# New constraints for sub-MeV DM from DM-electron direct detections

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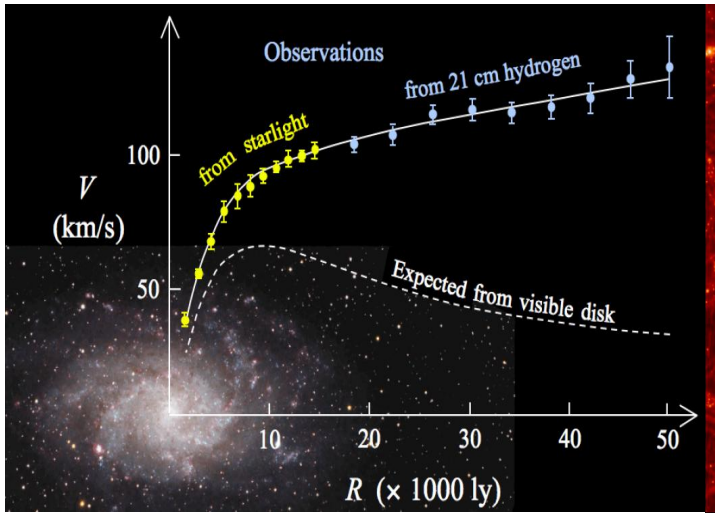
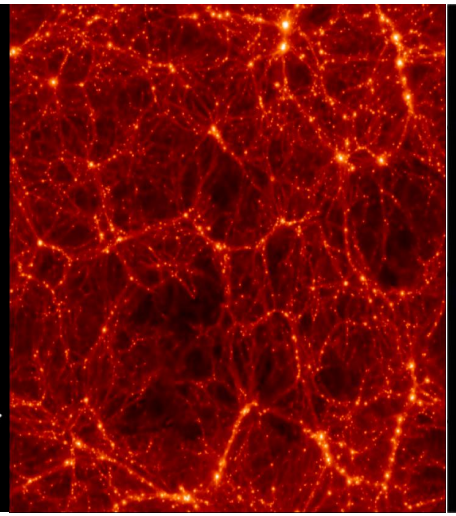
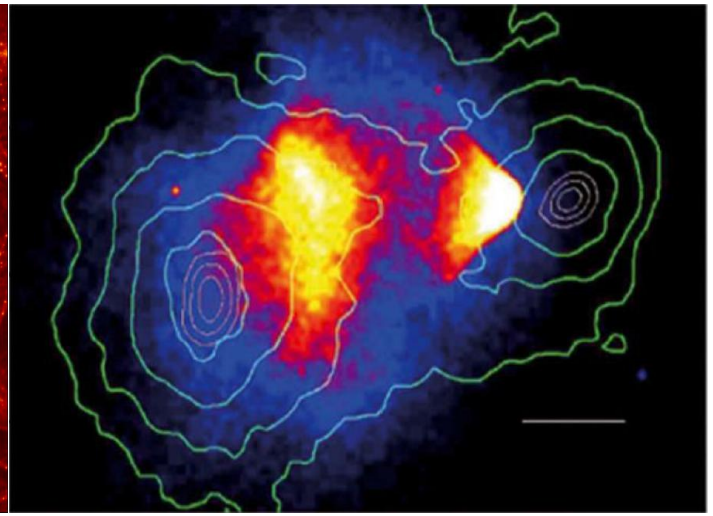
# Evidences for DM

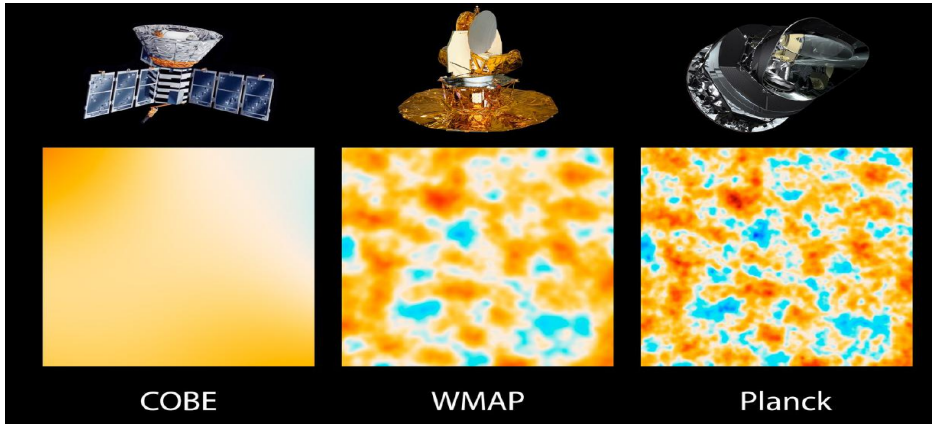
- Rotation curves
- LSS
- Bullet cluster





- CMB



# Dark sector candidates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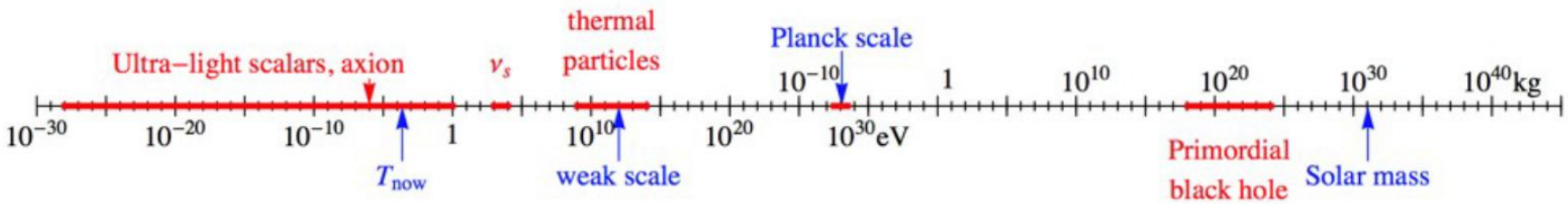
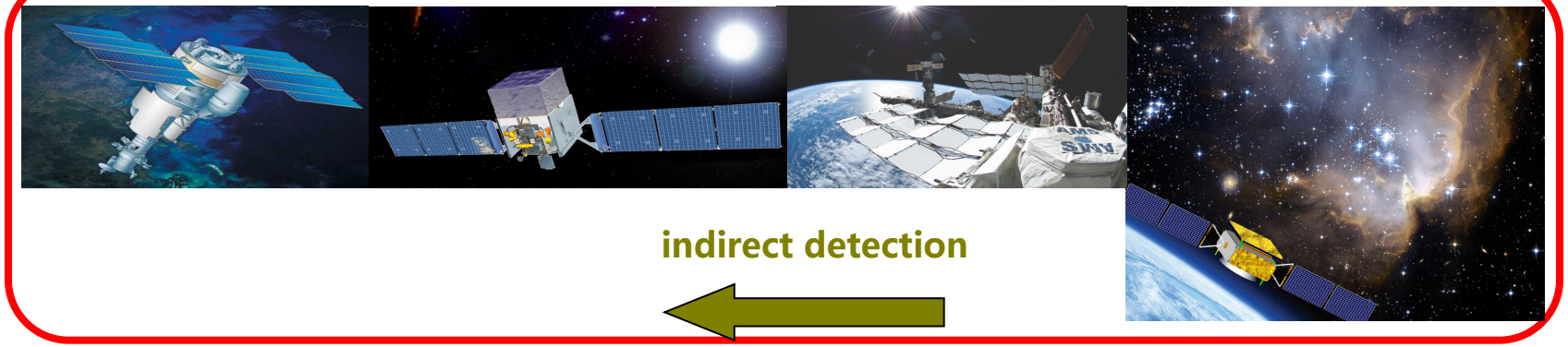


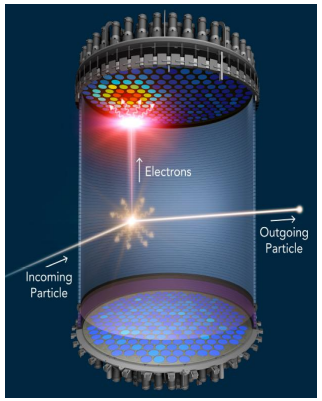
# DM detections

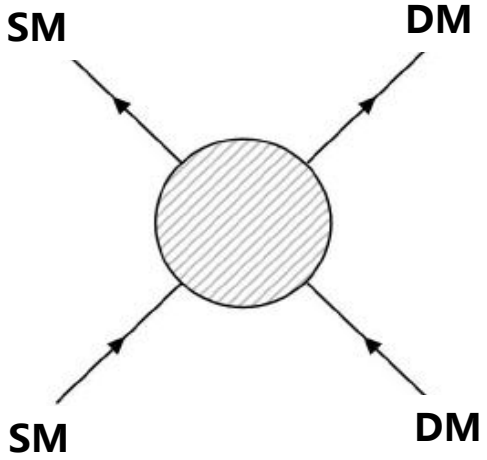


indirect detection

Cosmic-Ray (CR) physics

direct detection

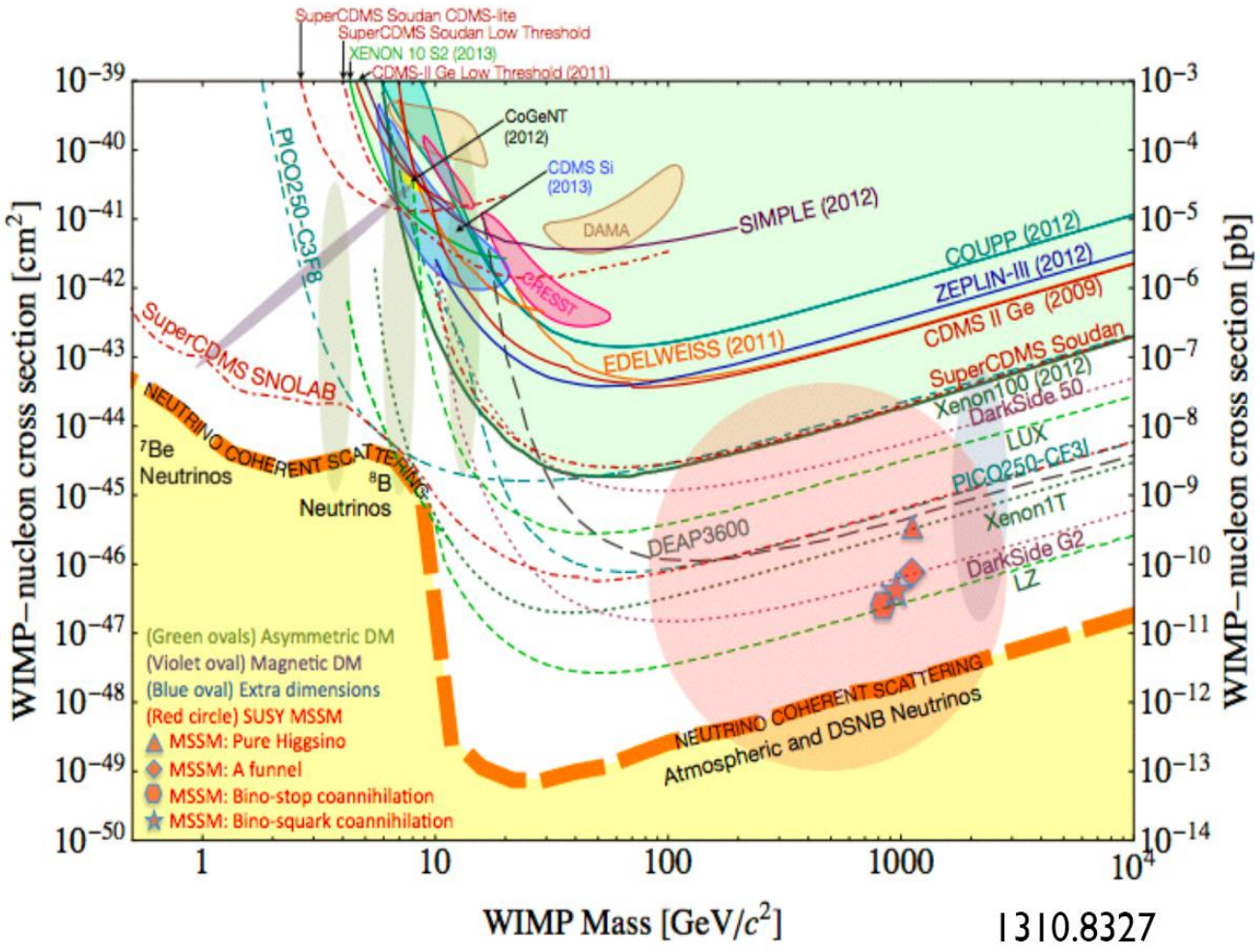


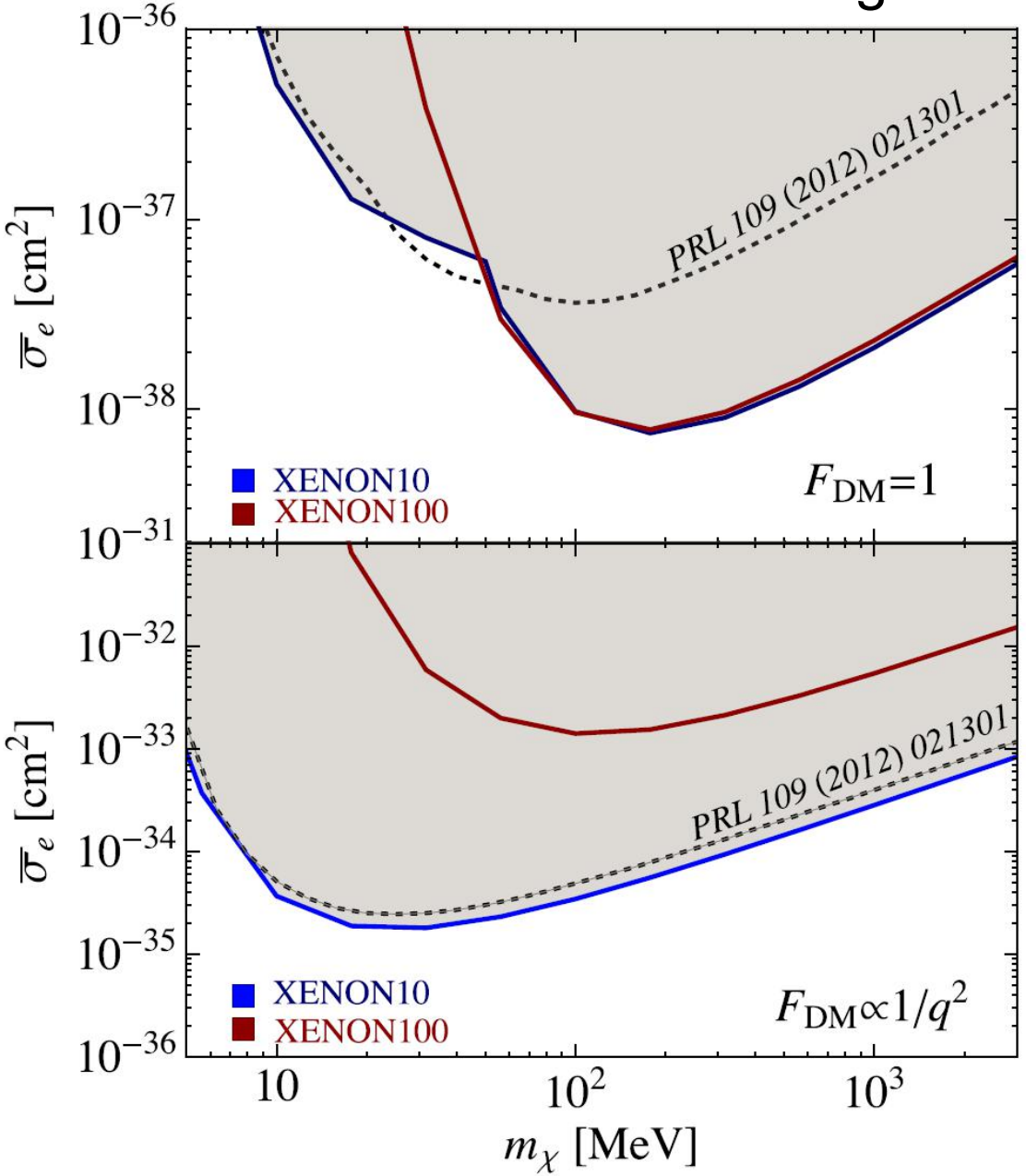

collider detection

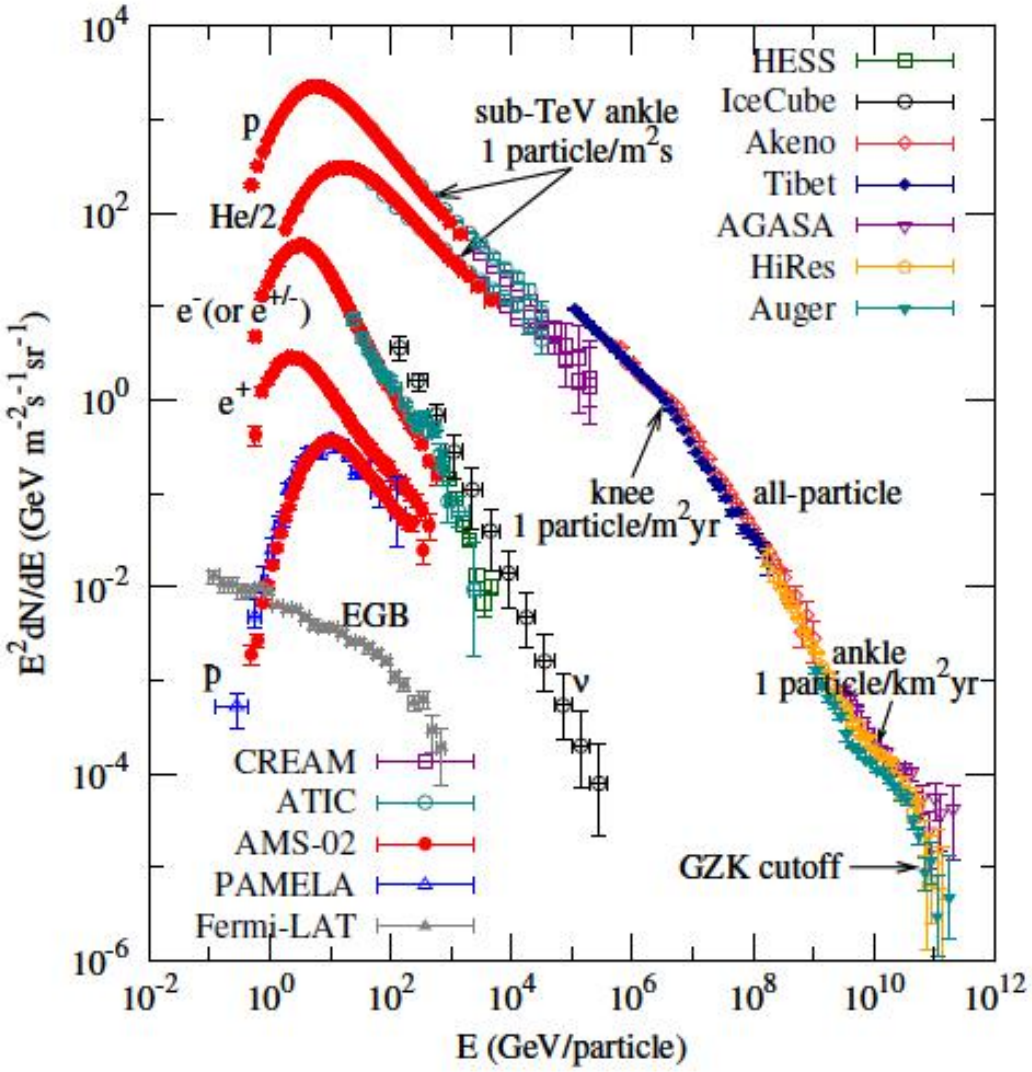
# Status of direct detections

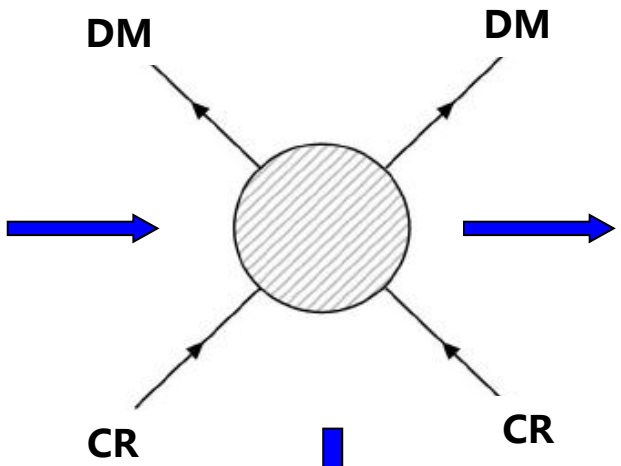
## Nucleon scattering



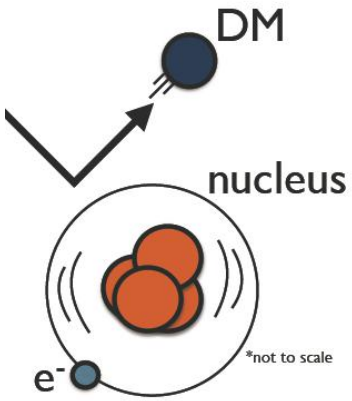

## Electron scattering



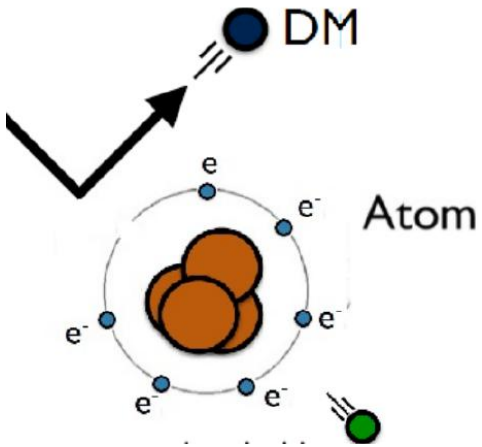


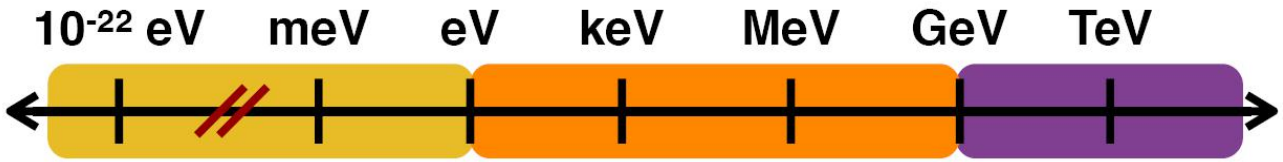




DM-nucleon scattering



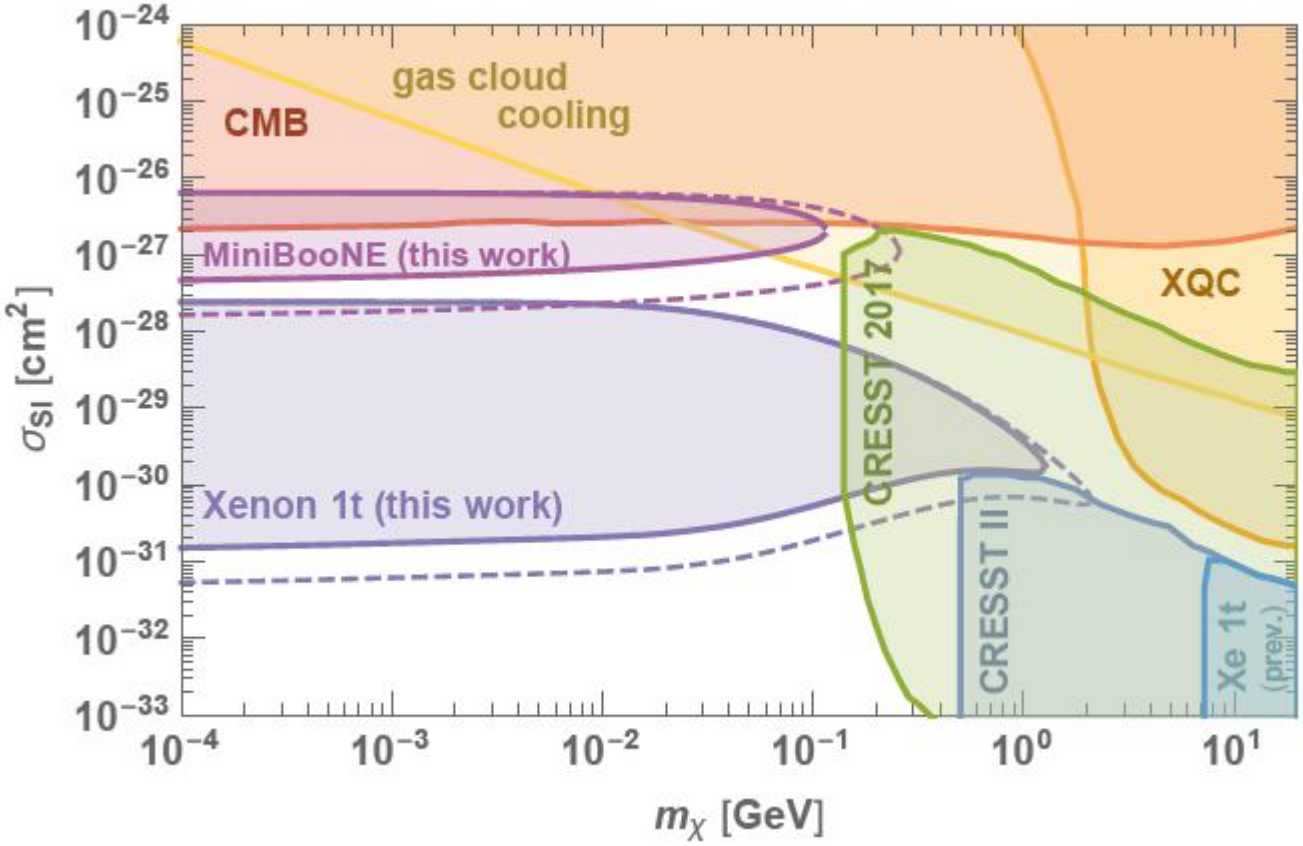

DM-electron scattering



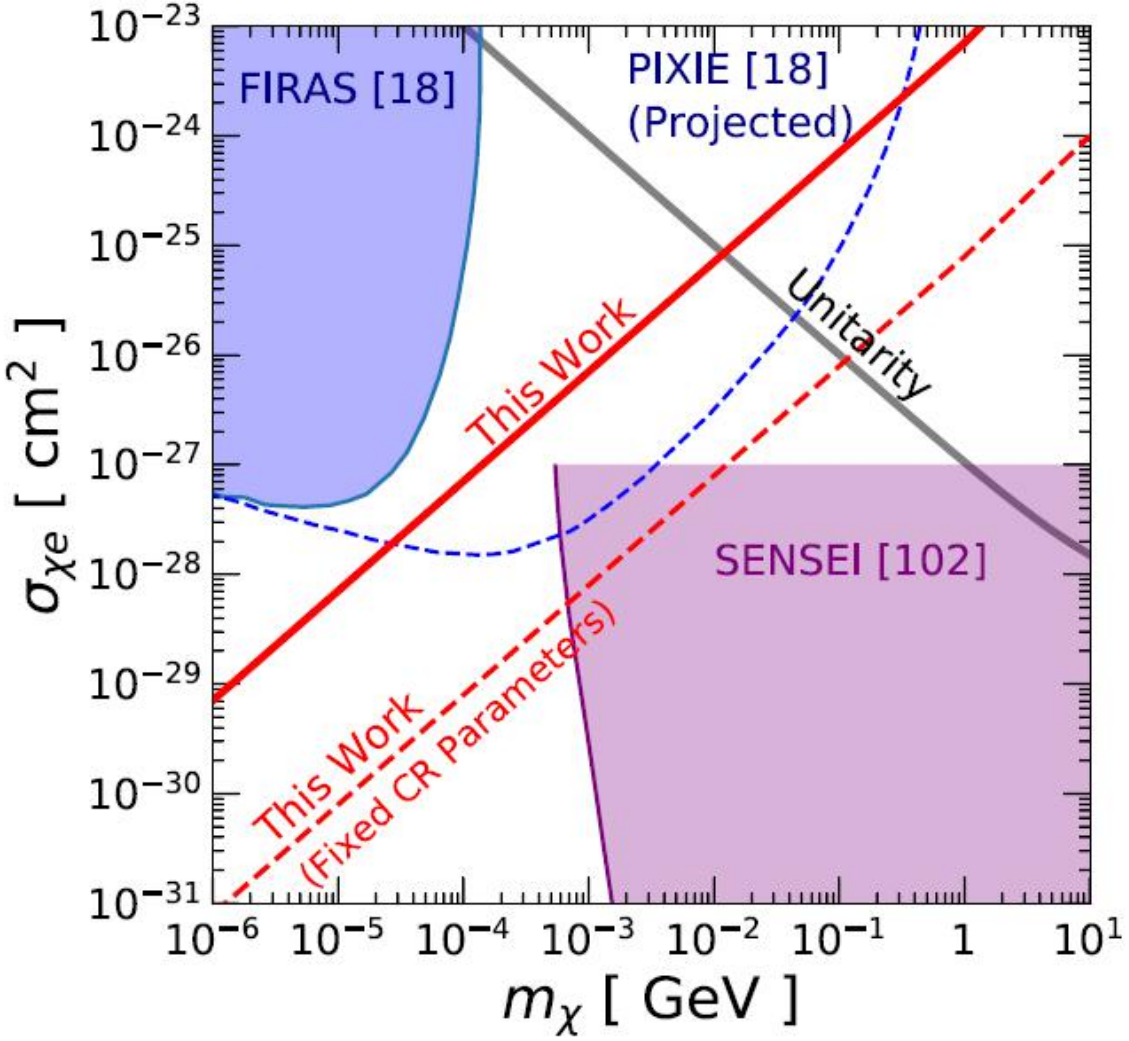
## Limits from DM-nucleon direct detection

T. Bringmann and M. Pospelov, arXiv:1810.10543




## Reverse Direct Detection

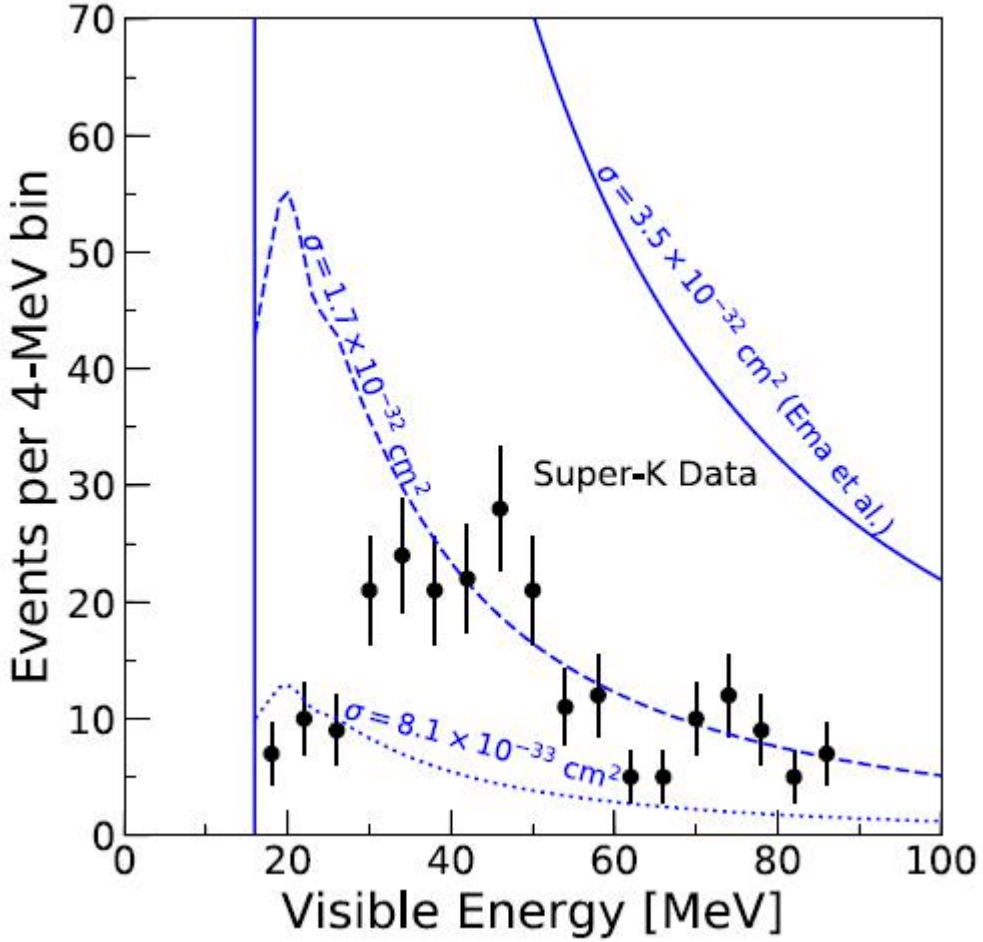
C. V. Cappiello, K. C. Y. Ng and J. F. Beacom, arXiv:1810.07705

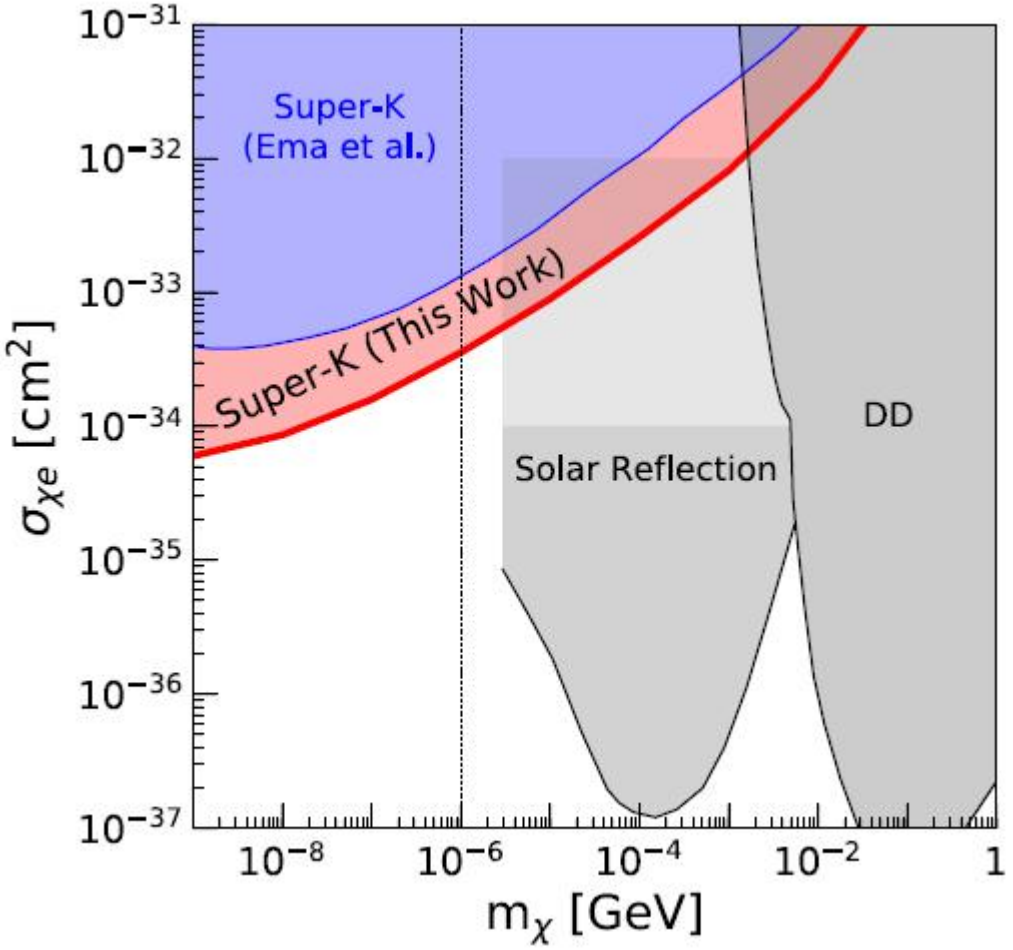


# Limits from Neutrino Experiments

Y. Ema, F. Sala and R. Sato, arXiv:1811.00520

C. Cappiello and J. F. Beacom, arXiv:1906.11283



# Theoretical motivation of light DM

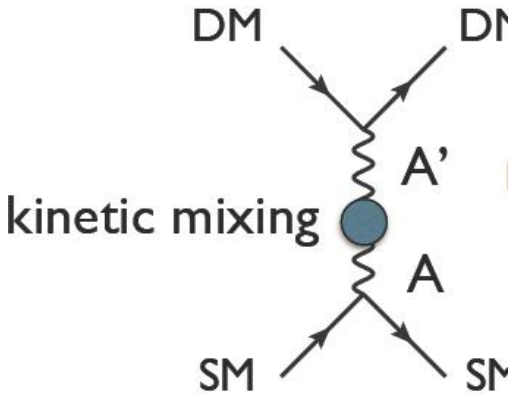
- Dark photon mediator, milli-charged DM, freeze-in DM,Strongly Interacting,MDM/EDM.....

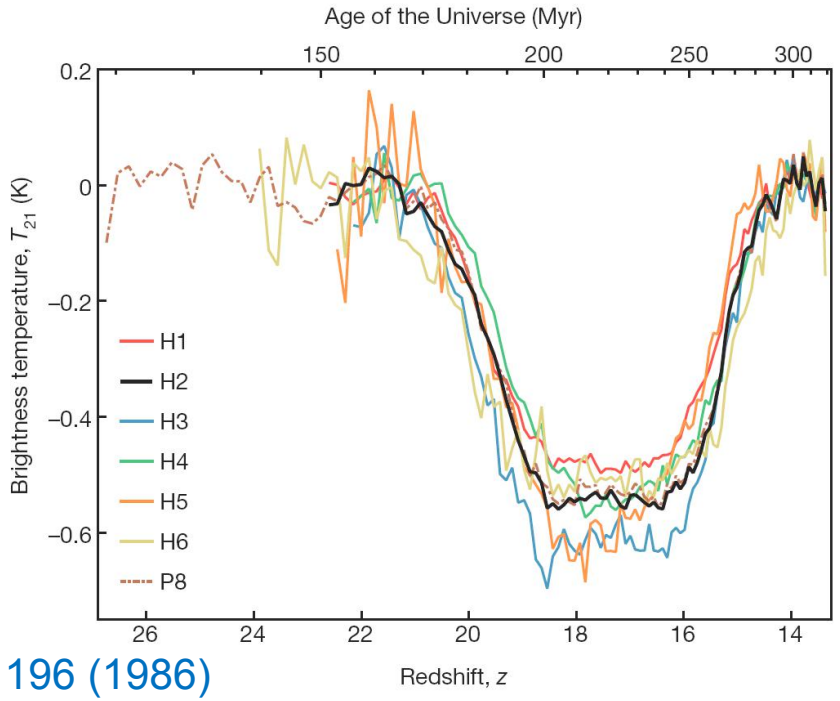
L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, arXiv:0911.112

R. Essig, J. Mardon, and T. Volansky, arXiv:1108.5383

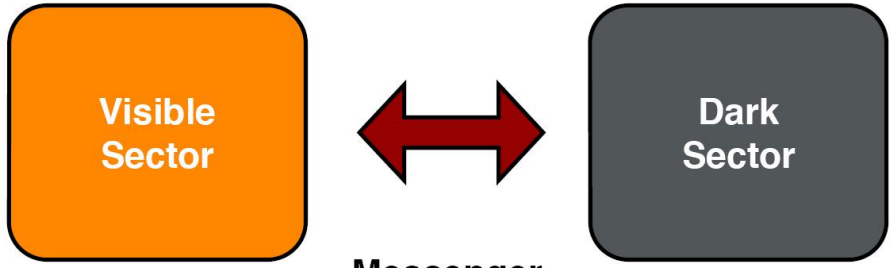
X. Chu, T. Hambye, and M. H. G. Tytgat, arXiv:1112.0493

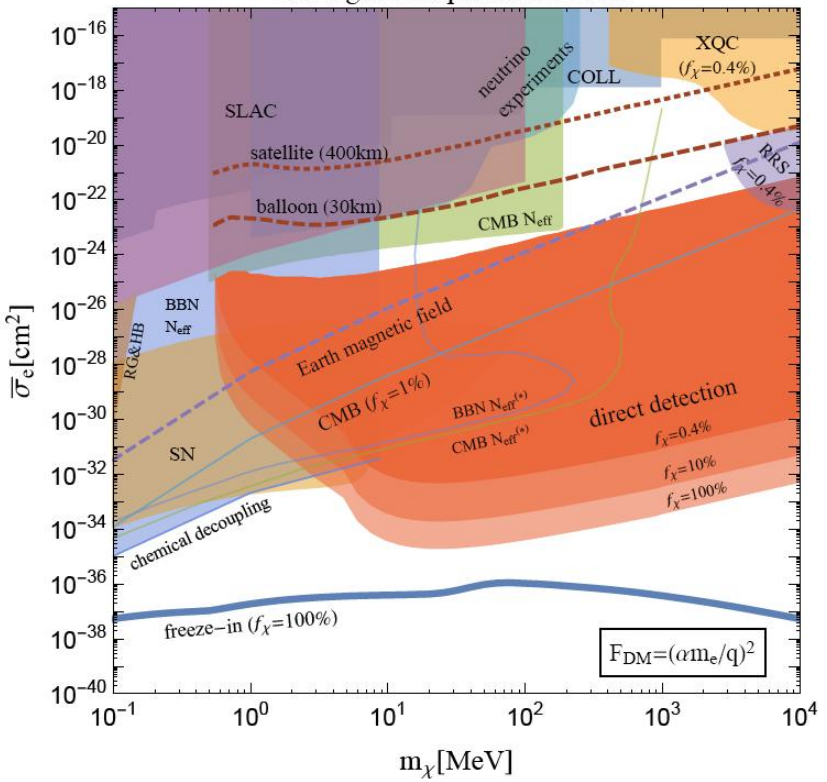
S. Knapen, T. Lin, and K. M. Zurek, arXiv:1709.07882




B. Holdom, Phys. Lett. 166B, 196 (1986)



# Benchmark model in this work

- Adding a new U(1)' gauge symmetry, A' serves as new gauge boson and receives mass if U(1) gauge group is broken through either the Higgs or Stuckelberg mechanisms

$$\mathcal{L} \supset g_\chi \overline{\chi} \gamma^\mu \chi A'_\mu + g_{\rm SM} \overline{f} \gamma^\mu f A'_\mu + \frac{1}{2} m^2_{A'} A'_\mu A'^\mu$$

ultralight A'

Dark photon mediator, milli-charged DM

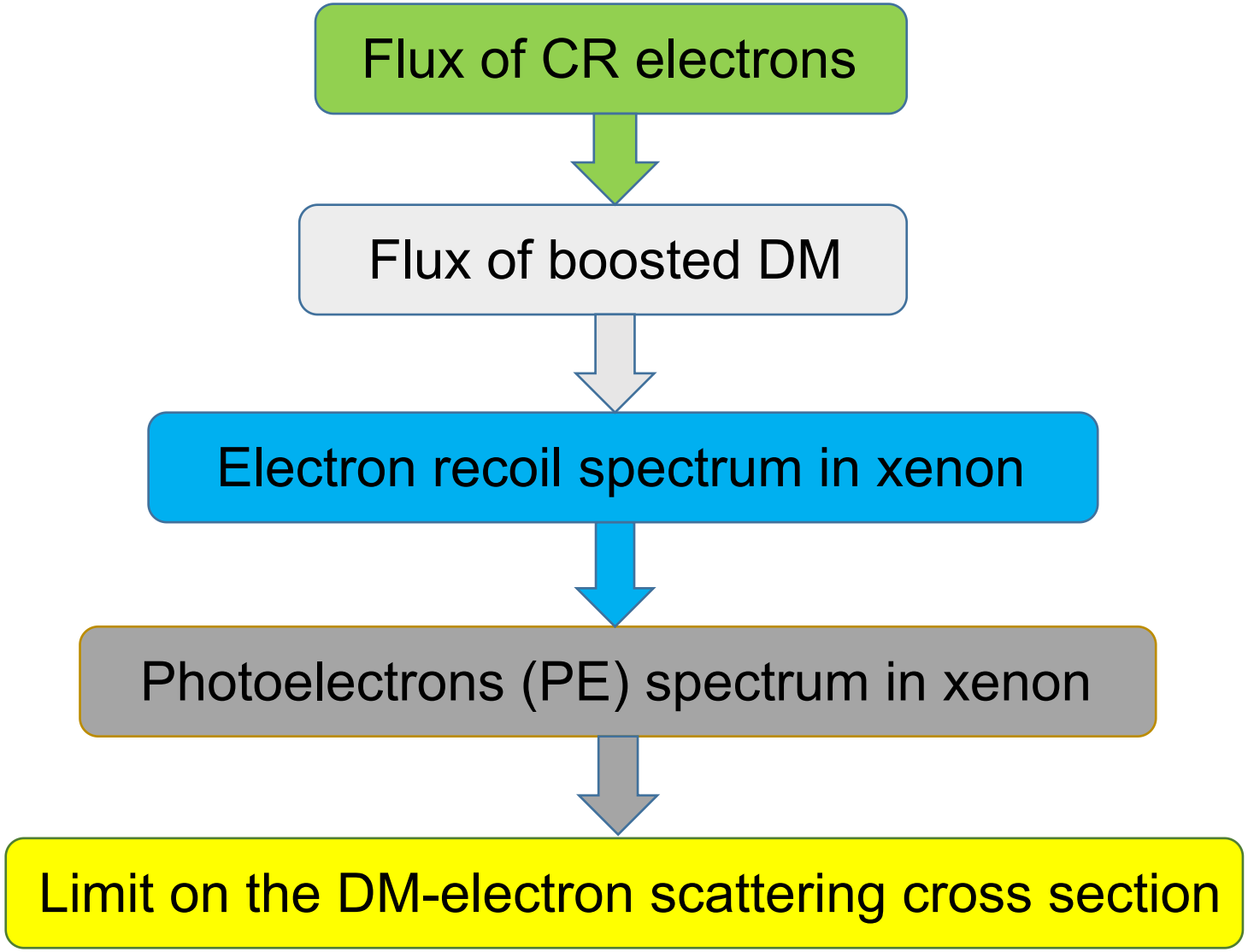
heavy A'

Z'-portal, leptophilic DM

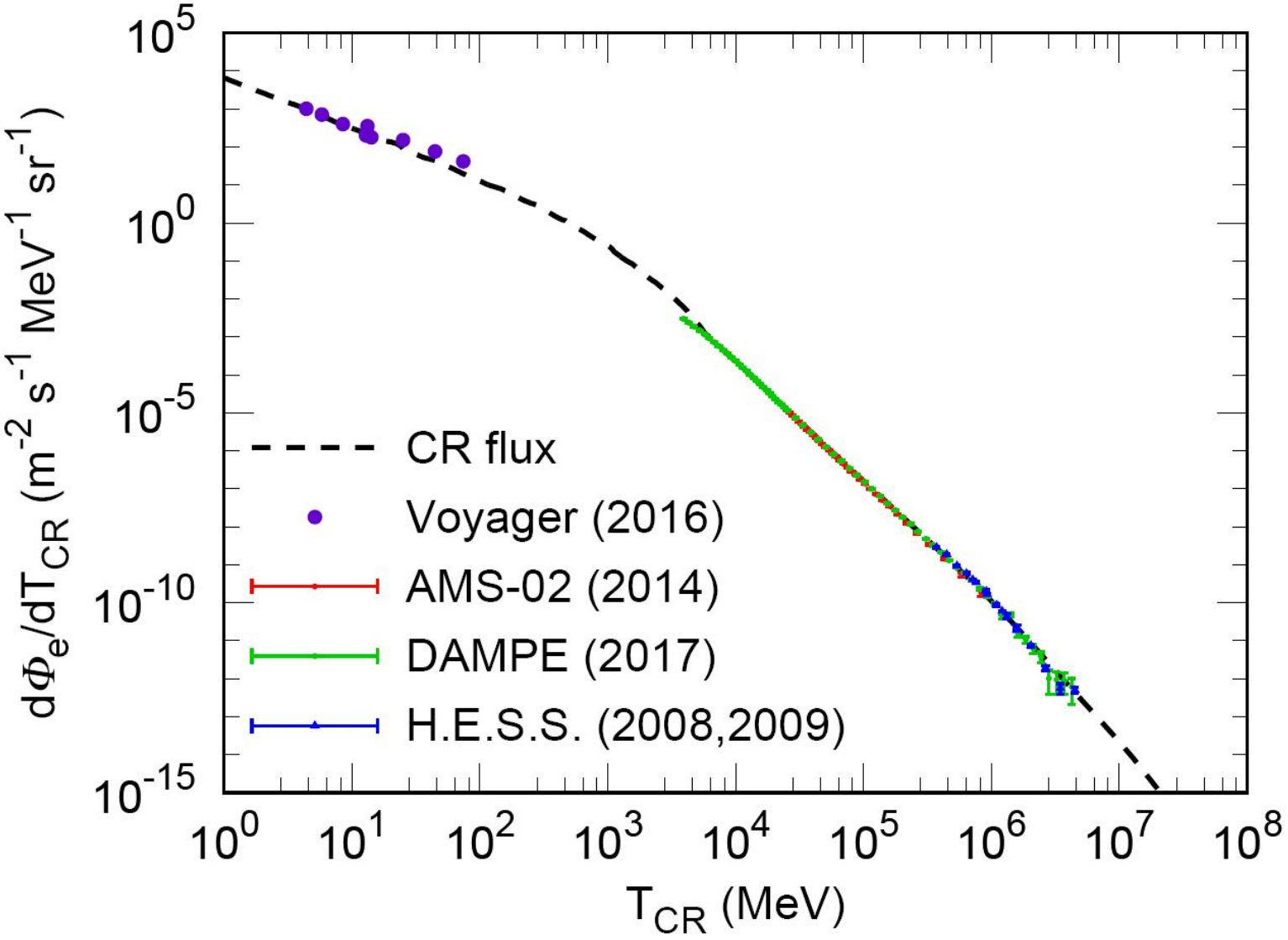
$$\mathcal{L} \supset -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\kappa}{2} F_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{A'} A'_\mu A'^\mu + e J^\mu_{\rm EM} A_\mu + g_\chi \bar{\chi} \gamma^\mu \chi A'_\mu + \bar{\chi}(i\partial - m_\chi)\chi,$$

$$g_\chi g_{\rm SM} = g_\chi \kappa e = \epsilon e^2$$

# Calculation framework



# Flux of CR electrons

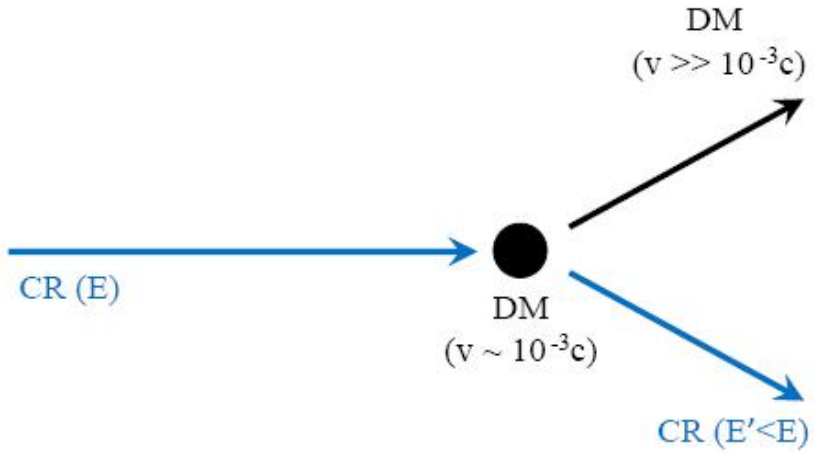


# Flux of boosted DM

- Kinematics of CR-DM scattering

$$T_\chi = T_\chi^{\max}\frac{(1-\cos\theta_{\rm CM})}{2}, \quad T_\chi^{\max} = \frac{2m_\chi T_{\rm CR}(T_{\rm CR}+2m_e)}{(m_e+m_\chi)^2+2T_{\rm CR}m_\chi}$$

$$T_{\rm CR}^{\min} = \left(\frac{T_\chi}{2}-m_e\right)\left(1\pm\sqrt{1+\frac{2T_\chi}{m_\chi}\frac{(m_e+m_\chi)^2}{(2m_e-T_\chi)^2}}\right)$$




- Differential flux at Earth in terms of the CR energy

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff}\frac{\rho_\chi^{\rm local}}{m_\chi}\int_{T_{\rm CR}^{\min}}^{\infty} dT_{\rm CR}\frac{d\Phi_e}{dT_{\rm CR}}\frac{d\sigma_{\chi e}}{dT_\chi}$$

Line-of-sight integration out to 10 kpc $D_{\rm eff} = 8.02\,{\rm kpc}$

# Flux of boosted DM

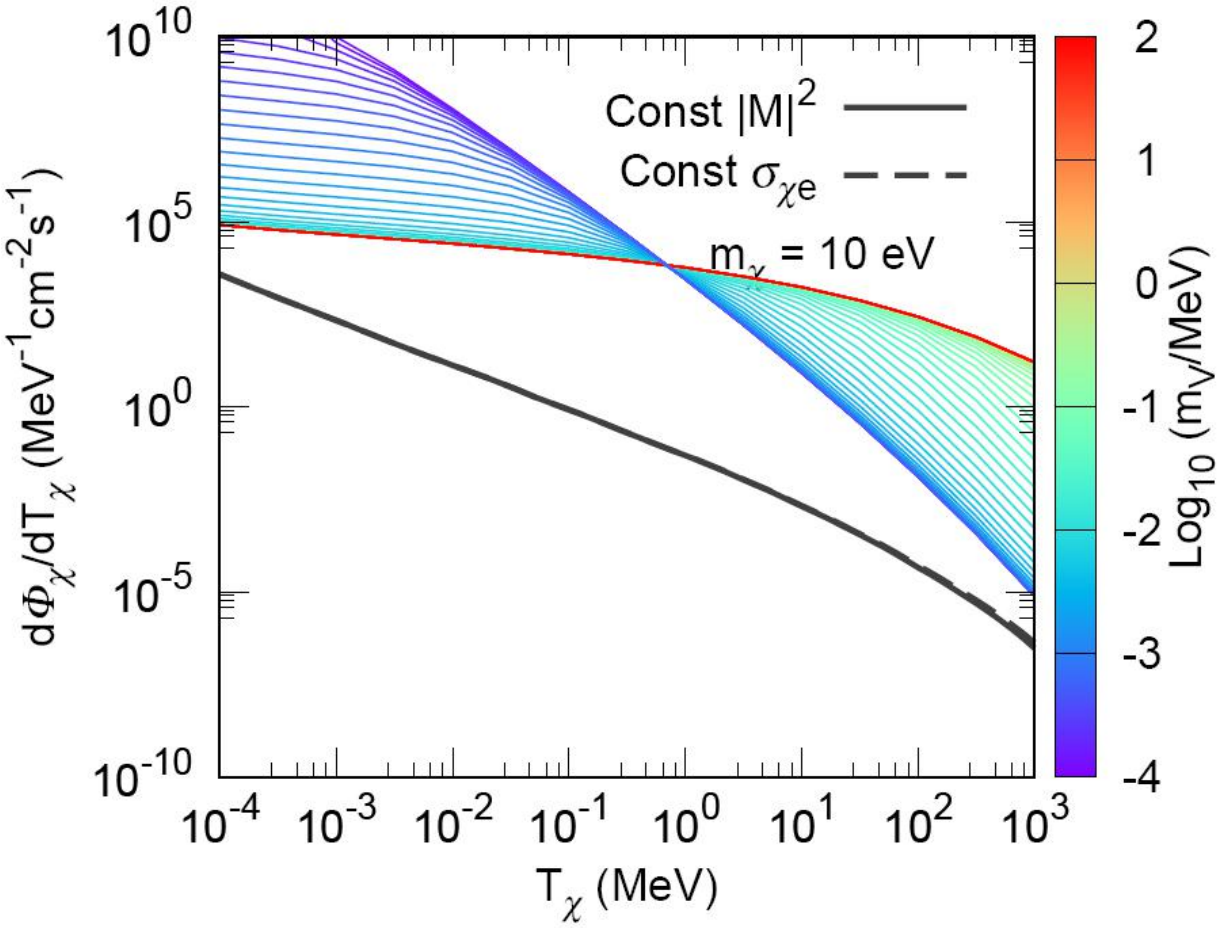
- Energy dependence in differential crosssection
  - benchmark model

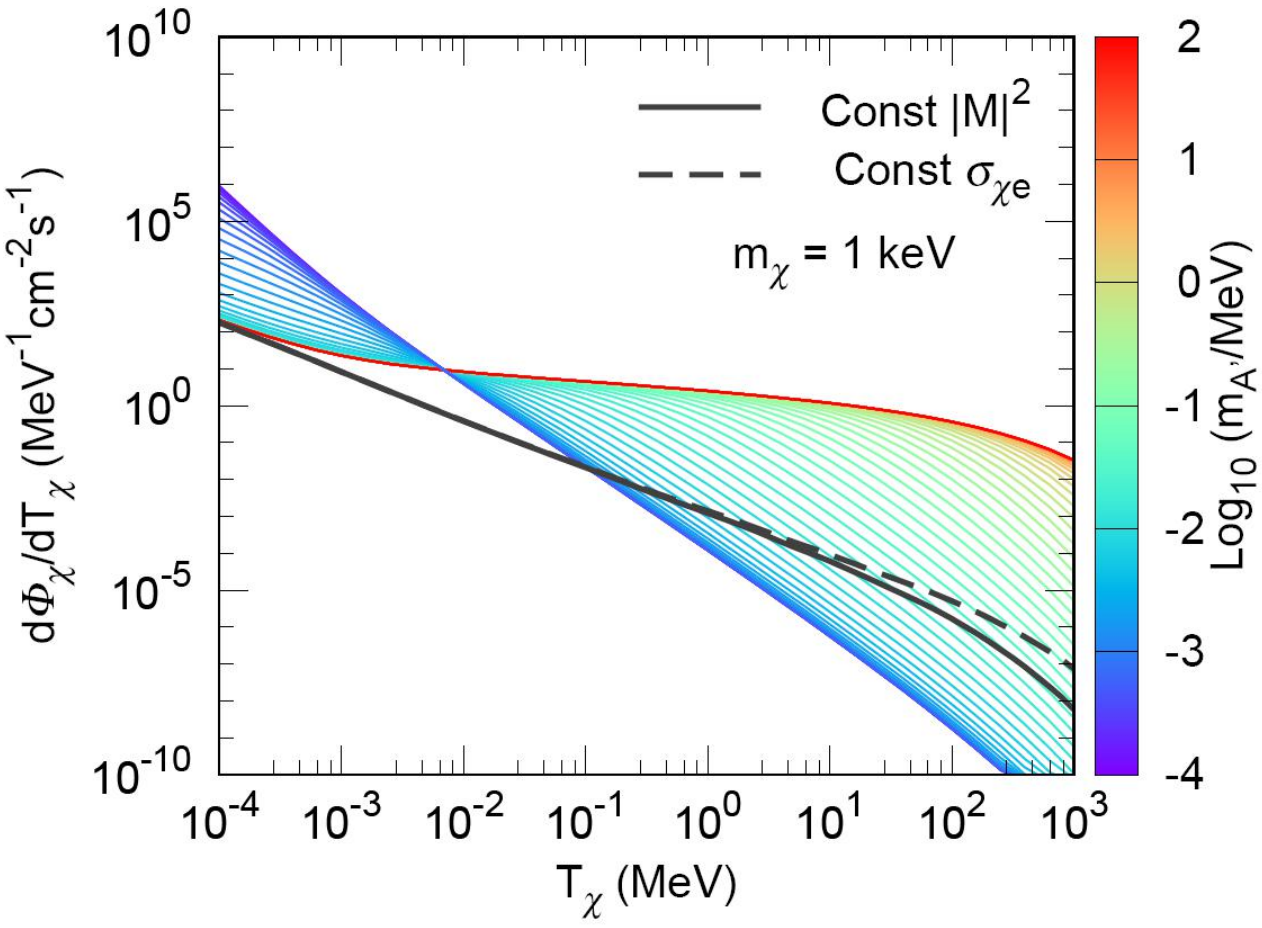
$$\frac{d\sigma_{\chi e}}{dT_\chi} = \bar{\sigma}_e \frac{\left(\alpha^2 m_e^2 + m_{A'}^2\right)^2}{\mu_{\chi e}^2} \frac{2m_\chi \left(m_e + T_{\rm CR}\right)^2 - T_\chi \left(\left(m_e + m_\chi\right)^2 + 2m_\chi T_{\rm CR}\right) + m_\chi T_\chi^2}{4\left(2m_e T_{\rm CR} + T_{\rm CR}^2\right)\left(2m_\chi T_\chi + m_{A'}^2\right)^2}$$

$$\simeq \bar{\sigma}_e \begin{cases} \frac{2m_\chi (m_e+T_{\rm CR})^2 - T_\chi\left((m_e+m_\chi)^2+2m_\chi T_{\rm CR}\right)+m_\chi T_\chi^2}{4\mu_{\chi e}^2\left(2m_e T_{\rm CR}+T_{\rm CR}^2\right)}, & \text{heavy } A' \\ \frac{\alpha^4 m_e^4}{16 m_\chi^2 T_\chi^2} \frac{2m_\chi (m_e+T_{\rm CR})^2 - T_\chi\left((m_e+m_\chi)^2+2m_\chi T_{\rm CR}\right)+m_\chi T_\chi^2}{\mu_{\chi e}^2\left(2m_e T_{\rm CR}+T_{\rm CR}^2\right)}, & \text{ultralight } A' \end{cases}$$

$$\frac{d\sigma_{\chi e}}{dT_\chi} = \bar{\sigma}_e \begin{cases} \frac{1}{T_\chi^{\rm max}}, & \text{const } \sigma_{\chi e} \\ \frac{(m_\chi+m_e)^2}{(m_\chi+m_e)^2+2m_\chi T_{\rm CR}} \frac{1}{T_\chi^{\rm max}}, & \text{const } \overline{|\mathcal{M}|^2} \end{cases}$$

# Flux of boosted DM



# Electron recoil spectrum in xenon

- Differential scattering rate

$$\chi(p) + e(k) \rightarrow \chi(p') + e(k')$$

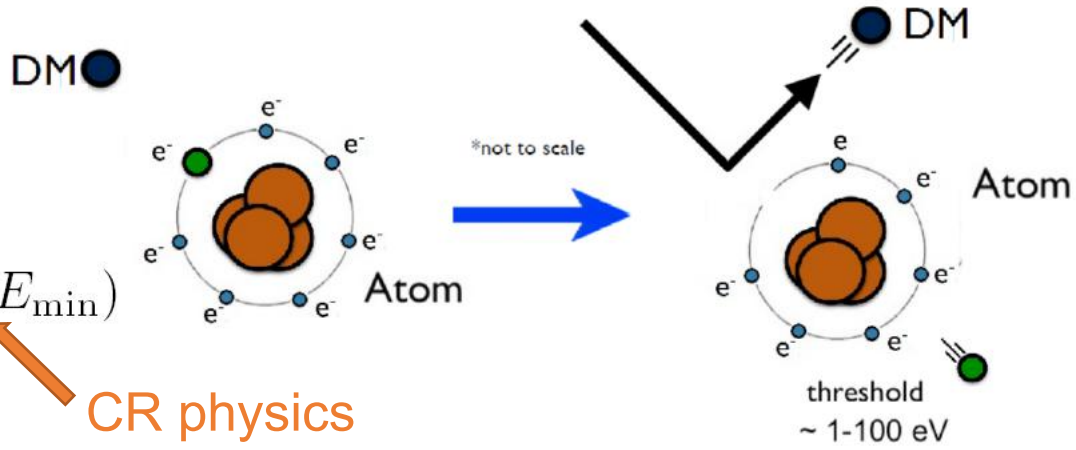
R. Essig, J. Mardon and T. Volansky, arXiv:1108.5383

Particle physics

$$\frac{d\langle\sigma_{ion}^{nl} v\rangle}{d\ln E_R} = \frac{\bar{\sigma}_e}{8\mu_{\chi e}^2} \int qdq \left|F_{DM}(q)\right|^2 \left|f_{ion}^{nl}(k',q)\right|^2 \eta\left(E_{\min}\right)$$

Atomic physics

CR physics




- Inverse mean speed function

$$\eta\left(E_{\min}\right) = \int_{E_{\min}} dE_\chi \Phi_{\text{halo}}^{-1} \frac{m_\chi^2}{pE_\chi} \frac{d\Phi_\chi}{dT_\chi}$$

non-relativstic limit

$$\eta(v_{\min}) = \int_{v_{\min}} \frac{1}{v} f(v) d^3v$$

Flux of boosted DM

Background DM flux

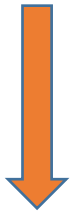
Minimal DM energy required to trigger $E_R$

# Electron recoil spectrum in xenon

- DM form factor

$$|F_{DM}(q)|^2 = \frac{\left(\alpha^2 m_e^2 + m_{A'}^2\right)^2}{2 m_e m_\chi^2} \frac{2 m_e \left(m_\chi + T_\chi\right)^2 - E_R \left(\left(m_\chi + m_e\right)^2 + 2 m_e T_\chi\right) + m_e E_R^2}{\left(2 m_e E_R + m_{A'}^2\right)^2}$$

$$\simeq \begin{cases} \frac{2 m_e (m_\chi + T_\chi)^2 - E_R\left((m_\chi + m_e)^2 + 2 m_e T_\chi\right) + m_e E_R^2}{2 m_e m_\chi^2}, & \text{heavy } A' \\ \frac{\alpha^4 m_e^4}{8 m_e^2 E_R^2} \frac{2 m_e (m_\chi + T_\chi)^2 - E_R\left((m_\chi + m_e)^2 + 2 m_e T_\chi\right) + m_e E_R^2}{m_e m_\chi^2}, & \text{ultralight } A' \end{cases}$$



non-relativstic limit

$$|F_{DM}(q)|^2 = \left(\left(\alpha^2 m_e^2 + m_{A'}^2\right)/\left(q^2 + m_{A'}^2\right)\right)^2$$

# Electron recoil spectrum in xenon

- Ionization from factor
  - Final state electron is free, taking as plane wave

J. Kopp, V. Niro, T. Schwetz and J. Zupan, arXiv:0907.3159

$$\left|f_{ion}^{nl}(k',q)\right|^2 = \frac{2k'^3}{(2\pi)^3}\sum_{\text{deg}}|f_{nl}(q)|^2 = \frac{(2l+1)k'^2}{4\pi^3 q}\int_{|k'-q|}^{|k'+q|} kdk \sum_{m=-l}^{l}|\chi_{nl}(k)|^2$$

  - Initial state electron is bounded: Roothaan Hartree Fock (RHF) method

$$\chi_{nl}(p) = 4\pi i^l \int dr r^2 R_{nl}(r) j_l(pr)$$

    - Radial wave functions: linear combination of Slater type orbitals

C. F. Bunge, J. A. Barrientos and A. V. Bunge (1993)

$$R_{nl}(r) = \sum_k C_{nlk}\frac{(2Z_{lk})^{n_{lk}+1/2}}{a_0^{3/2}\sqrt{(2n_{lk})!}}(r/a_0)^{n_{lk}-1}\exp\left(-\frac{Z_{lk}r}{a_0}\right)$$

    - Analytical expression

J. Kopp, V. Niro, T. Schwetz and J. Zupan, arXiv:0907.3159

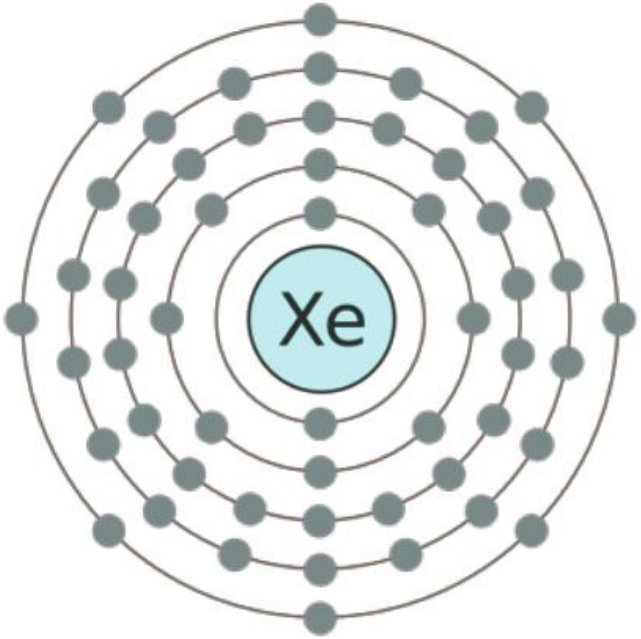
$$\chi_{nl}(p) = \sum_k C_{nlk}2^{n_{lk}-1}\left(\frac{2\pi a_0}{Z_{lk}}\right)^{3/2}\left(\frac{ipa_0}{Z_{lk}}\right)^l \frac{\Gamma(n_{lk}+l+2)}{\Gamma(l+\frac{3}{2})\sqrt{(2n_{lk})!}}$$

$$\times {}_2F_1\left[\frac{1}{2}(n_{lk}+l+2), \frac{1}{2}(n_{lk}+l+3), l+\frac{3}{2}, -\left(\frac{pa_0}{Z_{lk}}\right)^2\right]$$

# Electron recoil spectrum in xenon

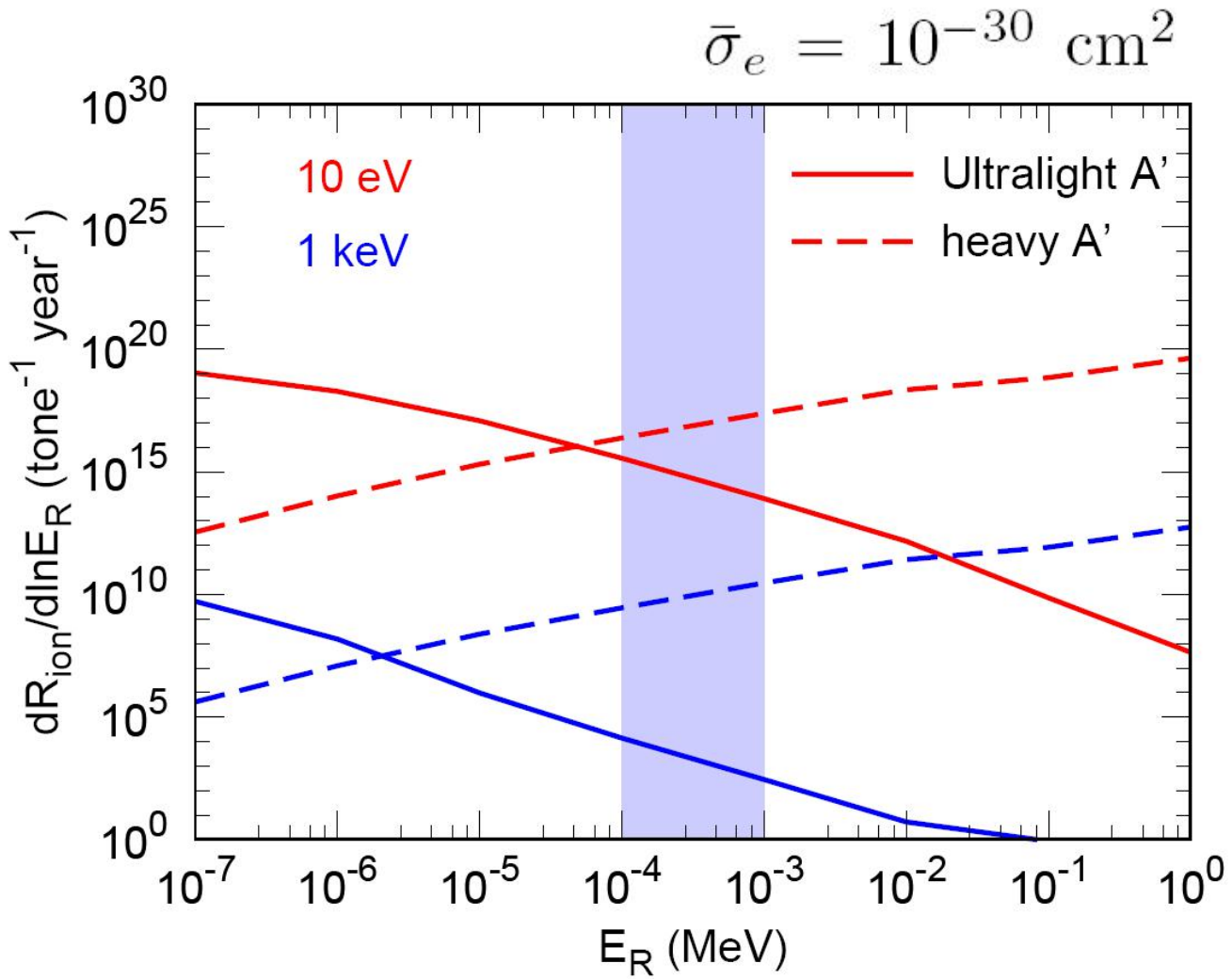
- Total differential ionization rate

$$\frac{dR_{ion}}{d\ln E_R} = N_T \Phi_{\rm halo} \sum_{nl} \frac{d\langle \sigma^{nl}_{ion} v\rangle}{d\ln E_R}$$

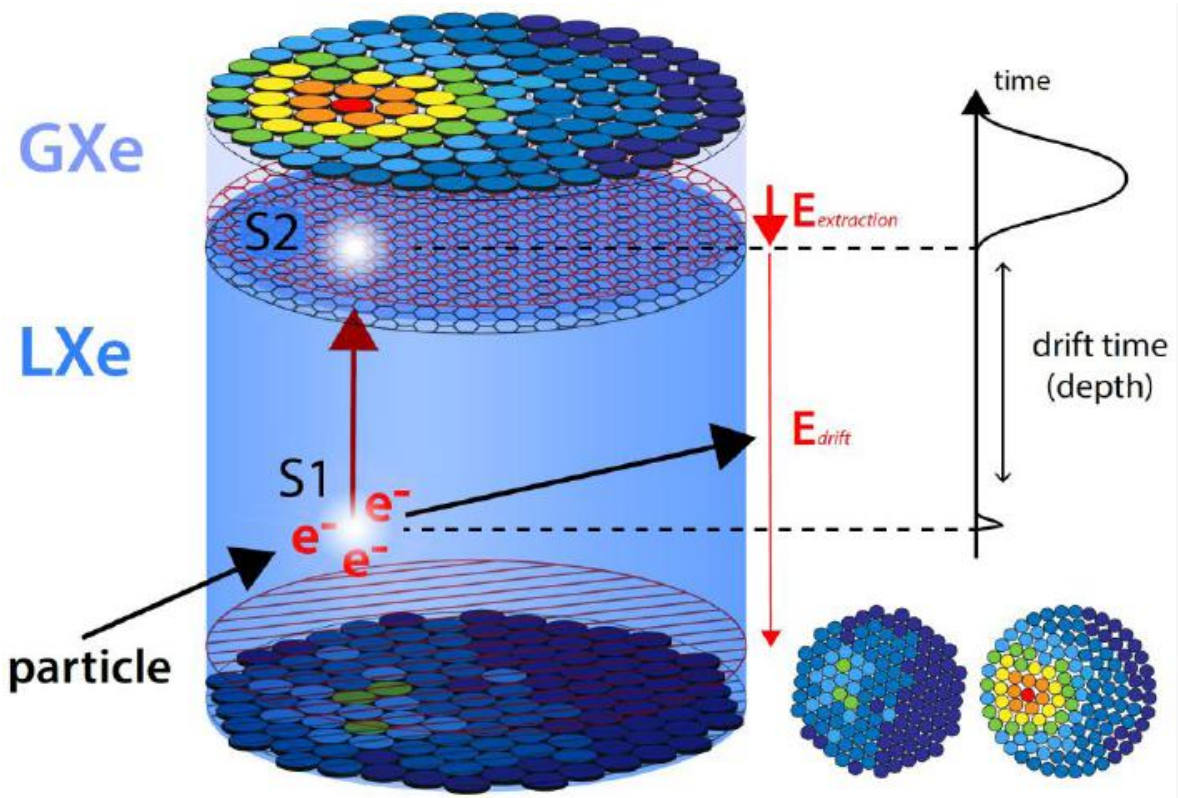



- Contributed shells

$$(5p^6, 5s^2, 4d^{10}, 4p^6, 4s^2)$$



# Spectrum of photoelectrons (PE) in xenon




- S1 (scintillation) signal: prompt scintillation photons
- S2 (ionization) signal: secondary scintillation photons from electroluminescence in Gxe due to drifted electrons

# Photoelectrons (PE) spectrumin in xenon

- Event rate for S2 signal responses

Trigger and acceptance efficiency

$$\frac{dN}{dS2} = T_{\rm exp} \cdot \varepsilon_{S2} \sum_{nl} \int dE_R \, {\rm pdf}\,(S2|\Delta E_e)\, \frac{dR^{nl}_{ion}}{dlnE_R}$$

Exposure

Conversion probability

- Conversion probability of S2

$${\rm pdf}\,(S2|\Delta E_e)$$

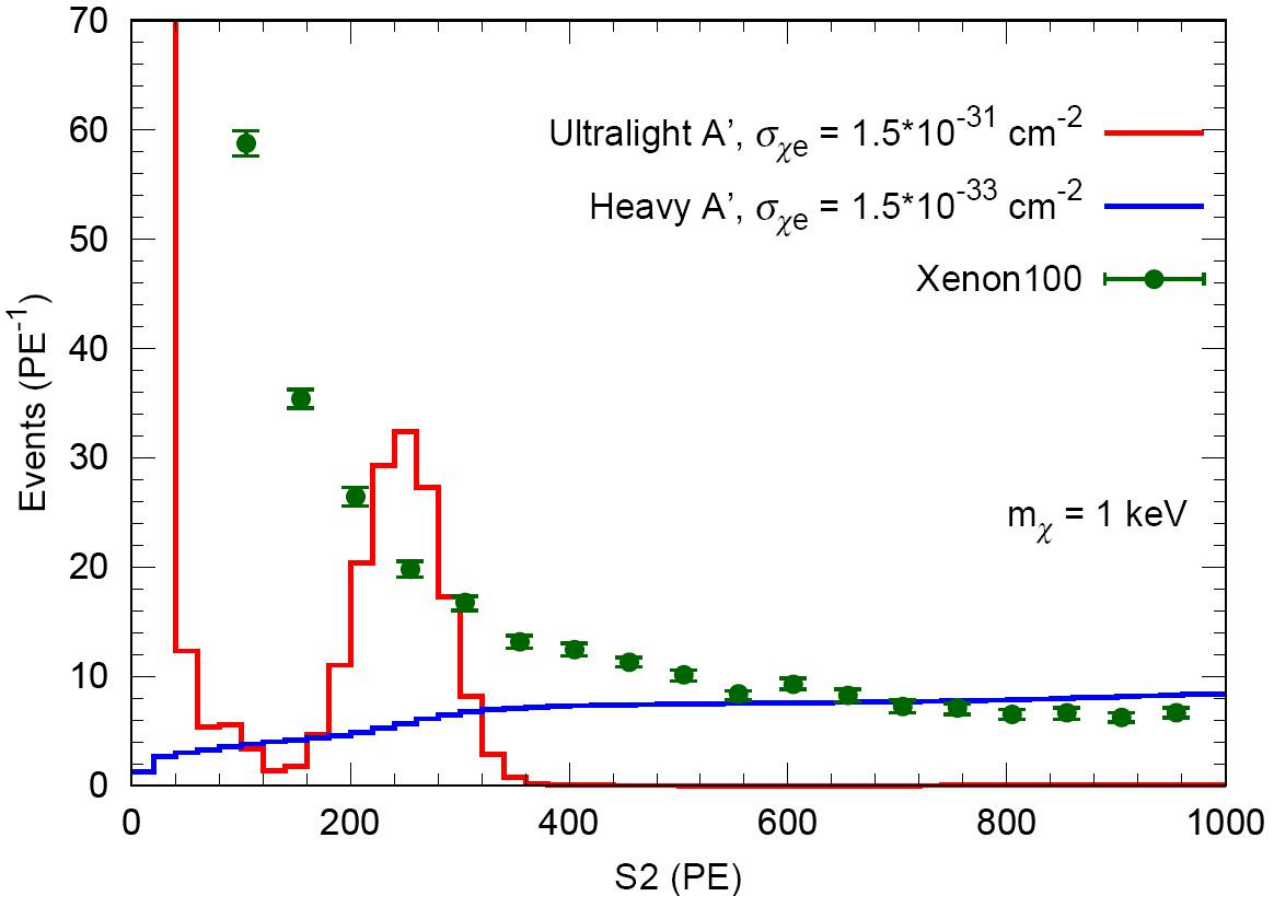
deposit energy $\Delta E_e = E_R + |E_B^{nl}|$

R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, arXiv:1206.2644

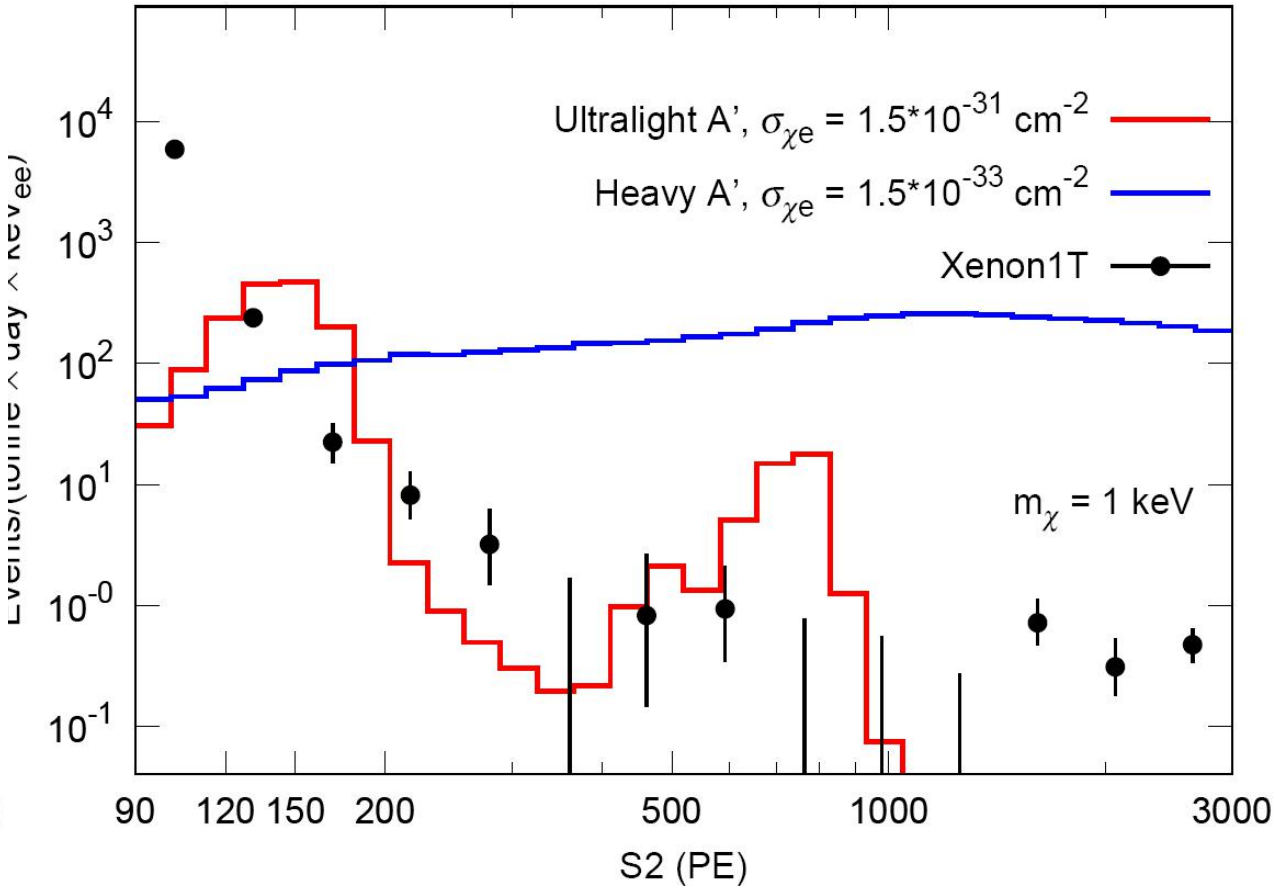
R. Essig, T. Volansky, and T.-T. Yu, arXiv:1703.00910

# Photoelectrons (PE) spectrumin in xenon

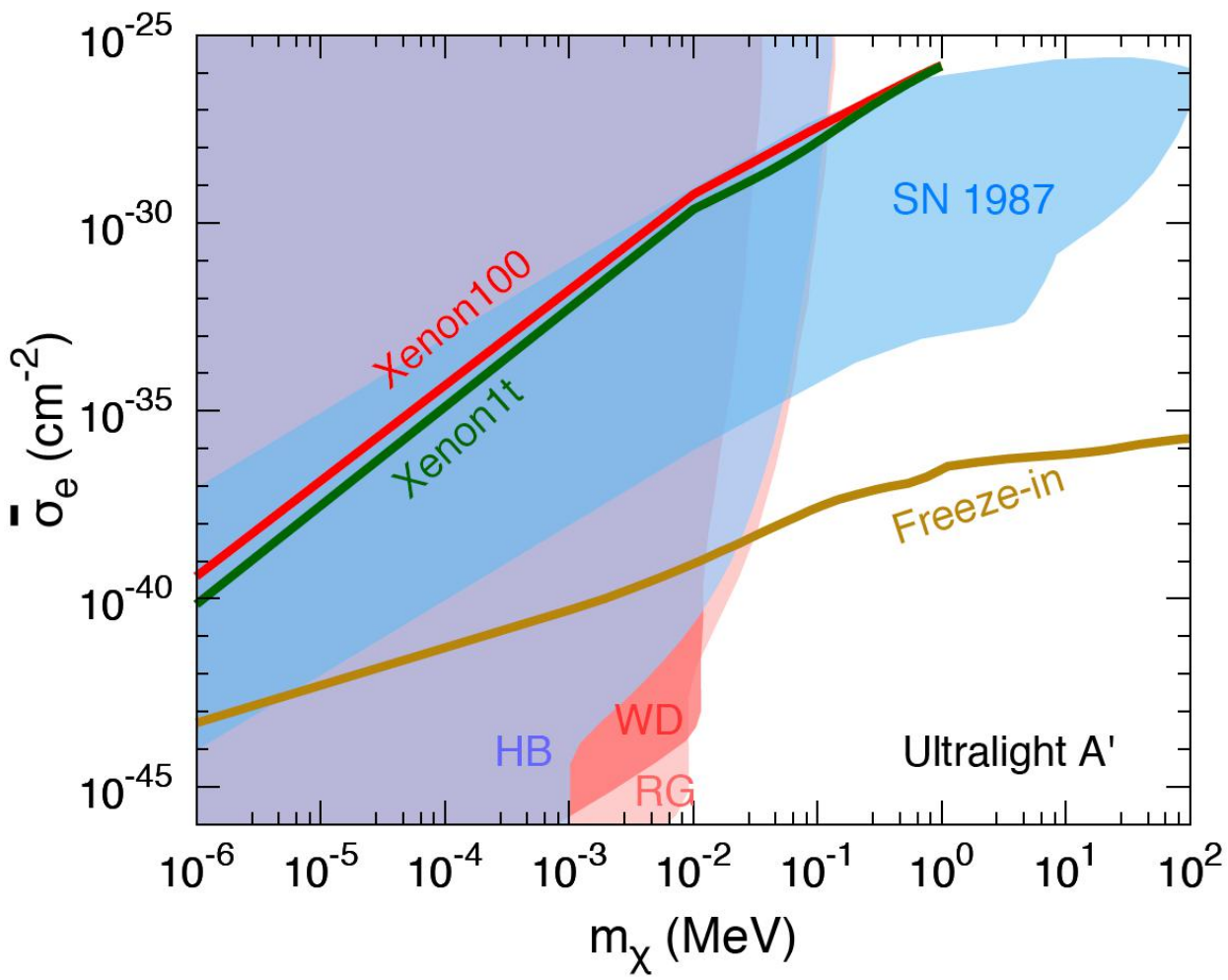
## Xenon100 ($T_{exp}$ = 30 kg-year)

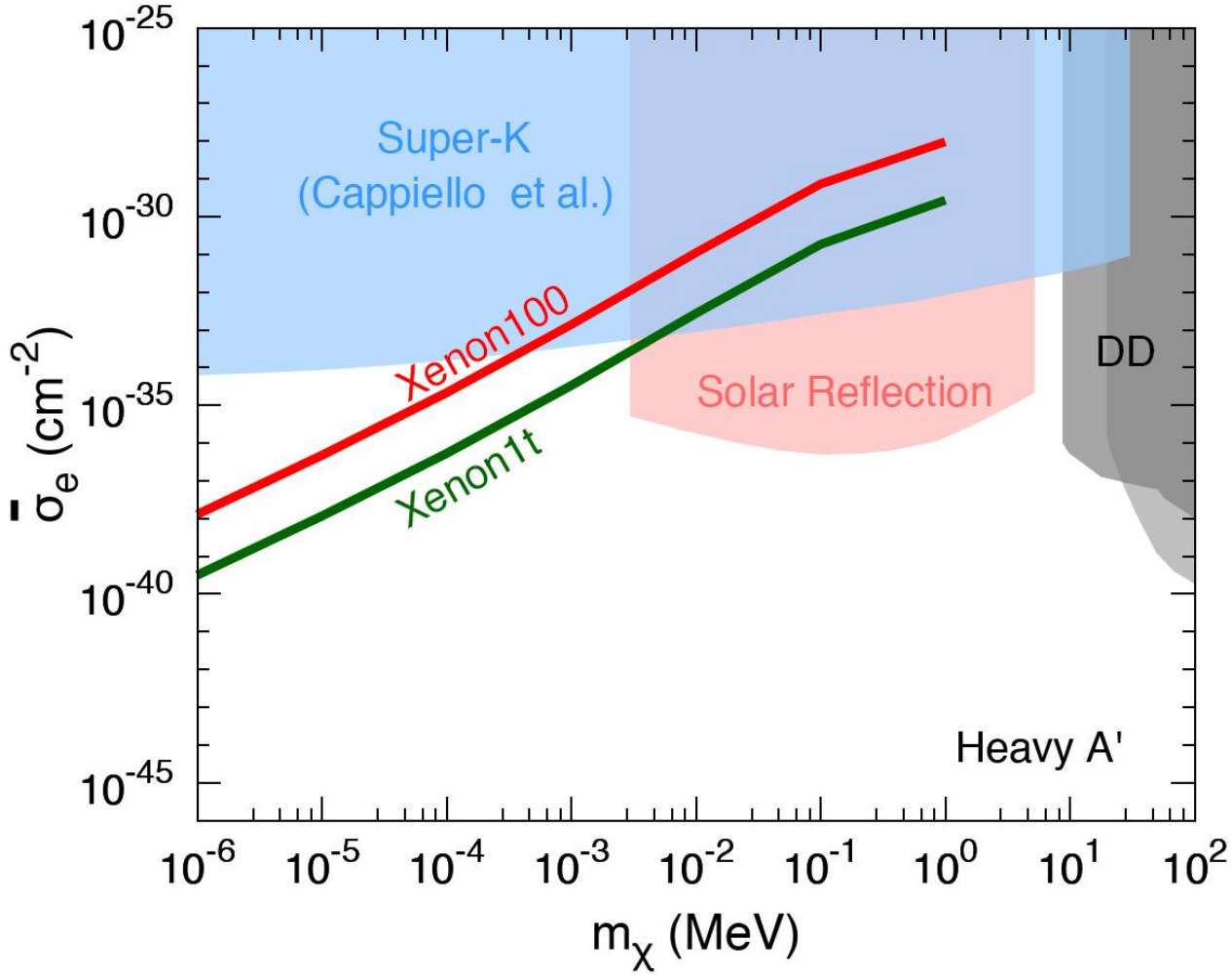



## Xenon1T ($T_{exp}$ = 22 tonne-days)



# Limit on the DM-electron scattering cross section



# Discussion

- Improving the sensitivity
- Complementarity between neutrino experiments and DM-electron direct detection
- Flux of boosted DM coming from Galactic center, high DM density and CR flux, morphology of signal is different from that originated from local interstellar
- Discrimination of signal degeneracy

# 谢谢大家