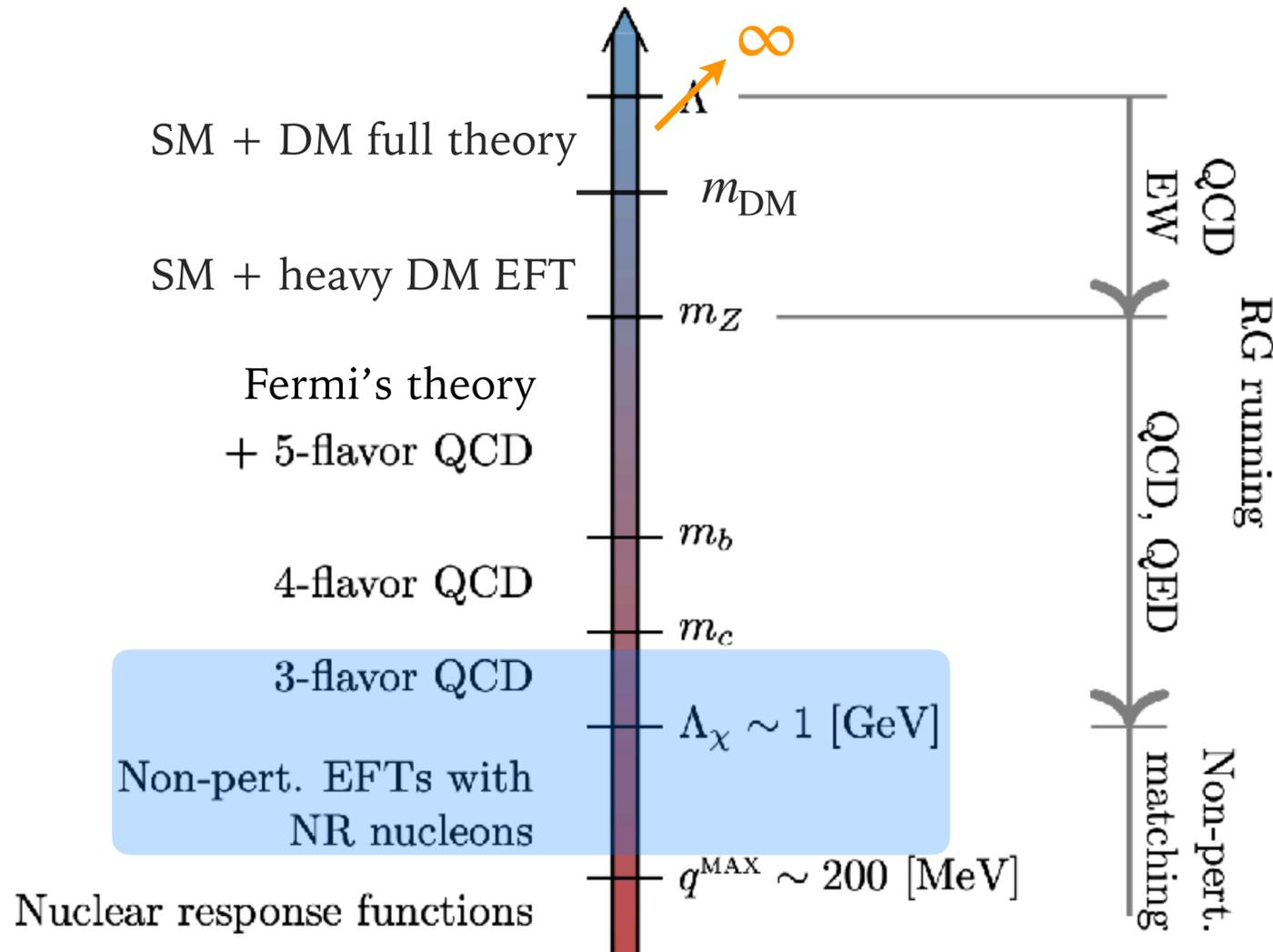
$$O_2^{(2)\mu\nu} = -G^{A\mu\lambda} G_{\lambda\nu}^A + \frac{1}{d} g^{\mu\nu} (G_{\alpha\beta}^A)^2.$$

RG evolve down to ~ 1 GeV (integrating out bottom and charm along the way).

Hill, Solon, 1409.8290.

Direct detection: an EFT pipeline

Example: electroweak-charged WIMPs (e.g. 3TeV thermal wino benchmark).



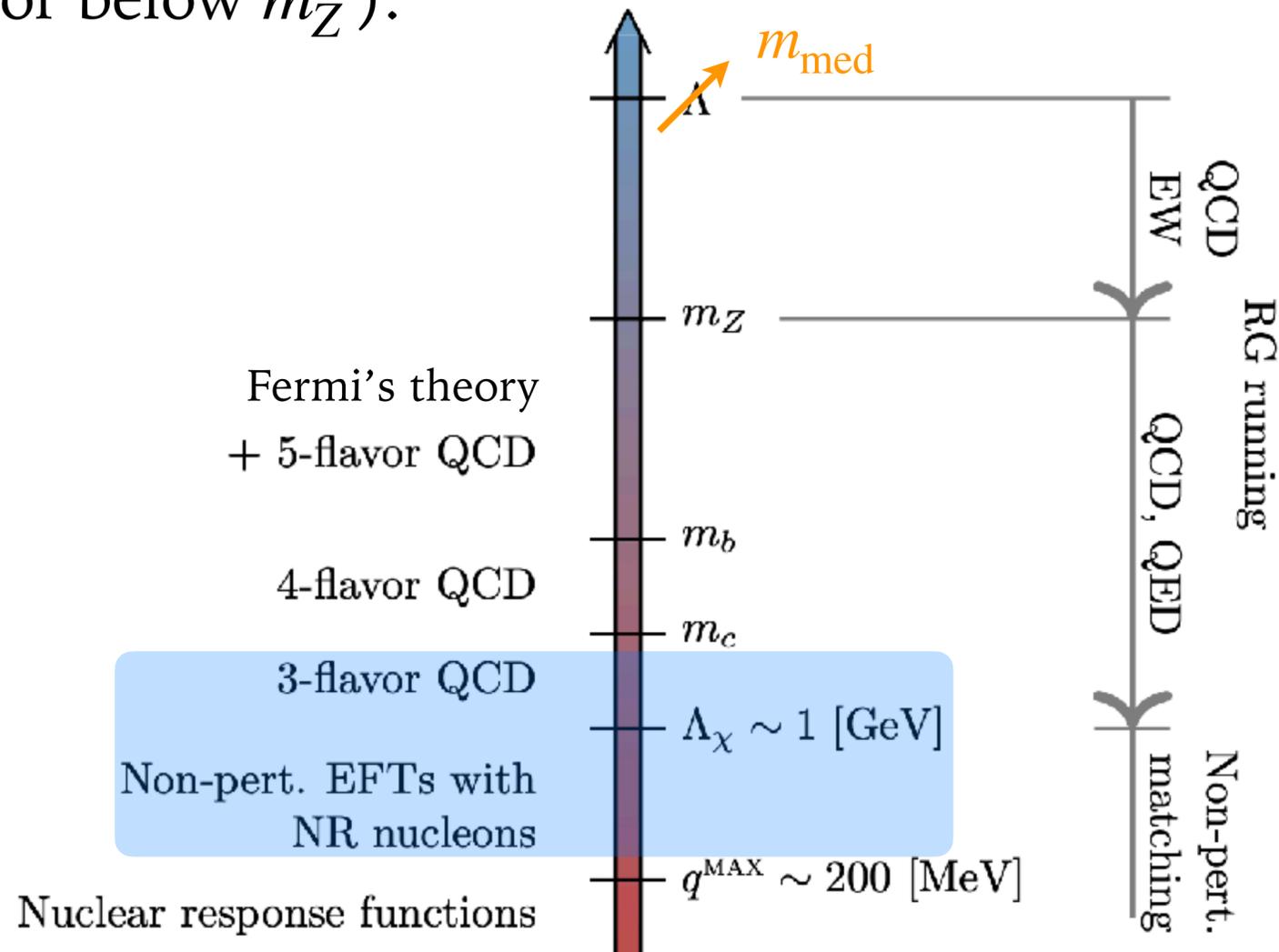
From quarks/gluons to nucleons (chiral expansion).

Cirigliano, Graesser, Ovanesyan, 1205.2695; + Shoemaker, 1311.5886.
 Hoferichter, Klos, Schwenk, 1503.04811; + Menéndez, 1812.05617.
 Bishara, Brod, Grinstein, Zupan, 1611.00368, 1707.06998, 1708.02678.

$$\begin{aligned} \mathcal{O}_1^N &= \mathbb{1}_X \mathbb{1}_N, & \mathcal{O}_2^N &= (v_\perp)^2 \mathbb{1}_X \mathbb{1}_N, \\ \mathcal{O}_3^N &= \mathbb{1}_X \vec{S}_N \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N} \right), & \mathcal{O}_4^N &= \vec{S}_X \cdot \vec{S}_N, \\ \mathcal{O}_5^N &= \vec{S}_X \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N} \right) \mathbb{1}_N, & \mathcal{O}_6^N &= \left(\vec{S}_X \cdot \frac{\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right), \\ \mathcal{O}_7^N &= \mathbb{1}_X (\vec{S}_N \cdot \vec{v}_\perp), & \mathcal{O}_8^N &= (\vec{S}_X \cdot \vec{v}_\perp) \mathbb{1}_N, \\ \mathcal{O}_9^N &= \vec{S}_X \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N \right), & \mathcal{O}_{10}^N &= -\mathbb{1}_X \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N} \right), \\ \mathcal{O}_{11}^N &= -\left(\vec{S}_X \cdot \frac{i\vec{q}}{m_N} \right) \mathbb{1}_N, & \mathcal{O}_{12}^N &= \vec{S}_X \cdot \left(\vec{S}_N \times \vec{v}_\perp \right), \\ \mathcal{O}_{13}^N &= -\left(\vec{S}_X \cdot \vec{v}_\perp \right) \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N} \right), & \mathcal{O}_{14}^N &= -\left(\vec{S}_X \cdot \frac{i\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \vec{v}_\perp \right), \end{aligned}$$

Direct detection: an EFT pipeline

Same nonrelativistic DM+nucleon EFT results from heavy mediator scenarios (with m_{DM} above or below m_Z).



$$\mathcal{L}_{\text{DMEFT}} = \sum_{d,a} \frac{C_a^{(d)}}{\Lambda^{d-4}} Q_a^{(d)}$$

Need to take into account mixing between higher-dimensional operators.

Crivellin, D'Eramo, Procura, 1402.1173.

D'Eramo, Procura, 1411.3342.

D'Eramo, Kavanagh, Panci, 1605.04917, 1702.00016.

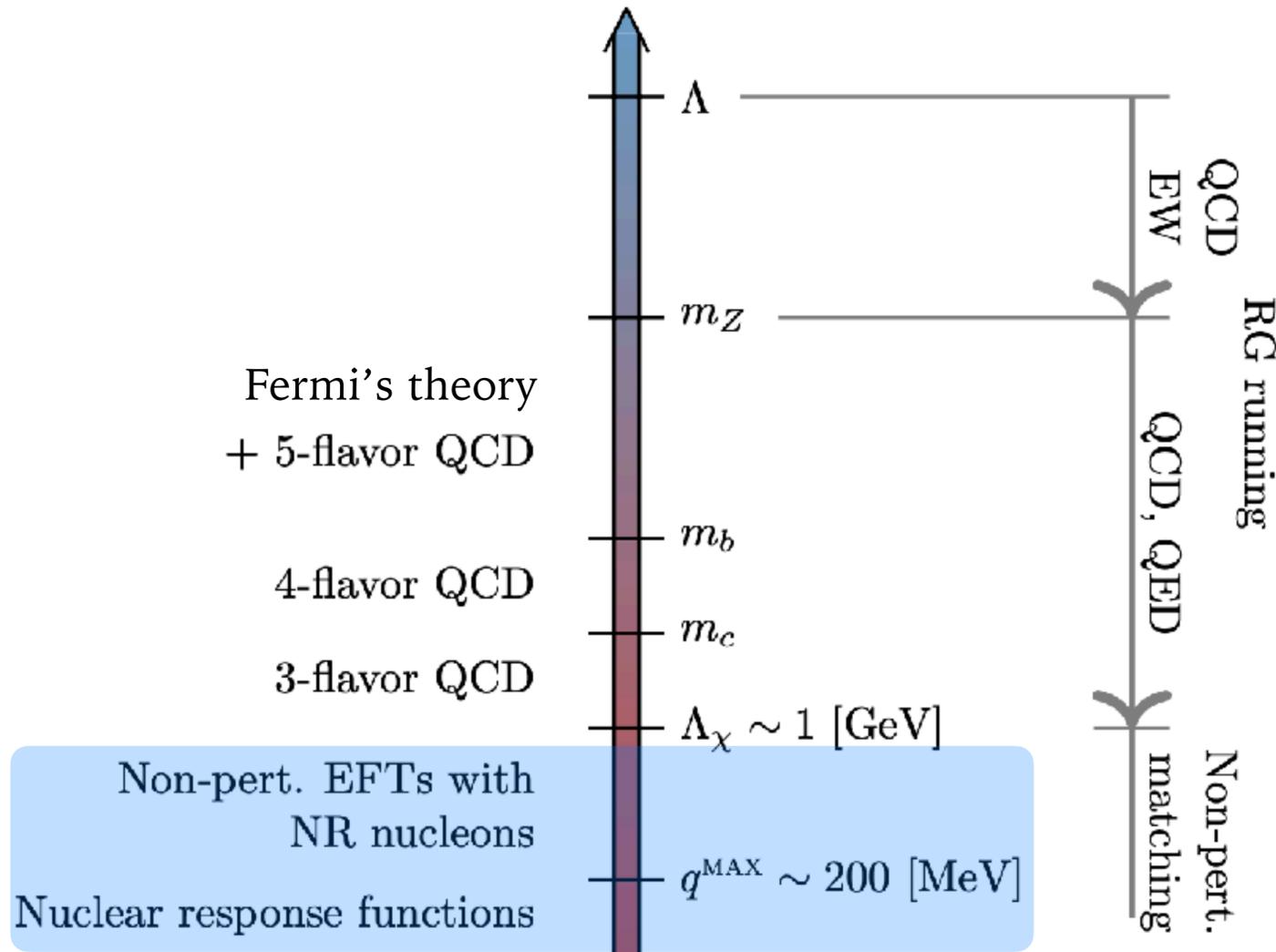
Brod, Gootjes-Dreesbach, Tamaro, Zupan, 1710.10218.

Bishara, Brod, Grinstein, Zupan, 1809.03506.

Alanne, Bishara, Fiaschi, Fischer, Gorbahn, Moldanazarova, 2202.02292.

Direct detection: an EFT pipeline

Regardless of UV origin, final step is to match onto **nuclear responses**.



Fan, Reece, Wang, 1008.1591.

Fitzpatrick, Haxton, Katz, Lubbers, Xu, 1203.3542, 1211.2818.

Cirelli, Del Nobile, Panci, 1307.5955.

Anand, Fitzpatrick, Haxton, 1308.6288.

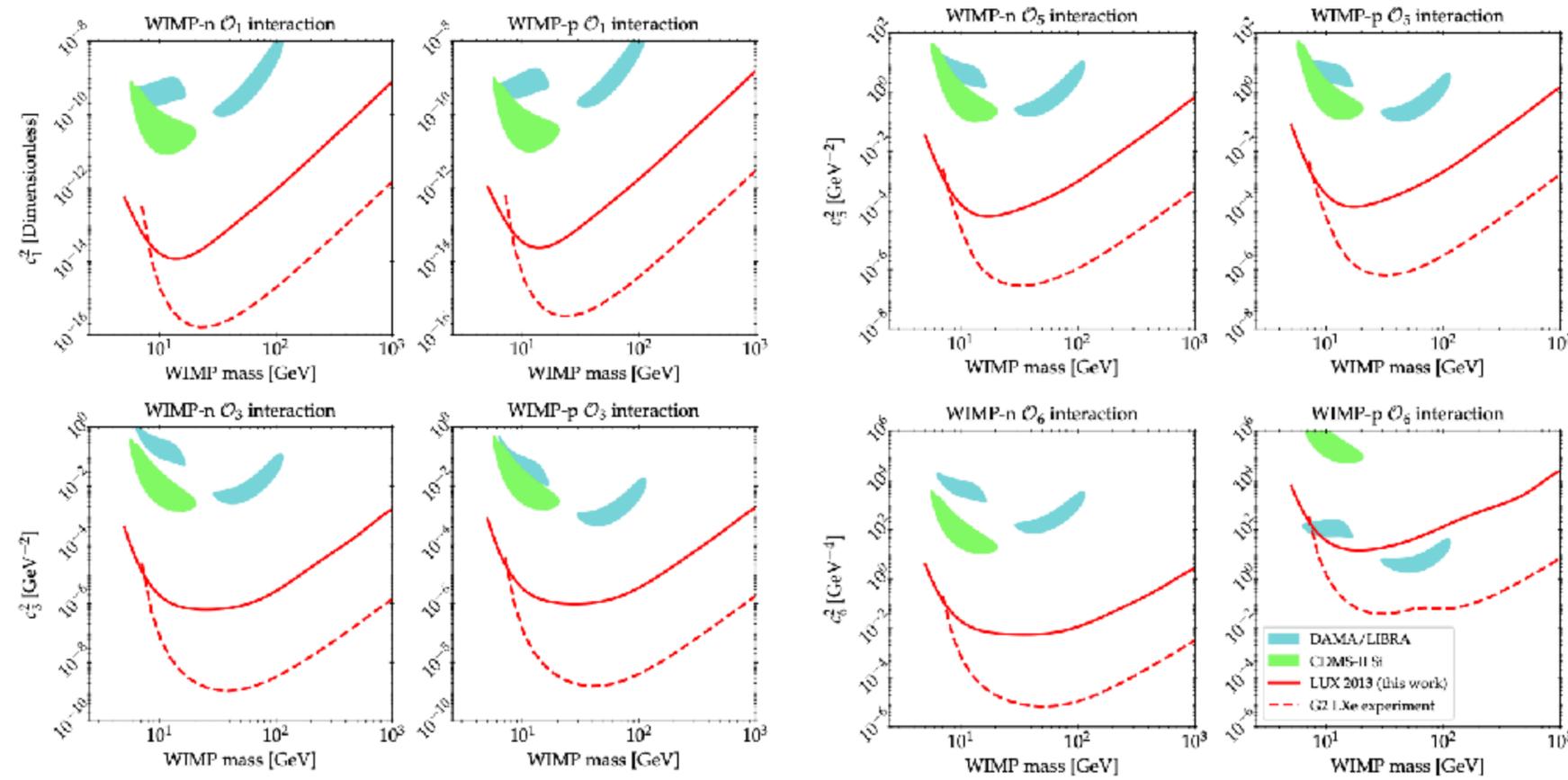
$$\frac{d\sigma}{dE_R} = \frac{2m_A}{(2j_A + 1)v^2} \sum_{\tau, \tau'} \left[R_M^{\tau\tau'} W_M^{\tau\tau'} + R_{\Sigma''}^{\tau\tau'} W_{\Sigma''}^{\tau\tau'} + R_{\Sigma'}^{\tau\tau'} W_{\Sigma'}^{\tau\tau'} + \frac{\vec{q}^2}{m_N^2} \left(R_{\Delta}^{\tau\tau'} W_{\Delta}^{\tau\tau'} + R_{\Delta\Sigma'}^{\tau\tau'} W_{\Delta\Sigma'}^{\tau\tau'} \right) \right].$$

X		$\frac{4\pi}{2J+1} W_X^{(p,p)}(0)$
M	spin-independent	Z^2
Σ''	spin-dependent (longitudinal)	$4 \frac{J+1}{3J} \langle S_p \rangle^2$
Σ'	spin-dependent (transverse)	$8 \frac{J+1}{3J} \langle S_p \rangle^2$
Δ	angular-momentum-dependent	$\frac{1}{2} \frac{J+1}{3J} \langle L_p \rangle^2$
Φ''	angular-momentum-and-spin-dependent	$\sim \langle \vec{S}_p \cdot \vec{L}_p \rangle^2$

table from Gresham, Zurek, 1401.3739.

Direct detection EFT: what have we achieved?

Specific interactions (SI, SD) \rightarrow large class of UV models.



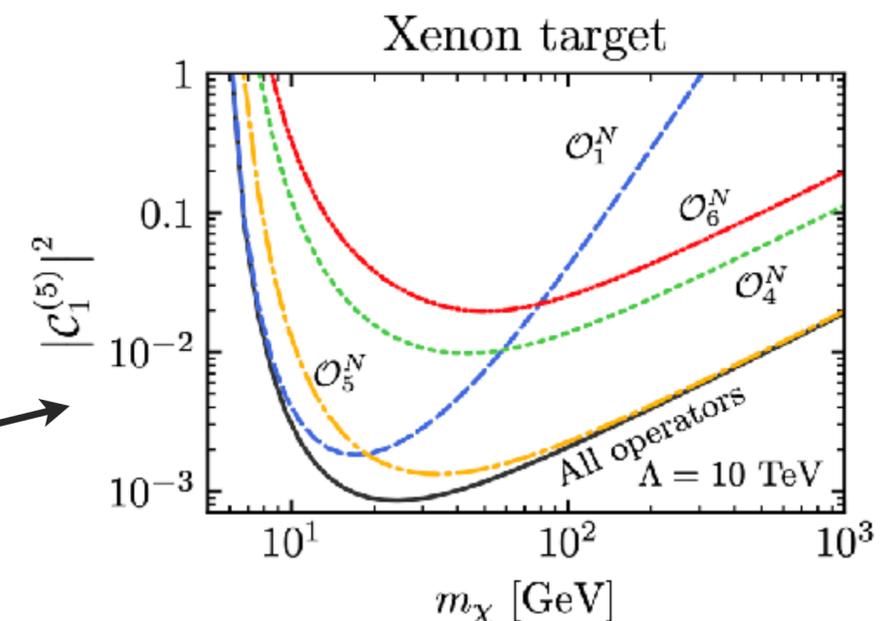
LUX Collaboration, 2003.11141.

EFT approach adopted by many experimental collaborations when interpreting their results.

- CDEX, 2007.15555.
- CRESST, 1809.03753.
- DarkSide-50, 2002.07794.
- IceCube, 2108.05203.
- LUX, 2102.06998.
- PandaX-II, 1807.01936.
- XENON, 1705.02614.

Also keep in mind possible interplay between operators. \rightarrow

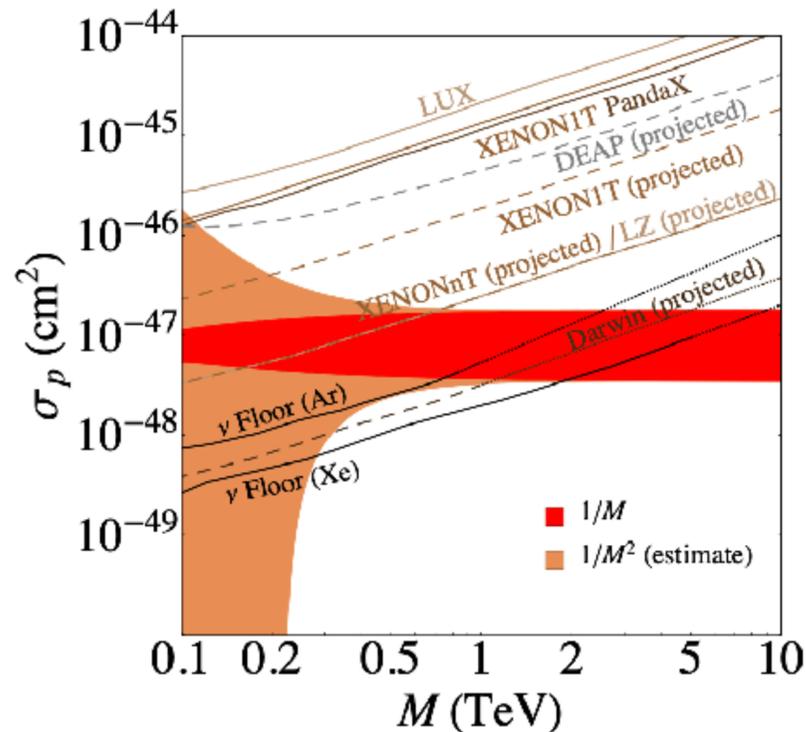
Bishara, Brod, Grinstein, Zupan, 1707.06998.



Direct detection EFT: what have we achieved?

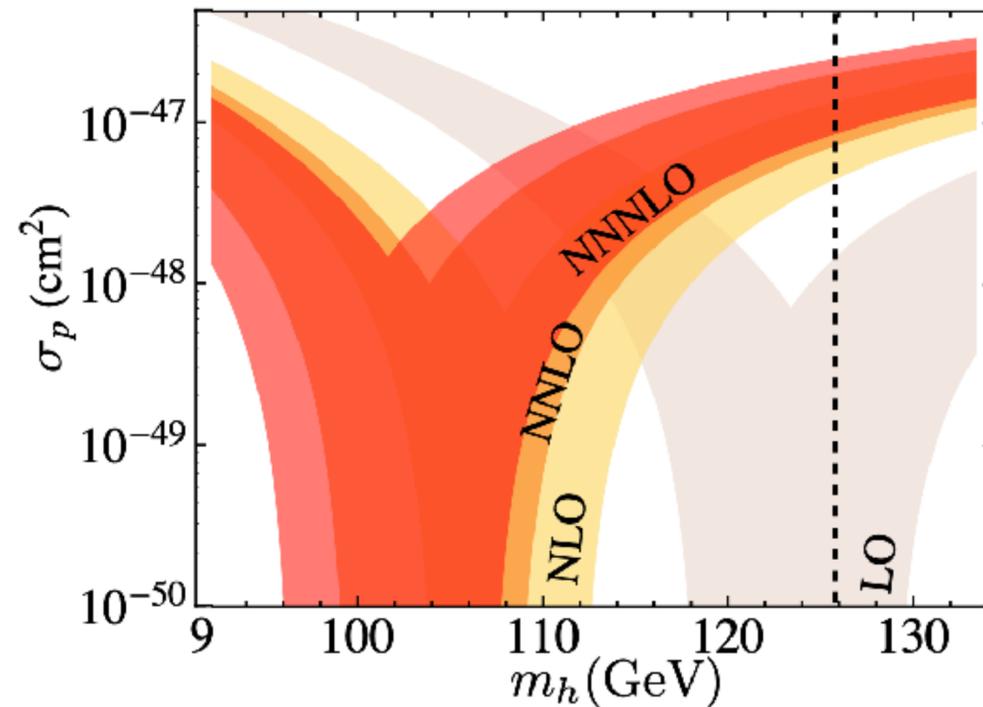
Specific interactions (SI, SD) \rightarrow large class of UV models.

Precise predictions and benchmark targets.



Chen, Hill, Solon, Wijangco, 1801.08551.

simplicity of universal prediction
 \Rightarrow concrete experimental target



Hill, Solon, 1309.4092.

importance of RG resummation
 in the EFT approach

See also:

Hisano, Ishiwata, Nagata, 1007.2601; + Takesako, 1104.0228.

Hisano, Nagai, Nagata, 1502.02244.

Dent, Krauss, Newstead, Sabharwal, 1505.03117.

Berlin, Robertson, Solon, Zurek, 1511.05964.

Brod, Grinstein, Stamou, Zupan, 1801.04240.

Chen, Hill, 1912.07795.

Aebischer, Altmannshofer, Jenkins, Manohar, 2202.06968.

Beyond nuclear recoils

Conventional nuclear recoil searches do not have sensitivity to sub-GeV DM.

WIMP DM

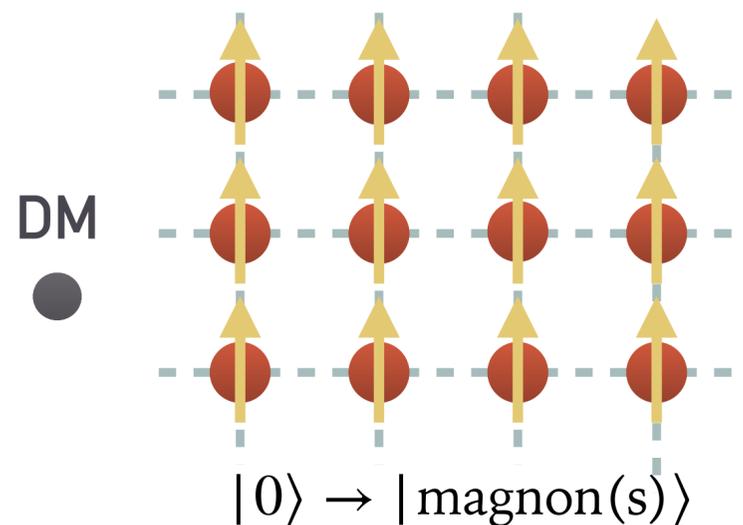
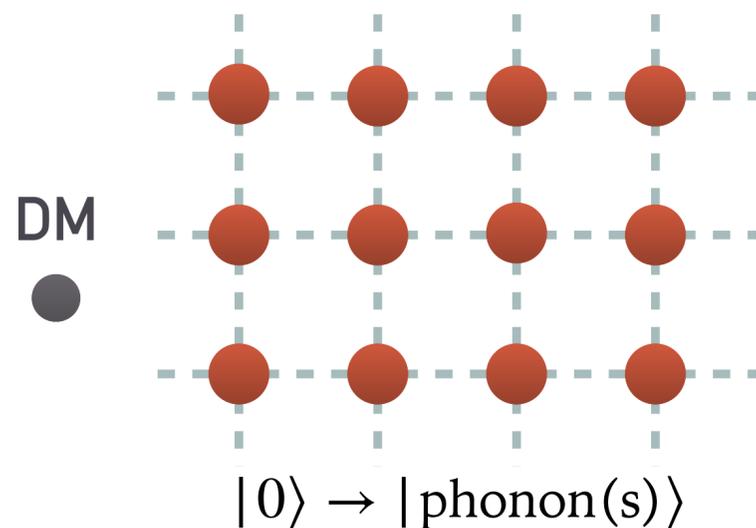
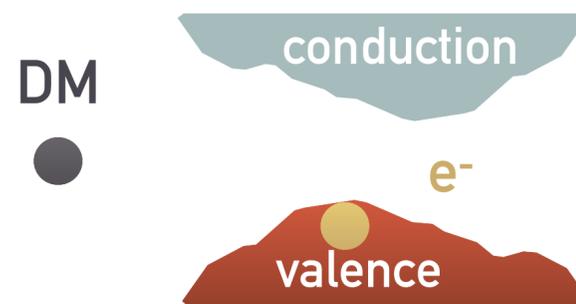
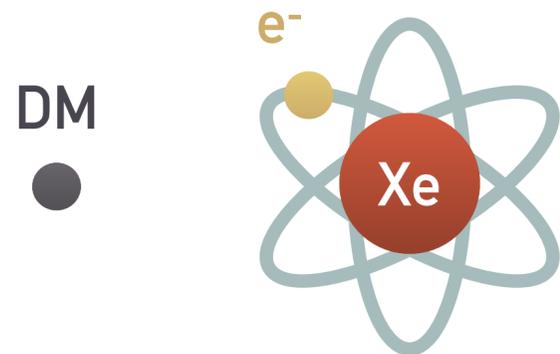


sub-GeV DM



Beyond nuclear recoils

Electronic & collective excitations efficiently extend the reach to sub-GeV DM.



Snowmass white papers:

Mitridate, Trickle, ZZ, Zurek, 2203.07492.

Essig, Giovanetti, Kurinsky, McKinsey, Ramanathan, Stifter, Yu, 2203.08297.

Essig, Kahn, Knapen, Ringwald, Toro, 2203.10089.

Also see review article:

Kahn, Lin, 2108.03239.

Actively pursued experimentally:

CDEX, 2206.04128, ...

DAMIC, 2003.09497, ...

Edelweiss, 2003.01046, ...

QUAX, 2001.08940, ...

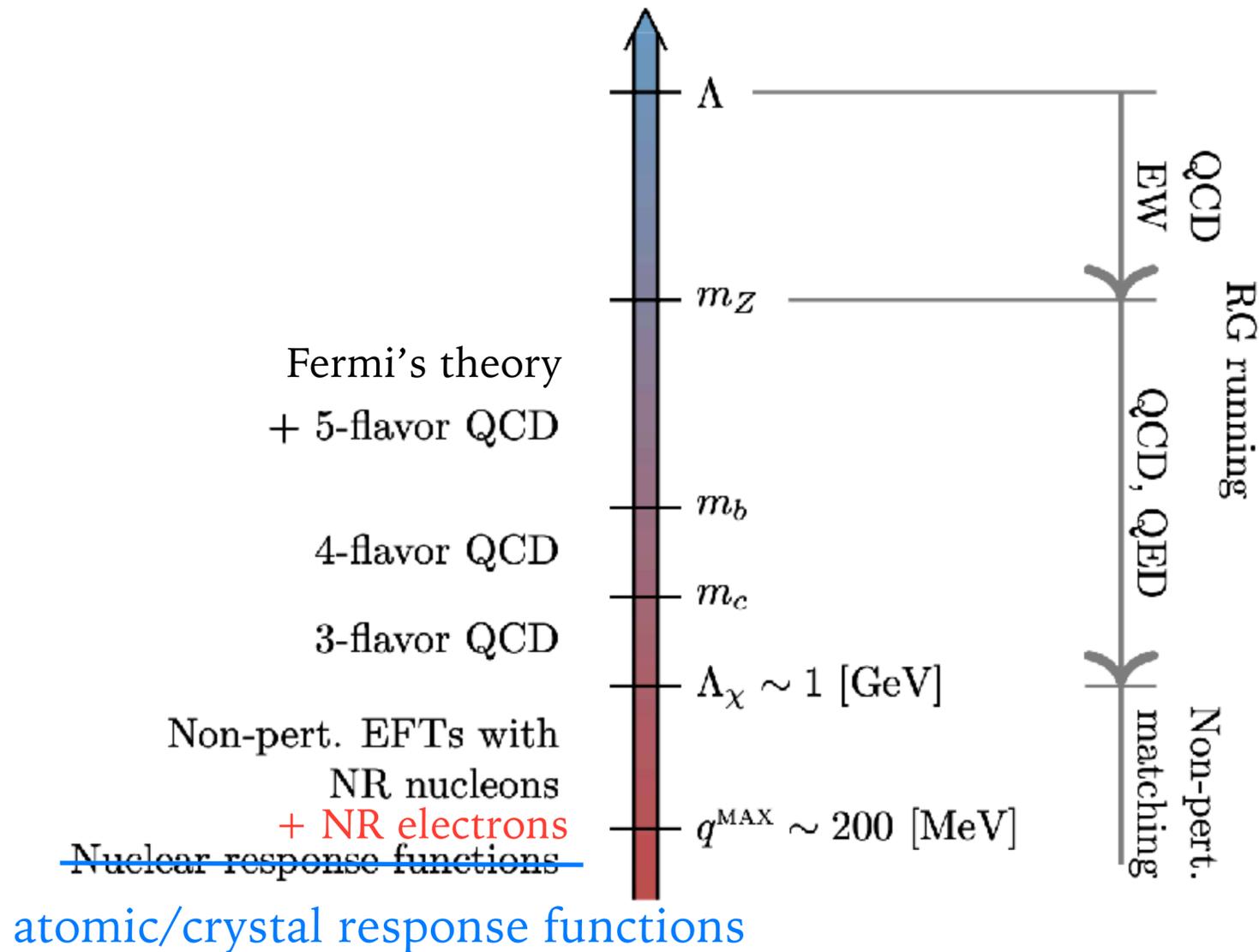
SENSEI, 2004.11378, ...

SuperCDMS, 2005.14067, ...

TESSERACT, Snowmass LOI, ...

Beyond nuclear recoils

EFTs have also been developed for sub-GeV DM direct detection.



e.g. single phonon excitation in crystal targets:

$$\Gamma(\mathbf{v}) = \frac{1}{\Omega} \int \frac{d^3q}{(2\pi)^3} \sum_{\nu=1}^{3n} 2\pi \delta(\omega_{\nu,\mathbf{k}} - \omega_{\mathbf{q}}) \frac{1}{2\omega_{\nu,\mathbf{k}}} \left| \sum_j e^{-W_j(\mathbf{q})} e^{i\mathbf{G}\cdot\mathbf{x}_j^0} \frac{\mathbf{q} \cdot \boldsymbol{\epsilon}_{\nu,\mathbf{k},j}^*}{\sqrt{m_j}} \tilde{\mathbf{v}}_j(-\mathbf{q}, \mathbf{v}) \right|^2$$

$$\sum_{\psi=p,n,e} \left[c_N^{(\psi)} \langle N_\psi \rangle_j + \mathbf{c}_S^{(\psi)} \cdot \langle \mathbf{S}_\psi \rangle_j + \mathbf{c}_L^{(\psi)} \cdot \langle \mathbf{L}_\psi \rangle_j + (c_{LS}^{(\psi)})^{ik} (\langle \mathbf{L}_\psi \otimes \mathbf{S}_\psi \rangle_j)^{ik} \right]$$

again, **simplicity** in the long wavelength limit
(coupling to just a few quantities)

See also EFT of direct detection with superfluid helium:
Acanfora, Esposito, Polosa, 1902.02361.

Caputo, Esposito, Polosa, 1907.10635; + Geoffray, Sun, 1911.04511.

Baym, Beck, Filippini, Pethick, Shelton, 2005.08824.

Matchev, Smolinsky, Xue, You, 2108.07275.

Catena, Emken, Spaladin, Tarantino, 1912.08204.

Trickle, ZZ, Zurek, 2009.13534; + Mitridate, 2106.12586.

Catena, Emken, Matas, Spaladin, Urdshals, 2105.02233.

Another EFT playground: heavy WIMP indirect detection

$$\propto \frac{M_\chi^2}{m_W^2}$$

resum using
(potential) NR EFT

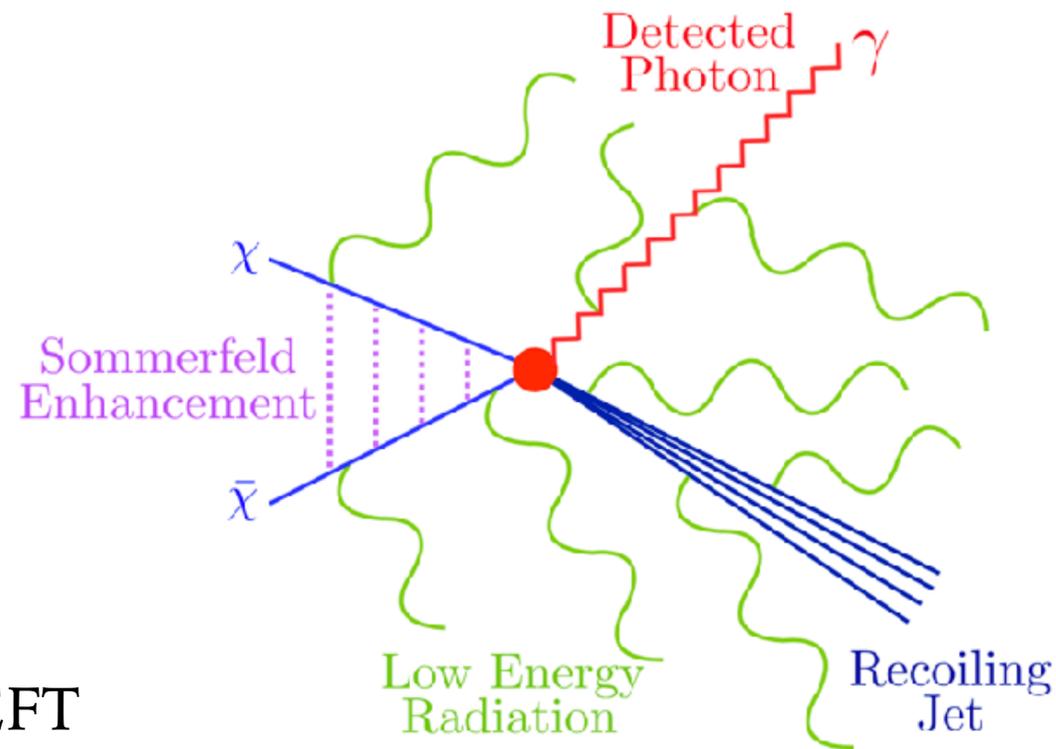
(also relevant for freeze-out, SIDM)

Hisano, Matsumoto, Nojiri, hep-ph/0307216; +Saito, hep-ph/0412403.

Hisano, Matsumoto, Nagai, Saito, Senami, hep-ph/0610249.

Beneke, Szafron, Urban, 1909.04584, 2009.00640.

Urban, 2108.07285.



$$\log^2\left(1 - \frac{E_\gamma}{M_\chi}\right)$$

resum using SCET
in the endpoint region

$$\propto \log^2 \frac{M_\chi}{m_W}$$

Baumgart, Rothstein, Vaidya, 1409.4415, 1412.8698.

Bauer, Cohen, Hill, Solon, 1409.7392.

Ovanesyan, Slatyer, Stewart, 1409.8294.

Baumgart, Vaidya, 1510.02470.

Baumgart et al, 1712.07656, 1808.08956.

Beneke, Broggio, Hasner, Vollmann, 1805.07367; + Urban, 1903.08702.

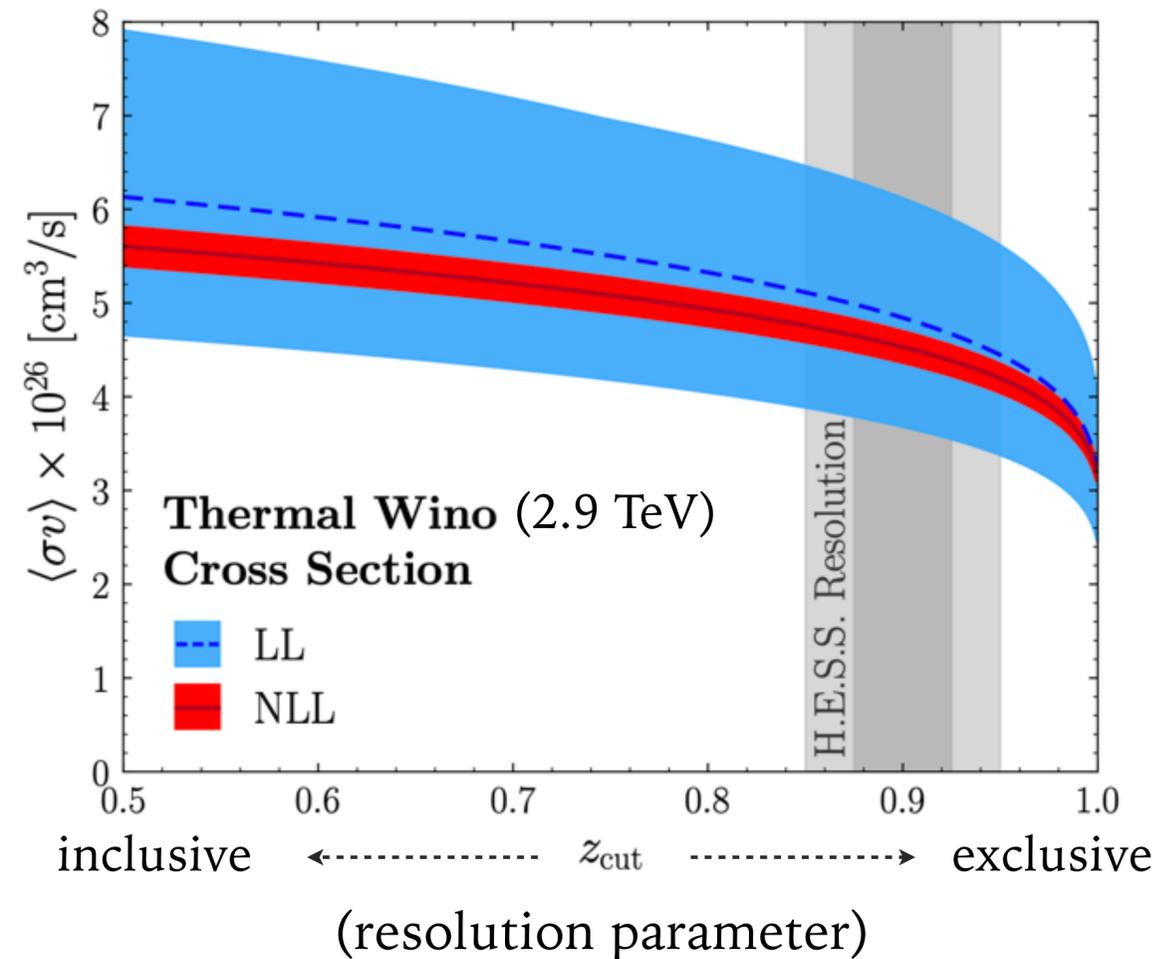
Rinchiuso et al, 1808.04388, 2008.00692.

Beneke, Hasner, Urban, Vollmann, 1912.02034.

Beneke, Urban, Vollmann, 2203.01692.

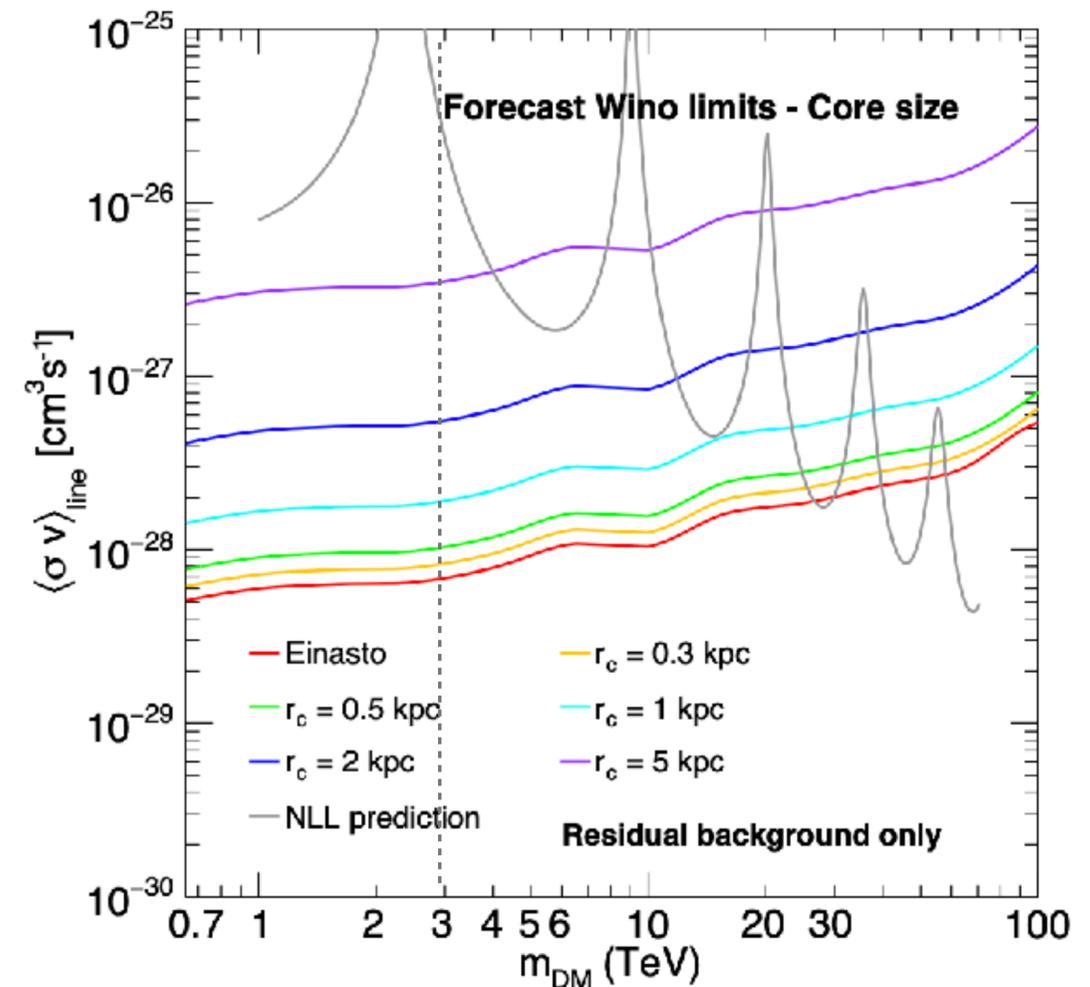
Precision predictions for gamma ray searches

NLL resummation reduces uncertainty from $O(1)$ to $\sim 5\%$
 (relevant for ongoing searches at imaging atmospheric
 Cherenkov telescopes: H.E.S.S., MAGIC, VERITAS)



Baumgart et al, 1808.08956.

thermal wino under tension
 conclusive exclusion with CTA sensitivity

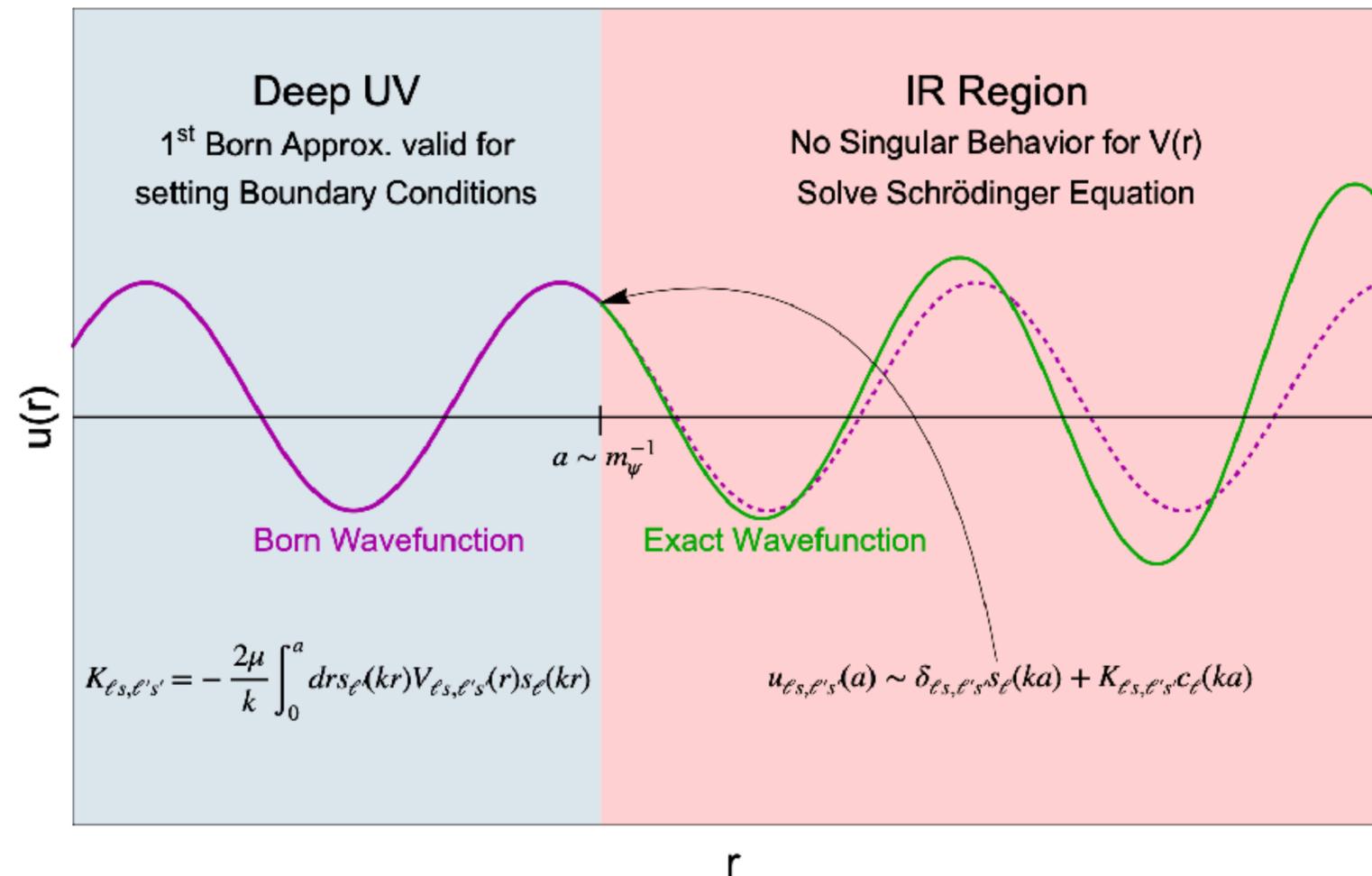


Rinchiuso et al, 2008.00692.

NR EFT for self-interacting DM; quantum mechanics swampland?

Consistent matching of QFT onto NR potential.

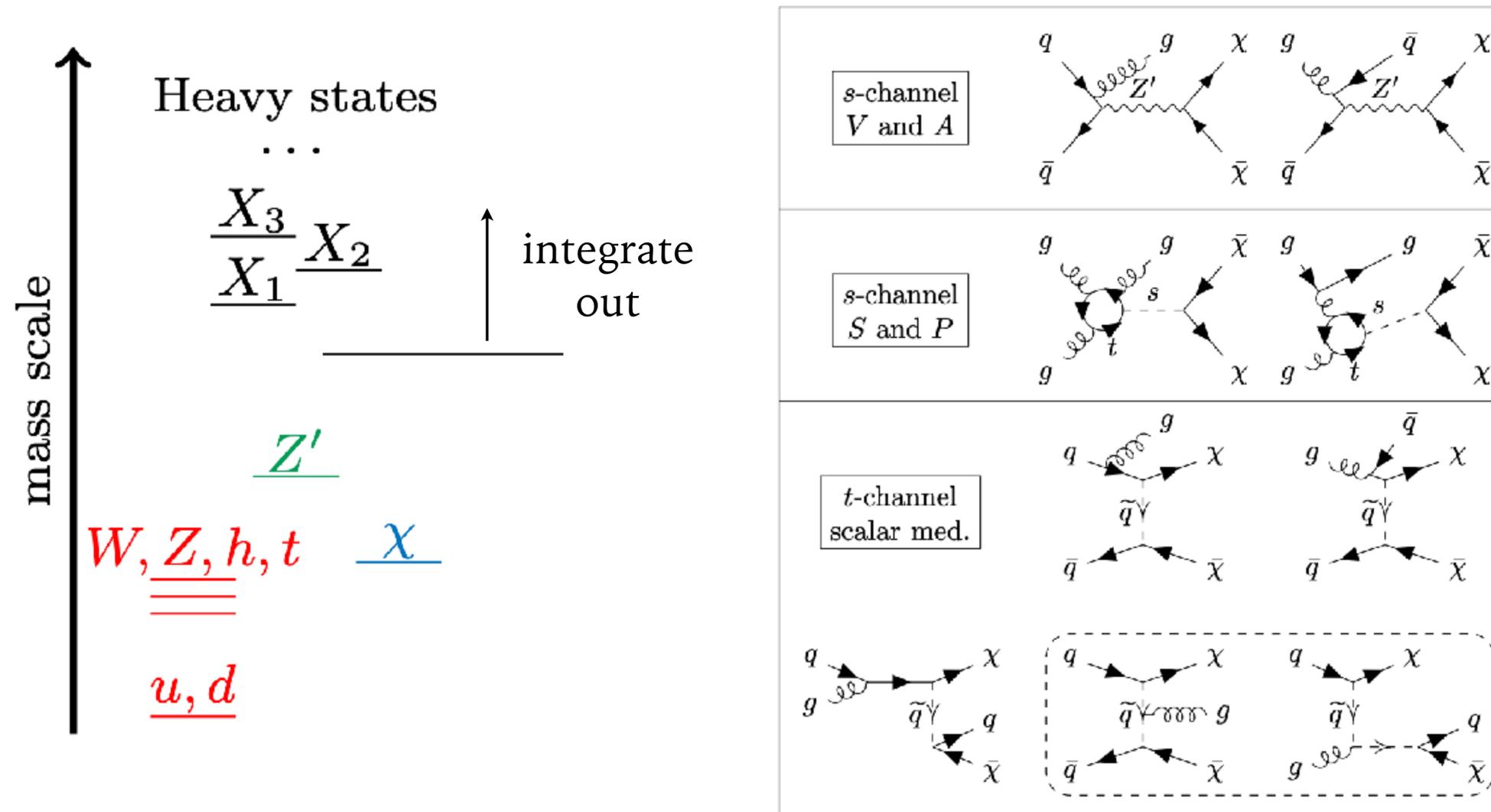
- ◉ SIDM: Sommerfeld enhancement or not? (resolved controversy for pseudoscalar mediator model)
- ◉ More generally: existence of UV completions of quantum mechanics potentials?



Agrawal, Parikh, Reece, 2003.00021.
Parikh, 2012.11606.

DM at colliders

Simplified models approach: EFT of SM + DM + mediator (+ additional states for consistency).



Figures from Morgante, 1804.01245.

See also:

Abdallah et al, 1409.2893, 1506.03116.

Abercrombie et al, 1507.00966.

Boveia et al, 1603.04156.

Albert et al, 1607.06680, 1703.05703.

Abe et al, 1810.09420.

Summary

Multi-scale problems in every aspect of DM physics.

Direct detection, indirect detection, SIDM, collider searches.

EFTs are both convenient and essential.

Exciting progress in the past decade of experimental relevance + theoretical interest.

Lots to look forward to in the near future; continued theory support for ongoing DM searches.

Thank you!